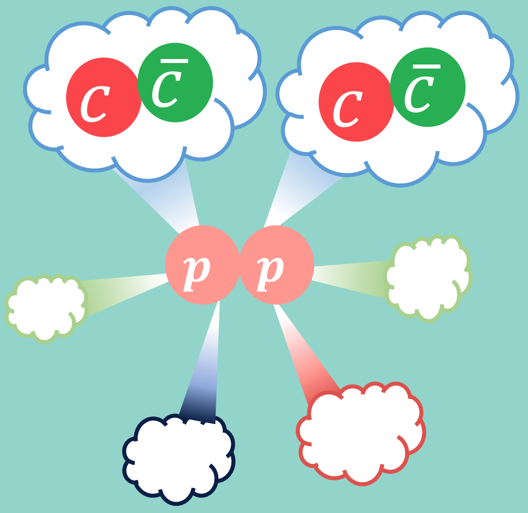
Experimental results on double J/ψ hadro-production



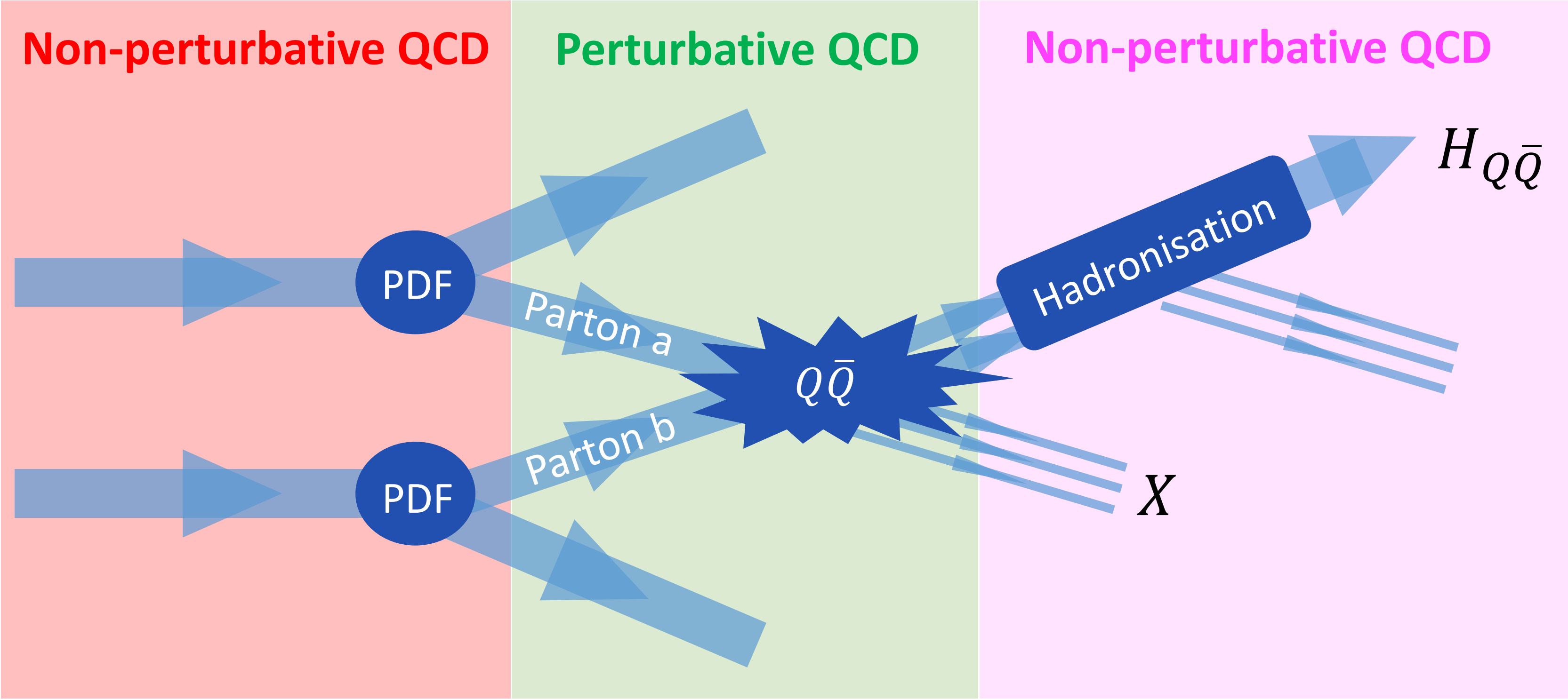
Liupan An

Peking University

Synergies between LHC and EIC for quarkonium physics @ ECT, 9 July 2024

Quarkonium production mechanism

- ***Heavy quarkonium***: ideal system to study hadronization mechanism
- Non-relativistic QCD (NRQCD) provides the most successful description
- Yet not able to coherently describe prod.&pol. measurements in all collision systems

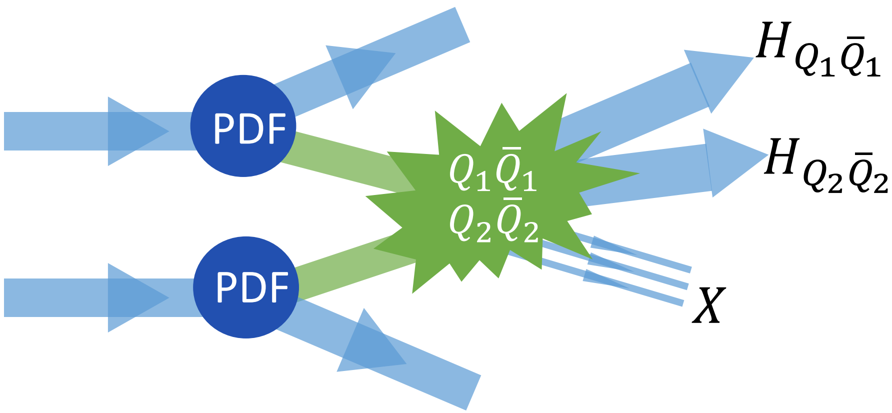


$$\sigma(H_{Q\bar{Q}}) = \sum_{a,b,n} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{a/p}(x_1) f_{b/p}(x_2) |\mathcal{A}(ab \to Q\bar{Q}[n] + X)|^2 \times \langle \mathcal{O}^H(n) \rangle$$

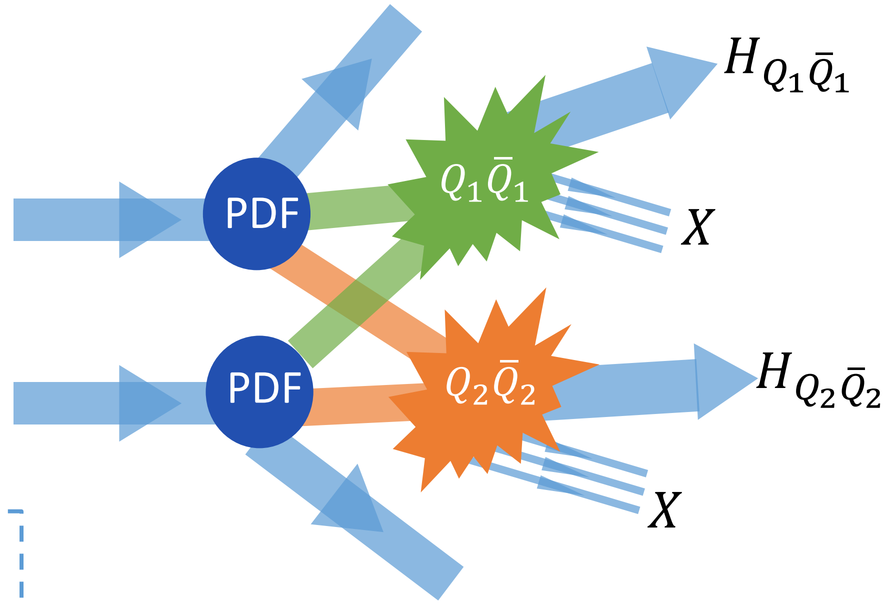
LDMEs: extracted from measurements & process independent

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

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

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

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

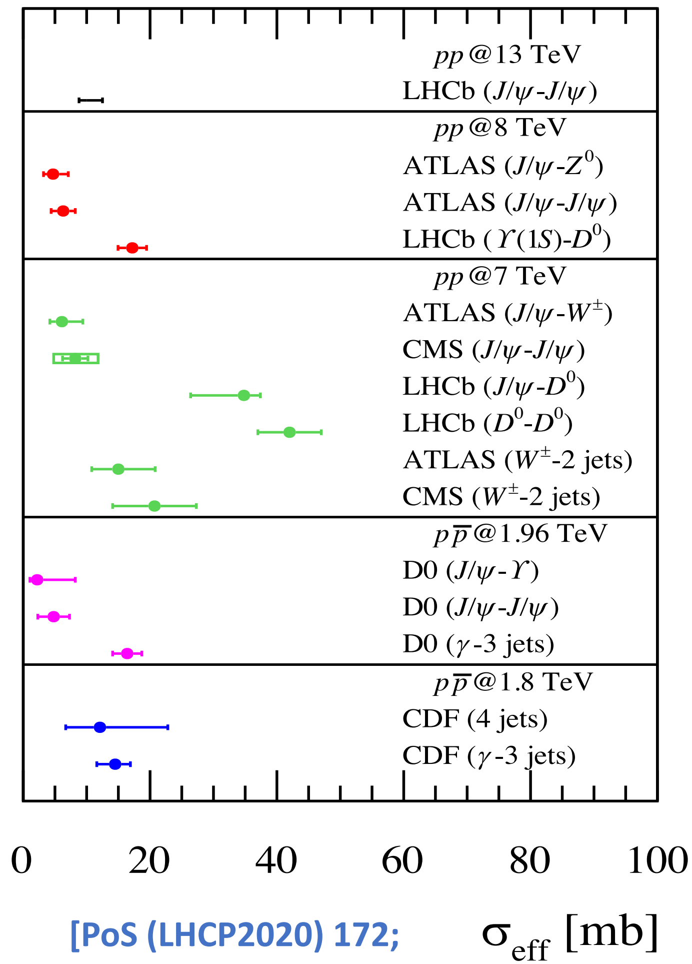
$$D_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2), T_{ij}(\boldsymbol{b}_1, \boldsymbol{b}_2) = T_i(\boldsymbol{b}_1) T_j(\boldsymbol{b}_2)$$

$\Rightarrow$

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

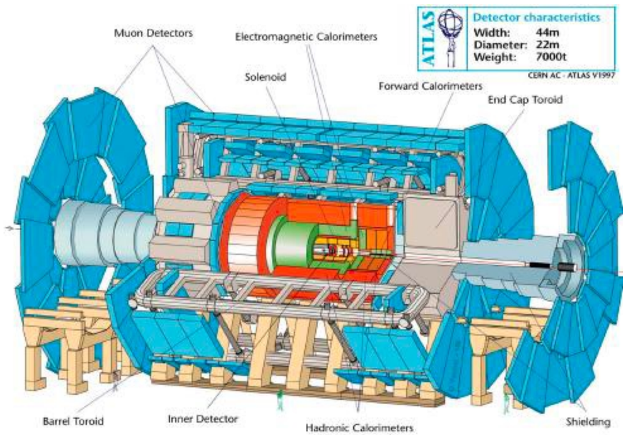
$$\sigma_{\mathrm{eff}} = 1 / \left[\int d^2\boldsymbol{b} F(\boldsymbol{b})^2 \right], F(\boldsymbol{b}) = \int T(\boldsymbol{b}_i) T(\boldsymbol{b}_i - \boldsymbol{b}) d^2\boldsymbol{b}_i$$

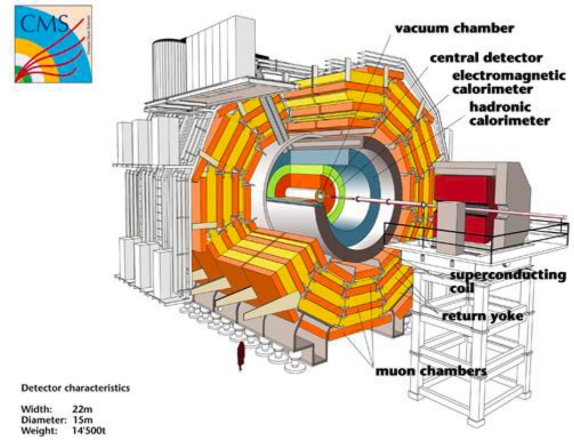
expected to be universal under the given assumptions

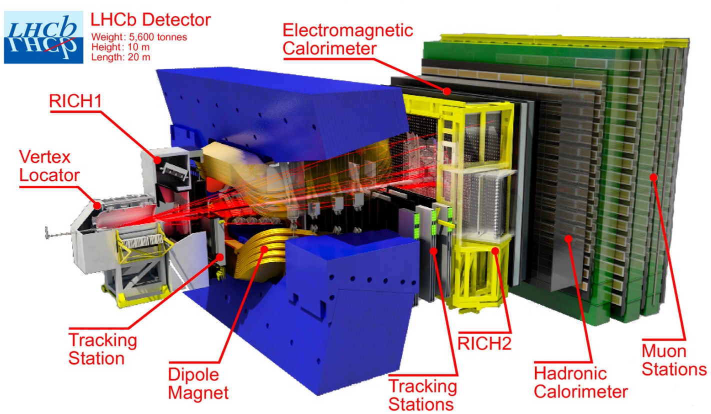


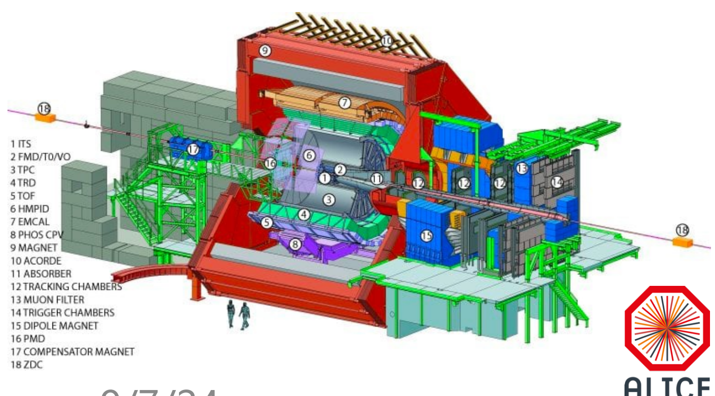
[PoS (LHCP2020) 172; arXiv: 2009.12555]

