J/ψ -Pair Production At Large Momenta At Hadron Colliders:

Indications for Double-Parton Scatterings and Large α_s^5 Contributions

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In Collaboration With Jean-Philippe Lansberg

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J/PSI POLARIZATION PUZZLE: OCTET VS SINGLET CHANNELS?

- Color-Singlet Model solely cannot account for yields and polarization of prompt J/ψ (as well as $\psi(2S)$, $\Upsilon(nS)$, χ_c etc) production at the Tevatron and the LHC.

- Color-Octet Mechanism at NLO level in QCD can describe large P_T data ($P_T \gg m$) in a consistent way, especially for the polarization observables [Chao, Ma, HSS, Wang et al., Phys. Rev. Lett '12; HSS, Ma, Wang, Chao, Phys. Rev. Lett '14 ...].

- Heavy quarkonium associated production processes provide more information on how non-perturbative QCD behaves in forming heavy quarkonium from heavy quark pair.

MOTIVATION TO STUDY QUARKONIUM PAIR PRODUCTION

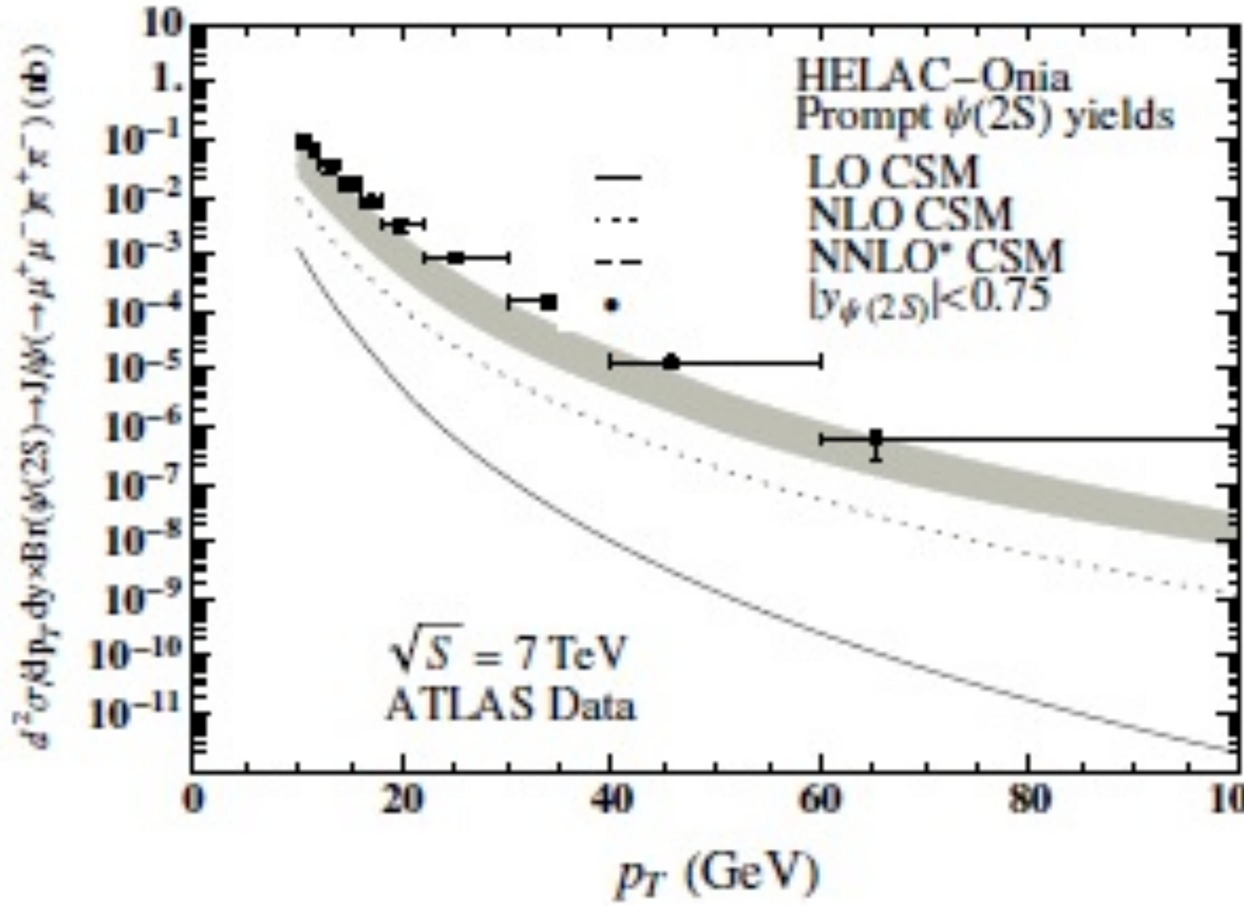
- The necessity for COM is a longstanding puzzle for heavy quarkonium production.
- Based on LO computations, J/ψ-pair production was proposed as a probe of COM.
- The CO+CO channels depend on the square of the CO transition probability.
- J/ψ - pair production was then discussed as a way to probe Double-Parton Scatterings at the Tevatron and the LHC.
- It is easy to trigger at the Tevatron and the LHC. In fact, data already exist (from LHCb, D0 and CMS).

