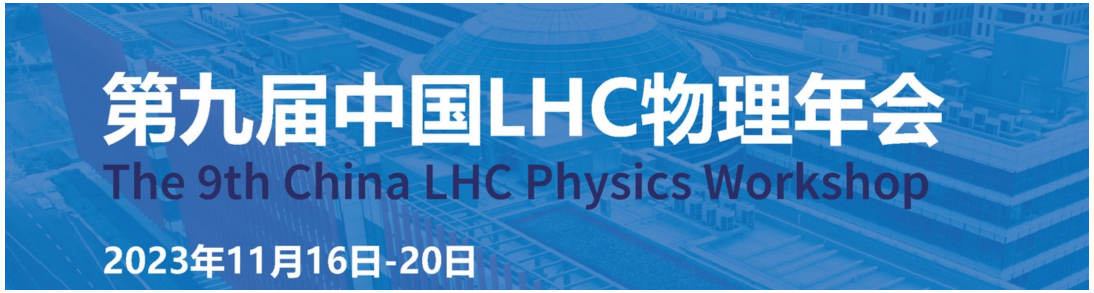


Study of associated quarkonium production in pp collisions at LHCb

Jialu Wang (Peking University)
On behalf of LHCb collaboration

Date: Nov 16, 2023

9th China LHC Physics Workshop @Shanghai, China

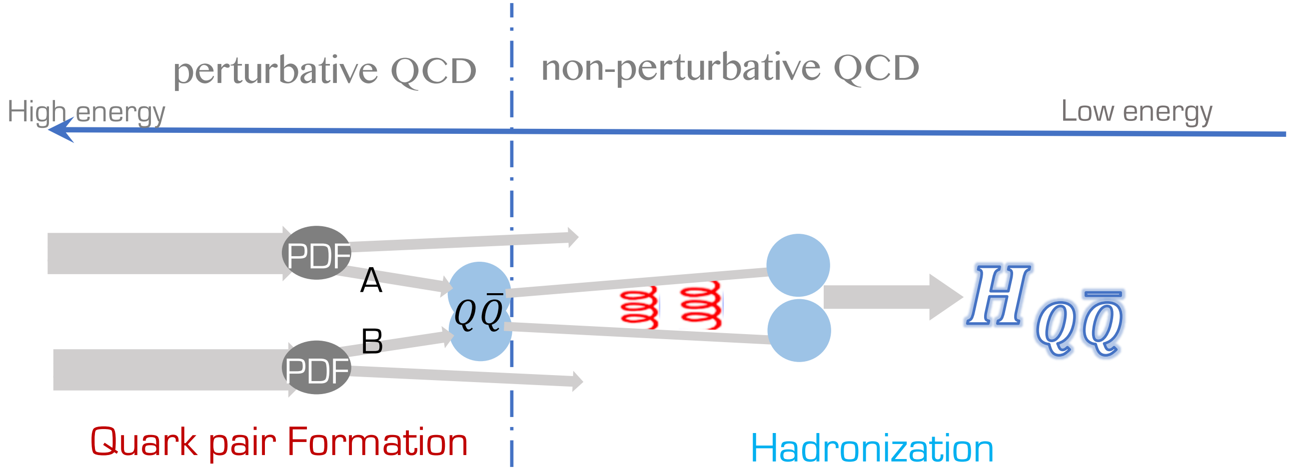
Outline

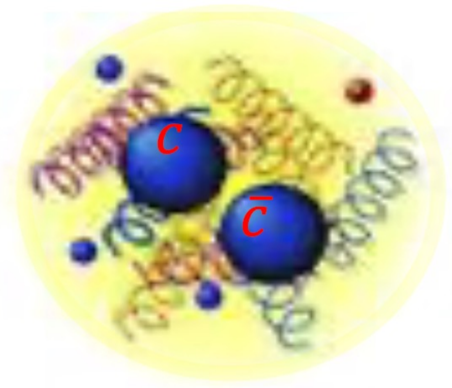
- ✪ Introduction
- ✪ Recent studies of associated quarkonium production at LHCb
  - ☆ $J/\psi + \Upsilon$ production @ 13 TeV [JHEP 08 (2023) 093]
  - ☆ $J/\psi + J/\psi$ production @ 13 TeV [LHCb-PAPER-2023-022]
  - ☆ $J/\psi + \psi(2S)$ production @ 13 TeV [LHCb-PAPER-2023-023]
- ✪ Summary and outlook

Quarkonium production

- Heavy quarkonium ($c\bar{c}, b\bar{b}$) production at high energy hadronic collisions is important to probe QCD
- The heavy quarkonium production can be factorized into two processes
  - ☆ **Quark pair formation**: perturbative QCD
  - ☆ **Hadronization**: (non-perturbative) Phenomenological models

$$d\sigma_{[p_1 p_2 \to H+X]} = \sum_n \int F_1(A) F_2(B) dA\, dB\, d\hat{\sigma}_{[A+B\to Q\bar{Q}(n)+X]} \times \langle O^H(n) \rangle$$

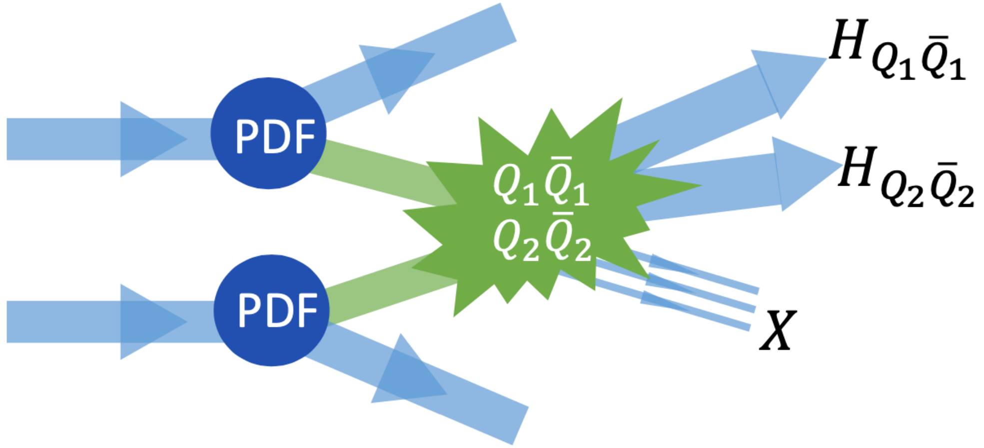




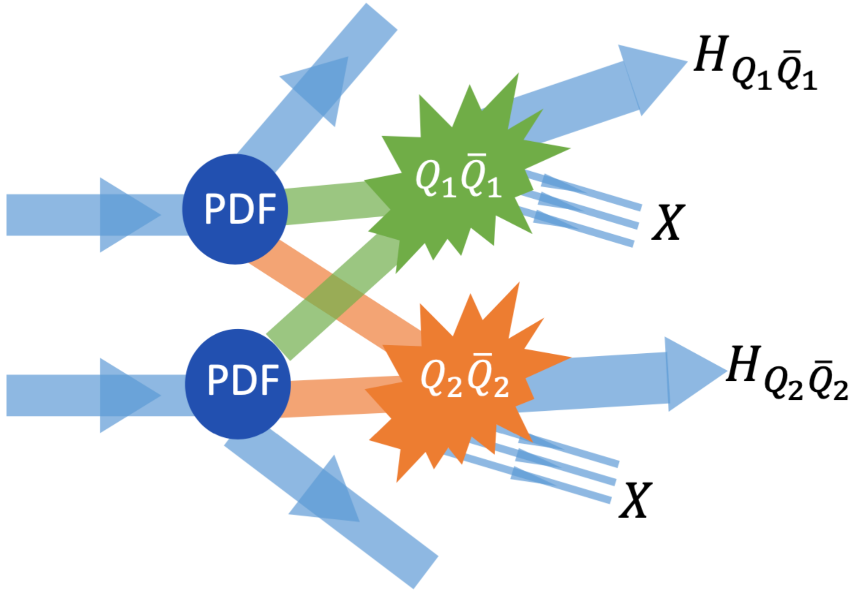
- Non-relativistic QCD (NRQCD) provides the most successful description, but yet not able to coherently describe prod.&pol. measurements in all collision systems

