LUND
UNIVERSITY

Vetenskapsrådet

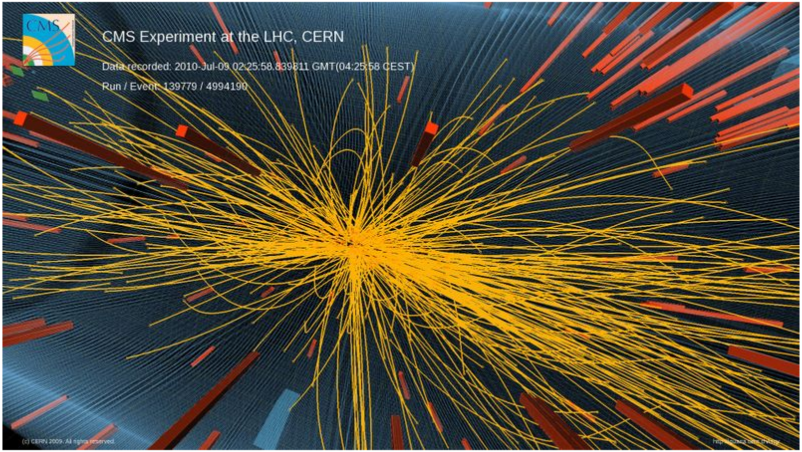
Soft Physics at the LHC: Insights and Challenges

Torbjörn Sjöstrand

Department of Astronomy and Theoretical Physics
Lund University
Sölvegatan 14A, SE-223 62 Lund, Sweden

Wien, 18 March 2014

Event topologies

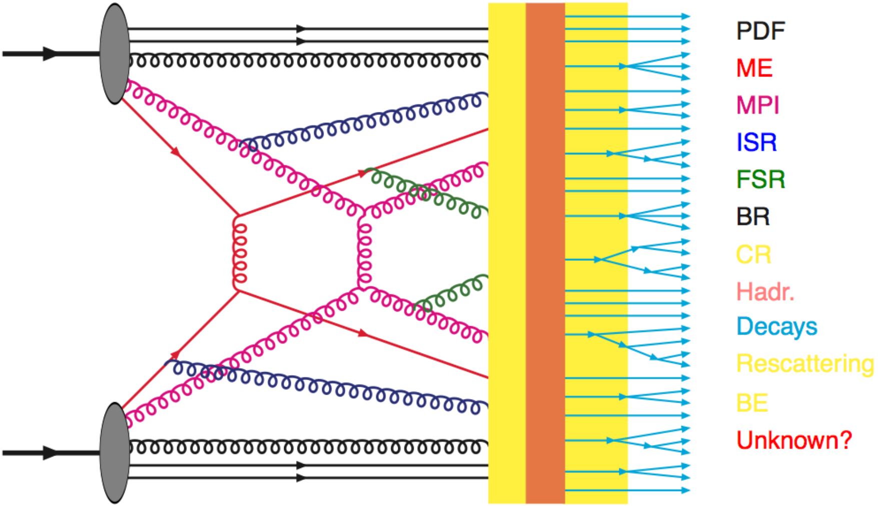


Expect and observe high multiplicities at the LHC.

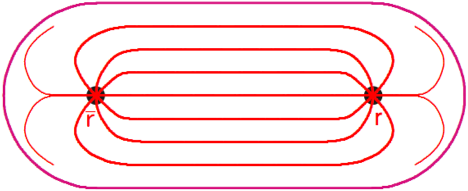
What are production mechanisms behind this?

The structure of an event

An event consists of many different physics steps, which have to be modelled by event generators:

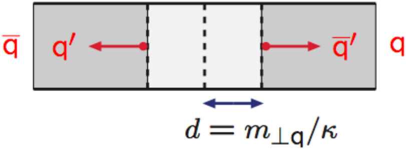


Hadronization: the Lund string model



Field lines compressed to tubelike regions: **strings**!
Linear confinement:
$V(r) \approx \kappa r$, $\kappa \approx 1$ GeV/fm
Lorentz invariant.

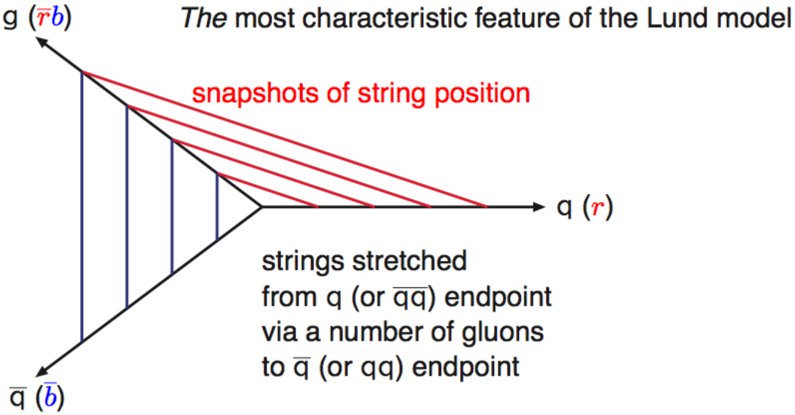
String breaking by tunneling:
$\mathcal{P} \propto \exp(-\pi m_{\perp q}^2/\kappa)$
with adjacent pairs forming mesons (and baryons).



- $\mathrm{d}n/\mathrm{d}y \approx 1$ flat, but with short-range (anti)correlations.
- Common Gaussian $p_\perp$ spectrum.
- Varied hadron production, with suppression of heavy quarks, and short-range flavour (anti)correlations.

Generally supported by LEP, but some unresolved flavour issues.

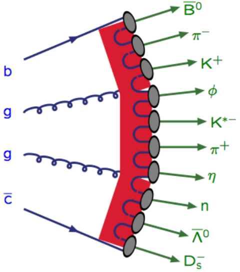
Hadronization: the Lund gluon picture

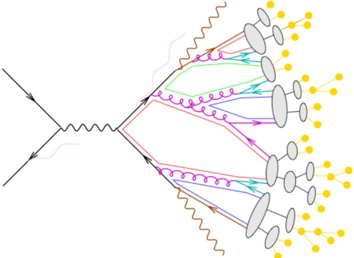


A gluon = an energy–momentum-carrying kink on the string.
Force ratio g/q = 2, cf. QCD $N_C/C_F = 9/4$, $\to 2$ for $N_C \to \infty$.
No new parameters introduced for gluon jet hadronization!

Predicted for & discovered at PETRA, verified at LEP!

Hadronization: string vs. cluster





program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
(space-time picture)	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	in-between	in-between
parameters	many	few(er)

Overall, string model unsurpassed, $>$ 30 years later (alas!)

Terminology for pp collisions

$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{elastic}} + \sigma_{\mathrm{single-diff}} + \sigma_{\mathrm{double-diff}} + \cdots + \sigma_{\mathrm{non-diff}}$

Minimum Bias (MB) $\approx$ “all events, with no bias from restricted trigger conditions”.

