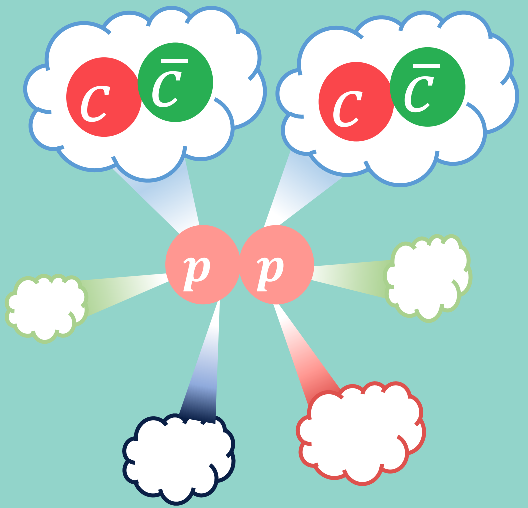
Associated quarkonium production in pp collisions at LHCb



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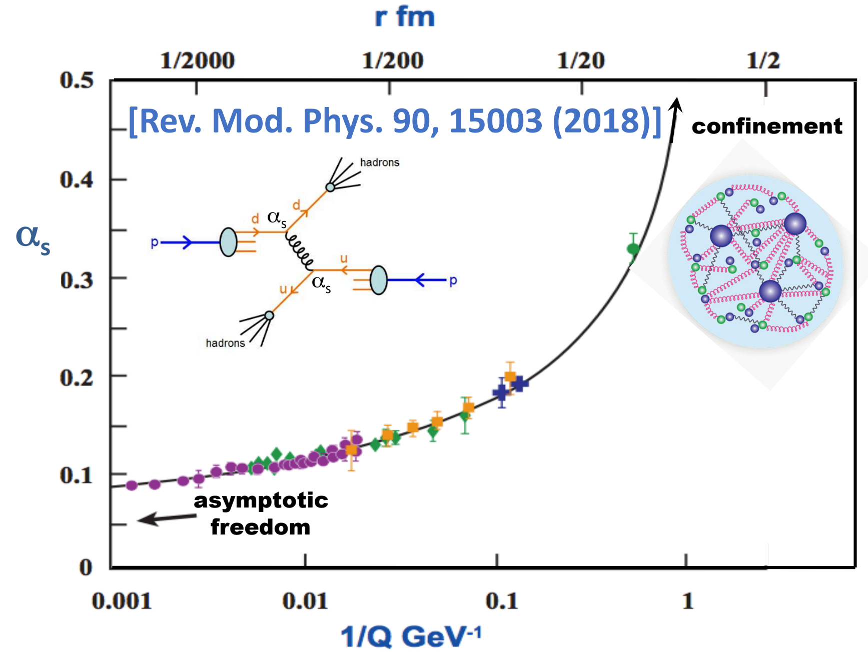
第四届LHCb前沿物理研讨会 @ 烟台，2024年7月31日

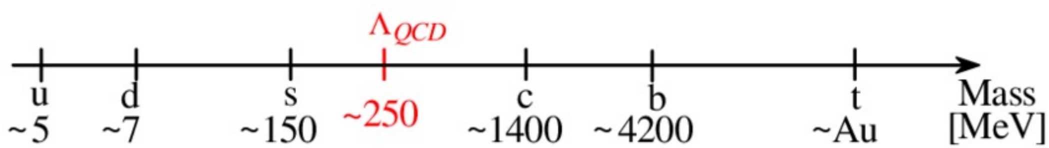
Quarkonium for QCD

➢ ***QCD dilemma***:
understanding the non-perturbative property of QCD at low-energy scale

➢ ***Confinement***:
- ✓ no analytic proof exists
- ⇒ what is the mechanism behind hadronization?



➢ ***Heavy quarkonium***: ideal system to study hadronization mechanism

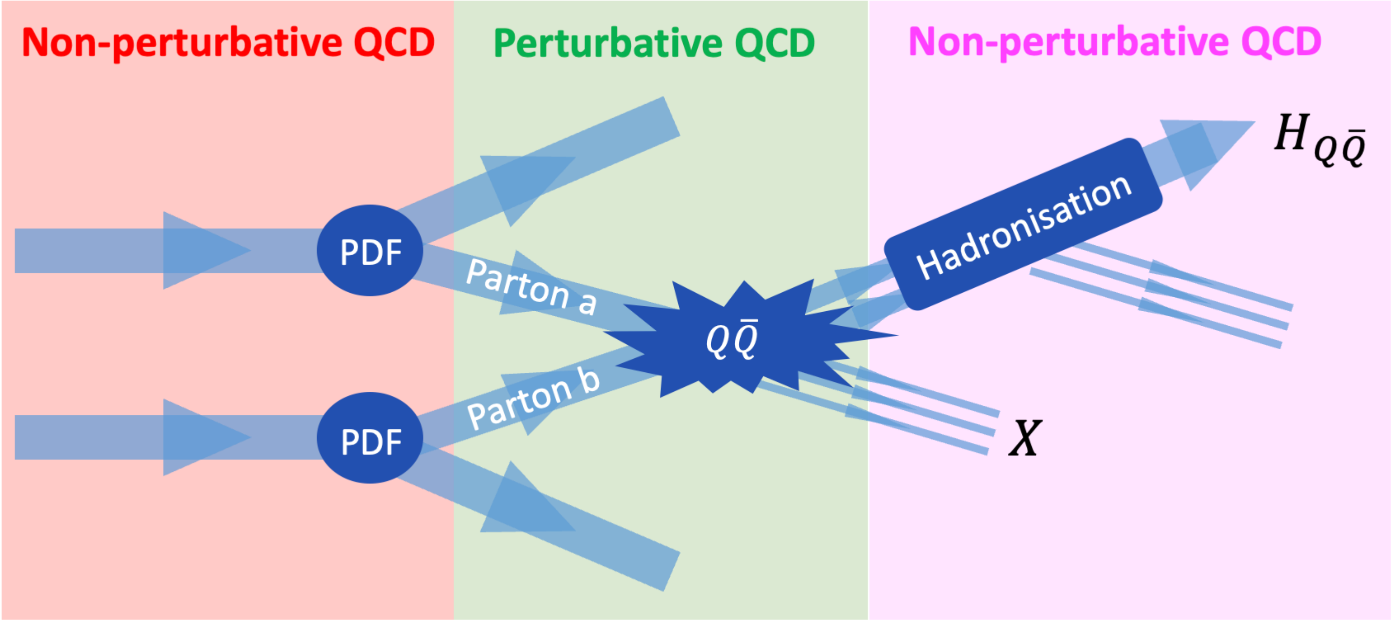


Perturbative	**Non-perturbative**	
m_Q ≫	$m_Q v$ ≫	$m_Q v^2$
mass	**momentum**	**kinetic energy**
$Q\bar{Q}$ creation	$Q\bar{Q}$ expansion	forming bound state

$v^2 \sim 0.3$ for $H_{c\bar{c}}$
$v^2 \sim 0.1$ for $H_{b\bar{b}}$

Quarkonium production mechanism

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



✓ excellent tool to study gluon PDF

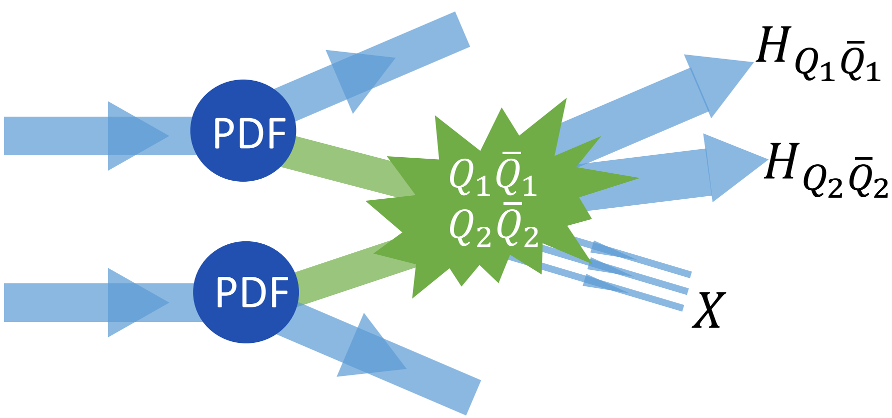
$$\sigma(H_{Q\bar{Q}}) = \sum_{a,b,n} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{a/p}(x_1) f_{b/p}(x_2) |\mathcal{A}(ab \to Q\bar{Q}[n] + X)|^2 \times \langle \mathcal{O}^H(n) \rangle$$

LDMEs: extracted from measurements & process independent

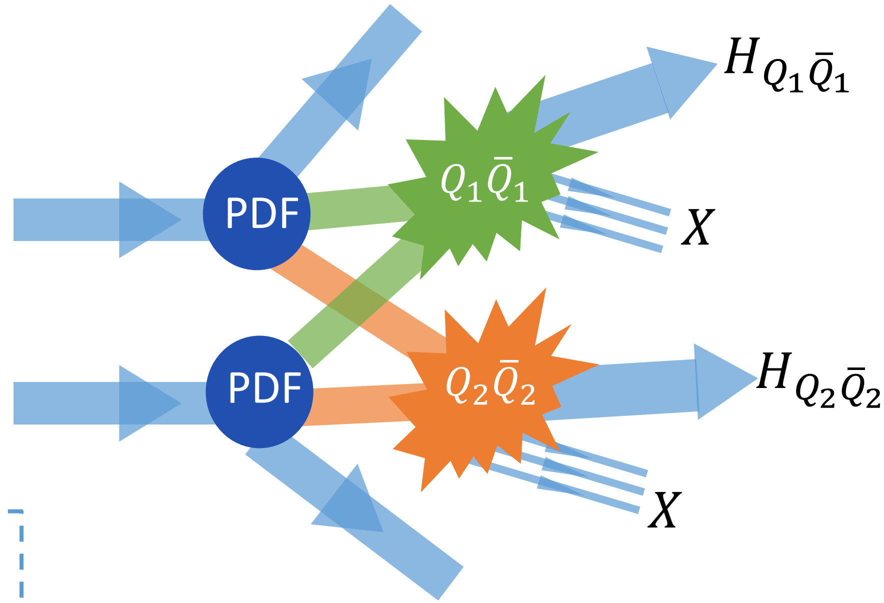
$$|J/\psi\rangle = O(1) \left| c\bar{c}\left[{}^3S_1^{(1)} \right] \right\rangle + O(v) \left| c\bar{c}\left[{}^3P_J^{(8)} \right] + g \right\rangle + O(v^{3/2}) \left| c\bar{c}\left[{}^1S_0^{(8)} \right] + g \right\rangle + \cdots$$

Associated Quarkonium production

Single-parton scattering (SPS)



Double-parton scattering (DPS)



✓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

[EPJC 80 (2020) 87]

