

Produkcja czarmonium w



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IFJ PAN

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- Introduction
- Hadroproduction and production in b-decays
- Charmonium production in pp collisions as an imaging tool
- Central exclusive production
- (Associated production)

Disclaimer: biased selection of illustrations

<https://www.ifj.edu.pl/jubileusz60/institut.html>

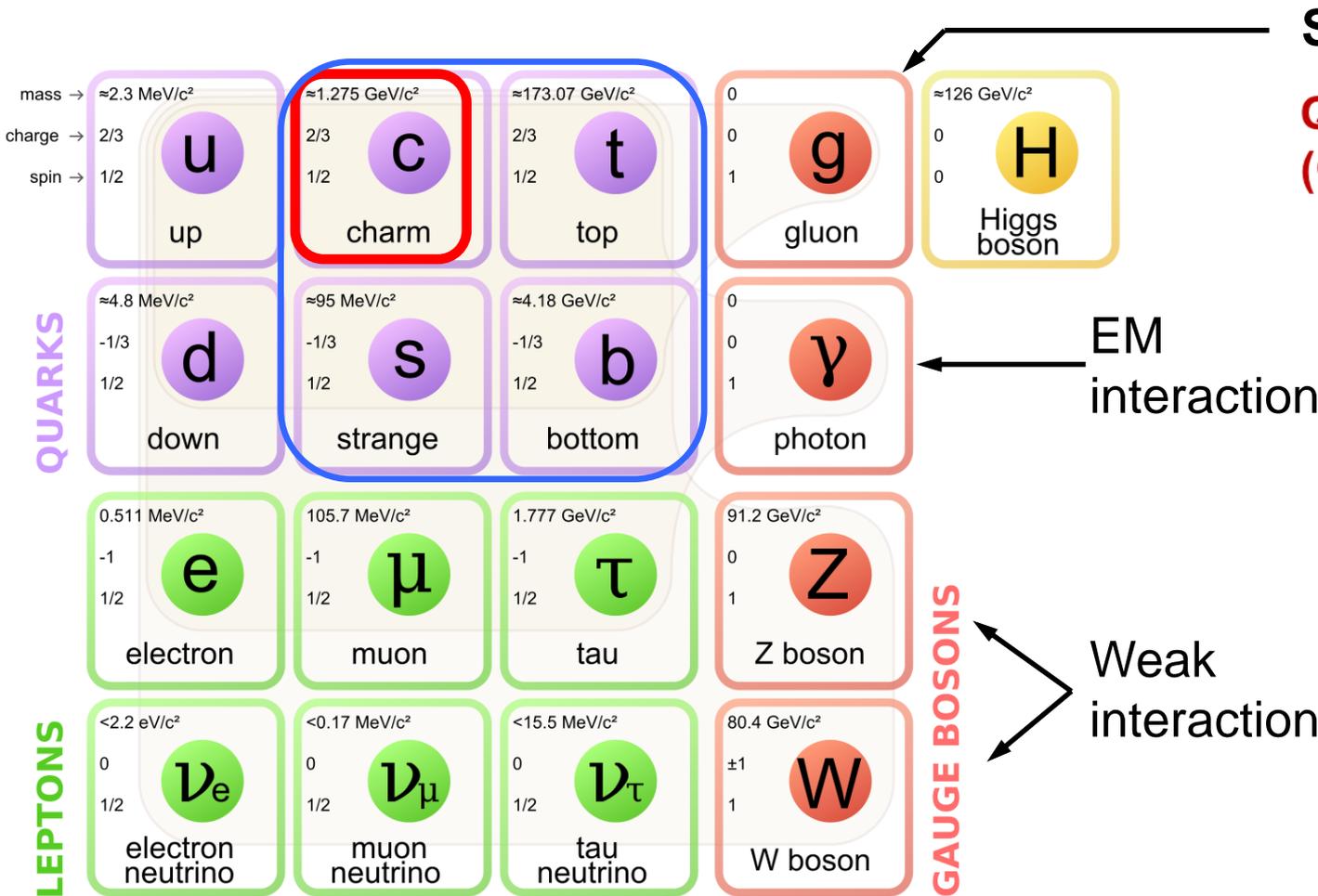
Introduction



M. Prymachenko

Elementary particles and their interactions

- «Truly » elementary particles: **fermions** (leptons and quarks) and **gauge bosons** + Higgs boson



Strong interaction

Quantum Chromodynamics (QCD):

- gluon self-coupling, carrying colour charge: SU(3)
- coupling constant α_s
 - scale-dependence, from asymptotic freedom to confinement
 - no free quarks
- intrinsic scale $\Lambda_{\text{QCD}} \approx 200 \text{ MeV}$

EM interaction

Weak interaction

- Described by a very successful so far **Standard Model of particle interactions**

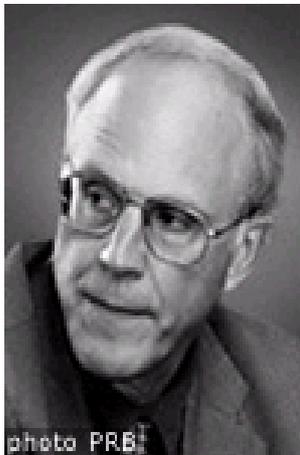
The α_s running (main property of QCD) was analytically computed in 1973



The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi} (11n - 2f) \log\left(\frac{Q^2}{\mu^2}\right)}$$



David J. Gross

🕒 1/3 of the prize

USA

Kavli Institute for
Theoretical Physics,
University of
California
Santa Barbara, CA,
USA

b. 1941



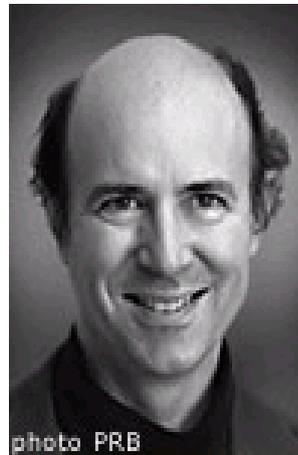
H. David Politzer

🕒 1/3 of the prize

USA

California Institute
of Technology
Pasadena, CA, USA

b. 1949



Frank Wilczek

🕒 1/3 of the prize

USA

Massachusetts
Institute of
Technology (MIT)
Cambridge, MA,
USA

b. 1951

Coupling constant, $\alpha_s(E)$

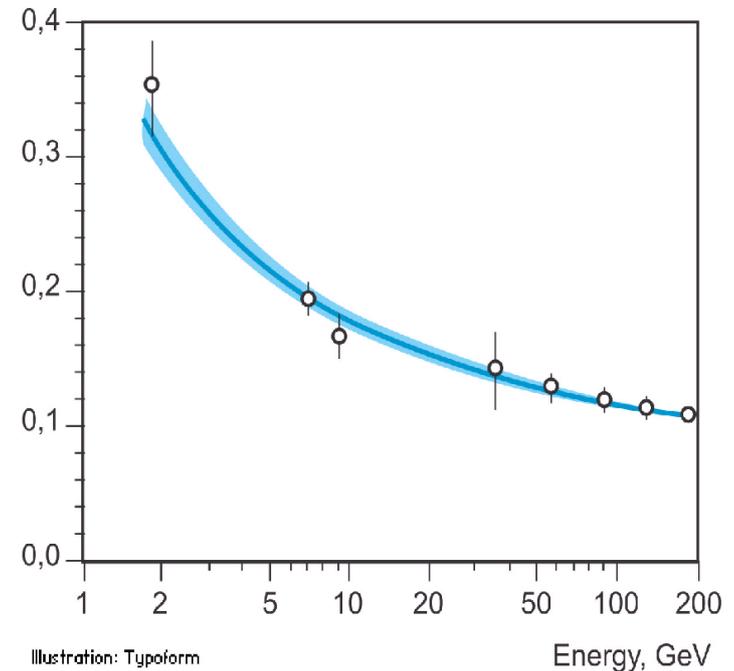


Illustration: Typoform

Hadrons

- ❑ Quarks are not observed alone but are always part of **hadrons**
- ❑ **Quark combinations** are classified as:

Allowed: $qqq, q\bar{q}$

Forbidden by confinement: $qq, qq\bar{q}, qqqq$

Non integer charge hadrons

Other allowed states: $qq\bar{q}\bar{q}, qqqq\bar{q}$

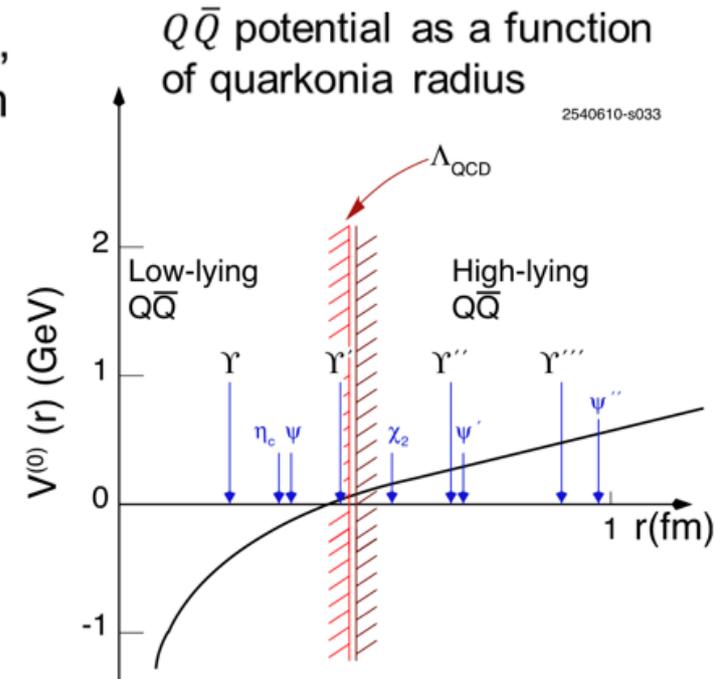
Quarkonium

Quarkonium is a bound state of two **heavy quarks** ($c\bar{c}$ or $b\bar{b}$), **charmonium** and bottomonium

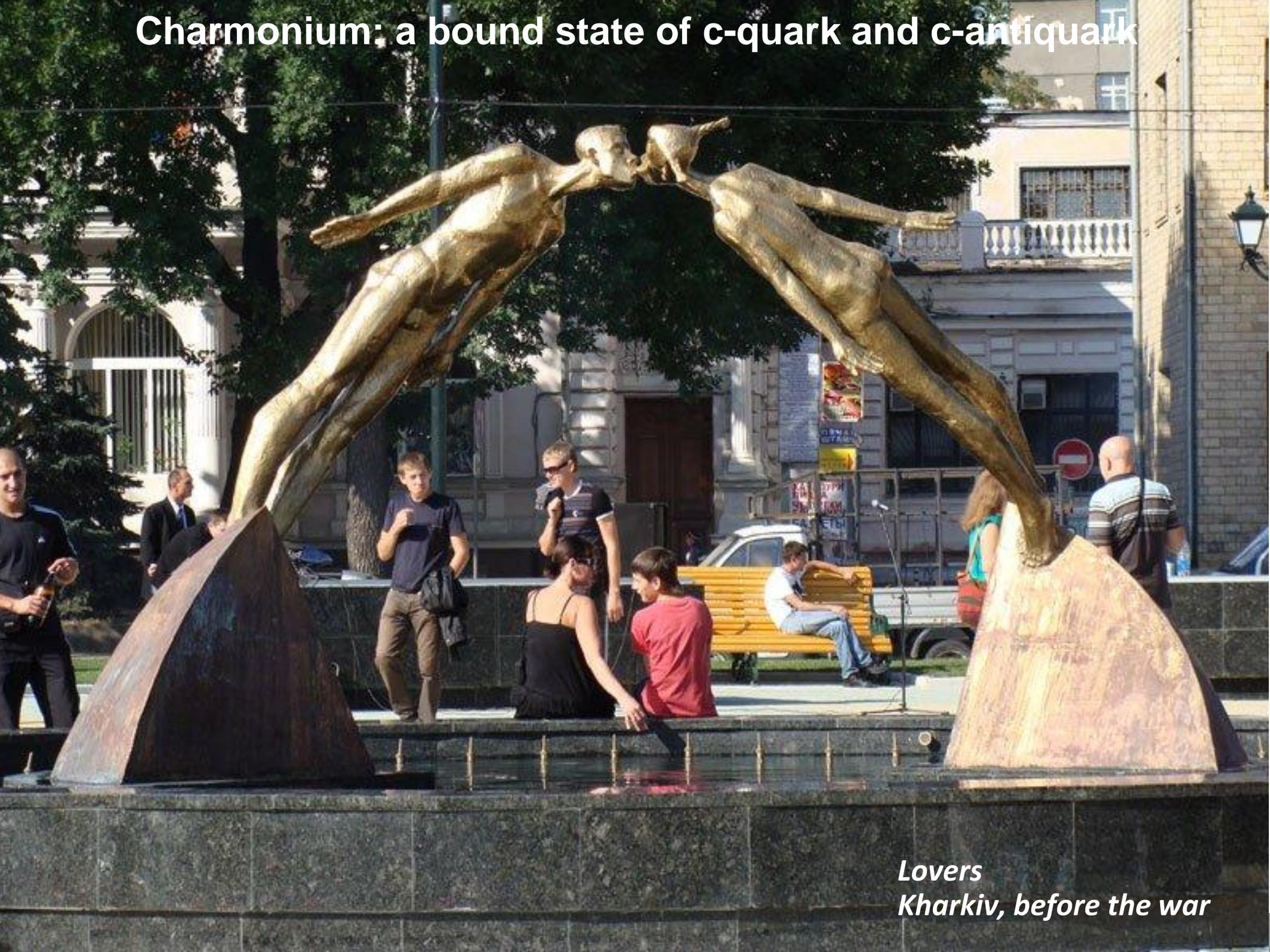
Non-relativistic QCD object:

charmonium: $v^2 \approx 0.3$, bottomonium: $v^2 \approx 0.1$

v - typical velocity of HQ in the quarkonium rest frame



Charmonium: a bound state of c-quark and c-antiquark



*Lovers
Kharkiv, before the war*

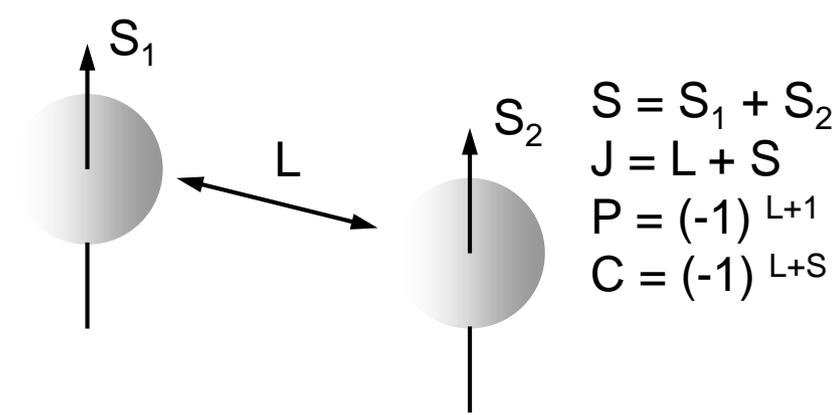
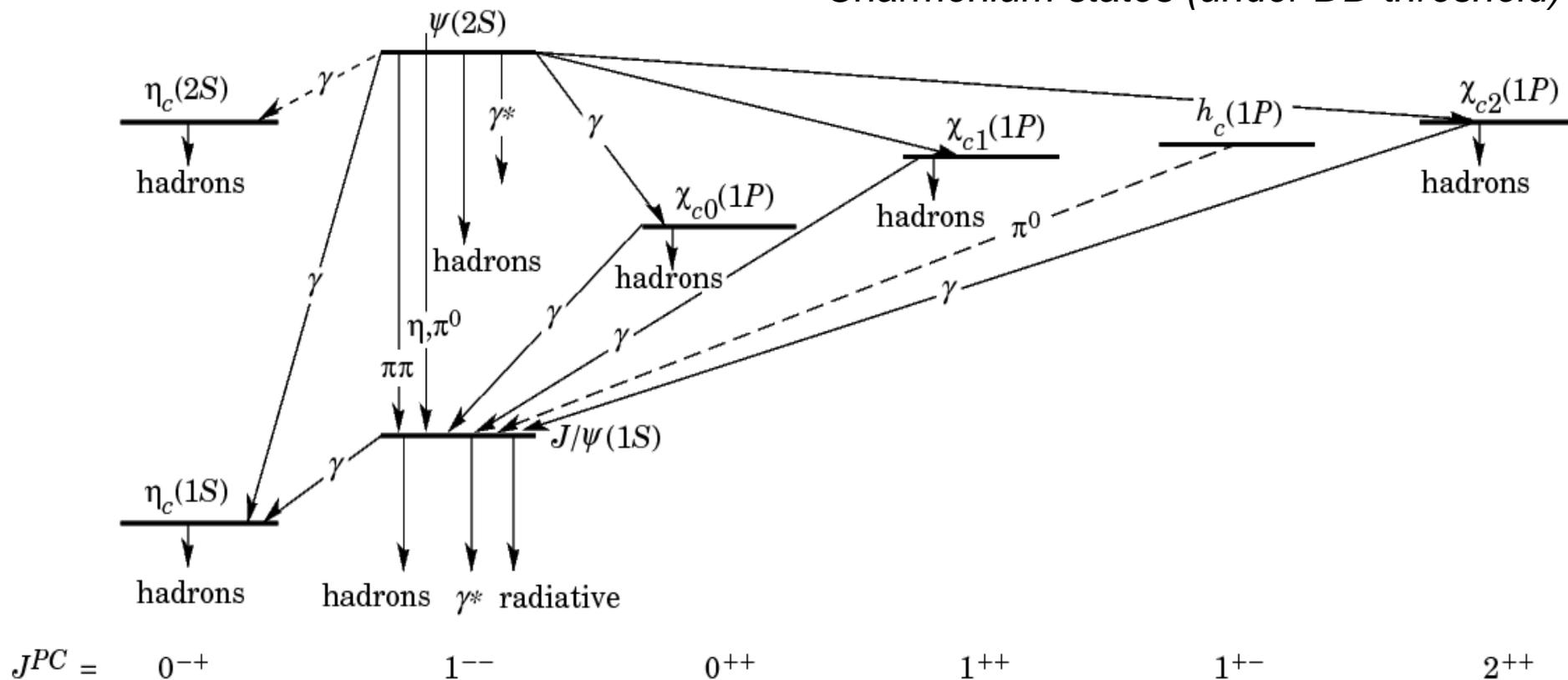
Charmonium: a bound state of c-quark and c-antiquark



*Lovers
Kharkiv, before the war*

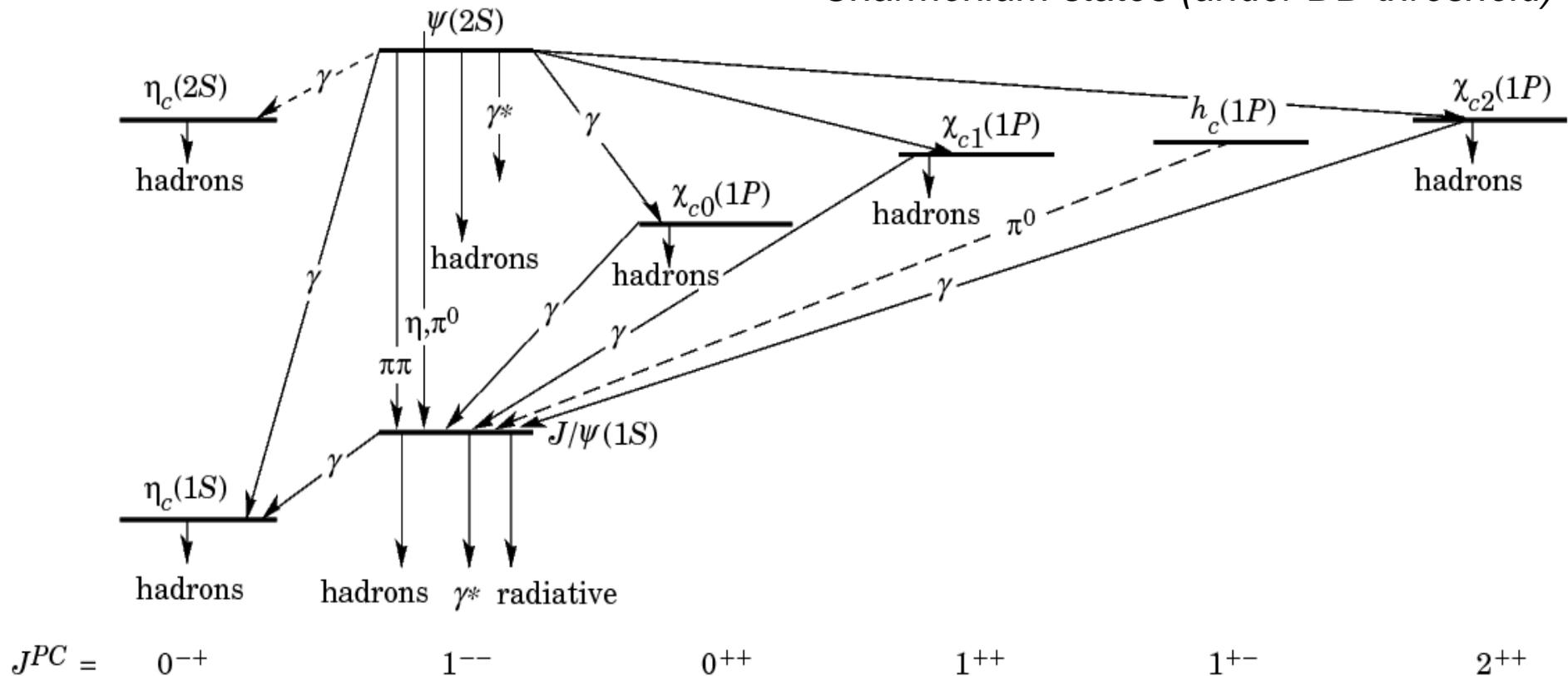
Charmonium

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

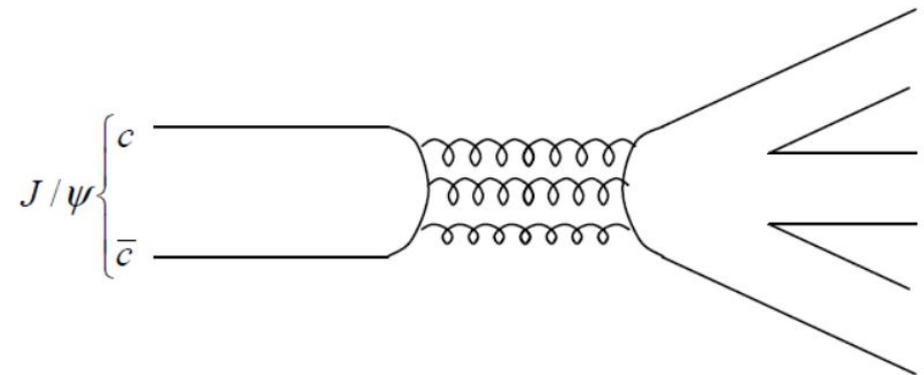


Charmonium decays: good, bad and very bad charmonia

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



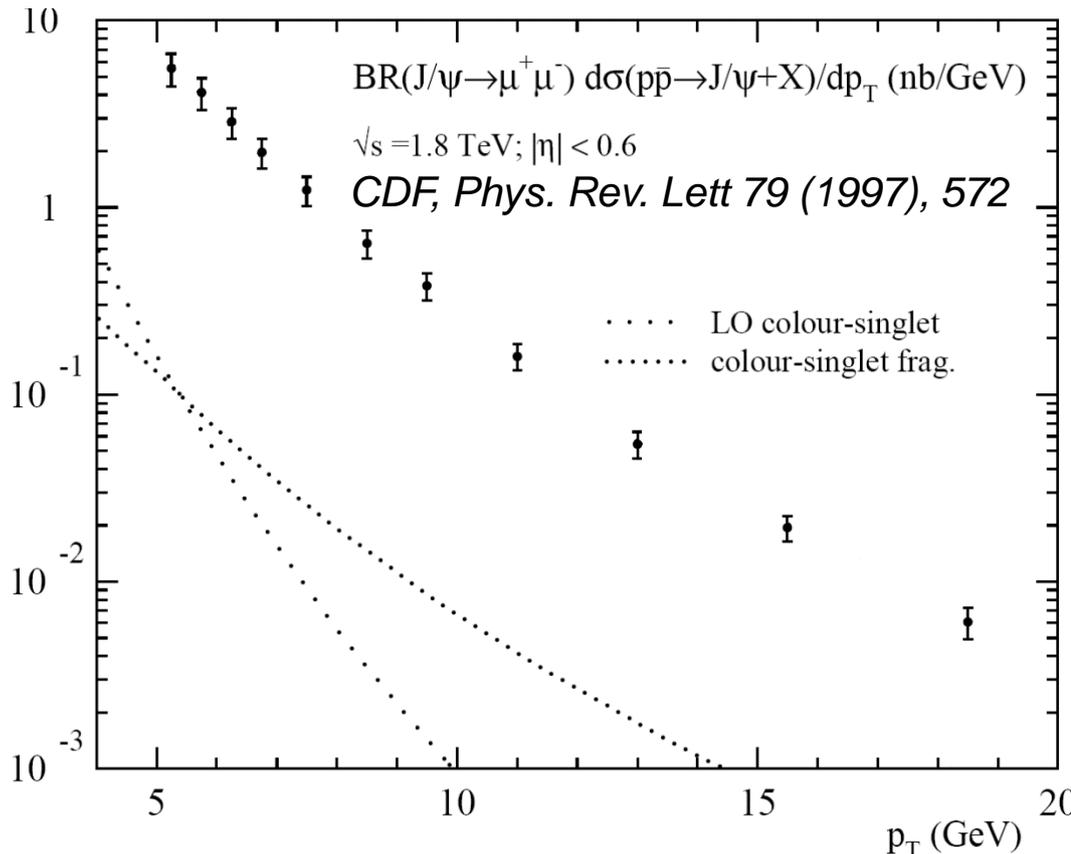
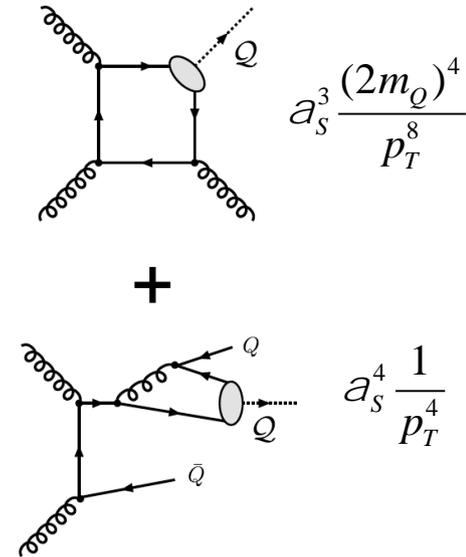
Charmonium production, history of puzzles: J/ψ hadroproduction puzzle

- ❑ Comparison of direct p_T differential J/ψ production cross-section measured by CDF with Color Singlet LO (most natural) process.
- ❑ Fails both in shape and magnitude.