Experiment: $\sigma_{\mathrm{min-bias}} \approx \sigma_{\mathrm{non-diff}} + \sigma_{\mathrm{double-diffractive}} \approx 2/3 \times \sigma_{\mathrm{tot}}$

Theory (here): $\sigma_{\mathrm{min-bias}} \approx \sigma_{\mathrm{non-diff}}$

Underlying Event (UE): particles in an event with a hard process, but not originating from the process as such.

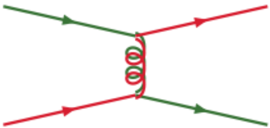
Pedestal effect: the UE contains more activity than a normal MB event does (even discarding diffractive events).

Trigger bias: a jet "trigger" criterion $E_{\perp\mathrm{jet}} > E_{\perp\mathrm{min}}$ is more easily fulfilled in events with upwards-fluctuating UE activity, since the UE $E_{\perp}$ in the jet cone counts towards the $E_{\perp\mathrm{jet}}$. *Not enough!*

Pileup: several pp collisions in a bunch crossing; separate issue.

The divergence of the QCD cross section

Cross section for $2 \to 2$ interactions is dominated by t-channel gluon exchange, so diverges like $\mathrm{d}\hat{\sigma}/\mathrm{d}p_{\perp}^2 \approx 1/p_{\perp}^4$ for $p_{\perp} \to 0$.



Integrate QCD $2 \to 2$

$\mathrm{qq}' \to \mathrm{qq}'$

$\mathrm{q\overline{q}} \to \mathrm{q}'\overline{\mathrm{q}}'$

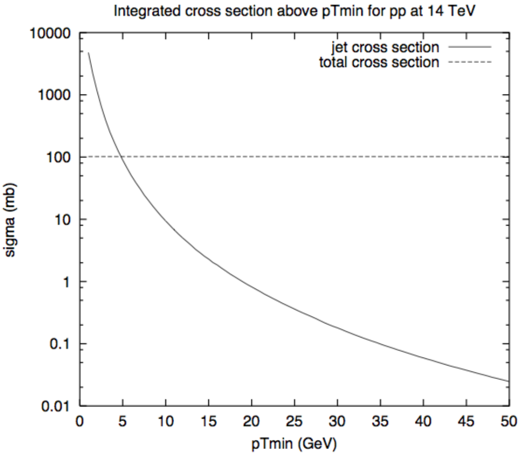
$\mathrm{q\overline{q}} \to \mathrm{gg}$

$\mathrm{qg} \to \mathrm{qg}$

$\mathrm{gg} \to \mathrm{gg}$

$\mathrm{gg} \to \mathrm{q\overline{q}}$

(with CTEQ 5L PDF's)



Multiple Partonic Interactions (MPI)

Note that $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}})$, the number of ($2 \to 2$ QCD) interactions above $p_{\perp\mathrm{min}}$, involves integral over PDFs,

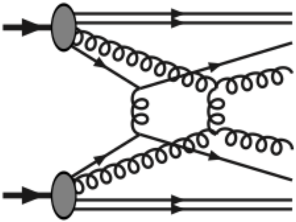
$$\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) = \iiint_{p_{\perp\mathrm{min}}} \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}p_\perp^2\, f_1(x_1, p_\perp^2)\, f_2(x_2, p_\perp^2)\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2}$$

with $\int \mathrm{d}x\, f(x, p_\perp^2) = \infty$, i.e. infinitely many partons.

So half a solution to $\sigma_{\mathrm{int}}(p_{\perp\mathrm{min}}) > \sigma_{\mathrm{tot}}$ is

many interactions per event: MPI (historically MI or MPPI)

$$\begin{aligned} \sigma_{\mathrm{tot}} &= \sum_{n=0}^{\infty} \sigma_n \\ \sigma_{\mathrm{int}} &= \sum_{n=0}^{\infty} n\, \sigma_n \\ \sigma_{\mathrm{int}} &> \sigma_{\mathrm{tot}} \iff \langle n \rangle > 1 \end{aligned}$$



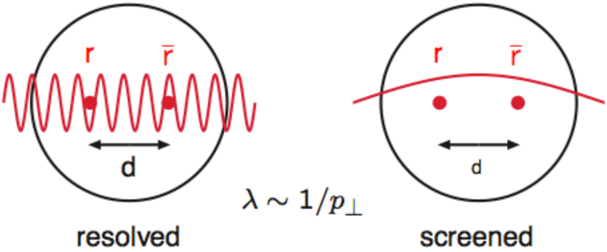
Colour screening

Other half of solution is that perturbative QCD is not valid at small $p_\perp$ since q, g are not asymptotic states (confinement!).

Naively breakdown at

$$p_{\perp\mathrm{min}} \simeq \frac{\hbar}{r_\mathrm{p}} \approx \frac{0.2\ \mathrm{GeV} \cdot \mathrm{fm}}{0.7\ \mathrm{fm}} \approx 0.3\ \mathrm{GeV} \simeq \Lambda_\mathrm{QCD}$$

. . . but better replace r_p by (unknown) colour screening length d in hadron:

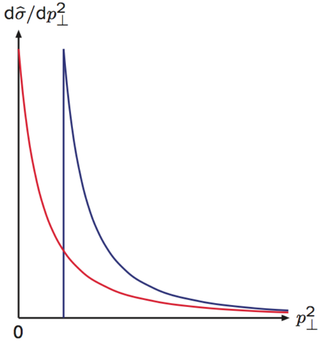


Regularization of low-$p_\perp$ divergence

so need $\boxed{\textbf{nonperturbative regularization for } p_\perp \to 0}$, e.g.

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4} \quad \to \quad \frac{\alpha_s^2(p_\perp^2)}{p_\perp^4}\,\theta\left(p_\perp - p_{\perp\min}\right) \qquad \text{(simpler)}$$

$$\text{or} \quad \to \quad \frac{\alpha_s^2(p_{\perp 0}^2 + p_\perp^2)}{(p_{\perp 0}^2 + p_\perp^2)^2} \qquad \text{(more physical)}$$

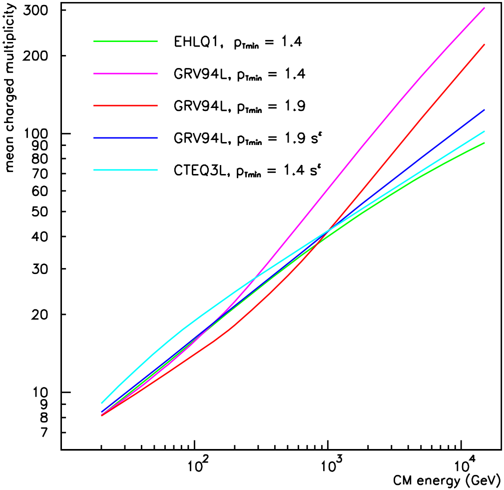


where $p_{\perp\min}$ or $p_{\perp 0}$ are free parameters, empirically of order **2 GeV**.