Associated quarkonium production

- Single-parton scattering (SPS)
  - ☆ Prob quarkonium production mechanism
  - ☆ Study the gluon transverse-momentum dependent parton distribution function (TMD)



- Double-parton scattering (DPS)
  - ☆ Provide information about correlations between partons inside the proton
  - ☆ Help understand multi-partcle background ($Z + b\bar{b},\ W^+W^-, etc.$) in search for NP



Gluon TMD parameterised at leading twist using two TMDs:

- ☆ f_1^g (unpolarized gluons): affect p_{T} spectrum
- ☆ $h_1^{\perp g}$ (linearly polarized gluons): lead to azimuthal asymmetries

Effective cross-section σ_{eff}

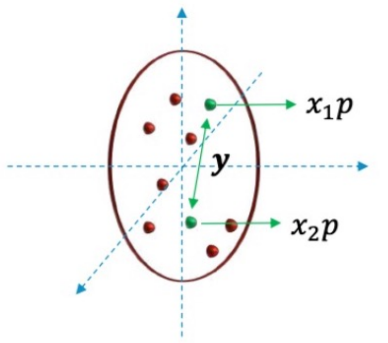
- Factorization formula of **associated quarkonium production cross-section** of DPS process:

$$\sigma_{H_1H_2} = \frac{1}{1+\delta_{H_1H_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx_1' dx_2' d^2y \times$$

$$F_{ik}(x_1, x_2, \boldsymbol{y}) F_{jl}(x_1', x_2', \boldsymbol{y}) \times \hat{\sigma}_{ij}(x_1, x_1') \hat{\sigma}_{kl}(x_2, x_2')$$

Generalized double parton PDF

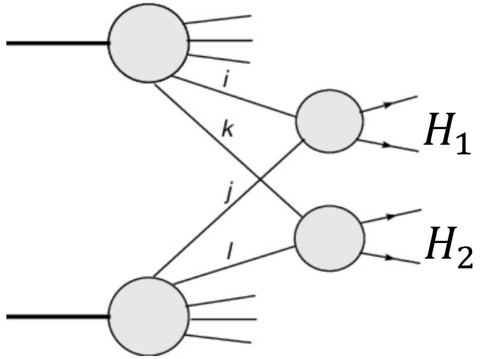
SPS parton-level cross-section



Double parton distributions

- ☆ Assuming: $F_{ik}(x_1, x_2, \boldsymbol{y}) \cong f_i(x_1) f_k(x_2) G(\boldsymbol{y})$
  - 1- factorization of transverse & longitudinal components
  - 2- no correlation between two sets of parton

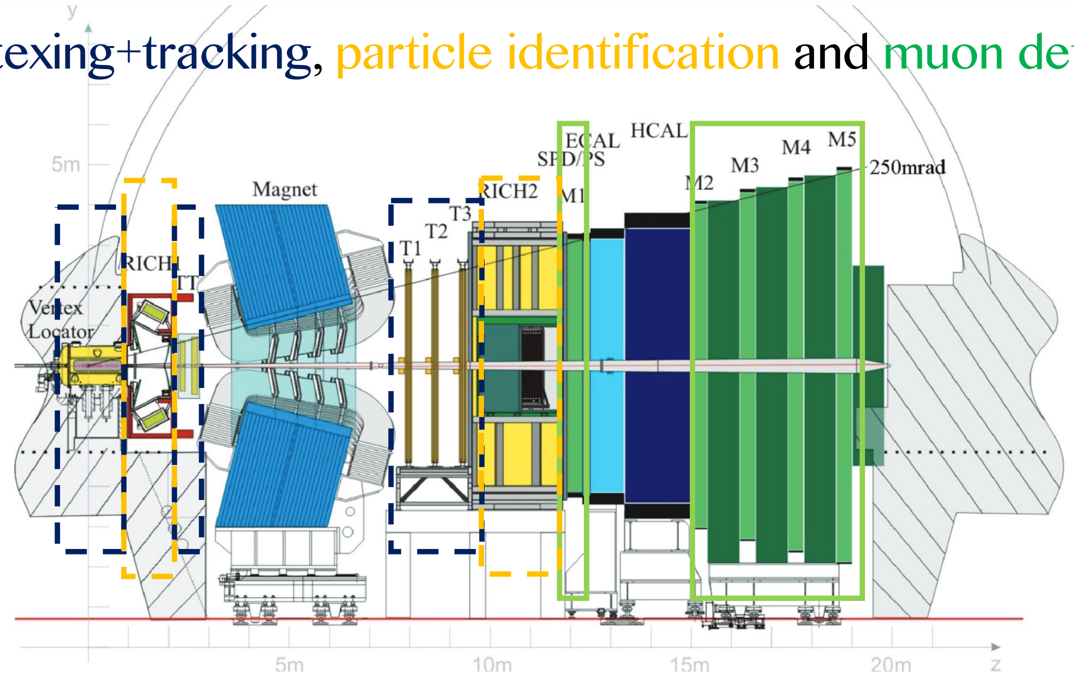
$$\Rightarrow \quad \sigma_{H_1H_2} = \frac{1}{1+\delta_{H_1H_2}} \frac{\sigma_{H_1}\sigma_{H_2}}{\boldsymbol{\sigma}_{\text{eff}}}, \qquad \left(\boldsymbol{\sigma}_{\text{eff}} = \left[\int d^2y G(\boldsymbol{y})^2\right]^{-1}\right)$$

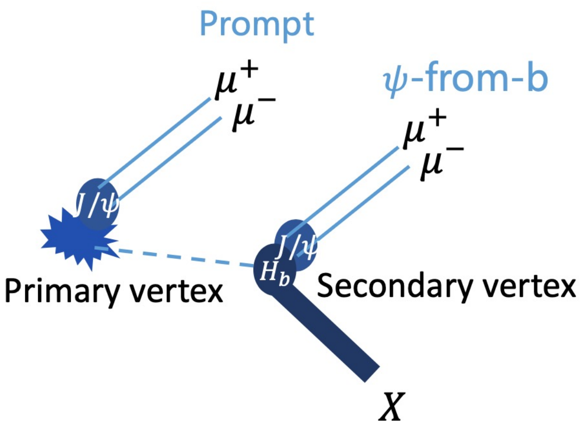


- Effective cross-section $\boldsymbol{\sigma}_{\text{eff}}$ is related to the transverse overlap function $G(\boldsymbol{y})$ between partons in proton
  - ☆ Expected to be universal under the given assumptions

New di-quarkonium results from LHCb

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



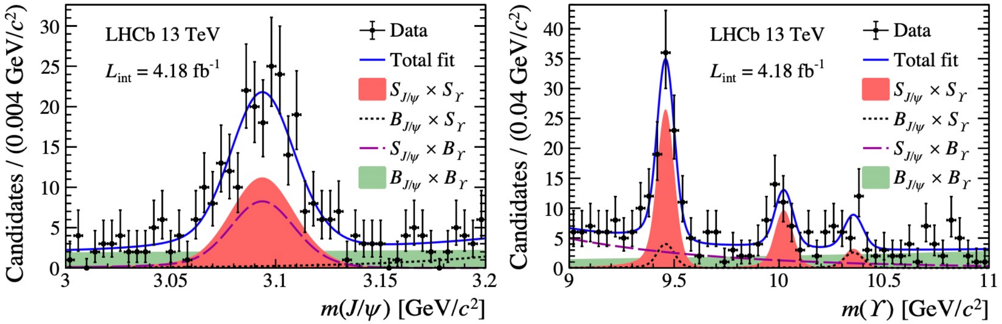


- Measurements performed using LHCb data at $\sqrt{s} = 13$ TeV
  - ☆ $J/\psi + J/\psi$: Update & TMD PDFs study [LHCb-PAPER-2023-022]
  - ☆ $J/\psi + \psi(2S)$ } First cross-section measurement [LHCb-PAPER-2023-023]
  - ☆ $J/\psi + \Upsilon$ } First cross-section measurement [JHEP 08 (2023) 093]

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

$J/\psi + \Upsilon$ production [JHEP 08 (2023) 093]

