Study of parton correlations via double parton scatterings in associated quarkonium production in high energy accelerator experiments

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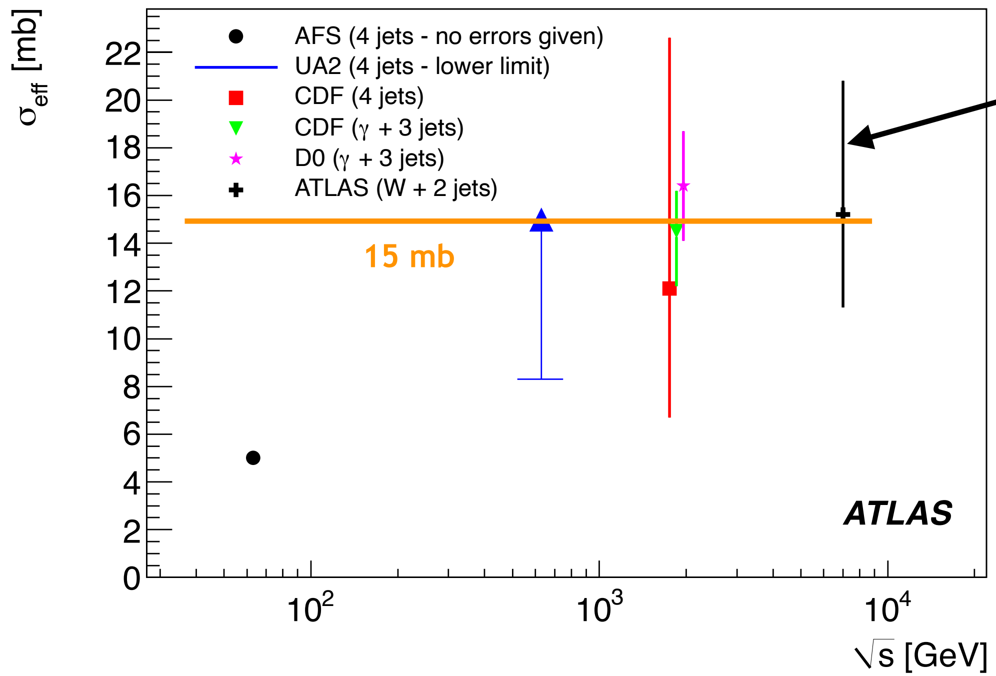
MPI@LHC

Double parton scattering (DPS)

To parametrize the DPS cross sections we often use the so-called pocket-formula:

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

Reference data, ATLAS W+2jets, with $\sigma_{\mathrm{eff}} \sim 15$ mb



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

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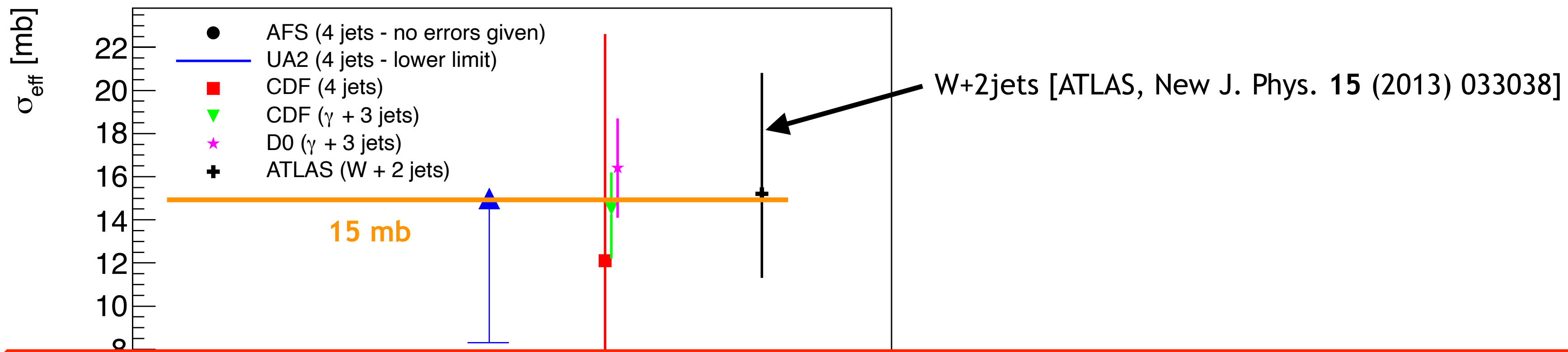


Let us see the extraction of σ_{eff} with quarkonia.

(and also color singlet (CS)/octet (CO) contributions to SPS since σ_{DPS} is usually obtained by $\sigma_{\mathrm{tot}} - \sigma_{\mathrm{SPS}}$)

$(J/\psi, \Upsilon)+c$

Quarkonium + open heavy flavor

Motivations for studying J/ψ+D :

Large production cross section compared to J/ψ+W,Z

Experimental advantages : efficient heavy flavor tagging

Measurable at LHCb, ATLAS, CMS, D0

Production of close 3 heavy quarks enhanced by color transfer

G. C. Nayak et al., PRL **99** (2007) 212001; PRD **77** (2008) 034022

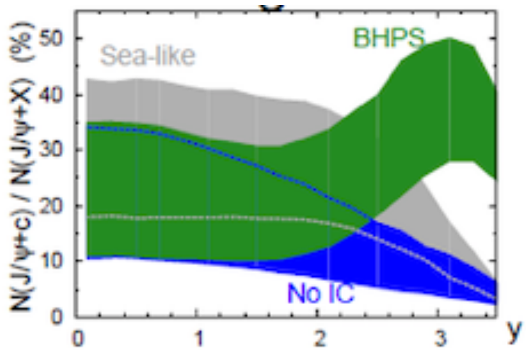
Test the DPS, CSM, heavy flavor PDF including intrinsic HQ, etc.

$J/\psi + c$

Good probe of intrinsic charm (via gc fusion)

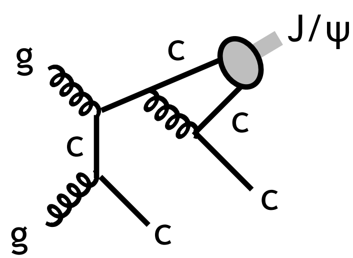
- High rapidity region
- J/ψ+lepton azimuthal angle

S.J.Brodsky and J. P. Lansberg, PRD **81**, 051502 (2010)



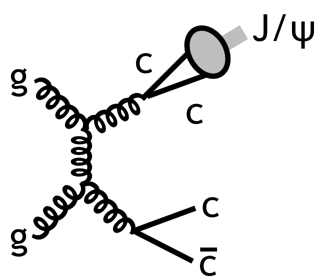
Discriminating CS / CO components of J/ψ

Near D-J/ψ at large p_T



No near D-J/ψ at large p_T

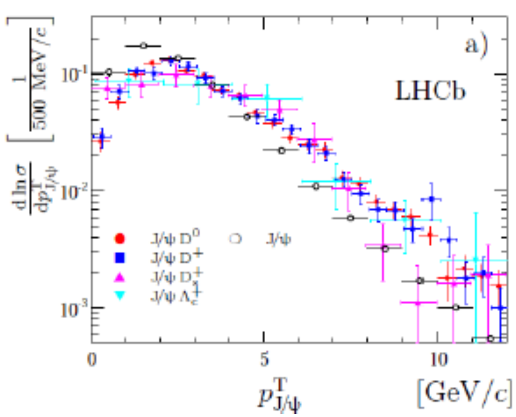
$\Rightarrow$ CO!

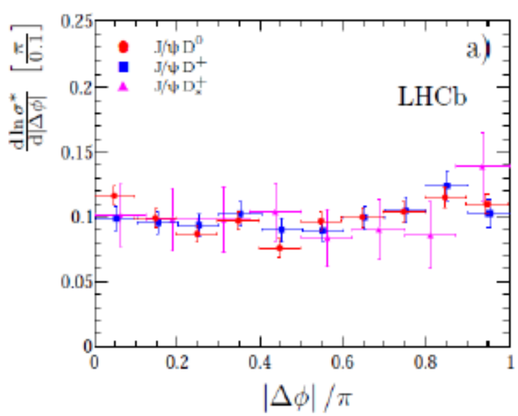


P. Artoisenet, J. P. Lansberg, and F. Maltoni, PLB **653** (2007) 60

First measurement by LHCb

LHCb Collaboration, JHEP **1206** (2012) 141

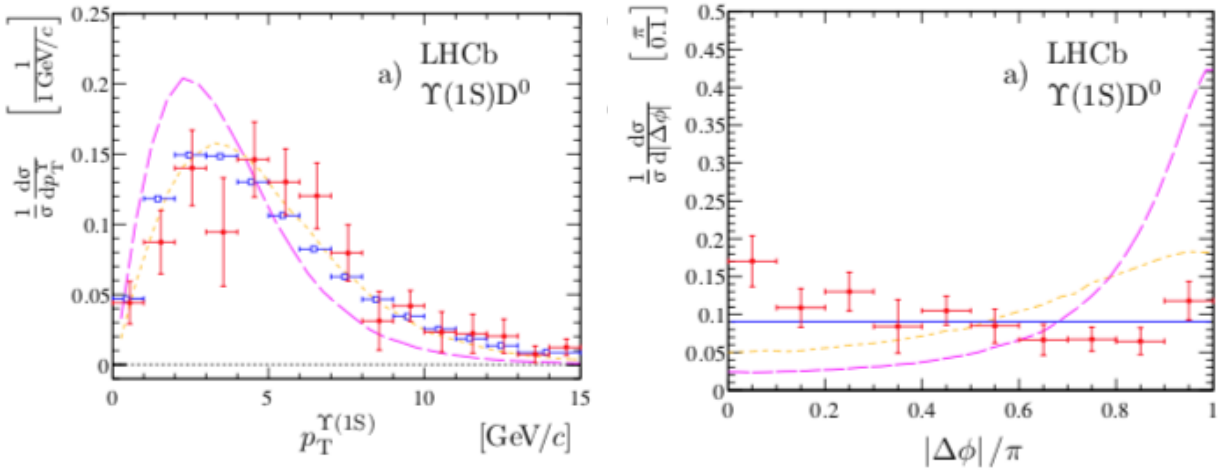




Flat $\Delta\varphi$ distribution:
DPS or
SPS smeared by k_T distribution?

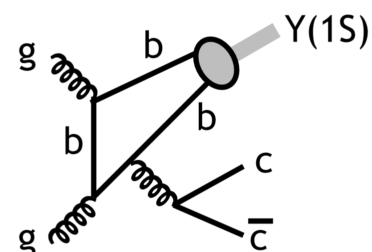
Upsilon + c(D meson)

Also measured by LHCb



LHCb Collaboration, JHEP **1607** (2016) 052

Theory estimation (SPS) not complete



$c\bar{c}$ from gluon splitting dominant?

