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DOUBLE-QUARKONIUM PRODUCTION: QCD CORRECTIONS AND DPS

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BASED ON WORK WITH
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QUARKONIUM2016, ECT*, TRENTO
02 MARCH 2016

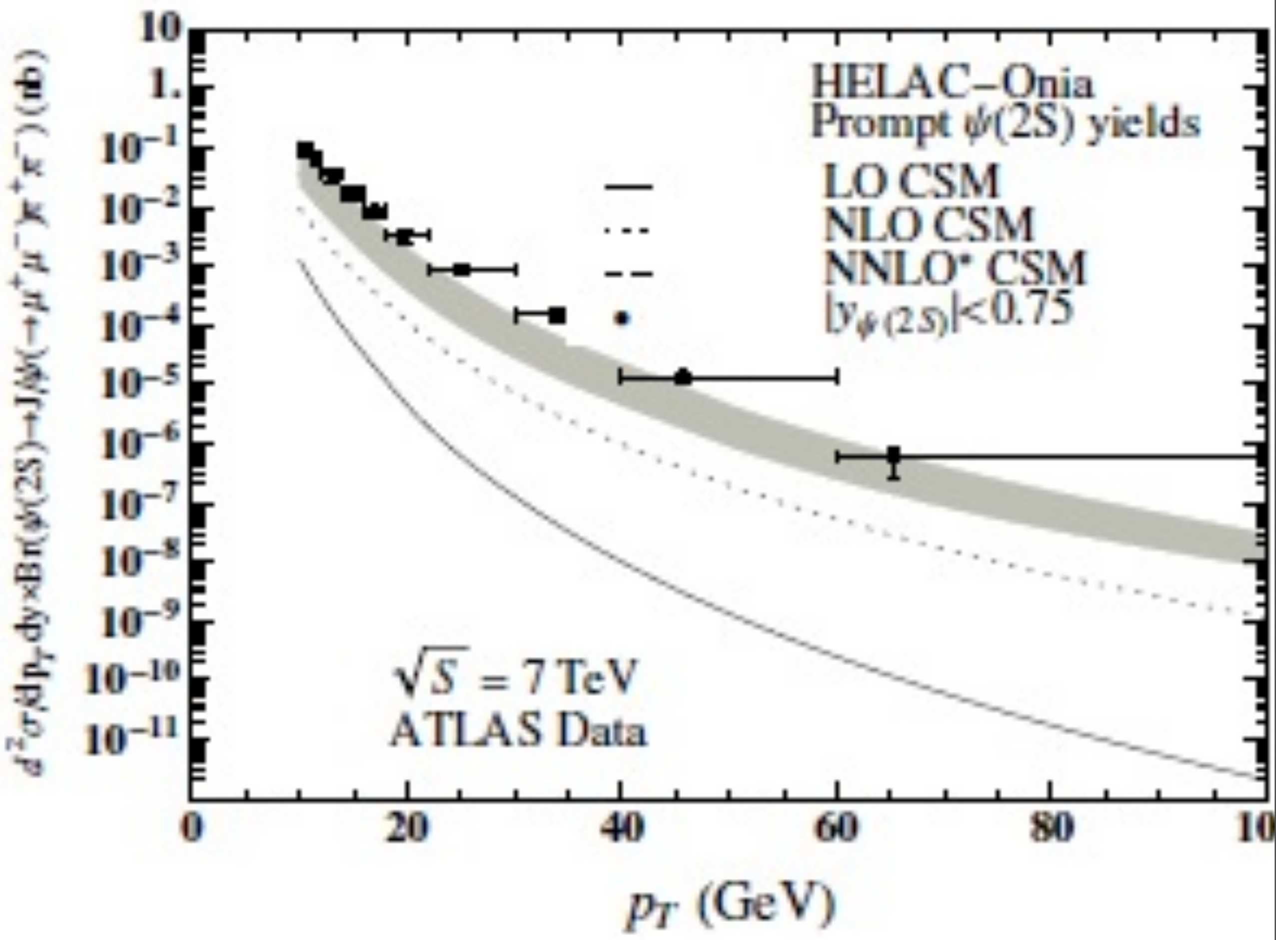
WHY DOUBLE-QUARKONIUM PRODUCTION ?

- Based on LO computations, J/ψ-pair production was proposed as a probe of COM.
- The CO+CO channels depend on the square of the CO transition probability.
- J/ψ - pair production was then discussed as a way to probe Double-Parton Scatterings at the Tevatron and the LHC.
- A "proposed" good channel to search η_b or to look for 4c tetraquark.
- It is easy to trigger at the Tevatron and the LHC. In fact, data already exist (from LHCb, D0 and CMS) and ongoing at ATLAS and LHCb.

IS A LO CALCULATION SUFFICIENT ?

A Lesson:

- In single prompt ψ hadroproduction, it is known that a large P_T -enhancement appears at higher-order in α_s.
- A higher power of α_s can be compensated by a less rapid fall off with P_T. [Campbell, Maltoni, Tramontano (2007); Artoisenet, Lansberg, Maltoni (2007)]



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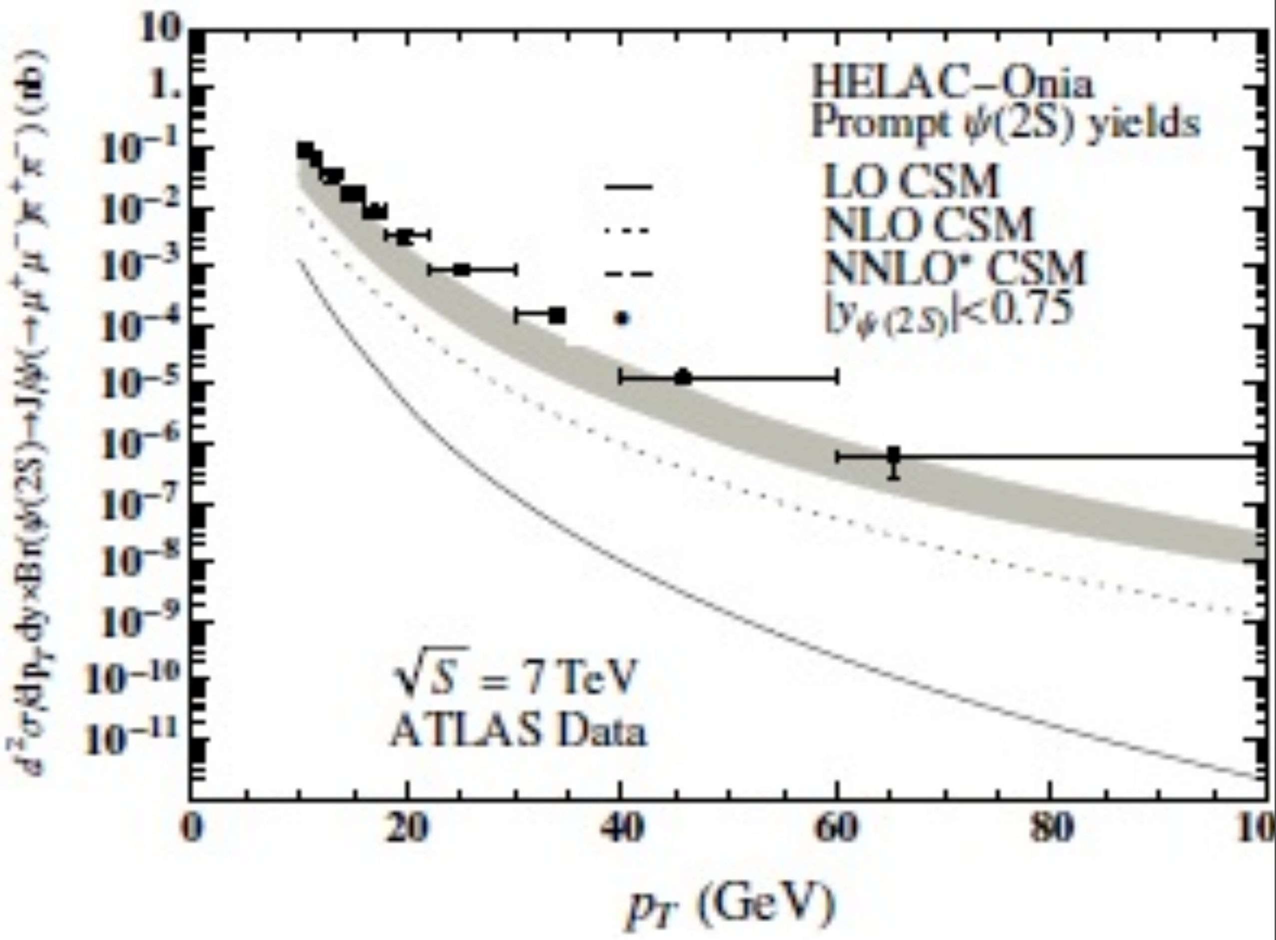
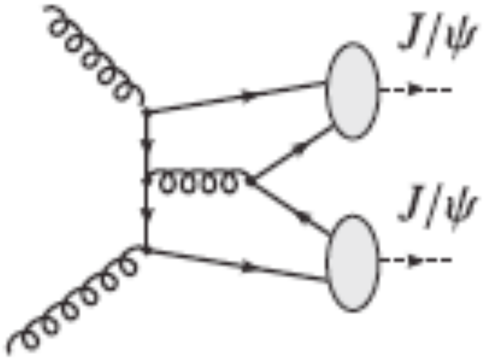


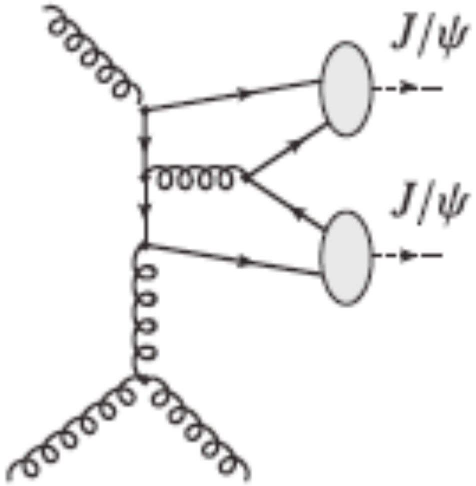
This should happen in J/ψ-pair production at large momenta !!!

QCD CORRECTIONS TO SPS

Lansberg, HSS (2013)



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



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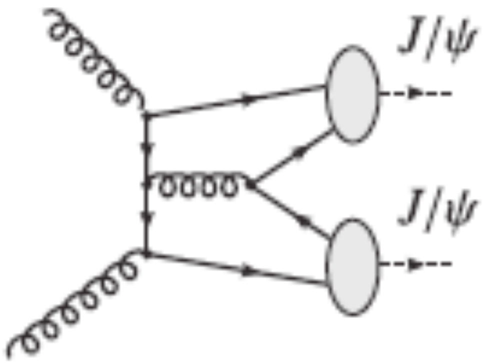

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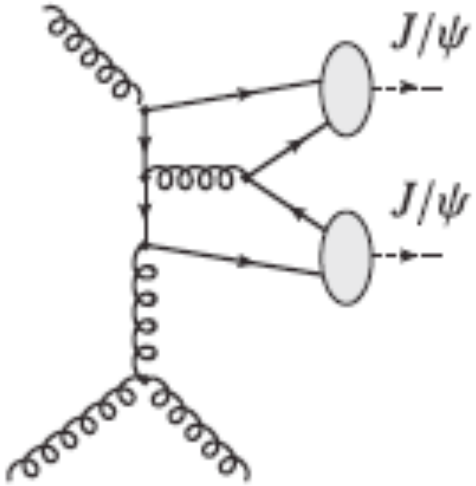

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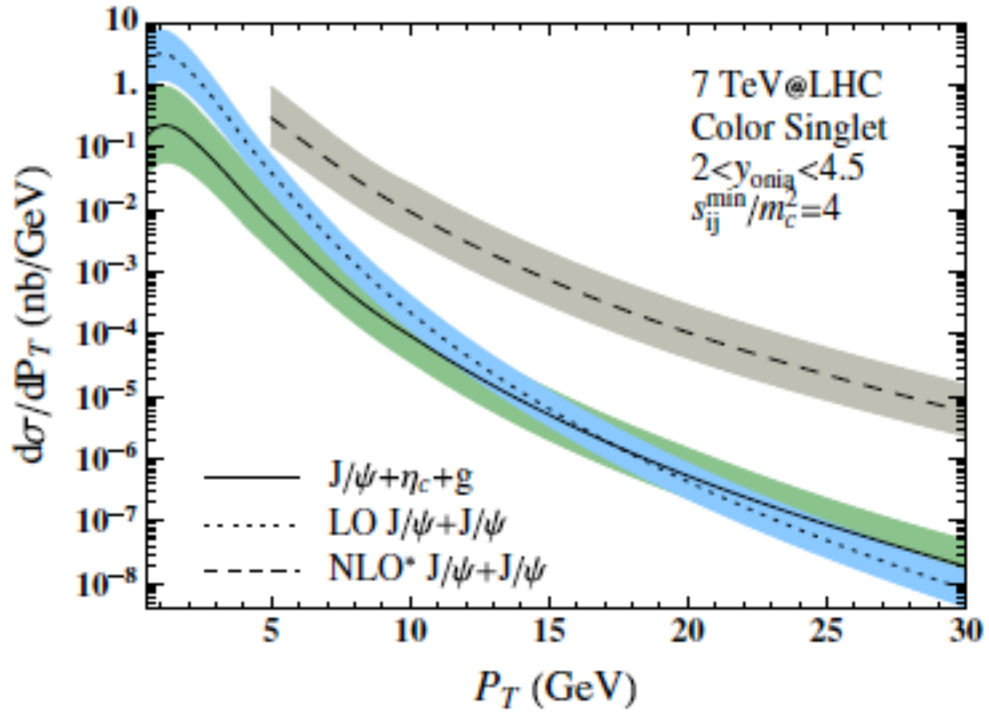
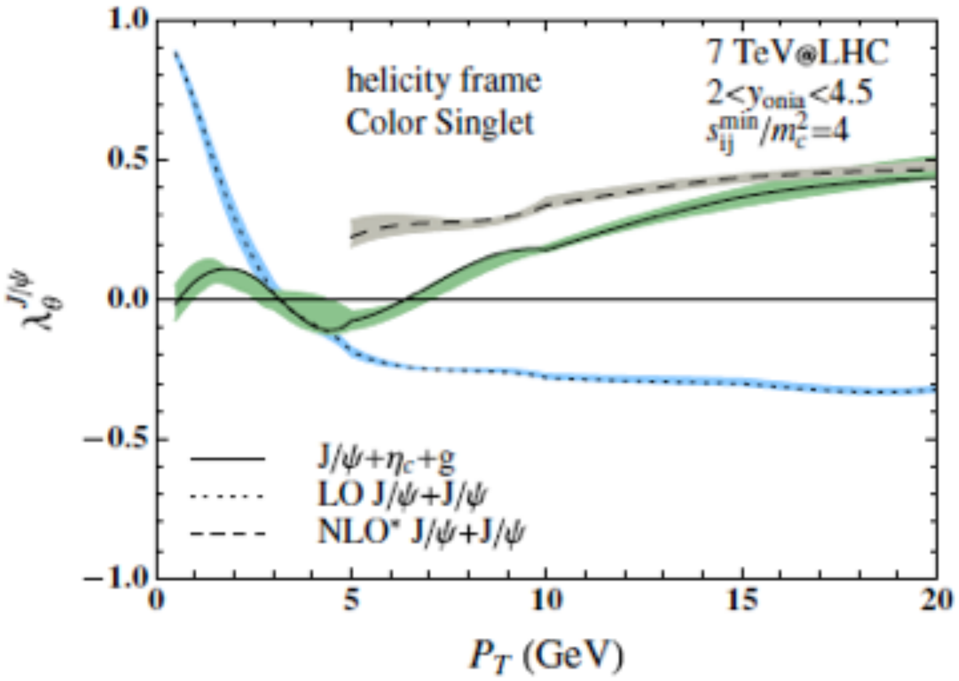
- For the first time, we calculated the leading-P_T contribution at α_s^5 with **HELAC-Onia** [HSS, CPC '13,'15].
- It was nicely confirmed by a complete NLO calculation [Sun, Han, Chao, '14].





