Charmonium production at

Sergey Barsuk, LAL Orsay
on behalf of the LHCb collaboration

Selected recent LHCb results on

- ❑ **Charmonium production**
- ❑ **Associated production**
- ❑ **Production in jets**
- ❑ **Central Exclusive Production**

- ❑ Talk on **applications of NRQCD to charmonium phenomenology** by Jia Yu
- ❑ Talk on **charmonium decays and transitions** by Jinzhi Zhang

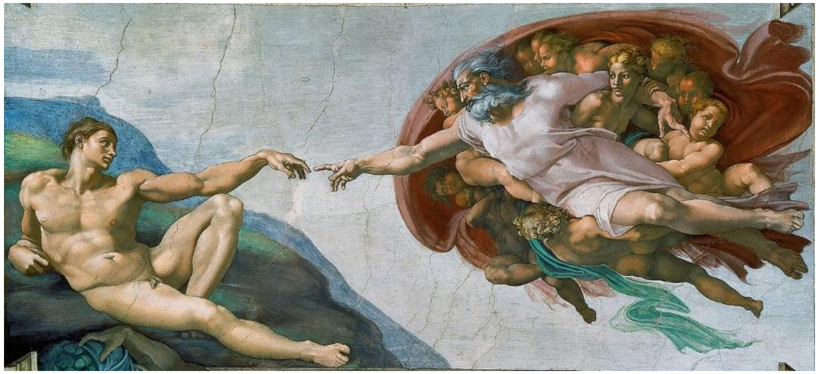
- ❑ Other **LHCb results** presented here:
  - ✓ ***Synergy of BESIII/HIEPA and LHCb physics programs***, *Wenbin Qian*
  - ✓ ***Experimental progress and prospect on Charm CPV search***, *Miroslav Saur*
  - ✓ ***Experimental review of rare charm decays***, *SB*

- ❑ Complete set of the LHCb results in https://cds.cern.ch/collection/LHCb%20Papers?ln=en

The 2nd International Workshop on
High Intensity Electron-Positron Accelerator (HIEPA) @ 2-7GeV in China (HIEPA2018)
March 19-21, 2018
University of Chinese Academy of Sciences (UCAS)
Yanqihu Campus, Huairou, Beijing, China

- **Powerful QCD tests**, instead of using QCD to estimate observables, use production measurements to qualify QCD

Michelangelo: 创建



Botticelli: 分娩

- New theory developments confronted to new experimental results. Impressive progress in both domains
- First clash to describe **« J/ψ production puzzle »**
- **« J/ψ production AND polarization puzzle »** boosted the progress
- Recently with the $\eta_c(1S)$ production measurement by LHCb more challenging **« J/ψ production AND polarization AND $\eta_c(1S)$ production puzzle »**
- **More precision** in conventional studies and **new sources of input**: associated production, isolation, production in pPb and PbPb collisions, …
- Comprehensive model of **charmonium production** still missing

Charmonium production

❑ Two scales of production:

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

❑ **Factorization**:

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

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

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

❑ 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

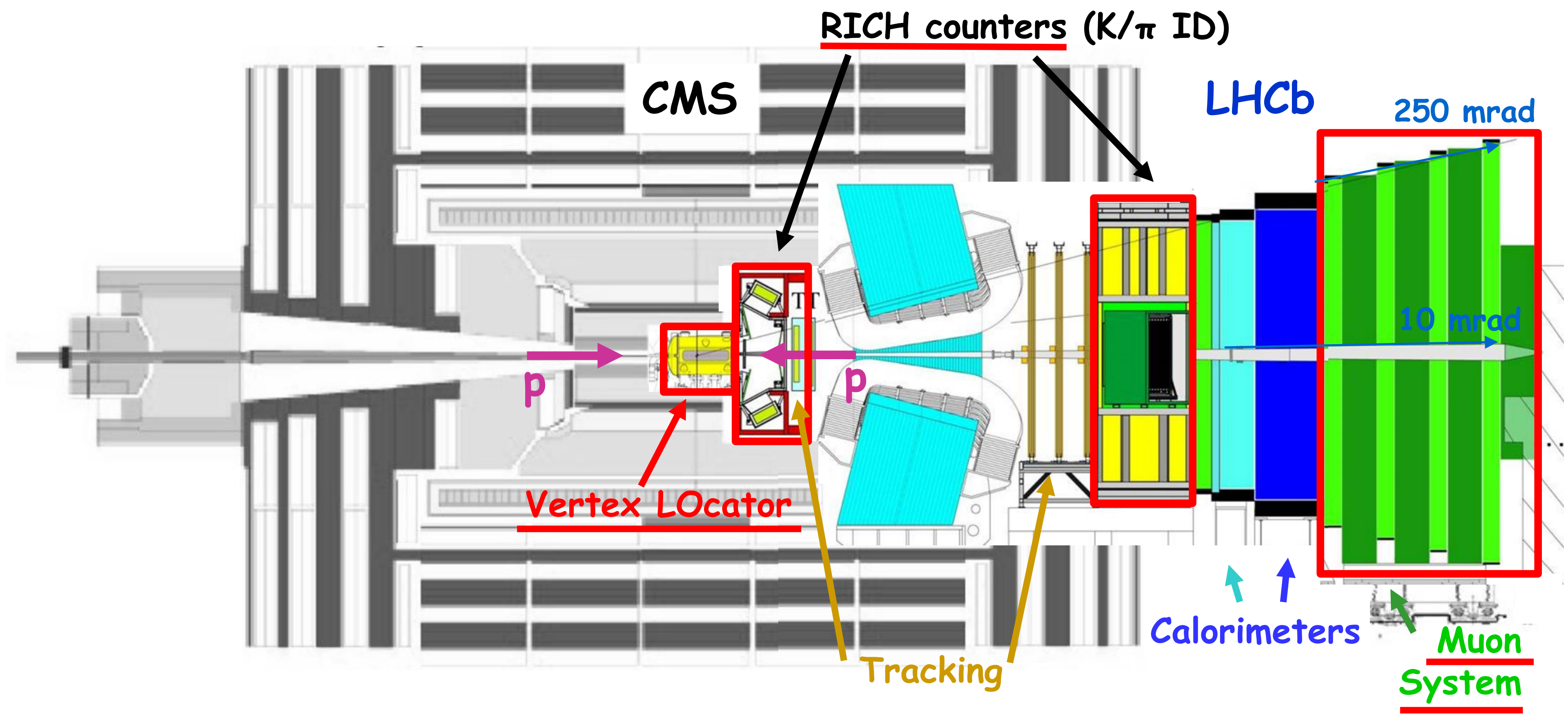
❑ **Universality**: *same LDME for prompt production and production in b-decays*

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

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

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

- **Forward peaked HQ production** at the LHC, second b in acceptance once the first b is in
- Forward region $1.9 < \eta < 4.9$, **~4% of solid angle**, but **~40% of HQ production x-section**

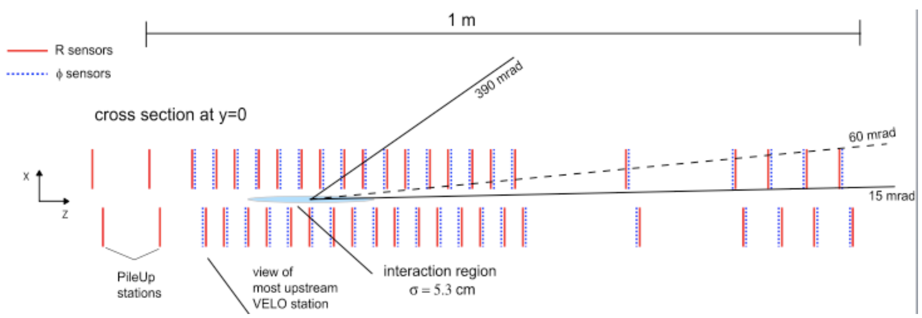


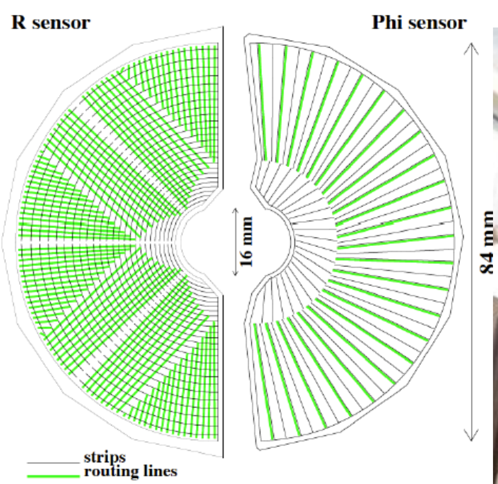
- **Complementary cross-section measurements** and overlap in terms of rapidity
- Key detector systems for production measurements: **vertex reconstruction (VELO), particle identification (Muon detector, RICHs), Trigger**

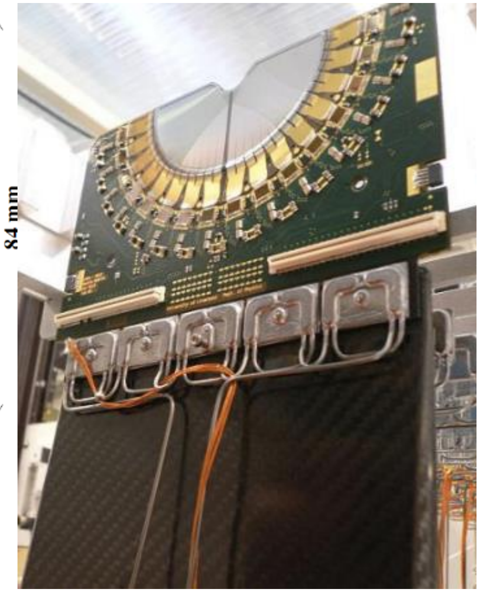
VELO: Vertex LOcator

JINST 8 (2013) P08002, arXiv:1405.7808

- 88 semi-circular **microstrip Si sensors**
- Double-sided, **R and φ** layout, in each module
- 300μ thick n-on-n sensors
- Strip pitches from 40 to 120μ







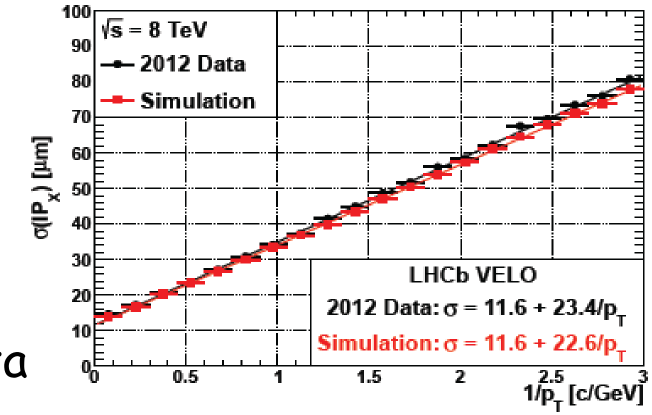
- **First active strip at 8.2mm from the beam axis**
- Moves away every fill and centers around the beam with self measured vertices

