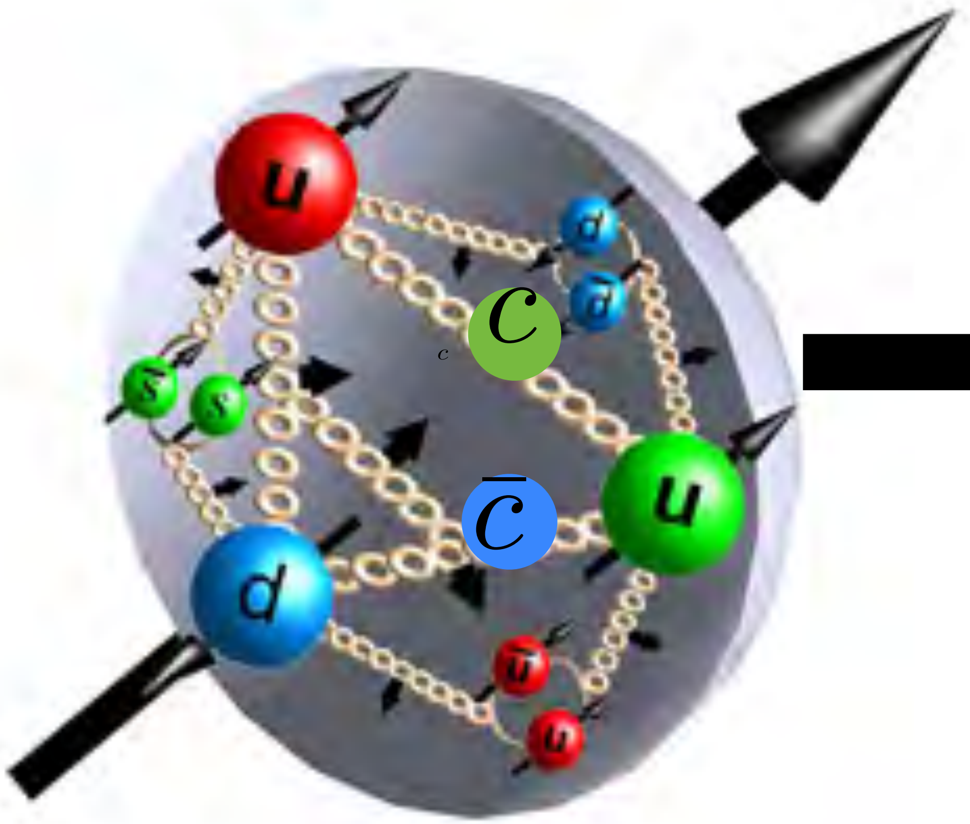
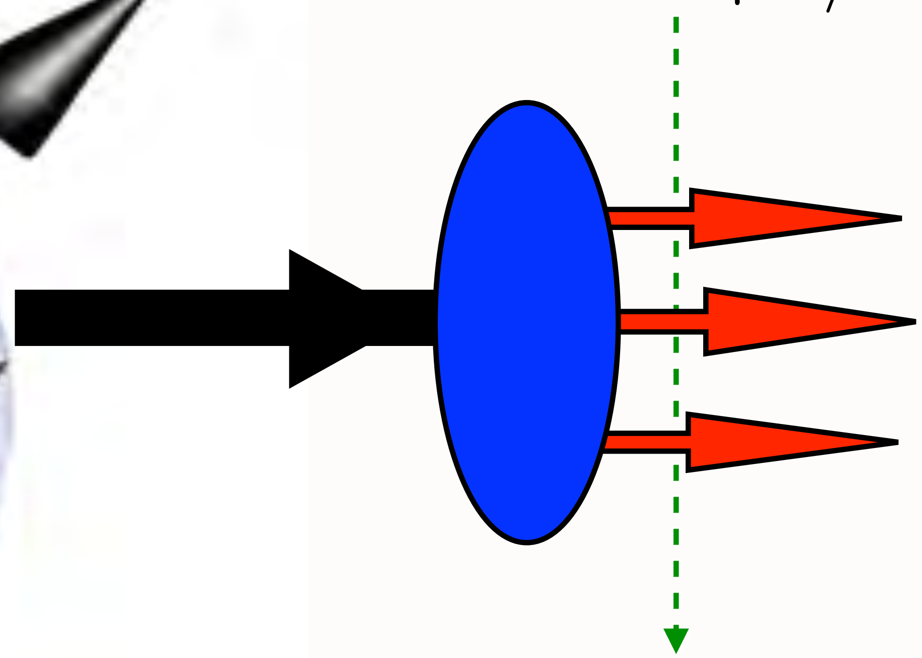
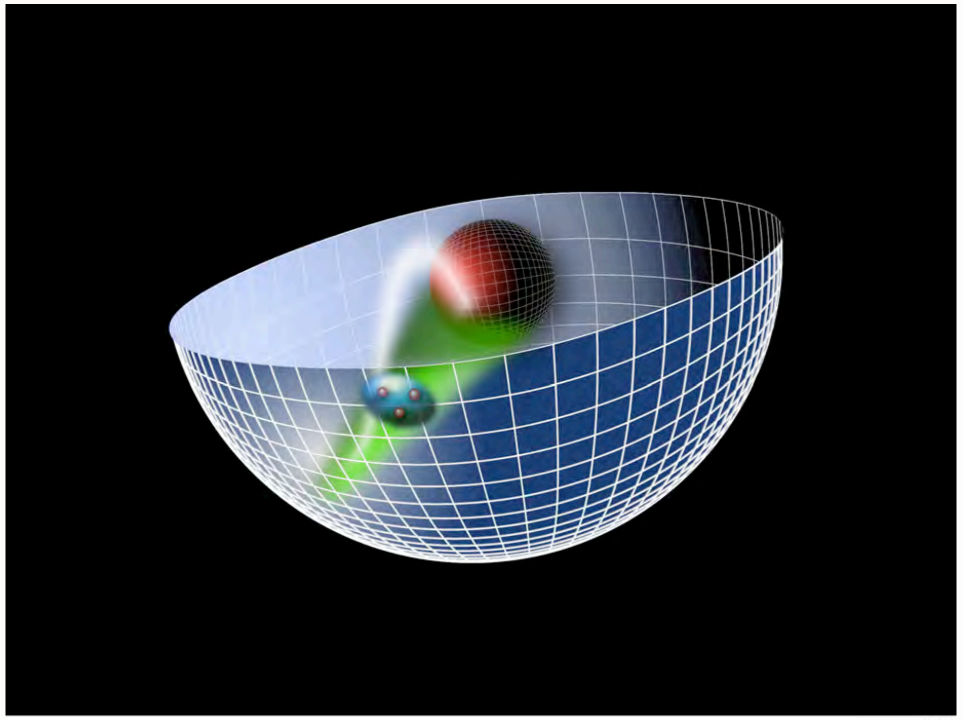
Novel QCD Phenomena







Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

LELAND STANFORD JUNIOR UNIVERSITY

ÖAW Österreichische Akademie der Wissenschaften

HEPHY Institut für Hochenergiephysik

October 30, 2012

HEPHY-SMI seminar on fundamental interactions and symmetries

Veranstalter: Verein zur Förderung der Theoretischen Physik in Österreich

Gefördert durch die Wissenschafts- und Forschungsförderung der Kulturabteilung der Stadt Wien

- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, rescattering, shadowing, non-universal antishadowing ...

Truth is stranger than fiction, but it is because Fiction is obliged to stick to possibilities.

—Mark Twain

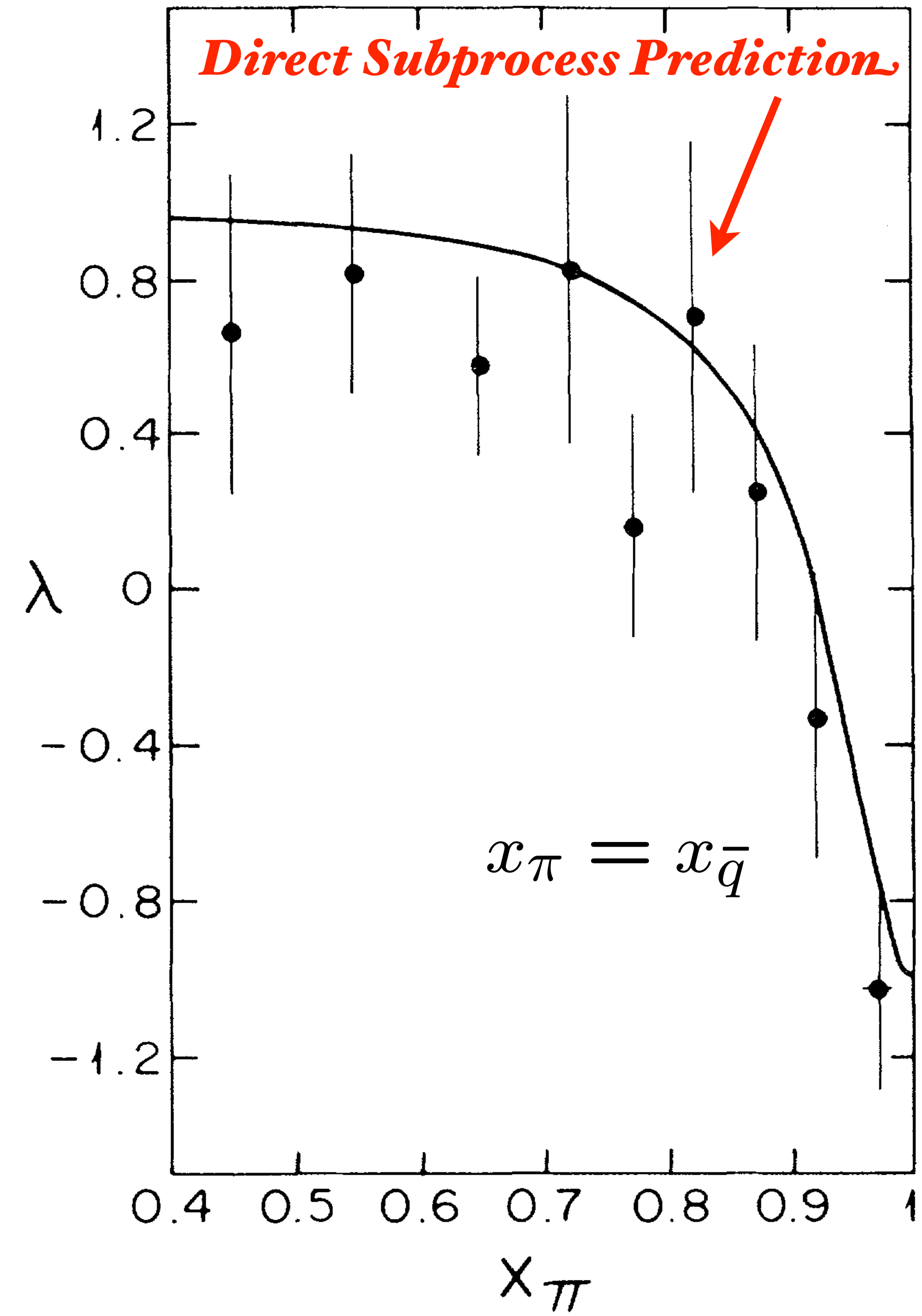
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi.$$

$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

$$\langle k_T^2 \rangle = 0.62 \pm 0.16 \ \ \mathrm{GeV}^2/c^2$$

$$Q^2 = M^2$$

Dramatic change in angular distribution at large x_F



Example of a "higher-twist direct" subprocess

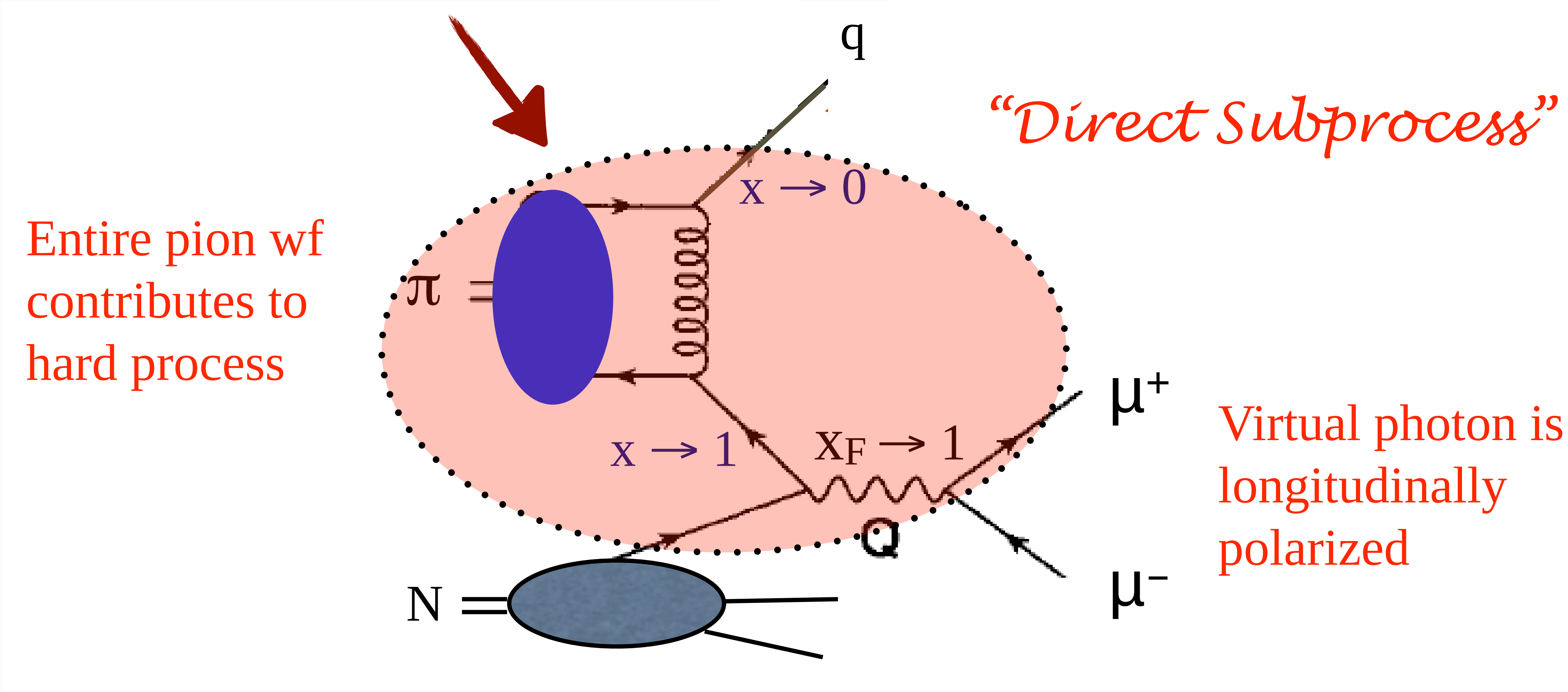
Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

$\pi N \rightarrow \mu^+ \mu^- X$ at high x_F

In the limit where $(1-x_F)Q^2$ is fixed as $Q^2 \rightarrow \infty$

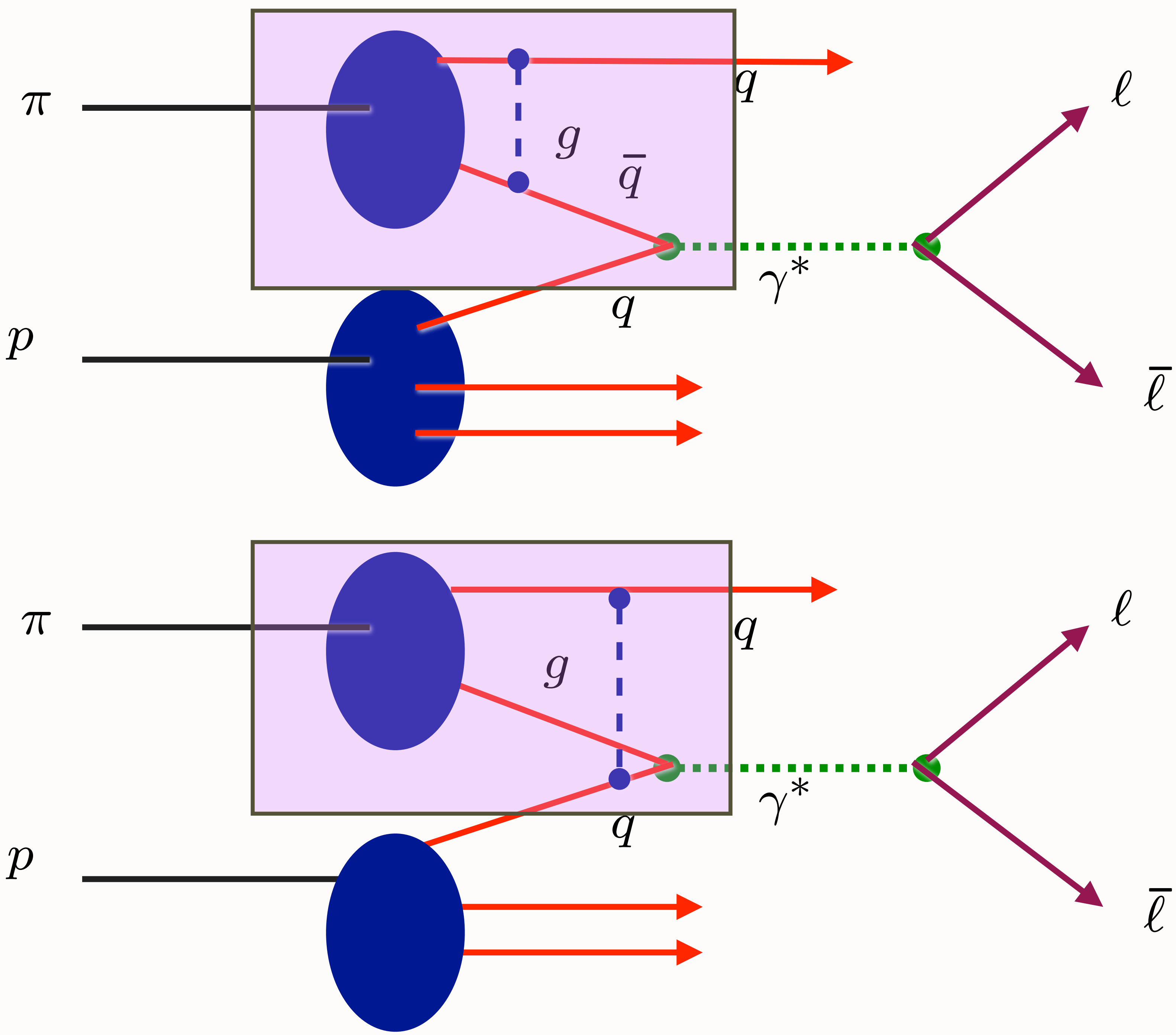
Light-Front Wavefunctions from AdS/CFT



Berger, sjb
Khoze, Brandenburg, Muller, sjb

Hoyer Vanttinen

Berger, Lepage, sjb



$$\pi q \to \gamma^* q$$

Initial State Interaction

Pion appears directly in subprocess at large x_F

All of the pion's momentum is transferred to the lepton pair

Lepton Pair is produced longitudinally polarized

Bjorken, Kogut, Soper; Blankenbecler, Gunion, sjb;
Blankenbecler, Schmidt

Crucial Test of Leading -Twist QCD:
Scaling at fixed x_T

$$E \frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm})}{p_T^{n_{\rm eff}}} \qquad x_T = \frac{2p_T}{\sqrt{s}}$$

Parton model: $n_{eff} = 4$

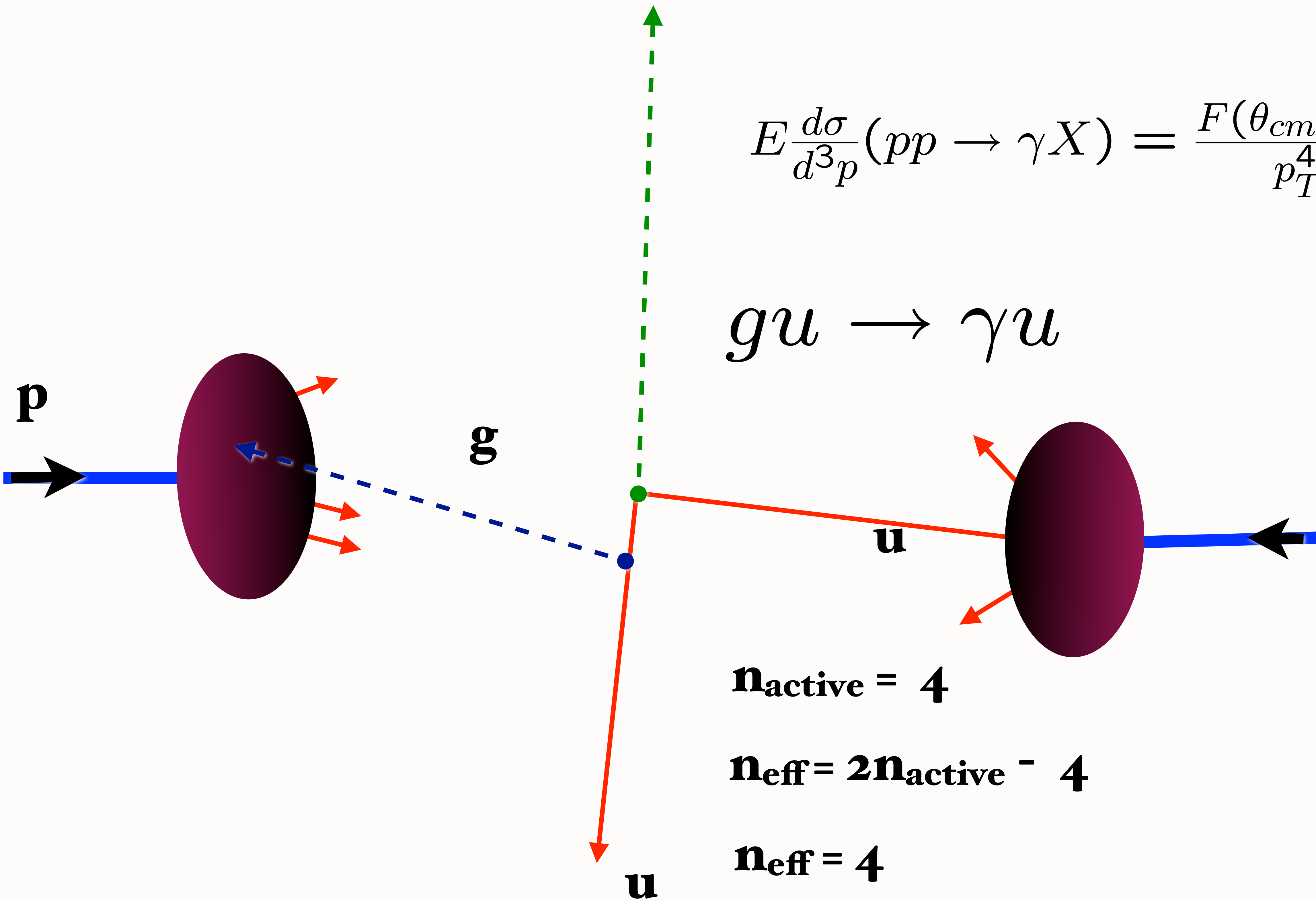
As fundamental as Bjorken scaling in DIS

scaling law: $n_{eff} = 2\, n_{active} - 4$

$$pp \to \gamma X$$

$$E\frac{d\sigma}{d^3p}(pp \to \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$$

$$gu \to \gamma u$$

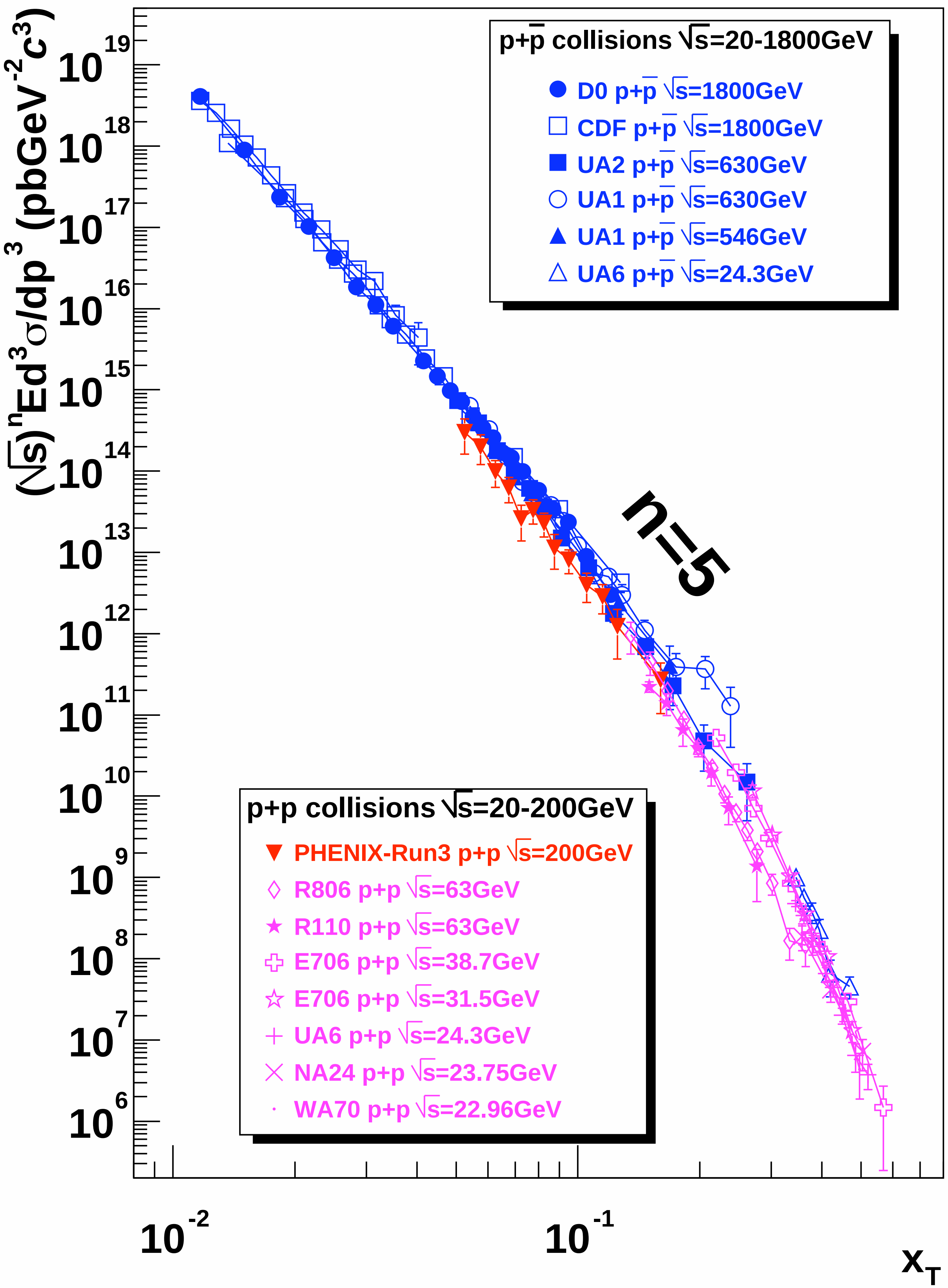


$\mathbf{n_{active} = 4}$

$\mathbf{n_{eff} = 2n_{active} - 4}$

$\mathbf{n_{eff} = 4}$

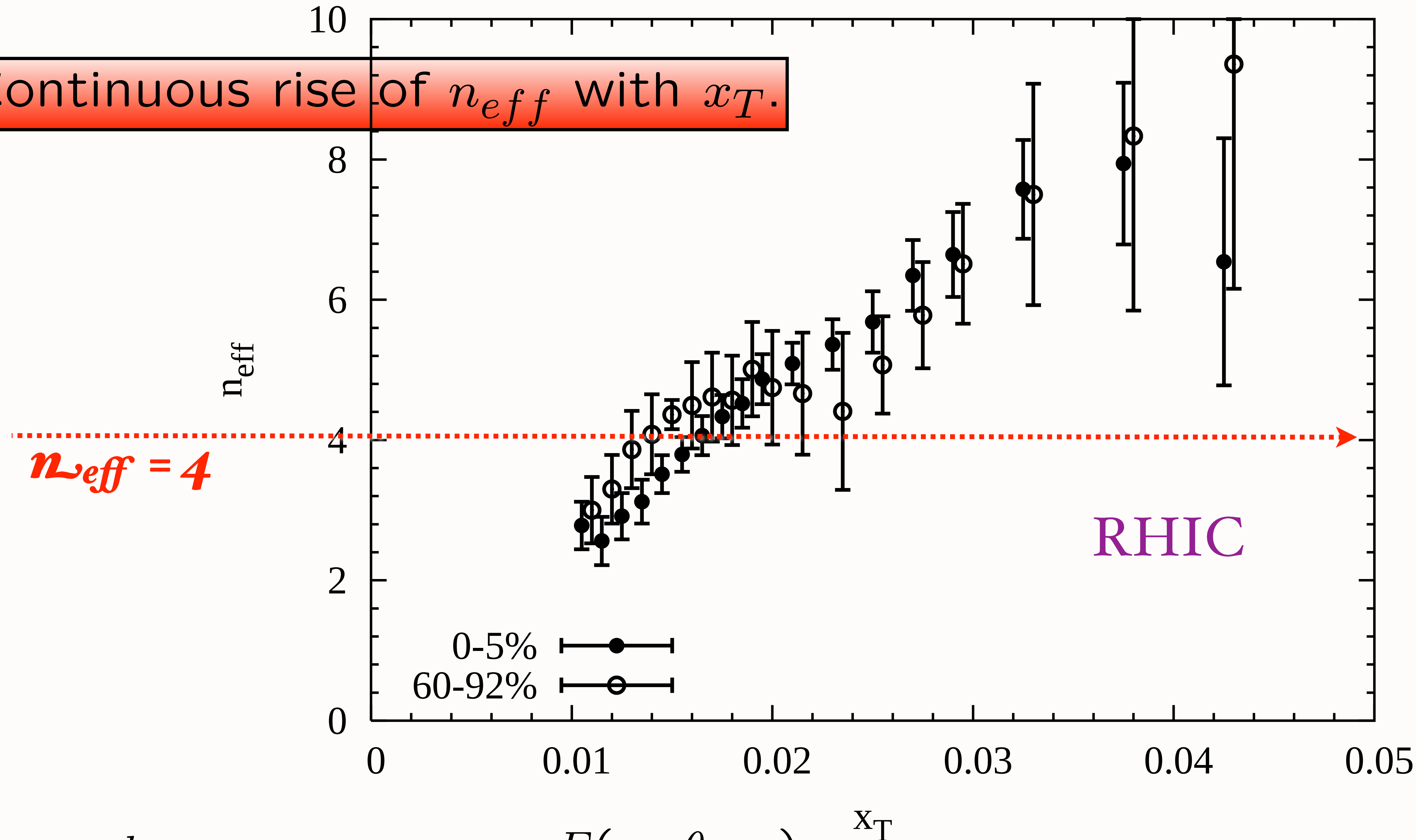
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T



x_T-scaling of direct photon production: consistent with PQCD

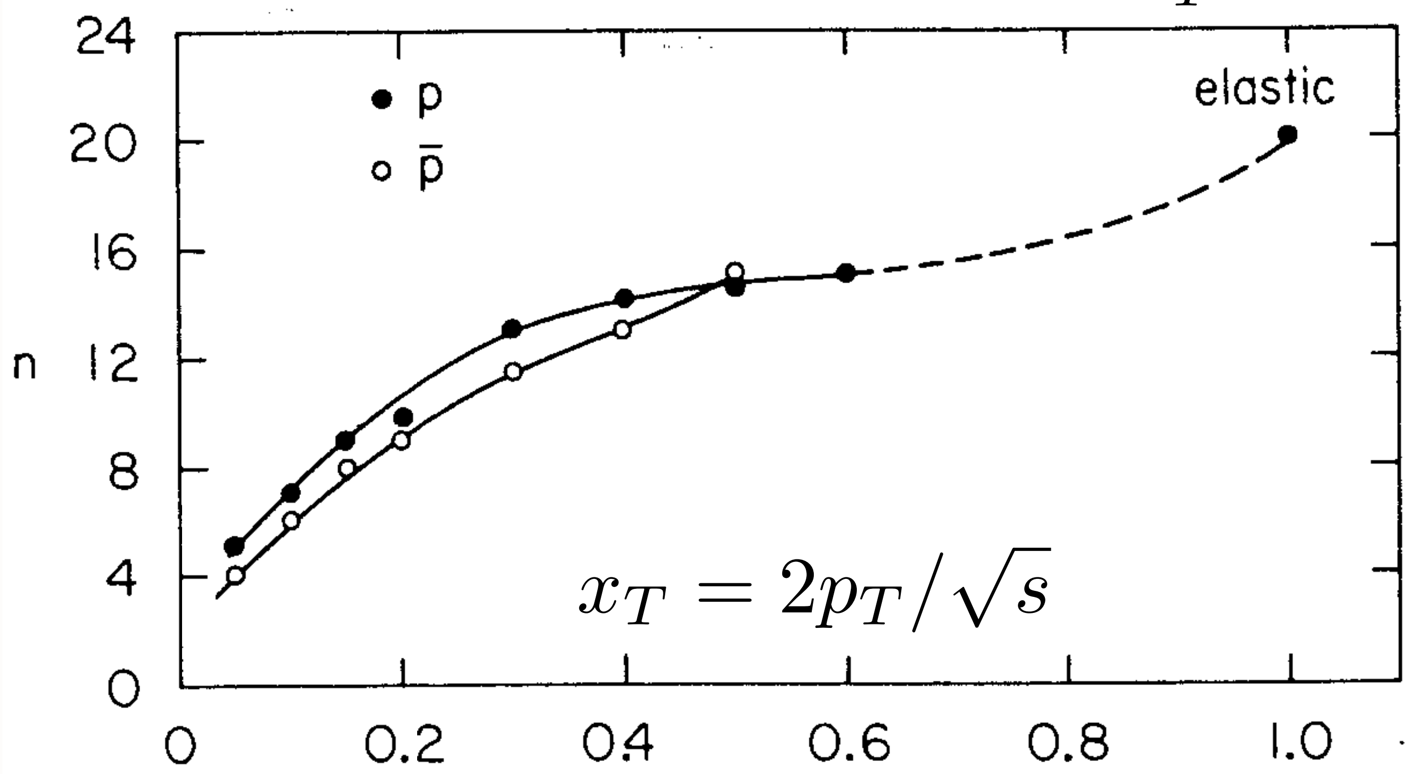
Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available p_T range. Shown are data for central $(0-5\%)$ and for peripheral $(60-90\%)$ collisions.

Continuous rise of n_{eff} with x_T.



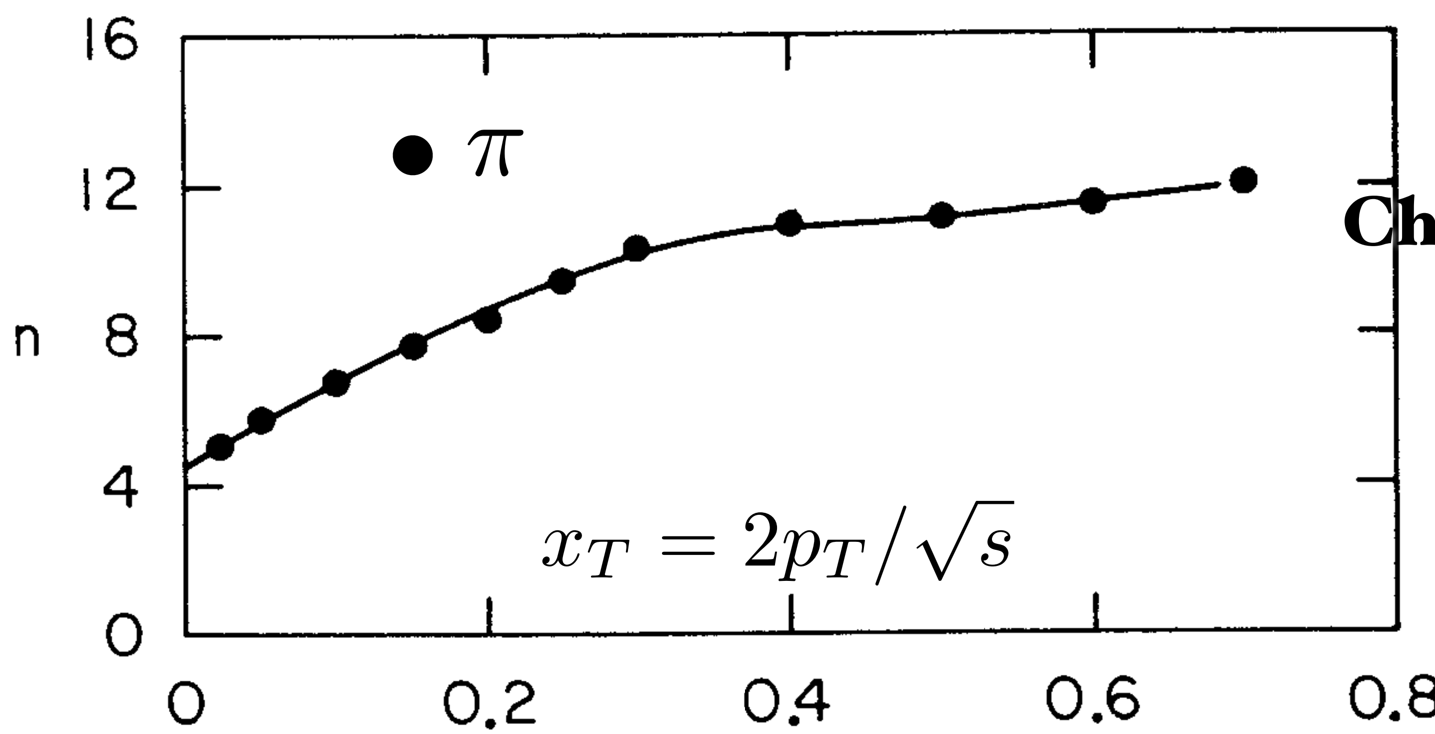
$$E\frac{d\sigma}{d^3p}(pN \to pX) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}}$$

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm} = \pi/2)}{p_T^n}$$



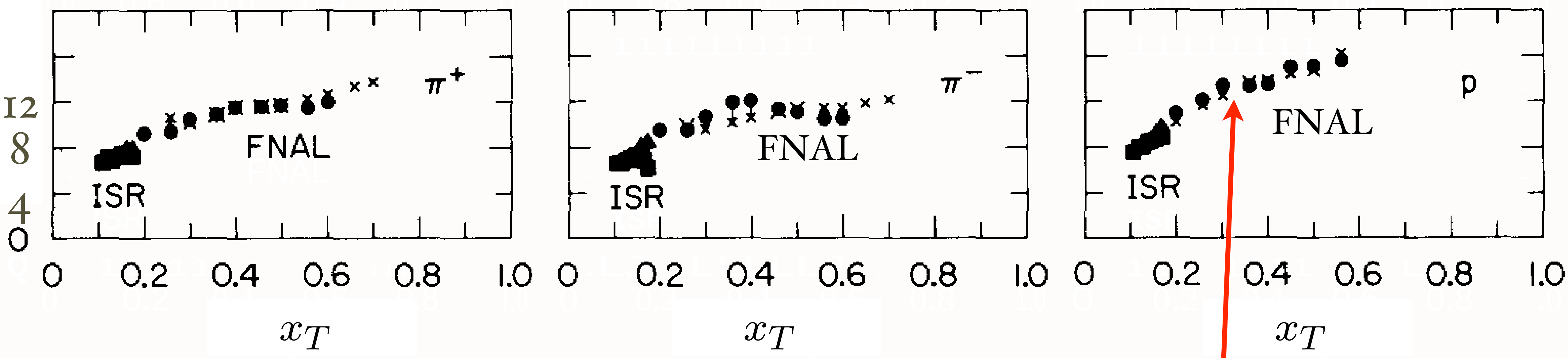
Clear evidence for higher-twist contributions

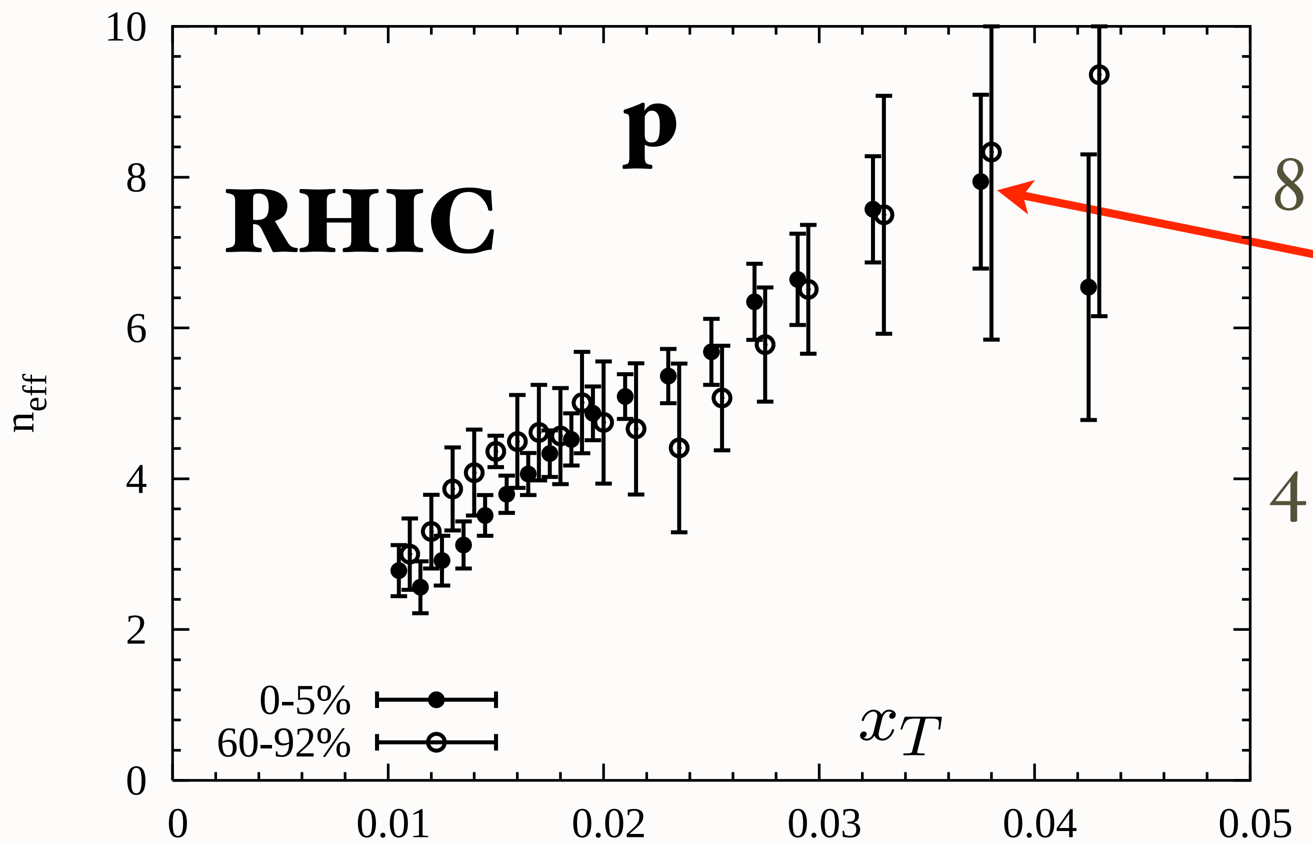
J. W. Cronin, SSI 1974



Chicago-Princeton FNA

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$



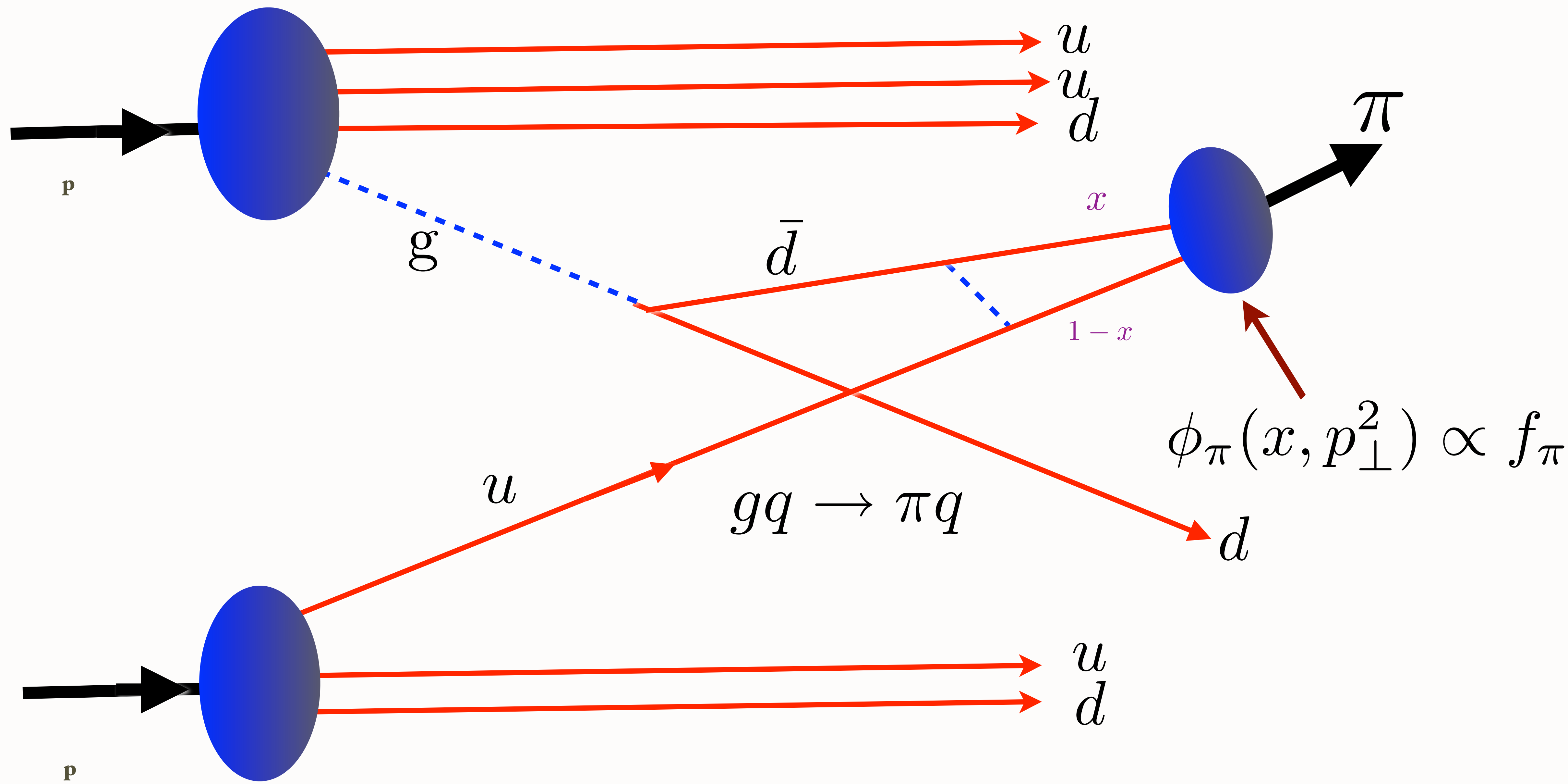


$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{8}}$$

Trend consistent with RHIC at small x_T

Direct Higher-Twist Contribution to Hadron Production

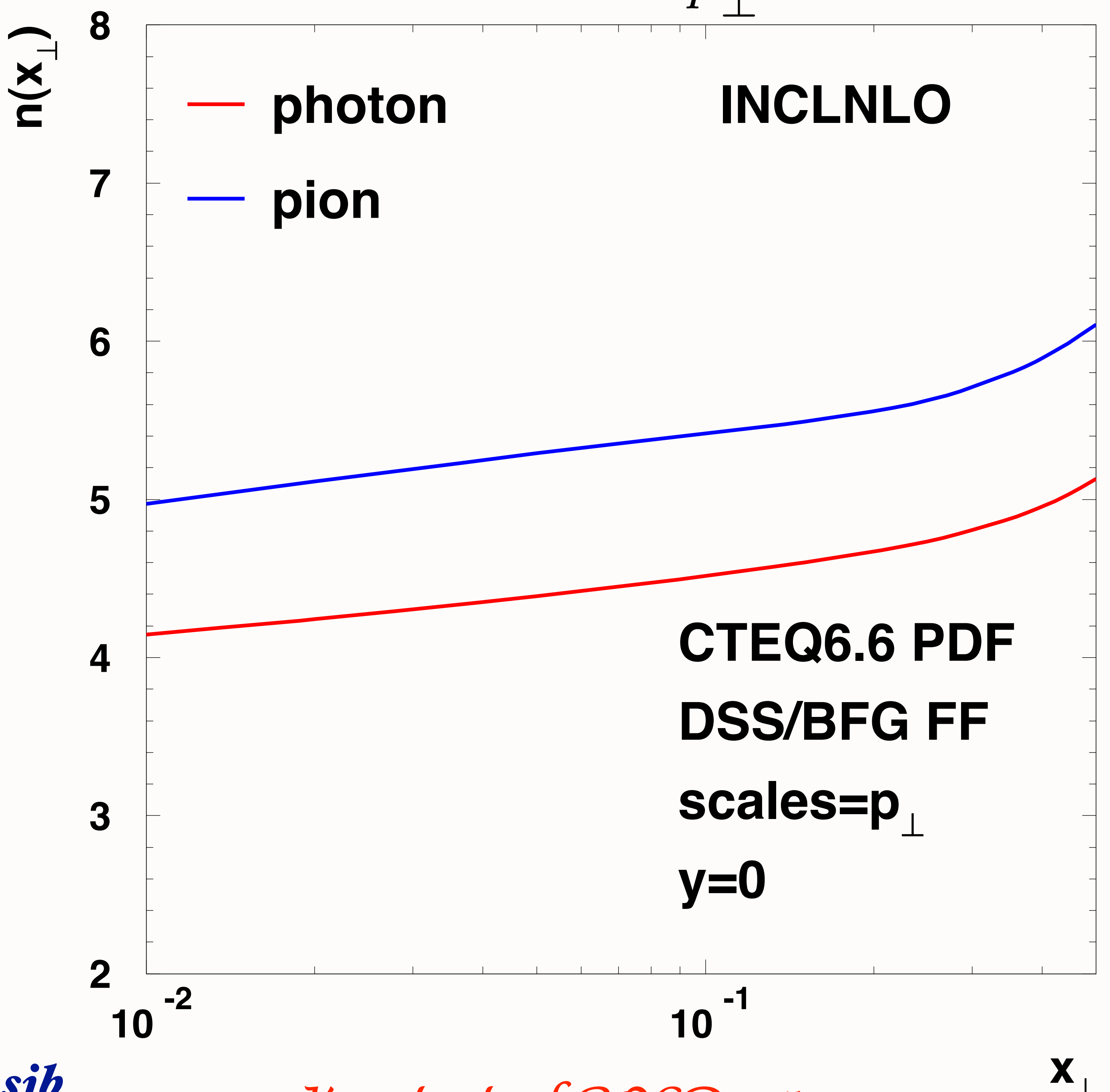


$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

No Fragmentation Function

QCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling

$$\frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_\perp^{n(x_\perp)}}$$



$pp \to \pi X$

$pp \to \gamma X$

$5 < p_\perp < 20\ GeV$

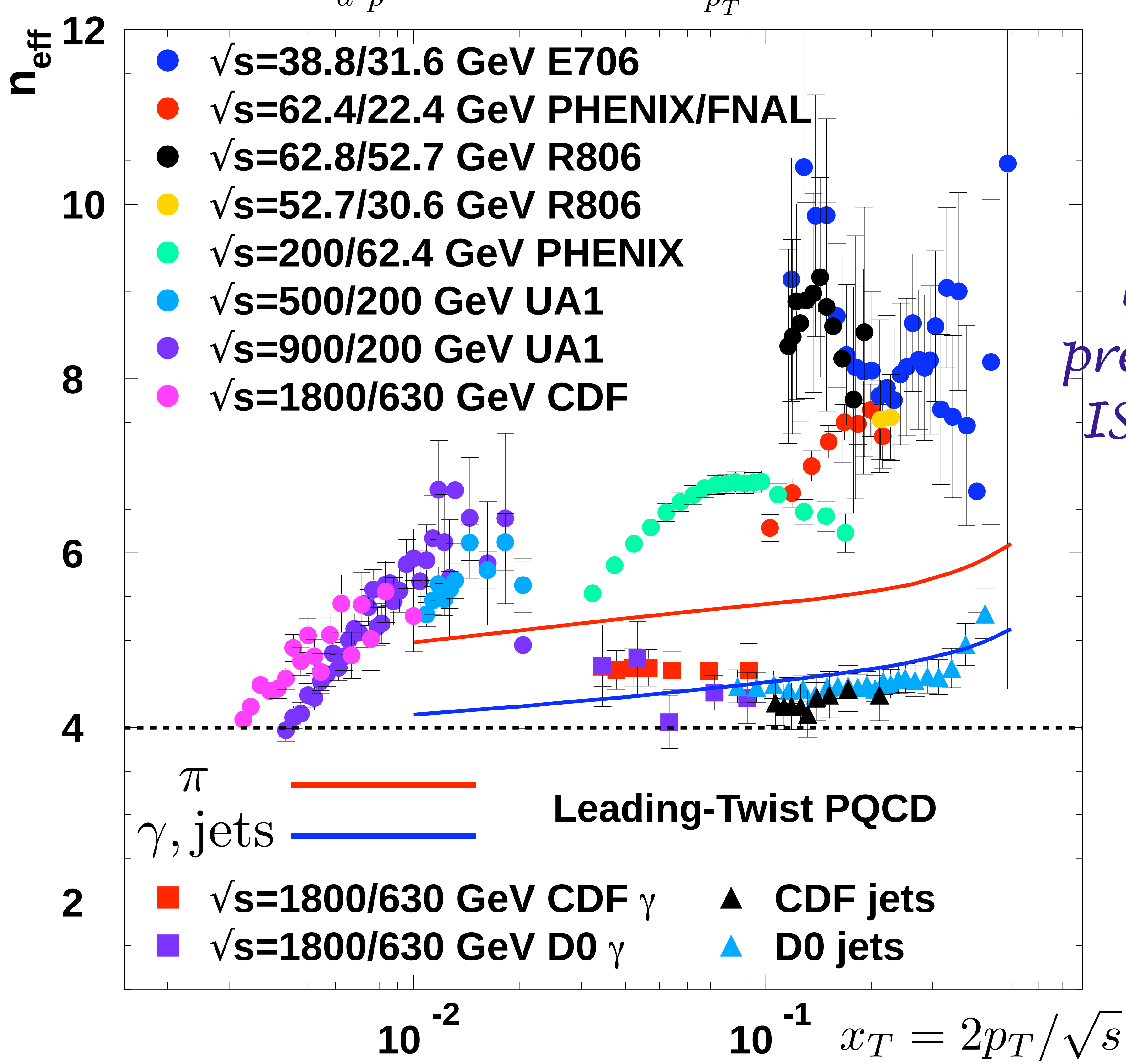
$70\ GeV < \sqrt{s} < 4\ TeV$

Arleo, Hwang, Sickles, sjb

Pirner, Raufeisen, sjb

Key test of PQCD: power-law fall-off at fixed x_T

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{CM} = \pi/2)}{p_T^{n_{\rm eff}}}$$



Leading-twist prediction fails at ISR, FNAL, RHIC, CDF!

Arleo, Hwang, Sickles, sjb

Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

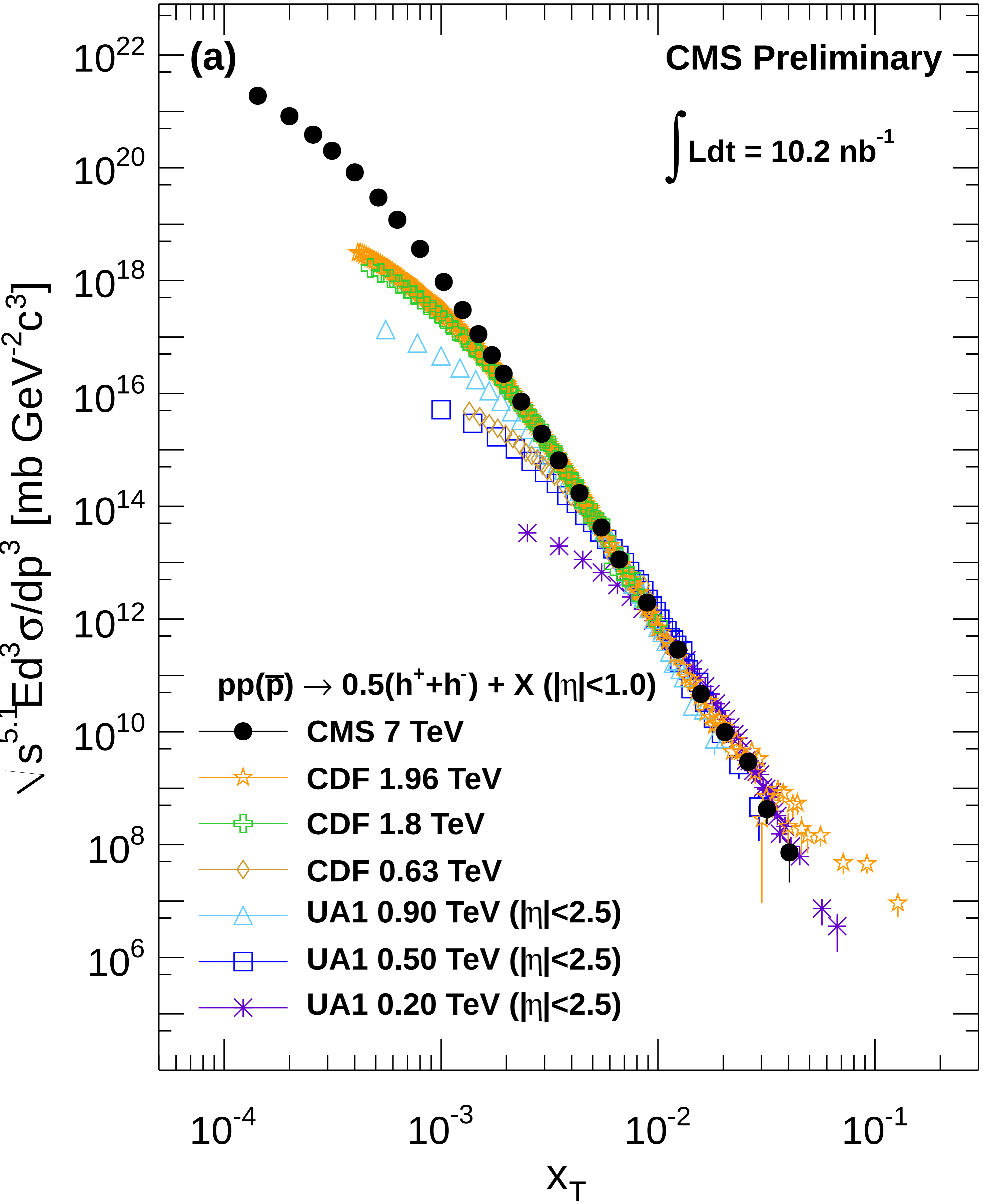
2-component toy-model

$$\sigma^{\mathrm{model}}(pp \to \pi\ \mathrm{X}) \propto \frac{A(x_\perp)}{p_\perp^4} + \frac{B(x_\perp)}{p_\perp^6}$$

Define effective exponent

$$\begin{aligned} n_{\mathrm{eff}}(x_\perp, p_\perp, B/A) &\equiv -\frac{\partial \ln \sigma^{\mathrm{model}}}{\partial \ln p_\perp} + n^{\mathrm{NLO}}(x_\perp, p_\perp) - 4 \\ &= \frac{2B/A}{p_\perp^2 + B/A} + n^{\mathrm{NLO}}(x_\perp, p_\perp) \end{aligned}$$

Arleo,Hwang, Sickles, sjb



Jet-triggered charged particle transverse momentum spectra in pp collisions at 7 TeV

The CMS Collaboration

x_T scaling fails at the LHC

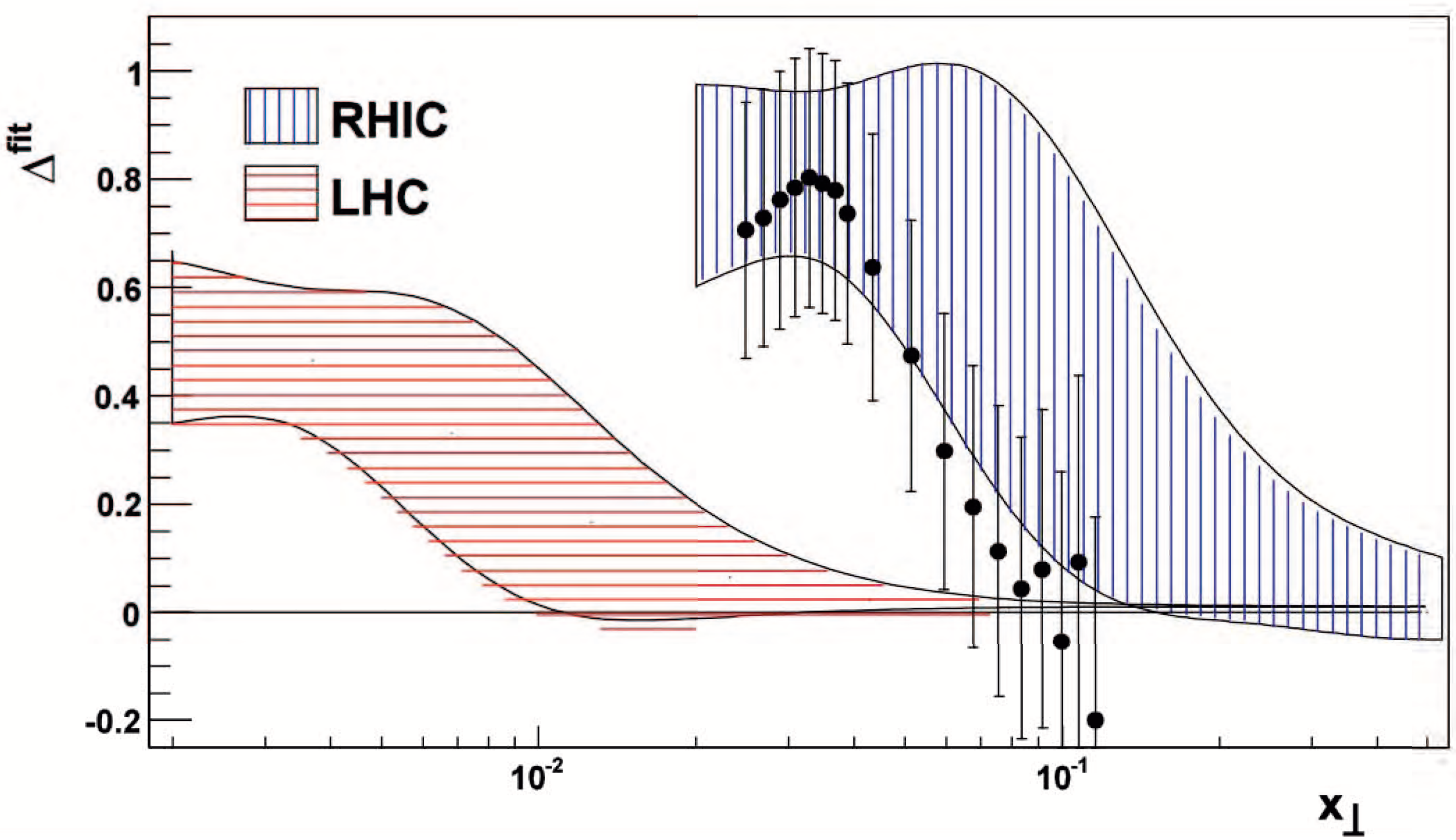
Inclusive invariant cross sections, scaled by $\sqrt{s}^{5.1}$

RHIC/LHC predictions

PHENIX results

Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

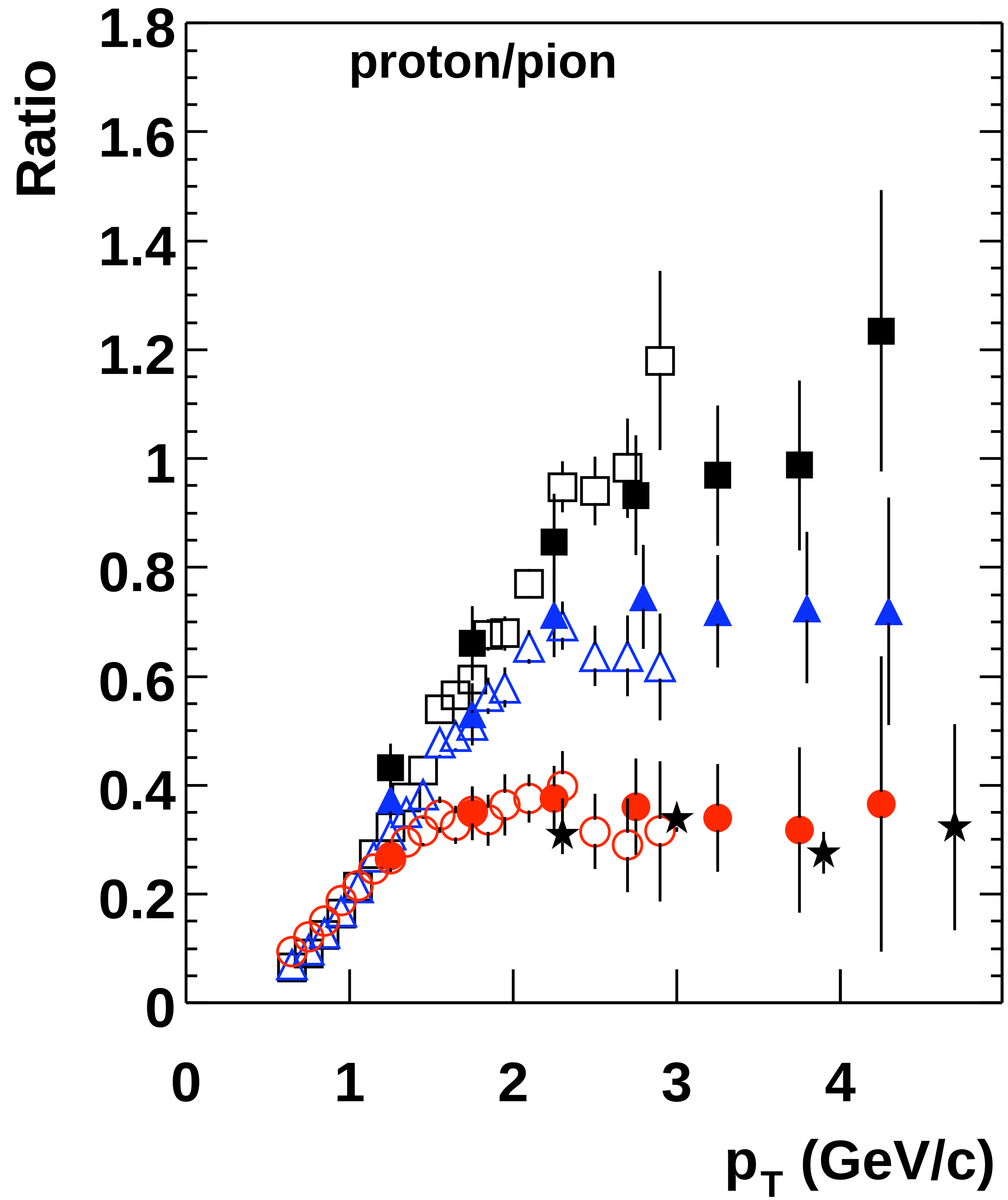
[A. Bezilevsky, APS Meeting]



- Magnitude of Δ and its $x_\perp$-dependence consistent with predictions

S. S. Adler *et al.* PHENIX Collaboration *Phys. Rev. Lett.* **91**, 172301 (2003).

Particle ratio changes with centrality!



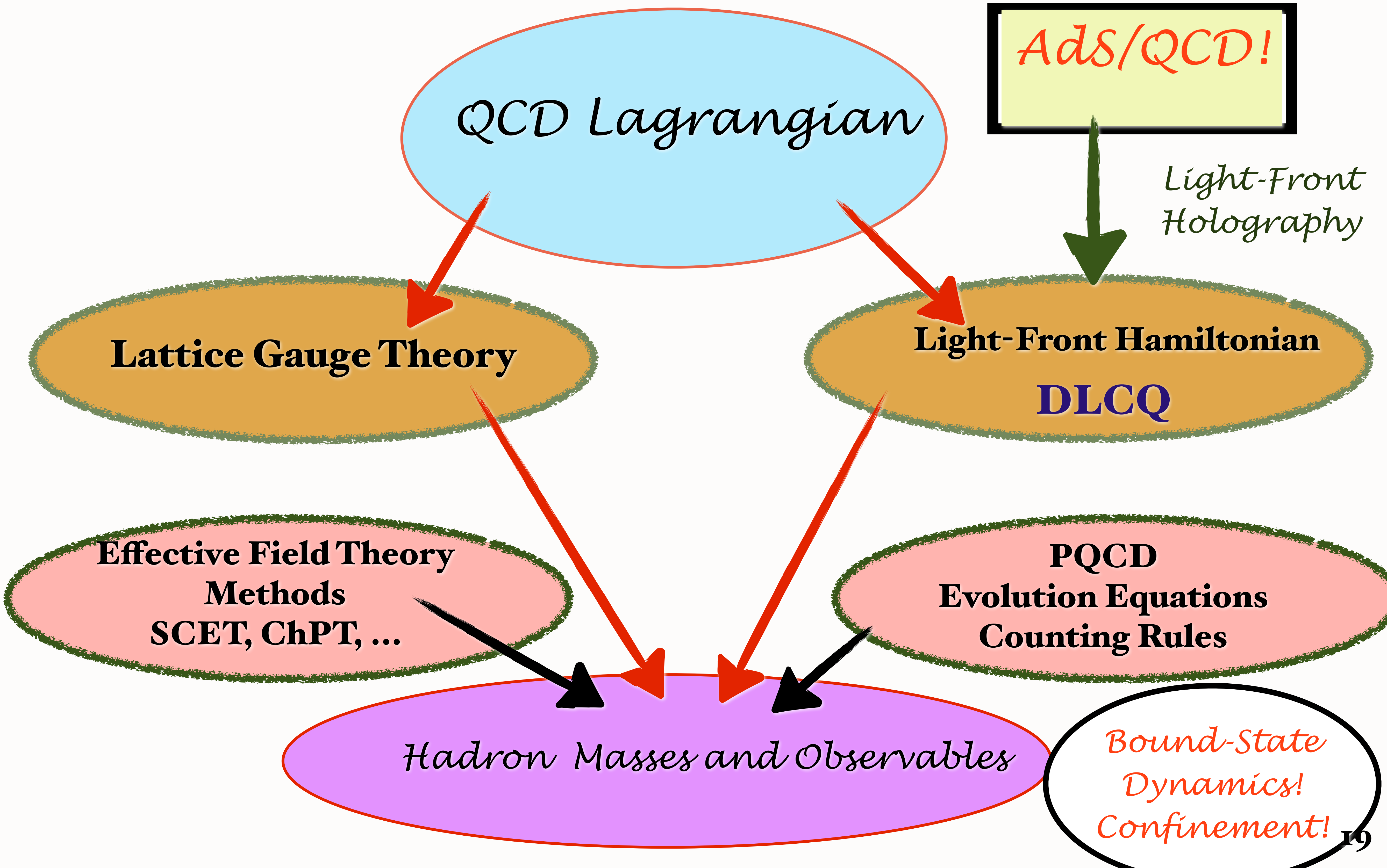
Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process

← **Central**

← **Peripheral**

Tannenbaum: Baryon Anomaly:

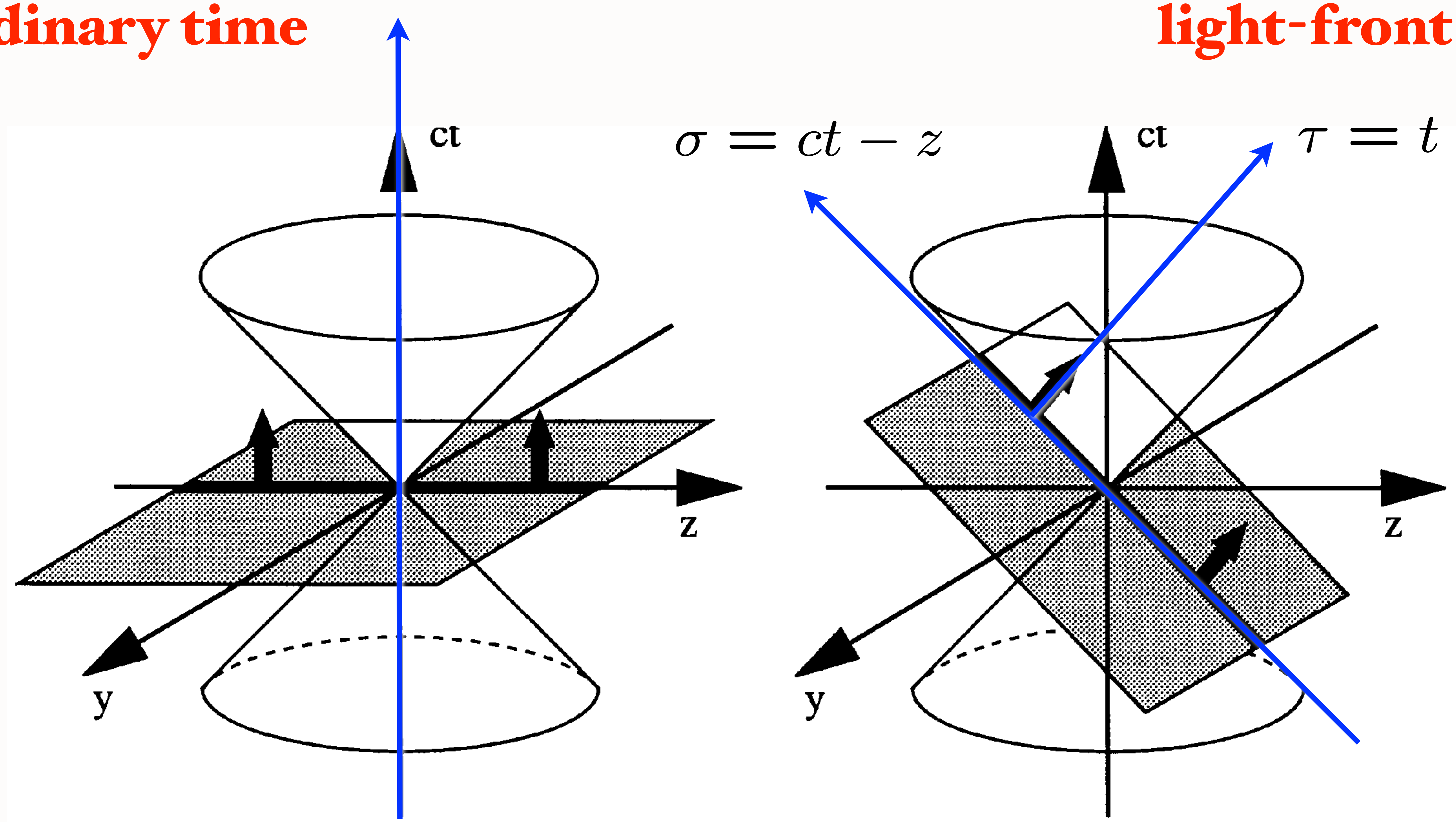
Goal: Predict Hadron Properties from First Principles!



Dirac's Amazing Idea: The Front Form

Evolve in ordinary time

Evolve in light-front time!



