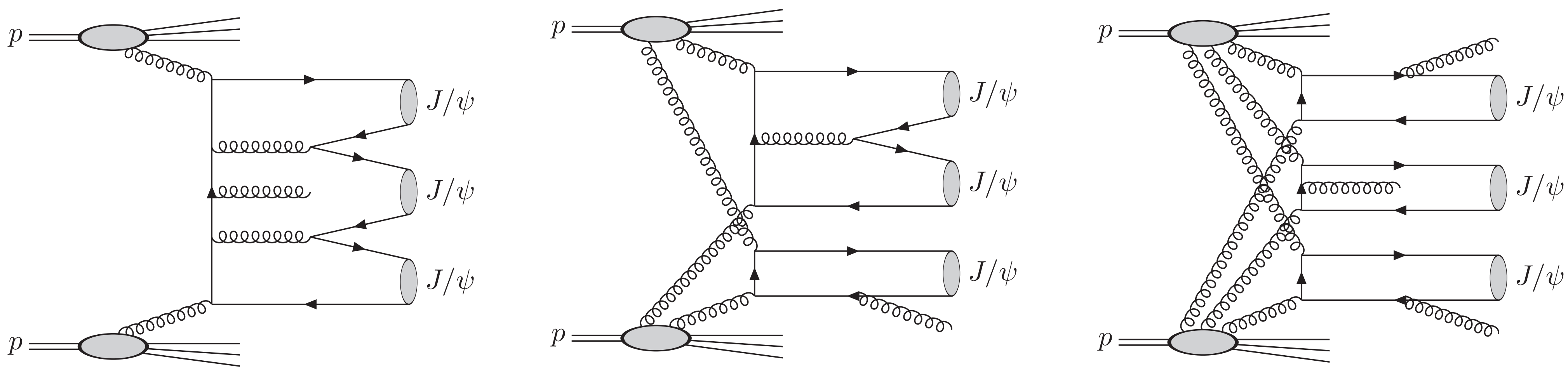
HADRON 2023

Multiple Parton Scattering

from both theoretical and experimental point of views



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HADRON 2023, Genova

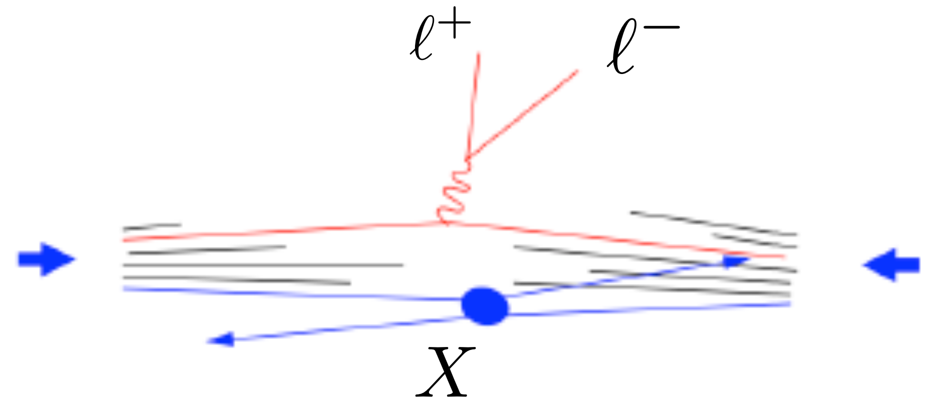
05 June 2023

A Brief Introduction

- **Cross section from factorization theorem (conjecture)**

$$\text{cross section} = \text{parton distribution} \times \text{partonic cross section}$$

- **Spectator-spectator interactions**
  - cancel in inclusive cross sections (unitarity)
  - affect final state X



- **Additional interaction (blue) will be sensitive if we probe X simultaneously**
- **If the second interaction is also hard → Double Parton Scattering**

e.g. $pp \to Z + H + X \to l\bar{l} + b\bar{b} + X$

- **DPS contributes to signals and to backgrounds in many analyses at the LHC**
- **Inclusive cross section:**

$$\sigma_{\text{SPS}} \sim \frac{1}{Q^2} \quad \text{v.s.} \quad \sigma_{\text{DPS}} \sim \frac{\Lambda^2_{\text{QCD}}}{Q^4}$$

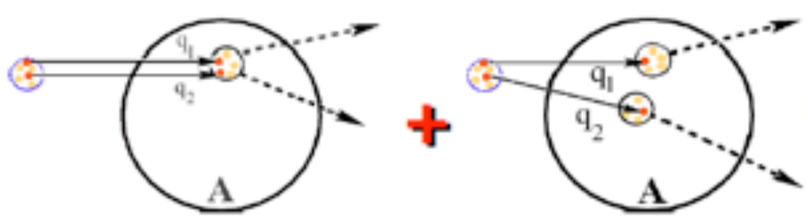
- **Higher energy ⇒ Larger parton density ⇒ enhance DPS**

$$\sigma_{\text{SPS}} \propto (\text{parton density})^2 \quad \text{v.s.} \quad \sigma_{\text{DPS}} \propto (\text{parton density})^4$$

A Brief Introduction

- **How to probe DPS at the LHC ?**
- **Processes of low hard scale Q (but still in the perturbative regime)**
    - multiply hadron production, e.g. $J/\psi + J/\psi$
- **Processes of large yields**
    - multi-jet production
- **Processes of precision measurements**
    - multi-lepton production
- **Enhancement of parton luminosity**
    - higher energy [8 TeV to 14 TeV to 100 TeV (FCC)]
    - probe in proton-nucleus and nucleus-nucleus collisions

[Strikman, Treleani (2002);D. d'Enterria, A. Snigirev (2013, 2014)]



$$\sigma_{\text{eff,pp}}/\sigma_{\text{eff,pA}} \approx 3\,A \approx 600$$

$$\sigma_{\text{eff,pp}}/\sigma_{\text{eff,AA}} \propto A^{3.3}/5 \simeq 9 \cdot 10^6$$

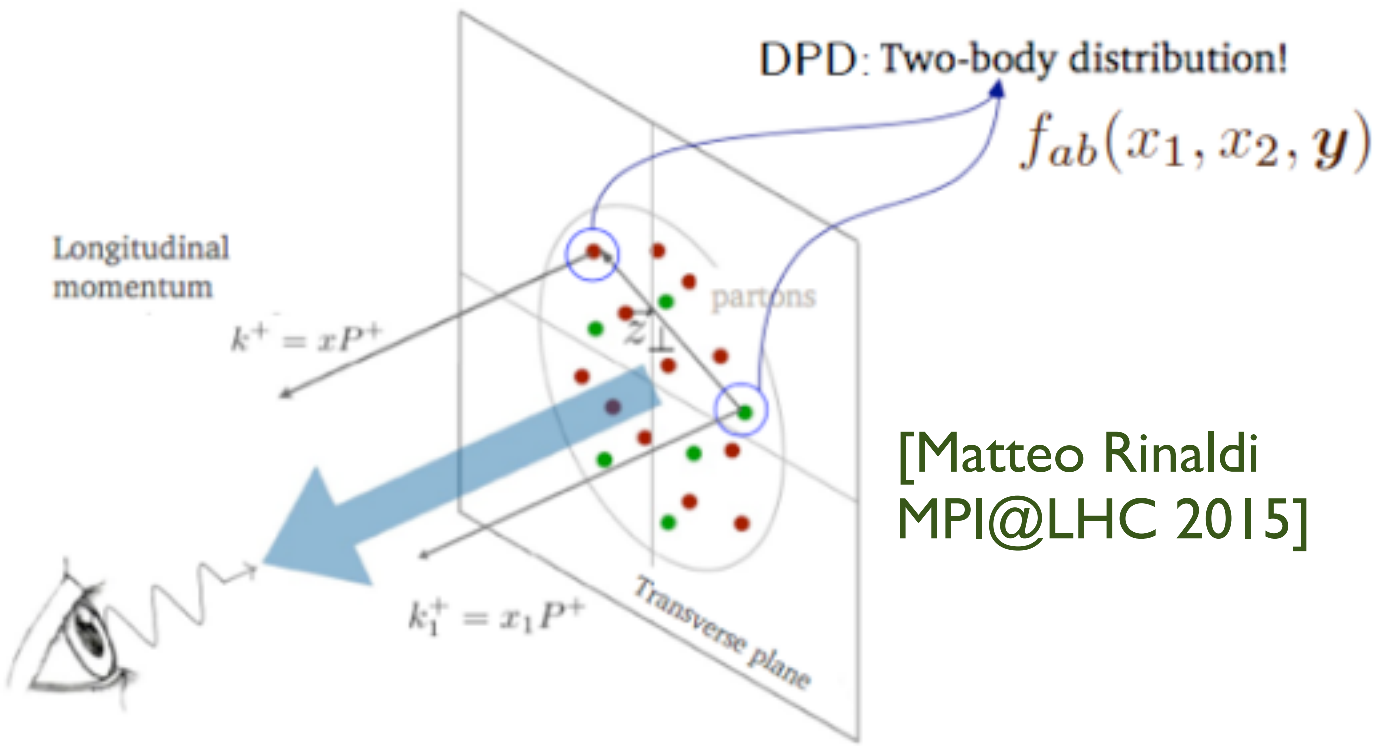
A DPS Theory Foundation

- **Like SPS, we now have a first proven factorisation theorem for DPS (double Drell-Yan)**

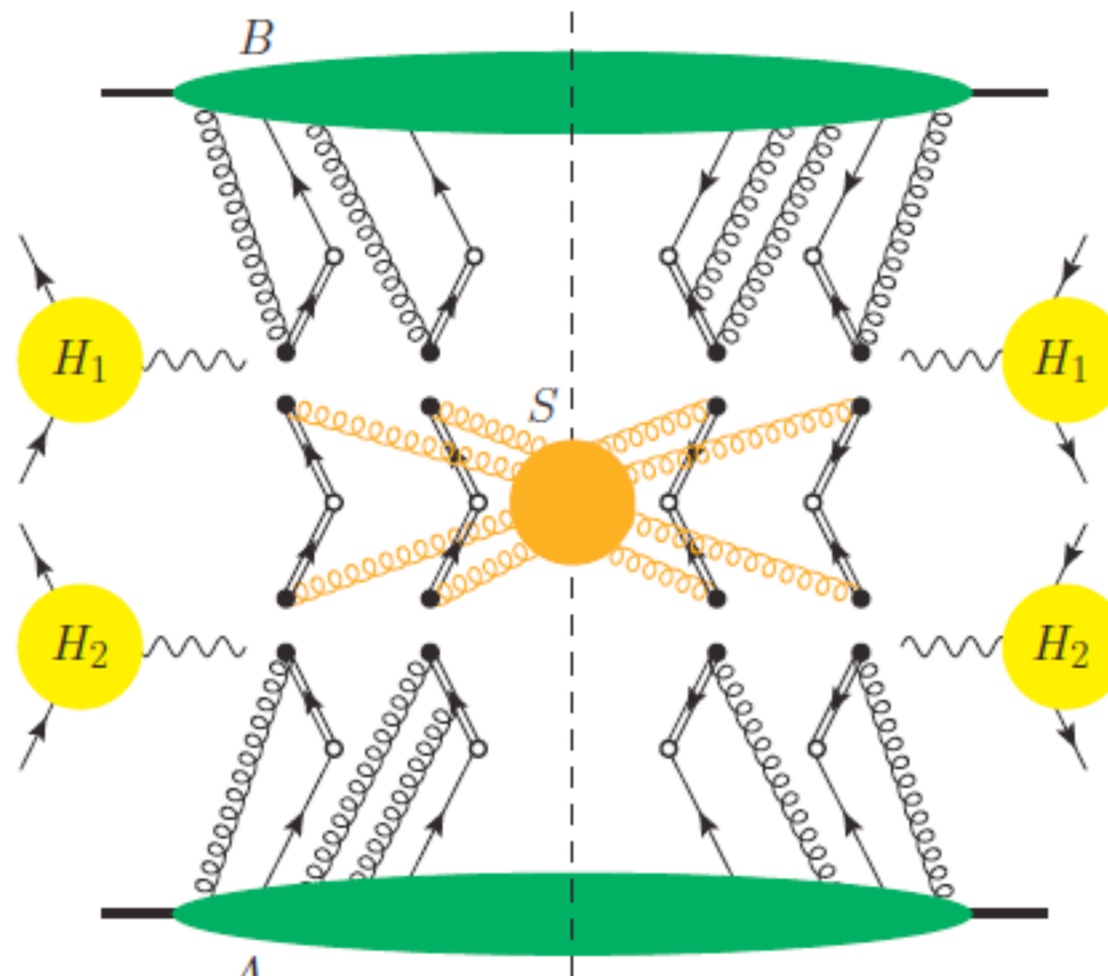
[Diehl, Gaunt, Ostermeier, Ploessl, Schafer (2015); Diehl, Nagar (2018)]

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx_1' dx_2' d^2\mathbf{b}_1 d^2\mathbf{b}_2 d^2\mathbf{b}$$

$$\times \Gamma_{ij}(x_1, x_2, \mathbf{b}_1, \mathbf{b}_2)\, \hat{\sigma}_{ik}^{Q_1}(x_1, x_1')\, \hat{\sigma}_{jl}^{Q_2}(x_2, x_2')\, \Gamma_{kl}(x_1', x_2', \mathbf{b}_1 - \mathbf{b}, \mathbf{b}_2 - \mathbf{b}),$$



[Matteo Rinaldi MPI@LHC 2015]



A new way to access the information of the nonperturbative structure of nucleons

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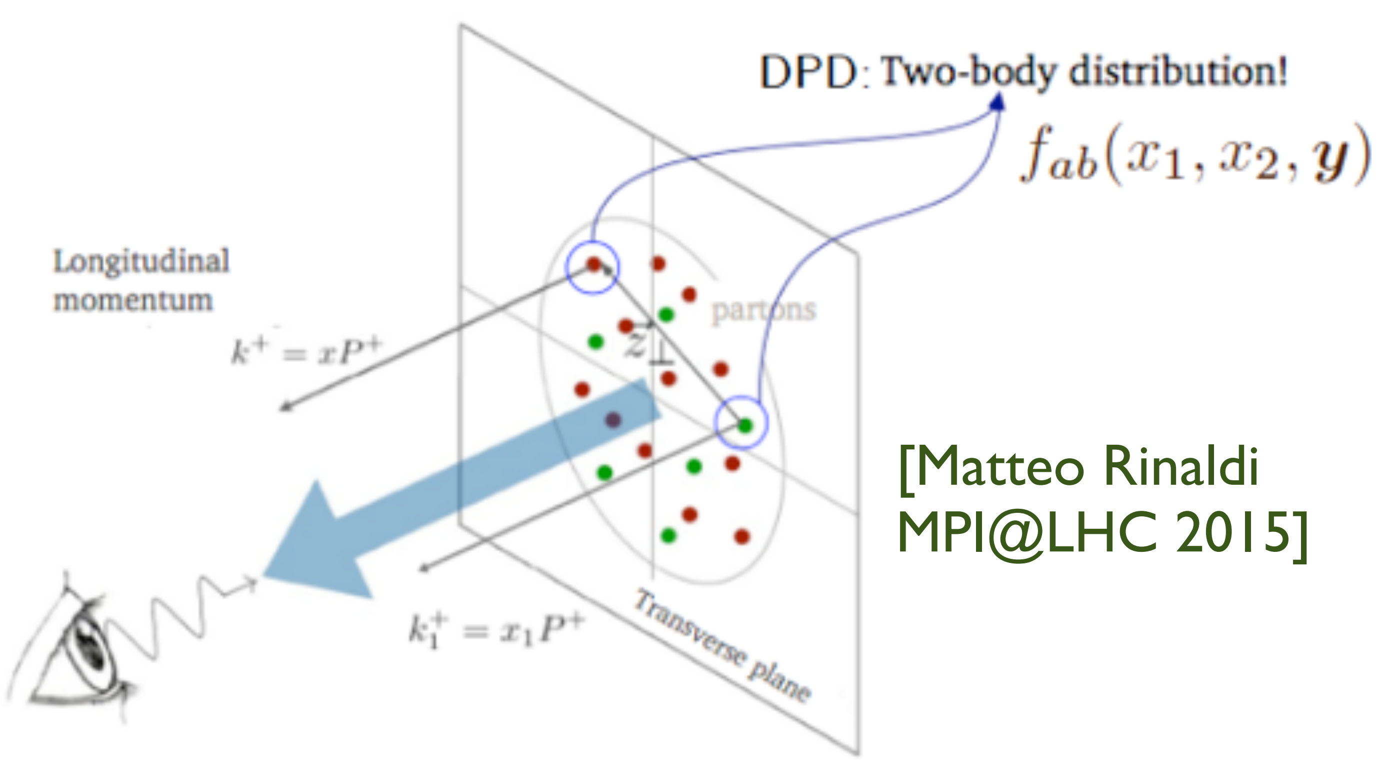
Generalised double parton distribution



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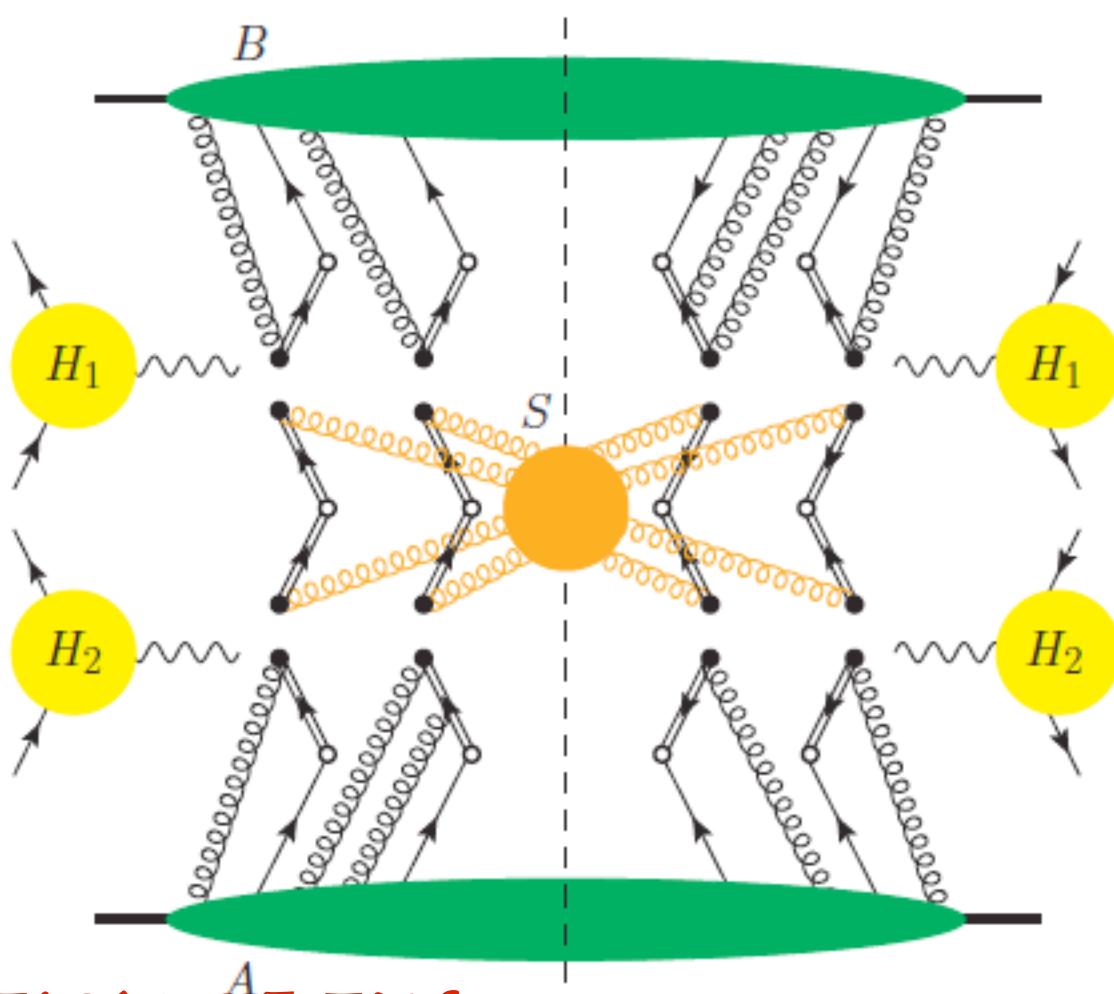

