Multiple Parton Interactions: Theory Progress

Jonathan Gaunt (U. of Manchester)

MANCHESTER 1824
The University of Manchester

THE ROYAL SOCIETY

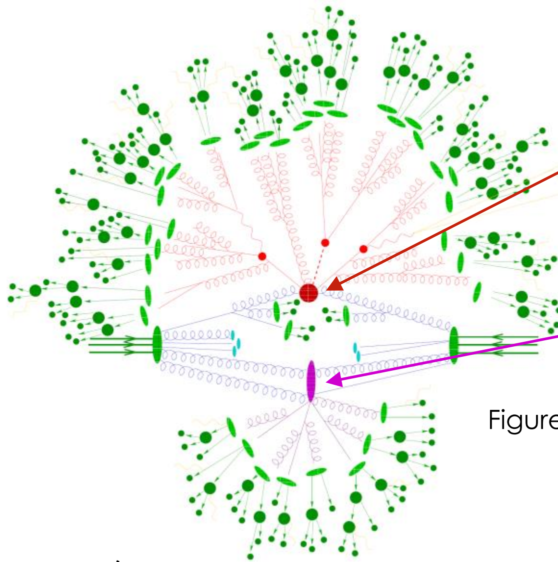
LHCPhysics
Belgrade, 22 - 26 May 2023

LHCP 2023

May 25th 2023

MULTIPLE INTERACTIONS: INTRODUCTION

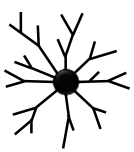
Protons are ‘bags’ of quarks and gluons – multiple interactions likely!



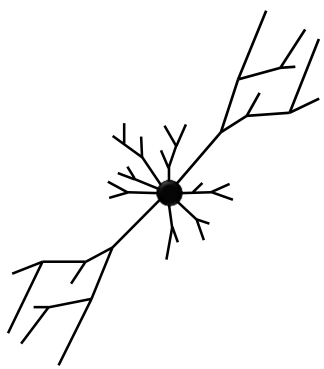
‘Primary process’

Additional scatters

Figure from Höche, 1411.4085

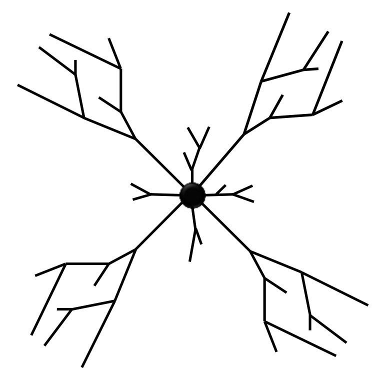


‘Minimum bias’



‘Underlying event’

<u>Ubiquitous!</u>



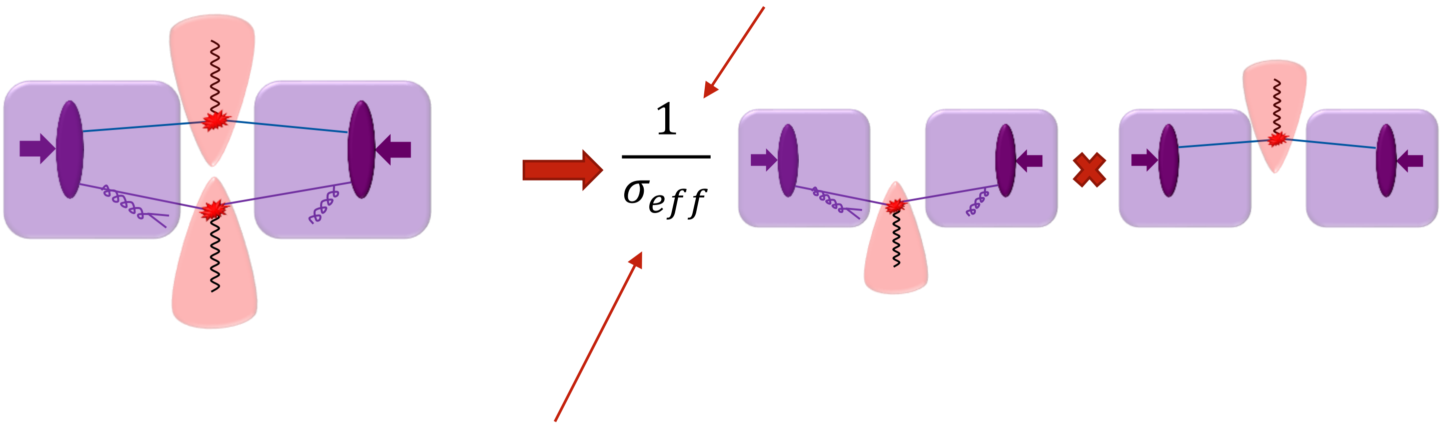
Double hard parton scattering (DPS). Rarer, but measured in several channels.

