Study of charmonium and associated charmonium production in pp collisions at LHCb

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on behalf of LHCb collaborations

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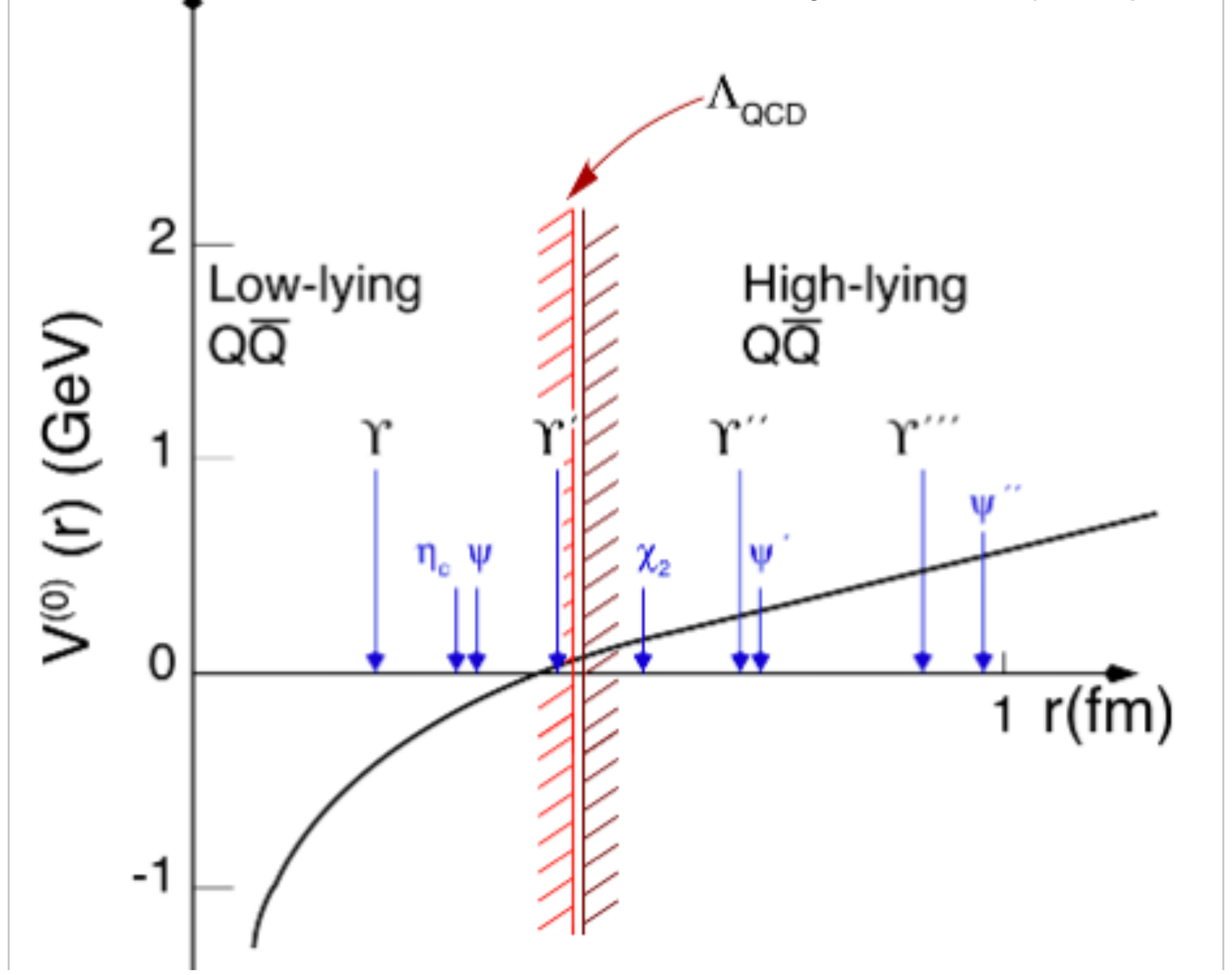
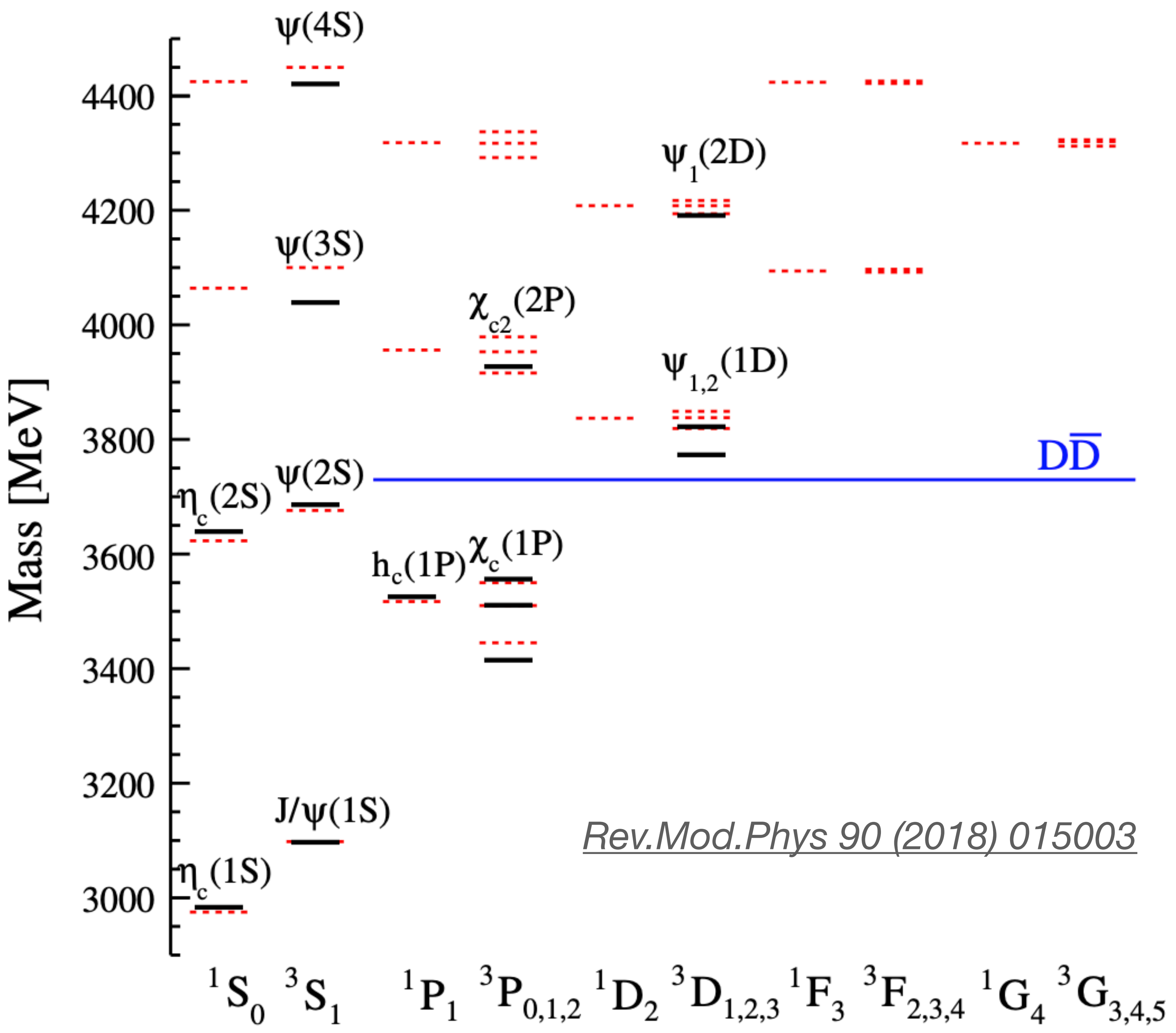
Charmonium system

- Charmonium — **bound state of $c\bar{c}$ quark pair**
- **Non-relativistic QCD object**
  - Velocity $v^2 \approx 0.3$
  - three intrinsic scales $m \gg mv \gg mv^2$
- **Ideal probe for different QCD scales**
- Decays to
  - $\eta_c(1S), \eta_c(2S)$: **hadrons** and $\gamma\gamma$
  - $J/\psi, \psi(2S)$: $\mu^+\mu^-/e^+e^-$ or **hadrons**
  - χ_{cJ}: ${}^3S_1\gamma$, ${}^3S_1\pi^+\pi^-$ or **hadrons**
  - h_c: ${}^1S_0\gamma$ or **hadrons**
- **Robust charged hadron identification at LHCb**
  - Access to all the charmonium states

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

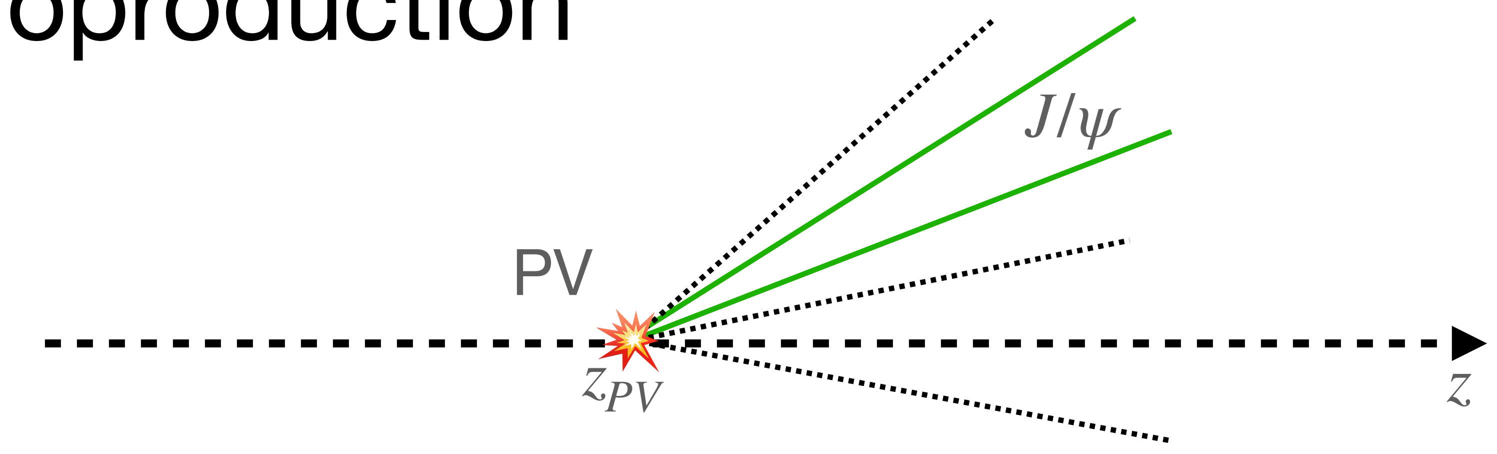




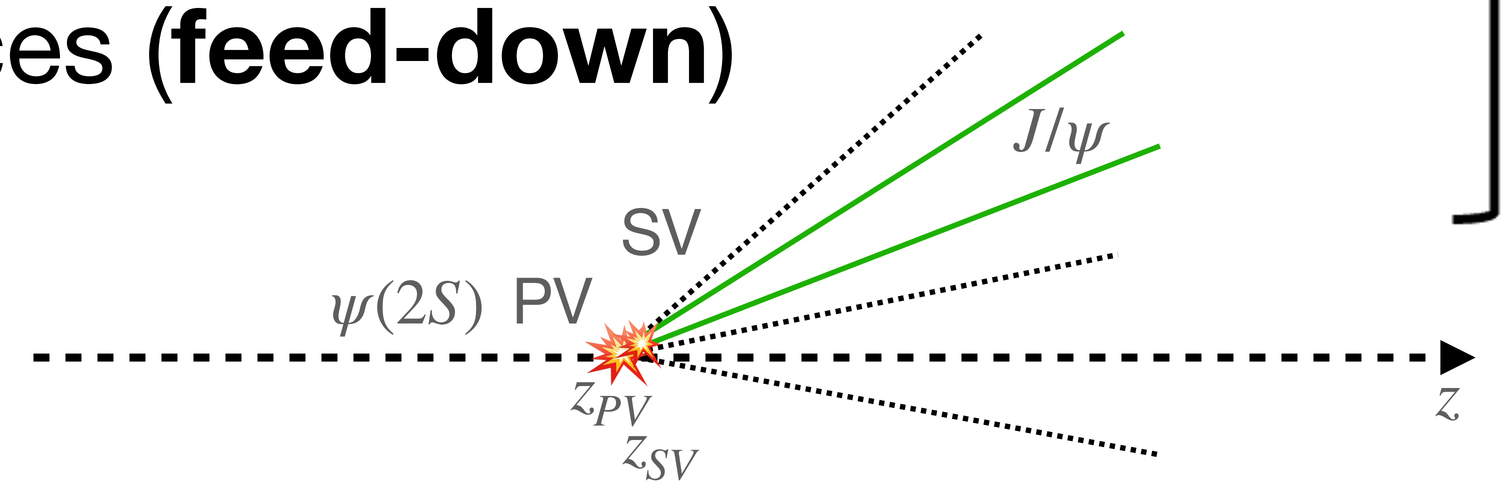
Rev.Mod.Phys 90 (2018) 015003

Charmonium production @ LHC

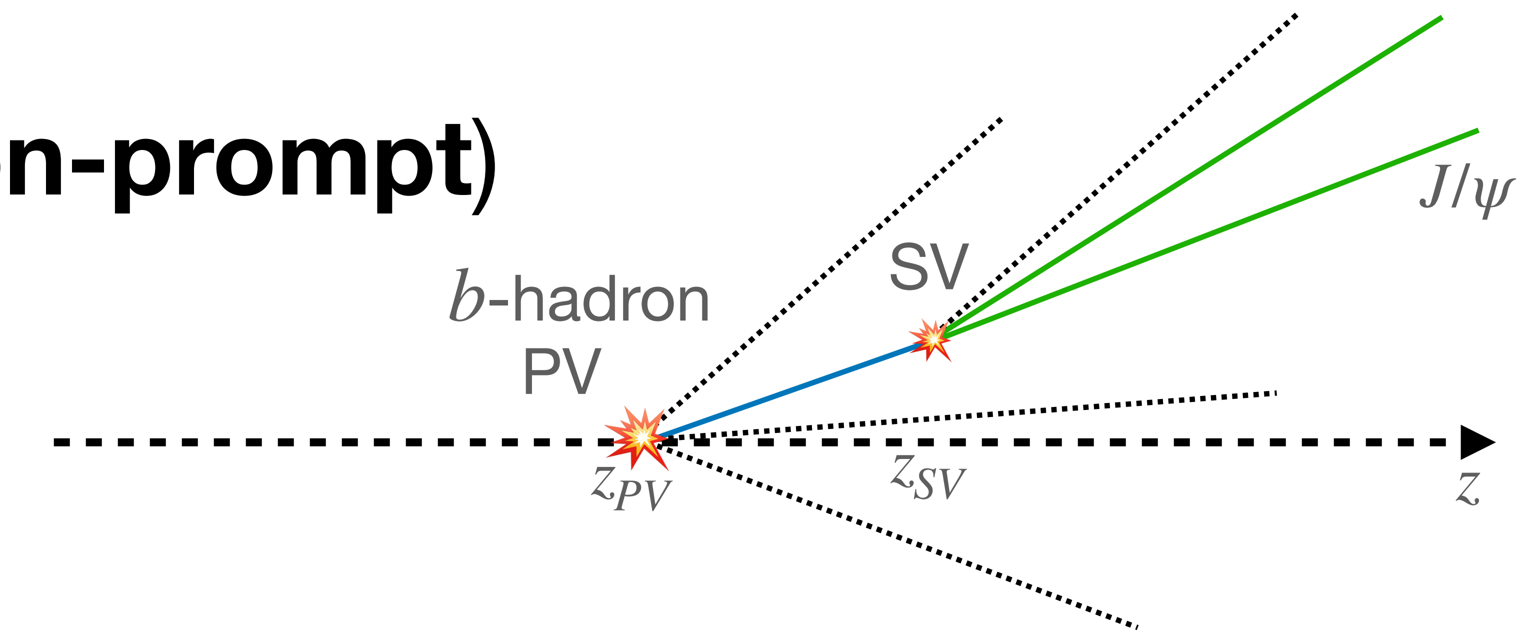
- Main production origin
  - **Prompt** (direct) hadroproduction



