Quarkonium pair production at hadron collider

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Quarkonia as Tools
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1. Motivation
2. Quarkonium pair production in single parton scattering (SPS)
3. Quarkonium pair production in double parton scattering (DPS)
4. Summary

Problem of single quarkonium production?

- General factorization formula:

$$\sigma_{(A+B\to quarkonium+X)} = \sum_n \int \sigma_{A+B\to(Q\bar{Q})_n+X} \times f[(Q\bar{Q})_n \to quarkonium]$$

- The models in market include color-singlet model(CSM), color evaporation model (CEM), and nonrelativistic QCD (NRQCD) factorization.

The challenge of NRQCD (see Butenschön's talk):

1. The long-standing J/ψ polarization puzzle.
2. The universality of the NRQCD LDMEs for J/ψ production.
3. For J/ψ production in e^+e^- annihilation, and η_c meson hadroproductin, the CSM itself can well describe the experimental measurements.

What can we benefit from quarkonium pair production?

1. More sensitive test for NRQCD hypothesis and additional crucial constraint on its LDMEs. (Barger et al. 1996)
2. Help to improve the NRQCD factorization formula for double $P-$wave production. (He et al. 2018)
3. Extract $\sigma_{\rm eff}$ in double parton scattering mechanism. (Kom, et al. 2011)
4. Study the transverse momentum dependent parton distribution function. (Lansberg et al. 2018)
5. Discover the new fully heavy tetraquark states ($Q\bar{Q}Q\bar{Q}$). (LHCb Collaboration 2020)

Experimental measurements of quarkonium pair hadroproduction

Table: The summary of experimental measurements of quarkonium pair hadroproduction (see Leontsinis's talk about experimental study DPS contribution).

Collaboration	$\sqrt{s}$	states	kinematic condition
LHCb	7 TeV	$J/\psi + J/\psi$	$P_T^{J/\psi} < 10\text{GeV}$ $2.0 < y^{J/\psi} < 4.5$
	13 TeV		
D0	1.96 TeV	$J/\psi + J/\psi$	$p_T^{J/\psi} > 4.0\text{GeV}, \lvert\eta^{J/\psi}\rvert < 2$
		$J/\psi + \Upsilon$	$p_T^{\mu} > 2.0\text{GeV}, \lvert\eta^{\mu}\rvert < 2$
CMS	7 TeV	$J/\psi + J/\psi$	$p_T^{J/\psi} > 4.5\text{GeV}, \lvert y^{J/\psi}\rvert < 2.2$ [1]
	8 TeV	$\Upsilon + \Upsilon$	$\lvert y^{\Upsilon}\rvert < 2.0$
	13 TeV		
ATLAS	8 TeV	$J/\psi + J/\psi$	$p_T^{J/\psi} > 8.5\text{GeV}, \lvert y^{J/\psi}\rvert < 2.1$

[1] The lower bound of $p_T^{J/\psi}$ depends on $y^{J/\psi}$

Highlight of theoretical literature about single parton scattering

- The J/ψ pair production was first proposed by Barger, et al. in 1996, in which the $2(c\bar{c}(^3S_1^{[8]}))$ contribution was studied.
- In 2002, Qiao found that the $2(c\bar{c}(^3S_1^{[1]}))$ channel contributes predominately to the total cross section.
- In 2011, it was suggested by Ko et al. that the $J/\psi + \Upsilon$ process may be a good probe of color octet (CO) mechanism.
- The higher order relativistic corrections to above subprocesses were calculated by Li, et al. in 2013.
- Baranov calculated the J/ψ pair production in $\mathrm{k_T}$ factorization approach in 2011, and in 2013 he and his collaborators considered the partial NNLO effect due to pseudodiffractive scattering.
- The α_s^5 order real gluon emission effect was studied by Lansberg and Shao in 2013.