- ✪ Fiducial region: $p_T(J/\psi) < 10\text{GeV}/c, p_T(\Upsilon) < 30\text{GeV}/c, 2.0 < y(J/\psi, \Upsilon) < 4.5$



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	$1.7\,\sigma$

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

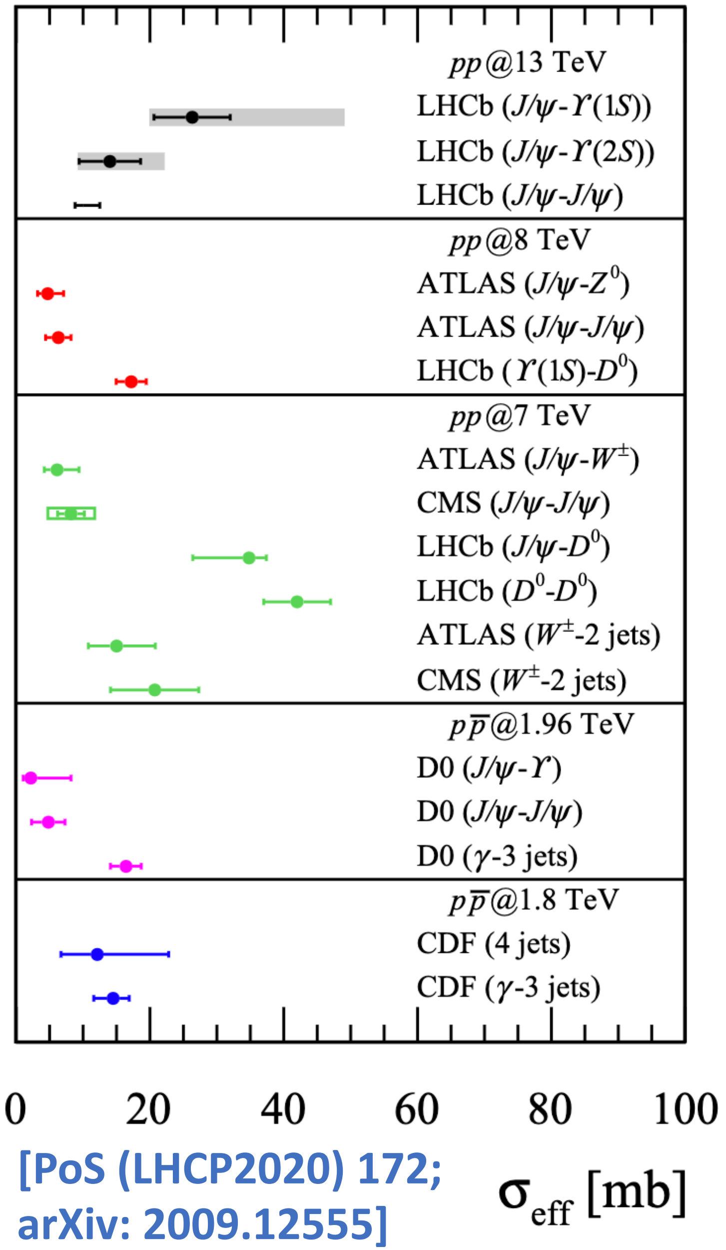
✓ $\sigma_{\text{eff}}(J/\psi - \Upsilon) \equiv \frac{\sigma(J/\psi)\times\sigma(\Upsilon)}{\sigma_{\text{DPS}}(J/\psi - \Upsilon)}$ determined

by subtracting SPS contribution

[PRL 117 (2016) 062001]

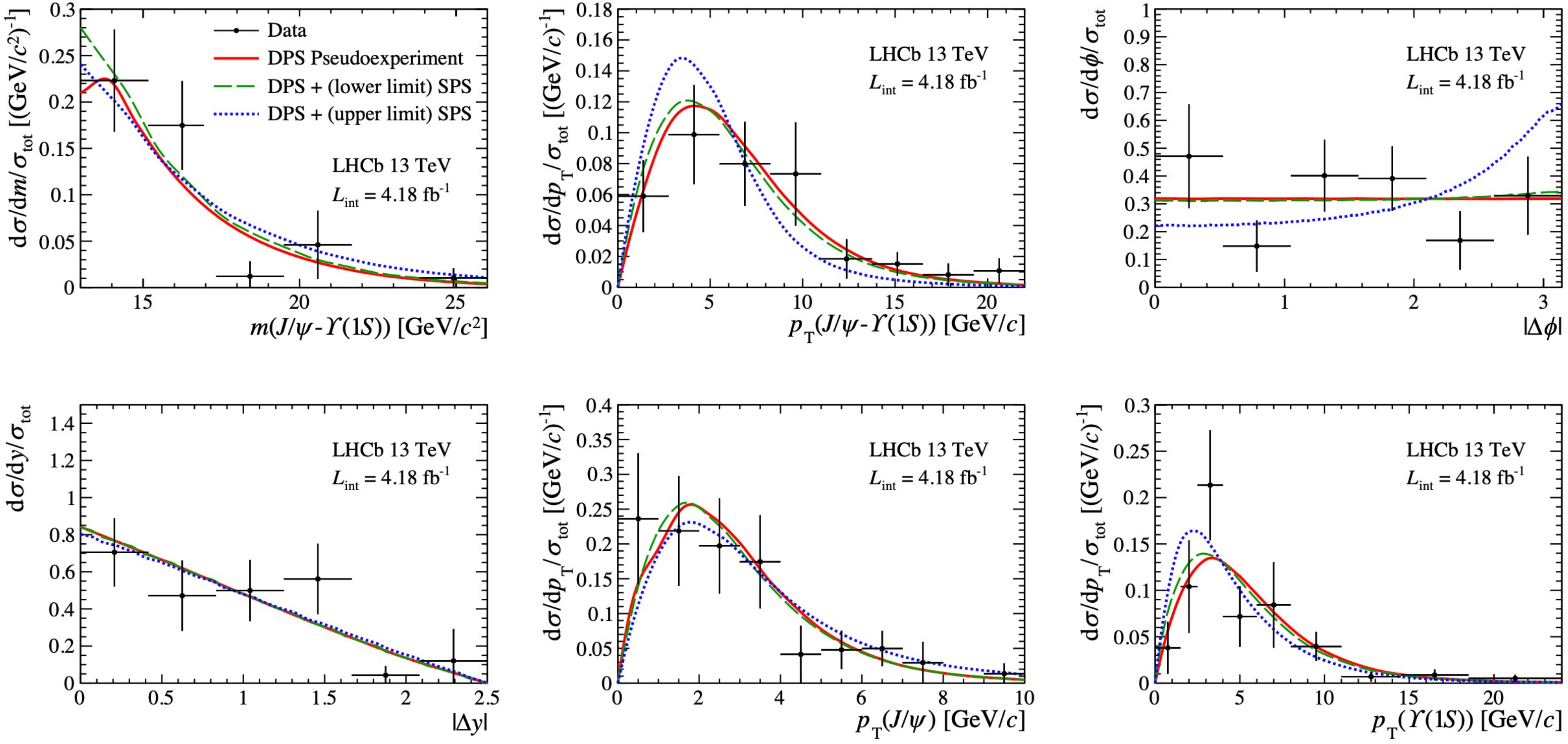
$$\sigma_{\text{SPS}}(J/\psi - \Upsilon(1S)) = 20^{+52}_{-15}\ \text{pb},\ \sigma_{\text{SPS}}(J/\psi - \Upsilon(2S)) = 8^{+22}_{-6}\ \text{pb}$$

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



[PoS (LHCP2020) 172; arXiv: 2009.12555]