  - Decay of higher resonances (**feed-down**)



  - Production in b-hadron decays (**non-prompt**)



prompt production

distinguished using pseudo-proper decay time

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

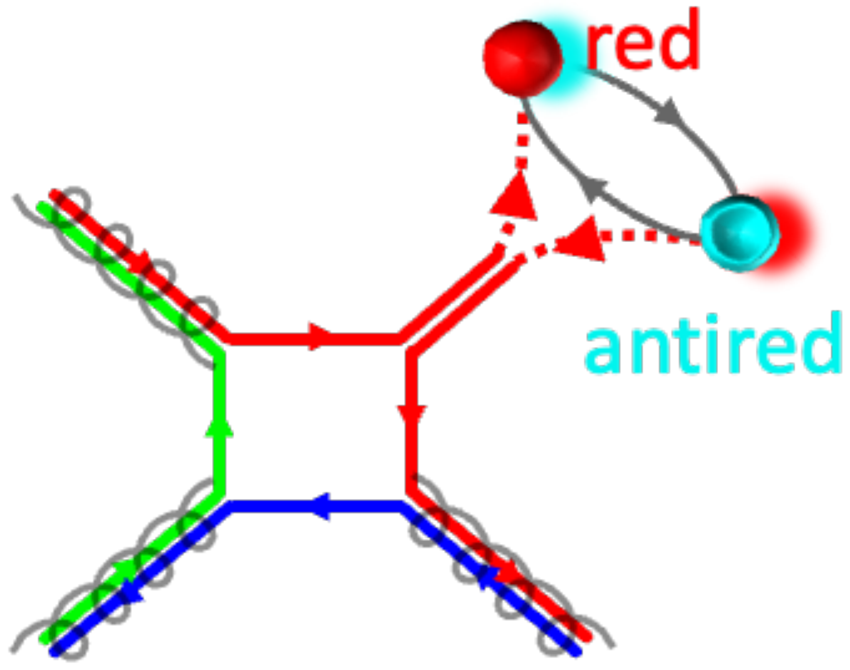
- **Existing measurements:**
  - **η_c** production
  - **η_c(2S)** production in b-decays
  - **J/ψ** and **ψ(2S)** production and polarization
  - **J/ψ+J/ψ/jet/Z/W$^\pm$, J/ψ+J/ψ+J/ψ** production
  - **χ_c** production and polarisation

Charmonium is a challenge both for theory and for experiment

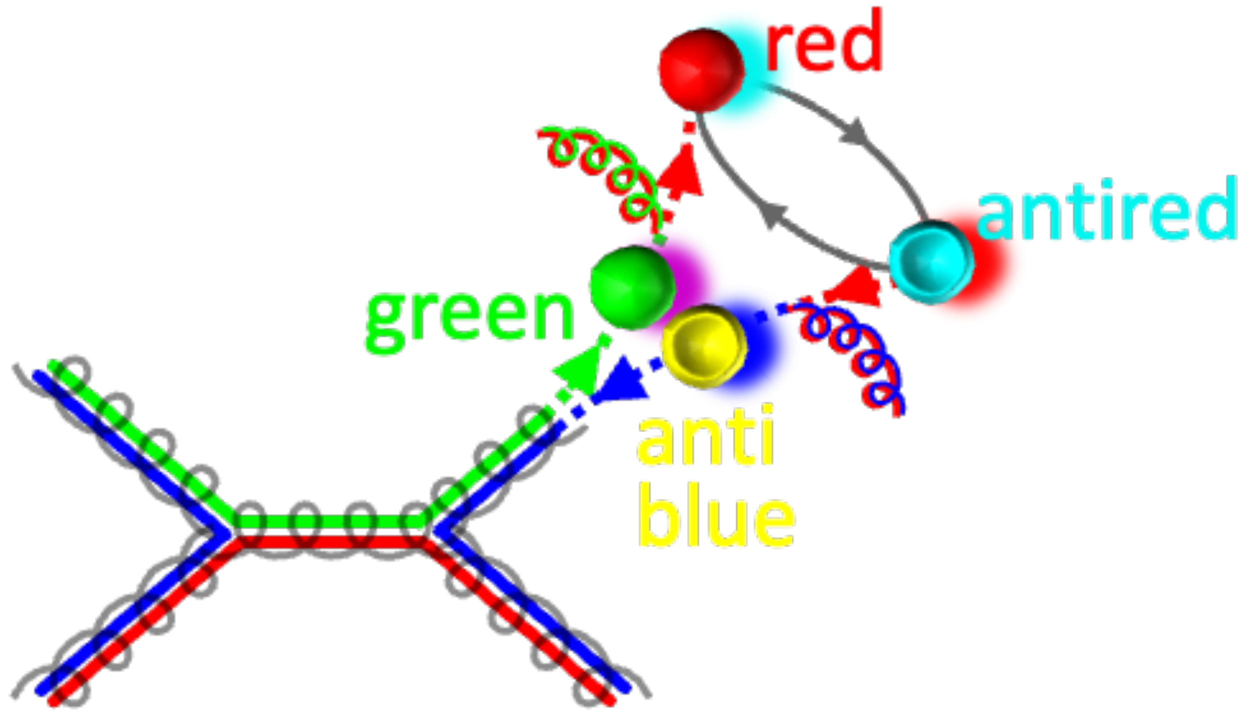
Charmonium production models

- Assumption: **factorization** between the scales
  - **Hard-scale $Q\overline{Q}$ pair production** — expansion in powers of α_s
  - **Soft-scale hadronization** — non-perturbative, mostly extracted from data
- Main **models**
  - **Colour evaporation model (CEM)**: application of quark-hadron duality; only the invariant mass matters;
  - **Colour-singlet model (CS)**: intermediate $Q\overline{Q}$ 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 $Q\overline{Q}$ state;

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



Color Singlet state



Color Octet state

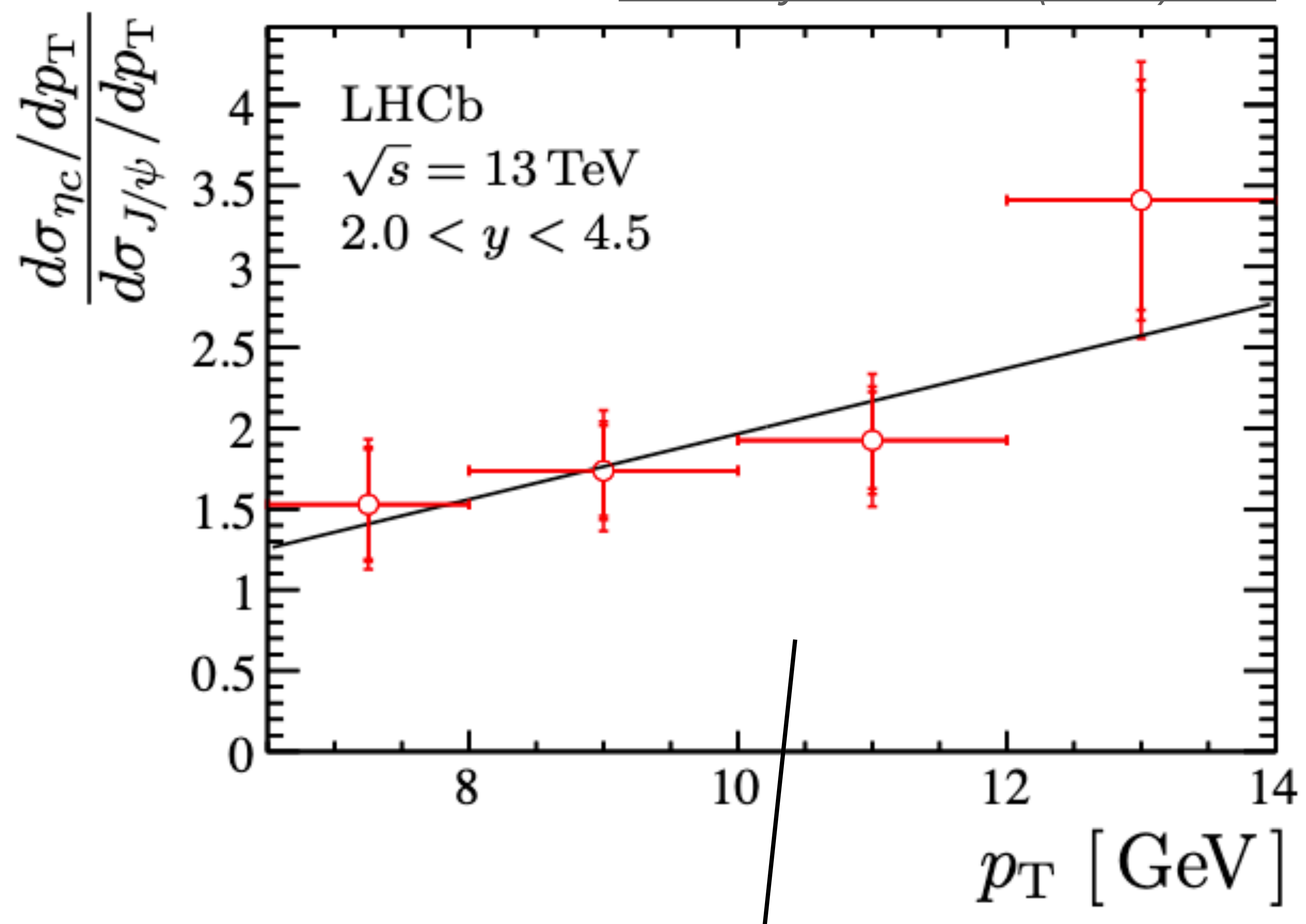
Courtesy of J.-P. Lansberg

Charmonium production via the decay to $p\bar{p}$

- Measurement of charmonia production reconstructed in decays to $p\bar{p}$
  - **Previous measurement** using LHCb 2015 and 2016 data [Eur. Phys. J. C 80 (2020) 191]
- Improved η_c **production measurement** with the LHCb 2018 data
  - **Extended p_{T} range**
  - **Differential in y** for the first time
- **Cross-section in kinematic range** $5.0 < p_{\mathrm{T}} < 14.0$ GeV/c and $2.0 < y^{J/\psi} < 4.0$
  - $\sigma_{\eta_c} = 1815 \pm 189 \pm 120 \pm 192$nb

