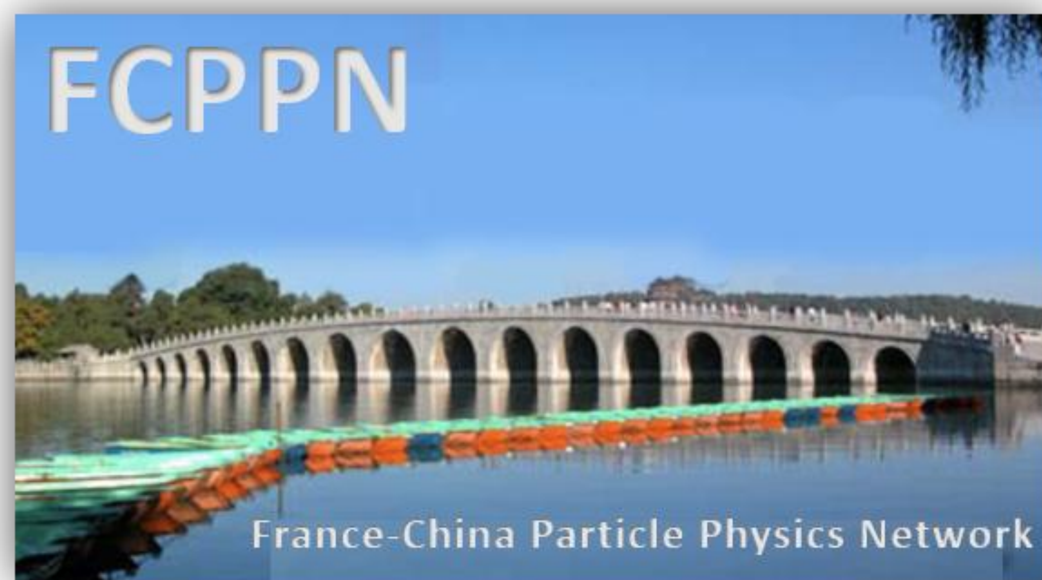
Charmonium production in LHCb



FCPPN/L 2025, Qingdao, 21-25/7/2025

Vladik Balagura, Yanting Fan, Feng-Kun Guo, Jibo He, Raoul Henderson, Jean-Philippe Lansberg, Zhijun Liu, Hua-Sheng Shao, Qi Shi, Yuxuan Tang, Zhenhong Wu, Vsevolod Yeroshenko, Yixiong Zhou, Valeriia Zhovkovska, SB

Contacts: Jibo He and Sergey Barsuk

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

LPTHE LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

中国科学院大学 University of Chinese Academy of Sciences

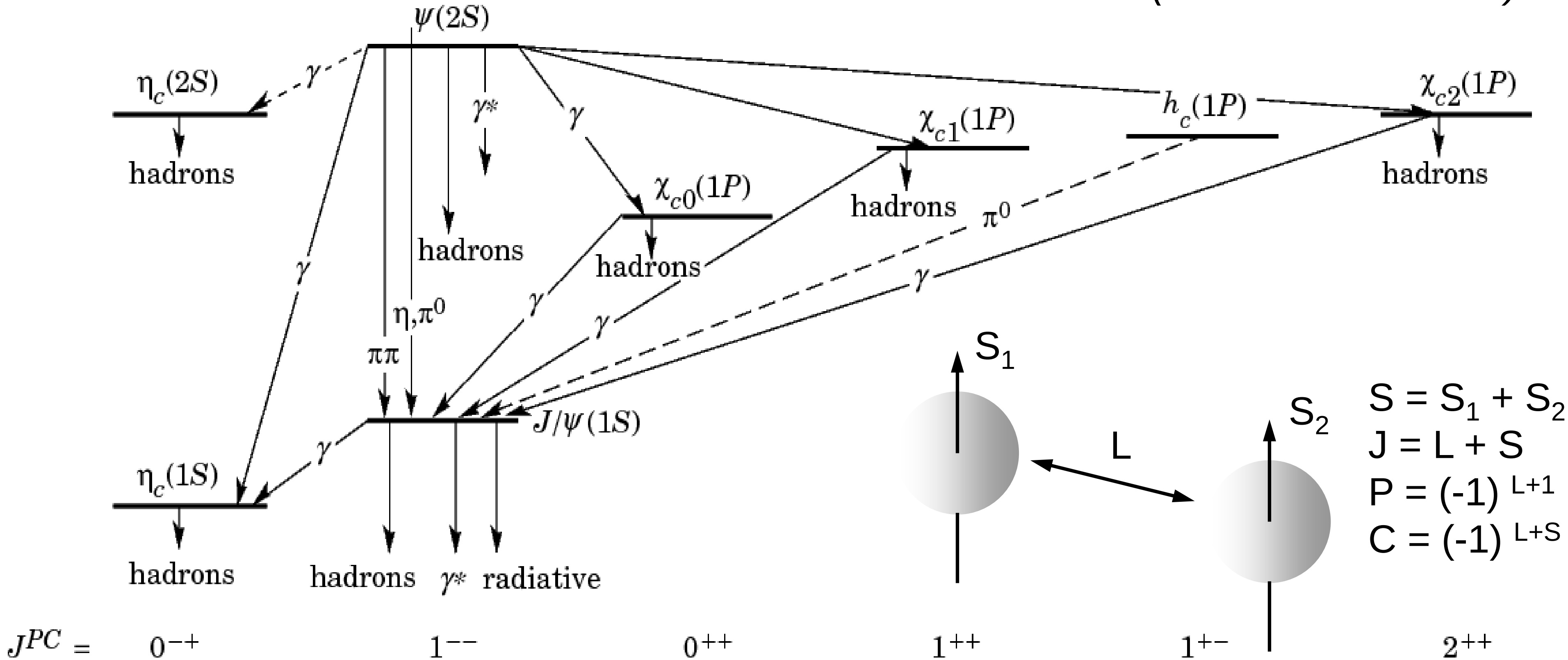
Charmonium : bound state of charm quark and anti-charm quark

Lovers
Kharkiv, before the war

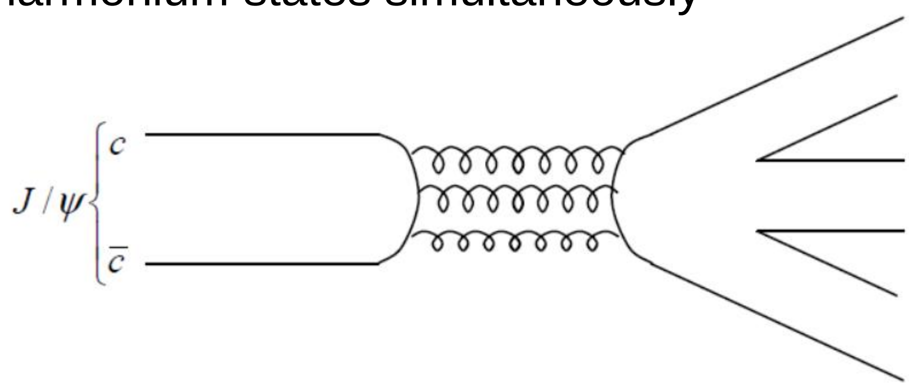
Charmonium : bound state of charm quark and anti-charm quark

Lovers
Kharkiv, before the war

Charmonium states (under $D\bar{D}$ threshold)



- **Hadronic final states** allow to study different charmonium states simultaneously



- **Below $D\bar{D}$ threshold: strong annihilation to two or three gluons**, α_S^4 or α_S^6 dependence
- **Above $D\bar{D}$ threshold: decays to $D\bar{D}$ via single gluon radiation**, α_S^2 dependence

J/ψ
$\eta_c(1S)$
χ_{c0}
χ_{c1}
h_c
χ_{c2}
$\eta_c(2S)$
after Steve Olsen
freepik.com

❑ Two scales of production:
hard process of **Q$\bar{\text{Q}}$ formation** and **hadronization of Q$\bar{\text{Q}}$** at softer scales

❑ **Factorization**: $d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle \mathcal{O}^H(n) \rangle$

Short distance: perturbative cross-sections + pdf for the production of a $Q\bar{Q}$ pair

Long distance matrix elements (LDME), non-perturbative part

❑ *Hadronization description*

❑ Colour evaporation model (CEM): application of quark-hadron duality; only the invariant mass matters

❑ Colour-singlet model: intermediate Q$\bar{\text{Q}}$ state is colourless and has the same J^{PC} quantum numbers as the final-state quarkonium

❑ NRQCD: all viable colours and J^{PC} allowed for the intermediate Q$\bar{\text{Q}}$ state, they are adjusted in the long-distance part with a given probability. Long-Distance Matrix Elements (LDME) from experimental data. *Most used since is based on an EFT and can be improved systematically*

❑ **Universality**: *same LDME for prompt production and production in b-decays; for e+e-, ep, pp, …; all beam energies; …*

❑ Heavy-Quark **Spin-Symmetry** (HQSS): **links between** colour-singlet (CS) and colour-octet (CO) **LDME of different quarkonium states**

- Many puzzles are still there
- Simultaneous description of **J/ψ production** and **polarization – “polarization puzzle“**
- Simultaneous description of $\boldsymbol{\eta_c}$ and **J/ψ** together with **J/ψ photoproduction - “HQSS puzzle”**
- Negative contribution in the cross-section
- Tension with **J/ψ+Z production**
- CEM not describing P-waves production

EPJC 75 (2015) 7, 313
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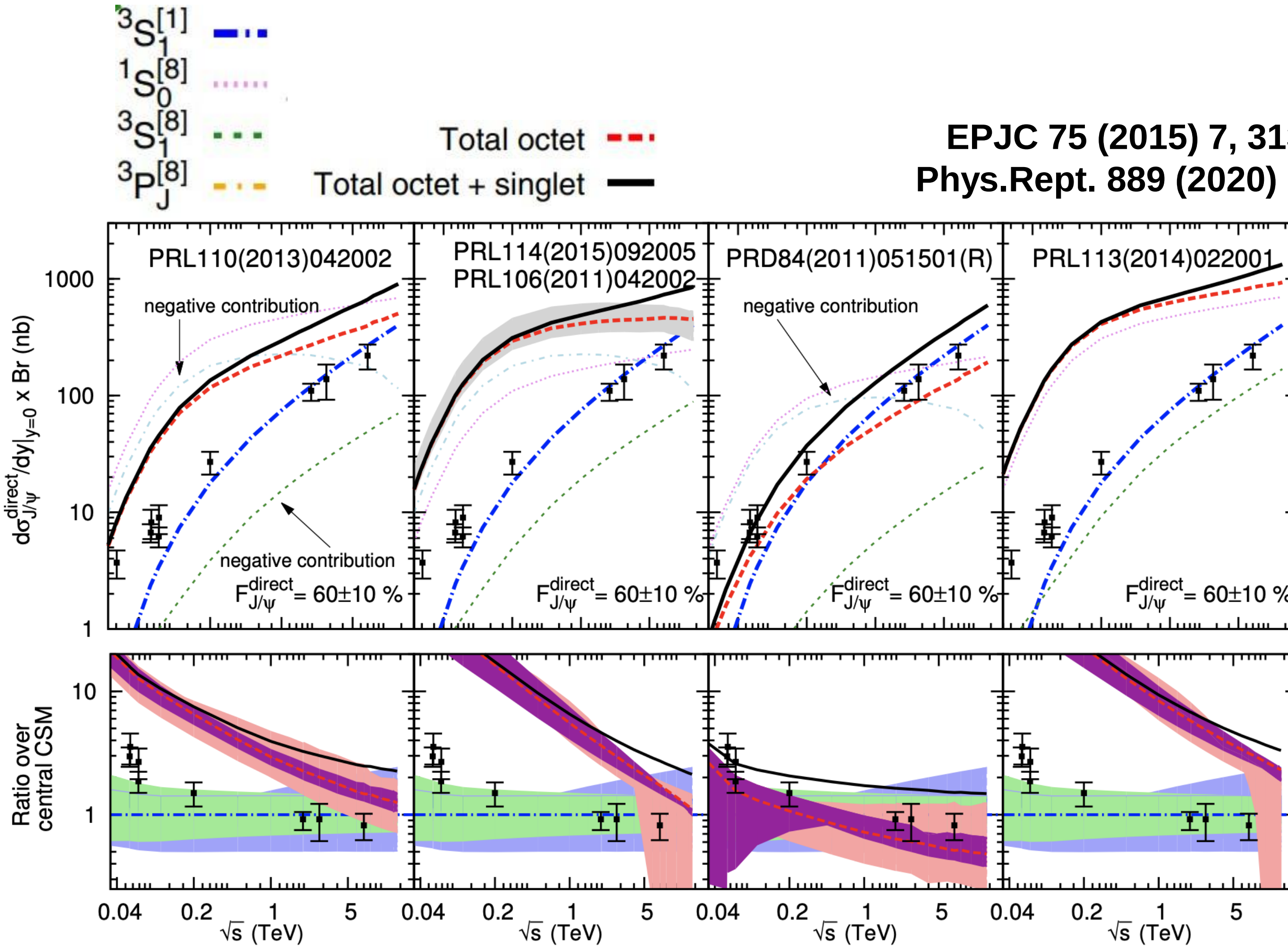


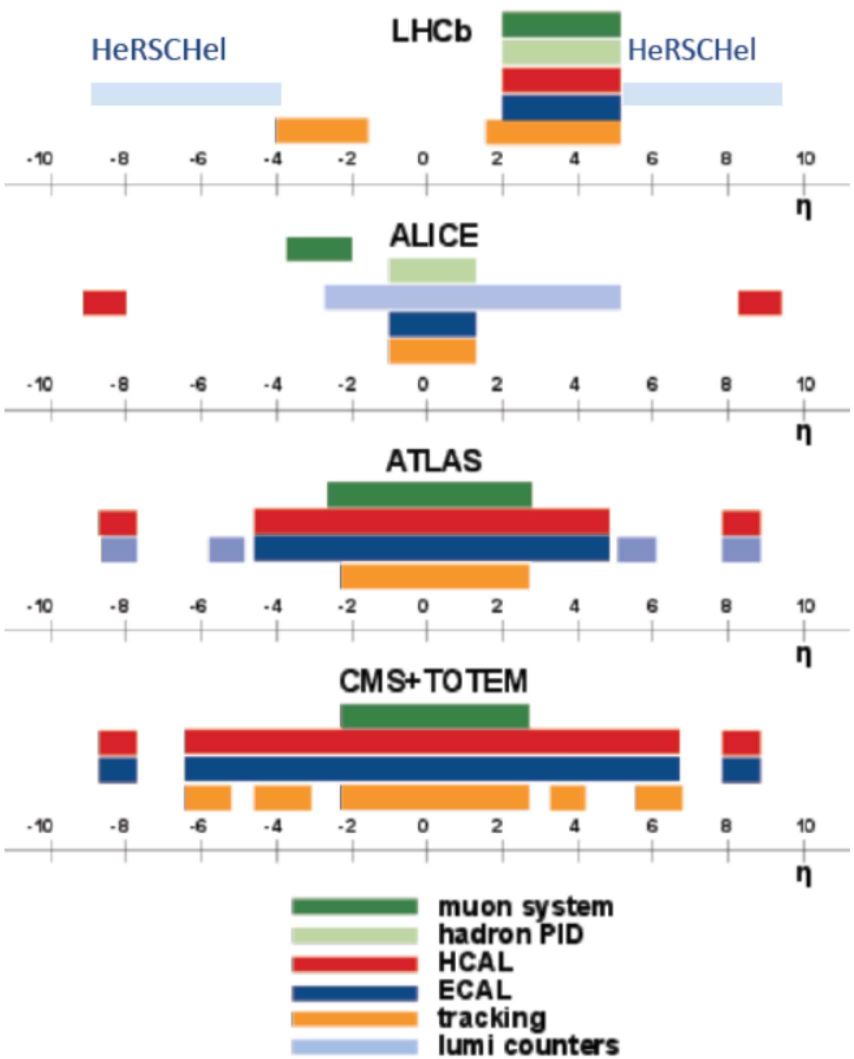
LDMEs	J/ψ hadropr.	J/ψ photopr.	J/ψ polar.	η_c hadropr.
Butenschön et al.	✓	✓	✗	✗
Chao et al. + η_c	✓	✗	✓	✓
Zhang et al.	✓	✗	✓	✓
Gong et al.	✓	✗	✓	✗
Chao et al.	✓	✗	✓	✗
Bodwin et al.	✓	✗	✓	✗