VELO: precise reconstruction of tracks and vertices

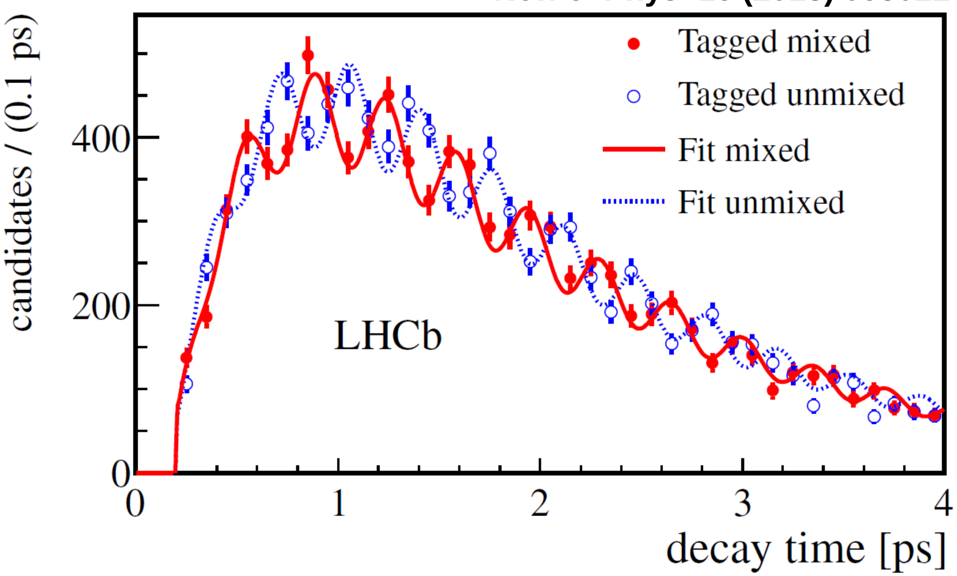
- Excellent **spatial resolution**, down to 4μ for single tracks
- Precise **impact parameter** measurement,
  σ_{IP} = 11.6 + 23.4/pT [μ]
- Precise **primary vertex** reconstruction,
  $\sigma_x = \sigma_x = 13\mu$, $\sigma_z = 69\mu$ for a vertex of 25 tracks
- Detector well understood, simulation describes data
- VELO provides excellent **proper time** resolution

Int.J.Mod.Phys. A30 (2015) 1530022

Impact parameter resolution



New J. Phys. 15 (2013) 053021



- **Vertex resolution** allows to resolve fast (x~27) $B_s\bar{B}_s$ oscillations

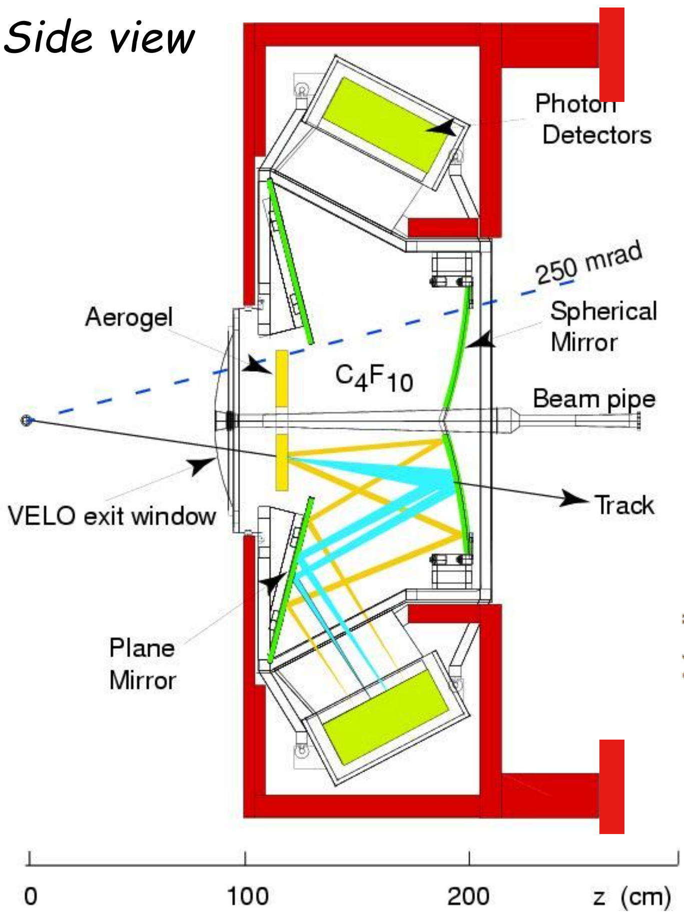
LHCb: charged hadron identification with RICH detectors

***2 Ring Imaging Cherenkov Detectors (RICH)**: **3 Radiators**, photons from Cerenkov cone focused onto rings recorded by **Hybrid Photon Detector** (HPD) arrays, out of acceptance*

RICH 1

Acceptance 25-300 mrad

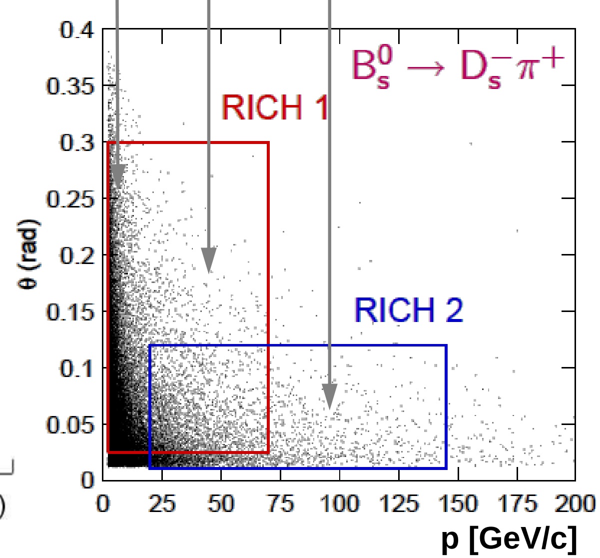
Side view



Silica Aerogel:
n=1.03
1-10 GeV/c

C_4F_{10}:
n=1.0014
Up to ~70 GeV/c

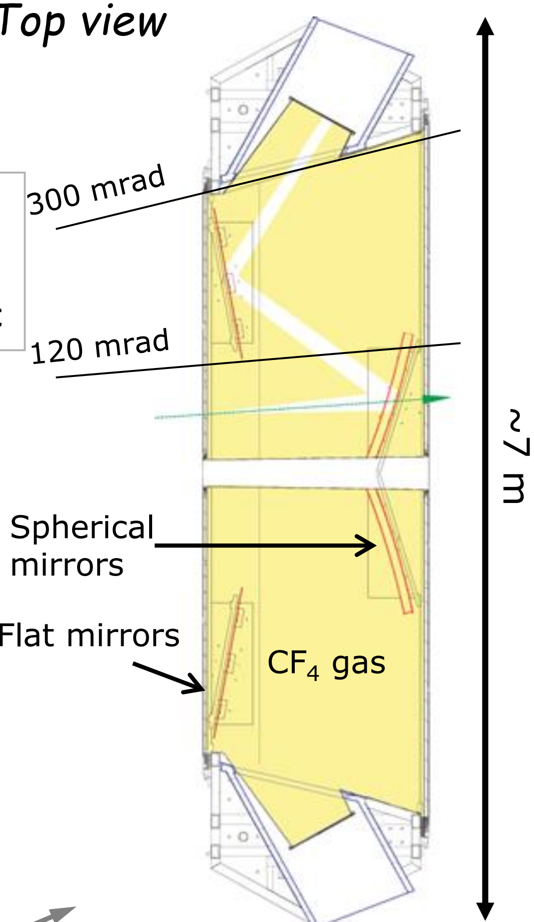
CF_4:
n=1.0005
Up to ~100 GeV/c



RICH 2

Acceptance 15-120 mrad

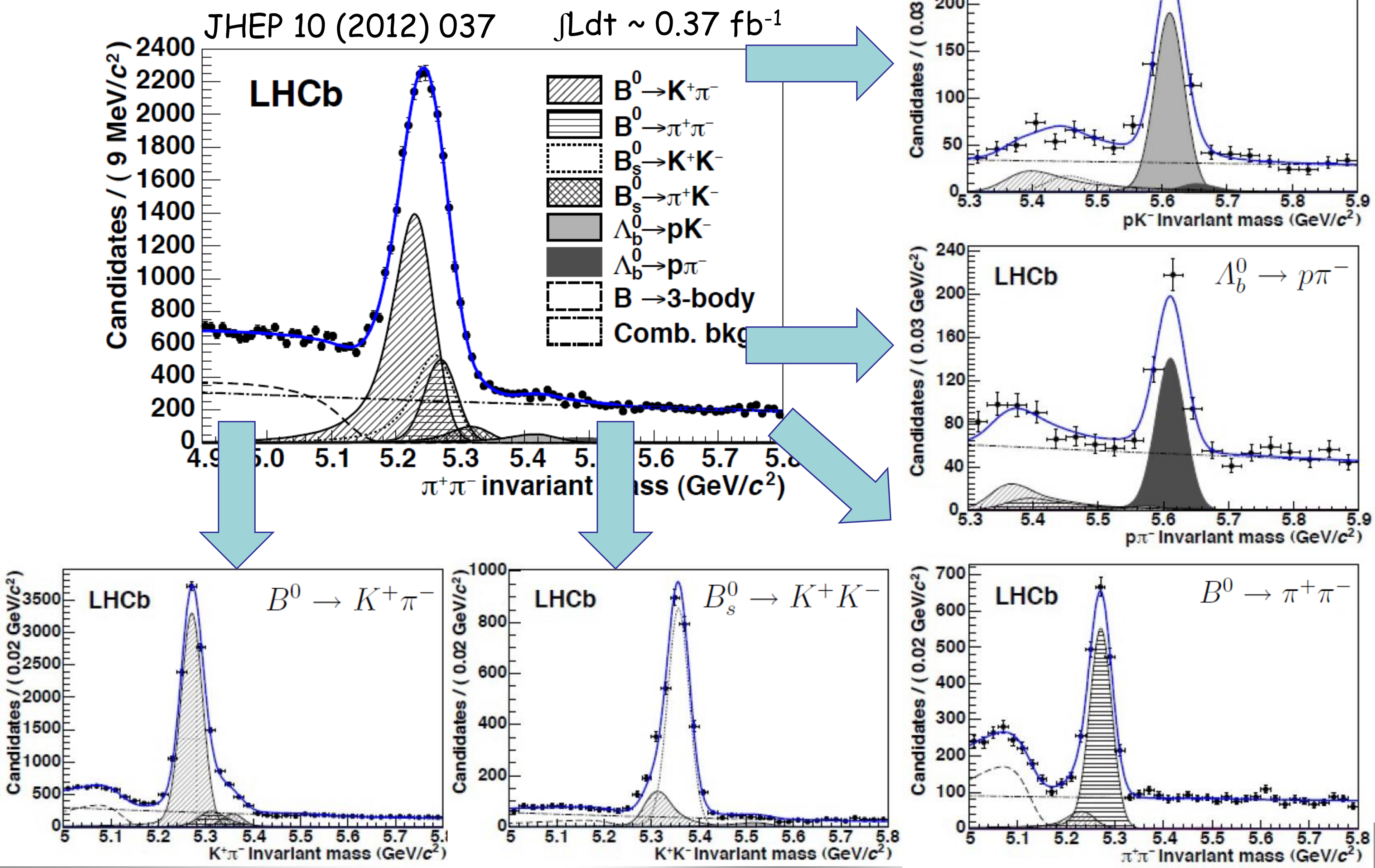
Top view



Note scale difference

LHCb: charged hadron ID with RICH

- *Charmless two-body b-hadron decays*



LHCb integrated luminosity
$\sqrt{s}$ = 7 TeV, $\int Ldt \sim 1.2\ fb^{-1}$
$\sqrt{s}$ = 8 TeV, $\int Ldt \sim 2.1\ fb^{-1}$
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 3.7\ fb^{-1}$

- **Quarkonia production** :
  - (*) J/ψ production ($\sqrt{s}$ = 13 TeV)
  - χ_c and $\eta_c(2S)$ production in b-hadron decays
- **Associated production** : Double J/ψ production ($\sqrt{s}$ = 13 TeV)
- **Production in jets** : J/ψ production ($\sqrt{s}$ = 13 TeV)
- **Central Exclusive Production** of J/ψ and ψ(2S) ($\sqrt{s}$ = 13 TeV)
- **Charmonium production in pPb collisions** : J/ψ and ψ(2S) ($\sqrt{s_{NN}}$ = 5 TeV)

(*) ***UPDATE****: An issue was identified in the simulated samples used to calculate* ***track reconstruction efficiencies for some LHCb Run II production papers.***

Reason: VELO simulation updated prior to Run II to account for radiation damage, but error in the parametric correction for the effect. Track efficiency calibration in data was unable to correct mis-modeling; track reconstruction efficiency underestimated in simulation; most affected: low pseudorapidity and low p_T.

