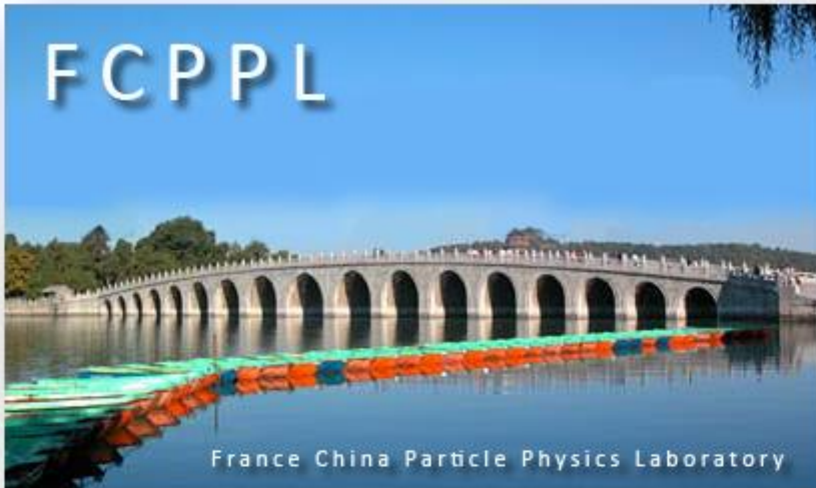
Charmonium production in LHCb



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FCPPL 2023, Zhuhai, 6-10/11/2023

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

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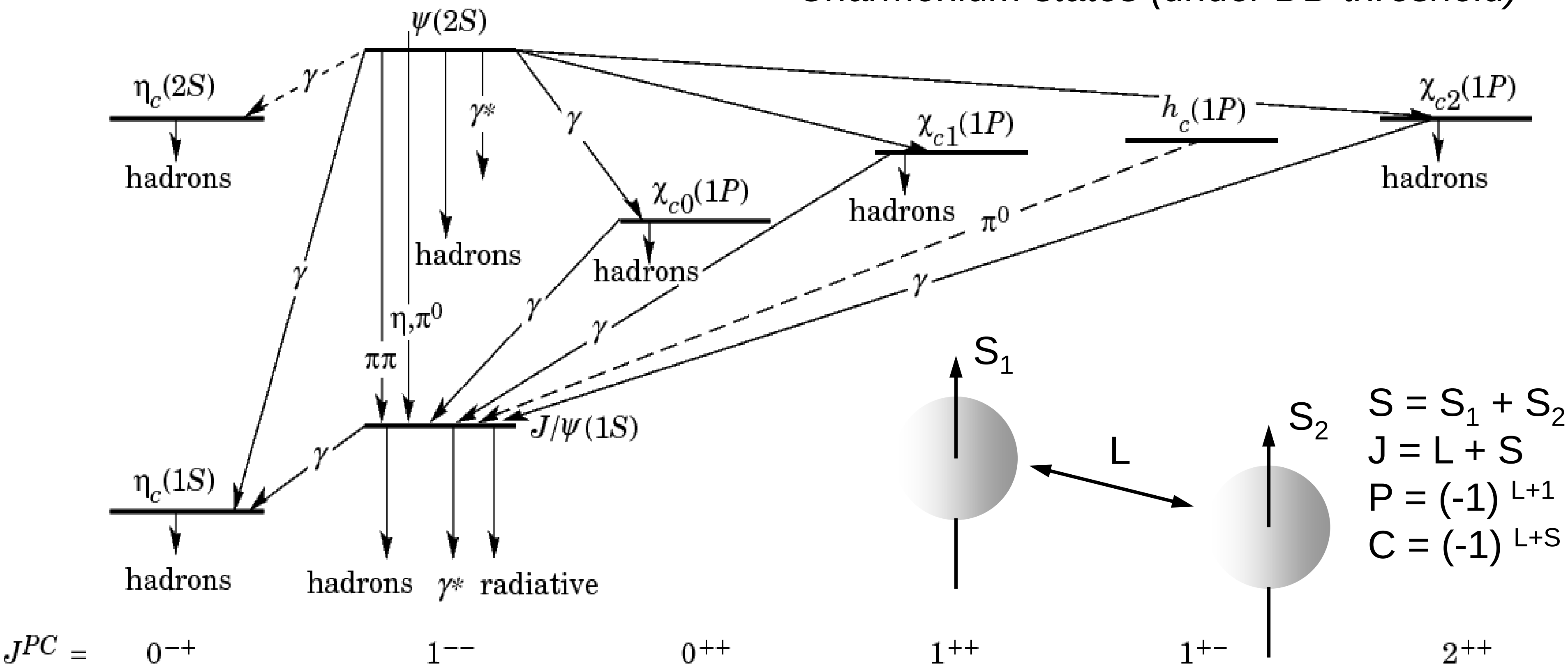
Charmonium production in LHCb

- Introduction to LHCb
- Charmonium production in LHCb
- Charmonia via decays to hadrons
- A phenomenology touch
- Outlook

Disclaimer: very biased selection of the results, no production in heavy-ion collisions, no diffractive processes, (almost) no charmonium-like states

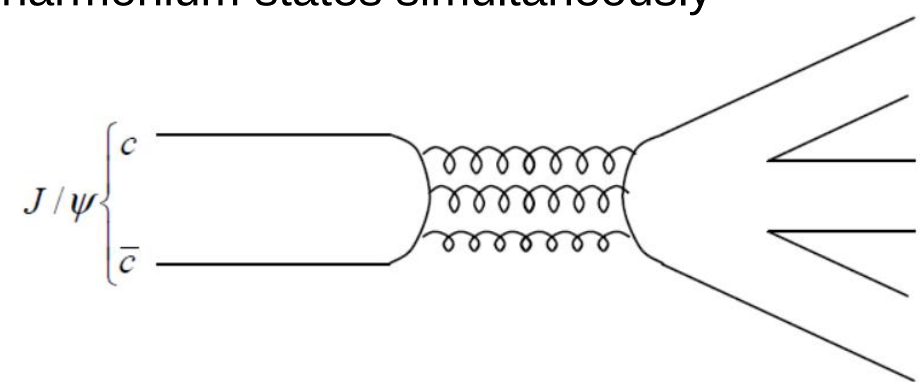
photo credit: www.sysu.edu.cn

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



- Two scales of production:

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

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

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 $Q\bar{Q}$ 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

Quarkonium production

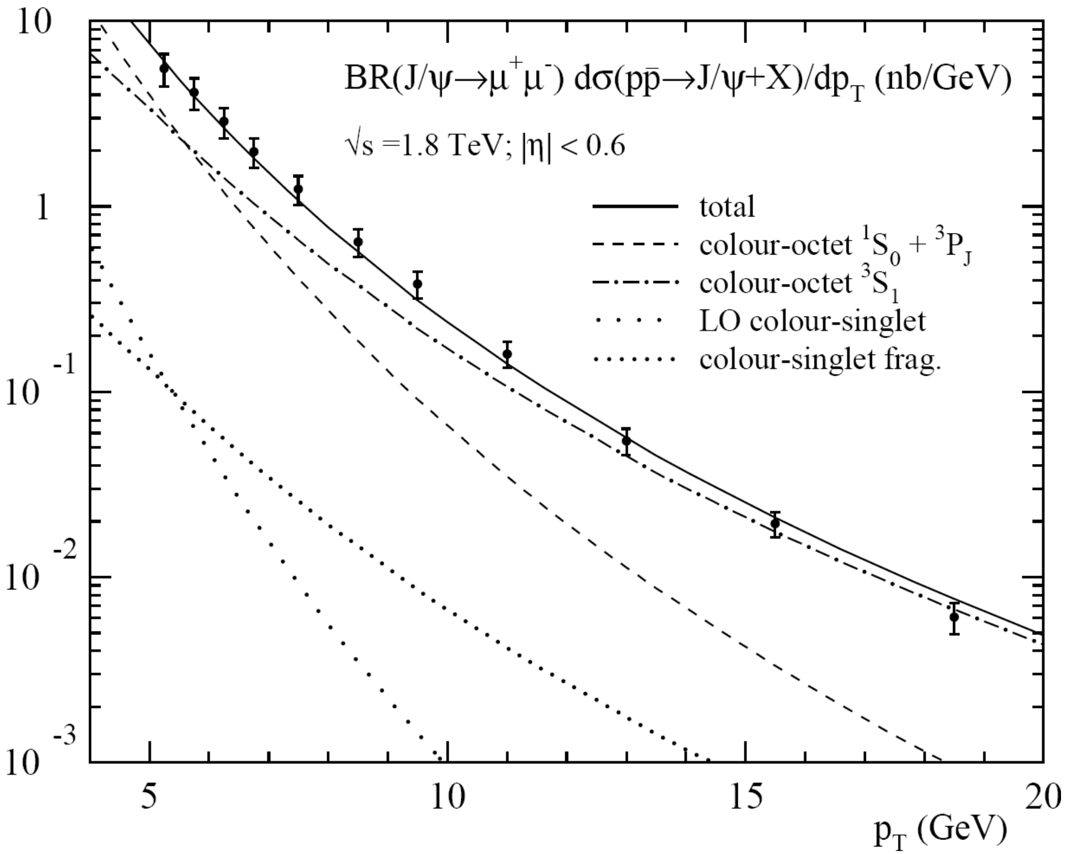
- **Powerful QCD tests**, instead of using QCD to estimate observables, use production measurements to qualify QCD
- New theory developments confronted to new experimental results. Impressive progress in both domains, **evolution by puzzles**
- First clash to describe **« J/ψ production puzzle »**
- **« J/ψ production AND polarization puzzle »** boosted the progress
- Recently with the η_c(1S) production measurement by LHCb more challenging **« J/ψ production AND polarization AND η_c(1S) production puzzle »**
- **More precision** in conventional studies and **new sources of input**: associated production, isolation, production in pPb and PbPb collisions, non-conventional states, …
- Comprehensive model of **quarkonium production** still missing

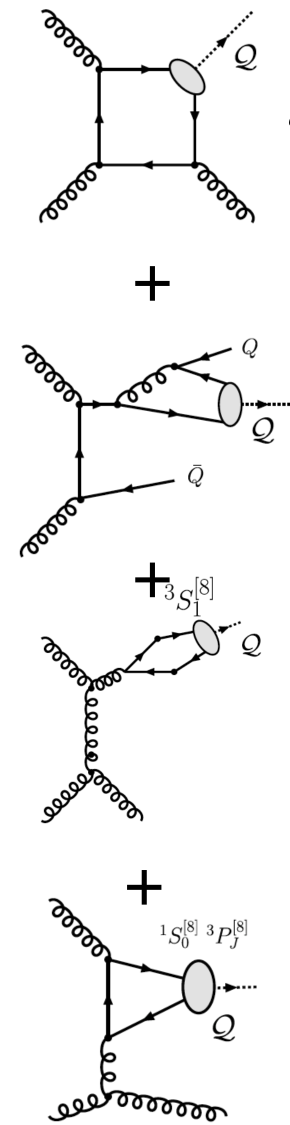
- Comparison of direct p_T differential **J/ψ production** cross-section measured by CDF
- Color-singlet and color-octet, LO and NLO contributions
- LDME fitted on the same data

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

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

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





$$a_S^3 \frac{(2m_Q)^4}{p_T^8}$$

+

$$a_S^4 \frac{1}{p_T^4}$$

+

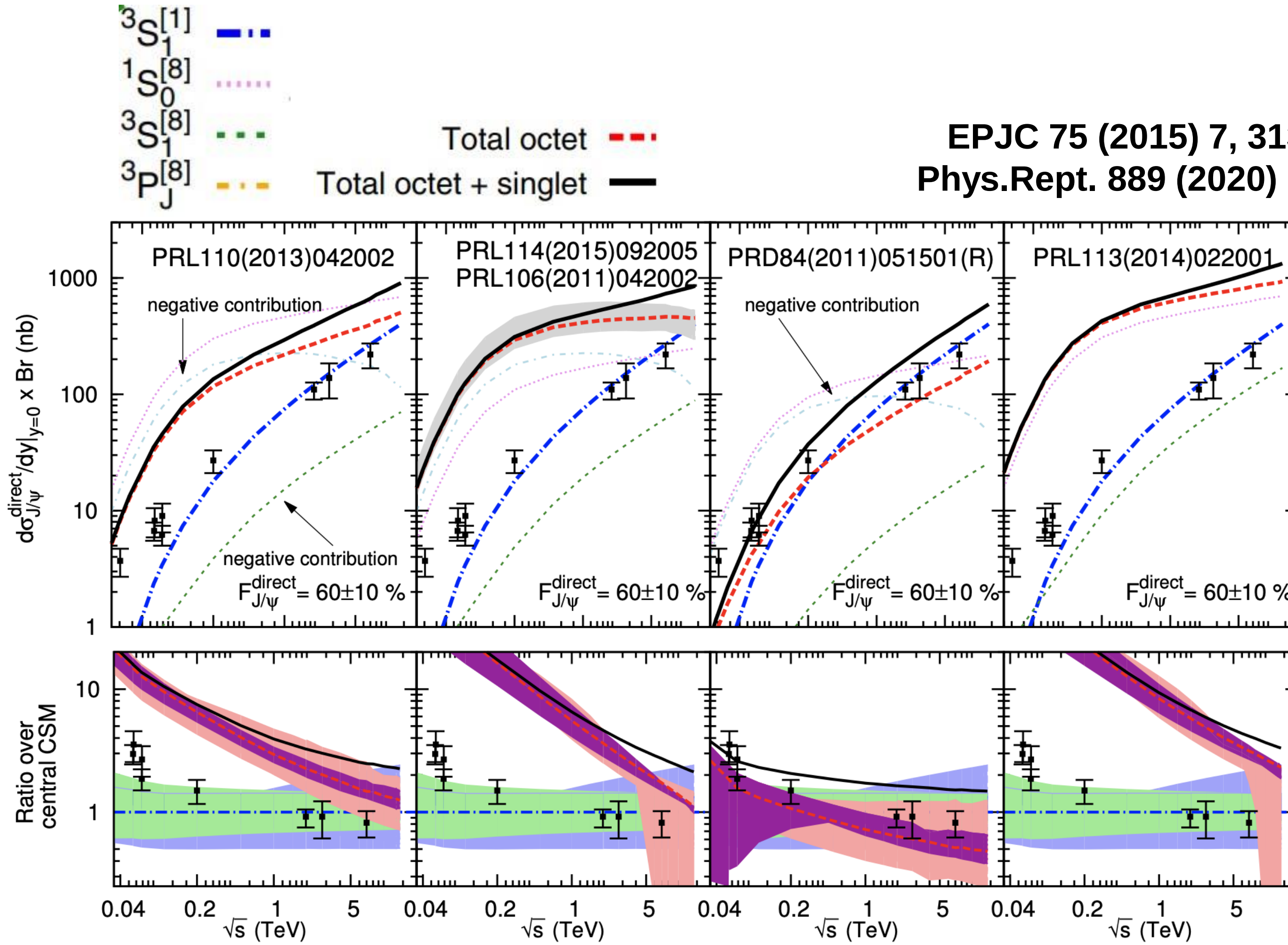
$$a_S^3 \frac{1}{p_T^4}$$

+

$$a_S^3 \frac{1}{p_T^6}$$

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

- Many puzzles are 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/ψ+Z production**
- CEM not describing P-waves production



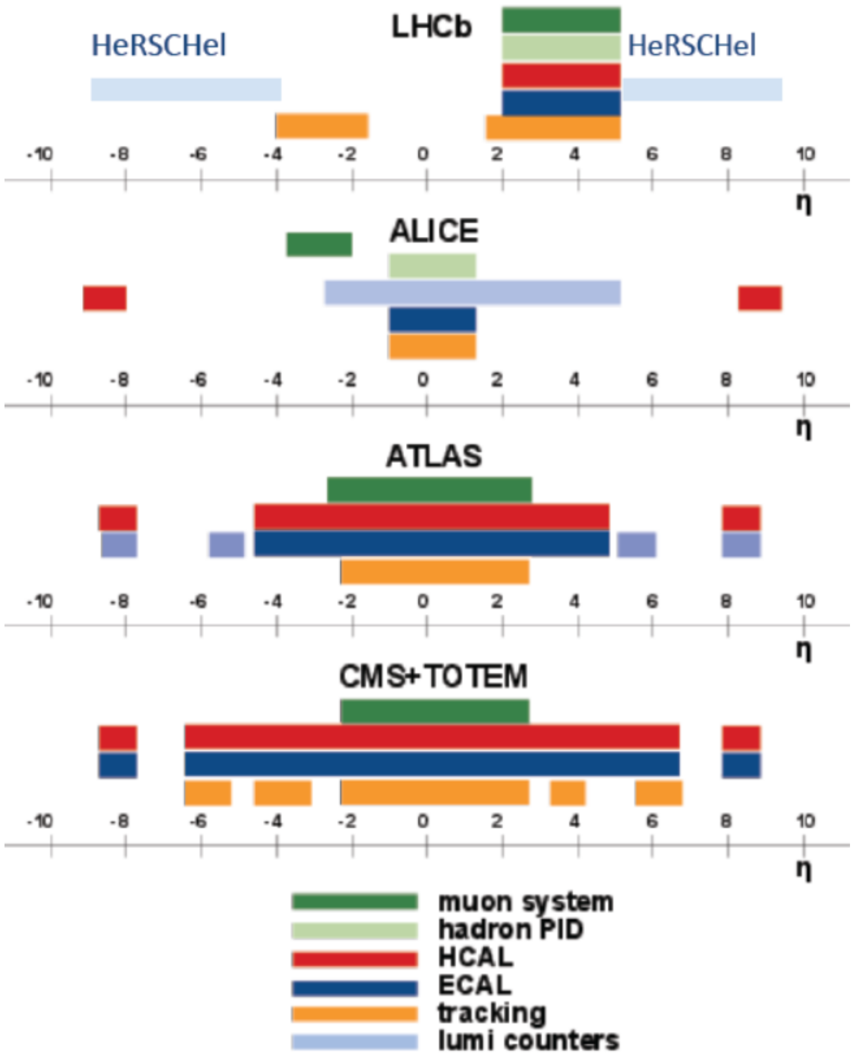
EPJC 75 (2015) 7, 313
Phys.Rept. 889 (2020) 1

