Associated production of a quarkonium and a vector boson

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Motivations for quarkonium+vector boson production studies

The study of quarkonium + vector boson (W/Z) production has been proposed to probe perturbative and nonperturbative properties of QCD.

Υ+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.

J/ψ+W was also 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

First searches were carried out by CDF Collaboration at FermiLab

CDF Coll., PRL **90** (2003) 221803; PRD **91** (2015) 052011

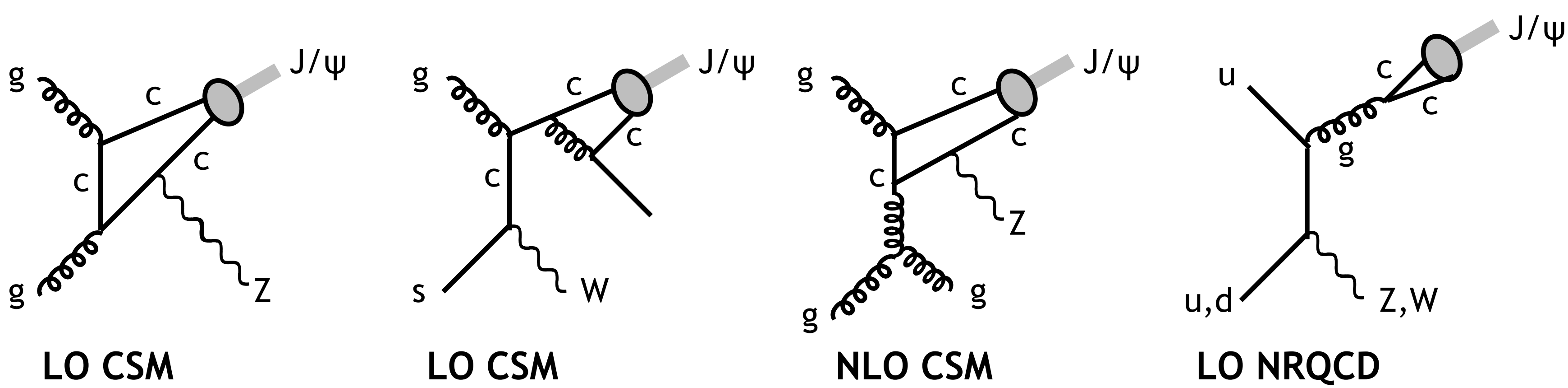
ATLAS observed J/ψ+W and J/ψ+Z

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

Quarkonium+vector boson production

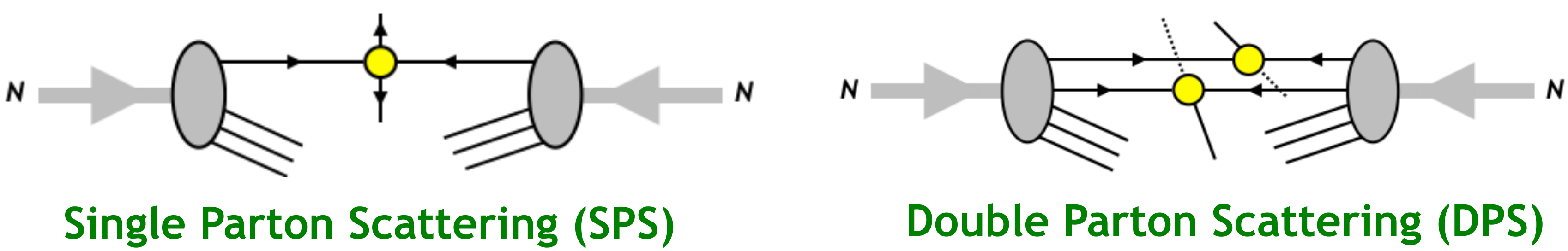
Recently, theoretical computations were carried out up to NLO in α_s

NLO NRQCD J/ψ+W : L. Gang et al., PRD **83** (2011) 014001;
NLO NRQCD J/ψ+Z : L. Gang et al., JHEP **02** (2011) 071 ;
NLO CSM J/ψ+Z : B. Gong, J.P. Lansberg, C. Lorce, J.X. Wang, JHEP **1303** (2013) 115;
Missing LO CSM J/ψ+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 γ+jet , W+Z, W+W productions