IS A LEADING-ORDER 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)]



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

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Production of $J/\psi + \eta_c$ versus $J/\psi + J/\psi$ at the LHC: Importance of Real α_s^5 Corrections

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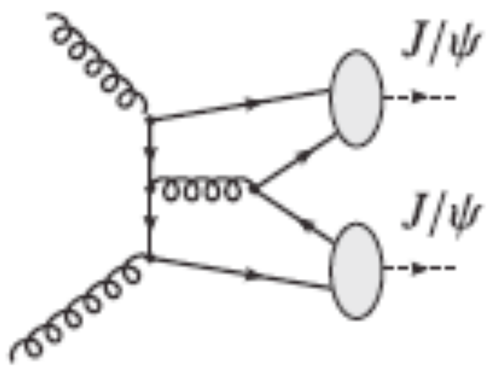
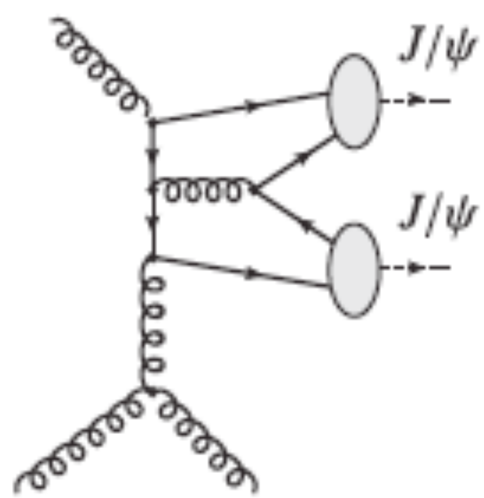


$$\sim \quad \alpha_s^4 \left(\frac{m_\psi}{P_T^\psi}\right)^8$$



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

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

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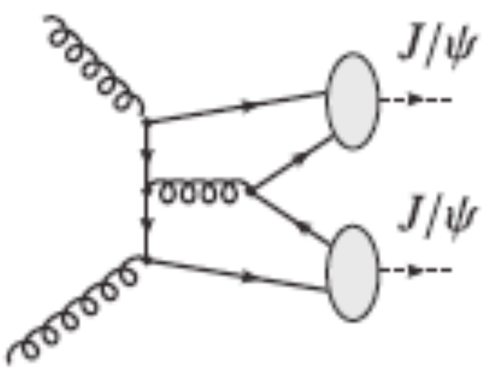

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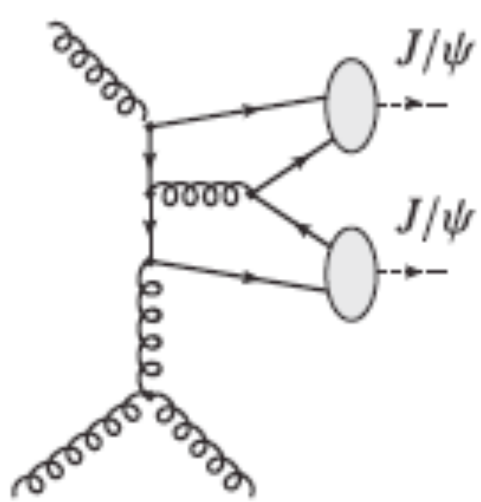

