



JSPS



Double parton scattering studies in associated quarkonium production at the LHC and Tevatron

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In collaboration with

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GDR QCD
Clermont

Motivations for associated quarkonium production studies

The study of quarkonium production has been proposed to probe perturbative and nonperturbative properties of QCD.

J/ ψ +W was proposed as a golden channel to probe the color octet contribution and thus to test NRQCD

V. D. Barger et al., PLB 371 (1996) 111

J/ ψ +J/ ψ production could be the key process to study the double parton scattering (DPS)

Motivation for BSM search:

Y+W could be a decay channel of a charged Higgs boson

J. A. Grifols, J. F. Gunion, A. Mendez. Phys. Lett. B 197 (1987) 266.

DPS becomes important in high \sqrt{s} collision :

⇒ Important background in multi-particle final states

Recent experimental progress:

ATLAS observed J/ ψ +W and J/ ψ +Z

ATLAS Coll. (J- ψ Z) Eur.Phys.J. C 75 (2015) 229; (J- ψ W) JHEP 1404 (2014) 172

CMS & ATLAS data of di-J/ Ψ in conflict with NRQCD (color singlet model)

CMS Collaboration, JHEP 1409 (2014) 094.

J/ψ+W/Z

Quarkonium+vector boson production

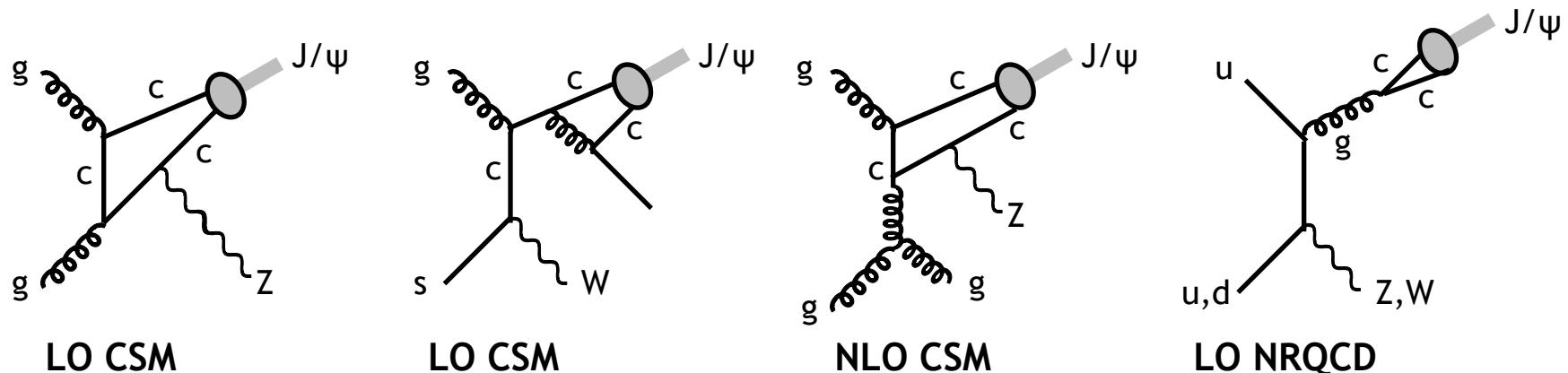
Theoretical computations were carried out up to NLO in α_s

NLO NRQCD $J/\psi + W$: L. Gang et al., PRD 83 (2011) 014001;

NLO NRQCD $J/\psi + Z$: L. Gang et al., JHEP 02 (2011) 071 ;

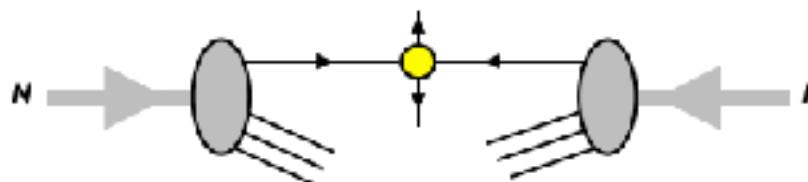
NLO CSM $J/\psi + Z$: B. Gong, J.P. Lansberg, C. Lorce, J.X. Wang, JHEP 1303 (2013) 115;

Missing LO CSM $J/\psi + W$: J.P. Lansberg, C. Lorce, PLB 726 (2013) 218

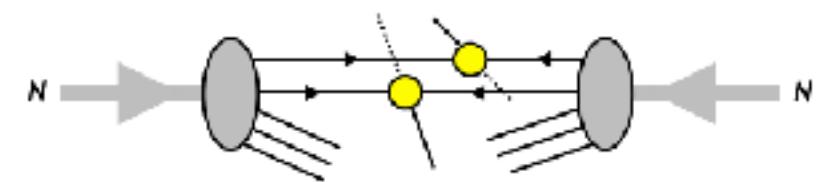


Based on these recent works, one expects the octet and singlet contributions to be on the same order of magnitude

Let us note that, in addition, double parton scattering (DPS) could also contribute to such an associated production, just as $\gamma + \text{jet}$, $W + Z$, $W + W$ productions



Single Parton Scattering (SPS)



Double Parton Scattering (DPS)

Quarkonium+vector boson production

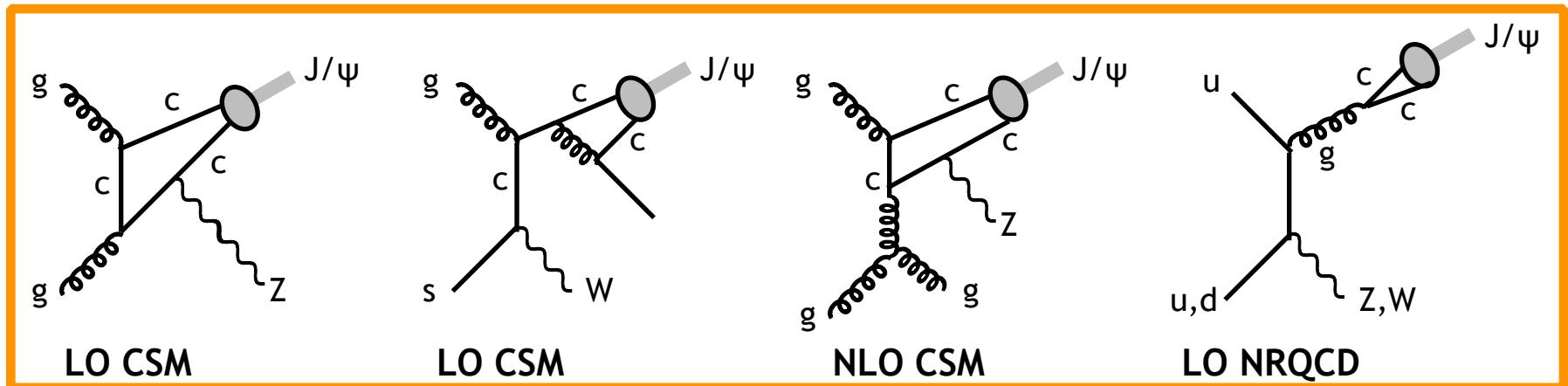
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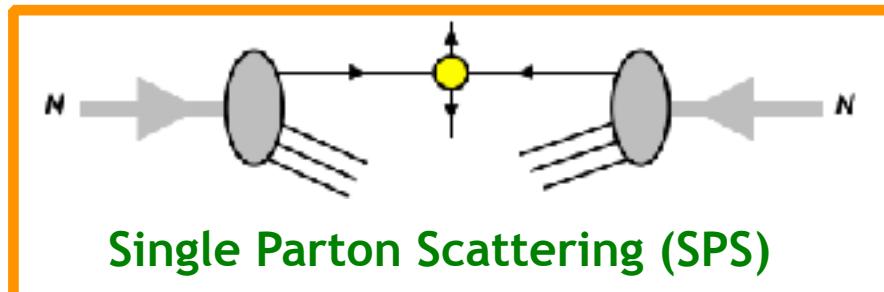
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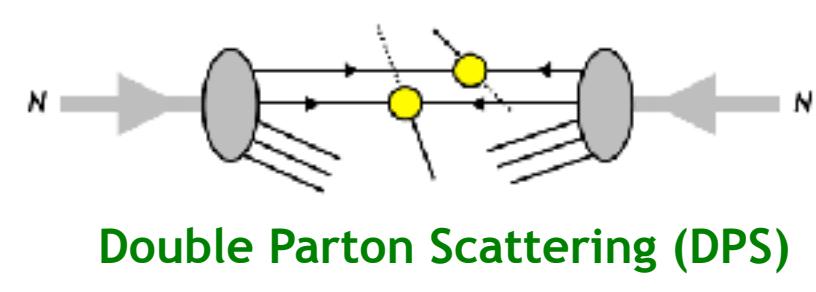


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Single Parton Scattering (SPS)



Double Parton Scattering (DPS)

ATLAS vs. “theory”

Overall, the ATLAS data-theory comparison looks as follows:

	<i>ATLAS</i>	<i>DPS</i> $(\sigma_{eff} = 15 \text{ mb})$	<i>CSM</i>	<i>COM</i>
Z+J/ ψ	$1.6 \pm 0.4 \text{ pb}$ [1]	0.46 pb	0.025 - 0.125 pb [5]	< 0.1 pb [4]
W+J/ ψ	$4.5^{+1.9}_{-1.5} \text{ pb}$ [2]	1.7 pb	$(0.11 \pm 0.04) \text{ pb}$ [6]	$(0.16 - 0.22) \text{ pb}$ [3]

[1] ATLAS Collaboration, Eur. Phys. J. C **75** (2015) 229

[2] ATLAS Collaboration, JHEP **1404** (2014) 172

[3] L. Gang et al., PRD **83** (2011) 014001

[4] L. Gang et al., JHEP **1102** (2011) 071

[5] B. Gong et al., JHEP **1303** (2013) 115

[6] J.P. Lansberg, C. Lorce, PLB **726** (2013) 218

ATLAS data are significantly above the SPS (CSM+COM), and the DPS can only account for a fraction of the data.
(> 3 σ for J/ ψ +Z, > 2 σ for J/ ψ +W)

A natural question arises : **Is SPS underestimated?**

Building up an upper limit to the SPS with the color evaporation model

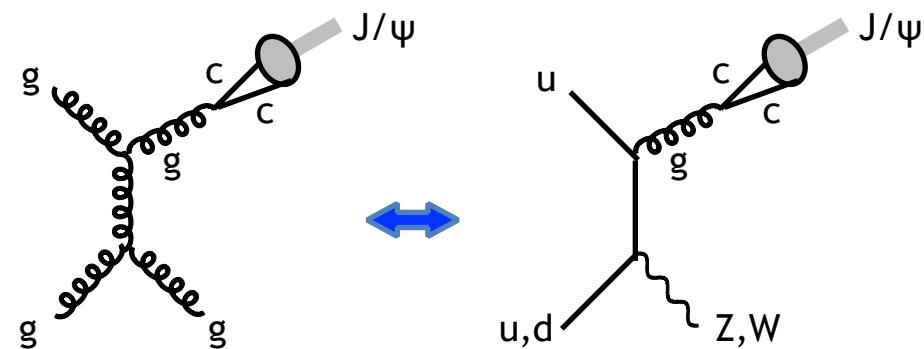
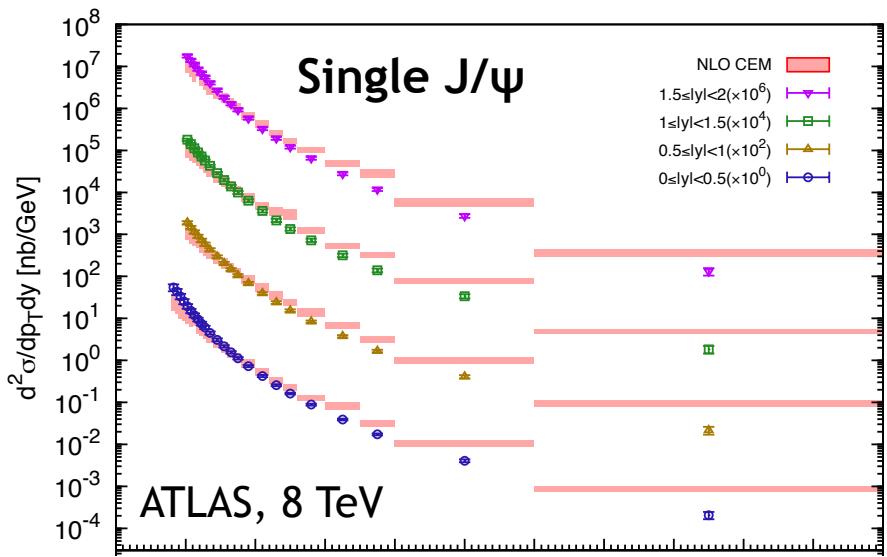
The CEM for single quarkonium production

overshoots the data at high p_T (see below).