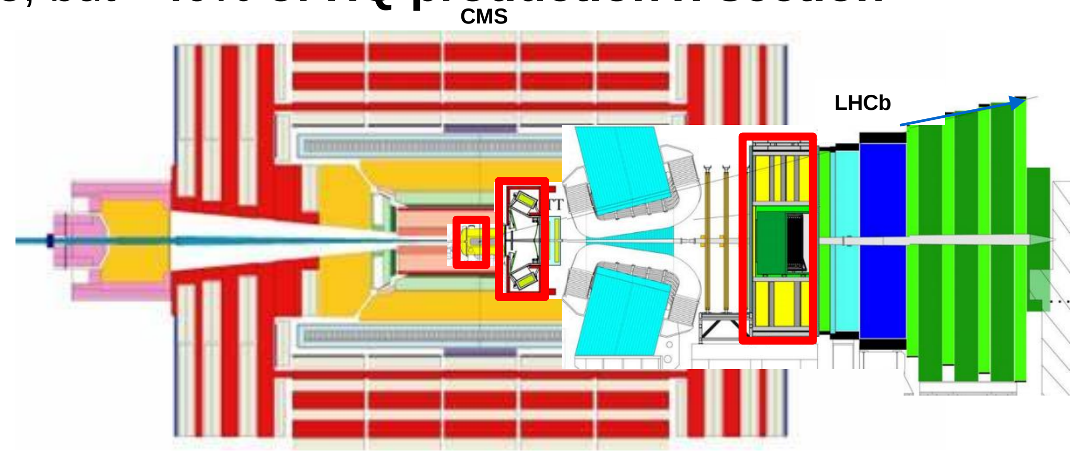
M. Nefedov

LHCb detector

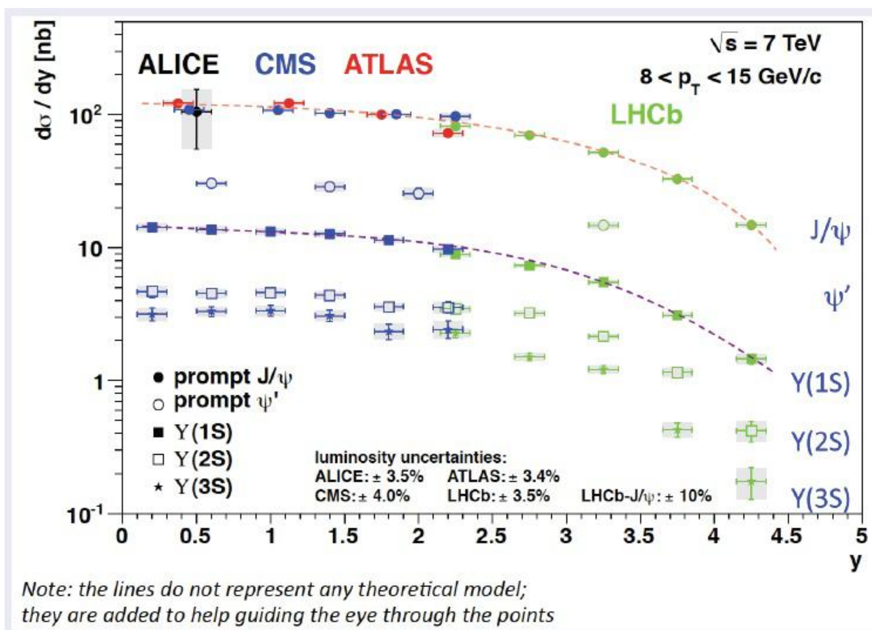
LHC detectors studying quarkonium

- Quarkonium production: **forward peaked & correlated HQ production** at the LHC
- ATLAS & CMS: mid-rapidity
- LHCb: forward region, **~4% of solid angle**, but **~40% of HQ production x-section**





Complementary cross-section measurements



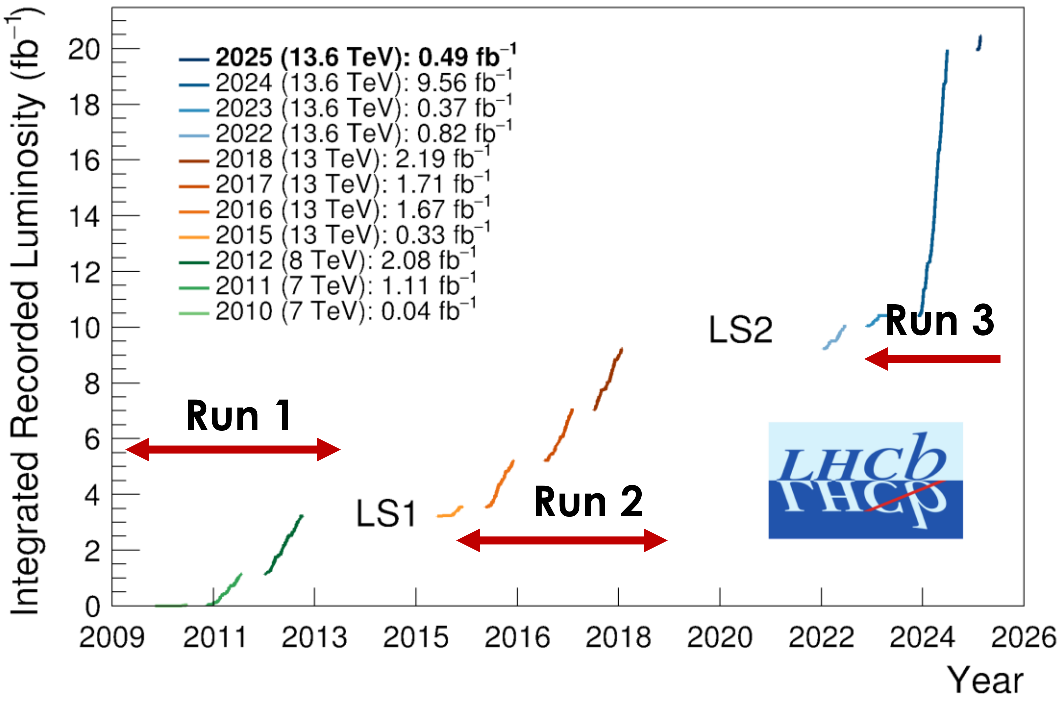
ALICE : 5.6 nb^{-1}
ATLAS : 2.2 pb^{-1}
CMS : 37, 36 pb^{-1}
LHCb : 5.2, 36, 25 pb^{-1}

ALICE: arXiv:1205.5880
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC71 (2011) 1645
LHCb: arXiv:1204.1258
CMS: BPH-11-001
LHCb: EPJC72 (2012) 2025

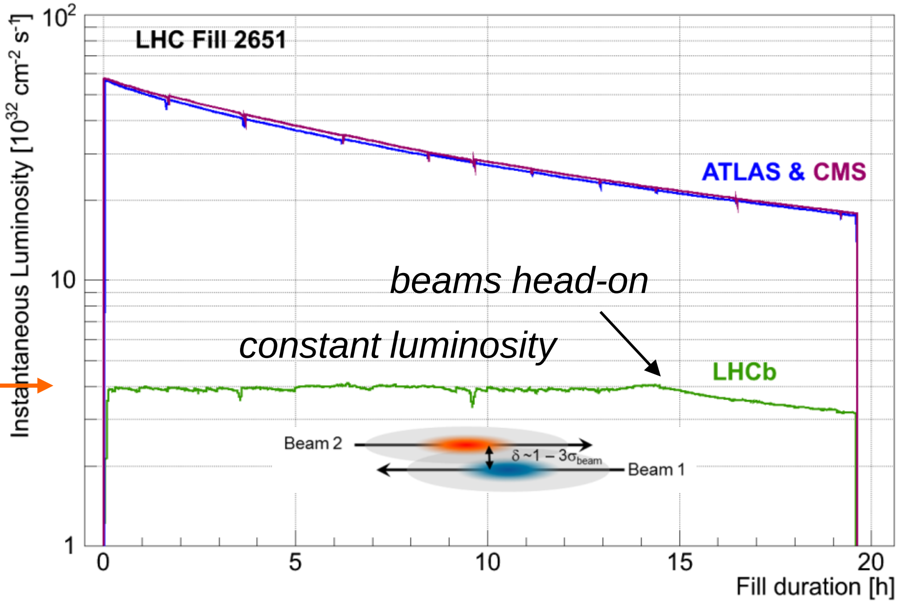
Acceptance coverage, trigger threshold, hadron ID, luminosity

- **Excellent performance of the LHC and the experiments**

- LHCb integrated luminosity : ∫Ldt ~ 20 fb^{-1}

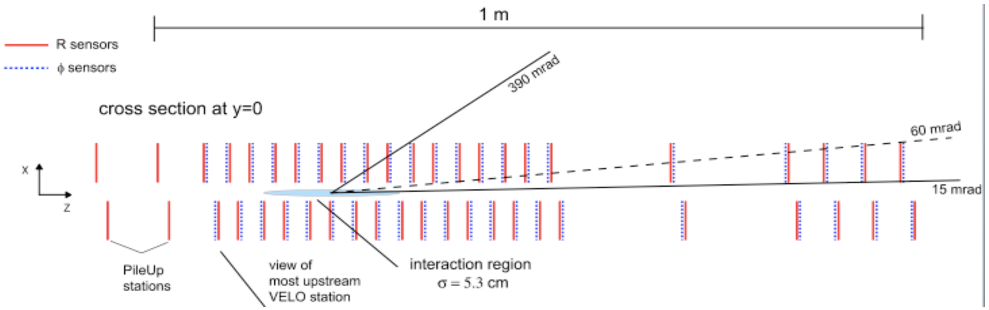


- Luminosity leveling for LHCb

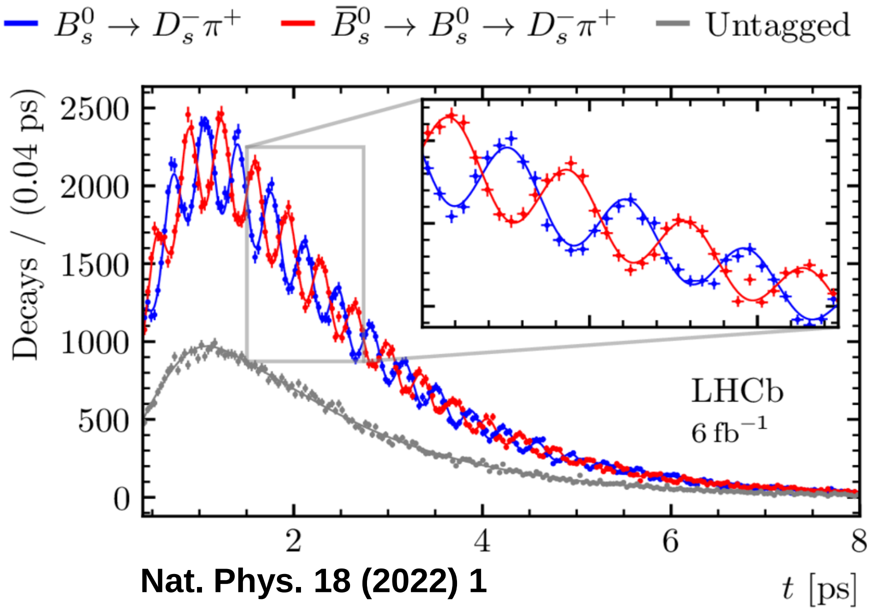


JINST 8 (2013) P08002, JINST 9 (2014) P09007

- 88 semi-circular **microstrip Si sensors**
- Double-sided, **R and φ** layout
- 300 μm thick n-on-n sensors, strip pitches from 40 to 120 μm
- **First active strip at 8 mm from beam axis**



- Excellent **spatial resolution**, down to 4 μm for single tracks
- Precise **impact parameter** measurement, $\sigma_{IP} = 11.6 + 23.4/pT$ [μm]
- Precise **primary vertex** reconstruction, $\sigma_{x,y}$ = 13 μm, σ_z = 69 μm for vertex of 25 tracks
- Excellent **proper time** resolution
- **Vertex resolution** allows to resolve fast (x~27) $B_s\bar{B}_s$ oscillations



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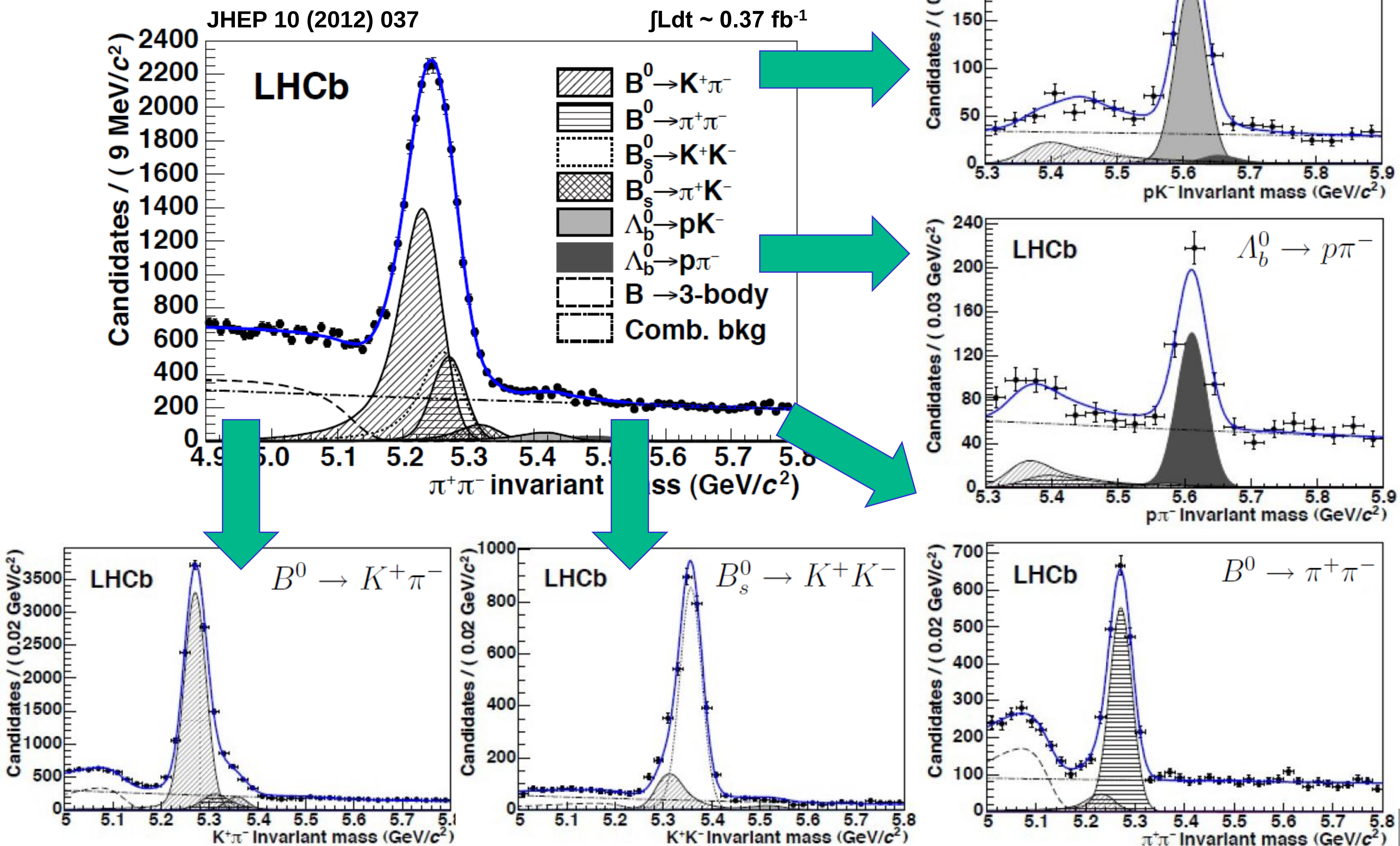
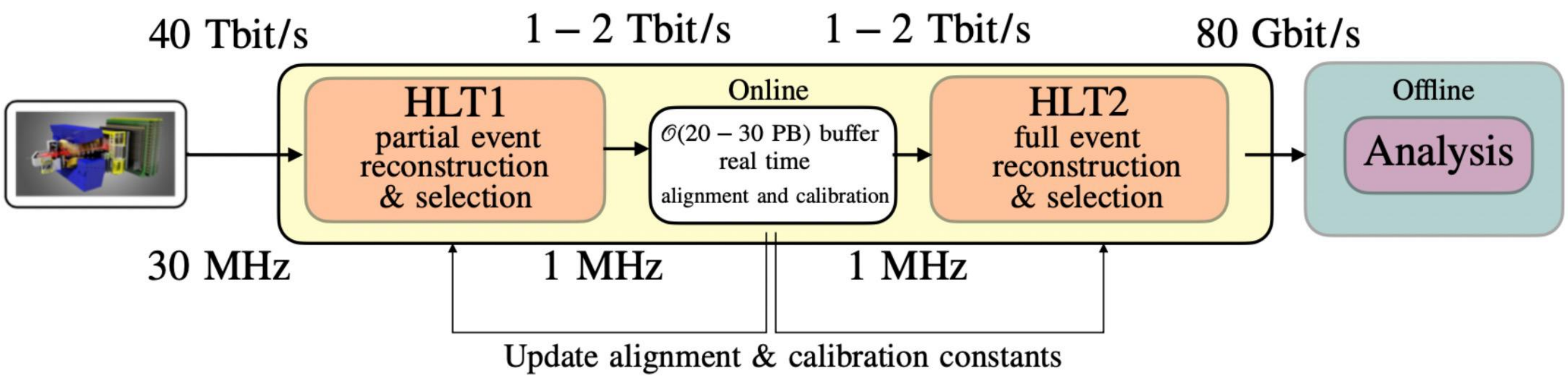
Charged hadron ID in LHCb: Cherenkov light detectors