For a summary see JG, Bartalini (eds.), *Adv.Ser.Direct.High Energy Phys.* 29 (2018)

POCKET FORMULA APPROACH

Crudest model for DPS: ‘Pocket formula’

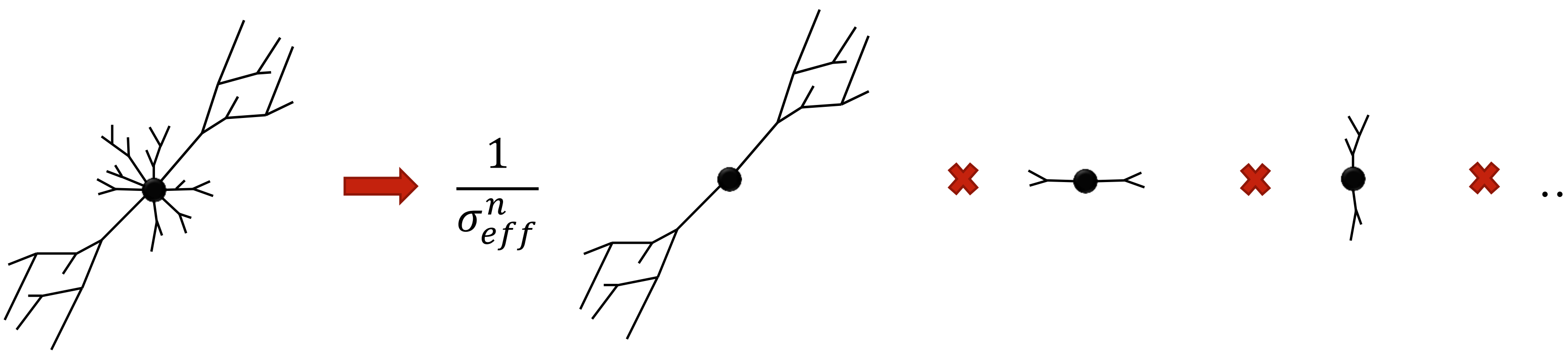
Geometrical factor



Partons fully uncorrelated: $\sigma_{eff} \sim (\text{proton radius})^2 \sim 60\text{mb}$

POCKET FORMULA APPROACH

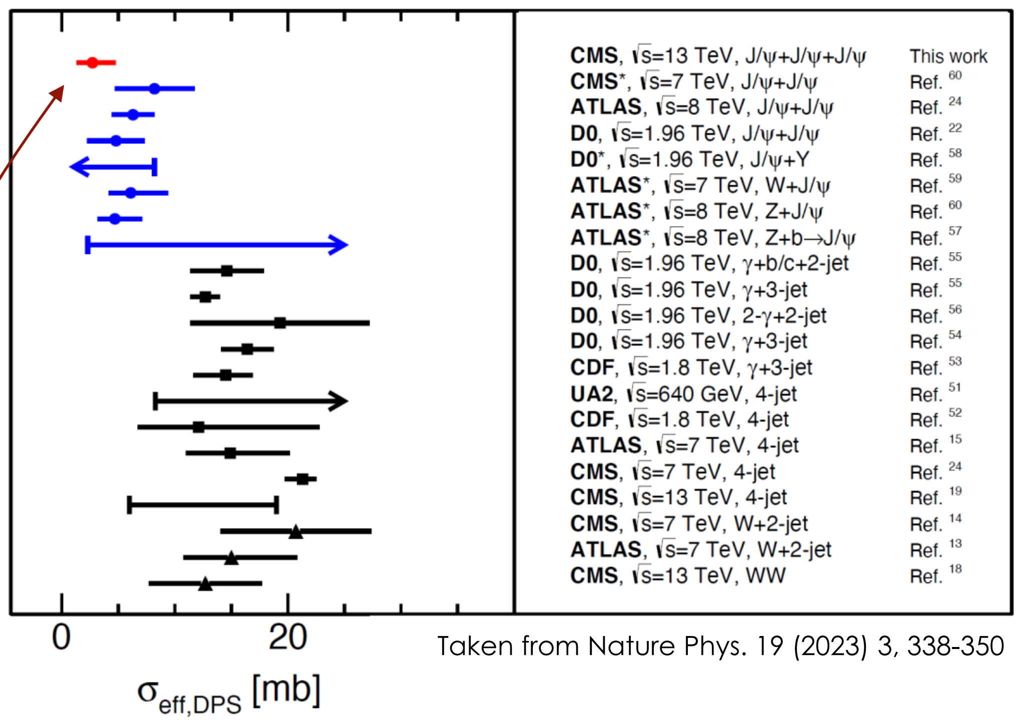
Crudest description of Underlying Event:



Roughly speaking, approach taken by most Monte Carlo event generators

EXPERIMENTAL DATA ON σ_{eff}

Some experimental extractions of σ_{eff}:



Taken from Nature Phys. 19 (2023) 3, 338-350

$\sigma_{eff,DPS} \ll 60\text{mb}!$

σ_{eff} with quarkonium $< \sigma_{eff}$ with high-p_T jets/EW bosons

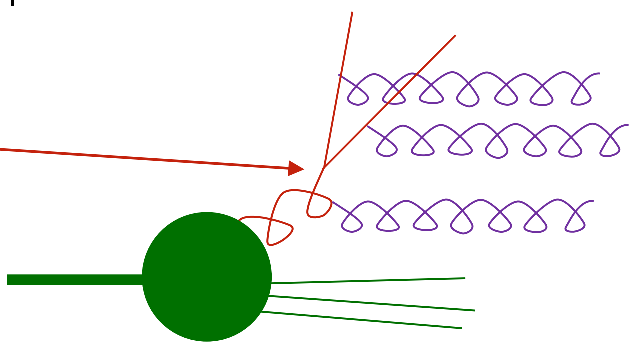
Measurement in triple J/ψ. Process receives contributions from triple parton scattering (TPS)!

CMS, Nature Phys. 19 (2023) 3, 338-350

BEYOND THE POCKET FORMULA

What is missing in simple pocket formula approach?

Perturbative correlations

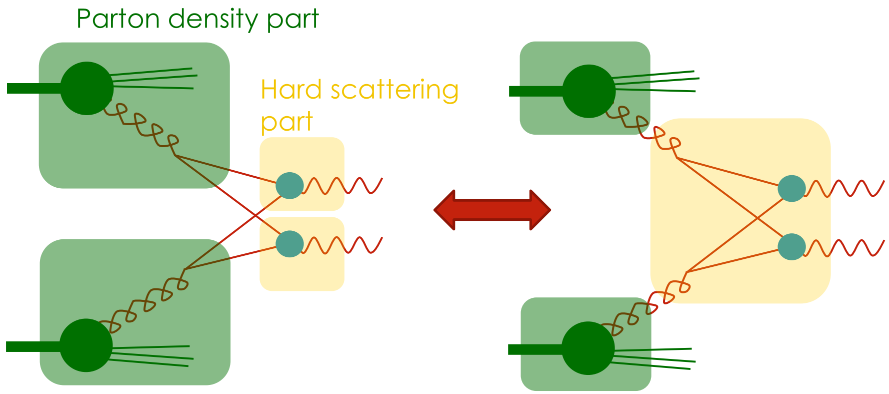


Favours small separation y – reduces $\sigma_{eff,DPS}$

See e.g. Blok et al., *Eur.Phys.J.C* 74 (2014) 2926

Issue with overlap between DPS and loop corrections to single scattering.
Now solved.

Diehl, JG, Schönwald JHEP 1706 (2017) 083.

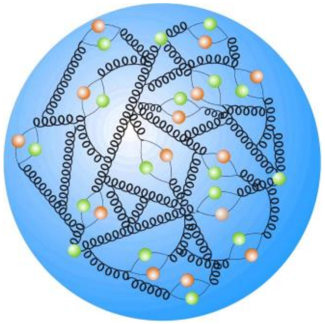


Double scattering Single scattering

BEYOND THE POCKET FORMULA

What is missing in simple pocket formula approach?

Non-perturbative correlations



Correlations in spin and colour between partons

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

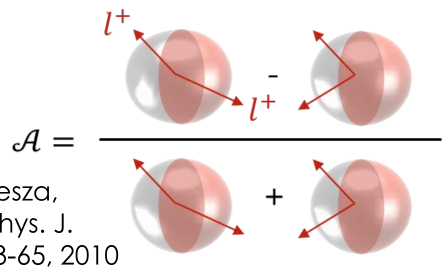
E.g. two quarks may prefer to have their spins aligned ↑↑, or anti-aligned ↑↓

All of these correlations are **intrinsically interesting** – aspect of proton structure not accessible via single scattering

MEASURING CORRELATIONS

Effects of these correlations will be more prominent at HL-LHC where we accumulate more statistics, and study final states in more detail