✓To search for fully heavy tetraquark states

✓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

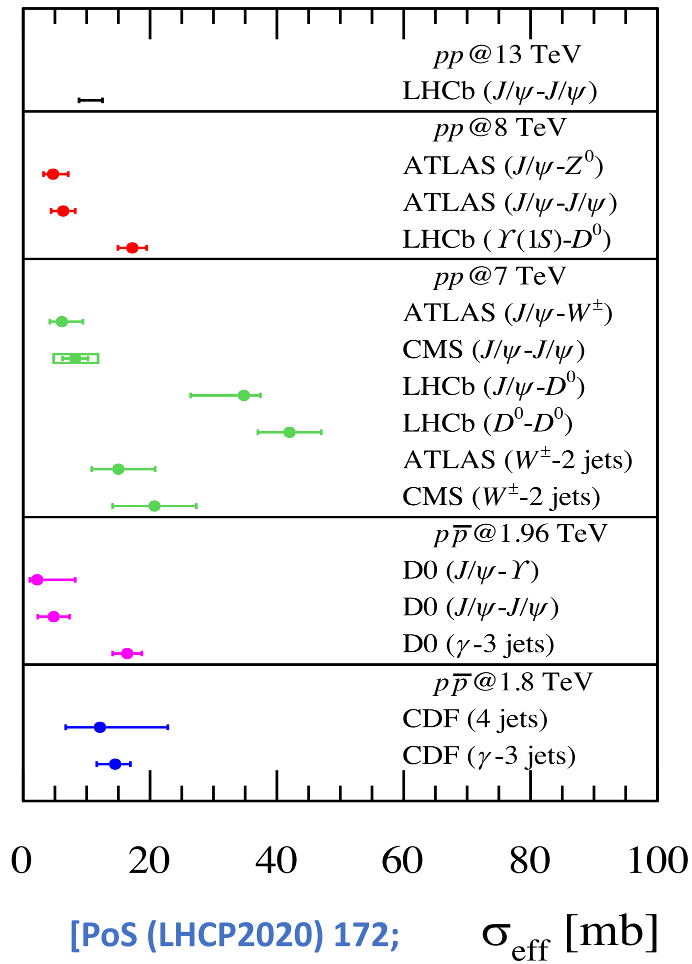
$$D_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2), T_{ij}(\boldsymbol{b}_1, \boldsymbol{b}_2) = T_i(\boldsymbol{b}_1) T_j(\boldsymbol{b}_2)$$

$\Rightarrow$

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

$$\sigma_{\text{eff}} = 1 \Big/ \left[\int d^2\boldsymbol{b} F(\boldsymbol{b})^2 \right], F(\boldsymbol{b}) = \int T(\boldsymbol{b}_i) T(\boldsymbol{b}_i - \boldsymbol{b}) d^2\boldsymbol{b}_i$$

expected to be universal under the given assumptions

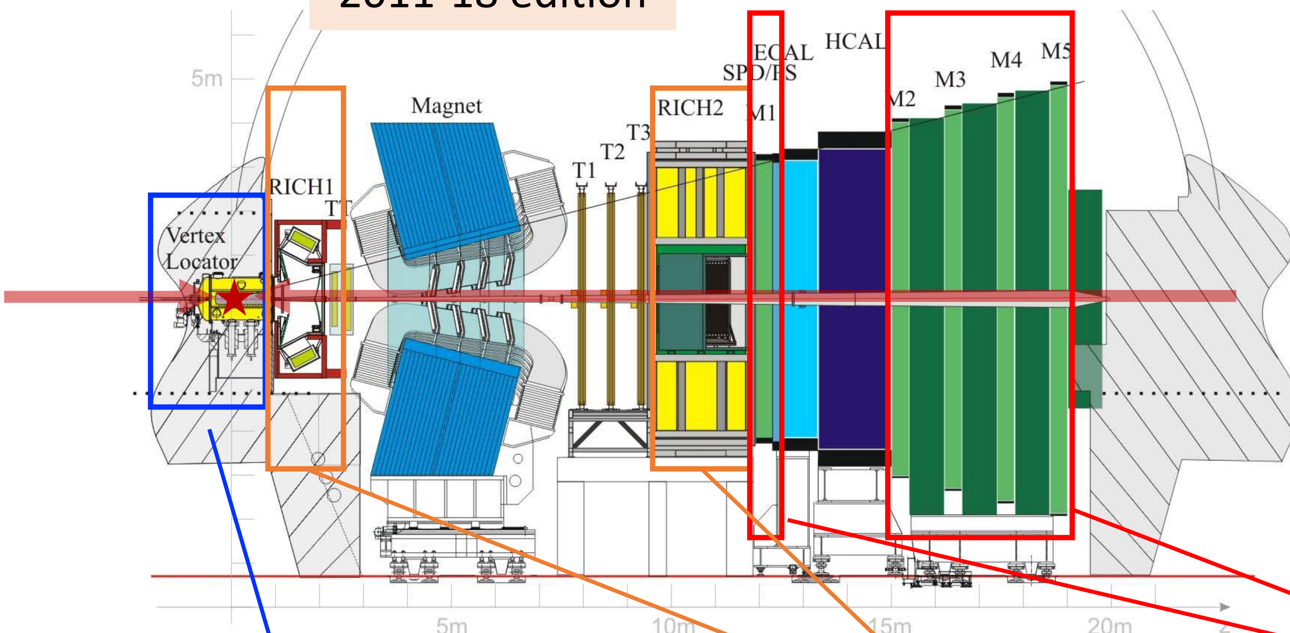


[PoS (LHCP2020) 172; arXiv: 2009.12555]

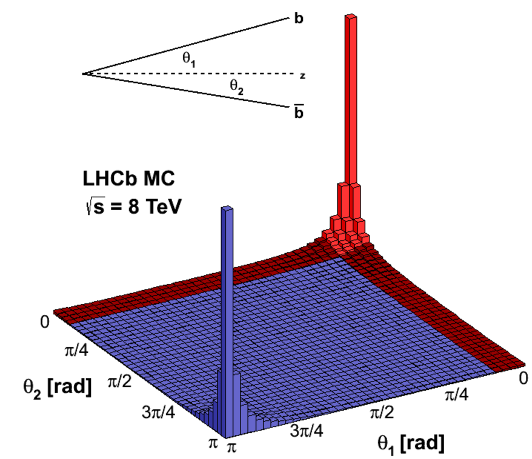
The LHCb detector

- ➢LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, dedicated to heavy flavor physics at the Large Hadron Collider

2011-18 edition



2.4% 4π angle
$\Rightarrow 25\%$ $b\bar{b}$



Vertex Locator: high precision; capable of separating b/c hadron production and decay vertices

$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$

RICHs: efficient identification of pions, kaons and protons

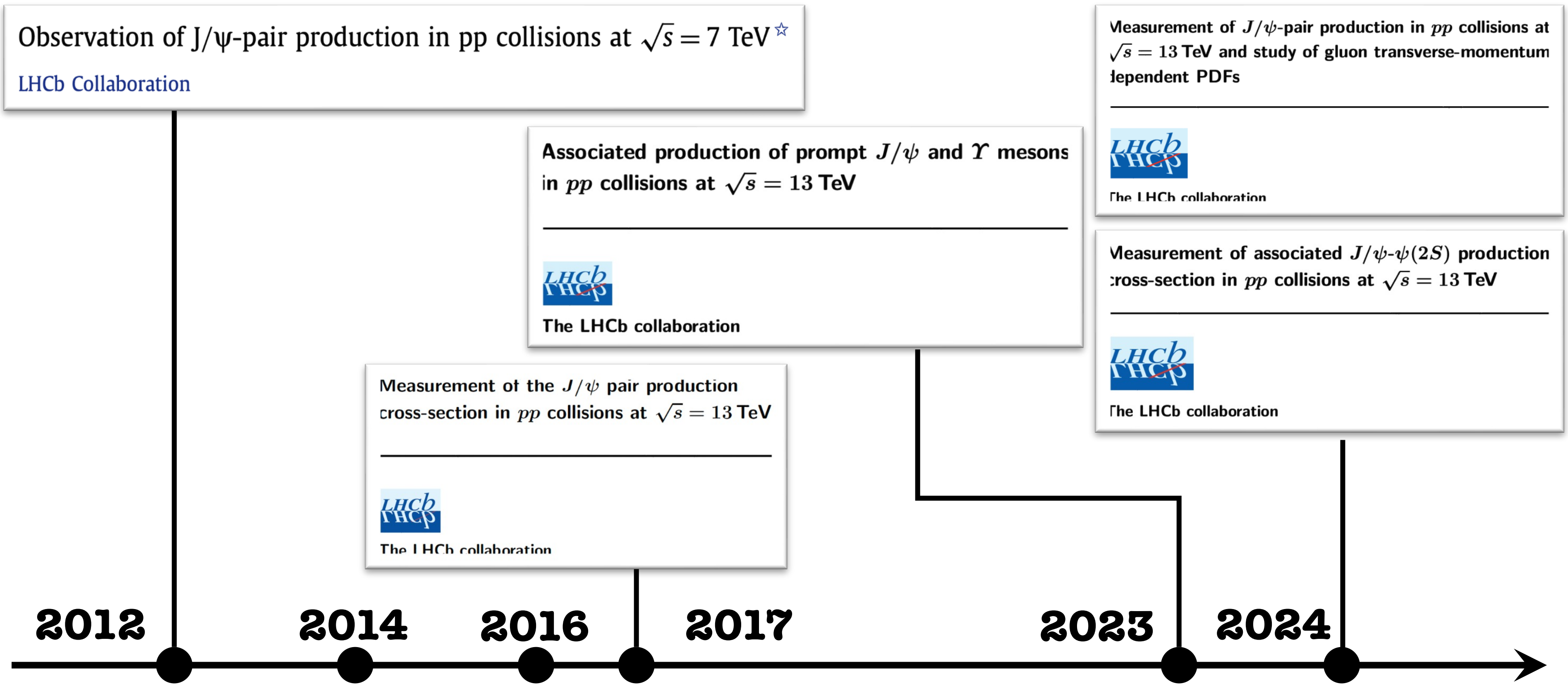
$\varepsilon(K \to K) \sim 95\%$
@ misID rate $(\pi \to K) \sim 5\%$

Muon system (M1-M5): efficient muon identification and trigger

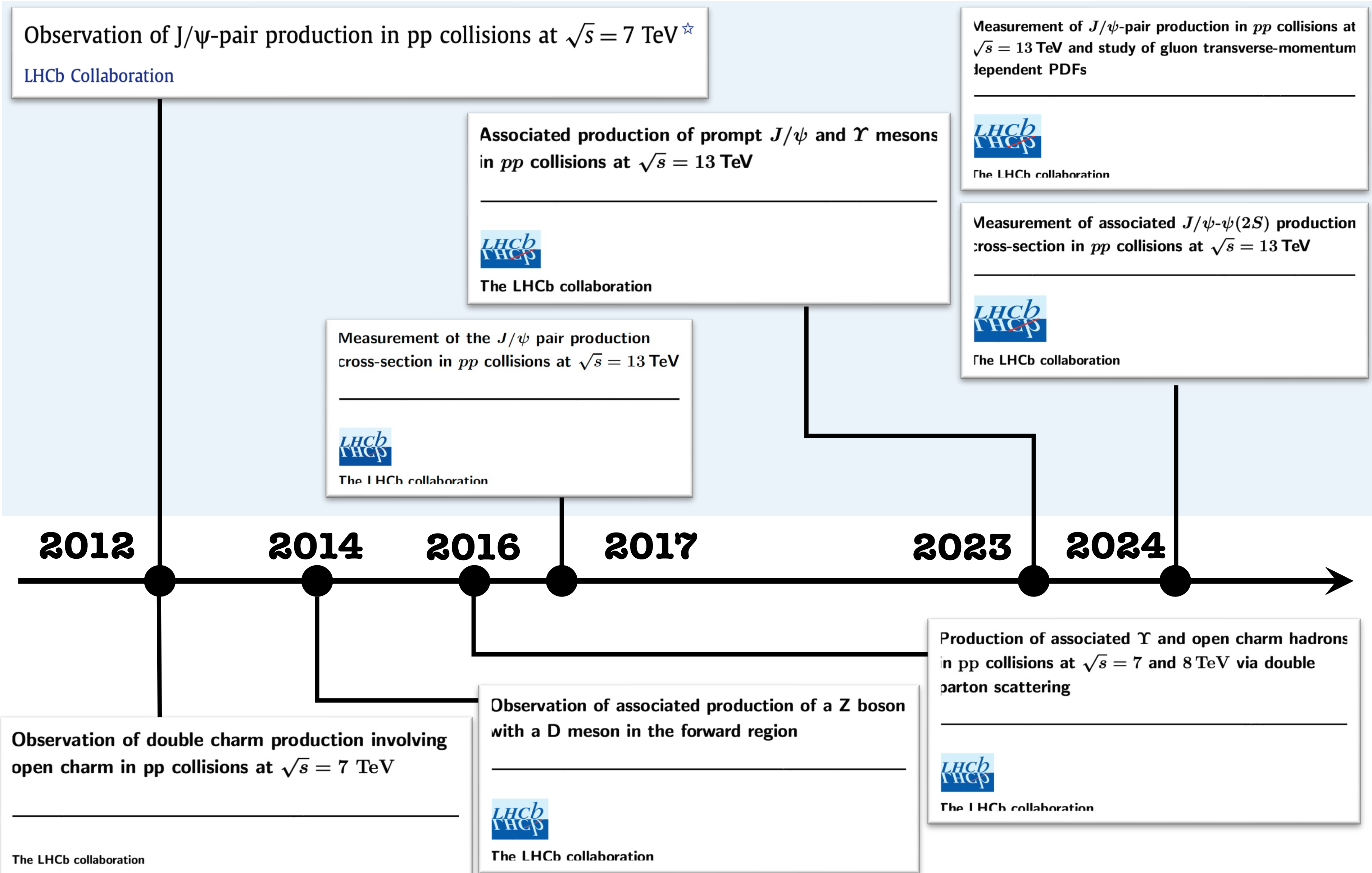
$\varepsilon(\mu \to \mu) \sim 97\%$
@ misID rate $(\pi \to \mu) \sim 1-3\%$

