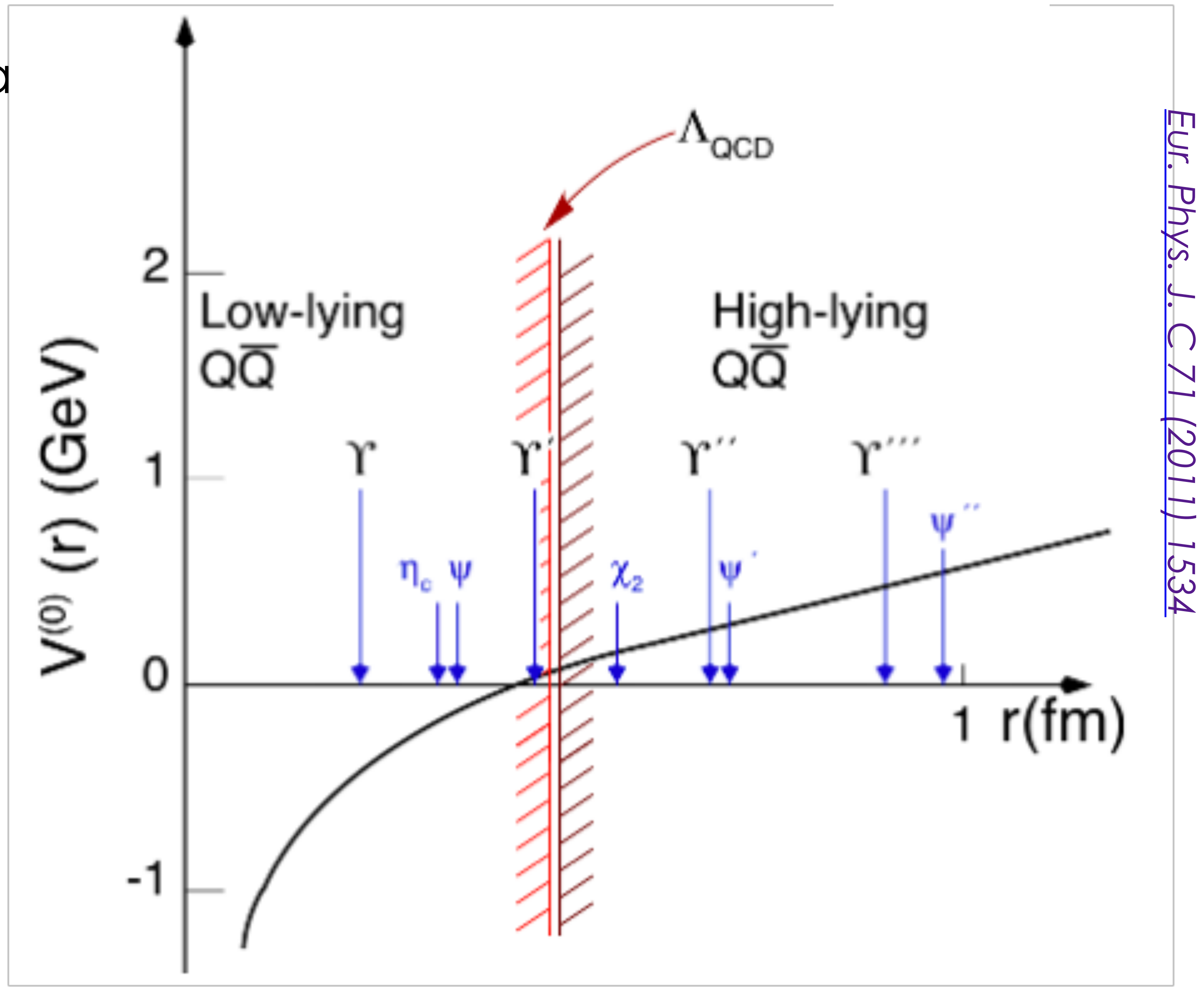
Multiple quarkonia production @ LHCb

Implication workshop
26/10/2023

Valeriia ZHOVKOVSKA

Quarkonium

v^2 - typical velocity of a heavy quark in the quarkonium rest frame

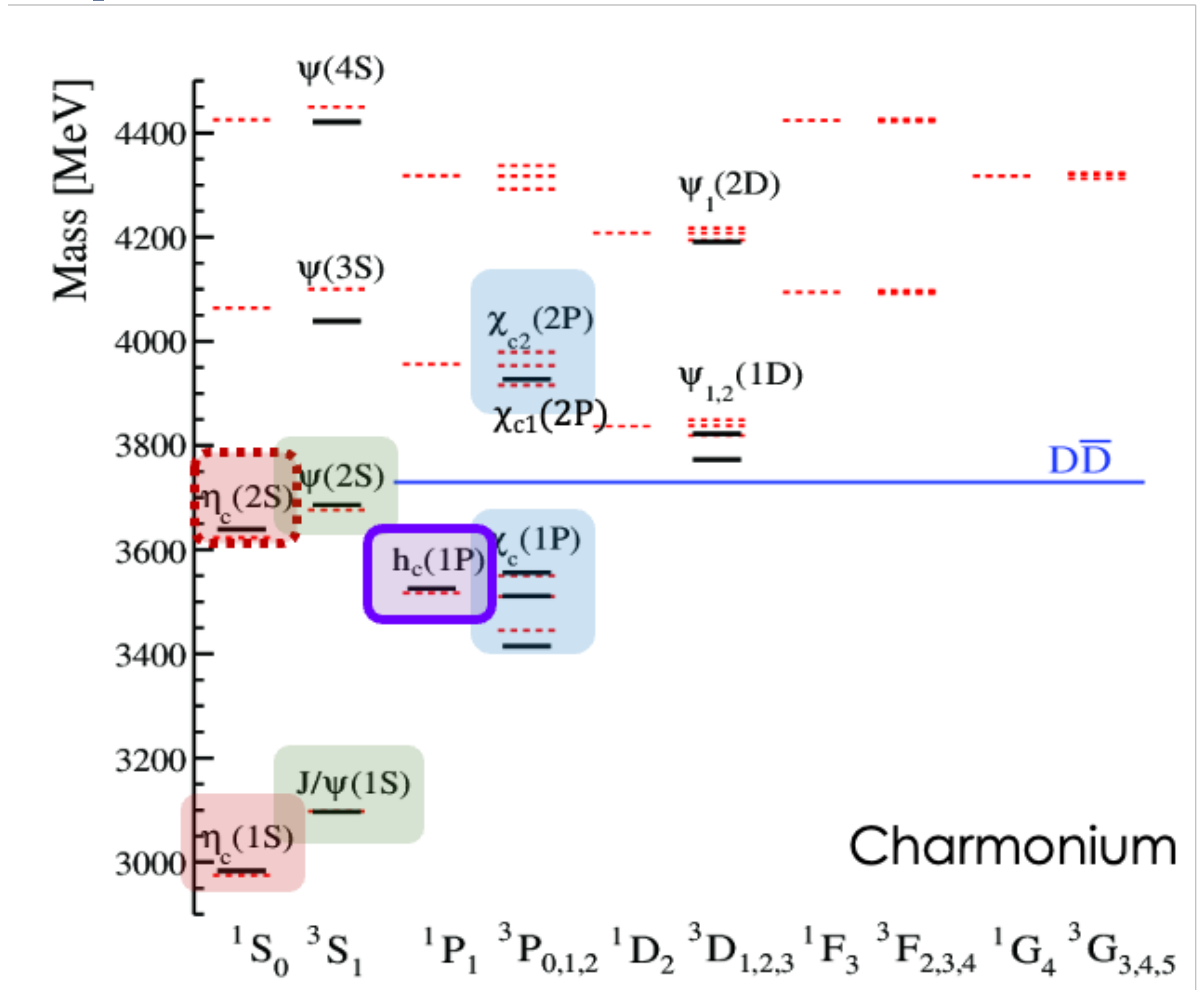


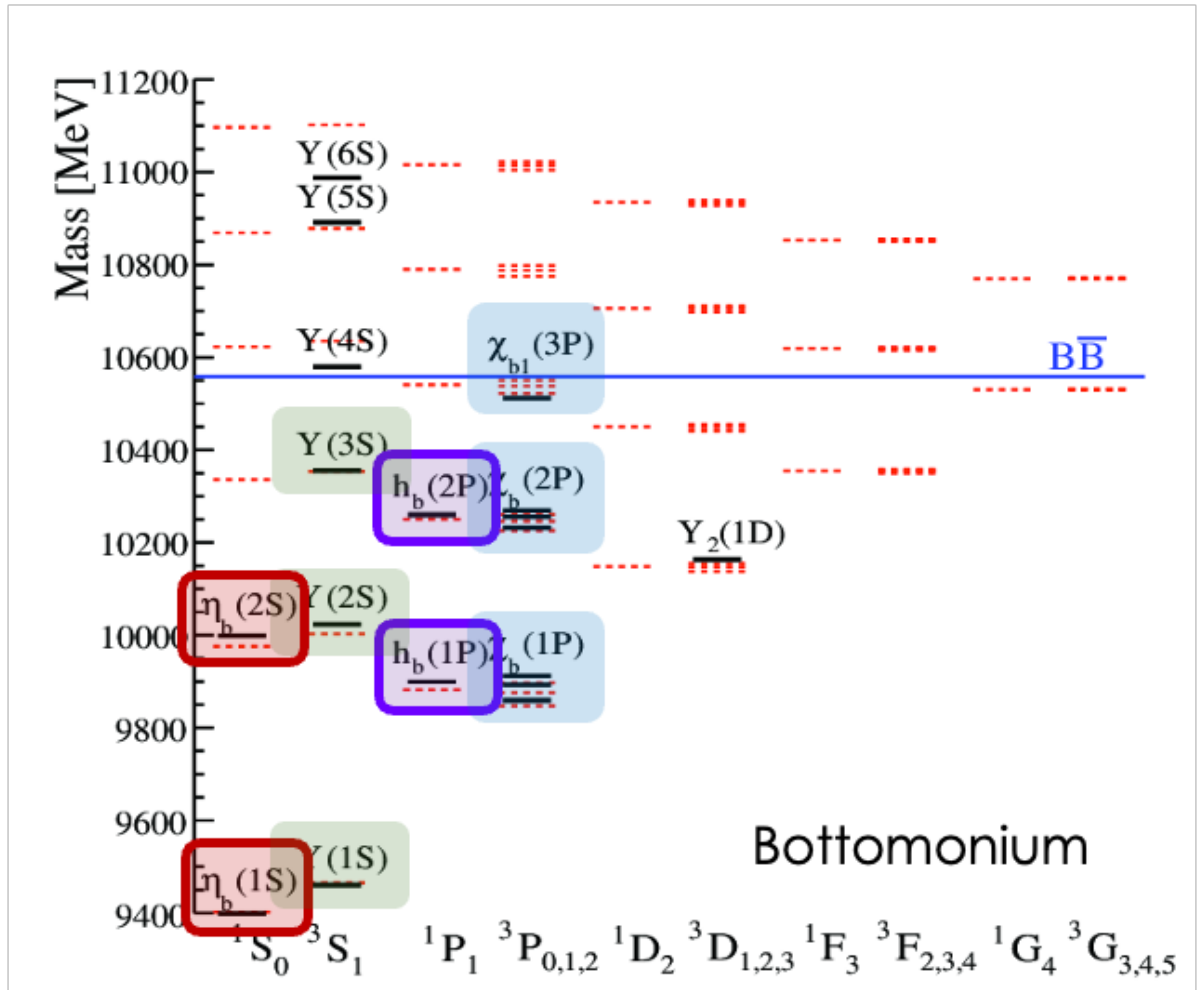
Eur. Phys. J. C 71 (2011) 1534

- A bound state of two **heavy quarks** ($c\bar{c}$ or $b\bar{b}$)
- **Non-relativistic QCD object**:
  - charmonium: $v^2 \approx 0.3$, bottomonium: $v^2 \approx 0.1$
  - three intrinsic scales $m \gg mv \gg mv^2$

Ideal probe for different QCD processes

- **Decay final states:**
  - hadrons or γγ
  - μ⁺μ⁻/e⁺e⁻ or *hadrons*
  - $^3S_1\gamma$, $^3S_1\pi^+\pi^-$ or *hadrons*
  - $^1S_0\gamma$ or *hadrons*



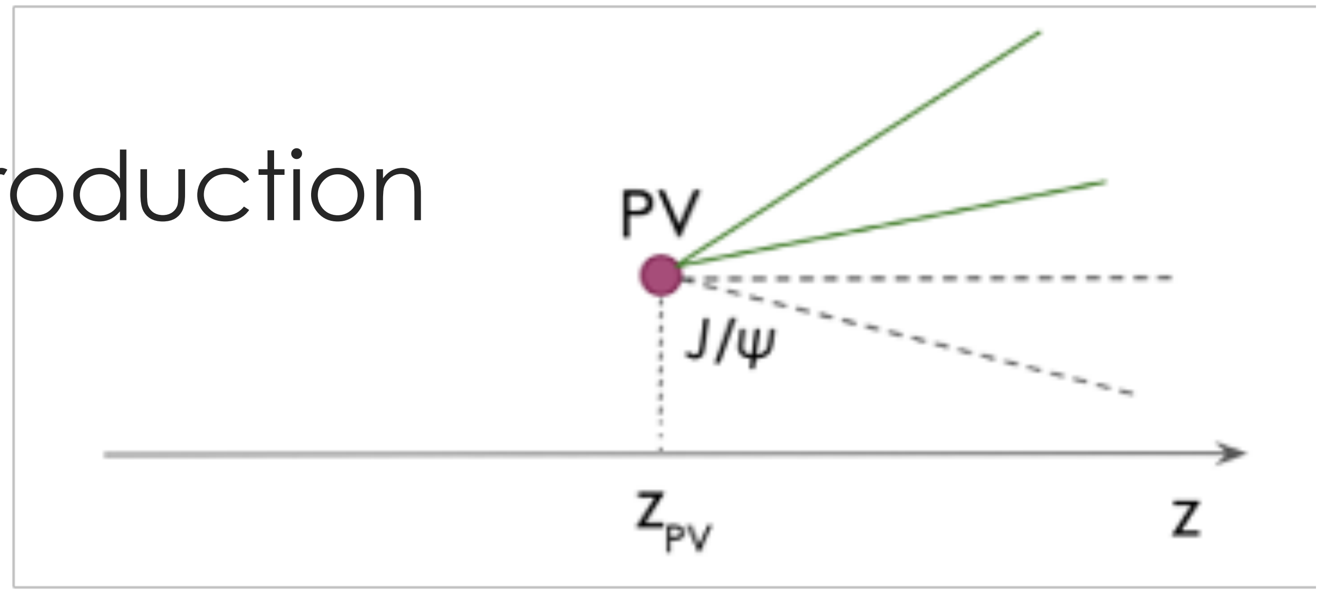


Rev.Mod.Phys 90 (2018) 015003

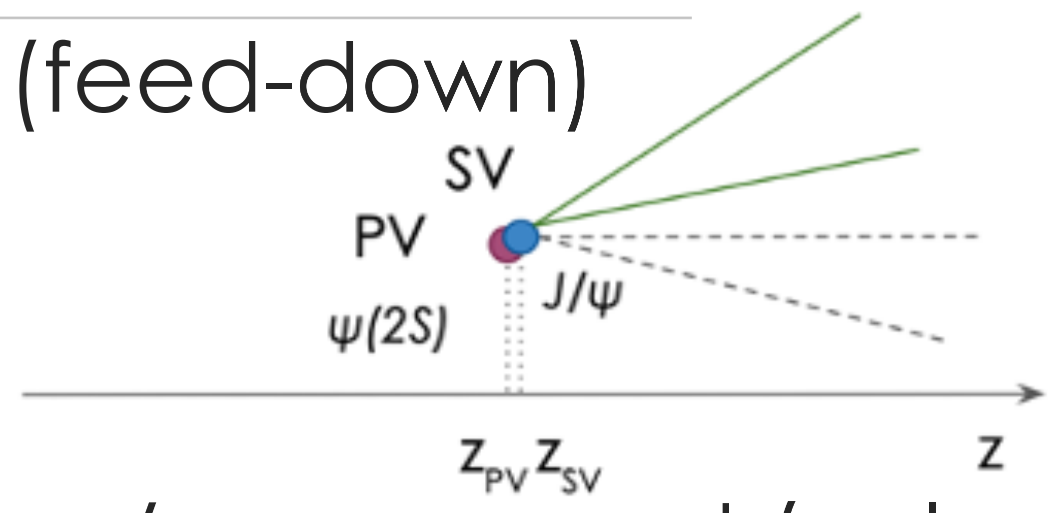
Information about many quarkonium states is still missing

Quarkonium production @ LHC

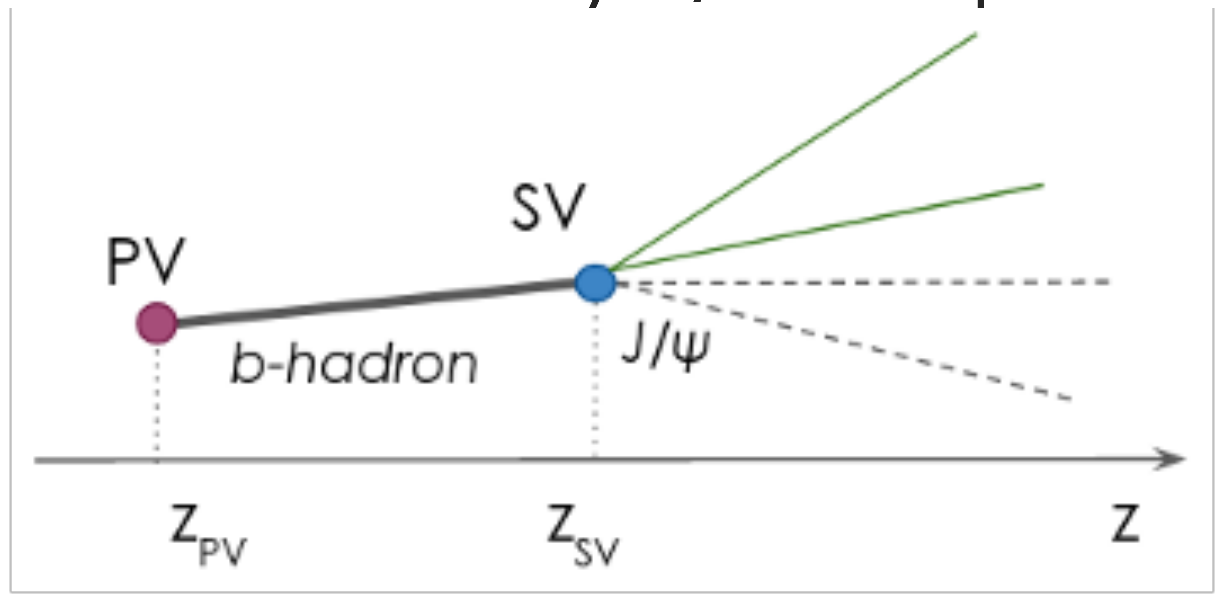
- **Origin**:
  - prompt hadroproduction



  - decays of higher resonances (feed-down)



  - production in b-hadron decays / non-prompt (only charmonium)



prompt production

distinguished via pseudo-proper decay time

$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{q\bar{q}} \text{ or } \tau = \frac{L_{xy}}{p_T} M_{q\bar{q}}$$

- **Existing measurements:**
  - $\boldsymbol{\eta_c}$ production
  - $\boldsymbol{\eta_c(2S)}$ production in b-decays
  - **J/ψ, ψ(2S)** and **Υ(nS)** production and polarization
  - **J/ψ+J/ψ/jet/Z/W$^{\pm}$, J/ψ+J/ψ+J/ψ** and **Υ(1S)+Υ(1S)** production
  - $\boldsymbol{\chi_c}$ production and polarization
  - $\boldsymbol{\chi_b}$ production

Understanding quarkonium production is challenging both experimentally and theoretically

Quarkonium production

Assumptions and Models

- Nearly all models assume **factorisation** between the **$Q\bar{Q}$-formation** and its **hadronization** into a meson
  - hard-scale **$Q\bar{Q}$-formation** – calculated as an expansion in powers of α_s
  - soft-scale **hadronization** – non-perturbative; mostly extracted from data; process-independent (**universal**)
- Factorisation depends on a chosen kinematic regime:
  - Collinear, $\sqrt{q^2} \approx q_\mathrm{T} \gg \Lambda_{QCD}$
  - Transverse Momentum Dependent, $\sqrt{q^2} \gg q_\mathrm{T} \gg \Lambda_{QCD}$
  - k_T or High Energy, $\sqrt{q^2} \gg q_\mathrm{T} \gg \Lambda_{QCD}$
- Additionally, intrinsic scales are used in hadronization description: $m \gg mv \gg mv^2$