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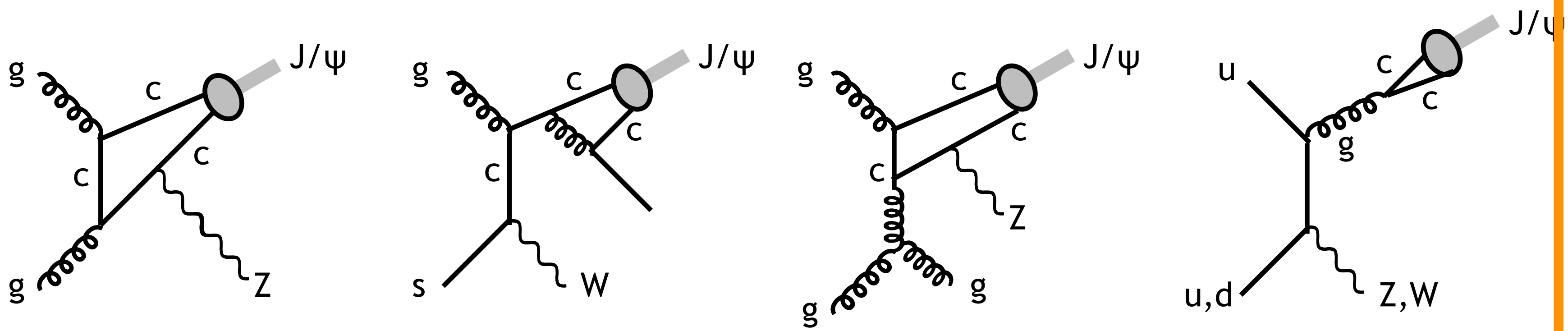

LO CSM **LO CSM** **NLO CSM** **LO NRQCD**

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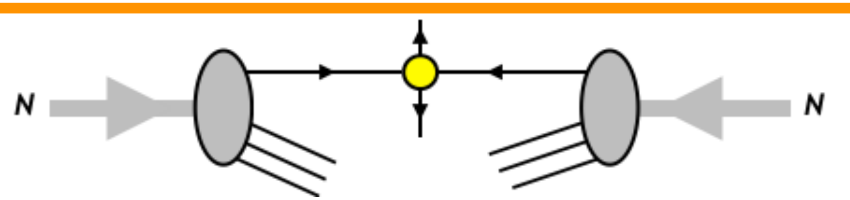
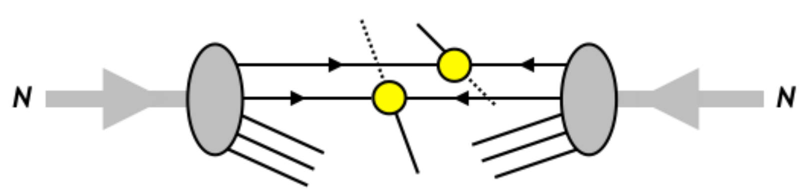


Single Parton Scattering (SPS)



Double Parton Scattering (DPS)

Digression on DPS

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

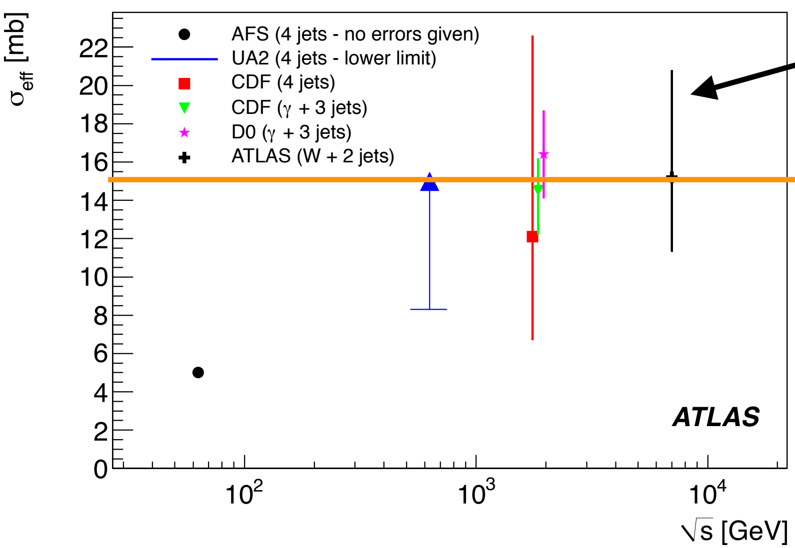
They are in fact necessary to restore the unitarity of the cross section and are related to the strong increase of the parton densities at high energy.

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:

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

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



15 mb

W+2jets [ATLAS, New J. Phys. **15** (2013) 033038]

ATLAS vs. "theory"

