PRECISION QCD FOR THE LHC: A MULTIFACETED APPROACH

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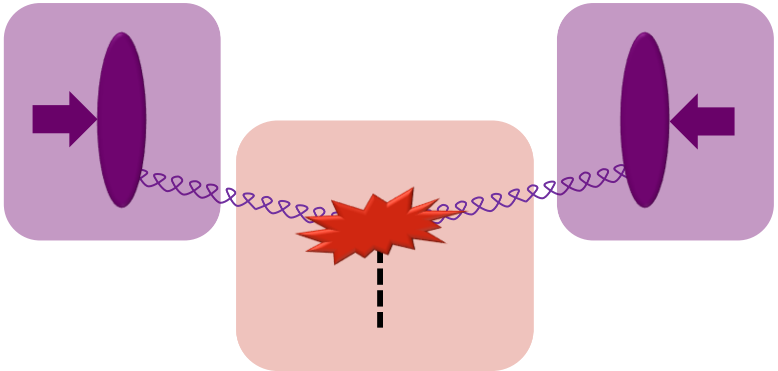
Vienna, 5th December 2019

FACTORISATION AT THE LHC

To maximise physics potential at LHC, need precise theory predictions – compare to precise measurements, conduct best possible 'stress-test' of Standard Model.

How do we make theory predictions at the LHC? Basic 'master formula':



$$\sigma_{pp\to H} = f_g(x) \otimes \hat{\sigma}_{gg\to H} \otimes f_g(x')$$

PDF | Short-distance cross section | PDF

COLLINEAR FACTORISATION FORMULA

RESUMMATION

Say one makes an additional measurement with associated scale $\mathcal{T} \ll Q$ (& $\mathcal{T} \gg \Lambda$). Then:

$$\sigma(\mathcal{T}) \simeq \sigma_{LO} \sum_m C_m \alpha_s^m \log^{2m}\left(\frac{Q}{\mathcal{T}}\right) + \cdots$$

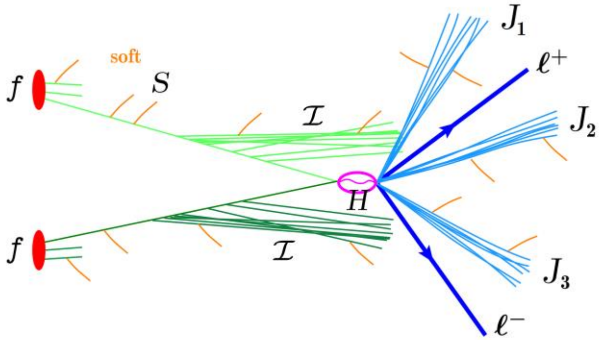
Can be $\mathcal{O}(1)$

For certain observables, we can write down a new factorisation formula that allows us to sum up these logarithms:

$$\frac{d\sigma}{d\mathcal{T}} = H \times [I_a \otimes I_b \otimes S \otimes J_1 \otimes \ldots \otimes J_n](\mathcal{T}) \otimes_{x_a} f_a \otimes_{x_b} f_b$$

PDFs

All of these perturbatively computable



HIGHER ORDERS AND PRECISION

One angle to improve precision: compute perturbative pieces in factorisation formulae to successively higher precision:

$$\sigma = f_a(x) \otimes \hat{\sigma} \otimes f_b(x') \qquad \hat{\sigma} = \hat{\sigma}^{(0)} + \alpha_s \hat{\sigma}^{(1)} + \alpha_s^2 \hat{\sigma}^{(2)} + \cdots$$

$$\frac{d\sigma}{d\mathcal{T}} = H \times [I_a \otimes I_b \otimes S \otimes J_1 \otimes \ldots \otimes J_n](\mathcal{T}) \otimes_{x_a} f_a \otimes_{x_b} f_b$$

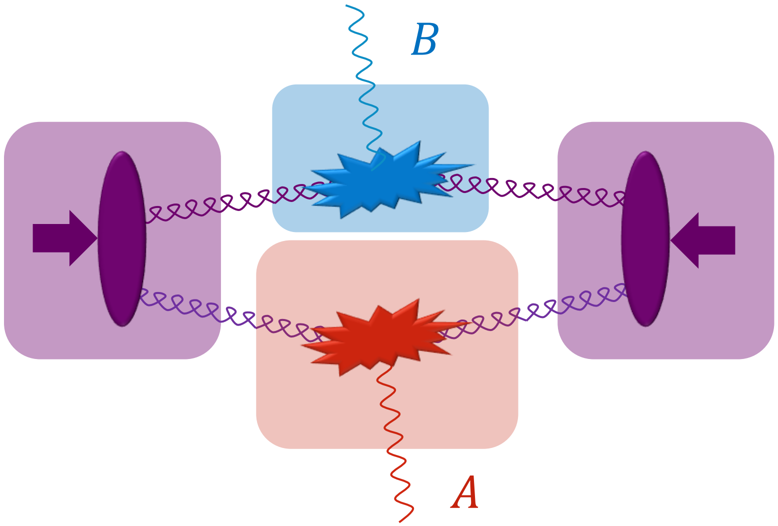
$$I = \mathbb{I} + \alpha_s I^{(1)} + \alpha_s^2 I^{(2)} + \cdots$$

However…the high precision being obtained on both the theoretical and experimental sides necessitates that we also examine the limitations of the existing factorisation paradigms, and compute effects beyond this where necessary.

POWER CORRECTIONS

One issue: factorisation formula is not exact:

$$\sigma = f_a(x) \otimes \hat{\sigma} \otimes \, f_b(x') \left[1 + \mathcal{O}\left({\Lambda^2_{\rm QCD}}/{Q^2} \right) \right]$$



If final state can be subdivided into two hard systems AB, one particularly important power correction is double parton scattering (DPS).

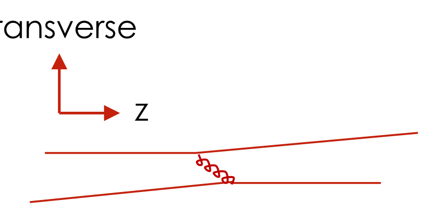
BREAKING OF FACTORISATION

Another issue: the factorisation formula is not always completely proven!

$$\frac{d\sigma}{d\mathcal{T}} \overset{?}{=} H \times [I_a \otimes I_b \otimes S \otimes J_1 \otimes \ldots \otimes J_n](\mathcal{T}) \otimes_{x_a} f_a \otimes_{x_b} f_b$$

In soft-collinear effective theory (SCET), proofs have been given for several cases, but under the assumption that soft, collinear, hard momentum regions are the only ones giving leading power contributions.

However there is another momentum region in QCD that is important: Glauber region.



Effect of Glauber exchanges, if uncancelled, can break factorisation! When does this happen, and why?

RESEARCH INTERESTS

Three main research interests, related to precision at hadron colliders:

I. High-precision Perturbative Computations (Fixed-order & Resummed)
II. Double Parton Scattering
III. Factorisation and Factorisation Breaking

I: HIGH-PRECISION PERTURBATIVE COMPUTATIONS

(FIXED-ORDER & RESUMMED)

PAST WORK

I've computed two-loop resummation ingredients (B, J, S) for various observables…

Virtuality-dependent beam function

JG, Stahlhofen, Tackmann, JHEP 1404 (2014) 113, JHEP 1408 (2014) 020

Double-differential virtuality + p_T dependent beam function

JG, Stahlhofen,, JHEP 1412 (2014) 146

Rapidity-dependent jet veto beam and soft functions

Gangal, JG, Stahlhofen, Tackmann, JHEP 1702 (2017) 026

…and been involved in the development of an NNLO subtraction technique for fixed-order computations ($\hat{\sigma}$) using these two-loop ingredients: the N-jettiness subtraction method.

JG, Stahlhofen, Tackmann, Walsh, JHEP 1509 (2015) 058

Many NNLO computations using this method, including first full computations of $Z + j$ and $W + j$.

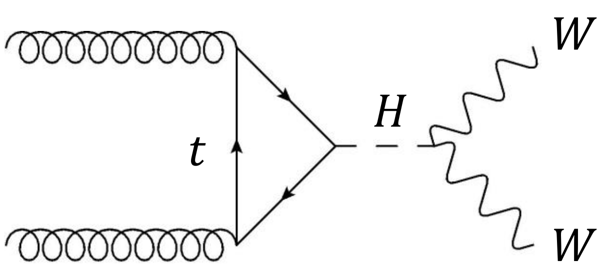
Boughezal, Liu, Petriello Phys.Rev.Lett. 115 (2015) no.6, 062002,
+ Campbell, Ellis, Focke, Giele, Phys.Rev.Lett. 116, 152001

JET VETOES

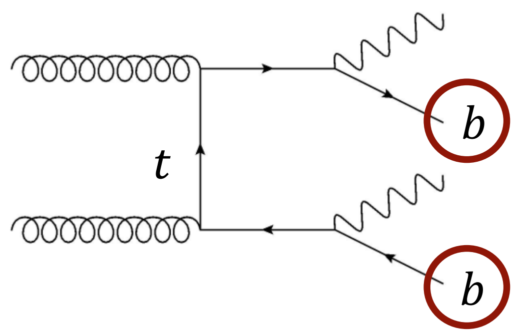
Let's look at the resummation for one particular observable in detail: rapidity dependent jet vetoes.

