EXPERIMENTAL STATUS OF NOT-SO-CONVENTIONAL QUARKONIUM PRODUCTION (χ_c, η_{cb}, X(3872))

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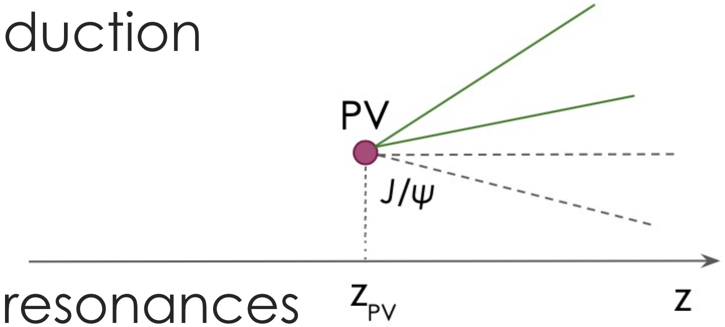
Quarkonia as Tools 2022

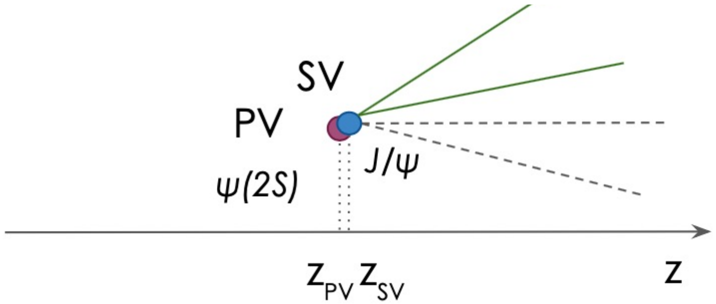
13/01/2022

QUARKONIUM PRODUCTION

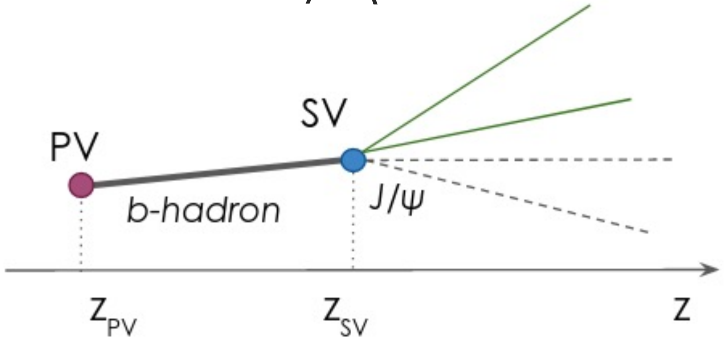
- **Sources of quarkonium:**
  - prompt hadroproduction



  - decays of higher resonances



  - production in b-hadron decays (charmonium only)



prompt production

distinguished via pseudo-proper decay time

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

PV – primary vertex
SV – secondary vertex

MODELS OF QUARKONIUM PRODUCTION

- **No consensus on the quarkonium production mechanism**
- Nearly all approaches assume **factorisation** between the **$Q\bar{Q}$ formation** and its **hadronization** into a meson
- Essential difference in various approaches is in the **description of the hadronization:**
  - **Colour evaporation model (CEM):** application of quark-hadron duality; only the invariant mass matters;
  - **Colour-singlet model (CS)**: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} as the final-state quarkonium;
  - **Colour-octet model (CO)** (encapsulated in NRQCD): all viable colours and J^{PC} allowed for the intermediate $Q\bar{Q}$ state;

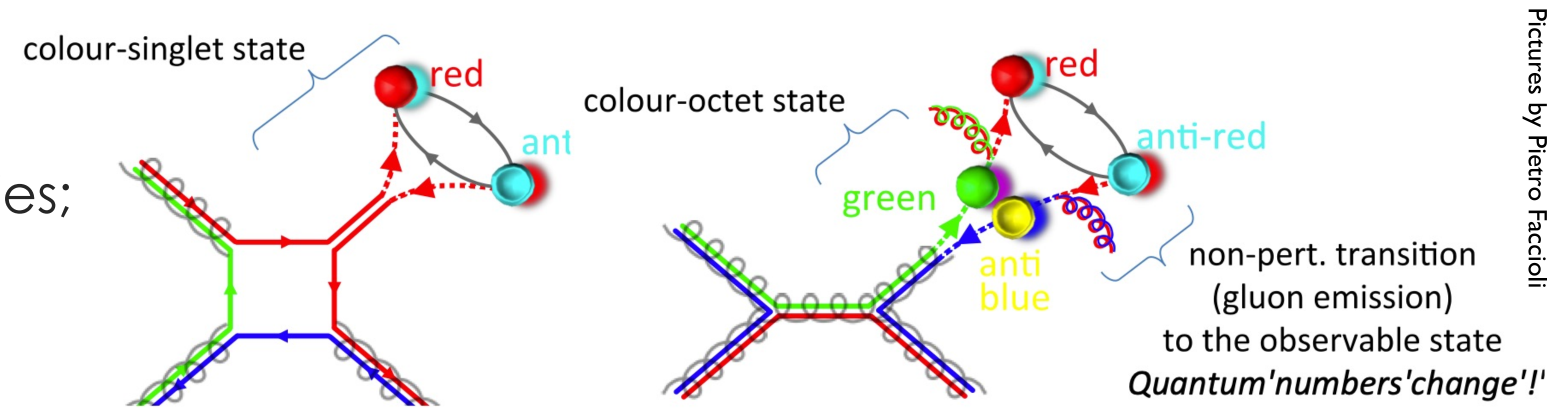
QUARKONIUM PRODUCTION IN NRQCD

- Two scales of production: hard process of **$Q\bar{Q}$ formation** and **hadronization of $Q\bar{Q}$** at softer scales
- **Factorization:** $d\sigma_{A+B\rightarrow H+X} = \sum_n d\sigma_{A+B\rightarrow Q\bar{Q}(n)+X} \times < O^H(n) >$

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

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

- Both **CS** and **CO states** are allowed with varying probabilities; LDMEs from experimental data

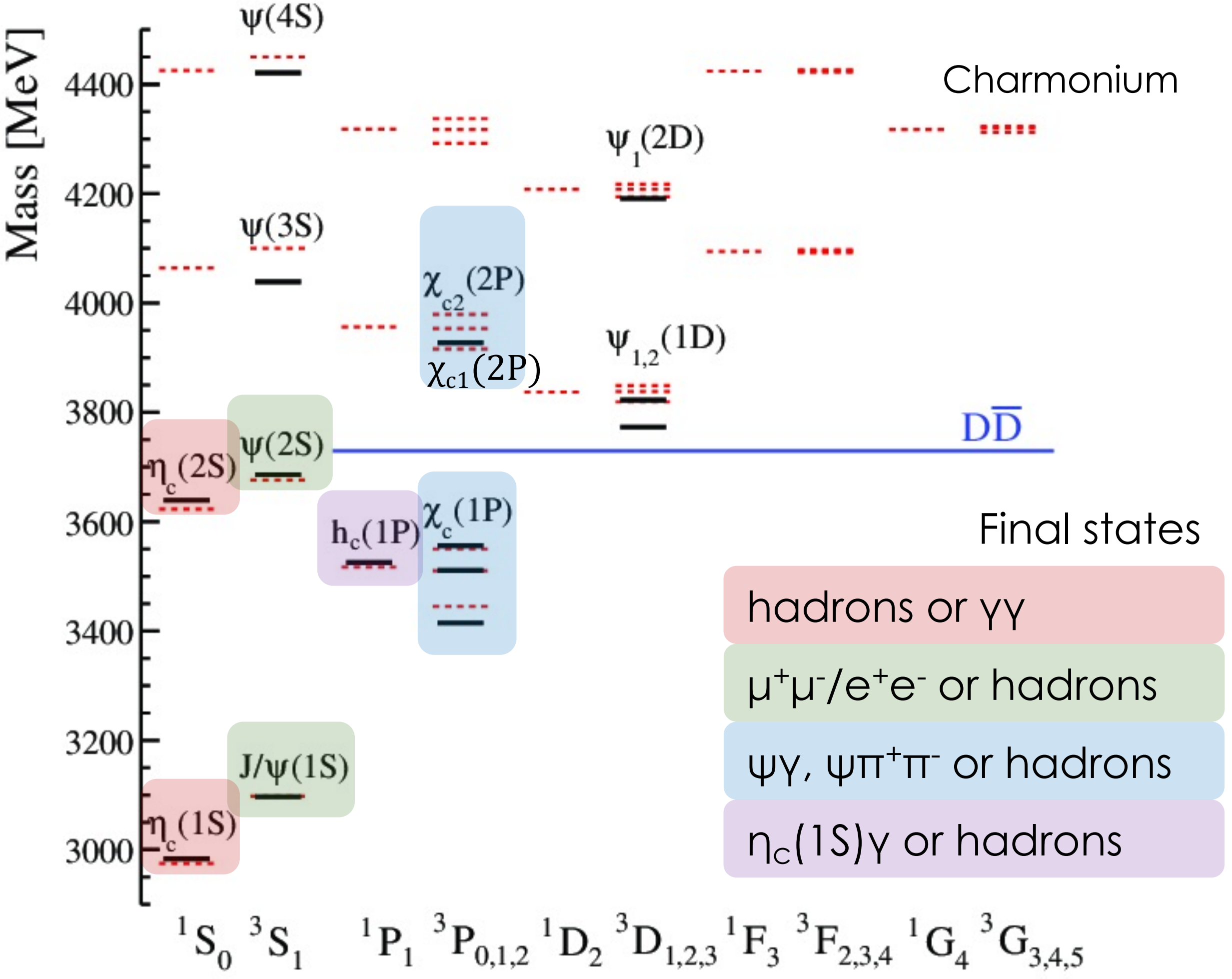


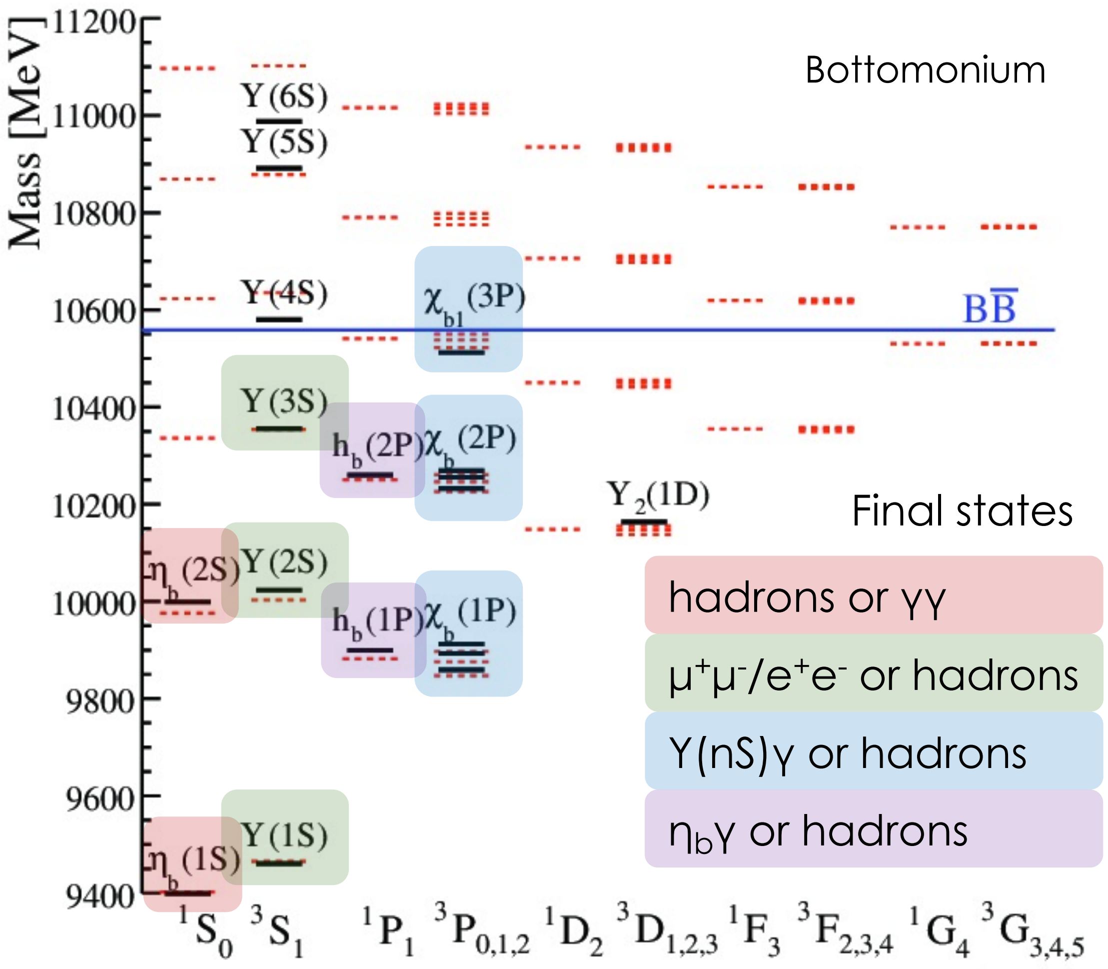
- **Universality**: same LDMEs for different √s, prompt production and production in b-decays
- Heavy-Quark **Spin-Symmetry**: links between CS and CO LDMEs of different quarkonium states

ACCESSIBLE CHANNELS FOR QUARKONIUM

Rev.Mod.Phys 90 (2018) 015003

- Current status of quarkonium spectrum



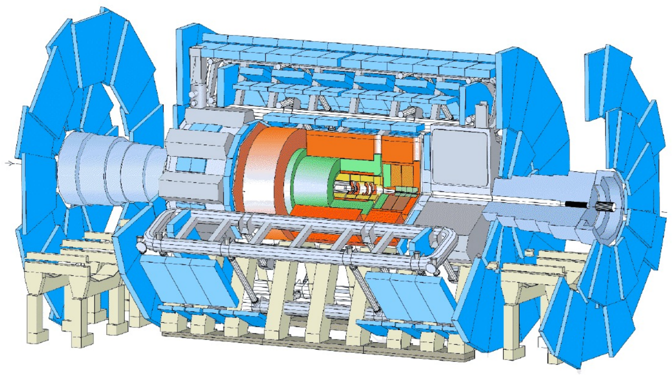


- **Hadronic final states allow to study different quarkonium states simultaneously**

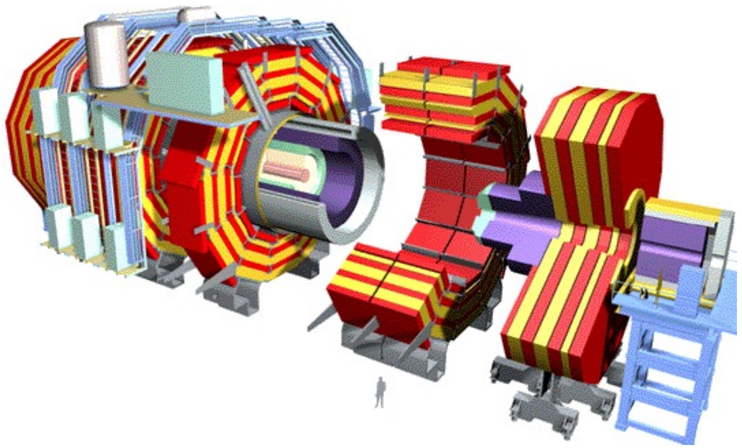
LHC DETECTORS HUNTING FOR QUARKONIUM

- **ATLAS** and **CMS**: mid-rapidity region, with muons in final state

ATLAS EXPERIMENT
JINST 3 (2008) S08003

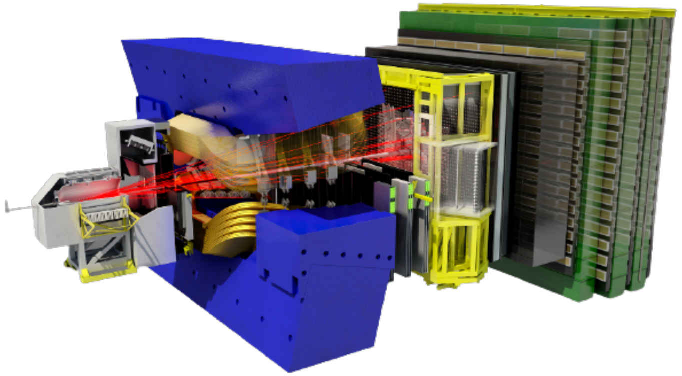


CMS
JINST 3 (2008) S08004



- **LHCb**: forward-rapidity region, with muons and hadrons in final state

LHCb
IJMPA 30 (2015) 1530022



- **ALICE**: both mid- and forward-rapidity regions, with muons and electrons in final state

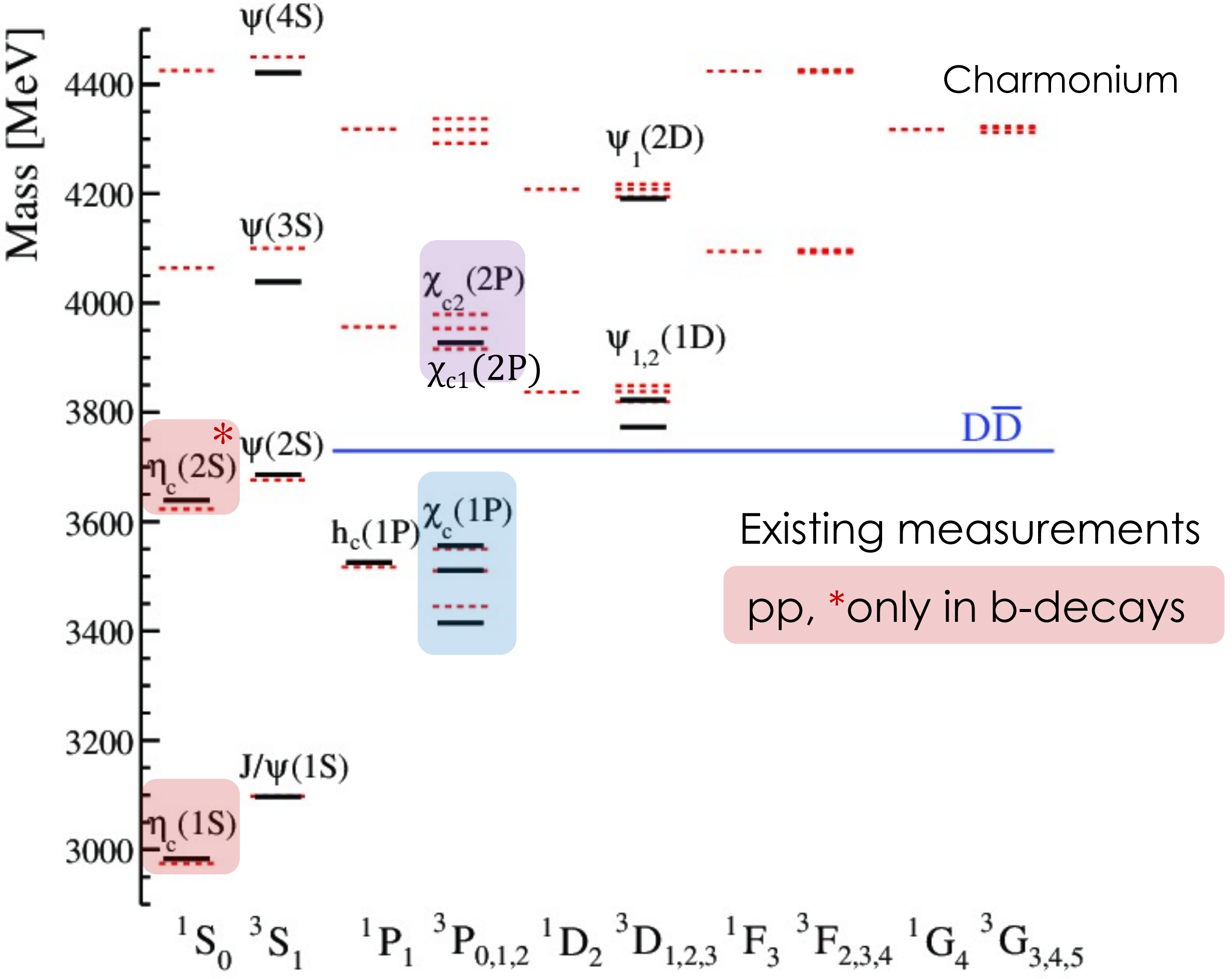
ALICE
JINST 3 (2008) S08002

- **Experiments provide complementary measurements**

CURRENT STATUS OF QUARKONIUM SPECTRUM

Rev.Mod.Phys 90 (2018) 015003

- Current status of quarkonium spectrum



- **η_c**

- Possible decays: hadronic or γγ

- **Challenging to study η_c** production due to **high combinatorial background**:

    - No η_c(2S) prompt production

    - No η_c measurements in heavy ion collisions

$\eta_c(1S)$ PRODUCTION AT LHCb

- $\eta_c(1S)$ reconstructed via decay to $p\bar{p}$
- Cross-section determination with J/ψ as normalization channel:

$$\frac{\sigma(\eta_c)}{\sigma(J/\psi)} = \frac{N^p_{\eta_c}}{N^p_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c\to p\bar{p}}}$$

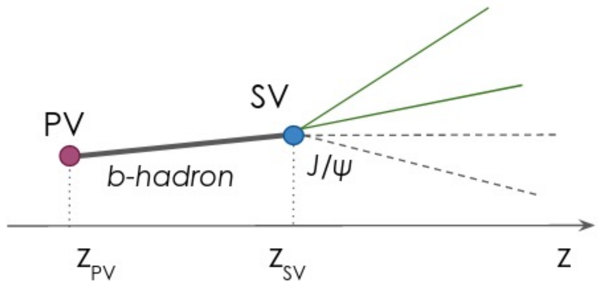
$$\frac{\mathcal{B}_{b\to\eta_c X}}{\mathcal{B}_{b\to J/\psi X}} = \frac{N^b_{\eta_c}}{N^b_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c\to p\bar{p}}}$$

- Extracted from DATA
- Calculated from PDG:

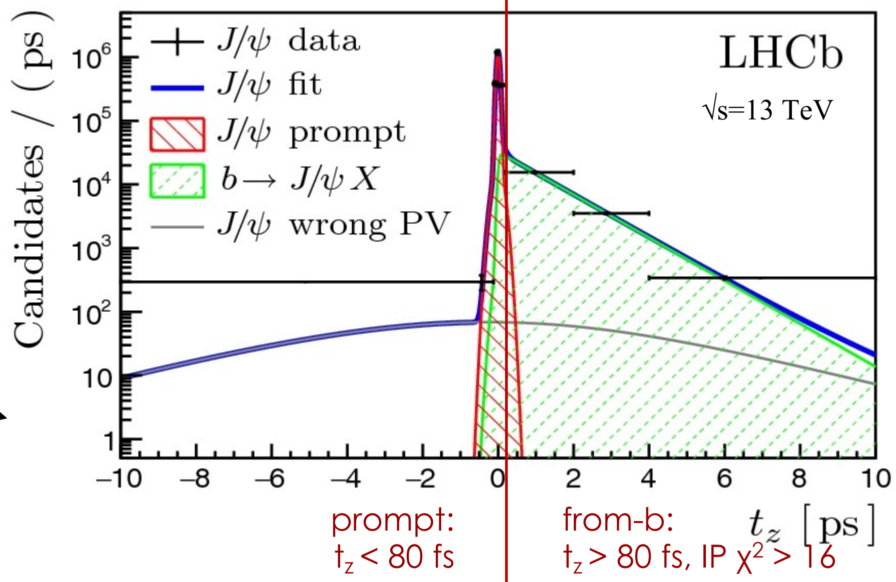
$$\mathcal{B}_{J/\psi\to p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3}$$
$$\mathcal{B}_{\eta_c(1S)\to p\bar{p}} = (1.45 \pm 0.14) \times 10^{-3}$$

- From Simulation

- **Prompt** and ***b*-decay production** distinguished via **decay time value**:



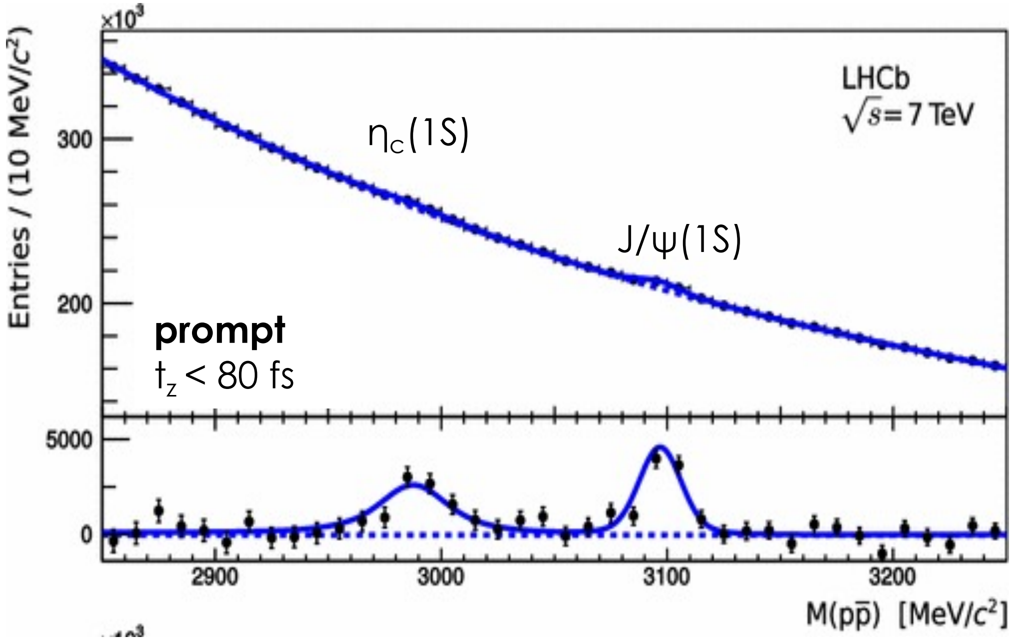
$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$$

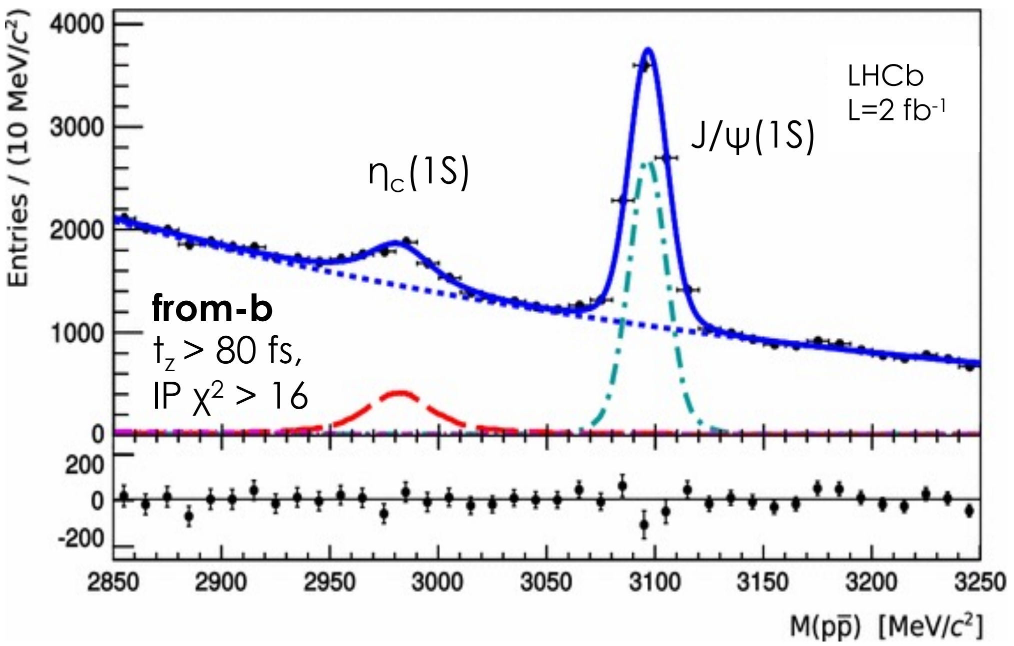


$\eta_C(1S)$ PRODUCTION AT LHCb AT $\sqrt{s}$=7 AND 8 TeV

Eur.Phys.J. C75(2015) 311

- t_z-cut technique: **prompt** and ***b*-decay production** separated using t_z-value
- **First measurements of $\eta_c(1S)$ prompt production** at 7 and 8 TeV and b-decay production





- **Challenging background conditions**

=> limited kinematic range (p_T>6.5 GeV/c) due to trigger requirements

$\eta_C(1S)$ PRODUCTION AT LHCb AT $\sqrt{s}$=7 AND 8 TeV

- Measurement of **p_T-differential production cross-sections**, experimental precision is worse than theoretical one

- **Strong impact on theory models**: contrary to theory expectations, $\eta_C(1S)$ prompt production entirely described by CS contribution

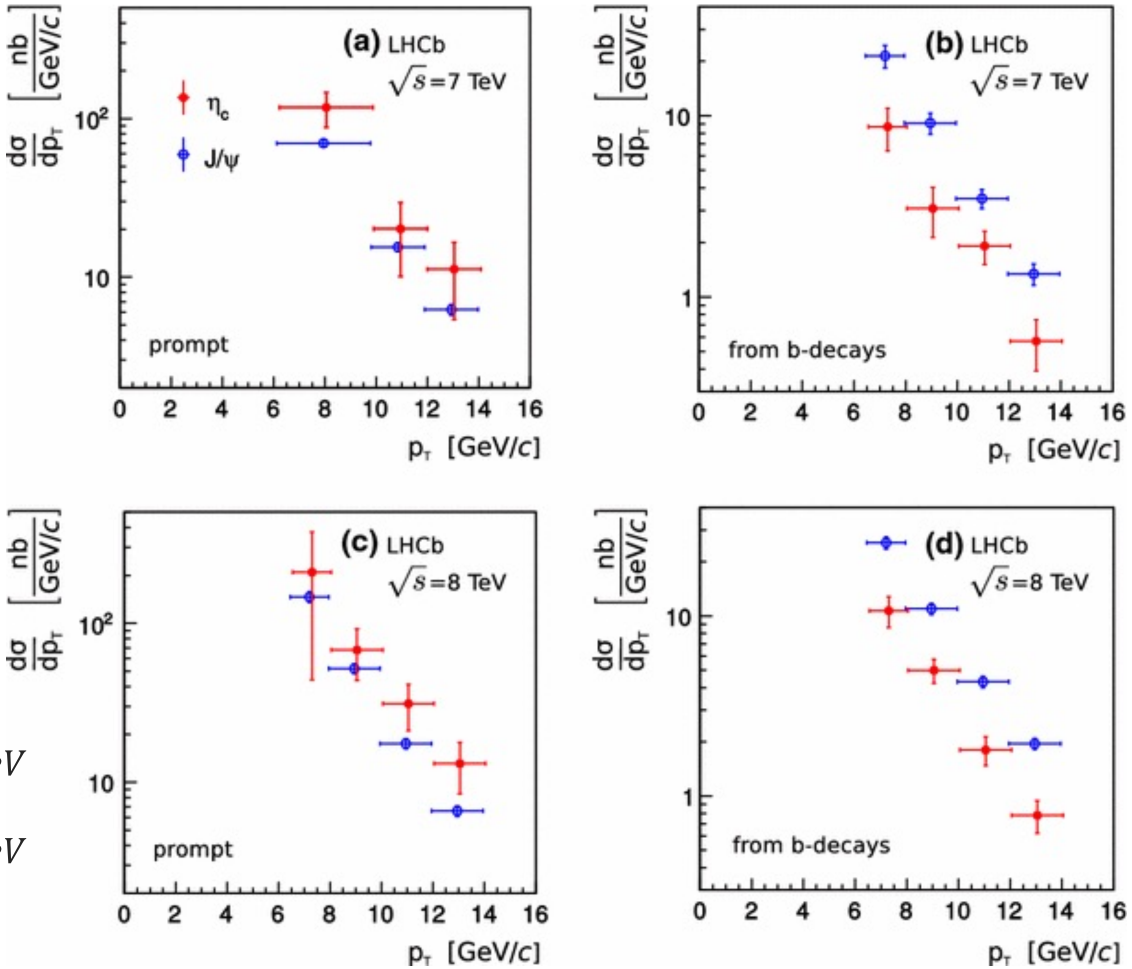
- **$\eta_c(1S)$ production:**

$6.5 < p_T < 14.0$ GeV/c, $2.0 < y < 4.5$

$\sigma_{\eta_c}^{prompt} = 0.52 \pm 0.09_{stat} \pm 0.08_{syst} \pm 0.06_{J/\psi}\ \mu b \quad \sqrt{s} = 7\ TeV$

$\sigma_{\eta_c}^{prompt} = 0.59 \pm 0.11_{stat} \pm 0.09_{syst} \pm 0.08_{J/\psi}\ \mu b \quad \sqrt{s} = 8\ TeV$

$\mathfrak{B}_{b\to\eta_c X} = (4.88 \pm 0.64_{stat} \pm 0.29_{syst} \pm 0.67_{J/\psi})\times 10^{-3}$



$\eta_c(1S)$ PRODUCTION AT THE LHC

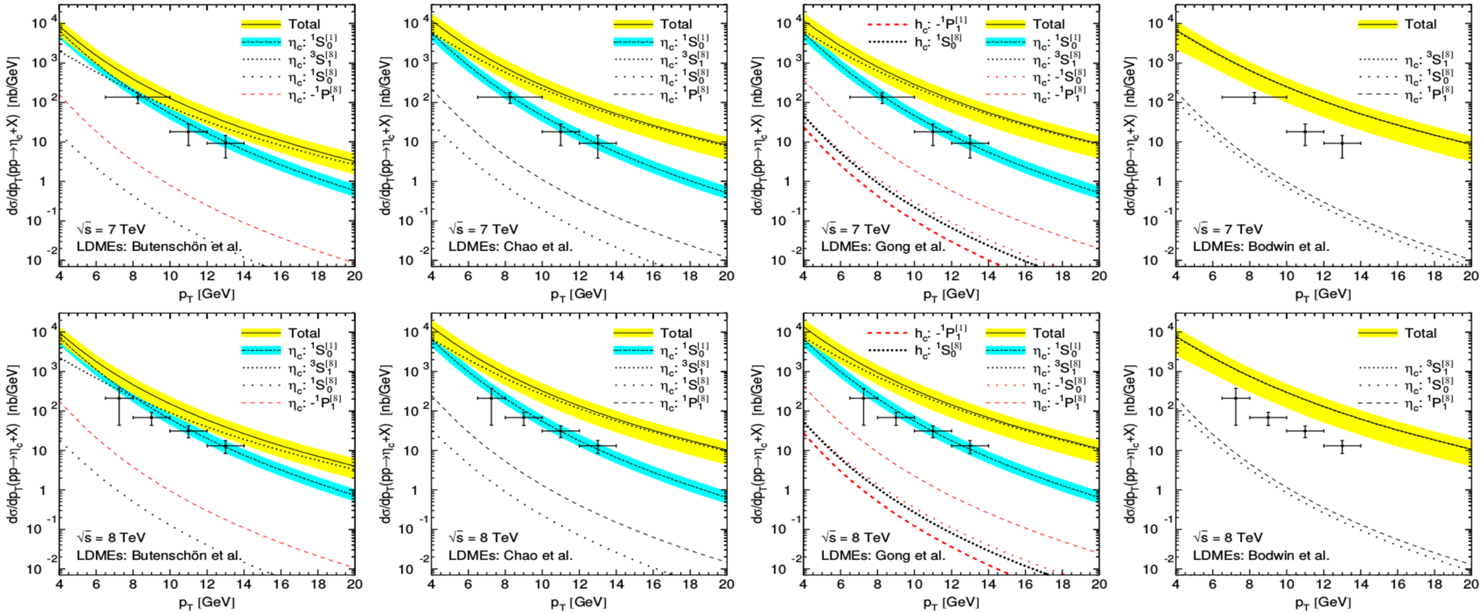
PRL 114(2015), 092004
Eur.Phys.J.C 75(2015) 311

- **$\eta_c(1S)$ LDMEs** determined
  from known HQSS relation for J/ψ

$$\langle \mathcal{O}^{\eta_c}_{1,8}(^1S_0)\rangle = \frac{1}{3}\langle \mathcal{O}^{J/\psi}_{1,8}(^3S_1)\rangle$$

$$\langle \mathcal{O}^{\eta_c}_{8}(^3S_1)\rangle = \langle \mathcal{O}^{J/\psi}_{8}(^1S_0)\rangle$$

$$\langle \mathcal{O}^{\eta_c}_{8}(^1P_1)\rangle = 3\langle \mathcal{O}^{J/\psi}_{8}(^3P_0)\rangle$$



