Quarkonium production at LHC in examples

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- ❑ Quarkonium production: hadroproduction and production in b-decays
- ❑ Associated production
- ❑ Central exclusive production
- ❑ Charmonium production in pp collisions as an imaging tool

Disclaimers

- ❑ *Biased selection of illustrations*
- ❑ *Mostly charmonium production*
- ❑ *Only production at hadron machines : LHC*
- ❑ *Production in heavy ion collisions not covered*

COMHEP

Villa De Leyva
02/12/2022

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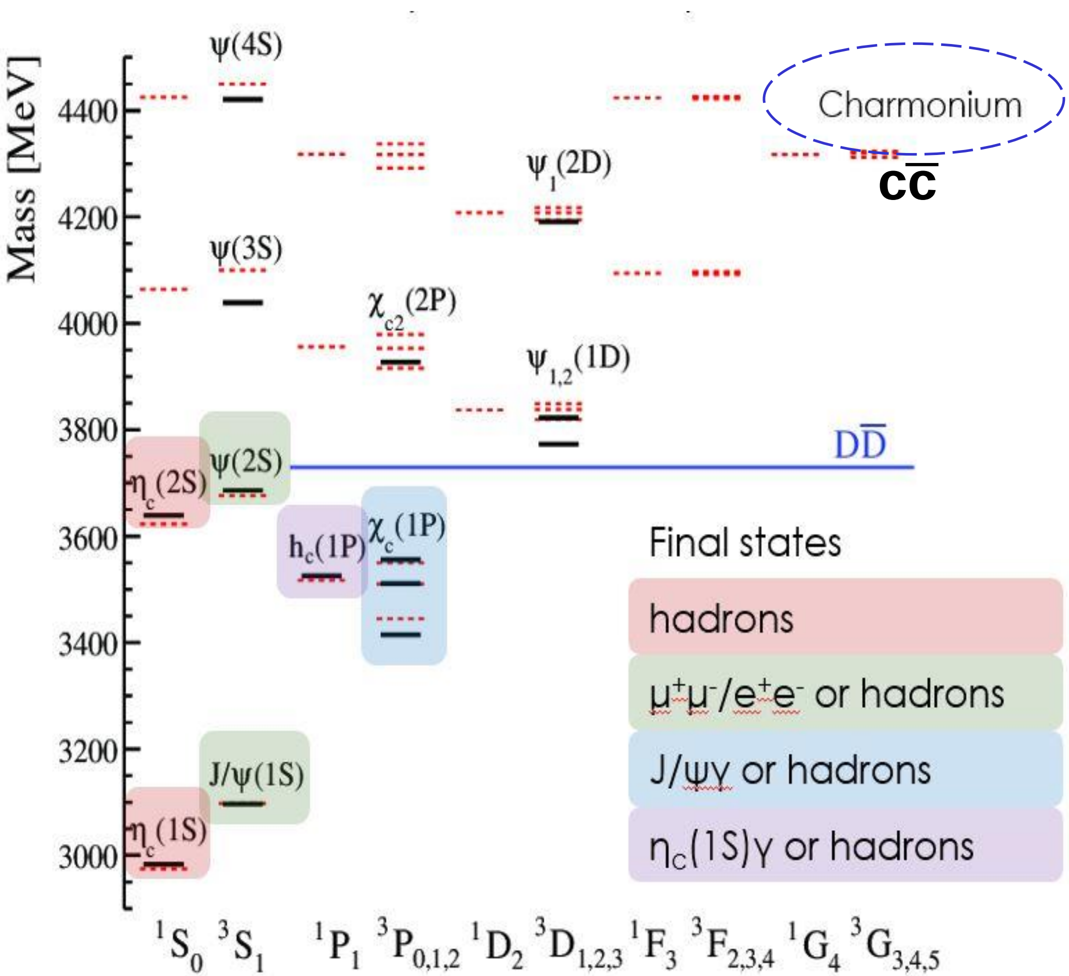
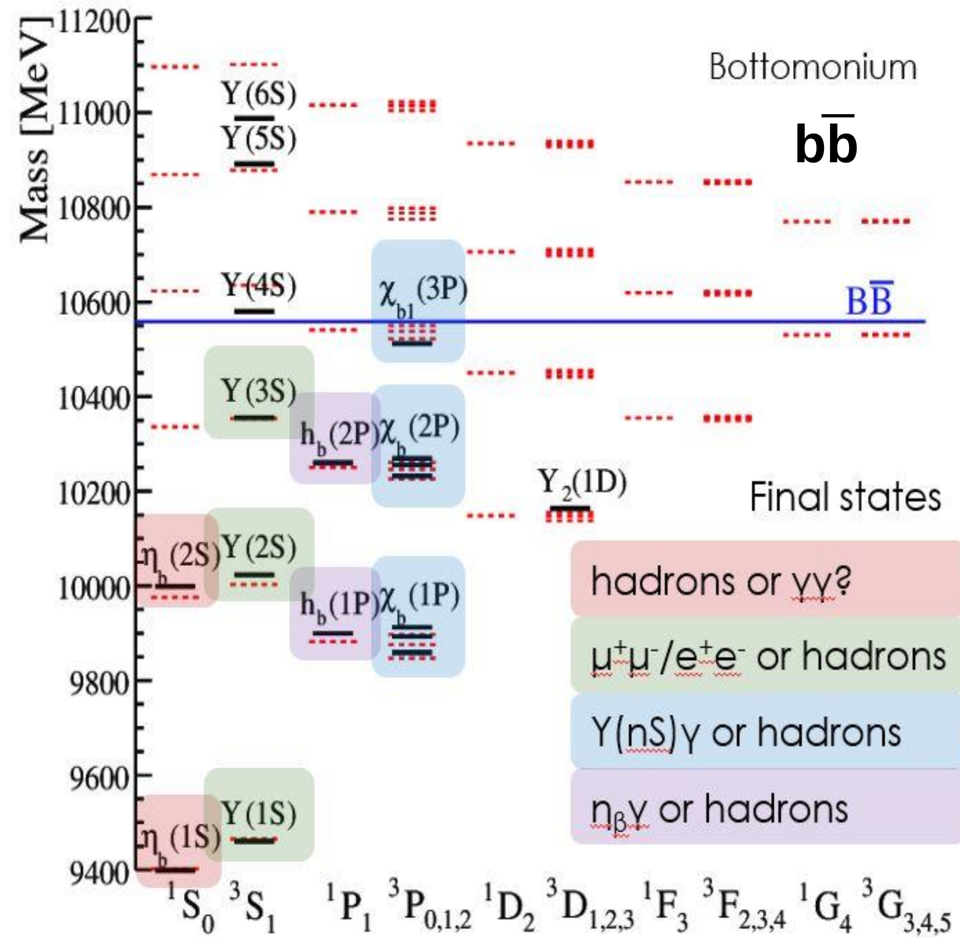
Rev.Mod.Phys 90 (2018) 015003

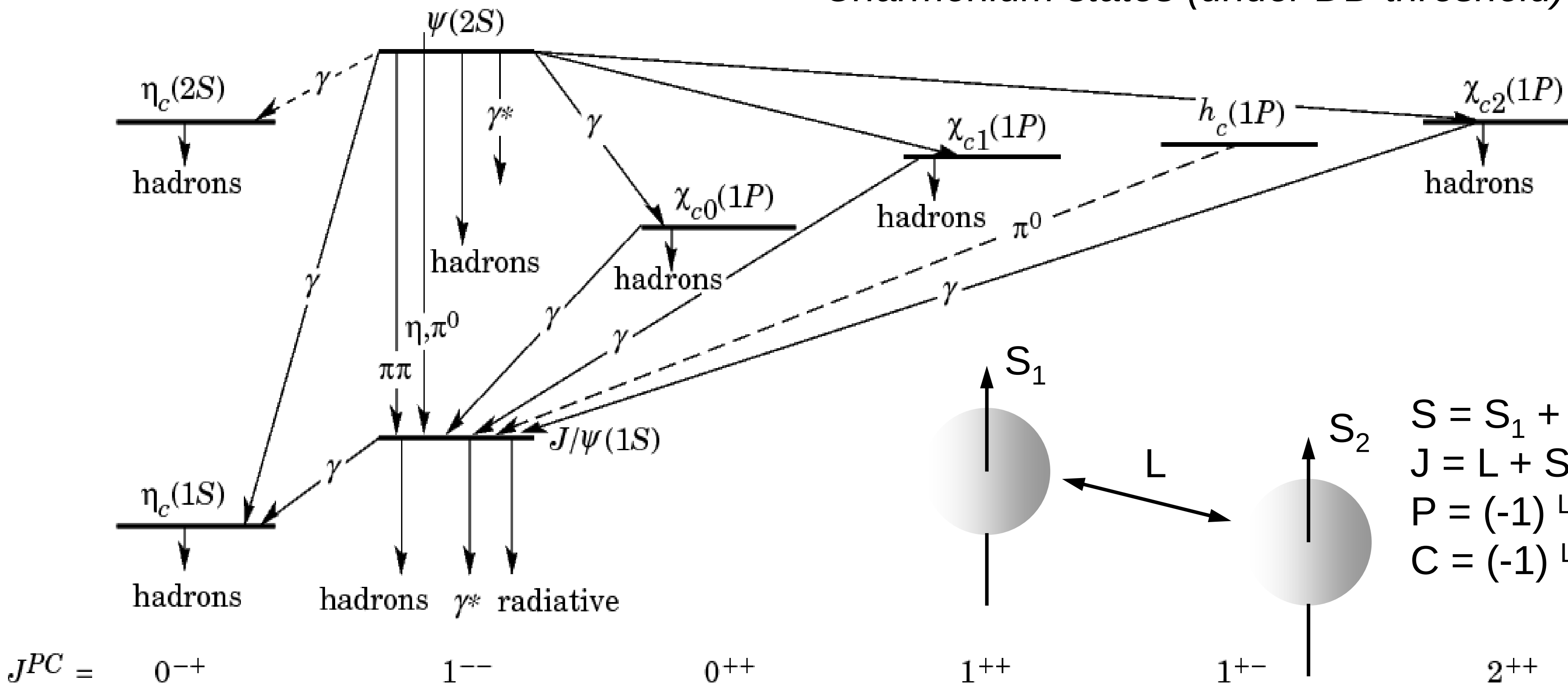
- **Quarkonium – bound state $Q\bar{Q}$**





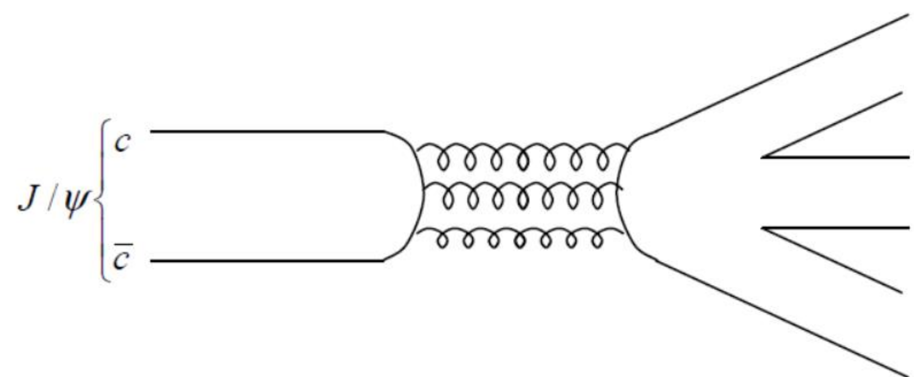
- *Focus on charmonium production*

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



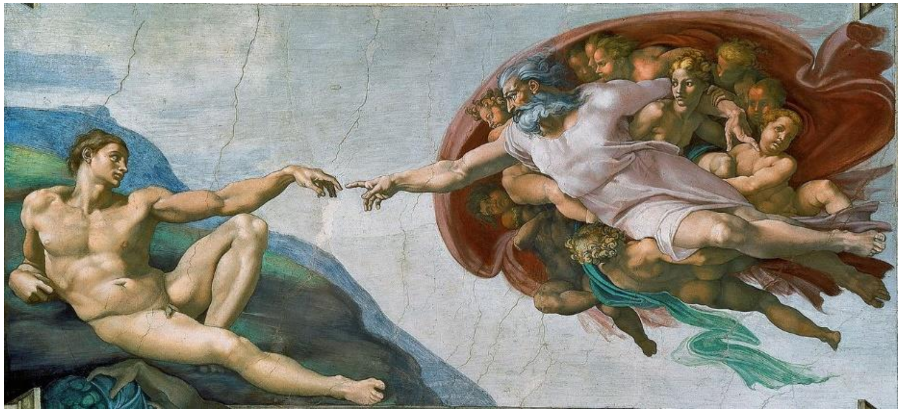
$S = S_1 + S_2$
$J = L + S$
$P = (-1)^{L+1}$
$C = (-1)^{L+S}$

- **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



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

Michelangelo: creación



Botticelli: nacimiento

❑ New theory developments confronted to new experimental results. Impressive progress in both domains, driven by **Puzzle story**

❑ First clash to describe **« J/ψ production puzzle »**

❑ **« J/ψ production AND polarization puzzle »** boosted the progress

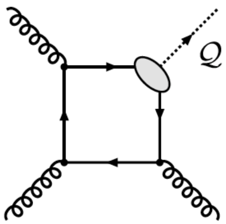
❑ Recently with the η_c(1S) production measurement by LHCb more challenging **« J/ψ production AND polarization AND η_c(1S) production puzzle »**

❑ **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

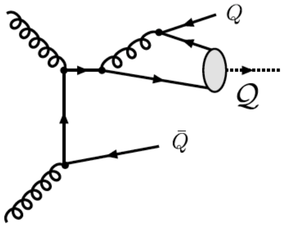
- Comparison of direct p_T differential J/ψ production cross-section measured by CDF with Color Singlet LO (most natural) process.
- Fails both in shape and magnitude.

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



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

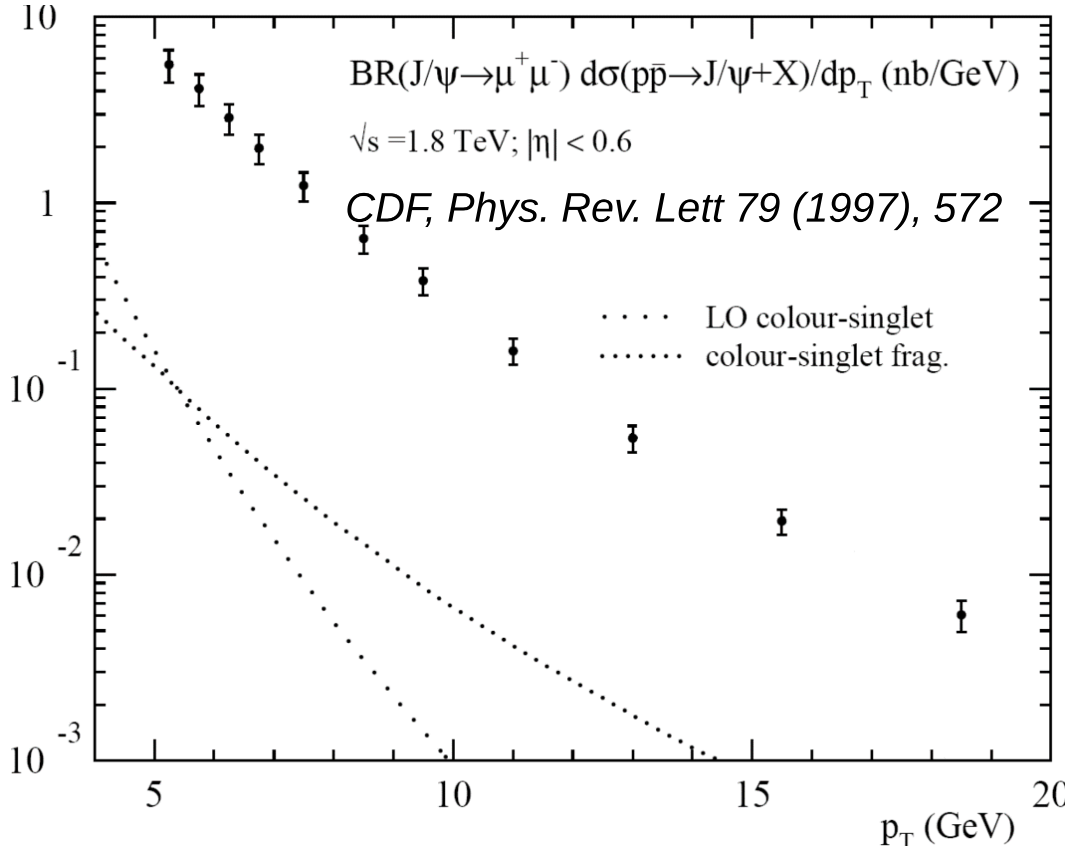
+



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

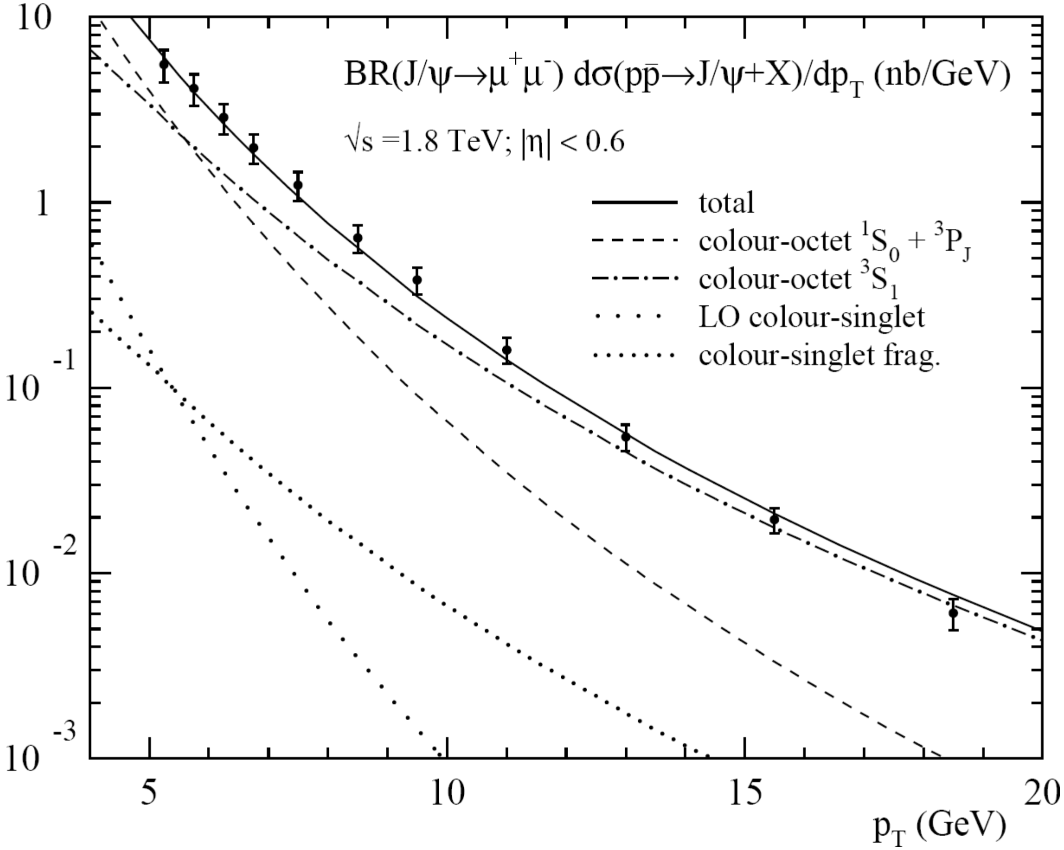
- Add gluon and quark fragmentation (NLO Color Singlet processes)
- Better shape but magnitude is factor 30 too low.