Instant Form

Front Form

Each element of flash photograph illuminated at same LF time

$$\tau = t + z/c$$

Causal, frame-independent

Evolve in LF time

$$P^- = i\frac{d}{d\tau}$$

Eigenstate -- independent of τ

$$H_{LF} = P^+P^- - \vec{P}_\perp^2$$

$$H^{QCD}_{LF}|\Psi_h> = \mathcal{M}^2_h|\Psi_h>$$

HELEN BRADLEY - PHOTOGRAPHY

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

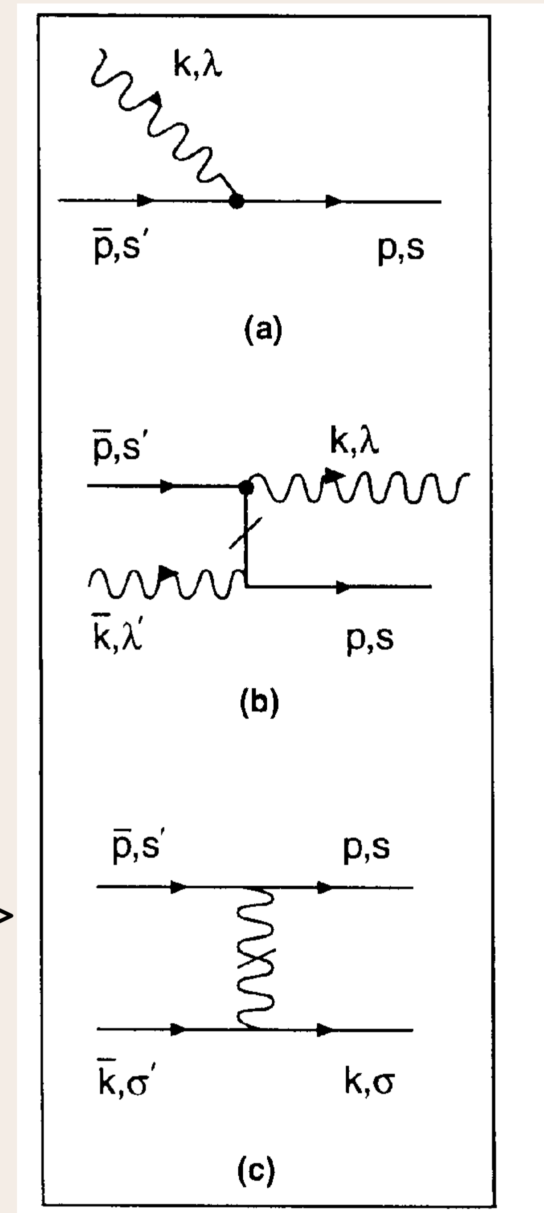
$$L^{QCD} \to H^{QCD}_{LF}$$

$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k^2_\perp}{x}]_i + H^{int}_{LF}$$

H^{int}_{LF}: Matrix in Fock Space

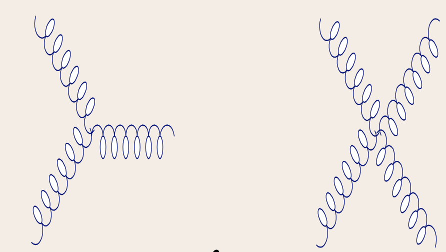
$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}^2_h |\Psi_h>$$

$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i>$$



Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions

LFWFs: Off-shell in P- and invariant mass

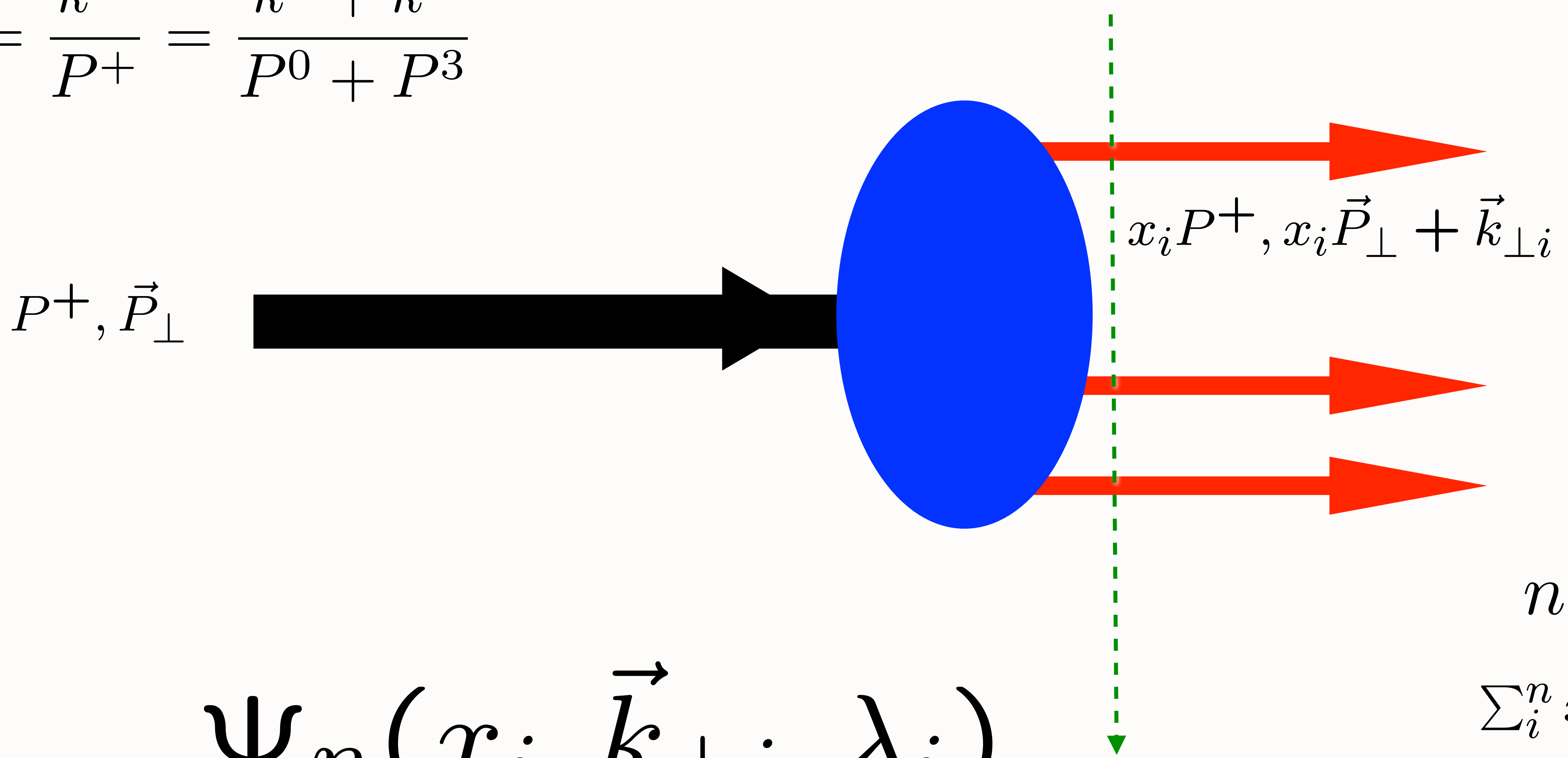


H^{int}_{LF}

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

Fixed $\tau = t + z/c$



$n = 3$

$\sum_i^n x_i = 1$

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Invariant under boosts! Independent of P^μ

Bethe-Salpeter WF integrated over k^-

Measured in DIS

Angular Momentum on the Light-Front

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

Conserved
LF Fock-State by Fock-State
Every Vertex

$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

Parke-Taylor Amplitudes **Stasto**

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

Drell, sjb

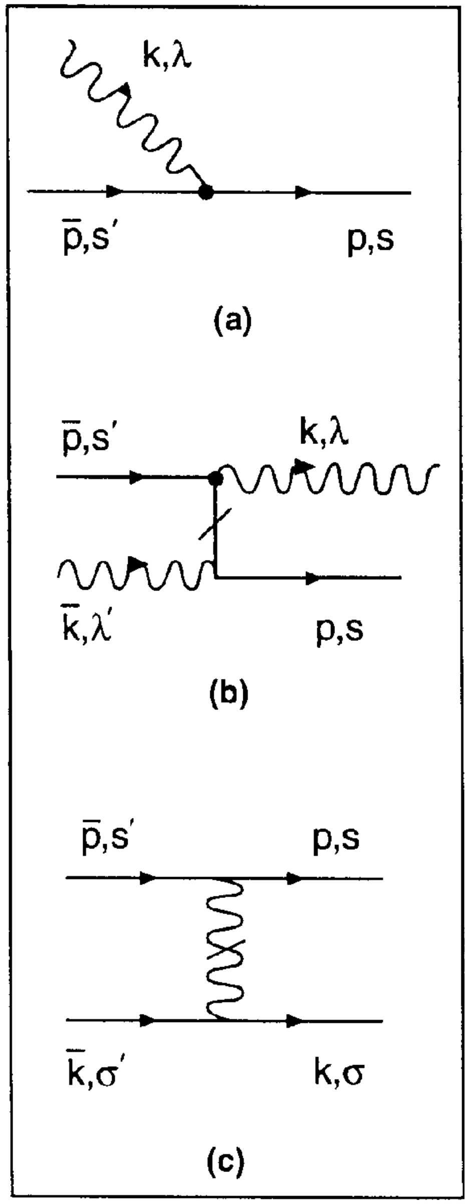
Light-Front QCD

Heisenberg Equation

$$\boxed{H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2\,|\Psi_h\rangle}$$

DLCQ

Pauli, Hornbostel, sjb



n	Sector	1 $q\bar q$	2 gg	3 $q\bar q\,g$	4 $q\bar q\,q\bar q$	5 $gg\,g$	6 $q\bar q\,gg$	7 $q\bar q\,q\bar q\,g$	8 $q\bar q\,q\bar q\,q\bar q$	9 $gg\,gg$	10 $q\bar q\,gg\,g$	11 $q\bar q\,q\bar q\,gg$	12 $q\bar q\,q\bar q\,q\bar q\,g$	13 $q\bar q\,q\bar q\,q\bar q\,q\bar q$
1	$q\bar q$					•		•	•	•	•	•	•	•
2	gg				•			•	•		•	•	•	•
3	$q\bar q\,g$								•	•		•	•	•
4	$q\bar q\,q\bar q$		•			•				•	•		•	•
5	$gg\,g$	•			•			•	•			•	•	•
6	$q\bar q\,gg$								•				•	•
7	$q\bar q\,q\bar q\,g$	•	•			•				•				•
8	$q\bar q\,q\bar q\,q\bar q$	•	•	•		•	•			•	•			
9	$gg\,gg$	•		•	•			•	•			•	•	•
10	$q\bar q\,gg\,g$	•	•		•				•				•	•
11	$q\bar q\,q\bar q\,gg$	•	•	•		•				•				•
12	$q\bar q\,q\bar q\,q\bar q\,g$	•	•	•	•	•	•			•	•			
13	$q\bar q\,q\bar q\,q\bar q\,q\bar q$	•	•	•	•	•	•	•		•	•	•		

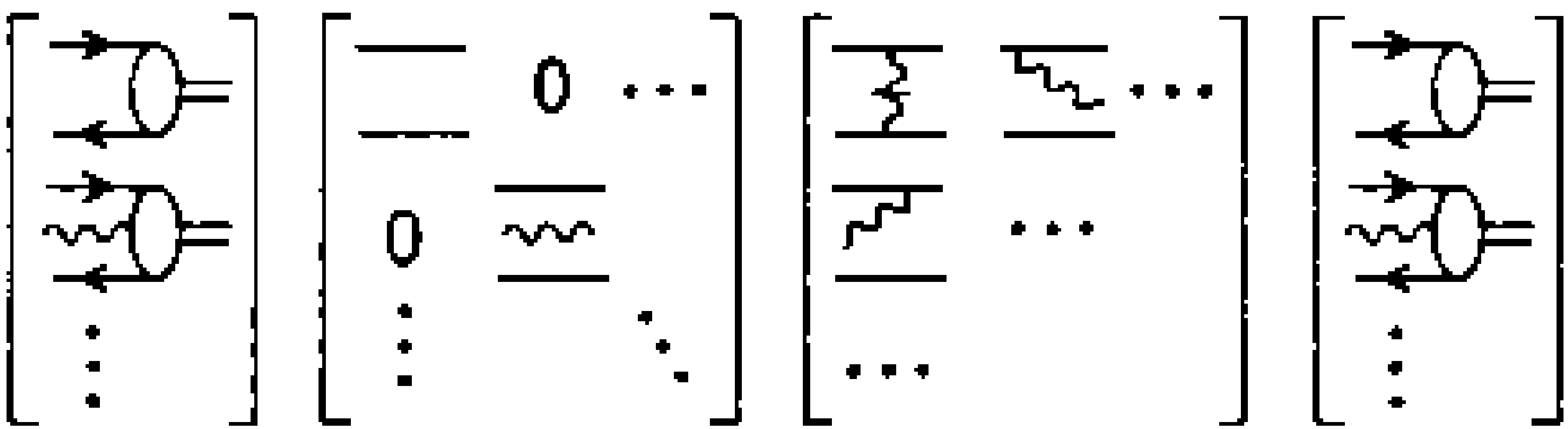
LIGHT-FRONT MATRIX EQUATION

G.P. Lepage, sjb

Rigorous Method for Solving Non-Perturbative QCD!

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^{\,2} + m_i^2}{x_i}\right) \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix} = \begin{bmatrix} \langle q\bar{q}|\,V\,|q\bar{q}\rangle & \langle q\bar{q}|\,V\,|q\bar{q}g\rangle & \cdots \\ \langle q\bar{q}g|\,V\,|q\bar{q}\rangle & \langle q\bar{q}g|\,V\,|q\bar{q}g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix}$$

$A^+ = 0$



Minkowski space; frame-independent; no fermion doubling; no ghosts

- ***Light-Front Vacuum = Vacuum of Free Hamiltonian!***

Causal, Frame-Independent

Possible zero modes

Goal: an analytic first approximation to QCD

- **As Simple as Schrödinger Theory in Atomic Physics**
- **Relativistic, Frame-Independent, Color-Confining**
- **QCD Coupling at all scales**
- **Hadron Spectroscopy**
- **Light-Front Wavefunctions**
- **Form Factors, Hadronic Observables, Constituent Counting Rules**
- **Insight into QCD Condensates**
- **Systematically improvable**
- **Eliminate scale ambiguities**

de Teramond, sjb

$$H_{QED}$$

QED atoms: positronium and muonium

$$(H_0 + H_{int})\ |\Psi >= E\ |\Psi >$$

Coupled Fock states

$$[-\frac{\Delta^2}{2m_{\rm red}} + V_{\rm eff}(\vec{S},\vec{r})]\ \psi(\vec{r}) = E\ \psi(\vec{r})$$

Effective two-particle equation

Includes Lamb Shift, quantum corrections

$$[-\frac{1}{2m_{\rm red}}\frac{d^2}{dr^2} + \frac{1}{2m_{\rm red}}\frac{\ell(\ell+1)}{r^2} + V_{\rm eff}(r,S,\ell)]\ \psi(r) = E\ \psi(r)$$

Spherical Basis r, θ, ϕ

$$V_{eff} \to V_C(r) = -\frac{\alpha}{r}$$

Coulomb potential

Bohr Spectrum

Semiclassical first approximation to QED

$$H_{QCD}^{LF}$$

QCD Meson Spectrum

$$(H^0_{LF} + H^I_{LF})|\Psi > = M^2|\Psi >$$

Coupled Fock states

$$[\frac{\vec{k}^2_\perp + m^2}{x(1-x)} + V^{LF}_{\rm eff}]\ \psi_{LF}(x,\vec{k}_\perp) = M^2\ \psi_{LF}(x,\vec{k}_\perp)$$

Effective two-particle equation

$$[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1+4L^2}{\zeta^2} + U(\zeta,S,L)]\ \psi_{LF}(\zeta) = M^2\ \psi_{LF}(\zeta)$$

$$\zeta^2 = x(1-x)b^2_\perp$$

Azimuthal Basis ζ, ϕ

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Confining AdS/QCD potential

Semiclassical first approximation to QCD

Light-Front Schrödinger Equation

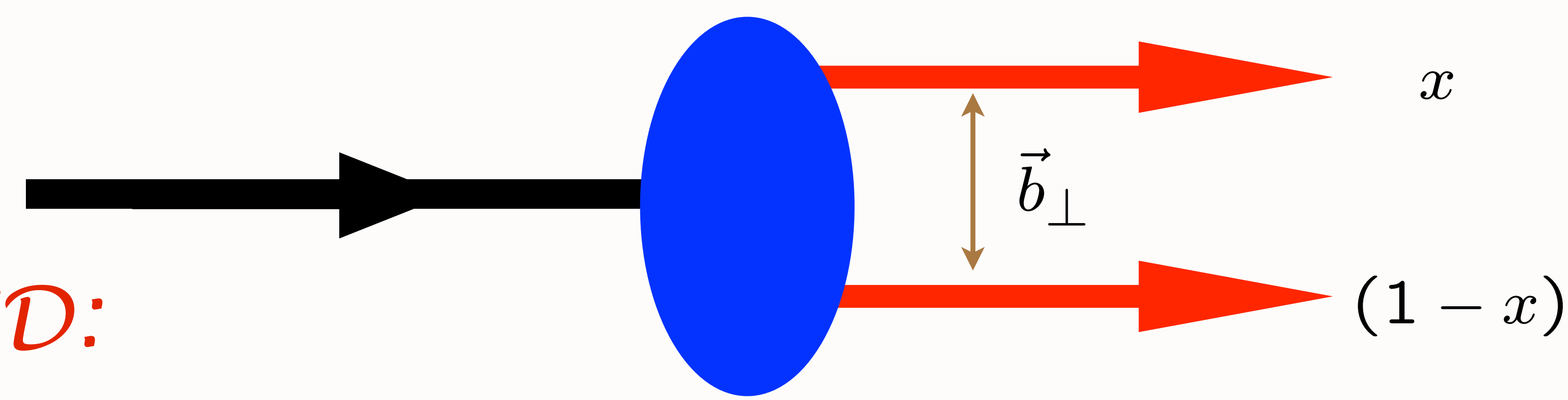
G. de Teramond, sjb

Relativistic LF single-variable radial equation for QCD & QED

Frame Independent!

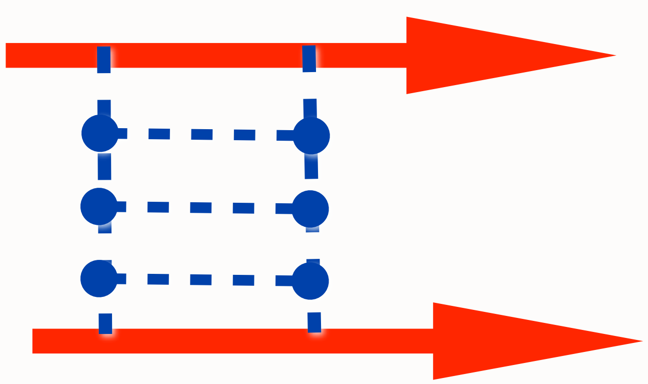
$$\left[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1+4L^2}{\zeta^2} + U(\zeta, S, L)\right] \psi_{LF}(\zeta) = M^2 \, \psi_{LF}(\zeta)$$

$$\zeta^2 = x(1-x)\mathbf{b}_\perp^2 .$$



AdS/QCD:

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

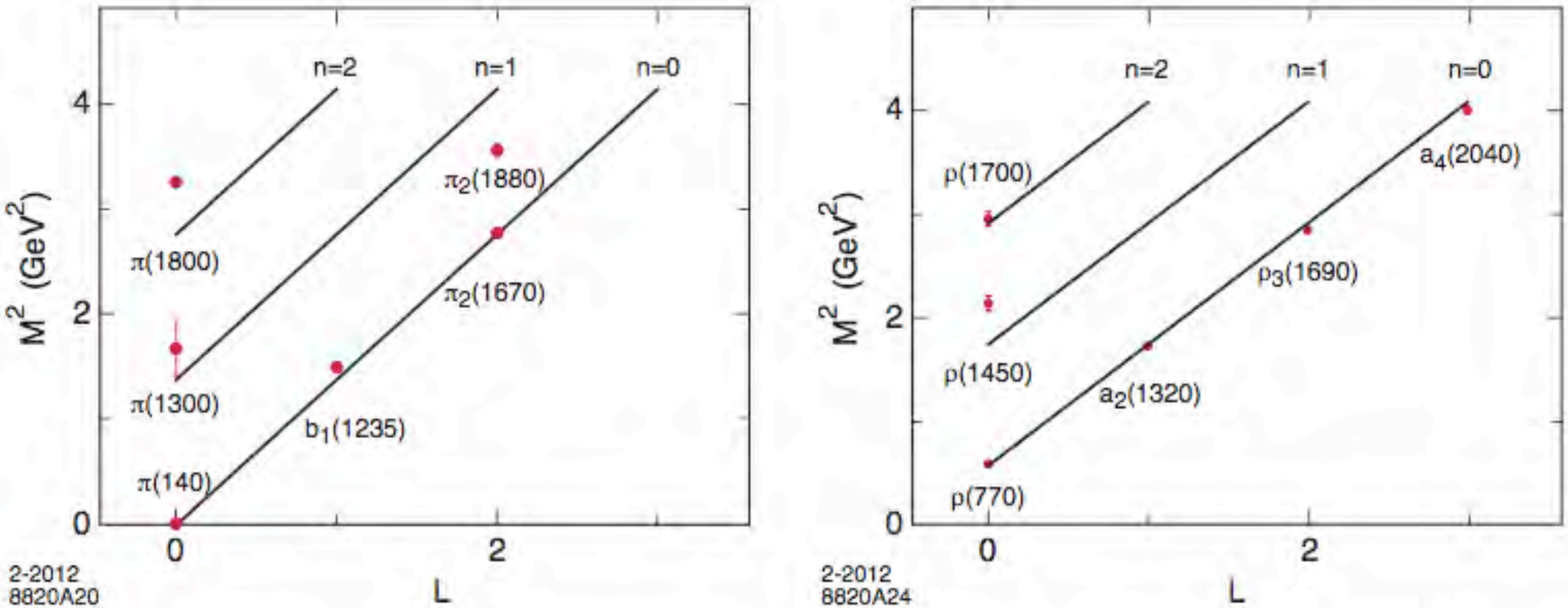


U is the exact QCD potential
Conjecture: 'H'-diagrams generate

- $J = L + S, I = 1$ meson families $\mathcal{M}^2_{n,L,S} = 4\kappa^2 (n + L + S/2)$

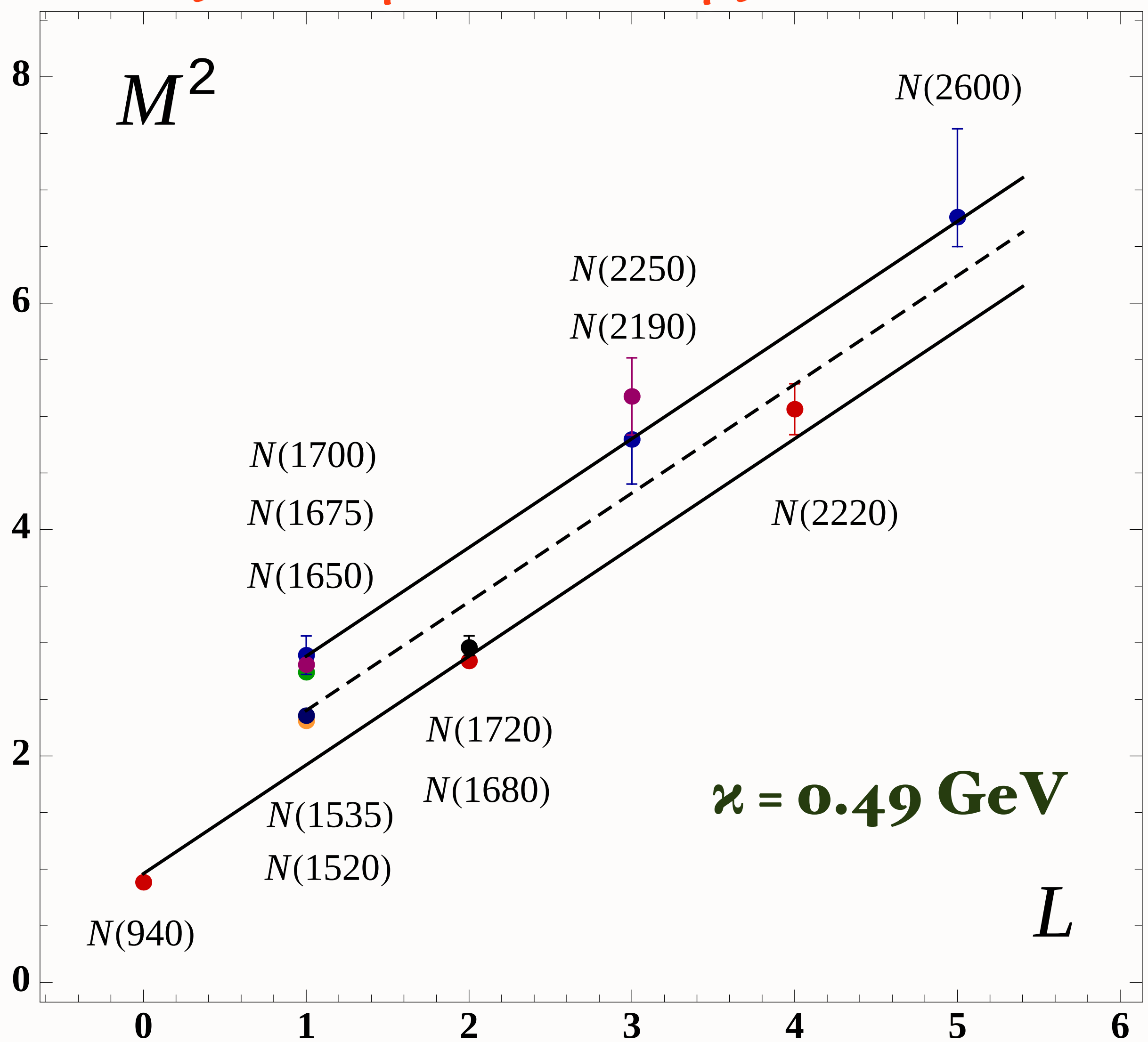
$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

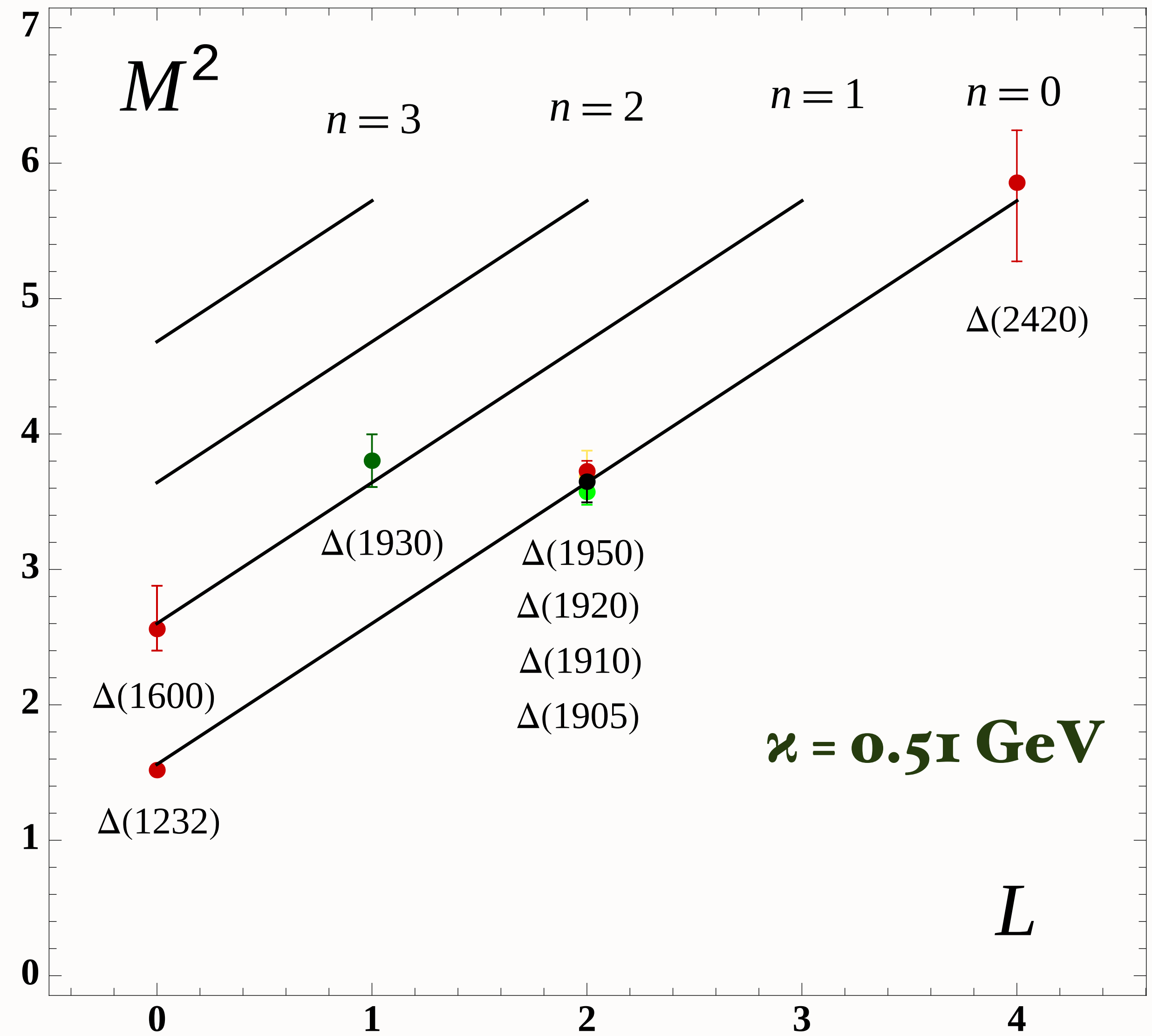
Same slope in n and L



Spectrum from AdS/QCD

Baryon Spectroscopy from AdS/QCD and Light-Front Holography





de Teramond, sjb

All confirmed resonances from PDG 2012

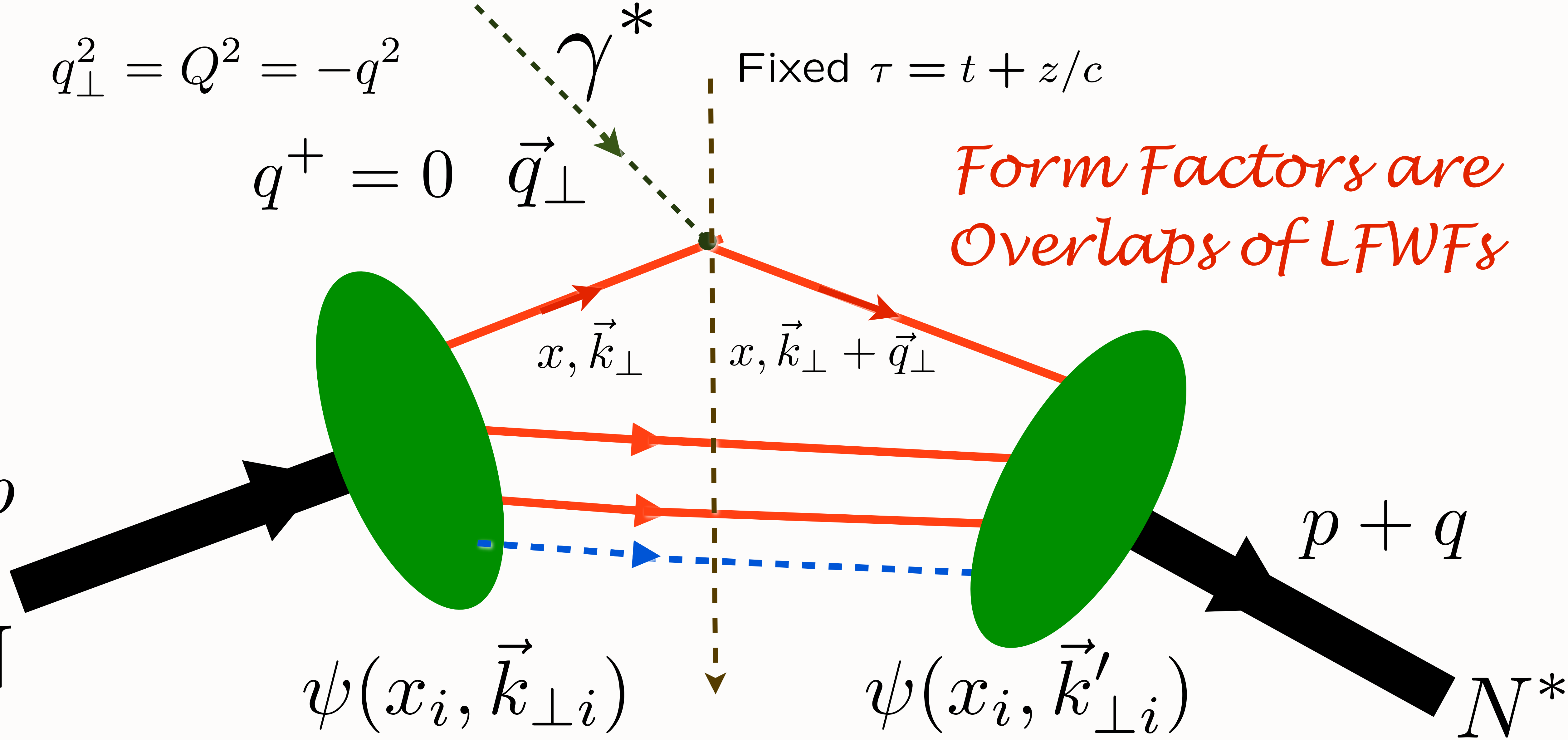
$$\mathcal{M}^{2\,(+)}_{n,L,S} = 4\kappa^2\left(n + L + \frac{S}{2} + \frac{3}{4}\right),$$ **positive parity**

$$\mathcal{M}^{2\,(-)}_{n,L,S} = 4\kappa^2\left(n + L + \frac{S}{2} + \frac{5}{4}\right),$$ **negative parity**

See also Forkel, Beyer, Federico, Klempt

$$< p+q|j^+(0)|p >= 2p^+F(q^2)$$

Interaction picture



Form Factors are Overlaps of LFWFs

struck $\quad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$

spectators $\quad \vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i\vec{q}_\perp$

Drell & Yan, West
Exact LF formula
Drell, sjb

Exact LF Formula for Pauli Form Factor

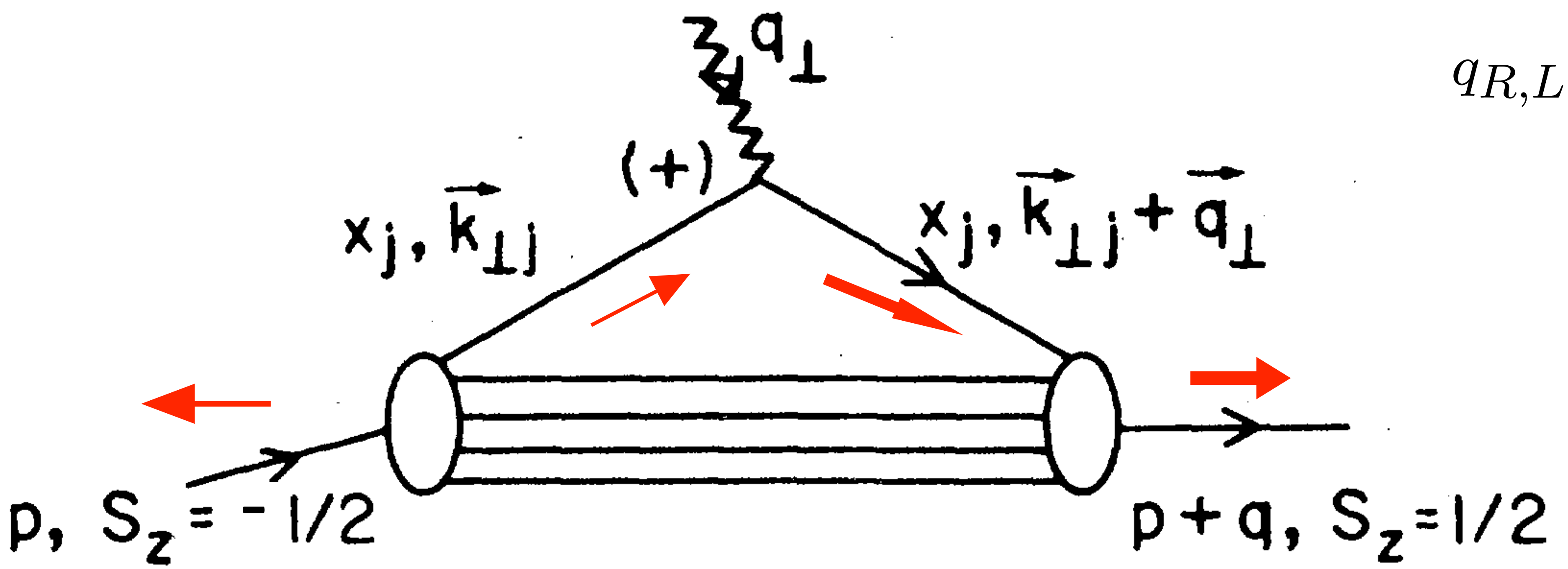
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

$$\Big[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \Big]$$

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$

$$q_{R,L} = q^x \pm i q^y$$

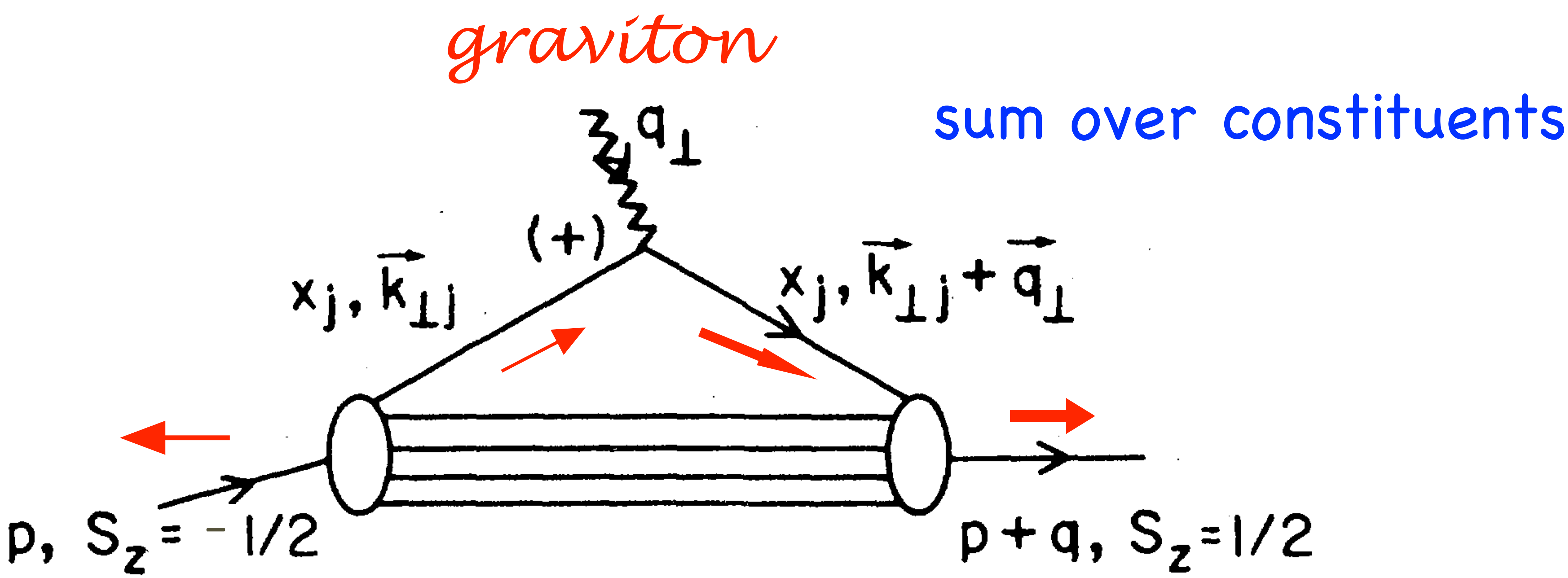


$\boxed{\text{Must have } \Delta\ell_z = \pm 1 \text{ to have nonzero } F_2(q^2)}$

Nonzero Proton Anomalous Moment -->
Nonzero orbital quark angular momentum

Anomalous gravitomagnetic moment B(0)

Terayev, Okun, et al: *B(0) Must vanish because of Equivalence Theorem*



Hwang, Schmidt, sjb; Holstein et al

$\boxed{B(0) = 0}$

Each Fock State

Angular Momentum on the Light-Front

LC gauge

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

Conserved
LF Fock state by Fock State

Gluon orbital angular momentum defined in physical lc gauge

$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

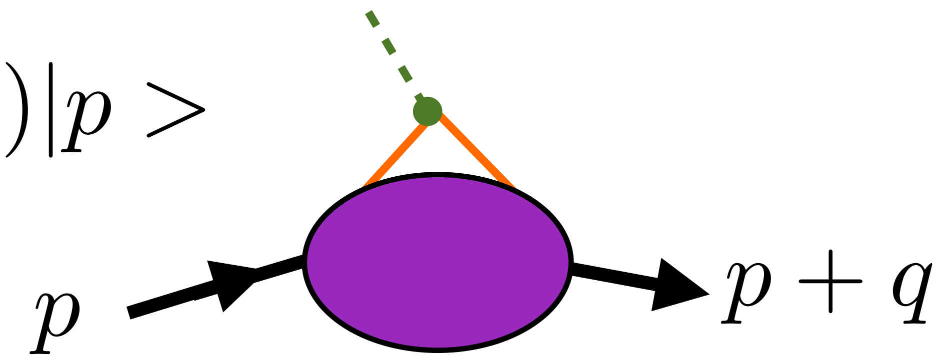
n-1 orbital angular momenta

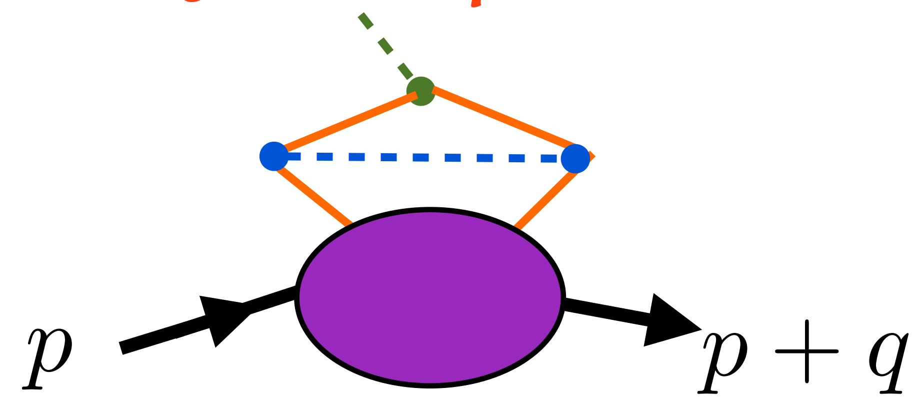
Orbital Angular Momentum is a property of LFWFS

Nonzero Anomalous Moment -->
Nonzero quark orbital angular momentum!

Calculation of proton form factor in Instant Form

$$< p + q | J^\mu(0) | p >$$

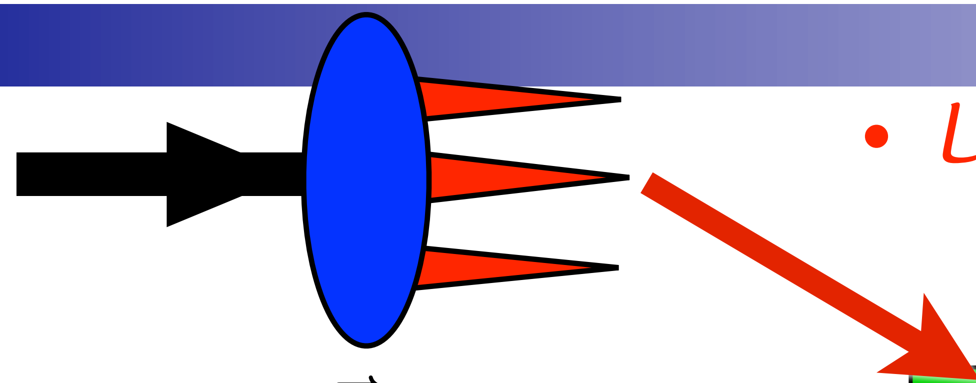




- **Need to boost proton wavefunction: p to p+q. Extremely complicated dynamical problem; particle number changes**
- **Need to couple to all currents arising from vacuum!! Remain even after normal-ordering**
- **Instant-form WFs insufficient to calculate form factors**
- **Each time-ordered contribution is frame-dependent**
- **Divide by disconnected vacuum diagrams**

Light-Front vs. Instant Form

- **Light-Front Wavefunctions are frame-independent**
- **Boosting an instant-form wavefunctions dynamical problem -- extremely complicated even in QED**
- **Need to couple to all currents arising from vacuum (Remain even after normal-ordering)**
- **Vacuum state is lowest energy eigenstate of Hamiltonian**
- **Light-Front Vacuum same as vacuum of free Hamiltonian**
- **Zero anomalous gravitomagnetic moment**
- **Instant-Form Vacuum infinitely complex even in QED**
- **n! time-ordered diagrams in Instant Form**
- **Causal commutators using LF time; cluster decomposition**



- *Light Front Wavefunctions:*

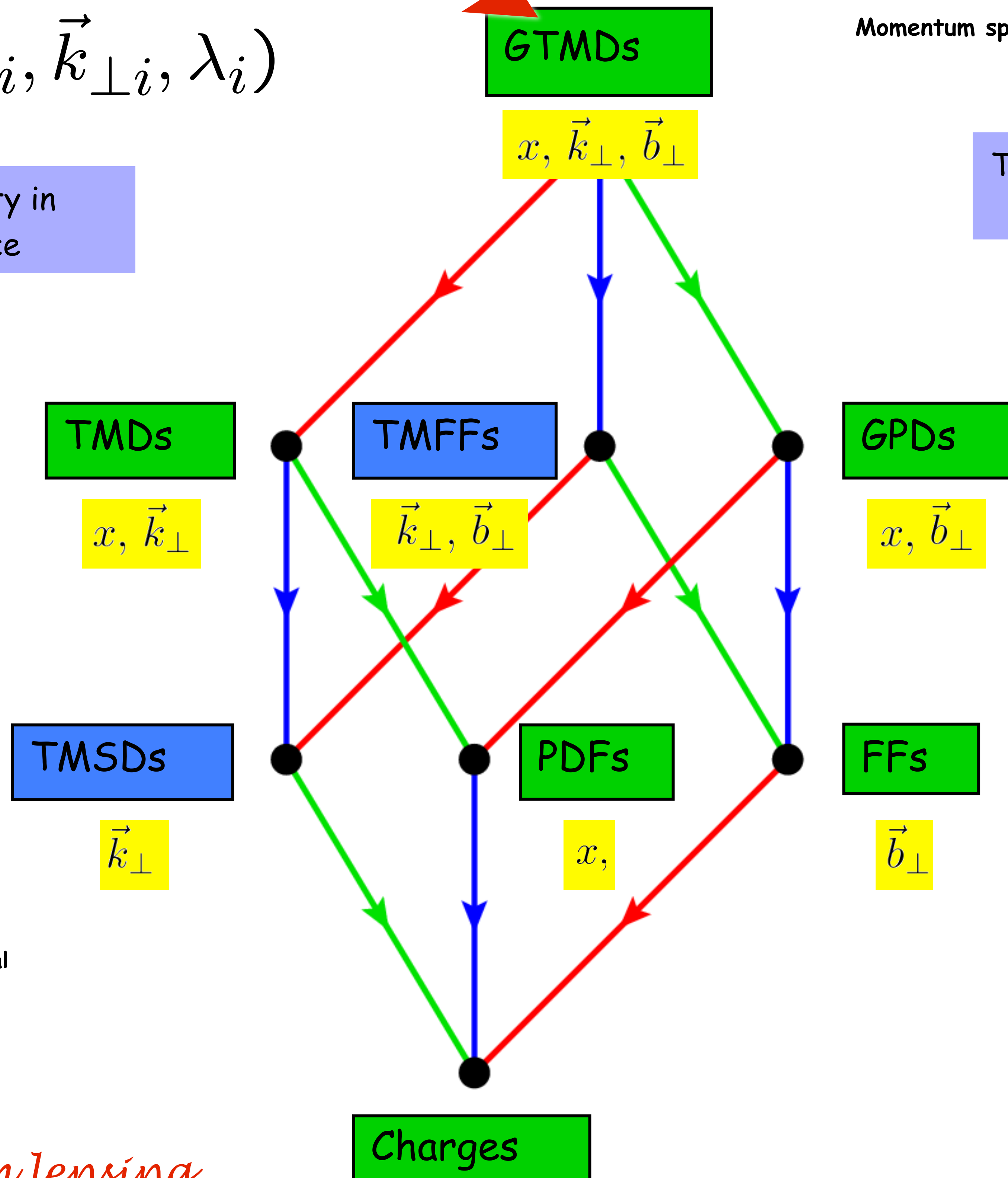
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

Transverse density in momentum space

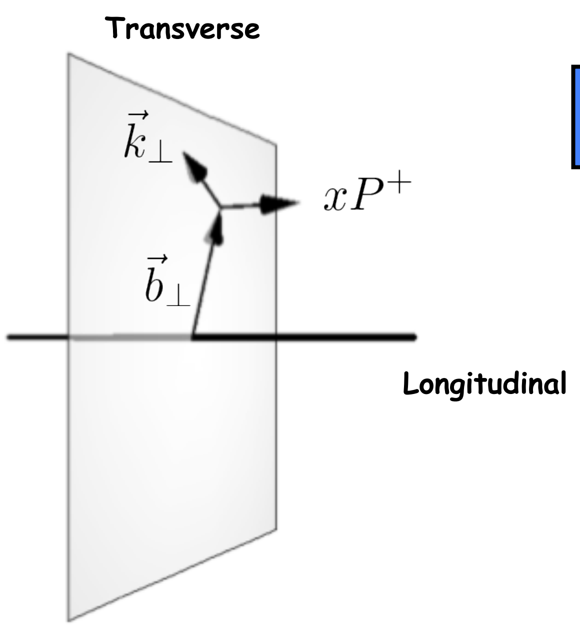
Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ **Position space**

$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

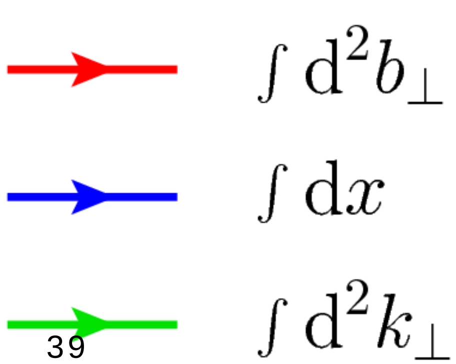
Transverse density in position space



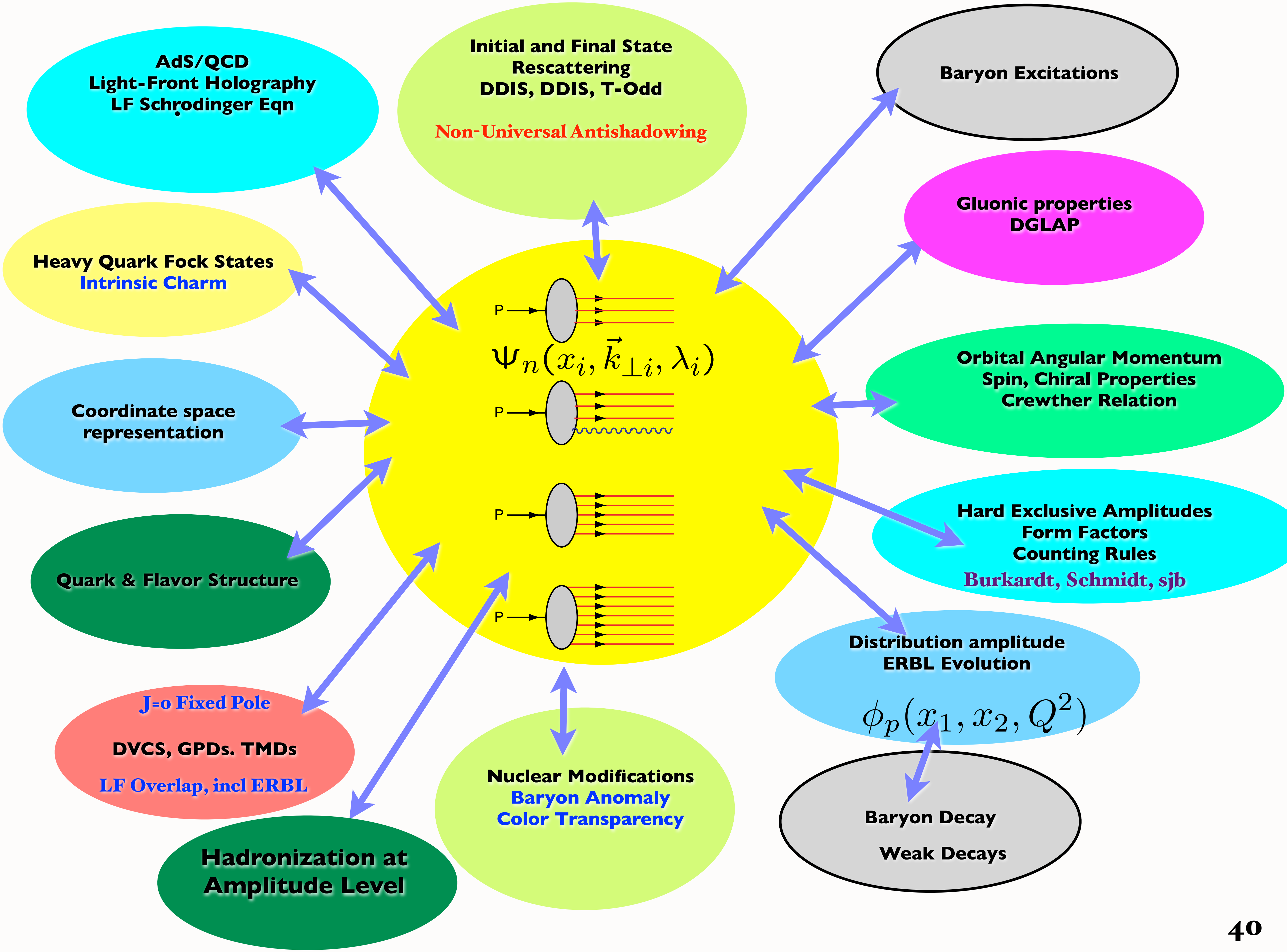
Lorce



Sivers, T-odd from lensing



QCD and the LF Hadron Wavefunctions

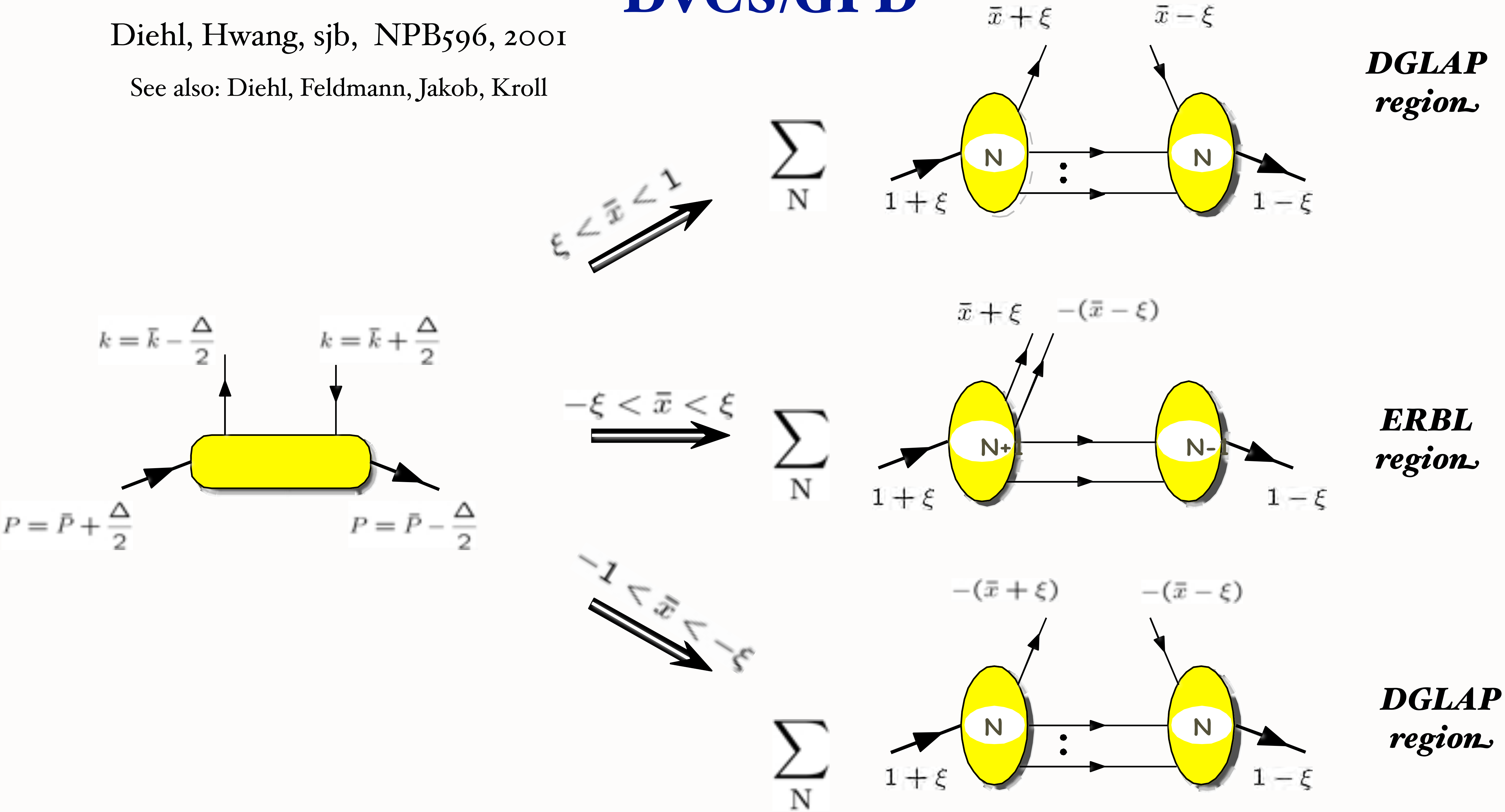


Light-Front Wave Function Overlap Representation

DVCS/GPD

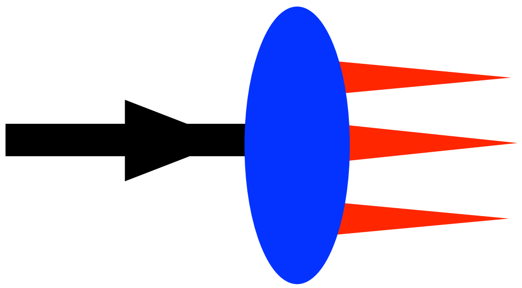
Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



Bakker & Ji
Lorce

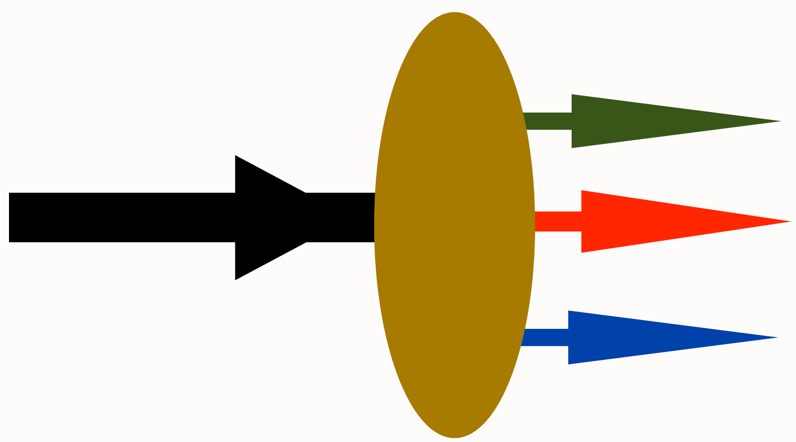
- LF wavefunctions play the role of Schrödinger wavefunctions in Atomic Physics
- LFWFs=Hadron Eigensolutions: Direct Connection to QCD Lagrangian
- Relativistic, frame-independent: no boosts, no disc contraction, Melosh built into LF spinors
- Hadronic observables computed from LFWFs: Form factors, Structure Functions, Distribution Amplitudes, GPDs, TMDs, Weak Decays, ... modulo `lensing' from ISIs, FSIs
- Cannot compute current matrix elements using instant or point form from eigensolutions alone -- need to include vacuum currents!



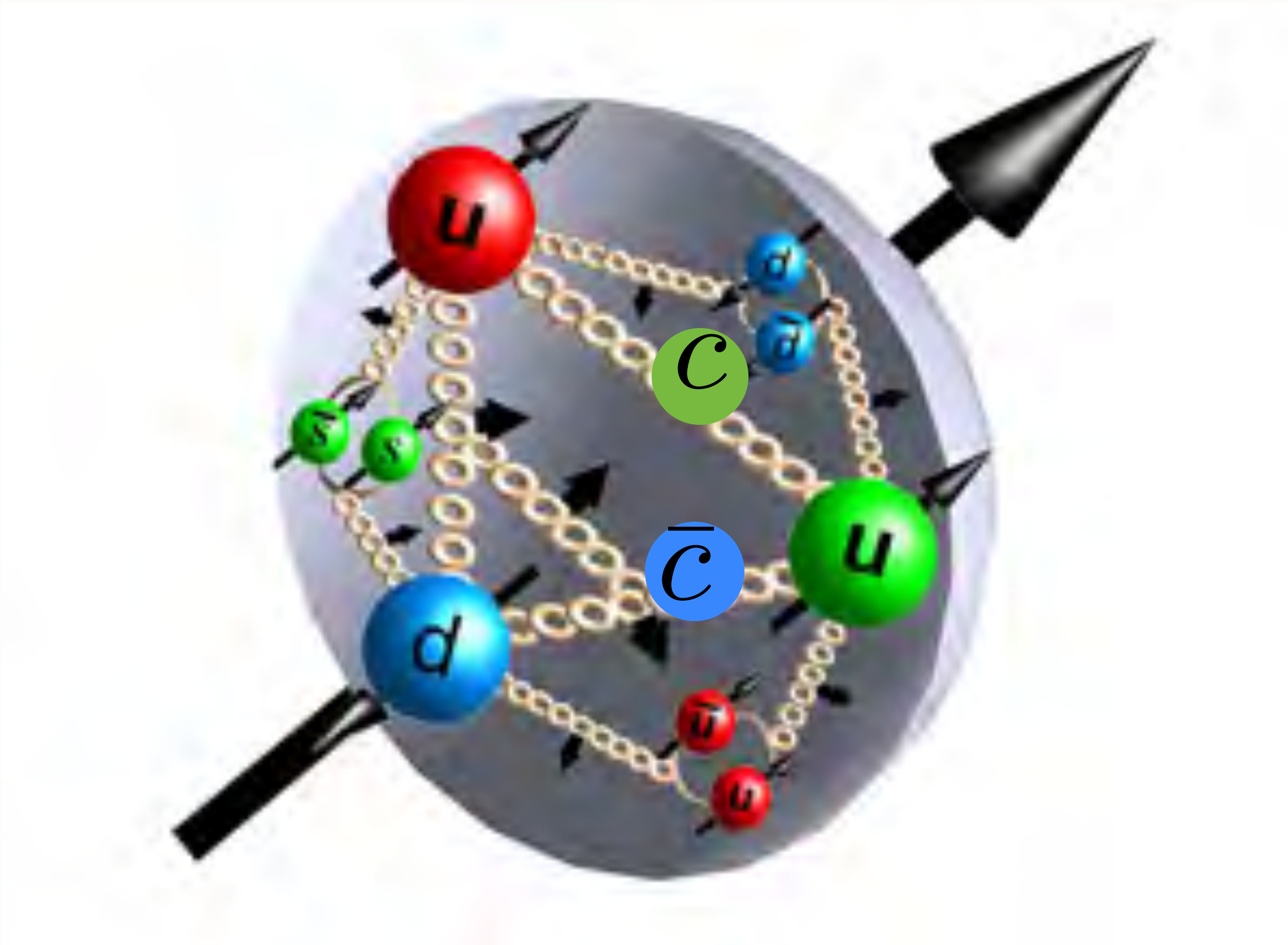
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

- *Hadron Physics without LFWFs is like Biology without DNA!*

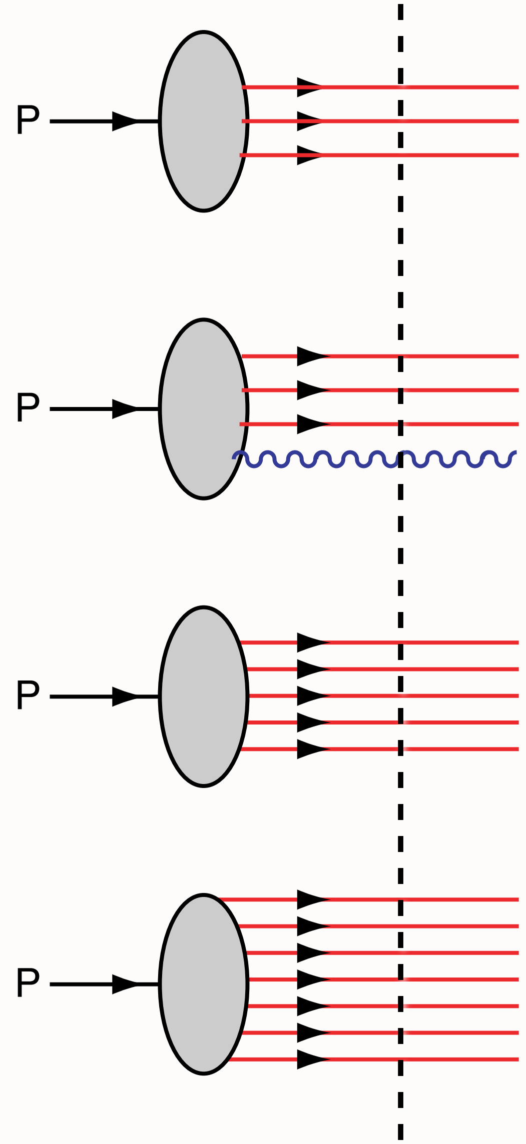
- *Hadron Physics without LFWFs is like Biology without DNA!*



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



Higher Fock States of the Proton



Fixed LF time

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; \vec{k}_{\perp_i}, \lambda_i>$$

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

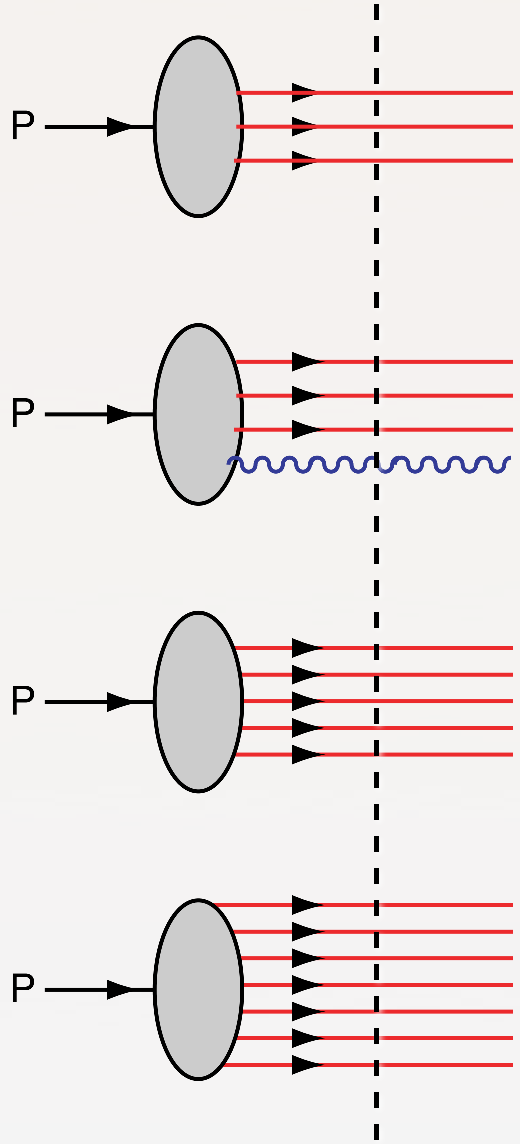
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Fixed LF time

Intrinsic heavy quarks

s(x), c(x), b(x) at high x !

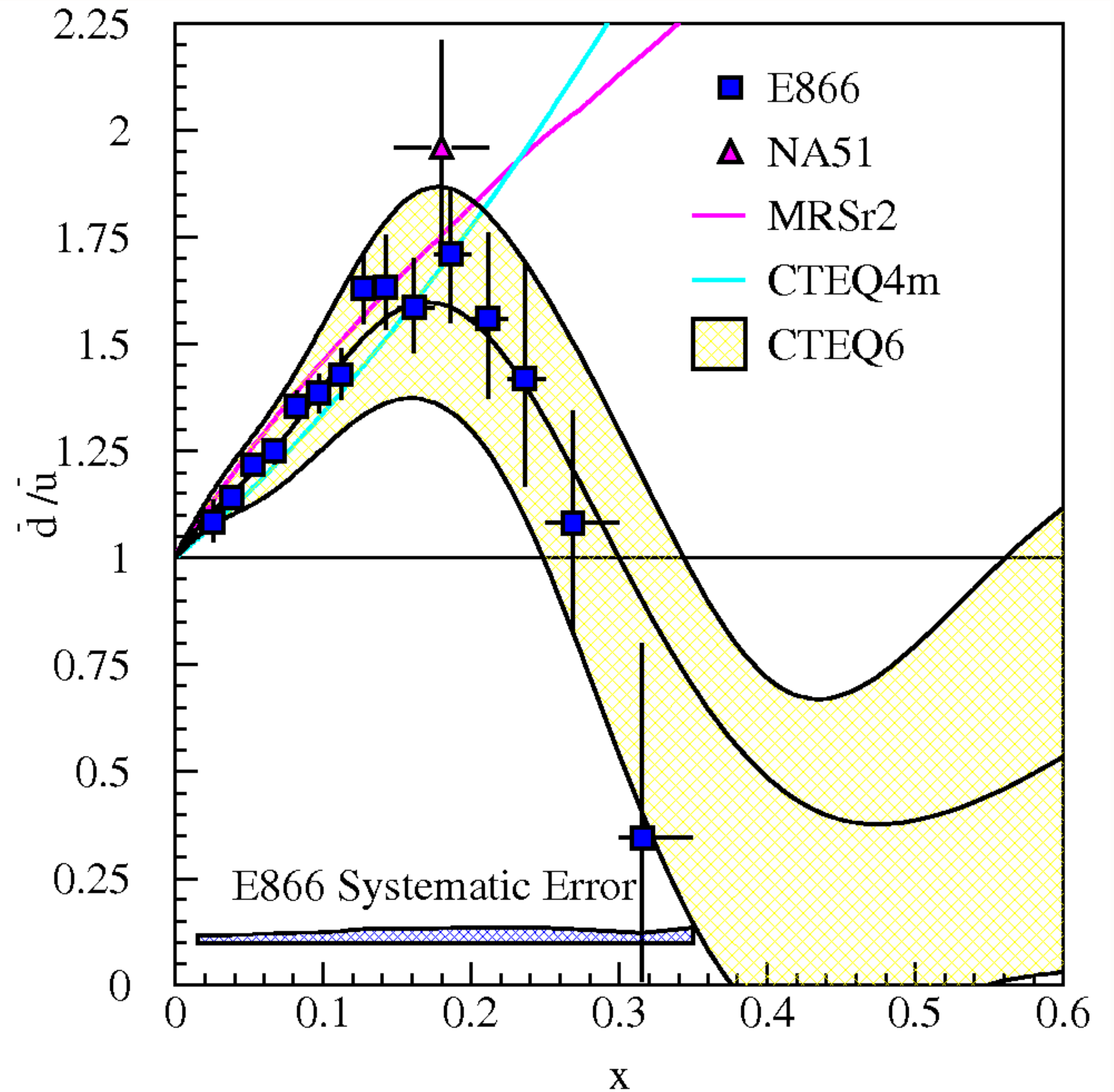
$\bar{s}(x) \neq s(x)$

$\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states BFKL Pomeron

Hidden Color

$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



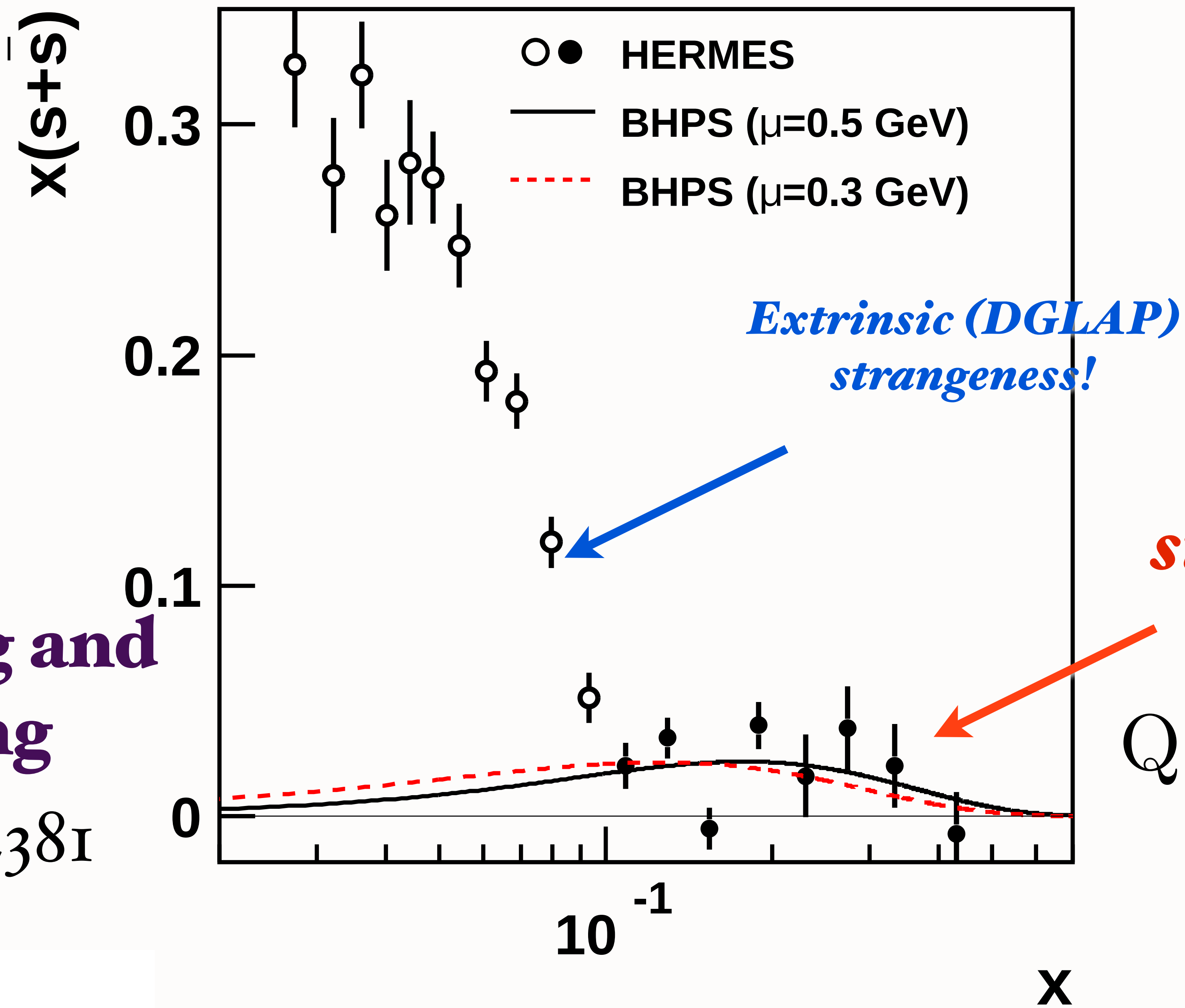
- E866/NuSea (Drell-Yan)

$$\bar{d}(x) \neq \bar{u}(x)$$

$$s(x) \neq \bar{s}(x)$$

Intrinsic glue, sea, heavy quarks

HERMES: Two components to s(x,Q²)!



W. C. Chang and J.-C. Peng

arXiv:1105.2381

Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

QCD: $\frac{1}{M_Q^2}$ scaling

Consistent with intrinsic charm data

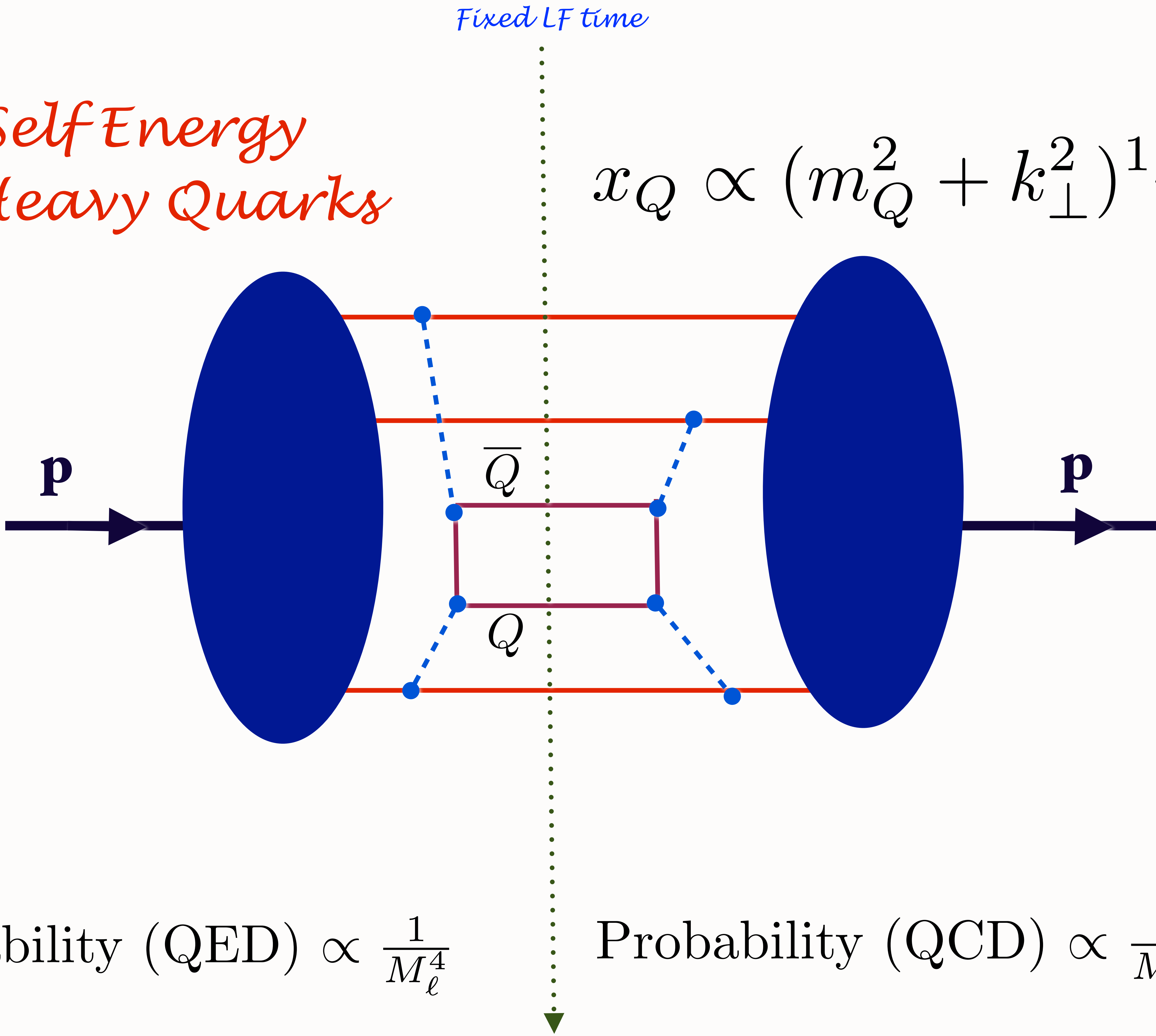
Affects Electroweak tests

$$s(x) \neq \bar{s}(x)?$$

$$s(x,Q^2) = s(x,Q^2)_{\text{extrinsic}} + s(x,Q^2)_{\text{intrinsic}}$$

Proton Self Energy
Intrinsic Heavy Quarks

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$



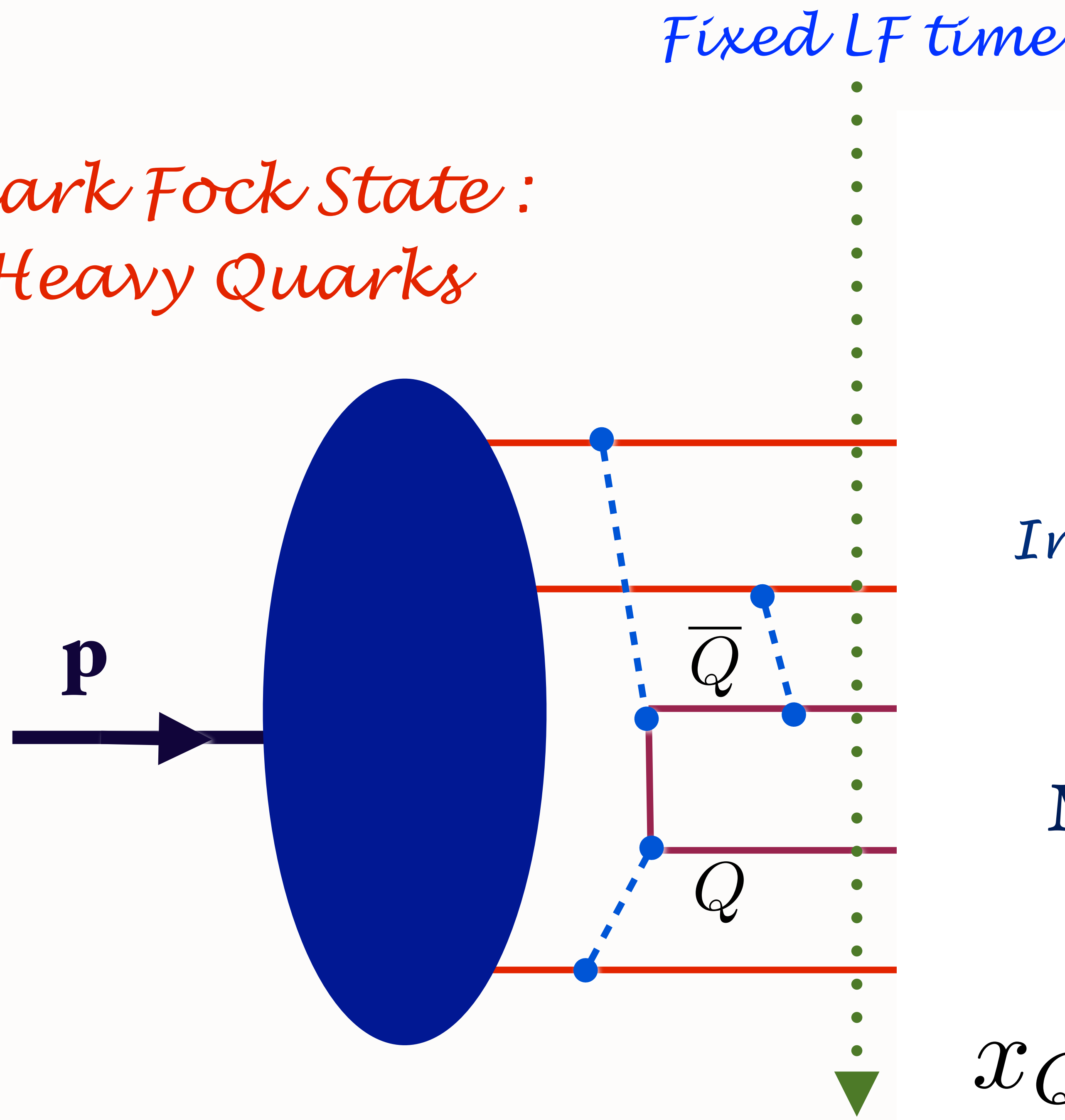
Probability (QED) $\propto \frac{1}{M_\ell^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov

Proton 5-quark Fock State :

Intrinsic Heavy Quarks



QCD predicts

Intrinsic Heavy Quarks

at high x!