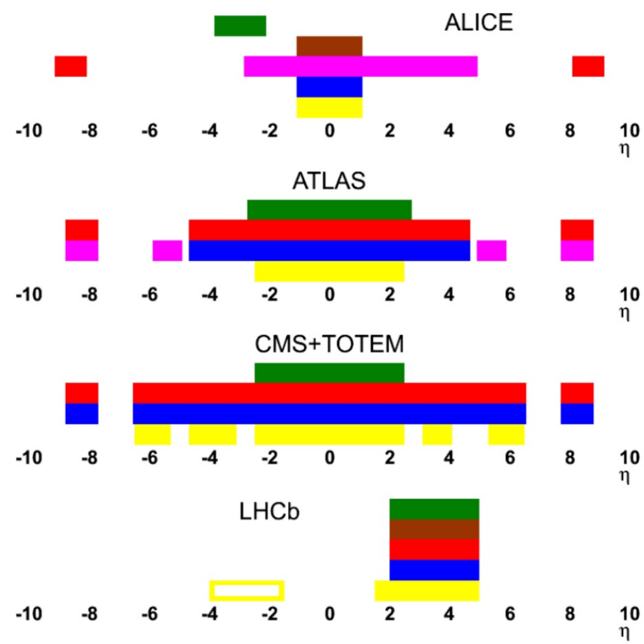
LHC experiments



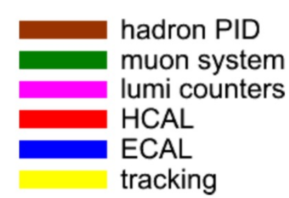






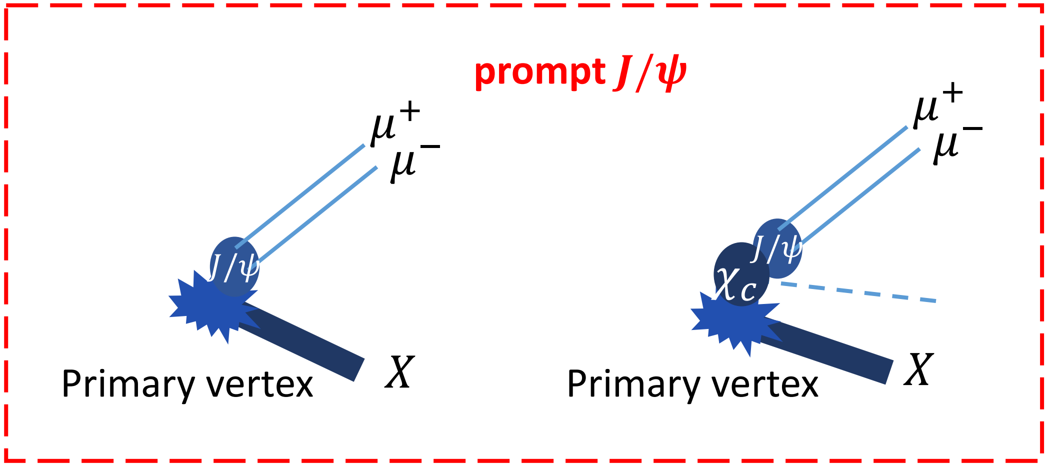


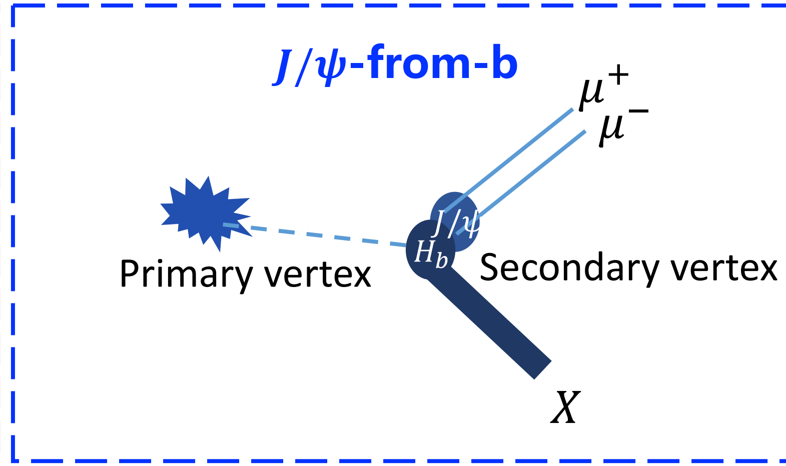
- ✓**ATLAS & CMS**
  - → central
  - → muon mode
- ✓**LHCb**
  - → forward
  - → excellent PID
- ✓**ALICE**
  - → central+forward muon coverage

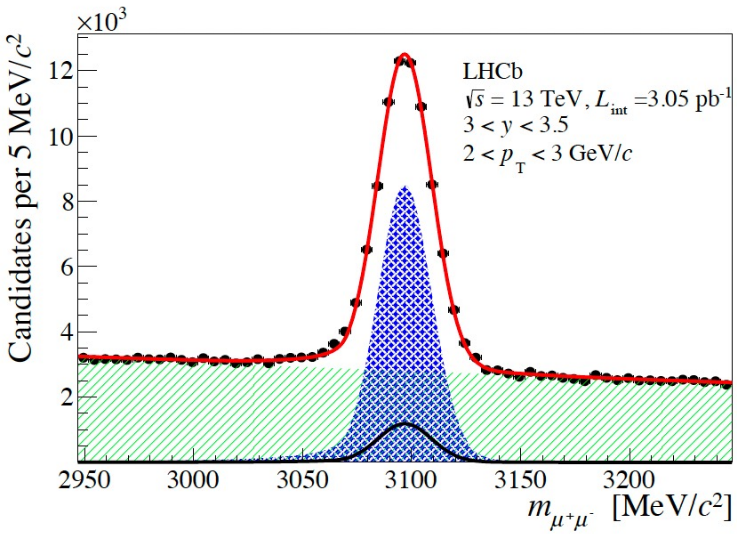


Analysis strategy

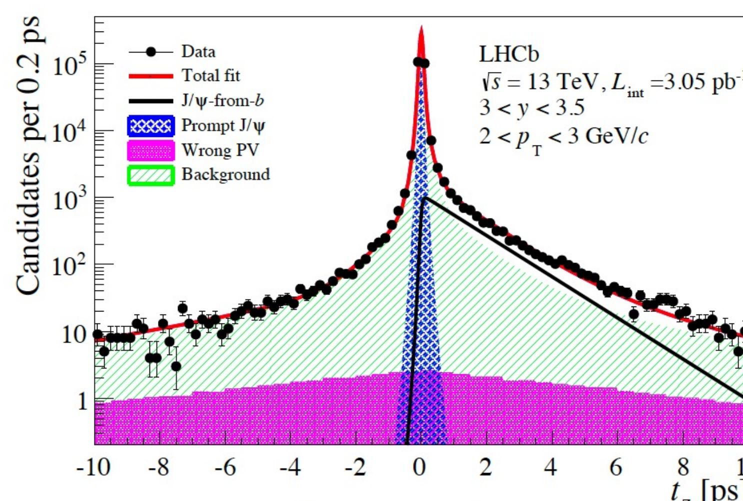
$$\frac{d\sigma}{d\text{v}} = \frac{\boldsymbol{N}}{\mathcal{L}\times\varepsilon\times\mathcal{B}(J/\psi \to \mu^+\mu^-)\times\Delta\text{v}}$$







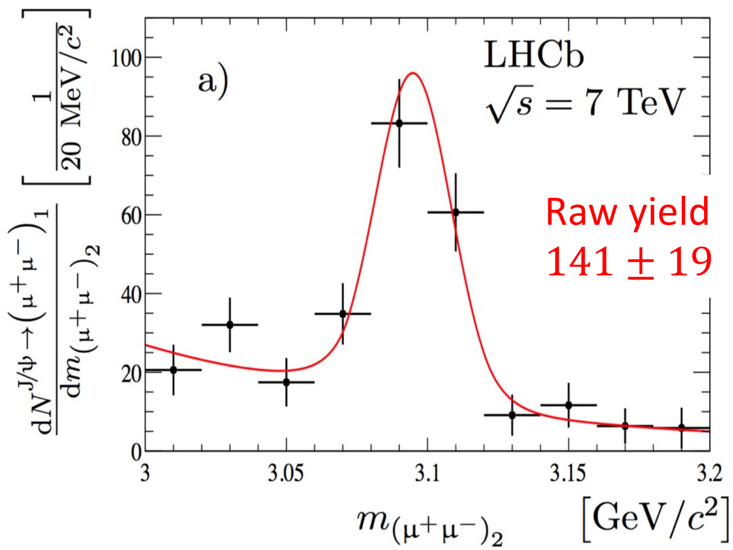
[JHEP 10 (2015) 172]

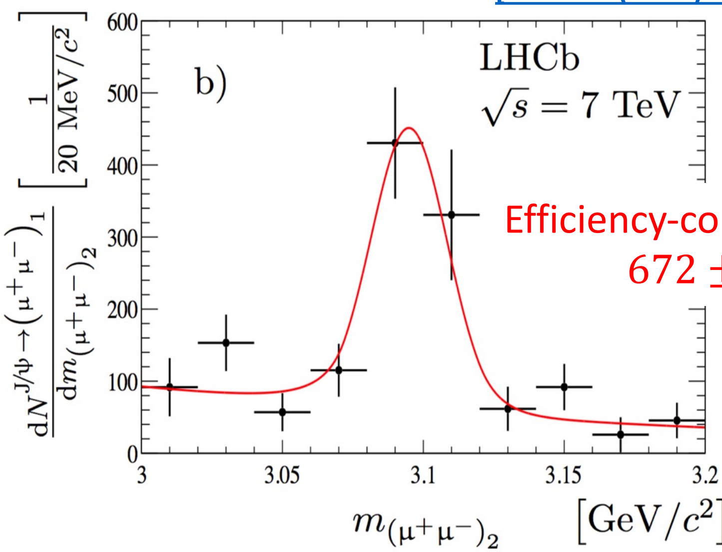


$$t_z = \frac{(z_{J/\psi} - z_{\mathrm{PV}}) \times M_{J/\psi}}{p_z}$$

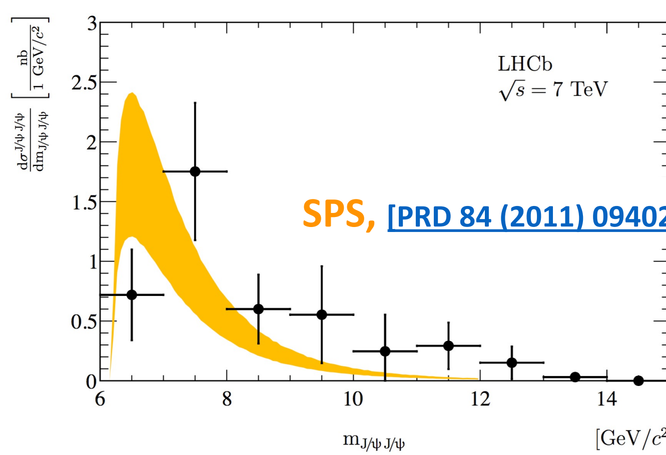
di-J/ψ @ 7 TeV

- Using 37.5 pb^{-1} data at $\sqrt{s} = 7$ TeV
- Fiducial region: $2 < y^{J/\psi} < 4.5$, $p_{\rm T}^{J/\psi} < 10$ GeV/c
- Observed with significance $> 6\sigma$ (from-b contribution negligible) [PLB 707 (2012) 52-59]





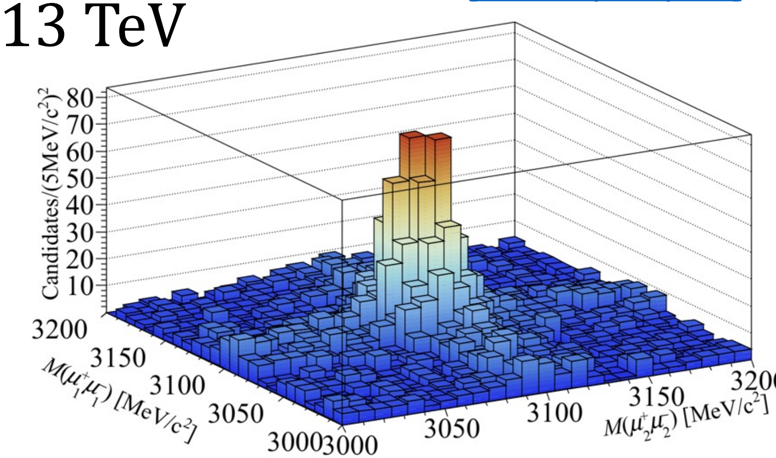
- $\sigma^{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1$ nb
  - ✓ $\sigma_{\rm SPS} = 4.1 \pm 1.2$ nb
  - ✓ $\sigma_{\rm DPS} \approx 2.5$ nb
- Not enough events to disentangle SPS and DPS contributions