Typically 2 – 3 interactions/event at the Tevatron, 4 – 5 at the LHC, but may be more in "interesting" high-$p_\perp$ ones.

Energy dependence of $p_{\perp\min}$ and $p_{\perp 0}$

HERA PDF data, with steeper small-x rise, introduced need for energy-dependent $p_{\perp\min}$ and $p_{\perp 0}$:



Larger collision energy
$\Rightarrow$ probe parton ($\approx$ gluon) density at smaller x
$\Rightarrow$ smaller colour screening length d
$\Rightarrow$ larger $p_{\perp\min}/p_{\perp 0}$
$\Rightarrow$ dampened multiplicity rise

$p_{\perp 0} \propto s^{\epsilon}, \epsilon \approx 0.08$ in DL tune to σ_{tot}

Indirect evidence for MPI – 1

without MPI:

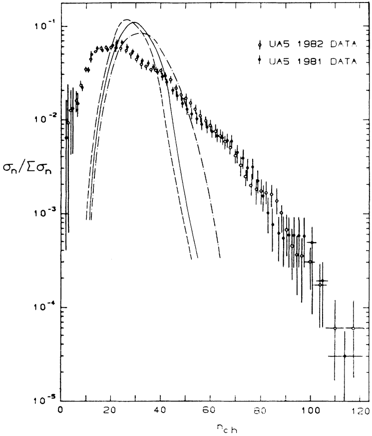


FIG. 3. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs simple models: dashed low p_T only, full including hard scatterings, dash-dotted also including initial- and final-state radiation.

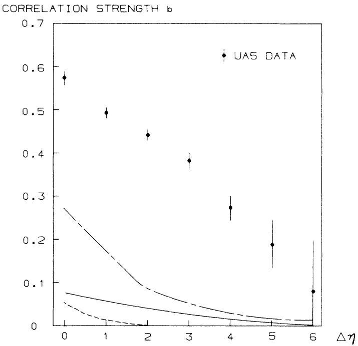


FIG. 4. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs simple models; the latter models with notation as in Fig. 3.

(TS & M. van Zijl, 1987)

Indirect evidence for MPI – 2

with MPI included:

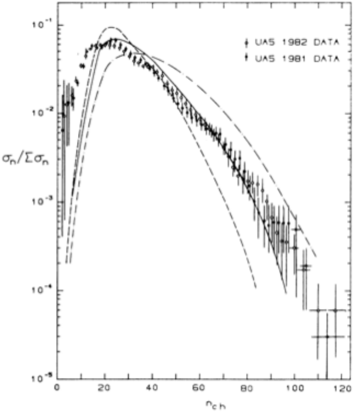


FIG. 5. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs impact-parameter-independent multiple-interaction model: dashed line, $p_{T\min}=2.0$ GeV; solid line, $p_{T\min}=1.6$ GeV; dashed-dotted line, $p_{T\min}=1.2$ GeV.

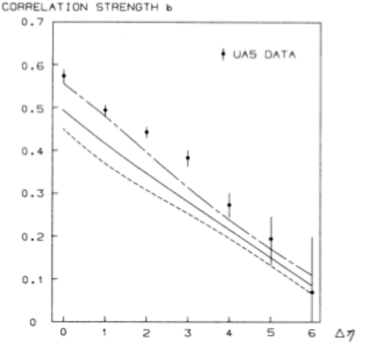
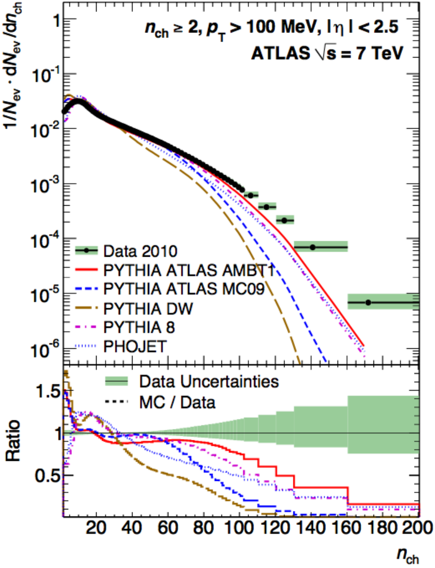


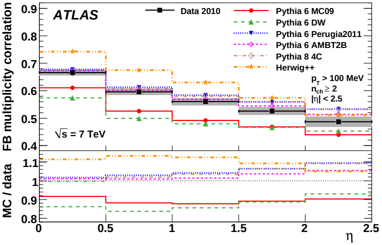
FIG. 6. Forward-backward multiplicity correlation at 540 GeV, UA5 results (Ref. 33) vs impact-parameter-independent multiple-interaction model; the latter with notation as in Fig. 5.

(TS & M. van Zijl, 1987)

Indirect evidence for MPI – 3



At the LHC:
Need fine-tuning of MPI,
but without it *way* off



MPI and event generators

All modern general-purpose generators are built on MPI concepts.

but details differ, both physics and technology, e.g.

- a single regularized hard component
  or separate hard + soft components
- multiparton PDFs
- MPIs generated ordered in $p_\perp$ or not
- MPIs before ISR+FSR, after ISR+FSR, or interleaved
- energy/momentum/flavour conservation
- impact-parameter profile
- energy dependence, e.g. of $p_{\perp 0}$
- beam-remnant structure
- colour connection & reconnection strategies
- other collective effects: ropes, QGP, flow, BE
- ...

Will concentrate on PYTHIA 8 in the following.

Basic generation of MPI

- Differential probability for interaction at $p_\perp$ is

$$\frac{\mathrm{d}P}{\mathrm{d}p_\perp} = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp}$$

  considering nondiffractive events only.

- Apply to sequence of decreasing $p_{\perp 1} > p_{\perp 2} > p_{\perp 3} > \ldots$

$$\mathcal{P}(p_\perp = p_{\perp i}) = \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} \exp\left[- \int_{p_\perp}^{p_{\perp(i-1)}} \frac{1}{\sigma_{\mathrm{nd}}} \frac{\mathrm{d}\sigma}{\mathrm{d}p'_\perp} \mathrm{d}p'_\perp \right]$$

  starting from $\mathrm{p}_{\perp\mathrm{max}} = E_{\mathrm{cm}}/2$,
  and including "Sudakov" factor (cf. radioactive decay).

- Use rescaled PDF's taking into account
  already used momentum and flavours.

- Require ≥ 1 interaction in an event
  or else pass through without anything happening.

Interleaved evolution

- Transverse-momentum-ordered parton showers for ISR and FSR.
- MPI also ordered in $p_\perp$.