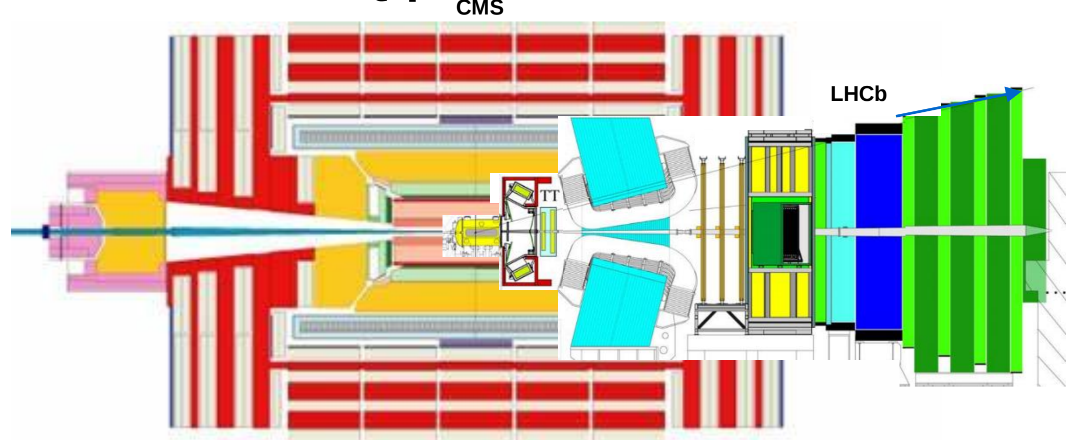
LDMEs	J/ψ hadropr.	J/ψ photopr.	J/ψ polar.	η_c hadropr.
Butenschön et al.	✓	✓	✗	✗
Chao et al. + η_c	✓	✗	✓	✓
Zhang et al.	✓	✗	✓	✓
Gong et al.	✓	✗	✓	✗
Chao et al.	✓	✗	✓	✗
Bodwin et al.	✓	✗	✓	✗

M. Nefedov

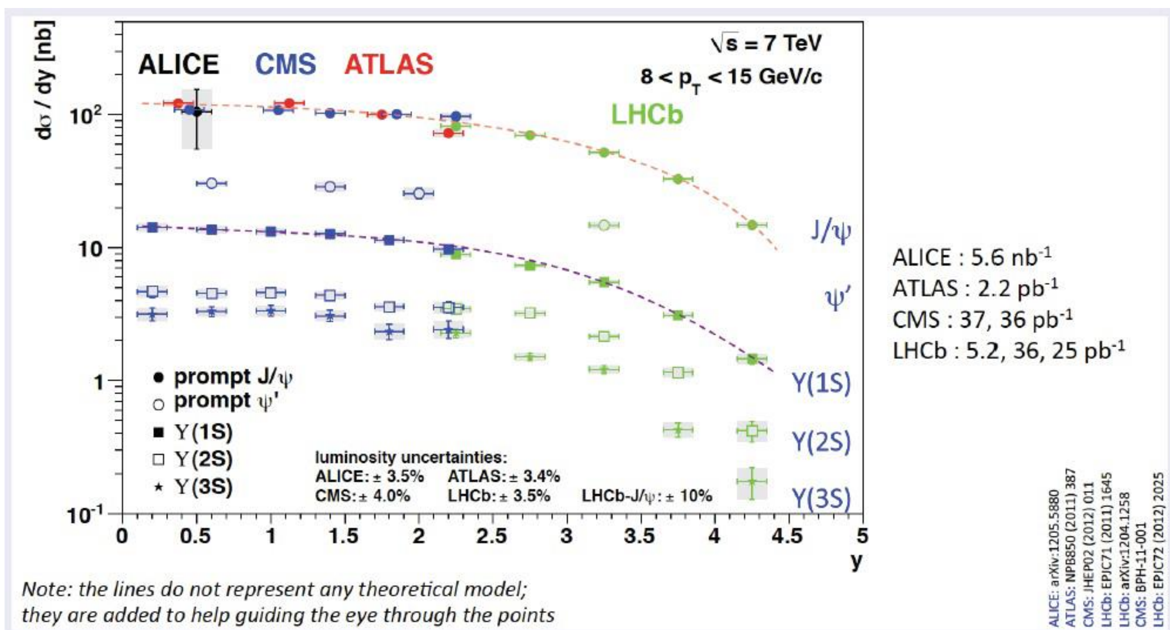
LHCb detector

- 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**



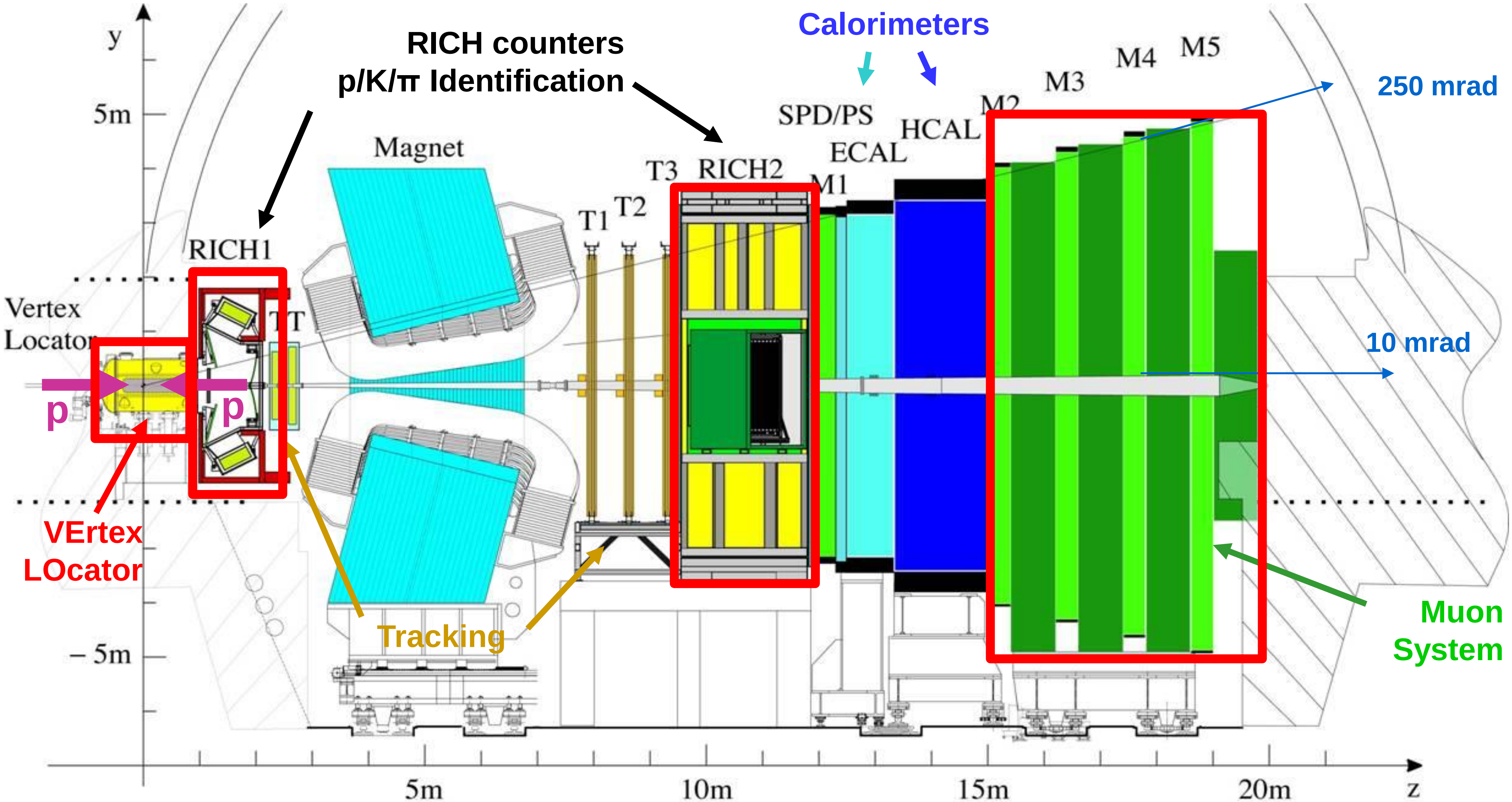


- **Complementary cross-section measurements**



- **Acceptance coverage, trigger threshold, hadron ID, luminosity**

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



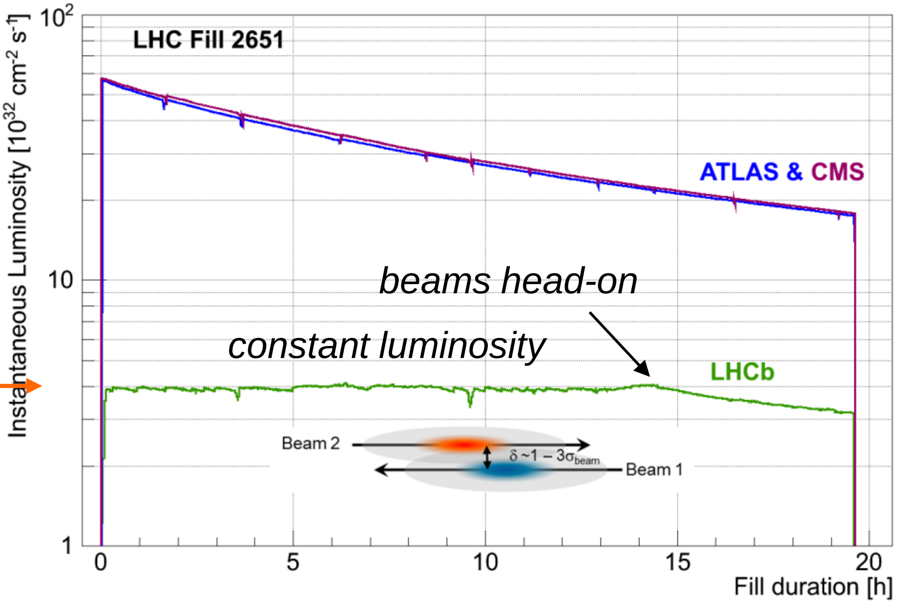
Vertex reconstruction:
VELO

Kinematics:
Magnet
Tracker
Calorimeters

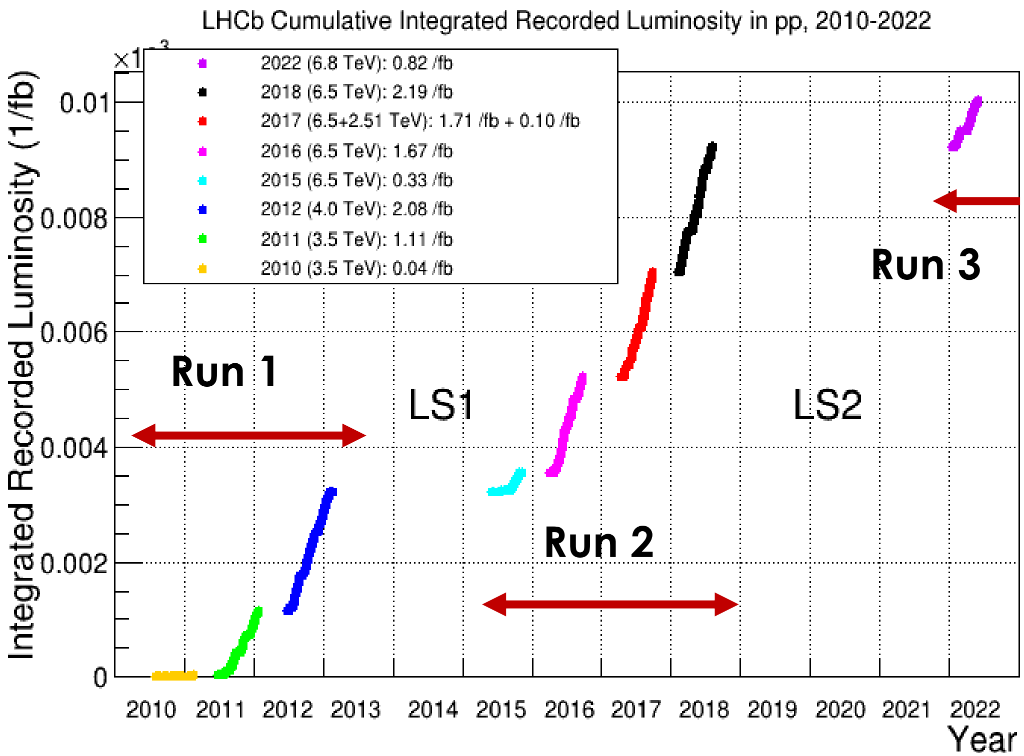
PID:
RICHs
Calorimeters
Muon Chambers

Trigger:
Muon Chambers
Calorimeters
Tracker

- **Excellent performance of the LHC and the experiments** during Runs I and II
- LHCb: ∫Ldt ~ 9 fb^{-1}
- Luminosity leveling for LHCb