Jet vetoes: common tool at LHC to separate different hard processes, reduce backgrounds. Example: $H \to WW^* \to l\nu l\nu$

Signal:



Background:



Standard way of imposing a jet veto: using p_T of the jet. When $p_{T,j} \ll Q$, large logs of $p_{T,j}/Q$ that need to be summed.

RAPIDITY DEPENDENT JET VETOES

Instead of a plain p_T veto, can have a veto that depends smoothly on rapidity of jets:

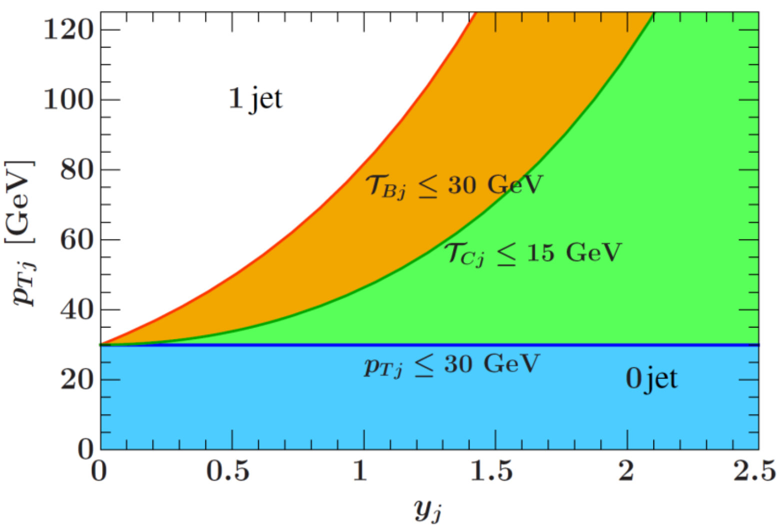
$m_{Tj} = \sqrt{p_{Tj}^2 + m_j^2} \approx p_{Tj}$ for small radius jets

$$\mathcal{T}_{Bcm,j} = m_{Tj} e^{-|y_j|} \qquad \mathcal{T}_{B,j} = m_{Tj} e^{-|y_j - Y|}$$

$$\mathcal{T}_{Ccm,j} = \frac{m_{Tj}}{2\cosh(y_j)} \qquad \mathcal{T}_{C,j} = \frac{m_{Tj}}{2\cosh(y_j - Y)}$$

Rapidity of jet w.r.t. centre of mass

Rapidity of jet w.r.t. hard system



Veto becomes more relaxed as one goes forward in rapidity

WHY USE RAPIDITY-DEPENDENT VETOES?

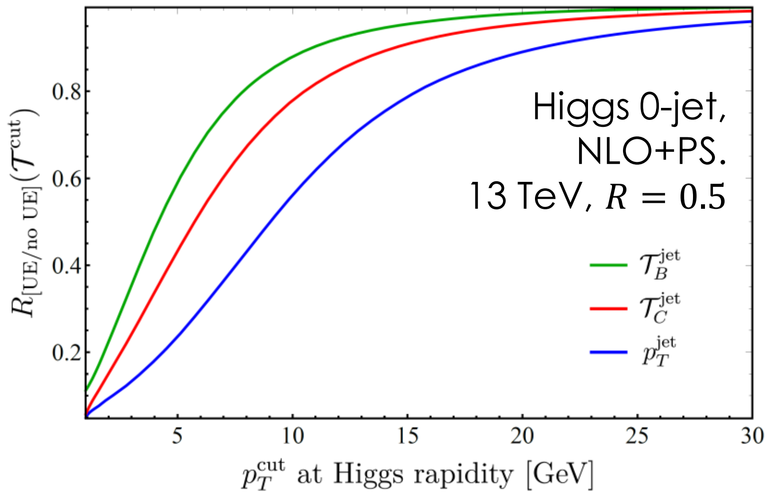
Why consider such alternative jet vetoes?

- In harsh pile-up conditions, hard to identify (and veto) low p_T jets at large rapidities. No tracking information at large $|\eta| \gtrsim 2.5$ → difficult to disentangle jets from pile-up jets at low p_T .

- Resummation structure very different. Technically: $\mathrm{SCET_I}$ observable rather than $\mathrm{SCET_{II}}$.

- Different way to divide cross section into jet bins.

- Sensitivity to underlying event effects is reduced.



Gangal, JG, Tackmann, Vryonidou, to appear

RESUMMATION BY FACTORISATION

Factorisation formula for 0-jet colour-singlet cross section (e.g. Higgs production), with jet veto imposed via $\mathcal{T}_{B,j}$ or $\mathcal{T}_{C,j}$:

Tackmann, Walsh, Zuberi, Phys.Rev. D86 (2012) 053011

$\log\left({}^{m_H}/_{\mu}\right)$ — Jet radius

$$\frac{d\sigma_0}{dY}(\mathcal{T} < \mathcal{T}^{cut}) = \sigma_B H_{gg}(m_t, m_H^2, \mu) B_g(m_H \mathcal{T}^{cut}, x_a, R, \mu) B_g(m_H \mathcal{T}^{cut}, x_b, R, \mu)$$
$$\times S_{gg}^{B,C}(\mathcal{T}^{cut}, R, \mu)$$

$\log\left({}^{\mathcal{T}^{cut}}/_{\mu}\right)$ $\log\left({}^{m_H \mathcal{T}^{cut}}/_{\mu}\right)$

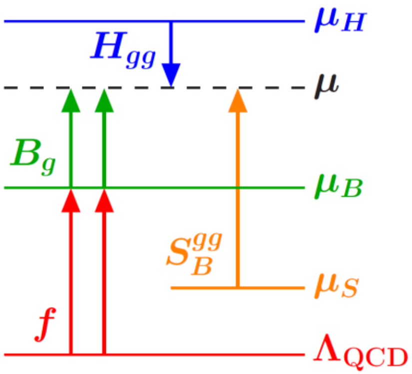
Resum logs in each piece using RGEs:

$\mu_H \sim m_H$

$$\frac{d\sigma_0}{dY}(\mathcal{T} < \mathcal{T}^{cut}) = \sigma_B H_{gg}(m_t, m_H^2, \mu_H) U_H(m_H, \mu_H, \mu)$$
$$\times B_g(m_H \mathcal{T}^{cut}, x_a, R, \mu_B) B_g(m_H \mathcal{T}^{cut}, x_b, R, \mu_B) U_B^2(m_H, \mu_B, \mu)$$
$$\times S_{gg}^{B,C}(\mathcal{T}^{cut}, R, \mu_S) U_S(\mu_S, \mu)$$

$\mu_B \sim m_H \mathcal{T}^{cut}$

$\mu_S \sim \mathcal{T}^{cut}$



LEVELS OF RESUMMATION PRECISION

$$\frac{d\sigma_0}{dY}(\mathcal{T} < \mathcal{T}^{cut}) = \sigma_B H_{gg}(m_t, m_H^2, \mu_H) U_H(m_H, \mu_H, \mu)$$
$$\times B_g(m_H \mathcal{T}^{cut}, x_a, R, \mu_B) B_g(m_H \mathcal{T}^{cut}, x_b, R, \mu_B) U_B^2(m_H, \mu_B, \mu)$$
$$\times S_{gg}^{B,C}(\mathcal{T}^{cut}, R, \mu_S) U_S(\mu_S, \mu)$$

GOAL: State-of-the-art NNLL' precision:

Resummation input (U)

	B, H, S	$\gamma_{H,B,S}$	Γ_{cusp}	β
NNLL'	NNLO	2-loop	3-loop	3-loop

✓ ✓

Must compute these via two-loop computations of B, S

TWO-LOOP RESUMMATION INGREDIENTS

Strategy for two-loop computation: compute difference from reference global measurement:

$$B_{\mathrm{jet}}(m_H \mathcal{T}^{cut}, x, R, \mu) = B_{\mathrm{G}}(m_H \mathcal{T}^{cut}, x, \mu) + \Delta B(m_H \mathcal{T}^{cut}, x, R, \mu)$$

Global reference measurement: Beam thrust

Computed fully analytically at two loops

JG, Stahlhofen, Tackmann, JHEP 1404 (2014) 113, JHEP 1408 (2014) 020

ΔB vanishes for one emission – only have to consider double-real graphs, most of UV/IR divergences cancel.