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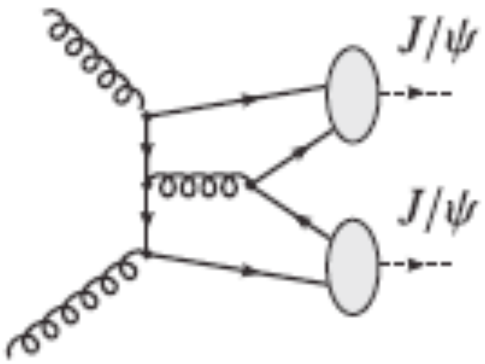

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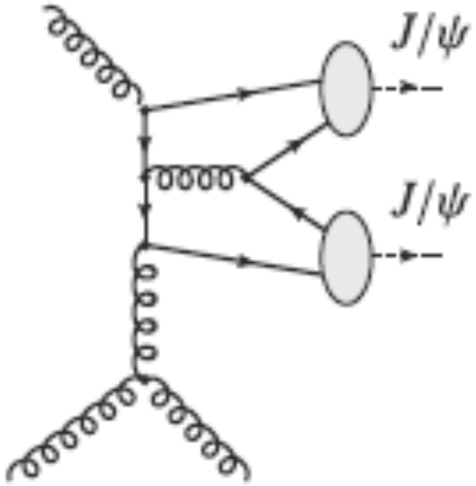

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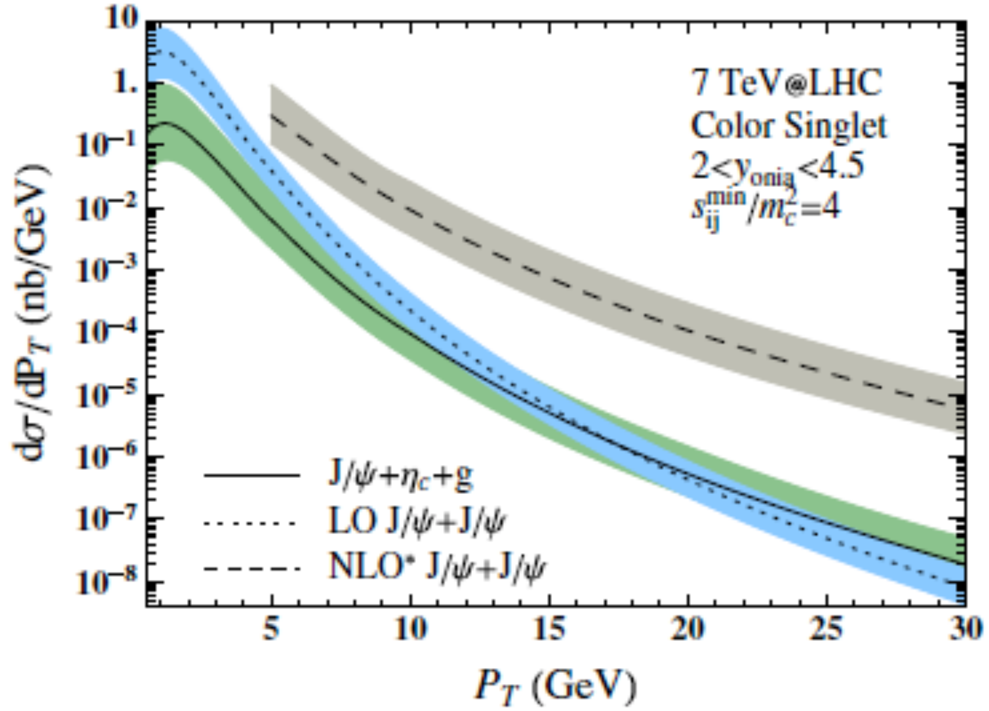
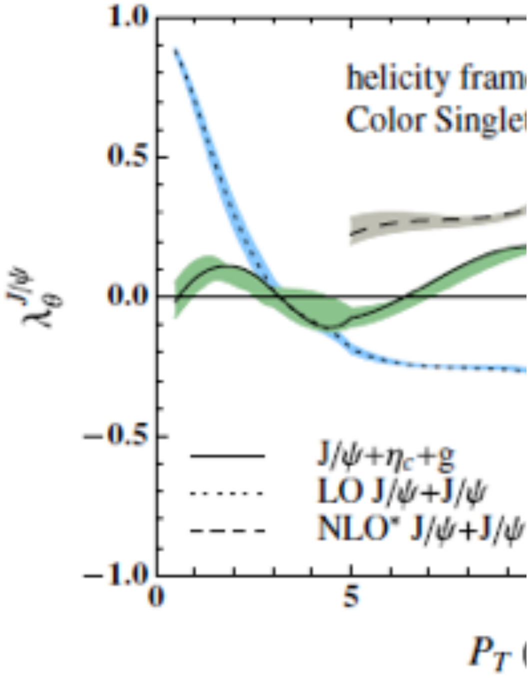
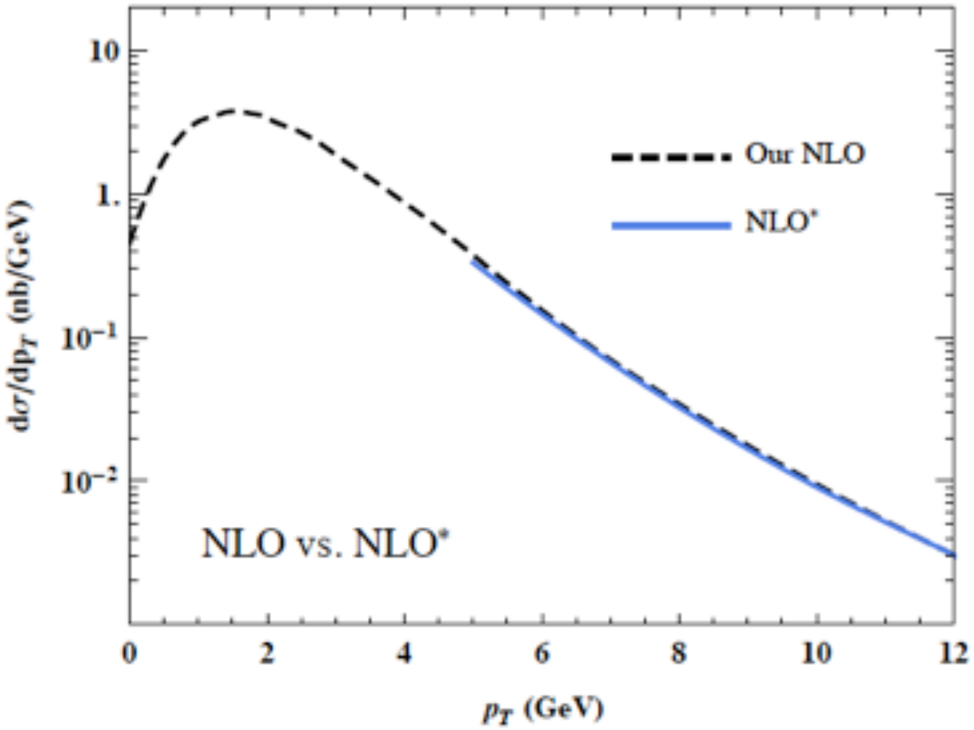
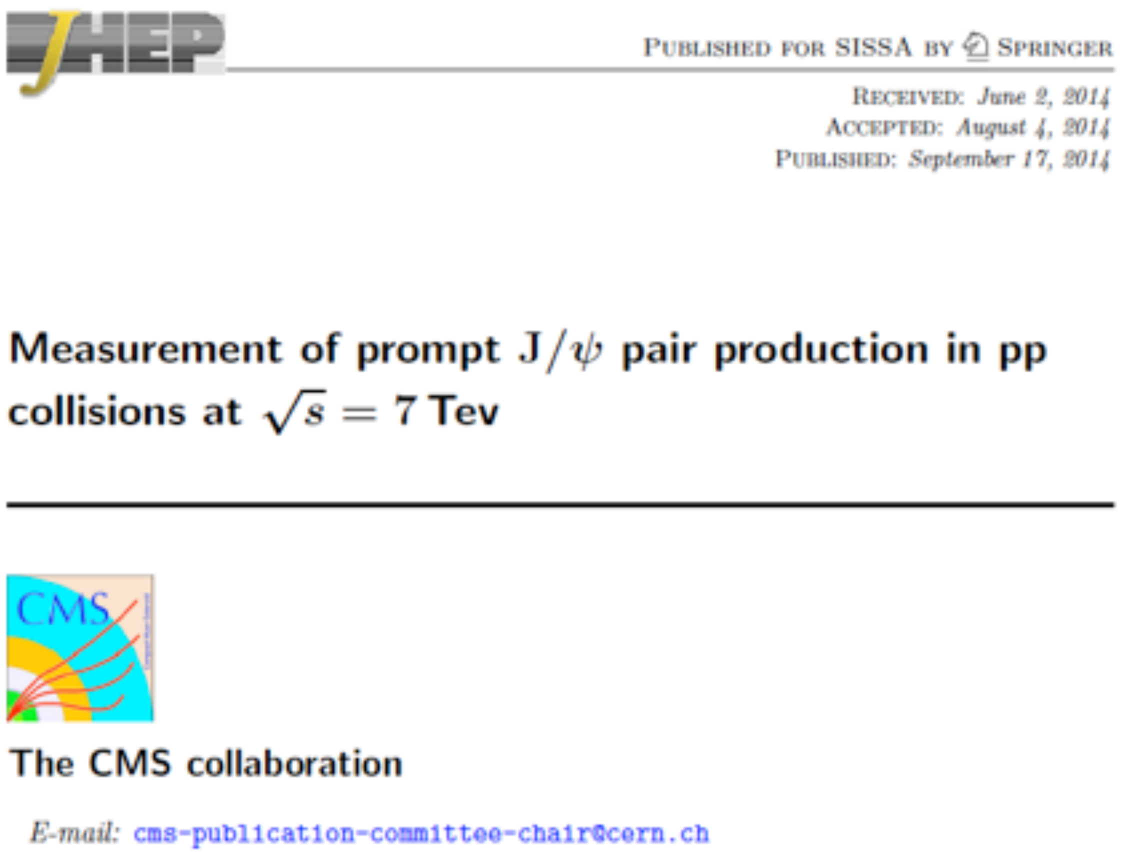






EVIDENCE OF DPS ?



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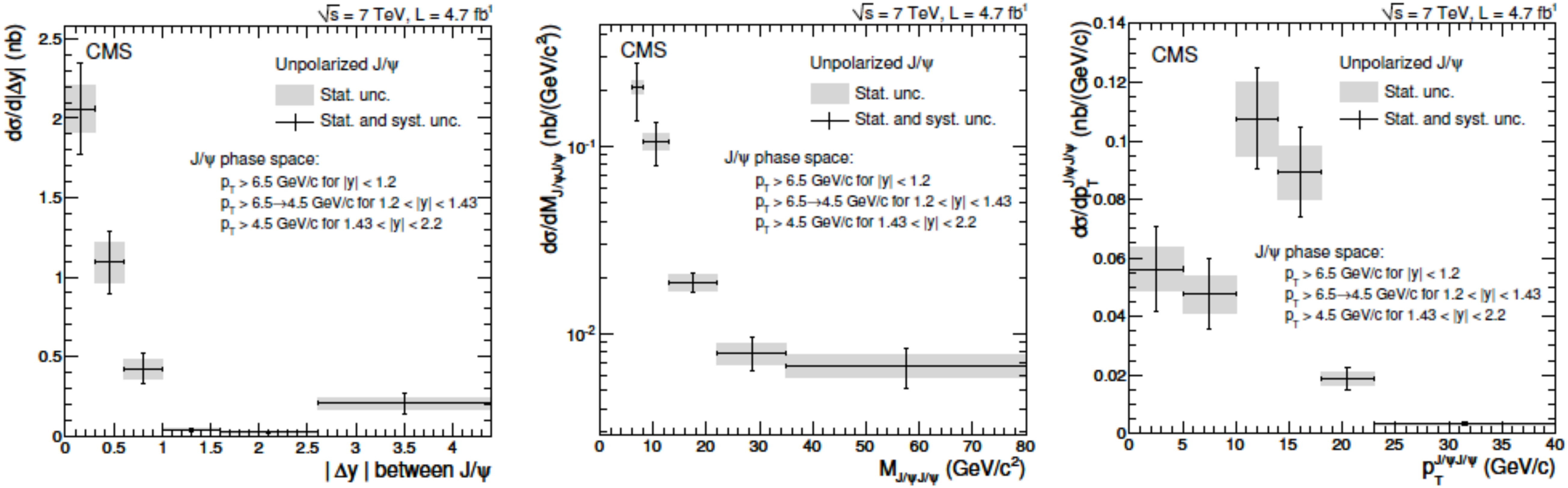
Measurement of prompt J/ψ pair production in pp collisions at $\sqrt{s} = 7$ Tev

