Valence and sea parton correlations in double parton scattering from data

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Table of Contents

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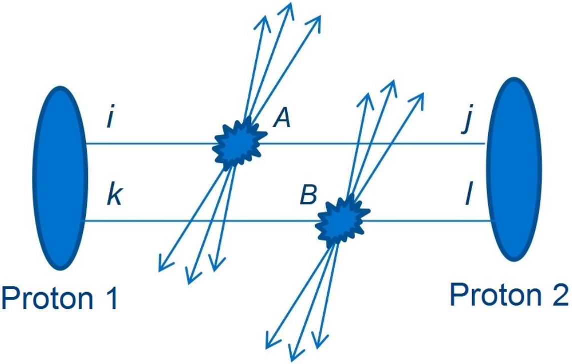
Introduction: General case

- In general, the inclusive σ_{D} for hadrons h, h' is

[Nuovo Cim. A 70, 215 (1982). JHEP 03, 089 (2012). JHEP 03, 005 (2010). Eur. Phys. J. C 72, 1963 (2012)]

$$\sigma_{\mathrm{D}}^{hh'} = \frac{N}{2}\sum_{ij;k'l'}\int dx_1 dx_2 dx'_1 dx'_2 d^2r \times \tag{1}$$
$$\times \quad \Gamma^{h}_{ij}(x_1,x_2,\mathbf{r})\hat{\sigma}^{A}_{ik'}(x_1,x'_1)\hat{\sigma}^{B}_{jl'}(x_2,x'_2)\Gamma^{h'}_{k'l'}(x'_1,x'_2,\mathbf{r}).$$



Introduction: uncorrelated case

- Considering the scenario where there is no correlation between x and $\mathbf{r}$.

$$\Gamma_{ij}(x_1,x_2,\mathbf{r}) = f_i(x_1)f_j(x_2)\ F(\mathbf{r})\ \theta(1-x_1-x_2)(1-x_1-x_2)^n, \quad (2)$$

- Here, $f_{i,j}$ are usual PDFs and F contain the geometrical information entering $\sigma_{\rm D}$.
- Note: that the function F doesn't depend on flavour i,j.
- The $n > 0$ is a parameter to be fixed phenomenologically, introduces the natural kinematical constraint $x_1 + x_2 \leq 1$.
- But this is important only if we consider large rapidity values.

Introduction: Pocket formula

- So, to simplify, we used the following ansatz

$$\Gamma_{ij}(x_1, x_2, \mathbf{r}) = f_i(x_1) f_j(x_2)\, F(\mathbf{r}). \tag{3}$$

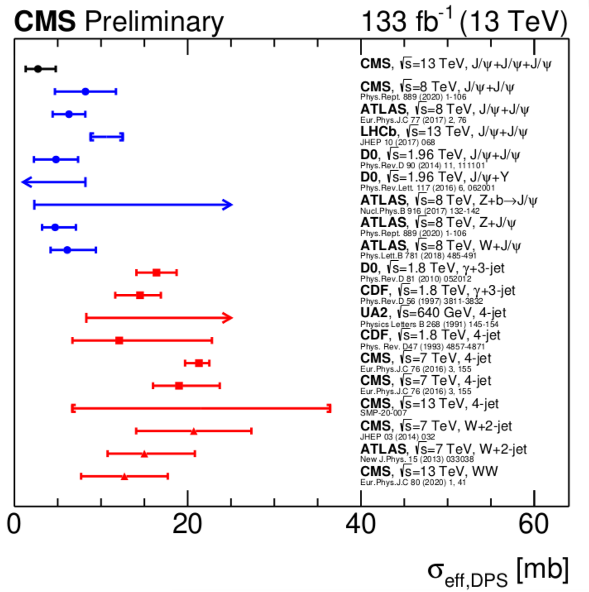
- Substituting this into the equation 1, we get the famous

Pocket formula

$$\sigma^{\mathrm{DPS}}_{p_1 p_2} = \frac{N}{2} \frac{\sigma^{\mathrm{SPS}}_A \sigma^{\mathrm{SPS}}_B}{\sigma^{pp}_{\mathrm{eff}}}$$

- The σ_{eff} is known as **effective cross section** and it contain all information about the transverse hadron structure.