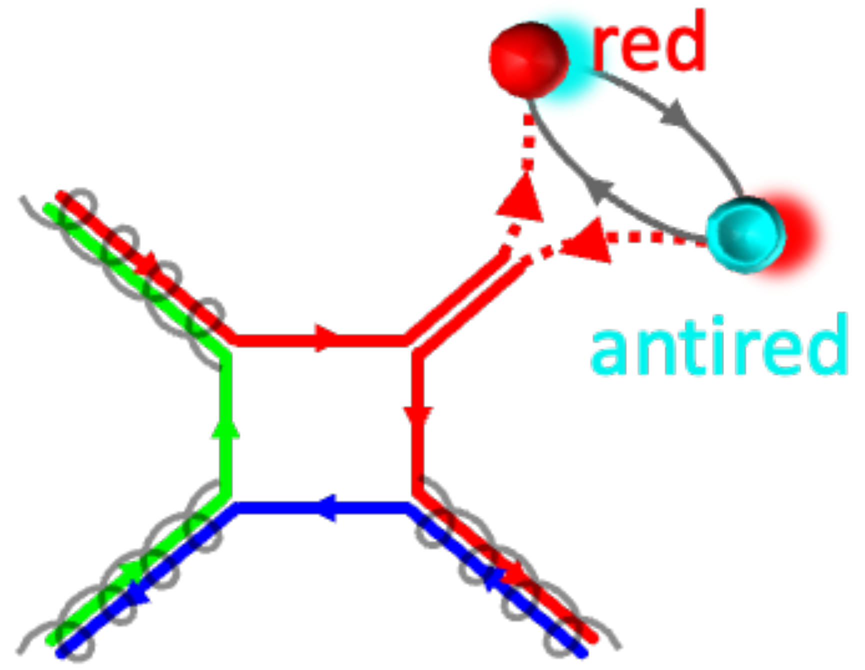
Production studies provide probes for different QCD processes

Quarkonium production

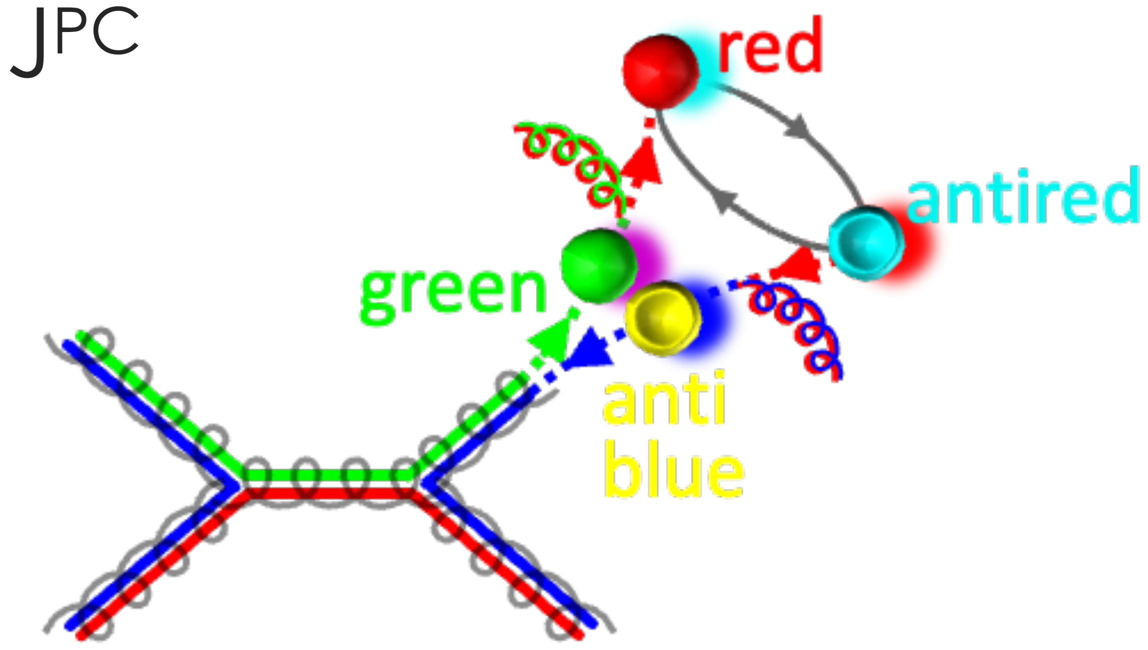
Models

- **No consensus on the quarkonium production mechanism**

- Three common models with the different **description of the hadronization:**
  - **Colour evaporation model (CEM):** application of quark-hadron duality; only the invariant mass matters;
  - **Colour-singlet model (CS)**: intermediate QQ state is colourless and has the same J^{PC} as the final-state quarkonium;
  - **Colour-octet model (CO)** (encapsulated in NRQCD): all viable colours and J^{PC} allowed for the intermediate QQ state;



Colour Singlet state



Colour Octet state

NRQCD is found to be the most used, because it is based on an EFT and can be improved systematically

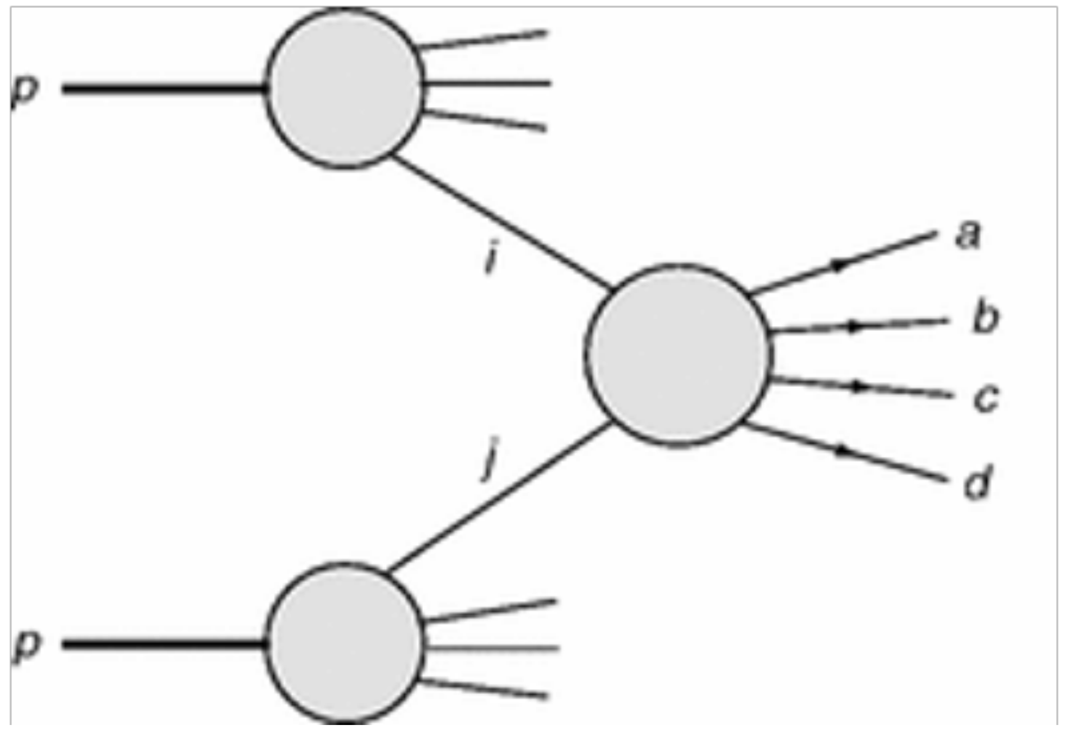
Associated production

DPS and SPS

PRD 84 (2011) 074021
ATL-PHYS-SLIDE-2021-129

The production of two particles A and B in the same *pp* collision can be due to

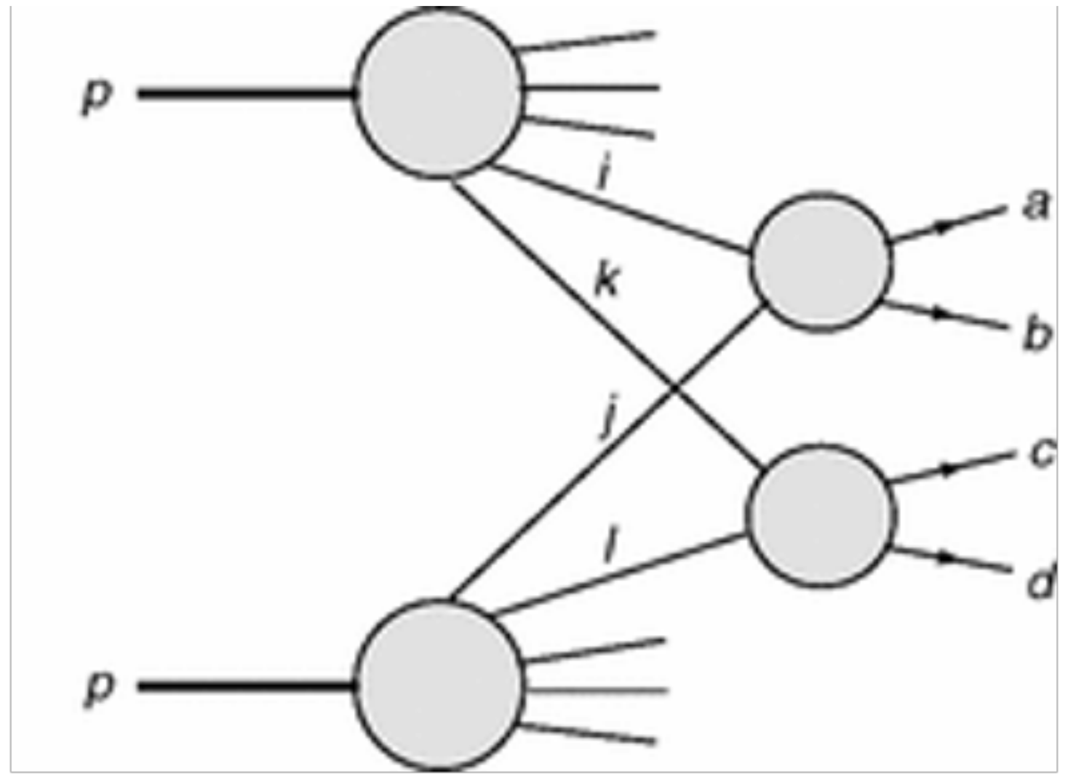
- **Single-Parton Scattering (SPS):**
  - the two particles are produced a **single interaction** of two partons
  - kinematics is correlated (neglected emission of additional gluons)
  - presence confirmed by observing such states as Ξ_{cc} and $X(6900)$



- **Double-Parton Scattering (DPS):**
  - simultaneous interaction of two pairs of partons, assumed to be **uncorrelated**
  - DPS "Pocket formula":

$$\sigma_{DPS}^{pp\to AB} = \frac{m}{2}\frac{\sigma_{SPS}^{pp\to AX}\sigma_{SPS}^{pp\to BX}}{\sigma_{eff,DPS}}$$, where m is a symmetry factor

  - can be estimated from single quarkonia production



Main challenge is to separate SPS and DPS experimentally

Associated production

New LHCb results at $\sqrt{s} = 13\ \text{TeV}$

- $J/\psi + J/\psi$ **production:** *LHCb-PAPER-2023-022*, in preparation
  - integrated and differential cross-section
  - production asymmetry
  - effective cross-section σ_{eff}

- $J/\psi + \psi(2S)$ **production:** *LHCb-PAPER-2023-023*, in preparation
  - integrated and differential cross-section
  - ratio to $J/\psi + J/\psi$

- $J/\psi + \Upsilon(nS)$ **production:** *JHEP 08 (2023) 093*
  - integrated and differential (for $\Upsilon(1S)$) cross-section
  - effective cross-section σ_{eff}

Many new promising results

Associated production

Expectations

- $J/\psi + J/\psi$ **production:**
  - small SPS CO contribution
  - DPS contribution is important at large J/ψ Δy
  - test gluon Transverse Momentum Dependent parton distribution functions (TMDs)
- $J/\psi + \psi(2S)$ **production:**
  - **feed-down** contribution depends on the production mechanism
  - SPS and DPS separation similar to $J/\psi + J/\psi$
- $J/\psi + \Upsilon(nS)$ **production:**
  - dominant SPS CO contribution

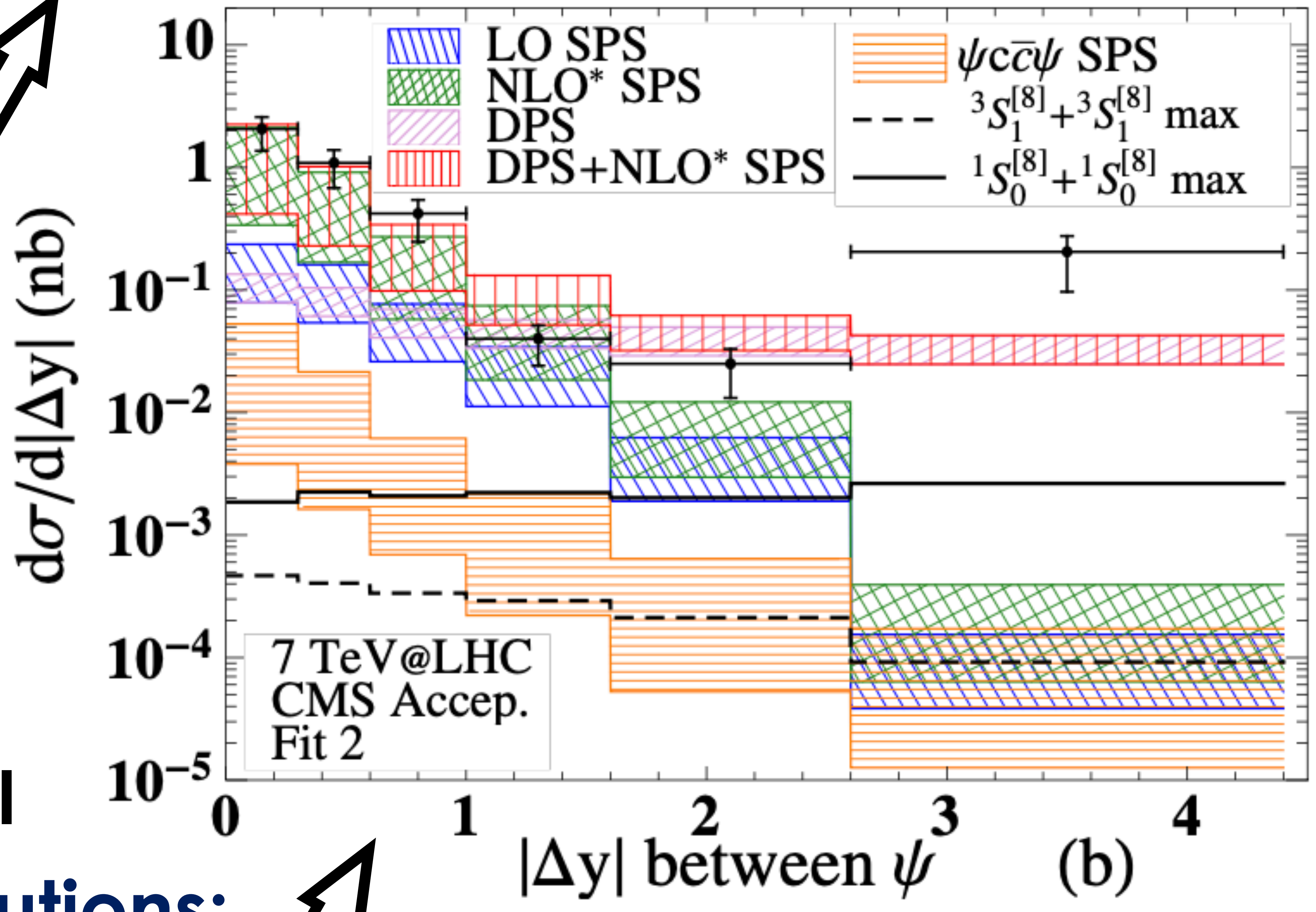
- **Effective cross-section** σ_{eff} is assumed to be **universal**

DPS and SPS are separated from kinematic distributions; Model-dependent separation

Feed-down contribution to $J/\psi + J/\psi$ production
J.P.Lansberg

	(CSM) SPS	"low"-P_T DPS	"high"-P_T DPS
$F^{\psi'}_{\psi\psi}$	50%	15%	15 %
$F^{\chi_c}_{\psi\psi}$	small	25%	50%

Comparison of data and **different models**



Phys. Lett. B751 (2015) 479–486

Cross-section measurement

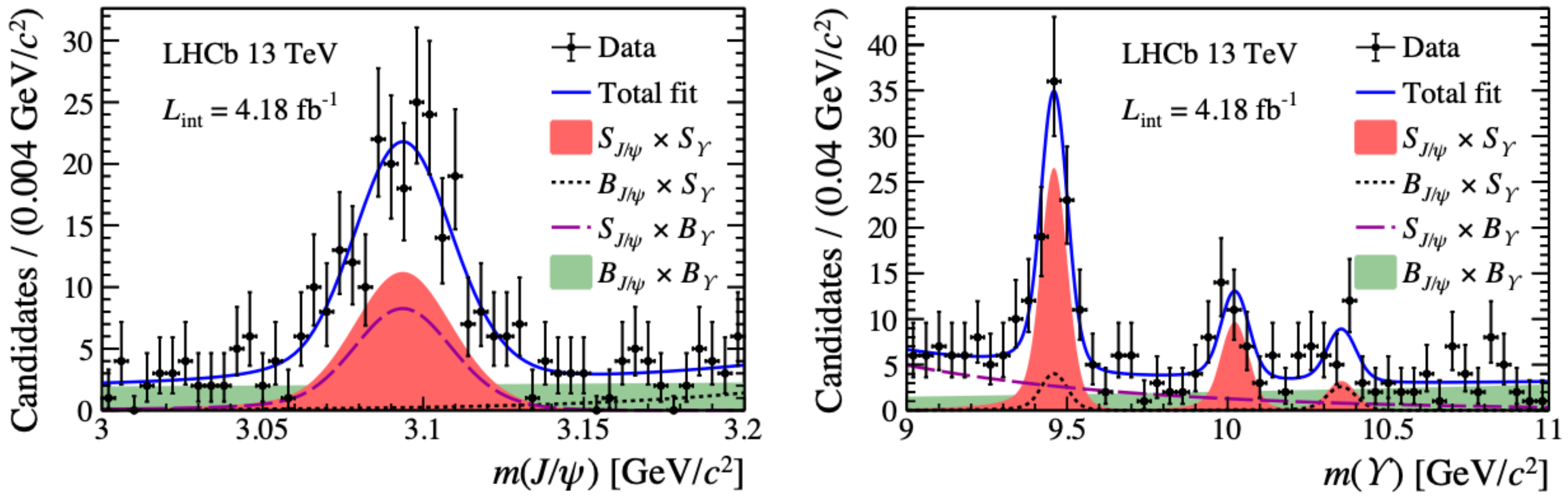
- Pair production cross-section:

$$\sigma(A-B) = \frac{N_{corr}}{\mathscr{L} \times \mathscr{B}_{A\to\mu^+\mu^-} \times \mathscr{B}_{B\to\mu^+\mu^-}},$$ where $N_{corr} = \frac{N}{\varepsilon_{tot}}$ is efficiency-corrected yield

- **Efficiency is factorised**:

$$\varepsilon_{tot} = \varepsilon_{acc} \times \varepsilon_{rec\&sel} \times \varepsilon_{PID} \times \varepsilon_{trig}$$ and $\varepsilon_i = \varepsilon_i^A \times \varepsilon_i^B$

