EPS-HEP2023 conference

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Universität Hamburg

Study of associated quarkonium production in *pp* collisions at LHCb

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On behalf of the LHCb collaboration

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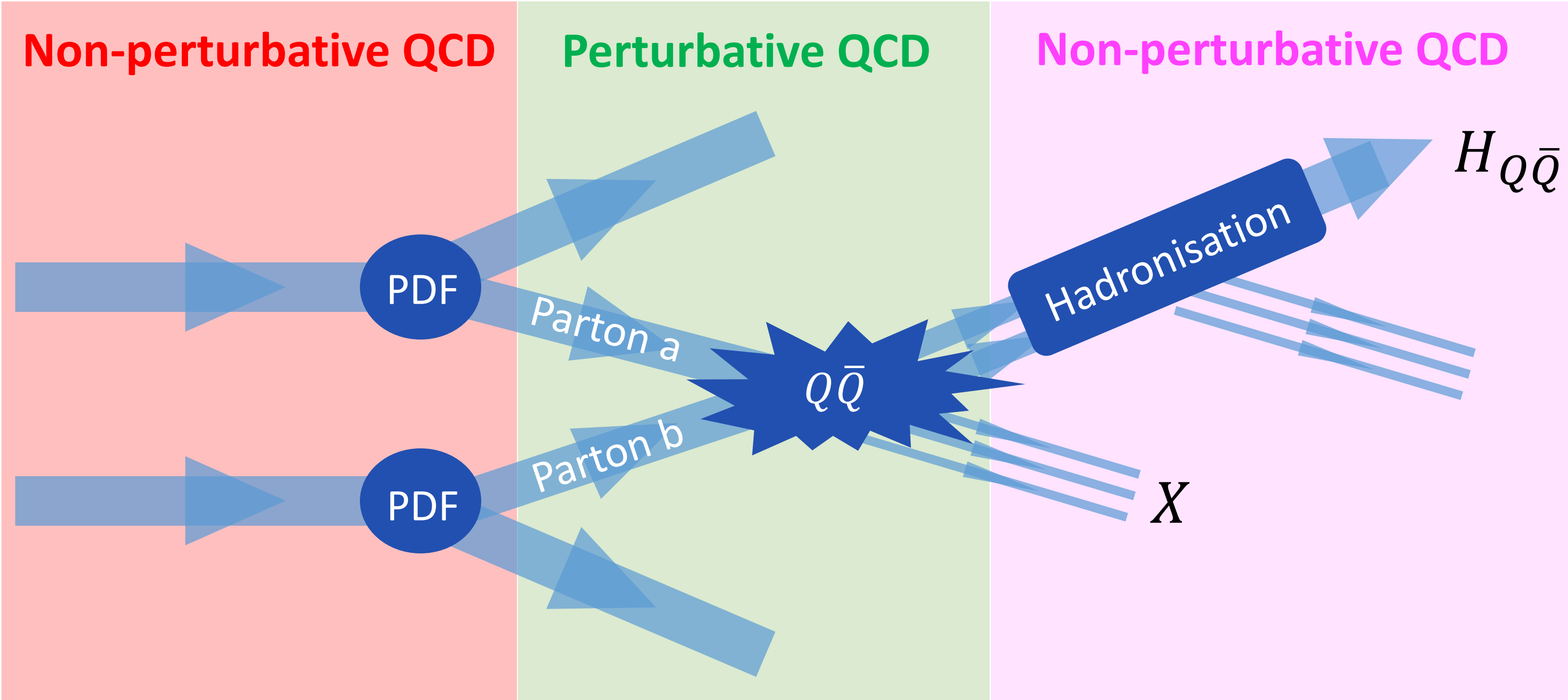
EPS-HEP2023, August 23rd 2023 @ Hamburg, Germany

Quarkonium production

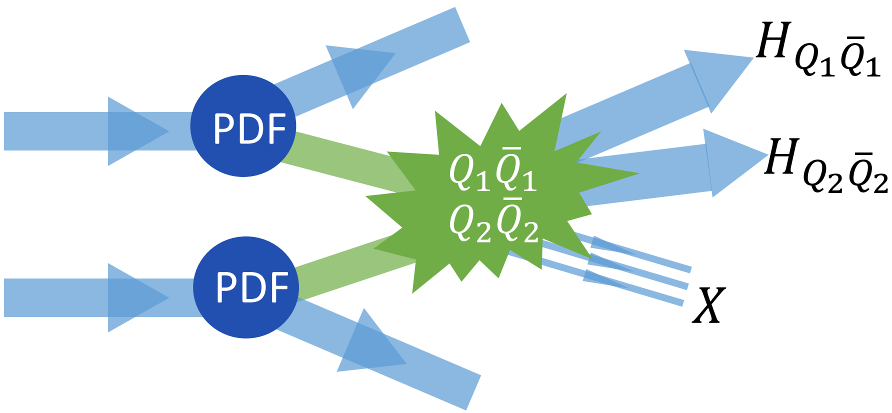


$$\sigma(H_{Q\bar{Q}}) = \sum_{a,b,n} \int \mathrm{d}x_1 \mathrm{d}x_2 \boldsymbol{f_{a/p}(x_1) f_{b/p}(x_2)} |\mathcal{A}(\boldsymbol{ab} \to \boldsymbol{Q\bar{Q}}[\boldsymbol{n}] + \boldsymbol{X})|^2 \times \langle \mathcal{O}^H(\boldsymbol{n}) \rangle$$

- Quarkonium production is a golden process to probe non-perturbative QCD
- Non-relativistic QCD (NRQCD) provides the most successful description but yet not able to coherently describe prod.&pol. measurements in all collision systems

Associated Quarkonium production

Single-parton scattering (SPS)

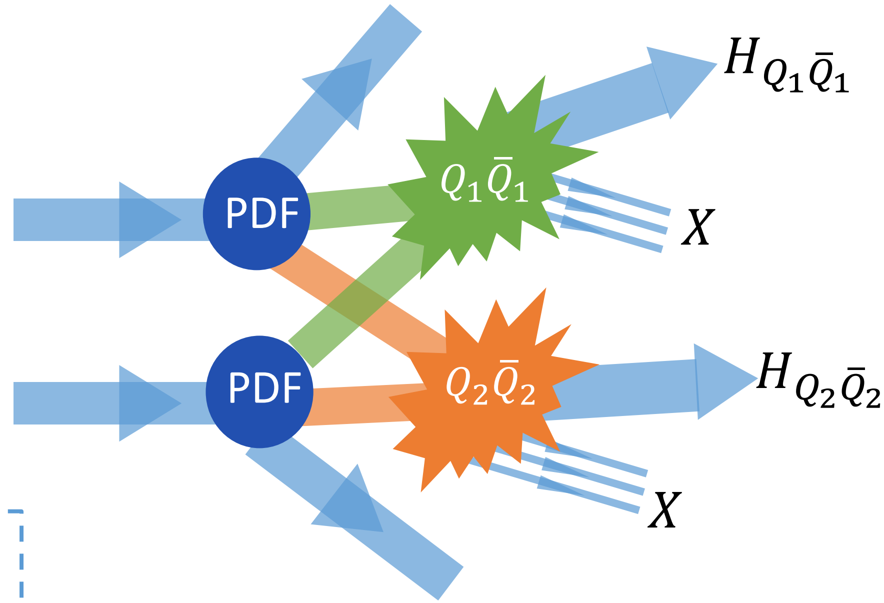


- ✓To probe the quarkonium production mechanism puzzle
- ✓Golden channel to probe gluon transverse momentum dependent (TMD) PDFs:
- • $h_1^{\perp g}(x, \boldsymbol{k}_\mathrm{T}^2, \mu) \Rightarrow$ azimuthal asymmetry
- • $f_1^g(x, \boldsymbol{k}_\mathrm{T}^2, \mu)$: affect p_T spectrum