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

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

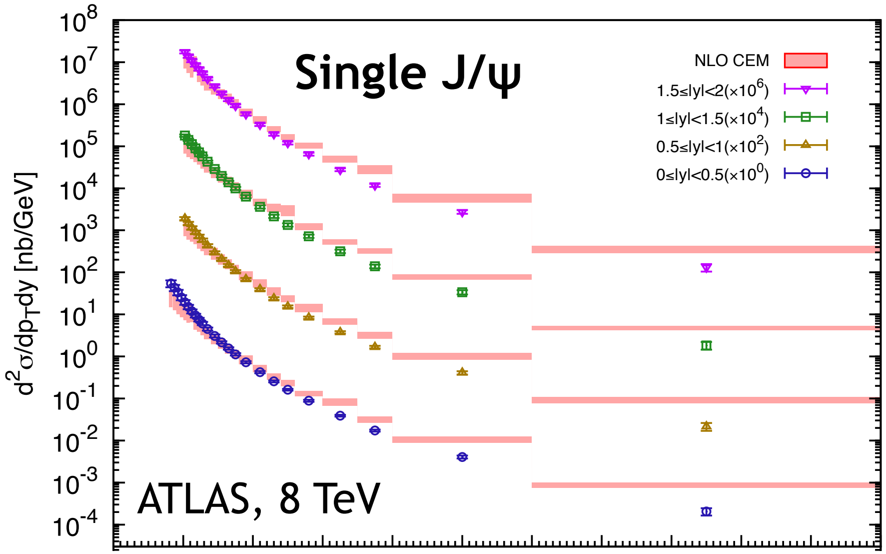
A natural question arises : Is SPS underestimated?

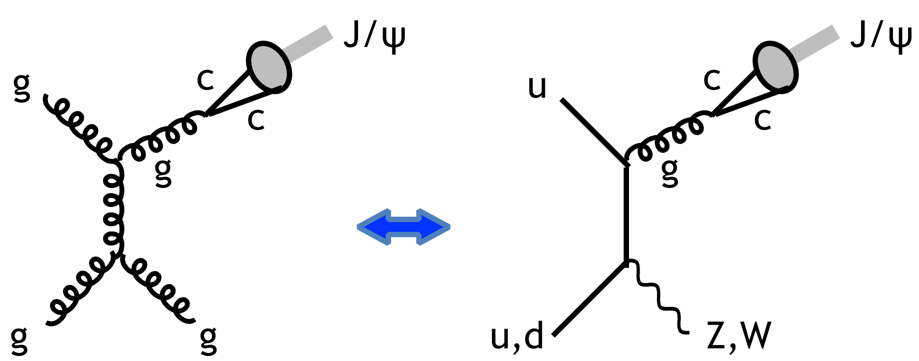
Building up an upper limit to the SPS with the color evaporation model

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 (~ $^3S_1^8$)

The same is expected to occur for J/ψ+W and J/ψ+Z.

⇒ CEM : conservative upper limit on the SPS yield



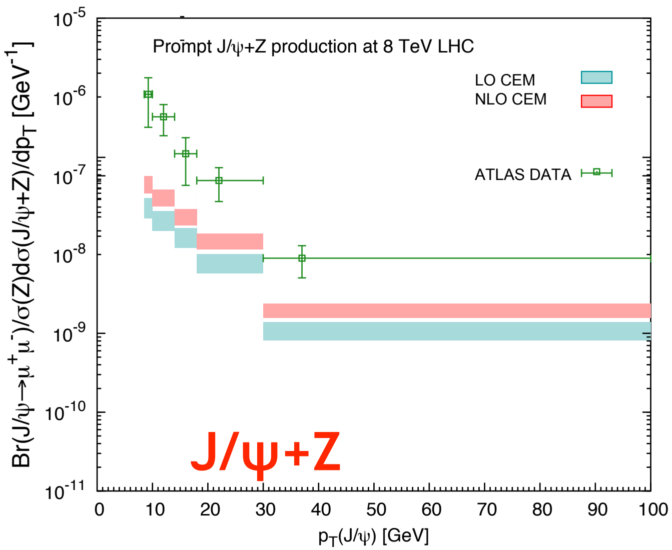


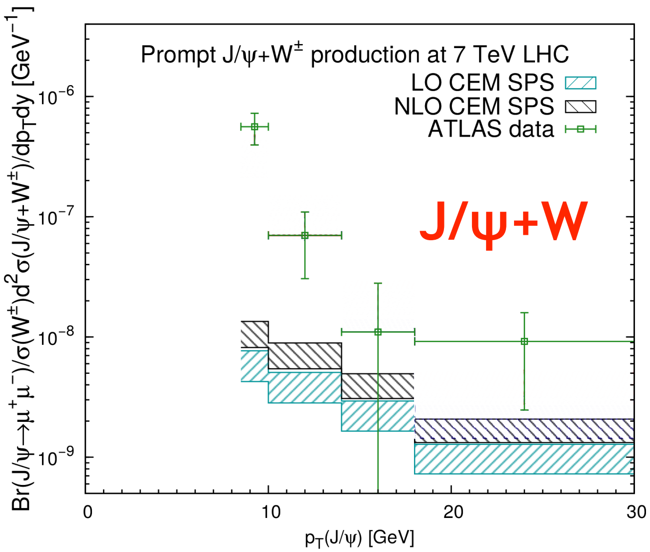
We will compute it in both cases at NLO with MadGraph5_AMC@NLO.
J. Alwall et al. , JHEP **07** (2014) 079