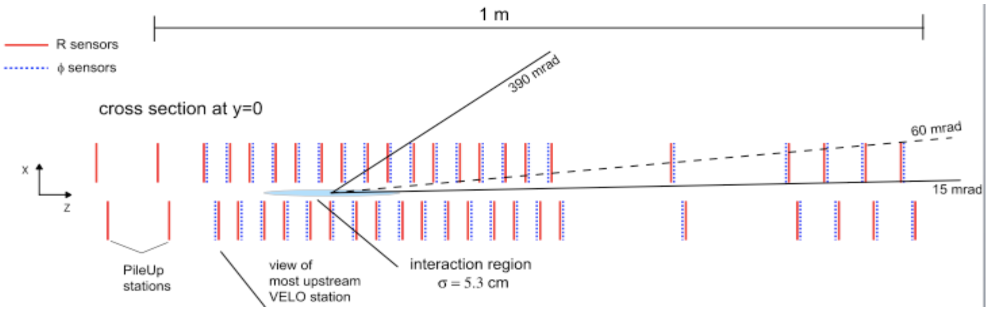


LHCb luminosity levelling

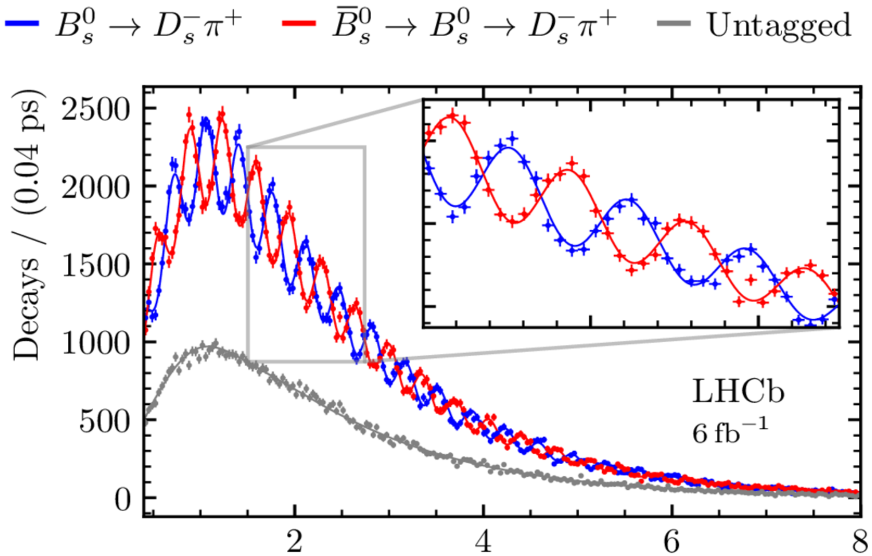


JINST 8 (2013) P08002, JINST 9 (2014) P09007

- 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**



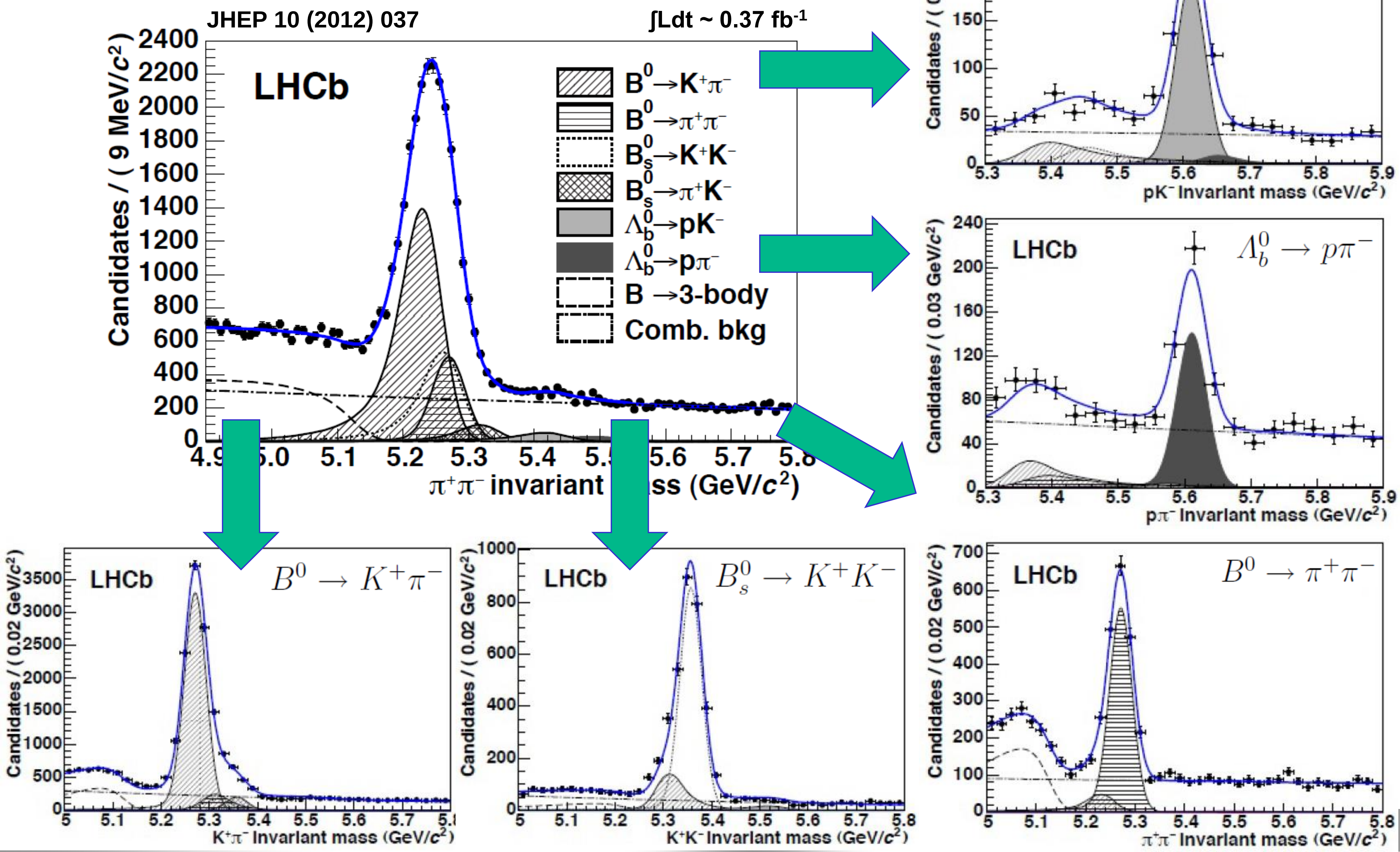
- Excellent **spatial resolution**, down to 4 μm for single tracks
- Precise **impact parameter** measurement, $\sigma_{IP} = 11.6 + 23.4/pT$ [μm]
- Precise **primary vertex** reconstruction, $\sigma_{x,y}$ = 13 μm, σ_z = 69 μm for vertex of 25 tracks
- Excellent **proper time** resolution
- **Vertex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



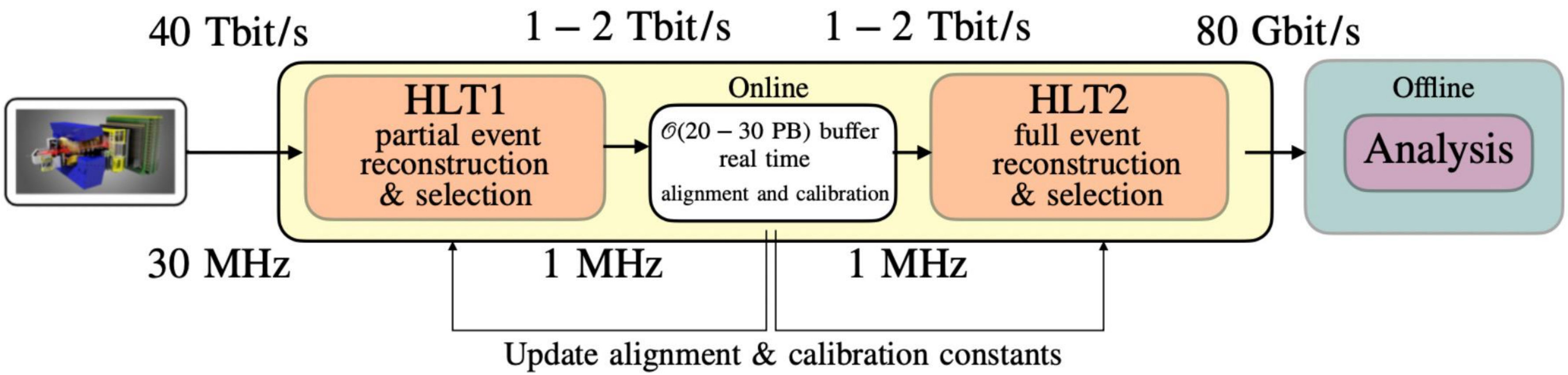
Nat. Phys. 18 (2022) 1

Charged hadron ID in LHCb: Cherenkov light detectors

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



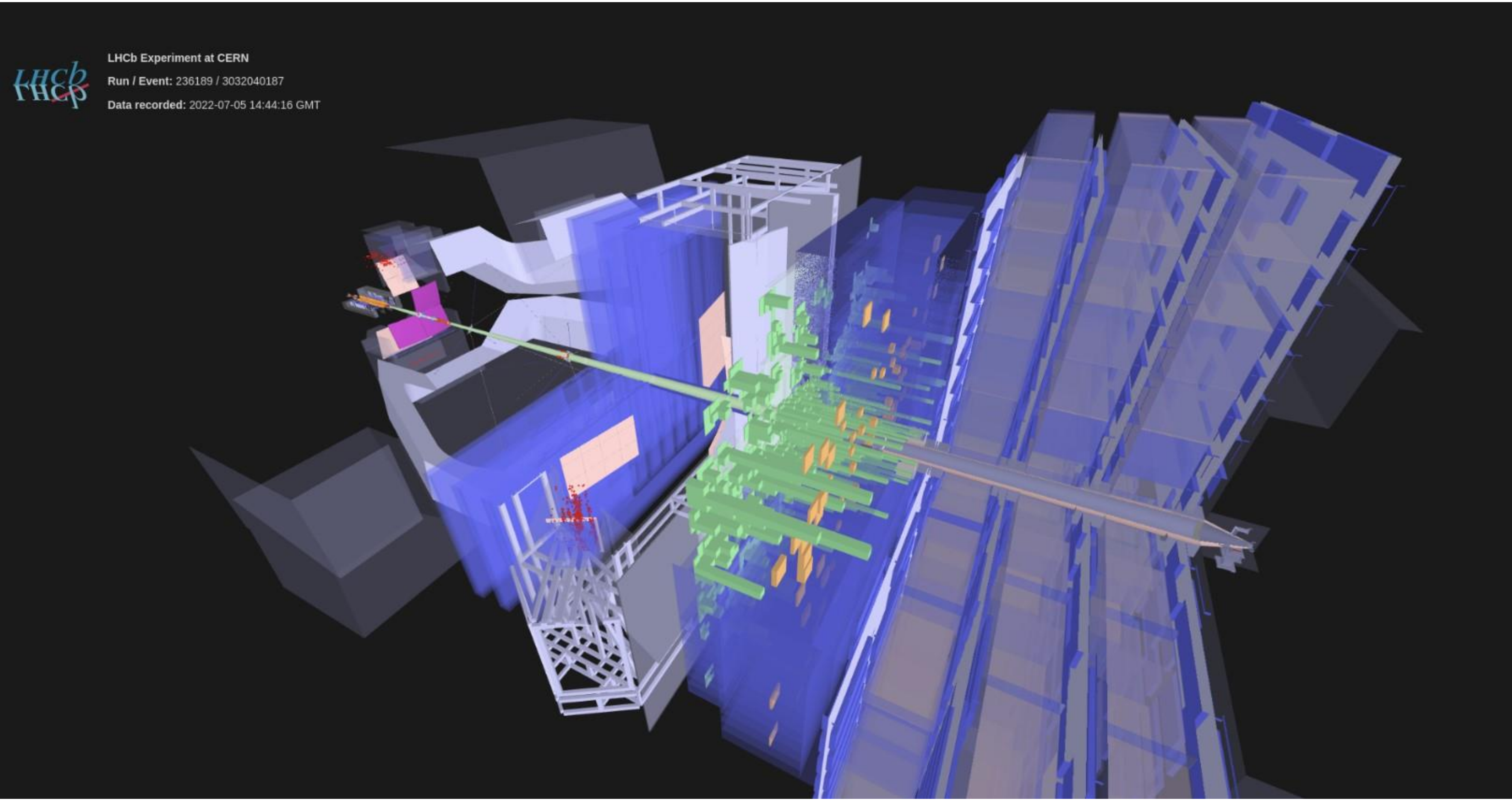
- LHCb upgrade I for runs 3 and 4
- Subdetectors readout at 40 MHz for a **fully sofrware trigger using GPUs**
- Can run at 5 x higher luminosity



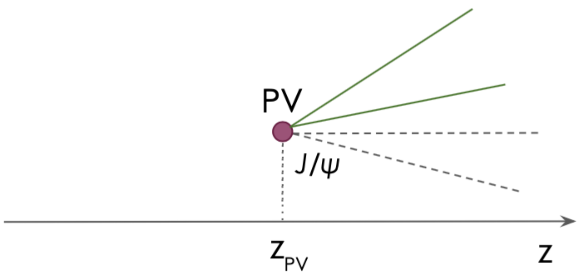
- 30 MHz of inelastic collisions will be reduced to ~1 MHz by the HLT1 (tracking/vertexing and muon ID) running on **GPUs**, **highest throughput of any HEP experiment**
- Many measurements will directly profit from higher stat precision (about x3 with run 3 only)

- **VELO**: Hybrid Pixel Detectors (55 μm pitch), 5 mm from the LHC beam axis at data taking
- **Upstream tracker**: 4 planes, silicon strips and integrated cooling, K_S,Λ decaying after VELO
- **SciFi**: new large scale tracking stations after magnet, scintillating fibres readout by SiPMs
- **RICH**: new photodetector MaPMTs with increased granularity, new RICH1 design
- **SMOG2 gas target**: new gas storage cell upstream of nominal IP, simultaneous p-p and p-gas
- **PLUME**: new luminometer upstream VELO

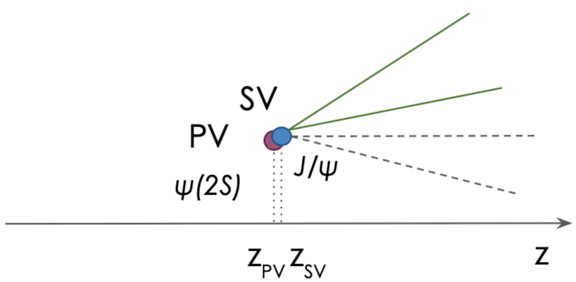
❑ First Run 3 collisions in LHCb at 13.6 TeV on 5/7/22



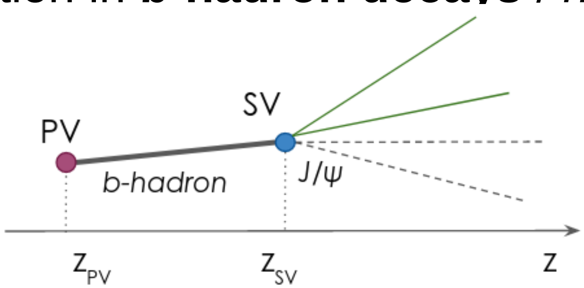
- **Hadroproduction**



- Decays of **higher resonances**



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



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

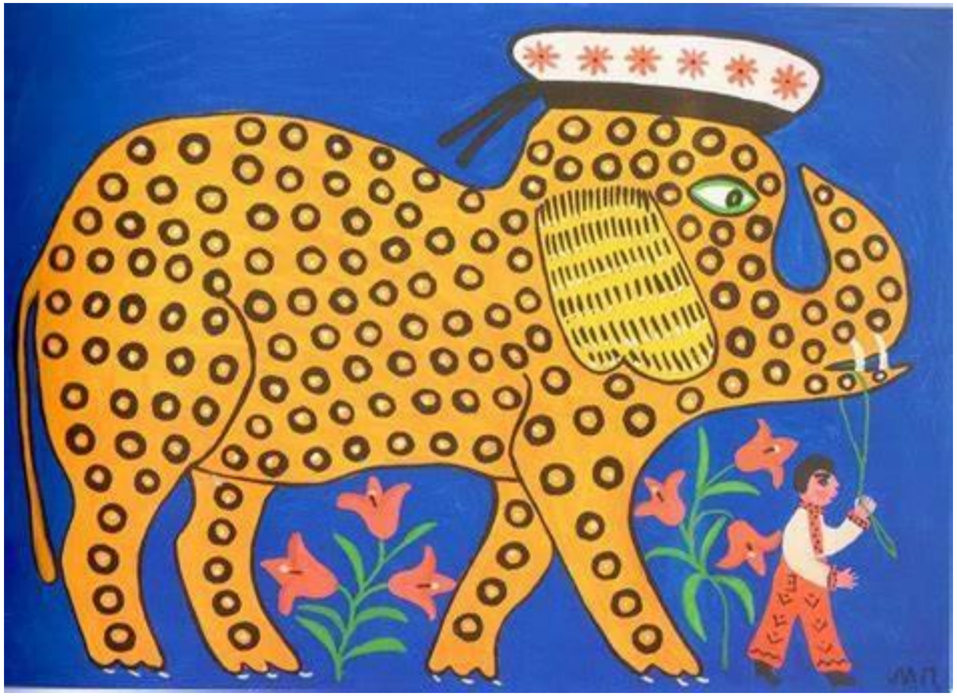
prompt production (hadroproduction and decays of higher resonances)

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



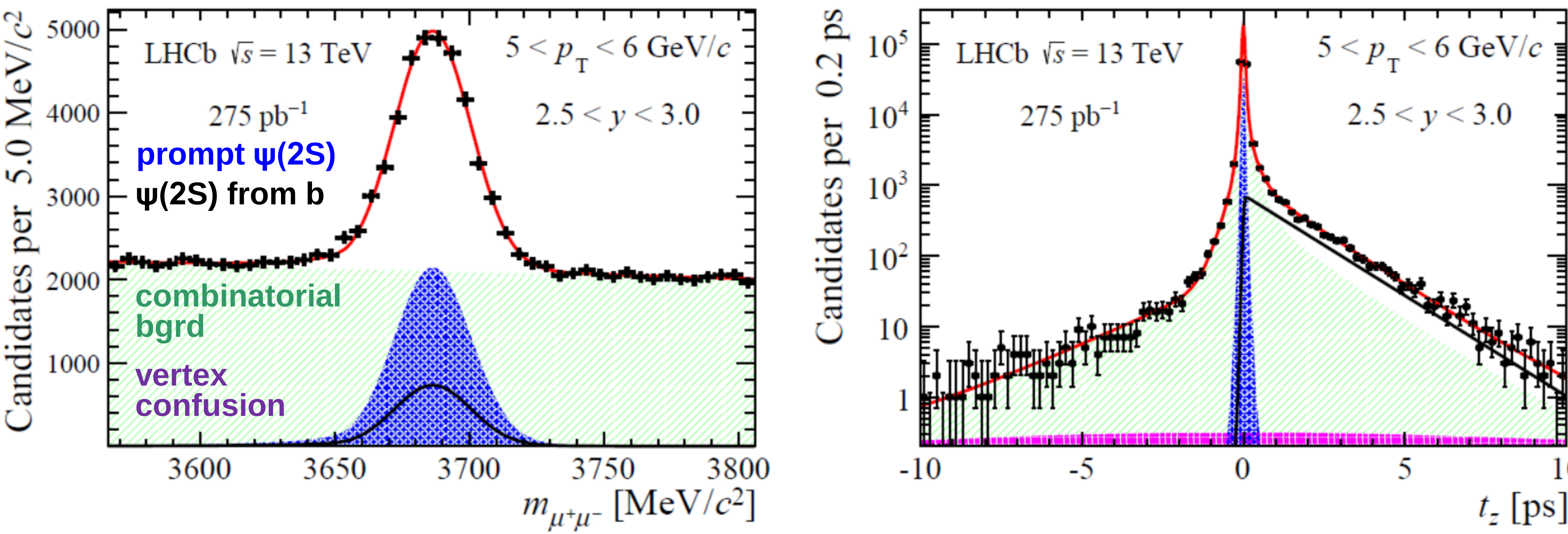
ψ(2S) production at 7 and 13 TeV

EPJC 80 (2020) 185

$\sqrt{s}$ = 7, 13 TeV, ∫Ldt ~ 614, 275 pb^{-1}

- **Negligible feed-down compared to J/ψ**
- **Prompt** (pp collision vertex) **ψ(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

