# Quarkonium Production At the LHC

## a tool to probe DPS

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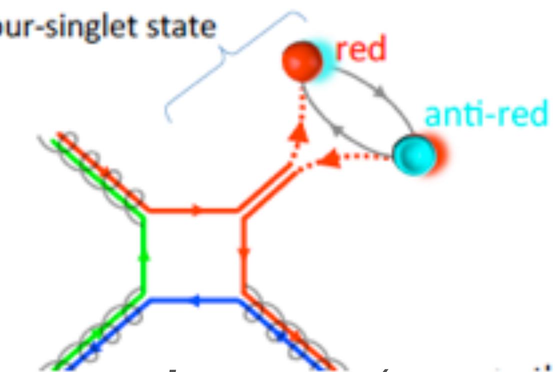
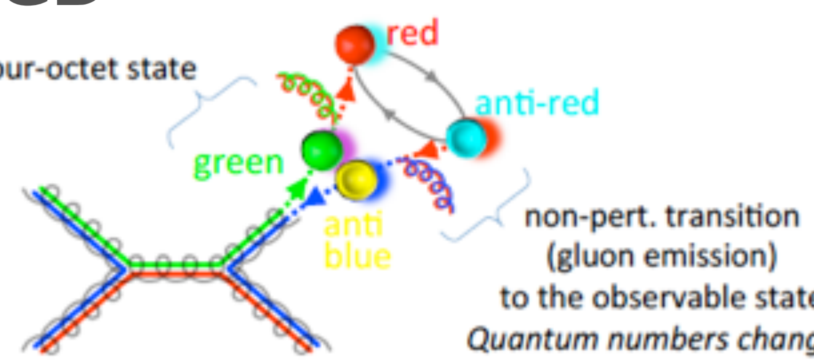
GDR QCD @ IPN Orsay
01 June 2017

# QUARKONIUM PRODUCTION: INTRODUCTION

- **Experiment:** **easy to measure and many precise data are available**
- **Theory:** **various production models**
  - Color-Singlet Model (CSM) back in the game
    - *Pro: good performance; In the game for the total yields*
    - *Con: large QCD corrections; Insufficient to explain inclusive onium production (=onium+jet)*
  - Color-Octet Mechanism (COM) predicted by (NR)QCD
    - *Pro: helps to describe the $P_T$ spectrum of inclusive onium*
    - *Con: debates on its magnitude; only partially works*



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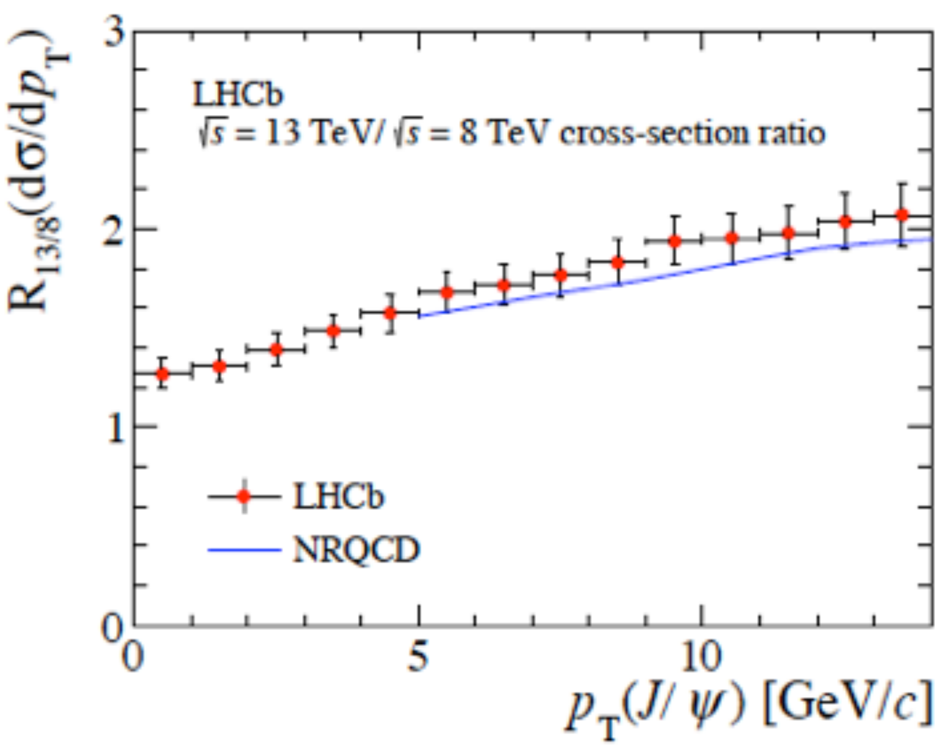


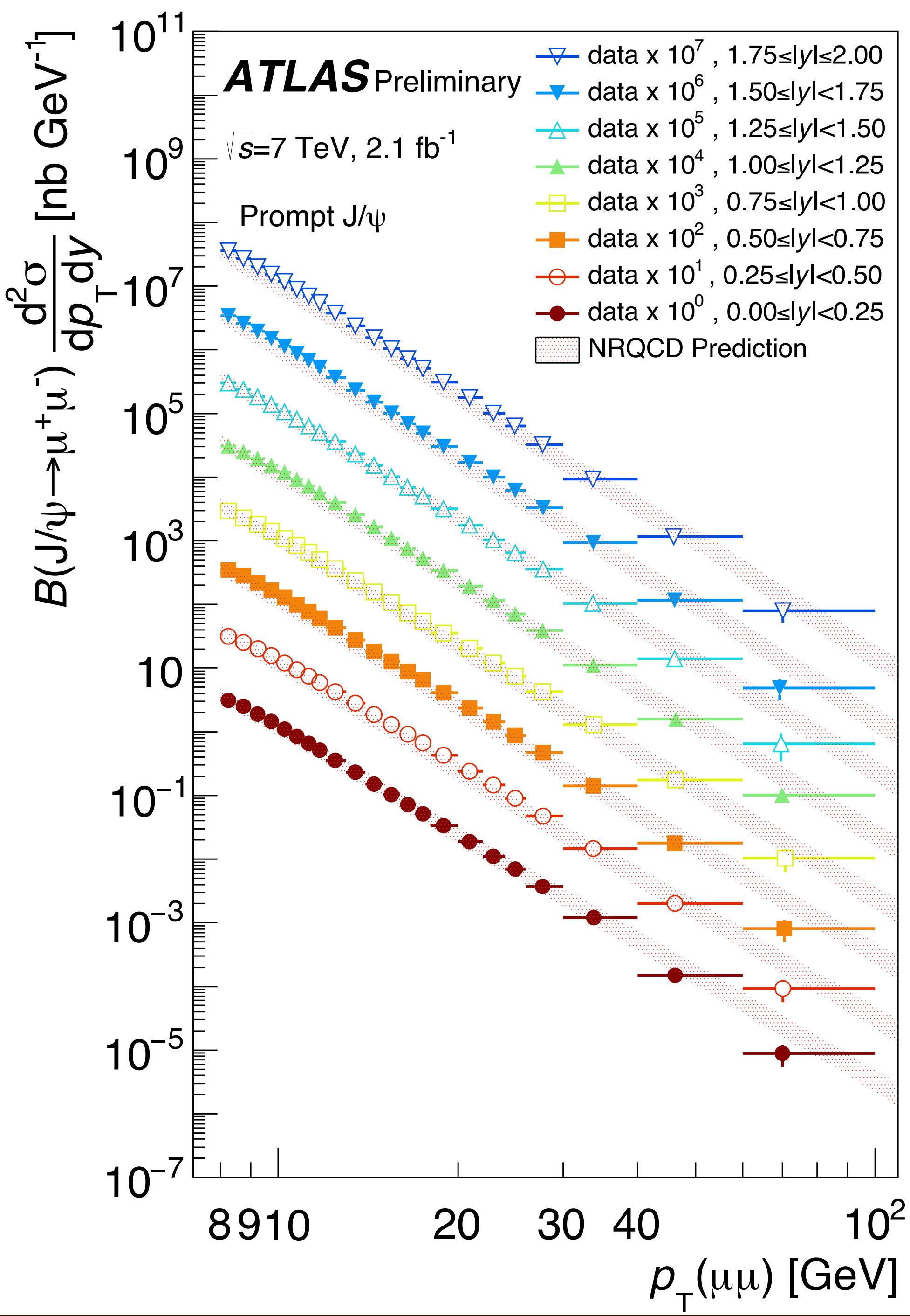




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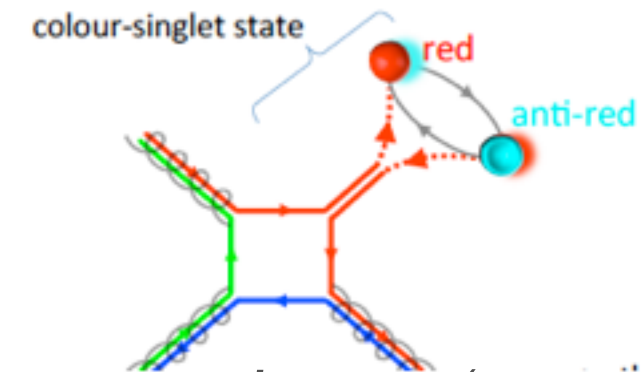


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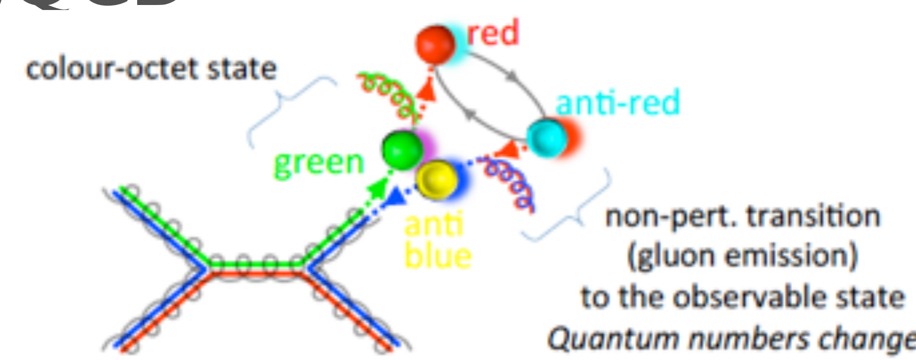
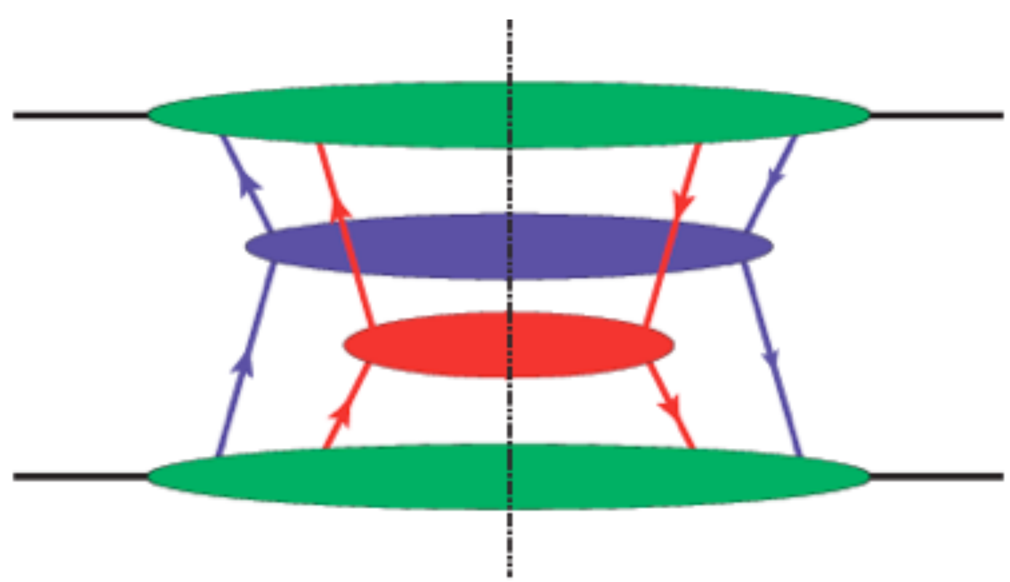



- All approaches have troubles in describing the onium inclusive production data
- This motivates the study of new observables which can be more discriminant for specific effects
- Quarkonium production at the LHC remains a very sensitive probe of the gluon density in the proton.

# Double-Parton Scatterings



# ASSOCIATED (HADRO)PRODUCTION MEASUREMENT

- **In associated quarkonium production, many measurements exist**

$J/\psi + J/\psi$

LHCb, Phys. Lett. B 707 (2012) 52; arXiv: 1612.07451
D0, Phys. Rev. D 90 (2014) 11, 111101
CMS, JHEP 1409 (2014) 094
ATLAS, Eur. Phys. J. C (2017) 77: 76

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$J/\psi + charm$

LHCb, JHEP 1206 (2012) 141

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- **Challenges in theory:**
  - taking into account all important SPS
  - quantifying DPS

# CALCULATION FRAMEWORK: SPS

- *All calculations are performed by the general-purposed matrix-element/event generator HELAC-Onia [HSS, CPC '12,'15] with the correct spin-entangled decay.*
- SPS is calculated in the framework of NRQCD:

$$\mathcal{A}_{ab\to\mathcal{Q}_1^{\lambda_1}(P_1)+\mathcal{Q}_2^{\lambda_2}(P_2)+X} = \sum_{s_1,s_2,c_1,c_2}\sum_{s_3,s_4,c_3,c_4} \frac{N(\lambda_1|s_1,s_2)N(\lambda_2|s_3,s_4)}{\sqrt{M_{\mathcal{Q}_1}M_{\mathcal{Q}_2}}}\frac{\delta_{c_1c_2}\delta_{c_3c_4}}{N_c}\frac{R_1(0)R_2(0)}{4\pi}\mathcal{A}_{ab\to Q_{c_1}^{s_1}\bar{Q}_{c_2}^{s_2}(\mathbf{p}_1=\mathbf{0})+Q_{c_3}^{s_3}\bar{Q}_{c_4}^{s_4}(\mathbf{p}_2=\mathbf{0})+X}, \quad (10)$$

WF@Orig or LDME

spin projector

color proj.

four-quark amp.

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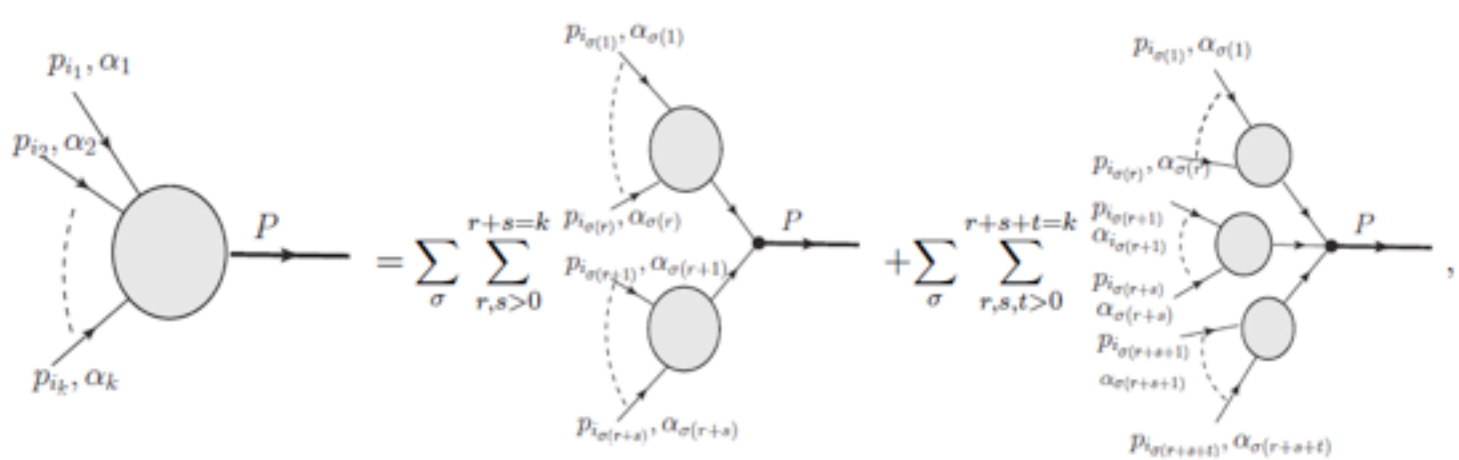



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  - via recursion relations
  - potential model or from data (but should be universal)

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

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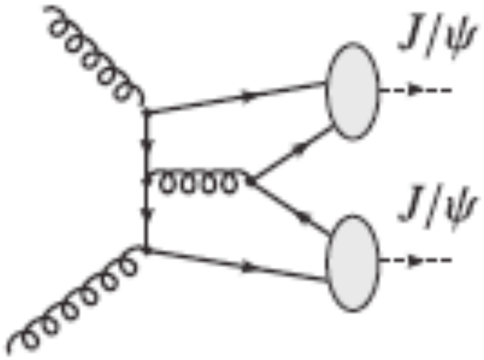
Pocket Formula

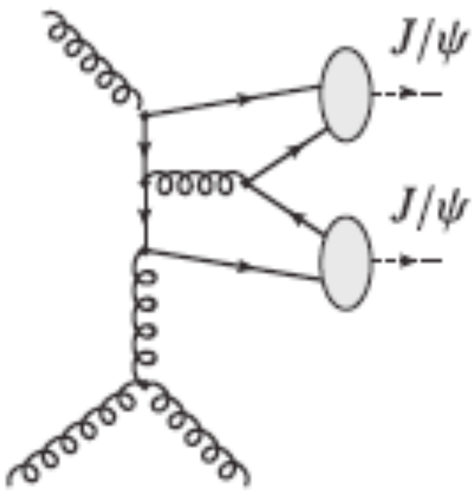
$$J/\psi + J/\psi$$

# QCD CORRECTIONS TO SPS

Lansberg, HSS PRL '13




$$\sim \quad \alpha_s^4 \left(\frac{m_\psi}{P_T^\psi}\right)^8$$

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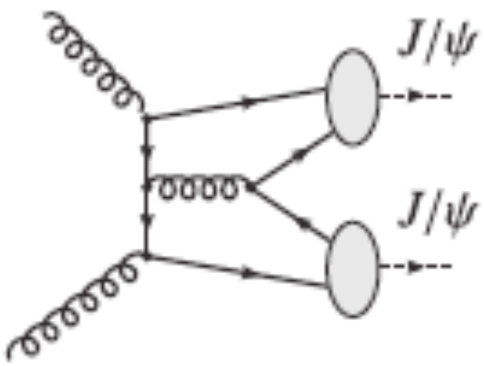


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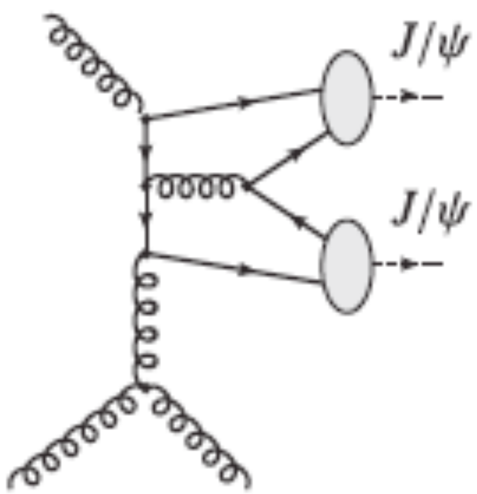