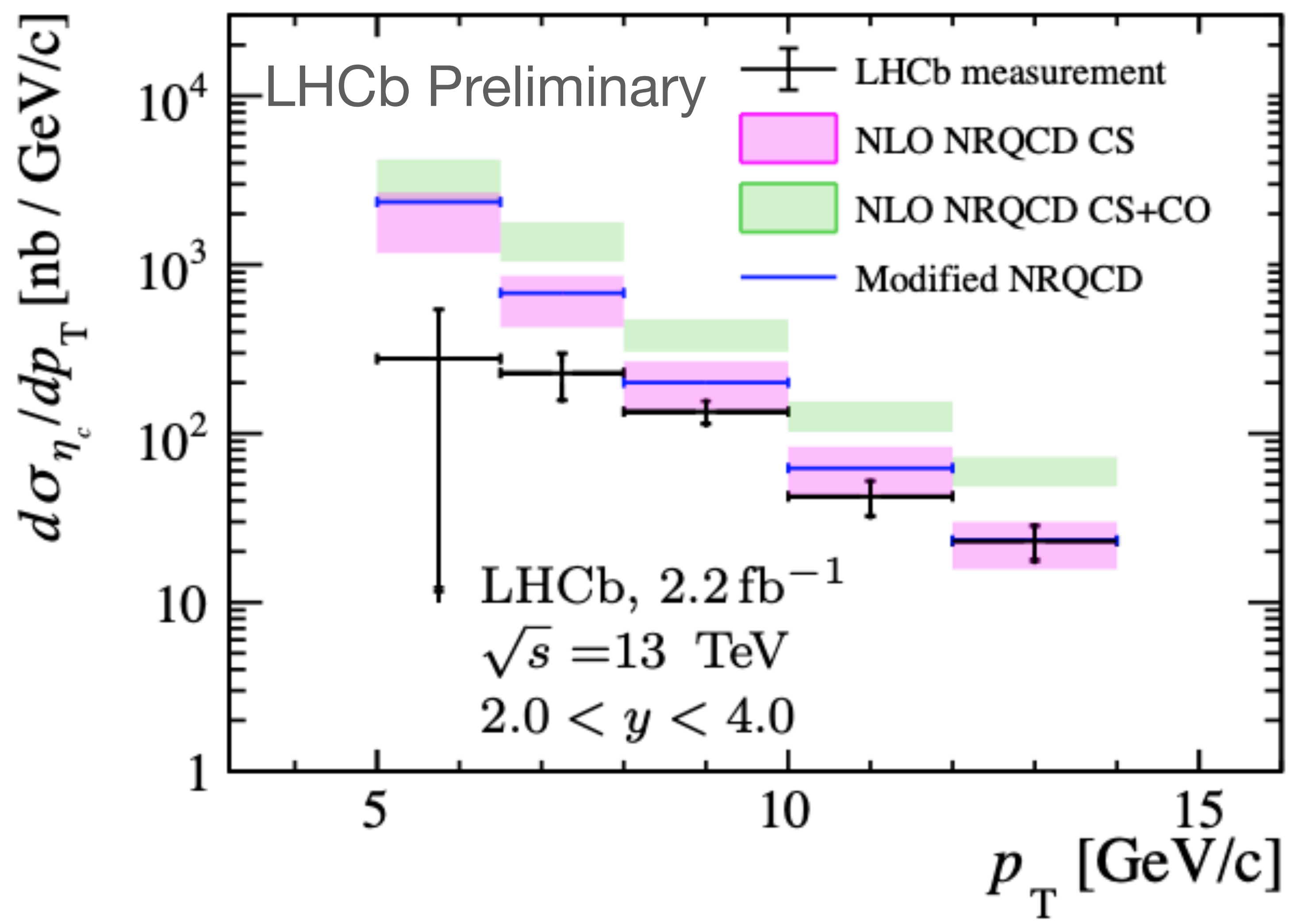
Submitted to arXiv

Eur. Phys. J. C 80 (2020) 191

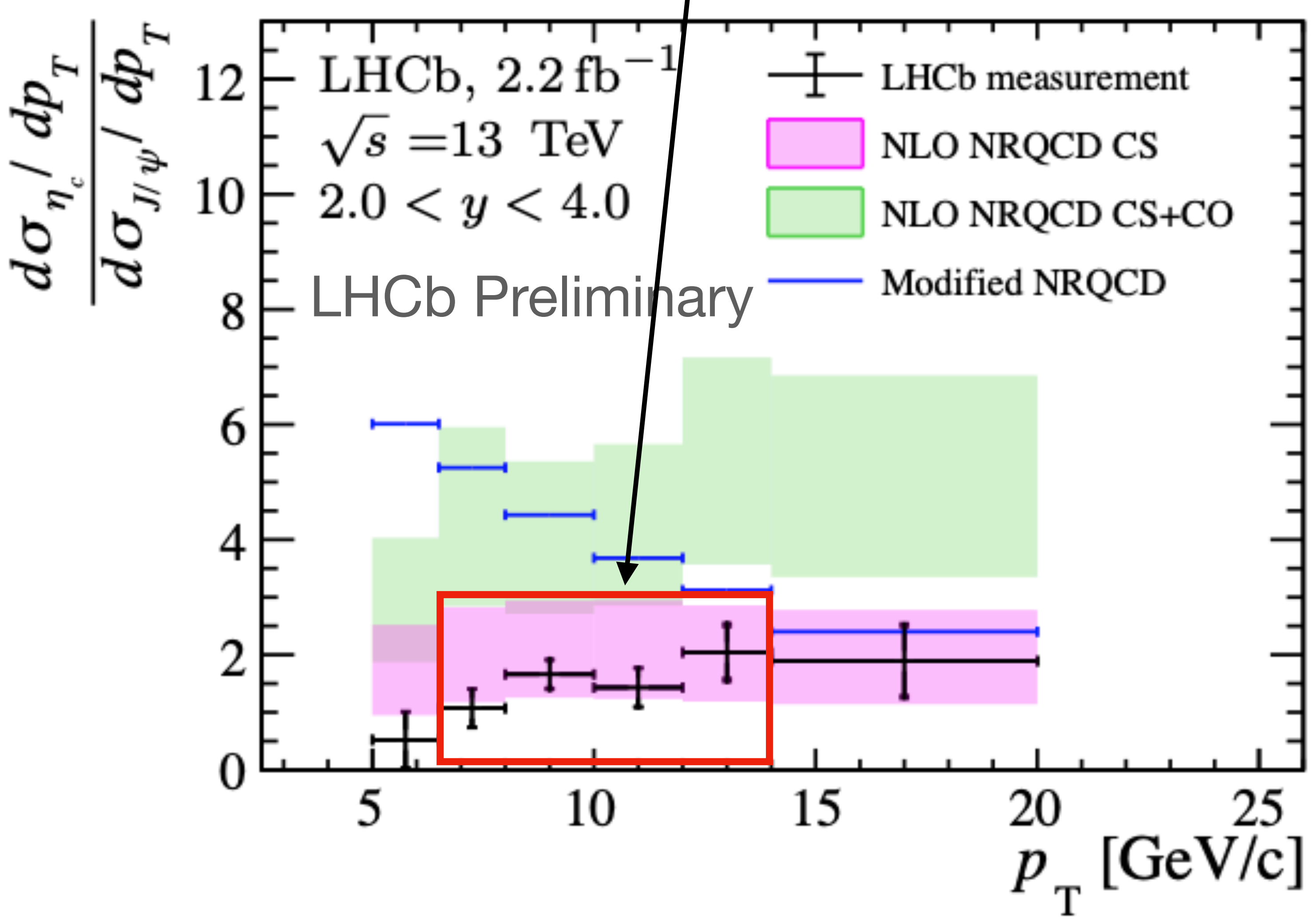


Overlaping p_{T} range

Prompt production



LHCb-PAPER-2024-004



Both CS and CO predictions overshoot the data at low p_{T}

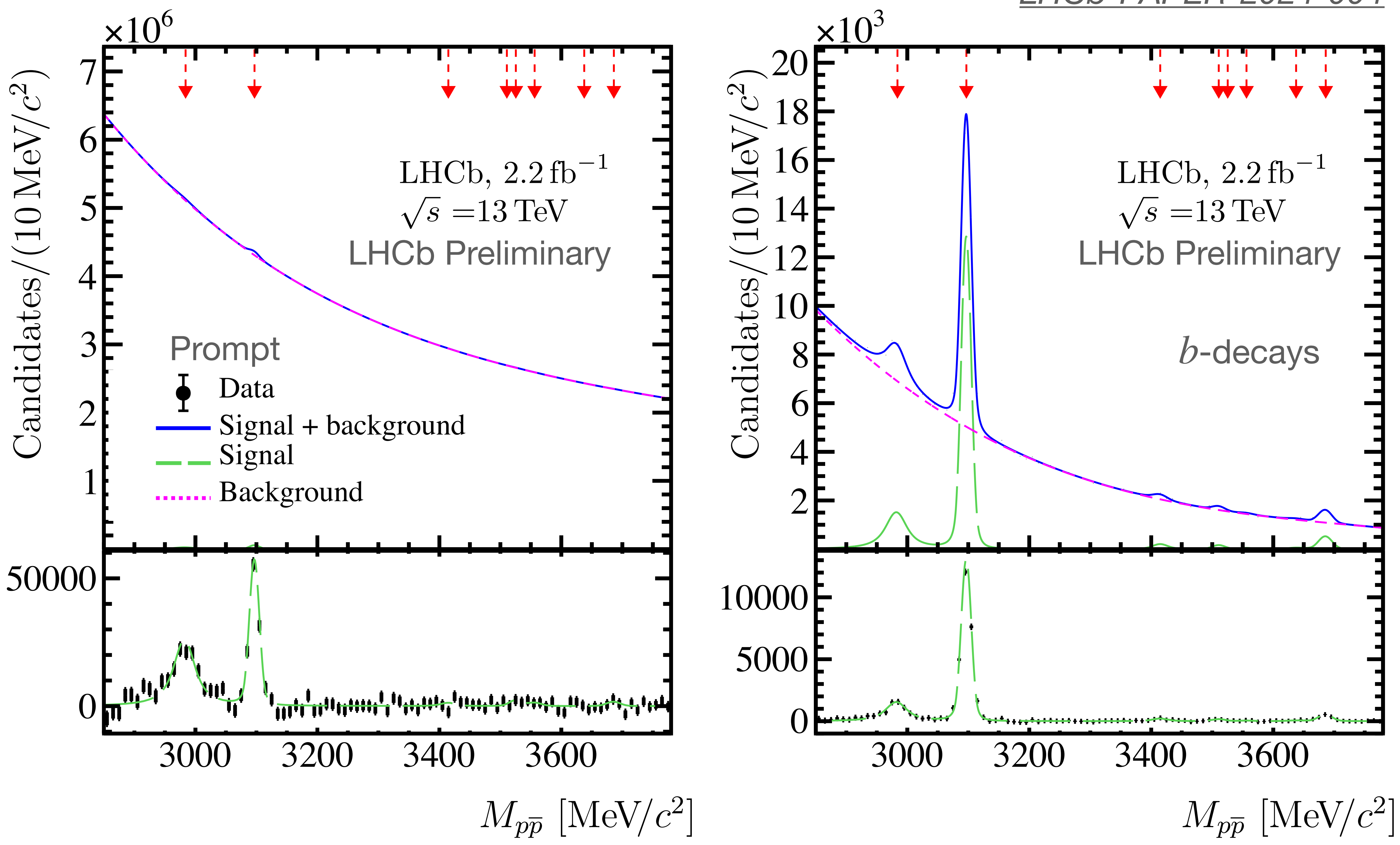
No evidence of CO contribution

Charmonium production via the decay to $p\bar{p}$

- Upper limits for prompt $\eta_c(2S)$ and $h_c(1P)$ @ 95% CL
  - $\sigma_{h_c(1P)} \times \mathcal{B}_{h_c(1P)\to p\bar{p}} < 0.401$ nb
  - $\sigma_{h_c(1P)} \times \mathcal{B}_{h_c(1P)\to p\bar{p}} < 0.375$ nb
- Measument of the η_c production in b-decays
  - $\mathcal{B}_{b\to\eta_c X} = (5.64 \pm 0.31 \pm 0.18 \pm 0.73) \times 10^{-3}$
- New χ_{c0}, χ_{c1} and χ_{c2} production measurement in b-decays
  - $\mathcal{B}_{b\to\chi_{c0} X} = (3.05 \pm 0.54 \pm 0.08 \pm 0.29) \times 10^{-3}$,
  - $\mathcal{B}_{b\to\chi_{c1} X} = (5.11 \pm 1.20 \pm 0.14 \pm 0.50) \times 10^{-3}$
  - $\mathcal{B}_{b\to\chi_{c2} X} = (1.54 \pm 1.13 \pm 0.04 \pm 0.15) \times 10^{-3}$
- Improvement in precision for χ_{c0}, χ_{c1}

Three uncertainties stand for statistical, systematic and uncertainty due to the branching fraction of charmonia decays to $p\bar{p}$

LHCb-PAPER-2024-004



State	Mass, MeV/c^2
$\eta_c(1S)$	2984.1 ± 0.4
$J/\psi(1S)$	3096.900 ± 0.006
$\chi_{c0}(1P)$	3414.71 ± 0.30
$\chi_{c1}(1P)$	3510.67 ± 0.05
$h_c(1P)$	3525.37 ± 0.14
$\chi_{c2}(1P)$	3556.17 ± 0.07
$\eta_c(2S)$	3637.7 ± 1.1
$\psi(2S)$	3686.10 ± 0.06

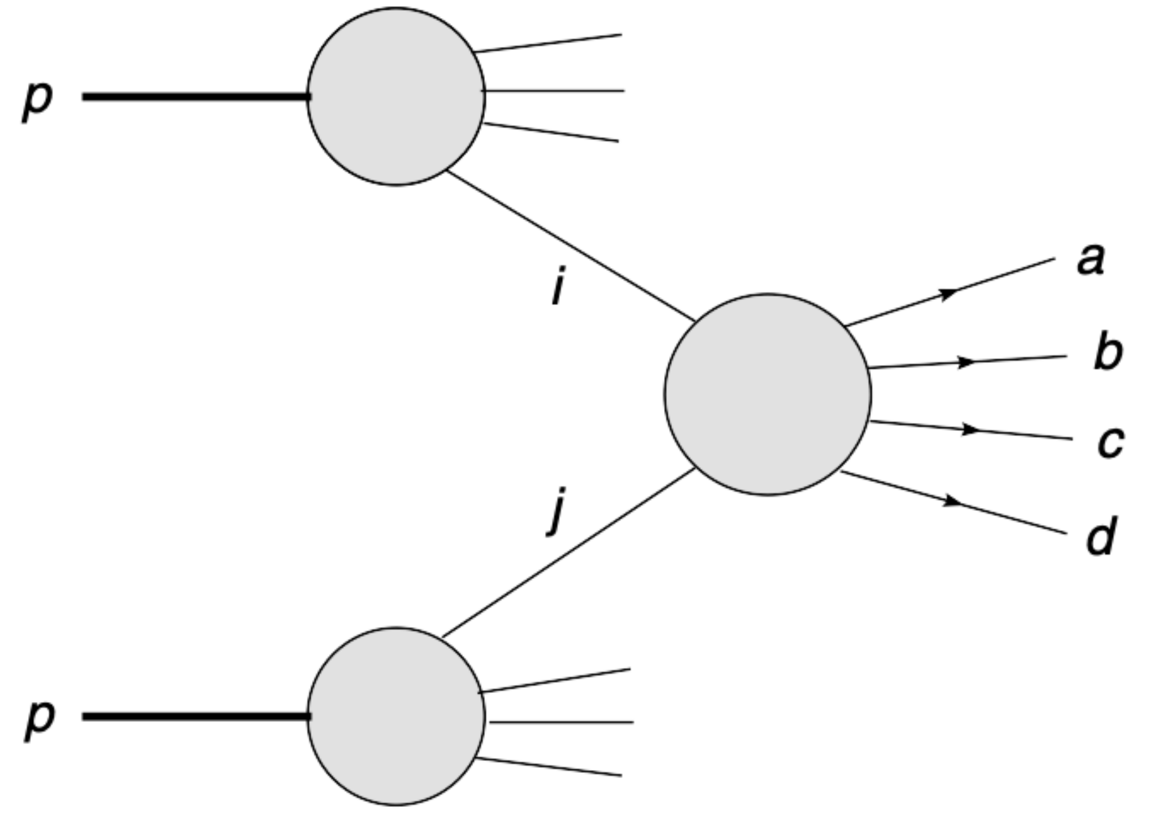
World average charmonia masses
[Prog. Theor. Exp. Phys. 2022, 083C01]