Computed as a power series in R up to R^2, nearly fully analytically

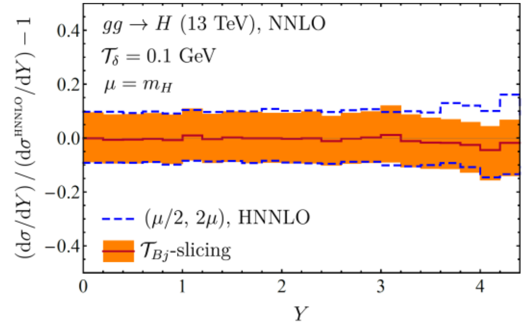
Gangal, JG, Stahlhofen, Tackmann, JHEP 1702 (2017) 026.

Both B and S computed at two-loops for all partonic channels for both $\mathcal{T}_{B,j}$, $\mathcal{T}_{C,j}$. Only explicit computation of jet-based veto ingredients at two loops.

HIGGS VETO CROSS SECTION

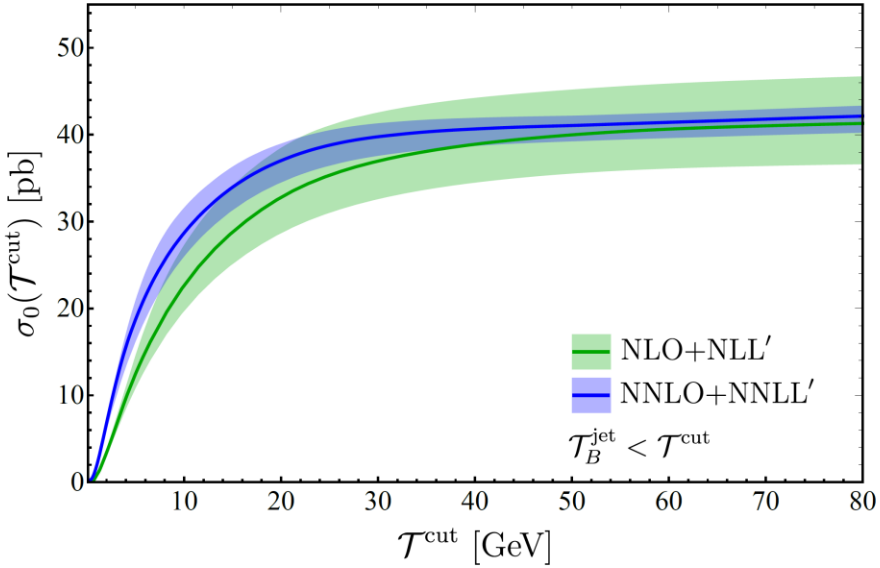
Ongoing work: application of these ingredients to achieve 0-jet Higgs cross section predictions at NNLL', matched to fixed order NNLO.

- Matching to fixed order obtained using NLO $H + j$ results from Madgraph5_aMC@NLO



- Include finite m_b, m_t at one loop.

Results for $\mathcal{T}_{B,j}$ at 13 TeV, $R = 0.5$

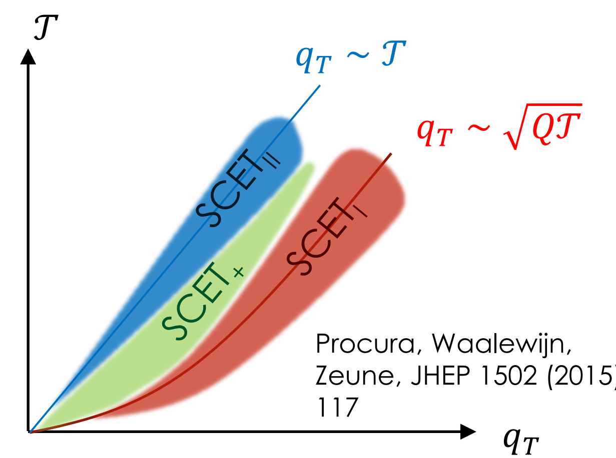


[Gangal, JG, Tackmann, Vryonidou, to appear]

FUTURE DIRECTIONS

Push boundaries of high-precision resummation at LHC:

- Computation of single-differential observables at N^{3}LL via computation of three-loop ingredients.
- Computation of multi-differential observables at NNLL' via computation of two-loop ingredients.

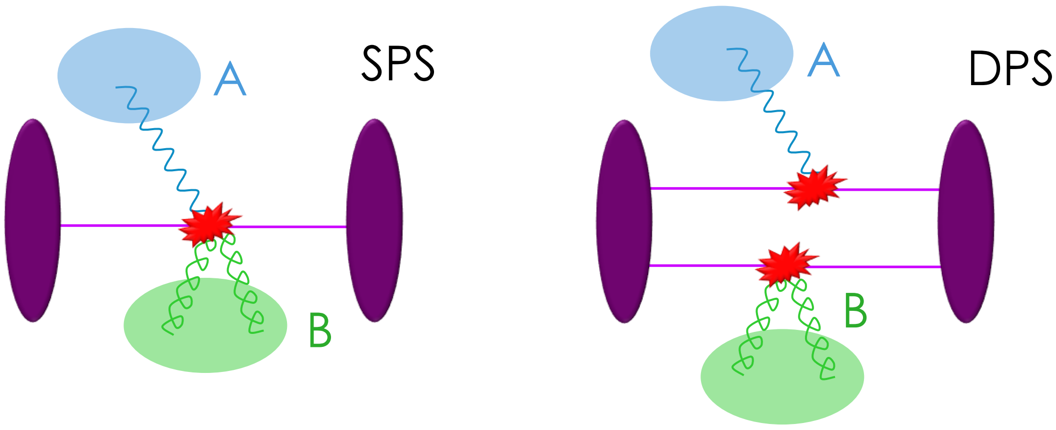


Procura, Waalewijn, Zeune, JHEP 1502 (2015) 117

- Further developments of N-jettiness subtraction technique.

II: DOUBLE PARTON SCATTERING

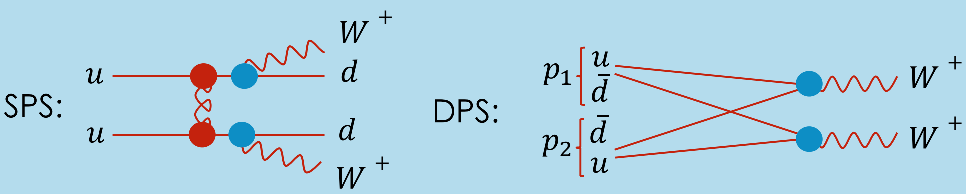
DOUBLE PARTON SCATTERING: BASICS

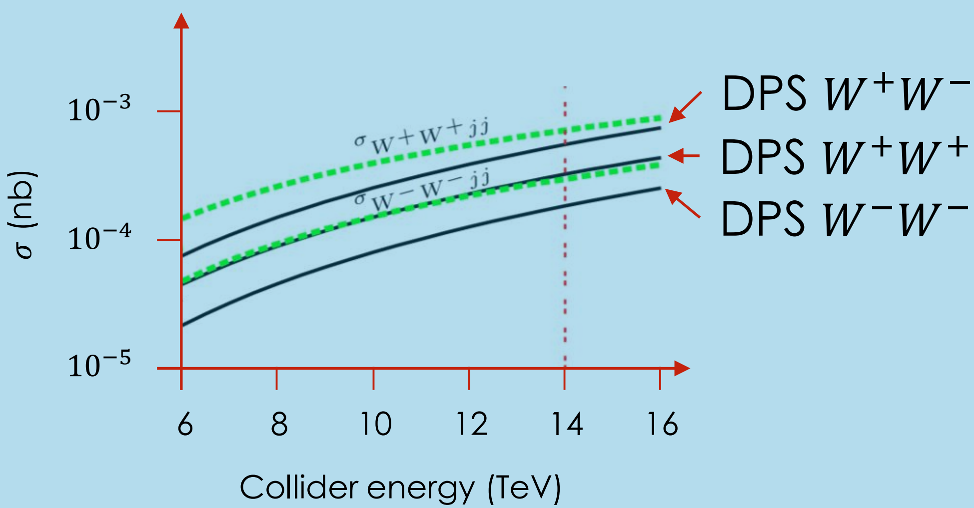


In terms of the total cross section for the production of AB, the DPS mechanism is power suppressed: $\sigma_{DPS}/\sigma_{SPS} \sim \Lambda_{QCD}^2/Q^2$

WHY STUDY DPS?