Minimal off-shellness

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/}$$

$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4} \qquad \text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

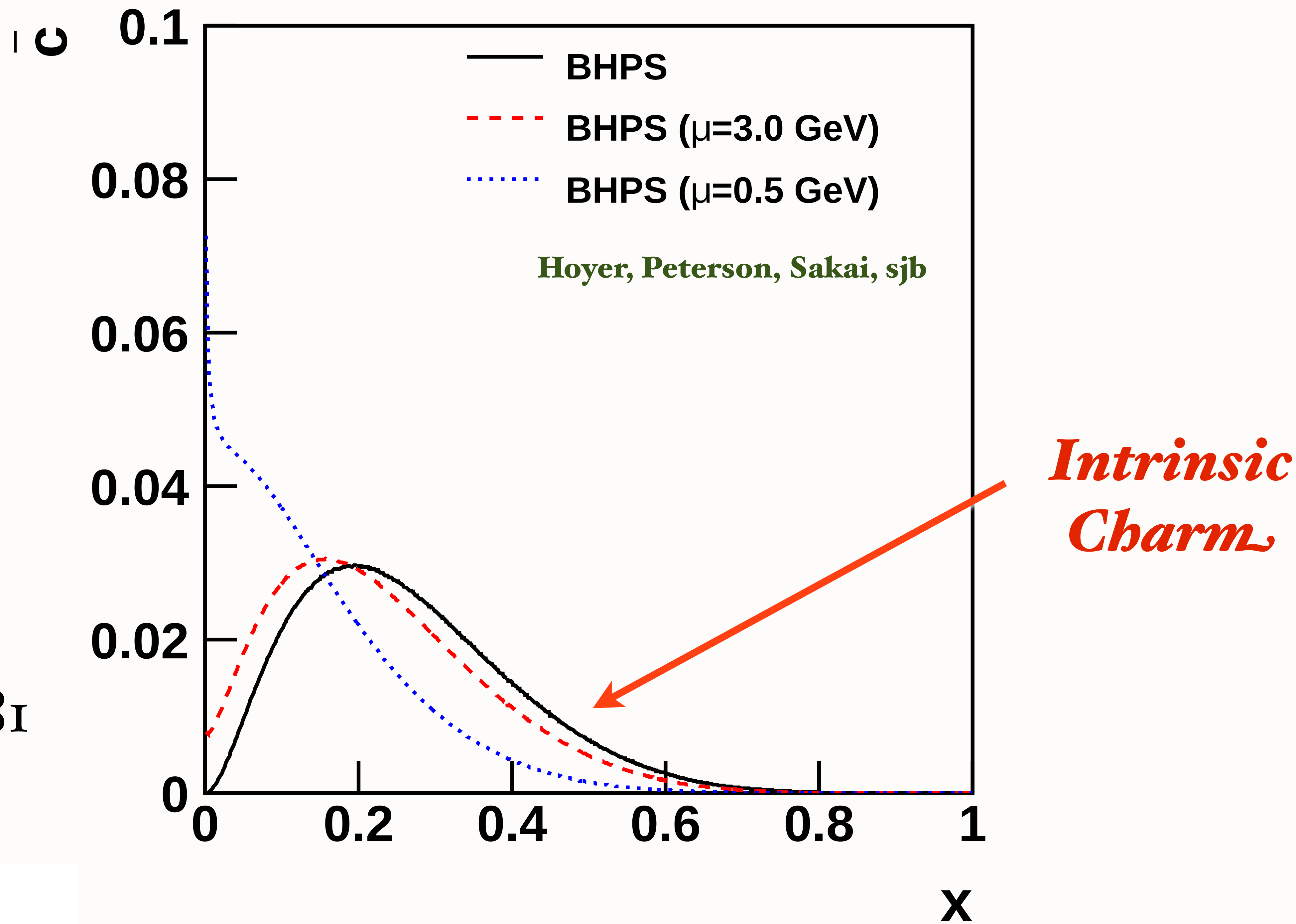
Collins, Ellis, Gunion, Mueller, sjb

M. Polyakov

QCD ($1/m_Q^2$) scaling: predict IC !

W. C. Chang and J.-C. Peng

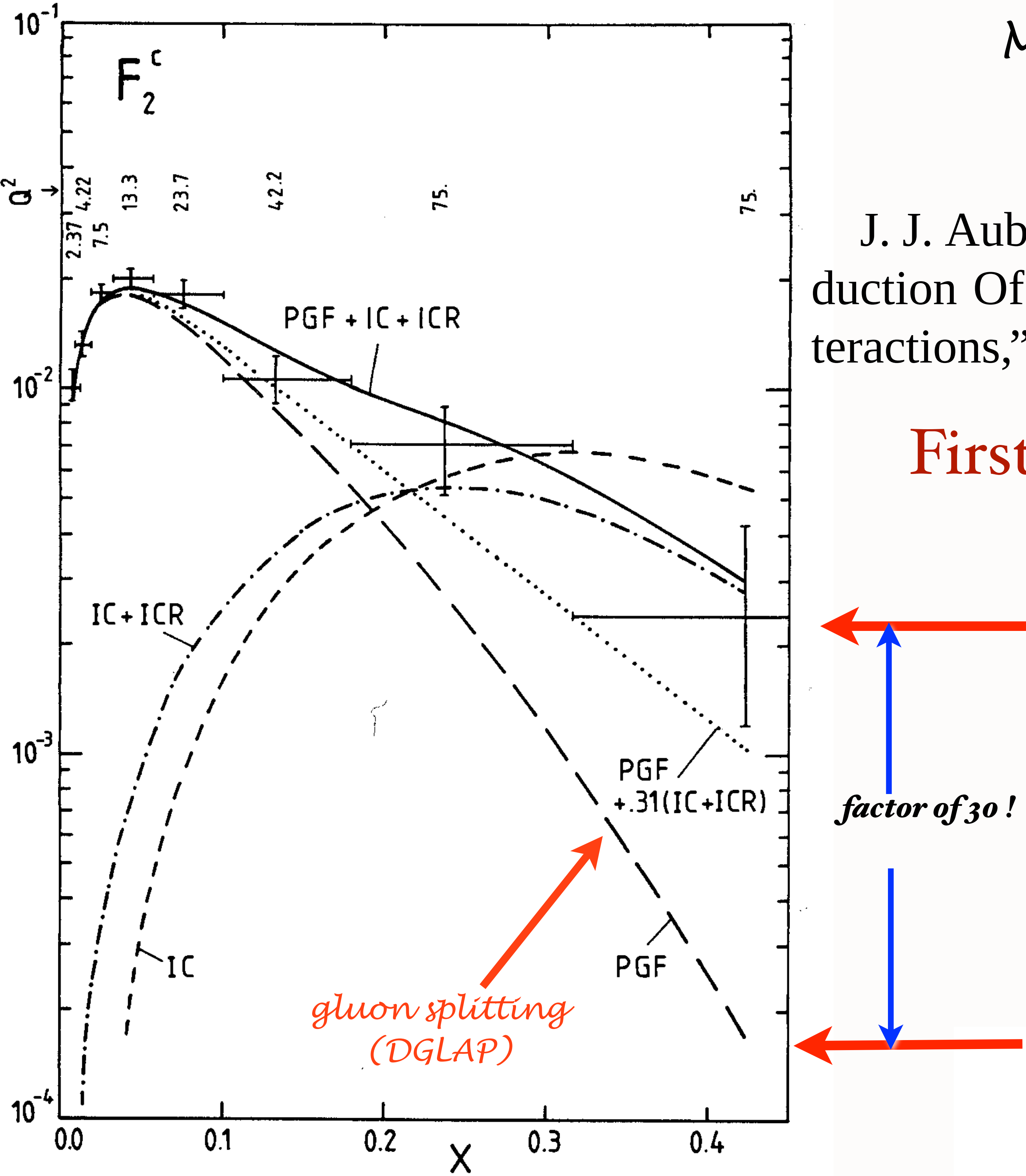
arXiv:1105.2381



Calculations of the $\bar{c}(x)$ distributions based on the BHPS model. The solid curve corresponds to the calculation using Eq. 1 and the dashed and dotted curves are obtained by evolving the BHPS result to $Q^2 = 75$ GeV^2 using $\mu = 3.0$ GeV, and $\mu = 0.5$ GeV, respectively. The normalization is set at $\mathcal{P}_5^{c\bar{c}} = 0.01$.

Consistent with EMC

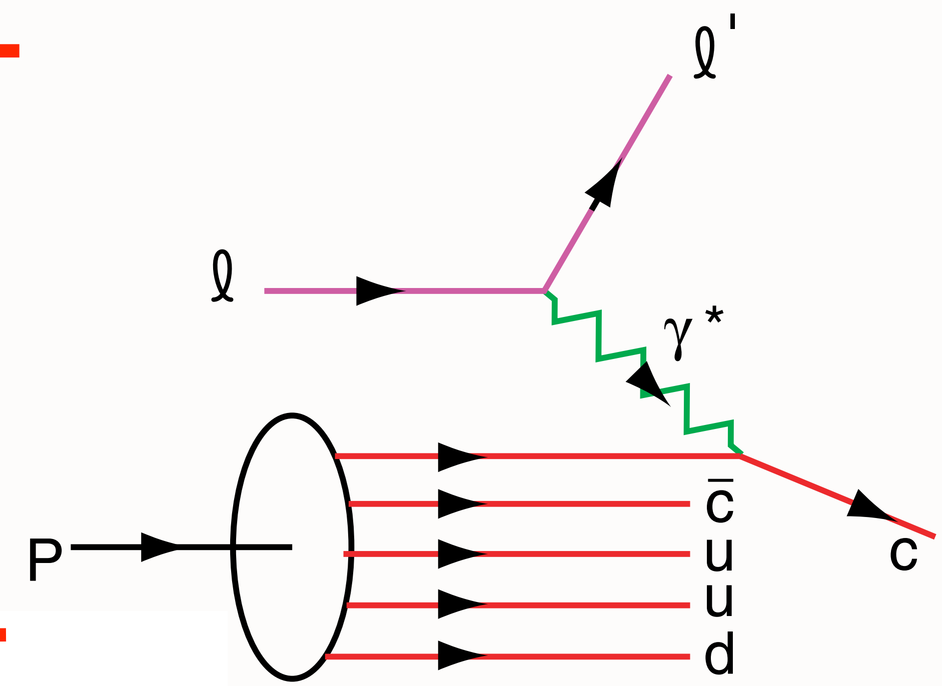
Measurement of Charm Structure Function



J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm

Hoyer, Peterson, Sakai, sjb



DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

All events have $x^F_{\psi\psi} > 0.4$!

Excludes color drag model

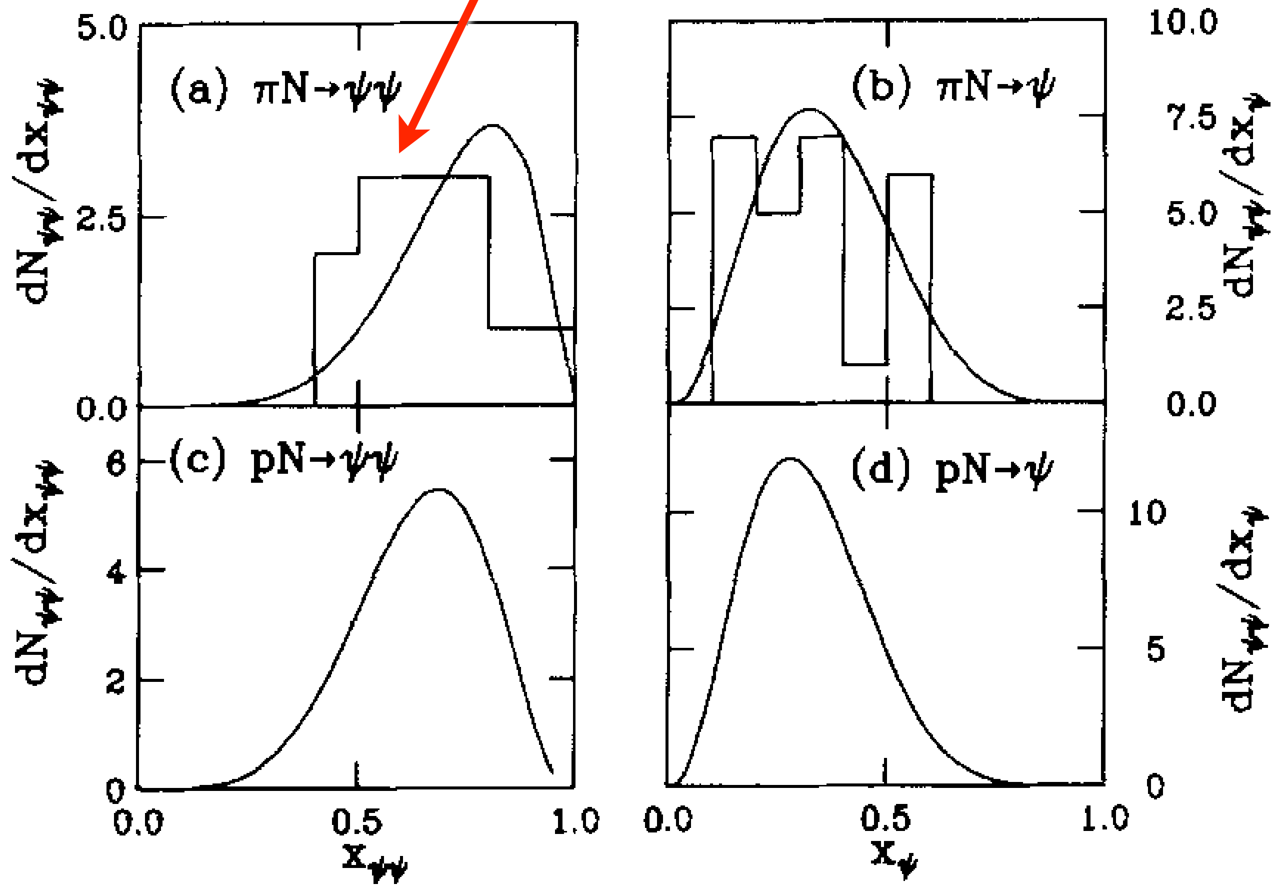


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

NA3 Data

$$\pi A \to J/\psi J/\psi X$$

Intrinsic charm contribution to double quarkonium hadroproduction ★

R. Vogt [a], S.J. Brodsky [b]

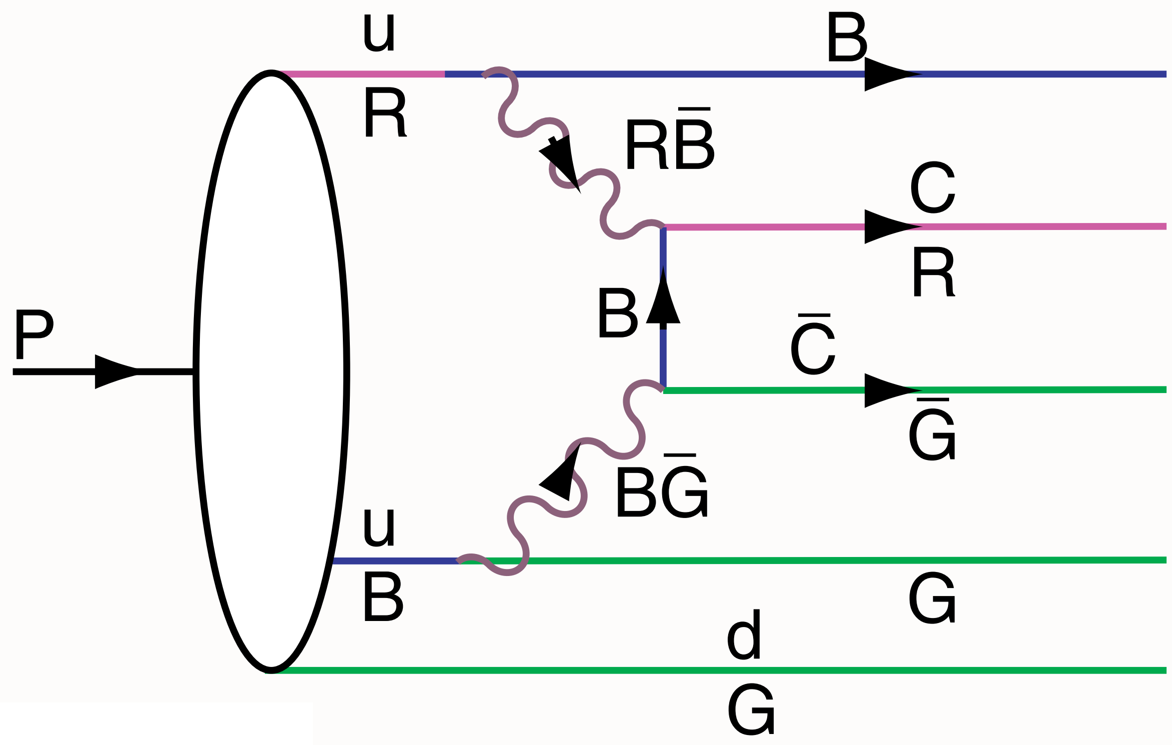
The probability distribution for a general n-parti intrinsic $c\bar{c}$ Fock state as a function of x and k_T written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^{n} dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^{n} k_{T,i})\delta(1-\sum_{i=1}^{n} x_i)}{(m_h^2 - \sum_{i=1}^{n}(m_{T,i}^2/x_i))^2},$$

JLab 12 GeV: An Exotic Charm Factory!

- **Charm quarks at high x -- allows charm states to be produced with minimal energy**
- **Charm produced at low velocities in the target -- the target rapidity domain** $x_F \sim -1$
- **Charm at threshold -- maximal domain for producing exotic states containing charm quarks**
- **Attractive QCD Van der Waals interaction -- "nuclear-bound quarkonium"**
  Miller, sjb; de Teramond,sjb
- **Dramatic Spin Correlations in the threshold Domain** σ_L vs. σ_T, A_{NN}
- **Strong SSS Threshold Enhancement**

Hoyer, Peterson, Sakai, sjb



$|uudcc >$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^- >$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

cc in Color Octet

Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

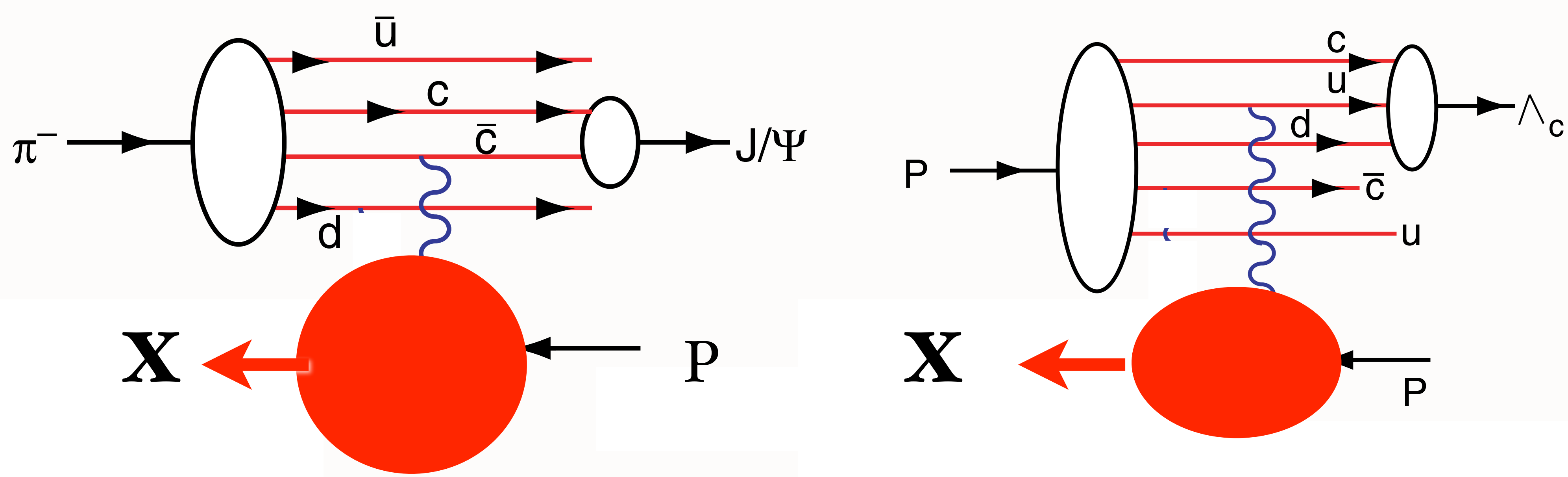
$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x strange and charm!

Heavy Quarks at Threshold

Action Principle: Minimum KE, maximal potential

Leading Hadron Production from Intrinsic Charm

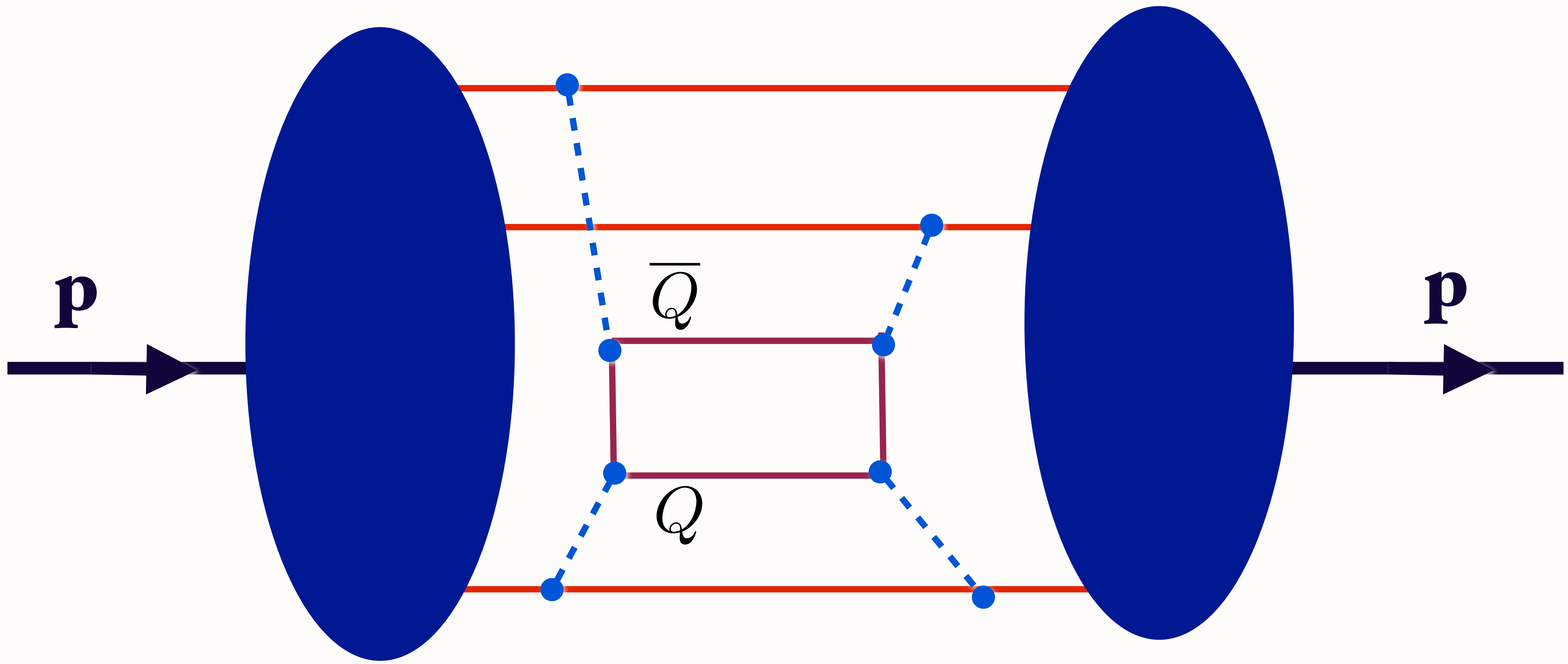


Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

Proton Self Energy from gluon-gluon scattering

QCD predicts Intrinsic Heavy Quarks!

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$



$$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$$

$$\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$$

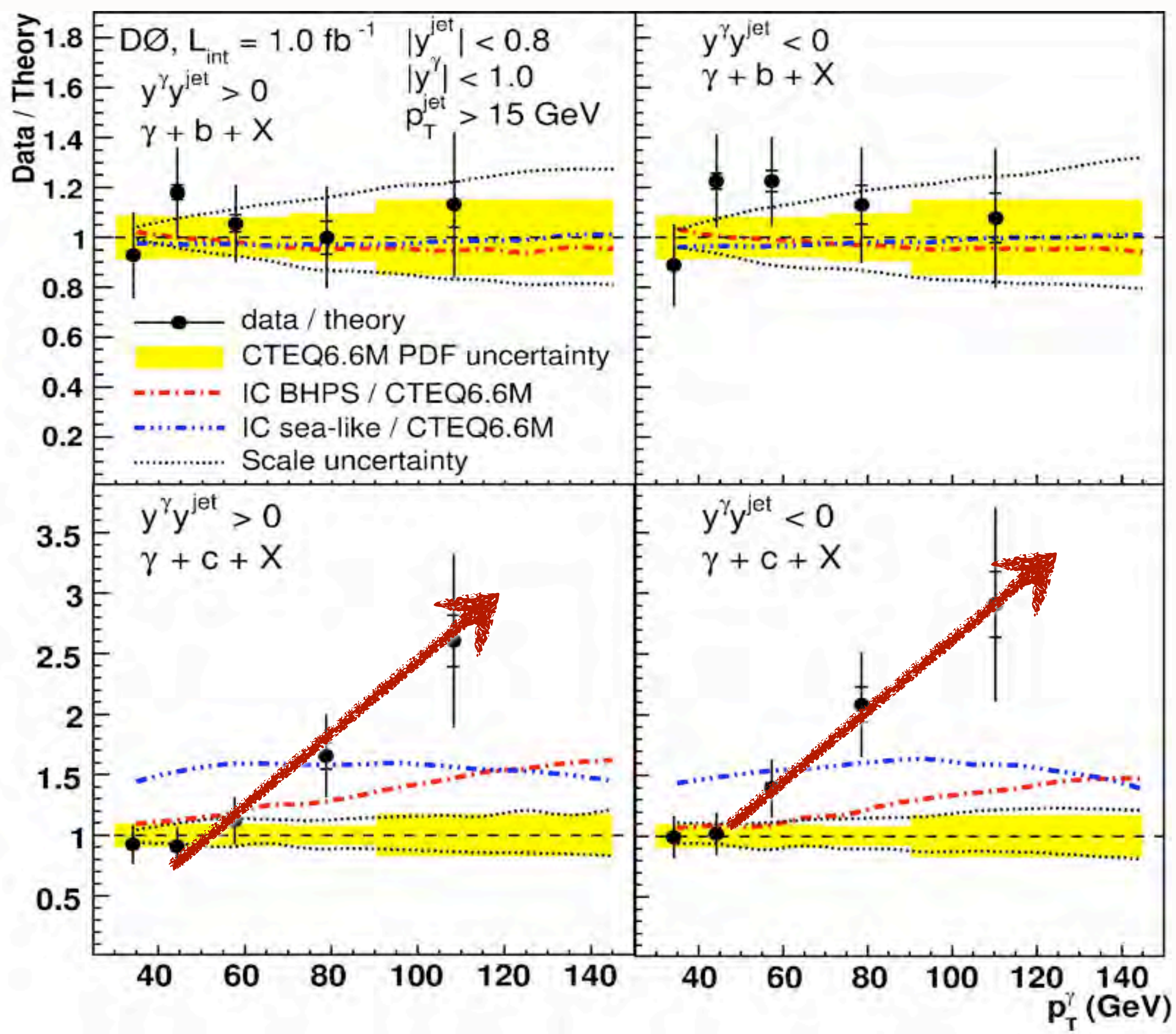
$$(g-2)_\mu \propto \frac{\alpha^3}{\pi^3} \log \frac{m_\mu^2}{m_e^2}$$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

from light-by-light scattering

PRL 102, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV



$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1 ?

- EMC data: $c(x,Q^2) > 30 \times \text{DGLAP}$
  $Q^2 = 75 \text{ GeV}^2$, $x = 0.42$

- High x_F $pp \to J/\psi X$

- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

C.H. Chang, J.P. Ma, C.F. Qiao and X.G.Wu,

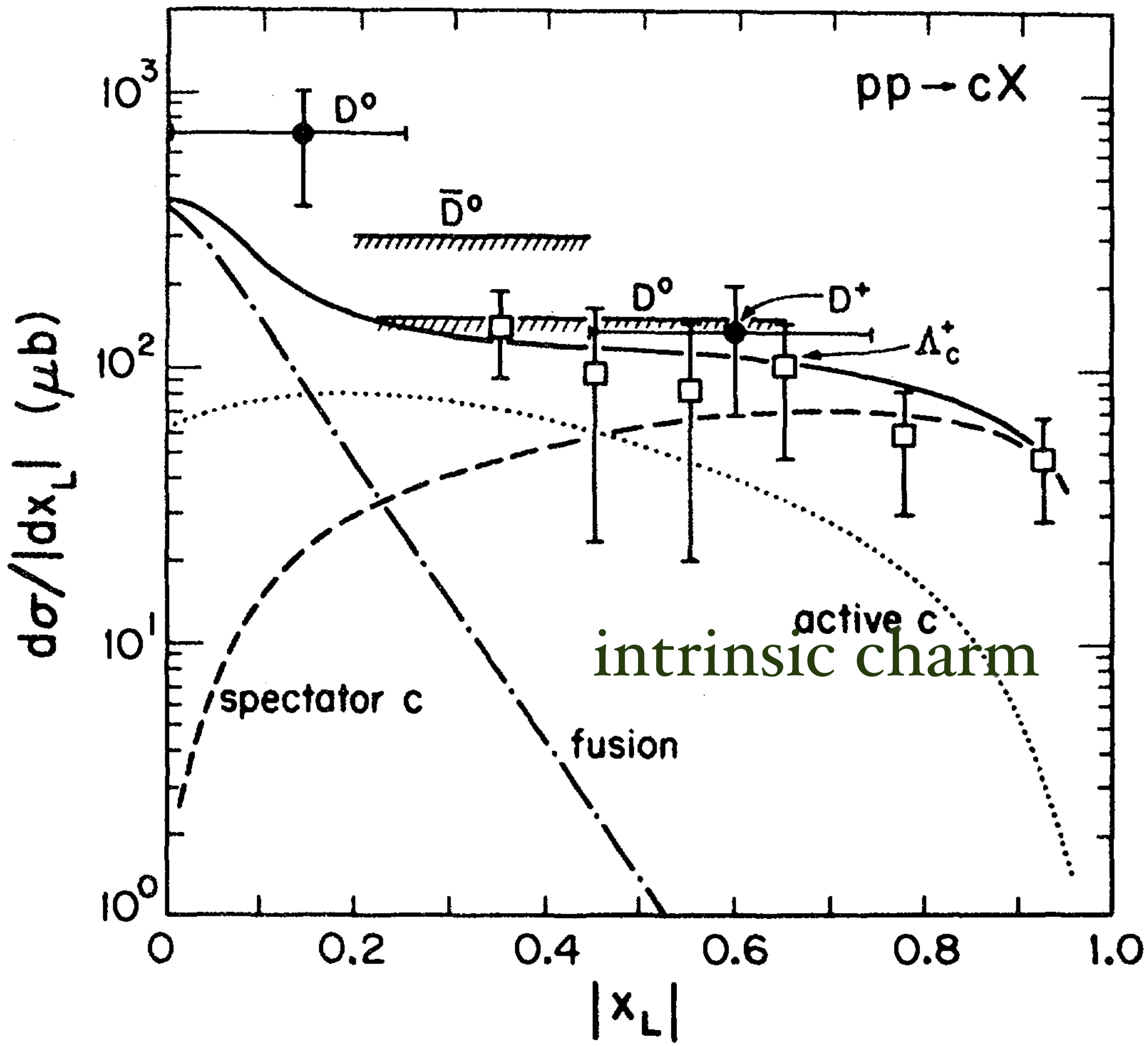
- High x_F $pp \to \Xi(ccd)X$ (SELEX)

Critical Measurements at threshold for JLab, PANDA

Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

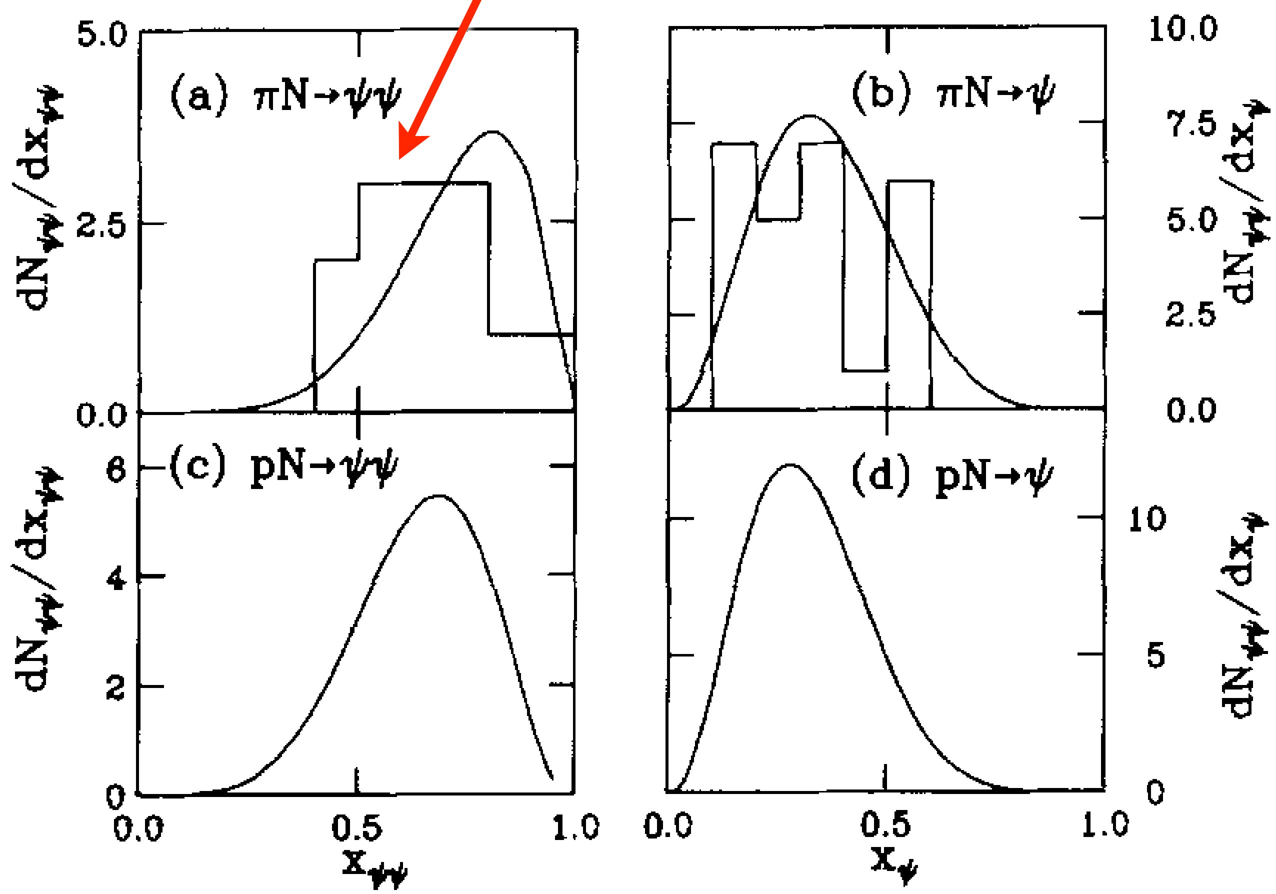


Barger, Halzen, Keung

Evidence for charm at large x

All events have $x^F_{\psi\psi} > 0.4$!

Excludes color drag model



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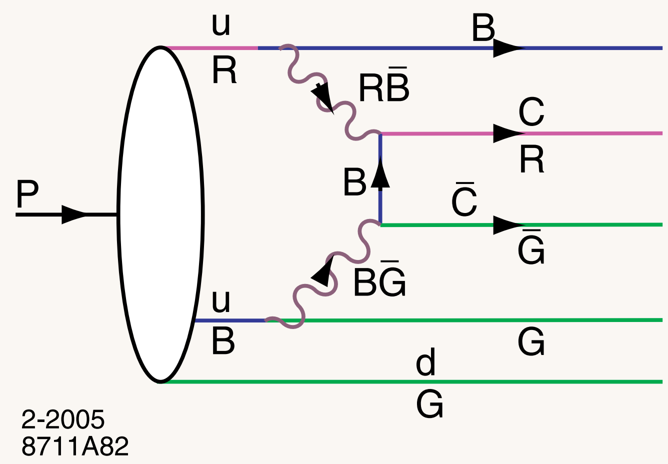
Hoyer, Peterson, Sakai, sjb
M. Polyakov, et. al

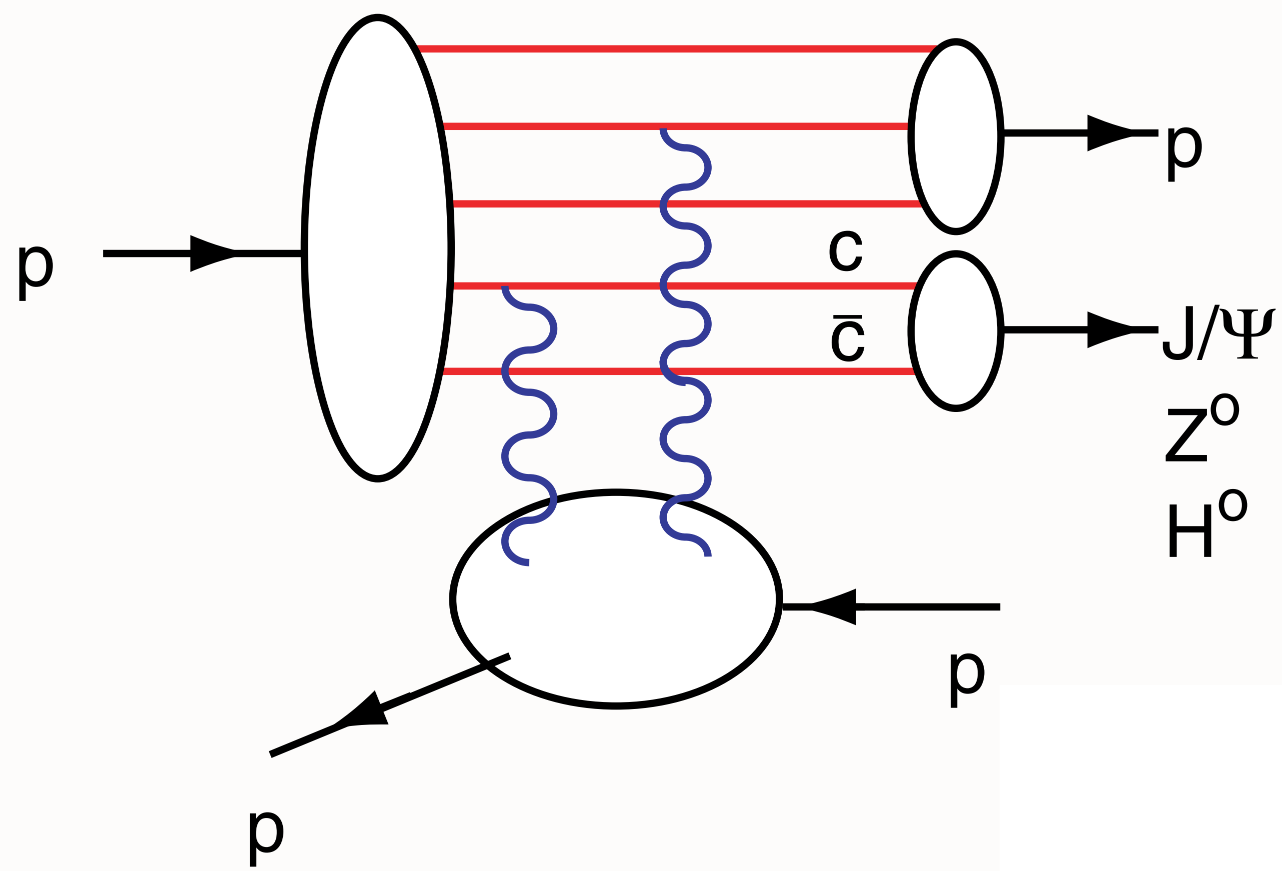
Intrinsic Heavy-Quark Fock States



- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $\quad P_{Q\bar{Q}} \propto \frac{1}{M_Q^2} \quad P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}} \quad P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production at high x_F (Kopeliovich, Schmidt, Soffer, Goldhaber, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests (Gardener, Karliner, ..), including B-decays

Solution to $J/\psi \to \rho\pi$ Puzzle

Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$p\,p \to J/\psi\; p\; p$$

$$x_{J/\psi} = x_c + x_c$$

Exclusive Diffractive
High-X_F Higgs Production

Kopeliovitch, Schmidt, Soffer, sjb

Intrinsic cc pair formed in color octet 8_C in proton wavefunction Large Color Dipole

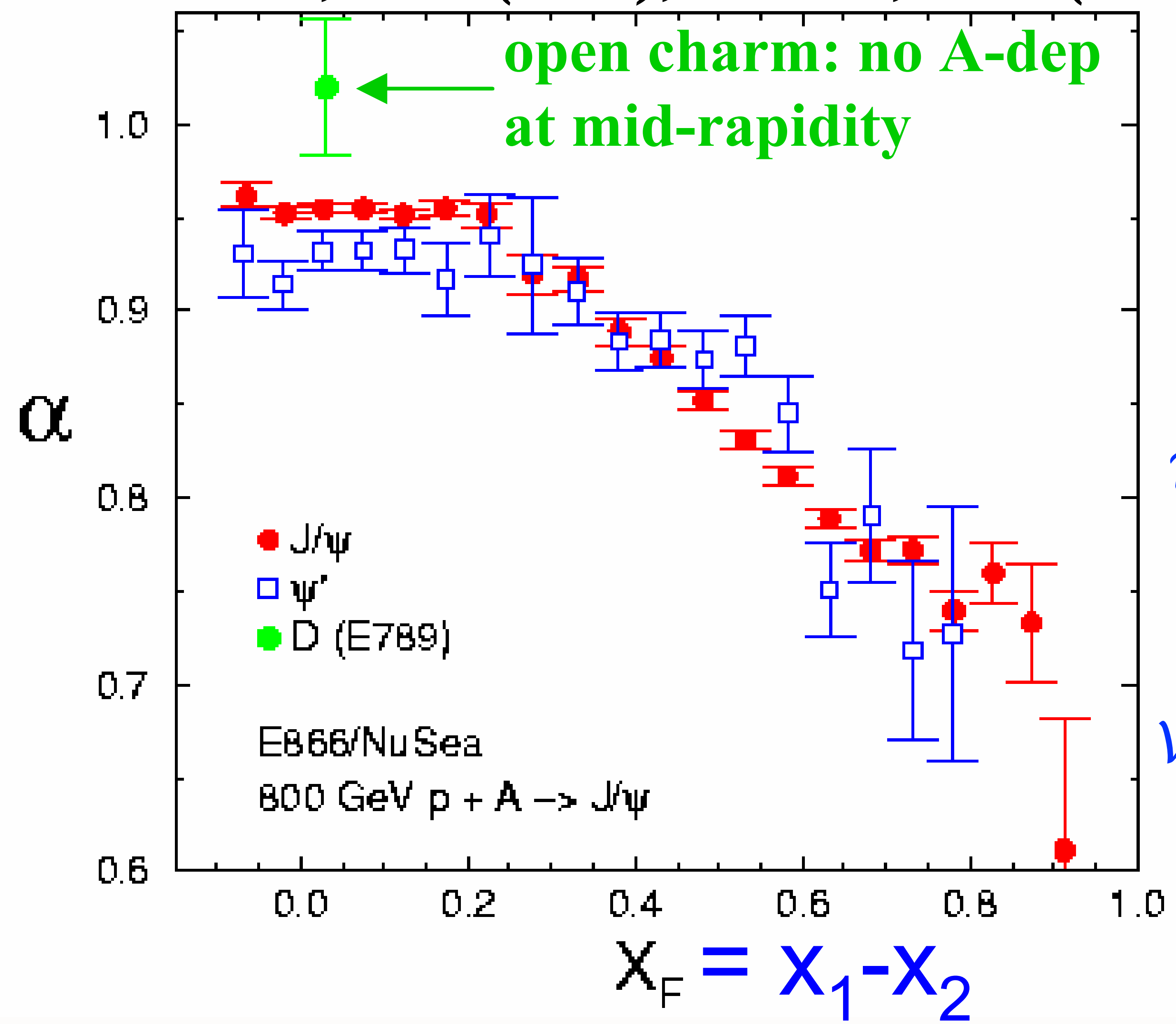
Collision produces color-singlet J/ψ through color exchange

RHIC Experiment

M. Leitch

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^{\alpha}$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Remarkably Strong Nuclear Dependence for Fast Charmonium

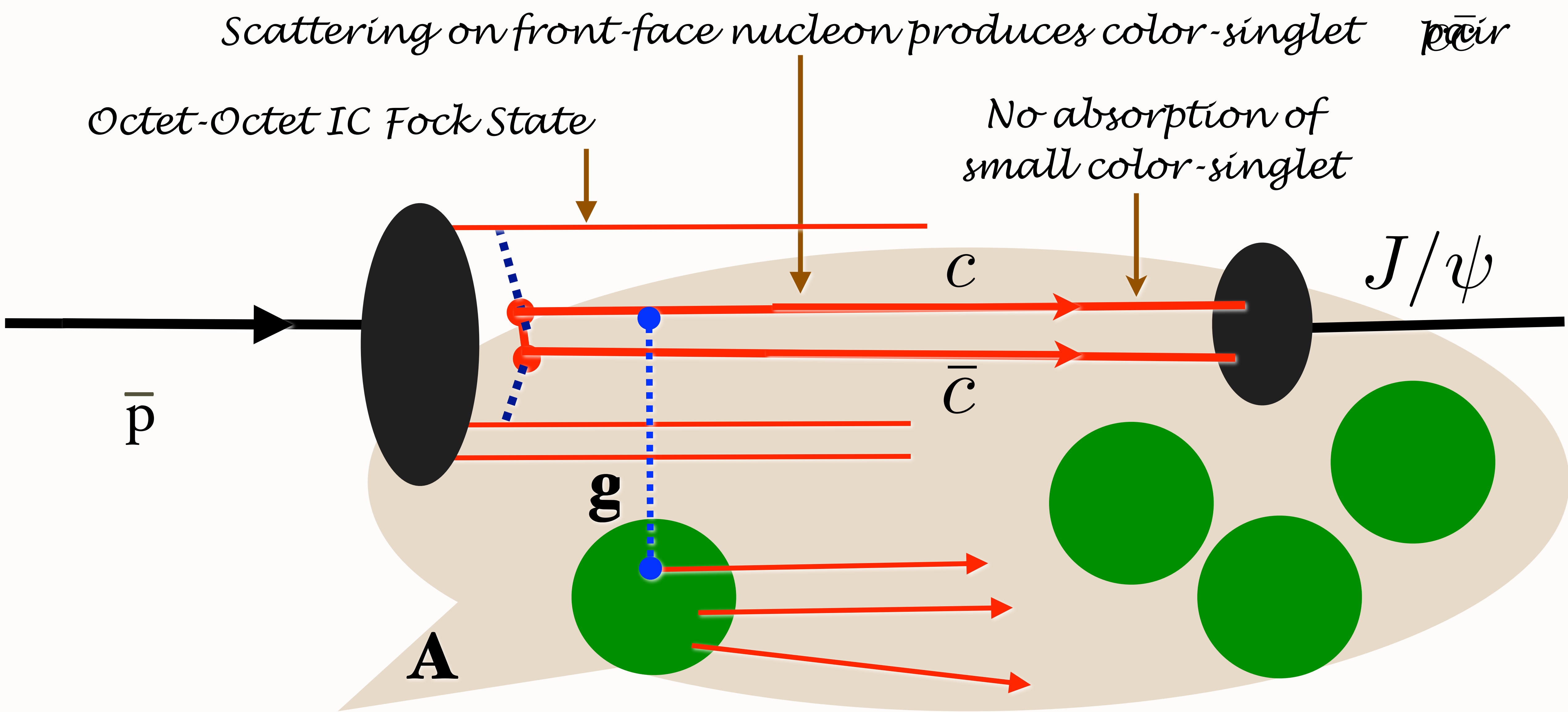
Violation of PQCD Factorization!

Violation of factorization in charm hadroproduction.

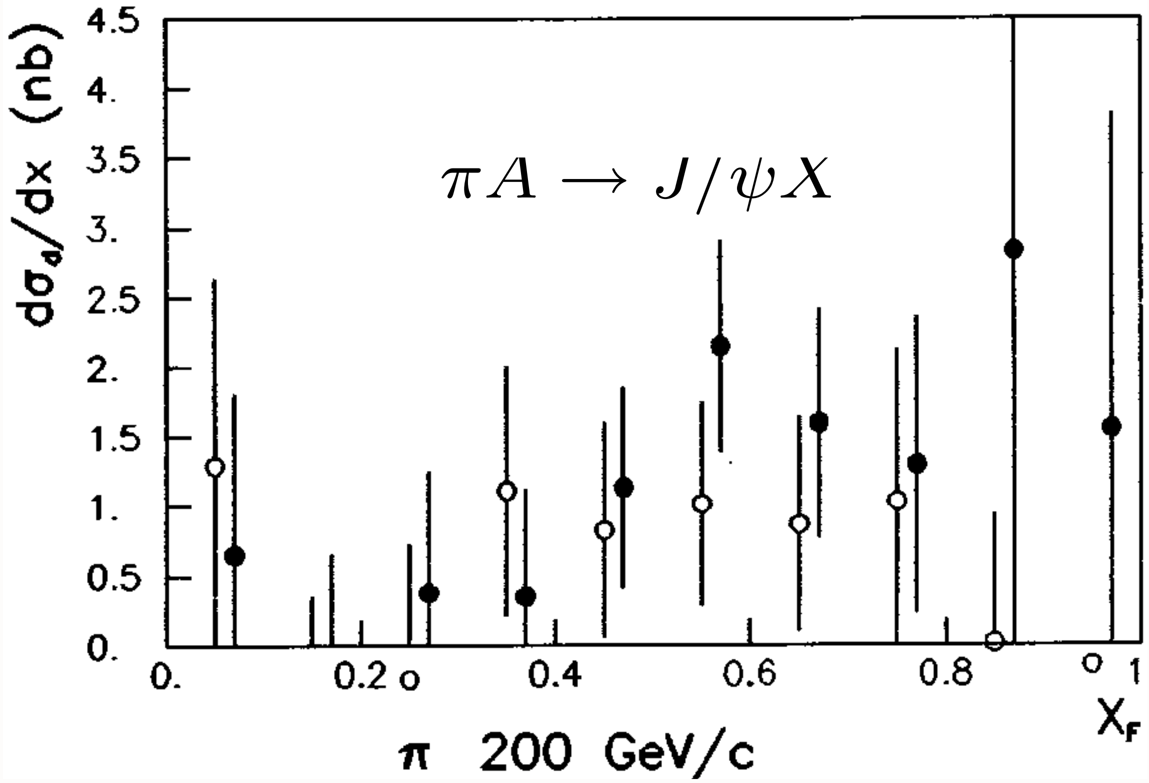
P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp. Published in Phys.Lett.B246:217-220,1990

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb

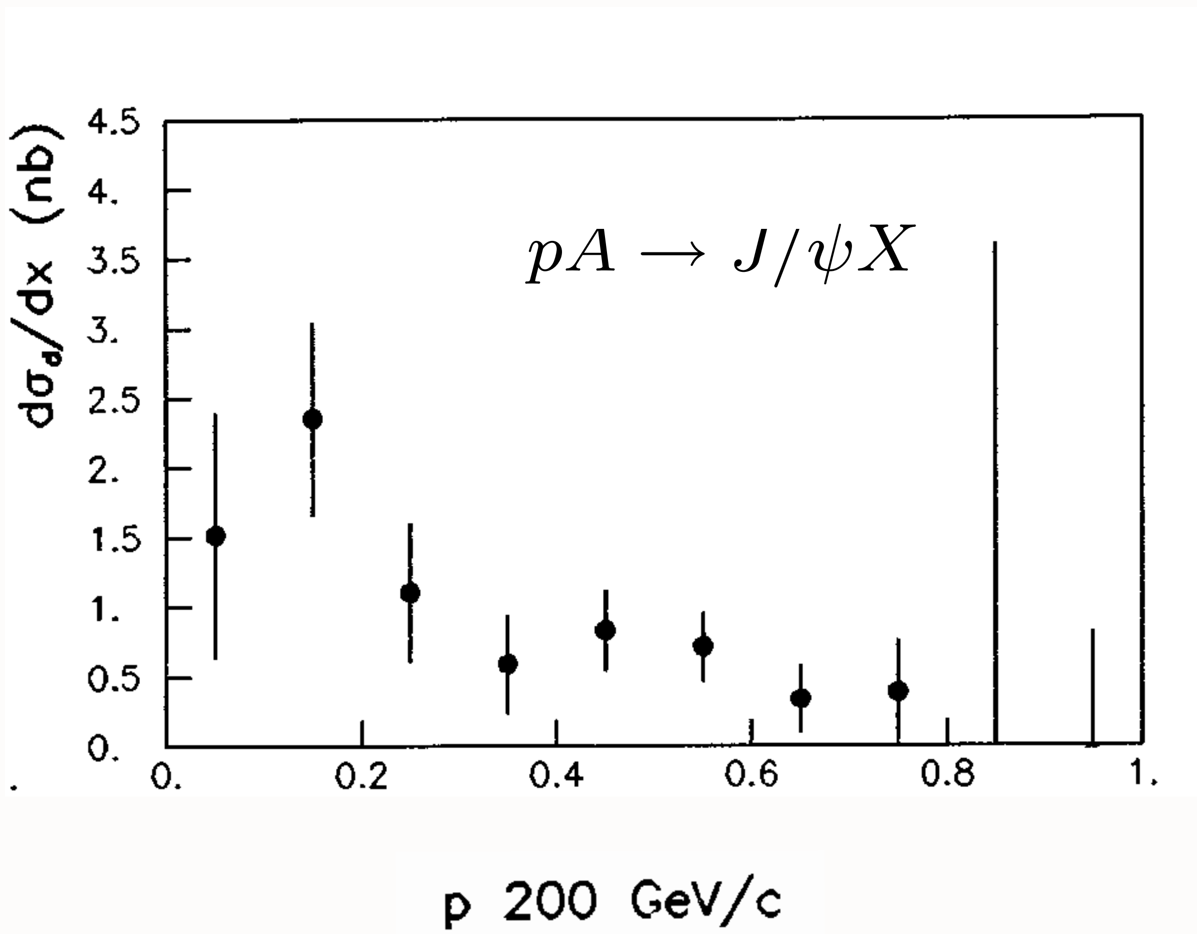


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$



$A^{2/3}$ component

J. Badier et al, NA3



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_{2/3}}{dx_F}$$

Excess beyond conventional PQCD subprocesses

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

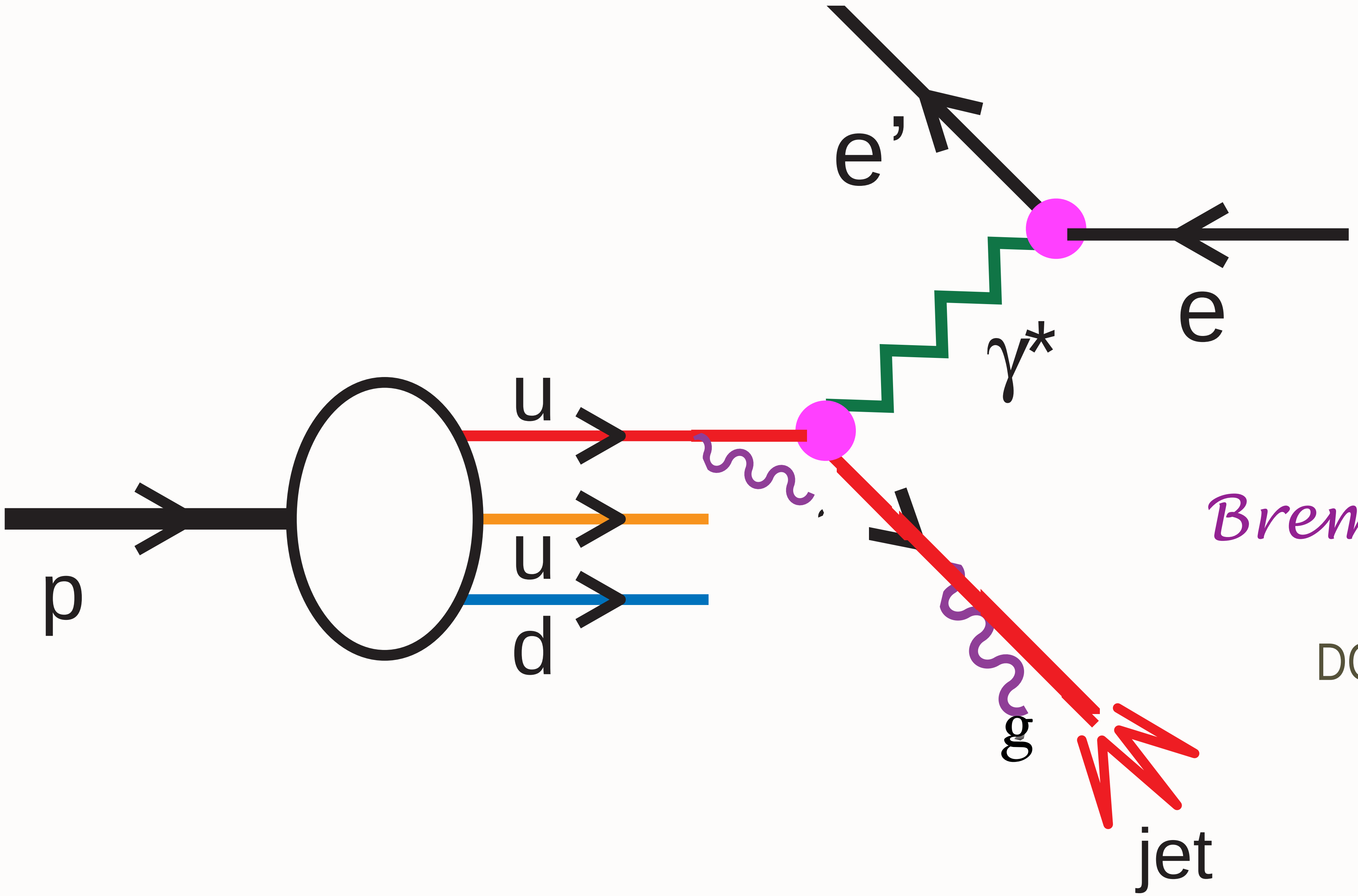
Color Opaqueness

- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- IC leads to new effects in B decay (Gardner, SJB)

Higgs production at x_F = 0.8

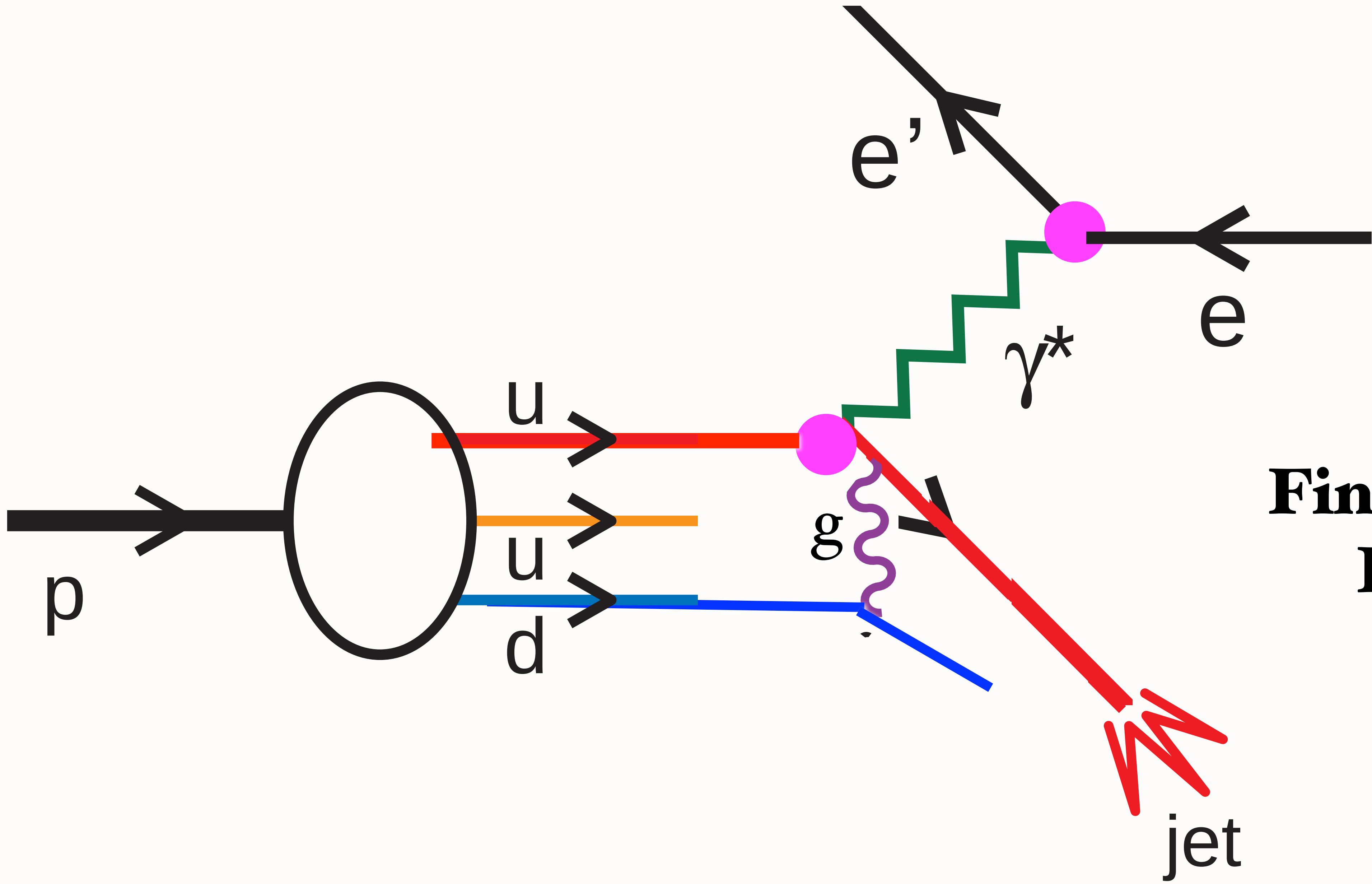
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:

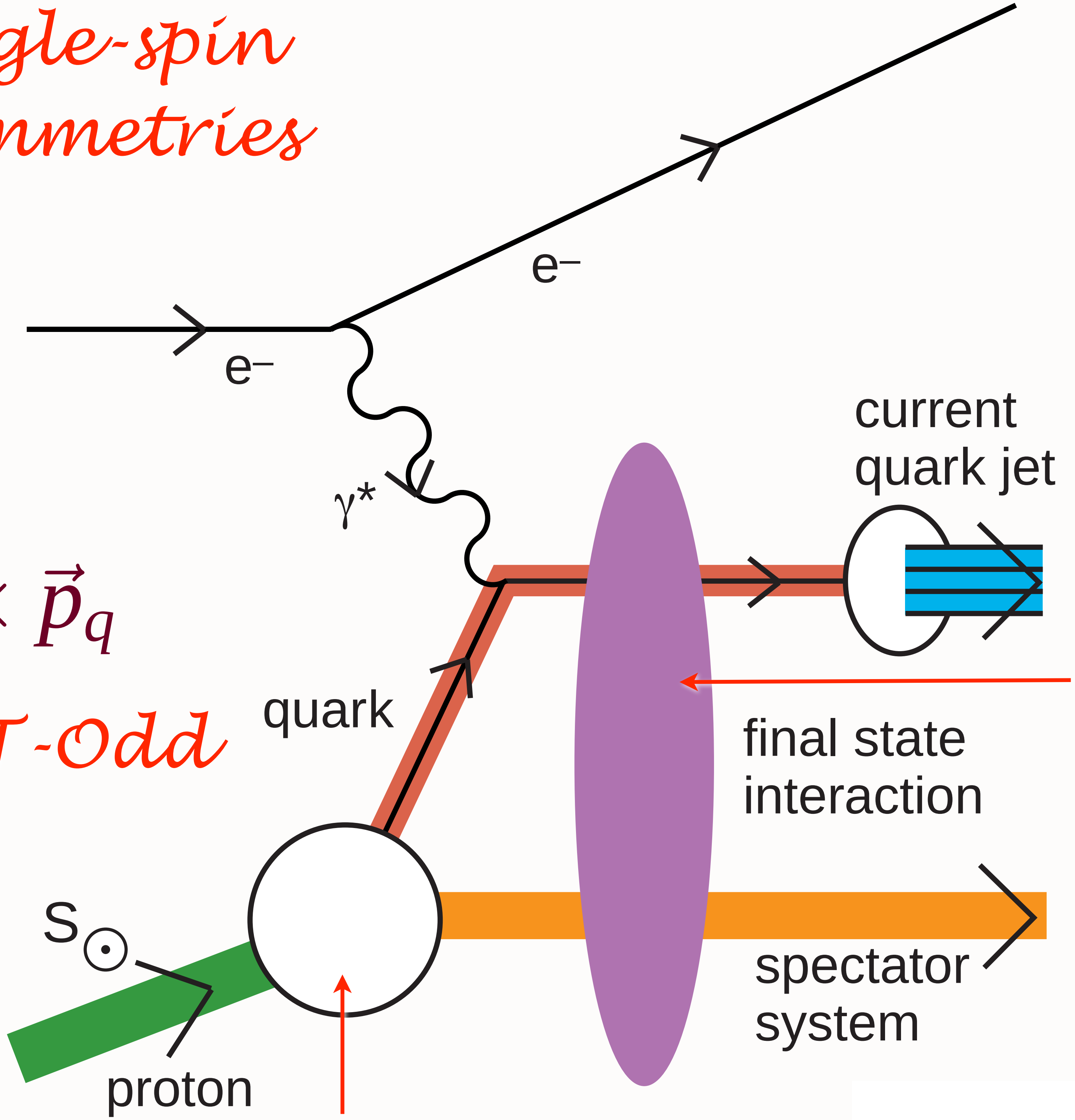
Final-state interactions of struck quark can be neglected

Single-spin asymmetries

Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt, Ji, Yuan. Pasquini, ...



$$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo- T-Odd

QED: Lensing involves soft scales

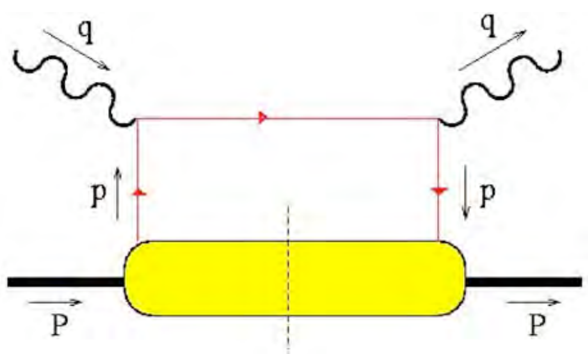
Light-Front Wavefunction S and P- Waves!

QCD S- and P- Coulomb Phases --Wilson Line

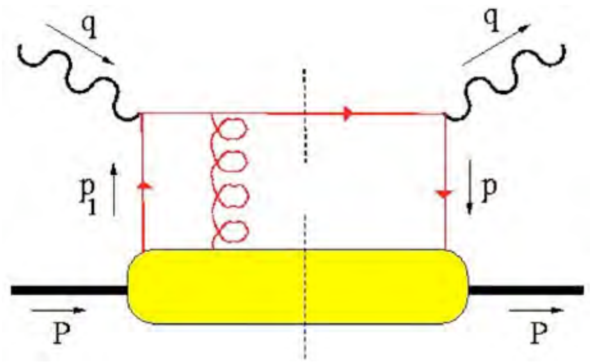
"Lensing Effect"

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!



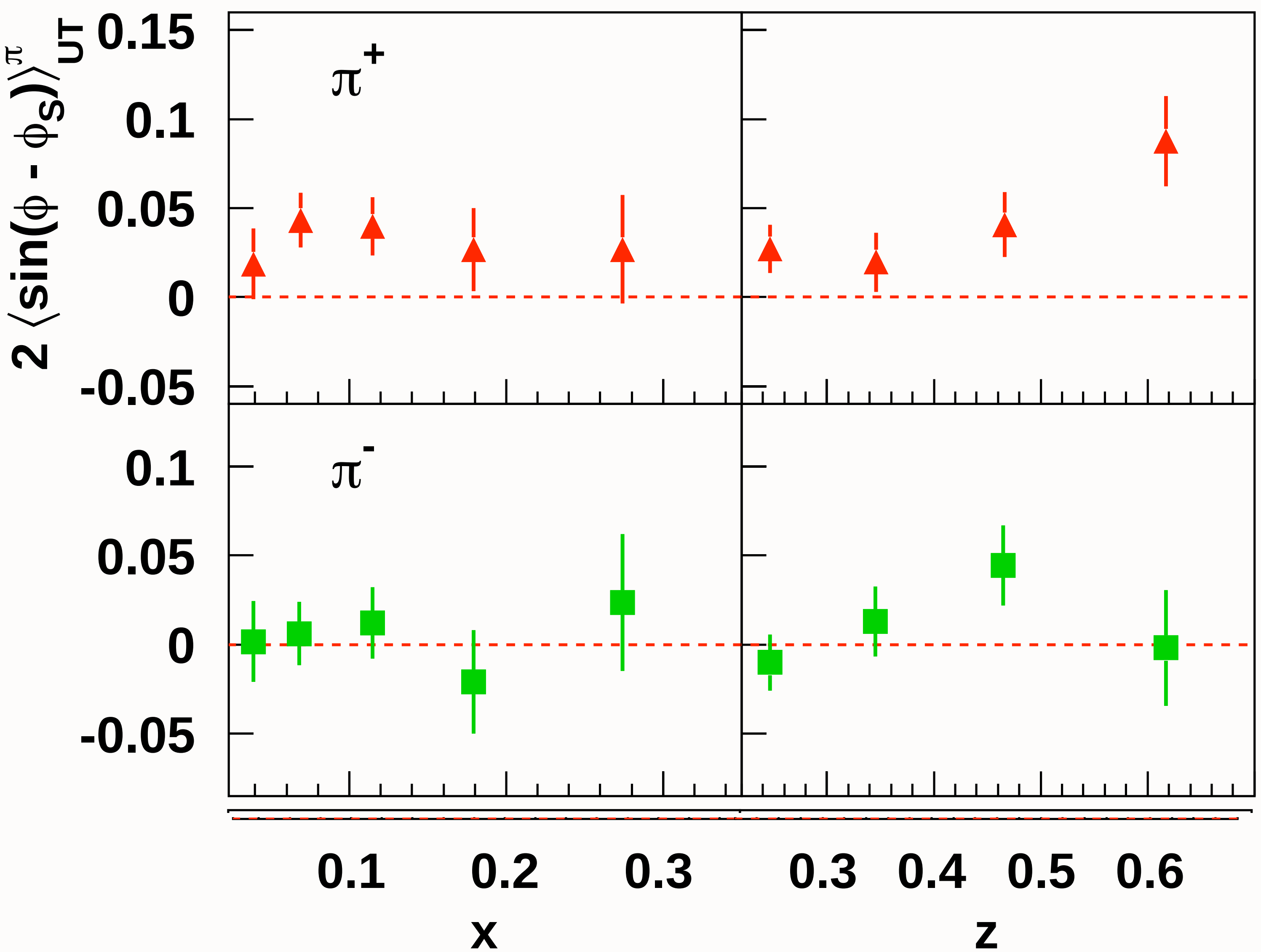
can interfere with



and produce a T-odd effect! (also need $L_z \neq 0$)

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

Sivers asymmetry from HERMES



- First evidence for non-zero Sivers function!
- $\Rightarrow$ presence of non-zero **quark orbital angular momentum**!
- Positive for π^+...
  Consistent with zero for π^-...