To be continued

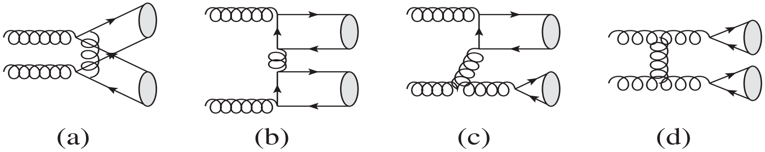
- The complete LO NRQCD calculation including χ_c feed down were obtained by He and Kniehl in 2015.
- The CO contribution to double J/ψ production in $\mathrm{k_T}$ factorization was taken into account by Baranov and Rezaeian in 2016.
- In 2016, the complete study of $J/\psi + \Upsilon$ production was carried out by Shao and Zhang.
- The NLO QCD corrections to the $2(c\bar{c}(^3S_1^{[1]}))$ channel was obtained by Sun et al. in 2016.
- It was found by He et al. in 2018 that the NRQCD factorization breakdown when double P-wave states are involved.
- In 2019 He et al. studied the J/ψ pair production in the parton reggeization approach (PRA) with high-energy resummation.
- The predictions of CEM for $2J/\psi$, $J/\psi + \Upsilon$ and 2Υ upto QCD NLO were obtained by Lansberg et al. in 2020.

Highlight of theoretical literature about double parton scattering

- In 2011, Kom et al. were the first to realize that the J/ψ pair production is a good probe of the double parton scattering (DPS).
- Soon after, the DPS contribution to $J/\psi + \Upsilon$ was obtained by Baranov et al. for 7 TeV LHCb case.
- $\sigma_{\rm eff}$ was first extracted from J/ψ pair production by Lansberg and shao in 2015.
- An upper bound of $\sigma_{\rm eff}$ was gotten by Shao and Zhang from $J/\psi + \Upsilon$ production in 2016.
- A detailed study of DPS contribution to $2J/\psi$ production at LHC was performed by Borschensky and Anna Kulesza in 2017.
- In 2020, $\sigma_{\rm eff}$ was determined by Prokhorov et al. from combined analysis of LHCb 7 and 13 TeV data, in which the single parton scattering contribution was calculated in $\rm k_T$ factorization approach.

Properties of quarkonium pair production in SPS I

- Representative Feynman diagrams at LO:



4 different topological Feynman diagrams:

- a) Non-gluon fragmentation type I
- b) Non-gluon fragmentation type II
- c) One gluon fragmentation like
- d) Two gluons fragmentation like

- The p_T and v^2 scaling of $d\sigma/dp_T^2$ for the each channel at QCD LO.

(m, n)	${}^3S_1^{[1]}$	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^3P_J^{[8]}$	${}^3P_J^{[1]}$
${}^3S_1^{[1]}$	$1/p_T^8$	v^4/p_T^8	v^3/p_T^8	v^4/p_T^8	0
${}^3S_1^{[8]}$	—	v^8/p_T^4	v^7/p_T^6	v^8/p_T^6	v^8/p_T^6
${}^1S_0^{[8]}$	—	—	v^6/p_T^8	v^7/p_T^8	v^7/p_T^8
${}^3P_J^{[8]}$	—	—	—	v^8/p_T^8	v^8/p_T^8
${}^3P_J^{[1]}$	—	—	—	—	v^8/p_T^8

The roles of CS and CO in quarkonium pair production of SPS

- The CS channel mainly contributes to total and differential cross sections at low p_T, small invariant mass, and small $|\Delta Y|$ regions.
- The CO contribution is predominant in large $|\Delta Y|$ and invariant mass regions due to the existence of diffraction-like gluon exchange.

NRQCD predictions @ D0 1.96 TeV $2J/\psi$

- The fiducial cross sections reported by D0 Collaborations:

$$\sigma^{\rm SPS}_{\rm D0,fid} = (70 \pm 6 \pm 22)\ {\rm fb}, \sigma^{\rm DPS}_{\rm D0,fid} = (59 \pm 6 \pm 22)\ {\rm fb},$$

- The CSM predictions in LO (Qiao and Sun 2013) , $\rm k_T$ factorization (Baranov 2013) and $\rm NLO^*$ calculations (Lansberg and Shao 2013):

$$\sigma^{\rm SPS}_{\rm D0,fid} = 51.9\ {\rm fb}, \sigma^{\rm SPS,kT}_{\rm D0,fid} = 55.1^{+28.5}_{-15.6}{}^{+31.0}_{-17.0}\ {\rm fb}, \sigma^{\rm SPS,NLO^*}_{\rm D0,fid} = 90^{+180}_{-50}\ {\rm fb}.$$

- LO NRQCD predictions (He et al. 2021):

$$\sigma^{\rm SPS,NRQCD}_{\rm D0,fid} = 86.1^{+59.7}_{-34.0}\ {\rm fb},$$

The D0 conclusion depended on the SPS inputs. When complete NRQCD calculation is taken into account their conclusion might change.