A.V. Berezhnoy et al., IMPJA **30** (2015) 1550125

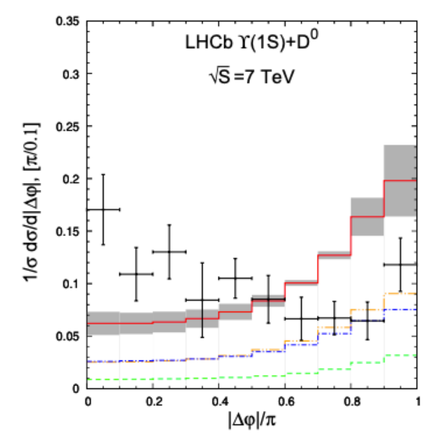
Feed down of χ_b+c+$\bar{c}$ at most 2%

A.Likhoded et al., Phys. Lett. B **755** (2016) 24

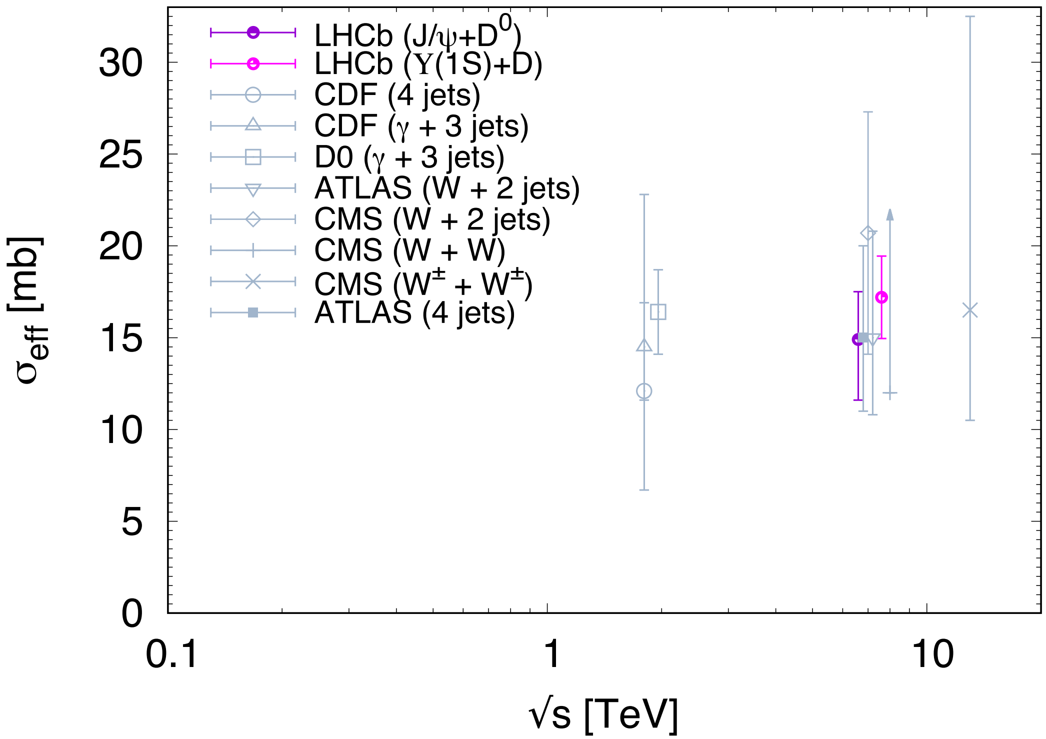
⇒ Dominated by DPS?

Recent study within Reggeization : g→D dominant, almost explains distributions, except |Δφ|

Karpishkov et al., PRD **99**, 096021 (2019)



DPS in $Q\bar{Q}$+D



⇒ The DPS for quarkonium+c production looks consistent with other jet, W, photon related DPS, at least in the kinematical region of LHCb (2 < y < 4.5)

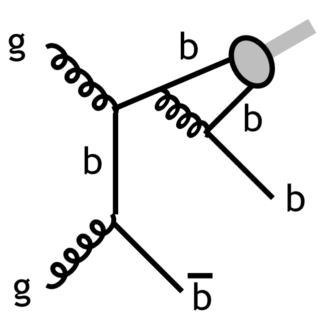
J/ψ+D^0 : σ_{eff} = 14.9 ± 0.4 (stat) ± 1.1 (sys) mb
J/ψ+D^+ : σ_{eff} = 17.6 ± 0.6 (stat) ± 1.3 (sys) mb
J/ψ+D^0_s : σ_{eff} = 12.8 ± 1.3 (stat) ± 1.1 (sys) mb
LHCb Collaboration, JHEP **1206** (2011) 141

Υ+D^0 : σ_{eff} = 19.4 ± 2.6 (stat) ± 1.3 (sys) mb
Υ+D^+ : σ_{eff} = 15.2 ± 3.6 (stat) ± 1.5 (sys) mb
LHCb Collaboration, JHEP **1607** (2016) 052

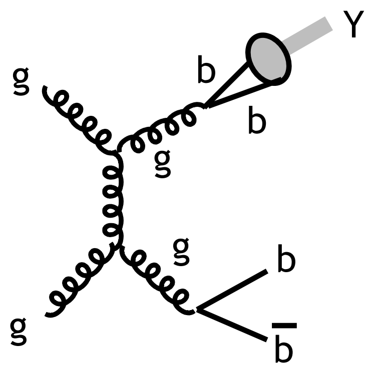
Extracted with the assumption σ_{SPS} = 0

Upsilon + b : theory

It is interesting to measure Υ+b because we may discriminate CSM/COM



CSM

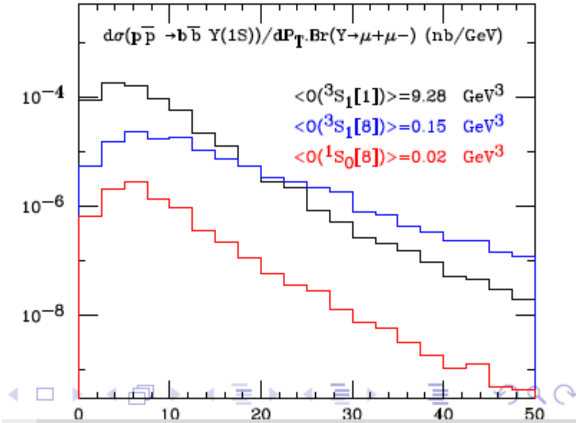


COM

Like for the case of J/ψ+c, but b-jet can be tagged!

In the LO COM, Υ(1S) is generated by 1-gluon fragmentation :
→ Slower p_T fall-off (harder at high p_T)

⇒ The shape of p_T spectrum probes the COM dominance

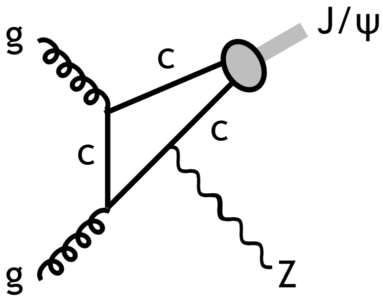


P. Artoisenet, J. P. Lansberg, and F. Maltoni, PLB **653** (2007) 60

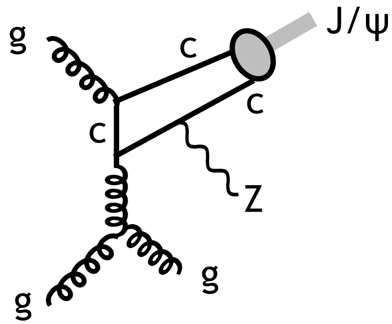
Of course, it is also possible to extract the DPS by looking into the flatness of Δφ distribution, large |Δy|, …

J/ψ+W/Z

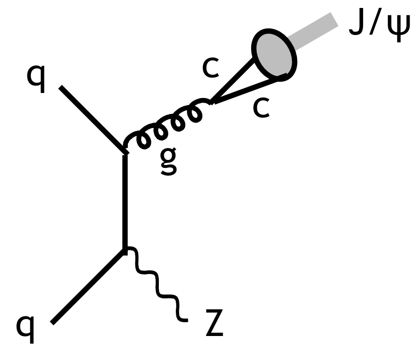
J/ψ+Z (SPS)



LO CSM



NLO CSM



LO NRQCD

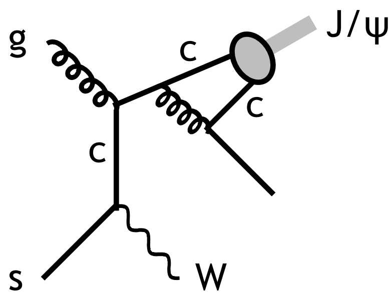
Small NLO correction at small and mid p_T

NLO correction (t-channel gluon exchange) becomes dominant at large p_T

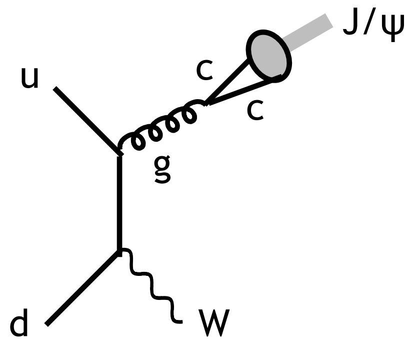
	ATLAS	*CSM (NRQCD)*	*COM (NRQCD)*
Z+J/ψ	1.6±0.4 pb [1]	0.025 - 0.125 pb [3]	< 0.1 pb [2]

[1] ATLAS Collaboration, Eur. Phys. J. C **75** (2015) 229
[2] L. Gang et al., JHEP **02** (2011) 071
[3] B. Gong, J.P. Lansberg, C. Lorce, J.X. Wang, JHEP **1303** (2013) 115

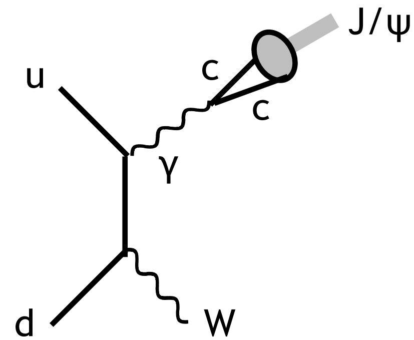
J/ψ+W (SPS)



LO CSM



LO NRQCD (COM)



LO CSM

Gluon fragmentation is dominant? ⇒ No!!

Photon fragmentation (CSM) is comparable (large CSM LDME)

Large CSM LDME compensates small α_{QED}

(Cannot say that "J/ψ+W is a good probe of COM")

	ATLAS	*CSM (NRQCD)*	*COM (NRQCD)*
W+J/ψ	$4.5^{+1.9}_{-1.5}$pb [1]	(0.11±0.04) pb [3]	(0.16 - 0.22) pb [2]

[1] ATLAS Collaboration, JHEP **1404** (2014) 172
[2] L. Gang et al., PRD **83** (2011) 014001
[3] J.P. Lansberg, C. Lorce, PLB **726** (2013) 218

Inclusion of DPS

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

	ATLAS	DPS (σ_{eff} = 15 mb)	CSM (NRQCD)	COM (NRQCD)
$Z+J/\psi$	1.6±0.4 pb [1]	0.46 pb	0.025 - 0.125 pb [5]	< 0.1 pb [4]
$W+J/\psi$	$4.5^{+1.9}_{-1.5}$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).

(> 3 σ for J/ψ+Z, > 2 σ for J/ψ+W)

A natural question arises : Is SPS underestimated?

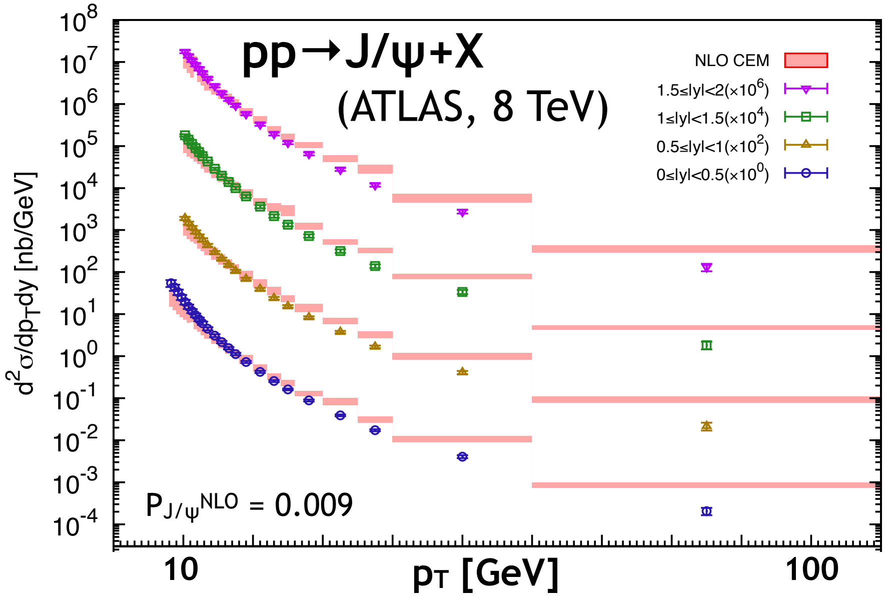
Building up an upper limit to the SPS with the color evaporation model

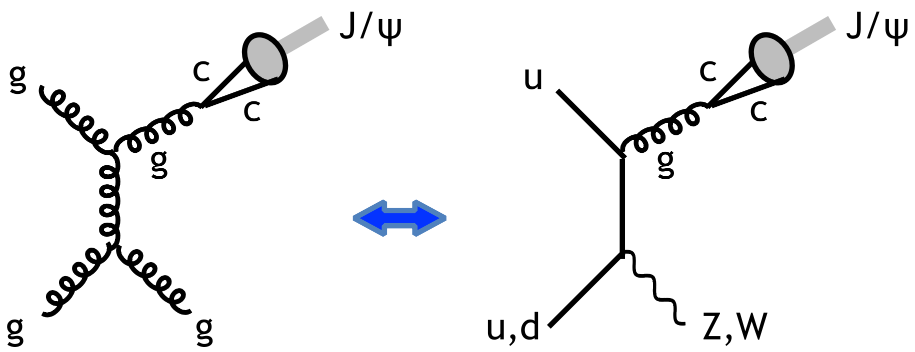
The CEM for single quarkonium production overshoots the data at high p_T (see below).

