A tale of Nine Cities and Many Partons: developments in MPI since the first MPI@LHC.

Jonathan Gaunt (CERN)
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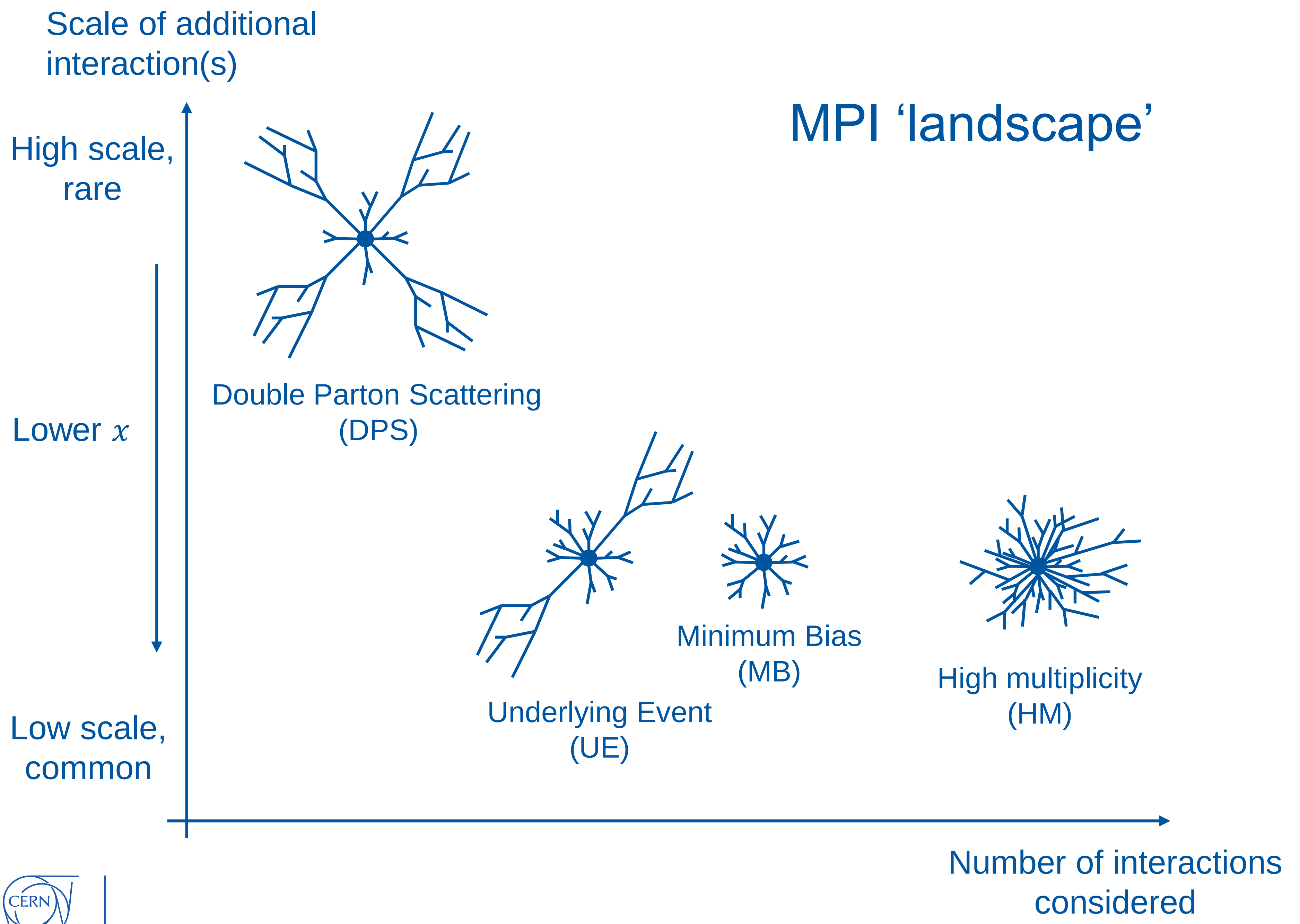
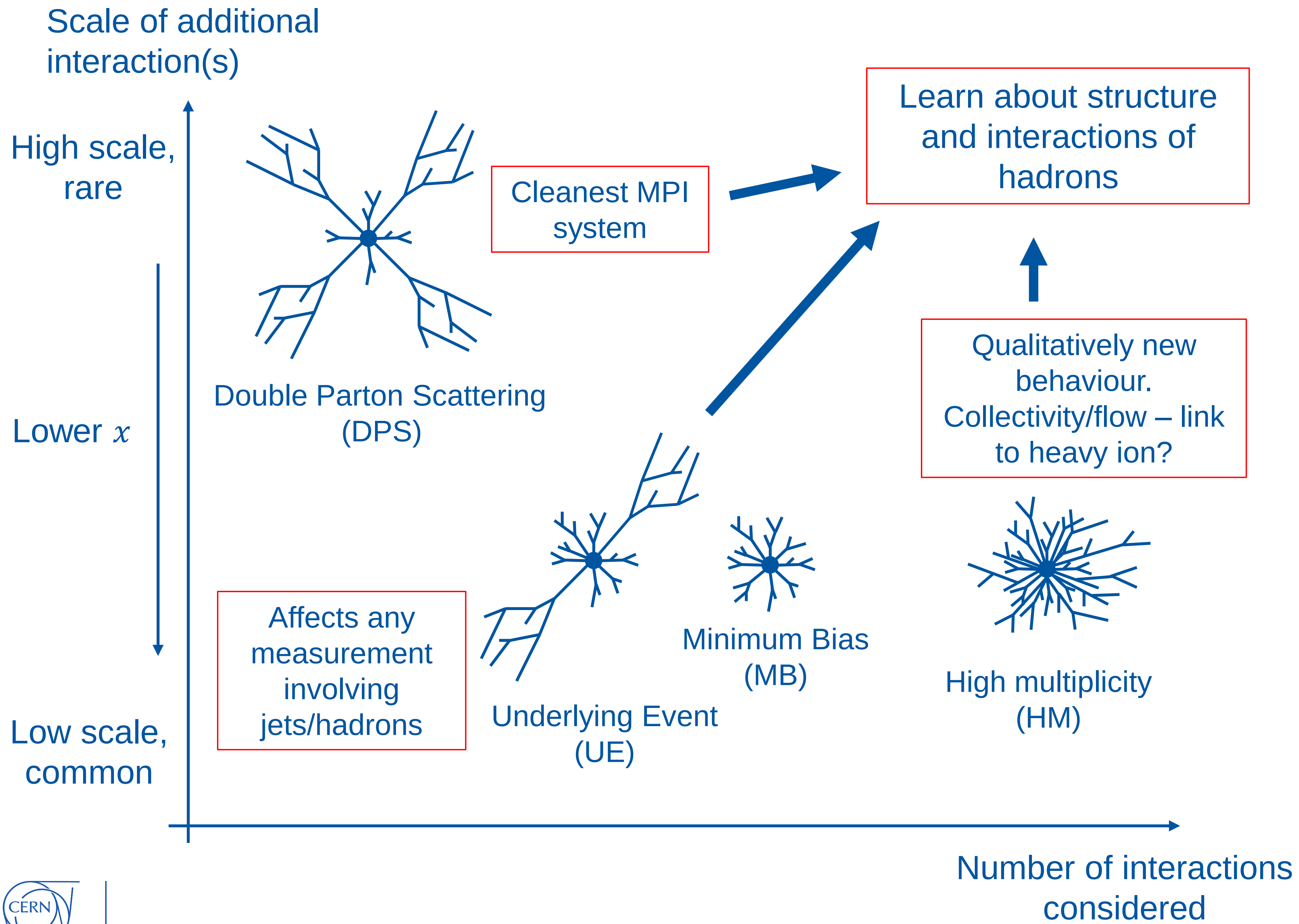
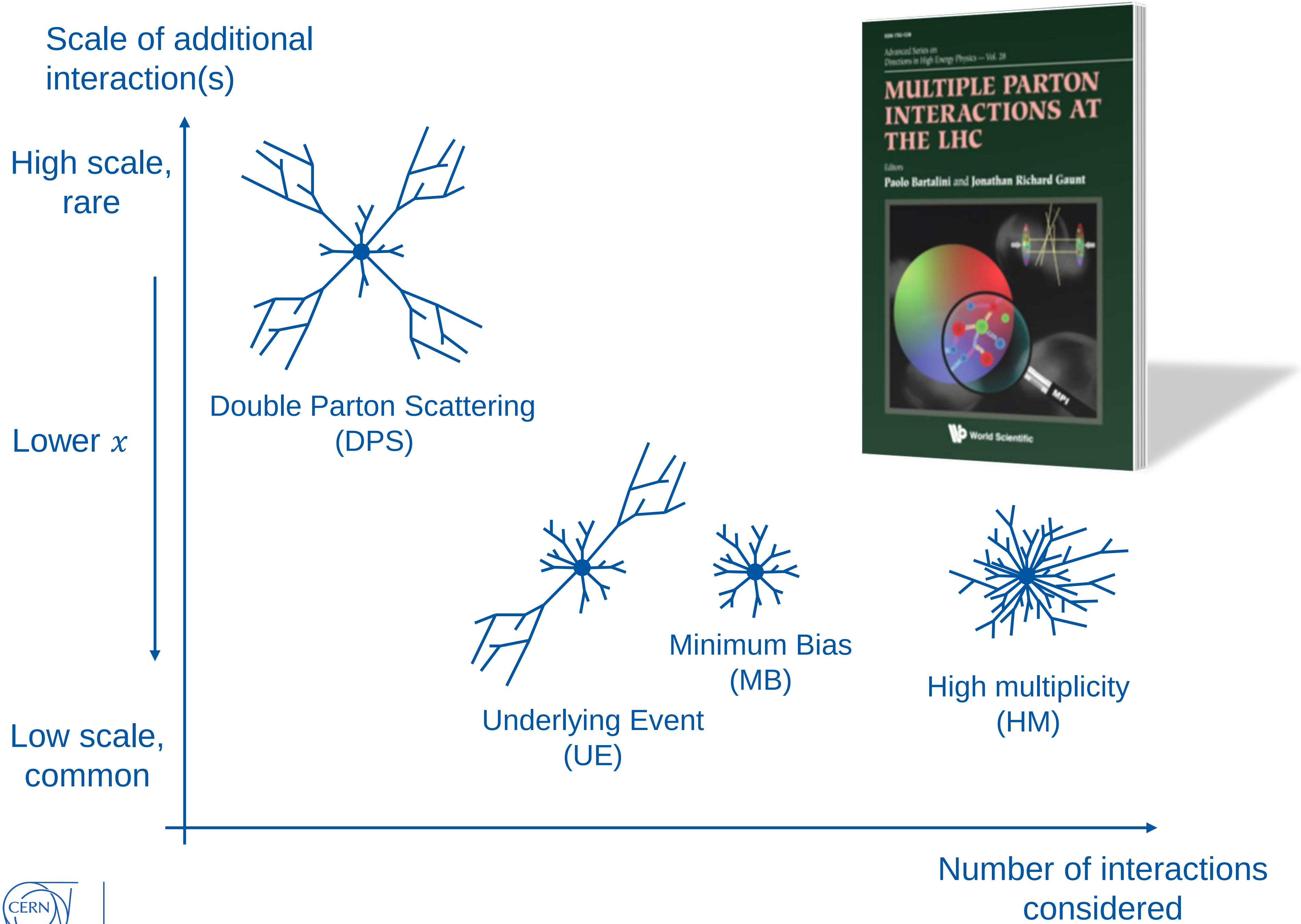
MPI ‘landscape’




Scale of additional interaction(s)
High scale, rare
Lower x
Low scale, common
Cleanest MPI system
Learn about structure and interactions of hadrons
Double Parton Scattering (DPS)
Qualitatively new behaviour. Collectivity/flow – link to heavy ion?
Affects any measurement involving jets/hadrons
Underlying Event (UE)
Minimum Bias (MB)
High multiplicity (HM)
Number of interactions considered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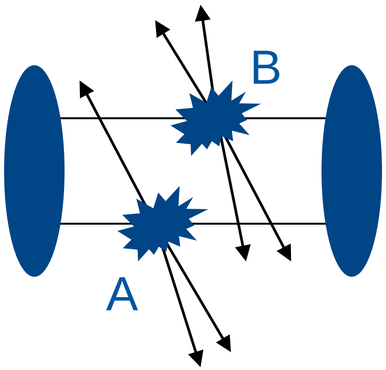
MULTIPLE PARTON INTERACTIONS AT THE LHC
Editors
Paolo Bartalini and Jonathan Richard Gaunt
MPI
World Scientific

Part I. Hard MPI: The Double Parton Scattering (DPS)

DPS: Basic features



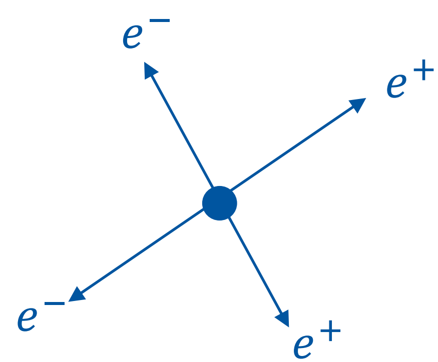
Double Parton Scattering (DPS) = two separate hard interactions in a single proton-proton collision

In terms of total cross section for production of AB, DPS is power suppressed with respect to single parton scattering (SPS) mechanism: $\frac{\sigma_{DPS}}{\sigma_{SPS}} \sim \frac{\Lambda^2}{Q^2}$

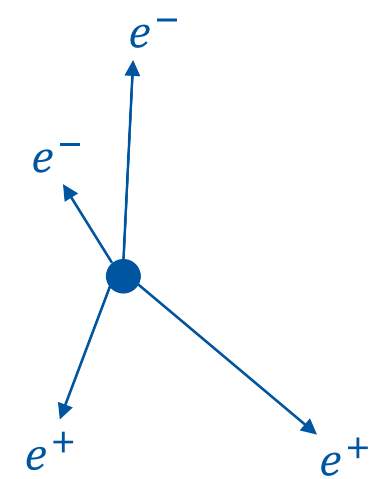
DPS populates the final state phase space in a different way from SPS. In particular, it tends to populate the region of small $\mathbf{q}_A$, $\mathbf{q}_B$ – competitive with SPS in this region.

e.g. pp → $\underbrace{\text{e+ e-}}_{A}\ \underbrace{\text{e+ e-}}_{B}$

DPS:



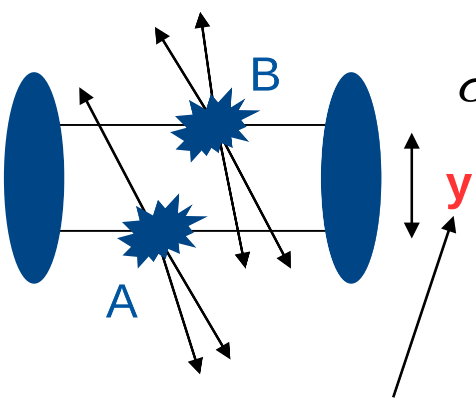
SPS:



DPS becomes more important relative to SPS as the collider energy grows, and we probe smaller *x* values where there is a larger density of partons.