[More in A. Colpani Serri's talk]

- ✓To search for fully heavy tetraquark states

Double-parton scattering (DPS)



- ✓To provide information on parton transverse profile & correlations in colliding hadrons
- ✓To understand multiparticle background ($Z + b\bar{b}$, W^+W^+ etc.) in both SM measurements and search for New Physics

Double Parton Scattering

$$\sigma^{\text{DPS}}_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \sum_{i,j,k,l} \int \mathrm{d}x_1 \mathrm{d}x_2 \mathrm{d}x_1' \mathrm{d}x_2' \mathrm{d}^2\mathbf{b_1} \mathrm{d}^2\mathbf{b_2} \mathrm{d}^2\mathbf{b}$$

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

Generalized double parton PDF

SPS parton-level cross-section

Assuming:

✓ factorization of trans. & long. components

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

✓ no correlation between two sets of partons

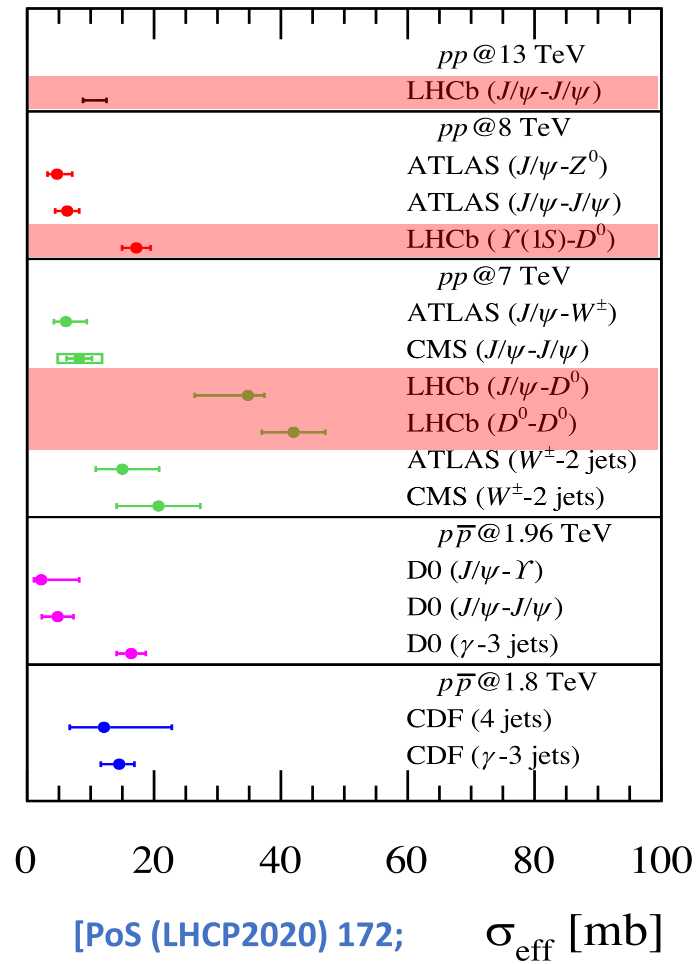
$$D_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2), T_{ij}(\boldsymbol{b}_1, \boldsymbol{b}_2) = T_i(\boldsymbol{b}_1) T_j(\boldsymbol{b}_2)$$

$\Rightarrow$

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

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

expected to be universal under the given assumptions



[PoS (LHCP2020) 172; arXiv: 2009.12555]

New di-quarkonium results from LHCb

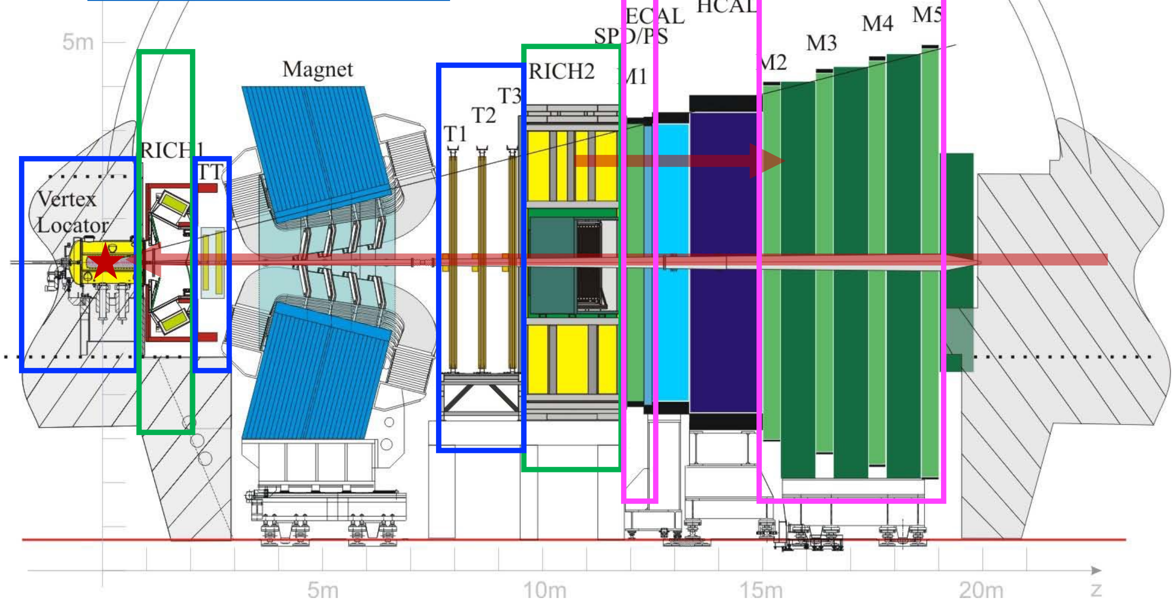
- Measurements performed using LHCb data at $\sqrt{s} = 13$ TeV corresponding to $4.2\ \text{fb}^{-1}$
  - ✓ $J/\psi - J/\psi$: Update & TMD PDFs study [LHCb-PAPER-2023-022, in preparation]
  - ✓ $J/\psi - \psi(2S)$ [LHCb-PAPER-2023-023, in preparation]
  - ✓ $J/\psi - \Upsilon$ [JHEP 08 (2023) 093]

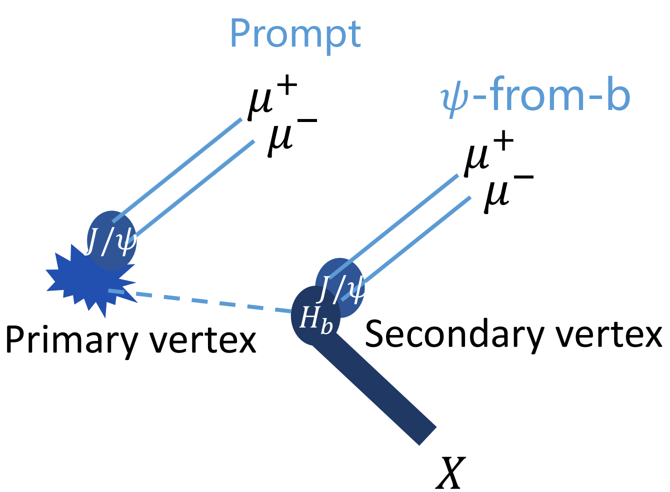
  } First cross-section measurement

  with J/ψ, $\psi(2S)$ and Υ all reconstructed from $\mu^+\mu^-$ final states

- LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, with excellent ***vertexing+tracking***, ***particle identification*** and ***muon detection*** performance