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





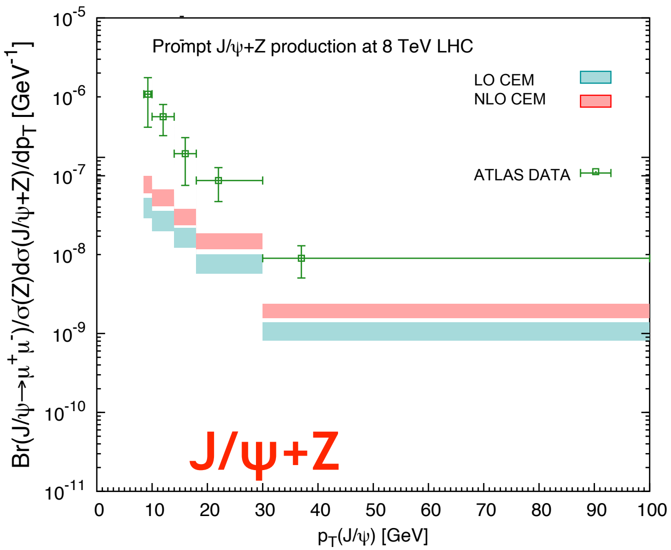
We will compute it in both cases at NLO with MadGraph5_AMC@NLO.

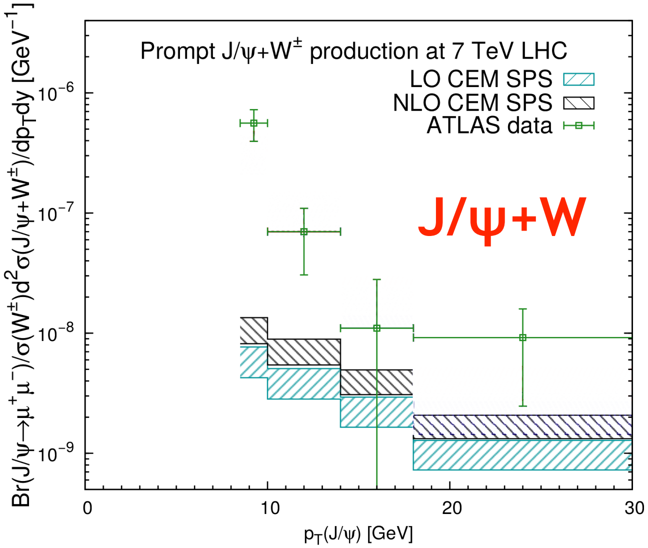
J. Alwall et al. , JHEP **07** (2014) 079

Results for the Color evaporation model at NLO

	ATLAS	DPS (σ_{eff} = 15 mb)	NRQCD (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, PLB **781** (2018) 485





⇒ Upper limit by CEM does not solve the problem.

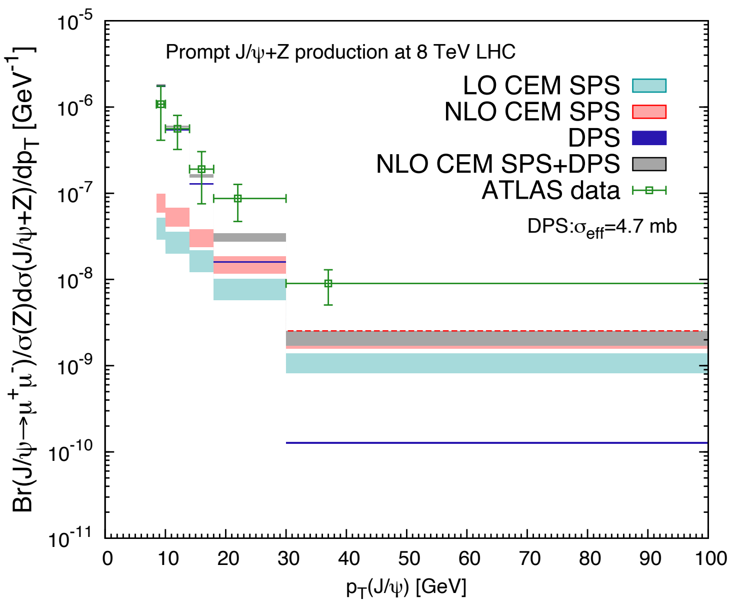
⇒ Can it be solved by increasing the DPS?

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

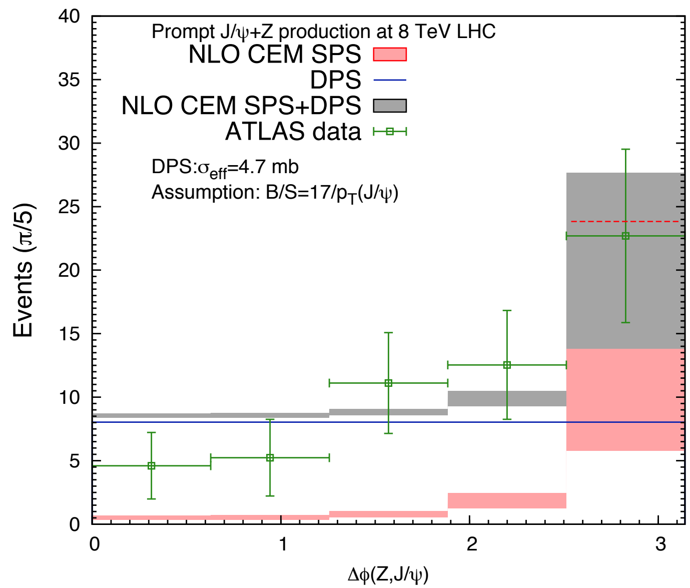
We fit σ_{eff} to the ATLAS data subtracted from the SPS

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

	ATLAS	DPS (σ_{eff} = 4.7 mb)	NRQCD (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

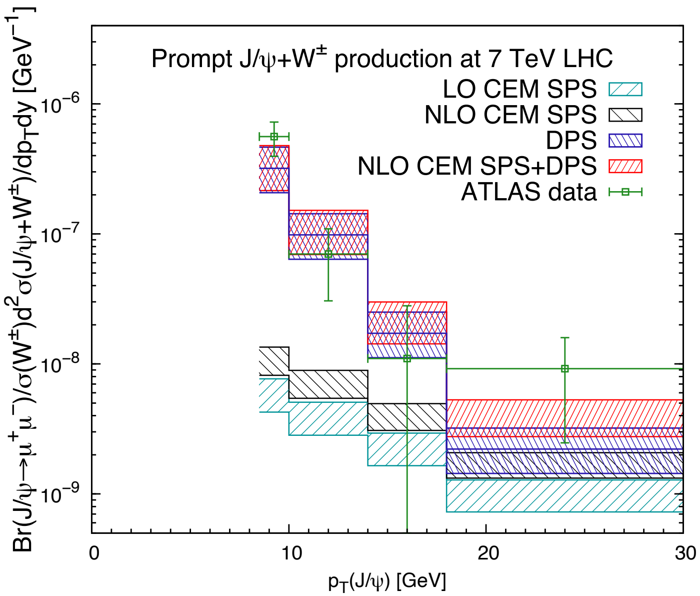
Increasing the DPS seems to solve the puzzle
(the SPS yield favored by ATLAS acceptance is visible at $\Delta\varphi=\pi$).

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

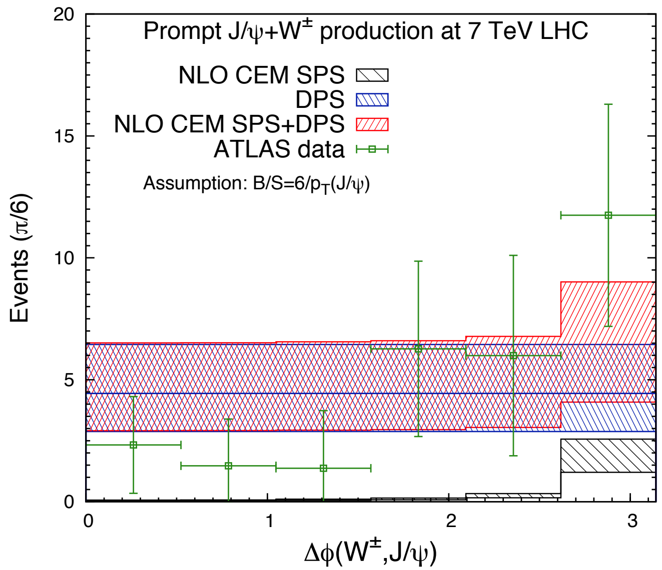
For J/ψ+W, we obtain $\sigma_{eff} = (6.1^{+3.3}_{-1.9})$ mb

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

	ATLAS	DPS (σ_{eff} = 6.1 mb)	NRQCD (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



p_T **distribution**



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

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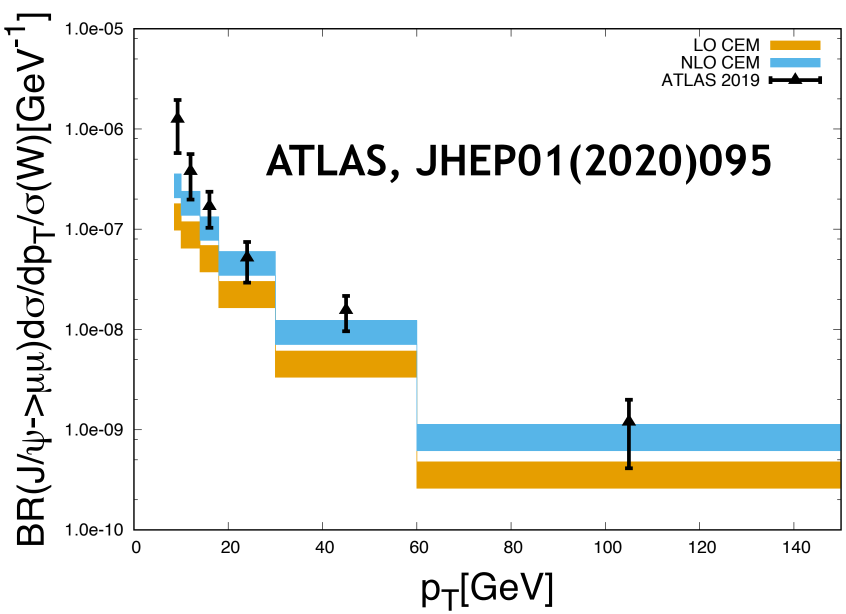

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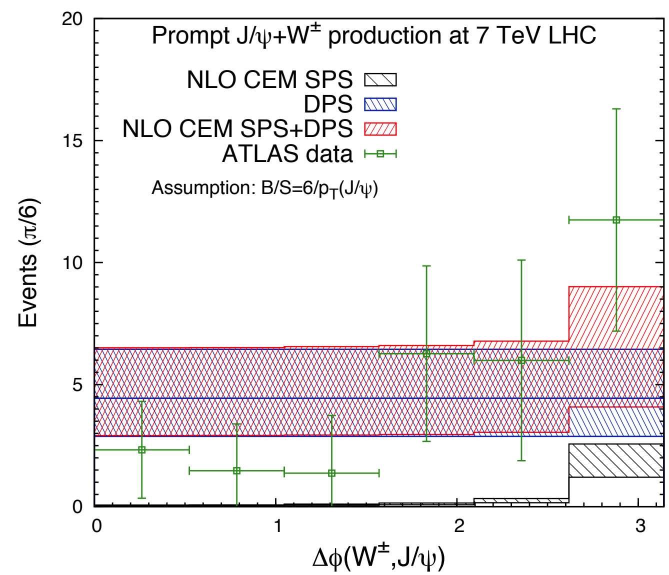

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J/ψ-pair

Quarkonium pairs

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

CMS Collaboration, JHEP **1409** (2014) 094
ATLAS Collaboration, EPJC **77**, 76 (2017)
LHCb Collaboration, JHEP **1706** (2017) 047
D0 Collaboration, PRD **90**, 111101(R) (2014)