Inclusive cross section for DPS

Postulated form for integrated double parton scattering cross section based on analysis of lowest order Feynman diagrams / parton model considerations:



Symmetry factor

$$\sigma_D^{(A,B)} = \frac{m}{2}\sum_{i,j,k,l}\int \overbrace{F_h^{ik}\left(x_1,x_2,\mathbf{y};Q_A,Q_B\right)F_h^{jl}\left(x_1',x_2',\mathbf{y};Q_A,Q_B\right)}^{\text{Collinear double parton distribution (DPD)}}$$

$$\times\underbrace{\hat{\sigma}_{ij}^{A}\left(x_1,x_1'\right)\hat{\sigma}_{kl}^{B}\left(x_2,x_2'\right)}_{\text{Parton level cross sections}}\mathrm{d}x_1\,\mathrm{d}x_1'\,\mathrm{d}x_2\,\mathrm{d}x_2'\,\mathrm{d}^2\mathbf{y}$$

y = separation in transverse space between the two partons

MPI@LHC 2010

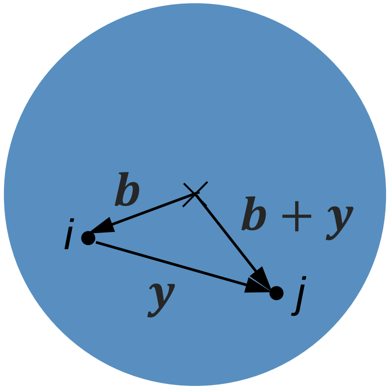
Paver, Treleani, Nuovo Cim. A70 (1982) 215.
Mekhfi, Phys. Rev. D32 (1985) 2371.
Blok, Dokshitzer, Frankfurt, Strikman, Phys.Rev. D83 (2011) 071501
Diehl, Ostermeier and Schäfer (JHEP 1203 (2012))

Simplifying assumptions for DPS cross section

If one ignores correlations between partons in the proton:

$$F^{ij}(x_1, x_2, \boldsymbol{y}) = \int d^2\boldsymbol{b}\, D^i(x_1, \boldsymbol{b})\; D^j(x_1, \boldsymbol{b} + \boldsymbol{y})$$

Impact parameter
dependent PDFs
(FT of GPD)



Common 'lore': approximately valid at low *x*, due to the large population of partons at such x values.

Further approximation that is often made: $D^i(x_1, \boldsymbol{b}) = D^i(x_1) G(\boldsymbol{b})$

$$\Rightarrow \quad F^{ij}(x_1, x_2, \boldsymbol{y}) = D^i(x_1)\; D^j(x_2) \int d^2\boldsymbol{b} G(\boldsymbol{b})(\boldsymbol{b} + \boldsymbol{y})$$

$$\Rightarrow \quad \sigma_D^{(A,B)} = \frac{\sigma_S^{(A)} \sigma_S^{(B)}}{\sigma_{eff}}$$

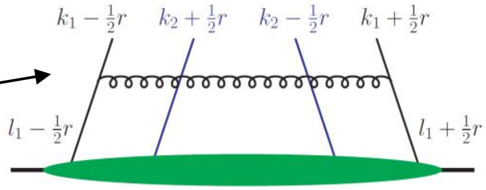
"Pocket formula"

Almost all phenomenological estimates of DPS use this equation

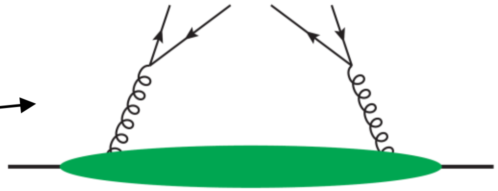
QCD evolution effects

Consider adding the effects of QCD evolution in DPS, going backwards from the hard interaction.

Some effects are similar to those encountered in SPS – i.e. (diagonal) emission from one of the parton legs. These can be treated in same way as for SPS.



However, there is a new effect possible here – when we go backwards from the hard interaction, we can discover that the two partons arose from the perturbative '1 → 2' splitting of a single parton.



This 'perturbative splitting' yields a contribution to the DPD of the following form:

Single PDF

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

Dimensionful part

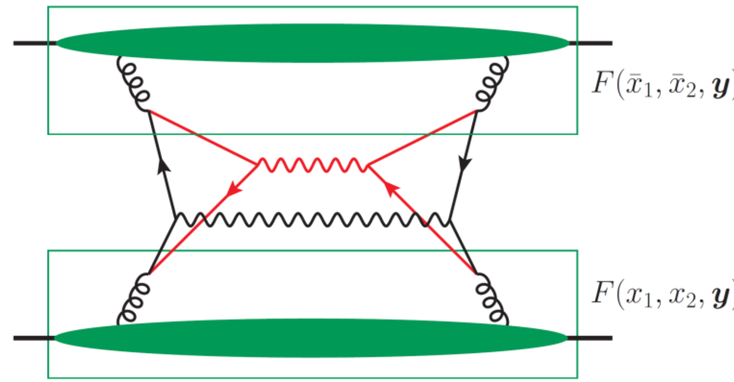
Perturbative splitting kernel

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

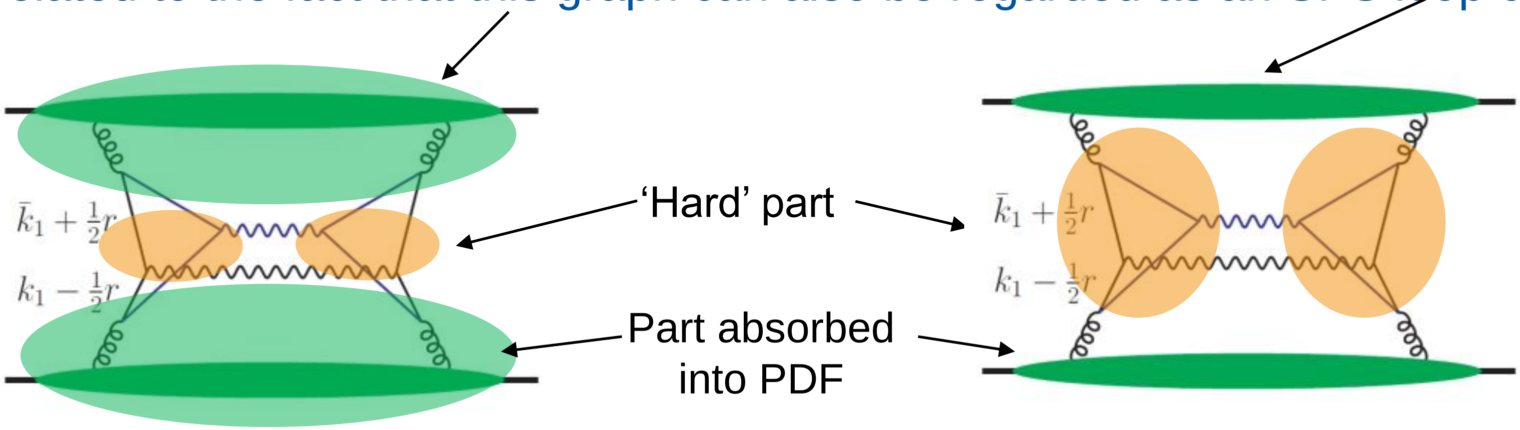
Problems...

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



$$\frac{\Lambda^2}{Q^4} \xrightarrow{\text{Power divergence!}} \frac{1}{Q^2}$$

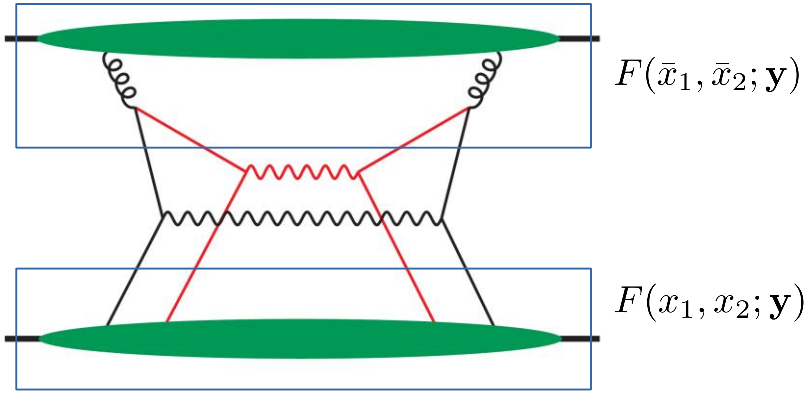
Issue raised MPI@LHC 2010

Single perturbative splitting graphs

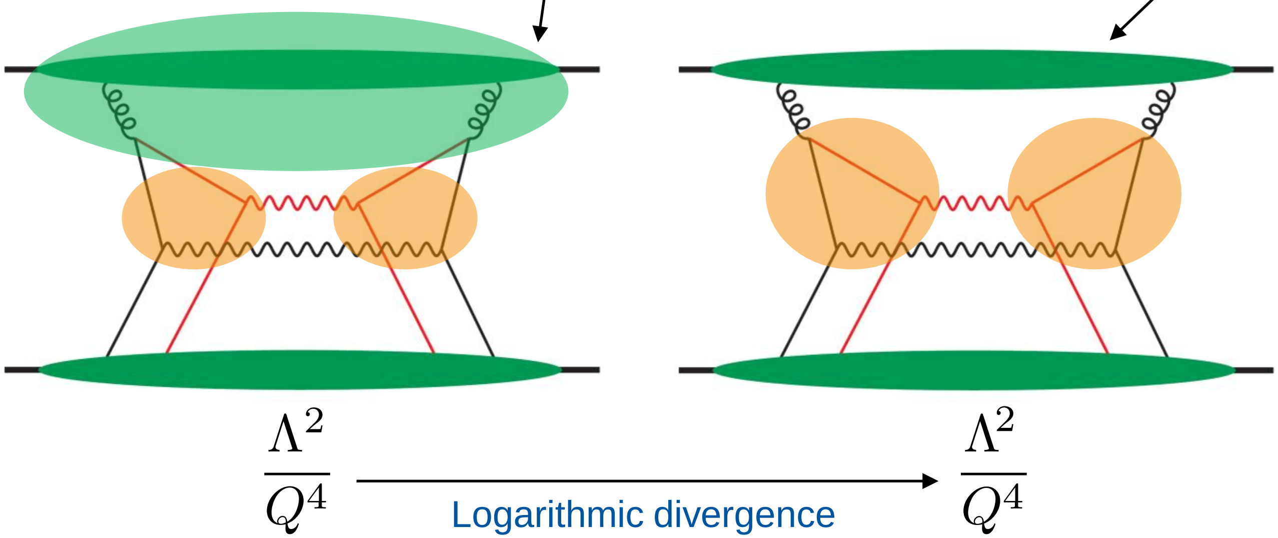
Also have graphs with perturbative 1→2 splitting in one proton only (2v1 graph).

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 a twist 4 x twist 2 contribution to AB cross section



Blok, Dokshitzer, Frankfurt, Strikman, MPI@LHC 2011

Solving the double counting problem

First approach to solve problem:

- Completely remove 1v1 graphs from DPS cross section, and consider these as pure SPS (no natural part of these graphs to separate off as DPS).
- Put (part of) 2v1 graphs in DPS – sum logs of 1→2 splitting + DGLAP emissions in this contribution.

Blok, Dokshitzer, Frankfurt, Strikman
Eur.Phys.J. C72 (2012) 1963
MPI@LHC 2011

JG
JHEP 1301 (2013) 042
MPI@LHC 2011

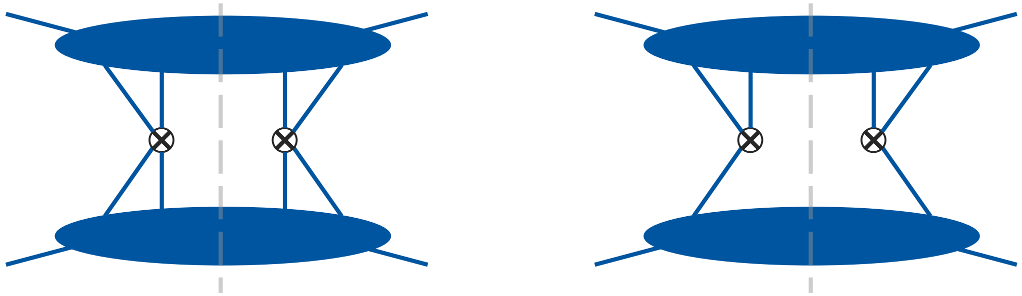
Manohar, Waalewijn
Phys.Lett. B713 (2012) 196-201
MPI@LHC 2013

This scheme comes out if one chooses to regulate y integral using dim reg:

$$\int d^2y/y^4 \to \int d^{2-2\epsilon}y/y^4 = 0$$

Manohar, Waalewijn,
Phys.Lett. B713 (2012) 196-201

In this case, cross section can no longer be written as parton level cross sections convolved with overall DPD factors for each hadron: appropriate hadronic operators involve both hadrons at once!