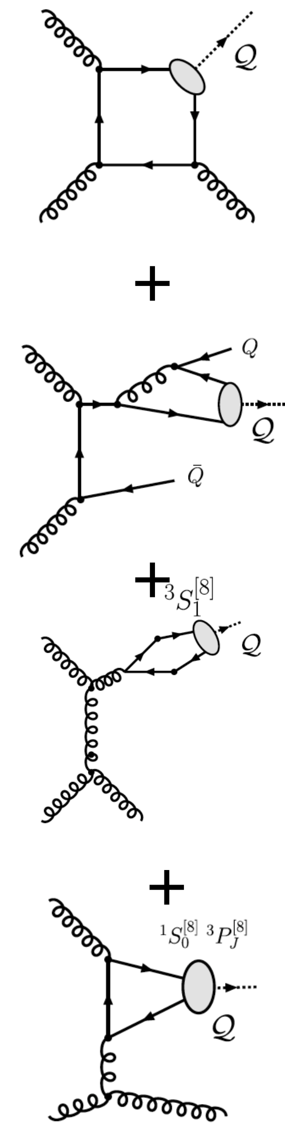
E. BRAATEN, M. A. DONCHESKI, S. FLEMING and M. L. MANGANO, PLB 333 (1994), 548



- ❑ Add LO Color-Octet processes from NRQCD
- ❑ LDME fitted on the same data

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

❑ 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

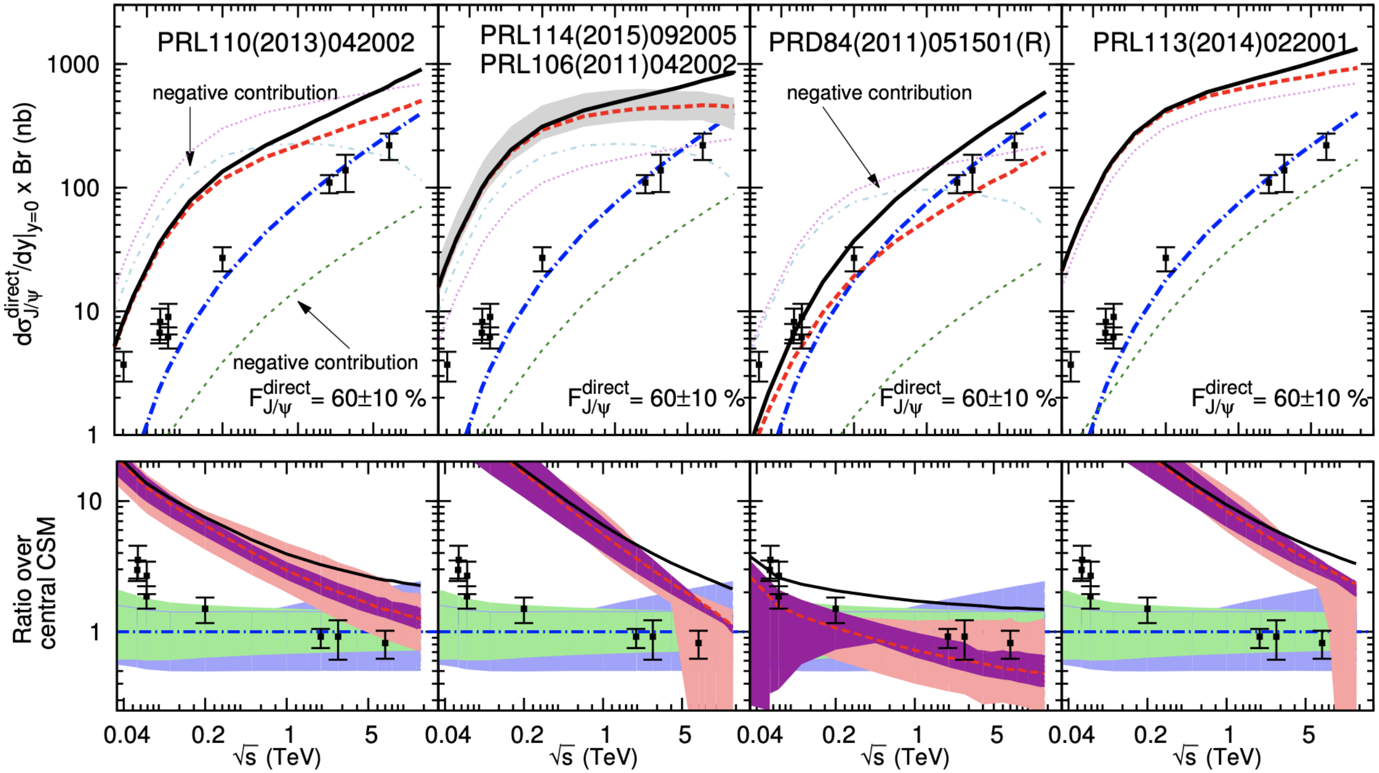
❑ NRQCD: all viable colours and J^{PC} allowed for the intermediate $Q\bar{Q}$ state, they are adjusted in the long-distance part with a given probability. Long-Distance Matrix Elements (LDME) from experimental data. *Most used since is based on an EFT and can be improved systematically*

❑ **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

- 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

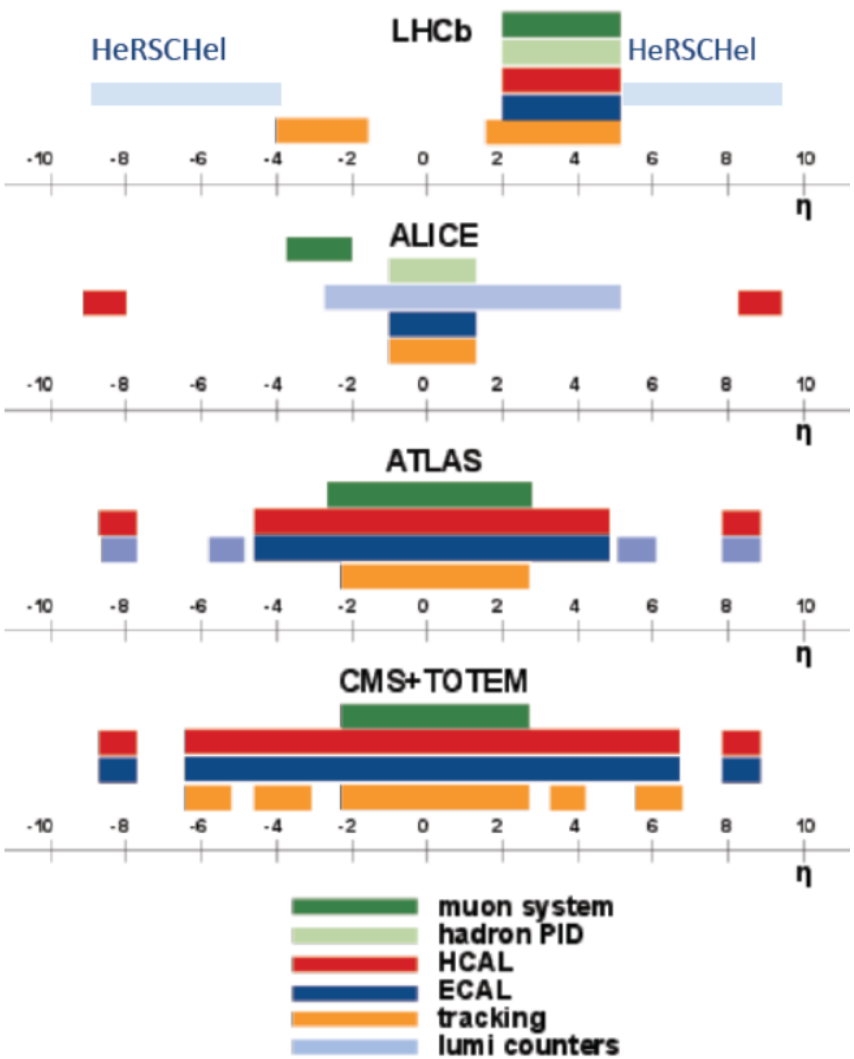
__Eur.Phys.J. C75 (2015) 7, 313__
Phys.Rept. 889 (2020) 1

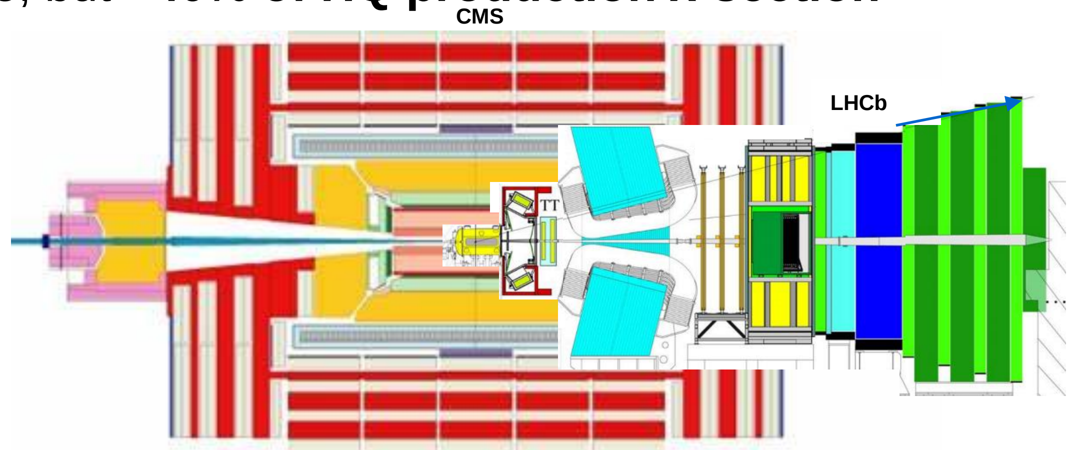


LDMEs	J/ψ hadropr.	J/ψ photopr.	J/ψ polar.	η_c hadropr.
Butenschön et al.	✓	✓	✗	✗
Chao et al. + η_c	✓	✗	✓	✓
Zhang et al.	✓	✗	✓	✓
Gong et al.	✓	✗	✓	✗
Chao et al.	✓	✗	✓	✗
Bodwin et al.	✓	✗	✓	✗

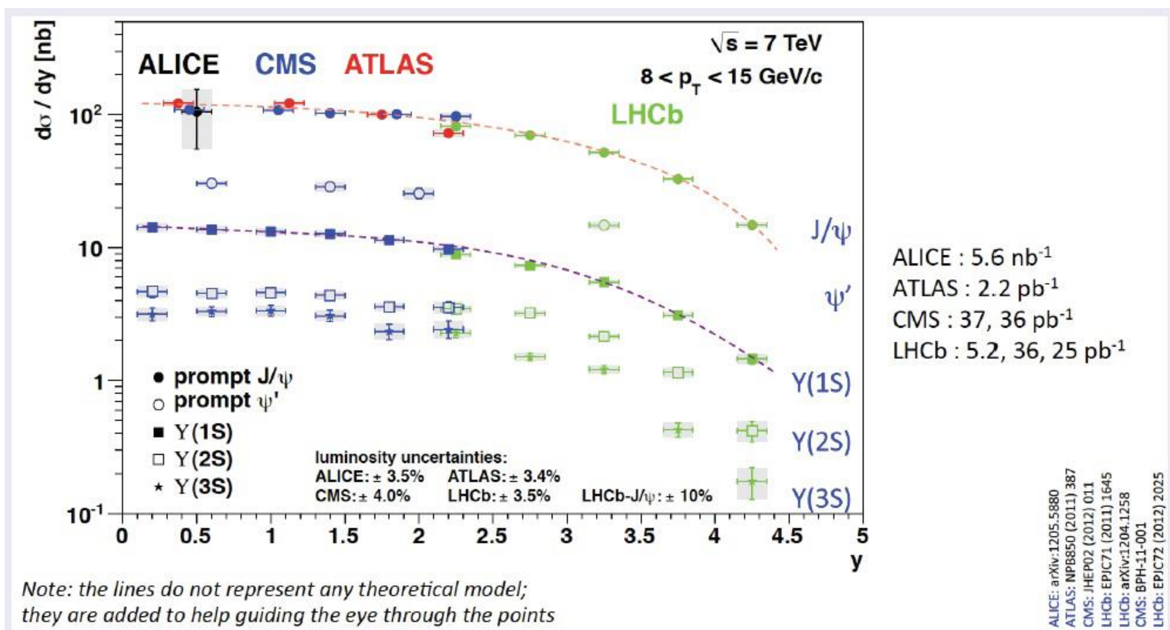
M. Nefedov

- ❑ 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**





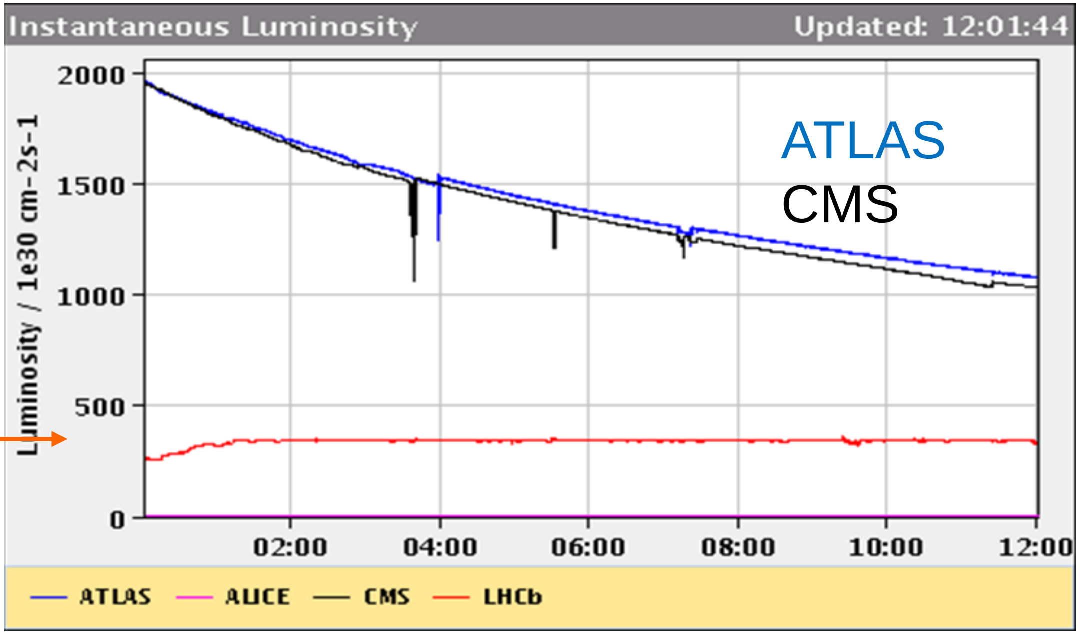
❑ **Complementary cross-section measurements**



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

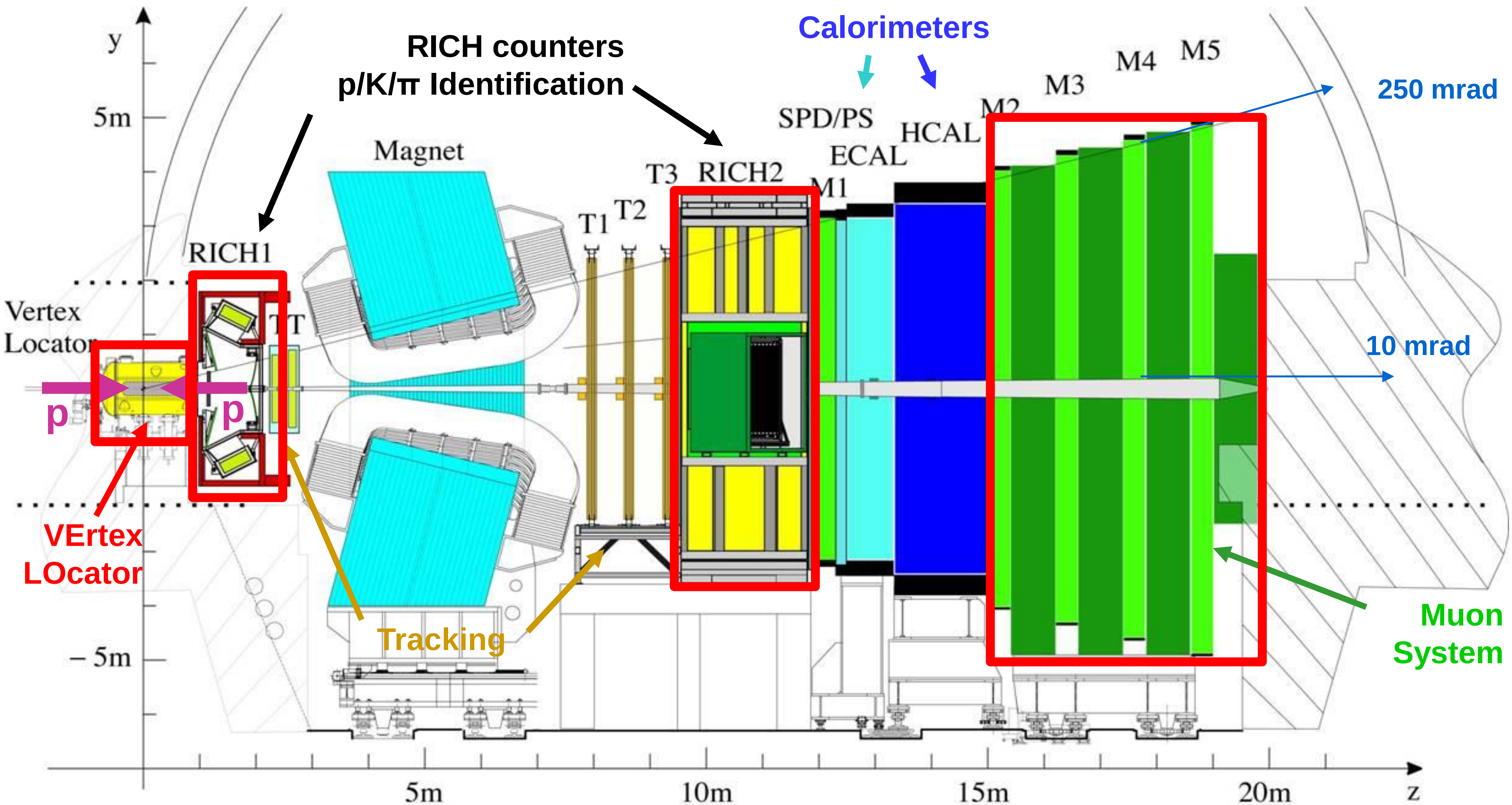
- **Excellent performance of the LHC and the experiments** during Runs I and II
- Collected data correspond to
  - ALICE: ∫Ldt ~ 0.1 fb^{-1}
  - ATLAS, CMS: ∫Ldt ~ 190 fb^{-1}
  - LHCb: ∫Ldt ~ 9 fb^{-1}

LHCb luminosity levelling



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

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



Vertex reconstruction:
VELO

Kinematics:
Magnet
Tracker
Calorimeters

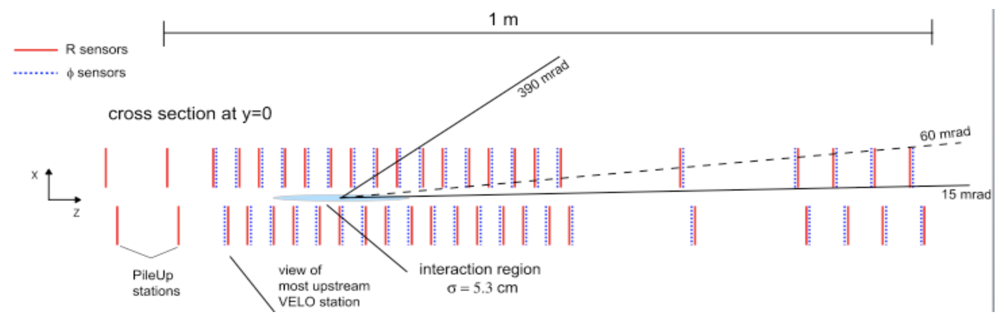
PID:
RICHs
Calorimeters
Muon Chambers

Trigger:
Muon Chambers
Calorimeters
Tracker

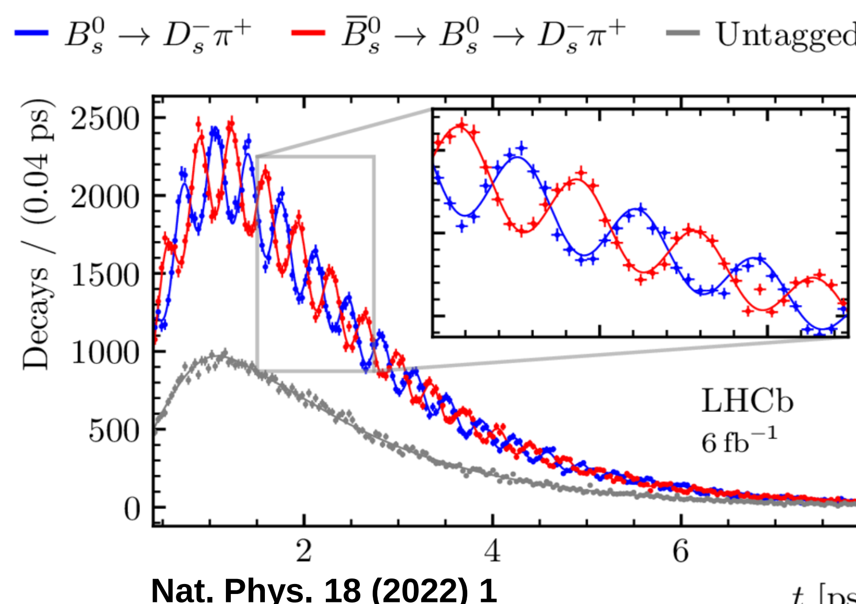
Vertex reconstruction in LHCb: VErtex LOcator