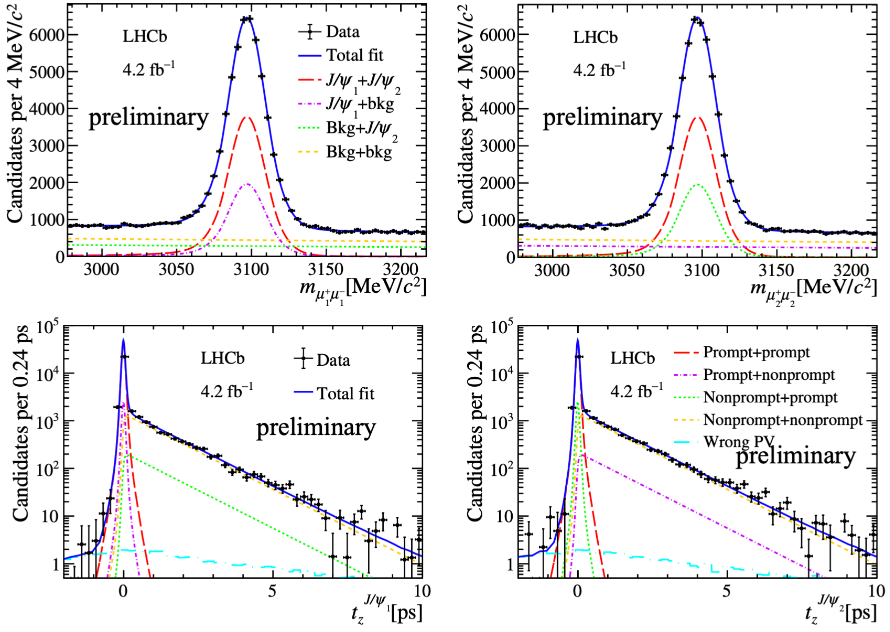
Differential $J/\psi + \Upsilon$ cross-sections [JHEP 08 (2023) 093]

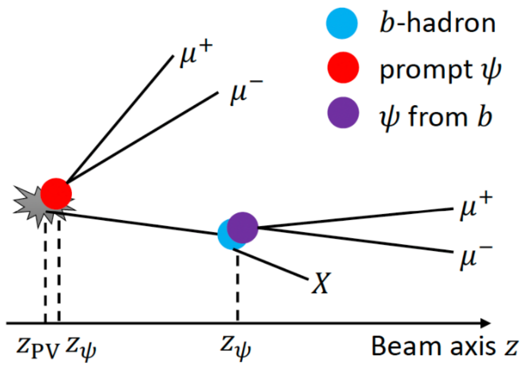


- Results consistent with both DPS-only and DPS+SPS scenarios

$J/\psi + J/\psi$ production [LHCb-PAPER-2023-022]

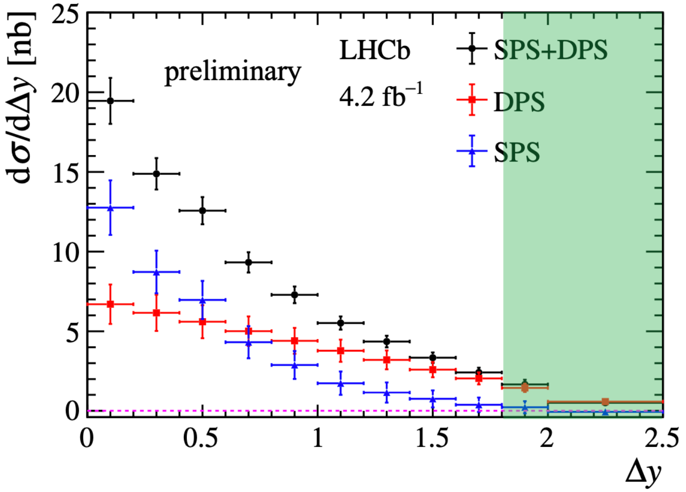
✪ Fiducial region: $p_T(J/\psi) < 14\text{GeV}/c$, $2.0 < y(J/\psi) < 4.5$





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

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

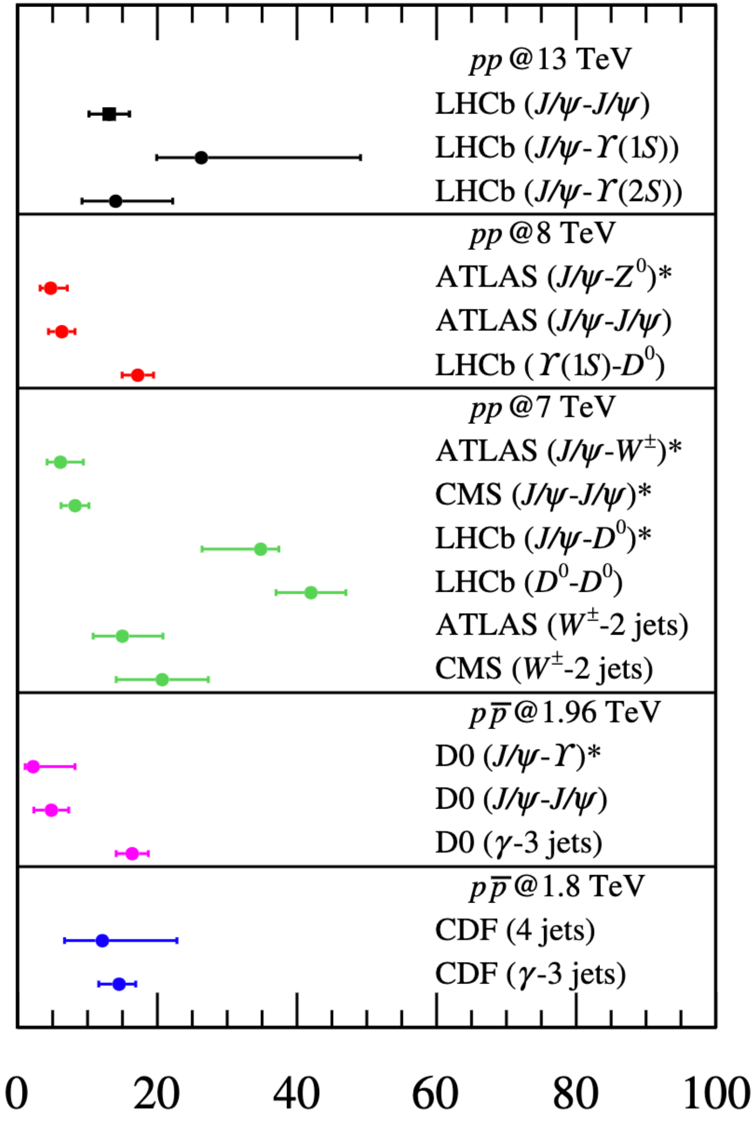


$$\sigma(J/\psi - J/\psi) = 16.36 \pm 0.28(\text{stat}) \pm 0.88(\text{syst})\text{ nb}$$

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

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

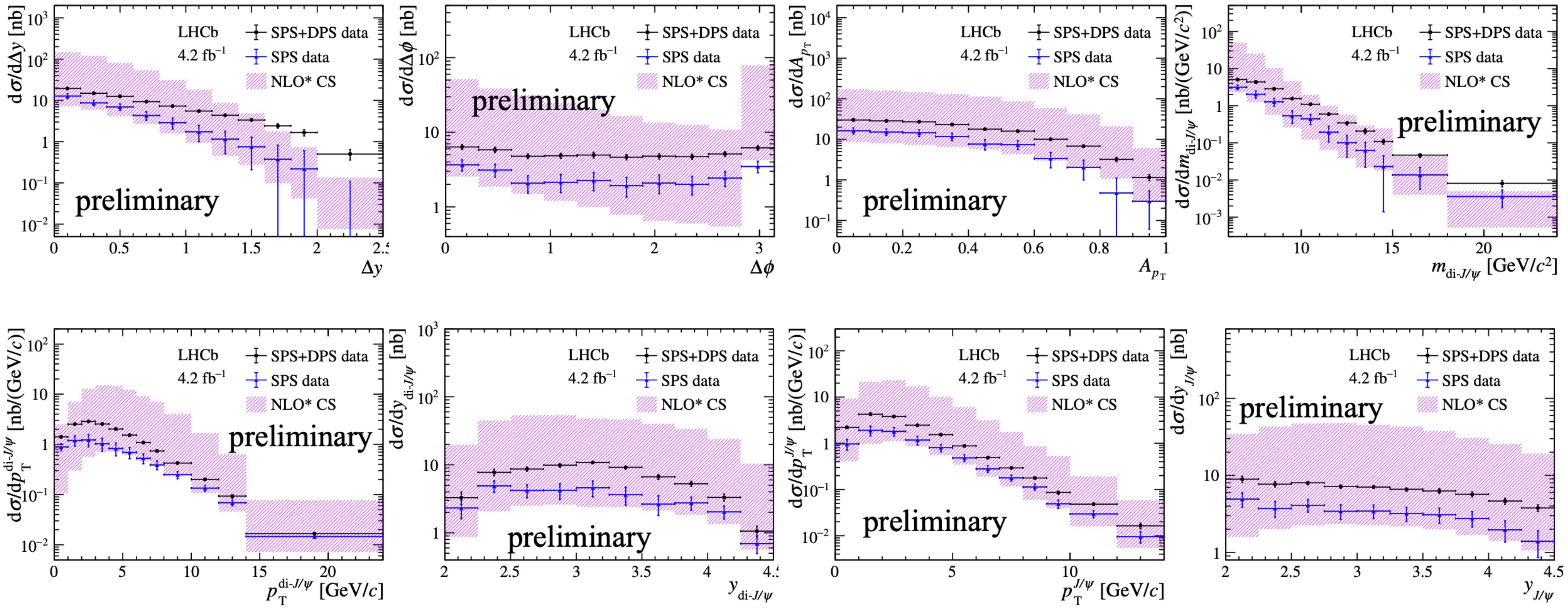
$$\sigma_{\text{eff}} = 13.1 \pm 1.8(\text{stat}) \pm 2.3(\text{syst})\text{ mb}$$



