EXPERIMENTAL QUARKONIUM STUDIES OF η_q and χ_q

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Aussois Quarkonium & QCD meeting

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MODELS OF QUARKONIUM PRODUCTION

- **Sources of quarkonium:**
  - prompt hadroproduction
  - decays of higher resonances
  - production in b-hadron decays (for charmonium)

  } prompt production

  } distinguished via pseudo-proper decay time $t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$

- **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;

© talk by J.-P. Lansberg at LHCb Implication workshop

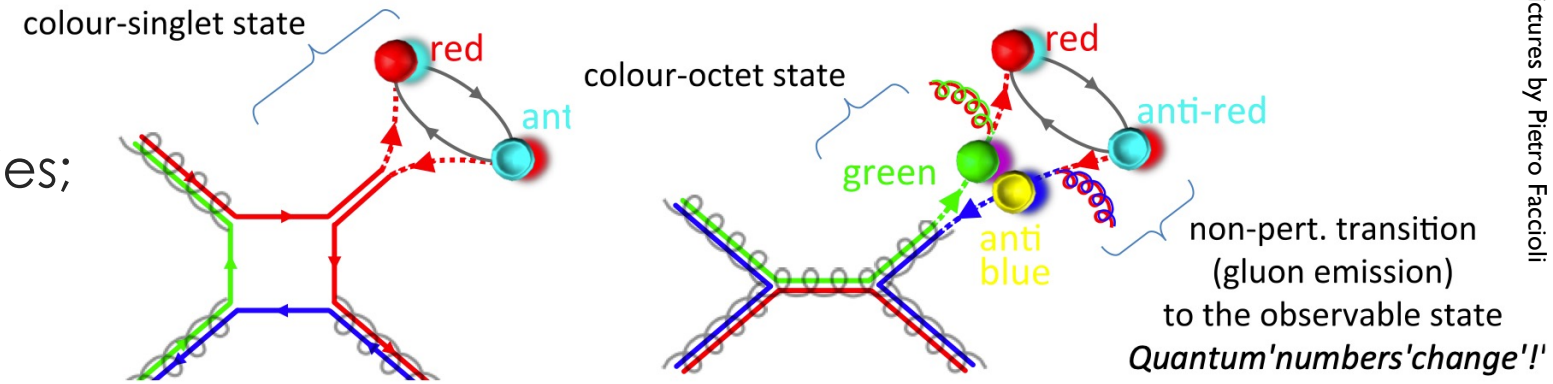
QUARKONIUM PRODUCTION IN NRQCD

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

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



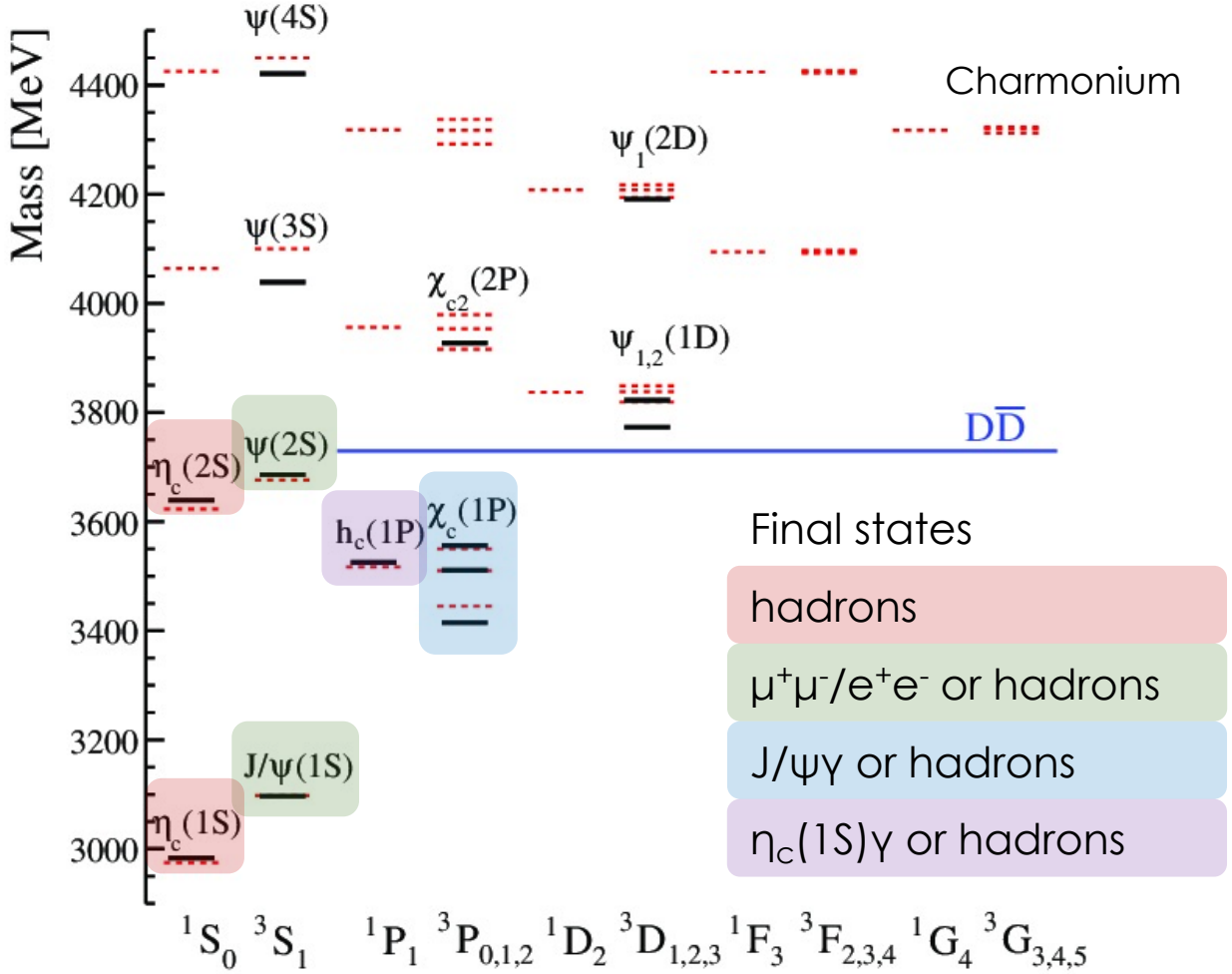
Pictures by Pietro Faccioli

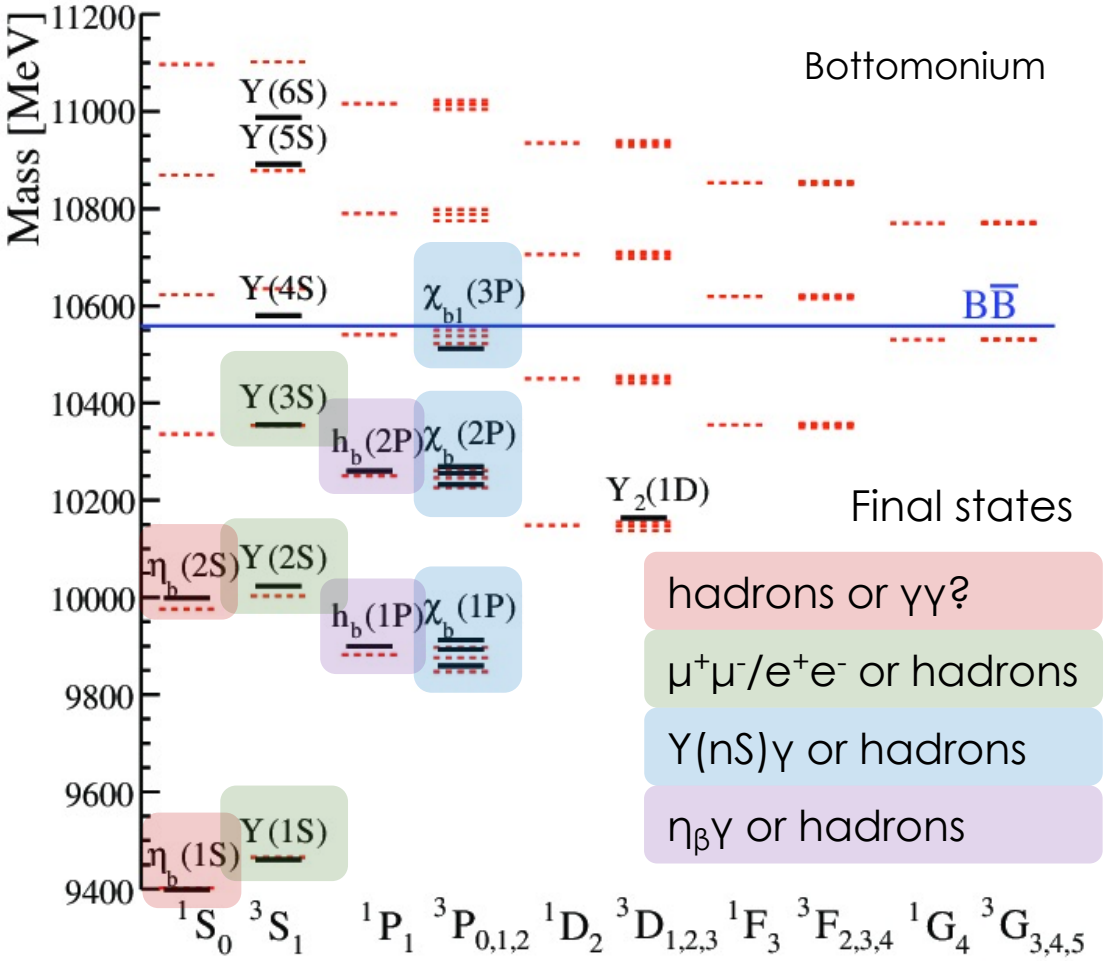
- **Universality**: same LDMEs for different √s, prompt production and production in b-decays
- Heavy-Quark **Spin-Symmetry**: links between CS and CO LDMEs of different quarkonium states

CURRENT STATUS OF QUARKONIUM SPECTRUM

Rev.Mod.Phys 90 (2018) 015003

- Current status of quarkonium spectrum





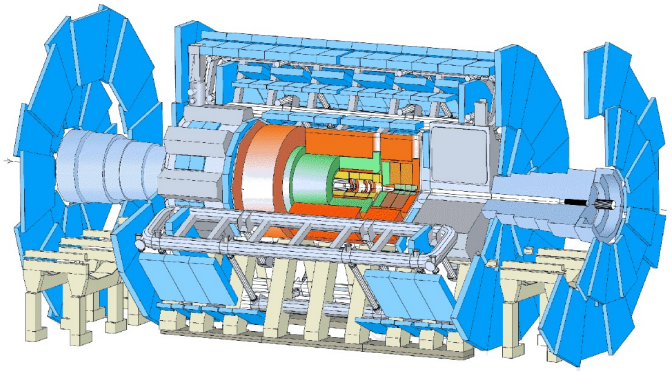
- **Hadronic final states allow to study different quarkonium states simultaneously**

LHC DETECTORS HUNTING FOR QUARKONIUM

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

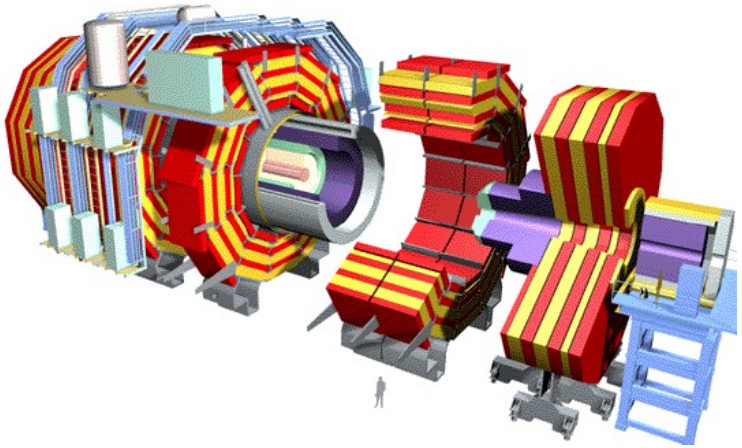
ATLAS EXPERIMENT

JINST 3 (2008) S08003



CMS

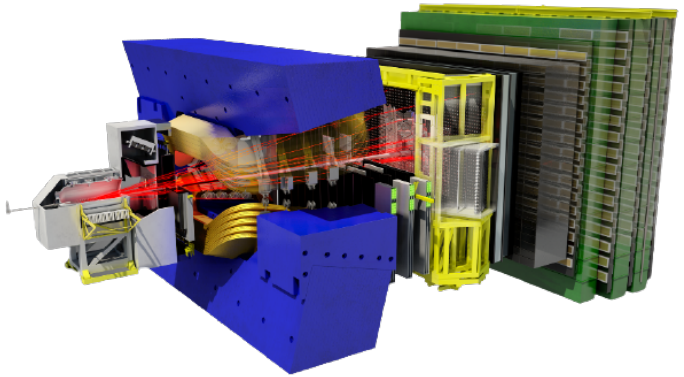
JINST 3 (2008) S08004



- **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**

THE LHCb EXPERIMENT

IJMPA 30 (2015) 1530022

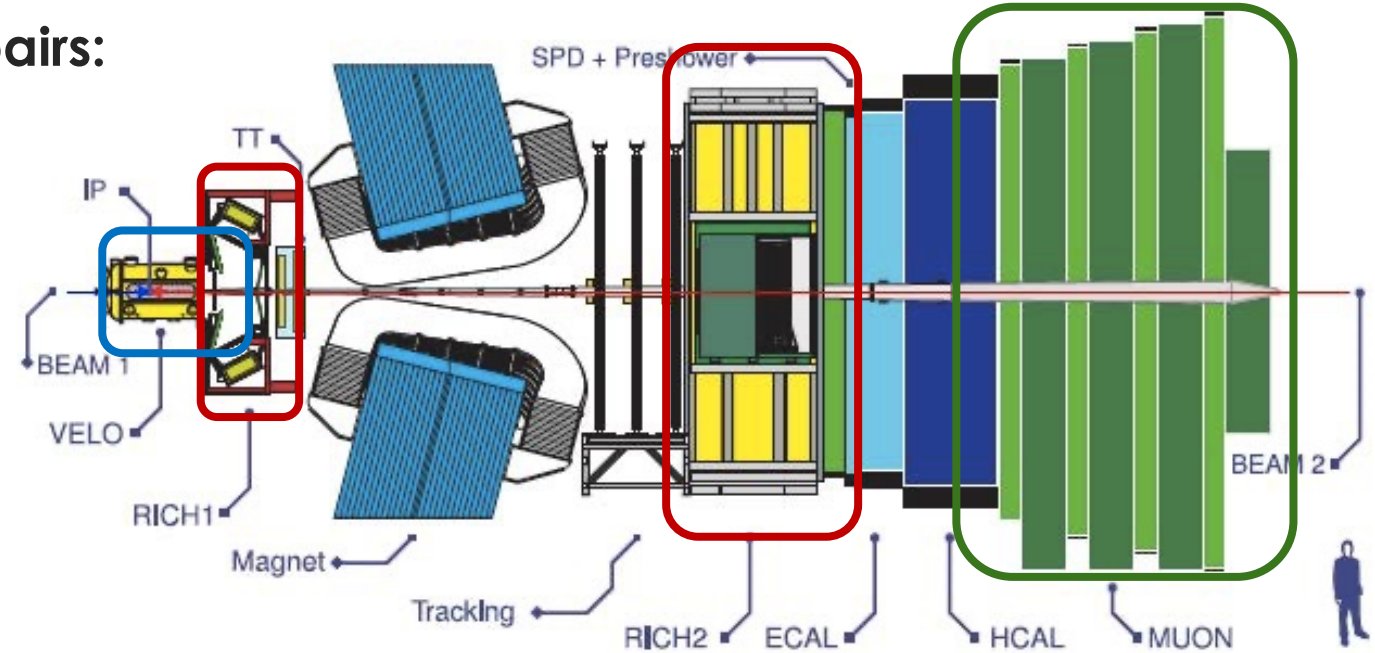
- **LHC provides large number of $b\bar{b}$ and $c\bar{c}$ pairs:**
  - $\sigma_{b\bar{b}} \sim 0.5$ mb
  - $\sigma_{c\bar{c}} \sim 3.0$ mb