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**



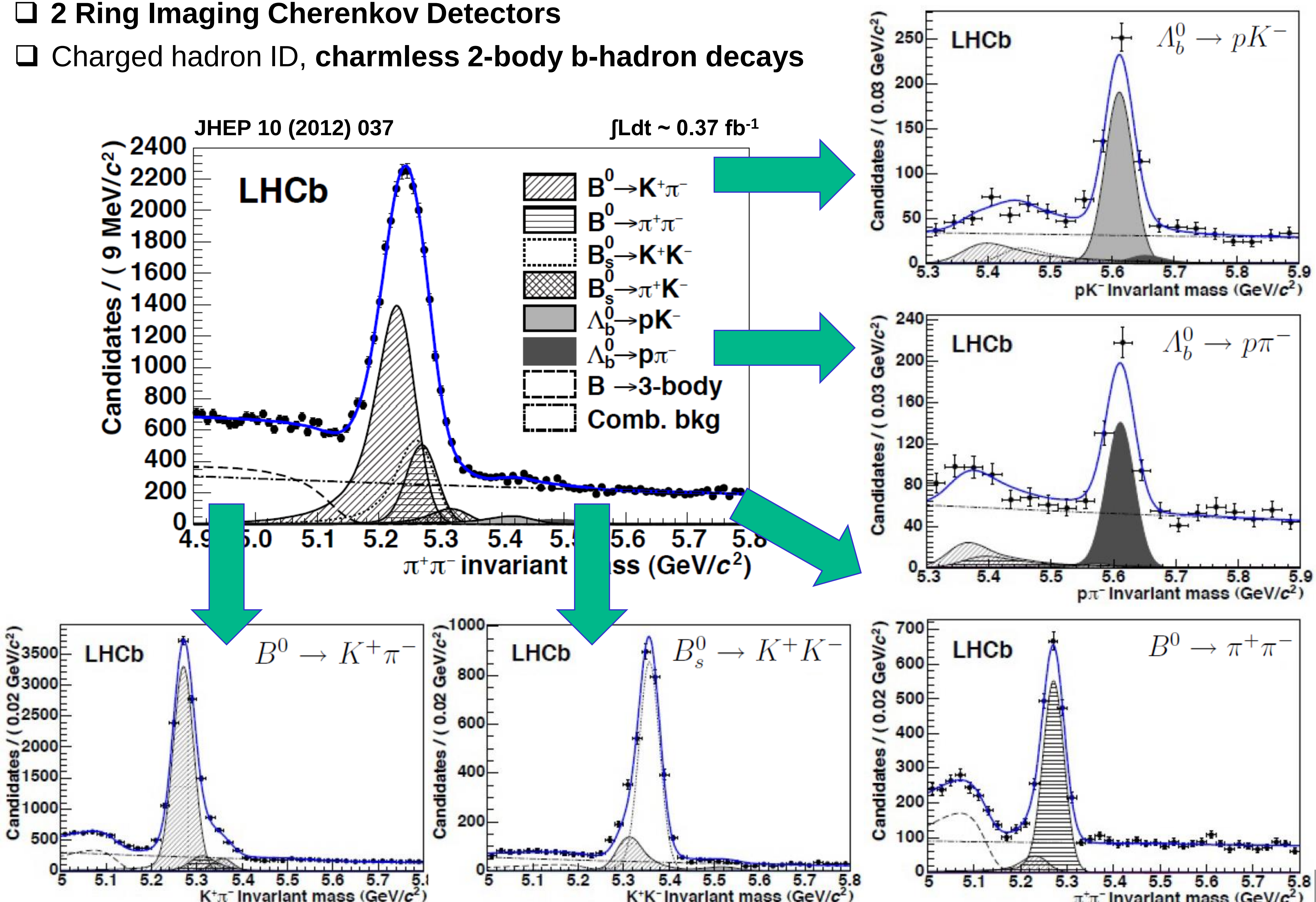
- ❑ Excellent **spatial resolution**, down to 4 μm for single tracks
- ❑ Precise **impact parameter** measurement, $\sigma_{IP} = 11.6 + 23.4/pT$ [μm]
- ❑ Precise **primary vertex** reconstruction, $\sigma_{x,y}$ = 13 μm, σ_z = 69 μm for vertex of 25 tracks
- ❑ Excellent **proper time** resolution
-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



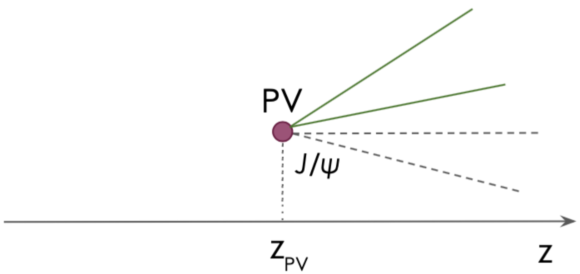
Nat. Phys. 18 (2022) 1

Charged hadron ID in LHCb: Cherenkov light detectors

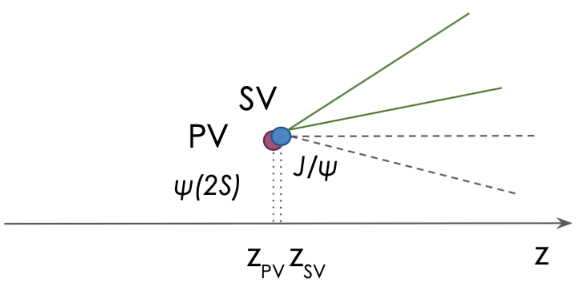
- **2 Ring Imaging Cherenkov Detectors**
- Charged hadron ID, **charmless 2-body b-hadron decays**



- **Hadroproduction**

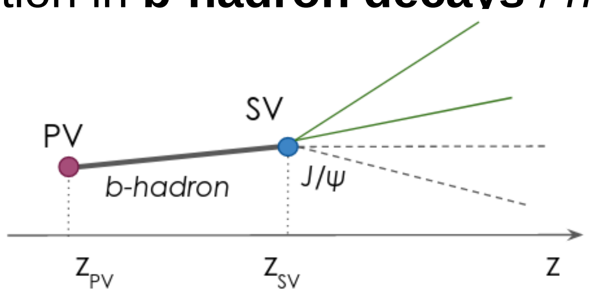


- Decays of **higher resonances**



prompt production

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



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

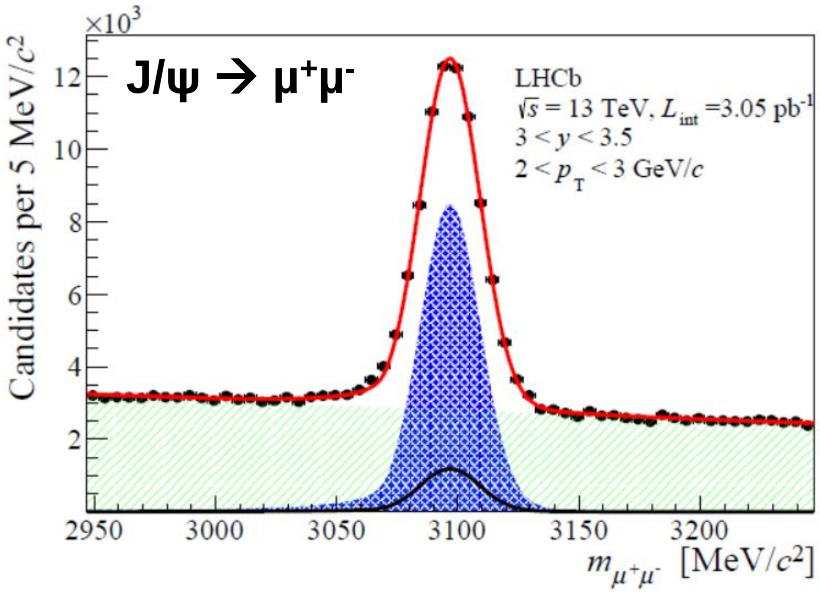
JHEP 1510 (2015) 172
JHEP 1705 (2017) 063

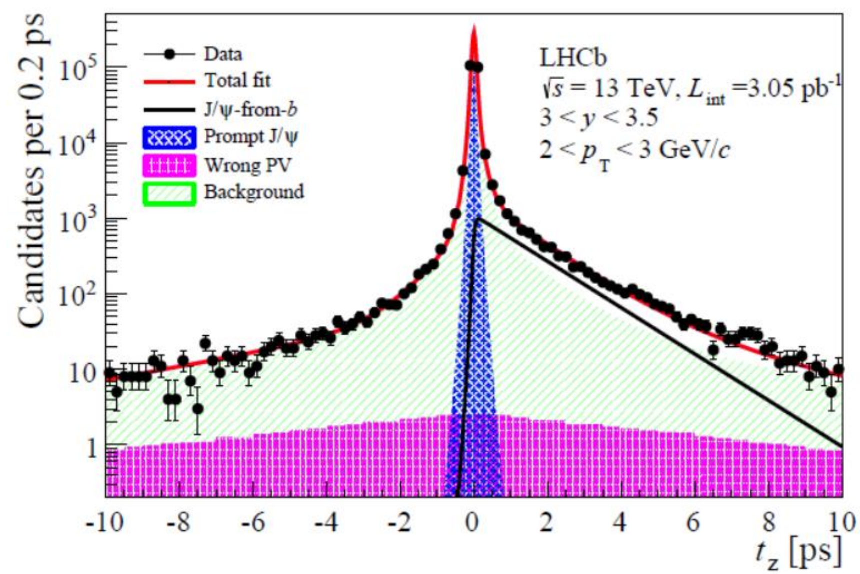
√s = 13 TeV, ∫Ldt ~ 3 pb^{-1}

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

Excellent **mass resolution** to suppress combinatorial background

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





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

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

$$\sigma(\text{prompt } J/\psi, p_{\rm T} < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 15.03 \pm 0.03 \pm 0.94\,\mu\text{b},$$
$$\sigma(J/\psi\text{-from-}b, p_{\rm T} < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 2.25 \pm 0.01 \pm 0.14\,\mu\text{b},$$

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

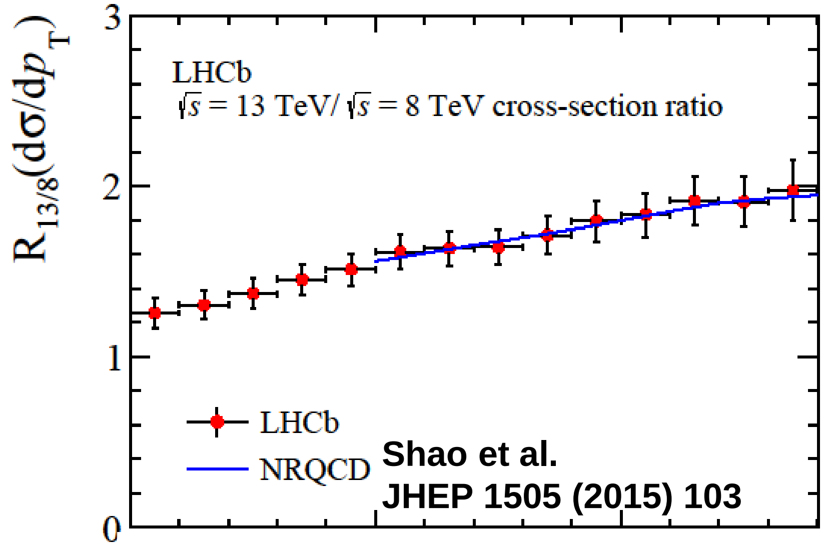
$$\sigma(pp \to b\bar{b}X) = 495 \pm 2 \pm 52\,\mu\text{b},$$

JHEP 1510 (2015) 172
JHEP 1705 (2017) 063

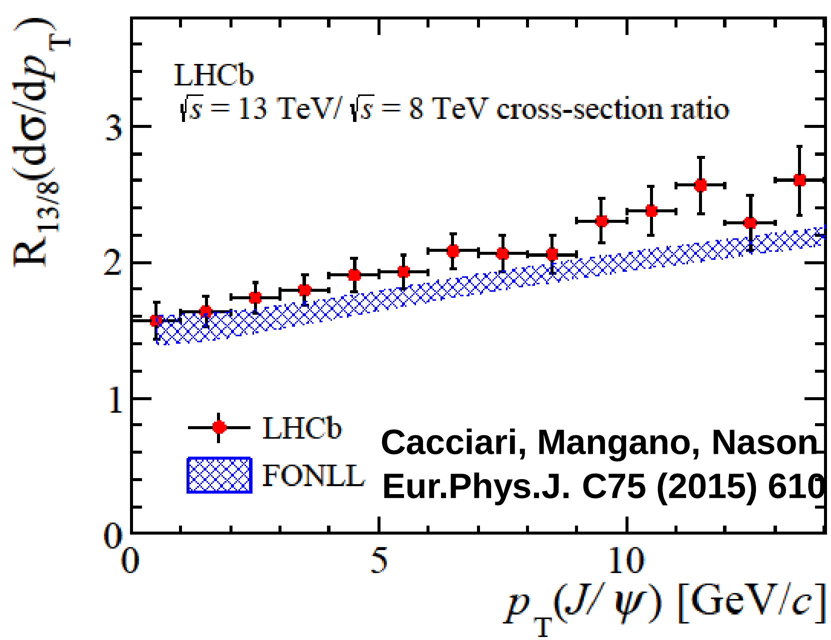
√s = 13 TeV, ∫Ldt ~ 3 pb^{-1}

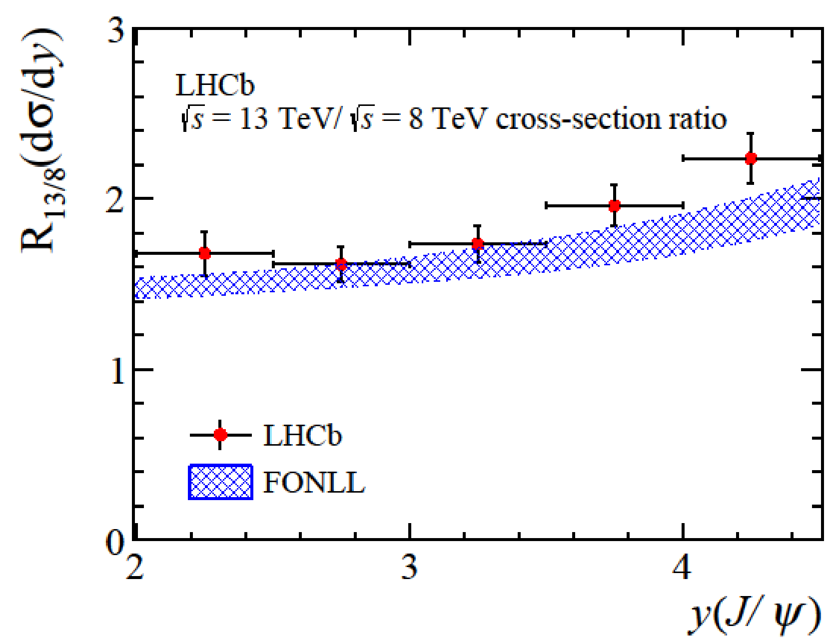
- The **J/ψ production** measured **at √s = 13 TeV** and compared to that **at √s = 8 TeV** and **theory**

- **Prompt production**



- **Production in b-decays**



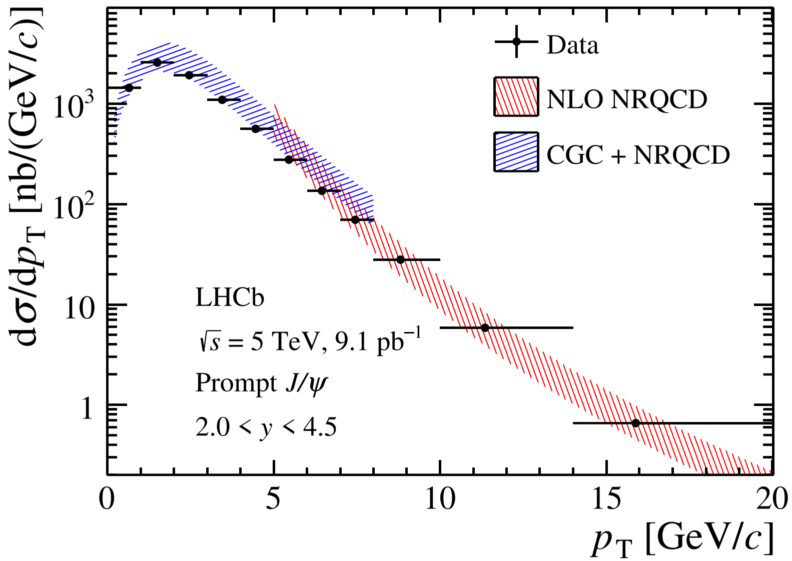


- Perfect (good) **theory-experiment agreement** for prompt (b-decay) production

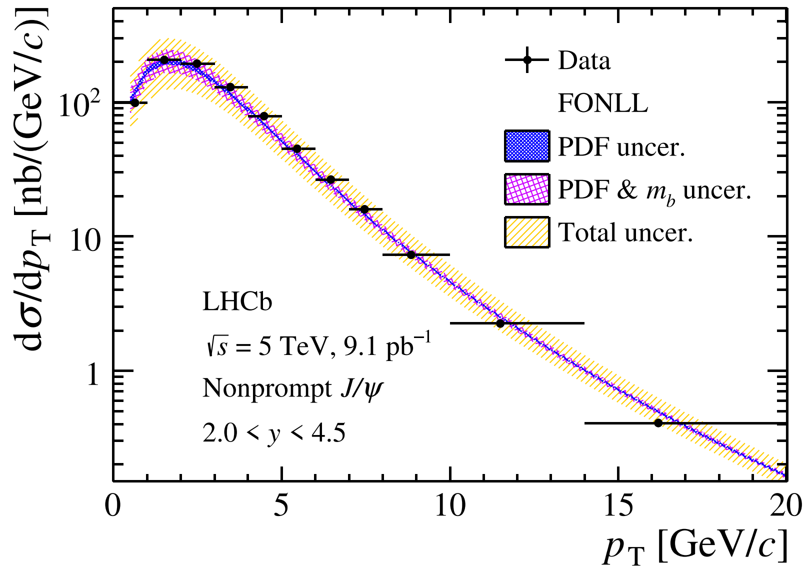
J/ψ production at √s = 5.02 TeV

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:

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

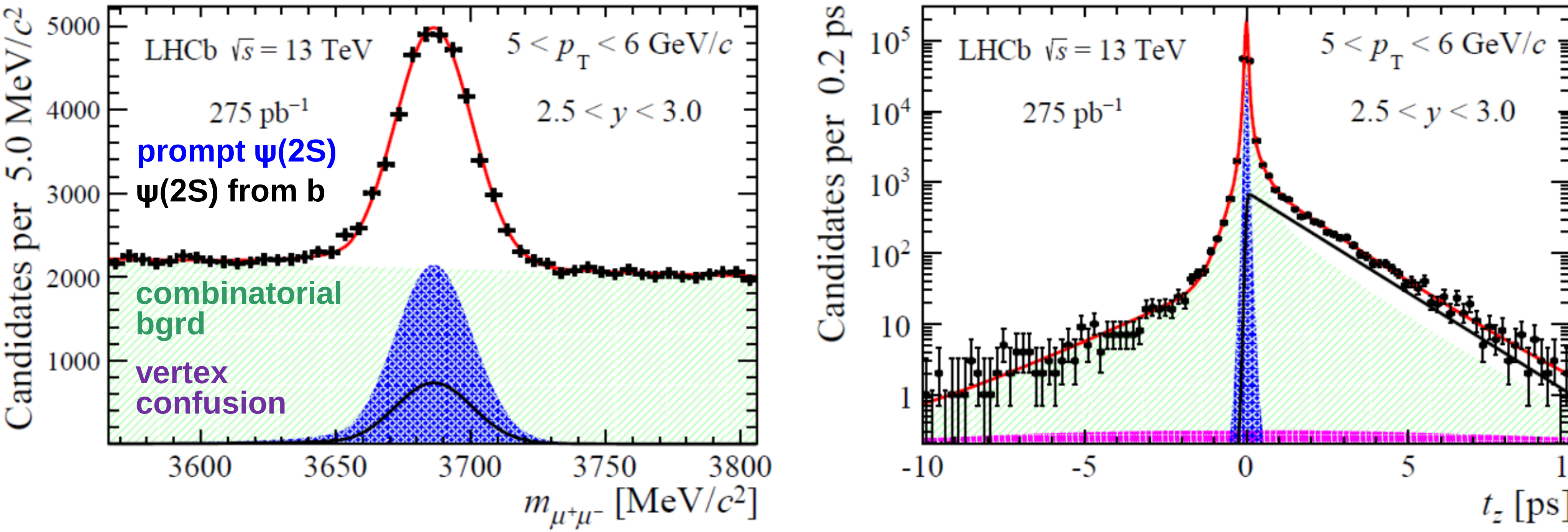
- Reasonable data description achieved down to low pT values

EPJC 80 (2020) 185

$\sqrt{s}$ = 7, 13 TeV, $\int L dt$ ~ 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