R. BAIER and R. RUECKL, Z. Phys C 19 (1983), 251

- ❑ Add gluon and quark fragmentation (NLO Color Singlet processes)
- ❑ Better shape but magnitude is factor 30 too low.

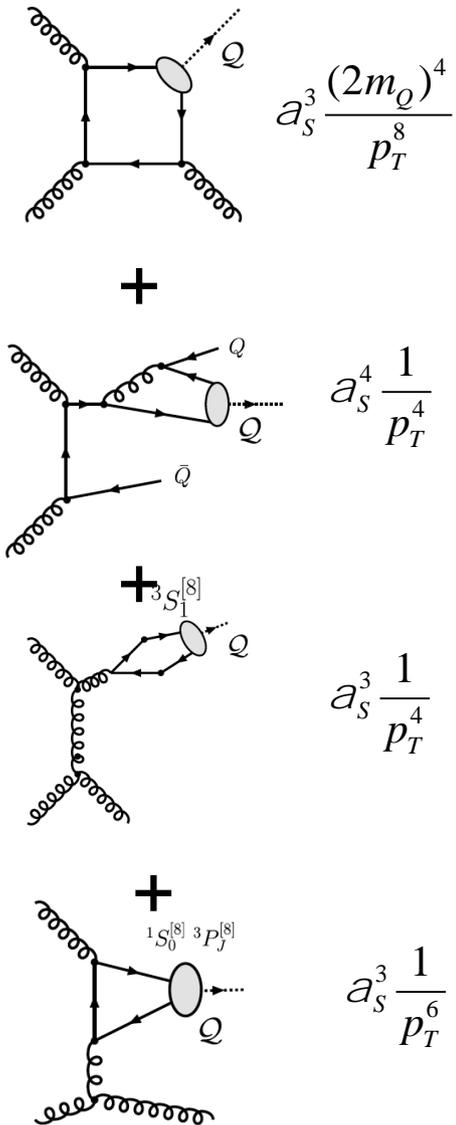
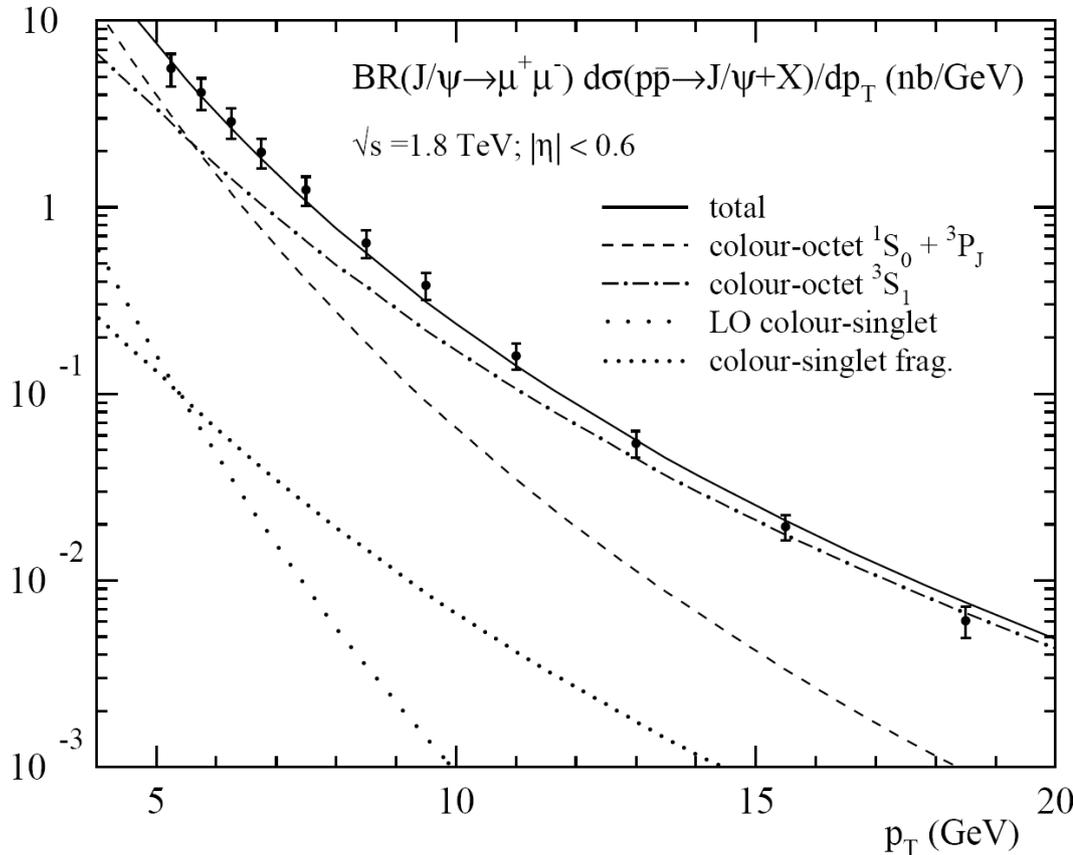
E. BRAATEN, M. A. DONCHESKI, S. FLEMING and M. L. MANGANO, PLB 333 (1994), 548



Charmonium production, history of puzzles: J/ψ hadroproduction puzzle

- ❑ Add LO Color-Octet processes from non-relativistic QCD (NRQCD)
- ❑ LDME fitted on the same data

P. L. CHO and A. K. LEIBOVICH, PRD 53 (1996) 150



- ❑ Excellent agreement when summing all contributions, with Color-Octet terms being dominant

Charmonium production

- Two scales of production:

hard process of **Q \bar{Q} formation** and **hadronization of Q \bar{Q}** at softer scales

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

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{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{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*

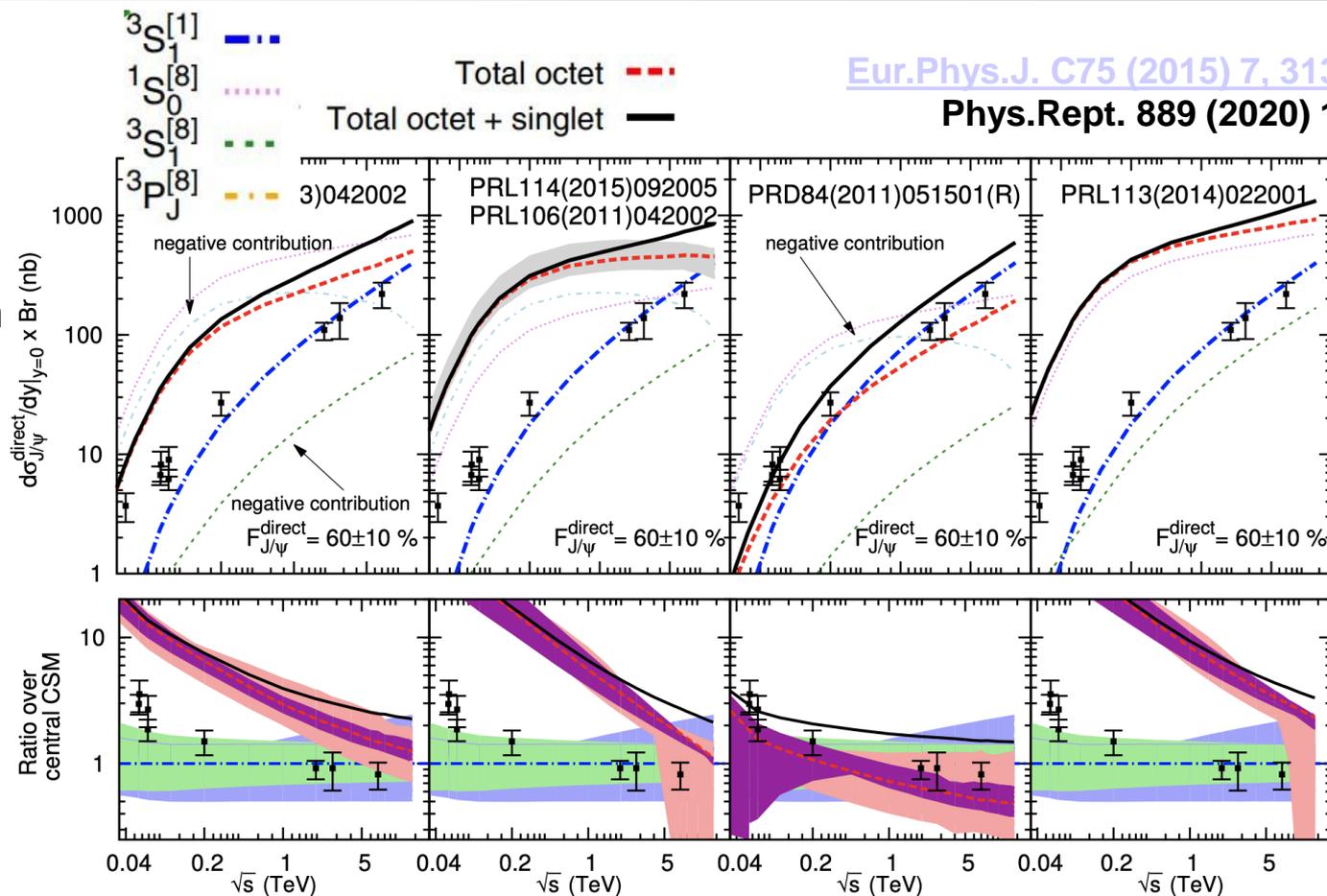
- **Universality**: *same LDME for prompt production and production in b-decays; for e+e-, ep, pp, ...; all beam energies; ...*

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

Charmonium production: challenges

Eur.Phys.J. C75 (2015) 7, 313
Phys.Rept. 889 (2020) 1

- ❑ Many puzzles still there
- ❑ Simultaneous description of J/ψ production and polarization – “polarization puzzle”
- ❑ Simultaneous description of η_c and J/ψ together with J/ψ photoproduction - “HQSS puzzle”
- ❑ Negative contribution in the cross-section
- ❑ Tension with $J/\psi+Z$ production

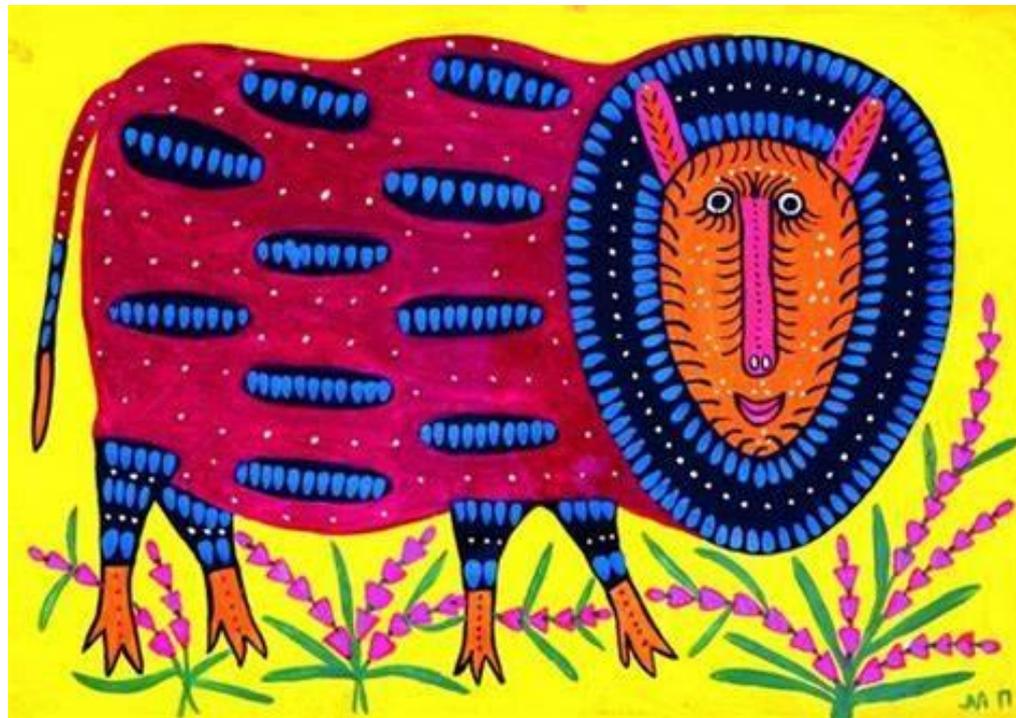


| LDMEs | J/ψ hadropr. | J/ψ photopr. | J/ψ polar. | η_c hadropr. |
|------------------------|-------------------|-------------------|-----------------|-------------------|
| Butenschön et al. | ✓ | ✓ | ✗ | ✗ |
| Chao et al. + η_c | ✓ | ✗ | ✓ | ✓ |
| Zhang et al. | ✓ | ✗ | ✓ | ✓ |
| Gong et al. | ✓ |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

M. Nefedov

- ❑ No model available that could describe simultaneously all linked measurements

LHCb detector



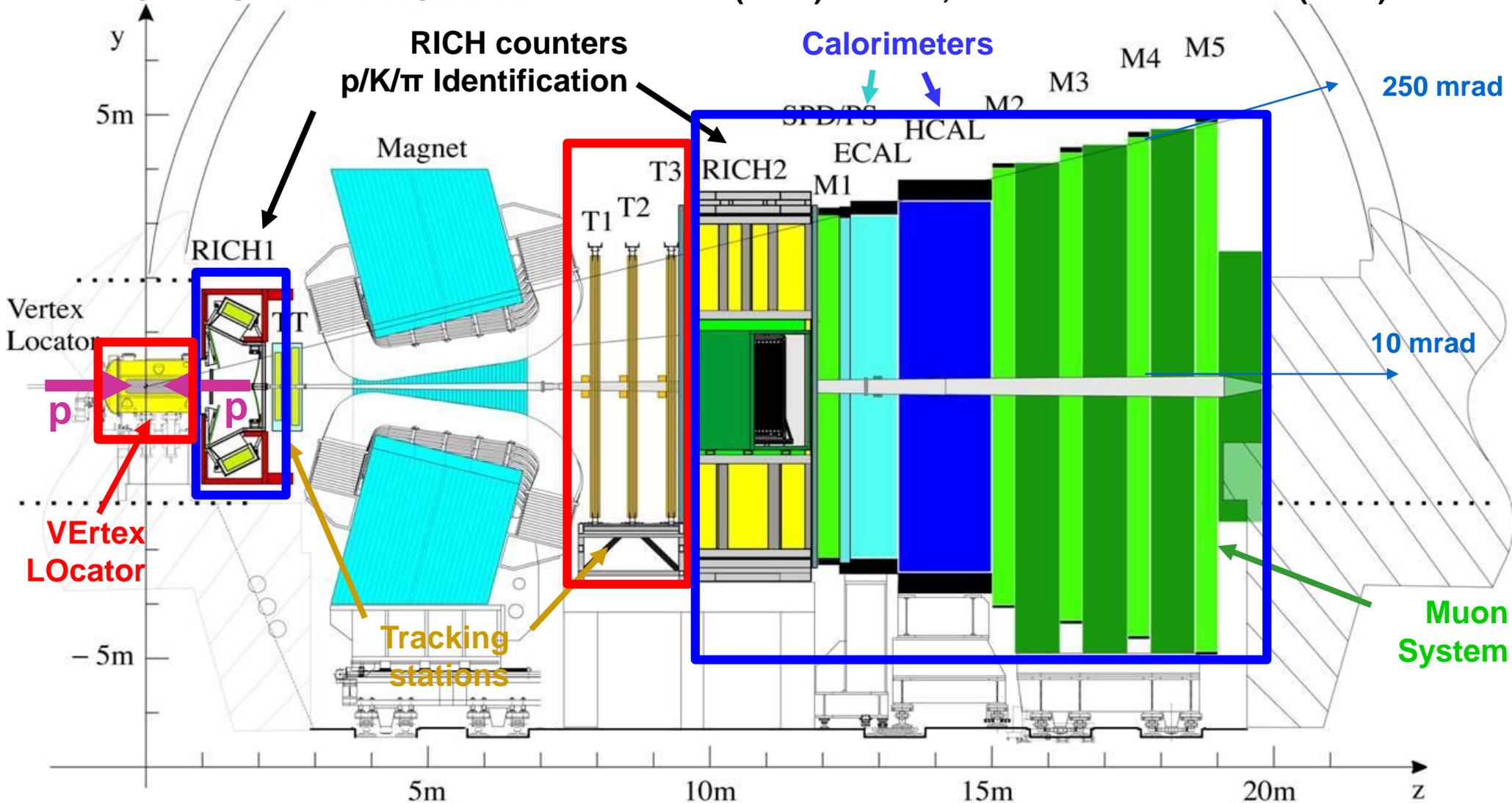
M. Prymachenko

LHCb – single-arm forward spectrometer, 10-250 mrad (V), 10-300 mrad (H)

TRACKING

PARTICLE ID

JINST 8 (2013) P08002, INT.J.MOD.PHYS.A30 (2015) 1530022



Vertex reconstruction:
VELO

Kinematics: Magnet,
Tracker, Calorimeters

PID: RICHs,
Calorimeters, Muon

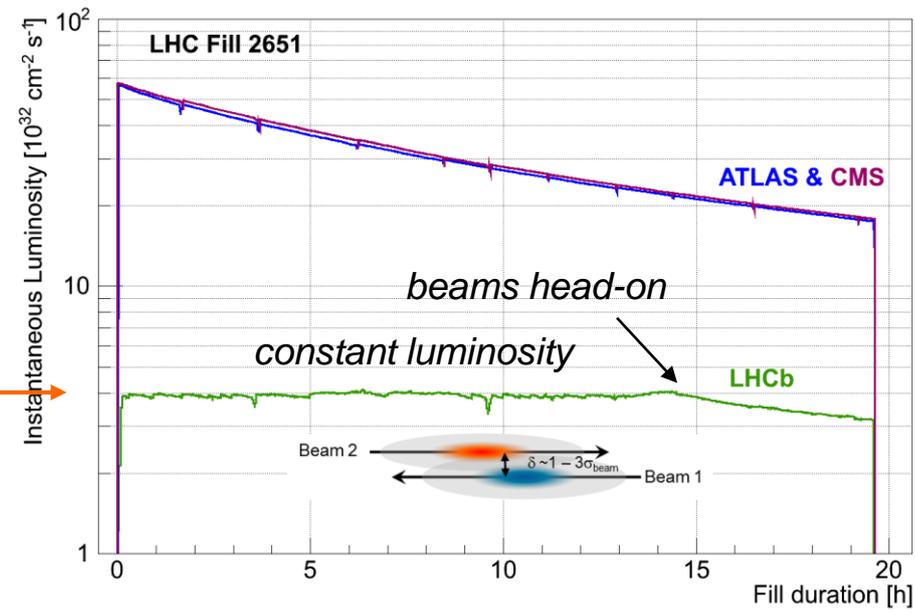
Trigger: Muon,
Calorimeters, Tracker

- ❑ Heavy flavour production at LHC: **prolific, forward peaked & correlated**
- ❑ LHCb ~4% of solid angle, but ~40% of HF production x-section

Excellent performance of LHC and LHCb

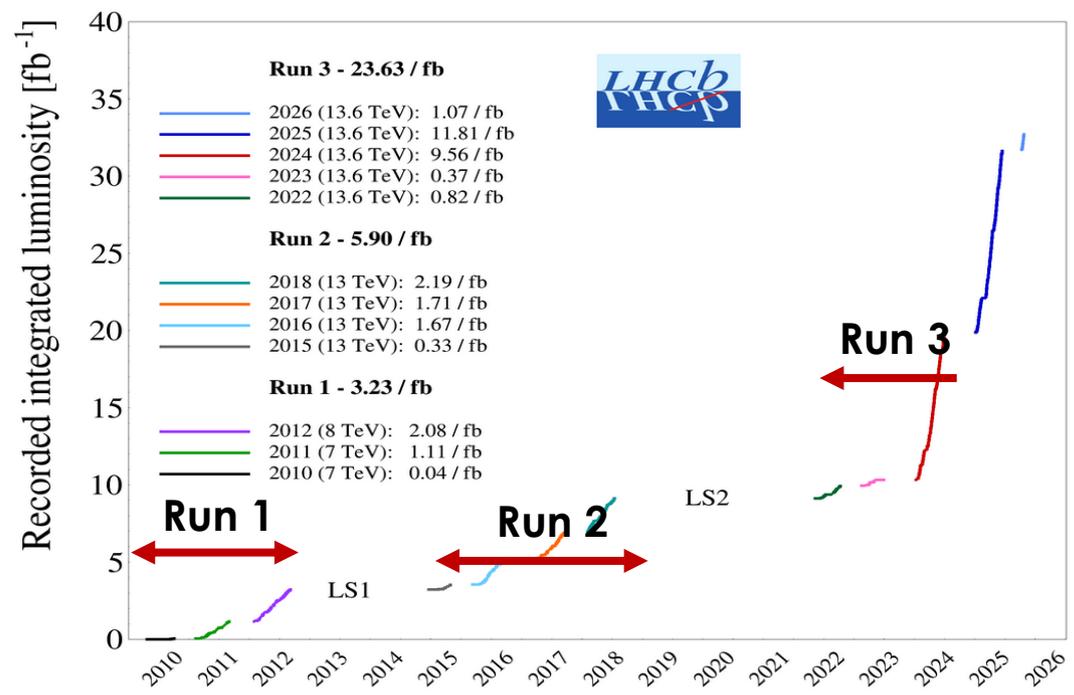
Luminosity leveling for LHCb

LHCb luminosity levelling

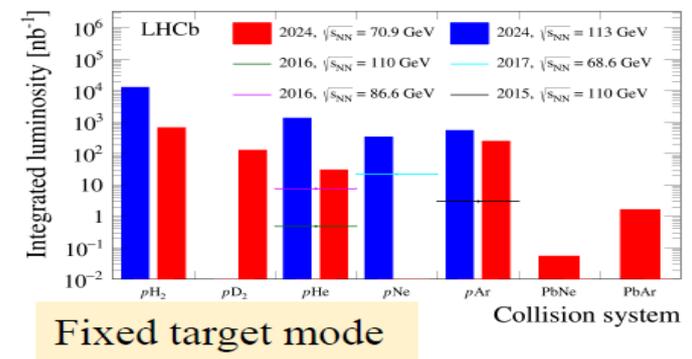
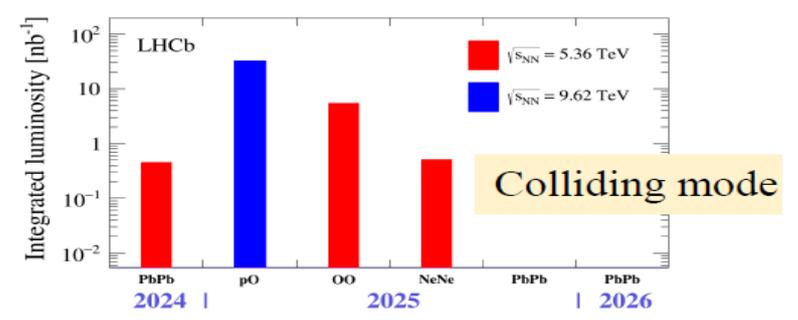