[PoS (LHCP2020) 172; arXiv: 2009.12555]

σ_{eff} [mb]

Differential $J/\psi + J/\psi$ cross-sections [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]

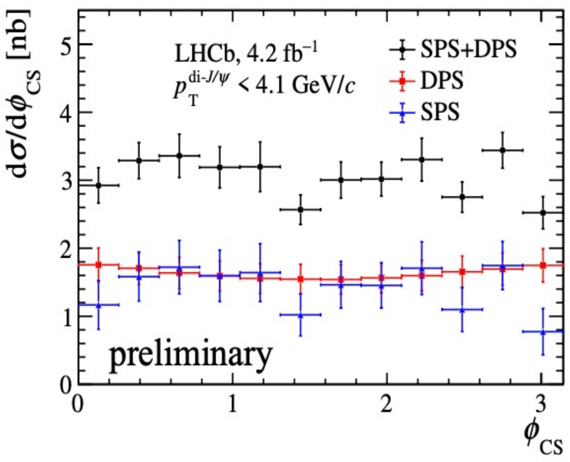
Gluon TMD study

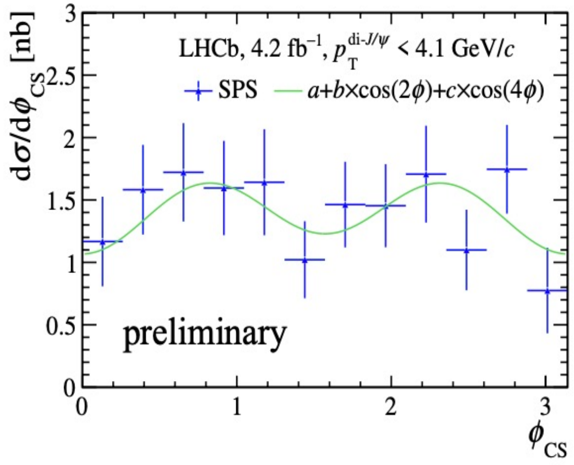
[LHCb-PAPER-2023-022]

➢ $h_1^{\perp g}(x, \boldsymbol{k}_T^2, \mu) \Rightarrow$ azimuthal asymmetry

$$\mathrm{d}\sigma/\mathrm{d}\phi_{CS} = a + b\times\cos(2\phi_{CS}) + c\times\cos(4\phi_{CS})$$

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





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

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

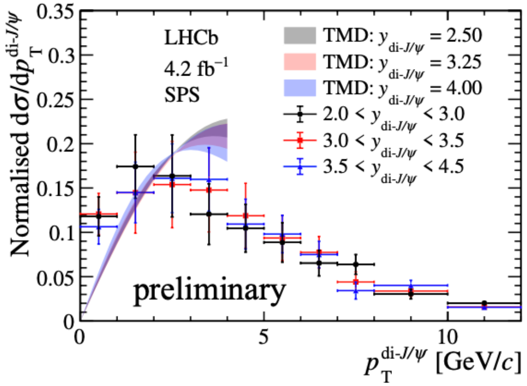
✓ Results consistent with zero, but the presence of an azimuthal asymmetry at a few percent level is allowed

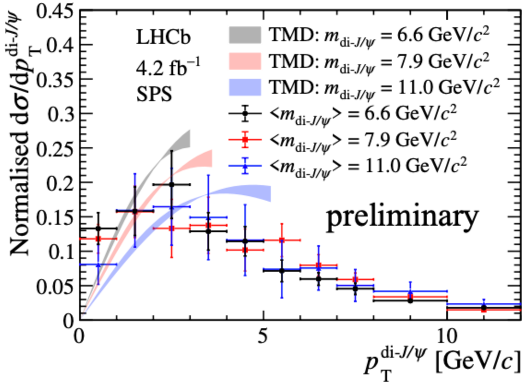
➢ $f_1^g(x, \boldsymbol{k}_T^2, \mu)$: affect p_T spectrum

✓ 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: $p_T(J/\psi) < 14\text{GeV}/c, 2.0 < y(J/\psi) < 4.5$

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

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

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

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

- Predictions on the ratio between $\sigma\big(J/\psi + \psi(2S)\big)$ and $\sigma(J/\psi + J/\psi)$ give

✓SPS: 0.940 ± 0.030 [PLB 751 (2015) 479]

✓DPS: 0.282 ± 0.027 [JHEP 10 (2015) 172] [EPJC 80 (2020) 185]

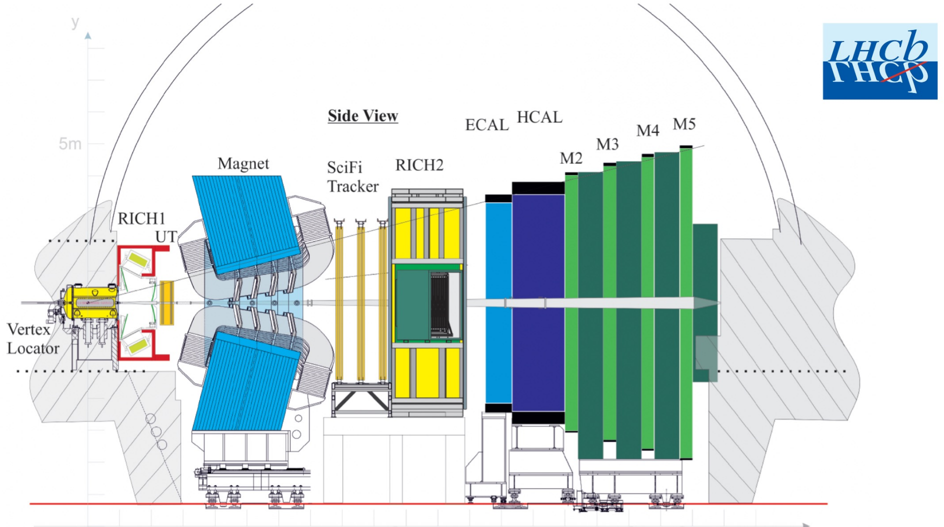
☛ Independent of the kinematic correlation of two J/ψ mesons, it confirms a significant DPS contribution to $J/\psi + J/\psi$ production in a novel way,

Summary and outlook

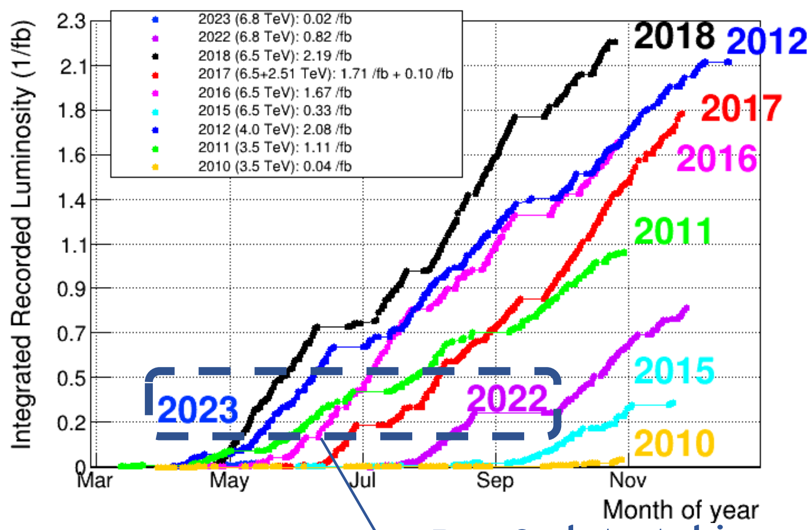
Studies on associated quarkonium production in pp collisions actively ongoing at LHCb