  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**

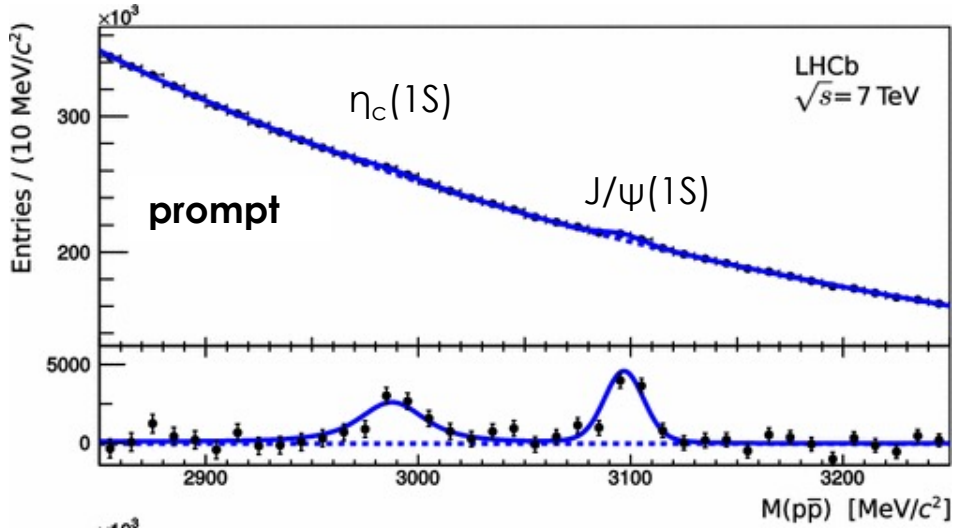


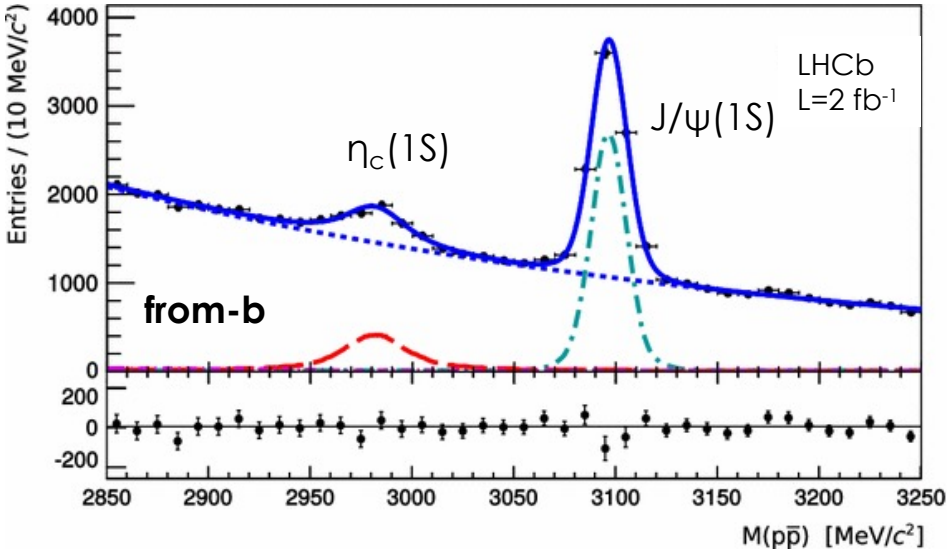
- **Forward peaked HQ production** at the LHC, second *b* in acceptance once the first *b* is in
- Key detector systems for production measurement:
  - **Vertex reconstruction** with **VELO**
  - **Particle identification** with **2 Ring Imaging Cherenkov Detectors (RICH)** and **Muon detector**
  -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

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

Eur.Phys.J. C75(2015) 311

- **Prompt** and ***b*-decay production** distinguished via **decay time**:
  $t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$
- **First measurements of $\eta_c(1S)$ prompt production** at 7 and 8 TeV and b-decay production





- **Challenging background conditions**

η_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, η_C(1S) prompt production entirely described by CS contribution

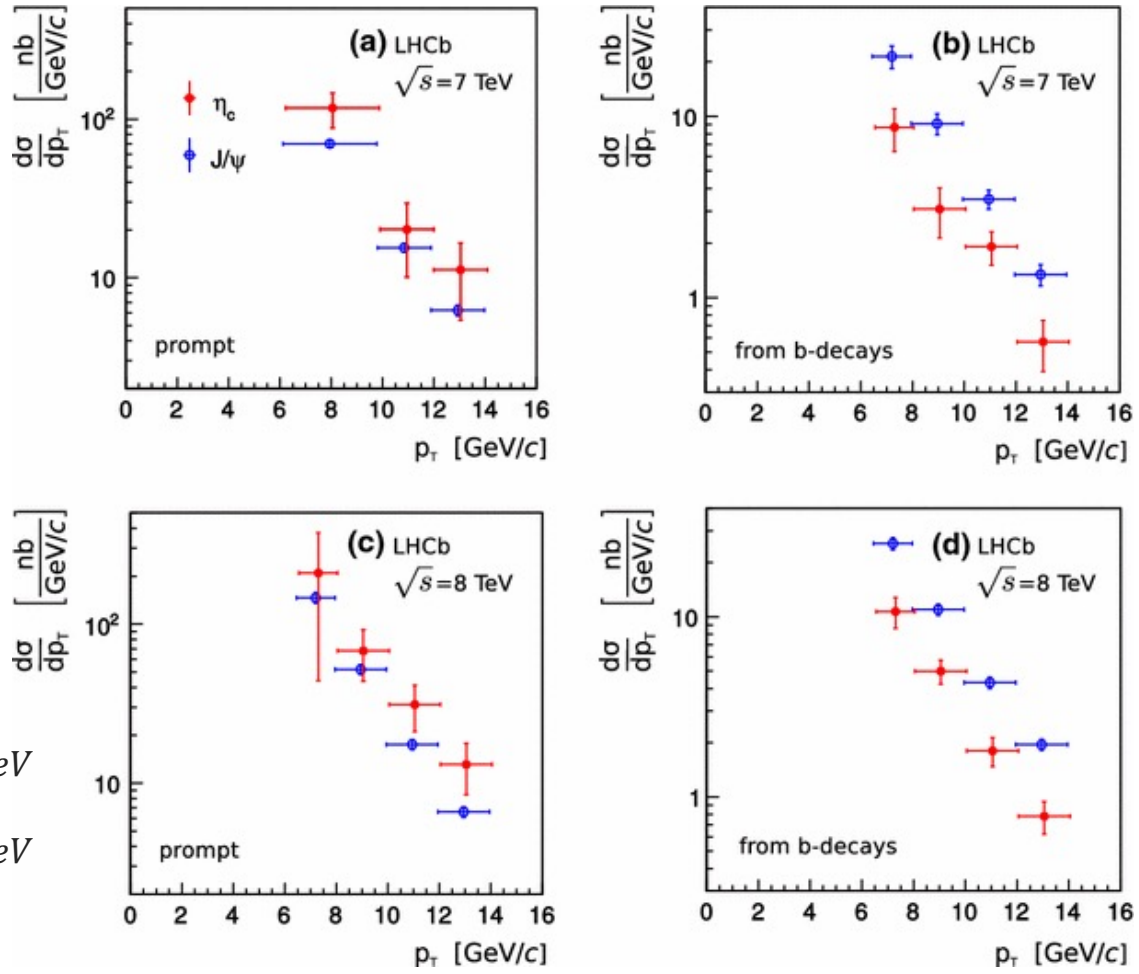
- **η_c(1S) production:**

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

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

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

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



η_c PRODUCTION AT THE LHC

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

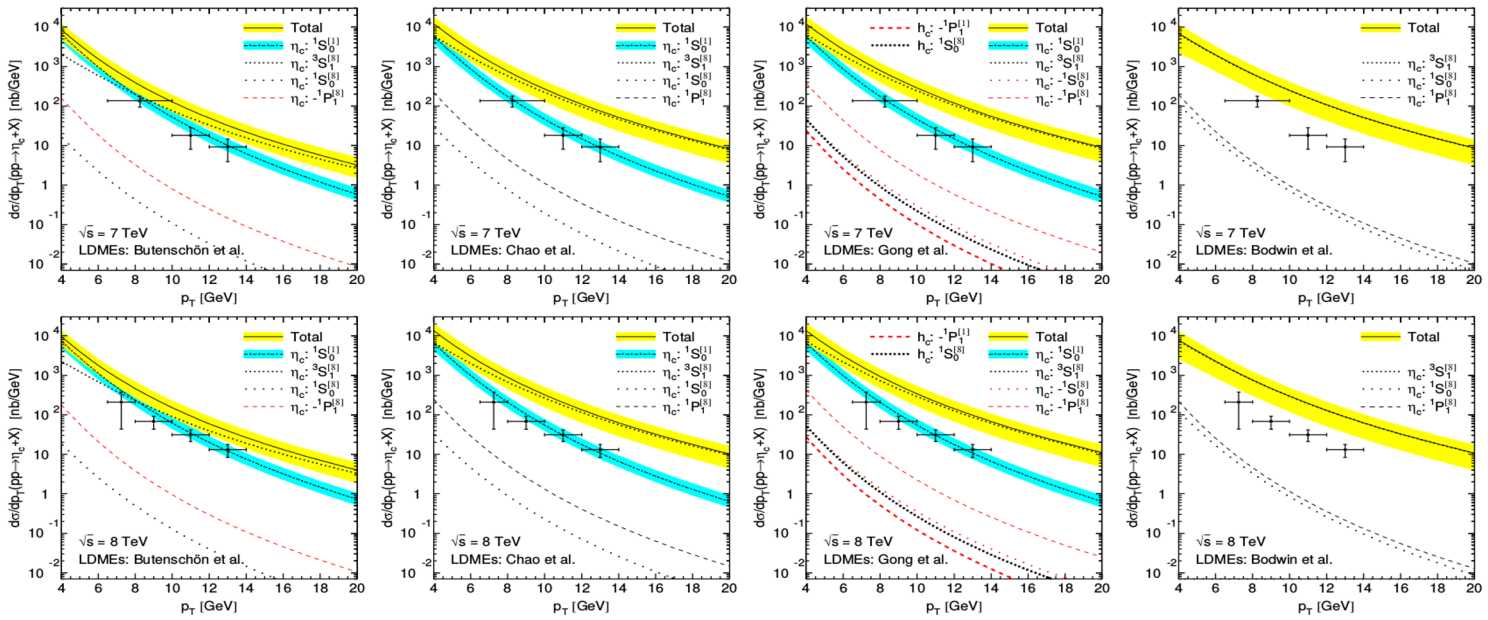
- **η_c(1S) LDMEs** determined from known HQSS relation for J/ψ

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

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

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

- 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?
- **Recent progress in theory**:

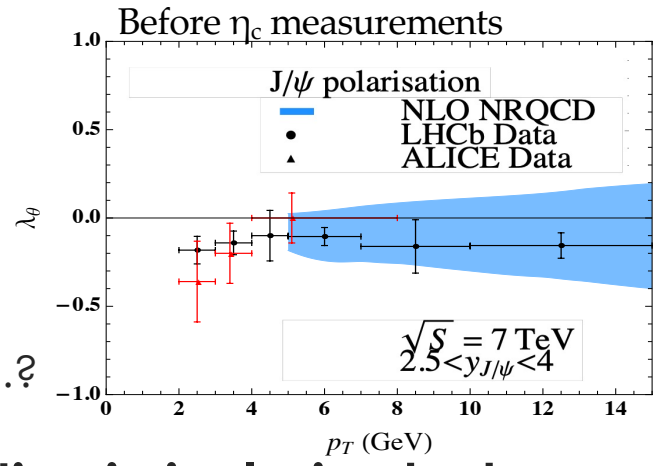
⇢ Phys.Rev.Lett. 114(2015), 092005
⇢ Phys.Rev.Lett. 114(2015), 092006
⇢ Eur.Phys.J.C 75(2015) 7, 313
⇢ Nucl.Phys.B 945(2019) 114662
⇢ Phys.Lett.B 786(2018) 342-346
⇢ JHEP 05(2015) 103
⇢ Phys.Rev.Lett. 110(2013) 042002
⇢ Phys.Rev.D 93 (2016) 034041

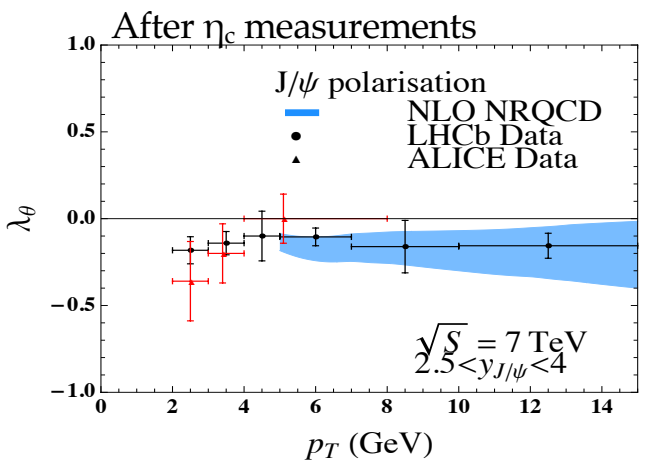
SIMULTANEOUS STUDY OF η_C AND J/ψ

PRL 114(2015), 092005
arXiv:1910.08796

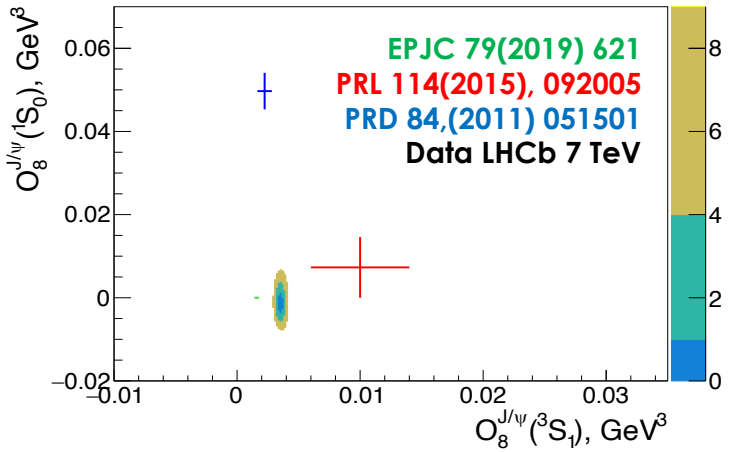
- η_c production @ $\sqrt{s}$=7 and 8 TeV sets new constraint on J/ψ polarization
- **Outcome**:
  - Impressive progress
  - Tension with CDF data
  - Two large CO contributions cancel each other ⇒

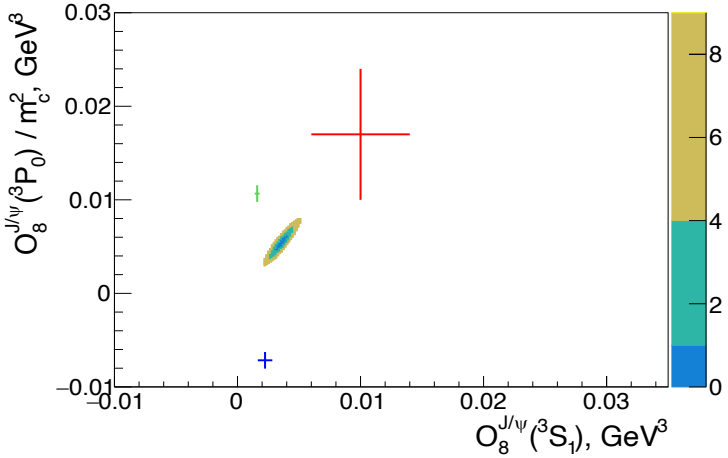
  ⇒ hierarchy problem ⇒ Soft Gluon Fragmentation, etc.?

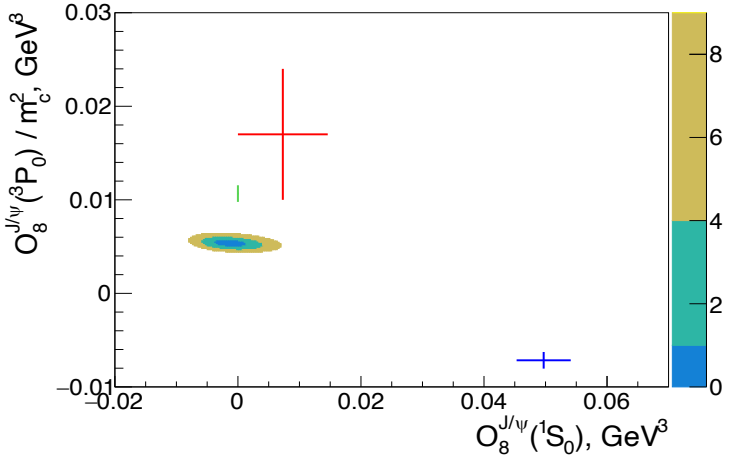




- **Joint study of hadroproduction and production in inclusive b-decays**







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

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

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

- Cross-section determination:

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

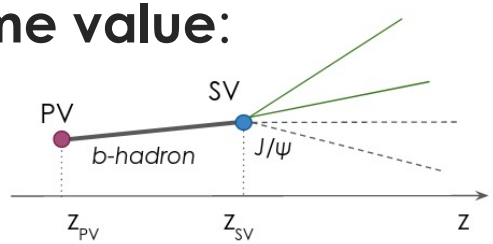
$$\frac{\mathcal{B}_{b\to\eta_c X}}{\mathcal{B}_{b\to J/\psi X}} = \frac{N^b_{\eta_c}}{N^b_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c\to p\bar{p}}}$$

- Extracted from DATA
- Calculated from PDG:

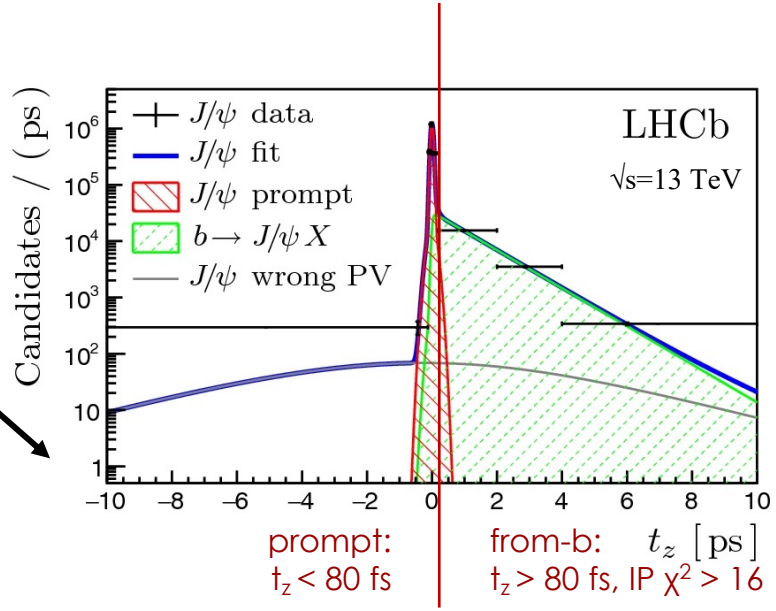
$$\mathcal{B}_{J/\psi\to p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3}$$
$$\mathcal{B}_{\eta_c(1S)\to p\bar{p}} = (1.45 \pm 0.14) \times 10^{-3}$$