- pp collisions: $\sqrt{s} = 7, 8, 13, 13.6 \text{ TeV}$
- At 13 TeV, $\sigma(bb) \approx 0.5 \text{ mb}$, $\sigma(cc) \approx 20 \times \sigma(bb)$
- LHCb integrated luminosity : $\int L dt \sim 33 \text{ fb}^{-1}$

Total recorded luminosity – pp – 32.8 fb^{-1}



Heavy ion collisions

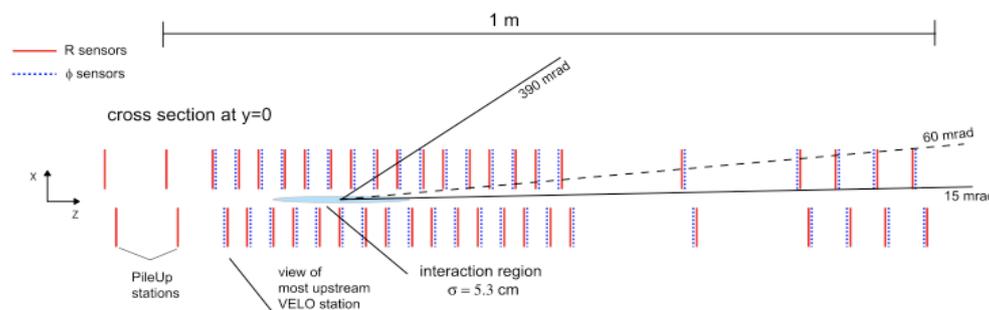


Vertex reconstruction in LHCb: VERtEX LOcator



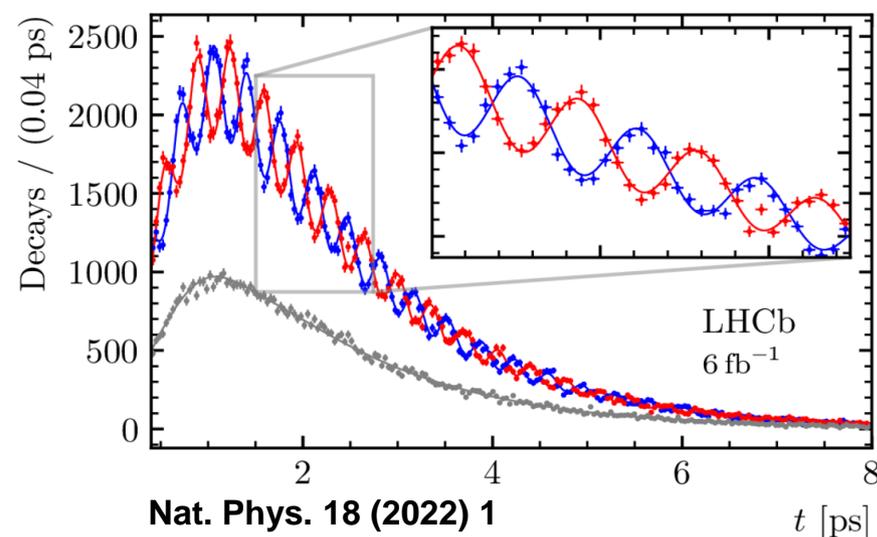
JINST 8 (2013) P08002, JINST 9 (2014) P09007

- ❑ 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**



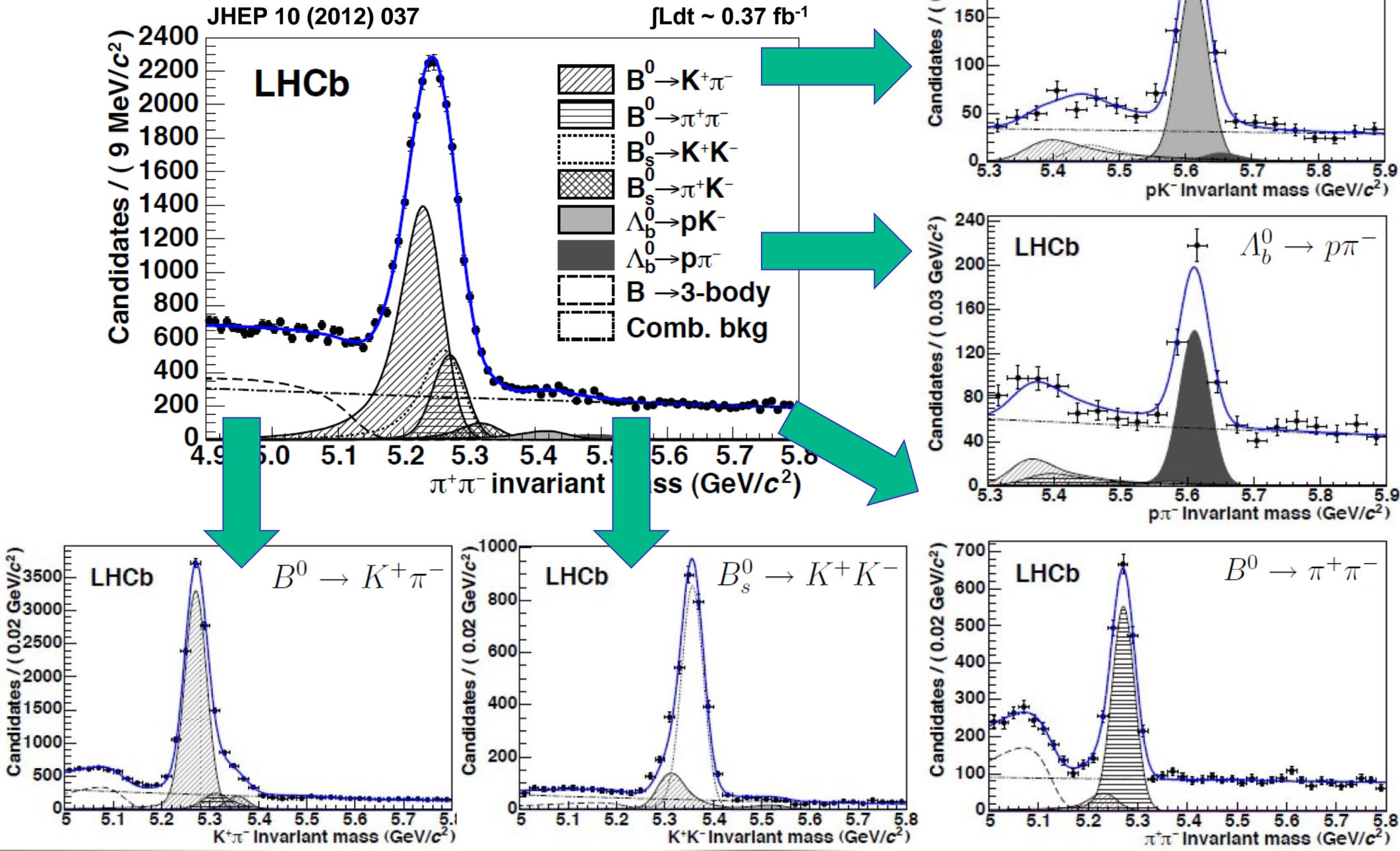
- ❑ Excellent **spatial resolution**, down to 4 μm for single tracks
- ❑ Precise **impact parameter** measurement, $\sigma_{\text{IP}} = 11.6 + 23.4/pT$ [μm]
- ❑ Precise **primary vertex** reconstruction, $\sigma_{x,y} = 13 \mu\text{m}$, $\sigma_z = 69 \mu\text{m}$ for vertex of 25 tracks
- ❑ Excellent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

— $B_s^0 \rightarrow D_s^- \pi^+$ — $\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+$ — Untagged



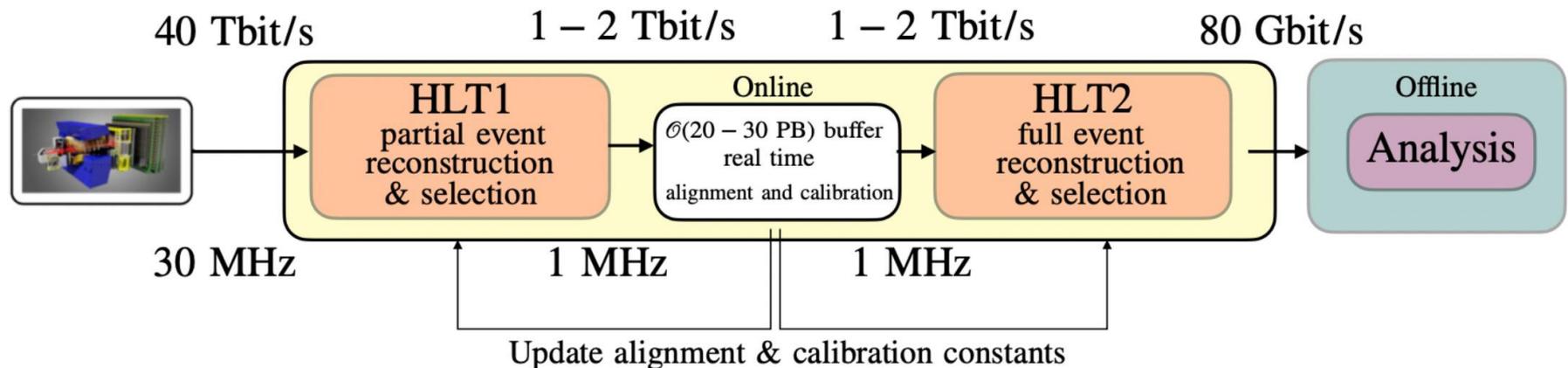
Charged hadron ID in LHCb: Cherenkov light detectors

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



LHCb Upgrade I

- ❑ 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

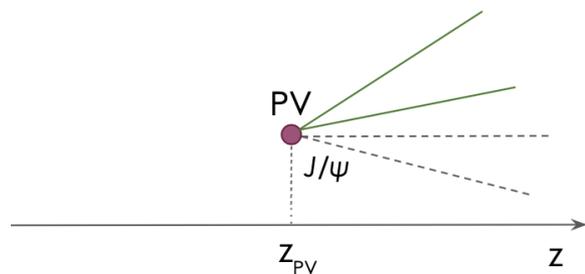


- ❑ 30 MHz of inelastic collisions will be reduced to ~1 MHz by the HLT1 (tracking/vertexing and muon ID) running on **GPUs**
- ❑ **Highest throughput of any HEP experiment**
- ❑ Many measurements directly profit from higher statistical precision (about x3 with run 3 only)

Charmonium production vertex

Prompt production (hadroproduction or decays of higher resonances)

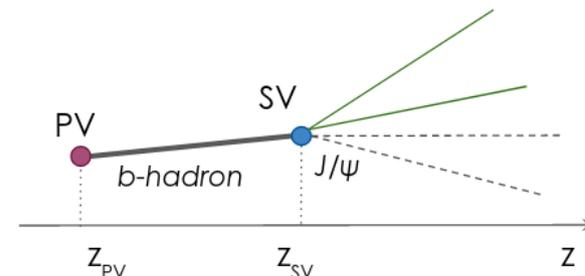
production at pp-collision vertex



versus

Production in **b-hadron decays**

production at displaced vertex



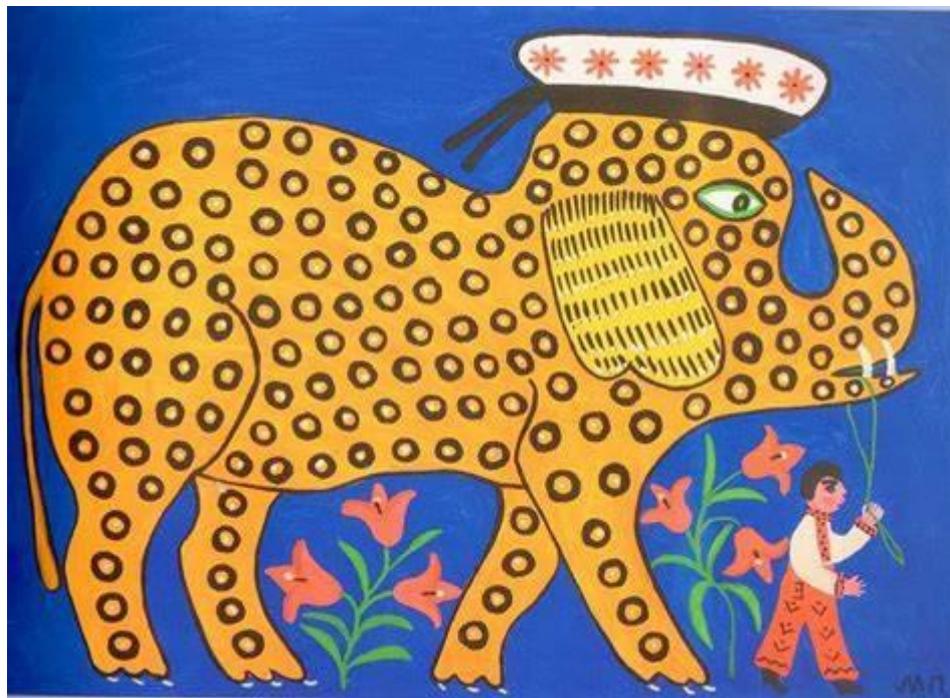
distinguished via **pseudo-proper decay time**

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

PV – primary vertex

SV – secondary vertex

Charmonium production in pp collisions



M. Prymachenko

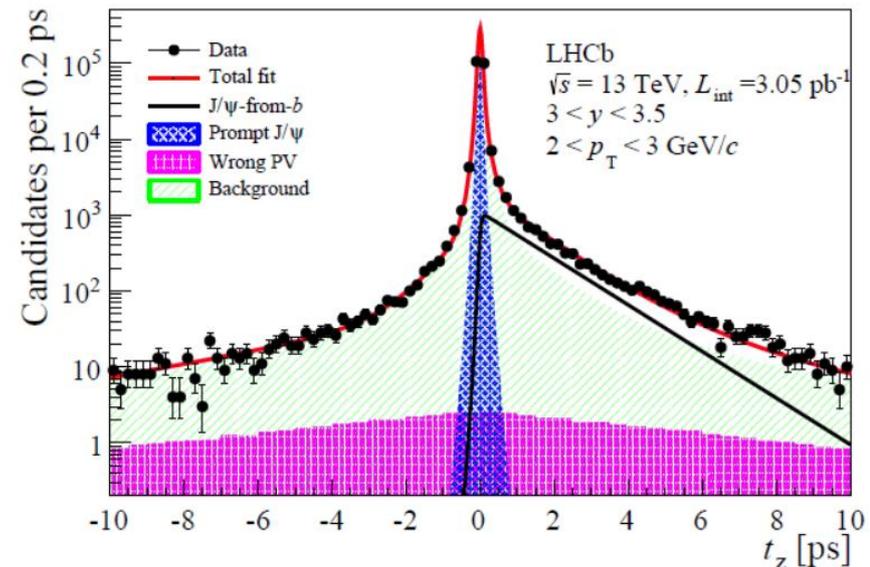
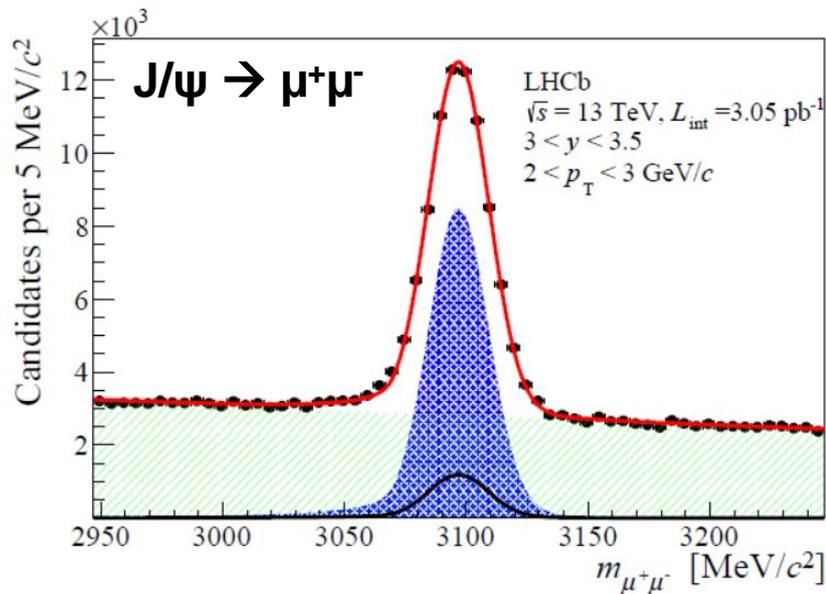
□ Prompt J/ψ production and production in b-hadron decays

extracted from the fit to pseudo-lifetime distribution

$\sqrt{s} = 13$ TeV, $\int L dt \sim 3$ pb⁻¹

Excellent **mass resolution** to suppress combinatorial background

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



Excellent **vertex resolution** to disentangle prompt production and production in b-decays

□ Production cross-section, integrated over acceptance :

$$\sigma(\text{prompt } J/\psi, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5) = 15.03 \pm 0.03 \pm 0.94 \mu\text{b.}$$

$$\sigma(J/\psi\text{-from-}b, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5) = 2.25 \pm 0.01 \pm 0.14 \mu\text{b.}$$

□ $b\bar{b}$ cross-section, integrated over 4π :

$$\sigma(pp \rightarrow b\bar{b}X) = 495 \pm 2 \pm 52 \mu\text{b.}$$

J/ψ production at $\sqrt{s} = 13$ TeV

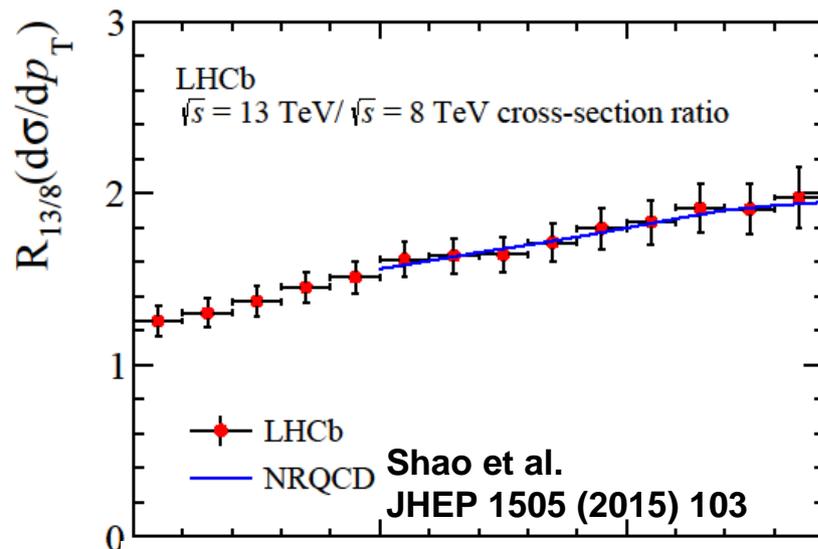
JHEP 1510 (2015) 172

JHEP 1705 (2017) 063

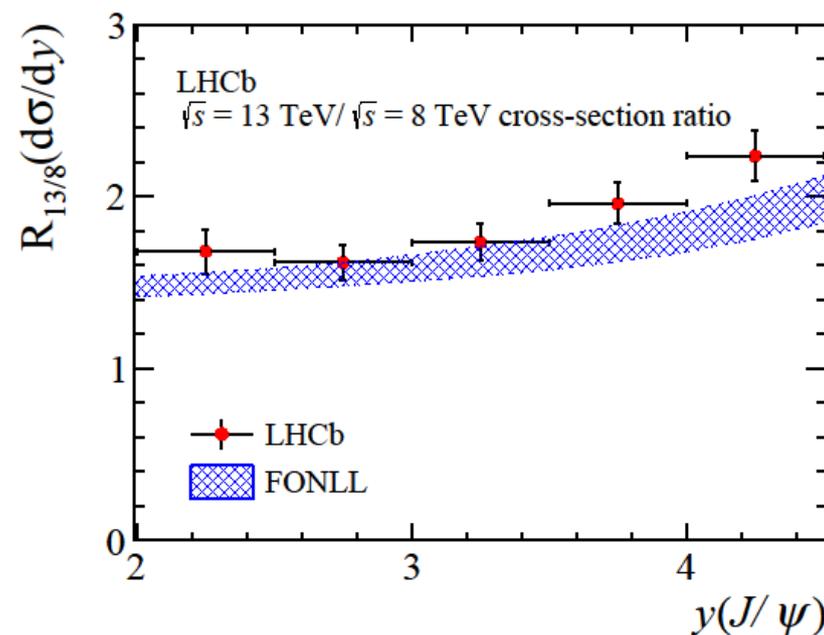
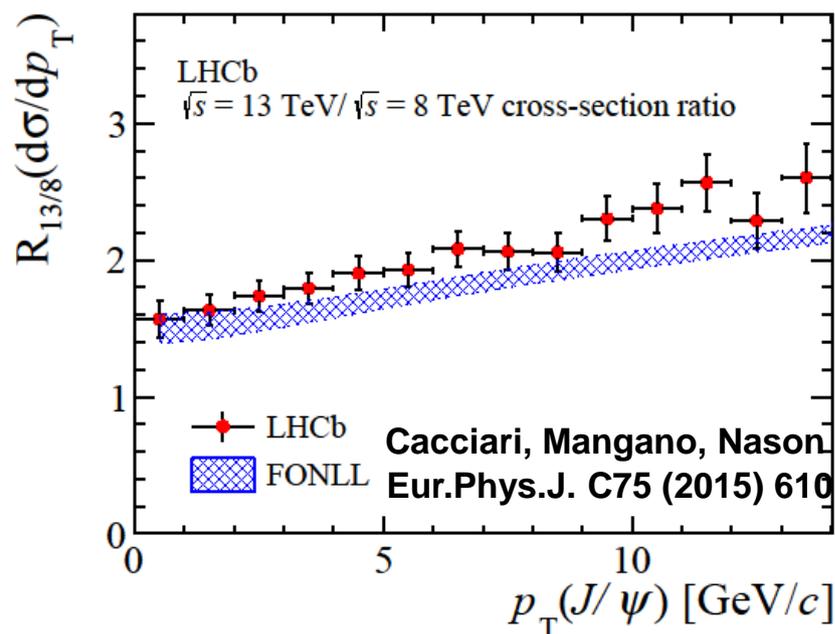
$\sqrt{s} = 13$ TeV, $\int L dt \sim 3$ pb⁻¹

- The **J/ψ production** measured at $\sqrt{s} = 13$ TeV and compared to that at $\sqrt{s} = 8$ TeV and theory

- **Prompt production**

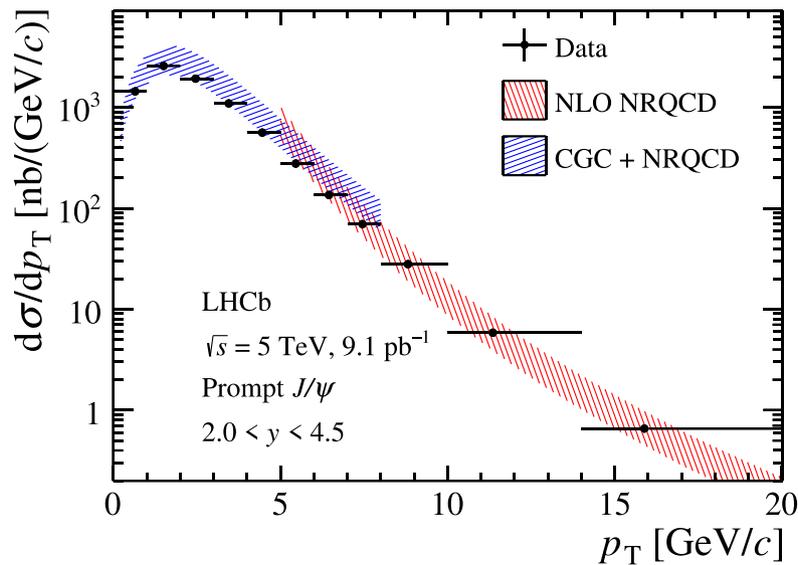


- **Production in b-decays**

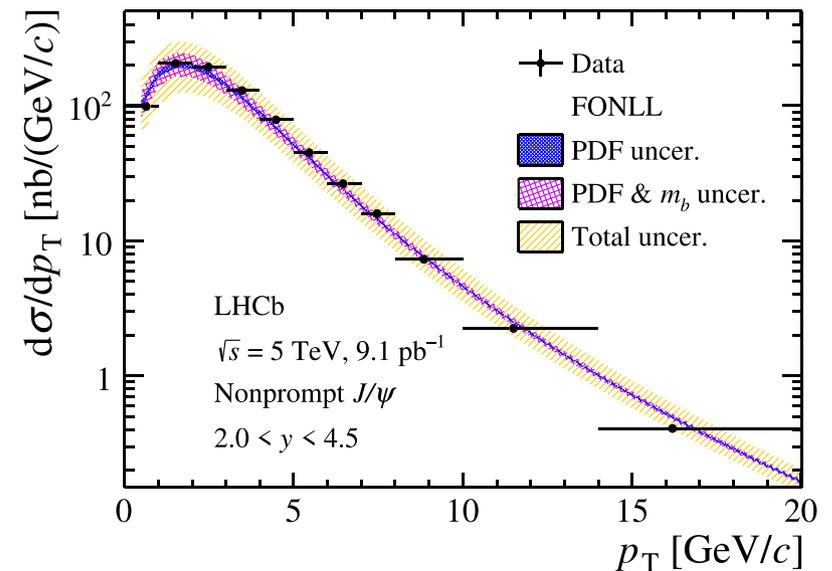


- Perfect (good) **theory-experiment agreement** for prompt (b-decay) production

□ Fiducial volume: $0 < p_T < 20$ GeV/c, $2.0 < y < 4.5$



NRQCD: [PRL 106 \(2011\) 042002](#)
 CGC: [PRL 113 \(2014\) 192301](#)