[JINST 3 (2008) S08005]

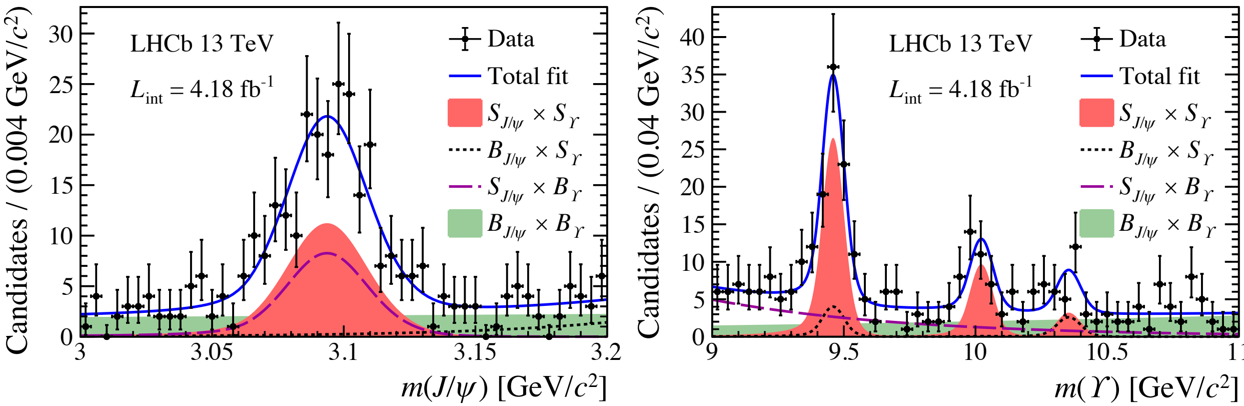




$J/\psi - \Upsilon$ production

[JHEP 08 (2023) 093]

➢ Fiducial region: $2 < y(J/\psi, \Upsilon) < 4.5$, $p_{\mathrm{T}}(J/\psi) < 10$ GeV, $p_{\mathrm{T}}(\Upsilon) < 30$ GeV



Signal	Raw yields	Significances
J/ψ–$\Upsilon(1S)$	76 ± 12	$7.9\,\sigma$
J/ψ–$\Upsilon(2S)$	30 ± 7	$4.9\,\sigma$
J/ψ–$\Upsilon(3S)$	10 ± 6	$1.7\,\sigma$

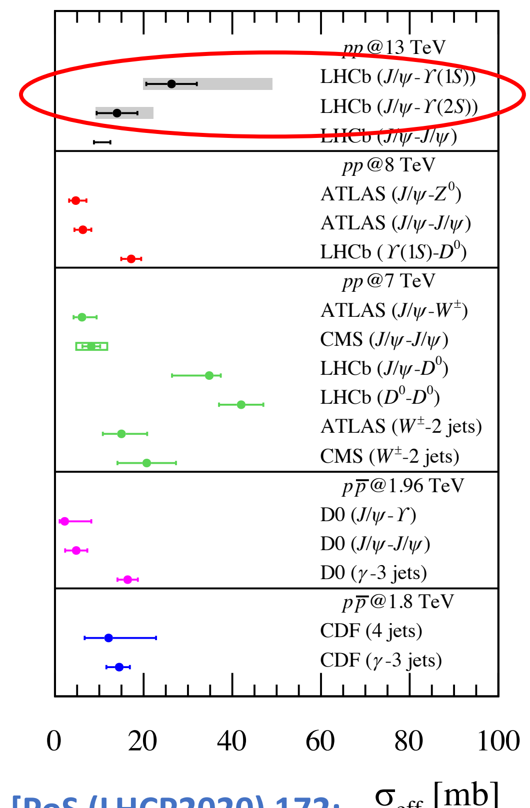
$$\sigma\big(J/\psi - \Upsilon(1S)\big) = 133 \pm 22(\text{stat}) \pm 7(\text{syst}) \pm 3(\mathcal{B})\ \text{pb}$$
$$\sigma\big(J/\psi - \Upsilon(2S)\big) = 76 \pm 21(\text{stat}) \pm 4(\text{syst}) \pm 7(\mathcal{B})\ \text{pb}$$

✓ $\sigma_{\text{eff}}(J/\psi - \Upsilon) \equiv \frac{\sigma(J/\psi)\times\sigma(\Upsilon)}{\sigma_{\text{DPS}}(J/\psi-\Upsilon)}$ determined by subtracting SPS contribution

[PRL 117 (2016) 062001]

$$\sigma_{\text{SPS}}\big(J/\psi - \Upsilon(1S)\big) = 20^{+52}_{-15}\ \text{pb},\ \sigma_{\text{SPS}}\big(J/\psi - \Upsilon(2S)\big) = 8^{+22}_{-6}\ \text{pb}$$