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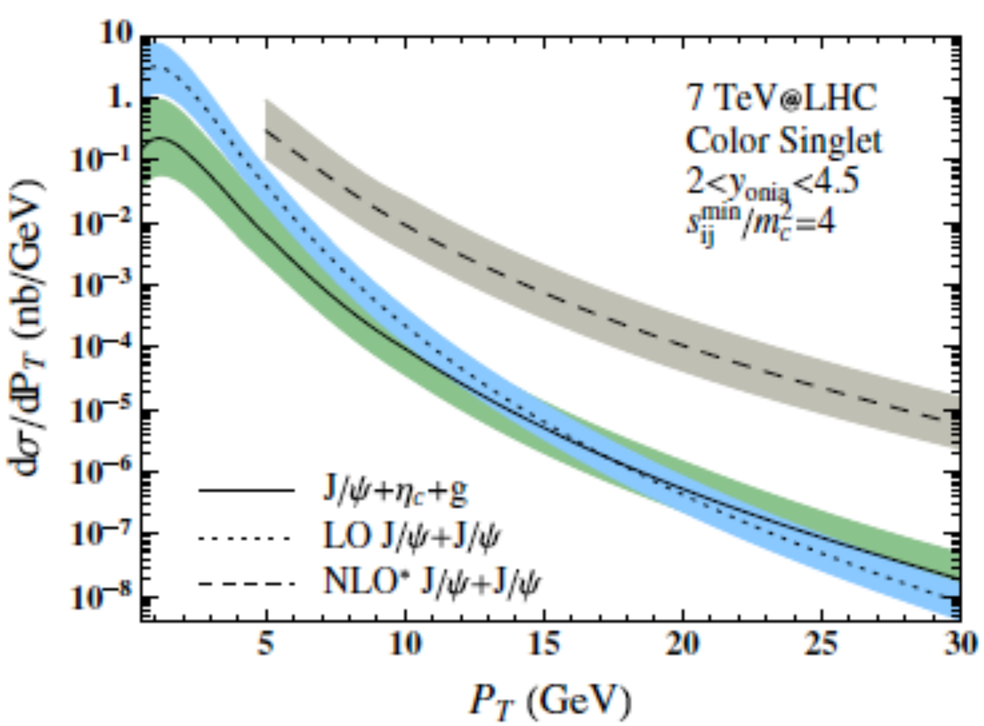
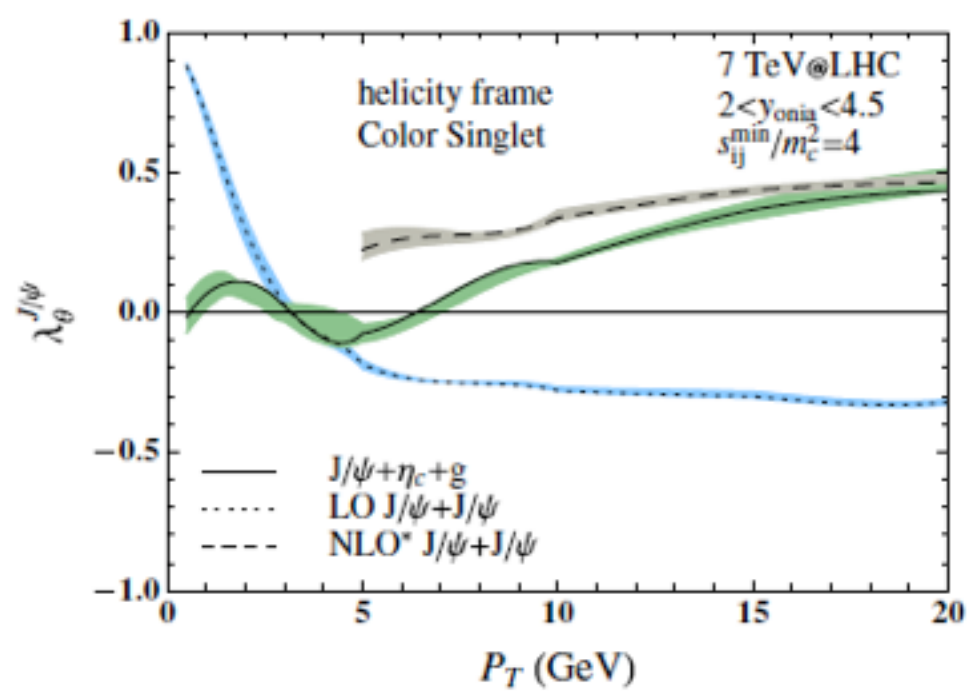
- It was nicely confirmed by a complete NLO calculation [Sun, Han, Chao, '14].



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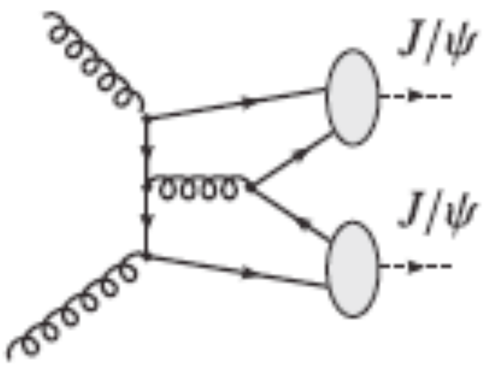


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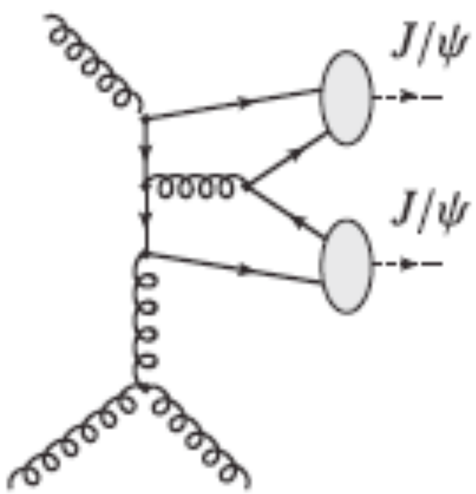


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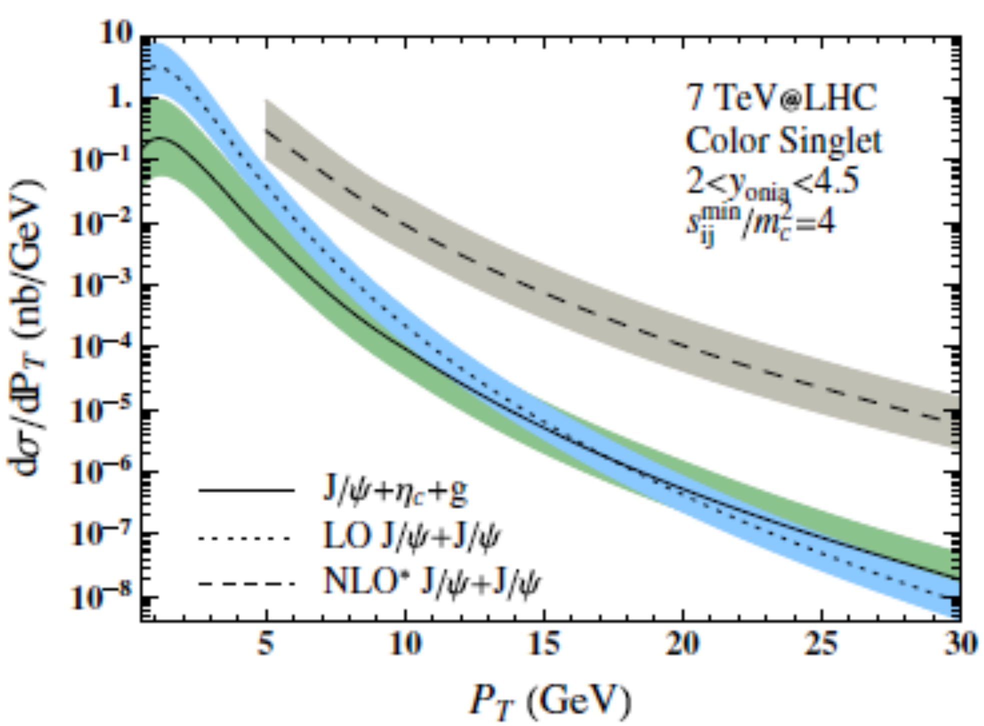


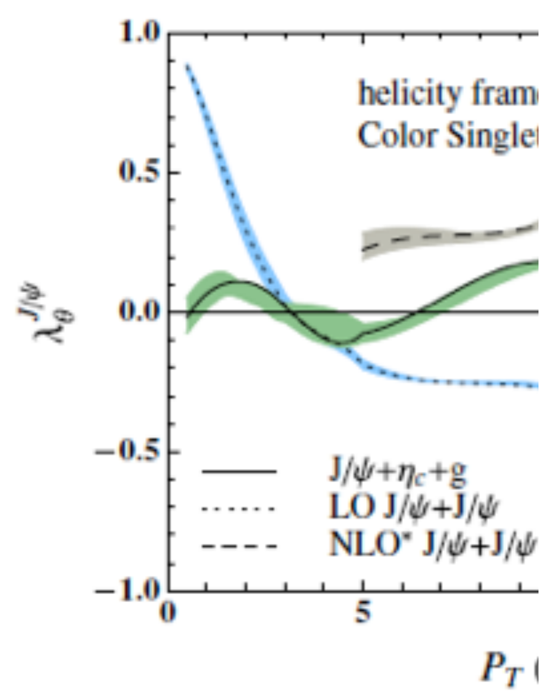


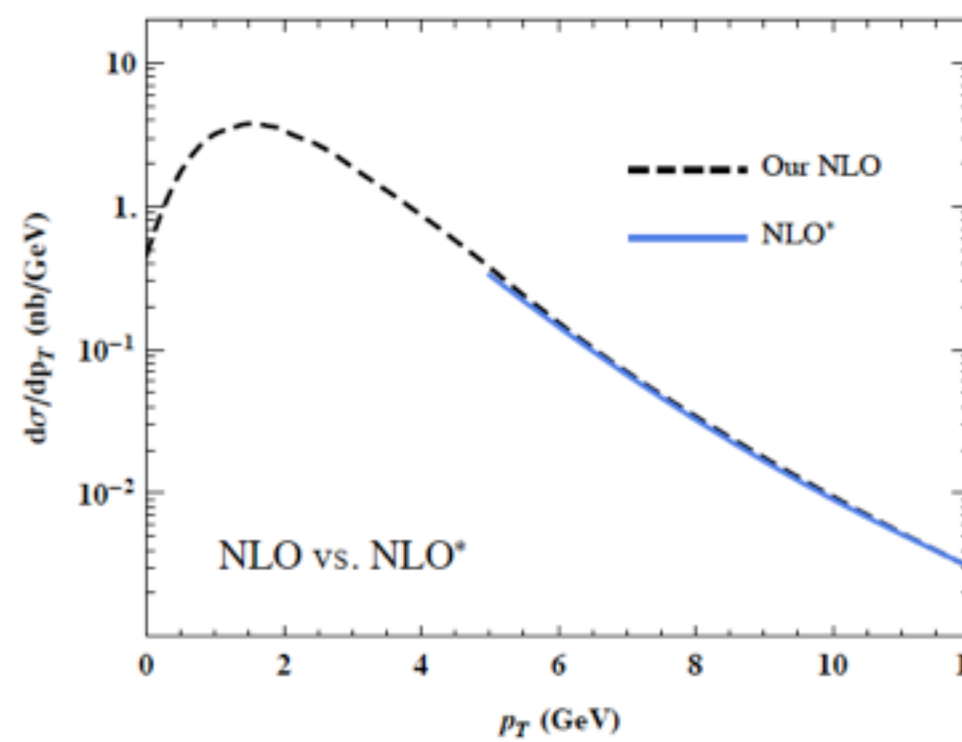

# EVIDENCE OF DPS ?


Published for SISSA by Springer

Received: June 2, 2014
Accepted: August 4, 2014
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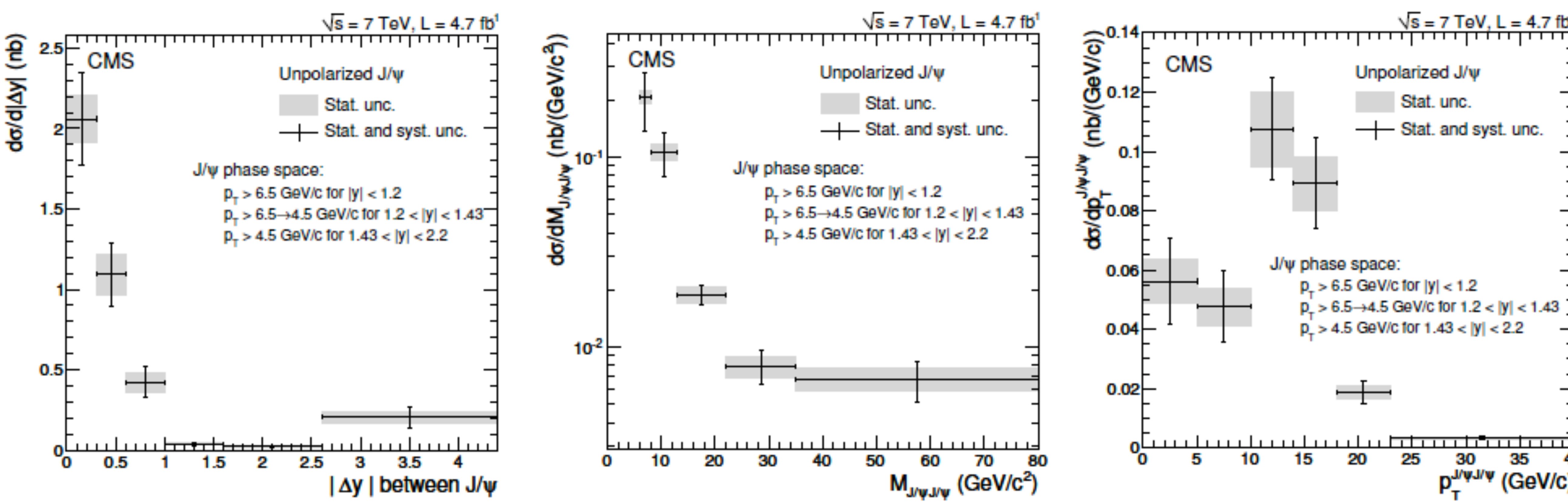
## Measurement of prompt $J/\psi$ pair production in pp collisions at $\sqrt{s} = 7$ Tev


The CMS collaboration

*E-mail:* cms-publication-committee-chair@cern.ch

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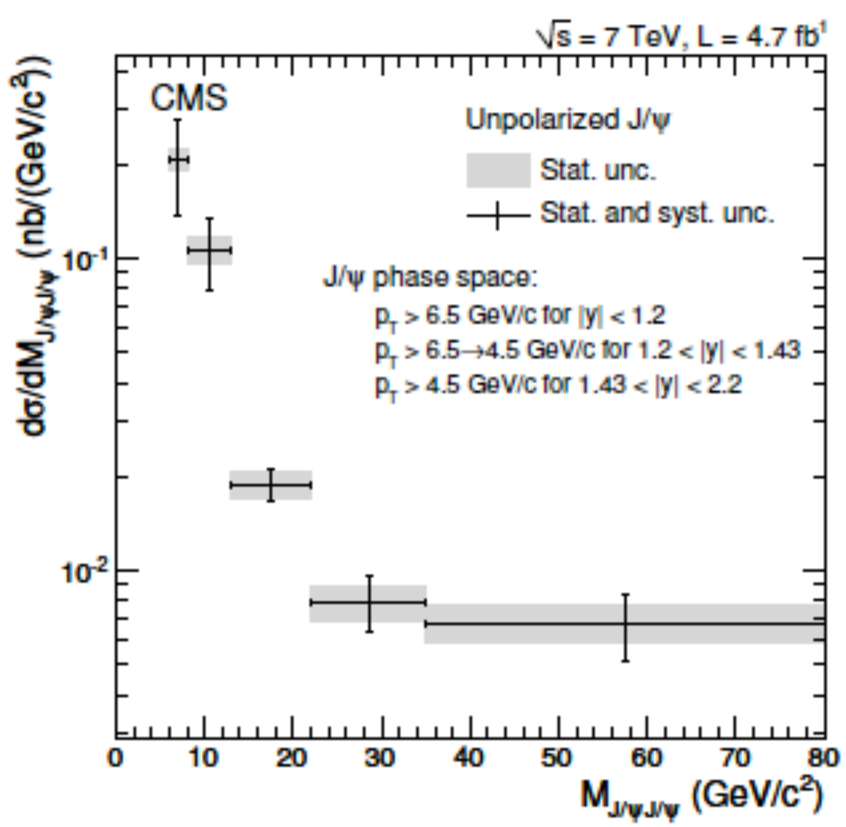
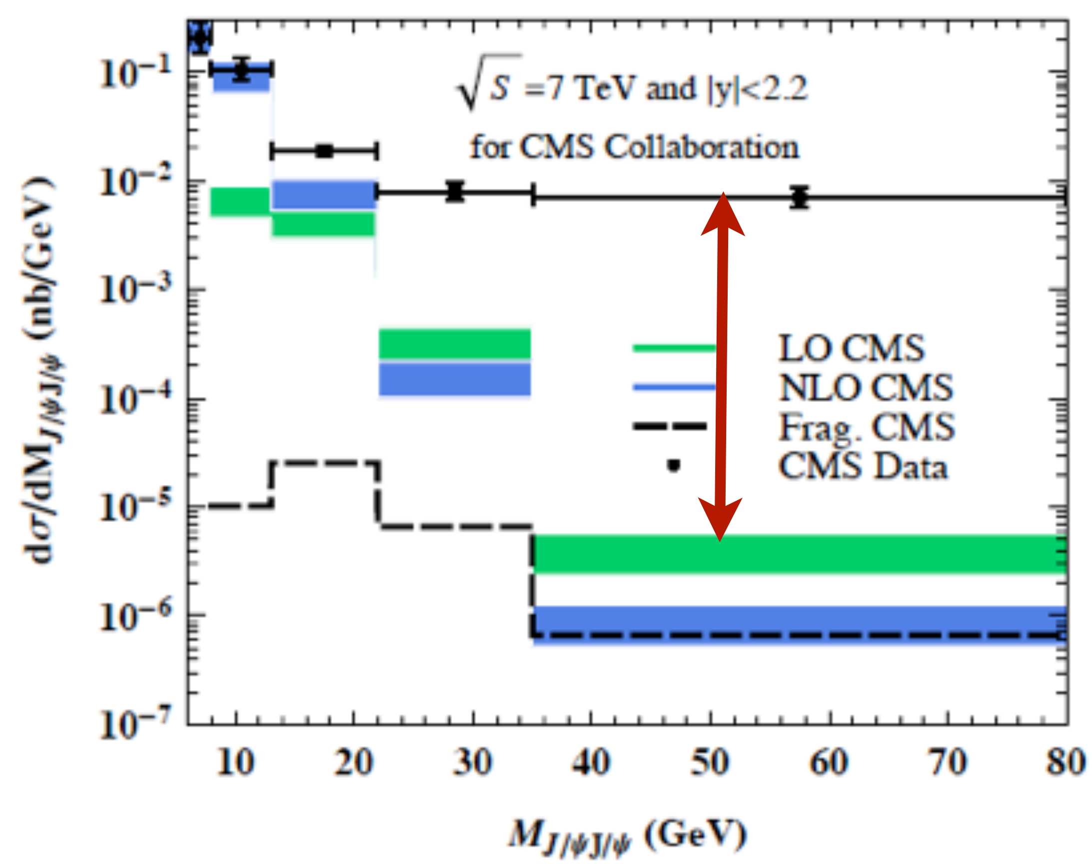
The CMS collaboration

*E-mail:* cms-publication-committee-chair@cern.ch




- Large discrepancy found with NLO-level Single-Parton Scatterings [Sun, Han, Chao, '14].