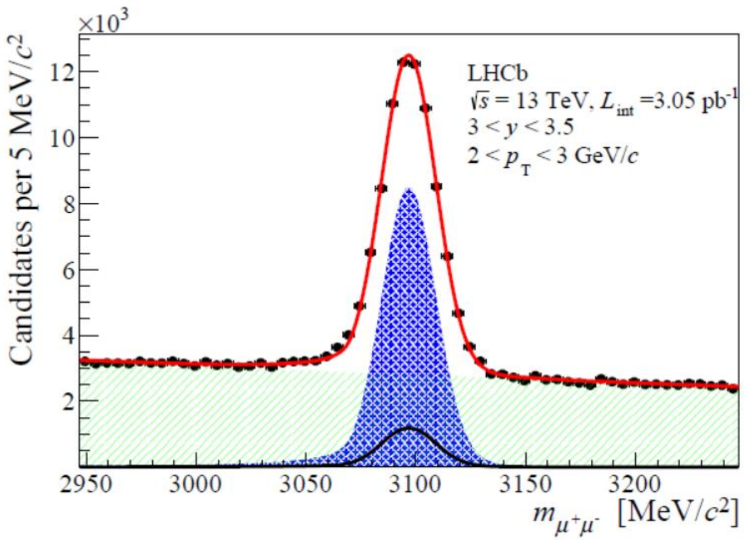
- Tests of **perturbative and non-perturbative regimes of QCD**
- **No consistent model describing simultaneously J/ψ and η_c production and J/ψ polarization in the whole p_T range**

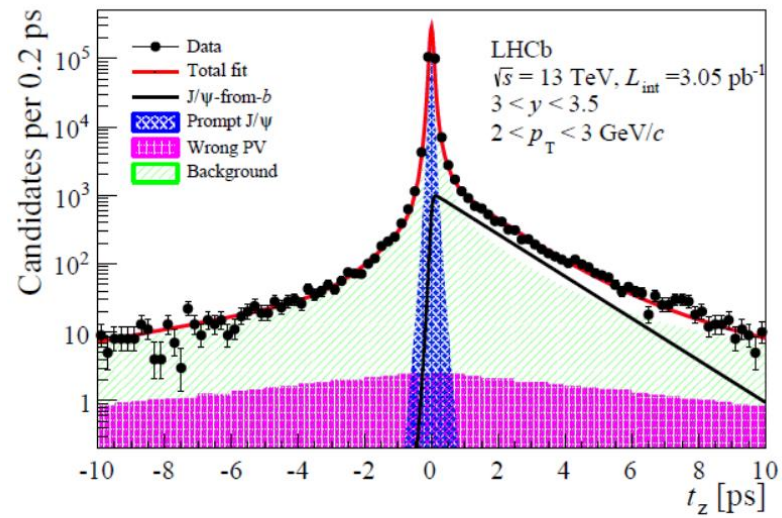
- J/ψ production at 2.76 TeV — **JHEP 1302 (2013) 041**
- J/ψ production at 7 TeV — **EPJC 71 (2011) 1645**
- J/ψ production at 8 TeV — **JHEP 1306 (2013) 064**
- J/ψ production at 13 TeV — **JHEP 1510 (2015) 172**, Err.: **JHEP 1705 (2017) 063**

- **Prompt J/ψ production** and **production in b-hadron 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

JHEP 1510 (2015) 172
JHEP 1705 (2017) 063
$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 3 pb^{-1}

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





- Production **cross-section, integrated over acceptance** :

$$\boxed{\begin{aligned}\sigma(\text{prompt } J/\psi, p_T < 14\,\text{GeV}/c, 2.0 < y < 4.5) &= 15.03 \pm 0.03 \pm 0.94\,\mu\text{b} \\ \sigma(J/\psi\text{-from-}b, p_T < 14\,\text{GeV}/c, 2.0 < y < 4.5) &= 2.25 \pm 0.01 \pm 0.14\,\mu\text{b}\end{aligned}}$$

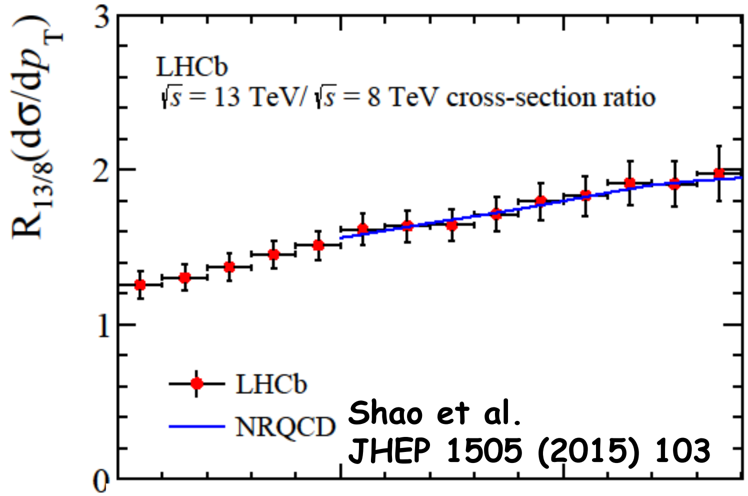
- **$b\bar{b}$ cross-section**, integrated over 4π : $\boxed{\sigma(pp \to b\bar{b}X) = 495 \pm 2 \pm 52\,\mu\text{b}}$

using extrapolation factor $\alpha_{4\pi}$ = 5.2 from the LHCb tuning of PYTHIA 6
JHEP 0605 (2006) 026

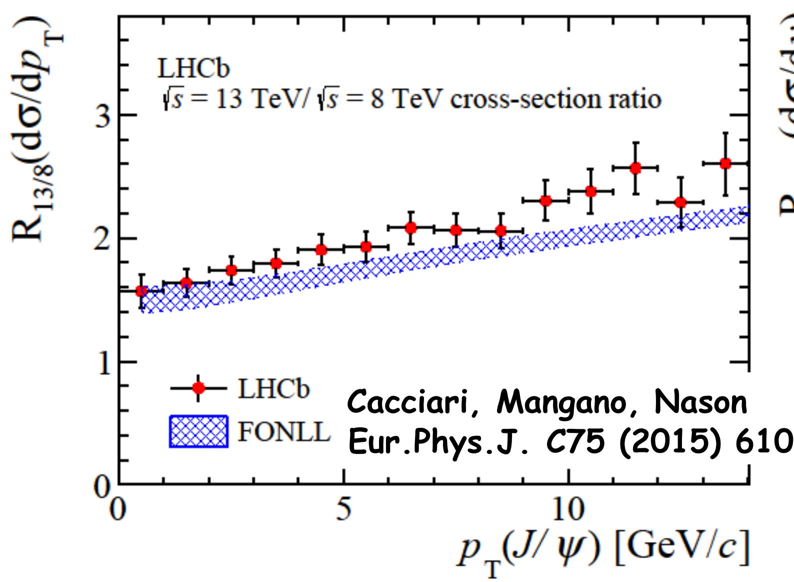
- The **J/ψ production** measured **at √s = 13 TeV** and compared to that **at √s = 8 TeV** and **theory**

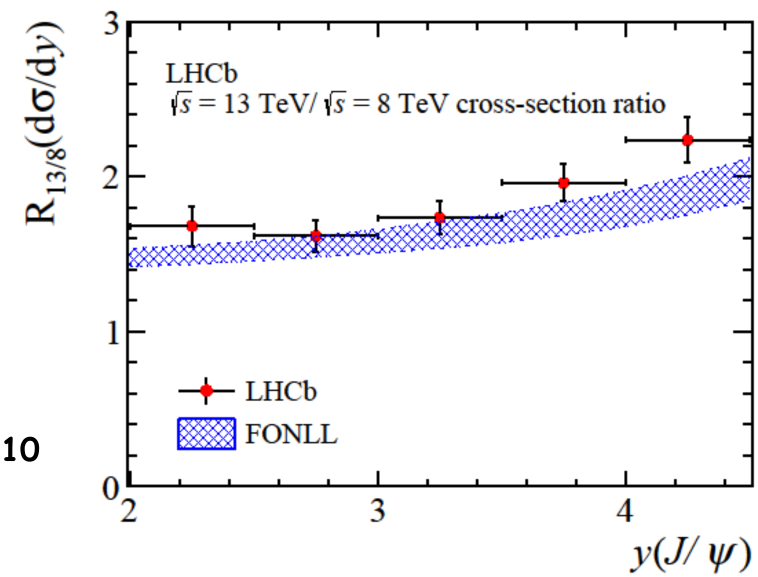
JHEP 1510 (2015) 172
JHEP 1705 (2017) 063
√s = 13 TeV, ∫Ldt ~ 3 pb^{-1}

- **Prompt production**



- **Production in b-decays**





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

J/ψ and $\eta_c(1S)$ production in inclusive b-decays

Usachov,Kou,SB, LAL-17-051

- From **EPJC 75 (2015) 311** and **Chin. Phys. C40 (2016) 100001**:

$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)} = 0.691 \pm 0.090 \pm 0.024 \pm 0.103$$

- Relation between LDME from HQSS:

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

- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**

- **Fit two LDME to measurements**
- Consecutively fix two remaining LDME from **Han et al., PRL 114 (2015) 092005**

- **4 LDME and 2 measurements:**

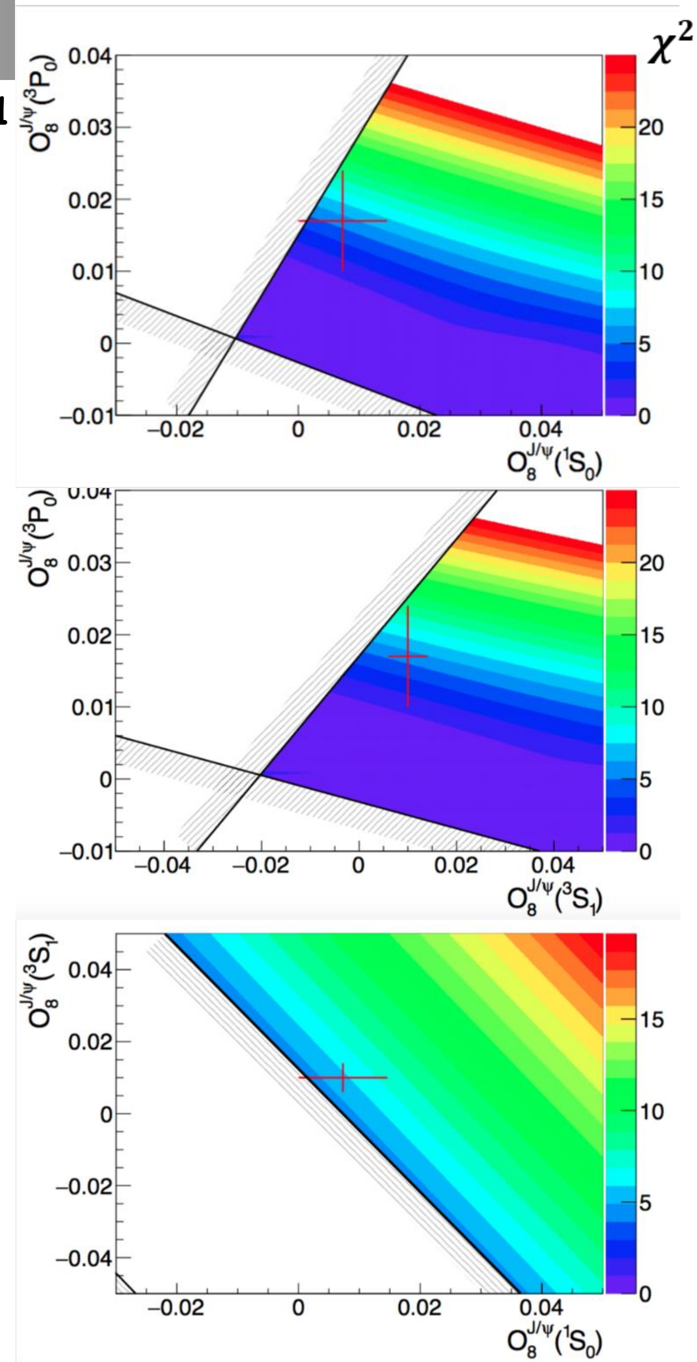
$$\boxed{\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)}} \qquad \boxed{\mathcal{B}(b \to J/\psi^{direct} X)}$$