FONLL: [JHEP 10 \(2012\) 137](#)
[EPJC 75 \(2015\) 610](#)

□ J/ψ production cross-section:

$$\sigma_{\psi}^{prompt} = 8.154 \pm 0.010_{stat} \pm 0.283_{syst} \mu b$$

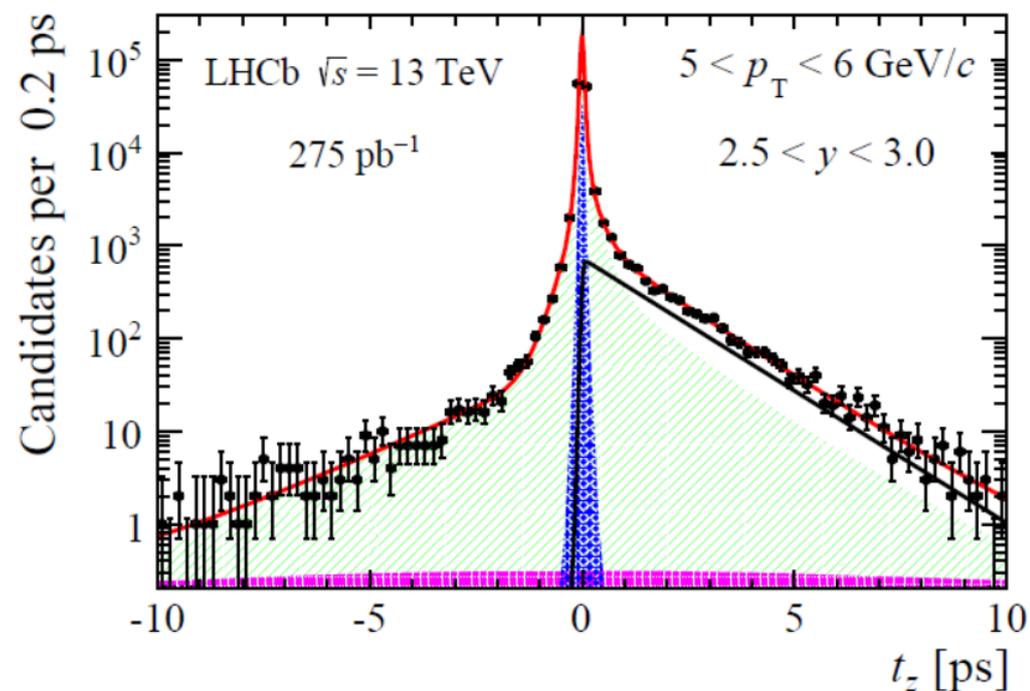
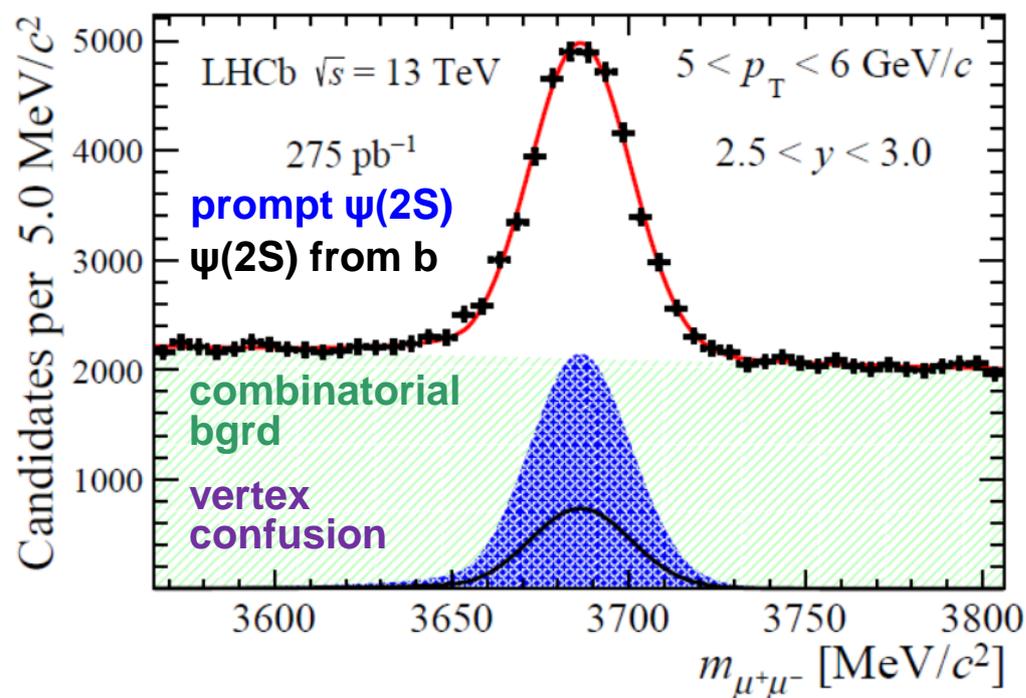
$\psi(2S)$ production at 7 and 13 TeV

EPJC 80 (2020) 185

$\sqrt{s} = 7, 13 \text{ TeV}, \int L dt \sim 614, 275 \text{ pb}^{-1}$

- ❑ Negligible feed-down compared to J/ψ
- ❑ Prompt (pp collision vertex) $\psi(2S)$ production and production in b-decays
- ❑ Double differential cross-sections from two-dimensional fit in bins of p_T and y
- ❑ Prompt and b-decay components are extracted from the fit to pseudo-lifetime distribution

$$t_z = \frac{(z_{\psi(2S)} - z_{PV}) \times M_{\psi(2S)}}{p_z}$$



- ❑ Integral cross sections:

$$\begin{aligned} \sigma(\text{prompt } \psi(2S), 7 \text{ TeV}) &= 0.471 \pm 0.001 (\text{stat}) \pm 0.025 (\text{syst}) \mu\text{b}, \\ \sigma(\psi(2S)\text{-from-}b, 7 \text{ TeV}) &= 0.126 \pm 0.001 (\text{stat}) \pm 0.008 (\text{syst}) \mu\text{b}. \end{aligned}$$

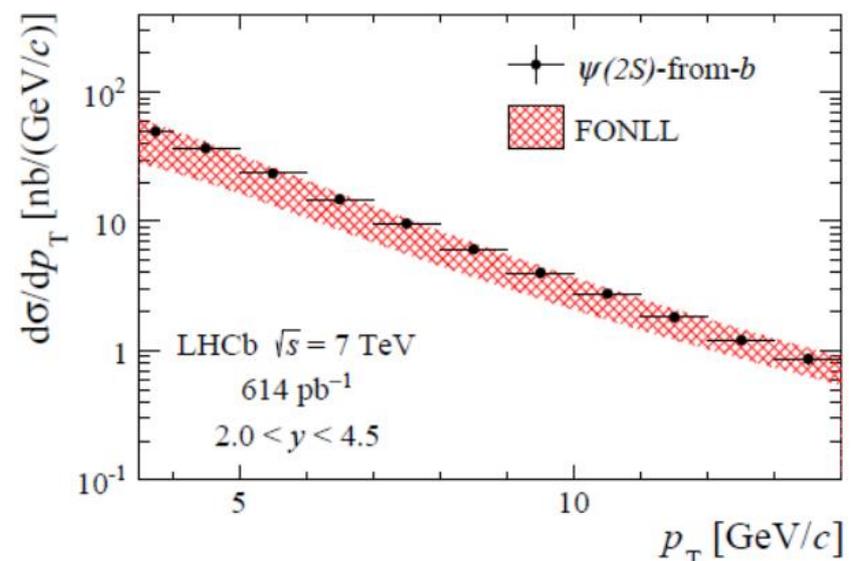
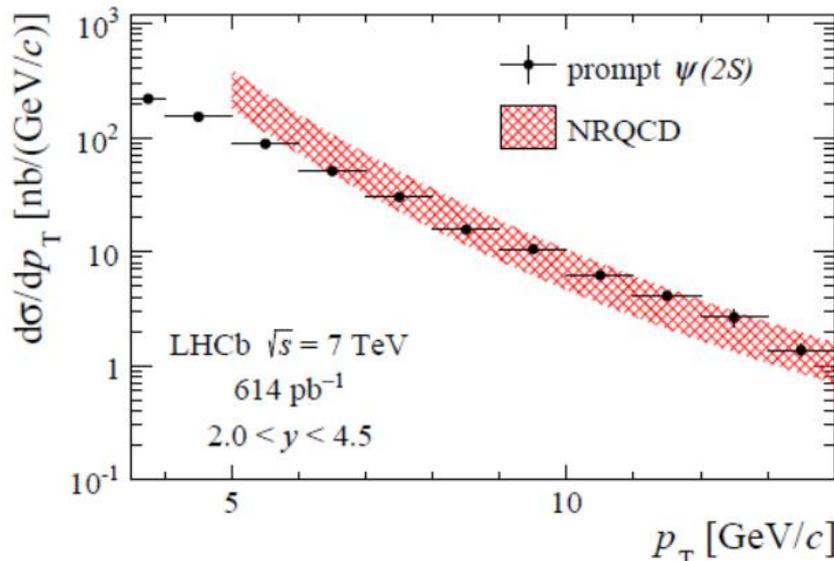
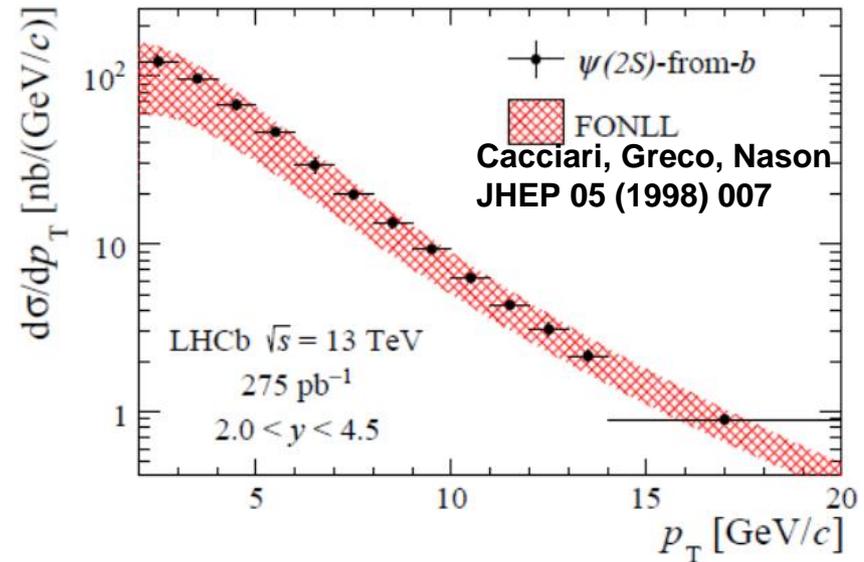
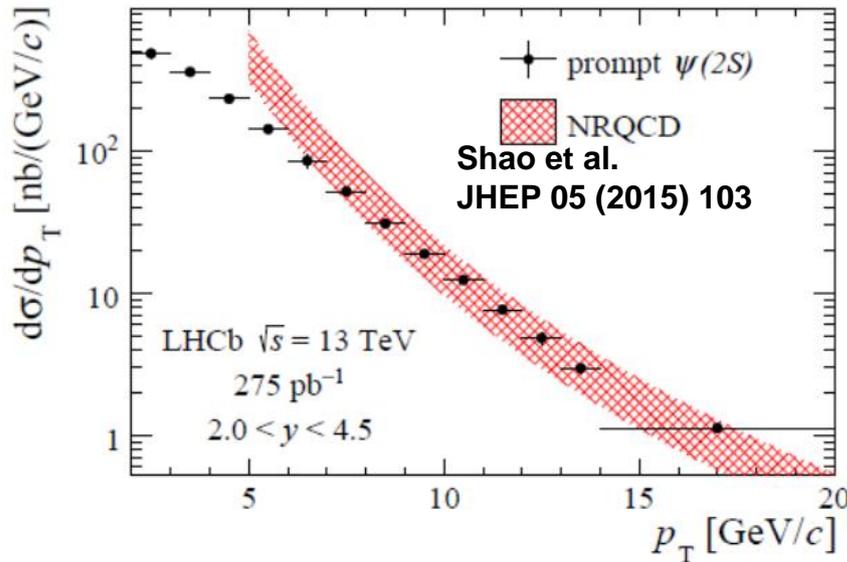
$$\begin{aligned} \sigma(\text{prompt } \psi(2S), 13 \text{ TeV}) &= 1.430 \pm 0.005 (\text{stat}) \pm 0.099 (\text{syst}) \mu\text{b}, \\ \sigma(\psi(2S)\text{-from-}b, 13 \text{ TeV}) &= 0.426 \pm 0.002 (\text{stat}) \pm 0.030 (\text{syst}) \mu\text{b}. \end{aligned}$$

$\psi(2S)$ production at 7 and 13 TeV

□ Prompt $\psi(2S)$ production and production in b-hadron decays

□ Differential cross sections

$\sqrt{s} = 7, 13 \text{ TeV}, \int L dt \sim 614, 275 \text{ pb}^{-1}$



□ Overall good agreement with predictions, with deviation at low p_T for prompt $\psi(2S)$

$\sqrt{s} = 7, 13 \text{ TeV}, \int L dt \sim 614, 275 \text{ pb}^{-1}$

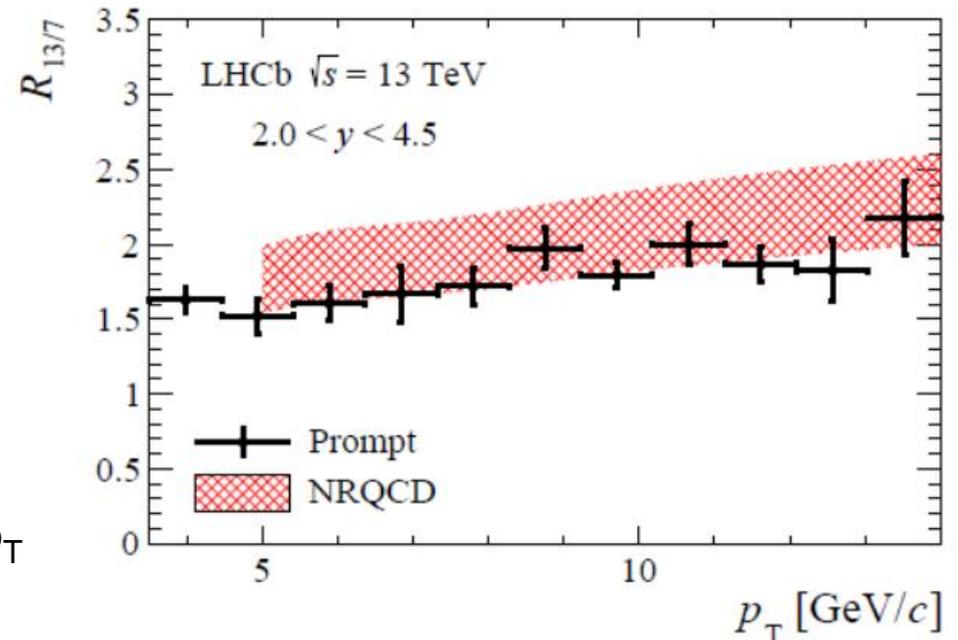
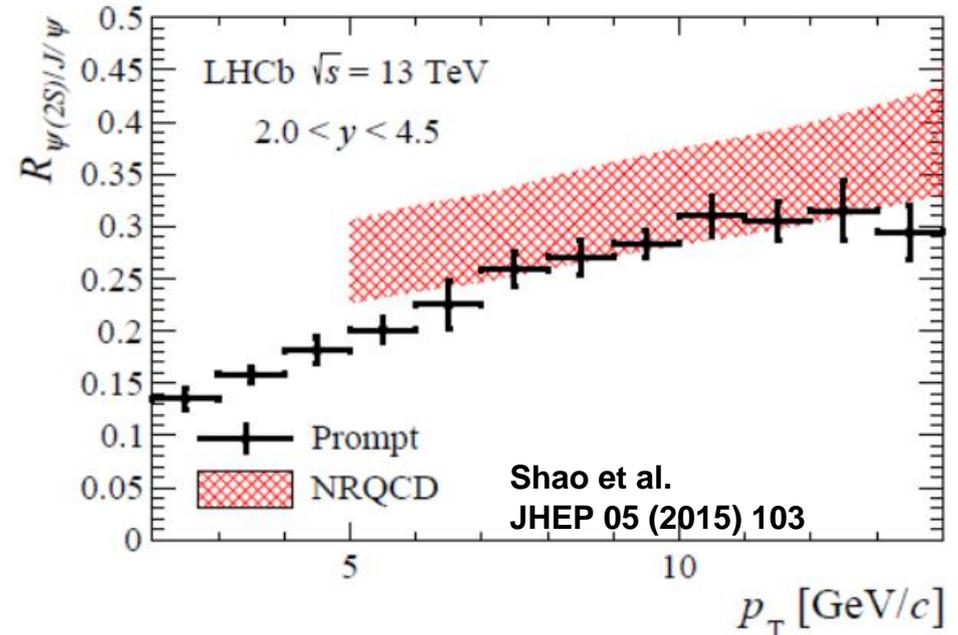
□ Uncertainties partly cancel in ratios

□ Ratio between the $\psi(2S)$ and J/ψ production cross-sections

□ Ratio between the $\psi(2S)$ production cross-sections at $\sqrt{s} = 13$ and 7 TeV

□ **Overall good description** for both ratios

□ Important to extend theory prediction to lower p_T



$\eta_c(1S)$ production

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

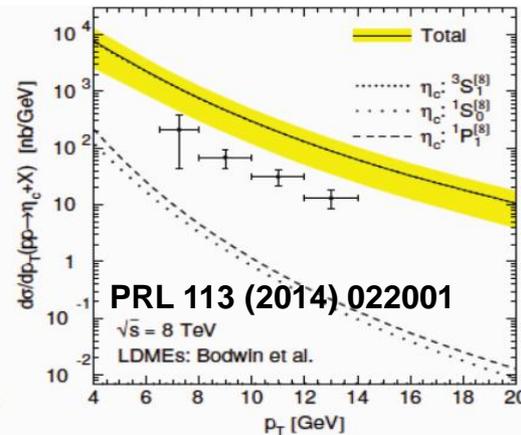
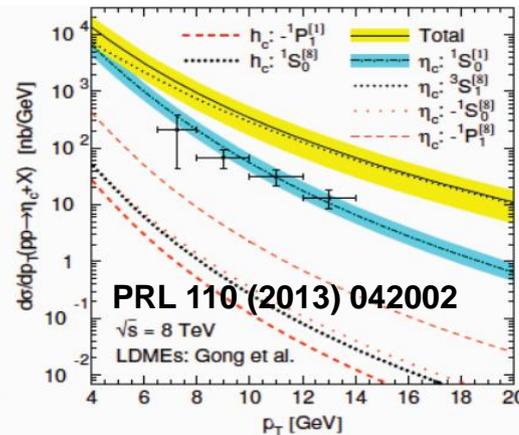
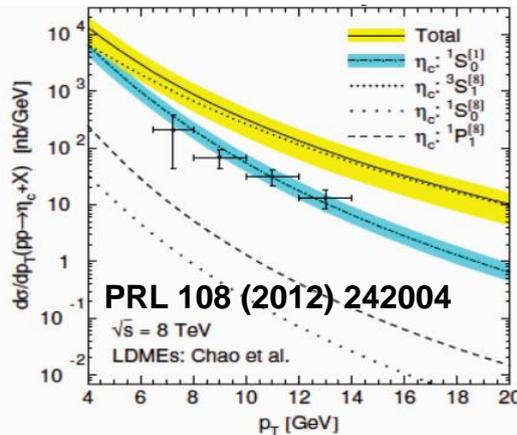
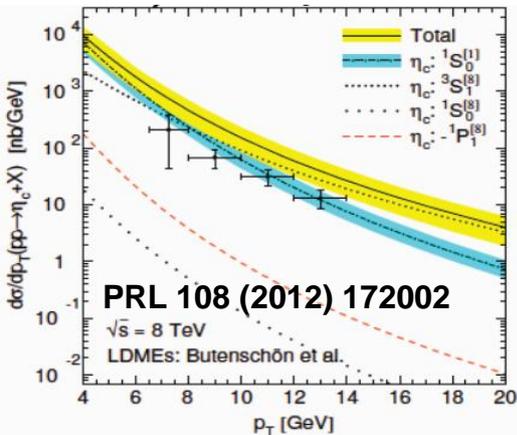
■ J/ψ prediction (NRQCD CS+CO)

■ CS prediction

LHCb: EPJC 75 (2015) 311

$\eta_c(1S) \rightarrow p\bar{p}$

Butenschoen, He, Kniehl, arXiv:1411.5287

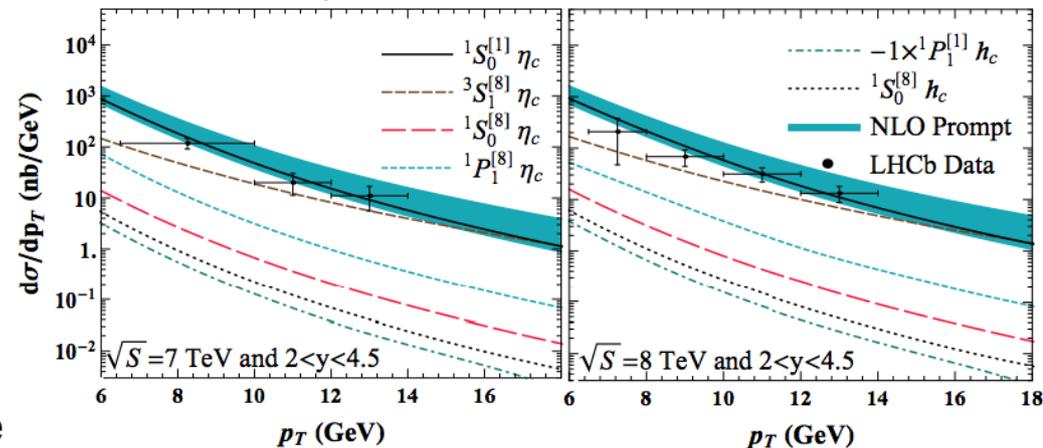


□ Results described by **CS NLO**, below expected CO contribution

□ Progress in theory description, integrating LHCb result on η_c production in LDME calculations

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

Han, Ma, Meng, Shao, and Chao [PRL 114\(2015\), 092004](#)



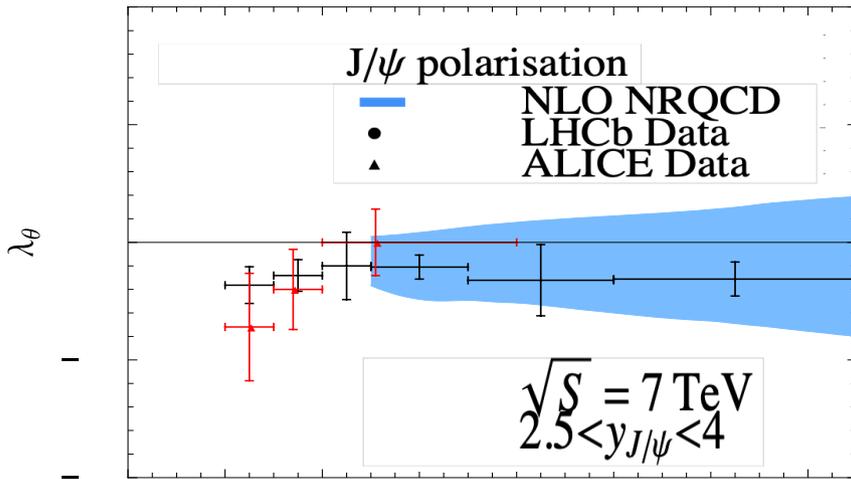
□ Theory description still covers limited p_T range

□ Further tests with measurements at different \sqrt{s} and of other linked observables

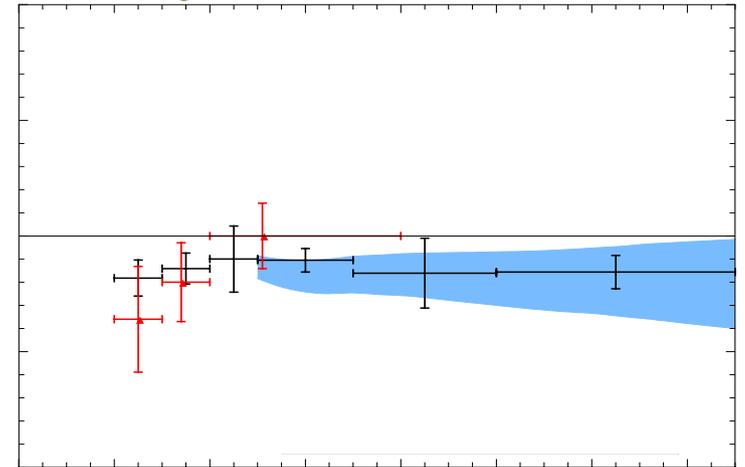
$\eta_c(1S)$ production

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

Before η_c measurements



After η_c measurements

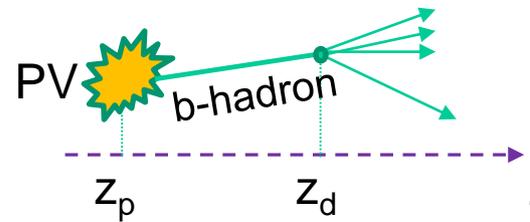


PRL 114(2015), 092004

- Impressive progress ! Still :
 - Tension with CDF data
 - Two large CO contributions cancel each other \Rightarrow hierarchy problem ?