A new way to access the information of the nonperturbative structure of nucleons

Thursday, June 1, 23

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- **Widespread simplifications (most phenomenology relies on. Go beyond ?)**
  - factorization I $\quad \Gamma_{ij}(x_1,x_2,\mathbf{b}_1,\mathbf{b}_2) = D_{ij}(x_1,x_2) T_{ij}(\mathbf{b}_1,\mathbf{b}_2),$ dPDF
  - factorization II $\quad D_{ij}(x_1,x_2) = f_i(x_1) f_j(x_2),$ PDF

    $T_{ij}(\mathbf{b}_1,\mathbf{b}_2) = T_i(\mathbf{b}_1) T_j(\mathbf{b}_2),$
  - assume flavor universality in T

$$\sigma_{\text{eff}} = \left[\int d^2\mathbf{b} F(\mathbf{b})^2\right]^{-1}.$$

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\text{eff}}},$$

$$F(\mathbf{b}) = \int T(\mathbf{b}_i) T(\mathbf{b}_i - \mathbf{b}) d^2\mathbf{b}_i,$$

Pocket Formula

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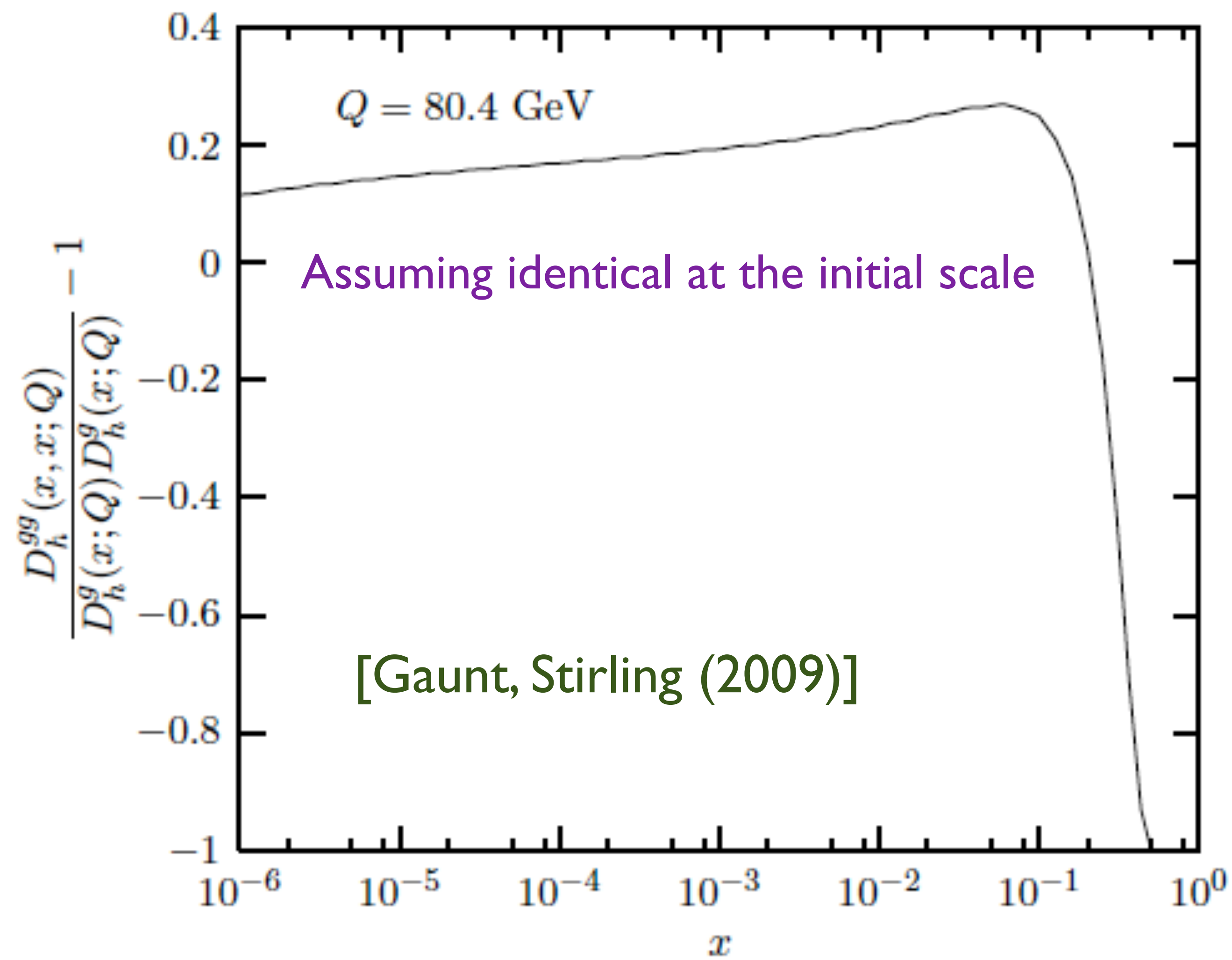
Pocket Formula

- Even these are complex objects to treat numerically

[Gaunt, Stirling; Elias, Golec-Biernat, Stasto; Diehl, Nagar, Tackmann]

DPS Theory Progress

- **Let us start with the pocket formula and take any deviation wrt experiment as an indication of calling for a more rigorous treatment.**
- **Possible deviations (a few examples):**
  - dDGLAP evolution (note high x !)



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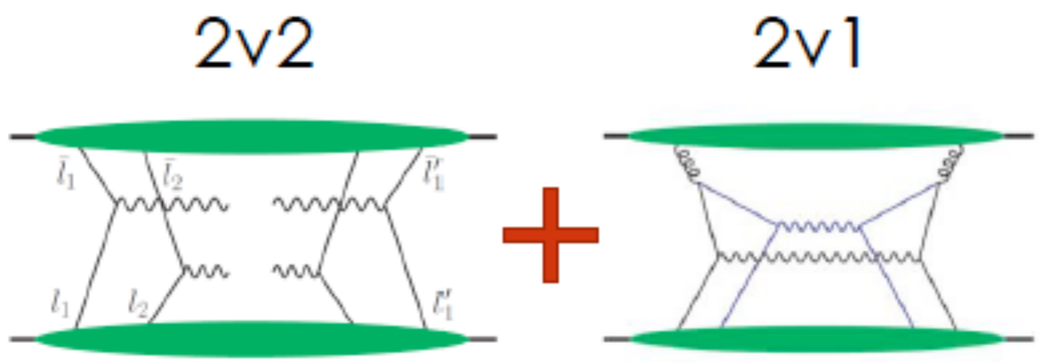
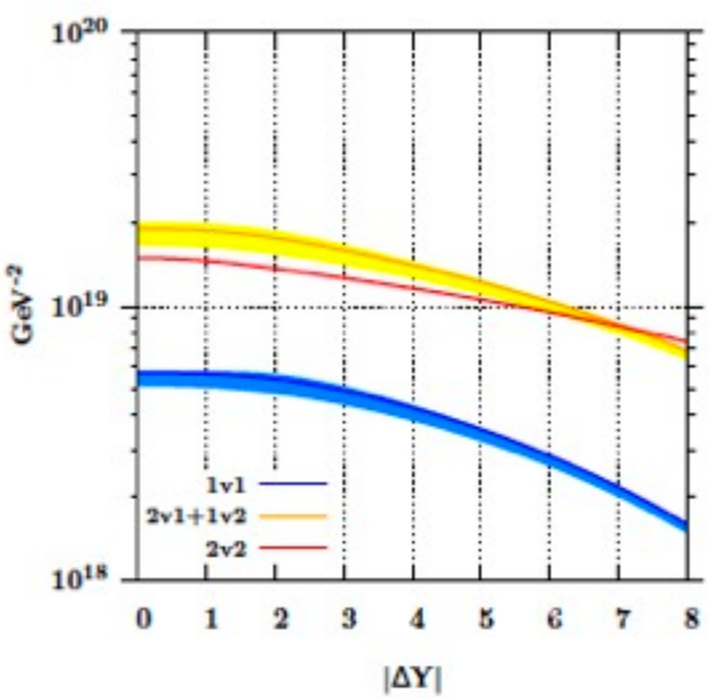
parton luminosity is not suppressed !

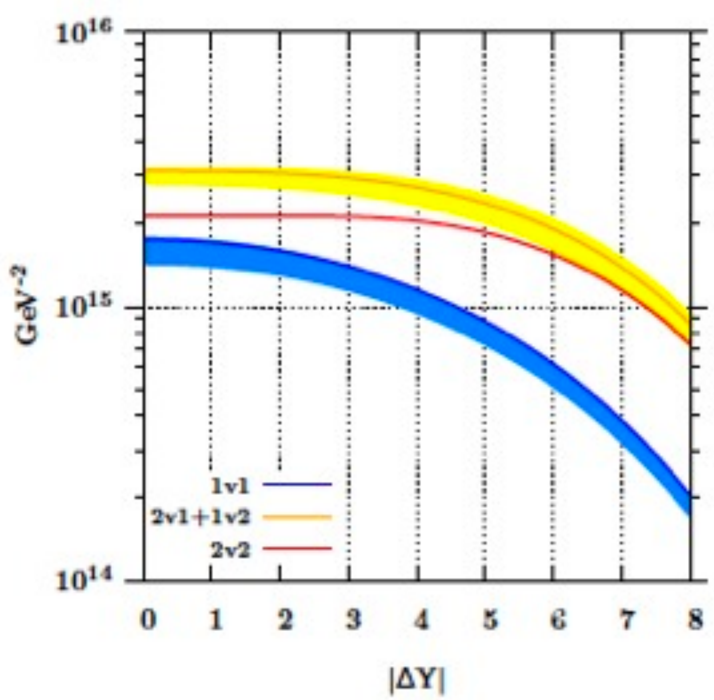
[Riccardo Nagar @ Quarkonia As Tools 2020]



[Gaunt, Stirling (2011); Block et al. (2012); Manohar, Waalewijn (2012)]



$\mathcal{L}_{gggg}\,(m_{J/\Psi},\, m_{J/\Psi})$



$\mathcal{L}_{gggg}\,(m_W,\, m_{J/\Psi})$

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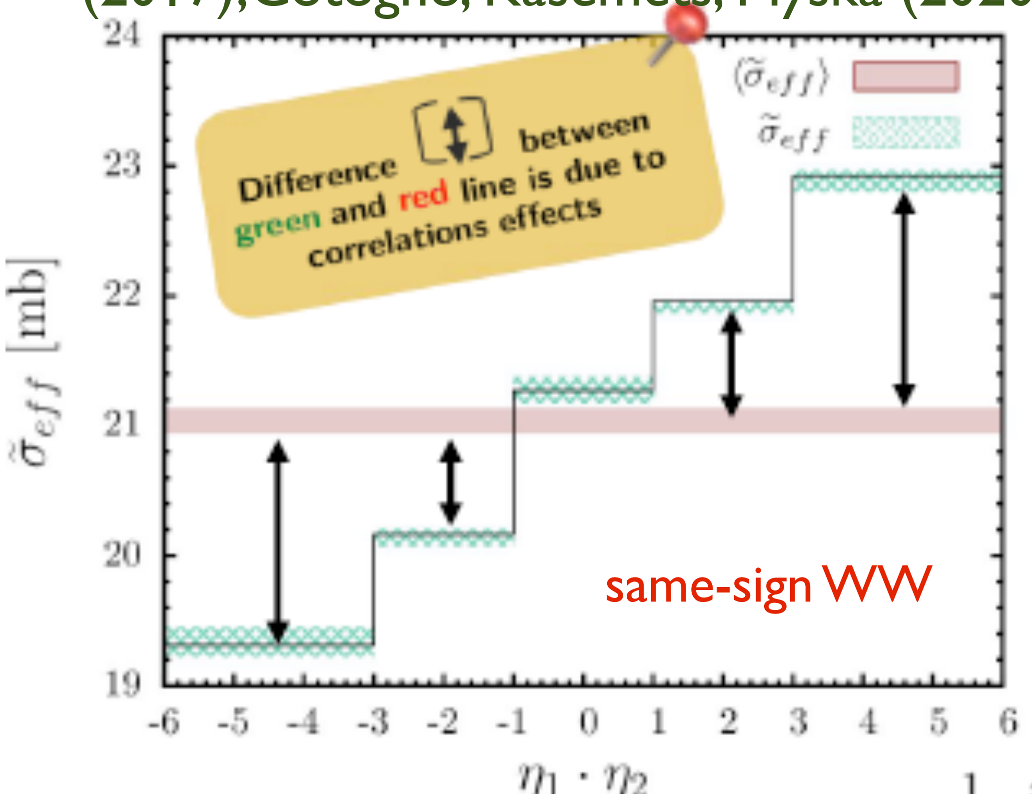
  - parton-parton correlations

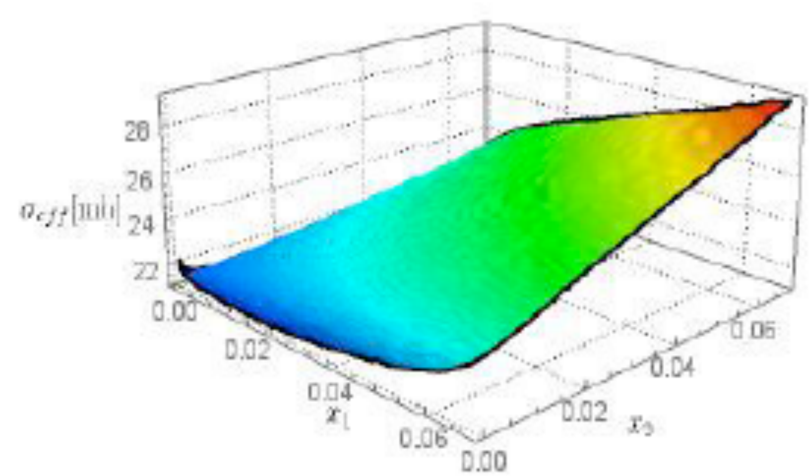
[Matteo Rinaldi @ Quarkonia As Tools 2020; Ceccopieri, Rinaldi, Scopetta (2017);Cotogno, Kasemets, Myska (2020)]



$$\eta_1 \cdot \eta_2 \simeq \frac{1}{4} ln\frac{x_1}{x_3} ln\frac{x_2}{x_4}$$

the first and the last bins differ by 1 sigma

$\mathcal{L} = 1000\ \text{fb}^{-1}$ is necessary to observe correlations



Gluons ⊗ Gluons

$$\sigma_{\text{eff}} \rightarrow \sigma_{\text{eff}}(x_1, x_2, \mu_F)$$

DPS Theory Progress

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- **Possible deviations (a few examples):**
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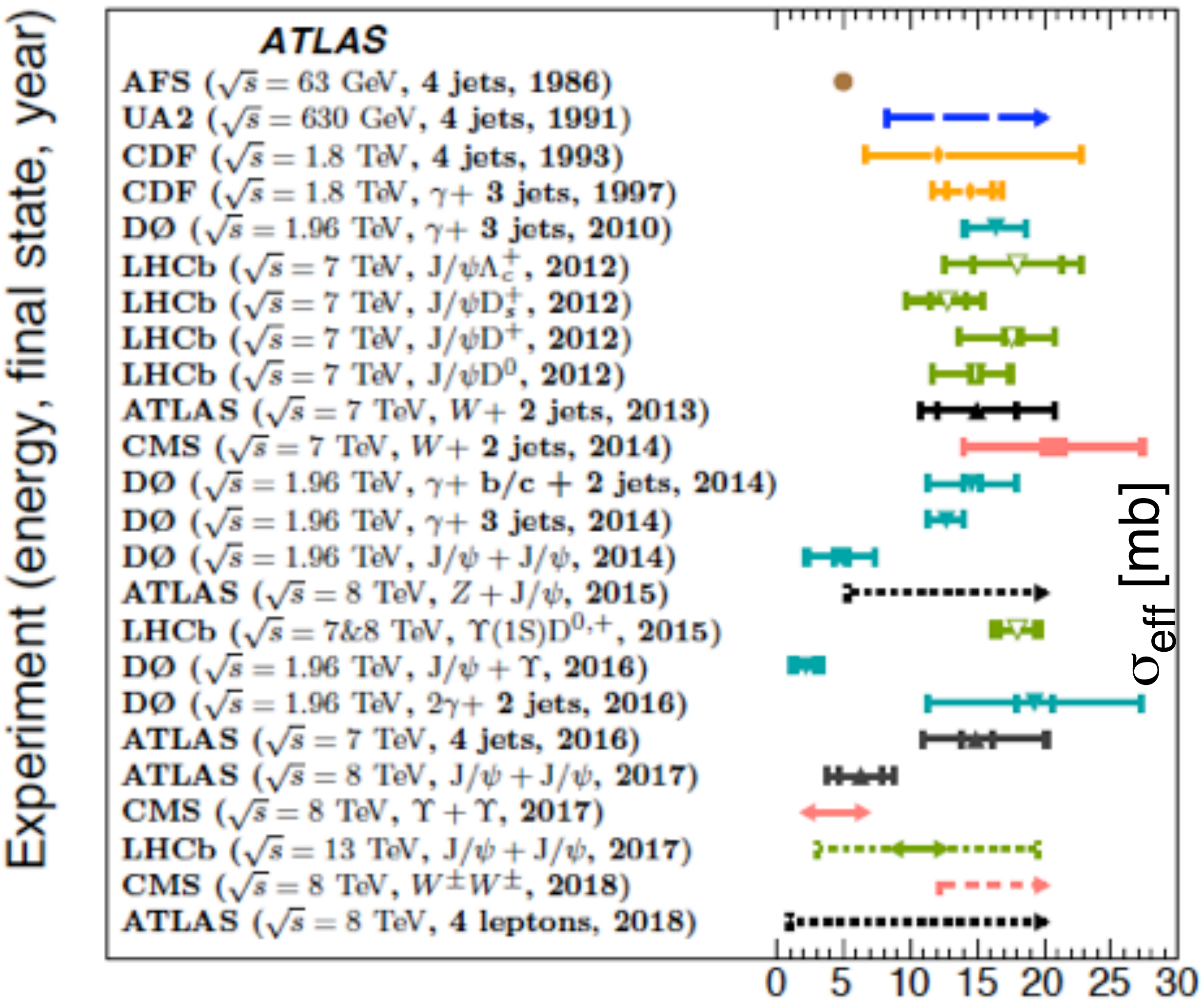
- **A few recent theoretical developments**
  - DPS shower dShower [Cabouat, Gaunt,Ostrolenk (2019); Cabouat, Gaunt (2020)]
  - dDGLAP evolution beyond LO ChiliPDF [Diehl et al. (2023)]
  - Double parton distributions from lattice QCD [Bali et al. (2021); Zhang (2023); Jaarsma et al. (2023)]