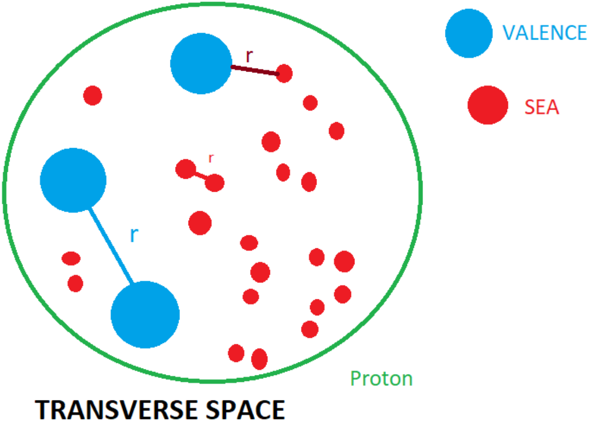
Problem



CMS Preliminary
133 fb^{-1} (13 TeV)
CMS, $\sqrt{s}$=13 TeV, J/ψ+J/ψ+J/ψ
CMS, $\sqrt{s}$=8 TeV, J/ψ+J/ψ
Phys.Rept. 889 (2020) 1-106
ATLAS, $\sqrt{s}$=8 TeV, J/ψ+J/ψ
Eur.Phys.J.C 77 (2017) 2, 76
LHCb, $\sqrt{s}$=13 TeV, J/ψ+J/ψ
JHEP 10 (2017) 068
D0, $\sqrt{s}$=1.96 TeV, J/ψ+J/ψ
Phys.Rev.D 90 (2014) 11, 111101
D0, $\sqrt{s}$=1.96 TeV, J/ψ+Y
Phys.Rev.Lett. 117 (2016) 6, 062001
ATLAS, $\sqrt{s}$=8 TeV, Z+b→J/ψ
Nucl.Phys.B 916 (2017) 132-142
ATLAS, $\sqrt{s}$=8 TeV, Z+J/ψ
Phys.Rept. 889 (2020) 1-106
ATLAS, $\sqrt{s}$=8 TeV, W+J/ψ
Phys.Lett.B 781 (2018) 485-491
D0, $\sqrt{s}$=1.8 TeV, γ+3-jet
Phys.Rev.D 81 (2010) 052012
CDF, $\sqrt{s}$=1.8 TeV, γ+3-jet
Phys.Rev.D 56 (1997) 3811-3832
UA2, $\sqrt{s}$=640 GeV, 4-jet
Physics Letters B 268 (1991) 145-154
CDF, $\sqrt{s}$=1.8 TeV, 4-jet
Phys. Rev. D47 (1993) 4857-4871
CMS, $\sqrt{s}$=7 TeV, 4-jet
Eur.Phys.J.C 76 (2016) 3, 155
CMS, $\sqrt{s}$=7 TeV, 4-jet
Eur.Phys.J.C 76 (2016) 3, 155
CMS, $\sqrt{s}$=13 TeV, 4-jet
SMP-20-007
CMS, $\sqrt{s}$=7 TeV, W+2-jet
JHEP 03 (2014) 032
ATLAS, $\sqrt{s}$=7 TeV, W+2-jet
New J.Phys. 15 (2013) 033038
CMS, $\sqrt{s}$=13 TeV, WW
Eur.Phys.J.C 80 (2020) 1, 41
0
20
40
60
$\sigma_{eff,DPS}$ [mb]

Problem

- This can be due the fact that we are neglecting all correlations.



- Let us introduce a parton–kind (valence or sea) dependence!

Theoretical background

- Neglecting again longitudinal–transverse correlations but including parton kind dependence:

$$\Gamma_{ij}(x_1,x_2,\mathbf{r}) = f_i(x_1)f_j(x_2)\, F_{ij}(\mathbf{r}), \quad i,j \in \{s,v\}. \tag{4}$$

- Then, the DPS cross section Eq. 1 is
[A. Del Fabbro and D. Treleani, Phys. Rev. D 63, 057901 (2001)]

$$\sigma_{\mathrm{D}}^{hh'} = \frac{N}{2} \sum_{ij;k'l'} \sigma_{ik'}(A)\sigma_{jl'}(B) / \sigma^{ij}_{k'l',\mathrm{eff}}, \tag{5}$$

where the geometrical coefficients

$$\left(\sigma^{ij}_{k'l',\mathrm{eff}}\right)^{-1} = \Theta^{ij}_{k'l'} = \int d^2r\, F_{ij}(\mathbf{r}) F_{k'l'}(\mathbf{r}), \tag{6}$$

are weighted differently depending on the final state.