J/ψ and $\eta_c(1S)$ production in inclusive b-decays

Usachov, Kou, SB, LAL-17-051

- **Fit two LDME to measurements**
- Consecutively fix two remaining LDME from
  Han et al., PRL 114 (2015) 092005
- Theory uncertainties are conservatively taken into account
- Points with error bars correspond to the matrix elements determined from prompt production in
  Han et al., PRL 114 (2015) 092005

$$\langle O_1^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$$



J/ψ and $\eta_c(1S)$ production in inclusive b-decays

Usachov, Kou, SB, LAL-17-051

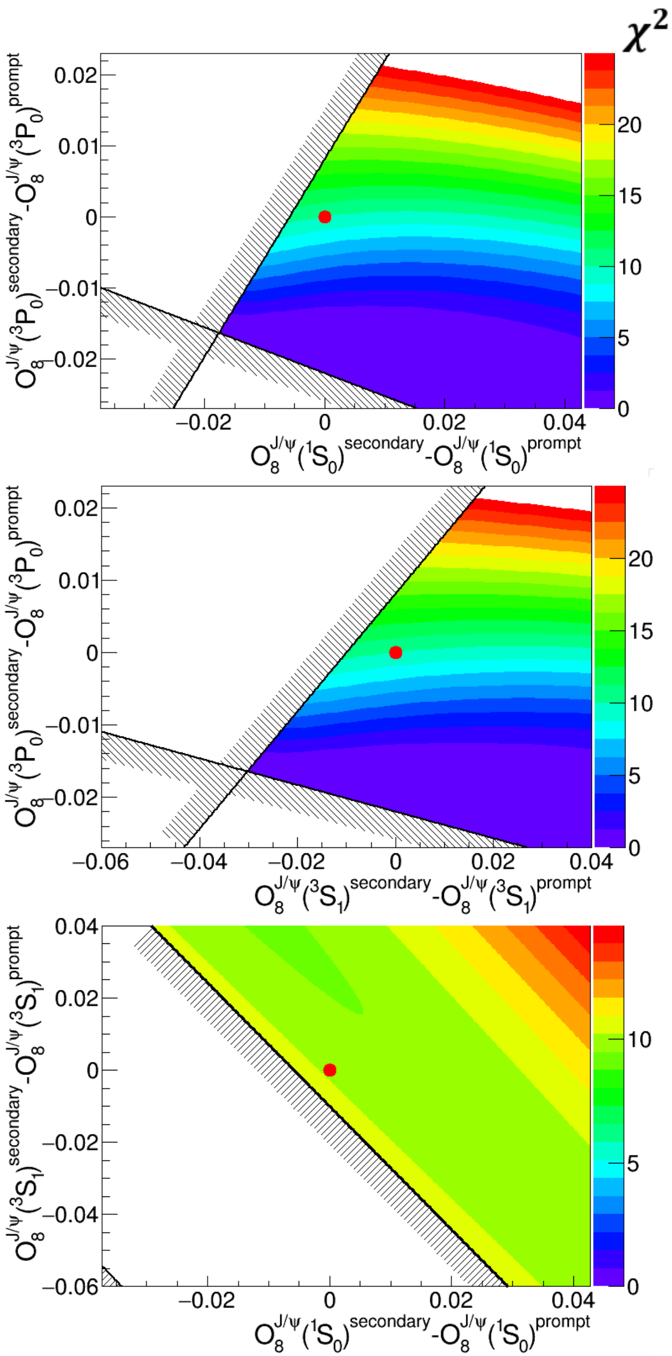
- **Fit two LDME to measurements**
- Shown are **differences between matrix elements determined from charmonium production in b-decays and those from prompt charmonium production**

  Han et al., PRL 114 (2015) 092005
- Consecutively fix two remaining LDME from

  Han et al., PRL 114 (2015) 092005
- Theory uncertainties are conservatively taken into account
- Red points correspond to identical matrix elements in b-decays and in prompt production

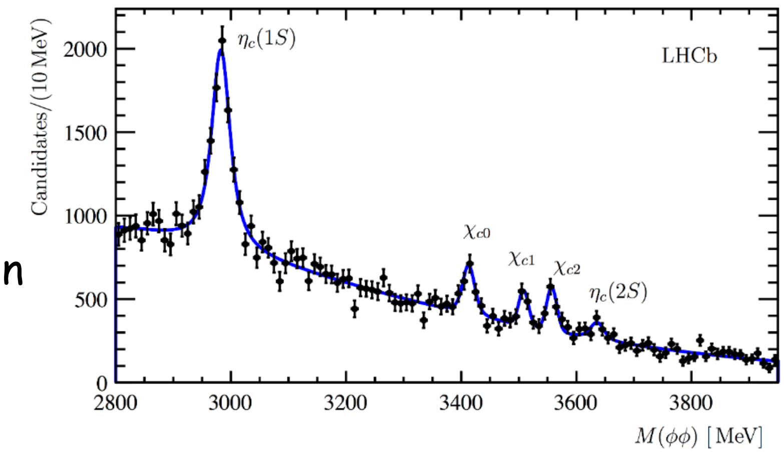
$$\langle O_1^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$$

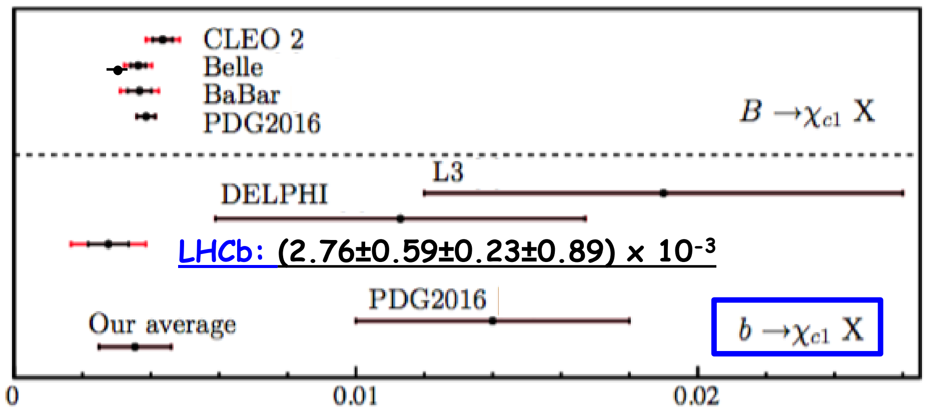
- Important to improve precision of $\eta_c(1S)$ hadroproduction measurements

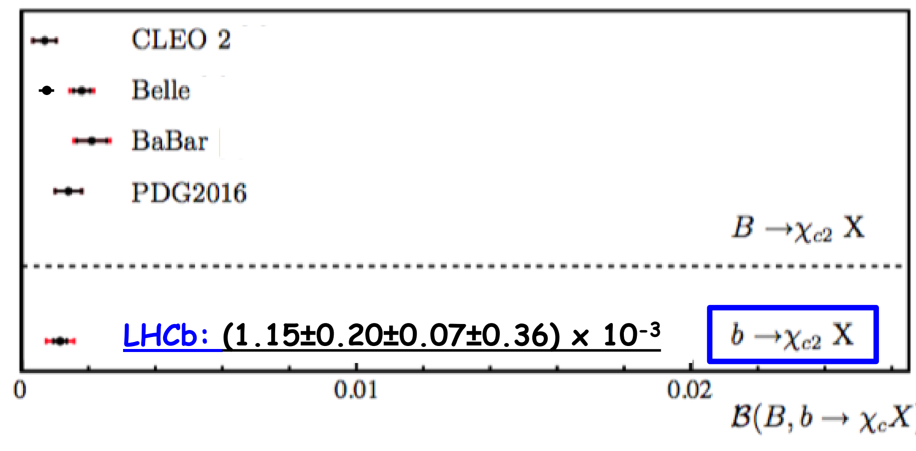


EPJC 77 (2017) 609

- Charmonium reconstructed via **decays to φφ**; true φφ combinations using 2D fit technique
- First measurement of χ_{c0} production in b-hadron decays: **BR(b→χ_{c0}X)=(3.02±0.47±0.23±0.94)x10^{-3}**
- Most precise measurements of χ_{c1} and χ_{c2} production in b-decays, consistent with B-factories







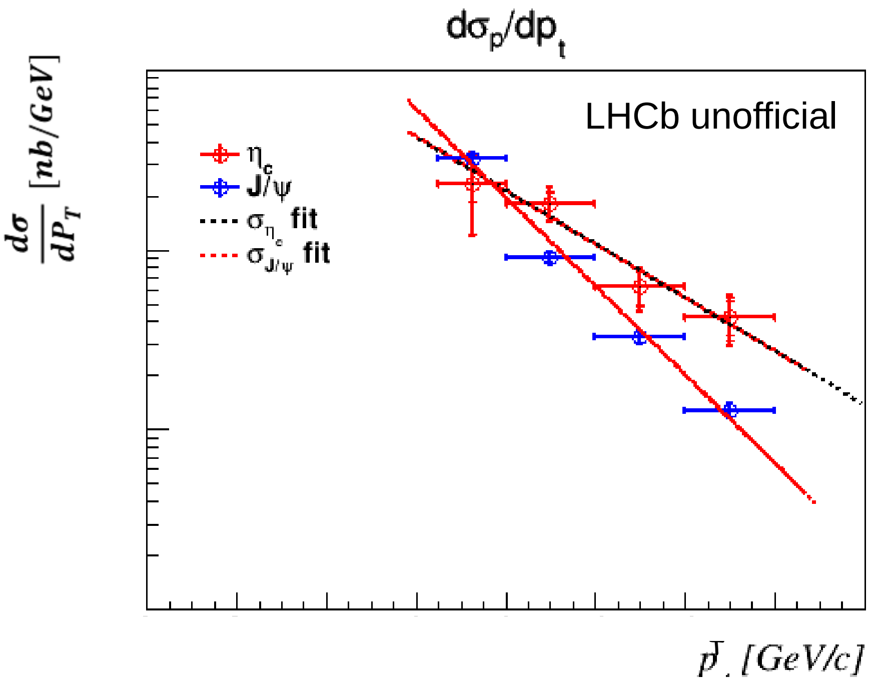
- First measurement of $\eta_c(2S)$ production in b-decays; first evidence for $\eta_c(2S)$→φφ

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

- Important to **measure hadroproduction of $\eta_c(2S)$**

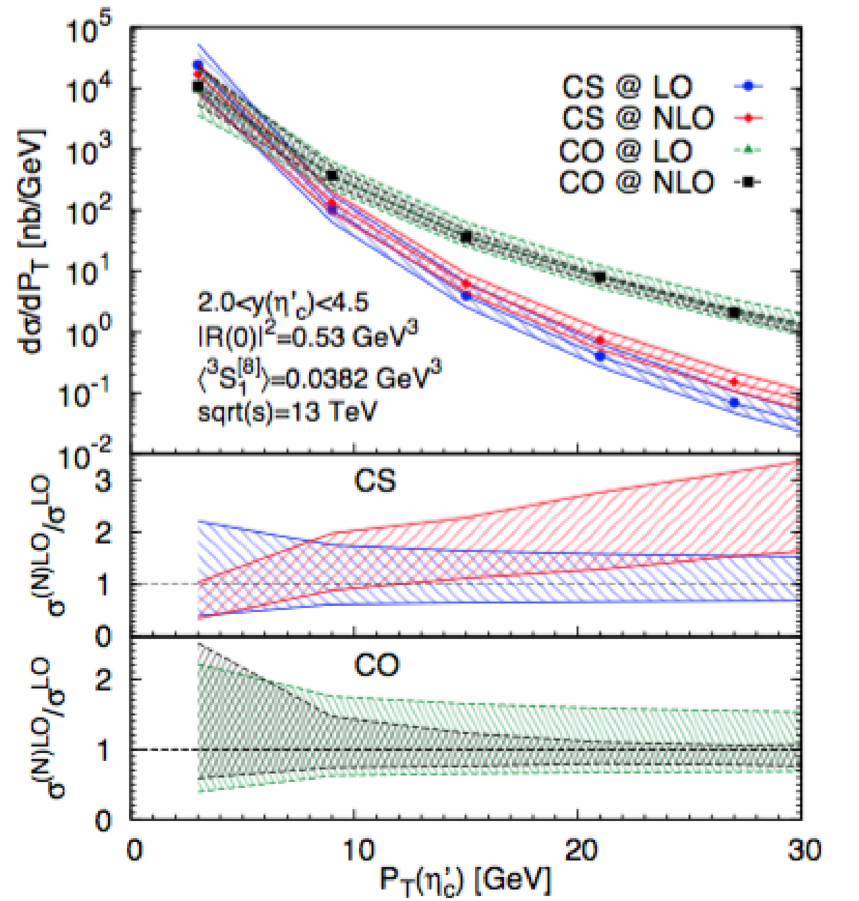
$\eta_c(2S)$ prompt production, perspectives

$\eta_c(1S)$ prompt production at $\sqrt{s} = 13\ TeV$
LHCb, example



$\eta_c(2S)$ prompt production at $\sqrt{s} = 13\ TeV$
Theory prediction

J.P.Lansberg, H.S.Shao, H.F.Zhang, arXiv:1711.00265



- ❑ Educated extrapolation from the hadroproduction of $\eta_c(1S)$: expecting evidence for $\eta_c(2S)$ hadroproduction with Run II data.