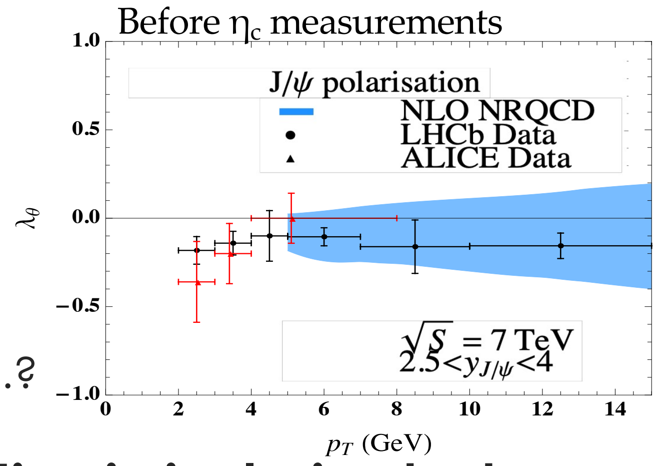
- Direct projection to LHCb data
- **LHCb data saturated by CS contribution**
- Tension in simultaneous description of η_c production and J/ψ production and polarization?
- **Progress in theory**:
  - Phys.Rev.Lett. 114(2015), 092005
  - Phys.Rev.Lett. 114(2015), 092006
  - Eur.Phys.J.C 75(2015) 7, 313
  - Nucl.Phys.B 945(2019) 114662
  - Phys.Lett.B 786(2018) 342-346
  - JHEP 05(2015) 103
  - Phys.Rev.Lett. 110(2013) 042002
  - Phys.Rev.D 93 (2016) 034041

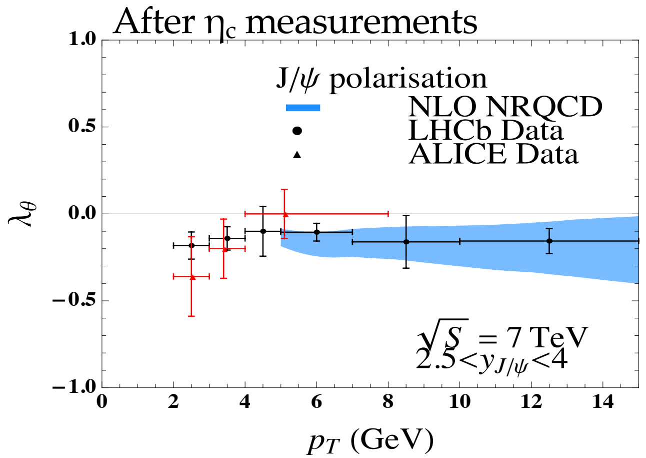
SIMULTANEOUS STUDY OF η_c AND J/ψ

[PRL 114(2015), 092005](#)
[arXiv:1910.08796](#)

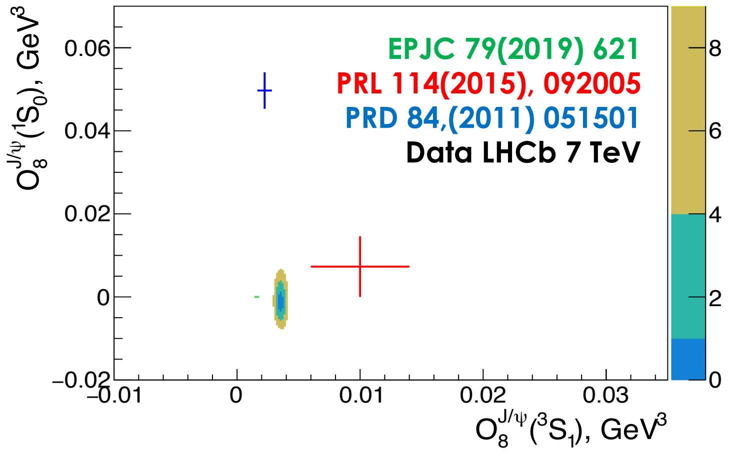
- η_c production @ $\sqrt{s}$=7 and 8 TeV sets new constraint on J/ψ polarization
- **Outcome**:
  - Impressive progress
  - Tension with CDF data
  - Two large CO contributions cancel each other ⇒

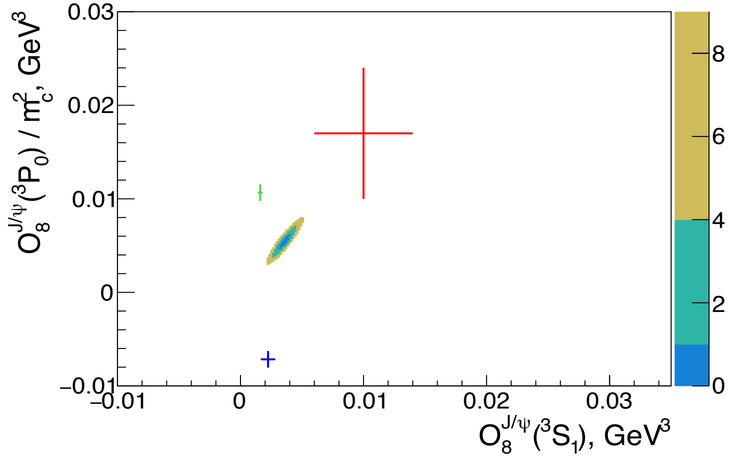
⇒ hierarchy problem ⇒ Soft Gluon Fragmentation, etc.?

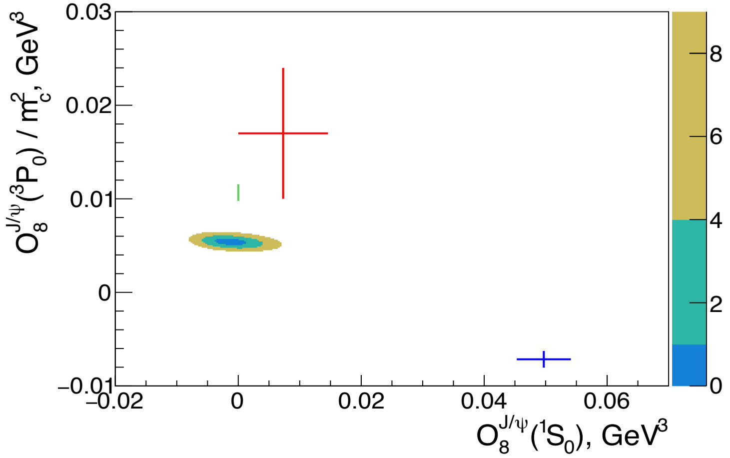




- **Joint study of hadroproduction and production in inclusive b-decays**





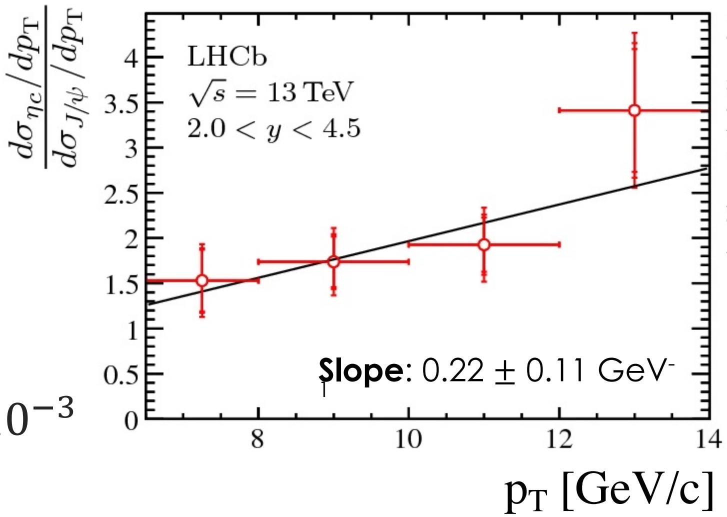


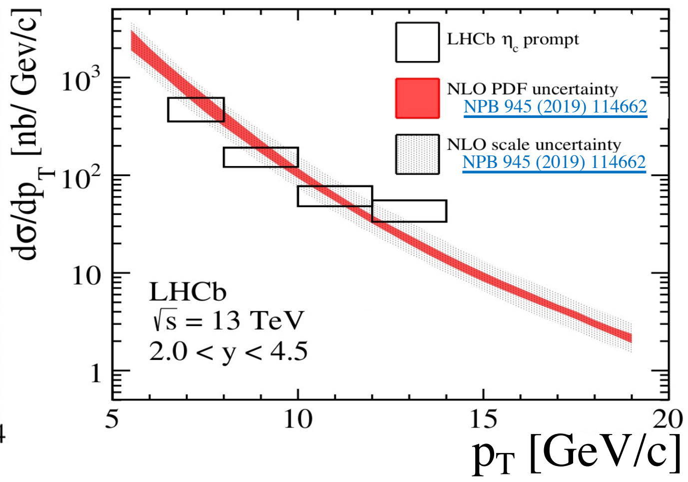
- **Same links for η_c(2S)** and **ψ(2S)** are expected ⇒ powerful test of NRQCD [Phys.Lett.B 786 (2018) 342-346](#)

η_c(1S) PRODUCTION AT $\sqrt{s}$=13 TeV

EPJC 80 (2020) 191

- **relative η_c/J/ψ** and **absolute η_c** p_T-differential production **cross-sections** using two techniques





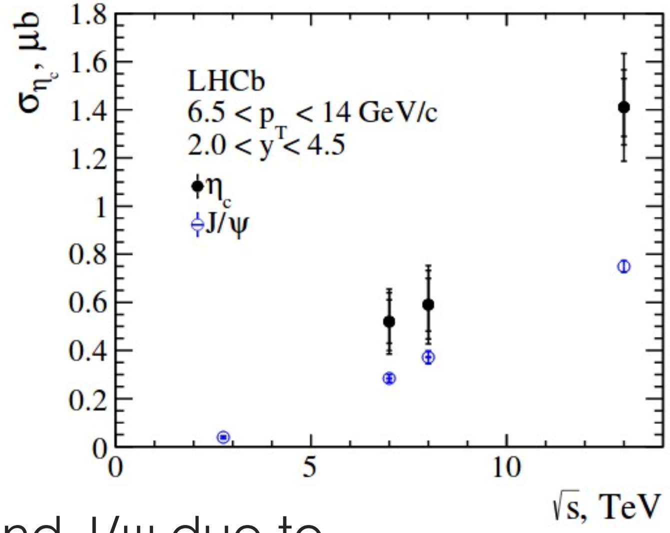
- **η_c(1S) production:**

  $6.5 < p_T < 14.0$ GeV/c, $2.0 < y < 4.5$

  $$\sigma_{\eta_c}^{prompt} = 1.26 \pm 0.11_{stat} \pm 0.08_{syst} \pm 0.14_{J/\psi}\ \mu b$$

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

- Important input to the theory simultaneously describing **J/ψ production, polarization and η_c(1S) production**

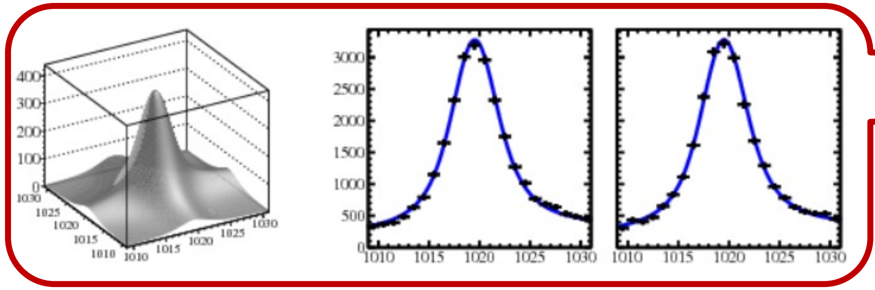


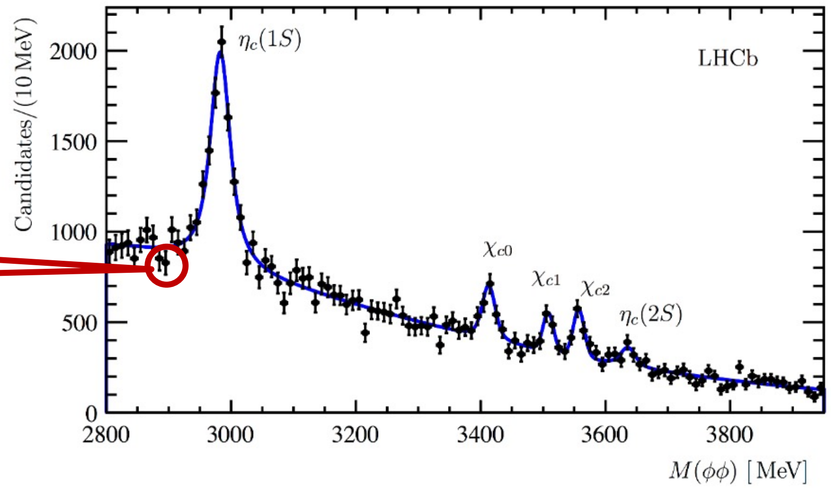
- **η_c(1S) production can be described by CS contribution only;** measurement in extended p_T is required

- **Interpretation of η_c(2S) and ψ(2S) much cleaner** than for η_c(1S) and J/ψ due to absence of feed-down contributions

$\eta_c(2S)$ PRODUCTION IN *b*-DECAYS AT $\sqrt{s}$=7 AND 8 TeV Eur.Phys.J.C 77(2017) 609

- **Production in *b*-decays via decays to φφ**; true φφ combinations extracted using 2D fit technique

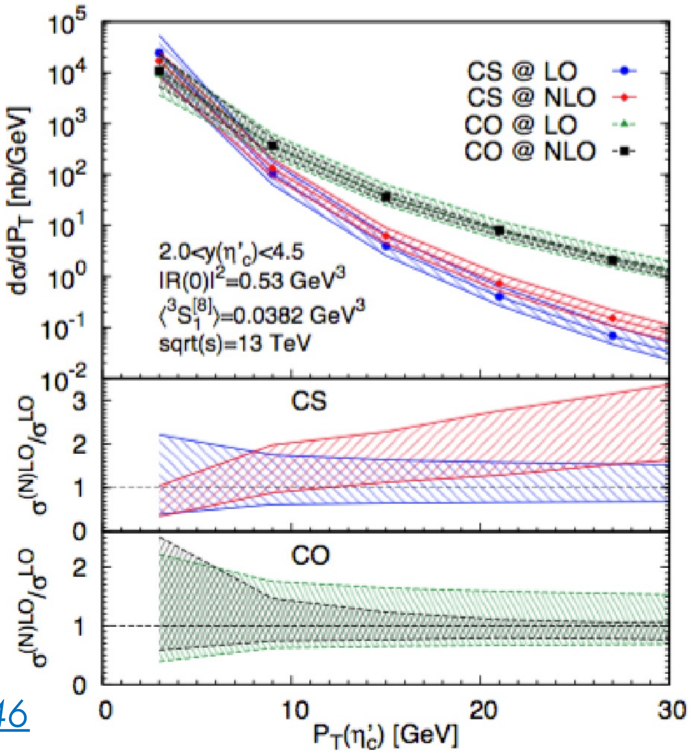




- First measurement of $\eta_c(2S)$ production in b-decays; first evidence for $\eta_c(2S)\to\phi\phi$

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

- **Important to measure $\eta_c(2S)$ hadroproduction**:
  - theory prediction ⇒
  - **dedicated LHCb trigger in 2018**

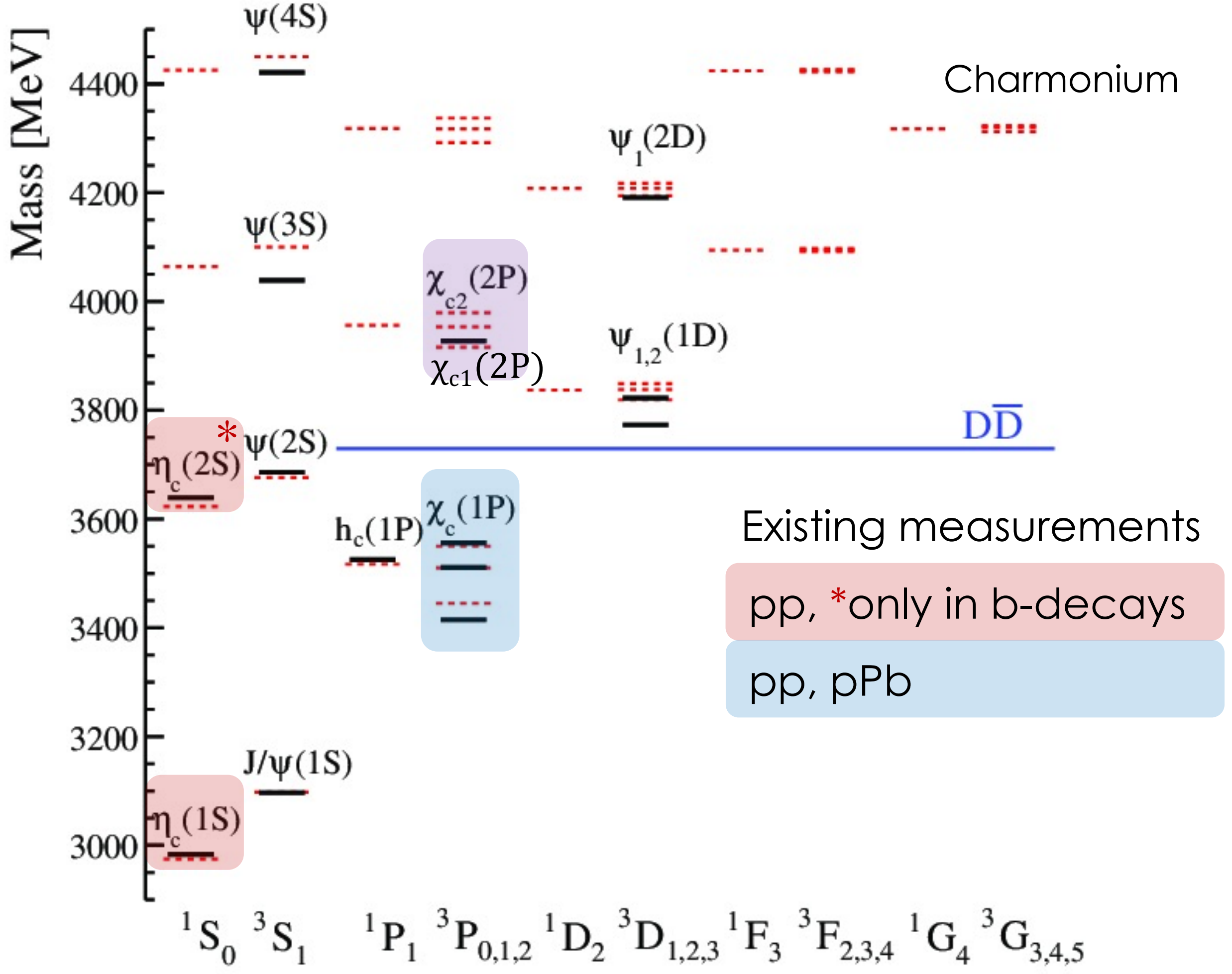


Phys.Lett.B 786 (2018) 342-346

CURRENT STATUS OF QUARKONIUM SPECTRUM

[Rev.Mod.Phys 90 (2018) 015003]