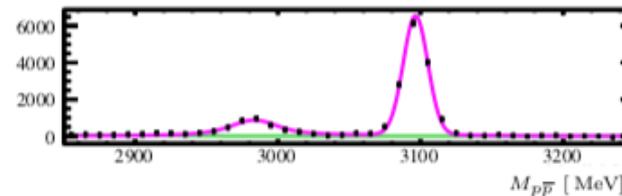
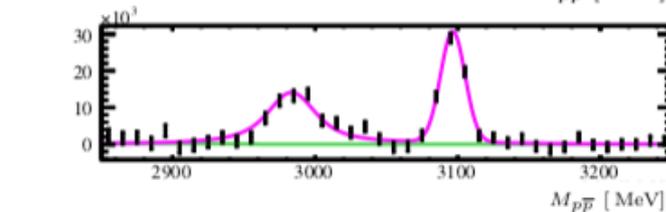
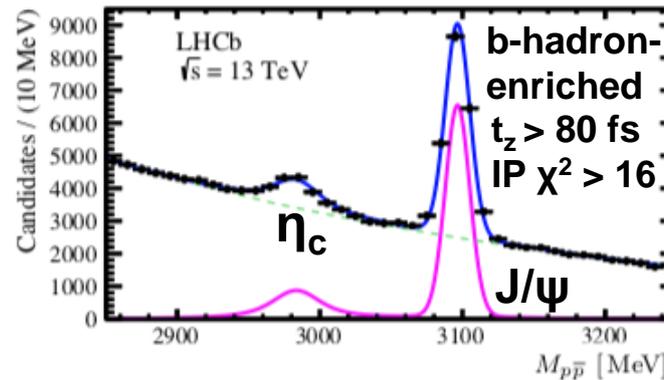
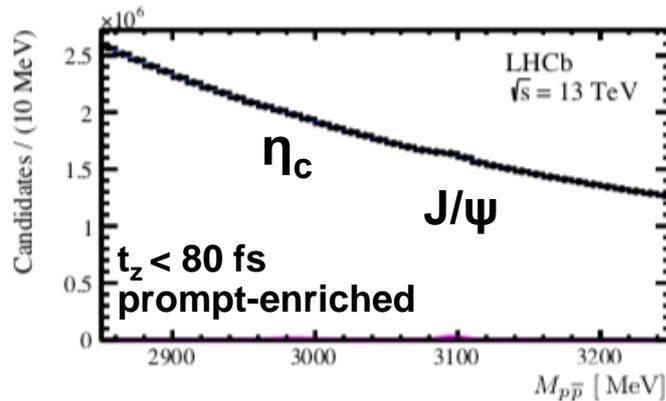
$\eta_c(1S)$ production

- Analysis with 13 TeV data, measurement relative to J/ψ
- Pseudo proper-time to separate prompt charmonium and charmonium from b-decays

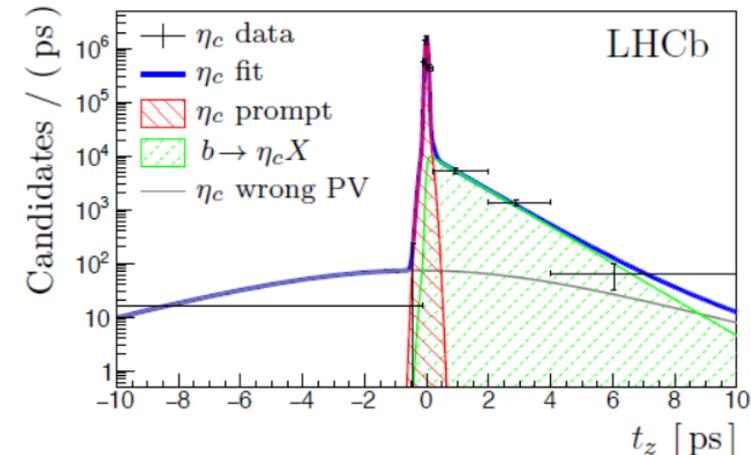
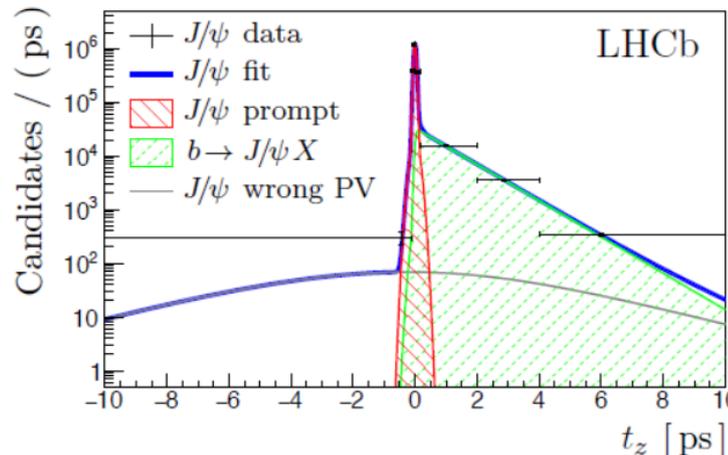


$$t_z = \frac{(z_d - z_p) M_{p\bar{p}}}{p_z}$$

- Selection (account for cross feed) ...



- ... or pseudo proper-time fit
- Good agreement between the results



□ New measurement $\eta_c(1S)$ production cross section at 13 TeV

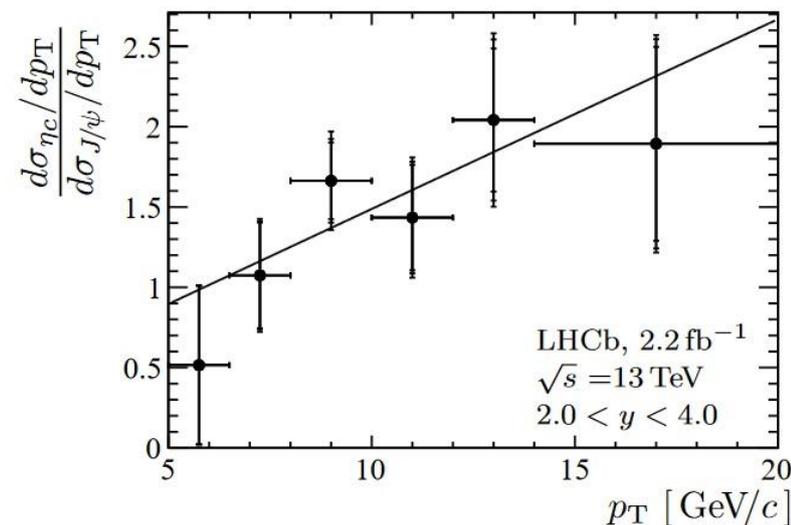
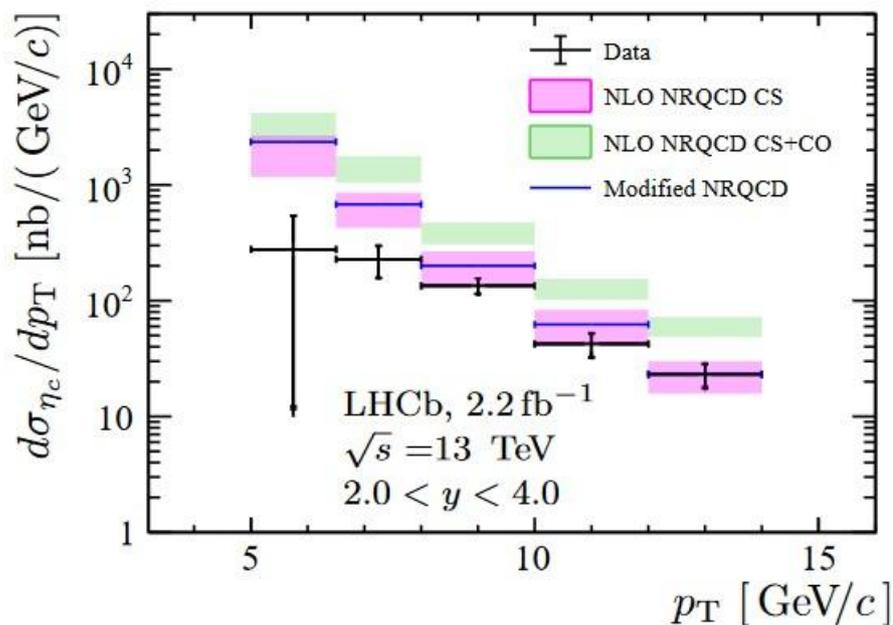
$$(\sigma_{\eta_c})_{13 \text{ TeV}}^{6.5 \text{ GeV} < p_T < 14.0 \text{ GeV}, 2.0 < y < 4.5} = 796.4 \pm 86.6 \pm 30.8 \pm 21.4 \pm 84.4 \text{ nb}$$

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

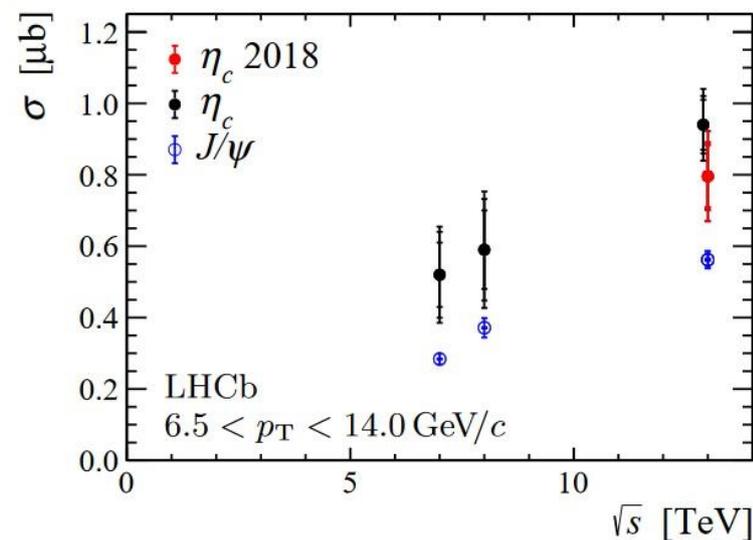
$$1.56_{-0.49}^{+0.83} \text{ scale }_{-0.17}^{+0.38} \text{ CT14NLO } \mu\text{b}$$

□ Consistent with being described by CSM

□ p_T -differential prompt production



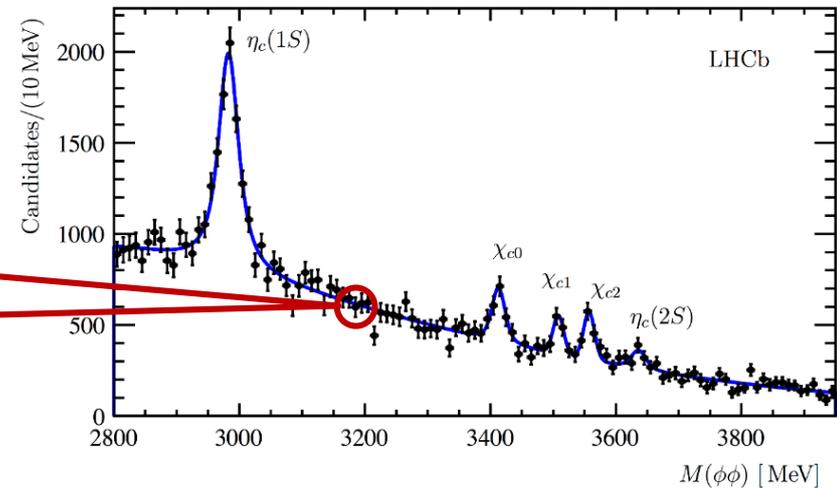
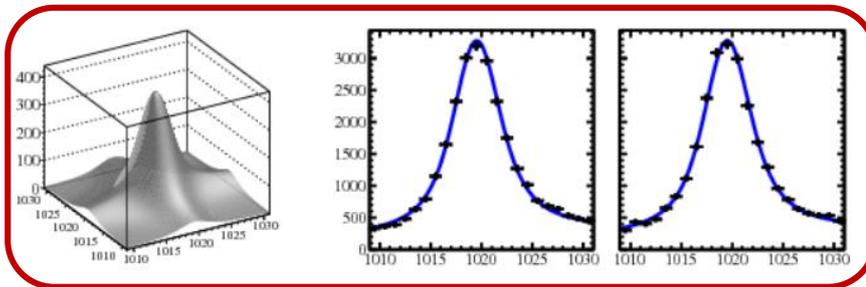
□ \sqrt{s} cross-section dependence



□ Inclusive production in b-decays:

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

- Charmonium reconstructed via **decays to $\phi\phi$**
- True $\phi\phi$ combinations extracted using 2D fit technique



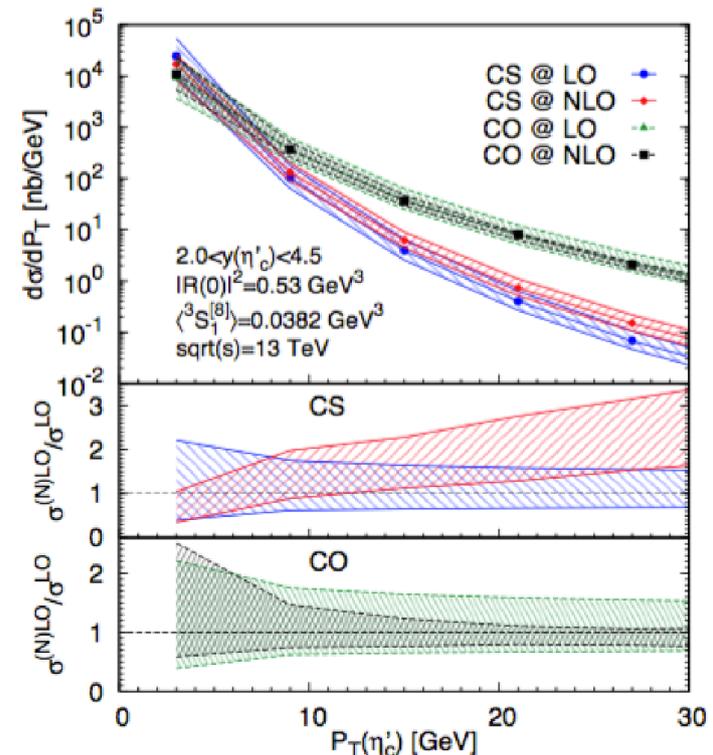
- First measurement of $\eta_c(2S)$ production in b-decays**
- First evidence for $\eta_c(2S) \rightarrow \phi\phi$**

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

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

Theory prediction \rightarrow

- Dedicated LHCb trigger in 2018**



Lansberg, Shao, Zhang, PLB 786 (2018) 342

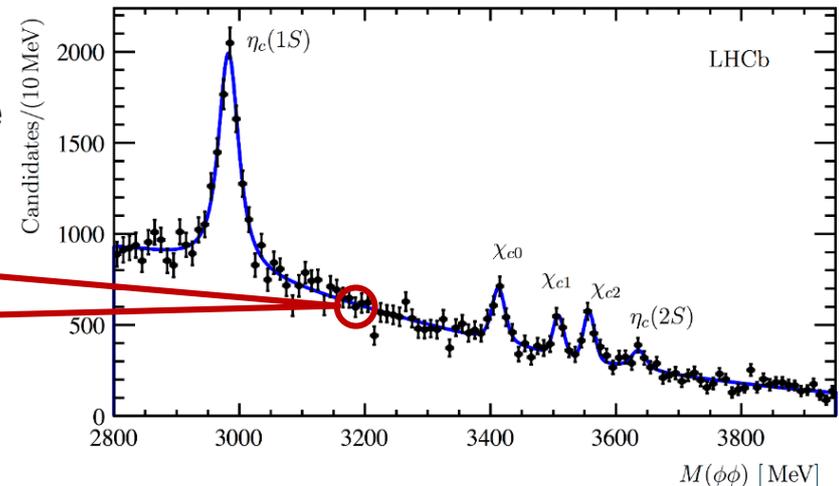
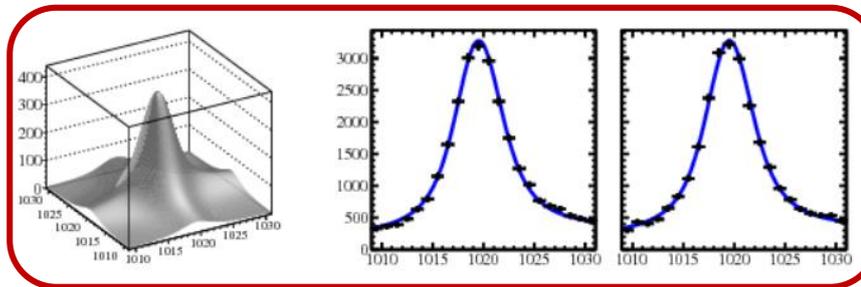
- UL on prompt production cross-section is compared to predictions for three different CO LDME sets

| $p_T, [\text{GeV}/c]$ | UL @95%CL | Shao et al. [40] | Gong et al. [39] | Bodwin et al. [41] |
|---|-----------|-------------------|-------------------|--------------------|
| $\sigma_{\eta_c(2S)} \times \mathcal{B}_{\eta_c(2S) \rightarrow p\bar{p}}, [pb]$ | | | | |
| 5.0–14.0 | < 361 | 664 ± 297 | 365 ± 135 | 855 ± 123 |
| 5.0–20.0 | < 340 | 674 ± 304 | 368 ± 138 | 870 ± 126 |
| $(\sigma_{\eta_c(2S)} \times \mathcal{B}_{\eta_c(2S) \rightarrow p\bar{p}}) / (\sigma_{J/\psi} \times \mathcal{B}_{J/\psi \rightarrow p\bar{p}})$ | | | | |
| 5.0–14.0, $y < 4$ | < 0.122 | 0.484 ± 0.217 | 0.266 ± 0.099 | 0.623 ± 0.093 |
| 5.0–14.0, $y < 4.5$ | < 0.122 | 0.428 ± 0.192 | 0.235 ± 0.088 | 0.551 ± 0.083 |
| 5.0–20.0, $y < 4$ | < 0.115 | 0.428 ± 0.192 | 0.235 ± 0.088 | 0.551 ± 0.083 |

- Inconsistency with the theory predictions from Bodwin et al.

- **Essential to understand and further constrain uncertainties in theory**

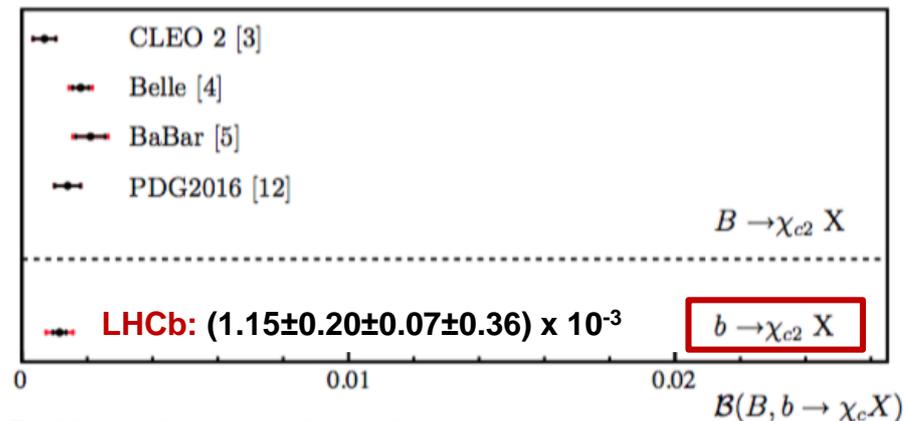
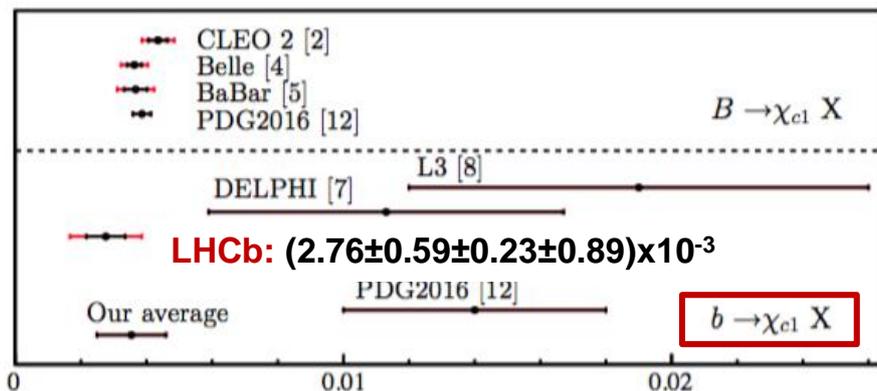
- Charmonium reconstructed via decays to $\phi\phi$
- True $\phi\phi$ combinations extracted using 2D fit technique



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

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

- 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

□ Inclusive branching fractions

| | $c\bar{c} \rightarrow p\bar{p}$, measured | $c\bar{c} \rightarrow \phi\phi$ [12] | PDG [14] |
|--|---|--------------------------------------|-----------------|
| $\mathcal{B}_{b \rightarrow \chi_{c0} X} \times \mathcal{B}_{\chi_{c0} \rightarrow p\bar{p}} \times 10^{-7}$ | $6.82 \pm 1.20_{stat} \pm 0.28_{syst} \pm 0.59_{\mathcal{B}}$ | 6.67 ± 2.40 | 33.2 ± 13.3 |
| $\mathcal{B}_{b \rightarrow \chi_{c0} X} \times 10^{-3}$ | $3.08 \pm 0.54_{stat} \pm 0.13_{syst} \pm 0.29_{\mathcal{B}}$ | 3.02 ± 1.08 | 15 ± 6 |
| $\mathcal{B}_{b \rightarrow \chi_{c1} X} \times \mathcal{B}_{\chi_{c1} \rightarrow p\bar{p}} \times 10^{-7}$ | $3.99 \pm 0.94_{stat} \pm 0.11_{syst} \pm 0.35_{\mathcal{B}}$ | 2.10 ± 0.83 | 10.6 ± 3.1 |
| $\mathcal{B}_{b \rightarrow \chi_{c1} X} \times 10^{-3}$ | $5.25 \pm 1.23_{stat} \pm 0.14_{syst} \pm 0.51_{\mathcal{B}}$ | 2.76 ± 1.09 | 14 ± 4 |
| $\mathcal{B}_{b \rightarrow \chi_{c2} X} \times \mathcal{B}_{\chi_{c2} \rightarrow p\bar{p}} \times 10^{-7}$ | $1.15 \pm 0.85_{stat} \pm 0.03_{syst} \pm 0.10_{\mathcal{B}}$ | 0.85 ± 0.31 | 4.6 ± 2.1 |
| $\mathcal{B}_{b \rightarrow \chi_{c2} X} \times 10^{-3}$ | $1.57 \pm 1.15_{stat} \pm 0.04_{syst} \pm 0.15_{\mathcal{B}}$ | 1.15 ± 0.42 | 6.2 ± 2.9 |