This is due to the dominance of the 1-gluon fragmentation ($\sim {}^3S_1{}^8$)

The same is expected to occur for $J/\psi + W$ and $J/\psi + Z$.

⇒ CEM : conservative **upper limit** on the SPS yield



We will compute it in both cases at NLO with **MadGraph5_AMC@NLO**.

Digression on DPS

At **high energies**, multiple parton interactions can become relevant, despite of being formally of higher twist.

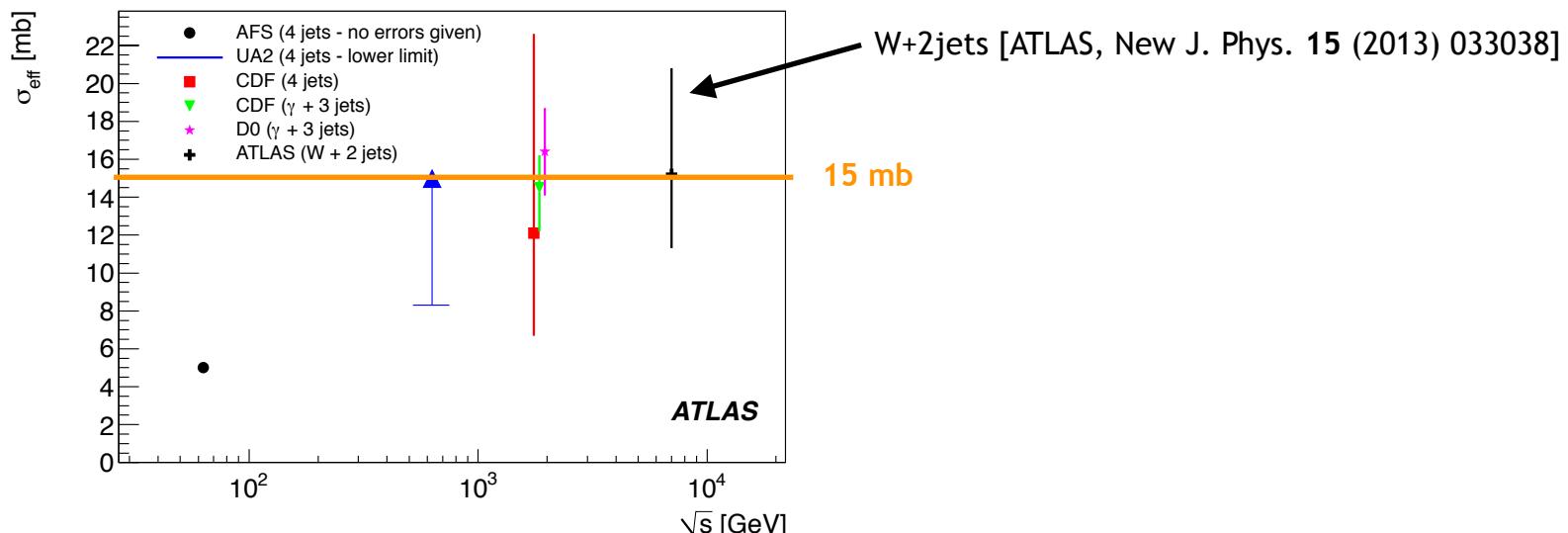
They are in fact necessary to restore the unitarity of the cross section and are related to the strong increase of the parton densities at high energy.

Similarly, this can also happen for **Double hard Parton Scatterings (DPS)**
which then occur **independently**.

As such it makes sense to parametrize the DPS cross sections by the so-called **pocket-formula**:

$$\sigma^{\text{DPS}}(A + B) = \frac{\sigma(A)\sigma(B)}{\sigma_{\text{eff}}}$$

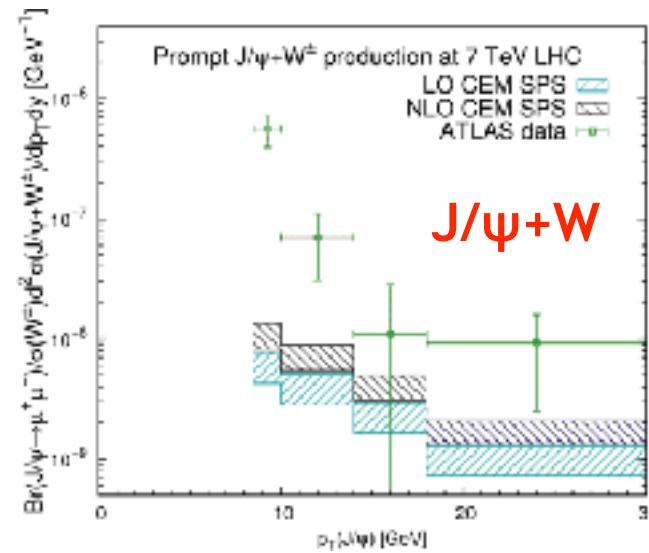
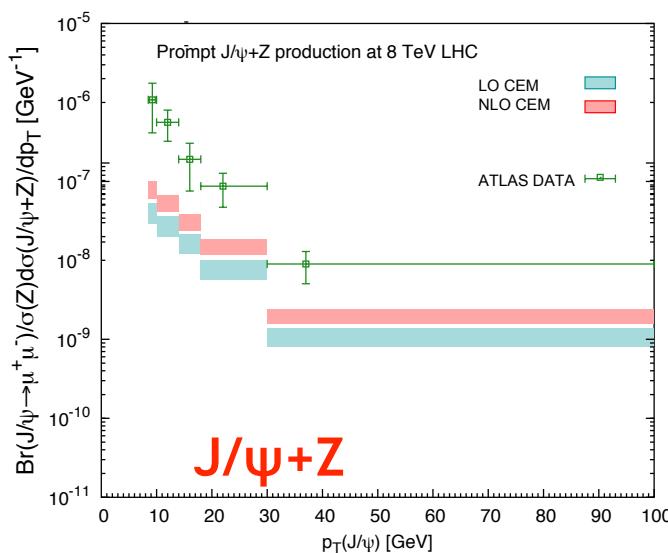
In the case of $\text{J}/\psi + \text{W}$ and $\text{J}/\psi + \text{Z}$, ATLAS used their measured cross sections for $\sigma(\text{J}/\psi)$, $\sigma(\text{W})$ and $\sigma(\text{Z})$, and σ_{eff} determined by their $\text{W} + 2\text{jets}$ data (see below).



Results for the Color evaporation model at NLO

	ATLAS	DPS $(\sigma_{eff} = 15 \text{ mb})$	CSM	COM	CEM (NLO)
Z+J/ ψ	$1.6 \pm 0.4 \text{ pb}$	0.46 pb	$0.025 - 0.125 \text{ pb}$	$< 0.1 \text{ pb}$	$0.19^{+0.05}_{-0.04} \text{ pb [1]}$
W+J/ ψ	$4.5^{+1.9}_{-1.5} \text{ pb}$	1.7 pb	$(0.11 \pm 0.04) \text{ pb}$	$(0.16 - 0.22) \text{ pb}$	$0.28 \pm 0.07 \text{ pb [2]}$

[1] J.-P. Lansberg and H.-S. Shao, JHEP 1610 (2016) 153
[2] J.-P. Lansberg, H.-S. Shao, NY, PLB 781 (2018) 485



⇒ Upper limit by CEM does not solve the problem.

⇒ Can it be solved by increasing the DPS?

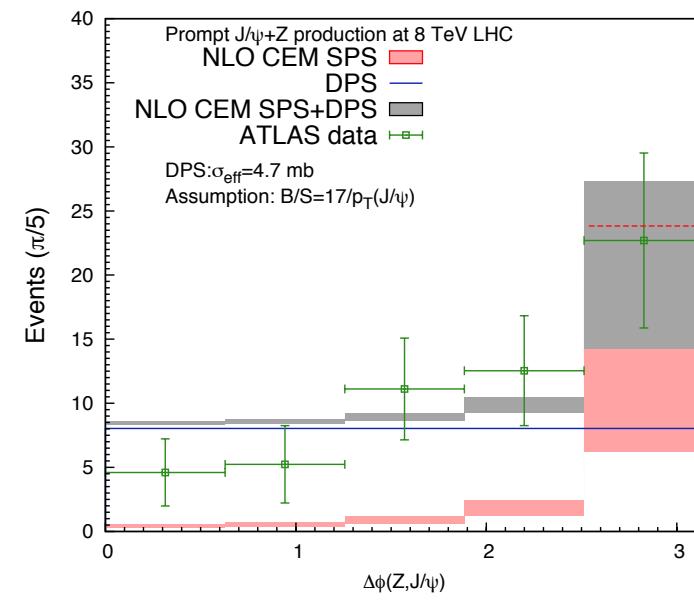
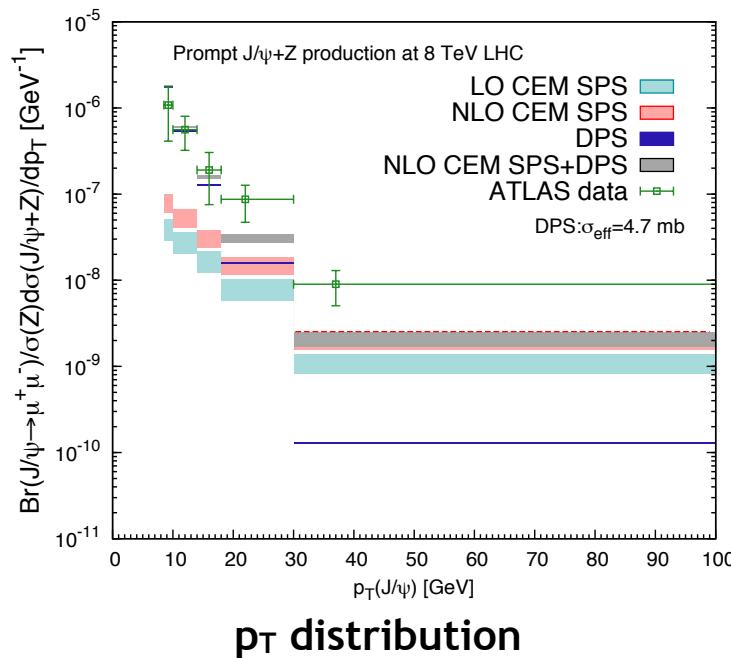
J/ ψ + Z : tuning the DPS with ATLAS data