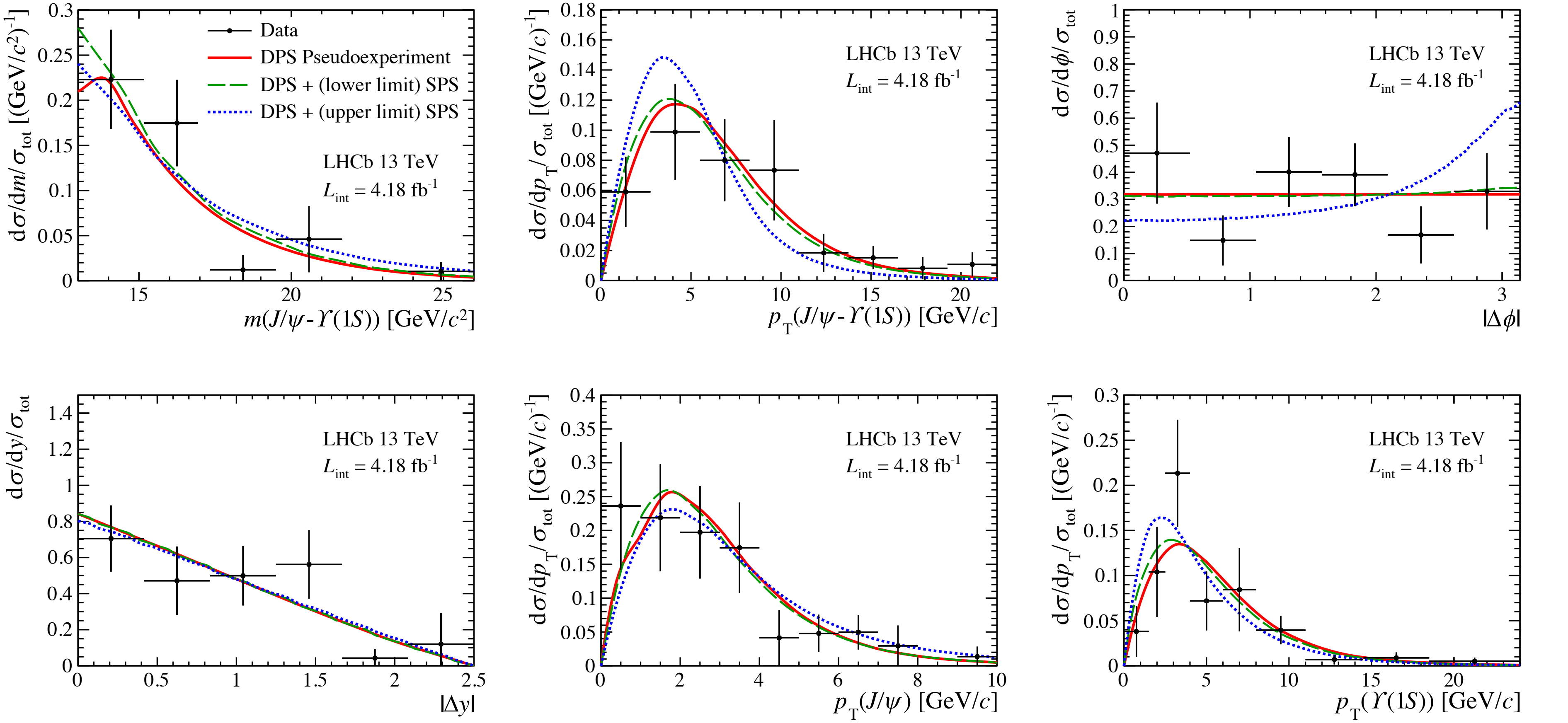
$$\sigma_{\text{eff}}\big(J/\psi - \Upsilon(1S)\big) = 26 \pm 5(\text{stat}) \pm 2(\text{syst})\ ^{+22}_{-3}(\text{th})\ \text{mb}$$
$$\sigma_{\text{eff}}\big(J/\psi - \Upsilon(2S)\big) = 14 \pm 5(\text{stat}) \pm 1(\text{syst})\ ^{+7}_{-1}(\text{th})\ \text{mb}$$



[PoS (LHCP2020) 172; arXiv: 2009.12555]

Differential $J/\psi - \Upsilon$ cross-sections

[JHEP 08 (2023) 093]

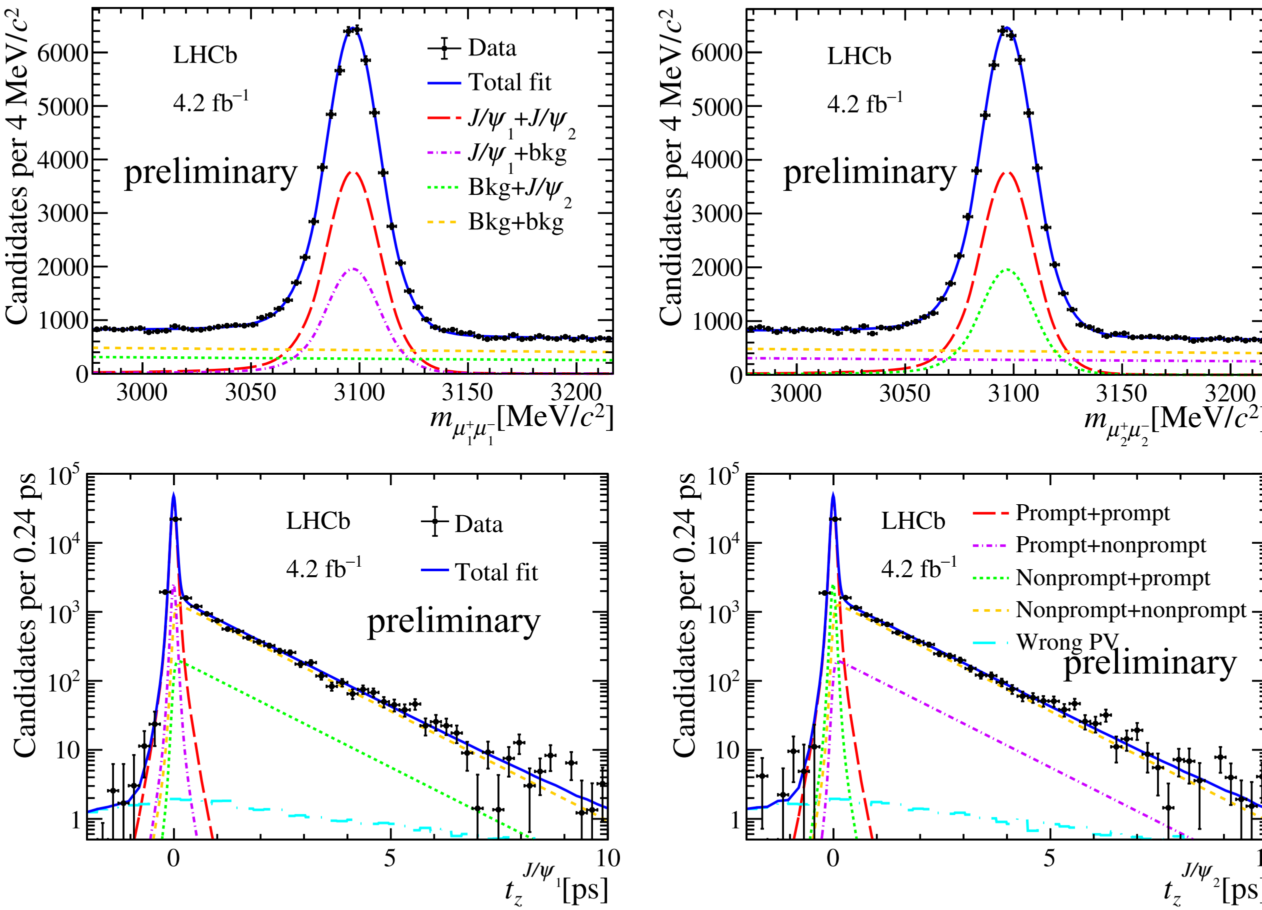


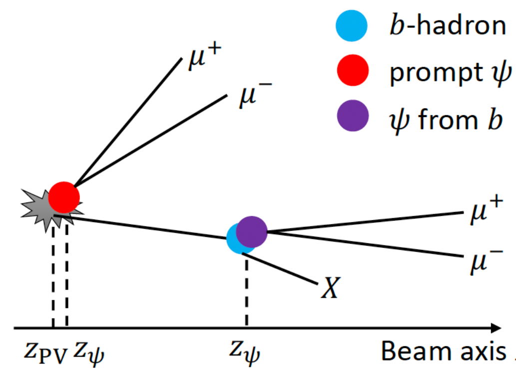
➢ Results consistent with both DPS-only and DPS+predicted SPS scenarios

$J/\psi - J/\psi$ production

[LHCb-PAPER-2023-022]