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

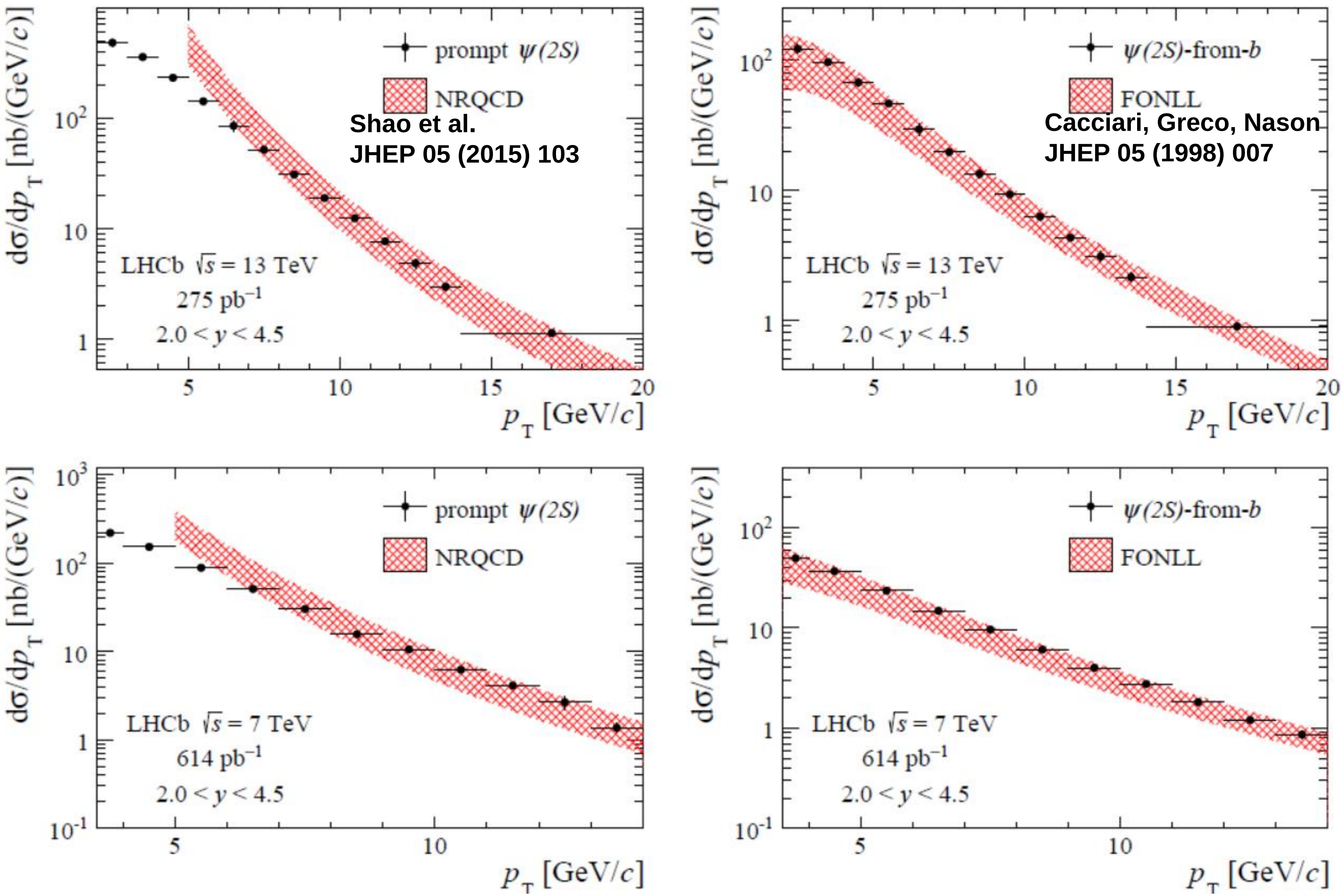


- **Integral** cross sections:

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

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

- **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}

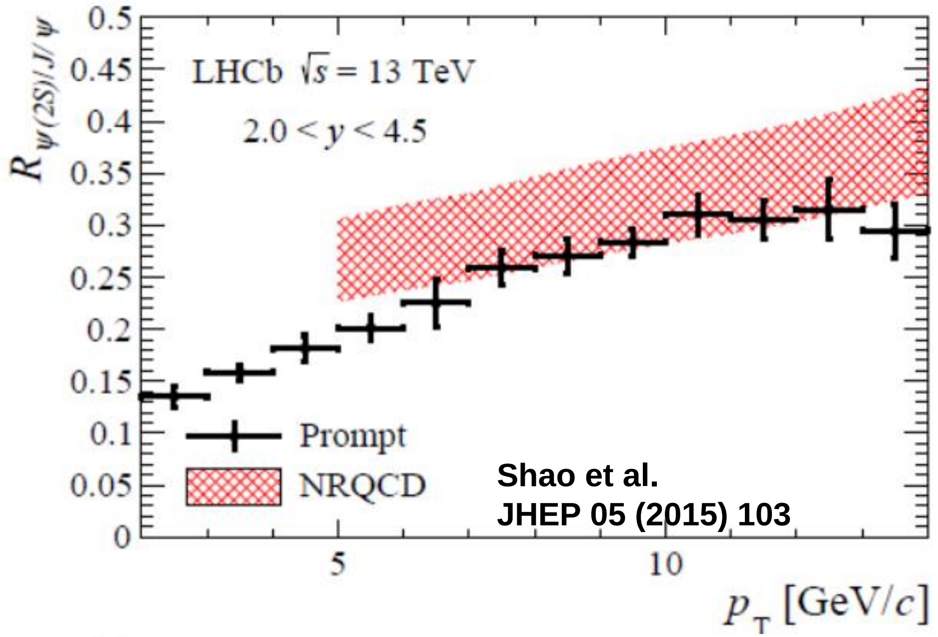


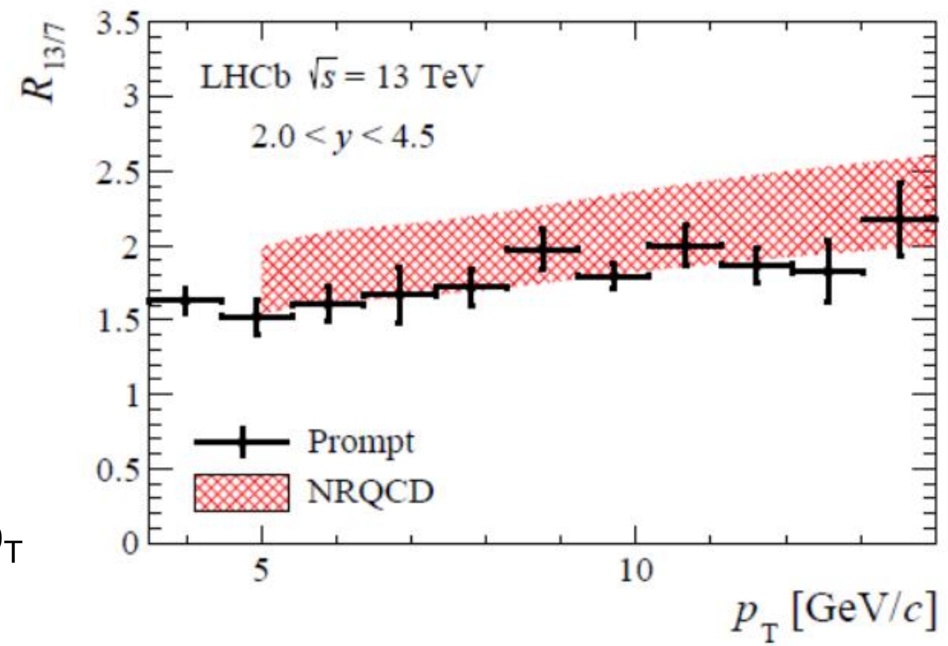
- Overall **good agreement with predictions, with deviation at low p_T** for prompt ψ(2S)

EPJC 80 (2020) 185

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

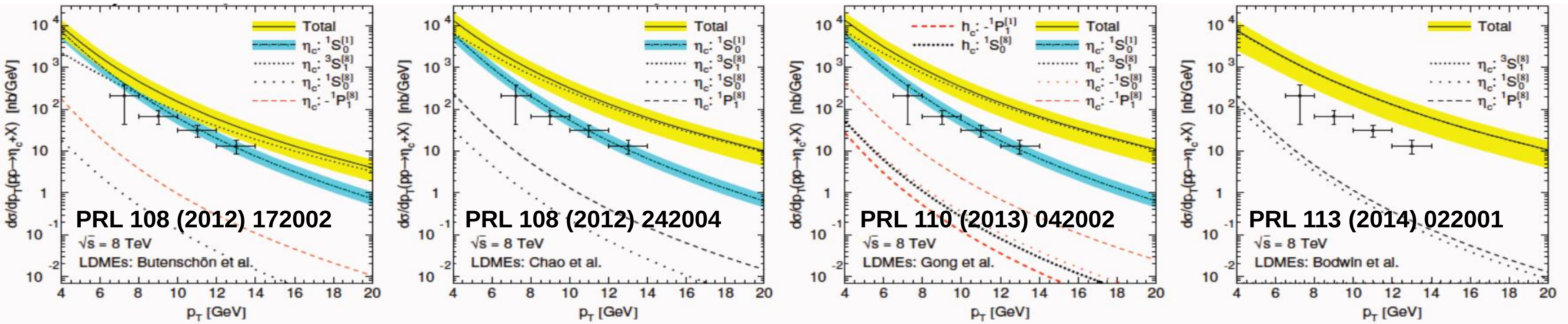
- Uncertainties partly cancel in ratios
- Ratio between the ψ(2S) and J/ψ production cross-sections
- Ratio between the ψ(2S) production cross-sections at $\sqrt{s}$ = 13 and 7 TeV
- **Overall good description** for both ratios
- Important to extend theory prediction to lower p_T





- Four LDMEs describing J/ψ production and polarization
- Linked to LDMEs describing η_c(1S) production
- First η_c(1S) prompt production measurement at 7, 8 TeV: LHCb using $\eta_c(1S) \to p\bar{p}$ **EPJC 75 (2015) 311**

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



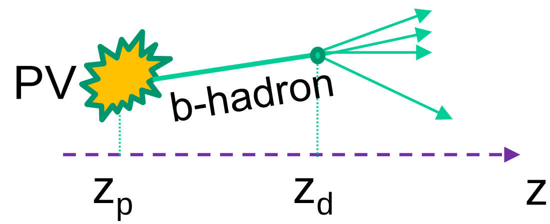
- Results described by **CS NLO**, below expected CO contribution
- Progress in theory description, integrating LHCb result in LDME calculations:
  - Han, Ma, Meng, Shao, Chao **PRL 114 (2015) 092005**
  - Zhang, Sun, Sang, Li **PRL 114 (2015) 092006**
  - Baranov. Lipatov **EPJC 79 (2019) 621**
  - Feng, He, Lansberg, Shao, Usachov, Zhang **NPB 945 (2019) 114662**
- Theory description still covers limited p_T range
- Further tests with **measurements at different √s and of other linked observables**

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

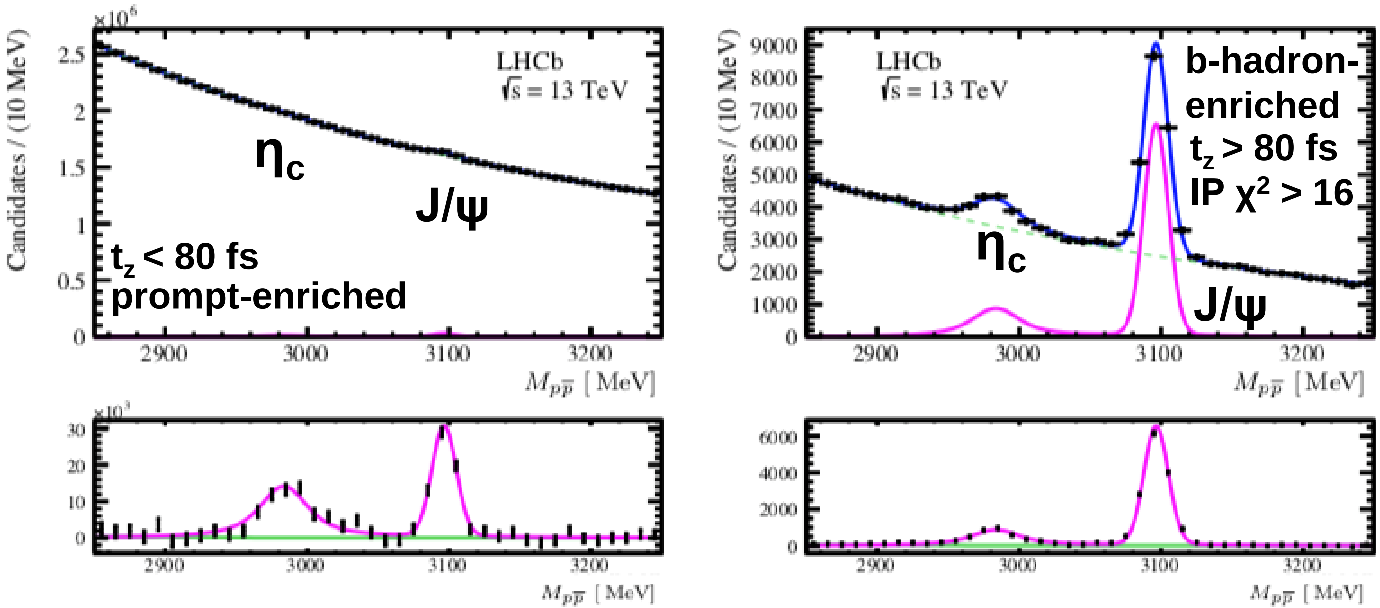
EPJC 80 (2020) 191

$\sqrt{s}$ = 13 TeV, ∫Ldt ~ 2 fb^{-1}

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



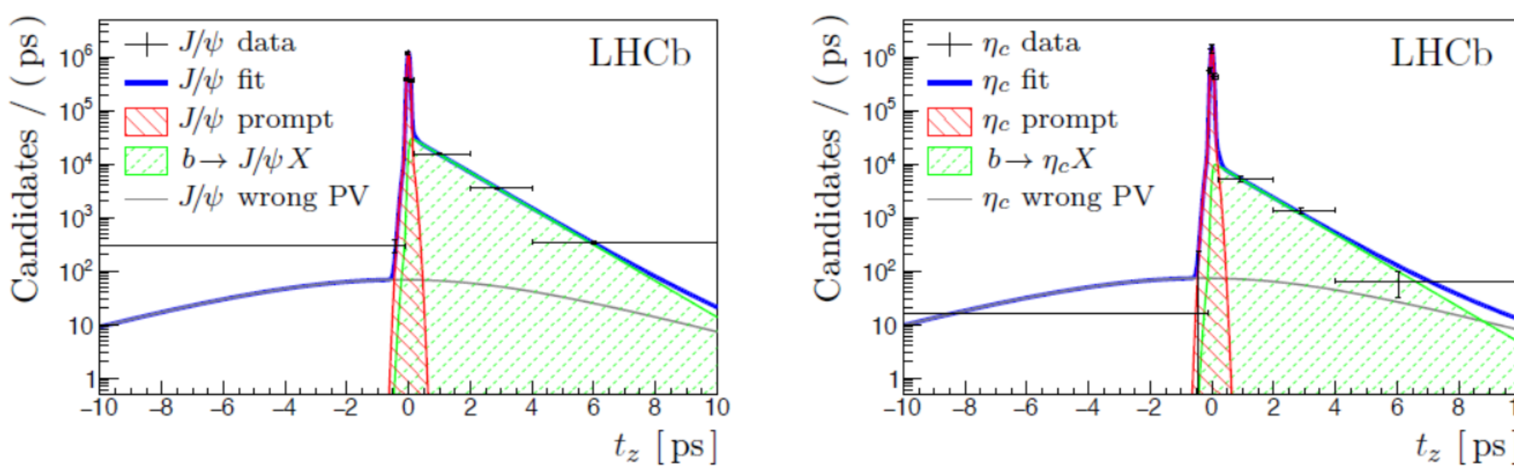
$$t_z = \frac{(z_d - z_p)M_{p\bar{p}}}{p_z}$$



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

- … or **pseudo proper-time fit**

- Good agreement between the results



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

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

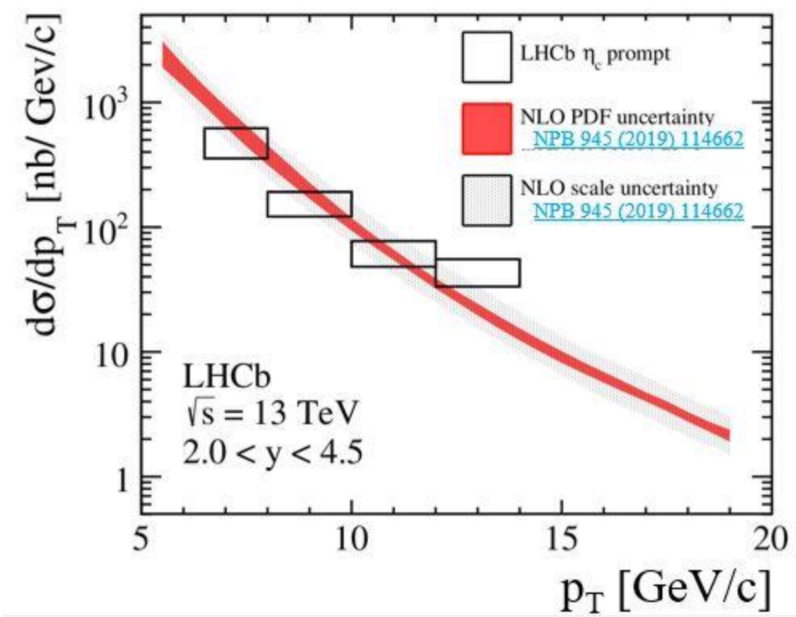
$$(\sigma_{\eta_c})^{6.5\,\mathrm{GeV}<p_T<14.0\,\mathrm{GeV},\,2.0<y<4.5}_{13\,\mathrm{TeV}} = 1.26 \pm 0.11 \pm 0.08 \pm 0.14\,\mu\mathrm{b}$$

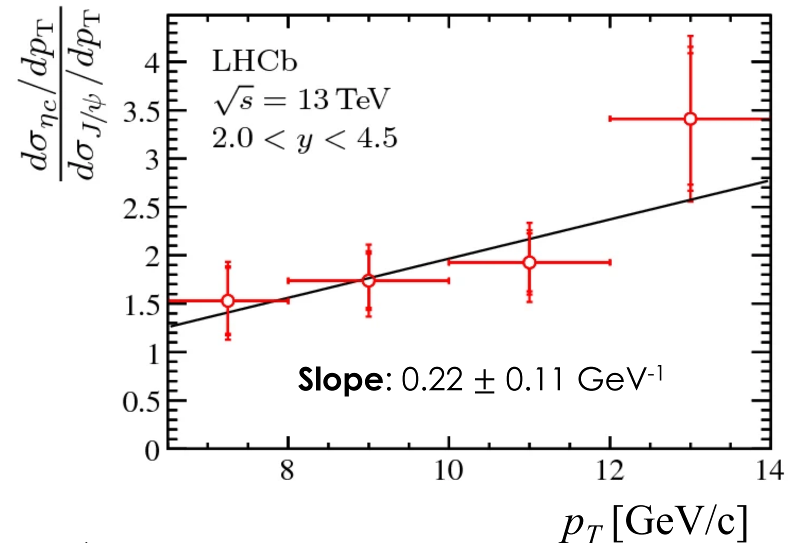
- Color Single model prediction: Feng,Shao,Lansberg,Zhang,Usachov,He **NPB 945 (2019) 114662**

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

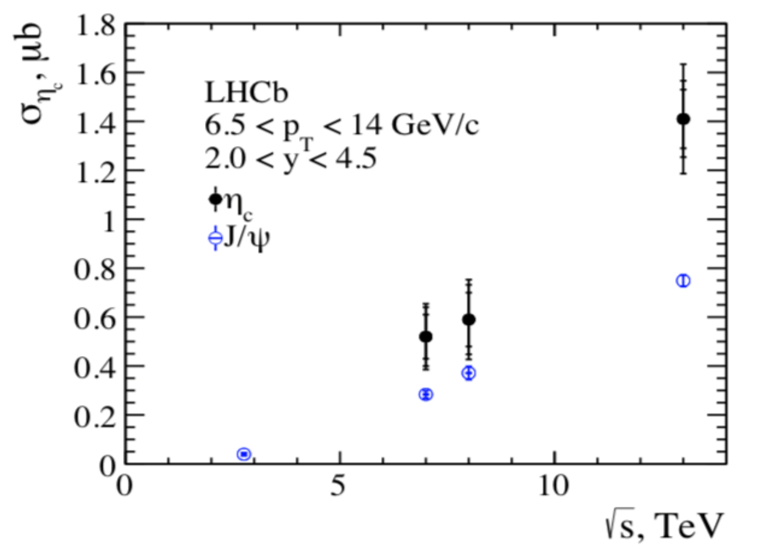
- **Consistent with being described by CSM**