□ Averages between different charmonium decay modes

$$\begin{aligned}
 \frac{\mathcal{B}(b \rightarrow \chi_{c1} X)}{\mathcal{B}(b \rightarrow \chi_{c0} X)} &= 0.98 \pm 0.19_{stat} \pm 0.05_{syst} \pm 0.08_{\mathcal{B}} & \mathcal{B}(b \rightarrow \chi_{c0} X) &= 3.07 \pm 0.36_{stat} \pm 0.07_{syst} \pm 0.52_{\mathcal{B}} \\
 \frac{\mathcal{B}(b \rightarrow \chi_{c2} X)}{\mathcal{B}(b \rightarrow \chi_{c0} X)} &= 0.38 \pm 0.07_{stat} \pm 0.01_{syst} \pm 0.03_{\mathcal{B}} & \mathcal{B}(b \rightarrow \chi_{c1} X) &= 3.23 \pm 0.53_{stat} \pm 0.11_{syst} \pm 0.45_{\mathcal{B}} \\
 & & \mathcal{B}(b \rightarrow \chi_{c2} X) &= 1.16 \pm 0.20_{stat} \pm 0.03_{syst} \pm 0.15_{\mathcal{B}}
 \end{aligned}$$

Combined fits of LDME



M. Prymachenko

Simultaneous study of J/ψ and $\eta_c(1S)$ prompt production

- Simultaneous fit for available J/ψ and $\eta_c(1S)$ prompt production results

- Relation between LDME from HQSS:

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

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

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

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

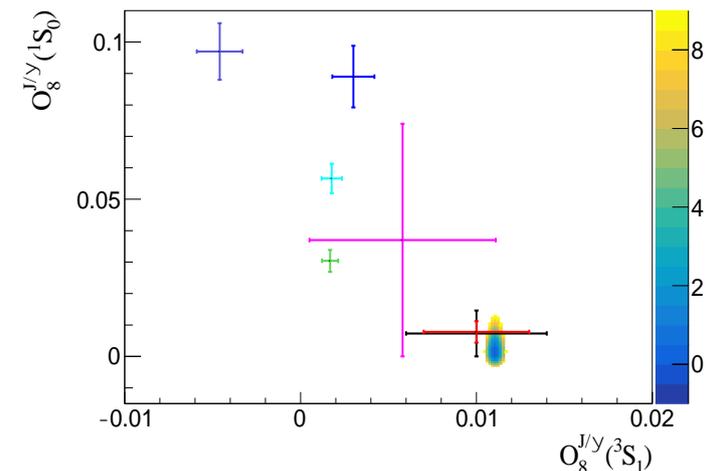
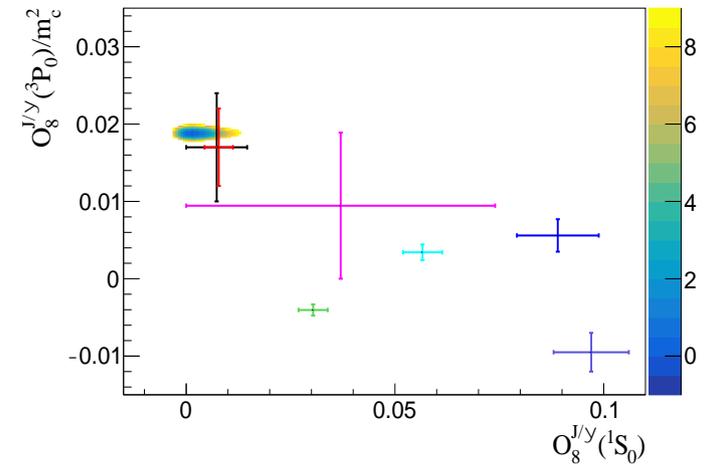
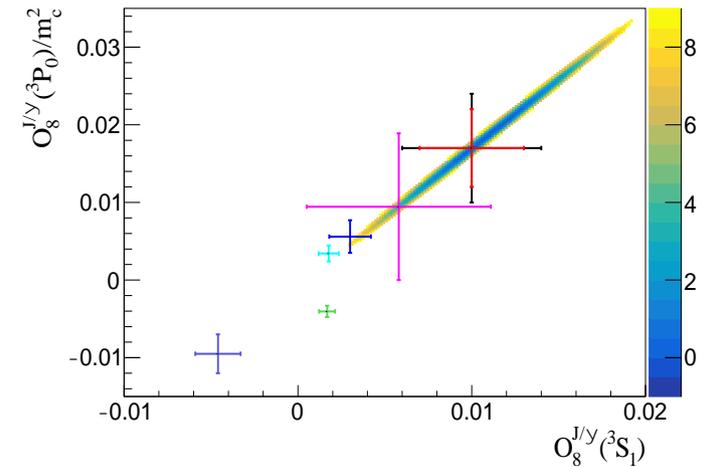
- Fix CS LDME from potential model

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

- 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 study of $\psi(2S)$ and $\eta_c(2S)$ prompt production

□ Simultaneous fit for available $\psi(2S)$ and $\eta_c(2S)$ 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

$$\langle \mathcal{O}_1^{\psi(2S)}(3S_1) \rangle = 0.76 \text{ GeV}^3$$

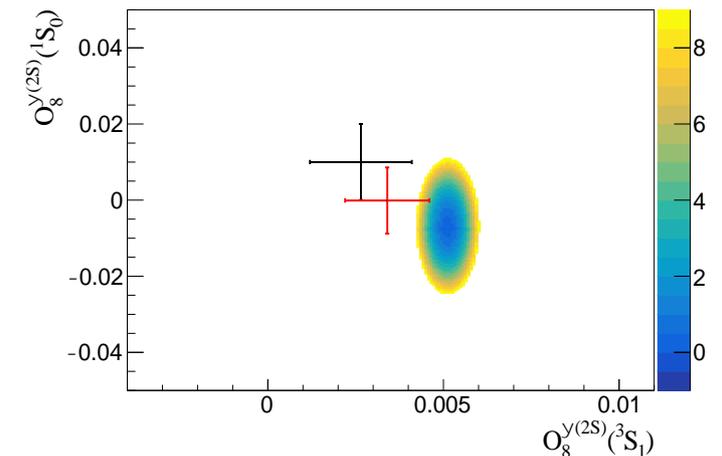
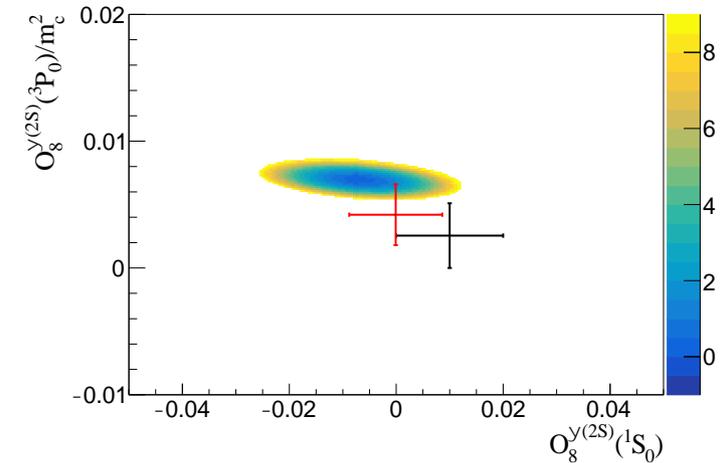
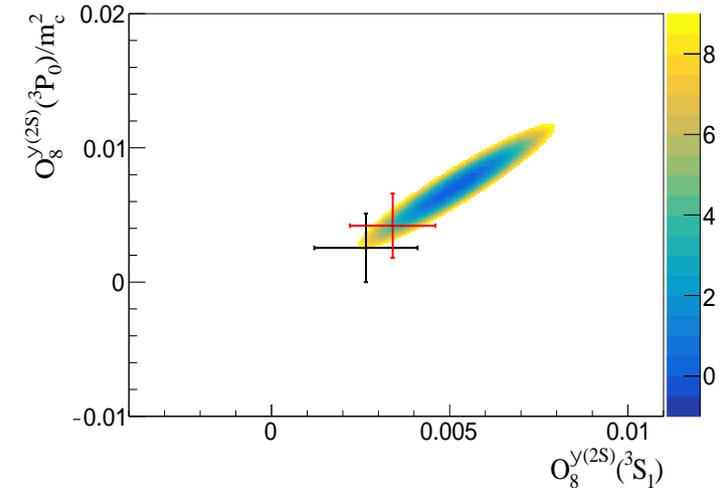
□ χ^2 minimization

— 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**

Charmonium suppression in large systems



M. Prymachenko

Charmonium suppression in large systems

J.Phys. G32 (2006) R25

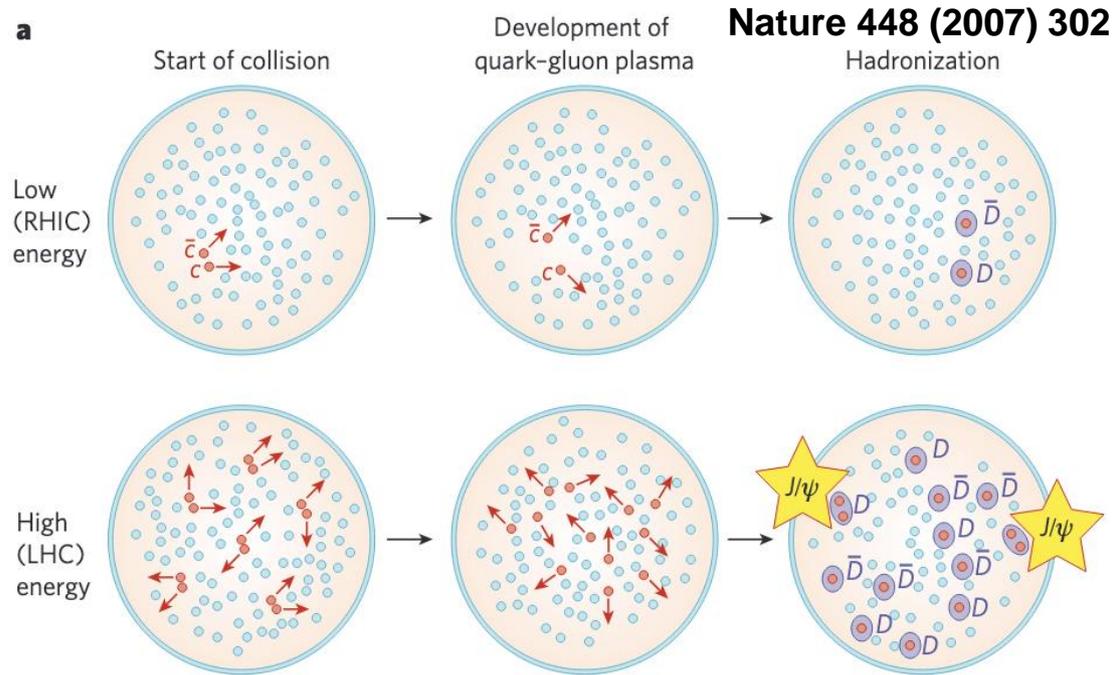
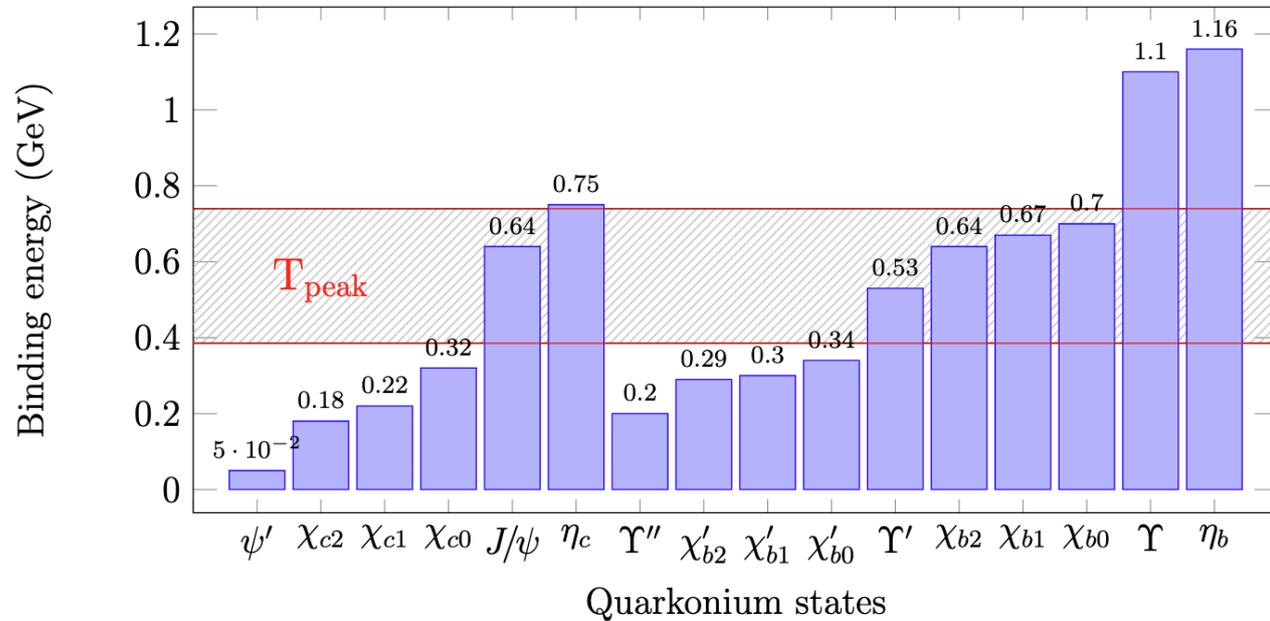
Charmonium suppression in large systems is influenced by several mechanisms

Colour screening effects:

$c\bar{c}$ pairs become unbound

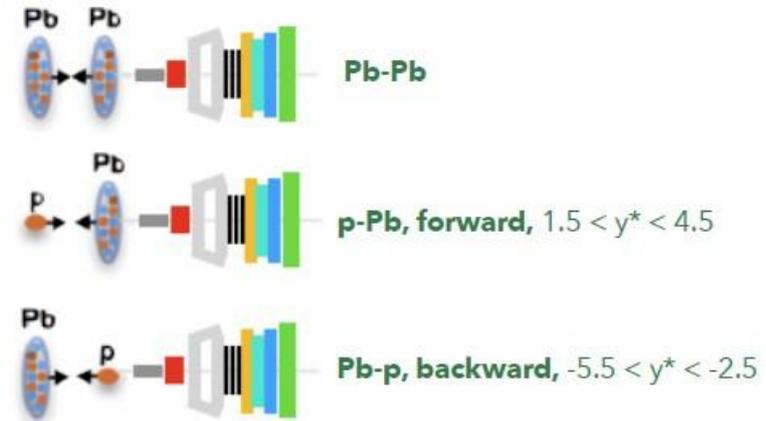
→ different states yields depending on their binding energy

Recombination processes lead to an enhancement at higher energies

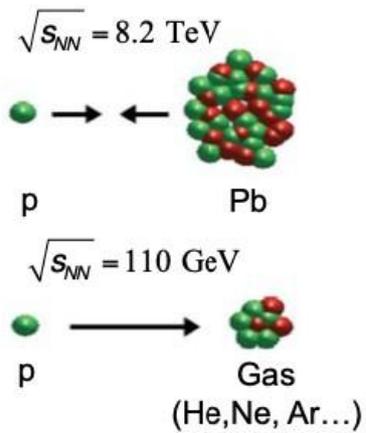


Charmonium suppression in large systems

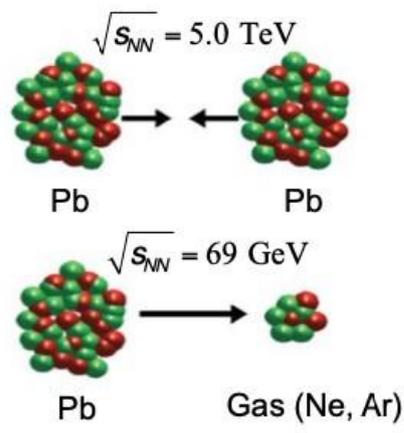
☐ Very relevant to study **heavy collision systems**



Cold Nuclear Matter



Quark Gluon Plasma



- ▶ pPb/Pbp
- ▶ $PbPb$
- ▶ pA
- ▶ PbA

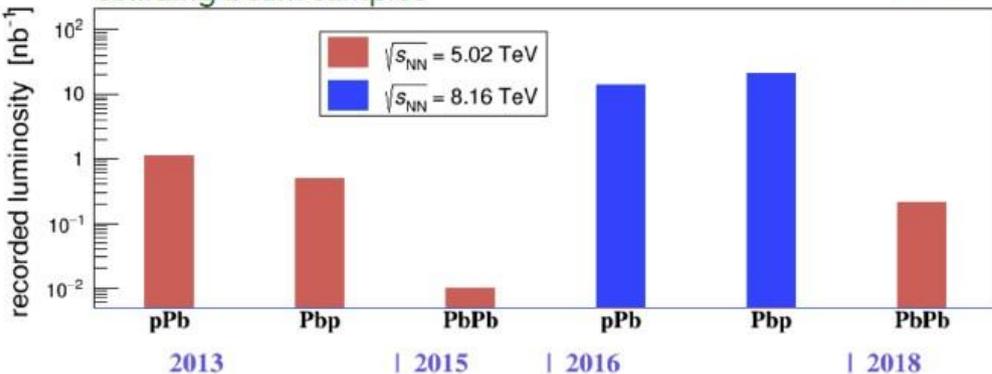
} colliding beam mode

} fixed-target mode (SMOG)

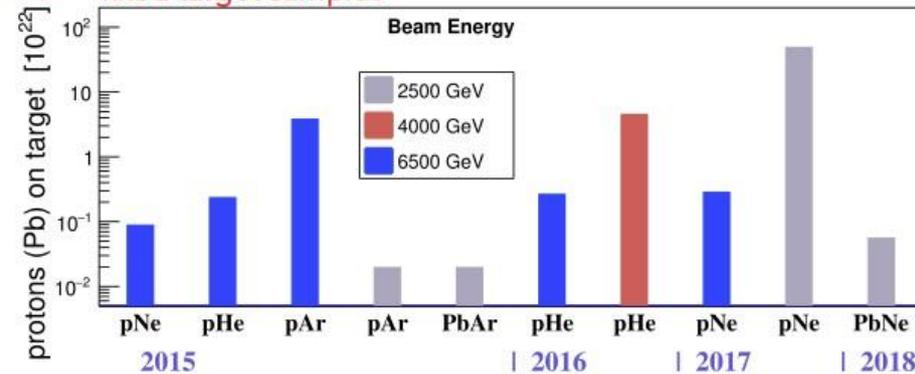
Injection of noble gases (He, Ne, Ar) into the interaction region → **unique kinematical region accessible!**

RUN2 SAMPLES

colliding beam samples



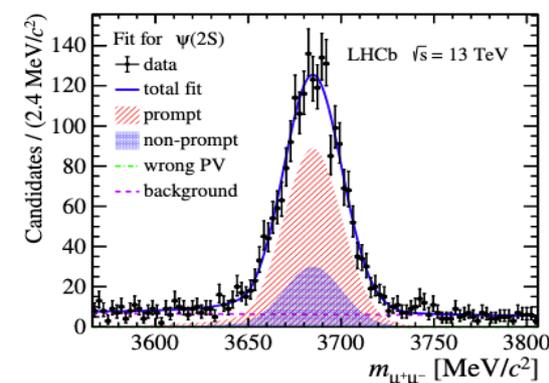
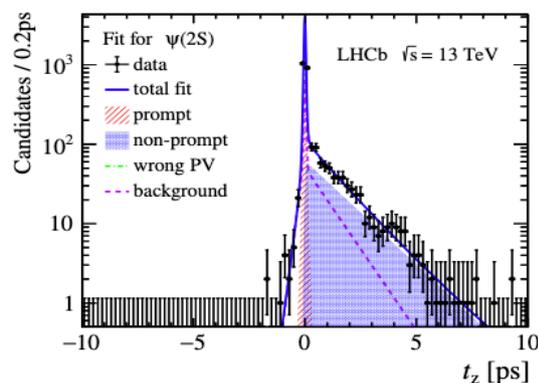
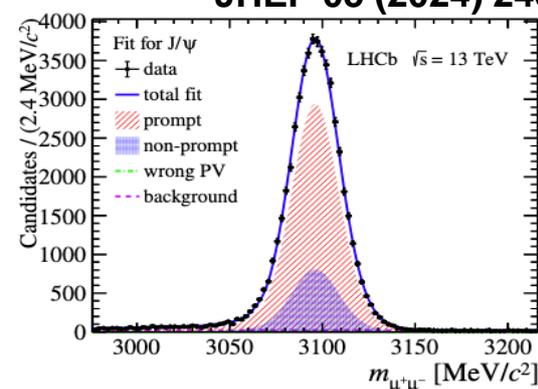
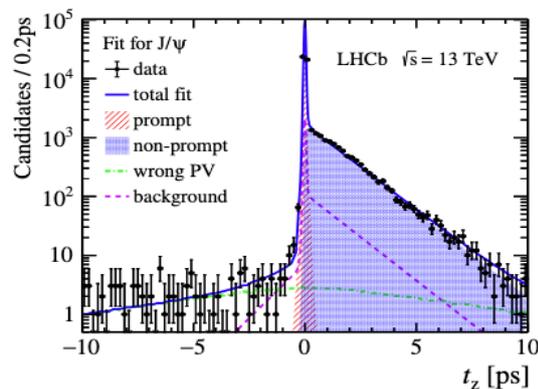
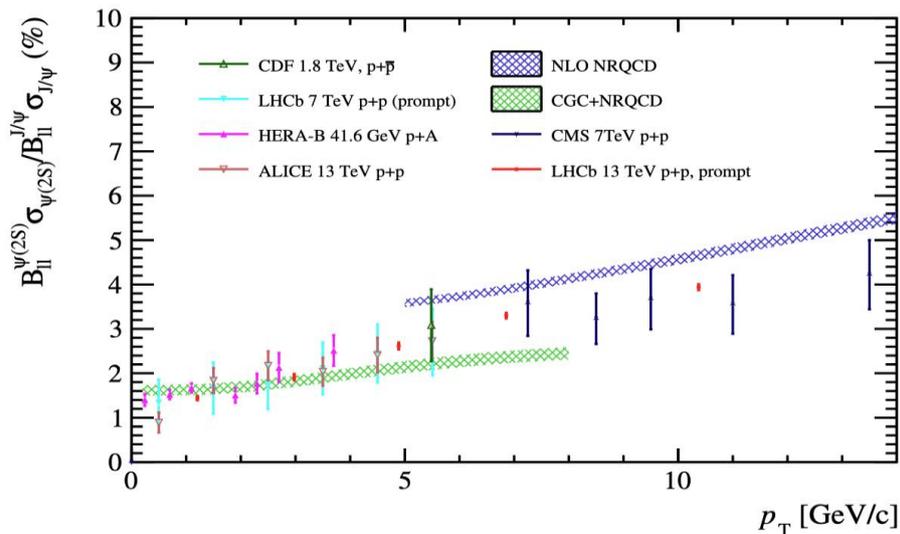
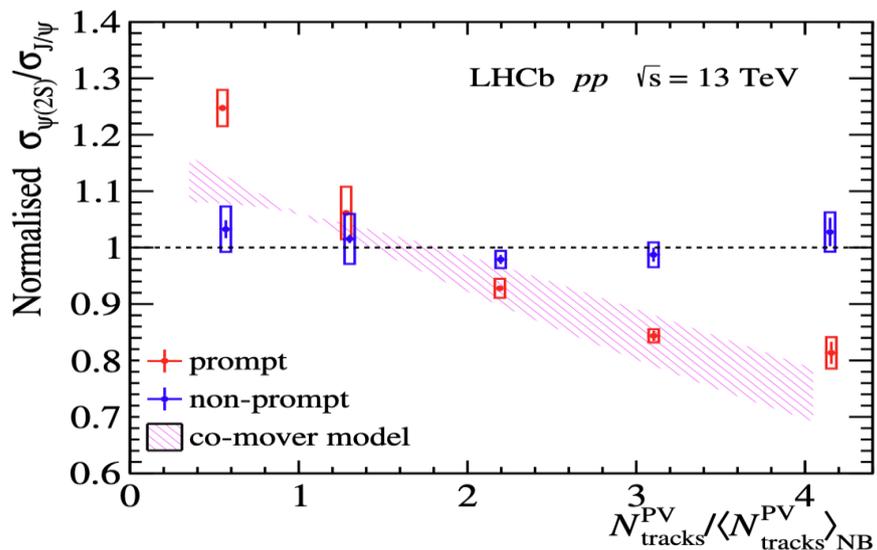
fixed target samples



$\sigma(\psi(2S))/\sigma(J/\psi)$ depending on multiplicity in pp collisions at $\sqrt{s} = 13$ TeV

JHEP 05 (2024) 243

- Relative production ratio measurement
- Distinguish prompt and b-decay production
- Multiplicity variable: number of VELO tracks for a PV



- b-hadron decays:** little dependence on multiplicity
- Prompt production:** evident **decrease of ratio with multiplicity**
- Agreement with the comovers model predictions and previous measurements
- Improved precision