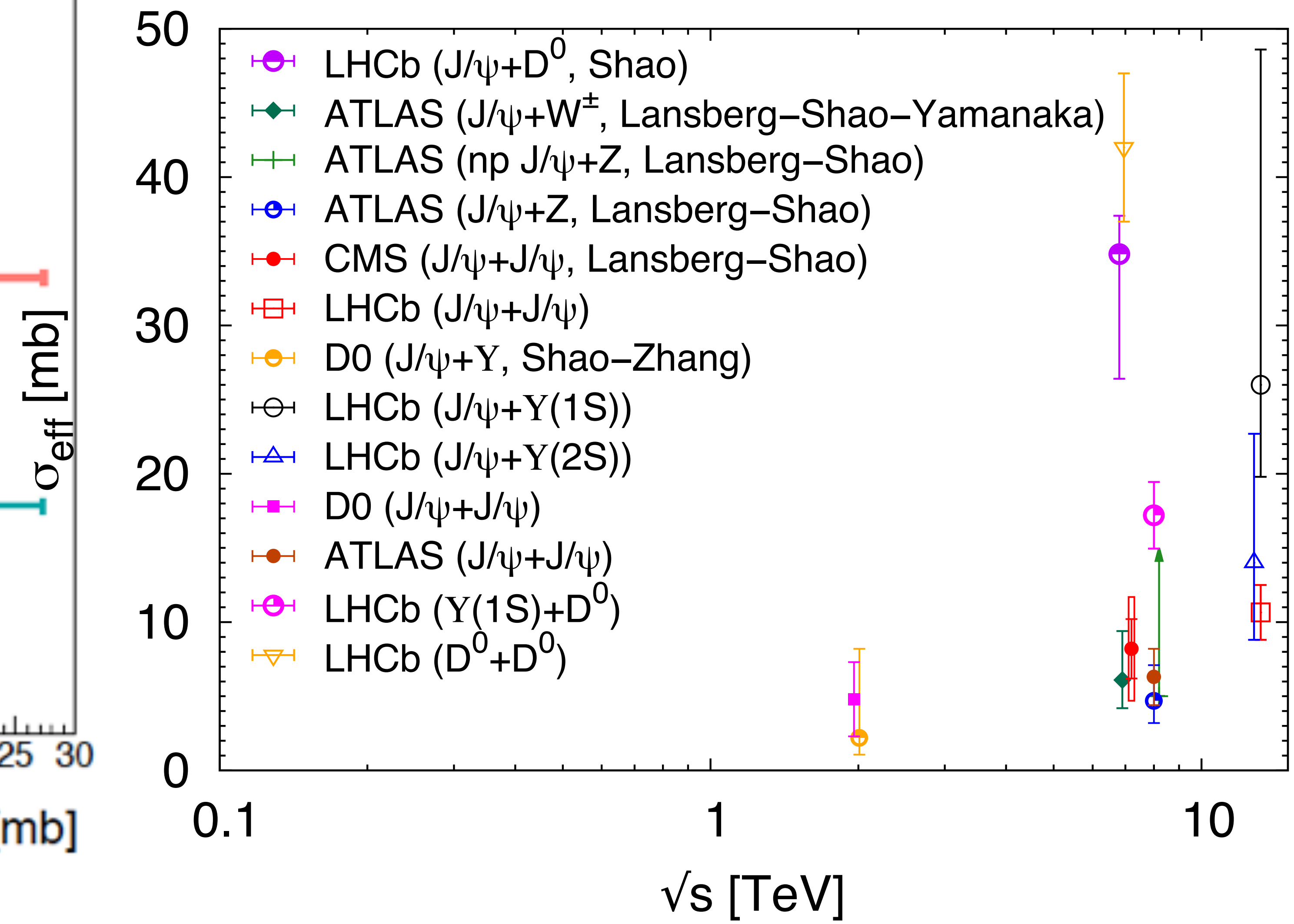
Also see the section 7 in arXiv:2012.14161

DPS Measurements

- **Many DPS measurements at the LHC (Tevatron) in pp (ppbar)**



[ATLAS (PLB'19)]



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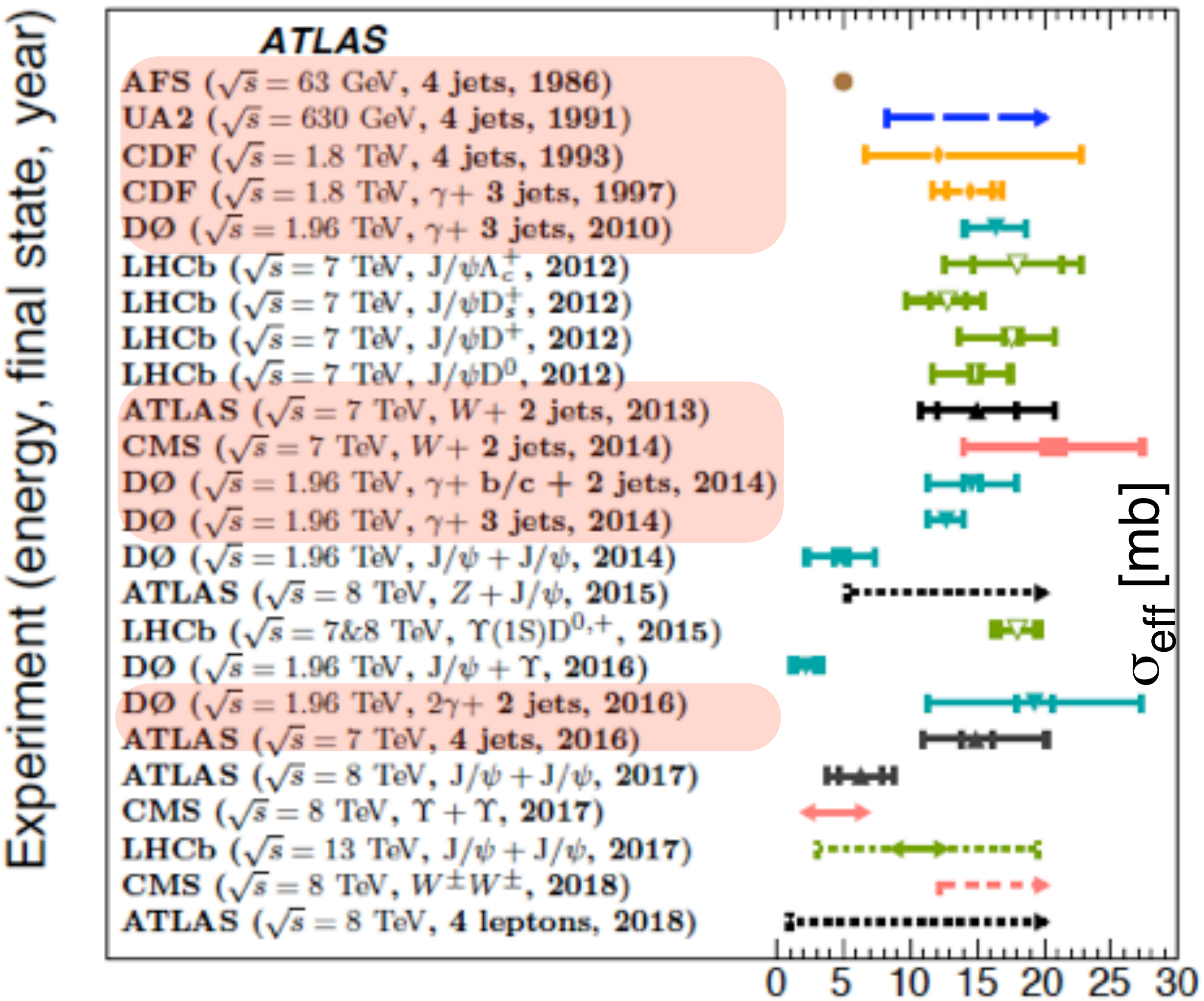

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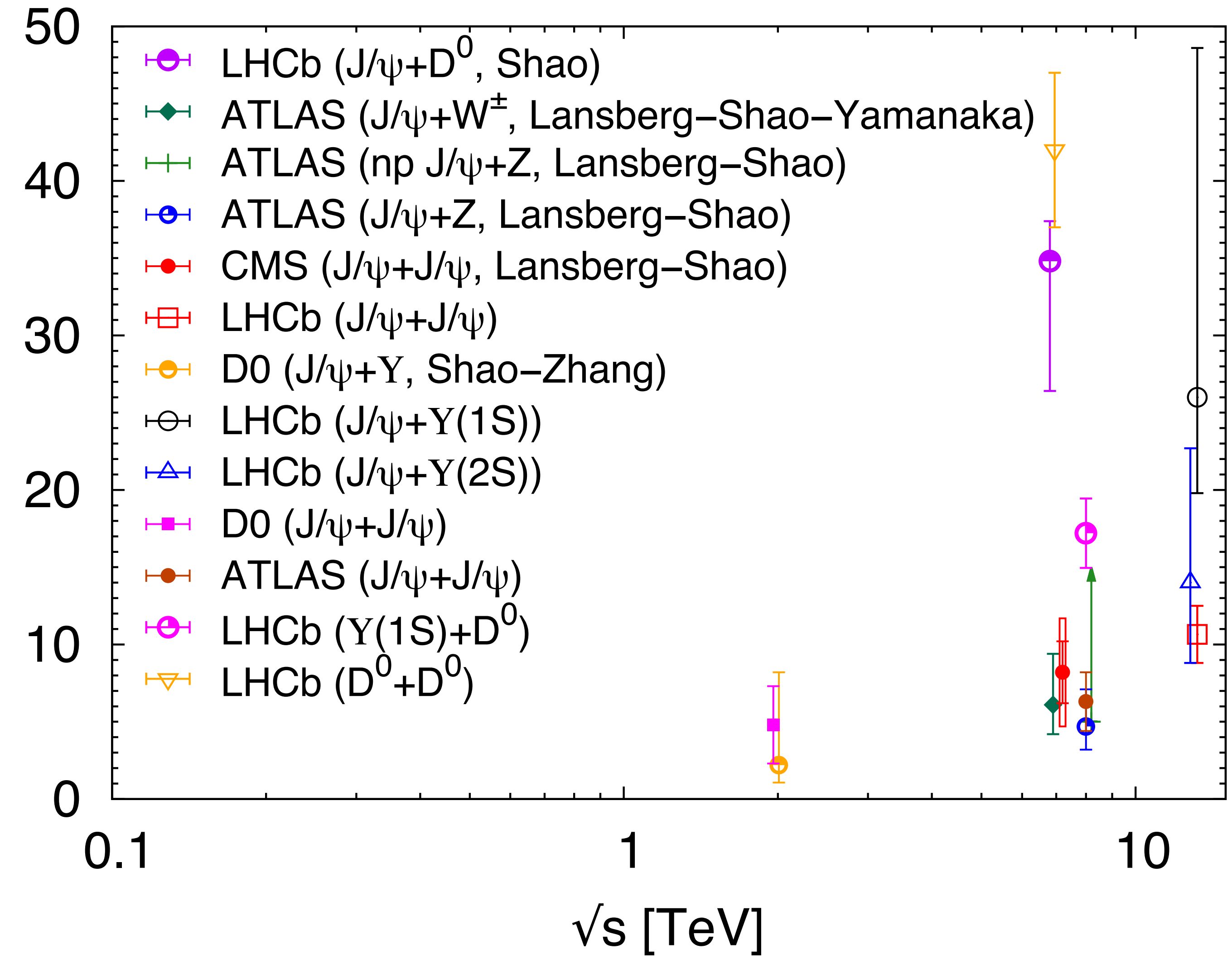
σ_{eff} [mb]



jets

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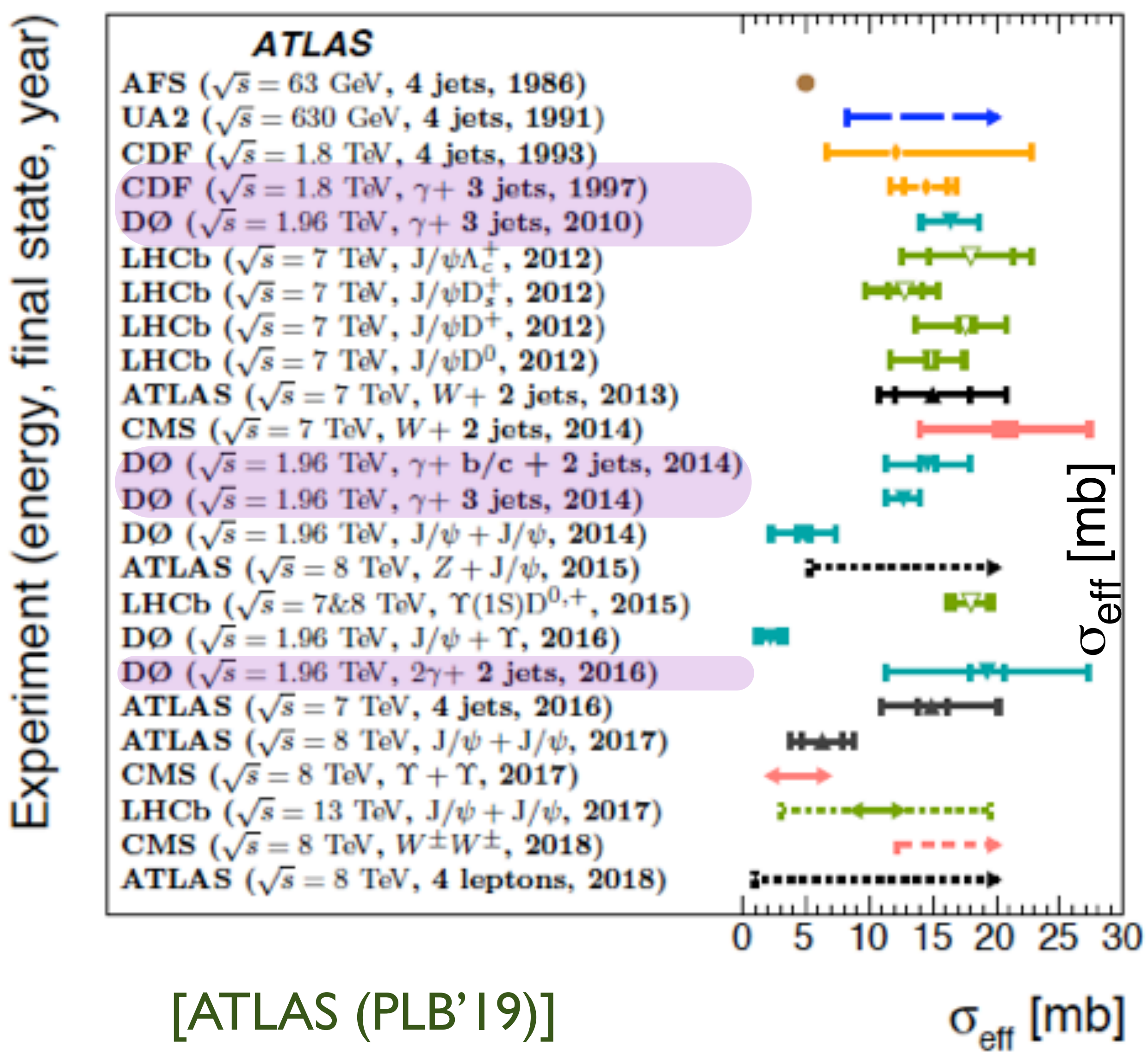

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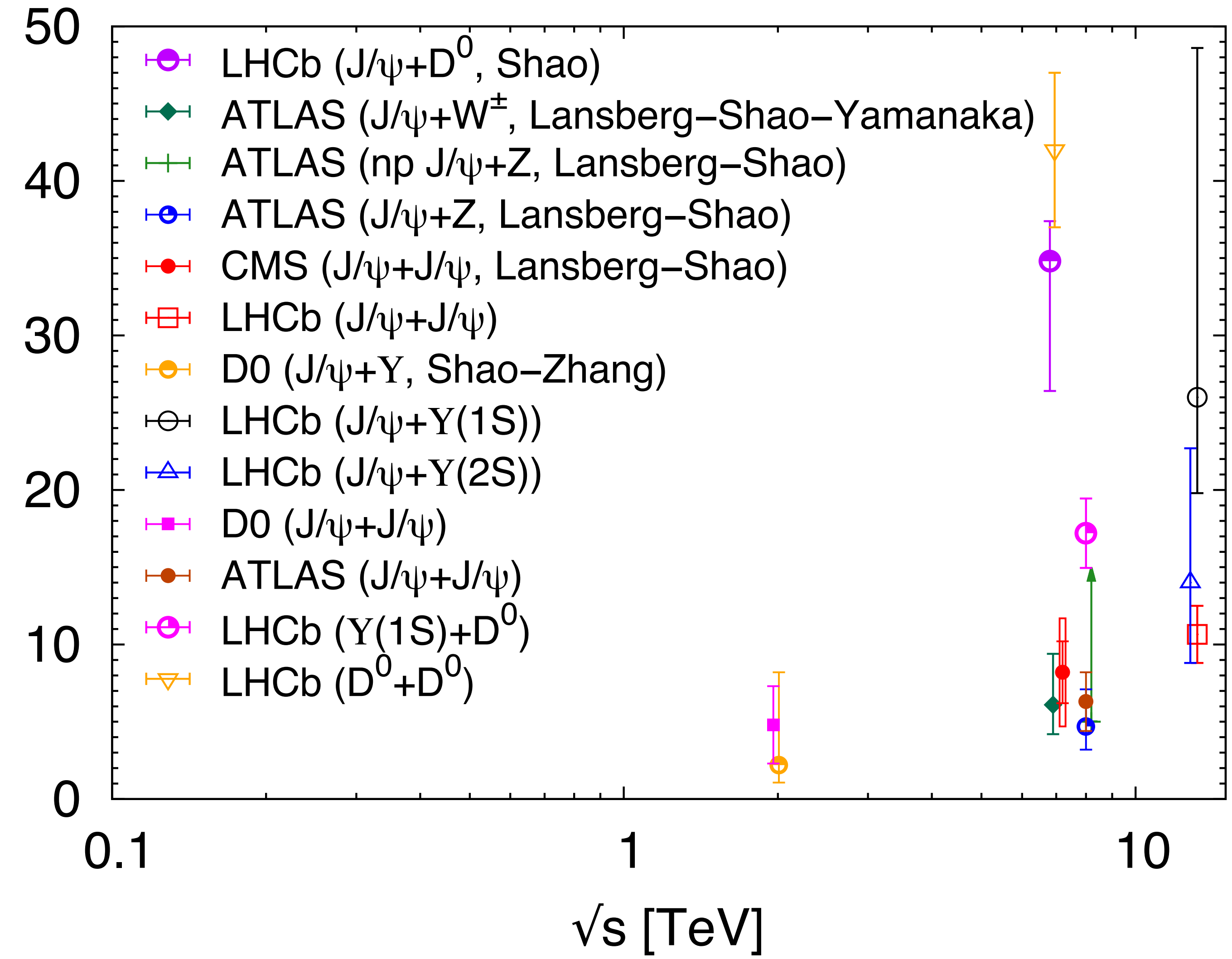

jets photons

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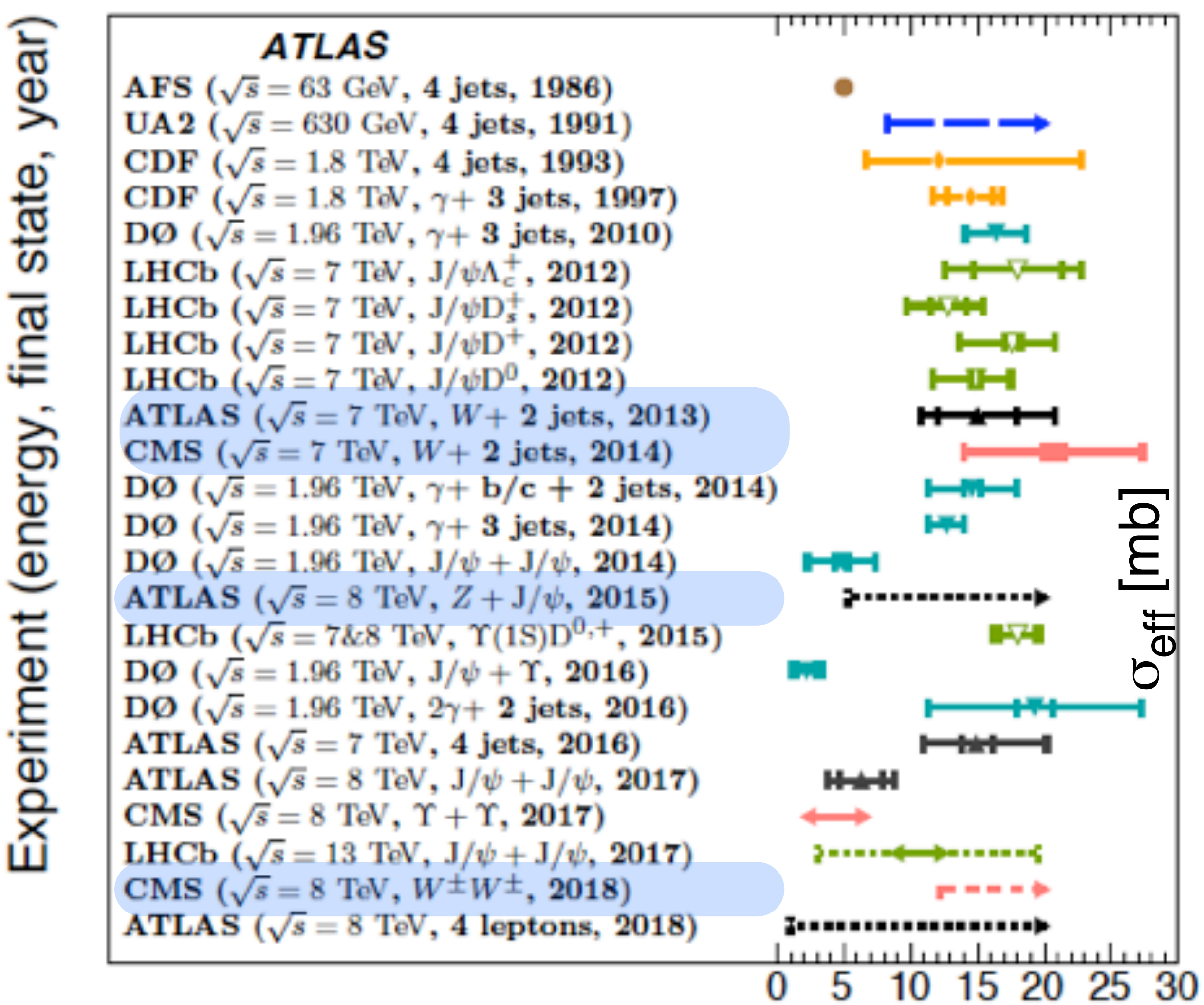