# EVIDENCE OF DPS ?

JHEP

Published for SISSA by Springer

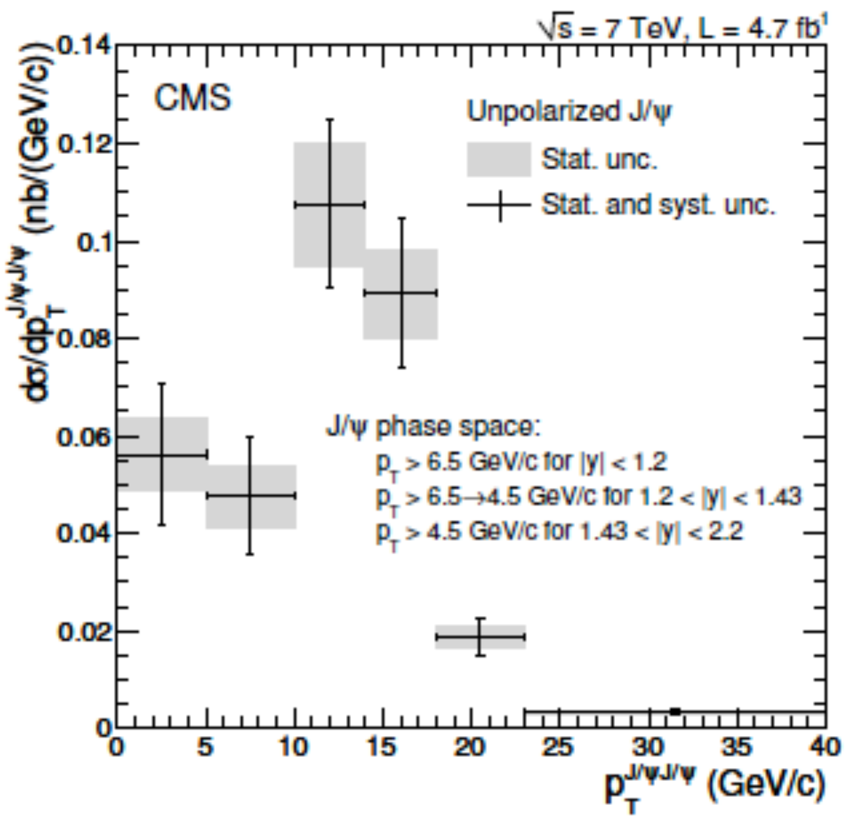
Received: June 2, 2014
Accepted: August 4, 2014
Published: September 17, 2014

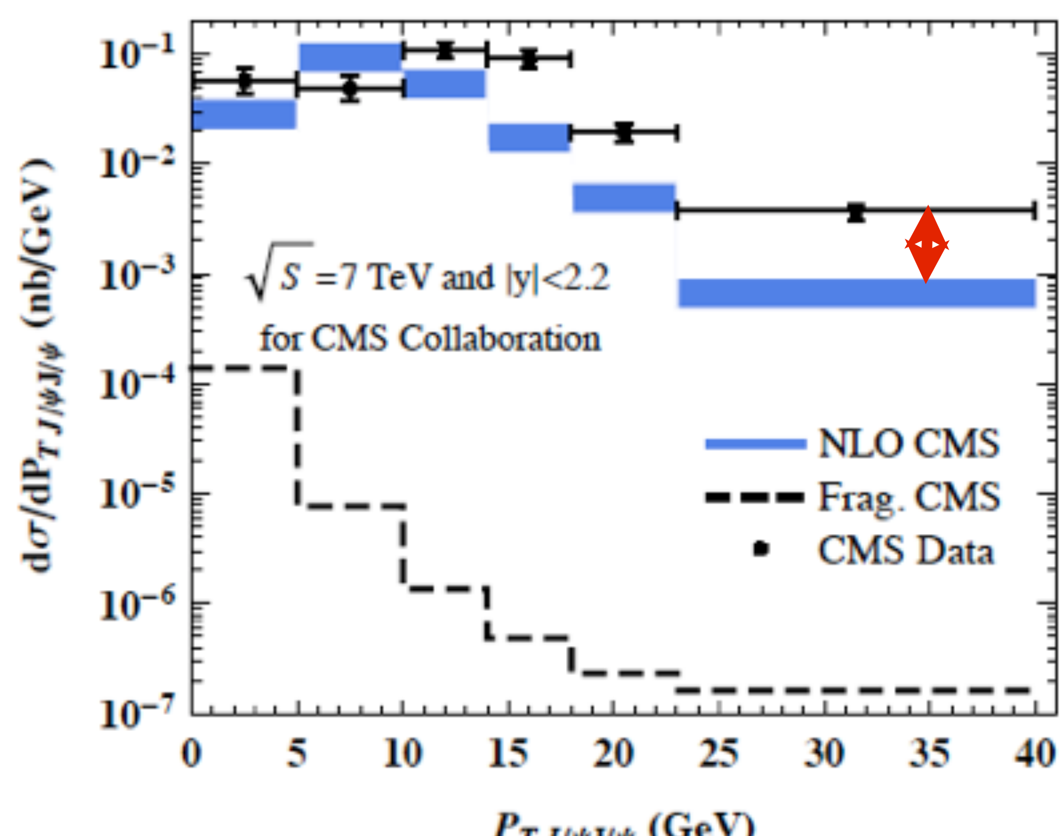
**Measurement of prompt $J/\psi$ pair production in pp collisions at $\sqrt{s} = 7$ Tev**

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

- Large discrepancy found with NLO-level Single-Parton Scatterings [Sun, Han, Chao, '14].



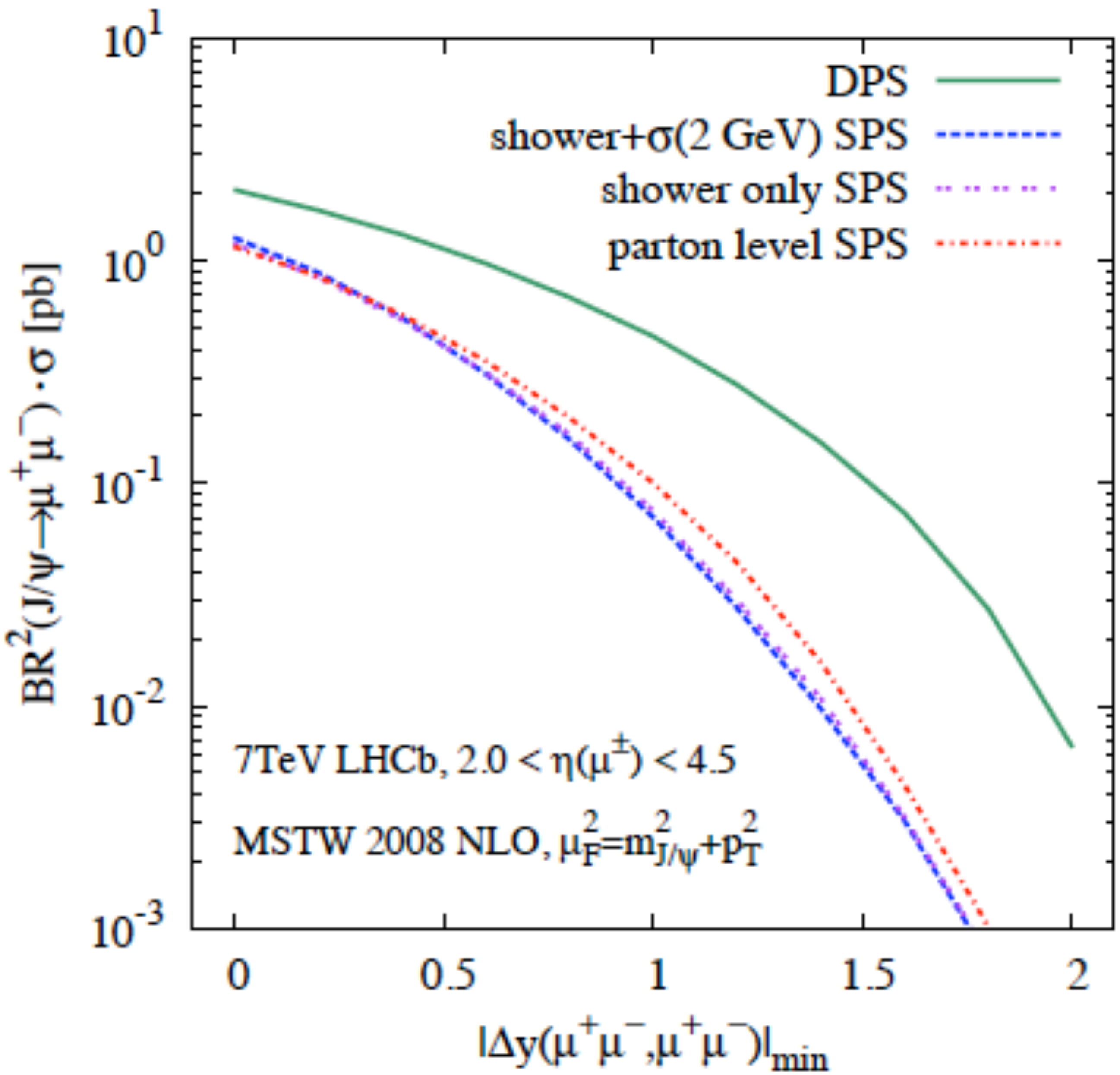






Tuesday, May 30, 17

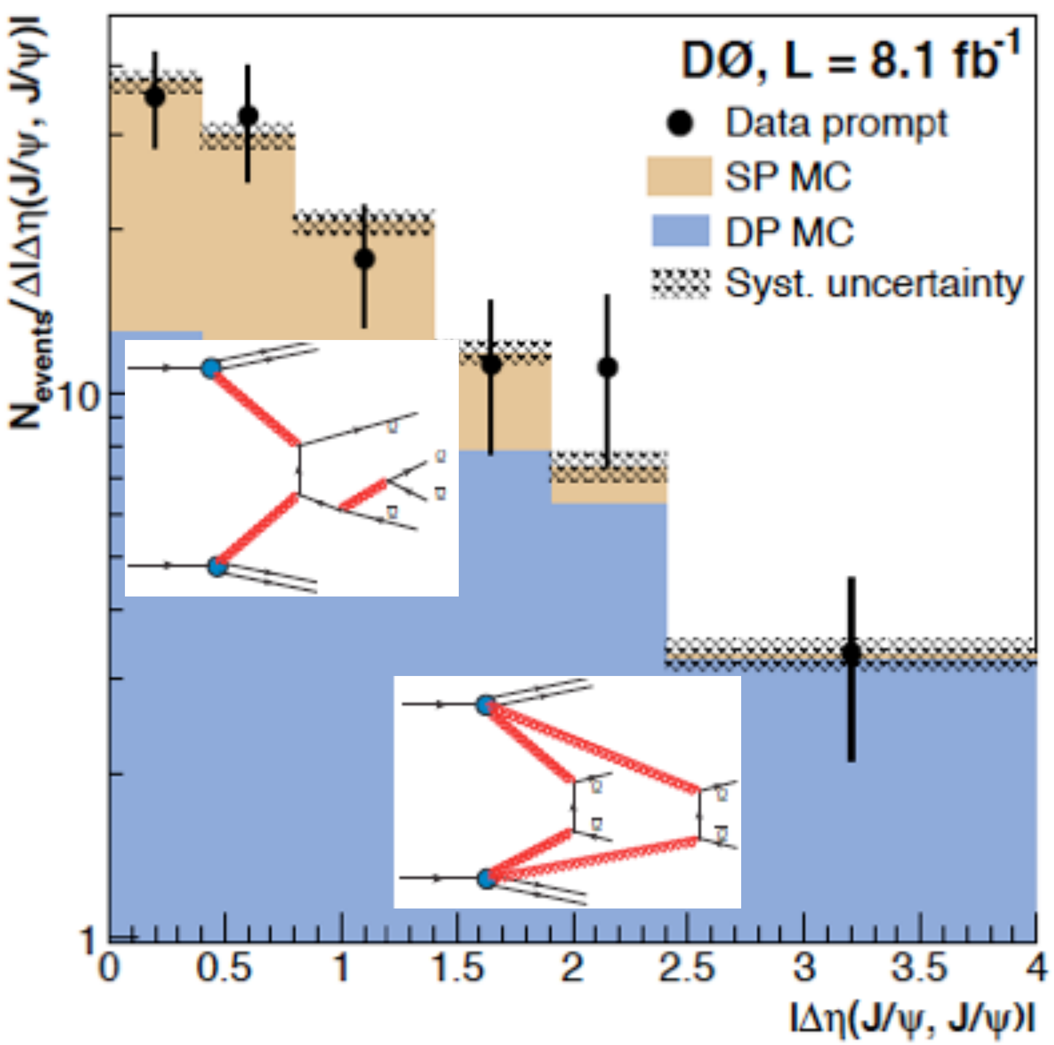
# DPS IN DZERO MEASUREMENT

- It was proposed by Kom et al. (2011) rapidity difference can be a good observable to measure DPS, which is little dependent on shower and primordial kT smearing.



# DPS IN DZERO MEASUREMENT

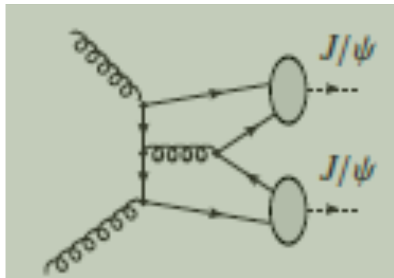
- It was proposed by Kom et al. (2011) rapidity difference can be a good observable to measure DPS, which is little dependent on shower and primordial kT smearing.
- D0 observed double $J/\psi$ at Tevatron and separated SPS and DPS for the first time.



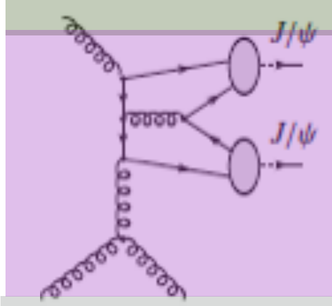
# $J/\psi$-Pair Production at Large Momenta: Indications for Double-Parton Scatterings and Large $\alpha_s^5$ Contributions

Lansberg, HSS PLB '14

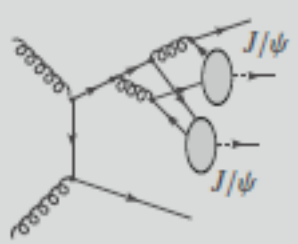
Jean-Philippe Lansberg[a], Hua-Sheng Shao[b,c]
[a] IPNO, Université Paris-Sud, CNRS/IN2P3,
Department of Physics and State Key Laboratory of Nuclear Physics and
[c] PH Department, TH Unit, CERN, CH-1211,




$$\sim \alpha_s^4 \left(\frac{m_\psi}{P_T^\psi}\right)^8$$

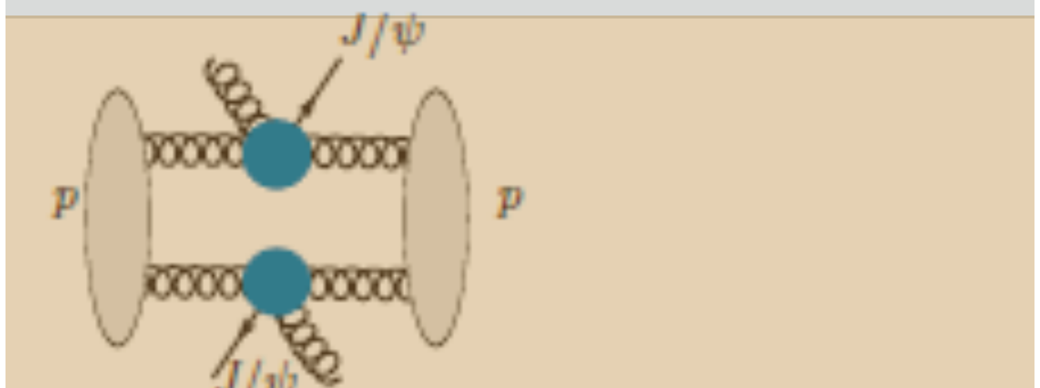



$$\sim \alpha_s^5 \left(\frac{m_\psi}{P_T^\psi}\right)^6$$




$$\sim \alpha_s^6 \left(\frac{m_\psi}{P_T^\psi}\right)^4$$

SPS




DPS

| | $\sigma_{\rm exp.}^{\rm prompt}$ | $\sigma_{\rm SPS}^{\rm LO,direct}$ | $\sigma_{\rm SPS}^{\rm NLO,direct}$ | $\sigma_{\rm SPS}^{\rm NLO,prompt}$ | $\sigma_{\rm DPS}^{\rm prompt}$ |
|---|---|---|---|---|---|
| LHCb | $18 \pm 5.3$ | $22^{+27.7}_{-13.1}$ | $24.3^{+30.6}_{-14.4}$ | $46.0^{+58.0}_{-27.3}$ | $36.0^{+44.0}_{-12.8}$ |
| D0 | SPS: $70 \pm 23$<br>DPS: $59 \pm 23$ | $28.9^{+30.7}_{-14.5}$ | $91^{+177}_{-55}$ | $173^{+335}_{-105}$ | $87^{+106}_{-31}$ |
| CMS | $5.25 \pm 0.52$ | $0.19^{+0.14}_{-0.09}$ | $0.82^{+1.18}_{-0.46}$ | $1.54^{+2.24}_{-0.87}$ | $1.46^{+1.78}_{-0.52}$ |
| ATLAS | N/A | $3.45^{+2.35}_{-1.40}$ | $35.5^{+48.9}_{-19.8}$ | $67.1^{+92.4}_{-37.6}$ | $39.1^{+47.7}_{-13.9}$ |

TABLE I: $\sigma(pp(\bar{p}) \to J/\psi + J/\psi + X) \times \mathcal{B}^2_{\mu\mu}$ [Values in units of pb for LHCb and CMS and fb for D0 and ATLAS. The kinematical cuts are given as supplemental material.]

- Using the D0 data to fix the DPS parameter
- If one used the D0 data to fixe the DPS yield, DPS and SPS are comparable in the CMS acceptance.
- Large pT: CMS and D0 measurements imply a large DPS yield.
- Small pT: LHCb data do NOT imply a large DPS yield

# CALCULATION FRAMEWORK: DPS

- *All calculations are performed by the general-purposed matrix-element/event generator HELAC-Onia [HSS, CPC '12,'15] with the correct spin-entangled decay.*
- DPS has

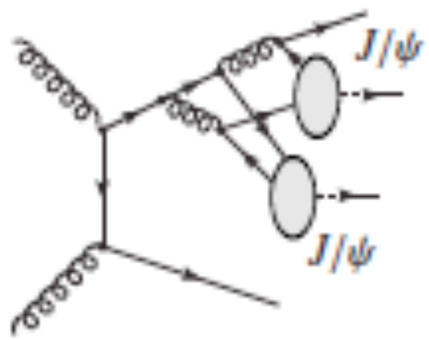
$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}}\frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\rm eff}},$$

- Normally, $\sigma_{\rm eff}$ is thought to be universal, i.e. process&energy independent. **However, it is important to be tested ?**
- Since no satisfying solution to describe single-quarkonium production cross sections $\sigma_\psi$, we decide to use a data-driven way because a lot of single quarkonium data are available.
- By doing so, we assume the amplitude of single quarkonium production in the Crystal-ball function form [Kom et al. (2011)]

$$\overline{|\mathcal{A}_{gg\to Q+X}|^2} = \begin{cases} K\exp(-\kappa\frac{P_T^2}{M_Q^2}) & \text{when } P_T \le \langle P_T\rangle \\ K\exp(-\kappa\frac{\langle P_T\rangle^2}{M_Q^2})\left(1+\frac{\kappa}{n}\frac{P_T^2-\langle P_T\rangle^2}{M_Q^2}\right)^{-n} & \text{when } P_T > \langle P_T\rangle \end{cases} \qquad K = \lambda^2\kappa\hat{s}/M_Q^2.$$

# OTHER CONTRIBUTIONS: SPS

- Beyond NLO contributions (new fragmentation topology):

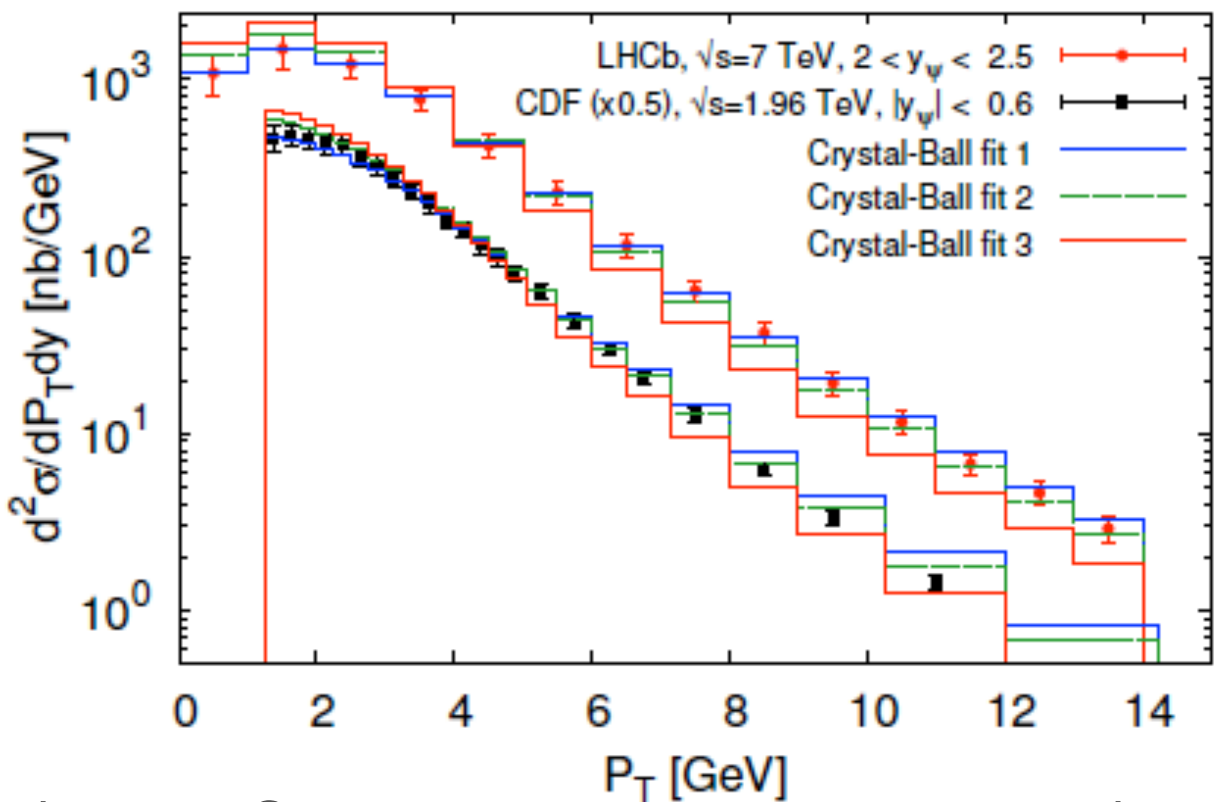



$$\sim \quad \alpha_s^5 \left(\frac{m_\psi}{P_T^\psi}\right)^4$$

- Feeddown from $J/\psi + \psi(2S)$ contributes 46% (i.e. 85% of direct), while others like $J/\psi + \chi_c$ are suppressed.
- CO contributions are also suppressed because of either smallness of CO LDMEs or no $p_T$-enhanced diagrams.
- In the accessible region, CO to SPS never dominants compared to CS SPS + DPS.