Results for the Color evaporation model at NLO

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

[1] J.-P. Lansberg and H.-S. Shao, JHEP **1610** (2016) 153
[2] J.-P. Lansberg, H.-S. Shao, and NY, arXiv:1707.04350 [hep-ph]





⇒ **Upper limit by CEM does not solve the problem.**

⇒ **Can it be solved by increasing the DPS?**

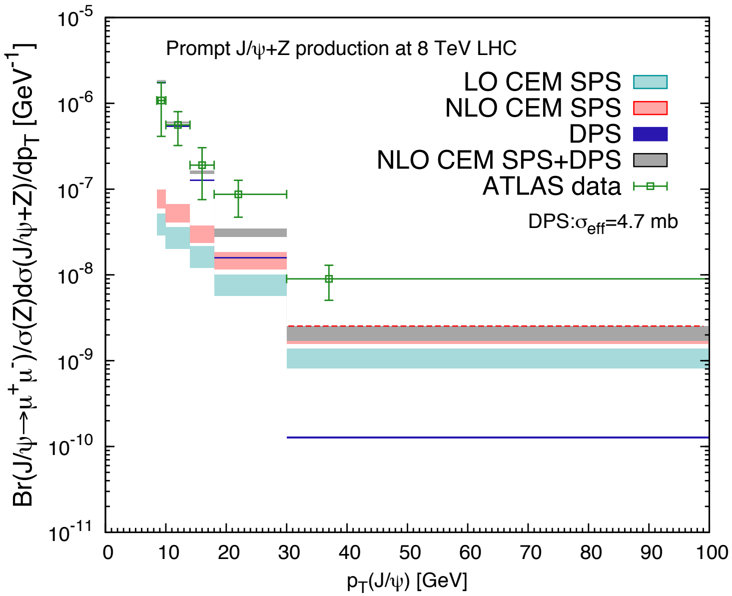
Indeed di-J/ψ , Υ+J/ψ data point at σ_{eff} < 10 mb

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

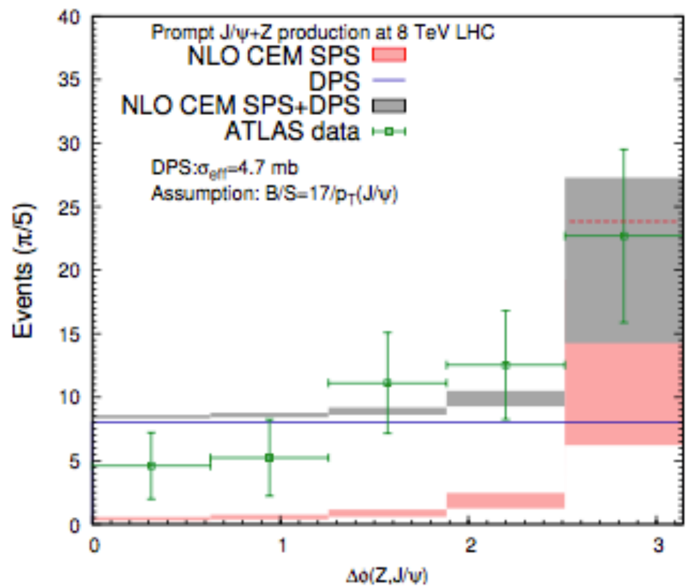
We fit σ_{eff} to the ATLAS data subtracted from the SPS

and we obtain $\sigma_{eff} = (4.7^{+2.4}_{-1.5})$ mb J.-P. Lansberg and H.-S. Shao, JHEP **1610** (2016) 153

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



p_T distribution



azimuthal distribution

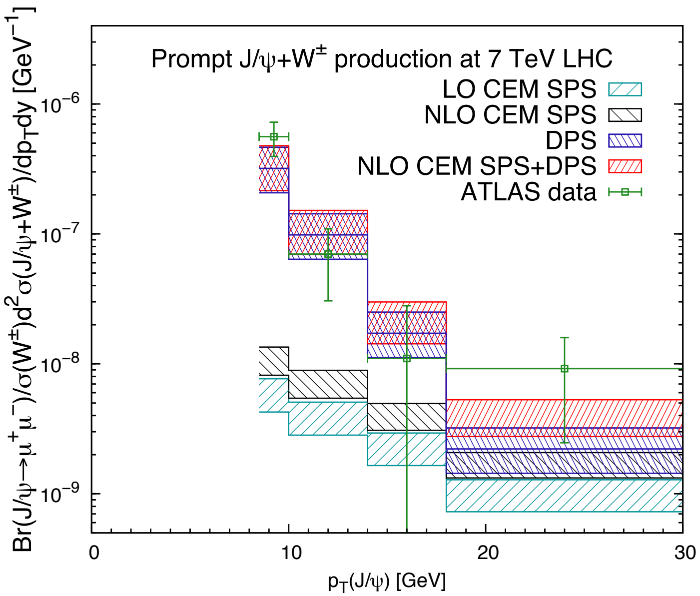
Increasing the DPS in a compatible amount to di-J/ψ and J/ψ+Y data seems to solve the puzzle.