Gamberg: Hermes data compatible with BHS model

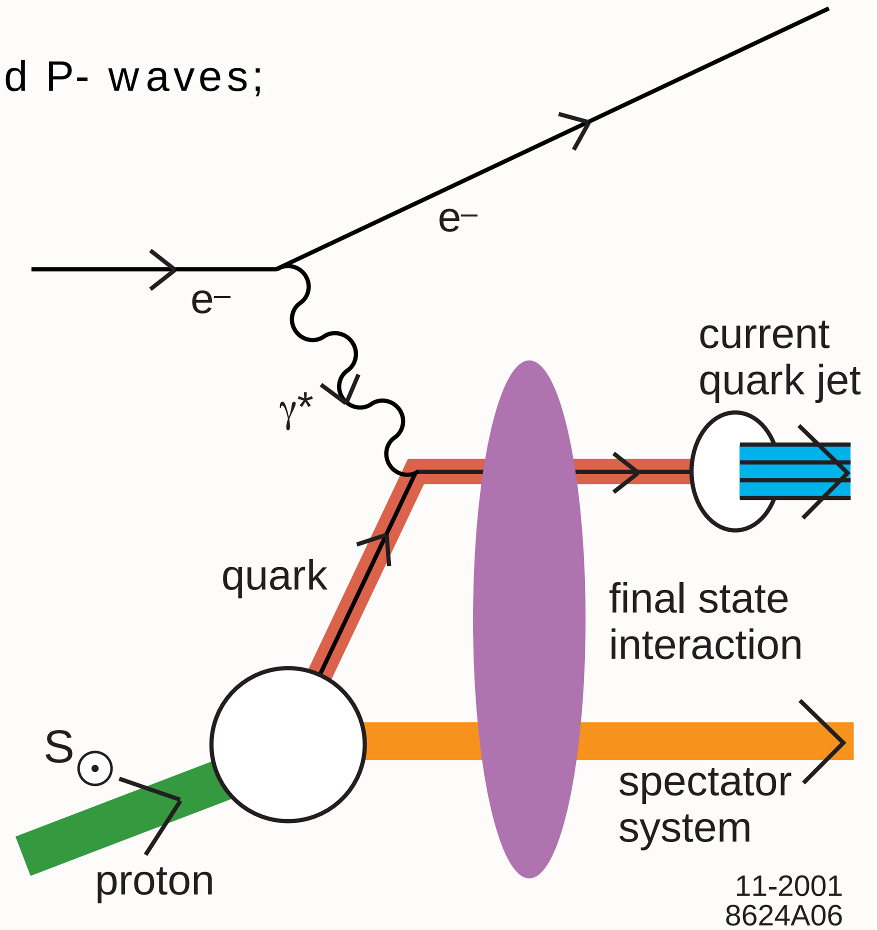
Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment

Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

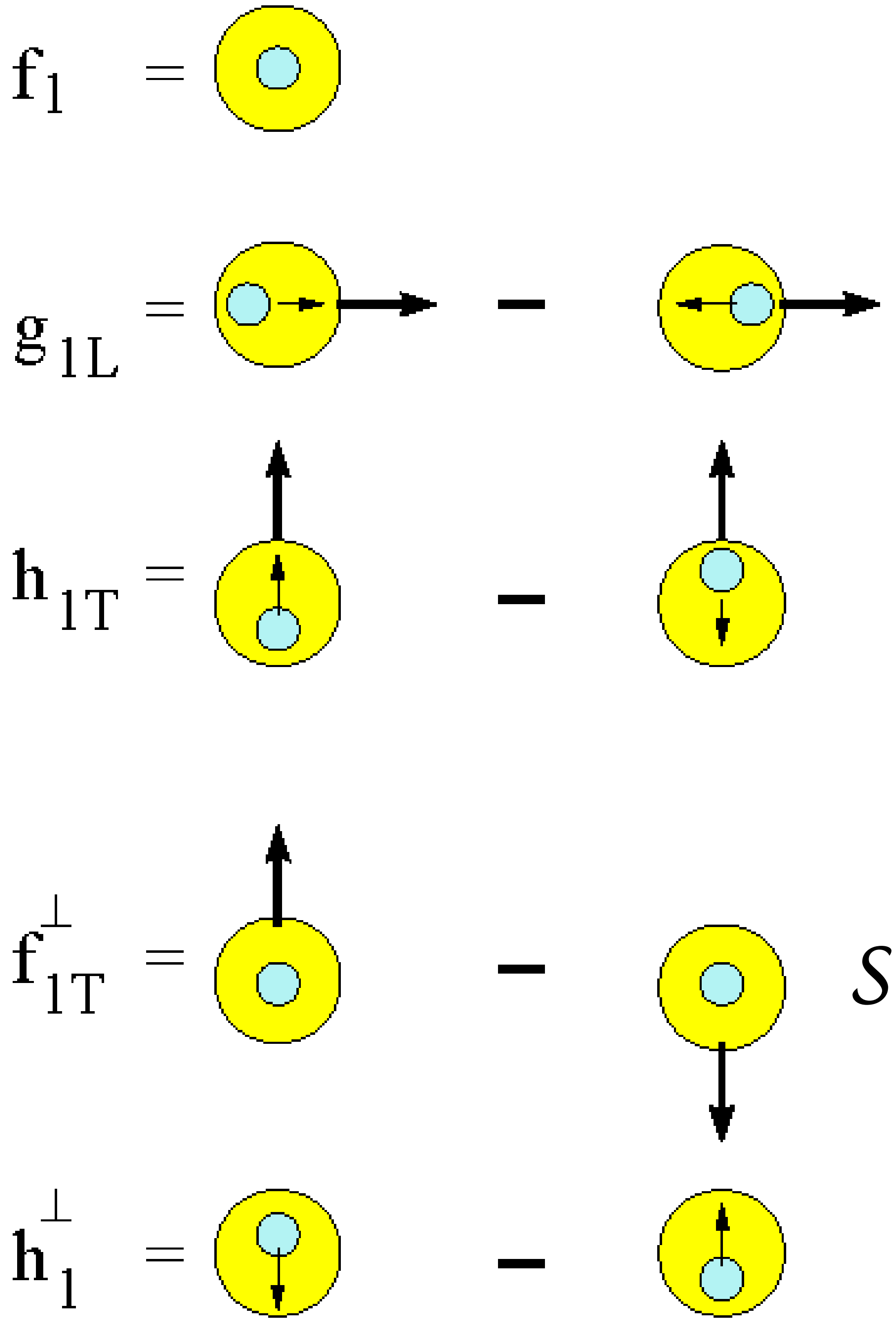
Hwang, Schmidt, sjb
Collins

$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves;
- Wilson line effect -- lc gauge prescription
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD phase at soft scale!
- New window to QCD coupling and running gluon mass in the IR
- QED S and P Coulomb phases infinite -- difference of phases finite!
- Alternate: Retarded and Advanced Gauge: Augmented LFWFs



Pasquini, Xiao, Yuan, sjb
Mulders, Boer   Qiu, Sterman



Unpolarized Distribution

Bj Sum Rule

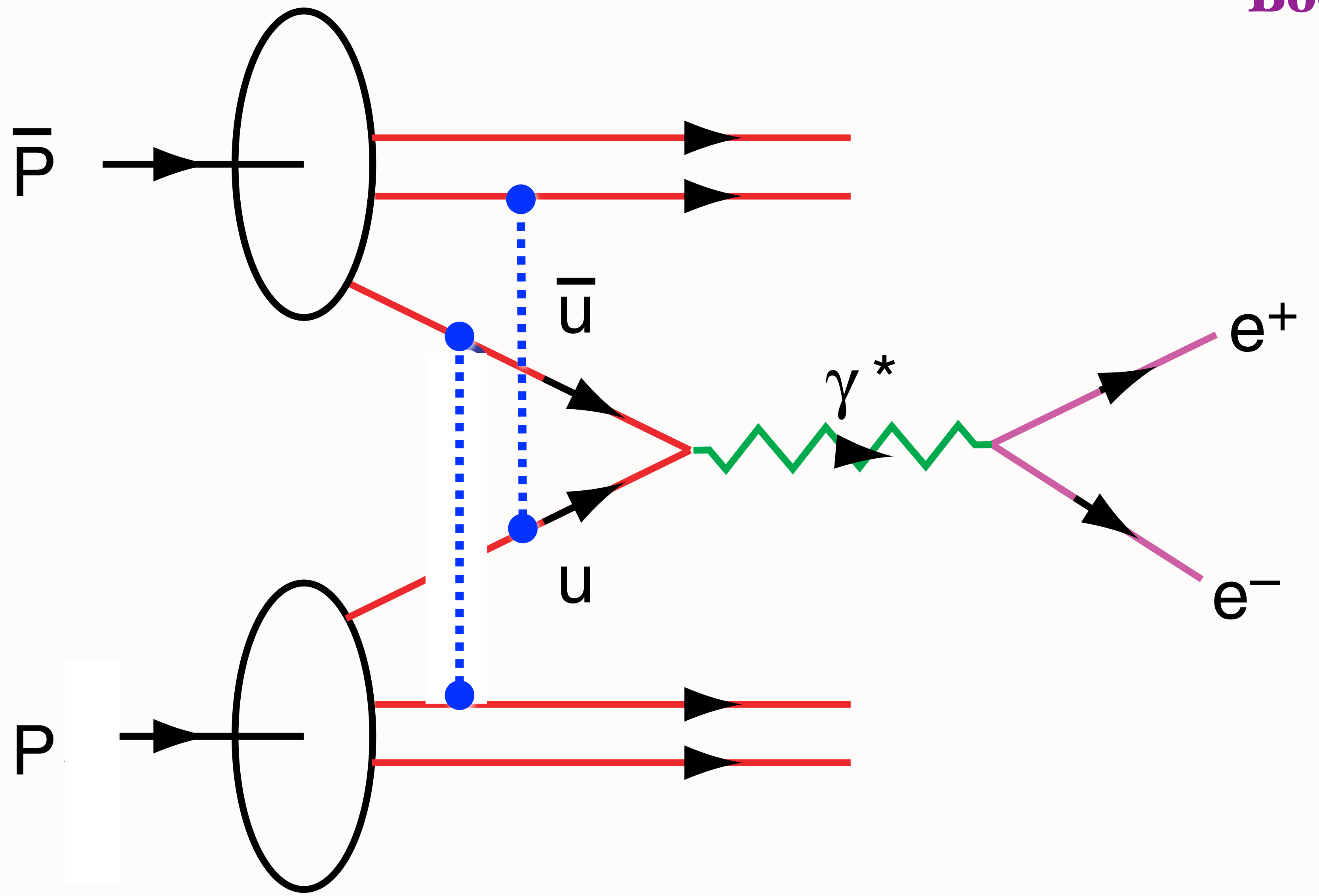
Transversity

Sivers Function

Boer-Mulders Function

T-Odd:
Require ISI or FSI

Boer, Hwang, sjb



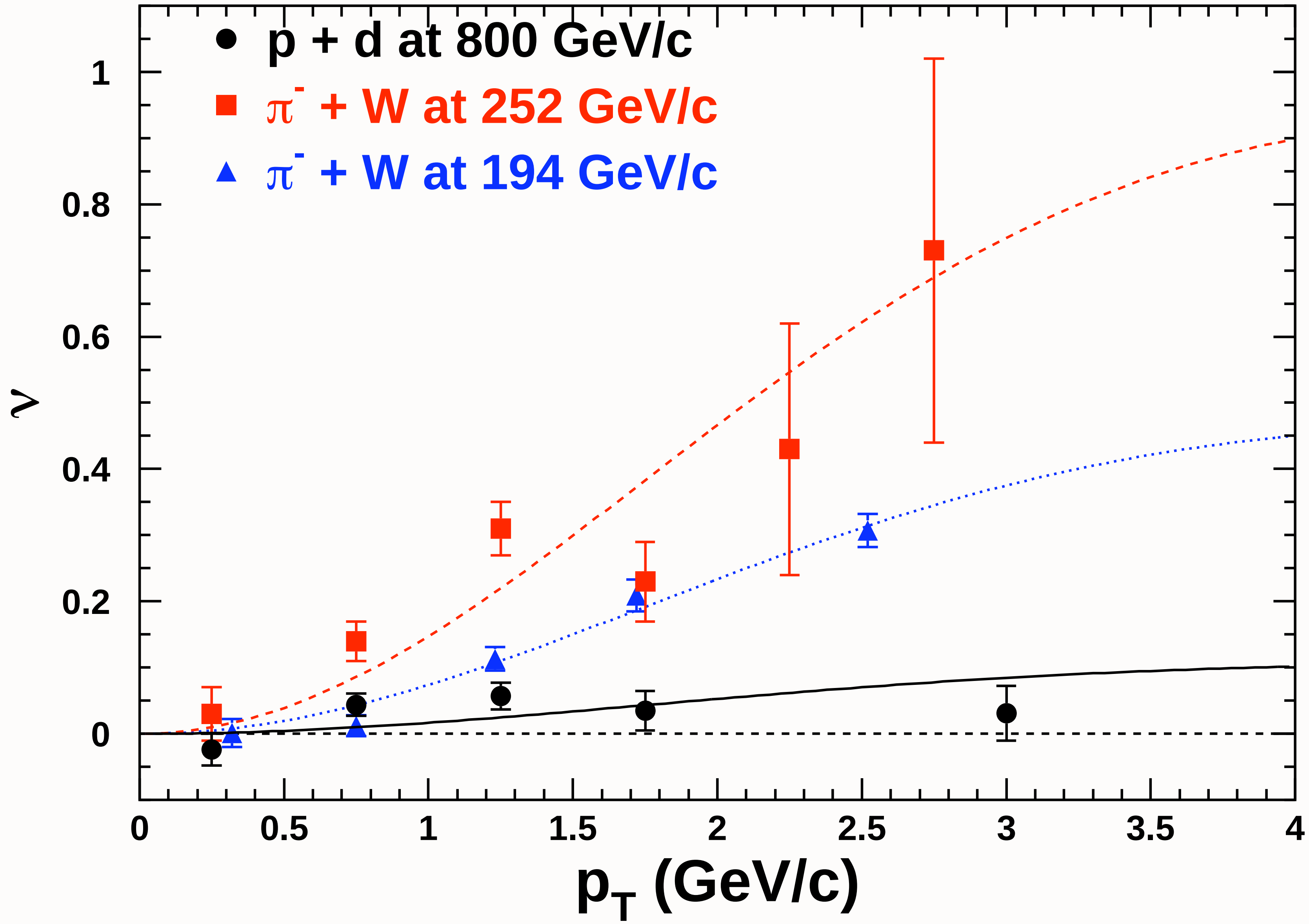
DY $\cos 2\phi$ correlation at leading twist from double ISI

Product of Boer - Mulders Functions

$$h_1^{\perp}(x_1, \boldsymbol{p}_\perp^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_\perp^2)$$

Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)



Huge Effect in $\pi W \to \mu^+\mu^- X$

Negligible Effect $pd \to \mu^+\mu^- X$

Parameter ν vs. p_T in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c^2 are also shown.

Double Initial-State Interactions generate anomalous $\cos 2\phi$

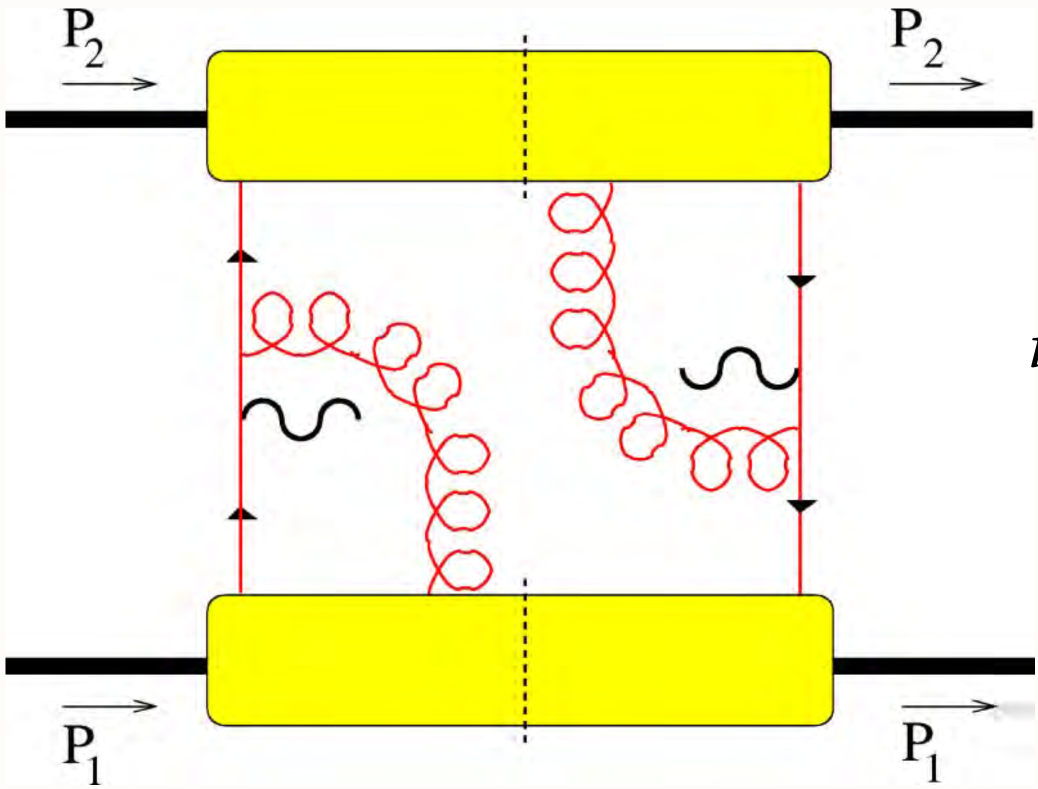
Drell-Yan planar correlations

Boer, Hwang, sjb

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\,\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

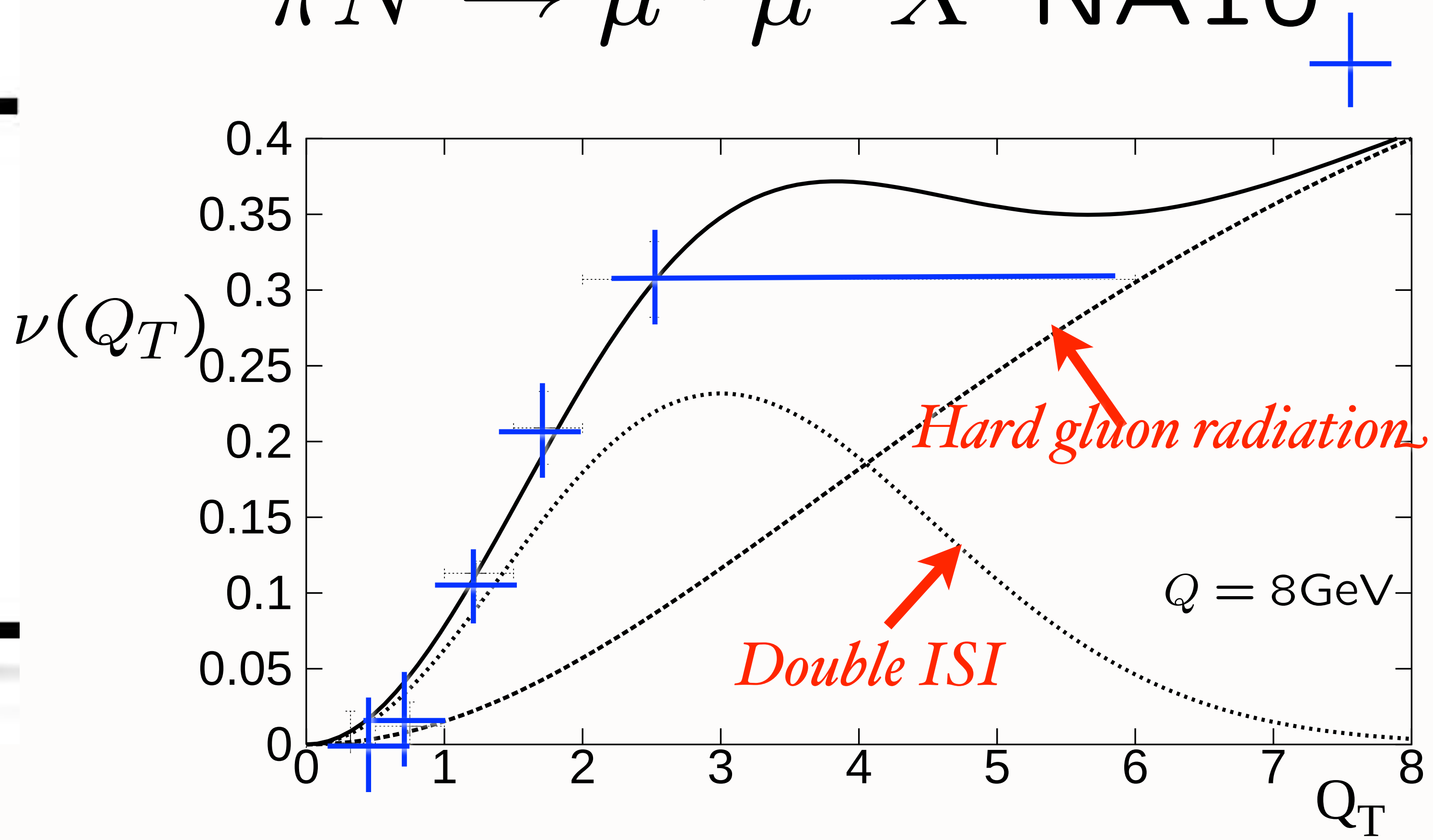
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^\perp(\pi)\, h_1^\perp(N)$$



Violates Lam-Tung relation!

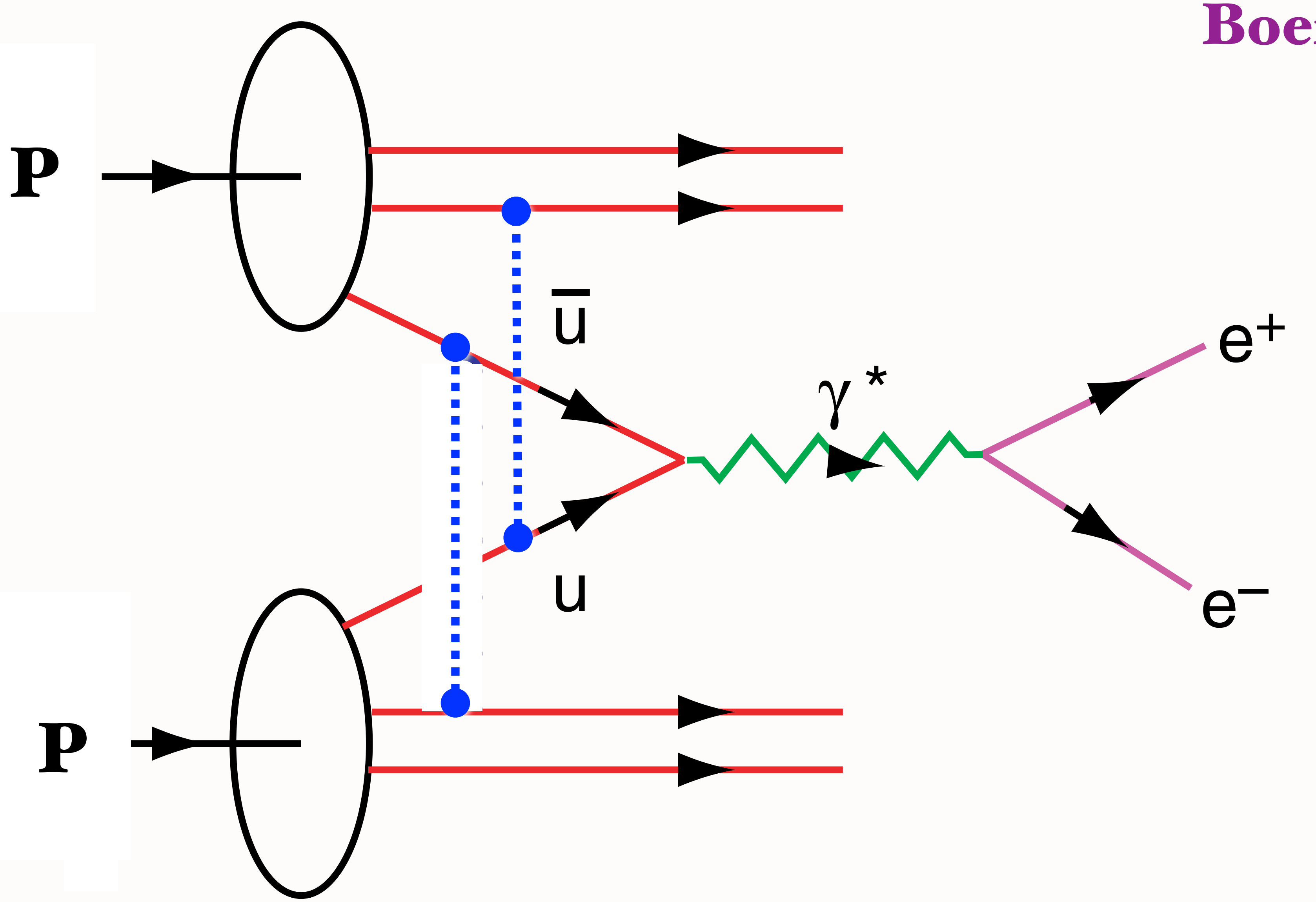
$\pi N \to \mu^+\mu^- X$ NA10



Model: Boer,

LHC Experiment

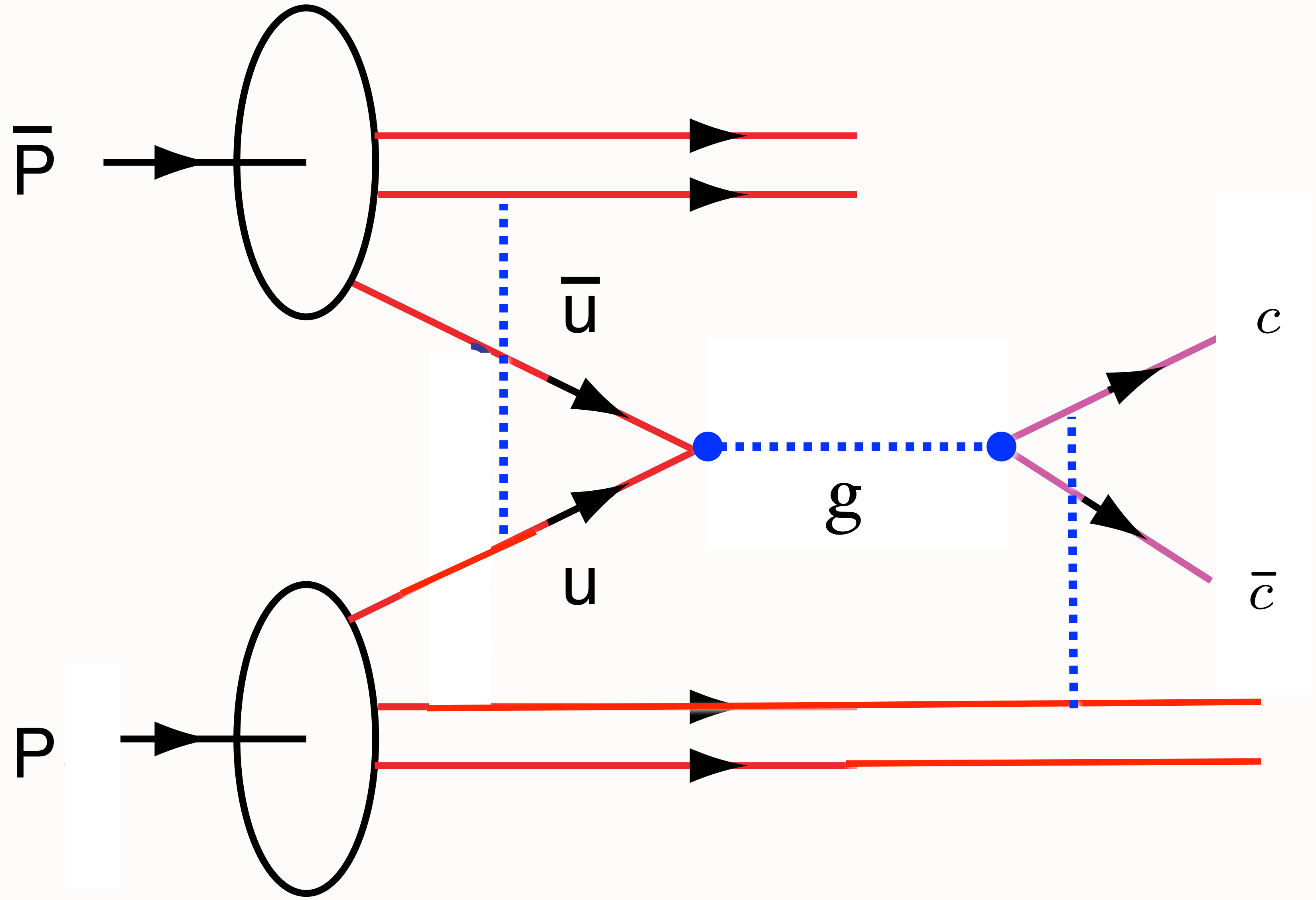
Boer, Hwang, sjb



DY $\cos 2\phi$ **correlation at leading twist from double ISI**

Product of Boer - Mulders Functions

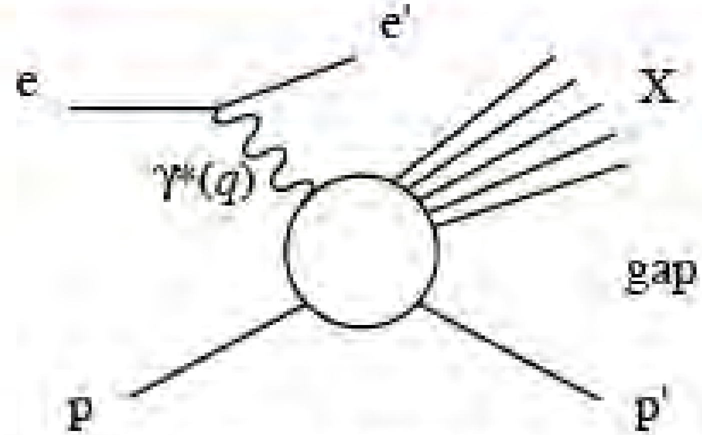
$$h_1^\perp(x_1, \boldsymbol{p}_\perp^2) \times \bar{h}_1^\perp(x_2, \boldsymbol{k}_\perp^2)$$



Problem for factorization when both ISI and FSI occur!

DDIS

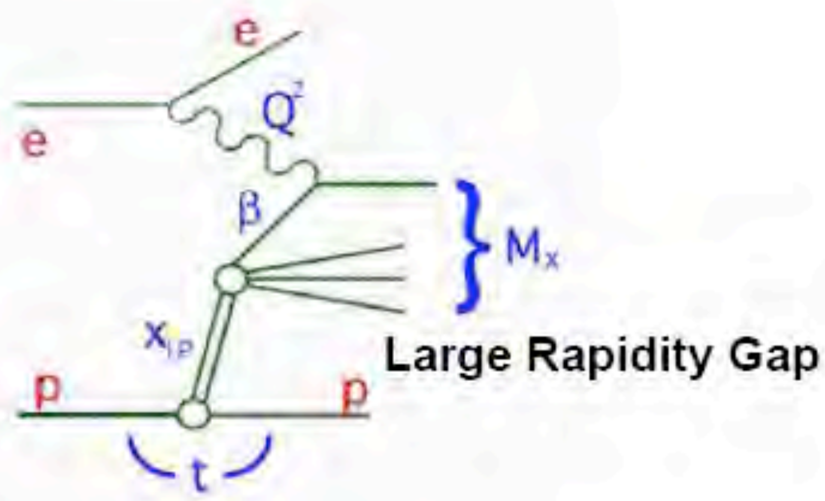
Diffractive Deep Inelastic Lepton-Proton Scattering



- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron

Remarkable: target stays intact despite production of a massive system X

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

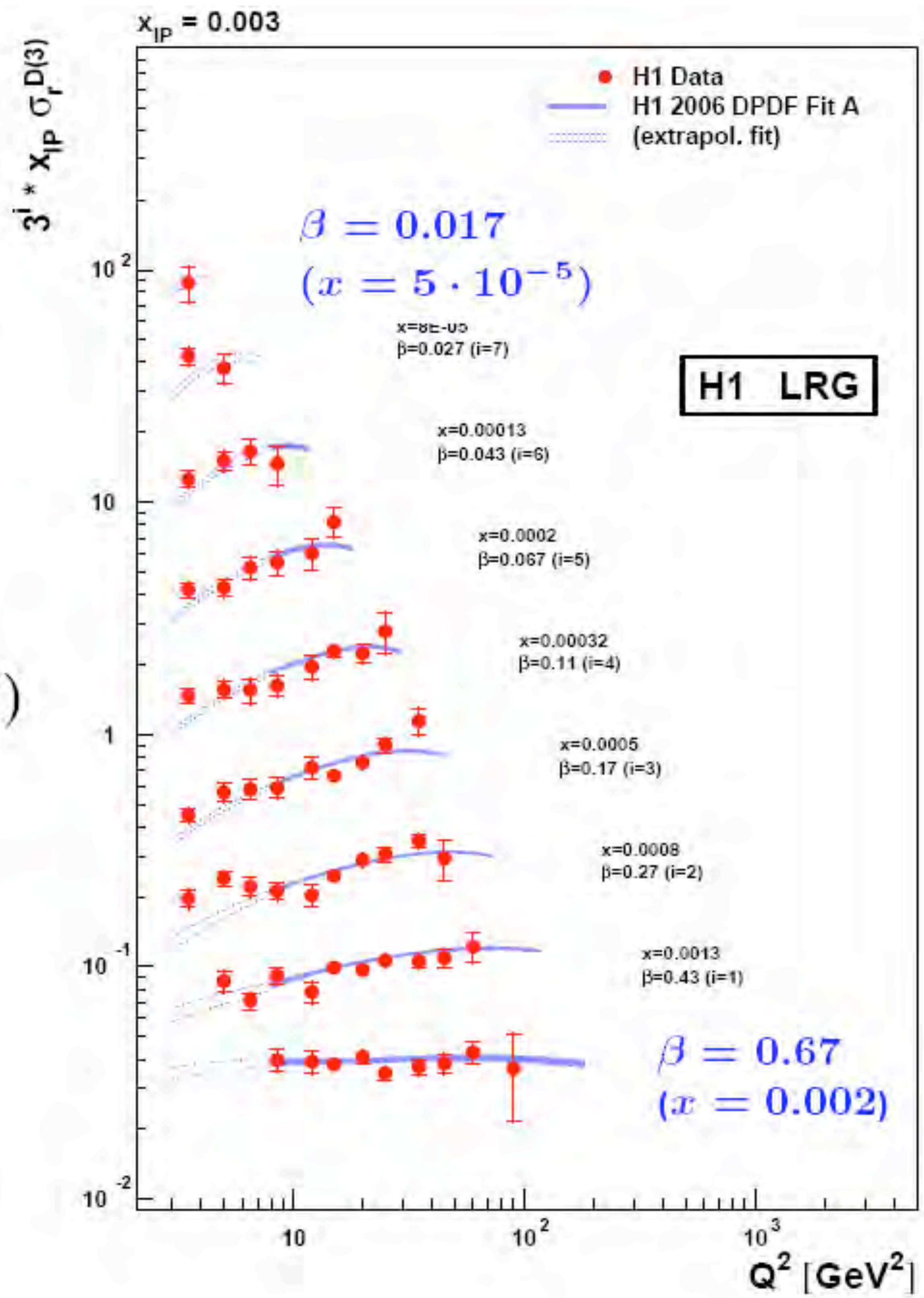
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\,d\beta\,dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P},\beta,Q^2)$$

$$F_2^D(x_{I\!P},\beta,Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta,Q^2)$$

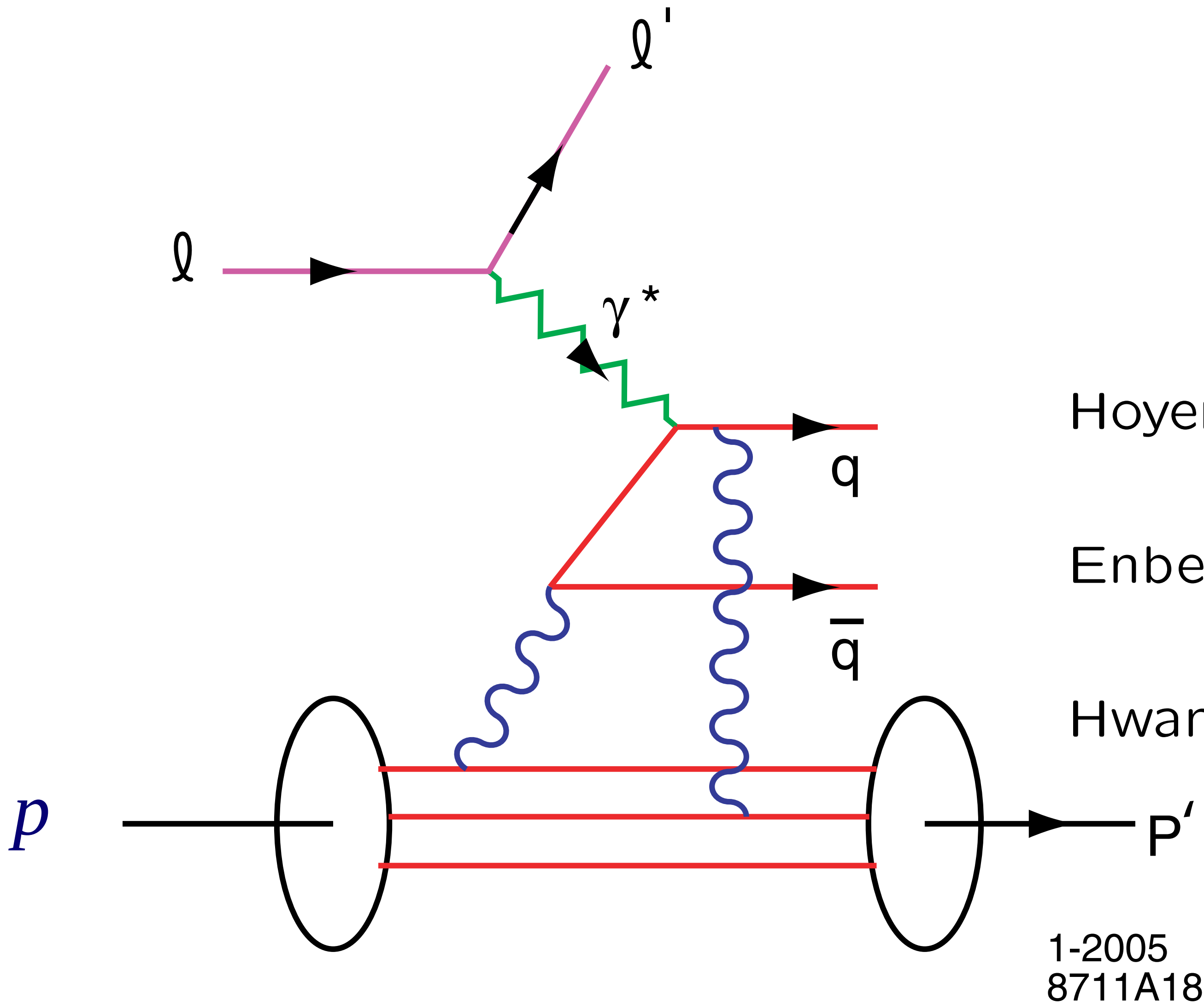
extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

Precise measurements *sys 5%, stat 5–20 %*



Final-State Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHMP

Enberg, Hoyer, Ingelman, SJB

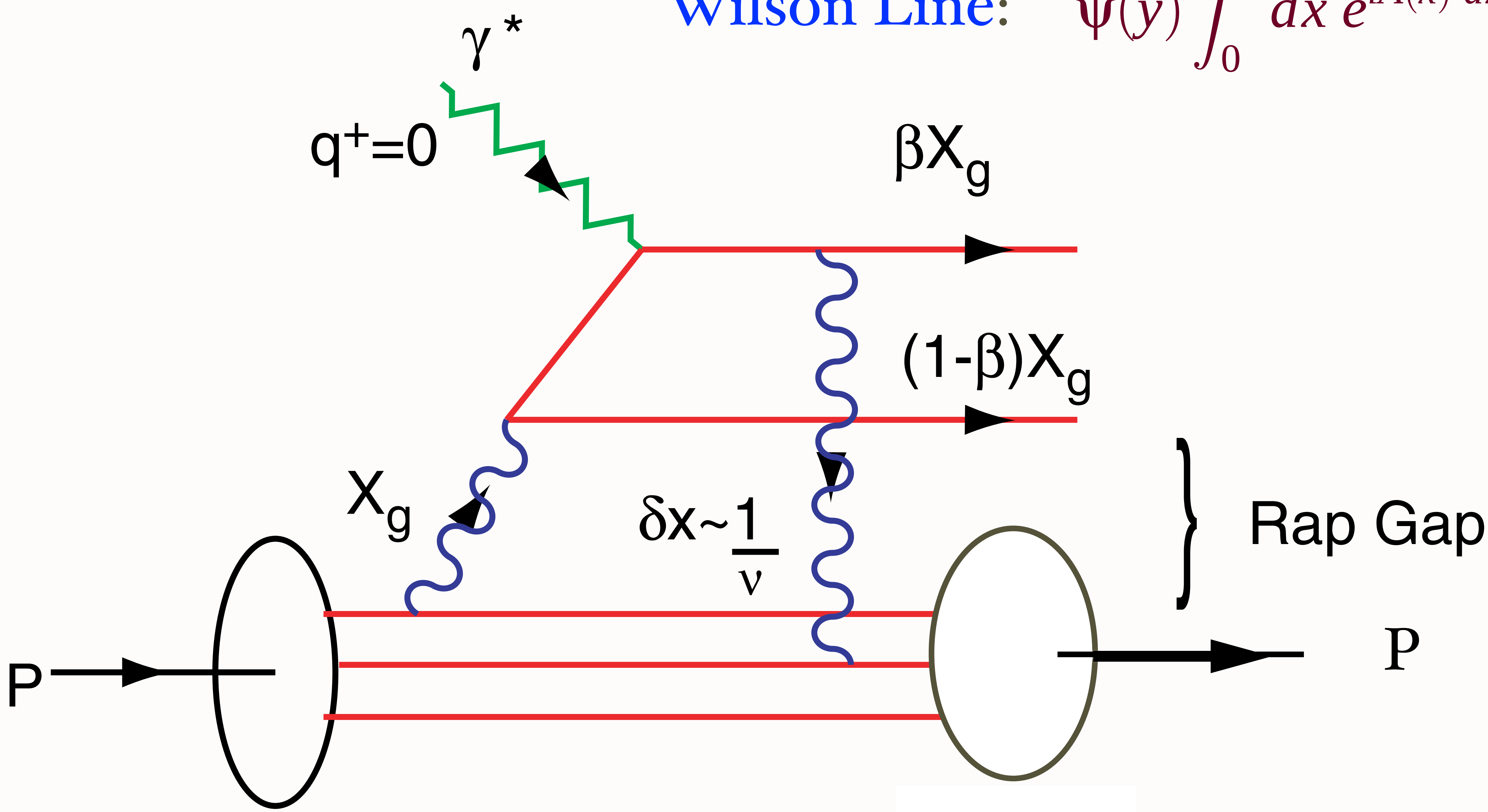
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

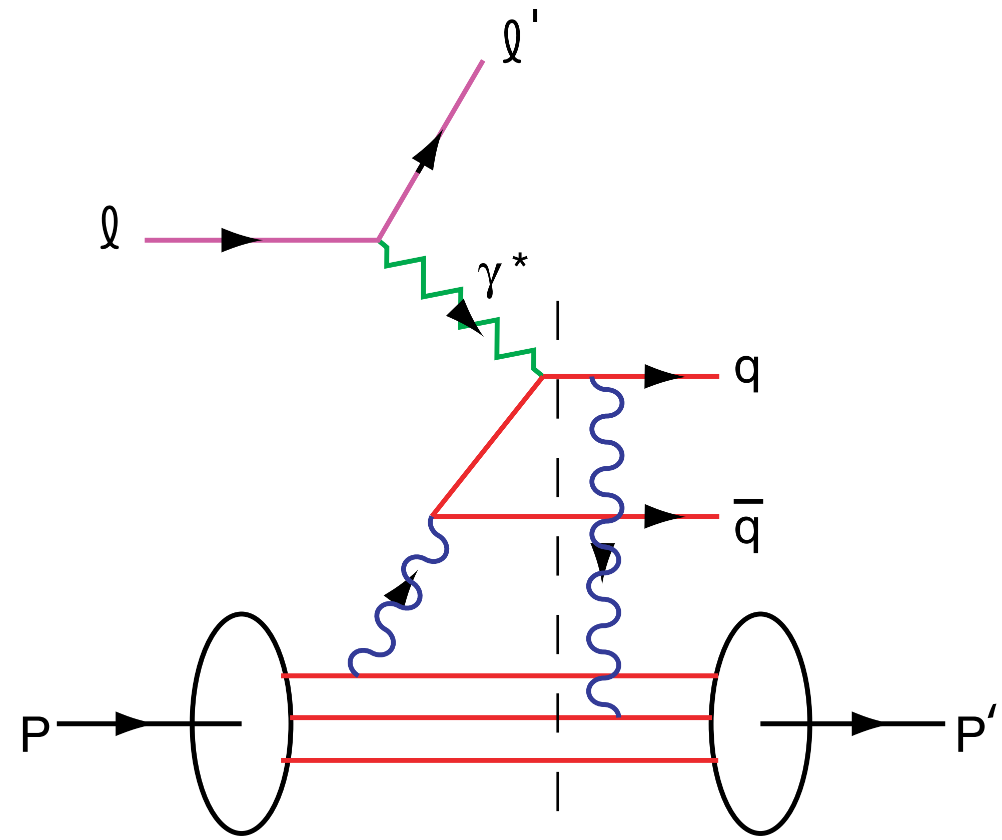
Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$



Reproduces lab-frame color dipole approach



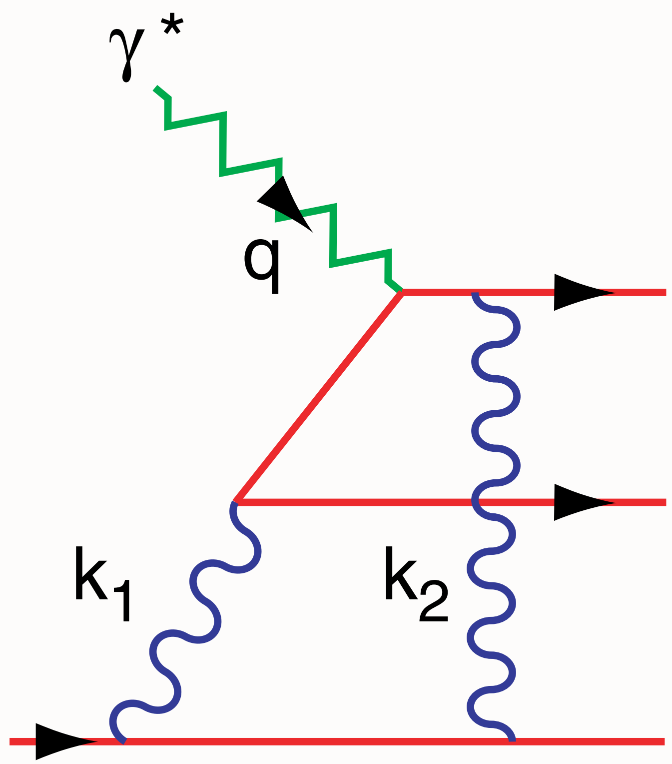
Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

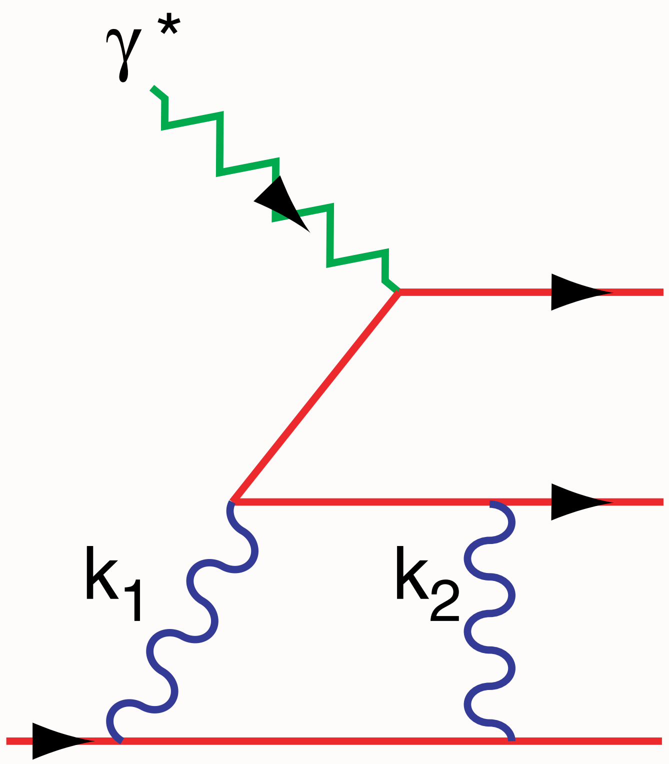
Need Imaginary Phase to Generate T-
Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target!

Final State Interactions in QCD



Feynman Gauge



Light-Cone Gauge

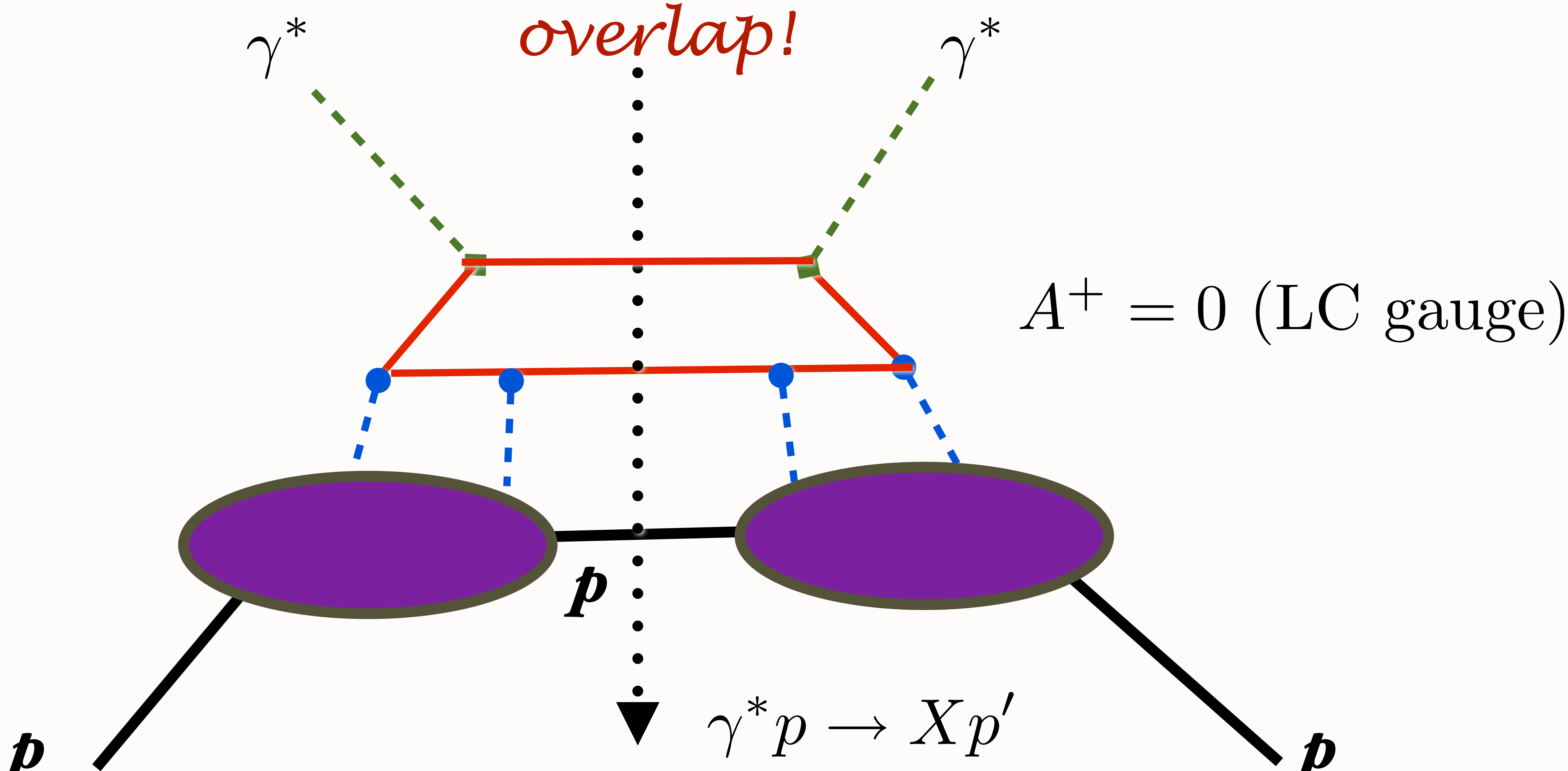
Result is Gauge Independent

Not power suppressed! Does not factorize in hadron collisions!

Leading-Twist Contribution to DVCS

Interactions occur between the LF times of the two virtual photon!!

Dynamic: Not in LFWF overlap!



Cut is Leading-Twist Diffractive DIS

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

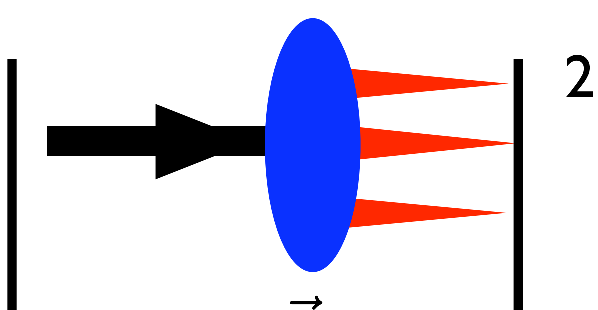
Hwang, Schmidt, sjb,

Mulders, Boer

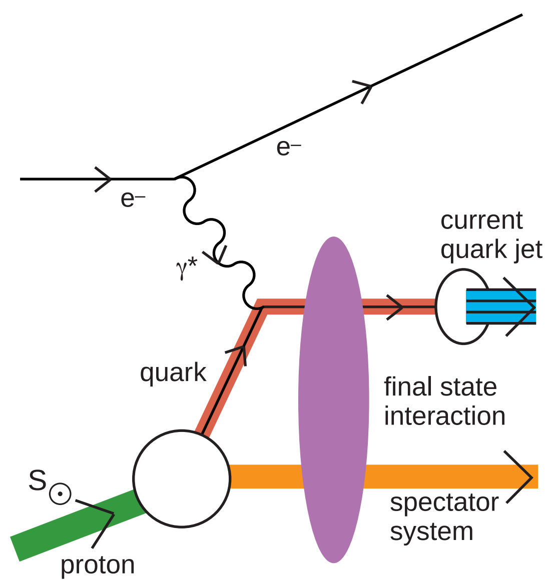
Qiu, Sterman

Collins, Qiu

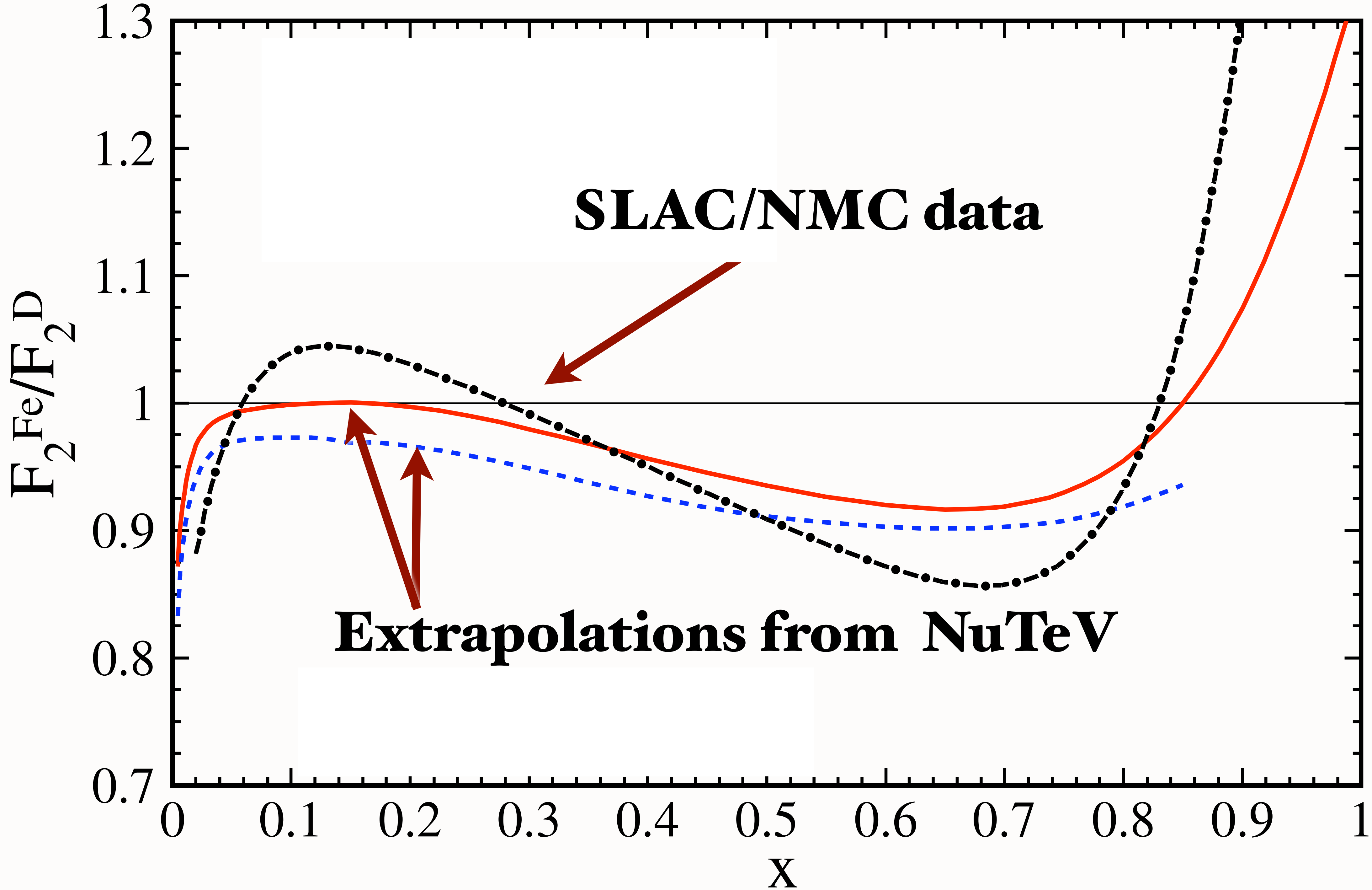
Pasquini, Xiao, Yuan, sjb



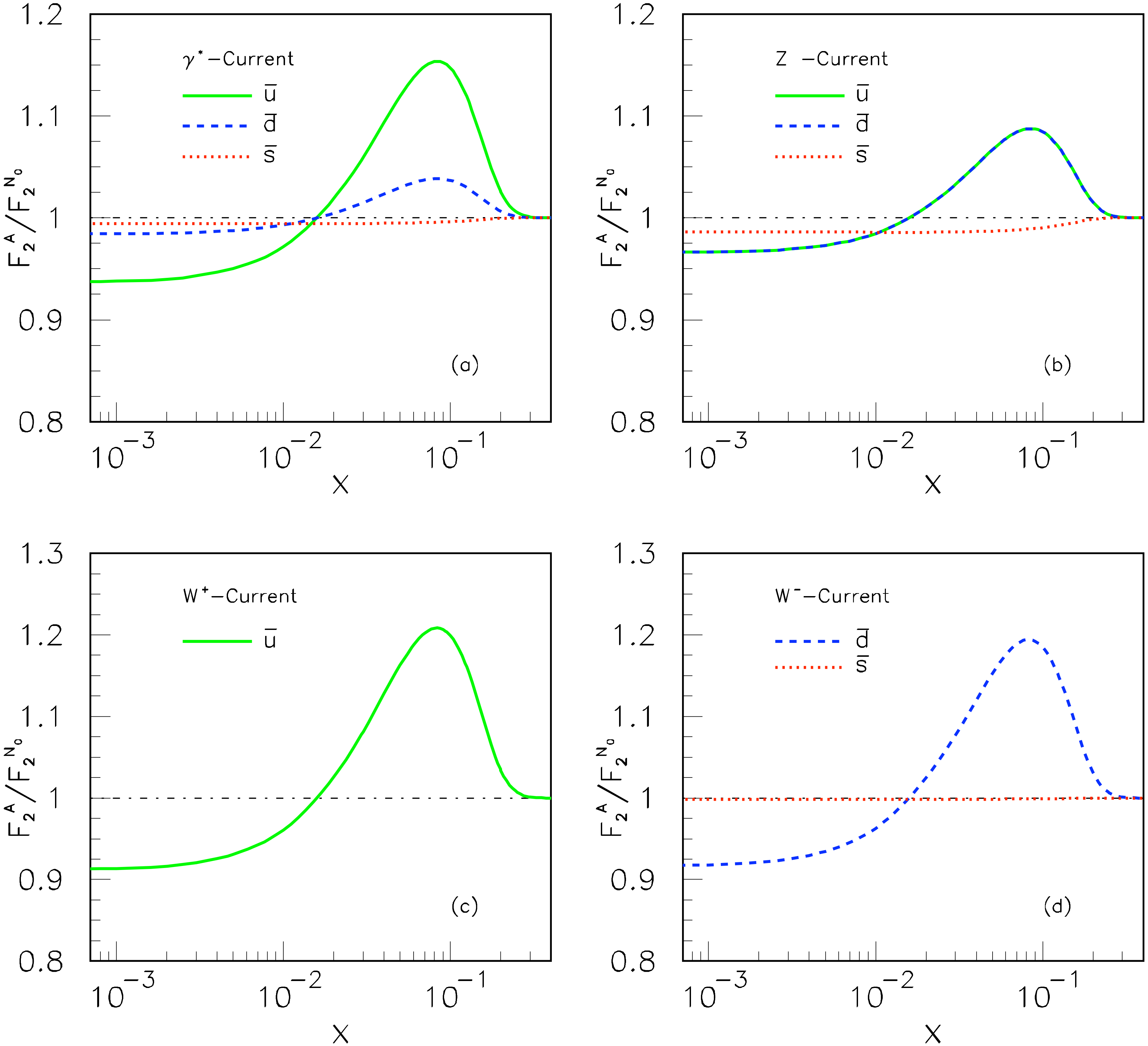
$$\left| \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2$$



$$Q^2 = 5\ \mathrm{GeV}^2$$



Scheinbein, Yu, Keppel, Morfin, Olness, Owens



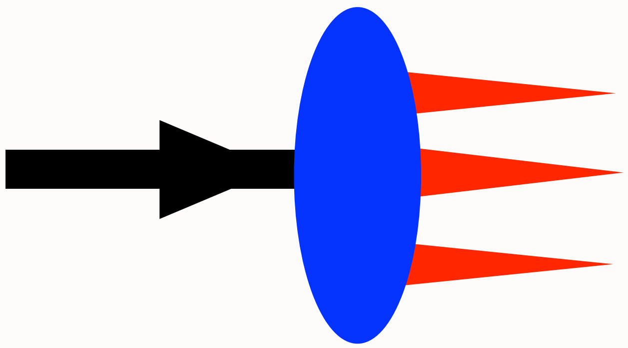
Schmidt, Yang; sjb

Nuclear Antishadowing not universal !

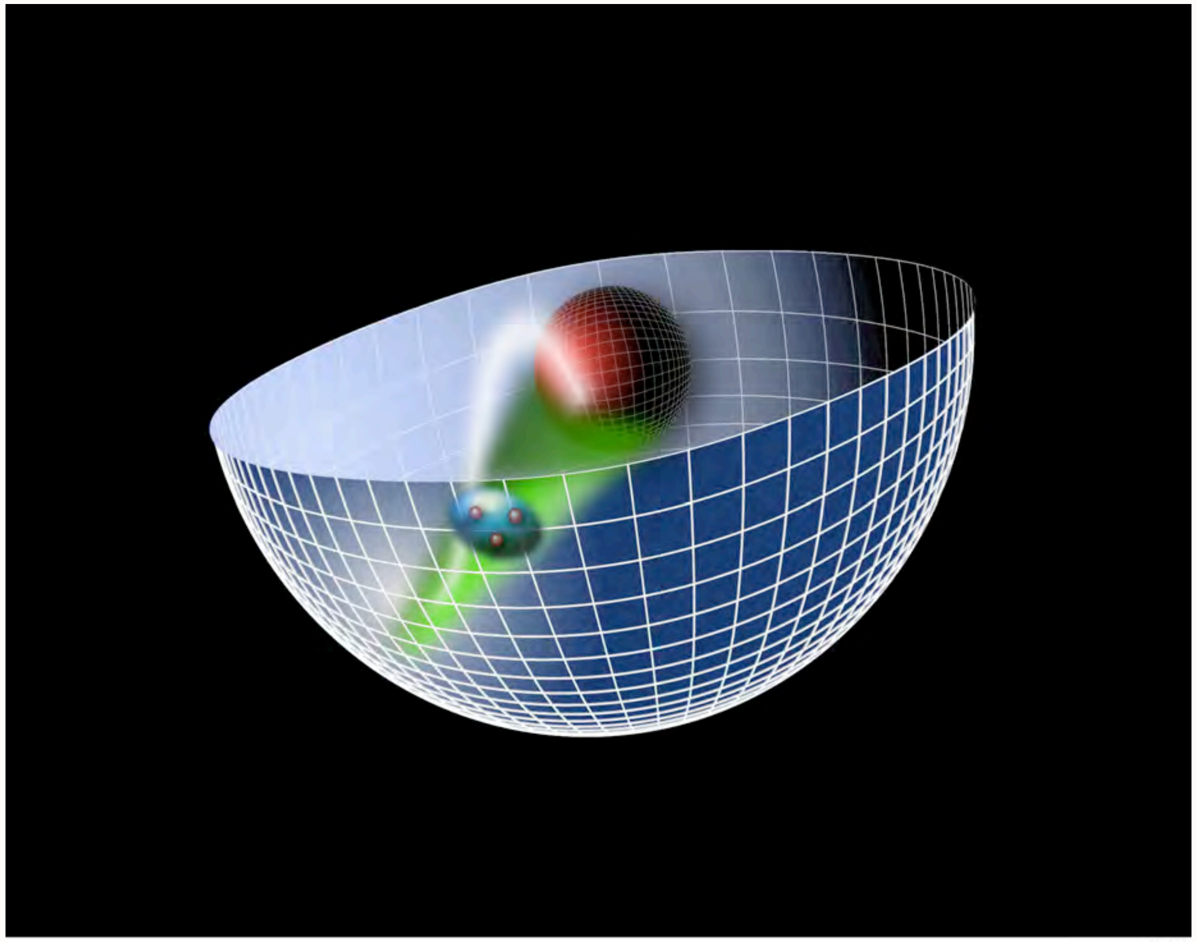
Light-Front Holography and Non-Perturbative QCD

Goal:
Use AdS/QCD duality to construct a first approximation to QCD

Hadron Spectrum
Light-Front Wavefunctions,
Running coupling in IR

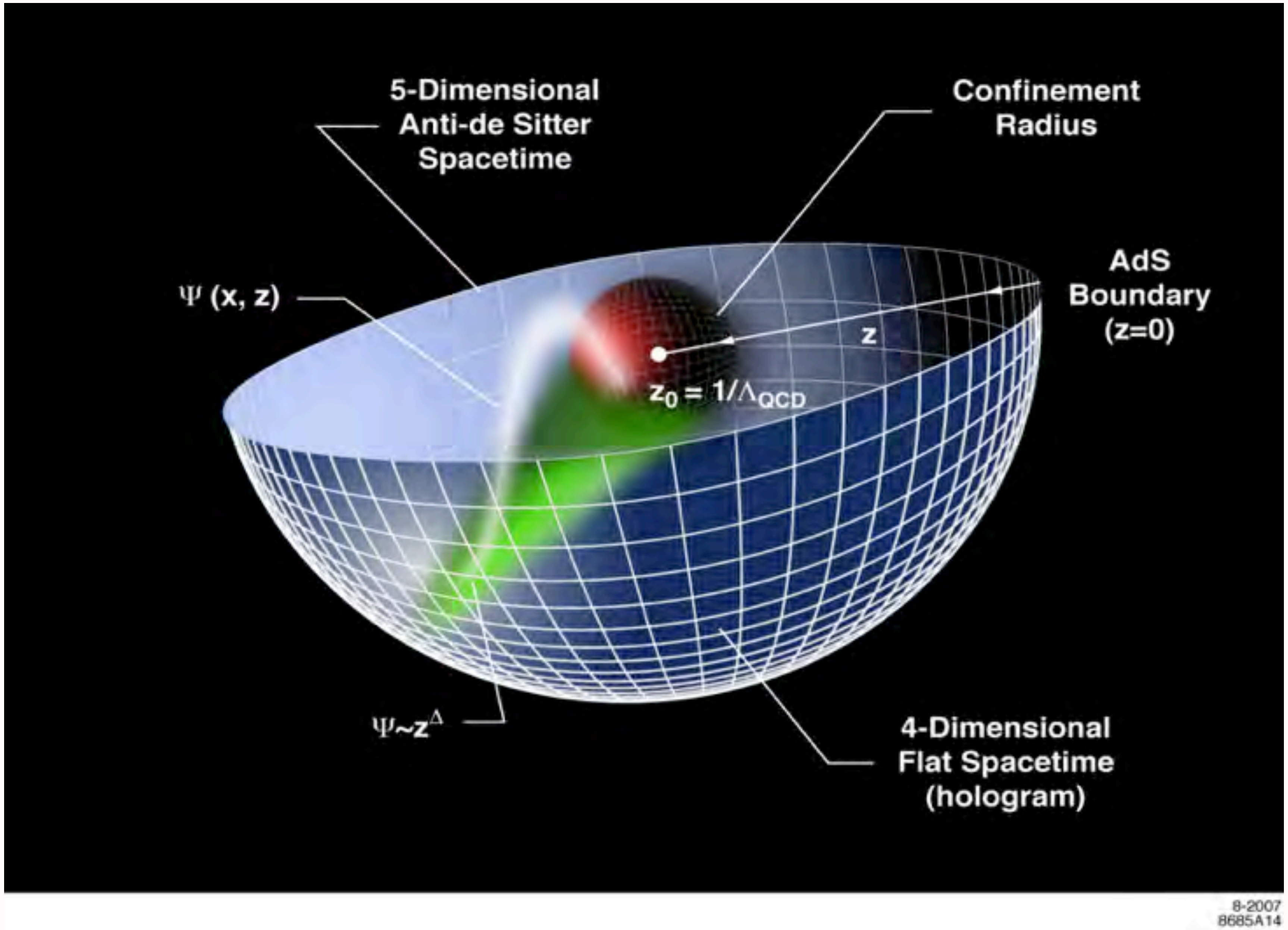


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



in collaboration with
Guy de Teramond

Central problem for strongly-coupled gauge theories



Changes in physical length scale mapped to evolution in the 5th dimension z

- Truncated AdS/CFT (Hard-Wall) model: cut-off at $z_0 = 1/\Lambda_{\rm QCD}$ breaks conformal invariance and allows the introduction of the QCD scale (Hard-Wall Model) Polchinski and Strassler (2001).

- Smooth cutoff: introduction of a background dilaton field $\varphi(z)$ – usual linear Regge dependence can be obtained (Soft-Wall Model) Karch, Katz, Son and Stephanov (2006).

Scale Transformations

- Isomorphism of $SO(4,2)$ of conformal QCD with the group of isometries of AdS space

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2),$$

invariant measure

$x^\mu \to \lambda x^\mu, \; z \to \lambda z$, maps scale transformations into the holographic coordinate z.

- AdS mode in z is the extension of the hadron wf into the fifth dimension.

- Different values of z correspond to different scales at which the hadron is examined.

$$x^2 \to \lambda^2 x^2, \quad z \to \lambda z.$$

$x^2 = x_\mu x^\mu$: invariant separation between quarks

- The AdS boundary at $z \to 0$ correspond to the $Q \to \infty$, UV zero separation limit.

Bosonic Solutions: Hard Wall Model

- Conformal metric: $ds^2 = g_{\ell m} dx^\ell dx^m$. $x^\ell = (x^\mu, z)$, $g_{\ell m} \to \left(R^2/z^2\right) \eta_{\ell m}$.
- Action for massive scalar modes on AdS$_{d+1}$:

$$S[\Phi] = \frac{1}{2} \int d^{d+1}x \sqrt{g}\, \tfrac{1}{2} \left[g^{\ell m} \partial_\ell \Phi \partial_m \Phi - \mu^2 \Phi^2 \right], \quad \sqrt{g} \to (R/z)^{d+1}.$$

- Equation of motion

$$\frac{1}{\sqrt{g}} \frac{\partial}{\partial x^\ell} \left(\sqrt{g}\, g^{\ell m} \frac{\partial}{\partial x^m} \Phi \right) + \mu^2 \Phi = 0.$$

- Factor out dependence along x^μ-coordinates , $\Phi_P(x,z) = e^{-iP\cdot x}\, \Phi(z)$, $P_\mu P^\mu = \mathcal{M}^2$:

$$\boxed{\left[z^2 \partial_z^2 - (d-1) z\, \partial_z + z^2 \mathcal{M}^2 - (\mu R)^2 \right] \Phi(z) = 0.}$$

- Solution: $\Phi(z) \to z^\Delta$ as $z \to 0$,

$$\Phi(z) = C z^{d/2} J_{\Delta - d/2}(z\mathcal{M}) \qquad \Delta = \tfrac{1}{2}\left(d + \sqrt{d^2 + 4\mu^2 R^2}\, \right).$$

$$\Delta = 2 + L \qquad d = 4 \qquad (\mu R)^2 = L^2 - 4$$

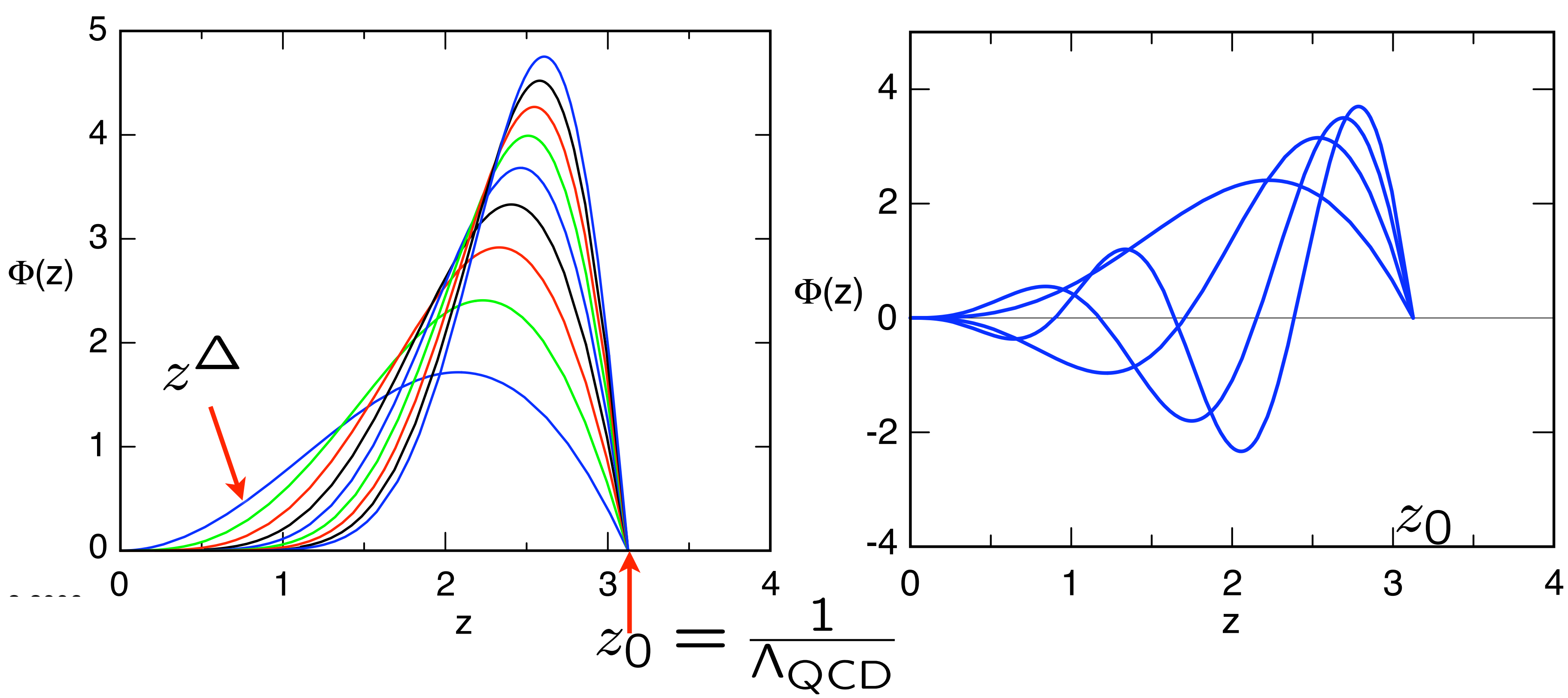
Match fall-off at small z to conformal twist-dimension at short distances

twist

- Pseudoscalar mesons: $\mathcal{O}_{2+L} = \overline{\psi}\gamma_5 D_{\{\ell_1} \dots D_{\ell_m\}}\psi$ ($\Phi_\mu = 0$ gauge). $\Delta = 2 + L$

- 4-d mass spectrum from boundary conditions on the normalizable string modes at $z = z_0$, $\Phi(x, z_o) = 0$, given by the zeros of Bessel functions $\beta_{\alpha,k}$: $\mathcal{M}_{\alpha,k} = \beta_{\alpha,k}\Lambda_{QCD}$

- Normalizable AdS modes $\Phi(z)$



$S = 0$ Meson orbital and radial AdS modes for $\Lambda_{QCD} = 0.32$ GeV.