E.g. same-sign WW

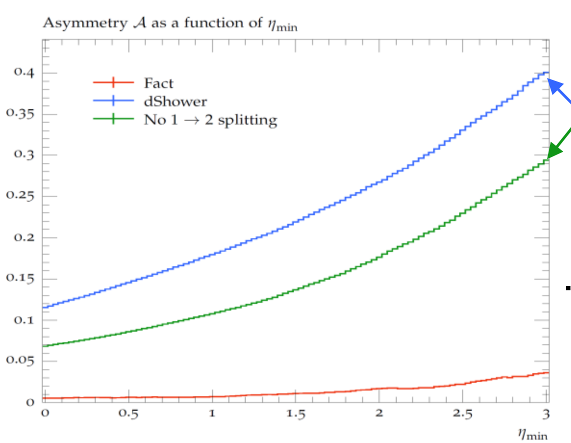


JG, Kom, Kulesza, Stirling, Eur. Phys. J. C69 (2010) 53-65, 2010

$\lvert\eta_i\rvert$	> 0	> 0.6	> 1.2
A	0.07	0.11	0.16
σ [fb]	0.51	0.29	0.13

Spin correlations: ~10% effect

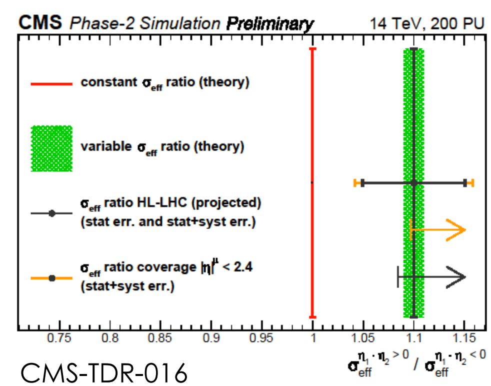
Cotogno, Kasemets, Myska, Phys.Rev. D100 (2019) 1, 011503, JHEP 10 (2020) 214



JG, Cabouat, Ostrolenk, JHEP 11 (2019) 061

Valence number constraints

+ pQCD correlations



CMS-TDR-016

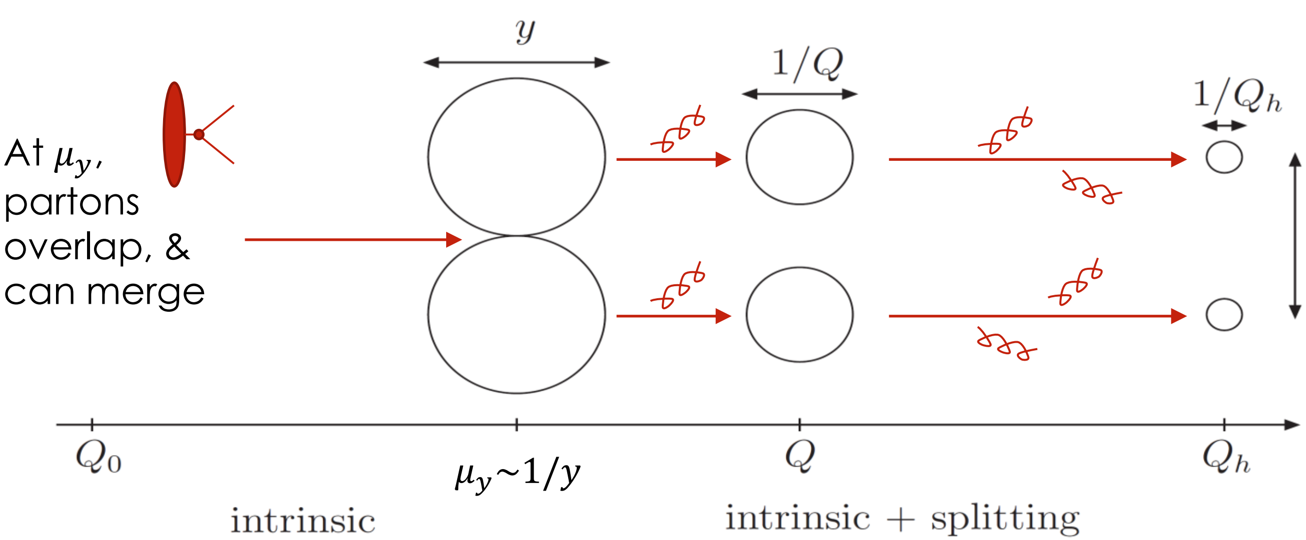
$\mathcal{A}$ values of a few per cent will be measurable at HL-LHC!

NEW TOOLS

dShower:
New Monte Carlo simulation of double scattering

- Proper account of **perturbative correlations**
- Non-perturbative correlations via input double parton densities

JG, Cabouat, Ostrolenk, JHEP 11 (2019) 061



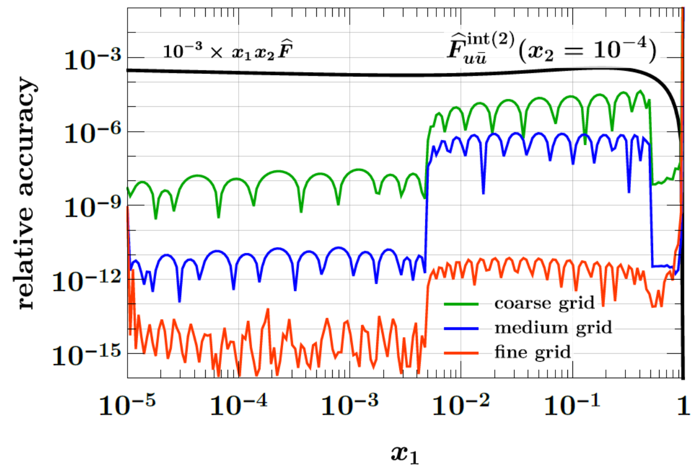
Methodology developed to combine single and double scattering in shower without double counting