We fit σ_{eff} to the ATLAS data subtracted from the SPS

and we obtain $\sigma_{\text{eff}} = (4.7^{+2.4}_{-1.5}) \text{ mb}$

J.-P. Lansberg and H.-S. Shao, JHEP 1610 (2016) 153

	ATLAS	DPS ($\sigma_{\text{eff}} = 4.7 \text{ mb}$)	CSM	COM	CEM (NLO)
Z+J/ ψ	$1.6 \pm 0.4 \text{ pb}$	1.47 pb	$0.025 - 0.125 \text{ pb}$	< 0.1 pb	$0.19^{+0.05}_{-0.04} \text{ pb [1]}$



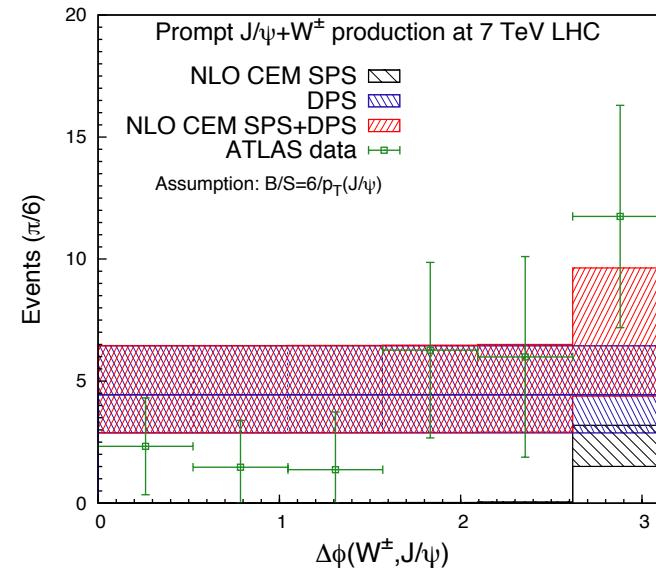
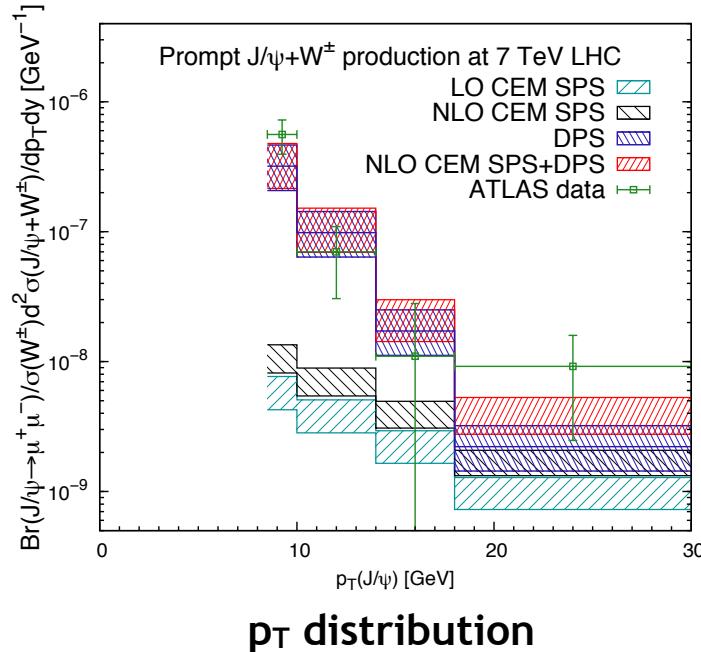
Increasing the DPS seems to solve the puzzle
(the SPS yield favored by ATLAS acceptance is visible at $\Delta\phi = \pi$).

J/ ψ + W : tuning the DPS with ATLAS data

For J/ ψ +W, we obtain $\sigma_{\text{eff}} = (6.1^{+3.3}_{-1.9}) \text{ mb}$

J.-P. Lansberg, H.-S. Shao, NY, PLB 781 (2018) 485.

	ATLAS	DPS	CSM	COM	CEM (NLO)
$(\sigma_{\text{eff}} = 6.1 \text{ mb})$					
W+J/ ψ	$4.5^{+1.9}_{-1.5} \text{ pb}$	4.18 pb	$(0.11 \pm 0.04) \text{ pb}$	$(0.16 - 0.22) \text{ pb}$	$0.28 \pm 0.07 \text{ pb}$



Like for the J/ ψ +Z case, increasing the DPS seems to solve the puzzle.

Quarkonium-pair

Quarkonium pairs

Di-J/ Ψ production studied by LHCb, CMS, ATLAS, D0

- Only D0 and ATLAS performed DPS extraction

- D0 : $\sigma_{\text{eff}} = (4.8 \pm 0.5(\text{stat}) \pm 2.5(\text{sys})) \text{ mb}$
- ATLAS : $\sigma_{\text{eff}} = (6.3 \pm 1.6(\text{stat}) \pm 1.0(\text{sys})) \text{ mb}$

- SPS uncertainty too large to extract σ_{eff} from LHCb (low pT \rightarrow SPS also flat in $\Delta\varphi$)

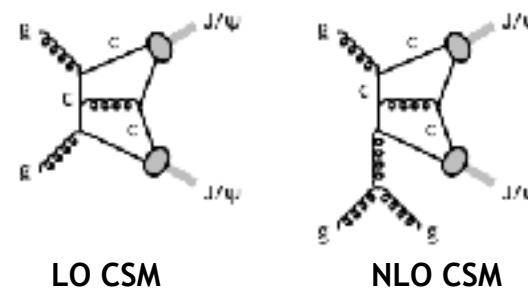
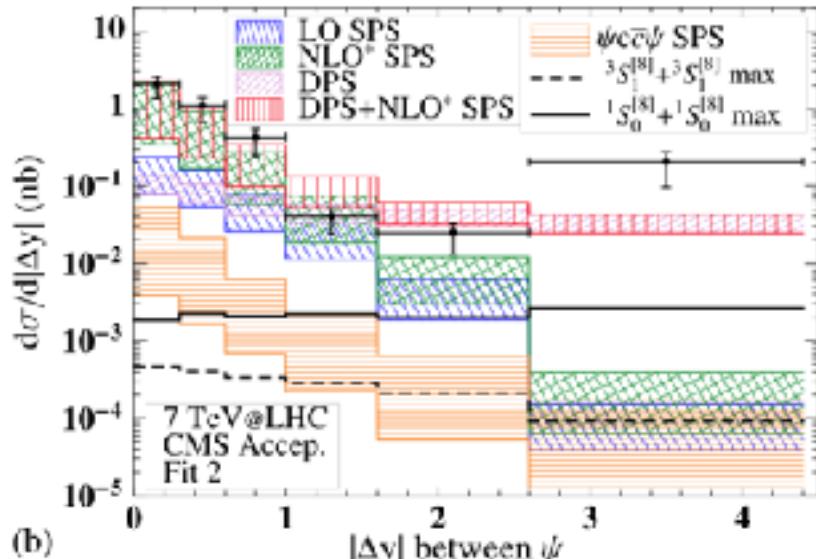
- CMS did not try to extract σ_{eff}

- DPS study by Lansberg and Shao $\sigma_{\text{eff}} = (8.2 \pm 2.0 \pm 2.9) \text{ mb}$

J.-P. Lansberg and H.-S. Shao, PLB751, 479 (2015)

- However on-going discussions about the actual size of SPS

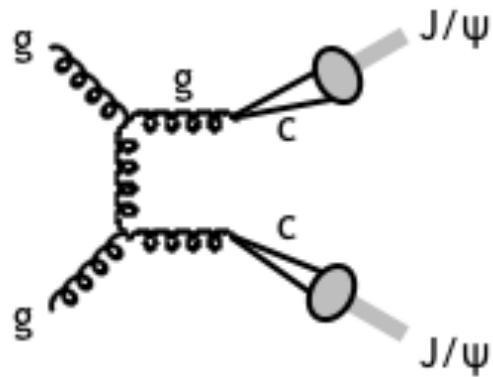
He and Kniehl, PRL 115, 022002 (2015)



The LO COM yield depends on $(\text{NRQCD LDME})^2$ and is thus affected by large uncertainties such that some colleagues wonder if the data could be described without the DPS.

Di- J/Ψ production and the CEM

To get the order of magnitude of the contribution from octet transition, we use again the CEM :

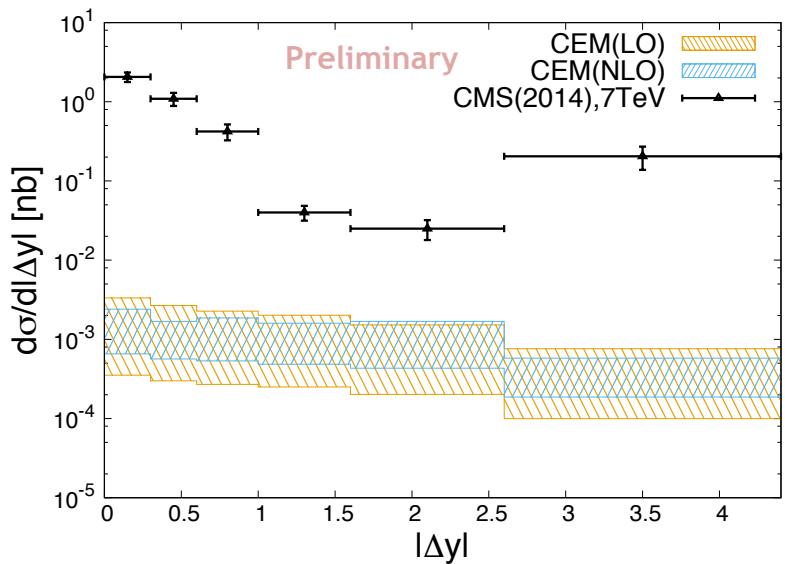


LO COM : gluon-fragmentation

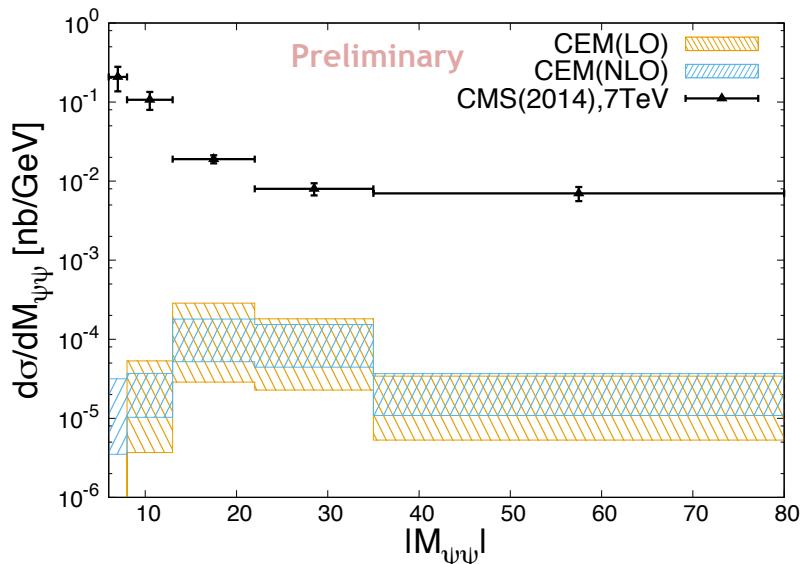
Like for $J/\Psi + Z/W$, CEM yield should give realistic estimation of the octet yield