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- **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 :** $\sigma_{\text{eff}} = (6.3 \pm 1.6(\text{stat}) \pm 1.0(\text{sys}))\,\text{mb}$

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J.-P. Lansberg, Phys. Rep. **889**, 1 (2020)

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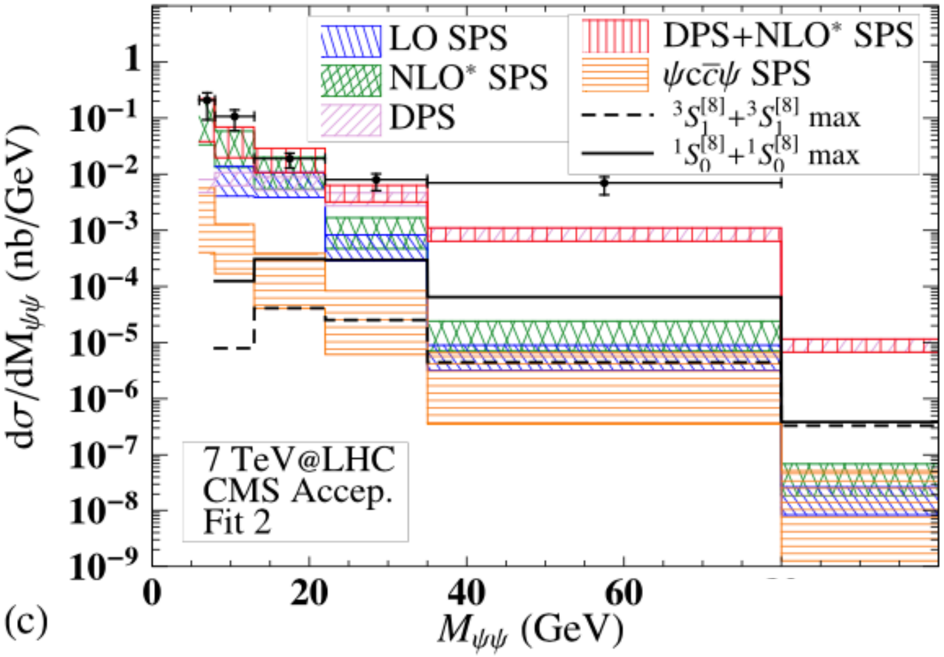

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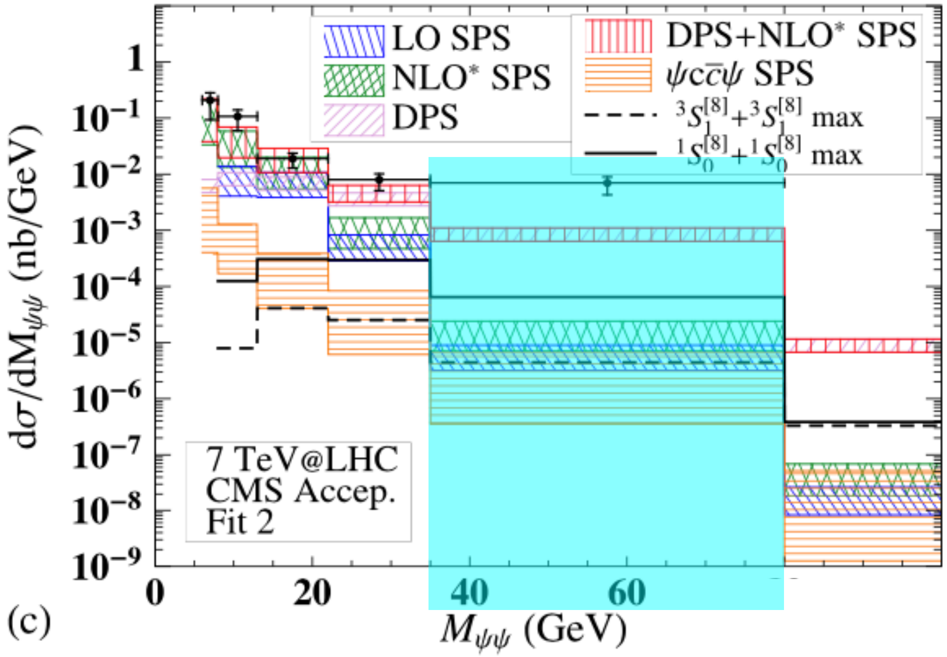

Large $M_{\psi\psi}$ bin :

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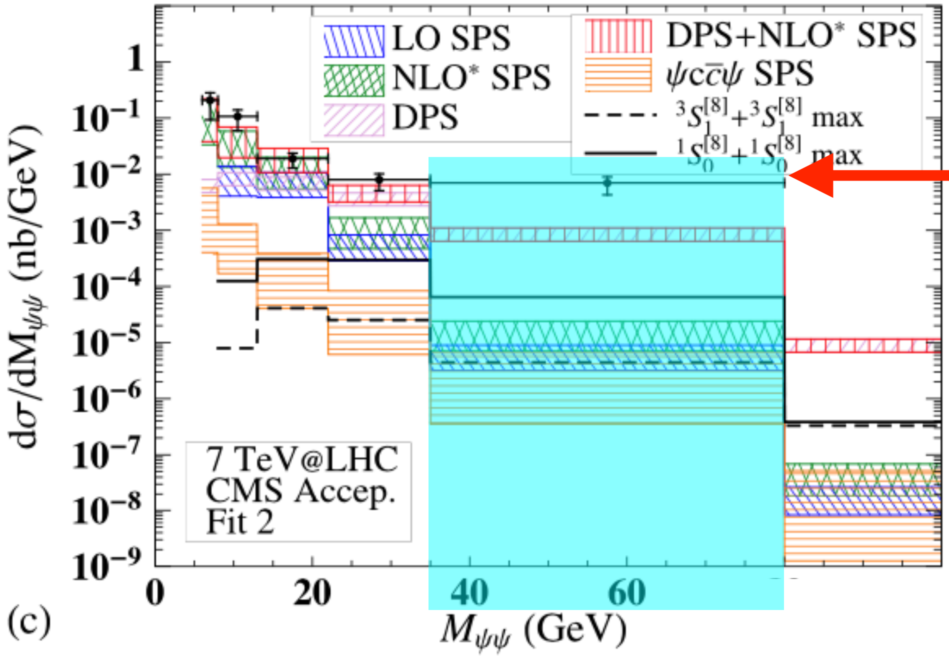

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Exp. data show enhancement

Quarkonium pairs

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

CMS Collaboration, JHEP **1409** (2014) 094
ATLAS Collaboration, EPJC **77**, 76 (2017)
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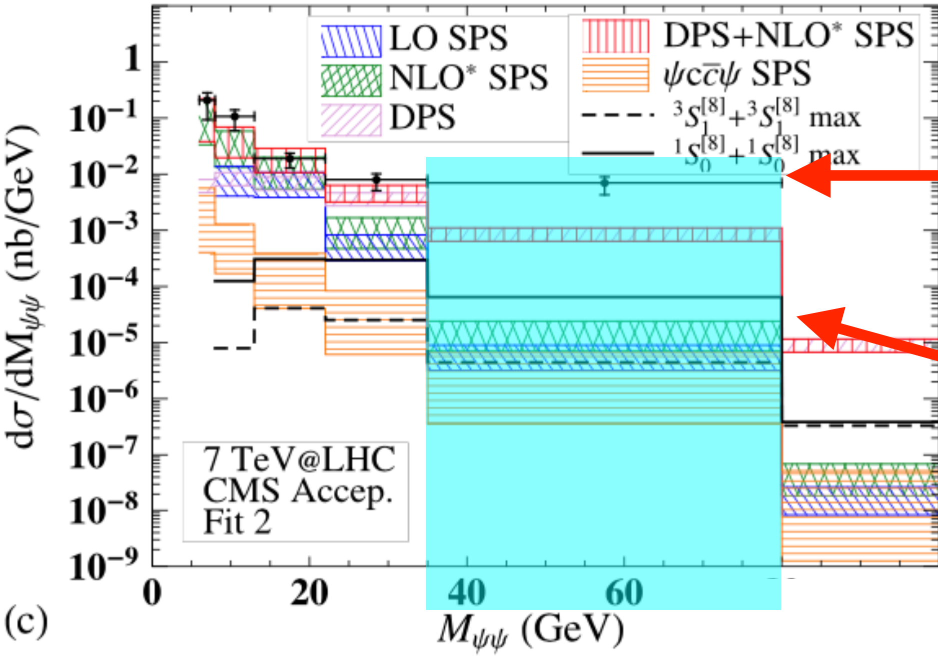

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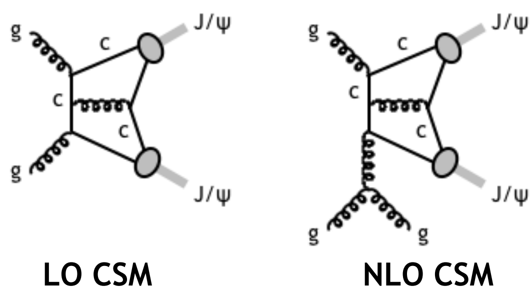

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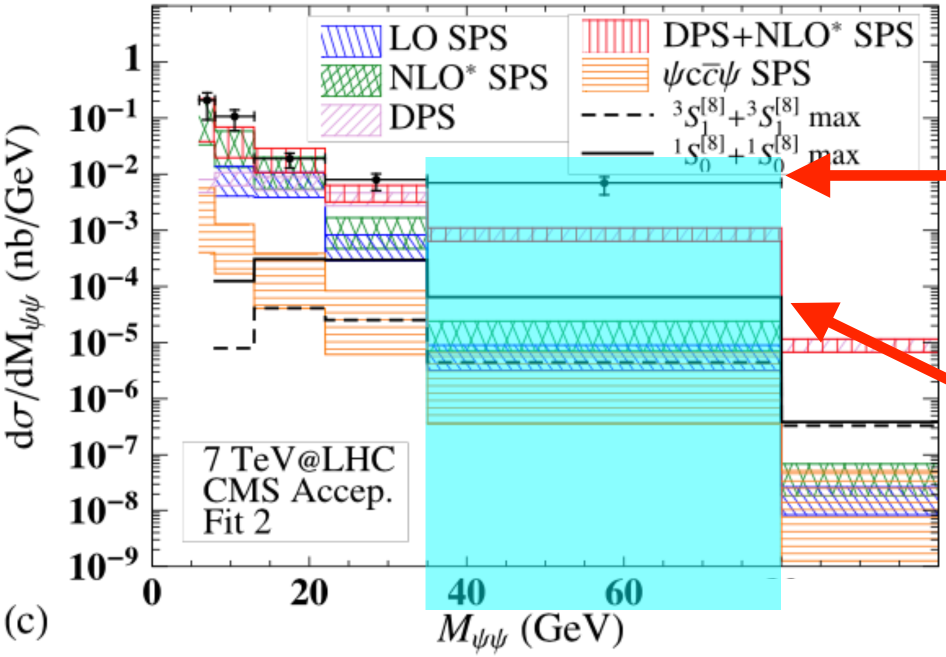

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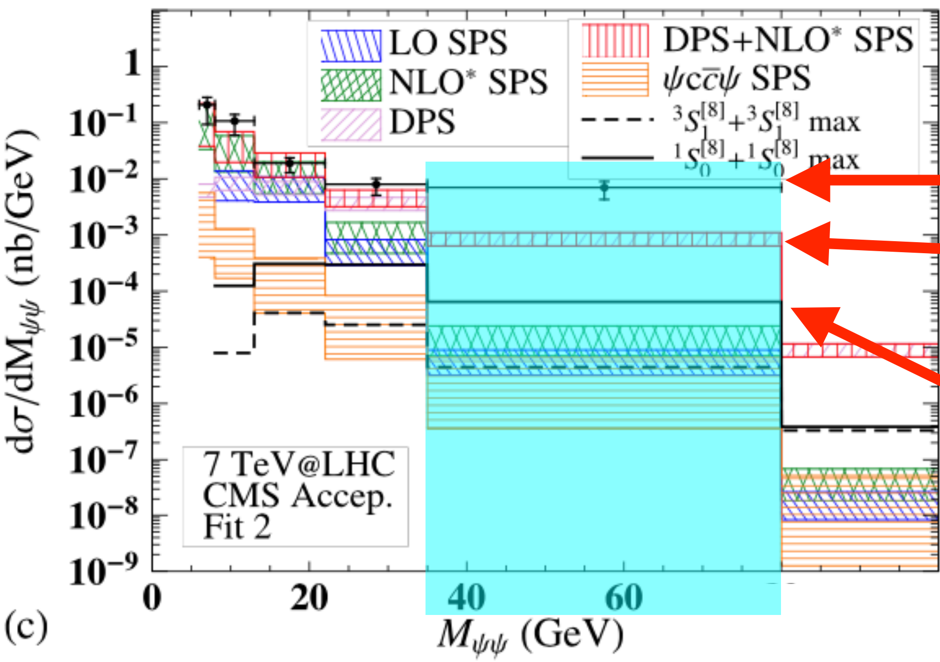