[JINST 3 (2008) S08005]

A glimpse of existing measurements



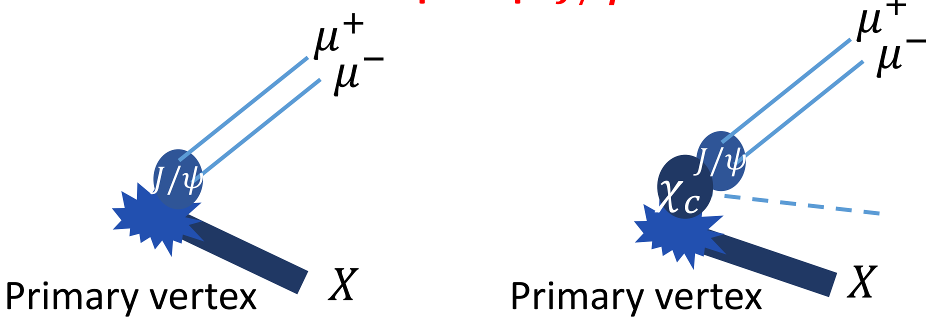
A glimpse of existing measurements



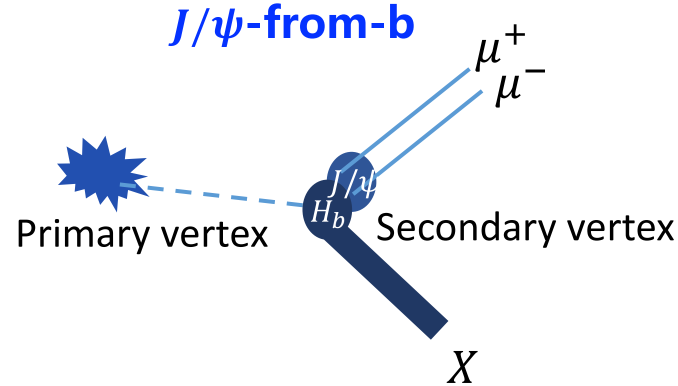
Analysis strategy

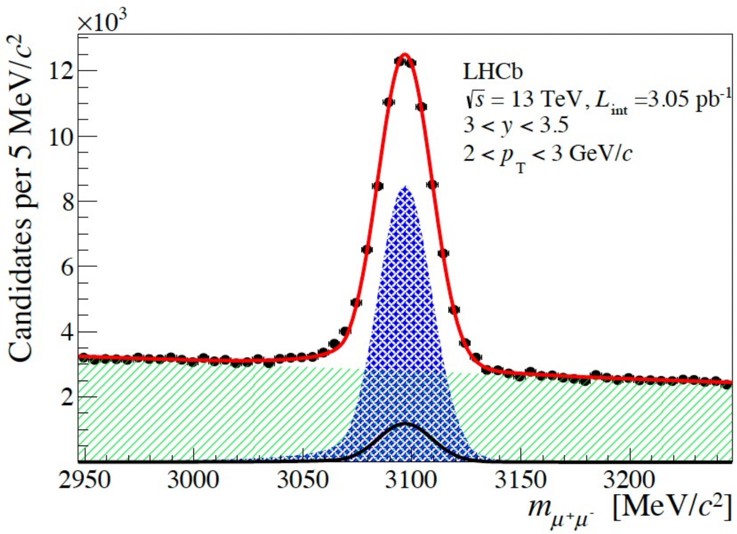
$$\frac{d\sigma}{d\mathrm{v}} = \frac{\boldsymbol{N}}{\mathcal{L}\times\varepsilon\times\mathcal{B}^2(J/\psi\to\mu^+\mu^-)\times\Delta\mathrm{v}}$$

prompt J/ψ

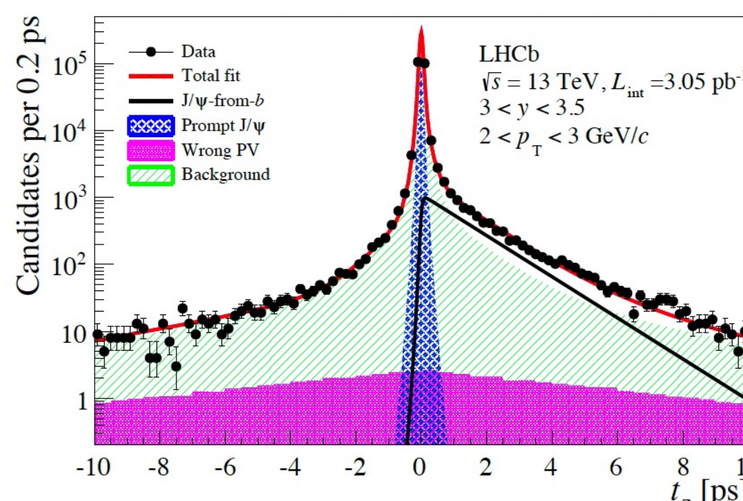


J/ψ-from-b





[JHEP 10 (2015) 172]

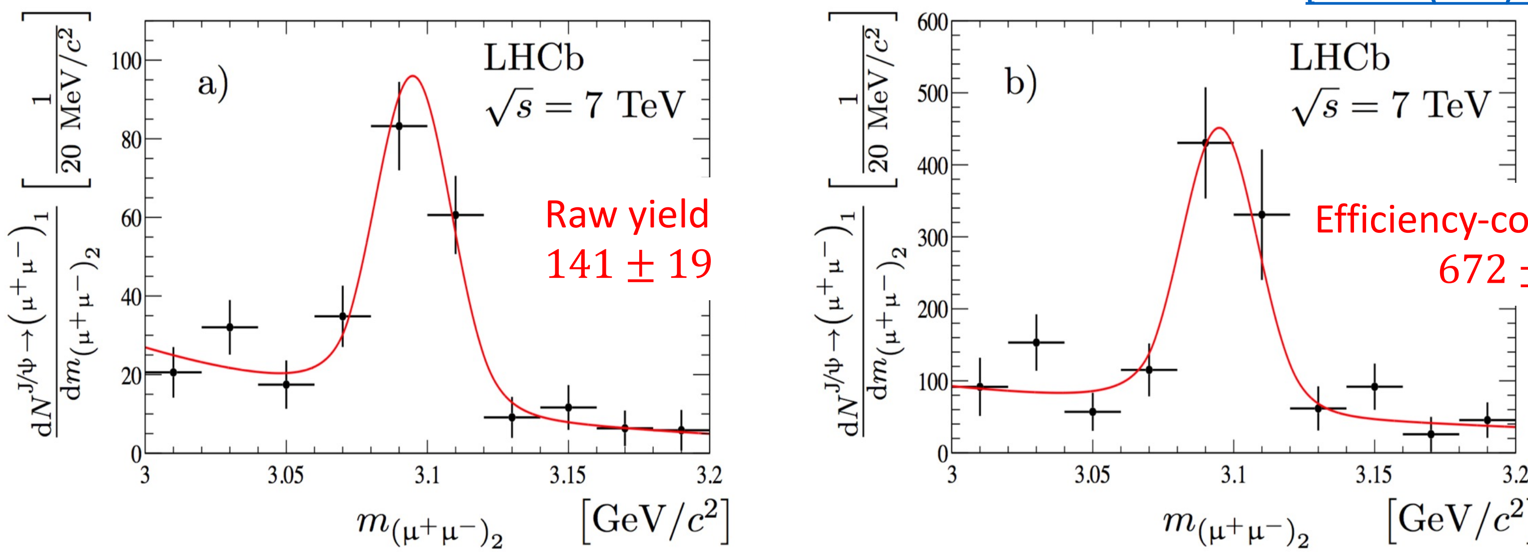


$$t_z = \frac{(z_{J/\psi} - z_{\mathrm{PV}}) \times M_{J/\psi}}{p_z}$$

di-J/ψ @ 7 TeV

- Using 37.5 pb^{-1} data at $\sqrt{s} = 7$ TeV
- Fiducial region: $2 < y^{J/\psi} < 4.5$, $p_T^{J/\psi} < 10$ GeV/c
- Observed with significance $> 6\sigma$ (from-b contribution negligible)

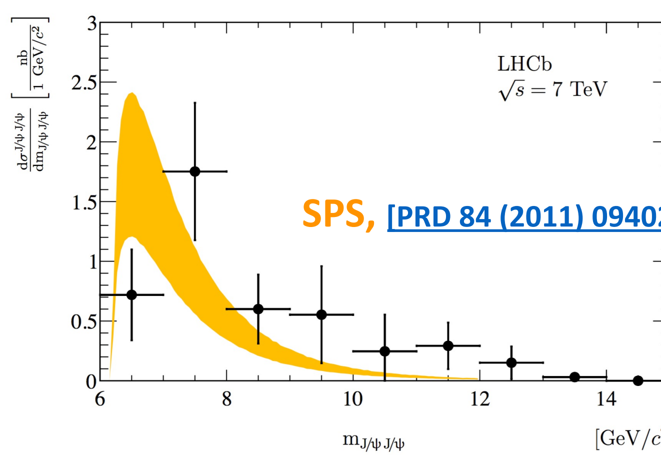
[PLB 707 (2012) 52-59]



Raw yield 141 ± 19

Efficiency-corrected yield 672 ± 129

- $\sigma^{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1$ nb
  - ✓ $\sigma_{SPS} = 4.1 \pm 1.2$ nb
  - ✓ $\sigma_{DPS} \approx 2.5$ nb
- Not enough events to disentangle SPS and DPS contributions