- p_T -differential **prompt production**





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

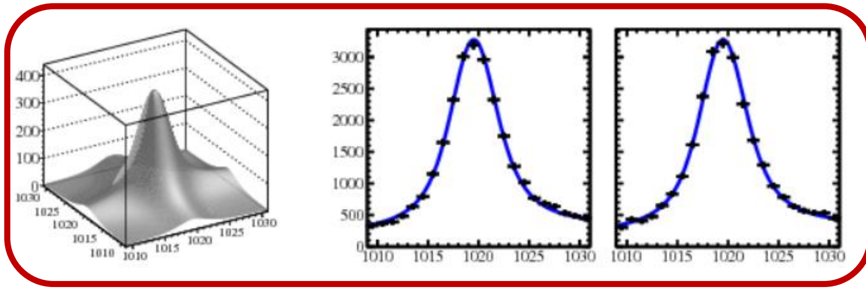


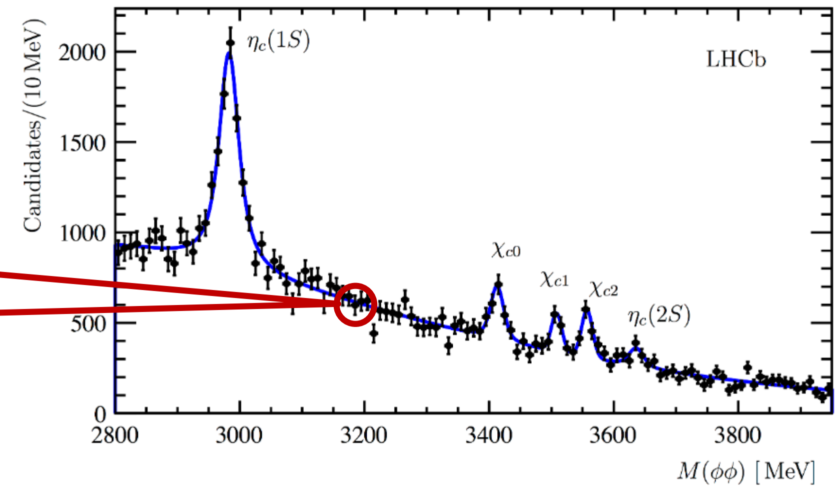
- **Inclusive production in b-decays**:

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

EPJC 77 (2017) 609

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





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

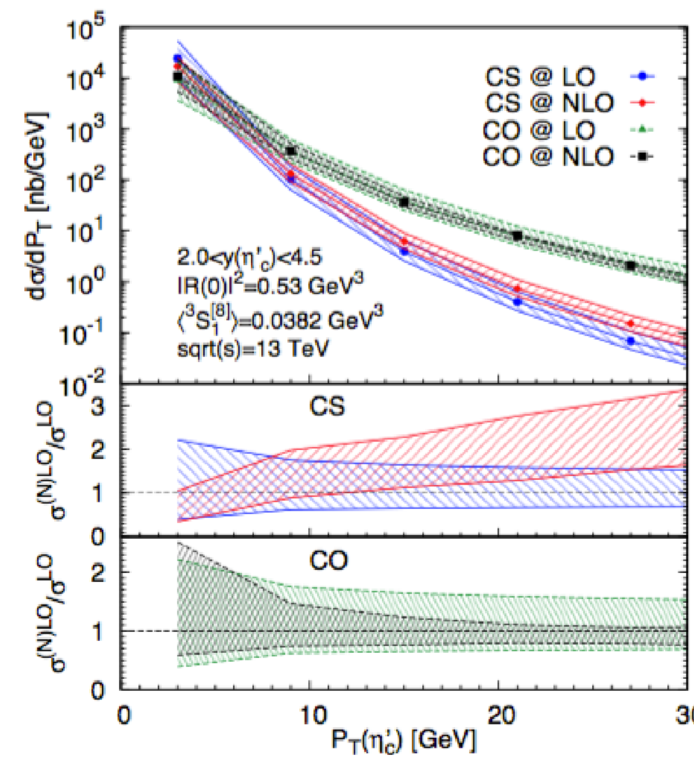
  First evidence for $\eta_c(2S) \to \phi\phi$

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

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

Theory prediction →

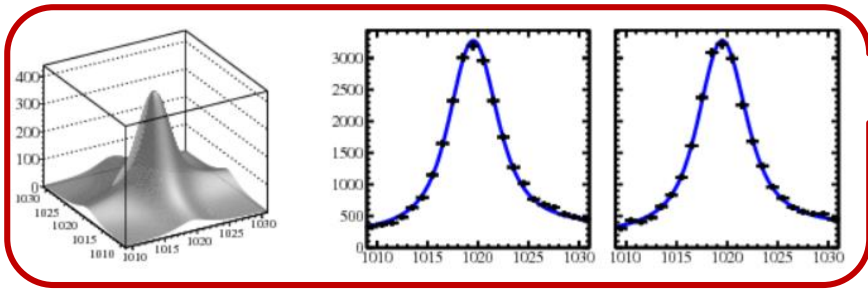
- ❑ **Dedicated LHCb trigger in 2018**

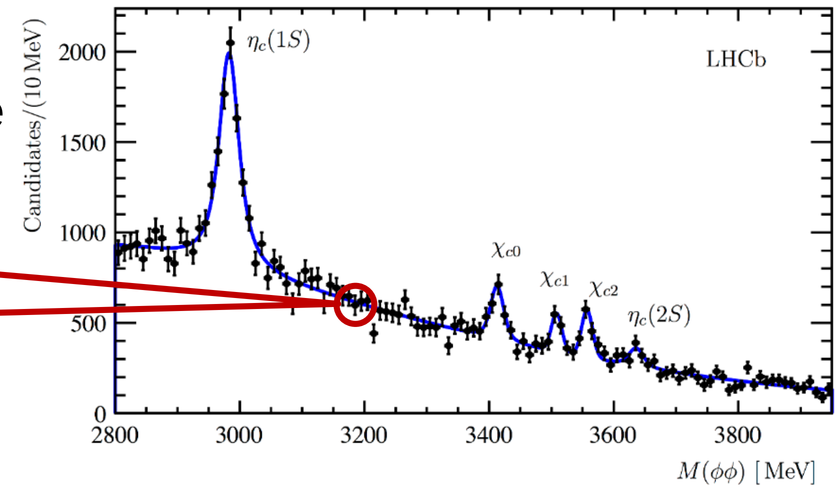


Lansberg, Shao, Zhang, PLB 786 (2018) 342

EPJC 77 (2017) 609

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

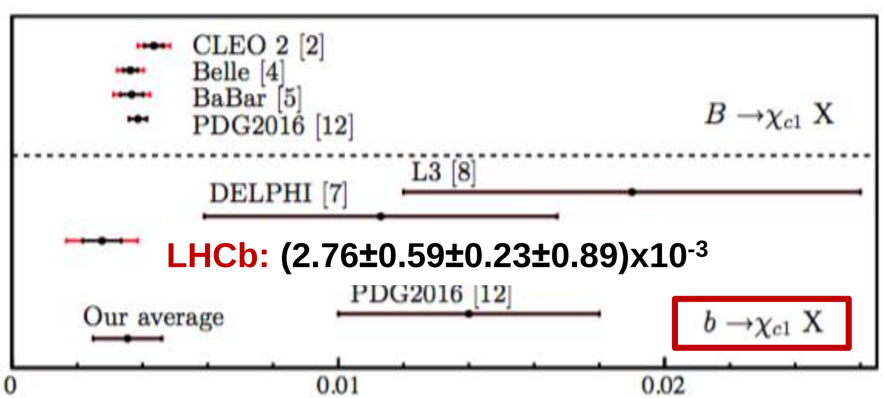


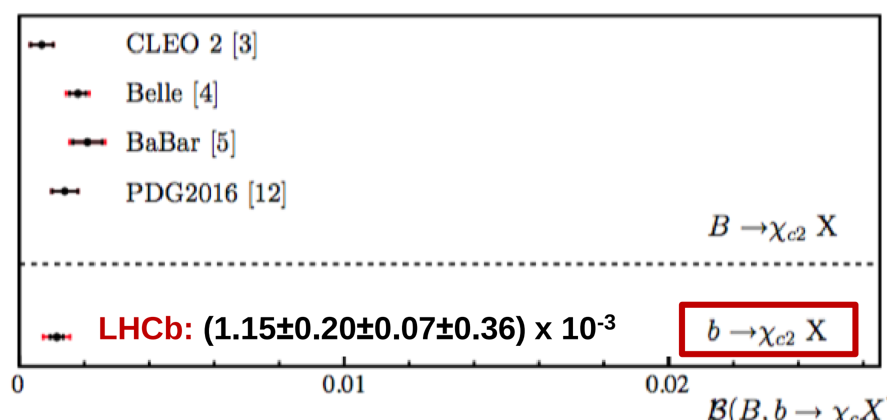


- ❑ **First measurement** of χ_{c0} production in b-decays

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

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



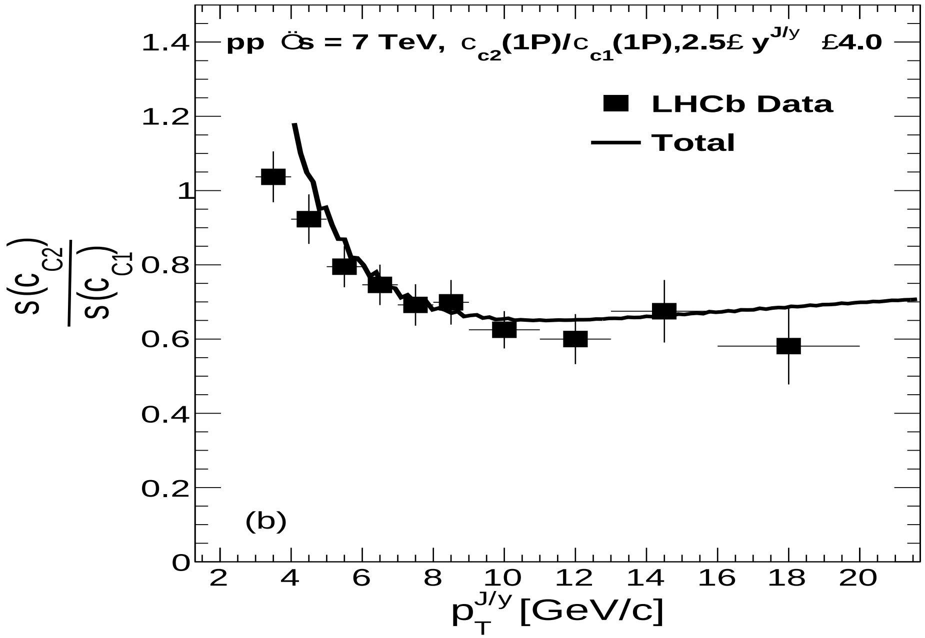


- ❑ Promising channel to study χ_c polarization

PRD 103 (2021) 9, 096006

J.Phys. G44 (2017) 8, 085003

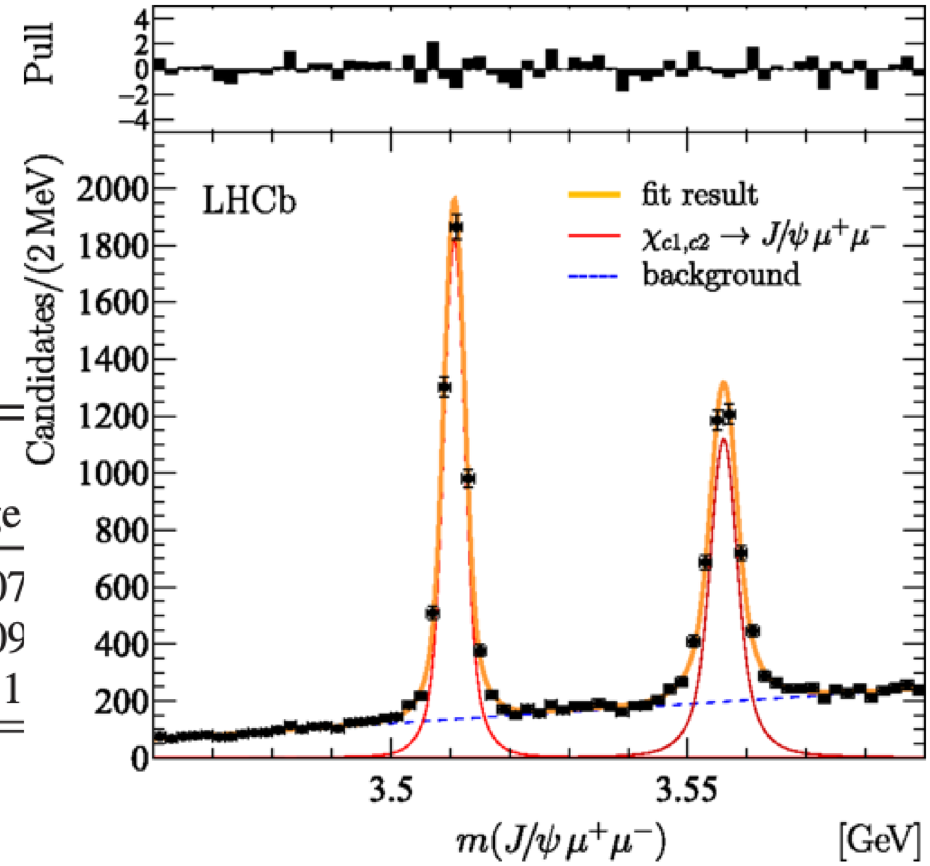
- NRQCD fit for production cross-section
- **CO LDME for χ_c is obtained from fit to data**
- Ratios more precise
- **Small p_T region has to be explored**



PRL 119 (2017) 22, 221801

- **First observation of $\chi_{c1,2} \to J/\psi\mu\mu$** decay modes
- Clean signals
- **$\chi_{c1,2}$ resonance parameters** measured with world average precision

Quantity [MeV]	LHCb measurement	Best previous measurement	World average
$m(\chi_{c1})$	3510.71 ± 0.10	3510.72 ± 0.05	3510.66 ± 0.07
$m(\chi_{c2})$	3556.10 ± 0.13	3556.16 ± 0.12	3556.20 ± 0.09
$\Gamma(\chi_{c2})$	2.10 ± 0.20	1.92 ± 0.19	1.93 ± 0.11



- New channel for production measurement
- **Promising channel for χ_c hadroproduction studies at low p_T**

Combined fits of LDME

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

Usachov, Shao et al.

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

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

- Relation between LDME from HQSS:

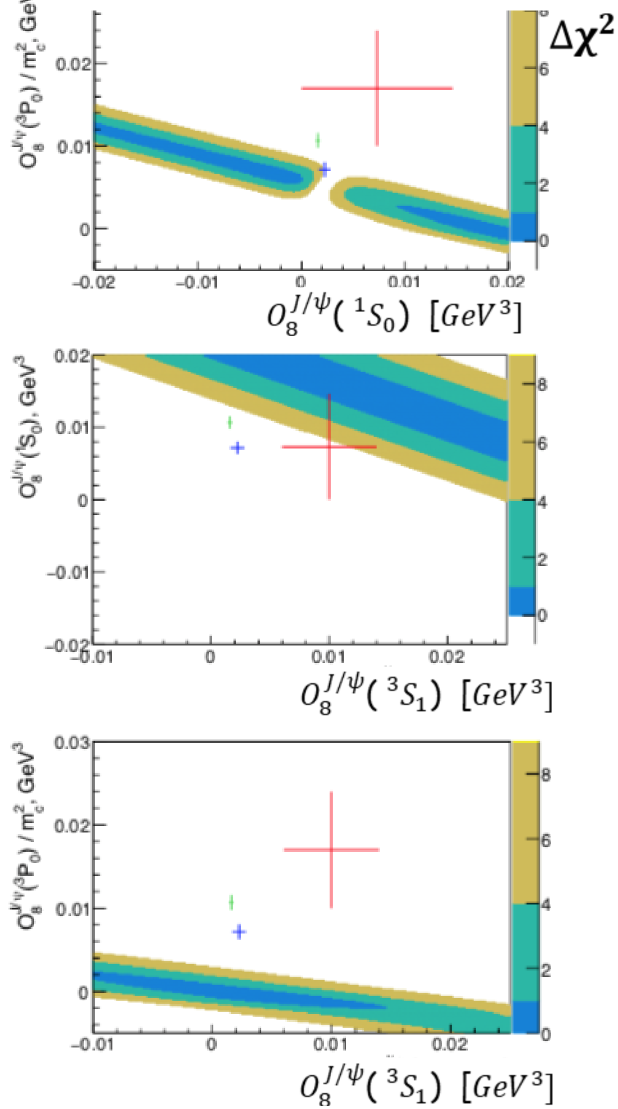
$$\langle O_1^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_1^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^1S_0)\rangle = \frac{1}{3}\langle O_8^{J/\psi}(^3S_1)\rangle,$$
$$\langle O_8^{\eta_c}(^3S_1)\rangle = \langle O_8^{J/\psi}(^1S_0)\rangle,$$
$$\langle O_8^{\eta_c}(^1P_1)\rangle = 3\langle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

- Branching fractions calculated in **Beneke, Maltoni, Rothstein PRD 59 (1999) 054003**
- Fix CS LDME from potential model $\langle O_8^{J/\psi}(^3S_1)\rangle = 1.16\,\mathrm{GeV}^3$
- **Fit three LDME to two measurements**

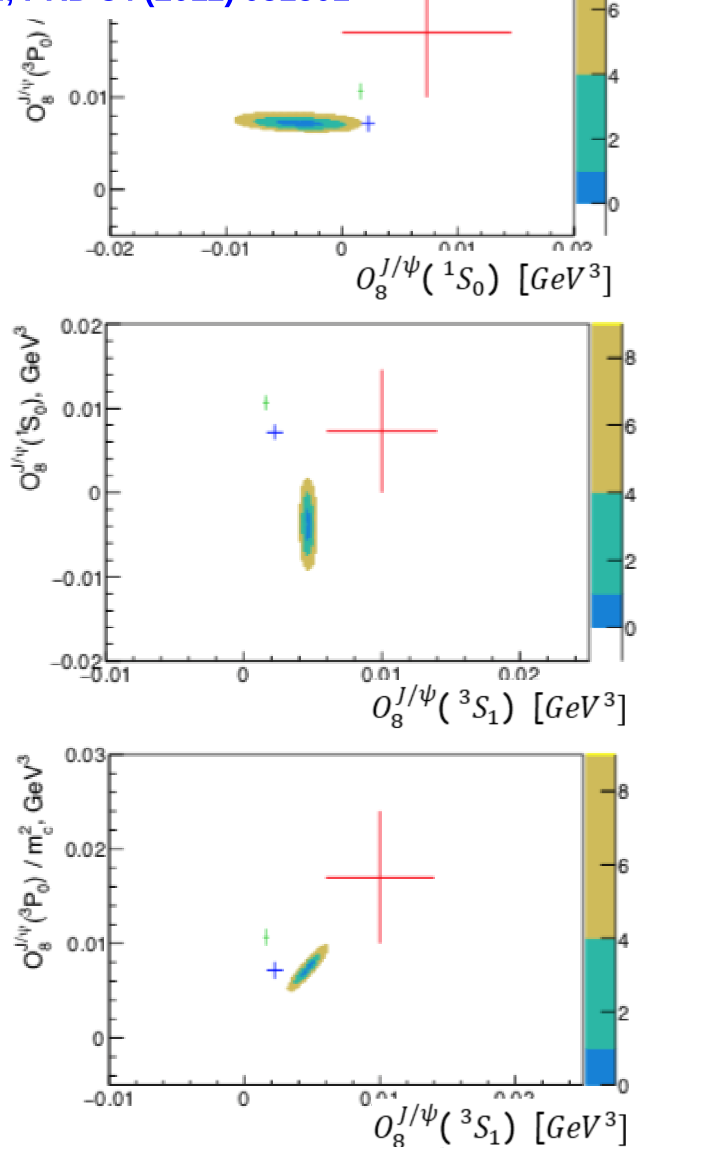
$$\frac{\mathcal{B}(b \to \eta_c(1S)^{direct} X)}{\mathcal{B}(b \to J/\psi^{direct} X)} \qquad \mathcal{B}(b \to J/\psi^{direct} X)$$

- Consecutively fix remaining LDME from **Chao et al., PRL 108 (2012) 242004**
- **Theory calculations should be revisited**, higher order corrections maybe needed

Shao et al., PRL 114 (2015) 092005
Baranov. Lipatov, arXiv:1904.00400
Butenschoen, Kniehl, PRD 84 (2011) 051501



Shao et al., PRL 114 (2015) 092005
Baranov. Lipatov arXiv:1904.00400
Butenschoen, Kniehl, PRD 84 (2011) 051501



- **Simultaneous fits to J/ψ and $\eta_c(1S)$ LDMEs, prompt and b-decay production**
- **Short distance coefficients** for prompt production from H.-S. Shao

- **Theory calculations should be revisited**, higher order corrections maybe needed

Usachov,Kou,SB, LAL-17-051

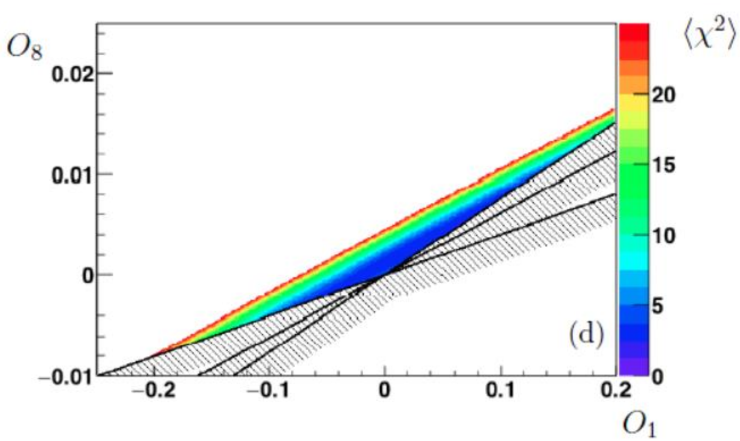
- From **EPJC 77 (2017) 609** and **Chin. Phys. C40 (2016) 100001:**