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

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

J.-P. Lansberg, H.-S. Shao, and NY, arXiv:1707.04350 [hep-ph]

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



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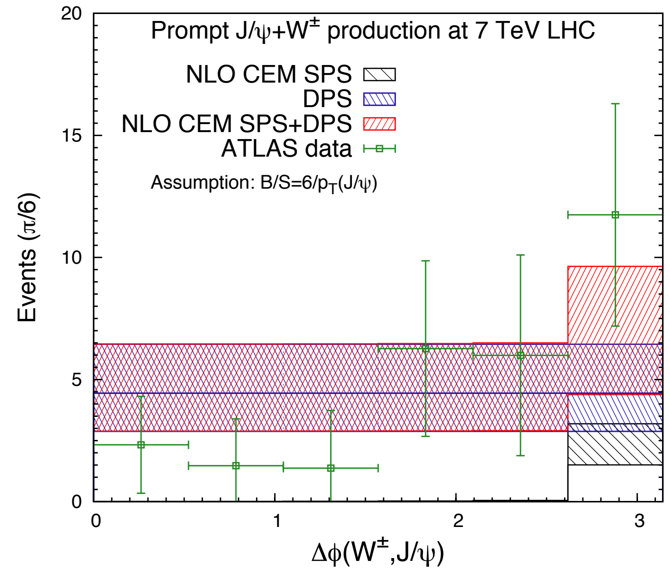
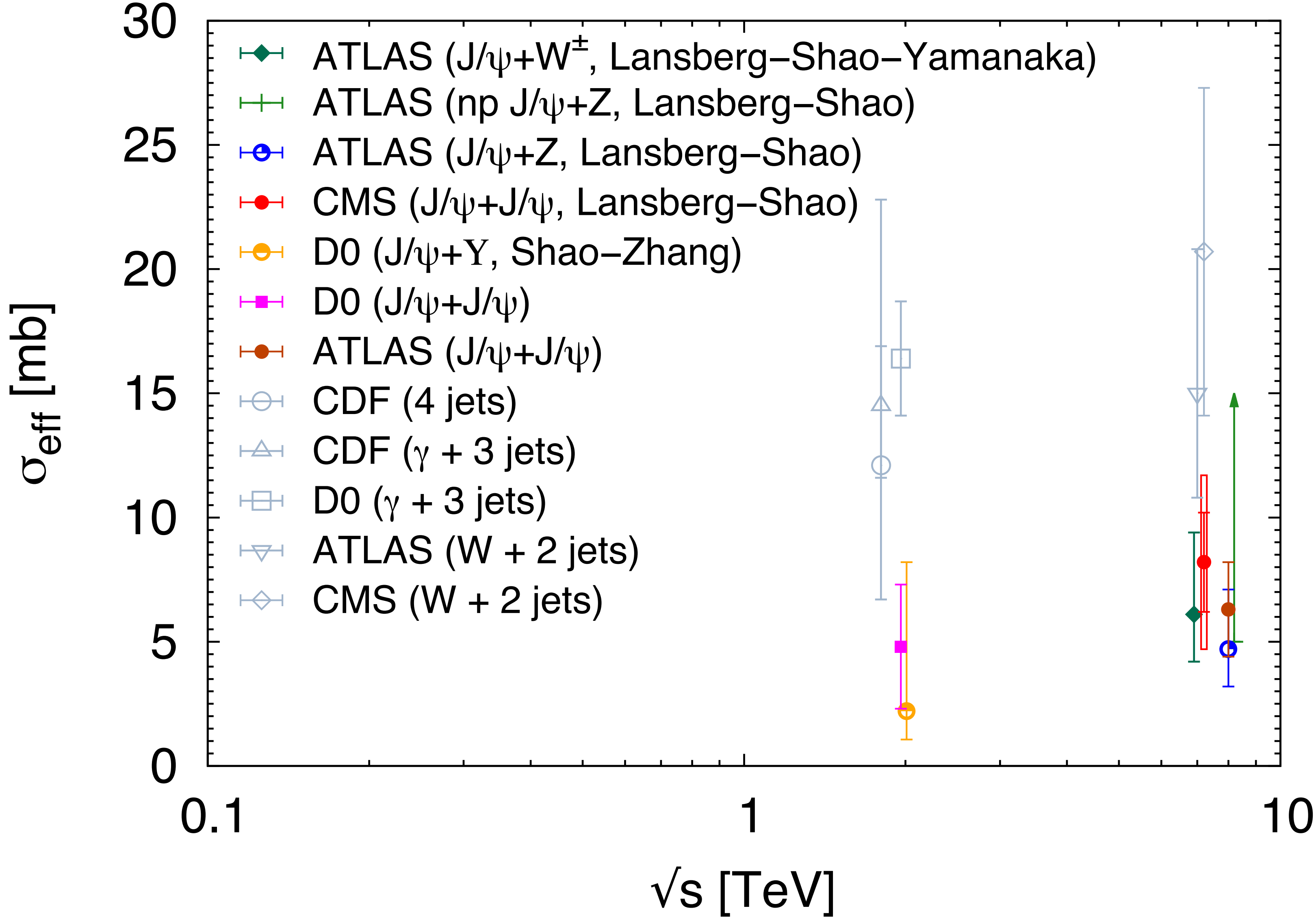