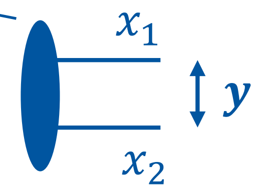


DPS framework of Diehl, Gaunt, Schönwald (DGS)

[JHEP 1706 (2017) 083]

Use double parton distributions (DPDs) in **y** space, insert cut-off into **y** integration:

$$\sigma_{\mathrm{DPS}} = \int d^2y \, \Phi^2(\nu y) \, F(x_1, x_2; y) F(\bar{x}_1, \bar{x}_2; y)$$



Cuts off integral for $\mathbf{y} \lesssim 1/\nu$, regulates power divergence

Use subtraction term in sum of SPS and DPS to avoid double counting:

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{DPS}} + \sigma_{\mathrm{SPS}} - \sigma_{\mathrm{sub}}$$

DPS cross section with both DPDs replaced by fixed order splitting expression

ν dependence cancelled order by order

Advantages:

- Retain concept of the DPD for an individual hadron.
- Resum logs in all diagrams where appropriate (2v2, 2v1 and 1v1).
- Permits all-order formulation. Corrections can be practicably computed.

MPI@LHC 2015, 16

Transverse momentum in DPS

Small $\boldsymbol{q}_i$ region particularly important for DPS – DPS & SPS same power

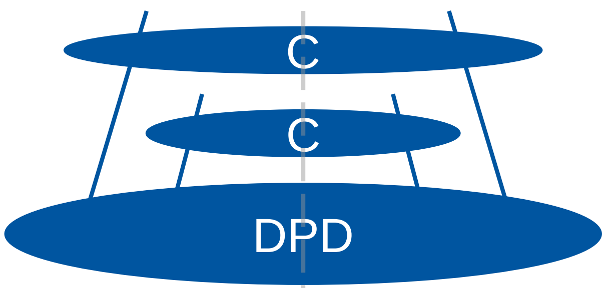
Parton model analysis: $\dfrac{d\sigma^{(A,B)}}{d^2\boldsymbol{q_1}\, d^2\boldsymbol{q_2}} \sim \int d^2\boldsymbol{y}\, d^2\boldsymbol{z}_i\, e^{-iz_1\cdot q_1 - iz_2\cdot q_2}\, \underbrace{F(\boldsymbol{z_1}, \boldsymbol{z_2}, \boldsymbol{y})}_{\text{DTMDs}}\ F(\boldsymbol{z_1}, \boldsymbol{z_2}, \boldsymbol{y})$

QCD treatment of transverse momentum in DPS (including DGS-style double counting subtraction) pursued in Buffing, Diehl, Kasemets JHEP 1801 (2018) 044

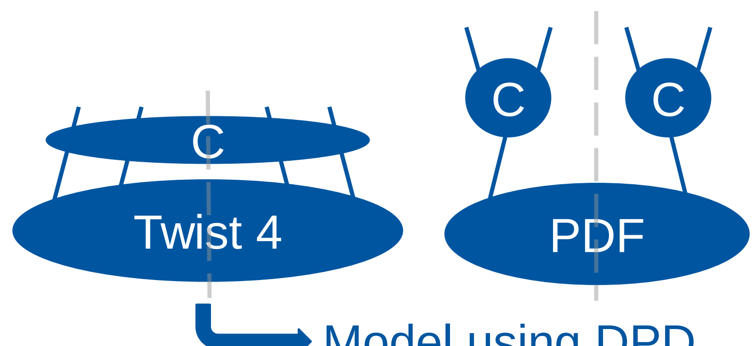
MPI@LHC 2016

For perturbative $|\boldsymbol{q}_i| \gg \Lambda$ can expand DTMDs in terms of collinear quantities:

Large $\boldsymbol{y} \sim 1/\Lambda$:



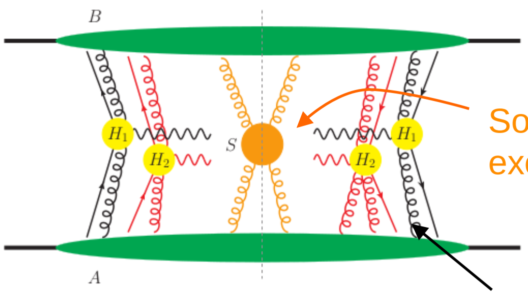
Small $\boldsymbol{y} \sim 1/q_T \sim |\boldsymbol{z_i}|$:



Model using DPD

Formal factorisation status of DPS

Formal factorization status of DPS producing two colour singlets is very good! [For coloured particle production at measured p_T, problems identified even in SPS case.]

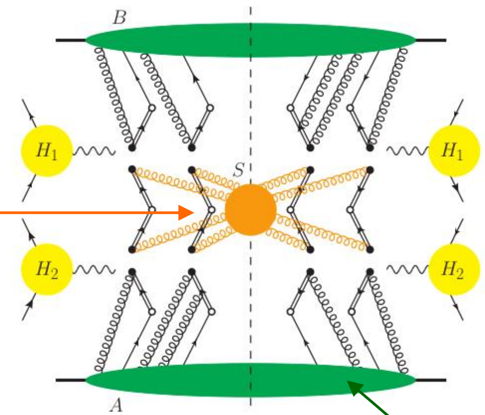


Soft and Glauber exchanges

Extra (unphysically polarised) gluon connections to hard

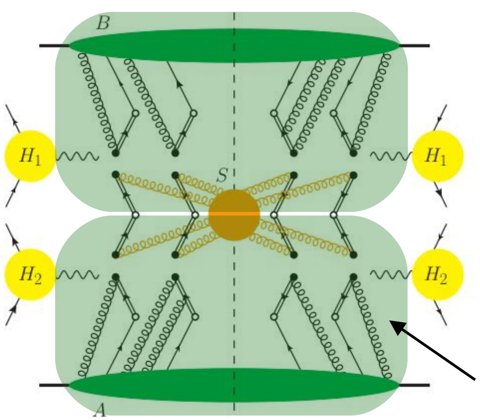
Initial picture

Diehl, JG, Ostermeier, Plößl, Schafer, JHEP 1601 (2016) 076, Diehl, Ostermeier, Schafer, JHEP 1203 (2012) 089, Diehl, Nagar, *to appear*



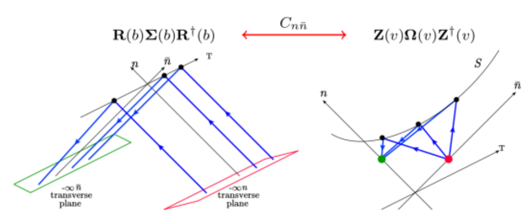
Soft factor

Collinear factor



DPDs/DTMDS

(Vladimirov, JHEP 1804 (2018) 045)



$\sigma \sim F \otimes F \otimes \hat{\sigma} \otimes \hat{\sigma}$

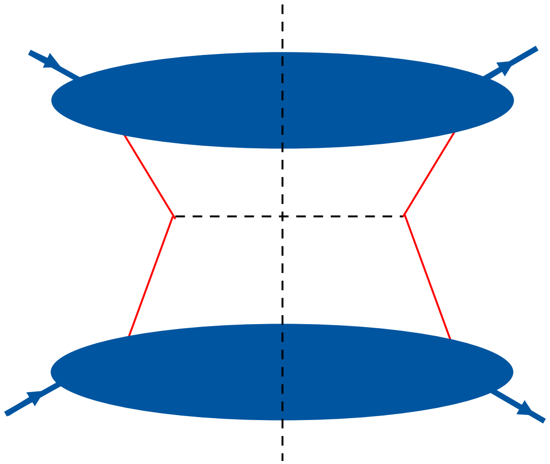
Interference contributions to proton-proton DPS

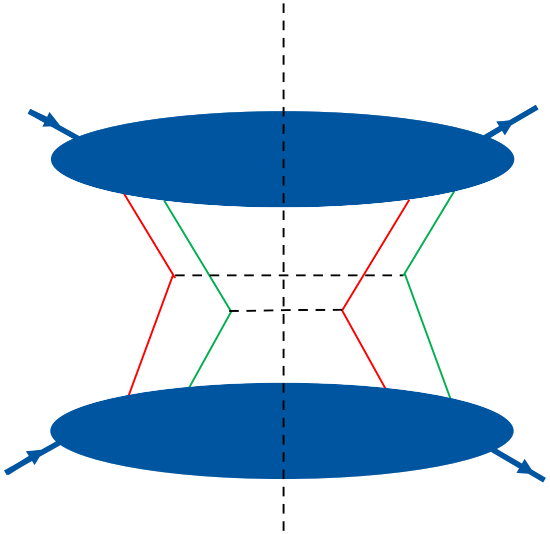
Mekhfi, Phys. Rev. D32 (1985) 2380
Diehl, Ostermeier and Schafer (JHEP 1203 (2012))
Manohar, Waalewijn, Phys.Rev. D85 (2012) 114009

SPS: One parton per proton 'leaves', interacts and 'returns'.

To reform proton, parton must return with same quantum numbers.

No interference contributions to SPS cross section.



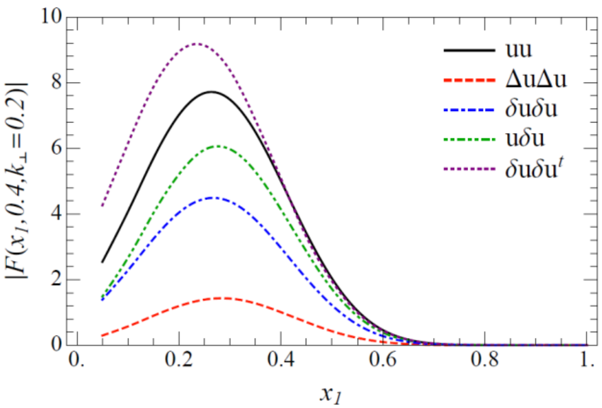


DPS: Here we have two partons per proton interacting.

Interference contributions to total cross section in which quantum numbers are swapped between parton legs. Complementary swap is required in other proton.

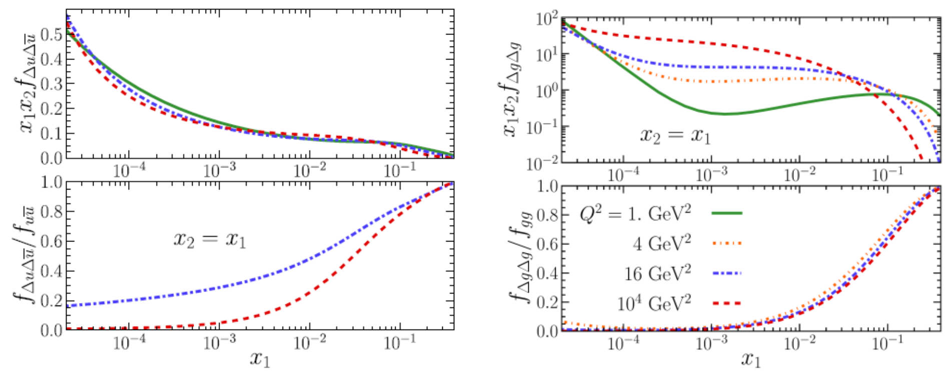
Can get interference contributions in colour, spin, flavour, and quark number. Also distributions associated with parton correlations!

Numerics of polarised distributions



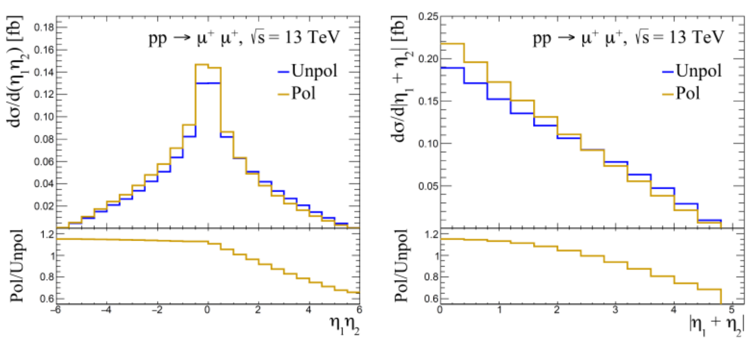
Model calculations indicate spin correlations are large at large x

Chang, Manohar, Waalewijn, Phys.Rev. D87 (2013) no.3, 034009



Evolution decreases relative importance of polarised distributions, especially at small x

Diehl, Kasemets, Keane, JHEP 1405 (2014) 118



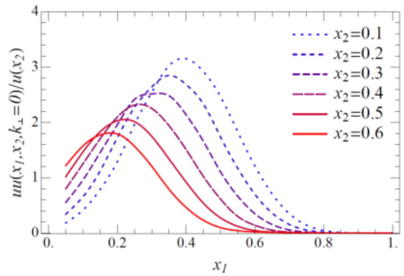
Recently shown that polarisation effects can have an important effect on η distributions of leptons in same-sign WW.