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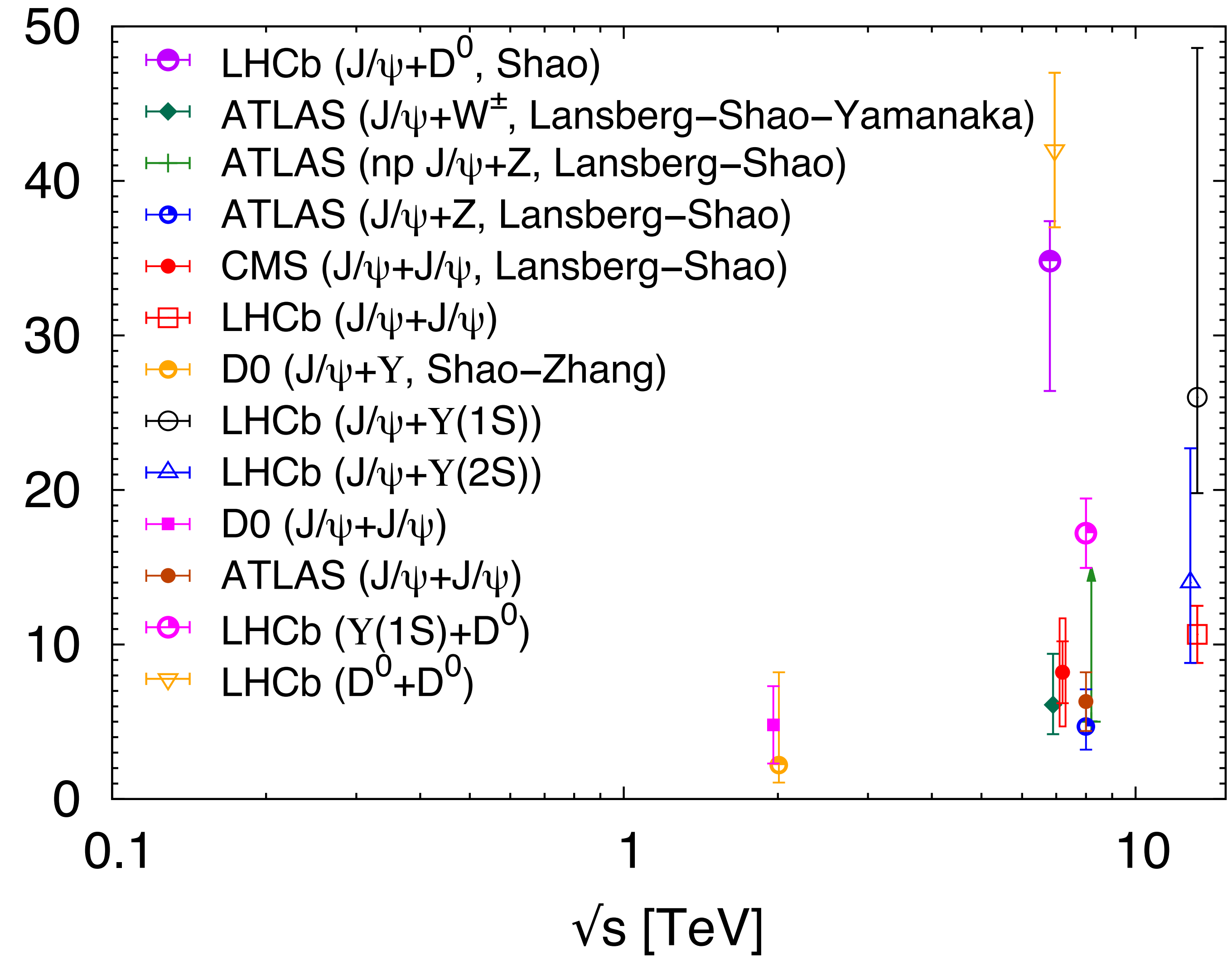

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W & Z

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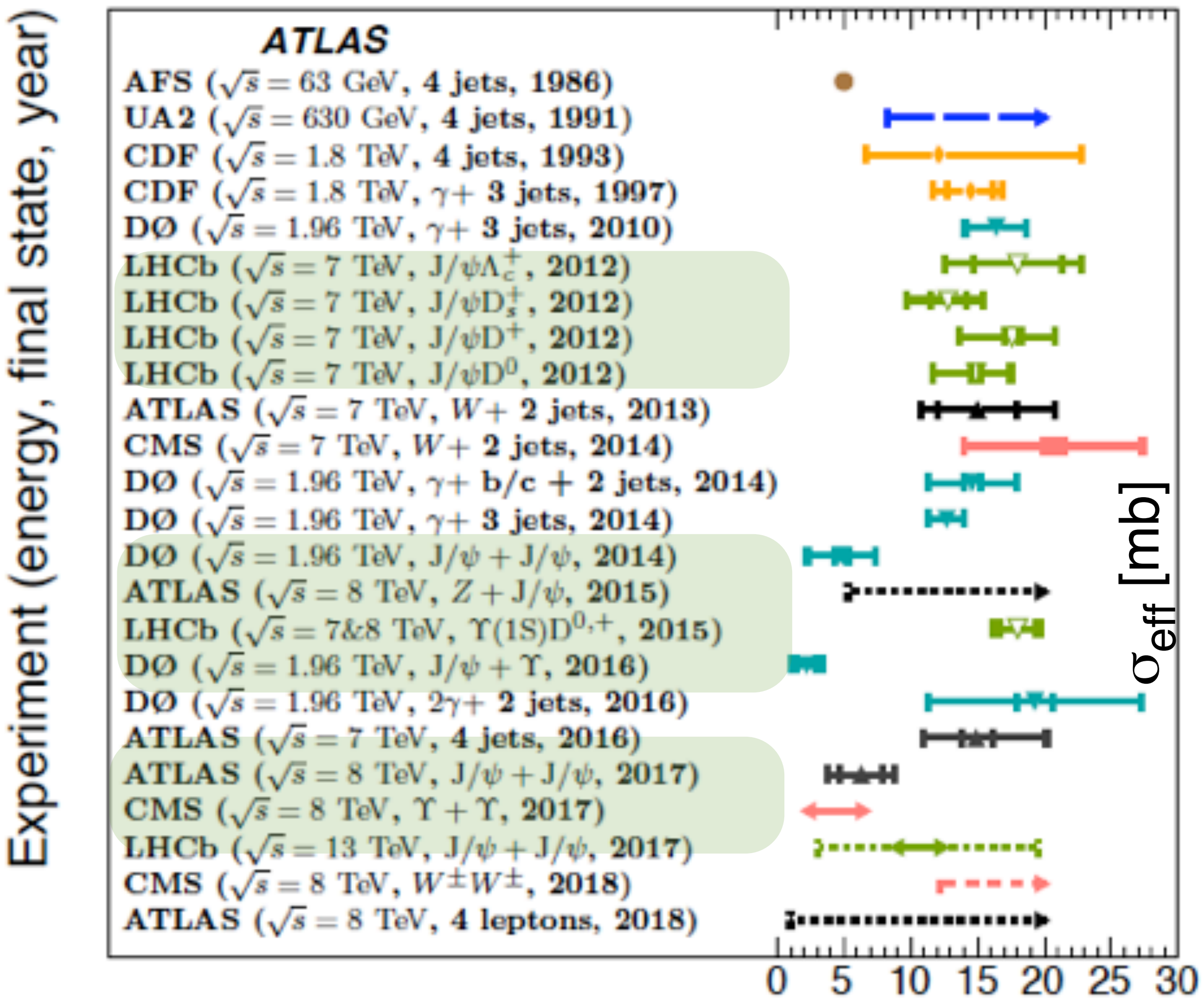

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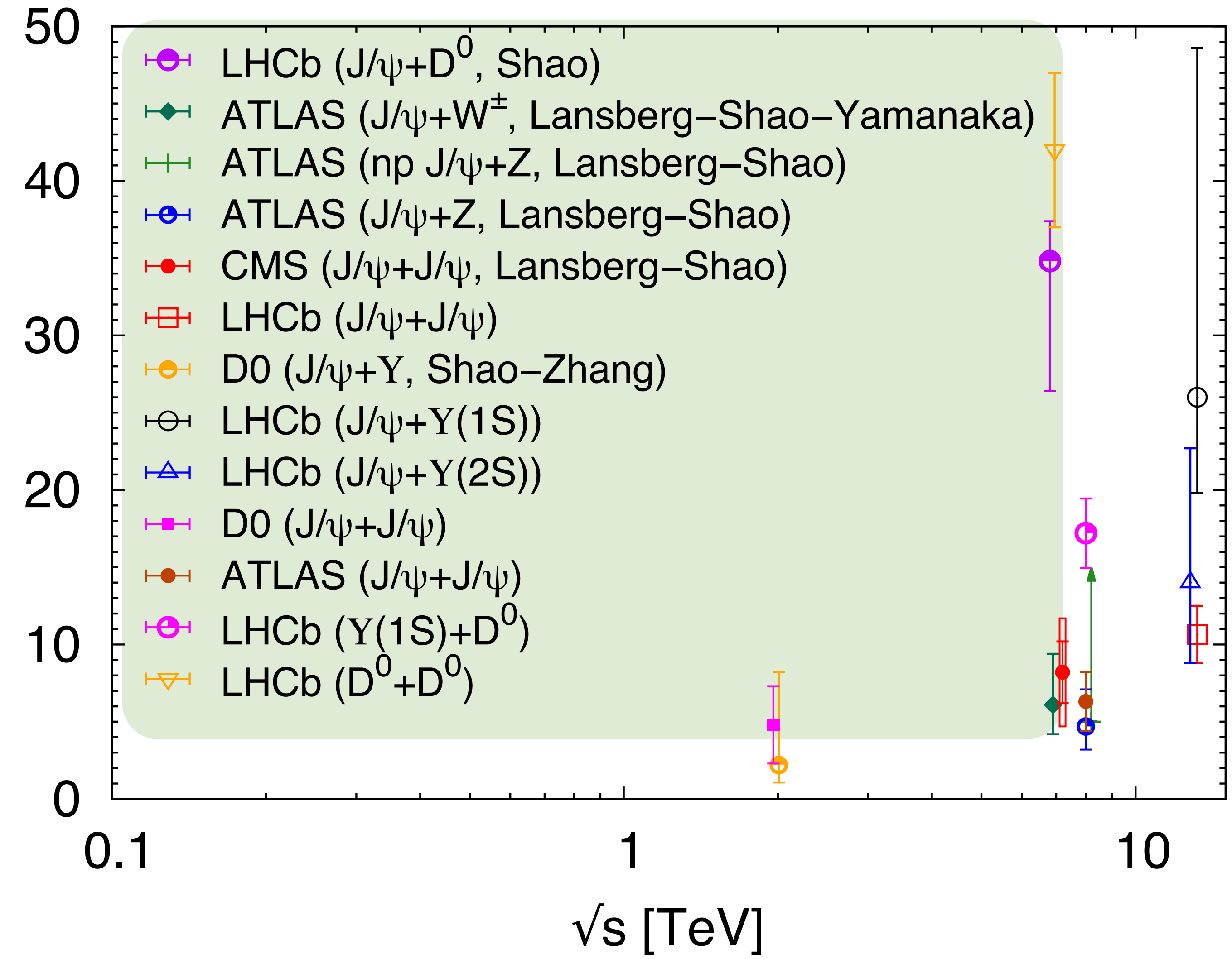

jets | photons | W & Z | heavy flav. & onia

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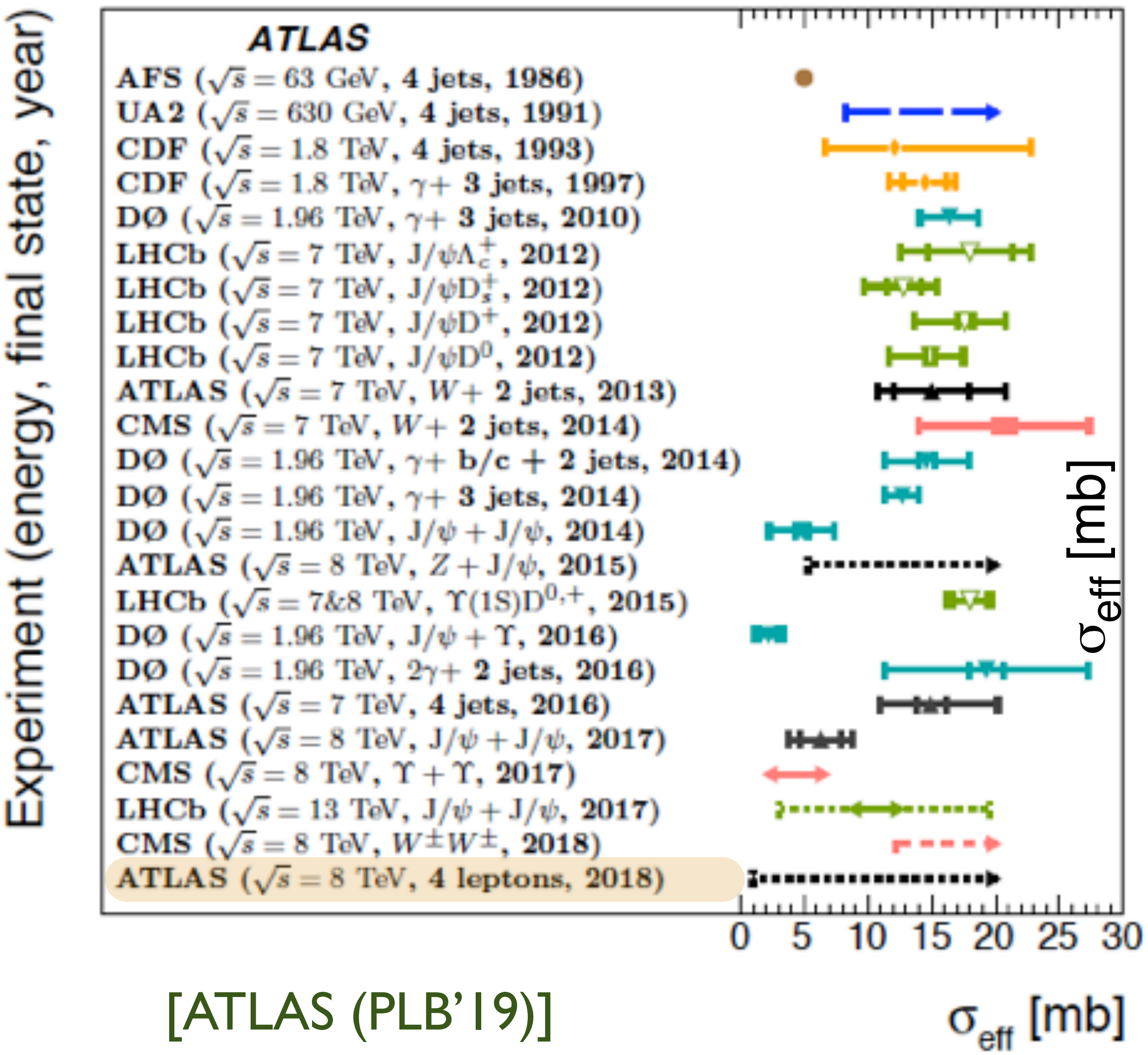

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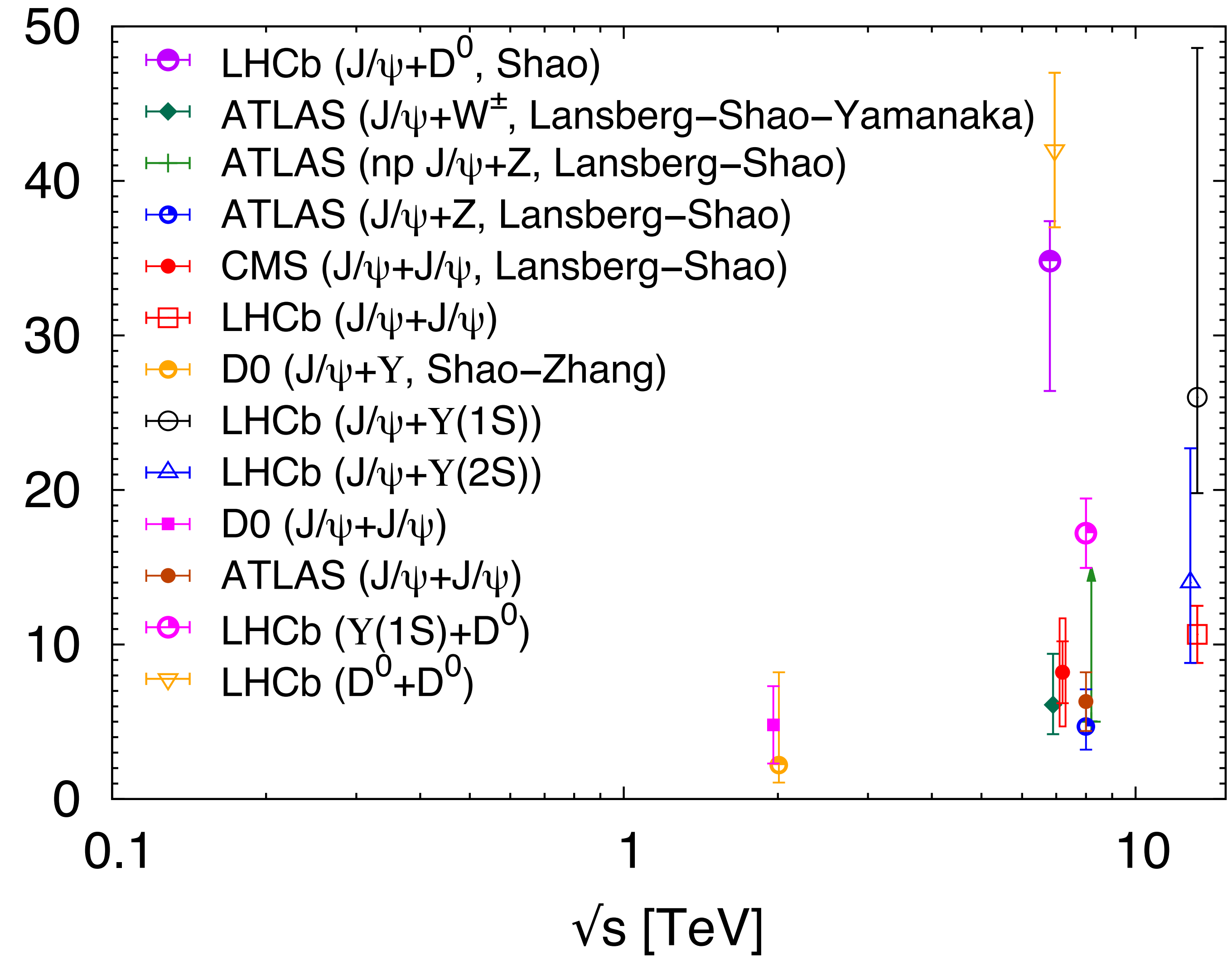

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DPS Measurements

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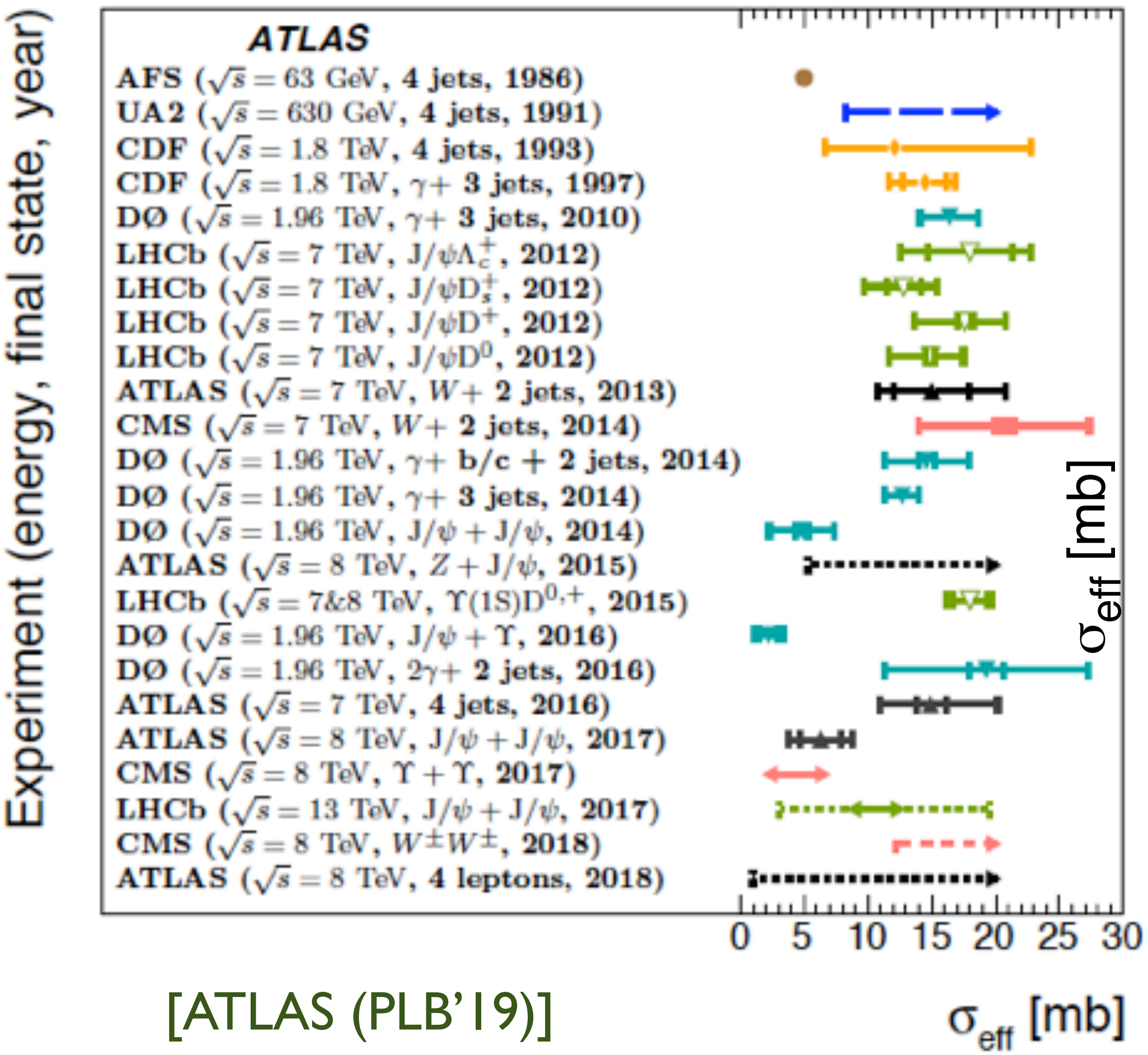
σ_{eff} :
- flavour dependent ?
- energy dependent ?
- kinematic dependent ?