- **2 Ring Imaging Cherenkov Detectors**
- Charged hadron ID, **charmless 2-body b-hadron decays**

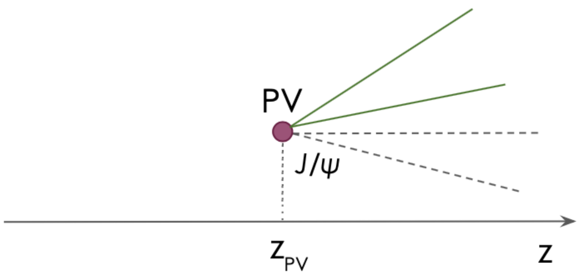


- LHCb upgrade I for runs 3 and 4
- **VELO** new design **with pixels**
- **Upstream tracker** with silicon strips, **main tracker** with scintillating fibers
- **RICH** photodetectors MAPMTs
- New dedicated **luminometer**
- SMOG2 **gas target** integrated in VELO
- All subdetectors readout at 40 MHz for a **fully software trigger using GPUs**
- Can run at 5 x higher luminosity

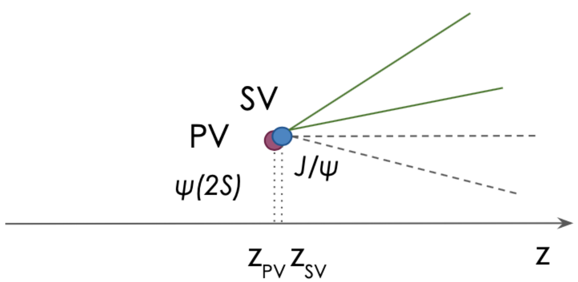


- 30 MHz of inelastic collisions will be reduced to ~1 MHz by the HLT1 (tracking/vertexing and muon ID) running on **GPUs**
- Highest throughput of any HEP experiment
- Many measurements directly profit from higher statistical precision (about x3 with run 3 only)

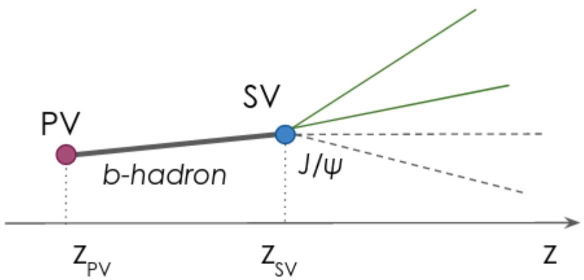
- **Hadroproduction**



- Decays of **higher resonances**



- Production in **b-hadron decays** / *non-prompt*



prompt production

- **Prompt J/ψ production** and **production in b-hadron decays** distinguished from the fit to pseudo-lifetime distribution

distinguished via pseudo-proper decay time

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

PV – primary vertex
SV – secondary vertex

Charmonium production in pp collisions

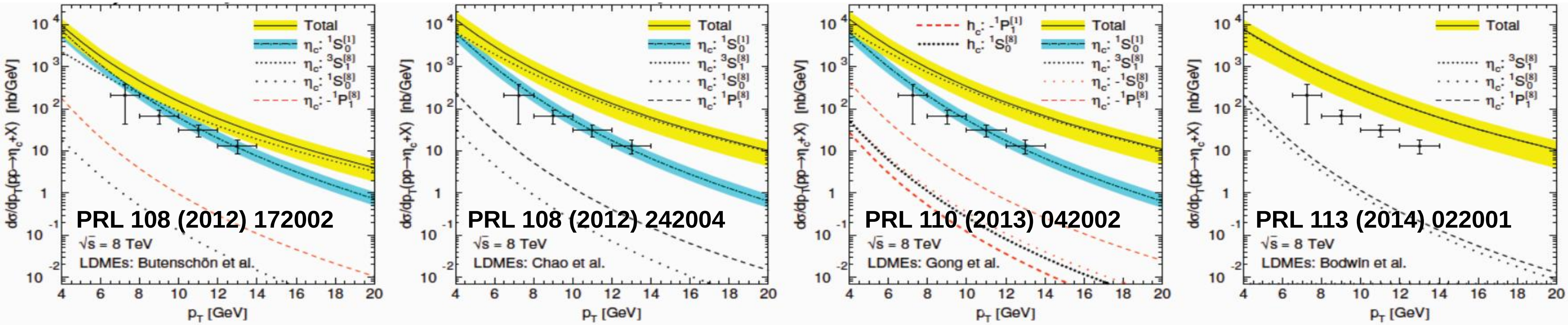
- $\eta_c(1S)$ LDMEs determined via known HQSS relations between $\eta_c(1S)$ and J/ψ and J/ψ production

J/ψ prediction (NRQCD CS+CO)

CS prediction

LHCb: EPJC 75 (2015) 311

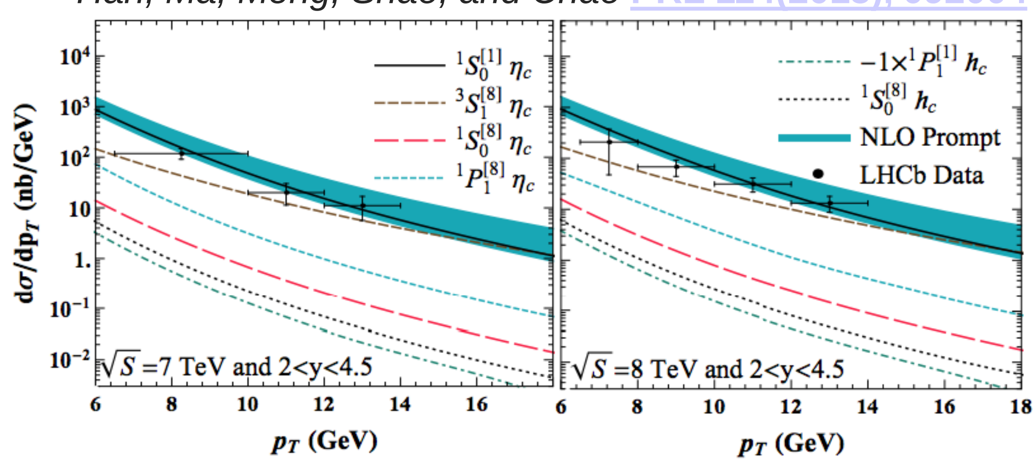
Butenschoen, He, Kniehl, **arXiv:1411.5287**



- Results described by **CS NLO**, below expected CO contribution
- Progress in theory description, integrating LHCb result on η_c production in LDME calculations

Han, Ma, Meng, Shao, and Chao PRL 114(2015), 092004

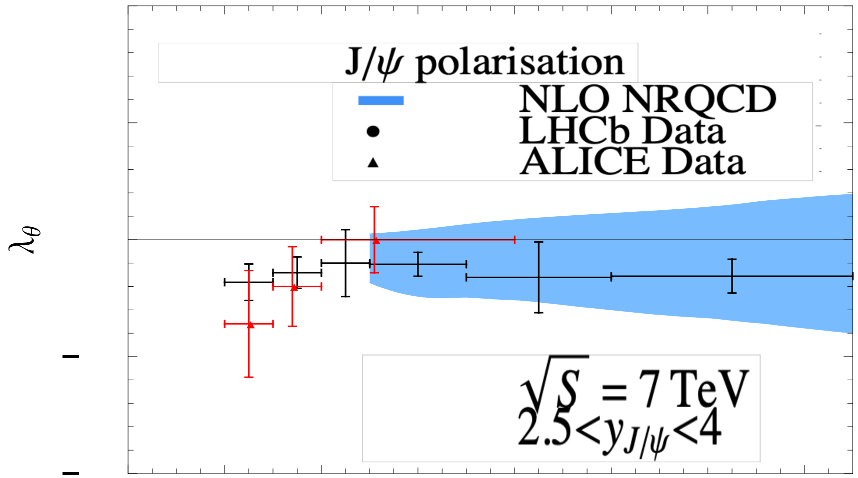
$$0 < O^{\eta_c}({}^3S_1^8) < 1.46 \times 10^{-3}\ \mathrm{GeV}^3$$



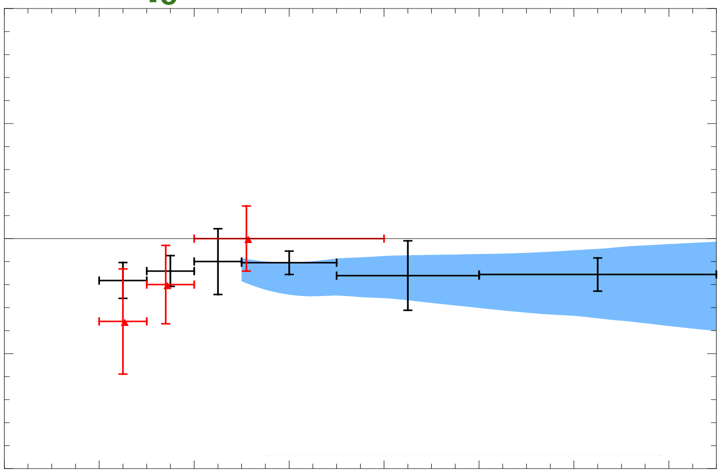
- Theory description still covers limited p_T range
- Further tests with **measurements at different √s and of other linked observables**

- η_c production at $\sqrt{s}$=7 and 8 TeV sets new constraint on J/ψ polarization

Before η_c measurements



After η_c measurements



PRL 114(2015), 092004

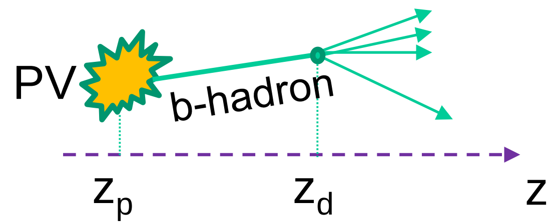
- Impressive progress !
- Still :
  - Tension with CDF data
  - Two large CO contributions cancel each other ⇒ hierarchy problem ⇒ Soft Gluon Fragmentation, etc.?

- Analysis with 13 TeV data, measurement relative to J/ψ

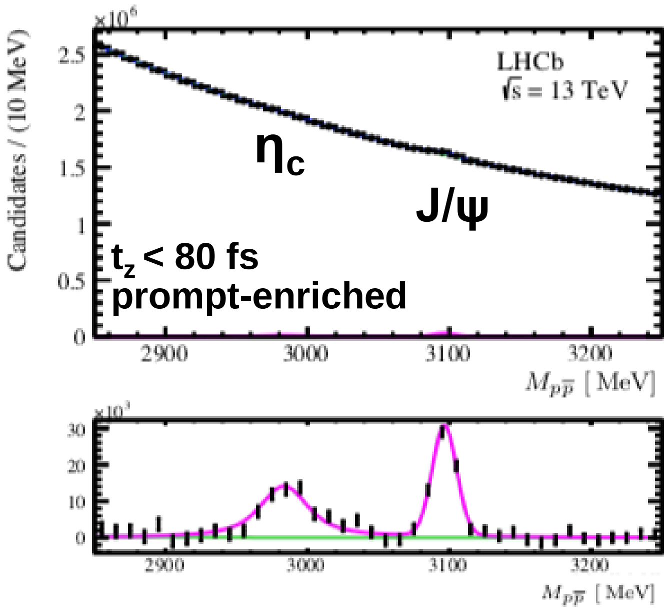
EPJC 80 (2020) 191

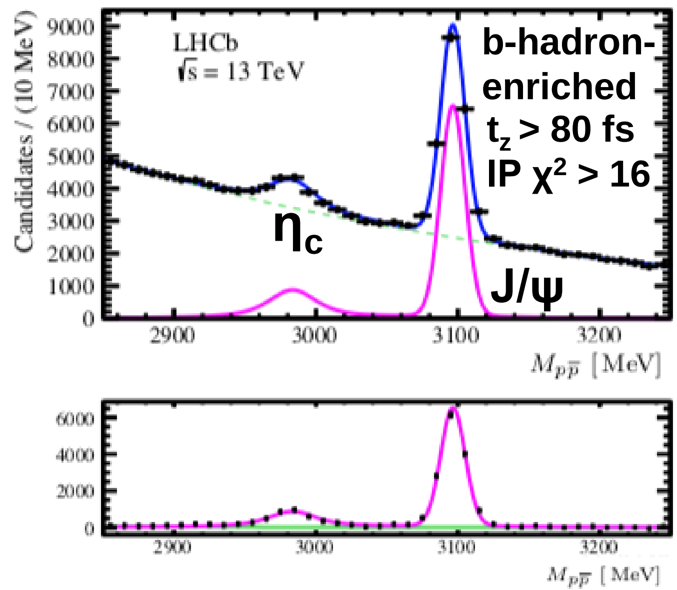
$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 2 fb^{-1}

- **Pseudo proper-time** to separate **prompt charmonium** and **charmonium from b-decays**



$$t_z = \frac{(z_d - z_p) M_{p\bar{p}}}{p_z}$$

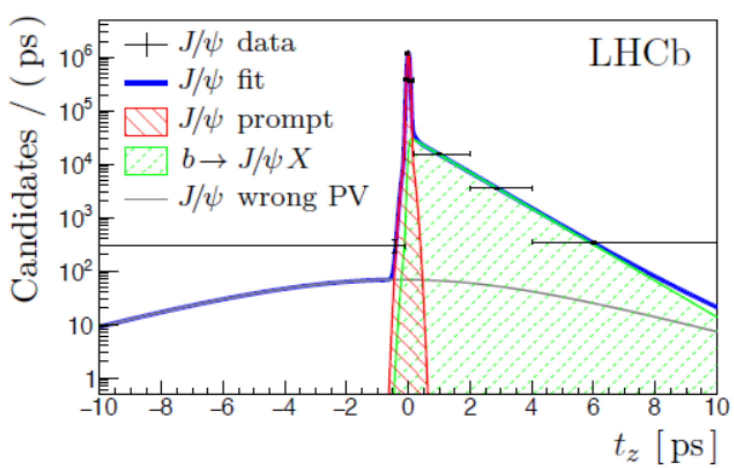


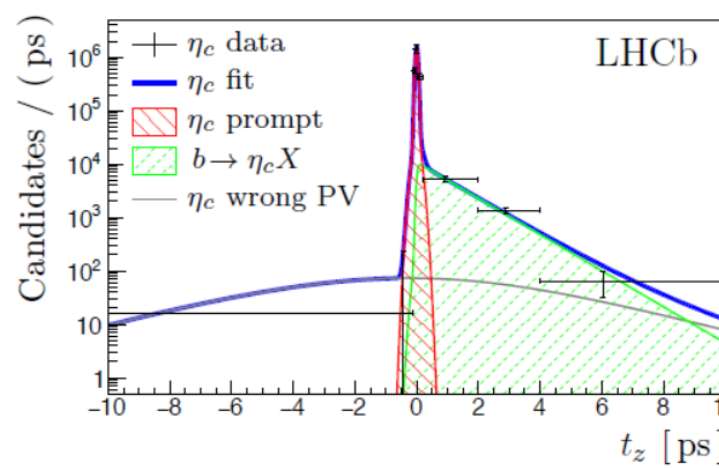


- **Selection** (account for cross feed)