- Current status of quarkonium spectrum



- # χ_c

- Possible decays: J/ψγ or hadronic

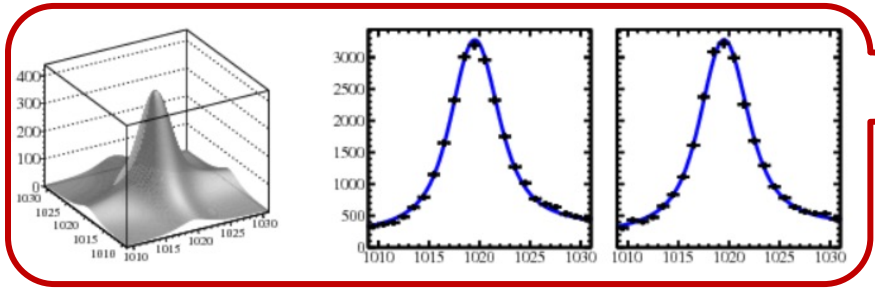
- **Challenging to study χ_c** production due to γ reconstruction:
  - Limited precision in pp
  - Very few measurements in heavy ion collisions

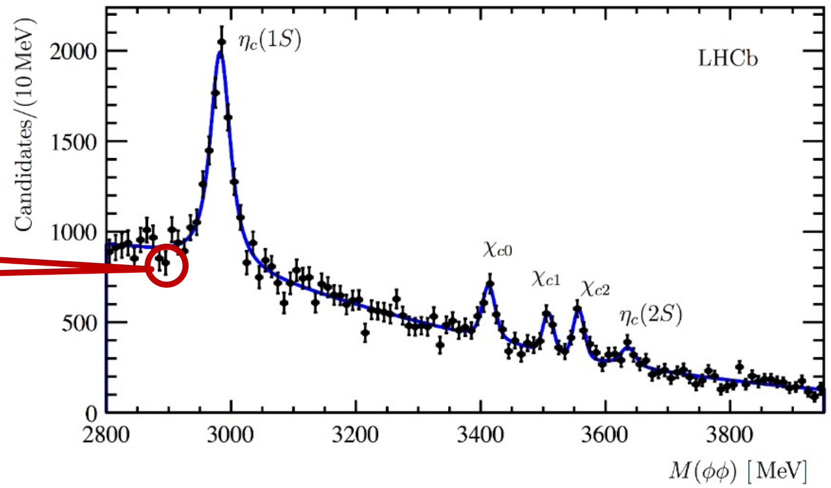
- 3 states, but 2 LDMEs => overconstrained system

χ_c PRODUCTION IN *b*-DECAYS AT √s=7 AND 8 TeV

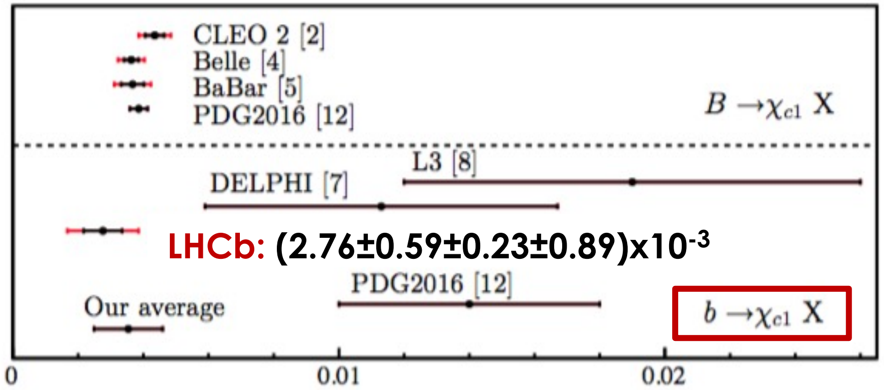
[Eur.Phys.J.C 77(2017) 609]

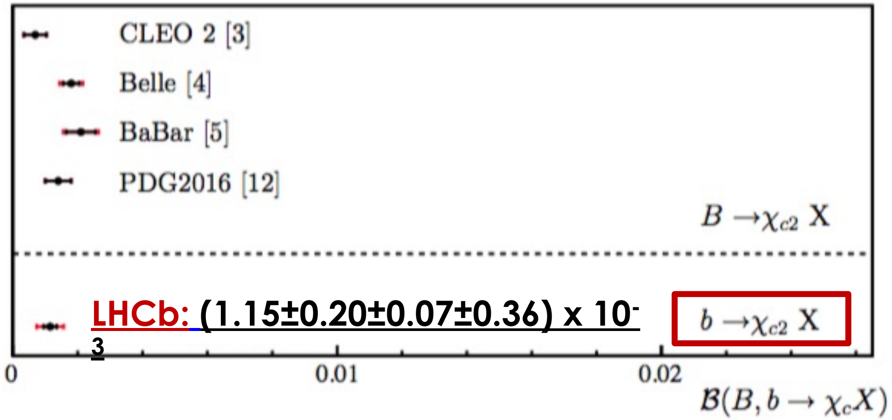
- **Production in *b*-decays via decays to φφ;** true φφ combinations extracted using 2D fit technique





- 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 polarizarion [**[Phys.Rev.D 103 (2021) 9, 096006]**]**

$\chi_{c0,1,2}$ PRODUCTION USING $\chi_{c0,1,2} \rightarrow J/\psi\gamma$

Eur. Phys. J. C 72 (2012) 2251
PLB 714 (2012) 215

- **χ_c prompt production** measured via decay to $J/\psi\gamma$ at $\sqrt{s}$=7 TeV
- Prompt contribution extracted using "pseudo-proper" decay time/length

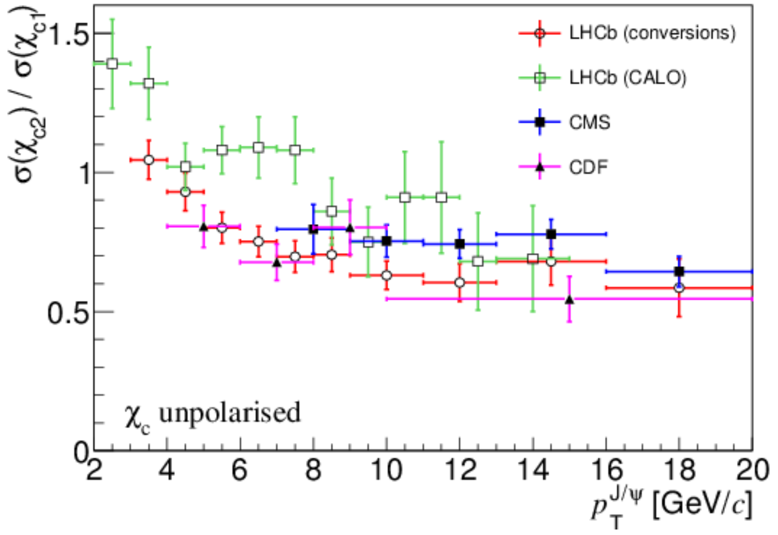
- **Relative χ_{c2}/χ_{c1}** prompt p_T-diferential production cross-section:

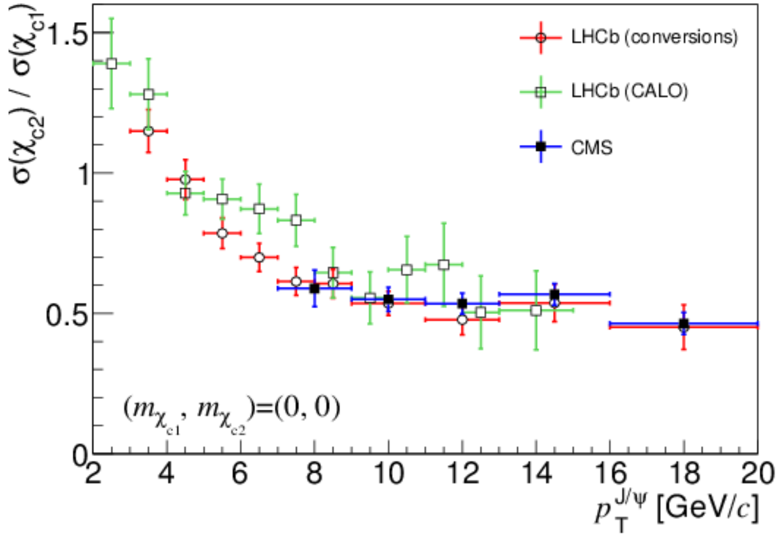
$$R_p = \frac{\sigma(pp\rightarrow\chi_{c2}X)\times\mathcal{B}(\chi_{c2}\rightarrow J/\psi\gamma)}{\sigma(pp\rightarrow\chi_{c1}X)\times\mathcal{B}(\chi_{c1}\rightarrow J/\psi\gamma)}$$

- **Relative χ_{c2}/χ_{c1} and χ_{c0}/χ_{c2}** prompt p_T-diferential production cross-section

- **χ_{c0} relative production** measured with **4σ** significance:

$$\sigma_{\chi_{c0}}/\sigma_{\chi_{c2}} = 1.19 \pm 0.27_{stat} \pm 0.29_{syst} \pm 0.16_{p_T\,model} \pm 0.09_{\mathcal{B}}$$

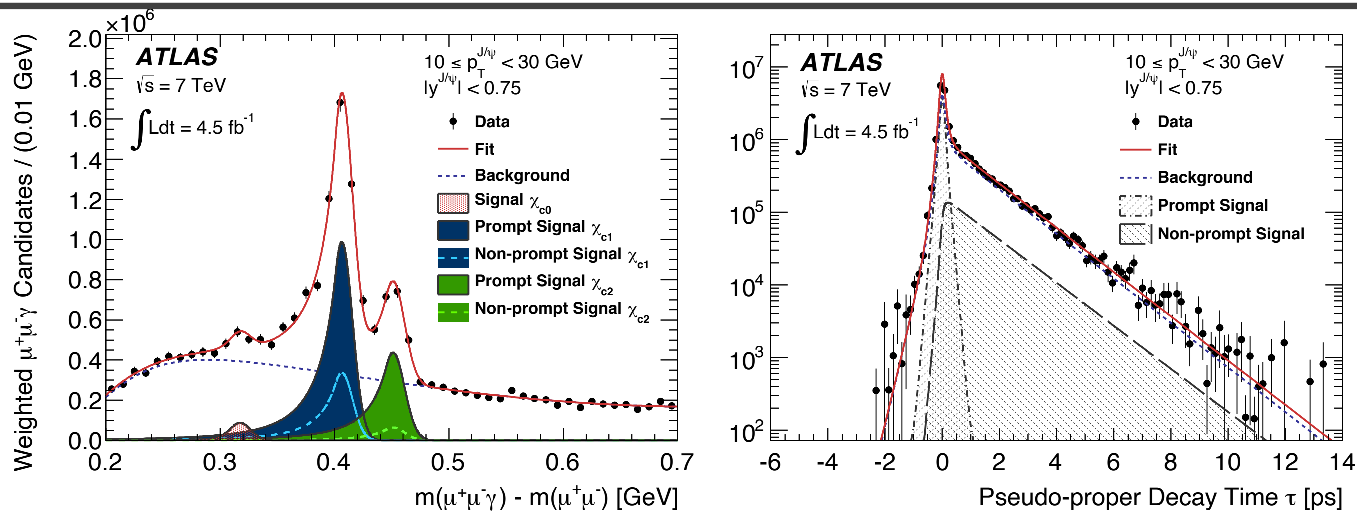




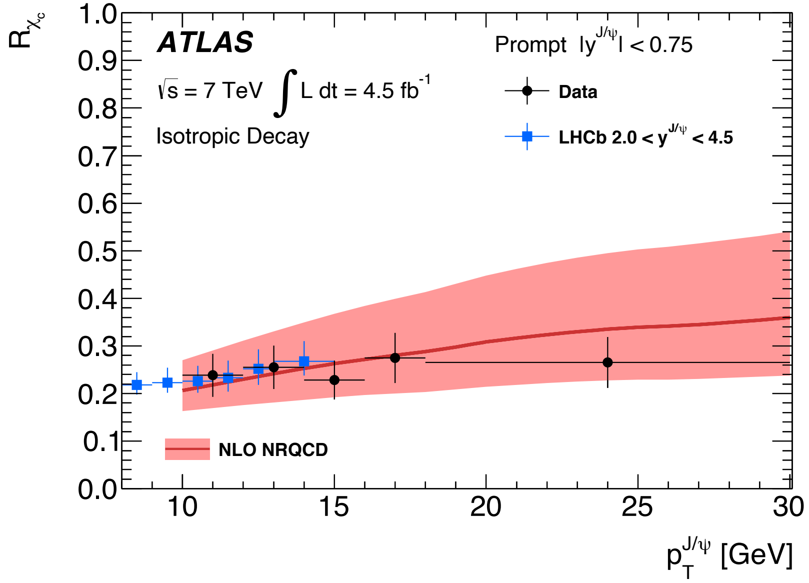
$\chi_{c1,2}$ PRODUCTION USING $\chi_{c1,2} \to J/\psi\gamma$

JHEP 07 (2014) 154

- ATLAS EXPERIMENT **χ_{c1} and χ_{c2} p_T-diferential production** at $\sqrt{s}$=7 TeV
- Prompt and b-decays are distinguished using simultaneous fit to mass difference and pseudo-proper decay time



- Estimated **J/ψ fraction from χ_c decays**: result in agreement with LHCb measurement [PLB 714 (2012) 215]

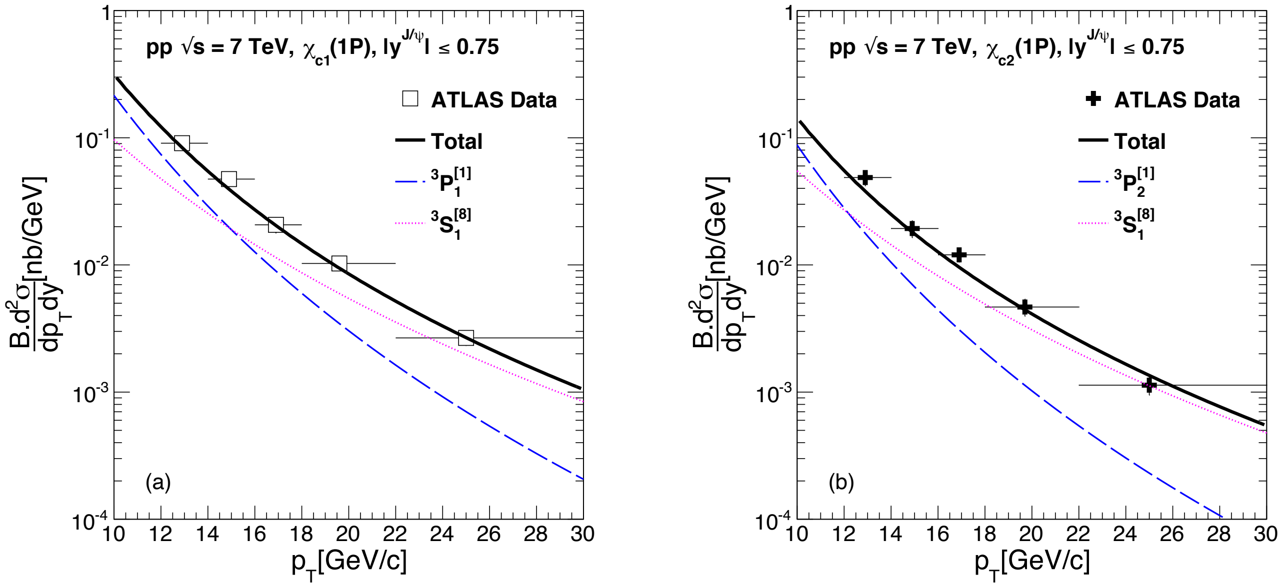


- Results compared with theoretical predictions: **good agreement with NRQCD**

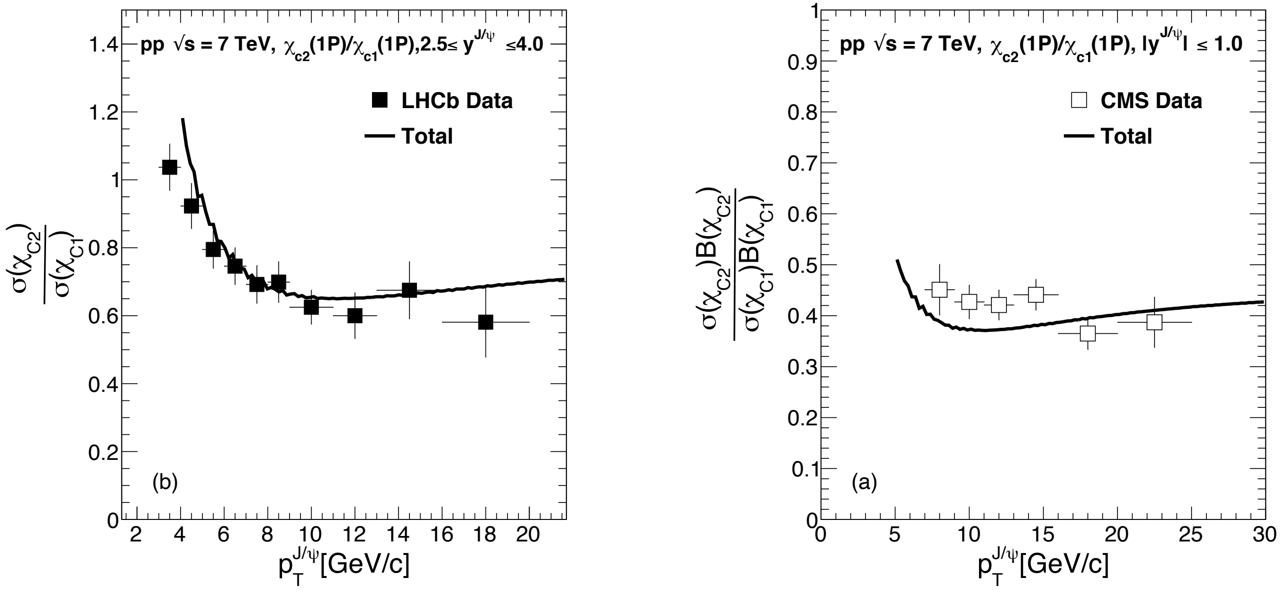
$\chi_{c1,2}$ PRODUCTION USING $\chi_{c1,2} \rightarrow J/\psi\gamma$