Probing charmonium-like states



M. Prymachenko

Multiplicity dependent production of $\chi_{c1}(3872)$ and $\psi(2S)$

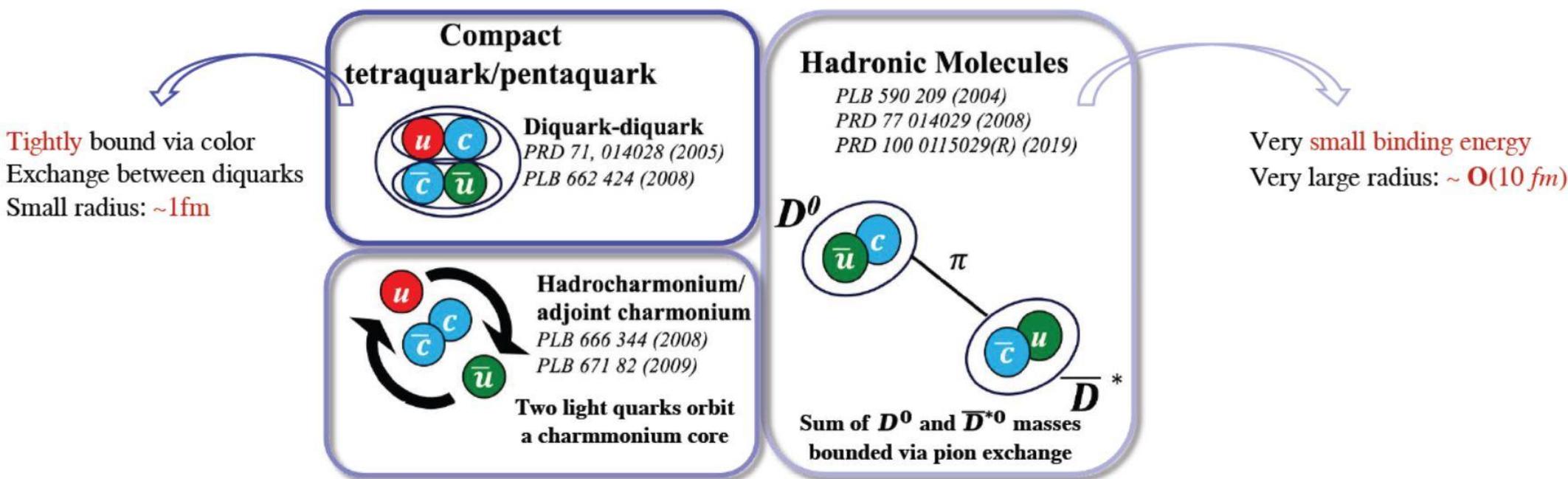
□ $\chi_{c1}(3872)$ is first discovered in 2003 by Belle in decay $J/\psi \pi^+\pi^-$ PRL 91 (2003) 262001

□ The LHCb has since measured the quantum numbers to be $J^{PC} = 1^{++}$ PRL 110 (2013) 222001

□ Mass difference is consistent with zero:

$$(M_{D^0} + M_{D^{*0}}) - M_{\chi_{c1}(3872)} = 0.07 \pm 0.12 \text{ MeV}/c^2$$

□ Multiple explanations of $\chi_{c1}(3872)$ explored in literature:



Matt Durham, Quark Matter 2019

Prompt production

- $\chi_{c1}(3872)$ produced at collision vertex can **be subject to** further interactions with co-moving particles produced in the event
- Interact with other produced particles with **break-up cross section**
- Assume no interaction at low multiplicity region

Production in b-decays

- Hadrons from b-decays originate away from the primary vertex, decays in vacuum
- $\chi_{c1}(3872)$ from b-decays **not subject** to further interactions
→ Control sample

High-multiplicity pp collisions plausibly **emulate a hadronic environment that approaches heavy ion collisions** in many respects

High-multiplicity pp collisions

- Provide a testing ground for **final state effects** observed on quarkonium in pA and AA
- Provide **new constraints on the structure of $\chi_{c1}(3872)$**

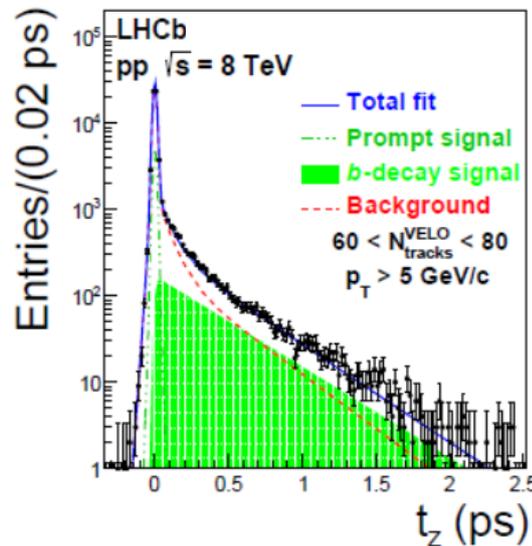
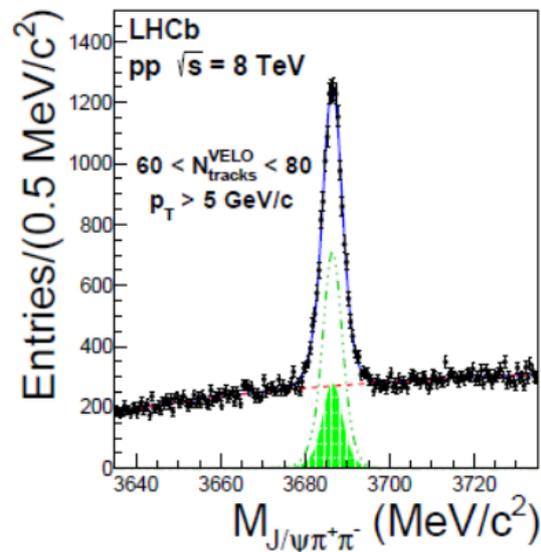
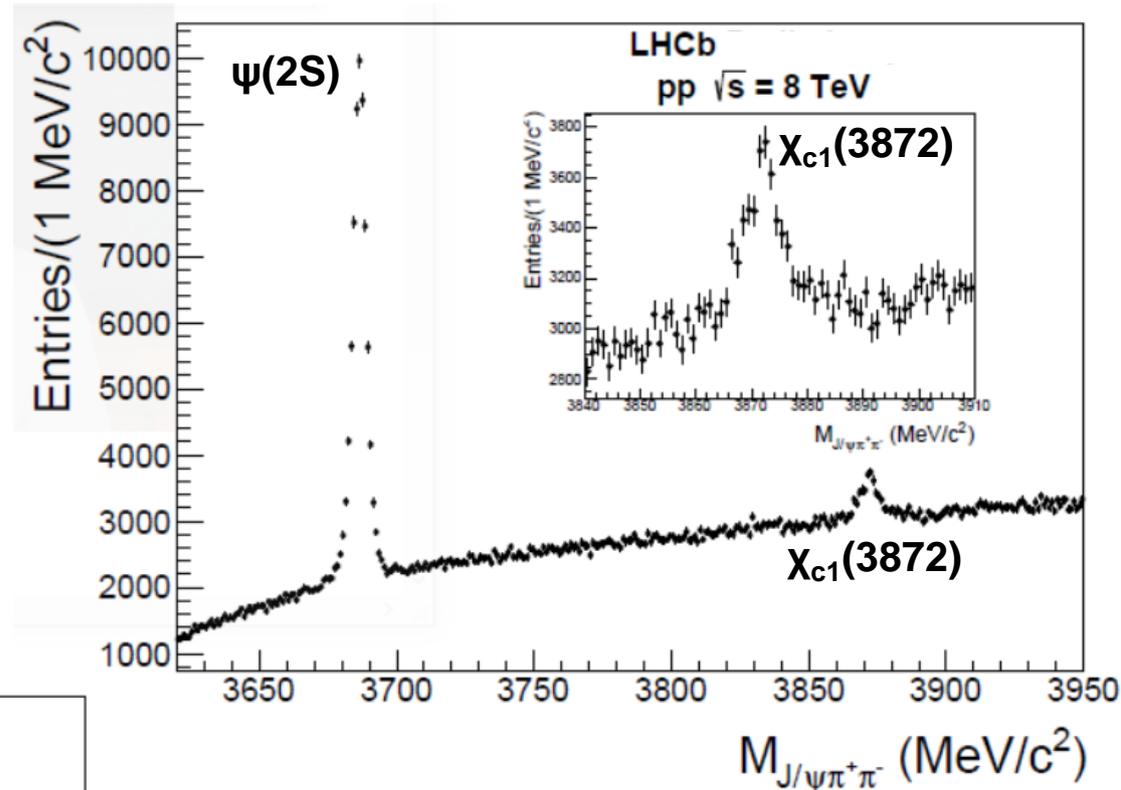
Multiplicity dependent production of $\chi_{c1}(3872)$ and $\psi(2S)$

PRL 126 (2021) 092001

$\sqrt{s} = 8 \text{ TeV}$, $\int L dt \sim 2 \text{ fb}^{-1}$

- If $\chi_{c1}(3872)$ is a hadronic molecule, then expect small binding energy, $0.01 \pm 0.27 \text{ MeV}$, and large radius $\sim 7 \text{ fm}$

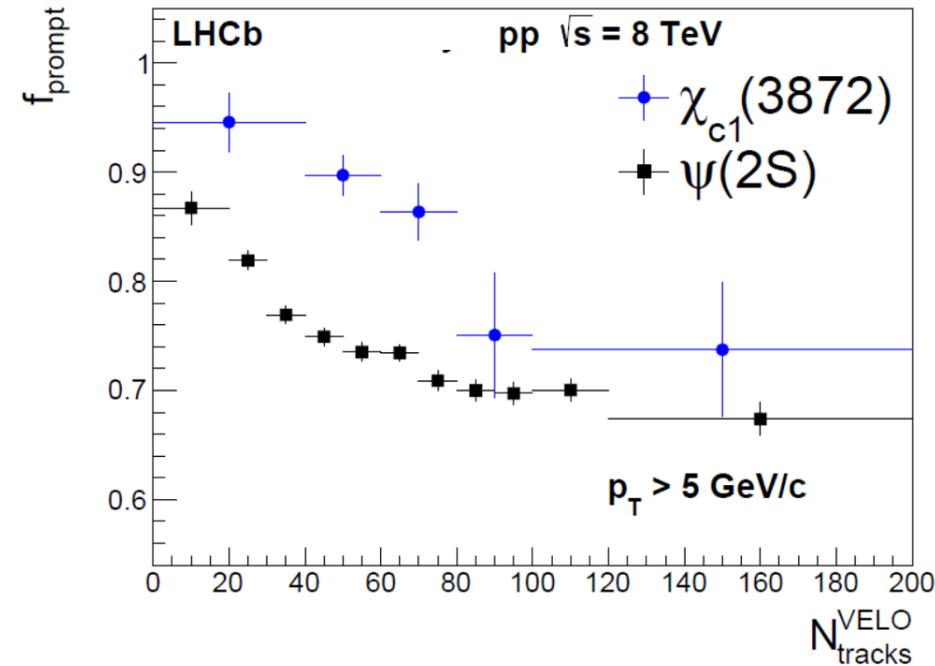
S.Coito, G.Rupp, E.van Beveren, EPJC 73 (2013) 2351
 N.A.Tornqvist, PLB 590 (2004) 209
 E.Braaten, M.Kusunoki, PRD 71 (2005) 074005
 M.Cardoso, G.Rupp, E.van Beveren, EPJC 75 (2015) 26



- Pseudo proper-time to distinguish **prompt** and **b-decay** components
- Measure ratios, $\chi_{c1}(3872)$ and $\psi(2S)$, for prompt and b-decay components

Multiplicity dependent production of $\chi_{c1}(3872)$ and $\psi(2S)$

- The **prompt fraction** decreases as the **event activity** increases, for both $\chi_{c1}(3872)$ and $\psi(2S)$

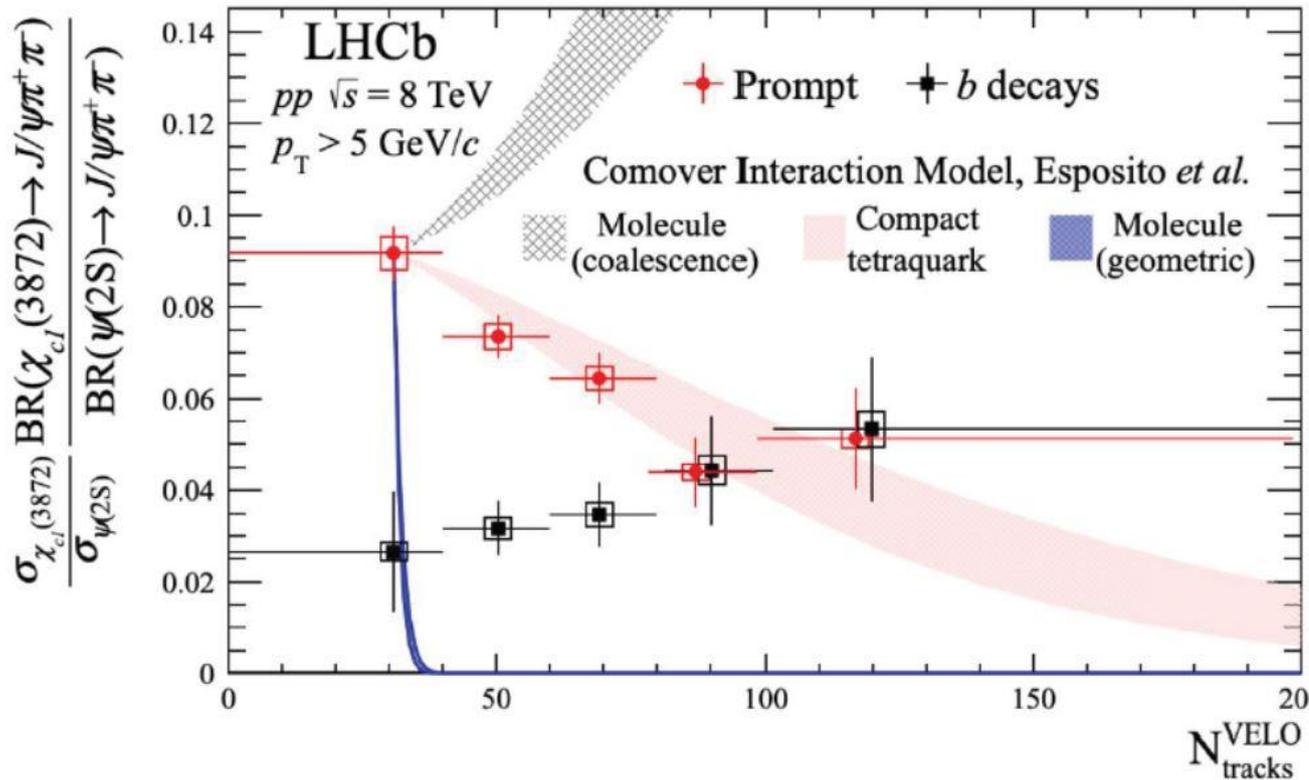


- Possible reasons:

- Larger average multiplicity of events with $b\bar{b}$ due to their fragmentation into hadrons and subsequent decays → **larger b-decay component in events with high multiplicity**
- Suppression of prompt $\chi_{c1}(3872)$ and $\psi(2S)$ production via interactions with other particles produced at the vertex → **reduced prompt production in high multiplicity events, production in b decays not affected**

Multiplicity dependent production of $\chi_{c1}(3872)$ and $\psi(2S)$

- Ratio of cross-sections, $\chi_{c1}(3872)$ and $\psi(2S)$, for prompt and b-decay production



- Comover interaction model by Esposito *et al.*, arXiv: 2006.15044, favours the **compact tetraquark scenario**

- A tweaked model by Braaten *et al.*, arXiv: 2012.13499, suggests the $\chi_{c1}(3872)$ is a **charm-meson molecule**

- Evidence for **relative $\chi_{c1}(3872)$ suppression for high-multiplicity events**
- Expected in a **scenario of interactions with co-moving hadrons** dissociating large weakly bound $\chi_{c1}(3872)$ against compact $\psi(2S)$
- Cross-check: production in b-decays

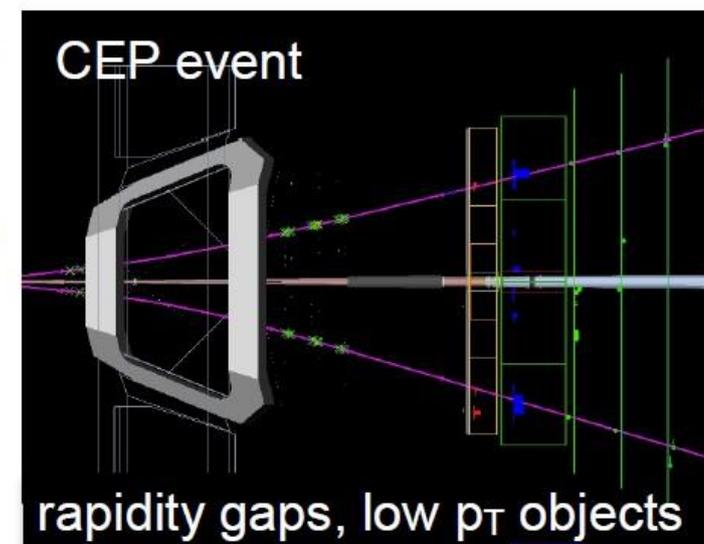
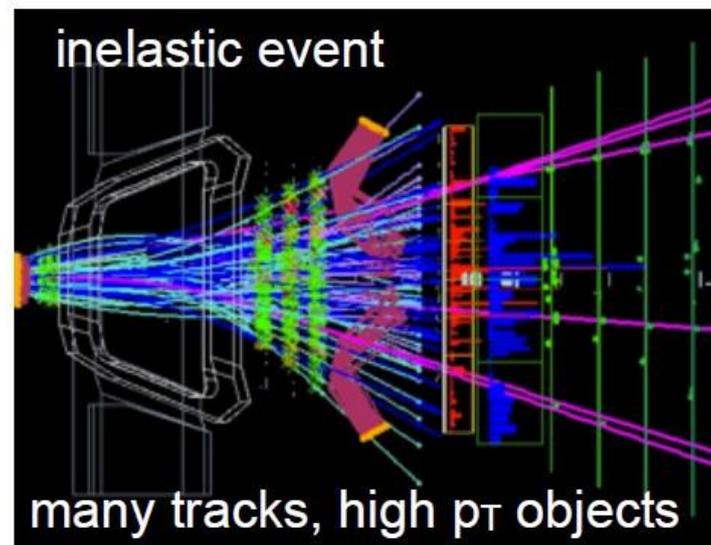
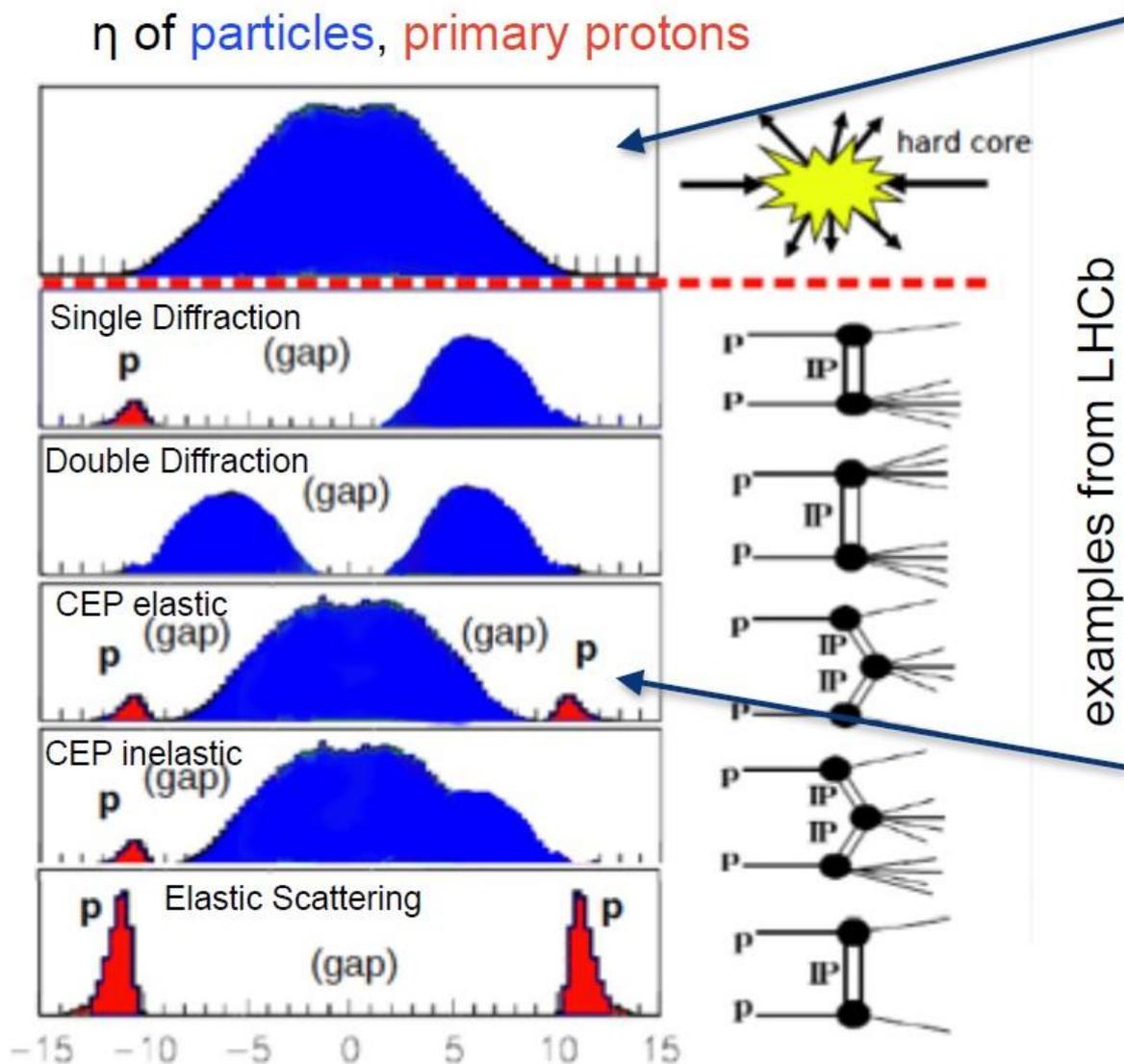
Central Exclusive Production of charmonium



M. Prymachenko

Central Exclusive Production

□ CEP event: diffractive process of the form $pp \rightarrow pXp$, large rapidity gap



After D. d'Enterria arxiv 0806.0883

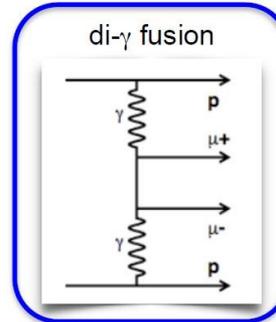
Central Exclusive Production of J/ψ and $\psi(2S)$ at 13 TeV

SciPost Phys. 18, 071 (2025)

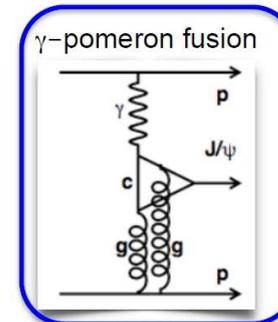
□ CEP: colourless object exchange, clean QCD tests