- **$J/\psi + \Upsilon$ production @ 13 TeV**
  - First observation of $J/\psi + \Upsilon(1S)$
  - σ_{eff} of DPS extracted
- **$J/\psi + J/\psi$ production @ 13 TeV**
  - SPS and DPS components separated
  - σ_{eff} of DPS extracted
  - Gluon TMD studied
- **$J/\psi + \psi(2S)$ production @ 13 TeV**
  - First measurement of $\sigma(J/\psi + \psi(2S))$
  - $\sigma(J/\psi + \psi(2S))/\ \sigma(J/\psi + J/\psi)$ studied

- In the future, with increased luminosity at $\sqrt{s} = 13.6$ TeV, LHCb will process more analyses on associated production



The new LHCb detector



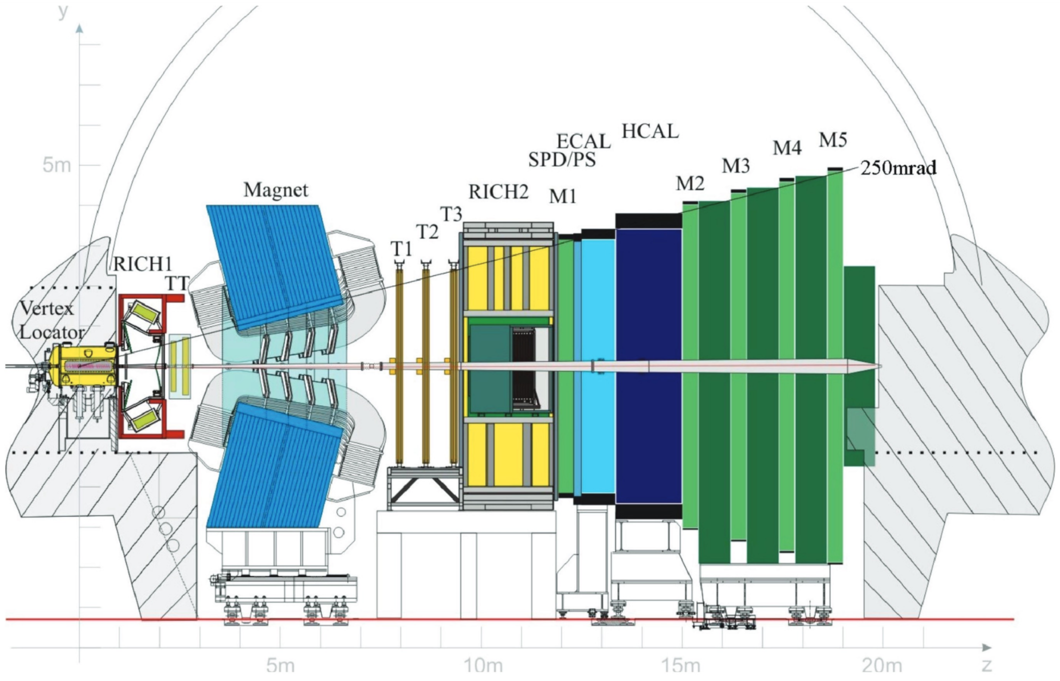
Run3 data taking

Thank you for attention!

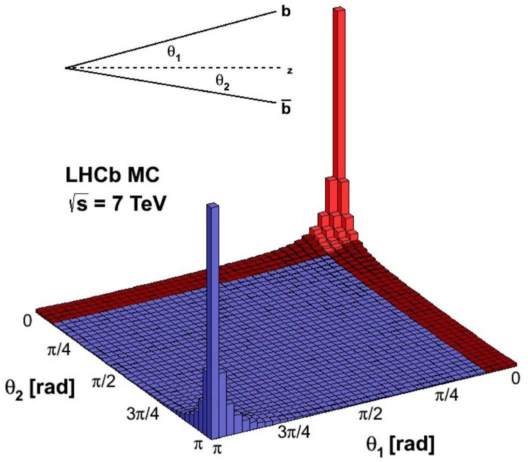
Back up

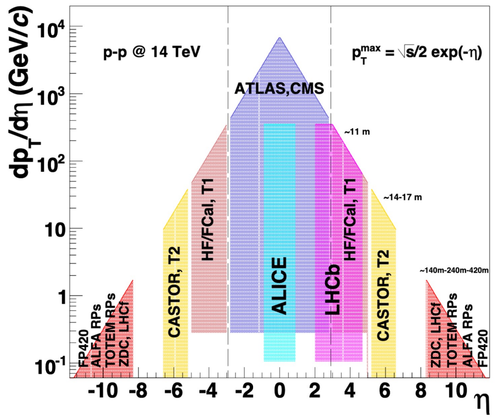
LHCb detector

- ✪ Designed for the studies of b and c physics
- ✪ Single-arm forward detector, forward region: $2 < \eta < 5$
  - ☆ ~4% of solid angle, but ~25% of $b\bar{b}$ quark pairs accepted
  - ☆ Complementary to other LHC experiments



JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

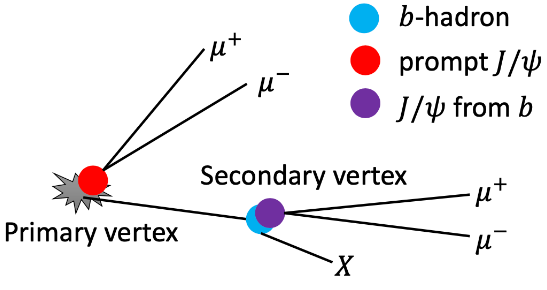




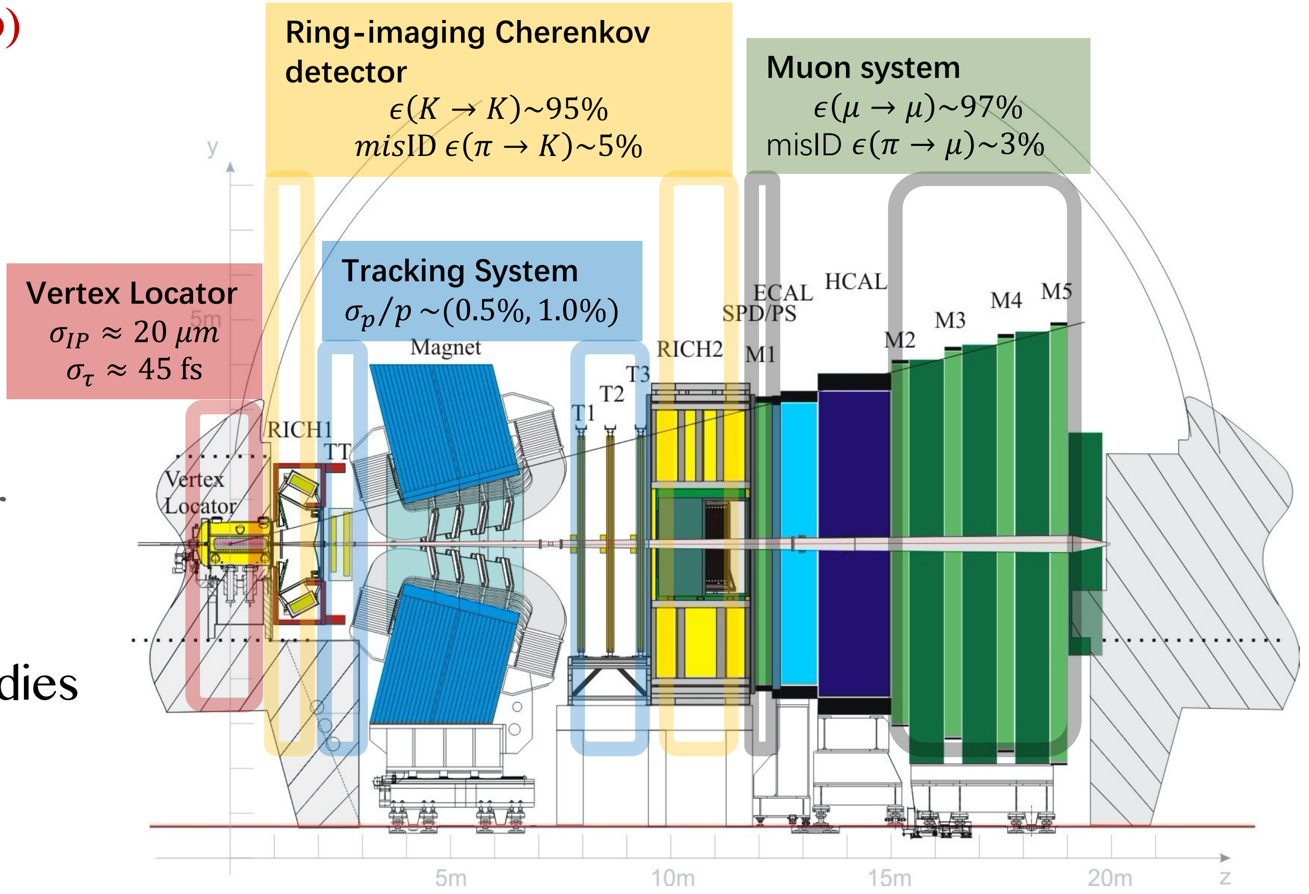
$p_T - \eta$ coverage of current detectors at the LHC. [arXiv:0708.0551]