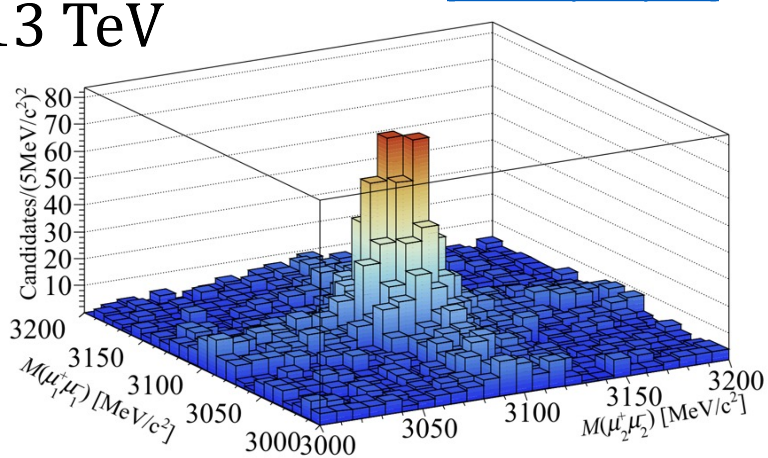


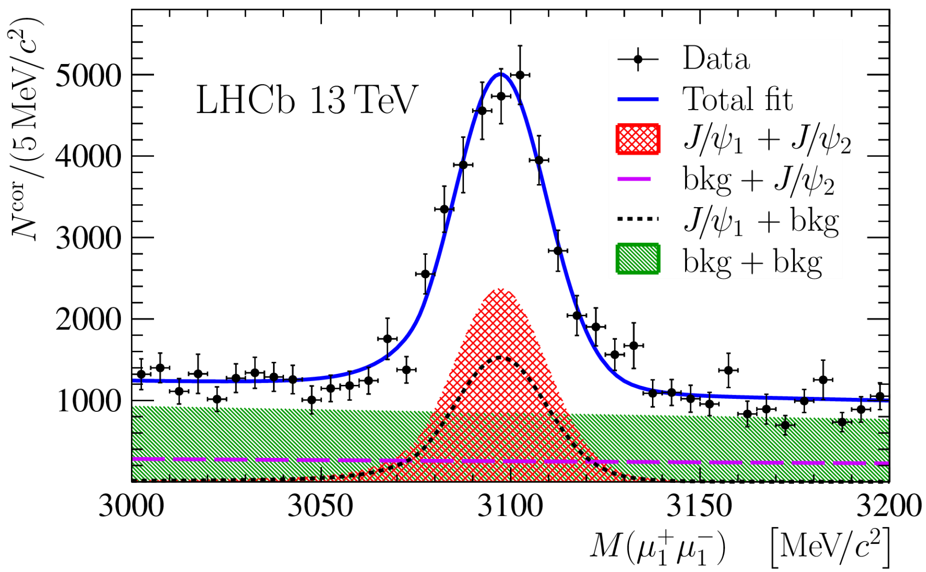
SPS, [PRD 84 (2011) 094023]

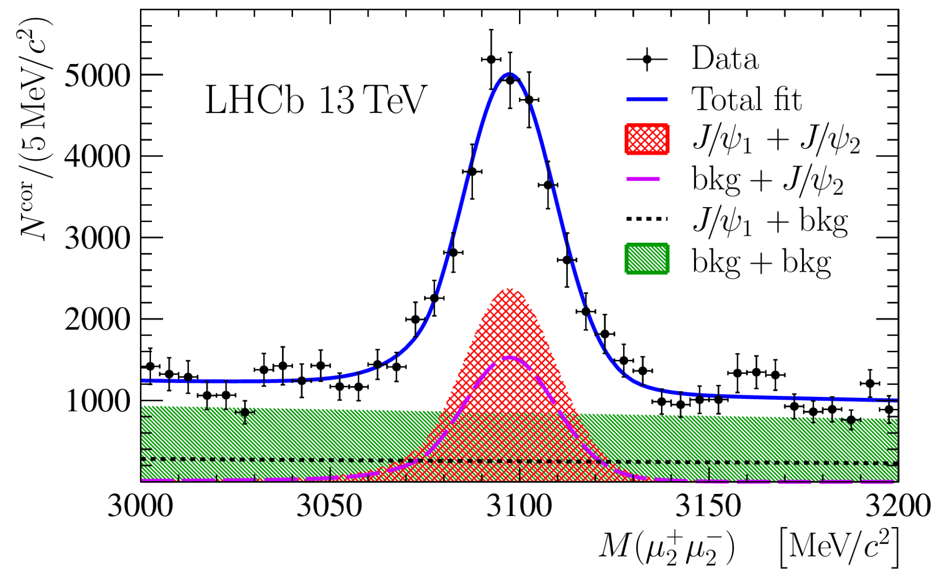
di-J/ψ @ 13 TeV

[JHEP 06 (2017) 047]

- $\mathcal{L} = 279\ \mathrm{pb}^{-1}$, pp collisions @ $\sqrt{s} = 13$ TeV
- Kinematic range of J/ψ:
  $p_{\mathrm{T}} < 10\ \mathrm{GeV}/c$ for $2.0 < y < 4.5$
- Signal yield determination
  - ✓Residual from-b component determined using simulation together with $\sigma(pp \to b\bar{b})$ and $\sigma(\text{prompt}\ J/\psi)$







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

Comparison to theory

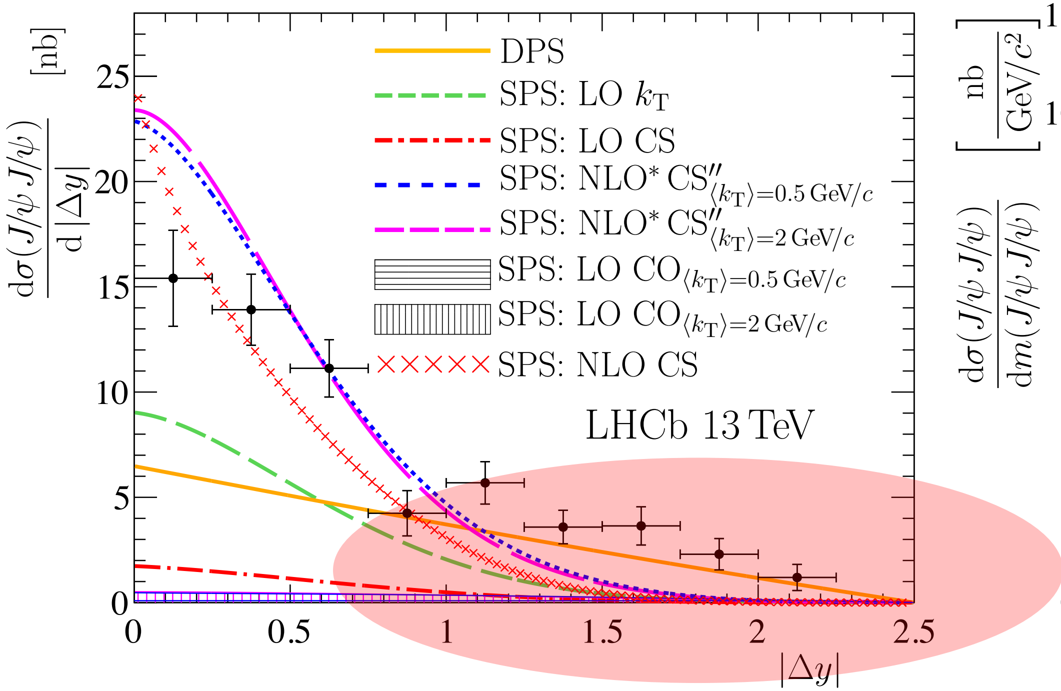
	$\sigma(J/\psi\, J/\psi)$ [nb] [JHEP 06 (2017) 047]		
	no p_{T} cut	$p_{\mathrm{T}} > 1\,\mathrm{GeV}/c$	$p_{\mathrm{T}} > 3\,\mathrm{GeV}/c$
SPS: LO Colour-singlet	$1.3 \pm 0.1^{+3.2}_{-0.1}$	—	—
SPS: LO Colour-octet	$0.45 \pm 0.09^{+1.42+0.25}_{-0.36-0.34}$	—	—
SPS: LO k_{T}	$6.3^{+3.8+3.8}_{-1.6-2.6}$	$5.7^{+3.4+3.2}_{-1.5-2.1}$	$2.7^{+1.6+1.6}_{-0.7-1.0}$
SPS: NLO* Colour-singlet’	—	$4.3 \pm 0.1^{+9.9}_{-0.9}$	$1.6 \pm 0.1^{+3.3}_{-0.3}$
SPS: NLO* Colour-singlet’’	$15.4 \pm 2.2^{+51}_{-12}$	$14.8 \pm 1.7^{+53}_{-12}$	$6.8 \pm 0.6^{+22}_{-5}$
SPS: NLO Colour-singlet	$11.9^{+4.6}_{-3.2}$	—	—
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	$15.2 \pm 1.0 \pm 0.9$	$13.5 \pm 0.9 \pm 0.9$	$8.3 \pm 0.6 \pm 0.5$

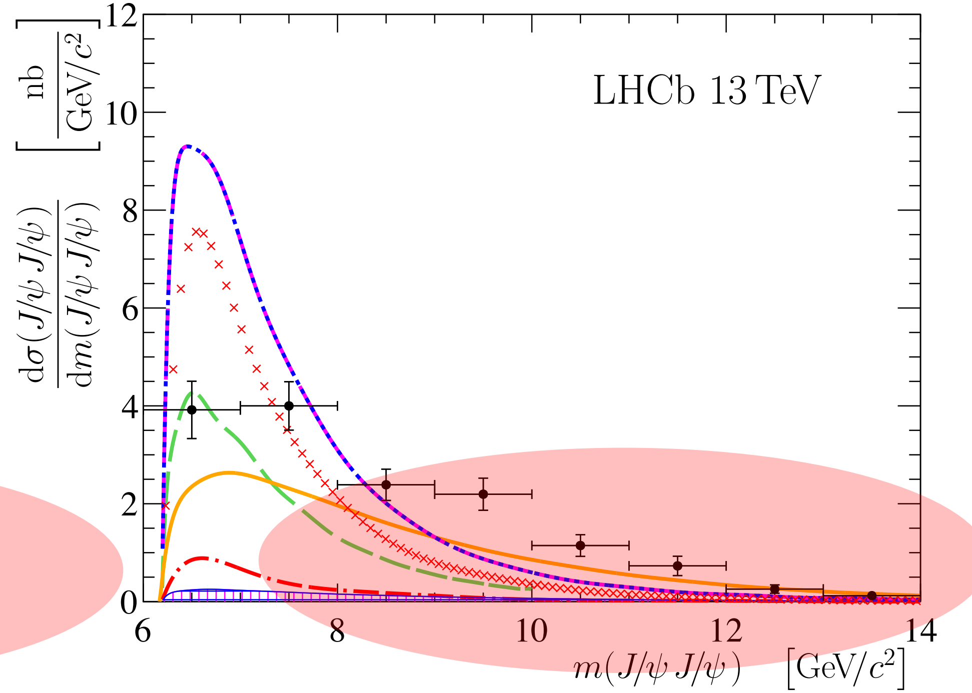
DPS: assuming $\sigma_{\mathrm{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb [PRD 56 (1997) 3811]

- LO Colour-octet : contribution very small
- LO Colour-singlet/ NLO* Colour-singlet’ and LO k_{T}: need DPS contribution
- NLO* Colour-singlet’’ and NLO Colour-singlet : consistent with our measurement by itself; overestimated if there is DPS contribution

Differential cross-sections

- 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]

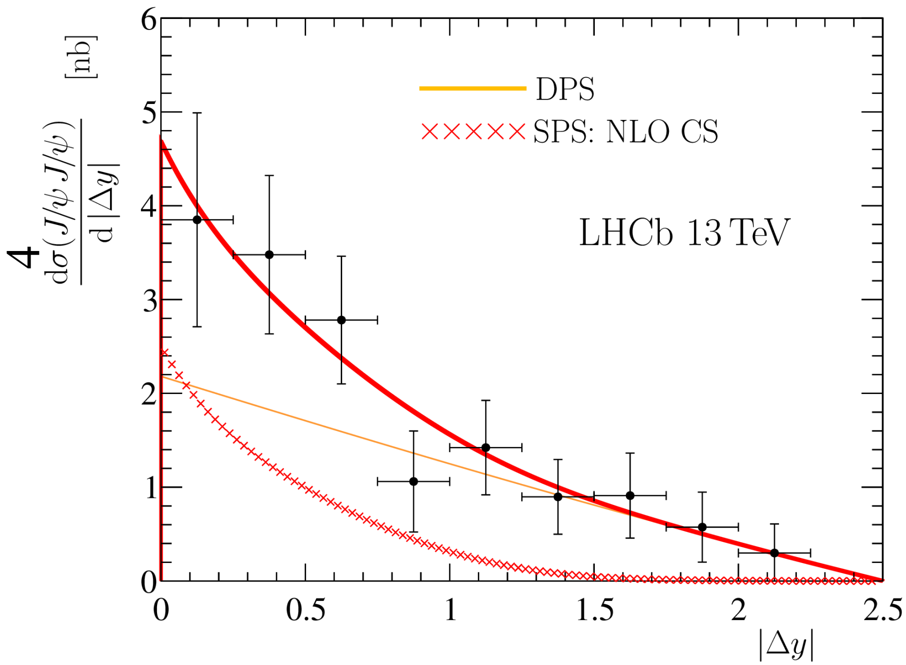
DPS extraction

[JHEP 06 (2017) 047]