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

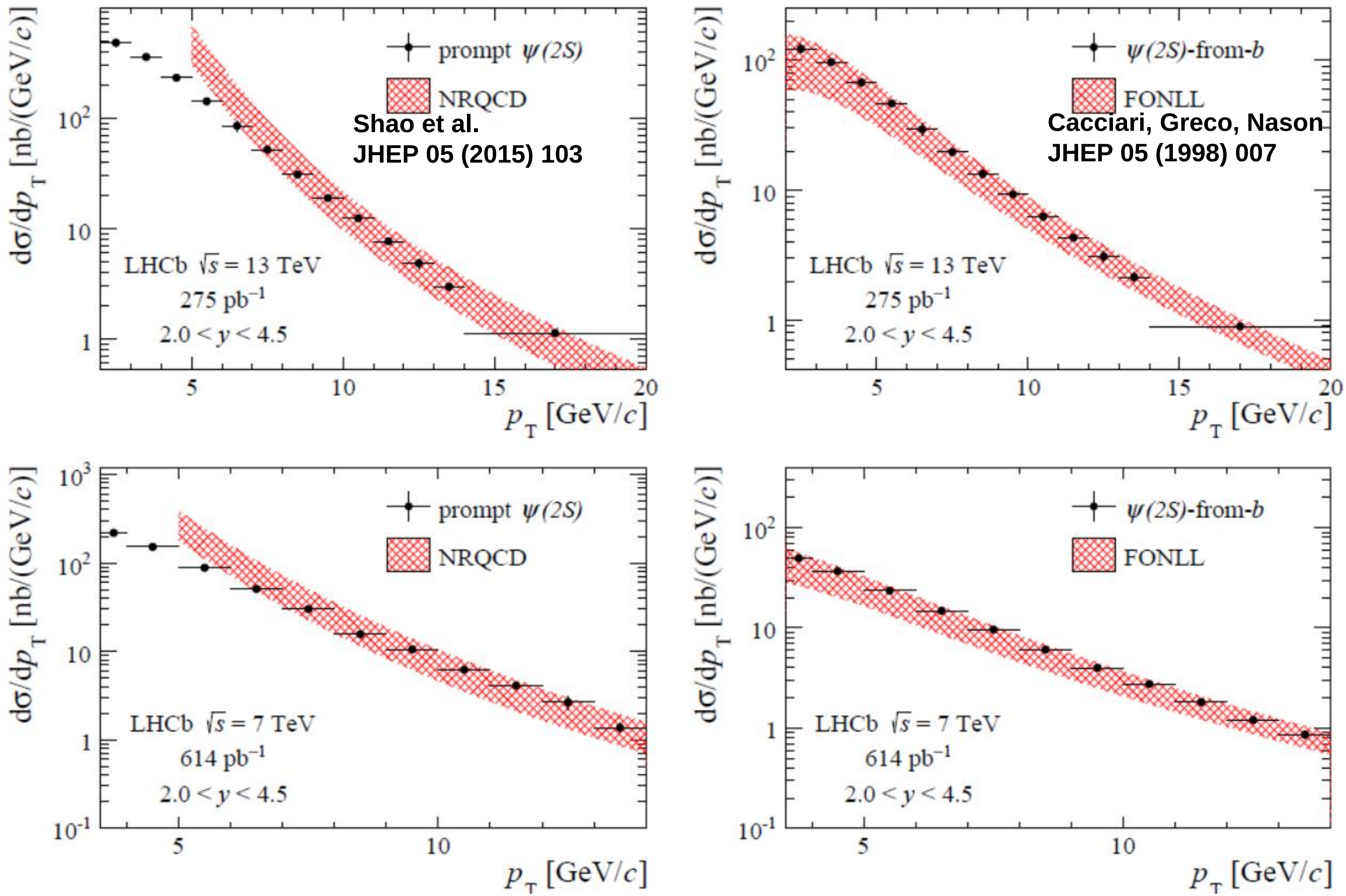


- **Integral** cross sections:

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

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

- **Prompt ψ(2S) production** and **production in b-hadron decays** **EPJC 80 (2020) 185**
- **Differential** cross sections $\sqrt{s}$ = 7, 13 TeV, ∫Ldt ~ 614, 275 pb^{-1}

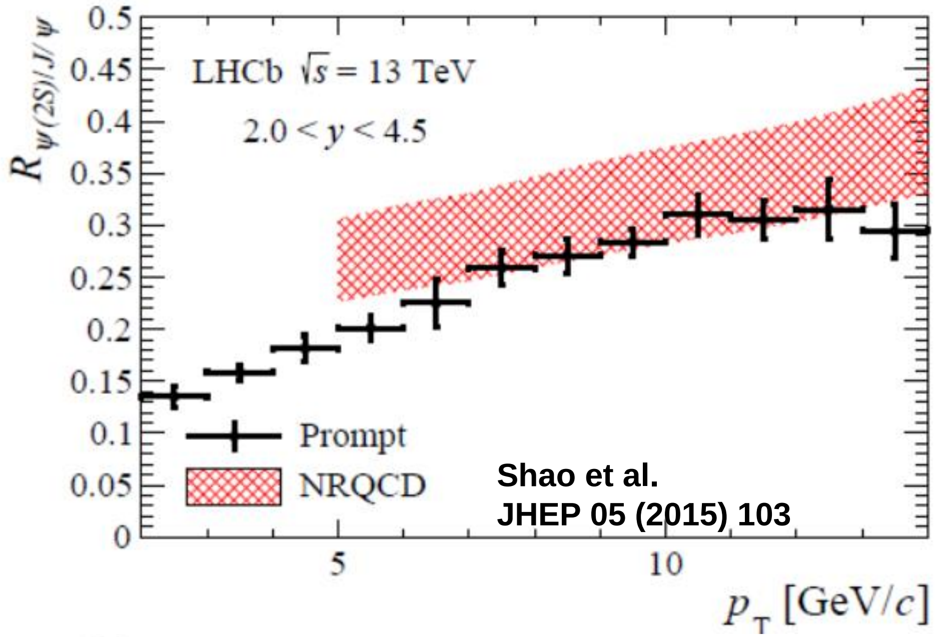


- Overall **good agreement with predictions, with deviation at low p_T** for prompt ψ(2S)

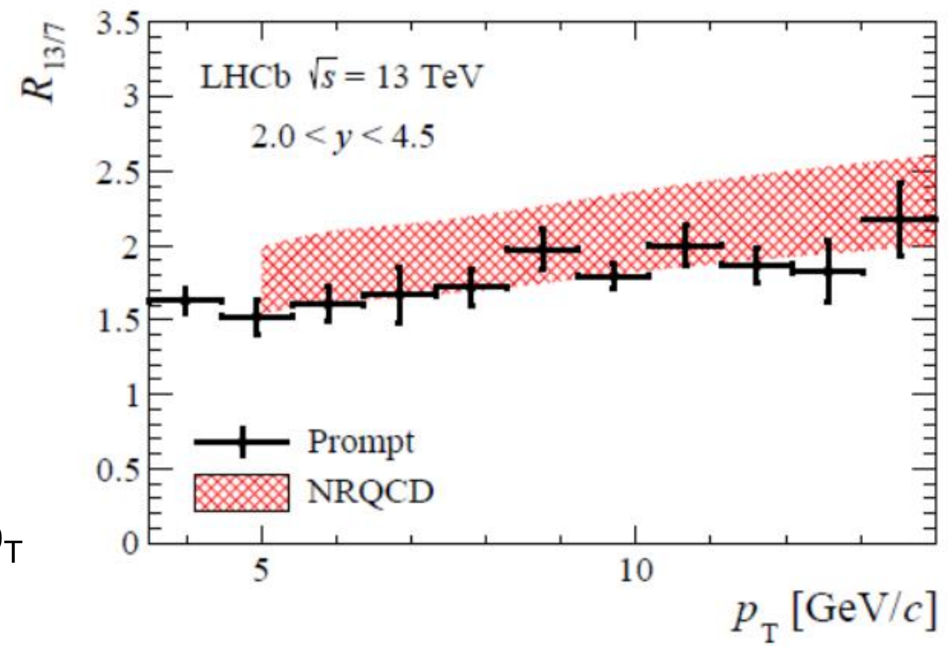
EPJC 80 (2020) 185

$\sqrt{s}$ = 7, 13 TeV, ∫Ldt ~ 614, 275 pb^{-1}

- Uncertainties partly cancel in ratios
- Ratio between the ψ(2S) and J/ψ production cross-sections



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

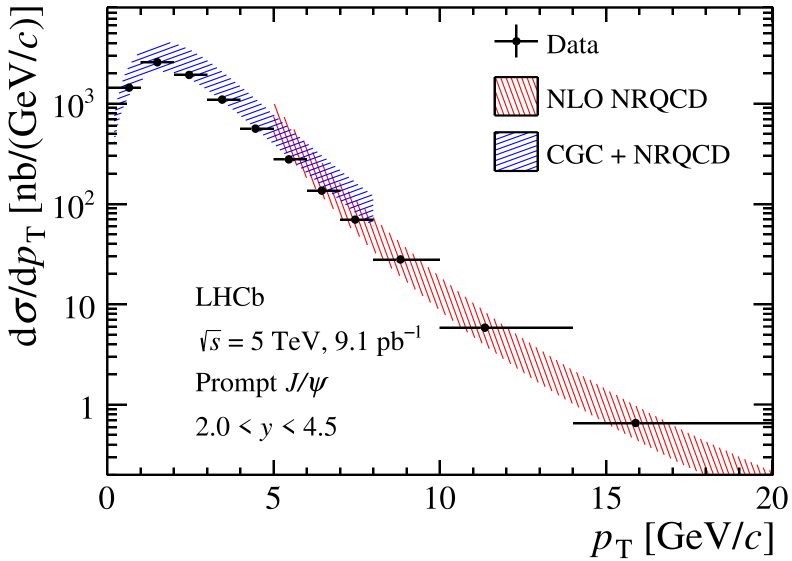


- **Overall good description** for both ratios
- Important to extend theory prediction to lower p_T

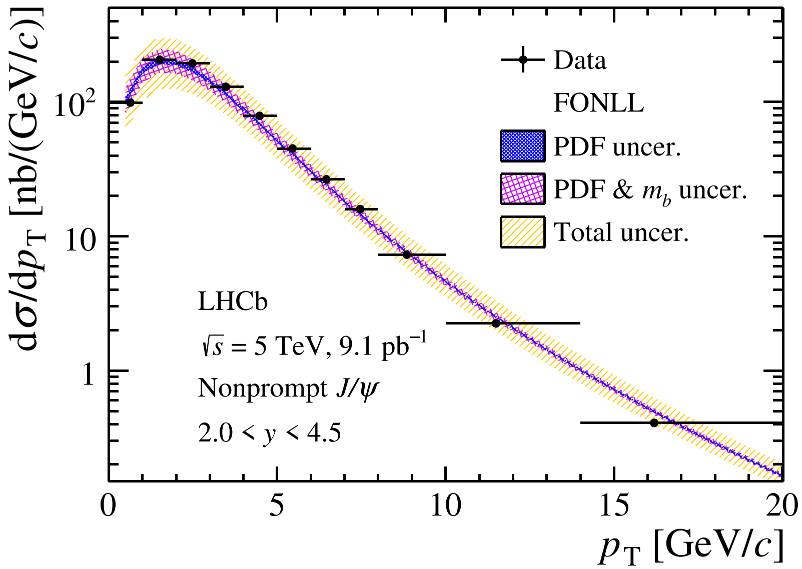
J/ψ production at √s = 5.02 TeV

JHEP 11 (2021) 181

- 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

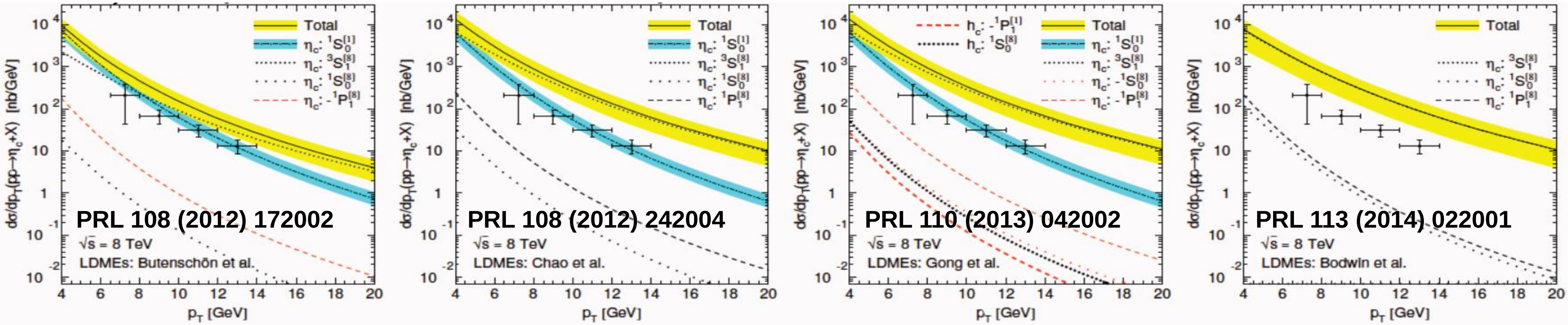
- J/ψ production cross-section:

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

- $\eta_c(1S)$ 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

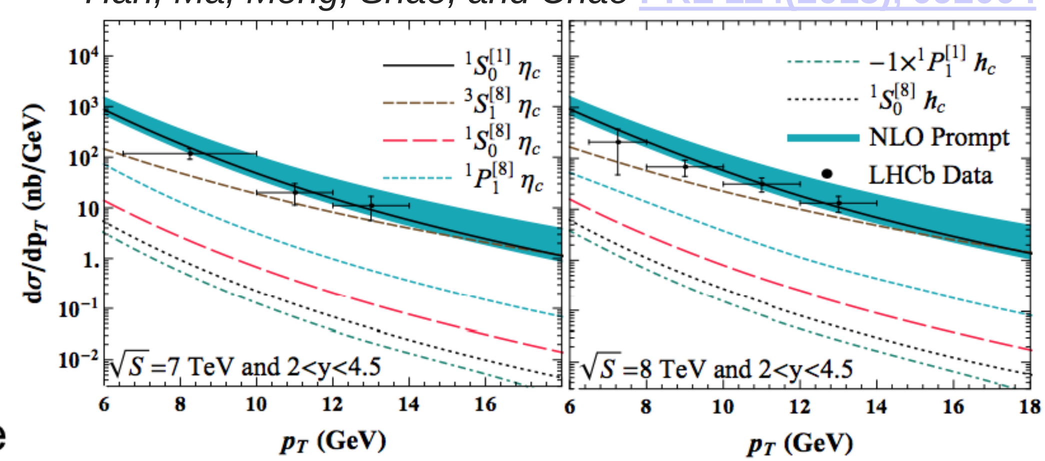
Butenschoen, He, Kniehl, **arXiv:1411.5287**