Associated production

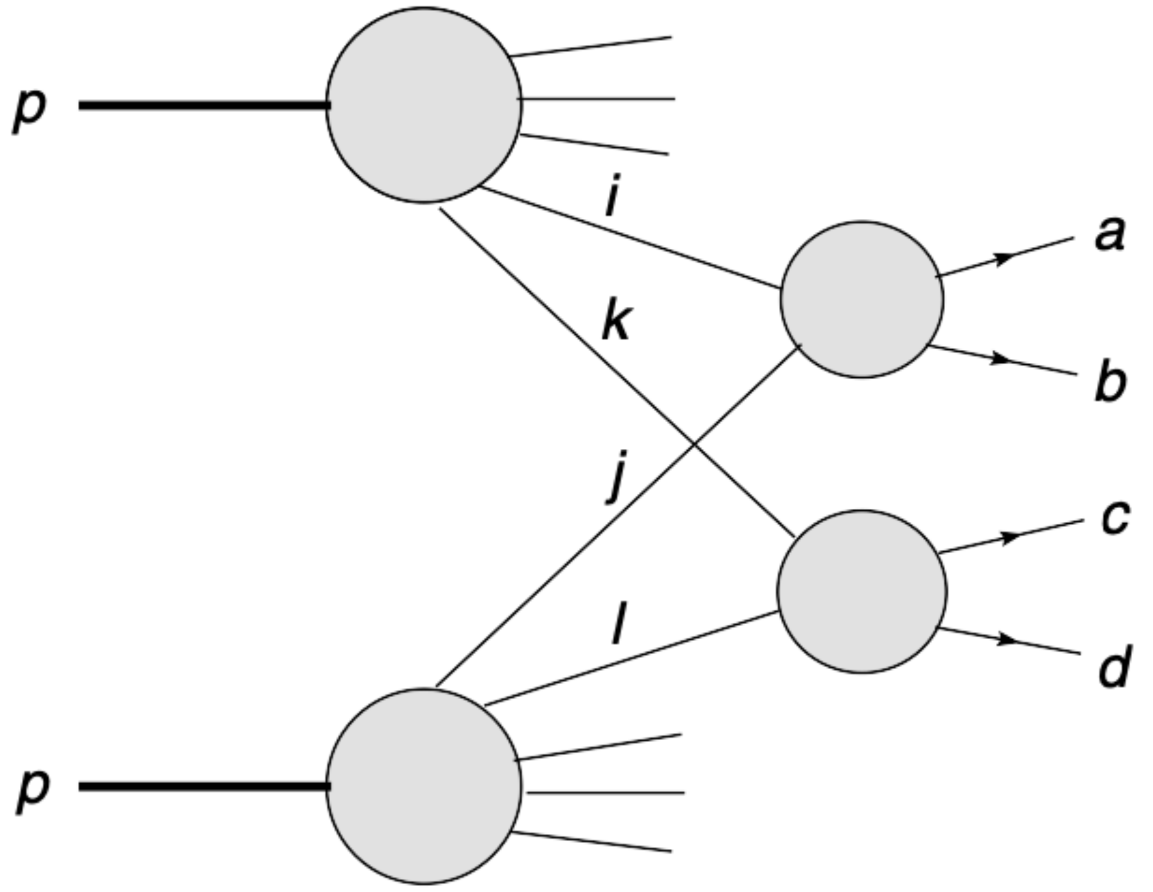
PRD 84 (2011) 074021

- 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)
  - **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



Single-Parton Scattering

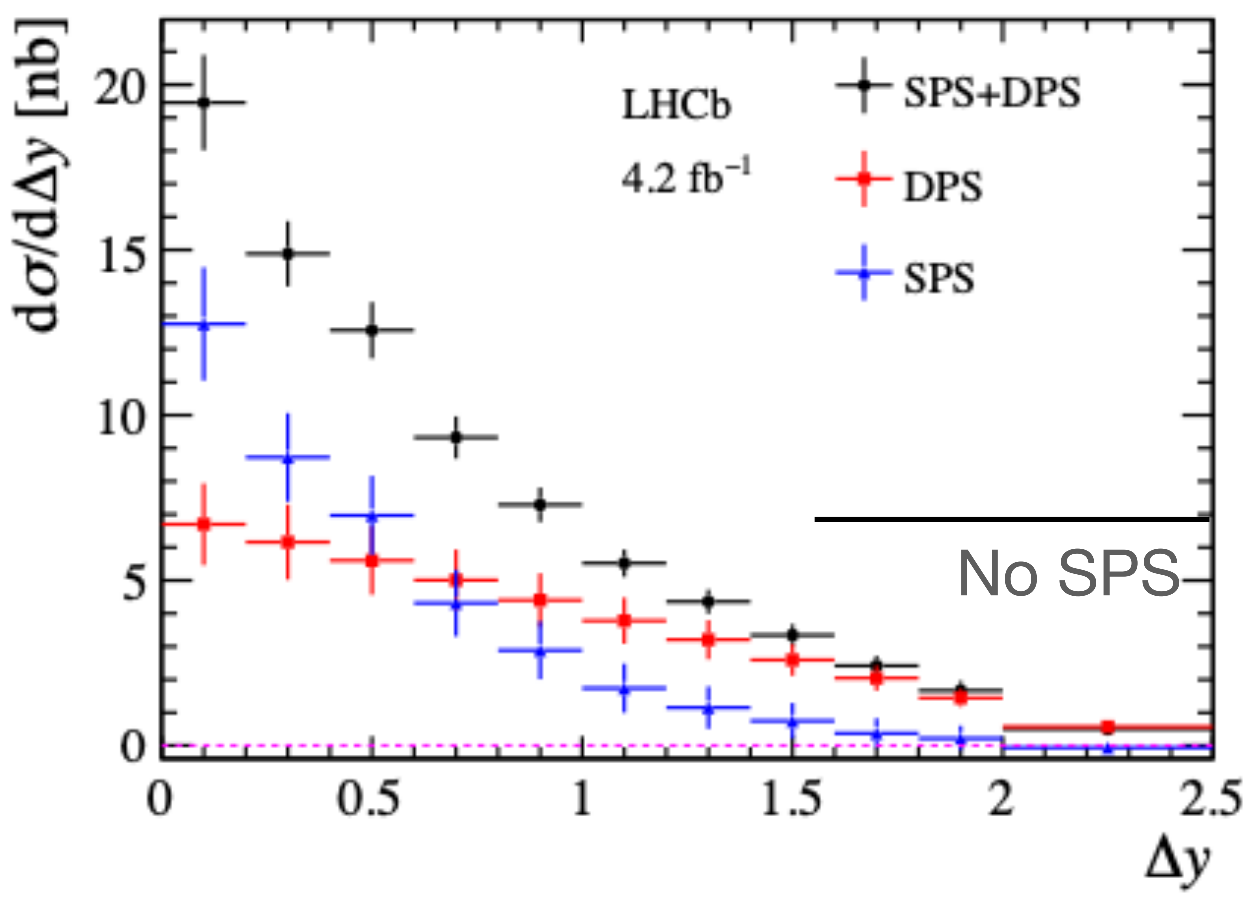


Double-Parton Scattering

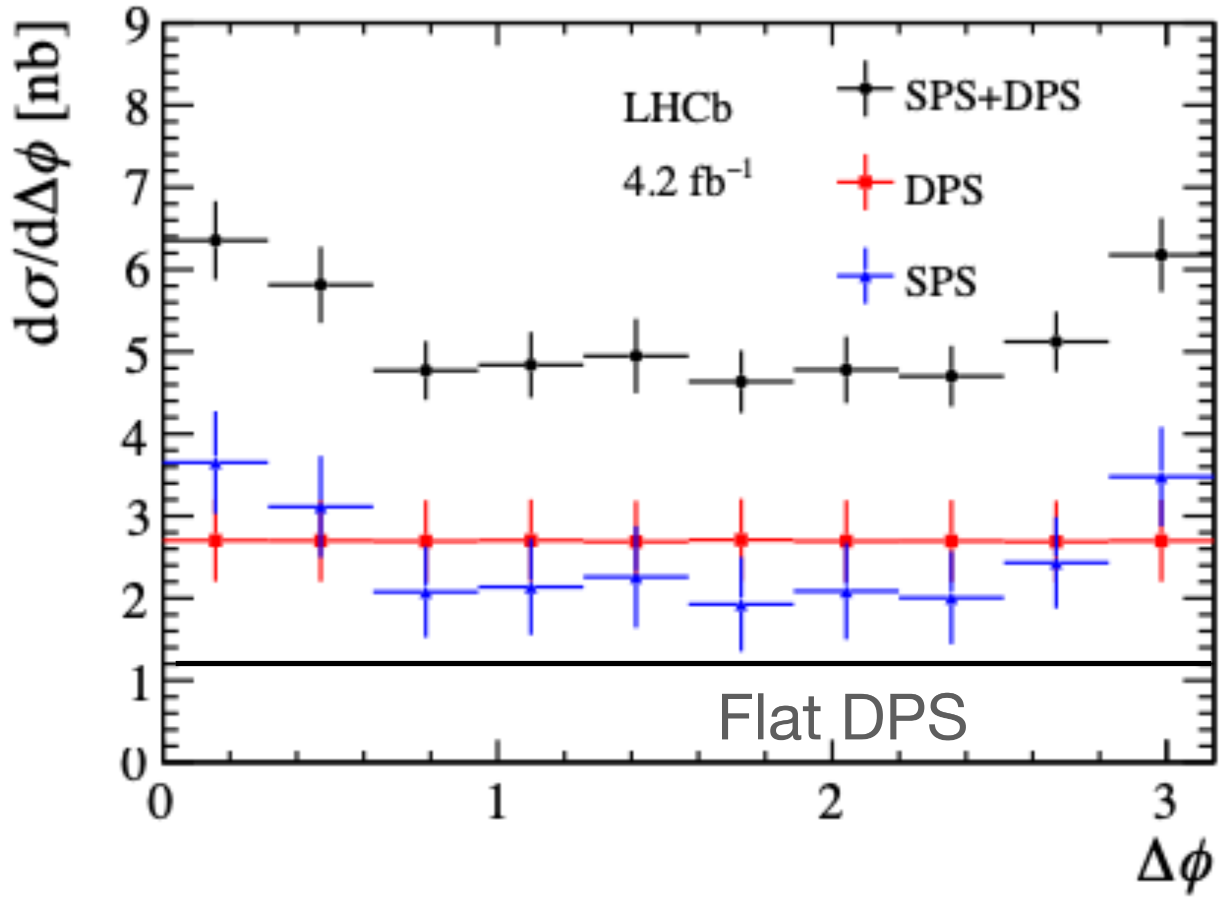
$J/\psi + J/\psi$ production

JHEP 2403 (2024) 088

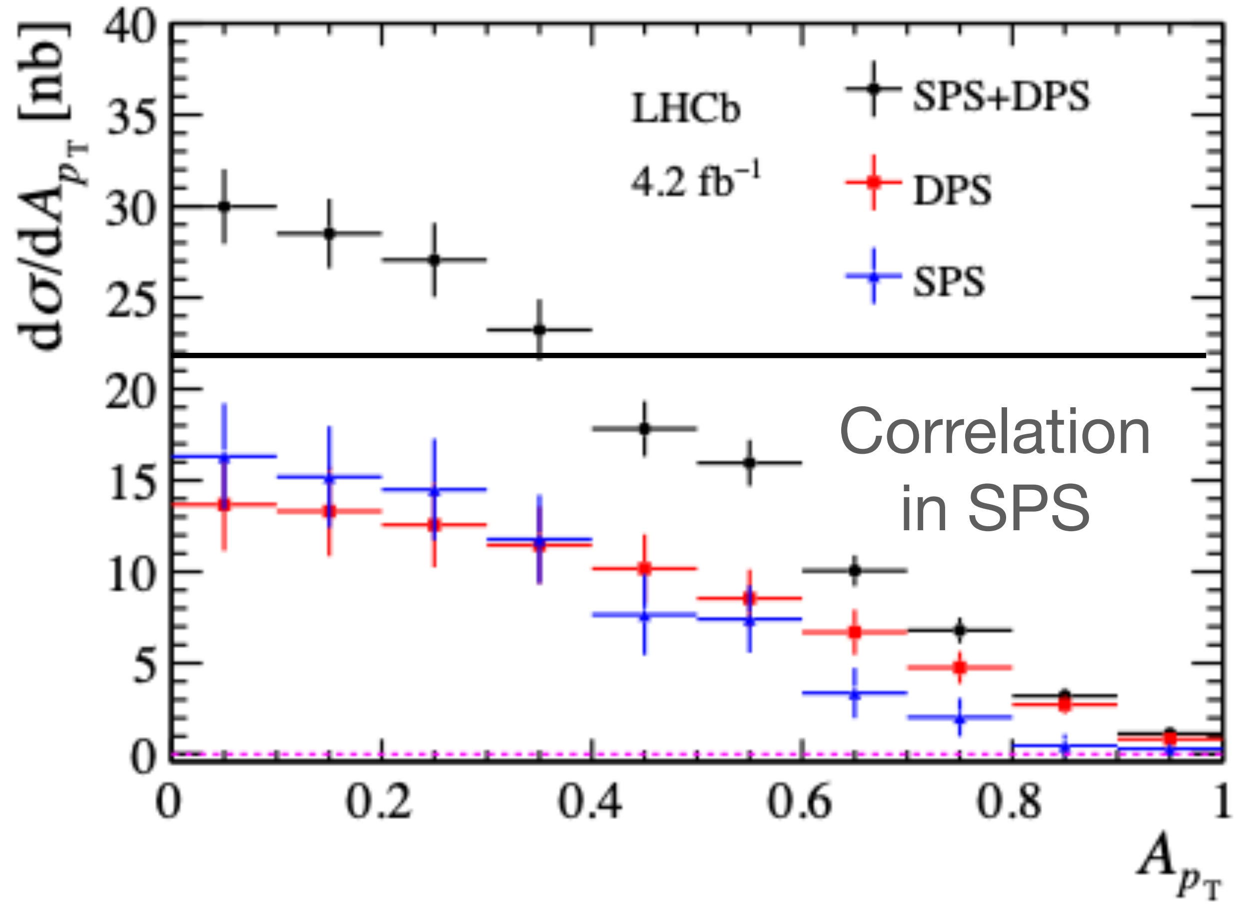
- **Cross-section in the kinematic range** $p_T^{J/\psi} < 14$ GeV/c and $2.0 < y^{J/\psi} < 4.5$
  - $\sigma_{di-J/\psi} = 16.36 \pm 0.28_{stat} \pm 0.88_{syst}$ nb
- **Differential study** in bins of
  - $\Delta y, \Delta\phi$
  - $p_T^{J/\psi}, y^{J/\psi}$,
  - $p_T^{di-J/\psi}, y^{di-J/\psi}, m_{di-J/\psi}$
  - $\mathcal{A}_{p_T} = \left| \frac{p_T^{J/\psi_1} - p_T^{J/\psi_2}}{p_T^{J/\psi_1} + p_T^{J/\psi_2}} \right|$
- **SPS and DPS** contributions are separated