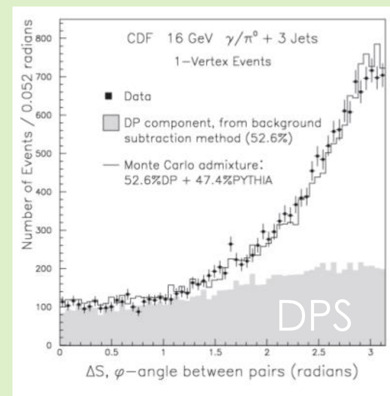
DPS can be a significant background to processes suppressed by small/multiple coupling constants…



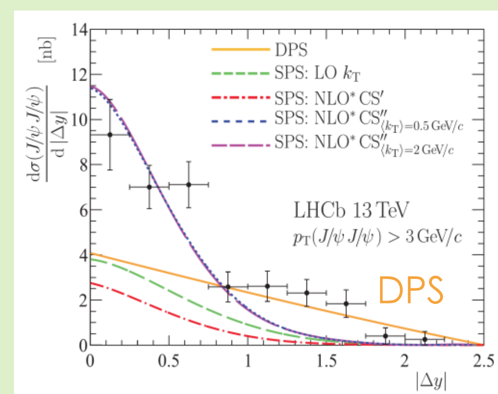


Gaunt, Kom, Kulesza, Stirling., Eur.Phys.J. C69 (2010) 53

…or in certain phase space regions



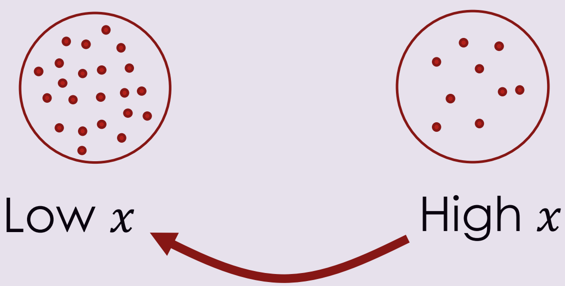
CDF, $\gamma + 3j$, Phys.Rev. D56 (1997) 3811-3832



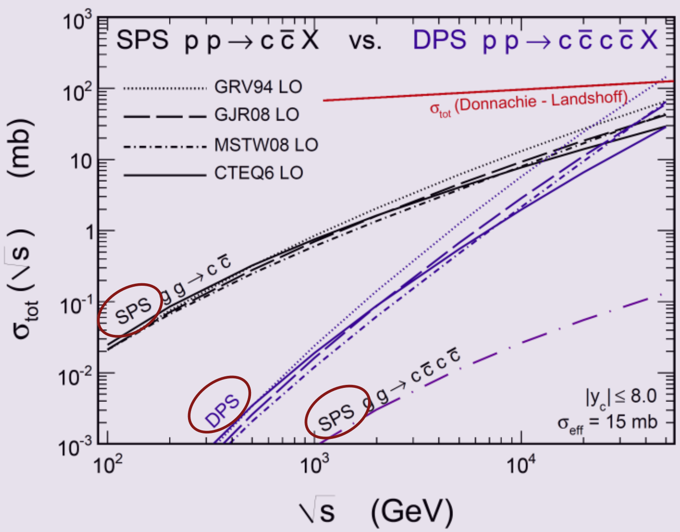
LHCb, double J/ψ, JHEP 06, 047, (2017)

WHY STUDY DPS?

DPS importance increases with collider energy:

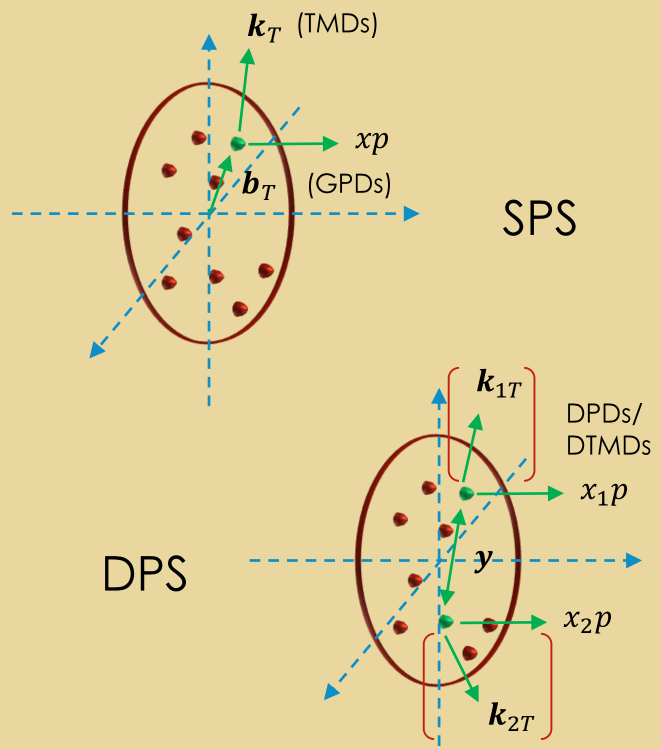


DPS probability increases

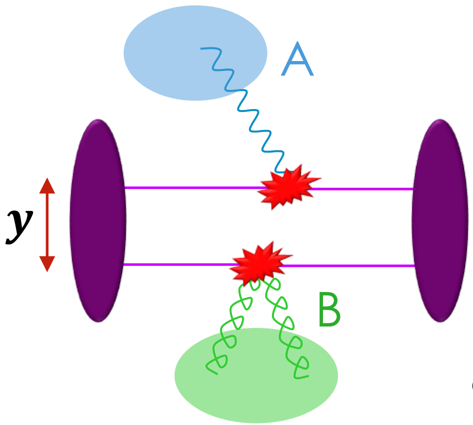


Łuszczak, Maciuła, Szczurek, Phys. Rev. D79, 094034 (2012)

DPS tells us new information on hadron structure:



DOUBLE PARTON SCATTERING



Ignoring QCD effects (parton model calculation), one anticipates the following form for the DPS cross section:

Double parton distributions (DPDs)

$$\sigma_{DPS}^{(A,B)} = \int F_{ik}(x_1, x_2, \mathbf{y}) F_{jl}(x'_1, x'_2, \mathbf{y}) \hat{\sigma}_{ij}^{A} \hat{\sigma}_{kl}^{B} dx_i dx'_i d^2\mathbf{y}$$

Paver, Treleani, Nuovo Cim. A70 (1982) 215
Diehl, Ostermeier, Schafer, JHEP 1203 (2012) 089

c.f. $\sigma_{SPS}^{(A)} = f_i(\mathrm{x}_1, \mathrm{Q}^2) \otimes \hat{\sigma}_{ik\to A}(\hat{\mathrm{s}} = \mathrm{x}_1\mathrm{x}_2\mathrm{s}) \otimes f_k(\mathrm{x}_2, \mathrm{Q}^2)$

Ignoring correlations between partons:

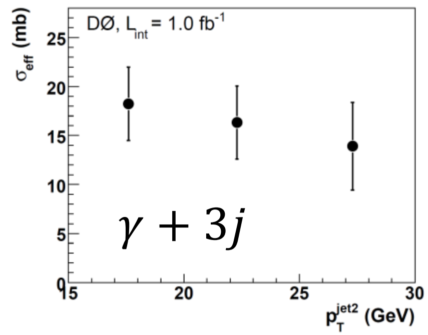
$$F_{ik}(x_1, x_2, \mathbf{y}) \to f_i(x_1) f_k(x_2) G(\mathbf{y})$$

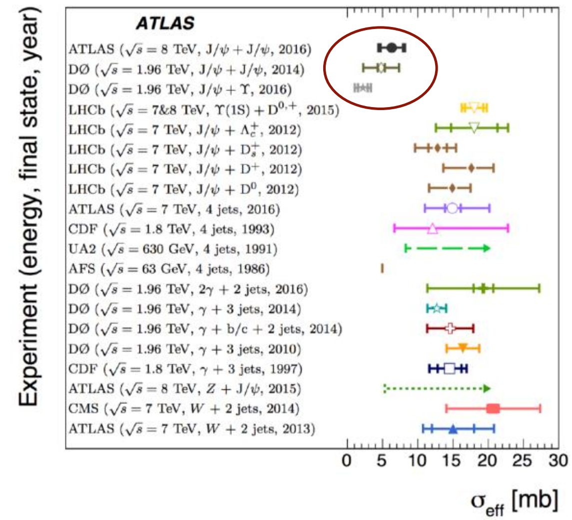
$$\sigma_{DPS}^{(A,B)} = \sigma_{SPS}^{(A)} \sigma_{SPS}^{(B)} / \sigma_{eff}$$

POCKET FORMULA

BEYOND THE POCKET FORMULA

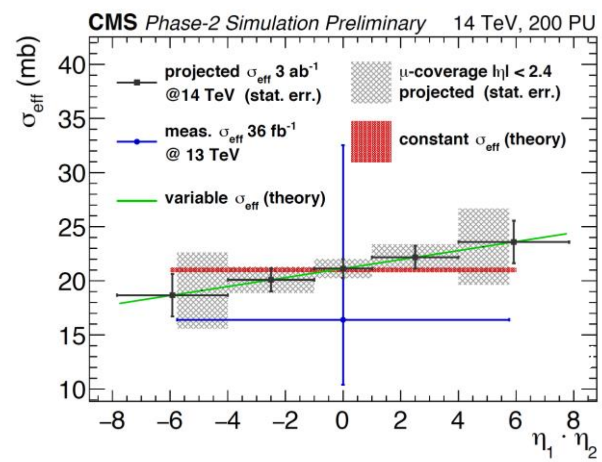
Pocket formula ok for order-of-magnitude estimates of DPS and rough experimental measurements of DPS so far. But…





Hints of effects beyond pocket formula:

Experiments will perform detailed differential measurements in future that will be sensitive to effects beyond pocket formula.