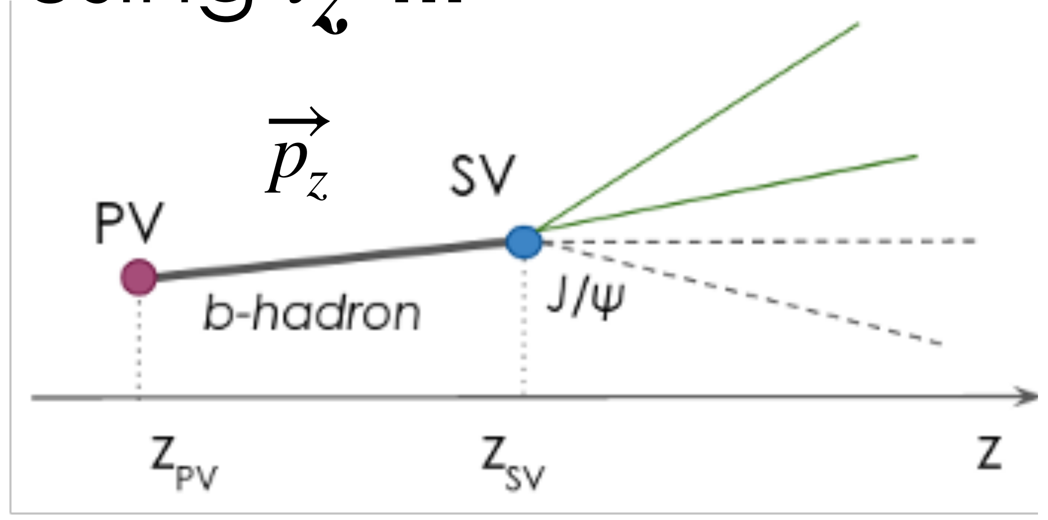
- **Yields** are extracted from 2D A and B **invariant mass fit**

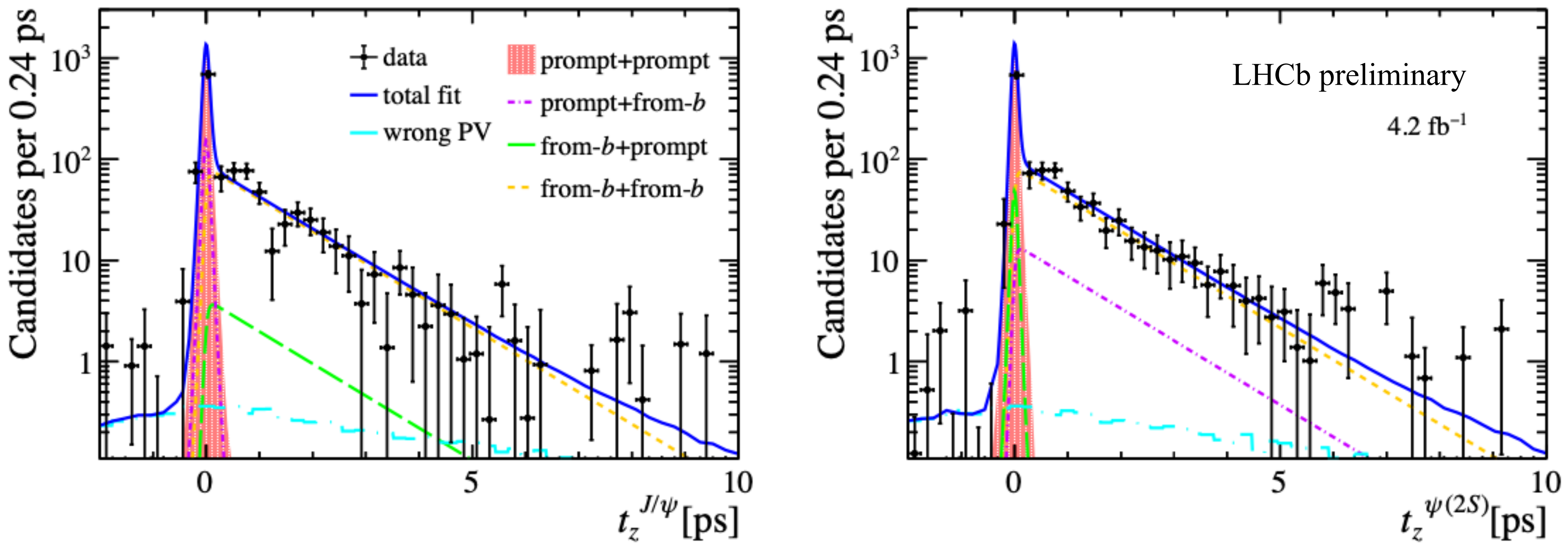


JHEP 08 (2023) 093

- **Separation** of prompt and non-prompt charmonium is done using t_z**-fit**

$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{q\bar{q}}$$



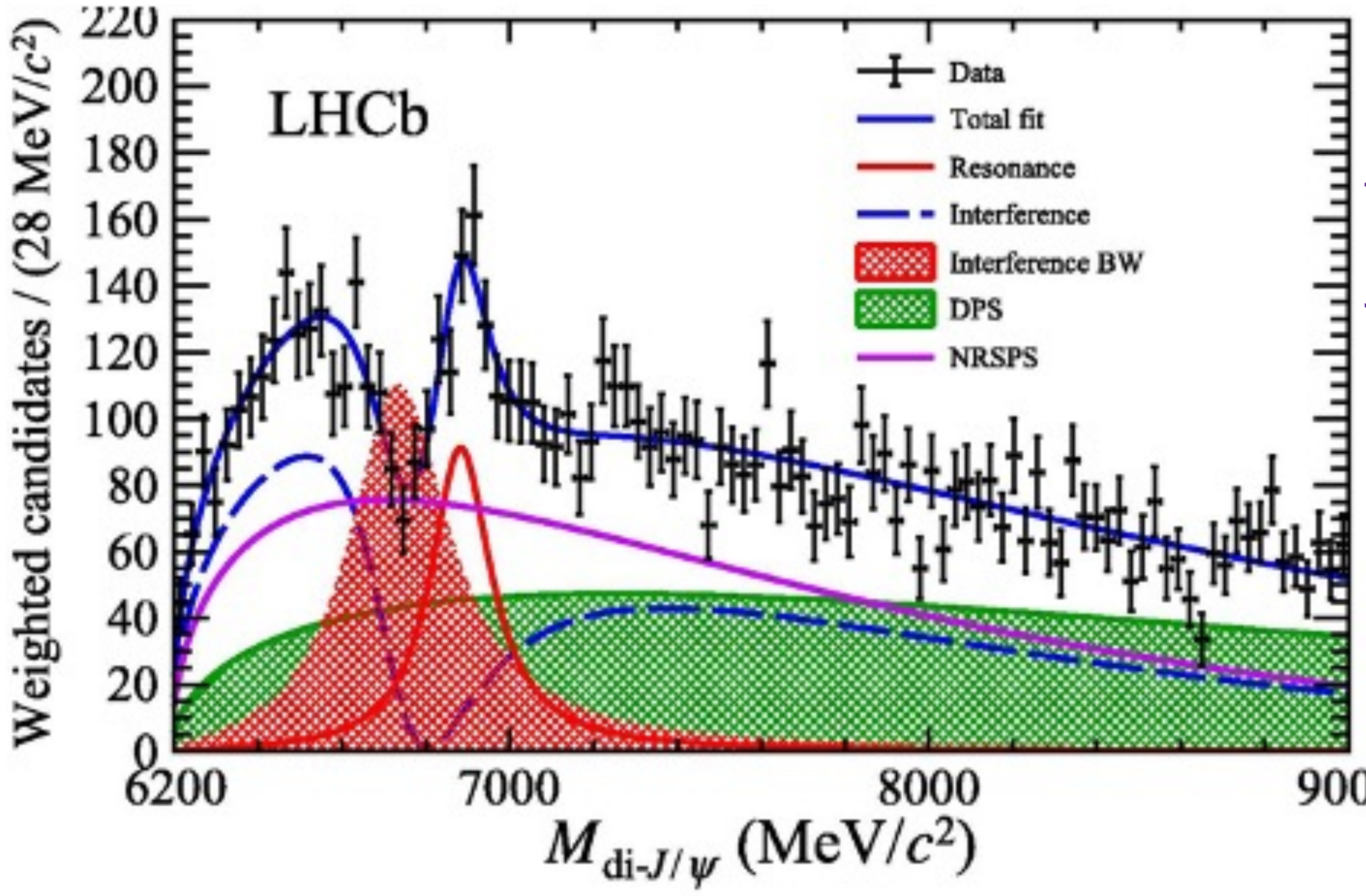


LHCb-PAPER-2023-023

$J/\psi + J/\psi$ production

Previous search for resonances

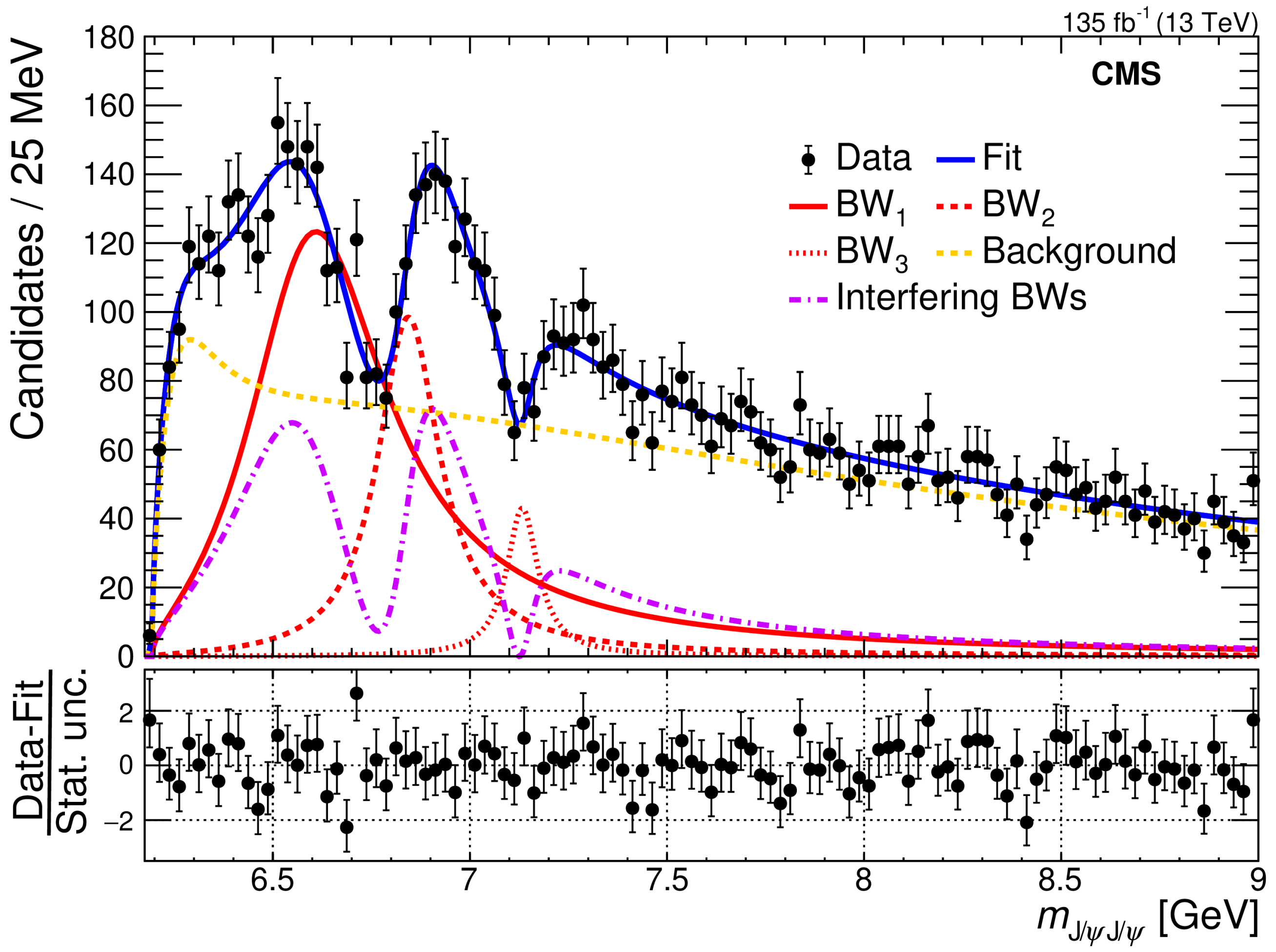
- **First observation of fully heavy tetraquark candidate X(6900)**
- **Observed similar structure + two more candidates X(6600) and X(7300)**



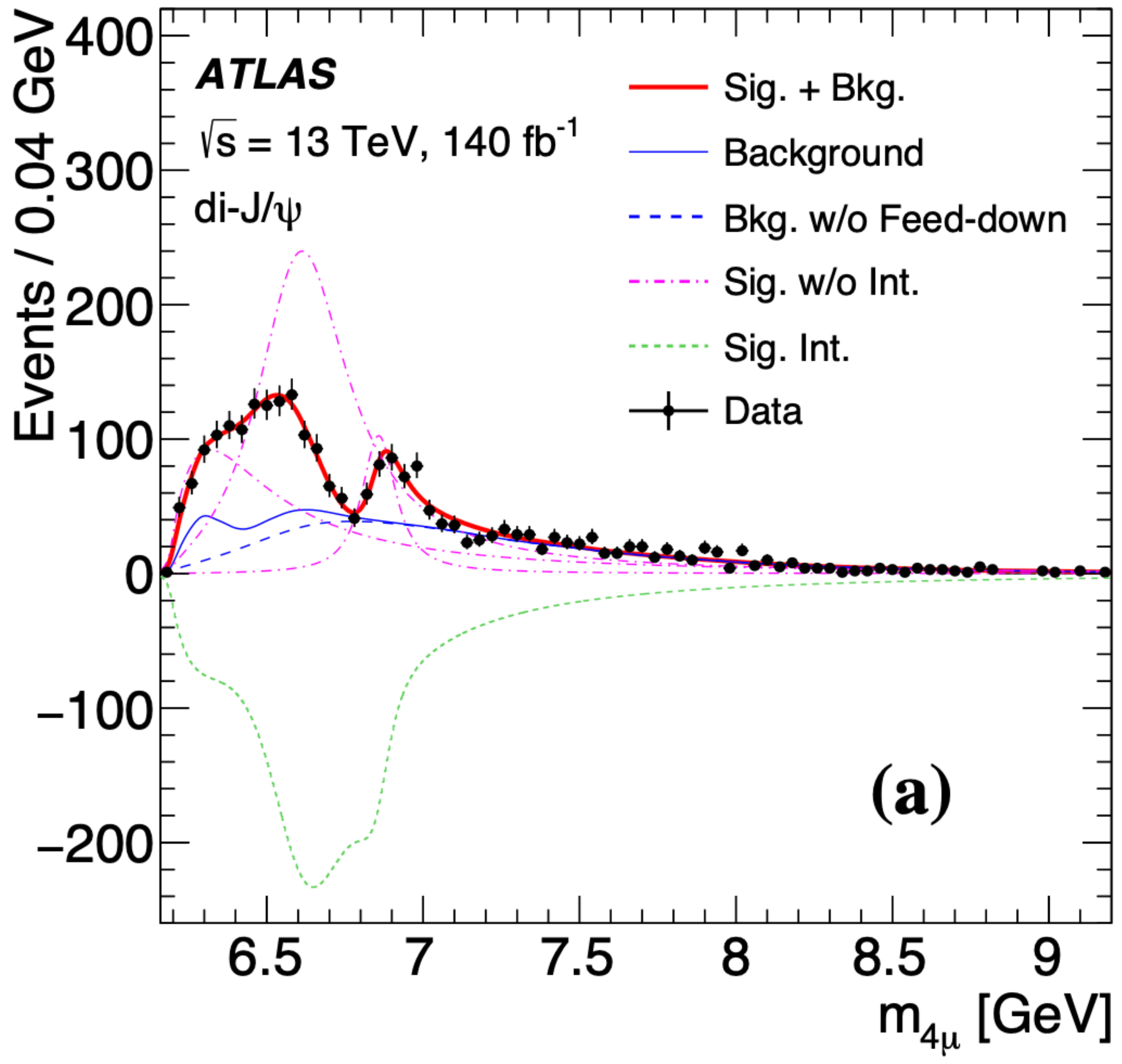
SB 65 (2020)23, 1983-1993

- Threshold structure with a few possible interpretations:
  - One BW, combination of two BWs, feed-down…

	m [GeV/c²]	Γ [GeV/c²]
LHCb	$6.89 \pm 0.01 \pm 0.01$	$0.17 \pm 0.03 \pm 0.07$
CMS	$6.93 \pm 0.01 \pm 0.01$	$0.12 \pm 0.02 \pm 0.02$
ATLAS	$6.87 \pm 0.03\, ^{+0.06}_{-0.01}$	$0.12 \pm 0.04\, ^{+0.03}_{-0.01}$



arXiv:2306.07164



Phys. Rev. Lett. 131 (2023) 151902

- Additional study together with spin-parity measurement required to explain nature of threshold structure

New fully heavy tetra quark candidates

$J/\psi + J/\psi$ production

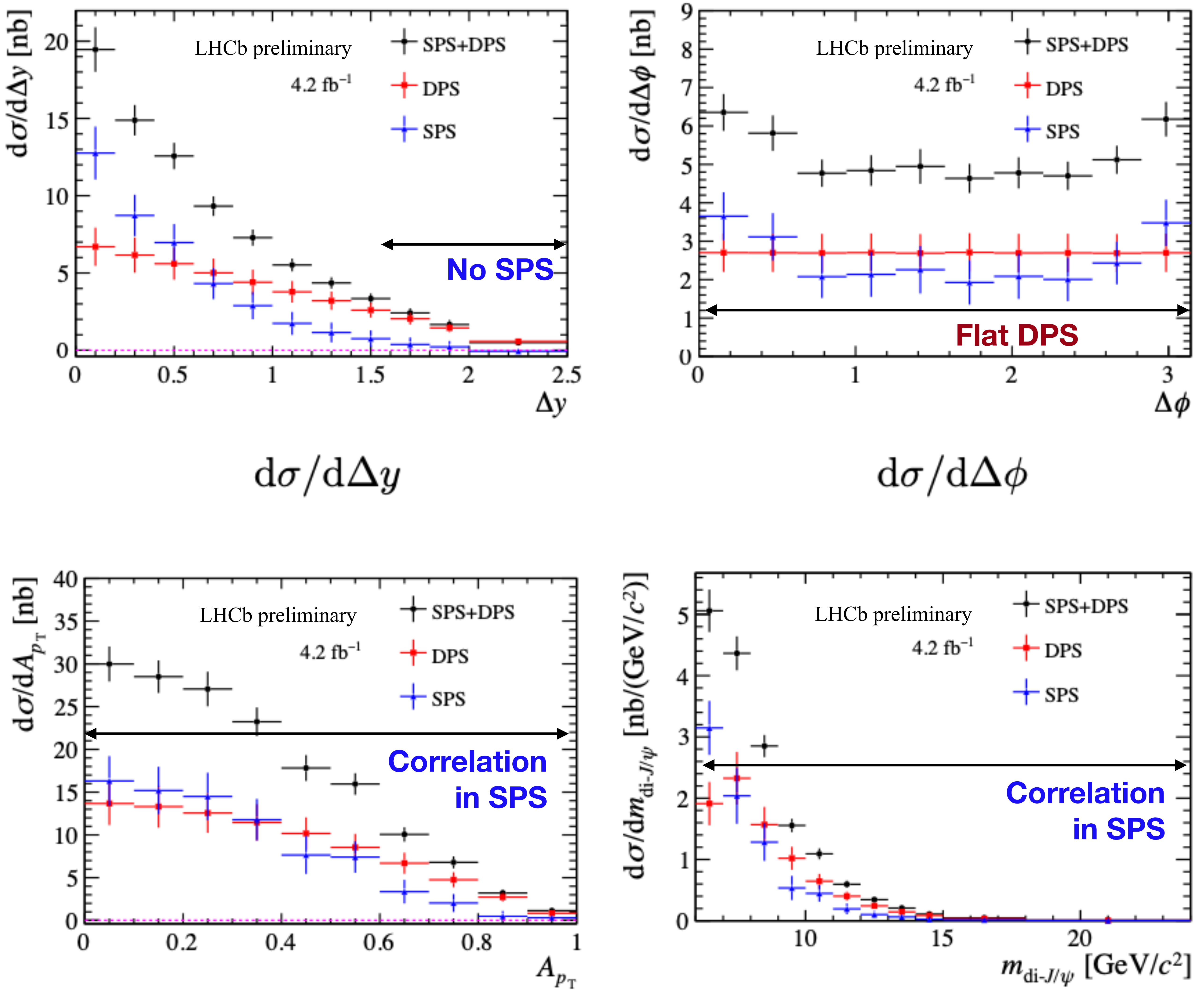
Production cross-section

- Data sample: $\mathscr{L} = 4.18 \pm 0.08\ \text{fb}^{-1}$
  $p_{\text{T}}^{J/\psi} < 14$ GeV/c and $2.0 < y^{J/\psi} < 4.5$

$$\sigma_{di-J/\psi} = 16.36 \pm 0.28_{stat} \pm 0.88_{syst}\ \text{nb}$$

- Differential study in bins of $\Delta y, \Delta\phi, p_{\text{T}}^{J/\psi}, y^{J/\psi}, p_{\text{T}}^{di-J/\psi}, y^{di-J/\psi}, m_{di-J/\psi},$ and $\mathscr{A}_{p_{\text{T}}} = \left| \frac{p_{\text{T}}^{J/\psi_1} - p_{\text{T}}^{J/\psi_2}}{p_{\text{T}}^{J/\psi_1} + p_{\text{T}}^{J/\psi_2}} \right|$