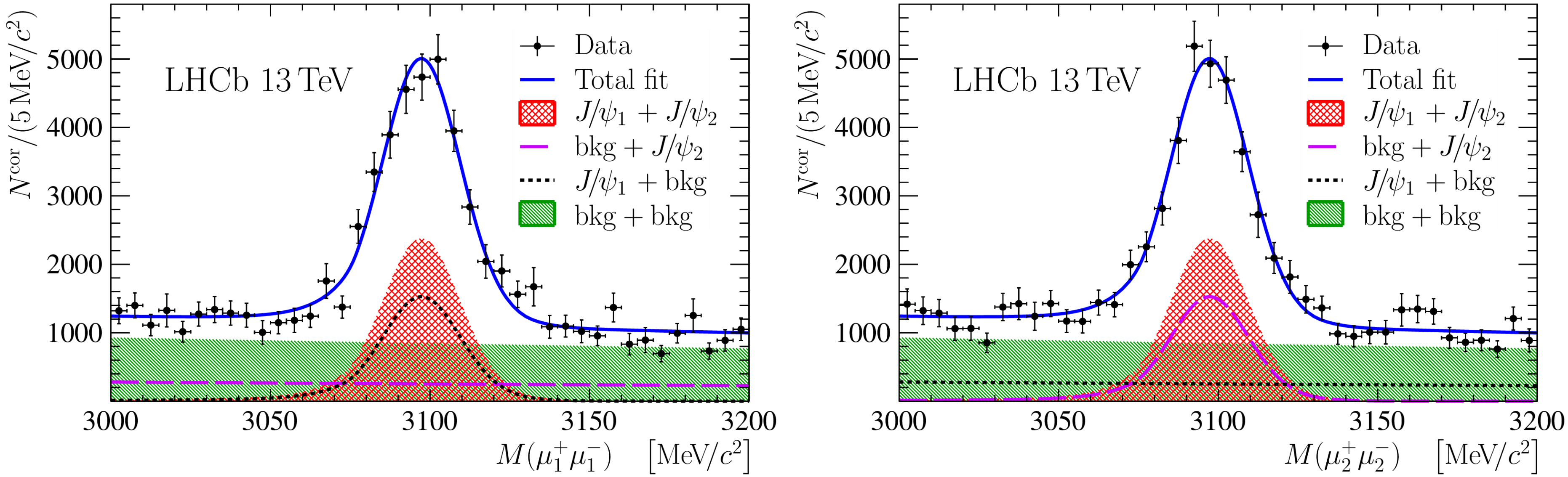


di-J/ψ @ 13 TeV

[JHEP 06 (2017) 047]

- $\mathcal{L} = 279\ \text{pb}^{-1}$, pp collisions @ $\sqrt{s} = 13$ TeV
- Kinematic range of J/ψ:
  $p_{\text{T}} < 10\ \text{GeV}/c$ 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 $\sigma(\text{prompt}\ J/\psi)$





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

Comparison to theory

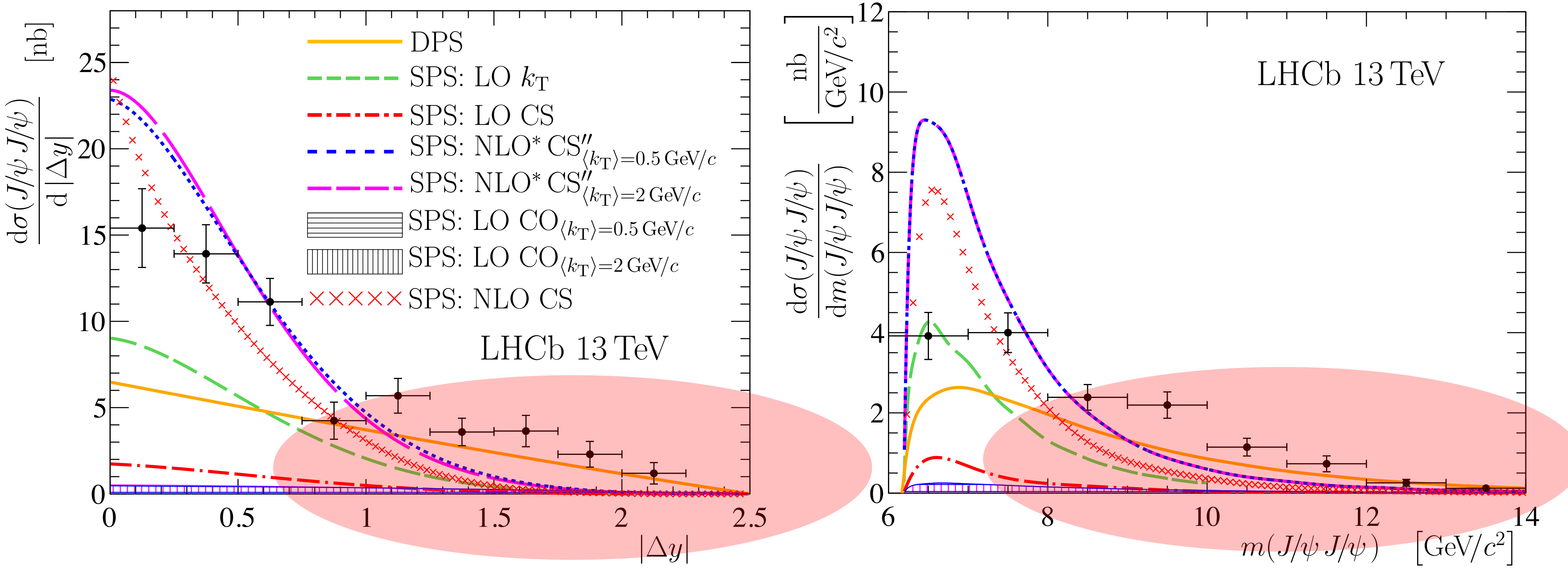
	$\sigma(J/\psi\, J/\psi)$ [nb] [JHEP 06 (2017) 047]		
	no p_{T} cut	$p_{\mathrm{T}} > 1\,\mathrm{GeV}/c$	$p_{\mathrm{T}} > 3\,\mathrm{GeV}/c$
SPS: LO Colour-singlet	$1.3 \pm 0.1^{+3.2}_{-0.1}$	—	—
SPS: LO Colour-octet	$0.45 \pm 0.09^{+1.42+0.25}_{-0.36-0.34}$	—	—
SPS: LO k_{T}	$6.3^{+3.8+3.8}_{-1.6-2.6}$	$5.7^{+3.4+3.2}_{-1.5-2.1}$	$2.7^{+1.6+1.6}_{-0.7-1.0}$
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 $m(J/\psi J/\psi)$



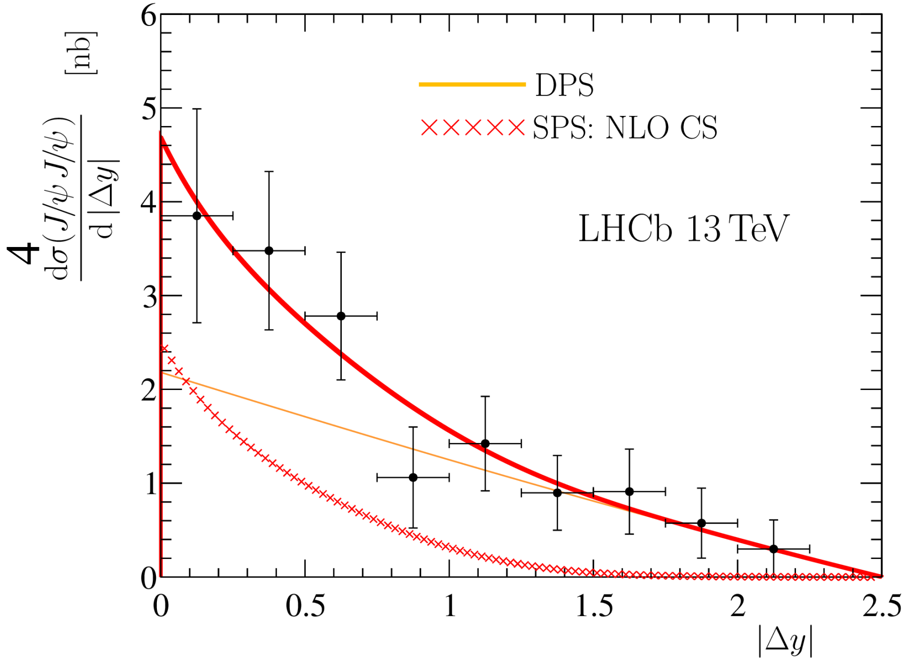
[JHEP 06 (2017) 047]

DPS extraction

[JHEP 06 (2017) 047]

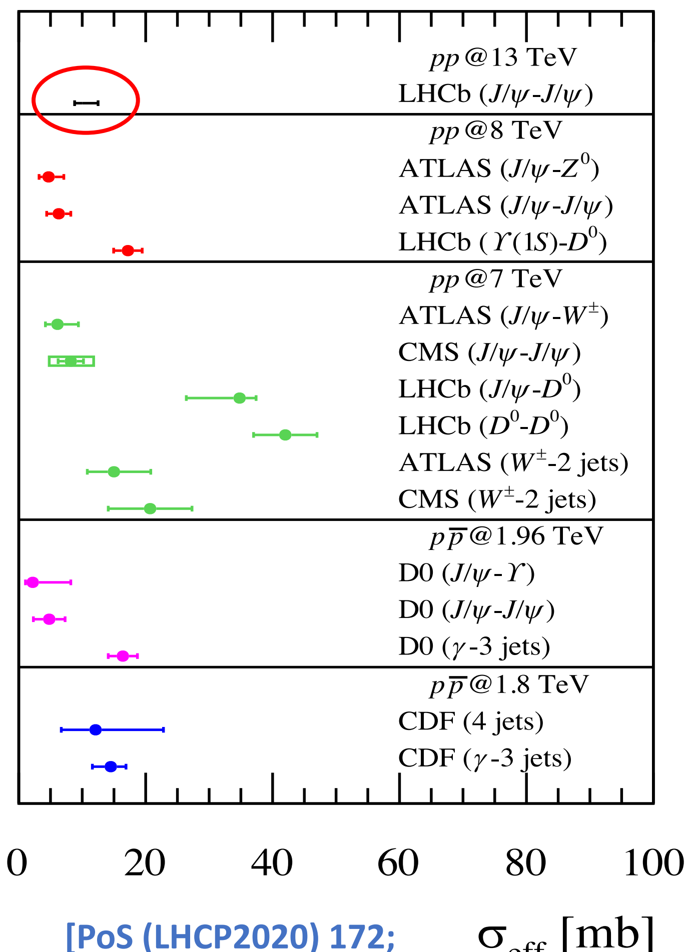
- Template DPS+SPS fits performed for different variables using various models

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



Variable	LO k_T	NLO* CS″ $\langle k_T\rangle = 2$ GeV/c	NLO* CS″ $\langle k_T\rangle = 0.5$ 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
$\|\Delta y\|$	12.5 ± 4.1	12.2 ± 3.7	12.4 ± 3.9	11.2 ± 2.9