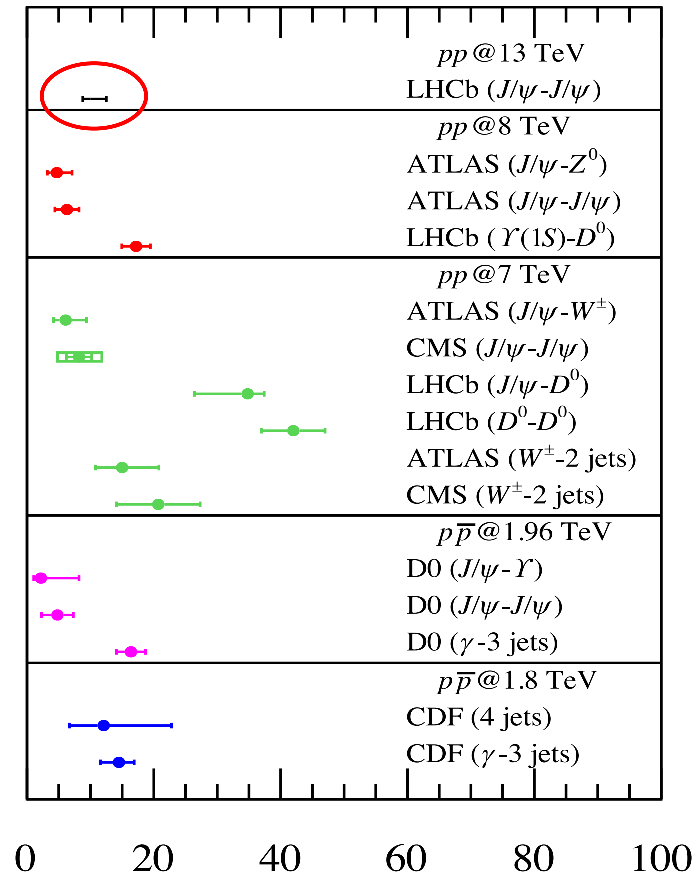
- Template DPS+SPS fits performed for different variables using various models

$$\frac{\mathrm{d}\sigma}{\mathrm{d}v} = \sigma_{\mathrm{DPS}} F_{\mathrm{DPS}}(v) + \sigma_{\mathrm{SPS}} F_{\mathrm{SPS}}(v)$$

σ_{eff}: 8.8~12.5 mb



Variable	LO k_{T}	NLO* CS″ $\langle k_{\mathrm{T}}\rangle = 2\,\mathrm{GeV}/c$	NLO* CS″ $\langle k_{\mathrm{T}}\rangle = 0.5\,\mathrm{GeV}/c$	NLO CS
$p_{\mathrm{T}}(J/\psi\, J/\psi)$	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



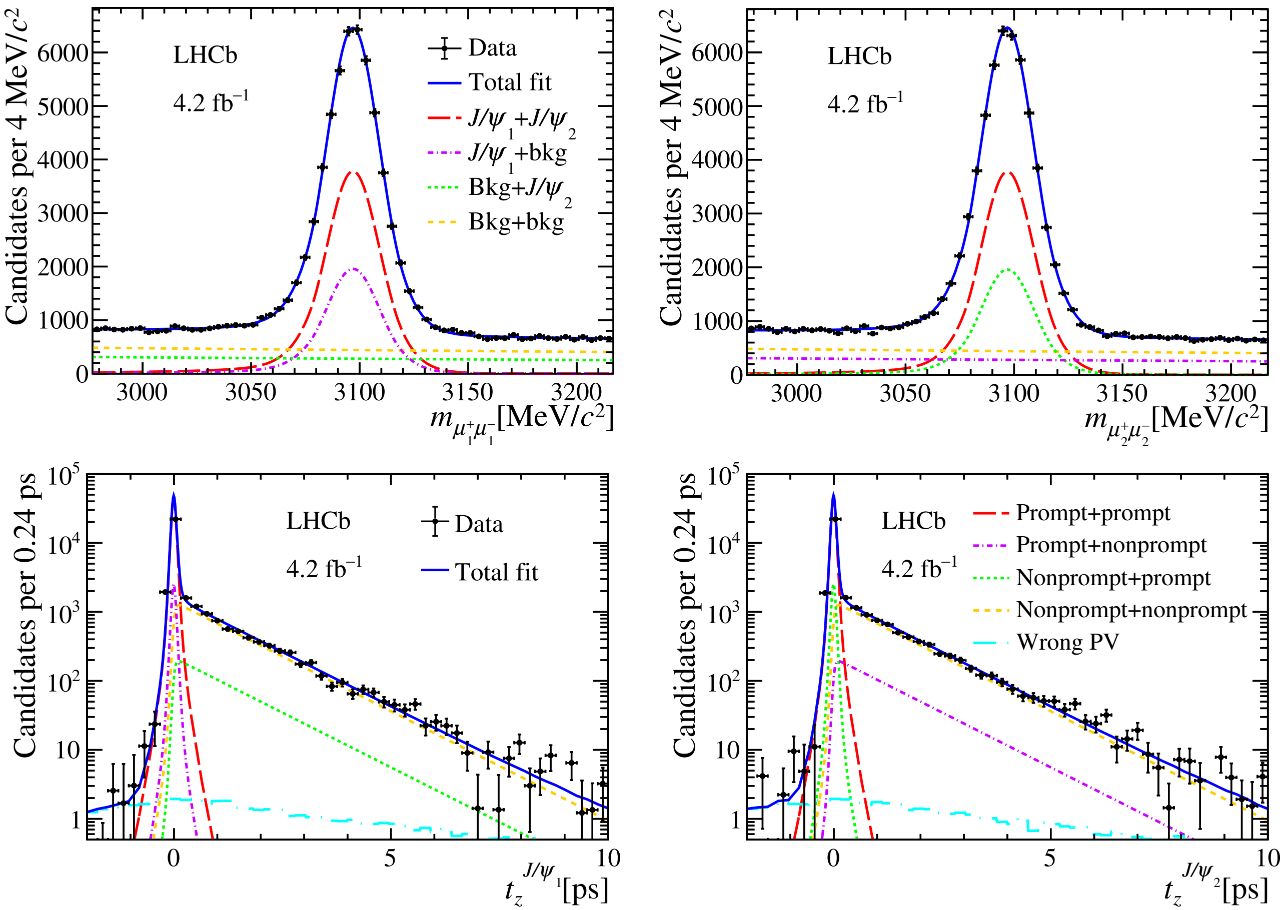
σ_{eff} [mb]

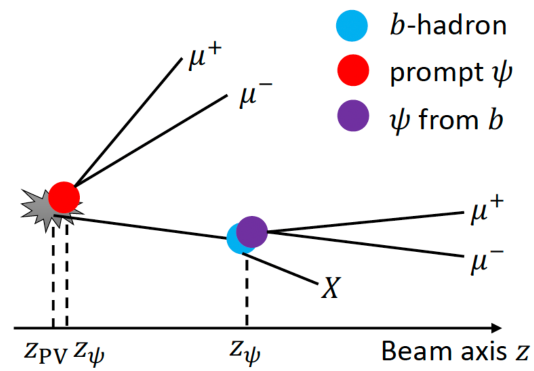
[PoS (LHCP2020) 172; arXiv: 2009.12555]

di-J/ψ @ 13 TeV update

[JHEP 03 (2024) 088]

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





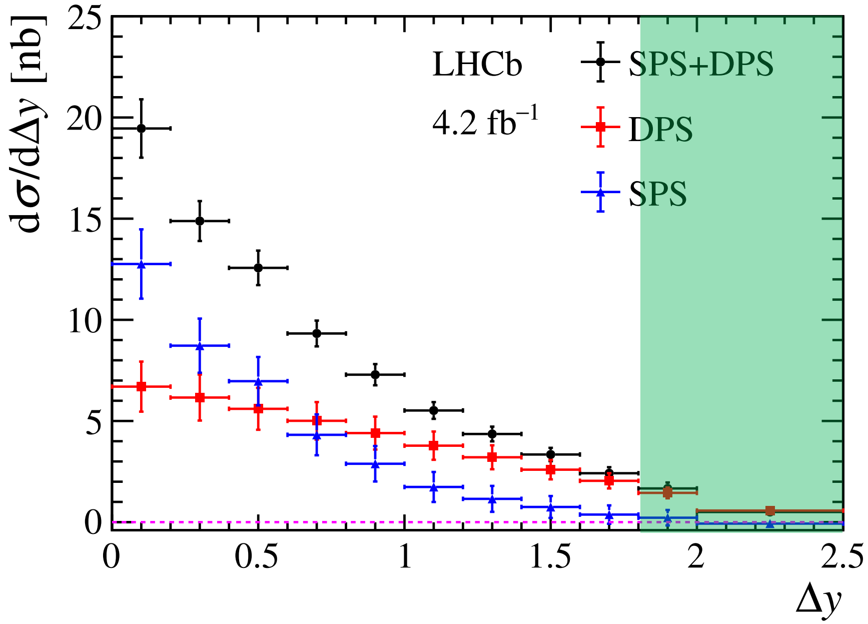
$$t_z = \frac{z_\psi - z_{\mathrm{PV}}}{p_z/m_\psi}$$

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

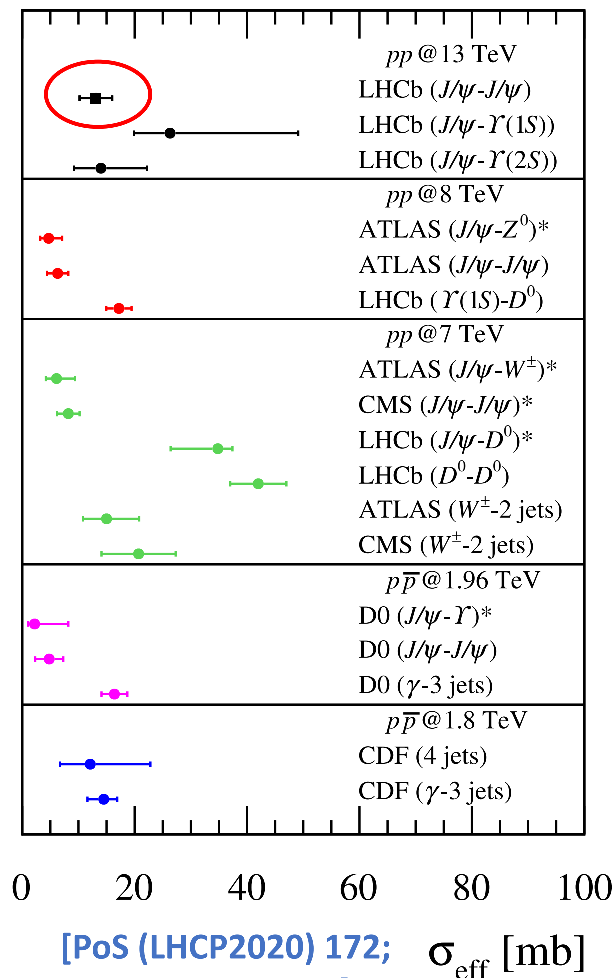
$$\sigma(J/\psi - J/\psi) = 16.36 \pm 0.28(\mathrm{stat}) \pm 0.88(\mathrm{syst})\ \mathrm{nb}$$