Cotogno, Kasemets, Myska,1809.09024

Knowledge of nonperturbative DPDs

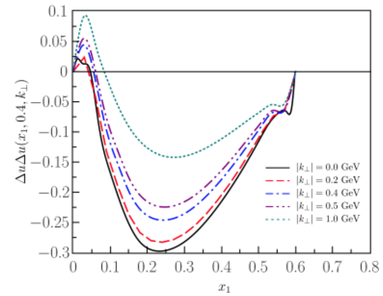
Model calculations:

MPI@LHC 2013,…



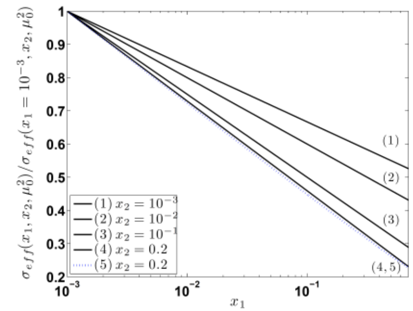
Bag model

[Phys. Rev. D 87, 034009 (2013), Manohar, Waalewijn, Chang]



Light-front CQM

[Rinaldi, Scopetta, Traini, Vento, JHEP 12 (2014) 028]



AdS/QCD

[Traini, Rinaldi, Scopetta, Vento, Phys. Lett. B 768 (2017) 270-273]

Momentum and number sum rules:

[JG, Stirling, JHEP 1003 (2010) 005
Diehl, Plößl, Schafer, arXiv:1811.00289]
Construction of DPDs to satisfy rules in e.g. JG, Stirling, JHEP 1003 (2010) 005, Golec-Biernat et al. Phys.Lett. B750 (2015) 559-564,.... Also see talk by Peter Plößl.

$$\sum_{j_2} \int_0^{1-x_1} \mathrm{d}x_2\, x_2\, F^{j_1 j_2}(x_1, x_2; \mu) = (1 - x_1) f^{j_1}(x_1; \mu)$$

$$\int_0^{1-x_1} \mathrm{d}x_2\, F^{j_1 j_{2,v}}(x_1, x_2; \mu) = \left(N_{j_{2,v}} + \delta_{j_1,\overline{j_2}} - \delta_{j_1,j_2}\right) f^{j_1}(x_1; \mu)$$

MPI@LHC 2010,…

$$F(x_1, x_2; \mu) = \int d^2\boldsymbol{y}\Phi(\mu y)F(x_1, x_2, \boldsymbol{y}; \mu) + \mathcal{O}(\alpha_s)$$

Lattice calculations (so far only for pion) → see talk by Christian Zimmermann

Experimental DPS extractions

Experimental extractions so far typically limited to one number, with large errors (and this is already tough!): $\sigma_{eff} \equiv \sigma_D^{(A,B)} / \sigma_S^{(A)} \sigma_S^{(B)}$

DPS characteristics simulated either using MC event generators, or independent SPS events overlaid (latter assumes no correlations).

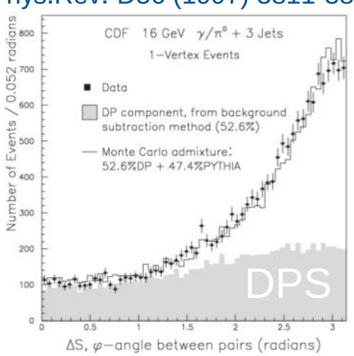
Typical observables considered:

$$\Delta S = arccos\left[\frac{\boldsymbol{p}_T(jet1,jet2)\cdot\boldsymbol{p}_T(jet1,jet2)}{|\boldsymbol{p}_T(jet1,jet2)|\cdot|\boldsymbol{p}_T(jet3,jet4)|}\right]$$

$$\Delta_{ij}^{p_T} = \frac{|\boldsymbol{p}_{T,i}+\boldsymbol{p}_{T,j}|}{|\boldsymbol{p}_{T,i}||\boldsymbol{p}_{T,j}|}$$

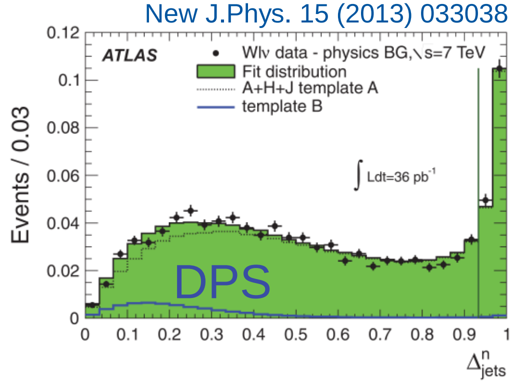
$$\Delta y = |y_A - y_B|$$

Phys.Rev. D56 (1997) 3811-3832



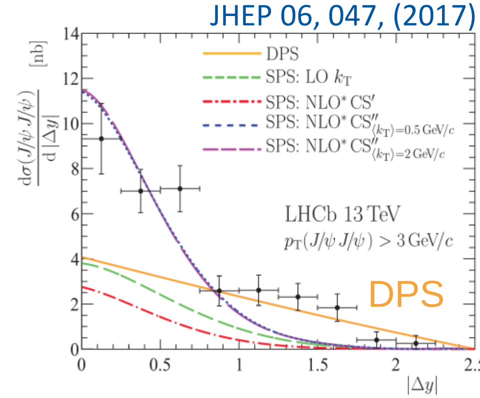
DPS has relatively flat distribution, SPS peaked near π

New J.Phys. 15 (2013) 033038



DPS peaked towards $\Delta_{ij}^{p_T} = 0$

JHEP 06, 047, (2017)



Generally wider distributions for DPS

Experimental DPS extractions

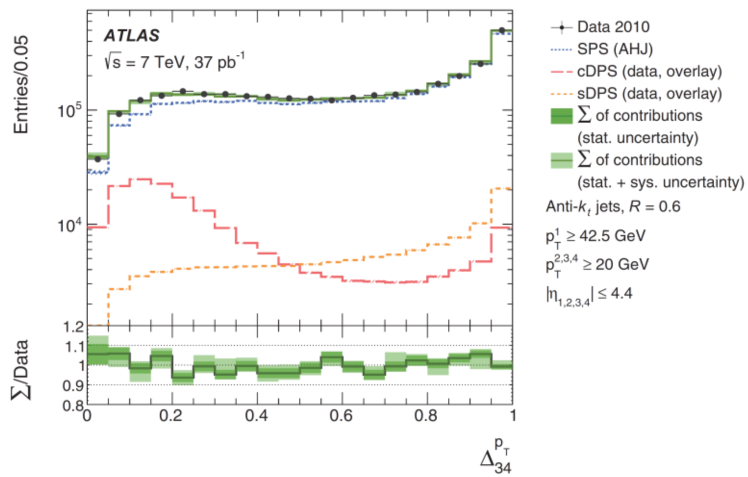
Two principal methods:

CMS, Eur.Phys.J. C76 (2016) no.3, 155

MPI@LHC 2015

‘Template method’

e.g. CDF, Phys.Rev. D47 (1993) 4857-4871

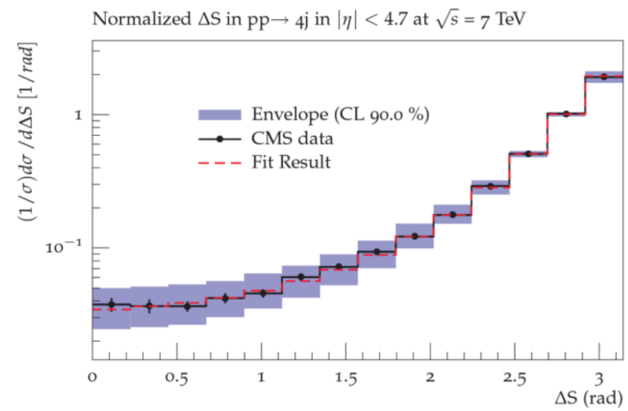


Generate SPS and DPS ‘templates’ in observables considered

Extract DPS fraction

Convert to σ_{eff}

‘Inclusive-fit method’



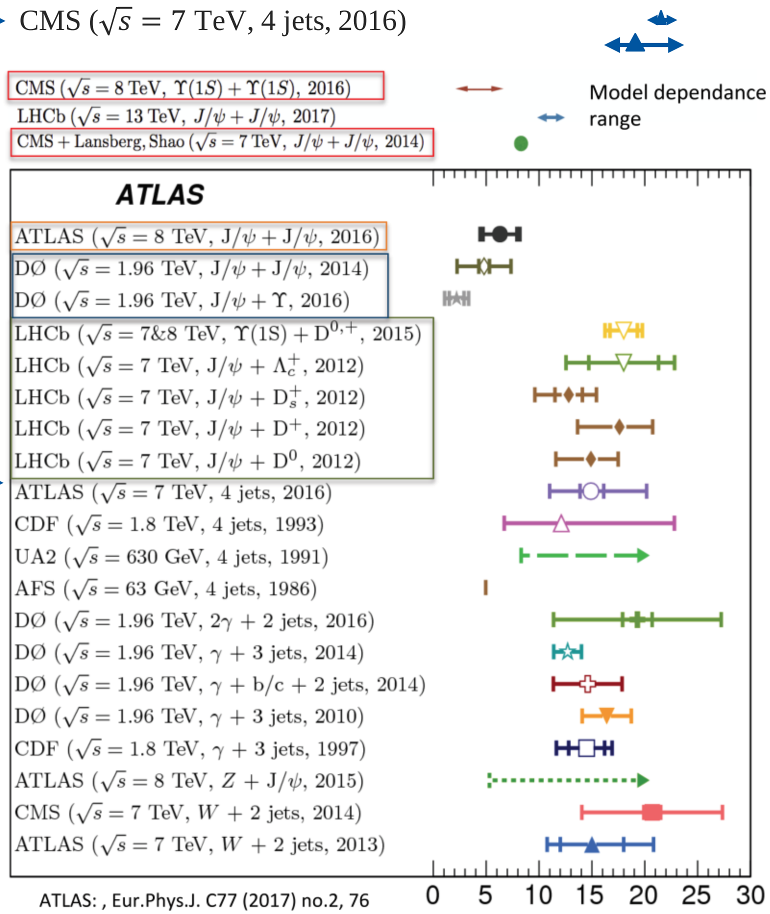
Based on MC generator tuning. Use DPS-sensitive data as input, and fit only MPI-sensitive parameters

Convert fitted MPI-parameters in MC to σ_{eff}

Results for σ_{eff}

4 jets

MPI@ LHC 2015



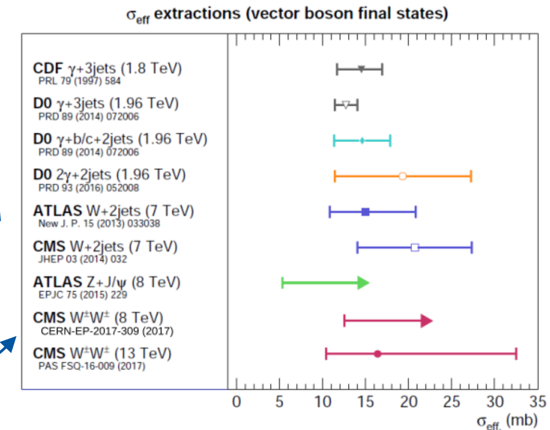
ATLAS: , Eur.Phys.J. C77 (2017) no.2, 76

V + jets

MPI@LHC 2011

Same-sign WW

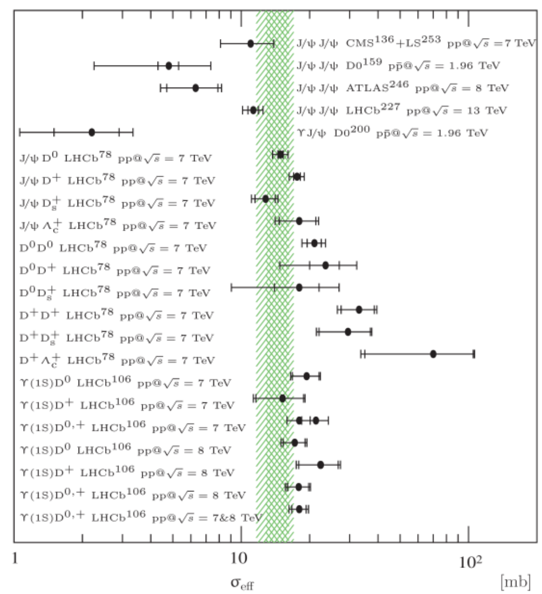
MPI@LHC 2015



Plot taken from talk by A. Mehta at MPI@LHC 2017

Heavy flavour

MPI@LHC 2012

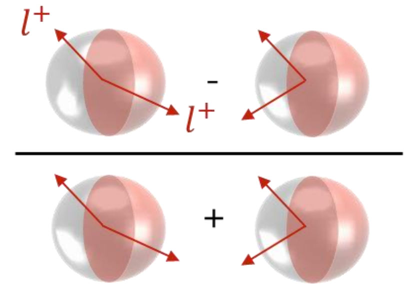


Plot from MPI book chapter by I. Belyaev and D. Savrina

Future prospects at HL-LHC

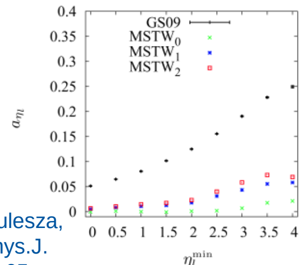
In same-sign WW, important observable

$a_{\eta l} \neq 0$ only if there are correlations in DPS

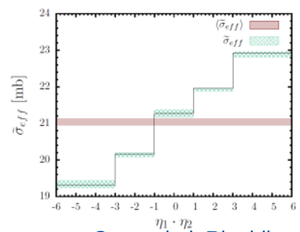
$a_{\eta l} =$ 

Various effects can cause a few per cent asymmetry:

x-space correlations, valence number effects



Gaunt, Kom Kulesza, Stirling, Eur.Phys.J. C69 (2010) 53-65



Ceccopieri, Rinaldi, Scopetta, Phys. Rev. D 95, 114030 (2017)

Polarised contributions

$\lvert\eta_i\rvert$	> 0	> 0.6	> 1.2
$a_{\eta l}$	0.07	0.11	0.16
σ [fb]	0.51	0.29	0.13

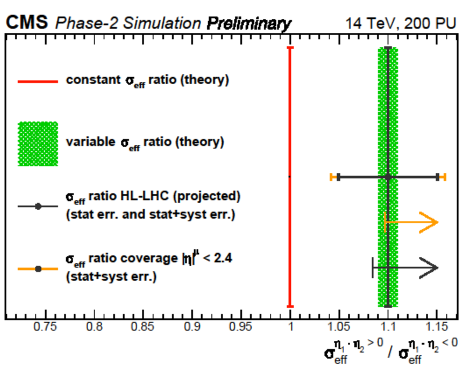
Cotogno, Kasemets, Myska,1809.09024

$1 \to 2$ splitting effects

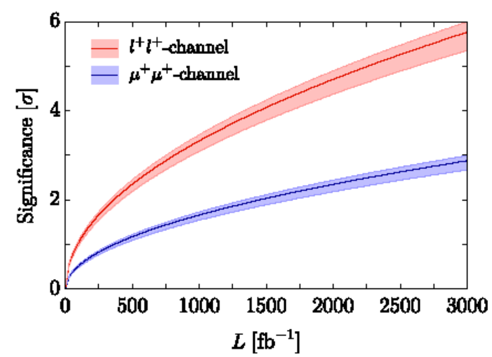
$$a_{\eta l} \approx 0.03$$

JG et al., CERN HL/HE-LHC YR

Asymmetry of a few per cent is observable at the HL-LHC – would be definitive sign of correlations!