CEM result with ATLAS setup (fiducial)

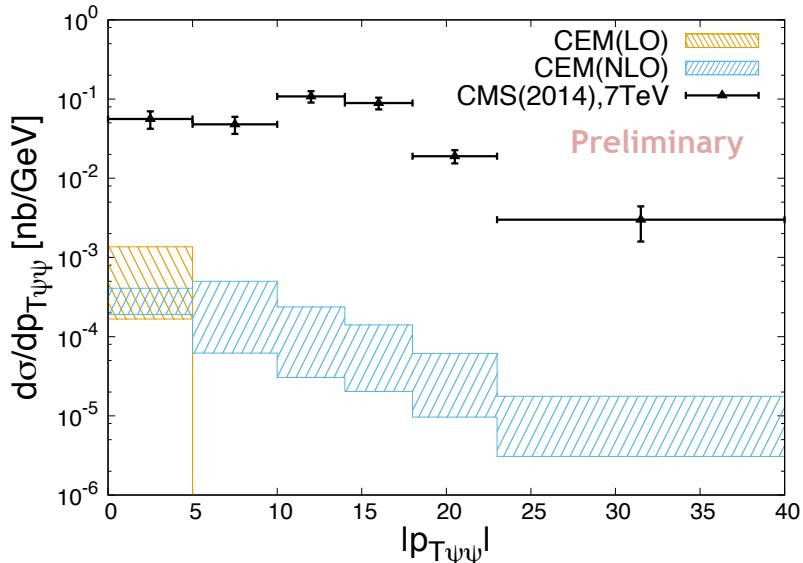
$|\Delta y| :$



$M_{\psi\psi} :$

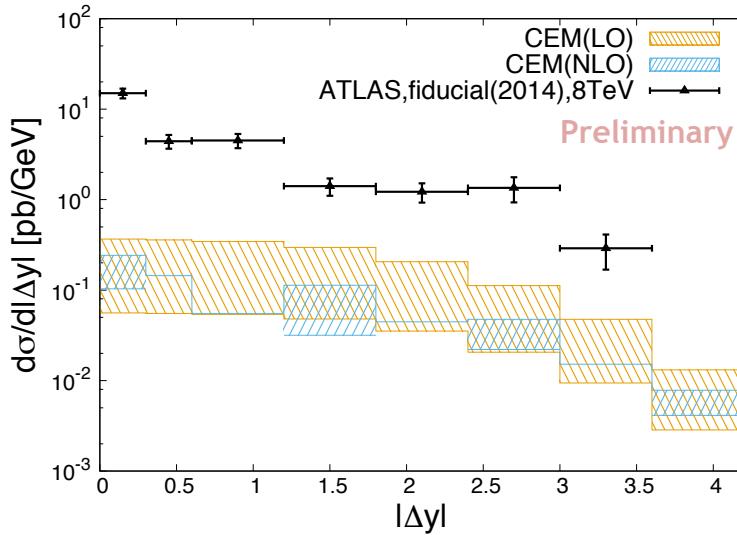


$p_{T\psi\psi} :$



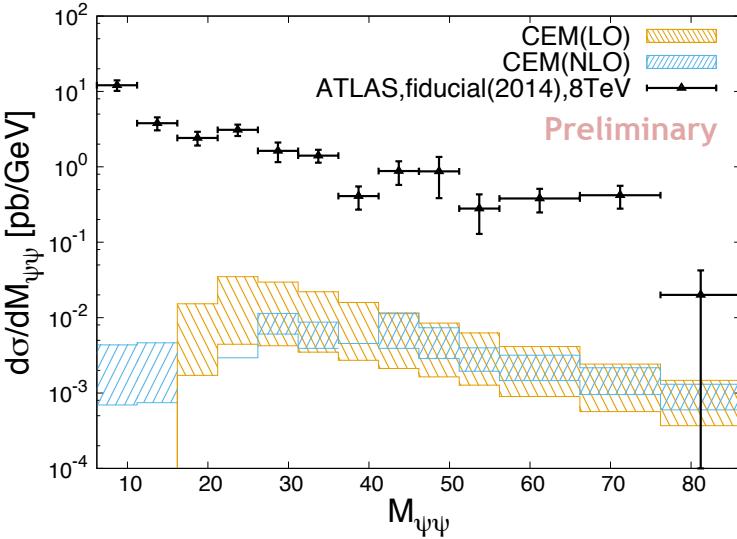
CEM result with ATLAS setup (fiducial)

$|\Delta y|$:

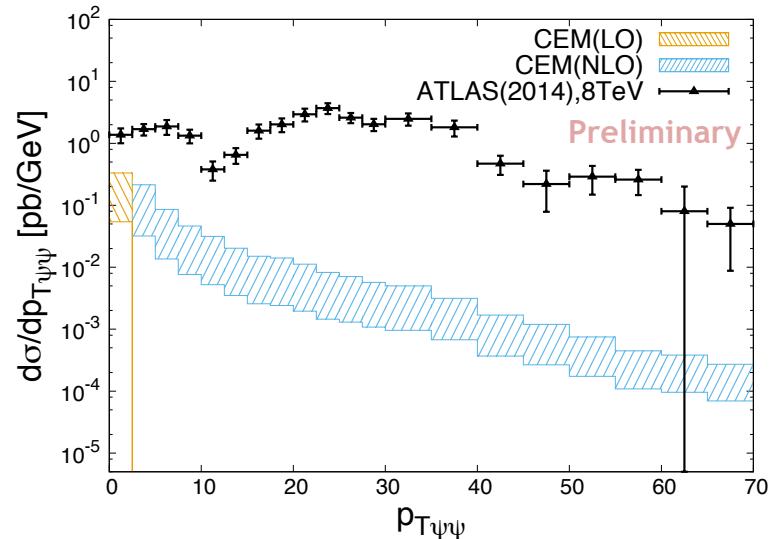


Experimental data :
ATLAS Collaboration, EPJC 76 (2017) 77.

$M_{\psi\psi}$:

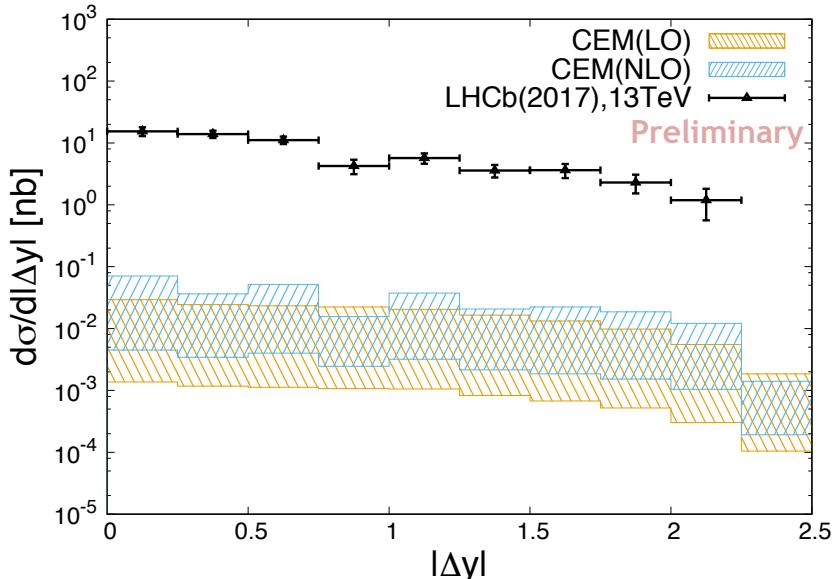


$p_{T\psi\psi}$:

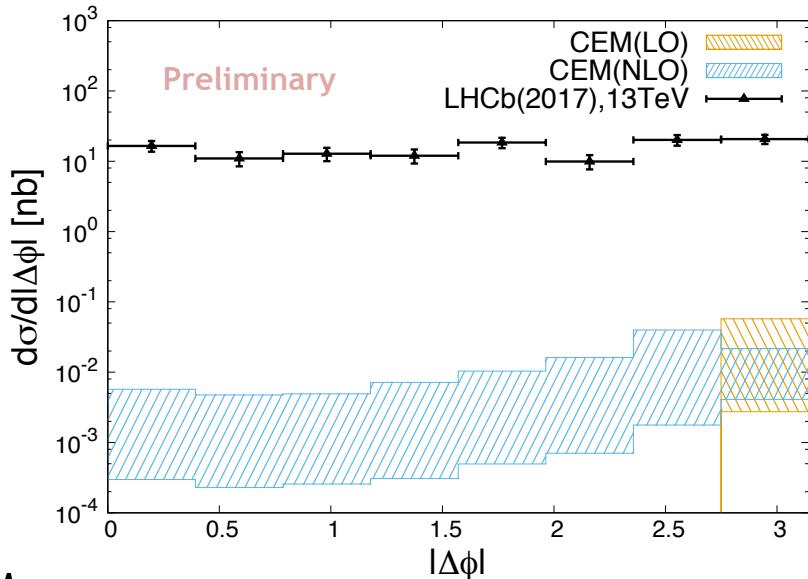


CEM result with LHCb setup

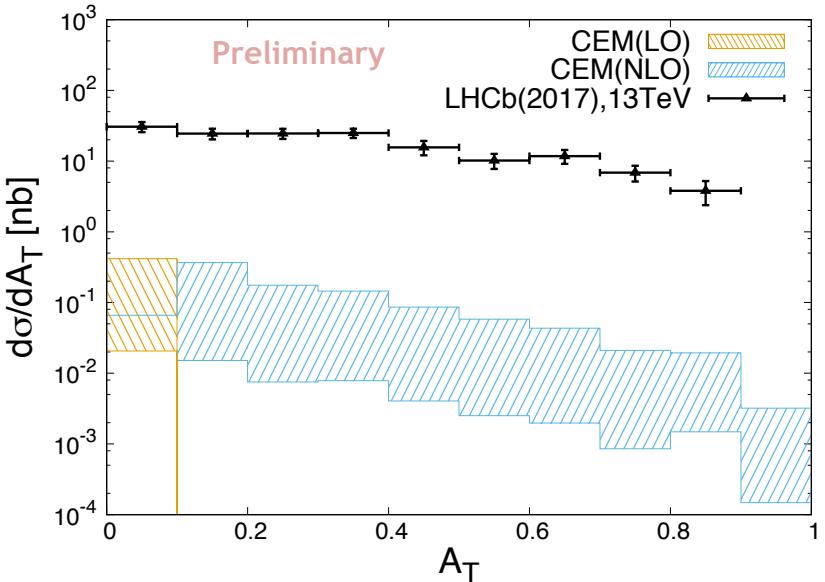
$|\Delta y| :$



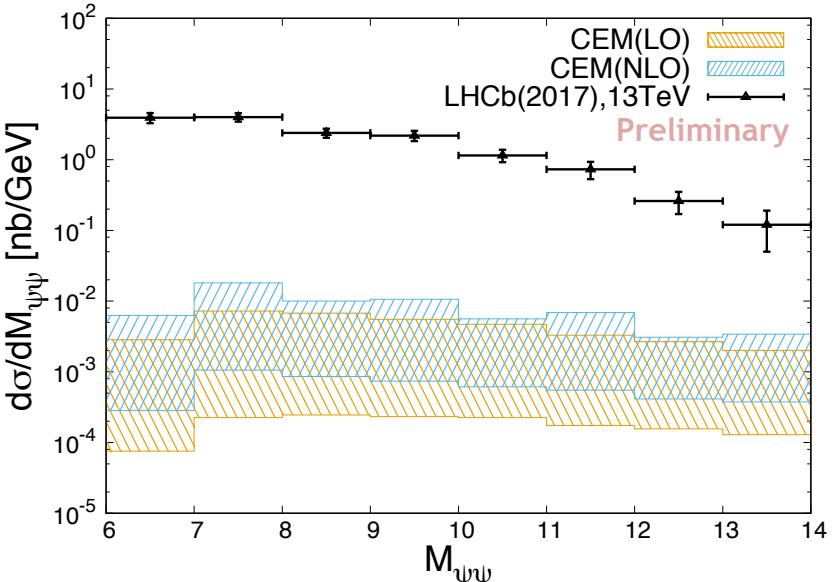
$|\Delta\phi| :$



$A_T :$

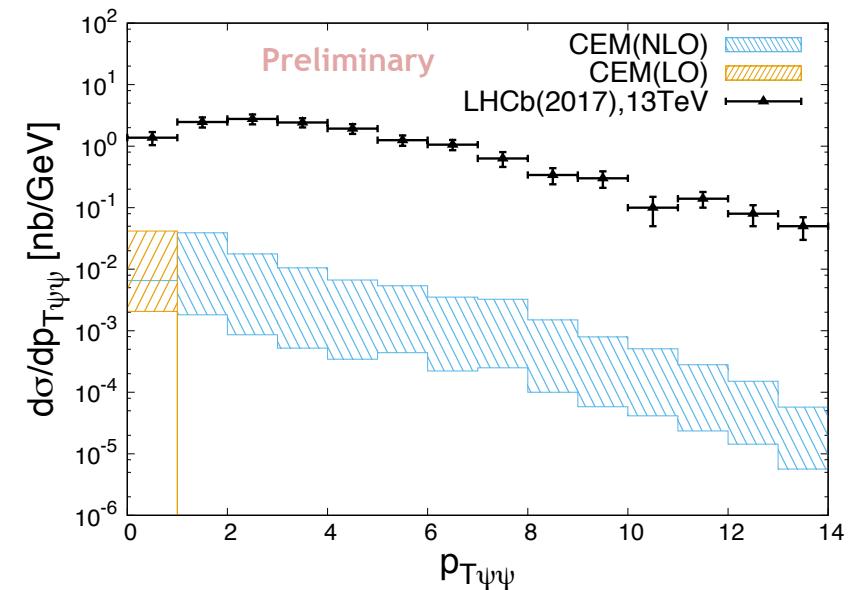


$M_{\psi\psi} :$



CEM result with LHCb setup

$p_{T\psi\psi}$:



Exp. data : LHCb Collaboration, JHEP 1706 (2017) 047.

CEM result

Since we found out that the LO NRQCD result of He & Kniehl overshoots our CEM result, we believe that their result is too optimistic (arguable choice of the LO LDMEs?)

We take this as the confirmation of the DPS extraction of Lansberg and Shao

(J.-P. Lansberg and H.-S. Shao, PLB751, 479 (2015))

Complete Study of Hadroproduction of a Y Meson Associated with a Prompt J/ ψ

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²*Beijing Key Laboratory of Advanced Nuclear Energy Materials and Physics, and School of Physics,
Beihang University, Beijing 100191, China*

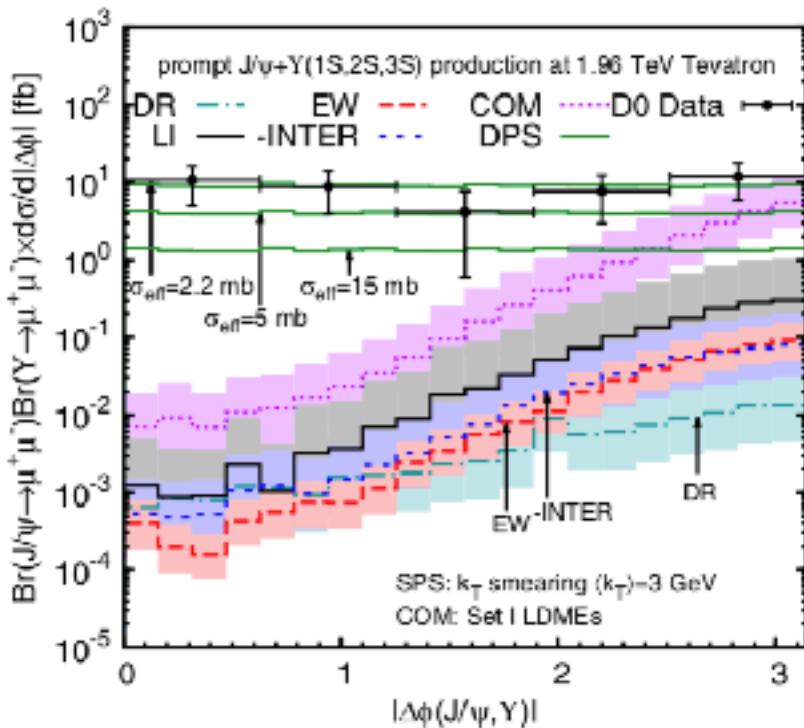
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(Received 12 May 2016; published 5 August 2016)

We present the first complete study of Y and prompt J/ ψ production from single-parton scattering, including the complete $O(\alpha_S^6)$ color singlet contribution, the $O(\alpha_S^2 m^2)$ electroweak contribution, and the complete nonrelativistic S-wave and P-wave color-octet contribution as well as the feeddown contribution. Our study was motivated by the recent evidence reported by the D0 Collaboration of prompt J/ ψ and Y simultaneous production at the Tevatron. With our complete evaluation, we are able to refine the determination of the double parton scattering contribution made by the D0 Collaboration. We find that the effective cross section characterizing the importance of double-parton scatterings is $\sigma_{\text{eff}} \leq 8.2$ mb at 68% confidence level from the D0 measurement.

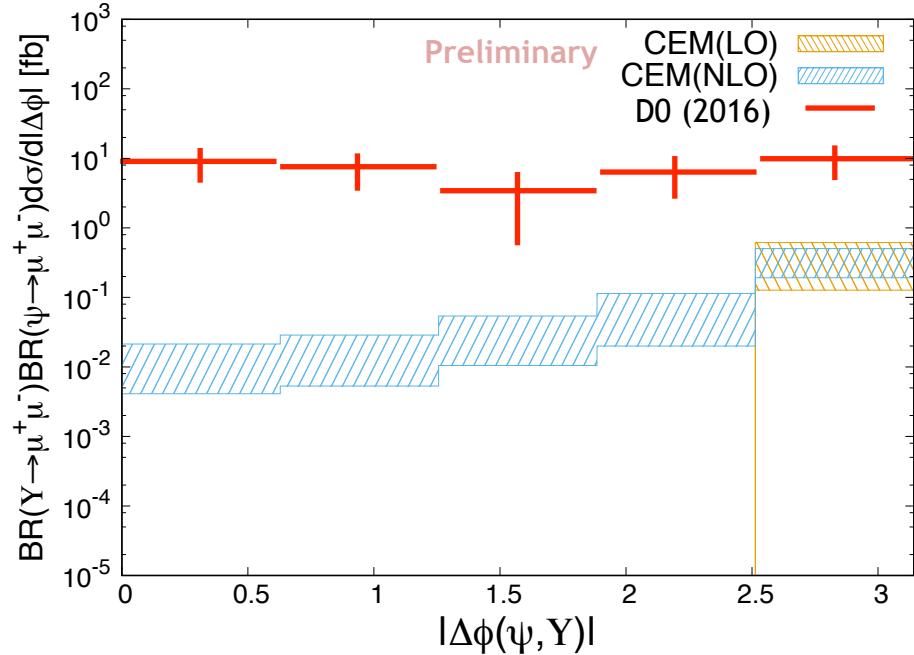
$J/\psi + Y$ production ($D0$, $p\bar{p}$, 1.96TeV)

$|\Delta\phi| :$



Shao and Zhang, PRL 117, 062001 (2016).

CEM calculation:



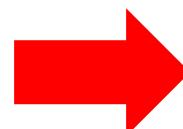
Experimental data :
D0 Collaboration, PRL 116, 082002 (2016).

$Y+Y$ production (CMS, 8TeV)

Exp. data ($\sigma_{\text{exp}} = 68.8 \pm 12.7(\text{stat}) \pm 7.4(\text{syst}) \pm 2.8(\text{B}) \text{ pb}$)

CMS Collaboration, JHEP 1705 (2017) 013.

Our result of calculation of di-Y (1S) production in CEM:

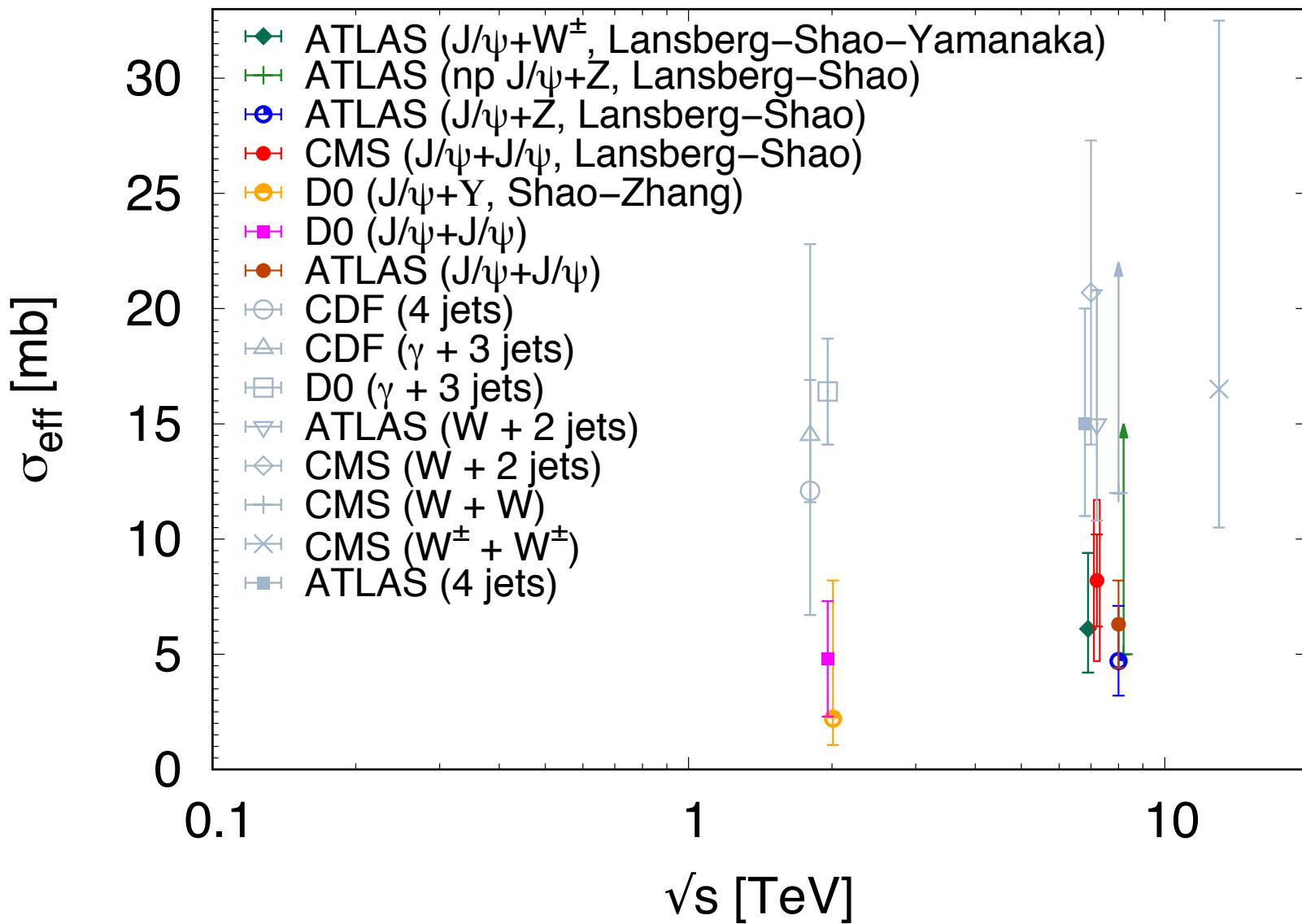


$$\begin{cases} 0.050 \text{ pb} < \sigma_{\text{CEM}} < 0.172 \text{ pb (NLO)} \\ 0.027 \text{ pb} < \sigma_{\text{CEM}} < 0.125 \text{ pb (LO)} \end{cases}$$

Preliminary

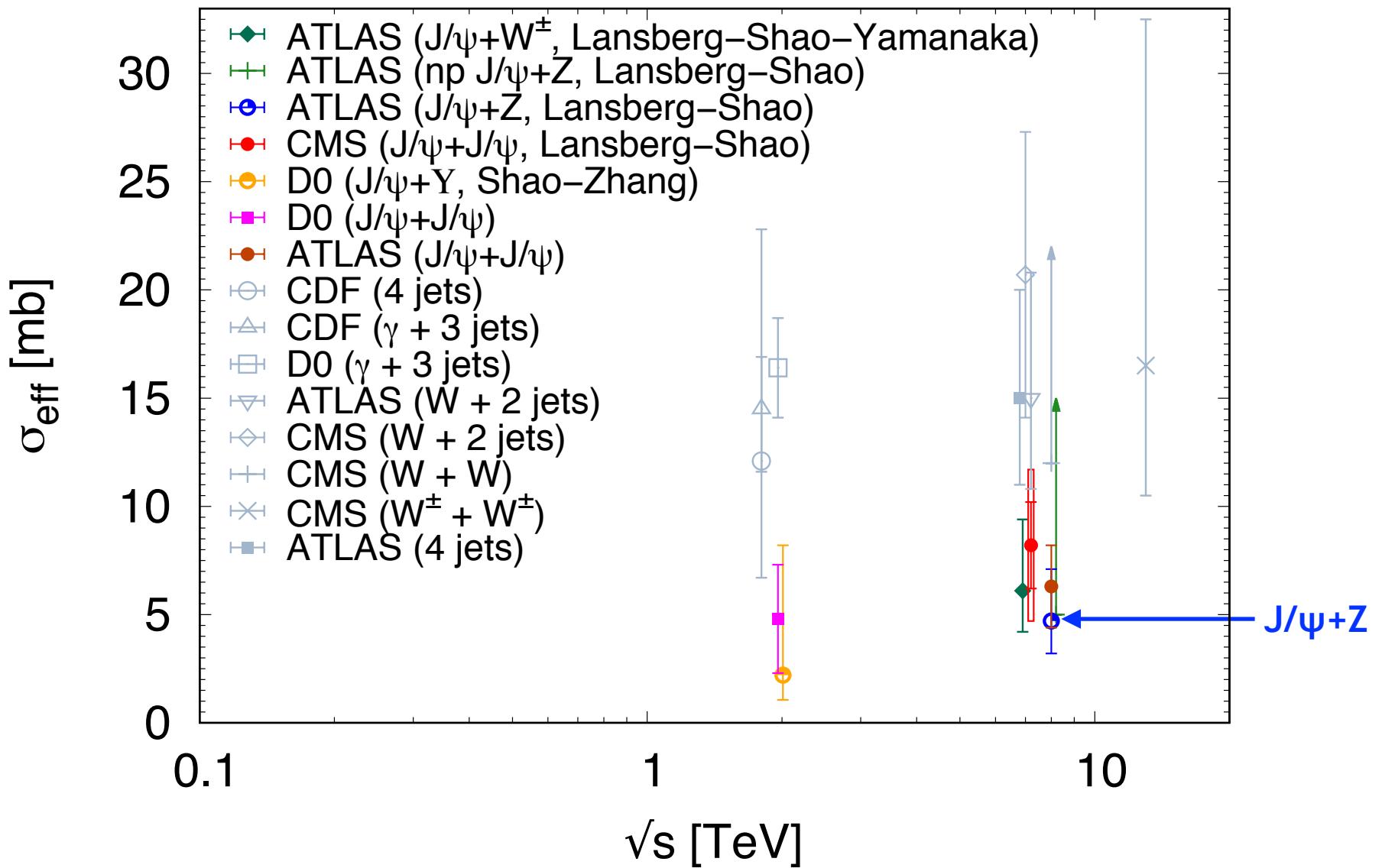
\Rightarrow Deviation by more than 4σ !

Overall



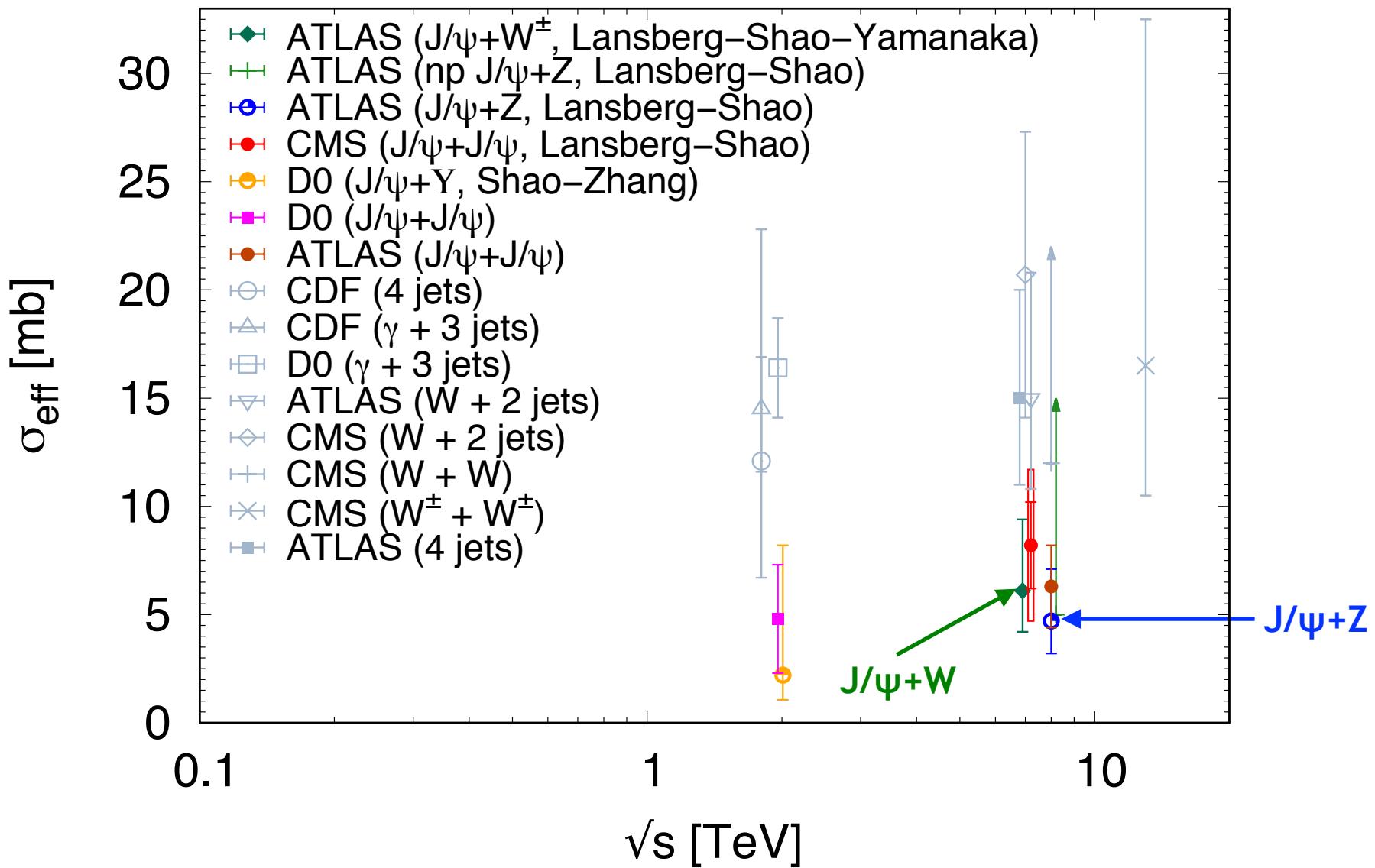
⇒ All central rapidity quarkonium data point at a small σ_{eff}