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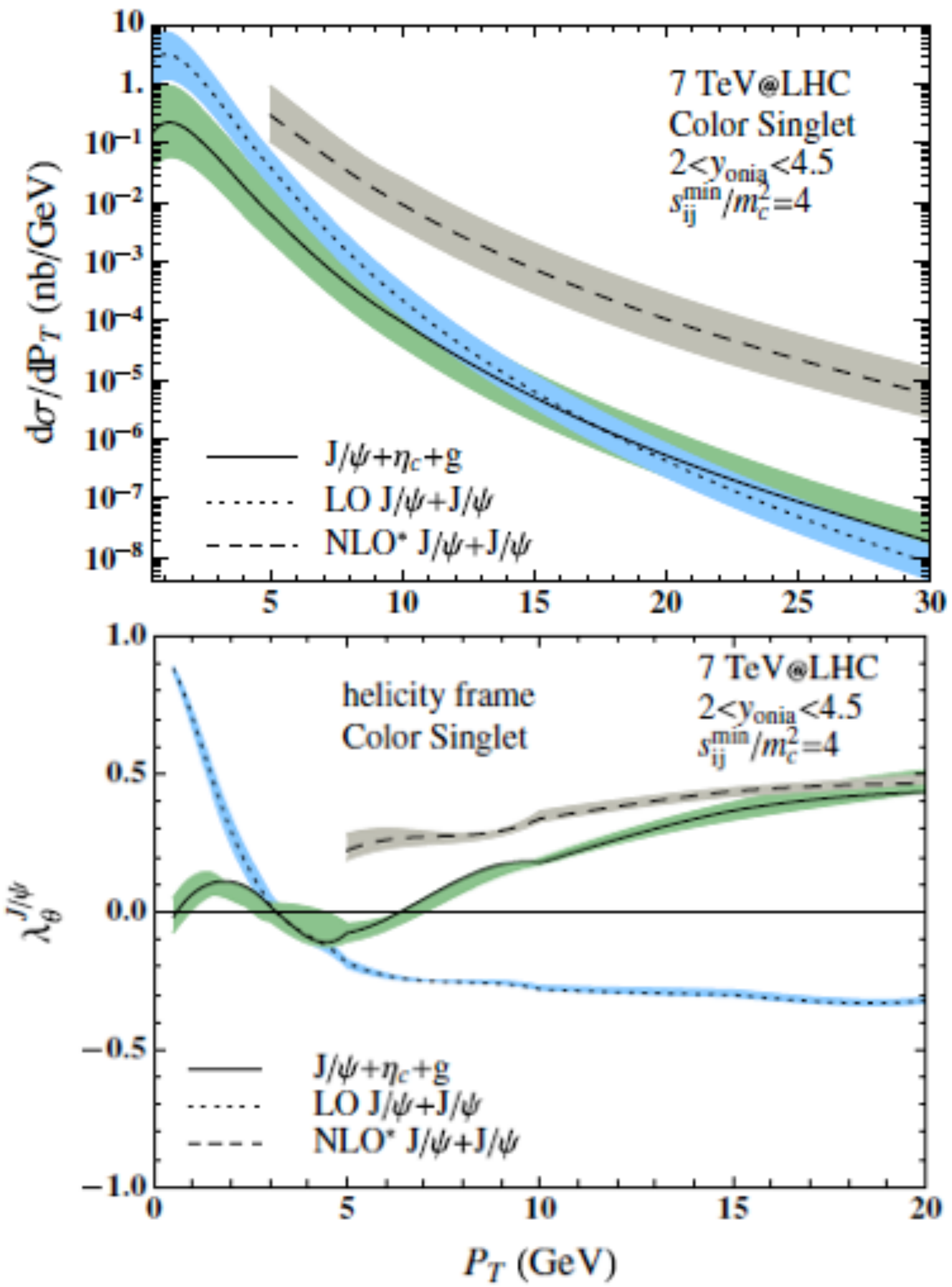

PUZZLE IN J/ψ -PAIR ?

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

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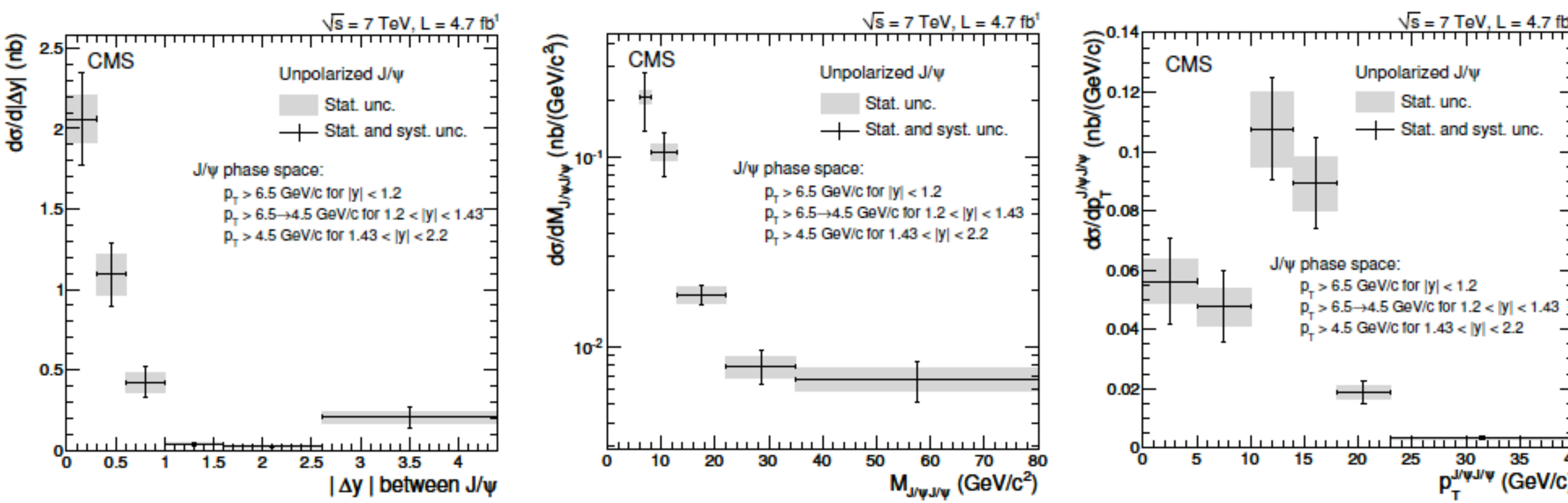

