PRODUCTION OF HEAVY QUARKONIA AT LHCb

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on behalf of the LHCb Collaboration

The 14th International Workshop on Heavy Quarkonium
March 17, 2021

QUARKONIA SPECTROSCOPY

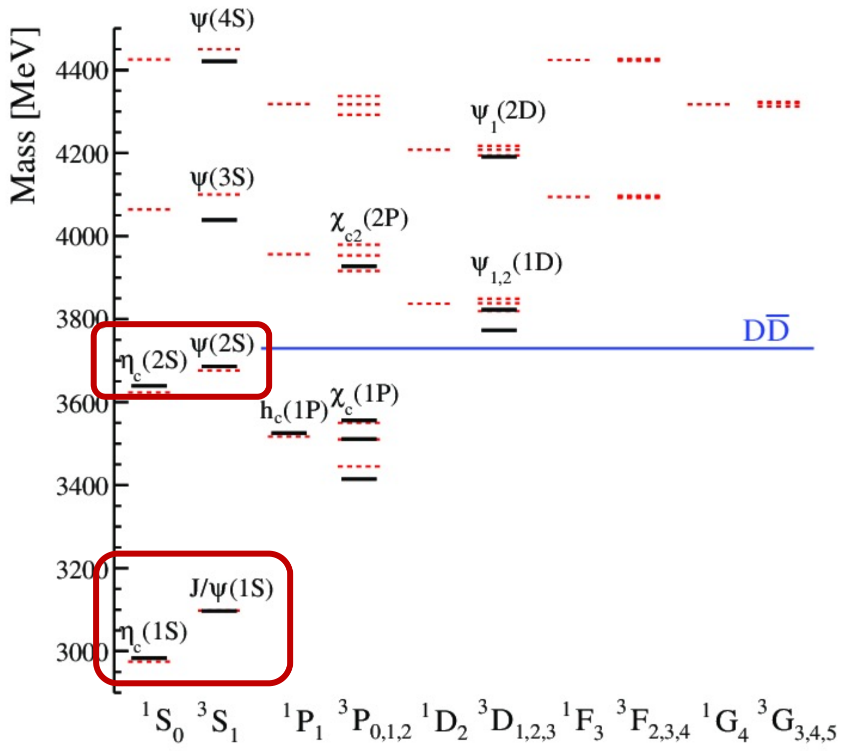
- **Sources of quarkonium:**
  - prompt hadroproduction
  - decays of higher resonances

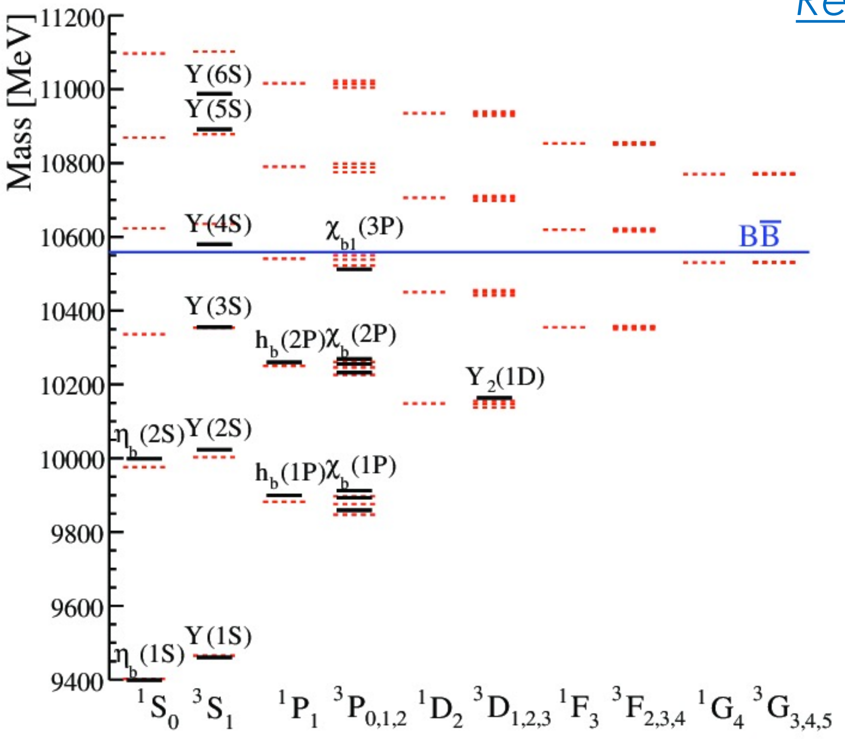
  } decay in collision vertex

  - production in b-hadron decays (for charmonium)

  } decay from other particles
- **Quarkonia production is described using NRQCD framework**

Rev.Mod.Phys 90 (2018) 015003





QUARKONIA PRODUCTION IN NRQCD

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

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

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

- **Colour-singlet model (CS)**: intermediate $Q\bar{Q}$ state is colourless and has the same J^{PC} quantum numbers as the final-state quarkonium
- **Colour-octet model (CO)**: 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. LDME from experimental data
- **Universality**: same LDMEs for prompt production and production in b-decays
- Heavy-Quark **Spin-Symmetry**: links between CS and CO LDME of different quarkonium states

η_c PRODUCTION AT THE LHC

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

- **η_c(1S) LDMEs** determined

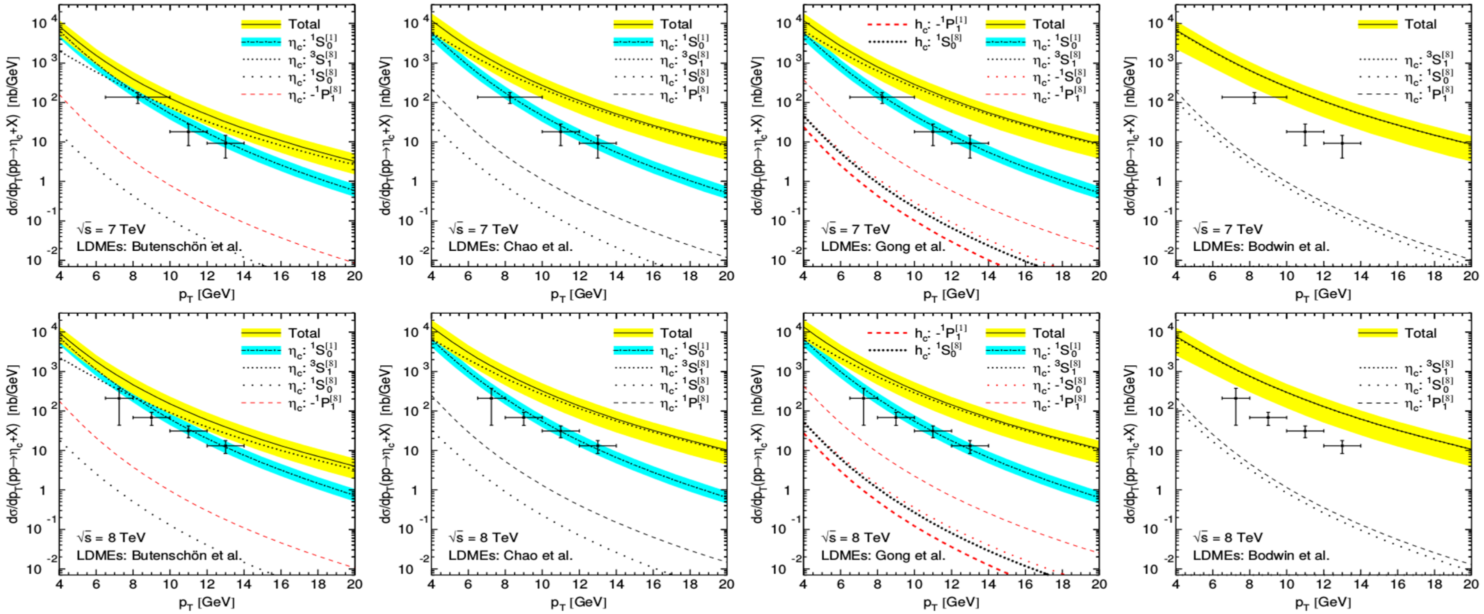
  from known HQSS relation for J/ψ

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

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

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

- Direct projection to LHCb data



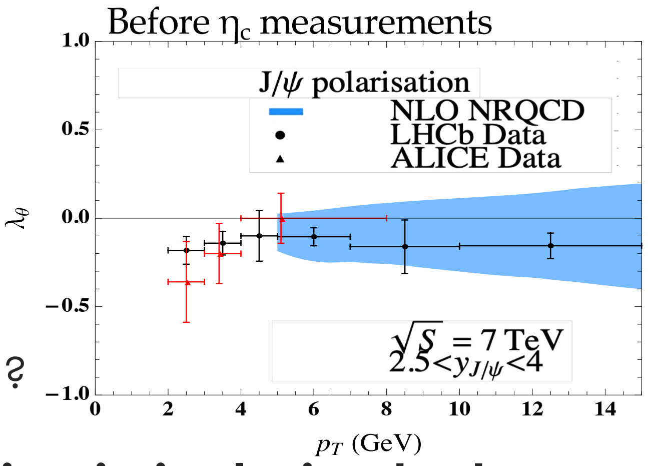
- **LHCb data saturated by CS contribution**
- Tension in simultaneous description of η_c production and J/ψ production and polarization?
- **Recent progress in theory**:
  - Phys.Rev.Lett. 114(2015), 092005
  - Phys.Rev.Lett. 114(2015), 092006
  - Eur.Phys.J.C 75(2015) 7, 313
  - Nucl.Phys.B 945(2019)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

