Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s} = 13$ TeV

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On behalf of the LHCb collaboration

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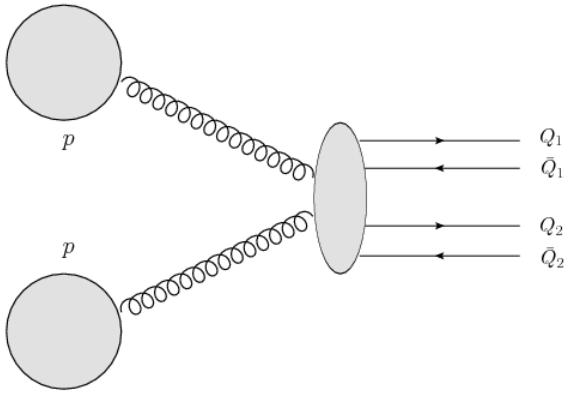
Motivation

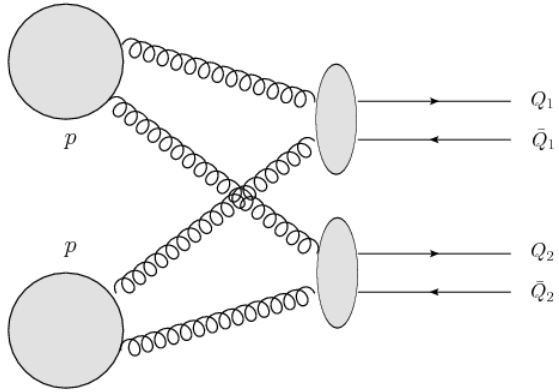
Quarkonium pair production

Single-parton scattering (SPS)



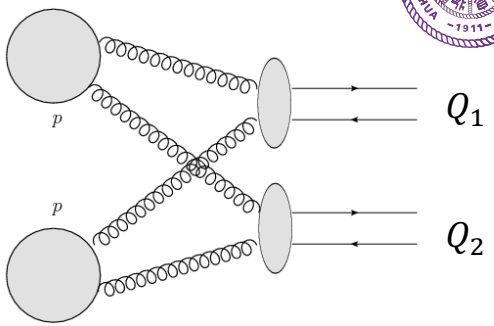
- ✓ **Probe the quarkonium production mechanism puzzle**; *color-singlet process in leading-order NRQCD forbids feed-down from excited C-even states
- ✓ **Access internal dynamics of protons**, *e.g.* pin down the linearly-polarized gluons inside unpolarized protons [arXiv:1710.01684]

Double-parton scattering (DPS)



- ✓ Provide information on parton transverse profile & correlations in proton
- ✓ Help better understand background ($Z + b\bar{b}$, W^+W^+ etc.) in searches for NP

Double parton scattering



➢ The most popular model due to **limited knowledge**:

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx_1' dx_2' d^2\mathbf{b_1} d^2\mathbf{b_2} d^2\mathbf{b}$$

$$\times \Gamma_{ij}(x_1, x_2, \mathbf{b_1}, \mathbf{b_2}) \times \hat{\sigma}_{ik}^{Q_1}(x_1, x_1') \hat{\sigma}_{jl}^{Q_2}(x_2, x_2') \times \Gamma_{kl}(x_1', x_2', \mathbf{b_1} - \mathbf{b}, \mathbf{b_2} - \mathbf{b})$$

Generalized double parton PDF

SPS parton-level cross-section

✓ Assumption 1: factorization of transverse & longitudinal components

$$\Gamma_{ij}(x_1, x_2, \boldsymbol{b}_1, \boldsymbol{b}_2) = D_{ij}(x_1, x_2) T_{ij}(\boldsymbol{b}_1, \boldsymbol{b}_2)$$

✓ Assumption 2: no correlation

$$D_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2), \qquad T_{ij}(\boldsymbol{b}_1, \boldsymbol{b}_2) = T_i(\boldsymbol{b}_1) T_j(\boldsymbol{b}_2)$$