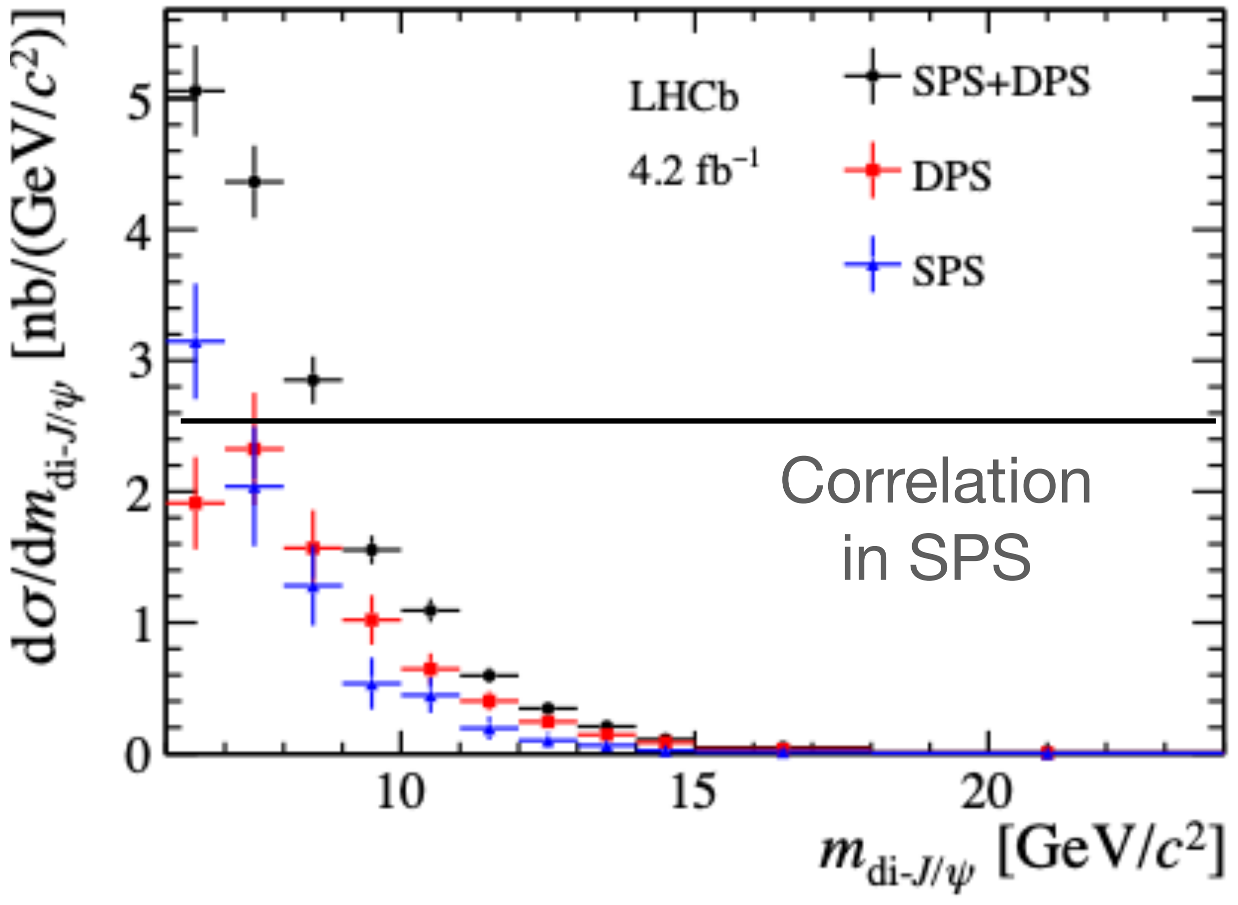
$d\sigma/d\Delta y$



$d\sigma/d\Delta\phi$



$d\sigma/d\mathcal{A}_{p_T}$

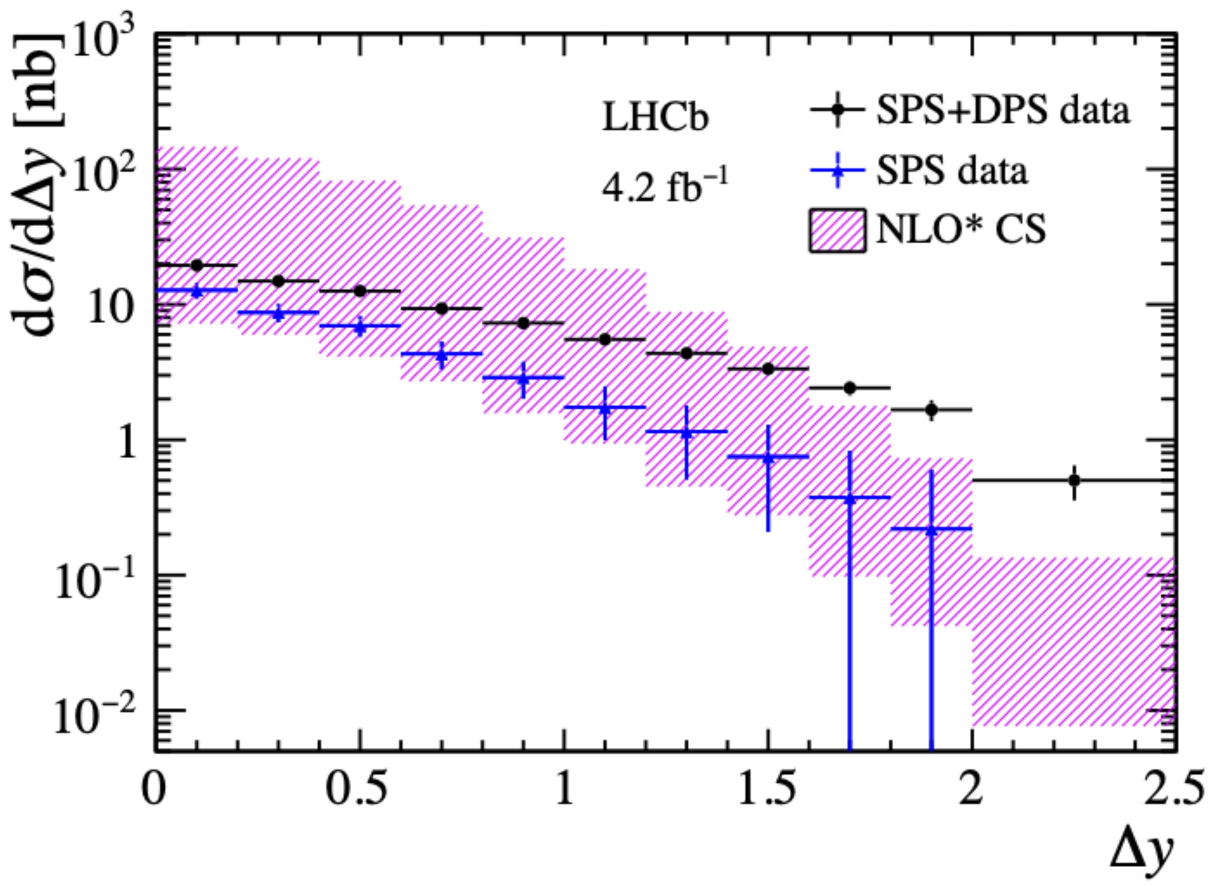


$d\sigma/dm_{di\text{-}J/\psi}$

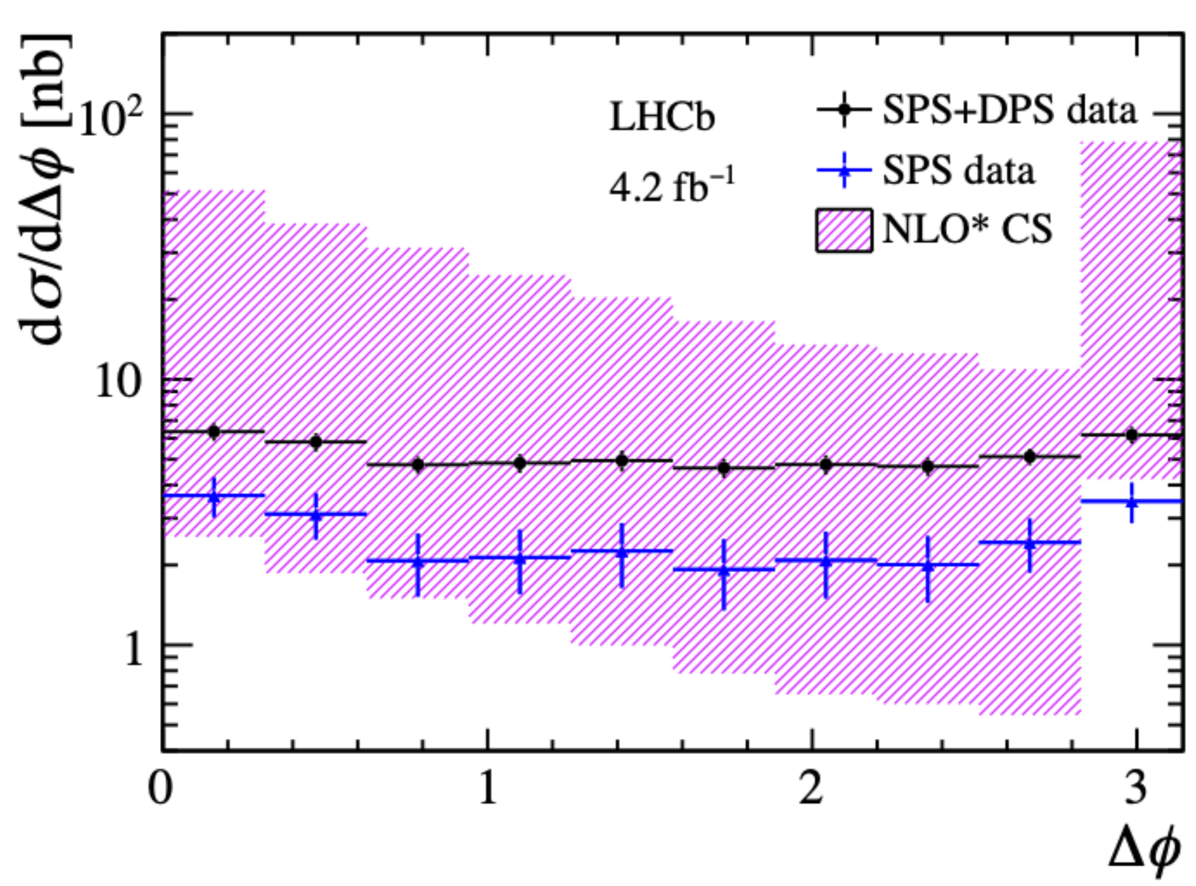
$J/\psi + J/\psi$ production

[JHEP 2403 (2024) 088]

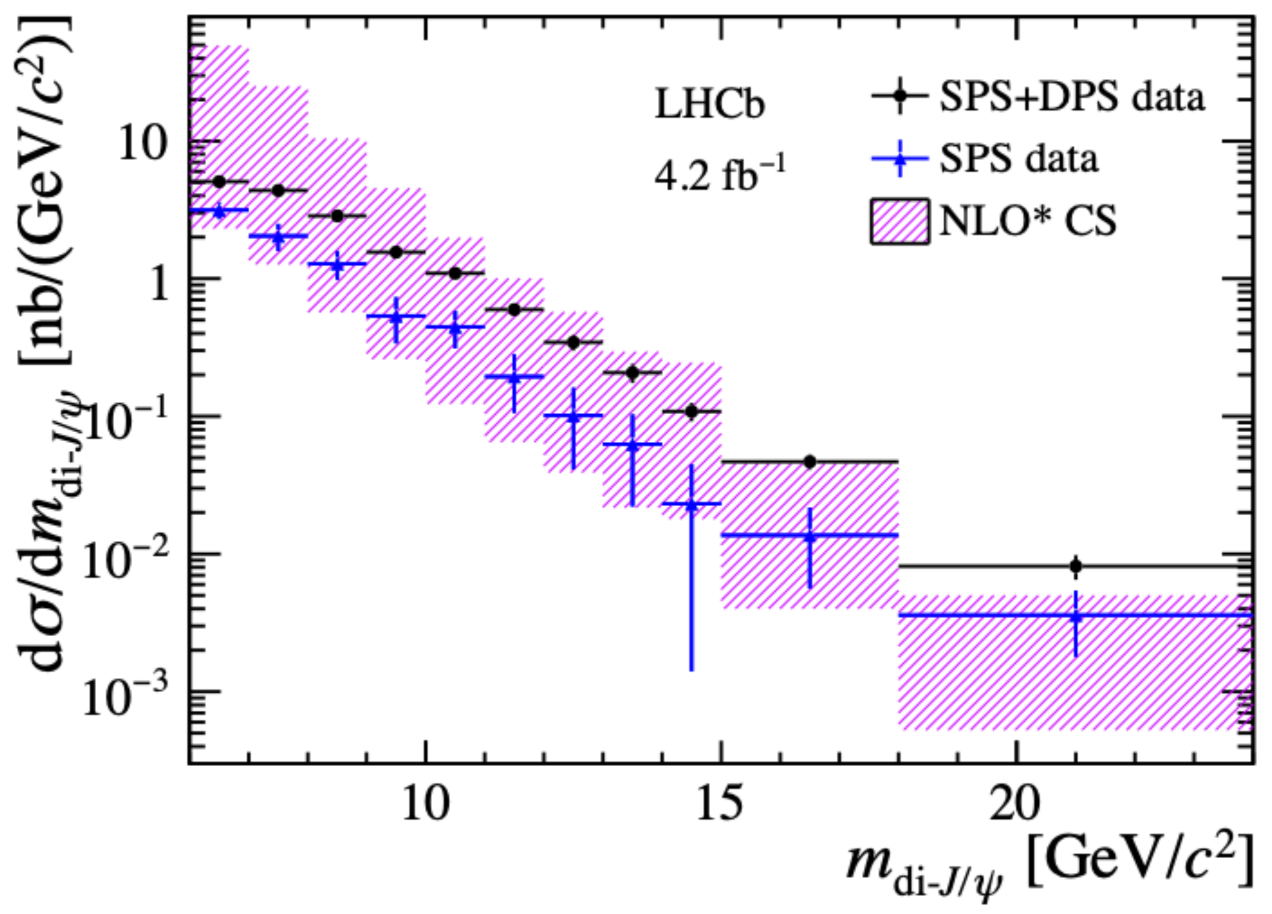
- **DPS contribution** is extracted from Δy distribution:
  - **SPS** contribution is **negligible** in range $1.8 < \Delta y < 2.5$
  - contribution from exotic **X(6900)** is small
  - **data-driven template** for DPS
    - $$\sigma_{eff} = \frac{1}{2}\frac{\sigma^2_{J/\psi}}{\sigma^{DPS}_{di-J/\psi}} = 13.1 \pm 1.8_{stat} \pm 2.3_{syst}\ \text{mb}$$
  - **Measurements are consistent with NLO* CS** prediction from Lansberg and Shao [Phys. Rev. Lett. 111, 122001]
- **Gluon TMDs are estimated for the first time**
  - azimuthal angle of J/ψ in **Collins-Soper frame**