# CALCULATION FRAMEWORK: DPS

- Single-$J/\psi$ cross sections input from fits of existing data




- We used three fits to assess systematical uncertainties.
- Together with $\sigma_{\rm eff}$, they allow to predict $\sigma_{\rm DPS}$.
- Our strategy is therefore to fit $\sigma_{\rm eff}$ from CMS data

  via $\sigma_{\rm SPS} + \sigma_{\rm DPS}$.

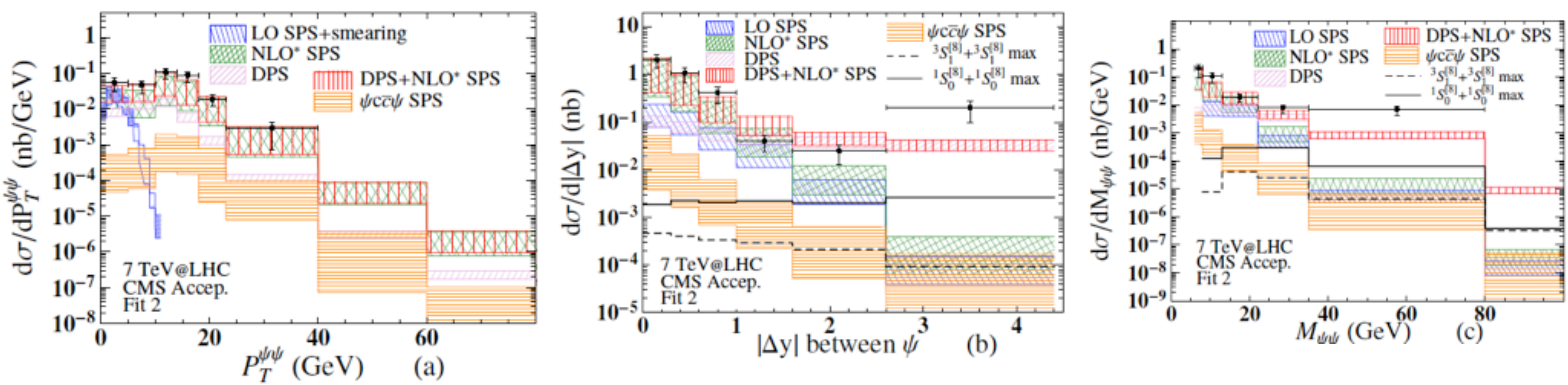
# FITTING SIGMA_EFF FROM CMS J/PSI-PAIR DATA

- $p_T^{\psi\psi}, |\Delta y_{\psi\psi}|$ & $M_{\psi\psi}$ distributions are fitted

| | $\sigma_{\rm eff}$ [mb] | $\chi^2_{\rm d.o.f.}$ | d.o.f. |
|---|---|---|---|
| $\sigma_\psi$ Fit 1 [25] | $11 \pm 2.9$ | 1.9 | 16 |
| $\sigma_\psi$ Fit 2 | $8.2 \pm 2.2$ | 1.8 | 16 |
| $\sigma_\psi$ Fit 3 | $5.3 \pm 1.4$ | 1.9 | 16 |
| Only LO SPS | N/A | 7.6 | 17 |
| Only NLO$^\star$ SPS | N/A | 2.6 | 17 |

Table 2: Result of the fit of the DPS yield via $\sigma_{\rm eff}$ on the 18 CMS values.

- Clear need for DPS (LO and NLO* SPS are not sufficient)



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# OUR EXTRACTION OF SIGMA_EFF

- Combining our three fits, we obtain

$$\sigma_{\rm eff} = 8.2 \pm 2.9|_{\sigma_\psi \ {\rm fit}} \pm 2.0|_{\rm SPS\ theory+CMS\ data}\ {\rm mb}$$

- The SPS theory uncertainty can in principle be removed by measuring a DPS cross section (as done by D0).
- The CMS data uncertainty can be reduced with more double quarkonium data.
- The last uncertainty is of course more tricky to deal with.

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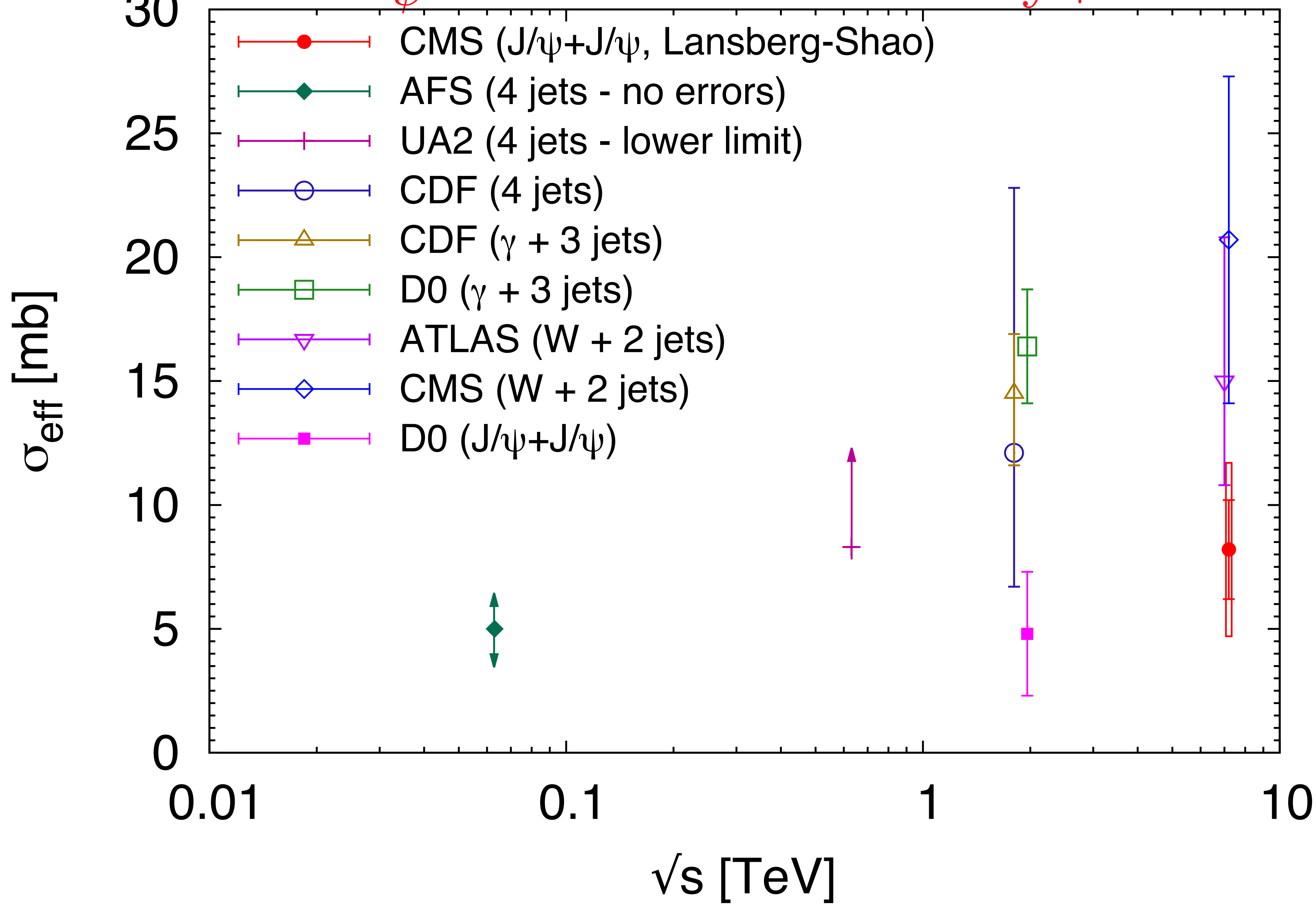

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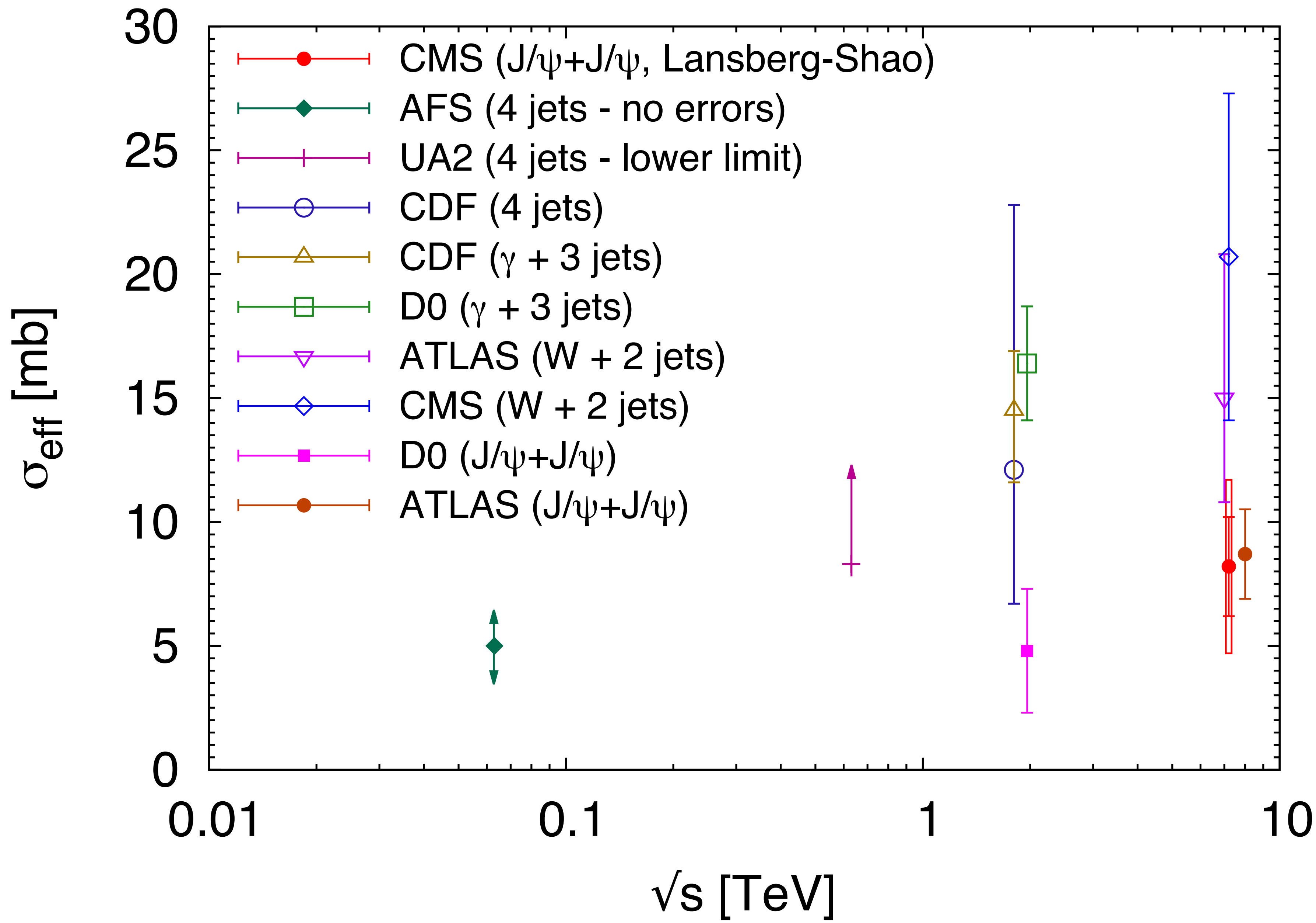
- The SPS theory uncertainty can in principle be removed by measuring a DPS cross section (as done by D0).
- The CMS data uncertainty can be reduced with more double quarkonium data.
- The last uncertainty is of course more tricky to deal with.
- Our extraction is compatible with that of D0.
- Both point at a small $\sigma_{\rm eff}$ compared to jet-related extraction.
- Does a smaller scale mean a smaller $\sigma_{\rm eff}$?
- Does gluon-induced process mean a smaller $\sigma_{\rm eff}$ ?

# RECENT ATLAS MEASUREMENT

ATLAS-CONF-2016-047

- With a data-driven way, ATLAS extracted the DPS with 8 TeV data

$$\sigma_{\text{eff}} = 8.7 \pm 1.1(stat) \pm 1.4(syst) \pm 0.1(BF) \pm 0.3(lumi)\ mb$$



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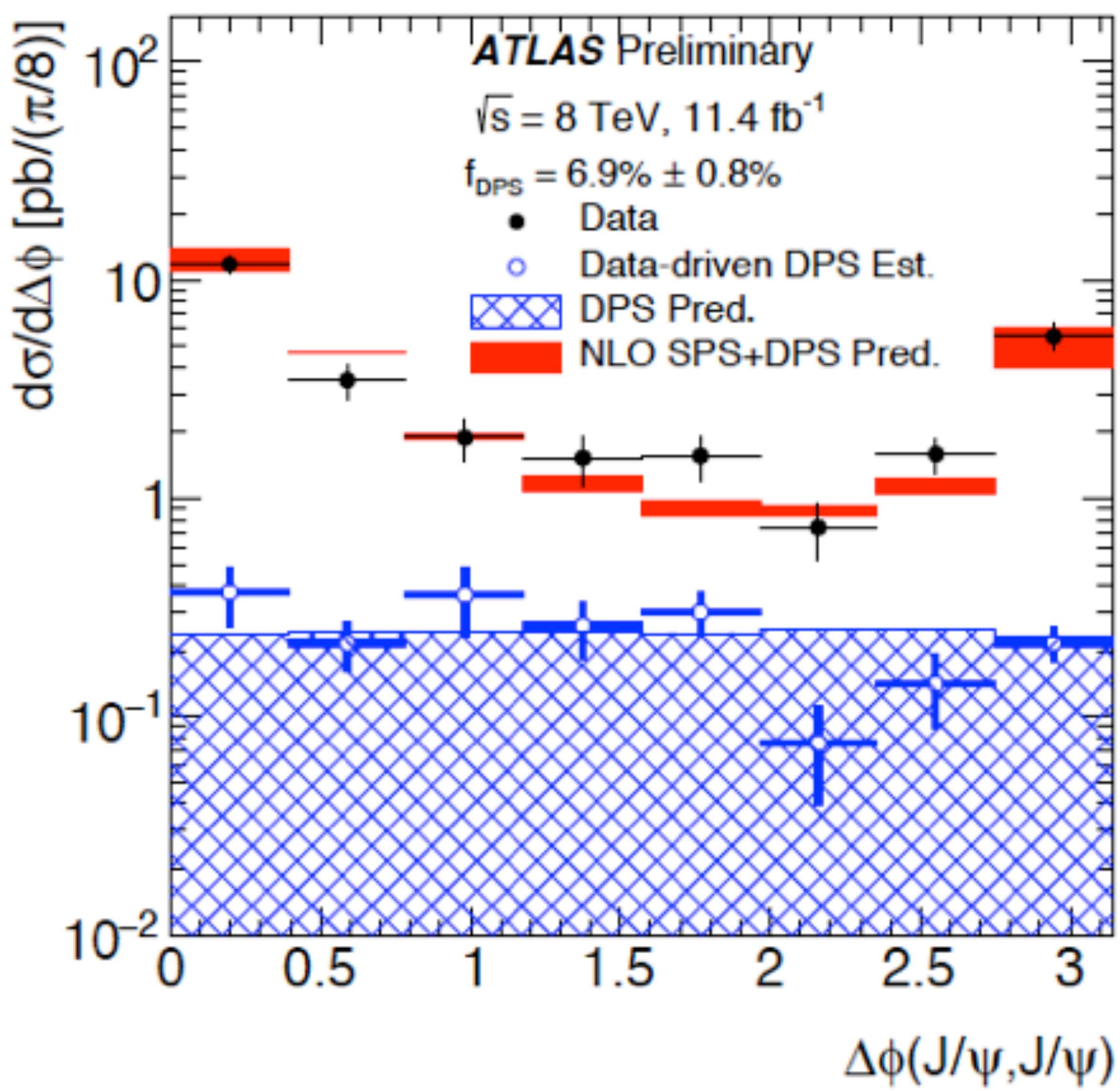
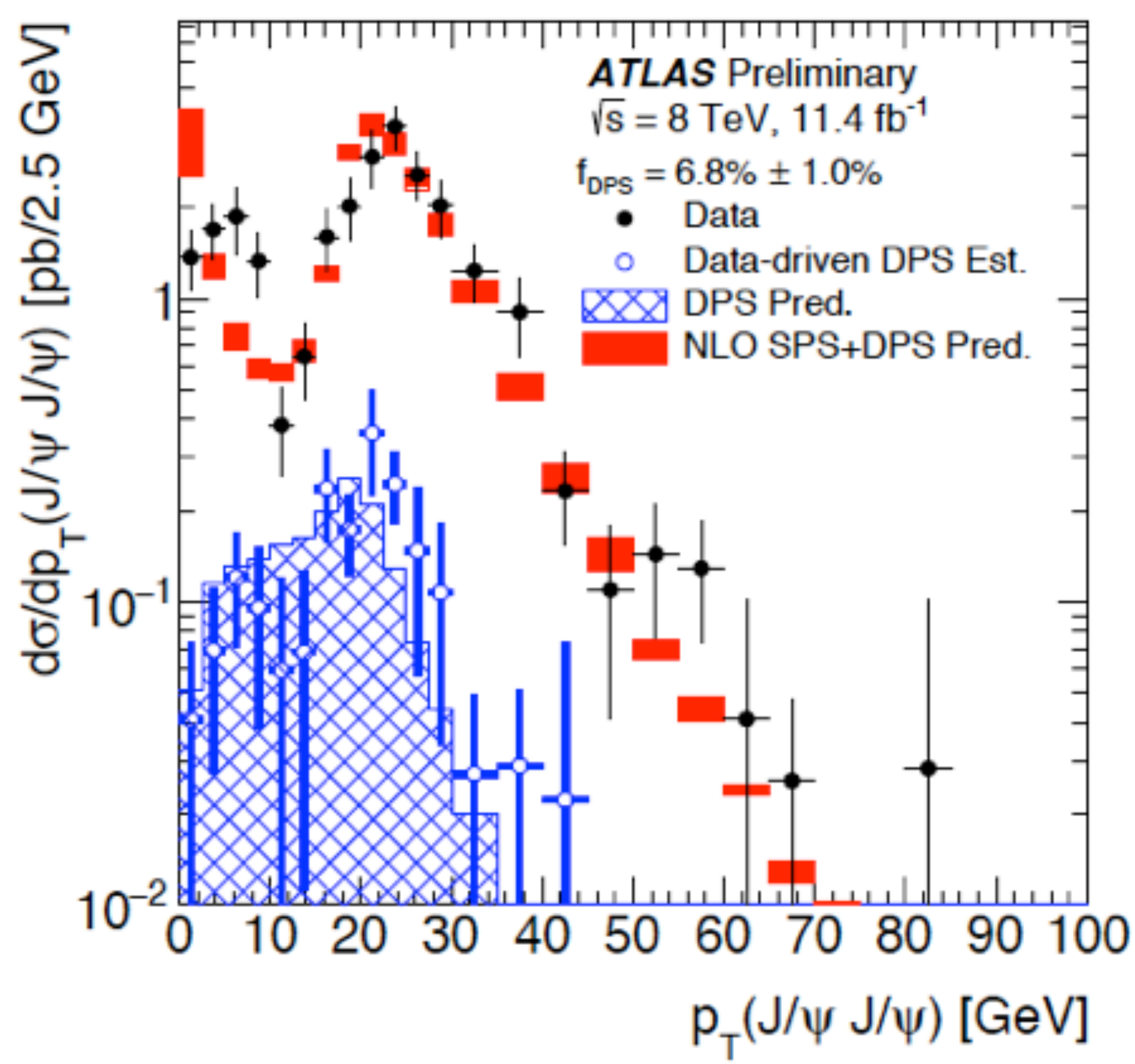
$$\sigma_{\text{eff}} = 8.7 \pm 1.1(stat) \pm 1.4(syst) \pm 0.1(BF) \pm 0.3(lumi)\ mb$$