- 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

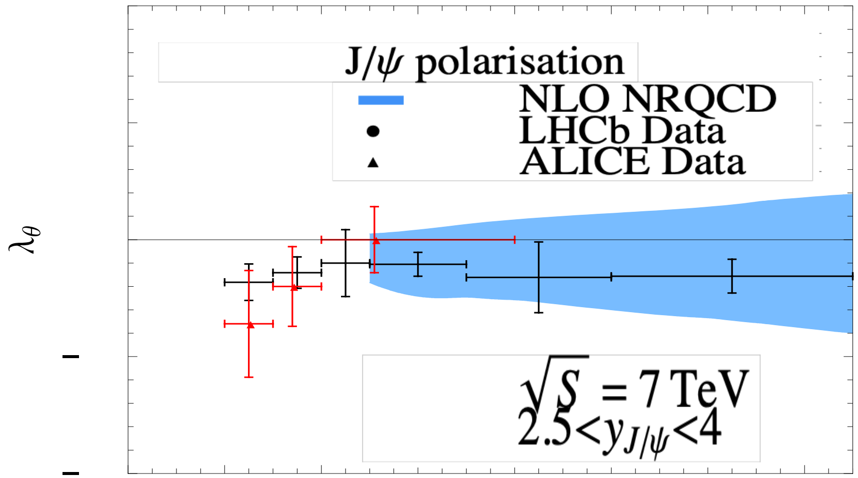
$$0 < O^{\eta_c}({}^3S_1^8) < 1.46 \times 10^{-3}\ \mathrm{GeV}^3$$



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

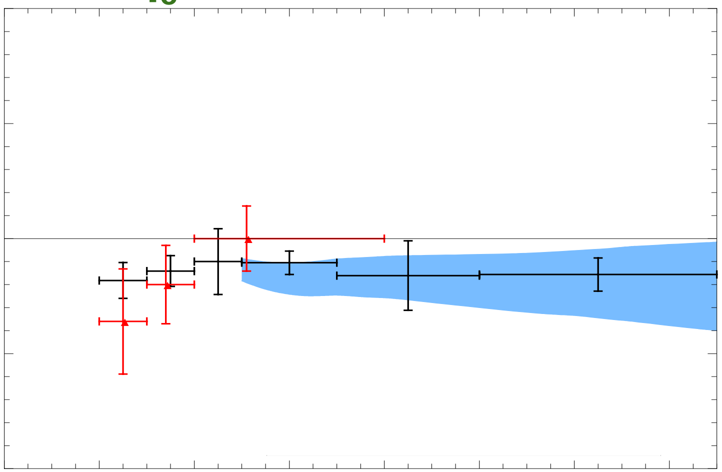
- η_c production at $\sqrt{s}$=7 and 8 TeV sets new constraint on J/ψ polarization

Before η_c measurements



⇒

After η_c measurements



PRL 114(2015), 092004

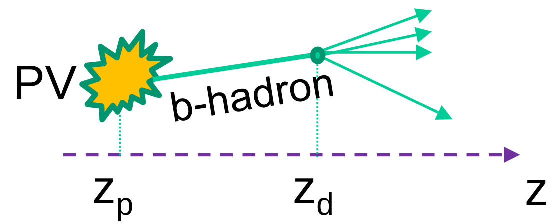
- Impressive progress !
- Still :
  - Tension with CDF data
  - Two large CO contributions cancel each other ⇒ hierarchy problem ⇒ Soft Gluon Fragmentation, etc.?

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

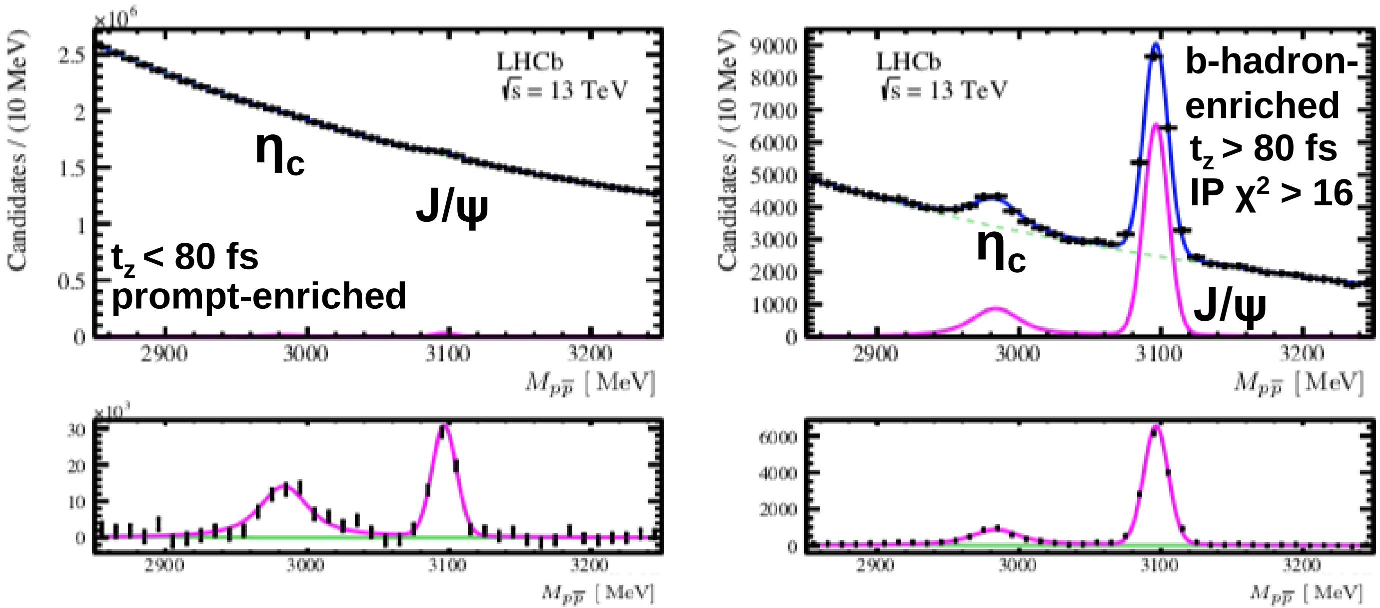
EPJC 80 (2020) 191

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

$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 2 fb^{-1}



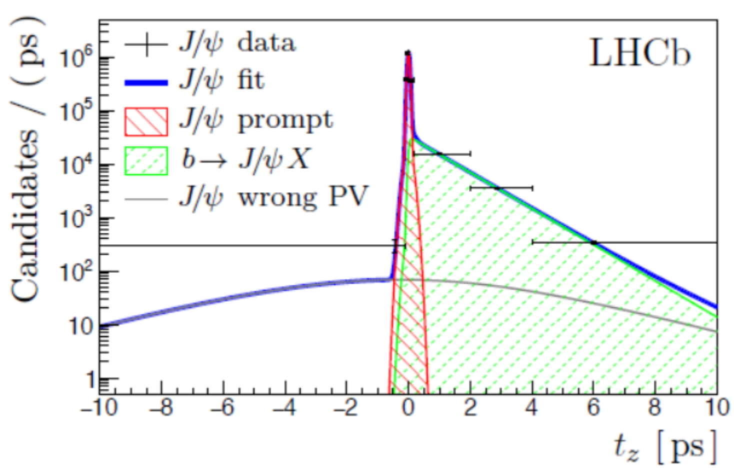
$$t_z = \frac{(z_d - z_p) M_{p\bar{p}}}{p_z}$$

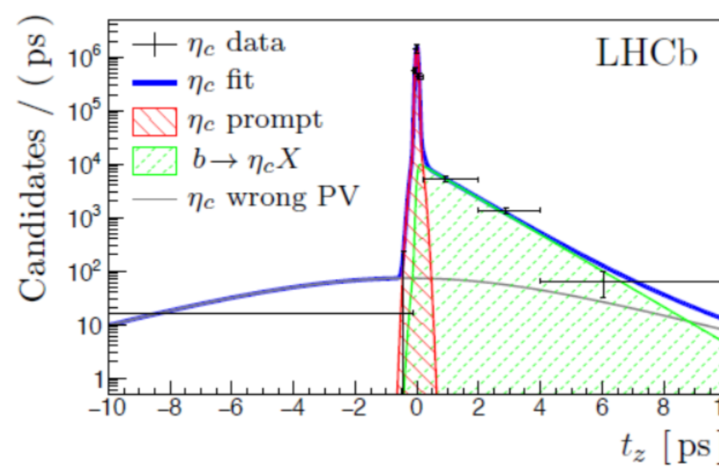


- **Selection** (account for cross feed)

- … or **pseudo proper-time fit**

- Good agreement between the results





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

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

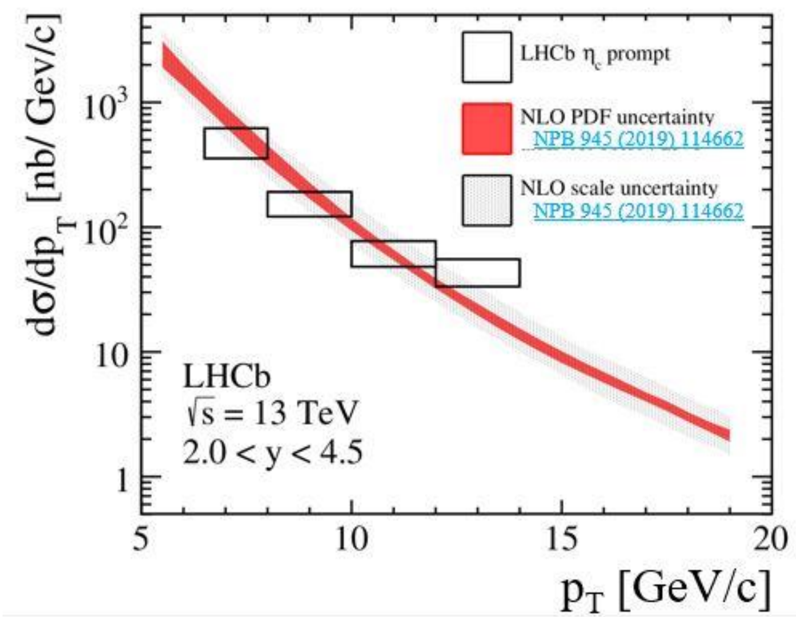
$$(\sigma_{\eta_c})^{6.5\,\mathrm{GeV}<p_T<14.0\,\mathrm{GeV},\,2.0<y<4.5}_{13\,\mathrm{TeV}} = 1.26 \pm 0.11 \pm 0.08 \pm 0.14\,\mu\mathrm{b}$$

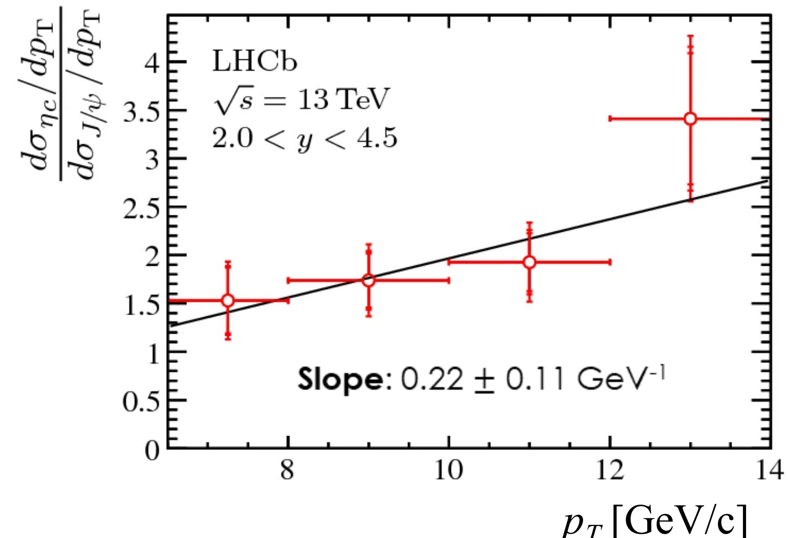
- Color Single model prediction: Feng,Shao,Lansberg,Zhang,Usachov,He **NPB 945 (2019) 114662**

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

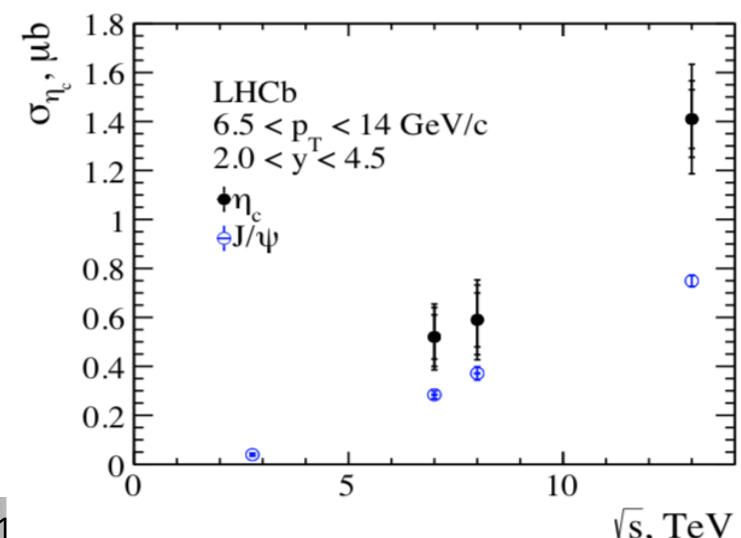
- **Consistent with being described by CSM**

- p_T -differential **prompt production**





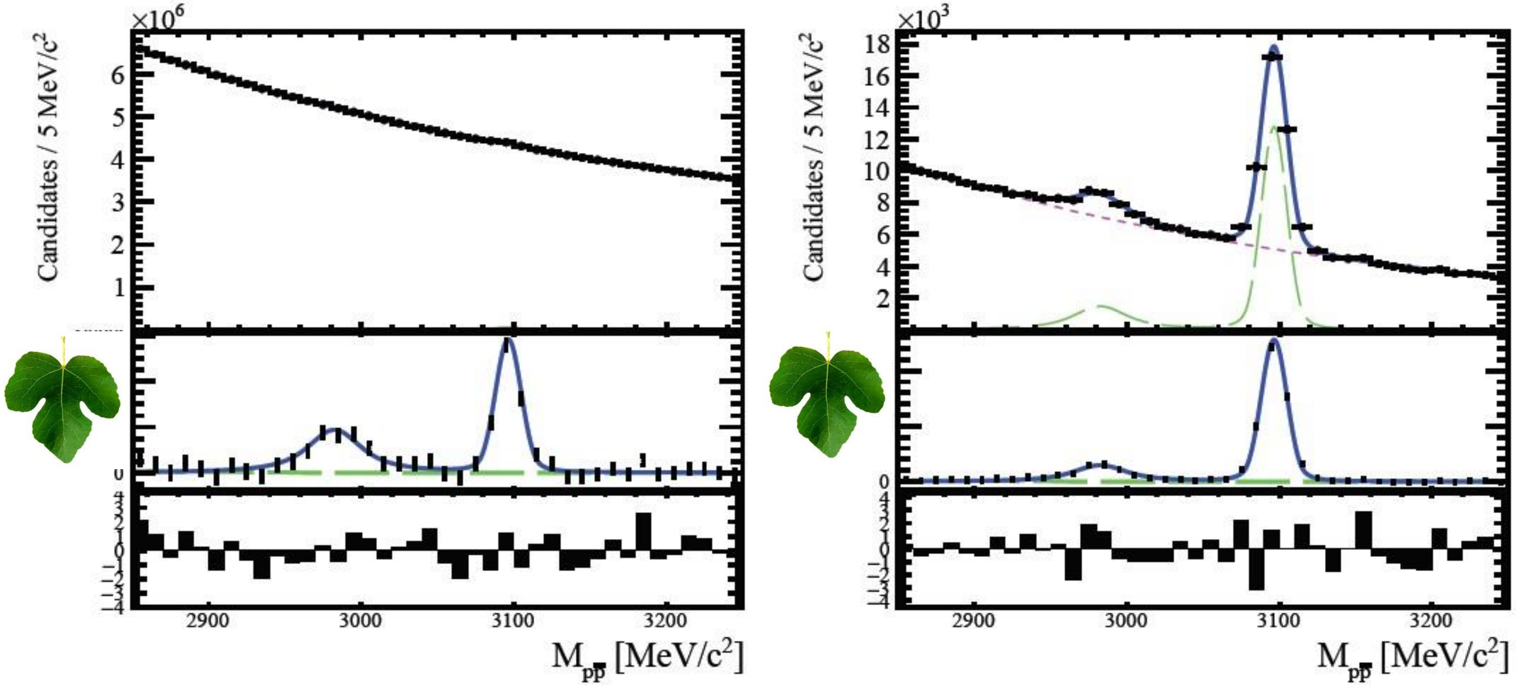
- $\sqrt{s}$ cross-section dependence



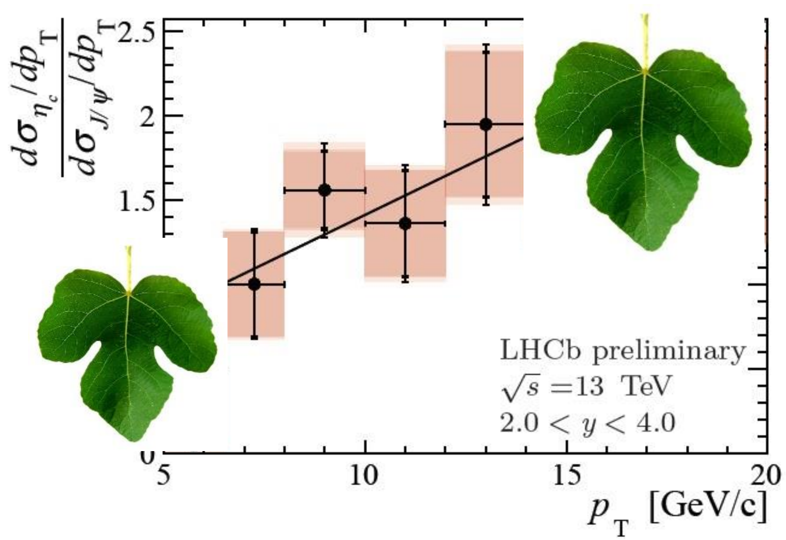
- **Inclusive production in b-decays**:

$$\mathcal{B}_{b\to\eta_c X} = (5.51 \pm 0.32_{stat} \pm 0.29_{syst} \pm 0.77_{norm}) \times 10^{-3}$$