The CMS collaboration

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



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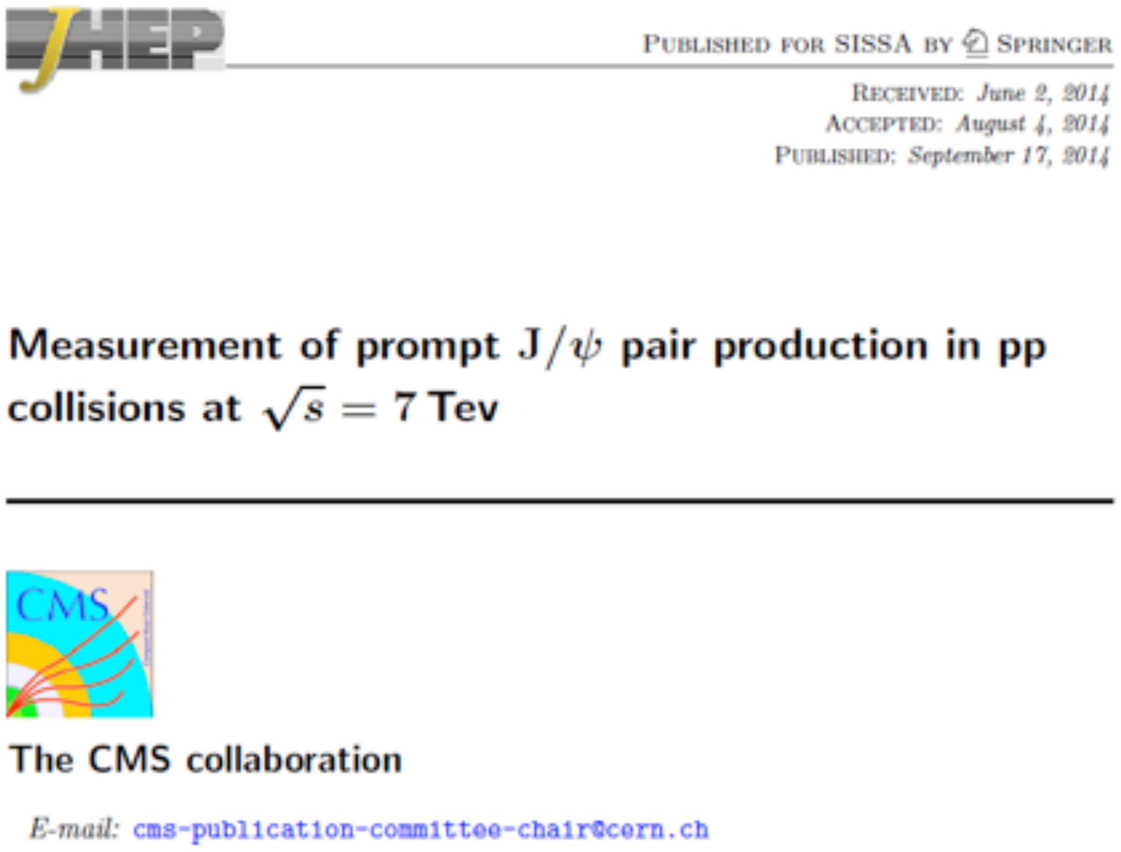

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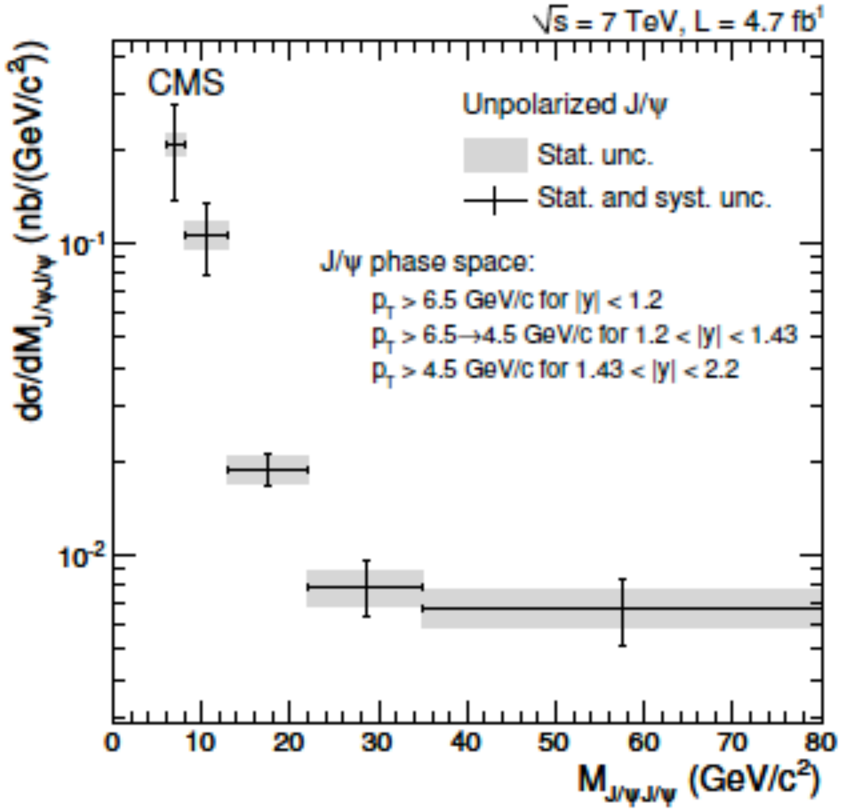
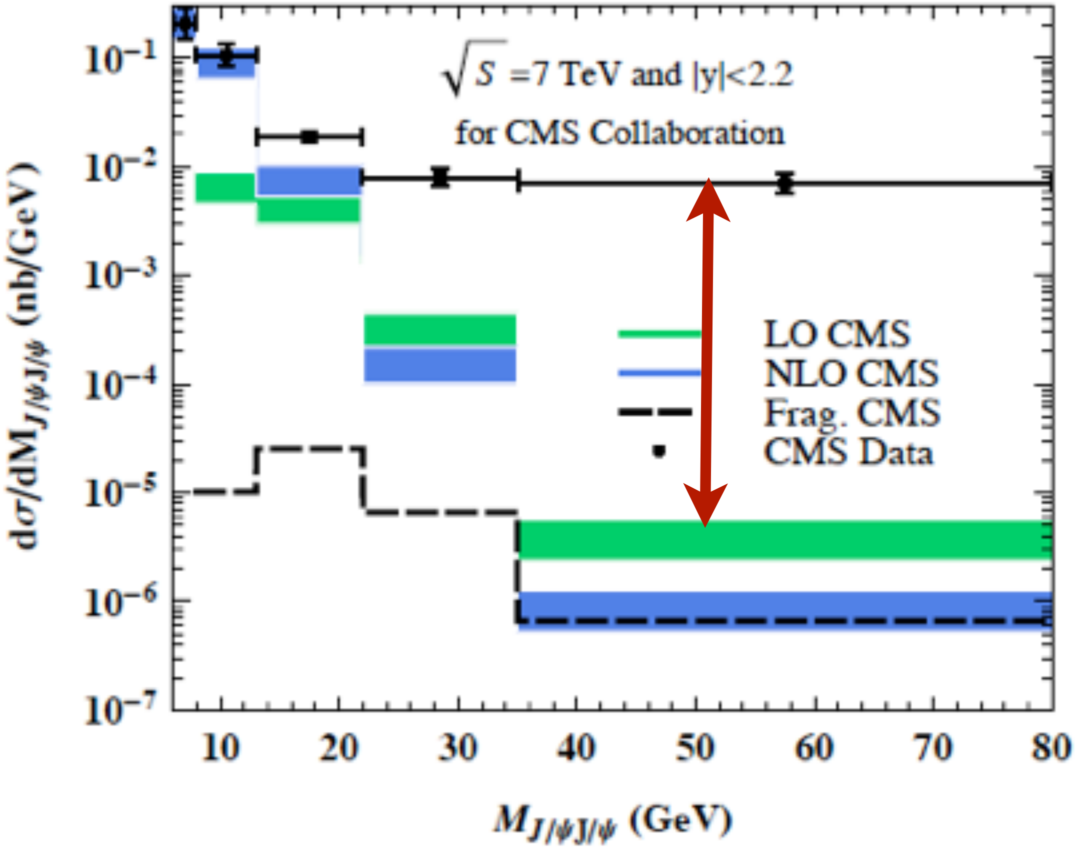


- Large discrepancy found with NLO-level Single-Parton Scatterings [Sun, Han, Chao, '14].



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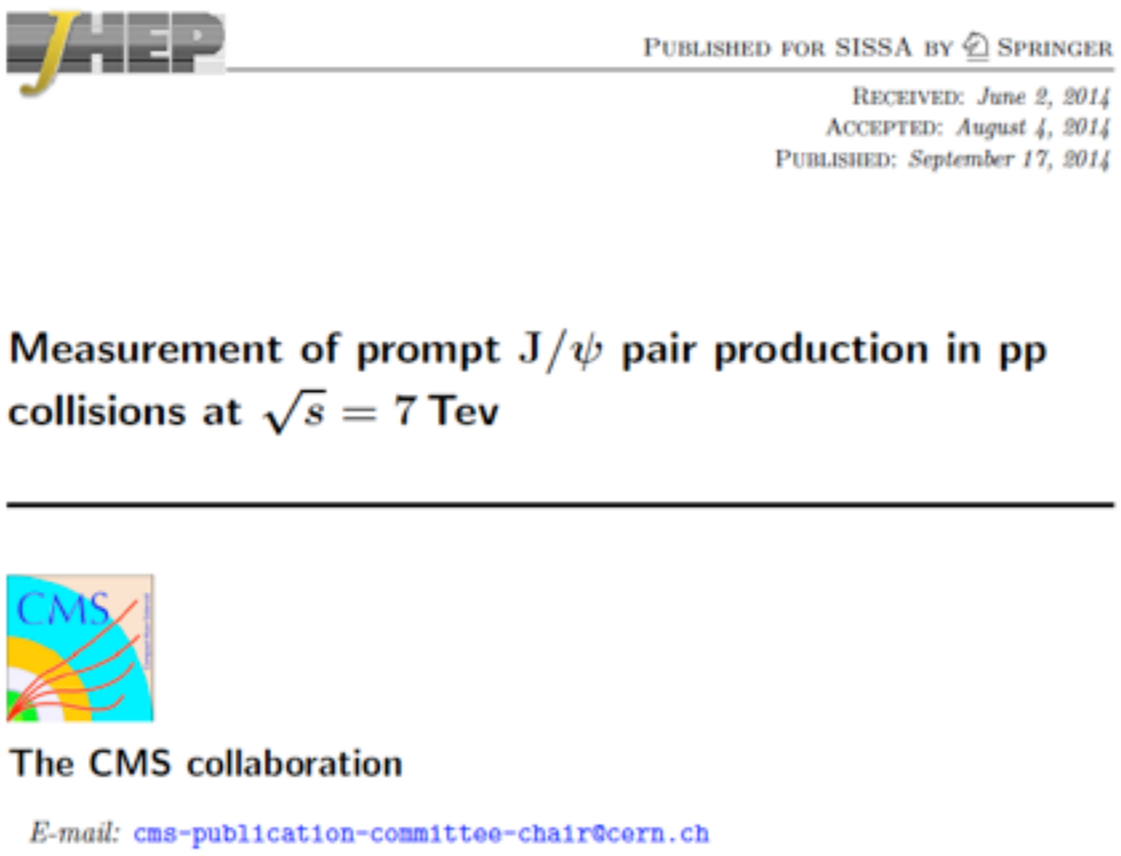

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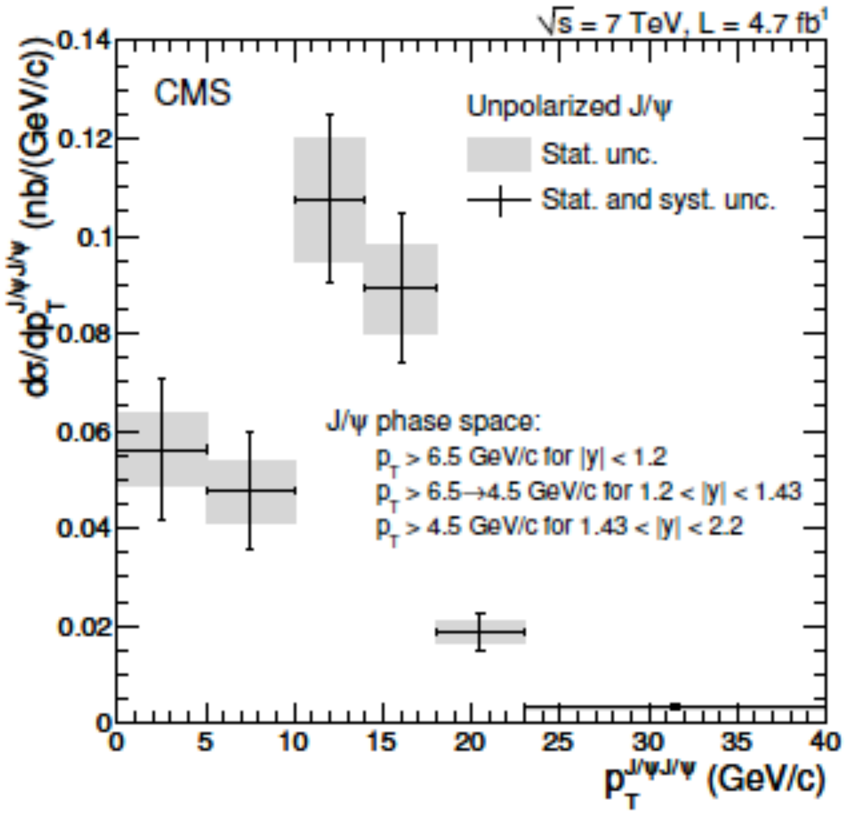

