Double parton scattering and forward physics measurements

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Forward Physics and QCD at the LHC and EIC

Bad Honnef, Germany, 24/10/23

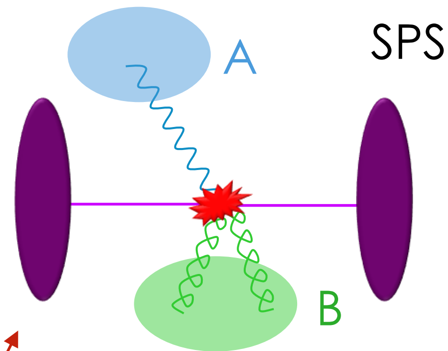
OUTLINE

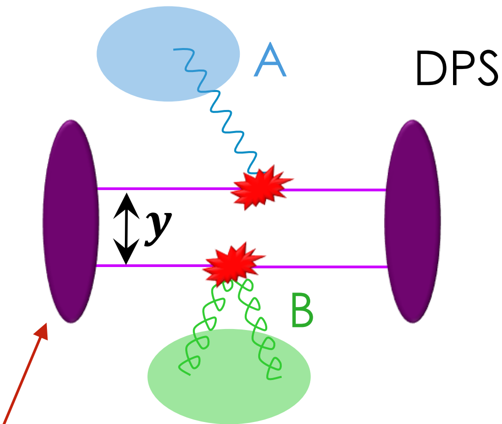
- General introduction to double parton scattering (DPS): what is it, why is it relevant/interesting. A little on theory of DPS.

- Why is DPS relevant in the forward region? What can we learn about DPS from measurements in the forward region?

DOUBLE PARTON SCATTERING: BASICS

Certain sets of scattering products can be formed either from one hard collision (SPS), or two separate hard collisions (double parton scattering, DPS):





Parton density functions (PDFs) Double parton densities (DPDs)

DPS cross section formula (schematic!):

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

Double parton density (DPD)

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))

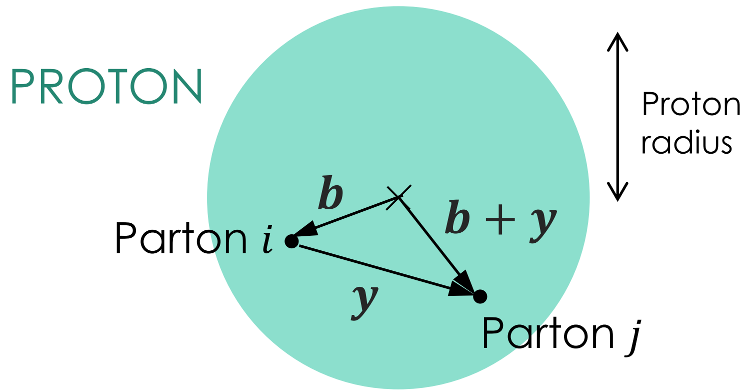
DPS 'POCKET FORMULA'

Crudest model for DPS:

(1) Ignore correlations between partons

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

GPD



(2) Assume GPD can be written as $f^i(x_1, \boldsymbol{b}) = f^i(x_1) G(\boldsymbol{b})$

$$\longrightarrow \boxed{\sigma_D^{(A,B)} = \frac{\sigma_S^{(A)}\sigma_S^{(B)}}{\sigma_{\text{eff}}}} \longrightarrow \sigma_D \sim \sigma_S \frac{\Lambda^2}{Q^2}$$

"DPS pocket formula"

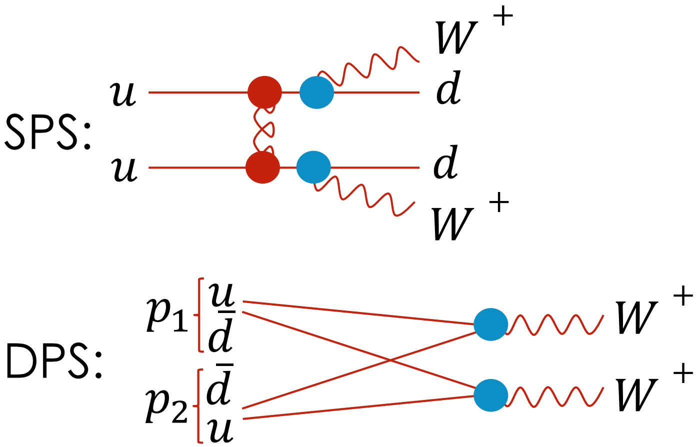
$[\sigma_{\text{eff}} \approx 10 - 20\text{ mb}]$

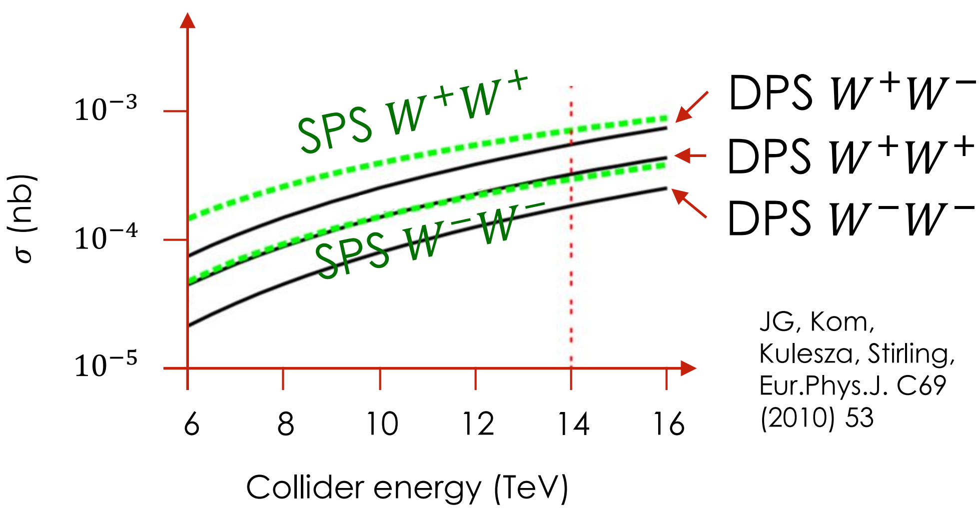
Why then should we care about DPS?