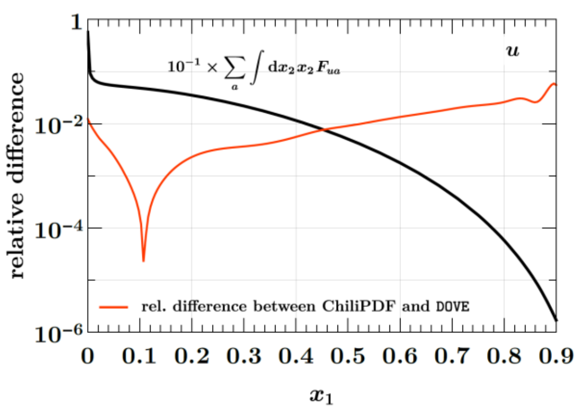
JG, Cabouat, JHEP 10 (2020) 012

NEW TOOLS

Diehl, Nagar, Plößl, Tackmann, arXiv:2305.04845

ChiliPDF:
Evolution + interpolation of double parton densities via Chebyshev polynomials.
Accurate interpolation even with relatively few points.





Cross-checked against existing DOVE code

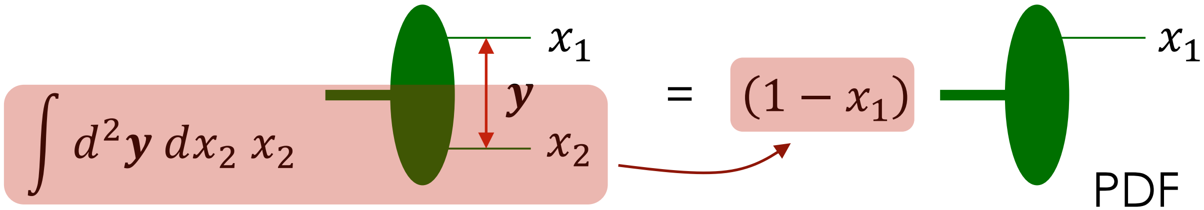
JG, Stirling, JHEP 03 (2010) 005
Diehl, JG, Schönwald JHEP 1706 (2017) 083

PROGRESS: NONPERTURBATIVE

SUM RULES

Double parton densities should obey momentum and valence number constraints.

Sum rules for double parton densities:



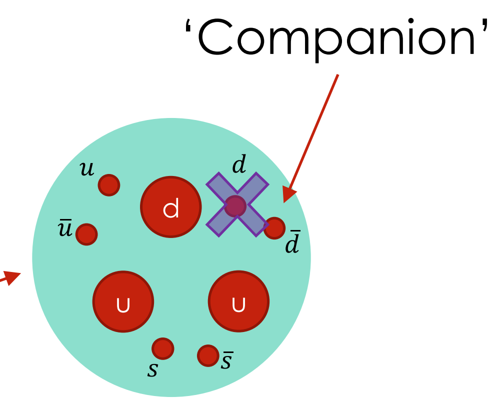
JG, Stirling, JHEP 03 (2010) 005
Blok et al., Eur.Phys.J.C 74 (2014) 2926
Diehl, Plößl, Schäfer, Eur.Phys.J.C 79 (2019) 3, 253

Pythia MPI model:

Sjostrand, Skands, JHEP 03 (2004) 053 , Eur.Phys.J.C 39 (2005) 129-154

Sequence of interactions ordered in hardness.

Number/momentum constraints taken account of by adjusting PDFs after each interaction.



SUM RULES: PYTHIA

How well do Pythia double parton distributions satisfy sum rules?

JG, Fedkevych, JHEP 02 (2023) 090

x_1	Momentum sum rule ($j_1 = u$). Should = 1.	$\bar{u}u$ number sum rule. Should = 3.
10^{-6}	0.979	2.961
10^{-3}	0.980	3.351
10^{-1}	1.014	3.491
0.2	1.047	3.580
0.4	1.133	3.858
0.8	1.679	7.048

Sum rules mostly satisfied at 10-25% level

Some larger deviations, particularly at large x

Derived sum rules for triple parton distributions and checked Pythia model.

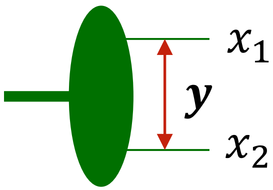
Similar picture.