- SPS and DPS contributions are separated



$d\sigma/d\Delta y$ $d\sigma/d\Delta\phi$ $d\sigma/d\mathcal{A}_{p_T}$ $d\sigma/dm_{di\text{-}J/\psi}$

LHCb-PAPER-2023-022

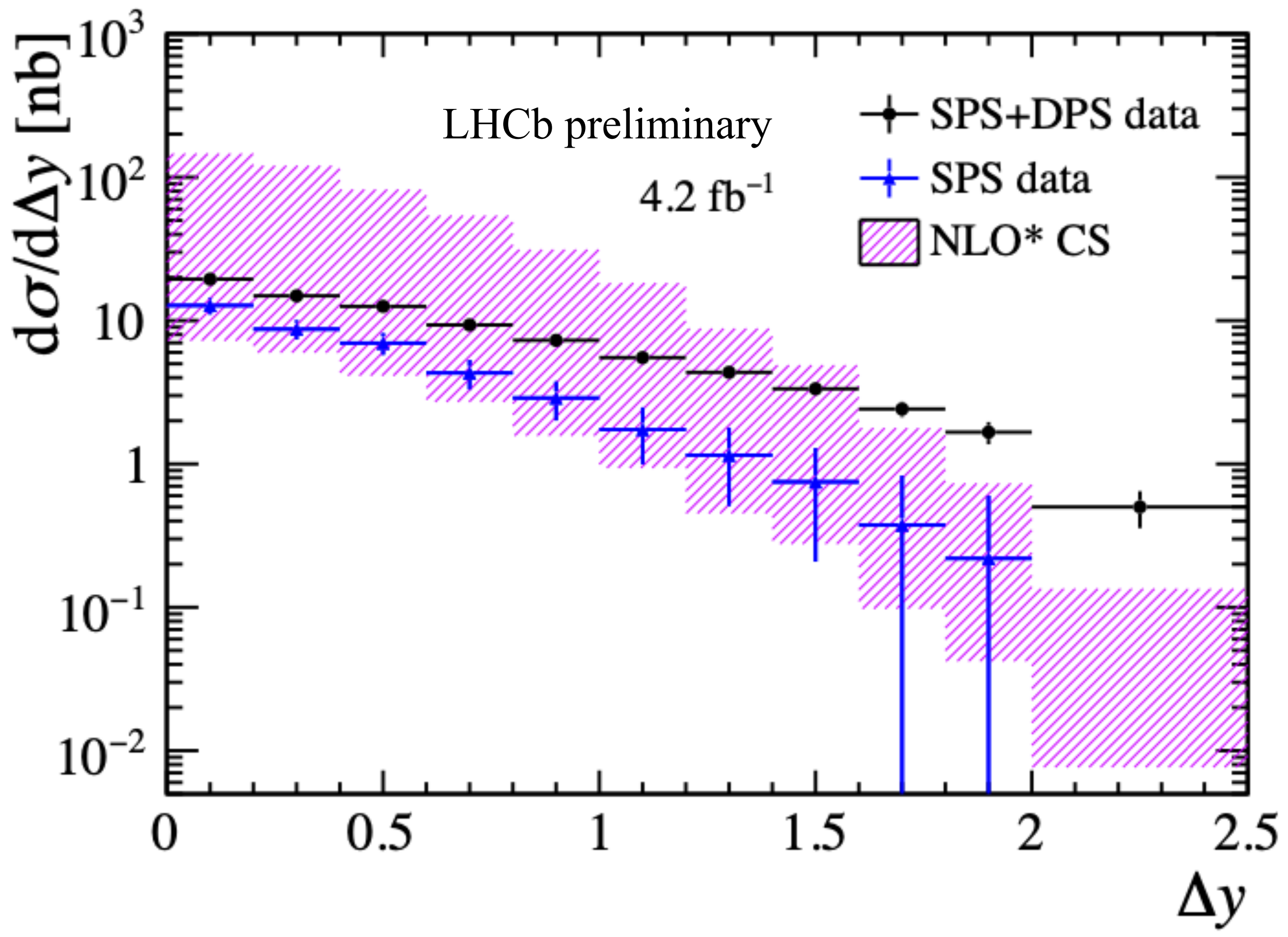
$J/\psi + J/\psi$ production

SPS and DPS separation

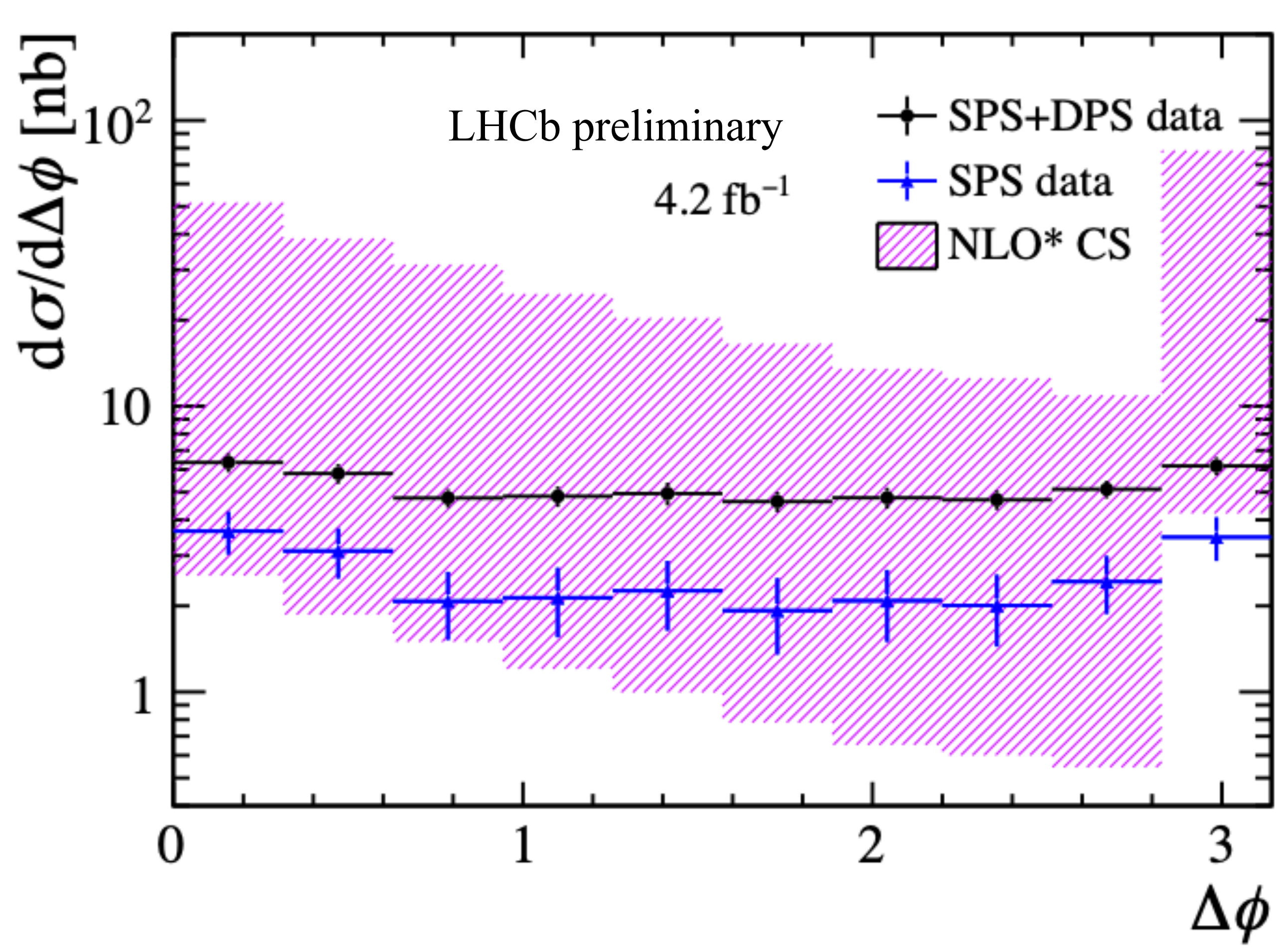
- DPS contribution is extracted from Δy distribution:
  - SPS contribution is negligible in range $1.8 < \Delta y < 2.5$
  - contribution from exotic X(6900) is small
  - data-driven template for DPS

$$\sigma_{eff} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{DPS}_{di-J/\psi}} = 13.1 \pm 1.8_{stat} \pm 2.3_{syst} \text{ mb}$$

Measurements are consistent with NLO* CS prediction from Lansberg and Shao [Phys. Rev. Lett. 111, 122001]

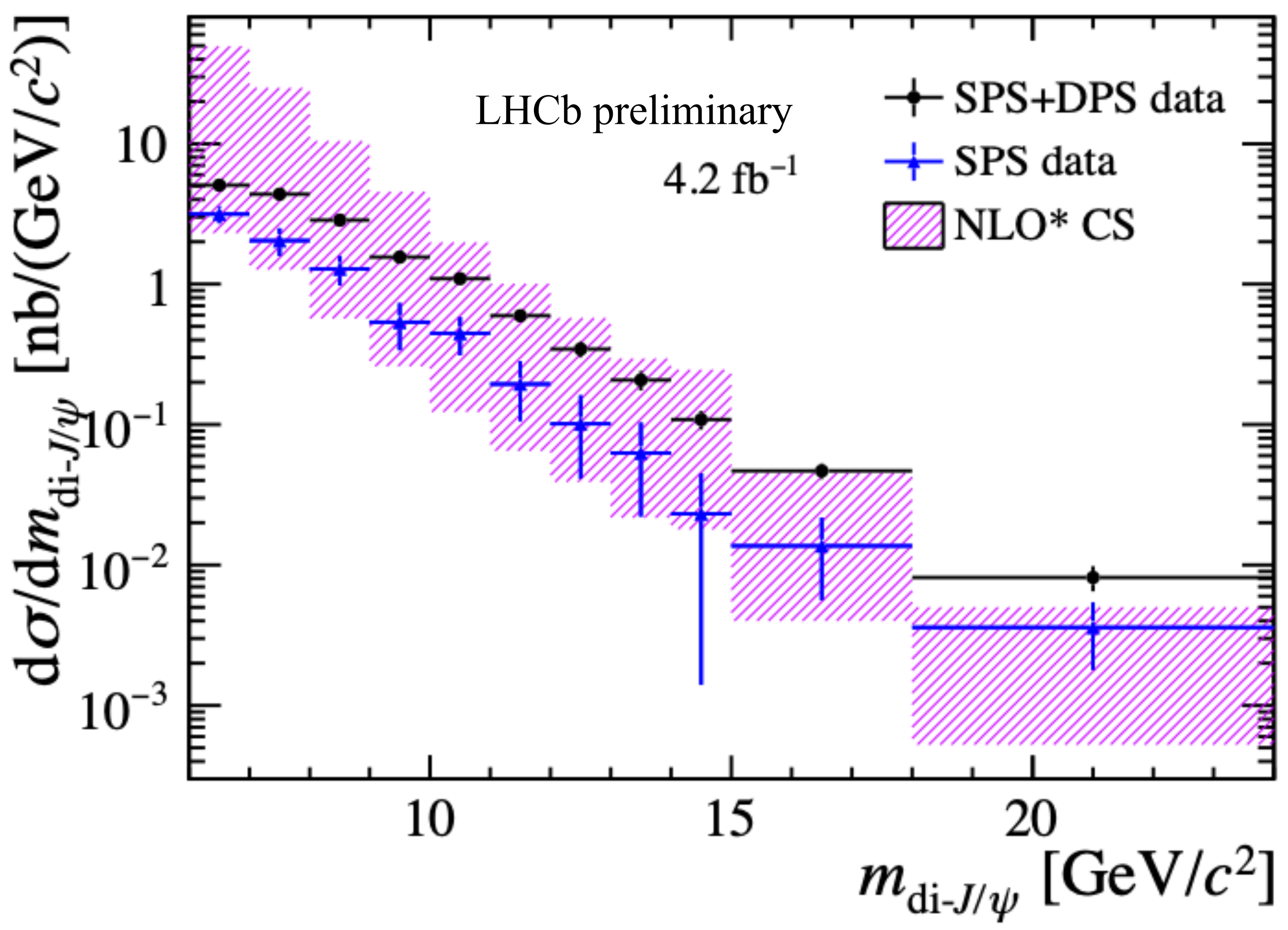


$d\sigma/d\Delta y$



$d\sigma/d\Delta\phi$

LHCb-PAPER-2023-022

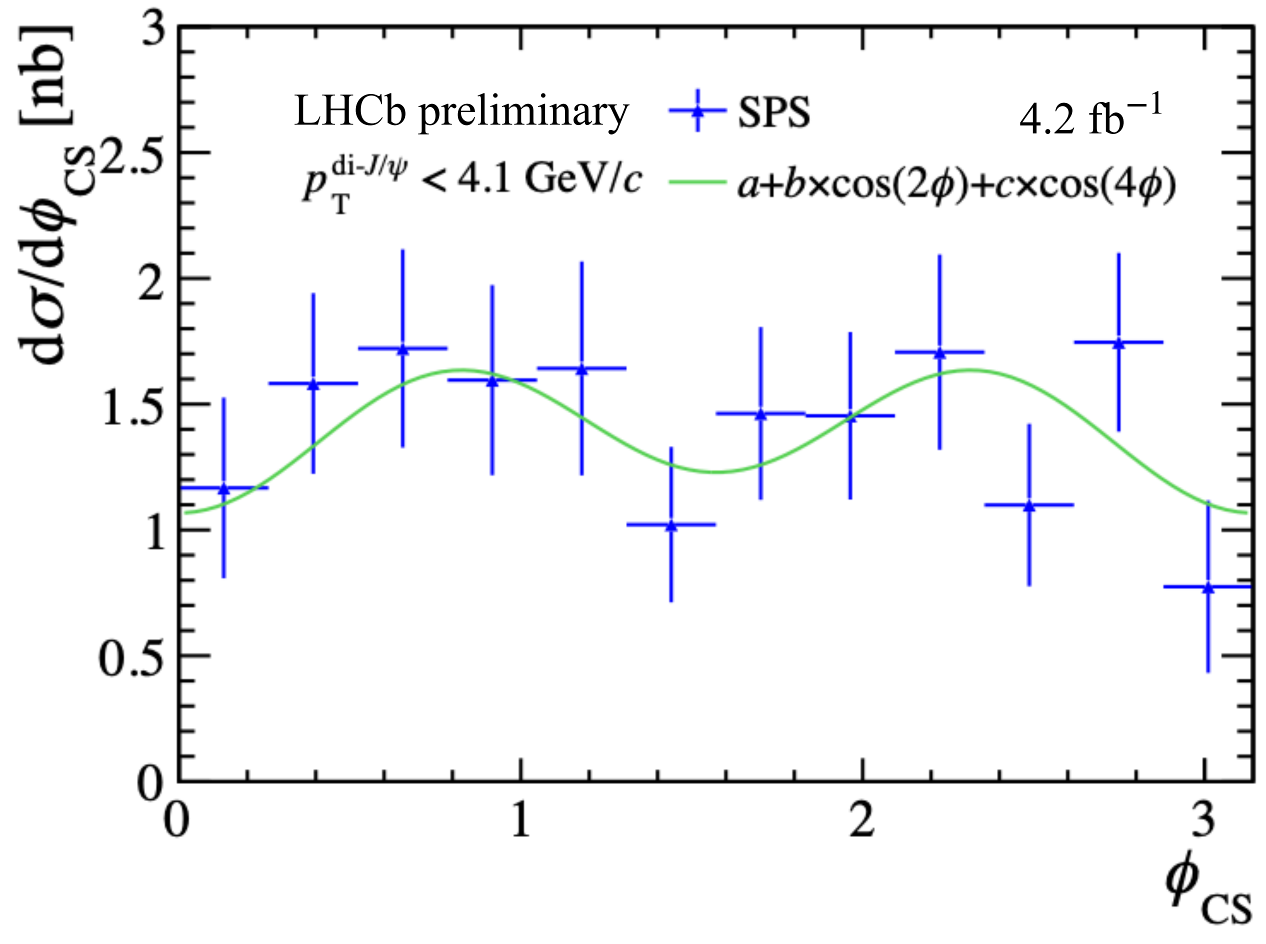


$d\sigma/dm_{\text{di-}J/\psi}$

$J/\psi + J/\psi$ production

Gluon TMD

- Gluon TMD can be probed using ϕ_{CS} distribution -
  - azimuthal angle of J/ψ in Collins-Soper frame



ϕ_{CS} distribution for SPS

- SPS production $\sim a + b \times \cos 2\phi_{CS} + c \times \cos 4\phi_{CS}$, coefficients encode information on TMD

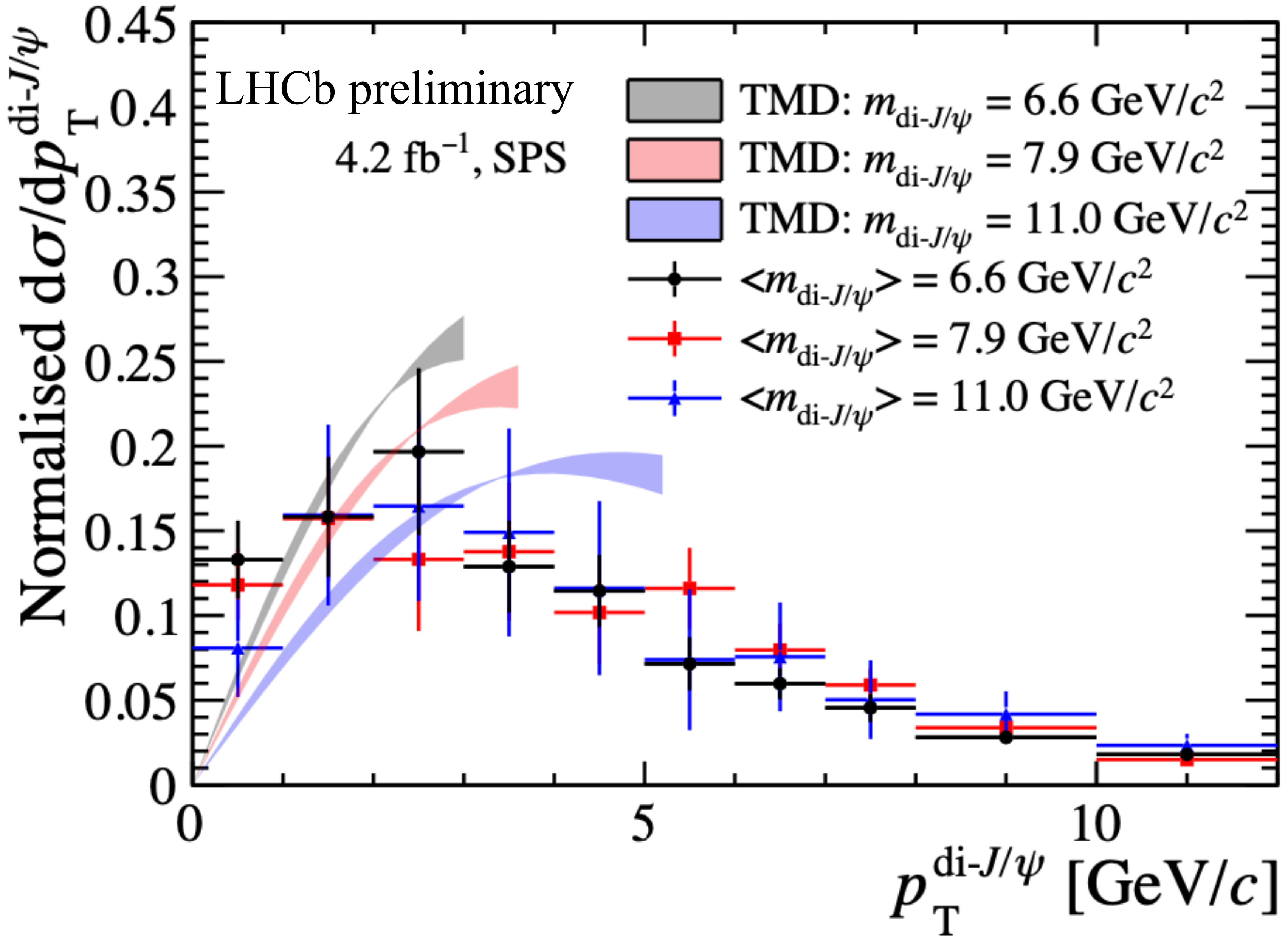
- Calculations are valid for $p_{\mathrm{T}}^{di-J/\psi} < \langle m_{di-J/\psi} \rangle /2 = 4.1\ \mathrm{GeV/c}$

$$\langle \cos 2\phi_{CS} \rangle = b/2a = -0.029 \pm 0.050_{stat} \pm 0.009_{syst}$$