Usachov, Kou, SB, LAL-17-051

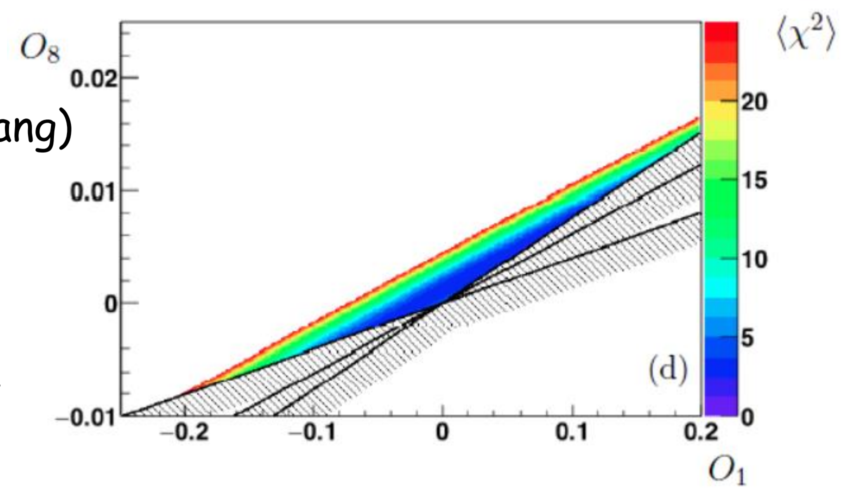
- From **EPJC 77 (2017) 609** and **Chin. Phys. C40 (2016) 100001:**

$$\mathcal{B}(b \to \chi_{c0}{}^{direct} X) = (2.74 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1}{}^{direct} X) = (2.49 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2}{}^{direct} X) = (0.89 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3}$$

- Relation between LDME from HQSS:

$$O_1 \equiv \langle O_1^{\chi_{c0}}(^3P_0)\rangle / m_c^2,$$
$$O_8 \equiv \langle O_8^{\chi_{c0}}(^3S_1)\rangle,$$
$$\langle O_1^{\chi_{cJ}}(^3P_J)\rangle / m_c^2 = (2J+1) O_1,$$
$$\langle O_8^{\chi_{cJ}}(^3S_1)\rangle = (2J+1) O_8.$$

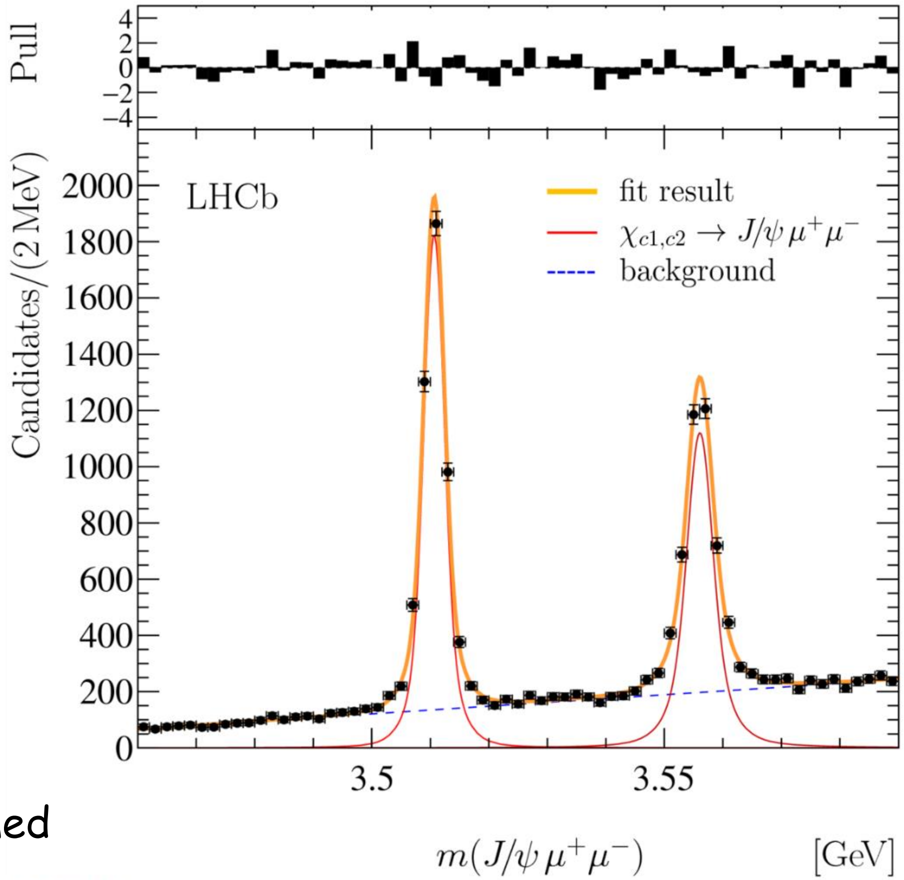
- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**
- **Fit two LDME to three measurements**
- Important to revisit theory calculations (H.-F. Zhang)
- This technique constrains theory using **simultaneously** results on **charmonia hadroproduction and** on **charmonia 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**.

PRL 119 (2017) 221801

- First observations of the decays
  $\chi_{c1,2} \rightarrow J/\psi\ \mu^+\ \mu^-$
- New avenue for hadron spectroscopy at the LHC
- These decay modes will be used to measure the **production of χ_{c1} and χ_{c2}** states with a similar precision to the converted photon studies. Importantly, it will be possible to extend measurements **down to very low p_T** values



- Masses and the natural width of χ_{c2} determined

$$m(\chi_{c1}) = 3510.71 \pm 0.04 \pm 0.09\,\mathrm{MeV}$$
$$m(\chi_{c2}) = 3556.10 \pm 0.06 \pm 0.11\,\mathrm{MeV}$$
$$m(\chi_{c2}) - m(\chi_{c1}) = 45.39 \pm 0.07 \pm 0.03\,\mathrm{MeV}$$
$$\Gamma(\chi_{c2}) = 2.10 \pm 0.20\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})\,\mathrm{MeV}$$

- Tests of **production mechanisms**
- In CS NRQCD LO no feed-down from cascade decays of excited C-even states.

- Double J/ψ production was observed by LHCb with 36 pb^{-1} **PLB 707 (2012) 052**
  In agreement with SPS and also DPS.
- Double charm production cross-section involving open charm **JHEP 1206 (2012) 141**
  Exceeds SPS predictions.
- Associated (bb)(cc) production via B_c^+ production **PRL 114 (2014) 132001**
  In agreement with SPS predictions.
- Associated (bb)(cc) production via Υ(nS) and open charm **JHEP 1607 (2016) 052**
  In agreement with DPS, exceeds SPS predictions.
- Double J/ψ production at 13 TeV **JHEP 1706 (2017) 047**

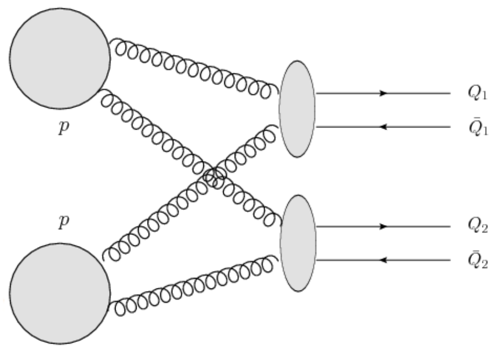
Double J/ψ production at $\sqrt{s}$=13 TeV

- Production via **Double Parton Scattering** (DPS) or **Single Parton Scattering** (SPS)

JHEP 1706 (2017) 047
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 279\ pb^{-1}$

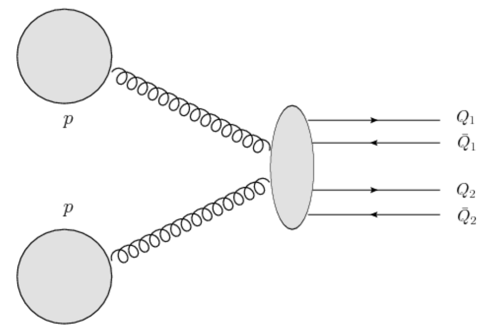
- **DPS**: two independent hard scatters that are assumed to factorize
- **SPS**: gluon splitting expected to dominate $c\bar{c}$ production

DPS

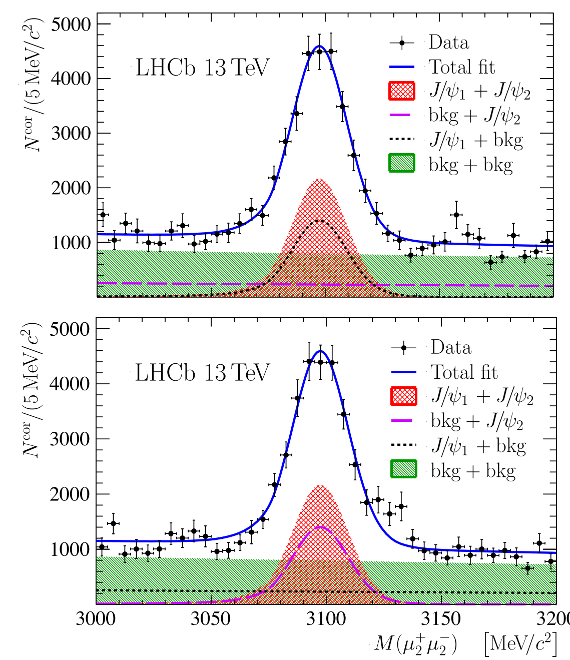


$$\sigma_{\mathrm{DPS}}(J/\psi\, J/\psi) = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma_{\mathrm{eff}}}$$

SPS



- DPS provides important information on gluon correlations and parton p_T-distribution



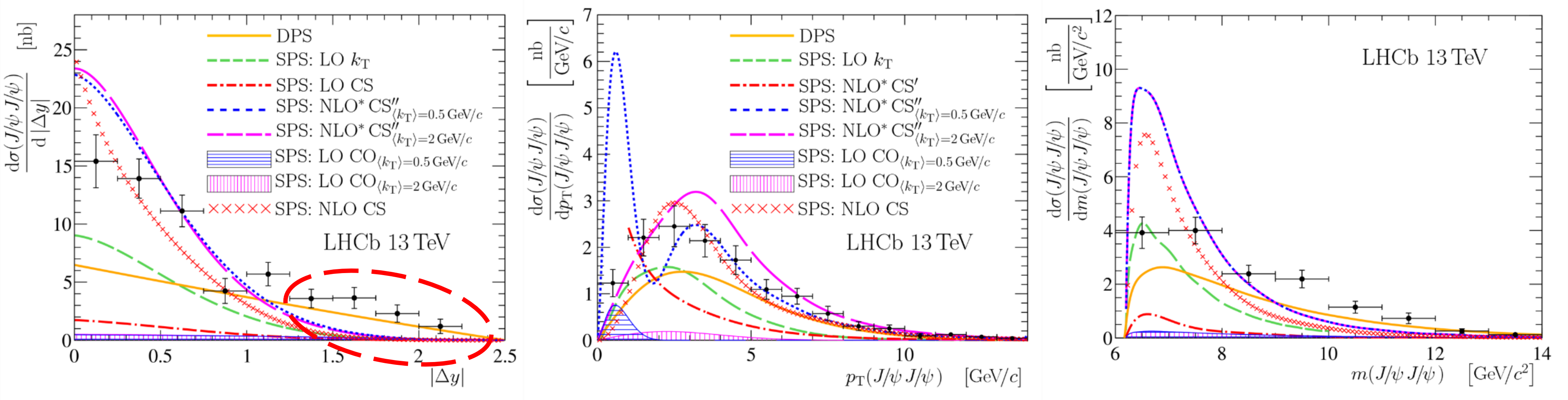
- Each J/ψ in the fiducial volume: p_T < 10 GeV/c, 2.0 < y < 4.5
- Assumed no J/ψ polarization
- The **J/ψ pair production cross-section**

$$\boxed{\sigma(J/\psi\, J/\psi) = 15.2 \pm 1.0\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst})\ \mathrm{nb}}$$