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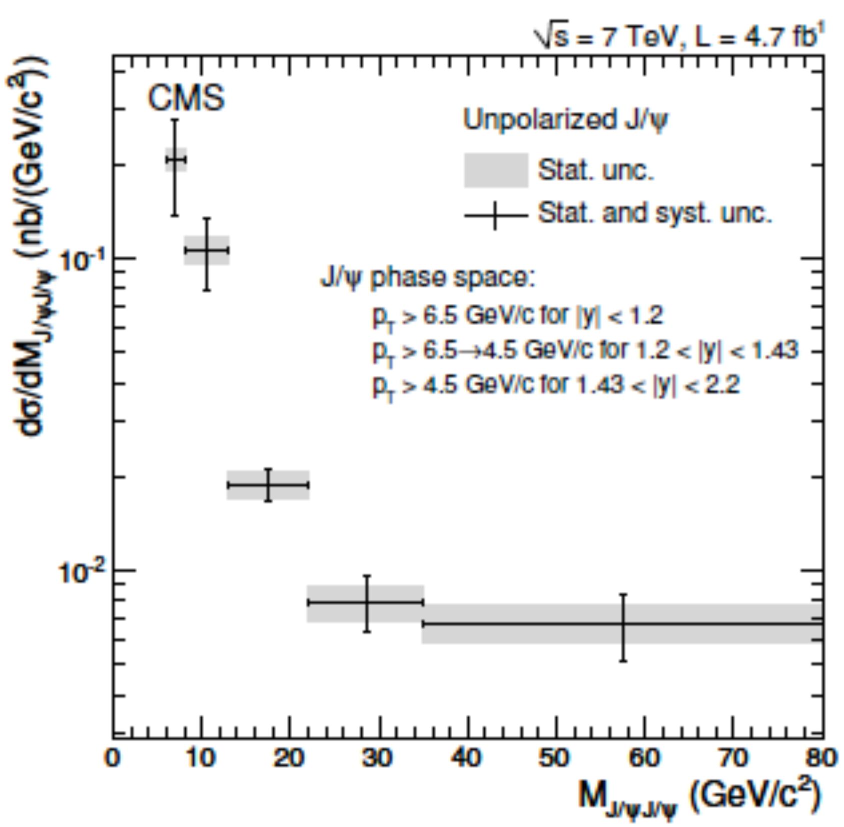