σ_{eff}: 8.8~12.5 mb

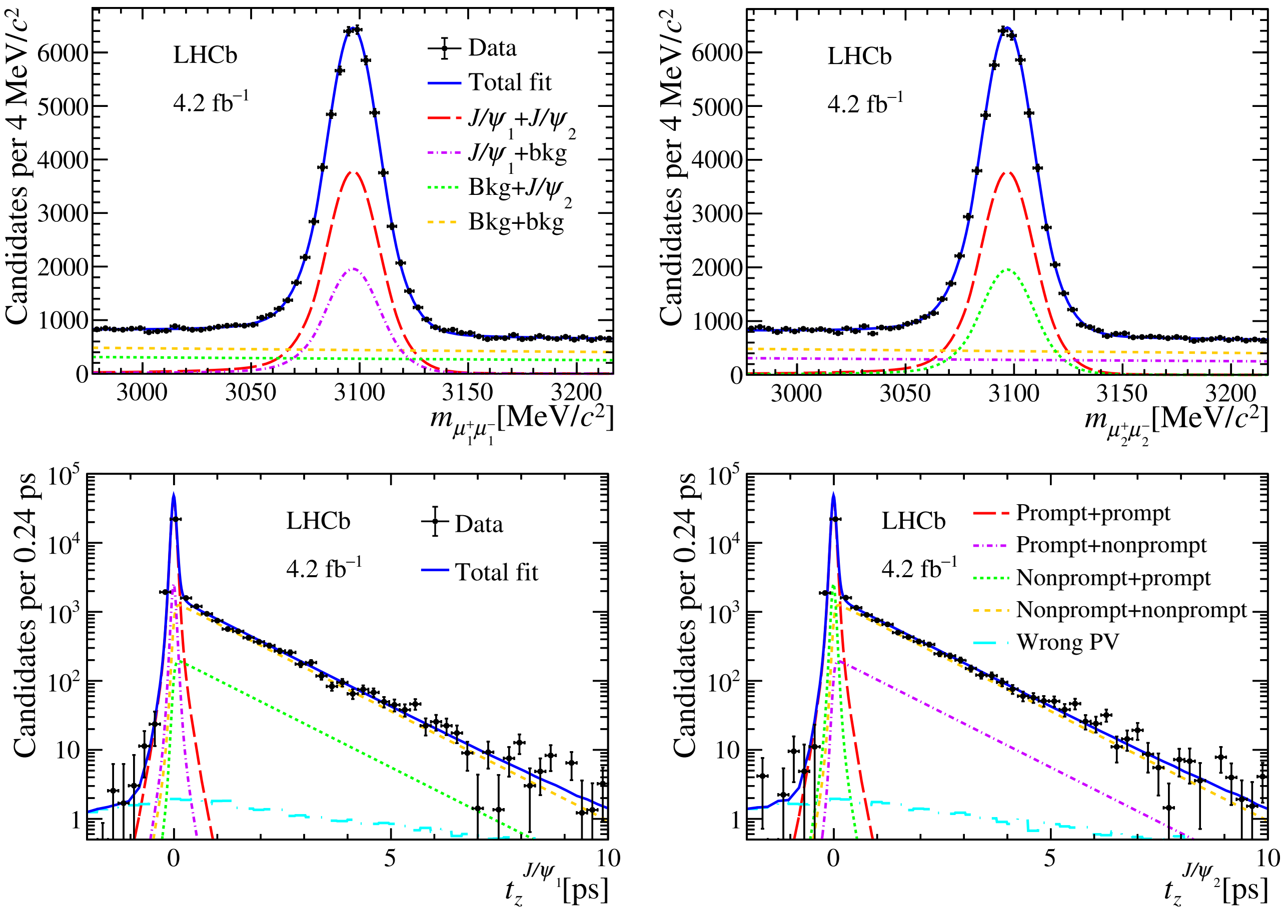


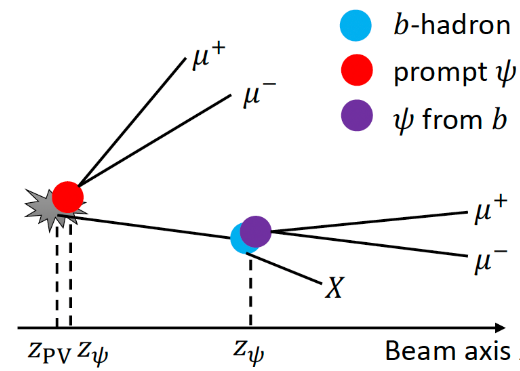
[PoS (LHCP2020) 172; arXiv: 2009.12555]

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





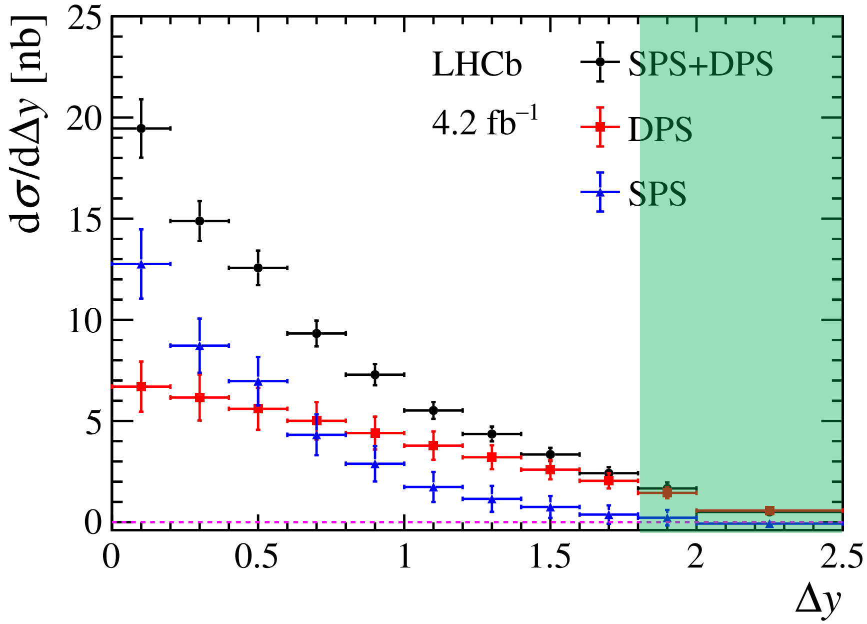
$$t_z = \frac{z_\psi - z_{\rm PV}}{p_z/m_\psi}$$

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

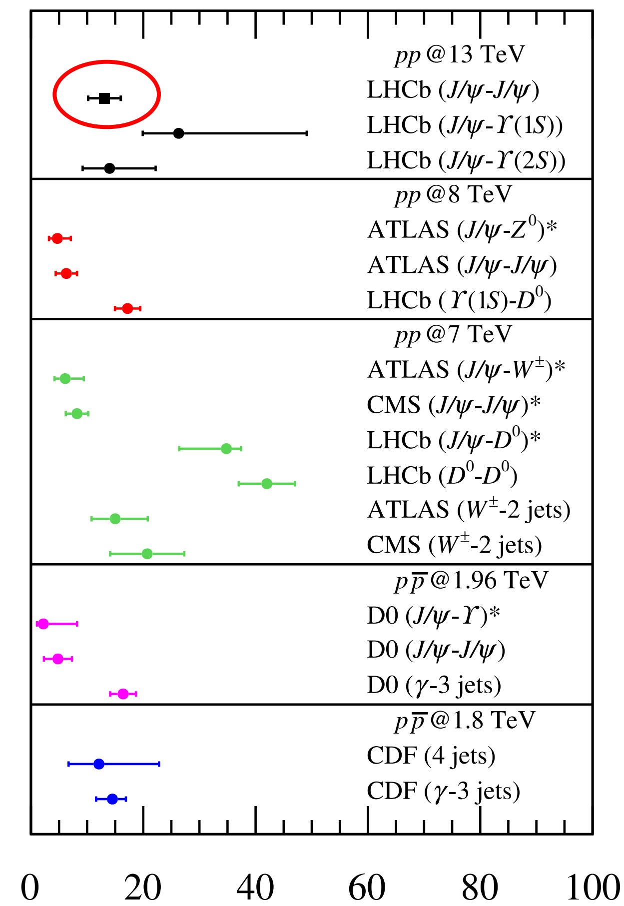
$$\sigma(J/\psi - J/\psi) = 16.36 \pm 0.28(\mathrm{stat}) \pm 0.88(\mathrm{syst})\ \mathrm{nb}$$

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



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

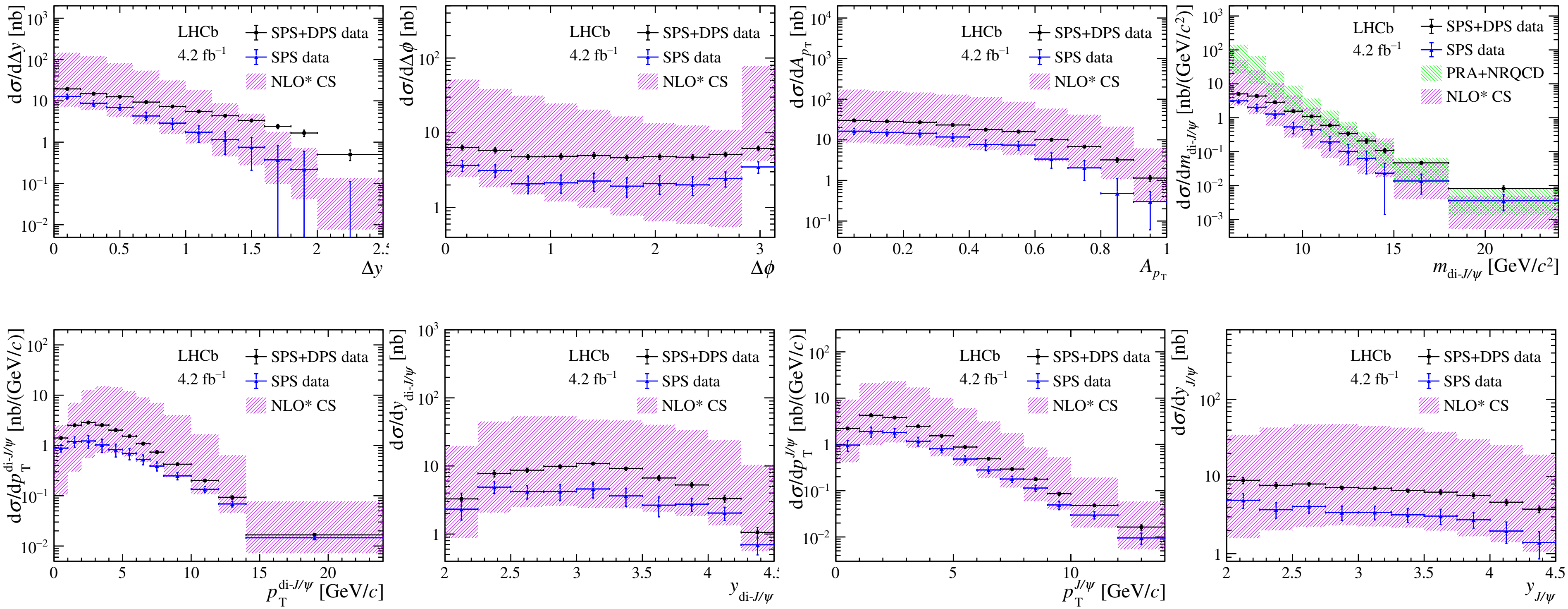
$$\sigma(J/\psi - J/\psi)_{\text{SPS}} = 7.9 \pm 1.2(\text{stat}) \pm 1.1(\text{syst})\ \text{nb}$$

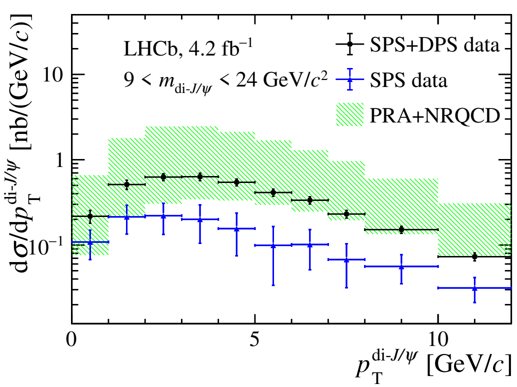
$$\sigma_{\text{eff}} = 13.1 \pm 1.8(\text{stat}) \pm 2.3(\text{syst})\ \text{mb}$$

[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]

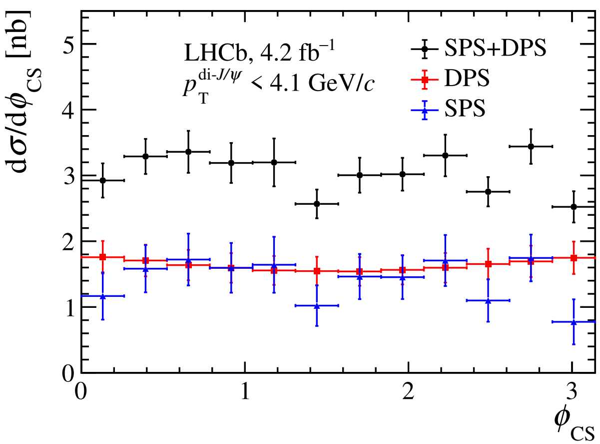
[Comput. Phys. Commun. 184 (2013) 2562] [Comput. Phys. Commun. 198 (2016) 238]

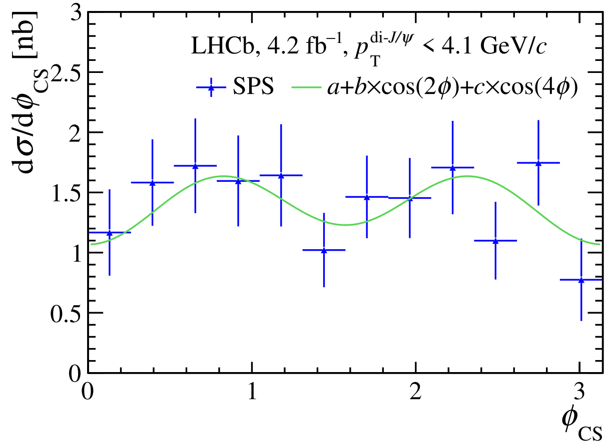
Gluon TMD PDFs study

[JHEP 03 (2024) 088]

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

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





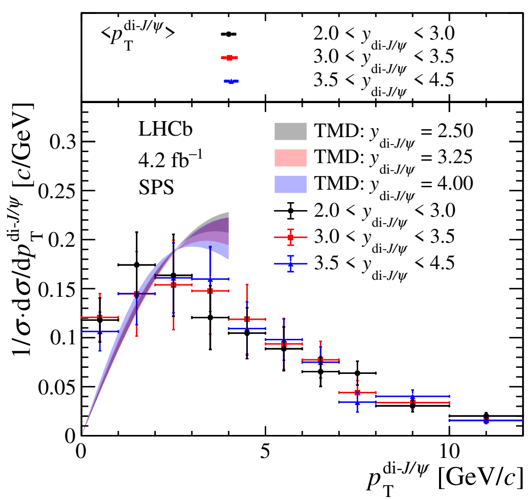
$\langle\cos(2\phi_\mathrm{CS})\rangle = b/2a$
$= -0.029 \pm 0.050 \pm 0.009$

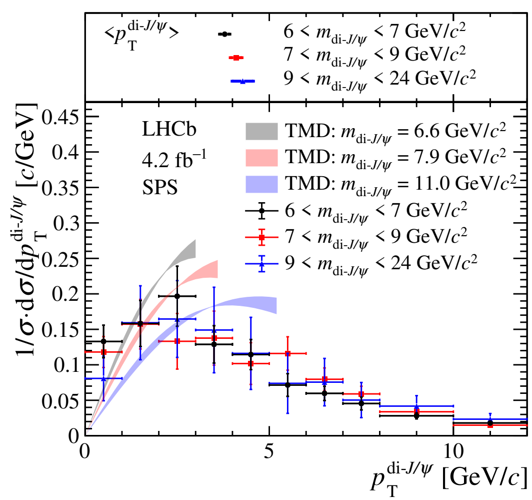
$\langle\cos(4\phi_\mathrm{CS})\rangle = c/2a$
$= -0.087 \pm 0.052 \pm 0.013$