- Fiducial region: $2 < y(J/\psi) < 4.5$, $p_\mathrm{T}(J/\psi) < 14$ GeV





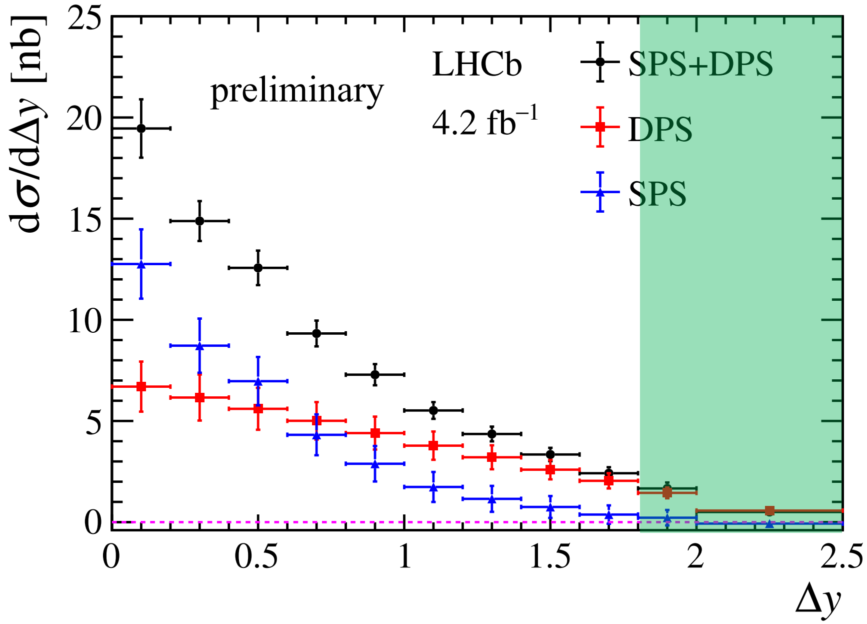
$$t_z = \frac{z_\psi - z_\mathrm{PV}}{p_z/m_\psi}$$

$$N(J/\psi - J/\psi)_\mathrm{prompt} = (2.187 \pm 0.020)\times 10^4$$

$$\boxed{\sigma(J/\psi - J/\psi) = 16.36 \pm 0.28(\mathrm{stat}) \pm 0.88(\mathrm{syst})\ \mathrm{nb}}$$

SPS and DPS separation

[LHCb-PAPER-2023-022]

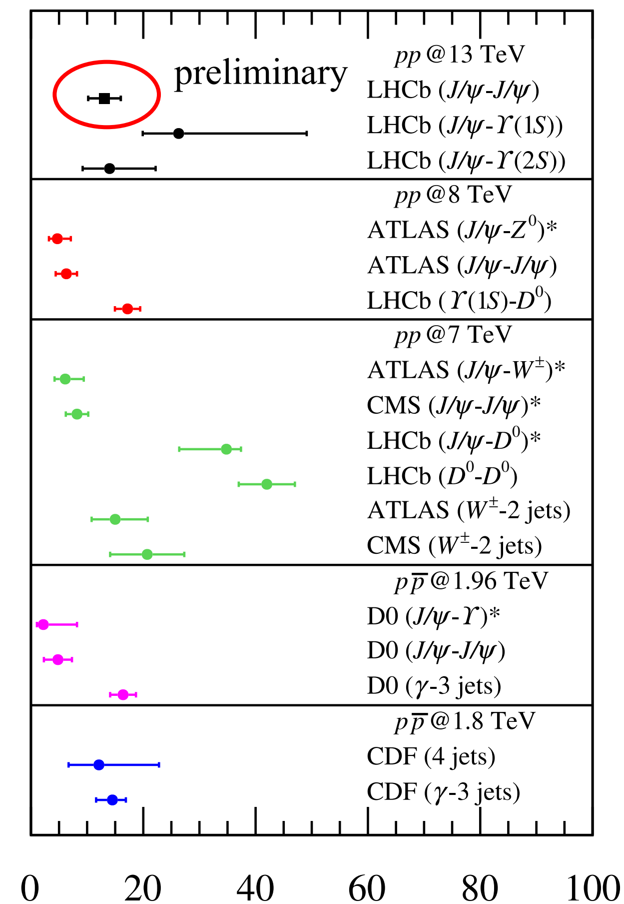


- SPS & DPS separated assuming negligible SPS contribution in $1.8 < \Delta y < 2.5$ according to NRQCD predictions

$$\sigma(J/\psi - J/\psi)_{\text{DPS}} = 8.6 \pm 1.2(\text{stat}) \pm 1.0(\text{syst})\ \text{nb}$$

$$\sigma(J/\psi - J/\psi)_{\text{SPS}} = 7.9 \pm 1.2(\text{stat}) \pm 1.1(\text{syst})\ \text{nb}$$

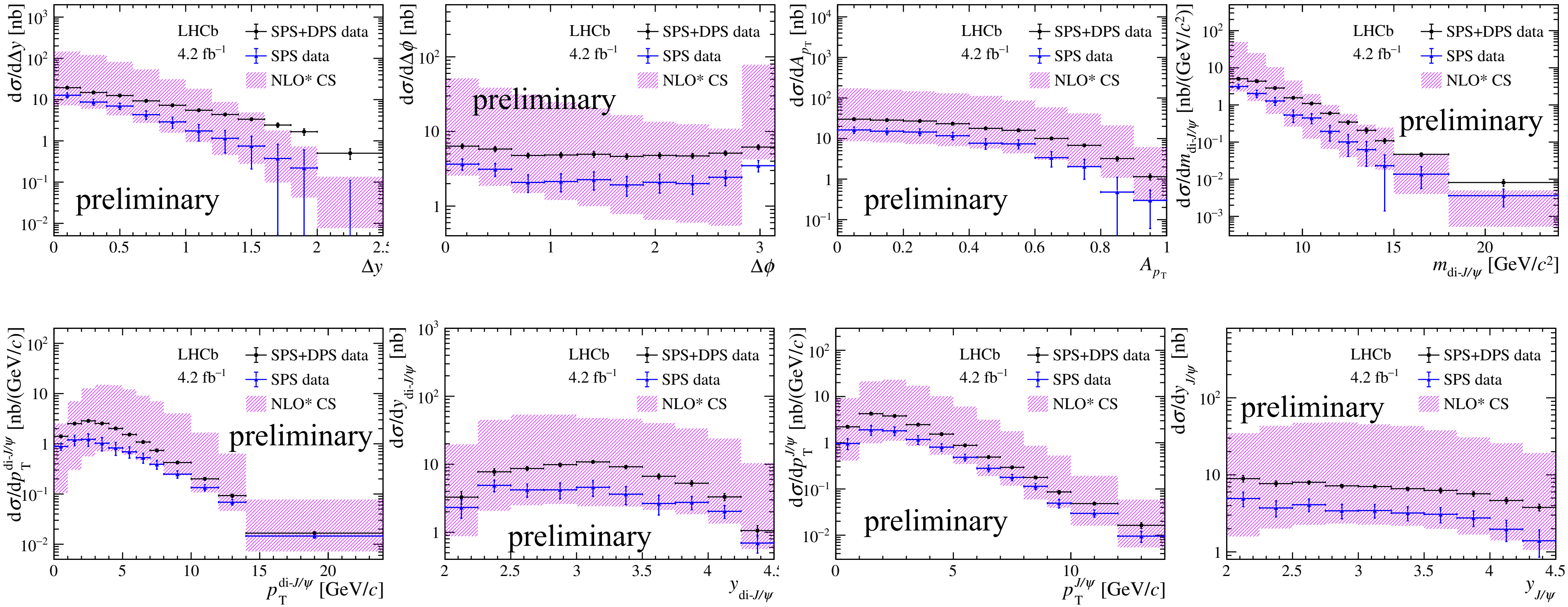
$$\sigma_{\text{eff}} = 13.1 \pm 1.8(\text{stat}) \pm 2.3(\text{syst})\ \text{mb}$$