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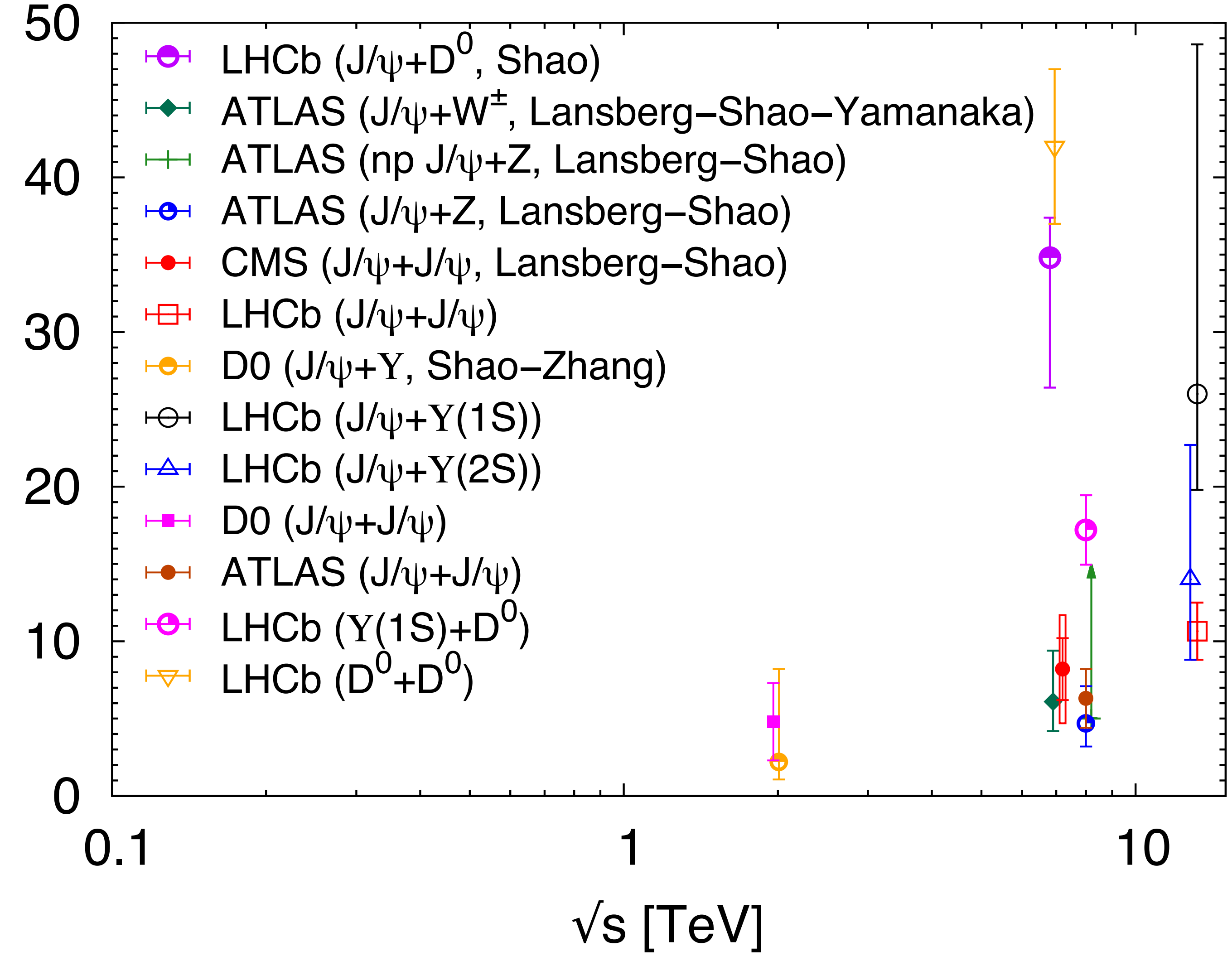

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    - Caveats with different extractions (challenging in differ. SPS & DPS)
        - How good are we understanding/controlling SPS ?

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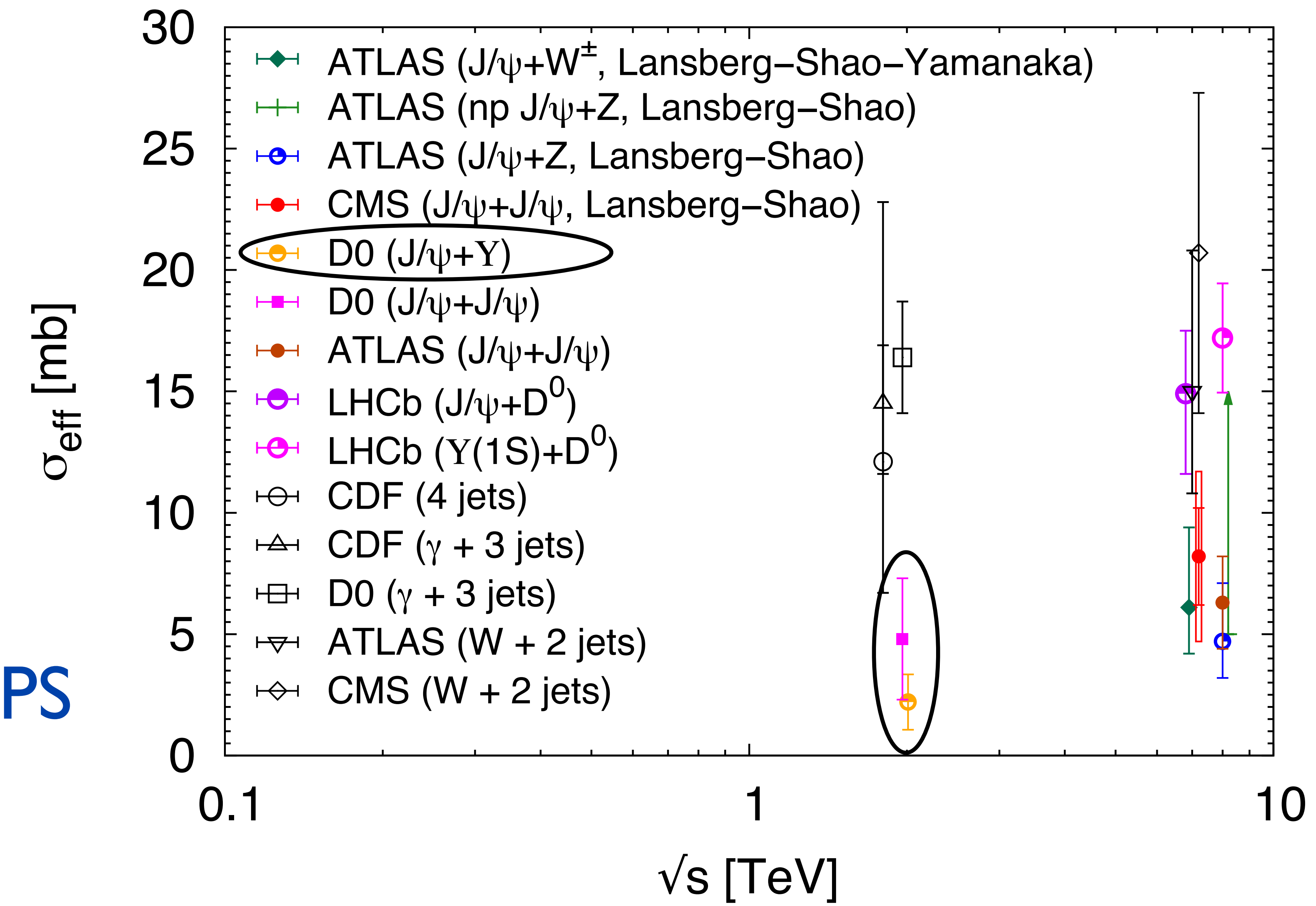

w/o SPS

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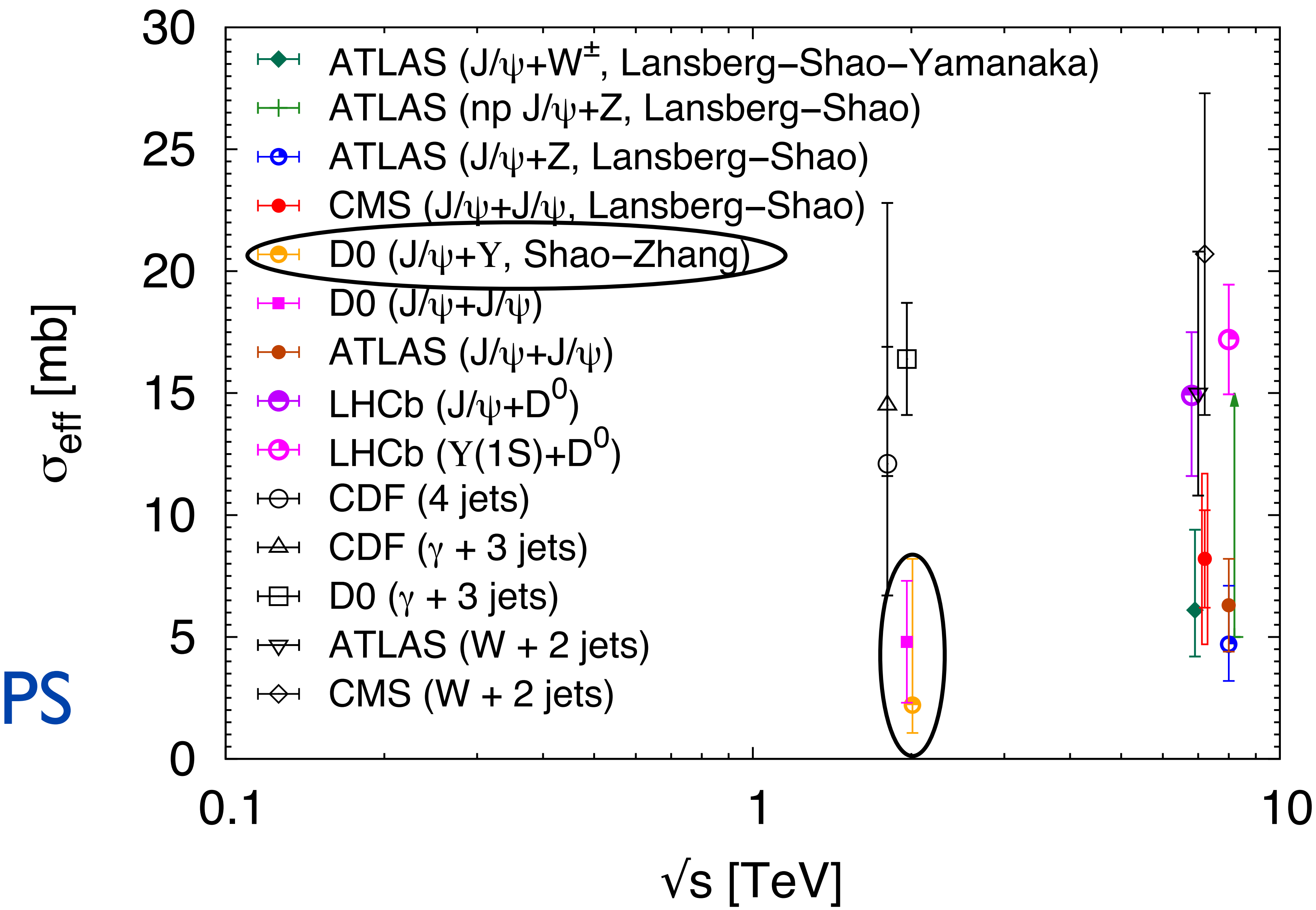

w SPS

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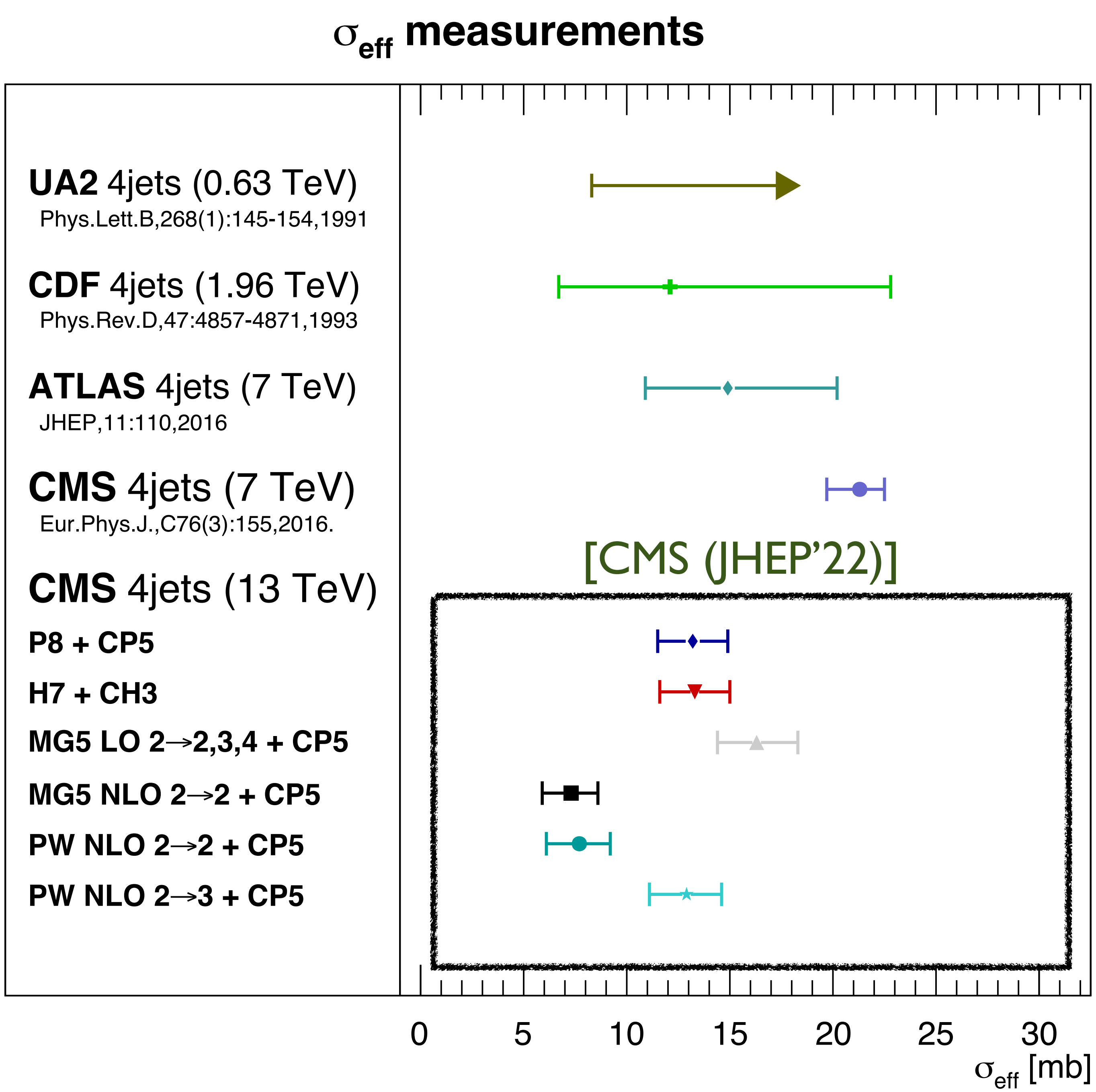


Same observable but different ME+MC

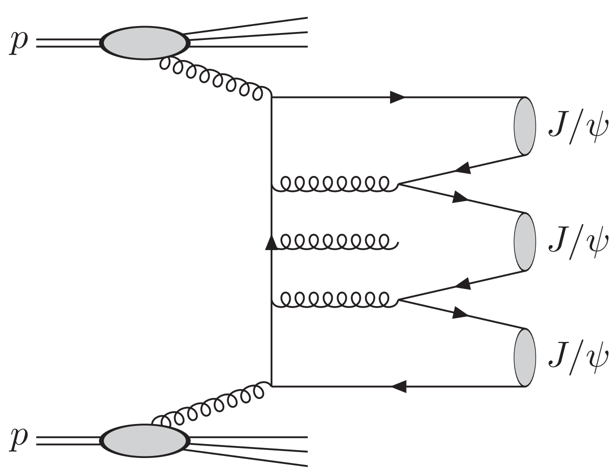
Two novel observables

- **In the rest of the talk, I will focus on two novel observables that have been firstly measured by CMS and LHCb respectively**

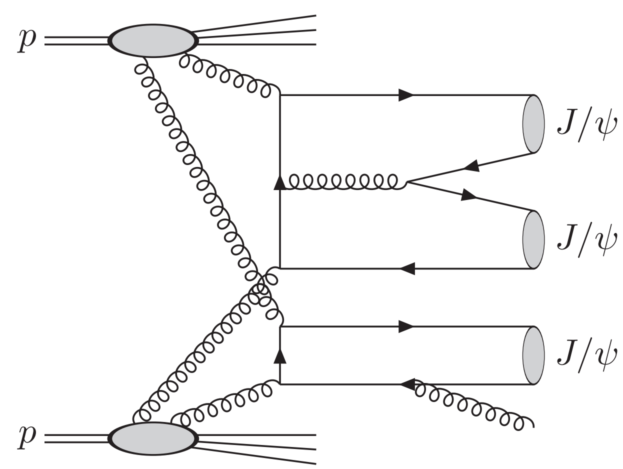
Triple Parton Scattering in pp

DPS in heavy-ion collisions

Triple Parton Scattering in pp



SPS



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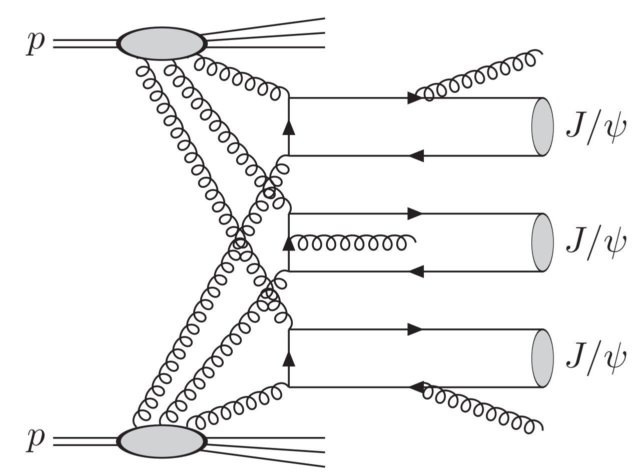