JHEP 1706 (2017) 047

$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 279\ pb^{-1}$

- **Differential production cross-section** in bins of kinematical variables

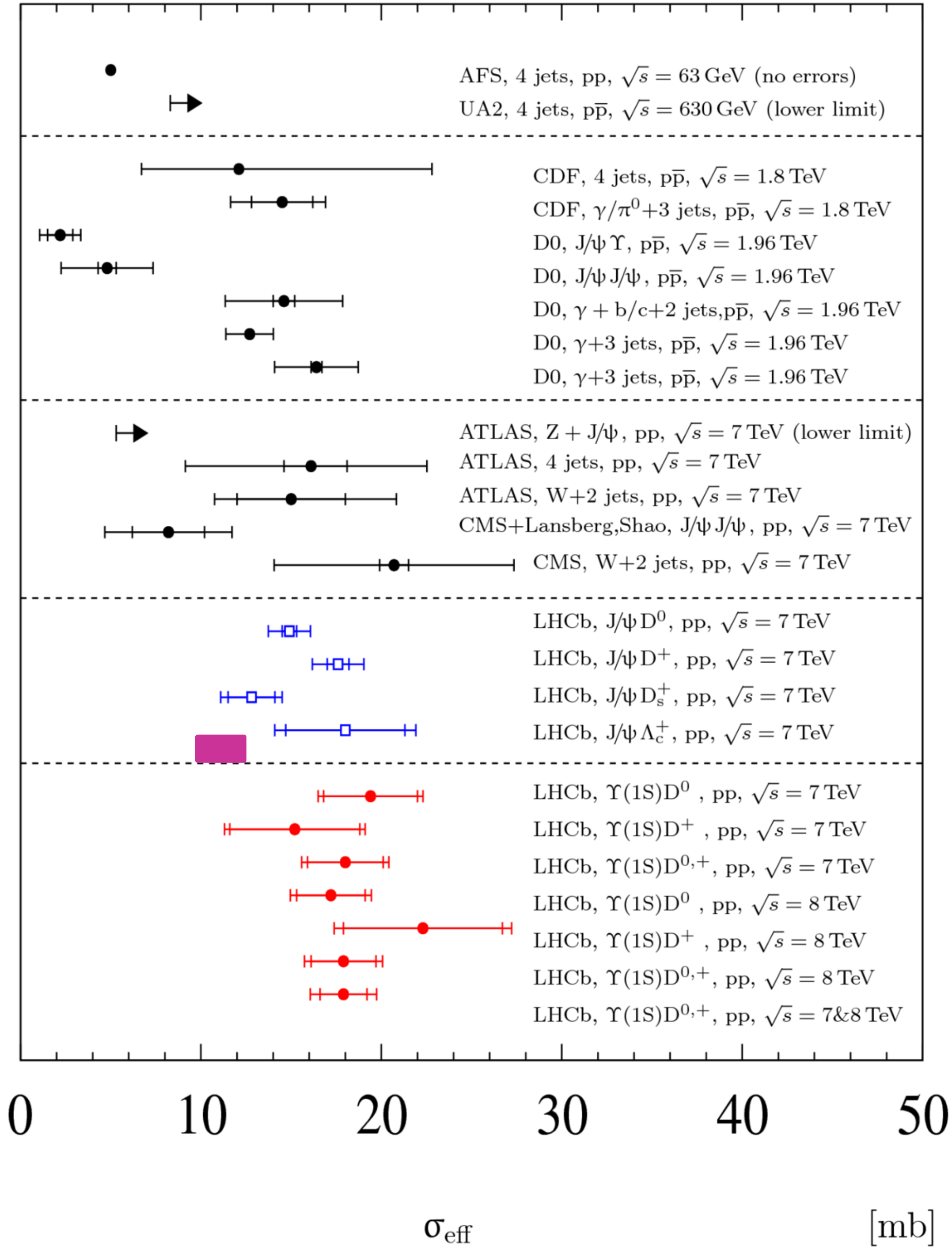


- **Evidence for DPS at high |Δy| region** — **Kom, Kulesza, Stirling, PRL 107 (2011) 082002**
- Fit of kinematical distributions to extract DPS fraction and σ_{eff}
- Agreement between fits of $|\Delta y|$, $p_T(J/\psi J/\psi)$, $y(J/\psi J/\psi)$, $m(J/\psi J/\psi)$
- Using various SPS descriptions, σ_{eff} ~ 10-12 mb

Double J/ψ production at $\sqrt{s}$=13 TeV

- Compilation of results on σ_{eff}

LHCb, $J/\psi J/\psi$, pp, $\sqrt{s}$=13 TeV
JHEP 1706 (2017) 047



J/ψ production in jets at $\sqrt{s}$=13 TeV

PRL 118 (2017) 192001
$\sqrt{s}$ = 13 TeV, $\int L dt \sim 1.4\ fb^{-1}$

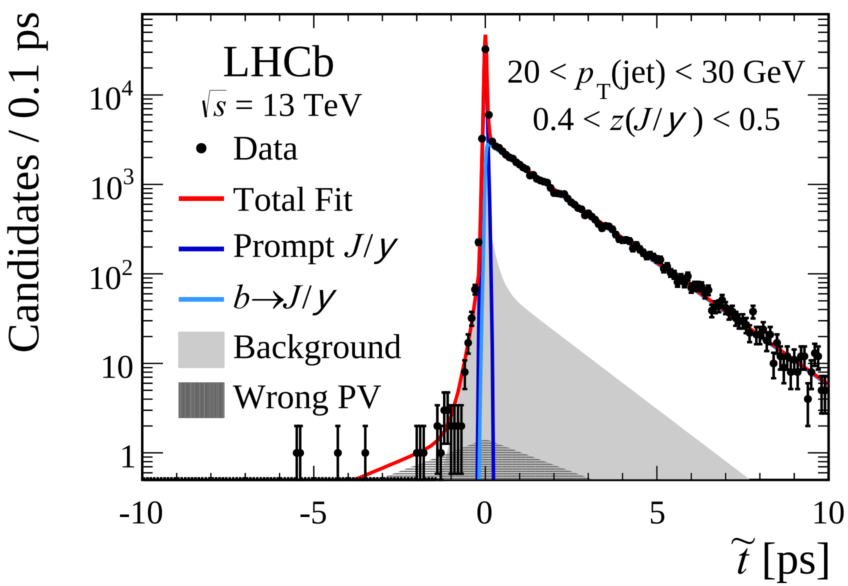
- J/ψ produced in direct **parton scattering** or through **parton showering**
- Significant J/ψ production in showers can explain lack of observed polarization
- Anti-k_T algorithm
- **Fiducial region**
  - Jets: $p_T > 20$ GeV/c, $2.5 < \eta < 4.0$
  - J/ψ: $2.0 < \eta < 4.5$

- Fraction of the jet transverse momentum carried by J/ψ:

$$z(J/\psi) = p_T(J/\psi) / p_T(\text{jet})$$

- Separate prompt J/ψ and J/ψ from b-decays using pseuso-lifetime:

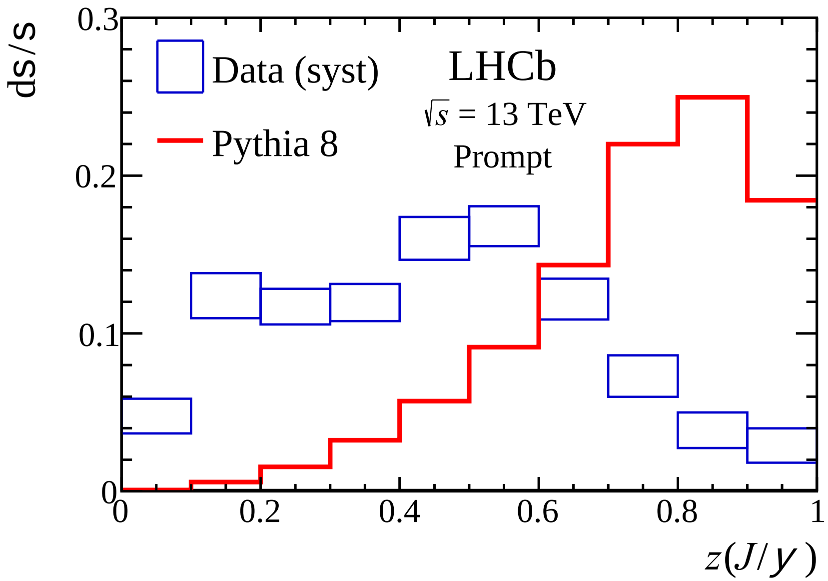
$$\tilde{t} \equiv \lambda m(J/\psi)/p_L(J/\psi)$$

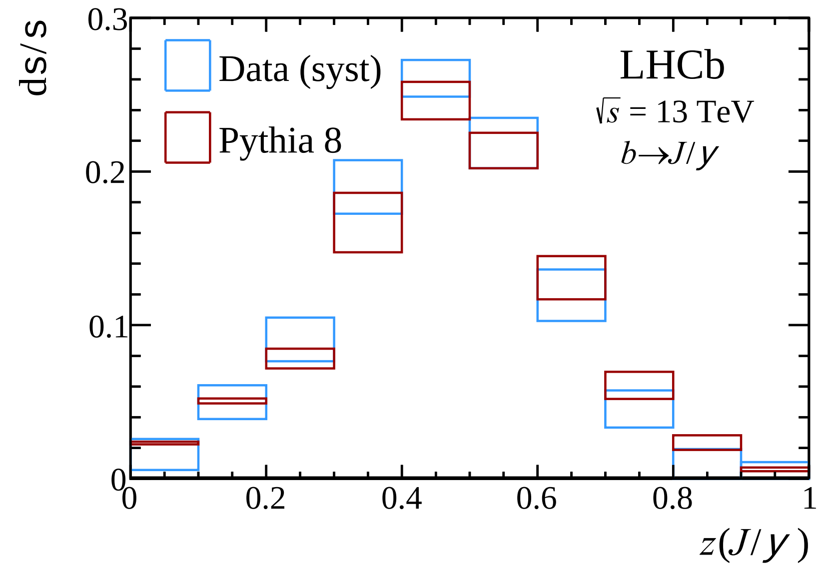


J/ψ production in jets at $\sqrt{s}$=13 TeV

- Fit in bins of z(J/ψ)
- J/ψ yields corrected for detection efficiency by applying per-candidate weights (no knowledge of J/ψ polarization required)

PRL 118 (2017) 192001
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 1.4\ fb^{-1}$

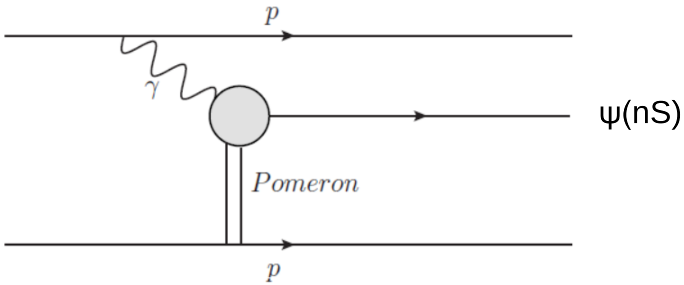




- z(J/ψ) distribution for J/ψ produced in b-decays is consistent with the Pythia 8 prediction
- **Prompt J/ψ are less isolated than the prediction of Pythia based on fixed-order NRQCD**
- Indication for significant contribution from parton showering