$\mathrm{d}\sigma/\mathrm{d}\Delta y$



$\mathrm{d}\sigma/\mathrm{d}\Delta\phi$

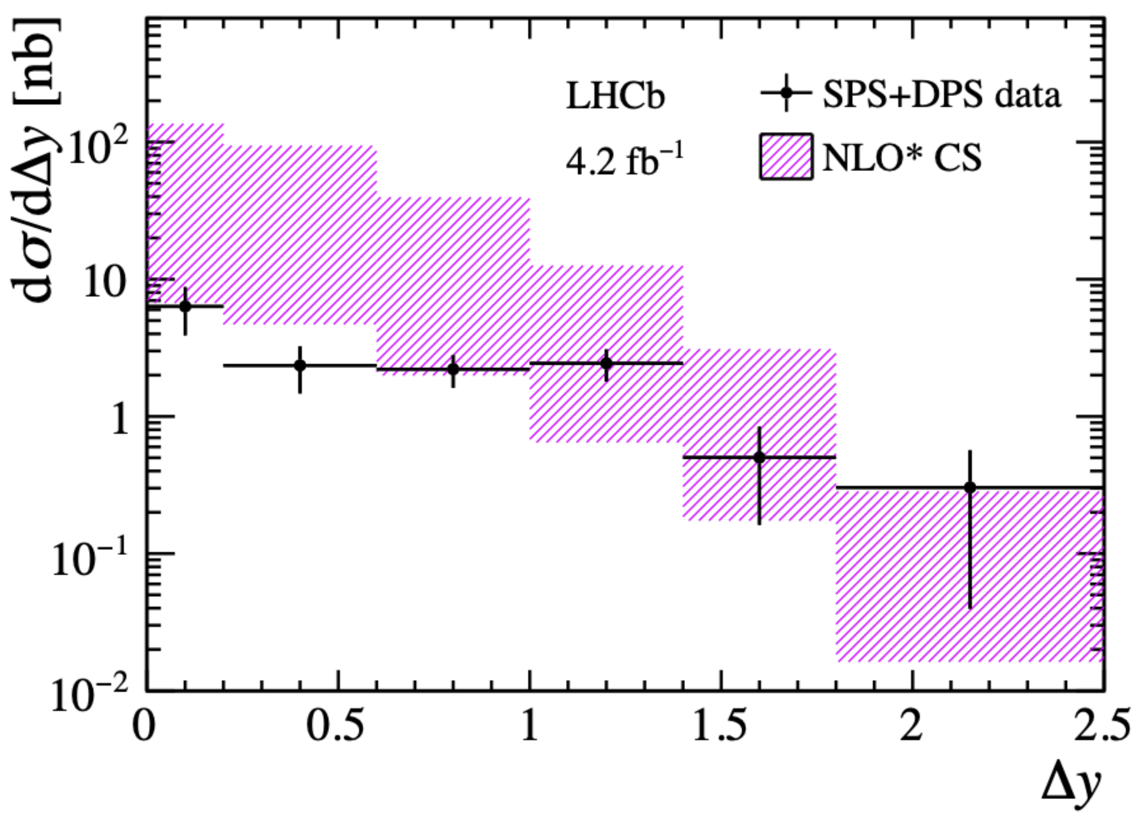


$\mathrm{d}\sigma/\mathrm{d}m_{\text{di-}J/\psi}$

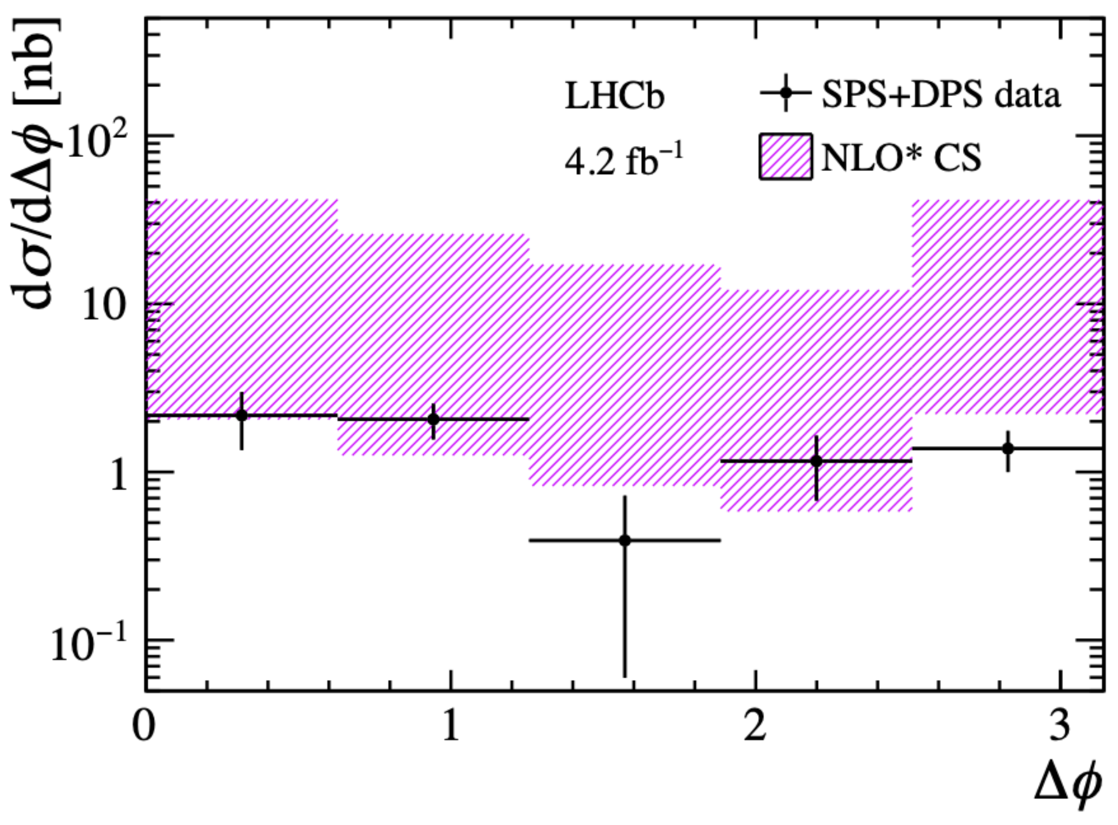
$J/\psi + \psi(2S)$ production

[JHEP 2405 (2024) 259]

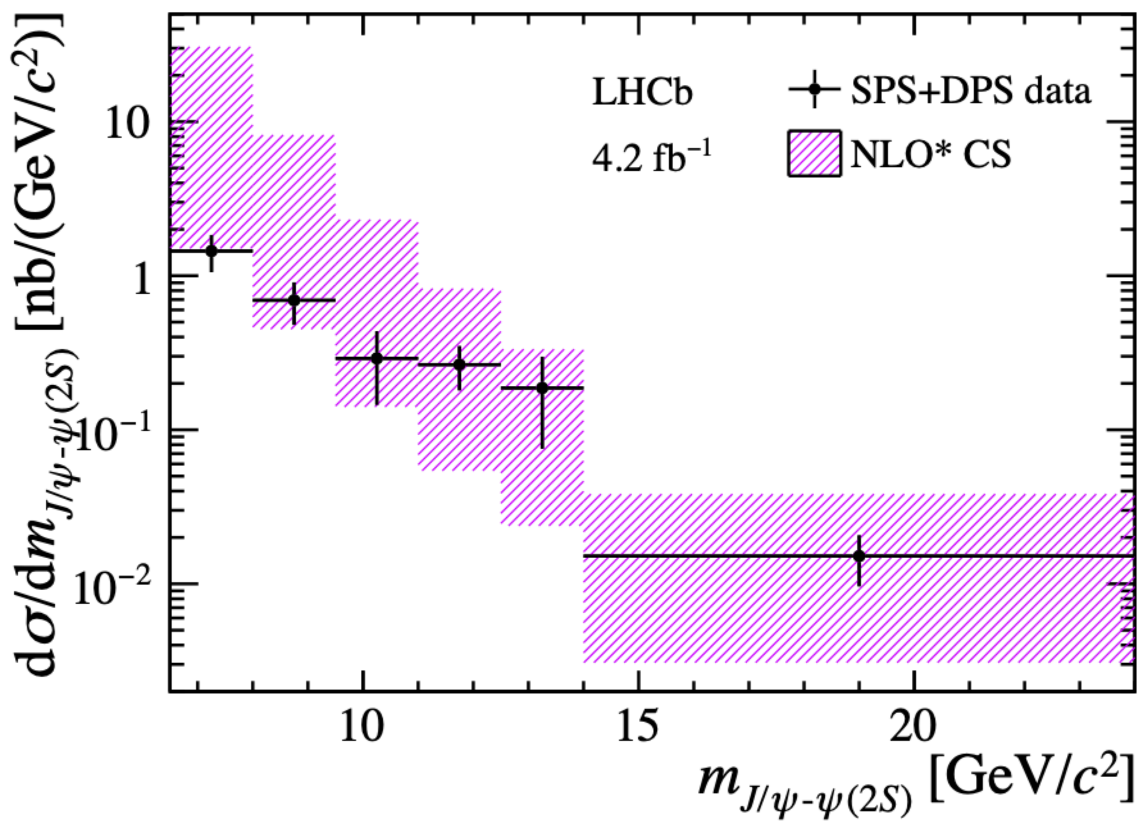
- **Cross-section in a kinematic range** $p_{\mathrm{T}}^{J/\psi,\psi(2S)} < 14$ GeV/c and $2.0 < y^{J/\psi,\psi(2S)} < 4.5$
  - $\sigma_{J/\psi-\psi(2S)} = 4.49 \pm 0.71_{stat} \pm 0.26_{syst}$ nb
- **Differential study** in bins of $\Delta y, \Delta\phi, p_{\mathrm{T}}^{J/\psi-\psi(2S)}, y^{J/\psi-\psi(2S)}, m_{J/\psi-\psi(2S)}$
  - **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**
  - $\mathscr{R} = \dfrac{\sigma_{J/\psi-\psi(2S)}}{\sigma_{J/\psi-J/\psi}} = 0.274 \pm 0.044_{stat} \pm 0.008_{syst}$
- **Consistent with DPS prediction**



$d\sigma/d\Delta y$



$d\sigma/d\Delta\phi$



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

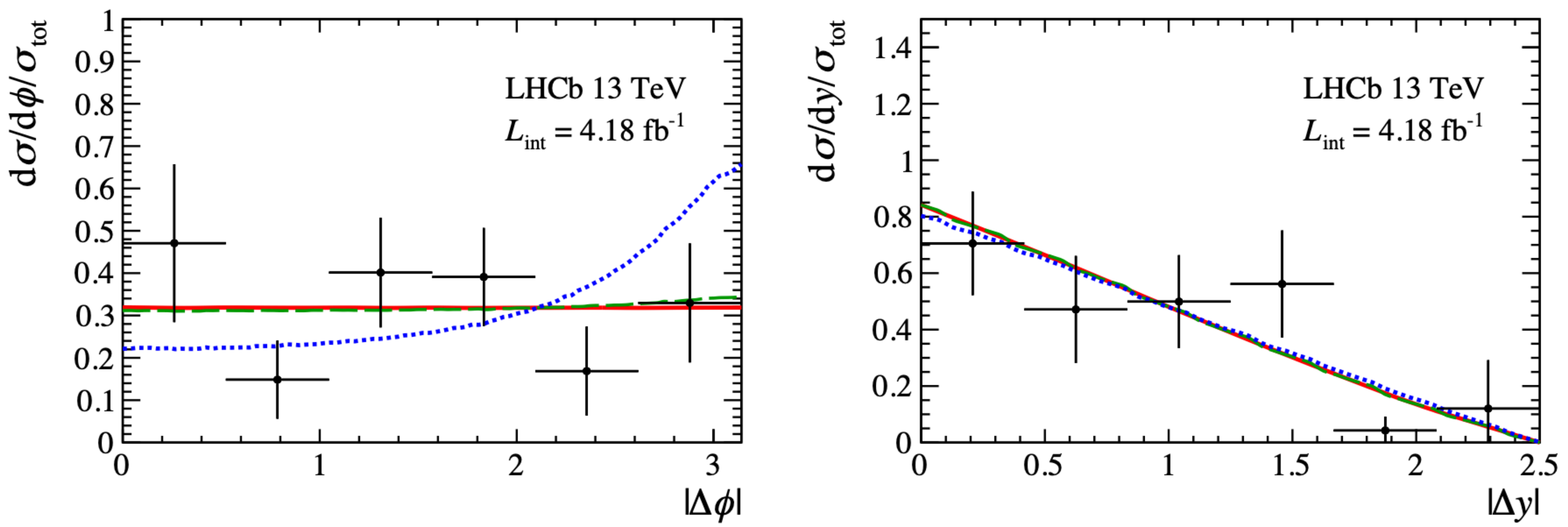
Prediction:

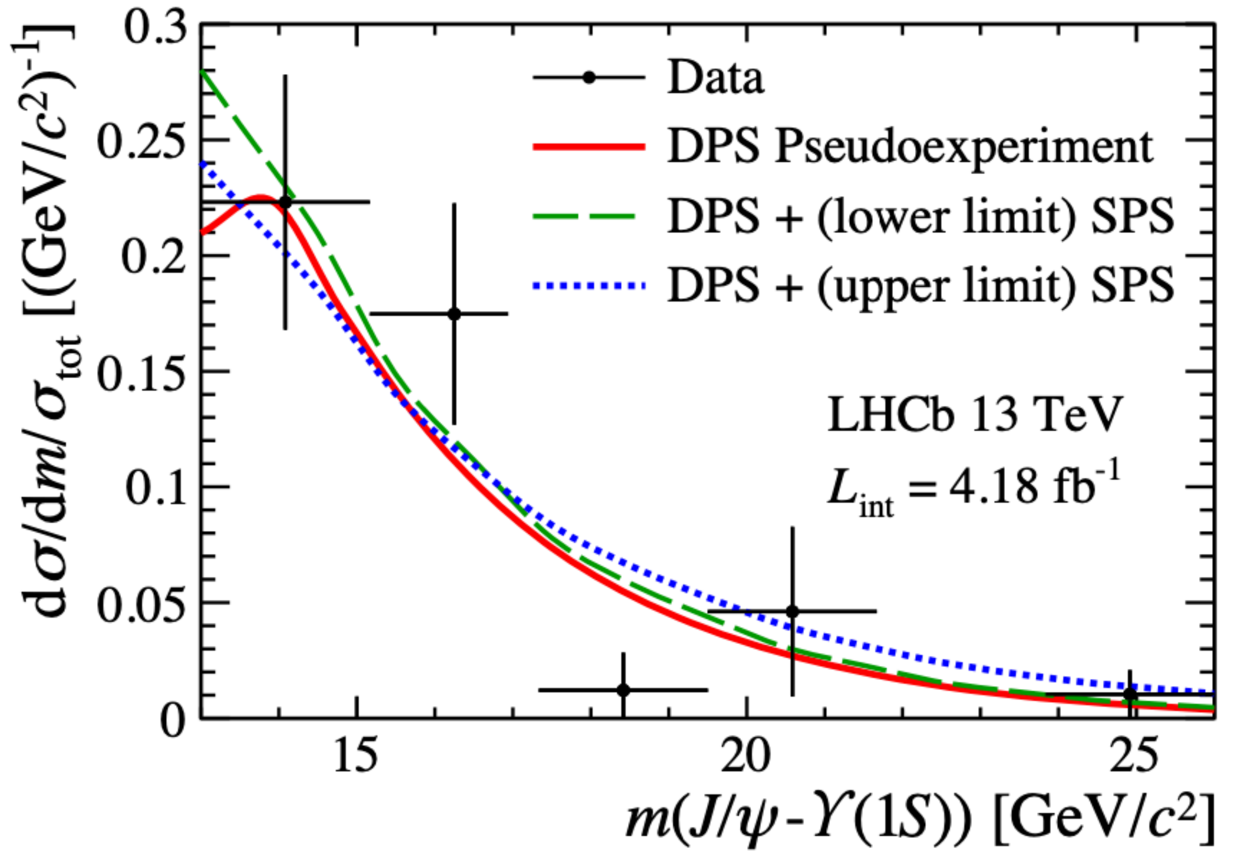
$\mathscr{R}_{SPS} = 0.94 \pm 0.30$

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

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

- **Cross-section in kinematic range** $p_T^{J/\psi(\Upsilon(nS))} < 10(30)$ GeV/c and $2.0 < y < 4.5$
  - $\sigma_{J/\psi-\Upsilon(1S)} = 133 \pm 22_{stat} \pm 7_{syst} \pm 3_{\mathscr{B}}$ pb (7.9σ)
  - $\sigma_{J/\psi-\Upsilon(2S)} = 76 \pm 21_{stat} \pm 4_{syst} \pm 7_{\mathscr{B}}$ pb (4.9σ)
- **Differential study for** $J/\psi + \Upsilon(1S)$ in bins of $\Delta y, \Delta\phi, p_T^{J/\psi}, p_T^{\Upsilon(1S)}, p_T^{J/\psi-\Upsilon(1S)}$, and $m_{J/\psi-\Upsilon(1S)}$
- **DPS contribution is extracted using SPS prediction from Shao and Zhang** [Phys. Rev. Lett. 117, 062001]
  - $\sigma_{eff} = \dfrac{\sigma_{J/\psi} \times \sigma_{\Upsilon(1S)}}{\sigma^{DPS}_{J/\psi-\Upsilon(1S)}} = 26 \pm 14_{stat} \pm 2_{syst}\ {}^{+22_{SPS}}_{-3_{SPS}}$ mb
  - $\sigma_{eff} = \dfrac{\sigma_{J/\psi} \times \sigma_{\Upsilon(2S)}}{\sigma^{DPS}_{J/\psi-\Upsilon(2S)}} = 14 \pm 5_{stat} \pm 1_{syst}\ {}^{+7_{SPS}}_{-1_{SPS}}$ mb