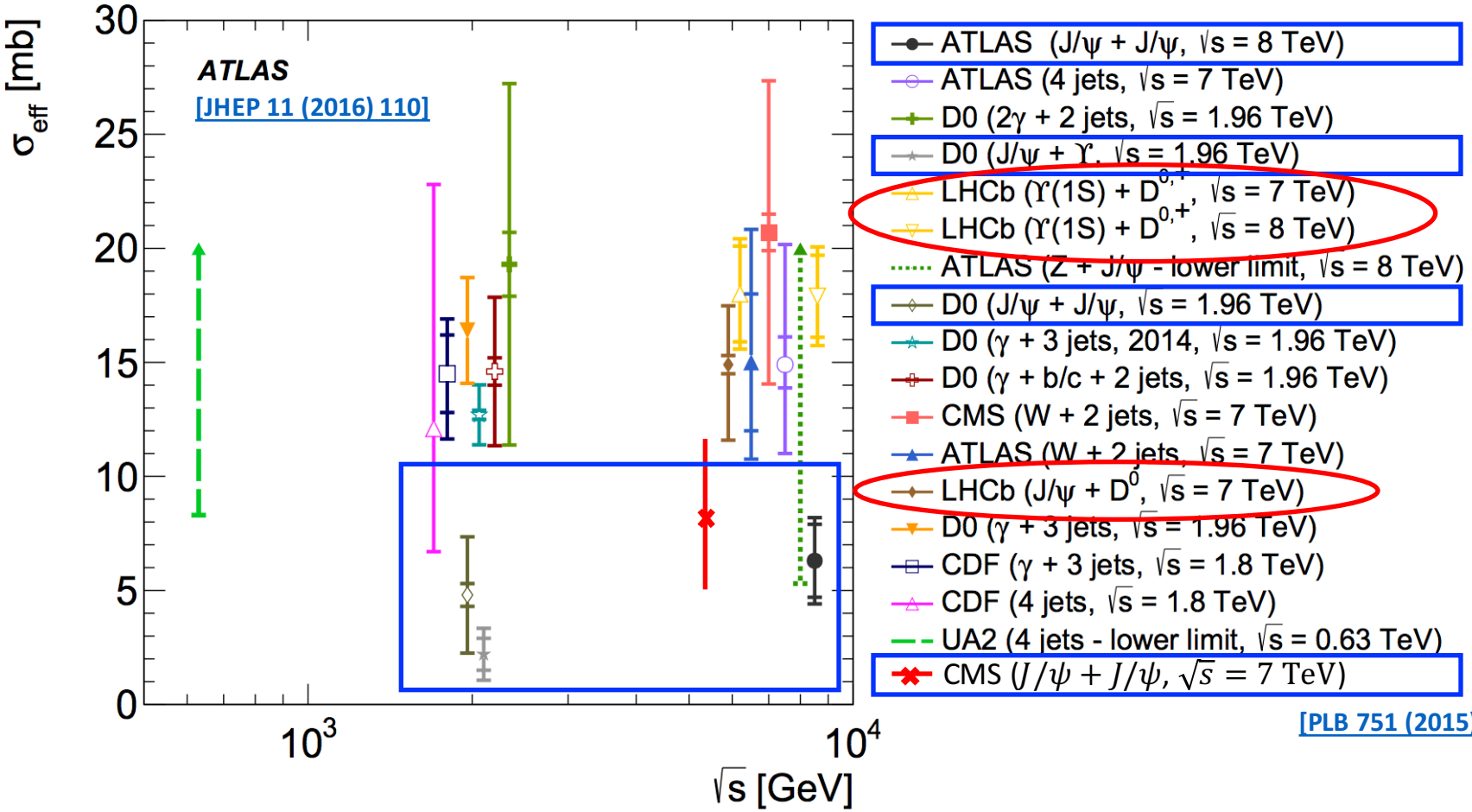
⇒ Pocket formula

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

✓ $\sigma_{\text{eff}} = \left[\int d^2\boldsymbol{b} F(\boldsymbol{b})^2\right]$, $F(\boldsymbol{b}) = \int T(\boldsymbol{b}_i) T(\boldsymbol{b}_i - \boldsymbol{b}) d^2\boldsymbol{b}_i$: should be universal!

Effective cross-section summary

- General purpose of DPS measurements: measure σ_{eff}
  - ✓ validate its universality or probe the dependence on process and energy



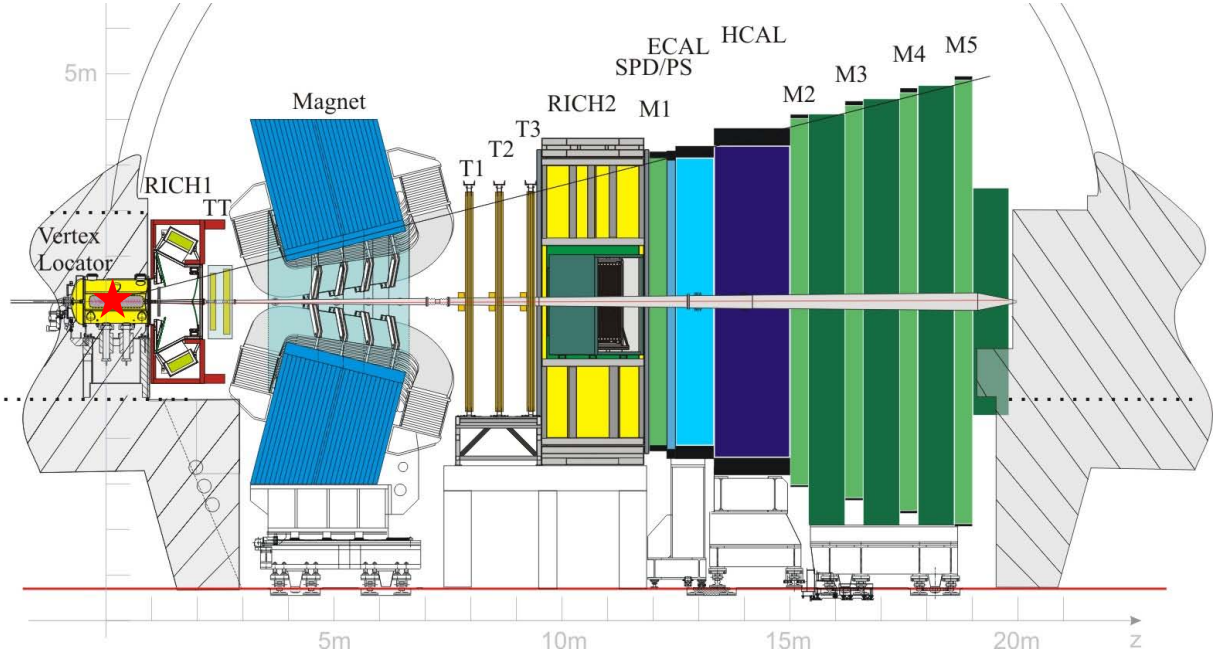
[PLB 751 (2015) 479]

- J/ψ pair production at LHCb will be an important input

The LHCb detector

- A single-arm forward region spectrometer covering $2 < \eta < 5$
- RunI (2011-2012): $\mathcal{L}_{\text{int}} = 3\ \text{fb}^{-1}$ @ 7 & 8 TeV; $\sigma(b\bar{b}) \approx 250\ \mu\text{b}^{-1}$ @ 7 TeV [EPJC 71 (2011) 1645]
- RunII (2015-2018): $\mathcal{L}_{\text{int}} = 5\ \text{fb}^{-1}$ @ 13 & 14 TeV; $\sigma(b\bar{b}) \approx 500\ \mu\text{b}^{-1}$ @ 13 TeV [JHEP 10 (2015) 172]

pp interaction point



[JINST 3 (2008) S08005]

- ✓ **Vertex Locator:** $\sigma_{\text{PV},x/y} \sim 10\ \mu\text{m}$, $\sigma_{\text{PV},z} \sim 60\ \mu\text{m}$
- ✓ **Tracking (TT, T1-T3):** $\Delta p/p = 0.5 - 0.6\%$ for $5 < p < 100\ \text{GeV}/c$
- ✓ **RICHs:** $\varepsilon(K \to K) \sim 95\%$ @ misID rate $(\pi \to K) \sim 5\%$
- ✓ **Muon system (M1-M5):** $\varepsilon(\mu \to \mu) \sim 97\%$ @ misID rate $(\pi \to \mu) \sim 1 - 3\%$
- ✓ **ECAL:** $\sigma_E/E \sim 10\%/\sqrt{E} \otimes 1\%$ (E in GeV)
- ✓ **HCAL:** $\sigma_E/E \sim 70\%/\sqrt{E} \otimes 10\%$ (E in GeV)

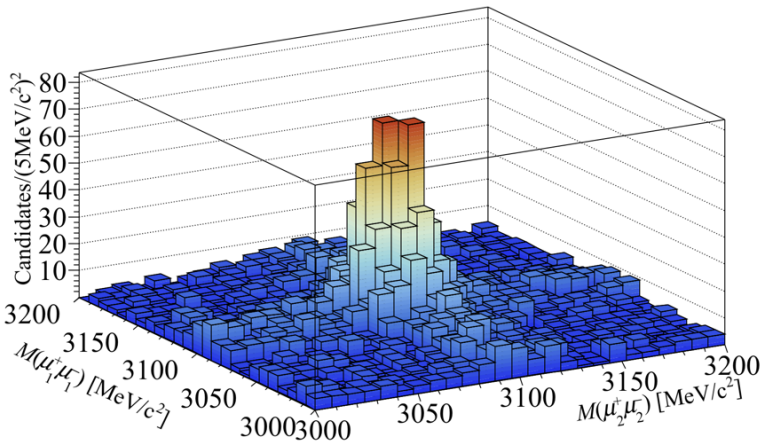
J/ψ pair @ 13 TeV [JHEP 06 (2017) 047]