$\Rightarrow$ Allows interleaved evolution for ISR, FSR and MPI:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p_\perp} \right) \times \exp\left(- \int_{p_\perp}^{p_{\perp\mathrm{max}}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MPI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{FSR}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

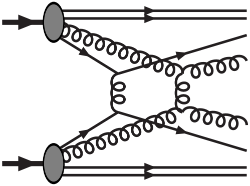
Ordered in decreasing $p_\perp$ using "Sudakov" trick.

Corresponds to increasing "resolution":
smaller $p_\perp$ fill in details of basic picture set at larger $p_\perp$.

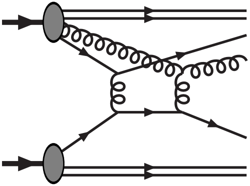
- Start from fixed hard interaction $\Rightarrow$ underlying event
- No separate hard interaction $\Rightarrow$ minbias events
- Possible to choose two hard interactions, e.g. $\mathrm{W}^-\mathrm{W}^-$

Rescattering

Often assume that MPI =



. . . but should also include



Same order in α_{s}, $\sim$ same propagators, but

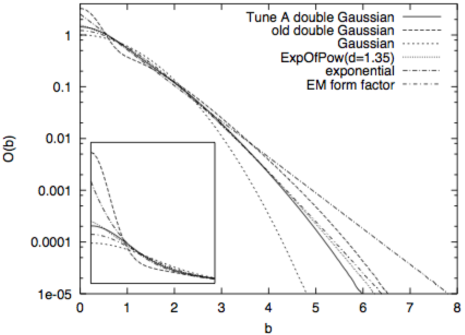
- one PDF weight less $\Rightarrow$ smaller σ
- one jet less $\Rightarrow$ QCD radiation background $2 \to 3$ larger than $2 \to 4$

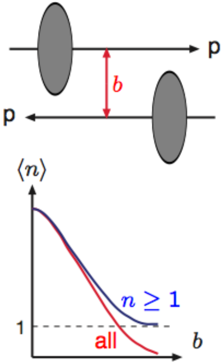
$\Rightarrow$ will be tough to find direct evidence.

Rescattering grows with number of “previous” scatterings:

	Tevatron		LHC	
	Min Bias	QCD Jets	Min Bias	QCD Jets
Normal scattering	2.81	5.09	5.19	12.19
Single rescatterings	0.41	1.32	1.03	4.10
Double rescatterings	0.01	0.04	0.03	0.15

Impact parameter dependence





- Events are distributed in impact parameter b

$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\;\rho_{1,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)\rho_{2,\mathrm{matter}}^{\mathrm{boosted}}(\mathbf{x},t)$$

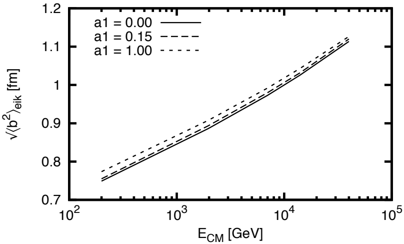
- Average activity at b proportional to $\mathcal{O}(b)$
  - ⋆ central collisions more active $\Rightarrow$ $\mathcal{P}_n$ broader than Poissonian
  - ⋆ peripheral passages normally give no collisions $\Rightarrow$ finite σ_{tot}

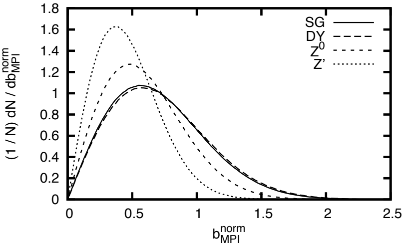
An x-dependent proton size

Reasonable to assume that low-x partons are more spread out:

$$\rho(r,x) \propto \frac{1}{a^3(x)} \exp\left(-\frac{r^2}{a^2(x)}\right) \quad \text{with} \quad a(x) = a_0 \left(1 + a_1 \ln \frac{1}{x}\right)$$

$a_1 \approx 0.15$ tuned to **rise** of σ_{ND}
a_0 tuned to **value** of σ_{ND}, given PDF, $p_{\perp 0}$, ...

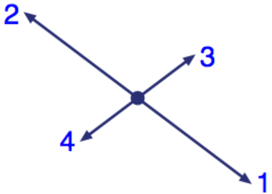




Consequence: collisions at large x will have to happen at small b, and hence further large-to-medium-x MPIs are enhanced.
$a_1 > 0$ not favoured by tunes so far!

Basic idea for direct observation goes back to AFS (1987):
Order 4 jets $\mathbf{p}_{\perp 1} > \mathbf{p}_{\perp 2} > \mathbf{p}_{\perp 3} > \mathbf{p}_{\perp 4}$ and define φ
as angle between $\mathbf{p}_{\perp 1} \mp \mathbf{p}_{\perp 2}$ and $\mathbf{p}_{\perp 3} \mp \mathbf{p}_{\perp 4}$ for AFS/CDF

Double Parton Scattering



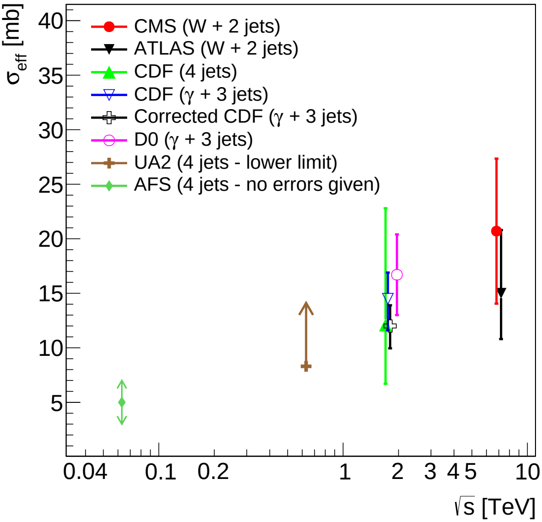
$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \approx 0$
$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \approx 0$
$\mathrm{d}\sigma/\mathrm{d}\varphi$ flat

Double BremsStrahlung

$|\mathbf{p}_{\perp 1} + \mathbf{p}_{\perp 2}| \gg 0$
$|\mathbf{p}_{\perp 3} + \mathbf{p}_{\perp 4}| \gg 0$
$\mathrm{d}\sigma/\mathrm{d}\varphi$ peaked at $\varphi \approx 0/\pi$ for AFS/CDF

Later extended to $\gamma + 3$ jet, $\mathrm{W} + 2$ jet.

Direct observation of MPI – 2



$$\sigma_{a+b} = \frac{1}{1+\delta_{ab}} \frac{\sigma_a \, \sigma_b}{\sigma_{\mathrm{eff}}}$$

with Kronecker δ for identical processes.

$f = \sigma_{nd}/\sigma_{\mathrm{eff}} > 1$ from impact parameter.

Beware of experimental issues!