Theoretical background

- The effective DPS cross section for each final state AB is

$$\sigma_{\text{eff}}^{\text{Theory}}(AB) = \frac{\sum_{i,k'} \sigma_{ik'}(A) \sum_{j,l'} \sigma_{jl'}(B)}{\sum_{ijk'l'} \sigma_{ik'}(A)\sigma_{jl'}(B) / \sigma_{k'l',\text{eff}}^{ij}}. \tag{7}$$

- The $\sigma_{ik'}(X)$ values were obtained with PYTHIA 8.3

[C. Bierlich et al., SciPost Phys. Codebases 8, (2022)]

Results – Fit

- The free parameters are the $\sigma^{ij}_{k'l',\mathrm{eff}}$
- By symmetry, only 6 are independent:
  $\sigma^{ss}_{ss,\mathrm{eff}}$, $\sigma^{ss}_{sv,\mathrm{eff}}$, $\sigma^{ss}_{vv,\mathrm{eff}}$, $\sigma^{sv}_{sv,\mathrm{eff}}$, $\sigma^{sv}_{vv,\mathrm{eff}}$, $\sigma^{vv}_{vv,\mathrm{eff}}$, .
- We minimize the χ^2 using Minuit2.
  [F. James and M. Winkler, MINUIT User's Guide (CERN, Geneva, 2004).]
- Current data is only sensitive to $\sigma^{ss}_{ss,\mathrm{eff}}$ and $\sigma^{ss}_{sv,\mathrm{eff}}$.
- The others are fixed to 38 mb but this value does not really matter.

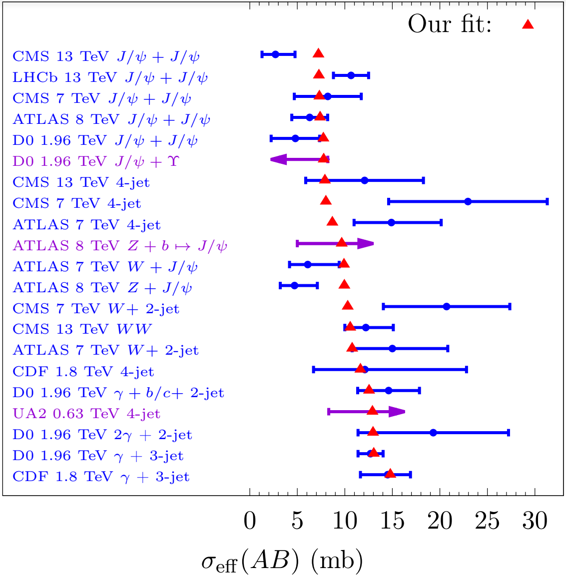
Results

- The basic pocket formula gives $\sigma_{\text{eff}} = 9.8 \pm 0.6\,\text{mb}$ with $\chi^2_{\text{dof}} = 46.45/(18-1) = 2.73$.
- This gives a p-value of only 0.00015 and as such the null hypothesis is rejected with confidence level of 3.8σ.
- In our study, we find that sea–sea correlations are really different from sea–valence:

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

Table: σ_{eff} found in our fit with goodness $\chi^2_{\text{dof}} = 1.70$. The notation $\sigma^{ij}_{k'l',\text{eff}}$ means that i interacts with k' and j interacts with l'.

Results


Our fit:
CMS 13 TeV $J/\psi + J/\psi$
LHCb 13 TeV $J/\psi + J/\psi$
CMS 7 TeV $J/\psi + J/\psi$
ATLAS 8 TeV $J/\psi + J/\psi$
D0 1.96 TeV $J/\psi + J/\psi$
D0 1.96 TeV $J/\psi + \Upsilon$
CMS 13 TeV 4-jet
CMS 7 TeV 4-jet
ATLAS 7 TeV 4-jet
ATLAS 8 TeV $Z + b \mapsto J/\psi$
ATLAS 7 TeV $W + J/\psi$
ATLAS 8 TeV $Z + J/\psi$
CMS 7 TeV $W+$ 2-jet
CMS 13 TeV WW
ATLAS 7 TeV $W+$ 2-jet
CDF 1.8 TeV 4-jet
D0 1.96 TeV $\gamma + b/c+$ 2-jet
UA2 0.63 TeV 4-jet
D0 1.96 TeV $2\gamma +$ 2-jet
D0 1.96 TeV $\gamma +$ 3-jet
CDF 1.8 TeV $\gamma +$ 3-jet
0 5 10 15 20 25 30
$\sigma_{\rm eff}(AB)$ (mb)

Conclusion

- These results were published in JHEP, arxiv.org/abs/2305.11106 https://doi.org/10.1007/JHEP09(2023)177.