LHCb detector

- Key detector systems for heavy flavour production measurement
  - Vertex reconstruction with Vertex Locator (Velo)
    - Separate primary and secondary vertices
  - Track reconstruction with Tracking System
    - Resolution of momentum from 0.5% to 1%
  - Particle identification (RICH & Muon System)
    - Charged hadron: ring-imaging Cherenkov detector
    - μ: muon detector
- An ideal laboratory for heavy flavour production studies



Example: J/ψ production

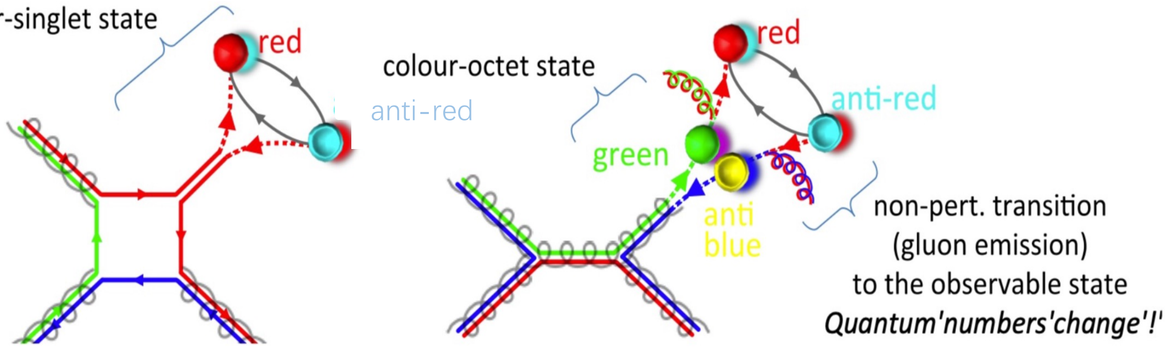


JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

Theoretical models

Color Singlet Model (CSM) : Phys. Rev. D14 (1976) 3115

- ☆ Colourless intermediate $Q\bar{Q}$
- ☆ Same spin-parity quantum number with final state
- ☆ Underestimate production cross-section



Non-Relativistic QCD (NRQCD): Phys. Rev. D51 (1995) 1125

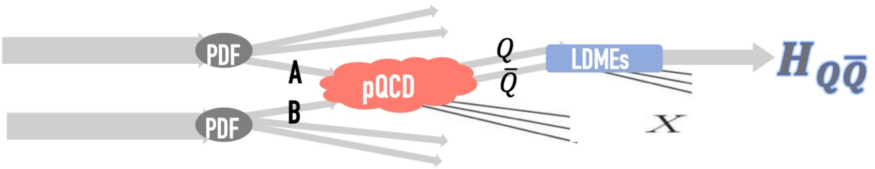
- ☆ Consider all possible colour-spin-parity quantum numbers
- ☆ Polarization puzzle

$$d\sigma_{[p_1 p_2 \to H+X]} = \sum_n \int F_1(A) F_2(B) dA\, dB\, d\hat{\sigma}_{[A+B\to Q\bar{Q}(n)+X]} \times \langle O^H(n) \rangle$$

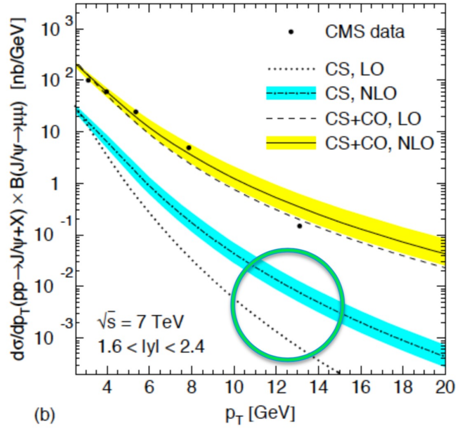
Parton distribution function

Production of heavy-quark pair

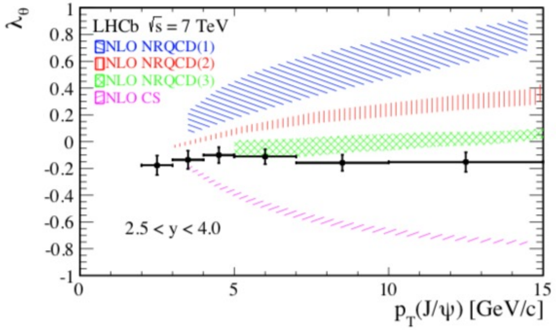
Long distance matrix elements (LDMEs)



LDMEs:
* The transition probability that the quark pair evolves into a heavy quarkonium.
* Determined from experimental results.



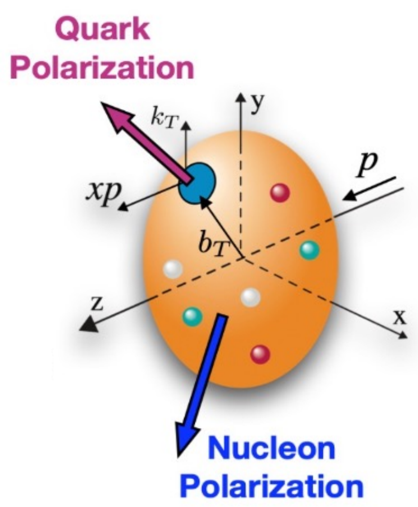
PRL 106, 022003 (2011)