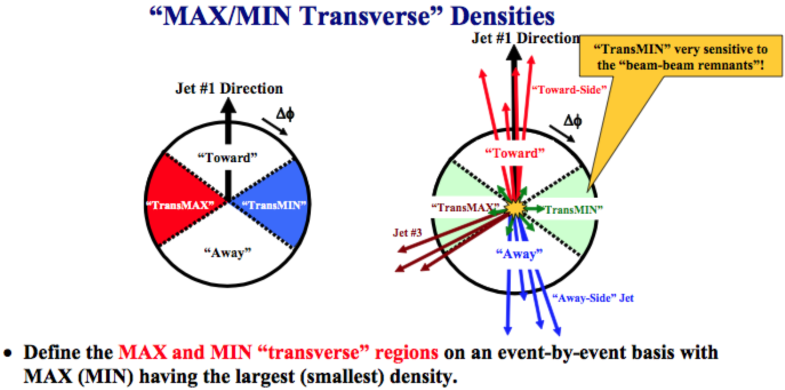
Interpretation not as trivial as it seems!

(> 2 MPI, x dependence, ...)

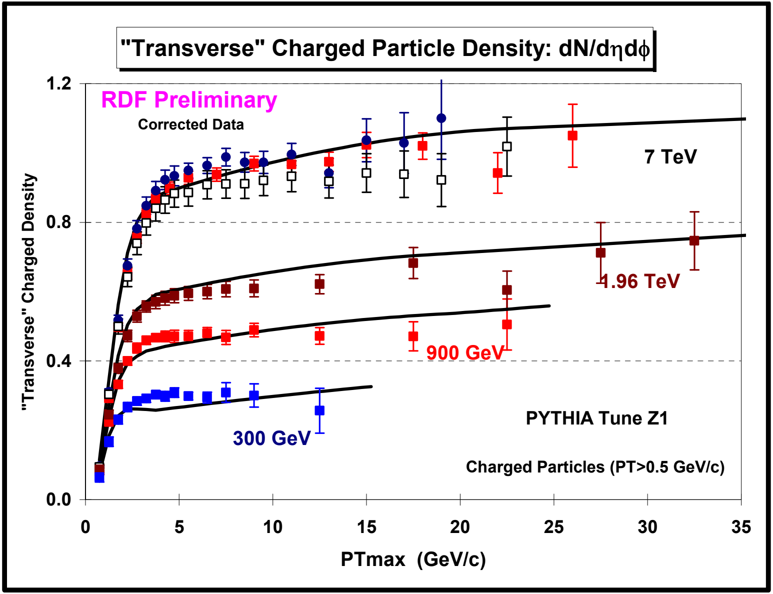
Jet pedestal effect – 1

Events with hard scale (jet, W/Z) have more underlying activity!
Events with n interactions have n chances that one of them is hard, so "trigger bias": hard scale $\Rightarrow$ central collision
$\Rightarrow$ more interactions $\Rightarrow$ larger underlying activity.

Studied in particular by Rick Field, with CDF/CMS data:

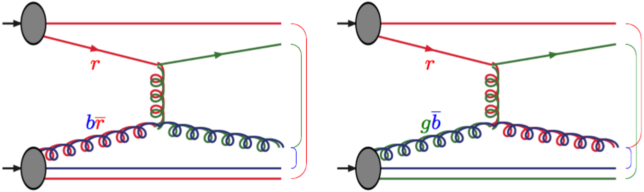


Jet pedestal effect – 2

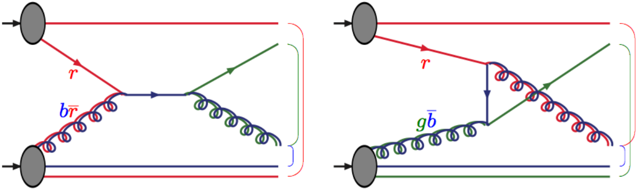


Colour flow in hard processes

One Feynman graph can correspond to several allowed colour flows, corresponding to different string drawings, e.g. for $\mathrm{qg} \to \mathrm{qg}$:

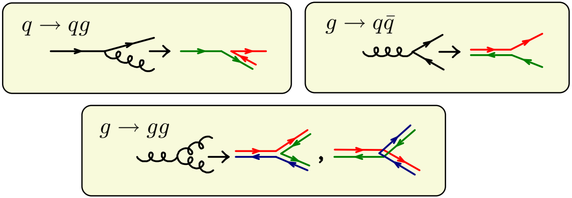


while other $\mathrm{qg} \to \mathrm{qg}$ graphs only admit one colour flow:

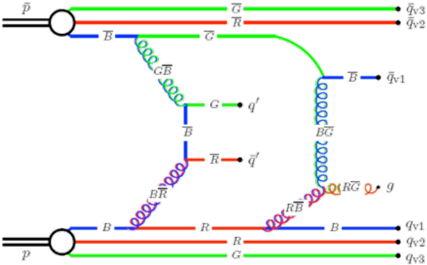


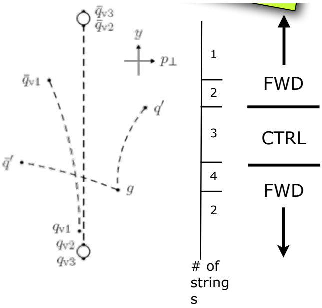
Interference term suppressed $\propto 1/(N_C^2 - 1)$,
so split cross section in proportions given by $N_C \to \infty$ limit.

Also parton showers conveniently traced in $N_C \to \infty$ limit.



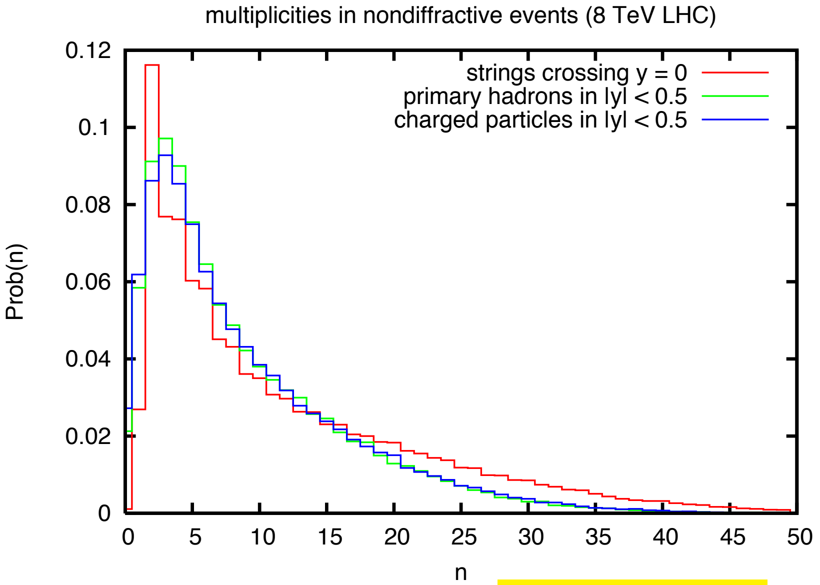
But hooking it all up at beam remnants relies on $N_C = 3$:





Sjöstrand & PS, JHEP 03(2004)053

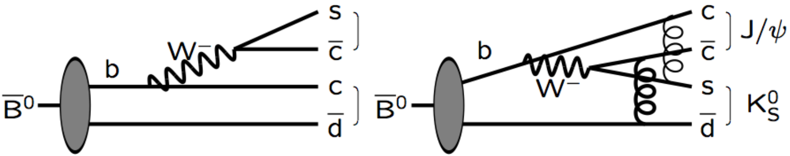
The Density of particle production



String width $\sim$ hadronic width $\Rightarrow$ Overlap factor $\sim$ 10!