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

The first estimate for TMD

Distributions show some discrepancies with theoretical predictions; more data are needed



LHCb-PAPER-2023-022, TMD: Scarpa [Eur. Phys. J. C 80 (2020) 87]

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

Production cross-section

- Data sample: $\mathscr{L} = 4.18 \pm 0.08\ \text{fb}^{-1}$, $p_T^{J/\psi,\psi(2S)} < 14$ GeV/c and $2.0 < y^{J/\psi,\psi(2S)} < 4.5$

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

- Differential study in bins of $\Delta y, \Delta\phi, p_T^{J/\psi-\psi(2S)}, y^{J/\psi-\psi(2S)}, m_{J/\psi-\psi(2S)}$

Measurements are consistent with NLO* CS prediction from Lansberg and Shao [Phys. Rev. Lett. 111, 122001]

- Ratio between $J/\psi + \psi(2S)$ and $J/\psi + J/\psi$ production

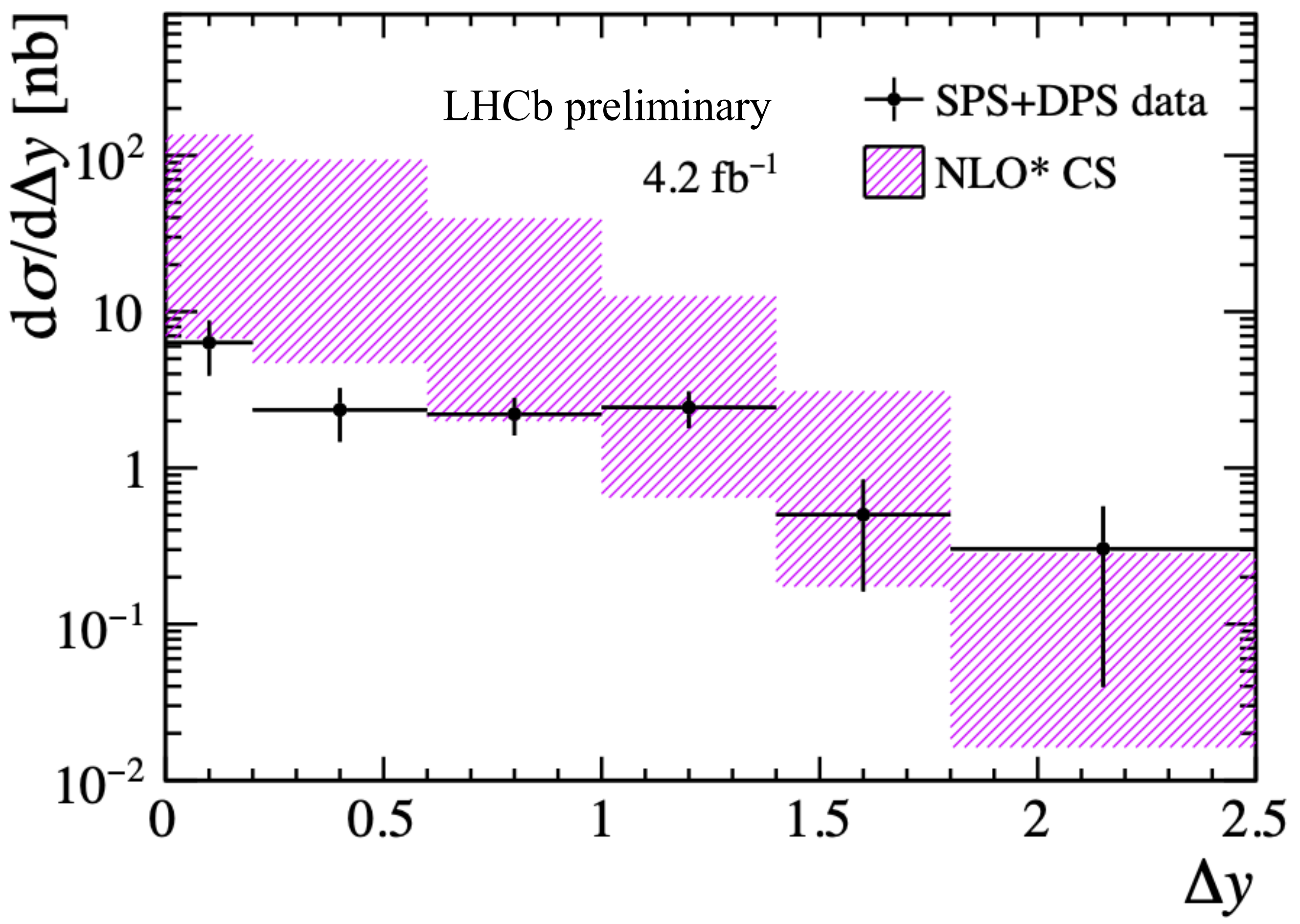
$$\mathscr{R} = \frac{\sigma_{J/\psi-\psi(2S)}}{\sigma_{J/\psi-J/\psi}} = 0.274 \pm 0.044_{stat} \pm 0.008_{syst}$$

$$\mathscr{R}_{SPS} = 0.94 \pm 0.30$$

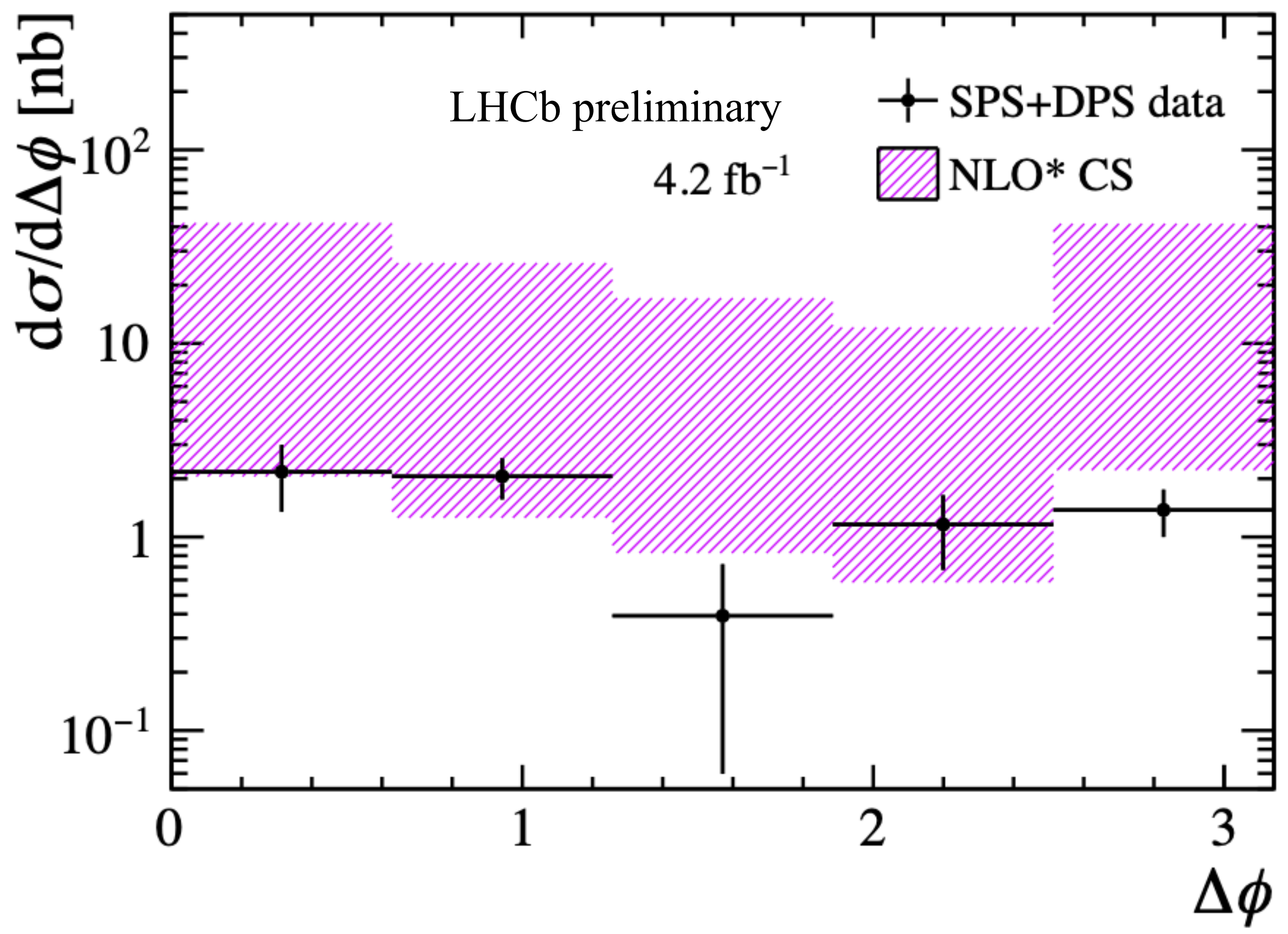
$$\mathscr{R}_{DPS} = 0.282 \pm 0.027$$

Consistent with DPS prediction

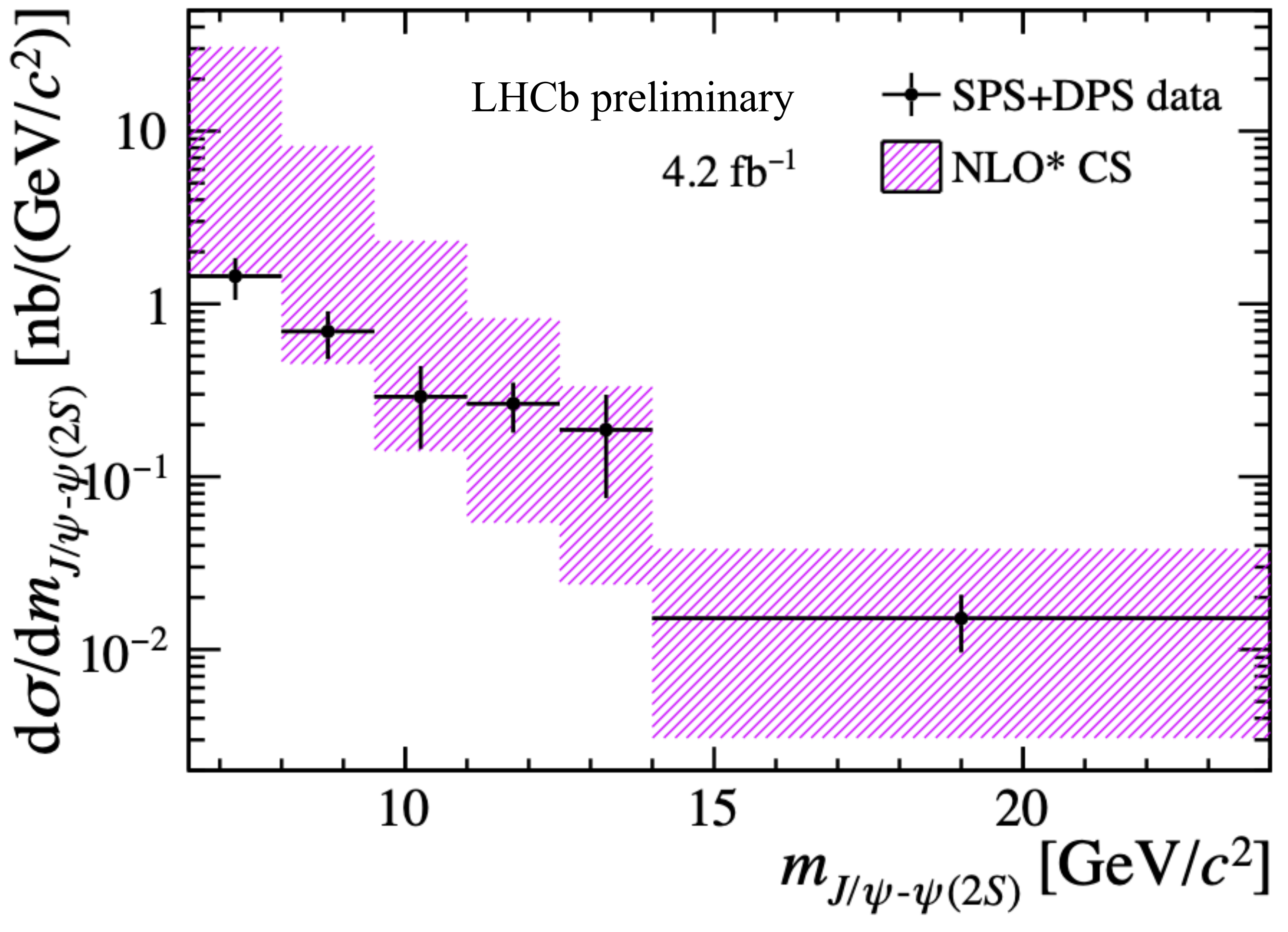
LHCb-PAPER-2023-023



dσ/dΔy



dσ/dΔϕ



dσ/dm$_{J/\psi\text{-}\psi(2S)}$

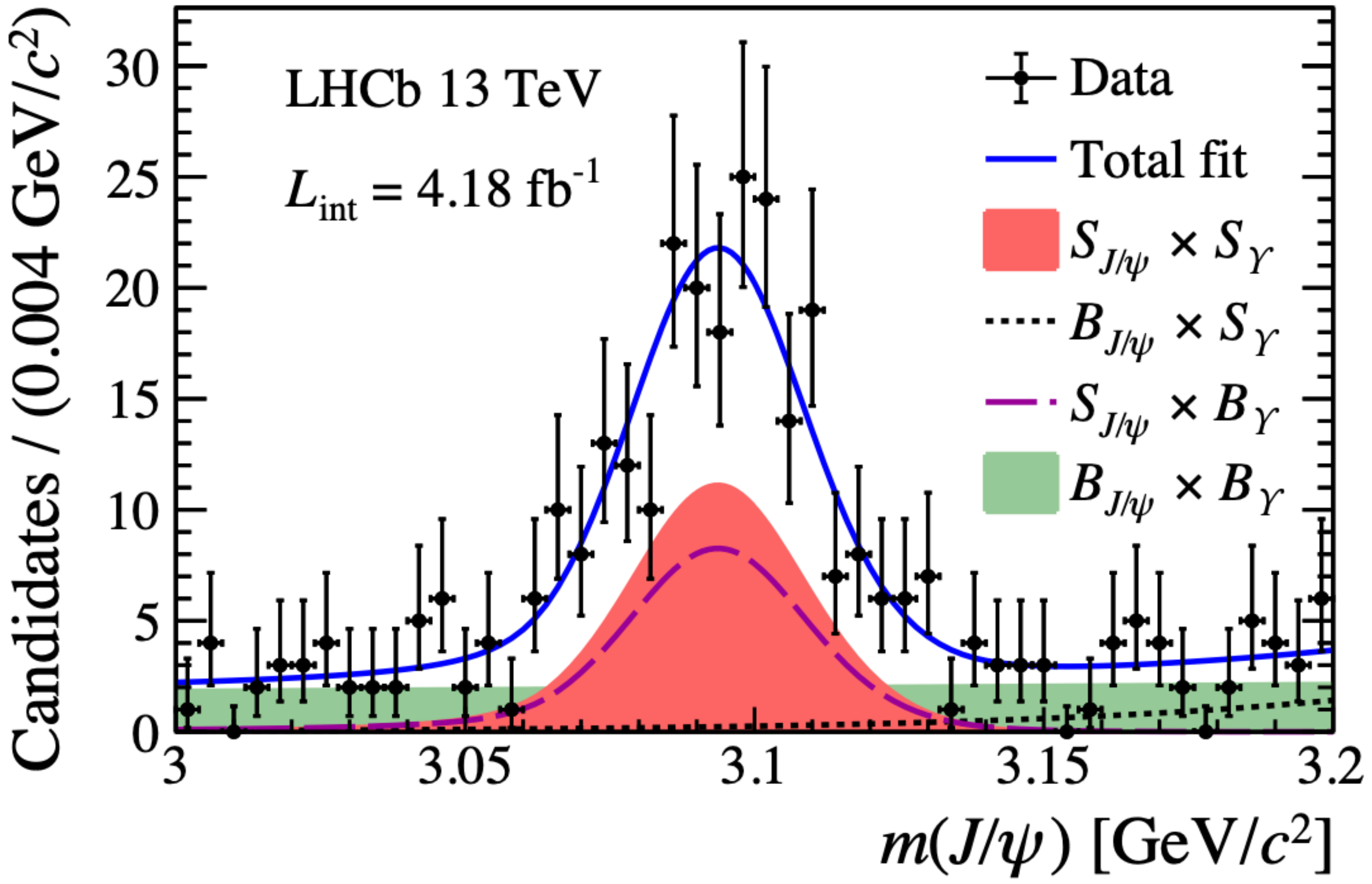
$J/\psi + \Upsilon(nS)$ production

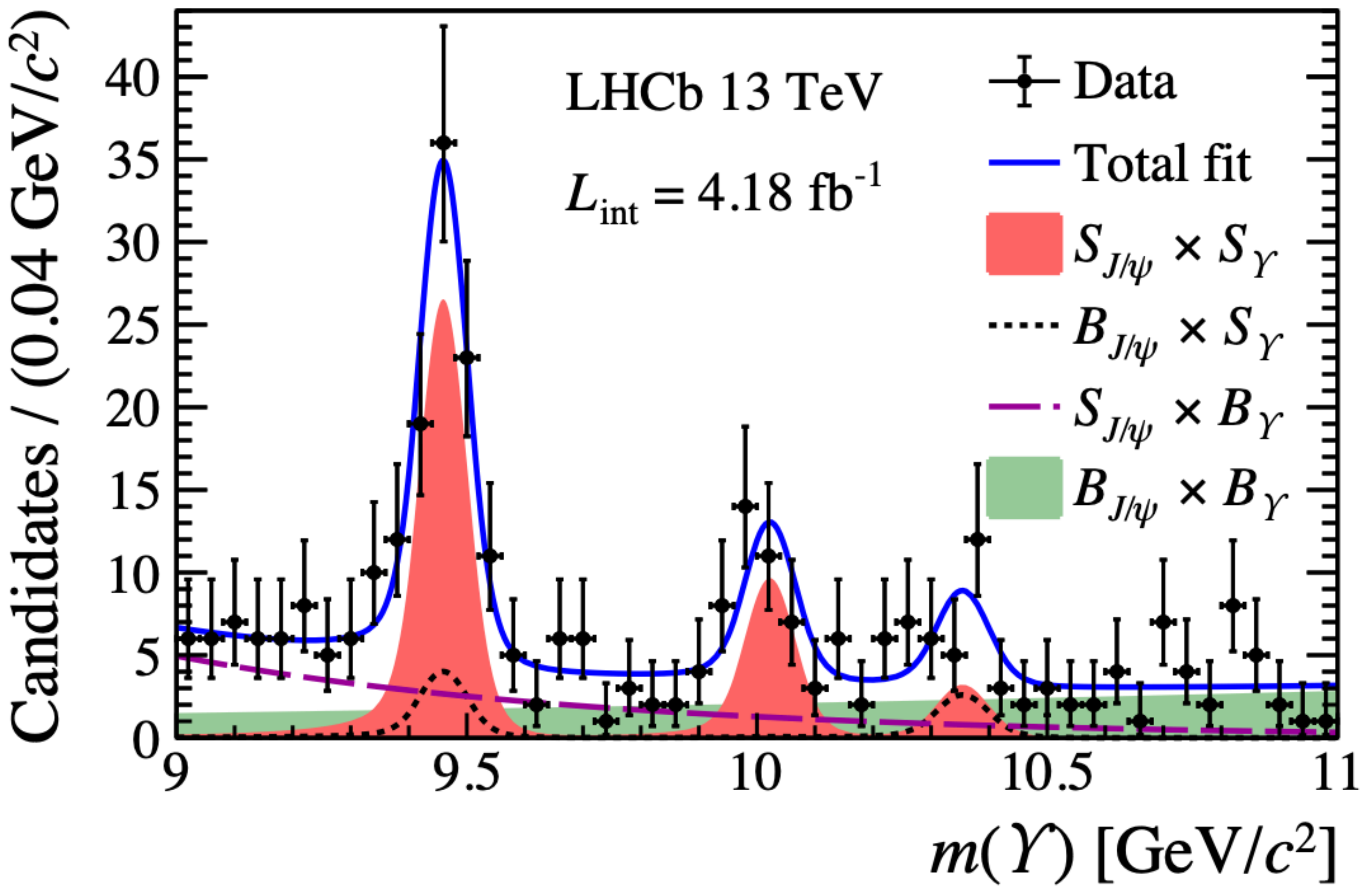
Production cross-section

- Data sample: $\mathscr{L} = 4.18 \pm 0.08\ \mathrm{fb}^{-1}$, $p_{\mathrm{T}}^{J/\psi(\Upsilon(nS))} < 10(30)$ GeV/c and $2.0 < y < 4.5$