WHY STUDY DPS?

(1) DPS can be a significant background to processes suppressed by small/multiple coupling constants.

'Classic' SM example: same-sign WW production.





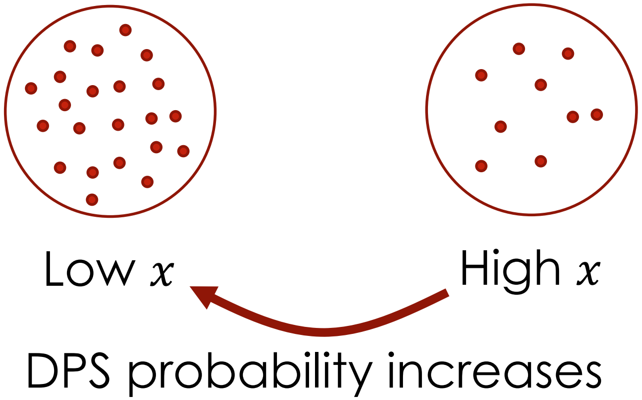
JG, Kom, Kulesza, Stirling, Eur.Phys.J. C69 (2010) 53

N.B. same-sign dilepton production an important channel for various new physics searches (doubly charged Higgs, SUSY,…)

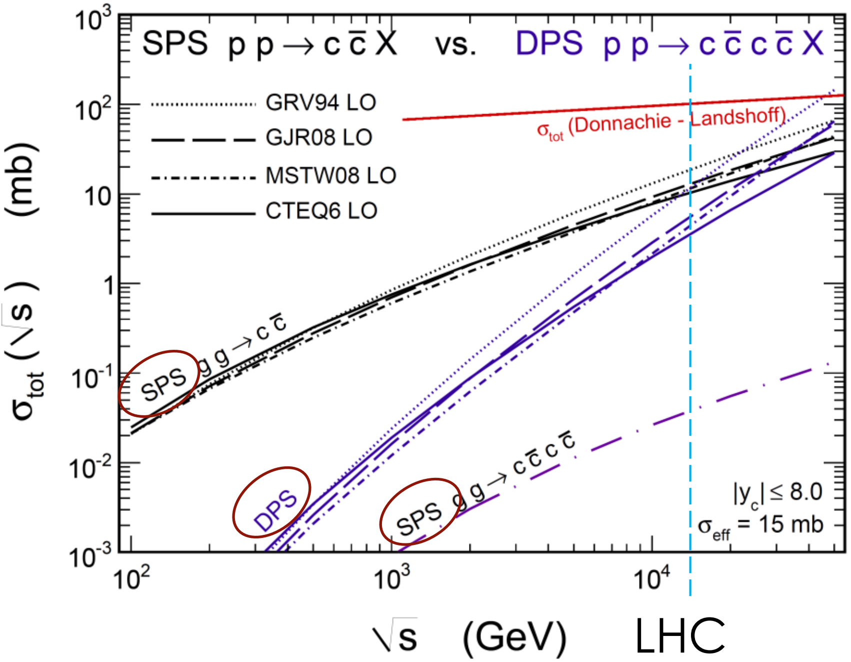
WHY STUDY DPS?

(2) DPS grows faster than SPS as collider energy grows.

For a process with given scale, an increase in collider energy means a decrease in x



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



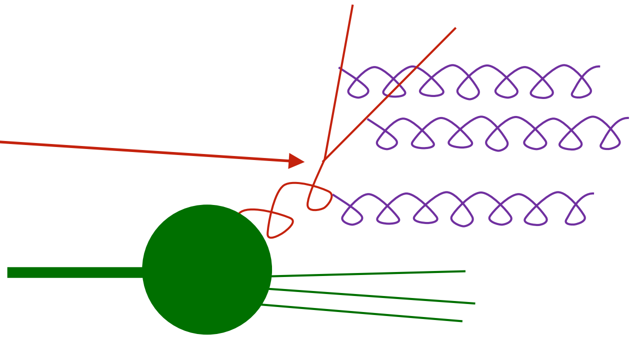
Growth particularly strong for low-scale processes

DPS particularly important for processes involving charm and bottom quarks. '10% of all "hard" events have an additional charm pair' v. *Belyaev, MPI@LHC 2017*

BEYOND THE POCKET FORMULA

What is missing in simple pocket formula approach?