- From Simulation

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



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

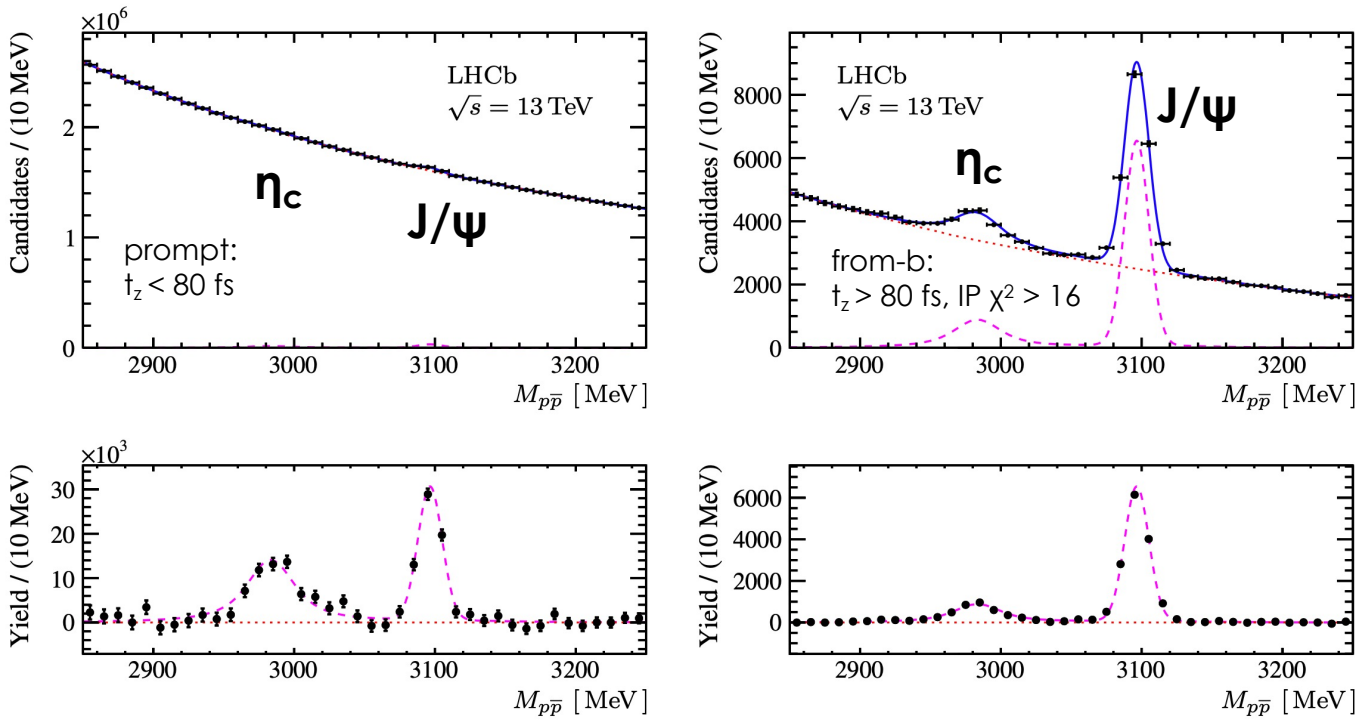


- **Cross-feed** between samples are accounted in simultaneous fit
- **Two techniques** are used for cross-section measurement

t_z-CUT TECHNIQUE

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

- **Prompt** and ***b*-decay production** separated using t_z-value



- Relative charmonium yields:

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

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

- Cross-feed probabilities:
  - $\varepsilon^{prompt \to prompt} = 0.965 \pm 0.021$
  - $\varepsilon^{prompt \to from-b} = 0.0002 \pm 0.0001$
  - $\varepsilon^{from-b \to prompt} = 0.066 \pm 0.005$
  - $\varepsilon^{from-b \to from-b} = 0.689 \pm 0.022$

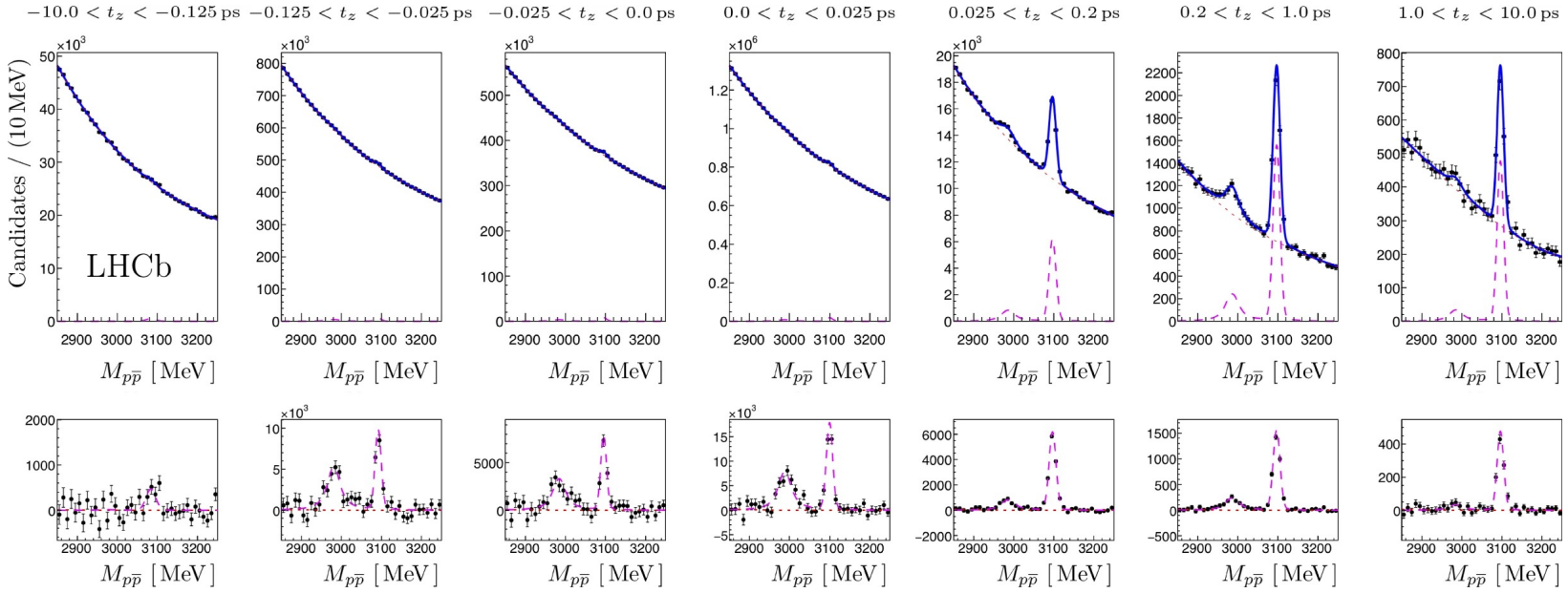
- The **most precise** determination of **η_c mass** up to date:

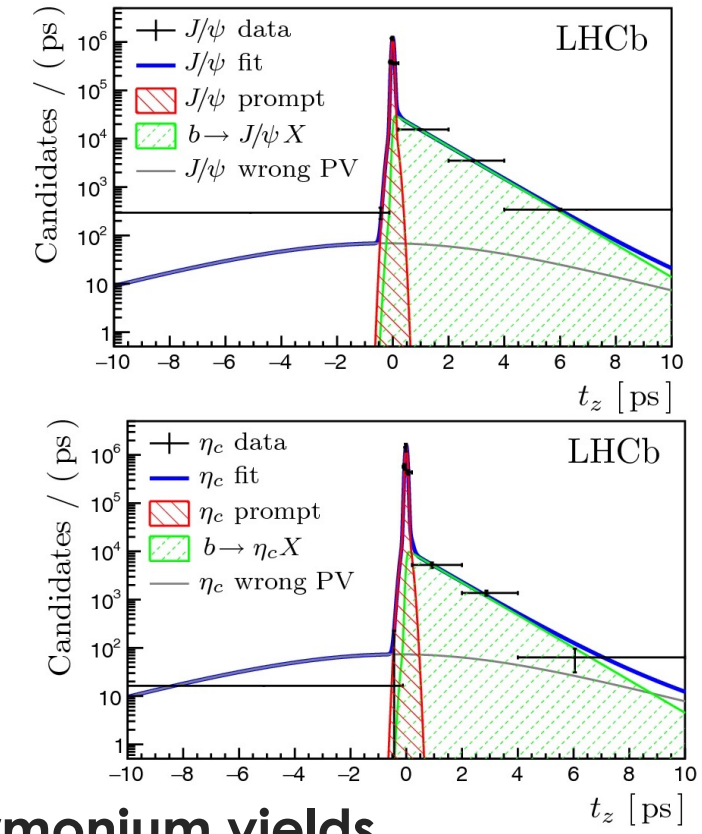
$$\Delta M_{J/\psi,\eta_c} = 113.0 \pm 0.7_{stat} \pm 0.1_{syst} MeV$$

t_z-FIT TECHNIQUE

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

$6.5 < p_T < 14$ GeV, $2.0 < y < 4.5$



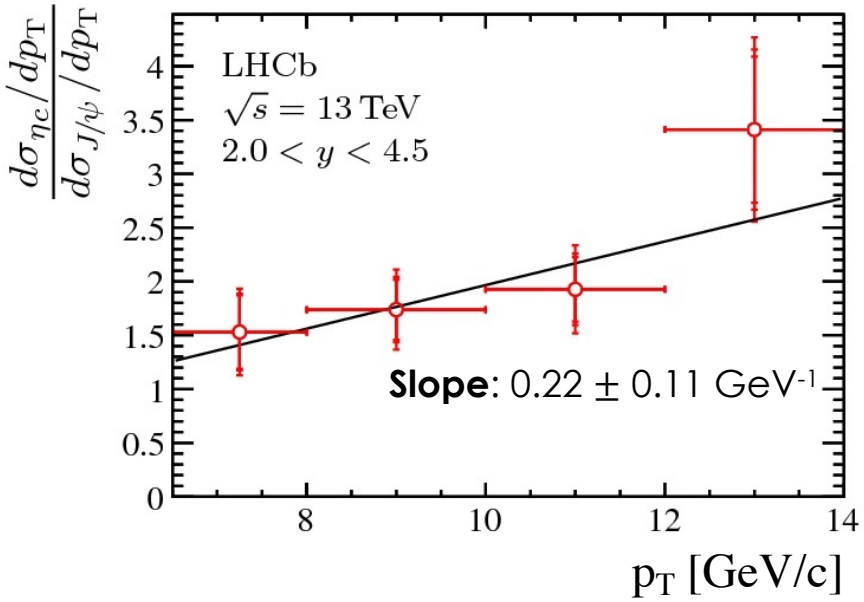


- Simultaneous likelihood **fit to $M_{p\bar{p}}$** in bins of **$[p_T, t_z]$ to extract charmonium yields**
- Simultaneous integral χ^2 **fit to t_z** in p_T-bins **to separate prompt** and **from *b*-decays charmonium**
- η_c mass correction applied in bins of t_z
- Results consistent with t_z-cut 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, $2.0 < y < 4.5$

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

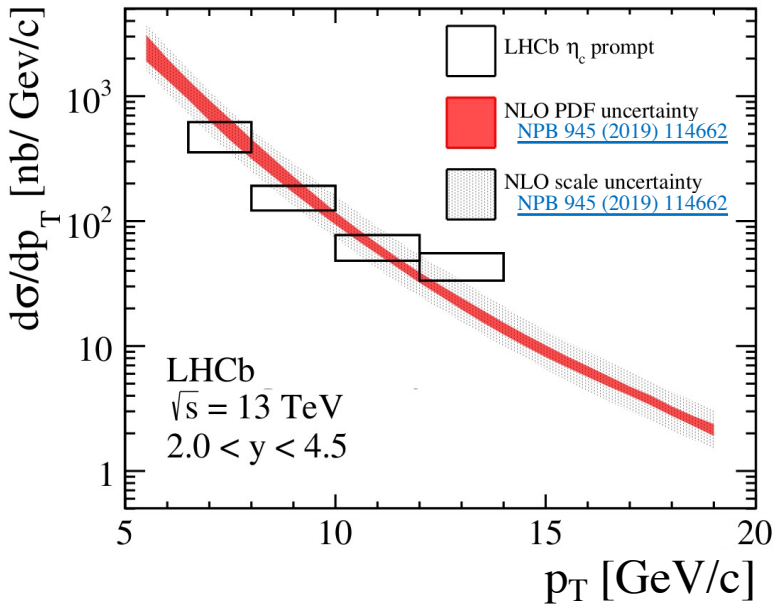
$$\mathfrak{B}_{b\to\eta_c X}/\mathfrak{B}_{b\to J/\psi X} = 0.48 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.05_{\mathfrak{B}_{c\bar{c}\to p\bar{p}}}$$

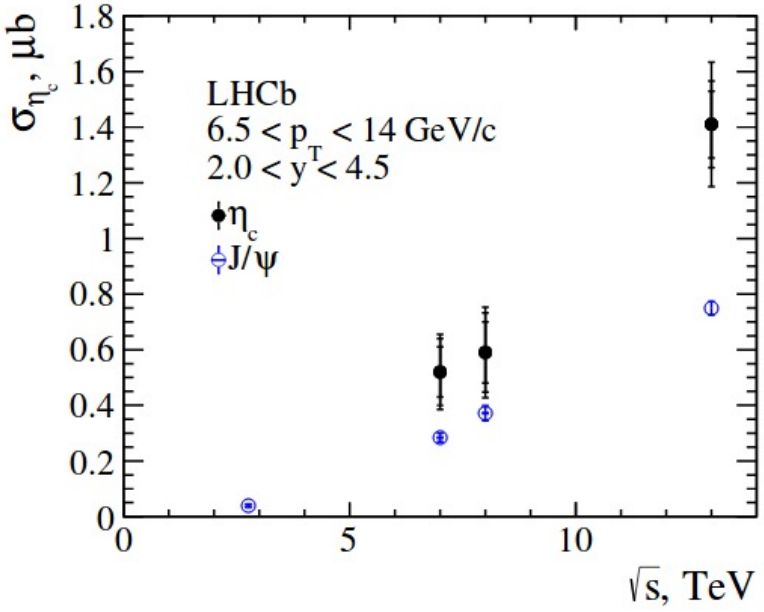
- Measurement in extended p_T is required
- **Larger slope** would indicate **possible CO contribution**
- **Interpretation of η_c(2S)/ψ(2S) much more clean** than of η_c(1S)/J/ψ due to absence of feed-down contributions

INTEGRATED AND DIFFERENTIAL CROSS-SECTIONS

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

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





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

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

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

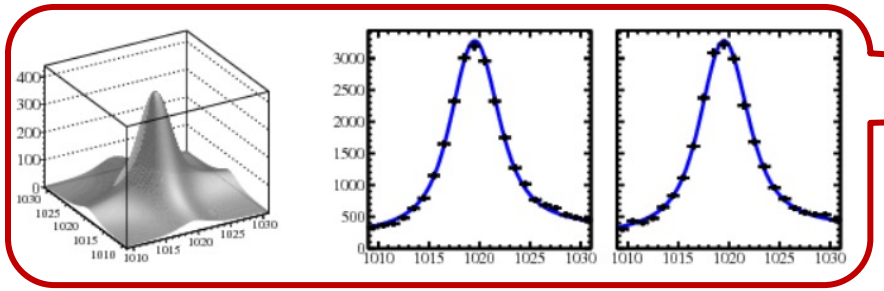
$$\mathfrak{B}_{b\to\eta_c X} = (5.51 \pm 0.32_{stat} \pm 0.29_{syst} \pm 0.77_{J/\psi})\times 10^{-3}$$

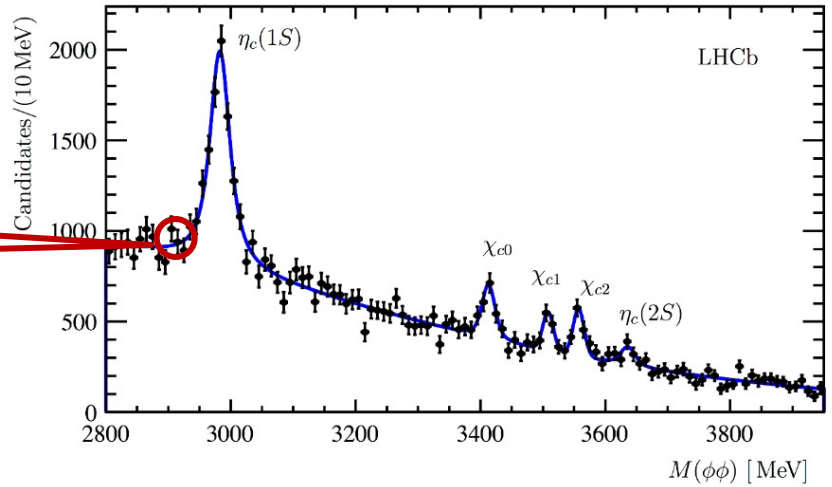
- **η_c(1S) production can be described by CS contribution only**

$\eta_c(2S)$ PRODUCTION IN *b*-DECAYS AT LHCb

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

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



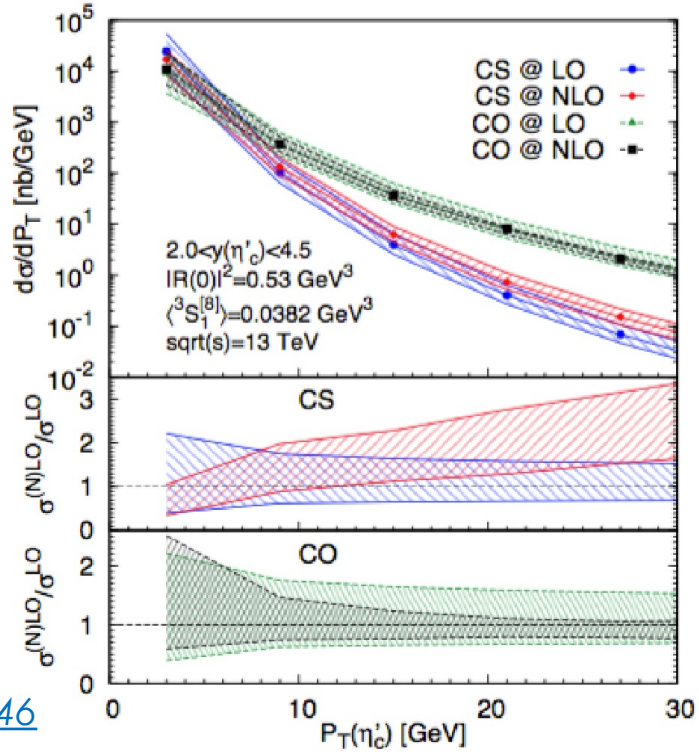


- First measurement of $\eta_c(2S)$ production in b-decays;