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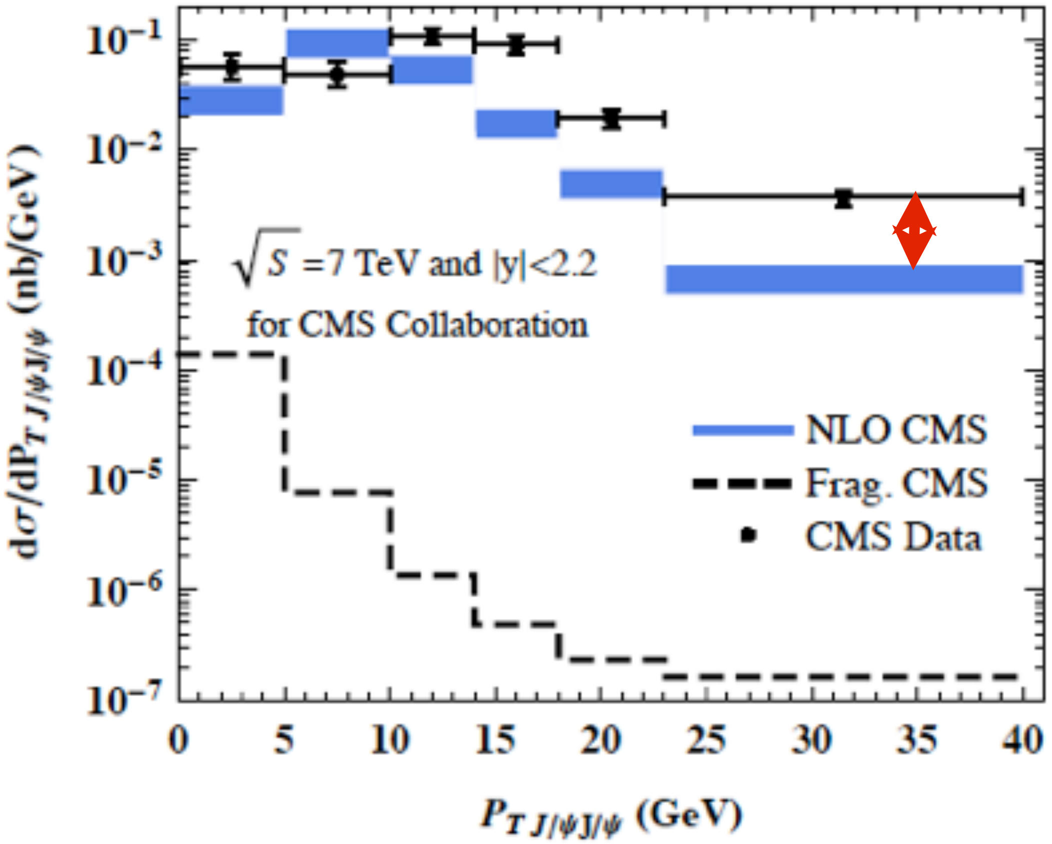
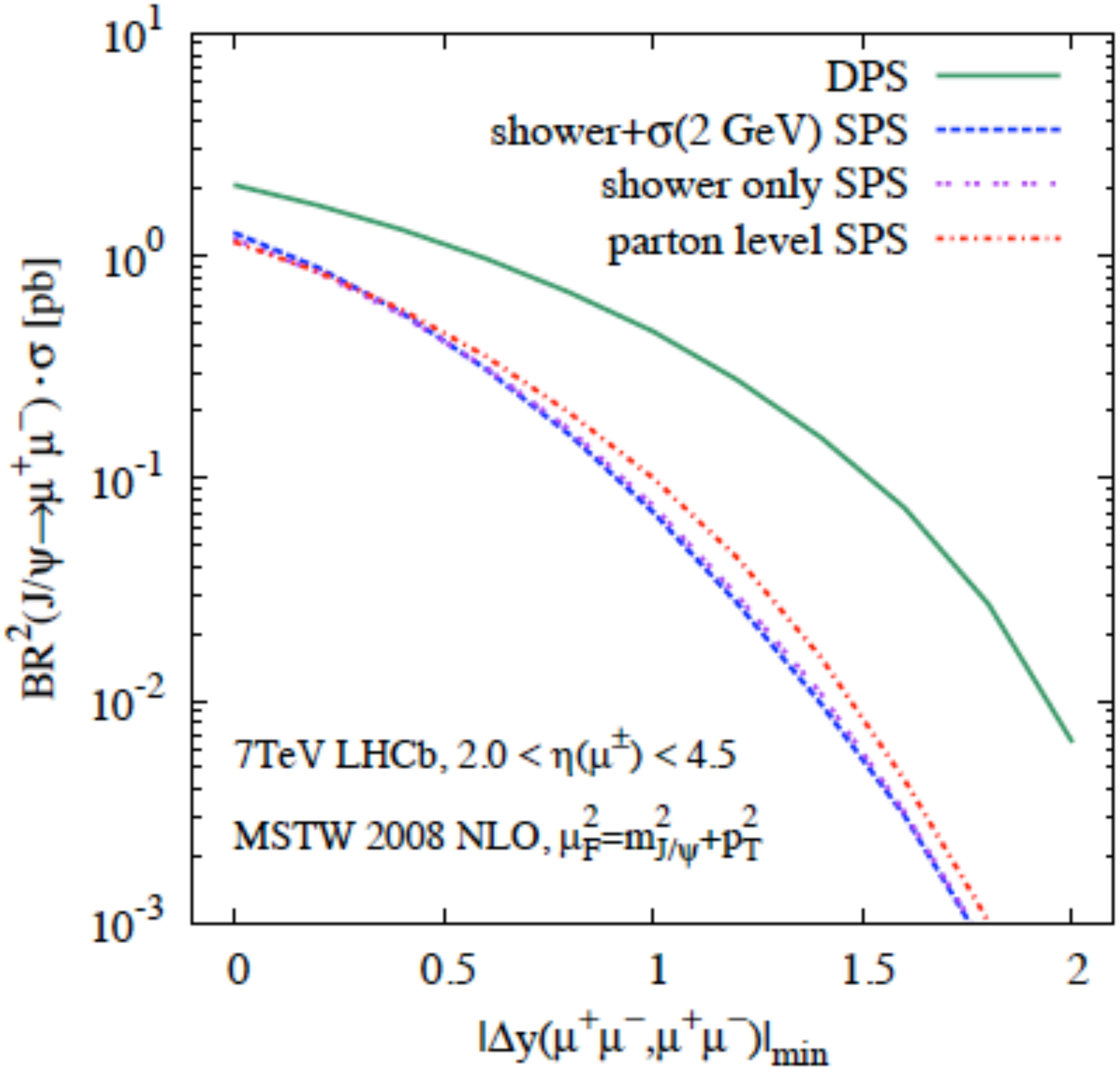


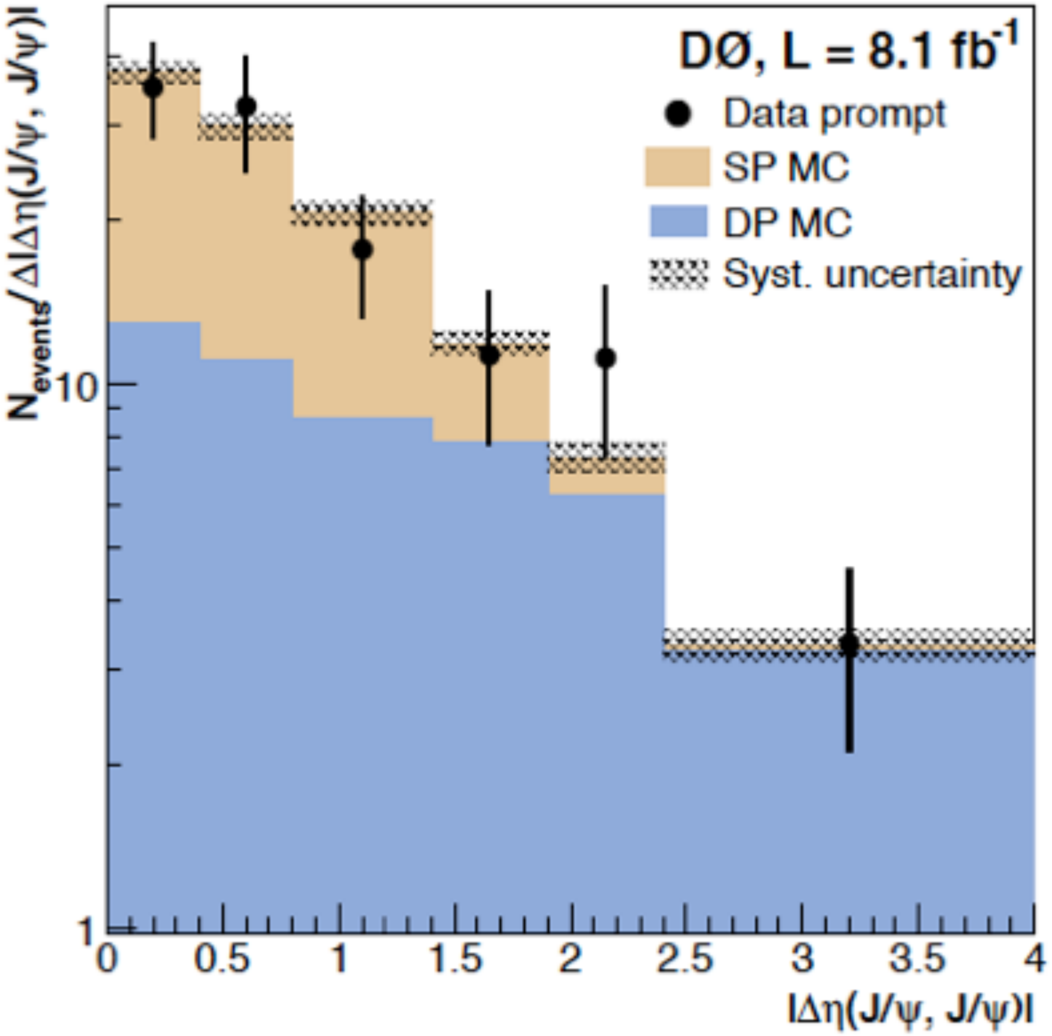
DPS IN DZERO MEASUREMENT

- 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/ψ at Tevatron and separated SPS and DPS for the first time.



J/ψ-Pair Production at Large Momenta: Indications for Double-Parton Scatterings and Large α_s^5 Contributions

PLB751(2015)479

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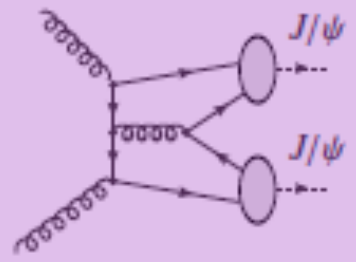
[a] IPNO, Université Paris-Sud, CNRS/IN2P3,
Department of Physics and State Key Laboratory of Nuclear Physics and
[c] PH Department, TH Unit, CERN, CH-1211,

	$\sigma^{\rm prompt}_{\rm exp.}$	$\sigma^{\rm LO,direct}_{\rm SPS}$	$\sigma^{\rm NLO,direct}_{\rm SPS}$	$\sigma^{\rm NLO,prompt}_{\rm SPS}$	$\sigma^{\rm prompt}_{\rm DPS}$
LHCb	18 ± 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 ± 23 DPS: 59 ± 23	$28.9^{+30.7}_{-14.5}$	91^{+177}_{-55}	173^{+335}_{-105}	87^{+106}_{-31}
CMS	5.25 ± 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.]



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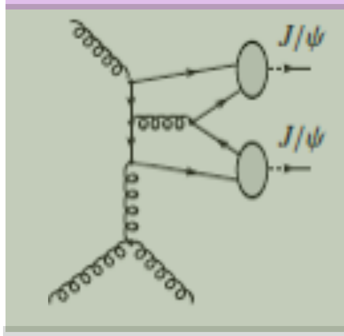

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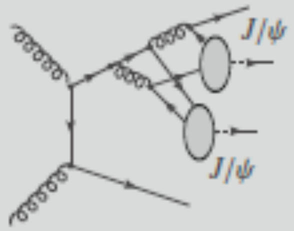
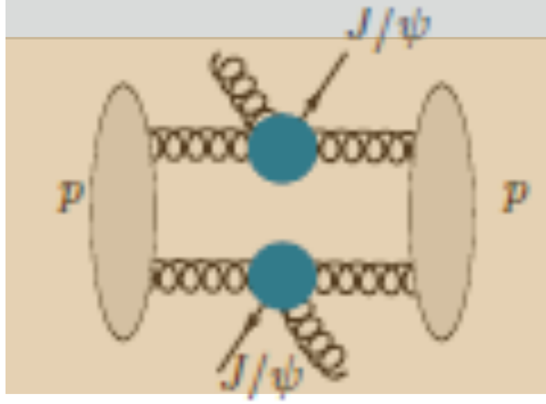


$$\sim \alpha_s^5 \left(\frac{m_\psi}{P_T^\psi}\right)^4$$

S P S

- Using the D0 data to fix the DPS parameter
- If one used the DO data to fixe the DPS yield, DPS and SPS are comparable in the CMS acceptance.