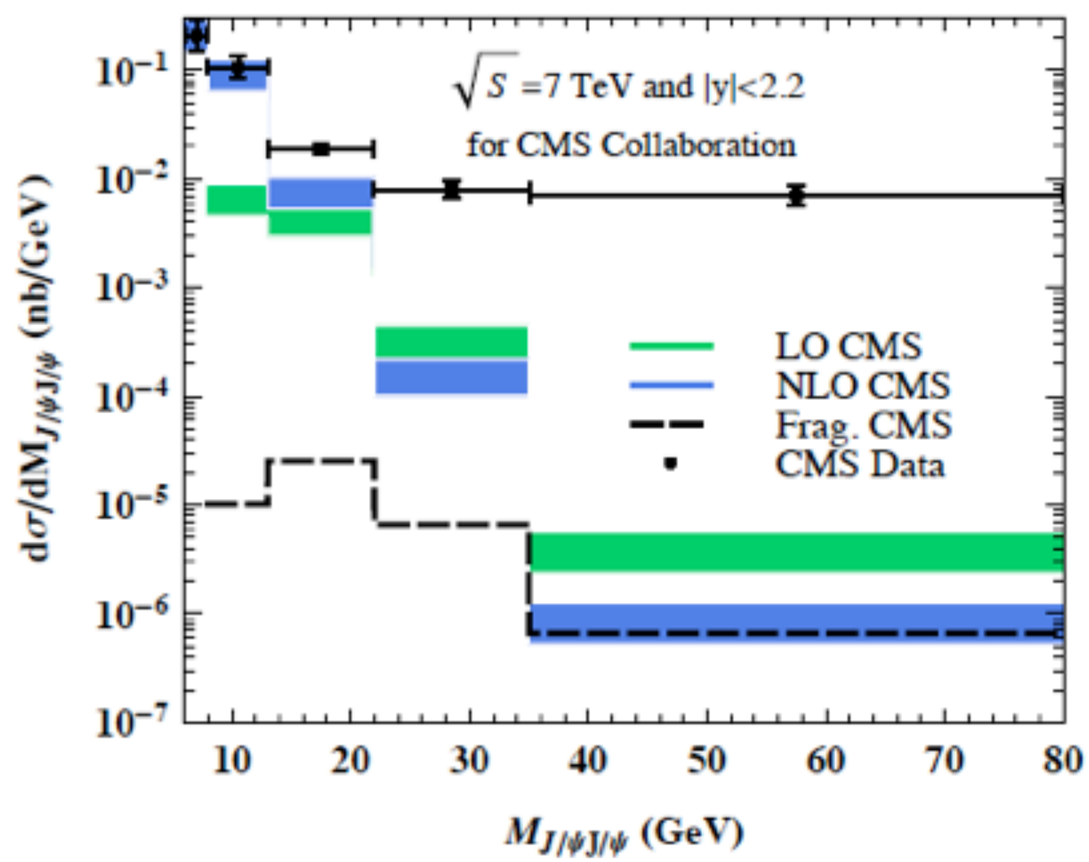

Tuesday, January 13, 15

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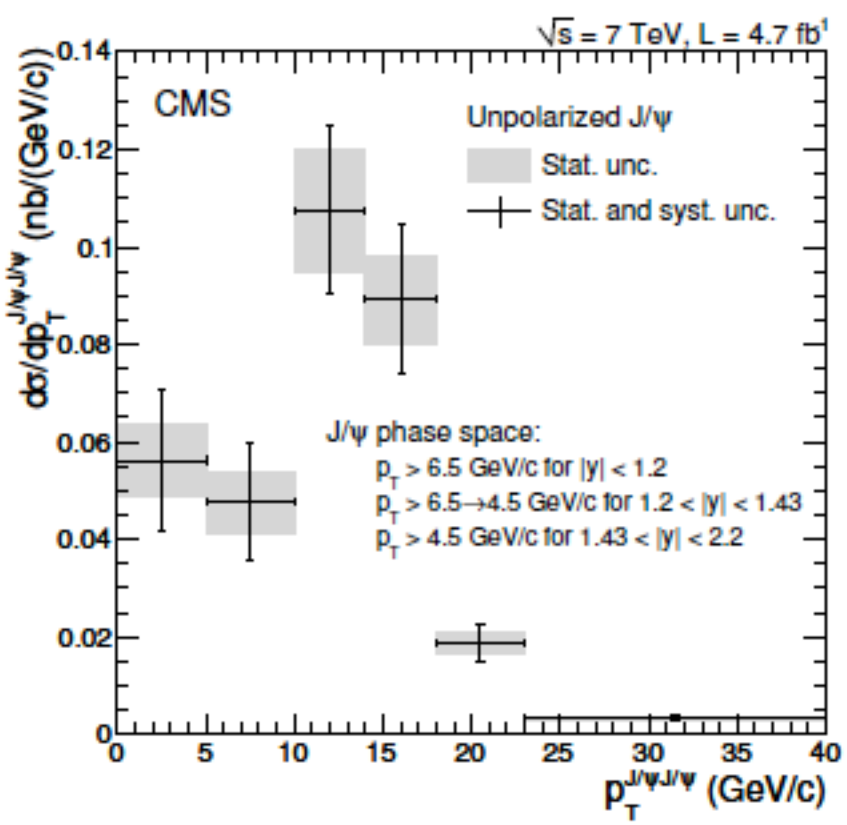