Perturbative correlations

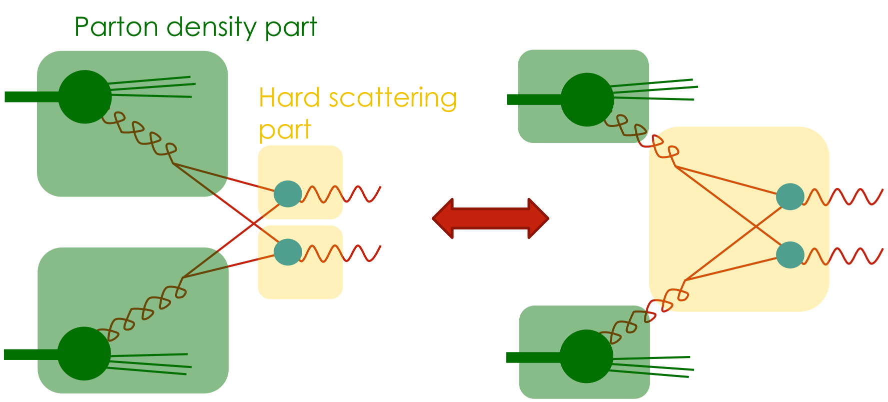


Favours small separation y – reduces $\sigma_{eff,DPS}$

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.

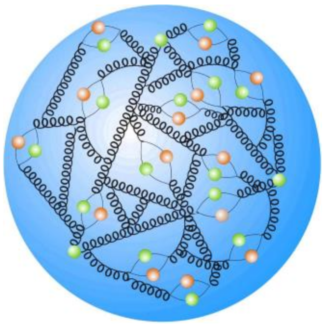


Double scattering Single scattering

BEYOND THE POCKET FORMULA

What is missing in simple pocket formula approach?

Non-perturbative correlations



Correlations in spin and colour between partons

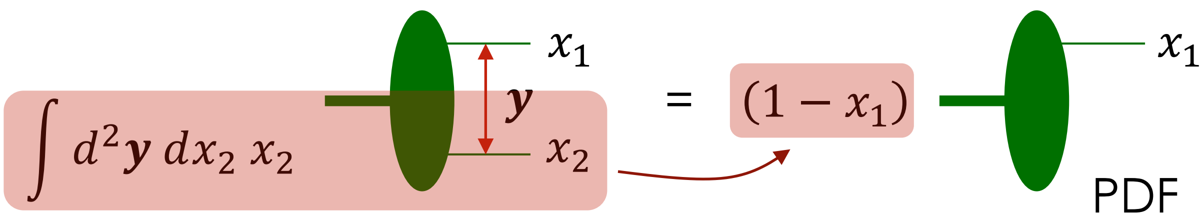
Mekhfi, Phys. Rev. D32 (1985) 2380
Diehl, Ostermeier and Schafer (JHEP 1203 (2012))
Manohar, Waalewijn, Phys.Rev. D85 (2012) 114009

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

BEYOND THE POCKET FORMULA

Also correlations linked to basic momentum and valence number constraints.

Encoded in sum rules for double parton densities. E.g. momentum sum rule:



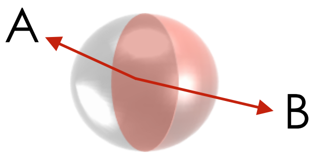
JG, Stirling, JHEP 03 (2010) 005
Blok et al., Eur.Phys.J.C 74 (2014) 2926
Diehl, Plößl, Schäfer, Eur.Phys.J.C 79 (2019) 3, 253

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

FORWARD PHYSICS AND DPS

How are forward physics measurements relevant to DPS (and vice versa)?

Region where *A* and *B* are both forward, but in opposite hemispheres, receives a relatively large DPS contribution.



Why?

For SPS process, hard scale of process $\sim m_{AB}$ becomes large → SPS suppressed.

But for DPS hard scales of two separate processes remain at m_A and m_B - large DPS contribution!

For SPS predictions should take care – can be an important contribution to this region from BFKL ladder configurations

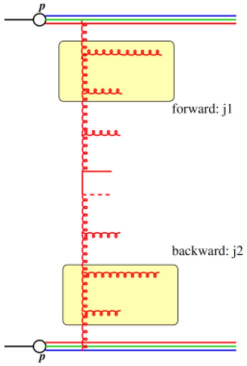
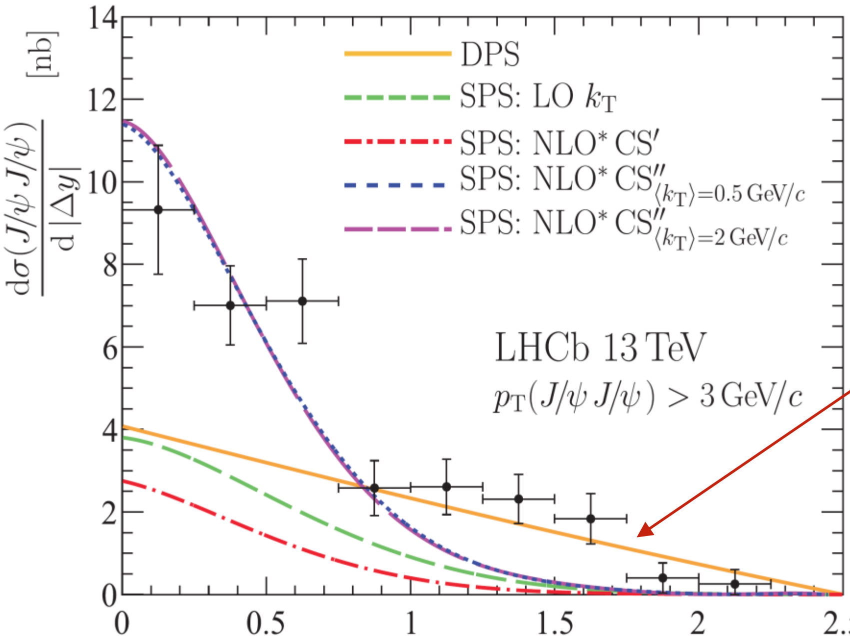