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

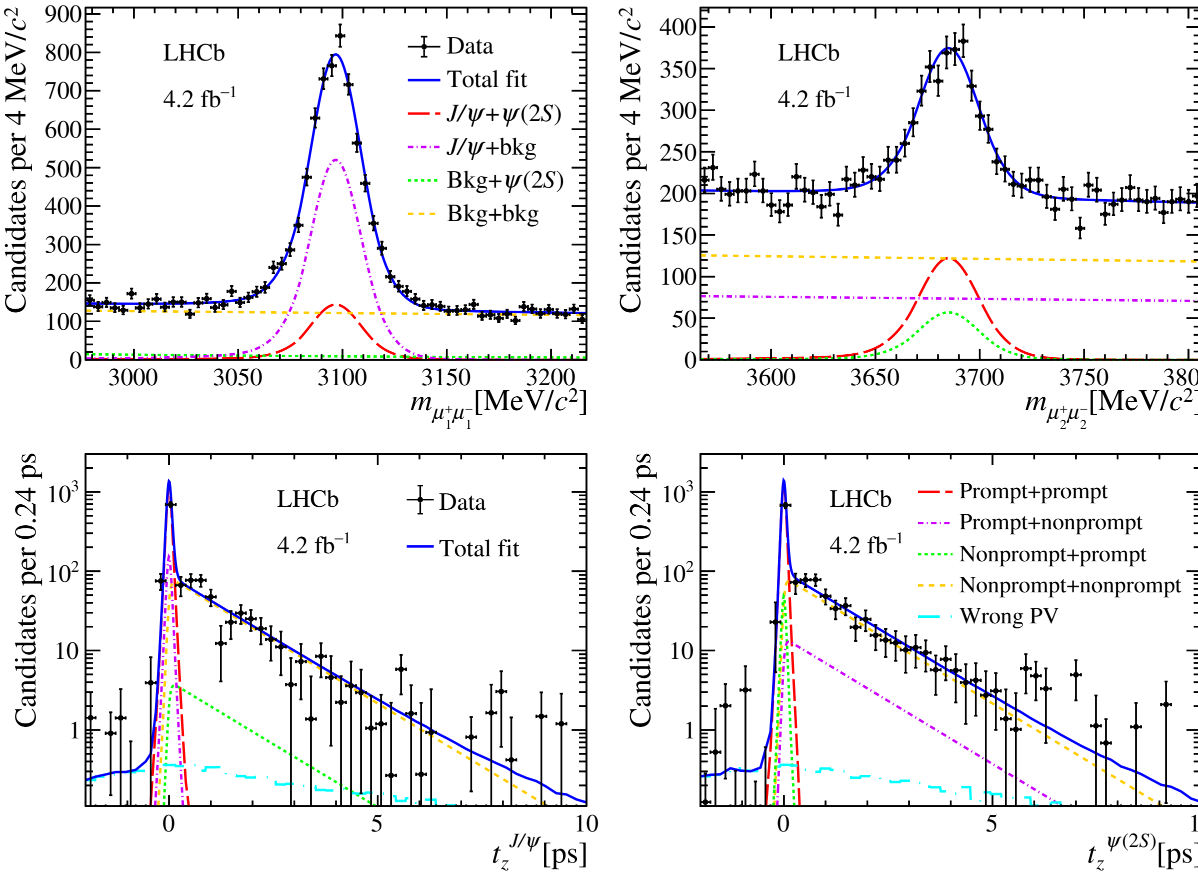


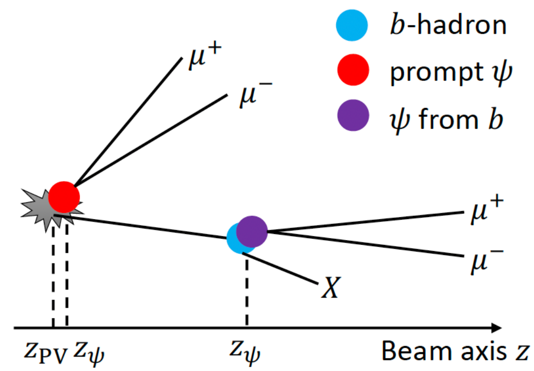


$J/\psi - \psi(2S)$ @ 13 TeV

[JHEP 05 (2024) 259]

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





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

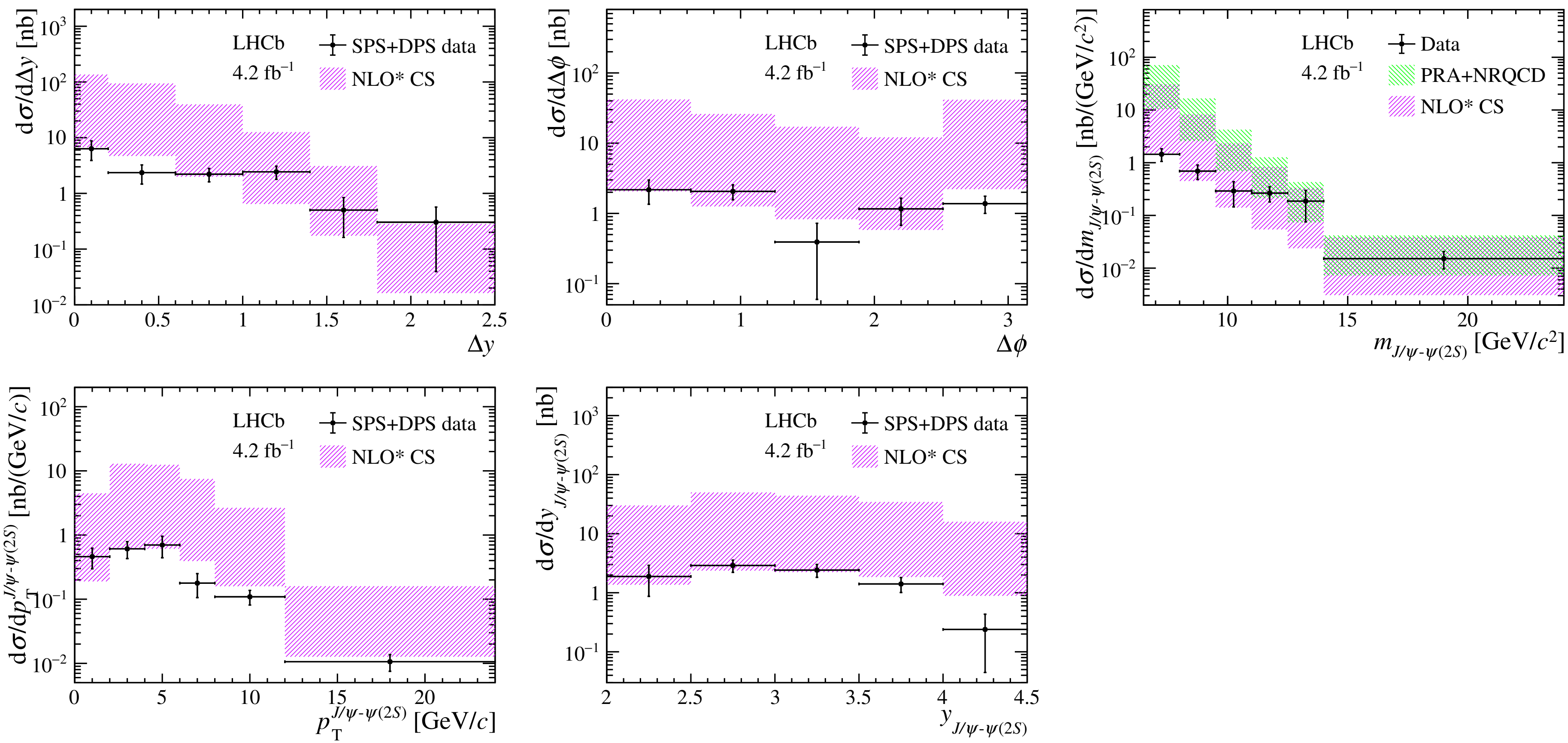
$$N\big(J/\psi - \psi(2S)\big)_{\mathrm{prompt}} = 629 \pm 50$$

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

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

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. $J/\psi - J/\psi$

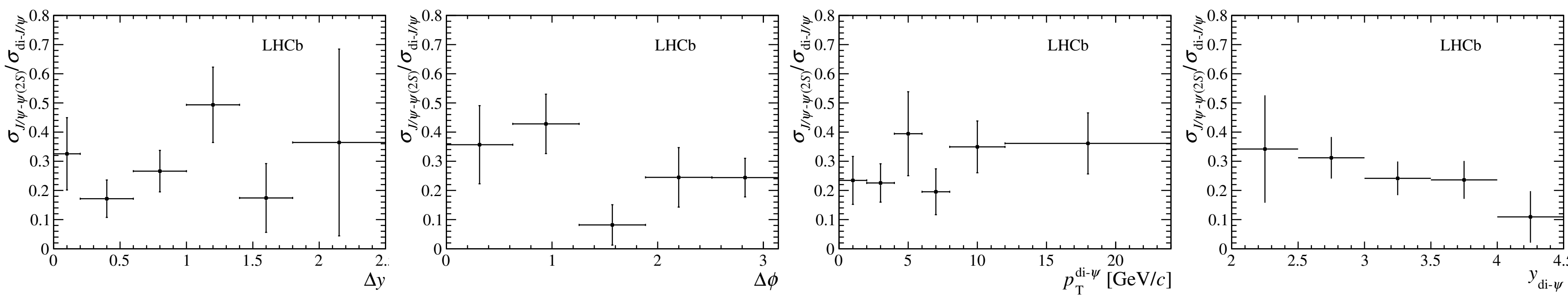
[JHEP 05 (2024) 259]

- 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]

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

⇒ 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

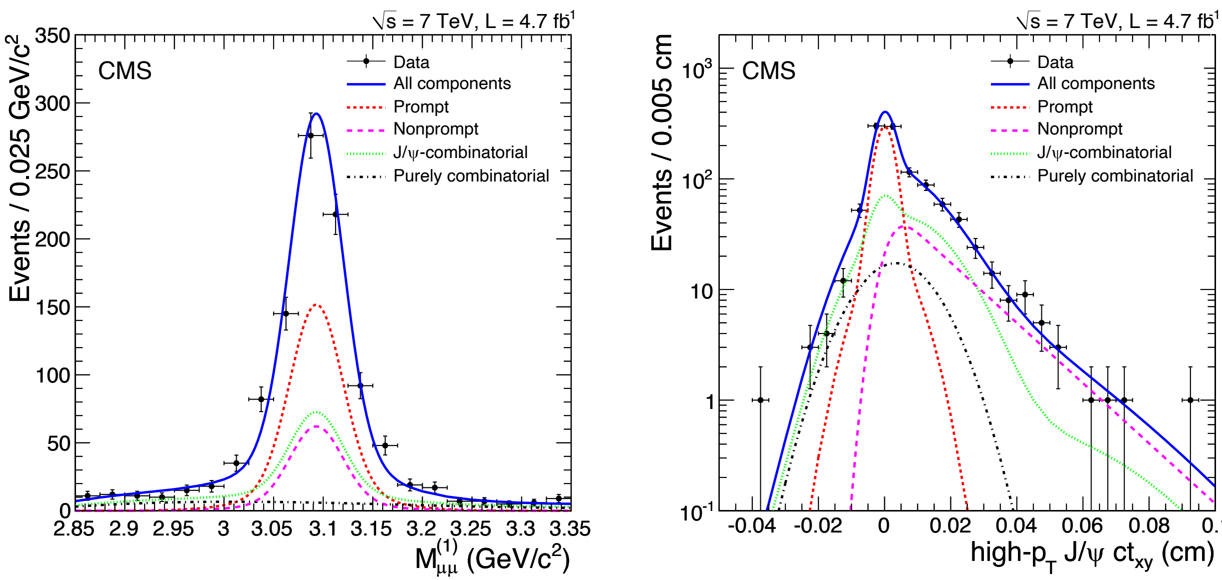
- Differential cross-section ratios are also measured, but more statistics needed



di-J/ψ @ 7 TeV

[JHEP 1409 (2014) 094]