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

More data are needed to separate and test SPS CO mechanism

Associated production

- 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 needed for precise test

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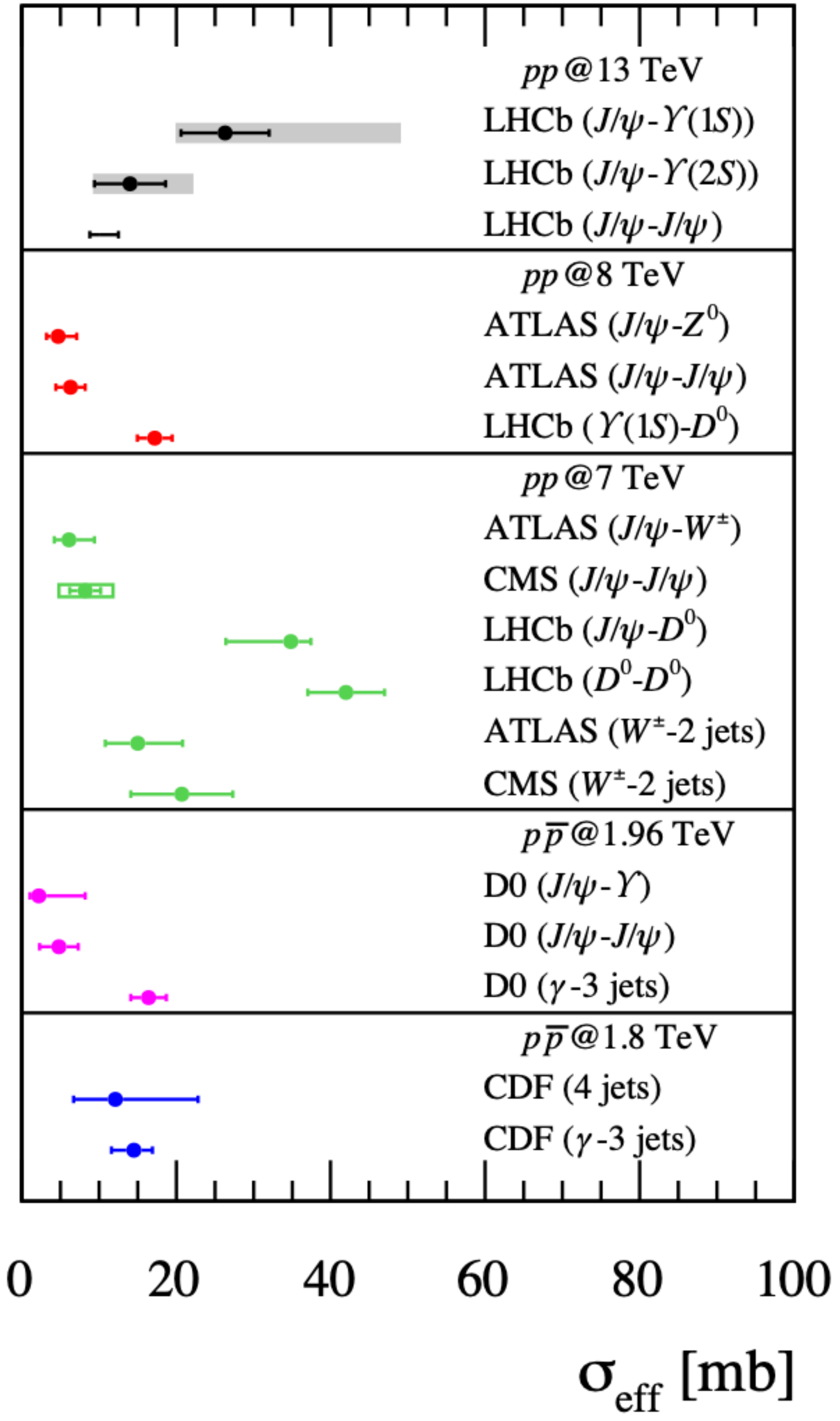
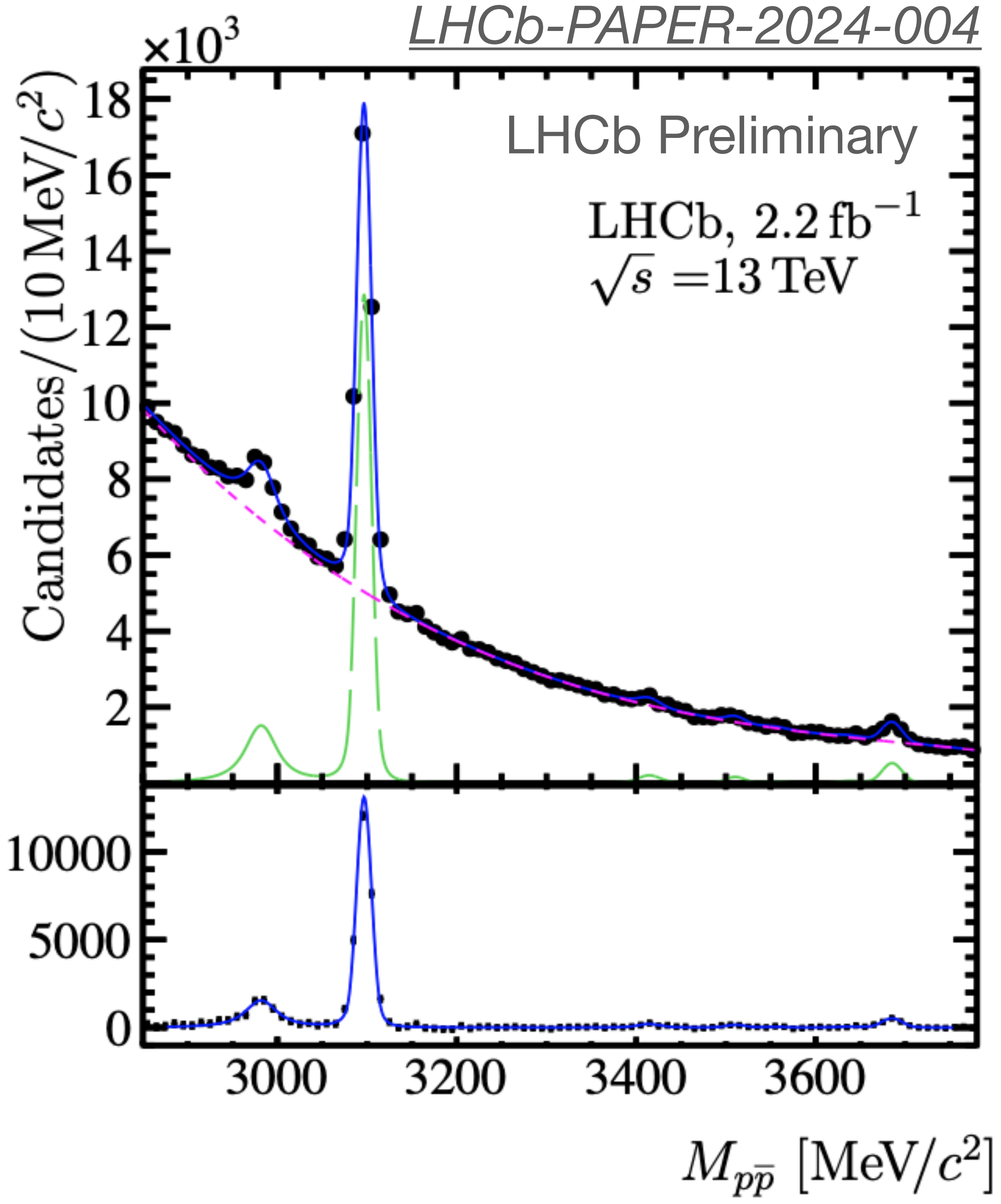


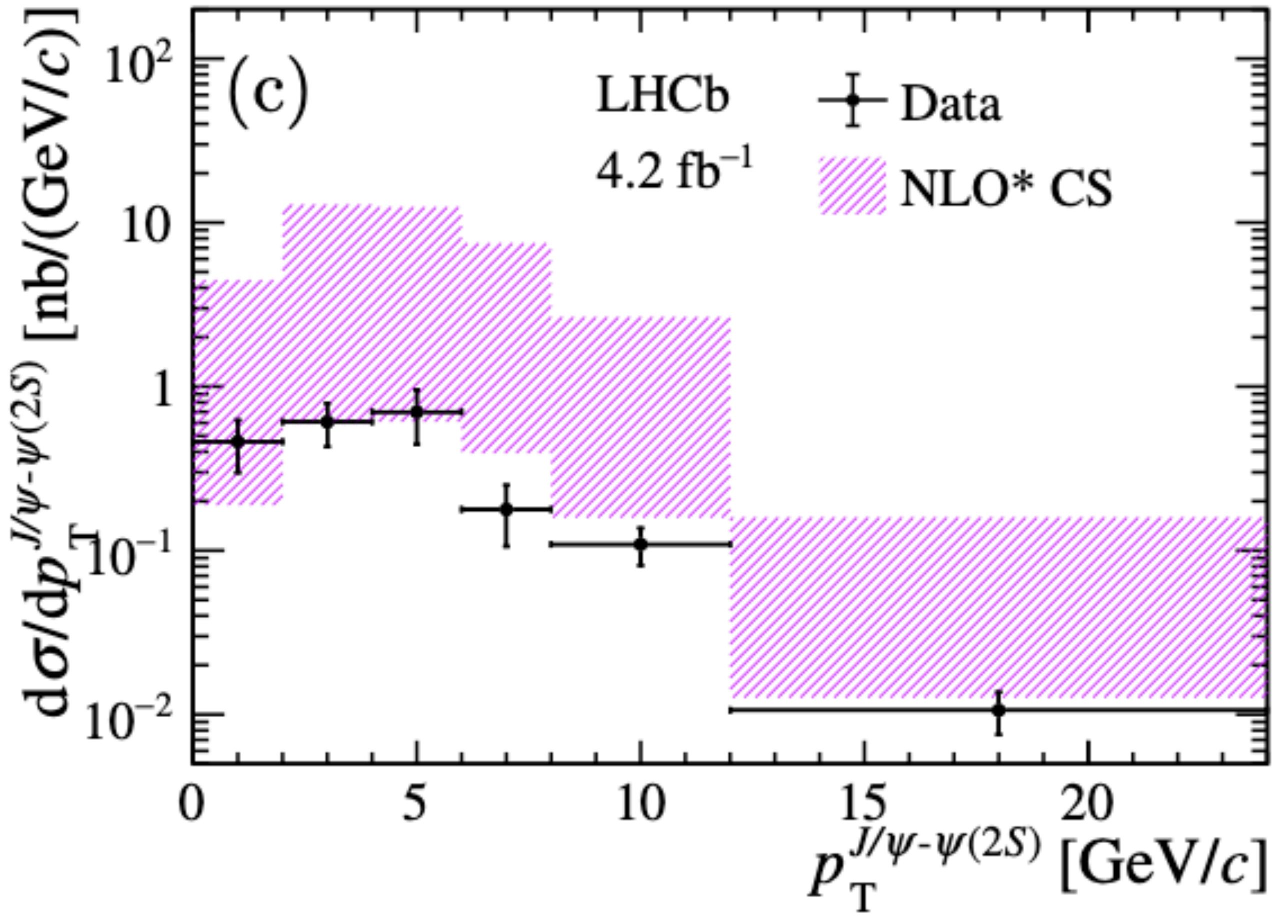
Summary

- Charmonia production is an essential probe for QCD at different scales
- **Many new results from LHCb**
- Extended η_c production measurement
  - *LHCb-PAPER-2024-004*
- Associated charmonia production measurements
  - $J/\psi + J/\psi$: *JHEP 2403 (2024) 088*
  - $J/\psi + \psi(2S)$: *JHEP 2405 (2024) 259*
  - $J/\psi + \Upsilon(nS)$: *JHEP 2308 (2023) 093*