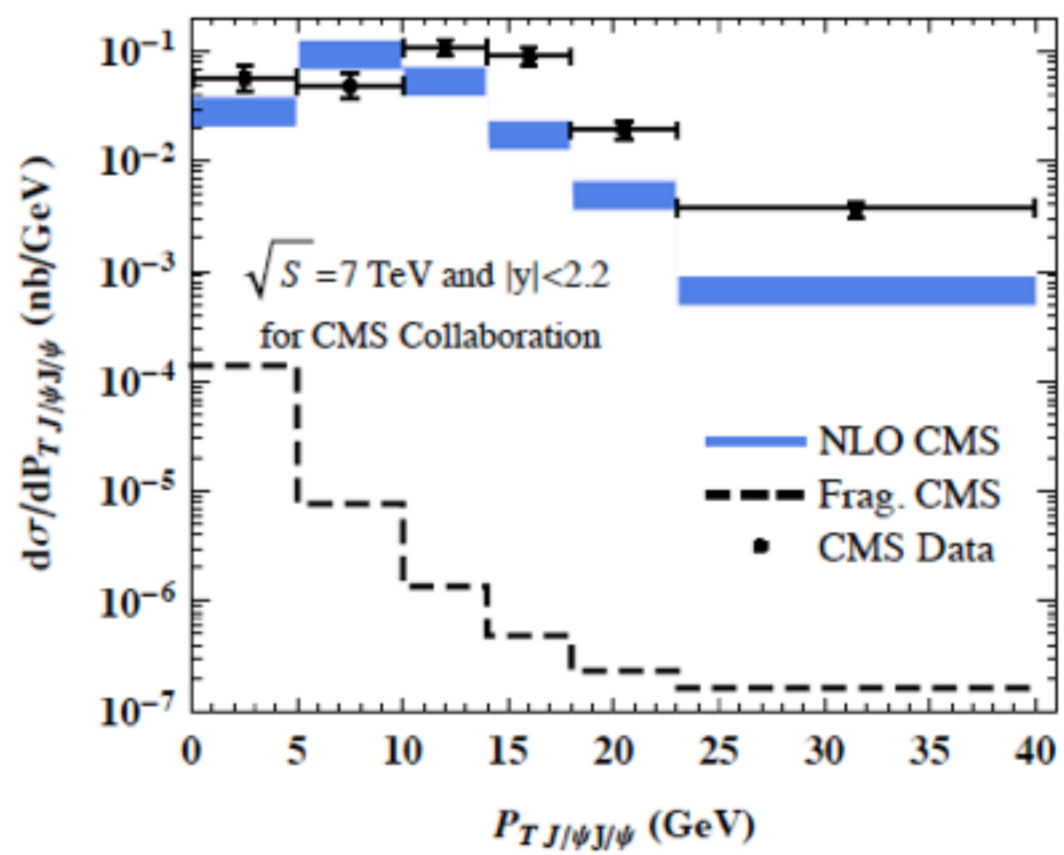

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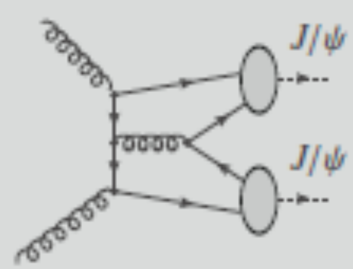

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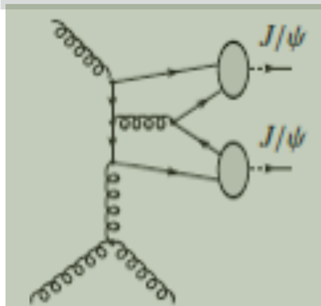

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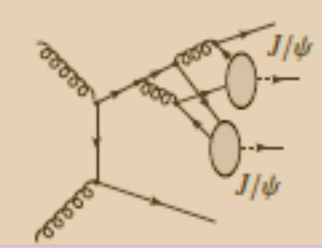
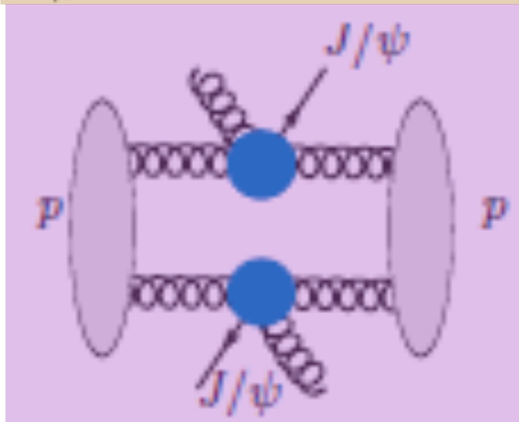


$$\sim \alpha_s^5 \left(\frac{m_\psi}{P_T^\psi}\right)^4$$

SPS



DPS

	$\sigma^{\text{prompt}}_{\text{exp.}}$	$\sigma^{\text{LO,direct}}_{\text{SPS}}$	$\sigma^{\text{NLO,direct}}_{\text{SPS}}$	$\sigma^{\text{NLO,prompt}}_{\text{SPS}}$	$\sigma^{\text{prompt}}_{\text{DPS}}$
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 unit of pb for LHCb and CMS and fb for D0 and ATLAS. The kinematical cuts are given as supplemental material.]

- DPS and SPS are comparable.
- We use the D0 data to fix the DPS parameter
- CMS and D0 measurements imply significant DPS contributions.

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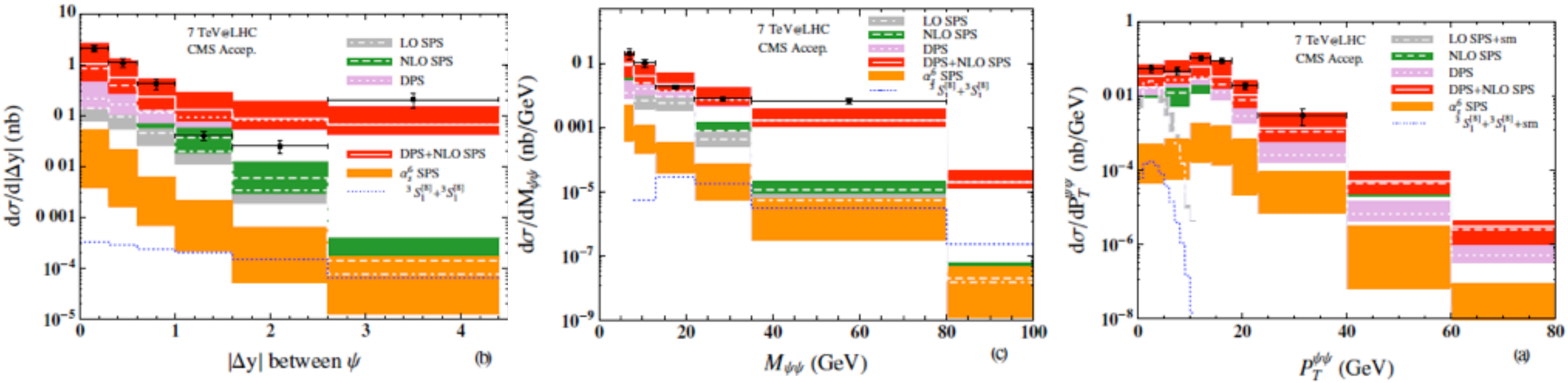