TPS

Triple Parton Scattering in pp

- **Analogously, ignoring the parton correlations, the NPS pocket formula:**

[D. d'Enterria, A. Snigirev (1708.07519)]

$$\sigma^{\rm NPS}_{f_1\cdots f_N} = \frac{m}{N!}\frac{\prod_{i=1}^{N}\sigma^{\rm SPS}_{f_i}}{\left(\sigma_{\rm eff,\mathit{N}}\right)^{N-1}}$$

- **A pure geometric consideration leads to**

[D. d'Enterria, A. Snigirev (PRL'17)]

$$\sigma_{\rm eff,3} = (0.82 \pm 0.11) \times \sigma_{\rm eff,2}$$

- **In general, the inclusive cross sections scale as**

$$\sigma_{\rm SPS} \sim \frac{1}{Q^2} \quad \textbf{v.s.} \quad \sigma_{\rm DPS} \sim \frac{\Lambda^2_{\rm QCD}}{Q^4} \quad \textbf{v.s.} \quad \sigma_{\rm TPS} \sim \frac{\Lambda^4_{\rm QCD}}{Q^6}$$

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- **Any chance to see TPS at the LHC ?**

Triple Parton Scattering in pp

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- **In general, the inclusive cross sections scale as**

$$\sigma_{\mathrm{SPS}} \sim \frac{1}{Q^2} \quad \text{v.s.} \quad \sigma_{\mathrm{DPS}} \sim \frac{\Lambda^2_{\mathrm{QCD}}}{Q^4} \quad \text{v.s.} \quad \sigma_{\mathrm{TPS}} \sim \frac{\Lambda^4_{\mathrm{QCD}}}{Q^6}$$

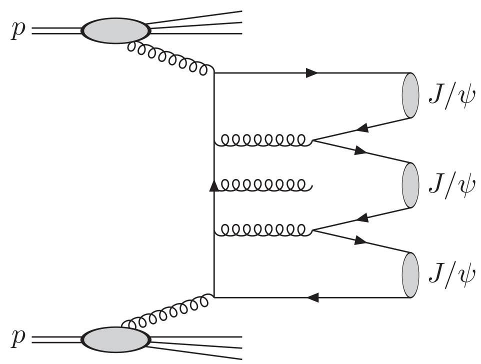
- **Any chance to see TPS at the LHC ?**

⇨ $J/\psi J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-\mu^+\mu^-$

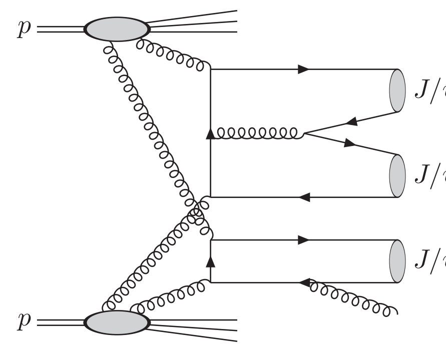
Triple Parton Scattering in pp

- **A first complete study of prompt triple J/psi as a probe of TPS**

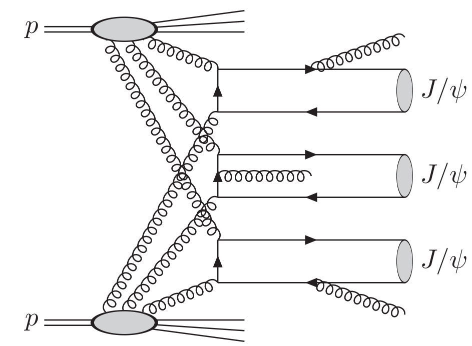
[HSS, Zhang (PRL'19)]



SPS



DPS



TPS

		inclusive	$2.0 < y_{J/\psi} < 4.5$	$\lvert y_{J/\psi}\rvert < 2.4$
13 TeV	SPS	$0.41^{+2.4}_{-0.34} \pm 0.0083$	$(1.8^{+11}_{-1.5} \pm 0.18) \times 10^{-2}$	$(8.7^{+56}_{-7.5} \pm 0.098) \times 10^{-2}$
	DPS	$(190^{+501}_{-140}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(7.0^{+18}_{-5.1}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(50^{+140}_{-37}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$
	TPS	$130 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$	$1.3 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$	$18 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$
27 TeV	SPS	$0.46^{+2.9}_{-0.39} \pm 0.022$	$(3.2^{+22}_{-2.8} \pm 0.21) \times 10^{-2}$	$(5.8^{+39}_{-5.1} \pm 0.29) \times 10^{-2}$
	DPS	$(560^{+2900}_{-480}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(19^{+97}_{-16}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(120^{+630}_{-100}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$
	TPS	$570 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$	$5.0 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$	$57 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$
75 TeV	SPS	$0.59^{+4.4}_{-0.52} \pm 0.016$	$(3.0^{+25}_{-2.7} \pm 0.23) \times 10^{-2}$	$(7.2^{+63}_{-6.5} \pm 0.38) \times 10^{-2}$
	DPS	$(1900^{+11000}_{-1600}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(57^{+340}_{-50}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(310^{+2000}_{-270}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$
	TPS	$3900 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$	$27 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$	$260 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$
100 TeV	SPS	$1.1^{+8.4}_{-1.0} \pm 0.044$	$(4.5^{+33}_{-4.0} \pm 0.72) \times 10^{-2}$	$(36^{+290}_{-32} \pm 1.8) \times 10^{-2}$
	DPS	$(3400^{+19000}_{-2900}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(100^{+550}_{-86}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$	$(490^{+3000}_{-430}) \times \frac{10\text{ mb}}{\sigma_{\text{eff},2}}$
	TPS	$6500 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$	$45 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$	$380 \times \left(\frac{10\text{ mb}}{\sigma_{\text{eff},3}}\right)^2$

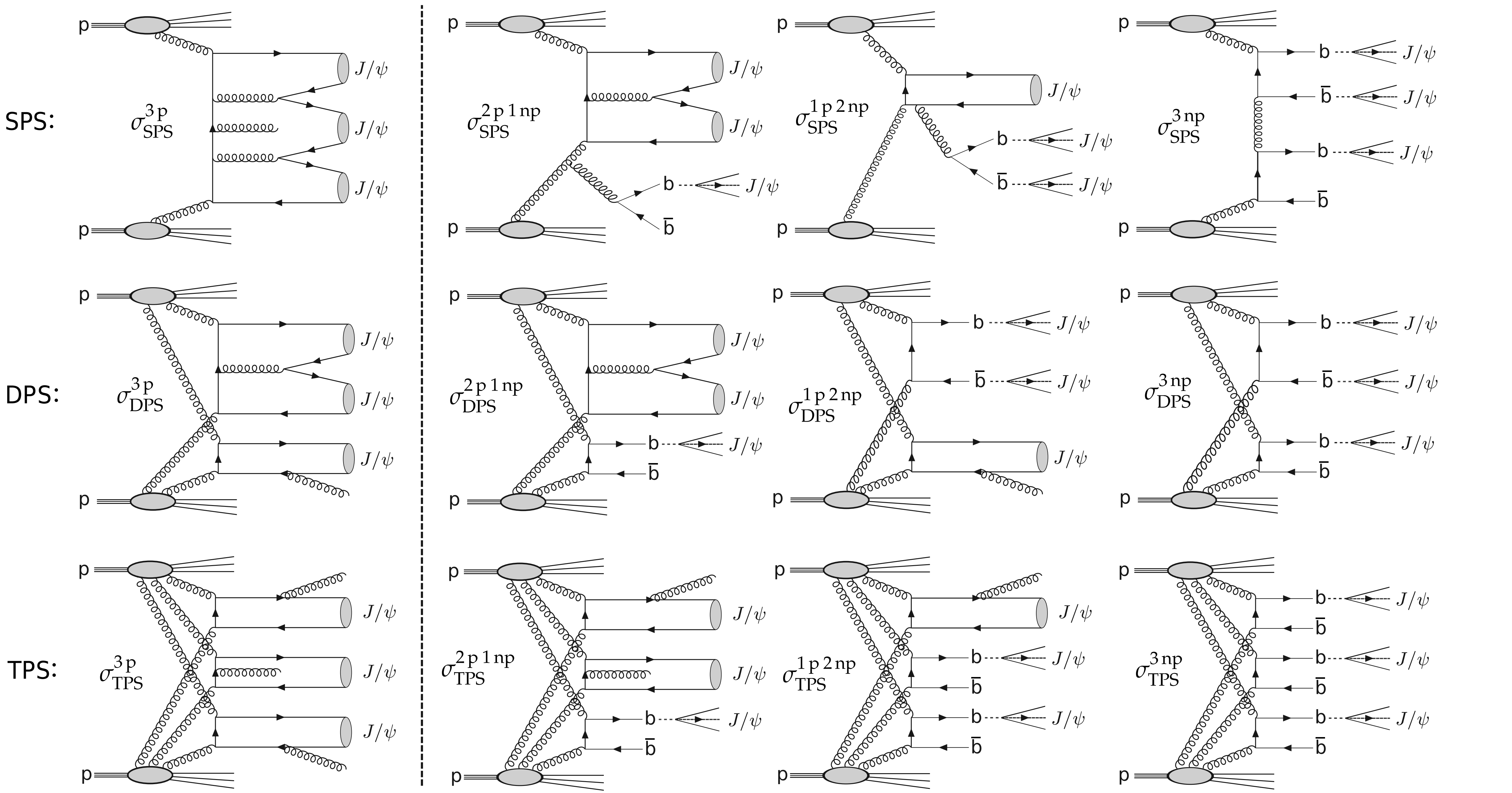
- With our knowledge of single J/psi and double J/psi, the process is predicted to be DPS and TPS dominant
- The number of events is large enough to be seen at the LHC unless $\sigma_{\text{eff},2}$ and $\sigma_{\text{eff},3}$ are significantly larger than 10 mb

Triple Parton Scattering in pp

- **First observation by CMS at 13 TeV in pp**

[CMS (Nature Physics'23)]

Pure prompt production: Nonprompt contributions:



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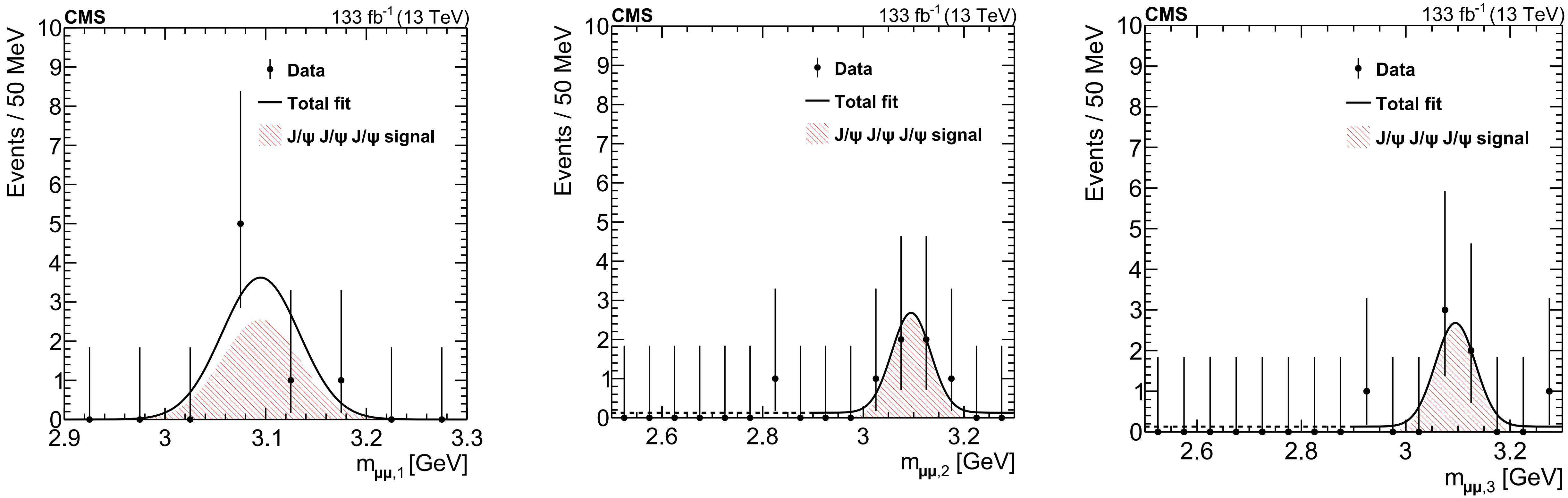
Triple Parton Scattering in pp

- **First observation by CMS at 13 TeV in pp**

[CMS (Nature Physics'23)]



- **Observation: 5 signal events + 1 background event**

- **The measurement of fiducial cross section**

$$\sigma(pp \to J/\psi J/\psi J/\psi X) = 272^{+141}_{-104}(\text{stat}) \pm 17(\text{syst})\ \text{fb}$$

Triple Parton Scattering in pp

- **Theoretical interpretation of the CMS measurement**

[CMS (Nature Physics'23)]

  - Using the pocket formula, we need to know the following theoretical inputs

SPS single-J/ψ production		SPS double-J/ψ production			SPS triple-J/ψ production			
HO(DATA)	MG5NLO+PY8	HO(NLO*)	HO(LO)+PY8	MG5NLO+PY8	HO(LO)	HO(LO)+PY8	HO(LO)+PY8	MG5NLO+PY8
σ^{1p}_{SPS}	σ^{1np}_{SPS}	σ^{2p}_{SPS}	σ^{1p1np}_{SPS}	σ^{2np}_{SPS}	σ^{3p}_{SPS}	σ^{2p1np}_{SPS}	σ^{1p2np}_{SPS}	σ^{3np}_{SPS}
570 ± 57 nb	600^{+130}_{-220} nb	40^{+80}_{-26} pb	24^{+35}_{-16} fb	430^{+95}_{-130} pb	< 5 ab	$5.2^{+9.6}_{-3.3}$ fb	14^{+17}_{-8} ab	12 ± 4 fb

HO: *HELAC-Onia*

MG5NLO: *MadGraph5_aMC@NLO*

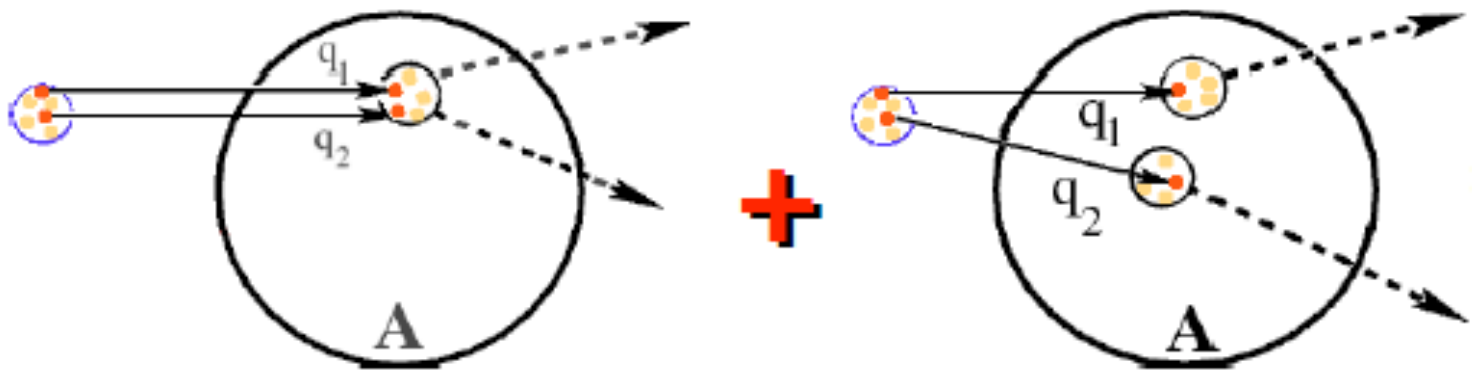
PY8: *Pythia8.2*

- Fixing $\sigma_{\mathrm{eff},3} = (0.82 \pm 0.11) \times \sigma_{\mathrm{eff},2}$ and fitting $\sigma_{\mathrm{eff},2}$

$$\sigma_{\mathrm{eff},2} = 2.7^{+1.4}_{-1.0}(\mathrm{exp})^{+1.5}_{-1.0}(\mathrm{theo})\ \mathrm{mb}$$

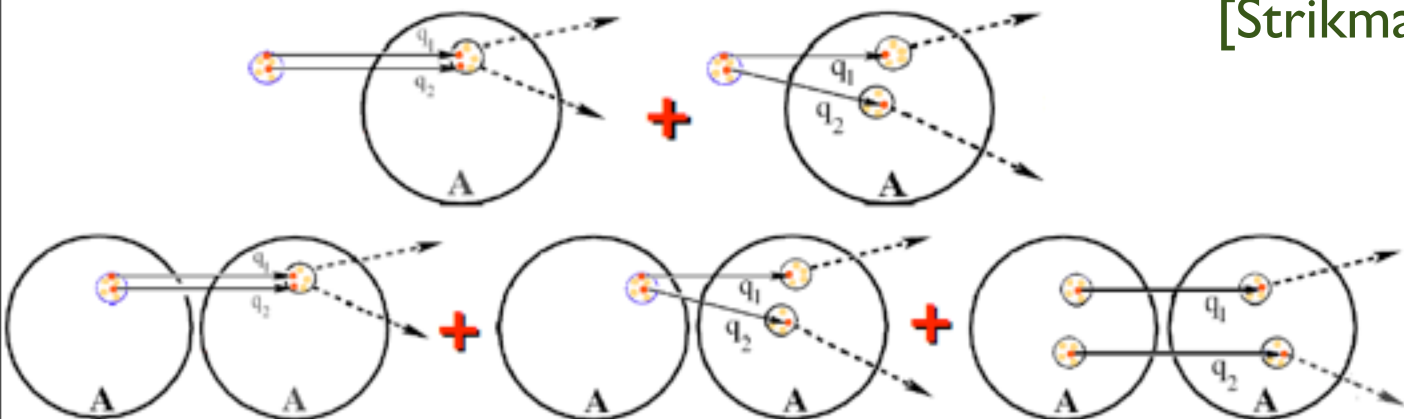
- Triple-J/psi fractions: ~6% SPS, ~74% DPS, ~20% TPS

DPS in heavy-ion collisions



DPS in Heavy-Ion Collisions

- **Geometrical enhancement because of several nucleons in a nucleus**



[Strikman, Treleani (2002); D. d'Enterria, A. Snigirev (2013, 2014)]

$$\sigma_{pA}^{\mathrm{DPS}} \approx 3A\sigma_{pp}^{\mathrm{DPS}}, \sigma_{pA}^{\mathrm{SPS}} \approx A\sigma_{pp}^{\mathrm{SPS}}$$