Reconnection in B decays

Colour operators in B decay $\Rightarrow$ some η_c:
A. Ali, J.G. Körner, G. Kramer, J. Willrodt, Z. Phys. **C1** (1979) 269

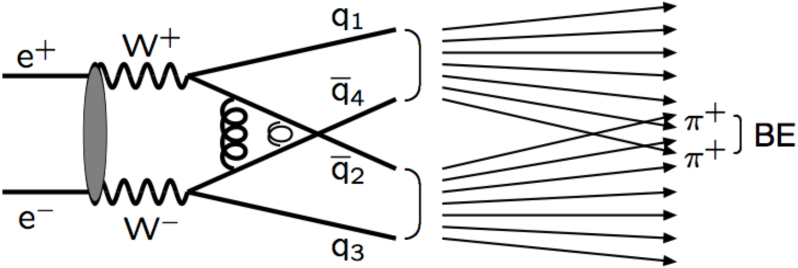


$\mathrm{B} \to \mathrm{J}/\psi \to \mu^+\mu^-$ good way to find B mesons:
H. Fritzsch, Phys. Lett. **B86** (1979) 164, 343
. . . soon confirmed by experiment

$\mathrm{g}^* \to \mathrm{c}\bar{\mathrm{c}} \to \mathrm{J}/\psi$ production mechanism in pp ("colour octet")
H. Fritzsch, Phys. Lett. **B67** (1977) 217
more complicated to test (at the time, later "confirmed")

Interconnection at LEP 2

$\mathrm{e^+e^- \to W^+W^- \to q_1\overline{q}_2\, q_3\overline{q}_4}$ reconnection limits m_{W} precision!



- perturbative $\langle \delta M_{\mathrm{W}} \rangle \lesssim 5$ MeV : negligible!
  (killed by dampening from off-shell W propagators)
- nonperturbative $\langle \delta M_{\mathrm{W}} \rangle \sim 40$ MeV : inconclusive.
  (but more extreme models from other authors ruled out)
- Bose-Einstein $\langle \delta M_{\mathrm{W}} \rangle \lesssim 100$ MeV : full effect ruled out.
  (but models with ~ 40 MeV barely acceptabe)

V.A. Khoze & TS, PRL 72 (1994) 28; L. Lönnblad & TS, EPJ C6 (1999) 271

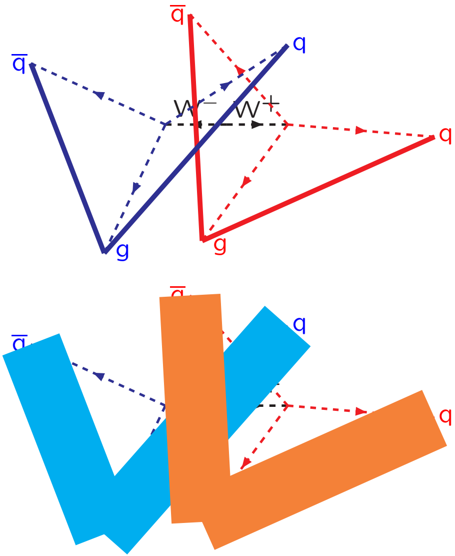
Colour rearrangement models for LEP 2

Colour rearrangement studied in several models, e.g.

Scenario II: vortex lines.
Analogy: type II superconductor.
Strings can reconnect only if central cores cross.

Scenario I: elongated bags.
Analogy: type I superconductor.
Reconnection proportional to space–time overlap.

In both cases favour reconnections that reduce total string length.



(schematic only; nothing to scale)

T.S. and M. van Zijl,
Phys.Rev. **D36** (1987) 2019

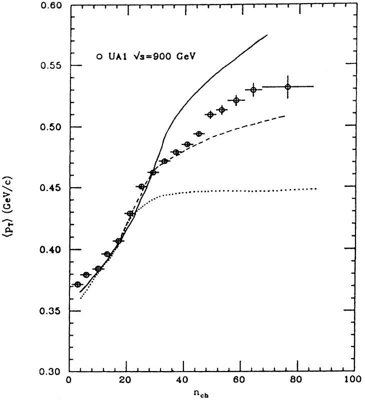
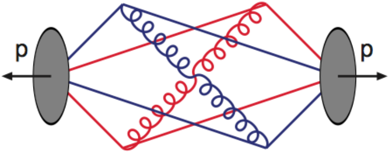
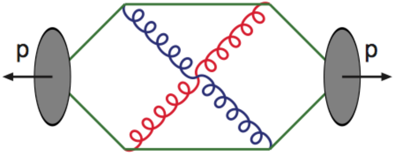


FIG. 27. Average transverse momentum of charged particles in $|\eta|<2.5$ as a function of the multiplicity. UA1 data points (Ref. 49) at 900 GeV compared with the model for different assumptions about the nature of the subsequent (nonhardest) interactions. Dashed line, assuming $q\bar{q}$ scatterings only; dotted line, gg scatterings with "maximal" string length; solid line gg scatterings with "minimal" string length.

$\langle p_\perp \rangle(n_{\mathrm{ch}})$ sensitive to colour flow.



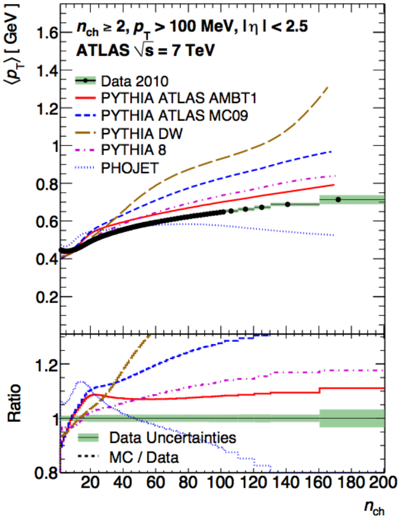
long strings to remnants
$\Rightarrow$ comparable n_{ch}/interaction
$\Rightarrow \langle p_\perp \rangle(n_{\mathrm{ch}}) \sim$ flat.