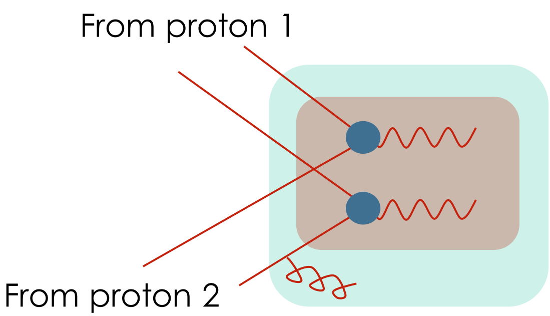
Motivates proper QCD description of DPS.

CMS-TDR-016

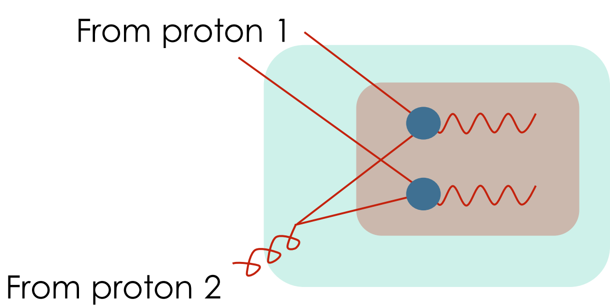
QCD EVOLUTION EFFECTS IN DPS

Big advances in theoretical description of DPS in previous years – I have played an important role in this.

Consider "zooming out" from the hard processes. What kind of QCD effects can occur?



Emission from single leg. Familiar from single scattering.



'1→2 splitting'. New effect!

Perturbative calculation at small y

$$F(x_1, x_2, y) \propto \alpha_s \frac{f(x_1 + x_2)}{x_1 + x_2} P\left(\frac{x_1}{x_1+x_2}\right) \frac{1}{y^2}$$

Single PDF

Perturbative splitting kernel

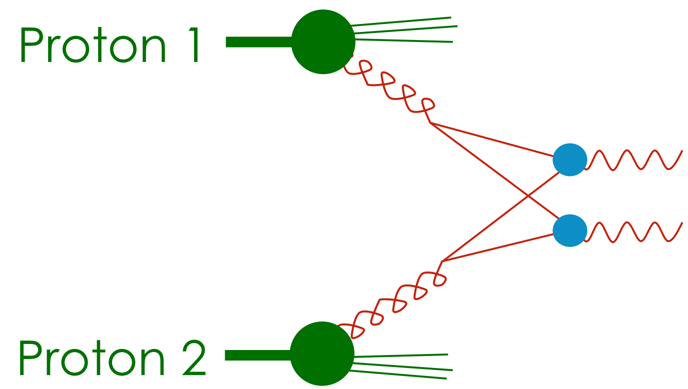
Dimensionful part

Diehl, Ostermeier and Schäfer (JHEP 1203 (2012))

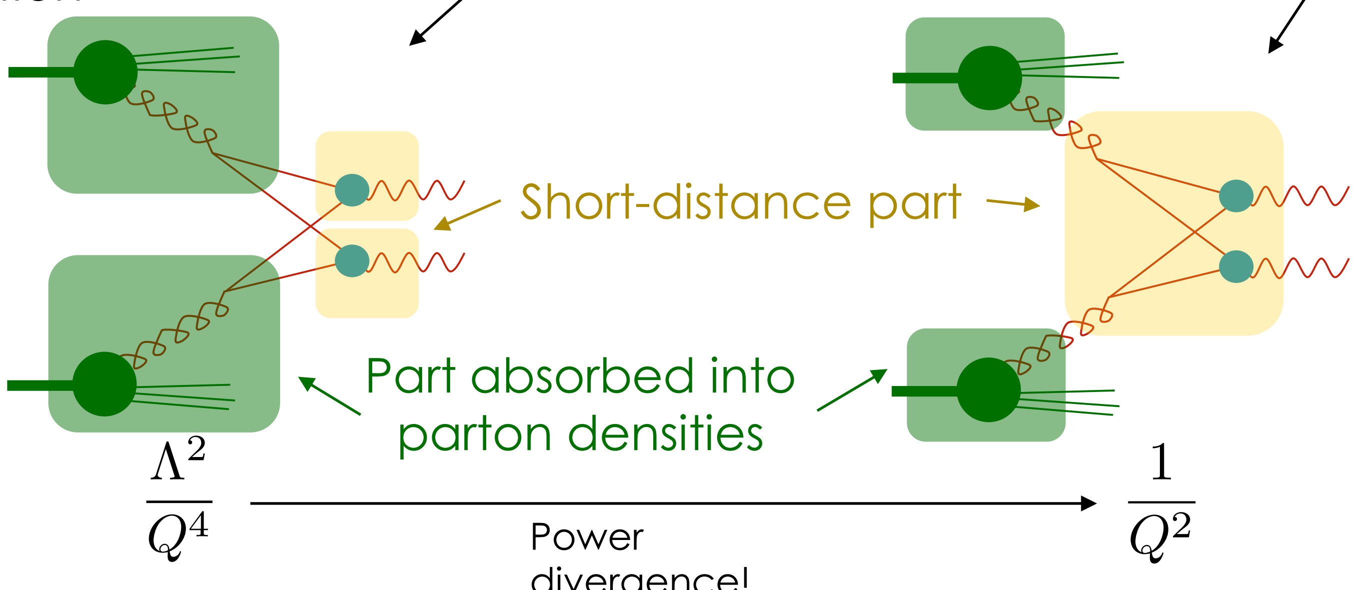
DOUBLE COUNTING PROBLEMS

Perturbative splitting can occur in both protons (1v1 graph) – gives power divergent contribution to DPS cross section!

$$\int \frac{d^2y}{y^4} = ?$$



This is related to the fact that this graph can also be regarded as an SPS loop correction

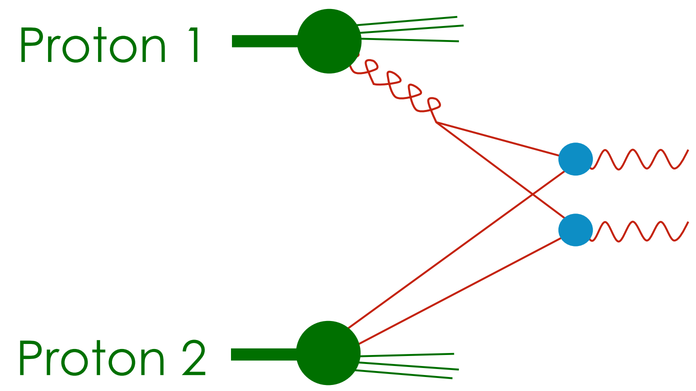


See e.g. JG and Stirling, JHEP 1106 048 (2011)

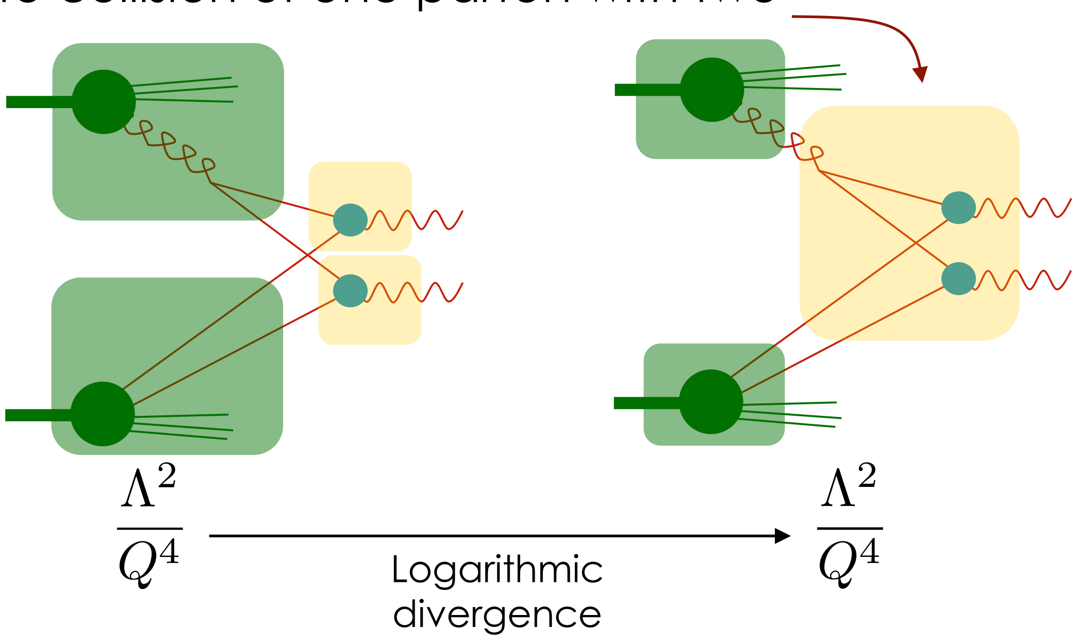
DOUBLE COUNTING PROBLEMS

Also have graphs with perturbative 1→2 splitting in one proton only (2v1 graph).