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

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

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

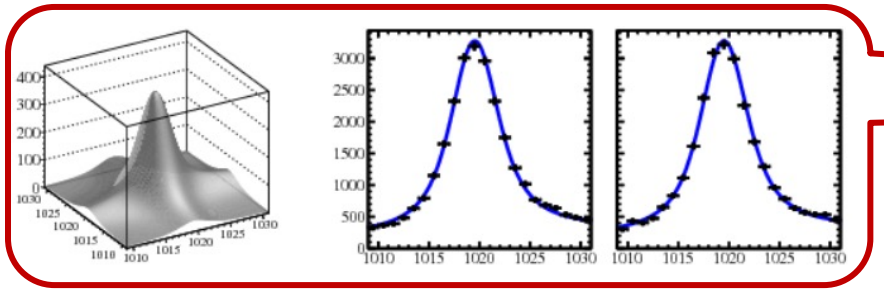


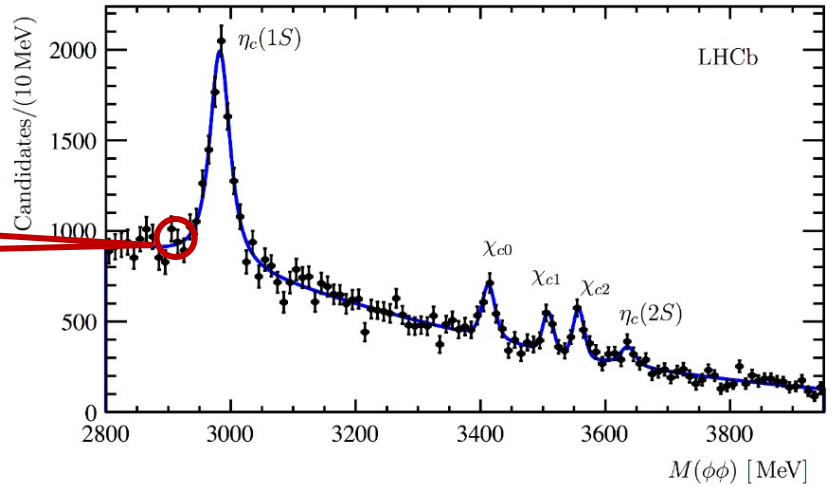
Phys.Lett.B 786 (2018) 342-346

χ_c PRODUCTION IN *b*-DECAYS AT LHCb

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

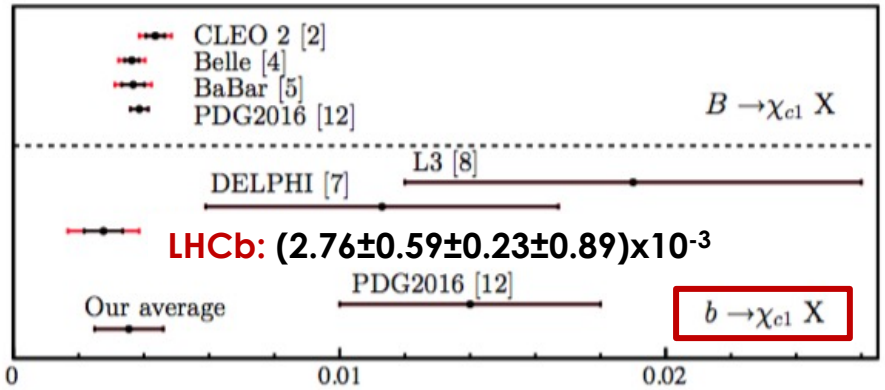
- Charmonium reconstructed via **decays to φφ**;
  true φφ combinations extracted using 2D fit technique

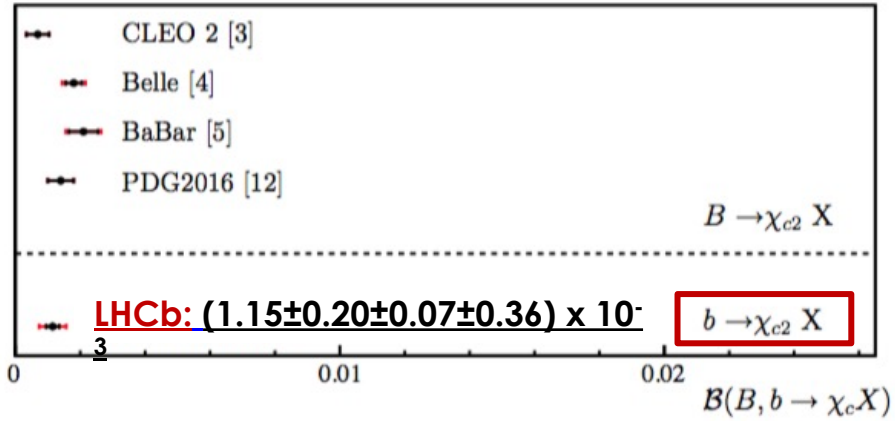




- **First measurement of χ_{c0}** production in b-decays:
  $\mathcal{B}(b \to \chi_{c0}X) = (3.02 \pm 0.47_{stat} \pm 0.23_{syst} \pm 0.94_{\mathcal{B}})\times 10^{-3}$

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



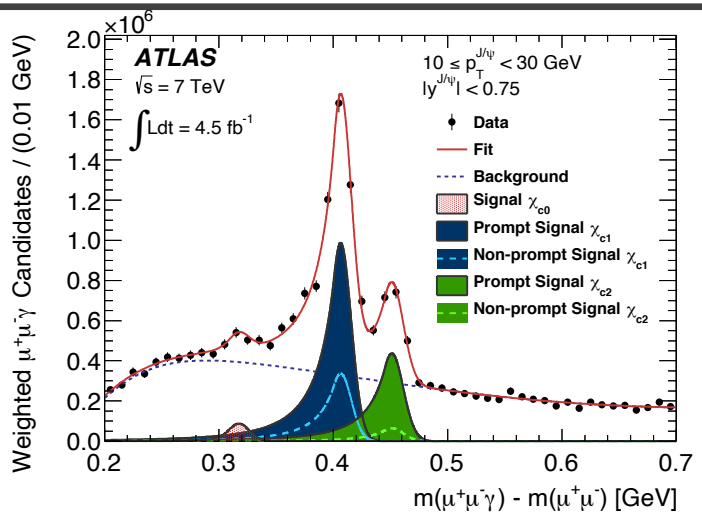


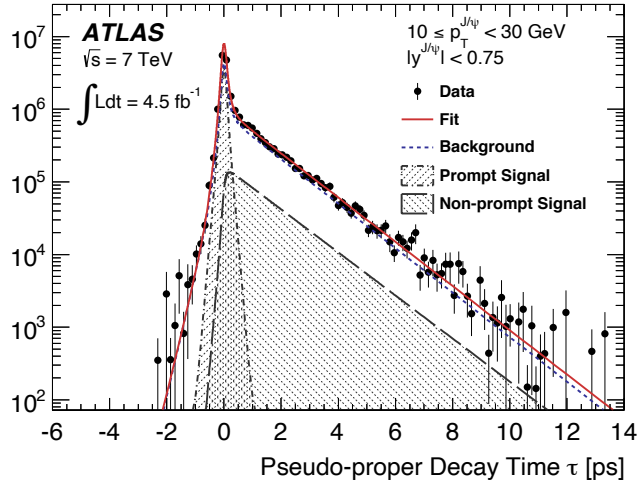
- **Promising channel to study χ_c polarizarion** [Phys.Rev.D 103 (2021) 9, 096006]

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

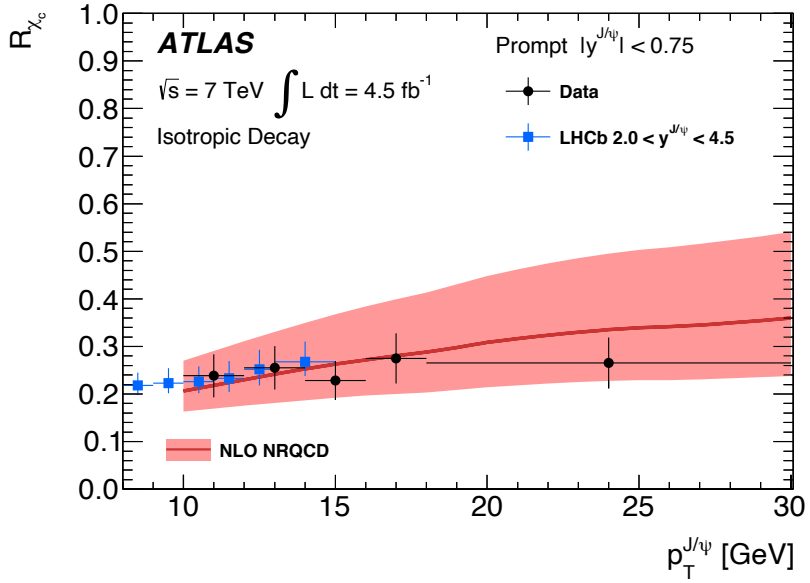
JHEP 07 (2014) 154

- ATLAS EXPERIMENT χ_{c1} and χ_{c2} p_T-diferential production cross-section
- Prompt and b-decays are distinguished using simultaneous fit 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 $\chi_{c1,2} \rightarrow J/\psi\gamma$

Eur. Phys. J. C 72 (2012) 2251

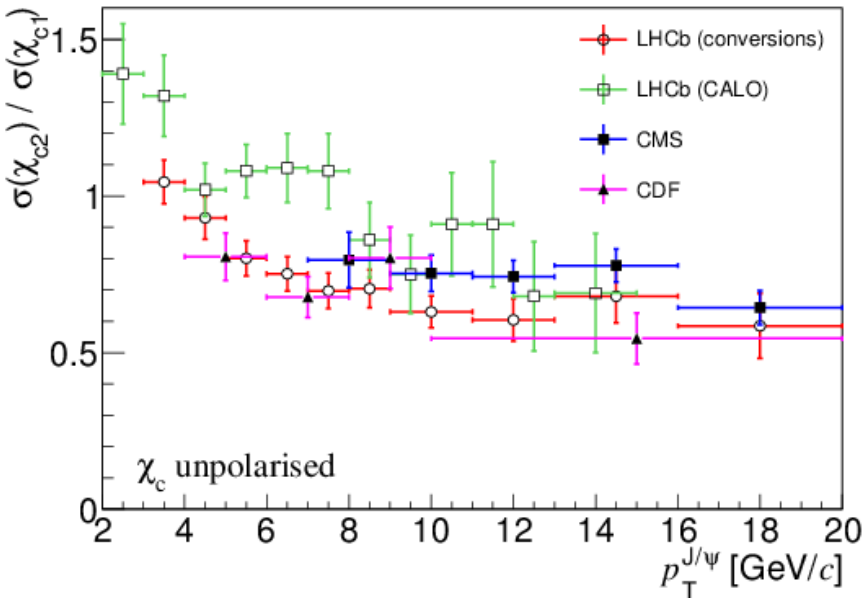
- **Relative χ_{c2}/χ_{c1}** prompt p_T-diferential **production** cross-section:

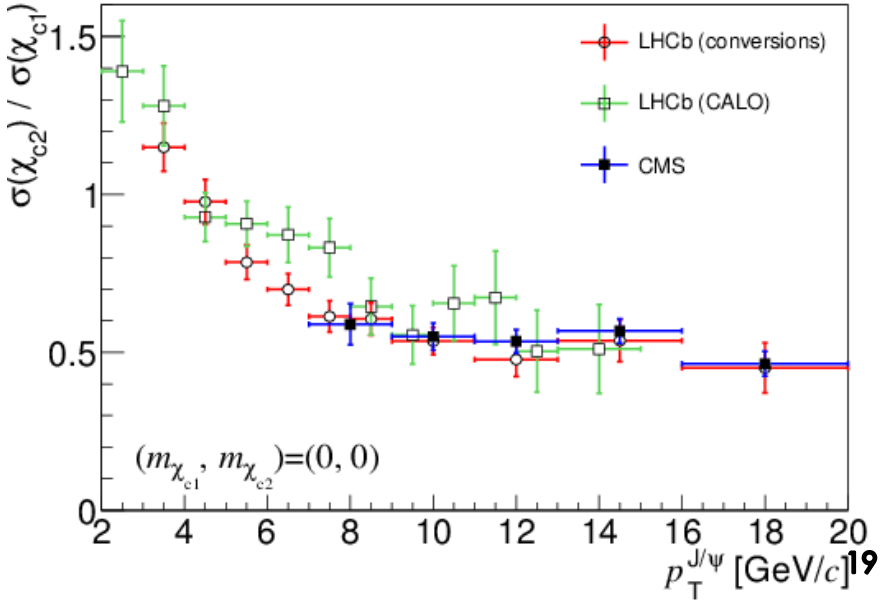
$$R_p = \frac{\sigma(pp \rightarrow \chi_{c2} X) \times \mathcal{B}(\chi_{c2} \rightarrow J/\psi\gamma)}{\sigma(pp \rightarrow \chi_{c1} X) \times \mathcal{B}(\chi_{c1} \rightarrow J/\psi\gamma)}$$

- **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:

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

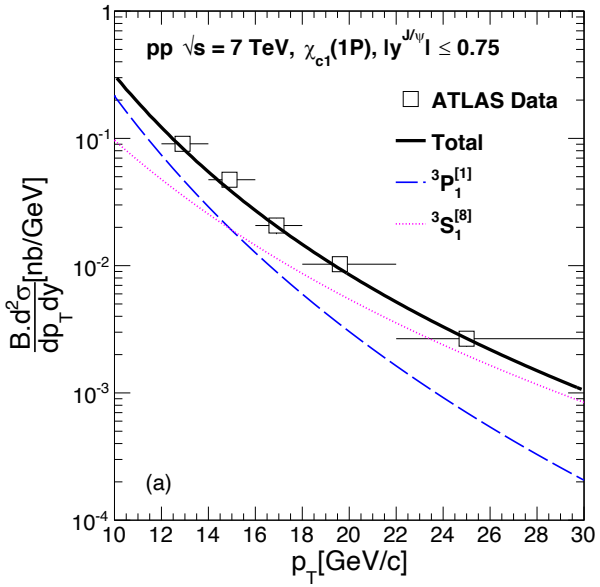


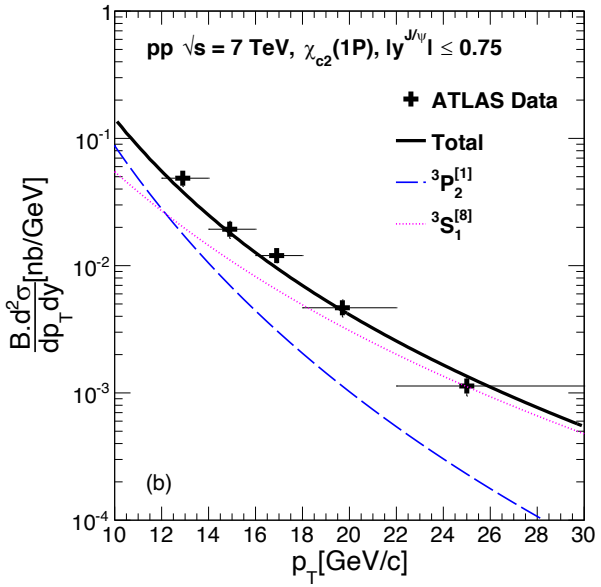


$\chi_{c1,2}$ PRODUCTION USING $\chi_{c1,2} \rightarrow J/\psi\gamma$

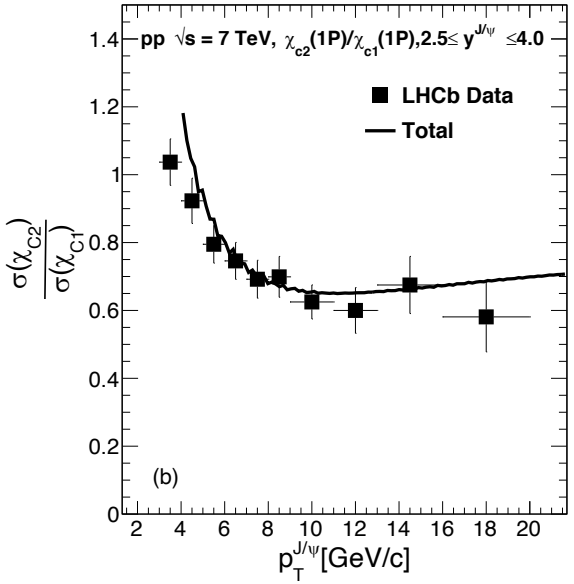
J.Phys.G 44 (2017) 8, 085003

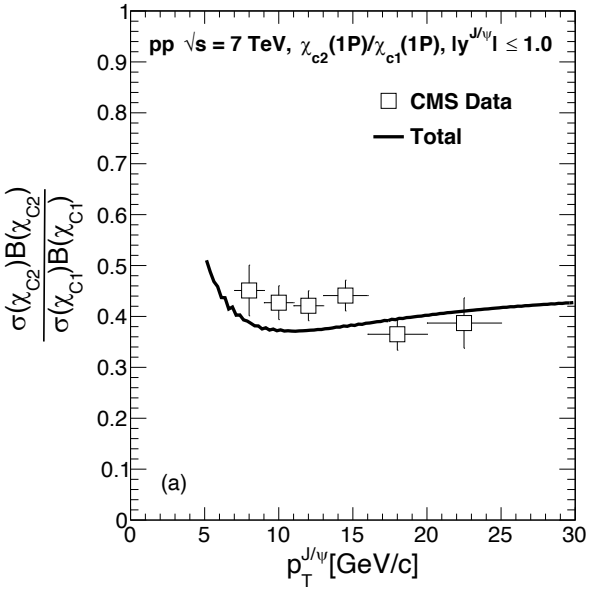
- NRQCD fit for production cross-section
  - absolute =>
  - relative =>