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

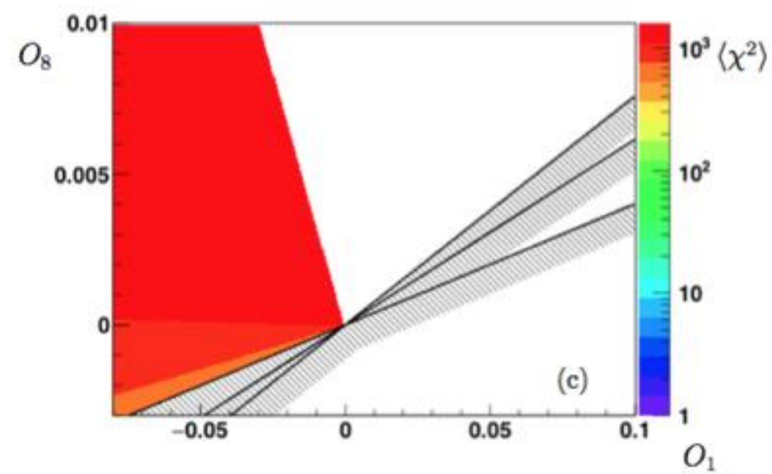
- Relation between LDME from HQSS:

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

- Branching fractions calculated in **Beneke, Maltoni, Rothstein, PRD 59 (1999) 054003**
- **Fit two LDME to two/three measurements**
- **Three BRs →**



Two ratios →



- Important to revisit theory calculations

- 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**

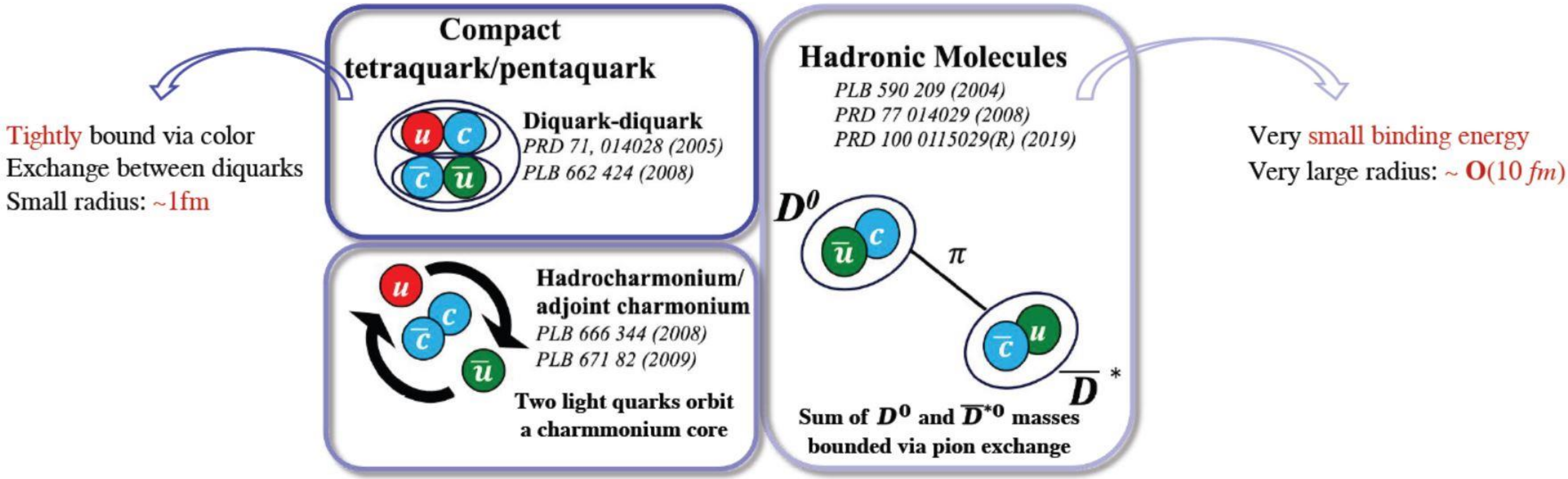
- Alternatively, once hadroproduction and production in b-decays measured for charmonium states with linked LDMEs,
  the above **assumptions can be tested quantitatively**

Probing charmonium-like states

- $\chi_{c1}(3872)$ is first discovered in 2003 by Belle in decay of $B \to J/\psi\ \pi^{+}\pi^{-}$ **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:

$$(M_{D^0} + M_{D^{*0}}) - M_{\chi c1(3872)} = 0.07 \pm 0.12 \text{ MeV/c2}$$

- 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

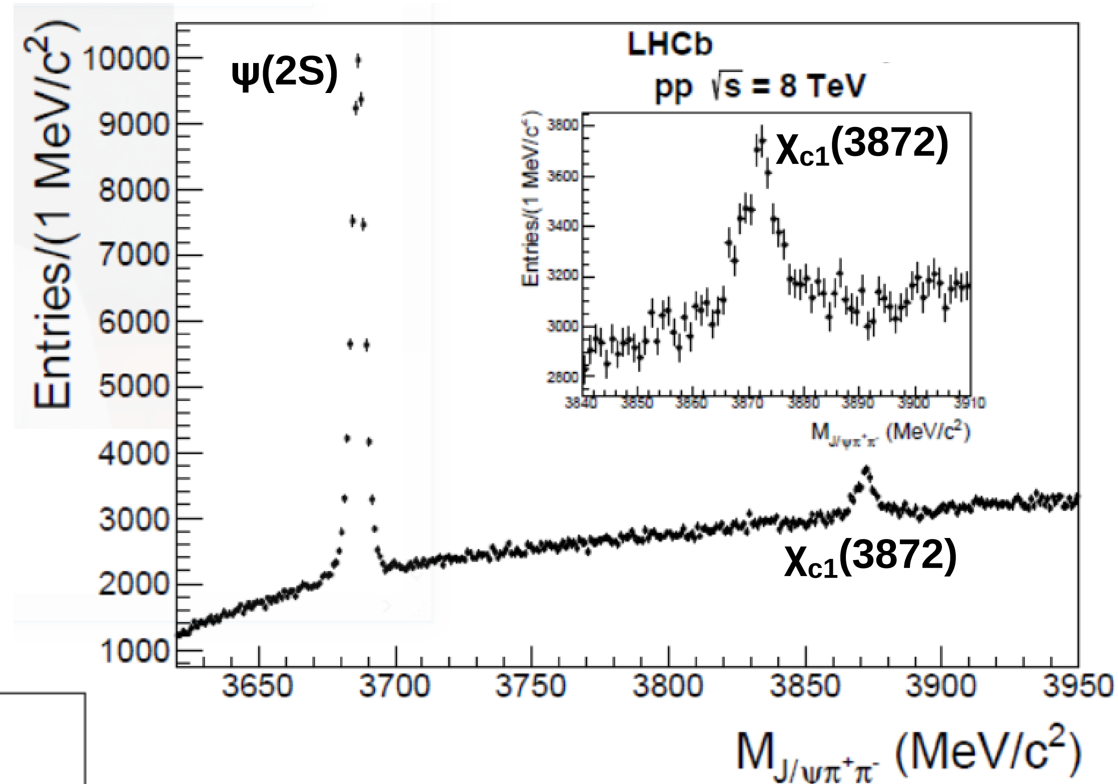
- **High-multiplicity pp collisions** plausibly **emulate a hadronic environment that approaches heavy ion collisions** in many respects

- **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 $\chi_{c1}(3872)$**

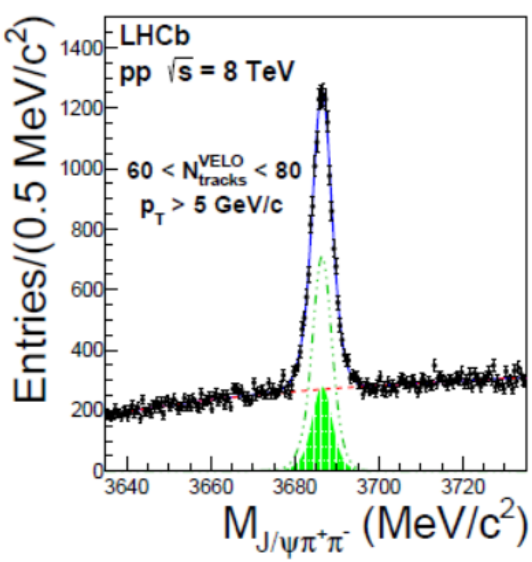
PRL 126 (2021) 092001

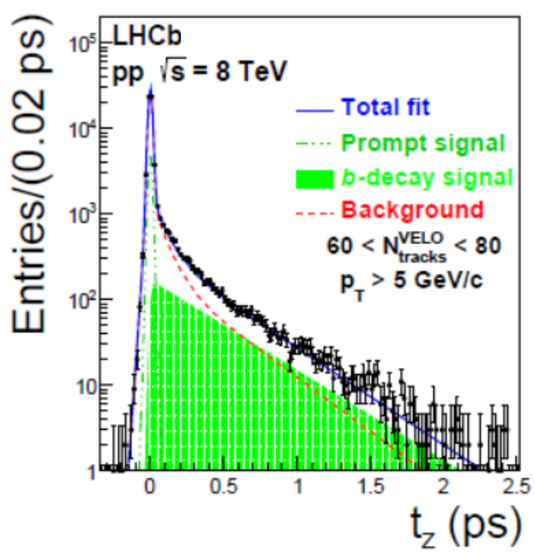
$\sqrt{s}$ = 8 TeV, $\int Ldt$ ~2 fb^{-1}

- If **χ_{c1}(3872)** is a hadronic molecule, then expect small binding energy, 0.01 ± 0.27 MeV, and large radius ~7 fm



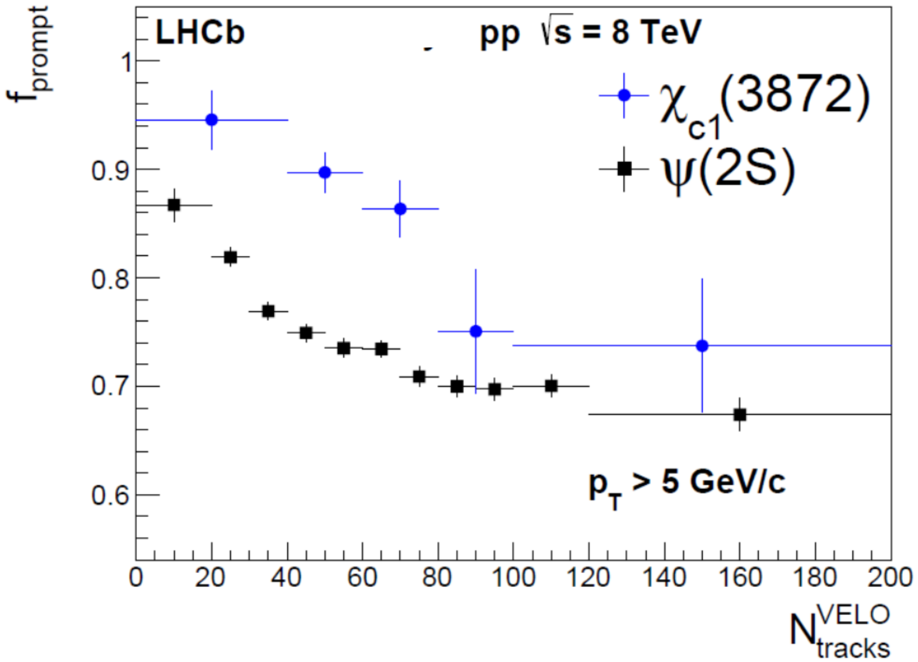
S.Coito, G.Rupp, E.van Beveren, EPJC 73 (2013) 2351
N.A.Tornqvist, PLB 590 (2004) 209
E.Braaten, M.Kusunoki, PRD 71 (2005) 074005
M.Cardoso, G.Rupp, E.van Beveren, EPJC 75 (2015) 26





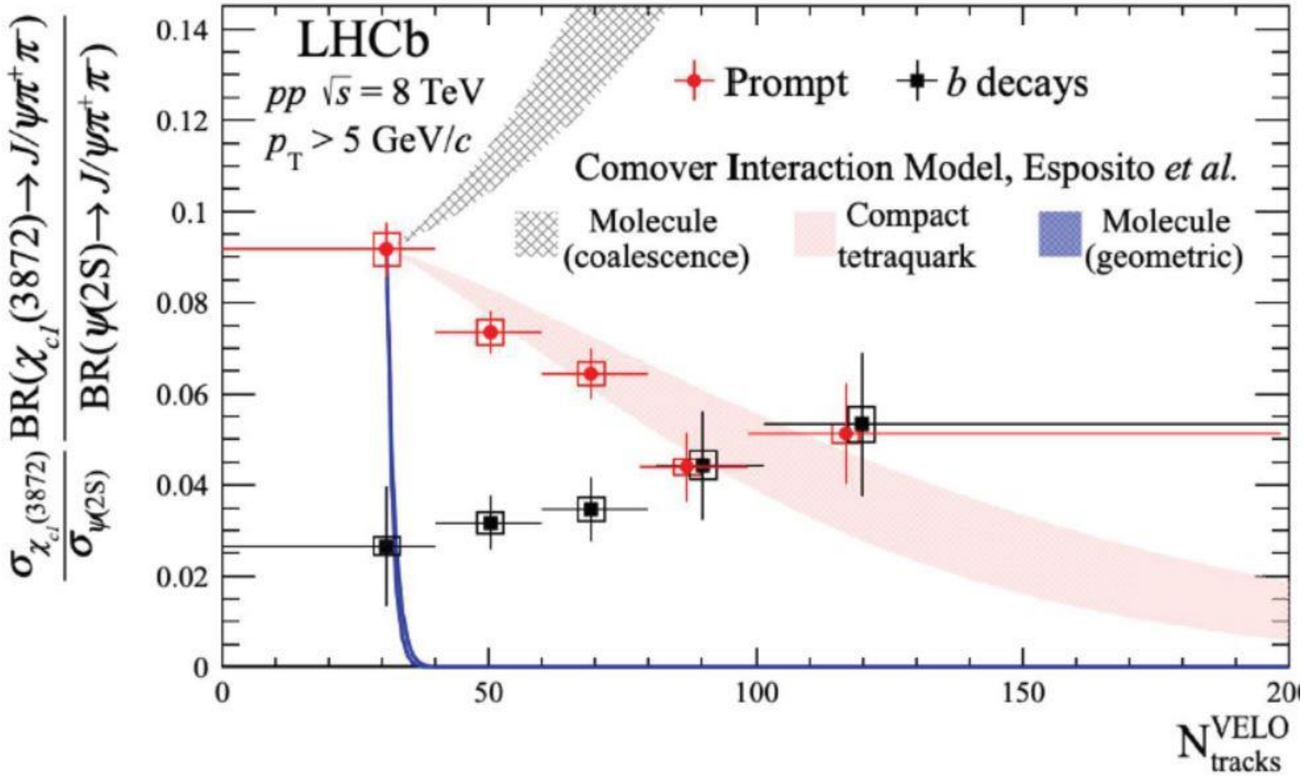
- Pseudo proper-time to distinguish **prompt** and **b-decay** components
- Measure **ratios, χ_{c1}(3872) and ψ(2S), for prompt and b-decay components**

- The **prompt fraction** decreases as the **event activity** increases, for both χ_{c1}(3872) and ψ(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 χ_{c1}(3872) and ψ(2S) production via interactions with other particles produced at the vertex → **reduced prompt production in high multiplicity events, production in b decays not affected**

- **Ratio of cross-sections, χ_{c1}(3872) and ψ(2S)**, for prompt and b-decay production



- 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**

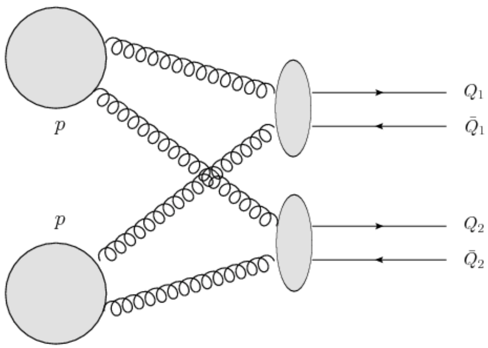
- Evidence for **relative χ_{c1}(3872) suppression for high-multiplicity events**
- Expected in a **scenario of interactions with co-moving hadrons** dissociating large weakly bound χ_{c1}(3872) against compact ψ(2S)
- Cross-check: production in b-decays

Associated Production

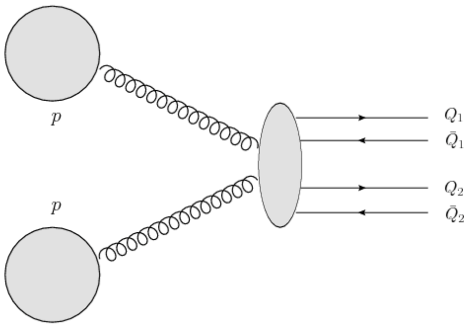
JHEP 1706 (2017) 047
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 279\ pb^{-1}$

- Production via **Double Parton Scattering** (DPS) or **Single Parton Scattering** (SPS)
- **DPS**: two independent hard scatters that are assumed to factorize
- **SPS**: gluon splitting expected to dominate $c\bar{c}$ production

DPS



SPS



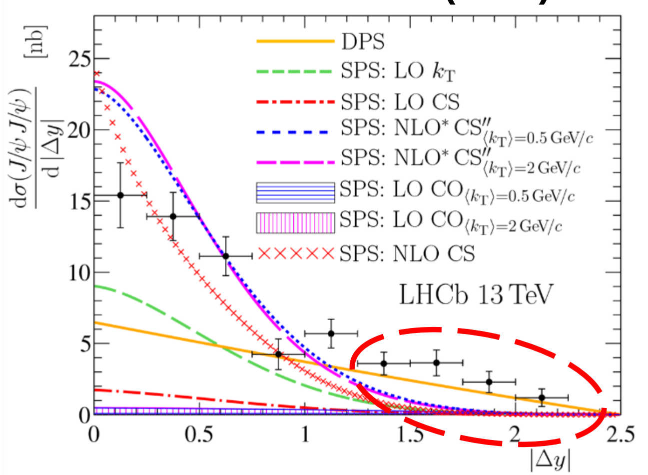
$$\sigma_{\rm DPS}\left(J/\psi\, J/\psi\right) = \frac{1}{2}\frac{\sigma\left(J/\psi\right)^2}{\sigma_{\rm eff}}$$

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

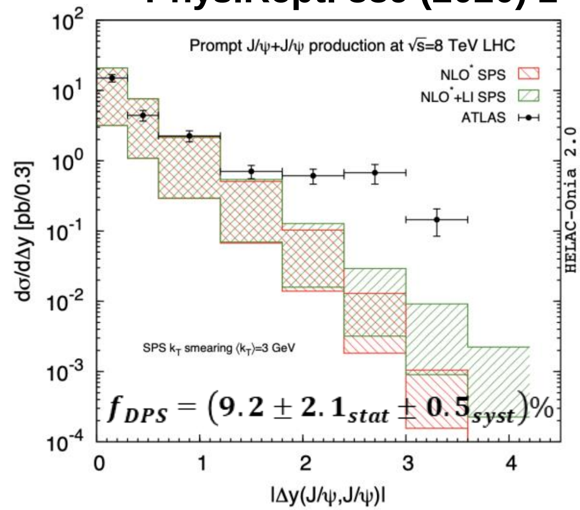
- **Di-J/ψ production**
  - Expected small SPS CO contribution
  - DPS contribution is important at large J/ψ Δy
  - Feed-down contribution depends on the production mechanism

- **Differential production cross-section** in bins of kinematical variables
- Fit of kinematical distributions to extract DPS fraction and σ_{eff}
- Agreement between fits of $|\Delta y|$, $p_T(J/\psi J/\psi)$, $y(J/\psi J/\psi)$, $m(J/\psi J/\psi)$