- Nonconformal metric dual to a confining gauge theory

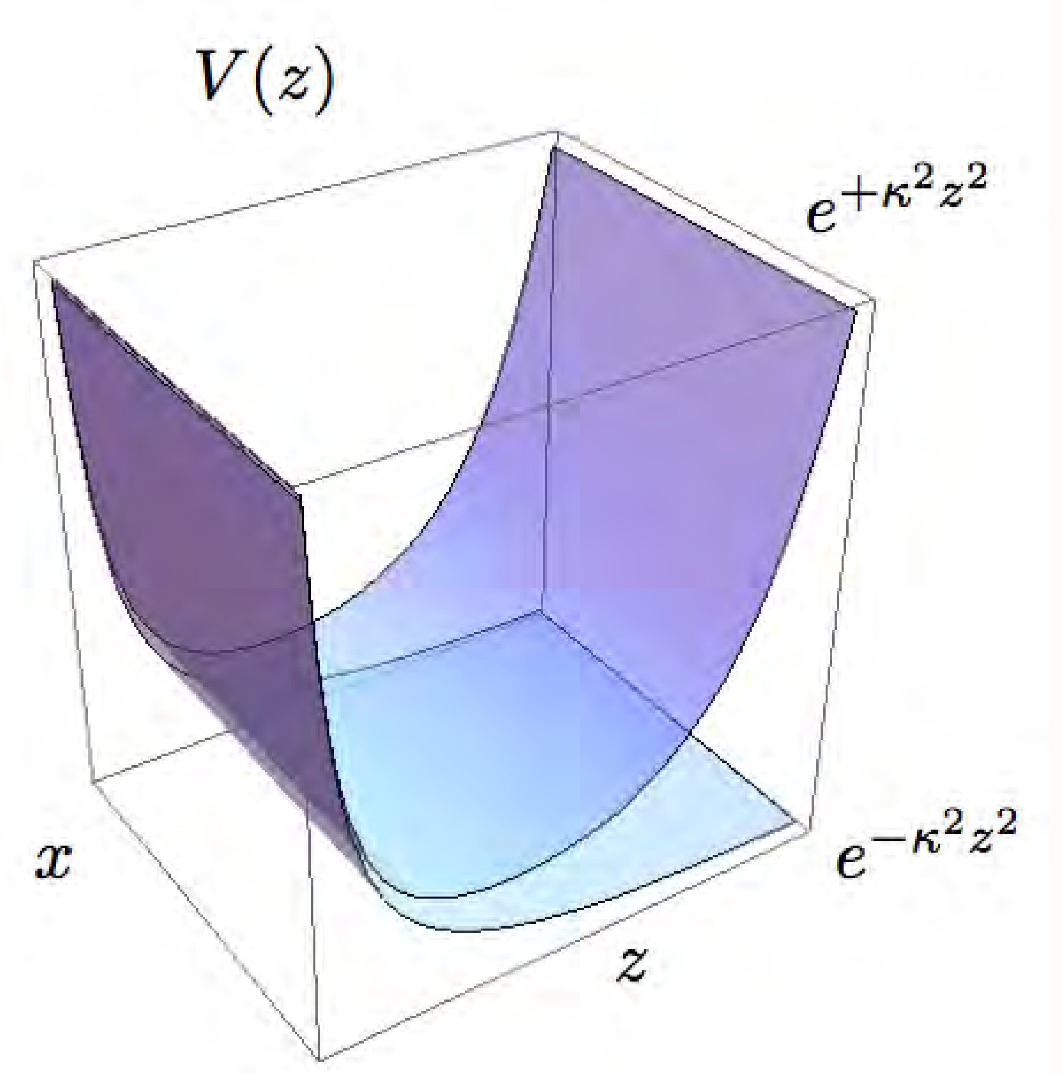
$$ds^2 = \frac{R^2}{z^2}\, e^{\varphi(z)} \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

where $\varphi(z) \to 0$ at small z for geometries which are asymptotically AdS_5

- Gravitational potential energy for object of mass m

$$V = mc^2 \sqrt{g_{00}} = mc^2 R\, \frac{e^{\varphi(z)/2}}{z}$$

- Consider warp factor $\exp(\pm\kappa^2 z^2)$
- Plus solution: $V(z)$ increases exponentially confining any object in modified AdS metrics to distances $\langle z \rangle \sim 1/\kappa$



Klebanov and Maldacena

Dual QCD Light-Front Wave Equation

$$\boxed{z \Leftrightarrow \zeta, \quad \Phi_P(z) \Leftrightarrow |\psi(P)\rangle}$$

[GdT and S. J. Brodsky, PRL **102**, 081601 (2009)]

- Upon substitution $z \to \zeta$ and $\phi_J(\zeta) \sim \zeta^{-3/2+J} e^{\varphi(z)/2}\, \Phi_J(\zeta)$ in AdS WE

$$\left[-\frac{z^{d-1-2J}}{e^{\varphi(z)}} \partial_z \left(\frac{e^{\varphi}(z)}{z^{d-1-2J}} \partial_z\right) + \left(\frac{\mu R}{z}\right)^2\right] \Phi_J(z) = \mathcal{M}^2 \Phi_J(z)$$

find LFWE $(d = 4)$

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1 - 4L^2}{4\zeta^2} + U(\zeta)\right) \phi_J(\zeta) = M^2 \phi_J(\zeta)$$

with

$$U(\zeta) = \frac{1}{2}\varphi''(z) + \frac{1}{4}\varphi'(z)^2 + \frac{2J - 3}{2z}\varphi'(z)$$

and $(\mu R)^2 = -(2 - J)^2 + L^2$

- AdS Breitenlohner-Freedman bound $(\mu R)^2 \geq -4$ equivalent to LF QM stability condition $L^2 \geq 0$

- Scaling dimension τ of AdS mode $\hat{\Phi}_J$ is $\tau = 2 + L$ in agreement with twist scaling dimension of a two parton bound state in QCD and determined by QM stability condition

de Teramond, Dosch, sjb

General-Spin Hadrons

- Obtain spin-J mode $\Phi_{\mu_1 \cdots \mu_J}$ with all indices along 3+1 coordinates from Φ by shifting dimensions

$$\Phi_J(z) = \left(\frac{z}{R}\right)^{-J} \Phi(z)$$

- Substituting in the AdS scalar wave equation for Φ

$$\left[z^2 \partial_z^2 - \left(3-2J - 2\kappa^2 z^2\right) z\, \partial_z + z^2 \mathcal{M}^2 - (\mu R)^2\right] \Phi_J = 0$$

- Upon substitution $z \to \zeta$

$$\phi_J(\zeta) \sim \zeta^{-3/2+J} e^{\kappa^2 \zeta^2/2}\, \Phi_J(\zeta)$$

we find the LF wave equation

$$\boxed{\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4 \zeta^2 + 2\kappa^2 (L+S-1)\right) \phi_{\mu_1 \cdots \mu_J} = \mathcal{M}^2 \phi_{\mu_1 \cdots \mu_J}}$$

with $(\mu R)^2 = -(2-J)^2 + L^2$

$$e^{\phi(z)} = e^{+\kappa^2 z^2}$$

- de Teramond, sjb

Positive-sign dilaton

AdS Soft-Wall Schrodinger Equation for bound state of two scalar constituents:

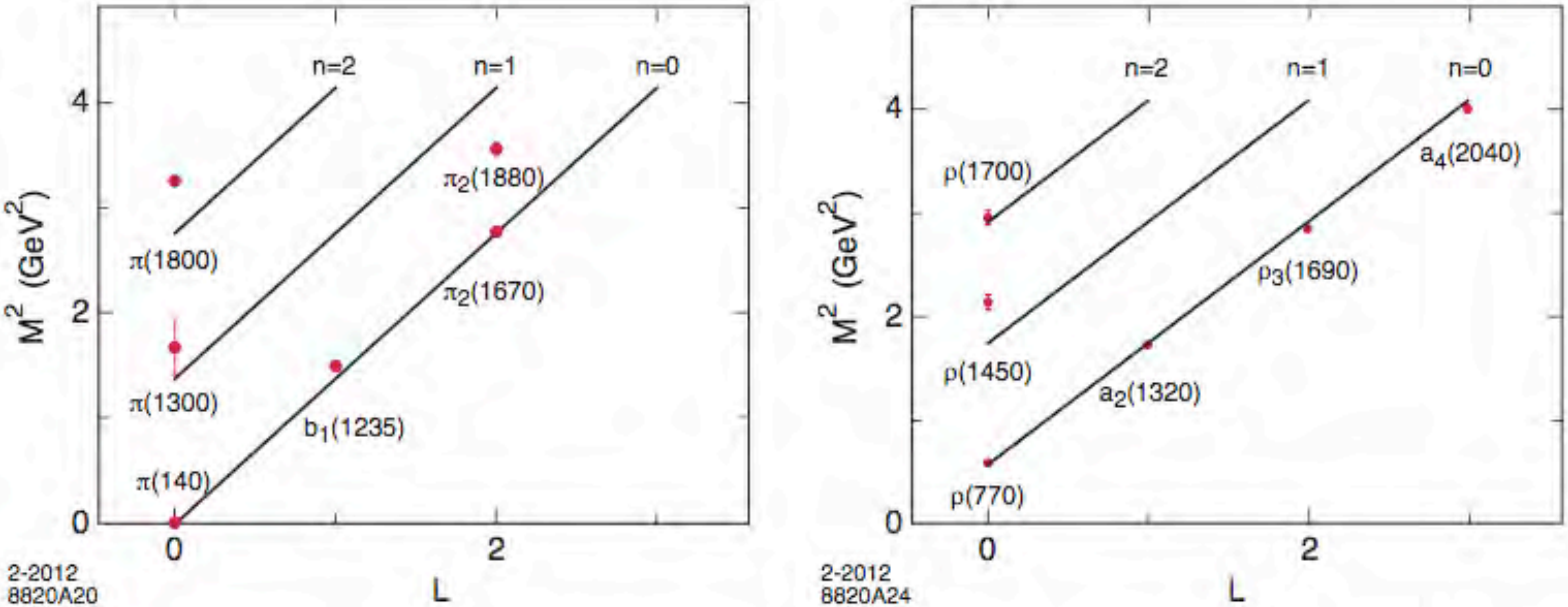
$$\left[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + U(z)\right]\Phi(z) = \mathcal{M}^2\Phi(z)$$

$$U(z) = \kappa^4 z^2 + 2\kappa^2(L+S-1)$$

Derived from variation of Action
Dilaton-Modified AdS_5

- $J = L + S, I = 1$ meson families $\mathcal{M}^2_{n,L,S} = 4\kappa^2 \left(n + L + S/2\right)$

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

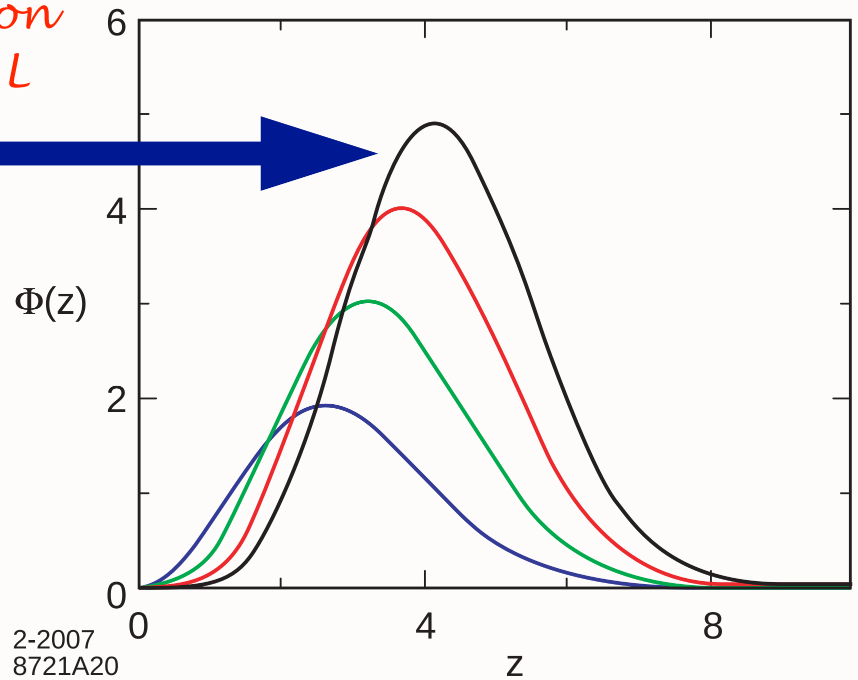


I=1 orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ-meson families ($\kappa = 0.54$ GeV)

- Triplet splitting for the $I = 1$, $L = 1$, $J = 0, 1, 2$, vector meson a-states

$$\mathcal{M}_{a_2(1320)} > \mathcal{M}_{a_1(1260)} > \mathcal{M}_{a_0(980)}$$

Quark separation increases with L



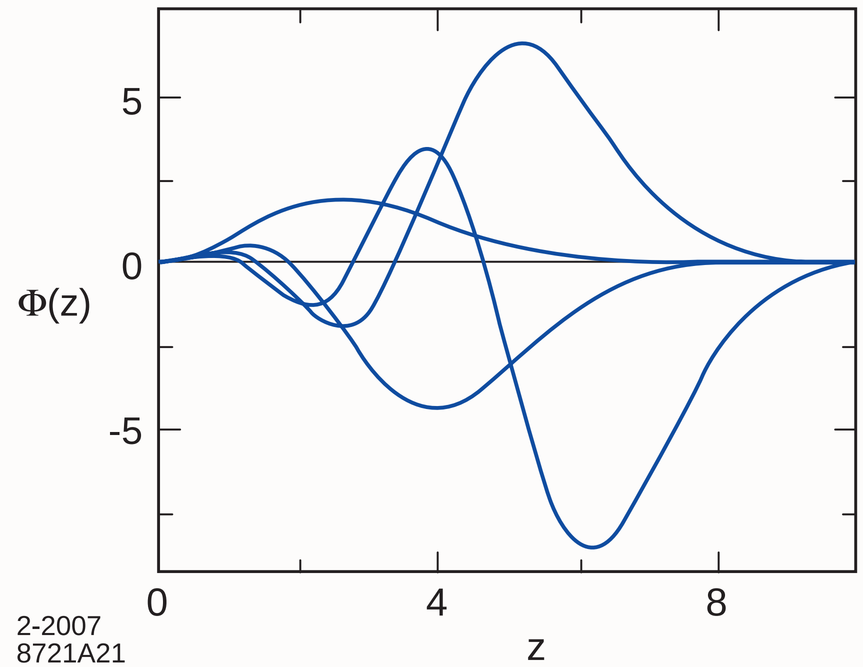
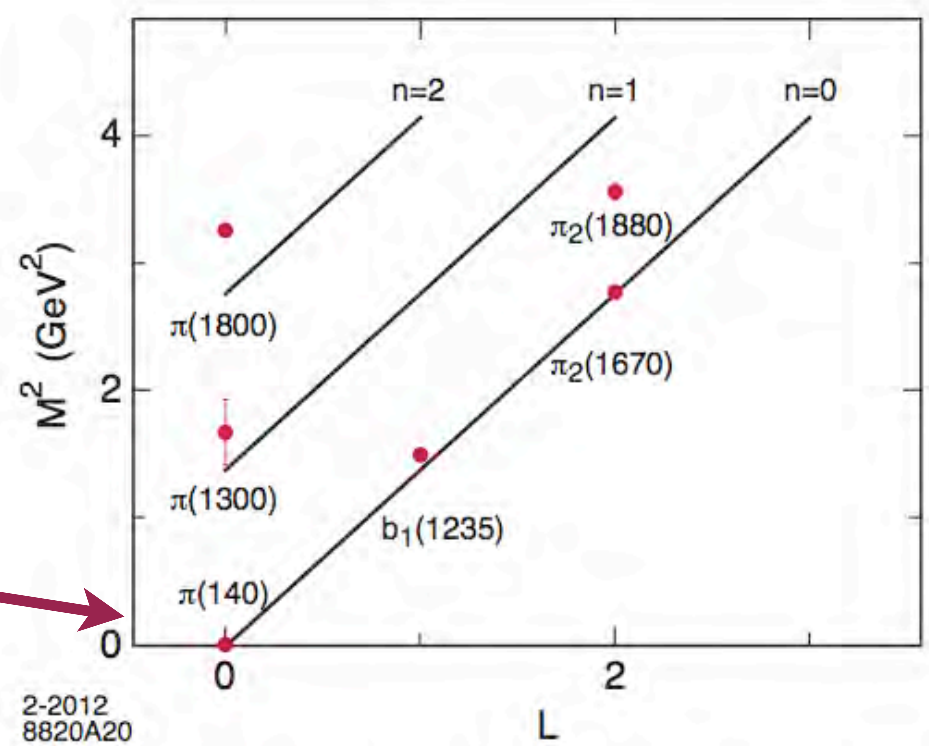
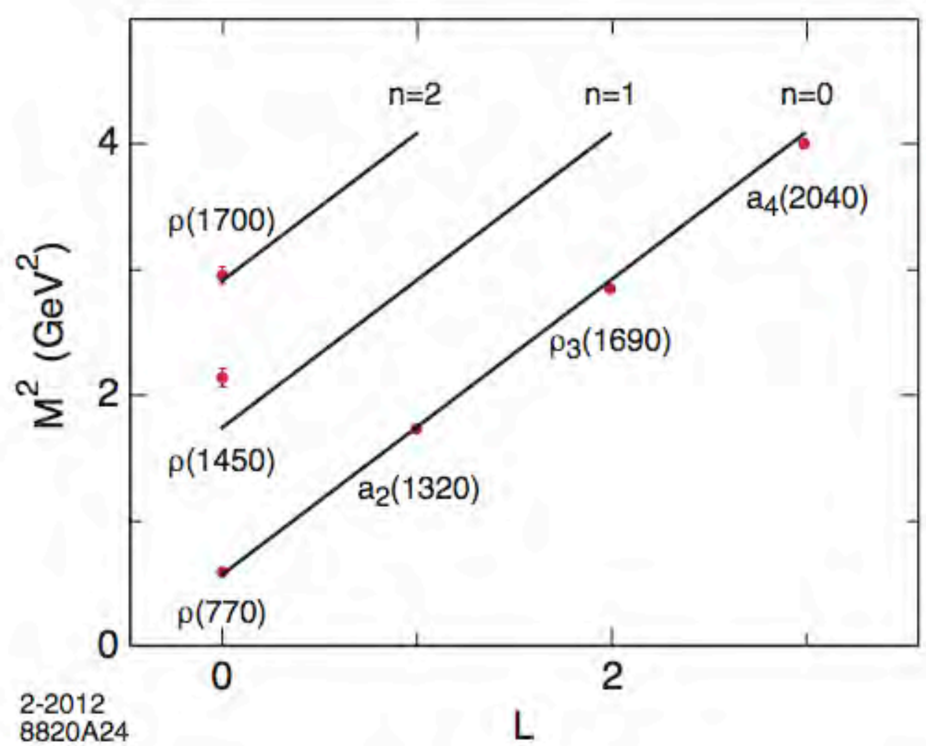


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model

Pion has zero mass!





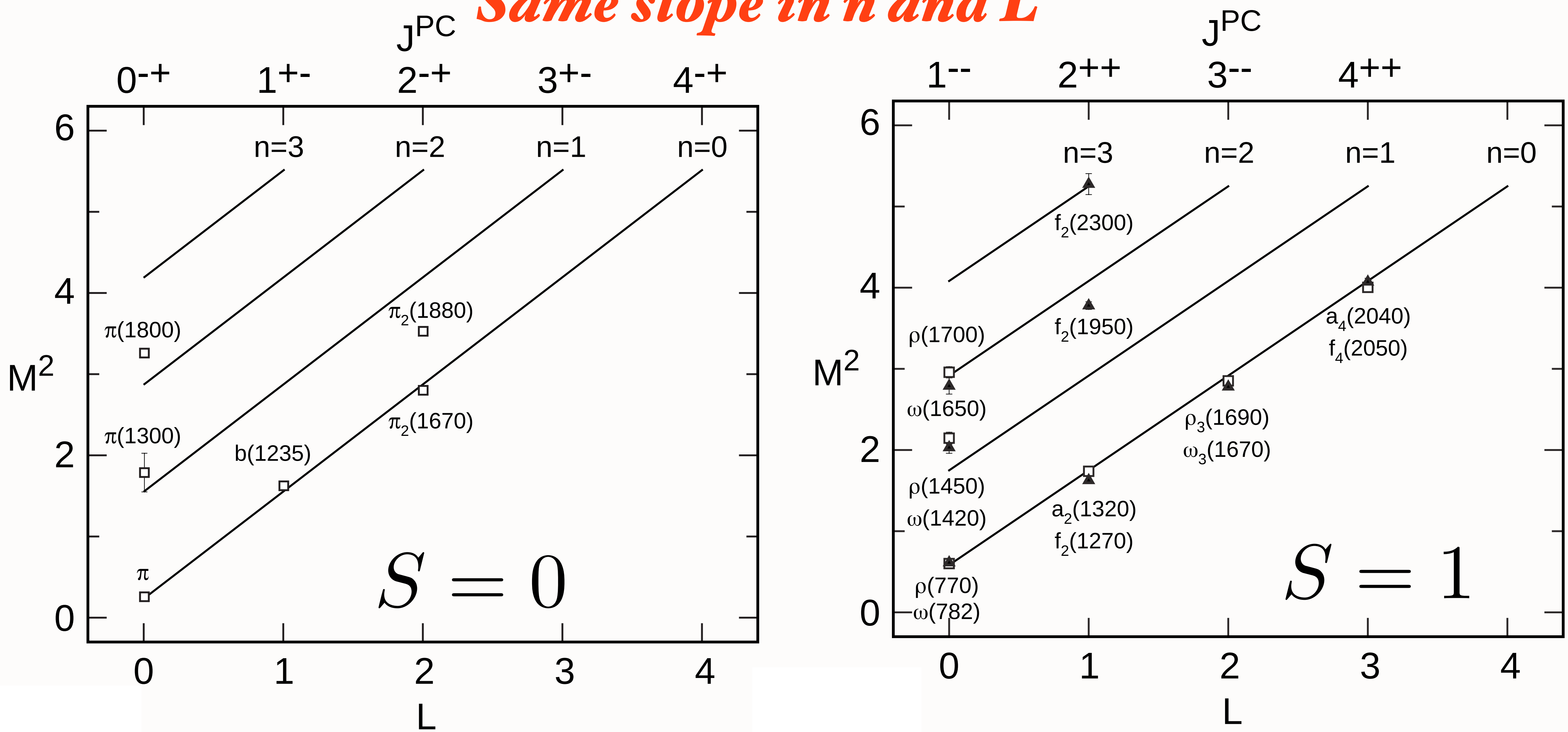
Orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ I=1meson families ($\kappa = 0.54$ GeV)

Bosonic Modes and Meson Spectrum

$$\mathcal{M}^2 = 4\kappa^2(n + J/2 + L/2) \to 4\kappa^2(n + L + S/2)$$

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

Same slope in n and L



Regge trajectories for the π ($\kappa = 0.6$ GeV) and the $I=1$ ρ-meson and $I=0$ ω-meson families ($\kappa = 0.54$ GeV)

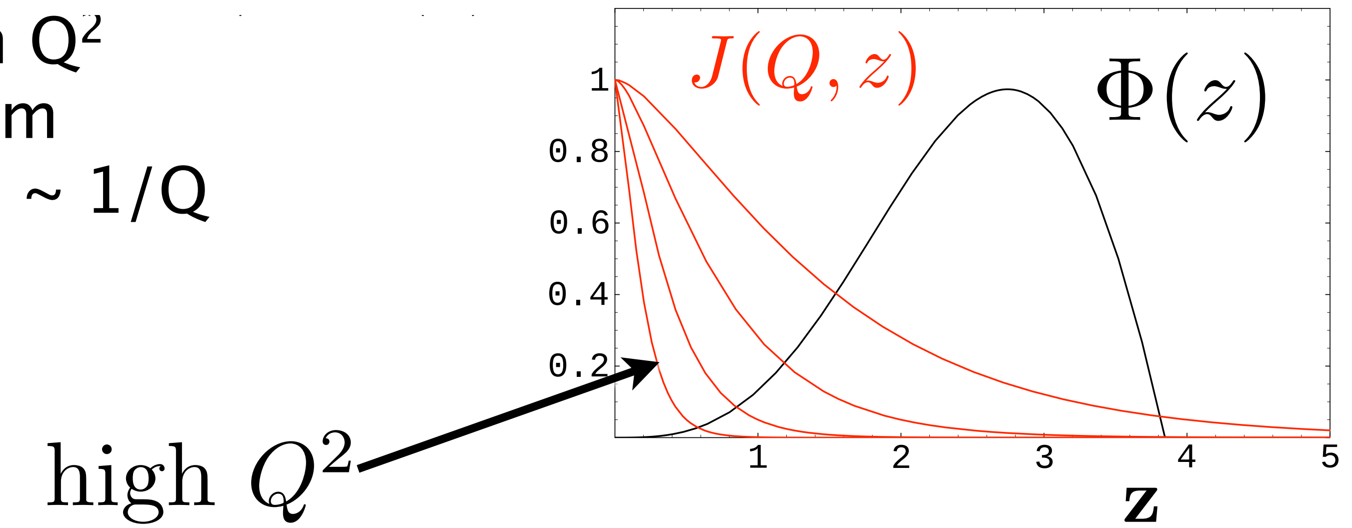
Hadron Form Factors from AdS/CFT

Propagation of external perturbation suppressed inside AdS.

$$J(Q,z) = zQK_1(zQ)$$

$$F(Q^2)_{I\to F} = \int \frac{dz}{z^3}\Phi_F(z)J(Q,z)\Phi_I(z)$$

High Q^2
from
small z ~ 1/Q



Polchinski, Strassler
de Teramond, sjb

Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, Φ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau-1},$$

Dimensional Quark Counting Rules:
General result from
AdS/CFT and Conformal Invariance

where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^n \sigma_i$. The twist is equal to the number of partons, $\tau = n$.

Current Matrix Elements in AdS Space (SW)

sjb and GdT
Grigoryan and Radyushkin

- Propagation of external current inside AdS space described by the AdS wave equation

$$\left[z^2\partial_z^2 - z\left(1 + 2\kappa^2 z^2\right)\partial_z - Q^2 z^2\right] J_\kappa(Q,z) = 0.$$

- Solution bulk-to-boundary propagator

$$J_\kappa(Q,z) = \Gamma\left(1 + \frac{Q^2}{4\kappa^2}\right) U\left(\frac{Q^2}{4\kappa^2}, 0, \kappa^2 z^2\right),$$

Soft Wall Model

where $U(a,b,c)$ is the confluent hypergeometric function

$$\Gamma(a)U(a,b,z) = \int_0^\infty e^{-zt} t^{a-1}(1+t)^{b-a-1} dt.$$

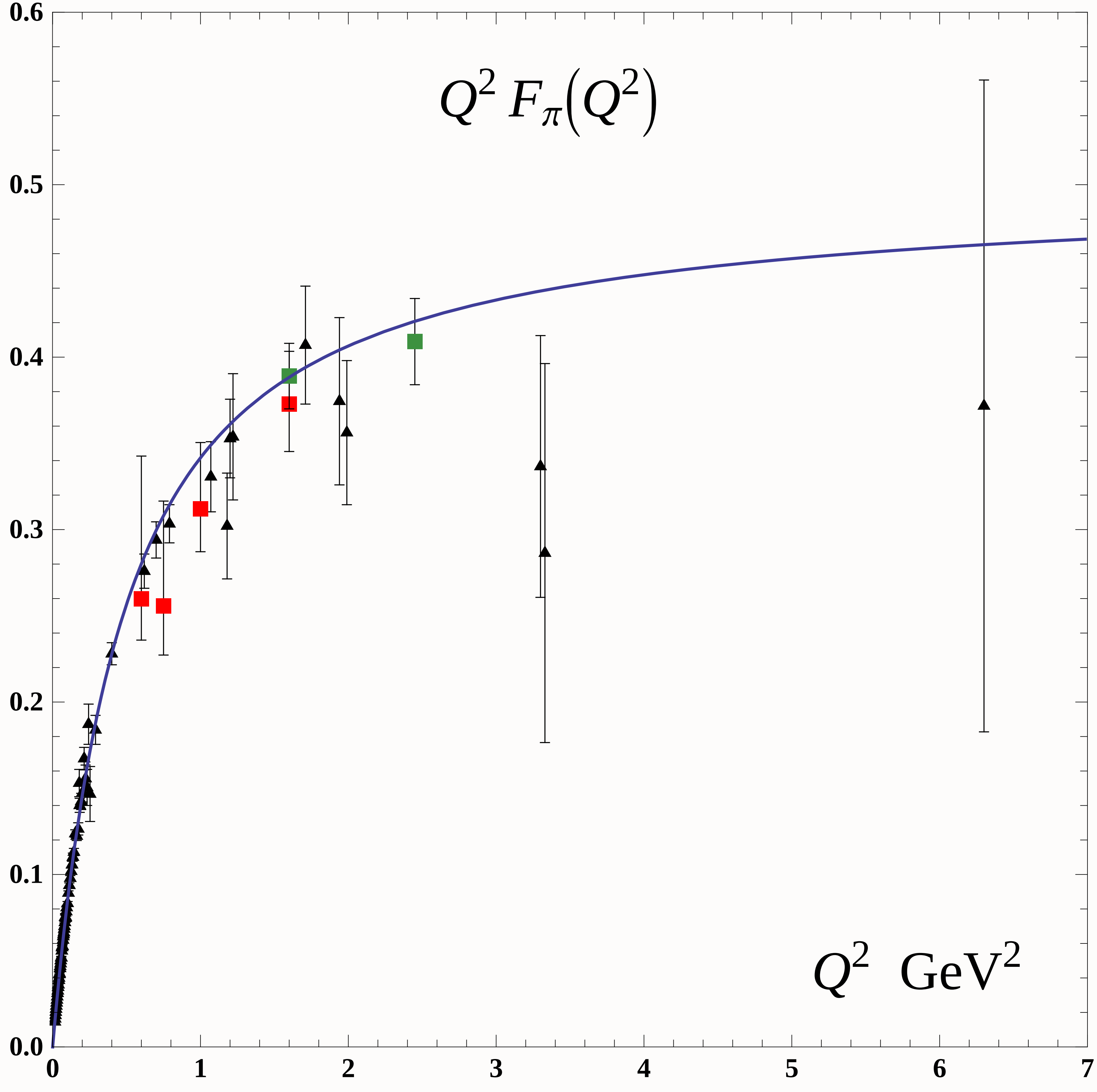
- Form factor in presence of the dilaton background $\varphi = \kappa^2 z^2$

$$F(Q^2) = R^3 \int \frac{dz}{z^3}\, e^{-\kappa^2 z^2} \Phi(z) J_\kappa(Q,z) \Phi(z).$$

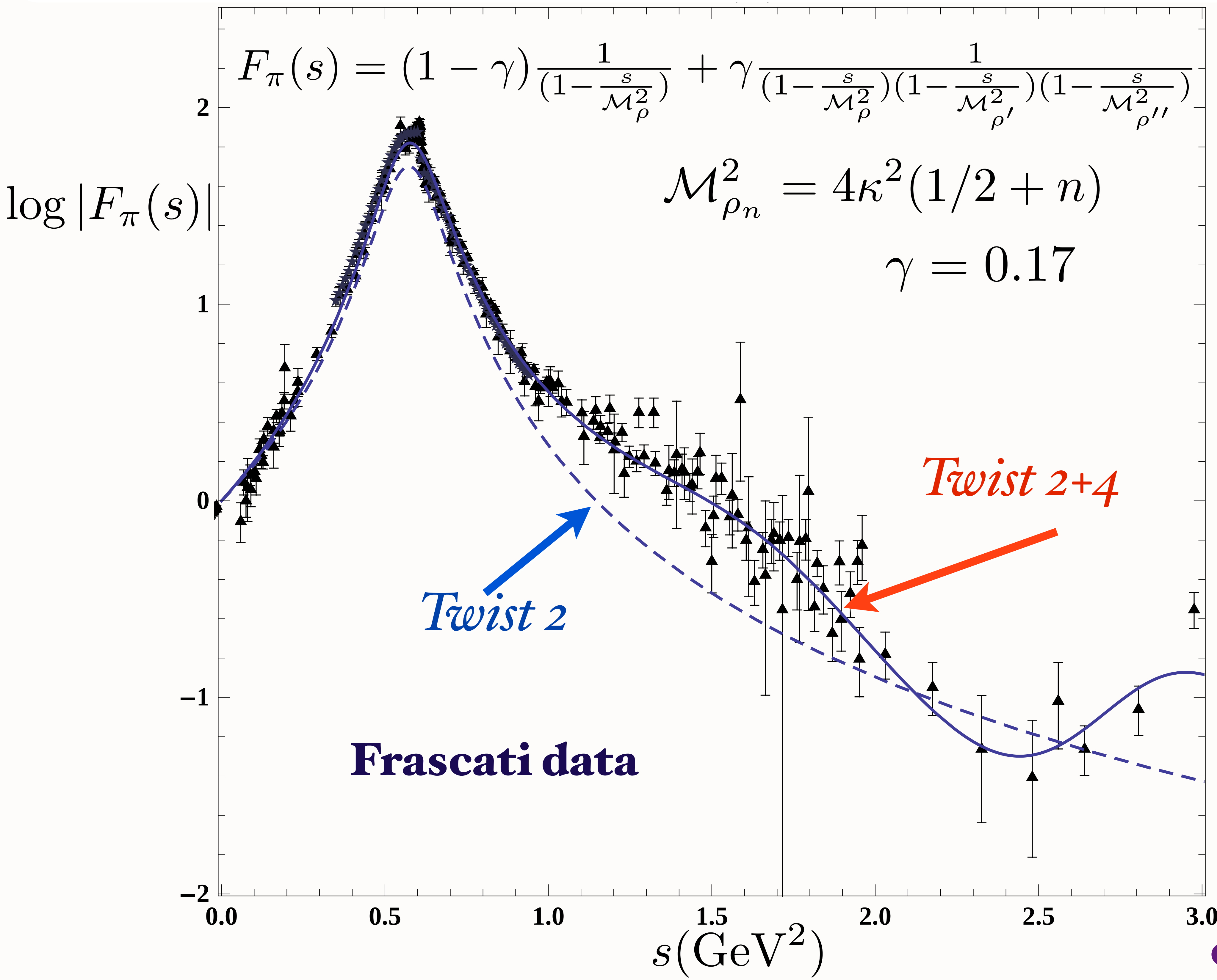
- For large $Q^2 \gg 4\kappa^2$

$$J_\kappa(Q,z) \to zQK_1(zQ) = J(Q,z),$$

the external current decouples from the dilaton field.


$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7

Timelike Pion Form Factor from AdS/QCD and Light-Front Holography

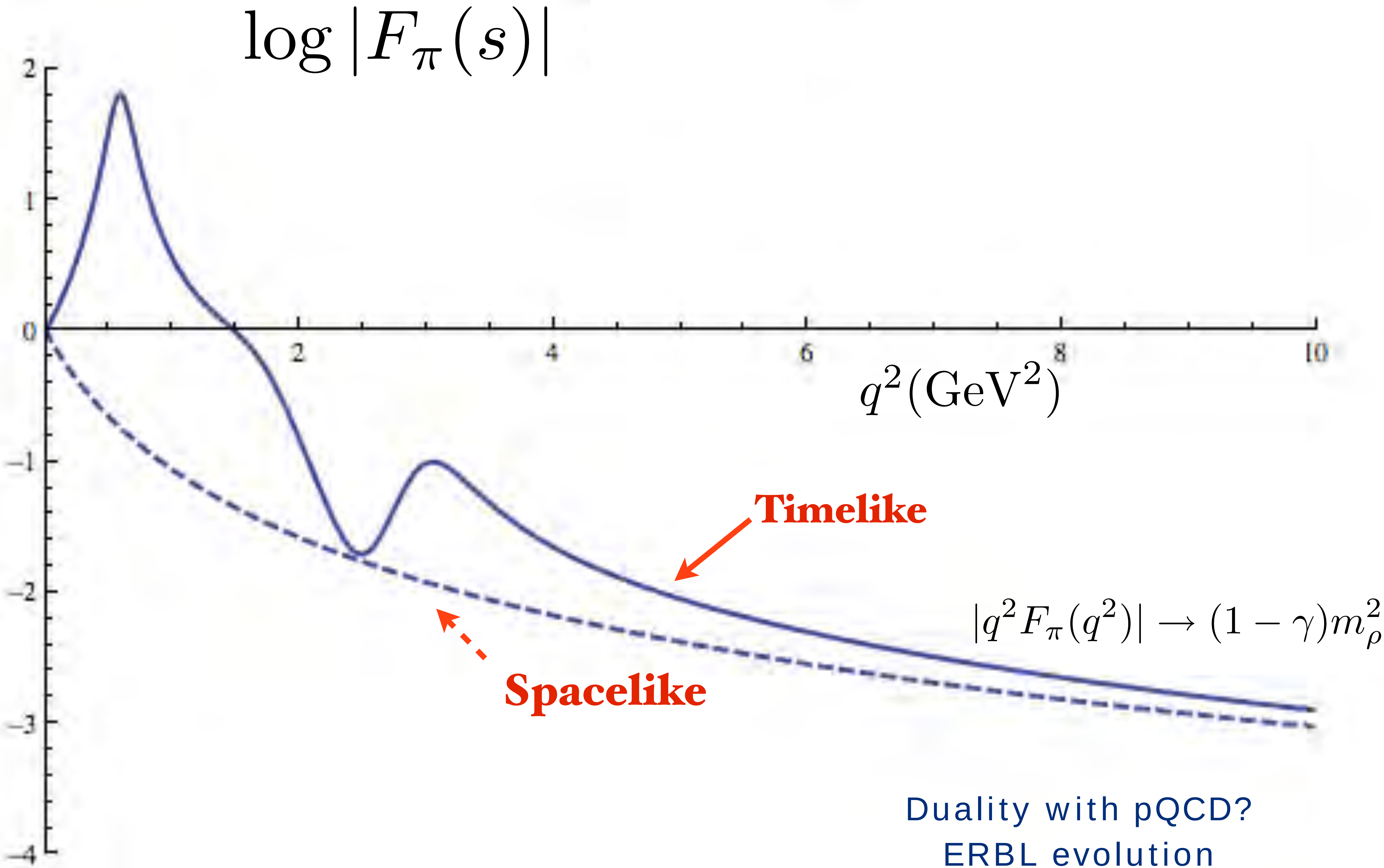


Prescription for Timelike poles :

$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

14% four-quark probability

G. de Teramond & sjb


$\log|F_\pi(s)|$
2
1
0
−1
−2
−3
−4
2
4
6
8
10
$q^2(\mathrm{GeV}^2)$
Timelike
Spacelike
$|q^2F_\pi(q^2)| \to (1-\gamma)m_\rho^2$
Duality with pQCD?
ERBL evolution

Note: Analytical Form of Hadronic Form Factor for Arbitrary Twist

- Form factor for a string mode with scaling dimension τ, Φ_τ in the SW model

$$F(Q^2) = \Gamma(\tau)\frac{\Gamma\left(1+\frac{Q^2}{4\kappa^2}\right)}{\Gamma\left(\tau+\frac{Q^2}{4\kappa^2}\right)}.$$

- For $\tau = N$, $\quad \Gamma(N+z) = (N-1+z)(N-2+z)\ldots(1+z)\Gamma(1+z).$

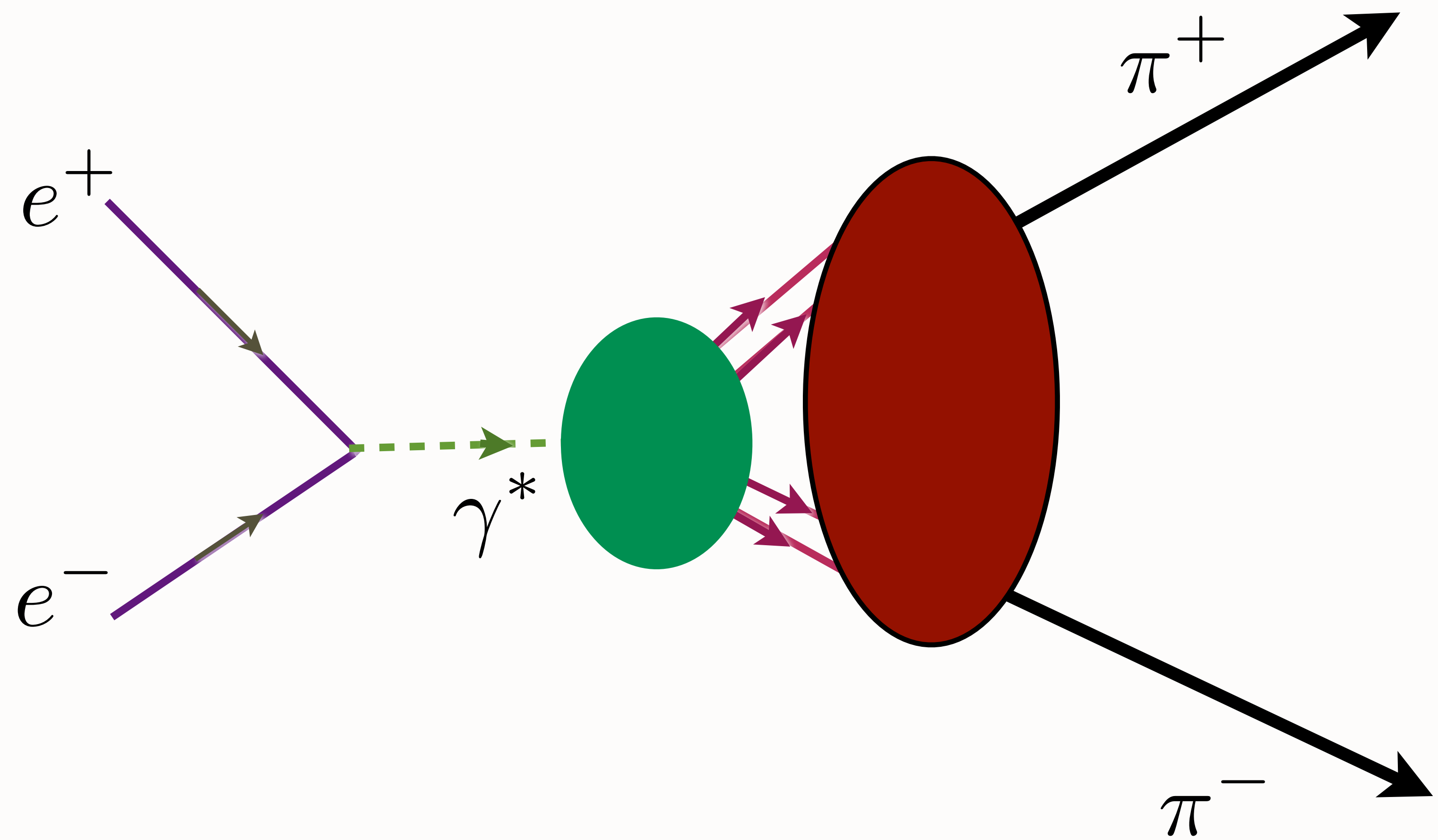
- Form factor expressed as $N-1$ product of poles

$$\begin{aligned}
F(Q^2) &= \frac{1}{1+\frac{Q^2}{4\kappa^2}}, \quad N=2, \\
F(Q^2) &= \frac{2}{\left(1+\frac{Q^2}{4\kappa^2}\right)\left(2+\frac{Q^2}{4\kappa^2}\right)}, \quad N=3, \\
&\cdots \\
F(Q^2) &= \frac{(N-1)!}{\left(1+\frac{Q^2}{4\kappa^2}\right)\left(2+\frac{Q^2}{4\kappa^2}\right)\cdots\left(N-1+\frac{Q^2}{4\kappa^2}\right)}, \quad N.
\end{aligned}$$

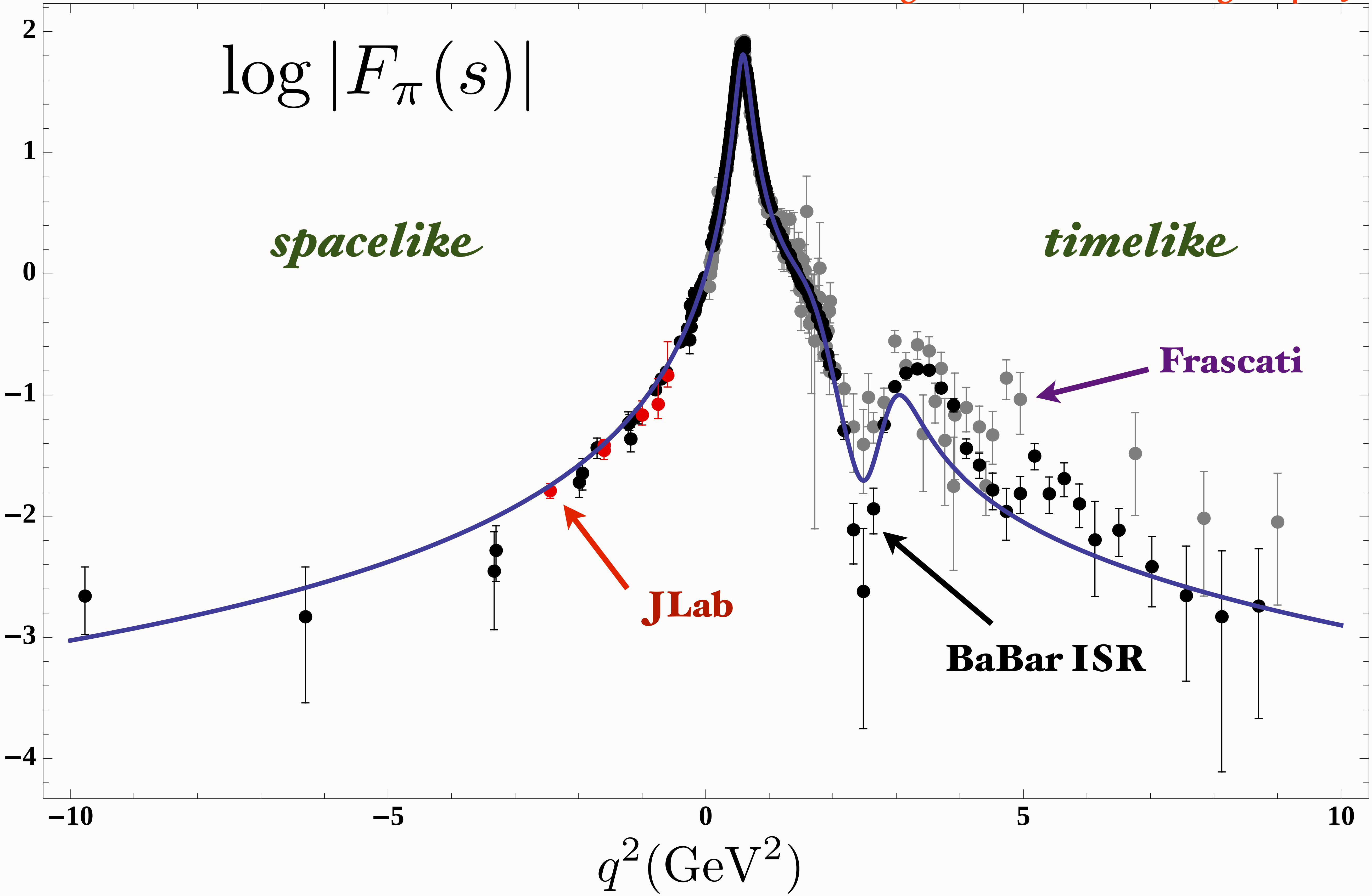
- For large Q^2:

$$F(Q^2) \to (N-1)!\left[\frac{4\kappa^2}{Q^2}\right]^{(N-1)}.$$

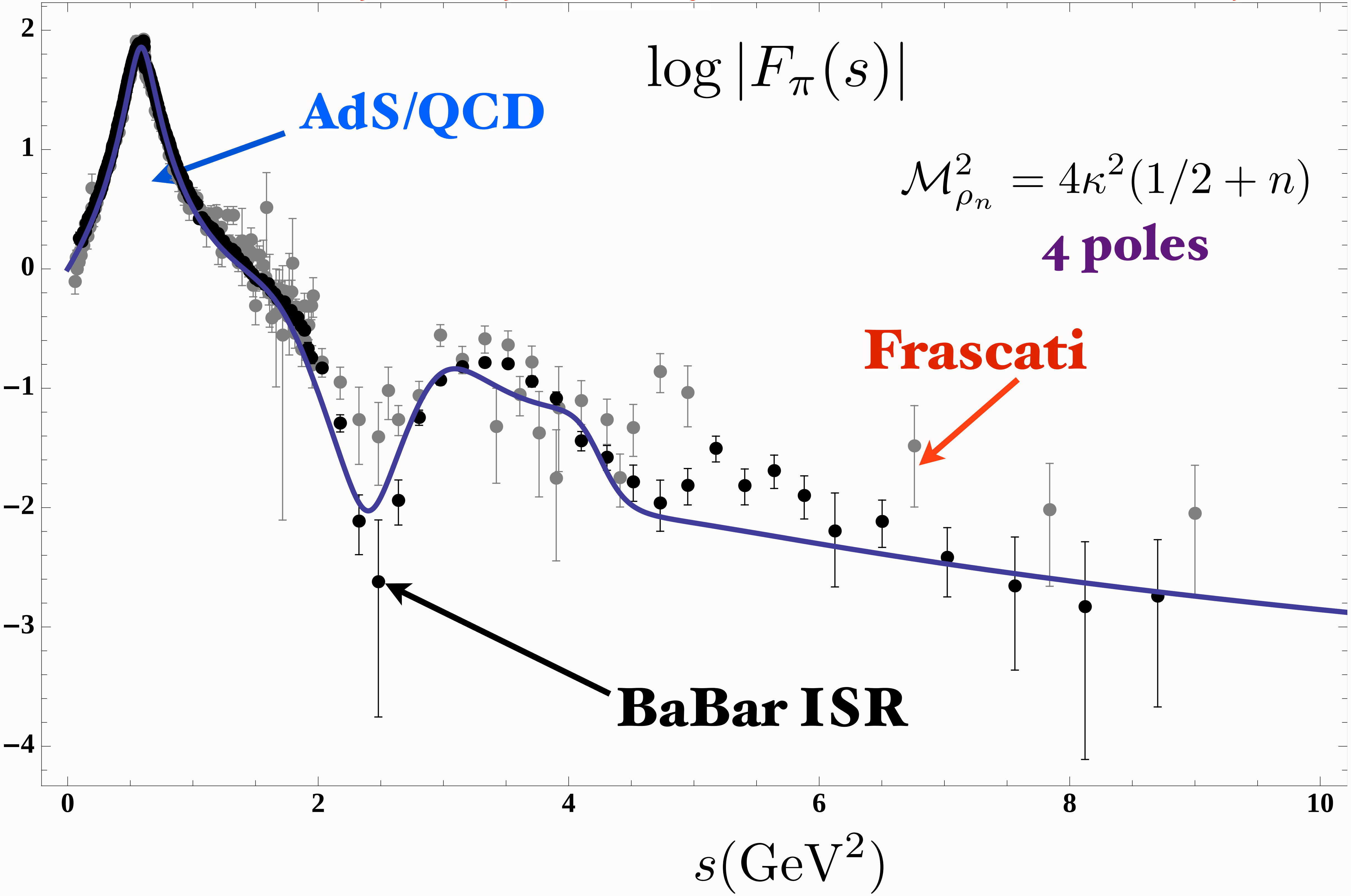
Dressed soft-wall current brings in higher Fock states and more vector meson poles



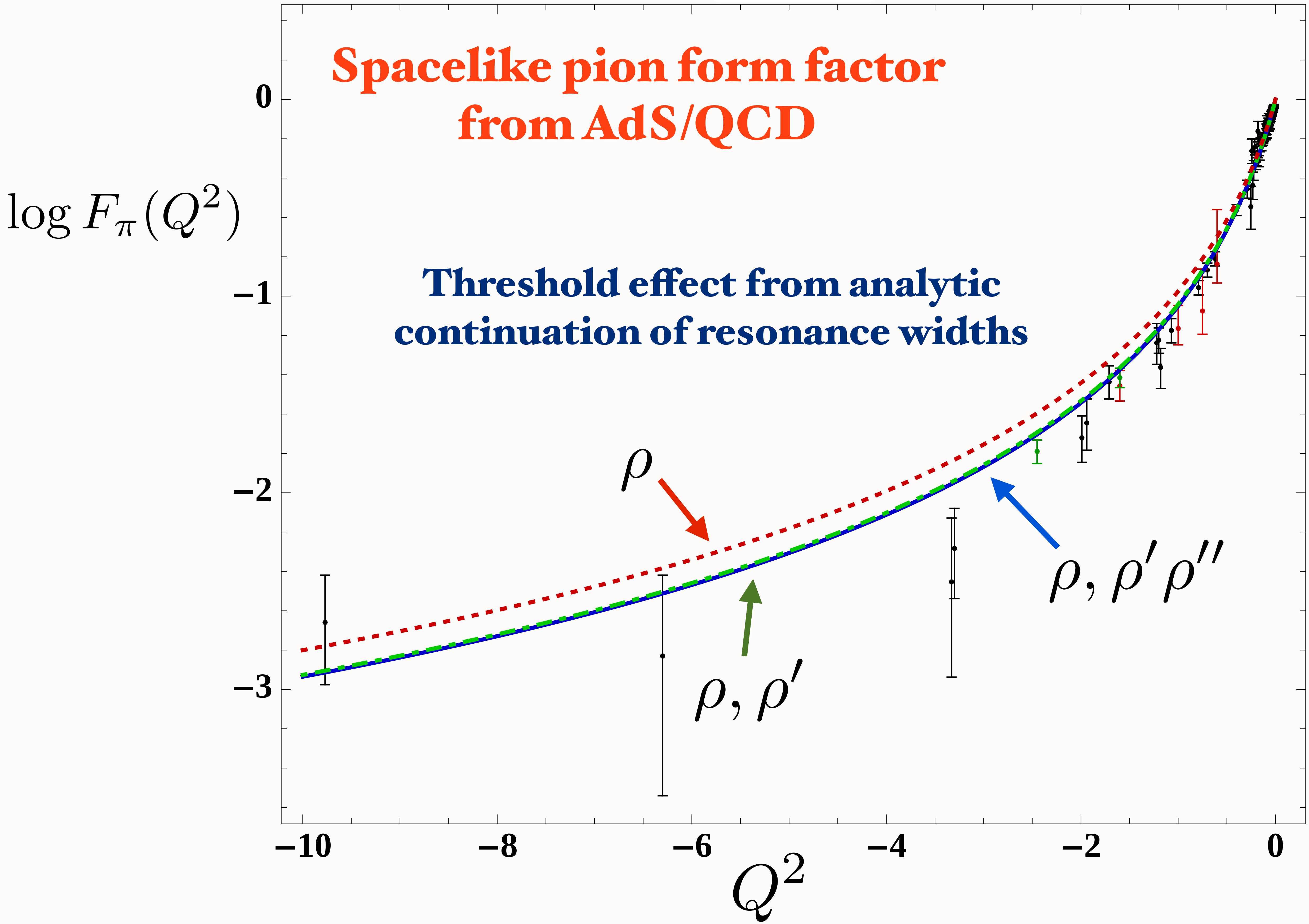
Pion Form Factor from AdS/QCD and Light-Front Holography



Pion Timelike Form Factor (Includes Twist 2 to 5)



Guy de Teramond, sjb
preliminary



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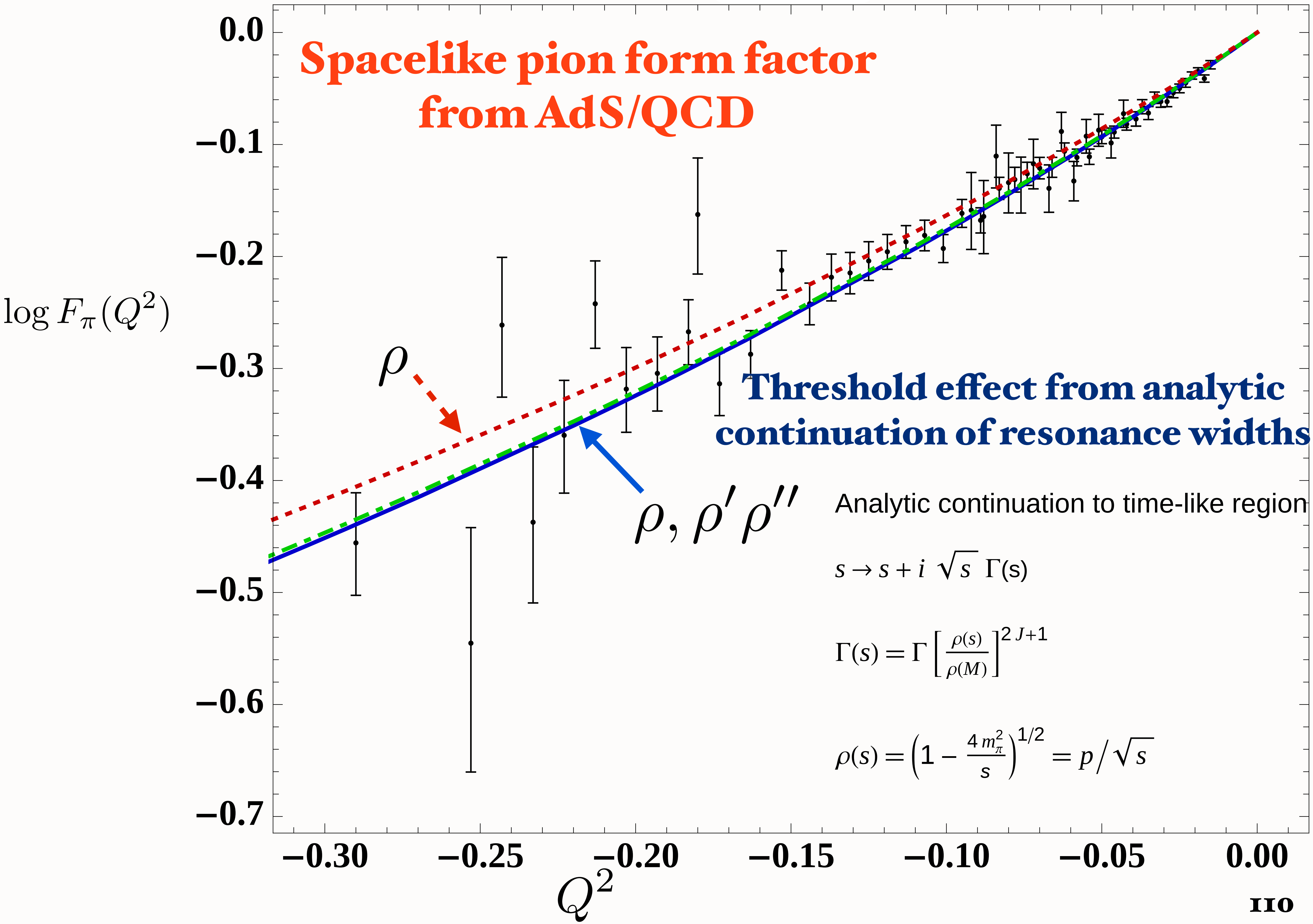
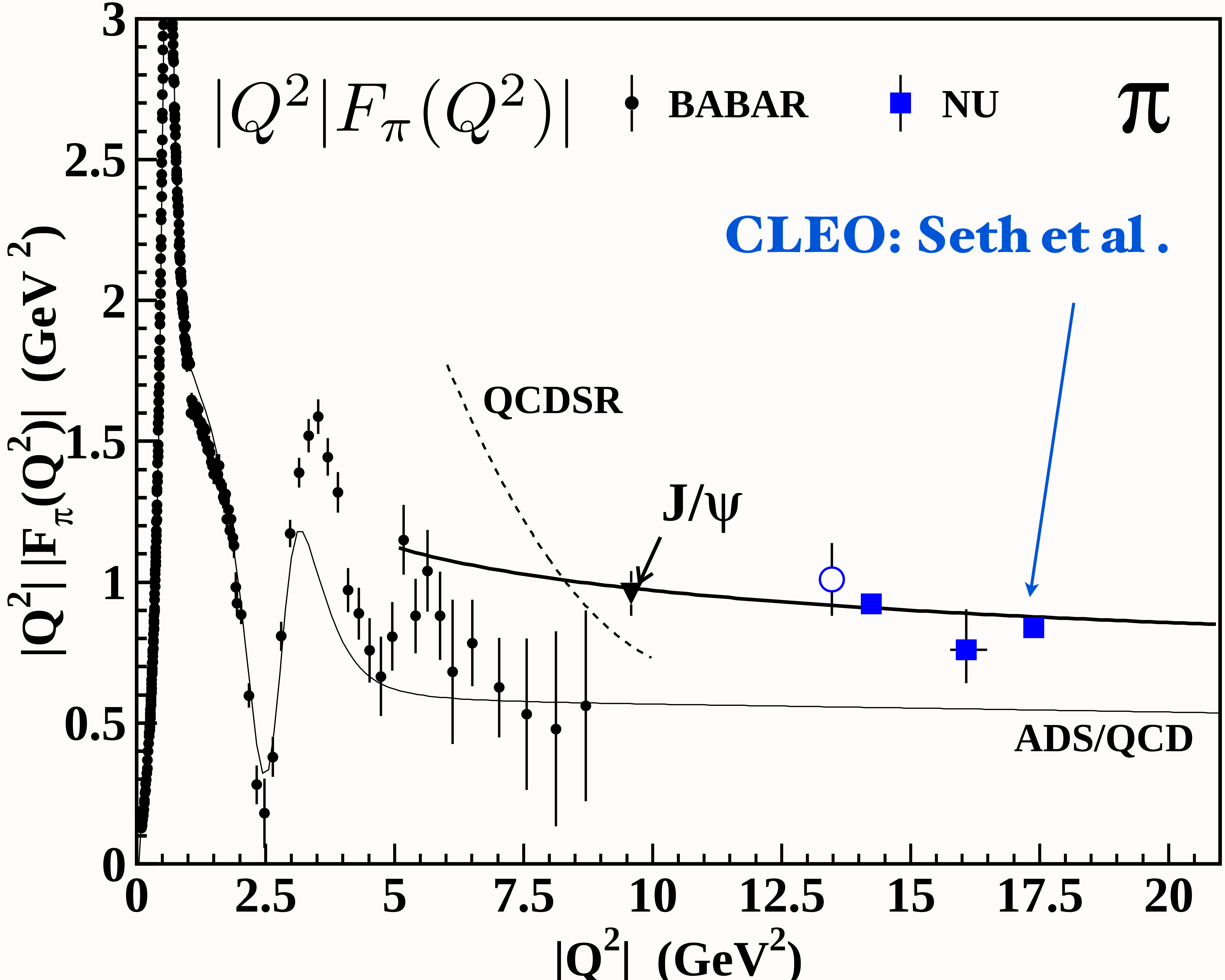
preliminary

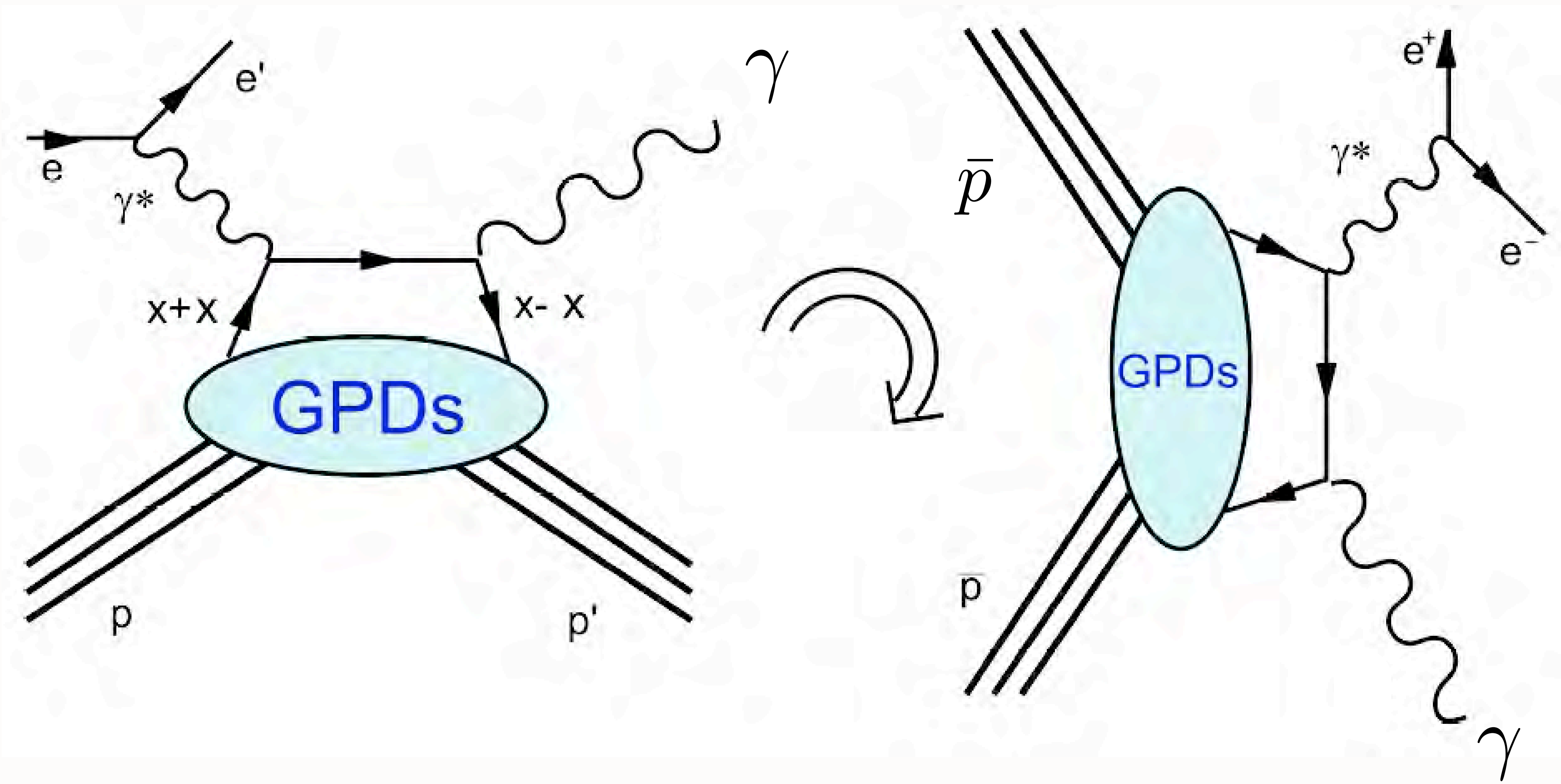


Consistent with log fall-off of pQCD

Timelike Pion Form Factor

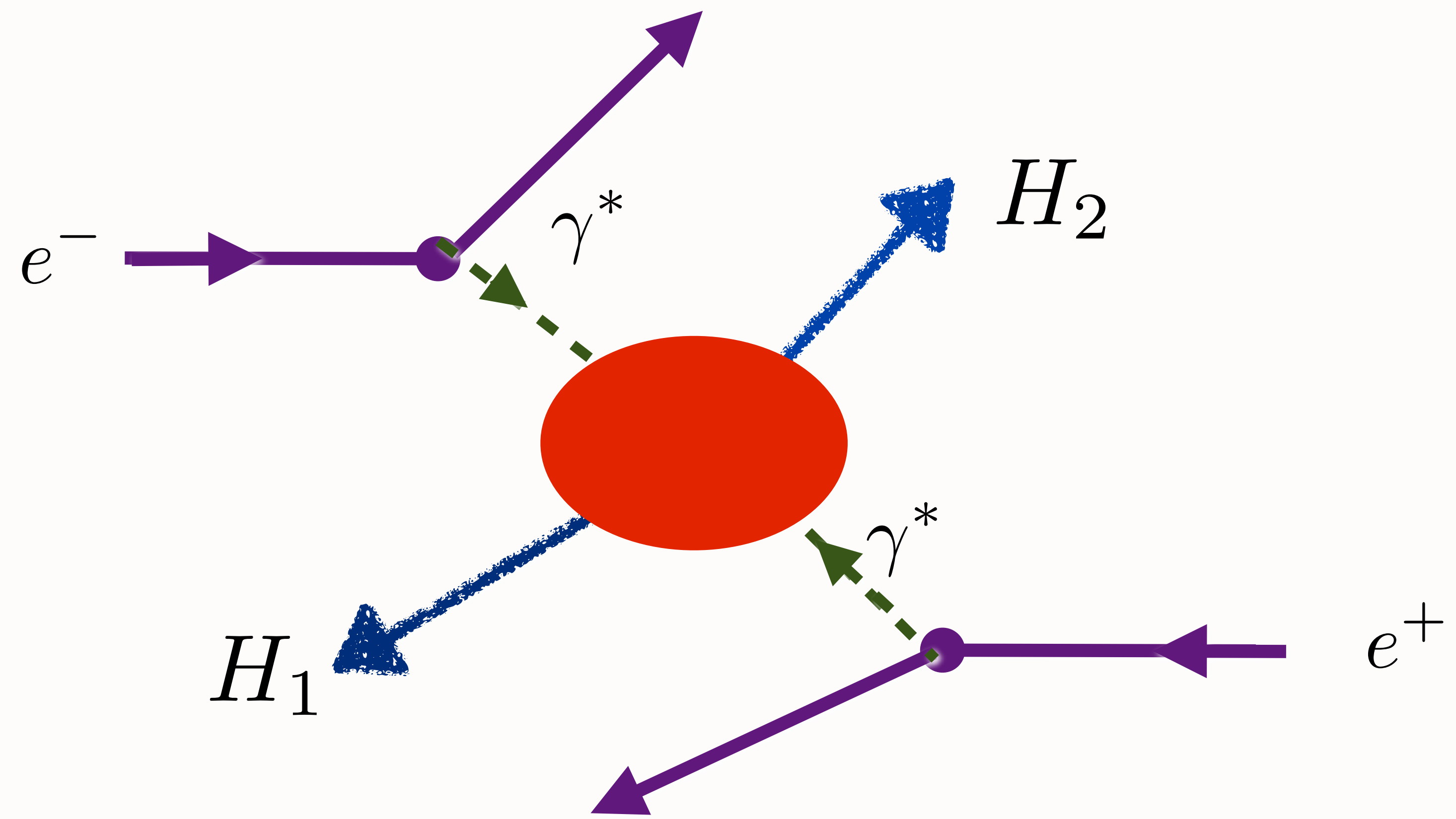


Measure timelike DVCS in $\bar{p}p \to \gamma^*\gamma$ (Panda) and $\gamma^*\gamma \to \bar{p}$ (Belle)



- **Need analytic representation of spacelike and timelike DVCS!**

Two Body Channels



$$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0, K^+K^-, K^0, K^0, \pi^0\eta, \phi\omega, \omega\omega, D^+D^-, p\bar{p}, \cdots$$

$$\text{Belle}: \ 1\ at^{-1}$$

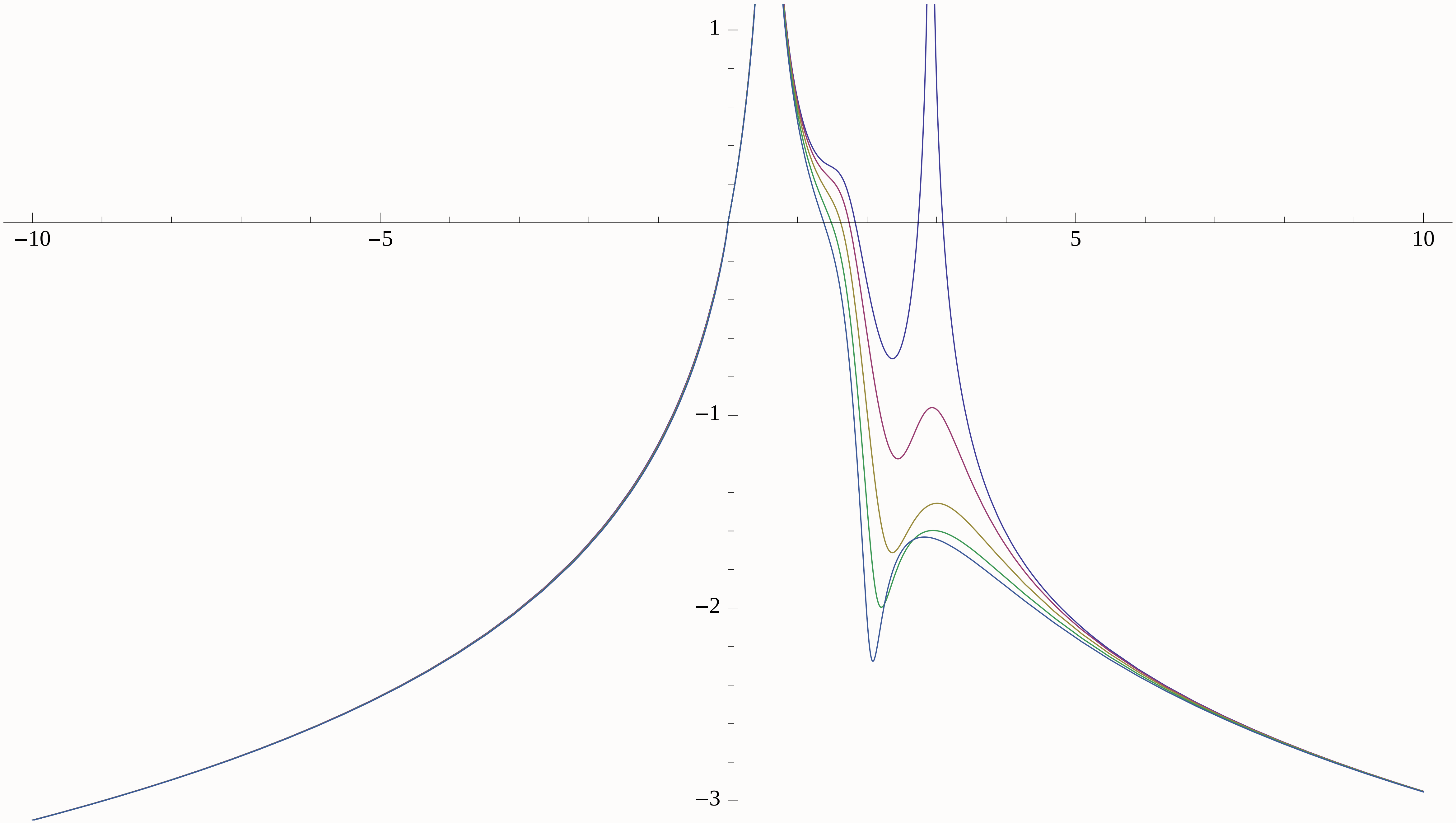
$$\text{Belle 2}: 10\ to\ 50\ at^{-1}$$

Apply AdS/QCD to Photon-Photon Amplitudes

- Use Scalar Current to compute J=0 C=+ resonance structure
- Scalar a_0 hadrons and their radial excitations
- Analytic connection to Spacelike DVCS
- J=0 Fixed pole from direct coupling of two photons to the quark current

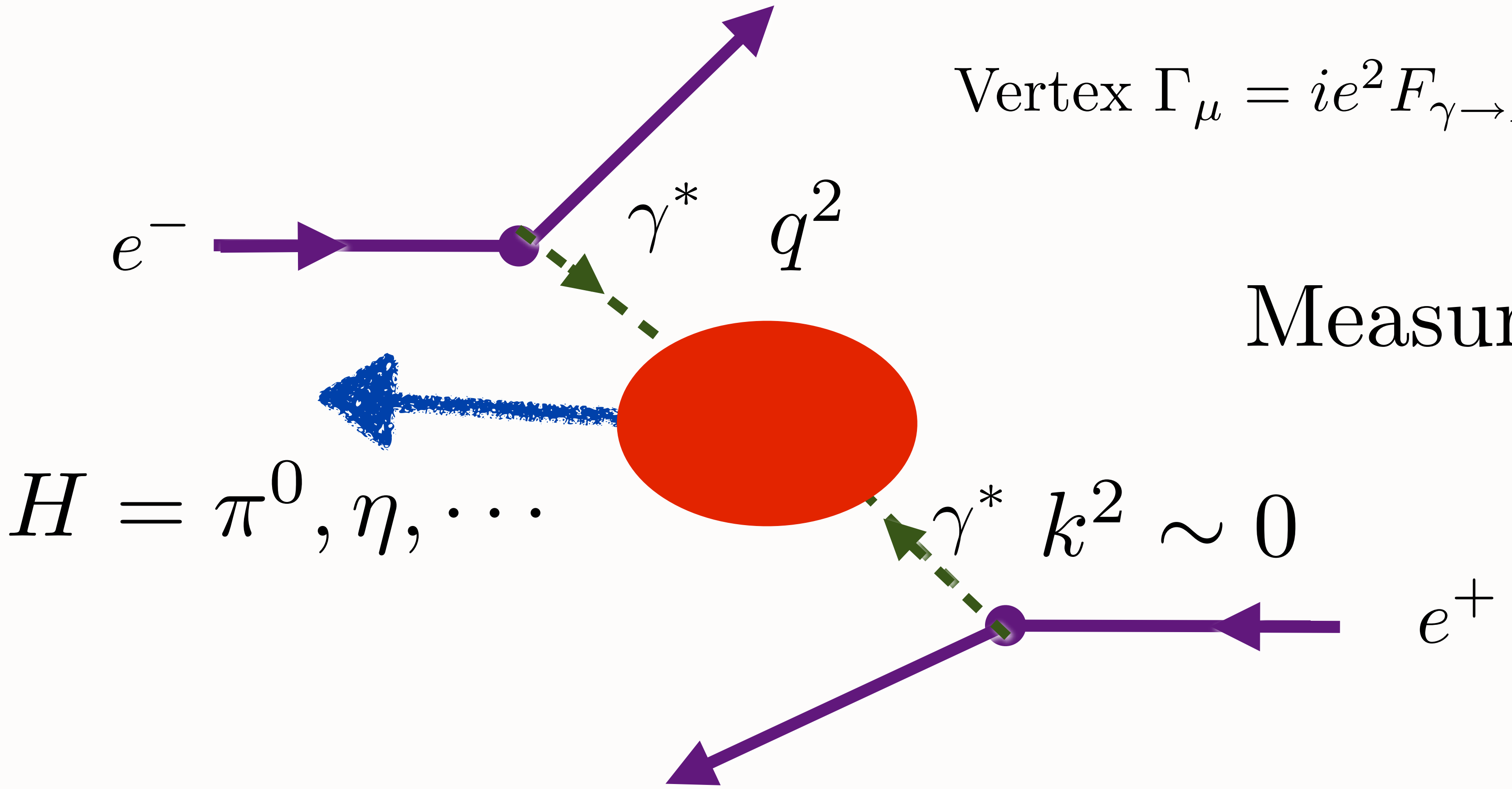
J. Day, G.de Teramond , sjb
in progress

J. Day, G.de Teramond , sjb
in progress



$$\text{AdS/QCD } a_0 \; n = 0, 1 \text{ resonances}$$

Photon-to-Hadron Transition Form Factor



Vertex $\Gamma_\mu = ie^2 F_{\gamma \to H^0}(Q^2) \epsilon_{\mu\nu\rho\sigma} P_H^\mu \epsilon^\rho q^\sigma$

Measure $F(Q^2)_{\gamma \to H^0}$

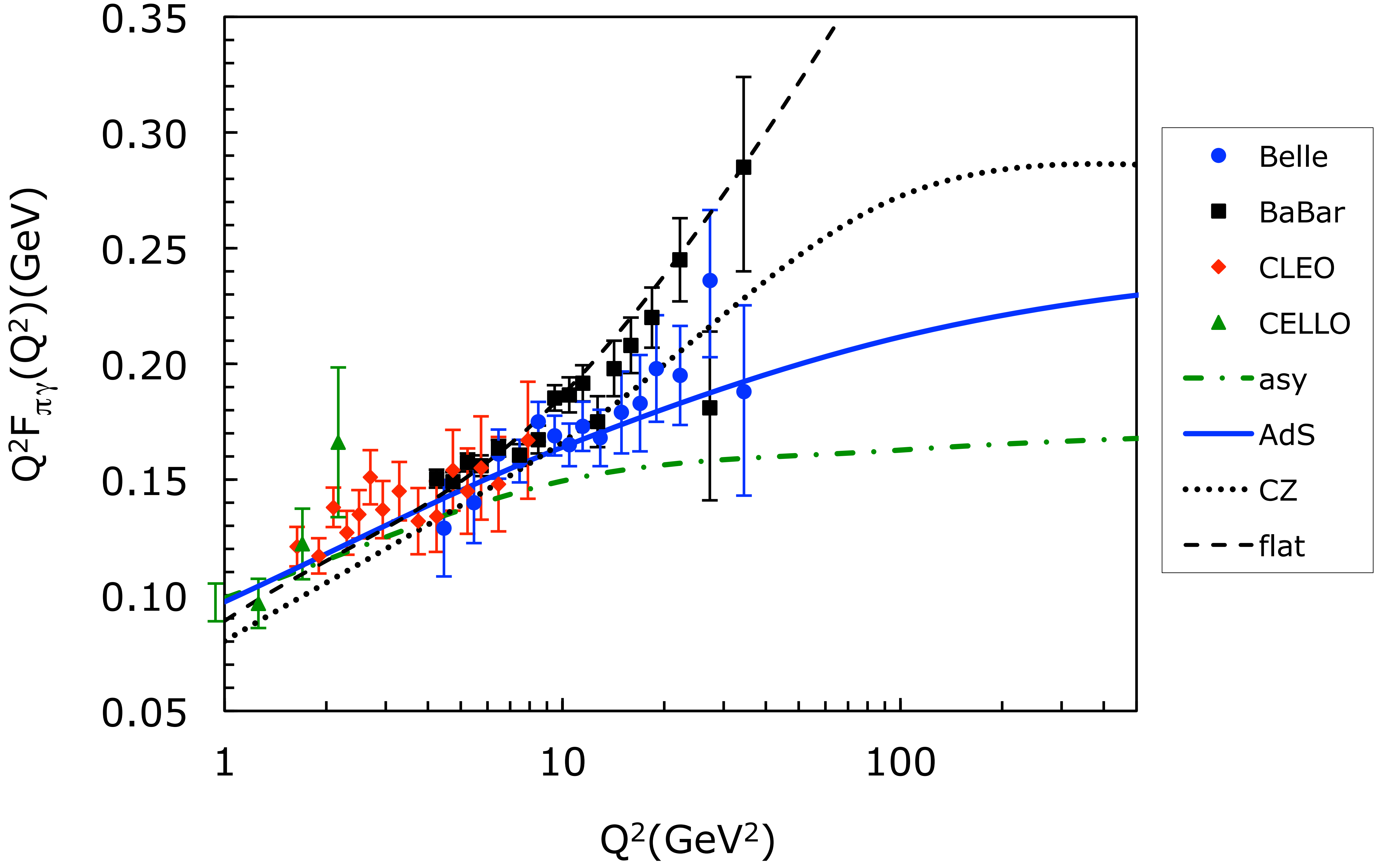
Fundamental leading order prediction from pQCD

$$F_{\pi\gamma}(Q^2) = \frac{2}{\sqrt{3}Q^2} \int_0^1 dx \frac{\phi_\pi^*(x, \widetilde{Q})}{x(1-x)} \left[1 + O\left[\alpha_s, \frac{m^2}{Q^2}\right]\right]$$

Lepage, sjb

$$Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2 f_\pi$$

Photon-to-pion transition form factor



Regge Representation of AdS/QCD

- Analytic Representation of spacelike and timelike DVCS!
- Contains all C=+ Resonances in t channel of DVCS
- Resonances linear in L corresponds to Regge poles
- Signature factor determines phase
- Resonances in n for each L: analytic partial wave amplitude
- J=0 fixed pole from Compton scattering on quarks

Resonance Structure of Photon-Photon Amplitudes

$$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0, K^+K^-, K^0, K^0, \pi^0\eta, \phi\omega, \omega\omega, D^+D^-, p\bar{p}, \cdots$$

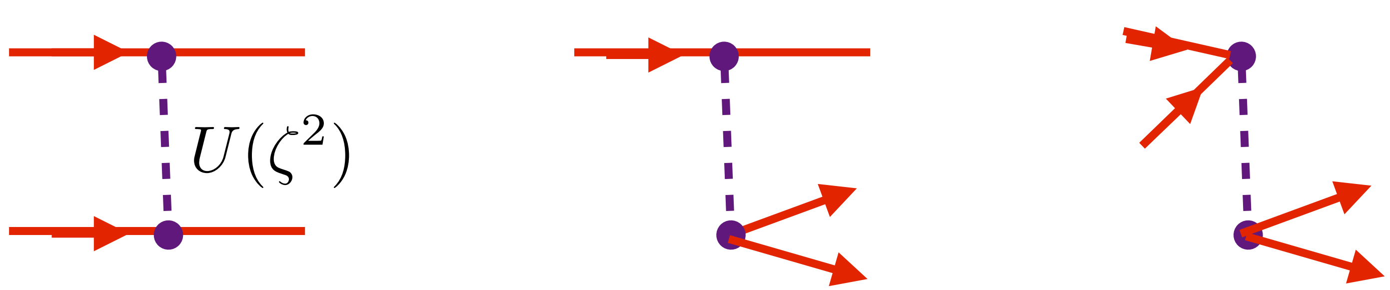
- **All $J^{PC} = 0^{++}$ resonances accessible**
- **Real and Virtual Photons**
- **Meson pairs and Baryon Pairs**
- **Heavy Quarkonia**
- **Decomposition in partial waves**
- **Analogous to timelike form factors**
- **AdS/QCD predicts analytic form: multi-resonance poles**
- **Relative phases and couplings**
- **Analytically continue to DVCS** $\gamma^* p \to \gamma p, \gamma^* \pi \to \gamma\pi$
- **Constraints from DHG and Low Energy Theorem (Pauk, Vanderhaeghen)**

Higher Fock States

- Exposed by timelike form factor through dressed current.
- Created by confining interaction

$$P^-_{\text{confinement}} \simeq \kappa^4 \int dx^- d^2\vec{x}_\perp \frac{\overline{\psi}\gamma^+ T^a \psi}{P^+} \frac{1}{(\partial/\partial_\perp)^4} \frac{\overline{\psi}\gamma^+ T^a \psi}{P^+}$$

- Similar to QCD(1+1) in lcg



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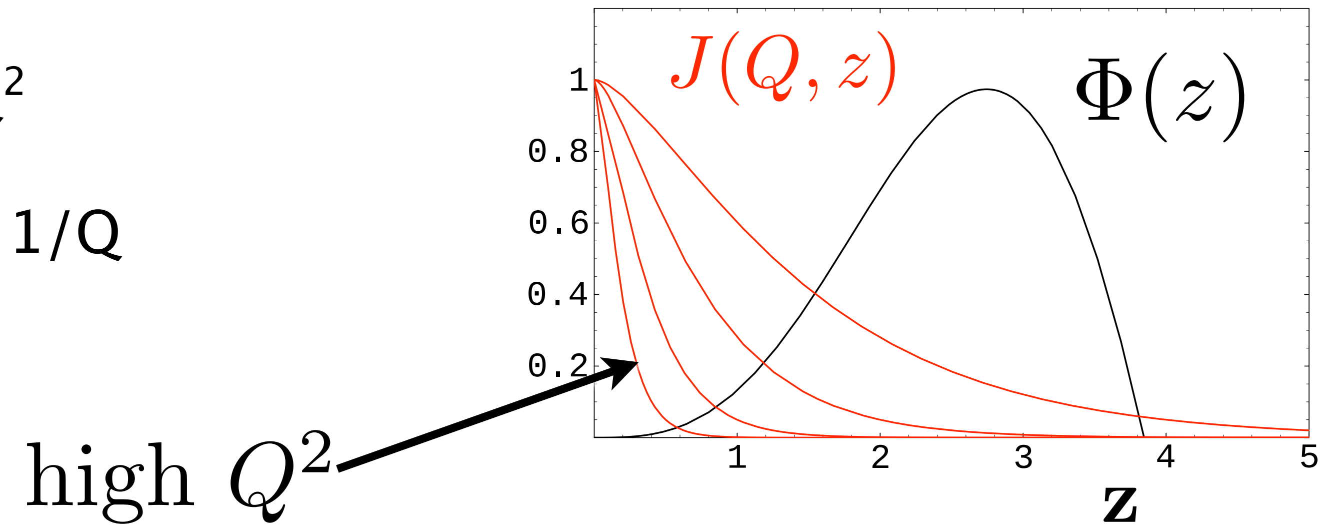
High Q^2
from
small z ~ 1/Q



Polchinski, Strassler
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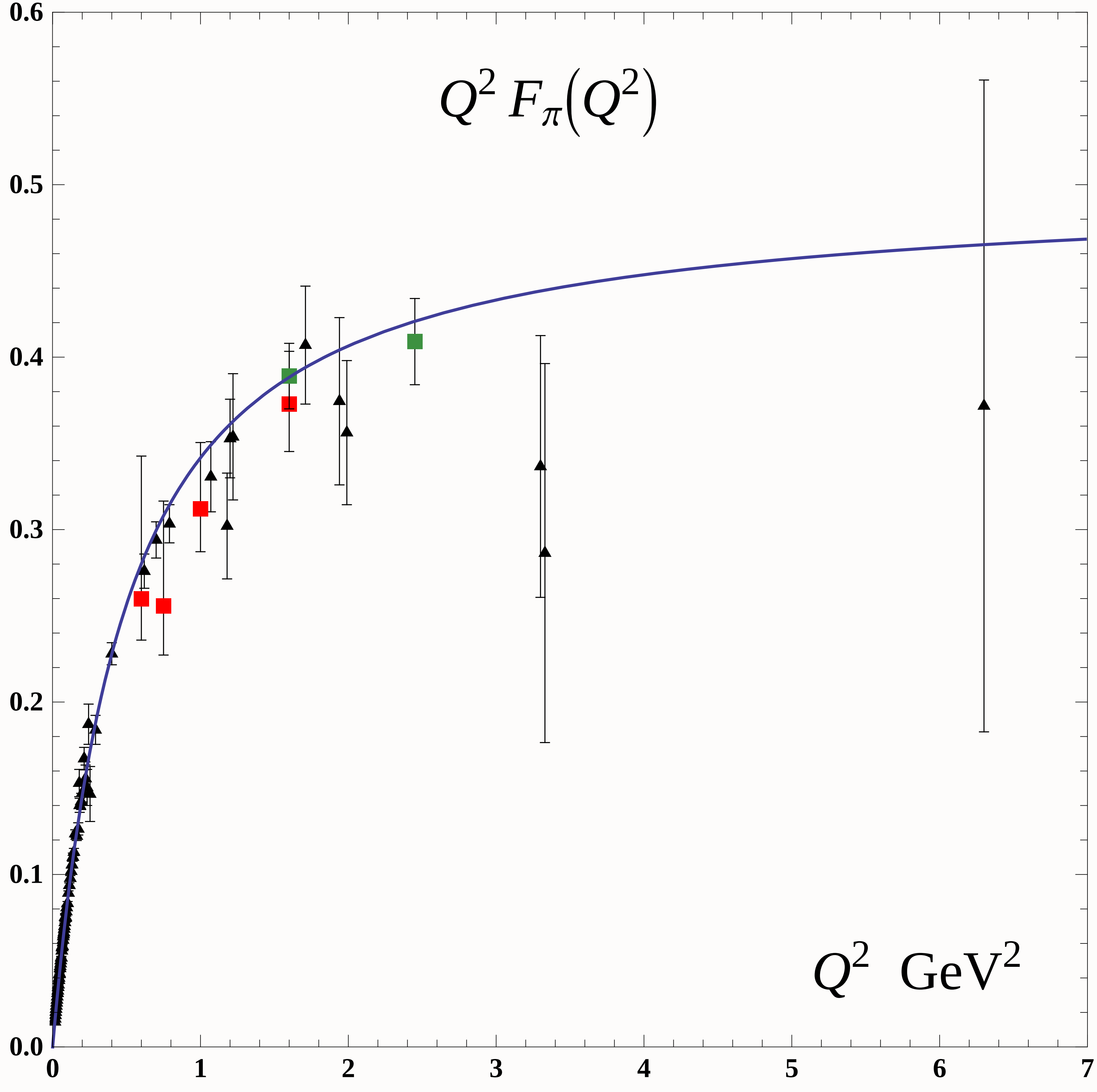


0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
$Q^2 F_\pi(Q^2)$
Q^2 GeV^2

Holographic Mapping of AdS Modes to QCD LFWFs

- Integrate Soper formula over angles:

$$F(q^2) = 2\pi \int_0^1 dx \, \frac{(1-x)}{x} \int \zeta d\zeta J_0\left(\zeta q \sqrt{\frac{1-x}{x}}\right) \tilde{\rho}(x, \zeta),$$

with $\widetilde{\rho}(x, \zeta)$ QCD effective transverse charge density.