CMS-TDR-017-003



Cotogno, Kasemets, Myska,1809.09024

Part II. Soft MPI: Phenomenology and Description in MC Generators

Handling MB/UE

MB/UE: Many scatters at low scale (nonperturbative physics)!

Handle with Monte Carlo event generators. Physics-inspired models with several adjustable parameters.

Treating MB/UE is some mixture of physics input and fitting

MCEG Parameters

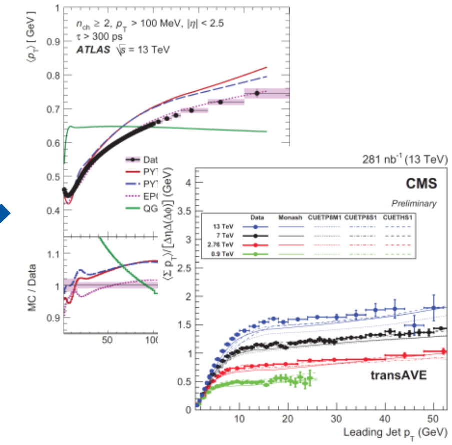
MPI	α_{strong} value at scale $Q^2 = M_Z^2$
MPI	p_{T} cutoff scale
MPI	Energy extrapolation exponent
MPI	Impact parameter/inverse hadron radius dependence
BBR	Primordial/intrinsic k_{T}
BBR	Strength of color reconnection
BBR	Length of color strings
…	…

Handling MB/UE

Monte Carlo Event Generators

MCEG Parameters

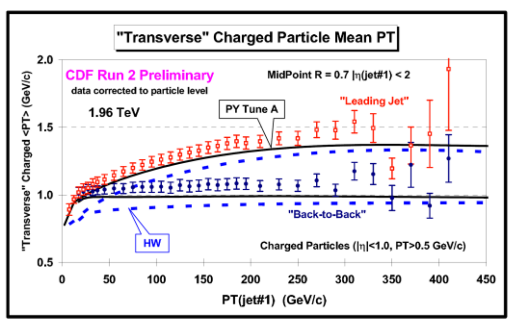
MB/UE Data



Multiple Interaction Model	MPI	$\alpha_{\rm strong}$ value at scale $Q^2 = M_Z^2$
	MPI	$p_{\rm T}$ cutoff scale
	MPI	Energy extrapolation exponent
	MPI	Impact parameter/inverse hadron radius dependence
Colour Reconnection	BBR	Primordial/intrinsic $k_{\rm T}$
	BBR	Strength of color reconnection
Hadronisation model	BBR	Length of color strings

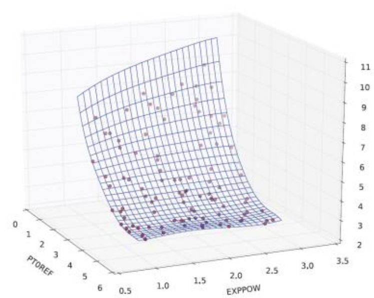
By hand/intuition — TUNING — Parameterisation of MC response

(R. Field,…)



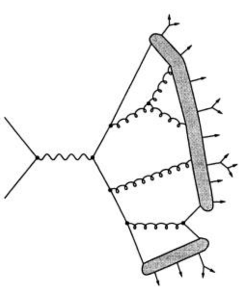
hep-ph/0510198 (2005)

Fitted MC parameters

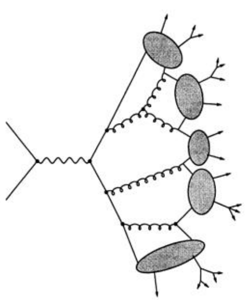


Professor

Buckley, Hoeth, Lacker, Schulz, von Seggern, Eur.Phys.J. C65 (2010) 331-357



String fragmentation (Pythia)

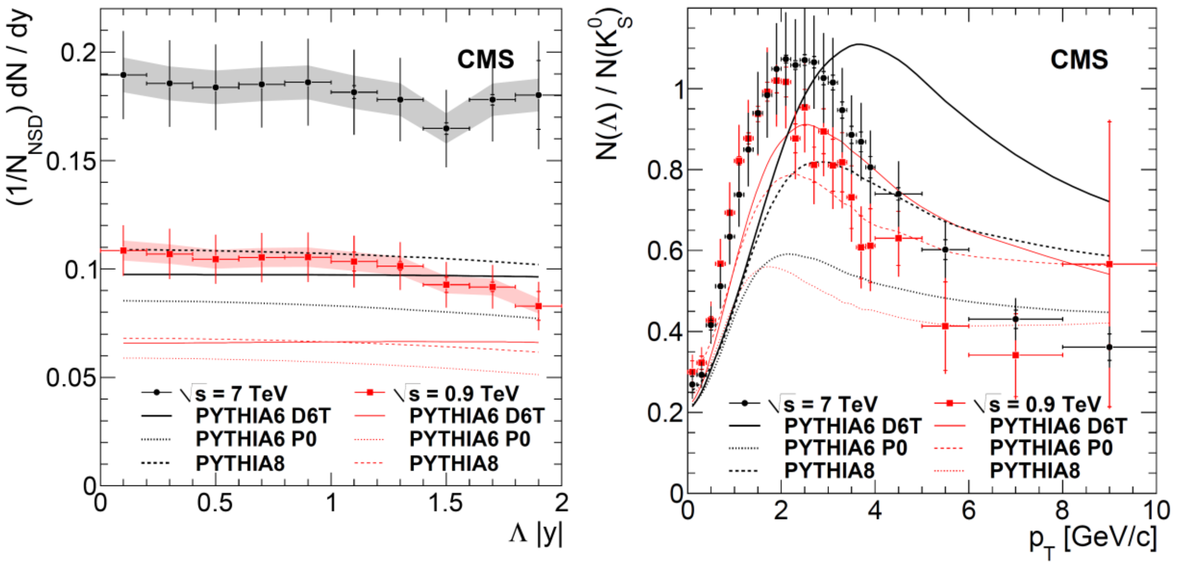


Cluster fragmentation (Herwig)

Handling MB/UE

Many distributions quite well described by the main MC event generators + tuning.

A few problematic distributions, for example related to strange particle production:



$\Lambda = uds$

$$K_s^0 = \frac{d\bar{s} + s\bar{d}}{\sqrt{2}}$$

CMS, JHEP 05 (2011) 064

MPI@LHC 2011, 12

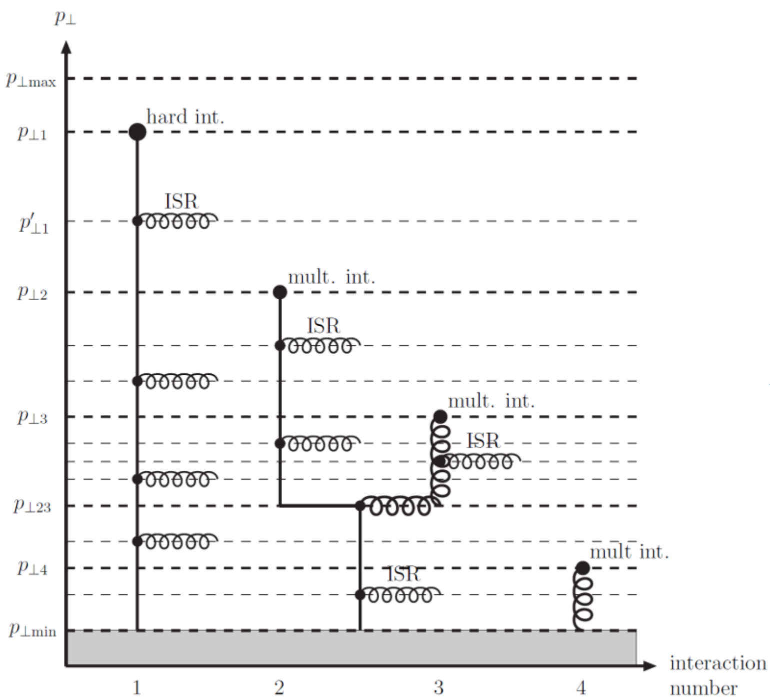
Motivates further development of MC models!
Anyway, always better to have more physics in the models – should enable more accurate extrapolations + ability to fit various different types of distributions.
Much recent work focussed on improving colour reconnection in particular.

Sjöstrand, van Zijl, Phys.Rev. D36 (1987) 2019,
Sjöstrand, Skands, JHEP 0403 (2004) 053
Eur.Phys.J. C39 (2005) 129-154 MPI@LHC 2008

MPI model in Pythia

Use perturbative 2 → 2 QCD scatters for additional scatters, regularise at low $p_\perp^2$:

$$\frac{d\hat{\sigma}}{dp_\perp^2} = \frac{8\pi\alpha_s^2(p_\perp^2)}{9p_\perp^4} \to \frac{8\pi\alpha_s^2(p_\perp^2 + p_{\perp 0}^2)}{9(p_\perp^2 + p_{\perp 0}^2)^2}$$



Evolution of MPI interleaved with initial-state radiation:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp}\right) \exp\left(-\int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp}\right) \mathrm{d}p'_\perp\right)$$

Adjust parton densities ‘after’ each additional scattering to take into account removal of flavour/momentum. E.g. valence quarks:

$$u_{i,\mathrm{val}}(x, Q^2) = \underbrace{\frac{N_{u,\mathrm{val,remain}}}{N_{u,\mathrm{val,original}}}}_{\text{Fraction of valence quarks left after higher-scale scatters}} \frac{1}{X} u_{\mathrm{val}}\left(\frac{x}{X}, Q^2\right) \quad \text{with} \quad X = \underbrace{1 - \sum_{j=1}^{i-1} x_j}_{\text{Mtm fraction left after higher-scale scatters}},$$

Also possibility for an x-dependent proton size, with Gaussian width $a(x) = a_0(1 - a_1 \ln x)$ [Corke, Sjöstrand, JHEP 1105 (2011) 009] MPI@LHC 2010

Borozan, Seymour, JHEP 0209 (2002) 015
Bahr, Gieseke, Seymour, JHEP 0807 (2008) 076

MPI model in Herwig

MPI@LHC 2008

Assume partons uncorrelated & x and **y** dependence factorizable → scatters Poissonian at given impact parameter.

$$\sigma_n = \int d^2b \frac{\bar{n}(b,s)^k}{k!} \exp(-\bar{n}(b,s))$$

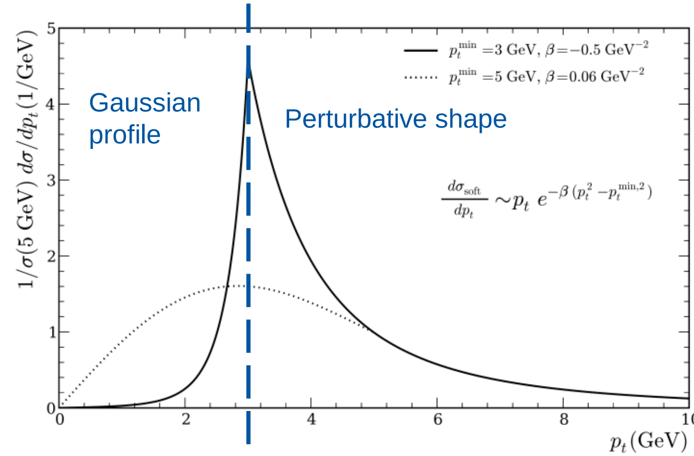
Two components – 'hard' and 'soft', applicable above and below p_t^{min} :

1 2 3 4

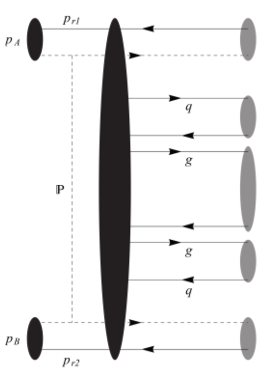
$$\bar{n}(b,s) = A(b,\mu)\sigma_{hard}^{inc}(s,p_t^{min}) + A(b,\mu_{soft})\sigma_{soft}^{inc}$$

Width parameter

Perturbative cross section

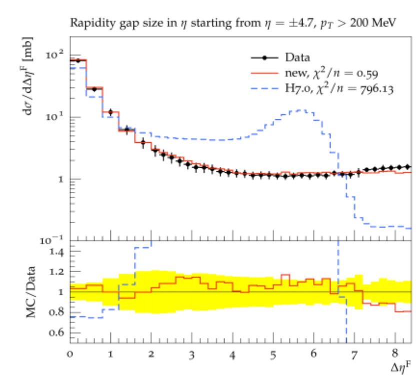


Use σ_{tot} and $\frac{d}{dt}\left(\ln\frac{d\sigma_{el}}{dt}\right)_{t=0}$ to fix 3, 4



Recent development: soft component altered to distribute particles evenly in rapidity according to multiperipheral model + model of diffraction added.