This has a log divergence: $\int d^2y/y^2 F_{\text{non-split}}(x_1, x_2; y)$



Related to the fact that this graph can also be thought of as an NLO correction to collision of one parton with two

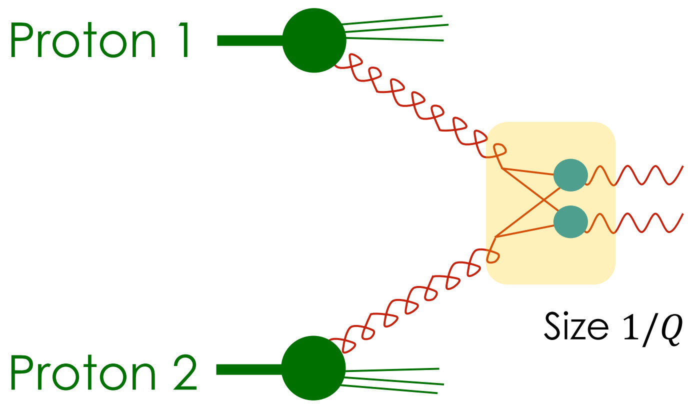


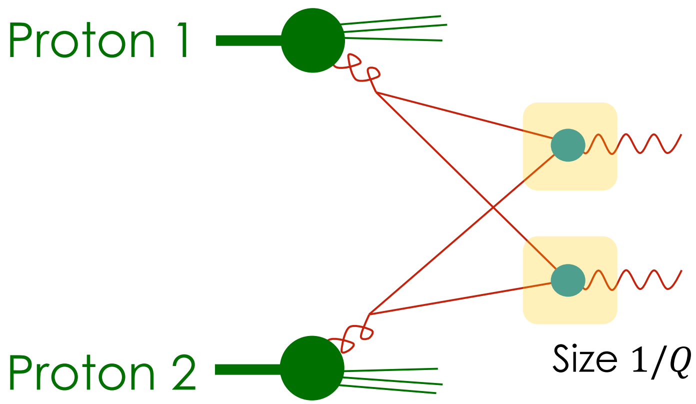
See e.g. JG, JHEP 1301 (2013) 042

DPS WITHOUT DOUBLE COUNTING

Consistent solution of double counting issues obtained in JG, Diehl, Schönwald, JHEP 1706 (2017) 083.

Combination of SPS and DPS terms, together with a subtraction term that ensures a smooth transition between DPS and SPS descriptions:





Small $y{\sim}1/Q$. SPS description appropriate. Subtraction term cancels DPS.

Large $y{\sim}1/Q$. DPS description appropriate. Subtraction term cancels SPS.

DPS WITHOUT DOUBLE COUNTING

Consistent solution of double counting issues obtained in JG, Diehl, Schönwald, JHEP 1706 (2017) 083.

C
t

Key features of this approach:

- Retain concept of double parton density for individual hadron with rigorous operator definition.
- Resum DGLAP logarithms in all types of DPS diagram where appropriate.
- All-order formulation, with corrections that are practicably computable.
- Re-use as many SPS results as possible.

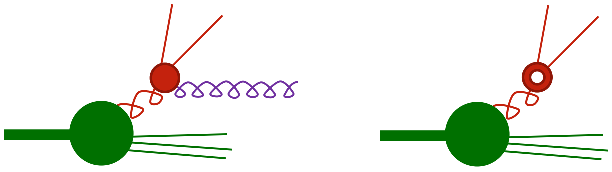
Sm ate.

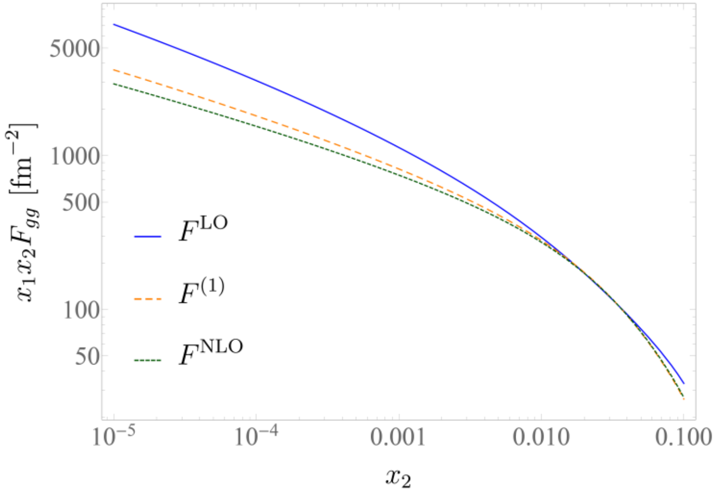
NLO CORRECTIONS TO DPS

New framework enables first full NLO computations of DPS.

Most ingredients needed for these calculations known.

Only missing ingredients were NLO corrections to 1 → 2 splitting. Recently computed in Diehl, JG, Plößl, Schäfer, SciPost Phys. 7 (2019) 2, 017





Initial investigations: NLO effects large, $\mathcal{O}(10-50\%)$.

Will be interesting to study at the process level.

PARTON SHOWER MODEL OF DPS

Despite rapid DPS theory developments, propagation of theoretical results into phenomenology has been rather slow.

For some processes, experimental extractions of DPS use distributions in multiple variables to separate DPS & SPS.
➔Would be very useful to have flexible tool that can easily produce DPS predictions in any variable.

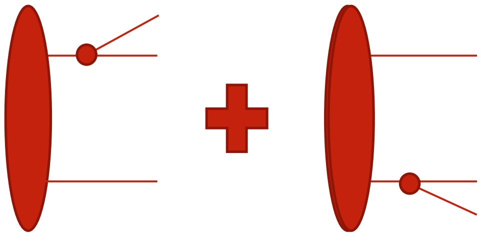
Motivated development of a parton shower model of DPS
➔ **dShower**. Cabouat, JG, Ostrolenk, JHEP 1911 (2019) 061

A DPS PARTON SHOWER

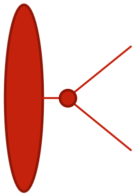
Basic overview of dShower algorithm:

- Select kinematics of hard processes and parton separation y according to DGS DPS formula.

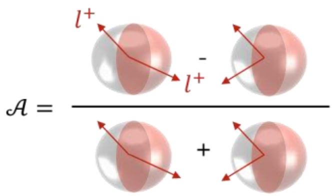
- Backward evolution from hard process with emissions from two legs. Angular ordered shower.