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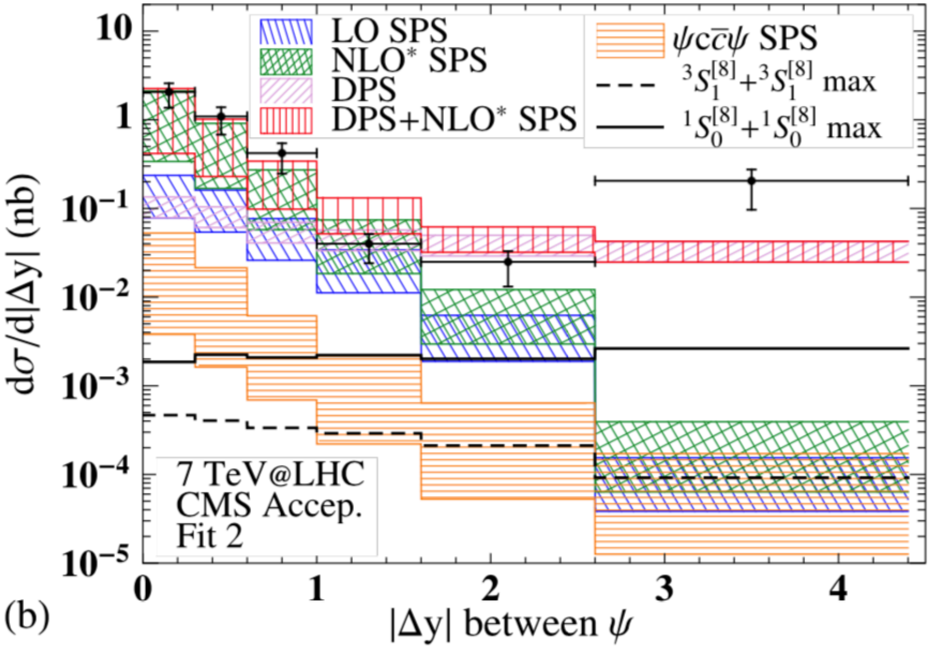
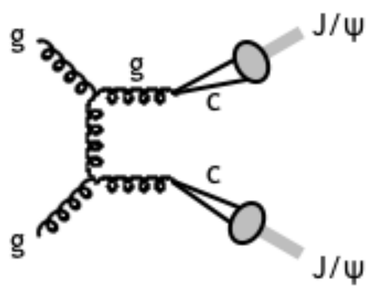


Same applies for large |Δy|, but

interplay with 1<|Δy|<3 bins are also to be refined

Recent discussions of SPS contribution to di-J/Ψ production

Full LO NRQCD with CO :



LO COM

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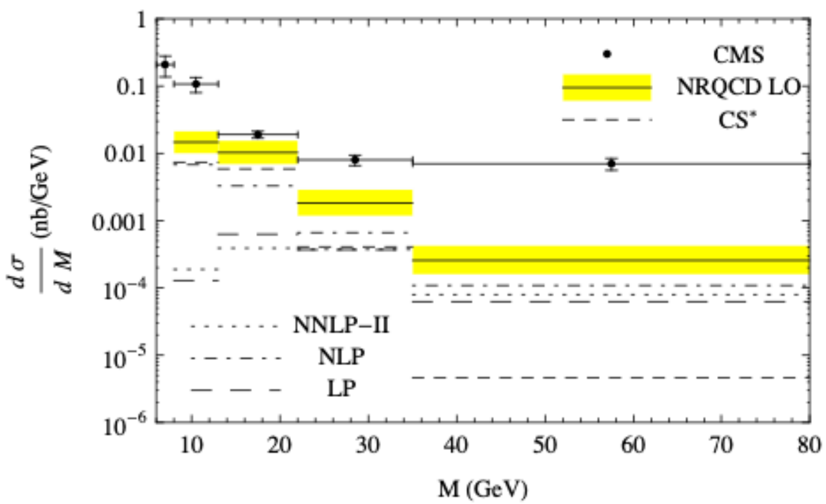

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NRQCD LDMEs chosen almost to maximize the yield within the uncertainty of CO ones
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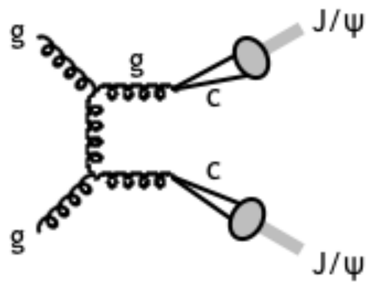

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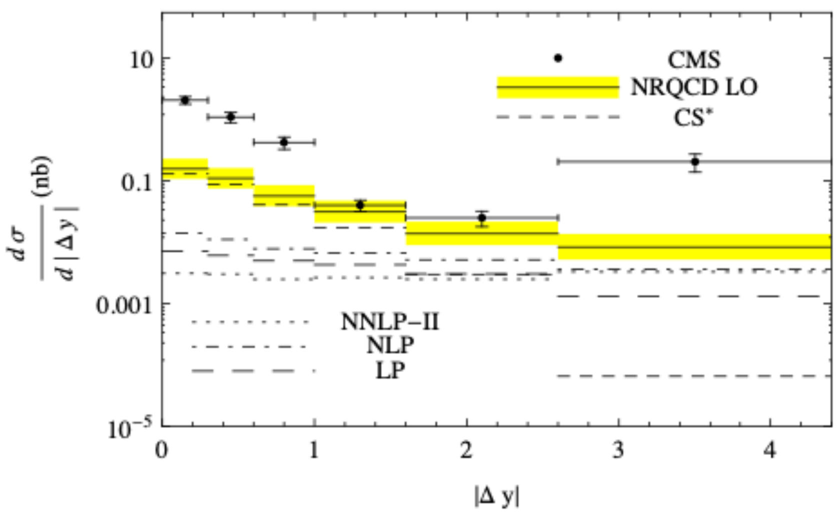

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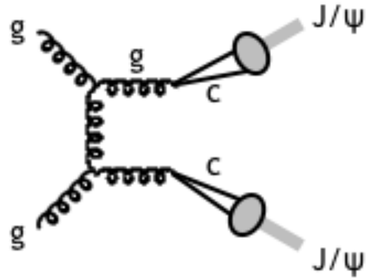

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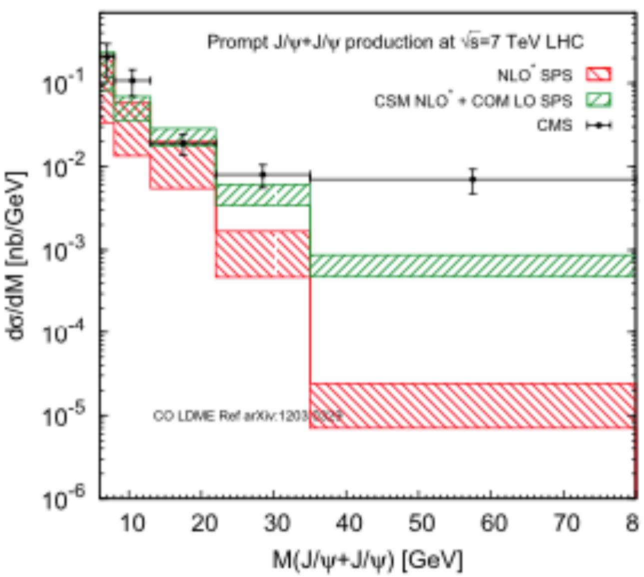

COM tested with 9 sets of LDMEs

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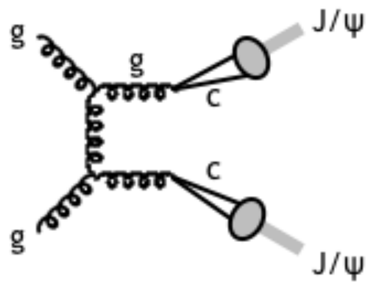

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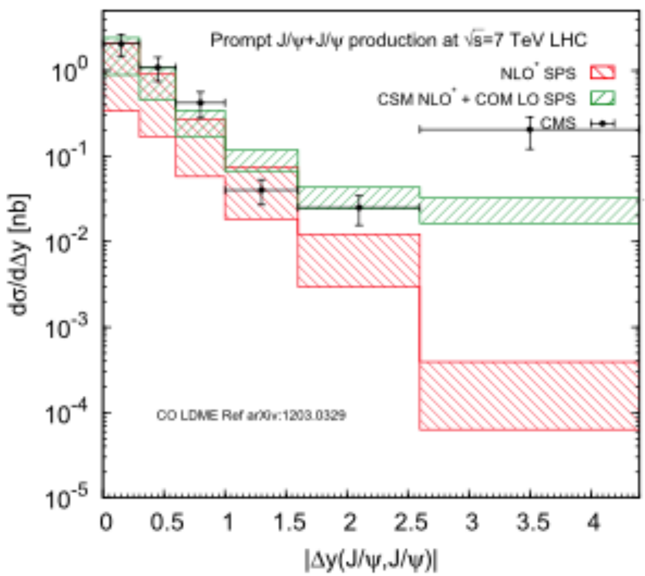

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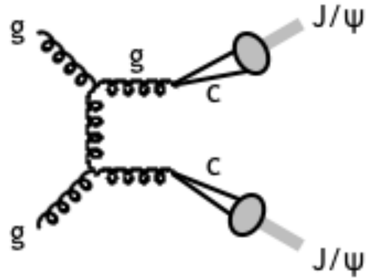

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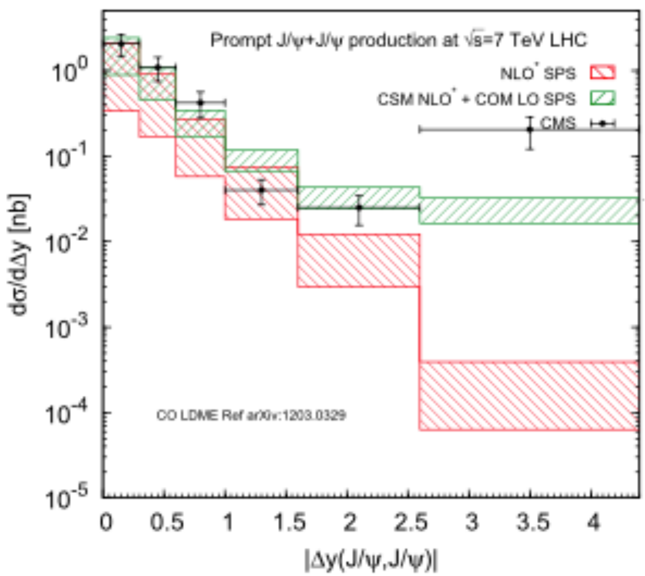