$x_2 = 10^{-4}$

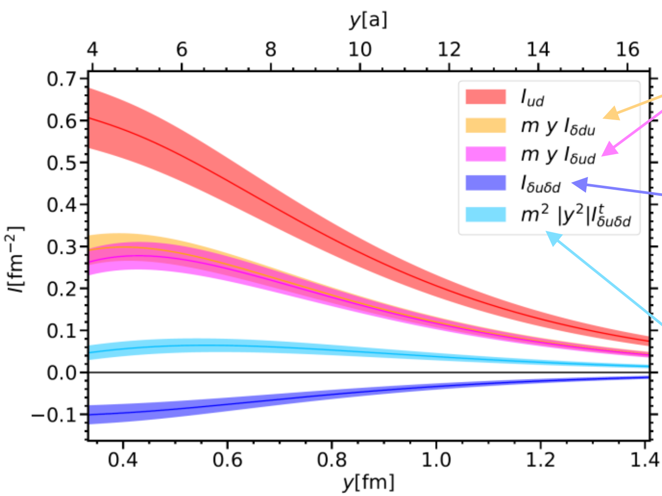
x_1	Momentum sum rule ($j_1 = j_2 = u$). Should = 1.	uuu number sum rule. Should = 0.
10^{-6}	0.965	0.108
10^{-3}	0.967	-0.276
10^{-1}	0.998	-0.232
0.2	1.029	-0.242
0.4	1.117	-0.317
0.8	1.719	-0.589

LATTICE CALCULATION OF DPDS

Calculation of lowest Mellin moment: $I(y^2) = \int dx_1 dx_2$



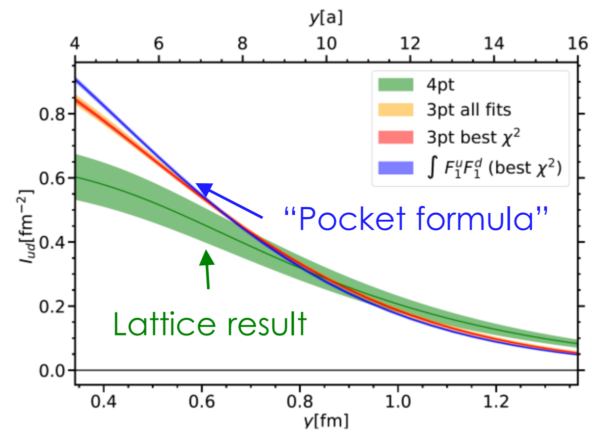
Bali et al., JHEP 09 (2021) 106



Correlation between one transverse spin and $\boldsymbol{y}$

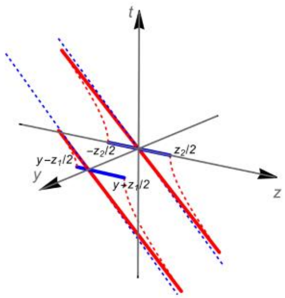
Correlation between transverse spins

Correlation between transverse spins and $\boldsymbol{y}$



In principle possible to access x_1, x_2 dependence of double parton distributions on lattice via quasi-PDF approach.

Zhang, arXiv:2304.12481
Jaarsma, Rahn, Waalewijn, arXiv:2305.09716

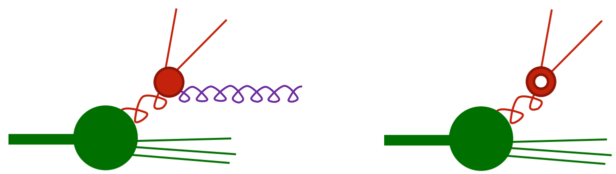


PROGRESS: PERTURBATIVE

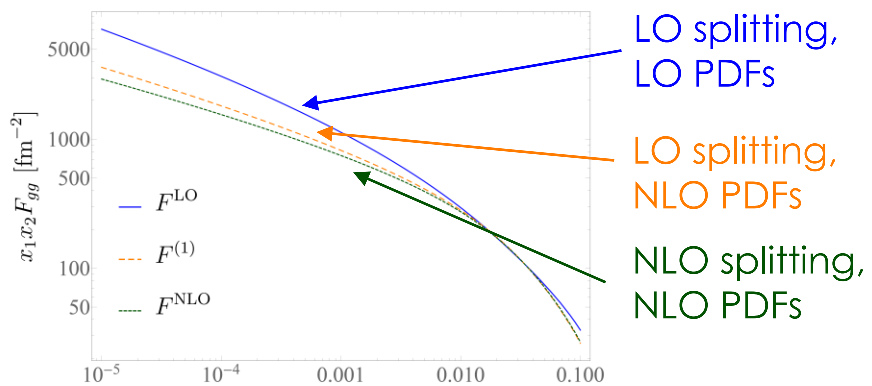
HIGHER ORDERS

Significant progress towards NLO computations for double scattering:

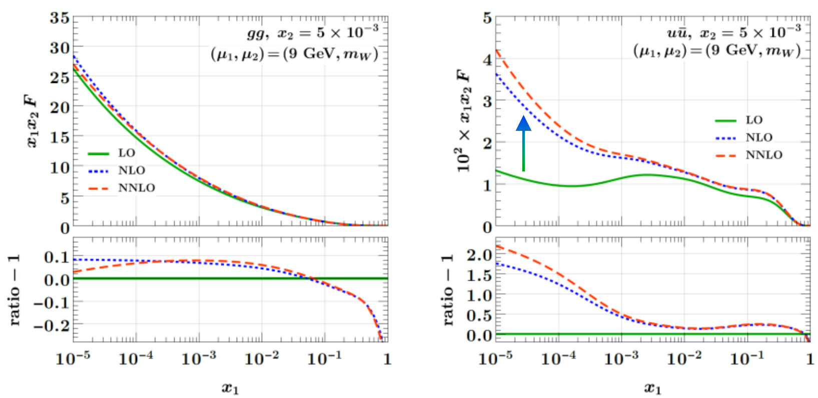
Perturbative correlations computed at NLO.



Diehl, JG, Plößl, Schäfer, SciPost Phys. 7 (2019) 2, 017

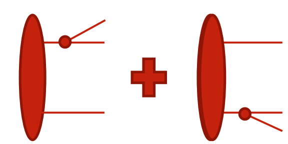


$x_1 = x_2$



(Double) DGLAP evolution evaluated beyond LO for first time in ChiliPDF

Diehl, Nagar, Plößl, Tackmann, arXiv:2305.04845

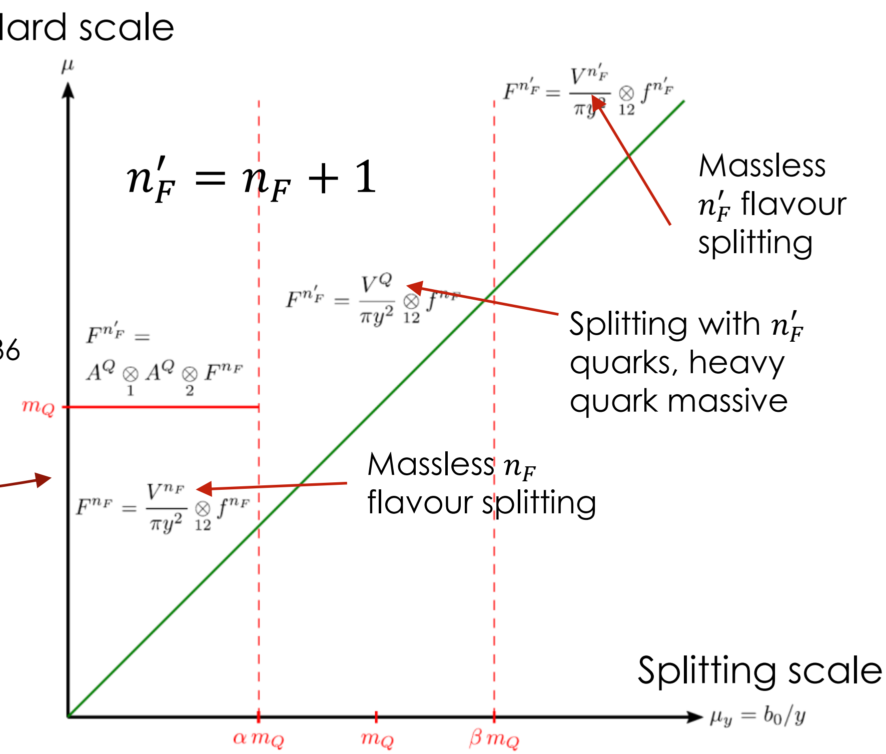


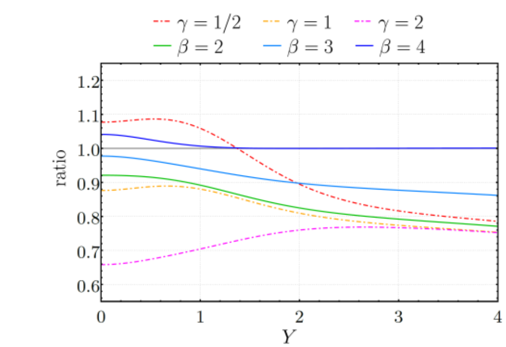
No full NLO predictions of DPS yet…

MASS EFFECTS IN PERTURBATIVE SPLITTING

Two schemes developed to include heavy quarks in perturbative splitting, "massless" and "massive" schemes.