Overall



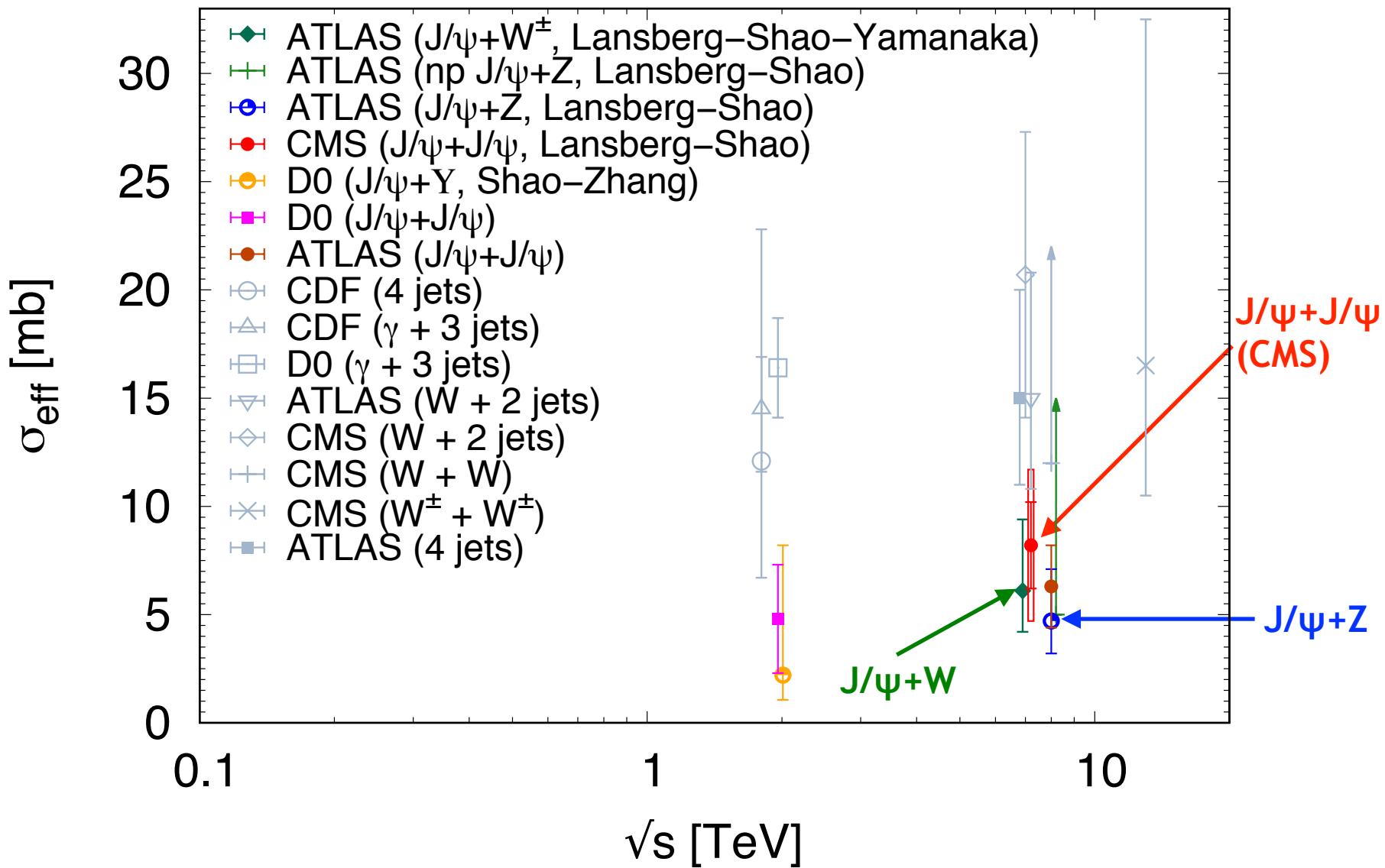
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Overall



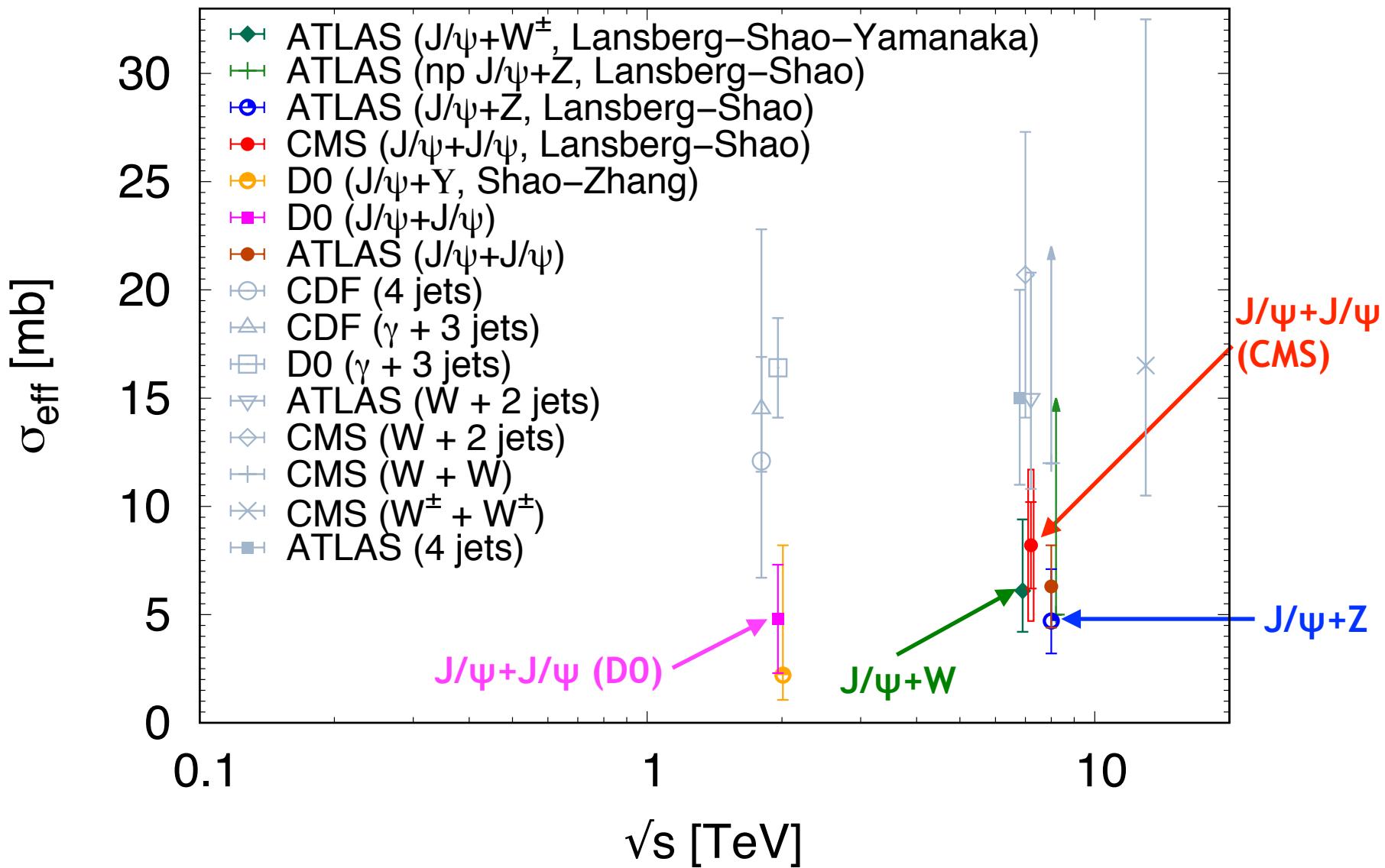
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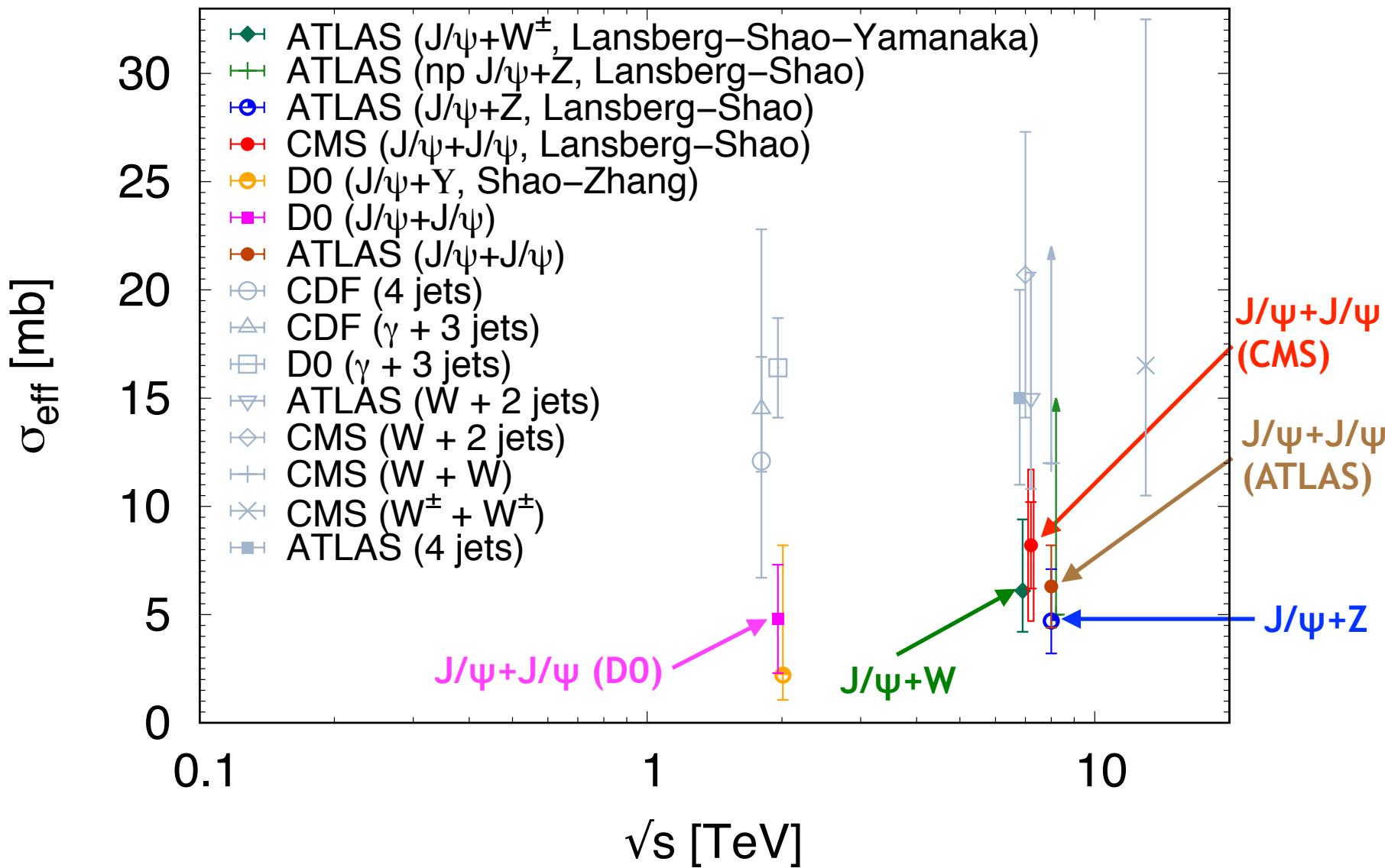
⇒ All central rapidity quarkonium data point at a small σ_{eff}

Overall



⇒ All central rapidity quarkonium data point at a small σ_{eff}

Overall



⇒ All central rapidity quarkonium data point at a small σ_{eff}

Summary

Summary:

- The associated production of J/ ψ +W/Z was measured by ATLAS: discrepancies with SPS+DPS ($\sigma_{\text{eff}}=15\text{mb}$) was seen.
- In order to check whether the SPS was underestimated, we evaluated the NLO CEM yield for J/ ψ +W/Z.
- The conservative upper limit set by the CEM does not solve the discrepancy with the ATLAS data.
- In fact, J/ ψ +W/Z show evidence for DPS.
J/ ψ +Z : $\sigma_{\text{eff}} = (4.7^{+2.4}_{-1.5}) \text{ mb}$
J/ ψ +W : $\sigma_{\text{eff}} = (6.1^{+3.3}_{-1.9}) \text{ mb}$
- J/ ψ +J/ ψ production also requires DPS contributions in some part of the phase space.
- σ_{eff} seems to be smaller for quarkonia than for jets:
hint for flavor dependence?