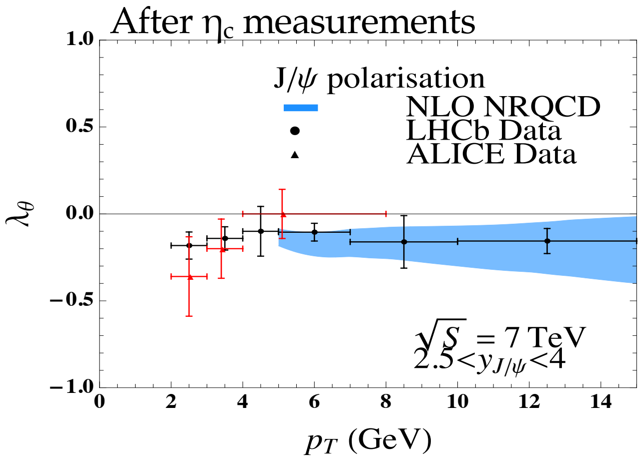
SIMULTANEOUS STUDY OF η_c AND J/ψ

PRL 114(2015), 092005
arXiv:1910.08796

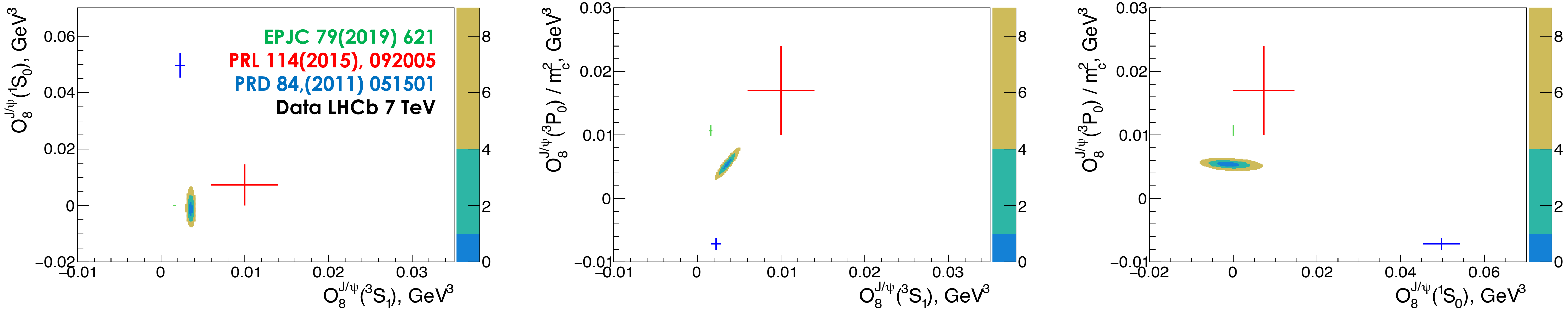
- η_c production @ $\sqrt{s}$=7 and 8 TeV sets new constraint on J/ψ polarization
- **Outcome**:
  - Impressive progress
  - Tension with CDF data
  - Two large CO contributions cancel each other ⇒

⇒ 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

THE LHCb EXPERIMENT

IJMPA 30 (2015) 1530022

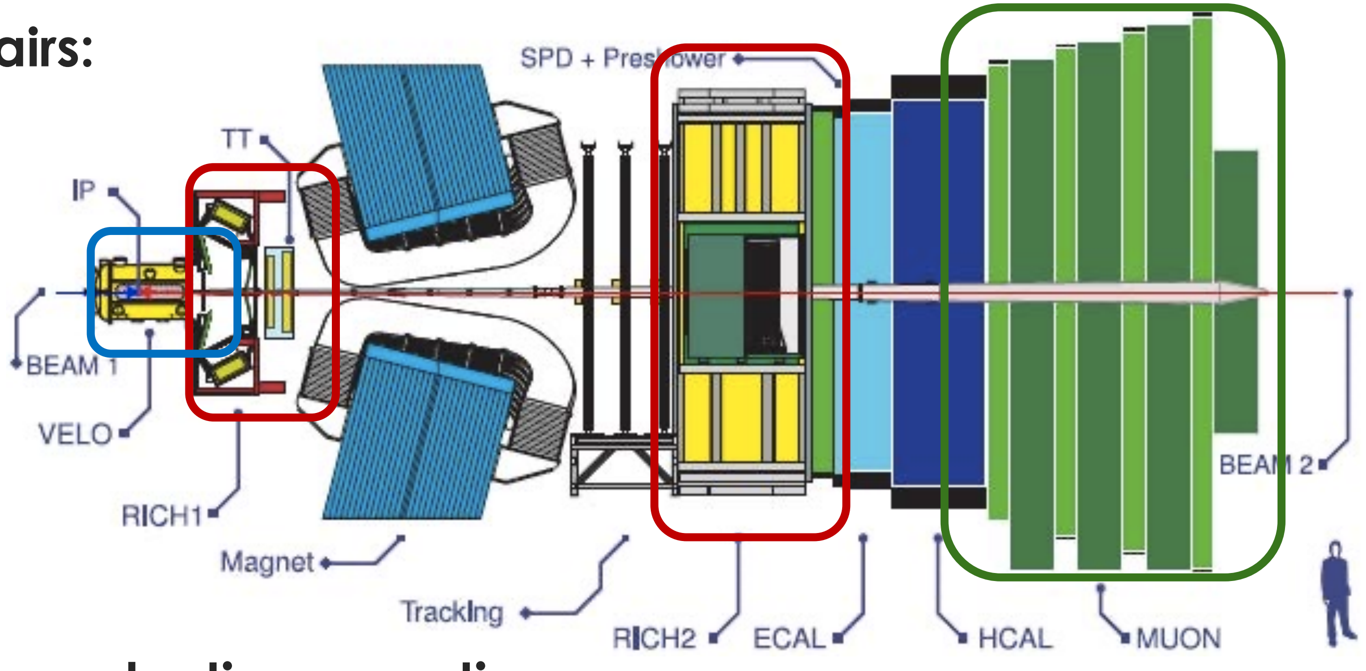
- **LHC provides large number of $b\bar{b}$ and $c\bar{c}$ pairs:**
  - $\sigma_{b\bar{b}} \sim 0.5$ mb
  - $\sigma_{c\bar{c}} \sim 3.0$ mb

  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 $\sqrt{s}$=13 TeV

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

- Cross-section determination:

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

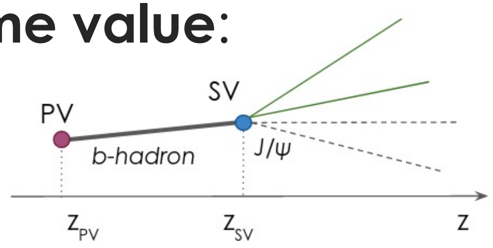
$$\frac{\mathcal{B}_{b\to\eta_c X}}{\mathcal{B}_{b\to J/\psi X}} = \frac{N^b_{\eta_c}}{N^b_{J/\psi}} \times \frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c\to p\bar{p}}} \times \frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c\to p\bar{p}}}$$

- Extracted from DATA
- Calculated from PDG:

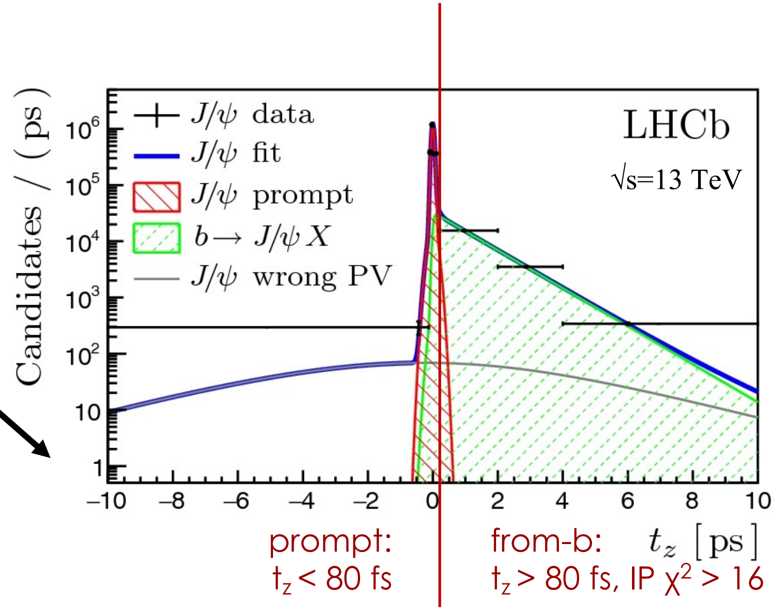
$$\mathcal{B}_{J/\psi\to p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3}$$
$$\mathcal{B}_{\eta_c(1S)\to p\bar{p}} = (1.45 \pm 0.14) \times 10^{-3}$$

- From Simulation

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



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

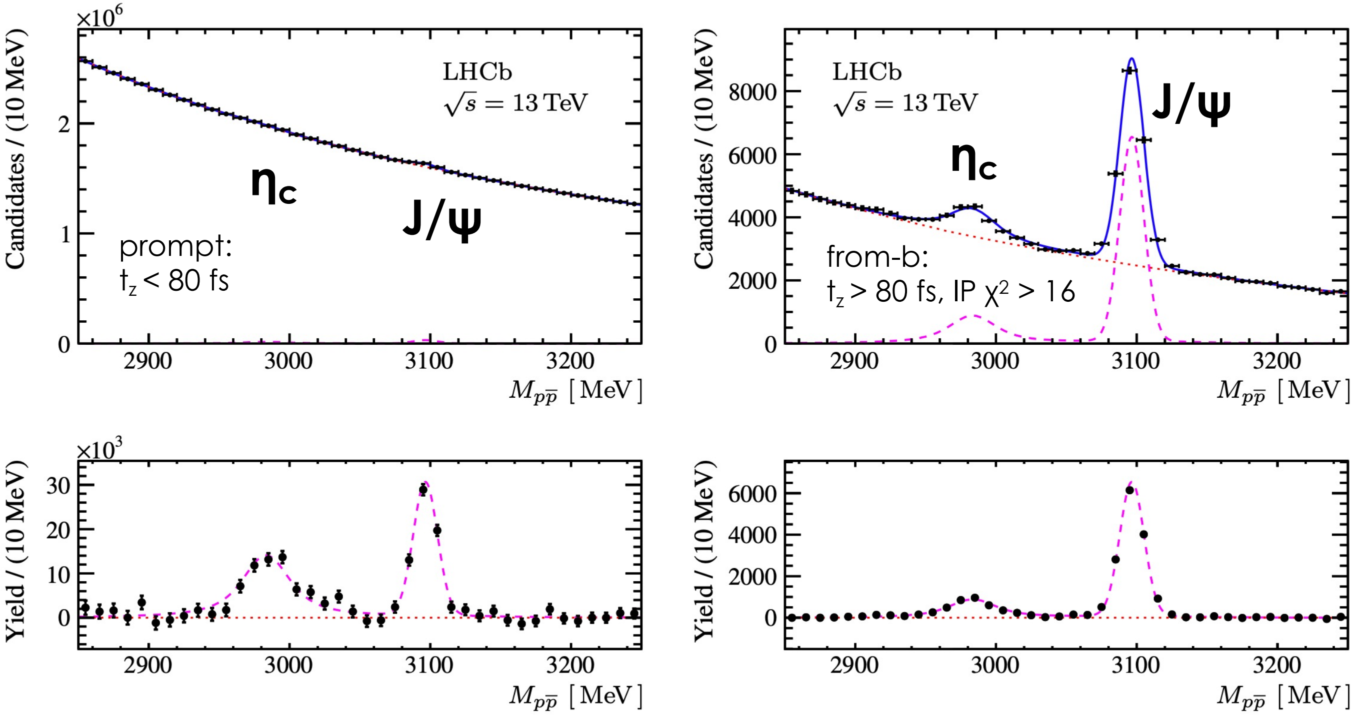


- **Cross-feed** between samples are accounted in simultaneous fit
- **Two techniques** are used for cross-section measurement

t_Z-CUT TECHNIQUE

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

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



- Relative charmonium yields:

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

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

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

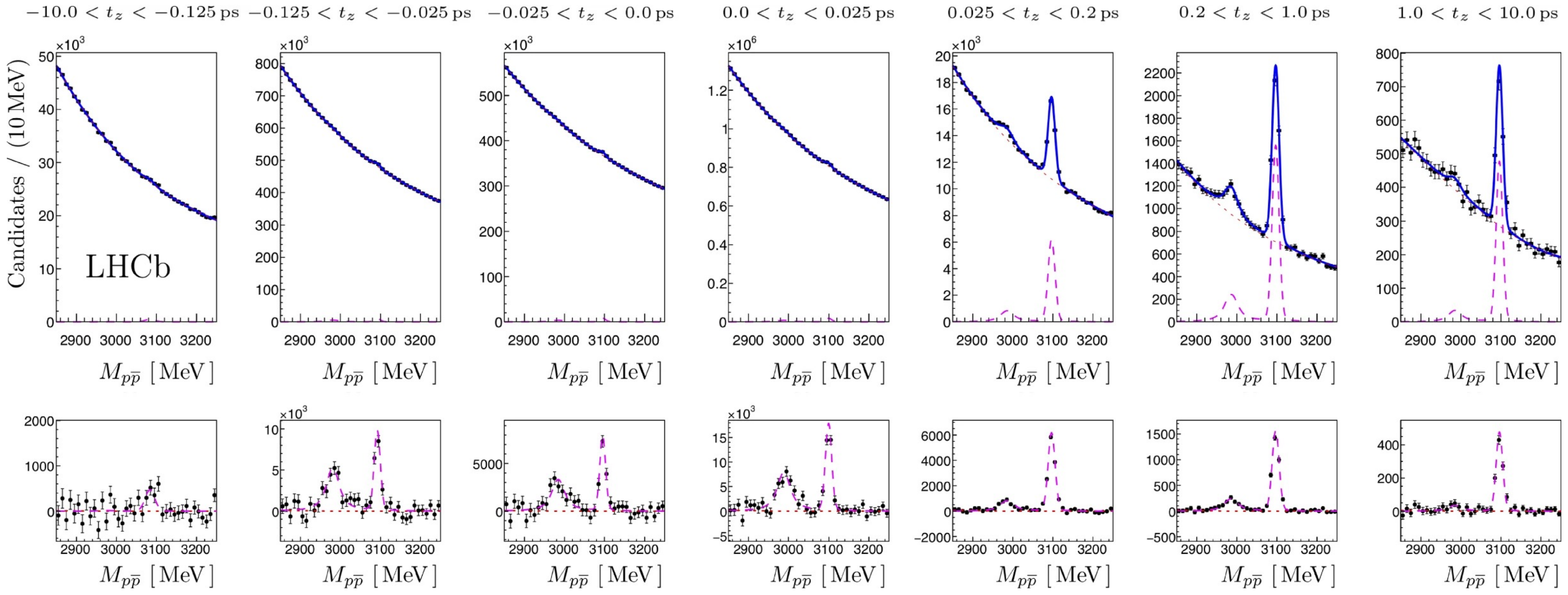
- The **most precise** determination of **η_c mass** up to date:

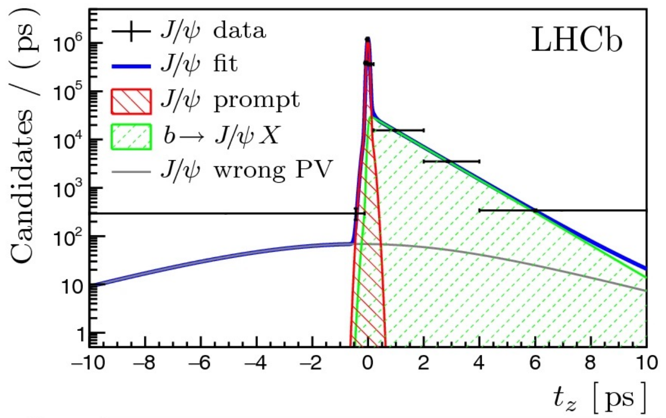
$$\Delta M_{J/\psi, \eta_c} = 113.0 \pm 0.7_{stat} \pm 0.1_{syst} MeV$$

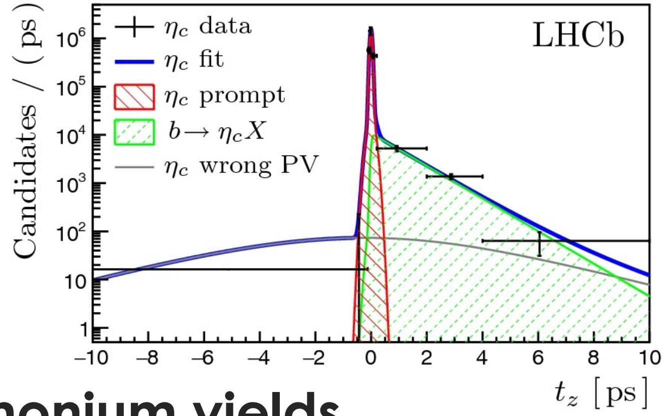
t_Z-FIT TECHNIQUE

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

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





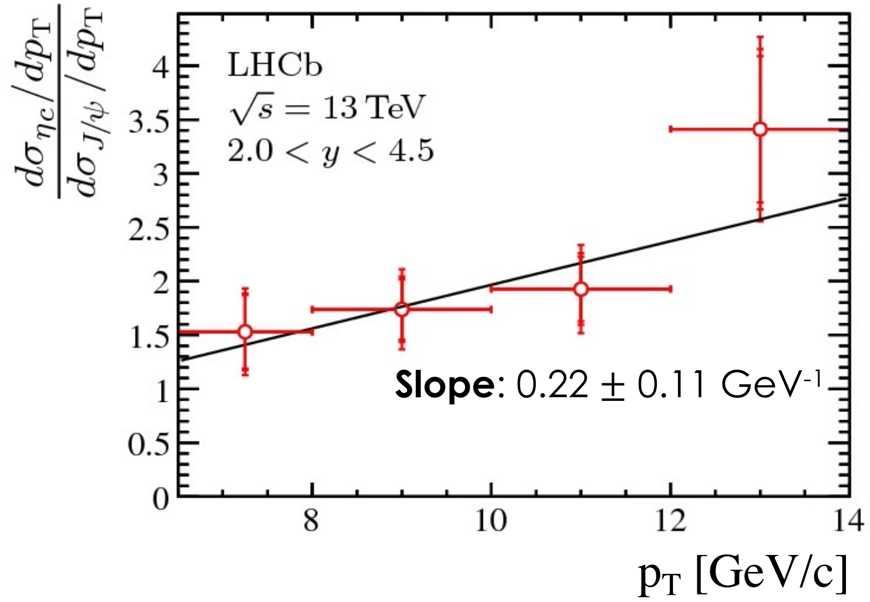


- Simultaneous likelihood **fit to $M_{p\bar{p}}$** in bins of **$[p_T, t_z]$ to extract charmonium yields**
- Simultaneous integral χ^2 **fit to t_z** in p_T-bins **to separate prompt** and **from *b*-decays charmonium**
- η_c mass correction applied in bins of t_z
- Results consistent with t_z-cut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

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

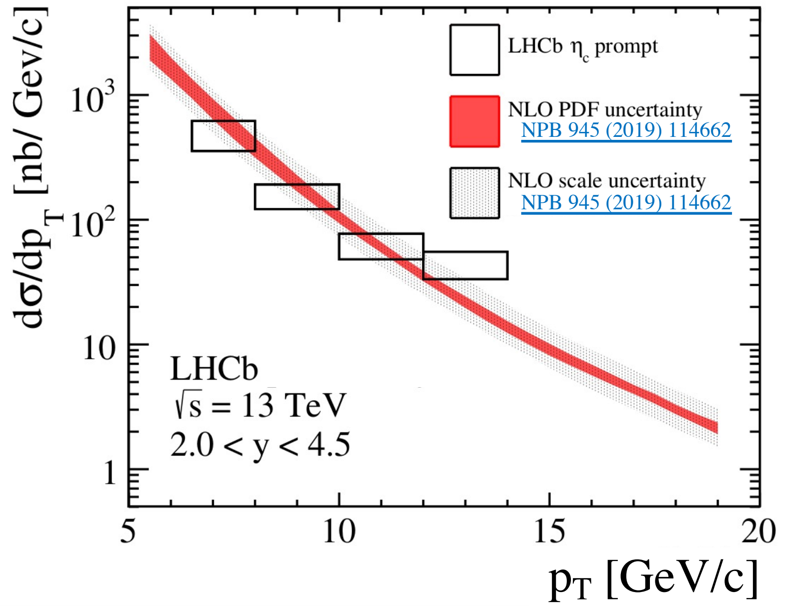
$$\mathfrak{B}_{b\to\eta_c X}/\mathfrak{B}_{b\to J/\psi X} = 0.48 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.05_{\mathfrak{B}_{c\bar{c}\to p\bar{p}}}$$