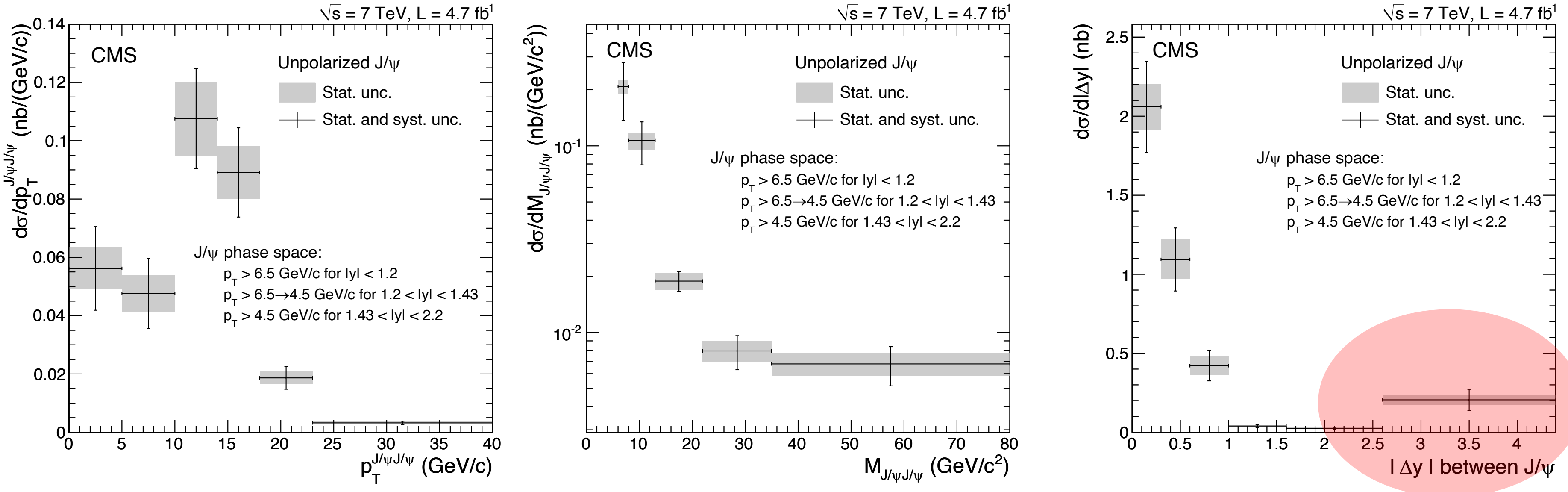
- $\mathcal{L} = 4.7\ \mathrm{fb}^{-1}$, pp collisions @ $\sqrt{s} = 7$ TeV
- Kinematic range of J/ψ:
  $p_{\mathrm{T}} > 6.5\ \mathrm{GeV}/c$ for $|y| < 1.2$;
  $p_{\mathrm{T}} > 6.5 - 4.5\ \mathrm{GeV}/c$ for $1.2 < |y| < 1.43$;
  $p_{\mathrm{T}} > 4.5\ \mathrm{GeV}/c$ for $1.43 < |y| < 2.2$
- Signal yield determination



- $\sigma(J/\psi J/\psi) = 1.49 \pm 0.07(\mathrm{stat}) \pm 0.13(\mathrm{syst})$ nb

Differential cross-sections

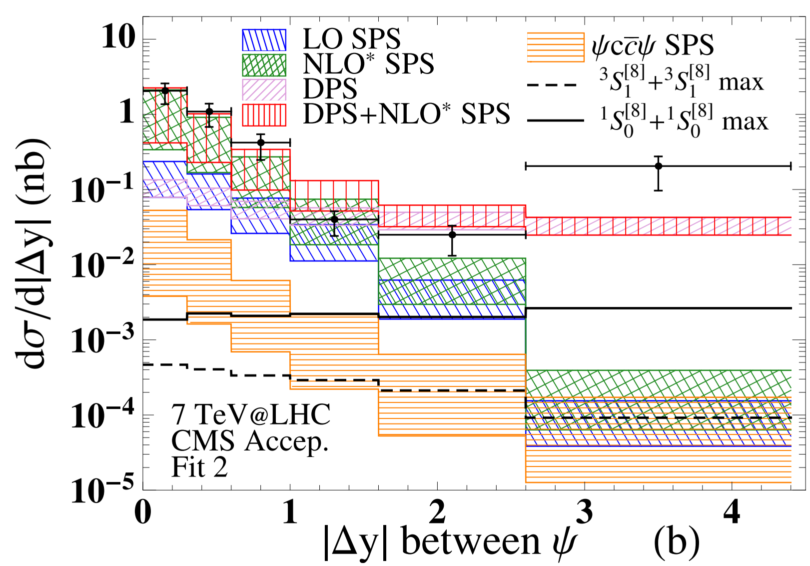
[JHEP 1409 (2014) 094]



➢ SPS and DPS contributions determined by performing SPS+DPS templated fits to these differential cross-sections:

$\sigma_{\text{eff}} = 8.2 \pm 2.0(\text{stat}) \pm 2.9(\text{syst})\ \text{mb}$

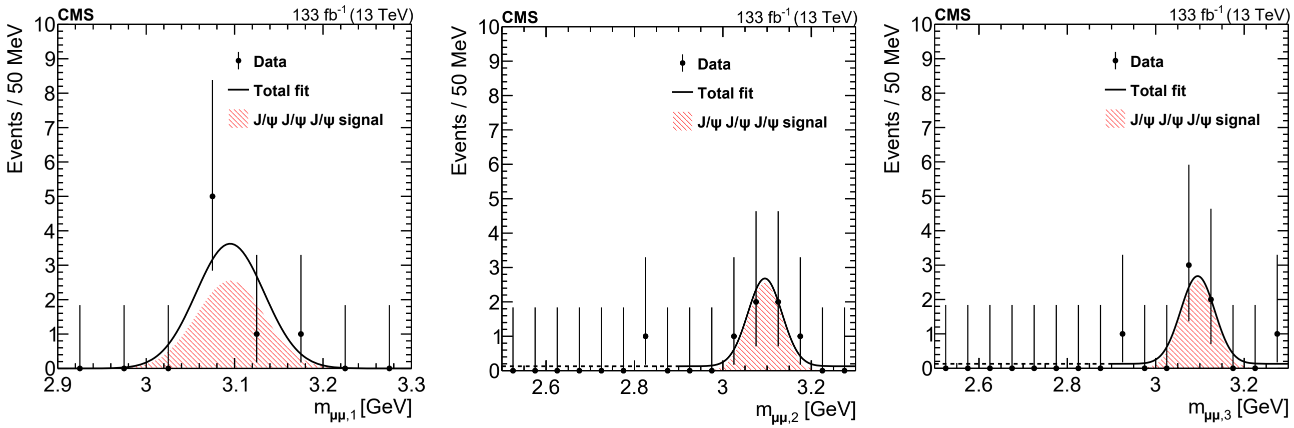
J. P. Lansberg, H. S. Shao: [PLB 751 (2015) 479]



tri-J/ψ @ 13 TeV

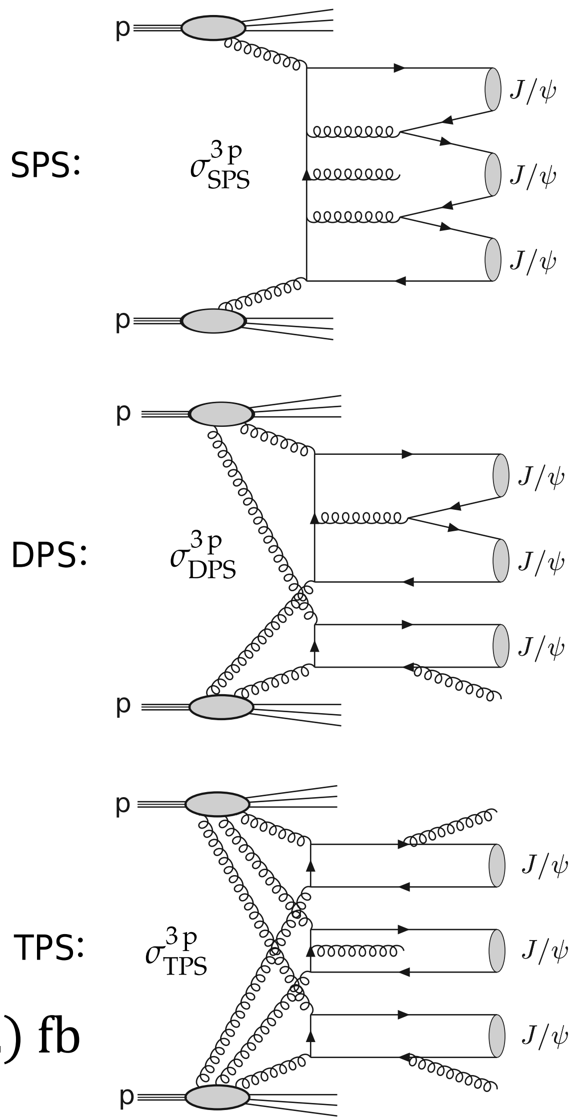
[Nat. Phys. 19 (2023) 338]

- First observation of triple J/ψ production



Decreasing p_T

Pure prompt production:



- 1 event → "3 non-prompt"
- 2 events → "2 non-prompt + 1 prompt"
- 1 event → "1 non-prompt + 2 prompt"
- 1 event → "3 prompt"

✓ Inclusive fiducial cross-section

$$\sigma(pp \to J/\psi J/\psi J/\psi + X) = 272^{+141}_{-104}\ (\text{stat.}) \pm 17\ (\text{syst.})\ \text{fb}$$

σ_{eff} determination

[Nat. Phys. 19 (2023) 338]

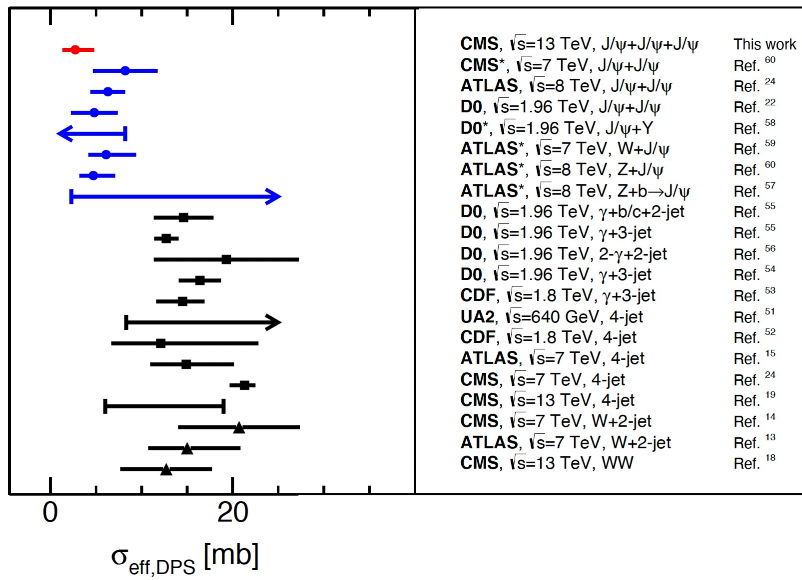
$$\begin{aligned}\sigma^{3J/\psi}_{\text{tot}} &= \sigma^{3J/\psi}_{\text{SPS}} + \sigma^{3J/\psi}_{\text{DPS}} + \sigma^{3J/\psi}_{\text{TPS}} \\ &= \left(\sigma^{3p}_{\text{SPS}} + \sigma^{2p1np}_{\text{SPS}} + \sigma^{1p2np}_{\text{SPS}} + \sigma^{3np}_{\text{SPS}}\right) \\ &\quad + \left(\sigma^{3p}_{\text{DPS}} + \sigma^{2p1np}_{\text{DPS}} + \sigma^{1p2np}_{\text{DPS}} + \sigma^{3np}_{\text{DPS}}\right) + \left(\sigma^{3p}_{\text{TPS}} + \sigma^{2p1np}_{\text{TPS}} + \sigma^{1p2np}_{\text{TPS}} + \sigma^{3np}_{\text{TPS}}\right)\end{aligned}$$

- ✓ SPS cross-sections taken from HELAC-ONIA at LO or NLO* (**prompt**) & MADGRAPH5_aMC@NLO + Pythia8 (**non-prompt**)
- ✓ Taking $\sigma_{\text{eff,TPS}} = (0.82 \pm 0.11)\ \sigma_{\text{eff,DPS}}$

$$\Rightarrow \boldsymbol{\sigma_{\text{eff,DPS}} = 2.7\ ^{+1.4}_{-1.0}\ (\text{exp.})\ ^{+1.5}_{-1.0}\ (\text{th.})\ \text{mb}}$$

- ✓ DPS and TPS dominate

Process:	3 prompt	2 prompt+1 nonprompt	1 prompt+2 nonprompt	3 nonprompt	Total
$\sigma^{3J/\psi}_{\text{SPS}}$ (fb)	<0.005	5.7	0.014	12	18
$N^{3J/\psi}_{\text{SPS}}$	0.0	0.10	0.0	0.22	0.32
$\sigma^{3J/\psi}_{\text{DPS}}$ (fb)	8.4	8.9	90	95	202
$N^{3J/\psi}_{\text{DPS}}$	0.15	0.16	1.65	1.75	3.7
$\sigma^{3J/\psi}_{\text{TPS}}$ (fb)	6.1	19.4	20.4	7.2	53
$N^{3J/\psi}_{\text{TPS}}$	0.11	0.36	0.38	0.13	1.0
$\sigma^{3J/\psi}_{\text{tot}}$ (fb)	15	34	110	114	272
$N^{3J/\psi}_{\text{tot}}$	0.3	0.6	2.0	2.1	5.0