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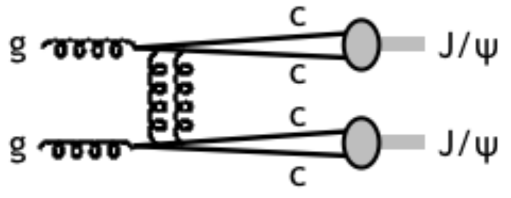
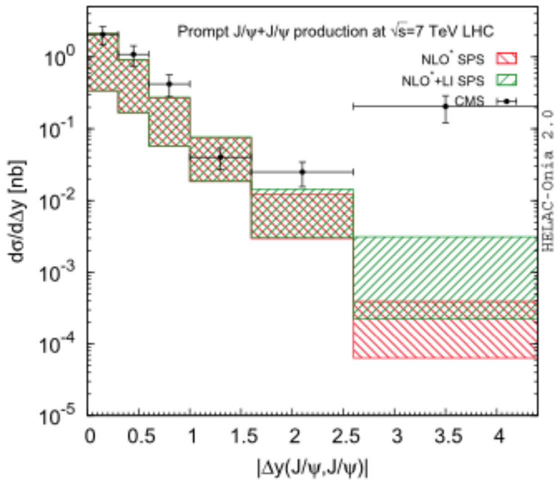
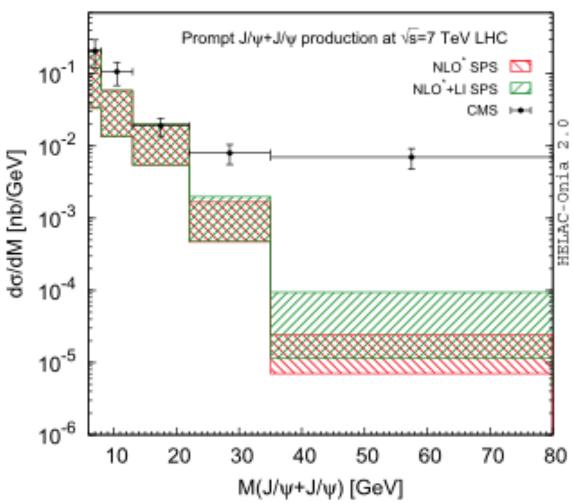
NRQCD with CO and CS loop-induced (LI) effect:

LI effect:

Higher order gauge invariant class of diagrams, but free of divergences







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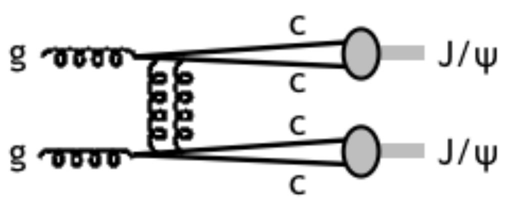

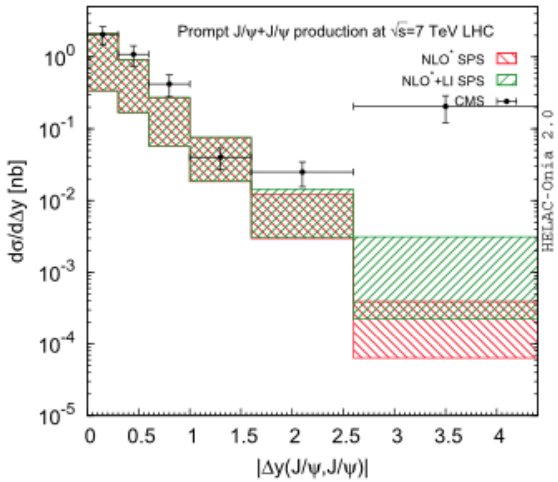

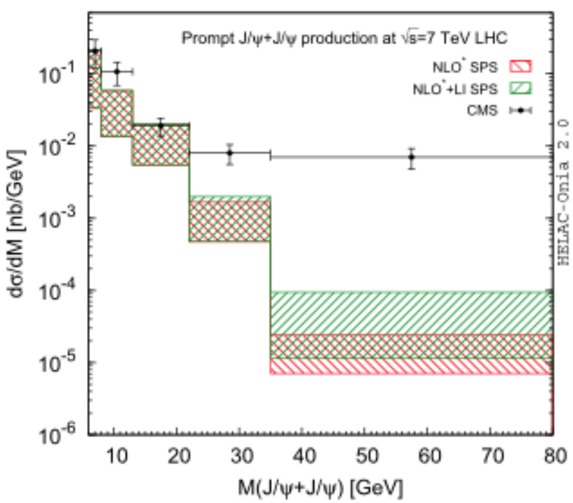

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NRQCD with parton Reggeization:

t-channel exchange of Reggeons : gauge invariant factorization

Improve calculation by BFKL resummation
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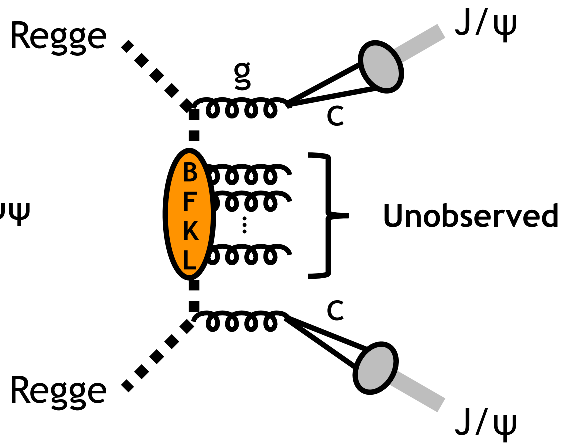
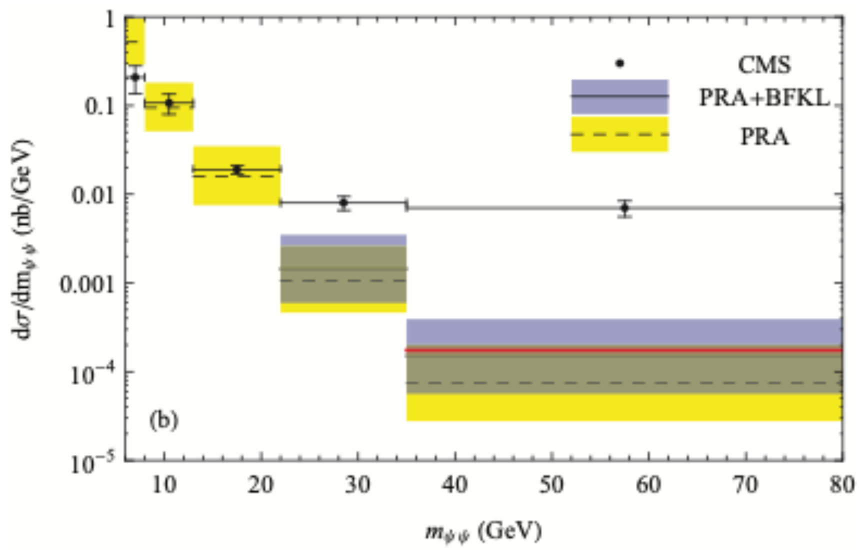
⇒ Important to release two J/ψ's at large |Δy|, $M_{\psi\psi}$





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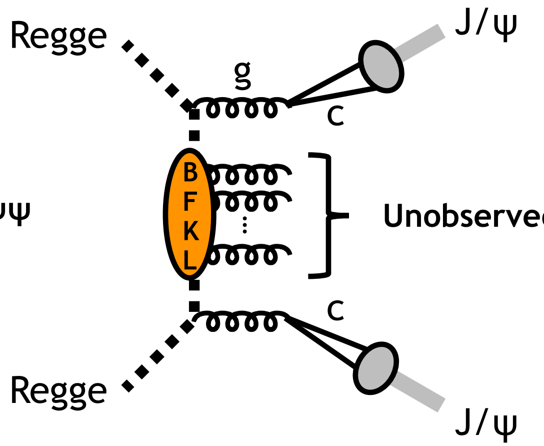

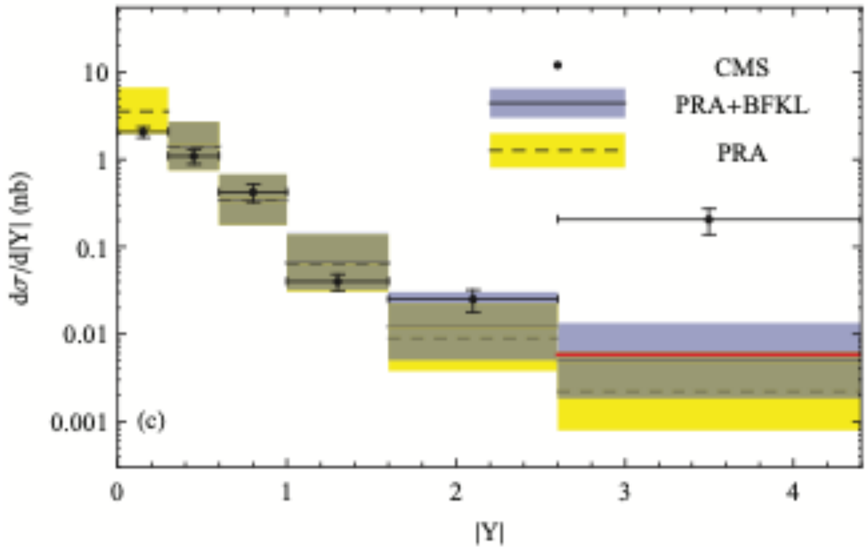

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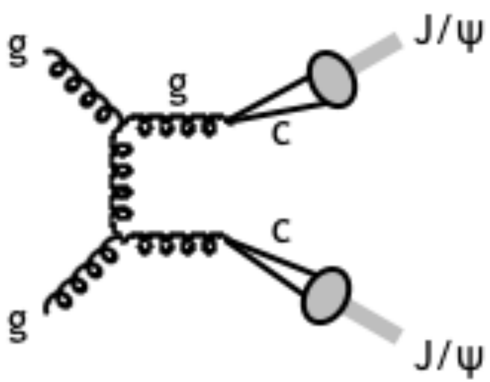

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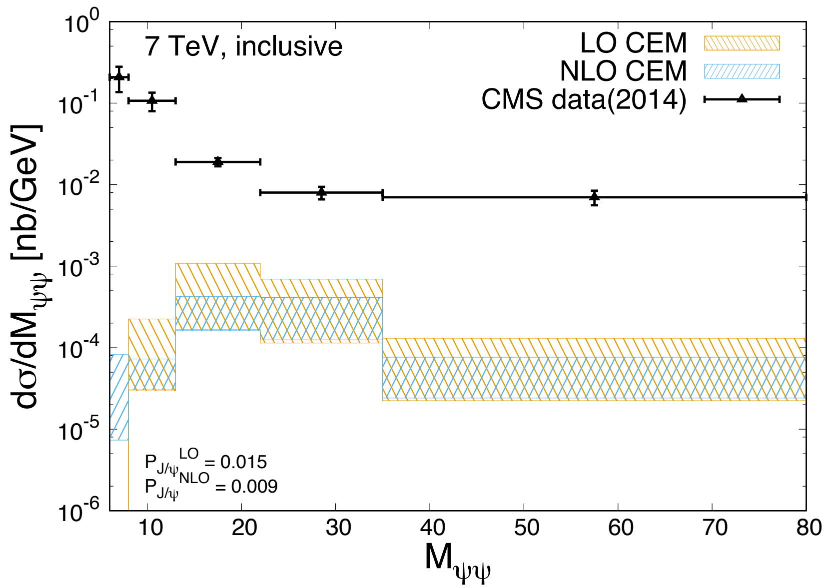

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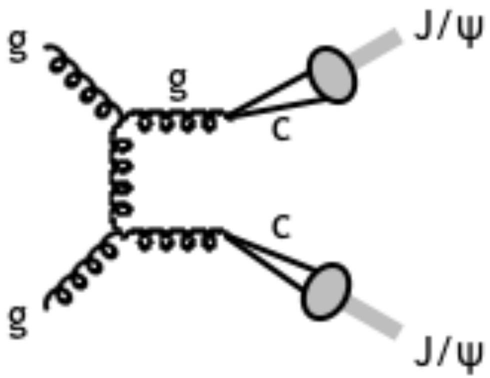

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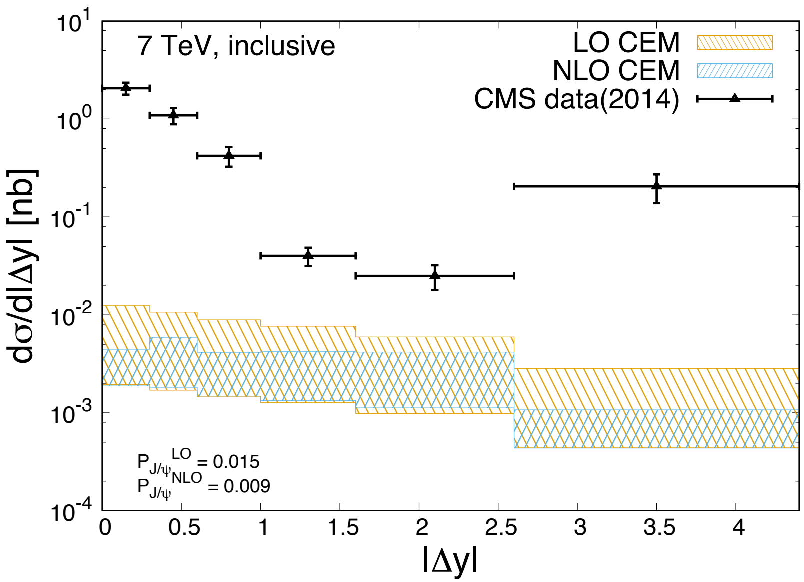