Signal	Raw yields	N_{cor}	Significances
J/ψ–$\Upsilon(1S)$	76 ± 12	840 ± 140	$7.9\,\sigma$
J/ψ–$\Upsilon(2S)$	30 ± 7	370 ± 100	$4.9\,\sigma$
J/ψ–$\Upsilon(3S)$	10 ± 6	-	$1.7\,\sigma$

First observation of $J/\psi + \Upsilon(1S)$ associated production





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$J/\psi + \Upsilon(nS)$ production

Production cross-section

- Integrated cross-section

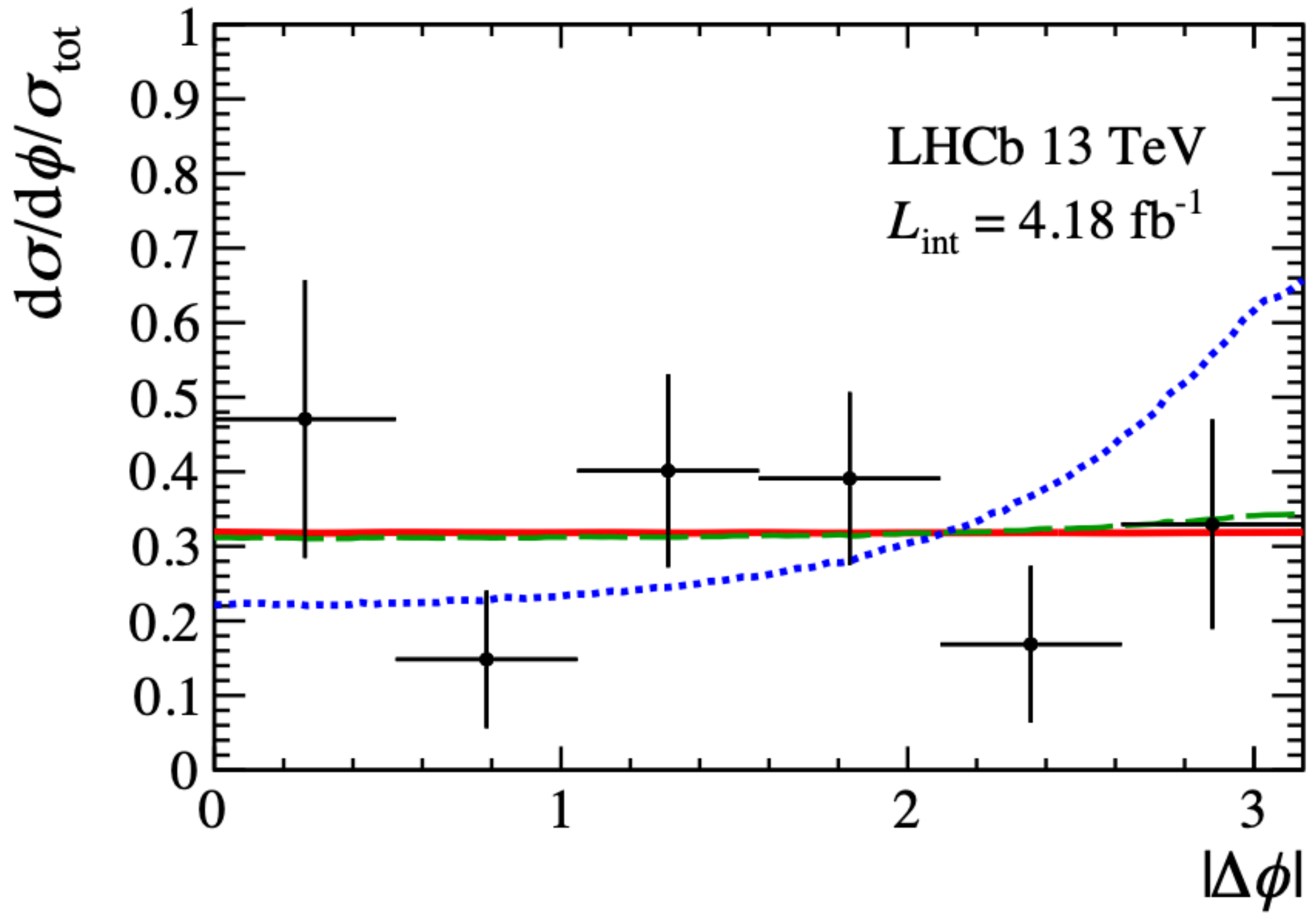
$$\sigma_{J/\psi-\Upsilon(1S)} = 133 \pm 22_{stat} \pm 7_{syst} \pm 3_{\mathscr{B}} \text{ pb} \quad (7.9\sigma)$$

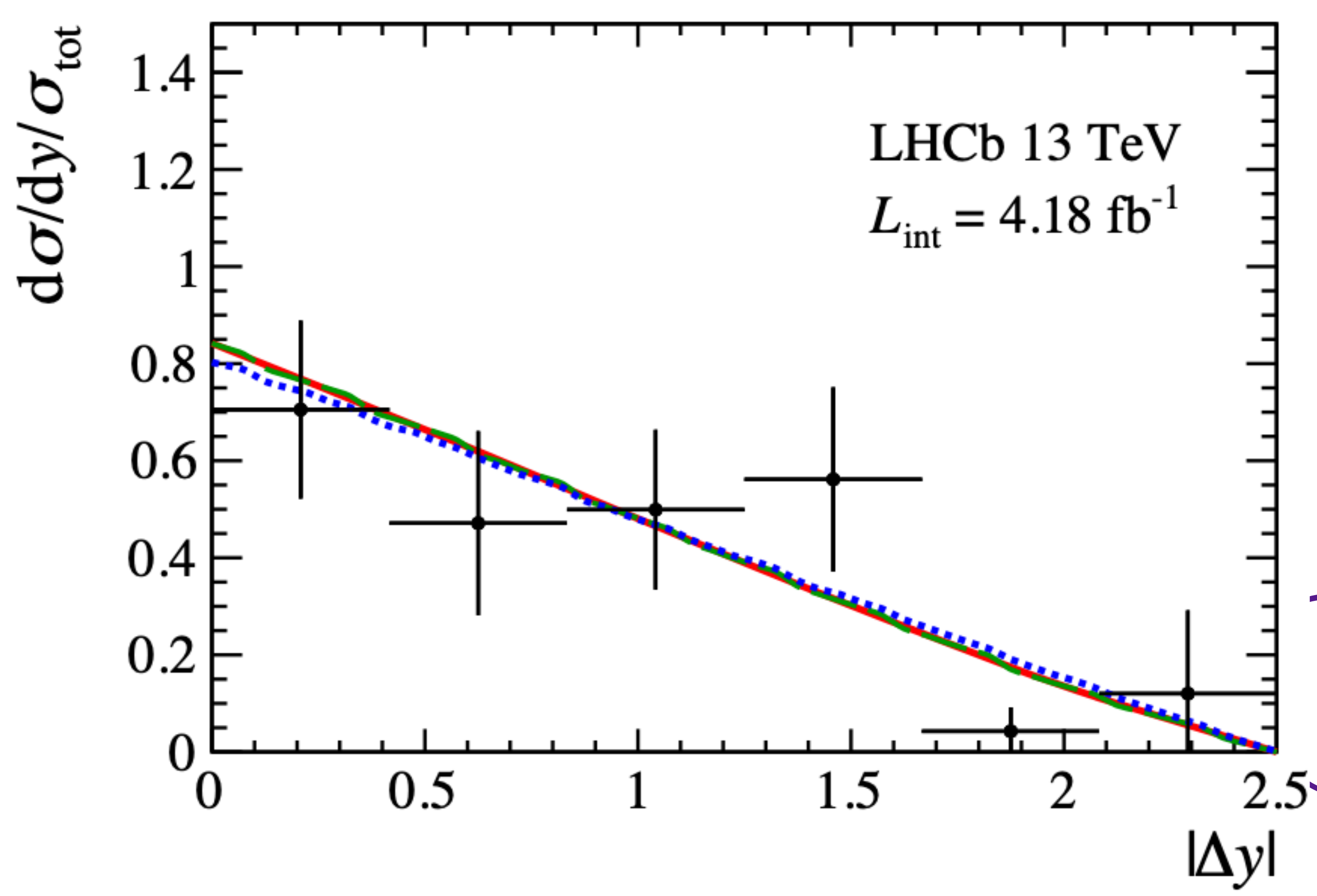
$$\sigma_{J/\psi-\Upsilon(2S)} = 76 \pm 21_{stat} \pm 4_{syst} \pm 7_{\mathscr{B}} \text{ pb} \quad (4.9\sigma)$$

- Differential study for $J/\psi + \Upsilon(1S)$ in bins of Δy, $\Delta\phi$, $p_{\mathrm{T}}^{J/\psi}$, $p_{\mathrm{T}}^{\Upsilon(1S)}$, $p_{\mathrm{T}}^{J/\psi-\Upsilon(1S)}$, and $m_{J/\psi-\Upsilon(1S)}$

Production is strongly dominated by DPS

Impossible to extract SPS to test CS and CO contribution





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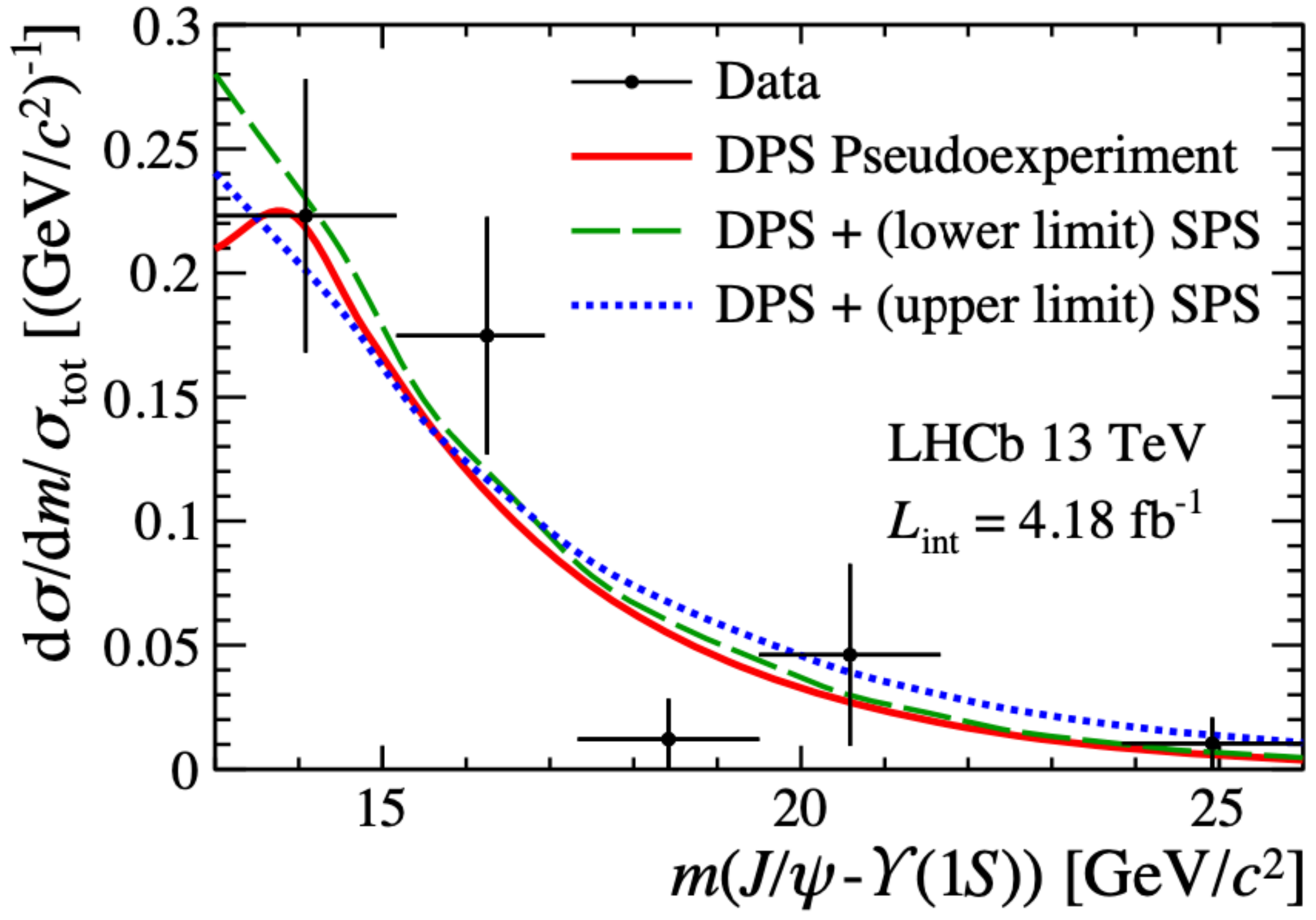

$J/\psi + \Upsilon(nS)$ production

SPS and DPS separation

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- DPS contribution is extracted using SPS prediction from *Shao and Zhang [Phys. Rev. Lett. 117, 062001]*

$$\sigma_{eff} = \frac{\sigma_{J/\psi} \times \sigma_{\Upsilon(1S)}}{\sigma^{DPS}_{J/\psi-\Upsilon(1S)}} = 26 \pm 14_{stat} \pm 2_{syst} \,{}^{+22_{SPS}}_{-3_{SPS}}\ \text{mb}$$

$$\sigma_{eff} = \frac{\sigma_{J/\psi} \times \sigma_{\Upsilon(2S)}}{\sigma^{DPS}_{J/\psi-\Upsilon(2S)}} = 14 \pm 5_{stat} \pm 1_{syst} \,{}^{+7_{SPS}}_{-1_{SPS}}\ \text{mb}$$

Results are consistent with both DPS and SPS+DPS mechanisms present

More data are needed to separate and test SPS CO mechanism

Associated production

Reality

- $J/\psi + J/\psi$ production:
  - ✓ small SPS CO contribution - ***results are consistent with NLO* CS within large uncertainties***
  - ✓ DPS contribution is important at large J/ψ Δy - ***limited by LHCb acceptance***
  - ✓ test gluon TMD - ***some discrepancies with theory predictions***

- $J/\psi + \psi(2S)$ production:
  - ✓ feed-down contribution depends on the production mechanism - ***consistent with DPS prediction***
  - \- SPS and DPS separation - ***large uncertainties***

- $J/\psi + \Upsilon(nS)$ production:
  - \- dominant SPS CO contribution - ***more data needed***

New QCD tests from associated production studies

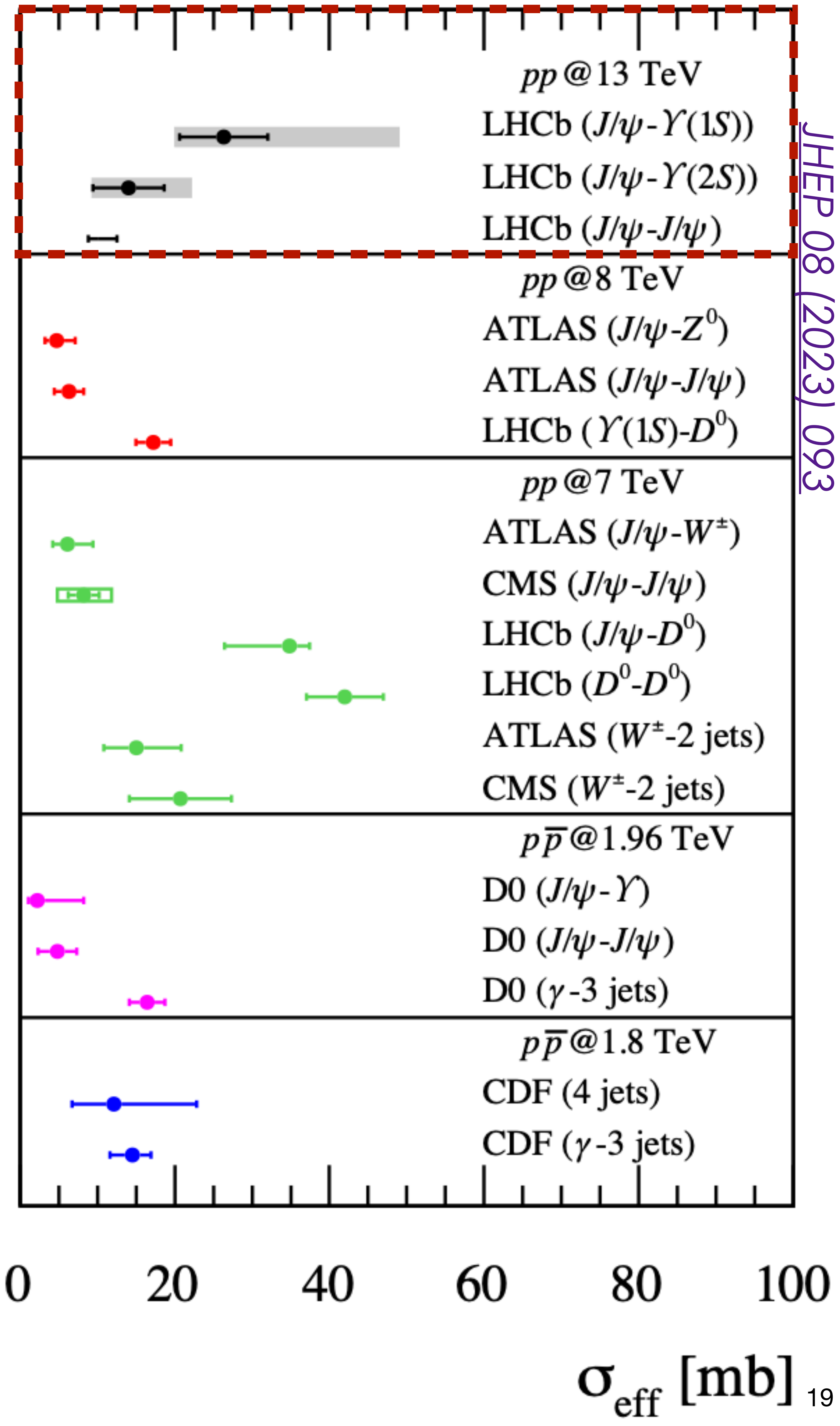
Associated production

Reality

✓ **Effective cross-section** σ_{eff} is assumed to be **universal**

- *all results are consistent with each other and other existing measurements*
- *some results have large uncertainties*

Good agreement
More data are needed for precise tests



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Summary

- **Many new results** on charmonia associated production
  - $J/\psi + J/\psi$: LHCb-PAPER-2023-022
  - $J/\psi + \psi(2S)$: LHCb-PAPER-2023-023
  - $J/\psi + \Upsilon(nS)$: JHEP 08 (2023) 093
- Production measurements allow to **test different QCD scales**
  - the first gluon TMD study
  - study of SPS and DPS
- Most of the **tests are limited by**:
  - statistical precision
  - theoretical inputs

Thank you for attention!