- **The dominance of α_s^4 (LO) contributions at low pT (from LHCb data).**
- **The dominance of α_s^5 (NLO) contributions at mid and large P_T .**
- **The dominance of DPS contributions at large Δy and invariant mass M.**
- **CO contributions as well as α_s^6 (NNLO) are not important in SPS.**

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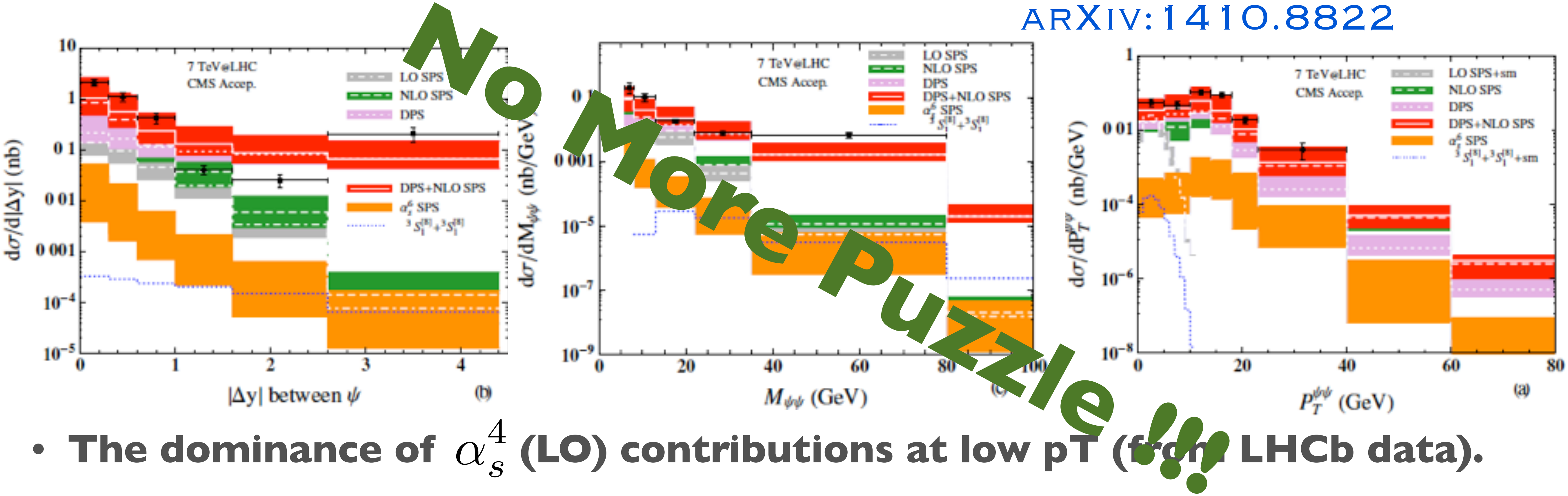