- Data sample: pp collision data collected by LHCb at $\sqrt{s} = 13$ TeV corresponding to $279\ \mathrm{pb}^{-1}$
- Fiducial region: both J/ψ mesons $p_{\mathrm{T}} < 10\ \mathrm{GeV}/c$, $2.0 < y < 4.5$
- The master relation

$$\sigma = \frac{N^{cor}}{L_{\mathrm{int}} \times \mathcal{B}^2(J/\psi \to \mu^+\mu^-)}$$

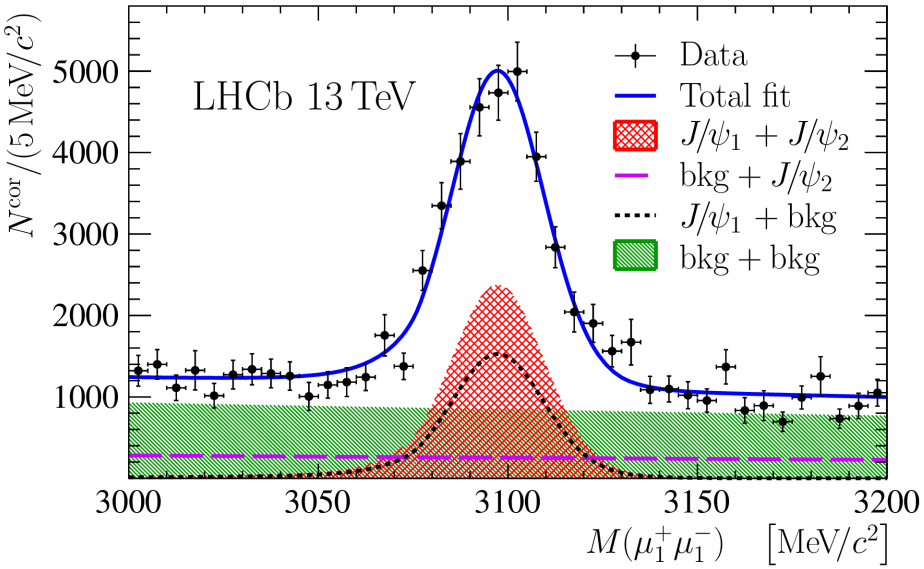
  - ✓ N^{cor}: signal yield after per-event efficiency correction
  - ✓ Efficiencies estimated using data & simulation

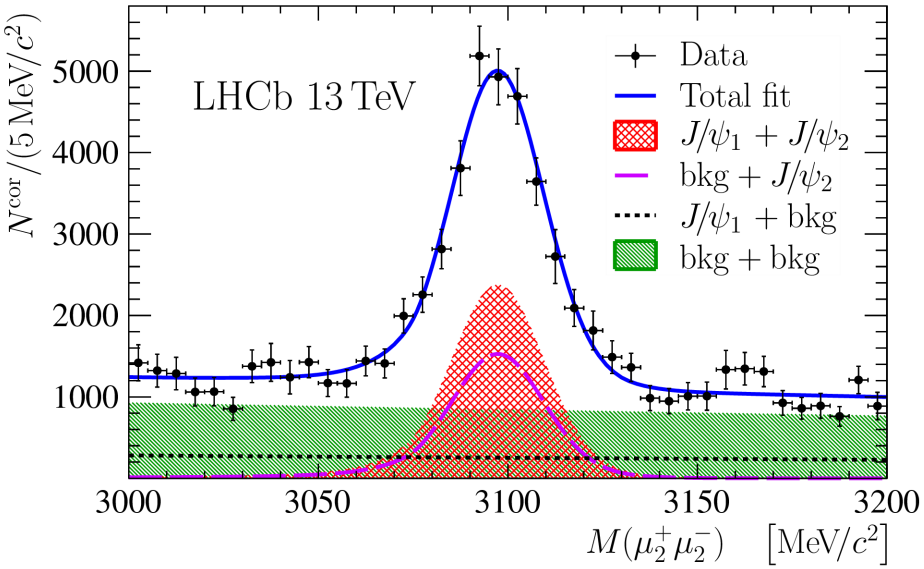
- Trigger targeted at selecting high quality muons; require either J/ψ to be triggered
- Simple cuts applied
  - ✓ Identified muons with good track quality; $p_{\mathrm{T}} > 0.65\ \mathrm{GeV}/c$; $6 < p < 200\ \mathrm{GeV}/c$; $2 < \eta < 5$; good quality dimuon vertex
  - ✓ Four muons to come from the same PV
  - ✓ Duplicate tracks and multiple candidates removed



Cross-section

- Signal yield obtained from simultaneous fit to the efficiency-corrected 2D $\left(M(\mu_1^+\mu_1^-), M(\mu_2^+\mu_2^-)\right)$ distribution





[JHEP 06 (2017) 047]

- Residual from-b component subtracted afterwards
  - ✓ The contribution determined using simulation together with $\sigma(pp \to b\bar{b})$ and $\sigma(\text{prompt}\, J/\psi)$ from J/ψ production measurement [JHEP 10 (2015) 172]

- Result:

$$\sigma(J/\psi J/\psi) = 15.2 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})\ \text{nb}$$

Comparison to theory

$\sigma(J/\psi\, J/\psi)$ [nb] [JHEP 06 (2017) 047]