Bain et al., JHEP 1606 (2016) 121
Bain et al., arXiv:1702.02947

- CEP: **QCD tests with clean theoretical interpretation**
- Only **CS production**
- Sensitivity with cross-sections in the LHCb coverage down to $x \sim 1.5 \times 10^{-5}$



Results at 7 and 8 TeV

- Exclusive J/ ψ and ψ(2S) production at 7 TeV — JPG 41 (2014) 055002
- Exclusive ϒ production at 7 and 8 TeV — JHEP 1509 (2015) 084
- Double charmonia production at 7 and 8 TeV — JPG 40 (2013) 045001
- Exclusive χ_c and $\mu^+\mu^-$ production (preliminary) — LHCb-CONF-2011-022

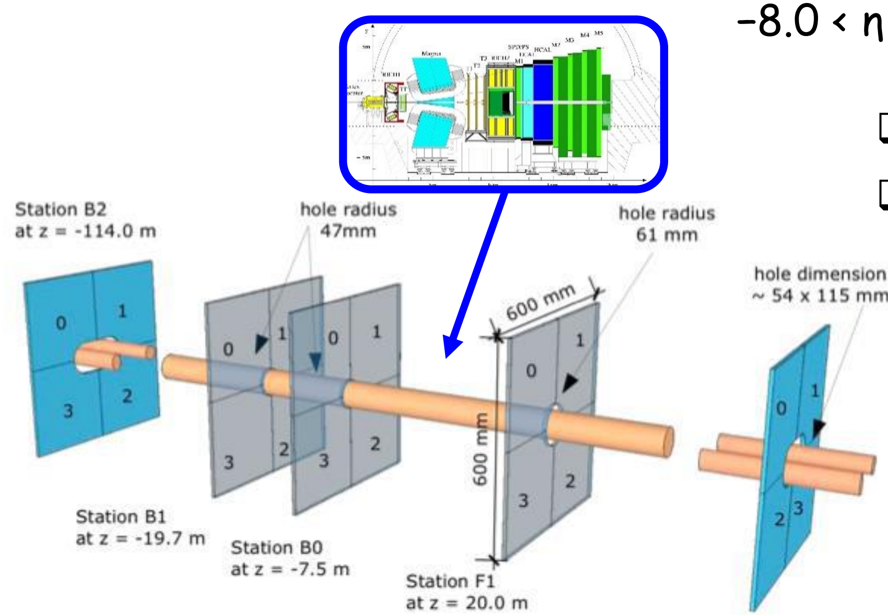
Results at 13 TeV (new Herschel detector)

- Exclusive J/ψ and ψ(2S) production at 13 TeV — LHCb-CONF-2016-007

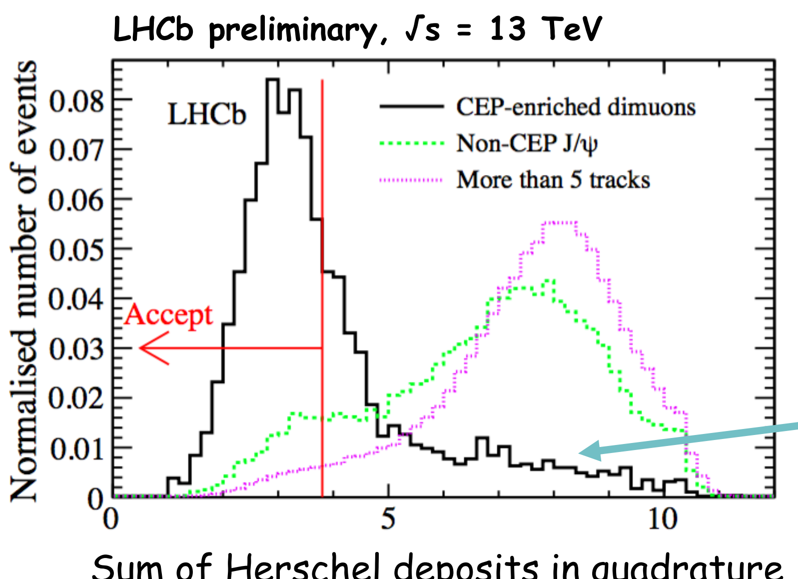
Central Exclusive Production of J/ψ and ψ(2S)

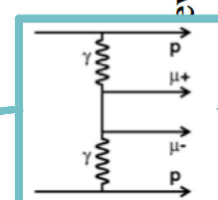
- New **Herschel detector** increases rapidity gap in forward region $-8.0 < \eta < -1.5$, $5.0 < \eta < 8.0$

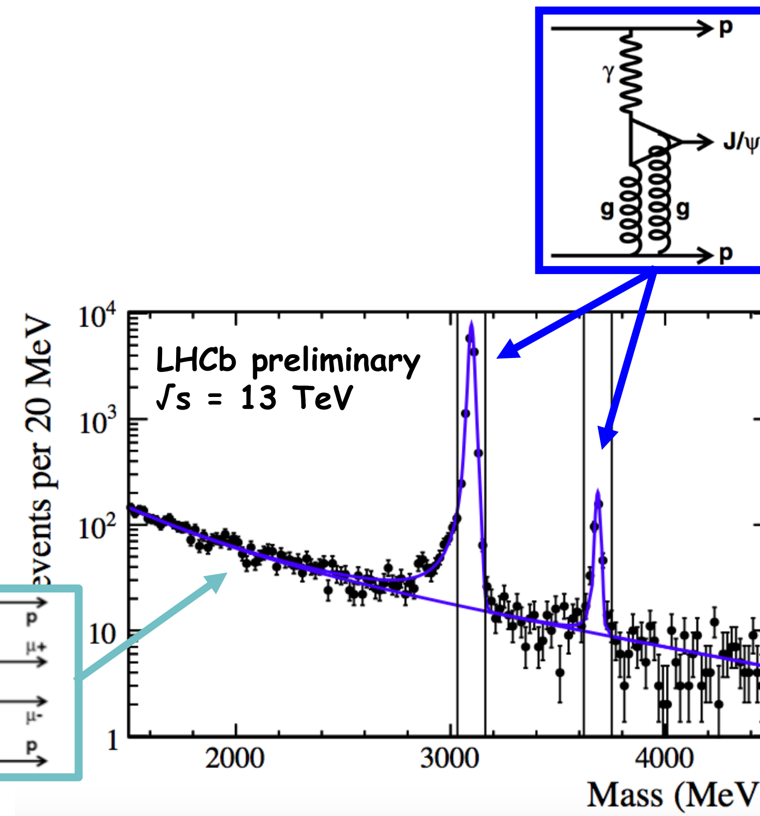
LHCb-CONF-2016-007
$\sqrt{s}$=13 TeV, $\int L dt \sim 0.2\ \mathrm{fb}^{-1}$



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







LHCb-CONF-2016-007

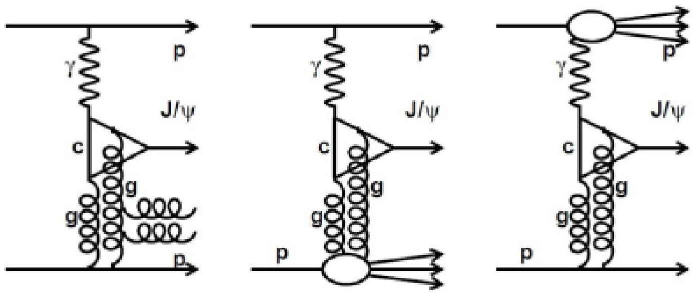
$\sqrt{s}$=13 TeV, $\int Ldt$ ~0.2 fb^{-1}

Signal shape

- Estimated from Superchic using exp(- b p_T^2)
- Slope b estimated from HERA data. Agreement to the fit of LHCb data

Inelastic backgrounds

- One/two protons dissociate(s) or additional gluon radiations. Extra particles are undetected.
- P_T shape estimated from data, cross checked with PYTHIA, LPAIR

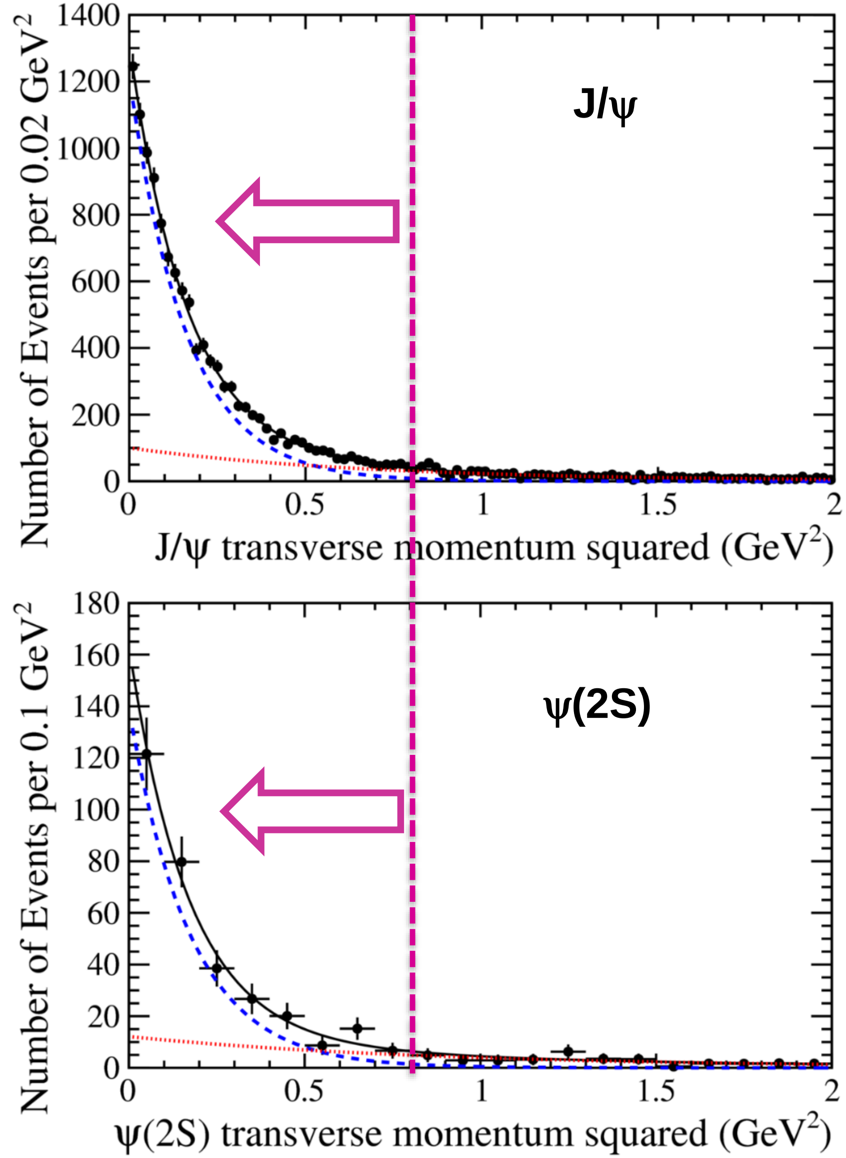


Feed-down

$\psi(2S) \rightarrow J/\psi\pi\pi$: $2.5 \pm 0.2\%$

$\chi_c \rightarrow J/\psi\gamma$ $7.6 \pm 0.9\%$

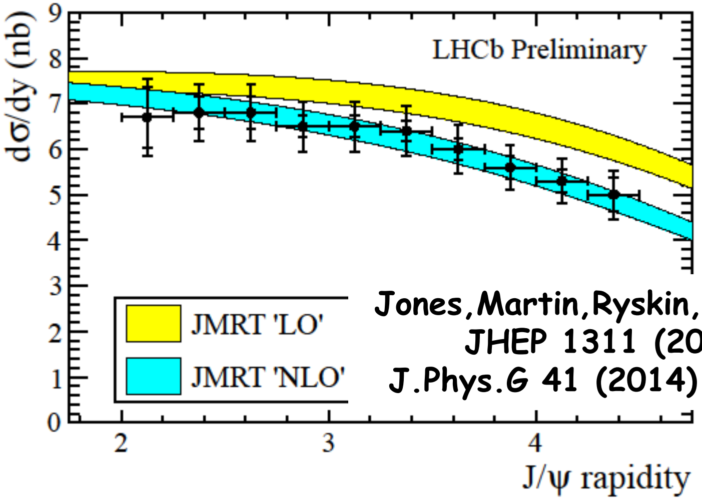
$X(3872) \rightarrow \psi(2S)\gamma$ $2.0 \pm 2.0\%$