- **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**

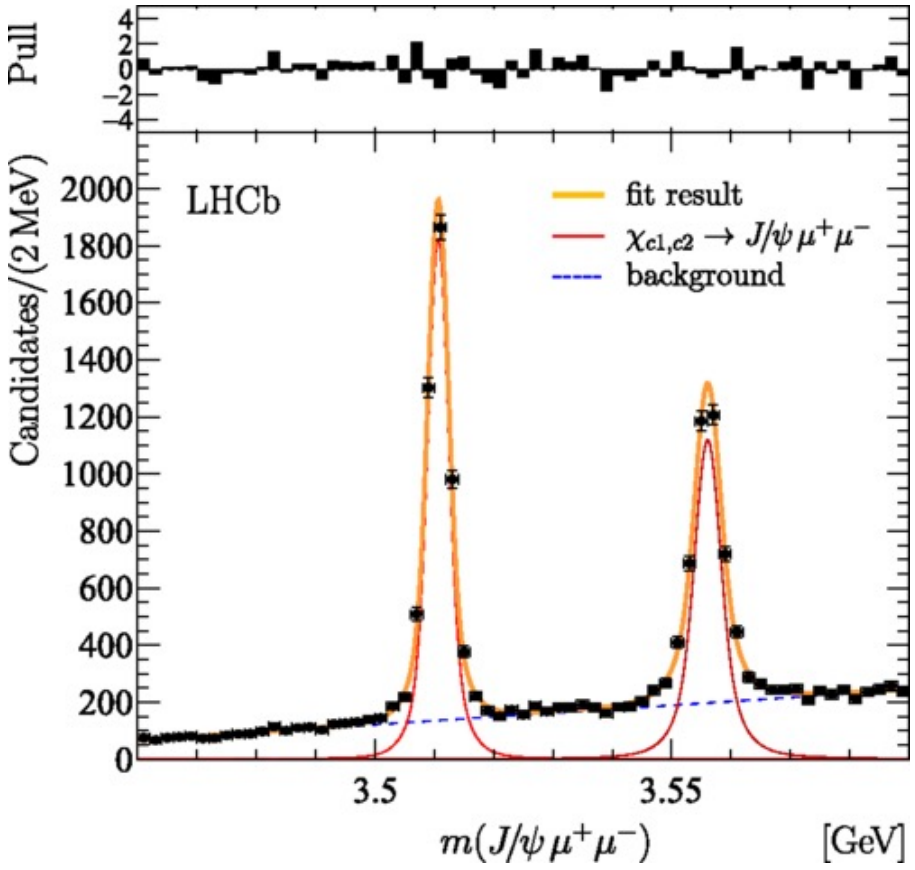
$\chi_{c1,2}$ PRODUCTION USING $\chi_{c1,2} \to J/\psi\mu^+\mu^-$

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

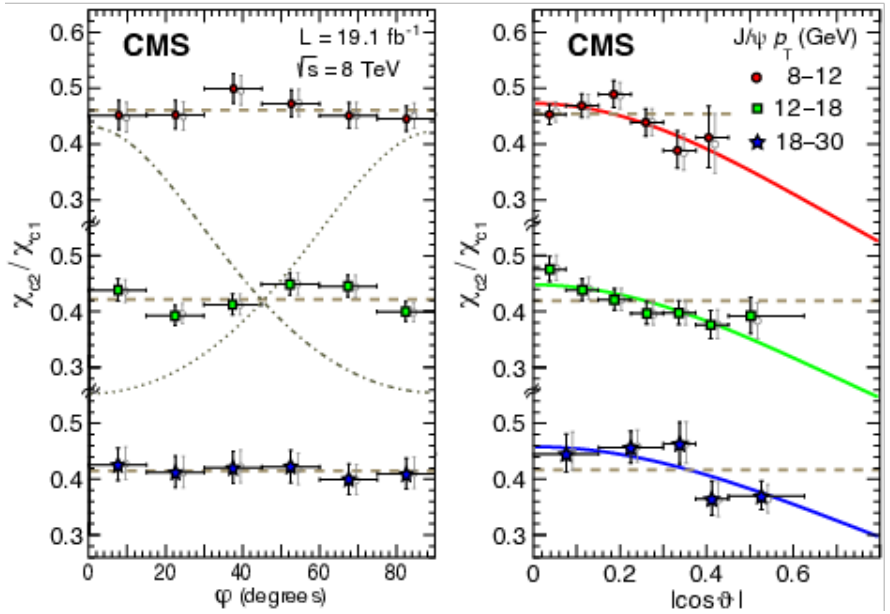
- New channel for production measurement

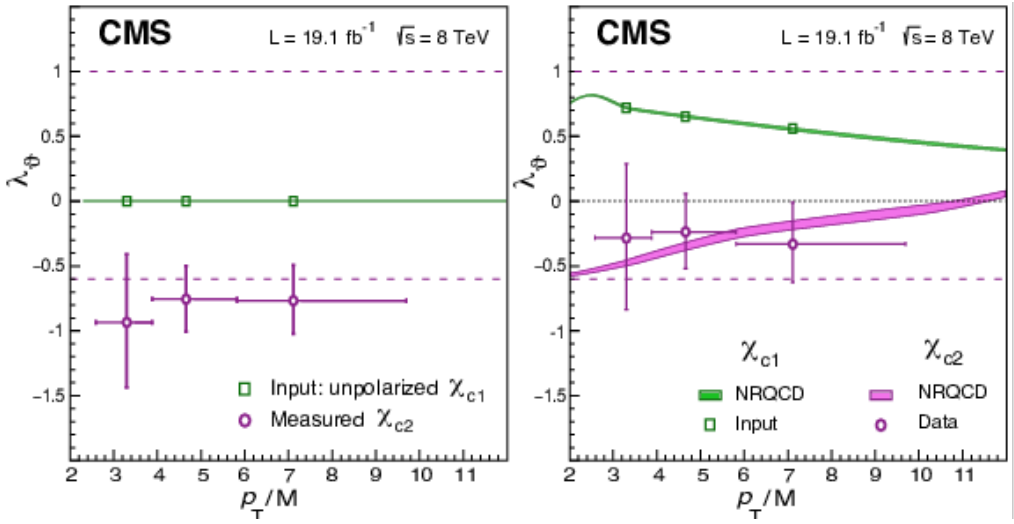


- **Promising channel for χ_c hadroproduction at low p_T**
- **Similar studies can be done at CMS?**

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

PRL 124 (2020) 162002



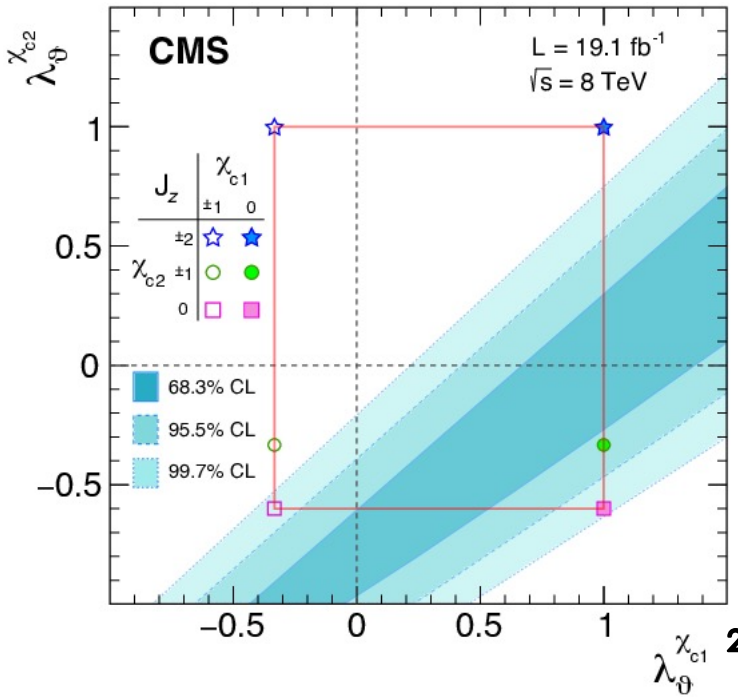


- **First measurement of *P*-wave quarkonium polarization** with χ_{c2}/χ_{c1} ratios as a function of $|\cos\Theta^{HX}|$ and φ^{HX}

- 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**



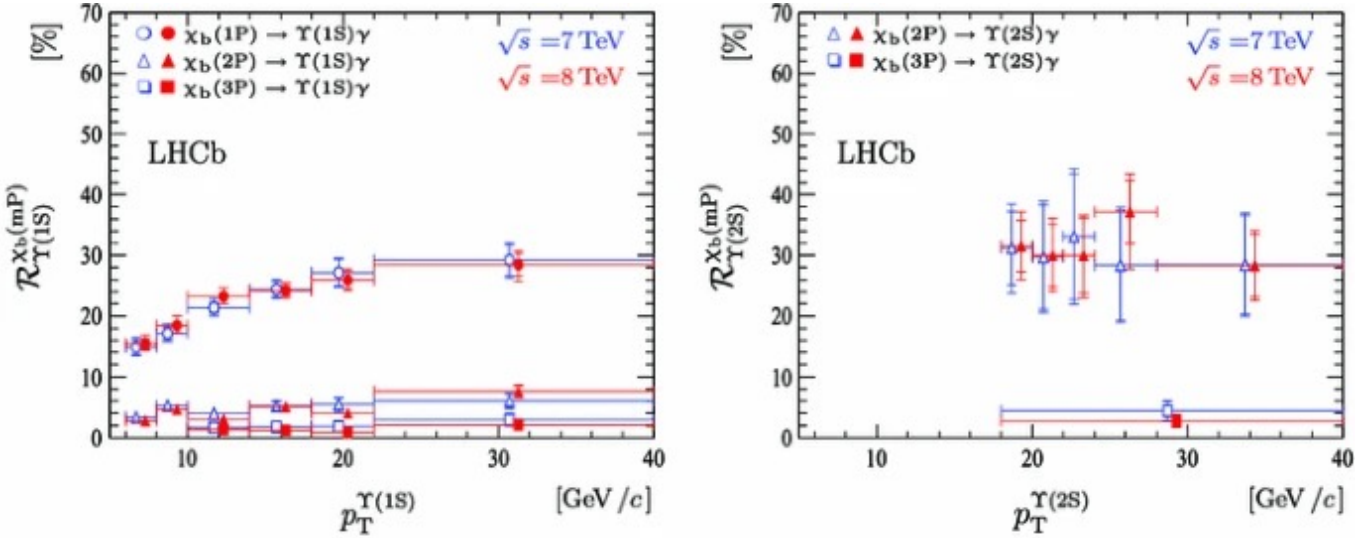
χ_b PRODUCTION IN LHCb AT $\sqrt{s}$=7 AND 8 TeV

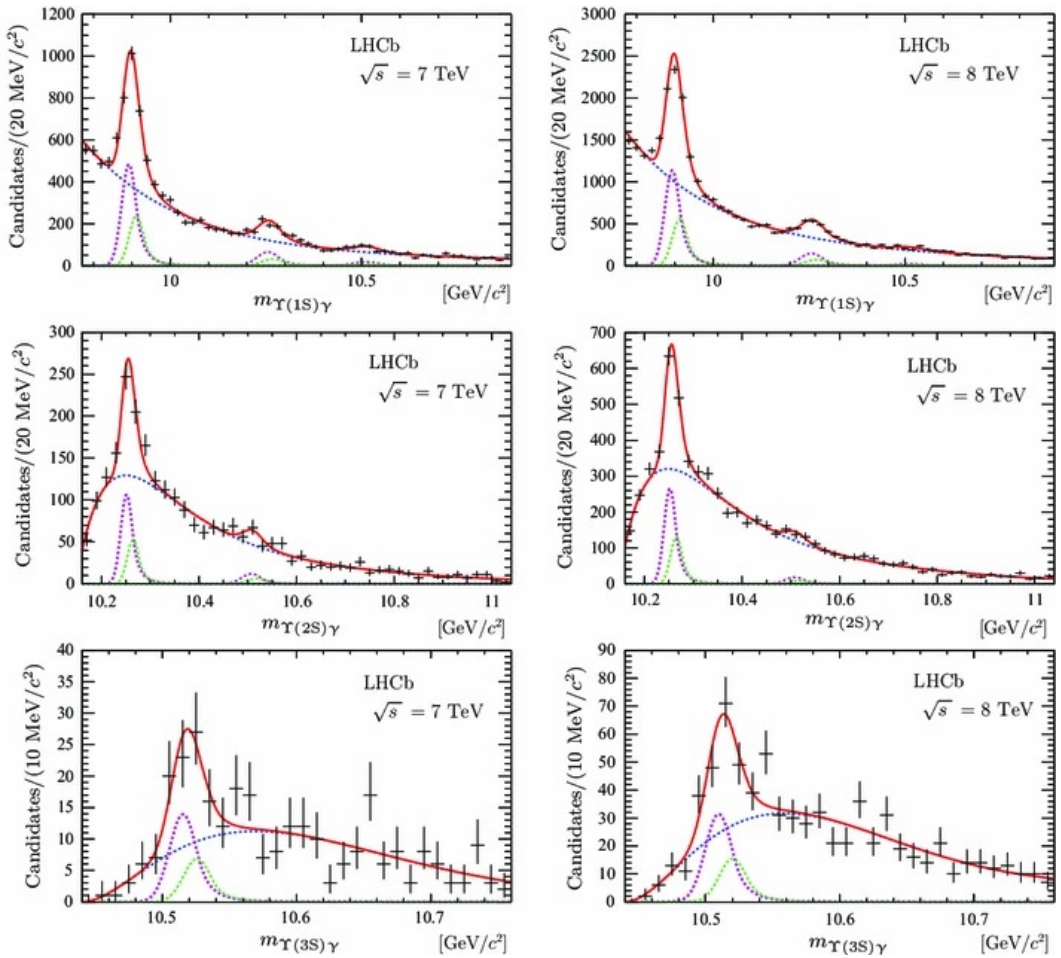
Eur.Phys.J.C 74(2014)10, 3092

- Search for χ_b(nP) using decay to Υ(nS)γ

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

- **Invariant mass fit** to extract yields





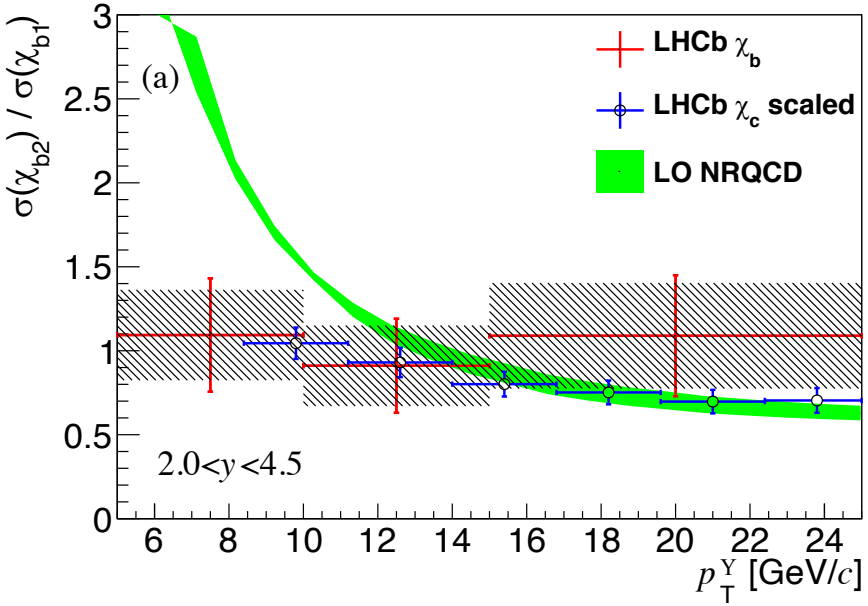
- Fraction $\mathcal{R}^{\chi_b(mP)}_{\Upsilon(nS)}$ measured in bins of p_T
- **χ_b(3S) → Υ(3S)γ observed for the first time**

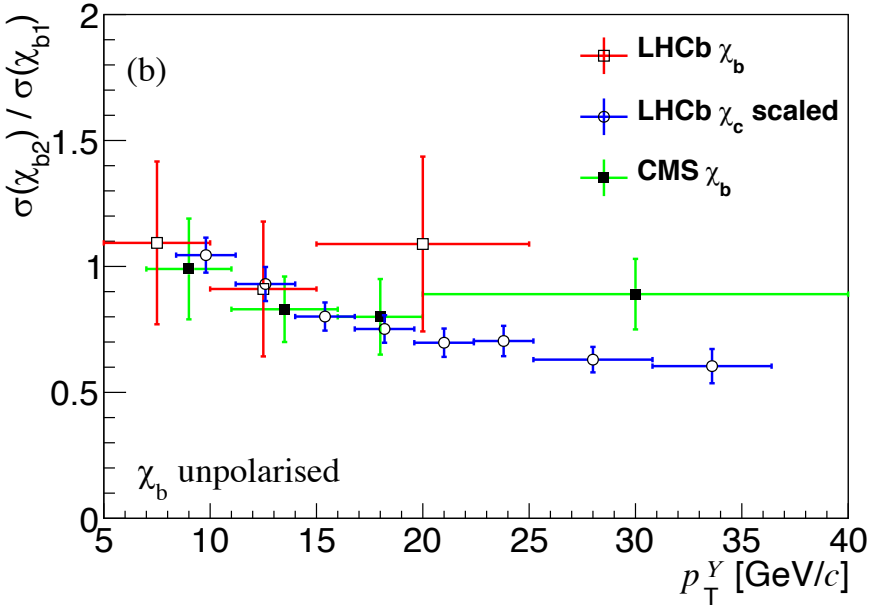
χ_b PRODUCTION IN LHCb AT $\sqrt{s}$=7 AND 8 TeV