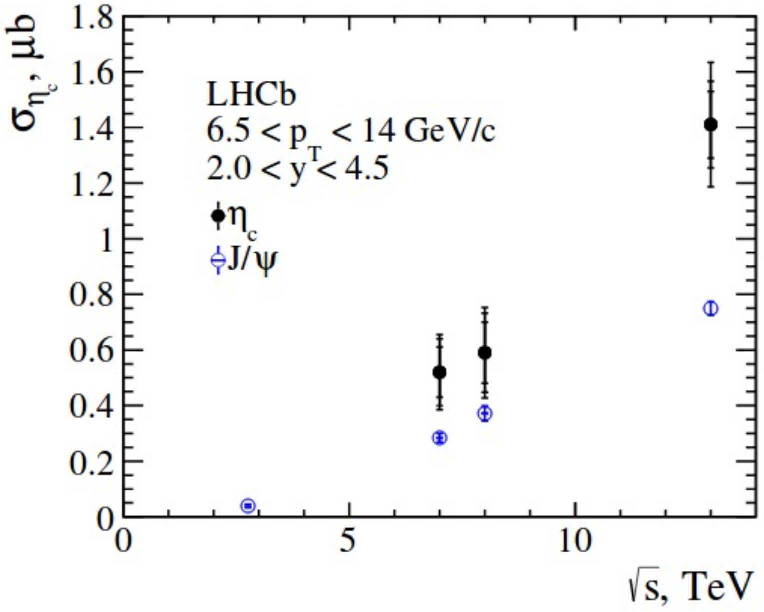
- Measurement in extended p_T is required
- **Larger slope** would indicate **possible CO contribution**
- **Interpretation of η_c(2S)/ψ(2S) much more clean** than of η_c(1S)/J/ψ due to absence of feed-down contributions

INTEGRATED AND DIFFERENTIAL CROSS-SECTIONS

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

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





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

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

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

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

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

$\psi(2S)$ PRODUCTION AT $\sqrt{s}$=7 AND 13 TeV

Eur.Phys.J.C 80(2020) 185

- Cross-section determination

  in bin[p_T,y] as a function of p_T($2 < p_T < 20$GeV/c) and y($2.0<y<4.5$)

$$\frac{d^2\sigma}{dy dp_T} = \frac{N(\psi(2S) \to \mu^+\mu^-)}{\mathcal{L} \times \varepsilon_{tot} \times k \cdot \mathcal{B}(\psi(2S) \to e^+e^-) \times \Delta y \times \Delta p_T}$$

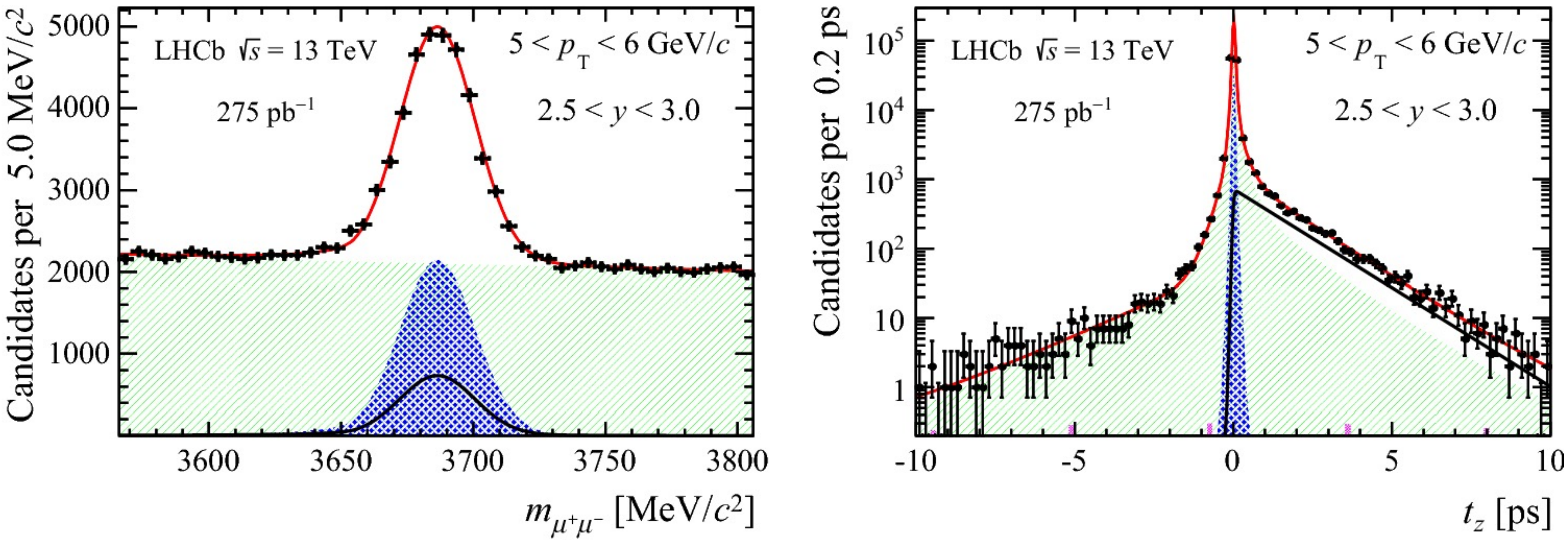
- number of signal candidates in the given (p_T, y) bin
- integrated luminosity
- total efficiency
- the phase space factor to correct dielectron channel
- bin width

$$k = \frac{(m^2_{\psi(2S)} + 2m^2_\mu) \cdot \sqrt{m^2_{\psi(2S)} - 4m^2_\mu}}{(m^2_{\psi(2S)} + 2m^2_e) \cdot \sqrt{m^2_{\psi(2S)} - 4m^2_e}}.$$

- **Prompt** and ***b*-decay production** distinguished via **combined mass-lifetime fits**
- **Full kinematic range cross-section**

COMBINED MASS-LIFETIME FITS

Eur.Phys.J.C 80(2020) 185

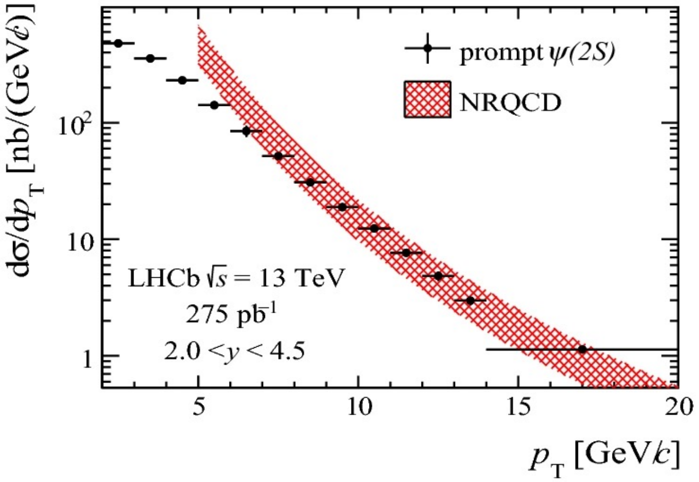


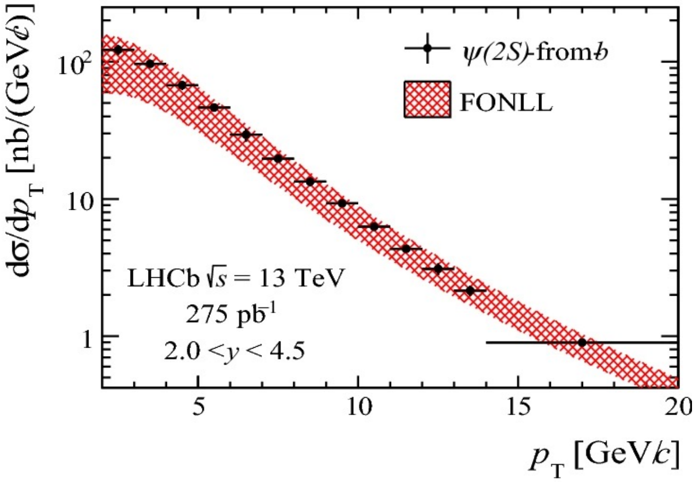
- **Prompt ψ(2S)** and **ψ(2S) from b-decay production** distinguished via decay time value:

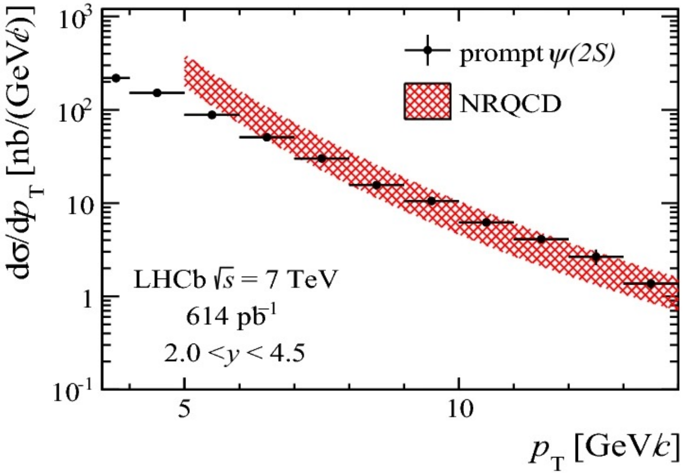
$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{\mu\mu}$$