Figure taken from Hautmann, Jung, arXiv:1712.01726

LARGE RAPIDITY SEPARATION



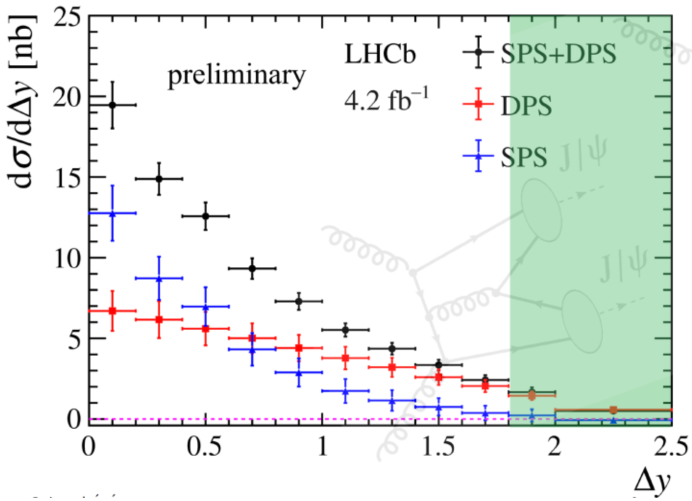
LHCb collaboration, JHEP 06, 047, (2017)

$\Delta y = |y_A - y_B|$

Example where DPS dominates at large Δy : J/ψ pair production.

Need DPS contribution at large Δy to explain data!

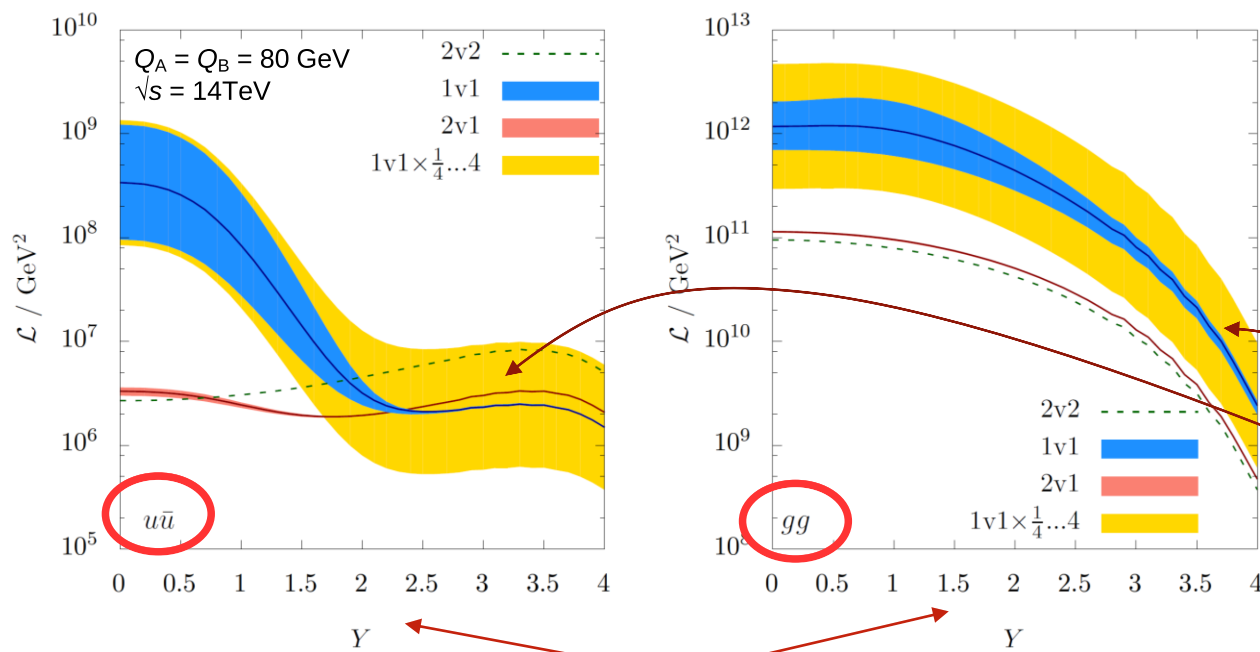
Updated results from LHCb for 2023 – similar picture
(see talk by S. Leontsinis at QCD@LHC 2023)



DPS/SPS OVERLAP AT LARGE ΔY

At large Δy, overlap issues between double and single scattering become less pronounced. More ‘clean’ DPS environment!

Illustration: DPS luminosities, pulling systems apart in rapidity



Blue band indicates severity of DPS/SPS overlap (yellow = worst possible)

Significant reduction at large Y!