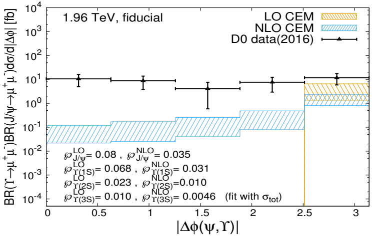
- The fiducial cross sections reported by D0 Collaborations:

$$\sigma^{\rm SPS}_{\rm D0,fid} = 0 \text{ fb}, \sigma^{\rm DPS}_{\rm D0,fid} = (27 \pm 9 \pm 7) \text{ fb},$$

- The complete study including LO NRQCD, α_s^6 real gluon radiation and loop induced, and photon fragmentation (Shao and Zhang 2016):

$$\sigma^{\rm SPS}_{\rm D0,fid} = 2.96^{+4.00}_{-1.66} \text{ fb}$$

- The $|\Delta\phi|$ distribution: CEM predictions(Lansberg et al. 2020)



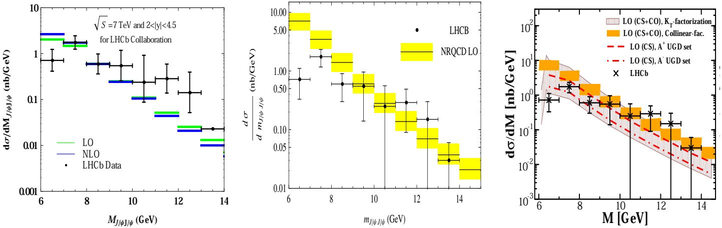
SPS contribution lies much below the D0 data.

NRQCD predictions @ LHCb 7 TeV

- Total cross section (nb): CSM predictions at QCD NLO (Sun eta al. 2016) and complete LO NRQCD (He, Kniehl 2015)

LHCb	LO CSM	NLO CSM	LO NRQCD
$5.1 \pm 1.0 \pm 1.1$	4.56 ± 1.13	$5.41^{+2.73}_{-1.14}$	$13.2^{+5.2}_{-4.1}$

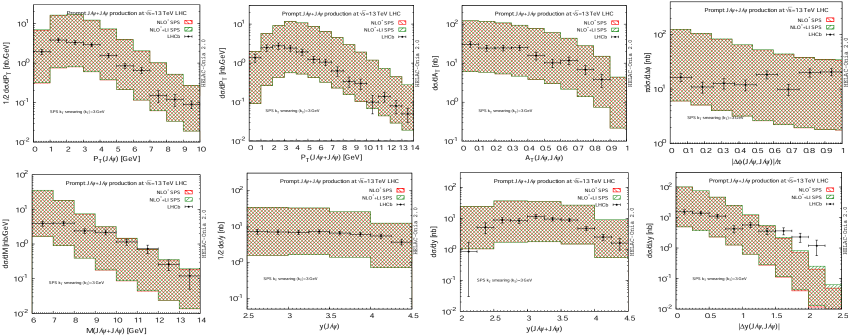
- The invariant mass spectrum: NLO CSM, NRQCD LO, and $\mathrm{k_T}$(Baranov, Rezaeian 2016)



The theoretical predictions below threshold strongly depend on the choice of m_c, and NLO QCD corrections of CSM is not large.