- Transversality variable

$$\boxed{\zeta = \sqrt{x(1-x)\vec{b}_\perp^2}}$$

- Compare AdS and QCD expressions of FFs for arbitrary Q using identity:

$$\int_0^1 dx J_0\left(\zeta Q \sqrt{\frac{1-x}{x}}\right) = \zeta Q K_1(\zeta Q),$$

the solution for $J(Q, \zeta) = \zeta Q K_1(\zeta Q)$!

Gravitational Form Factor in AdS space

- Hadronic gravitational form-factor in AdS space

$$A_\pi(Q^2) = R^3 \int \frac{dz}{z^3}\, H(Q^2, z)\, \left|\Phi_\pi(z)\right|^2 ,$$

Abidin & Carlson

where $H(Q^2, z) = \frac{1}{2} Q^2 z^2 K_2(zQ)$

- Use integral representation for $H(Q^2, z)$

$$H(Q^2, z) = 2 \int_0^1 x\, dx\, J_0\!\left(zQ \sqrt{\frac{1-x}{x}}\right)$$

- Write the AdS gravitational form-factor as

$$A_\pi(Q^2) = 2R^3 \int_0^1 x\, dx \int \frac{dz}{z^3}\, J_0\!\left(zQ \sqrt{\frac{1-x}{x}}\right) \left|\Phi_\pi(z)\right|^2$$

- Compare with gravitational form-factor in light-front QCD for arbitrary Q

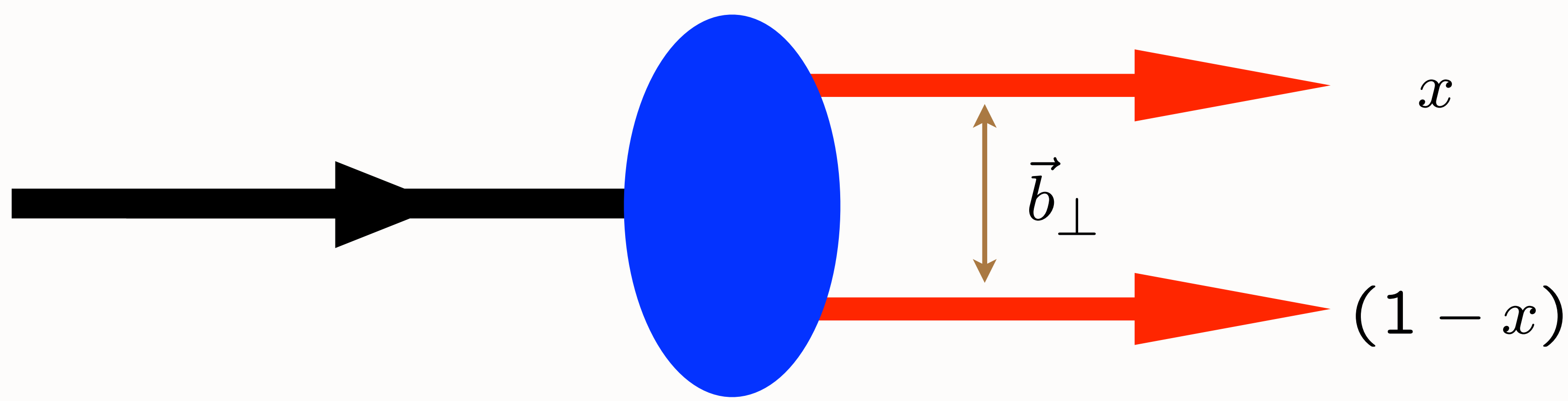
$$\boxed{\left|\tilde{\psi}_{q\bar{q}/\pi}(x, \zeta)\right|^2 = \frac{R^3}{2\pi}\, x(1-x) \frac{\left|\Phi_\pi(\zeta)\right|^2}{\zeta^4},}$$

Identical to LF Holography obtained from electromagnetic current de Teramond, sjb

LF(3+1) $\longleftrightarrow$ AdS$_5$

$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$

$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^{\,2}} \longleftrightarrow z$$



$$\psi(x,\zeta) = \sqrt{x(1-x)}\,\zeta^{-1/2}\phi(\zeta)$$

Light Front Holography: Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements

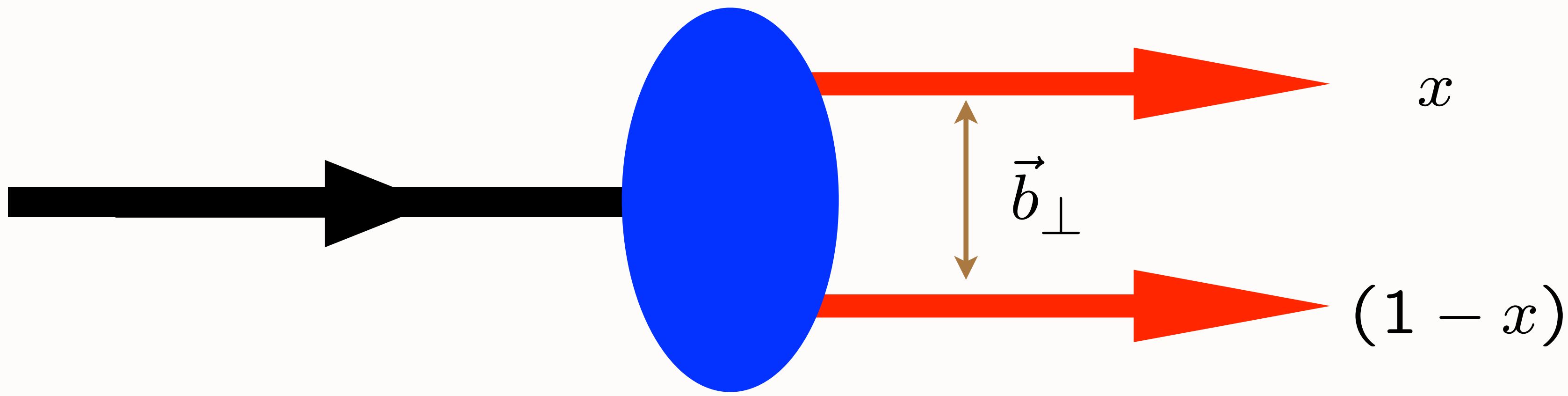
Light-Front Holography: Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation

Frame Independent

$$\left[-\frac{d^2}{d\zeta^2}+\frac{1-4L^2}{4\zeta^2}+U(\zeta)\right]\psi(\zeta)=\mathcal{M}^2\psi(\zeta)$$

$$\zeta^2 = x(1-x)\mathbf{b}^2_\perp .$$



$$U(\zeta)=\kappa^4\zeta^2+2\kappa^2(L+S-1)$$

soft wall confining potential:

G. de Teramond, sjb

Light-Front Schrödinger Equation

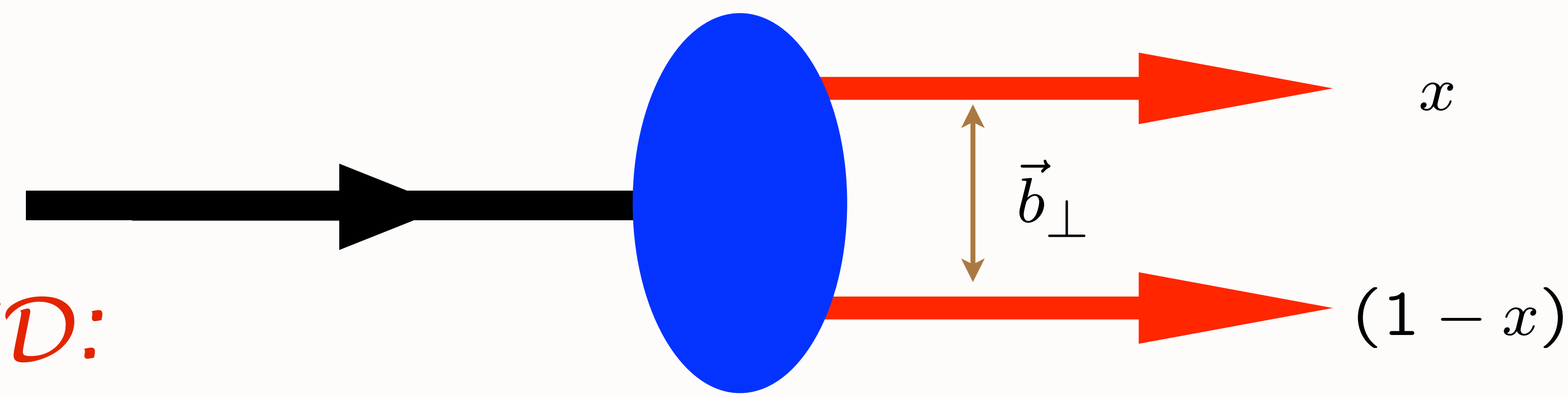
G. de Teramond, sjb

Relativistic LF single-variable radial equation for QCD & QED

Frame Independent!

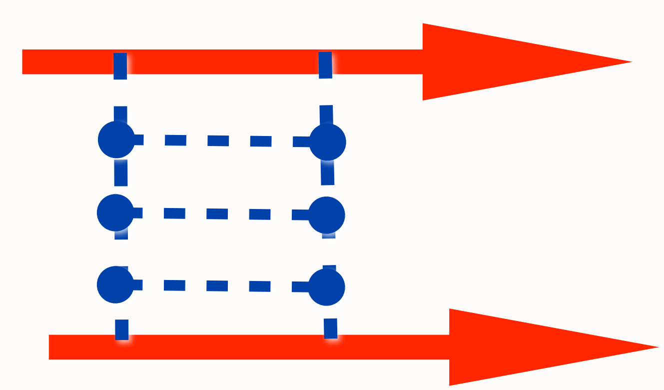
$$\left[-\frac{d^2}{d\zeta^2}+\frac{m^2}{x(1-x)}+\frac{-1+4L^2}{\zeta^2}+U(\zeta,S,L)\right]\psi_{LF}(\zeta)=M^2\,\psi_{LF}(\zeta)$$

$$\zeta^2=x(1-x)\mathrm{b}_\perp^2.$$



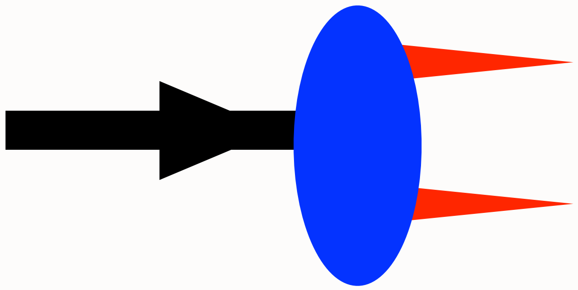
AdS/QCD:

$$U(\zeta,S,L)=\kappa^2\zeta^2+\kappa^2(L+S-1/2)$$

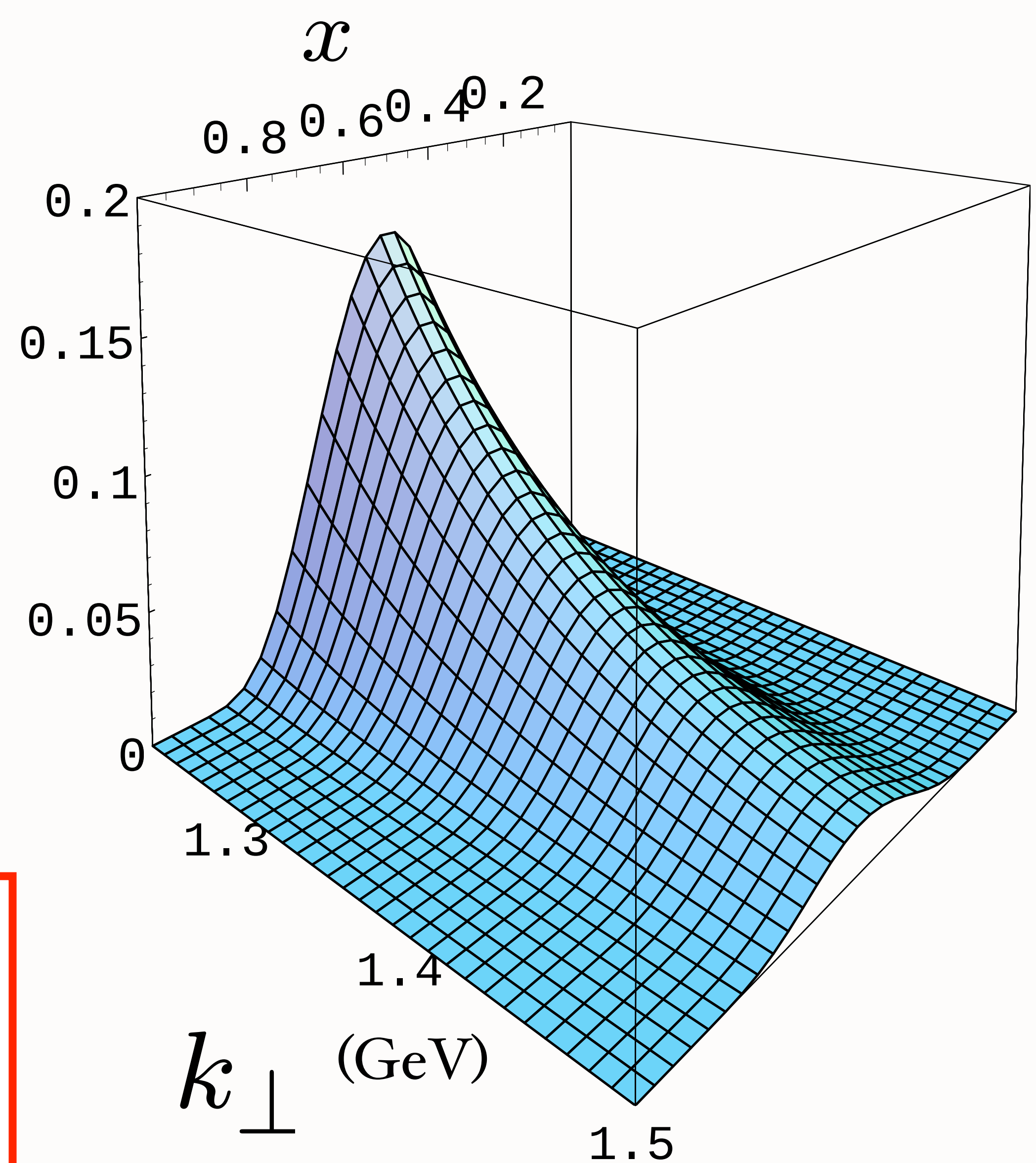


U is the exact QCD potential
Conjecture: 'H'-diagrams generate

Prediction from AdS/CFT: Meson LFWF



$\psi_M(x, k^2_\perp)$



de Teramond, sjb

"Soft Wall" model

$\kappa = 0.375$ GeV

massless quarks

Note coupling

$k^2_\perp, x$

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k^2_\perp}{2\kappa^2 x(1-x)}}$$

$$\boxed{\phi_M(x, Q_0) \propto \sqrt{x(1-x)}}$$

Connection of Confinement to TMDs

PRL 109, 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction

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(Received 5 April 2012; published 20 August 2012)

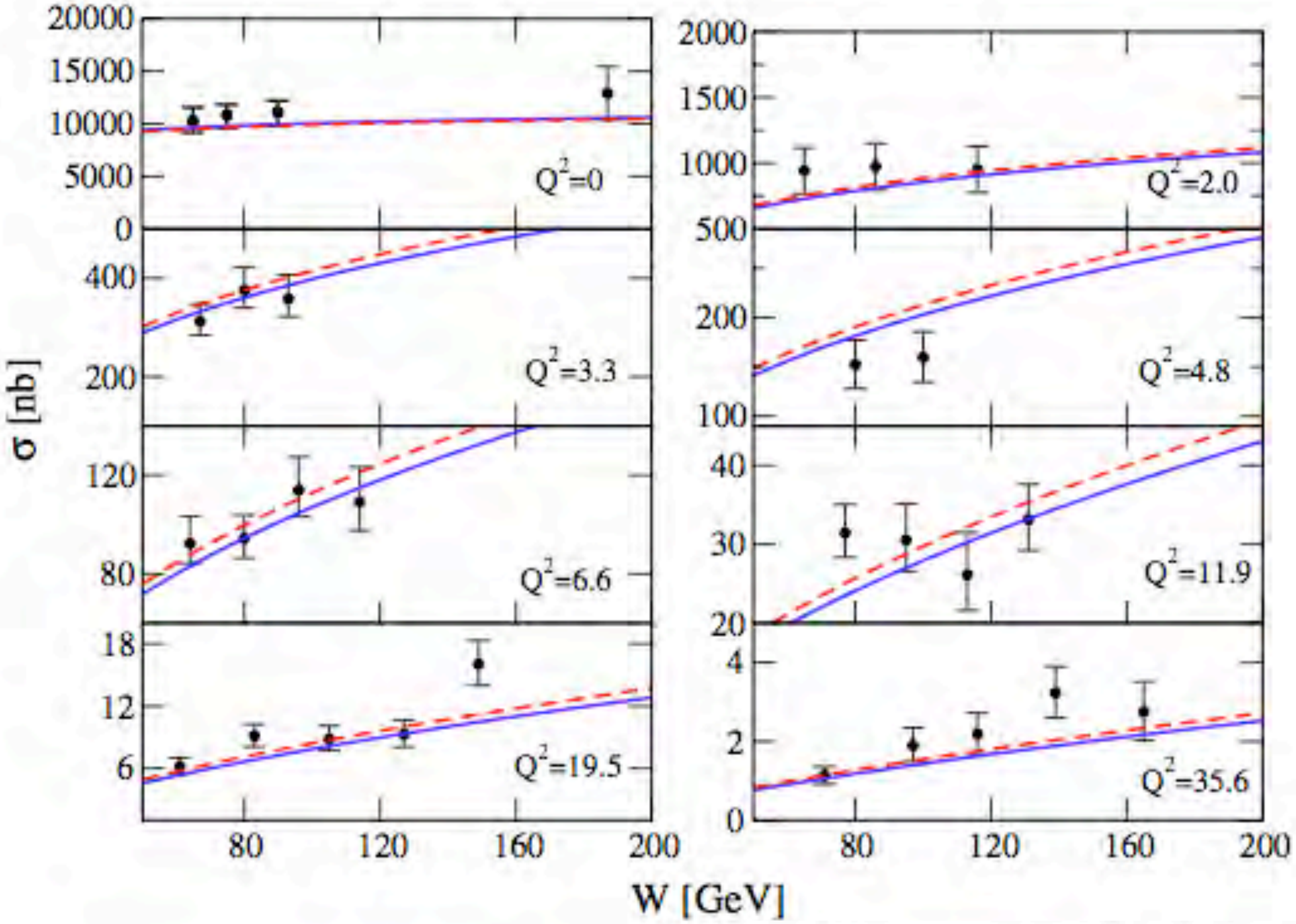
We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive

$$\phi(x, \zeta) = \mathcal{N} \frac{\kappa}{\sqrt{\pi}} \sqrt{x(1-x)} \exp\left(-\frac{\kappa^2 \zeta^2}{2}\right),$$

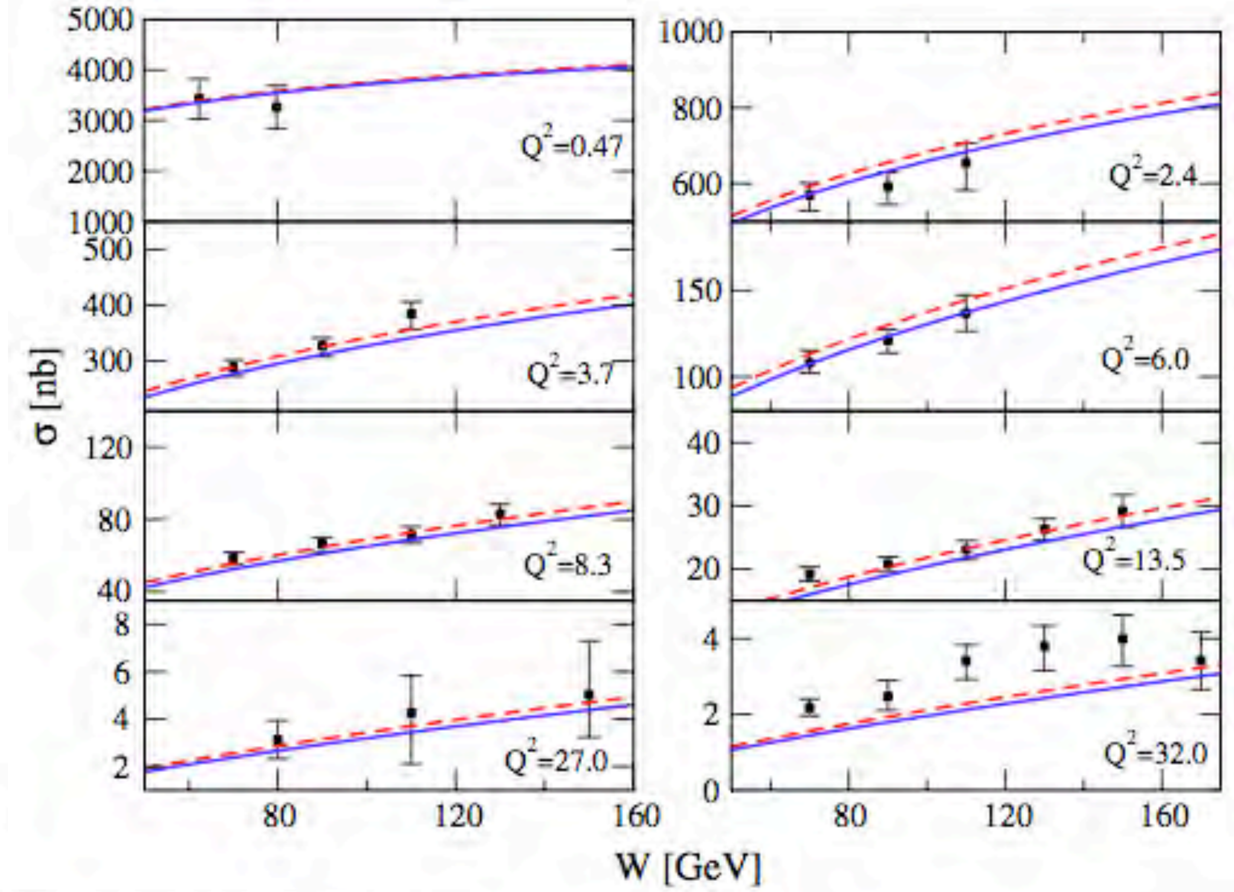
$$\tilde{\phi}(x, k) \propto \frac{1}{\sqrt{x(1-x)}} \exp\left(-\frac{M_{q\bar{q}}^2}{2\kappa^2}\right),$$

PRL 109, 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

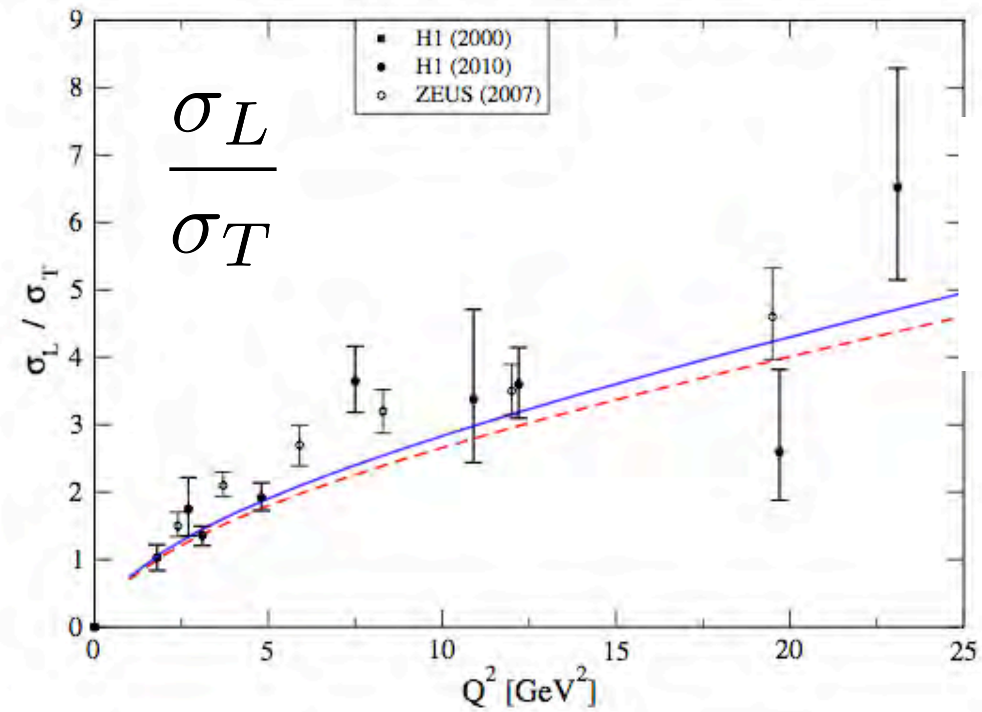
AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction



(a) H



(b) ZEUS



$$\frac{\sigma_L}{\sigma_T}$$

J. R. Forshaw, R. Sandapen

$$\gamma^* p \to \rho^0 p'$$

$$\tilde{\phi}(x,k) \propto \frac{1}{\sqrt{x(1-x)}} \exp\left(-\frac{M_{q\bar{q}}^2}{2\kappa^2}\right),$$

Second Moment of Pion Distribution Amplitude

$$< \xi^2 >= \int_{-1}^{1} d\xi \; \xi^2 \phi(\xi)$$

$$\xi = 1 - 2x$$

$$< \xi^2 >_\pi = 1/5 = 0.20 \qquad \phi_{asympt} \propto x(1-x)$$

$$< \xi^2 >_\pi = 1/4 = 0.25 \qquad \phi_{AdS/QCD} \propto \sqrt{x(1-x)}$$

Lattice (I) $< \xi^2 >_\pi = 0.28 \pm 0.03$ Donnellan et al.

Lattice (II) $< \xi^2 >_\pi = 0.269 \pm 0.039$ Braun et al.

- In terms of $n-1$ independent transverse impact coordinates $\mathbf{b}_{\perp j}$, $j = 1, 2, \ldots, n-1$,

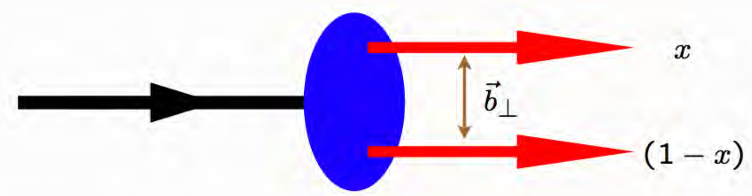
$$\mathcal{M}^2 = \sum_n \prod_{j=1}^{n-1} \int dx_j d^2\mathbf{b}_{\perp j} \psi_n^*(x_i, \mathbf{b}_{\perp i}) \sum_\ell \left(\frac{-\nabla_{\mathbf{b}_{\perp \ell}}^2 + m_\ell^2}{x_q} \right) \psi_n(x_i, \mathbf{b}_{\perp i}) + \text{interactions}$$

- Relevant variable conjugate to invariant mass in the limit of zero quark masses

$$\zeta = \sqrt{\frac{x}{1-x}} \left| \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j} \right|$$

the x-weighted transverse impact coordinate of the spectator system (x active quark)

- For a two-parton system $\zeta^2 = x(1-x)\mathbf{b}_\perp^2$



- To first approximation LF dynamics depend only on the invariant variable ζ, and hadronic properties are encoded in the hadronic mode $\phi(\zeta)$ from

$$\psi(x, \zeta, \varphi) = e^{iM\varphi} X(x) \frac{\phi(\zeta)}{\sqrt{2\pi\zeta}}$$

factoring angular φ, longitudinal $X(x)$ and transverse mode $\phi(\zeta)$

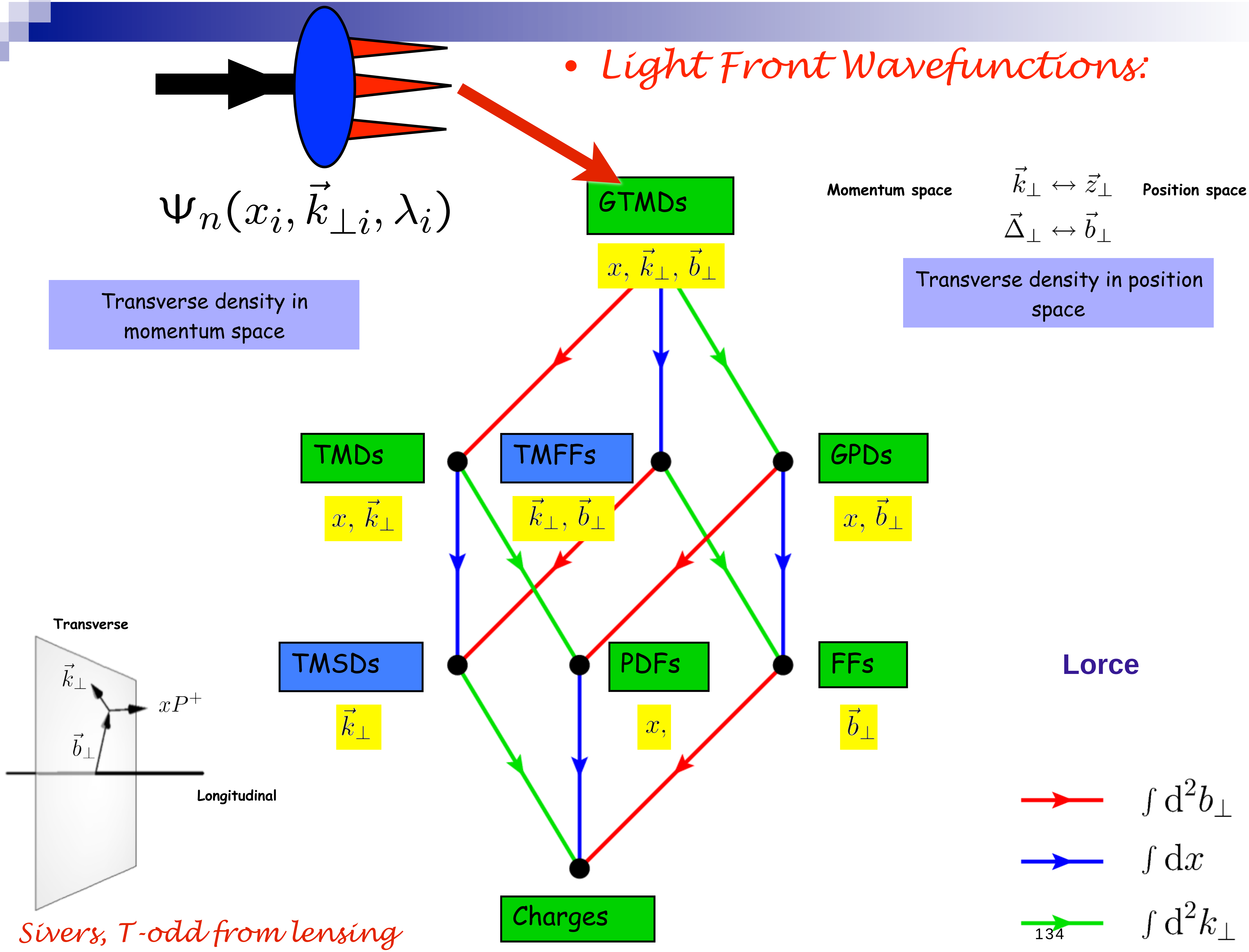
Use AdS/CFT orthonormal Light Front Wavefunctions as a basis for diagonalizing the QCD LF Hamiltonian

Pauli, Hornbostel, Hiller, Chabysheva, sjb

- Good initial approximation
- Better than plane wave basis
- DLCQ discretization -- highly successful 1+1
- Use independent HO LFWFs, remove CM motion
- Similar to Shell Model calculations
- **Hamiltonian light-front field theory within an AdS/QCD basis.**
  J.P. Vary, H. Honkanen, Jun Li, P. Maris, A. Harindranath,

  G.F. de Teramond, P. Sternberg, E.G. Ng, C. Yang, sjb

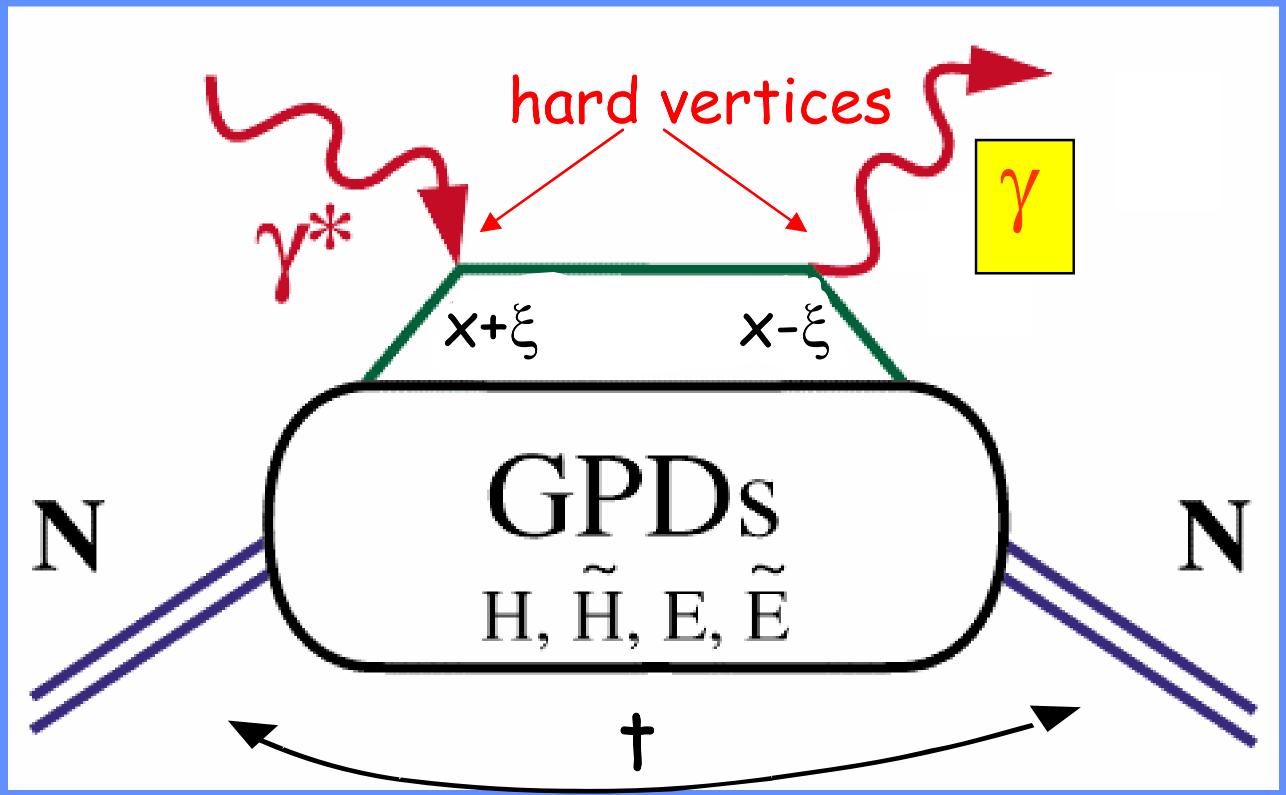
- *Light Front Wavefunctions:*



Sivers, T-odd from lensing

GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

$H(x,\xi,t), E(x,\xi,t), \ldots$ "Generalized Parton Distributions"

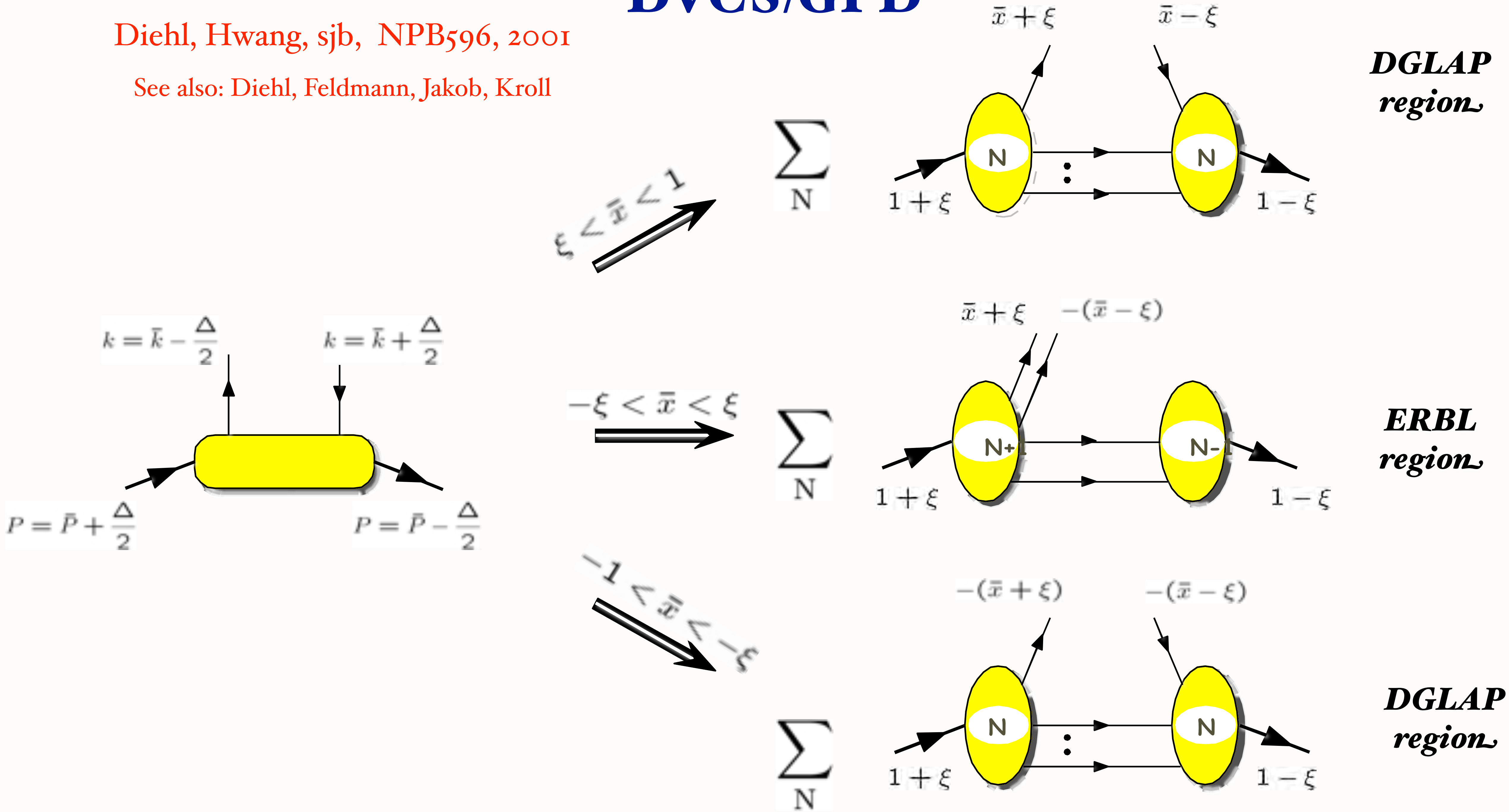
Timelike DVCS: **Mukhurjee,Afanasev, Carlson,sjb**

Light-Front Wave Function Overlap Representation

DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



Bakker & Ji
Lorce

Example of LFWF representation of GPDs (n+1 => n-1)

Diehl, Hwang, sjb

$$\frac{1}{\sqrt{1-\zeta}}\frac{\Delta^1 - i\Delta^2}{2M} E_{(n+1\to n-1)}(x,\zeta,t)$$

$$= \left(\sqrt{1-\zeta}\right)^{3-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n+1} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3}\, 16\pi^3 \delta\left(1-\sum_{j=1}^{n+1} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n+1} \vec{k}_{\perp j}\right)$$

$$\times\, 16\pi^3 \delta(x_{n+1}+x_1-\zeta)\, \delta^{(2)}(\vec{k}_{\perp n+1}+\vec{k}_{\perp 1}-\vec{\Delta}_\perp)$$

$$\times\, \delta(x-x_1)\, \psi^{\uparrow *}_{(n-1)}(x'_i, \vec{k}'_{\perp i}, \lambda_i)\, \psi^{\downarrow}_{(n+1)}(x_i, \vec{k}_{\perp i}, \lambda_i)\, \delta_{\lambda_1 - \lambda_{n+1}},$$

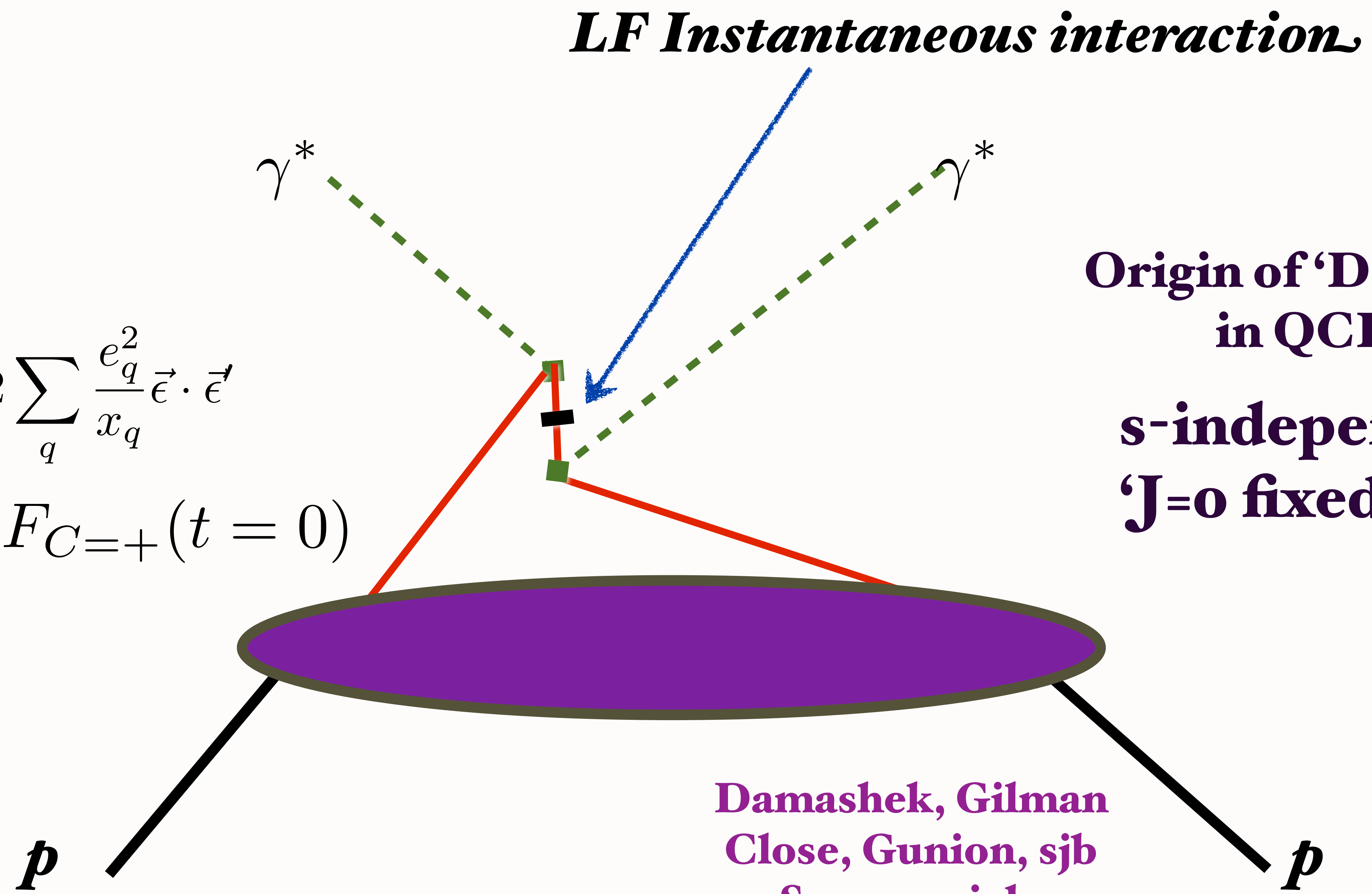
where $i = 2, \ldots, n$ label the $n-1$ spectator partons which appear in the final-state hadron wavefunction with

$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp .$$

Leading-Twist Contribution to Real Part of DVCS

$$T = -2 \sum_q \frac{e_q^2}{x_q} \vec{\epsilon} \cdot \vec{\epsilon}'$$

$$T \propto s^0 F_{C=+}(t=0)$$

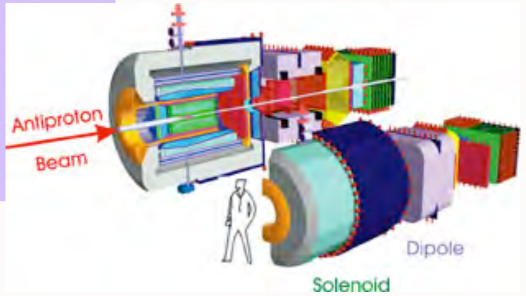


Origin of 'D-Term' in QCD

s-independent 'J=0 fixed pole'

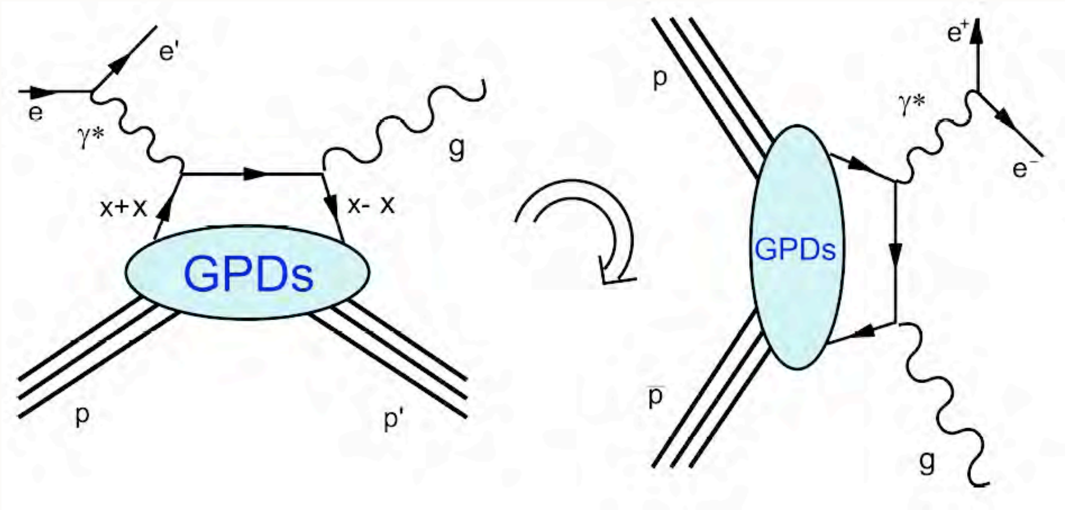
Damashek, Gilman
Close, Gunion, sjb
Szczepaniak, Llanes Estrada, sjb

Key QCD $\bar{P}$ANDA Experiment



$$\bar{p}p \to \gamma^*\gamma$$

- Test DVCS in Timelike Regime
- J=0 Fixed pole: q^2 independent
- Analytic Continuation of GPDs
- Light-Front Wavefunctions
- charge asymmetry from interference



$$\bar{p}p \to \gamma^* \to \ell^+\ell^- \to \ell^+\ell^-\gamma$$

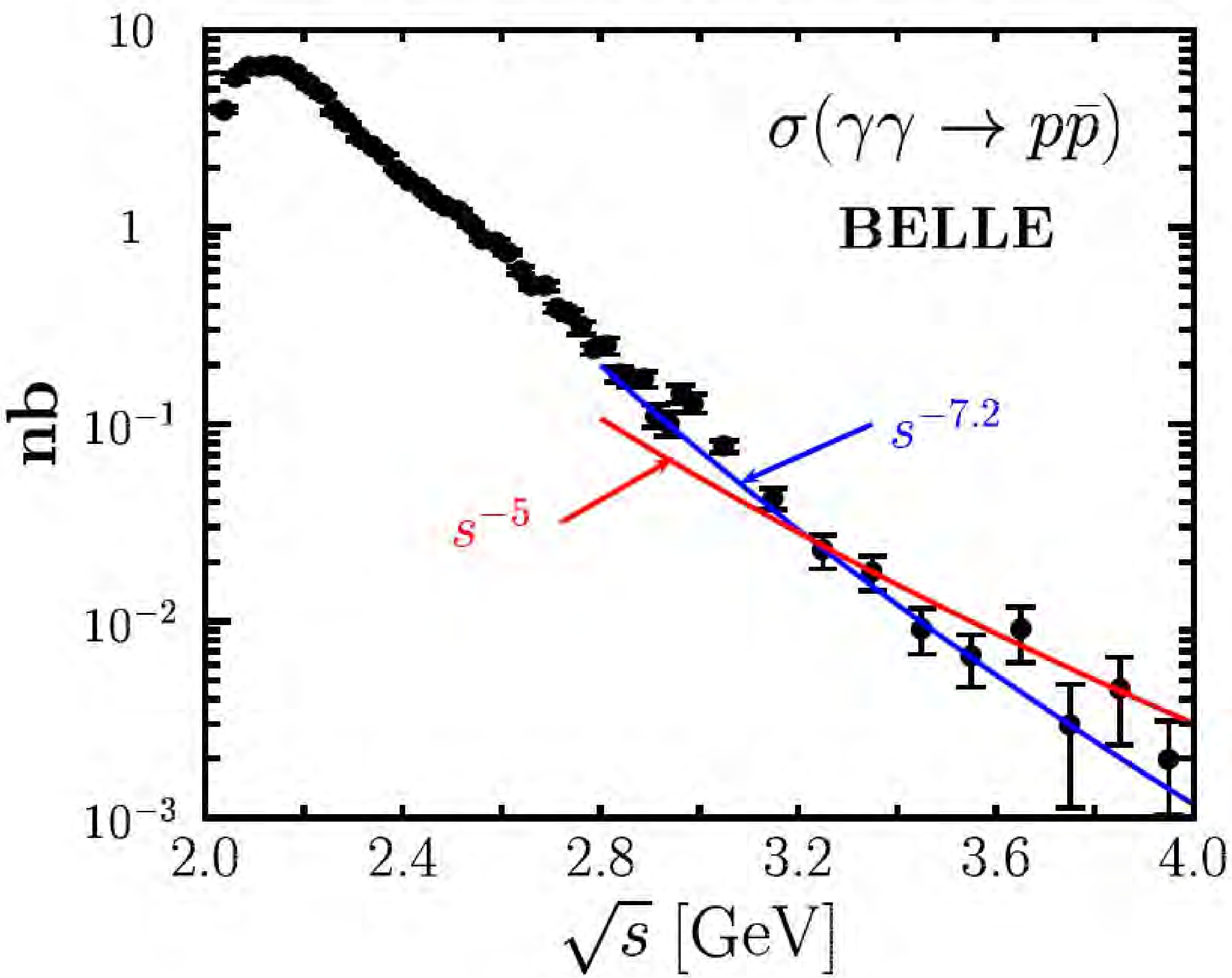
$$\bar{p}p \to \bar{p}p\gamma \to \gamma^*\gamma \to \ell^+\ell^-\gamma$$

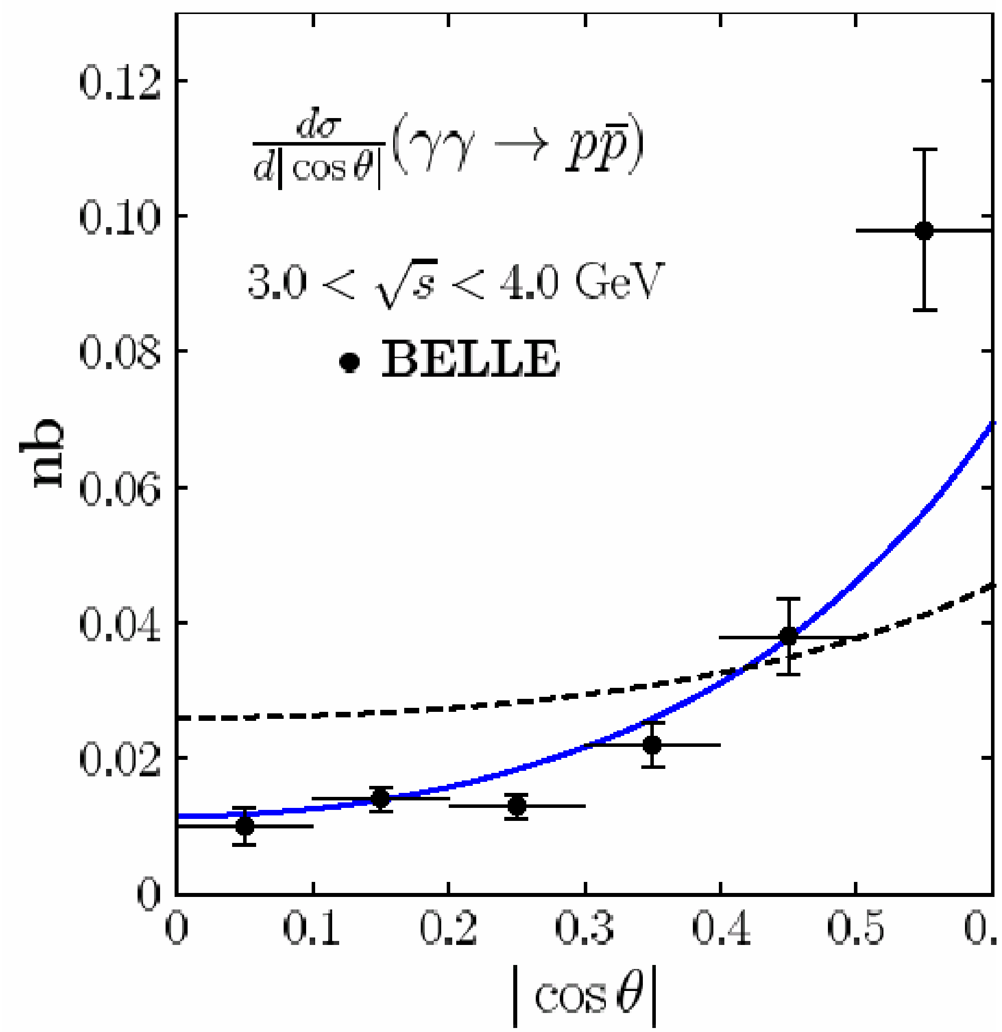
Recent results from Belle

$\gamma\gamma \to p\bar{p}$

PQCD Conformal Scaling for range of θ_{CM}

$s^5 \Delta\sigma(\gamma\gamma \to \bar{p}p) \simeq \text{const}$





Energy dependence

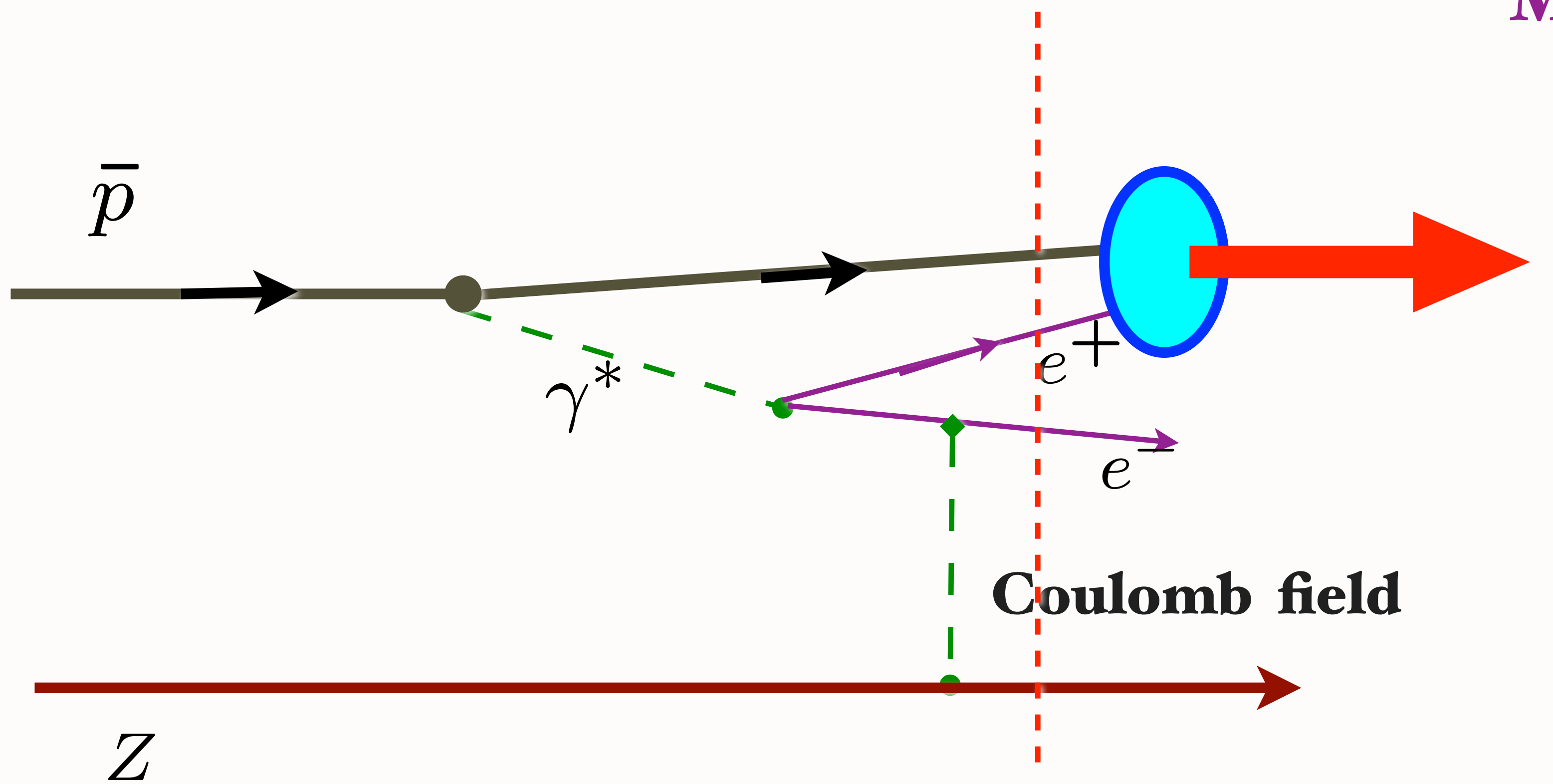
Angular dependence
(GPD curve from Kroll/Schäfer)

Michael Düren

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



$$b_\perp \leq \frac{1}{m_{red}\alpha}$$

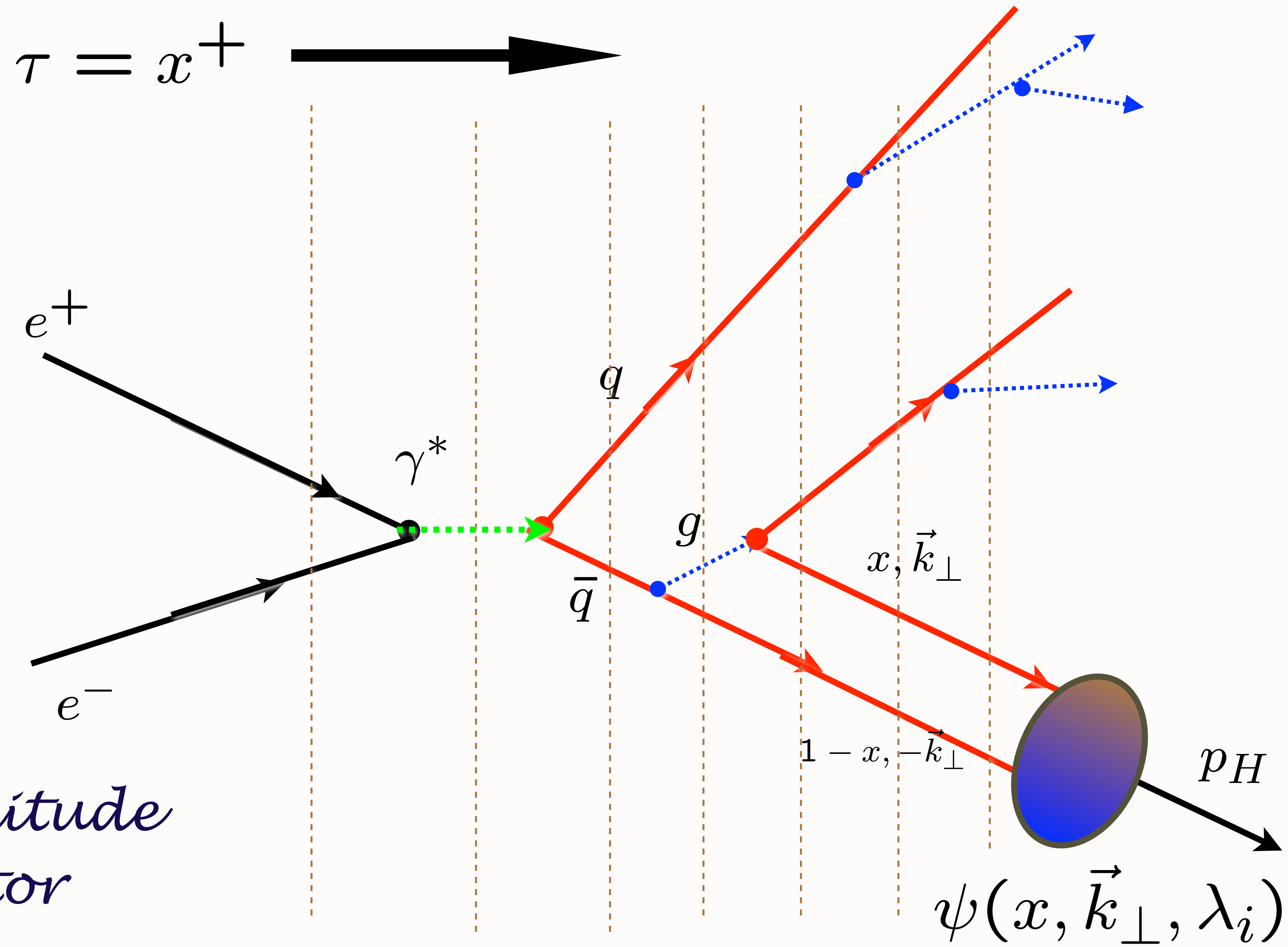
$$y_{\bar{p}} \simeq y_{e^+}$$

Coalescence of off-shell co-moving positron and antiproton

Wavefunction maximal at small impact separation and equal rapidity

"Hadronization" at the Amplitude Level

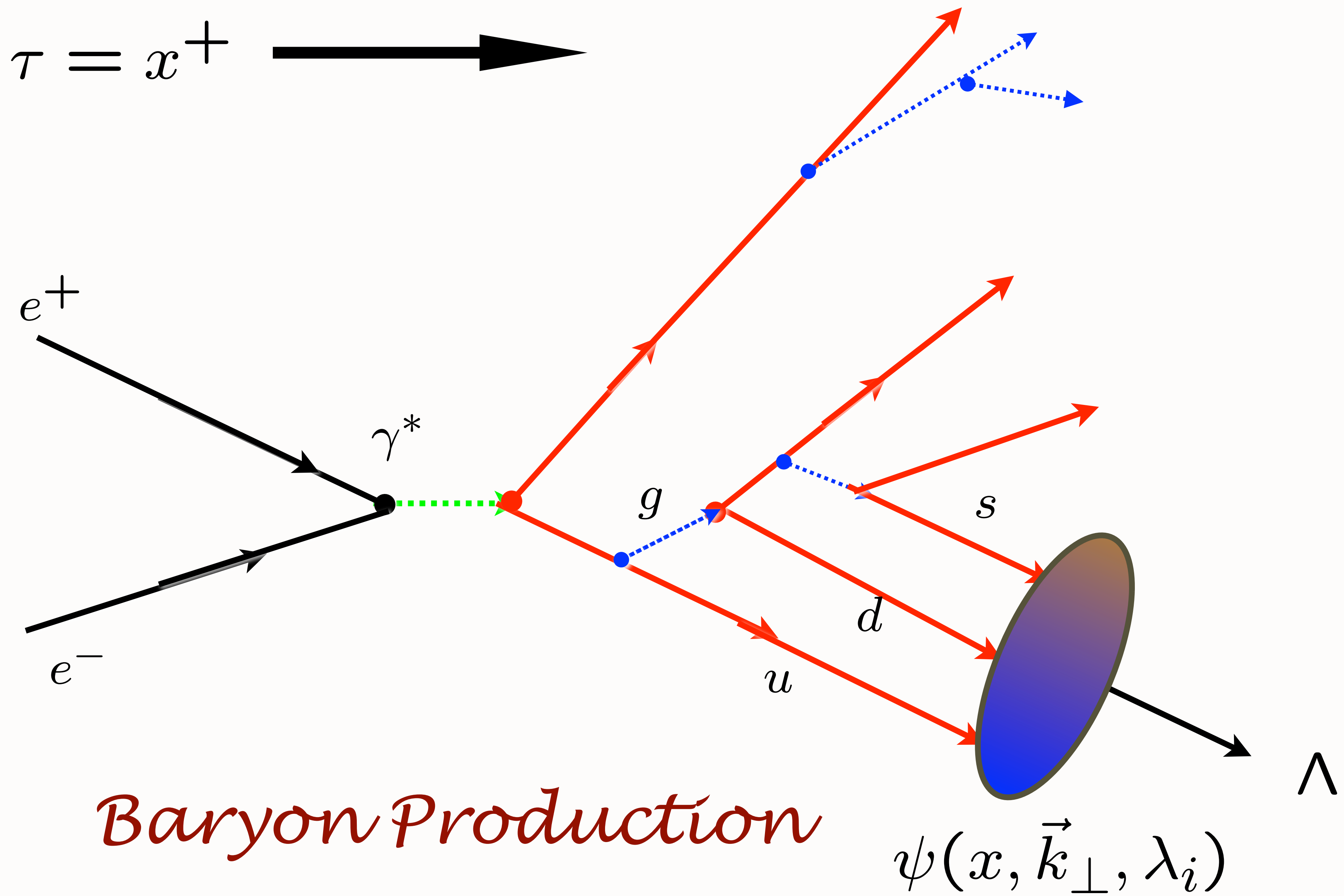
Hadronization at the Amplitude Level



Event amplitude generator

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

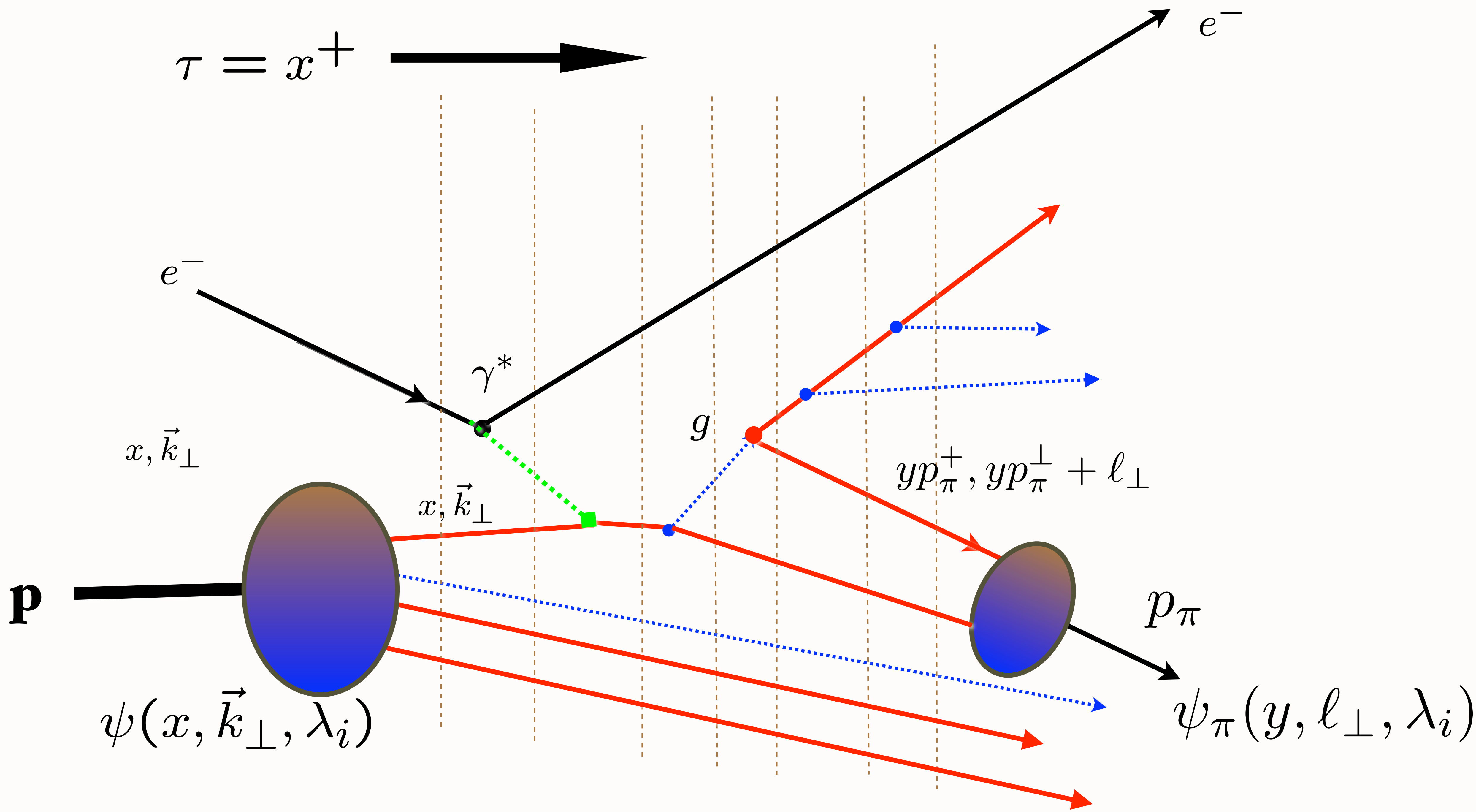
Hadronization at the Amplitude Level



Baryon Production

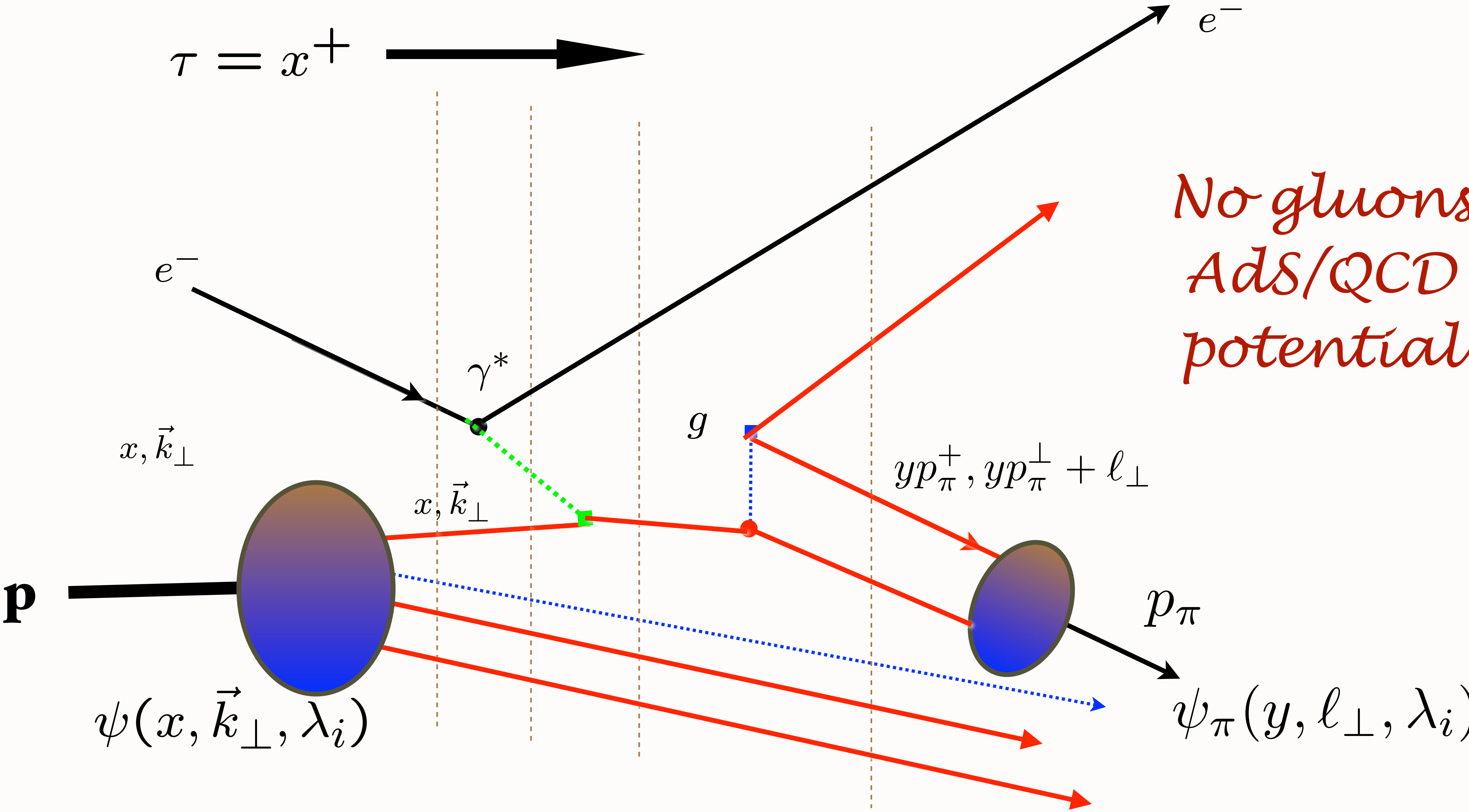
Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Hadronization at the Amplitude Level



Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Hadronization at the Amplitude Level

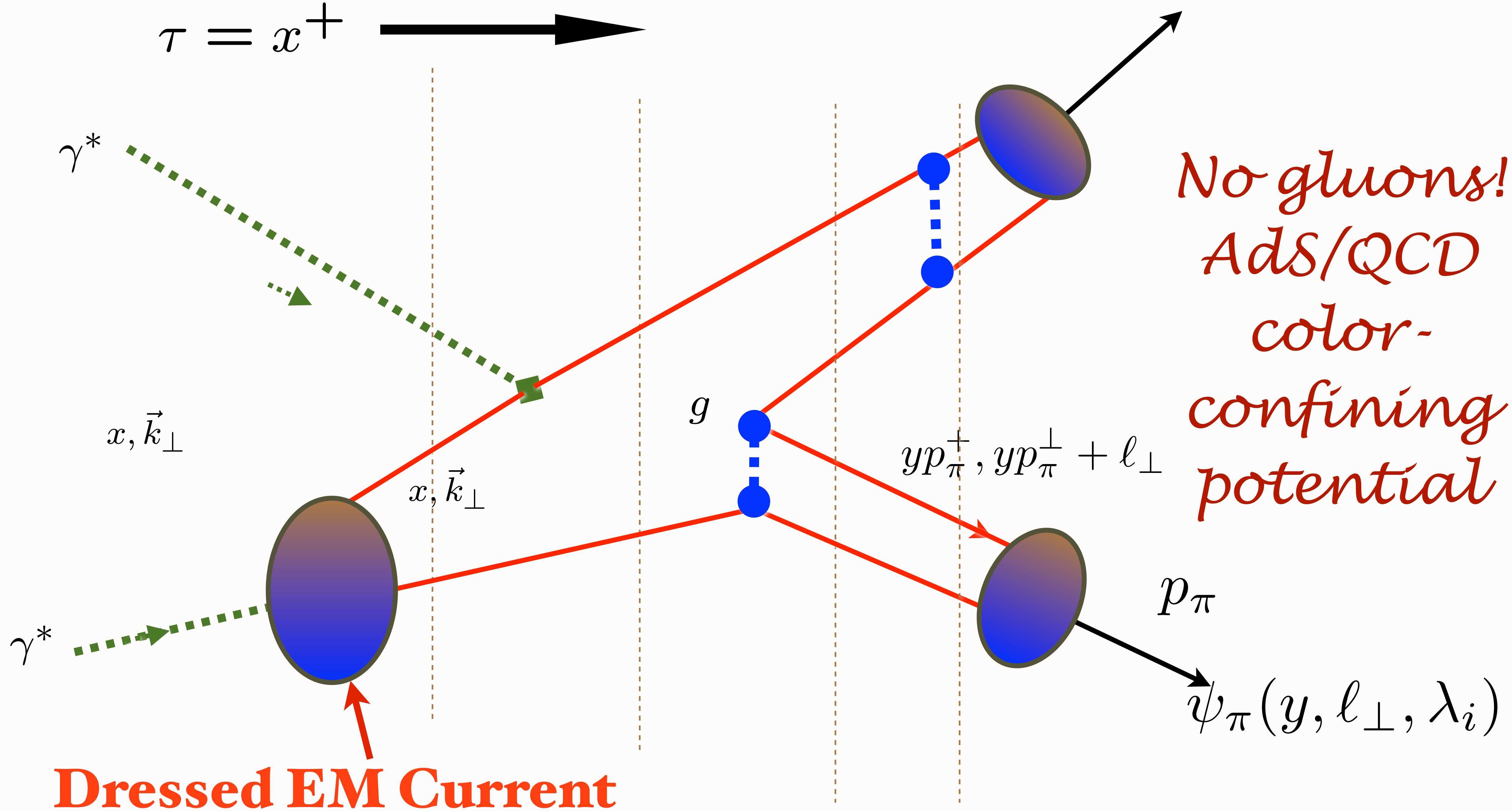


No gluons
AdS/QCD
potential

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Hadronization at the Amplitude Level

Justify Handbag of Kroll et al.?