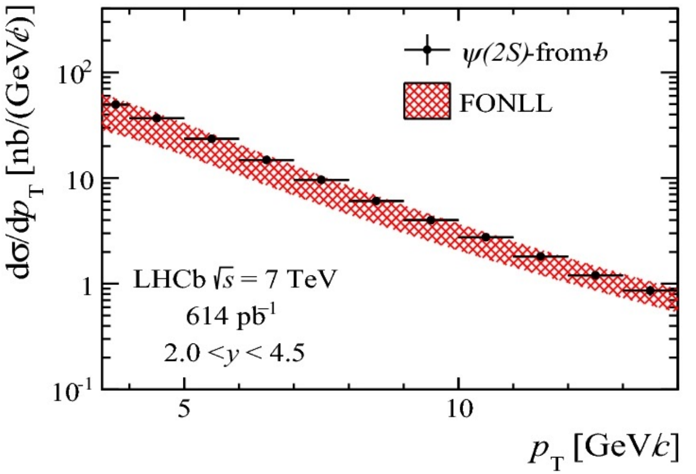
- Unbinned maximum likelihood fit in bins of **[p_T, y]** to $M_{\mu^+\mu^-}$ and t_z

Eur.Phys.J.C 80(2020) 185









ψ(2S) production in LHCb:

- **√s=13 TeV**

$2 < p_T < 20\ GeV/c\,, 2.0 < y < 4.5$

$\sigma_{\psi(2S)}^{prompt} = 1.430 \pm 0.005_{stat} \pm 0.099_{syst}\ \mu b$

$\sigma_{\psi(2S)}^{from-b} = 0.426 \pm 0.002_{stat} \pm 0.030_{syst}\ \mu b$

- **√s=7 TeV**:

$3.5 < p_T < 14\ GeV/c\,, 2.0 < y < 4.5,$

$\sigma_{\psi(2S)}^{prompt} = 0.471 \pm 0.001_{stat} \pm 0.025_{syst}\ \mu b$

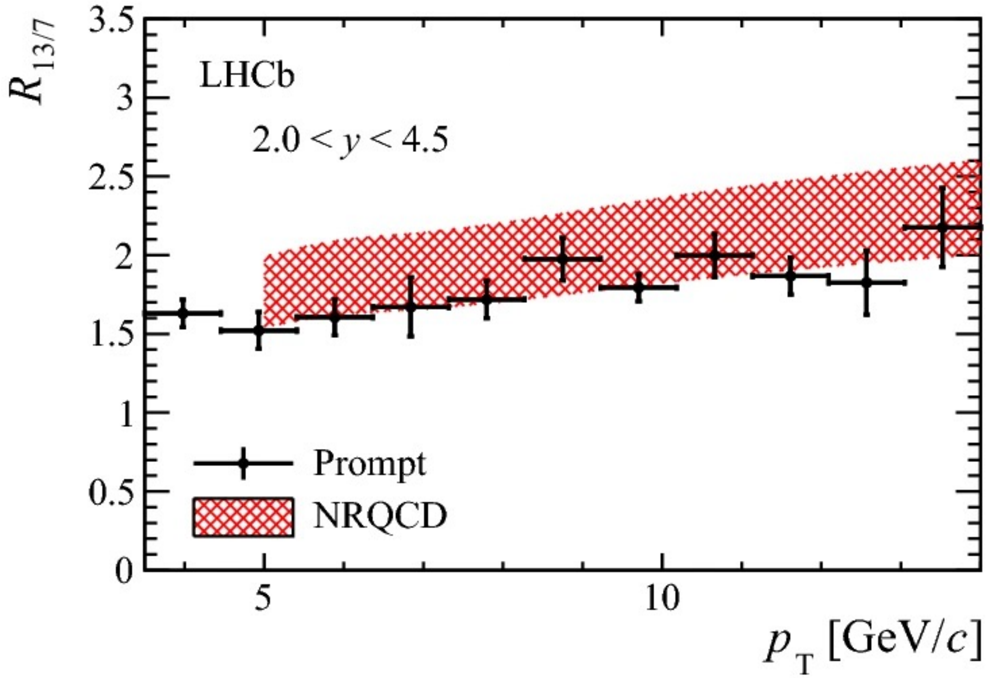
$\sigma_{\psi(2S)}^{from-b} = 0.126 \pm 0.001_{stat} \pm 0.008_{syst}\ \mu b$

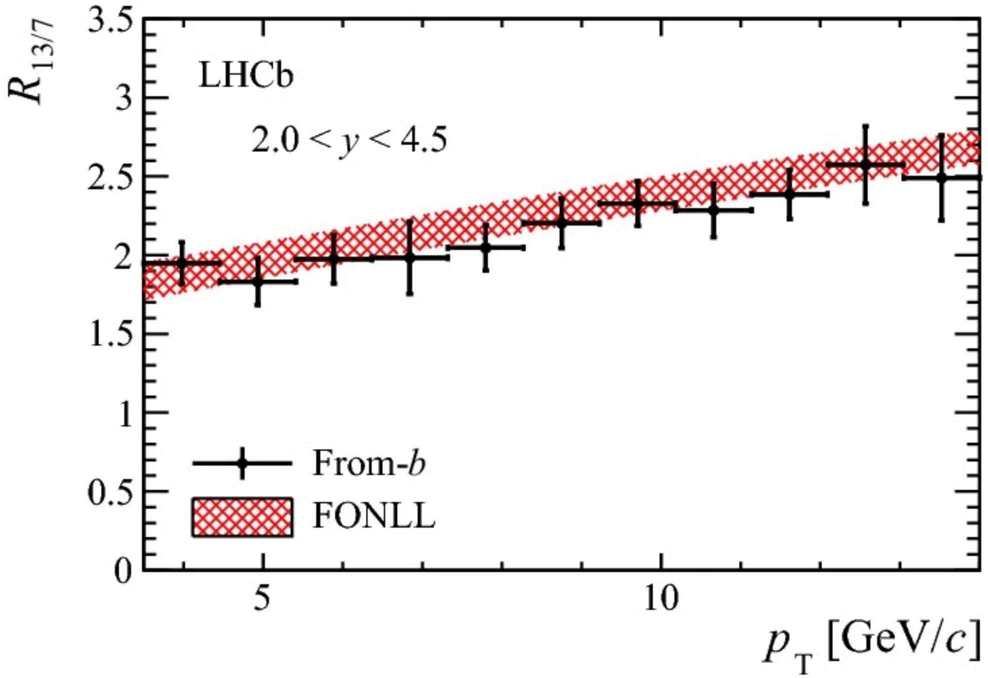
- Reasonable agreement between NRQCD and data for $p_T > 7$ GeV/c
- Good agreement for FONLL

RATIOS BETWEEN 13 AND 7 TeV

Eur.Phys.J.C 80(2020) 185

- Systematic uncertainty related to the branching fraction is cancelled
- Uncertainties due to luminosity, fit model and tracking correction are partially correlated



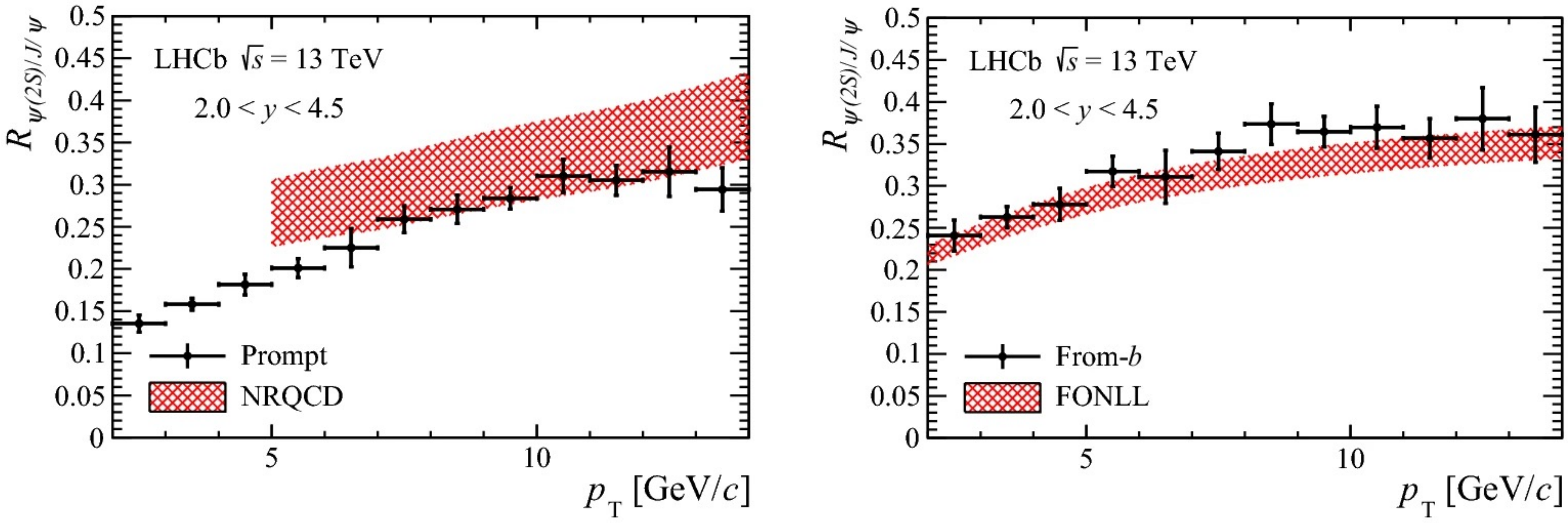


- Good agreement between NRQCD and data
- Good agreement for FONLL

RATIOS BETWEEN ψ(2S) AND J/ψ

[Eur.Phys.J.C 80(2020) 185]

- Systematic uncertainties due to luminosity, tracking correction, and fit model are fully correlated.