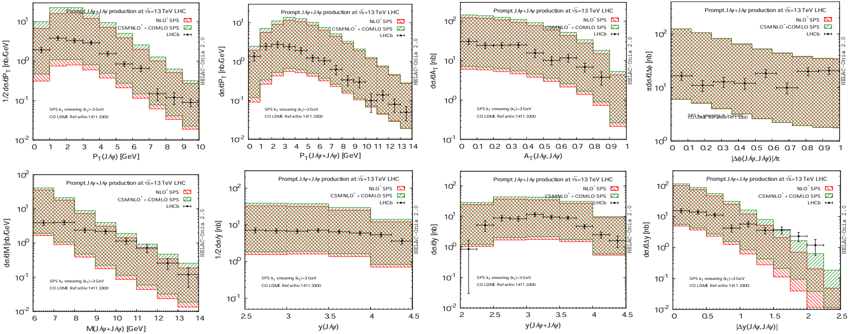
CSM predictions @ LHCb 13 TeV

- Various differential cross sections: $\mathrm{NLO}^* + \alpha_s^6(\mathrm{k_T}\ \mathrm{smearing})$ loop induced (Lansberg et al. 2019)



CSM model can describe almost all LHCb data point except for the upper $|\Delta y|$ bins.

- Various differential cross sections: $\mathrm{NLO}^{*}\mathrm{CS}+\mathrm{CO}(\mathrm{k_T}\ \mathrm{smearing})$ (Lansberg et al. 2019)



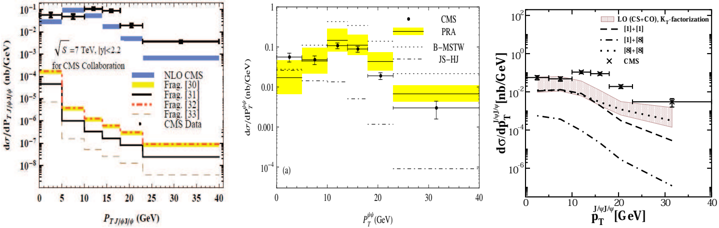
CO contribution remedies the discrepancy.

NRQCD predictions @ CMS 7 TeV $2J/\psi$ I

- Total cross section (nb): NLO CSM (Sun eta al. 2016), complete LO NRQCD (He, Kniehl 2015), PRA (He et al. 2019)

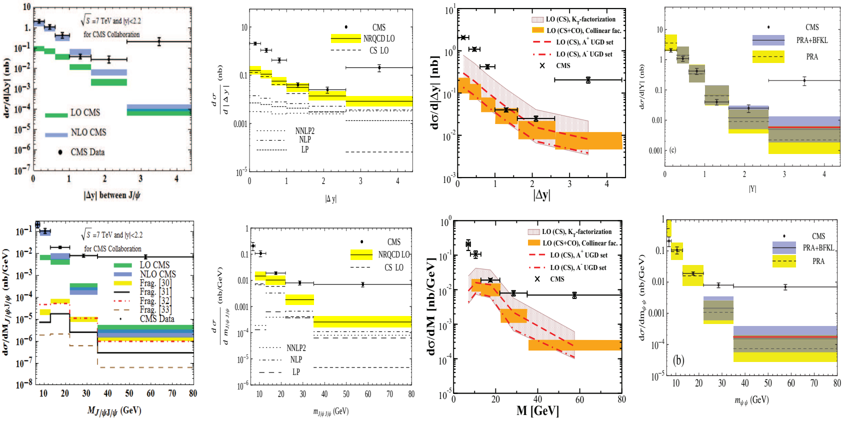
CMS	LO CSM	NLO CSM	LO NRQCD	PRA
1.49 ± 0.07	0.08 ± 0.02	0.93 ± 0.25	$0.15^{+0.08}_{-0.05}$	$1.68^{+1.32}_{-0.78}$

- The J/ψ pair $\mathrm{p_T}$ distribution including prediction of $\mathrm{k_T}$ factorization (Baranov and Rezaeian 2016):



Different way of generating the $\mathrm{k_T}$ dependent PDF could lead to complete different predictions.

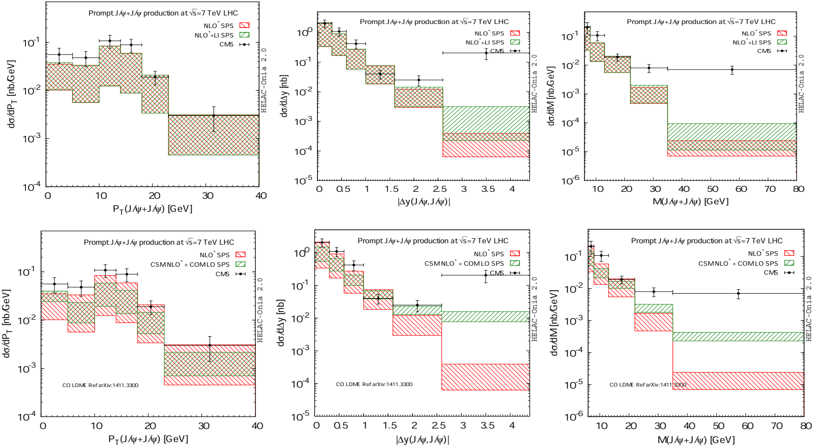
- $|\Delta y|$ and $m_{\psi\psi}$ distributions: NLO CSM, LO NRQCD,k_T and PRA