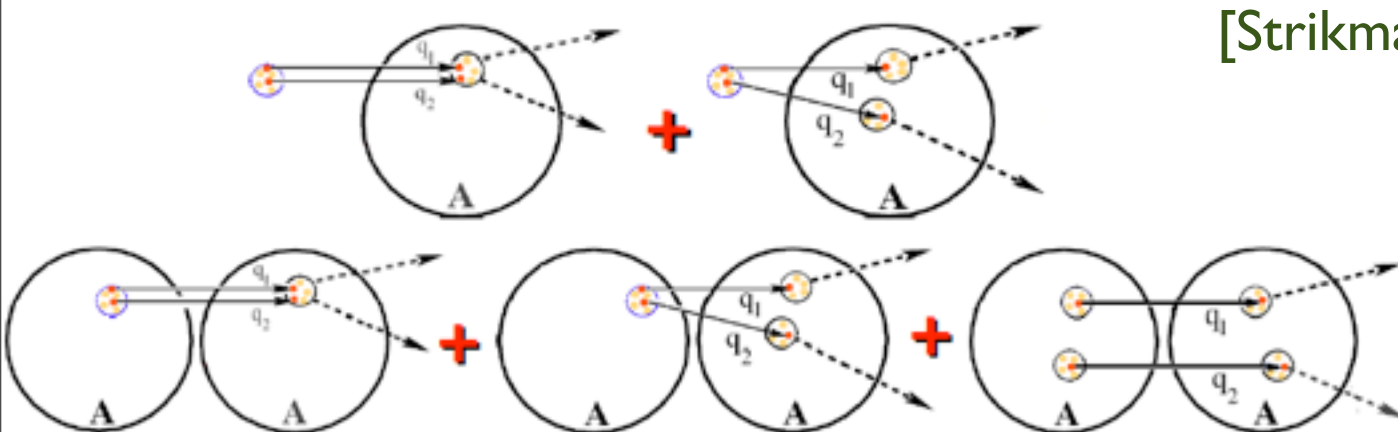
$$\sigma_{AA}^{\mathrm{DPS}} \approx \frac{A^{3.3}}{5}\sigma_{pp}^{\mathrm{DPS}}, \sigma_{AA}^{\mathrm{SPS}} \approx A^2\sigma_{pp}^{\mathrm{SPS}}$$

Assumptions: no nuclear modification and $\sigma_{\mathrm{eff},pp} \simeq 15$ mb

DPS in Heavy-Ion Collisions

- **Geometrical enhancement because of several nucleons in a nucleus**

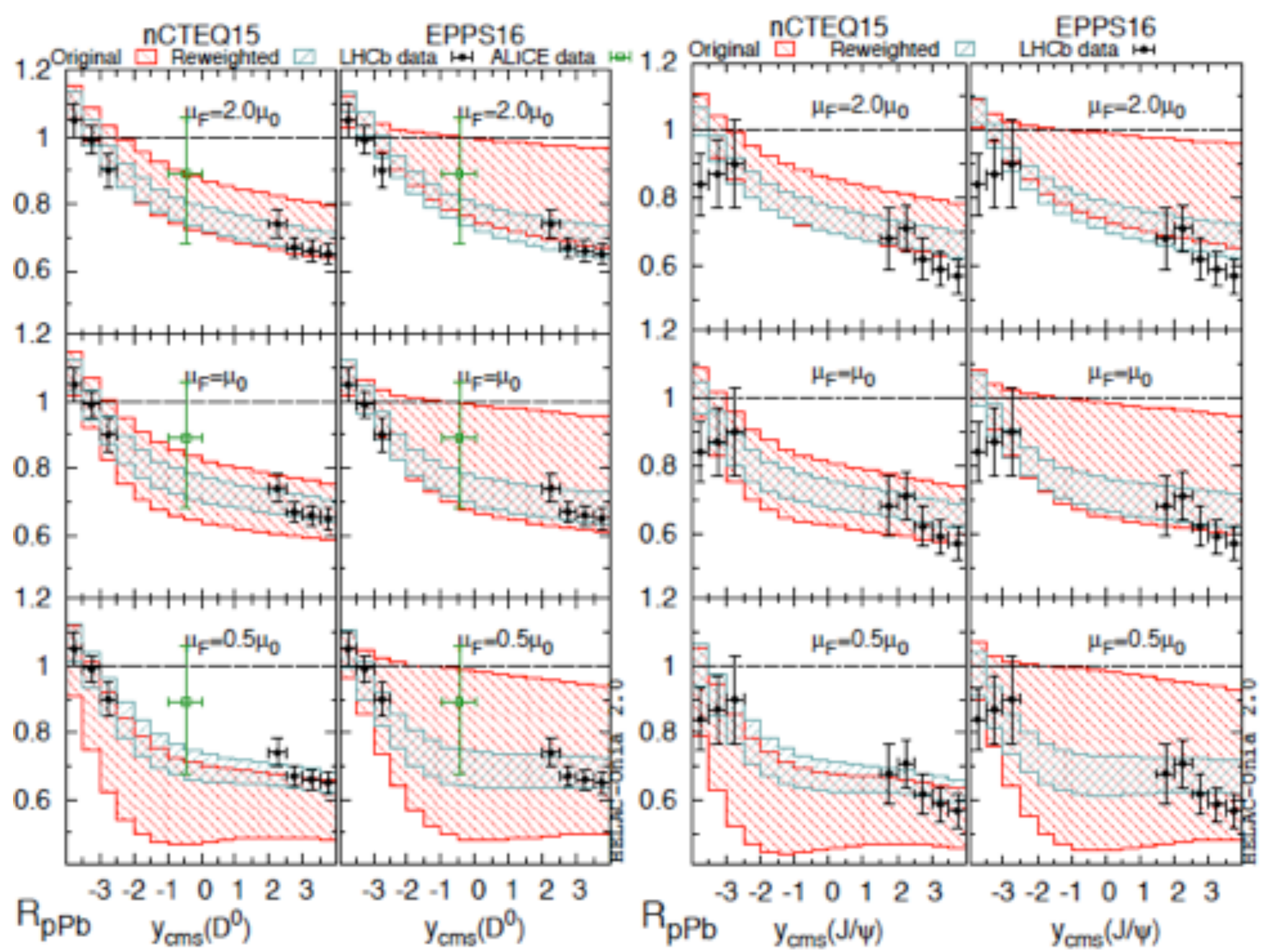
[Strikman, Treleani (2002); D. d'Enterria, A. Snigirev (2013, 2014)]

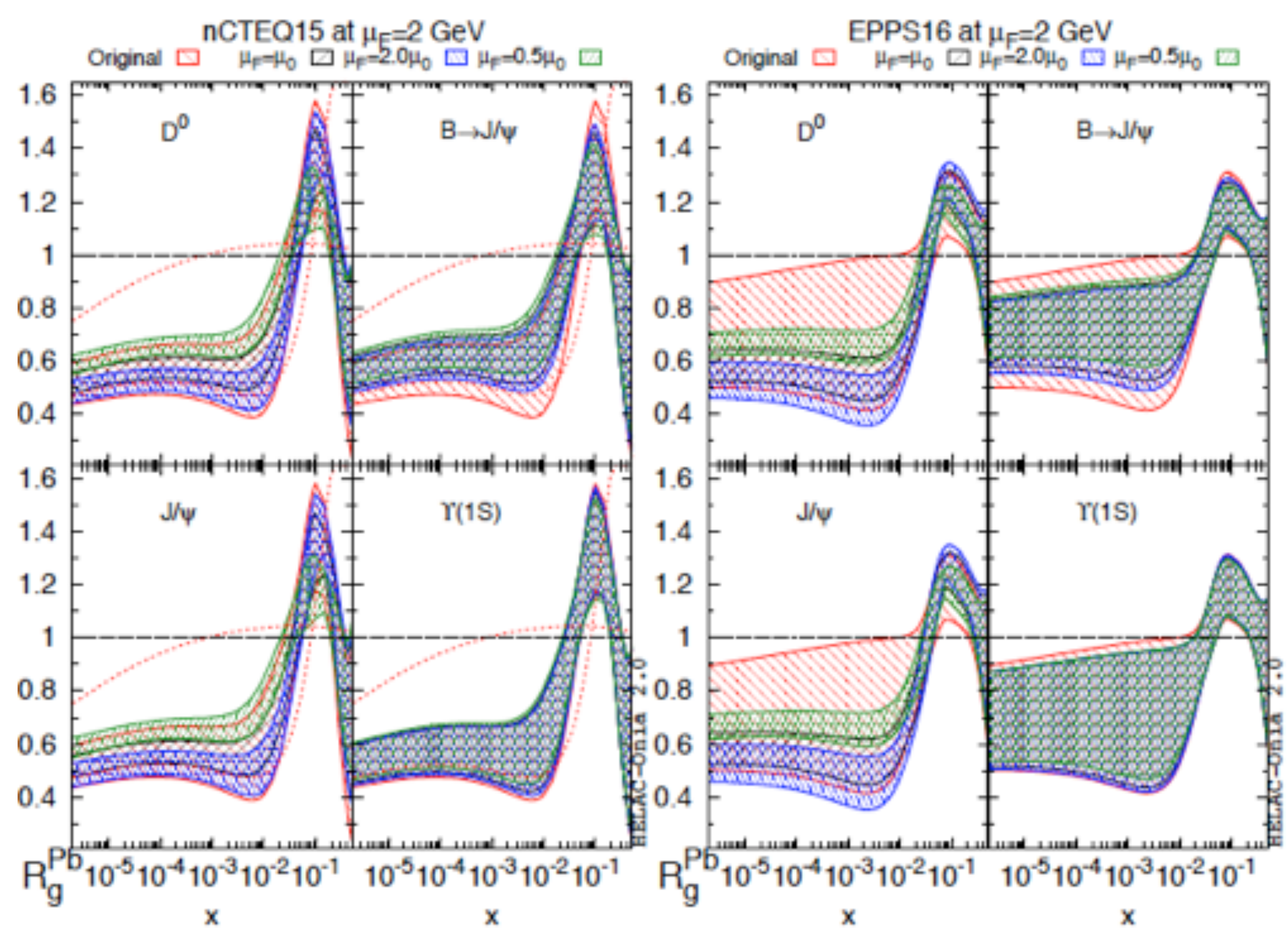


$$\sigma_{pA}^{\rm DPS} \approx 3A\sigma_{pp}^{\rm DPS}, \sigma_{pA}^{\rm SPS} \approx A\sigma_{pp}^{\rm SPS}$$

$$\sigma_{AA}^{\rm DPS} \approx \frac{A^{3.3}}{5}\sigma_{pp}^{\rm DPS}, \sigma_{AA}^{\rm SPS} \approx A^2\sigma_{pp}^{\rm SPS}$$

- **Of course, we know we cannot neglect the nuclear modifications ...**
  - E.g. gluon (anti)shadowing for heavy flavour and quarkonia [Kusina, et al. (PRL'18)]



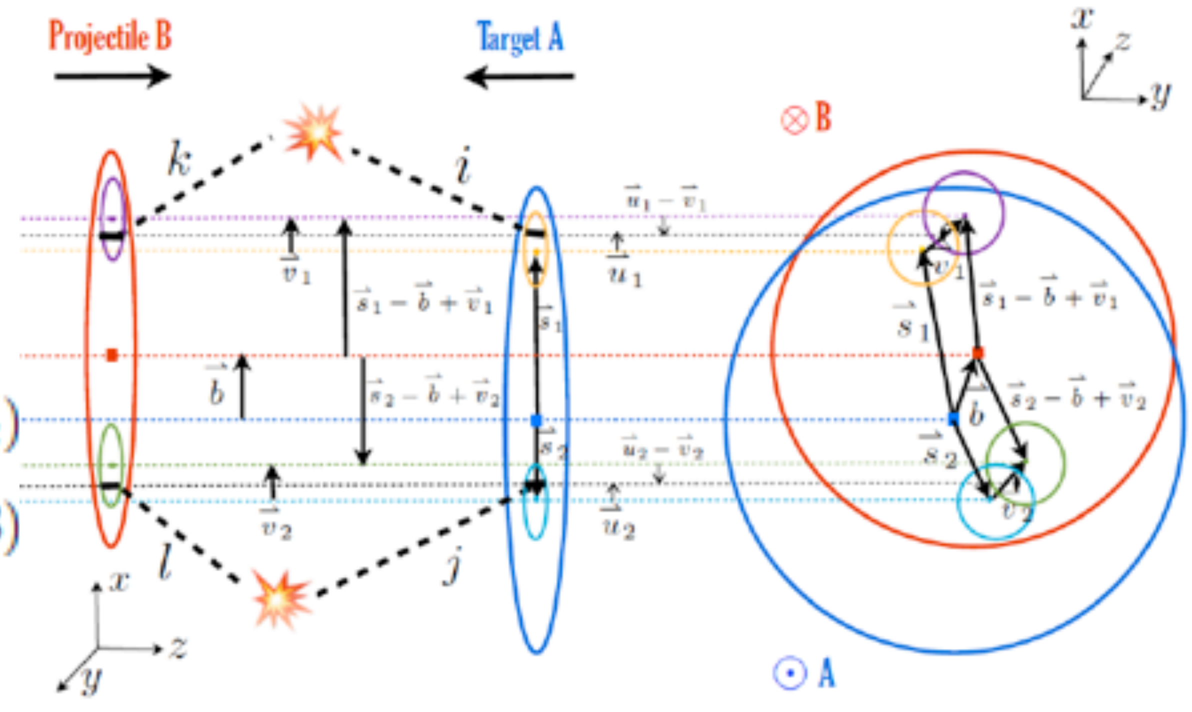


DPS in Heavy-Ion Collisions

- **Let us accommodate both nPDF and geometric effect** [HSS (PRD'20)]

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx_1' dx_2' d^2\mathbf{b}_1 d^2\mathbf{b}_2 d^2\mathbf{b}$$
$$\times \Gamma_{ij}(x_1, x_2, \mathbf{b}_1, \mathbf{b}_2)\, \hat{\sigma}_{ik}^{Q_1}(x_1, x_1')\, \hat{\sigma}_{jl}^{Q_2}(x_2, x_2')\, \Gamma_{kl}(x_1', x_2', \mathbf{b}_1 - \mathbf{b}, \mathbf{b}_2 - \mathbf{b}),$$

$$\sigma^{\rm DPS}_{AB\to f_1 f_2} = \frac{1}{1+\delta_{f_1 f_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx_1' dx_2'$$
$$\Gamma_A^{ij}(x_1, x_2, \vec{s}_1, \vec{s}_2, \vec{u}_1, \vec{u}_2) \hat{\sigma}_{ik}^{f_1}(x_1, x_1') \hat{\sigma}_{jl}^{f_2}(x_2, x_2') \times$$
$$\Gamma_B^{kl}(x_1', x_2', \vec{s}_1 - \vec{b} + \vec{v}_1, \vec{s}_2 - \vec{b} + \vec{v}_2, \vec{u}_1 - \vec{v}_1, \vec{u}_2 - \vec{v}_2)$$
$$d^2\vec{u}_1 d^2\vec{u}_2 d^2\vec{v}_1 d^2\vec{v}_2 d^2\vec{s}_1 d^2\vec{s}_2 d^2\vec{b}, \qquad (8)$$



(a) Side view (b) Beam view

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DPS in Heavy-Ion Collisions

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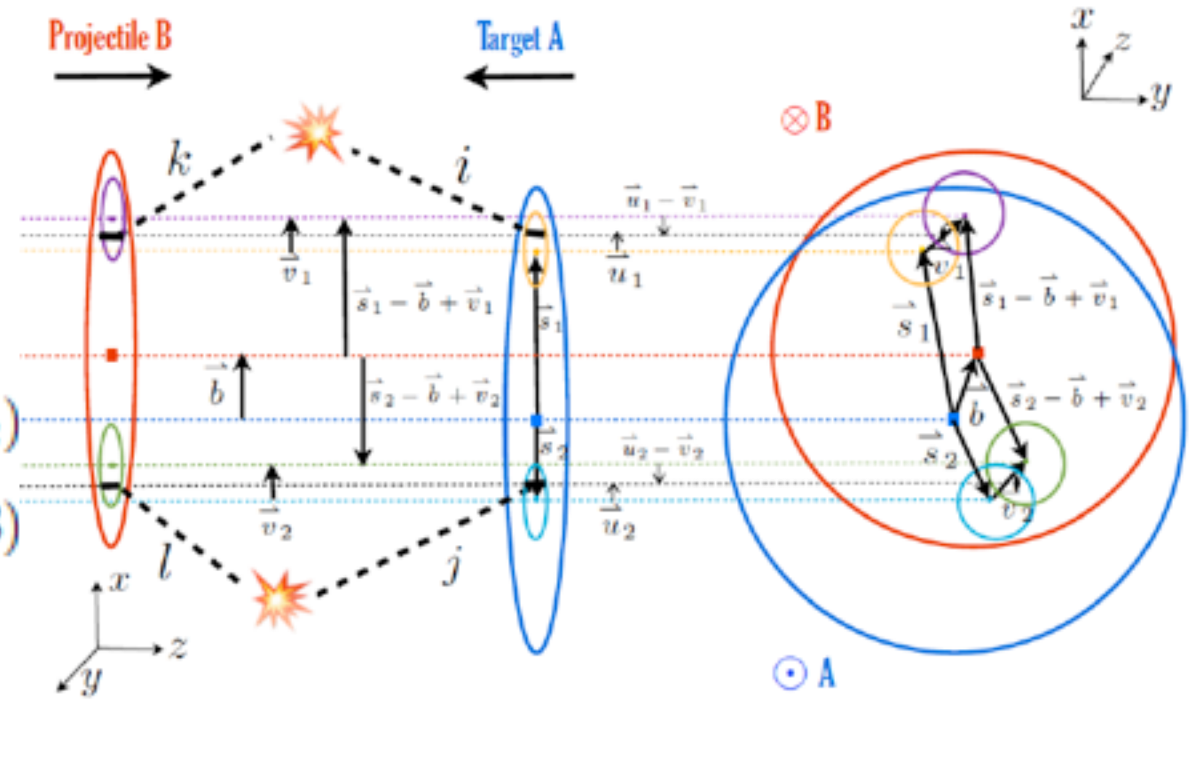
$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx'_1 dx'_2 d^2\mathbf{b}_1 d^2\mathbf{b}_2 d^2\mathbf{b}$$
$$\times \Gamma_{ij}(x_1,x_2,\mathbf{b}_1,\mathbf{b}_2)\,\hat{\sigma}^{Q_1}_{ik}(x_1,x'_1)\,\hat{\sigma}^{Q_2}_{jl}(x_2,x'_2)\,\Gamma_{kl}(x'_1,x'_2,\mathbf{b}_1-\mathbf{b},\mathbf{b}_2-\mathbf{b}),$$

$$\sigma^{\rm DPS}_{AB\to f_1f_2} = \frac{1}{1+\delta_{f_1f_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx'_1 dx'_2$$
$$\Gamma^{ij}_A(x_1,x_2,\vec{s}_1,\vec{s}_2,\vec{u}_1,\vec{u}_2)\hat{\sigma}^{f_1}_{ik}(x_1,x'_1)\hat{\sigma}^{f_2}_{jl}(x_2,x'_2)\times$$
$$\Gamma^{kl}_B(x'_1,x'_2,\vec{s}_1-\vec{b}+\vec{v}_1,\vec{s}_2-\vec{b}+\vec{v}_2,\vec{u}_1-\vec{v}_1,\vec{u}_2-\vec{v}_2)$$
$$d^2\vec{u}_1 d^2\vec{u}_2 d^2\vec{v}_1 d^2\vec{v}_2 d^2\vec{s}_1 d^2\vec{s}_2 d^2\vec{b}, \qquad (8)$$



(a) Side view (b) Beam view

- **We also need the knowledge of nuclear modification at different positions**

$$R^A_k(x,\vec{b})-1 = \left(R^A_k(x)-1\right) G\left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right) \qquad k=g,q,\bar{q}$$

  - Ubiquitous in centrality-dependent observables
  - ...but most assume $G\left(\frac{T_A(\vec{s})}{T_A(\vec{0})}\right) = \frac{AT_A(\vec{s})}{T_{AA}(\vec{0})}$

DPS in Heavy-Ion Collisions

- **For example, considering** $p\mathrm{Pb} \to D^0 D^0 X$ [HSS (PRD'20)]

$$R^{\mathrm{DPS}}_{p\mathrm{Pb}\to D^0+D^0} = R^{D^0}_{p\mathrm{Pb}} R^{D^0}_{p\mathrm{Pb}} \left[\frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\frac{9^{1-a}(a+3)^{2a}}{4(a+2)}\right]$$

$$+\left(R^{D^0}_{p\mathrm{Pb}} + R^{D^0}_{p\mathrm{Pb}}\right)\left[1 - \frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\left(\frac{3^{2-a}(a+3)^{a}}{2(a+4)} - \frac{9^{1-a}(a+3)^{2a}}{4(a+2)}\right)\right]$$

$$+\left[-1 + \frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\left(\frac{9}{8} + \frac{9^{1-a}(a+3)^{2a}}{4(a+2)} - \frac{3^{2-a}(a+3)^{a}}{(a+4)}\right)\right]$$

$$G\left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right) \propto \left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right)^a$$

$$R^f_{pA} \equiv \frac{\sigma_{pA\to f}}{A\sigma_{pp\to f}}$$

DPS in Heavy-Ion Collisions

- **For example, considering** $p\mathrm{Pb} \to D^0 D^0 X$ [HSS (PRD'20)]

$$R^{\mathrm{DPS}}_{p\mathrm{Pb}\to D^0+D^0} = R^{D^0}_{p\mathrm{Pb}} R^{D^0}_{p\mathrm{Pb}} \left[\frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\frac{9^{1-a}(a+3)^{2a}}{4(a+2)}\right]$$
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$$G\left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right) \propto \left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right)^a$$