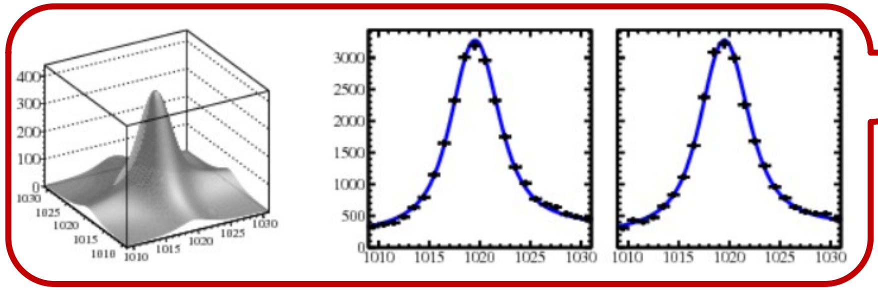
- Reasonable agreement between NRQCD and data
- Good agreement for FONLL
- **Same study for $\eta_c(2S)$** is needed

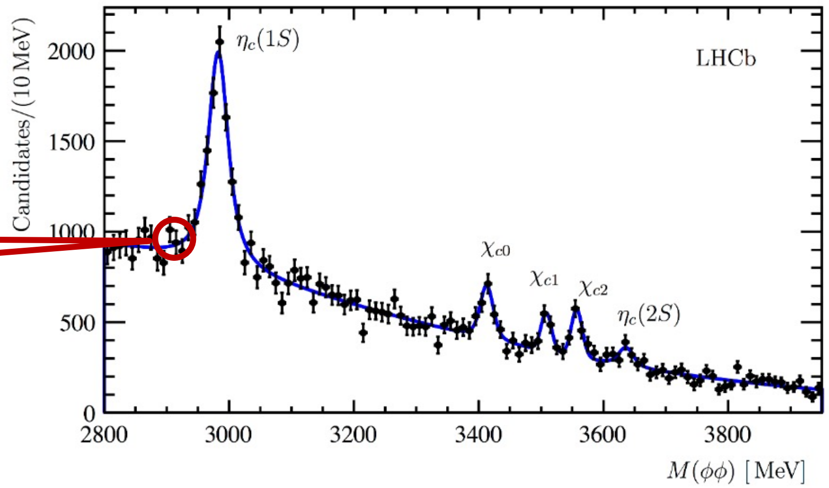
$\eta_c(2S)$ PRODUCTION IN *b*-DECAYS AT LHCb

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

- Charmonium reconstructed via **decays to φφ**;

  true φφ combinations extracted using 2D fit technique



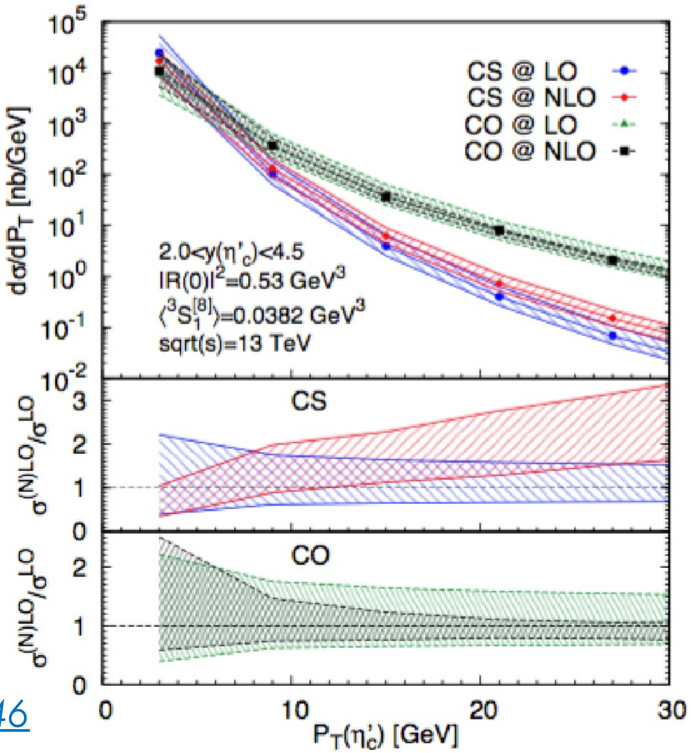


- First measurement of $\eta_c(2S)$ production in b-decays;

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

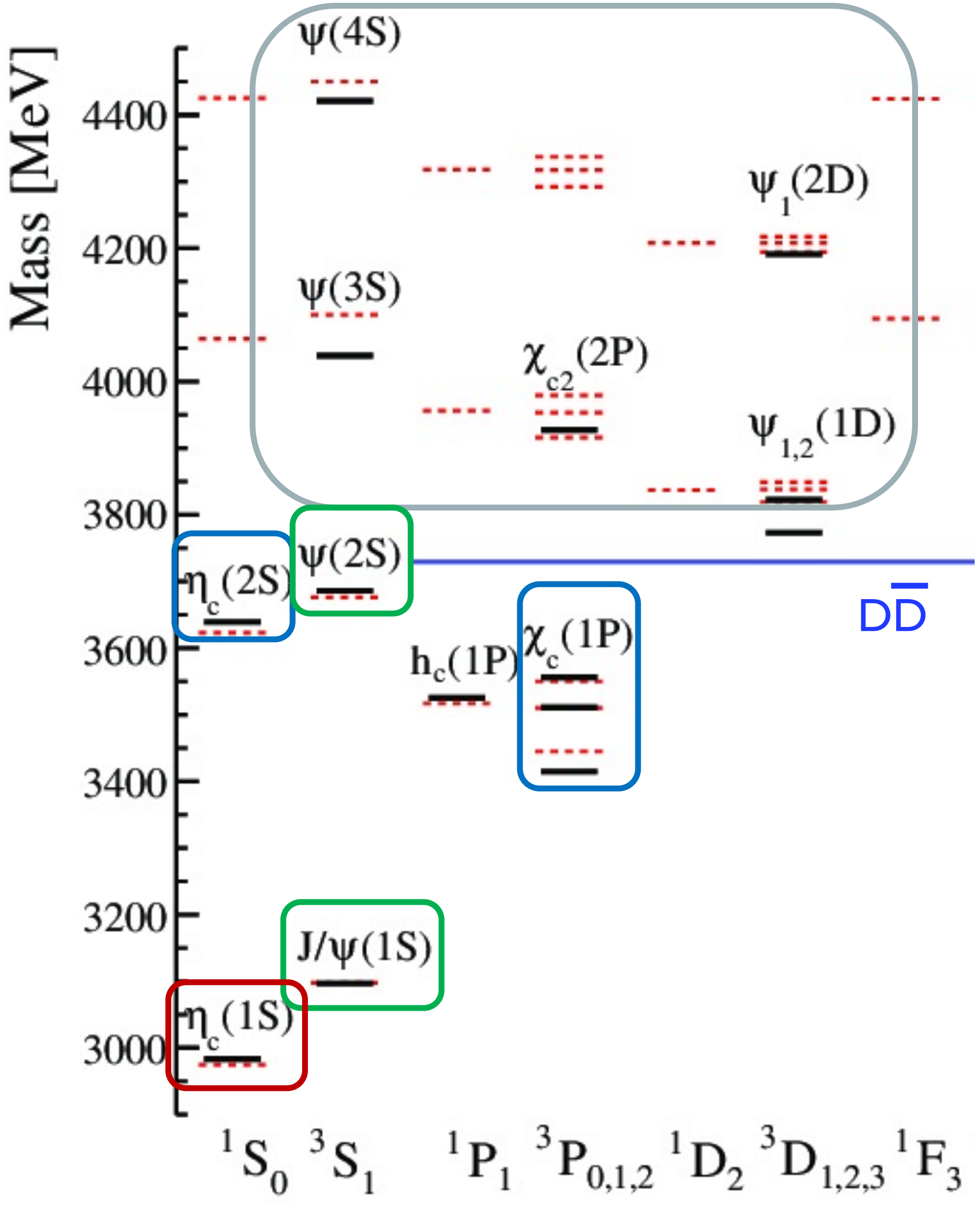
$$\frac{\mathcal{B}(b \to \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \to \phi\phi)}{\mathcal{B}(b \to \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \to \phi\phi)} = 0.040 \pm 0.011 \pm 0.004$$

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



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

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*

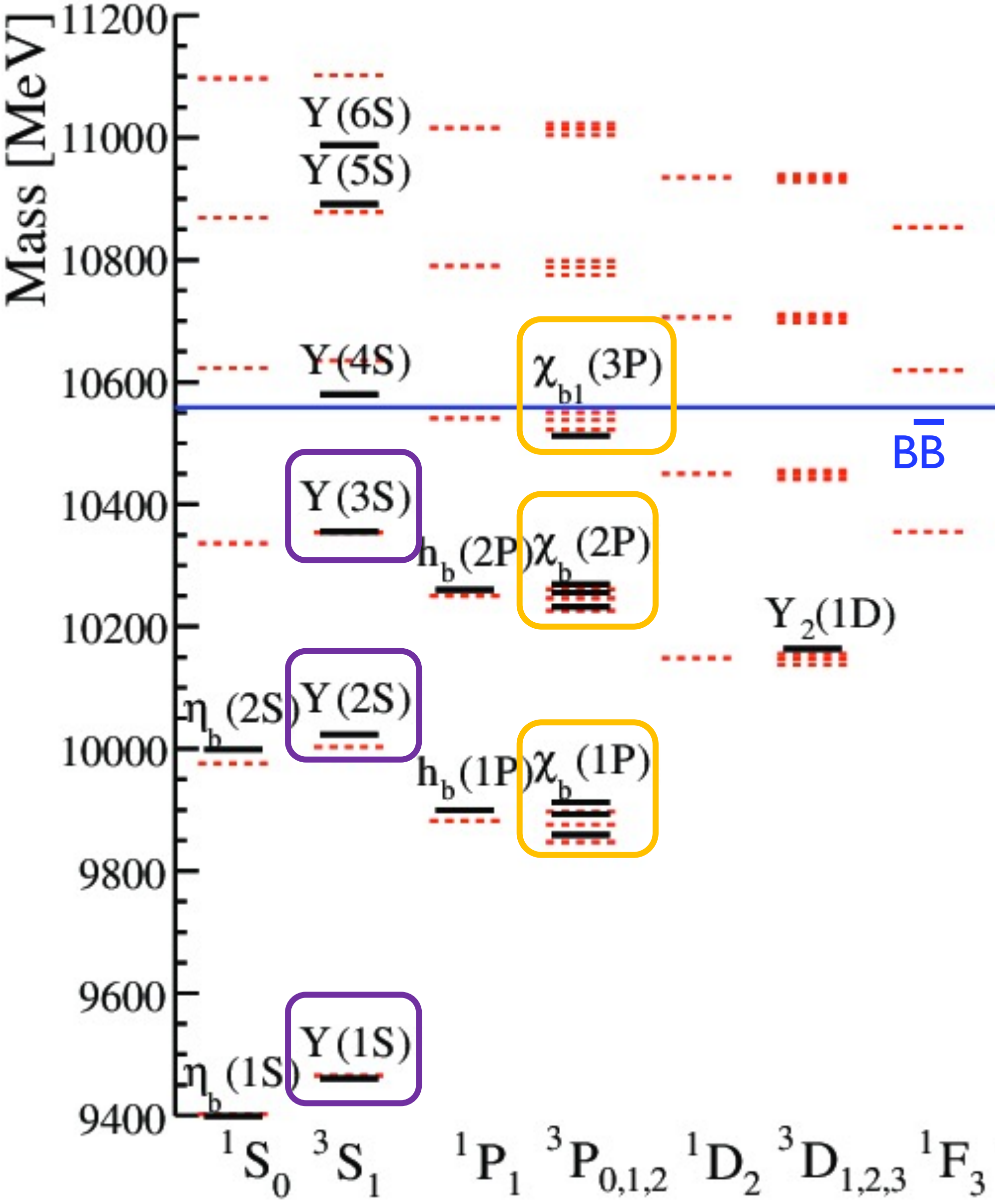
Non-conventional charmonia:
talk by Matthew Needham at QWG2021