azimuthal distribution

As for the J/ψ+Z case, increasing the DPS in a compatible amount to di-J/ψ and J/ψ+Y data seems to solve the puzzle.

Overall

Our results: $\sigma_{\rm eff} = (4.7^{+2.4}_{-1.5})\mathrm{mb}$ **(J/ψ+Z)** $\sigma_{\rm eff} = (6.1^{+3.3}_{-1.9})\mathrm{mb}$ **(J/ψ+W)**



⇒ Consistent with other quarkonium data

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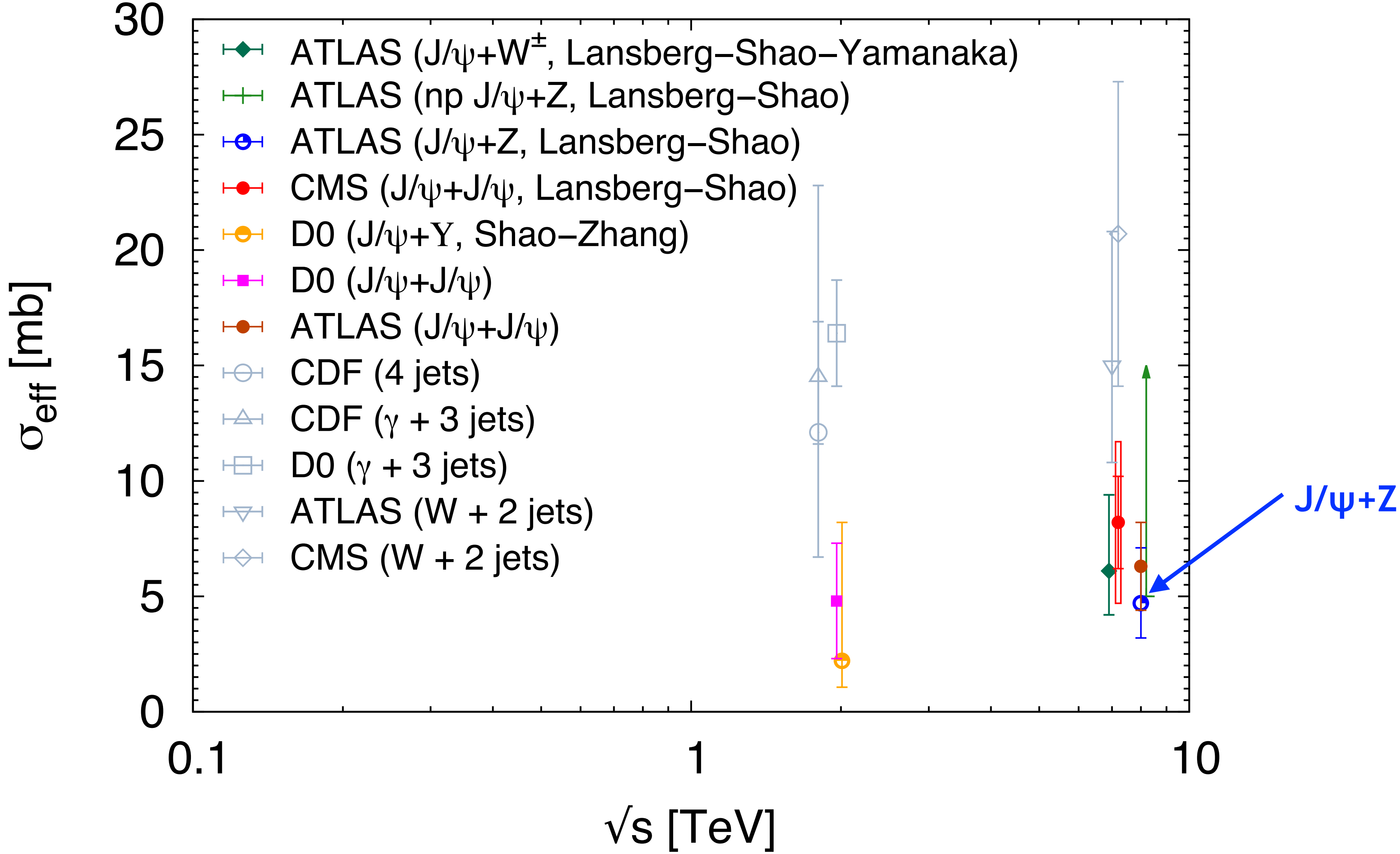