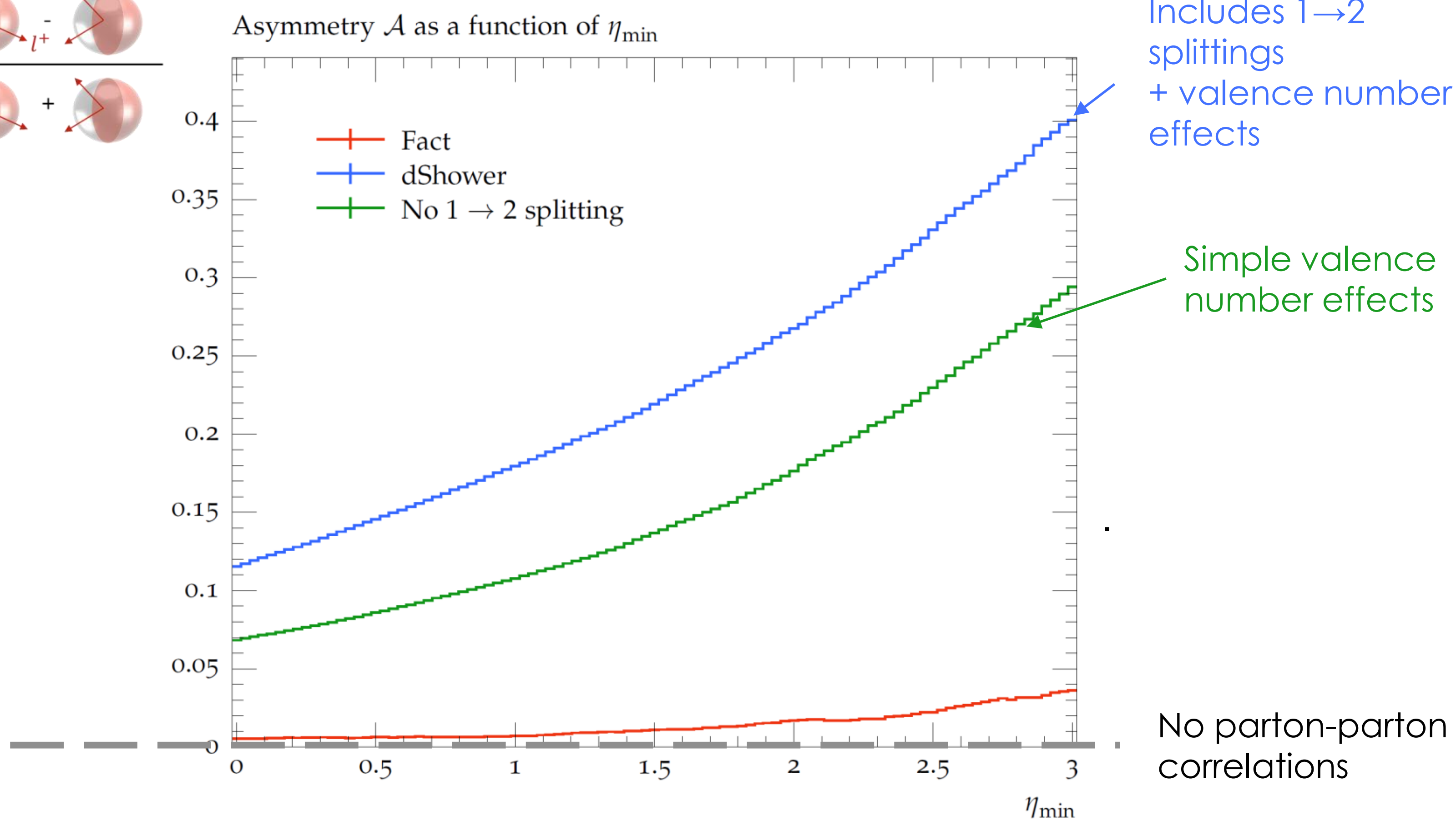


- At natural scale of $1 \to 2$ splitting, $\mu_y \sim 1/y$, $2 \to 1$ 'mergings' in backward evolution with appropriate probability.



ASYMMETRY IN WW





FUTURE DIRECTIONS

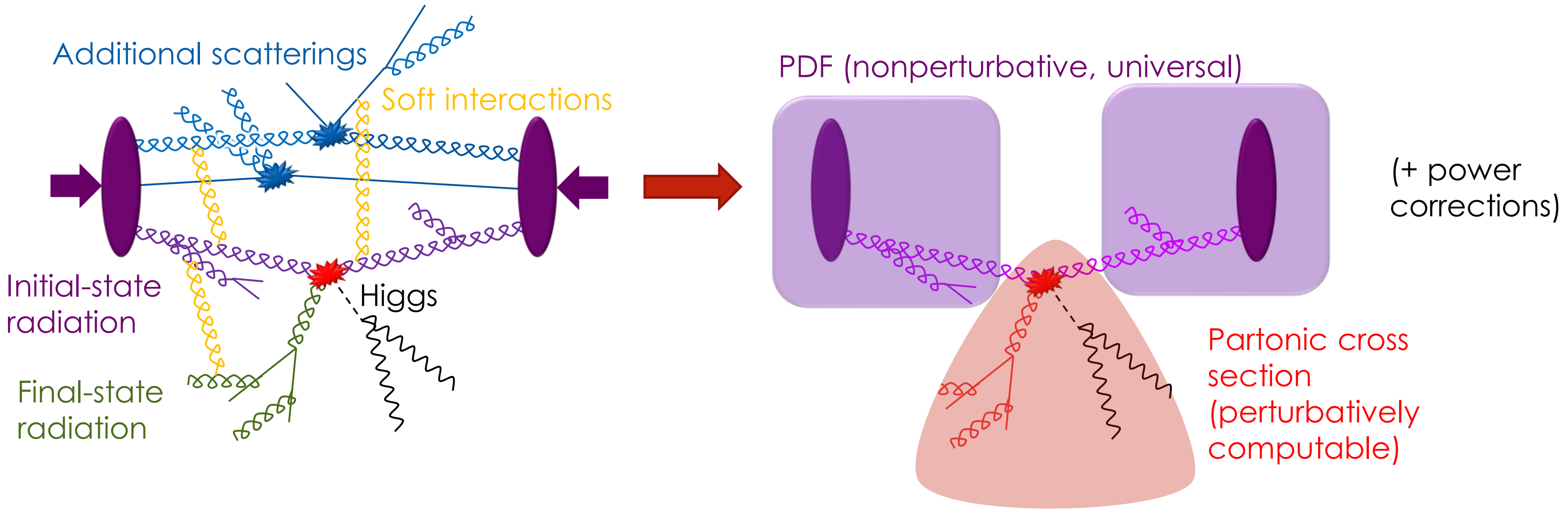
Many steps still to be undertaken in development of dShower:

- Generate SPS and DPS together, together with mechanism to avoid double counting.
- Incorporate possibility of including spin and colour correlations between partons.
- Generalise model to many multiple scatterings.
- Interface with hadronization model. Incorporate into Herwig.

III: FACTORISATION AND FACTORISATION BREAKING

FACTORISATION

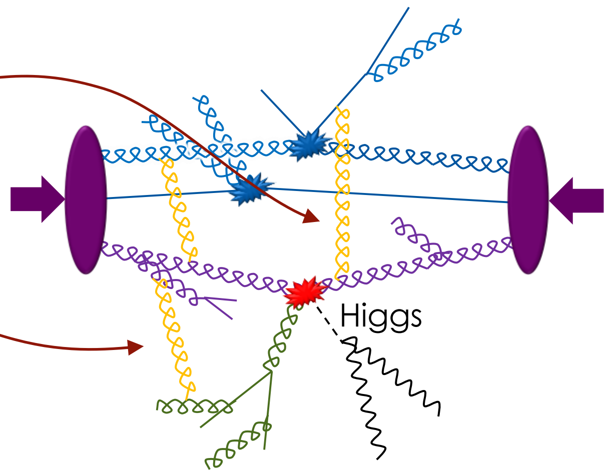
Task to obtain factorisation formula (example total cross section for $pp \to H + X$):



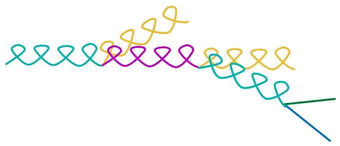
Achieved in Bodwin Phys. Rev. 31 (1985) 2616, Collins, Soper, Sterman Nucl. Phys. B261 (1985) 104, Nucl. Phys. B308 (1988) 833, Collins, pQCD book.

FACTORISATION: SOFT EXCHANGES

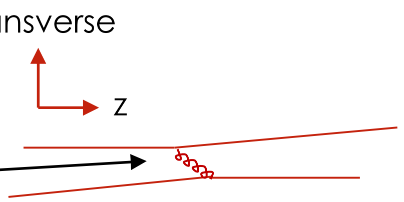
Key step to proving factorisation: need to separate off all soft connections entangling beam and final state jets.



For 'normal' soft exchanges, this can be achieved via Ward identities:



However, there is a particular type of soft exchange for which this doesn't work: Glauber exchanges. Soft particles mediating forward scattering.



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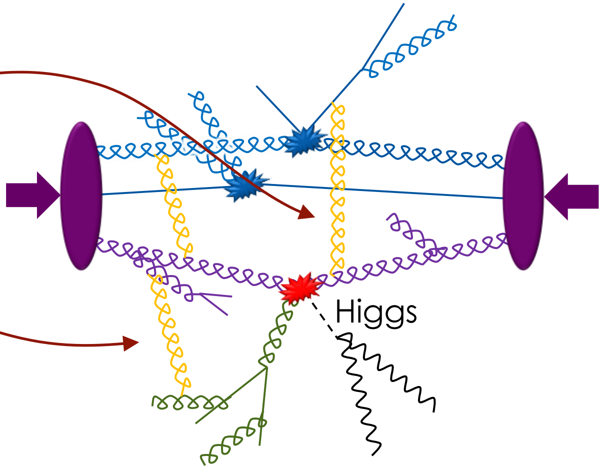

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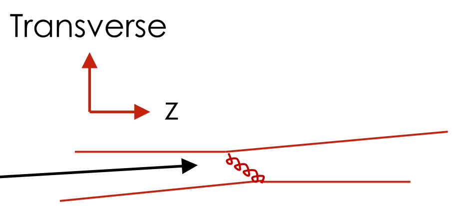
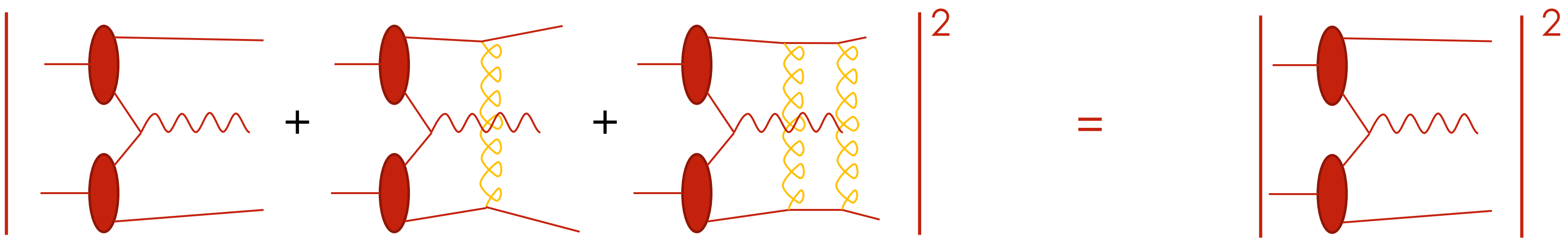


FACTORISATION: SOFT EXCHANGES

Treatment of Glauber exchanges is the trickiest part of a factorisation proof!