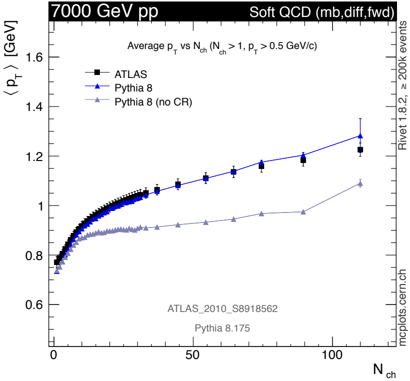


shorter extra strings
for each consecutive interaction
$\Rightarrow \langle p_\perp \rangle(n_{\mathrm{ch}})$ rising.

Reconnection at the LHC

$\langle p_\perp \rangle (n_{\mathrm{ch}})$ effect alive and kicking:





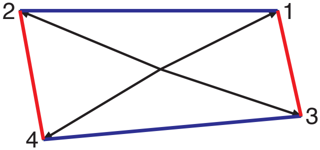
Reconnection important also for other generators, e.g. Herwig++

Colour rearrangement models for the LHC

Space–time models too complicated
$\Rightarrow$ simplified (in PYTHIA)

Common aspect: reduce string length
$\lambda = \sum \ln(m_{ij}^2/m_0^2) \sim$ multiplicity

Ingelman, Rathsman: reduce $\sum m_{ij}^2$;
Generalized Area Law



In total 12 scenarios in PYTHIA 6, mainly annealing:

- $P_{\mathrm{reconnect}} = 1 - (1 - \chi)^{n_{\mathrm{MPI}}}$ with χ strength parameter.
- Random assignment by $P_{\mathrm{reconnect}}$ for each string piece.
- Choose new combinations that reduce λ (with restrictions).

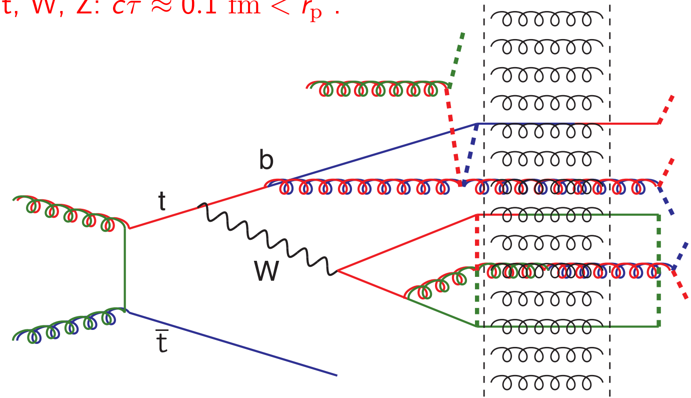
PYTHIA 8 still only primitive:
let each MPI either form a separate system, or attach its partons to a higher-$p_{\perp}$ MPI where it gives minimal λ increase.

Much room for improvement; work ongoing.

The Mass of Unstable Coloured Particles

MC: close to pole mass, in the sense of Breit–Wigner mass peak.

t, W, Z: $c\tau \approx 0.1\ \mathrm{fm} < r_\mathrm{p}$.



At the Tevatron: $m_\mathrm{t} = 173.20 \pm 0.51 \pm 0.71$ GeV $=$ `PMAS(6,1)`

At the LHC (CMS): $m_\mathrm{t} = 173.54 \pm 0.33 \pm 0.96$ GeV $=$ `6:m0` ?

Now severely limited by colour reconnection uncertainty

Top mass shift in Pythia 6

Studies for the Tevatron.

Green bands: old virtuality-ordered showers.

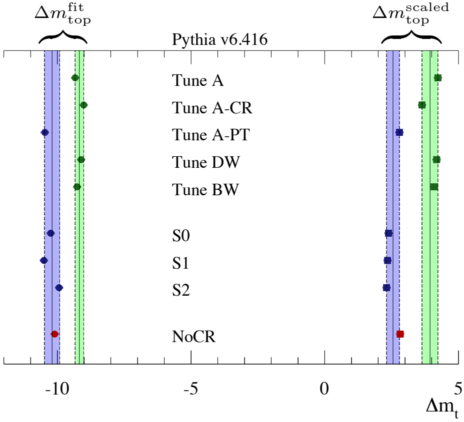
Blue bands: new $p_\perp$-ordered showers.

In total ± 1.0 GeV,

whereof ± 0.7 GeV perturbative,

and ± 0.5 GeV nonperturbative.

Fit $\rightarrow$ scaled: Jet Energy Scaling.



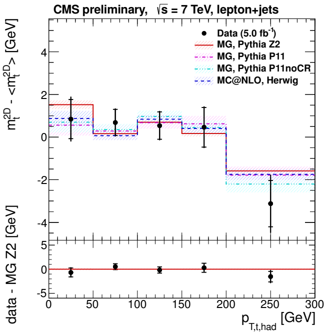
(M.Sandhoff and P.Z Skands, FERMILAB-CONF-05-518-T;)
D. Wicke and P.Z. Skands, EPJ C52 (2007) 133, Nuovo Cim. B123 (2008) S1

Kinematics dependence of mass determinations

Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-12-029

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b-quark kin.	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$



NEW

- *First top mass measurement binned in kinematic observables.*
- Additional validation for the top mass measurements.
- With the current precision, no mis-modelling effect due to
  - color reconnection, ISR/FSR, b-quark kinematics, difference between pole or MS~ masses.

E. Yazgan

(Moriond 2013)

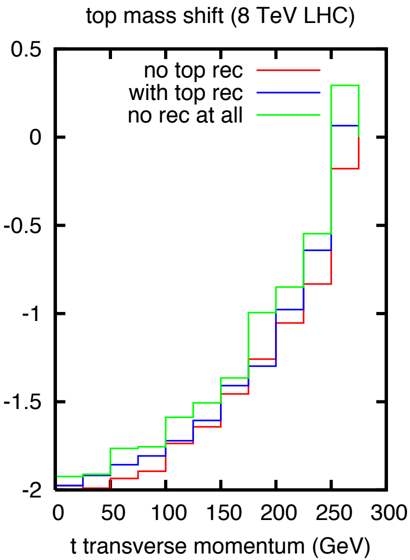
1(

Top mass shift in PYTHIA 8

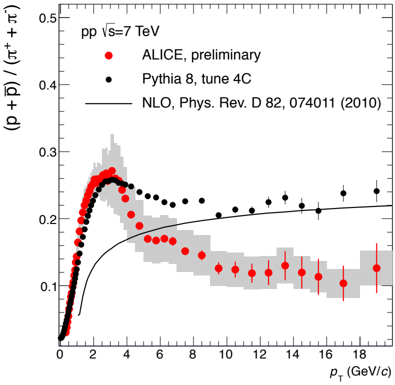
- Semileptonic top decay.
- Find jets with anti-$k_\perp$, $R = 0.5$, $p_{\perp\mathrm{min}} = 20$ GeV.
- Request $n_{\mathrm{jet}} \geq 4$.
- Find two jets closest to m_{W}.
- Kill if $|m_{12} - m_{\mathrm{W}}| > 5$ GeV.
- Find third jet closest to m_{t}.
- Kill if $|m_{123} - m_{\mathrm{t}}| > 20$ GeV.