D P S

- Large pT: CMS and D0 measurements imply a large DPS yield.
- Small pT: LHCb data do NOT imply a large DPS yield

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:

$$\mathcal{A}_{ab\to \mathcal{Q}_1^{\lambda_1}(P_1)+\mathcal{Q}_2^{\lambda_2}(P_2)+X} = \sum_{s_1,s_2,c_1,c_2}\sum_{s_3,s_4,c_3,c_4} \underbrace{\frac{N(\lambda_1|s_1,s_2)N(\lambda_2|s_3,s_4)}{\sqrt{M_{Q_1}M_{Q_2}}}}_{\text{spin projector}}\underbrace{\frac{\delta_{c_1c_2}\delta_{c_3c_4}}{N_c}}_{\text{color proj.}}\frac{\overbrace{R_1(0)R_2(0)}^{\text{WF@Orig or LDME}}}{4\pi}\underbrace{\mathcal{A}_{ab\to Q_{c_1}^{s_1}\bar{Q}_{c_2}^{s_2}(\mathbf{p}_1=0)+Q_{c_3}^{s_3}\bar{Q}_{c_4}^{s_4}(\mathbf{p}_2=0)+X}}_{\text{four-quark amp.}}, \tag{10}$$

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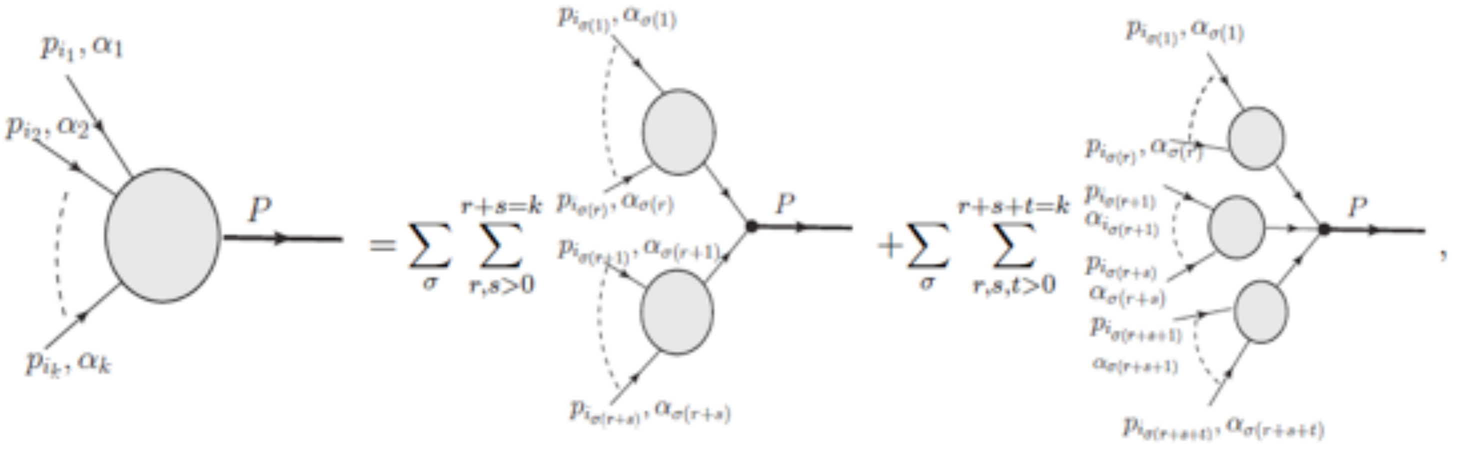
  - via recursion relations



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

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 the general formula via

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}}\sum_{i,j,k,l}\int dx_1dx_2dx'_1dx'_2d^2\mathbf{b}_1d^2\mathbf{b}_2d^2\mathbf{b} \times \Gamma_{ij}(x_1,x_2,\mathbf{b}_1,\mathbf{b}_2)\,\hat{\sigma}^{Q_1}_{ik}(x_1,x'_1)\,\hat{\sigma}^{Q_2}_{jl}(x_2,x'_2)\,\Gamma_{kl}(x'_1,x'_2,\mathbf{b}_1-\mathbf{b},\mathbf{b}_2-\mathbf{b}),$$

Generalised double distribution

Single-quarkonium parton-level XS

- Factorization I $\Gamma_{ij}(x_1,x_2,\mathbf{b}_1,\mathbf{b}_2) = D_{ij}(x_1,x_2)T_{ij}(\mathbf{b}_1,\mathbf{b}_2),$

dPDF

- Factorization II $D_{ij}(x_1,x_2) = f_i(x_1)f_j(x_2),$

$$T_{ij}(\mathbf{b}_1,\mathbf{b}_2) = T_i(\mathbf{b}_1)T_j(\mathbf{b}_2),$$

PDF

- 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

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

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

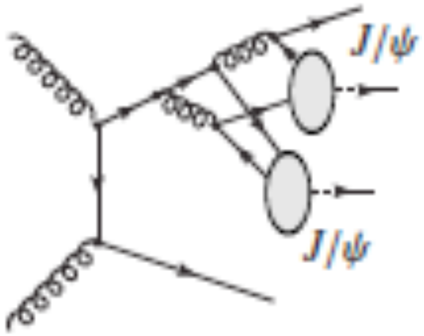
- Normally, σ_{eff} is thought to be universal, i.e. process&energy independent. **However, is it always true ?**
- Since no satisfying solution to describe single-quarkonium production cross sections σ_{ψ}, we decide to use a data-driven way because a lot of single quarkonium data are available.
- By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

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

$$K = \lambda^2\kappa\hat{s}/M_Q^2.$$

OTHER CONTRIBUTIONS: SPS

- Beyond NLO contributions (new fragmentation topology):

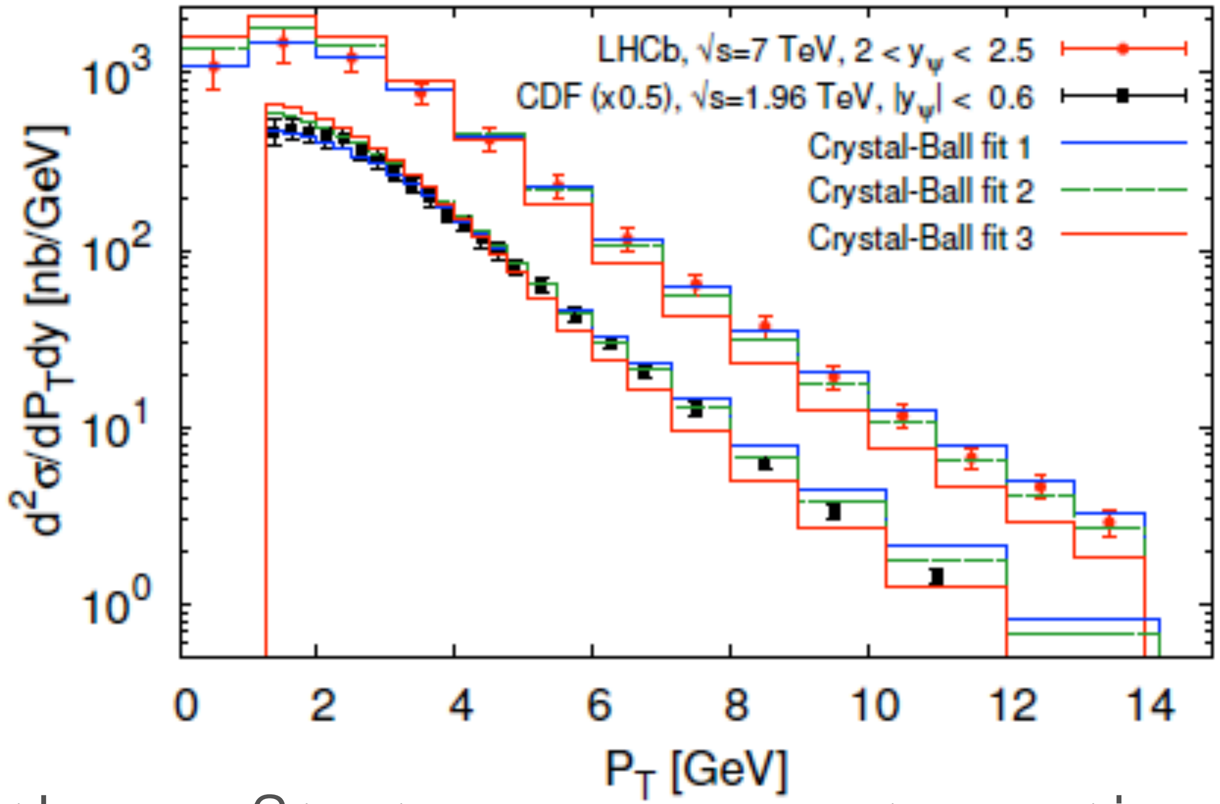


$$\sim \quad \alpha_s^5 \left(\frac{m_\psi}{P_T^\psi}\right)^4$$

- 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/ψ cross sections input from fits of existing data



- We used three fits to assess systematical uncertainties.

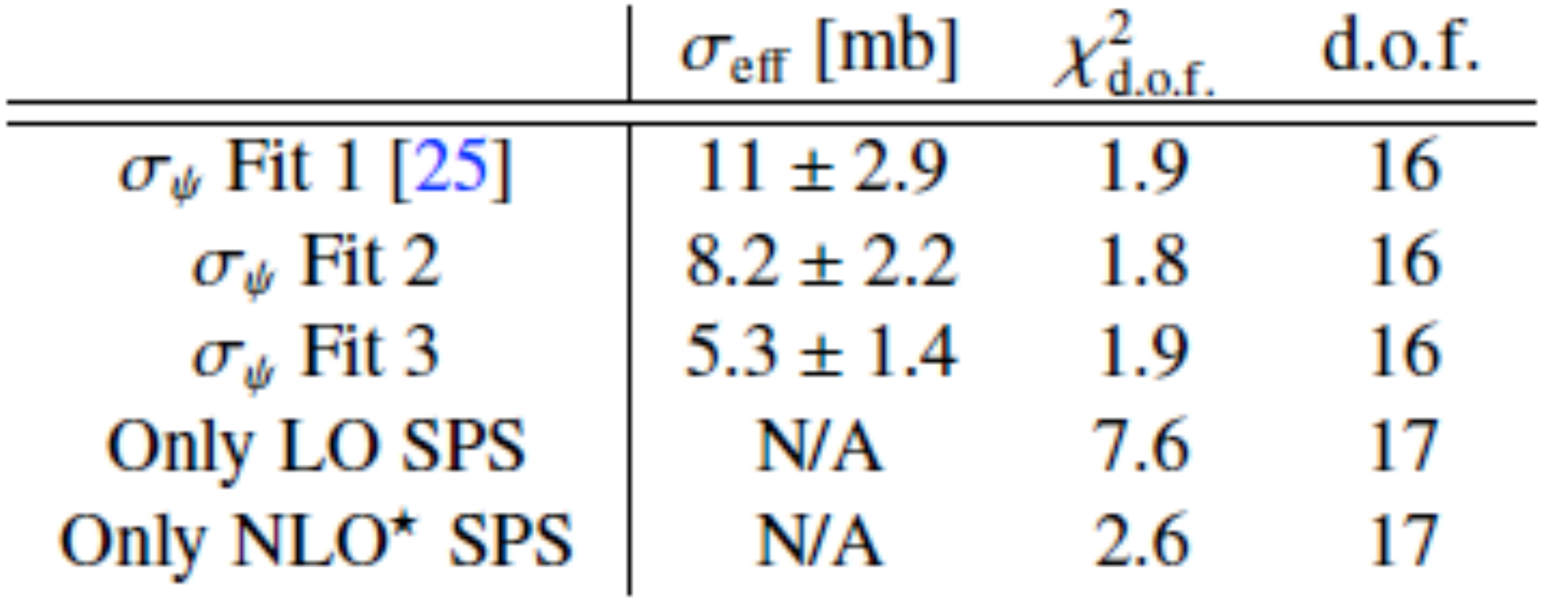
- Together with $\sigma_{\rm eff}$, they allow to predict $\sigma_{\rm DPS}$.

- 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

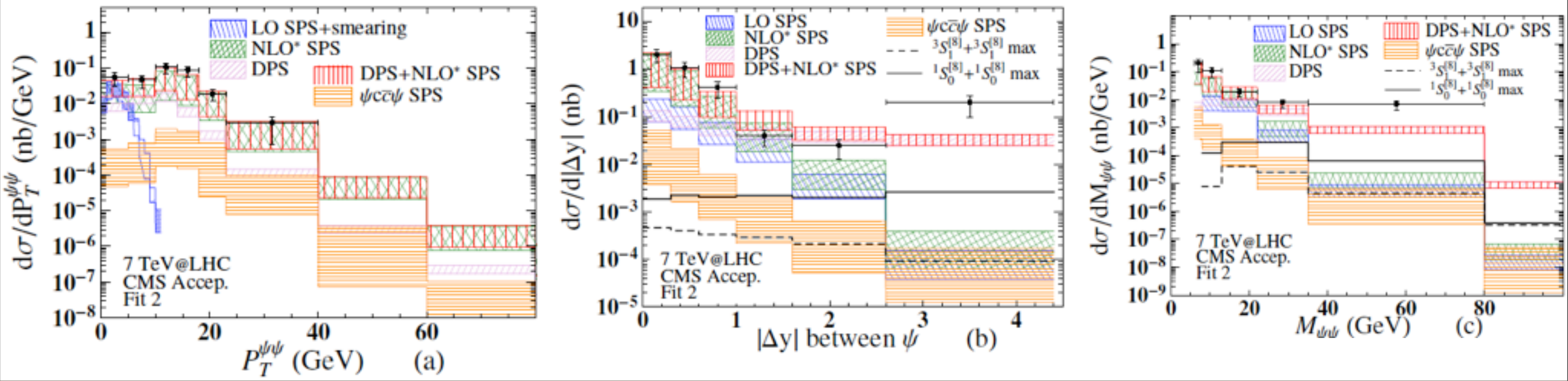
- $p_T^{\psi\psi}, |\Delta y_{\psi\psi}|$ & $M_{\psi\psi}$ distributions are fitted



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



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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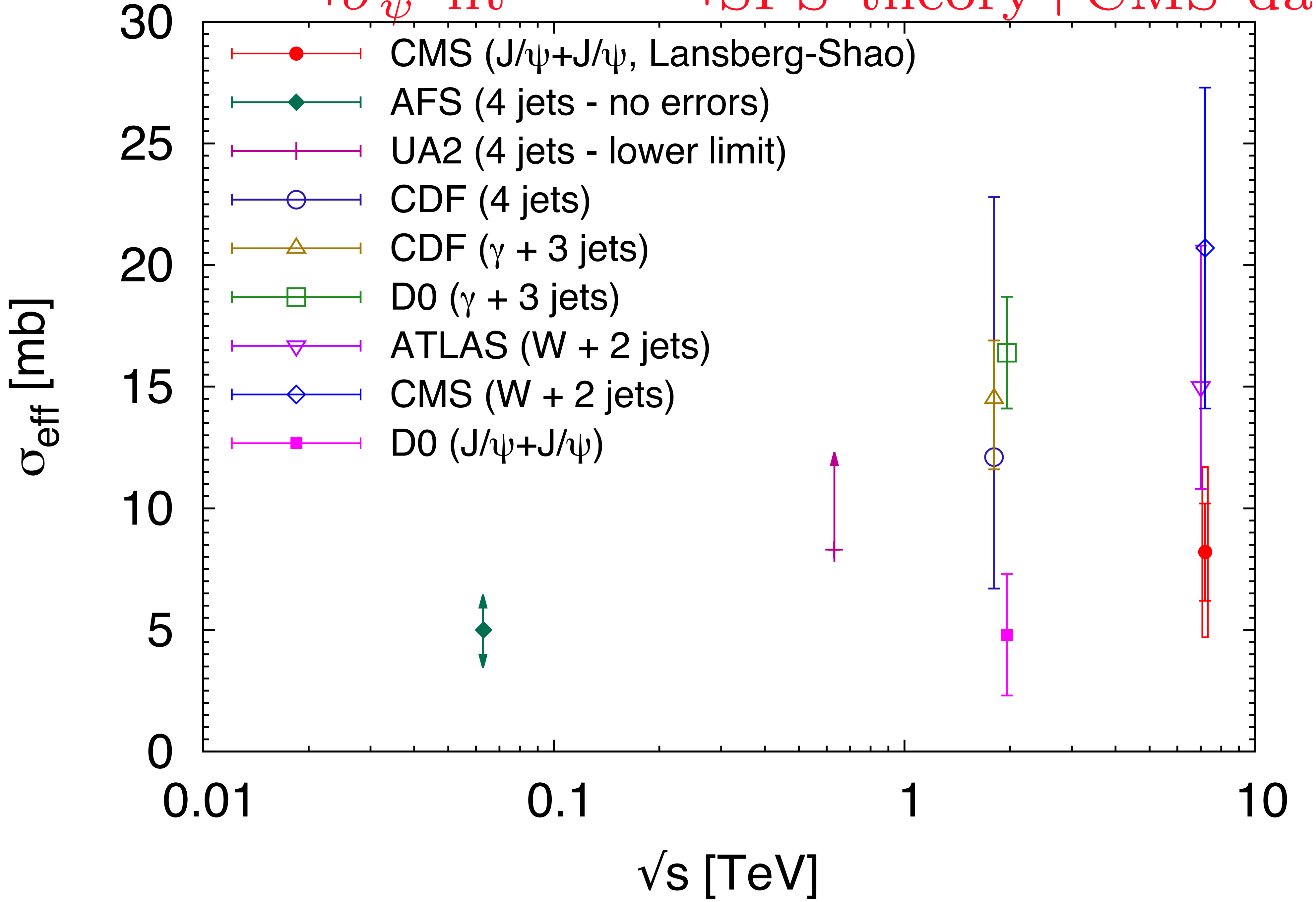