[PoS (LHCP2020) 172; arXiv: 2009.12555]

Differential $J/\psi - J/\psi$ cross-section

[LHCb-PAPER-2023-022]



➢ SPS differential cross-sections are within uncertainties of the incomplete (no-loops) next-to-leading order (NLO*) color-singlet (CS) NRQCD calculations

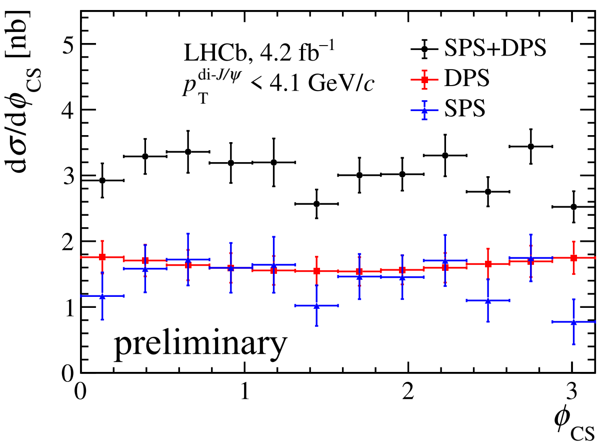
[PRL 111 (2013) 122001] [Comput. Phys. Commun. 184 (2013) 2562] [Comput. Phys. Commun. 198 (2016) 238]

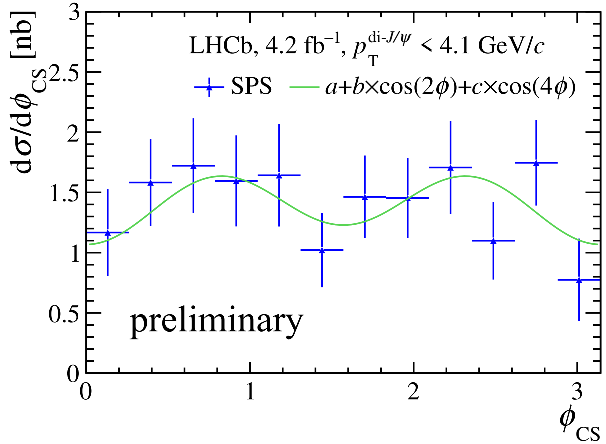
Gluon TMD PDFs study

[LHCb-PAPER-2023-022]

- $h_1^{\perp g}(x, \boldsymbol{k}_{\mathrm{T}}^2, \mu) \Rightarrow$ azimuthal asymmetry
  $\mathrm{d}\sigma/\mathrm{d}\phi_{\mathrm{CS}} = a + b \times \cos(2\phi_{\mathrm{CS}}) + c \times \cos(4\phi_{\mathrm{CS}})$

$$a = F_1 \mathcal{C}[f_1^g f_1^g] + F_2 \mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}],$$
$$b = F_3 \mathcal{C}[w_3 f_1^g h_1^{\perp g}] + F_3' \mathcal{C}[w_3' h_1^{\perp g} f_1^g],$$
$$c = F_4 \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}],$$





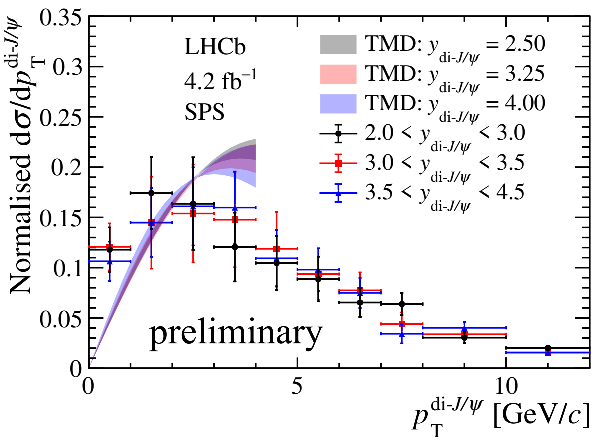
$\langle \cos(2\phi_{\mathrm{CS}}) \rangle = b/2a$
$= -0.029 \pm 0.050 \pm 0.009$

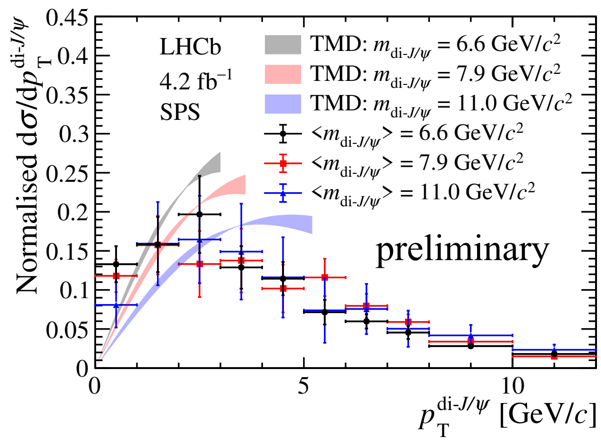
$\langle \cos(4\phi_{\mathrm{CS}}) \rangle = c/2a$
$= -0.087 \pm 0.052 \pm 0.013$

- $f_1^g(x, \boldsymbol{k}_{\mathrm{T}}^2, \mu)$: affect p_{T} spectrum
  - ✓ p_{T} shape shows no dependence on y

[EPJC 80 (2020) 87]

✓ No obvious broadening of p_{T} spectrum wrt increasing m given large uncertainties