t/W decay after → before CR:
$\langle \delta n_{\mathrm{ch}} \rangle = -0.26 \pm 0.09$
$\langle \delta m_{\mathrm{t}} \rangle = +0.060 \pm 0.020$ GeV

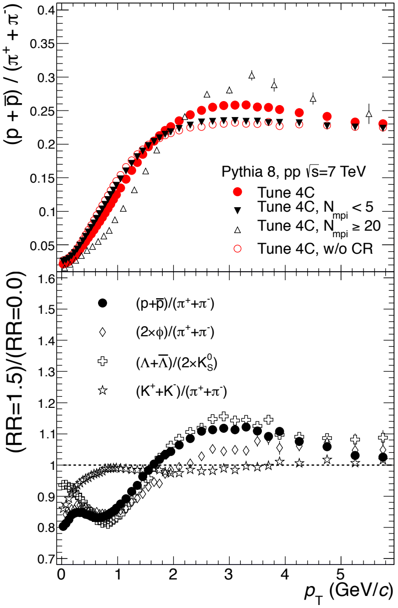
t/W decay after → no CR:
$\langle \delta n_{\mathrm{ch}} \rangle = +36.44 \pm 0.09$
$\langle \delta m_{\mathrm{t}} \rangle = +0.149 \pm 0.020$ GeV



Transverse boosts $\Rightarrow$
$\sim$ collective particle vecocity.
More common with reconnection.



A. Ortiz Velasquez et al.,
Phys. Rev. Lett. 111 (2013) 042001



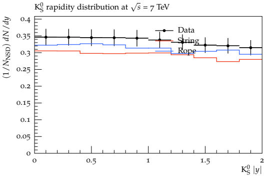
Ongoing work

P. Skands, J. Christiansen, (TS): colour wavefunction of incoming partons for $N_C = 3$ gives new connection model, as start for reconnection

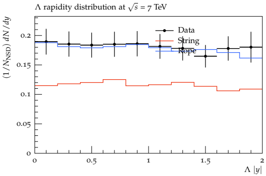
S. Argyropoulos, TS: worst-case scenarios for top mass

C. Bierlich, G. Gustafson, L. Lönnblad: DIPSY contains space–time dipole picture, colour ropes in high-density regions, higher string tension gives more strangeness and baryons:

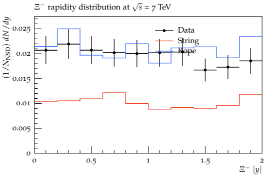
K $dn/d\eta$



Λ $dn/d\eta$

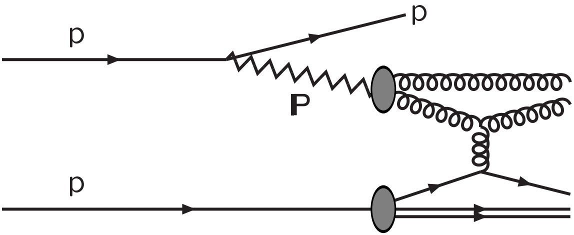


Ξ $dn/d\eta$



Diffraction

Ingelman-Schlein: Pomeron as hadron with partonic content
Diffractive event = (Pomeron flux) $\times$ ($\mathbb{P}$p collision)



Used e.g. in
POMPYT
POMWIG
PHOJET

1) σ_{SD} and σ_{DD} taken from existing parametrization or set by user.

2) $f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}}, t) \Rightarrow$ diffractive mass spectrum, $p_{\perp}$ of proton out.

3) Smooth transition from simple model at low masses to $\mathbb{P}$p with full pp machinery: multiple interactions, parton showers, etc.

4) Choice between 5 Pomeron PDFs, incl. Min Bias Rockefeller.

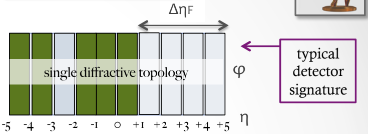
5) Free parameter $\sigma_{\mathbb{P}\mathrm{p}}$ needed to fix $\langle n_{\mathrm{interactions}} \rangle = \sigma_{\mathrm{jet}} / \sigma_{\mathbb{P}\mathrm{p}}$.

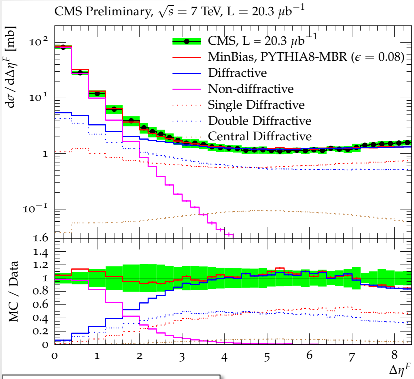
Diffraction data

σ_{inel} as a function of $\Delta\eta_F$

- non-diffractive events dominate at small gaps
- diffractive plateau observed for large gaps

$\Delta\eta_F$ = largest empty pseudorapidity interval, from edge of detector

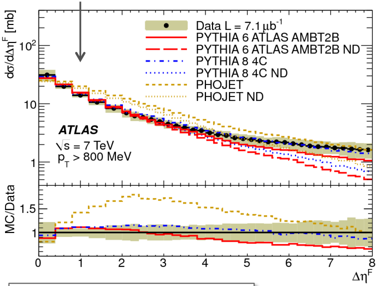




CMS Coll., PAS FSQ-12-005

PYTHIA8 models provide reasonable description

- increasing particle threshold requirement results in more ND events with large gaps; confirms that inclusive events are dominated by low p_T production



ATLAS Coll., EPJ C72 (2012) 1926

5

(C. Gwenlan, EPSHEP 2013)

Summary and Outlook

- Lund string still best hadronization description?
- MPI mechanism well established, with b dependence.
- Low-$p_\perp$ regularization by colour screening?
  Energy dependence related to low-x PDFs and σ_{tot} rise?
- Rescattering and x-dependent b profile marginal?
- Reconnection well established, from $\mathrm{B} \to \mathrm{J}/\psi$ to $\langle p_\perp \rangle (n_{\mathrm{ch}})$.
- No understanding of detailed mechanism!
  One step: better space–time picture & colour algebra?
- Missed chance for clean tests at LEP 2. TLEP ideal?
- Multitude of algorithms for PYTHIA 6 $\Rightarrow$ uncertainty band.
  More algorithms on the way!
- Predict (possibility of) significant effects on m_{t}.
- High string density may preclude any definitive answers?
  Or breakthrough from new precision differential data?

Let's aim for more than a flying circus . . .