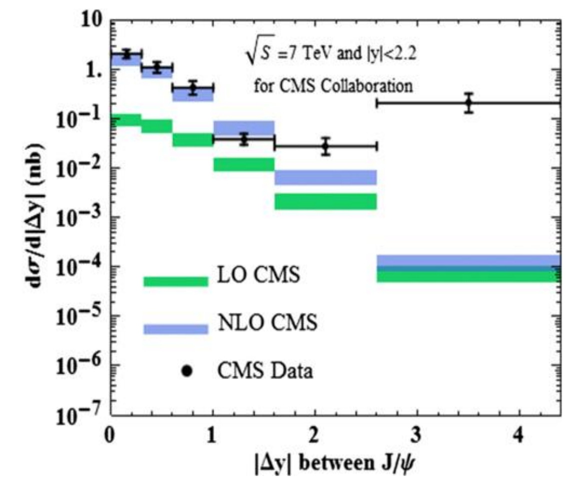
JHEP 1706 (2017) 047



Phys.Rept. 889 (2020) 1



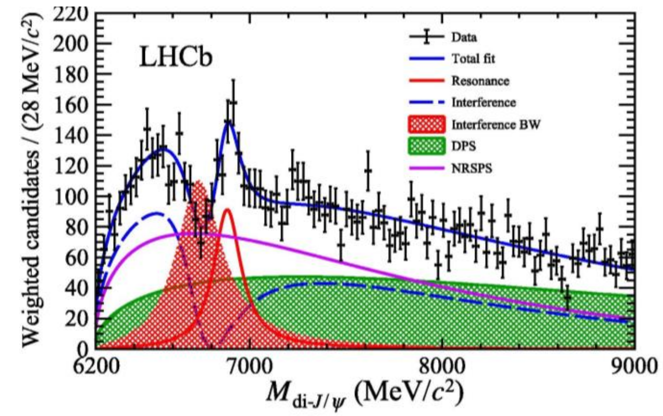
PRD 94 (2016) 7, 074033



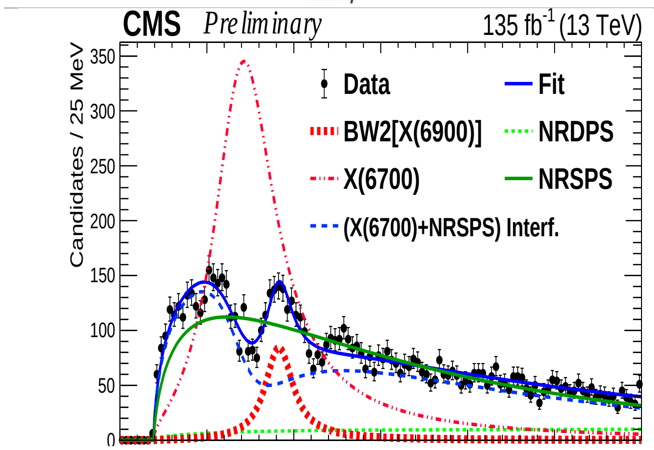
- ATLAS ($p_T > 8.5$ GeV/c, $|y| < 2.1$): $\sigma_{eff} = 6.3 \pm 1.6_{stat} \pm 1.0_{syst}\, mb$
- LHCb ($p_T < 10$ GeV/c, $2.0 < y < 4.5$): $\sigma_{eff} = 8.8 \pm 5.6\, mb \ldots 12.5 \pm 4.1\, mb$
- An **improvement in the precision for SPS predictions** for a better discrimination between theory approaches
- **Feed-down contribution** can amount up to 40% of SPS contribution → to be accounted for

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

First observation of **fully heavy tetraquark candidate X(6900)**



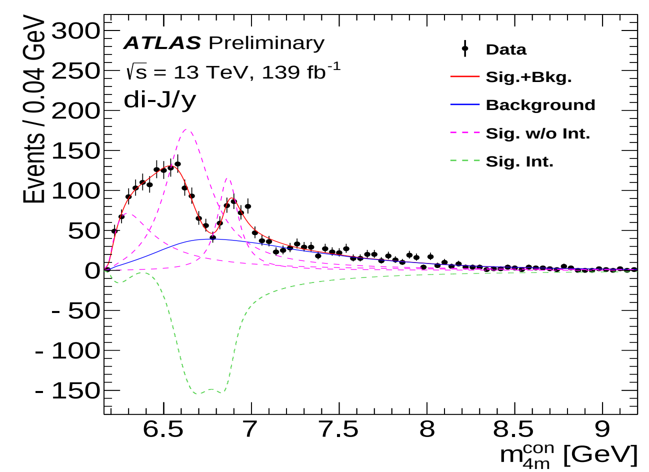
Two more candidates **X(6600) and X(7300)**



Threshold structure with a few possible interpretations:

One BW, combination of two BWs, feed-down…

	m [GeV/c²]	Γ [GeV/c²]
LHCb	$6.89 \pm 0.01 \pm 0.01$	$0.17 \pm 0.03 \pm 0.07$
CMS	$6.93 \pm 0.01 \pm 0.01$	$0.12 \pm 0.02 \pm 0.02$
ATLAS	$6.87 \pm 0.03 ^{+0.06}_{-0.01}$	$0.12 \pm 0.04 ^{+0.03}_{-0.01}$



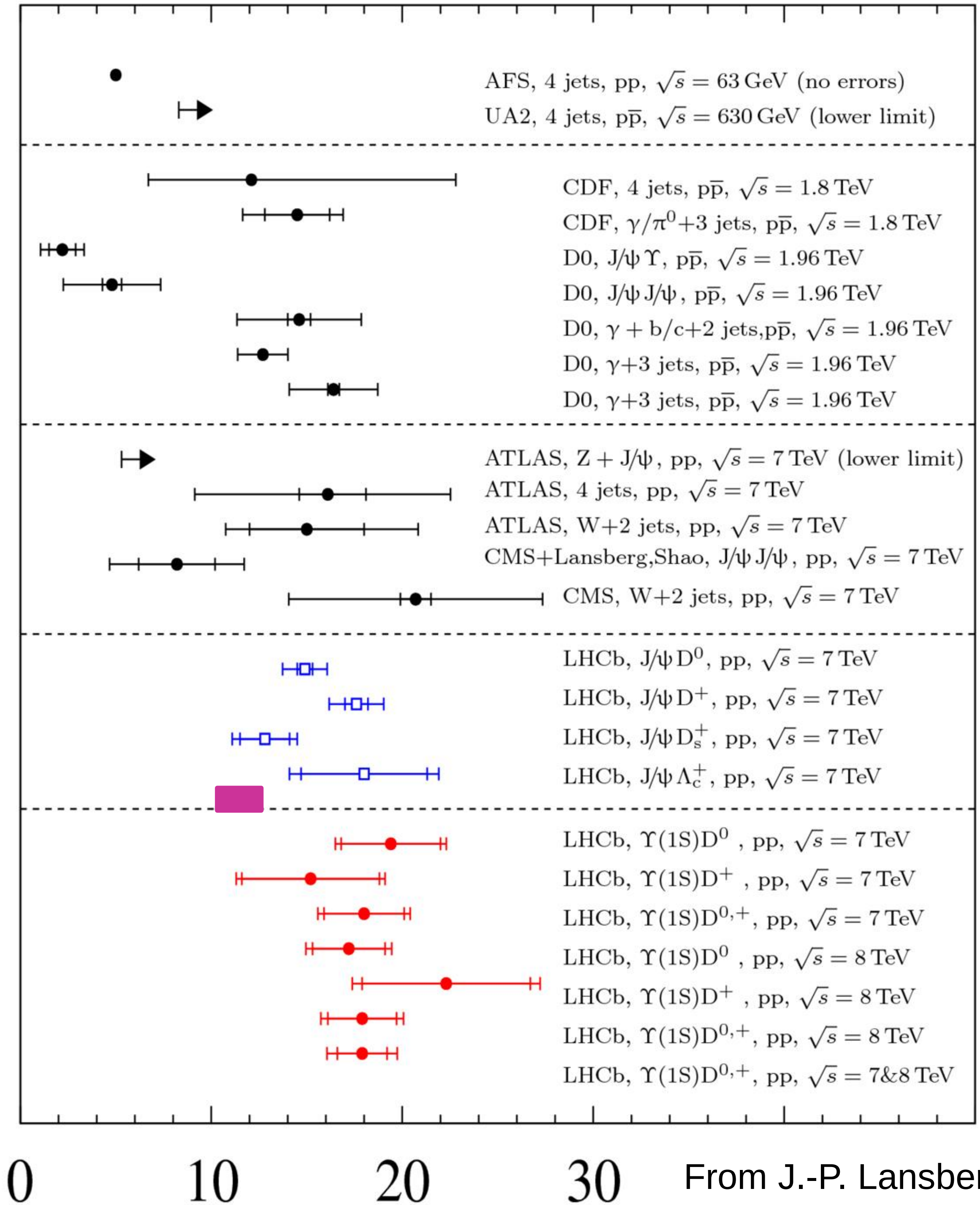
Additional study together with spin-parity measurement to explain nature of threshold structure

Revisit associate production results

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

- ❑ Compilation of results on σ_{eff}, mb

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

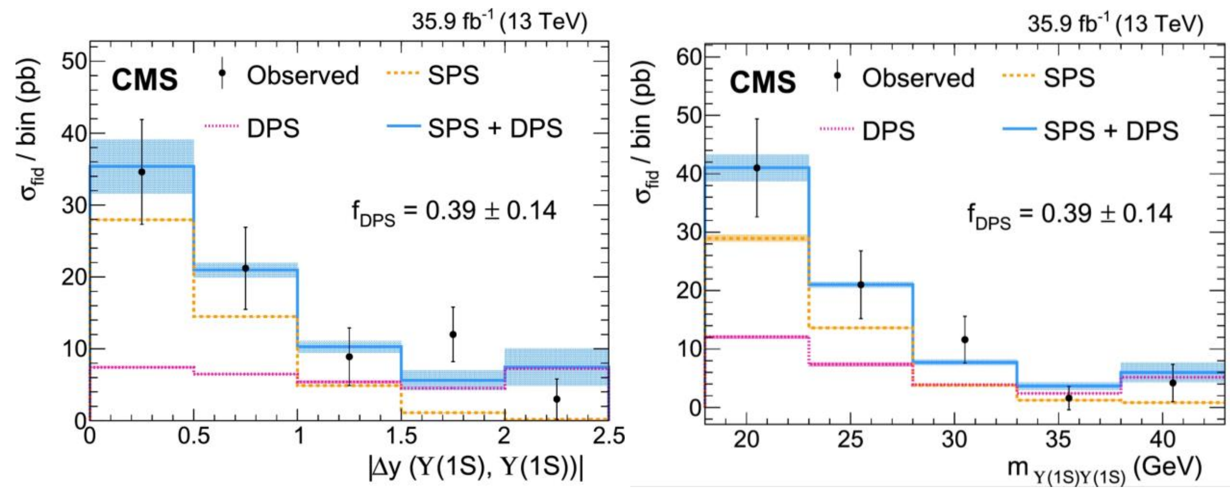


From J.-P. Lansberg

- ❑ Should σ_{eff} be universal ?
- ❑ Results to be updated

PLB 808 (2020) 135578
$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 35.9\ fb^{-1}$

- **DPS process** can provide **information on partons** p_T, their correlations inside proton



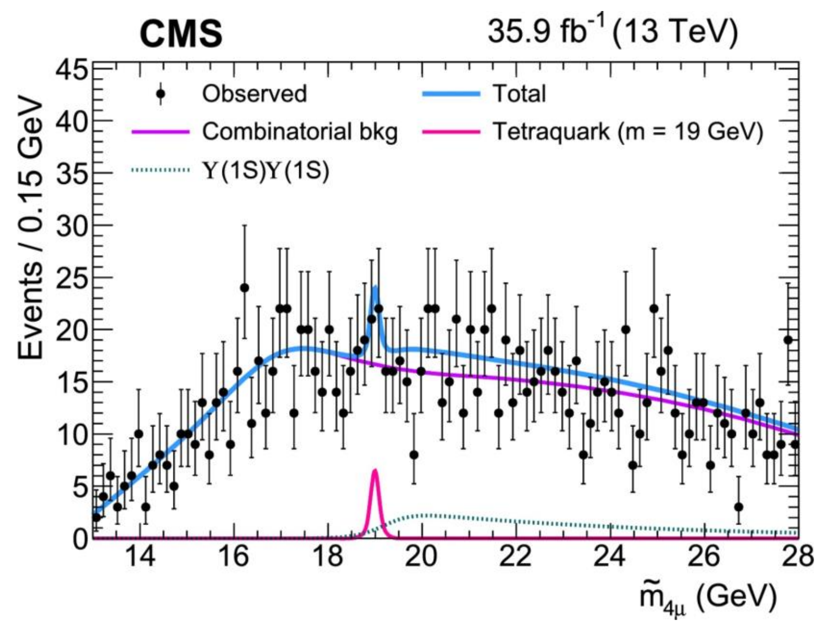
- **Υ(1S) pair production** (assuming no polarization)

$$\sigma_{\Upsilon(1S)\Upsilon(1S)} = 79 \pm 11_{stat} \pm 6_{syst} \pm 3_{\mathfrak{B}}\ pb,\ |y|<2.0$$

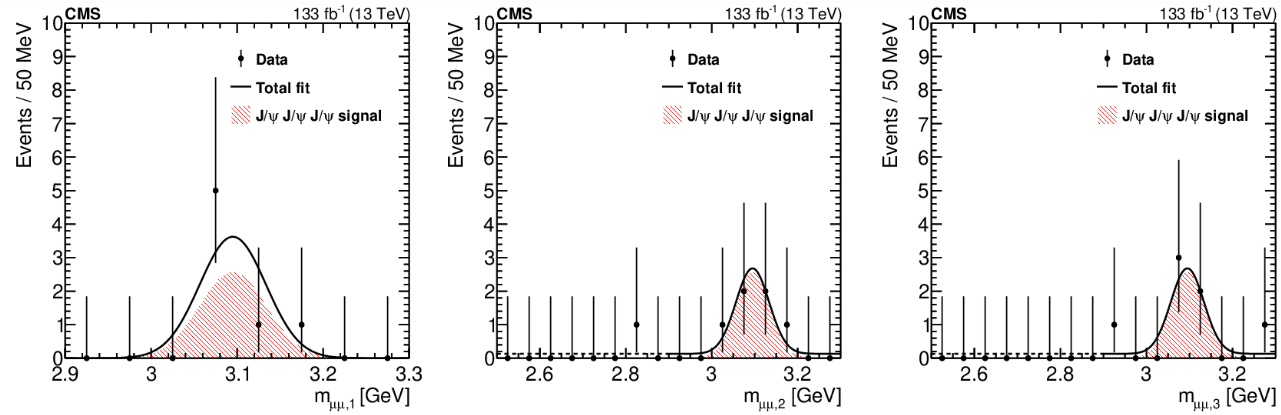
- First measurement of DPS contribution to $\sigma_{\Upsilon(1S)\Upsilon(1S)}$

$$f_{DPS} = (39 \pm 14)\%$$

- **No significant excess** of events



arXiv:2111.05370



- First observation of **triple-J/ψ production**

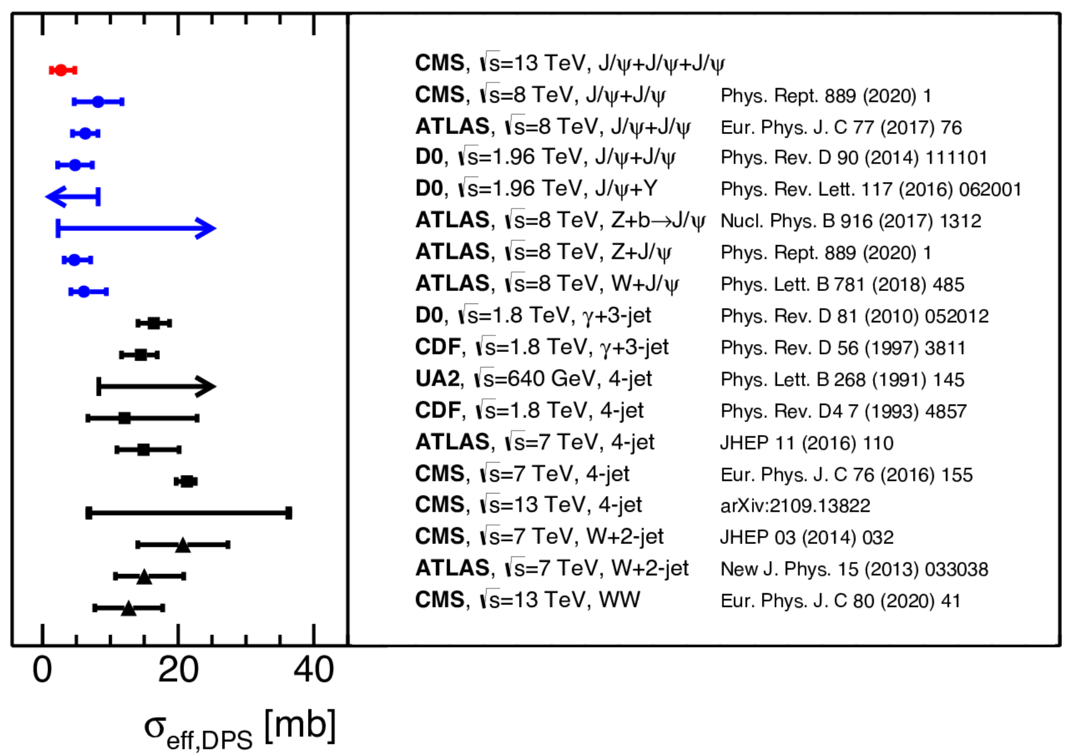
- Cross-section:

$\sigma_{3J/\psi} = 272^{+141}_{-101}{}_{stat} \pm 16_{syst}\, fb$, $|y_{J/\psi}|<2.4$

- Contributions of DPS and TPS:

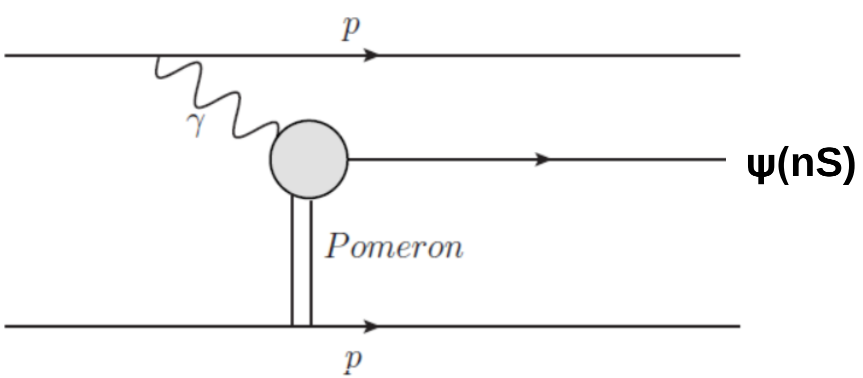
f_{DPS}~76% and f_{TPS}~20%

- Measured $\sigma_{eff} = 2.7^{+1.4}_{-1.0}{}_{stat}{}^{+1.5}_{-1.0}{}_{syst}\, mb$ is consistent with di-J/ψ results, but lower that jet/W/Z results



Central Exclusive Production of charmonium

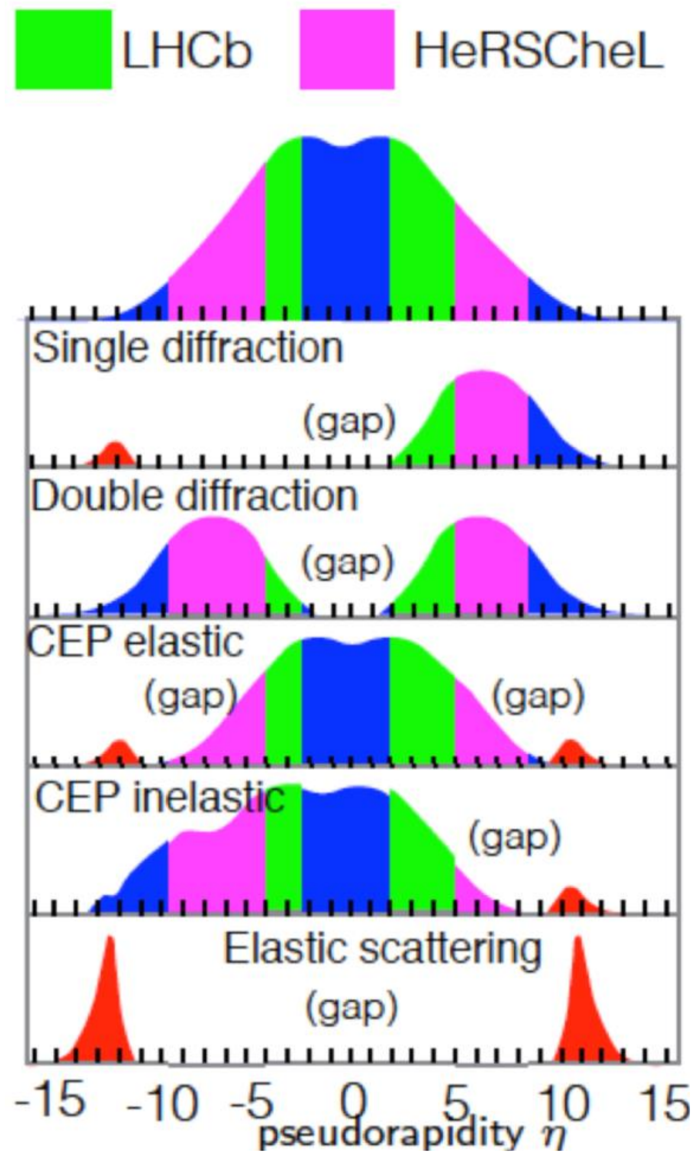
- ❑ **Mediated by the exchange of a colourless object**
- ❑ **QCD tests with clean theoretical interpretation**
- ❑ Only **CS production**
- ❑ Cross-section can be calculated in pQCD and (at LO) is proportional to the square of the gluon PDF, g(x)