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

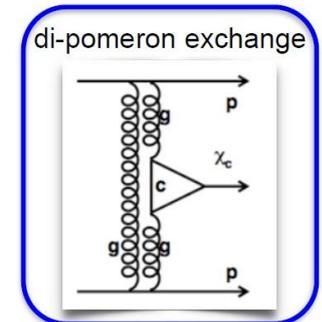
□ Large rapidity gap



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



$\rho, J/\psi, Y, Z, \dots$

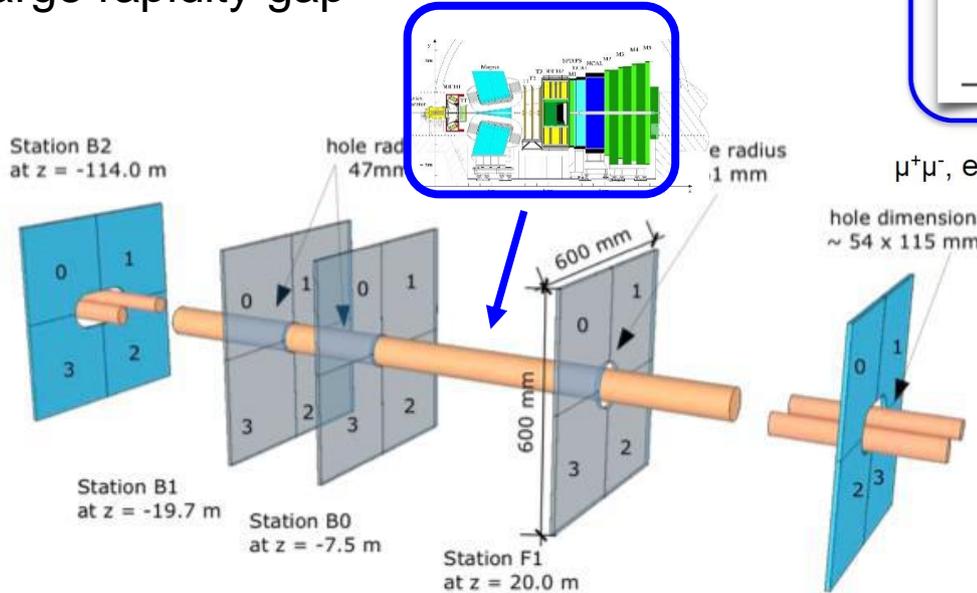


$\chi_c, \chi_b, \pi^+\pi^-, \text{Dijet}, gg, \dots$

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

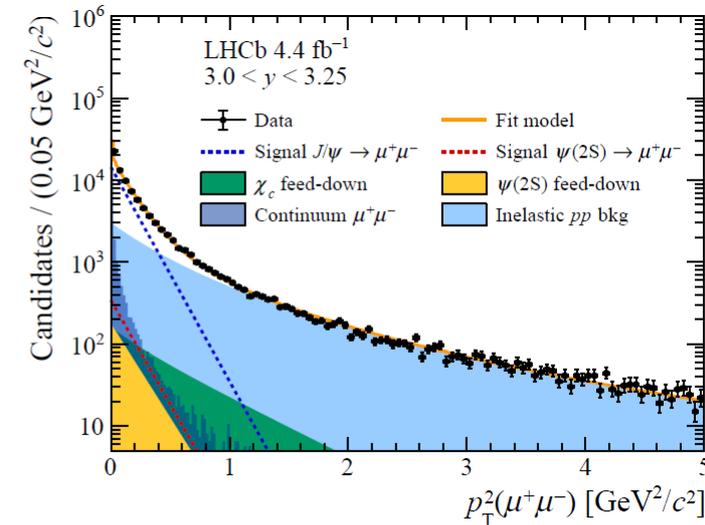
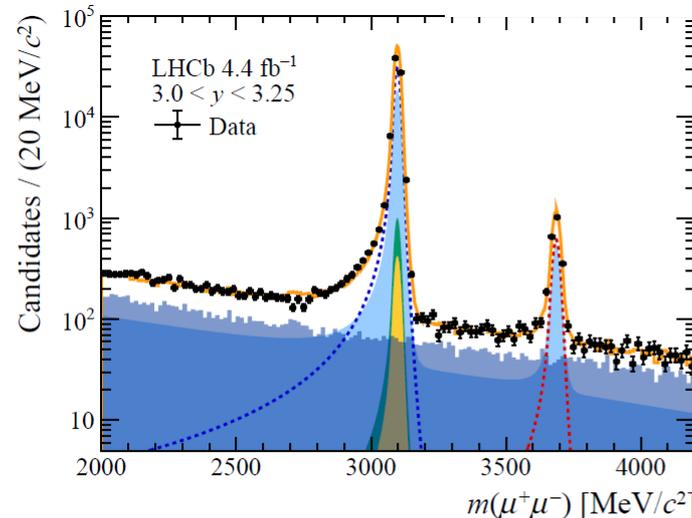
□ Dedicated CEP trigger

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

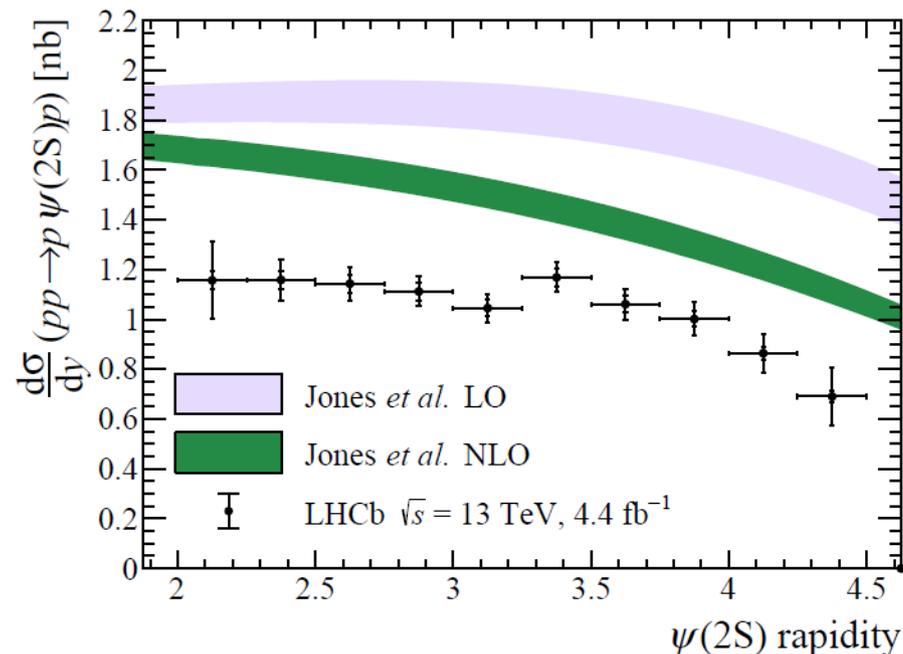
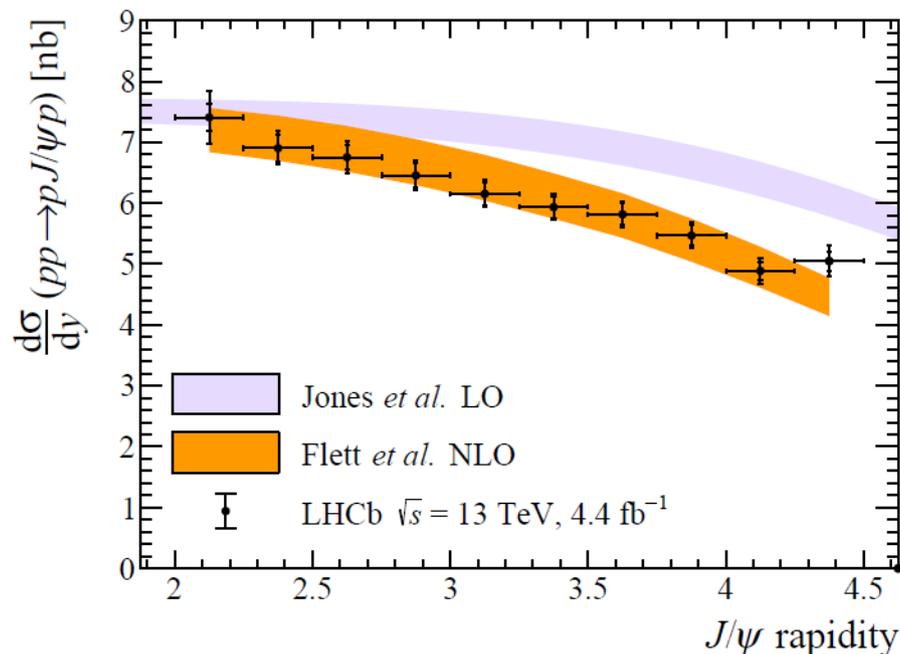


□ Differential cross sections in rapidity bins

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



□ Differential cross-sections compared to theory predictions



□ Integrated cross-sections times branching fractions

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

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

□ Good agreement with J/ψ NLO pre-(post-)diction

□ $\psi(2S)$ calculations to be revisited

□ Confirms a hint of NLO importance from the analysis at 7 TeV

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

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

CEP
LHCb

Gap survival

Photon flux

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

Photoproduction
HERA, fixed target

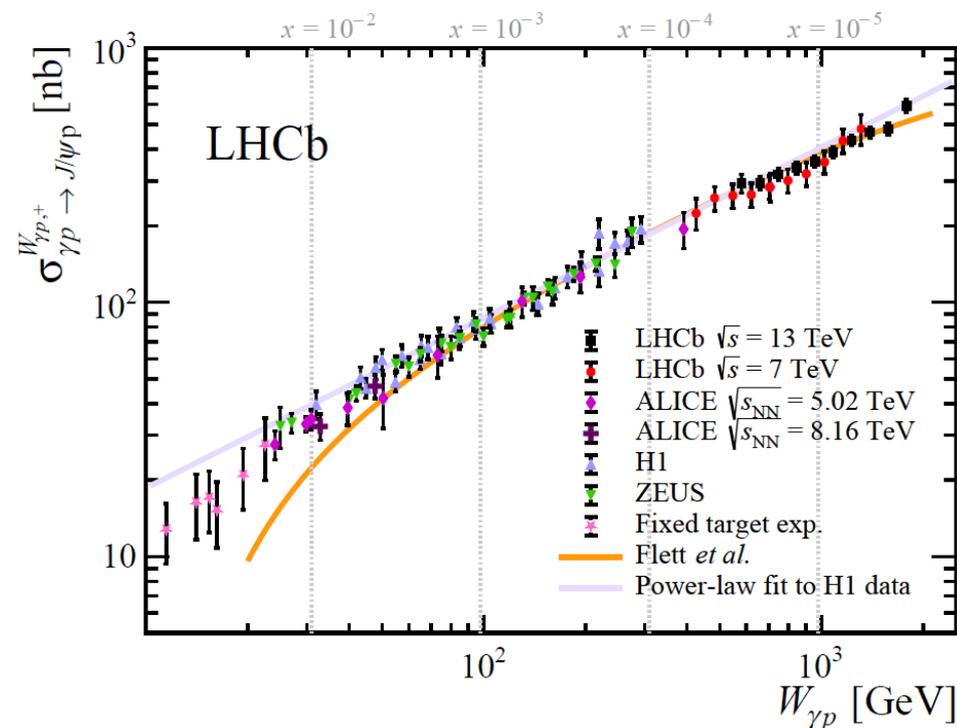
- Compilation of photo-production cross-section measurements

- H1 measured power-law:

$$\sigma_{\gamma p \rightarrow J/\psi p}(W) = 81(W/90 \text{ GeV})^{0.67} \text{ nb}$$

- 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**



Future program

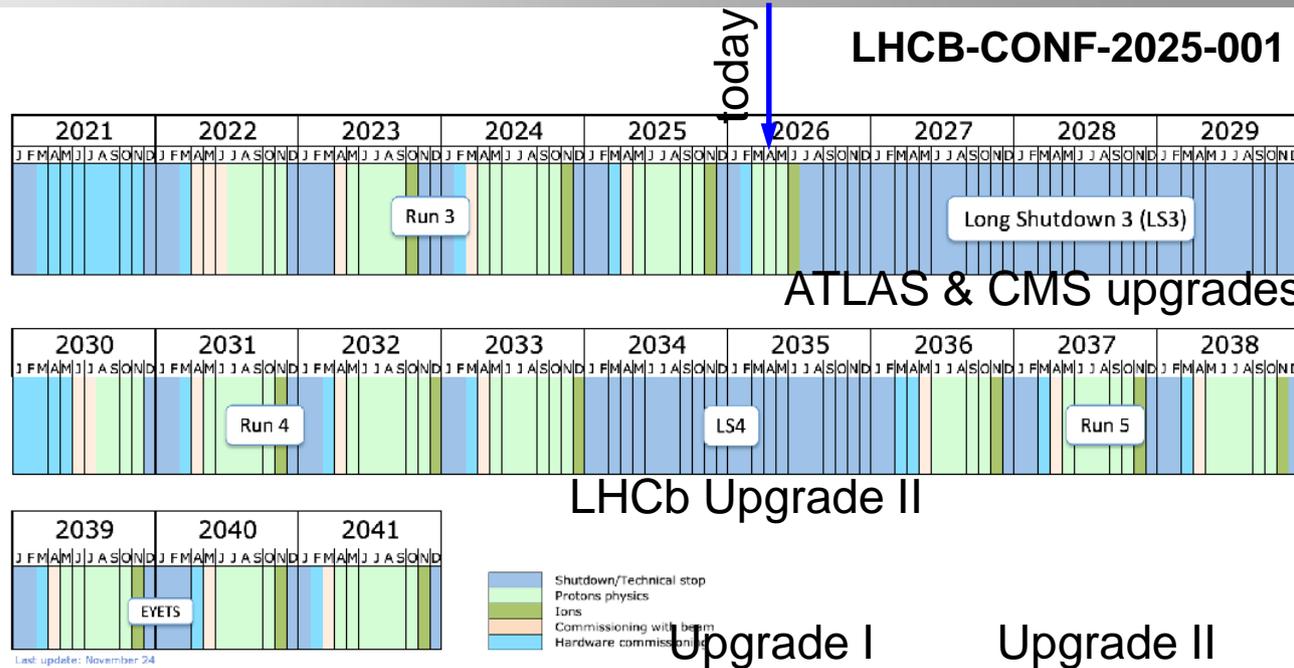
LHCB-CONF-2025-001

LHCb and LHC timeline

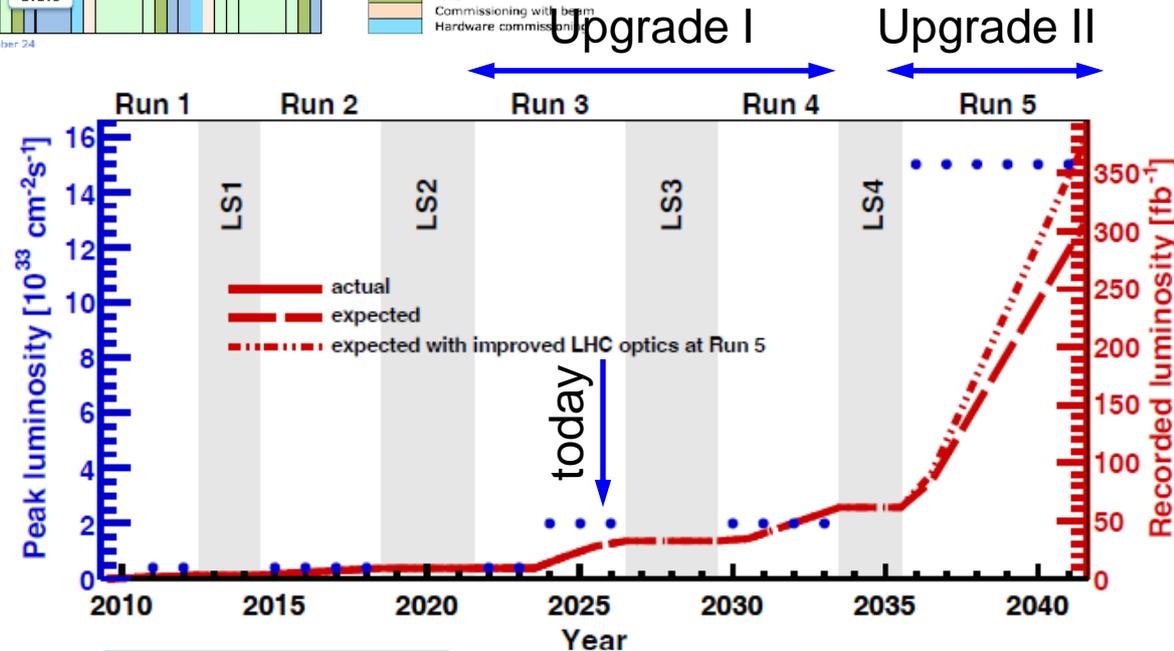
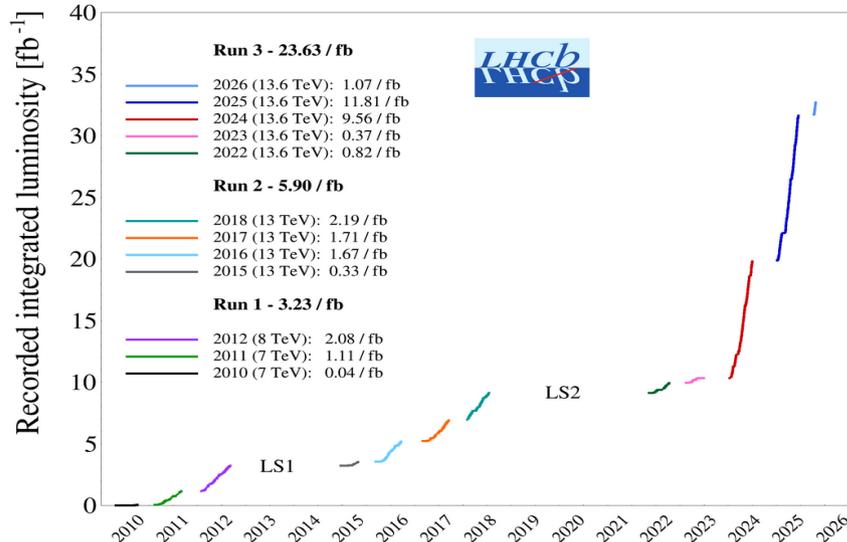
LHCb Runs 3+4

Higher pile-up + software trigger

Collect 50 fb⁻¹ by 2033



Total recorded luminosity – pp – 32.8 fb⁻¹



LHCb Upgrade II in LS4

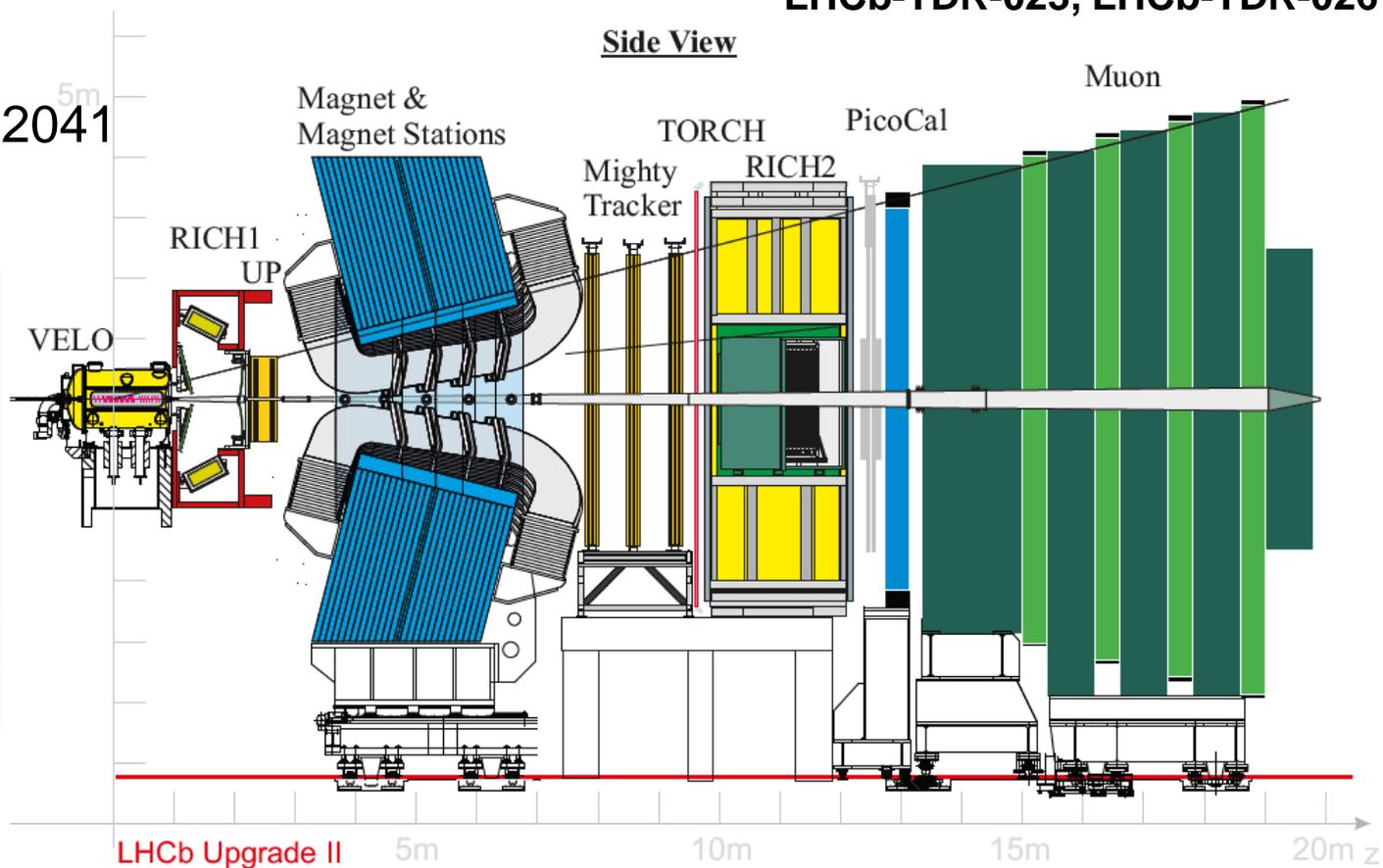
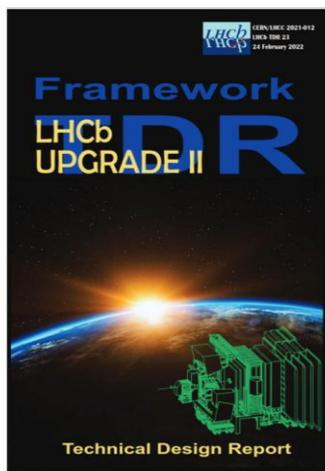
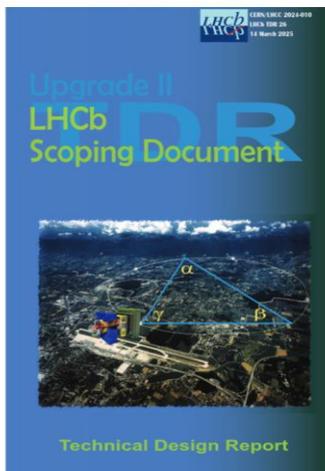
Collect > 300 fb⁻¹ by 2041

| | | |
|---|---|---|
| $\mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ | $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ | $\mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ |
| 1.1 visible interactions / crossing | 5.5 visible interactions / crossing | 55 visible interactions / crossing |
| 8 fb ⁻¹ collected | 50 fb ⁻¹ collected | 300 fb ⁻¹ collected |

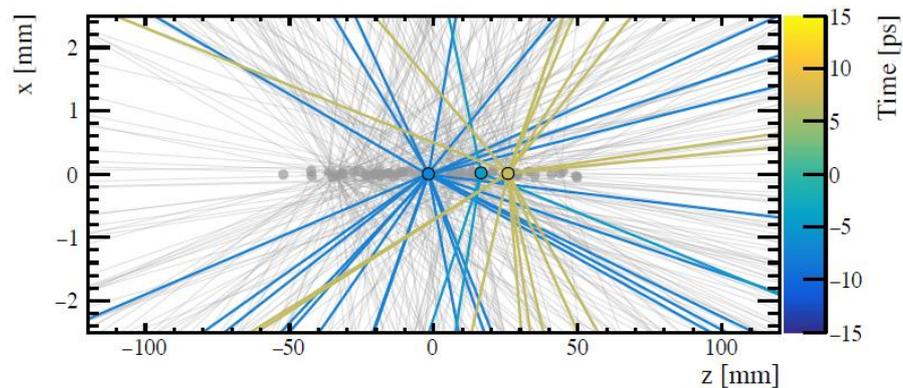
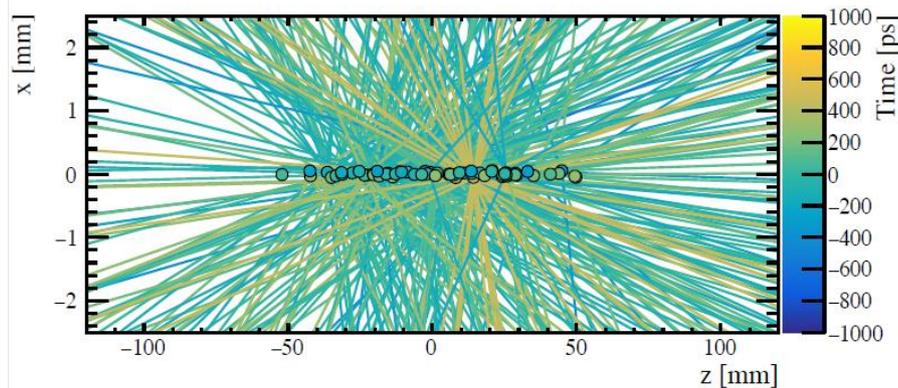
LHCb Upgrade II (LHC Run5)

LHCb-TDR-023, LHCb-TDR-026

- ❑ LHCb Upgrade II in LS4
 - ❑ Collect > 300 fb⁻¹ by 2041
 - ❑ Pile-up of 28 – 42



- ❑ Timing capabilities for 4D tracking



- ❑ New vertex, tracking, PID, and CALO detector, and upgraded MUON detector

Outlook

- ❑ Quarkonium serves a powerful probe for **QCD-driven production mechanisms** ... consistency with minimum number of free parameters wanted
- ❑ Many more practical user cases, e.g. a tool for an insight on nature of charmonium-like states

- ❑ 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 mechanism

☐ Illustrations from Maria Prymachenko (1909-1997)

Maria Prymachenko