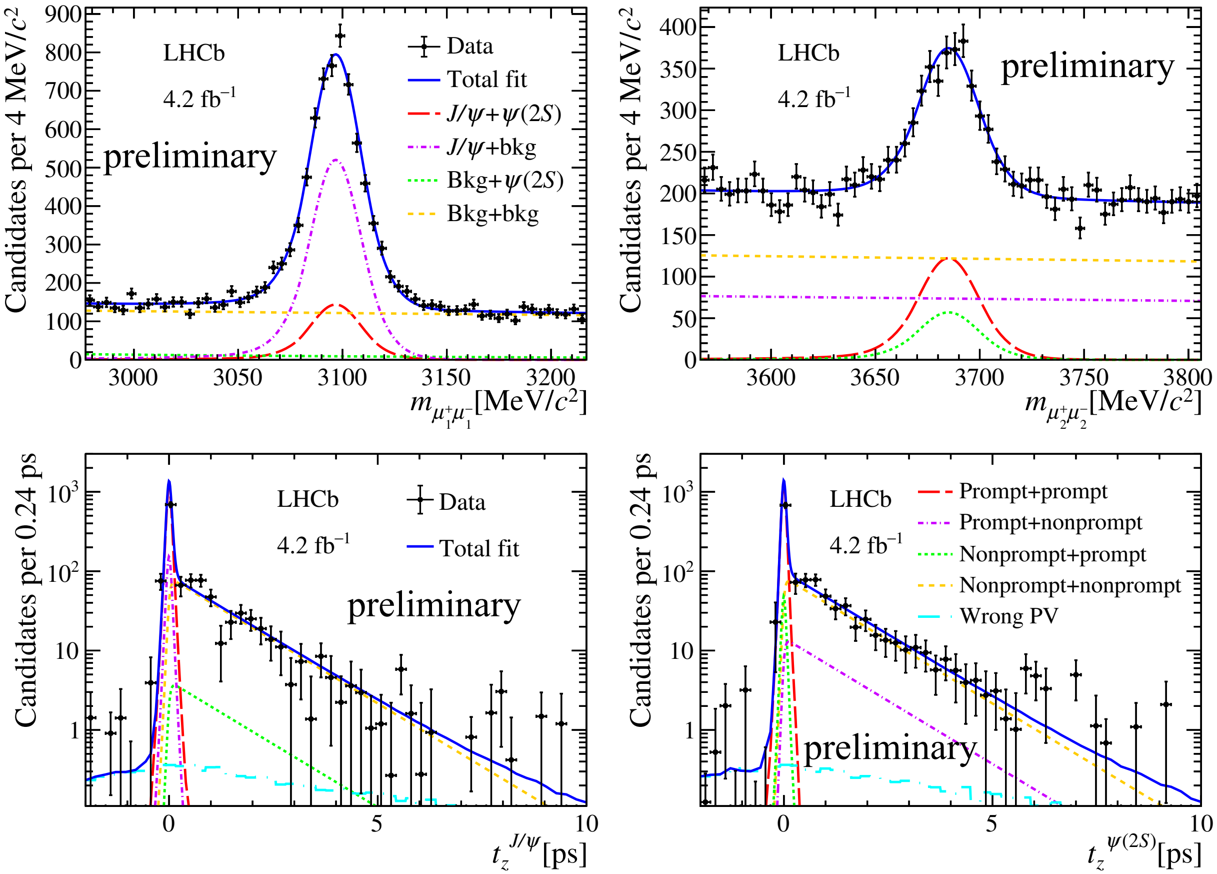


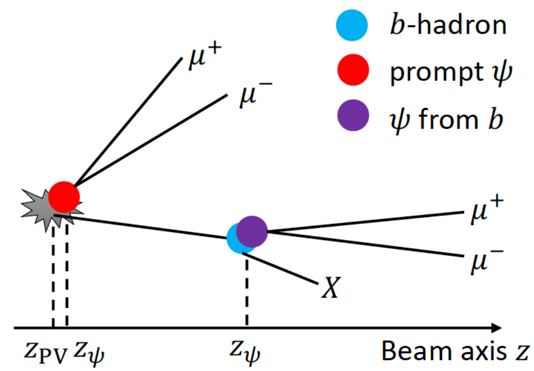


$J/\psi - \psi(2S)$ production

[LHCb-PAPER-2023-023]

- Fiducial region: $2 < y(\psi) < 4.5$, $p_{\mathrm{T}}(\psi) < 14$ GeV





$$t_z = \frac{z_\psi - z_{\mathrm{PV}}}{p_z/m_\psi}$$

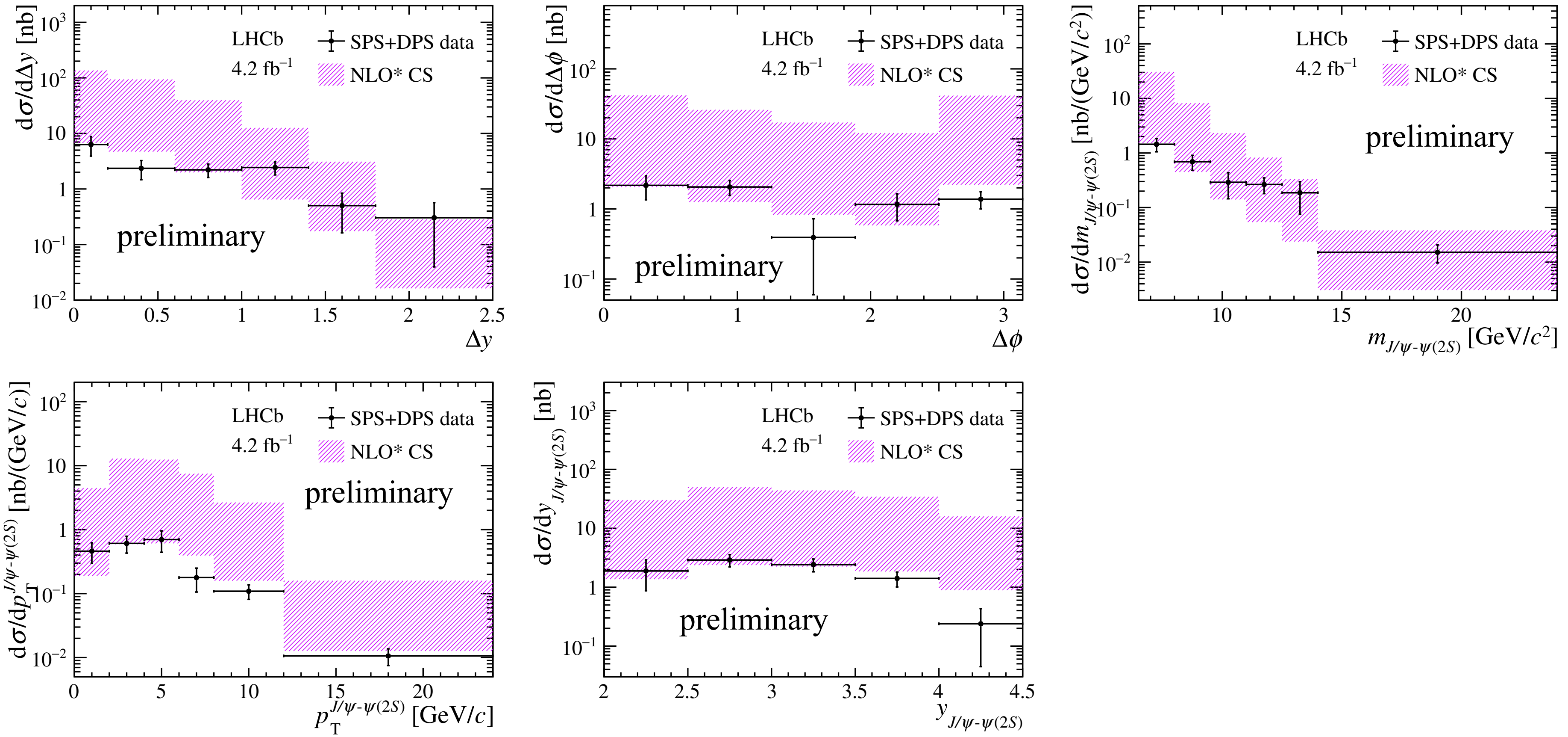
$$N\big(J/\psi - \psi(2S)\big)_{\mathrm{prompt}} = 629 \pm 50$$

$$\sigma\big(J/\psi - \psi(2S)\big) = 4.49 \pm 0.71(\mathrm{stat}) \pm 0.26(\mathrm{syst})\ \mathrm{nb}$$

$$\sigma_{\mathrm{eff}}(\mathrm{lower\ limit}) = \frac{\sigma(J/\psi)\sigma\big(\psi(2S)\big)}{\sigma\big(J/\psi - \psi(2S)\big)} = 7.1 \pm 1.1(\mathrm{stat}) \pm 0.8(\mathrm{syst})\ \mathrm{mb}$$

Differential $J/\psi - \psi(2S)$ cross-section

[LHCb-PAPER-2023-023]



➢ Results consistent with NLO* CS NRQCD calculations albeit the DPS contribution is not subtracted

[PRL 111 (2013) 122001] [Comput. Phys. Commun. 184 (2013) 2562] [Comput. Phys. Commun. 198 (2016) 238]