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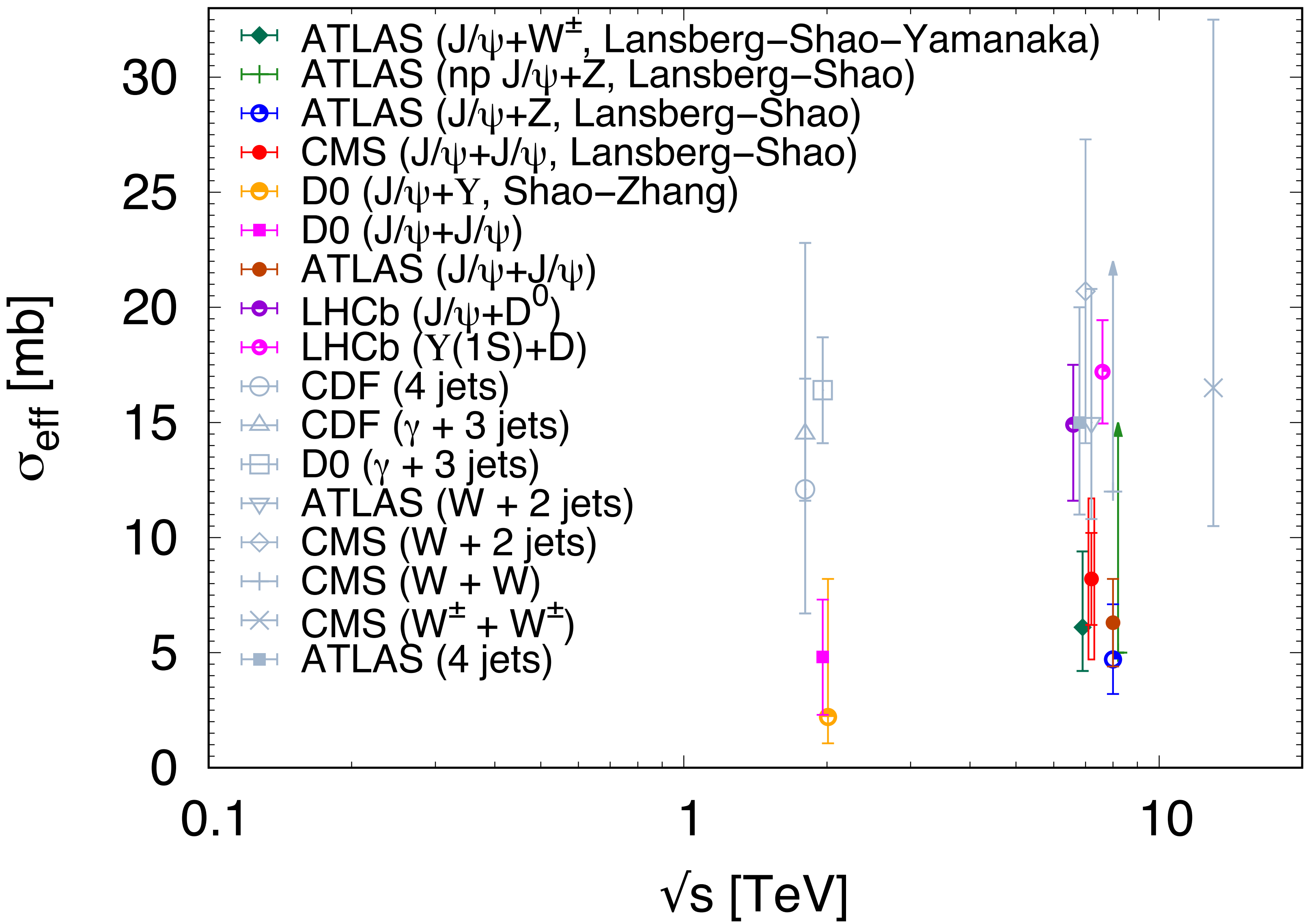

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LHCb (Υ(1S)+D)
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CDF (γ + 3 jets)
D0 (γ + 3 jets)
ATLAS (W + 2 jets)
CMS (W + 2 jets)
CMS (W + W)
CMS (W± + W±)
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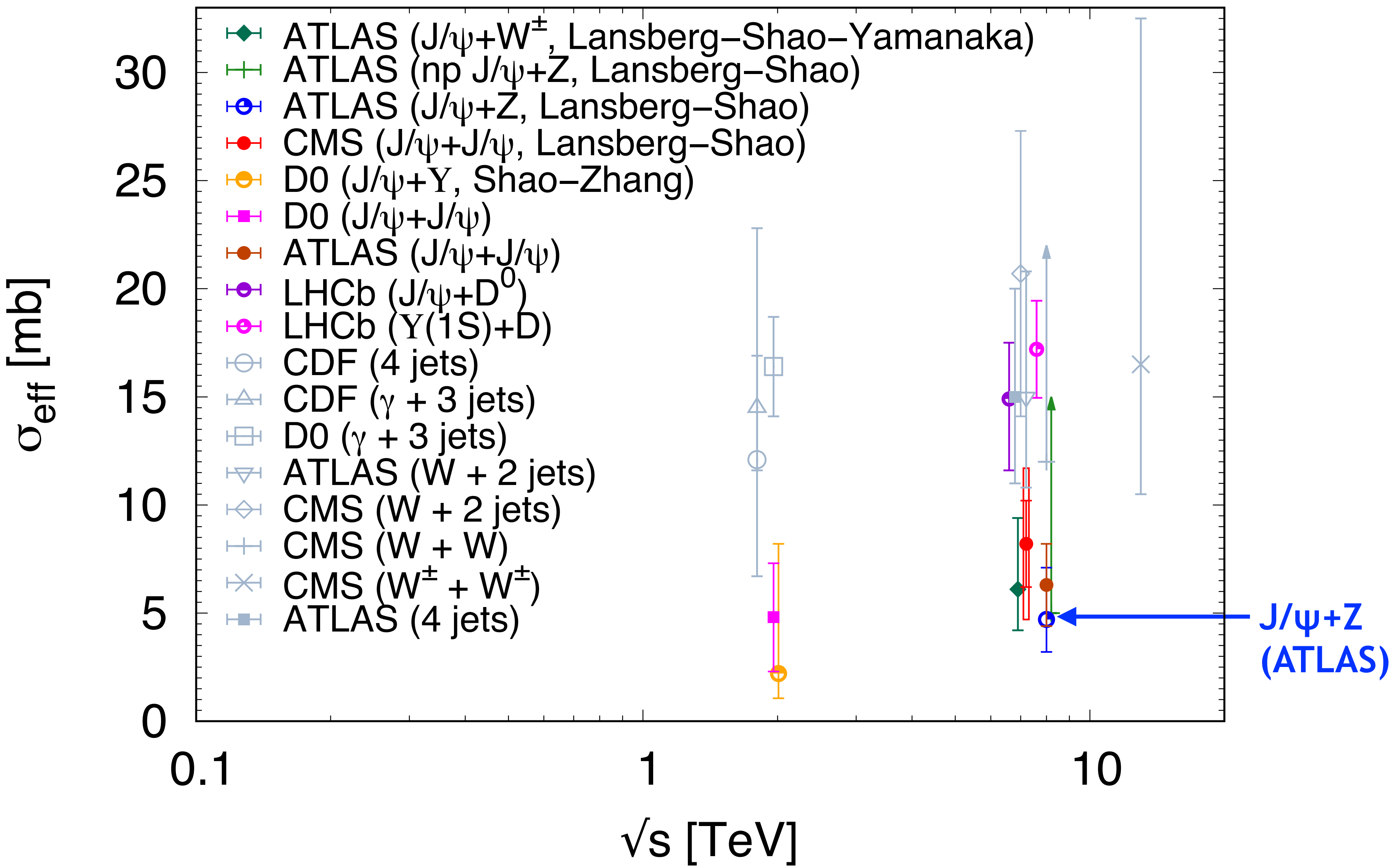
σeff [mb]
√s [TeV]
0
5
10
15
20
25
30
0.1
1
10

Overall



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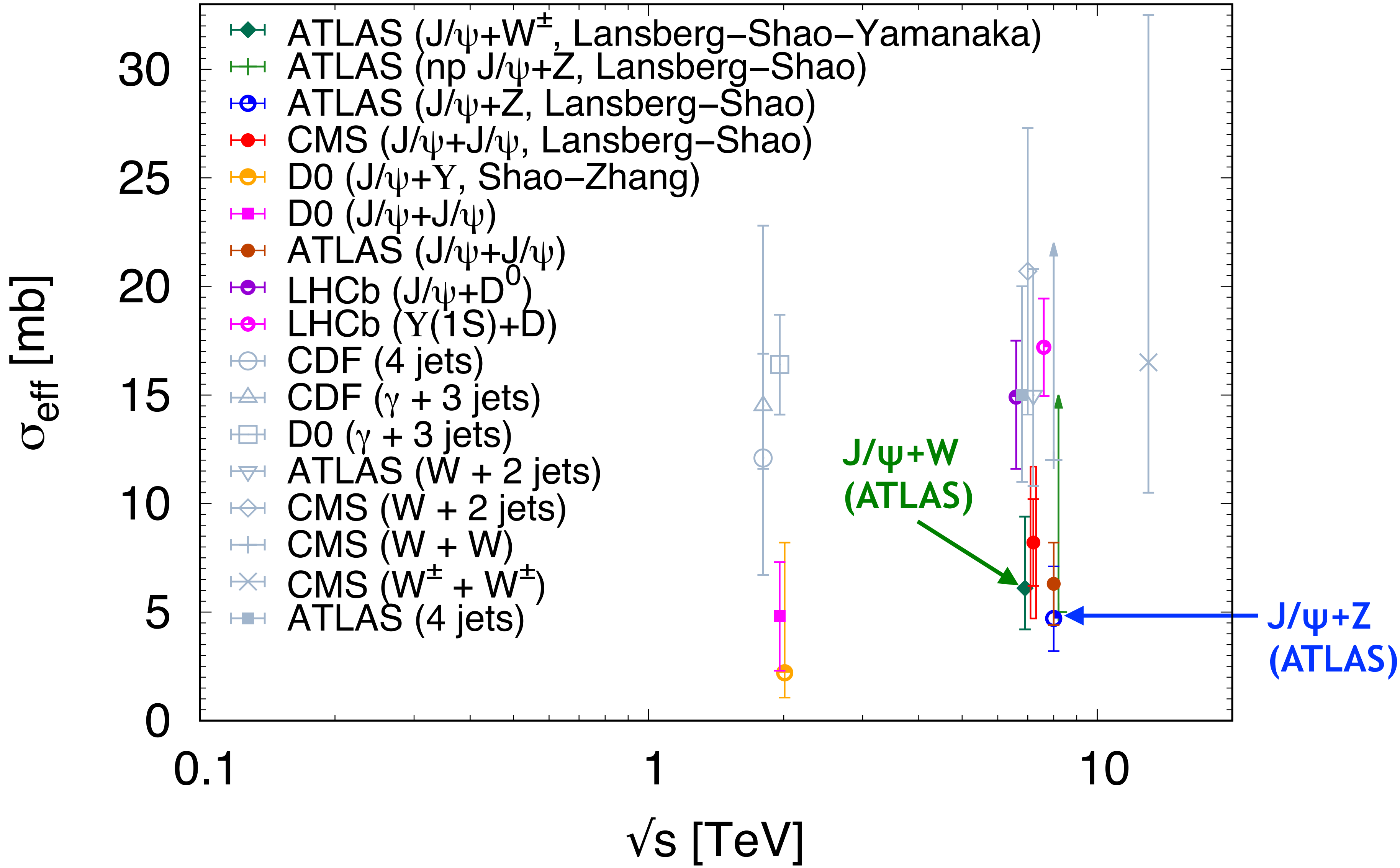