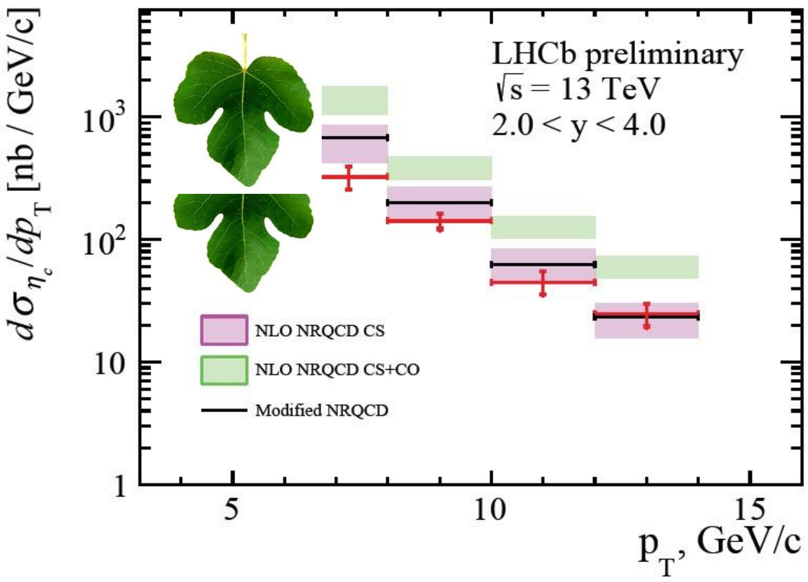
- New study of $\eta_c(1S)$ production at 13 TeV, with a dedicated trigger, data 2018



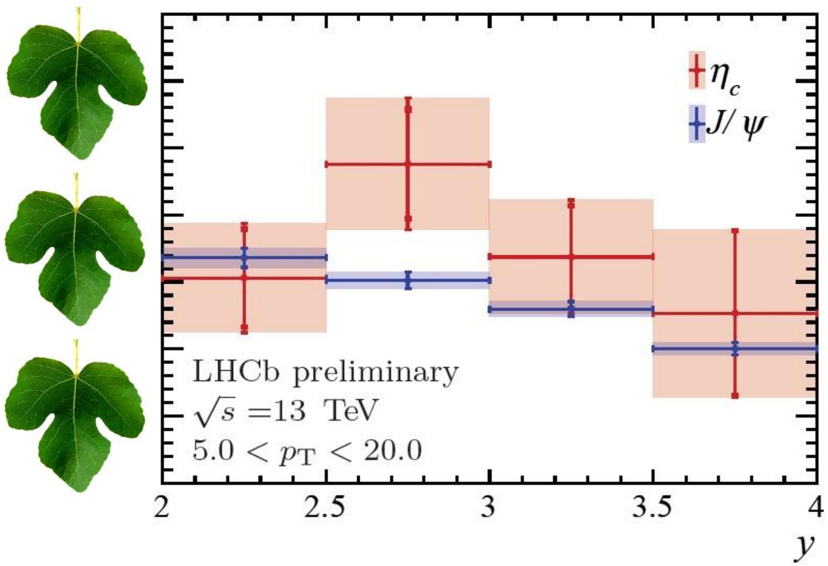
- Slope persists at the level of ≥ 3σ, different spectra for the two states



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



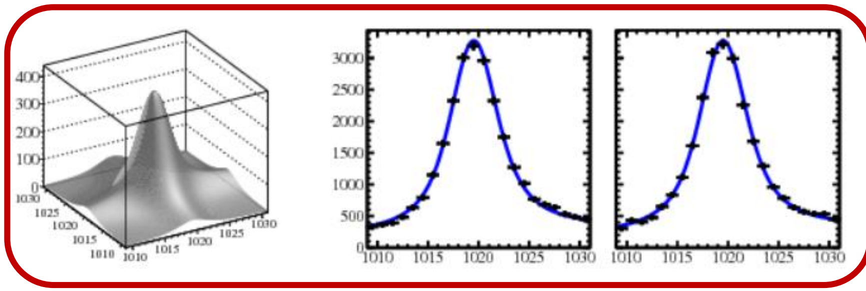
- First rapidity-differential cross-section (inspired by Hua-Sheng Shao)

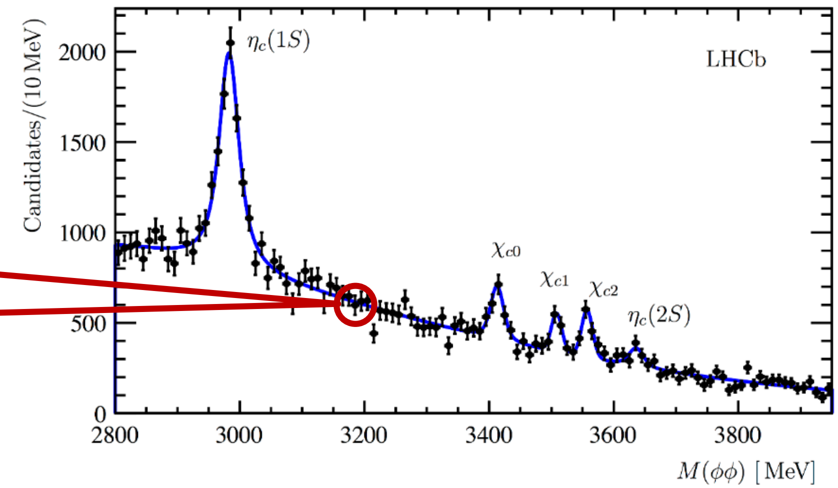


$\eta_c(2S)$ production at LHCb

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

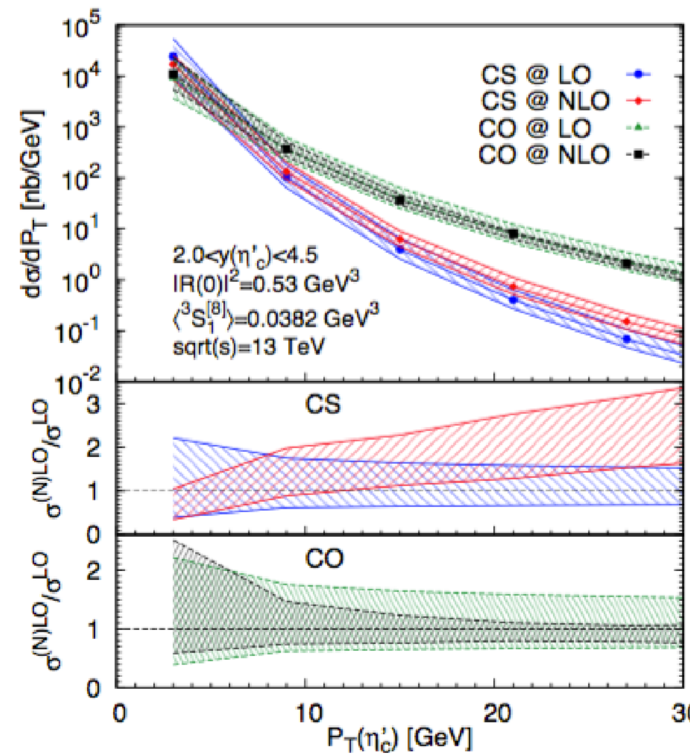
  First evidence for $\eta_c(2S)\to\phi\phi$

$$\frac{\mathcal{B}(b\to\eta_c(2S)X)\times\mathcal{B}(\eta_c(2S)\to\phi\phi)}{\mathcal{B}(b\to\eta_c(1S)X)\times\mathcal{B}(\eta_c(1S)\to\phi\phi)} = 0.040\pm0.011\pm0.004$$

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

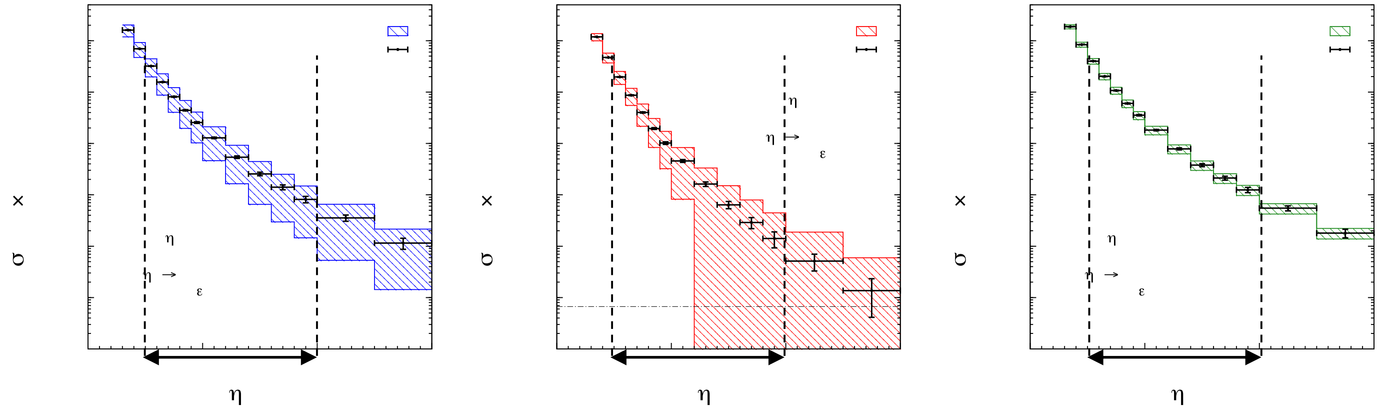
Theory prediction →

- ❑ **Dedicated LHCb trigger in 2018**



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

- Predictions for three different CO LDME sets



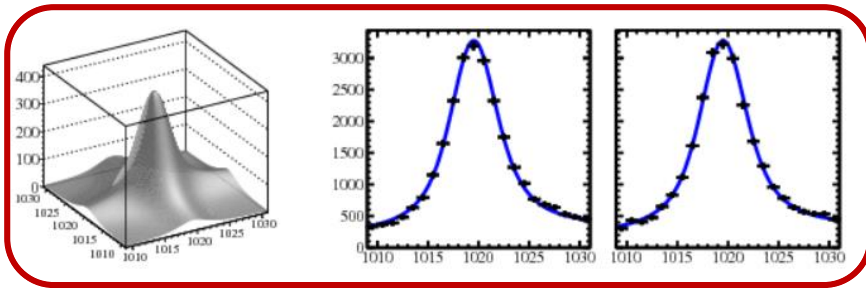
p_T, [GeV/c]	UL @95%CL	Shao et al. [40]	Gong et al. [39]	Bodwin et al. [41]
	$\sigma_{\eta_c(2S)} \times \mathcal{B}_{\eta_c(2S)\to p\bar{p}}$, [$pb$]			
5.0–14.0		664 ± 297	365 ± 135	855 ± 123
5.0–20.0		674 ± 304	368 ± 138	870 ± 126
	$(\sigma_{\eta_c(2S)} \times \mathcal{B}_{\eta_c(2S)\to p\bar{p}})/(\sigma_{J/\psi}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

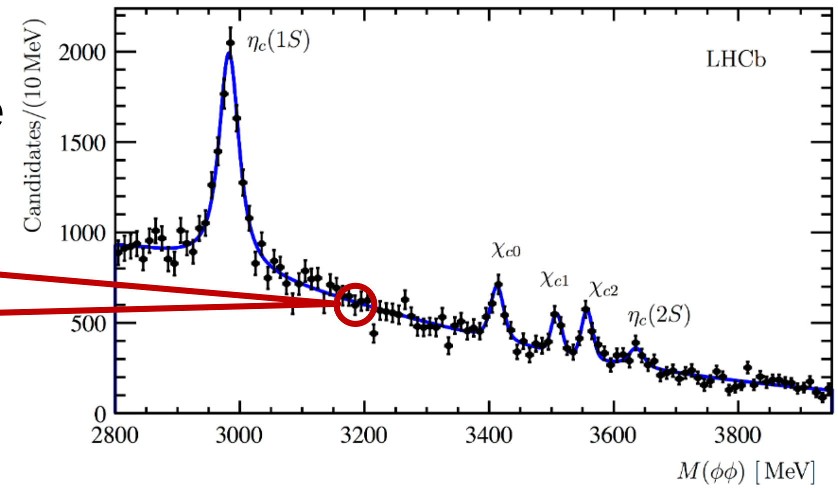
- Essential to understand and further constrain **uncertainties in theory**

- 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 77 (2017) 609

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

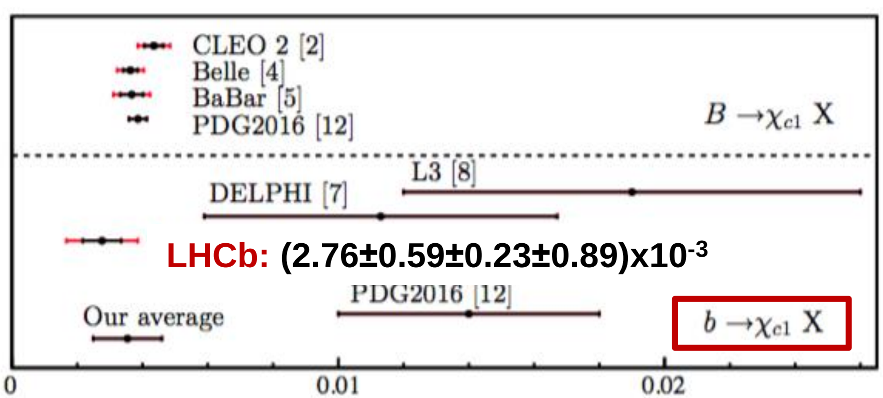


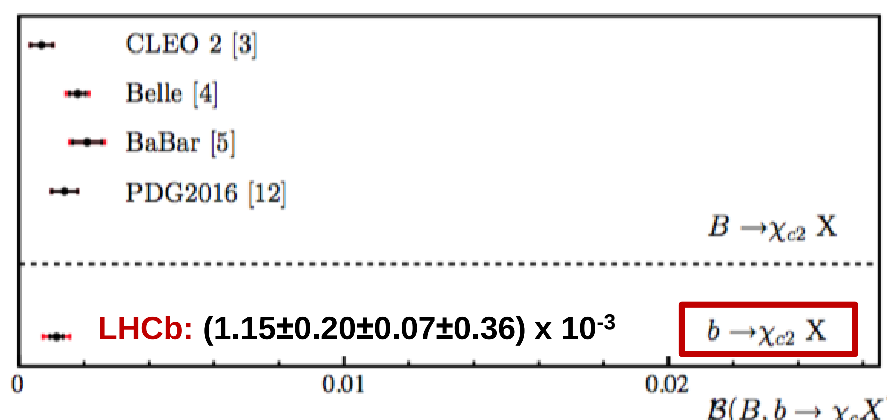


- **First measurement** of χ_{c0} production in b-decays

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

- **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

- Charmonium reconstructed via **decays to ppbar**

	$c\bar{c} \to p\bar{p}$, measured	$c\bar{c} \to \phi\phi$ [12]
$\mathcal{B}_{b\to\chi_{c0}X} \times \mathcal{B}_{\chi_{c0}\to p\bar{p}} \times 10^{-7}$	 $\pm 1.20_{stat} \pm 0.28_{syst} \pm 0.59_{\mathcal{B}}$	6.67 ± 2.40
$\mathcal{B}_{b\to\chi_{c0}X} \times 10^{-3}$	$\pm 0.54_{stat} \pm 0.13_{syst} \pm 0.29_{\mathcal{B}}$	3.02 ± 1.08
$\mathcal{B}_{b\to\chi_{c1}X} \times \mathcal{B}_{\chi_{c1}\to p\bar{p}} \times 10^{-7}$	$\pm 0.94_{stat} \pm 0.11_{syst} \pm 0.35_{\mathcal{B}}$	2.10 ± 0.83
$\mathcal{B}_{b\to\chi_{c1}X} \times 10^{-3}$	 $\pm 1.23_{stat} \pm 0.14_{syst} \pm 0.51_{\mathcal{B}}$	2.76 ± 1.09
$\mathcal{B}_{b\to\chi_{c2}X} \times \mathcal{B}_{\chi_{c2}\to p\bar{p}} \times 10^{-7}$	$\pm 0.85_{stat} \pm 0.03_{syst} \pm 0.10_{\mathcal{B}}$	0.85 ± 0.31
$\mathcal{B}_{b\to\chi_{c2}X} \times 10^{-3}$	$\pm 1.15_{stat} \pm 0.04_{syst} \pm 0.15_{\mathcal{B}}$	1.15 ± 0.42