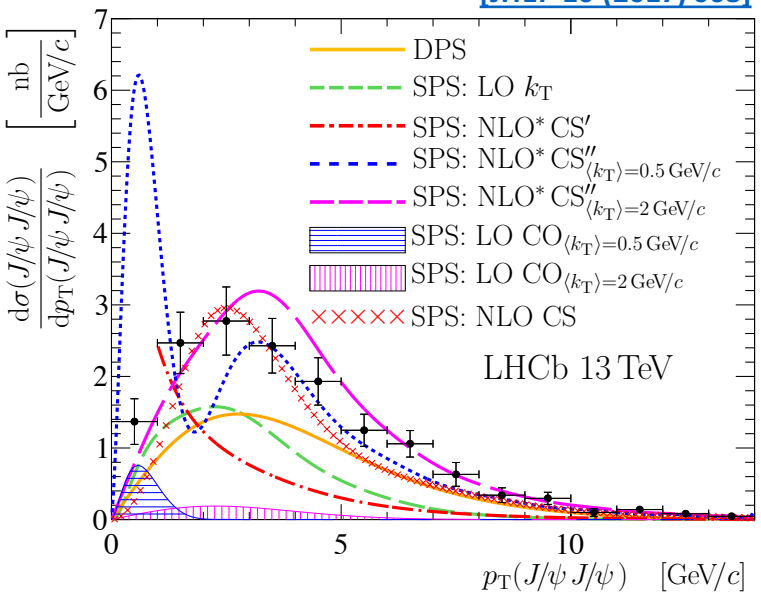
		no $p_{\rm T}$ cut	$p_{\rm T} > 1\,{\rm GeV}/c$	$p_{\rm T} > 3\,{\rm GeV}/c$
SPS	LO CS	$1.3 \pm 0.1^{+3.2}_{-0.1}$	—	—
	LO CO	$0.45 \pm 0.09^{+1.42+0.25}_{-0.36-0.34}$	—	—
	LO $k_{\rm T}$	$6.3^{+3.8+3.8}_{-1.6-2.6}$	$5.7^{+3.4+3.2}_{-1.5-2.1}$	$2.7^{+1.6+1.6}_{-0.7-1.0}$
	NLO* CS′	—	$4.3 \pm 0.1^{+9.9}_{-0.9}$	$1.6 \pm 0.1^{+3.3}_{-0.3}$
	NLO* CS″	$15.4 \pm 2.2^{+51}_{-12}$	$14.8 \pm 1.7^{+53}_{-12}$	$6.8 \pm 0.6^{+22}_{-5}$
	NLO CS	$11.9^{+4.6}_{-3.2}$	—	—
	DPS	$8.1 \pm 0.9^{+1.6}_{-1.3}$	$7.5 \pm 0.8^{+1.5}_{-1.2}$	$4.9 \pm 0.5^{+1.0}_{-0.8}$
	LHCb result	$15.2 \pm 1.0 \pm 0.9$	$13.5 \pm 0.9 \pm 0.9$	$8.3 \pm 0.6 \pm 0.5$

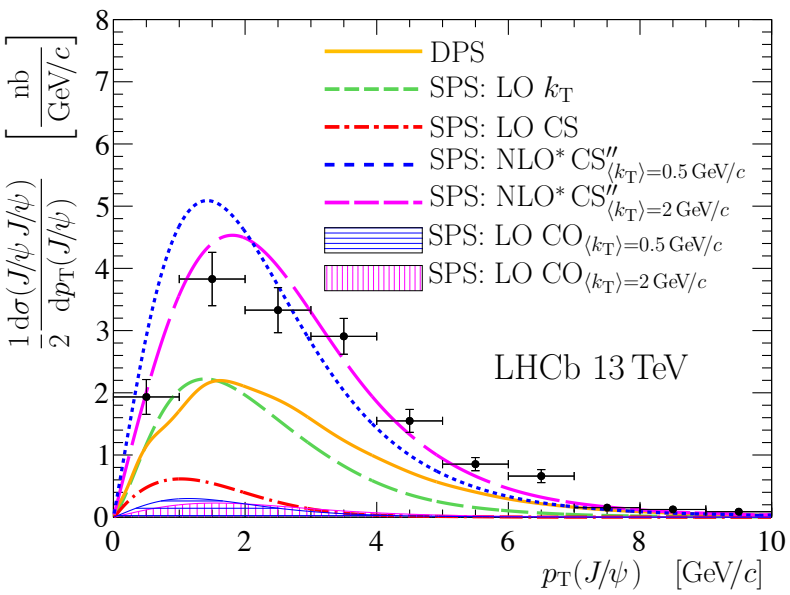
DPS: assuming $\sigma_{\rm eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb [PRD 56 (1997) 3811]

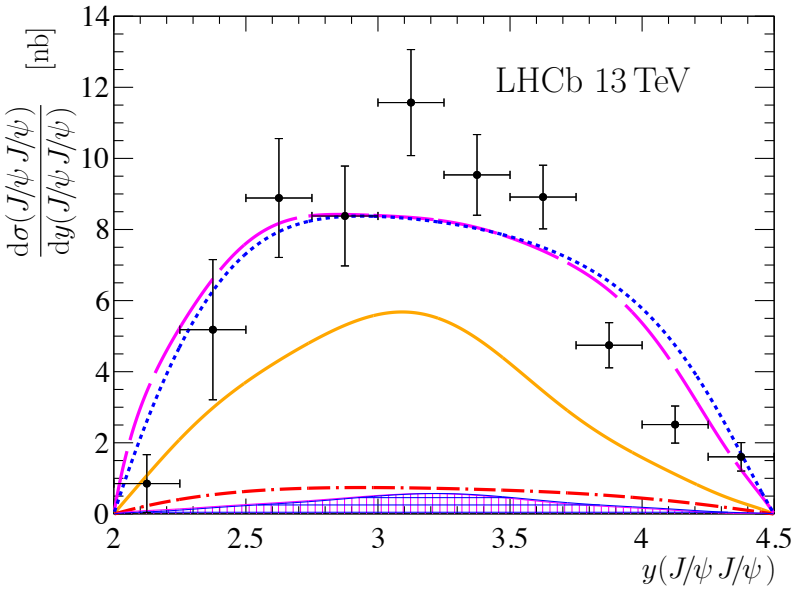
- LO CO : contribution very small
- LO CS/ NLO* CS' and LO $k_{\rm T}$: need DPS contribution
- NLO* CS'' and NLO CS : consistent with our measurement by itself; overestimated if there is DPS contribution

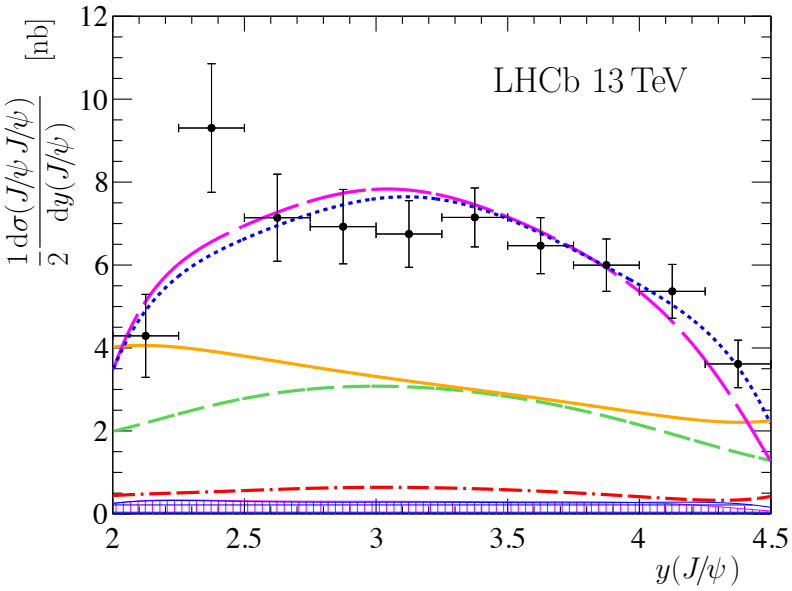
Differential cross-sections (I)