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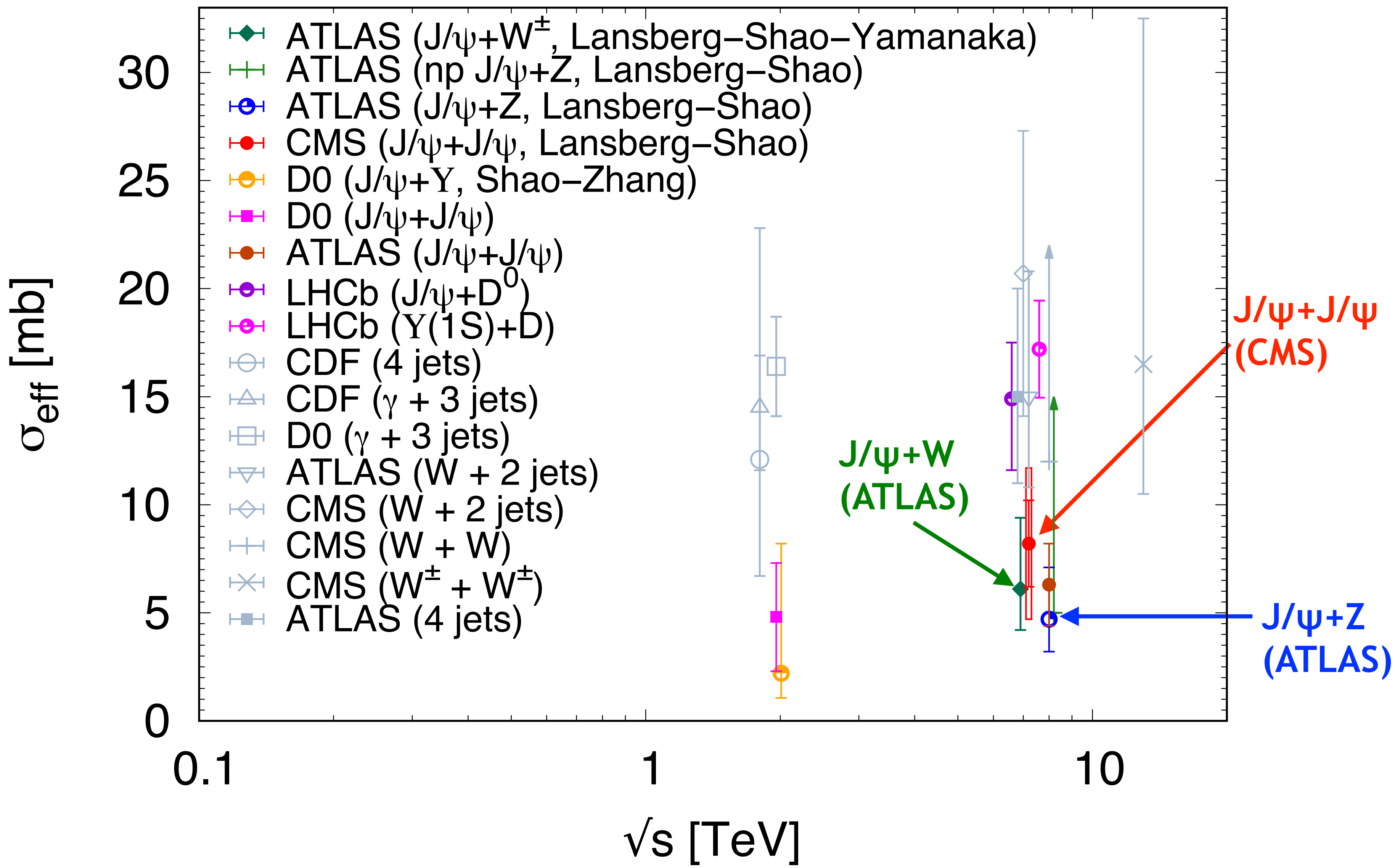

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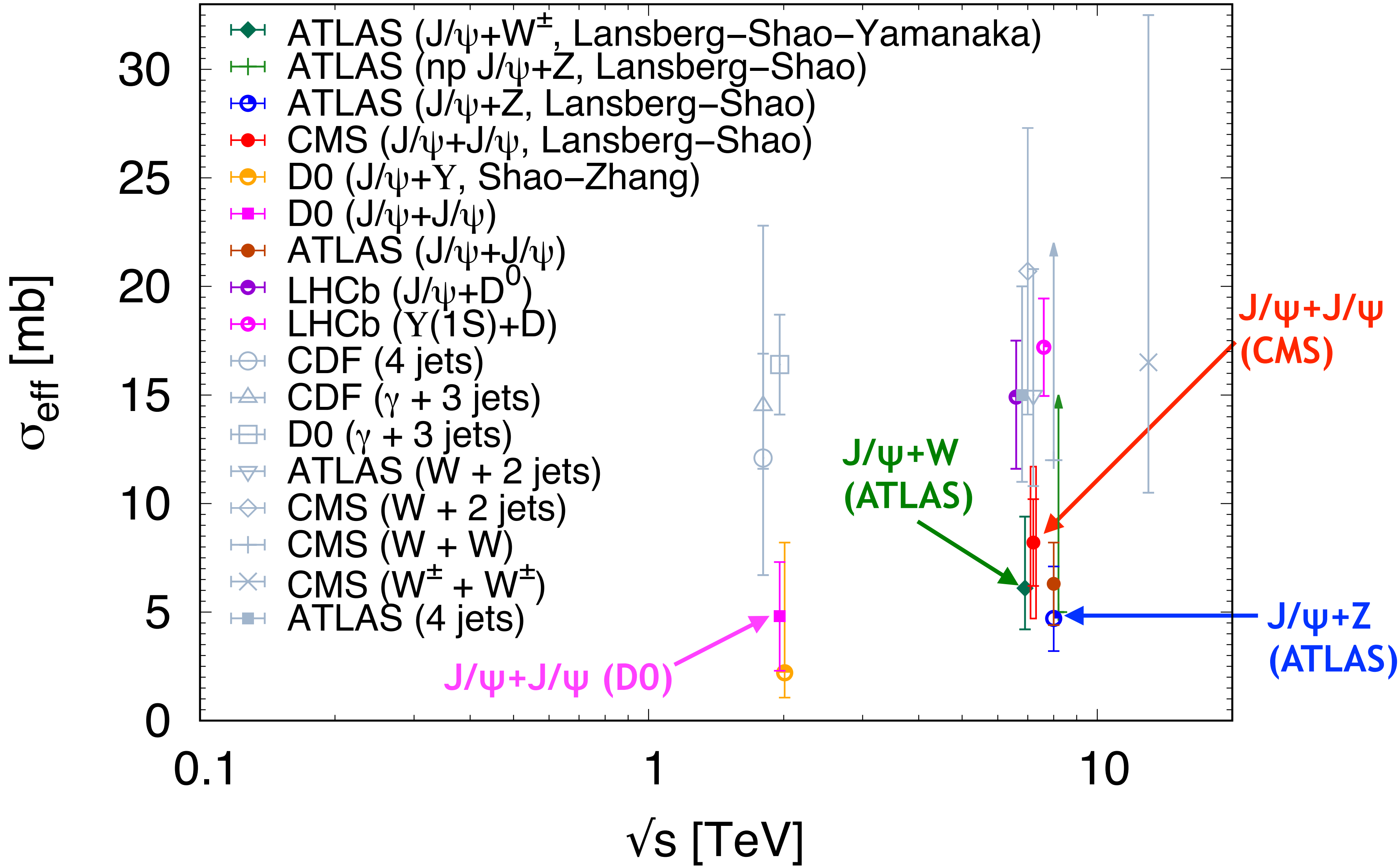
Overall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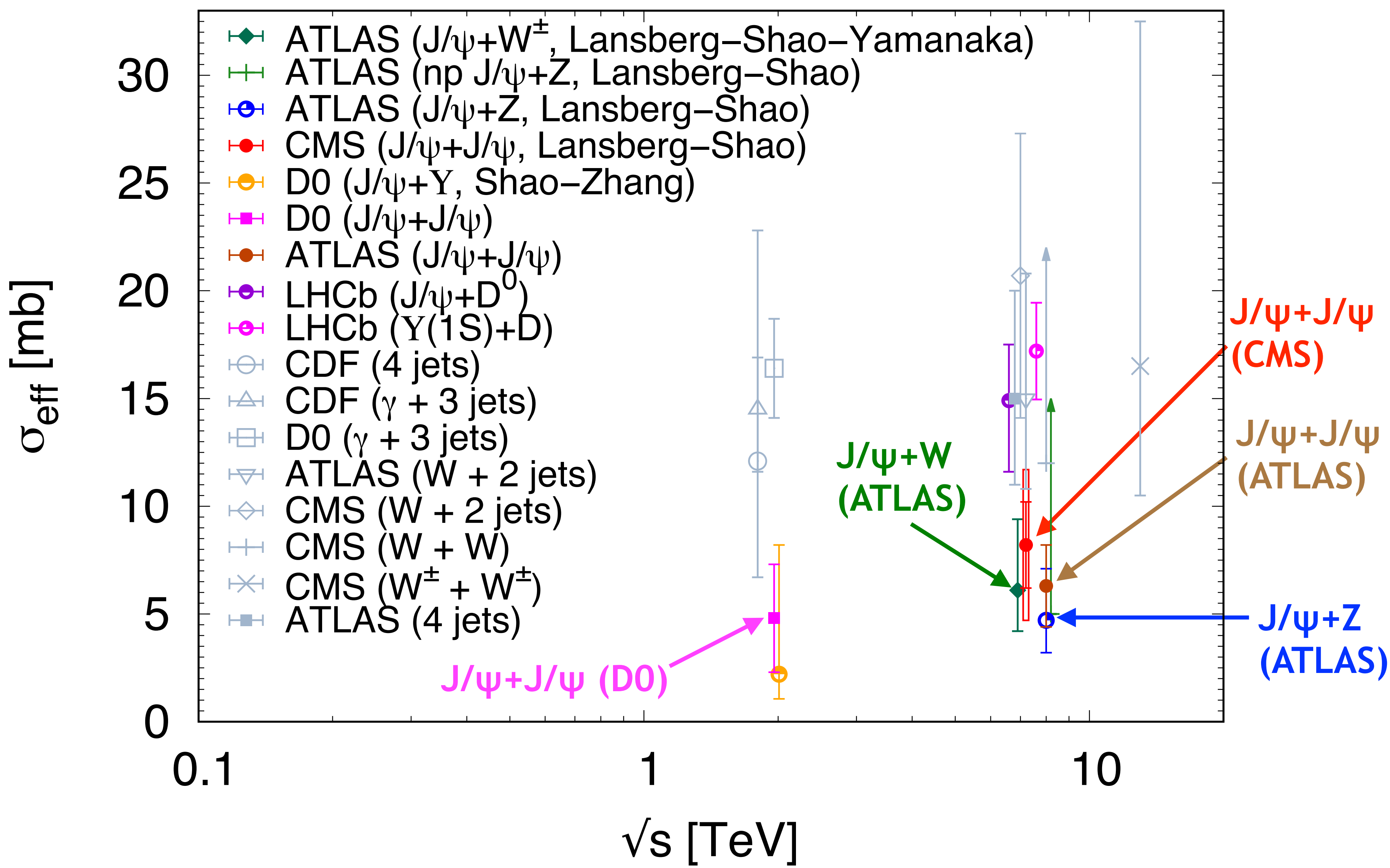

⇒ All central rapidity quarkonium data point at a small σ_{eff}

Summary

- Quarkonium+open heavy flavor production is interesting in many points: DPS, test CSM, intrinsic HQ, etc
- The DPS of quarkonium+open HQ is consistent with jet, W, photon DPSs.
- J/ψ+W/Z: we set a conservative upper limit on SPS using the NLO CEM.
- The ATLAS experimental data on 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
- J/Ψ+J/Ψ : no large SPS yield at large |Δy| in all previous works → also requires DPS contributions to fill the gap with exp. data, namely $\sigma_{eff} = (6.3 \pm 1.9)$ mb (ATLAS) or $\sigma_{eff} = (8.2 \pm 3.5)$ mb (CMS).
- σ_{eff} seems to be smaller (i.e. large DPS) for central rapidity quarkonia than for jets, W, photons, quarkonium+open charm, or forward rapidity quarkonia : hint for flavor dependence? Rapidity? Or some other explanation?

End