Backup

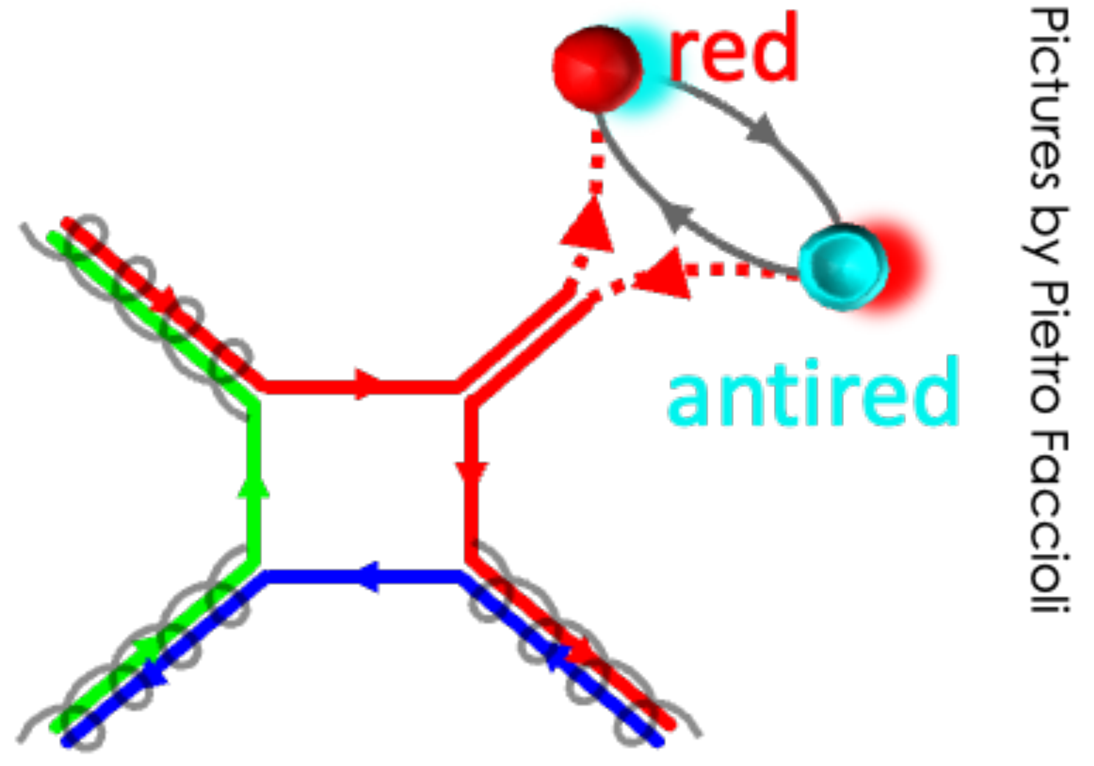
Existing measurements of quarkonia production

Some of LHCb results

- **η_c** production: EPJC 75(2015) 311, EPJC 80(2020) 191
- **η_c(2S)** production in b-decays: EPJC 77(2017) 609
- **J/ψ, ψ(2S)** and **Υ(nS)** production and polarization: JHEP 10(2015) 172, EPJC 80(2020) 185, Eur.Phys.J.C 74(2014) 2835 JHEP 11(2015) 103, JHEP 07(2018) 134...
- **χ_c** production and polarization: JHEP 10(2013) 115, PLB 714(2012) 215-223
- **χ_b** production: Eur.Phys.J.C 74(2014) 3092

Colour Singlet Model (CSM)

- **Main assumption**: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} as the final-state quarkonium



Colour Singlet state

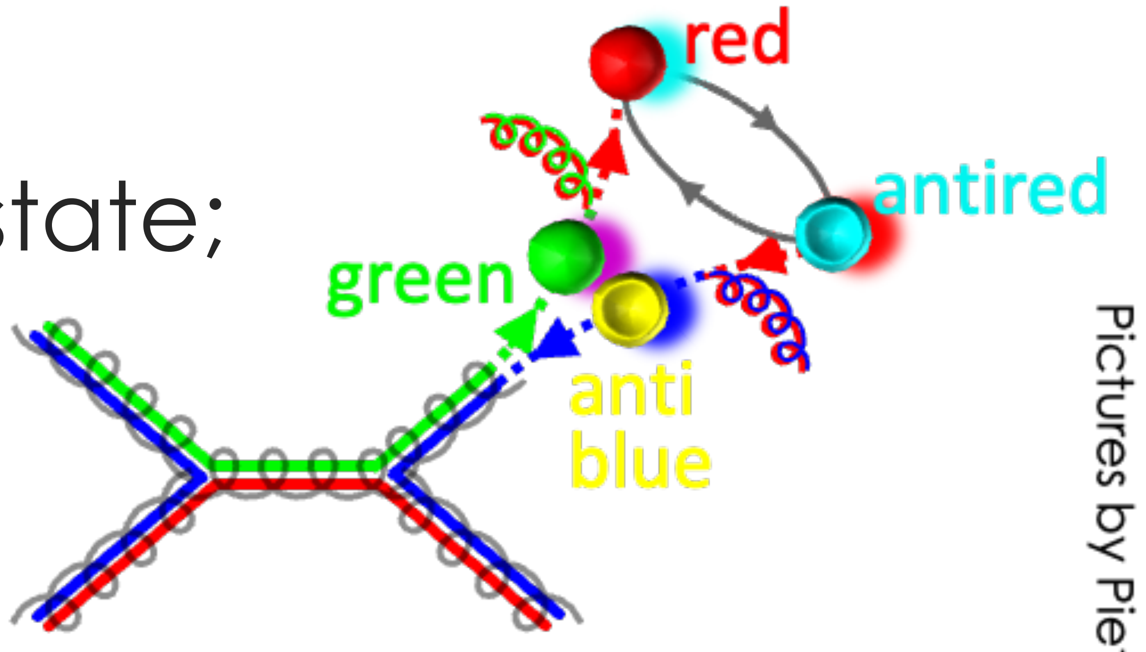
- Cross-section depends on the colour-singlet (CS) wave function or its derivative

- **Cross-section**:

$$d\sigma^{CSM}_{[H+X]} = \sum_{i,j} \int dx_i dx_j f_i(x_i, \mu_F) f_j(x_j, \mu_F) d\sigma_{i+j \to Q\bar{Q}+X}(\mu_R, \mu_F) \langle Q\bar{Q} \rangle$$

- **Problems**:
  - uncanceled IR divergence in χ_{cJ} and h_c production
  - description of hadroproduction at low p_T

Non-Relativistic QCD



Pictures by Pietro Faccioli

- **Main assumption:** all viable colours and J^{PC} allowed for the intermediate $Q\bar{Q}$ state; hadronisation from a colour-octet (CO) state requires a soft-gluon emission

- Cross-section is parametrised using **Long-Distance Matrix Elements** (**LDME**s)

- **Heavy-Quark Spin-Symmetry**: links between CS and CO LDMEs of different quarkonium states:

$$\langle \mathcal{O}_{1,8}^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle \mathcal{O}_{1,8}^{J/\psi}(^3S_1)\rangle$$

$$\langle \mathcal{O}_{8}^{\eta_c}(^3S_1)\rangle = \langle \mathcal{O}_{8}^{J/\psi}(^1S_0)\rangle$$

$$\langle \mathcal{O}_{8}^{\eta_c}(^1P_1)\rangle = 3\langle \mathcal{O}_{8}^{J/\psi}(^3P_0)\rangle$$

- **Cross-section**:

$$d\sigma^{NRQCD}_{[H+X]} = \sum_{i,j,n} \int dx_i dx_j f_i(x_i,\mu_F) f_j(x_j,\mu_F) d\sigma_{i+j\to(Q\bar{Q})_n+X}(\mu_R,\mu_F,\mu_\Lambda)\left\langle O_n^H \right\rangle$$

- **Problems:**
  - unphysical behaviour of the $J^{PC} = 1^{--}$ integrated production cross-section
  - simultaneous description of linked states in limited p_{T}

NRQCD is found to be the most used, because it is based on an Effective Field Theory and can be improved systematically

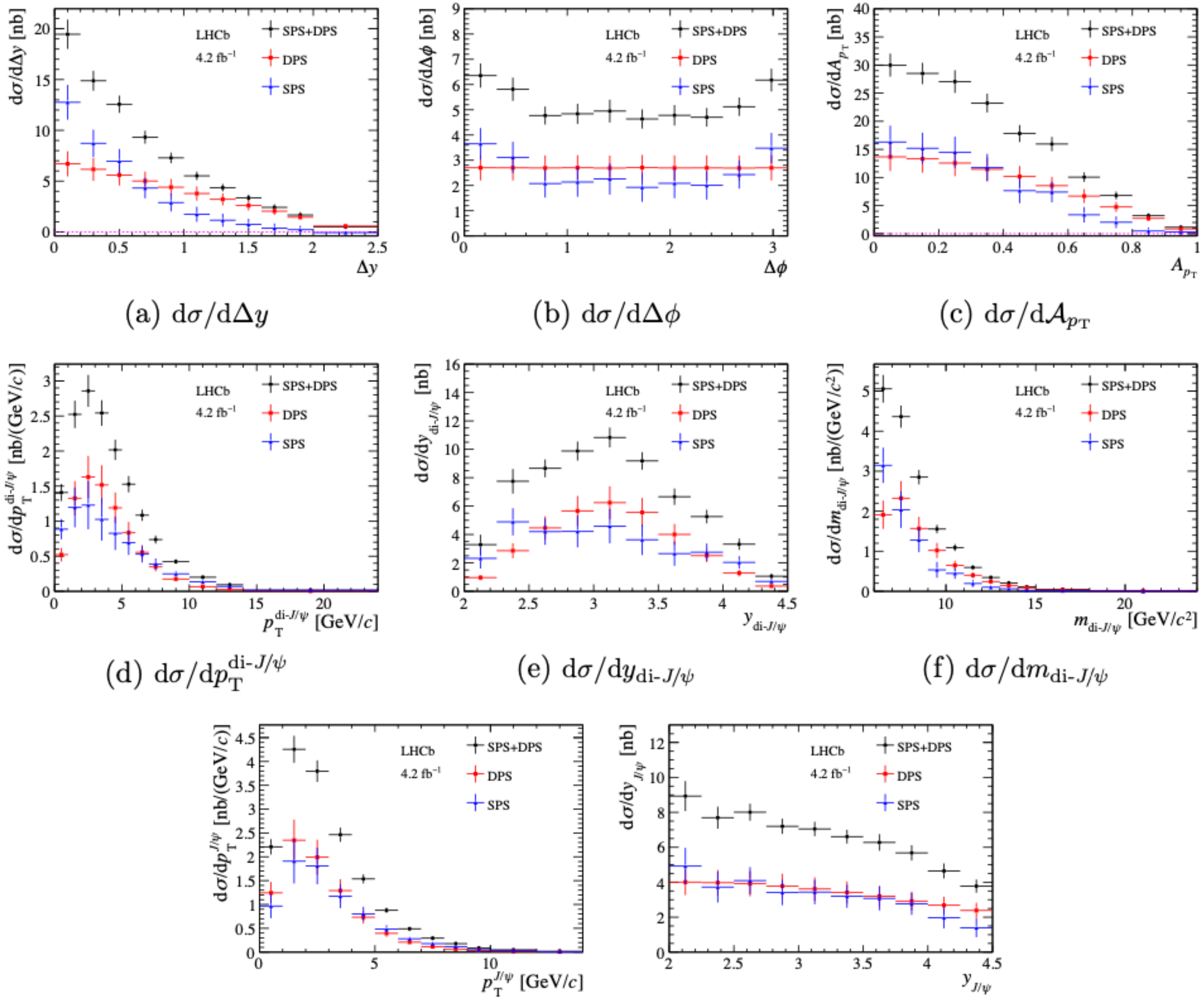
$J/\psi + J/\psi$ production

Cross-section

- Fiducial range: $p_T < 14$ GeV/c and $2.0 < y < 4.5$

$$\sigma_{di-J/\psi} = 16.36 \pm 0.28_{stat} \pm 0.88_{syst} \text{ nb}$$

- Differential study in bins of $\Delta y, \Delta\phi, p_T^{J/\psi}, y^{J/\psi}, p_T^{di-J/\psi}, y^{di-J/\psi}, m_{di-J/\psi}$, and $\mathscr{A}_{p_T} = \left| \frac{p_T^{J/\psi_1} - p_T^{J/\psi_2}}{p_T^{J/\psi_1} + p_T^{J/\psi_2}} \right|$



(a) $d\sigma/d\Delta y$ (b) $d\sigma/d\Delta\phi$ (c) $d\sigma/d\mathcal{A}_{p_T}$

(d) $d\sigma/dp_T^{di\text{-}J/\psi}$ (e) $d\sigma/dy_{di\text{-}J/\psi}$ (f) $d\sigma/dm_{di\text{-}J/\psi}$

(g) $d\sigma/dp_T^{J/\psi}$ (h) $d\sigma/dy_{J/\psi}$

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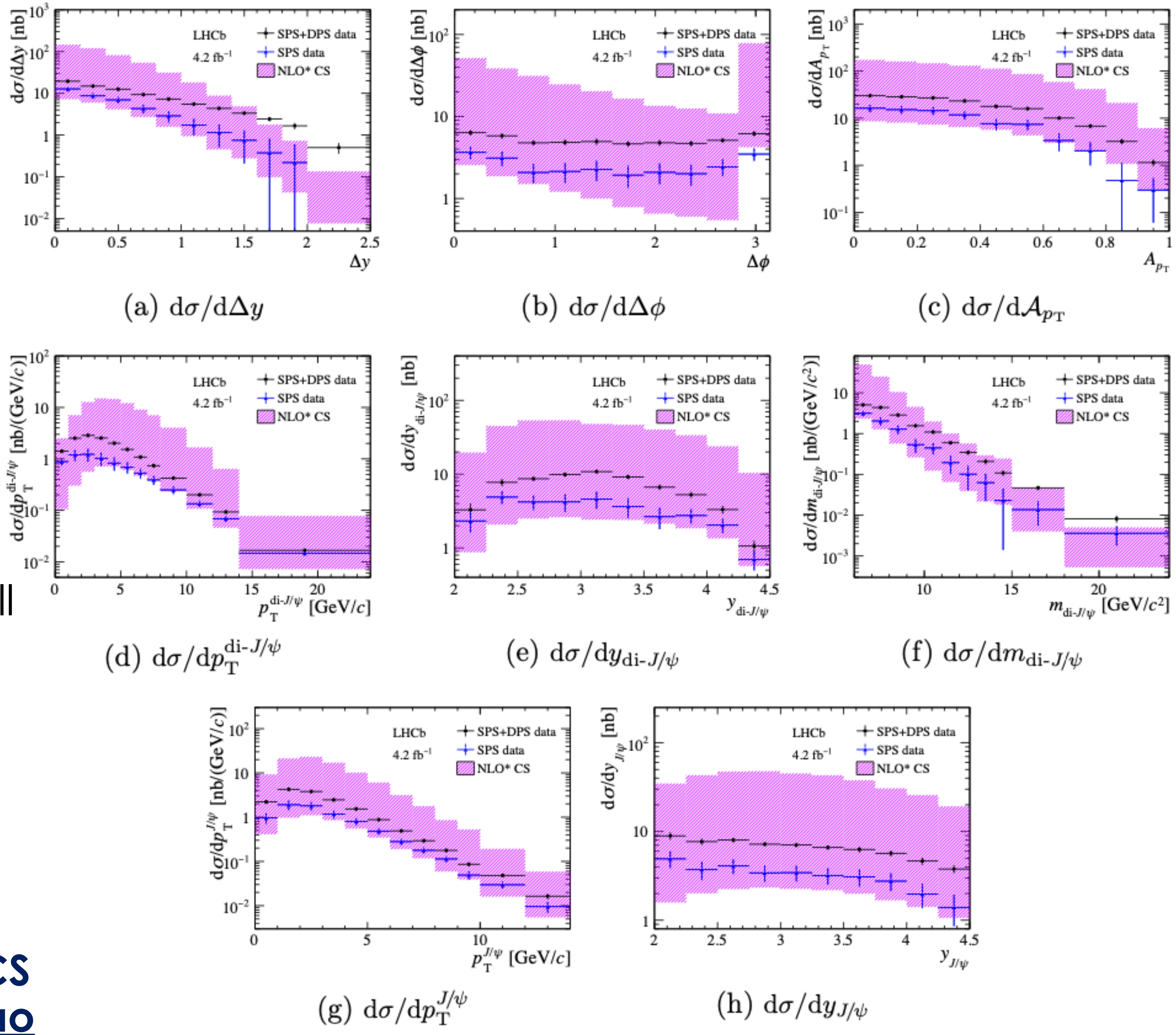
$J/\psi + J/\psi$ production

SPS and DPS separation

- DPS contribution is extracted from Δy distribution:
  - SPS contribution is negligible in range $1.8 < \Delta y < 2.5$
  - contribution from exotic X(6900) is small
  - data-driven template for DPS

$$\sigma_{eff} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{DPS}_{di-J/\psi}} = 13.1 \pm 1.8_{stat} \pm 2.3_{syst}$$

Measurements are consistent with NLO* CS prediction from J.P.Lansberg and H.-S.Shao