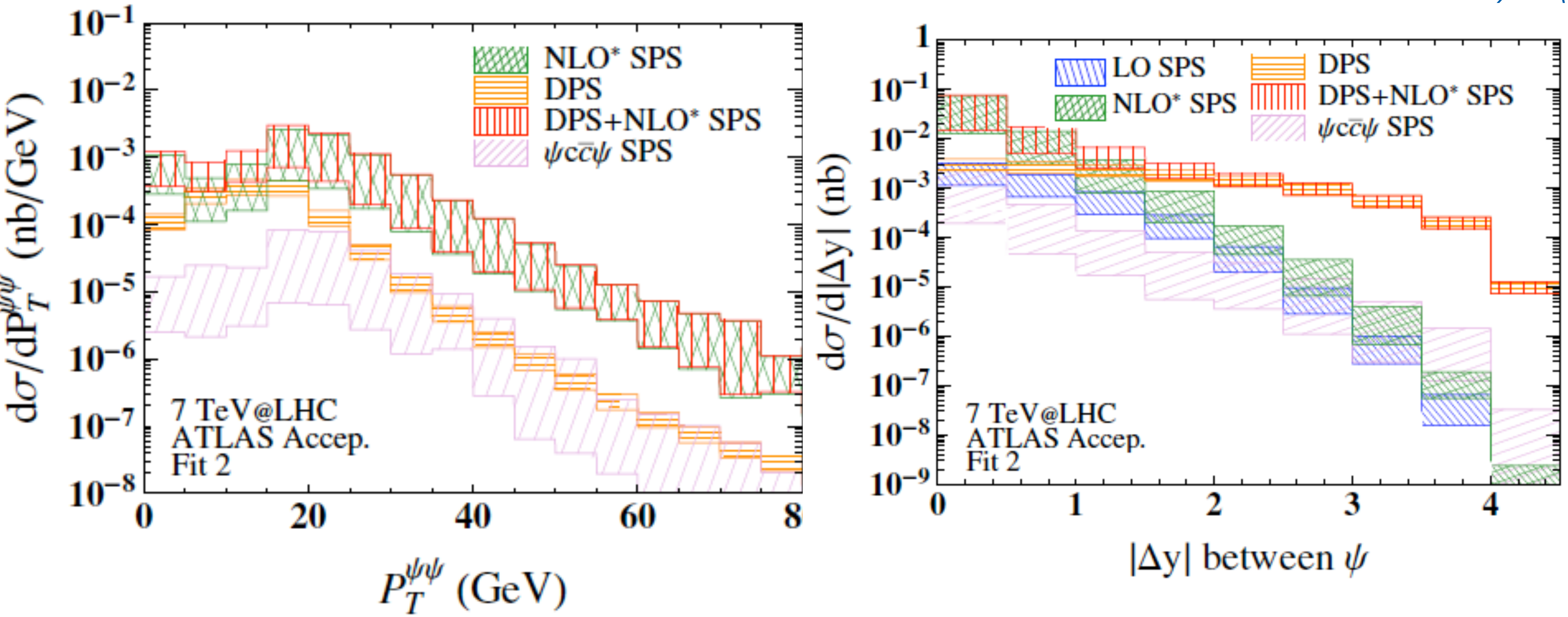
OUR EXTRACTION OF SIGMA_EFF

- Combining our three fits, we obtain

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

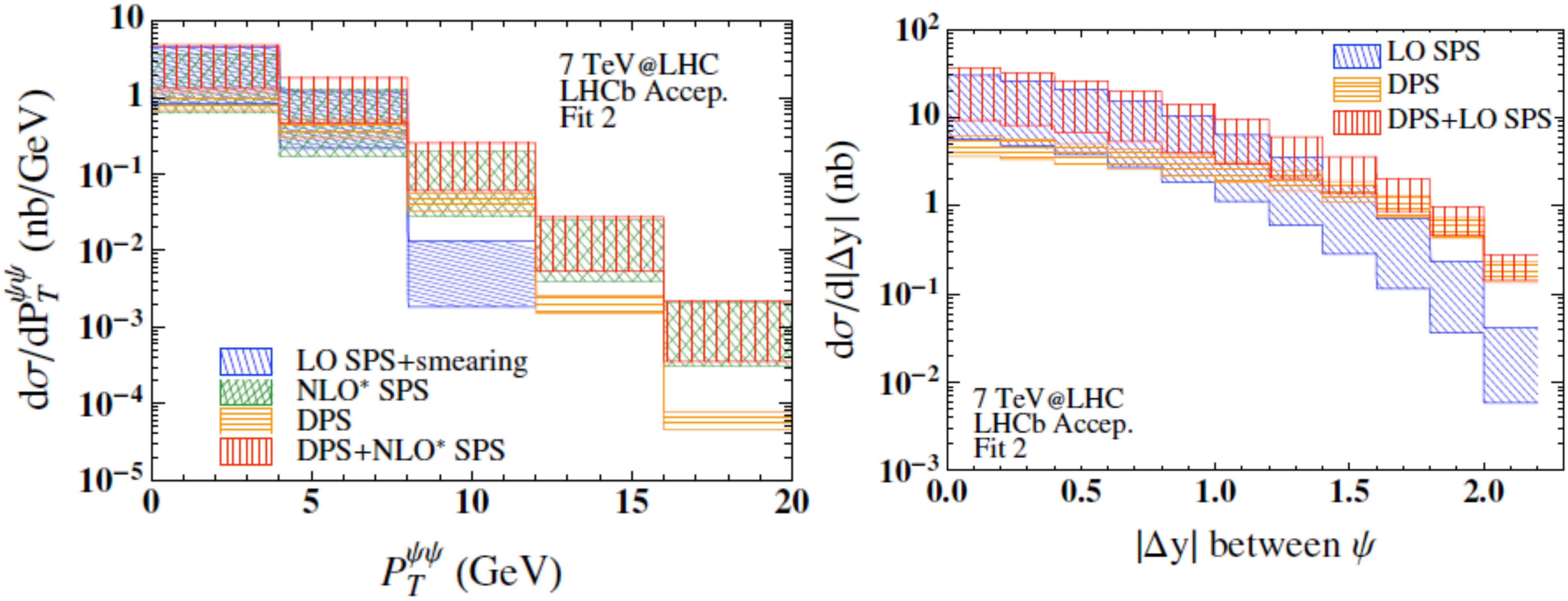
- The SPS theory uncertainty can in principle be removed by measuring a DPS cross section (as done by D0).
- The CMS data uncertainty can be reduced with more double quarkonium data.
- The last uncertainty is of course more tricky to deal with.
- Our extraction is compatible with that of D0.
- Both point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

PREDICTIONS: ATLAS & LHCB



- ATLAS data are analyzed: their wider rapidity coverage allows for a better separation of DPS v.s. SPS.

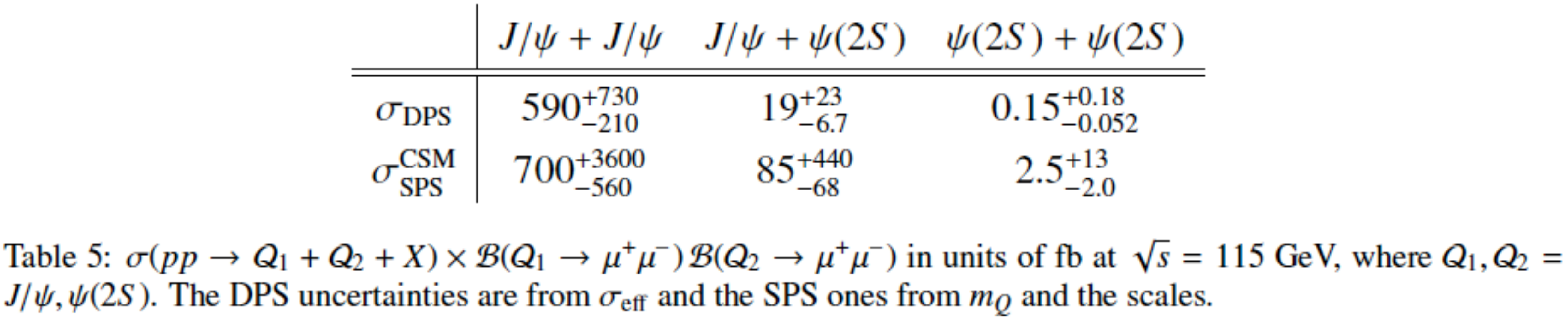
PREDICTIONS: ATLAS & LHCB



- ATLAS data are analyzed: their wider rapidity coverage allows for a better separation of DPS v.s. SPS.
- On the contrary, it might be difficult for LHCb to separate them due to the restricted rapidity range.

PREDICTIONS: AFTER@LHC

- pp collisions at sqrt(s)=115 GeV (7 TeV protons on a fixed target)
- Taking $\sigma_{\rm eff}$ extracted by D0 (5mb) as a reference number:



	$J/\psi + J/\psi$	$J/\psi + \psi(2S)$	$\psi(2S) + \psi(2S)$
$\sigma_{\rm DPS}$	590^{+730}_{-210}	$19^{+23}_{-6.7}$	$0.15^{+0.18}_{-0.052}$
$\sigma^{\rm CSM}_{\rm SPS}$	700^{+3600}_{-560}	85^{+440}_{-68}	$2.5^{+13}_{-2.0}$

Table 5: $\sigma(pp \to Q_1 + Q_2 + X) \times \mathcal{B}(Q_1 \to \mu^+\mu^-)\mathcal{B}(Q_2 \to \mu^+\mu^-)$ in units of fb at $\sqrt{s} = 115$ GeV, where $Q_1, Q_2 = J/\psi, \psi(2S)$. The DPS uncertainties are from $\sigma_{\rm eff}$ and the SPS ones from m_Q and the scales.

- With 20 fb-1/yr, there will be more than 10K $J/\psi + J/\psi$ events

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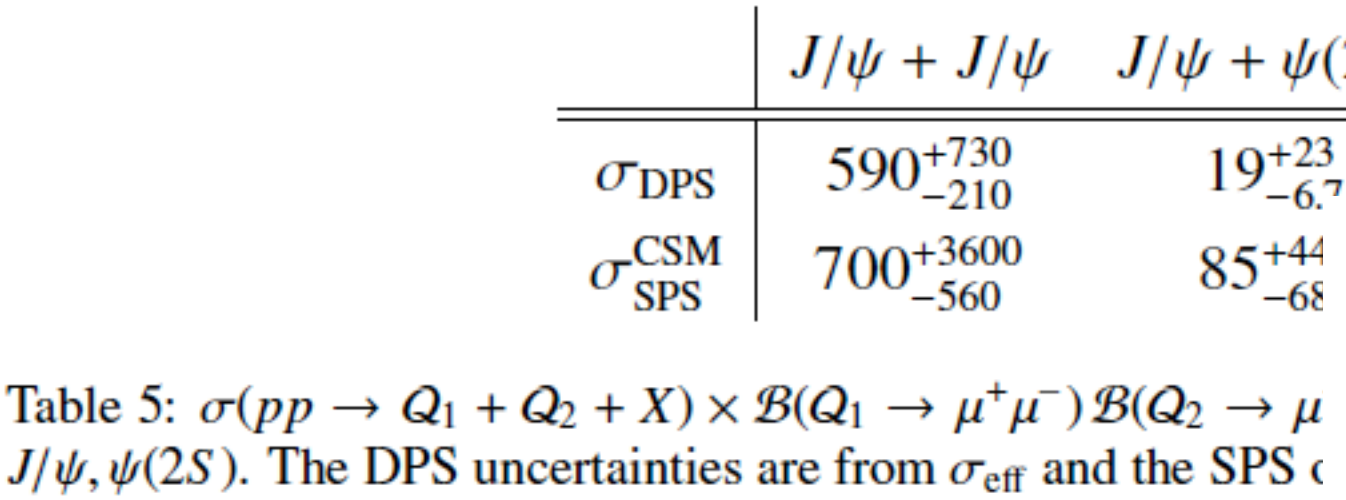