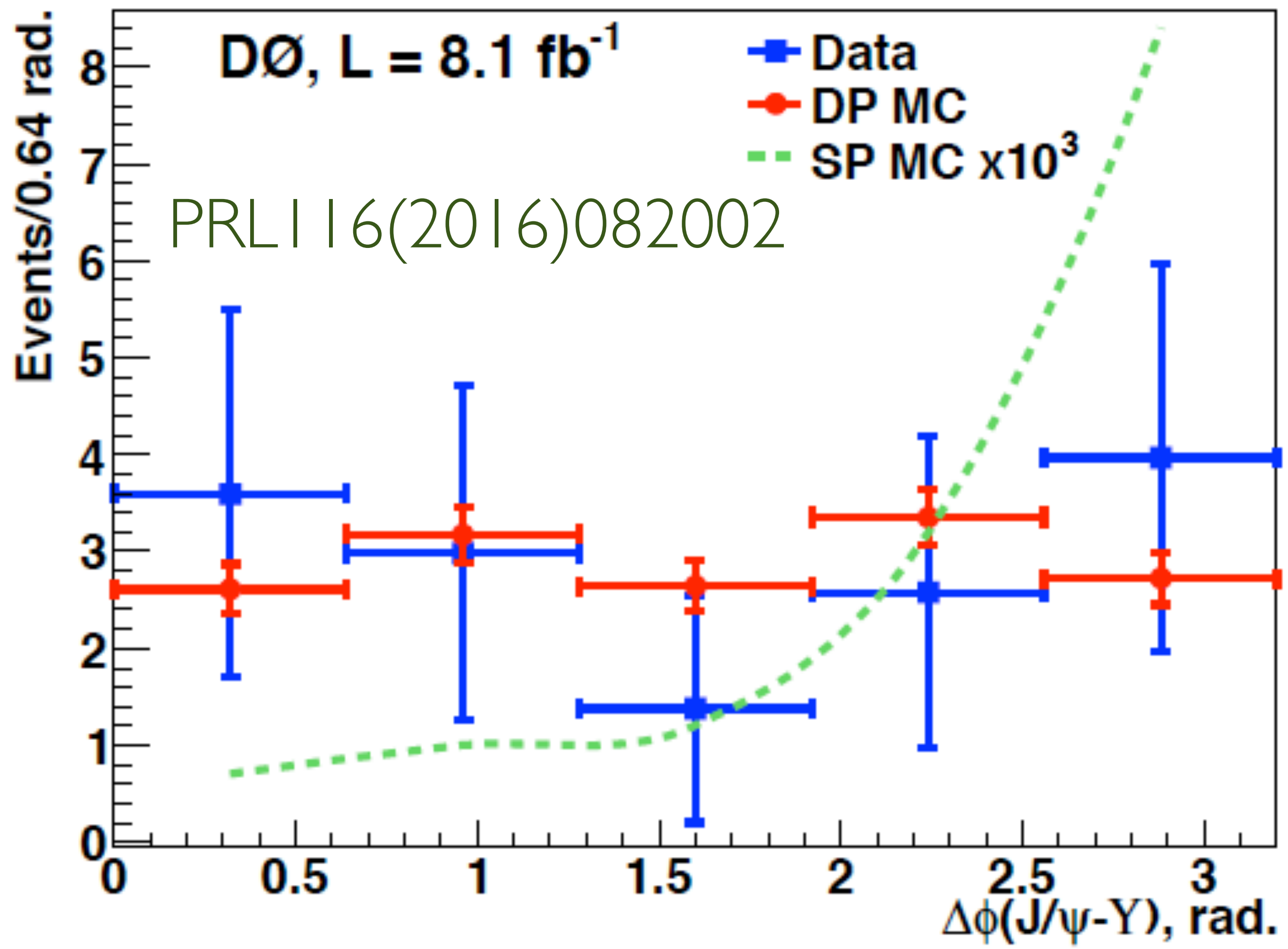
- It also confirms the CS dominant in the SPS of this process

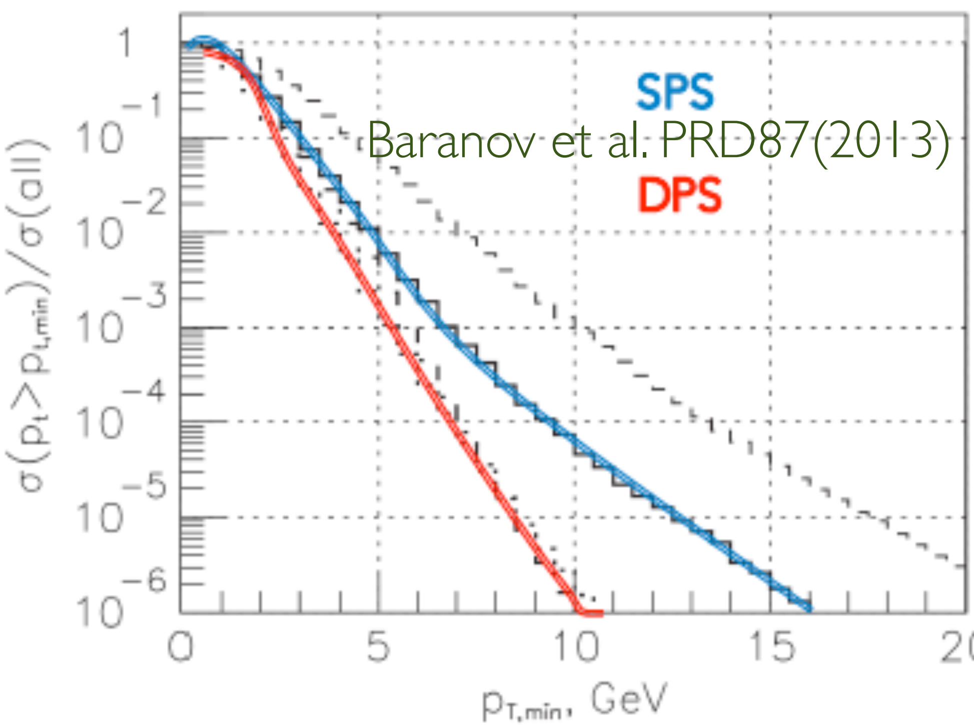


$$J/\psi + \Upsilon$$

# RECENT DZERO MEASUREMENT: J/PSI+Y



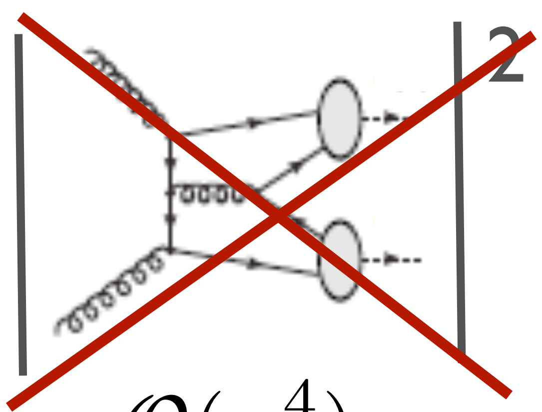

$$\sigma_{\rm eff} = 2.2 \pm 0.7\,({\rm stat}) \pm 0.9\,({\rm syst})\ {\rm mb}.$$

- Does it indicate a significant SPS contribution ?
- The value of $\sigma_{\rm eff}$ is a little bit too small if one assumes all contributions are DPS ?
- Would LHC measurements (especially LHCb) give a clarification in the future ?
- Is SPS can be completely negligible (even at low pT) ?

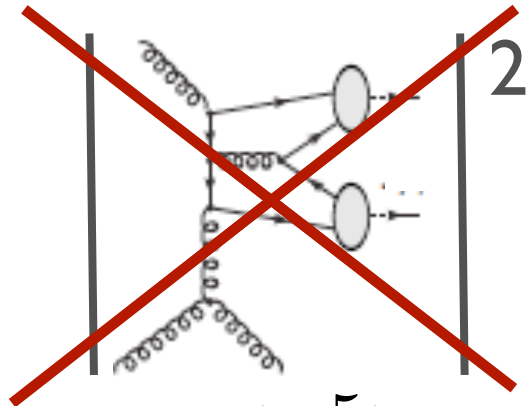
# PROMPT J/PSI+Y: SPS

HSS, Zhang PRL'16

- In pQCD, there are NO $\mathcal{O}(\alpha_s^4)$ and $\mathcal{O}(\alpha_s^5)$ CS contributions




$\mathcal{O}(\alpha_s^4)$

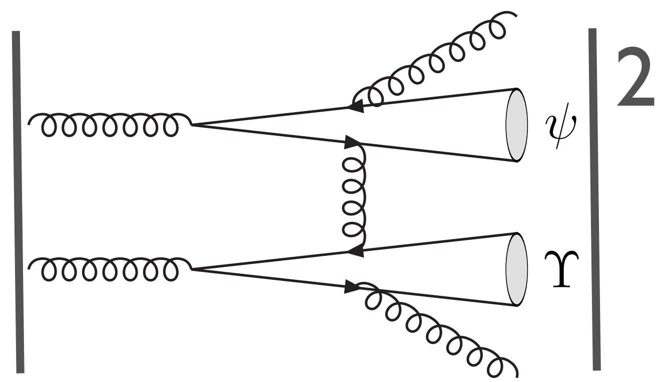



$\mathcal{O}(\alpha_s^5)$

# PROMPT J/PSI+Y: SPS

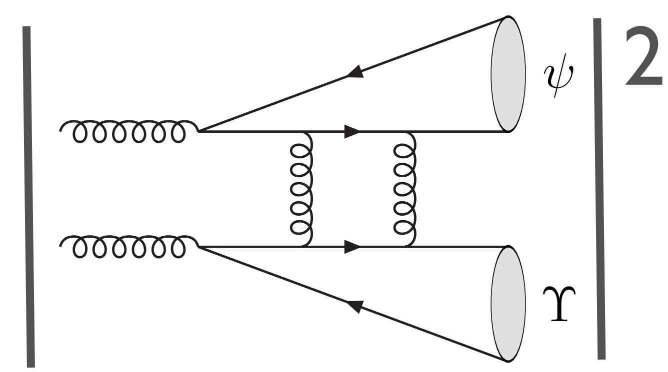
HSS, Zhang PRL'16

- In pQCD, there are NO $\mathcal{O}(\alpha_s^4)$ and $\mathcal{O}(\alpha_s^5)$ CS contributions
- The LO in pQCD is $\mathcal{O}(\alpha_s^6)$




$\mathcal{O}(\alpha_s^6)$

Double Real



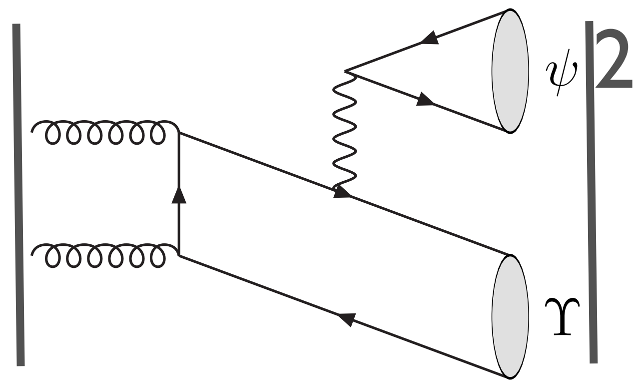

$\mathcal{O}(\alpha_s^6)$

Loop Induced

# PROMPT J/PSI+Y: SPS

HSS, Zhang PRL'16

- In pQCD, there are NO $\mathcal{O}(\alpha_s^4)$ and $\mathcal{O}(\alpha_s^5)$ CS contributions
- The LO in pQCD is $\mathcal{O}(\alpha_s^6)$
- There is also EW contribution $\mathcal{O}(\alpha_s^2\alpha^2)$



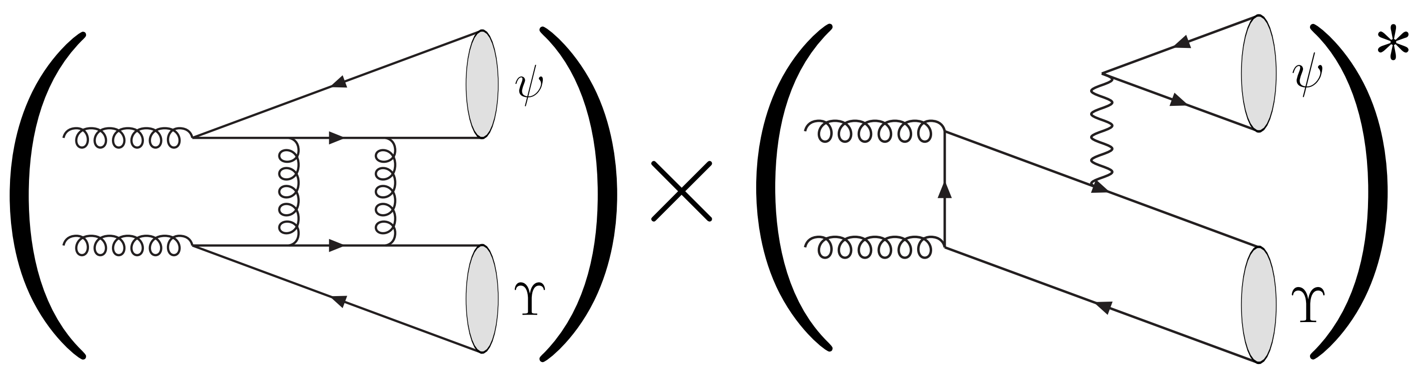

$\mathcal{O}(\alpha_s^2\alpha^2)$

ElectroWeak

# PROMPT J/PSI+Υ: SPS

HSS, Zhang PRL'16

- In pQCD, there are NO $\mathcal{O}(\alpha_s^4)$ and $\mathcal{O}(\alpha_s^5)$ CS contributions
- The LO in pQCD is $\mathcal{O}(\alpha_s^6)$
- There is also EW contribution $\mathcal{O}(\alpha_s^2\alpha^2)$
- LI and EW can have interference $\mathcal{O}(\alpha_s^4\alpha)$




+ c.c.

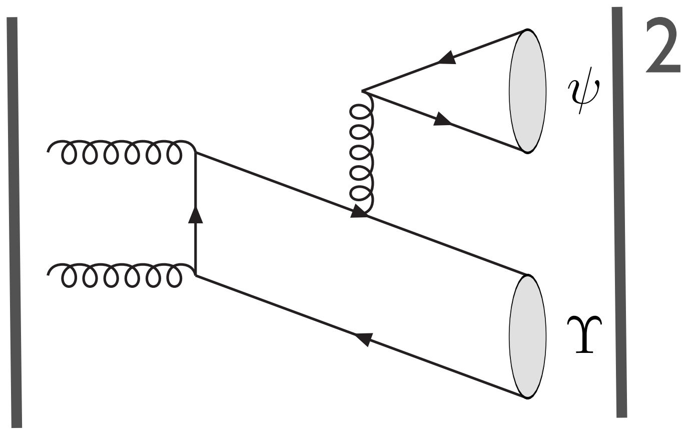
$$\mathcal{O}(\alpha_s^4\alpha)$$

INTERference

# PROMPT J/PSI+Y: SPS

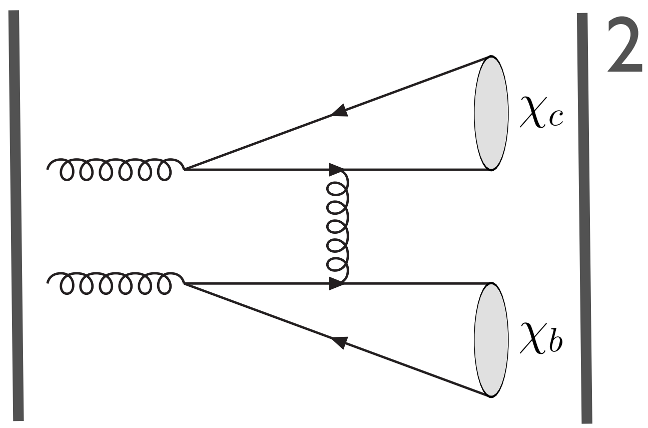
HSS, Zhang PRL'16

- In pQCD, there are NO $\mathcal{O}(\alpha_s^4)$ and $\mathcal{O}(\alpha_s^5)$ CS contributions
- The LO in pQCD is $\mathcal{O}(\alpha_s^6)$
- There is also EW contribution $\mathcal{O}(\alpha_s^2\alpha^2)$
- LI and EW can have interference $\mathcal{O}(\alpha_s^4\alpha)$
- CO contributes at $\mathcal{O}(\alpha_s^4 v_c^i v_b^j), i+j \geq 4$




$\mathcal{O}(\alpha_s^4 v_c^i v_b^j), i+j \geq 4$

Color-Octet Mechanism




Feeddown



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# PROMPT J/PSI+Y: SPS

HSS, Zhang PRL'16

- In pQCD, there are NO $\mathcal{O}(\alpha_s^4)$ and $\mathcal{O}(\alpha_s^5)$ CS contributions
- The LO in pQCD is $\mathcal{O}(\alpha_s^6)$
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- CO contributes at $\mathcal{O}(\alpha_s^4 v_c^i v_b^j), i+j \geq 4$

| Label | HELAC-ONIA 2.0 syntax | First order | Description |
|---|---|---|---|
| DR | `g g > cc~(3S11) bb~(3S11) g g` | $\mathcal{O}(\alpha_S^6)$ | Double Real (DR) CS contribution |
| LI | `addon 8` | $\mathcal{O}(\alpha_S^6)$ | Loop-Induced (LI) CS contribution |
| EW | `p p > cc~(3S11) bb~(3S11)` | $\mathcal{O}(\alpha_S^2\alpha^2)$ | ElectroWeak (EW) CS contribution |
| INTER | `addon 8` | $\mathcal{O}(\alpha_S^4\alpha)$ | INTERference (INTER) between LI and EW |
| COM | `g g > jpsi y(1s)` | $\mathcal{O}(\alpha_S^4 v_c^i v_b^j), i+j \geq 4$ | CO $\mathcal{O}(\alpha_S^4)$ contribution |

Similar leading contributions

$$\mathcal{O}(\alpha_s^6) \approx \mathcal{O}(\alpha_s^2\alpha^2) \approx \mathcal{O}(\alpha_s^4\alpha) \approx \mathcal{O}(\alpha_s^4 v_c^i v_b^j)$$