SPS and DPS separation

[JHEP 03 (2024) 088]



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



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

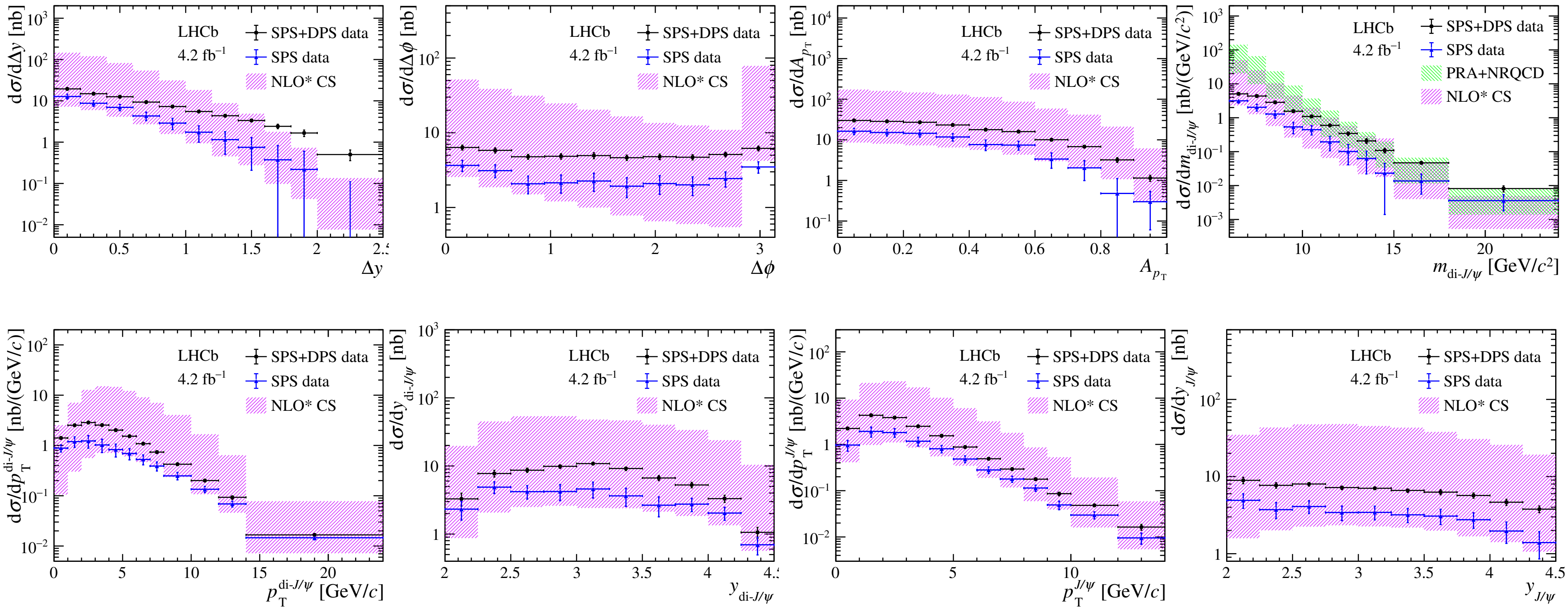
$$\sigma(J/\psi - J/\psi)_{\text{SPS}} = 7.9 \pm 1.2(\text{stat}) \pm 1.1(\text{syst})\ \text{nb}$$

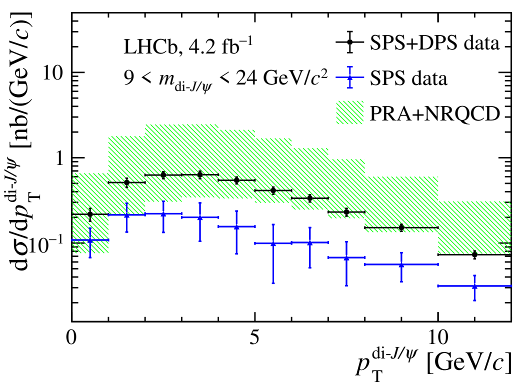
$$\sigma_{\text{eff}} = 13.1 \pm 1.8(\text{stat}) \pm 2.3(\text{syst})\ \text{mb}$$

[PoS (LHCP2020) 172; arXiv: 2009.12555]

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

[JHEP 03 (2024) 088]





- ➢ 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]
- ➢ PRA+NRQCD overestimates SPS data at low mass and high p_T

[PRL 123 (2019) 162002]

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

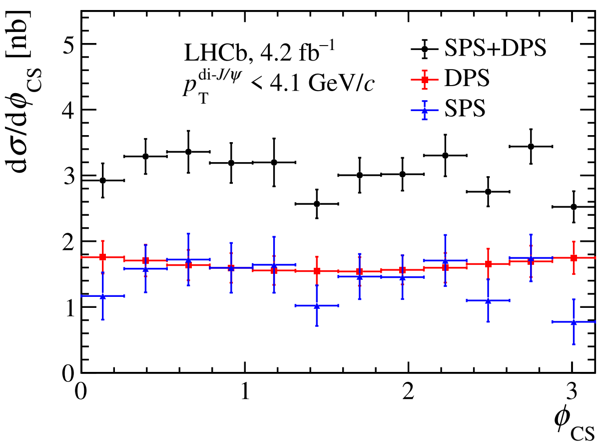
Gluon TMD PDFs study

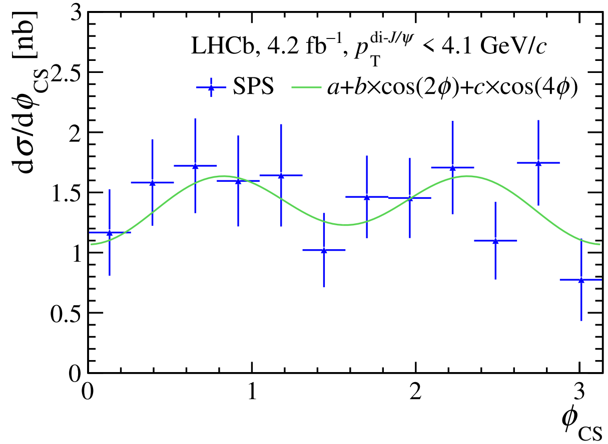
[JHEP 03 (2024) 088]

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

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

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





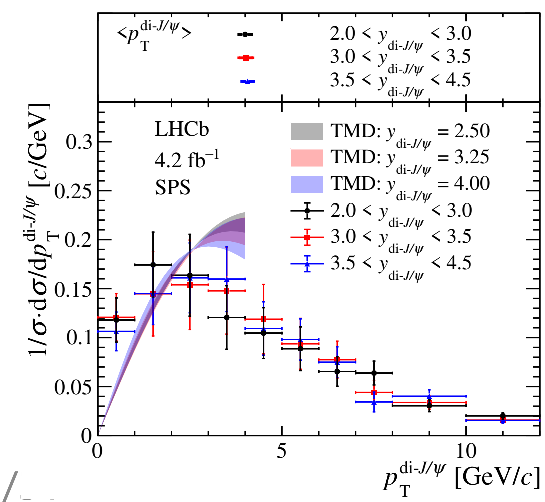
$\langle\cos(2\phi_{CS})\rangle = b/2a$
$= -0.029 \pm 0.050 \pm 0.009$

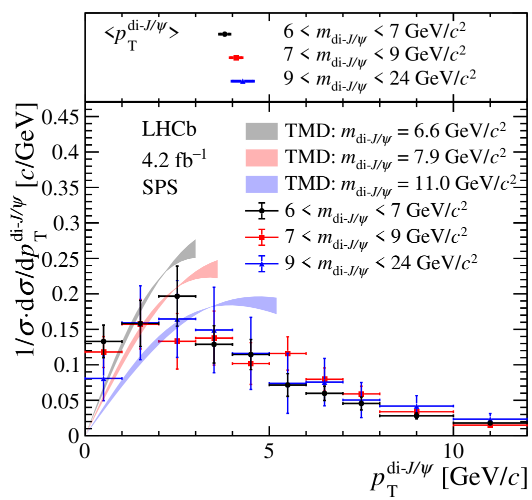
$\langle\cos(4\phi_{CS})\rangle = c/2a$
$= -0.087 \pm 0.052 \pm 0.013$

- $f_1^g(x, \boldsymbol{k}_T^2, \mu)$: 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

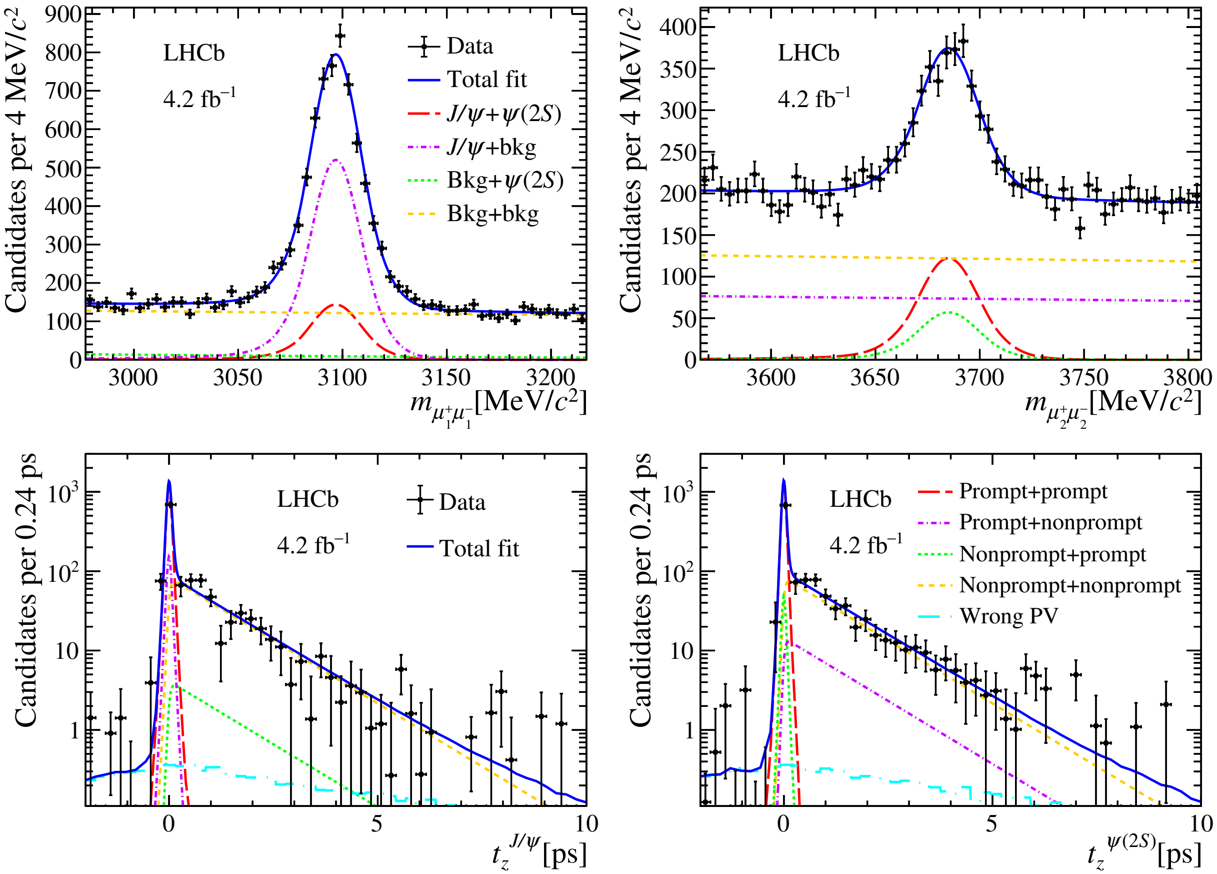


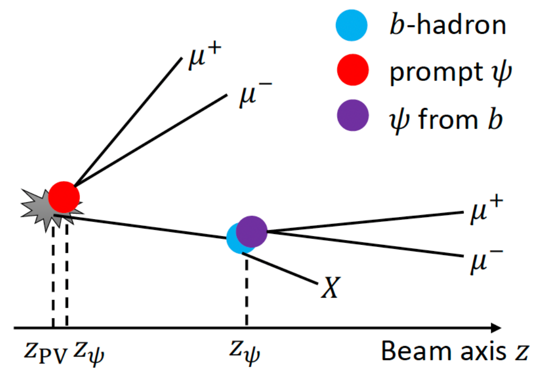


$J/\psi - \psi(2S)$ @ 13 TeV

[JHEP 05 (2024) 259]