- … or **pseudo proper-time fit**

- Good agreement between the results



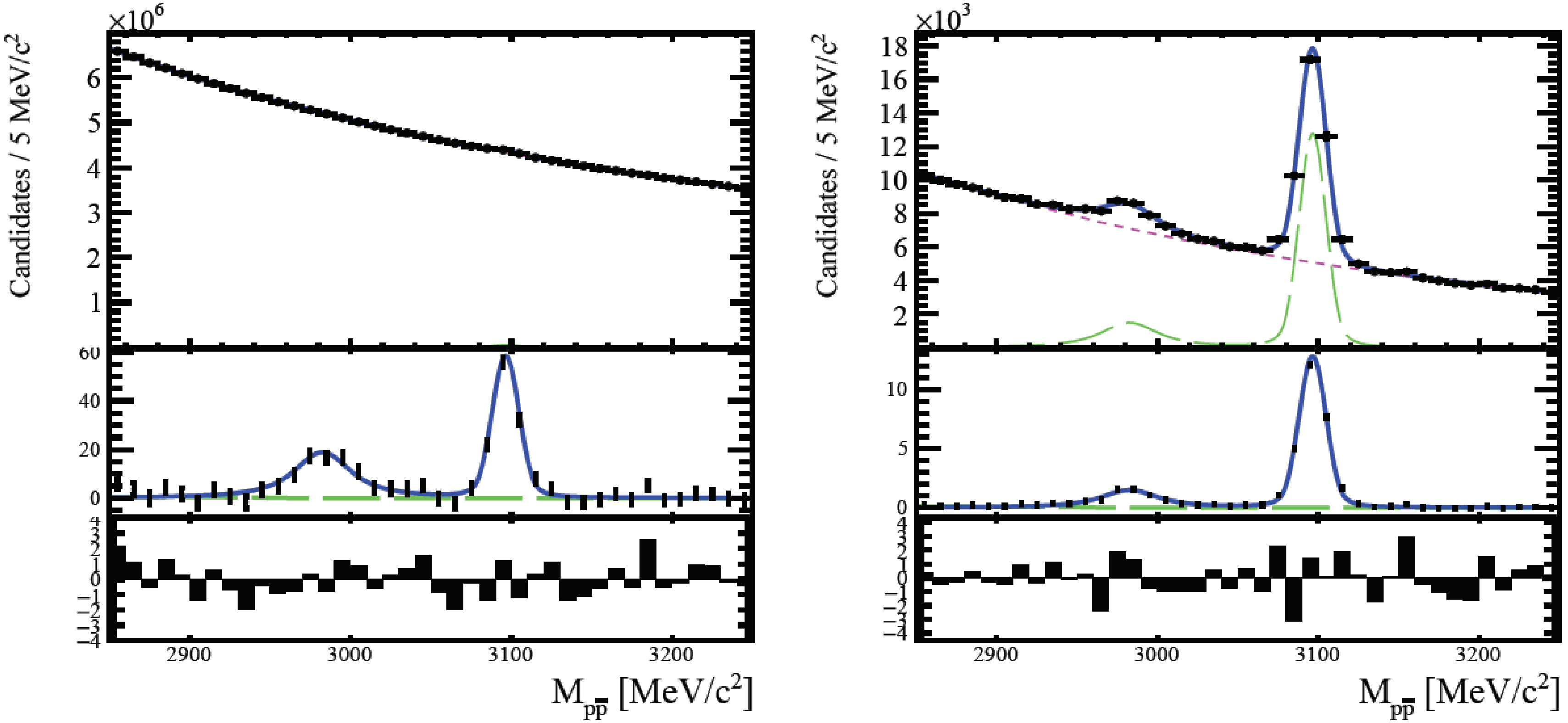


$\eta_c(1S)$ production

- Analysis with 13 TeV data, measurement relative to J/ψ

EPJC 84 (2024) 1274
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 2.2\ fb^{-1}$

- **Run 2, 2018, dedicated trigger : new or more precise results**



- **Almost 3 x more signal sample**

- **First measurement of $\eta_c(1S)$ production cross section at 13 TeV**

EPJC 80 (2020) 191
$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 2 fb^{-1}

$$(\sigma_{\eta_c})^{6.5\,\mathrm{GeV}<p_T<14.0\,\mathrm{GeV},\,2.0<y<4.5}_{13\,\mathrm{TeV}} = 1.26 \pm 0.11 \pm 0.08 \pm 0.14\,\mu\mathrm{b}$$

- Color Single model prediction: Feng,Shao,Lansberg,Zhang,Usachov,He **NPB 945 (2019) 114662**

$$1.56^{+0.83}_{-0.49}\,{}_{scale}\;{}^{+0.38}_{-0.17}\,{}_{CT14NLO}\;\mu\mathrm{b}$$

- **Consistent with being described by CSM**

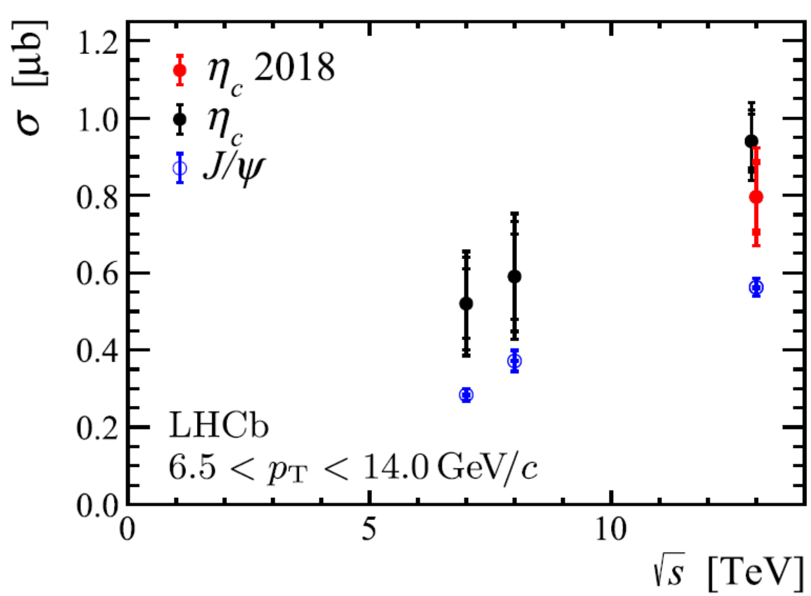
- **Run 2, 2018, dedicated trigger : new or more precise results**

EPJC 84 (2024) 1274
$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 2.2 fb^{-1}

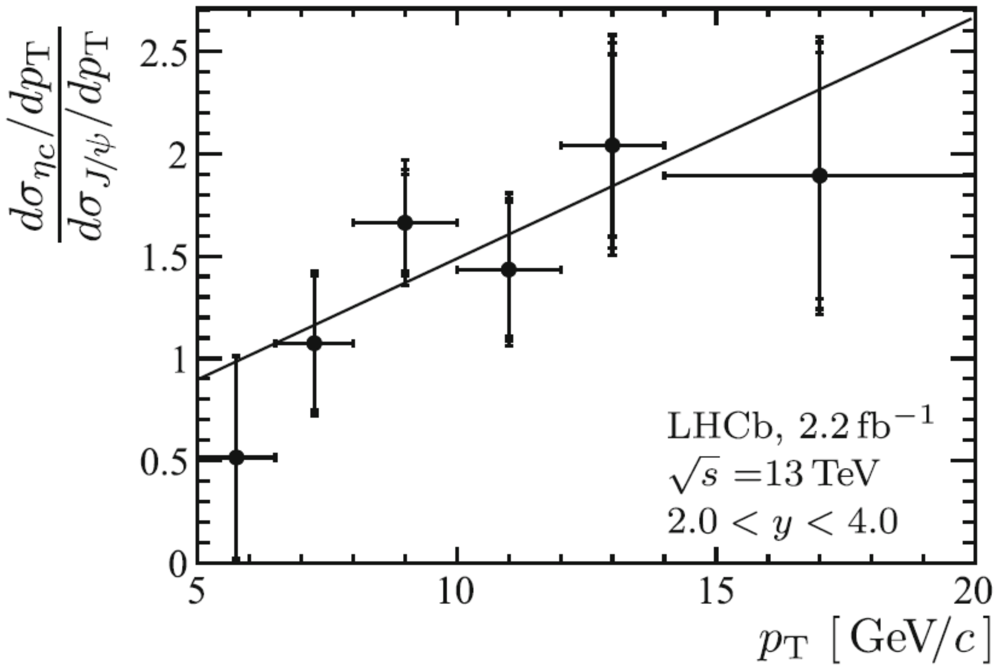
$$(\sigma_{\eta_c}/\sigma_{J/\psi})^{5.0<p_T<20.0\,\mathrm{GeV}/c,\;2.0<y<4.0} = 1.32 \pm 0.14 \pm 0.09 \pm 0.13.$$

$$(\sigma_{\eta_c})^{5.0<p_T<14.0\,\mathrm{GeV}/c,\;2.0<y<4.0} = 1815 \pm 189 \pm 120 \pm 192\,\mathrm{nb}$$

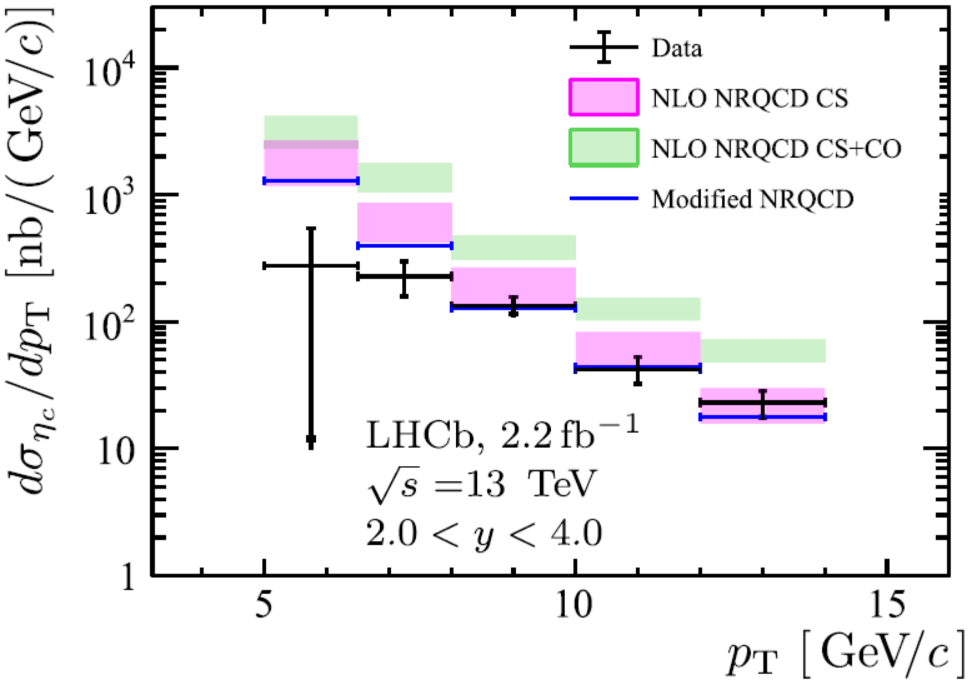
- $\sqrt{s}$ cross-section dependence



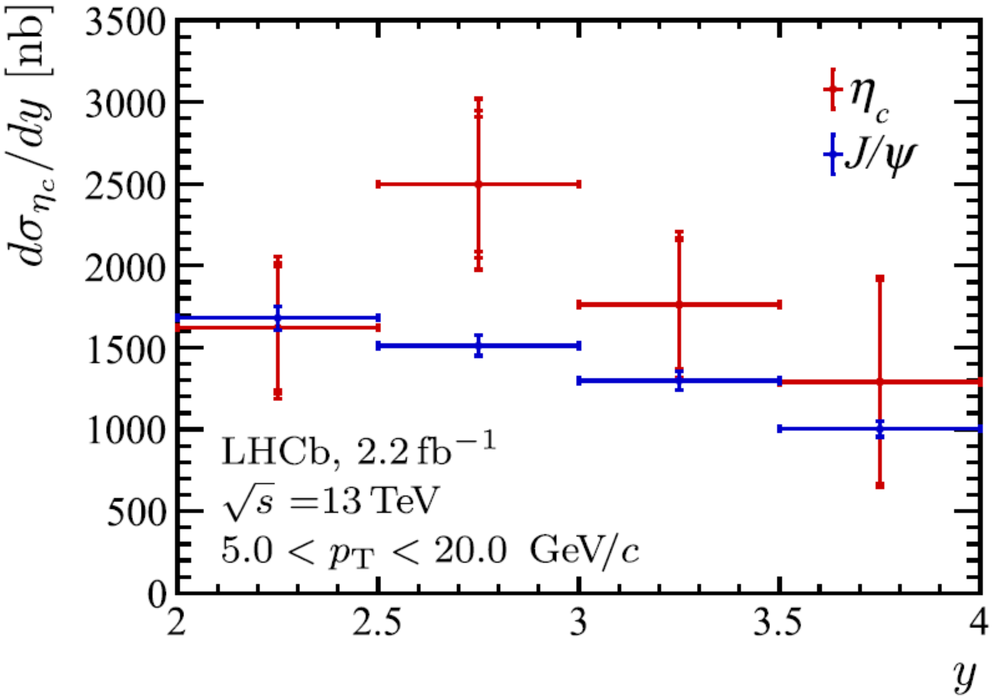
- Slope persists at the level of ≥ 3σ, different spectra for the two states



- **p_T-differential cross-section**, how reliable a description at p_T~5 GeV ?