Solved 'bump problem'



Gieseke, Loshaj, Kirchgaeßer,
Eur.Phys.J. C77 (2017) no.3, 156

MPI@LHC 2014-16

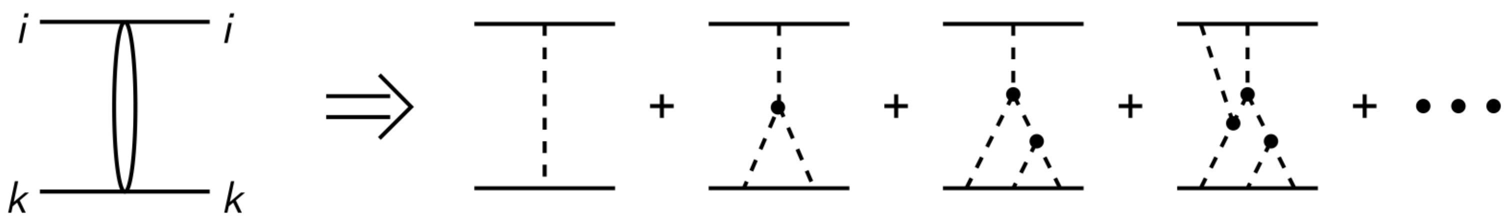
MPI models in SHERPA

AMISIC++ model: simple version of Pythia MPI model

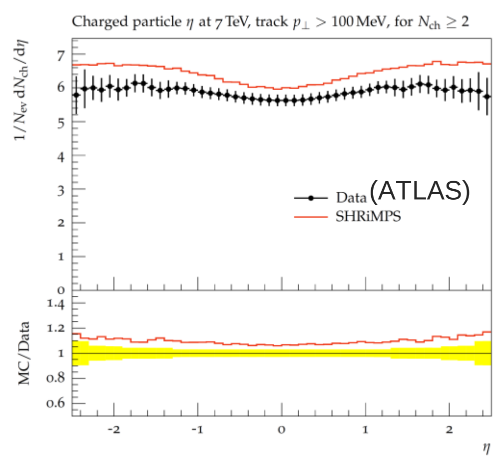
SHRiMPS model: designed to describe MB data

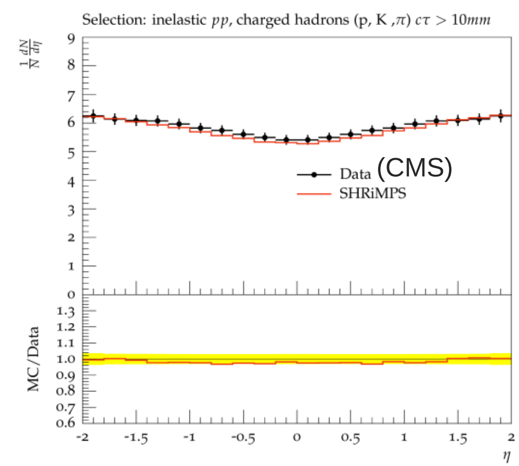
Martin, Hoeth, Khoze, Krauss, Ryskin, Zapp, PoS QNP2012 (2012) 017
MPI@LHC 2010

Uses Khoze-Martin-Ryskin (KMR) model, multi-pomeron scattering



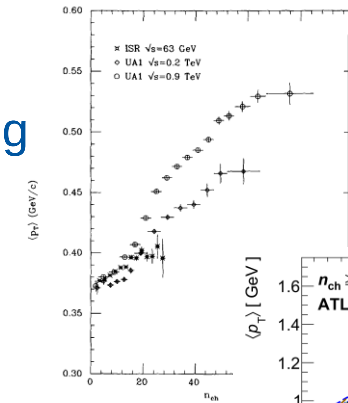
Reasonable description of MB data with only few parameters.



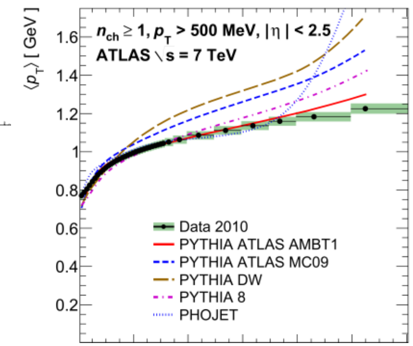


Colour reconnection

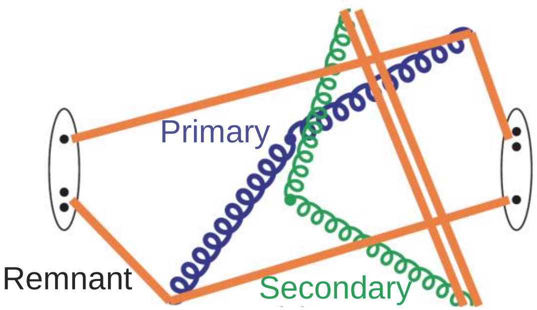
Original motivation for colour reconnection: rising $\langle p_T \rangle(n_{ch})$ at $Sp\bar{p}S$.



UA1, Nucl.Phys. B335 (1990) 261-287



ATLAS, New J.Phys. 13 (2011) 053033



If all MPIs completely independent, each MPI contributes same $\langle p_T \rangle$ and $\langle n_{ch} \rangle \rightarrow$ predicts flat $\langle p_T \rangle(n_{ch})$

If MPIs can ‘reconnect’ in colour in ways such that string length is reduced, each additional MPI contributes same amount to p_T but less and less to $n_{ch} \rightarrow d\langle p_T \rangle / dn_{ch} > 0$

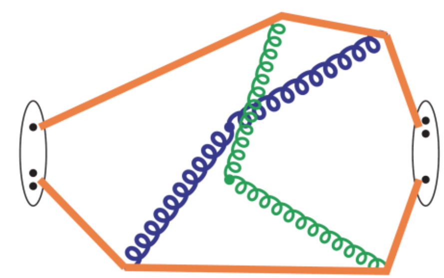


Figure credit: Sjöstrand, arXiv:1706.02166

Colour reconnection in Pythia 8

'MPI-based model' MPI@LHC 2008

MPI with hardness scale $p_\perp$ reconnected with harder system with probability:

$\mathcal{O}(1)$ parameter

$$\mathcal{P} = \frac{p_{\perp Rec}^{2}}{(p_{\perp Rec}^{2} + p_{\perp}^{2})} \qquad p_{\perp Rec} = RR * p_{\perp 0}^{MI}$$

Soft systems reconnect more

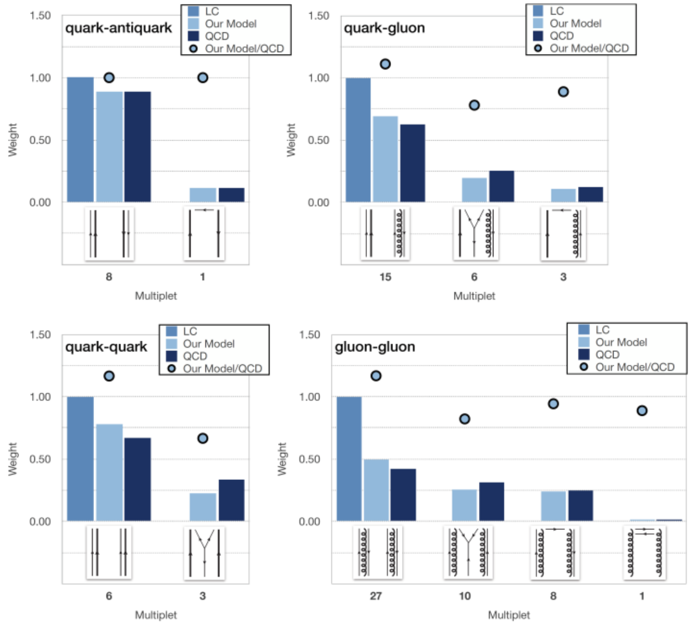
Gluons from softer MPI inserted into harder MPI dipole in such a way to minimise increase in string length λ

'QCD-based model'

Christiansen, Skands, JHEP 1508 (2015) 003
MPI@LHC 2014

Try to incorporate more of the structure of QCD into the description, go beyond leading colour.

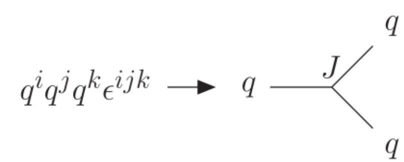
- Establish what kinds of reconnections are allowed, using a simplified model approximating SU(3)



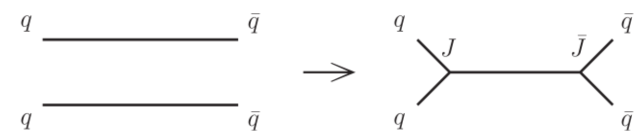
Colour reconnection in Pythia 8

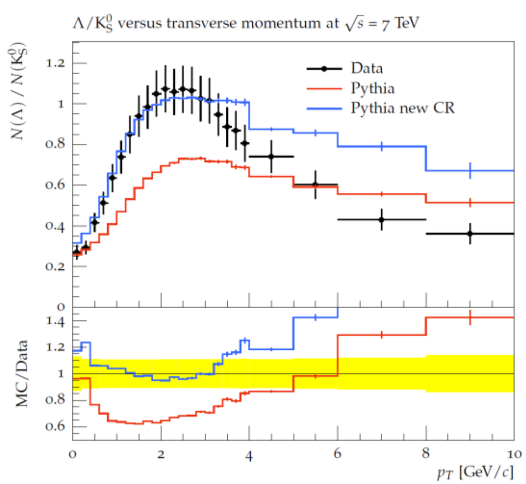
- Use simplistic space-time picture to determine if two strings coexist
- Reconnect colours to minimise string length λ (local deterministic minimisation)

New type of string connection: junction

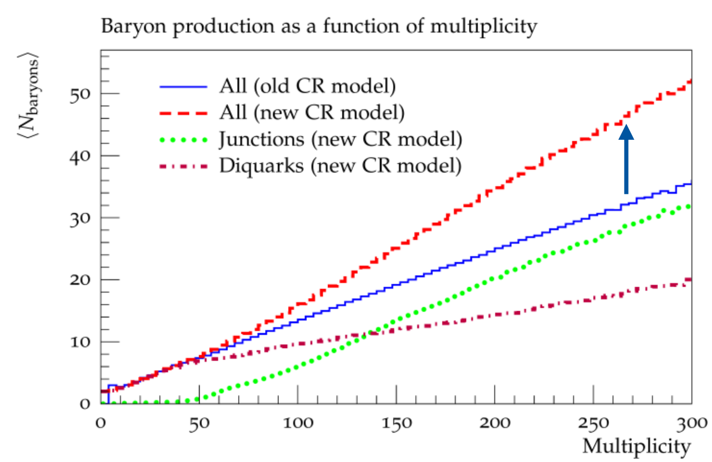


Enables new types of colour reconnection, e.g.





Christiansen, Skands, JHEP 1508 (2015) 003



Better description of Λ/K for $p_T < 5$ GeV

Number of baryons increases faster with multiplicity

Colour reconnection in Herwig

Plain colour reconnection: consider reconnecting $q\bar{q}$ cluster to all other clusters in the event, and accept reconnection that gives minimal cluster masses with probability p_{reco}

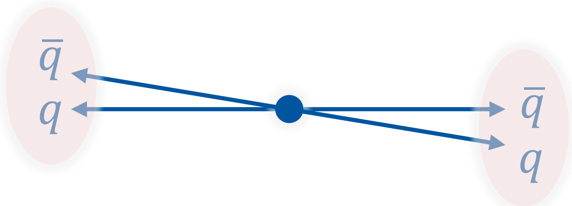
Statistical colour reconnection: similar to PCR, but allows reconnections which increase colour length $\lambda \equiv \Sigma_i m_i^2$ with probability $\exp(-\Delta\lambda/T)$ (simulated annealing).

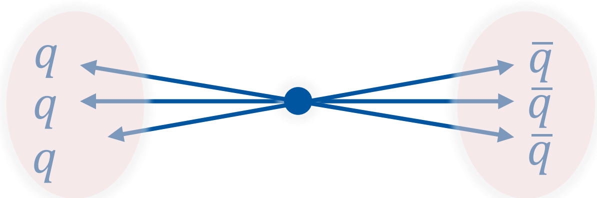
MPI@LHC 2012

Recent developments:

MPI@LHC 2017

Rapidity-based reconnection algorithm, with baryonic clusters:





Consider for mesonic reconnection

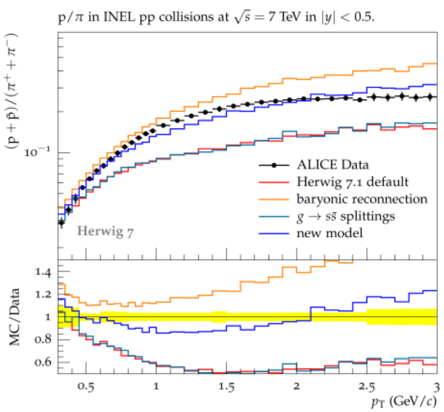
Consider for baryonic reconnection

Clusters with maximal $|y_q| + |y_{\bar{q}}|$ considered for reconnection

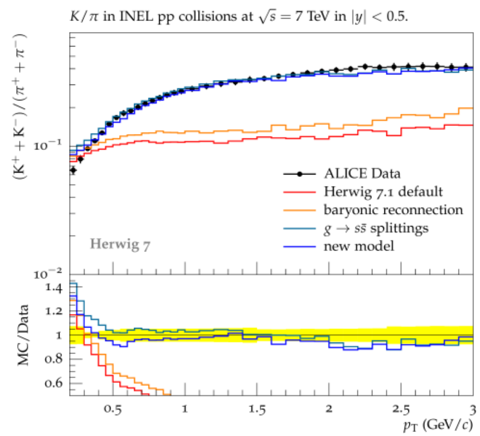
New, more elementary pathway to produce baryons

Gieseke, Plätzer, Kirchgaeßer, **Eur.Phys.J. C78 (2018) no.2, 99**

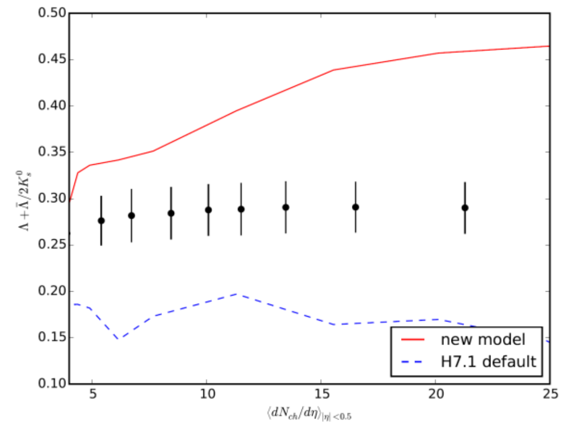
Colour reconnection in Herwig



Improved description of p/π with baryonic clusters



Need nonperturbative $g \longrightarrow s\bar{s}$ splittings to improve agreement for measurements involving strange particles