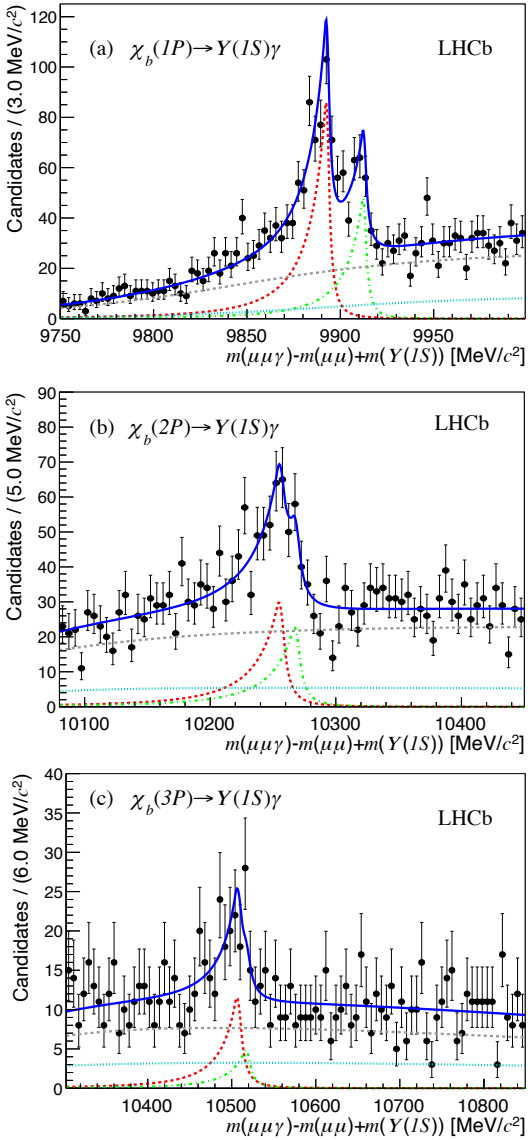
JHEP10 (2014) 088

- **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

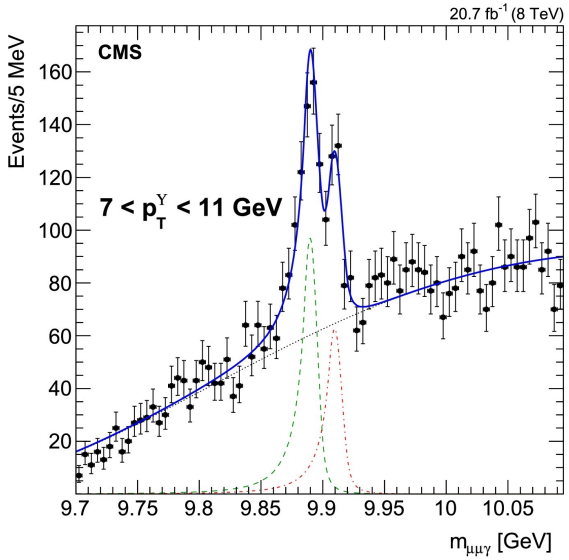
- **Precise measurement of $\chi_{b2}(1P)/\chi_{b1}(1P)$ production cross-section** in complementary region to LHCb: $5 < p_T^{\Upsilon} < 25$ GeV/c, $|y| < 1.5$

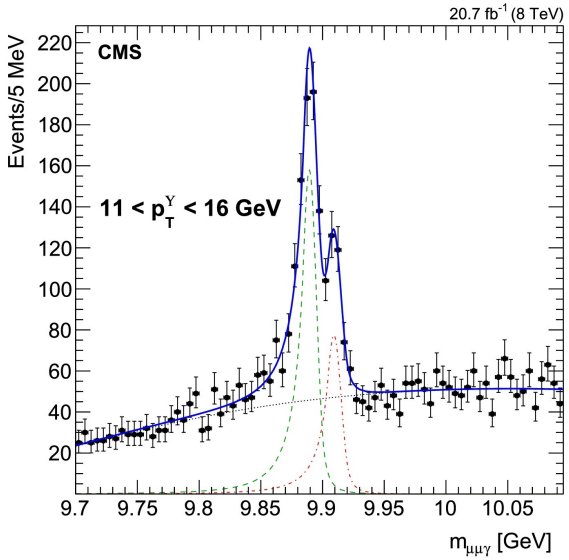
- **χ_b relative production** in integrated p_T-range:

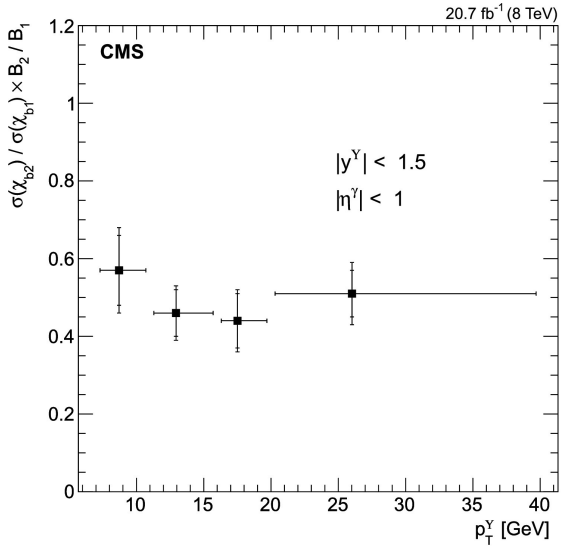
$$\sigma_{\chi_{b2}}/\sigma_{\chi_{b1}} = 0.85 \pm 0.07_{stat+syst} \pm 0.08_{\mathcal{B}}$$

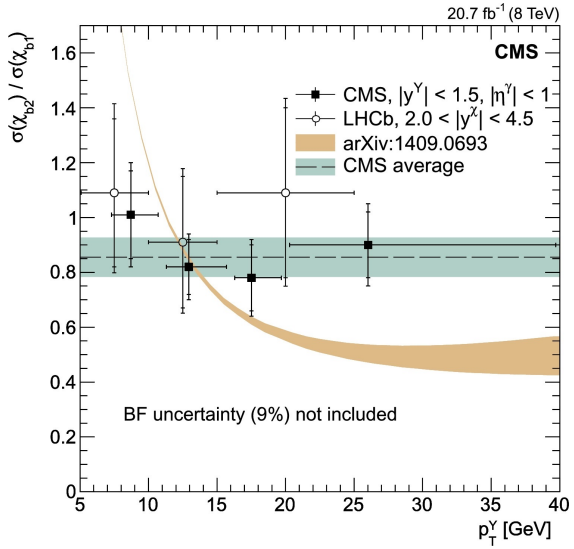
- Ratio does not show significant dependence on Υ(1S) p_T

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









SUMMARY

- Comprehensive model still missing to describe Heavy Flavor production
- LHC results allow to perform powerful tests of QCD and constrain theory
  - $\eta_c(1S)$ prompt production measurement constrains CO LDMEs
- Current progress:
  - prompt χ_c observed in decay to $J/\psi\mu\mu$
  - χ_c production from b-decays measured via $\varphi\varphi$
  - first evidence of $\eta c(2S)$ production
- Y and χ_b hadroproduction has been measured at LHC
- Prospects for future study:
  - **$\eta_b(1S)$, $h_{c,b}$** and **$\eta_c(2S)$** production
  - simultaneous study of **$\psi(2S)$** and **$\eta_c(2S)$**
  - decays to **$\Lambda\Lambda$, $\Lambda^*\Lambda^*$, $\Sigma\Sigma$, $\Xi\Xi$** final states

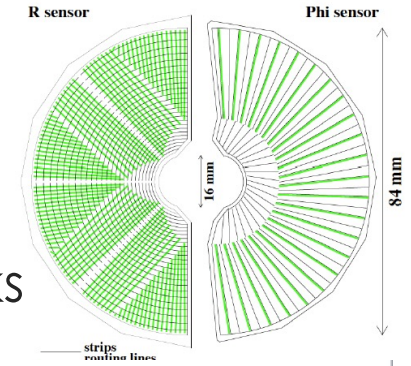
BACKUP

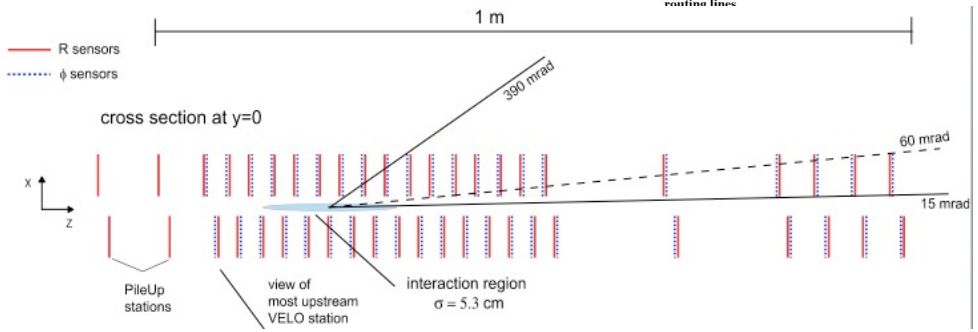
KEY LHCb SYSTEMS FOR PRODUCTION MEASUREMENTS

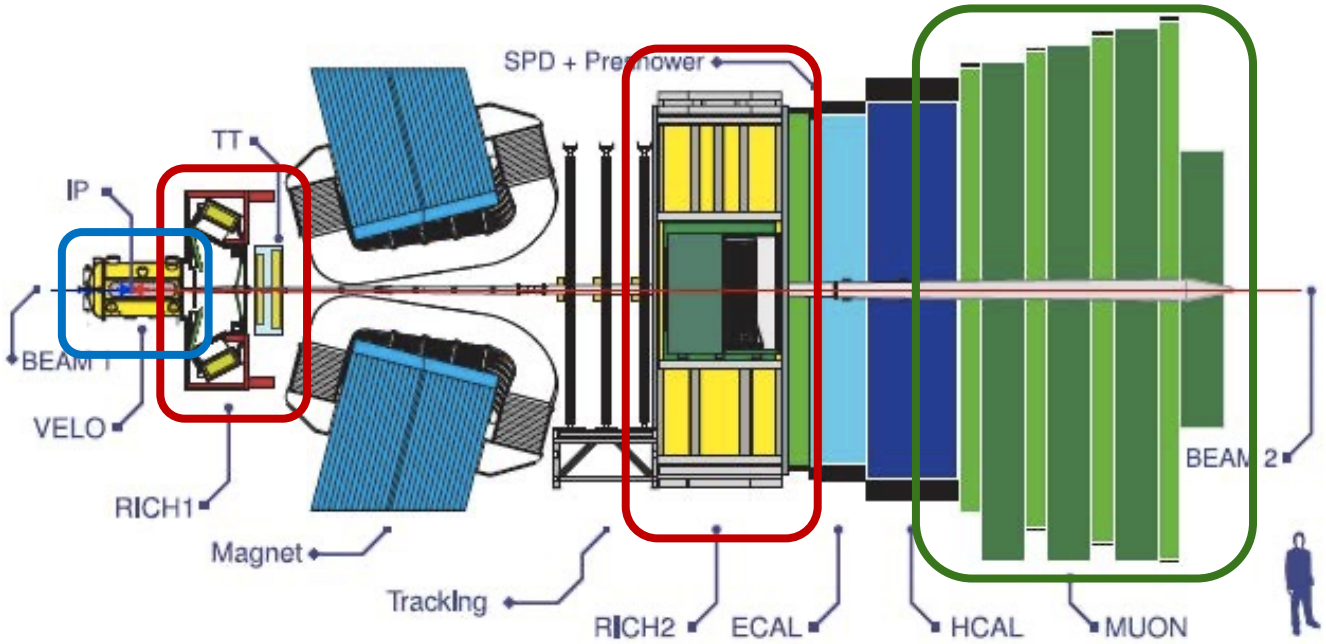
JINST 9(2014) P09007

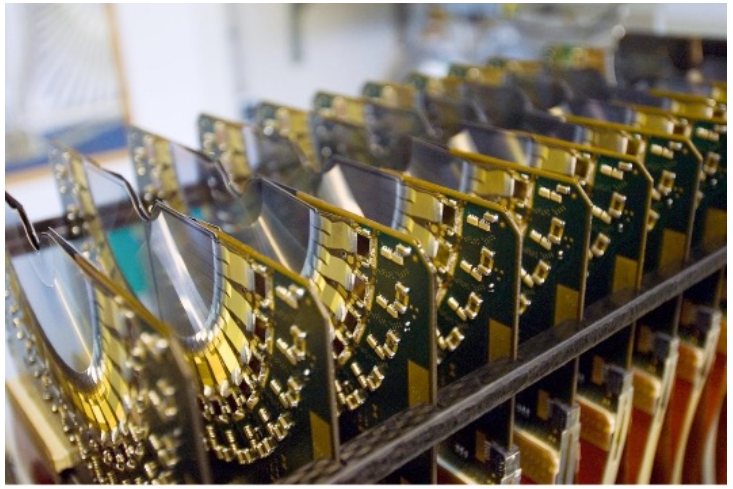
Vertex reconstruction VELO

- **Spatial resolution**, down to 4 μm for single tracks
- **Impact parameter** measurement, $\sigma_{IP} = 15 + 29/p_T$ [μm]
- **Primary vertex** reconstruction, $\sigma_x = \sigma_x = 13$ μm, $\sigma_z = 71$ μm for vertex of 25 tracks







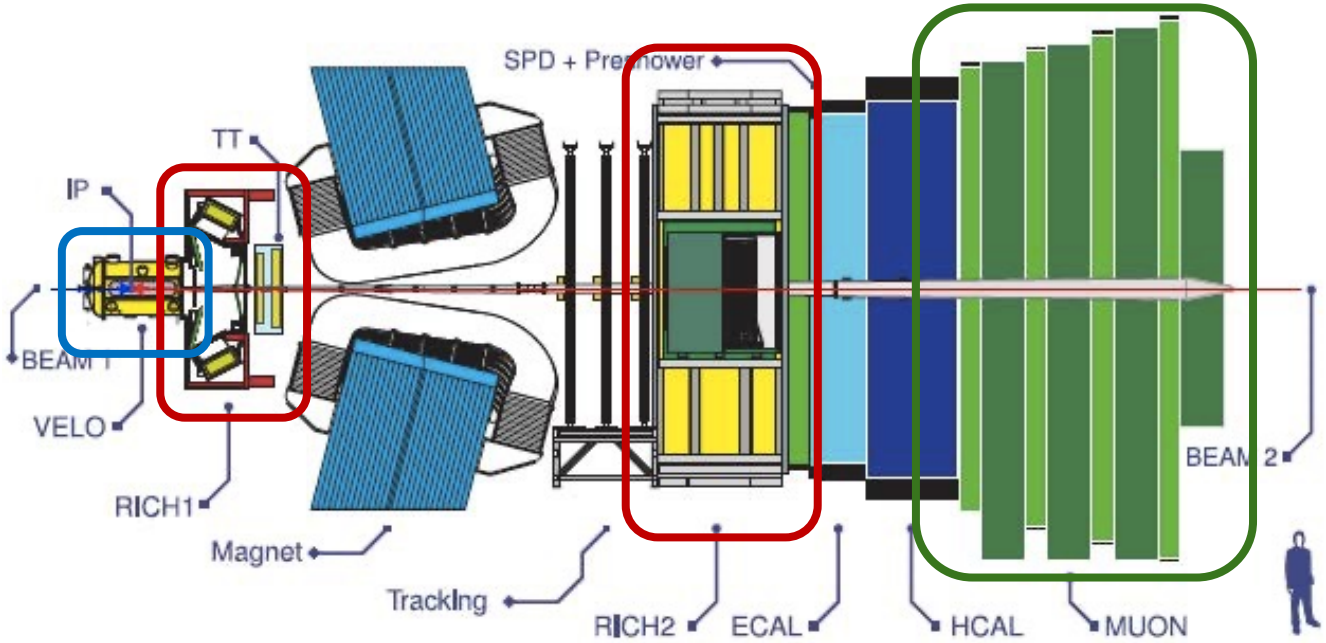


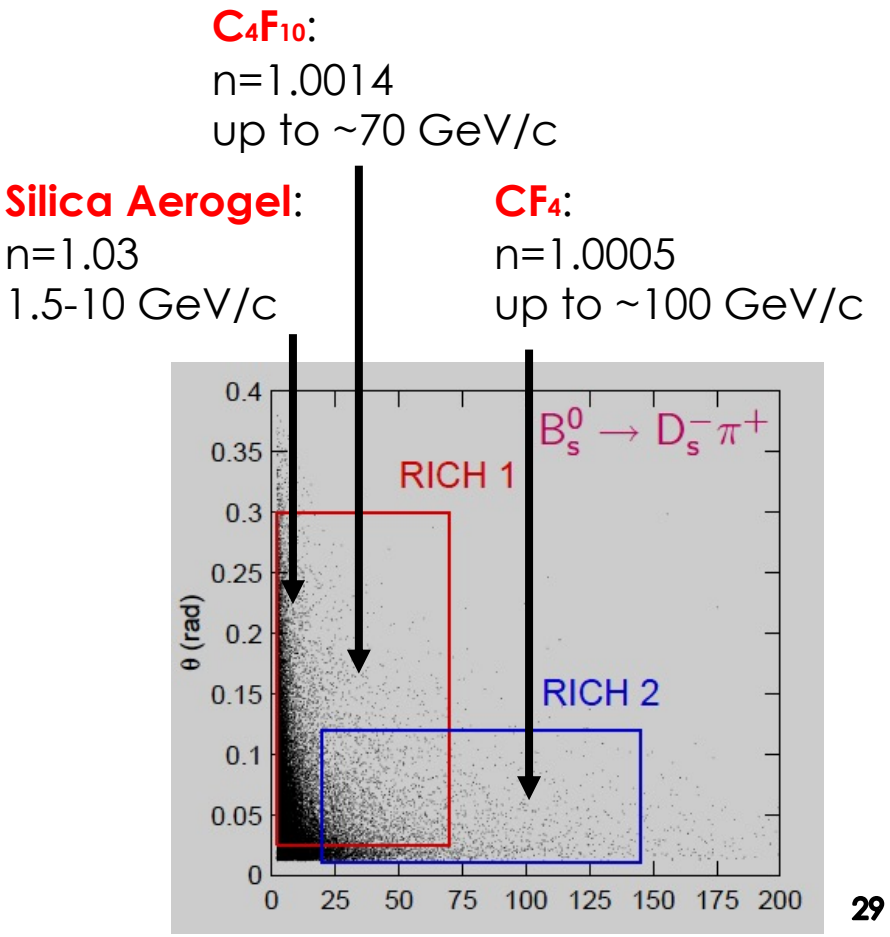
KEY LHCb SYSTEMS FOR PRODUCTION MEASUREMENTS