T-channel gluon exchange effect is significant and BKFL resummation can further enlarge fixed order calculations by a factor of 2.

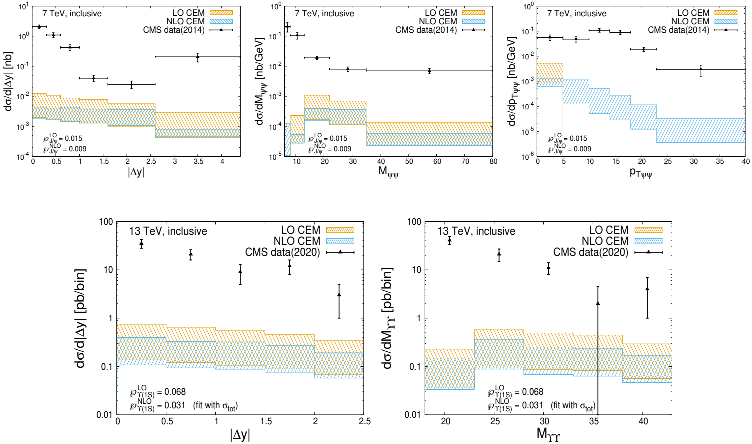
Theoretical predictions @ CMS 7 TeV $2J/\psi$ III

- Higher order contribution (Lansberg et al. 2019):



The α_s^6 loop induced contribution largely enhances that of the α_s^5 NLO*, however the SPS total results can not explain CMS measurements.

- CEM predictions of $2J/\psi$ and 2Υ production(Lansberg et al. 2020):



CEM predictions systematically undershoot the CMS data.

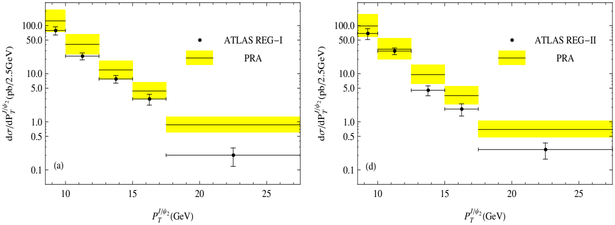
NRQCD predictions @ ATLAS 8 TeV $2J/\psi$ I

- Total cross section: PRA (He et al. 2019)

$$\sigma(pp \to J/\psi J/\psi + X) = \begin{cases} 82.2 \pm 8.3\,(\text{stat}) \pm 6.3\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.6\,(\text{lumi})\,\text{pb}, \text{ for } |y| < 1.05, \\ 78.3 \pm 9.2\,(\text{stat}) \pm 6.6\,(\text{syst}) \pm 0.9\,(\text{BF}) \pm 1.5\,(\text{lumi})\,\text{pb}, \text{ for } 1.05 \leq |y| < 2.1. \end{cases}$$

$$\sigma^{\text{PRA}}_{\text{ATLAS}} = \begin{cases} 133.6^{+89.6}_{-52.2}\ \text{pb, for} |y(J/\psi_2)| < 1.05 \\ 105.2^{+73.8}_{-41.6}\ \text{pb, for} 1.05 < |y(J/\psi_2)| < 2.1 \end{cases}$$

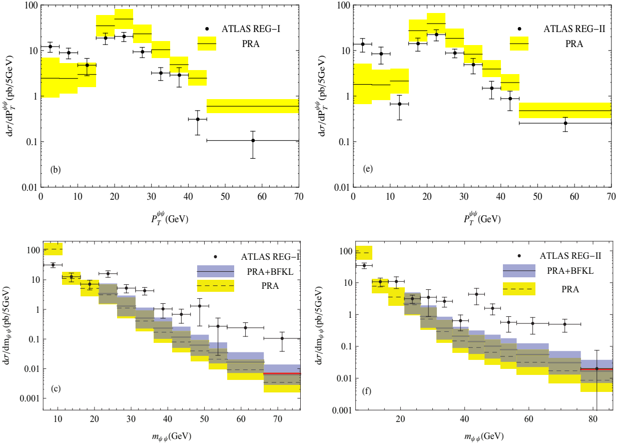
- p_T distribution of the J/ψ



PRA predictions agree well with ATLAS measurements.