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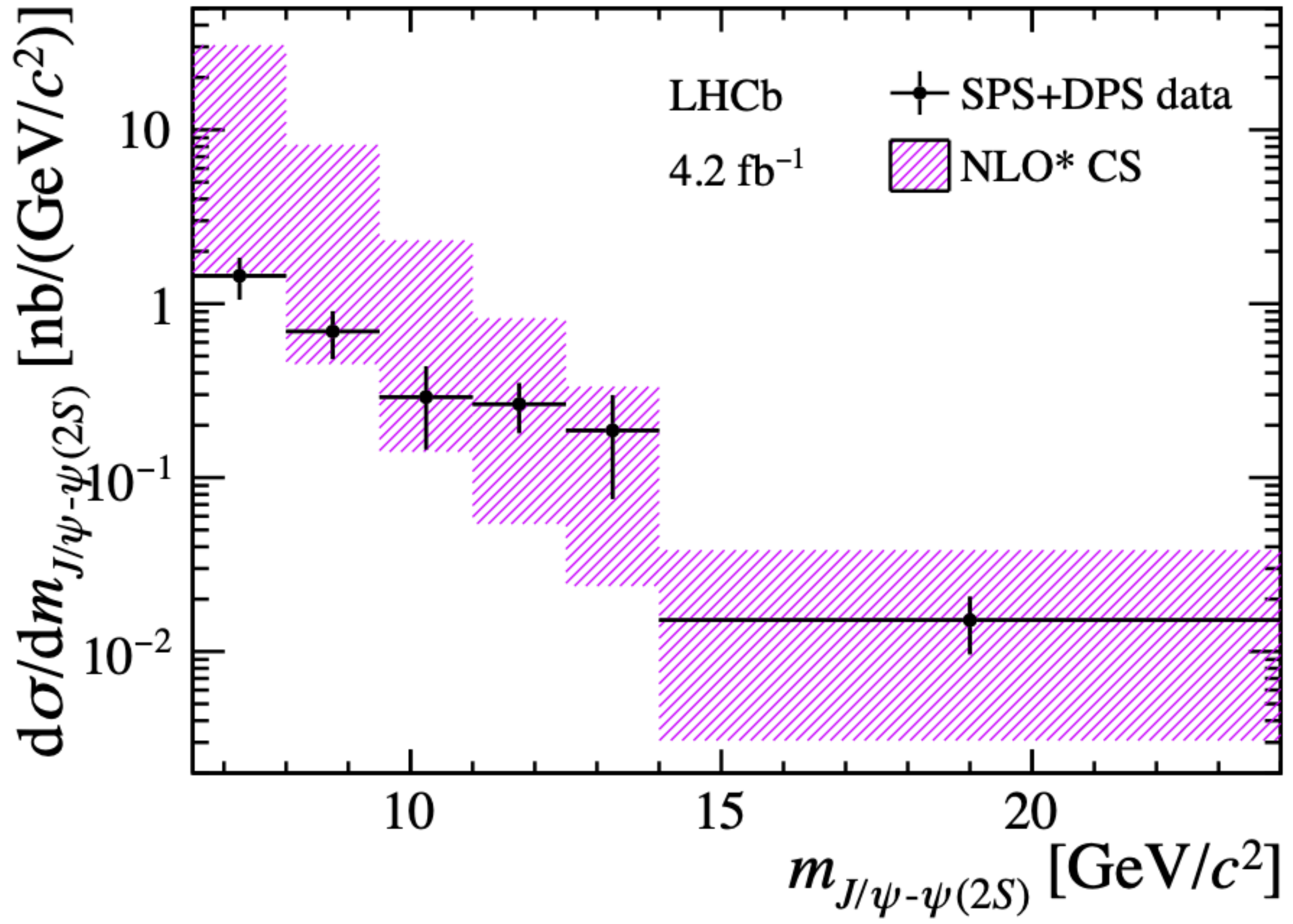
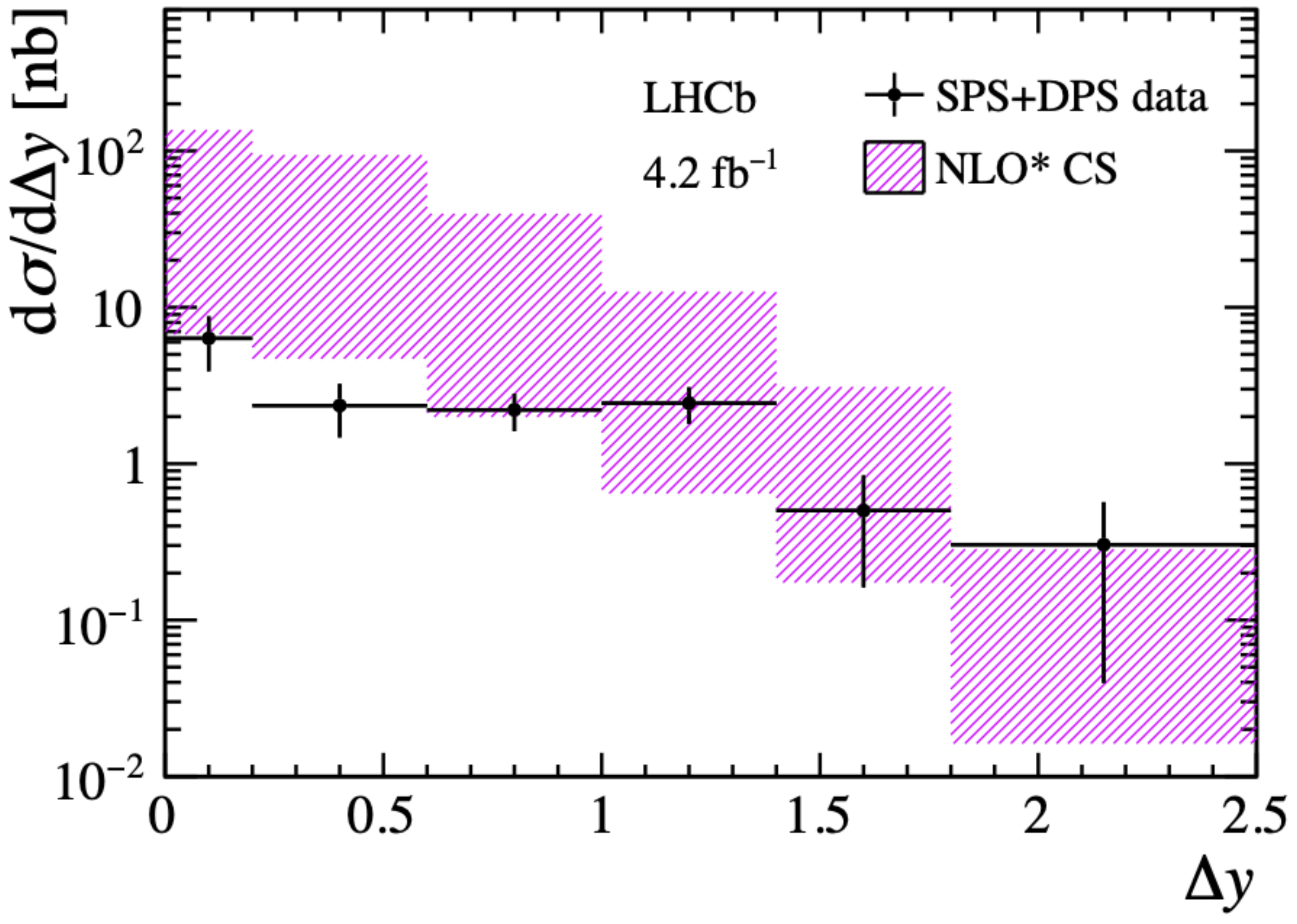
$J/\psi + \psi(2S)$ production

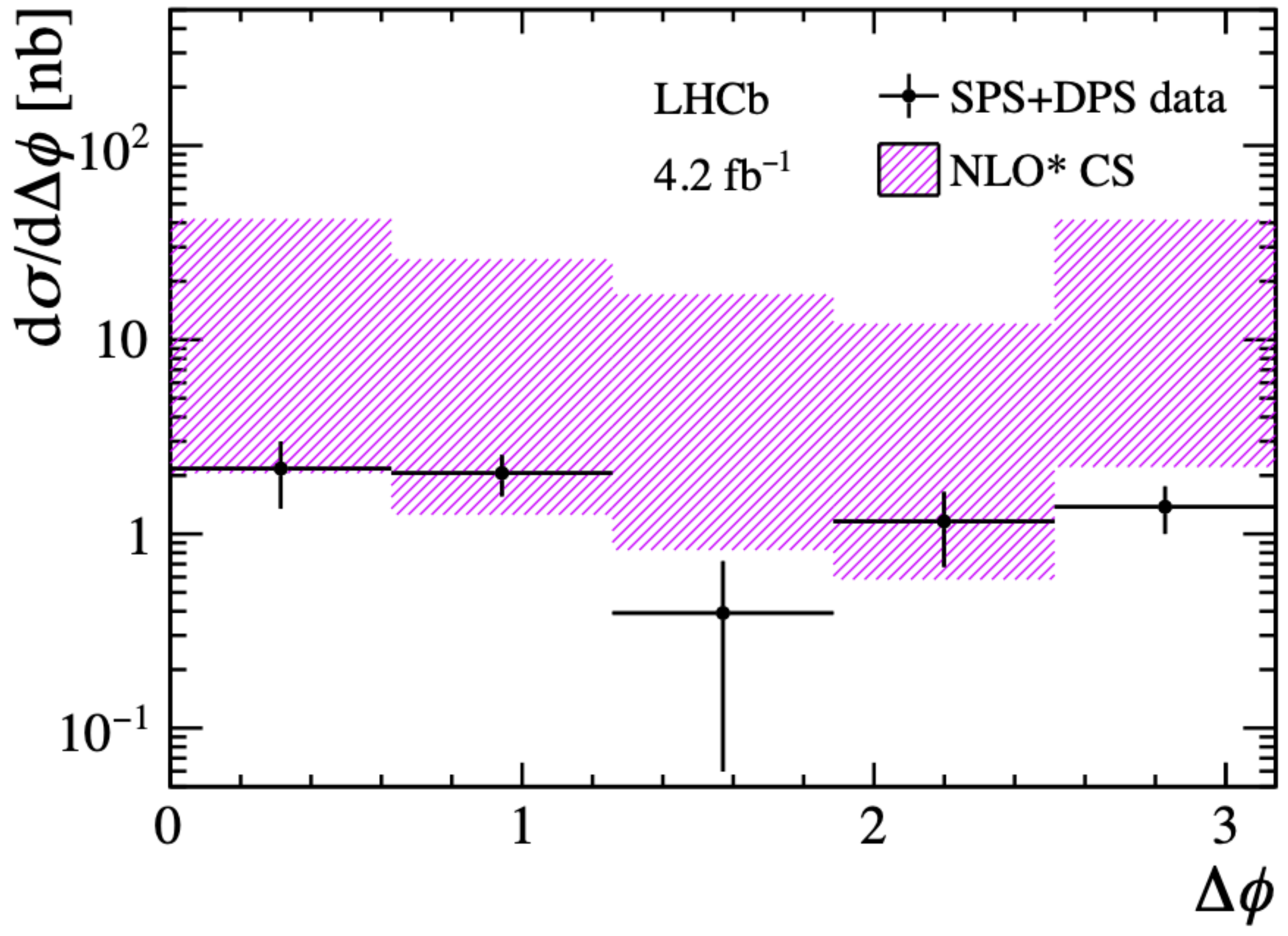
Differential cross-section



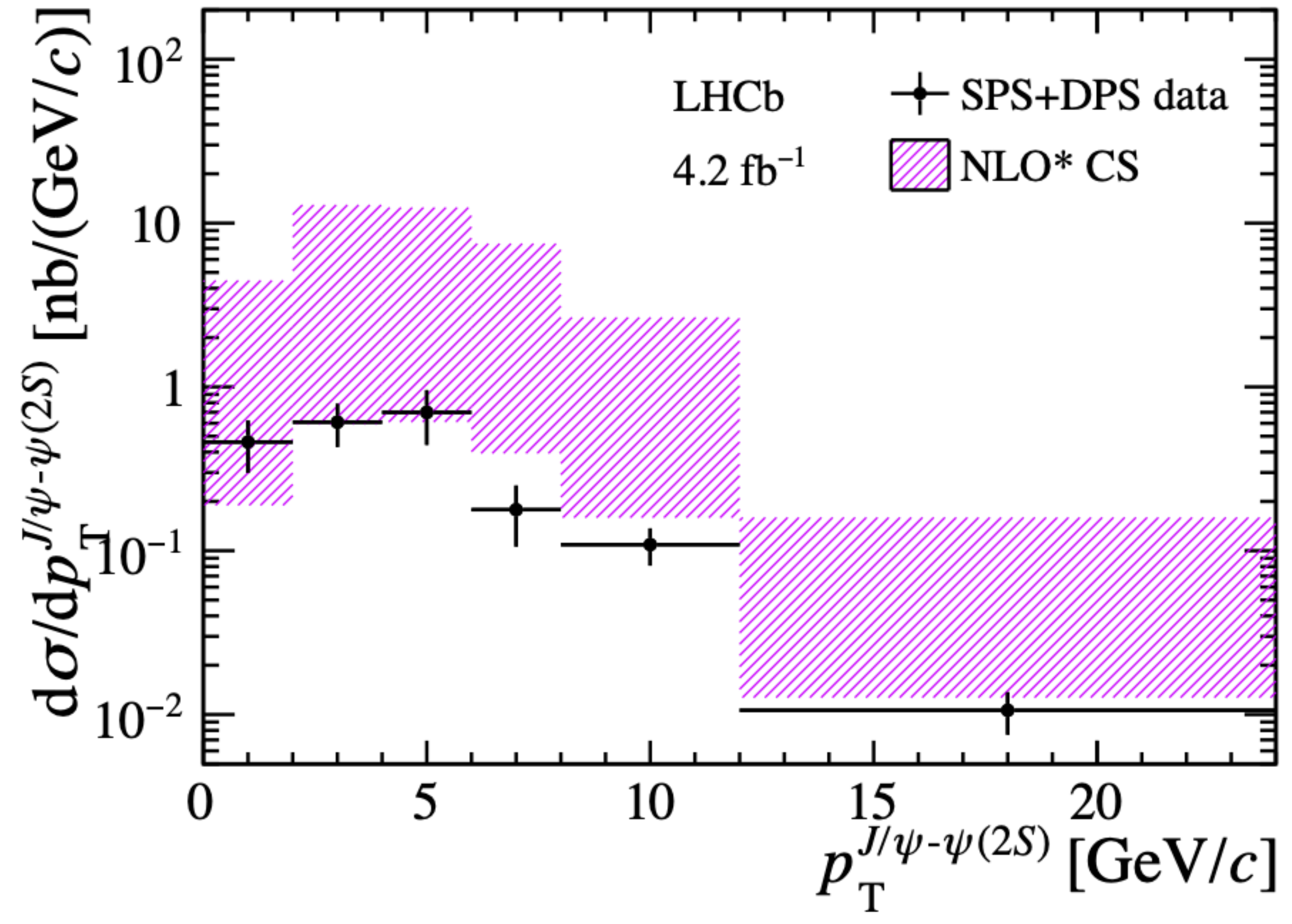
(e) $\mathrm{d}\sigma/\mathrm{d}m_{J/\psi\text{-}\psi(2S)}$



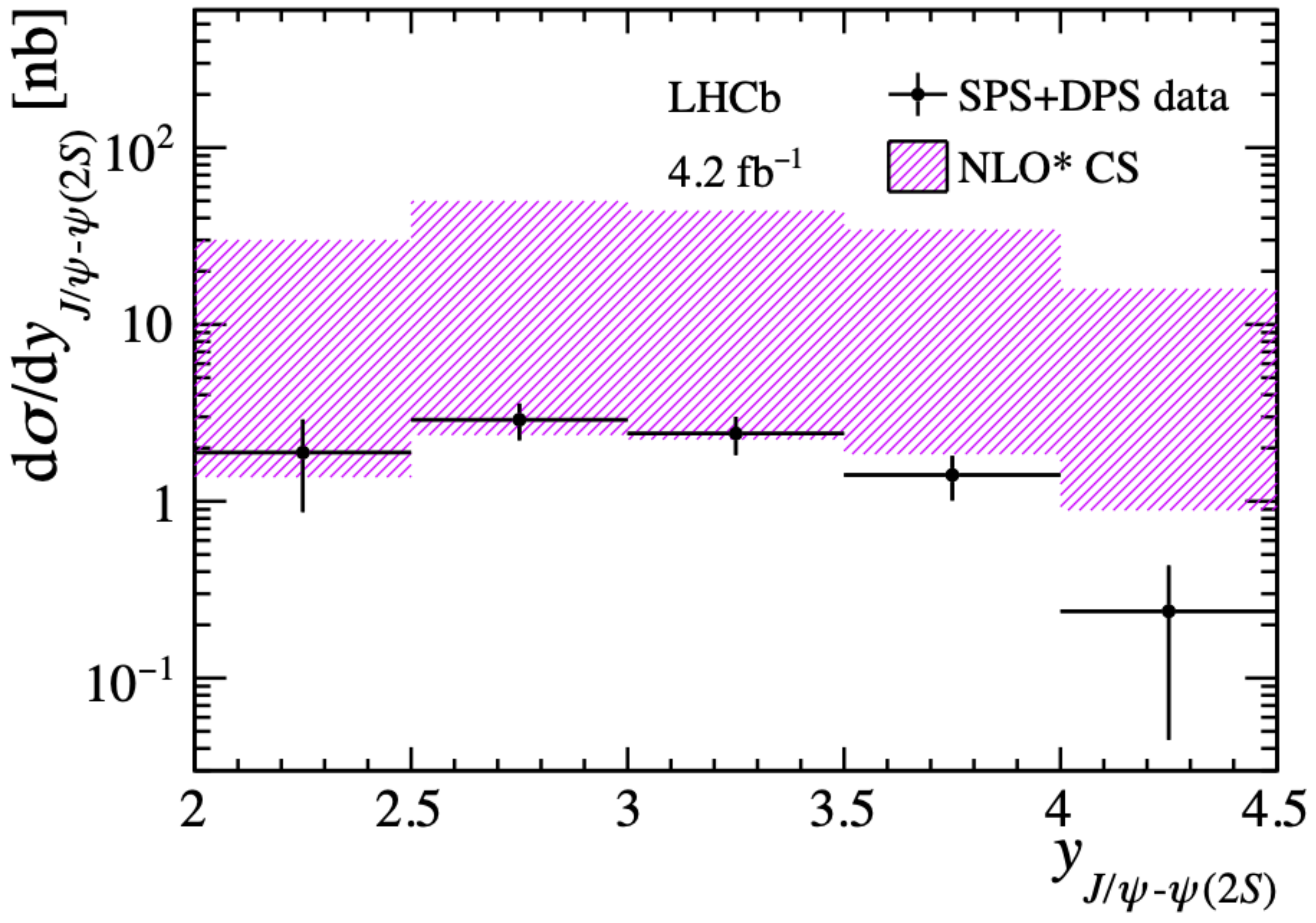
(a) $\mathrm{d}\sigma/\mathrm{d}\Delta y$



(b) $\mathrm{d}\sigma/\mathrm{d}\Delta\phi$



(c) $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{J/\psi\text{-}\psi(2S)}$



(d) $\mathrm{d}\sigma/\mathrm{d}y_{J/\psi\text{-}\psi(2S)}$

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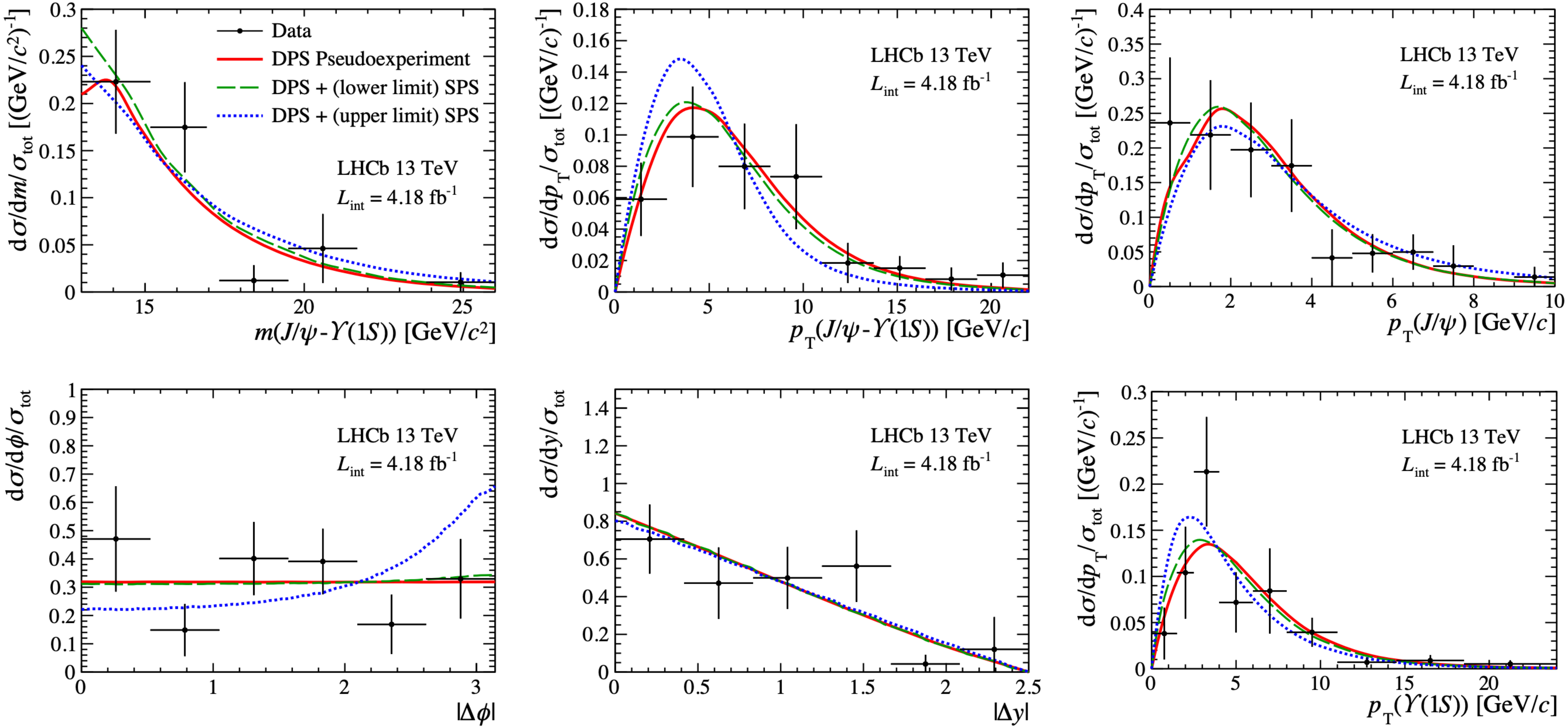
$J/\psi + \Upsilon(nS)$ production

Differential production cross-section



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