J.Phys.G 44 (2017) 8, 085003

- NRQCD fit for production cross-section
    - absolute =>



- relative =>



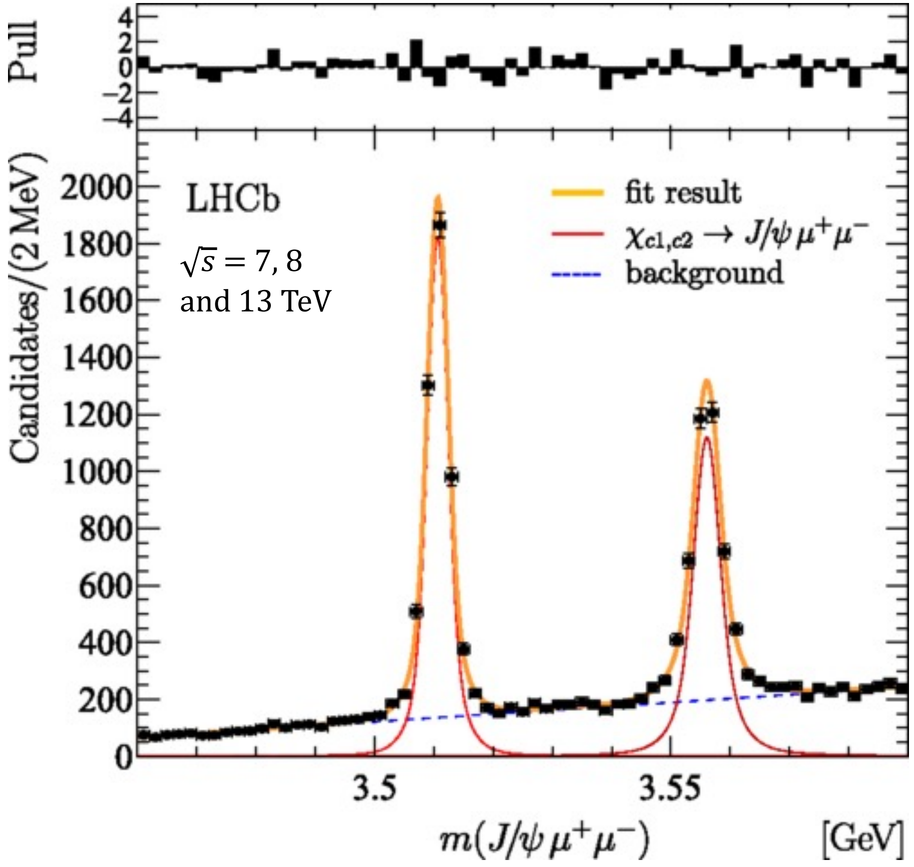
- **CO LDME for χ_c is obtained from fit to data**
- More precise when looking for ratio
- **Small p_T region has to be explored**

$\chi_{c1,2}$ PRODUCTION USING $\chi_{c1,2} \to J/\psi\mu^+\mu^-$

PRL 119 (2017) 22, 221801

- **First observation** of $\chi_{c1,2} \to J/\psi\mu^+\mu^-$ decay modes
- Extremely 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



- **Promising channel for χ_c hadroproduction at low p_T**
- **Similar studies can be done at CMS and ATLAS?**

$\chi_{c1,2}$ PRODUCTION in pPb

JHEP01 (2017) 117

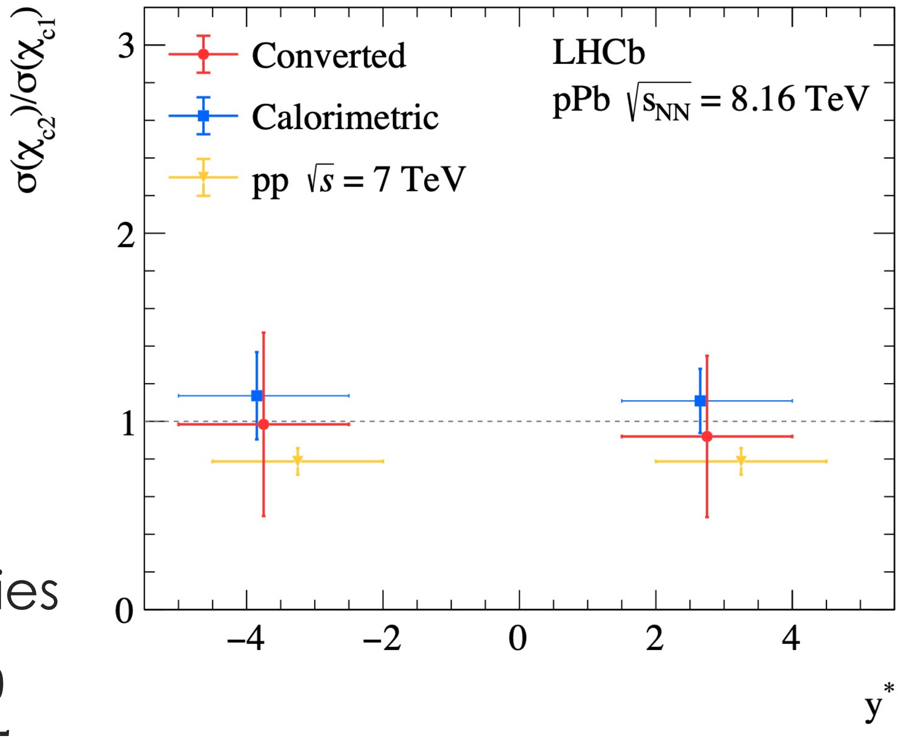
- **First relative χ_{c2}/χ_{c1}** prompt p_T-diferential **production** cross-section **in pPb** at $\sqrt{s}$=8.16 TeV

- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ consistent with unity for both forward and backward rapidity regions

- Comparison with pp collisions hints at suppression pattern between two states, which is comparable within uncertainties

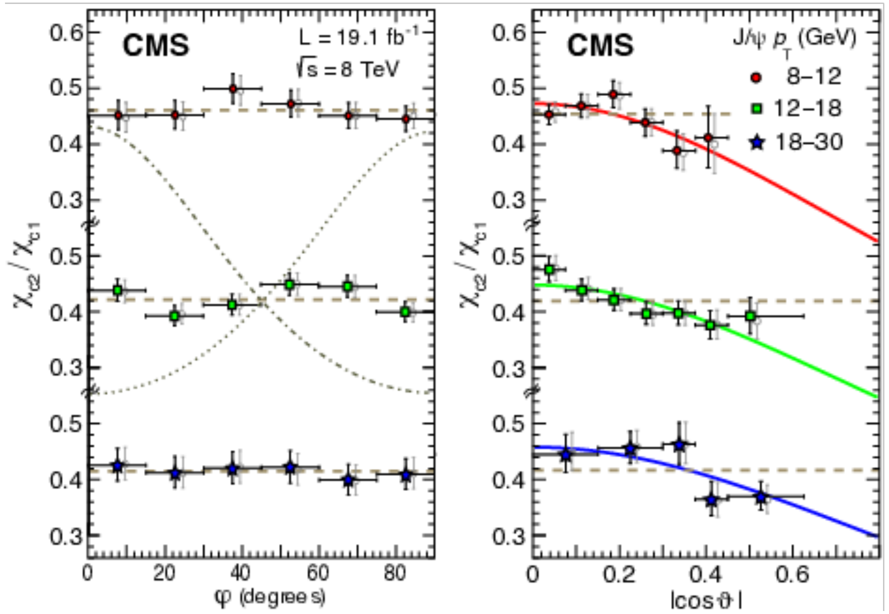
$$\mathcal{R} \equiv \frac{\sigma(\chi_{c2})/\sigma(\chi_{c1})|_{pPb}}{\sigma(\chi_{c2})/\sigma(\chi_{c1})|_{pp}} = \begin{cases} 1.41 \pm 0.21_{stat} \pm 0.18_{stat}, & 1.5 < y < 4.0 \\ 1.44 \pm 0.24_{stat} \pm 0.25_{stat}, & -5.0 < y < -2.5 \end{cases}$$

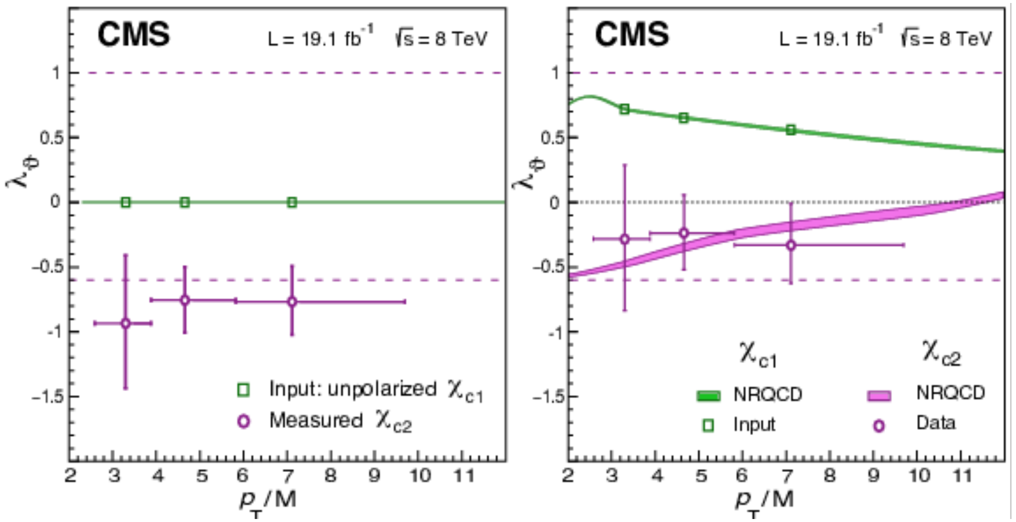
=> **final-state nuclear effects impact both states similarly**



χ_{c1} VS χ_{c2} POLARIZATION AT $\sqrt{s}$=8 TeV

[PRL 124 (2020) 162002]



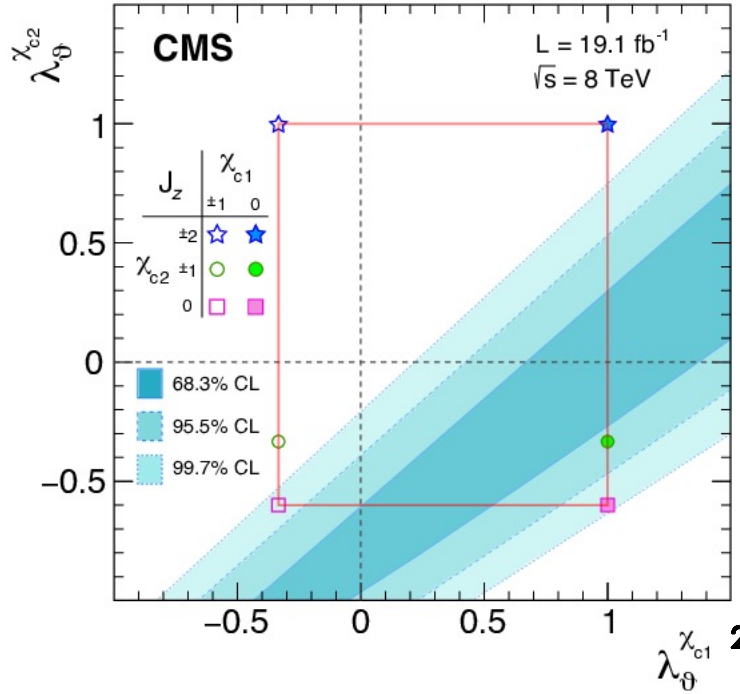


- **First measurement of *P*-wave quarkonium polarization** with χ_{c2}/χ_{c1} ratios as a function of $|\cos\theta^{HX}|$ and φ^{HX}

- Unpolarized scenario and large part of the physically allowed region (red rectangle) excluded at 99.7 % CL

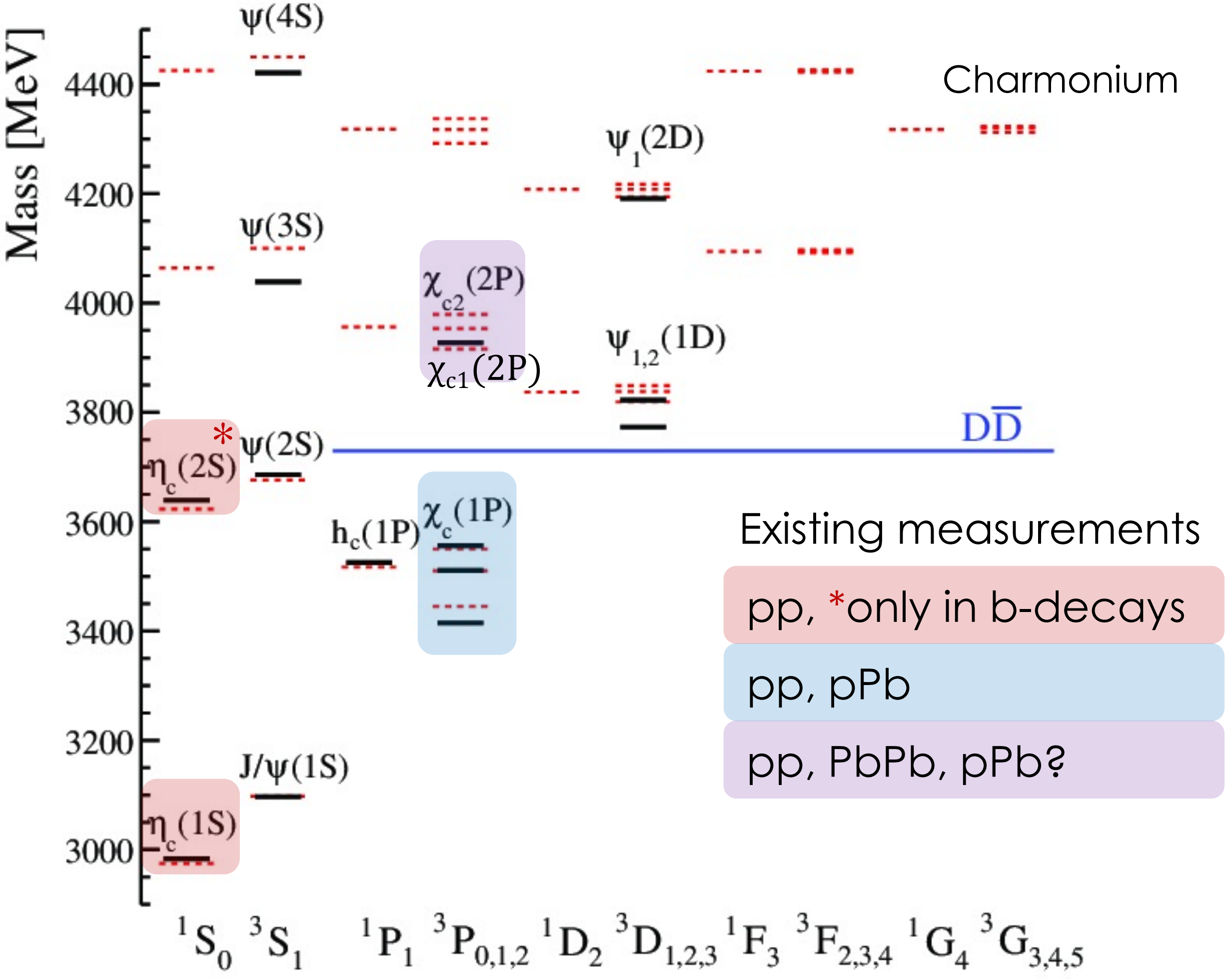
  → at least one state is strongly polarized

- **Good agreement with NRQCD prediction**



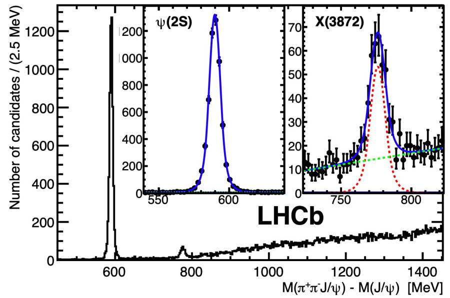
[Rev.Mod.Phys 90 (2018) 015003]

- Current status of quarkonium spectrum



X(3872) aka $\chi_{c1}(3872)$

- **First exotic state** discovered in $J/\psi\pi^+\pi^-$ decay [PRL 91 262001 (2003)]
- Charmonium hypothesis **disfavoured** by measured mass and quantum numbers:
  - $M_{D\bar{D}} - M_{X(3872)} = 0.07 \pm 0.12\ \mathrm{MeV}/c^2$ [JHEP 08(2020)123]
  - $J^{PC} = 1^{++}$, with $f_D < 4\%\ @\ CL\ 95\%$ [PRD92 (2015) 011102]
- Other possible explanations:
  - hadronic molecule
  - tetraquark
  - something else?



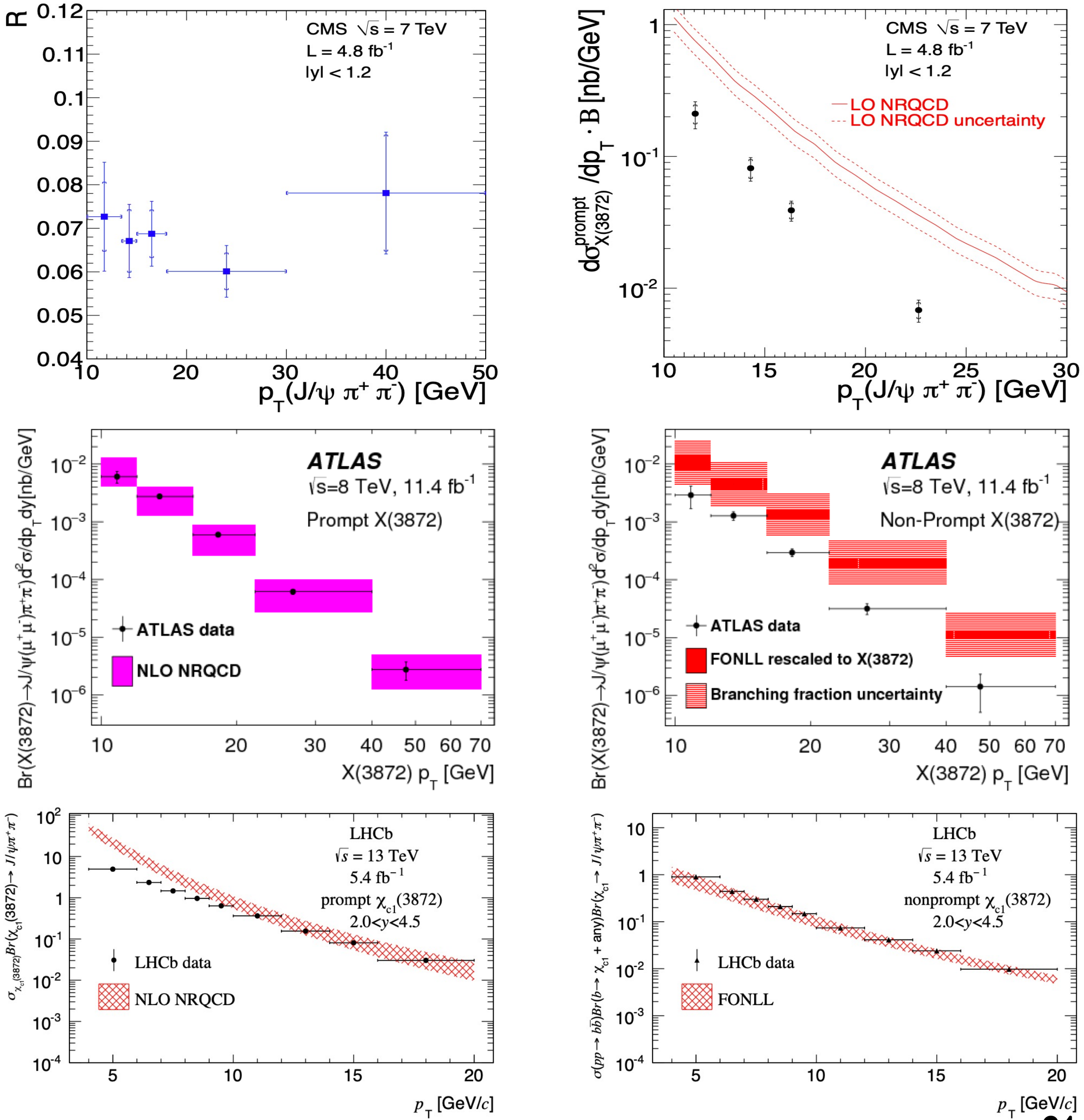
X(3872) PRODUCTION IN pp

JHEP04 (2013) 154
JHEP01 (2017) 117
arXiv:2109.07360

- **X(3872) prompt production** measured at different energies and rapidity in $J/\psi\pi^+\pi^-$ decay
- Prompt contribution extracted using "pseudo-proper" decay time/length
- $\psi(2S)$ used as normalization channel