[JHEP 10 (2017) 068]









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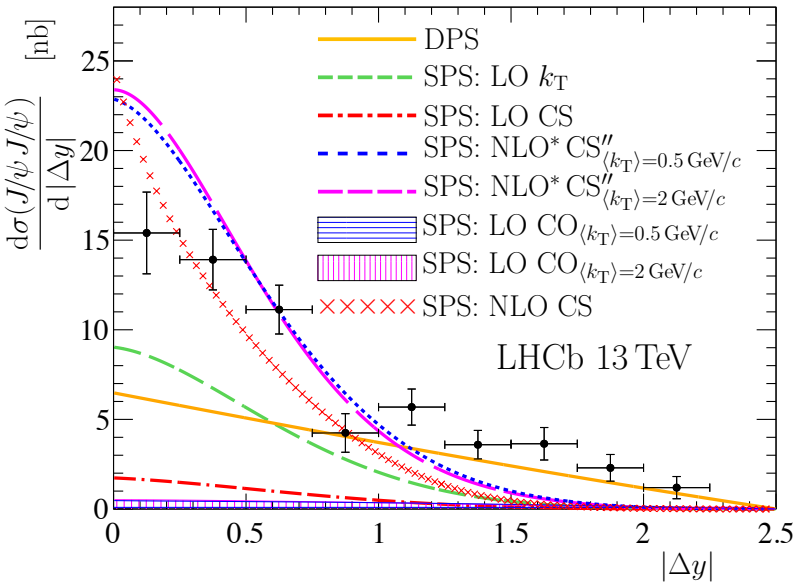
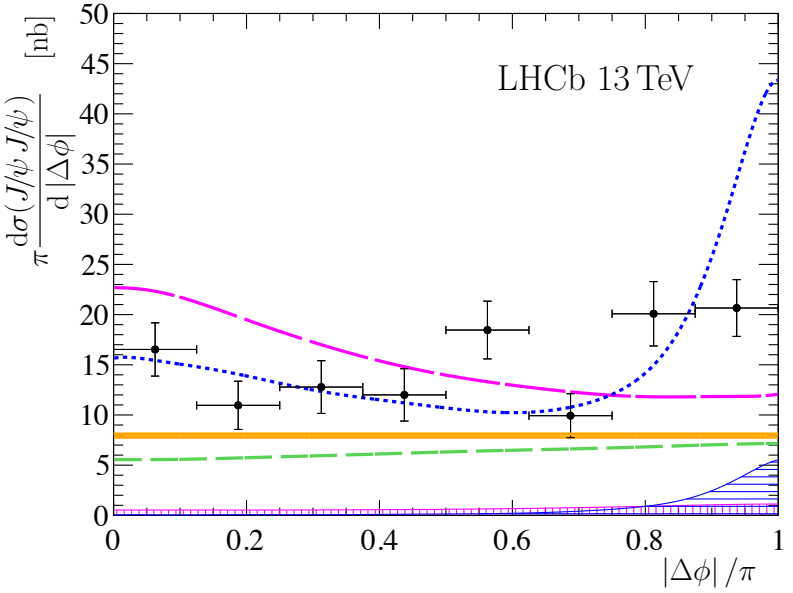
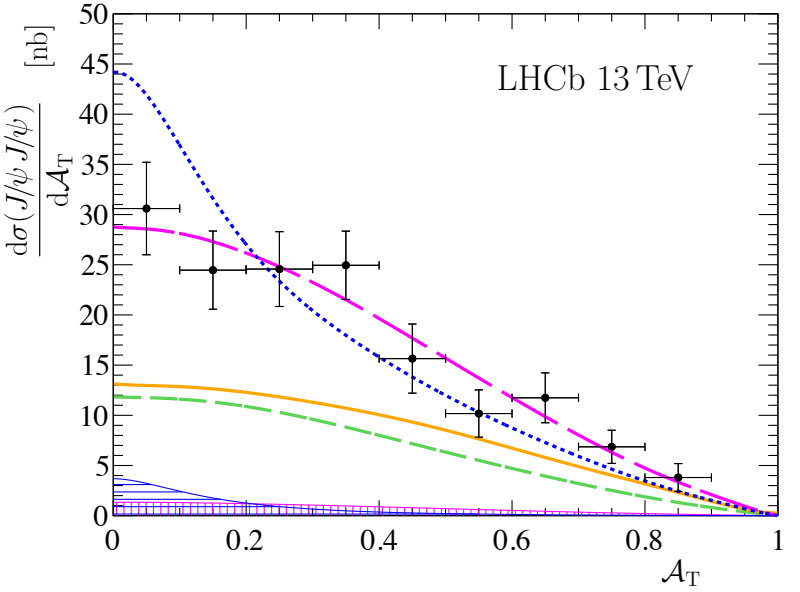
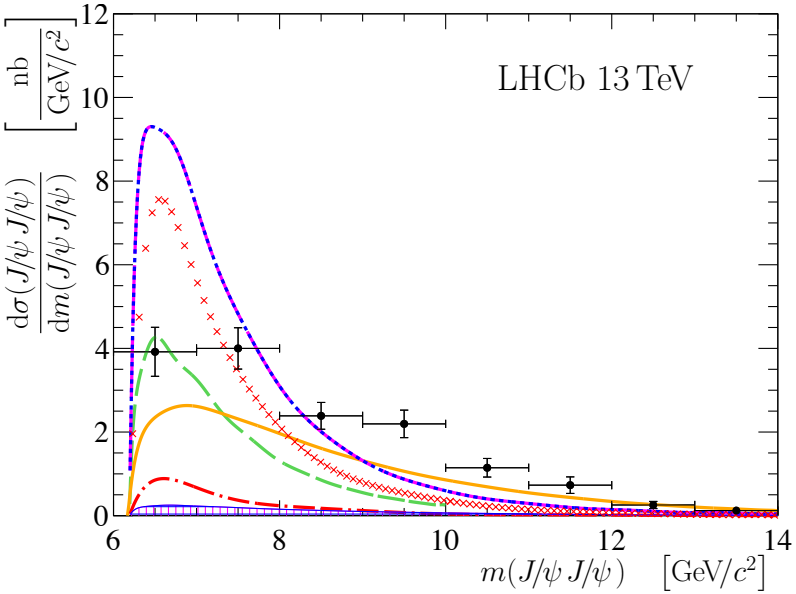
Differential cross-sections (II)