For colour singlet production: Collins, Soper, Sterman showed that effect of Glauber exchanges cancels if we measure only properties of V, and sum over everything else!



Unitarity: $P(anything\ happening) = 1$

MORE EXCLUSIVE CROSS SECTIONS

Restriction to inclusive cross sections for colour singlet processes would be a severe one. Want to study:

- exclusive cross sections (e.g. use a jet veto to maximise signal over background)
- processes with colour in the final state (e.g. $t\bar{t}$).

Predictions for many such processes obtained, assuming that Glauber exchanges cancel.

But is this the case? Very important to really establish when and where factorisation works or doesn't work.

I have studied the factorisation of various observables in pp colour singlet production.

- Global event shapes (factorisation broken!). JG, JHEP 1407 (2014) 110
- Double Drell-Yan (factorisation works at all orders) Diehl, JG, Ostermeier, Ploessl, Schaefer, JHEP 1601 (2016) 076
- Double Boer-Mulders effect. Boer, van Daal, JG, Kasemets, Mulders, SciPost Phys. 3, 040 (2017)

COLOUR ENTANGLEMENT IN THE DRELL-YAN PROCESS?

Factorisation formula for the Drell-Yan process ($pp \rightarrow Z/\gamma + X \rightarrow l^+l^- + X$), including full dependence on kinematics of produced leptons:

Azimuthal angle dependent term

$$\frac{d\sigma}{d\Omega d^2\boldsymbol{q}} \sim f_1 \otimes \bar{f}_1\, \hat{\sigma}_U(q,\theta) \quad + \quad h_1^\perp \otimes \overline{h}_1^\perp\, \hat{\sigma}_{BM}(q,\theta) cos(2\phi)$$

Boer, Brodsky, Huang, Phys. Rev. D67, 054003 (2003)
Boer, Phys. Rev. D60, 014012 (1999)

Unpolarised transverse momentum dependent PDF (TMD)

Boer-Mulders function – measures correlation between quark spin and transverse momentum

Can construct an azimuthal asymmetry to isolate ϕ-dependent term. Of experimental interest:

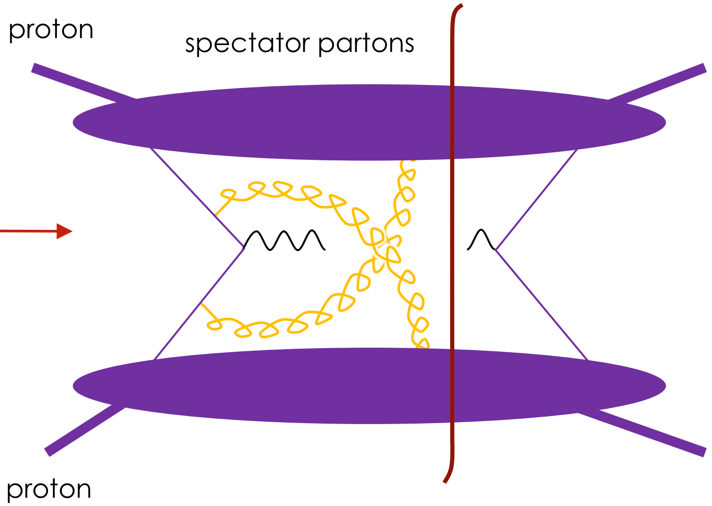
E866/NuSea experiment	COMPASS (CERN)	SeaQuest (Fermilab)	NICA (JINR)	J-PARC
Measured	Under investigation		Planned	

COLOUR ENTANGLEMENT IN THE DRELL-YAN PROCESS?

It was proposed in PRL 112 (2014), 092002 (Buffing, Mulders) that factorisation formula is not correct for spin-dependent part.

'Factorisation-breaking' effects start with this 'crossed gluon' diagram. Prediction that there is an extra colour factor of $-1/(N_C^2 - 1)$

Reduction in size, sign change!



- Important implications for experimental measurements!
- Would indicate a loophole in the Glauber cancellation proof for spin-dependent processes.

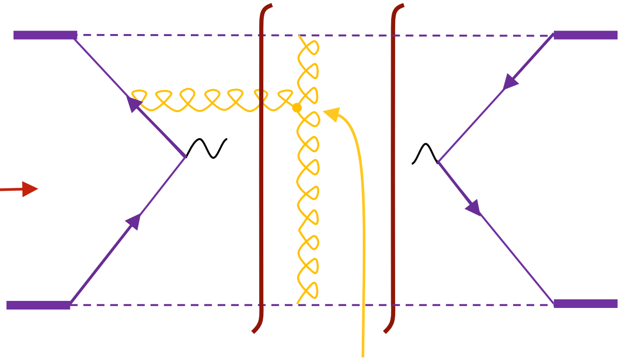
COLOUR ENTANGLEMENT IN THE DRELL-YAN PROCESS?

Studied using a model calculation if this effect exists, going up to the order including the crossed gluon diagram, but including all diagrams. Calculation at four loop level!

Boer, van Daal, JG, Kasemets, Mulders, SciPost Phys. 3, 040 (2017)

In Σ over diagrams, factorisation restored ✓

Key additional ingredient



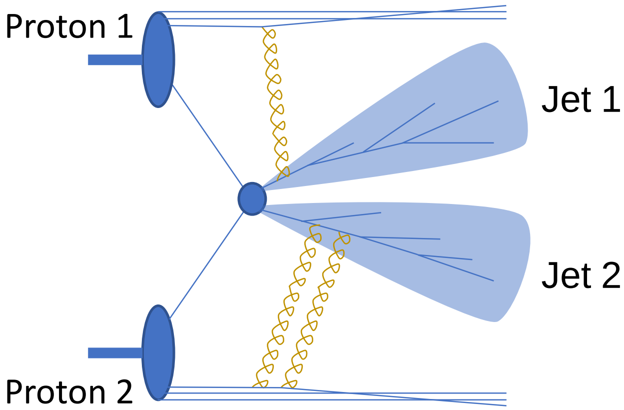
(non-Wilson line part of Lipatov vertex)

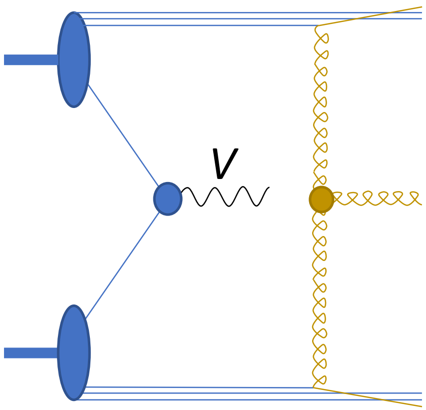
Very general techniques developed to study Glauber exchanges during this study.

Illuminates detailed mechanics of Glauber cancellation in Drell-Yan.

FUTURE GLAUBER STUDIES

Two cases where we know factorisation in violated:





Coloured particle production at measured p_T
Mulders, Rogers, Phys.Rev. D81 (2010) 094006

Global event shapes in hadron-hadron collisions
JG, JHEP 1407 (2014) 110

Can one develop some 'extended factorisation framework' to incorporate the Glauber effects? How big are the Glauber effects for processes of interest (e.g. top pair)?

SUMMARY

My research focusses on three topics of importance to precision understanding of proton-proton collisions:

- Higher order perturbative computations: Jet vetoes, resummation for multi-differential observables, *N*-jettiness subtraction method for fixed-order computations

- Double parton scattering: Moving from development of full QCD theory to tools for phenomenology: e.g. DPS parton shower.

- Factorisation and factorisation breaking: When is factorisation broken, and why? Can we compute the beyond-factorisation effects in these cases?