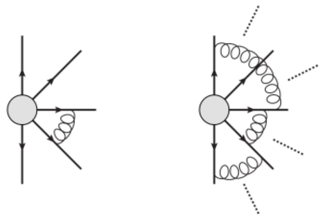
Some data still not described well

Gieseke, Plätzer, Kirchgaeßer, **Eur.Phys.J. C78 (2018) no.2, 99**

Colour reconnection in Herwig

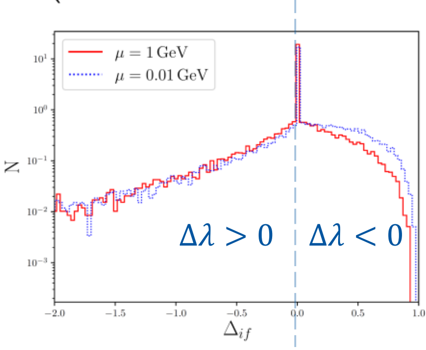
Gieseke, Plätzer, Kirchgaeßer, Siodmok JHEP 1811 (2018) 149, MPI@LHC 2018

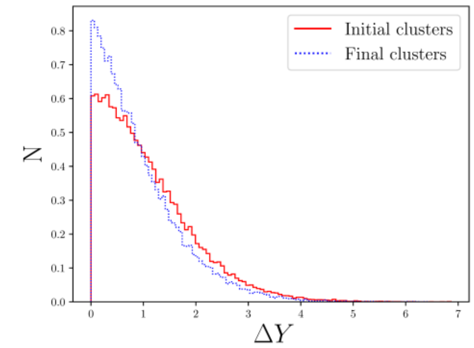
Investigation using perturbative picture extended into NP region – reconnections achieved by soft gluon exchanges:



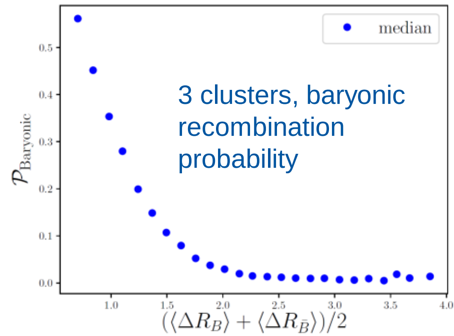
$$\mathbf{U}\left(\{p\},\mu^2,\{M_{ij}^2\}\right) = \exp\left(\sum_{i\neq j}\mathbf{T}_i\cdot\mathbf{T}_j\frac{\alpha_s}{2\pi}\left(\frac{1}{2}\ln^2\frac{M_{ij}^2}{\mu^2} - i\pi\ln\frac{M_{ij}^2}{\mu^2}\right)\right)$$

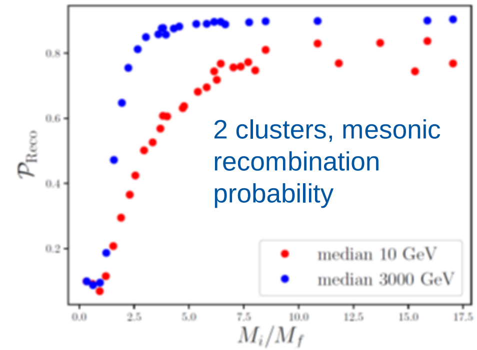
Evolution of a few clusters investigated – perturbative evolution generically reduces λ and ΔY





Not feasible to use on realistic events with many clusters, but recombination probabilities computed using few clusters can be used as input in other models



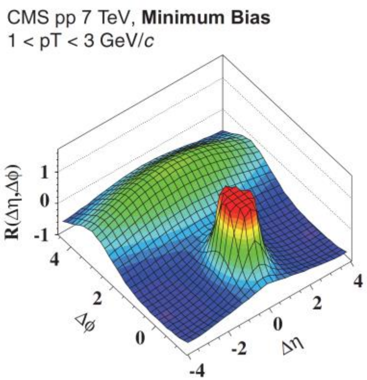


High-multiplicity collisions

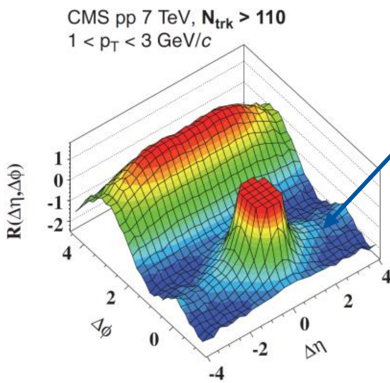
Several interesting phenomena in high-multiplicity pp collisions – seem to resemble those found in heavy ion collisions!

Near-side ridge in two particle correlations

MPI@LHC 2010

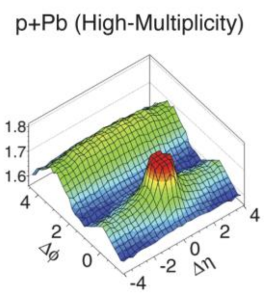


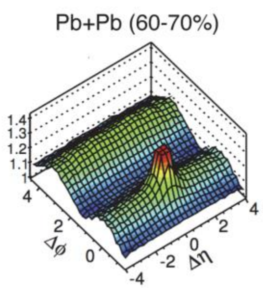
Low multiplicity pp



High multiplicity pp

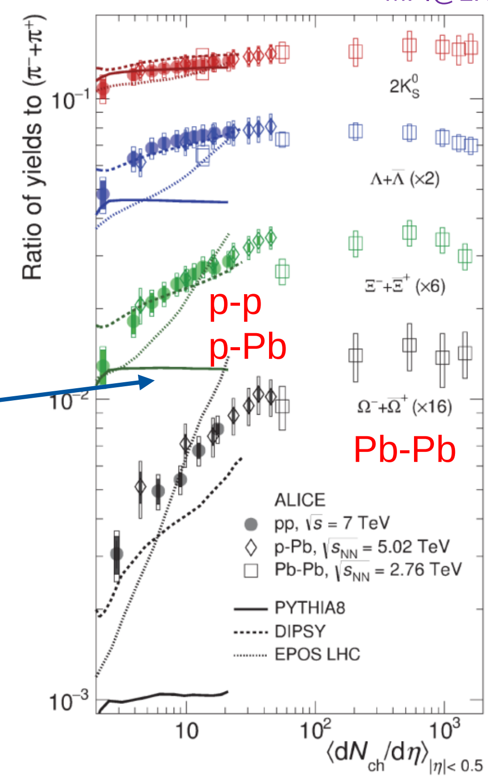
Near side ridge!





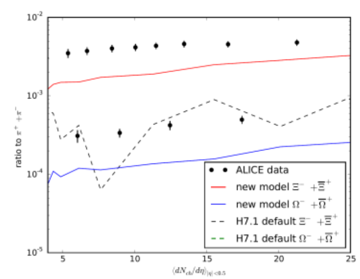
Increasing strangeness fraction with multiplicity

ALICE, Nature Phys. 13 (2017) 535-539
MPI@LHC 2016



p-p
p-Pb
Pb-Pb

Bad description by Pythia

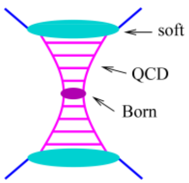


Herwig plot: new CR model seems to help somewhat

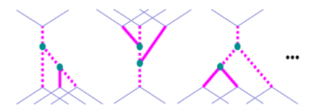
EPOS

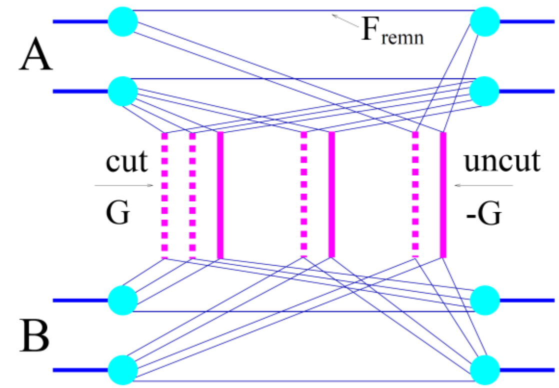
Werner, Guiot, Karpenko,
Knospe, Markert, Pierog,
Sophys, Stefaniak

First step: interactions described using ‘Parton Based Gribov Regge Theory’ (PBGRT) – language in terms of cut and uncut pomerons



Each ‘pomeron’ is a DGLAP ladder with hard scattering in the centre. Saturation effects incorporated in effective way by modifying G



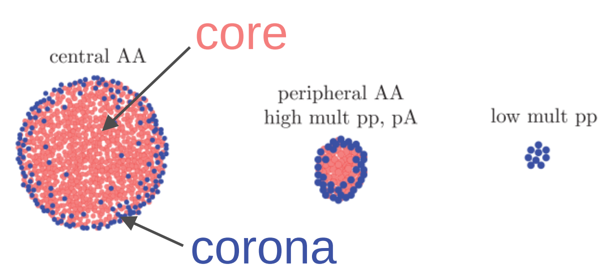


Parton ladders = colour strings/flux tubes

Second step: string segments organised into ‘core’ and ‘corona’ pieces, depending on transverse momentum p_t and local string density ρ

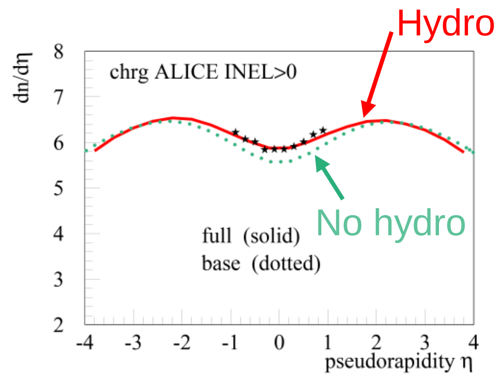
High ρ, small $p_t \rightarrow$ core. Hydrodynamic evolution + hadronic cascade.
Low ρ, large $p_t \rightarrow$ corona. Simply escape as hadrons.

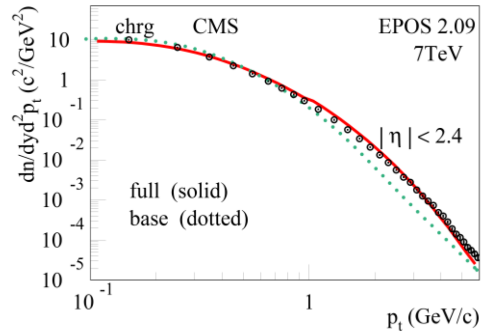
EPOS has core contributions even in high multiplicity *pp*



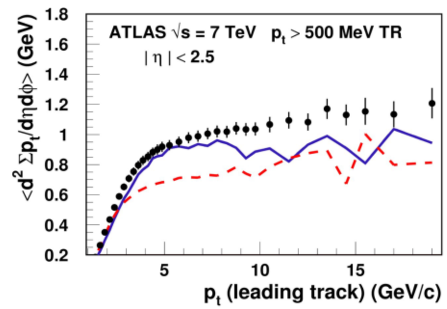
EPOS

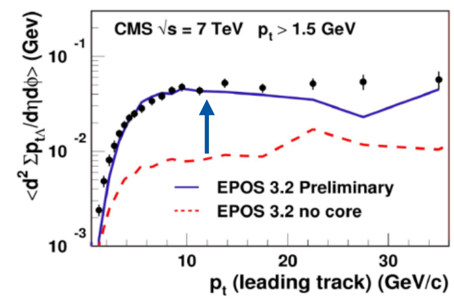
Achieve good description of minimum bias data:





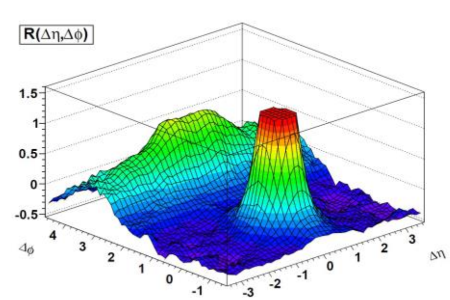
Underlying event also fair. Strangeness production enhanced by collective effects.



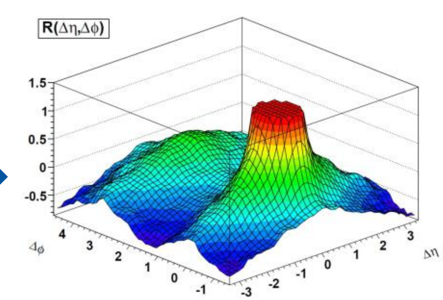


EPOS produces near-side ridge in high multiplicity pp, but only with hydro

Random distribution of flux tubes in transverse space $\rightarrow$ azimuthal asymmetry (ellipse), but longitudinal invariance $\rightarrow$ ridge after hydro



No hydro



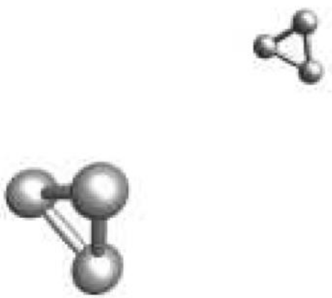
Hydro

DIPSY

Avsar,
Gustafson,
Lonnblad,
…

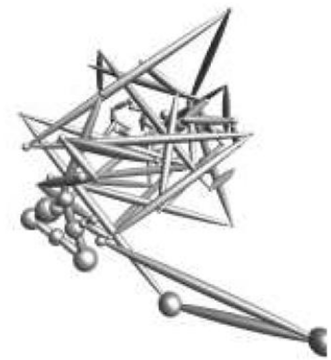
Based on Mueller’s dipole model (LL BFKL in transverse coordinate space), but with various improvements beyond LL:

- Energy-momentum conservation, projectile-target symmetry, running coupling…
- Subleading N_c corrections – the dipole ‘swing’
- Confinement effects



Initial configuration

Just before collision



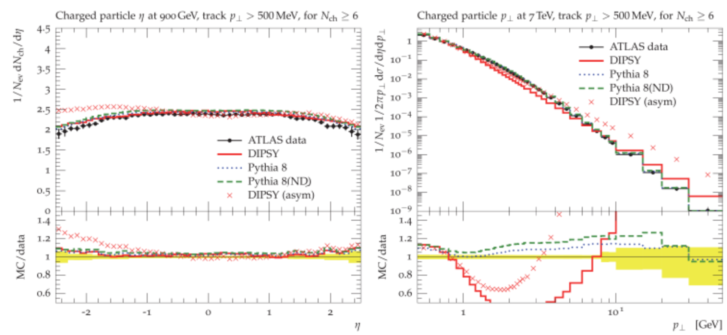
Just after collision

Naturally includes saturation effects and MPI

Only few tuneable parameters

Fair description of minimum bias data (nb DIPSY has only gluons)