- First time **rapidity-differential cross-section** (inspired by Hua-Sheng Shao)



- Predictions for three different CO LDME sets

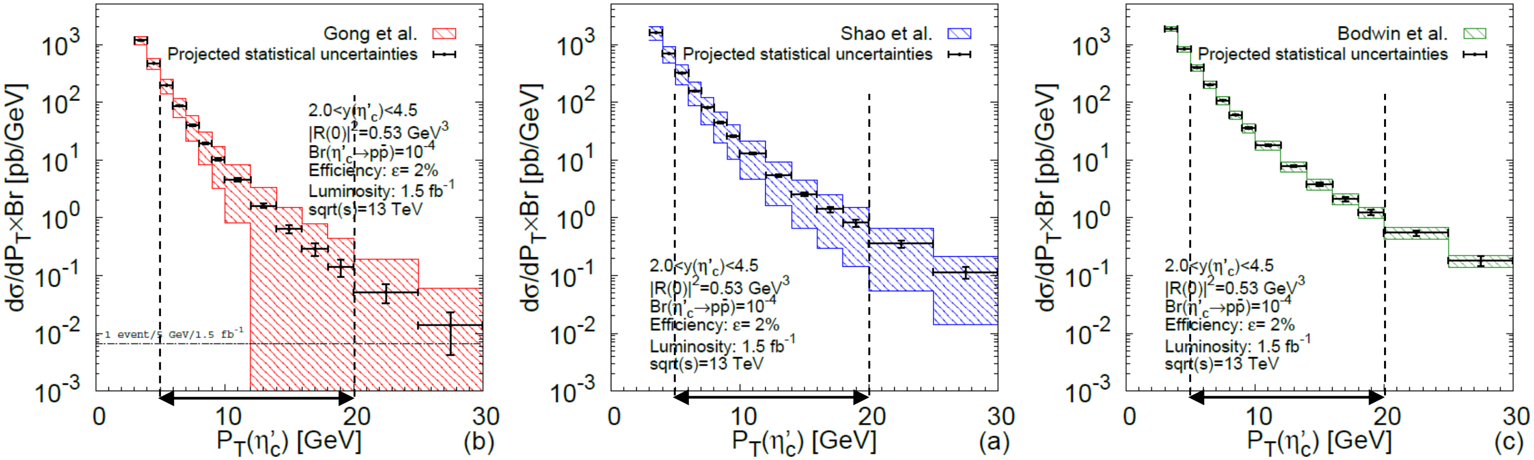


Table 7 Upper limits (UL) at 95% CL for $\eta_c(2S)$ relative to J/ψ and $\eta_c(2S)$ absolute prompt production cross-section, and its comparison with NLO NRQCD theoretical prediction (Refs. [7–10])

p_T [GeV/c]	UL 95% CL	Shao et al. [8]	Gong et al. [9]	Bodwin et al. [10]
	$\sigma_{\eta_c(2S)} \times \mathcal{B}_{\eta_c(2S)\to p\overline{p}}$ [pb]			
5.0–14.0	< 426	664 ± 297	365 ± 135	855 ± 123
5.0–20.0	< 401	674 ± 304	368 ± 138	870 ± 126
	$(\sigma_{\eta_c(2S)} \times \mathcal{B}_{\eta_c(2S)\to p\overline{p}})/(\sigma_{J/\psi} \times \mathcal{B}_{J/\psi\to p\overline{p}})$			
5.0–14.0, y <4.0	< 0.14	0.48 ± 0.22	0.27 ± 0.10	0.62 ± 0.09
5.0–14.0, y <4.5		0.43 ± 0.19	0.24 ± 0.09	0.55 ± 0.08
5.0–20.0, y <4.0	< 0.14			

- Essential to understand and further constrain **uncertainties in theory**
- Essential input for accounting **feeddown contributions** to lower states
- **h_c and $\eta_c(2S)$ production cross-sections and decay branching ratios** are needed

EPJC 84 (2024) 1274

$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 2.2 fb^{-1}

- Essential input for accounting **feeddown contributions** to lower states
- **h_c and $\eta_c(2S)$ production cross-sections times decay branching ratios** are measured for the first time

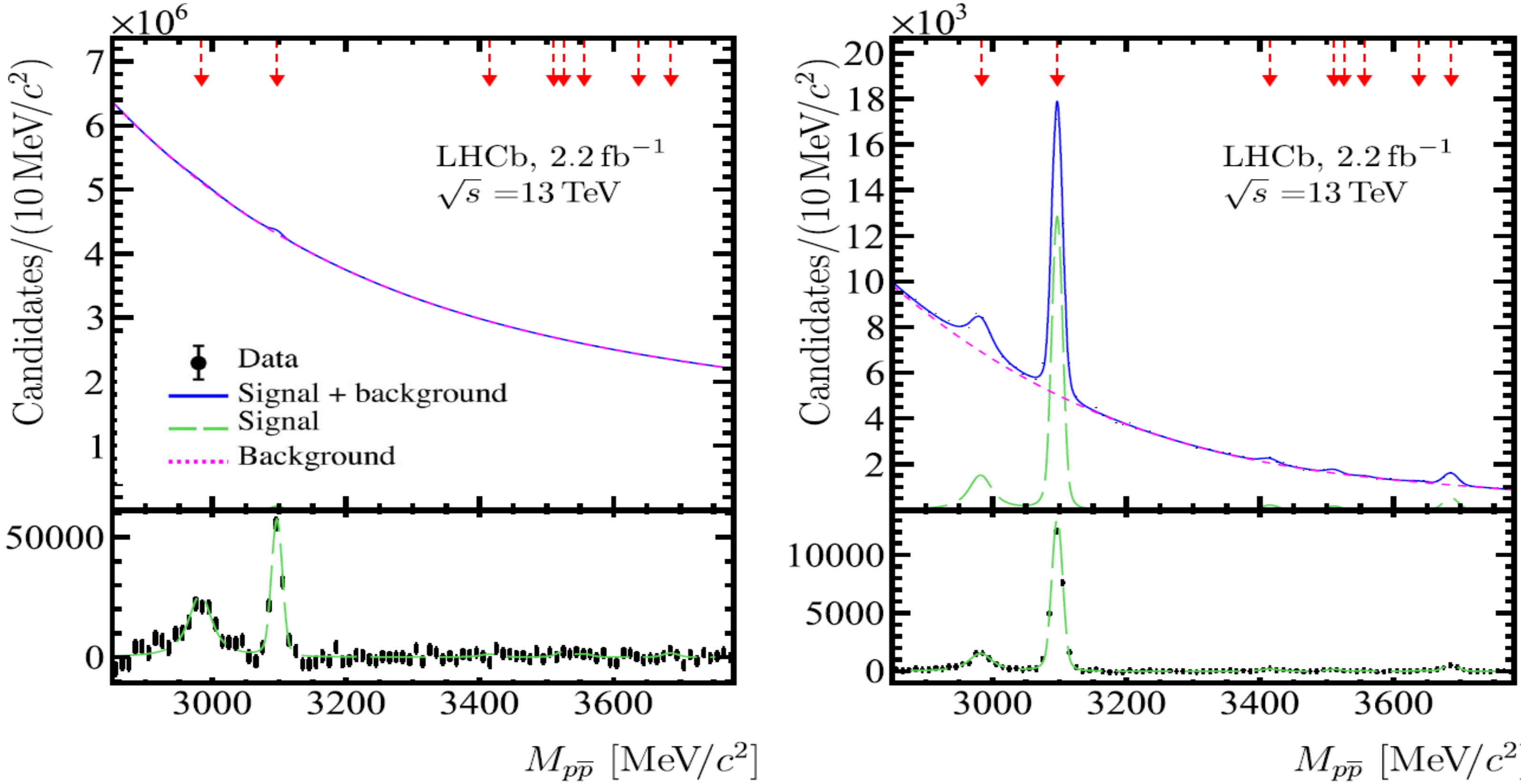
$$\frac{(\sigma_{\eta_c(2S)} \times \mathcal{B}_{\eta_c(2S)\to p\overline{p}})}{(\sigma_{J/\psi} \times \mathcal{B}_{J/\psi\to p\overline{p}})} < 0.11\ (0.14),$$

$$\frac{(\sigma_{h_c(1P)} \times \mathcal{B}_{h_c(1P)\to p\overline{p}})}{(\sigma_{J/\psi} \times \mathcal{B}_{J/\psi\to p\overline{p}})} < 0.12\ (0.13)$$

- **Branching fractions of $\eta_c(2S)$ → ppbar** needed
- Call for BES III measurement

- Inclusive production in b-decays, **charmonium decays to proton-antiproton**

EPJC 84 (2024) 1274
$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 2.2 fb^{-1}



$$\mathcal{B}_{b\to\eta_c X}/\mathcal{B}_{b\to J/\psi X} = 0.49 \pm 0.03 \pm 0.02 \pm 0.05.$$

$$\mathcal{B}_{b\to\eta_c X} = (5.64 \pm 0.31 \pm 0.18 \pm 0.73) \times 10^{-3}$$

- Precision limited by systematic **uncertainties on branching fractions of η_c(1S) → ppbar and b → J/ψ X**
- Call to publish the BES III analysis

❑ Charmonium reconstructed via **decays to ppbar**

Table 8 Branching fractions of χ_{cJ} production in inclusive b-hadron decays. The quoted uncertainties are statistical, systematic and the related to the $\mathcal{B}_{\chi_{cJ}\to p\bar{p}}$, $\mathcal{B}_{J/\psi\to p\bar{p}}$, and $\mathcal{B}_{b\to J/\psi X}$ uncertainties. The values are compared with results from analysis of charmonia production using decays to $\phi\phi$ [38] and the world average values [11]

	$c\bar{c} \to p\bar{p}$, measured	$c\bar{c} \to \phi\phi$ [38]	World average [11]
$\mathcal{B}_{b\to\chi_{c0}X} \times 10^{-3}$	$3.05 \pm 0.54 \pm 0.08 \pm 0.29$	3.02 ± 1.08	15 ± 6
$\mathcal{B}_{b\to\chi_{c1}X} \times 10^{-3}$	$5.11 \pm 1.20 \pm 0.14 \pm 0.50$	2.76 ± 1.09	14 ± 4
$\mathcal{B}_{b\to\chi_{c2}X} \times 10^{-3}$	$1.54 \pm 1.13 \pm 0.04 \pm 0.15$	1.15 ± 0.42	6.2 ± 2.9

❑ Statistically limited

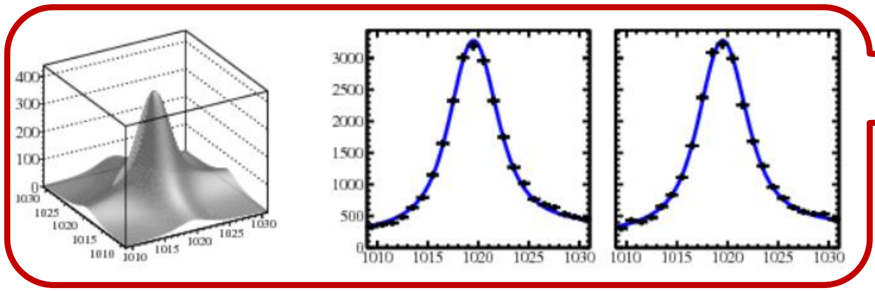
❑ Spin counting not observed

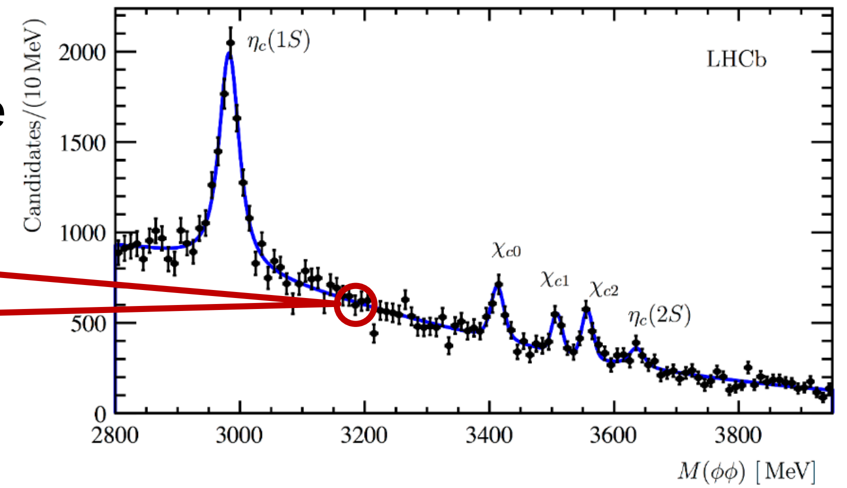
❑ Improved precision (or contributed to a better average) for χ_{c0} (and χ_{c1}) production in b-decays, consistent with previous LHCb results

❑ Improving precision for **branching fractions of χ_{ci} decays** to ppbar and φφ will further improve precision

EPJC 77 (2017) 609

- Charmonium reconstructed via **decays to φφ**
- True φφ combinations extracted using 2D fit technique





- **First measurement of $\eta_c(2S)$ production** in b-decays

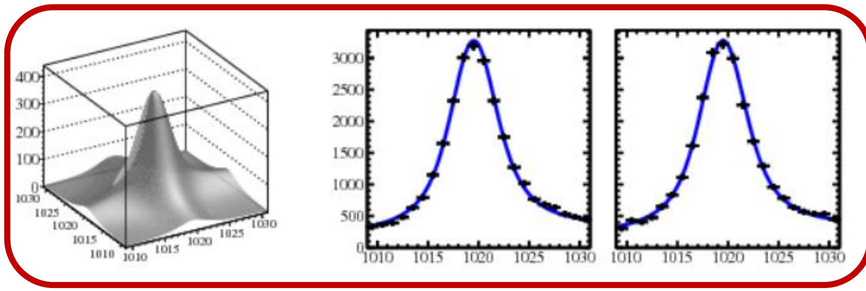
First evidence for $\eta_c(2S)\to\phi\phi$

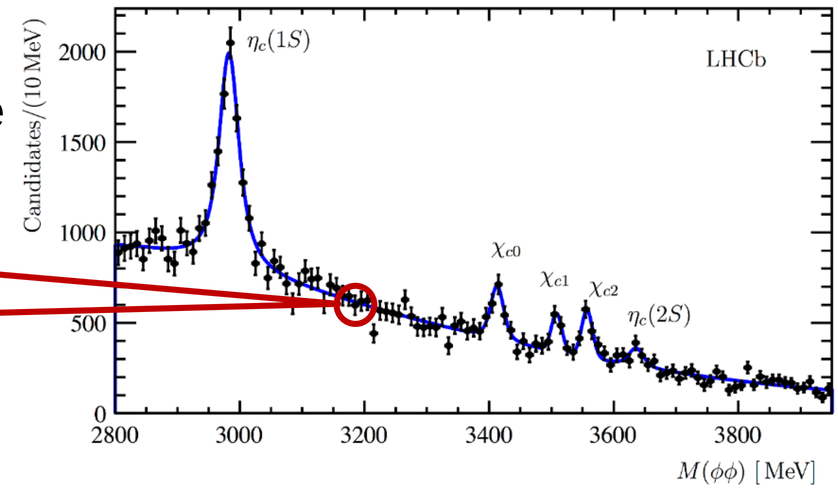
$$\frac{\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi)}{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to \phi\phi)} = 0.040 \pm 0.011 \pm 0.004$$

- Measure **$\eta_c(2S)$ hadroproduction**, free from feed-down contributions

EPJC 77 (2017) 609

- Charmonium reconstructed via **decays to φφ**
- True φφ combinations extracted using 2D fit technique

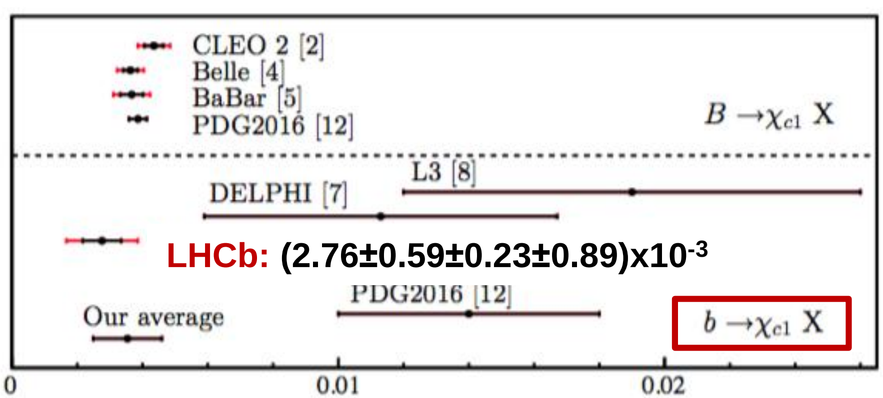


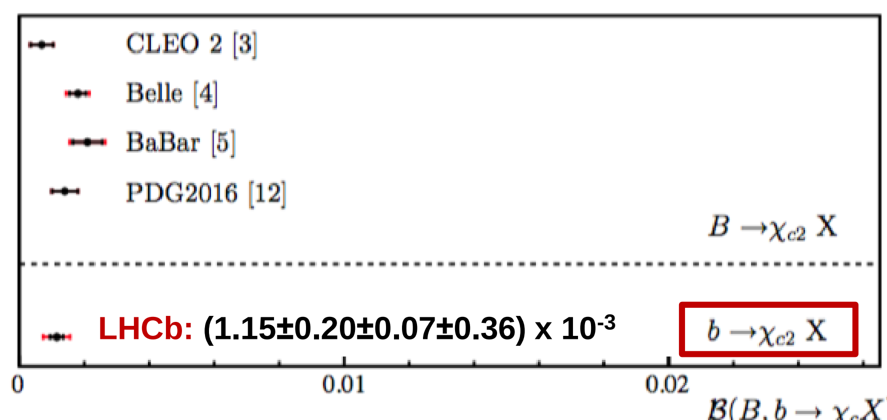


- **First measurement** of χ_{c0} production in b-decays

$$\mathcal{B}(b \to \chi_{c0} X) = (3.02 \pm 0.47_{stat} \pm 0.23_{syst} \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$