Valence and sea parton correlations in double parton scattering from data

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Abstract

The effective cross section of double parton scattering in proton collisions has been measured by many experiments with rather different results. Motivated by this fact, we assumed that the parton correlations in the transverse plane are different whether we have valence or sea partons. With this simple approach, we were able to fit the available data and found that sea parton pairs are more correlated in the transverse plane than valence–sea parton pairs.

Conclusion

- We use the assumption that the transversal distributions of valence and sea parton kinds could be different in the proton to fit σ_{eff} to data on several processes and experiments.
- This hypothesis can be important since it affect the value of σ_{eff} and make it depend on the final state.
- The quality of the fit was not bad and the calculated values of the σ_{eff} are in good agreement with the data.
- Allowing transverse correlations between parton populations is an important improvement in the description of DPS.
- The sea-sea correlations are the larger than sea–valence ones.

Future research: x-dependence

- Now, in a simple scenario where there is correlation between x and $\mathbf{r}$, the dPDF factorizate like

$$\Gamma_{ij}(x_1,x_2,\mathbf{r}) = f_i(x_1)f_j(x_2)\, F_{ij}(x_1,x_2;\mathbf{r}). \tag{8}$$

- But this correlation prevents us from obtaining the formula 5.

- We are left with a term like

$$\sum_{i,j;k',l'} \int \Theta^{ij}_{k'l'}(x_1,x_2;x_1',x_2') f_i(x_1) f_{k'}(x_1')\, \hat{\sigma}_{ik'}(x_1,x_1') \times$$

$$\times\, \hat{\sigma}_{jl'}(x_2,x_2') f_j(x_2) f_{l'}(x_2')\; dx_1 dx_2 dx_1' dx_2', \tag{9}$$

where

$$\Theta^{ij}_{k'l'}(x_1,x_2;x_1',x_2') = \int d^2r\, F_{ij}(x_1,x_2;r) F_{k'l'}(x_1',x_2';r). \tag{10}$$

Future research: x-dependence

- One way to introduce it is using ansatz

$$F_{ij}(x_1,x_2,r) = \int d\mathbf{s}_1 d\mathbf{s}_2\ \delta^{(2)}(\mathbf{s}_2 - \mathbf{s}_1 - \mathbf{r})\rho_i(x_1,\mathbf{s}_1)\rho_j(x_2,\mathbf{s}_2), \quad (11)$$

where the x-dependence comes from the **transverse density** $\rho_i(x,\mathbf{s})$.

- A possible profile that encapsulate this x-dependence is the gaussian approach

$$\rho_i(x,r) := \frac{1}{2\pi\delta(x)^2}\exp\left\{-\frac{r^2}{2\delta(x)^2}\right\}, \quad (12)$$

$$\delta(x) = w\sqrt{(1-x)\ln\frac{1}{x}}, \quad (13)$$

or $$\delta(x) = B_0 + 2K_Q \ln\left(\frac{x_0}{x}\right). \quad (14)$$

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Future research: x-dependence

- The last parameterization comes from the J/ψ-SPS data.

[L. Frankfurt, M. Strikman, and C. Weiss, Phys. Rev. D 83, 054012 (2011)]

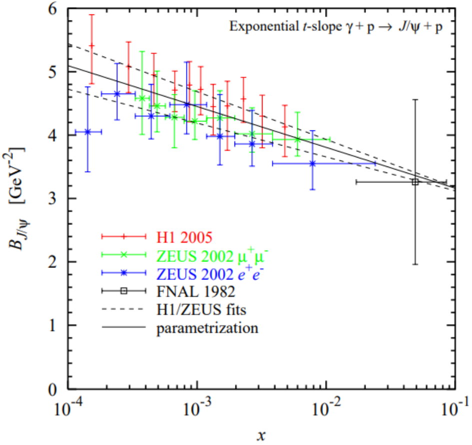

Figure: The exponential t–slope, $B_{J/\psi}$, of the differential cross section of exclusive J/ψ photoproduction measured in the FNAL E401/E458, HERA H1, and ZEUS experiments, as a function of $x = M^2_{J/\psi}/W^2$.

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