- 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

Combined fits of LDME, teaser

Simultaneous study of J/ψ and η_c(1S) prompt production

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

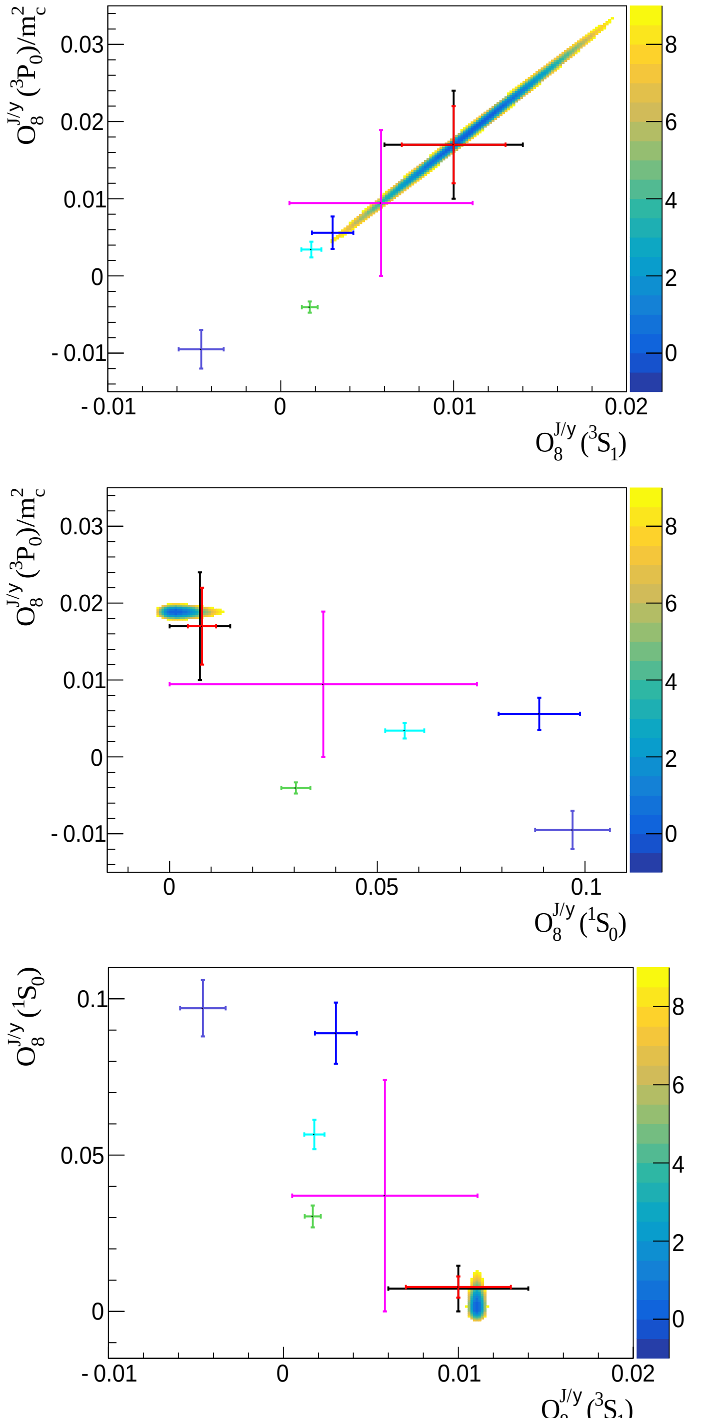
- Relation between LDME from HQSS:

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

- Fix CS LDME from potential model

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

- χ^2 minimization



- Reasonable agreement with some predictions

Simultaneous study of ψ(2S) and η_c(2S) prompt production

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

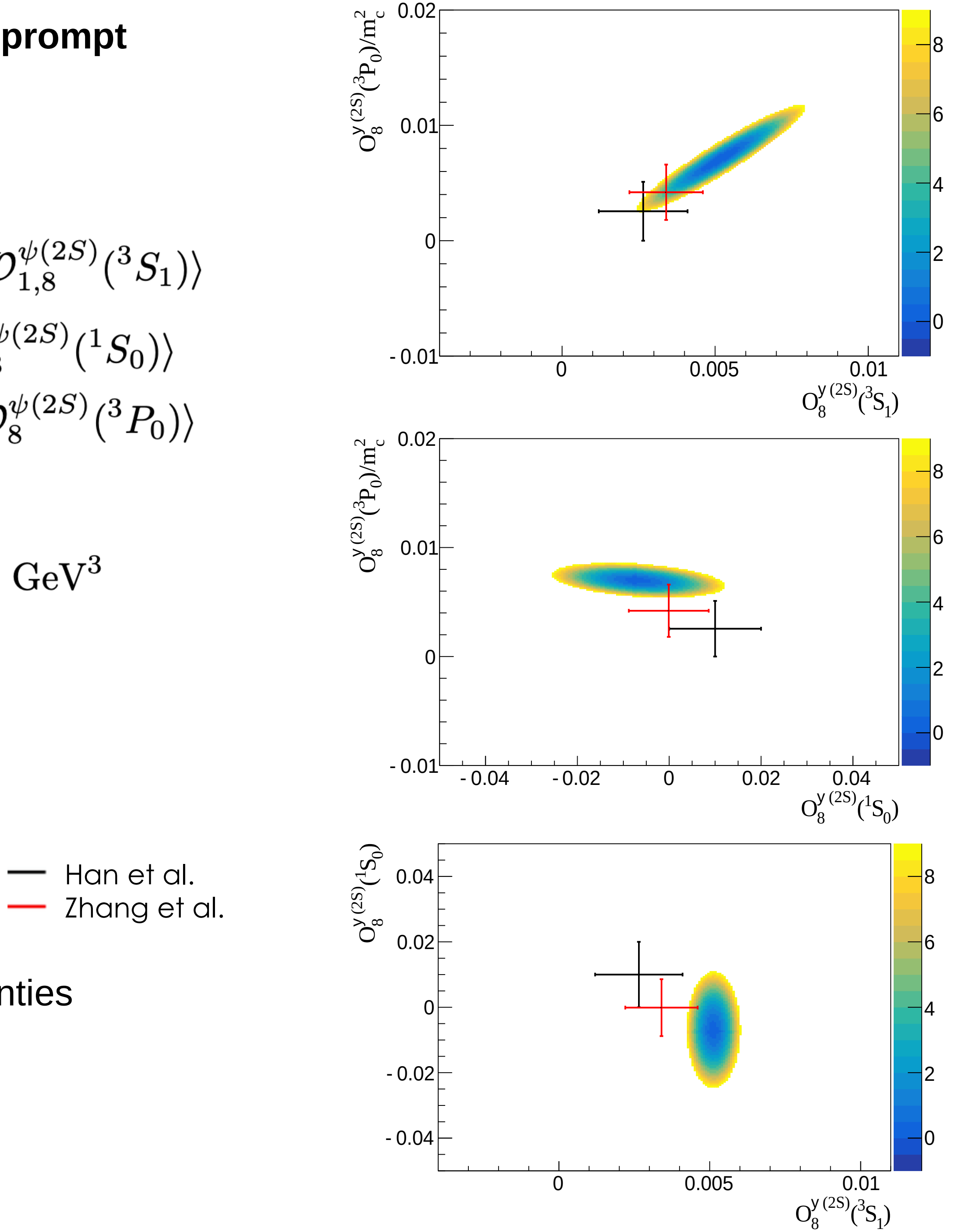
- Relation between LDME from HQSS:

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

- Fix CS LDME from potential model

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

- χ^2 minimization



- 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**

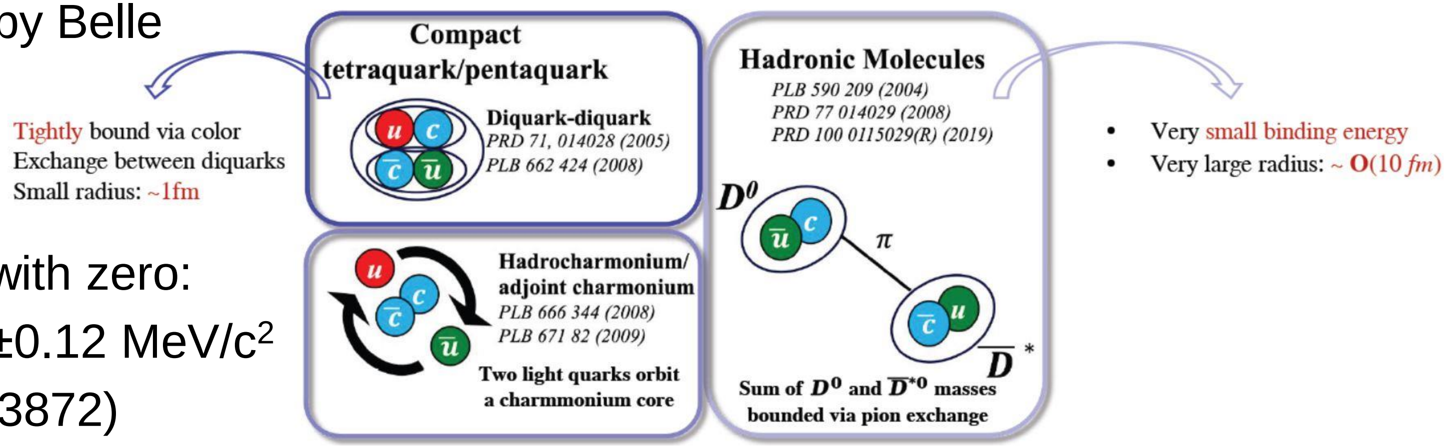
- Alternatively, once hadroproduction and production in b-decays measured for charmonium states with linked LDMEs,
  the above **assumptions can be tested quantitatively**

Other examples

- **χ_{c1}(3872) state** discovered by Belle in the decay $B \rightarrow J/\psi\, \pi^+\pi^-$
- Quantum numbers measured by LHCb: $\mathbf{J^{PC} = 1^{++}}$
- Mass difference consistent with zero:

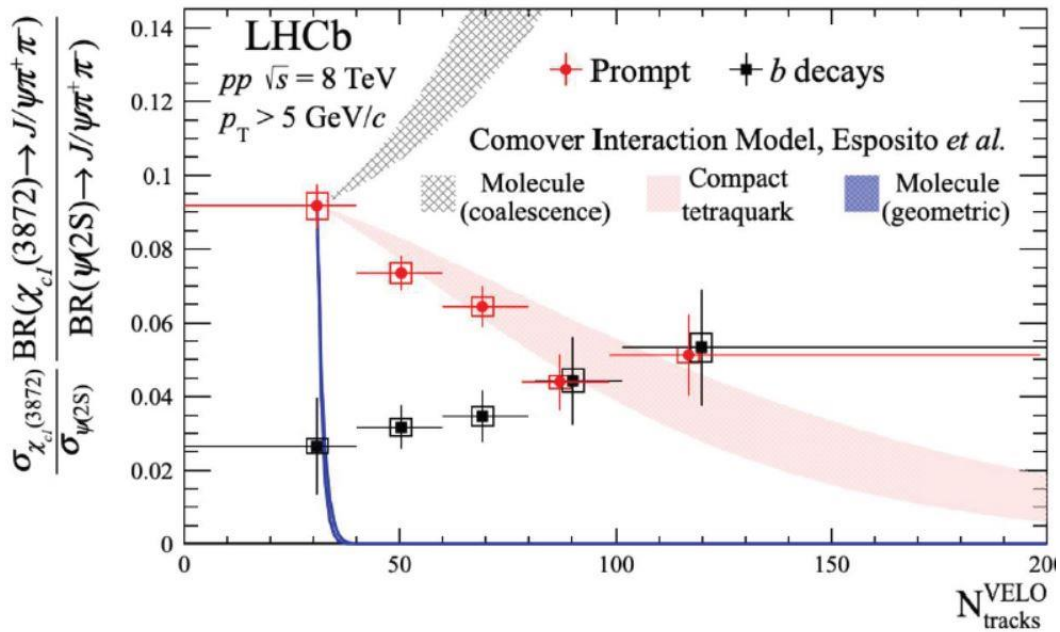
$(M_{D0} + M_{D^{*0}}) - M_{\chi c1(3872)} = 0.07 \pm 0.12$ MeV/c^2

- Multiple explanations of χ_{c1}(3872)



Matt Durham, Quark Matter 2019

- **Multiplicity dependent production of χ_{c1}(3872) and ψ(2S)**



PRL 126 (2021) 092001

- Comover interaction model by Espacito et al., arXiv: 2006.15044, favours the **compact tetraquark scenario**
- A tweaked model by Braaten et al., arXiv: 2012.13499, suggests the χc1(3872) is a **charm-meson molecule**

- Evidence for **relative χ_{c1}(3872) suppression for high-multiplicity events**
- Expected in a **scenario of interactions with co-moving hadrons** dissociating large weakly bound χ_{c1}(3872) against compact ψ(2S)

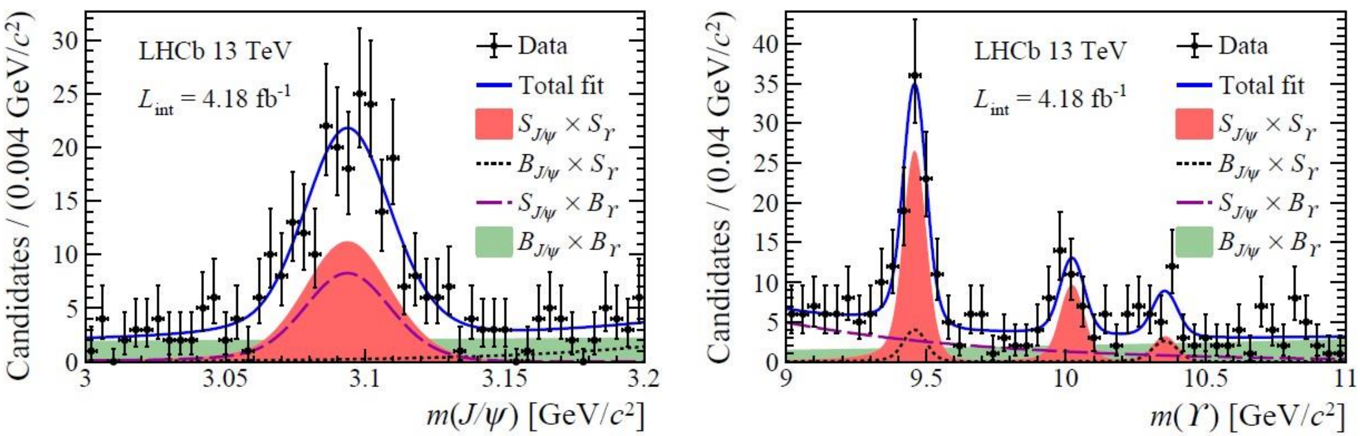
- **J/ψ-Υ associated production at $\sqrt{s}$ = 13 TeV**

arXiv:2305.15580

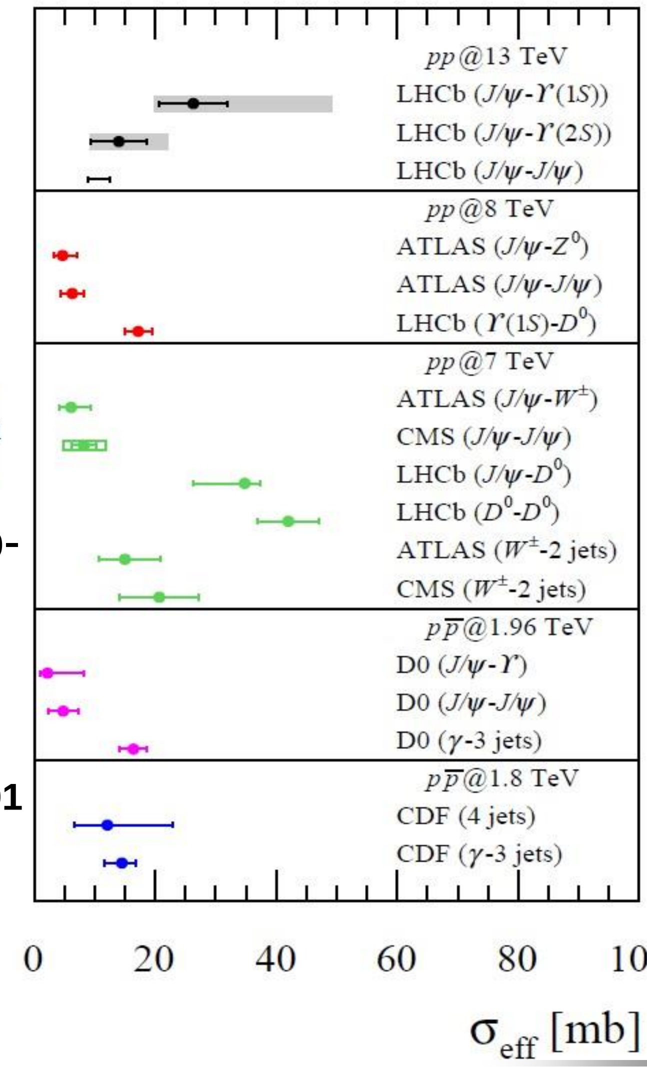
- Production via two independent hard scatters that are assumed to factorize (**DPS**) or gluon splitting expected to dominate cc production (**SPS**)
- DPS provides important information on gluon correlations and parton p_T-distribution

$$\sigma_{\text{DPS}}(J/\psi\text{–}\Upsilon) = \frac{\sigma(J/\psi) \times \sigma(\Upsilon)}{\sigma_{\text{eff}}}$$