Giving $\alpha_s \approx \sqrt{\alpha} \approx v_c^2 \approx v_b^2$

# PROMPT J/PSI+Y: SPS VS DATA

HSS, Zhang PRL '16

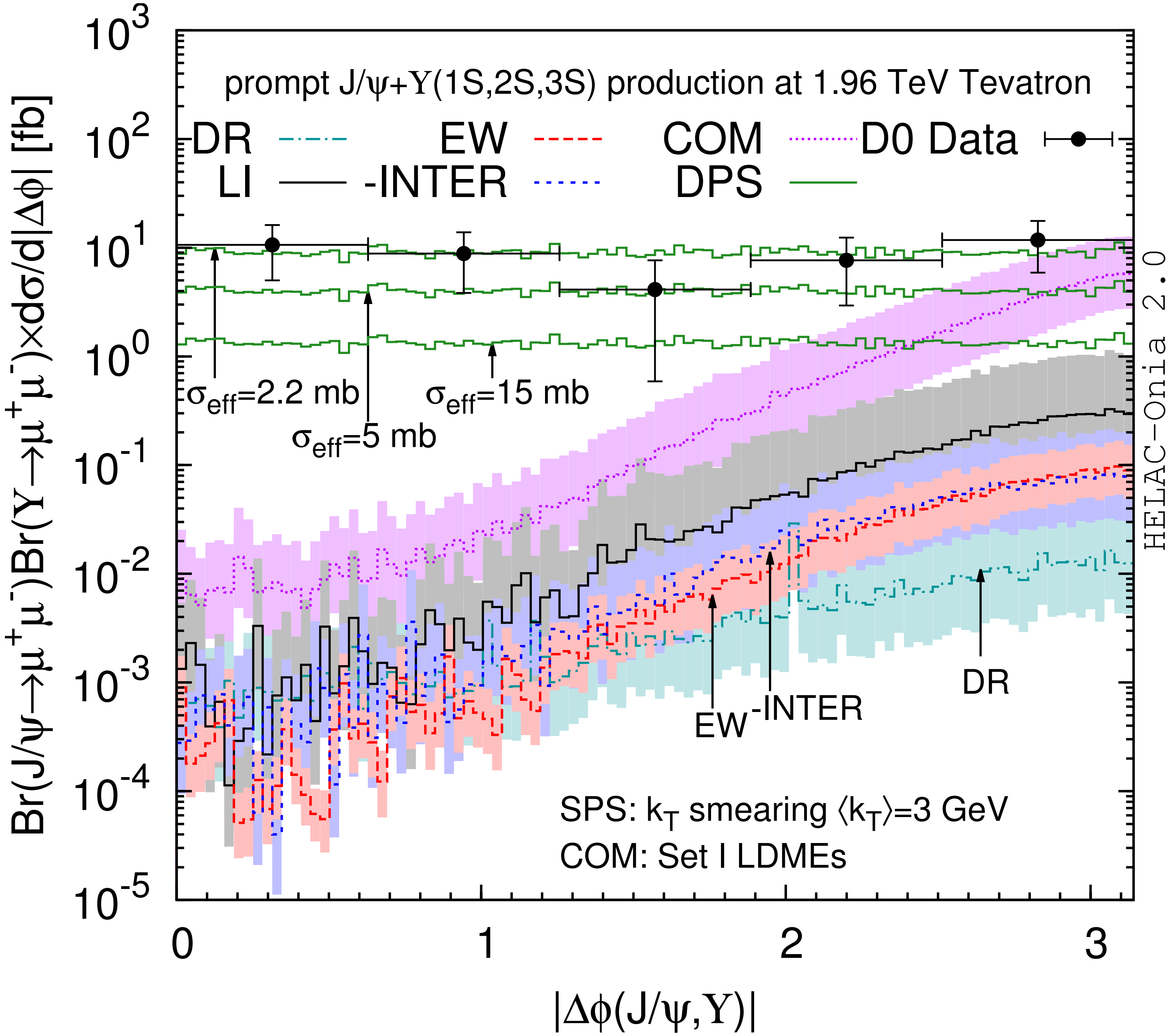
| exp. | CSM | | | | COM | | | |
|---|---|---|---|---|---|---|---|---|
| | DR | LI | EW | INTER | Set I | Set II | Set III | Set IV |
| D0: $27 \pm 42.2\%$ | $0.0146^{+233\%}_{-66.6\%}$ | $0.229^{+264\%}_{-70.4\%}$ | $0.065^{+75.5\%}_{-46.6\%}$ | $-0.068^{+162\%}_{-62.2\%}$ | $2.96^{+135\%}_{-56.2\%}$ | $1.41^{+160\%}_{-77.6\%}$ | $1.80^{+143\%}_{-58.0\%}$ | $0.418^{+144\%}_{-58.3\%}$ |
| LHCb | $0.255^{+391\%}_{-79.7\%}$ | $6.05^{+436\%}_{-82.2\%}$ | $1.71^{+135\%}_{-65.2\%}$ | $-3.23^{+262\%}_{-75.9\%}$ | $38.8^{+238\%}_{-73.0\%}$ | $21.2^{+243\%}_{-73.6\%}$ | $28.1^{+243\%}_{-73.8\%}$ | $6.57^{+243\%}_{-73.9\%}$ |

- SPS is smaller than the central value of D0 data
- SPS is NOT completely negligible
- COM SPS is strongly dependent on CO LDMEs
  - Set I: *Kramer, Prog.Part.Nucl.Phys. 47 (2001) 141*
  - Set II: *Sharma, Vitev, Phys. Rev. C 87 (2013) 044905*
  - Set III: *HSS et al, JHEP 1505 (2015) 103; Han et al, arXiv:1410.8537 [hep-ph]*
  - Set IV: *Gong et al, Phys. Rev. Lett. 110 (2013) 042002; Feng et al, Chin. Phys. C 39 (2015) 123102*

# PROMPT J/PSI+Y: THEORY VS DATA

HSS, Zhang PRL'16

- With SPS, we can derive $\sigma_{\text{eff}} \leq 8.2\ \text{mb}$ at 68% C.L.



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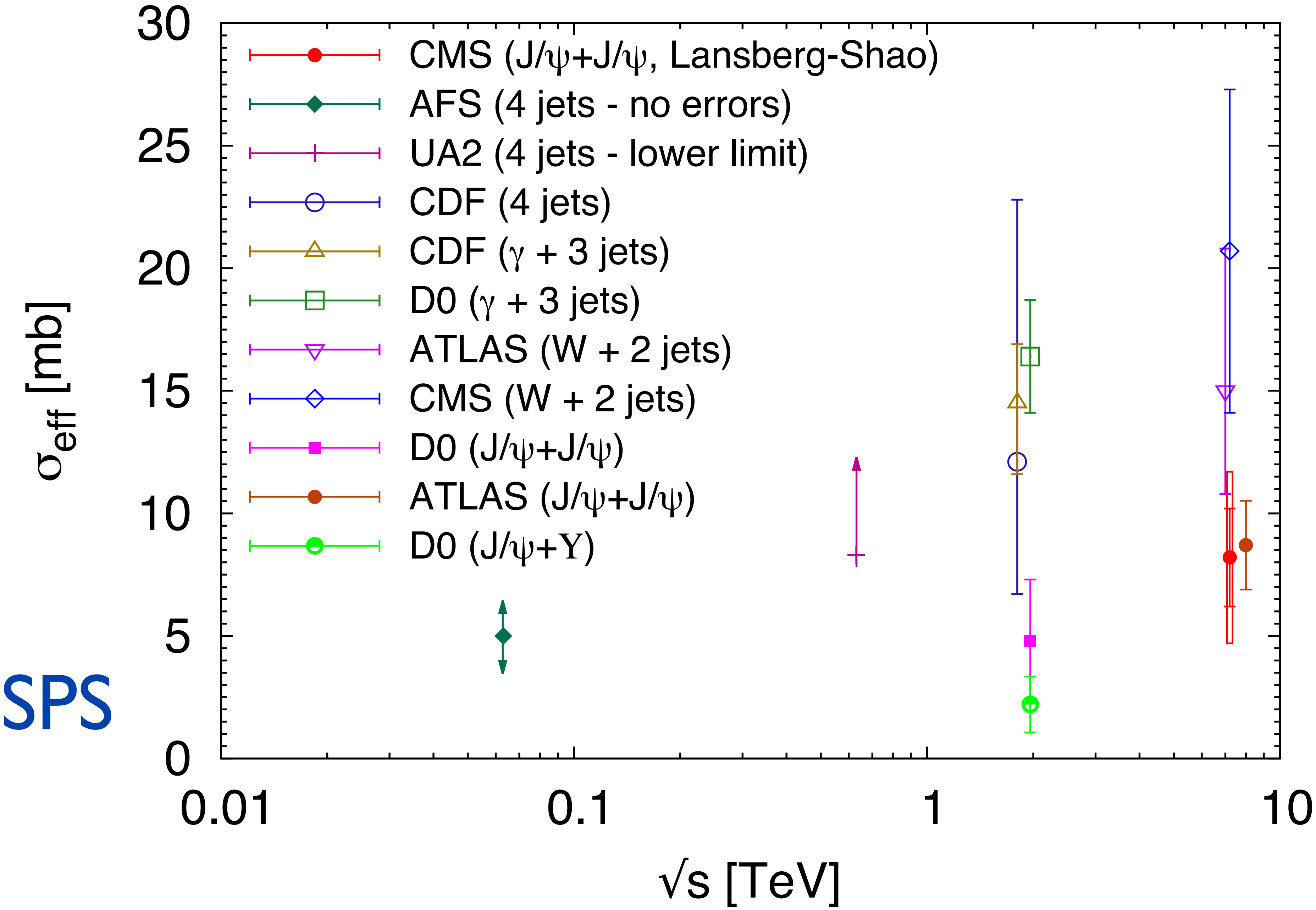


w/o SPS

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HSS, Zhang PRL'16

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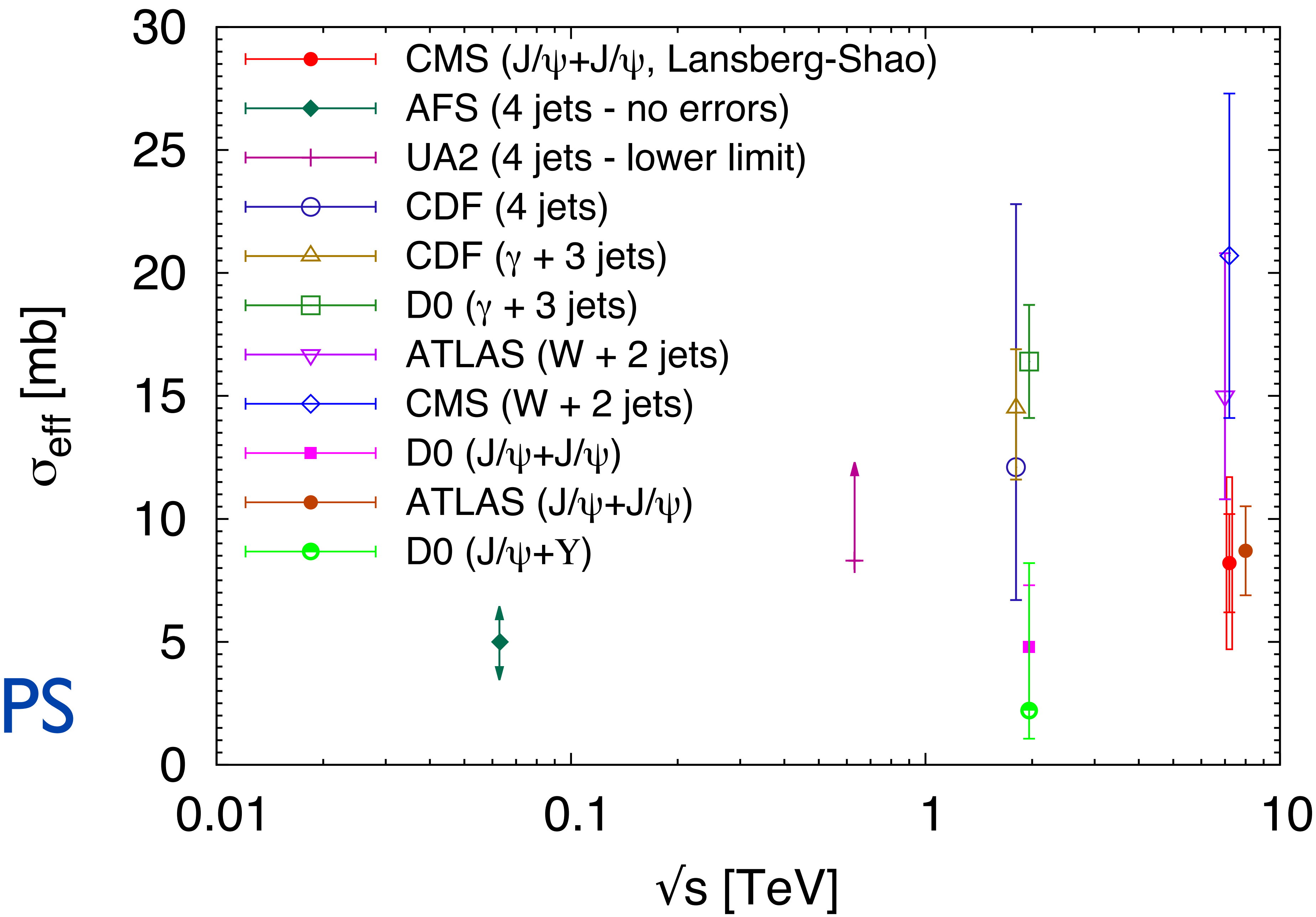


w SPS

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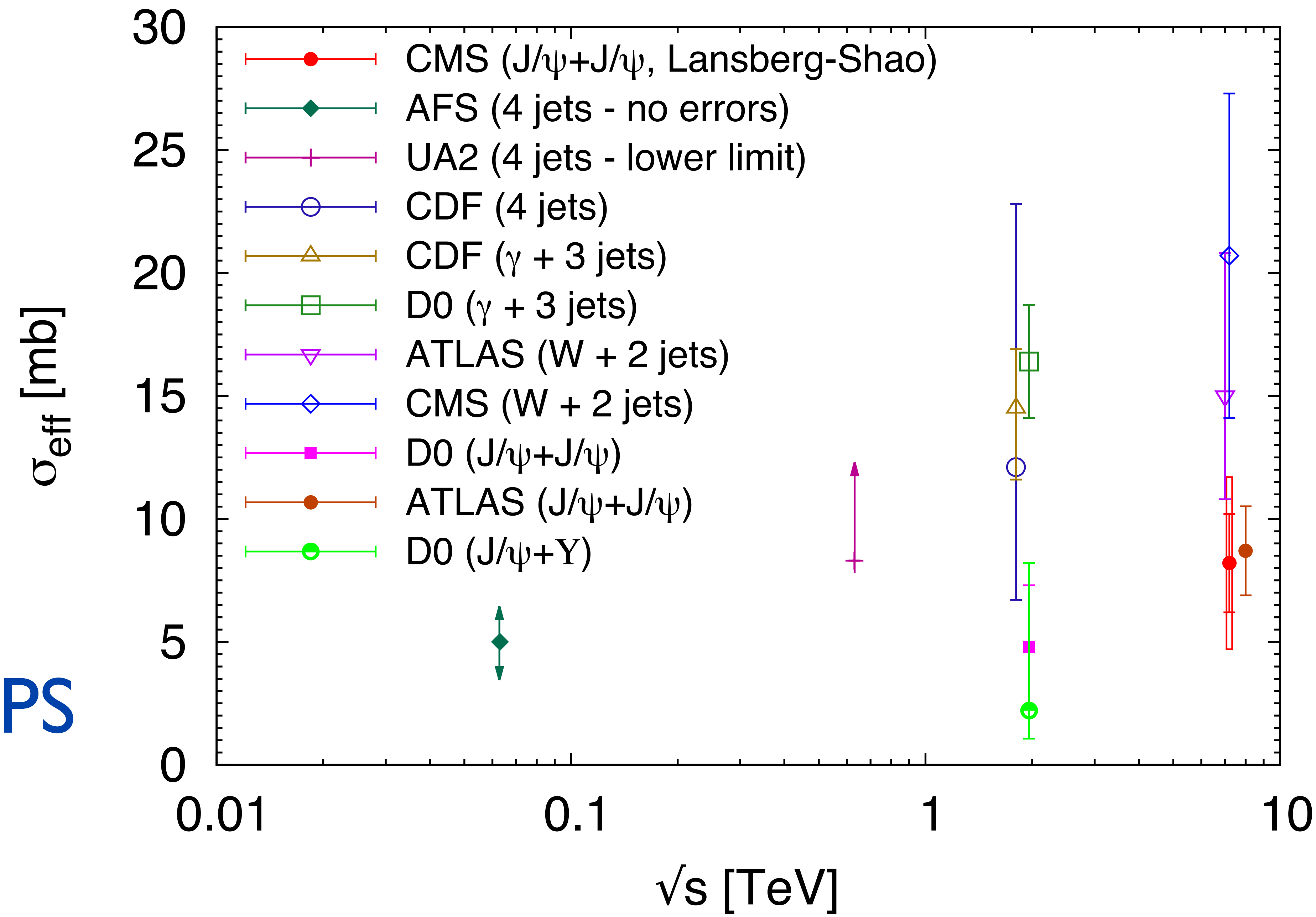
w SPS



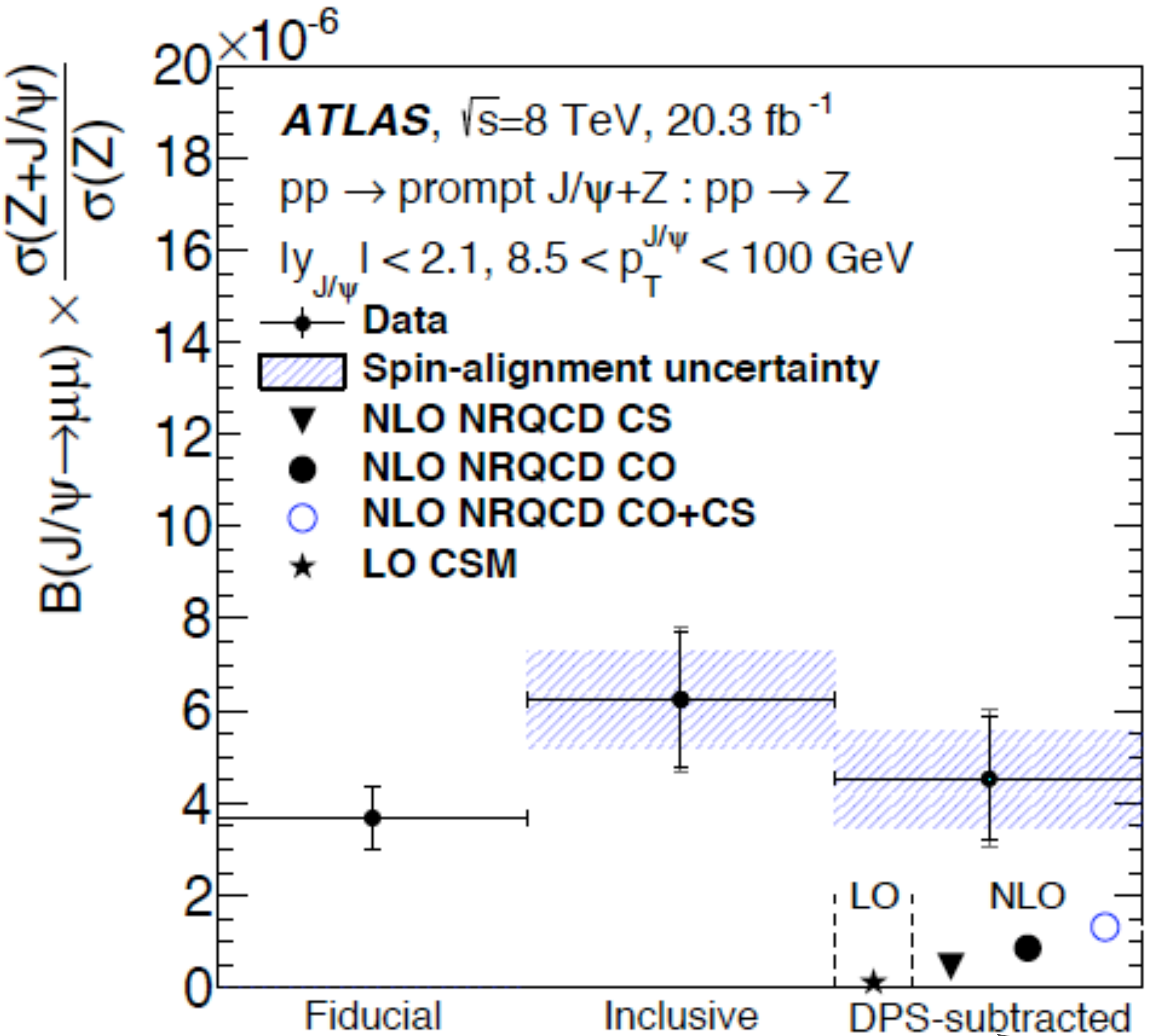

- Future measurement at the LHC ?

$$J/\psi + Z$$

# RECENT ATLAS MEASUREMENT: PROMPT J/PSI+Z

ATLAS EPJC'15

- First measurement by ATLAS
- Compare to theoretical calculations: DPS is dominant