End

CM energy = 7 TeV

Cuts:

$$p_T > 4.5 \text{ GeV}$$

$$1.43 < |y_\Psi| < 2.2 \quad (p_T > 4.5 \text{ GeV})$$

$$\text{Linear in } p_T \text{ from boundaries} \quad (4.5 \text{ GeV} < p_T < 6.5 \text{ GeV})$$

$$|y_\Psi| < 1.2 \quad (p_T > 6.5 \text{ GeV})$$

(Rapidity depends on the p_T region)

CM energy = 8 TeV

Cuts:

$$p_T > 8.5 \text{ GeV} \quad |y_\psi| < 2.1 \quad (\text{Inclusive})$$

Fiducial cuts (cuts on muons from J/Ψ decay):

Trigger muons from J/Ψ : $p_T(\mu) > 4 \text{ GeV}$

$$|\eta(\mu)| > 2.3$$

ATLAS Collaboration, EPJC 76 (2017) 77.

Setup LHCb

CM energy = 13 TeV

Cuts (inclusive):

$p_T < 10 \text{ GeV}$

$2.0 < y_\psi < 4.5$
(asymmetric)

LHCb Collaboration, JHEP 1706 (2017) 047.

Setup D0

CM energy = 1.96 TeV

p \bar{p} collision

Measure final states with Y(1S), Y(2S) or Y(3S) associated with a J/ ψ

Fiducial cuts (cuts on muons from J/ Ψ and Y decays):

$$p_T(\mu) > 2 \text{ GeV}$$

$$|\eta(\mu)| > 2.0$$

D0 Collaboration, PRL 116, 082002 (2016).

$Y+Y$ production (CMS, 8 TeV)

CM energy = 8 TeV

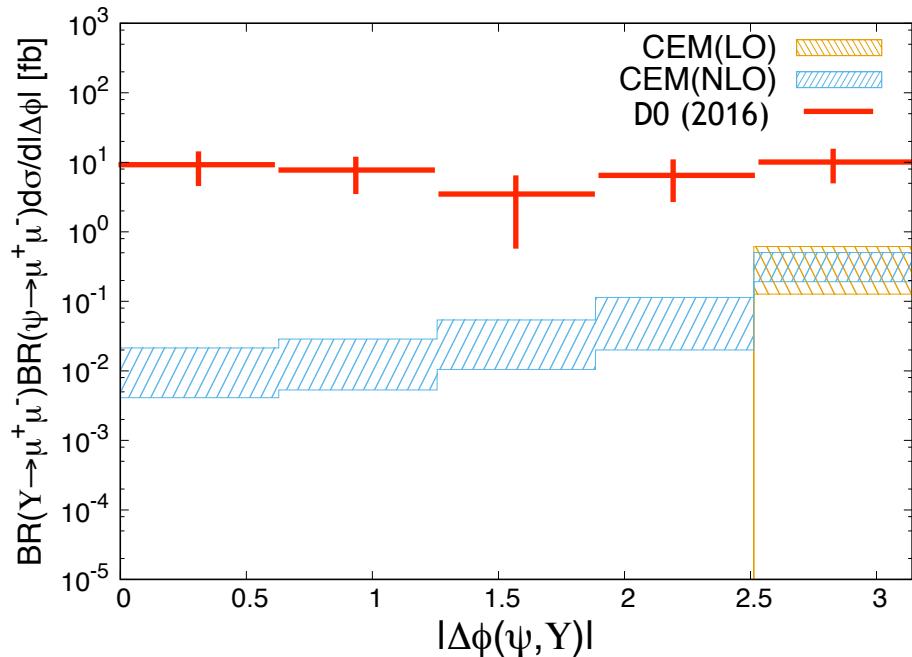
Cut (inclusive):

$$|y| < 2.0$$

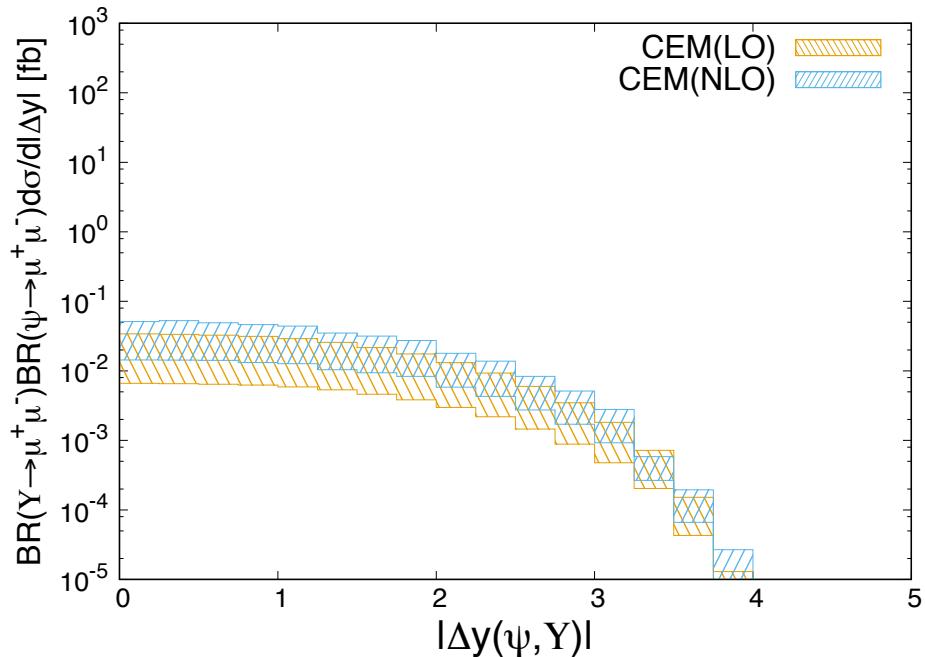
CMS Collaboration, JHEP 1705 (2017) 013.

J/ ψ +Y production ($D0$, $p\bar{p}$, 1.96TeV)

$|\Delta\phi|$:



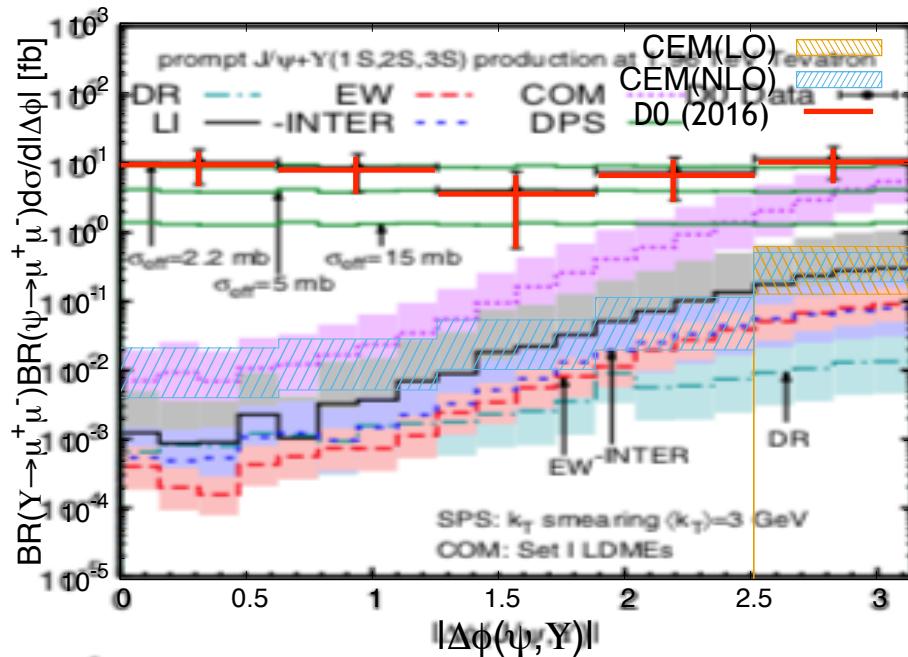
$|\Delta y|$:



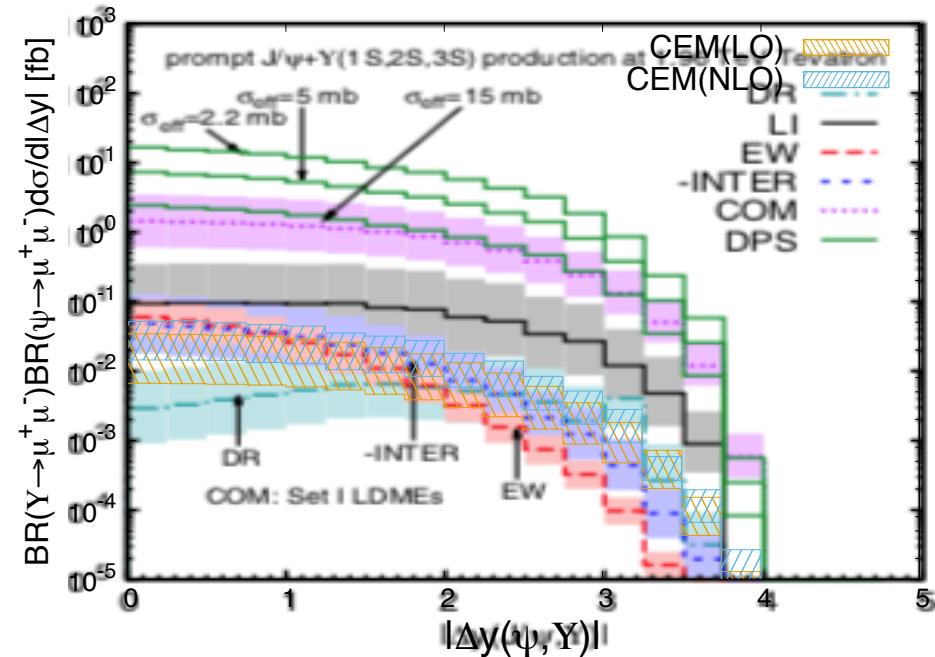
Experimental data :
D0 Collaboration, PRL 116, 082002 (2016).

$J/\psi + Y$ production ($D0$, $p\bar{p}$, 1.96TeV)

$|\Delta\phi| :$



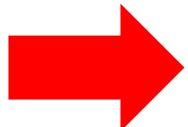
$|\Delta y| :$



Experimental data :
D0 Collaboration, PRL 116, 082002 (2016).

Upsilon production

Fit from CMS data (7 TeV)



$$\mathcal{P}_Q^{(N)\text{LO}, \frac{\text{direct}}{\text{prompt}}}$$

$$= \begin{cases} \text{LO} : 0.0178 \pm 0.0002 & [\Upsilon(1S)] \\ \text{NLO} : 0.0121 \pm 0.0001 & \end{cases}$$

$$= \begin{cases} \text{LO} : 0.0098 \pm 0.0001 & [\Upsilon(2S)] \\ \text{NLO} : 0.0064 \pm 0.0001 & \end{cases}$$

$$= \begin{cases} \text{LO} : 0.0073 \pm 0.0001 & [\Upsilon(3S)] \\ \text{NLO} : 0.0047 \pm 0.0001 & \end{cases}$$