Either calculable or fixable by other measurements

$$R^f_{pA} \equiv \frac{\sigma_{pA\to f}}{A\sigma_{pp\to f}}$$

DPS in Heavy-Ion Collisions

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$$+\left(R^{D^0}_{p\mathrm{Pb}} + R^{D^0}_{p\mathrm{Pb}}\right)\left[1 - \frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\left(\frac{3^{2-a}(a+3)^{a}}{2(a+4)} - \frac{9^{1-a}(a+3)^{2a}}{4(a+2)}\right)\right]$$

$$+\left[-1 + \frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\left(\frac{9}{8} + \frac{9^{1-a}(a+3)^{2a}}{4(a+2)} - \frac{3^{2-a}(a+3)^{a}}{(a+4)}\right)\right]$$

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$$\frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1) \simeq 5.23\left(\frac{\sigma_{\mathrm{eff},pp}}{34.8\ \mathrm{mb}}\right)$$

$$R^f_{pA} \equiv \frac{\sigma_{pA\to f}}{A\sigma_{pp\to f}}$$

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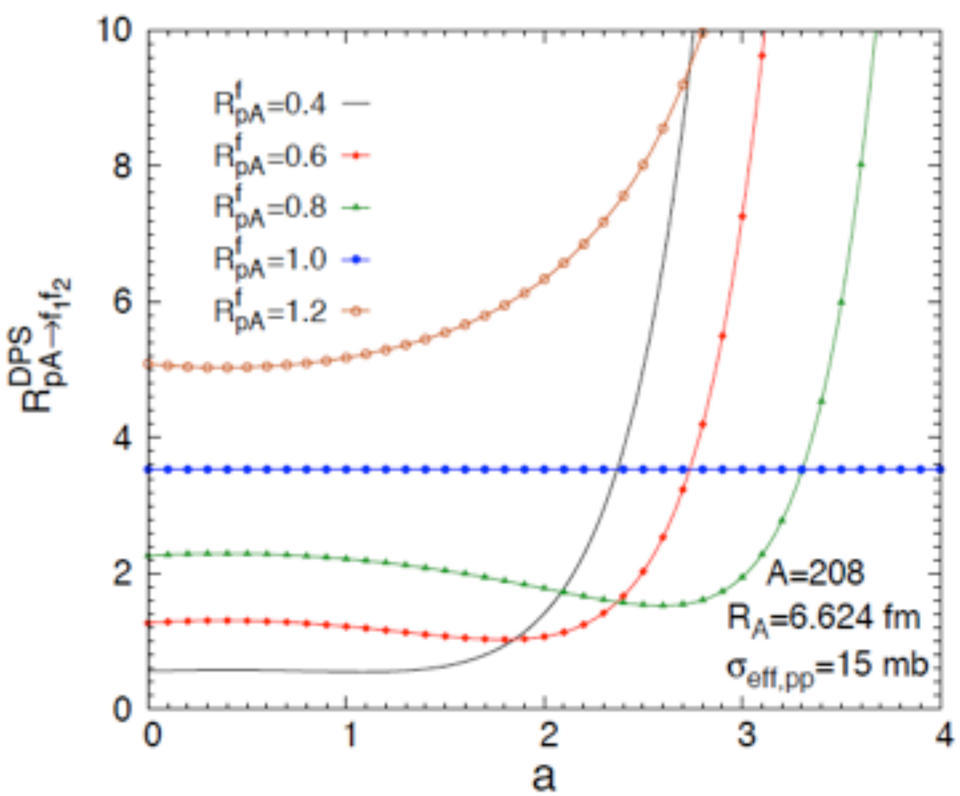


$$R^f_{pA} \equiv \frac{\sigma_{pA\to f}}{A\sigma_{pp\to f}}$$

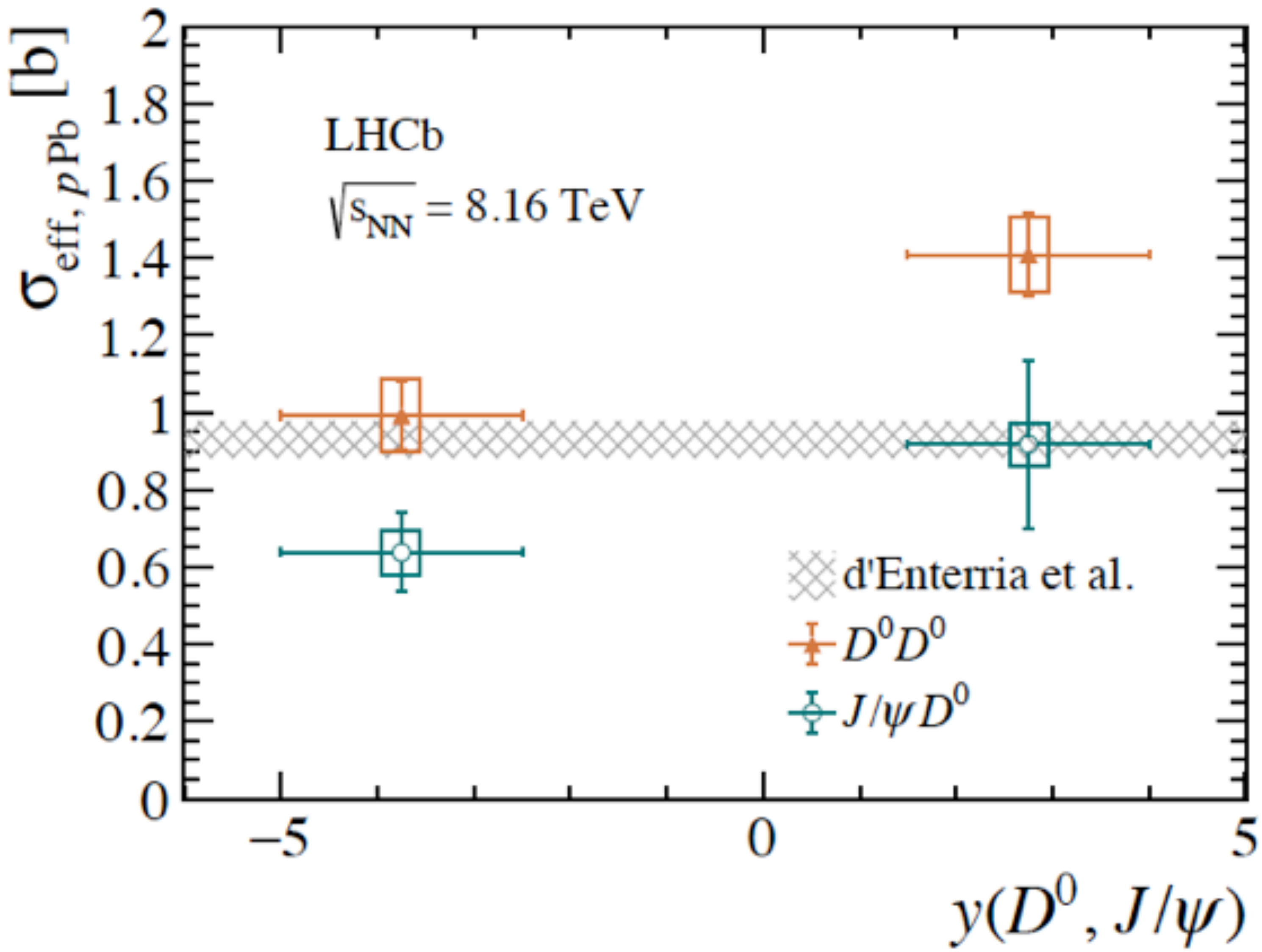
- DPS in heavy-ion potential to constrain G() !

DPS in Heavy-Ion Collisions

- **First DPS measurement in heavy-ion collisions by LHCb** [LHCb (PRL'20)]

$$\sigma_{\text{eff}} = \frac{1}{1+\delta_{f_1 f_2}} \frac{\sigma_{p\text{Pb}\to f_1}\sigma_{p\text{Pb}\to f_2}}{\sigma_{p\text{Pb}\to f_1 f_2}}$$

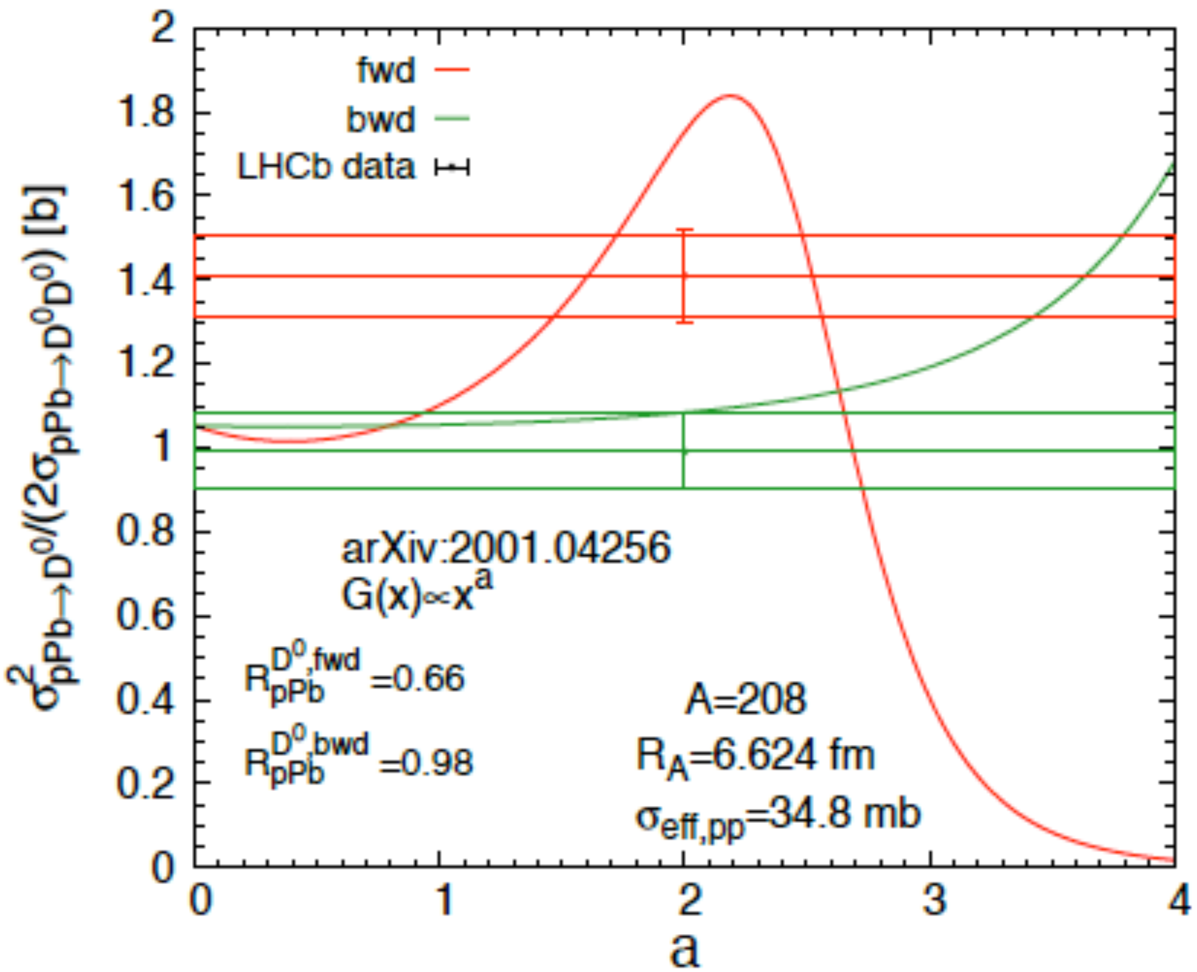
Caveats: $\sigma_{\text{eff}} \equiv \sigma_{\text{eff},p\text{Pb}} \neq \sigma_{\text{eff},pp}$

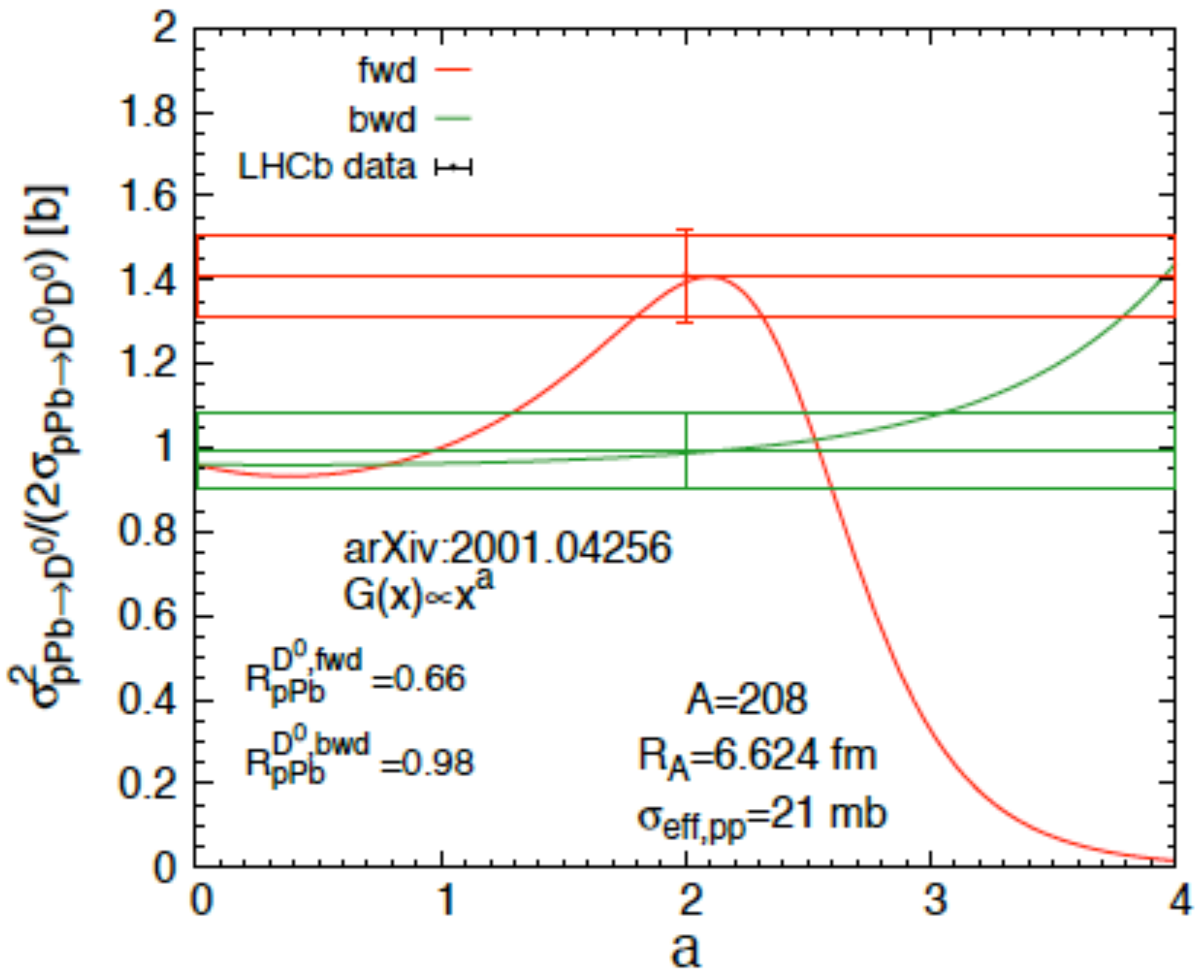


- Observe ~3A enhancement in DPS wrt ~A enhancement in SPS by comparing pA vs pp xs
- The pure geometric effect cannot explain the rapidity dependence

DPS in Heavy-Ion Collisions

- **Theoretical interpretation of the LHCb measurement**
  - J/psi+D^0 has the sizable SPS component [HSS (PRD'20)]
  - The SPS of D^0+D^0 is negligible in NLO pQCD caclulations [Helenius, Paukkunen (PLB'20)]
  - The b-dependent gluon shadowing can explain the rapidity dependence [HSS (PRD'20)]





$$G\left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right) \propto \left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right)^a$$

favoring a~2 and disfavoring a~1

Conclusion

- **LHC program offers an unprecedented avenue to study DPS & TPS.**
- **A lot of theoretical, phenomenological and experimental progress.**
- **NPS will reveal the first-ever multiple-body parton correlations in nucleon and nucleus**
- **Some novel observables can even tell us more (e.g. the impact parameter-dependent gluon shadowing)**
- **Don't be shy to attempt a 1st-ever measurement (e.g. TPS in pPb or DPS in PbPb ?)**

Conclusion

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- Don't be shy to attempt a 1st-ever measurement (e.g. TPS in pPb or DPS in PbPb ?)

Thank you for your attention !

Backup Slides

DPS in Heavy-Ion Collisions

- **As a concrete example, let us take** $p\mathrm{Pb} \to J/\psi + D^0$ [HSS (PRD'20)]

$$R^{\mathrm{DPS}}_{p\mathrm{Pb}\to J/\psi+D^0} = R^{J/\psi}_{p\mathrm{Pb}} R^{D^0}_{p\mathrm{Pb}} \left[\frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\frac{9^{1-a}(a+3)^{2a}}{4(a+2)}\right]$$

$$+\left(R^{J/\psi}_{p\mathrm{Pb}} + R^{D^0}_{p\mathrm{Pb}}\right)\left[1 - \frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\left(\frac{3^{2-a}(a+3)^{a}}{2(a+4)} - \frac{9^{1-a}(a+3)^{2a}}{4(a+2)}\right)\right]$$

$$+\left[-1 + \frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\left(\frac{9}{8} + \frac{9^{1-a}(a+3)^{2a}}{4(a+2)} - \frac{3^{2-a}(a+3)^{a}}{(a+4)}\right)\right]$$

$$G\left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right) \propto \left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right)^a$$

DPS in Heavy-Ion Collisions

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Either calculable or fixable by other measurements

DPS in Heavy-Ion Collisions

- **As a concrete example, let us take** $p\text{Pb} \to J/\psi + D^0$ [HSS (PRD'20)]

$$
\begin{aligned}
R^{\text{DPS}}_{p\text{Pb}\to J/\psi+D^0} = \; & R^{J/\psi}_{p\text{Pb}} R^{D^0}_{p\text{Pb}} \left[\frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\text{eff},pp}}{\pi R_A^2}(A-1)\frac{9^{1-a}(a+3)^{2a}}{4(a+2)}\right] \\
& + \left(R^{J/\psi}_{p\text{Pb}} + R^{D^0}_{p\text{Pb}}\right)\left[1 - \frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\text{eff},pp}}{\pi R_A^2}(A-1)\left(\frac{3^{2-a}(a+3)^{a}}{2(a+4)} - \frac{9^{1-a}(a+3)^{2a}}{4(a+2)}\right)\right] \\
& + \left[-1 + \frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\text{eff},pp}}{\pi R_A^2}(A-1)\left(\frac{9}{8} + \frac{9^{1-a}(a+3)^{2a}}{4(a+2)} - \frac{3^{2-a}(a+3)^{a}}{(a+4)}\right)\right]
\end{aligned}
$$

$$
G\left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right) \propto \left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right)^a
$$

$$
\boxed{\frac{\sigma_{\text{eff},pp}}{\pi R_A^2}(A-1) \simeq 5.23\left(\frac{\sigma_{\text{eff},pp}}{34.8\text{ mb}}\right)}
$$

DPS in Heavy-Ion Collisions

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$$+ \left[-1 + \frac{3^{1-2a}(a+3)^{2a}}{2a+3} + \frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1)\left(\frac{9}{8} + \frac{9^{1-a}(a+3)^{2a}}{4(a+2)} - \frac{3^{2-a}(a+3)^a}{(a+4)}\right)\right]$$

$$G\left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right) \propto \left(\frac{T_A(\vec{b})}{T_A(\vec{0})}\right)^a$$

$$\frac{\sigma_{\mathrm{eff},pp}}{\pi R_A^2}(A-1) \simeq 5.23\left(\frac{\sigma_{\mathrm{eff},pp}}{34.8\ \mathrm{mb}}\right)$$