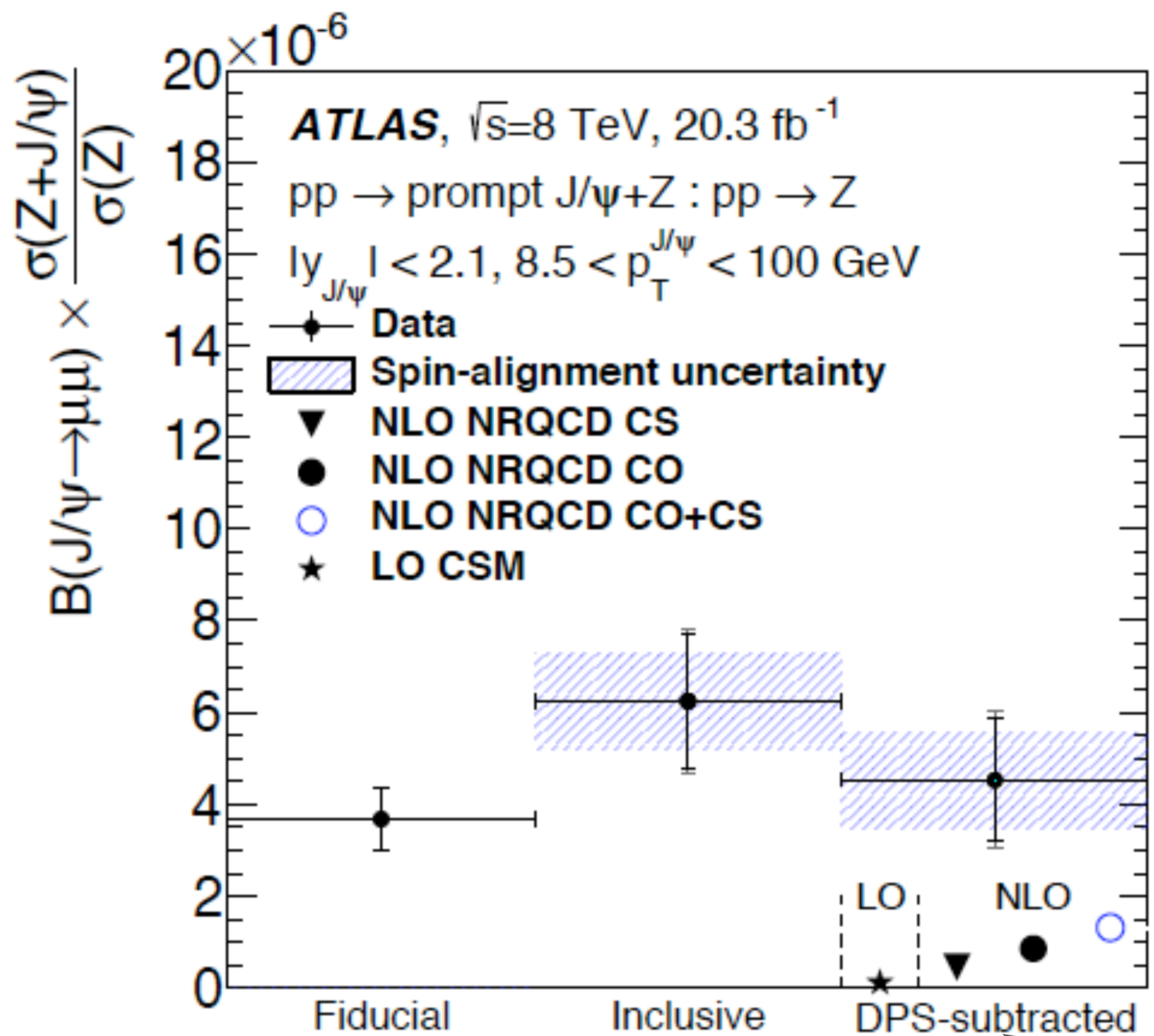



$$\sigma_{\rm eff} = 15\ mb$$

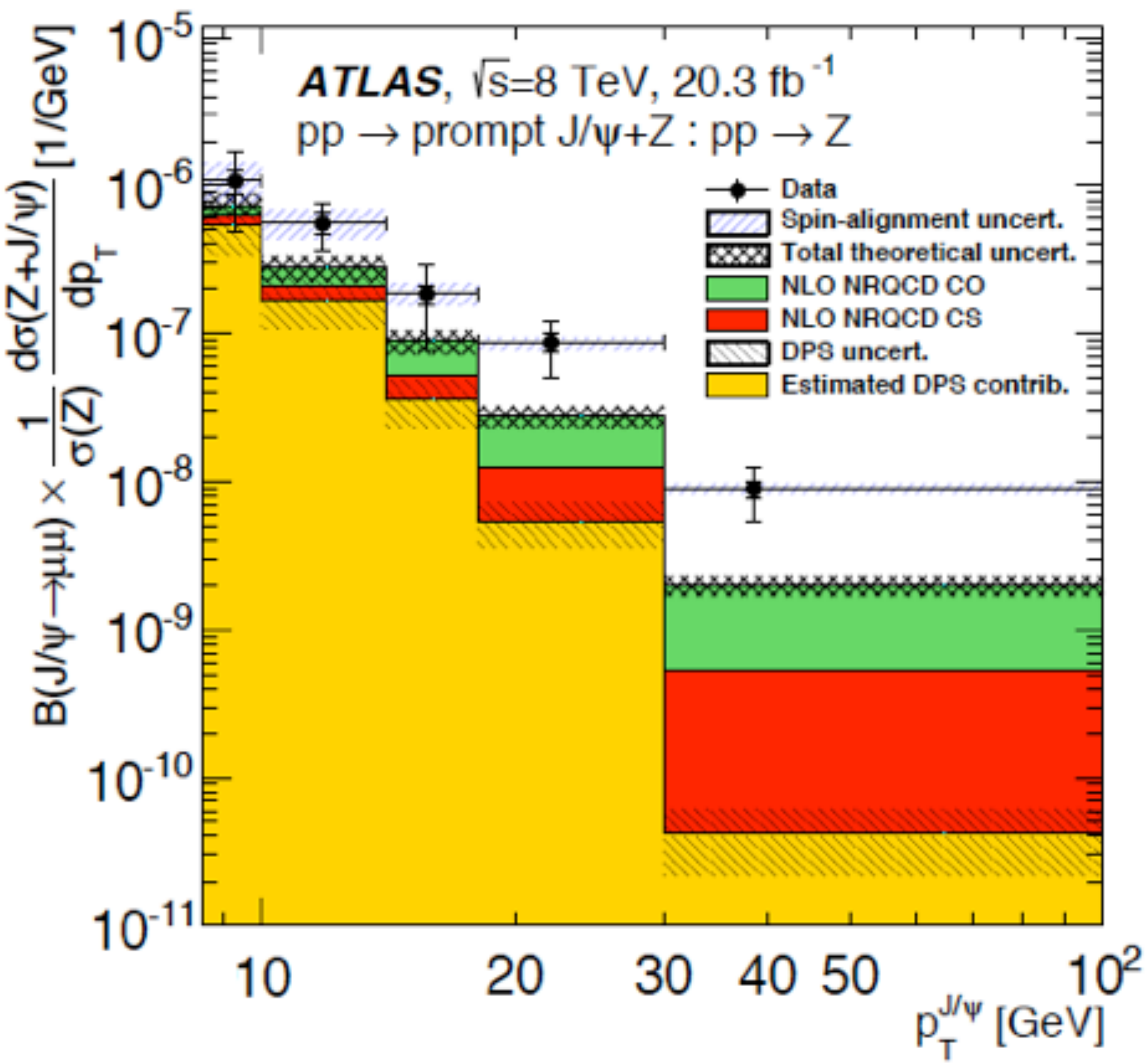
# RECENT ATLAS MEASUREMENT: PROMPT J/PSI+Z

ATLAS EPJC'15

- First measurement by ATLAS
- Compare to theoretical calculations: DPS is dominant
- Compare to theoretical calculations: large discrepancy




$\sigma_{\rm eff} = 15\ mb$



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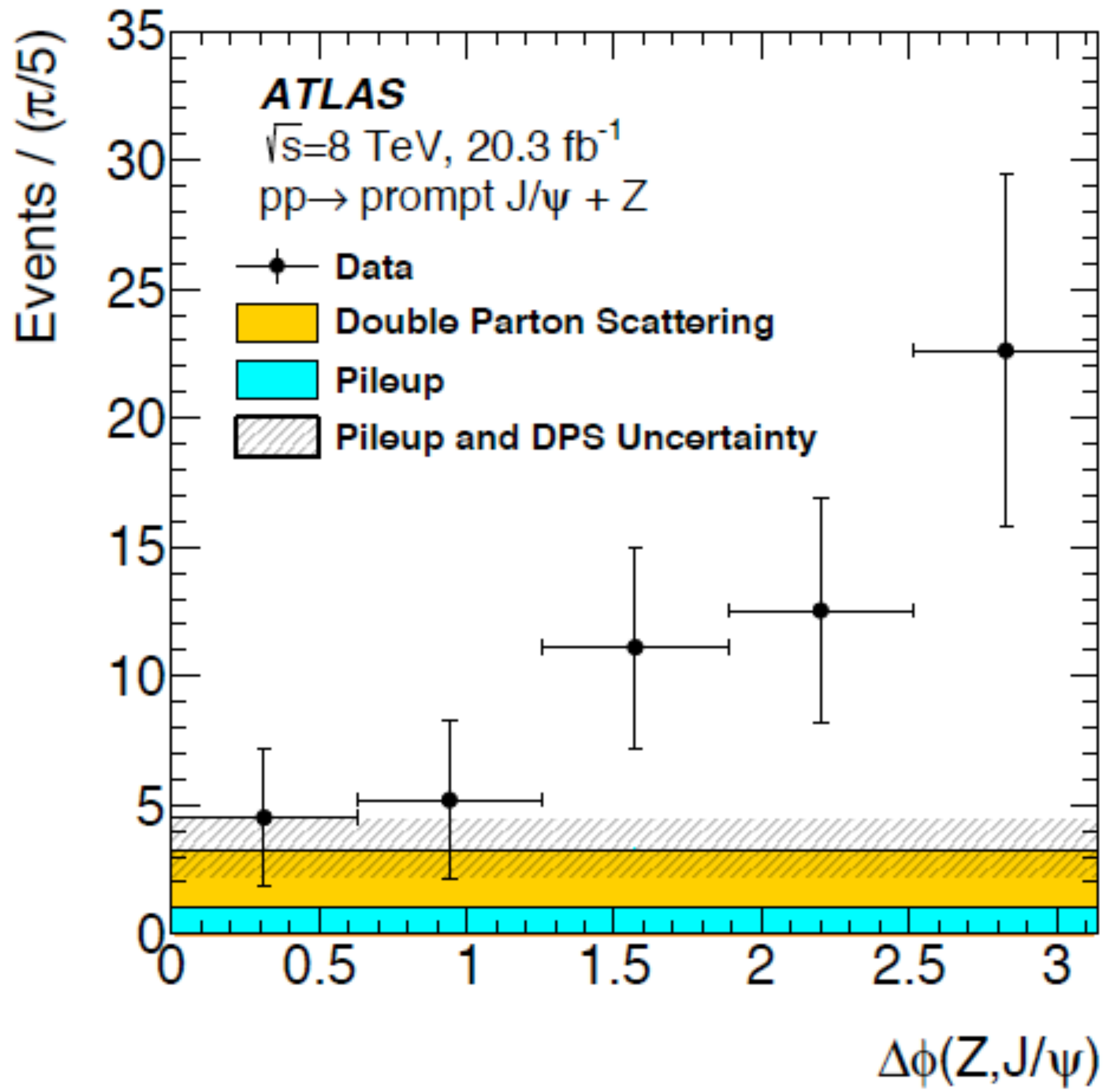
# RECENT ATLAS MEASUREMENT: PROMPT J/PSI+Z

ATLAS EPJC'15

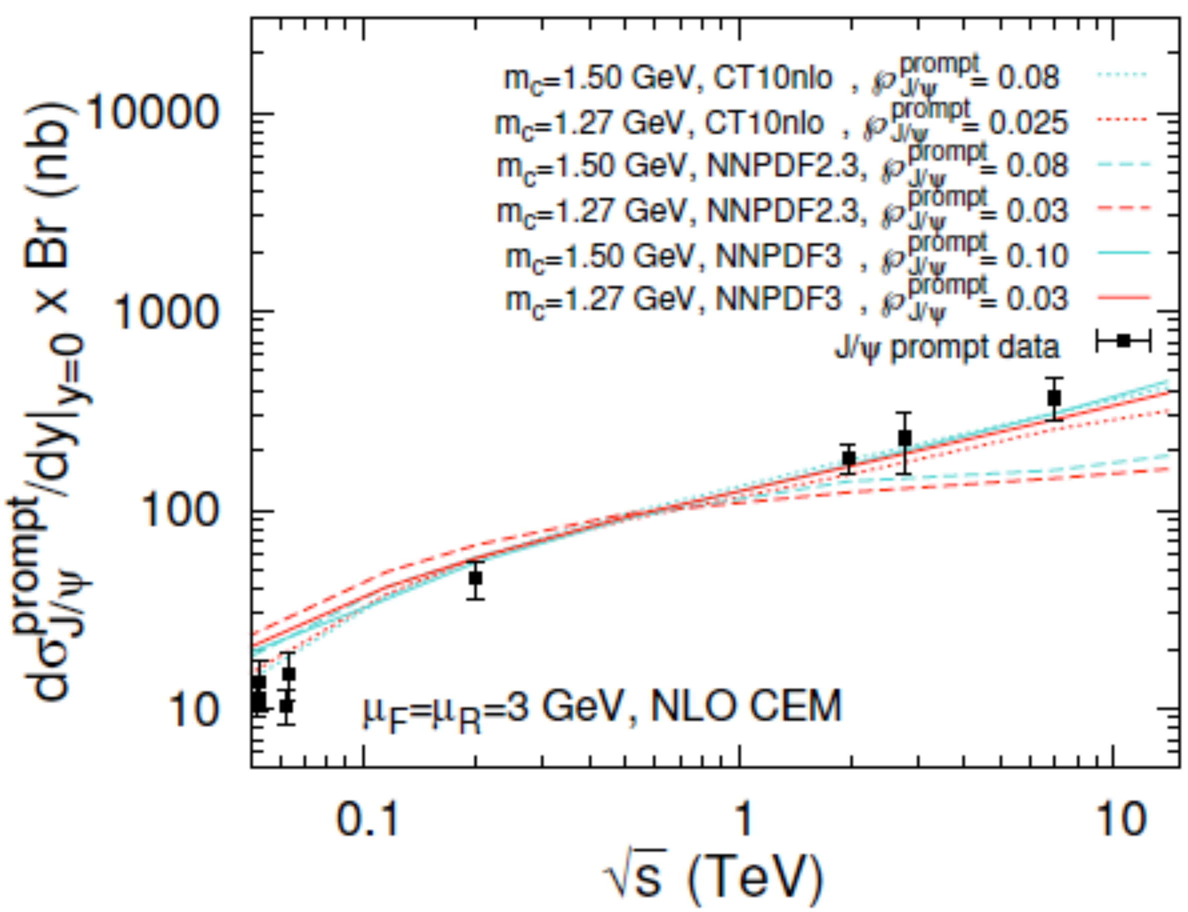
- First measurement by ATLAS
- Compare to theoretical calculations: DPS is dominant
- Compare to theoretical calculations: large discrepancy
- However, it seems one needs SPS

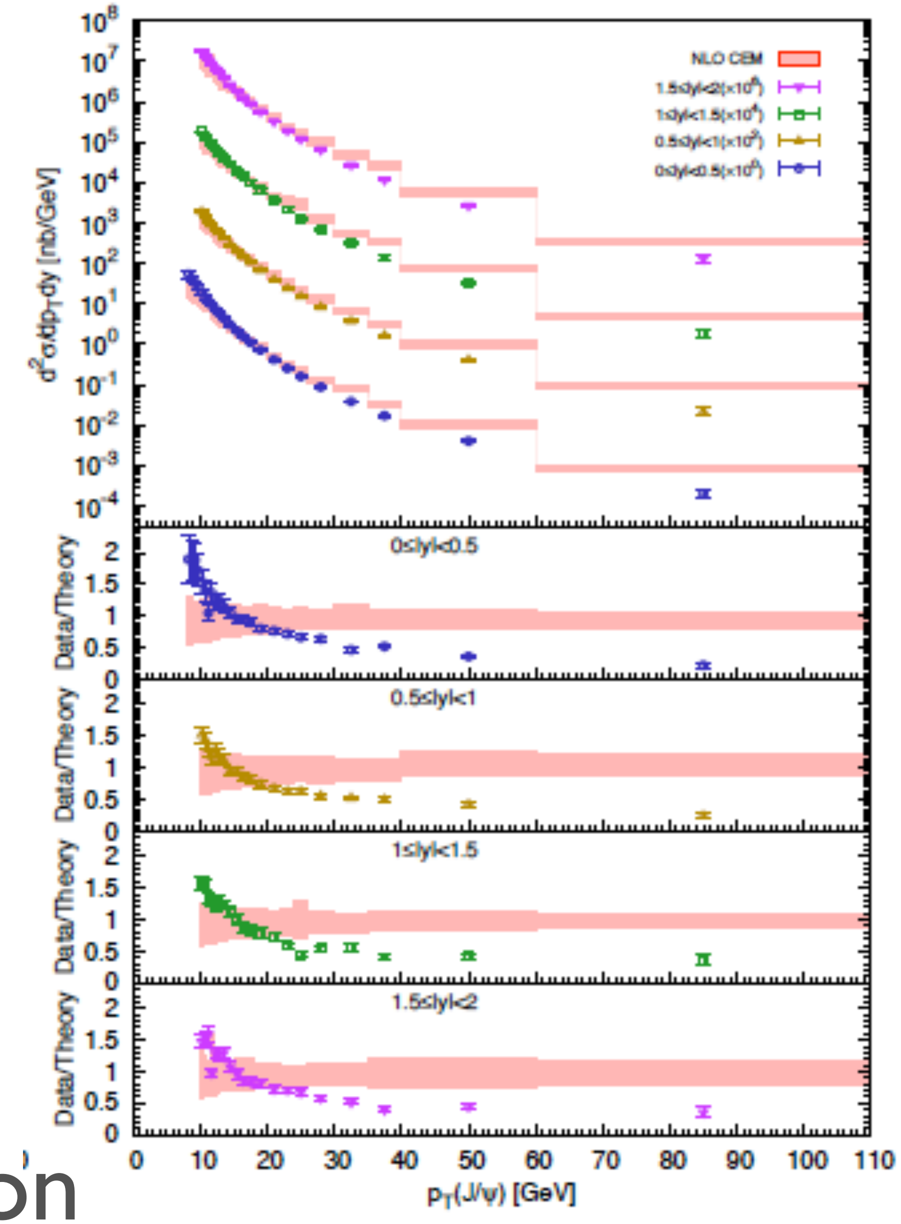


# REANALYSIS J/PSI PRODUCTION IN CEM

- Prompt J/psi production in quark-hadron duality (CEM)
- Pro: only one parameter and easy to include higher order
- Con: not good to describe the pt spectrum