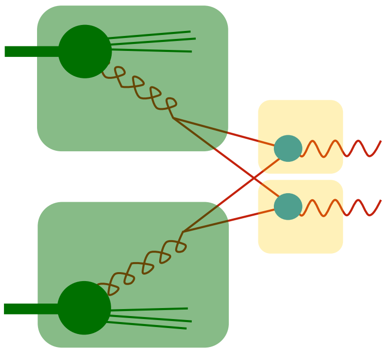
System A at rapidity Y, system B at rapidity –Y ($\Delta y = 2Y$)

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

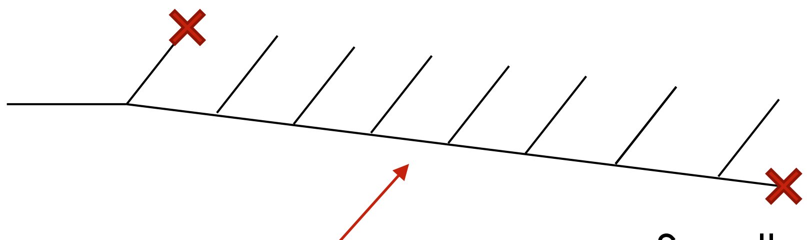
DPS/SPS OVERLAP AT LARGE ΔY

Why does the overlap issue become less pronounced in this configuration?

Overlap issues significant when direct splitting into pair initiating double scattering is important.



Large x parton



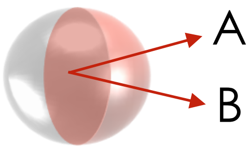
Small x parton

Can generate lots of small x logs in this emission sequence going from large to small x

For large Δy configurations, preferred splitting configurations look like this!

BOTH A AND B FORWARD

What about the configuration in which both A and B are going forward in the same hemisphere?



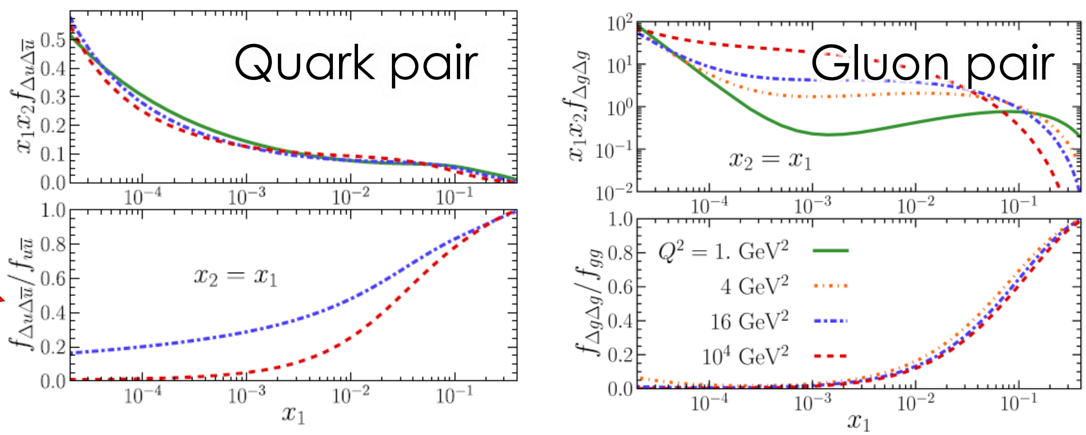
Probes: $\int F_{ik}(x_1, x_2, \boldsymbol{y}) \otimes \hat{\sigma}^A_{ij}\, \hat{\sigma}^B_{kl} \otimes F_{jl}(x'_1, x'_2, \boldsymbol{y})$

large small

Interesting to study correlations – tend to be strongest when both x large

E.g. spin correlations

Strength of correlations

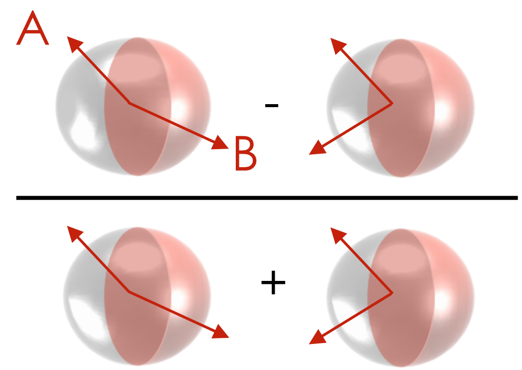


Diehl, Kasemets, Keane, JHEP 1405 (2014) 118

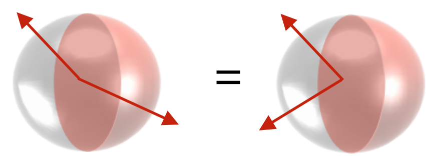
ASYMMETRIES

Can construct an asymmetry to measure in detail the correlations:

$\mathcal{A} =$



If no correlations $\mathcal{A} = 0$:



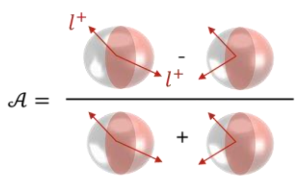
Can plot as a function of minimum absolute rapidity of two systems y_{cut} - larger y_{cut} pushes further into forward region