- **First measurement** at $\sqrt{s}$=7 TeV and $|y| < 1.2$
- Production at $\sqrt{s}$=8 TeV and $|y| < 0.75$
- Production at $\sqrt{s}$=8 and 13 TeV, $2.0 < y < 4.5$

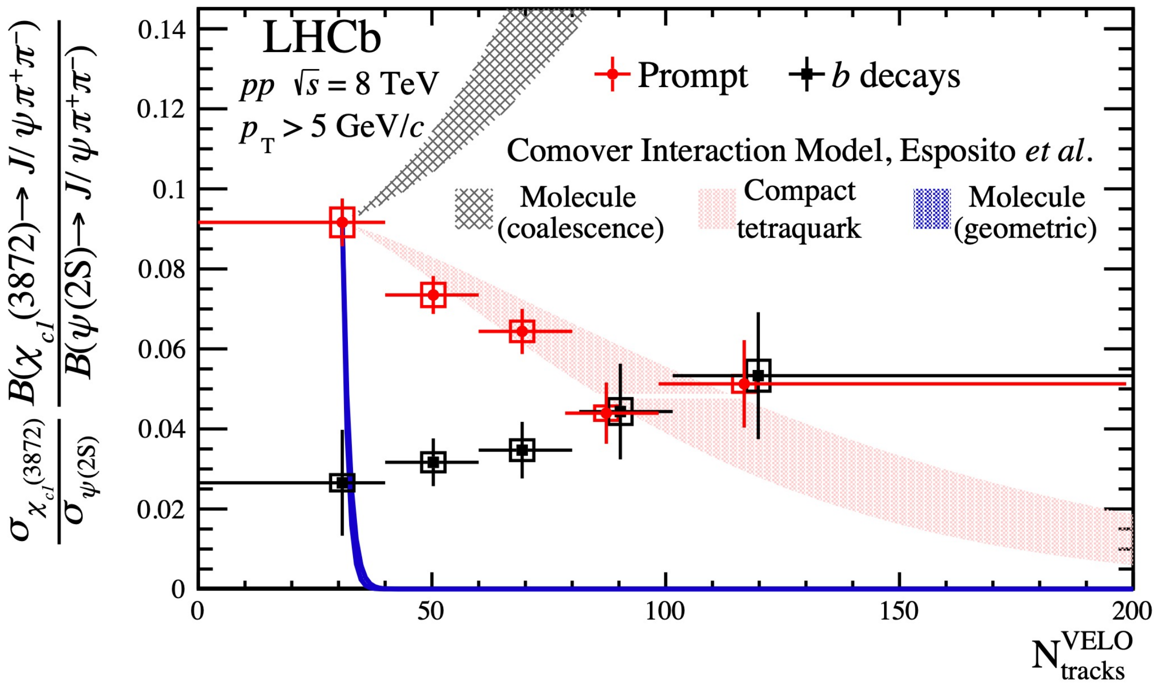
- NRQCD here considers X(3872) to be a mixture of $\chi_{c1}(2P)$ and a $D^0\overline{D}^{*0}$ molecular state. It shows good agreement with ATLAS and LHCb (only at high-p_T)



X(3872) PRODUCTION VS MULTIPLICITY

PRL126 (2021) 092001

- Event-activity dependence may provide understanding of internal structure
- **X(3872) production** vs **Multiplicity**
- **Increasing supression of** relative **X(3872)** to ψ(2S) production as multiplicity increases **in prompt**
- **No significant dependence** on multiplicity **in *b*-decays**
- Results **favour tetraquark nature** of the *X*(3872)



X(3872) PRODUCTION IN PbPb and pPb

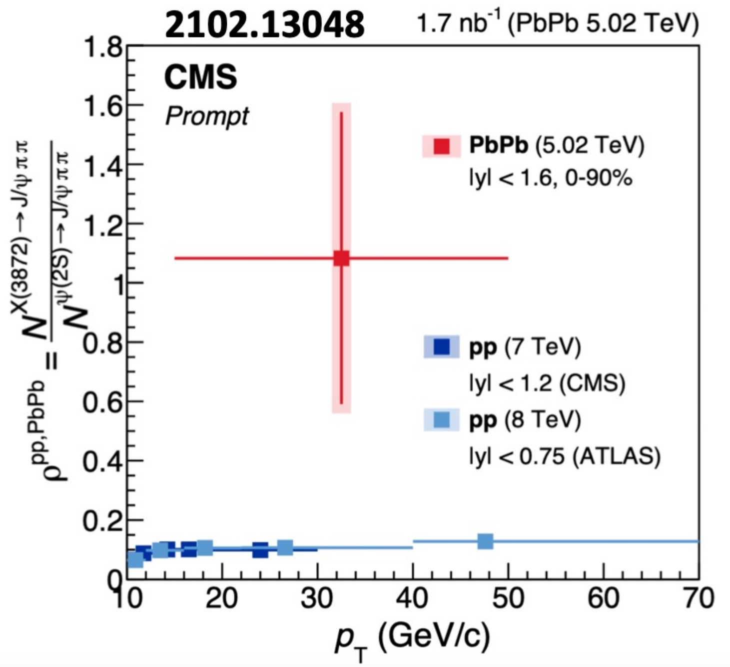
arxiv:2102.13048 [hep-ex]

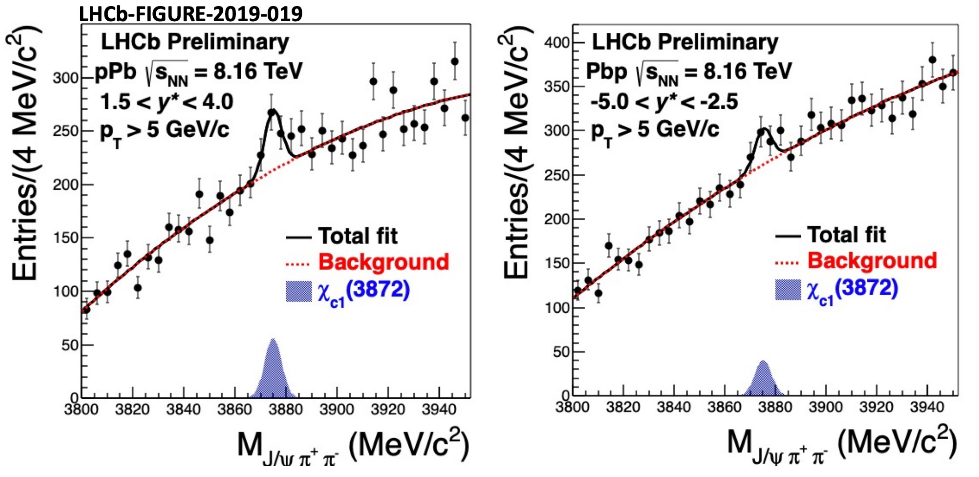
- X(3872) production in PbPb at √s=5.02 TeV

- $1 < R_{AA}^{X(3872)} < R_{AA}^{\psi(2S)}$ => it is possible that prompt X(3872) has either no suppression in PbPb, or as much suppression as $\psi(2S)$

- **PbPb enhancement favours molecular nature** due to coalescence mechanisms

- Upcoming X(3872) production in pPb at √s=5.02 TeV will fill critical gap between pp and PbPb

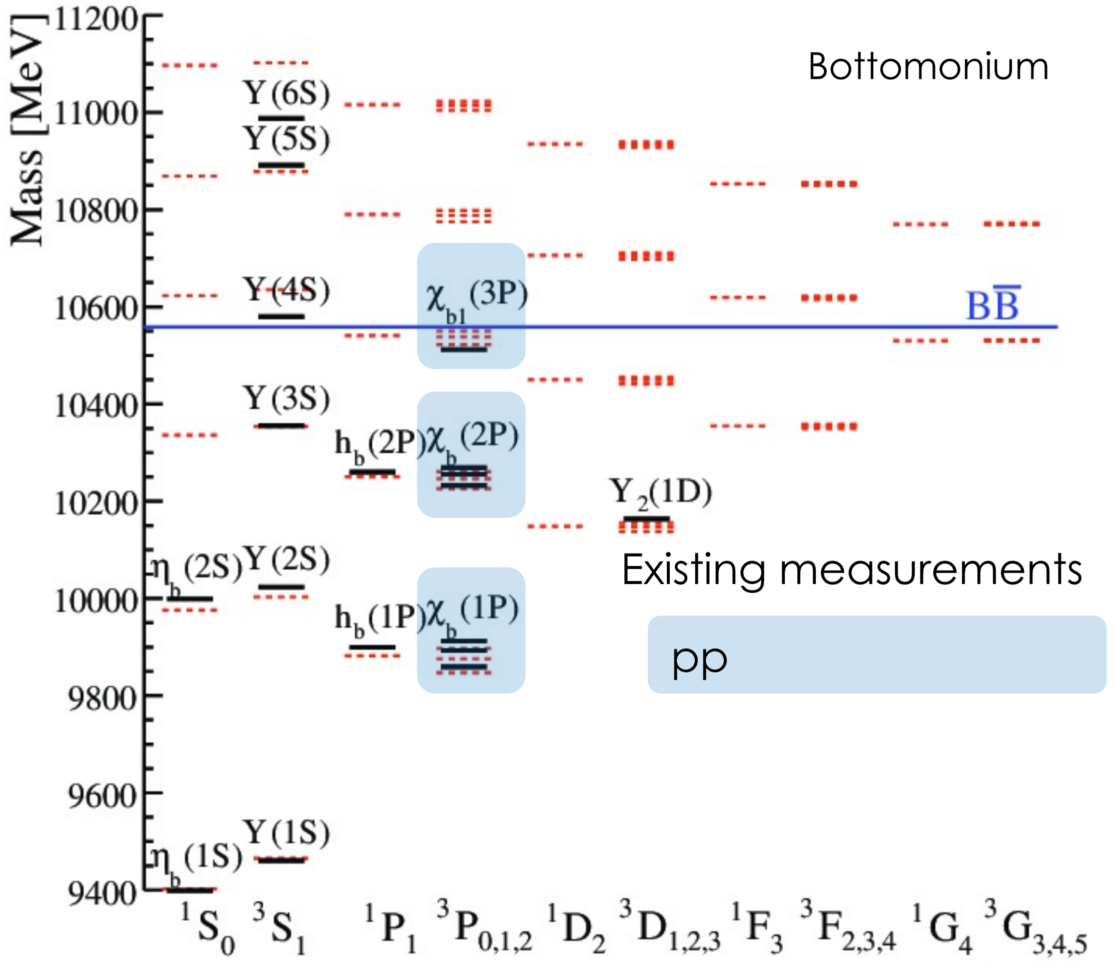




CURRENT STATUS OF QUARKONIUM SPECTRUM

[Rev.Mod.Phys 90 (2018) 015003]

- Current status of quarkonium spectrum



- χ_b
  - Possible decays: Υγ or hadronic
  - **Same problems as for χ_c**
  - No measurements in heavy ions

- η_b
  - Possible decays: hadronic or **γγ**
  - No existing measurements

SUMMARY

- Comprehensive model still missing to describe Heavy Flavour production
- Current progress:
  - prompt $\eta_c(1S)$, χ_c from b-decays and χ_b measured in pp
  - prompt χ_c production measured in pp and pPb
  - first evidence of $\eta_c(2S)$ production from b-decays
  - X(3872) measured in pp and PbPb and vs multiplicity

    => to be understood?
- Prospects for future study:
  - **$\eta_b(1S)$**, **$h_{c,b}$** and **$\eta_c(2S)$** production in pp
  - **χ_c** production via $J/\psi\mu^+\mu^-$
  - Upcoming **X(3872)** in pPb
  - **$\eta_c(1S)$** and **χ_c** production in heavy ion collisions
  - associated quarkonia production

Thank you for your attention!

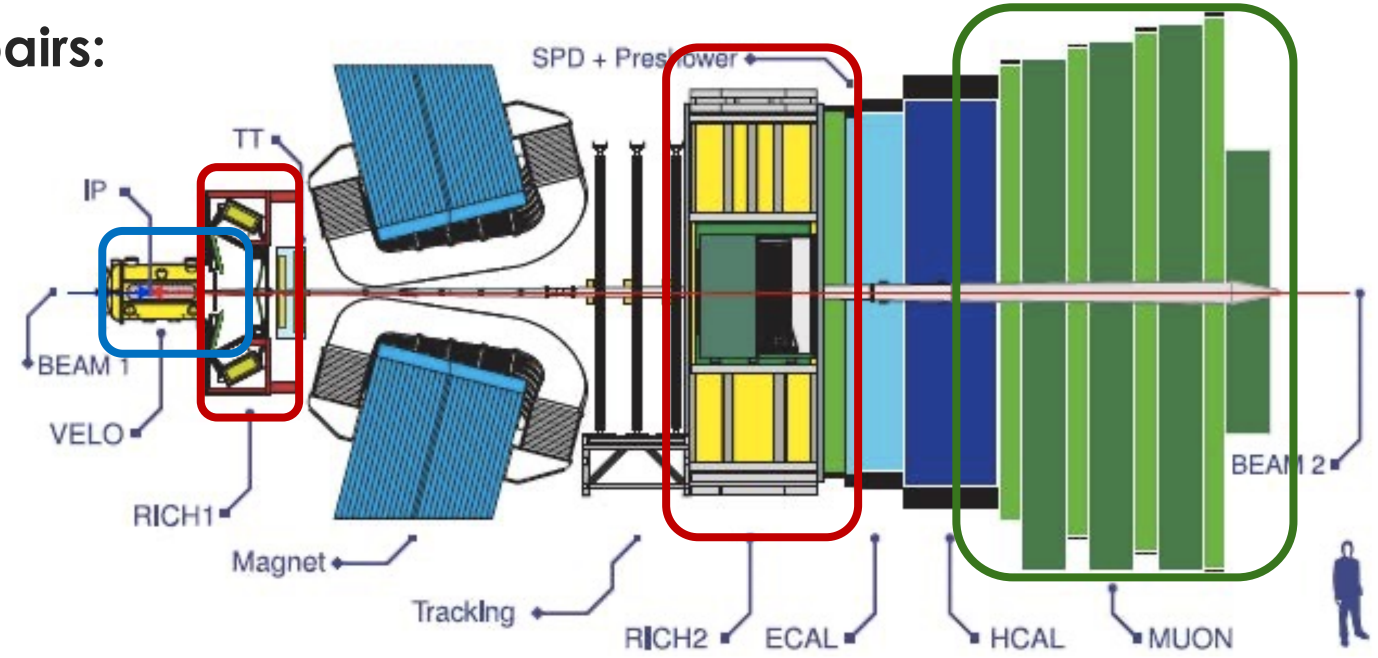
BACKUP

THE LHCb EXPERIMENT

IJMPA 30 (2015) 1530022

- **LHC provides large number of $b\bar{b}$ and $c\bar{c}$ pairs:**
  - $\sigma_{b\bar{b}} \sim 0.5$ mb
  - $\sigma_{c\bar{c}} \sim 3.0$ mb

  in LHCb @ √s =13 TeV



- **Single-arm forward spectrometer:**

  10-250 mrad (V), 10-300 mrad (H)
- Forward region 2.0 < η < 5.0,

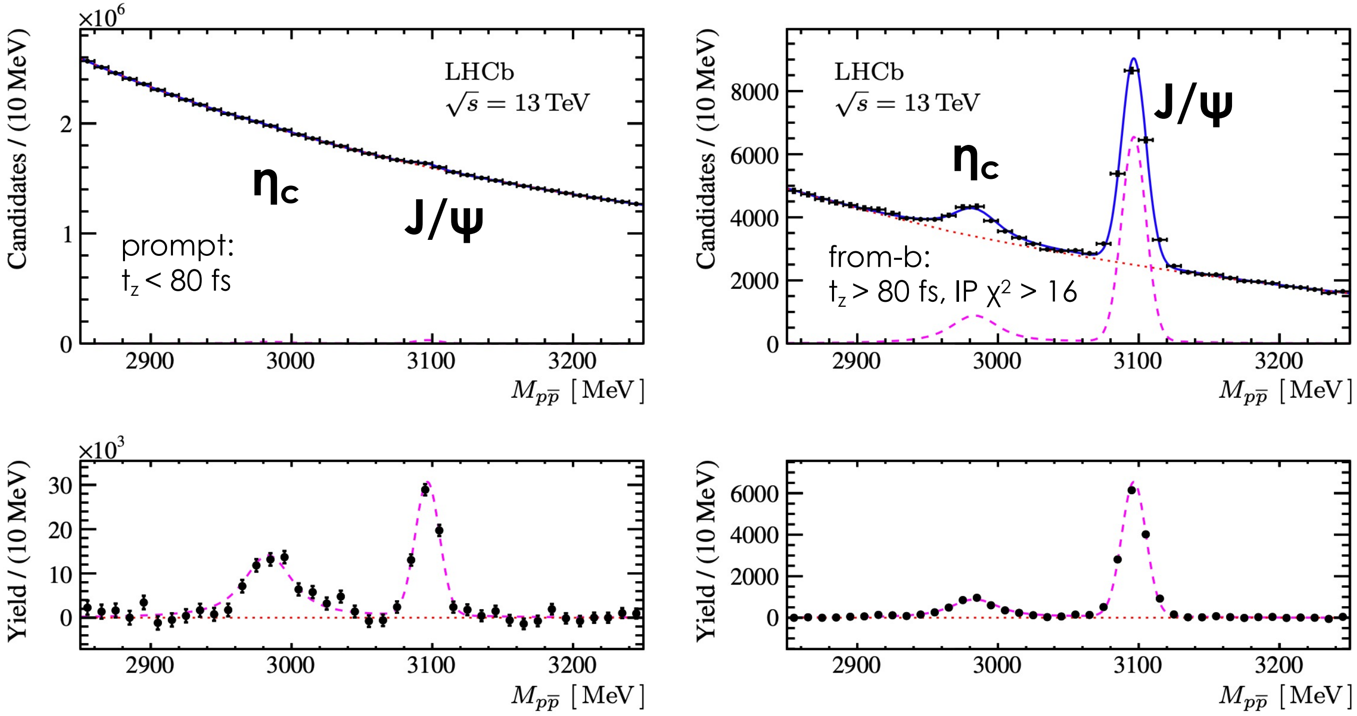
  ~4% of solid angle,

  but **~40% of heavy quarkonium (HQ) production x-section**
- **Forward peaked HQ production** at the LHC, second *b* in acceptance once the first *b* is in
- Key detector systems for production measurement:
  - **Vertex reconstruction** with **VELO**
  - **Particle identification** with **2 Ring Imaging Cherenkov Detectors (RICH)** and **Muon detector**
  - **Trigger**