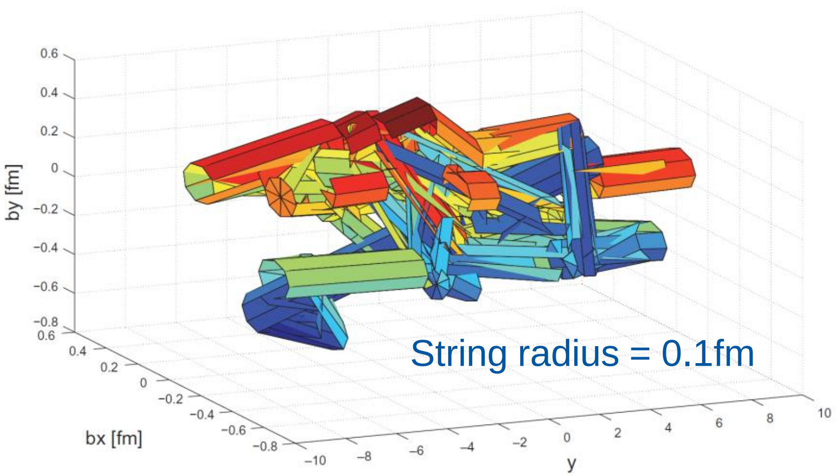
Easily generalised to nuclear collisions



MPI@LHC 2013

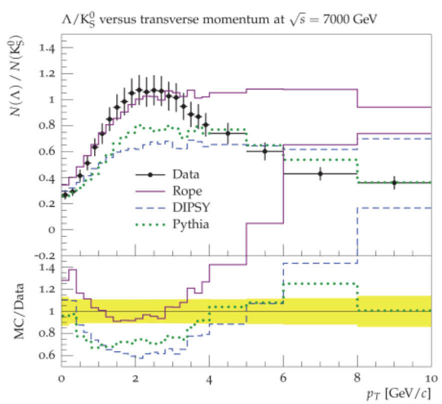
Rope formation

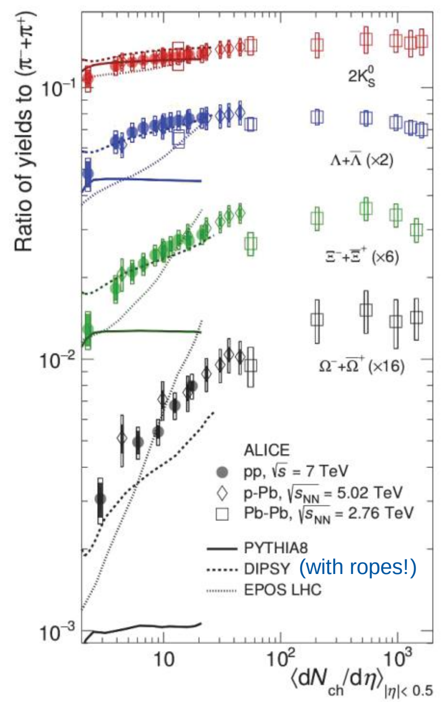
Biro, Nielsen, Knoll, Nucl.Phys. B245 (1984) 449-468
Bierlich, Gustafson, Lönnblad, Tarasov, JHEP 1503 (2015) 148



Density of strings very high in LHC environment – possibility for strings to interact and form ‘colour ropes’ of higher colour representation.

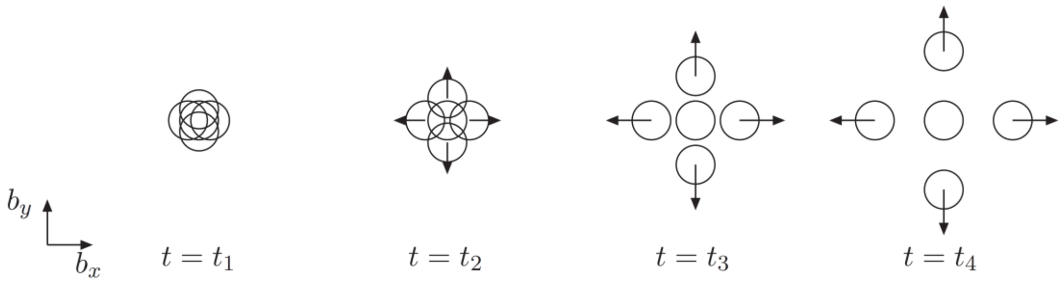
Larger Casimir for higher colour rep → larger string tension → more strange quarks and baryons, in agreement with data.



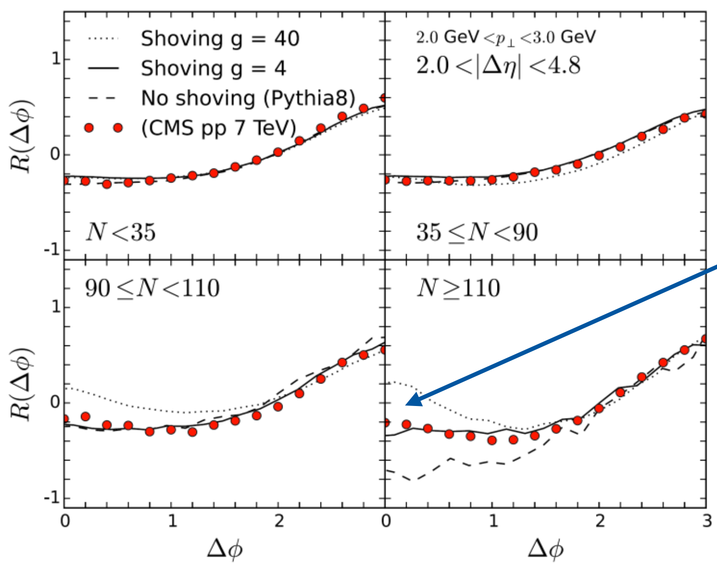


Rope shoving

Higher energy density in string overlap region than outside → dynamically generates pressure → flow effects (but without thermal equilibrium)



Bierlich, Gustafson, Lönnblad arXiv:1612.05132, Phys.Lett. B779 (2018) 58-63

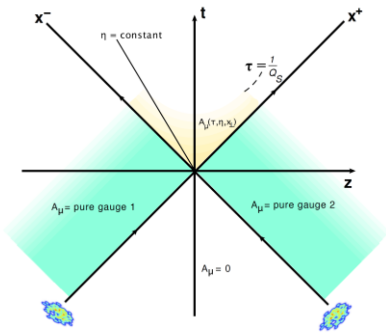


Can induce a near-side ridge!

CGC + Lund model

MPI@LHC 2016

Separation of dynamics between fast and slow partons

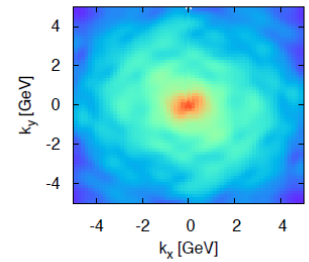


$$J^{\nu} = \delta^{\nu\pm}\rho_{A(B)}(x^{\mp}, \boldsymbol{x}_{\perp})$$

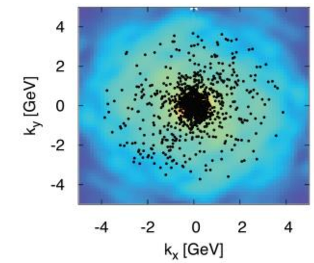
Classical colour field associated with fast partons used as source for classical gluon field of slow partons

$$[D_{\mu}, F_{\mu\nu}] = J_{\nu}$$

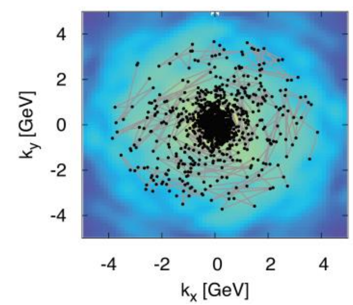
$$\frac{dN}{d\mathbf{k}_T dy}$$



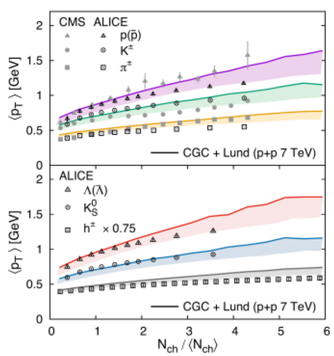
Gluon multiplicity distribution from CGC calculation



Generate gluons from distribution

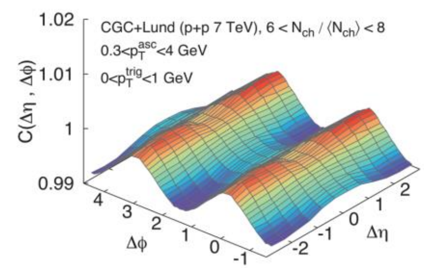


Connect gluons with strings, fragment using Pythia



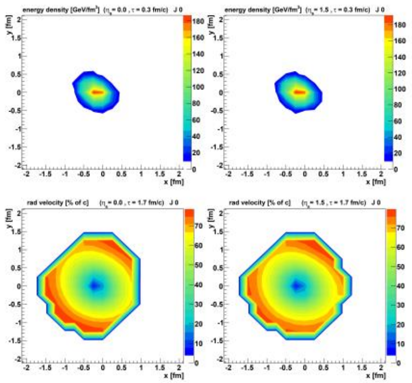
Increase in $\langle p_T \rangle$ with n_{ch} mainly from CGC

Ridge effect from initial state correlations

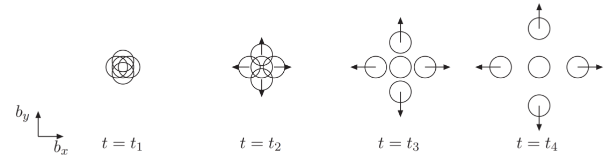


Schenke, Schlichting, Tribedy, Venugopalan, Phys.Rev.Lett. 117 (2016) no.16, 162301

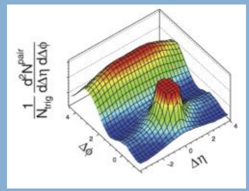
Hydrodynamics/QGP?



String shoving?

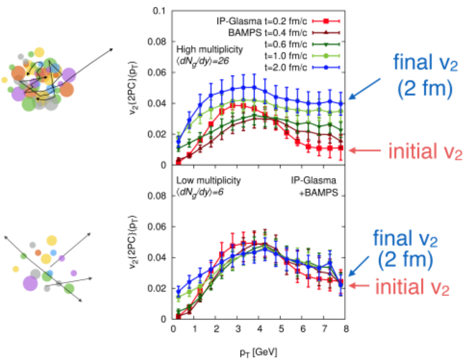


Ridge effect in *pp*



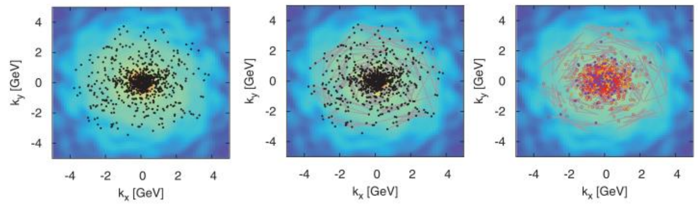
MPI@LHC 2017

Partonic transport?



Greif, Greiner, Schenke, Schlichting, Xu, Phys. Rev. D 96, 091504 (2017)

Initial-state correlations in CGC?



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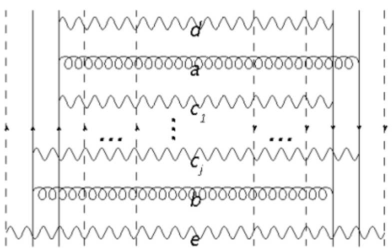
Quantum-mechanical interference effects?



Blok, Jäkel, Strikman, Wiedemann JHEP 1712 (2017) 074

Many interesting developments in MPI physics in the last 10 years.

We look forward to hearing more at this workshop!

CERN

Correlated parton contributions to DPS

There are also contributions to the unpolarised p-p DPS cross section associated with correlations between partons:

e.g. $$\Delta q_1 \Delta q_2 = \underbrace{q_1\!\uparrow q_2\!\uparrow + q_1\!\downarrow q_2\!\downarrow}_{\text{Same spin}} - \underbrace{q_1\!\uparrow q_2\!\downarrow - q_1\!\downarrow q_2\!\uparrow}_{\text{Opposing spin}}$$

Can construct limits on size of colour/spin correlated distributions based on probabilistic picture of parton densities ('positivity bounds'):

Simple case: $|f_{\Delta q \Delta q}| \leq f_{qq}$

More general:

$$\rho = \frac{1}{4}\begin{pmatrix} f_{qq} + f_{\Delta q\Delta q} & -ie^{i\varphi_y} yM f_{\delta qq} & -ie^{i\varphi_y} yM f_{q\delta q} & 2e^{2i\varphi_y} y^2 M^2 f^t_{\delta q\delta q} \\ ie^{-i\varphi_y} yM f_{\delta qq} & f_{qq} - f_{\Delta q\Delta q} & 2f_{\delta q\delta q} & -ie^{i\varphi_y} yM f_{q\delta q} \\ ie^{-i\varphi_y} yM f_{q\delta q} & 2f_{\delta q\delta q} & f_{qq} - f_{\Delta q\Delta q} & -ie^{i\varphi_y} yM f_{\delta qq} \\ 2e^{-2i\varphi_y} y^2 M^2 f^t_{\delta q\delta q} & ie^{-i\varphi_y} yM f_{q\delta q} & ie^{-i\varphi_y} yM f_{\delta qq} & f_{qq} + f_{\Delta q\Delta q} \end{pmatrix} \qquad \sum_{\lambda_1'\lambda_2'\lambda_1\lambda_2} v^*_{\lambda_1'\lambda_2'}\, \rho_{(\lambda_1'\lambda_2')(\lambda_1\lambda_2)}\, v_{\lambda_1\lambda_2} \geq 0$$