$J/\psi - \psi(2S)$ vs. $J/\psi - J/\psi$

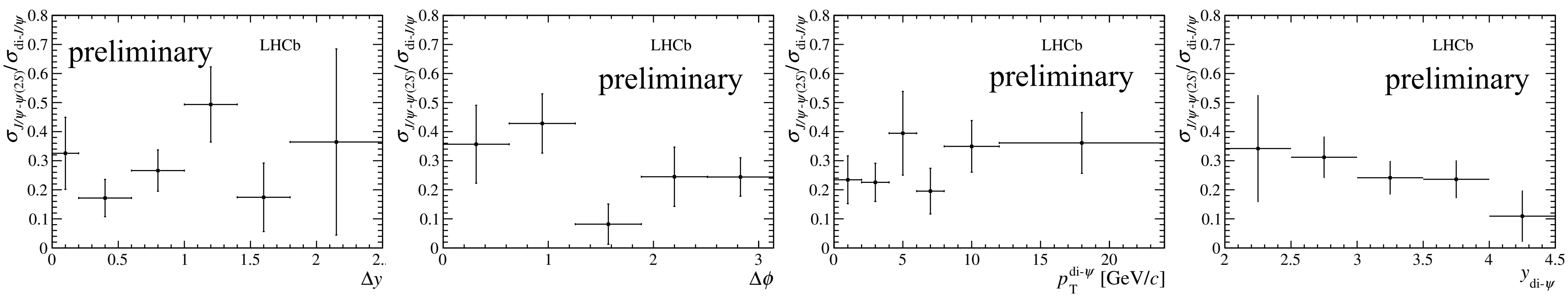
[LHCb-PAPER-2023-023]

- Predictions on the ratio between $\sigma\big(J/\psi - \psi(2S)\big)$ and $\sigma(J/\psi - J/\psi)$ give
  - ✓SPS: 0.94 ± 0.030 [PLB 751 (2015) 479]
  - ✓DPS: 0.282 ± 0.027 [JHEP 10 (2015) 172] [EPJC 80 (2020) 185]

$$\boxed{\frac{\sigma(J/\psi - \psi(2S))}{\sigma(J/\psi - J/\psi)} = 0.274 \pm 0.044(\text{stat}) \pm 0.008(\text{syst})}$$

$\Rightarrow$ it confirms a prominent DPS contribution to $J/\psi - J/\psi$ production in a novel way, independent of the kinematic correlation of two J/ψ mesons

- Differential cross-section ratios are also measured, but more statistics needed



Summary

- Studies on associated quarkonium production actively ongoing at LHCb

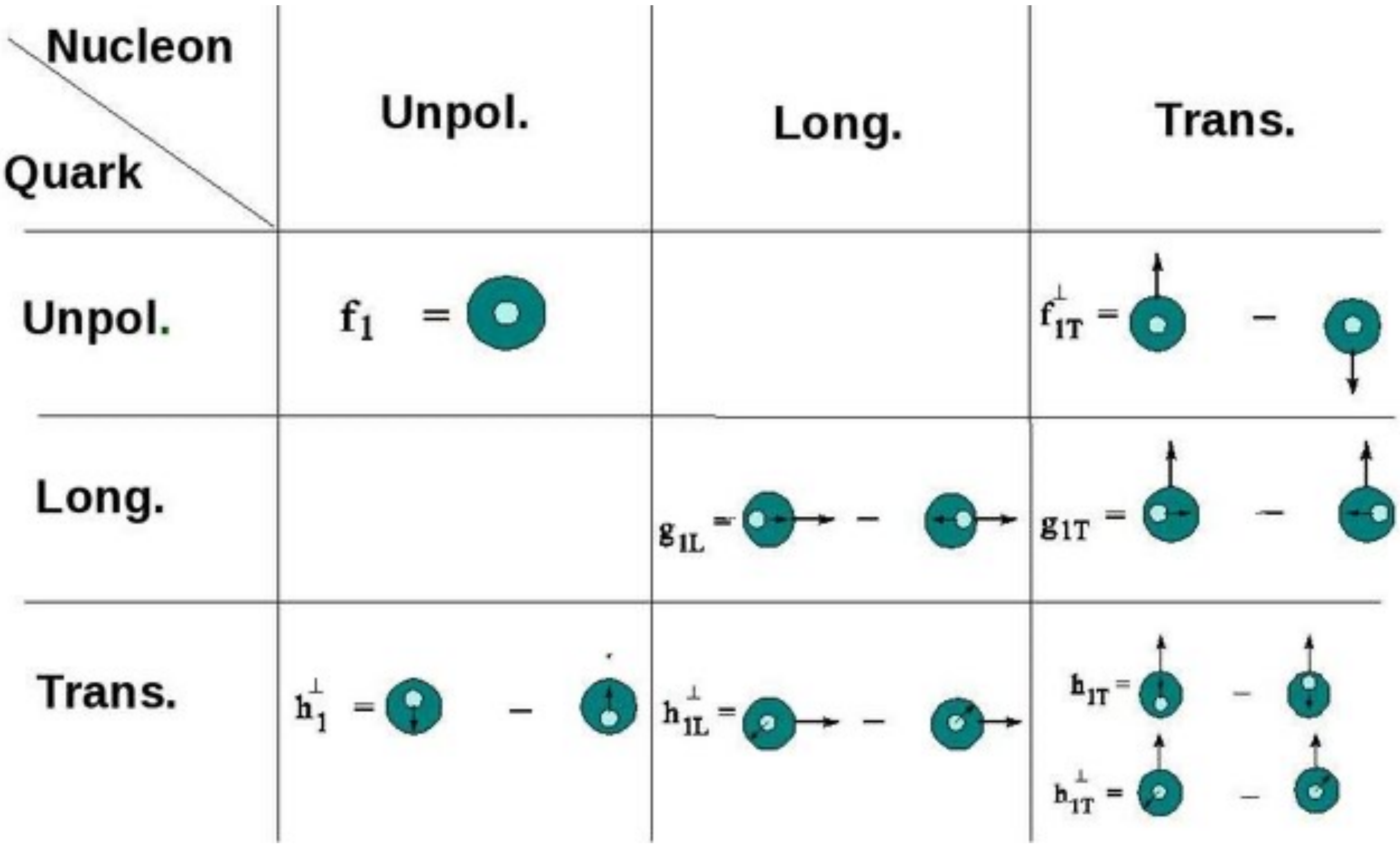
- **$J/\psi-\Upsilon$ @ 13 TeV**
  - ✓ First observation of $J/\psi-\Upsilon(1S)$ production in *pp* collisions
  - ✓ σ_{eff} of DPS extracted
- **$J/\psi-J/\psi$ @ 13 TeV**
  - ✓ SPS and DPS components separated and σ_{eff} of DPS extracted
  - ✓ Azimuthal asymmetry and p_{T} spectrum in y and m bins measured for gluon TMD PDFs study
  - ✓ Azimuthal asymmetry consistent with zero, but still allowing for asymmetry at a few percent level
- **$J/\psi-\psi(2S)$ @ 13 TeV**
  - ✓ first measurement of $\sigma\left(J/\psi-\psi(2S)\right)$ in *pp* collisions
  - ✓ confirms DPS component in $J/\psi-J/\psi$ production in a novel way

- More to come in the future…

Back up

Leading twist TMD PDFs

[PR12-09-014]



Sketch of CS frame