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



Rev.Mod.Phys 90 (2018) 015003

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 η_b(1S) production

SUMMARY

- Comprehensive model still missing to describe **Heavy Flavour production**

- LHCb results allow to perform **powerful tests of QCD** via quarkonium production:
  - joint study of charmonium hadroproduction and production in b-decays
  - $\eta_c(1S)$ prompt production measurement constrains CO LDMEs

- 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

Thank you for attention!
Questions?

BACKUP SLIDES

QUARKONIA PRODUCTION MECHANISMS

- **Production mechanisms:**

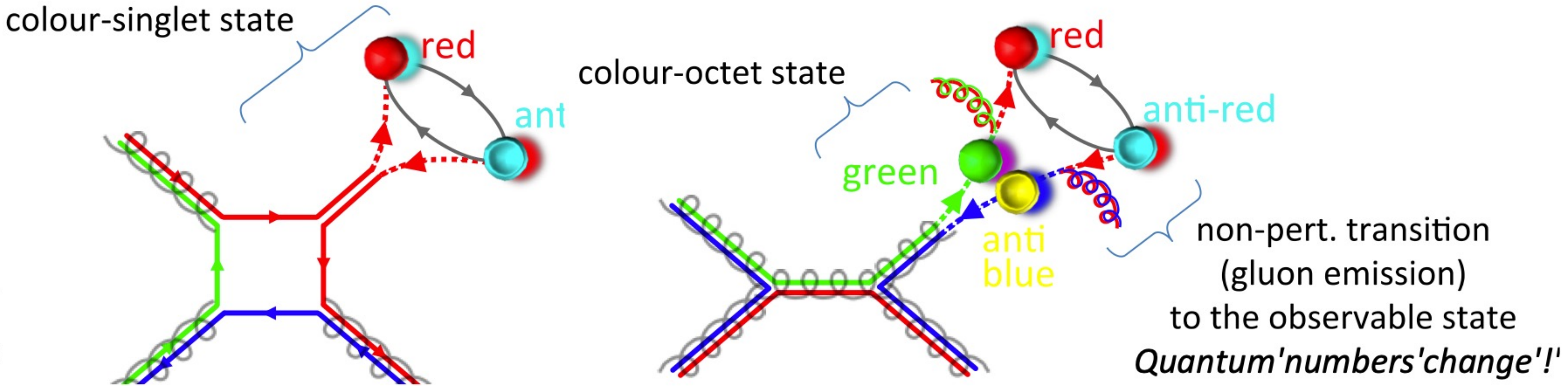
$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X} \times \langle O^H(n)\rangle$$

- Color Singlet (CS):

  quantum numbers of $Q\bar{Q}$ pair and quarkonium match

- Color Octet (CO):

  quantum numbers of $Q\bar{Q}$ pair in CO state are different from quarkonium; soft gluons emitted at later stage of hadronization



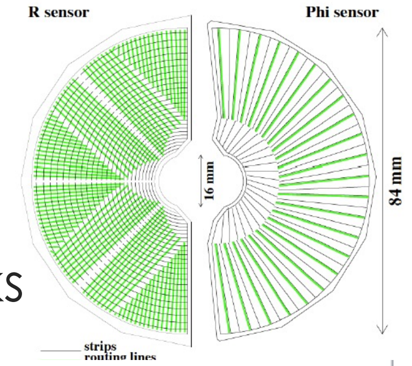
Figures by Pietro Faccioli

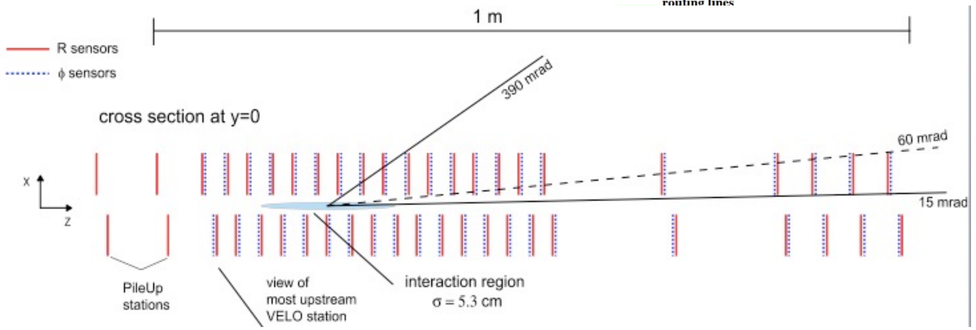
KEY LHCb SYSTEMS FOR PRODUCTION MEASUREMENTS

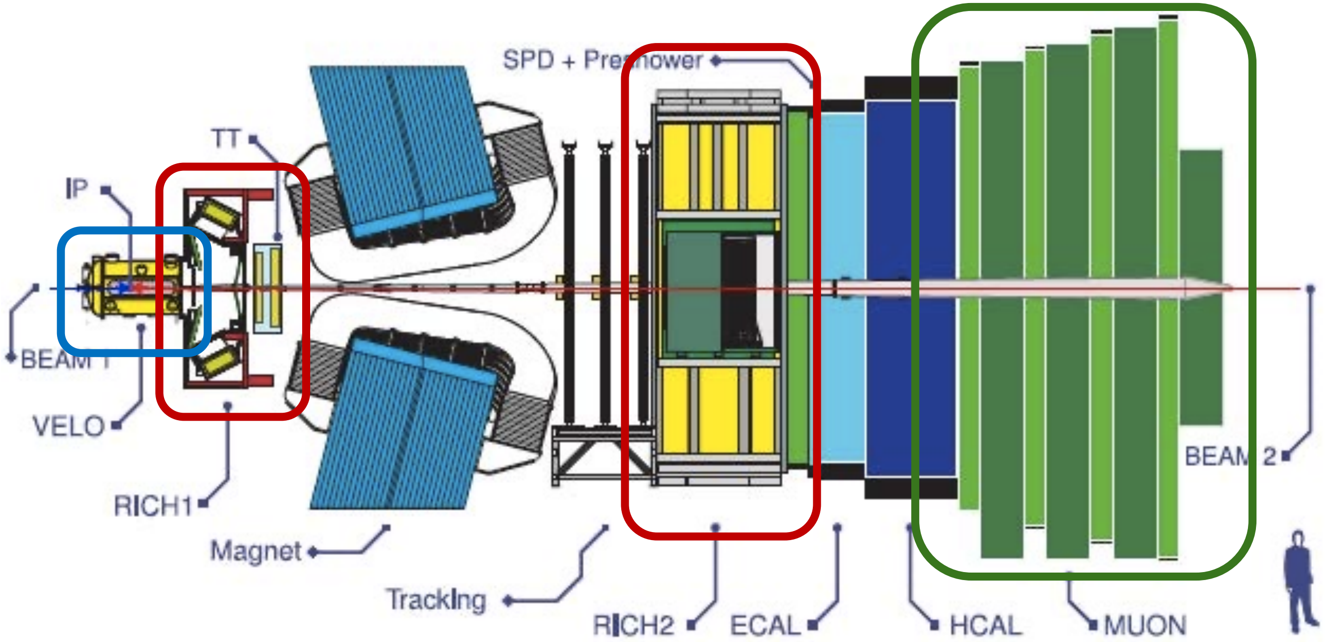
[JINST 9(2014) P09007]