- **Most precise measurements** of χ_{c1} and χ_{c2} production in b-decays, consistent with B-factories





- Promising channel to study χ_c polarization

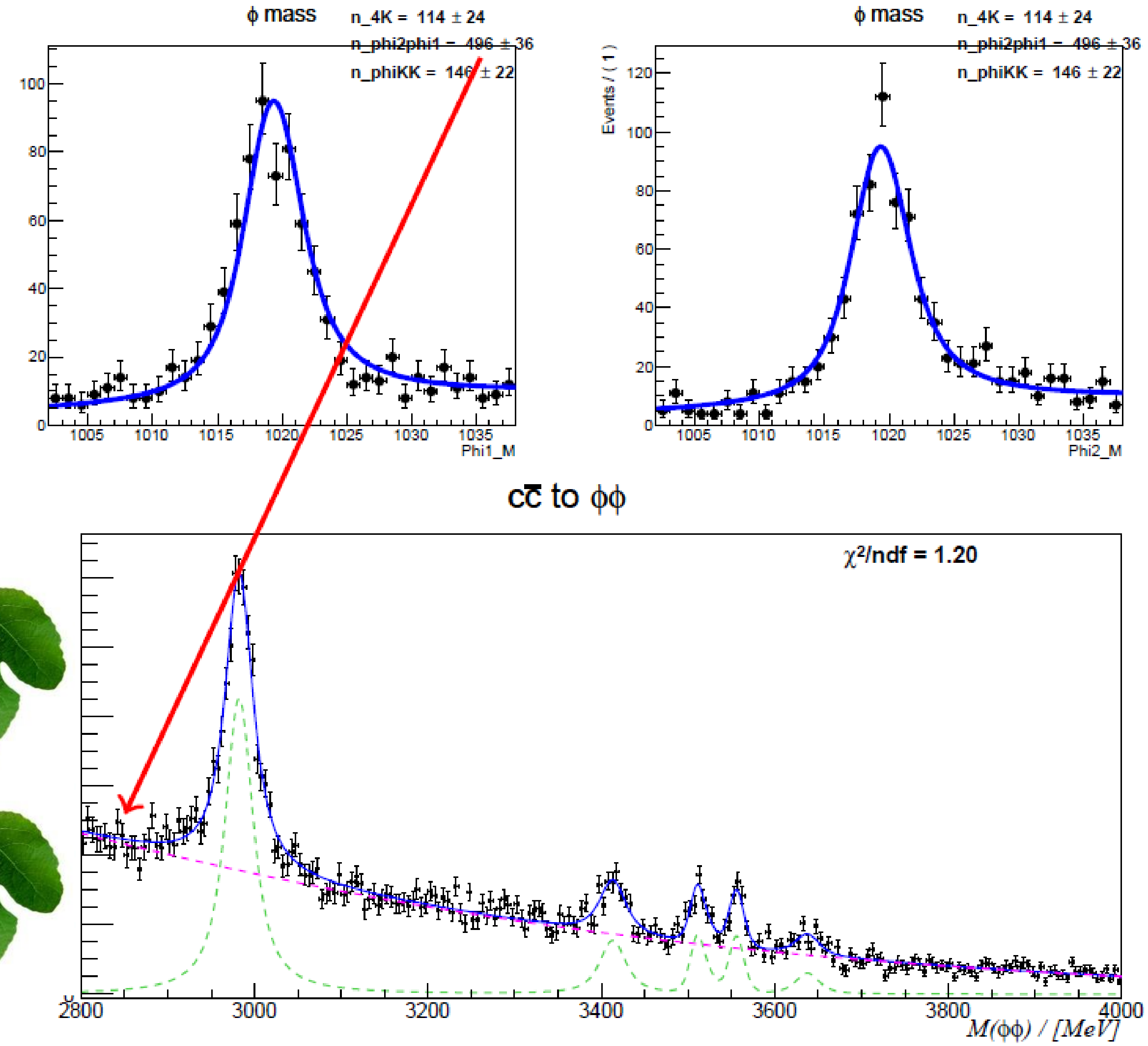
PRD 103 (2021) 9, 096006

Less public results, coverage quality intermezzo

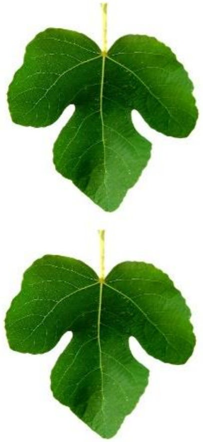
- Results with LHCb physics reviews, with LHCb working group or analysis being finalized

VS

- Charmonium reconstructed via **decays to φφ**
- True φφ combinations extracted using 2D fit technique
- **New analysis with Run 2 data**



- Interference effects with φφ continuum considered for the first time



Adding interference term with non-resonant $\phi\phi$ background

Plane wave $(\frac{K(x)}{K(M)})^L Ce^{i\varphi}$ allowed to interfere with RBW
Creates interfering term with the sum of a $\sin\varphi$ and a $\cos\varphi$ contribution

$$RBW_{wl}(x) = \frac{x \times \Gamma_f}{(\Delta M^2)^2 + M^2\Gamma_f^2} + 2C(\frac{K(x)}{K(M)})^L \frac{\sqrt{x \times \Gamma_f} \times (\Delta M^2 \cos\varphi - M\Gamma_f \sin\varphi)}{(\Delta M^2)^2 + M^2\Gamma_f^2}$$

But degeneracy between $\sin\varphi$ part and RBW, so introducing $D = C\cos\varphi$ and the simpler model:

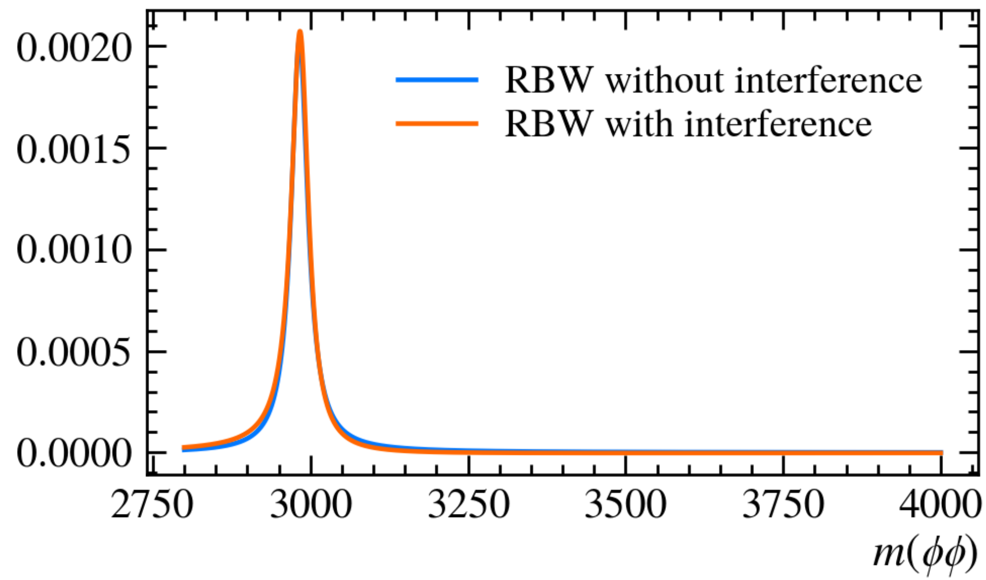
$$RBW_{wl}^{simple} = \frac{x \times \Gamma_f}{(x^2 - M^2)^2 + M^2\Gamma_f^2} + 2D(\frac{K(x)}{K(M)})^L \frac{\sqrt{x \times \Gamma_f} \times (x^2 - M^2)}{(x^2 - M^2)^2 + M^2\Gamma_f^2}$$

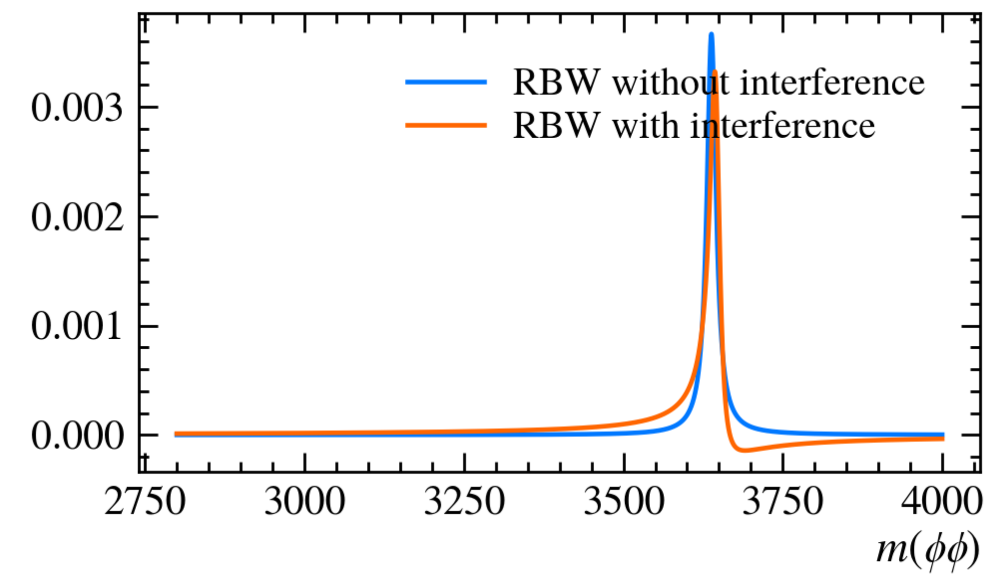
Impact on mass and width modeled perfectly
But $\sin\varphi$ part absorbed in the RBW shape
$\Rightarrow$ extra systematic on ratios by comparing without interference

- **Interference effects with φφ continuum**

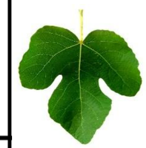
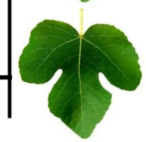
considered for the first time

- About 2σ and 3σ for η_c states (L = 1), compatible to zero for others





- Charmonium reconstructed via decays to φφ
- New **analysis with Run 2 data, main results**

	$c\bar{c} \to p\bar{p}$	Run 1 $c\bar{c} \to \phi\phi$	Run 2 $c\bar{c} \to \phi\phi$	Average $c\bar{c} \to \phi\phi$
$\mathcal{B}(b \to \chi_{c0}X)(10^{-3})$	3.05 ± 0.54 ± 0.08 ± 0.29	3.12 ± 0.49 ± 0.23 ± 0.87	 0.22 ± 0.20 ± 0.65	2.47 ± 0.20 ± 0.23 ± 0.69
$\mathcal{B}(b \to \chi_{c1}X)(10^{-3})$	5.11 ± 1.20 ± 0.14 ± 0.50	3.08 ± 0.68 ± 0.25 ± 0.86	0.21 ± 0.28 ± 0.74	2.68 ± 0.20 ± 0.28 ± 0.75
$\mathcal{B}(b \to \chi_{c2}X)(10^{-3})$	1.54 ± 1.13 ± 0.04 ± 0.15	1.18 ± 0.19 ± 0.07 ± 0.33	0.15 ± 0.12 ± 0.30	1.10 ± 0.12 ± 0.12 ± 0.31
$\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi)(10^{-7})$	/	7.19 ± 1.98 ± 0.72 ± 1.98	 0.97 ± 0.58 ± 2.09	7.49 ± 0.87 ± 0.72 ± 2.07
M_{η_c}	/	2982.81 ± 0.99 ± 0.45	46 ± 0.50 ± 0.39	2984.12 ± 0.45 ± 0.45

- **Branching fractions and mass** measurements agree between run 1 and run 2, between different data samples, and different charmonium reconstruction modes
- Precision improves with more data as expected
- **Complementary reconstruction modes for χ_c states**
- **Most precise single measurement of the η_c(1S) mass**

Combined fits of LDME

- Simultaneous fit for available **J/ψ and η_c(1S) prompt production** results

- Relation between LDME from HQSS:

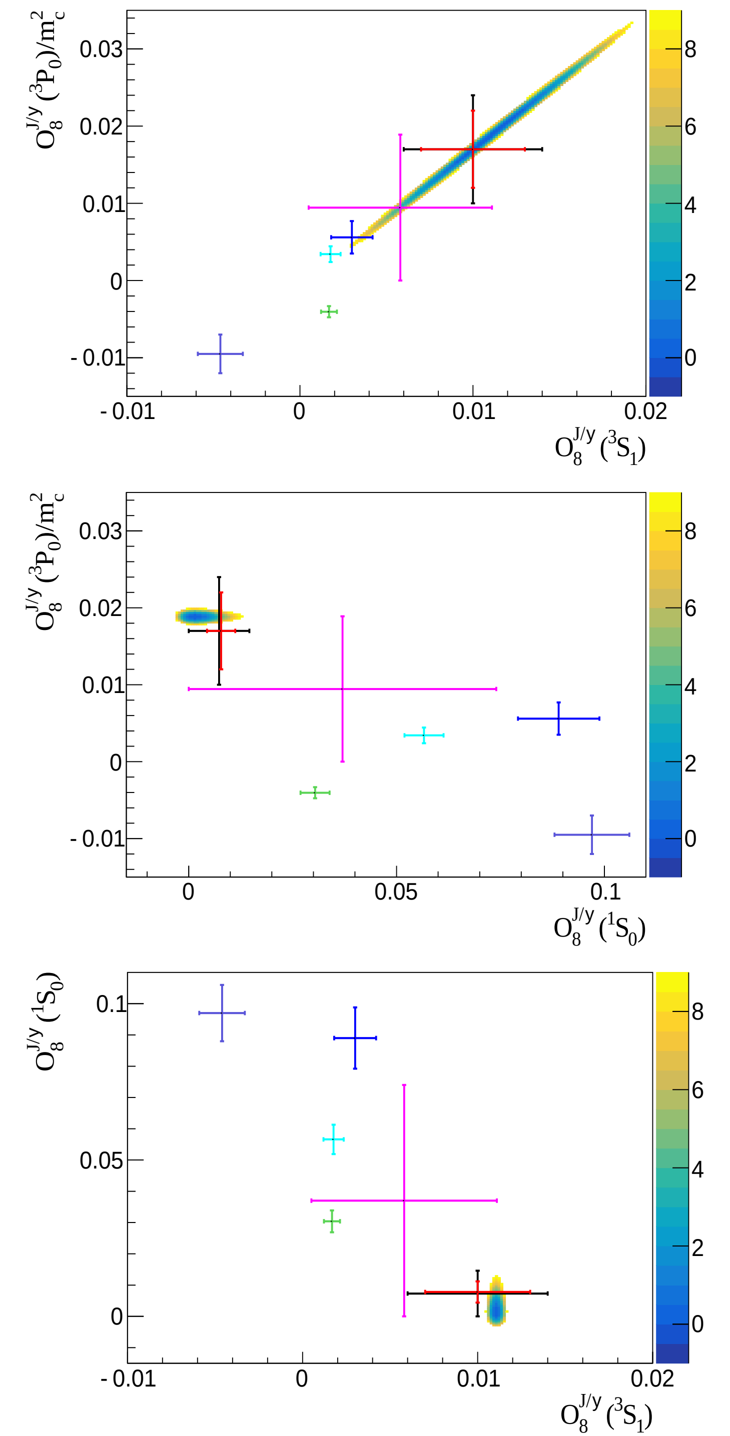
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle O_8^{J/\psi}(^3P_0)\rangle.$$

- Fix CS LDME from potential model

$$\langle O_8^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$$

- χ^2 minimization

Han et al.
Zhang et al.
Shao et al.
Chao et al.
Butenshoen et al.
Gaon et al.
Feng et al.