$\eta_C(1S)$ PRODUCTION AT LHCb AT $\sqrt{s}$=13 TeV

Eur.Phys.J.C 80(2020) 191

- t_z-cut technique: **prompt** and ***b*-decay production** separated using t_z-value



- Relative charmonium yields:

$6.5 < p_T < 14.0\, GeV/c\,, 2.0 < y < 4.5$

$$\frac{N_{\eta_c}^{prompt}}{N_{J/\psi}^{prompt}} = 1.18 \pm 0.10 \qquad \frac{N_{\eta_c}^{from-b}}{N_{J/\psi}^{from-b}} = 0.33 \pm 0.02$$

- Cross-feed probabilities accounted in the simultaneous fit:
  - $\varepsilon^{prompt\rightarrow prompt} = 0.965 \pm 0.021$
  - $\varepsilon^{prompt\rightarrow from-b} = 0.0002 \pm 0.0001$
  - $\varepsilon^{from-b\rightarrow prompt} = 0.066 \pm 0.005$
  - $\varepsilon^{from-b\rightarrow from-b} = 0.689 \pm 0.022$

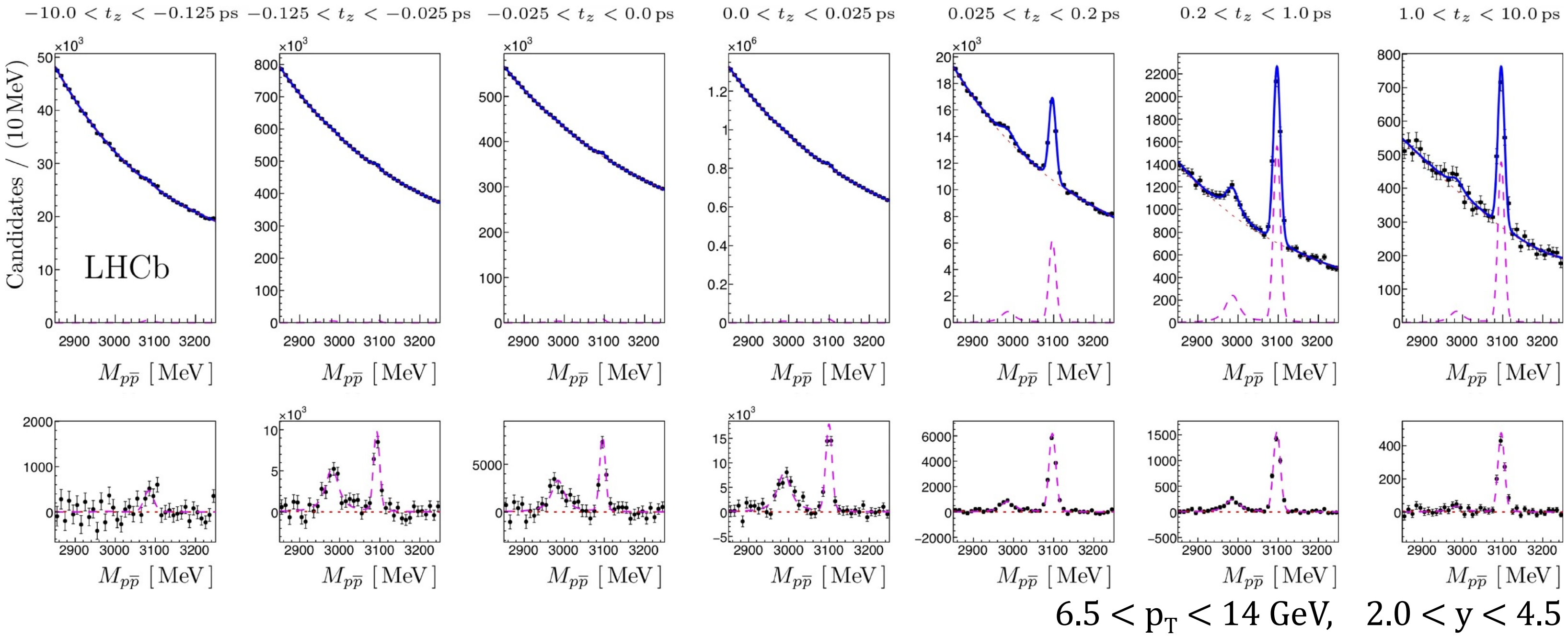
- The **most precise** determination of **η_c mass** up to date:

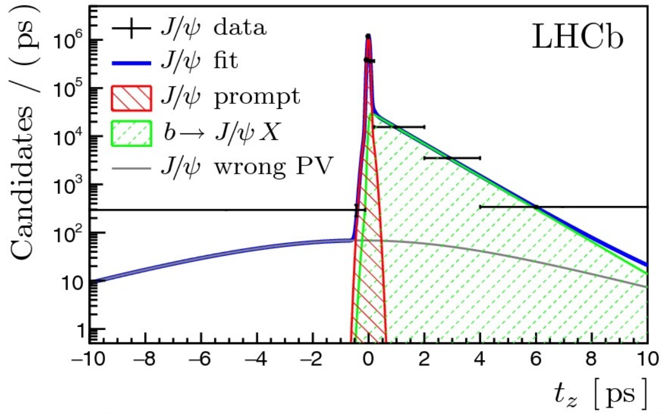
$$\Delta M_{J/\psi,\eta_c} = 113.0\ \pm 0.7_{stat} \pm 0.1_{syst} MeV$$

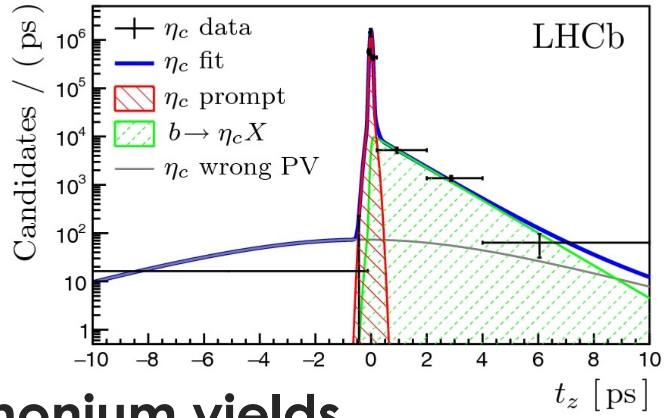
$\eta_C(1S)$ PRODUCTION AT LHCb AT $\sqrt{s}$=13 TeV

Eur.Phys.J.C 80(2020) 191

- t_z-fit technique





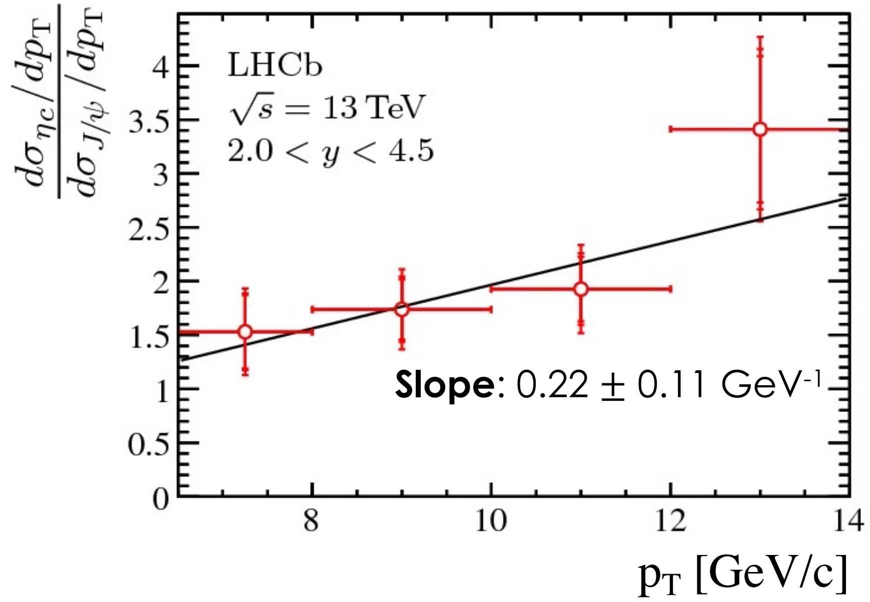


- Simultaneous likelihood **fit to $M_{p\bar{p}}$** in bins of **[p_T, t_z] to extract charmonium yields**
- Simultaneous integral χ² **fit to t_z** in p_T-bins **to separate prompt** and **from *b*-decays charmonium**
- η_c mass correction applied in bins of t_z
- Results consistent with t_z-cut technique

RATIO BETWEEN η_C AND J/ψ PRODUCTION

Eur.Phys.J.C 80(2020) 191

- Relative η_c to J/ψ p_T-differential production cross-sections



- **Relative η_c(1S) to J/ψ production** in LHCb at √s=13 TeV

$6.5 < p_T < 14.0$ GeV/c, $2.0 < y < 4.5$

$$\sigma^{prompt}_{\eta_c}/\sigma^{prompt}_{J/\psi} = 1.69 \pm 0.15_{stat} \pm 0.10_{syst} \pm 0.18_{\mathfrak{B}_{c\bar{c}\to p\bar{p}}}\ \mu b$$

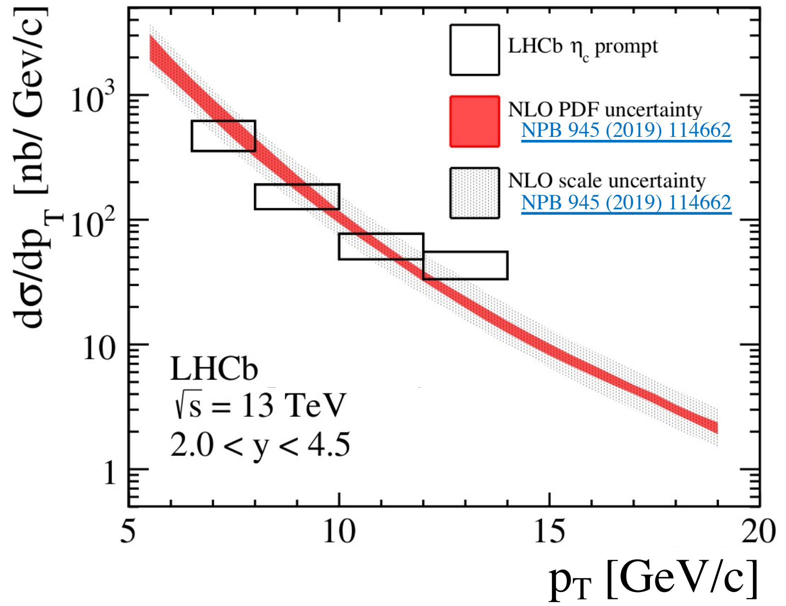
$$\mathfrak{B}_{b\to\eta_c X}/\mathfrak{B}_{b\to J/\psi X} = 0.48 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.05_{\mathfrak{B}_{c\bar{c}\to p\bar{p}}}$$

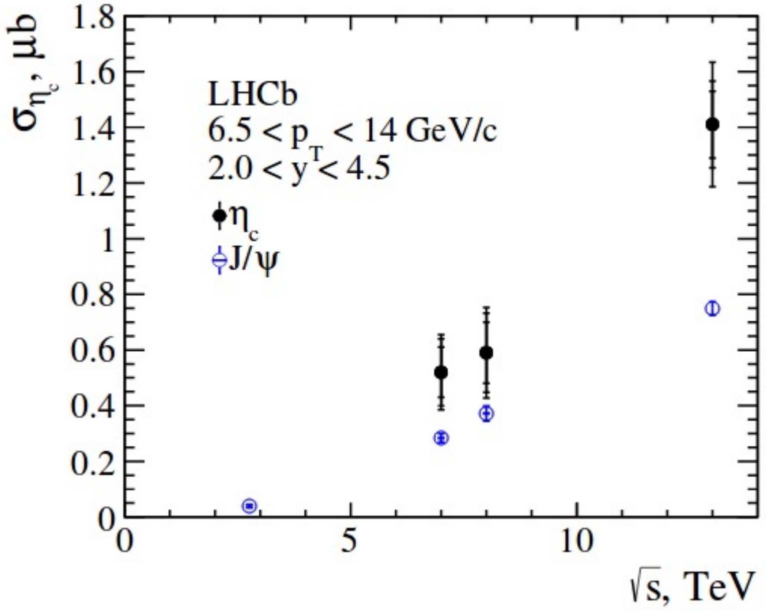
- Measurement in extended p_T is required
- **Interpretation of η_c(2S)/ψ(2S) much more clean** than of η_c(1S)/J/ψ due to absence of feed-down contributions

INTEGRATED AND DIFFERENTIAL CROSS-SECTIONS

Eur.Phys.J.C 80(2020) 191

- Measurement of **integrated** and **p_T -differential production cross-sections**





- **$\eta_c(1S)$ production** in LHCb at √s=13 TeV:

$6.5 < p_T < 14.0\ \mathrm{GeV/c}, 2.0 < y < 4.5$

$$\sigma_{\eta_c}^{prompt} = 1.26 \pm 0.11_{stat} \pm 0.08_{syst} \pm 0.14_{J/\psi}\ \mu b$$

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

- **$\eta_c(1S)$ production can be described by CS contribution only**

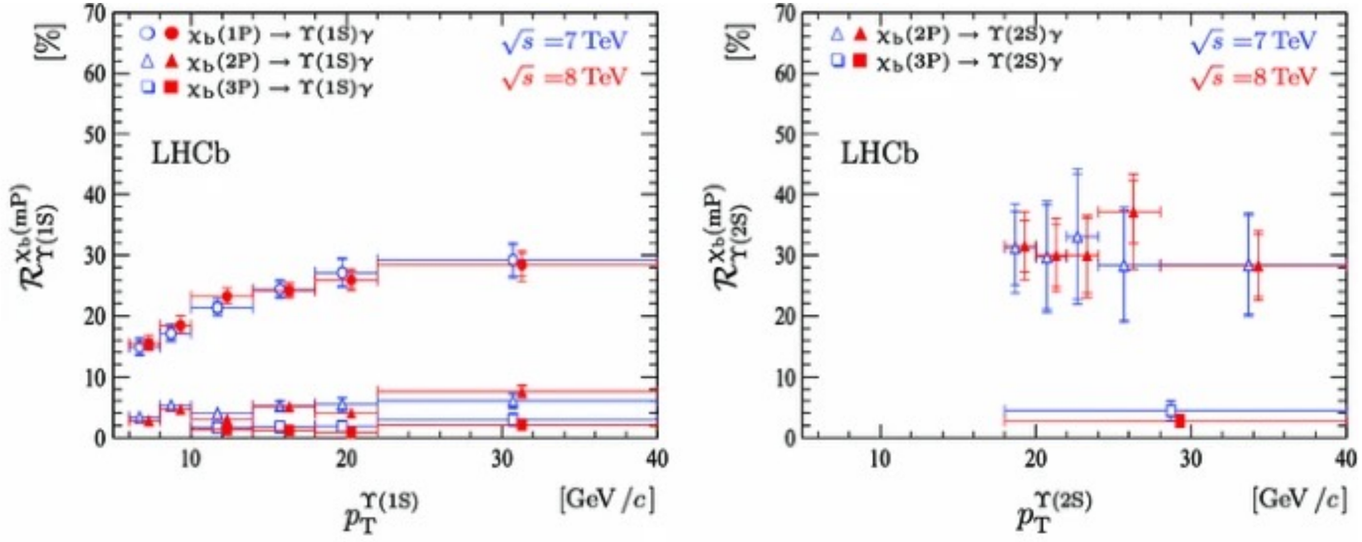
χ_b PRODUCTION IN LHCb AT $\sqrt{s}$=7 AND 8 TeV

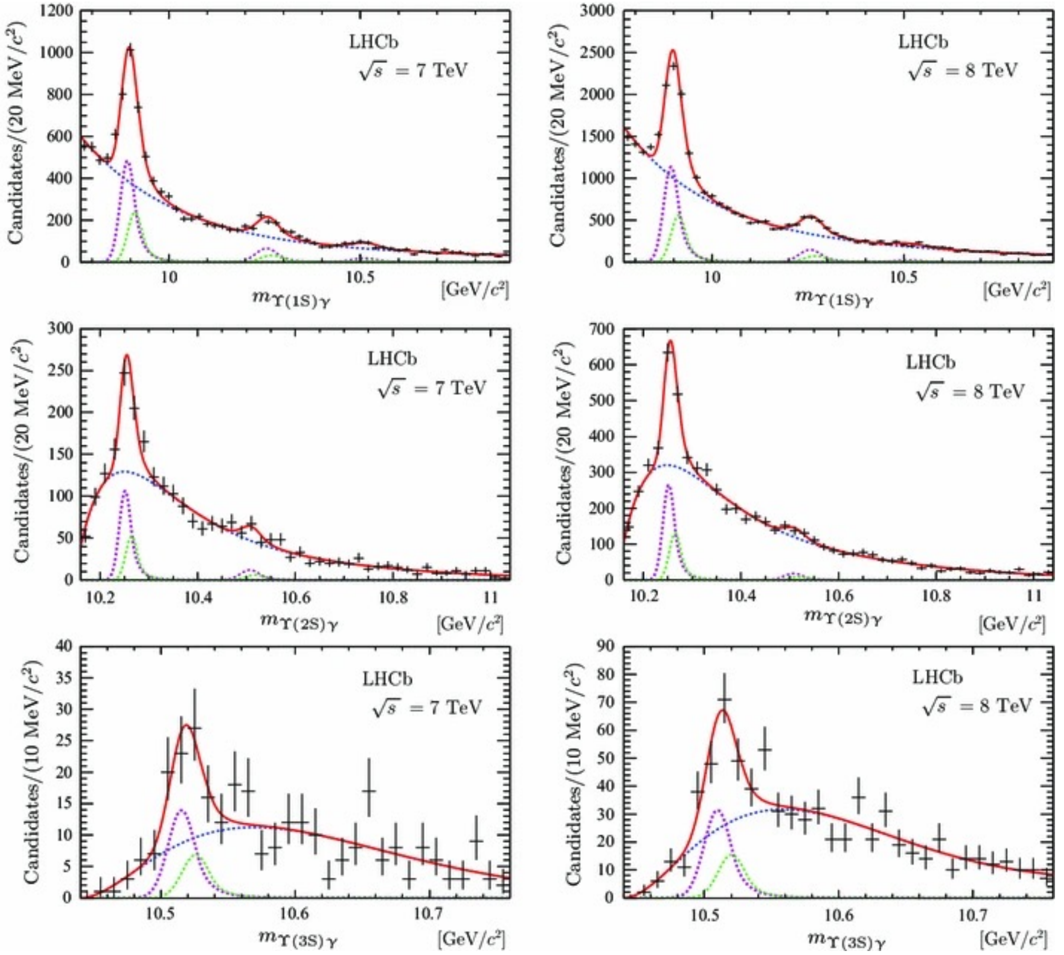
Eur.Phys.J.C 74(2014)10, 3092

- Search for $\chi_b(nP)$ using decay to $\Upsilon(nS)\gamma$

$$\mathcal{R}^{\chi_b(mP)}_{\Upsilon(nS)} = \frac{N_{\chi_b(mP)}}{N_{\Upsilon(nS)}} \times \frac{\varepsilon_{\Upsilon(nS)}}{\varepsilon_{\chi_b(mP)}}$$