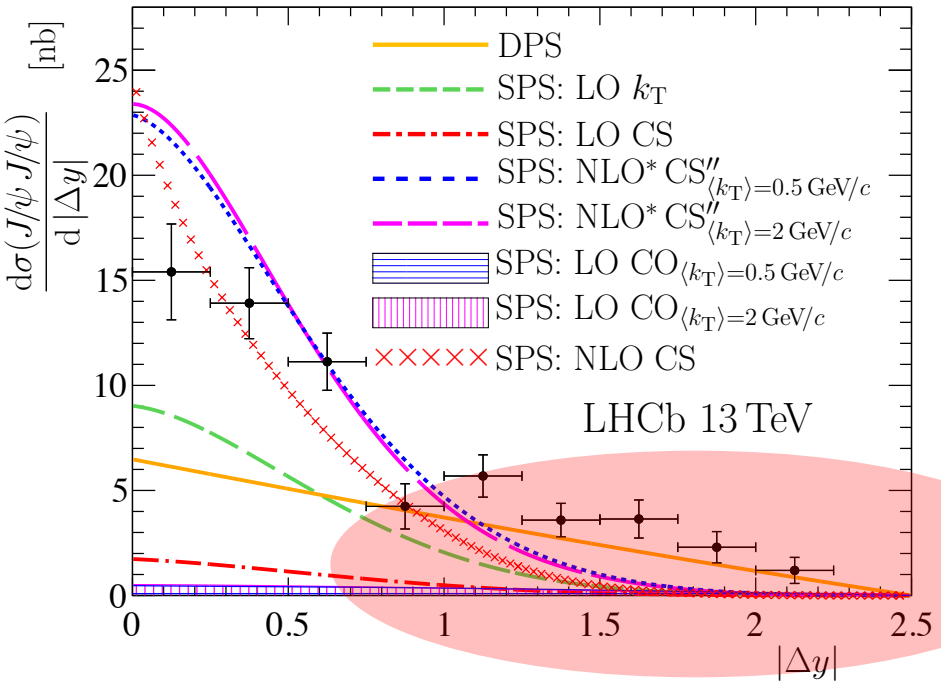


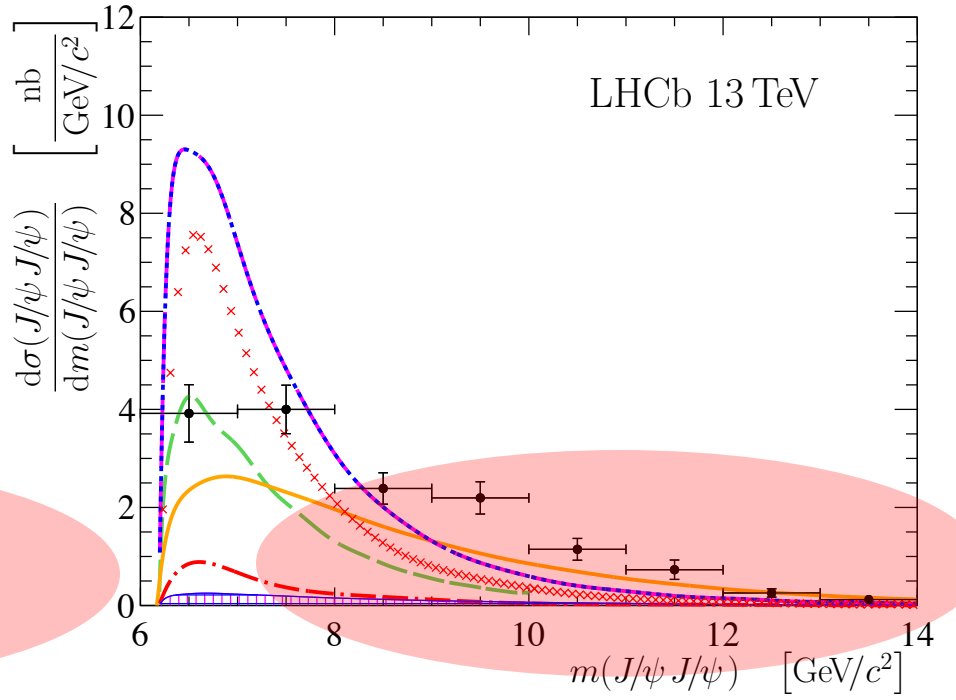




Comparison to theory

- Differential cross-sections of different variables compared to theory predictions
  - ✓ Most significant indication of DPS comes from $|\Delta y|$
  - ✓ DPS contribution essential for the region $|\Delta y| > 1.5$
  - ✓ Also clear indication from $m(J/\psi J/\psi)$