- Reasonable agreement with some predictions

- Simultaneous fit for available **ψ(2S) and η_c(2S) prompt production** results

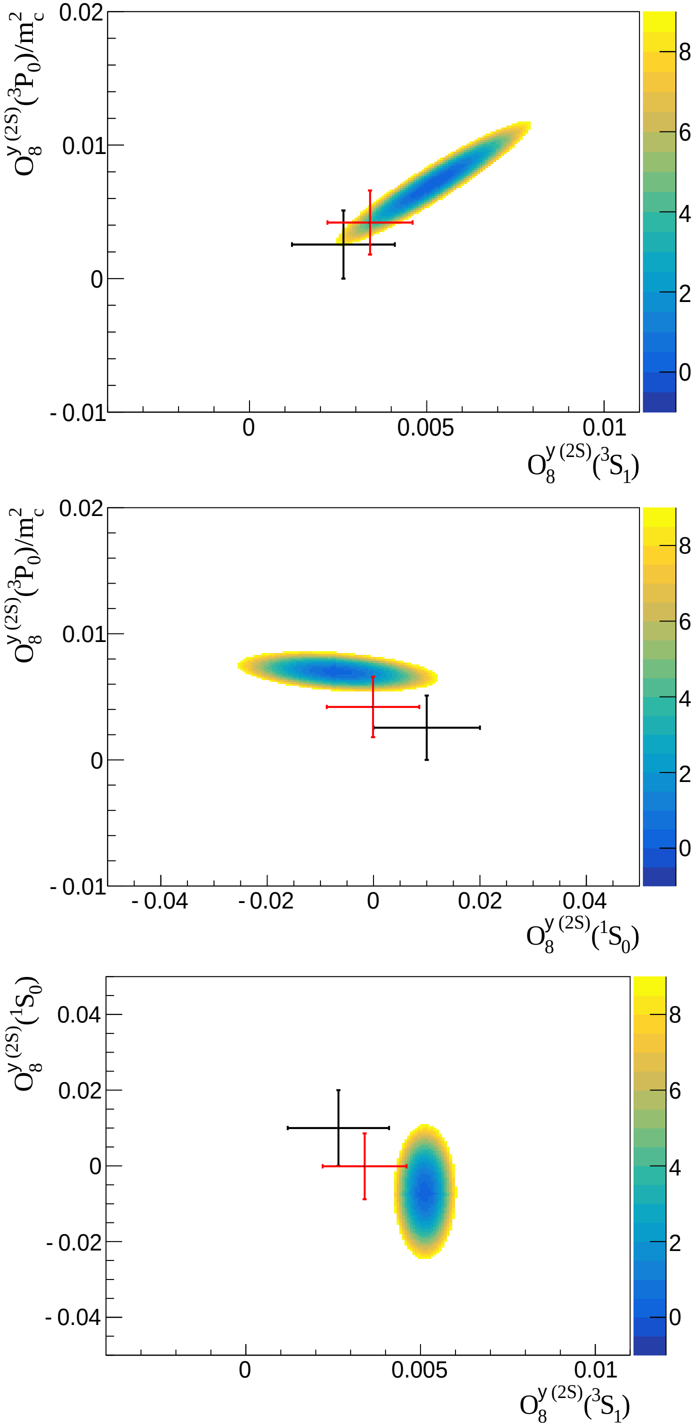
- Relation between LDME from HQSS:

$$\langle \mathcal{O}_{1,8}^{\eta_c(2S)}(^1S_0)\rangle = \frac{1}{3}\langle \mathcal{O}_{1,8}^{\psi(2S)}(^3S_1)\rangle$$
$$\langle \mathcal{O}_{8}^{\eta_c(2S)}(^3S_1)\rangle = \langle \mathcal{O}_{8}^{\psi(2S)}(^1S_0)\rangle$$
$$\langle \mathcal{O}_{8}^{\eta_c(2S)}(^1P_1)\rangle = 3\langle \mathcal{O}_{8}^{\psi(2S)}(^3P_0)\rangle$$

- Fix CS LDME from potential model

$$\langle \mathcal{O}_{1}^{\psi(2S)}(^3S_1)\rangle = 0.76\ \mathrm{GeV}^3$$

- χ^2 minimization



Han et al.
Zhang et al.

- **Agreement with predictions** given large uncertainties

- **Negative LDME values ?**

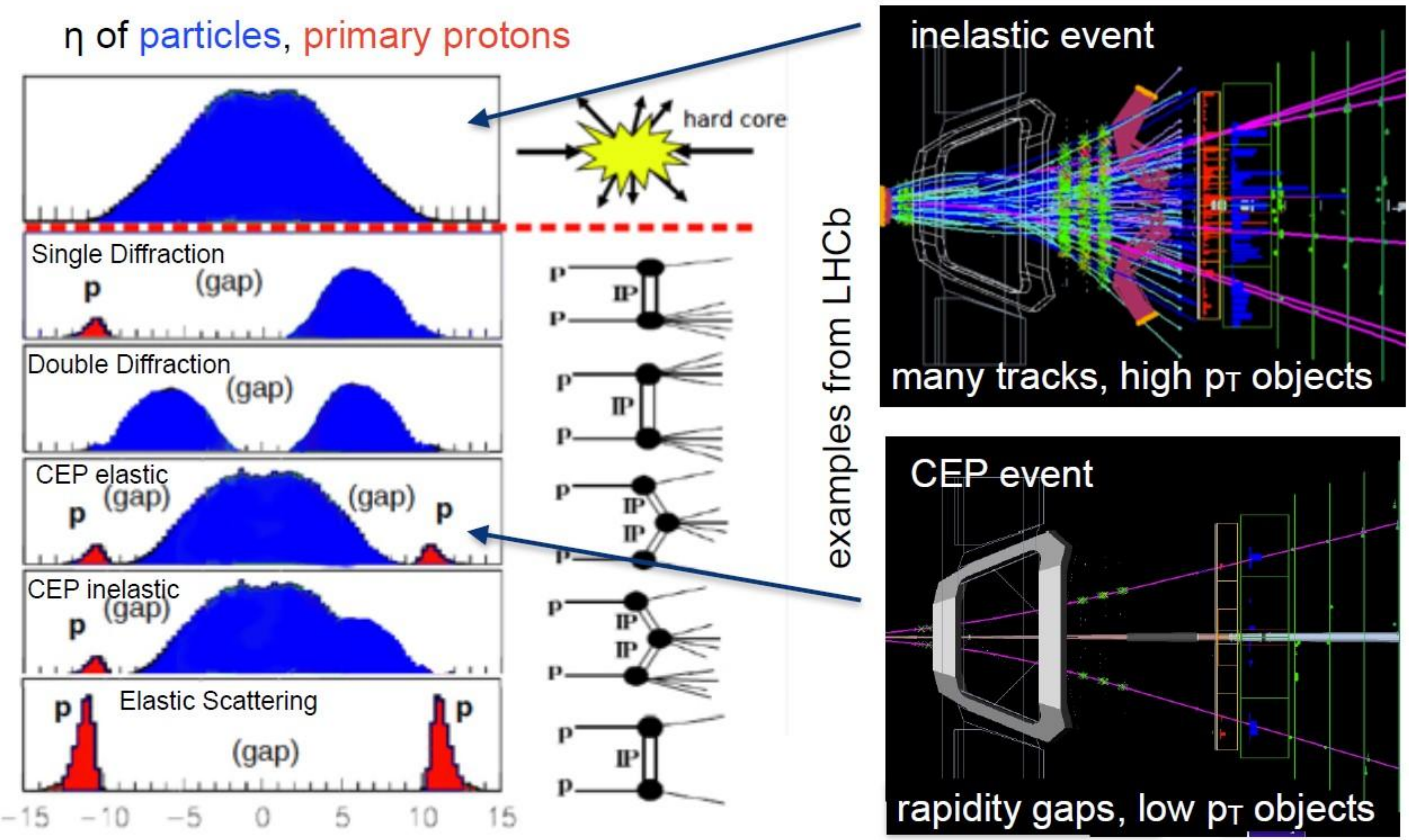
- Charmonia from b-decays will be added

- This technique constrains theory using **simultaneously** results on **charmonia hadroproduction and** on **charmonia from b-inclusive decays** under **assumptions of factorization, universality and HQSS**, with **different charmonium states**

- Alternatively, once hadroproduction and production in b-decays measured for charmonium states with linked LDMEs,
  the above **assumptions can be tested quantitatively**

Central Exclusive Production of charmonium

- CEP event: diffractive process of the form pp → pXp, **large rapidity gap**



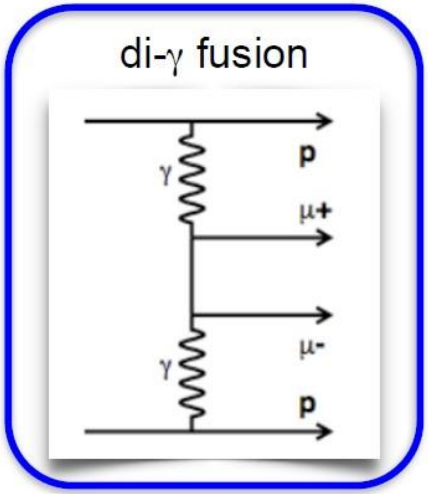
After D. d'Enterria arxiv 0806.0883

- **Mediated by the exchange of a colourless object**
- **QCD tests with clean theoretical interpretation**
- Only **CS production**
- Cross-section can be calculated in pQCD and (at LO) is proportional to the square of the gluon PDF, g(x)

$$pp(\bar{p}) \rightarrow p + X + p(\bar{p})$$

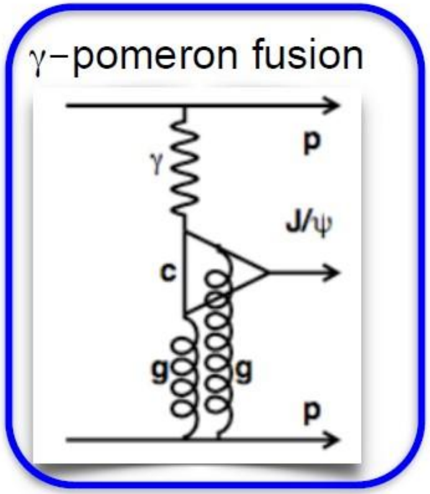
t-channel exchange of a colourless object: γ, pomeron → X + rapidity gaps

Single elastic process → protons escape undetected in beampipe



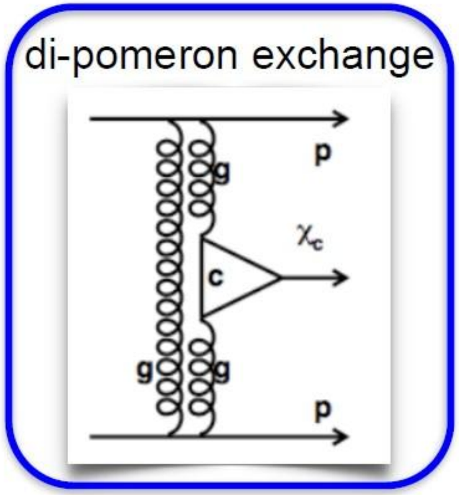
$\mu^+\mu^-$, e^+e^-, $\pi^+\pi^-$, W^+W^-

QED "standard candle" process continuum lepton pair production



ρ, J/ψ, Y, Z, …

Photoproduction: Test of QCD and description of diffraction and soft processes. Sensitive to diffractive PDF at very low x (to 5 x 10^{-6})



X_c, X_b, $\pi^+\pi^-$, Dijet, gg, …

Test of QCD,and hadron spectroscopy Pomeron content at low Q^2 dominated by gluons; access to scalar and tensor glueballs

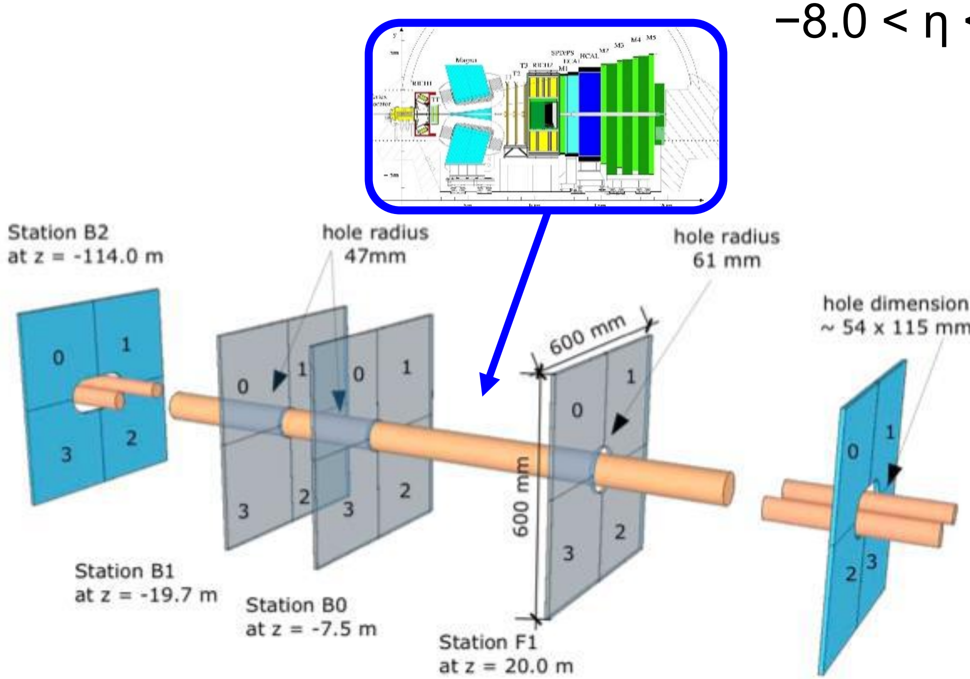
- **With LHCb:** In pp collisions, probe at very low Bjorken values, down to $x \sim 10^{-6}$

Central Exclusive Production of J/ψ and ψ(2S) at 13 TeV

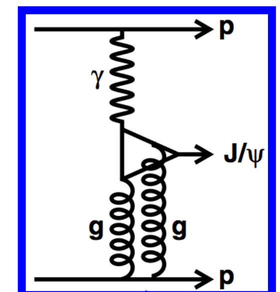
- **Herschel detector** increases rapidity gap in forward region

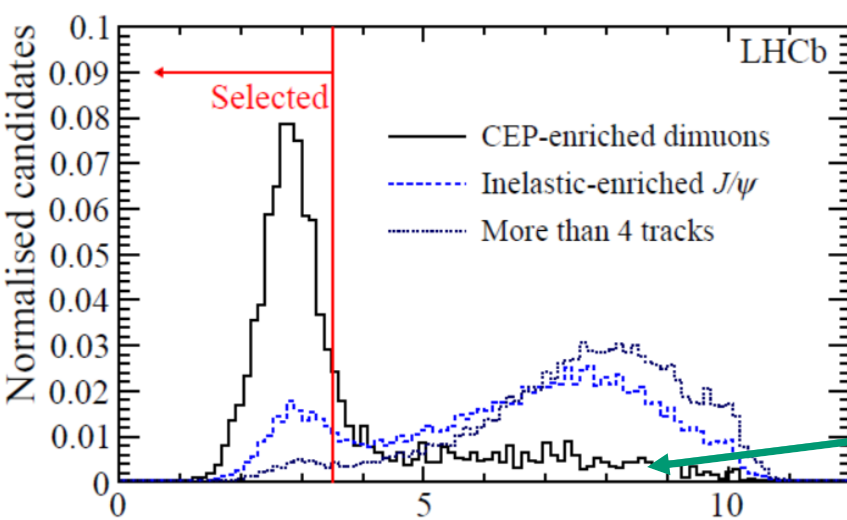
SciPost Phys. 18, 071 (2025)

$-8.0 < \eta < -1.5$, $5.0 < \eta < 8.0$

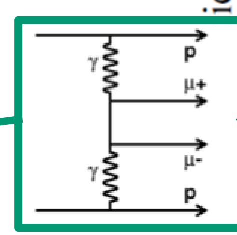


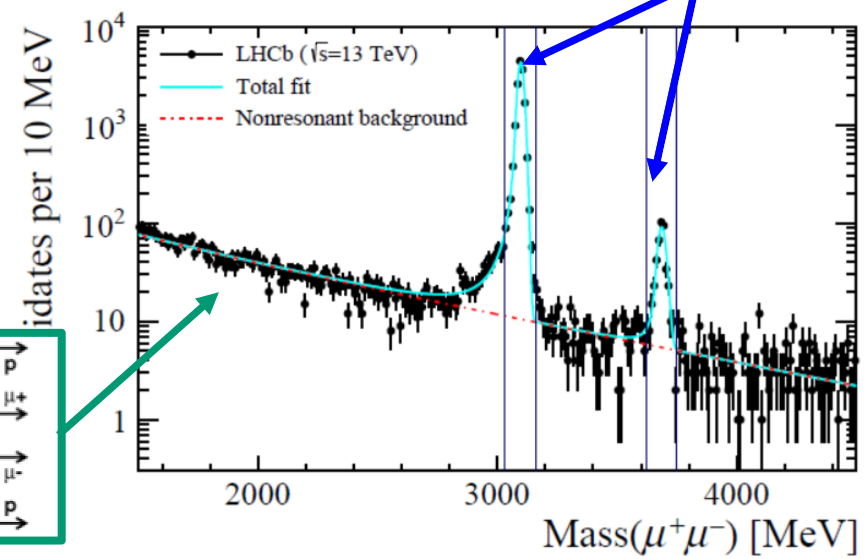
- Dedicated CEP trigger
- **Exclusivity**: precisely two forward muons; no backward tracks; no activity in SPD (< 10 hits). Quantify with p_T spectrum.