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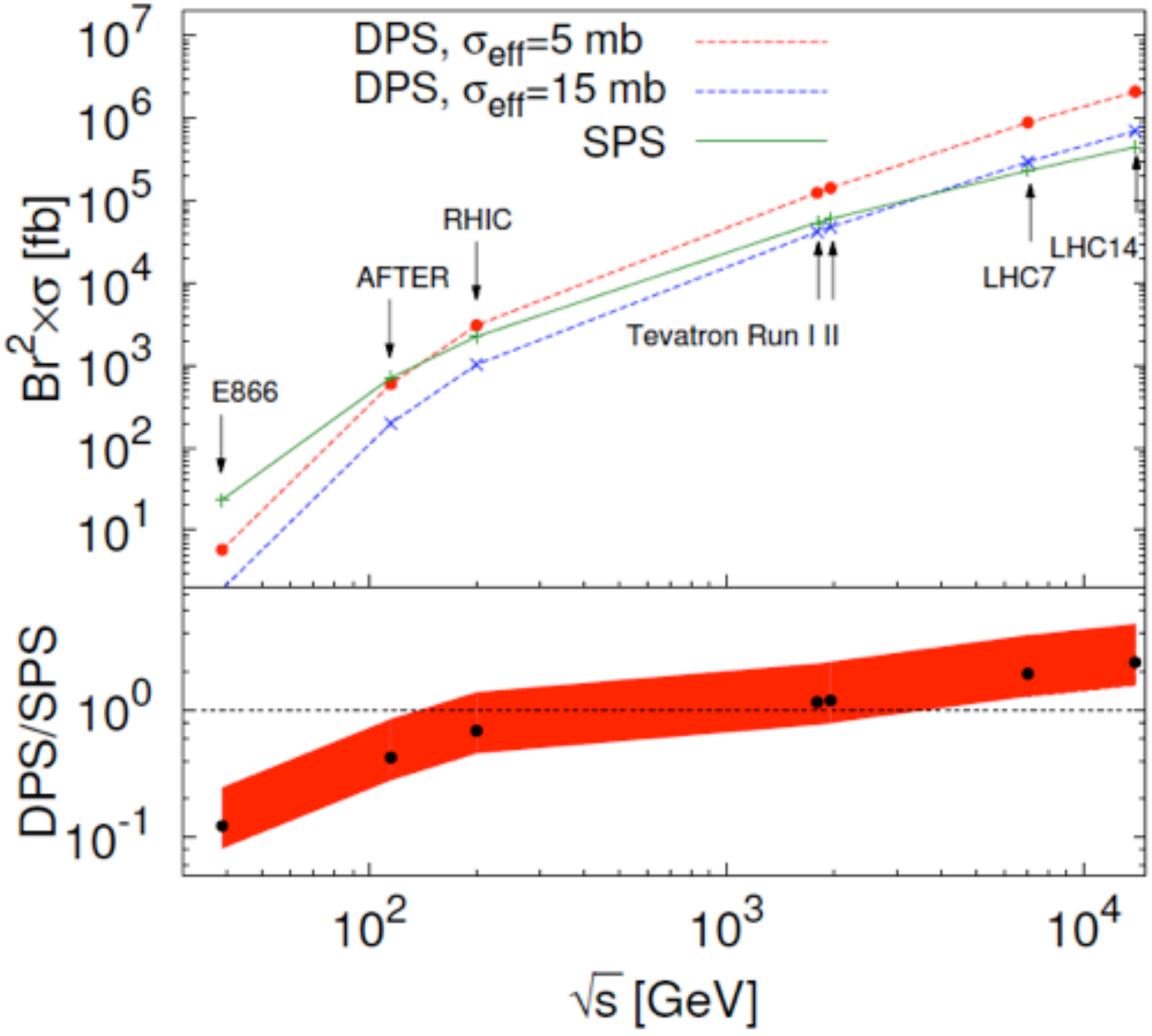
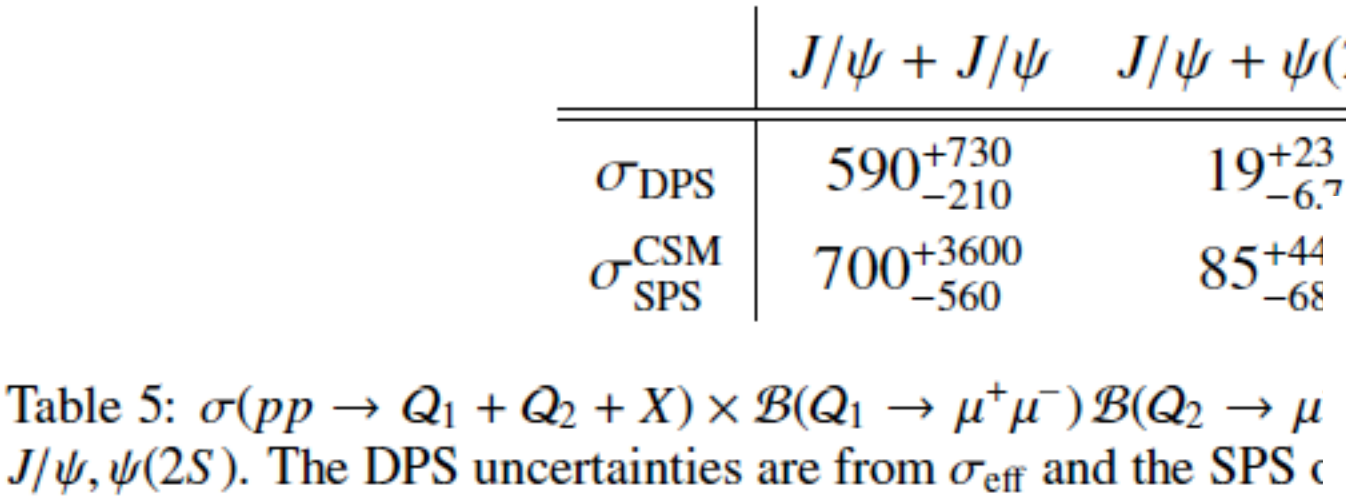


- With 20 fb-1/yr, there will be m
- It is important to investigate energy dependence of $\sigma_{\rm eff}$

PREDICTIONS: AFTER@LHC

- pp collisions at sqrt(s)=115 GeV (7 TeV protons on a fixed target)
- Taking σ_{eff} extracted by D0 (5mb) as a reference number:



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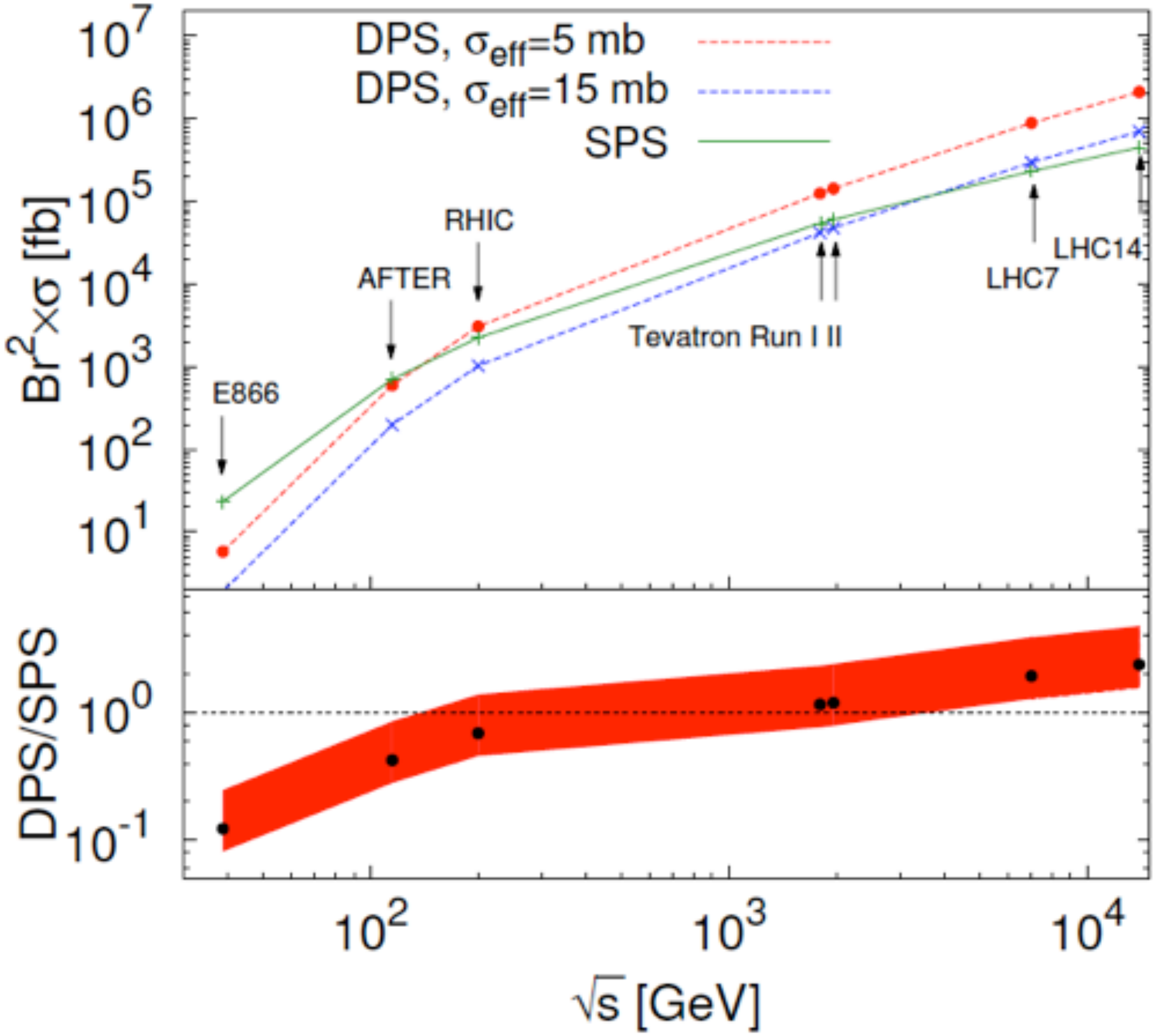

- With 20 fb-1/yr, there will be m
- It is important to investigate energy dependence of σ_{eff}
- Extensive discussions/plots can be found in arXiv: 1504.06531

A NEW WAY TO SEE DPS V.S. SPS

- The **fractions of feed-down** contributions also provide a way to distinguish SPS and DPS due to their completely different predictions.

$$F_{\psi\psi}^{\chi_c} = F_{\psi}^{\chi_c} \times (F_{\psi}^{\chi_c} + 2F_{\psi}^{\rm direct} + 2F_{\psi}^{\psi'}),$$
$$F_{\psi\psi}^{\psi'} = F_{\psi}^{\psi'} \times (F_{\psi}^{\psi'} + 2F_{\psi}^{\rm direct} + 2F_{\psi}^{\chi_c}),$$
$$F_{\psi\psi}^{\rm direct} = (F_{\psi}^{\rm direct})^2.$$

	SPS	DPS
$F_{\psi\psi}^{\psi'}$	46%	20%
$F_{\psi\psi}^{\chi_c}$	small	50%

- It is possible to measure the **fractions of feed-down** to separate DPS and SPS. Especially, in the region one contribution is dominant. It helps to distinguish which one is dominant without knowing the value of $\sigma_{\rm eff}$.

- Strong motivation to look at J/psi+ excited charmonia. .

J/PSI+Y

Lansberg, HSS (2015)

- No diagram survives at LO and NLO in CSM. Hence, it is expected to be a good channel to probe COM.
- On the other hand, DPS should be significant.

J/PSI+Y

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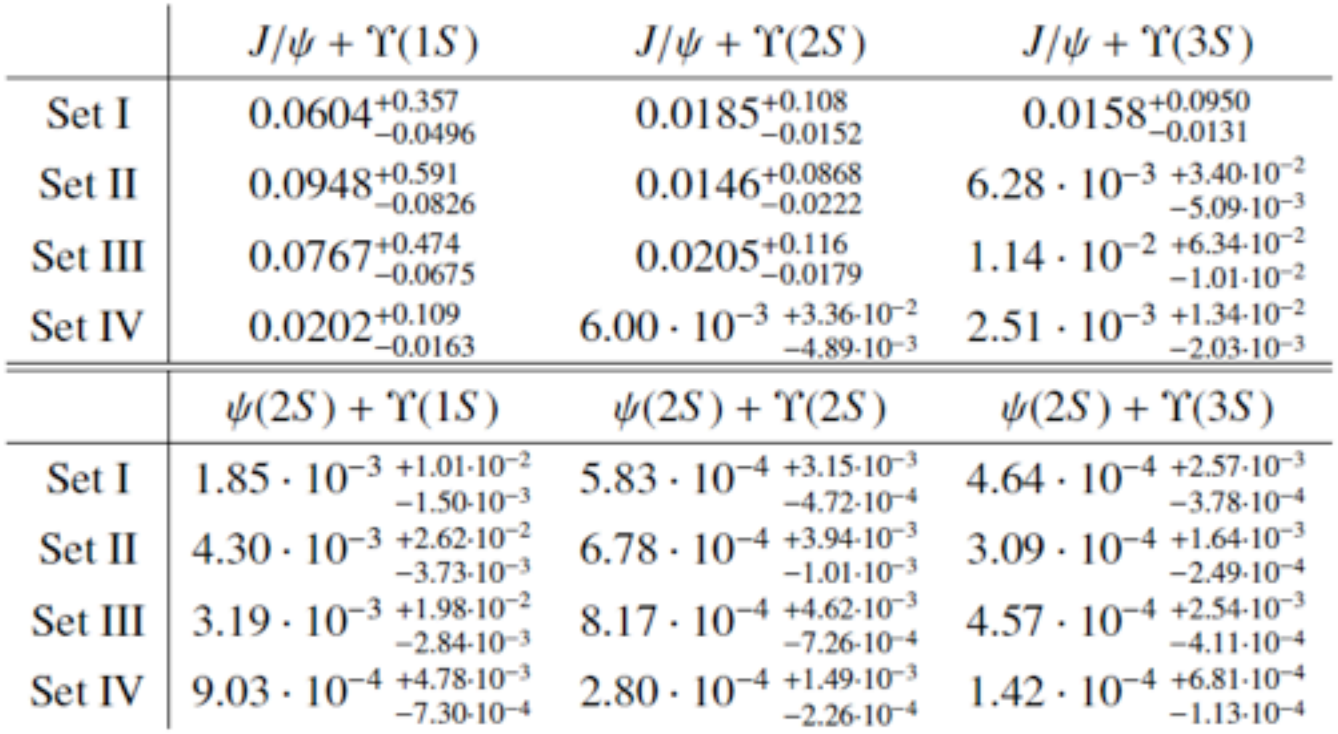
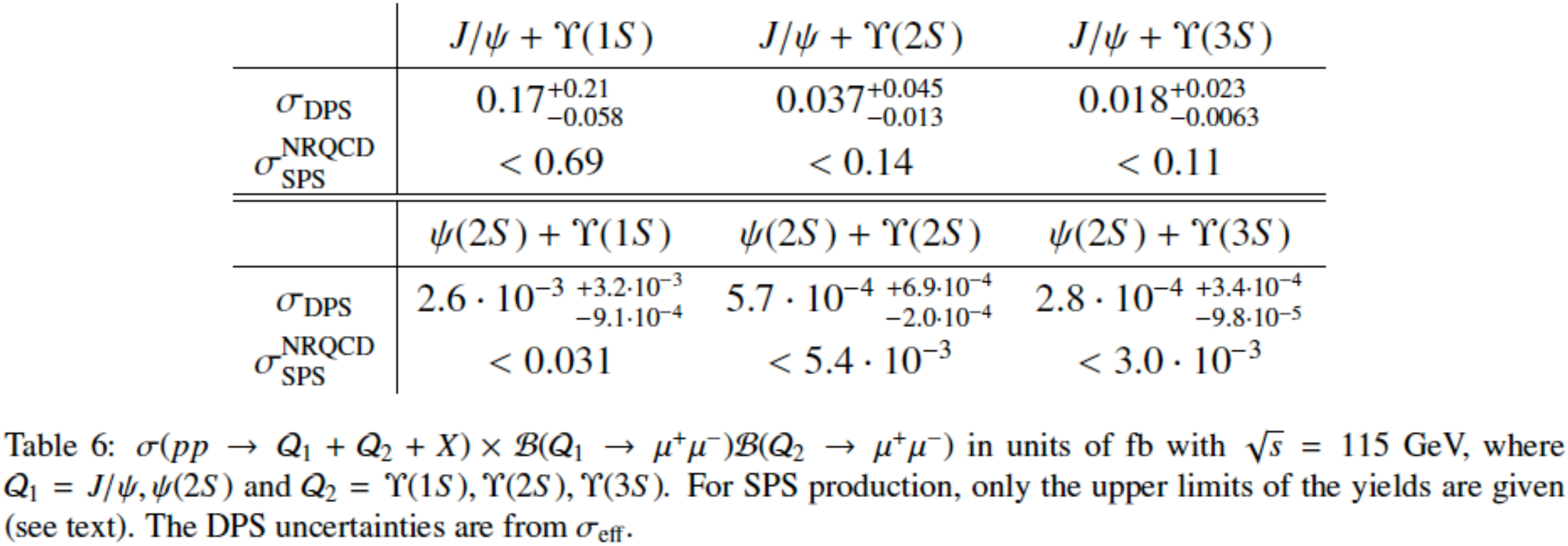
- No diagram survives at LO and NLO in CSM. Hence, it is expected to be a good channel to probe COM.
- On the other hand, DPS should be significant.
- At center-of-mass energy 115 GeV, SPS depends on CO LDMEs a lot.