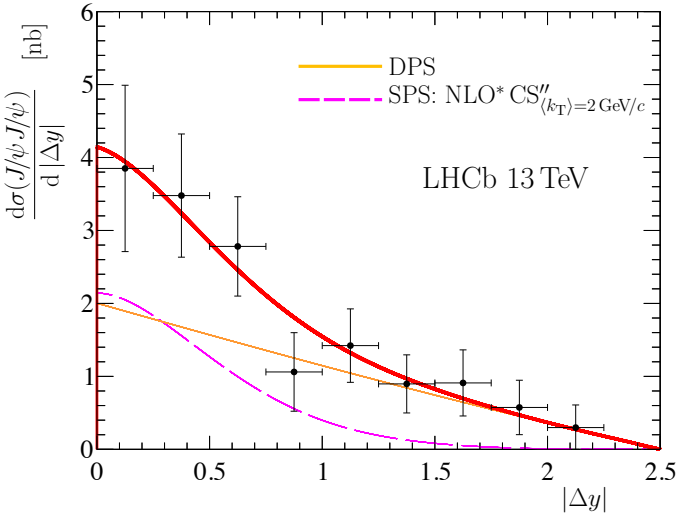


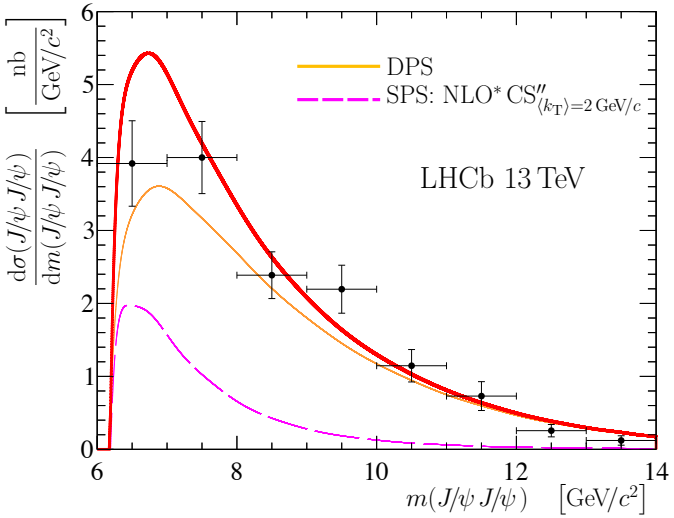


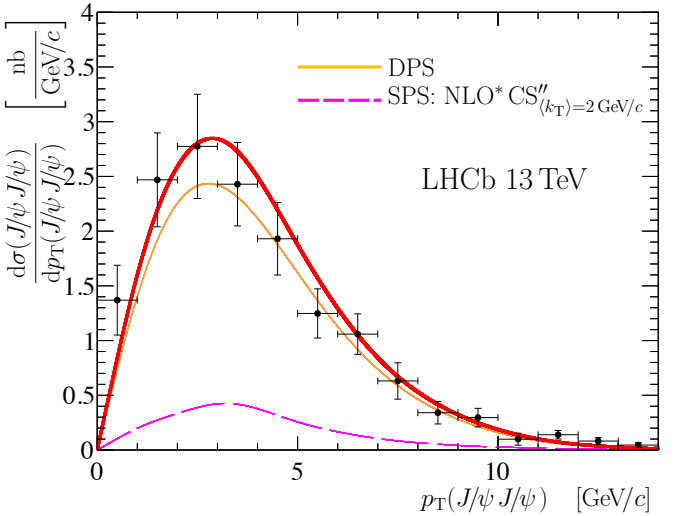
[JHEP 06 (2017) 047]

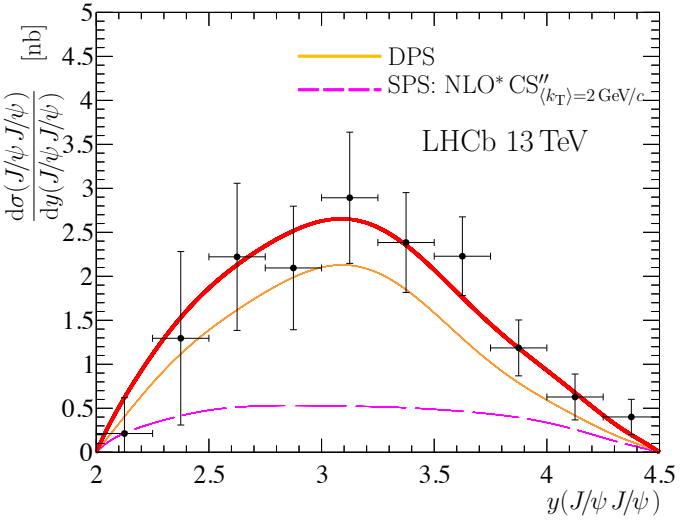
DPS+SPS fits

- Template DPS+SPS fits performed as $\frac{\mathrm{d}\sigma}{\mathrm{d}v} = \sigma_{\mathrm{DPS}} F_{\mathrm{DPS}}(v) + \sigma_{\mathrm{SPS}} F_{\mathrm{SPS}}(v)$









[JHEP 10 (2017) 068]

[JHEP 06 (2017) 047]

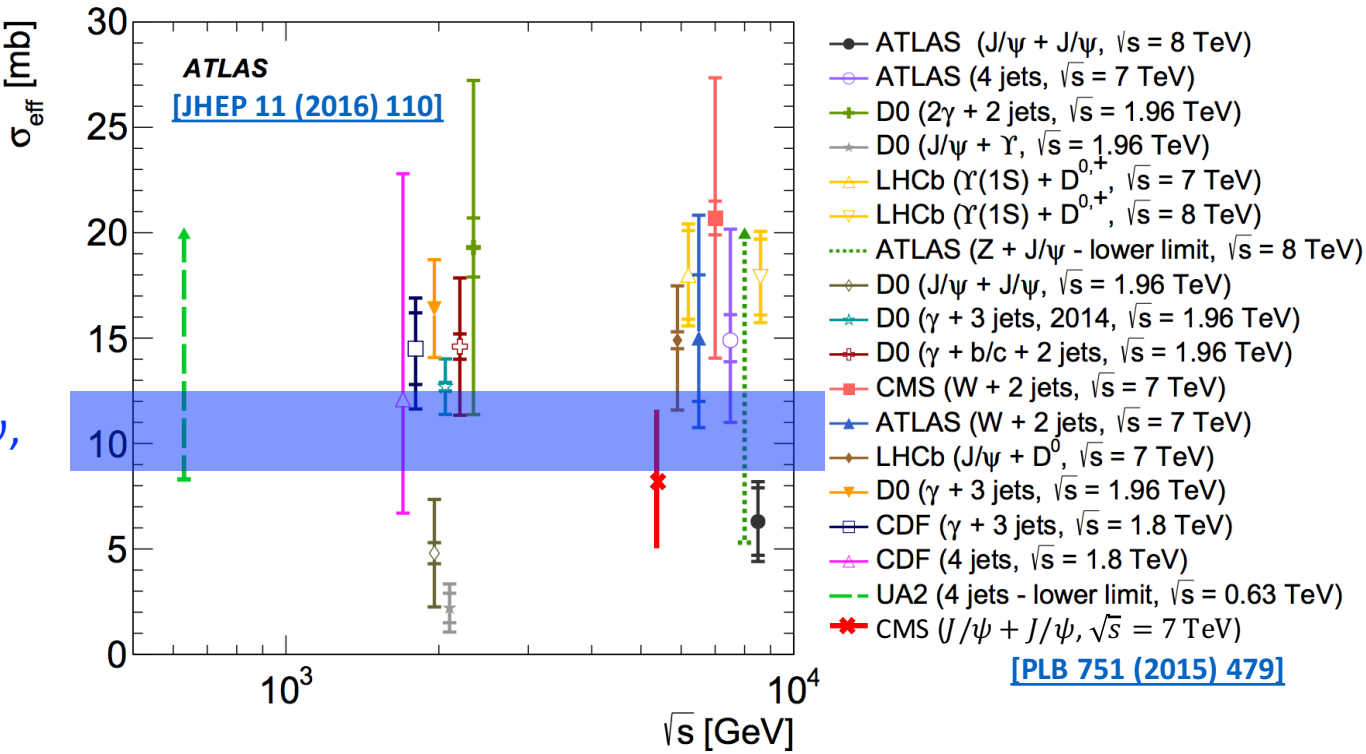
Effective cross-section

- Determined using $\sigma_{\text{eff}} = \frac{1}{2}\frac{\sigma\,(J/\psi)^2}{\sigma_{\text{DPS}}}$; lying between 8.8~12.5 mb