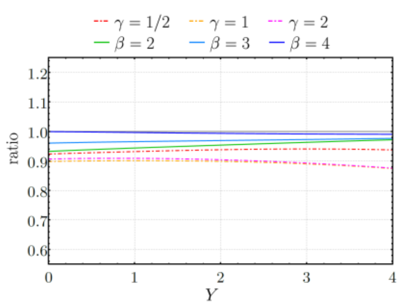
Diehl, Nagar, Plößl, arXiv:2212.07736





(c) $c\bar{c}b\bar{b}$, 2v1

$$r(\beta) = \frac{\mathcal{L}_{\text{massive}}(1/\alpha = \beta)}{\mathcal{L}_{\text{massive}}(\alpha = 1/4, \beta = 2)}\,, \qquad r(\gamma) = \frac{\mathcal{L}_{\text{massless}}(\gamma)}{\mathcal{L}_{\text{massive}}(\alpha = 1/4, \beta = 2)}\,,$$



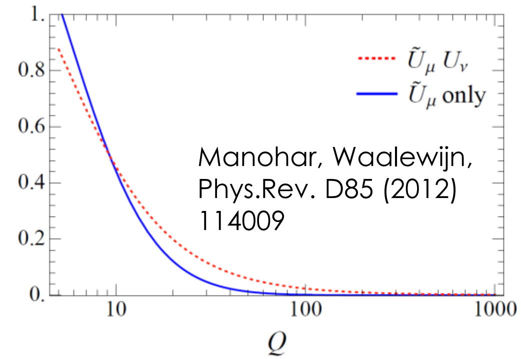
(b) $cbgg$, 1v2

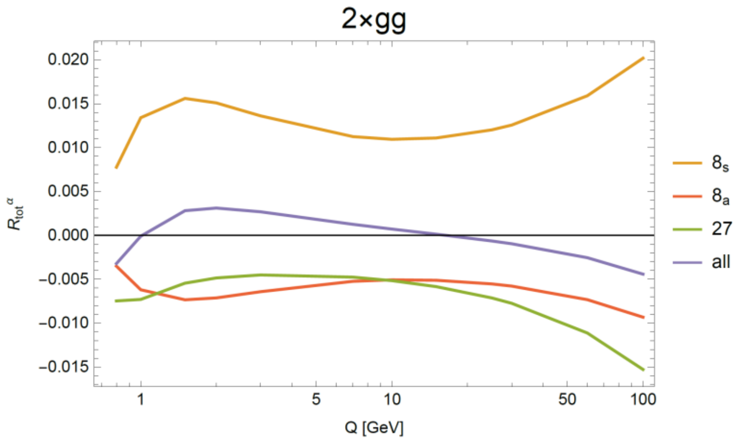
Predictions of schemes compared at level of DPS luminosities

COLOUR CORRELATIONS

Colour correlations: decrease rapidly with scale, could be relevant at intermediate scale.

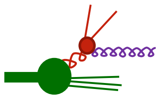
Colour interference suppression factor





Exception: interplay between perturbative and colour correlations for coloured particle production. Few % effect.

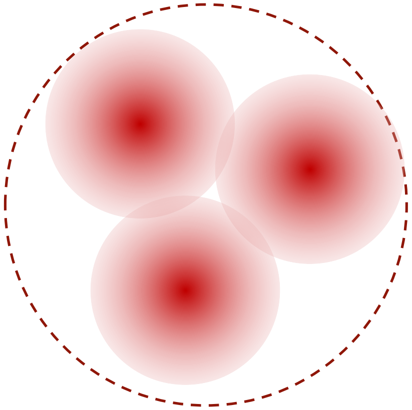
Blok, Mehl, arXiv:2210.13282



Colour correlations in perturbative splitting (Diehl, JG, Plößl, JHEP 08 (2021) 040), and DGLAP evolution (Diehl, Fabry, Vladimirov, JHEP 05 (2023) 067), computed at NLO

DPS & NUCLEAR STRUCTURE MODELS

Double scattering data can be a valuable input to models of nuclear structure.



E.g. hot spot model developed in Mäntysaari et al. Phys. Lett. B 833 (2022), 137348, Phys. Rev. D 106 (2022) no.7, 074019. Two choices of parameters with $N_q = 3$ and $N_q = 7$ give agreement with DIS data.

In Blok, Segev, Strikman Eur.Phys.J.C 83 (2023) 5, 415, σ_{eff} values are computed from this model:

$$N_q = 3: \quad \sigma_{eff} = 10.5 \text{ mb}$$
$$N_q = 7: \quad \sigma_{eff} = 17 \text{ mb}$$

Tension with data (esp. when including PT correlations)

SUMMARY

- Spectrum of multiple parton interactions: **underlying event/minimum bias** (soft) and **double parton scattering** (hard).
- Simplest approach to multiple parton interactions is **pocket formula: ignore all correlations.**
- Misses **nonperturbative** and **perturbative** correlations, also in **spin and colour**.
- Existing data shows **tension with pocket formula predictions**, and future statistics should allow a **more detailed probe of correlations** → motivation to improve theory predictions and tools.
- New tools: **dShower, ChiliPDF**
- Improvements to understanding/modelling of nonperturbative correlations: **sum rules, lattice calculations**.
- Improvements to description of perturbative correlations: **higher orders**, **mass effects**.
- Improvements to theoretical description of **colour correlations**.