Lansberg, HSS '16



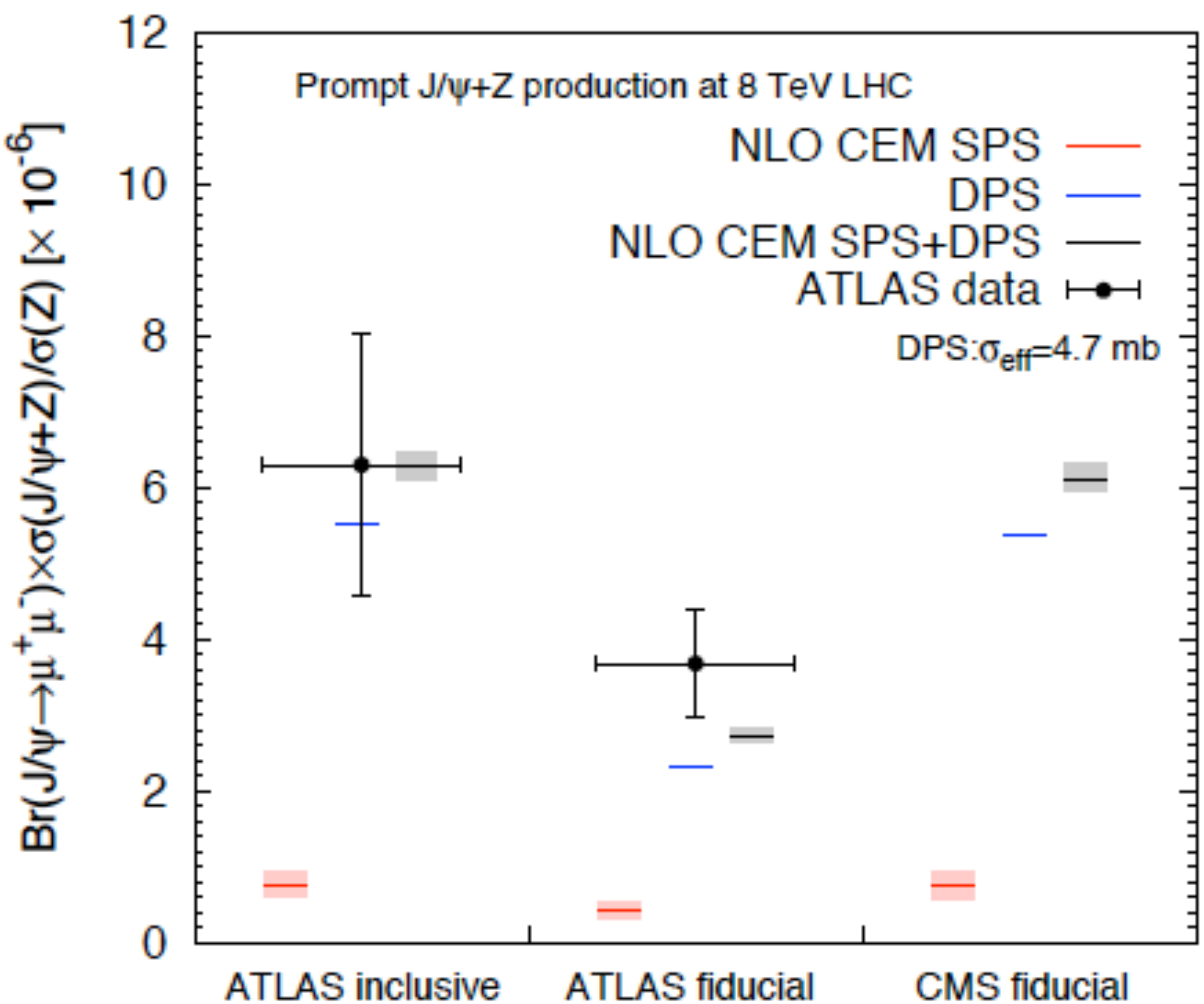



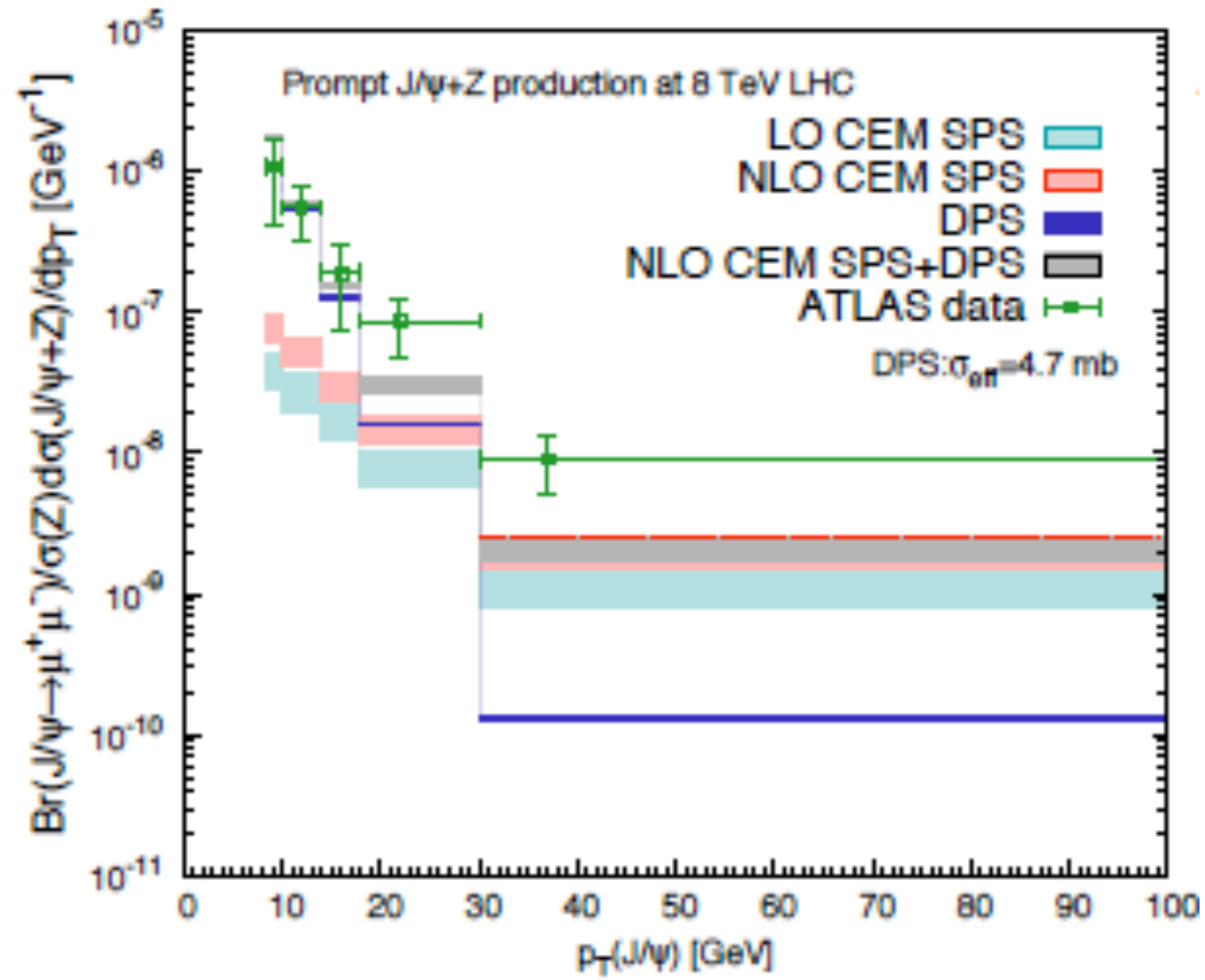

- Upper limit yields for J/psi production

# PROMPT J/PSI+Z: NLO CEM VS DATA

Lansberg, HSS '16

- Applying CEM to J/psi+Z: NLO QCD vs ATLAS data
- Confirm DPS is dominant and small effective sigma



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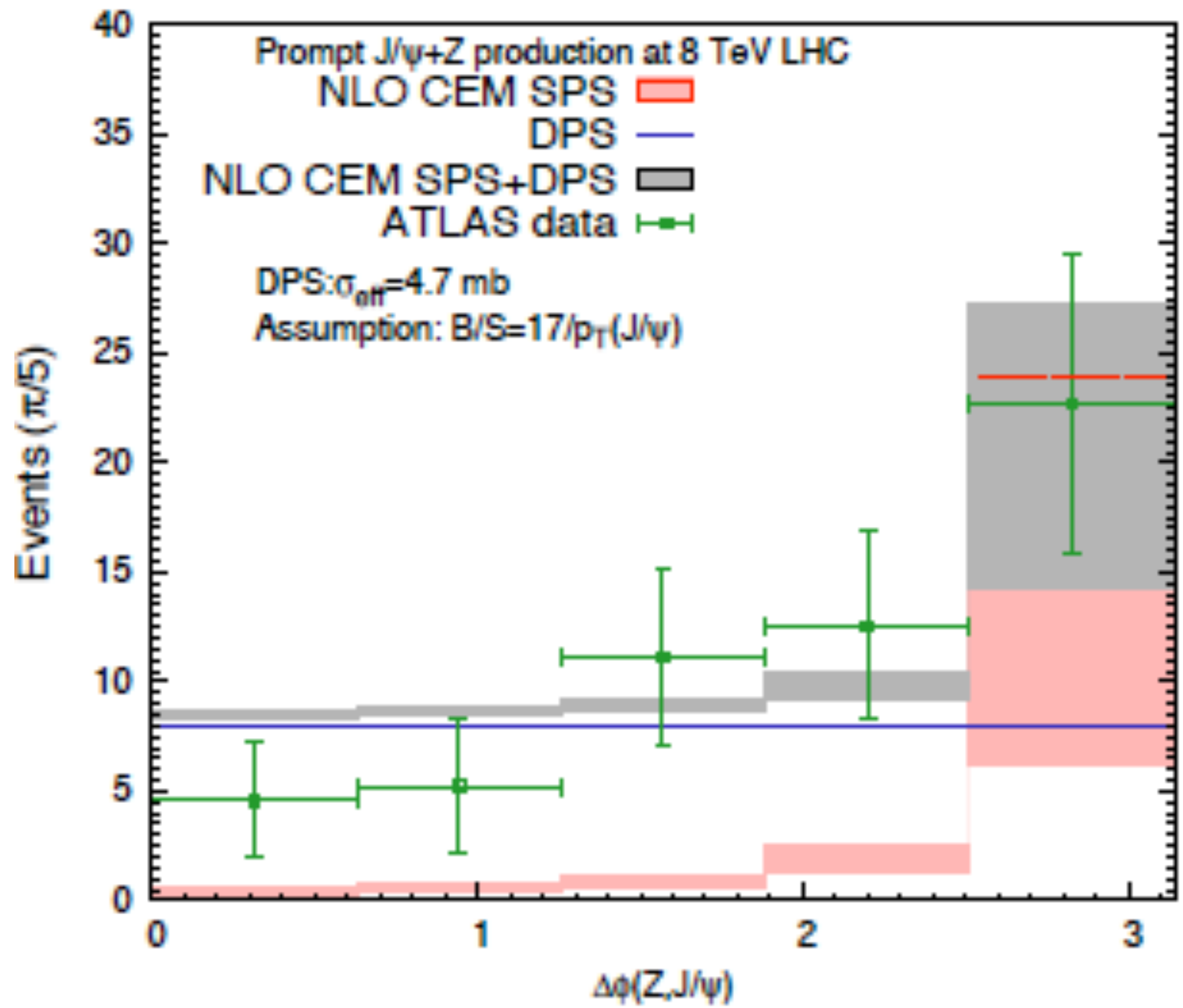
# PROMPT J/PSI+Z: NLO CEM VS DATA

Lansberg, HSS '16

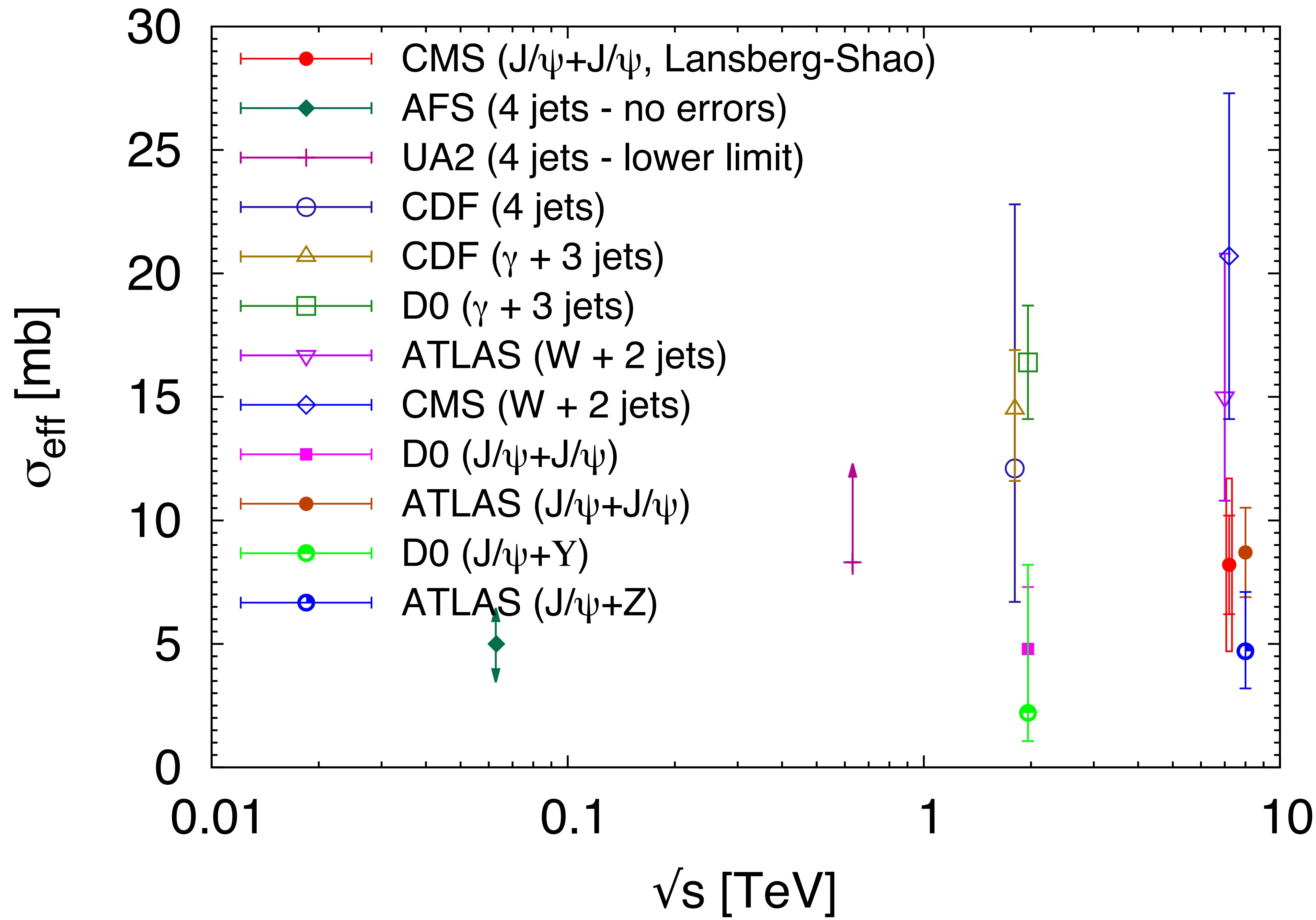
- Azimuthal angular can be described well with SPS+DPS



# PROMPT J/PSI+Z: NLO CEM VS DATA

Lansberg, HSS '16

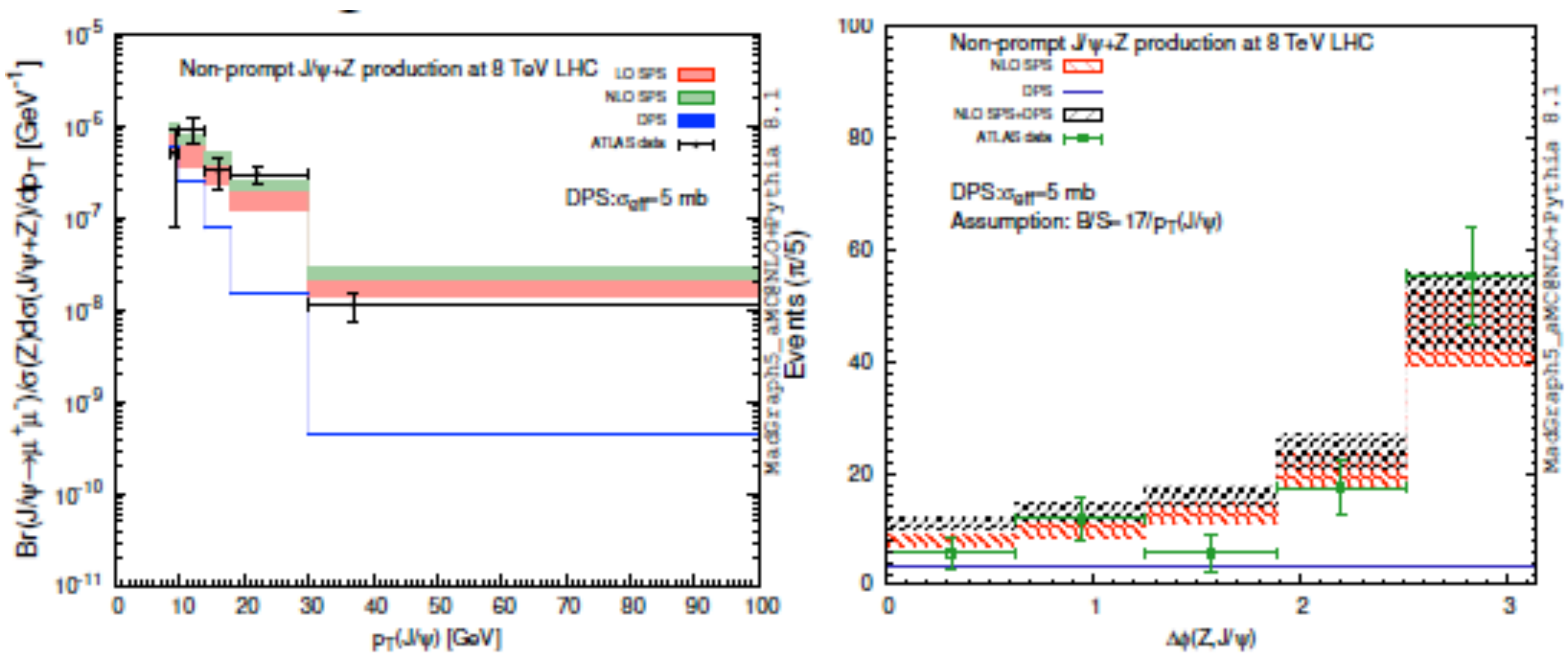
- Azimuthal angular can be described well with SPS+DPS
- Refine the sigma effective



# NONPROMPT J/PSI+Z: NLO+PYTHIA8 VS DATA

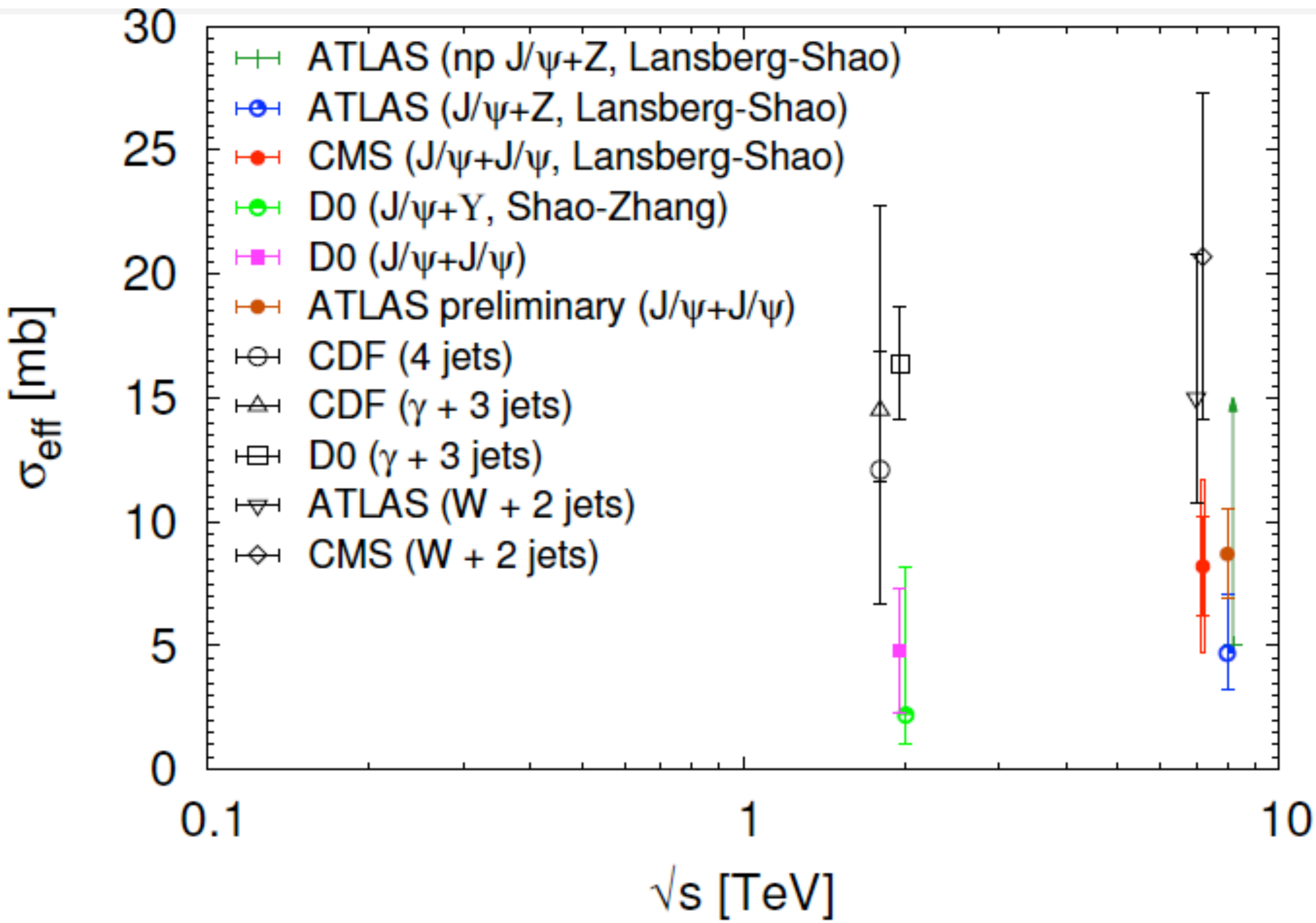
Lansberg, HSS '17

- In the same analysis, ATLAS reported on Z+nonprompt J/psi
- This gives an original handle on Z+b at lower $P_T$ than b-jets
- Interesting check that nothing went wrong with the prompt analysis
- SPS predictions were absent at the time. We filled the gap using MadGraph5_aMC@NLO and Pythia 8.1.




- In general, SPS is dominant here, which helps to refine the lower limit of the effective sigma.

# DPS IN QUARKONIUM PRODUCTION: CONCLUSION




4 quarkonium extractions using theory ingredients