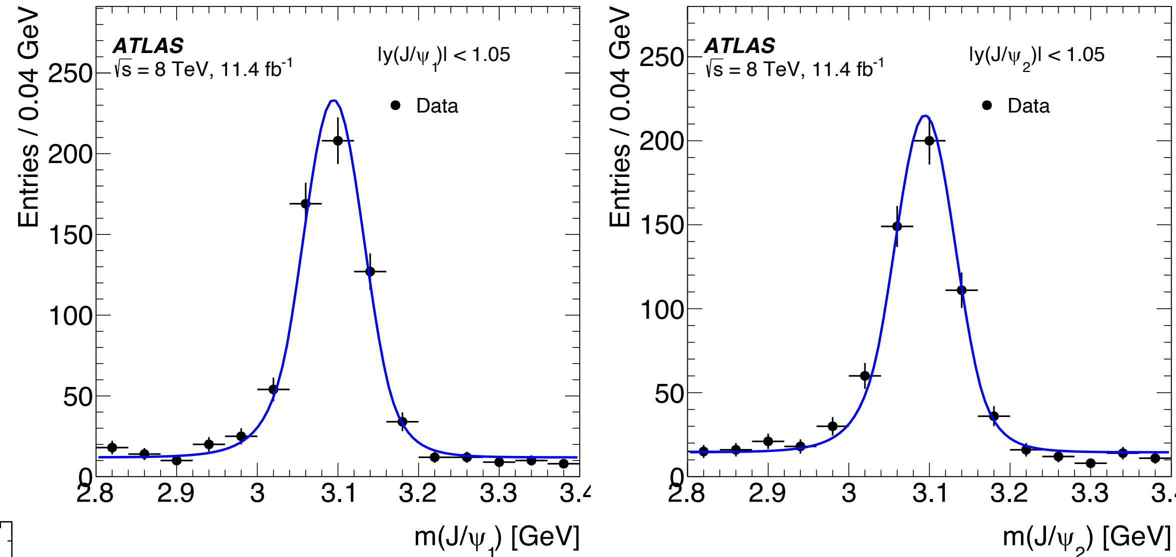
di-J/ψ @ 8 TeV

- $\mathcal{L} = 11.4\ \text{fb}^{-1}$, pp collisions @ $\sqrt{s} = 8$ TeV
- Kinematic range of J/ψ: $p_\text{T} > 8.5$ GeV$/c$ for $|y| < 2.1$

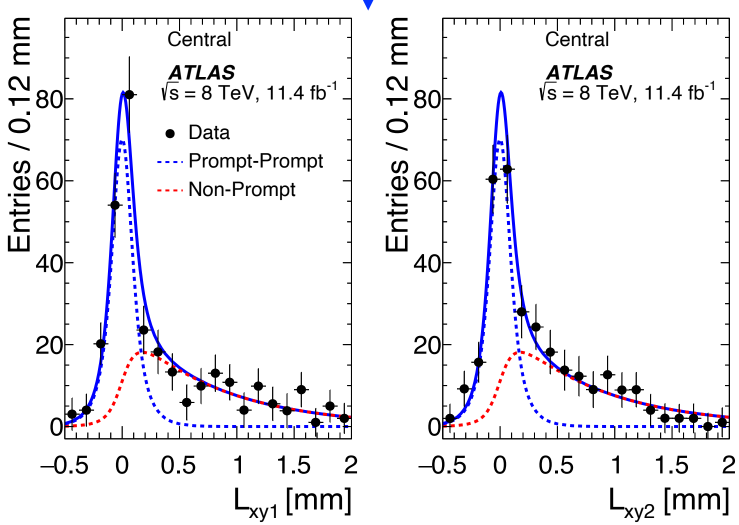
[EPJC 77 (2017) 76]

- Signal extraction

Non-J/ψ background

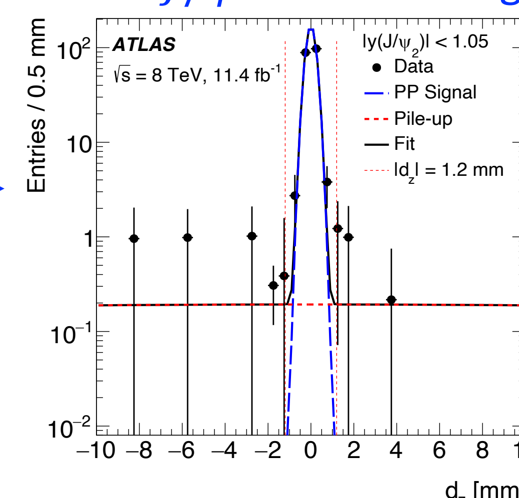


Non-prompt background



d_z: distance between two J/ψ vertices along z direction

Pile-up



Cross-sections

[EPJC 77 (2017) 76]

- Fiducial cross-section measured in two $y(J/\psi)$ regions due to different mass resolutions

- Within the muon kinematic acceptance: $p_{\mathrm{T}}^{\mu} > 2.5\ \mathrm{GeV}/c$, $|\eta^{\mu}| < 2.3$

$$15.6 \pm 1.3\ (\mathrm{stat}) \pm 1.2\ (\mathrm{syst}) \pm 0.2\ (\mathrm{BF}) \pm 0.3\ (\mathrm{lumi})\ \mathrm{pb},\ \text{for } |y| < 1.05,$$
$$13.5 \pm 1.3\ (\mathrm{stat}) \pm 1.1\ (\mathrm{syst}) \pm 0.2\ (\mathrm{BF}) \pm 0.3\ (\mathrm{lumi})\ \mathrm{pb},\ \text{for } 1.05 \le |y| < 2.1$$

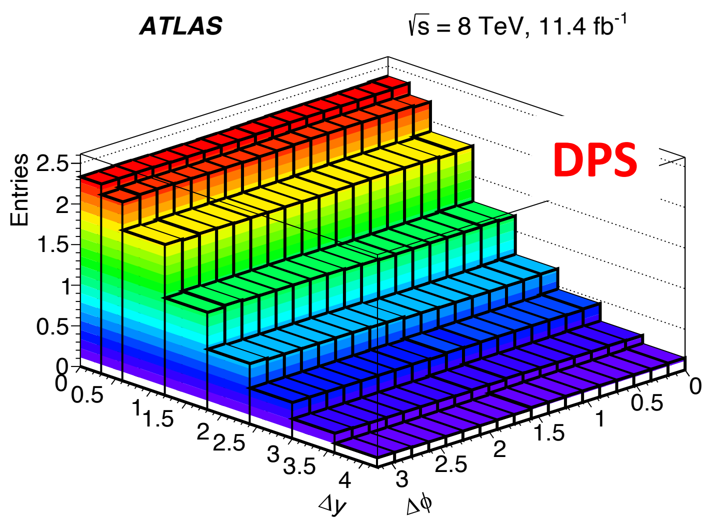
- Extrapolating to the full fiducial region assuming zero polarisation

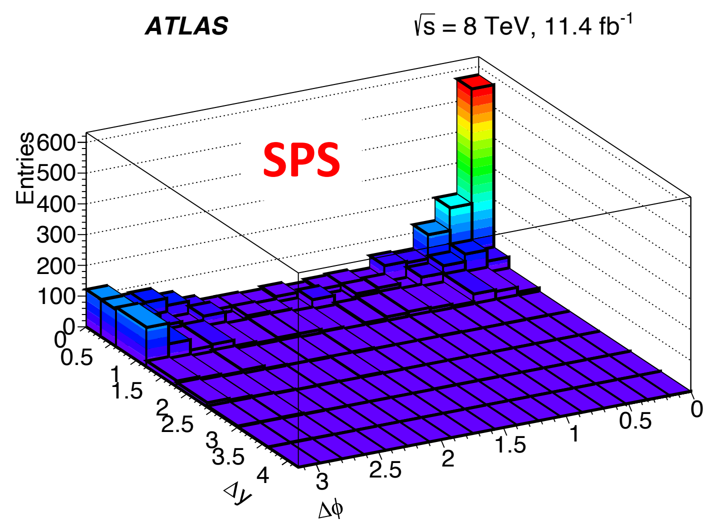
$$82.2 \pm 8.3\ (\mathrm{stat}) \pm 6.3\ (\mathrm{syst}) \pm 0.9\ (\mathrm{BF}) \pm 1.6\ (\mathrm{lumi})\ \mathrm{pb},\ \text{for } |y| < 1.05,$$
$$78.3 \pm 9.2\ (\mathrm{stat}) \pm 6.6\ (\mathrm{syst}) \pm 0.9\ (\mathrm{BF}) \pm 1.5\ (\mathrm{lumi})\ \mathrm{pb},\ \text{for } 1.05 \le |y| < 2.1$$

DPS extraction

[EPJC 77 (2017) 76]

- Data-driven DPS template
  - J/ψ mesons taken from two random events of the di- J/ψ data sample
  - Normalized to the data in the region $\Delta y > 1.8$ and $\Delta\phi \leq \pi/2$, where there is negligible SPS contribution
- Data-driven SPS template
  - Subtracting the DPS template from the $(\Delta y, \Delta\phi)$ distribution of the background-subtracted data





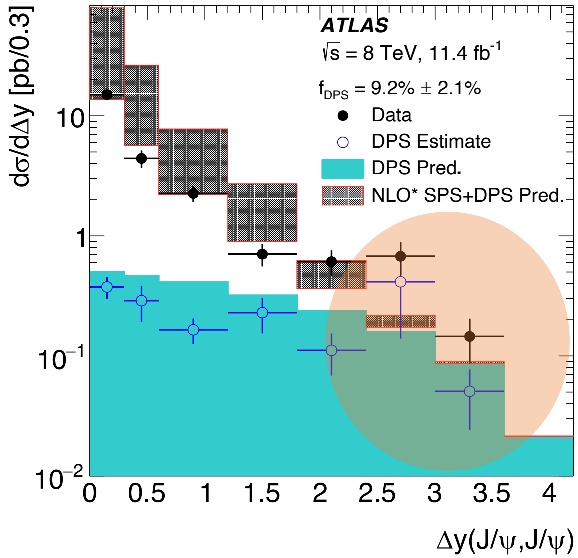
- Each candidate is assigned w_{DPS} and w_{SPS}
- $f_{\mathrm{DPS}} = (9.2 \pm 2.1 \pm 0.5)\%$

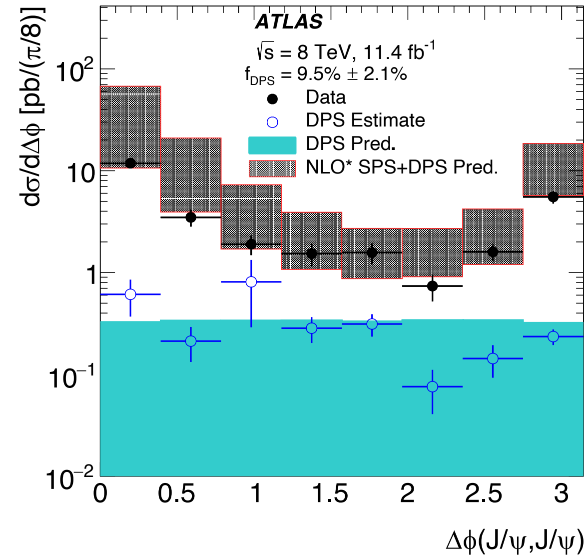
$\sigma_{\mathrm{eff}} = 6.3 \pm 1.6(\mathrm{stat}) \pm 1.0(\mathrm{syst}) \pm 0.1(\mathrm{BF}) \pm 0.1(\mathrm{lumi})$ mb

Comparison to theory (I)

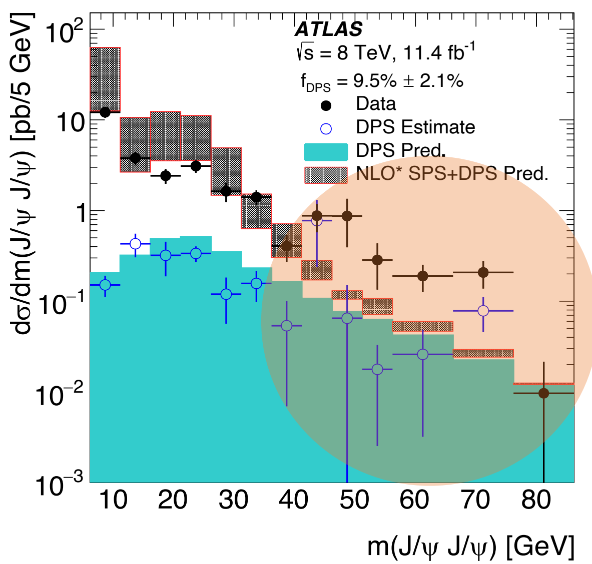
[EPJC 77 (2017) 76]

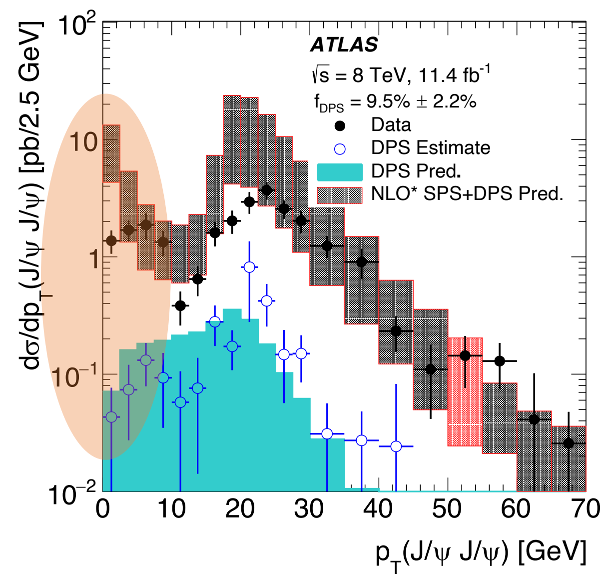
- Compared to DPS + NLO* SPS predictions
- DPS fraction fixed to measured f_{DPS}





- ✓ Some discrepancy for the total cross-section in regions of away topology
- ✓ Maybe due to the constant factor for feed-down in NLO* SPS