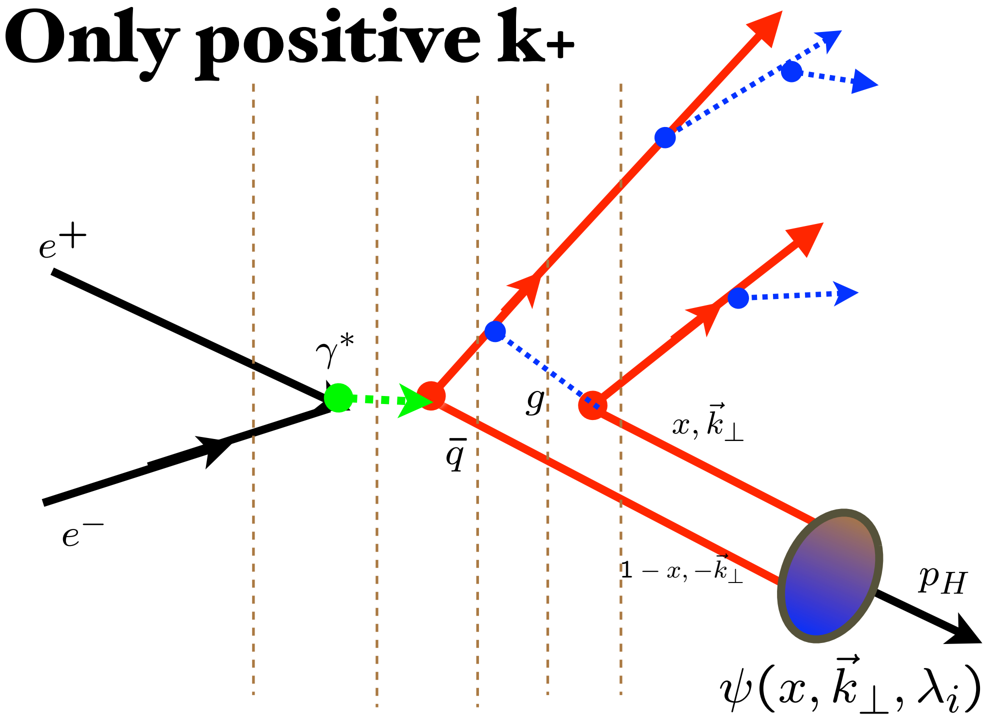


Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Off -Shell T-Matrix

Event amplitude generator

- **Quarks and Gluons Off-Shell**
- **LFPth: Minimal Time-Ordering Diagrams-Only positive k+**
- **J^z Conservation at every vertex**
- **Frame-Independent**
- **Cluster Decomposition** **Chueng Ji, sjb**
- **"History"-Numerator structure universal**
- **Renormalization- alternate denominators**
- **LFWF takes Off-shell to On-shell**
- **Tested in QED: g-2 to three loops**

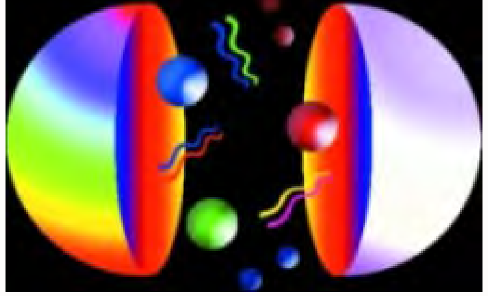


Roskies, Suaya, sjb

Fermionic Modes and Baryon Spectrum

GdT and sjb, PRL 94, 201601 (2005)

Yukawa interaction in 5 dimensions



From Nick Evans

- Action for Dirac field in AdS$_{d+1}$ in presence of dilaton background $\varphi(z)$ [Abidin and Carlson (2009)]

$$S = \int d^{d+1}\sqrt{g}e^{\varphi}(z)\left(i\overline{\Psi}e^M_A\Gamma^A D_M\Psi + h.c + \varphi(z)\overline{\Psi}\Psi - \mu\overline{\Psi}\Psi\right)$$

- Factor out plane waves along 3+1: $\Psi_P(x^\mu, z) = e^{-iP\cdot x}\Psi(z)$

$$\left[i\left(z\eta^{\ell m}\Gamma_\ell\partial_m + 2\Gamma_z\right) + \mu R + \kappa^2 z\right]\Psi(x^\ell) = 0.$$

- Solution $\left(\nu = \mu R - \frac{1}{2},\ \nu = L+1\right)$

$$\Psi_+(z) \sim z^{\frac{5}{2}+\nu}e^{-\kappa^2 z^2/2}L_n^\nu(\kappa^2 z^2), \quad \Psi_-(z) \sim z^{\frac{7}{2}+\nu}e^{-\kappa^2 z^2/2}L_n^{\nu+1}(\kappa^2 z^2)$$

- Eigenvalues (how to fix the overall energy scale, see arXiv:1001.5193)

$$\mathcal{M}^2 = 4\kappa^2(n + L + 1)$$

positive parity

- Obtain spin-J mode $\Phi_{\mu_1\cdots\mu_{J-1/2}}$, $J > \frac{1}{2}$, with all indices along 3+1 from Ψ by shifting dimensions
- Large N_C: $\mathcal{M}^2 = 4\kappa^2(N_C + n + L - 2) \implies \mathcal{M} \sim \sqrt{N_C}\,\Lambda_{\rm QCD}$

Non-Conformal Extension of Algebraic Structure (Soft Wall Model)

- We write the Dirac equation

$$(\alpha\Pi(\zeta) - \mathcal{M})\,\psi(\zeta) = 0,$$

in terms of the matrix-valued operator Π

$$\nu = L + 1$$

$$\Pi_\nu(\zeta) = -i\left(\frac{d}{d\zeta} - \frac{\nu + \frac{1}{2}}{\zeta}\gamma_5 - \kappa^2\zeta\gamma_5\right),$$

and its adjoint $\Pi^\dagger$, with commutation relations

Soft Wall

$$\left[\Pi_\nu(\zeta), \Pi_\nu^\dagger(\zeta)\right] = \left(\frac{2\nu+1}{\zeta^2} - 2\kappa^2\right)\gamma_5.$$

- Solutions to the Dirac equation

$$\begin{aligned}\psi_+(\zeta) &\sim z^{\frac{1}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^\nu(\kappa^2\zeta^2),\\ \psi_-(\zeta) &\sim z^{\frac{3}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^{\nu+1}(\kappa^2\zeta^2).\end{aligned}$$

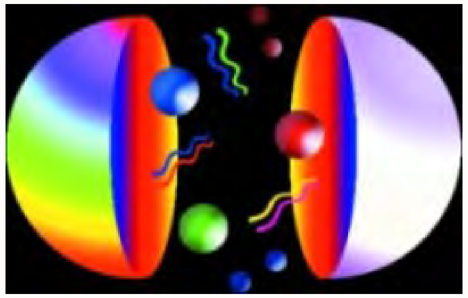
- Eigenvalues

$$\mathcal{M}^2 = 4\kappa^2(n + \nu + 1).$$

Fermionic Modes and Baryon Spectrum

[Hard wall model: GdT and S. J. Brodsky, PRL **94**, 201601 (2005)]

[Soft wall model: GdT and S. J. Brodsky, (2005), arXiv:1001.5193]



From Nick Evans

- Nucleon LF modes

$$\psi_+(\zeta)_{n,L} = \kappa^{2+L}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{3/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+1}\left(\kappa^2\zeta^2\right)$$

$$\psi_-(\zeta)_{n,L} = \kappa^{3+L}\frac{1}{\sqrt{n+L+2}}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{5/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+2}\left(\kappa^2\zeta^2\right)$$

- Normalization

$$\int d\zeta\,\psi_+^2(\zeta) = \int d\zeta\,\psi_-^2(\zeta) = 1$$

- Eigenvalues

$$\mathcal{M}^2_{n,L,S=1/2} = 4\kappa^2\left(n+L+1\right)$$

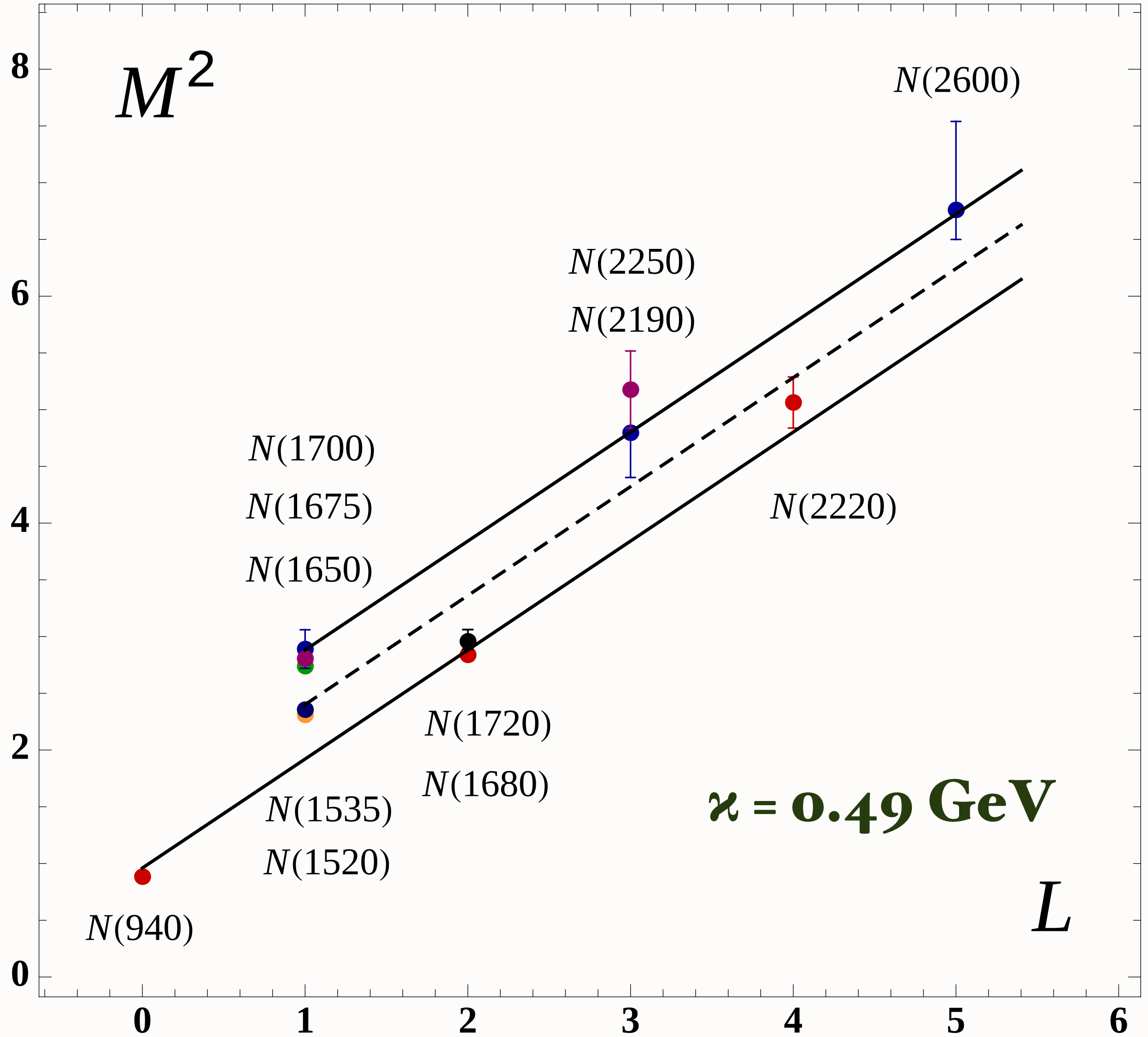
- "Chiral partners"

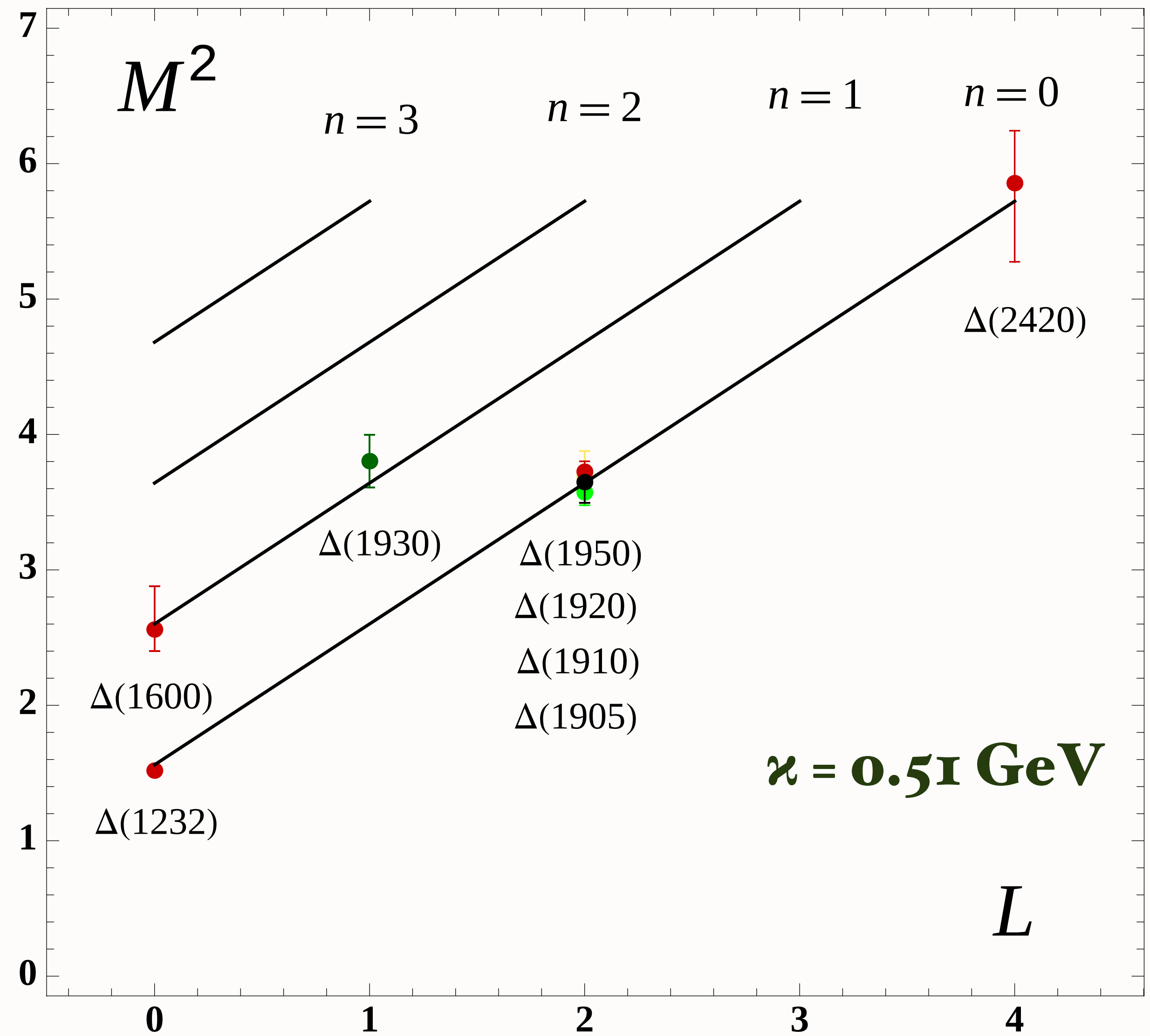
$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$

Table 1: $SU(6)$ classification of confirmed baryons listed by the PDG. The labels S, L and n refer to the internal spin, orbital angular momentum and radial quantum number respectively. The $\Delta\frac{5}{2}^-(1930)$ does not fit the $SU(6)$ classification since its mass is too low compared to other members **70**-multiplet for $n = 0$, $L = 3$.

$SU(6)$	S	L	n	Baryon State
56	$\frac{1}{2}$	0	0	$N\frac{1}{2}^+(940)$
	$\frac{1}{2}$	0	1	$N\frac{1}{2}^+(1440)$
	$\frac{1}{2}$	0	2	$N\frac{1}{2}^+(1710)$
	$\frac{3}{2}$	0	0	$\Delta\frac{3}{2}^+(1232)$
	$\frac{3}{2}$	0	1	$\Delta\frac{3}{2}^+(1600)$
70	$\frac{1}{2}$	1	0	$N\frac{1}{2}^-(1535)$ $N\frac{3}{2}^-(1520)$
	$\frac{3}{2}$	1	0	$N\frac{1}{2}^-(1650)$ $N\frac{3}{2}^-(1700)$ $N\frac{5}{2}^-(1675)$
	$\frac{3}{2}$	1	1	$N\frac{1}{2}^-$ $N\frac{3}{2}^-(1875)$ $N\frac{5}{2}^-$
	$\frac{1}{2}$	1	0	$\Delta\frac{1}{2}^-(1620)$ $\Delta\frac{3}{2}^-(1700)$
56	$\frac{1}{2}$	2	0	$N\frac{3}{2}^+(1720)$ $N\frac{5}{2}^+(1680)$
	$\frac{1}{2}$	2	1	$N\frac{3}{2}^+(1900)$ $N\frac{5}{2}^+$
	$\frac{3}{2}$	2	0	$\Delta\frac{1}{2}^+(1910)$ $\Delta\frac{3}{2}^+(1920)$ $\Delta\frac{5}{2}^+(1905)$ $\Delta\frac{7}{2}^+(1950)$
70	$\frac{1}{2}$	3	0	$N\frac{5}{2}^-$ $N\frac{7}{2}^-$
	$\frac{3}{2}$	3	0	$N\frac{3}{2}^-$ $N\frac{5}{2}^-$ $N\frac{7}{2}^-(2190)$ $N\frac{9}{2}^-(2250)$
	$\frac{1}{2}$	3	0	$\Delta\frac{5}{2}^-$ $\Delta\frac{7}{2}^-$
56	$\frac{1}{2}$	4	0	$N\frac{7}{2}^+$ $N\frac{9}{2}^+(2220)$
	$\frac{3}{2}$	4	0	$\Delta\frac{5}{2}^+$ $\Delta\frac{7}{2}^+$ $\Delta\frac{9}{2}^+$ $\Delta\frac{11}{2}^+(2420)$
70	$\frac{1}{2}$	5	0	$N\frac{9}{2}^-$ $N\frac{11}{2}^-$
	$\frac{3}{2}$	5	0	$N\frac{7}{2}^-$ $N\frac{9}{2}^-$ $N\frac{11}{2}^-(2600)$ $N\frac{13}{2}^-$

PDG 2012





de Teramond, sjb

All confirmed resonances from PDG 2012

$$\mathcal{M}^{2\,(+)}_{n,L,S} = 4\kappa^2\left(n + L + \frac{S}{2} + \frac{3}{4}\right),$$ **positive parity**

$$\mathcal{M}^{2\,(-)}_{n,L,S} = 4\kappa^2\left(n + L + \frac{S}{2} + \frac{5}{4}\right),$$ **negative parity**

See also Forkel, Beyer, Federico, Klempt

Baryon Spectrum in Soft-Wall Model

- Upon substitution $z \longrightarrow \zeta$ and

$$\Psi_J(x, z) = e^{-iP\cdot x} z^2 \psi^J(z) u(P),$$

find LFWE for $d = 4$

$$\begin{aligned} \frac{d}{d\zeta}\psi_+^J + \frac{\nu + \frac{1}{2}}{\zeta}\psi_+^J + U(\zeta)\psi_+^J &= \mathcal{M}\psi_-^J, \\ -\frac{d}{d\zeta}\psi_-^J + \frac{\nu + \frac{1}{2}}{\zeta}\psi_-^J + U(\zeta)\psi_-^J &= \mathcal{M}\psi_+^J, \end{aligned}$$

where $U(\zeta) = \frac{R}{\zeta} V(\zeta)$

- Choose linear potential $U = \kappa^2 \zeta$
- Eigenfunctions

$$\psi_+^J(\zeta) \sim \zeta^{\frac{1}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^{\nu}(\kappa^2\zeta^2), \qquad \psi_-^J(\zeta) \sim \zeta^{\frac{3}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^{\nu+1}(\kappa^2\zeta^2)$$

- Eigenvalues

$$\mathcal{M}^2 = 4\kappa^2(n + \nu + 1), \quad \nu = L + 1 \quad (\tau = 3)$$

- Full $J - L$ degeneracy (different J for same L) for baryons along given trajectory !

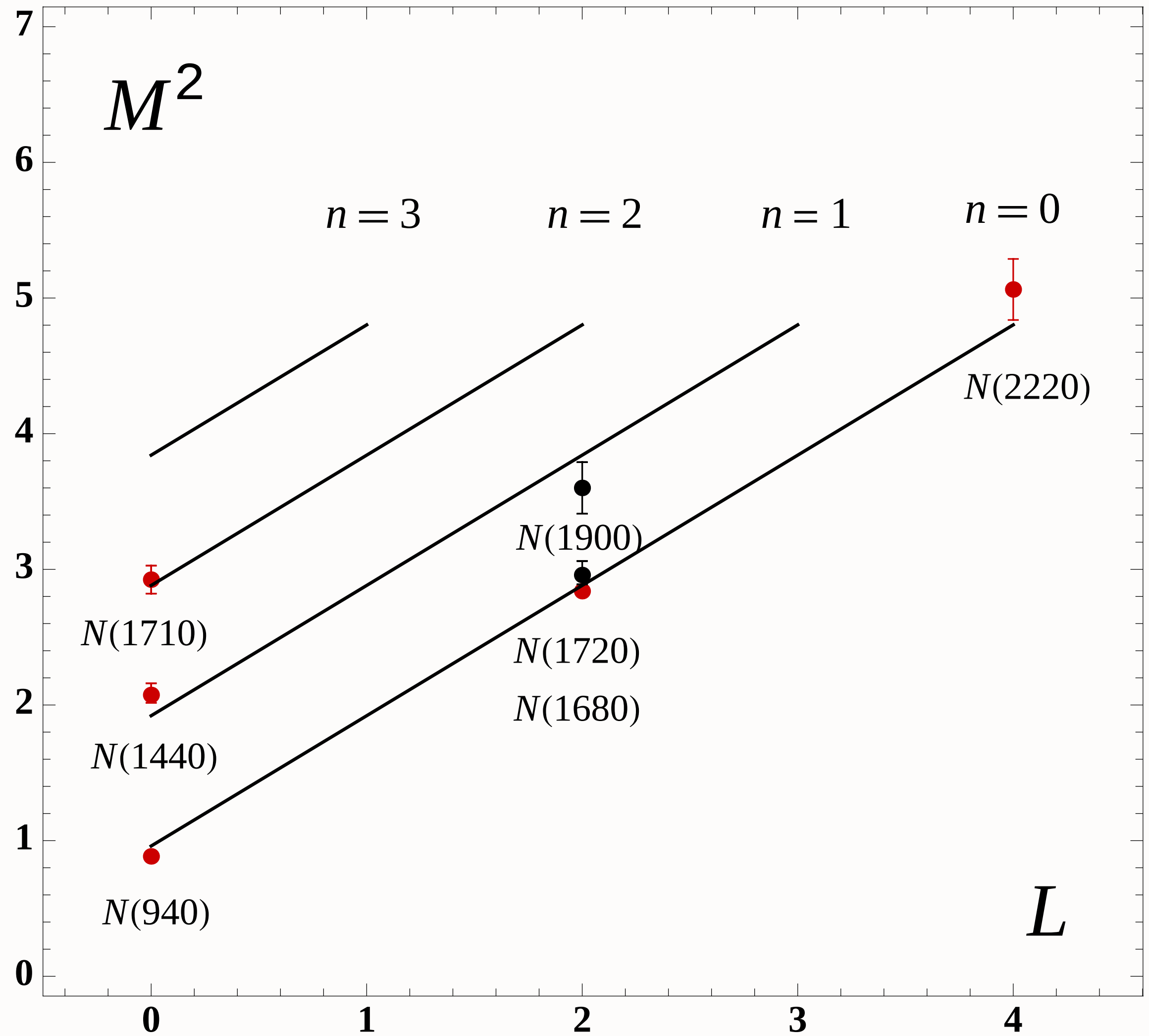
Chiral Features of Soft-Wall AdS/QCD Model

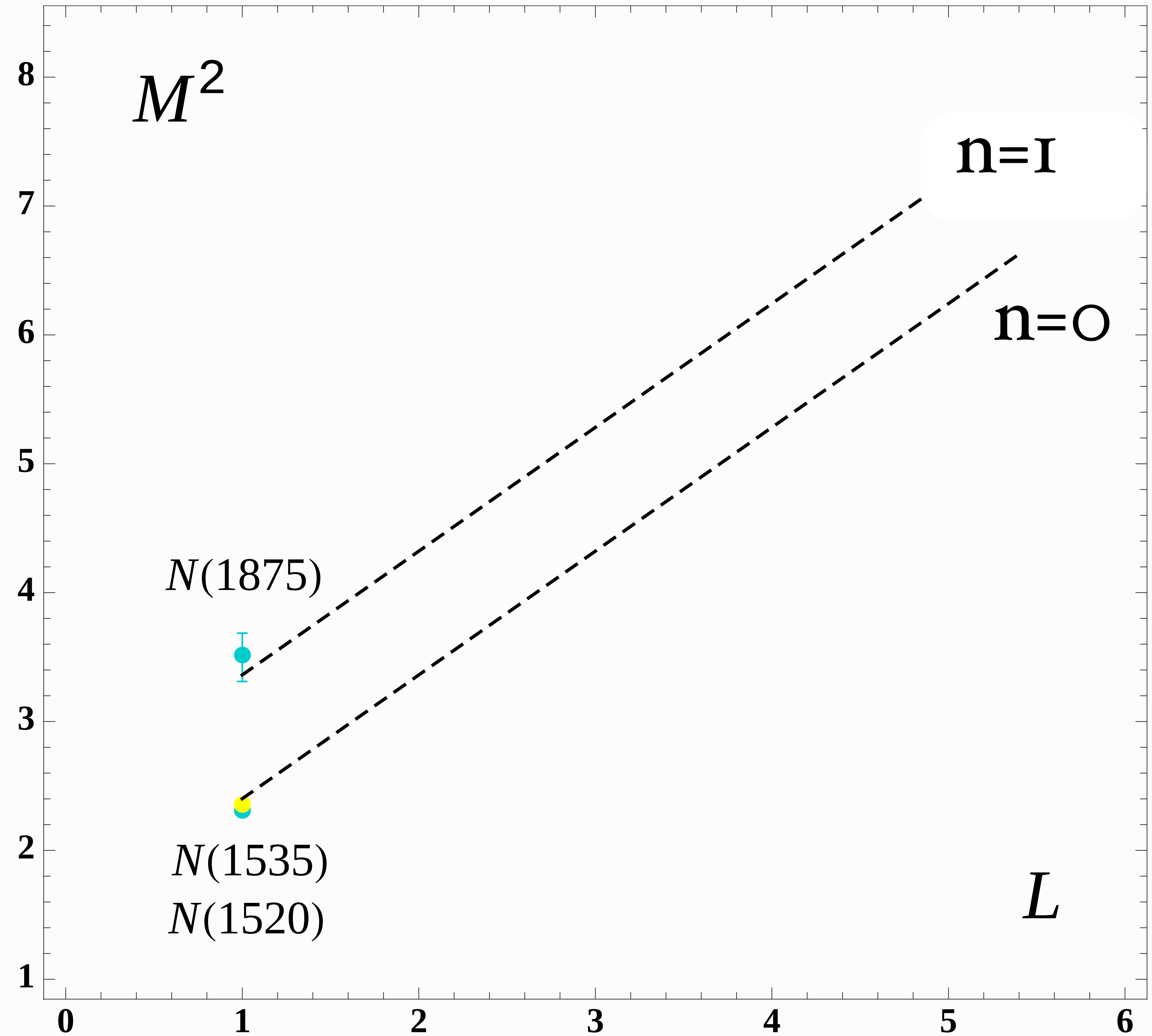
- **Boost Invariant**
- **Trivial LF vacuum.**
- **Massless Pion**
- **Hadron Eigenstates have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 :< L^z >= 1/2, < S_q^z = 0 >$$

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

PDG 2012





LF Virial Theorem:

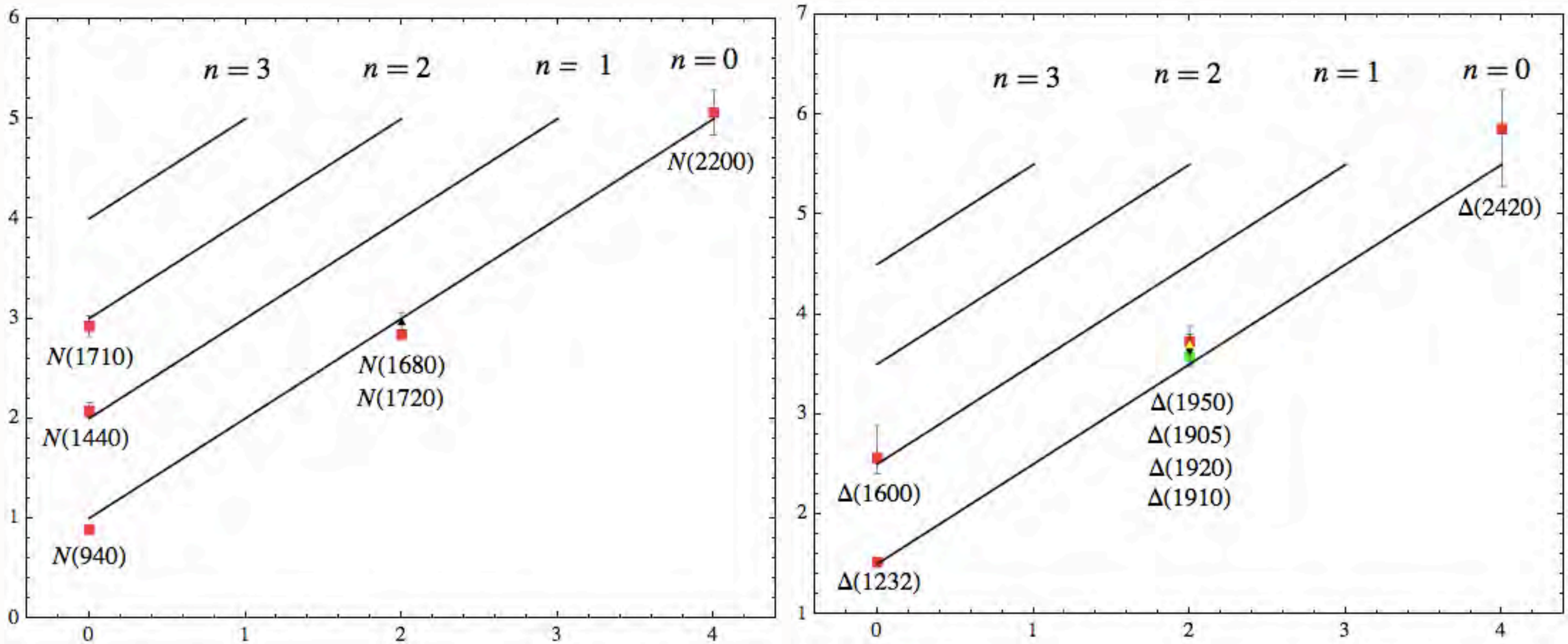
Nucleon Mass: 1/2 from LFKE and 1/2 from Confinement Potential

• **Δ spectrum identical to Forkel and Klempt, Phys. Lett. B 679, 77 (2009)**

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

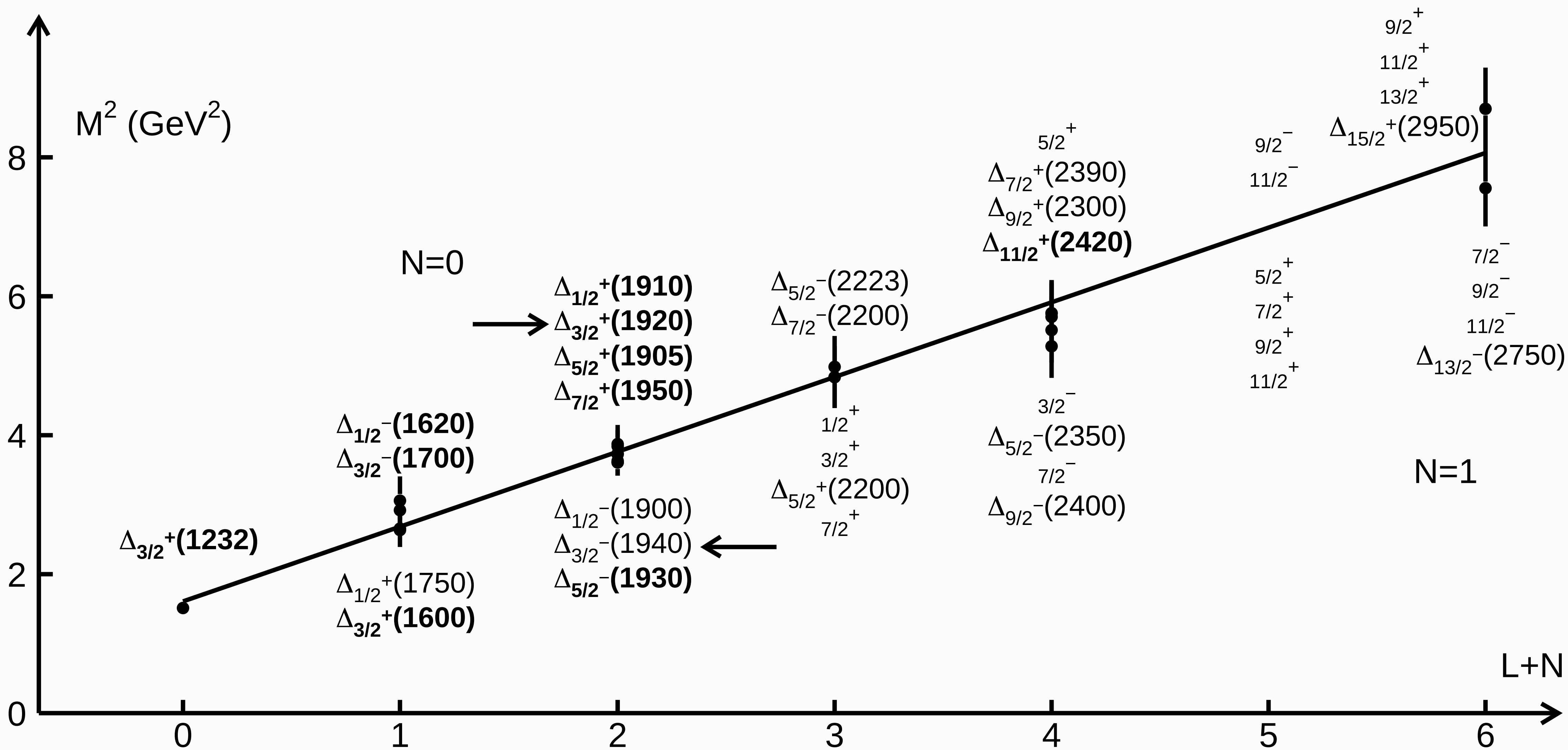
Same multiplicity of states for mesons and baryons!

$\mathcal{M}^2$



L

Parent and daughter **56** Regge trajectories for the N and Δ baryon families for $\kappa = 0.5$ GeV



E. Klempt *et al.*: Δ^* resonances, quark models, chiral symmetry and AdS/QCD

H. Forkel, M. Beyer and T. Frederico, JHEP **0707** (2007) 077.
H. Forkel, M. Beyer and T. Frederico, Int. J. Mod. Phys. E **16** (2007) 2794.

Space-Like Dirac Proton Form Factor

- Consider the spin non-flip form factors

$$
\begin{aligned}
F_+(Q^2) &= g_+ \int d\zeta \, J(Q,\zeta) |\psi_+(\zeta)|^2, \\
F_-(Q^2) &= g_- \int d\zeta \, J(Q,\zeta) |\psi_-(\zeta)|^2,
\end{aligned}
$$

  where the effective charges g_+ and g_- are determined from the spin-flavor structure of the theory.

- Choose the struck quark to have $S^z = +1/2$. The two AdS solutions $\psi_+(\zeta)$ and $\psi_-(\zeta)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

- For $SU(6)$ spin-flavor symmetry

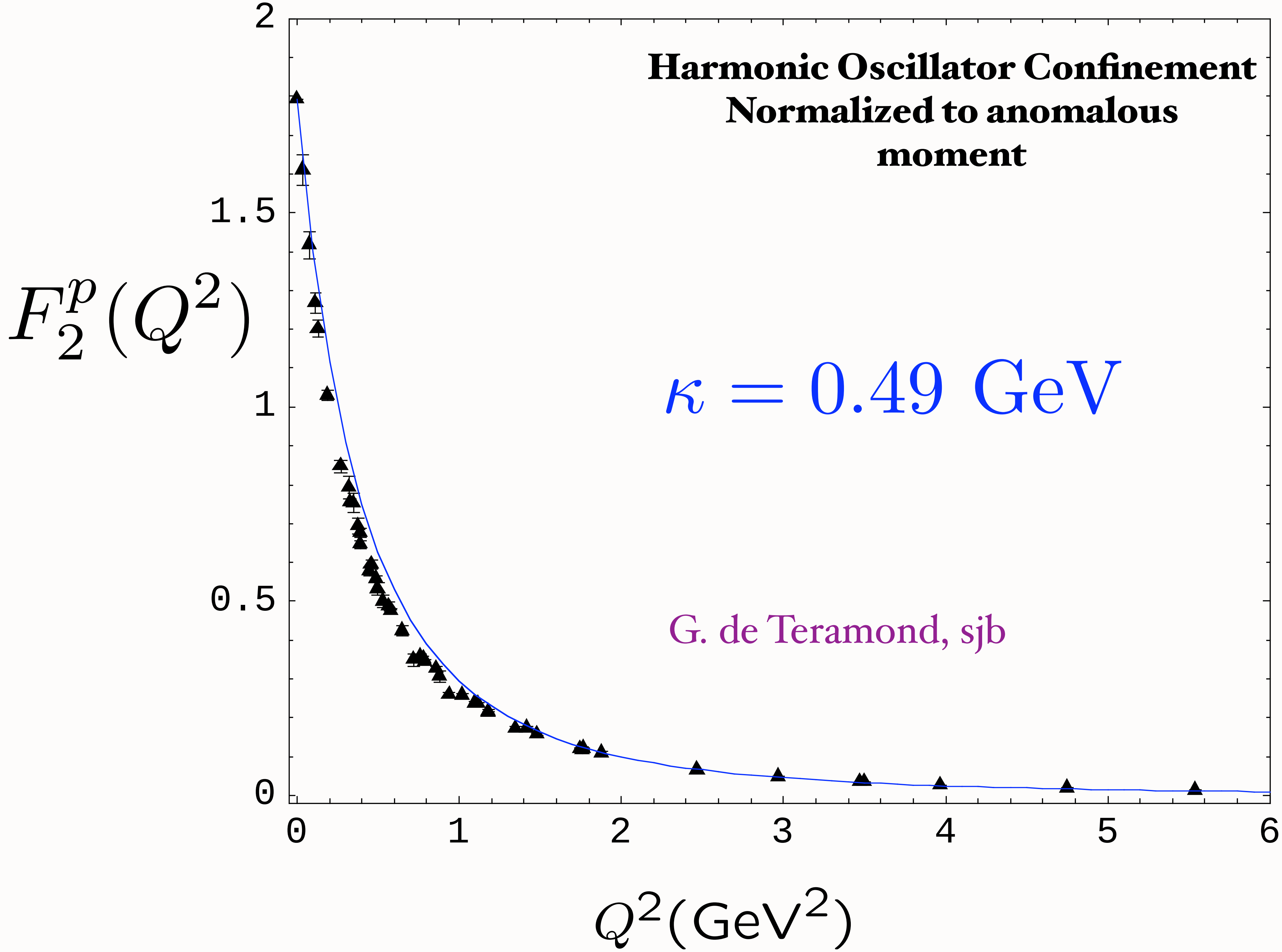
$$
\begin{aligned}
F_1^p(Q^2) &= \int d\zeta \, J(Q,\zeta) |\psi_+(\zeta)|^2, \\
F_1^n(Q^2) &= -\frac{1}{3} \int d\zeta \, J(Q,\zeta) \left[|\psi_+(\zeta)|^2 - |\psi_-(\zeta)|^2 \right],
\end{aligned}
$$

  where $F_1^p(0) = 1$, $F_1^n(0) = 0$.

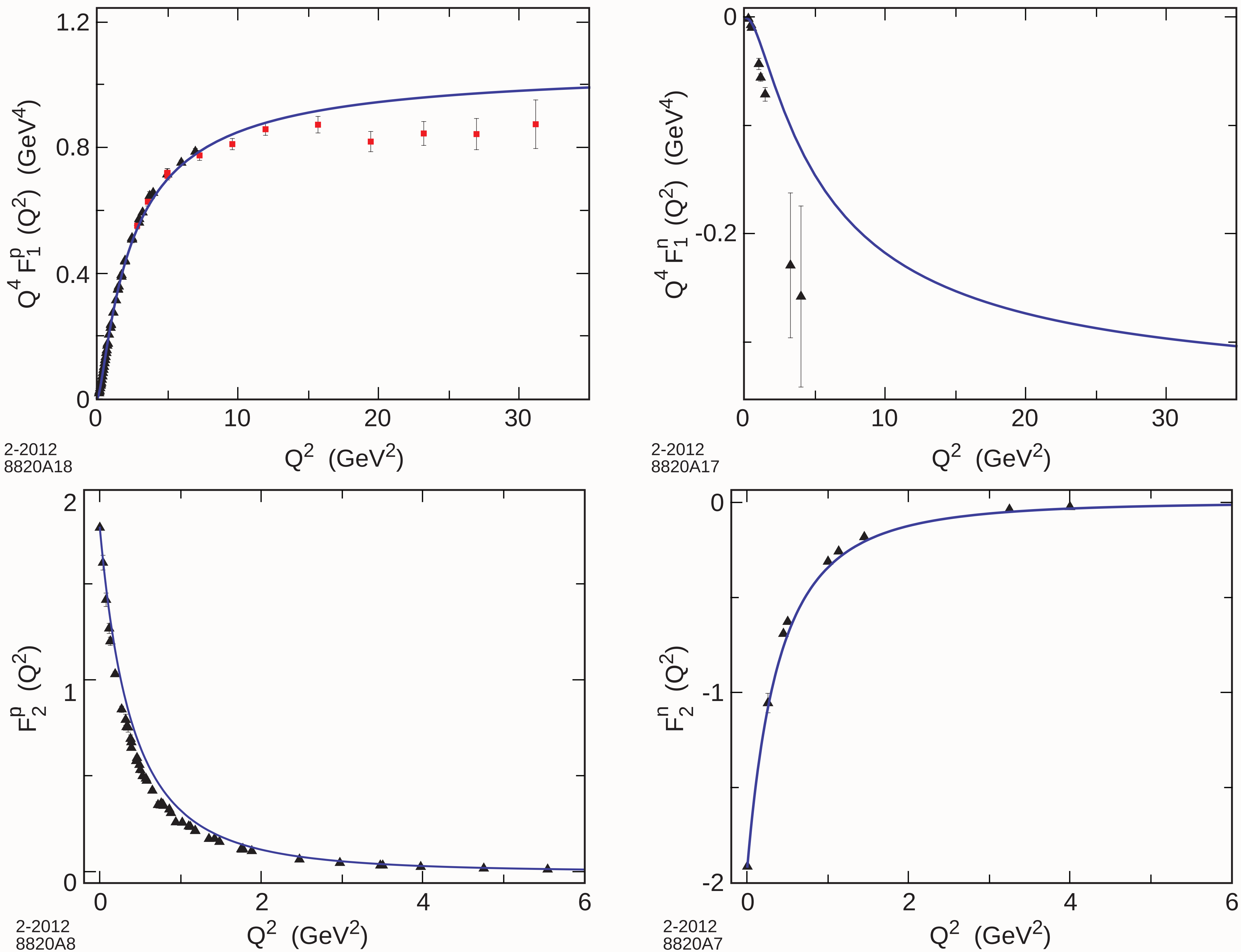
Spacelike Pauli Form Factor

Preliminary

From overlap of $L = 1$ and $L = 0$ LFWFs



Using $SU(6)$ flavor symmetry and normalization to static quantities



Nucleon Transition Form Factors

- Compute spin non-flip EM transition $N(940) \to N^*(1440)$: $\Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$
- Transition form factor

$$F_{1\,N\to N^*}^{\,p}(Q^2) = R^4 \int \frac{dz}{z^4}\, \Psi_+^{n=1,L=0}(z) V(Q,z) \Psi_+^{n=0,L=0}(z)$$

- Orthonormality of Laguerre functions $\left(F_{1\,N\to N^*}^{\,p}(0) = 0, \quad V(Q=0,z) = 1\right)$

$$R^4 \int \frac{dz}{z^4}\, \Psi_+^{n',L}(z) \Psi_+^{n,L}(z) = \delta_{n,n'}$$

- Find

$$F_{1\,N\to N^*}^{\,p}(Q^2) = \frac{2\sqrt{2}}{3} \frac{\frac{Q^2}{M_P^2}}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}$$

with $\mathcal{M}_{\rho_n}^{\;2} \to 4\kappa^2(n+1/2)$

de Teramond, sjb

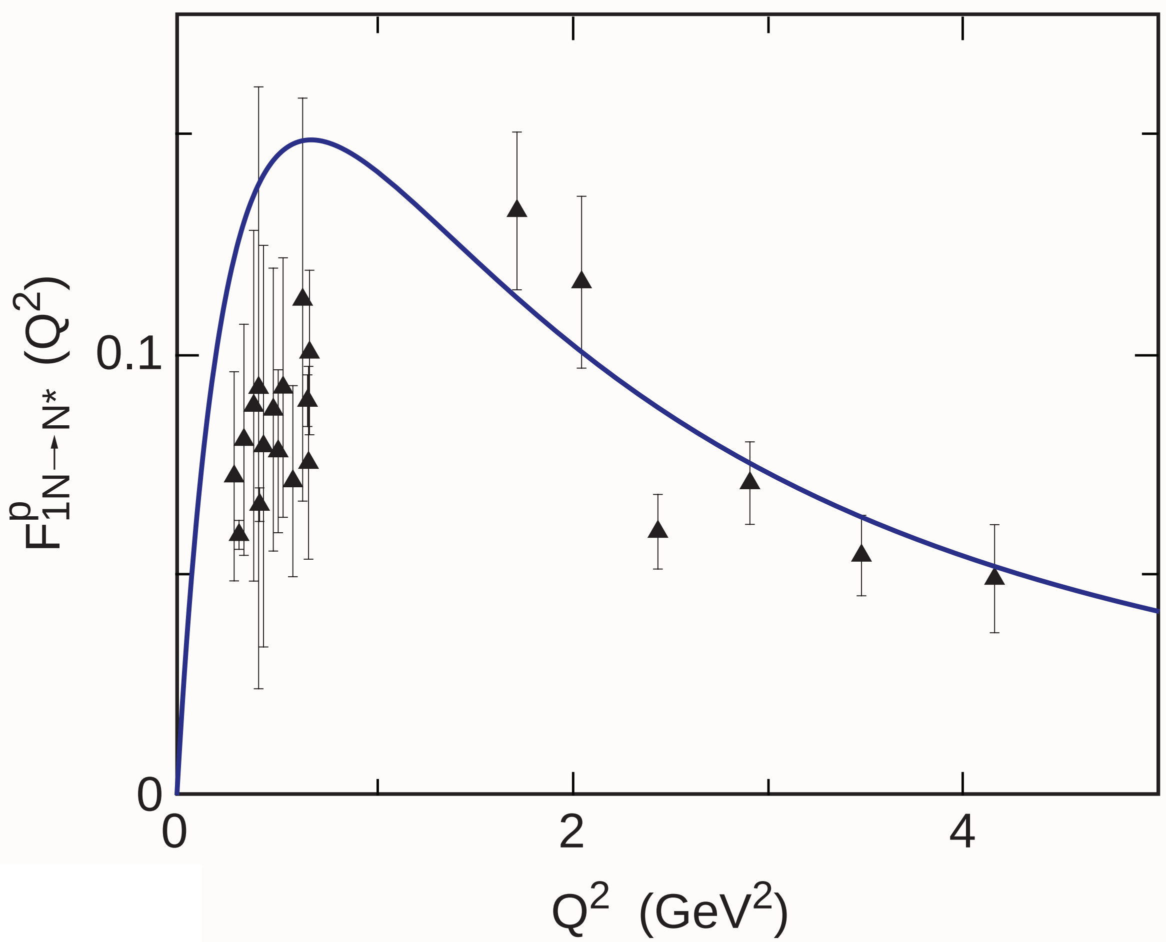
Consistent with counting rule, twist 3

Nucleon Transition Form Factors

$$F^p_{1\,N\to N^*}(Q^2) = \frac{\sqrt{2}}{3}\,\frac{\frac{Q^2}{\mathcal{M}^2_\rho}}{\left(1+\frac{Q^2}{\mathcal{M}^2_\rho}\right)\left(1+\frac{Q^2}{\mathcal{M}^2_{\rho'}}\right)\left(1+\frac{Q^2}{\mathcal{M}^2_{\rho''}}\right)}.$$

AdS\QCD Light-Front Holography

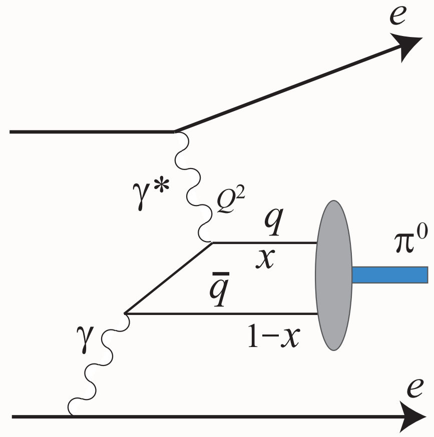
G. de Teramond, sjb



Proton transition form factor to the first radial excited state. Data from JLab

Pion Transition Form-Factor

Cao, de Teramond, sjb



- Definition of $\pi - \gamma$ TFF from $\gamma^* \pi^0 \to \gamma$ vertex in the amplitude $e\pi \to e\gamma$

$$\Gamma^\mu = -ie^2 F_{\pi\gamma}(q^2)\epsilon_{\mu\nu\rho\sigma}(p_\pi)_\nu \epsilon_\rho(k) q_\sigma, \quad k^2 = 0$$

- Asymptotic value of pion TFF is determined by first principles in QCD:
  $Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2 f_\pi$ [Lepage and Brodsky (1980)]

- Pion TFF from 5-dim Chern-Simons structure [Hill and Zachos (2005), Grigoryan and Radyushkin (2008)]

$$\int d^4x \int dz \, \epsilon^{LMNPQ} A_L \partial_M A_N \partial_P A_Q$$
$$\sim (2\pi)^4 \delta^{(4)} \left(p_\pi + q - k\right) F_{\pi\gamma}(q^2) \epsilon^{\mu\nu\rho\sigma} \epsilon_\mu(q)(p_\pi)_\nu \epsilon_\rho(k) q_\sigma$$

- Find for $A_z \propto \Phi_\pi(z)/z$

$$F_{\pi\gamma}(Q^2) = \frac{1}{2\pi} \int_0^\infty \frac{dz}{z} \, \Phi_\pi(z) V\left(Q^2, z\right)$$

  with normalization fixed by asymptotic QCD prediction

- $V(Q^2, z)$ bulk-to-boundary propagator of γ^*

[S. J. Brodsky, Fu-Guang Cao and GdT, arXiv:1005.39XX]

- Pion TFF from 5-dim Chern-Simons structure [Hill and Zachos (2005), Grigoryan and Radyushkin (2008)]

$$\int d^4x \int dz \, \epsilon^{LMNPQ} A_L \partial_M A_N \partial_P A_Q$$

$$\sim (2\pi)^4 \delta^{(4)} \left(p_\pi + q - k\right) F_{\pi\gamma}(q^2) \epsilon^{\mu\nu\rho\sigma} \epsilon_\mu(q) (p_\pi)_\nu \epsilon_\rho(k) q_\sigma$$

- Take $A_z \propto \Phi_\pi(z)/z, \quad \Phi_\pi(z) = \sqrt{2P_{q\bar{q}}} \, \kappa \, z^2 e^{-\kappa^2 z^2/2}, \quad \langle \Phi_\pi | \Phi_\pi \rangle = P_{q\bar{q}}$
- Find $\left(\phi(x) = \sqrt{3} f_\pi x(1-x), \quad f_\pi = \sqrt{P_{q\bar{q}}} \, \kappa/\sqrt{2}\pi\right)$

$$Q^2 F_{\pi\gamma}(Q^2) = \frac{4}{\sqrt{3}} \int_0^1 dx \frac{\phi(x)}{1-x} \left[1 - e^{-P_{q\bar{q}} Q^2 (1-x)/4\pi^2 f_\pi^2 \, x}\right]$$

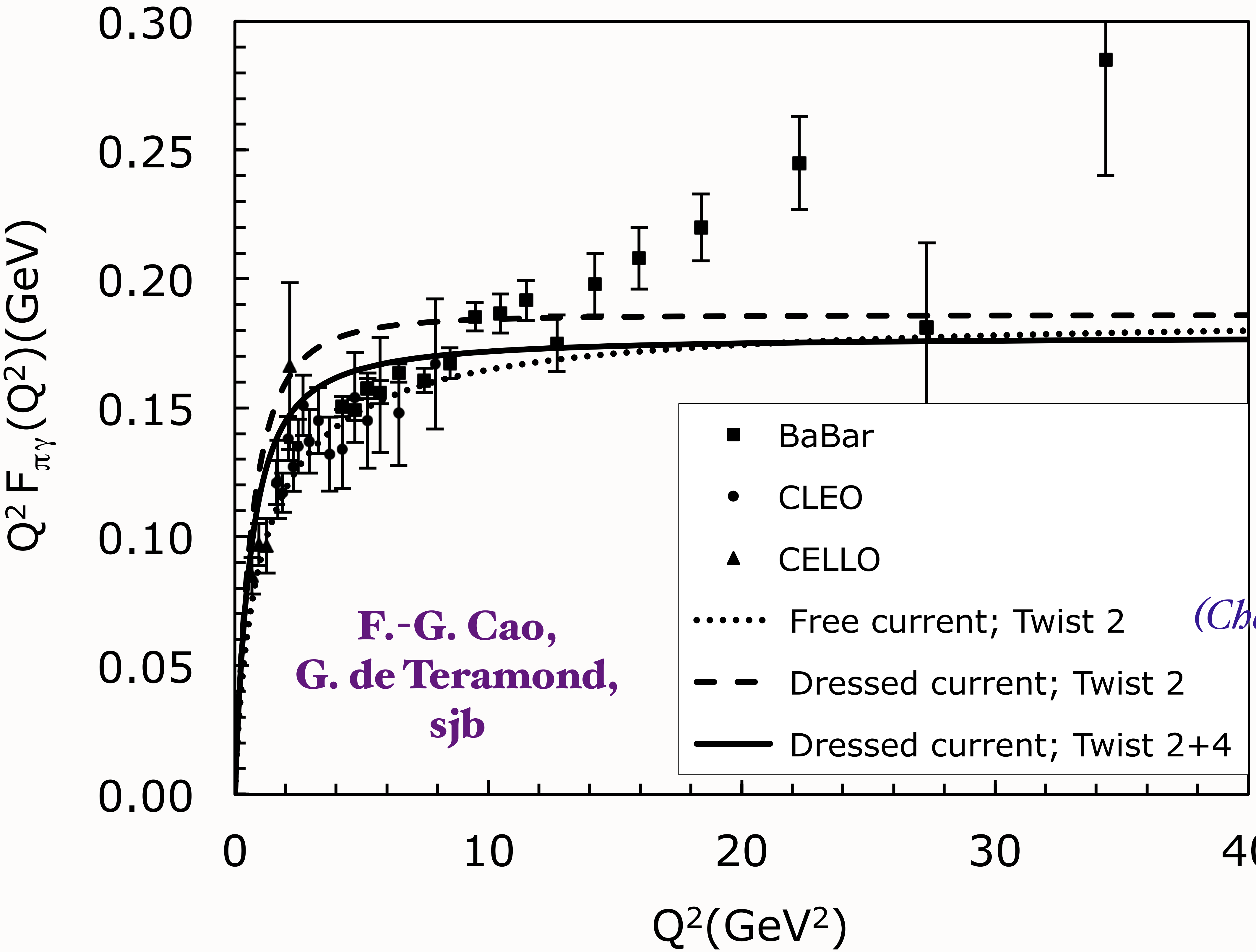
G.P. Lepage, sjb

normalized to the asymptotic DA $[P_{q\bar{q}} = 1 \rightarrow$ Musatov and Radyushkin (1997)]

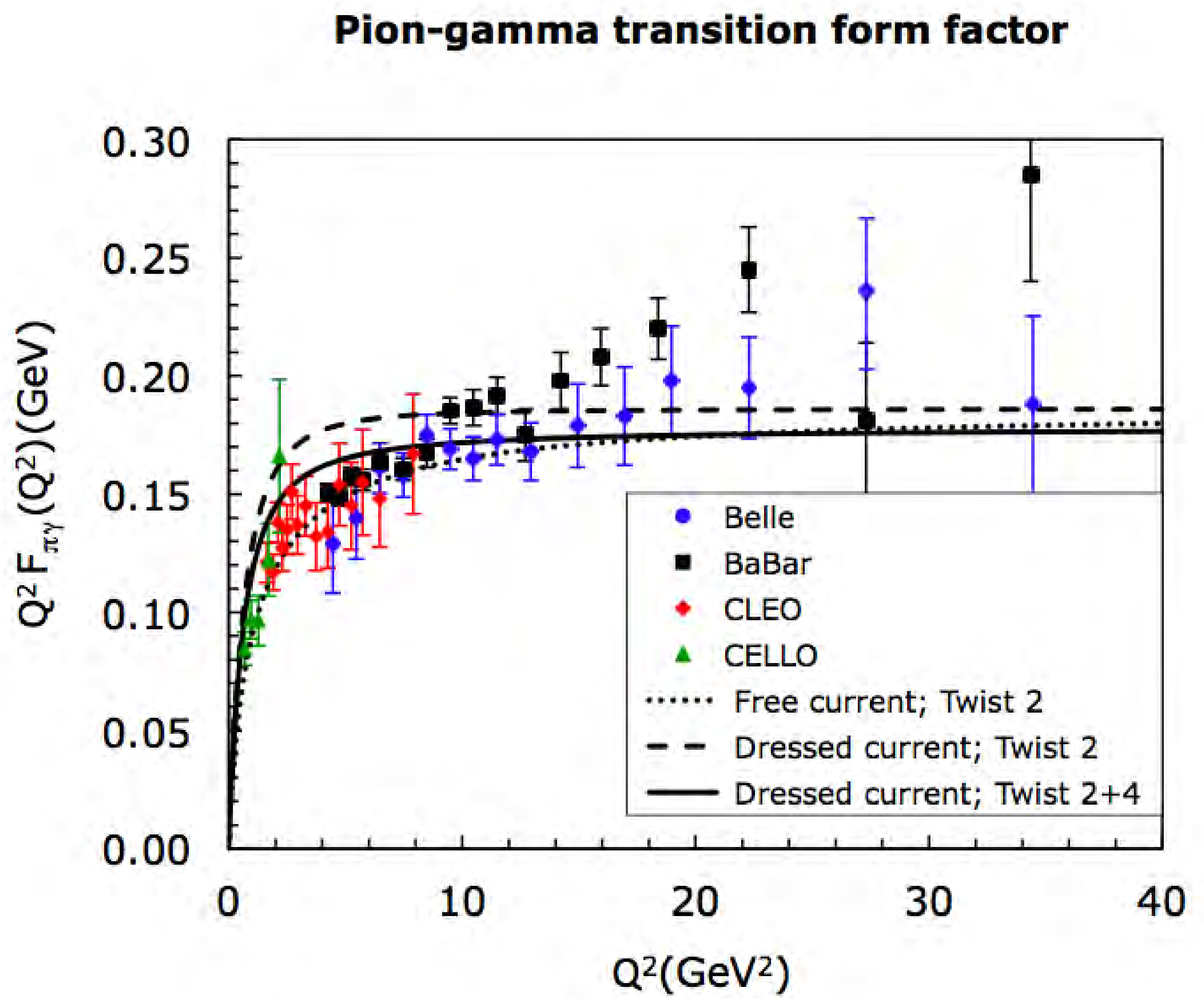
- Large Q^2 TFF is identical to first principles asymptotic QCD result $Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2 f_\pi$
- The CS form is local in AdS space and projects out only the asymptotic form of the pion DA

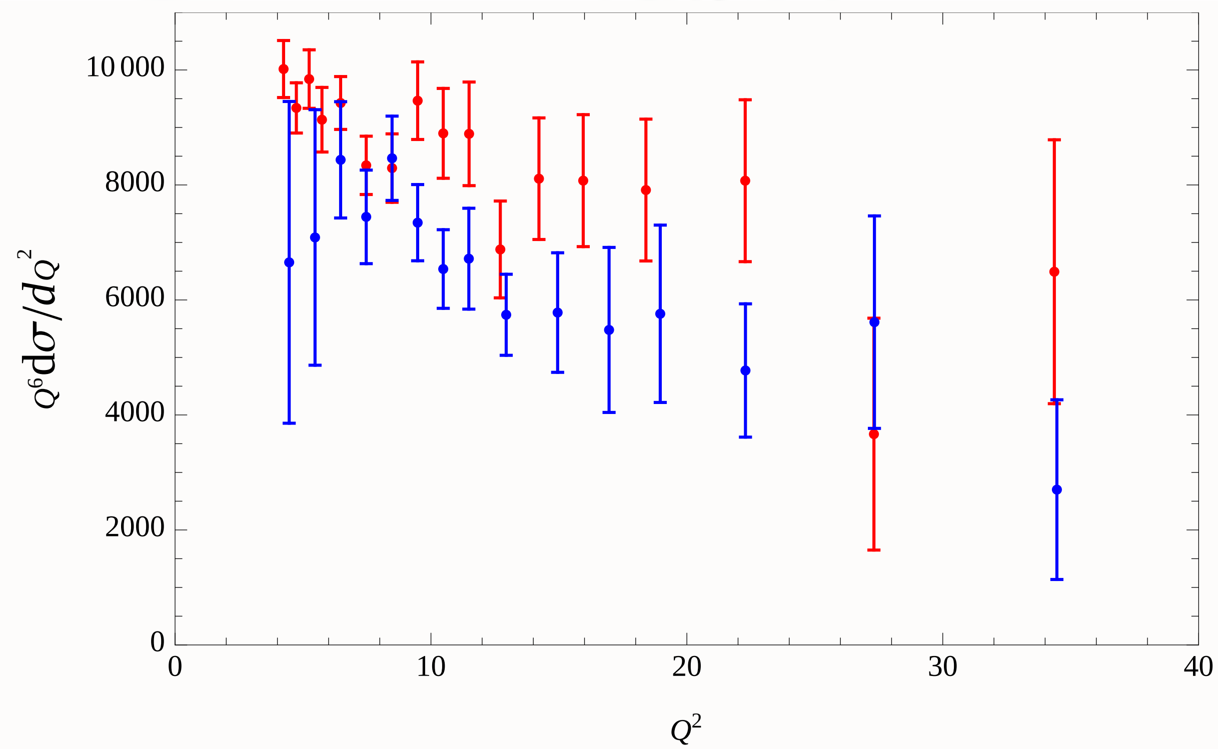
Photon-to-pion transition form factor

Lepage, sjb $\quad Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2 f_\pi$



(Chern-Simons)

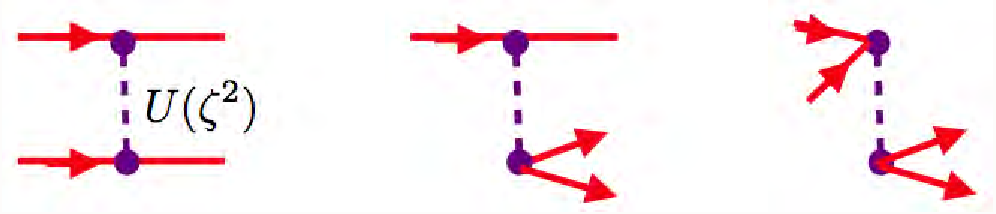

Pion-gamma transition form factor
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
$Q^2 F_{\pi\gamma}(Q^2)$(GeV)
Q^2(GeV^2)
Belle
BaBar
CLEO
CELLO
Free current; Twist 2
Dressed current; Twist 2
Dressed current; Twist 2+4


10 000
8000
6000
4000
2000
0
0
10
20
30
40
$Q^6 d\sigma/dQ^2$
Q^2

46

Confinement Interaction and Higher Fock States

- Is the AdS/QCD confinement interaction responsible for quark pair creation?
- Only interaction in AdS/QCD is the confinement potential
- In QFT the resulting LF interaction is a 4-point effective interaction wich leads to $qq \to qq$, $q \to qq\bar{q}$, $q\bar{q} \to q\bar{q}$ and $\bar{q} \to \bar{q}q\bar{q}$



- Create Fock states with extra quark-antiquark pairs.
- No mixing with $q\bar{q}g$ Fock states (no dynamical gluons)
- Explain the dominance of quark interchange in large angle elastic scattering

  [C. White *et al.* Phys. Rev D **49**, 58 (1994)

- Effective confining potential can be considered as an instantaneous four-point interaction in LF time, similar to the instantaneous gluon exchange in LC gauge $A^+ = 0$. For example

$$P^-_{\text{confinement}} \simeq \kappa^4 \int dx^- d^2\vec{x}_\perp \frac{\overline{\psi}\gamma^+ T^a \psi}{P^+} \frac{1}{(\partial/\partial_\perp)^4} \frac{\overline{\psi}\gamma^+ T^a \psi}{P^+}$$

AdS/QCD and Light-Front Holography

- AdS/QCD: Incorporates scale transformations characteristic of QCD with a single scale -- RGE
- Light-Front Holography; unique connection of AdS_5 to Front-Form
- Profound connection between gravity in 5th dimension and physical 3+1 space time at fixed LF time τ
- Gives unique interpretation of z in AdS to physical variable ζ in 3+1 space-time

Features of AdS/QCD LF Holography

- **Based on Conformal Scaling of Infrared QCD Fixed Point**
- **Conformal template: Use isometries of AdS5**
- **Interpolating operator of hadrons based on twist, superfield dimensions**
- **Finite Nc = 3: Baryons built on 3 quarks -- Large Nc limit not required**
- **Break Conformal symmetry with dilaton**
- **Dilaton introduces confinement -- positive exponent**
- **Origin of Linear and HO potentials: Stochastic arguments (Glazek); General 'classical' potential for Dirac Equation (Hoyer)**
- **Effective Charge from AdS/QCD at all scales**
- **Conformal Dimensional Counting Rules for Hard Exclusive Processes**

Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

- Consider five-dim gauge fields propagating in AdS$_5$ space in dilaton background $\varphi(z) = \kappa^2 z^2$

$$S = -\frac{1}{4} \int d^4x \, dz \, \sqrt{g} \, e^{\varphi(z)} \, \frac{1}{g_5^2} \, G^2$$

- Flow equation

$$\frac{1}{g_5^2(z)} = e^{\varphi(z)} \frac{1}{g_5^2(0)} \quad \text{or} \quad g_5^2(z) = e^{-\kappa^2 z^2} g_5^2(0)$$

where the coupling $g_5(z)$ incorporates the non-conformal dynamics of confinement

- YM coupling $\alpha_s(\zeta) = g_{YM}^2(\zeta)/4\pi$ is the five dim coupling up to a factor: $g_5(z) \to g_{YM}(\zeta)$
- Coupling measured at momentum scale Q

$$\alpha_s^{AdS}(Q) \sim \int_0^\infty \zeta d\zeta \, J_0(\zeta Q) \, \alpha_s^{AdS}(\zeta)$$

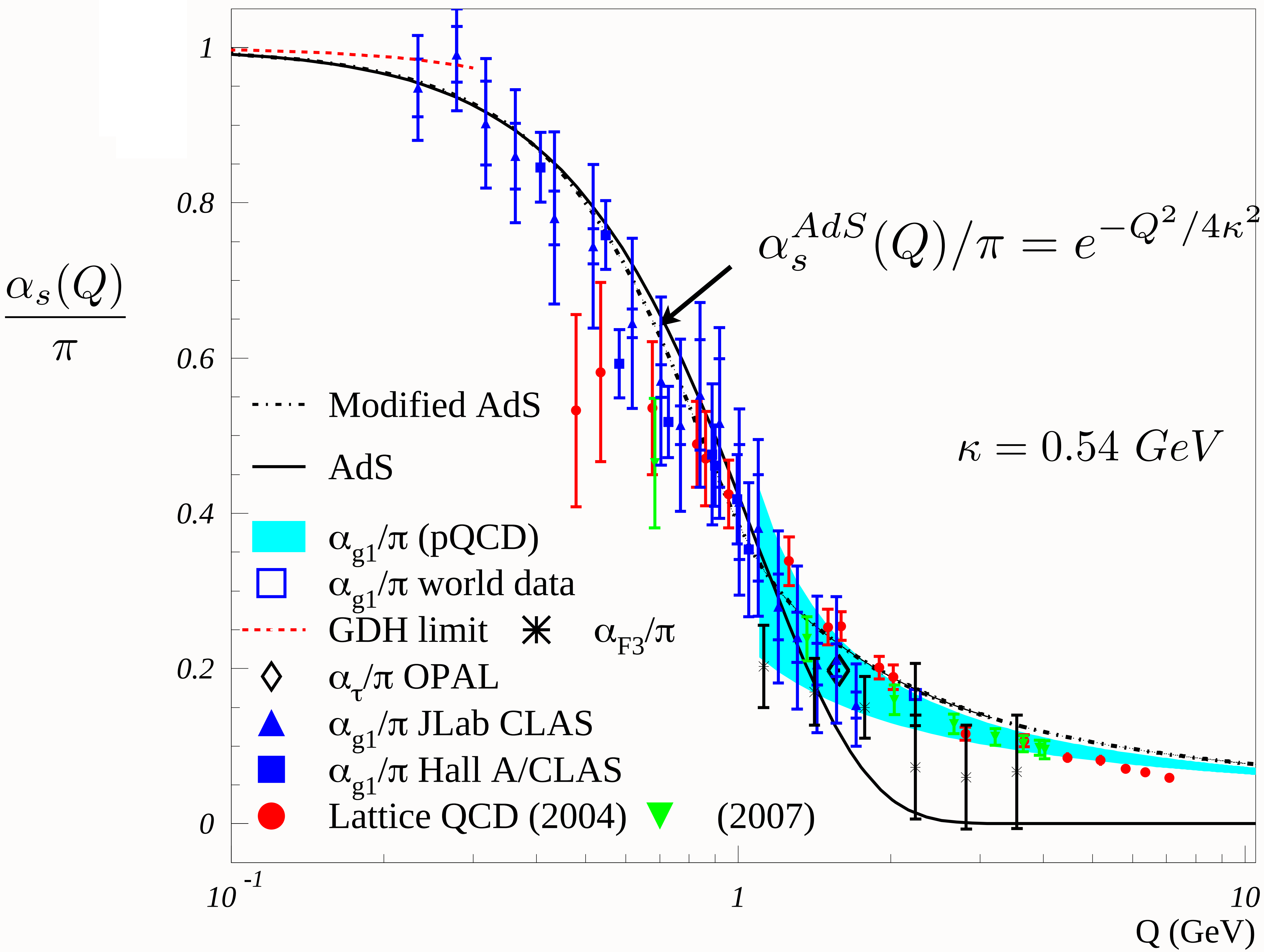
- Solution

$$\alpha_s^{AdS}(Q^2) = \alpha_s^{AdS}(0) \, e^{-Q^2/4\kappa^2}.$$

where the coupling α_s^{AdS} incorporates the non-conformal dynamics of confinement

Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point



Deur, de Teramond, sjb

String Theory

Goal: First Approximant to QCD

AdS/CFT

Mapping of Poincare' and Conformal SO(4,2) symmetries of 3+1 space to AdS5 space

Counting rules for Hard Exclusive Scattering
Regge Trajectories

AdS/QCD

Conformal behavior at short distances
+ Confinement at large distance

QCD at the Amplitude Level

Semi-Classical QCD / Wave Equations

Holography

Boost Invariant 3+1 Light-Front Wave Equations

J =0,1,1/2,3/2 plus L

Integrable!