ASYMMETRY IN $W^{\pm}W^{\pm}$

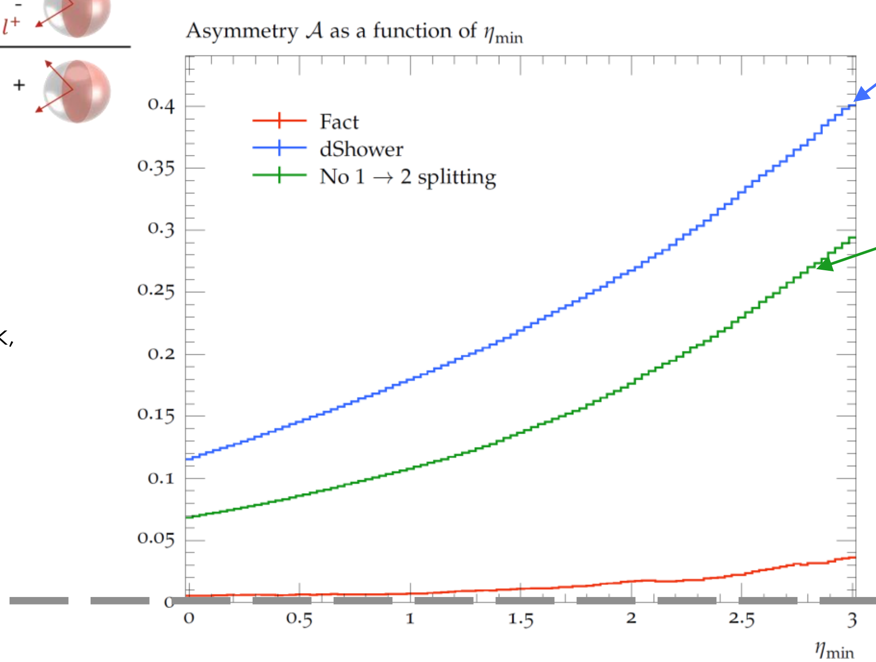
Studied in detail in the context of $W^{\pm}W^{\pm} \to l^{\pm}l^{\pm}\nu\nu$ (use leptons to define the two directions)

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

E.g. study using dShower DPS Monte Carlo. Includes effects of momentum and valence constraints + perturbative 1→2 splittings



Cabouat, JG, Ostrolenk, JHEP 1911 (2019) 061



Includes 1→2 splittings + valence number effects

Simple valence number effects

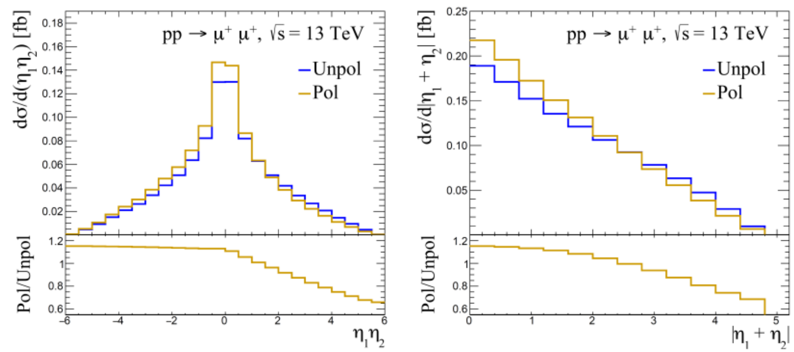
No parton-parton correlations

ASYMMETRY IN $W^{\pm}W^{\pm}$: SPIN

Spin polarisation effects can also affect this asymmetry
[Cotogno, Kasemets, Myska, Phys.Rev. D100 (2019) 1, 011503, JHEP 10 (2020) 214]

$W^{\pm}W^{\pm}$ is particularly strongly affected by spin polarisation effects:

- involves quarks.
- Ws couple only to left-handed quarks

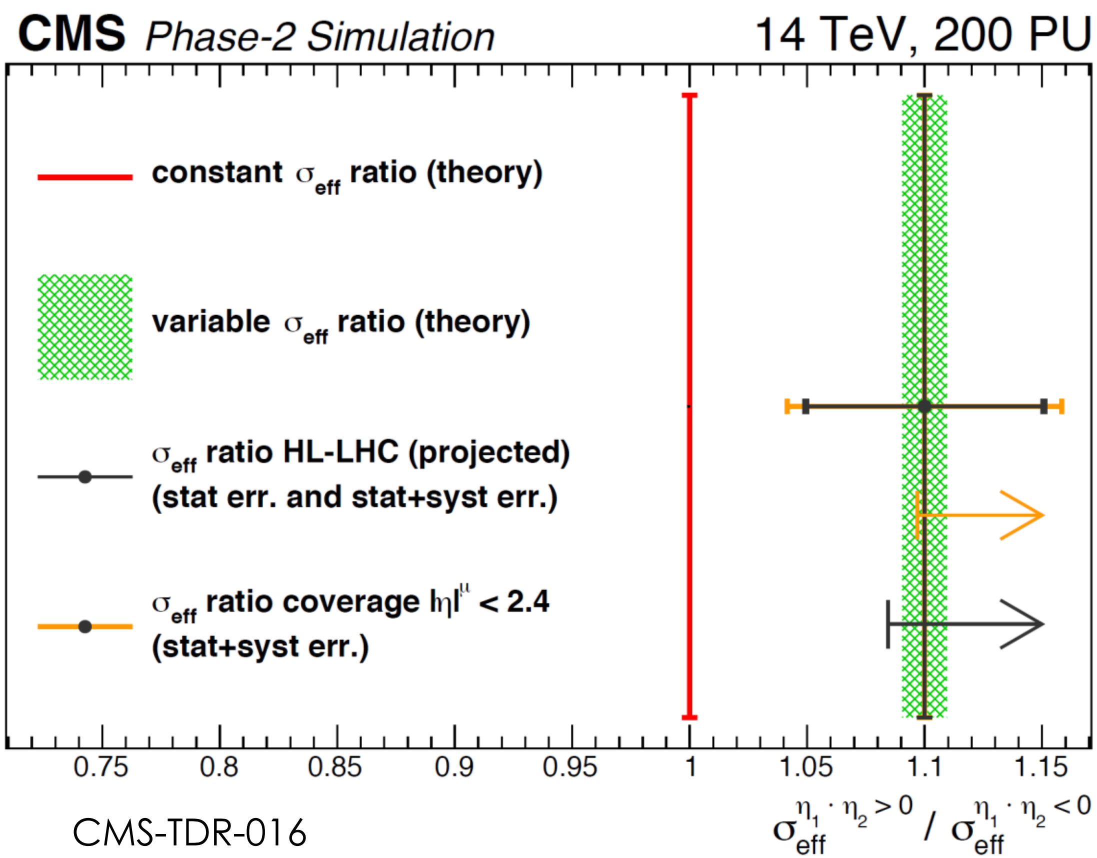


If we choose spin correlations at 1 GeV to be as large as possible, can see a few per cent effect on asymmetry