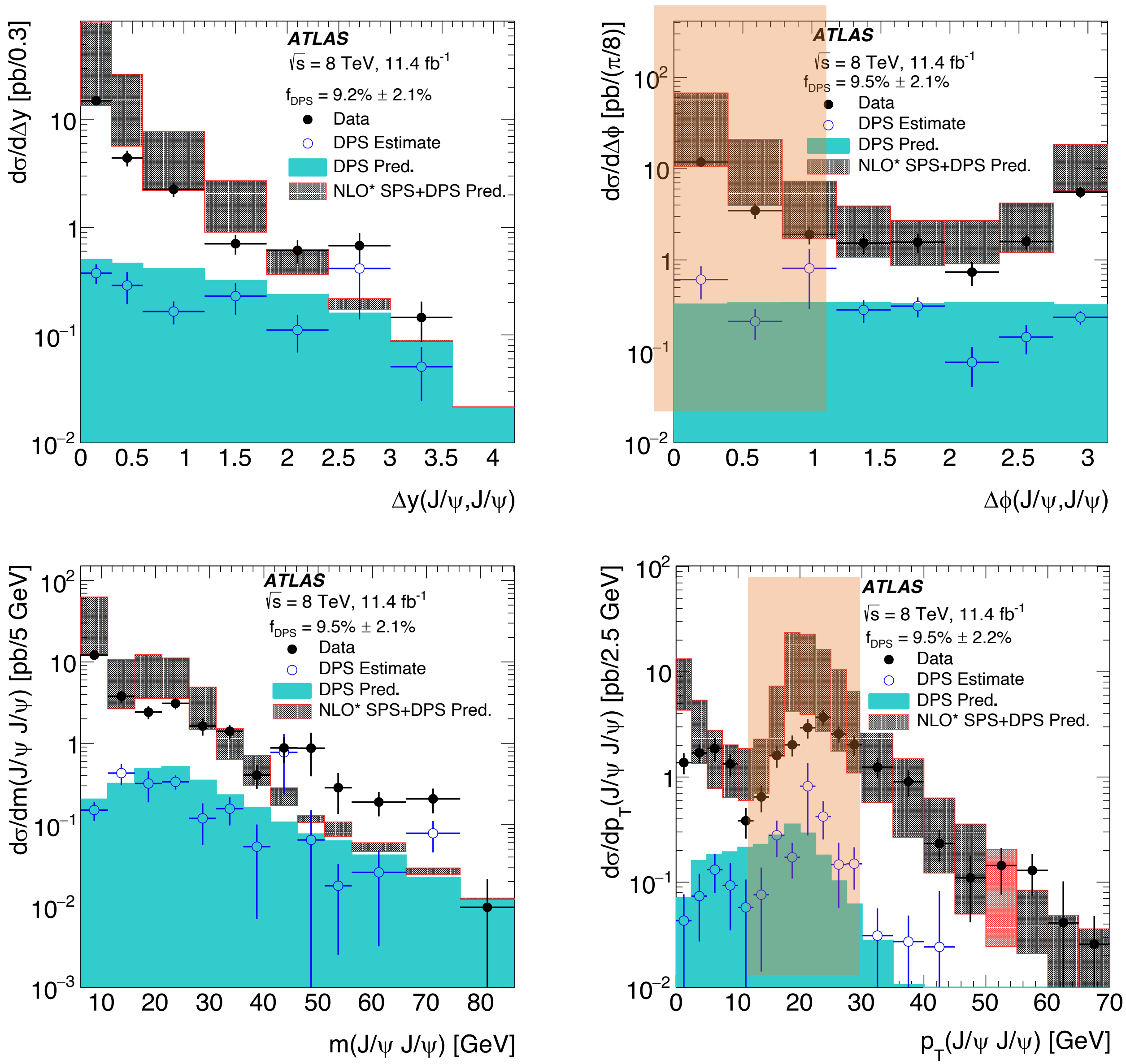




Comparison to theory (II)

[EPJC 77 (2017) 76]

- ➢ Compared to DPS + NLO* SPS predictions
- ➢ DPS fraction fixed to measured f_{DPS}

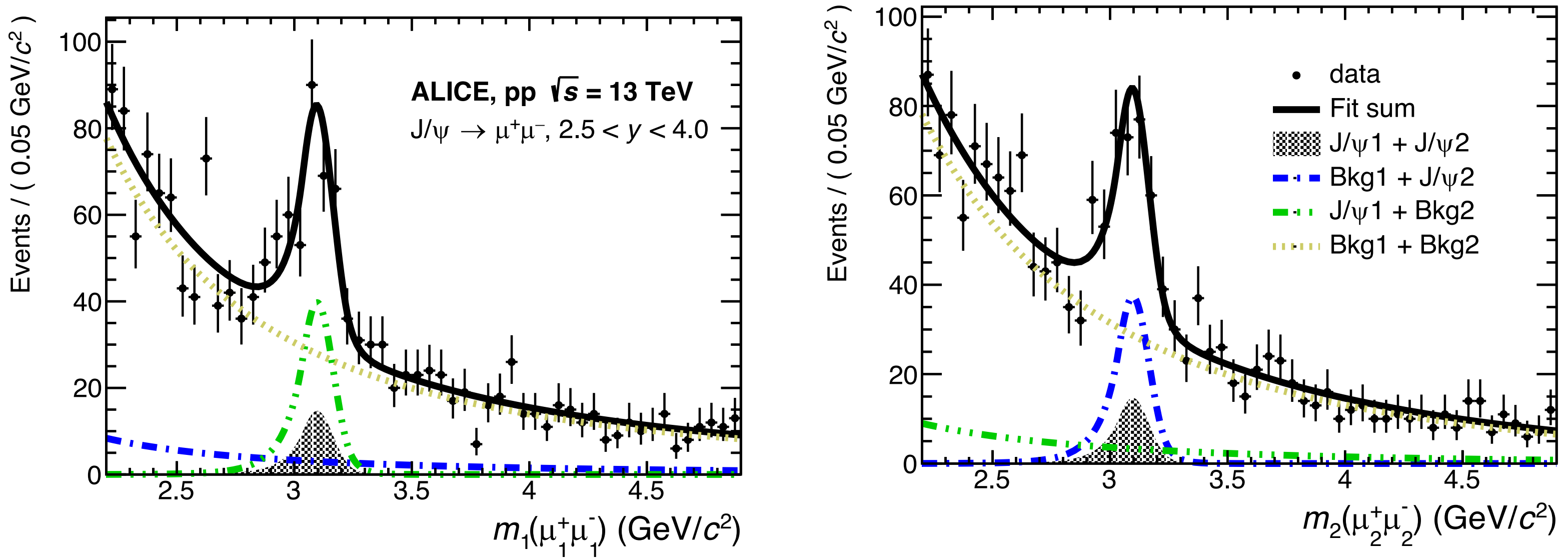


- ✓ Large SPS contribution to events with towards topology
- ✓ LO SPS predictions do not include towards topology
- ✓ NLO SPS necessary to describe the data!

di-J/ψ @ 13 TeV

[PRC 108 (2023) 045203]

- $\mathcal{L} = 24.11\ \mathrm{pb}^{-1}$, pp collisions @ $\sqrt{s} = 13$ TeV
- Kinematic range of J/ψ: $p_{\mathrm{T}} > 0$ GeV/c for $2.5 < y < 4$



✓ $\sigma(J/\psi - J/\psi) = 10.3 \pm 2.3(\mathrm{stat.}) \pm 1.3(\mathrm{syst.})$ nb

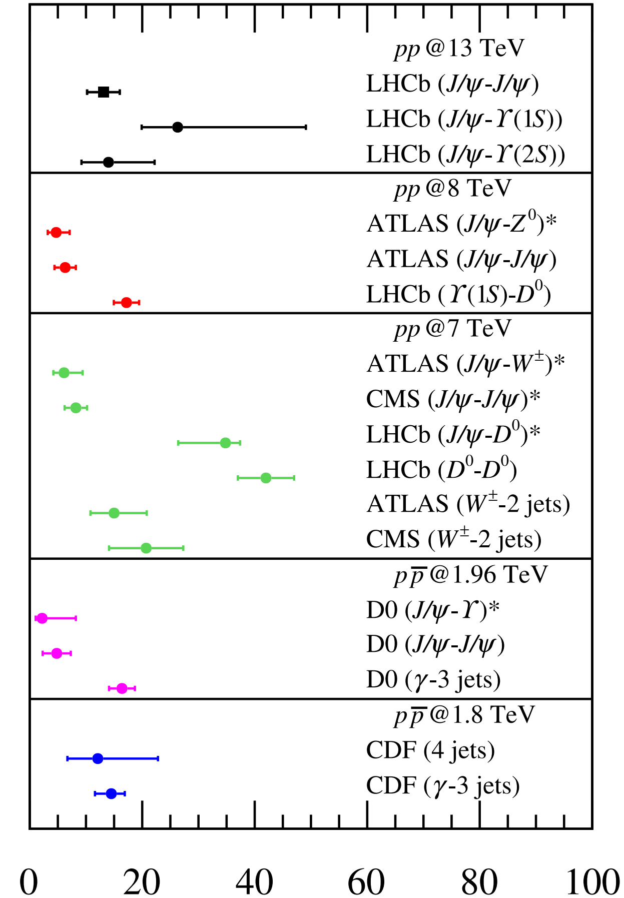
✓ $\sigma_{\mathrm{prompt}}\ (J/\psi - J/\psi) = 7.3 \pm 1.7(\mathrm{stat.})^{+1.9}_{-2.1}(\mathrm{syst.})$ nb

✓ Assuming only the DPS process contributes:

✓ $\sigma_{\mathrm{eff}}(J/\psi - J/\psi) = \frac{1}{2}\frac{\sigma_{\mathrm{prompt}}(J/\psi)^2}{\sigma_{\mathrm{prompt}}(J/\psi - J/\psi)} = 6.7 \pm 1.6(\mathrm{stat.}) \pm 2.7(\mathrm{syst.})$ mb

Summary and prospects

- **Double J/ψ production measured by all four LHC experiments**
  - ✓LHCb: 7&13 TeV
  - ✓CMS: 7 TeV
  - ✓ATLAS: 8 TeV
  - ✓ALICE: 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
  - ✓…
- **Other di-quarkonium modes of interest?**
  - ✓$J/\psi + \chi_c, J/\psi + \eta_c$ …

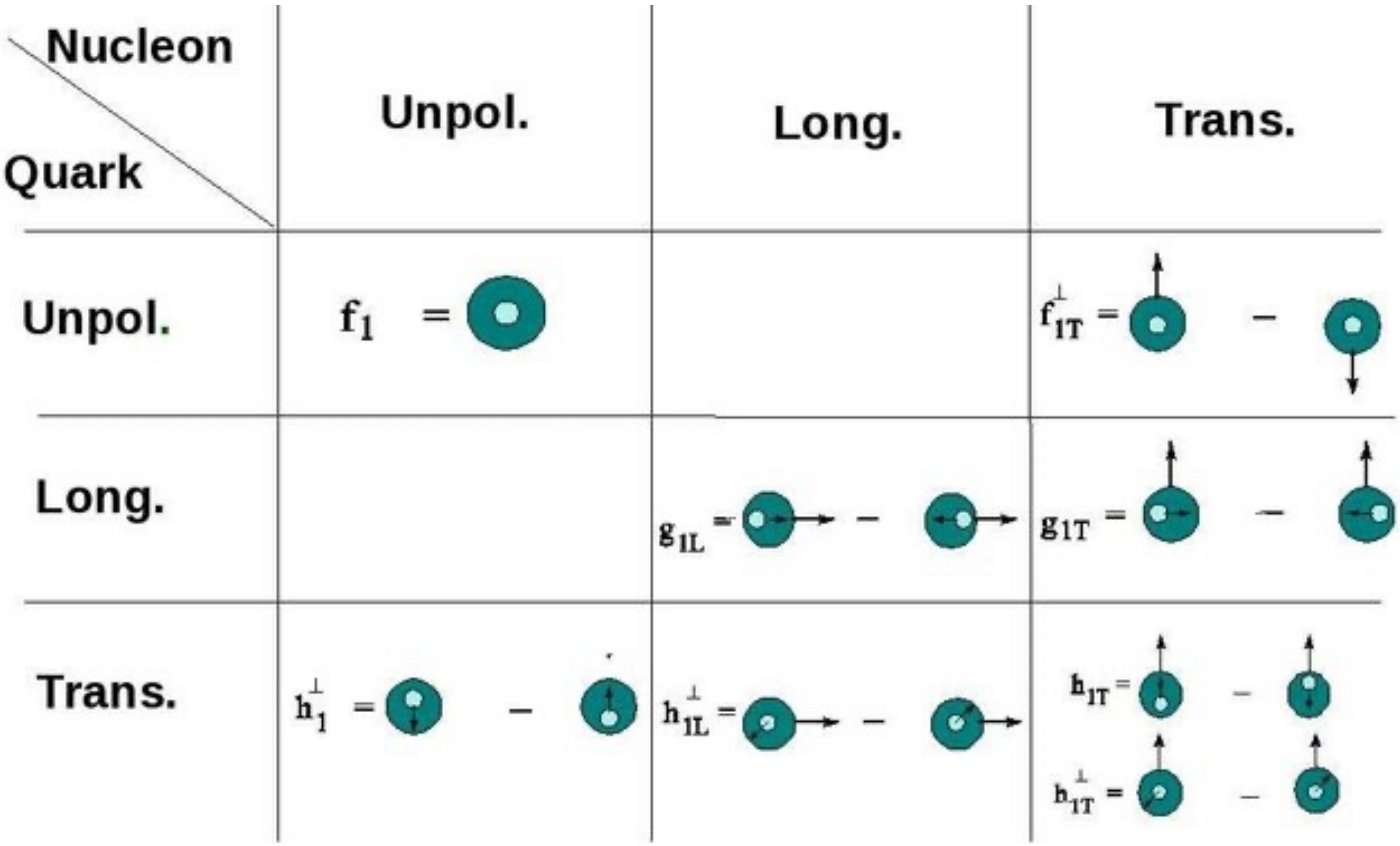


[PoS (LHCP2020) 172; arXiv: 2009.12555]

Back up

Leading twist TMD PDFs

[PR12-09-014]



Sketch of CS frame