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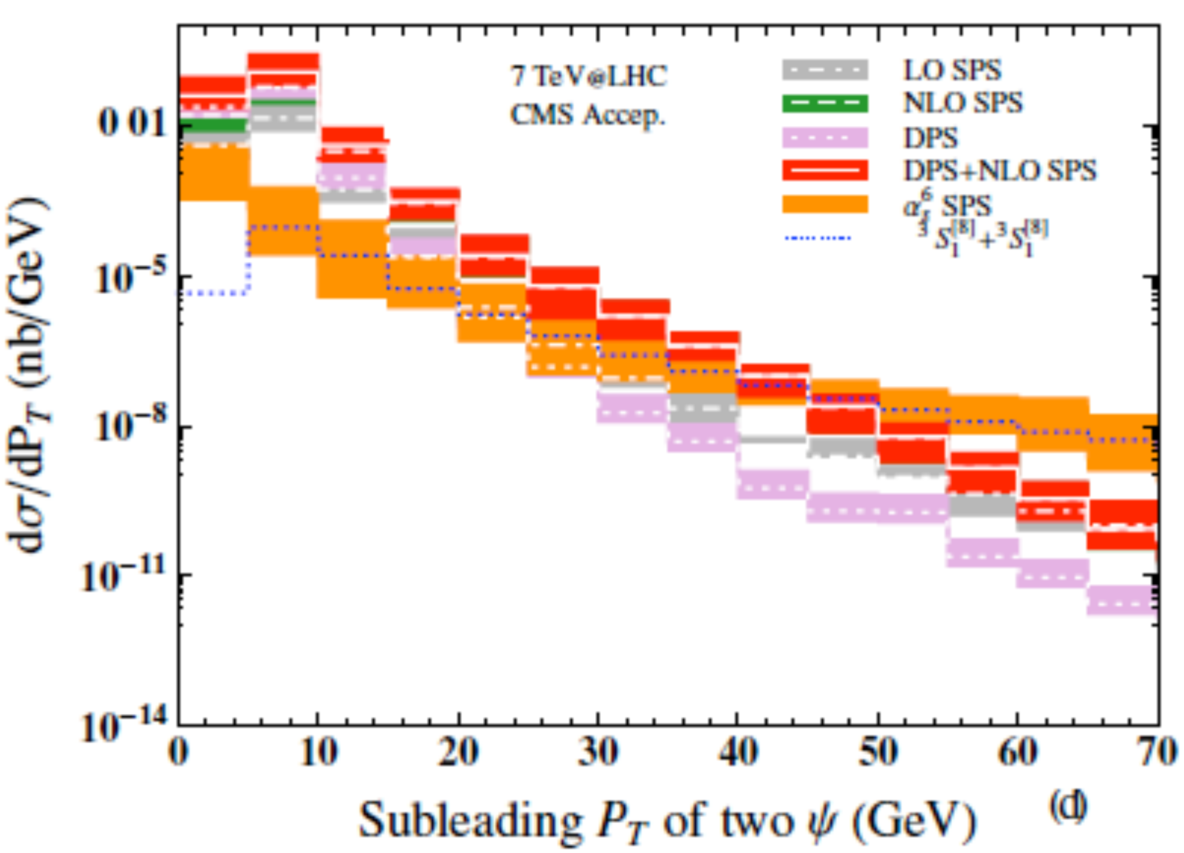

$$F_{\psi\psi}^{\{\chi_c,\psi'\}} = \frac{\sigma(\{\chi_c,\psi'\}+J/\psi)\times\mathcal{B}(\{\chi_c,\psi'\}\to J/\psi)}{\sigma(J/\psi+J/\psi)}$$

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

- Subleading P_T is a good kinematical variable to discriminate CO contribution as well as α_s^6 SPS contribution.
- The **fractions of feed-down** contributions also provide a way to distinguish SPS and DPS due to their completely different predictions.

CONCLUSIONS

- Prompt J/ψ -pair production has recently been measured at the LHC and the Tevatron.
- The comparison (without tuning any parameter) between theory and experiment reveals the presence of different production mechanisms in different kinematical regions.
- Both SPS and DPS contributions are important to account for the experimental data.
- We solved the puzzle raised by Sun et al..
- In general, associated-quarkonium production at the LHC provides a good way to probe DPS physics.

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- In general, associated-quarkonium production at the LHC provides a good way to probe DPS physics.

Thank you for your attention !

BACKUP SLIDES

COLOR OCTET CONTRIBUTIONS IN SINGLE PARTON SCATTERINGS

- CO+CO channels are nowhere important when $P_T < 50\ \mathrm{GeV}$ with the CO transition probability extracted from LO [Sharma, Vitev, Phys. Rev. C '13] or NLO [Chao, Ma, HSS, Wang et al., Phys. Rev. Lett. '12; HSS, Han, Ma, Meng et al., '14; Butenschoen, Kniehl, Phys. Rev. Lett. '12; Gong et al., Phys. Rev. Lett. '13] calculations.

- CO+CS channels are suppressed by the small value of CO transition probability compared to the CS one but no P_T enhancement.

- Feeddown contributions from $\psi + \chi_c$ can be ignored because they are absent at α_s^4 in CSM and their CO transition probability is small [HSS, Ma, Wang, Chao, Phys. Rev. Lett. '14]

CALCULATIONS IN HELAC-ONIA

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

- SPS is calculated based on the recursion relations implemented in HELAC-Onia.

- DPS is based on the 'pocket' formula

$$\sigma^{\rm DPS}_{\psi\psi} = \frac{1}{2}\frac{\sigma_\psi \sigma_\psi}{\sigma_{\rm eff}}$$

- $\sigma_{\rm eff} = 5.0 \pm 0.27\ {\rm mb}$ is extracted from D0 measurement.

- σ_ψ is tuned to the LHC and the Tevatron data in the form of crystal ball function [Kom, Kulesza, Stirling, Phys. Rev. Lett. '11].