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

ASYMMETRY IN $W^{\pm}W^{\pm}$

$\mathcal{A}$ values of $\simeq 0.1$ will be measurable at hi-lumi LHC



CMS-TDR-016

TRANSVERSE CORRELATIONS FROM DATA

Study by Huayra, Lovato, de Oliveira, investigating if existing data gives an indication of correlations in transverse space

JHEP 09 (2023) 177

$$\sigma^{\mathrm{DPS}} = \sum_{ij;k'l'} \frac{\sigma_{ik'}(A)\sigma_{jl'}(A)}{\sigma^{ij}_{k'l',\mathrm{eff}}}$$

Pocket formula, but allowing for different geometric factors $\sigma^{ij}_{k'l',\mathrm{eff}}$ depending on whether i, j, k', l' are sea or valence quarks.

Take all $\sigma^{ij}_{k'l',\mathrm{eff}}$ to be free parameters and fit to existing data.

TRANSVERSE CORRELATIONS FROM DATA

One key result: Fit insensitive to the σ_{eff} values in which two or more valence partons appear - $\sigma_{ss,\text{eff}}^{vv}$, $\sigma_{sv,\text{eff}}^{vs} = \sigma_{sv,\text{eff}}^{sv}$, $\sigma_{vv,\text{eff}}^{vs}$, $\sigma_{vv,\text{eff}}^{vv}$.

Data from forward measurements would be helpful to pin these down – in particular:

Measurements with large Δy_{AB} would give info on $\sigma_{sv,\text{eff}}^{vs}$
Measurements with A, B forward in same direction would give info on $\sigma_{ss,\text{eff}}^{vv}$

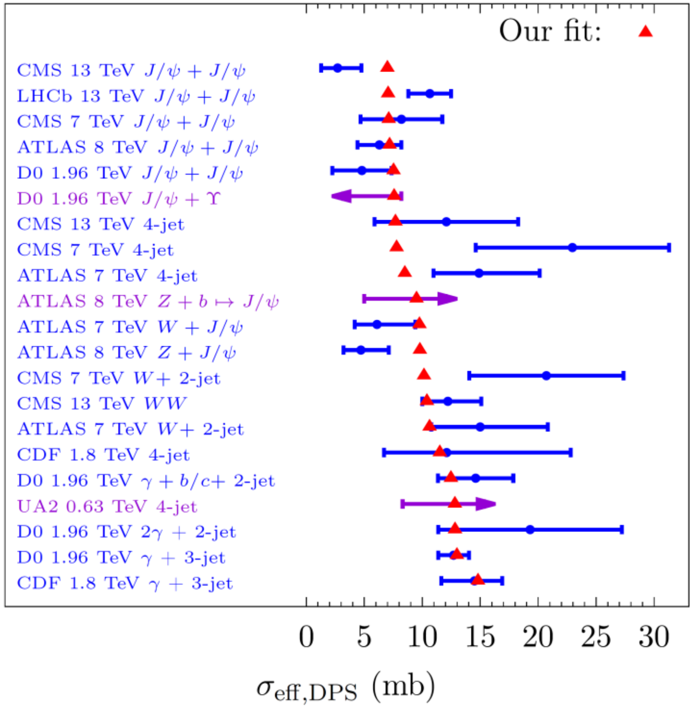
TRANSVERSE CORRELATIONS FROM DATA

Another key result: Fit does not prefer universal σ_{eff}!

Effective cross section	Fit result (mb)
$\sigma^{ss}_{ss,\text{eff}}$	6.5 ± 0.9
$\sigma^{ss}_{sv,\text{eff}}$	27 ± 15

Sea quarks closer together than sea-valence pairs

Null hypothesis of universal σ_{eff} rejected at 3.8σ level



DPS VS ΔY

DPS data at different Δy values would allow a more detailed study of parton correlations, and allow to discriminate between different models of DPS:

Study in the context of double Drell-Yan. Three "DPD models" compared:

Fedkevych, JG, JHEP 02 (2023) 090

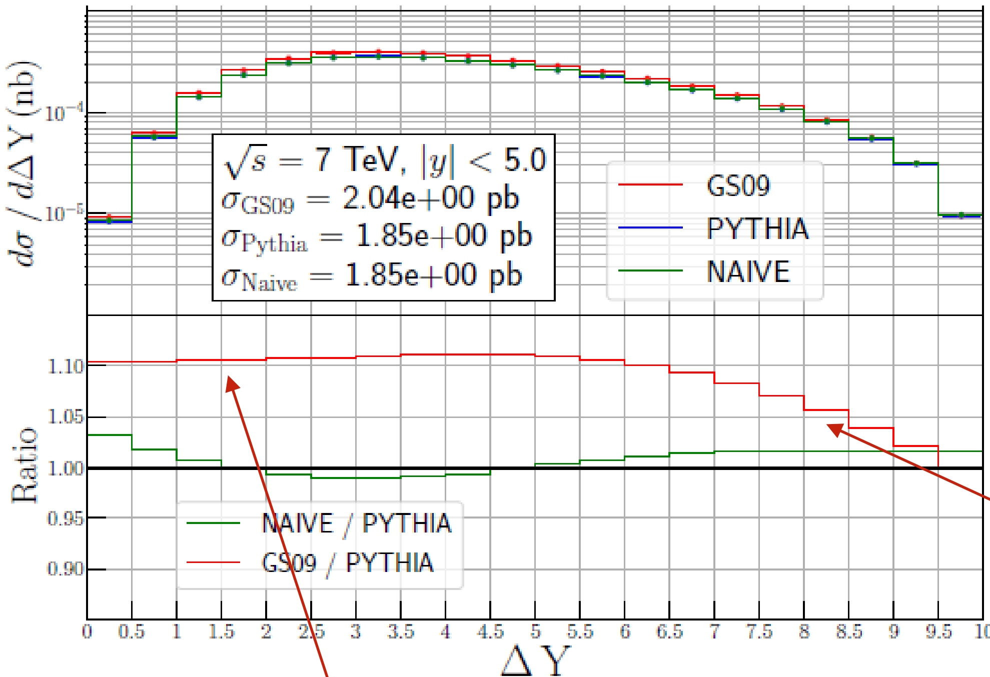
NAÏVE: DPD is product of single PDFs

PYTHIA: Pythia simulation of DPS, adjusts DPDs to take account of mtm/valence number constraints at high scale.

GS09 (JG, Stirling, JHEP 03 (2010) 005): contains 1→2 splitting effects, adjusts DPDs to take account of mtm/valence number constraints at low scale and evolve upwards.

(n.b. this set only incorporates longitudinal correlations and does not appropriately account for transverse correlations in the 1→2 splitting)

DPS VS ΔY



$$\Delta Y = \max|y_i - y_j|$$

GS09 falls relative to naïve/Pythia at large ΔY. Arises from evolution effects 'transporting' sum rule suppressions to lower x values

GS09 higher than naïve/Pythia predictions at small ΔY – driven by extra 1→2 splitting contributions

SUMMARY

- DPS is formally power suppressed wrt SPS, but can compete with it for certain processes and/or kinematic regions. Simplest approach to modelling DPS → pocket formula, ignores correlations. In reality, have both perturbative and nonperturbative correlations.

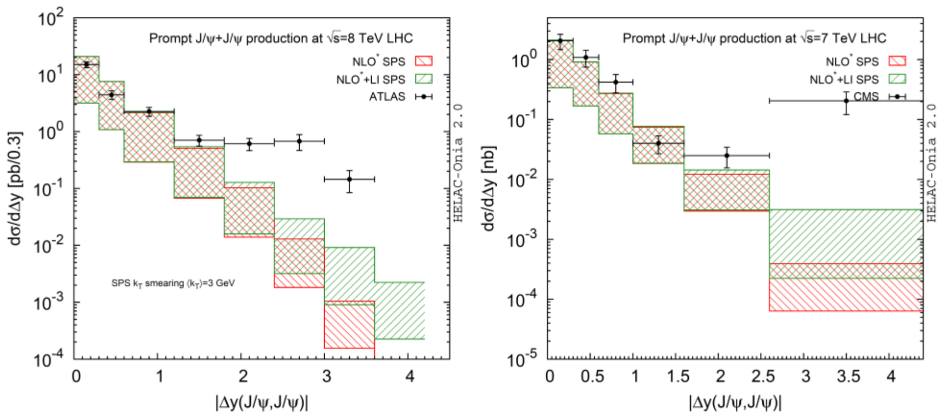
- Region in which both A and B are forward, opposite hemispheres – DPS can compete with or dominate over SPS. Example: J/ψ pair production.

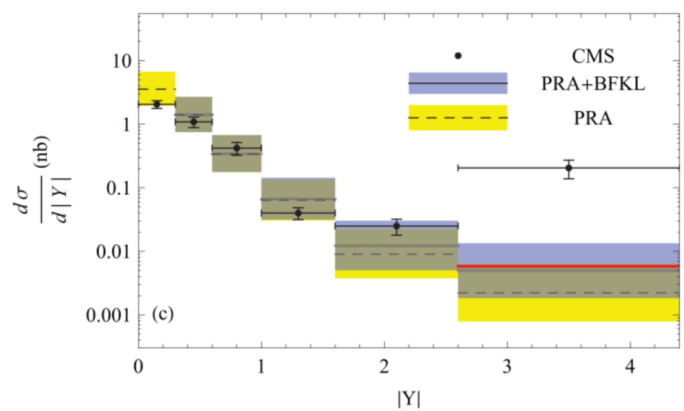
- Region in which A and B are forward in same hemisphere should be relatively strongly affected by parton correlations. Enhancement of $W^{\pm}W^{\pm} \to l^{\pm}l^{\pm}\nu\nu$ rapidity asymmetry as one goes further forward.

- Further measurements of DPS in forward region would be very useful to probe parton correlations in more detail!

BACKUP SLIDES

DOUBLE J/Ψ SPS THEORY PREDICTIONS





Lansberg, Shao, Yamanaka, Zhang
arXiv:1906.10049

He, Kniehl, Nefedov, Saleev
Phys.Rev.Lett. 123 (2019) no.16, 162002