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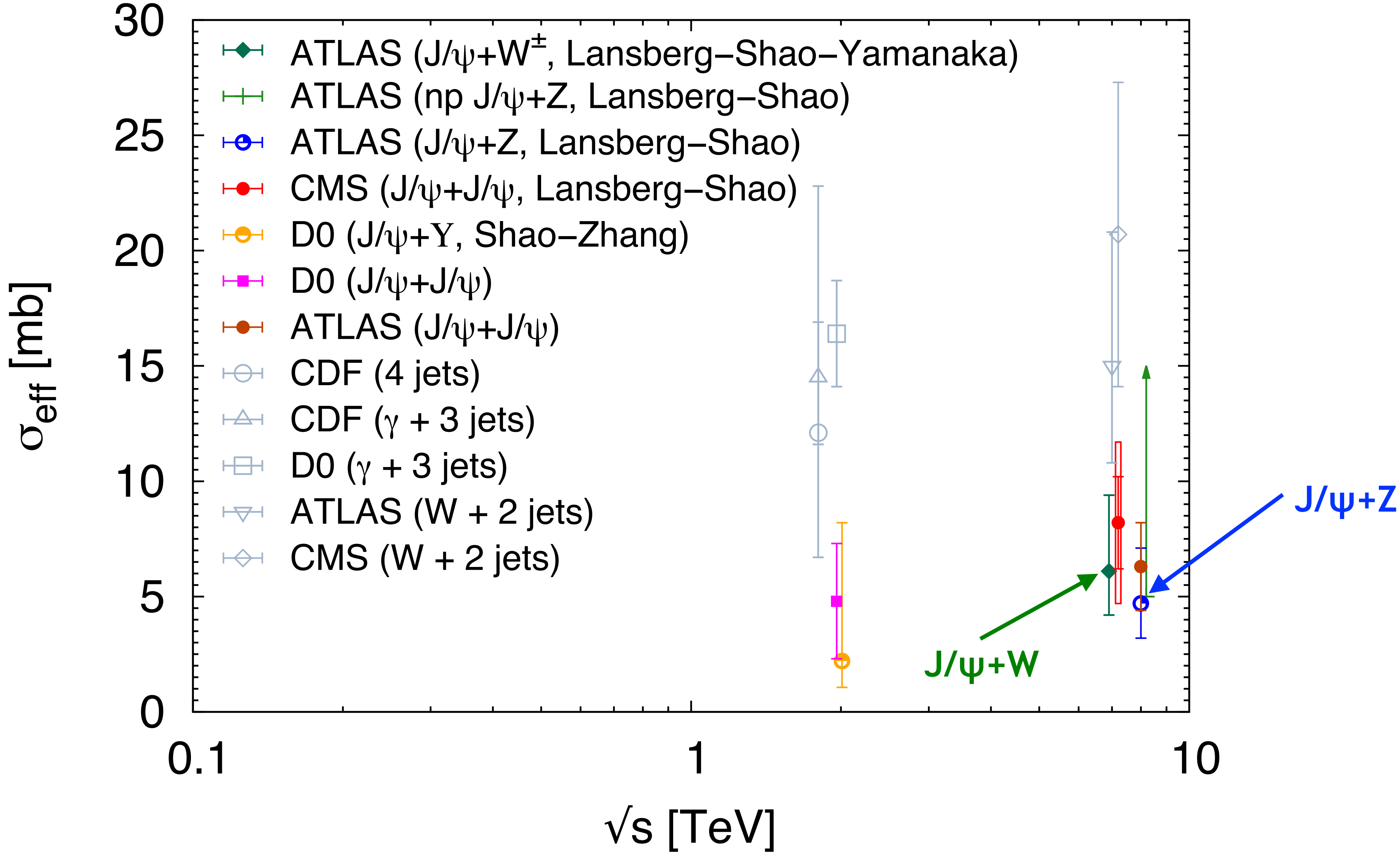