Variable	LO k_T	NLO* CS″ $\langle k_T\rangle = 2\,\text{GeV}/c$	NLO* CS″ $\langle k_T\rangle = 0.5\,\text{GeV}/c$	NLO CS
$p_T(J/\psi\,J/\psi)$	9.7 ± 0.5	8.8 ± 5.6	9.3 ± 1.0	—
$y(J/\psi\,J/\psi)$	—	11.9 ± 7.5	10.0 ± 5.0	—
$m(J/\psi\,J/\psi)$	10.6 ± 1.1	10.2 ± 1.0		10.4 ± 1.0
$\lvert\Delta y\rvert$	12.5 ± 4.1	12.2 ± 3.7	12.4 ± 3.9	11.2 ± 2.9

[JHEP 10 (2017) 068]

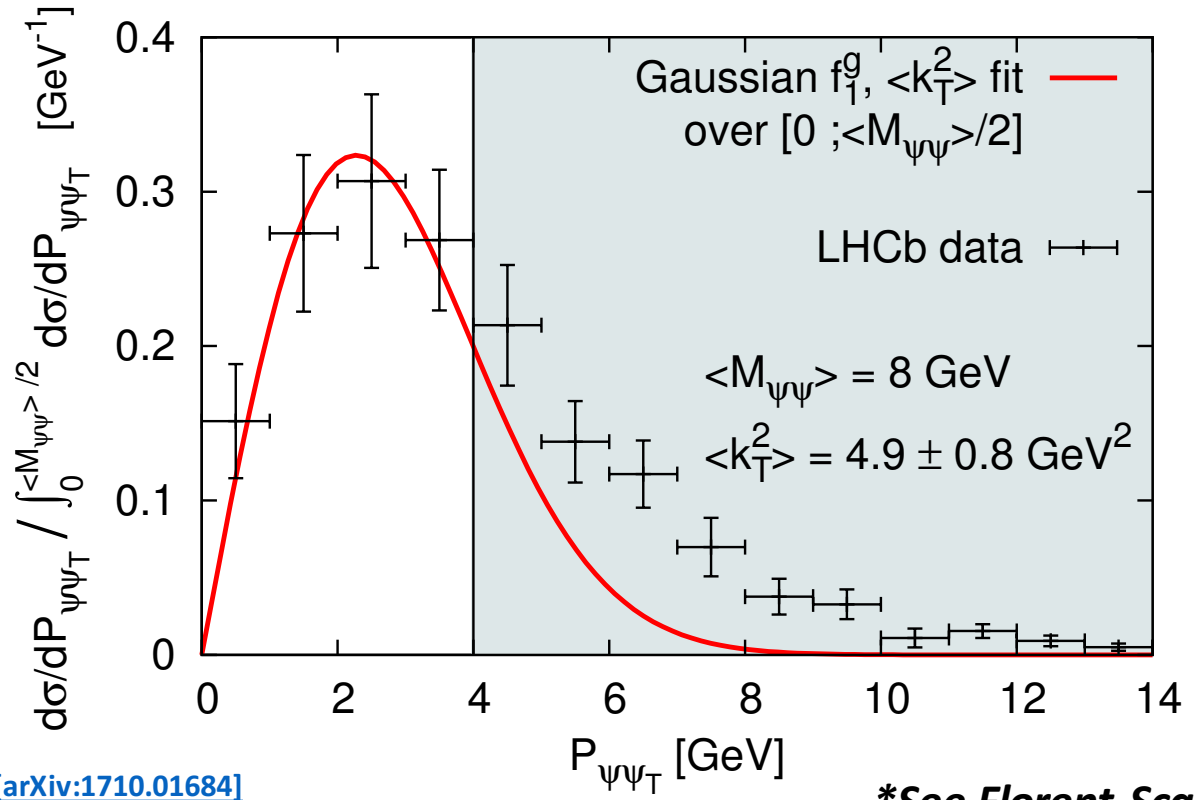
LHCb ($J/\psi + J/\psi$, $\sqrt{s} = 13$ TeV)



[PLB 751 (2015) 479]

One theoretical application

- With the differential production cross-sections measured, our measurement contains a wealth of information!
- It helps to measure the momentum-distribution of linearly-polarized gluons inside unpolarized protons



[arXiv:1710.01684]

***See Florent Scarpa's talk for details**

Summary

- J/ψ pair production at $\sqrt{s} = 13$ TeV measured at LHCb
  - ✓Differential cross-sections as functions of various variables are given
  - ✓Results show evidence for DPS contribution
  - ✓σ_{eff} determined using SPS+DPS template fits
  - ✓HepData record available http://dx.doi.org/10.17182/hepdata.79484

Thank you!

Back up

Efficiency estimation

➢ $\varepsilon_{\mathrm{tot}} = \varepsilon_{\mathrm{acc}} \times \varepsilon_{\mathrm{GEC}} \times \varepsilon_{\mathrm{rec\&sel}} \times \varepsilon_{\mathrm{PID}} \times \varepsilon_{\mathrm{trig}}$

✓ $\varepsilon_{\mathrm{acc}} \& \varepsilon_{\mathrm{rec\&sel}} \& \varepsilon_{\mathrm{PID}}$
- Factorization: $\varepsilon(J/\psi\, J/\psi) = \varepsilon(J/\psi 1) \times \varepsilon\ (J/\psi 2)$
- $\varepsilon(J/\psi)$ estimated using simulated J/ψ sample; in bins of J/ψ p_{T} and y
- Track detection efficiency corrected using data-driven method
- $\varepsilon_{\mathrm{PID}}$ calibrated using data sample

✓ $\varepsilon_{\mathrm{GEC}}$: global event cut efficiency
- Estimated from data

✓ $\varepsilon_{\mathrm{trig}}$
- Factorization: $\varepsilon_{\mathrm{trig}}(J/\psi\, J/\psi) = 1 - (1 - \varepsilon_{\mathrm{trig}}(J/\psi 1)) \times (1 - \varepsilon_{\mathrm{trig}}(J/\psi 2))$
- $\varepsilon_{\mathrm{trig}}(J/\psi)$ estimated using simulated J/ψ sample; in bins of J/ψ p_{T} and y
- Validated using data sample