LHCb-PAPER-2024-004



JHEP 2405 (2024) 259



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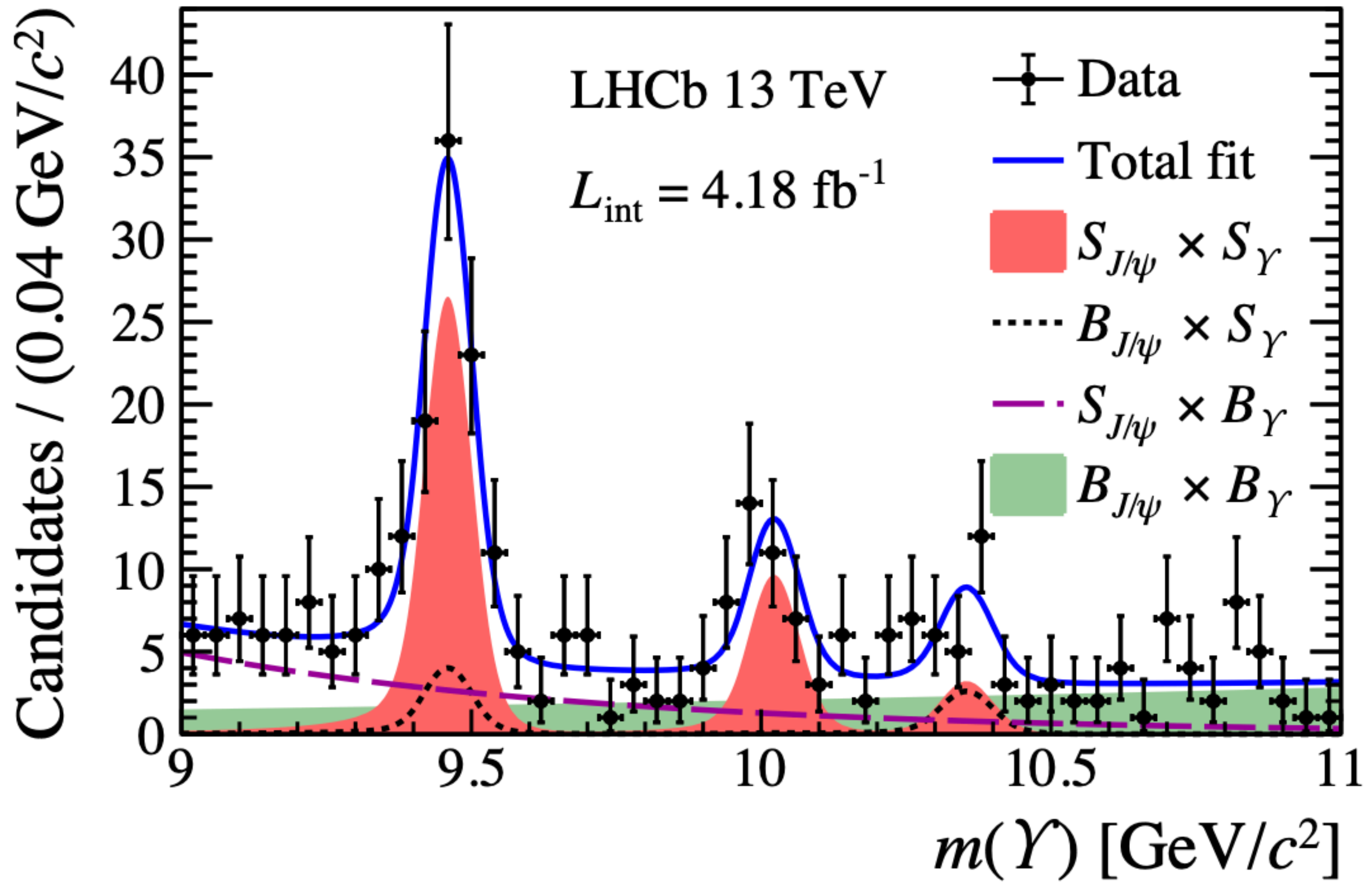

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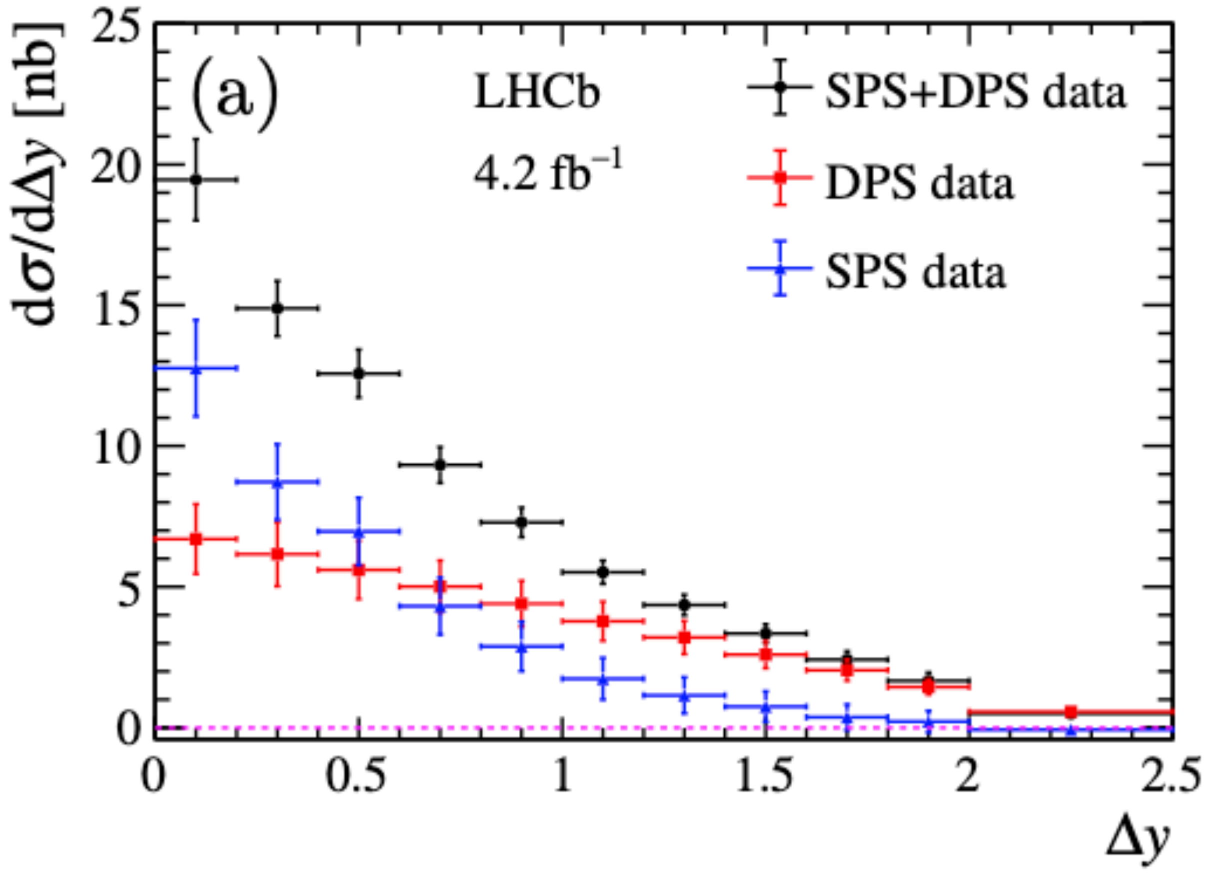


Backup

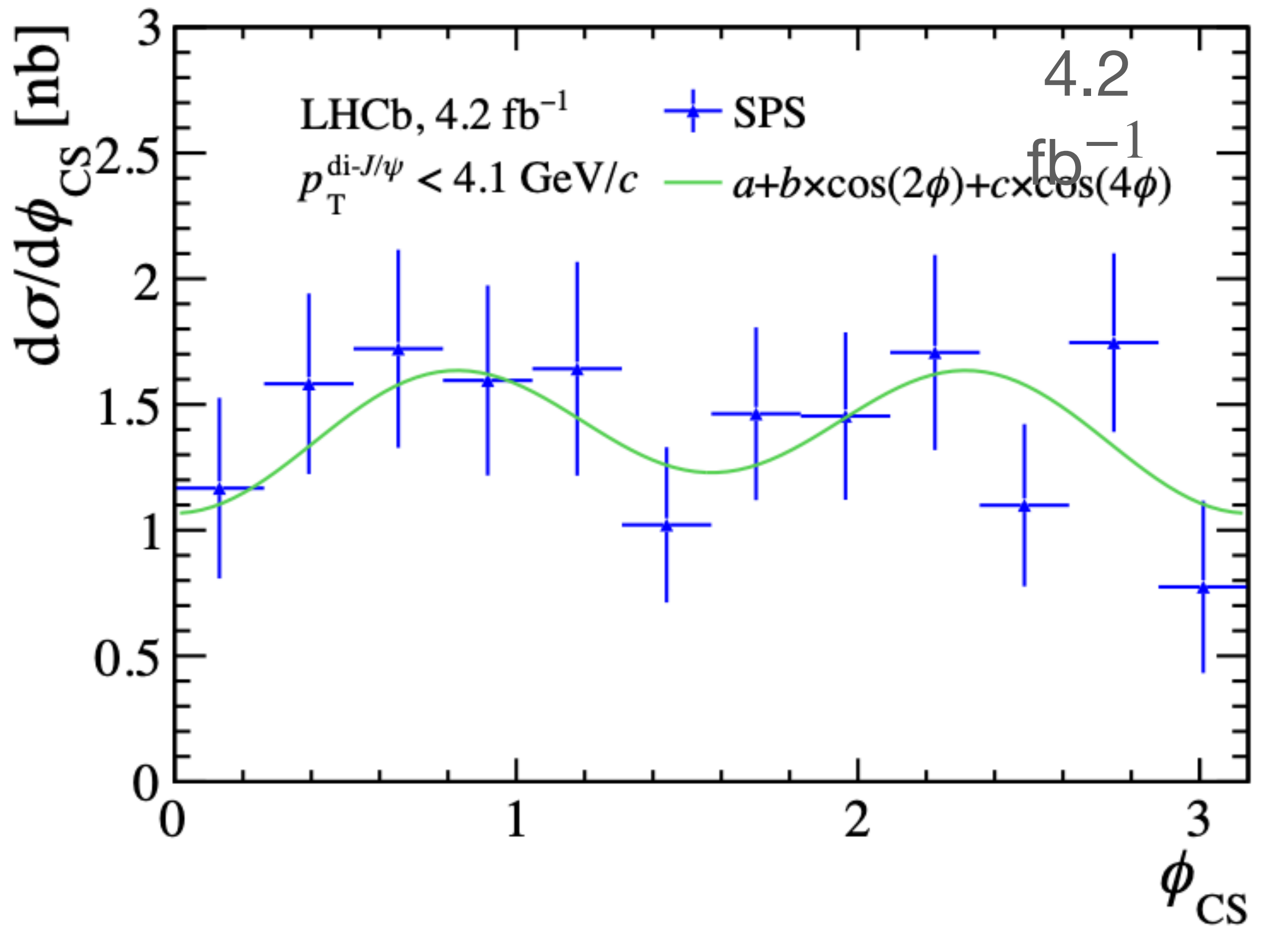
$J/\psi + J/\psi$ production

- Gluon TMD can be probed using ϕ_{CS} distribution
  - azimuthal angle of J/ψ in Collins-Soper frame
- 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 $p_{\mathrm{T}}^{di-J/\psi} < \langle m_{di-J/\psi}\rangle/2 = 4.1$ GeV/c
  - $\langle \cos 2\phi_{CS}\rangle = b/2a = -0.029 \pm 0.050_{stat} \pm 0.009_{syst}$
  - $\langle \cos 4\phi_{CS}\rangle = c/2a = -0.087 \pm 0.052_{stat} \pm 0.013_{syst}$

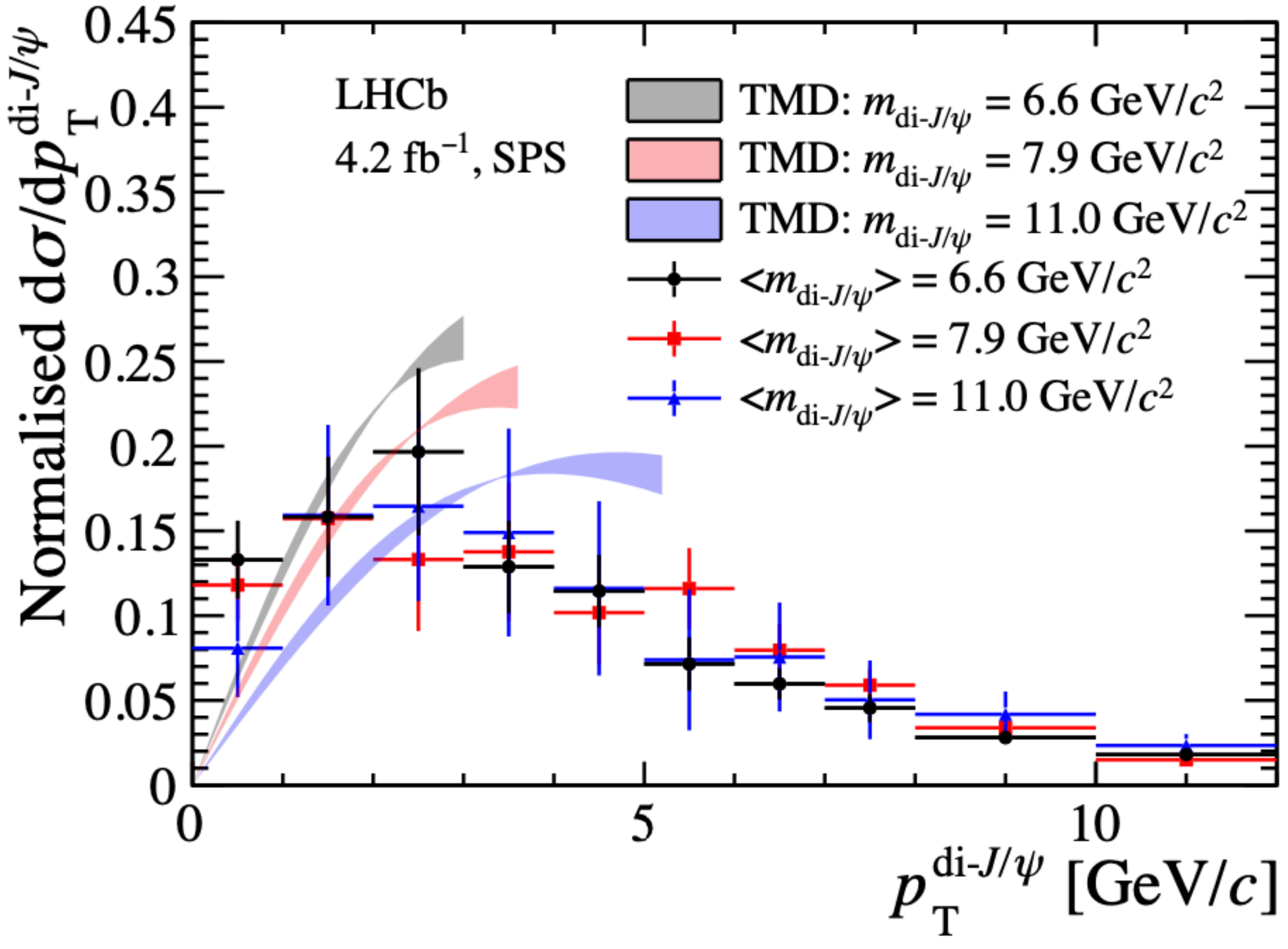
The first estimate for TMD

Theory shows some discrepancy, more data are needed

LHCb-PAPER-2023-022



ϕ_{CS} distribution for SPS



TMD: Scarpa [Eur. Phys. J. C 80 (2020) 87]