⇒ Consistent with other quarkonium data

$Z + b\ (\rightarrow J/\psi)$

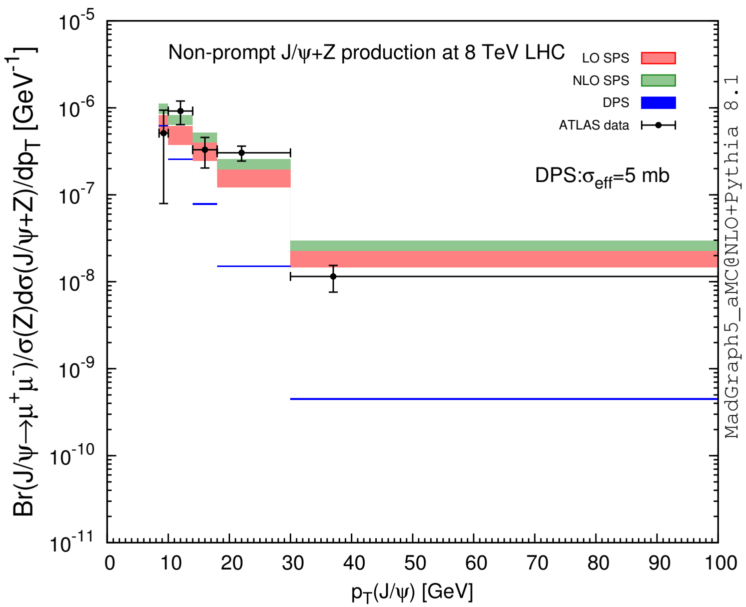
ATLAS also analyzed p+p → $^{\text{nonprompt}}J/\psi$ + Z

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

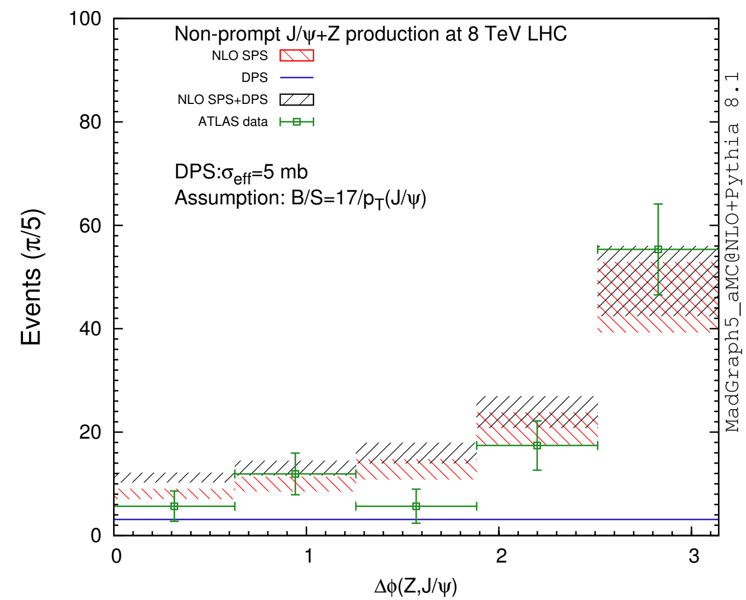
⇒ Probe p+p → Z + b

Analysis of the SPS contribution to p+p → $^{\text{nonprompt}}J/\psi$ + Z at NLO:

J.-P. Lansberg and H.-S. Shao, Nucl. Phys. B **916** (2016) 132



p_T distribution



azimuthal distribution

⇒ Agreement with ATLAS experimental data

Constraint to DPS : σ_{eff} > 5.0 mb (68% CL.) (> 2.3 mb (95% CL.))

(Weak constraint due to the uncertainty in low p_T region)

Summary:

- Associated production of J/ψ+W/Z was measured by ATLAS: discrepancies with SPS+DPS (σ_{eff}=15mb) 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.
- On the other hand, decreasing σ_{eff} in an amount compatible with di-J/ψ and J/ψ+Y provides a simple solution to the puzzle.
- In fact, J/ψ+W/Z show evidence for DPS.
  J/ψ+Z : $\sigma_{eff} = (4.7^{+2.4}_{-1.5})$ mb
  J/ψ+W : $\sigma_{eff} = (6.1^{+3.3}_{-1.9})$ mb
- σ_{eff} seems to be smaller for quarkonia than for jets: hint for flavor dependence?

End

Color evaporation model and J/ψ production

The CEM takes into account all $\bar{q}$ q final states with (collinear) momenta, between $\bar{q}$q and open charm thresholds.

$$\sigma_{Q}^{(N)LO,\ \frac{\mathrm{direct}}{\mathrm{prompt}}} = \mathcal{P}_{Q}^{(N)LO,\ \frac{\mathrm{direct}}{\mathrm{prompt}}} \int_{2m_Q}^{2m_H} \frac{d\sigma_{Q\bar{Q}}^{(N)LO}}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$$

$$\mathcal{P}_{Q}^{(N)LO,\ \frac{\mathrm{direct}}{\mathrm{prompt}}} = \begin{cases} 0.014 \pm 0.001 & \text{(LO)} \\ 0.009 \pm 0.0004 & \text{(NLO)} \end{cases}$$

Color evaporation model (CEM):

- Based on quark-hadron duality
- Larger cross section for high pT
  ⇒ conservative upper limit on single parton scattering

J/ψ production cross section:

CEM takes into account all q $\bar{q}$ final states with (collinear) momenta, between q$\bar{q}$ and open charm thresholds.

In CEM, final states are not color singlet, this reflects the shuffling of color with soft gluon radiations.

Soft physics is factorized into the transition probability, fitted from exp.