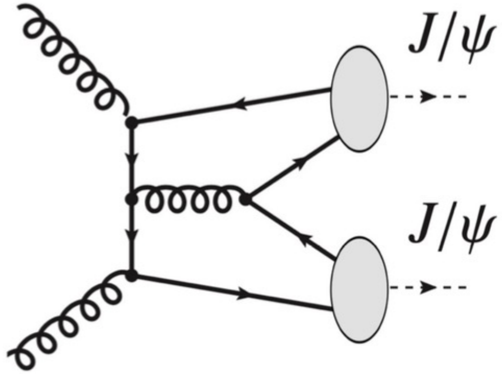


Eur. Phys. J. C (2016) 76:107

Associated quarkonium production-TMD

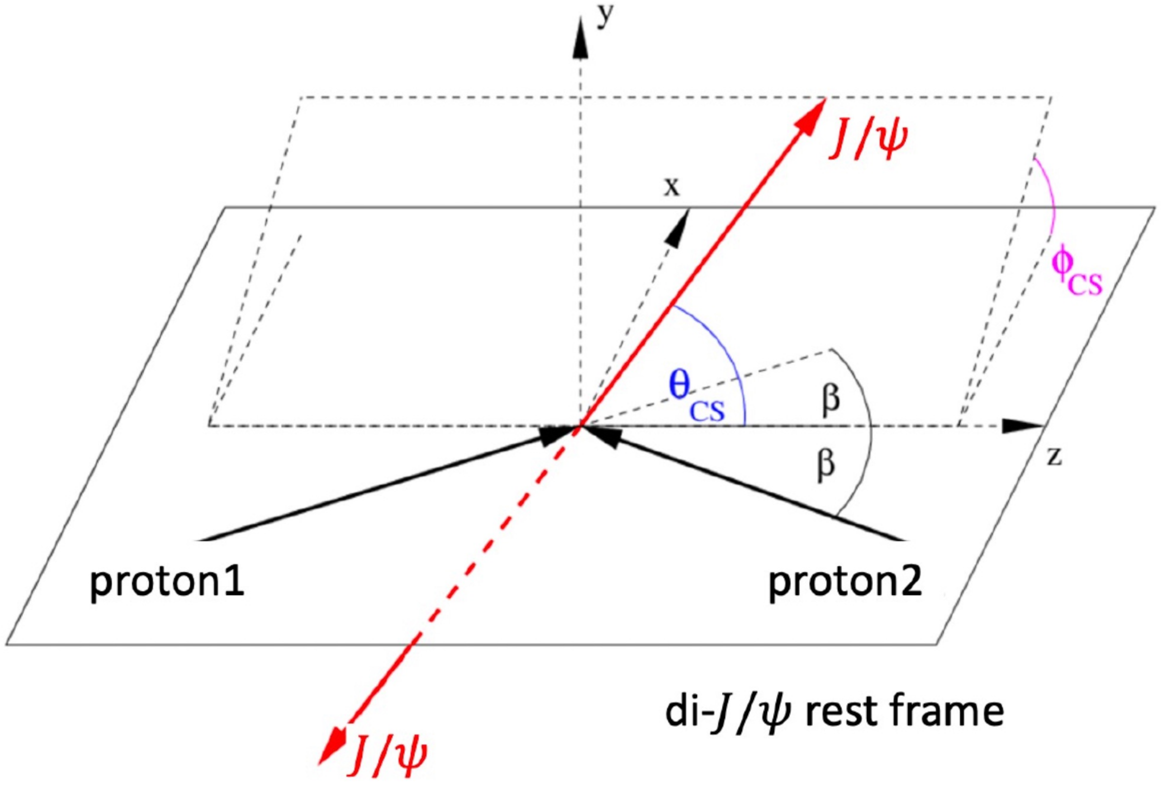
- PDF $f(x) \rightarrow$ TMD $f(x, \boldsymbol{k}_\mathrm{T})$
  - Provide more information about nucleon structure
  - Need to be extracted from experiment
- Currently our knowledge of gluon TMD is still very limited
  - The production of associated quarkonium is a promising process to study the gluon TMD
- Gluons inside unpolarised protons can be described at leading twist using two TMDs f_1^g and $h_1^{\perp g}$
  - f_1^g describe unpolarized gluons
  - $h_1^{\perp g}$ describe linearly polarized gluons
- The presence of polarised gluons inside the unpolarised proton has effects on the associated quarkonium cross-sections
  - Affect the p_T spectrum
  - Azimuthal asymmetries





Sketch of CS frame

This frame is the rest frame of the J/ψ pair with the polar axis (z-axis) bisecting the angle between the momentum of one proton and the reverse of the momentum of the other proton, the y-axis defined to be perpendicular to the plane spanned by the momenta of two protons, and the x-axis defined to complete a right-handed Cartesian coordinate system

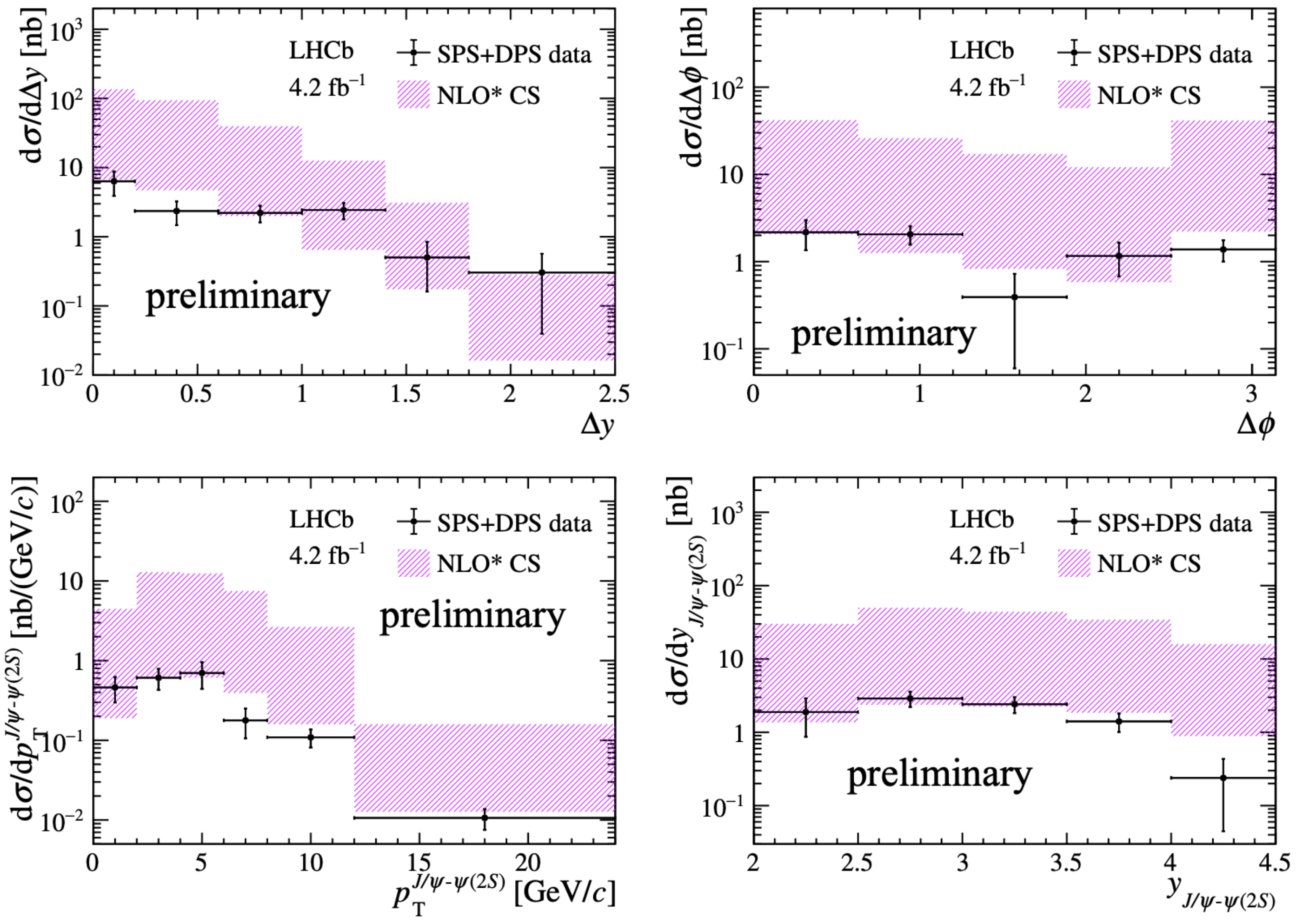


Summary

- Studies on associated quarkonium production actively ongoing at LHCb
  - $\boldsymbol{J/\psi - \Upsilon}$ **@ 13 TeV**
    - ✓First observation of $J/\psi - \Upsilon(1S)$ production in *pp* collisions
    - ✓σ_{eff} of DPS extracted
  - $\boldsymbol{J/\psi - J/\psi}$ **@ 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
  - $\boldsymbol{J/\psi - \psi(2S)}$ **@ 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…

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

[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 $\sigma(J/\psi + \psi(2S))$ 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]

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

☛ 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