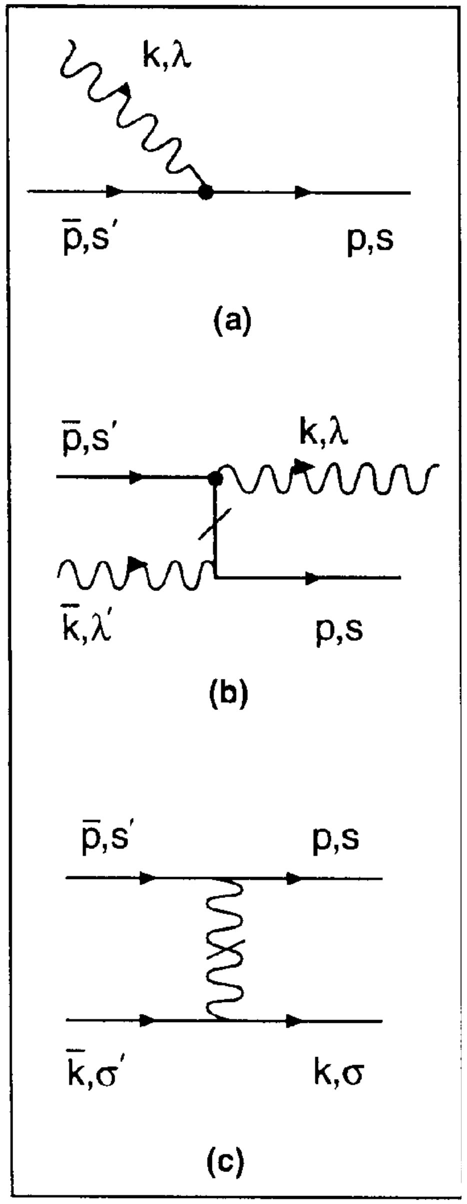
Hadron Spectra, Wavefunctions, Dynamics

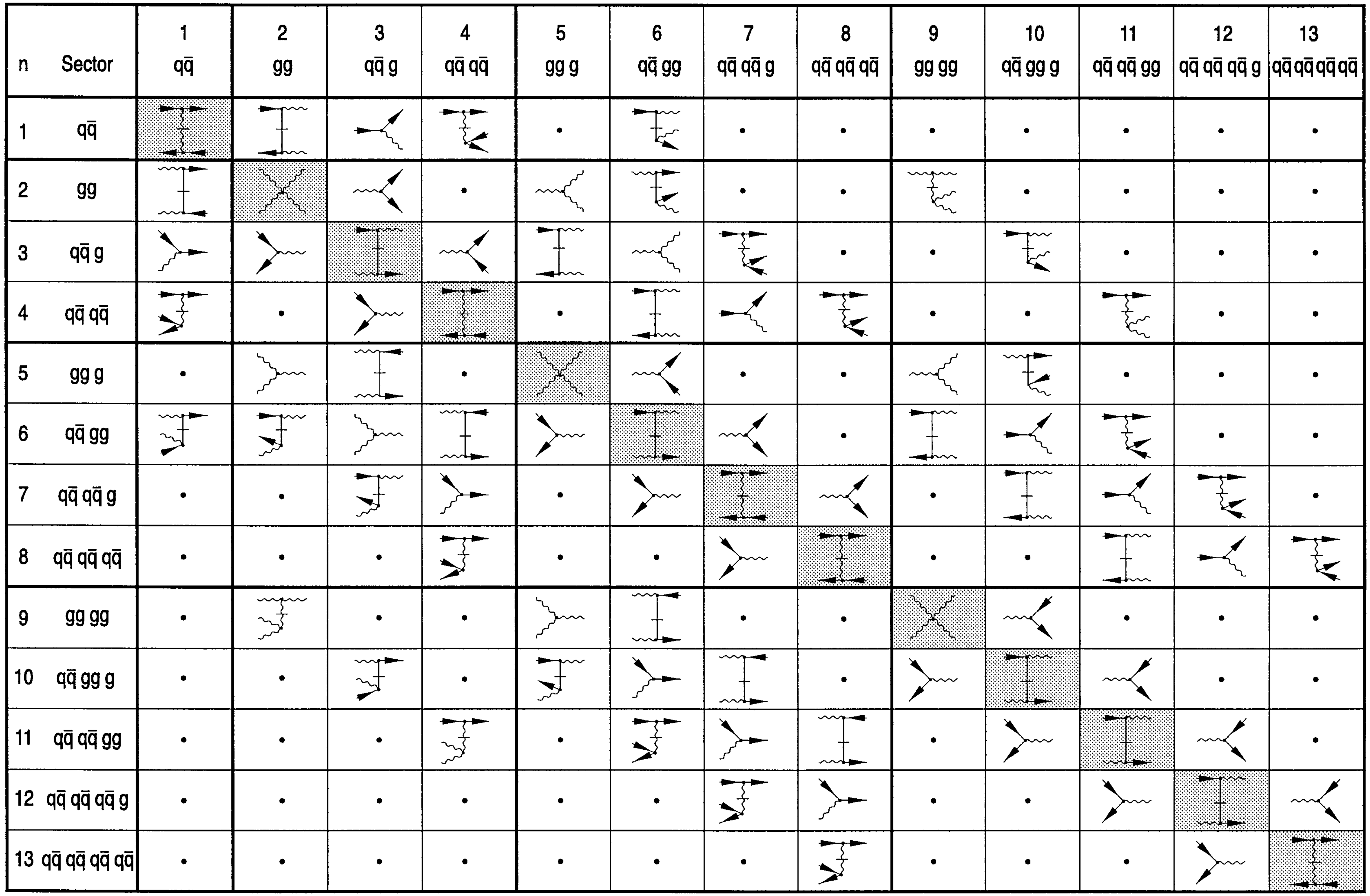
Features of Soft-Wall AdS/QCD

- **Single-variable frame-independent radial Schrodinger equation**
- **Massless pion (m_q =0)**
- **Regge Trajectories: universal slope in n and L**
- **Valid for all integer J & S.**
- **Dimensional Counting Rules for Hard Exclusive Processes**
- **Phenomenology: Space-like and Time-like Form Factors**
- **LF Holography: LFWFs; broad distribution amplitude**
- **No large Nc limit required**
- **Add quark masses to LF kinetic energy**
- **Systematically improvable -- diagonalize H_{LF} on AdS basis**

Light-Front QCD Heisenberg Equation

$$H^{QCD}_{LC}|\Psi_h\rangle = \mathcal{M}^2_h\ |\Psi_h\rangle$$





Use AdS/QCD basis functions!

Future Directions

Vary
Honkanen
et al.

- **BLFQ -- use AdS/QCD basis to diagonalize H_{LF}**

- **Lippmann-Schwinger -- perturbatively generate higher Fock States and systematically approach QCD** *Hiller and Chabysheva*

- **Transverse Lattice**

Burkardt
Dalley
Hiller

- **Hadronization at the Amplitude Level -- Off-Shell T-matrix convoluted with AdS/QCD LFWFs**

- **Hidden Color** *C. Ji , Lepage, sjb*

- **Intrinsic Heavy Quarks from confinement interaction**

- **BLM/PMC -- Automatic Scale Setting -- pinch scheme**

Binosi,
Cornwall,
Popavassiliu
Binger
di Giustino
sjb

- **Direct Processes at the LHC**

- **Dynamic vs. Static Structure Functions**

- **AdS/QCD for DVCS, Hadrons with Heavy Quarks**

- **LF Vacuum, In-Hadron Condensates, Zero-Modes, and the Cosmological Constant**

Use AdS/CFT orthonormal LFWFs as a basis for diagonalizing the QCD LF Hamiltonian

- Good initial approximant
- Better than plane wave basis

Pauli, Hornbostel, Hiller, McCart
sjb

- DLCQ discretization -- highly successful 1+1
- Use independent HO LFWFs, remove CM motion

Vary, Harinandrath, Maris, sjb

- Similar to Shell Model calculations

Features of AdS/QCD LF Holography

- Based on Conformal Scaling of Infrared QCD Fixed Point
- Conformal template: Use isometries of AdS5
- Interpolating operator of hadrons based on twist, superfield dimensions
- Finite Nc = 3: Baryons built on 3 quarks -- Large Nc limit not required
- Break Conformal symmetry with dilaton
- Dilaton introduces confinement -- positive exponent for spacelike observables
- Origin of Linear and HO potentials: Stochastic arguments (Glazek); General 'classical' potential for Dirac Equation (Hoyer)
- Effective Charge from AdS/QCD at all scales
- Conformal Dimensional Counting Rules for Hard Exclusive Processes
- Use CRF (LF Constituent Rest Frame) to reconstruct 3D Image of Hadrons (Glazek, de Teramond, sjb)

Goals

- Test QCD to maximum precision
- High precision determination of $\alpha_s(Q^2)$ at all scales
- Relate observable to observable --no scheme or scale ambiguity
- Eliminate renormalization scale ambiguity in a scheme-independent manner
- Relate renormalization schemes without ambiguity
- Maximize sensitivity to new physics at the colliders

Principle of Maximum Conformality

Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

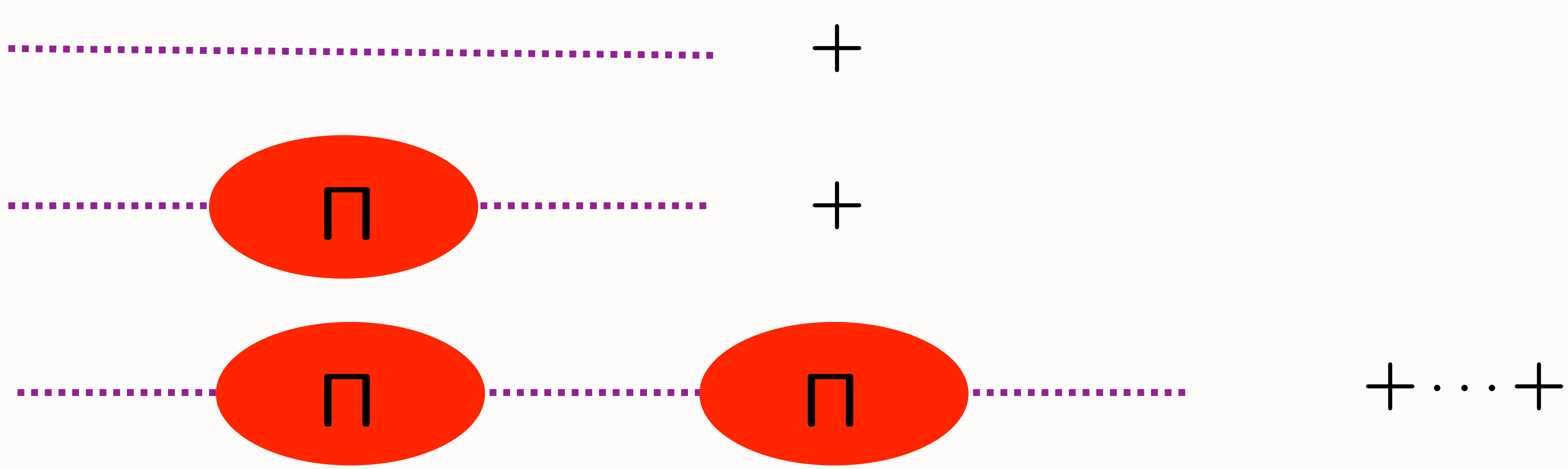
$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell-Mann--Low Effective Charge

QED Effective Charge

$$\alpha(t) = \frac{\alpha(0)}{1 - \Pi(t)}$$

All-orders lepton-loop corrections to dressed photon propagator

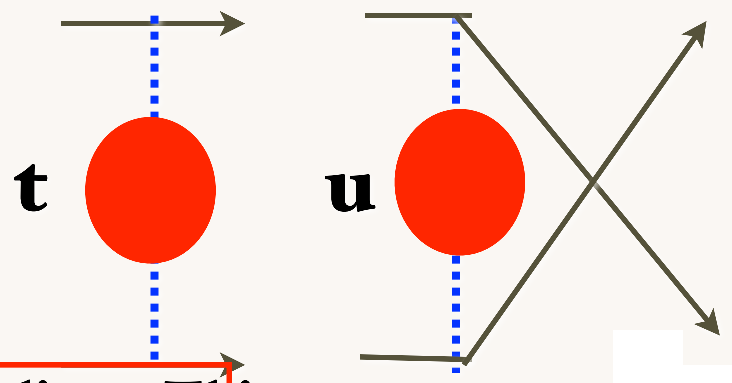


$$\alpha(t) = \frac{\alpha(t_0)}{1 - \Pi(t, t_0)} \qquad \Pi(t, t_0) = \frac{\Pi(t) - \Pi(t_0)}{1 - \Pi(t_0)}$$

Initial **scale t_0 is arbitrary -- Variation gives RGE Equations**
Physical renormalization scale t not arbitrary!

Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$



- **Two separate physical scales: t, u = photon virtuality**
- **Gauge Invariant. Dressed photon propagator**
- **Sums all vacuum polarization, non-zero beta terms into running coupling. This is the purpose of the running coupling!**
- **If one chooses a different initial scale, one must sum an infinite number of graphs -- but always recover same result!**
- **Number of active leptons correctly set**
- **Analytic: reproduces correct behavior at lepton mass thresholds**
- **No renormalization scale ambiguity!**

Myths concerning scale setting

- Renormalization scale “unphysical”: No optimal physical scale
- Can ignore possibility of multiple physical scales
- Accuracy of PQCD prediction can be judged by taking arbitrary guess with an arbitrary range
- Factorization scale should be taken equal to renormalization scale

$$\mu_F = \mu_R$$

Guessing the scale: Wrong in QED. Scheme dependent!

Features of BLM Scale Setting

On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.

Lepage, Mackenzie, sjb Phys.Rev.D28:228,1983

Di Giustino, Wu, sjb

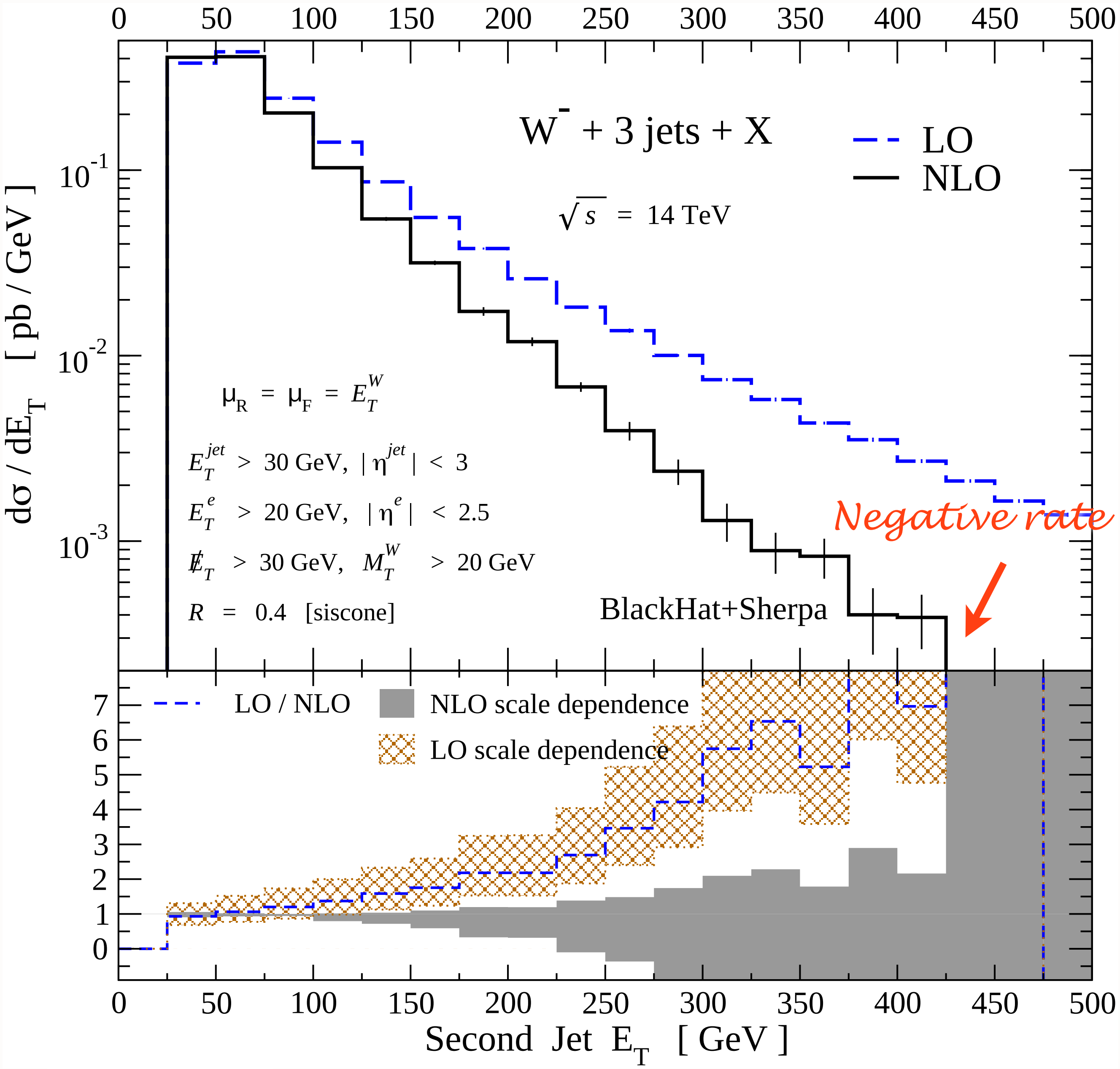
- **"Principle of Maximum Conformality"**
- **All terms associated with nonzero beta function summed into running coupling**
- **Standard procedure in QED**
- **Resulting series identical to conformal series**
- **Renormalon n! growth of PQCD coefficients from beta function eliminated!**
- *Scheme Independent* **!!!**
- **In general, BLM/PMC scales depend on all invariants**
- **Single Effective PMC scale at NLO**

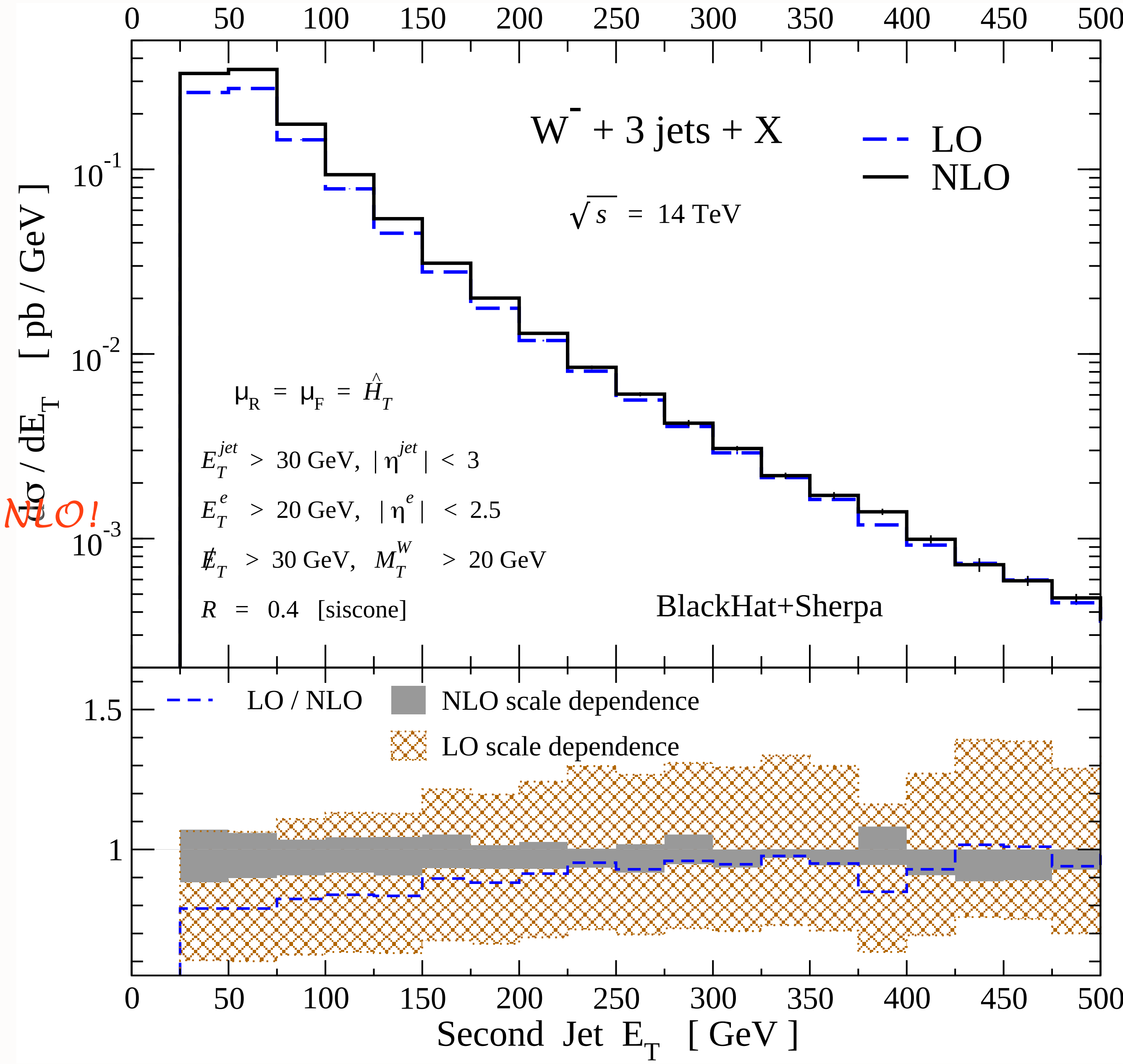
Next-to-Leading Order QCD Predictions for W + 3-Jet Distributions at Hadron Colliders

Black Hat

$$\mu_R = \mu_F = E_T^W$$

$$\mu_R = \mu_F = \hat{H}_T$$





C. F. Berger, Z. Bern, L. J. Dixon, F. Febres Cordero, D. Forde, T. Gleisberg, H. Ita, D. A. Kosower, and D. Maıtre

Huet, sjb

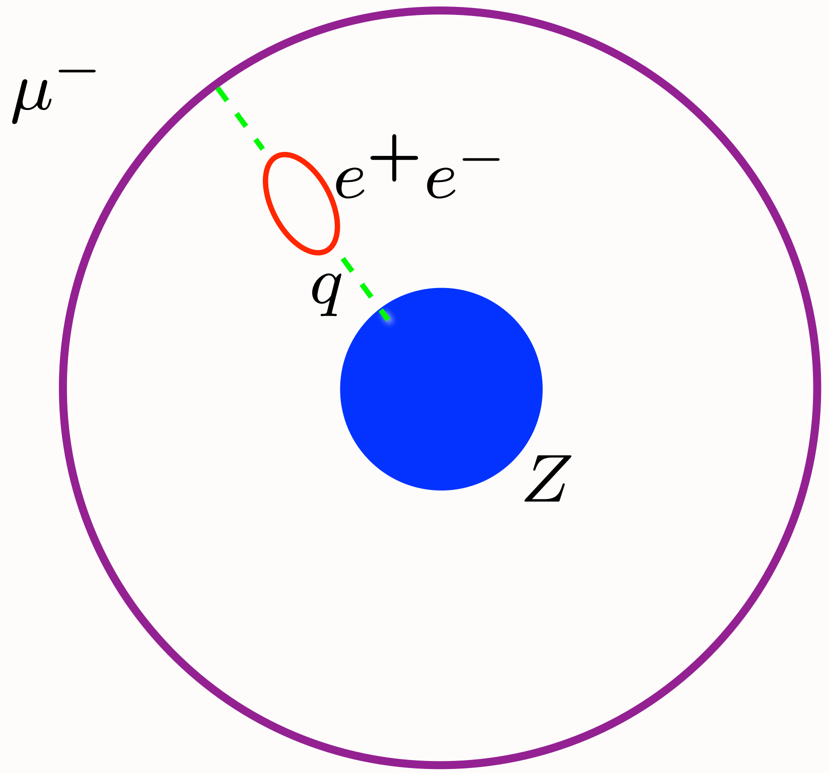
$$\lim N_C \to 0 \text{ at fixed } \alpha = C_F \alpha_s, n_\ell = n_F / C_F$$

$$\text{QCD} \to \text{Abelian Gauge Theory}$$

Analytic Feature of SU(Nc) Gauge Theory

All analyses for Quantum Chromodynamics must be applicable to Quantum Electrodynamics

Another Example in QED: Muonic Atoms



$$V(q^2) = -\frac{Z\alpha_{QED}(q^2)}{q^2}$$

$$\mu_R^2 \equiv q^2$$

$$\alpha_{QED}(q^2) = \frac{\alpha_{QED}(0)}{1-\Pi(q^2)}$$

Scale is unique: Tested to ppm

Gyulassy: Higher Order VP verified to 0.1% precision in μ Pb

QCD Observables

$$\mathcal{O} = C(\alpha_s(\mu_0^2)) + B(\beta \log \frac{Q^2}{\mu_0^2}) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

Scale-Free Conformal Series

Running Coupling Effects

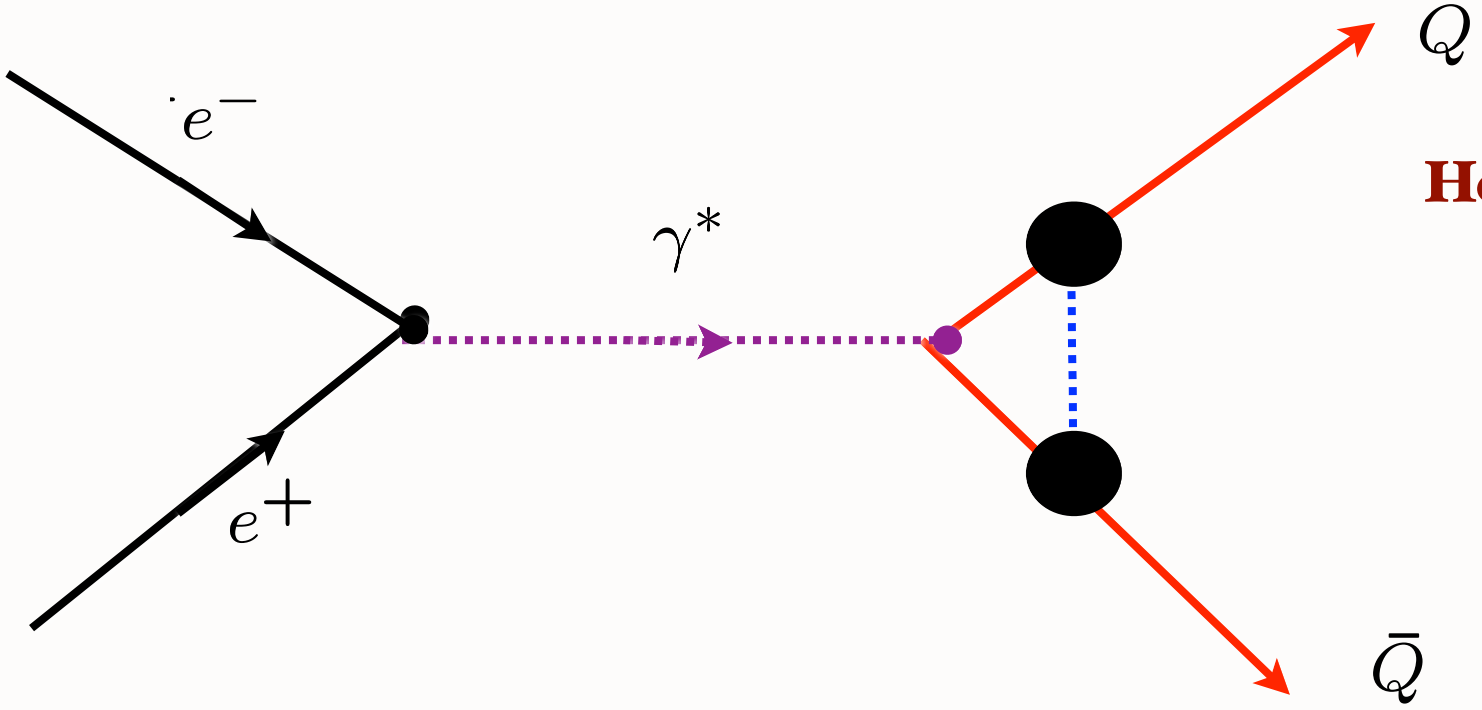
Higher Twist from Hadron Dynamics

Intrinsic Heavy Quarks

Light by Light Loops

BLM/PMC: Absorb β-terms into running coupling

$$\mathcal{O} = C(\alpha_s(Q^{*2})) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$



Hoang, Kuhn, Teubner, sjb

$$F_1 + F_2 = \left[1 - 2\frac{\alpha_s(se^{3/4}/4)}{\pi}\right] \times \left[1 + \frac{\pi\alpha_s(sv^2)}{4v}\right]$$

Angular distributions of massive quarks close to threshold.

Example of Multiple BLM Scales

Need QCD coupling at small scales at low relative velocity v

Relation between scales of the Gell-Mann--Low and $\overline{\text{MS}}$ schemes

$$\log \frac{\mu_0^2}{m_\ell^2} = 6 \int_0^1 x(1-x) \log \frac{m_\ell^2 + Q_0^2 x(1-x)}{m_\ell^2}$$

$$\log \frac{\mu_0^2}{m_\ell^2} = \log \frac{Q_0^2}{m_\ell^2} - 5/3$$

$$\boxed{\mu_0^2 = Q_0^2 \, e^{-5/3}} \quad \text{when } Q_0^2 >> m_\ell^2$$

D. S. Hwang, sjb

M. Binger

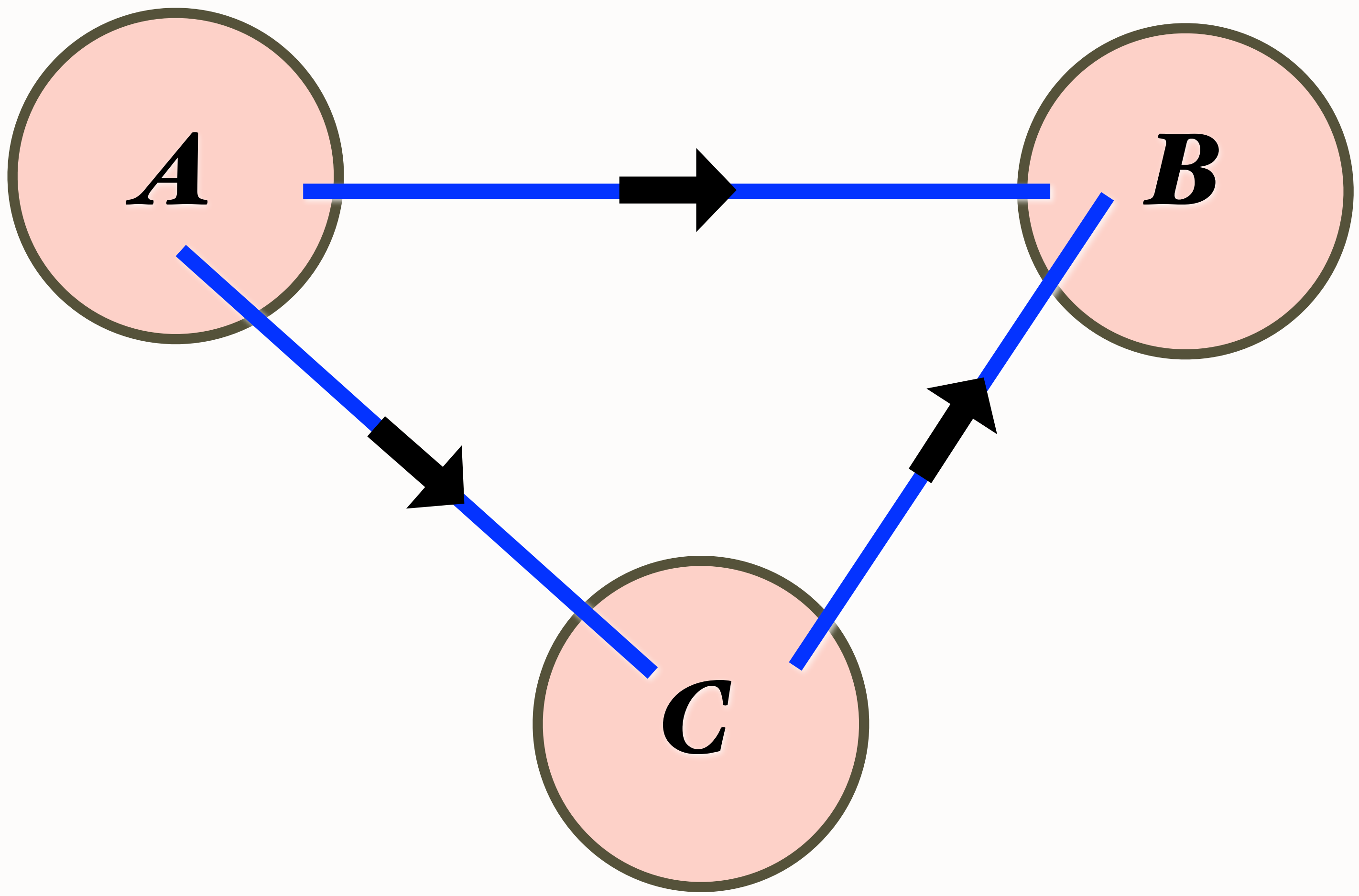
Can use $\overline{\text{MS}}$ scheme in QED; answers are scheme independent
Analytic extension: coupling is complex for timelike argument

The Renormalization Scale Problem

- No renormalization scale ambiguity in QED
- Gell Mann-Low QED Coupling defined from physical observable
- Sums all Vacuum Polarization Contributions
- Recover conformal series
- Renormalization Scale in QED scheme: Identical to Photon Virtuality
- Analytic: Reproduces lepton-pair thresholds -- number of active leptons set
- Examples: muonic atoms, g-2, Lamb Shift
- Time-like and Space-like QED Coupling related by analyticity
- Uses Dressed Skeleton Expansion
- Results are scheme independent!
- *Predictions for physical observables cannot be scheme dependent*

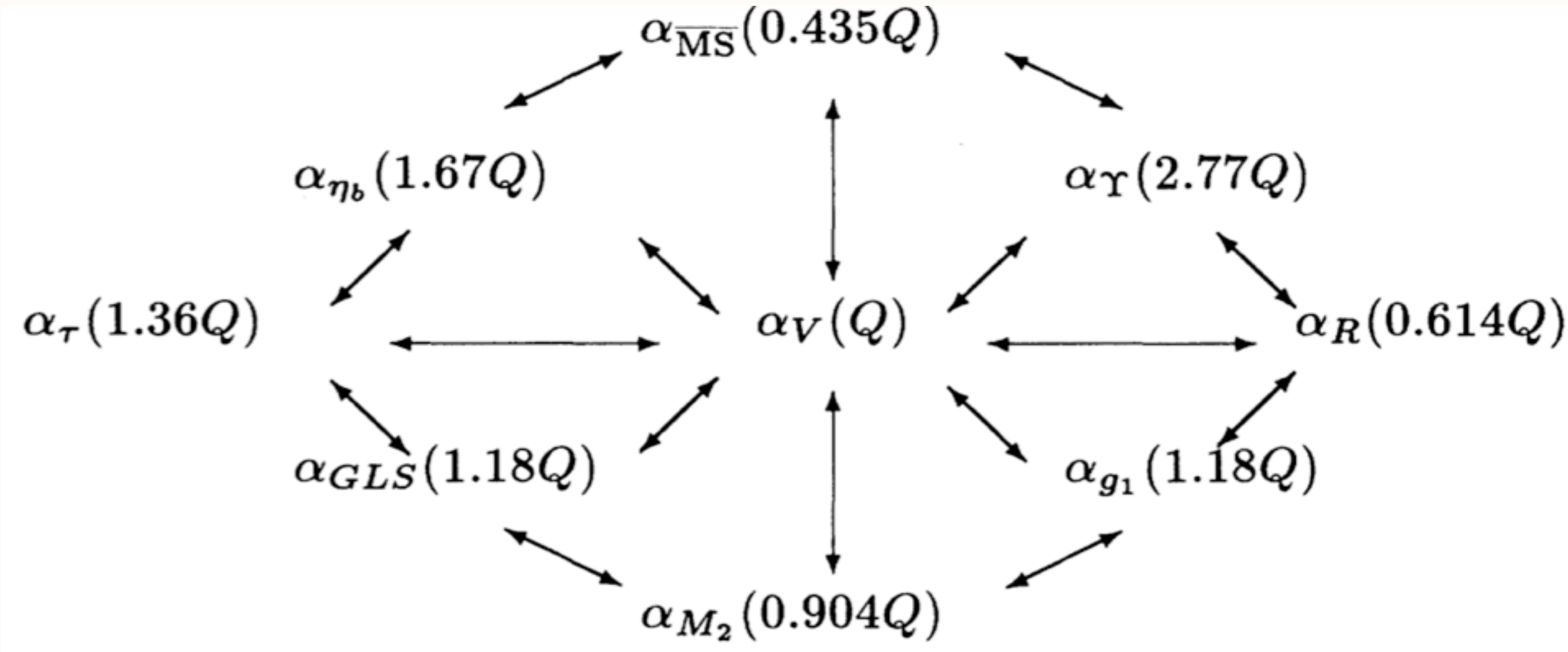
Transitivity Property of Renormalization Group

Relation of observables must be independent of intermediate scheme



A ➡ C **C ➡ B** ***identical to*** **A ➡ B**

Violated by PMS!


$\alpha_{\overline{\mathrm{MS}}}(0.435Q)$
$\alpha_{\eta_b}(1.67Q)$
$\alpha_{\Upsilon}(2.77Q)$
$\alpha_{\tau}(1.36Q)$
$\alpha_V(Q)$
$\alpha_R(0.614Q)$
$\alpha_{GLS}(1.18Q)$
$\alpha_{g_1}(1.18Q)$
$\alpha_{M_2}(0.904Q)$

Need to set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

Choose renormalization scheme; e.g. $\alpha_s^R(\mu_R^{\text{init}})$

↓

Choose μ_R^{init}*; arbitrary initial renormalization scale*

↓

Identify $\{\beta_i^R\}$ *− terms using* n_f *− terms through the PMC − BLM correspondence principle*

↓

Shift scale of α_s *to* μ_R^{PMC} *to eliminate* $\{\beta_i^R\}$ *− terms*

↓

Conformal Series

Result is independent of μ_R^{init} *and scheme at fixed order*

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

Same as QED Scale Setting

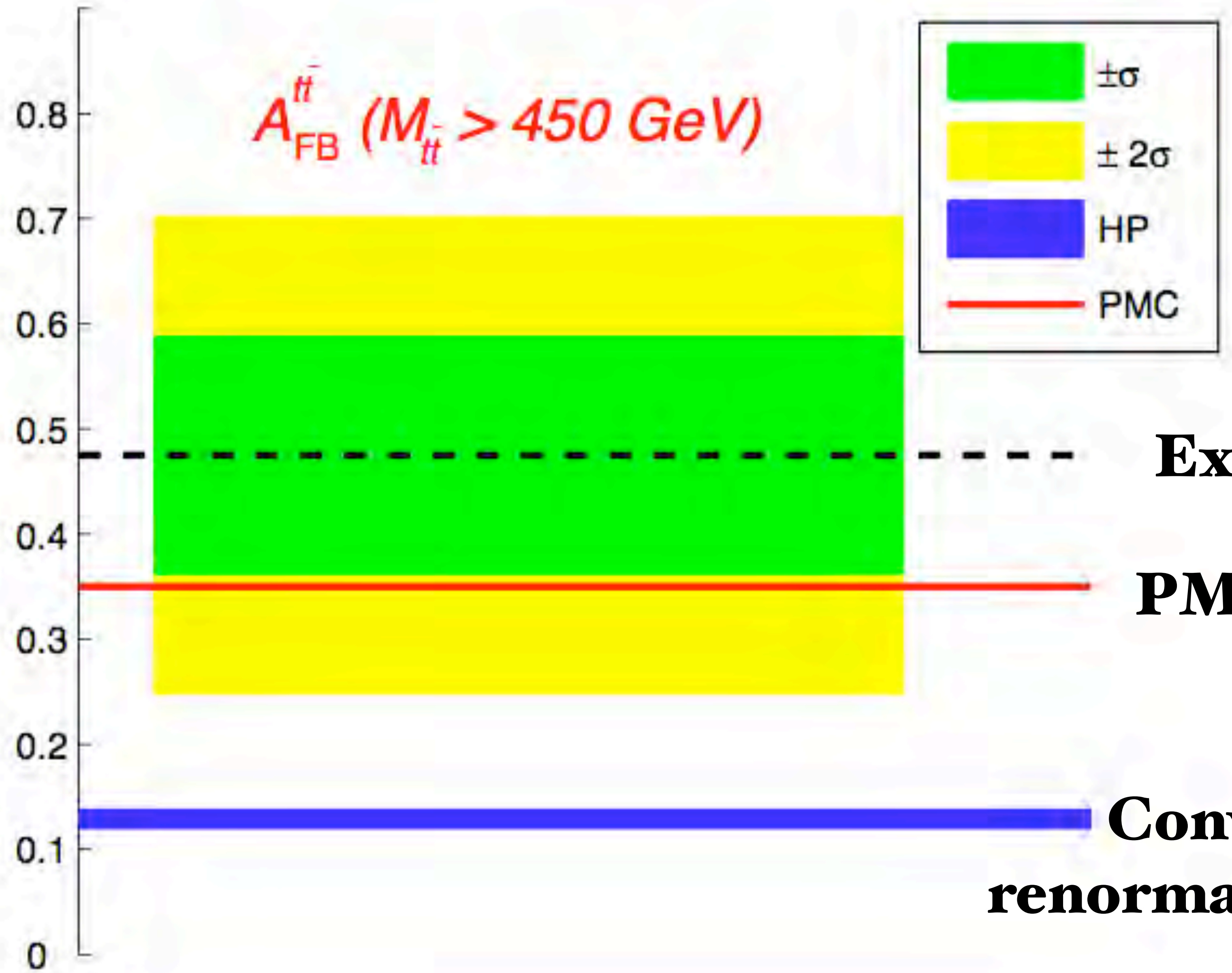
Apply to Evolution kernels, hard subprocesses

Eliminates unnecessary systematic uncertainty

Xing-Gang Wu
Leonardo di Giustino, SJB

Principle of Maximum Conformality

Eliminating the Renormalization Scale Ambiguity for Top-Pair Production Using the 'Principle of Maximum Conformality' (PMC)



Xing-Gang Wu
SJB

Experimental asymmetry

PMC Prediction

Conventional: guess for renormalization scale and range

$t\bar{t}$ asymmetry predicted by pQCD NNLO within
1 σ of CDF/D0 measurements using PMC/BLM scale setting

Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Conformal Template
- Example: Generalized Crewther Relation

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q{}^2 \left[1 + \frac{\alpha_R(Q)}{\pi} \right] .$$

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8}C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$
$$+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32}C_F^2\right.$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$
$$\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12}C_A - \frac{7}{8}C_F - \frac{1}{3}f\right]$$
$$+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32}C_F^2\right.$$
$$\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648} f^2\right\}.$$

Eliminate MSbar,
Find Amazing Simplification

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

$$[1 + \frac{\alpha_R(s^*)}{\pi}][1 - \frac{\alpha_{g_1}(q^2)}{\pi}] = 1$$

$$\sqrt{s^*} \simeq 0.52 Q$$

Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

Nonconformal terms set relative scales (BLM)

No renormalization scale ambiguity!

Both observables go through new quark thresholds at commensurate scales!

Huet, sjb

$$\lim N_C \to 0 \text{ at fixed } \alpha = C_F\alpha_s, n_\ell = n_F/C_F$$

$$\text{QCD} \to \text{Abelian Gauge Theory}$$

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD must be applicable to QED

The Renormalization Scale Problem

- **No renormalization scale ambiguity in QED**
- **Gell Mann-Low QED Coupling defined from physical observable**
- **Sums all Vacuum Polarization Contributions**
- **Recover conformal series**
- **Renormalization Scale in QED scheme: Identical to Photon Virtuality**
- **Analytic: Reproduces lepton-pair thresholds**
- **Examples: muonic atoms, g-2, Lamb Shift**
- **Time-like and Space-like QED Coupling related by analyticity**
- **Uses Dressed Skeleton Expansion**
- **Results are scheme independent**

What is the evidence for a nonzero vacuum quark condensate?

Gell-Mann - Oakes - Renner Relation (1968)

$$f_\pi^2 m_\pi^2 = -2\, m(\zeta) \langle \bar{q} q \rangle_0^\zeta$$

- Pion's leptonic decay constant, mass-dimensioned observable which describes rate of process $\pi^+ \to \mu^+ \nu$
- *Vacuum quark condensate*

ζ: renormalization scale

Derived in current algebra using an effective pion field

How is this modified in QCD for a composite pion?

Gell-Mann Oakes Renner Formula in QCD

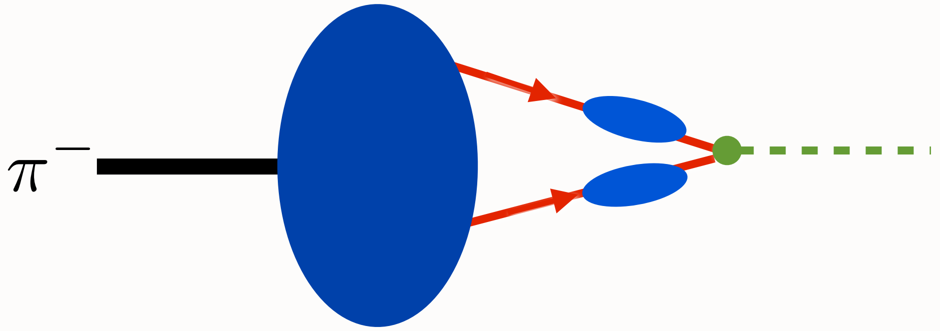
$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi^2} < 0|\bar{q}q|0 >$$

current algebra: effective pion field

$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi} < 0|i\bar{q}\gamma_5 q|\pi >$$

QCD: composite pion Bethe-Salpeter, LF

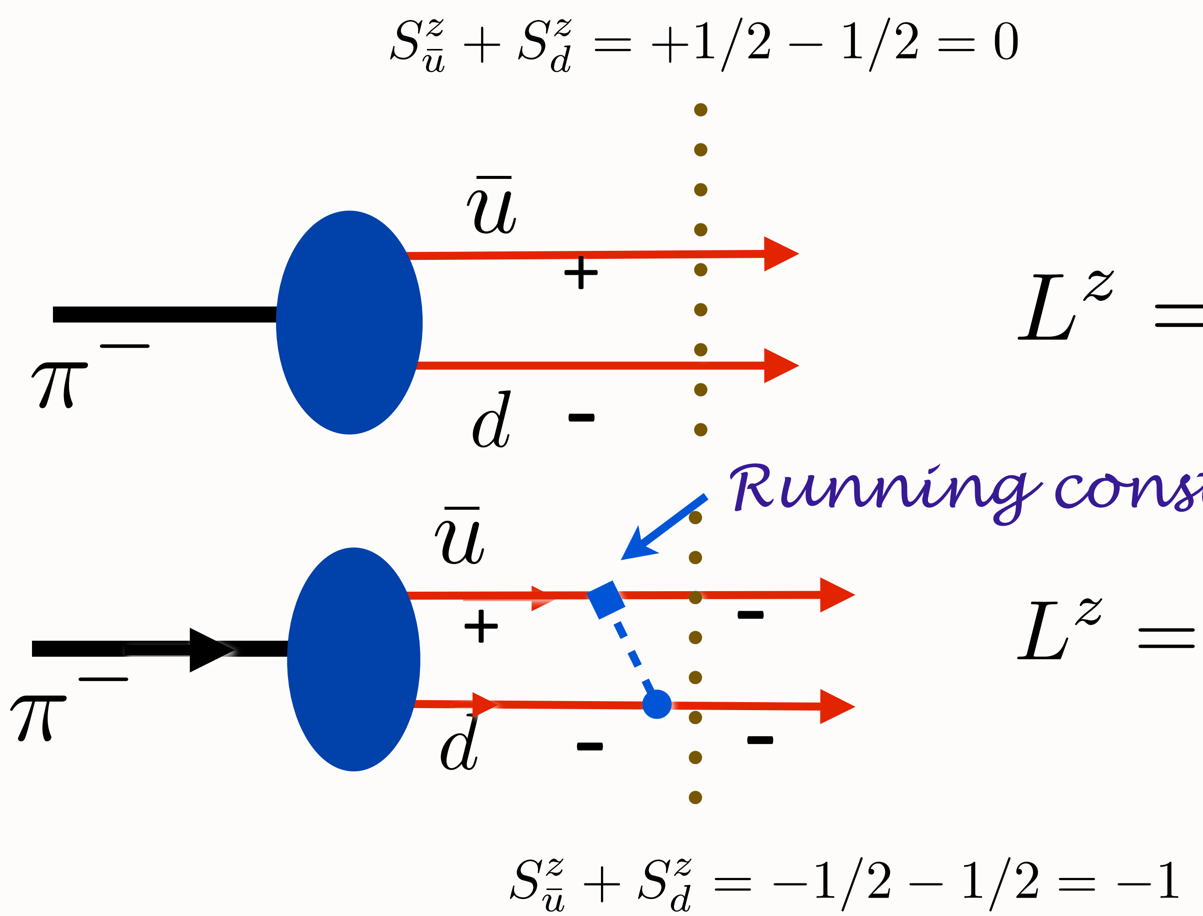
vacuum condensate actually is an "in-hadron condensate"



$$< 0|\bar{q}\gamma_5 q|\pi >$$

Maris, Roberts, Tandy

Light-Front Pion Valence Wavefunctions



Couples to

$L^z = 0, S^z = 0 \quad < \pi|\bar\gamma^\mu q\gamma_5 q|0 > \sim f_\pi$

$L^z = +1, S^z = -1 \quad < \pi|\bar q\gamma_5 q|0 > \ \sim \rho_\pi$

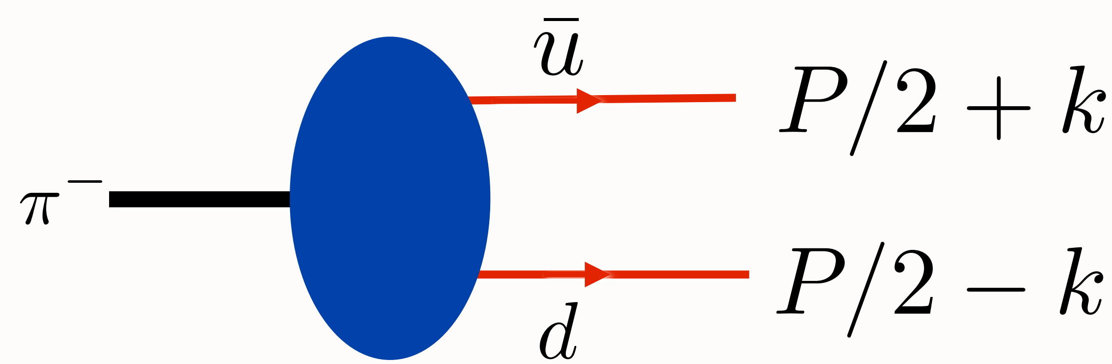
Angular Momentum Conservation

$$J^z = \sum_i^n S^z_i + \sum_i^{n-1} L^z_i$$

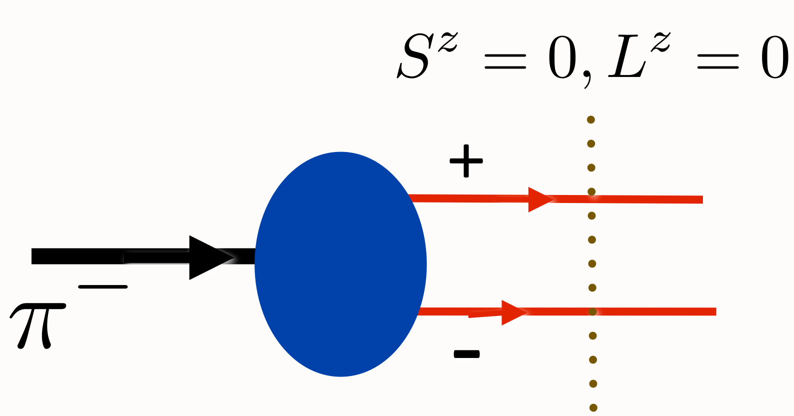
General Form of Bethe-Salpeter Wavefunction

$$
\Gamma_\pi(k;P) = i\gamma_5 E_\pi(k,P) + \gamma_5\gamma\cdot P F_\pi(k;P)
+\gamma_5\gamma\cdot k G_\pi(k;P) - \gamma_5\sigma_{\mu\nu}k^\mu P^\nu H_\pi(k;P)
$$

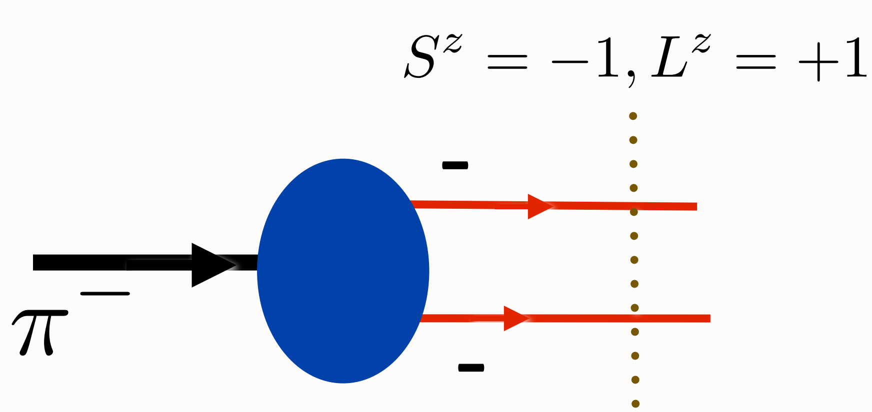
$\Gamma_\pi(k;P)$



Allows both $< 0|\bar{q}\gamma_5\gamma_\mu q|\pi >$ and $< 0|\bar{q}\gamma_5 q|\pi >$



LFWFs



“One of the gravest puzzles of theoretical physics”

**DARK ENERGY AND
THE COSMOLOGICAL CONSTANT PARADOX**

A. ZEE

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$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

$$\Omega_\Lambda = 0.76(expt)$$

$$(\Omega_\Lambda)_{EW} \sim 10^{56}$$

QCD Problem Solved if Quark and Gluon condensates reside within hadrons, not vacuum!

R. Shrock, sjb

arXiv:0905.1151 [hep- th], Proc. Nat’l. Acad. Sci., (in press);
``Condensates in Quantum Chromodynamics and the Cosmological Constant.”

Light-Front vacuum can simulate empty universe

Shrock, Tandy, Roberts, sjb

- Independent of observer frame
- Causal
- Lowest invariant mass state M= 0.
- Trivial up to k^+=0 zero modes-- already normal-ordering
- Higgs theory consistent with trivial LF vacuum (Srivastava, sjb)
- QCD and AdS/QCD: In hadron condensates (Maris, Tandy Roberts)
- QED vacuum; no loops
- Zero cosmological constant

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New perspectives on the quark condensate

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We show that the chiral-limit vacuum quark condensate is qualitatively equivalent to the pseudoscalar meson leptonic decay constant in the sense that they are both obtained as the chiral-limit value of well-defined gauge-invariant hadron-to-vacuum transition amplitudes that possess a spectral representation in terms of the current-quark mass. Thus, whereas it might sometimes be convenient to imagine otherwise, neither is essentially a constant mass-scale that fills all spacetime. This means, in particular, that the quark condensate can be understood as a property of hadrons themselves, which is expressed, for example, in their Bethe-Salpeter or light-front wave functions.

Chiral Symmetry Breaking in AdS/QCD

Erlich et al.

- **Chiral symmetry breaking effect in AdS/QCD depends on weighted z^2 distribution, not constant condensate**

$$\delta M^2 = -2m_q < \bar{\psi}\psi > \times \int dz \ \phi^2(z) z^2$$

- **z^2 weighting consistent with higher Fock states at periphery of hadron wavefunction**
- **mass shift depends on hadron size, etc.**
- **AdS/QCD: confined condensate**
- **Suggests "In-Hadron" Condensates**

Shrock, Roberts, Tandy, sjb

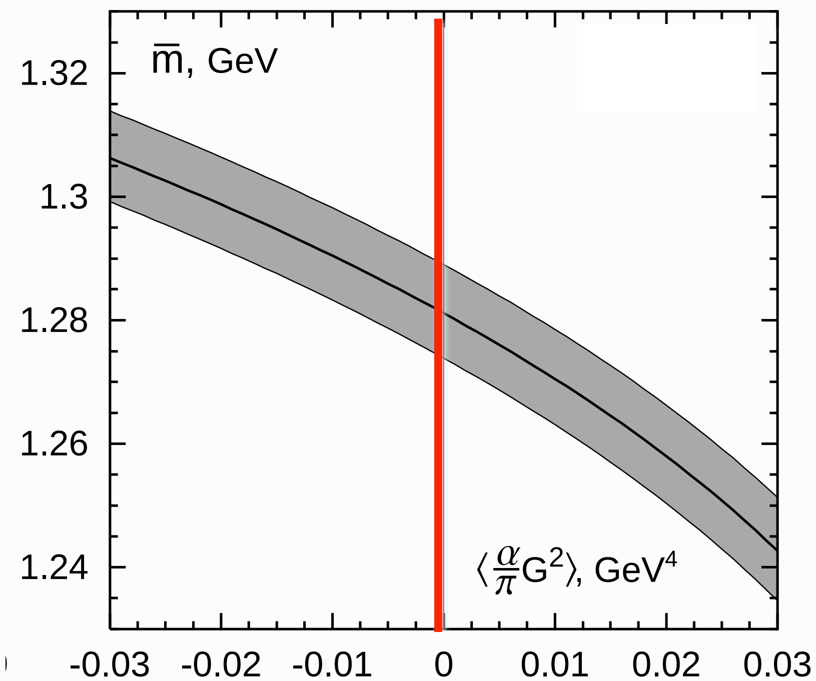
Determinations of the vacuum Gluon Condensate

$$< 0|\frac{\alpha_s}{\pi}G^2|0> [\mathrm{GeV}^4]$$

-0.005 ± 0.003 from τ decay. Davier et al.

$+0.006 \pm 0.012$ from τ decay. Geshkenbein, Ioffe, Zyablyuk

$+0.009 \pm 0.007$ from charmonium sum rules Ioffe, Zyablyuk

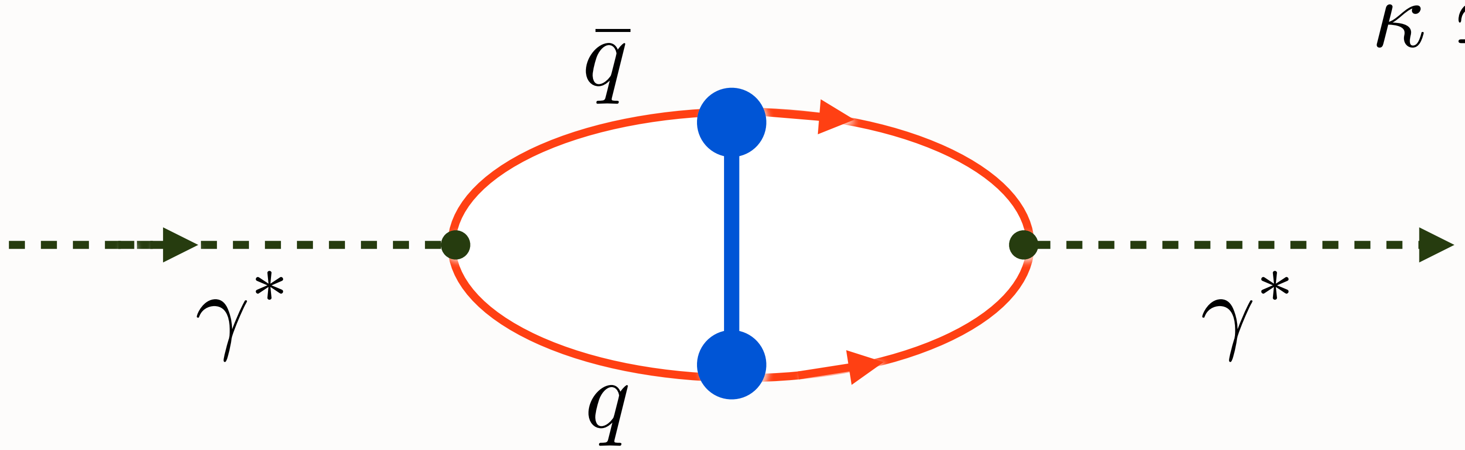


Consistent with zero vacuum condensate

Effective Confinement potential from soft-wall AdS/QCD gives Regge Spectroscopy plus higher-twist correction to current propagator

$$M^2 = 4\kappa^2(n + L + S/2)$$ light-quark meson spectra

$\kappa \simeq 0.5$ GeV



$$R_{e^+e^-}(s) = N_c \sum_q e_q^2 (1 + \mathcal{O}\frac{\kappa^4}{s^2} + \cdots)$$

mimics dimension-4 gluon condensate $< 0|\frac{\alpha_s}{\pi} G^{\mu\nu}(0) G_{\mu\nu}(0)|0 >$ in

$e^+e^- \to X$, τ decay, $Q\bar{Q}$ phenomenology

Light-Front Schrödinger Equation

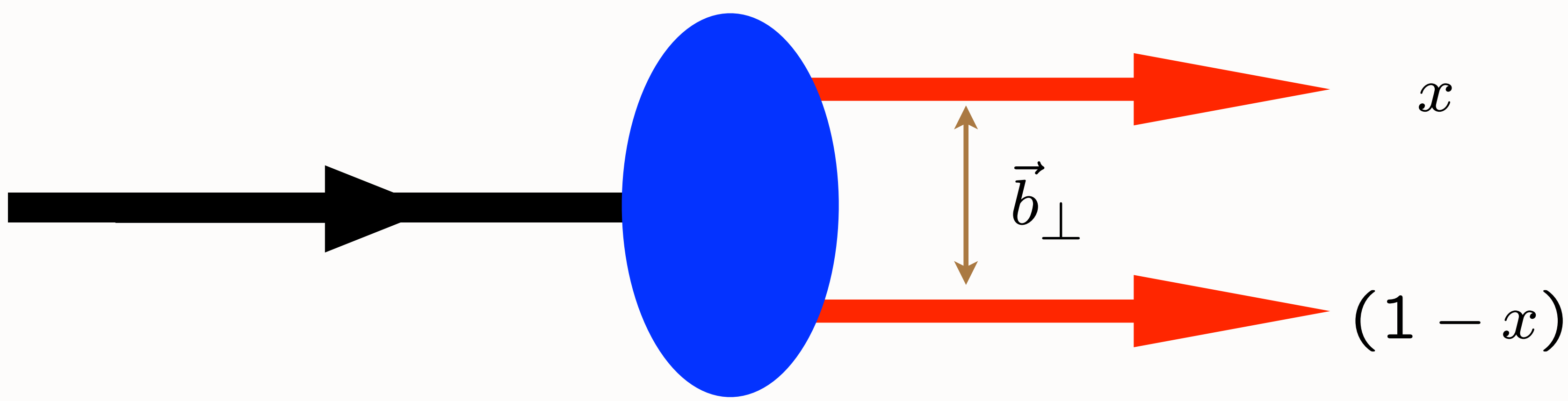
G. de Teramond, sjb

Relativistic LF single-variable radial equation for QCD & QED

Frame Independent!

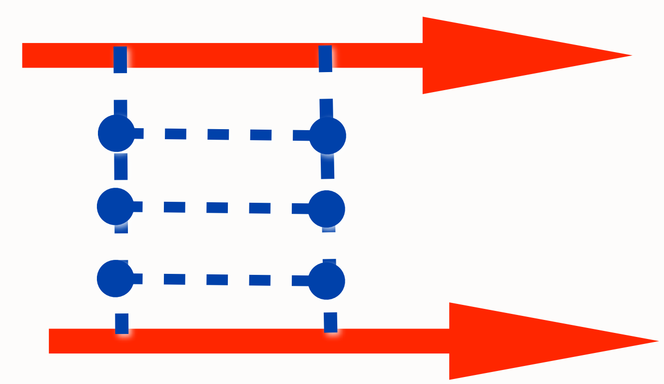
$$\left[-\frac{d^2}{d\zeta^2}+\frac{4L^2-1}{4\zeta^2}+U(\zeta^2,J,L,M^2)\right]\Psi_{J,L}(\zeta^2)=M^2\Psi_{J,L}(\zeta^2)$$

$$\zeta^2 = x(1-x)\mathbf{b}_\perp^2 .$$



U is the exact QCD potential
Conjecture: 'H'-diagrams generate

$$U(\zeta,S,L)=\kappa^2\zeta^2+\kappa^2(L+S-1/2)$$



Future QCD Facilities

- **AFTER-- Fixed Target at the LHC**
- **LHeC**
- **NICA**
- **FAIR-PANDA**
- **JLAb 12**
- **EIC**
- **JPARC**
- **Fermilab Fixed Target**
- **CERN Fixed Target (Compass)**

AFTER @ LHC

Physics at A Fixed Target ExpeRiment (AFTER) using the LHC beams

3-13 February 2013 *ECT* Trento*

Europe/Rome timezone

Overview

Scientific Programme

Appel à Communication

- View my abstracts
- Submit a new abstract

Programme

AFTER@LHC

ECT* Trento

This is an exploratory workshop which aims at studying in detail the opportunity and feasibility of a fixed-target experiment using the LHC beams extracted by a bent crystal.
Complementarity with existing experiments at the LHC, at SPS, at CEBAF, at Fermilab will also be the cornerstone of the discussions. The contribution of everyone is therefore welcome.

The workshop will consist of morning sessions with invited speakers and afternoon sessions devoted to work in groups on the following themes:

- nucleon and nucleus pdf extraction in hadronic processes
- spin physics
- QGP physics
- nuclear matter studies in pA
- diffractive physics and ultra-peripheral collisions
- beam extraction and secondary beams
- target polarization
- modern detector technologies
- event generator and detector simulation
- etc...

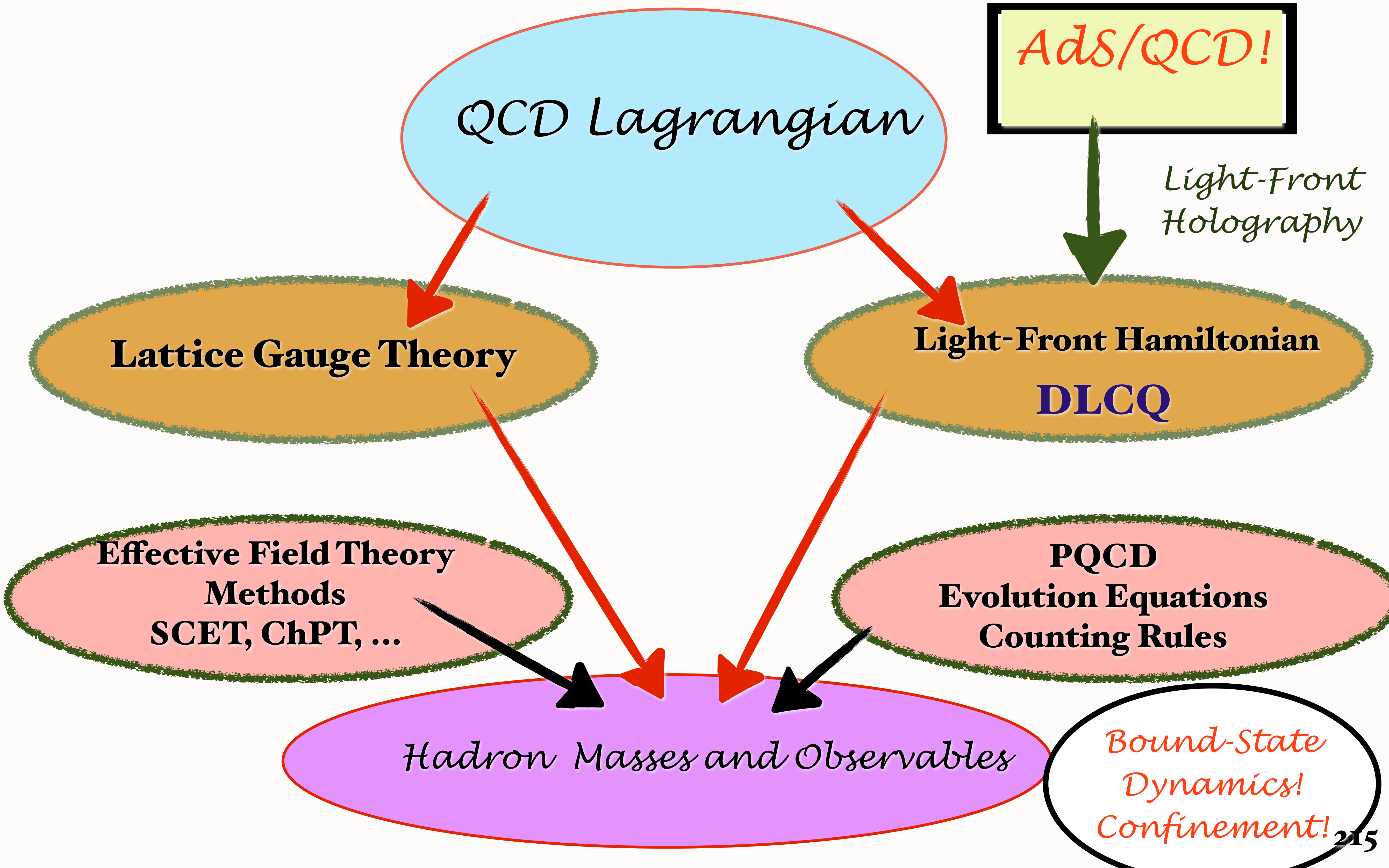
Fixed Target Physics with the LHC Beams **AFTER**

- **7 TeV proton beam, nuclear beams**
- **Full Range of Nuclear and Polarized Targets**
- **Cosmic Ray simulations!**
- **Single-Spin Asymmetries, Transversity Studies, A_N**
- **High-x_F Dynamics at Forward and Backward Rapidities**
- **High-x_F Nuclear Anomalies**
- **Production of ccc to bbb baryons**
- **Quark-Gluon Plasma in Nuclear Rest System--No Ellipse in LF**

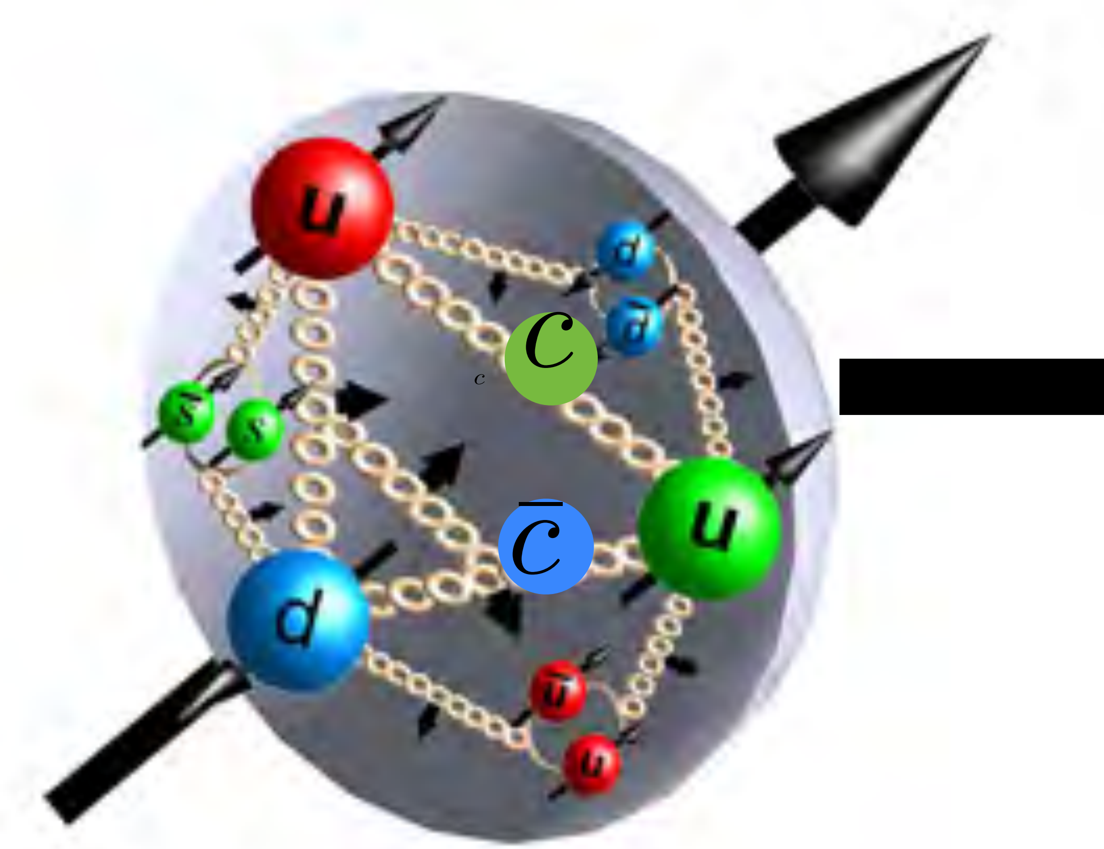
QCD Myths

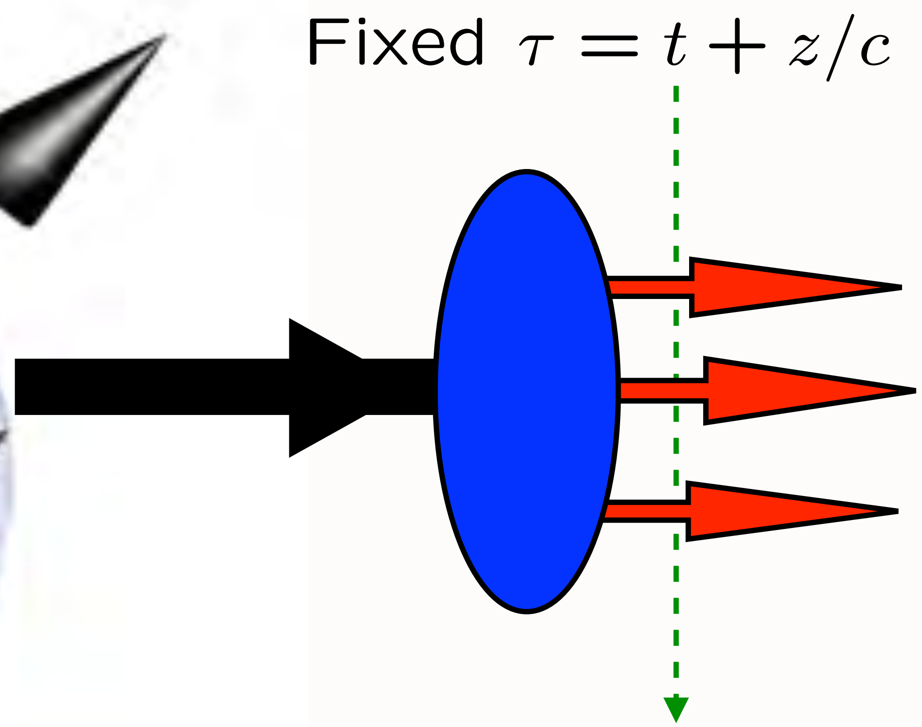
- Anti-Shadowing is Universal
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- heavy quarks only from gluon splitting
- renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- Infrared Slavery
- Nuclei are composites of nucleons only
- Real part of DVCS arbitrary

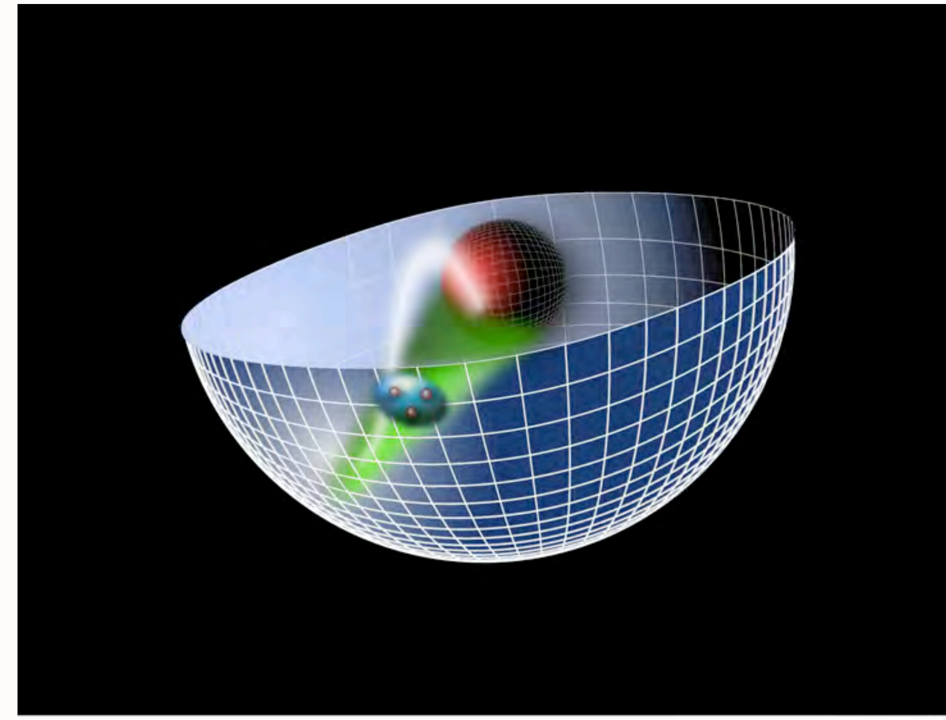
Goal: Predict Hadron Properties from First Principles!



Novel QCD Phenomena







Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Leland Stanford Junior University · Die Luft der Freiheit weht · 1891

ÖAW Österreichische Akademie der Wissenschaften

HEPHY Institut für Hochenergiephysik

October 30, 2012

HEPHY-SMI seminar on fundamental interactions and symmetries

Veranstalter: Verein zur Förderung der Theoretischen Physik in Österreich

Gefördert durch die Wissenschafts- und Forschungsförderung der Kulturabteilung der Stadt Wien