Sum of Herschel deposits in quadrature

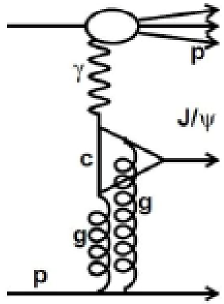


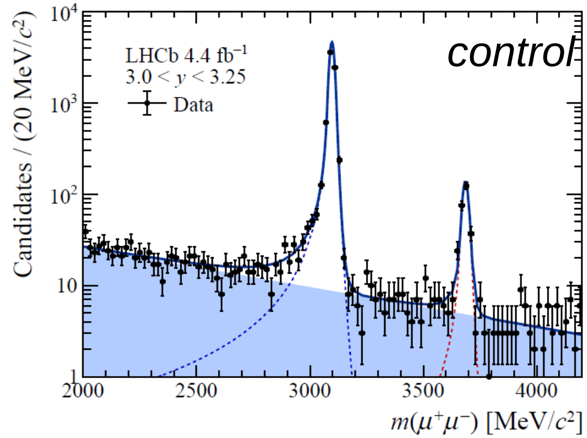


Central Exclusive Production of J/ψ and ψ(2S) at 13 TeV

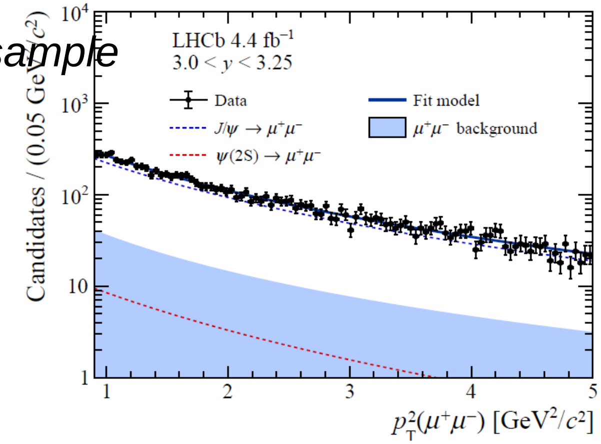
SciPost Phys. 18, 071 (2025)

- ❑ Differential cross sections in rapidity bins
- ❑ Control sample – proton dissociation

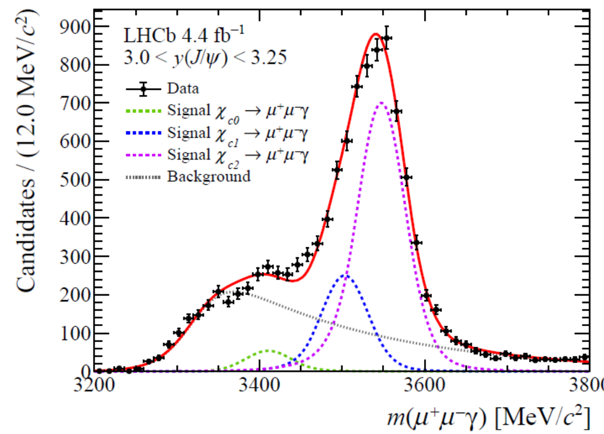


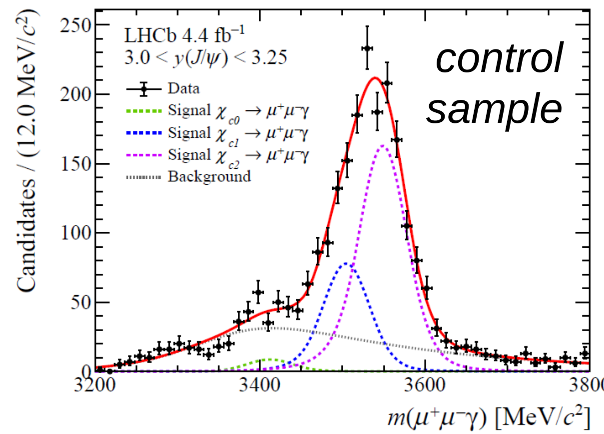


control sample

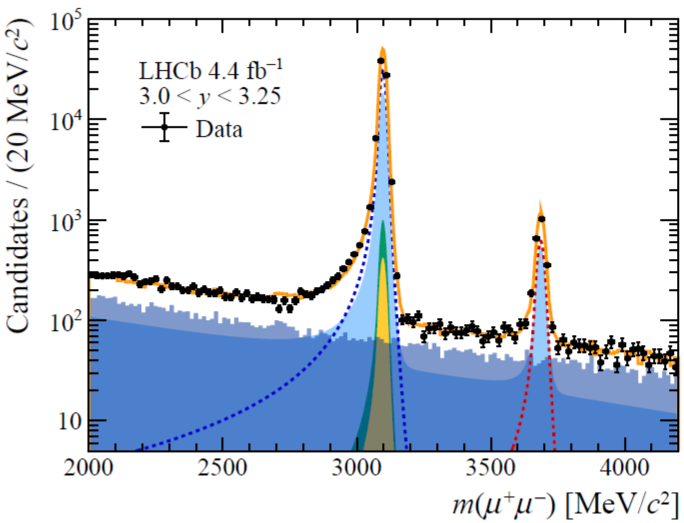


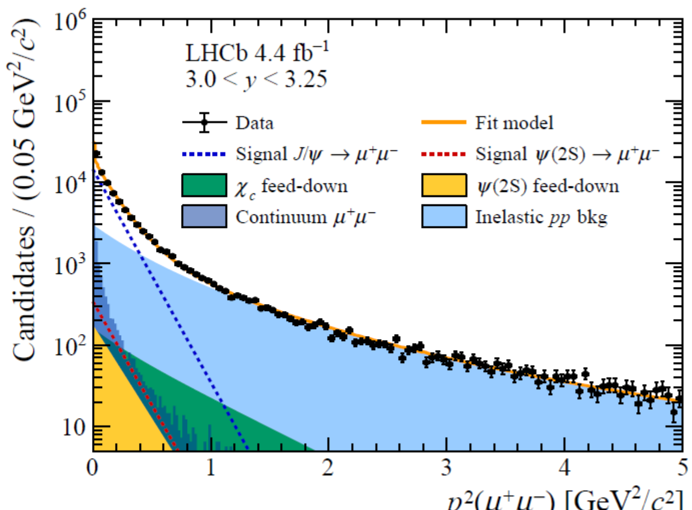
- ❑ Feeddown from higher charmonium states (ψ(2S), χ_{ci}, $\chi_{c1}(3872)$) to the J/ψ sample taken into account





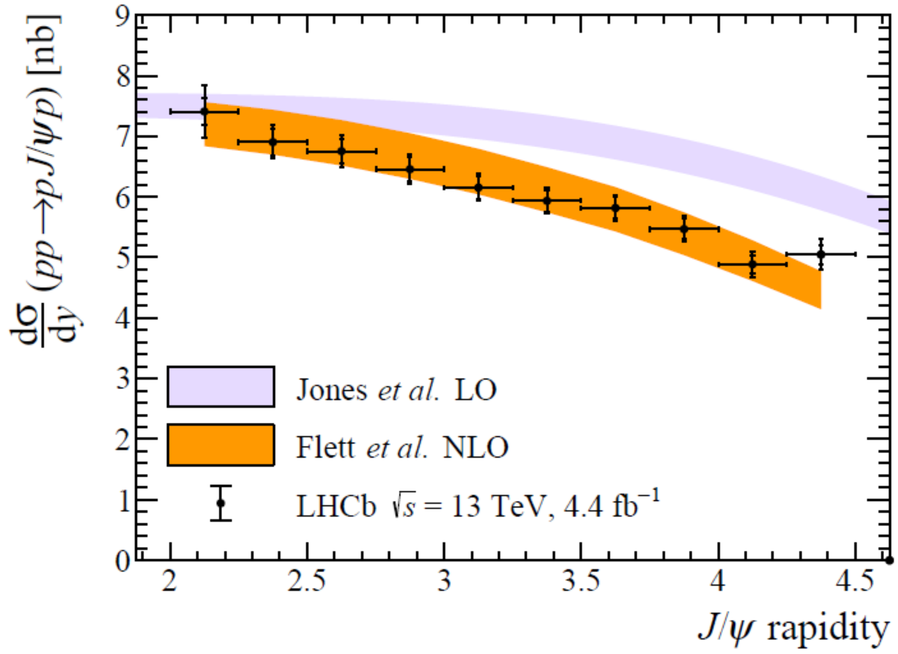
control sample

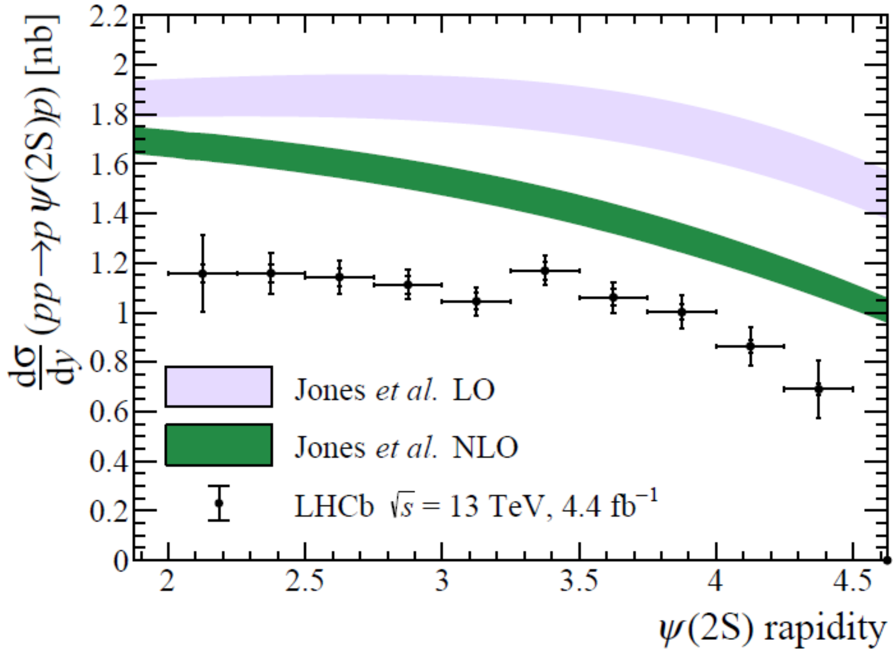




SciPost Phys. 18, 071 (2025)

- **Differential cross-sections** compared to theory predictions





- **Integrated cross-sections** times branching fractions

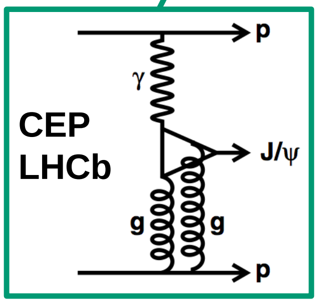
$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0 < y_{J/\psi} < 4.5, 2.0 < \eta_{\mu^\pm} < 4.5) = 400 \pm 2 \pm 5 \pm 12\,\text{pb},$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 < y_{\psi(2S)} < 4.5, 2.0 < \eta_{\mu^\pm} < 4.5) = 9.40 \pm 0.15 \pm 0.13 \pm 0.27\,\text{pb}$$

- **Good agreement with J/ψ NLO pre-(post-)diction**
- **ψ(2S) calculations to be revisited**
- Confirms a hint of NLO importance from the analysis at 7 TeV

SciPost Phys. 18, 071 (2025)

- The cross-section for the CEP of vector mesons in pp collisions is related to the **photo-production cross-section**:

$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{dn}{dk_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_-\frac{dn}{dk_-}\sigma_{\gamma p\to\psi p}(W_-)$$



Gap survival

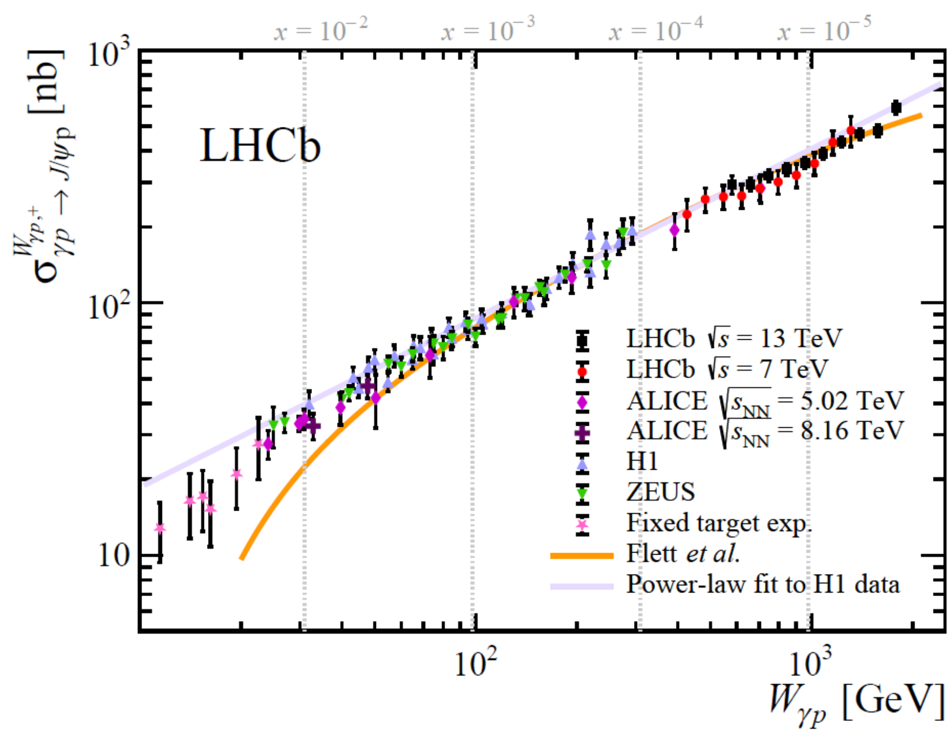
Photon flux

Jones,Martin,Ryskin,Teubner, JHEP 1311 (2013) 085, J.Phys.G 41 (2014) 055009, and update

- Compilation of photo-production cross-section measurements
- H1 measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\text{ GeV})^{0.67}$ nb

- Good agreement between LHCb results at 7 and 13 TeV

- J/ψ photo-production cross-section: **agreement to theory prediction ; no deviation from a pure power-law extrapolation of HERA data**



Outlook

- Quarkonium serves a powerful probe for **QCD-driven production mecanisms** … consistency with minimum number of free parameters wanted

- The way to understanding **quarkonium production** is long and challenging … but enjoyable
- An impressive progress – both in theory and in experiment – marked with discoveries and bright ideas …

  … and perhaps still doing the very first steps

- **More precision and more consistency checks** open the path to understanding quarkonium production mecanism

- Major contributions from students to the presented results : (analysis part of) thesis of Valeriia Zhovkovska, long internships and ongoing theses by Shu Xian and Raoul Henderson
- Other interesting analyses awaiting new strong and motivated students

- Rapidity

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

- Pseudorapidity

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$