EPJC 73(2013) 2431
JINST 8 P02022

Particle identification

- **2 Ring Imaging Cherenkov Detectors (RICH)**: 3 Radiators covering p_T range 1.5-100 GeV/c
- **Muon detector** – triggering muons and measuring muon momenta
- Particle ID efficiency:
  - $K^{\pm}$ ID ~ 95 % for ~ 5 % $\pi \rightarrow K$ mis-id probability
  - $\mu^{\pm}$ ID ~ 97 % for 1-3 % $\pi \rightarrow \mu$ mis-id probability



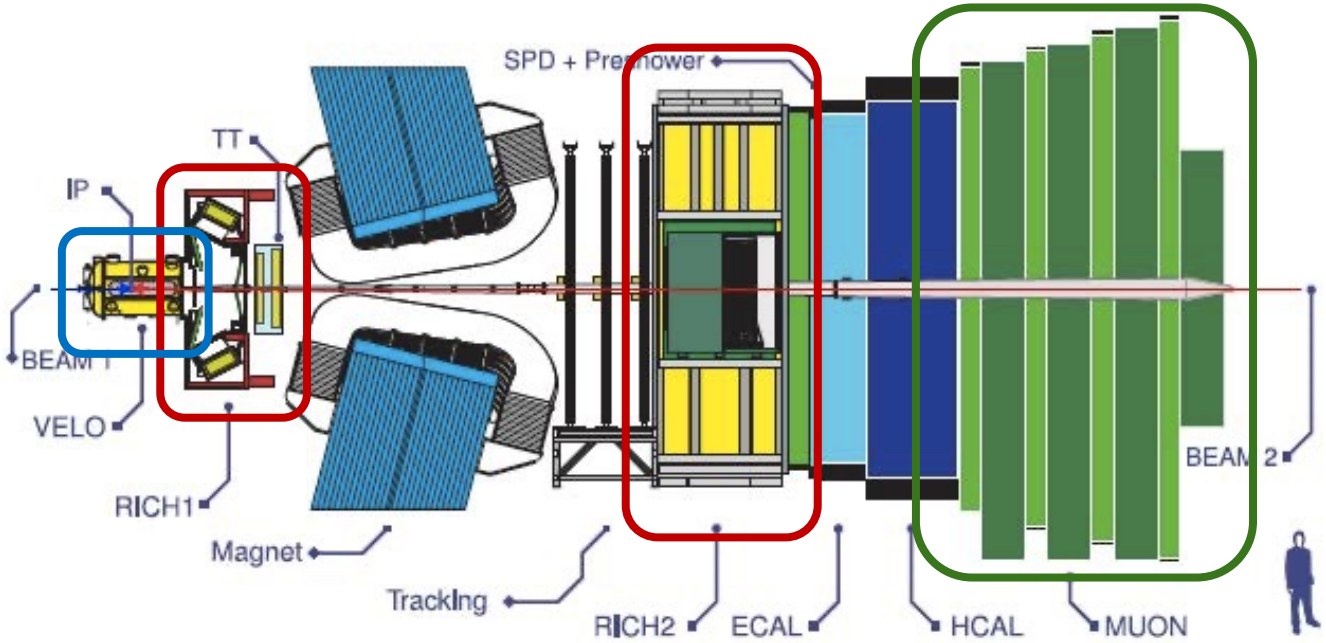


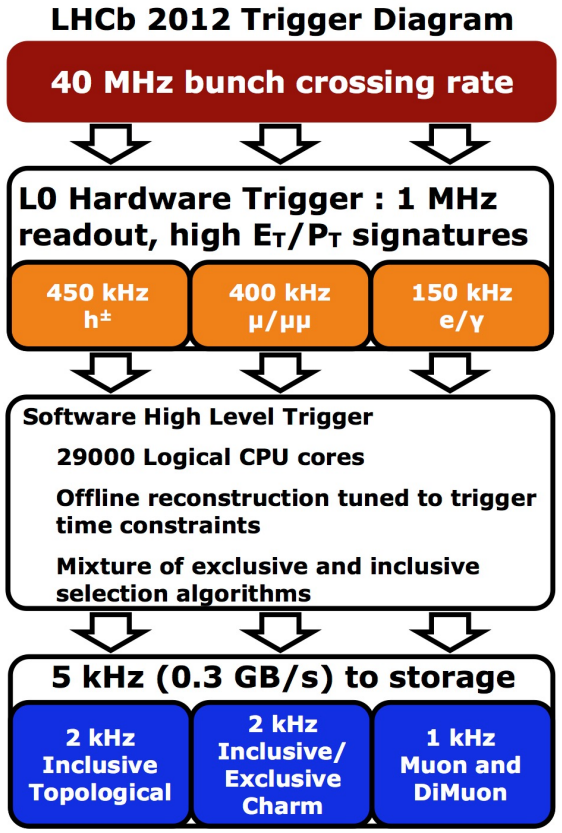
KEY LHCb SYSTEMS FOR PRODUCTION MEASUREMENTS

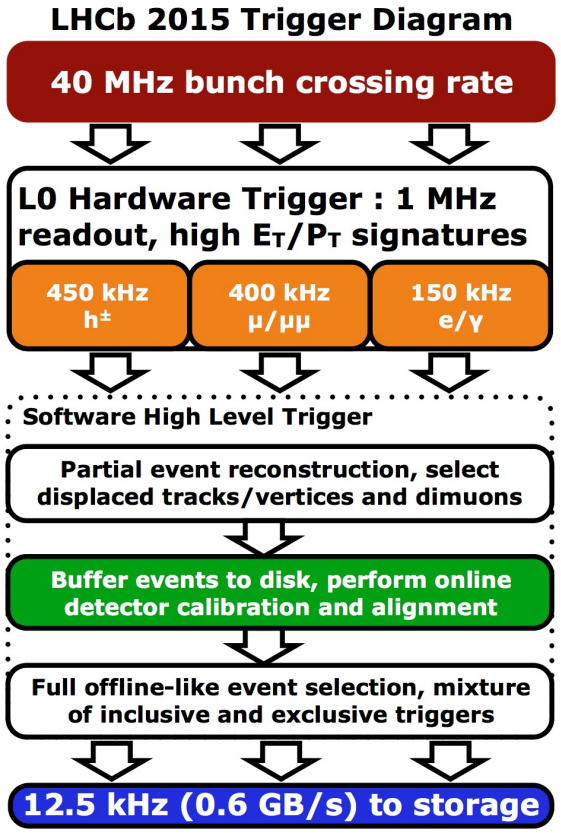
JINST 14 (2019) P04013

Trigger

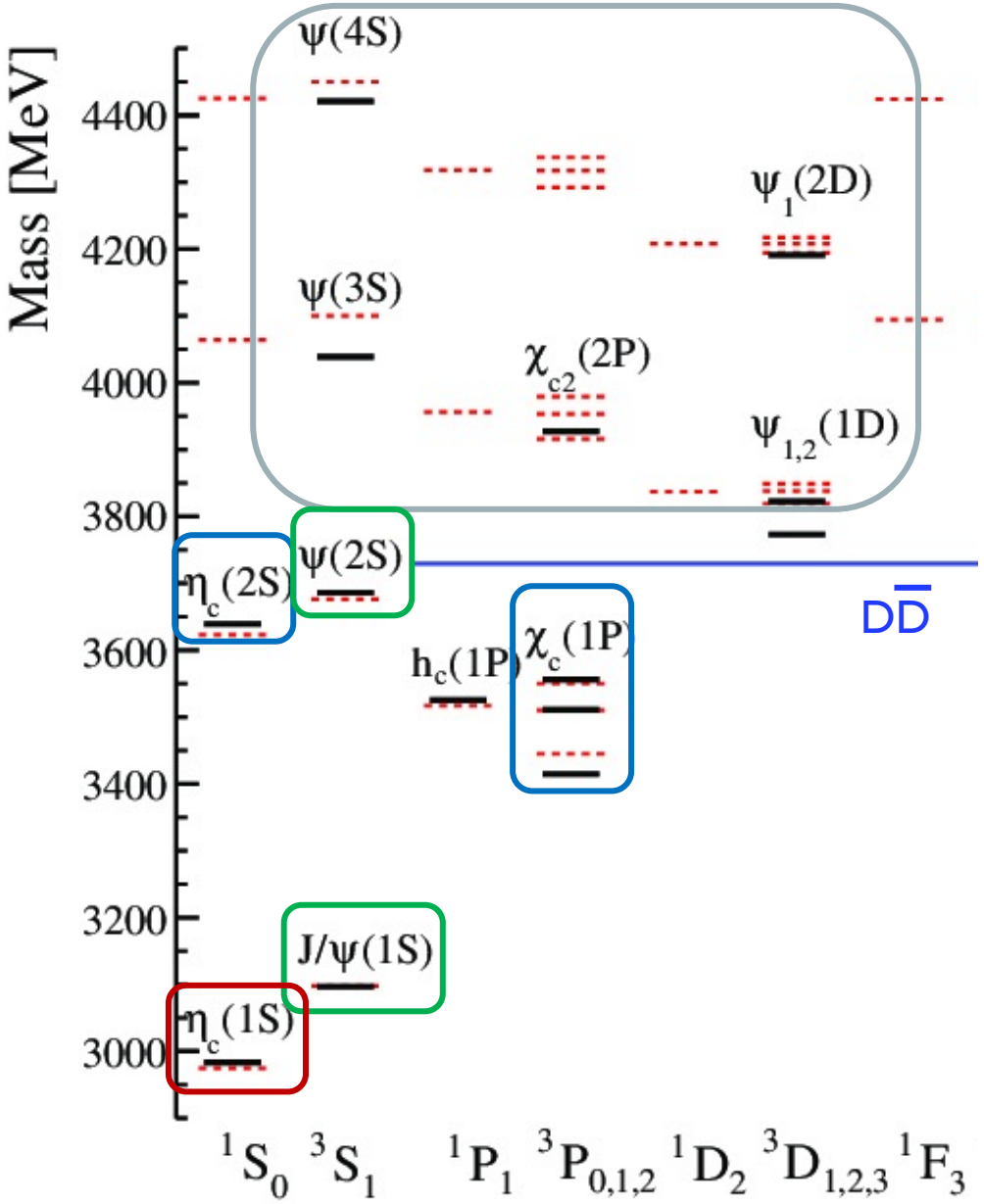
- **Two-level** trigger system
- LHCb detector designed to **trigger on decay products of *b* or *c* hadrons**: moderate p_T physics
- Trigger efficiency:
  - ~ 90 % for dimuon channels
  - ~ 30 % for multi-body hadronic final states







CHARMONIUM SPECTROSCOPY: LHCb PROGRESS



χ_c prompt production measured via **J/ψγ**
7 TeV: JHEP 10(2013) 115, PLB 714(2012) 215-223
χ_c and **η_c(2S)** b-decays production measured via **ϕϕ**,
7 and 8 TeV: EPJC 77(2017) 609

J/ψ and **ψ(2S)** prompt, b-decays production
and polarization measured via **μμ**
7, 8 and 13 TeV: JHEP 10(2015) 172, EPJC 80(2020) 185 …

η_c(1S) prompt and b-decays production measured via **pp**
7, 8 and 13 TeV: EPJC 75(2015) 311, EPJC 80(2020) 191

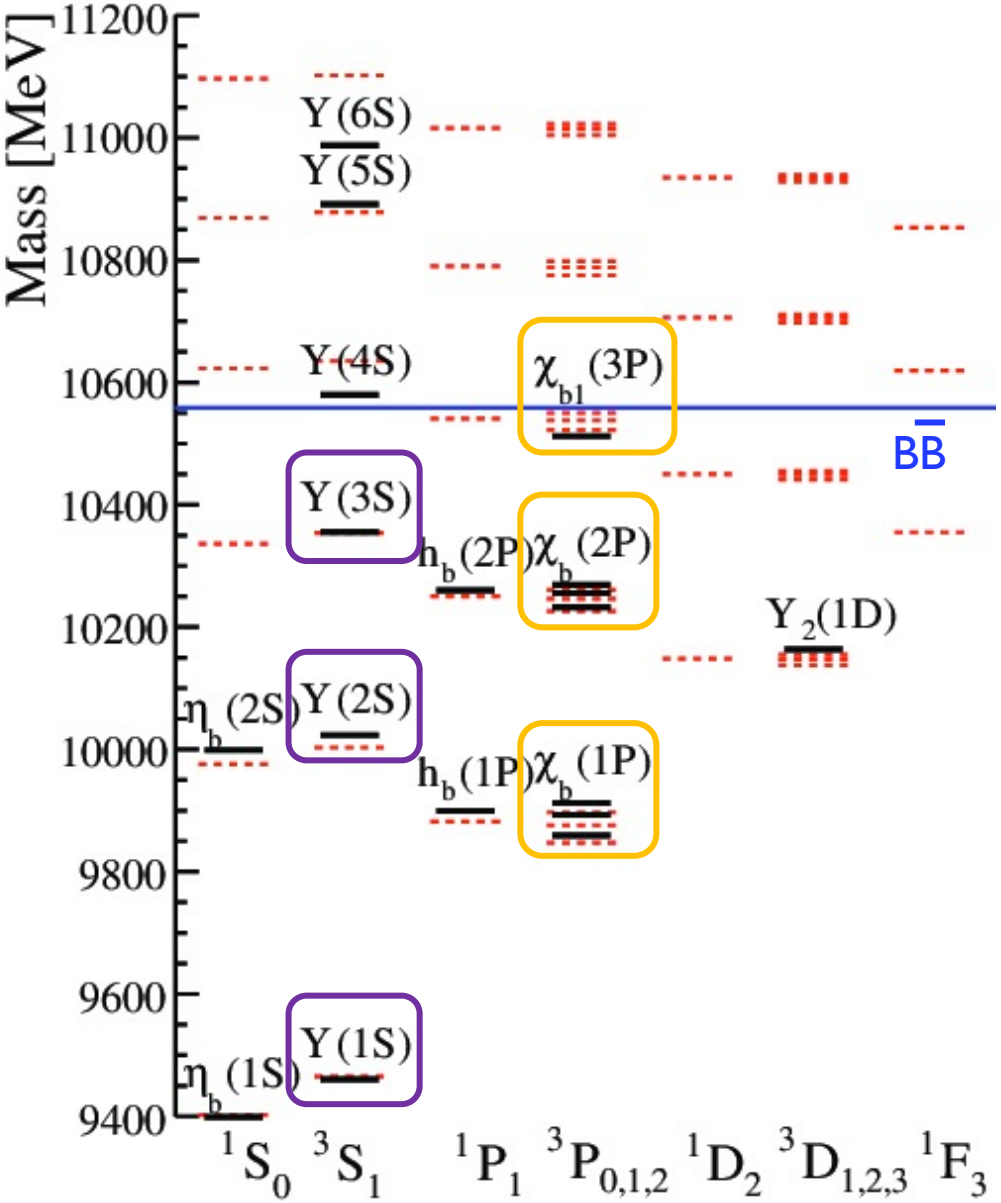
Non-conventional charmonia:
talk by Matthew Needham at QWG2021

Prospects:

- h_c and η_c(2S) prompt production
- All states accessible via hadronic decays
  → study decays to ΛΛ, Λ*Λ*, ΣΣ, ΞΞ final states