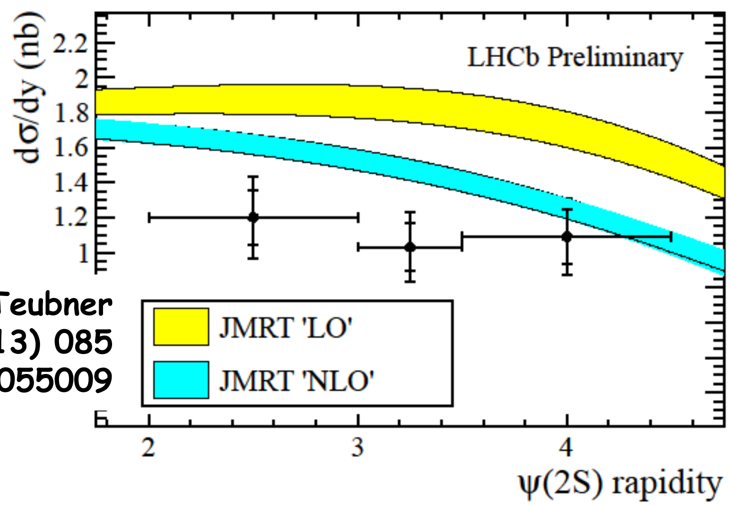
- Differential cross-section compared to theory predictions

LHCb-CONF-2016-007

$\sqrt{s}$=13 TeV, $\int Ldt$ ~0.2 fb^{-1}



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



- Integrated cross-sections times branching fractions

$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 407 \pm 8 \pm 24 \pm 16 \text{ pb}$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 9.4 \pm 0.9 \pm 0.6 \pm 0.4 \text{ pb}$$

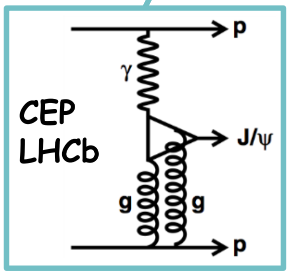
- **Good agreement with NLO predictions**
- Confirms a hint of NLO importance from the analysis at 7 TeV

Photo-production cross-section

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

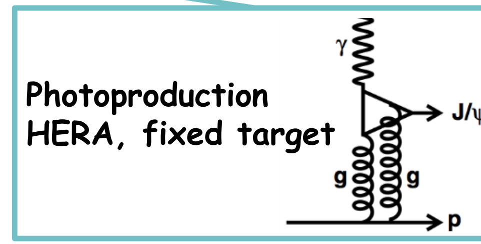
LHCb-CONF-2016-007
$\sqrt{s}$=13 TeV, $\int Ldt$ ~0.2 fb^{-1}

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



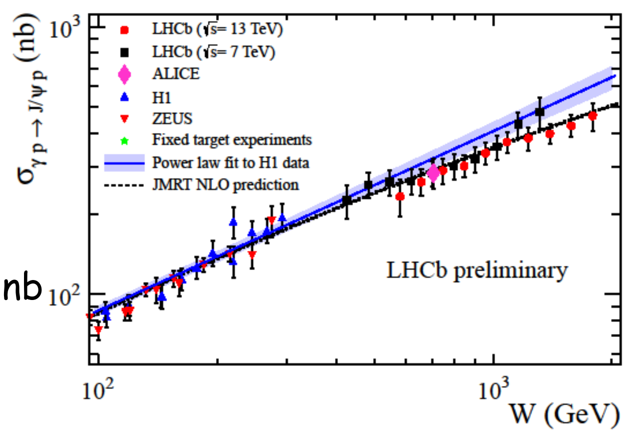
Gap survival

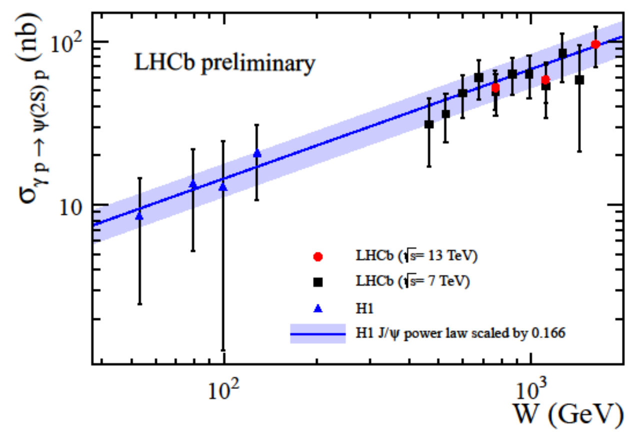
Photon flux



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

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





- Good agreement between LHCb results at 7 and 13 TeV
- J/ψ photo-production cross-section: **deviation from a pure power-law extrapolation of HERA data; agreement to theory prediction**

198.– Les lutteurs

- **Suppression of heavy quarkonia** production in heavy ion collisions as a **signature of QGP formation**
- **Distinguish CNM** expected in proton-ion collisions **from QGP**

- Systematic studies of the production of J/ψ and ψ(2S) in pPb collisions.

- **Prompt ψ(2S) production** and **production in b-hadron decays**

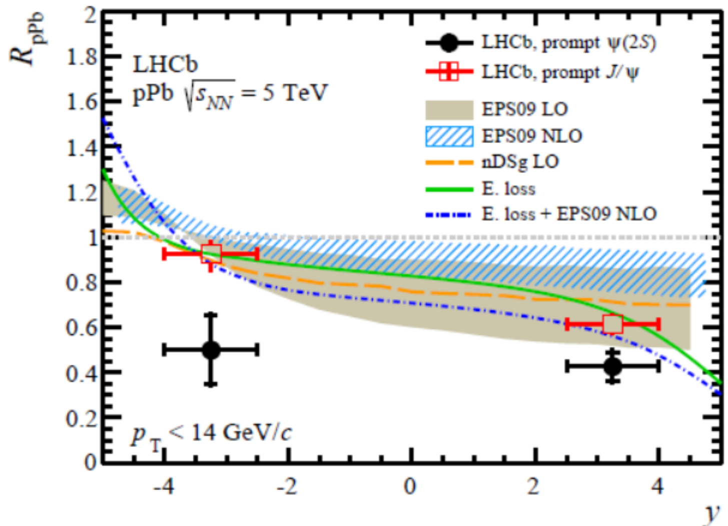
JHEP 03 (2016) 133

$\sqrt{s_{NN}}$ = 5 TeV, ∫Ldt ~ 1.6 nb^{-1}

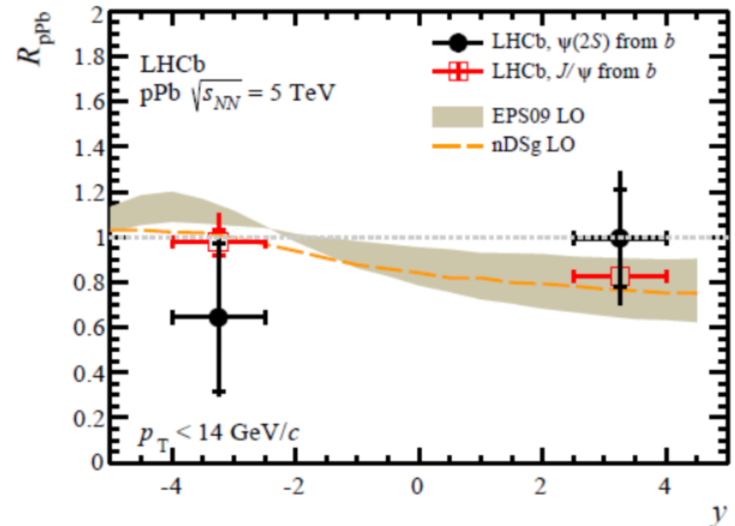
- Measure double differential cross-section in the kinematic regime $0 < p_T < 14$ GeV/c , $-5 < y < -2.5$ and $1.5 < y < 4$
- Measure **nuclear modification factor R_{pPb}** and **forward-backward ratio R_{FB}**

- The **$b\bar{b}$ cross-section in pPb** is determined from the J/ψ and ψ(2S) production measurements

Prompt production



Production **in b-decays**

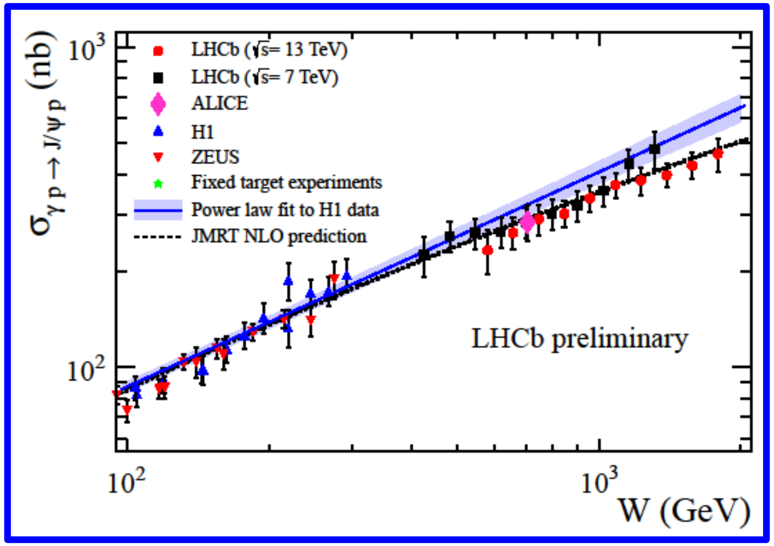


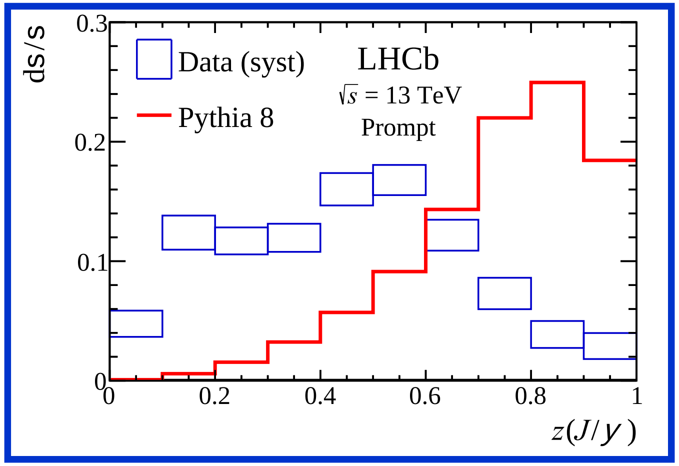
- **Prompt ψ(2S) mesons are significantly more suppressed than prompt J/ψ mesons in the backward region**; this result is not well described by theoretical predictions based on shadowing and energy loss mechanisms
- **Suppression of the ψ(2S) production** discussed by Y.-Q. Ma, R. Venugopalan, K. Watanabe and H.-F. Zhang

arXiv:1707.07266

Summary

- Thanks to excellent LHC and LHCb operation, LHCb performs **new precision tests** of our QCD comprehension to systematically qualify/constrain theory
- New results with Run II data, at $\sqrt{s}$ = 13 TeV, bigger datasets, better sensitivities and new measurements, access to larger p_T range





- Theory/experiment agreement made great progress since Tevatron days
- FONLL describes b-hadron production reasonably well, with caveats; prompt charmonia still puzzle

- New complementary probes from associated production, production in jets, CEP, …
- Link between charmonium production in e^+e^-, ep, pp (H.F. Zhang)
- Yet another **effort needed in both theory and experiment to establish a consistent picture of HF production**