NRQCD predictions @ ATLAS 8 TeV $2J/\psi$ II

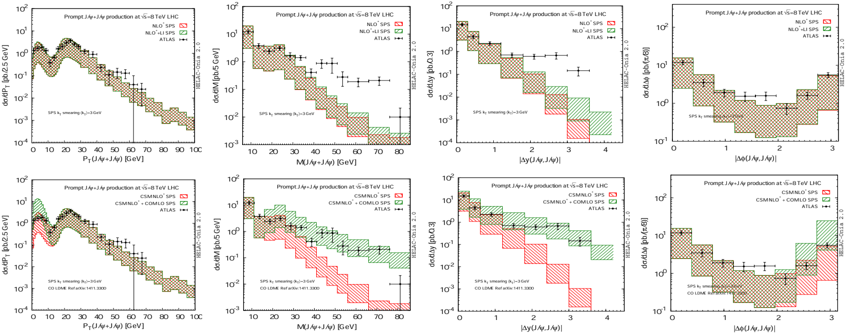
- p_T and invariant mass distributions of the J/ψ pair:



SPS can not account for the invariant mass distribution in the upper bins.

Theoretical predictions @ ATLAS 8 TeV $2J/\psi$ III

- Differential cross sections of the J/ψ pair in fiducial: $\mathrm{CS\ NLO^* + LI\ (k_T\ smearing)}$, $\mathrm{NLO^*CS + CO\ (k_T\ smearing)}$ (Lansberg al et. 2019)



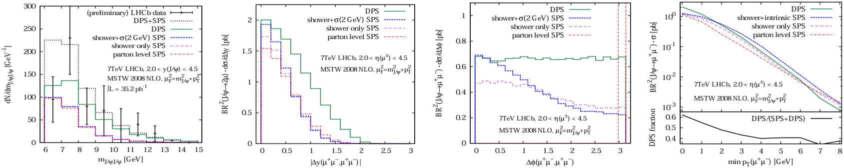
SPS itself can describe well ATLAS measurements in fiducial with proper choice of the LDMEs in NRQCD.

DPS investigation @ LHCb 7 TeV

- A crystal ball form function (Kom et al. 2011):

$$\overline{|M_{gg\to J/\psi+X}|^2} = \begin{cases} K\exp\left(-\kappa\frac{p_T^2}{m_{J/\psi}^2}\right) & p_T \le \langle p_T\rangle \\ K\exp\left(-\kappa\frac{\langle p_T\rangle^2}{m_{J/\psi}^2}\right)\left(1+\frac{\kappa}{n}\frac{p_T^2-\langle p_T\rangle^2}{m_{J/\psi}^2}\right)^{-n} & p_T > \langle p_T\rangle \end{cases}$$

- The differential cross sections:



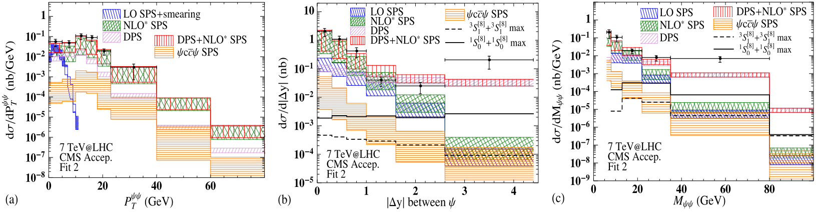
- Total cross sections: (Baranov et al. 2011 and Borschensky and Kulesza 2017):

$$\sigma^{\psi\psi}_{\rm DPS} = 1.7~{\rm nb}, \sigma^{\psi\psi}_{\rm DPS}({\rm both~from}\chi_c) = 0.9~{\rm nb}, \sigma^{\psi\psi}_{\rm DPS} = 3.41^{+1.31}_{-0.65}~{\rm nb}.$$