	$J/\psi + \Upsilon(1S)$	$J/\psi + \Upsilon(2S)$	$J/\psi + \Upsilon(3S)$
Set I	$0.0604^{+0.357}_{-0.0496}$	$0.0185^{+0.108}_{-0.0152}$	$0.0158^{+0.0950}_{-0.0131}$
Set II	$0.0948^{+0.591}_{-0.0826}$	$0.0146^{+0.0868}_{-0.0222}$	$6.28 \cdot 10^{-3}\,{}^{+3.40 \cdot 10^{-2}}_{-5.09 \cdot 10^{-3}}$
Set III	$0.0767^{+0.474}_{-0.0675}$	$0.0205^{+0.116}_{-0.0179}$	$1.14 \cdot 10^{-2}\,{}^{+6.34 \cdot 10^{-2}}_{-1.01 \cdot 10^{-2}}$
Set IV	$0.0202^{+0.109}_{-0.0163}$	$6.00 \cdot 10^{-3}\,{}^{+3.36 \cdot 10^{-2}}_{-4.89 \cdot 10^{-3}}$	$2.51 \cdot 10^{-3}\,{}^{+1.34 \cdot 10^{-2}}_{-2.03 \cdot 10^{-3}}$
	$\psi(2S) + \Upsilon(1S)$	$\psi(2S) + \Upsilon(2S)$	$\psi(2S) + \Upsilon(3S)$
Set I	$1.85 \cdot 10^{-3}\,{}^{+1.01 \cdot 10^{-2}}_{-1.50 \cdot 10^{-3}}$	$5.83 \cdot 10^{-4}\,{}^{+3.15 \cdot 10^{-3}}_{-4.72 \cdot 10^{-4}}$	$4.64 \cdot 10^{-4}\,{}^{+2.57 \cdot 10^{-3}}_{-3.78 \cdot 10^{-4}}$
Set II	$4.30 \cdot 10^{-3}\,{}^{+2.62 \cdot 10^{-2}}_{-3.73 \cdot 10^{-3}}$	$6.78 \cdot 10^{-4}\,{}^{+3.94 \cdot 10^{-3}}_{-1.01 \cdot 10^{-3}}$	$3.09 \cdot 10^{-4}\,{}^{+1.64 \cdot 10^{-3}}_{-2.49 \cdot 10^{-4}}$
Set III	$3.19 \cdot 10^{-3}\,{}^{+1.98 \cdot 10^{-2}}_{-2.84 \cdot 10^{-3}}$	$8.17 \cdot 10^{-4}\,{}^{+4.62 \cdot 10^{-3}}_{-7.26 \cdot 10^{-4}}$	$4.57 \cdot 10^{-4}\,{}^{+2.54 \cdot 10^{-3}}_{-4.11 \cdot 10^{-4}}$
Set IV	$9.03 \cdot 10^{-4}\,{}^{+4.78 \cdot 10^{-3}}_{-7.30 \cdot 10^{-4}}$	$2.80 \cdot 10^{-4}\,{}^{+1.49 \cdot 10^{-3}}_{-2.26 \cdot 10^{-4}}$	$1.42 \cdot 10^{-4}\,{}^{+6.81 \cdot 10^{-4}}_{-1.13 \cdot 10^{-4}}$

Table A.9: $\sigma_{\rm SPS}(pp \to Q_1 + Q_2) \times \mathcal{B}(Q_1 \to \mu^+\mu^-)\mathcal{B}(Q_2 \to \mu^+\mu^-)$ in units of fb with $\sqrt{s} = 115$ GeV, where $Q_1 = J/\psi, \psi(2S)$ and $Q_2 = \Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$. We take four sets of LDMEs.

J/PSI+Y



	$J/\psi + \Upsilon(1S)$	$J/\psi + \Upsilon(2S)$	$J/\psi + \Upsilon(3S)$
$\sigma_{\rm DPS}$	$0.17^{+0.21}_{-0.058}$	$0.037^{+0.045}_{-0.013}$	$0.018^{+0.023}_{-0.0063}$
$\sigma^{\rm NRQCD}_{\rm SPS}$	< 0.69	< 0.14	< 0.11
	$\psi(2S) + \Upsilon(1S)$	$\psi(2S) + \Upsilon(2S)$	$\psi(2S) + \Upsilon(3S)$
$\sigma_{\rm DPS}$	$2.6 \cdot 10^{-3}\ {}^{+3.2\cdot 10^{-3}}_{-9.1\cdot 10^{-4}}$	$5.7 \cdot 10^{-4}\ {}^{+6.9\cdot 10^{-4}}_{-2.0\cdot 10^{-4}}$	$2.8 \cdot 10^{-4}\ {}^{+3.4\cdot 10^{-4}}_{-9.8\cdot 10^{-5}}$
$\sigma^{\rm NRQCD}_{\rm SPS}$	< 0.031	$< 5.4 \cdot 10^{-3}$	$< 3.0 \cdot 10^{-3}$

Table 6: $\sigma(pp \to Q_1 + Q_2 + X) \times \mathcal{B}(Q_1 \to \mu^+\mu^-)\mathcal{B}(Q_2 \to \mu^+\mu^-)$ in units of fb with $\sqrt{s} = 115$ GeV, where $Q_1 = J/\psi, \psi(2S)$ and $Q_2 = \Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$. For SPS production, only the upper limits of the yields are given (see text). The DPS uncertainties are from $\sigma_{\rm eff}$.

- DPS normally should be bigger than SPS since CO LDMEs used here are from fitting to large pT single-quarkonium production data. It overestimates the yields of single-quarkonium production in the small pT region. e,g, Feng et al. (2015)

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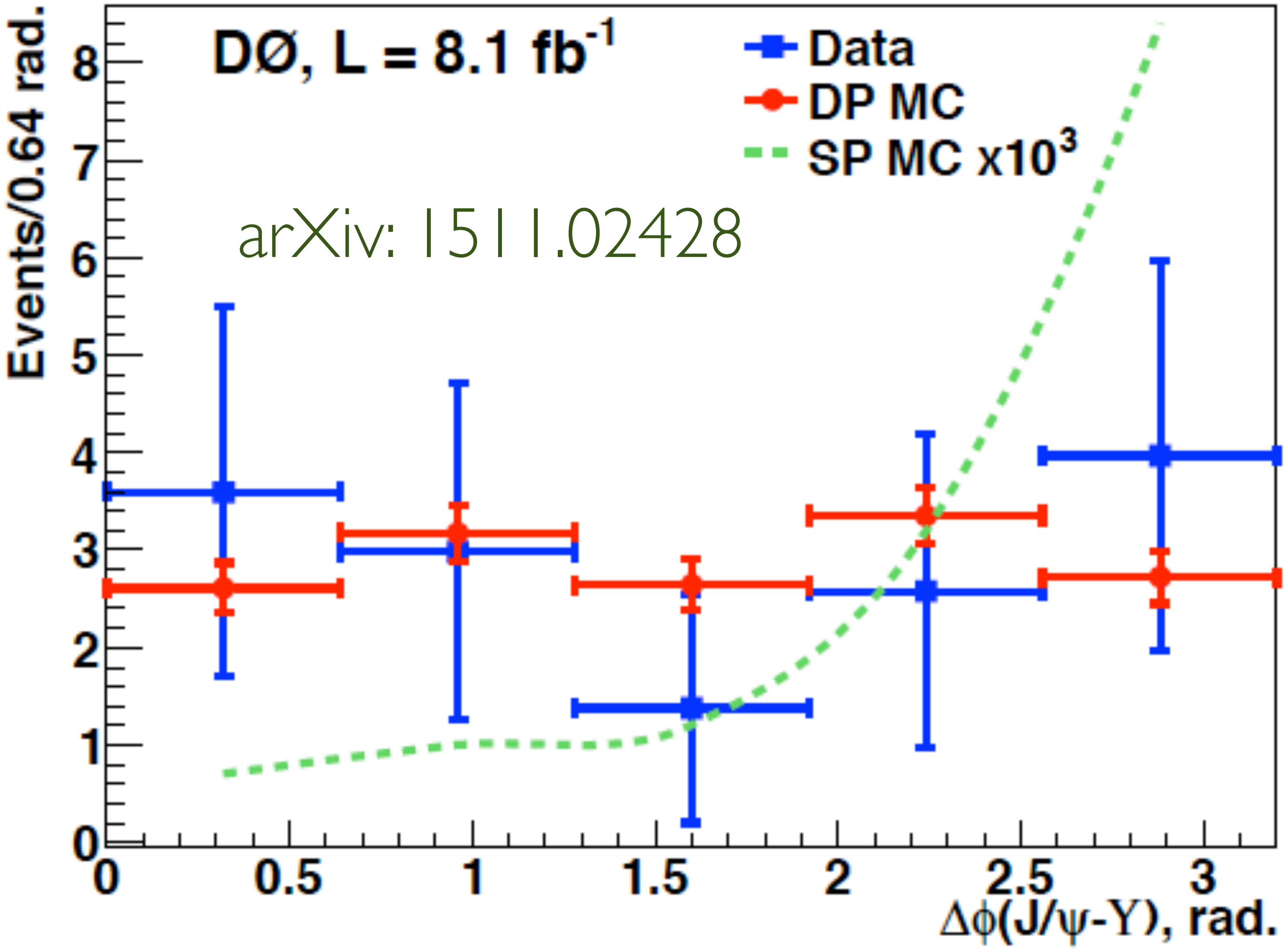
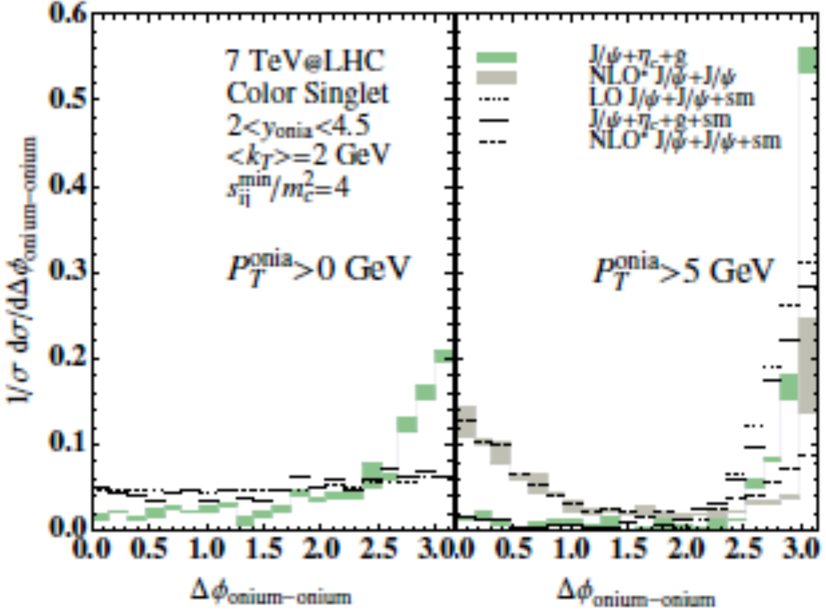
RECENT DZERO MEASUREMENT: J/PSI+Y



arXiv: 1511.02428

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

Lansberg, HSS (2013)



- 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 give a clarification in the future ?

SUMMARY & OUTLOOK

- We presented a first comprehensive analysis on double quarkonium production.

- Such processes help to study QCD models of heavy quarkonium production and to probe Double Parton Scattering.

- We have fitted $\sigma_{\rm eff}$ from the CMS double J/psi data.

- Our value is compatible to D0 extraction and favors a smaller value compared to jet-related measurements.

- All this can be checked with J/psi+ excited charmonia.

SUMMARY & OUTLOOK

- AFTER@LHC: important to look at the sqrt(s) dependence of DPS/SPS.

- J/psi+J/psi can also be used to extract the distribution of linearly-polarised gluons in unpolarised protons (gluon TMDs) at the LHC.

- Quarkonium pair production can also be a key observable in heavy-ion collisions A. Snigirev et al. (2013)

- Looking forward to new emerging measurements both at the Tevatron and the LHC.

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Thank you for your attention !