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





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

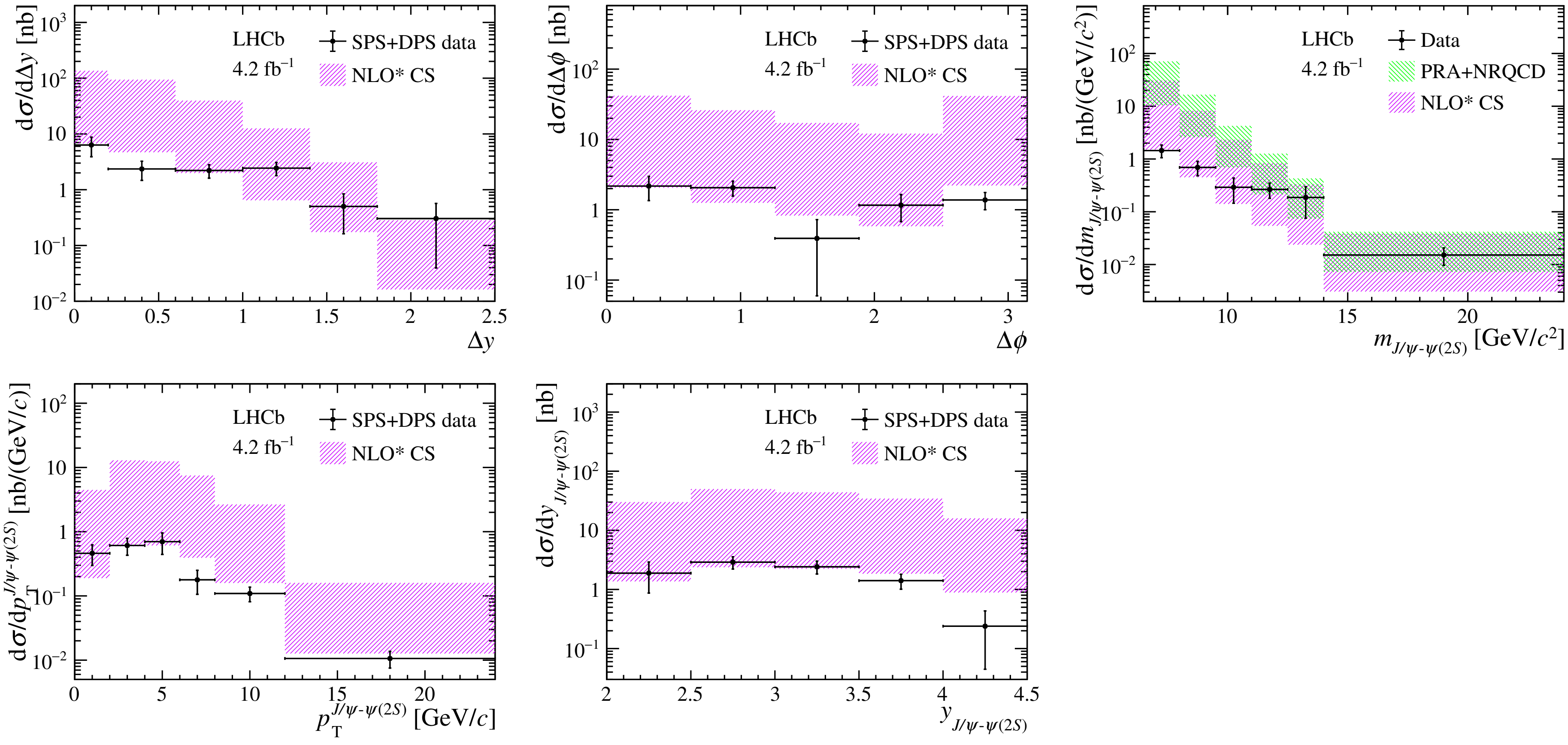
$$N\big(J/\psi - \psi(2S)\big)_{\mathrm{prompt}} = 629 \pm 50$$

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

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

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

[JHEP 05 (2024) 259]



- Results consistent with NLO* CS NRQCD calculations albeit DPS is not subtracted

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

- PRA+NRQCD overestimates SPS data at low mass

  [PRL 123 (2019) 162002]

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

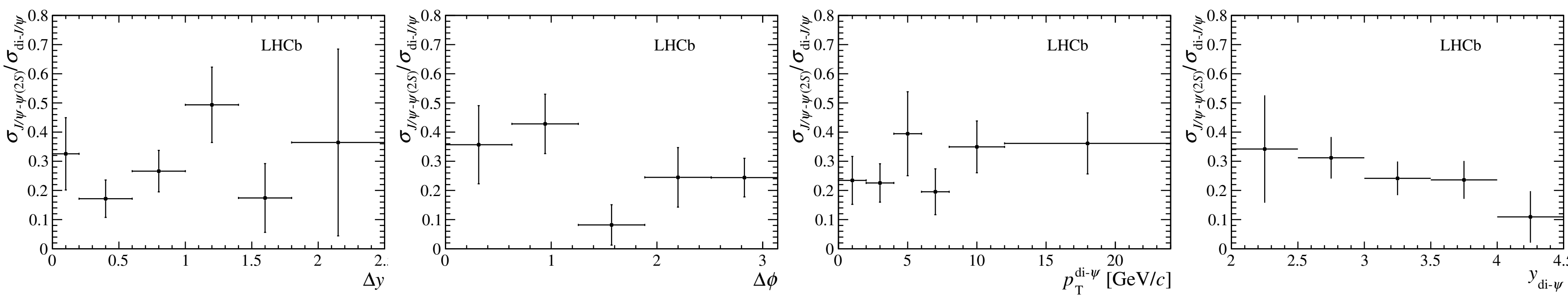
[JHEP 05 (2024) 259]

- 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]

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

⇒ 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

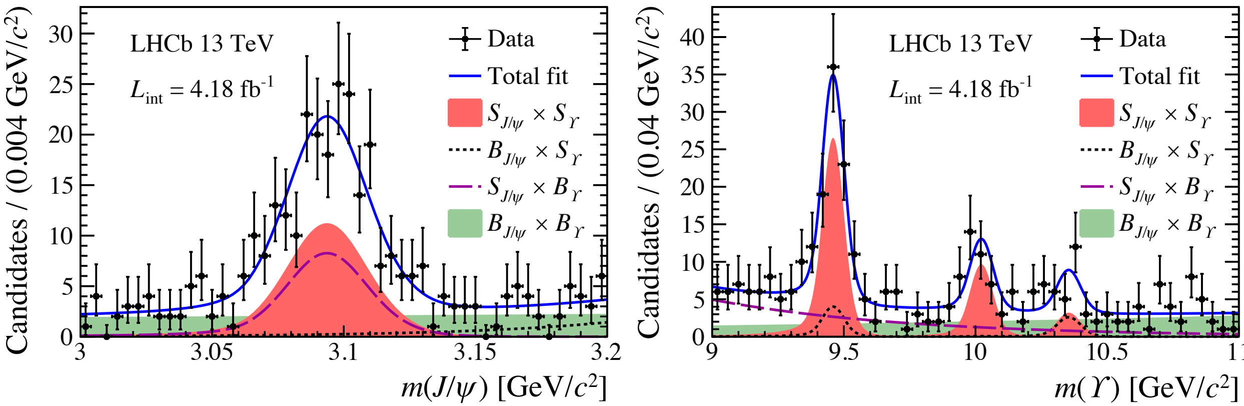
- Differential cross-section ratios are also measured, but more statistics needed



$J/\psi - \Upsilon$ production

[JHEP 08 (2023) 093]

- Fiducial region: $2 < y(J/\psi, \Upsilon) < 4.5$, $p_T(J/\psi) < 10$ GeV, $p_T(\Upsilon) < 30$ 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	$1.7\,\sigma$

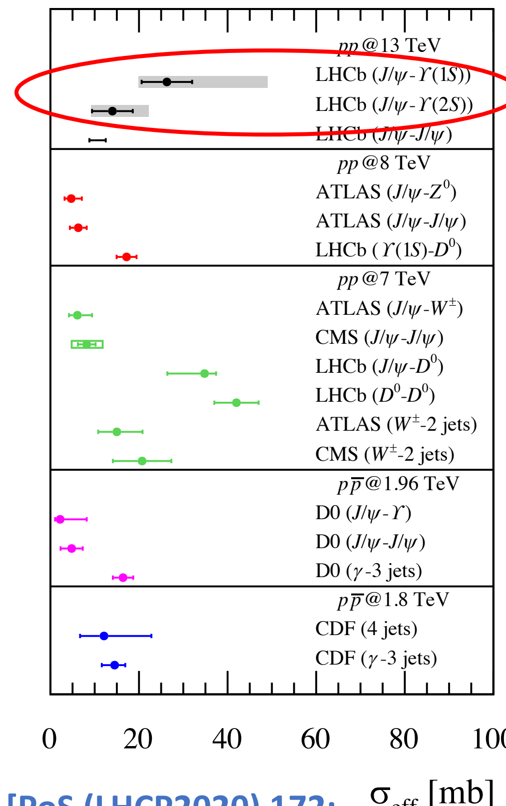
$$\sigma(J/\psi - \Upsilon(1S)) = 133 \pm 22(\text{stat}) \pm 7(\text{syst}) \pm 3(\mathcal{B})\ \text{pb}$$
$$\sigma(J/\psi - \Upsilon(2S)) = 76 \pm 21(\text{stat}) \pm 4(\text{syst}) \pm 7(\mathcal{B})\ \text{pb}$$

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

[PRL 117 (2016) 062001]