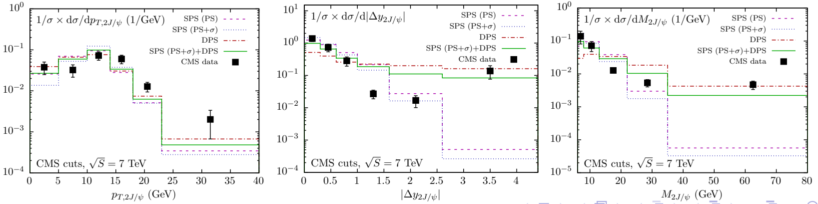
The $m_{\psi\psi}$, $|\Delta y|$ and $|\Delta\phi|$ distributions are key probes of DPS.

DPS investigation @ CMS 7 TeV

- $\sigma_{\text{eff}} = 8.2 \pm 2.2\text{mb}$ was exacted for the first time from CMS data (Lansberg and Shao 2015):

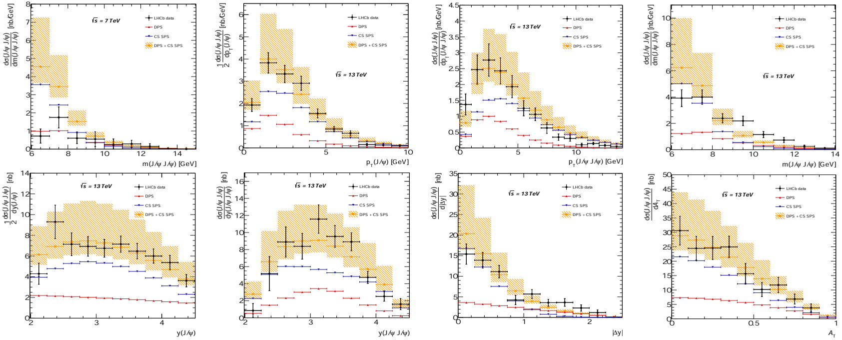


- Predictions with $\sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}\text{mb}$ (Borschensky and Kulesza 2017):



DPS investigation @ LHCb 7 and 13 TeV

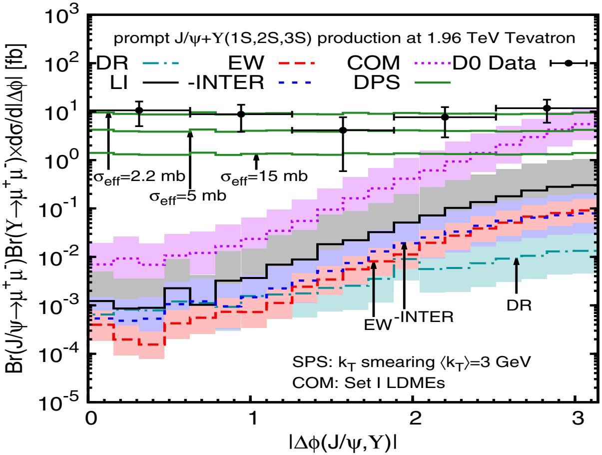
- $\sigma_{\text{eff}} = 17.5 \pm 4.1\text{mb}$ (Prokhorov et al.2020):



Both SPS and DPS contributions are needed, but not be able to explain the $|\Delta\phi|$ distribution at LHCb 13 TeV.

DPS investigation @ D0 1.96 TeV

- $\sigma_{\text{eff}} < 8.2\text{mb}$ at 68% confidence level (Shao and Zhang 2016):



$\sigma_{\text{eff}} = 2.2\text{mb}$ can perfectly describe the data.

Summary

1. Quarkonium pair can provide very rich information about the perturbative and nonperturbative aspects of QCD as well as the patrons inside proton.
2. In different kinematic region, the roles of SPS and DPS are different.
3. The value of σ_{eff} extracted from J/ψ pair production do not consistent with each other.
4. To clarify the source of inconsistent conclusions and to understand the production mechanism of quakonium pair, more works are needed on theoretical and experimental sides.

Thank you!