Rev.Mod.Phys 90 (2018) 015003

BOTTOMONIUM SPECTROSCOPY: LHCb PROGRESS



Υ(nS) production measured via **μμ**

2.76 TeV: *Eur.Phys.J.C 74(2014) 2835*

7 and 8 TeV: *JHEP 11(2015) 103*

13 TeV: *JHEP 07(2018) 134*

talk by C.Patrignani at QWG2019

Υ(nS) polarization measured via **μμ**

7 and 8 TeV: *JHEP 12(2017) 110*

χ_b(nP) production measured via **Υ(nS)γ**

7 and 8 TeV: *Eur.Phys.J.C 74(2014) 3092*

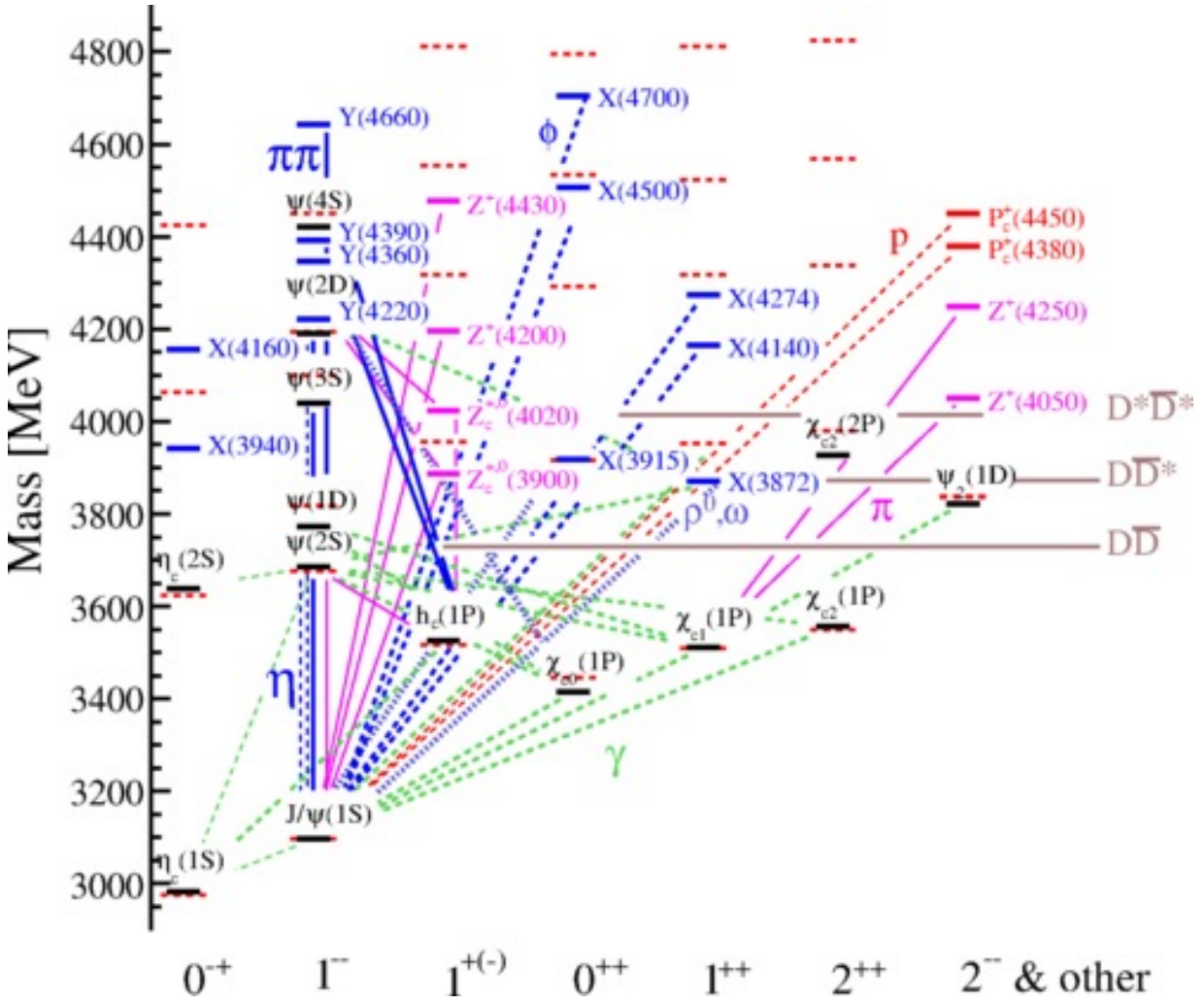
Prospects:

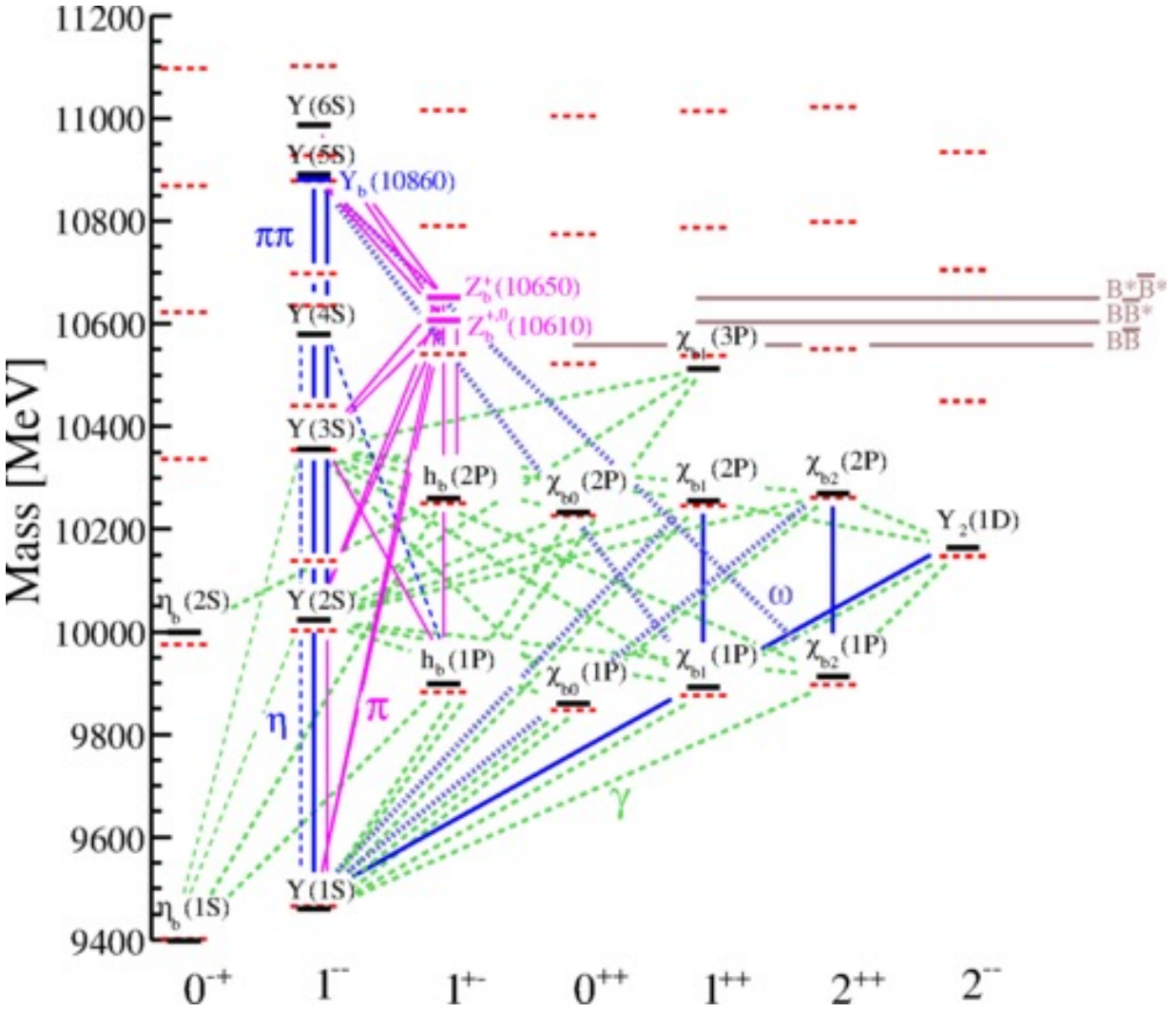
- h_b and $\eta_b(1S)$ production

Rev.Mod.Phys 90 (2018) 015003

QUARKONIUM DECAYS

- Possible transitions between quarkonium states





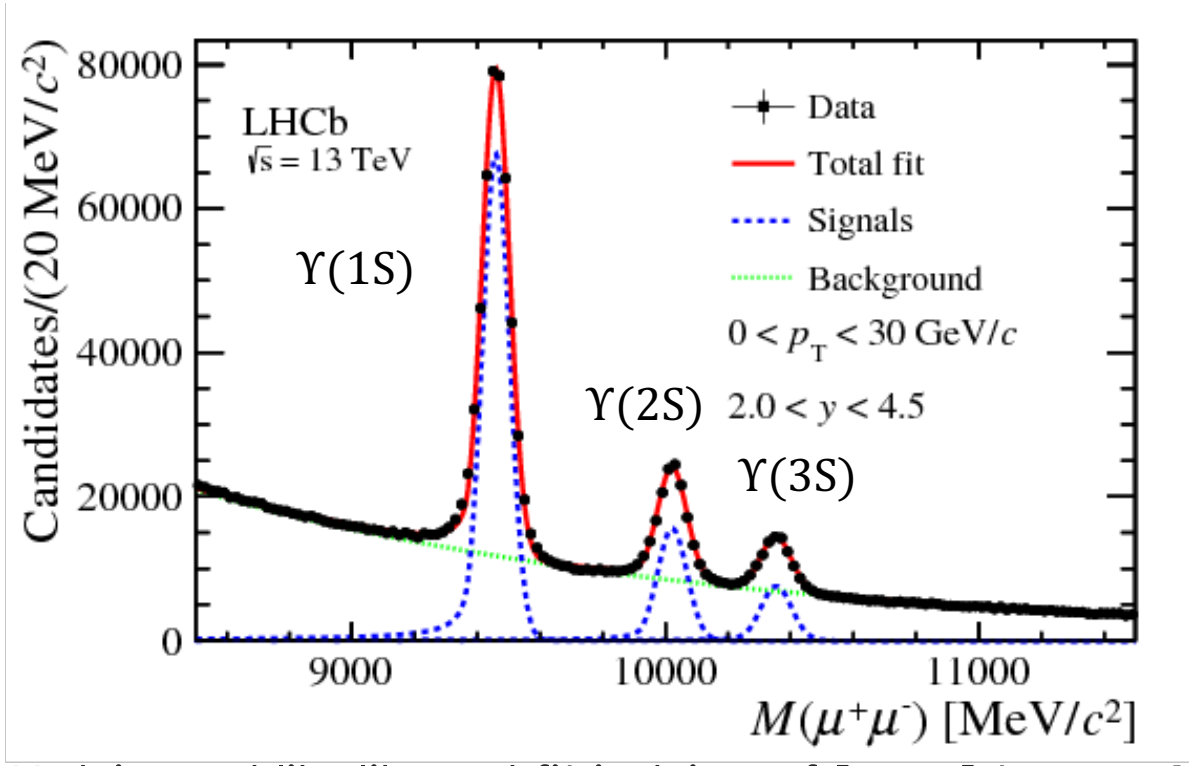
Υ(nS) PRODUCTION AT √s=13 TeV

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)

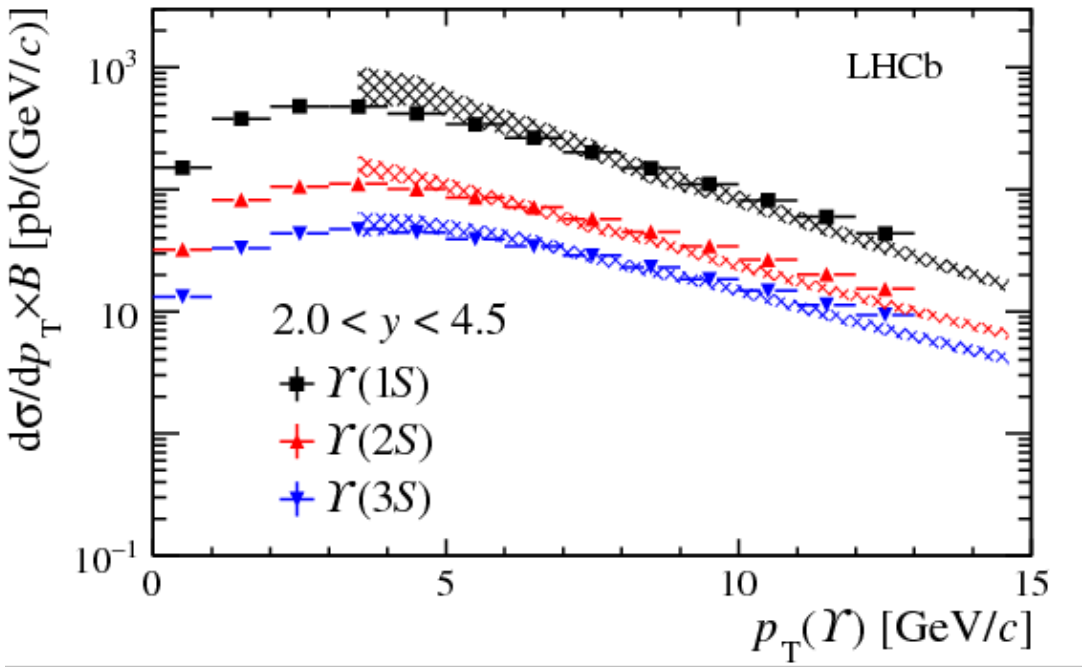
$$\frac{d^2\sigma}{dydp_T} = \frac{N(\Upsilon\to\mu^+\mu^-)}{\mathcal{L}\times\varepsilon_{tot}\times\mathcal{B}(\Upsilon\to\mu^+\mu^-)\times\Delta y\times\Delta p_T}$$

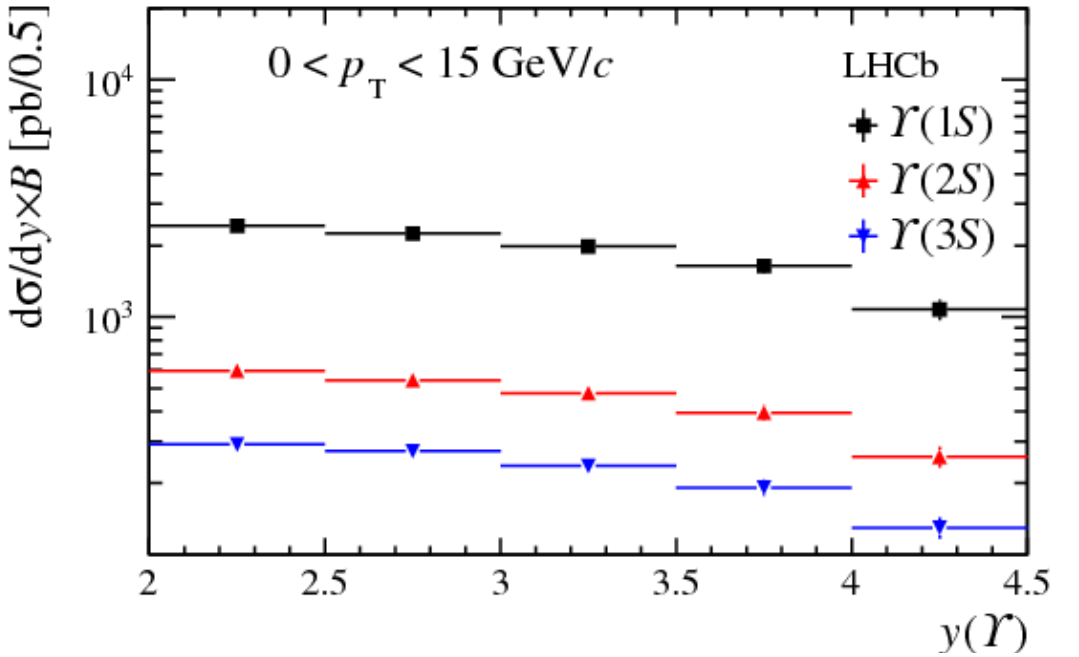


- Unbinned likelihood fit in bins of **[p_T, y]** to $M_{\mu\mu}$ **to extract Υ(nS) yields**

Υ(nS) PRODUCTION AT √s=13 TeV

JHEP07 (2018) 134
JHEP05 (2019) 076

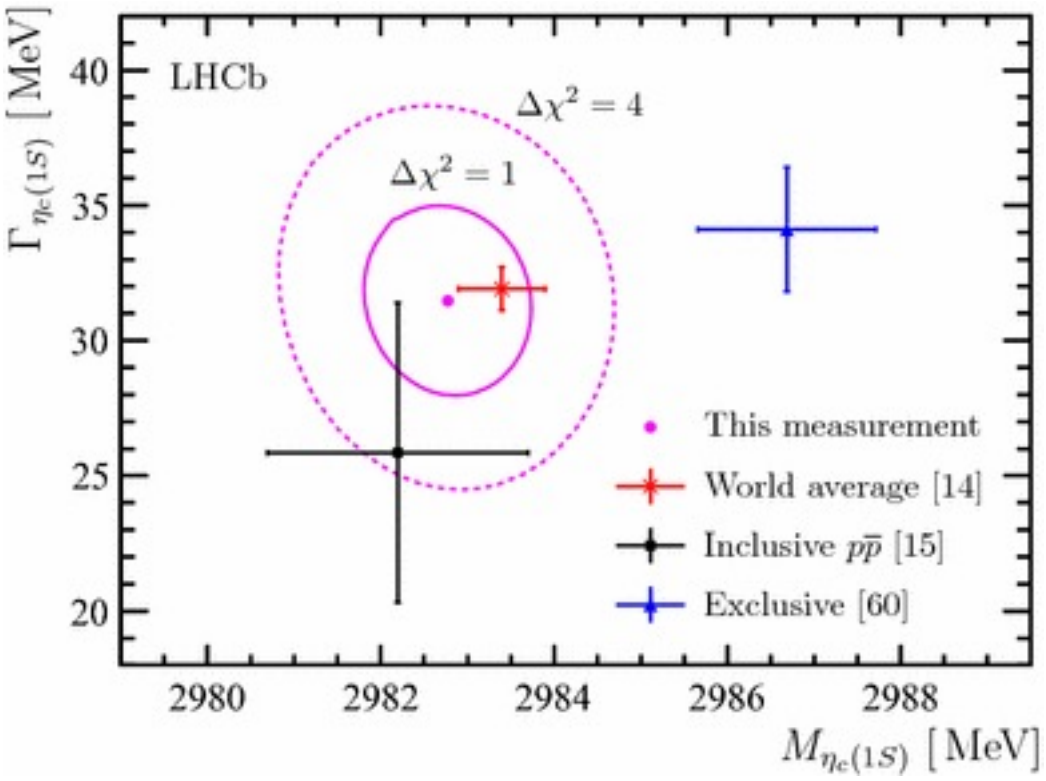




- Double differential production cross-section measured in range $0 < p_T < 30$ GeV/c and $2.0 < y < 4.5$
- **Good agreement between NRQCD and data** at high p_T for all states

η_C MASS MEASUREMENT

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



ADDITIONAL PAPERS

- BESIII: $\mathcal{B}(\chi_{c1,2} \to J/\psi\mu\mu)$ *PRD 99 (2019) 5, 051101*