- ❑ **With LHCb:**

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

- ❑ **CEP: large rapidity gap**

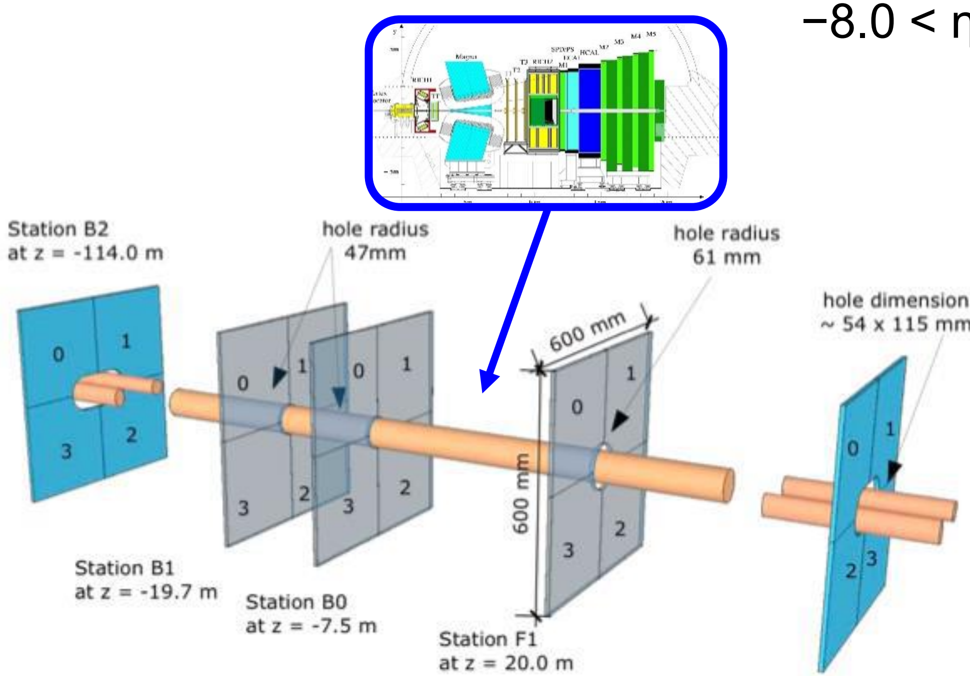


Central Exclusive Production of J/ψ and ψ(2S) at 13 TeV

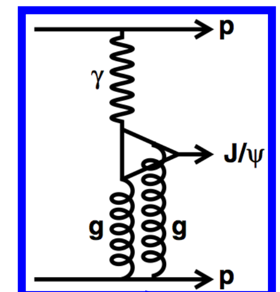
JHEP 10 (2018) 167

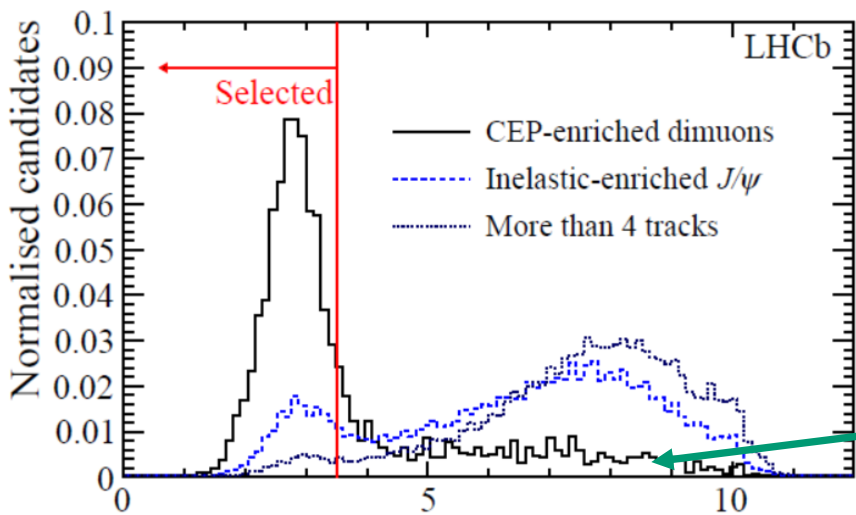
$\sqrt{s}$=13 TeV, ∫Ldt ~0.2 fb^{-1}

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

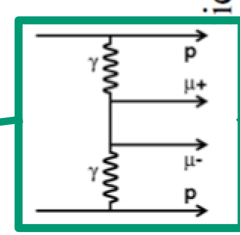


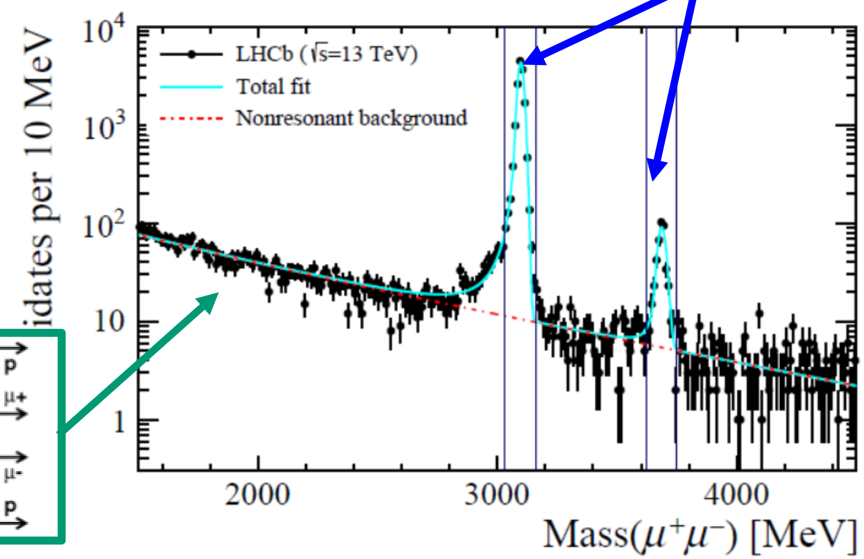
- Dedicated CEP trigger
- **Exclusivity**: precisely two forward muons; no backward tracks; no activity in SPD (< 10 hits). Quantify with p_T spectrum.



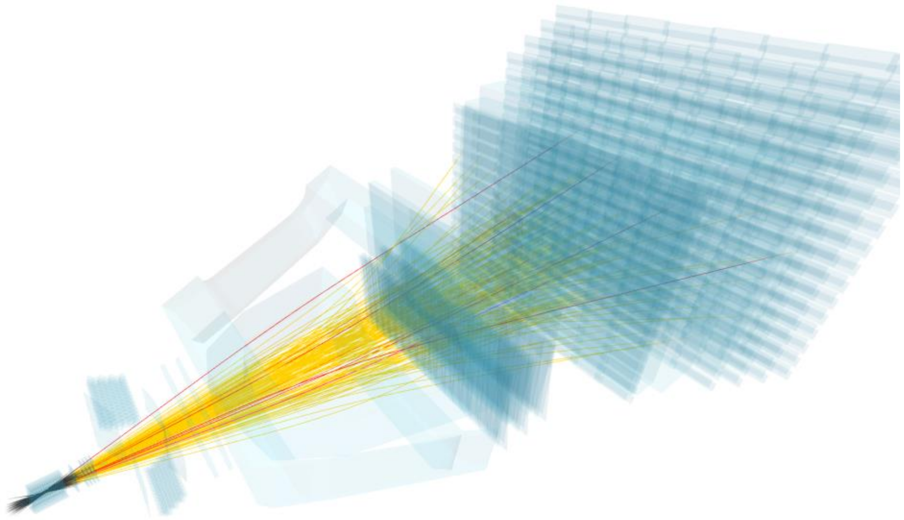


Sum of Herschel deposits in quadrature

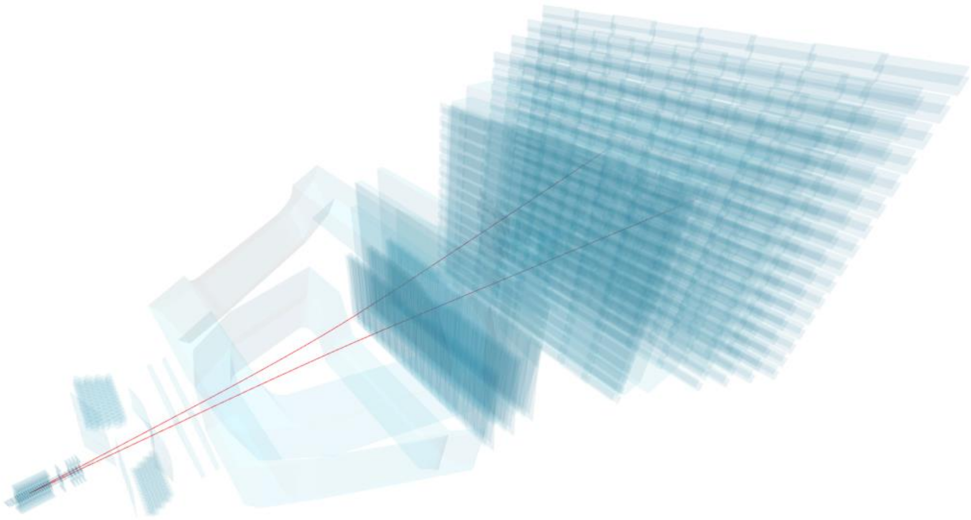




- CEP event in LHCb: diffractive process of the form pp → pXp



Inelastic pp collision



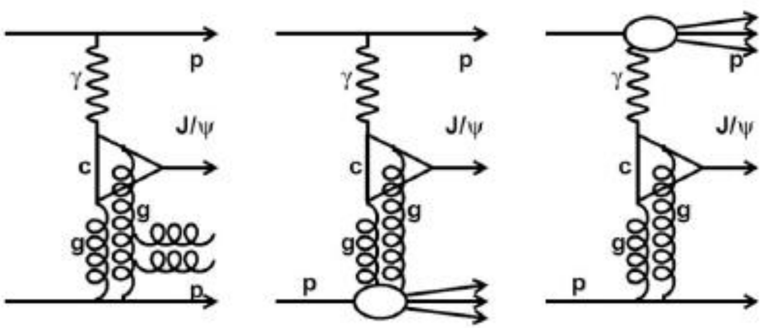
CEP pp collision

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

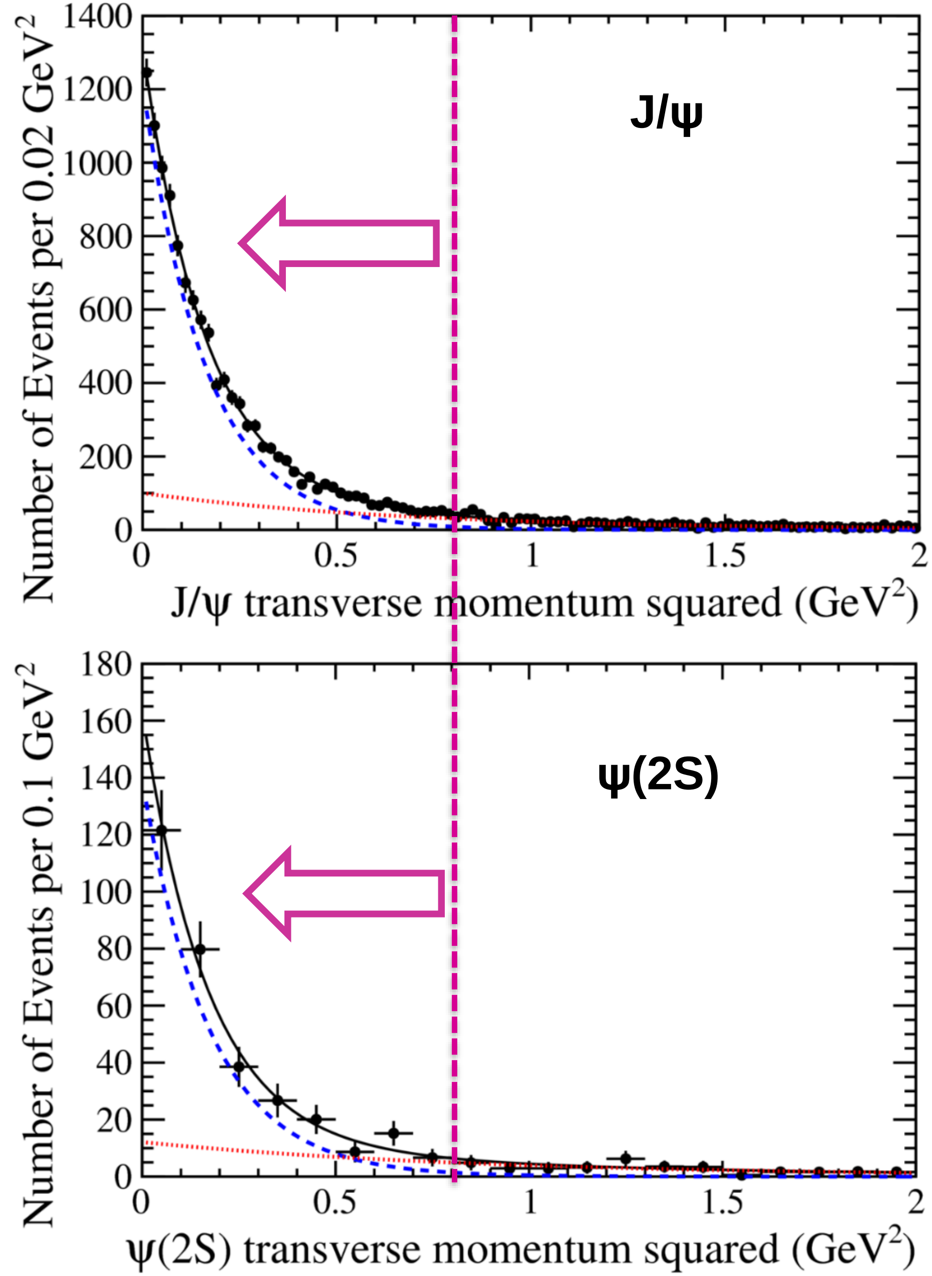
$\psi(2S) \to J/\psi\pi\pi$: $2.5 \pm 0.2\%$

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

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

JHEP 10 (2018) 167

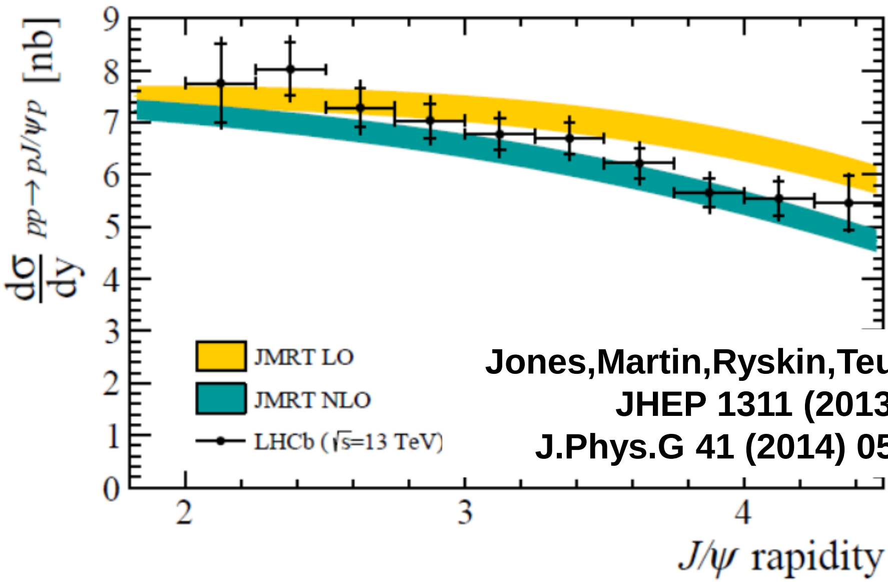
$\sqrt{s}$=13 TeV, ∫Ldt ~0.2 fb^{-1}



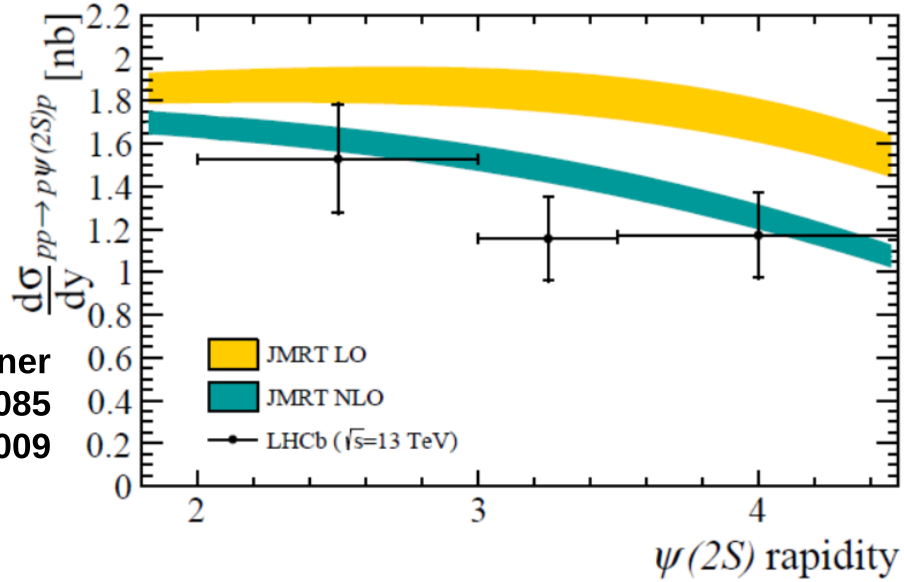
JHEP 10 (2018) 167

$\sqrt{s}$=13 TeV, ∫Ldt ~0.2 fb^{-1}

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



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



- **Integrated cross-sections** times fractions

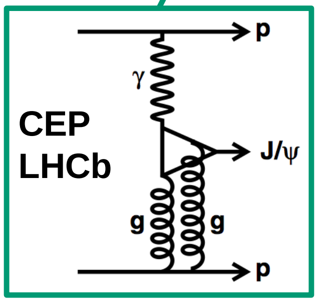
$$\sigma_{J/\psi\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 407 \pm 8 \pm 24 \pm 16 \text{ pb}$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2.0 < \eta_{\mu^+}, \eta_{\mu^-} < 4.5) = 9.4 \pm 0.9 \pm 0.6 \pm 0.4 \text{ pb}$$

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

JHEP 10 (2018) 167
$\sqrt{s}$=13 TeV, ∫Ldt ~0.2 fb^{-1}

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

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

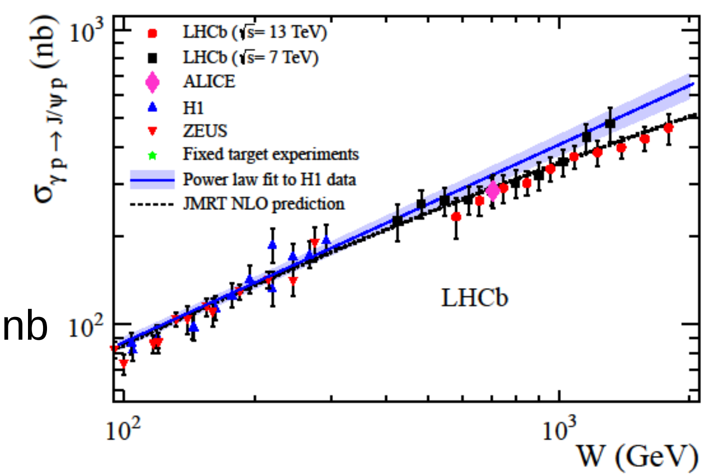


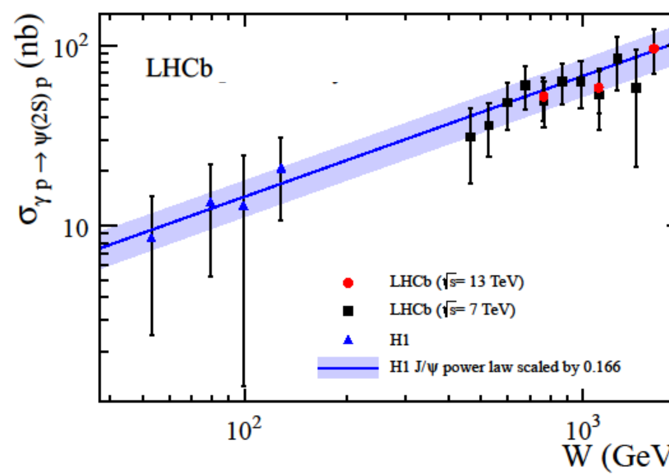
Gap survival

Photon flux

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

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





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

Outlook

- Quarkonium serves a powerful probe for **QCD-driven production mecanisms** … 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 mecanism

- We do not know yet 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 …

Foto: Google Arts & Culture

- Rapidity

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

- Pseudorapidity

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