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

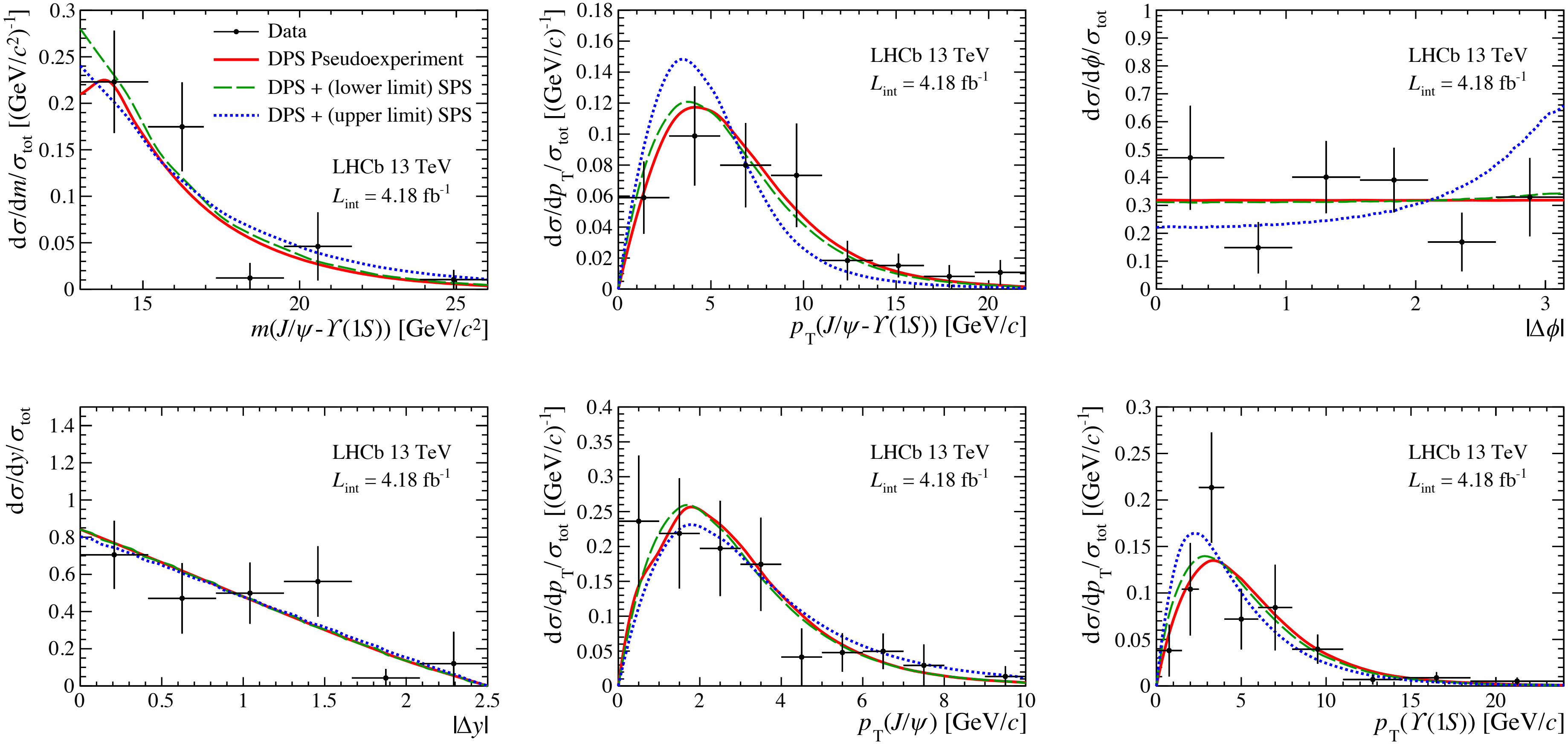
$$\sigma_{\text{eff}}(J/\psi - \Upsilon(1S)) = 26 \pm 5(\text{stat}) \pm 2(\text{syst})\ ^{+22}_{-3}(\text{th})\ \text{mb}$$
$$\sigma_{\text{eff}}(J/\psi - \Upsilon(2S)) = 14 \pm 5(\text{stat}) \pm 1(\text{syst})\ ^{+7}_{-1}(\text{th})\ \text{mb}$$



[PoS (LHCP2020) 172; arXiv: 2009.12555]

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

[JHEP 08 (2023) 093]



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

Where do we stand?

◆**Di-quarkonium production actively measured by the LHCb experiment**

✓di-J/ψ: 7&13 TeV

✓$J/\psi - \psi(2S)$: 13 TeV

✓$J/\psi - \Upsilon$: 13 TeV

◆**What we have learned on DPS?**

✓Similar-level σ_{eff}: a good starting point

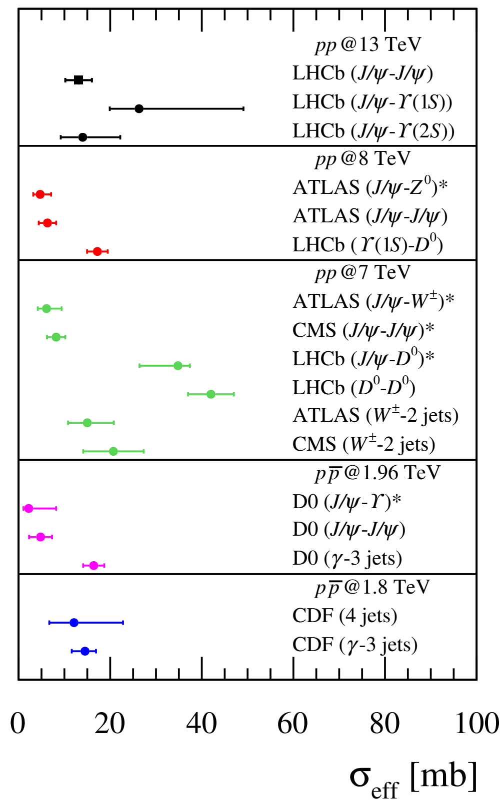
☐How to further investigate the discrepancies?

☐A unified way to separate SPS and DPS?

◆**What else we can learn from di-quarkonium prod.?**

✓gluon TMD

☐...

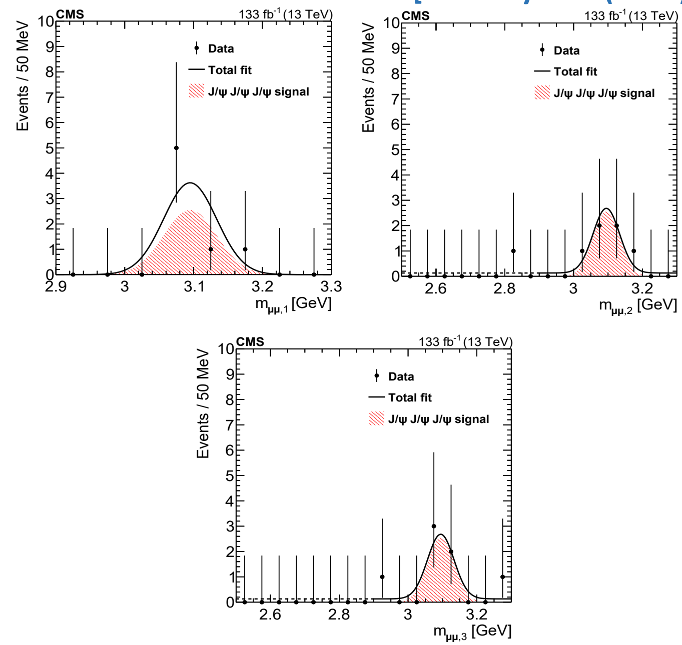


[PoS (LHCP2020) 172; arXiv: 2009.12555]

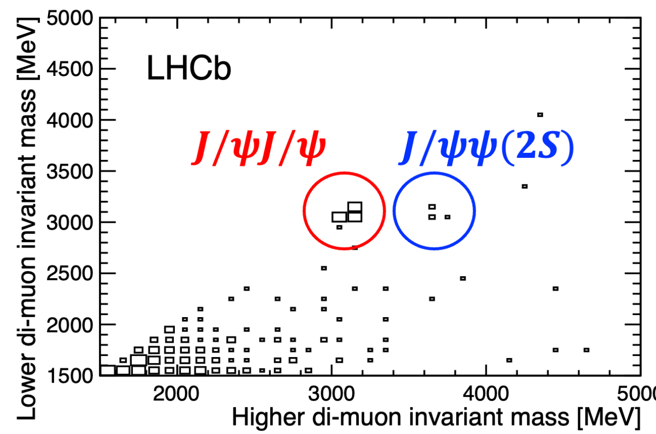
What we can further do?

*Tri-J/ψ at CMS

[Nat. Phys. 19 (2023) 338]



- **New di-quarkonium modes of interest?**
  - ✓ $J/\psi + \chi_c, J/\psi + \eta_c$ …
- **New observables?**
  - ✓ polarisation in associated production
- **DPS → TPS (Triple-parton scattering)**
  - ✓ triple charm
  - ✓ $J/\psi + \Upsilon + \phi$
- **Quarkonium associated with others?**
  - ✓ quarkonium + W, Z (info beyond DPS?)
  - ✓ quarkonium + γ
- **Di-quarkonium in exclusive production?**

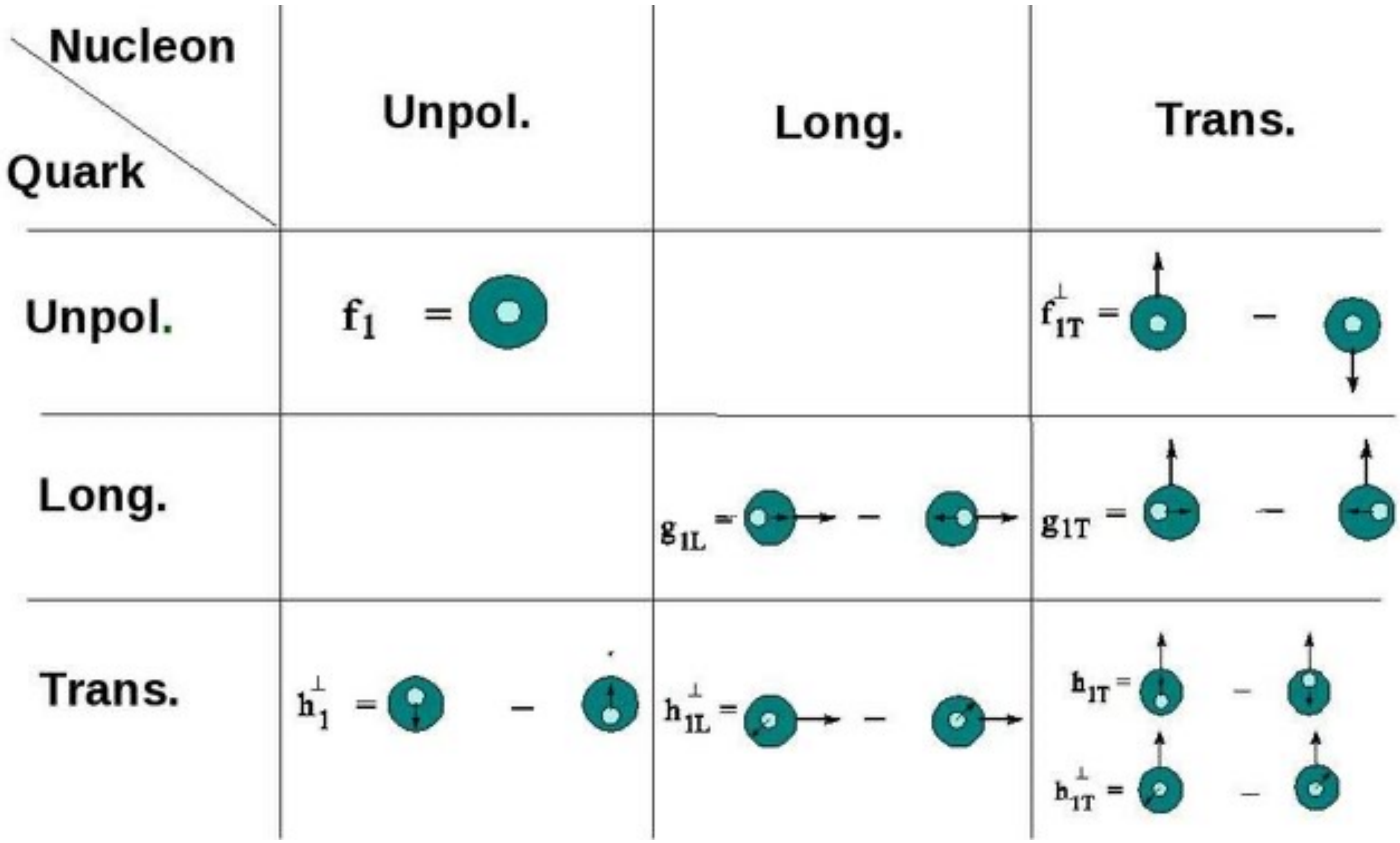


[J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002]

Back up

Leading twist TMD PDFs

[PR12-09-014]



Sketch of CS frame