2D fit projected to J/ψ and Y di-muon masses



Compilation of results on σ_{eff}



- Differential production cross-section in bins of kinematical variables to probe **kinematical correlations** between the two mesons
- Pseudoexperiments with DPS from single productions and SPS from NRQCD calculations

H.-S. Shao and Y.-J. Zhang, **PRL 117 (2016) 062001**

- Data points are described by the model

- **Should σ_{eff} be universal ?**

Outlook

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

- We do not know the exact underlying mecanism,

  but this is certainly a beautiful product of Nature …

- We do not know the exact underlying mecanism,
  but this is certainly a beautiful product of Nature …

- Illustrations from Maria Prymachenko (1909-1997)

Maria Prymachenko

- Rapidity

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

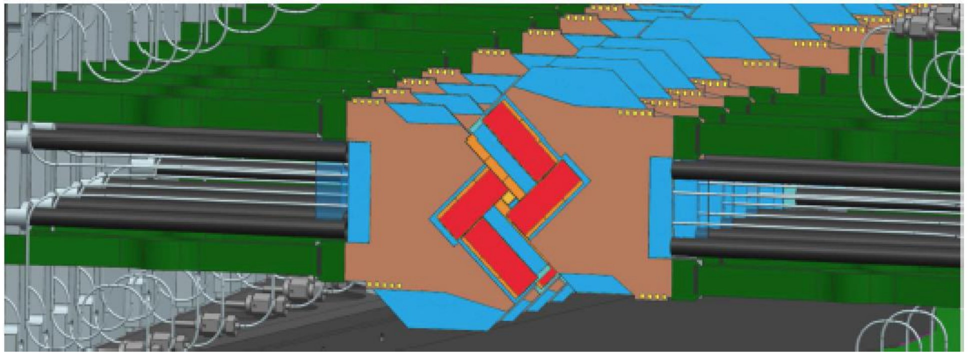
- Pseudorapidity

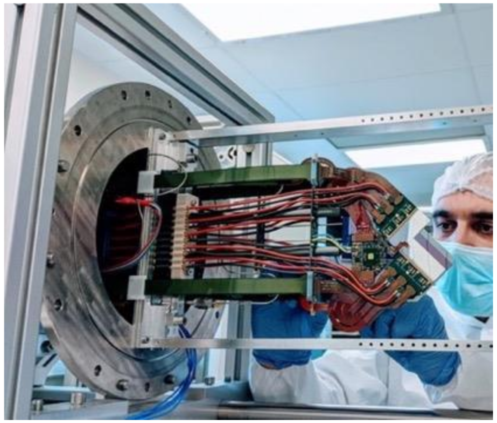
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

LHCb reincarnation: Upgrade I

CERN-LHCC-2013-021

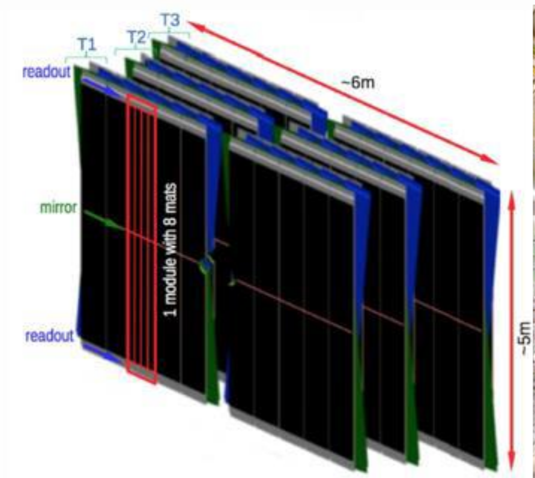
- **VELO**: Hybrid Pixel Detectors (55 μm pitch)
- 5 mm from the LHC beam axis at data taking
- Innovative silicon microchannel substrate, Bi-phase CO2 cooling
- DAQ capable of handling 40 TB/s
- Installation completed, commissioning ongoing

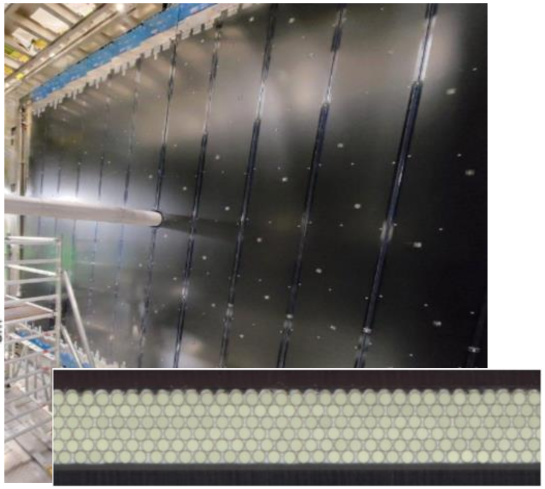




CERN-LHCC-2014-001

- **Upstream tracker**: 4 planes, silicon strips and integrated cooling
- Fast p_T determination for track extrapolation → reduce ghost track rate, and improve trigger bandwidth
- Long lived particles (K_S,Λ) decaying after VELO
- Assembly being completed, installation later this year, not critical for early physics operation

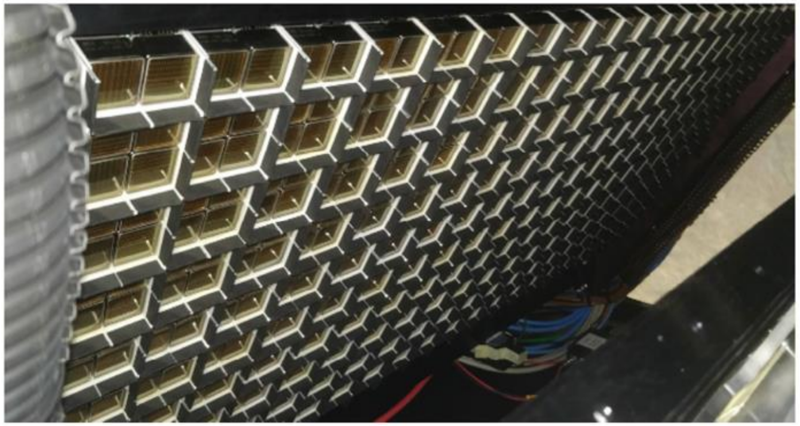




- **SciFi**: Large scale tracking stations after magnet
- Scintillating fibres, 250 μm dia, 2.5 m long
- Signal readout by SiPMs operated at -40 C
- 12 layers of mats, 12 000 km of fibre
- Installation completed, now commissioning

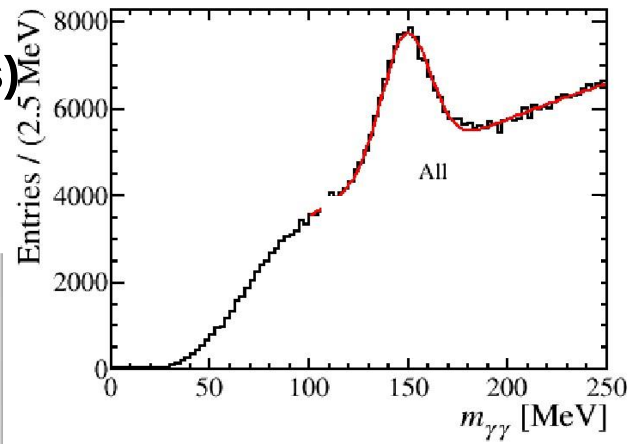
- **RICH**: charged hadron identification, essential for success of physics programme
- RICH 1 & 2: new photodetector MaPMTs with increased granularity and 40 MHz readout
- RICH 1: new design with new optical system with increased focal length, to halve occupancy
- Installed, commissioned, taking data

RICH 1: MaPMTs upper side

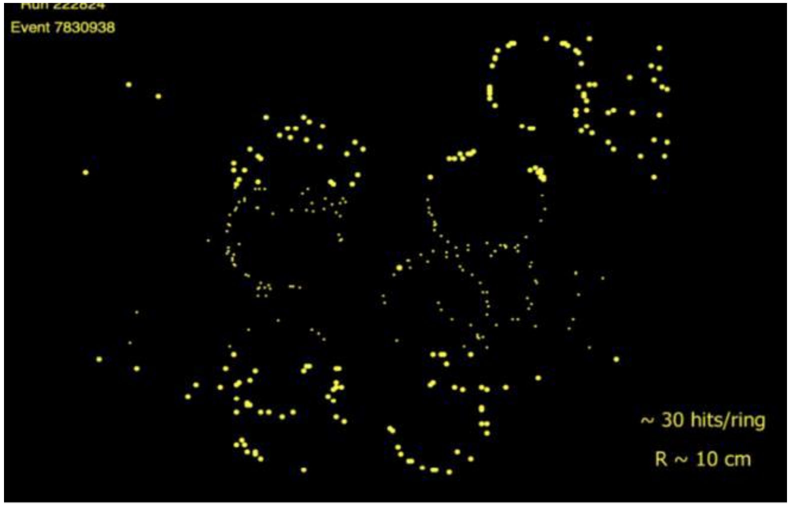


- **Calorimeter (Shashlyk) and Muon detector (MWPCs)**

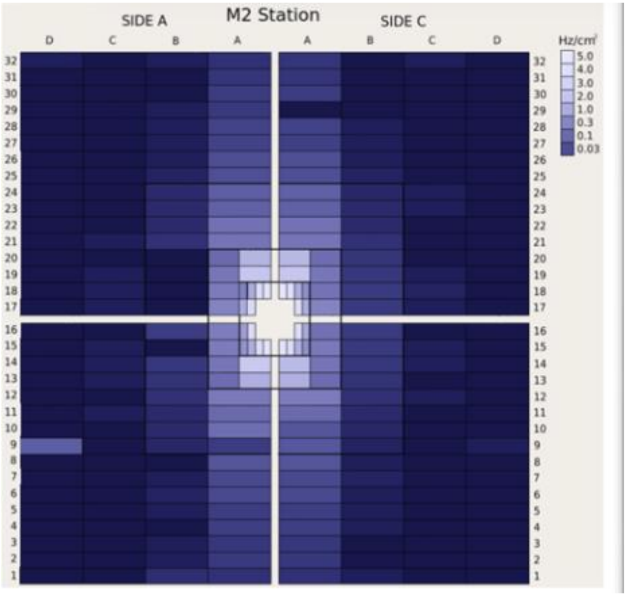
π^0 with Run 3 data



RICH 2: first rings, LHC October 21 test



Muon station 2, occupancy

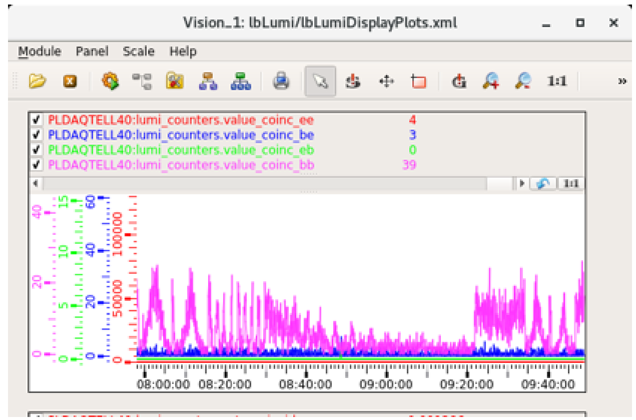


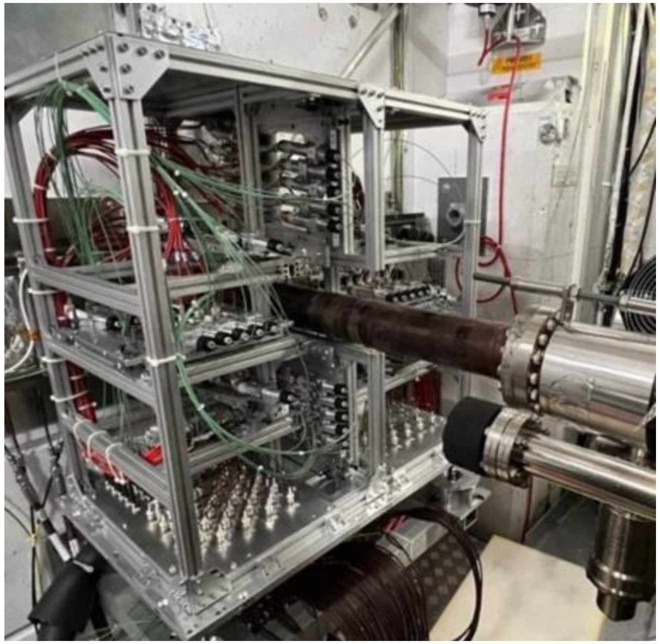
- Existing detectors able to stand increased luminosity of Run 3
- New 40 MHz readout electronics
- Reduced gains in calorimeter PMTs
- Taking data

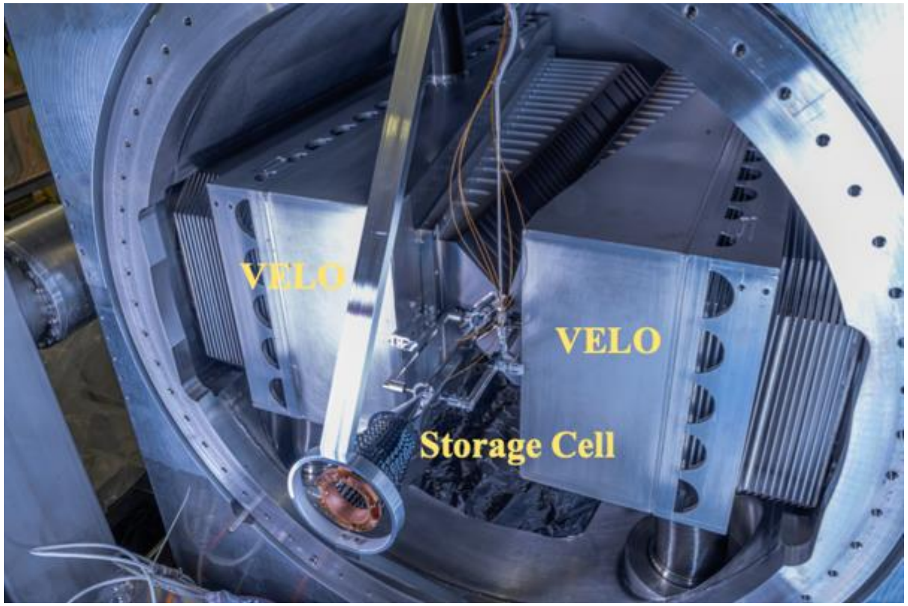
LHCb reincarnation: Upgrade I

CERN-LHCC-2021-002

- ❑ **PLUME**: luminometer for Run 3, upstream VELO
- ❑ Measures Cherenkov light emitted in quartz tablet by charged particles flying from collision vertex
- ❑ Online & offline per bunch luminosity measurement
- ❑ Periodic calibration via Van der Meer scans
- ❑ Taking data







CERN-LHCC-2019-005

- ❑ **SMOG2 gas target**: new storage cell for the gas upstream of the nominal IP
- ❑ Gas density increased by up to two orders of magnitude → much higher luminosity
- ❑ Gas targets: He,Ne,Ar + possibly H_2,D_2,N_2,Kr,Xe
- ❑ Installed & tested
- ❑ Simultaneous p-p and p-gas data taking possible