- **Invariant mass fit** to extract yields





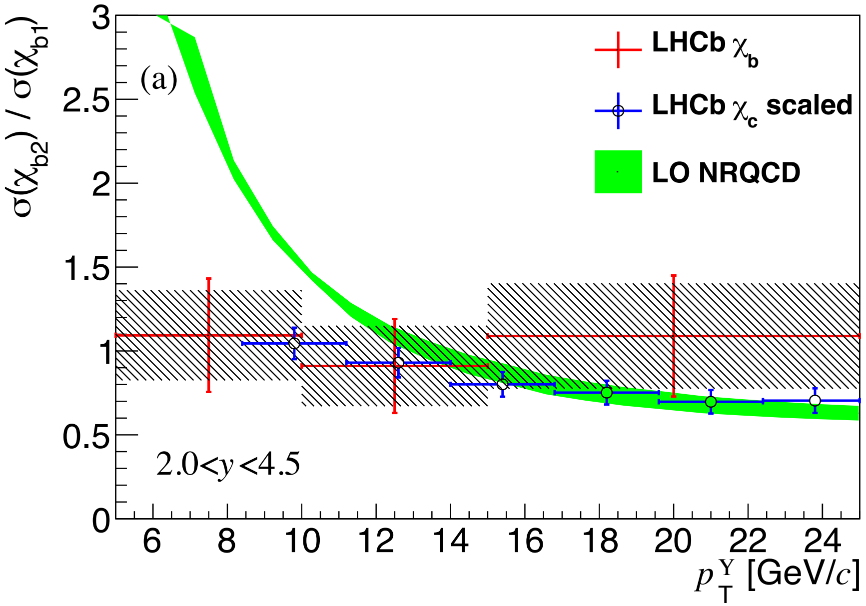
- Fraction $\mathcal{R}^{\chi_b(mP)}_{\Upsilon(nS)}$ measured in bins of p_T
- **$\chi_b(3S) \rightarrow \Upsilon(3S)\gamma$ observed for the first time**

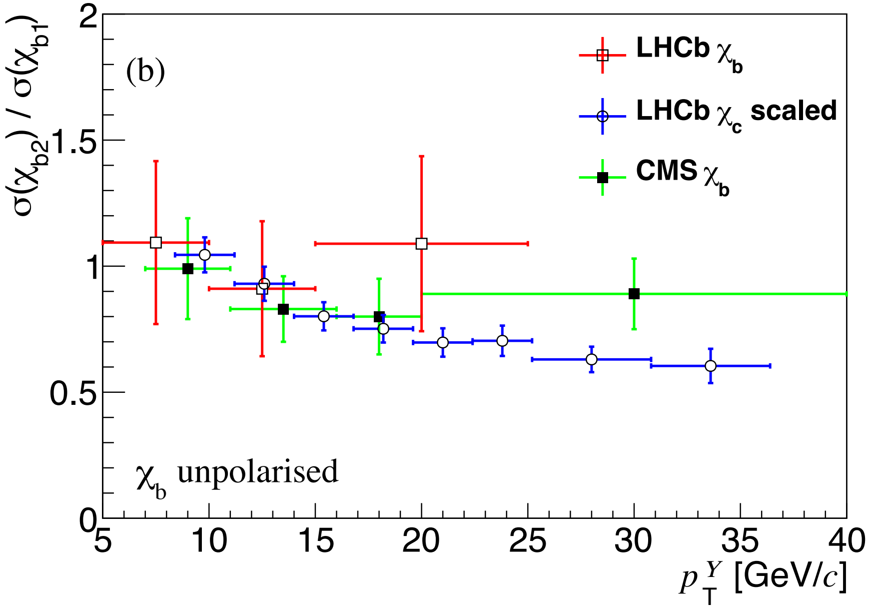
χ_b PRODUCTION IN LHCb AT $\sqrt{s}$=7 AND 8 TeV

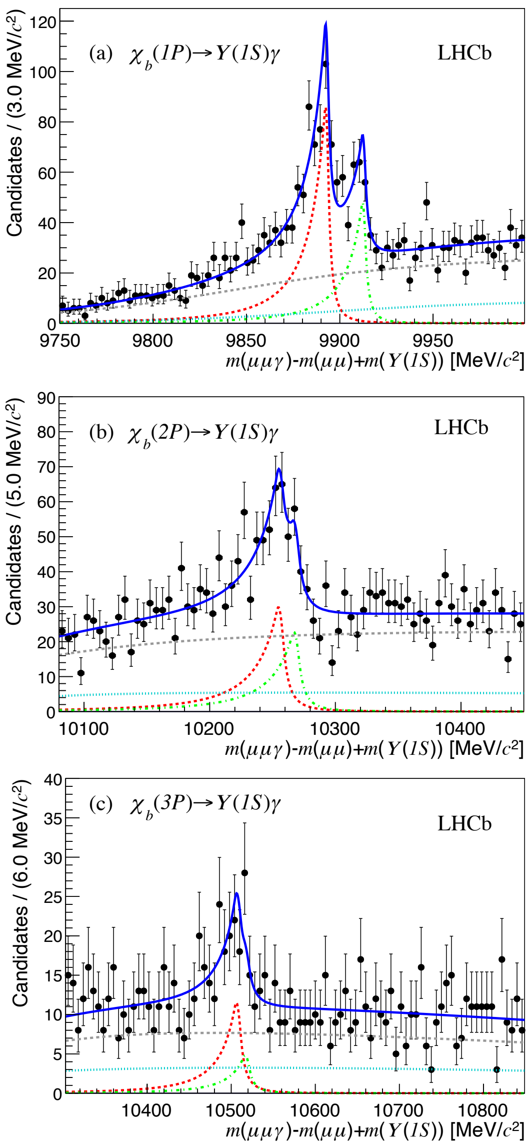
JHEP10 (2014) 088

- **First measurement of $\chi_{b2}(1P)/\chi_{b1}(1P)$ production** using decay to $\Upsilon(1S)\gamma$
  $5 < p_T^{\Upsilon} < 25$ GeV/c, $2. < y < 4.5$

$$\frac{\sigma_{\chi_{b2}(1P)}}{\sigma_{\chi_{b1}(1P)}} = \frac{N_{\chi_{b2}(1P)}}{N_{\chi_{b1}(1P)}} \times \frac{\varepsilon_{\chi_{b1}(1P)}}{\varepsilon_{\chi_{b2}(1P)}} \times \frac{\mathcal{B}(\chi_{b1}\to\Upsilon(1S)\gamma)}{\mathcal{B}(\chi_{b2}\to\Upsilon(1S)\gamma)}$$







- **Results have reasonable agreement with CMS** results and LHCb-based **LO NRQCD prediction** [JHEP 10 (2013) 115] at high-p_T

χ_b PRODUCTION IN CMS AT $\sqrt{s}$=8 TeV

Phys.Lett.B 743 (2015) 383-402

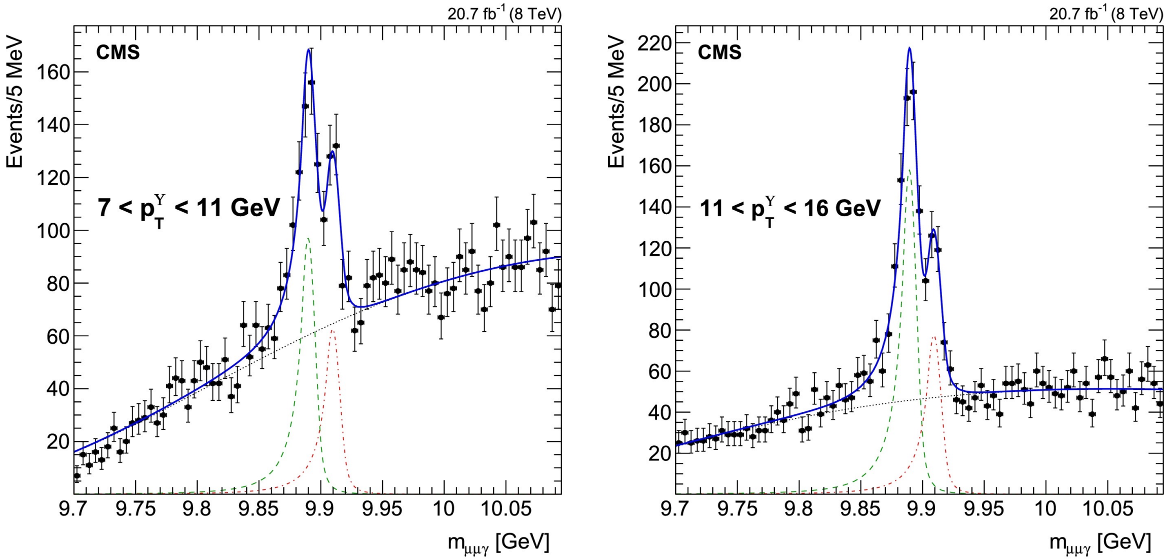
- **Precise measurement of $\chi_{b2}(1P)/\chi_{b1}(1P)$ production cross-section** in complementary region to LHCb: $5 < p_T^{\Upsilon} < 25$ GeV/c, $|y| < 1.5$

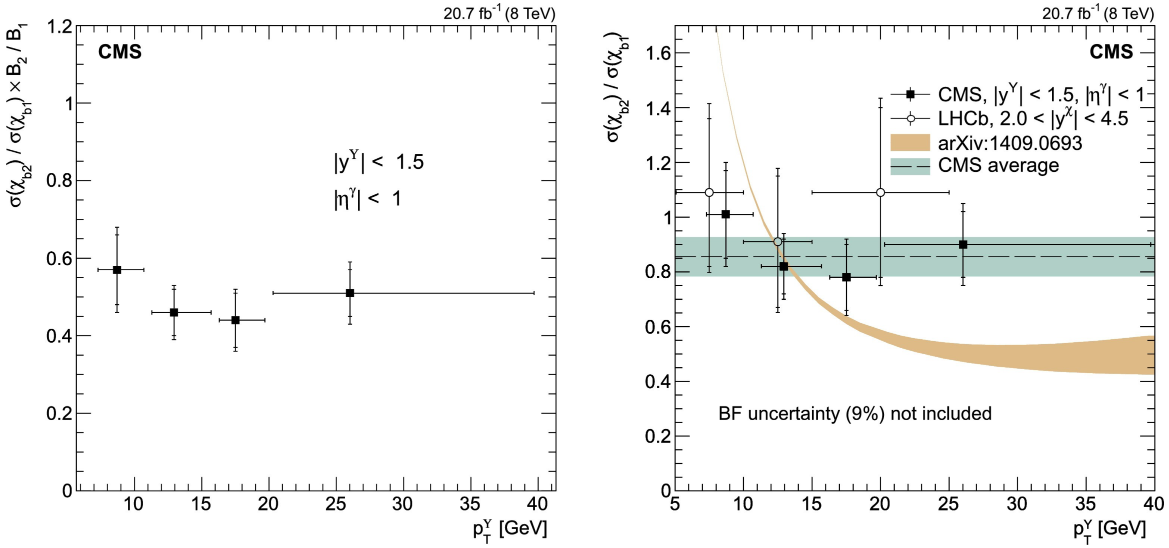
- **χ_b relative production** in integrated p_T-range:

$$\sigma_{\chi_{b2}}/\sigma_{\chi_{b1}} = 0.85 \pm 0.07_{stat+syst} \pm 0.08_{\mathcal{B}}$$

- Ratio does not show significant dependence on Υ(1S) p_T

- >2σ discrepancy with NRQCD prediction at high-p_T





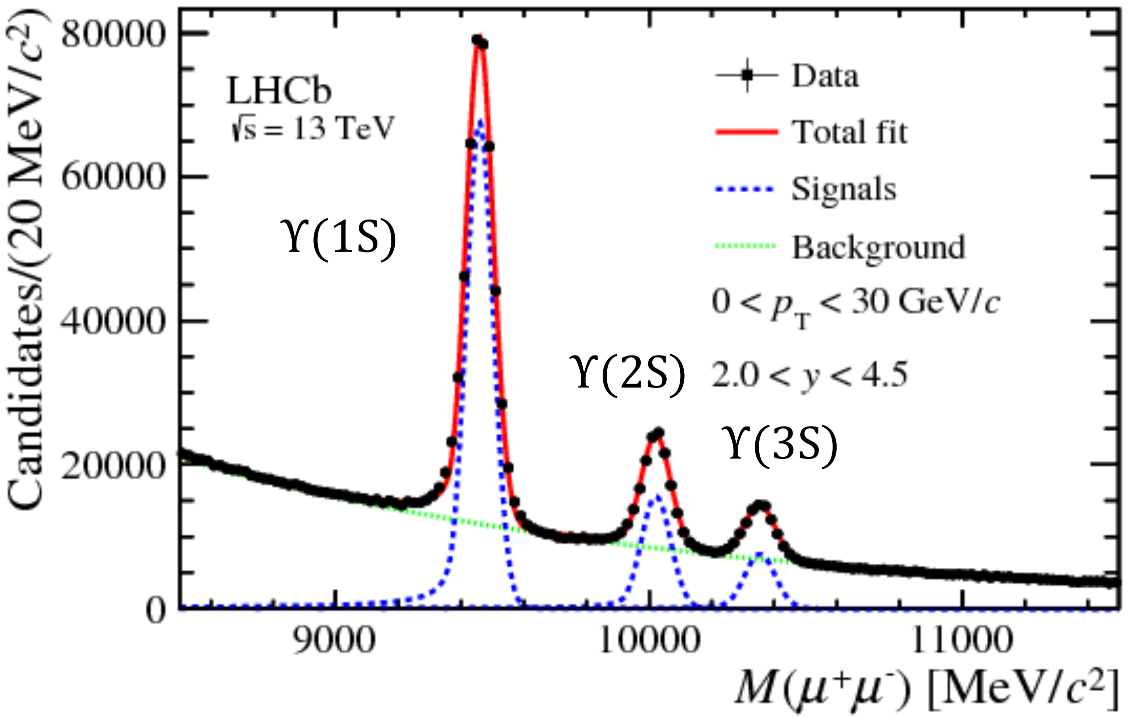
Υ(nS) PRODUCTION AT √s=13 TeV

JHEP07 (2018) 134
JHEP05 (2019) 076

- Cross-section determination

  in bin[p_T,y] as a function of p_T(0< p_T< 30GeV/c) and y(2.0<y<4.5)

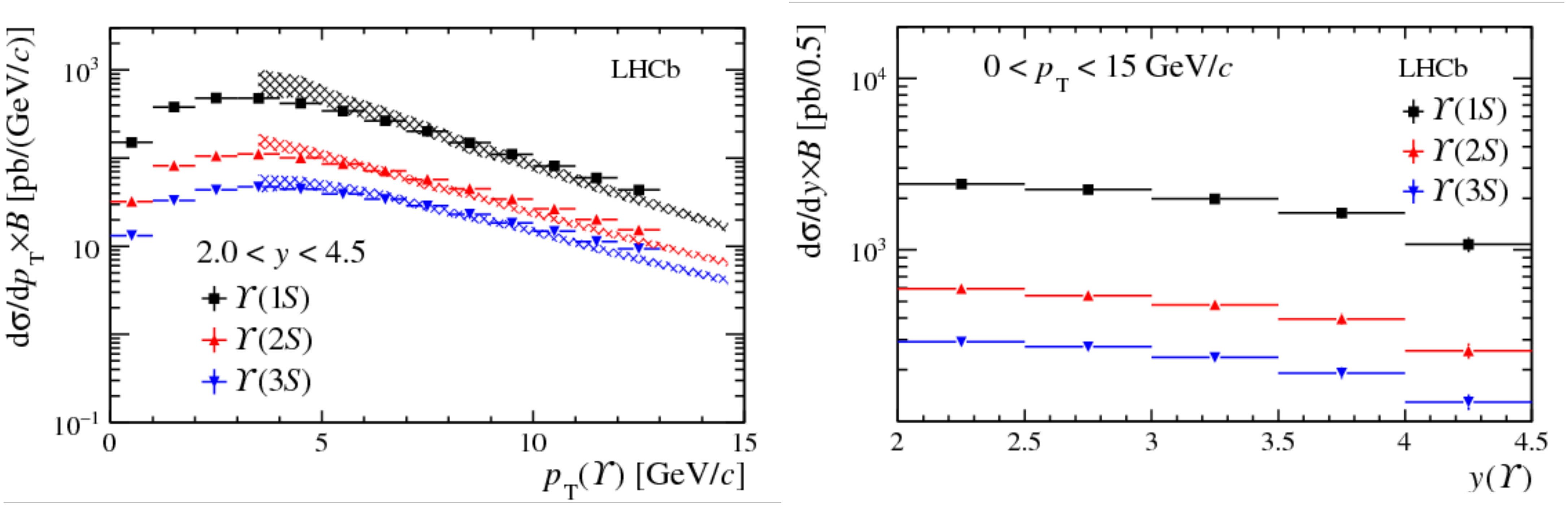
$$\frac{d^2\sigma}{dydp_T} = \frac{N(\Upsilon\to\mu^+\mu^-)}{\mathcal{L}\times\varepsilon_{tot}\times\mathcal{B}(\Upsilon\to\mu^+\mu^-)\times\Delta y\times\Delta p_T}$$



- Unbinned likelihood fit in bins of **[p_T, y]** to $M_{\mu\mu}$ **to extract Υ(nS) yields**

Υ(nS) PRODUCTION AT √s=13 TeV

JHEP07 (2018) 134
JHEP05 (2019) 076



- Double differential production cross-section measured in range $0 < p_T < 30$ GeV/c and $2.0 < y < 4.5$
- **Good agreement between NRQCD and data** at high p_T for all states