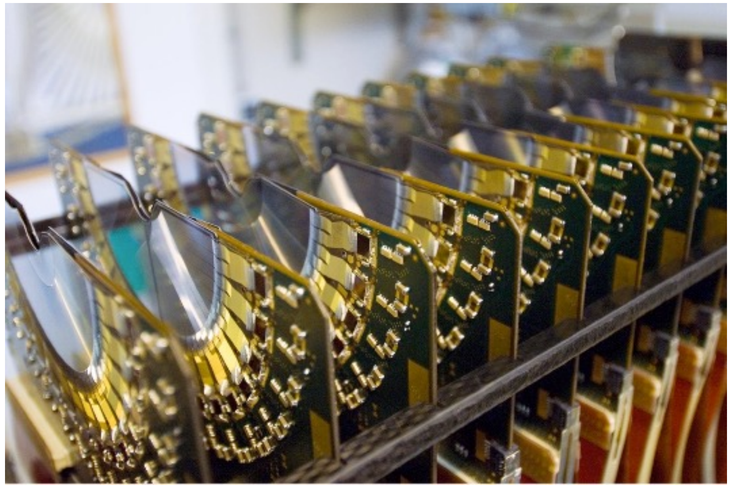
Vertex reconstruction VELO

- **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







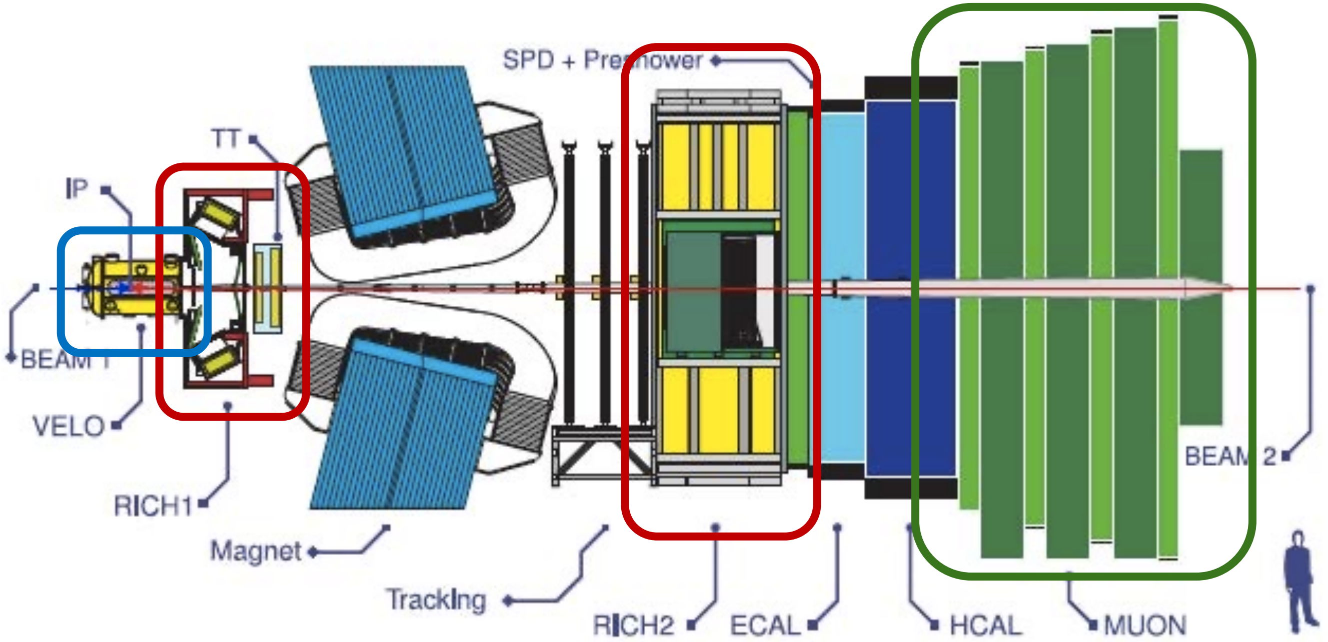


KEY LHCb SYSTEMS FOR PRODUCTION MEASUREMENTS

EPJC 73(2013) 2431
JINST 8 P02022

Particle identification

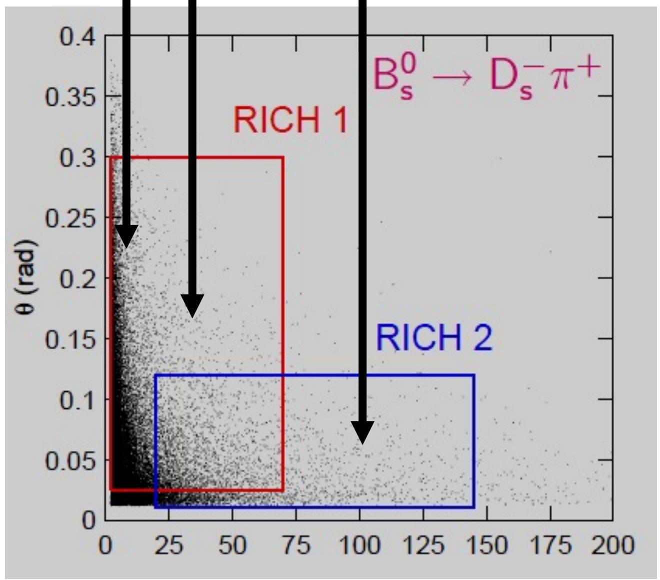
- **2 Ring Imaging Cherenkov Detectors (RICH)**: 3 Radiators covering p_T range 1.5-100 GeV/c
- **Muon detector** – triggering muons and measuring muon momenta
- Particle ID efficiency:
  - $e^{\pm}$ ID ~ 90 % for ~ 5 % e→h mis-id probability
  - $K^{\pm}$ ID ~ 95 % for ~ 5 % π→K mis-id probability
  - $\mu^{\pm}$ ID ~ 97 % for 1-3 % π→μ mis-id probability



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

Silica Aerogel:
n=1.03
1.5-10 GeV/c

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

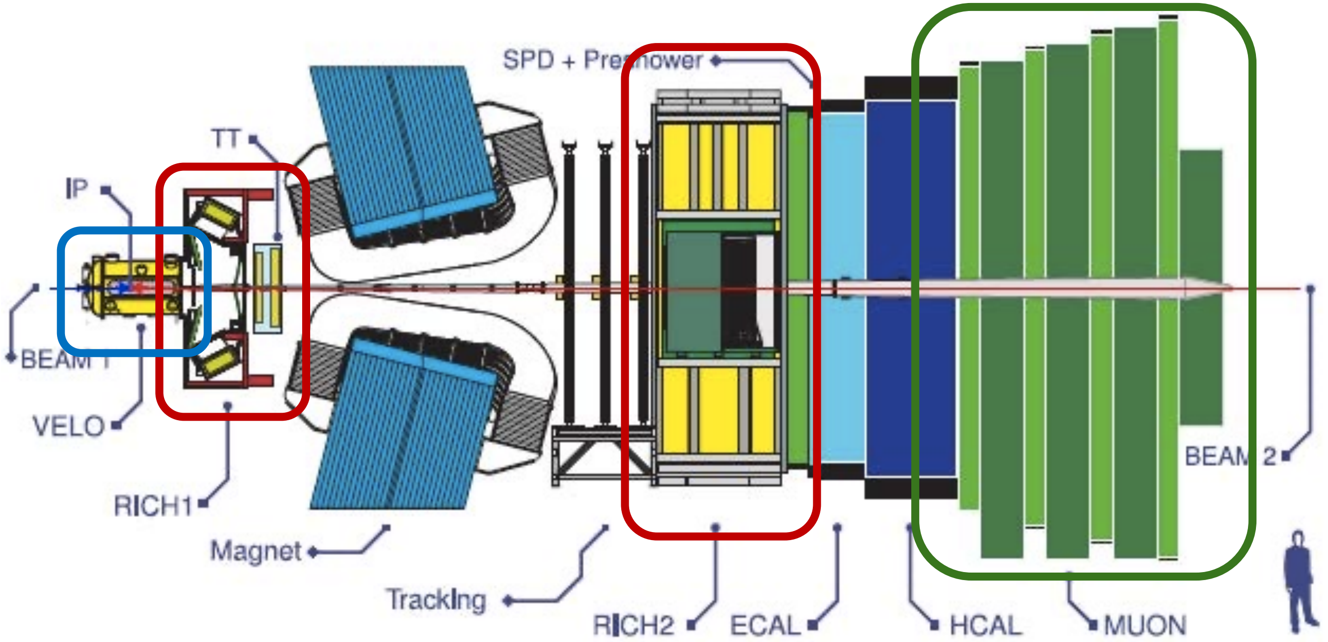


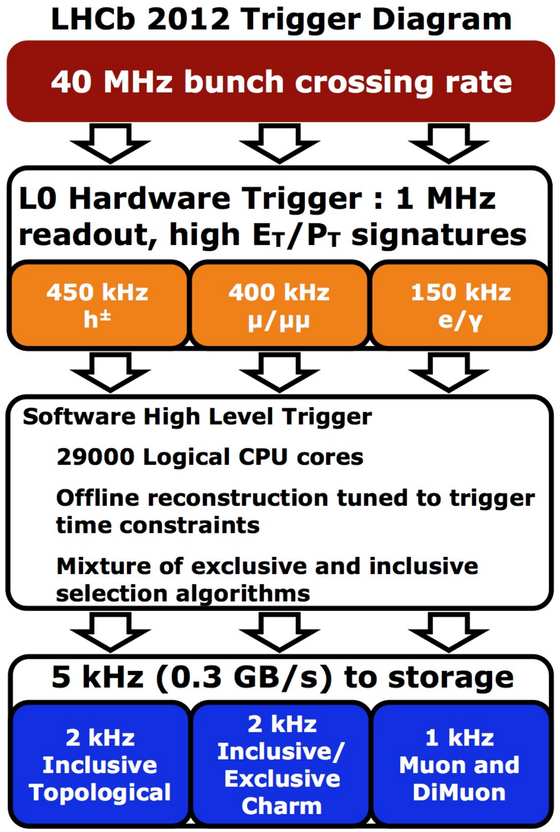
KEY LHCb SYSTEMS FOR PRODUCTION MEASUREMENTS

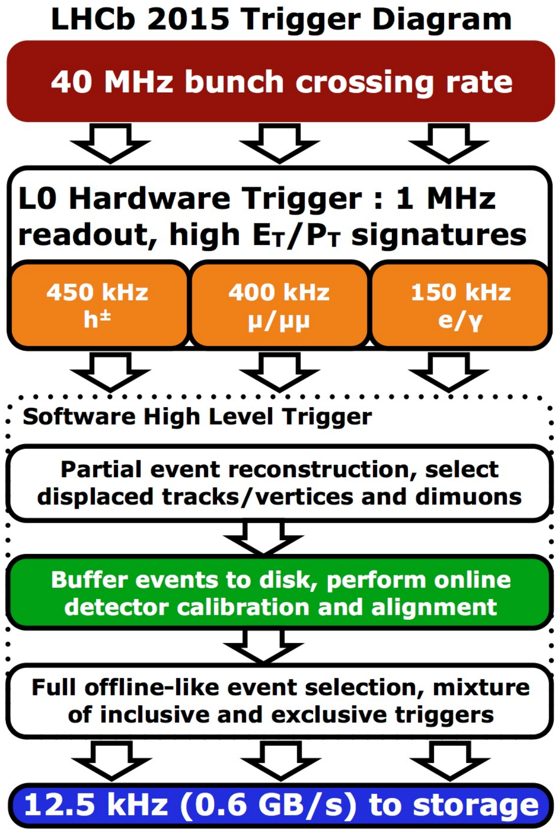
JINST 14 (2019) P04013

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







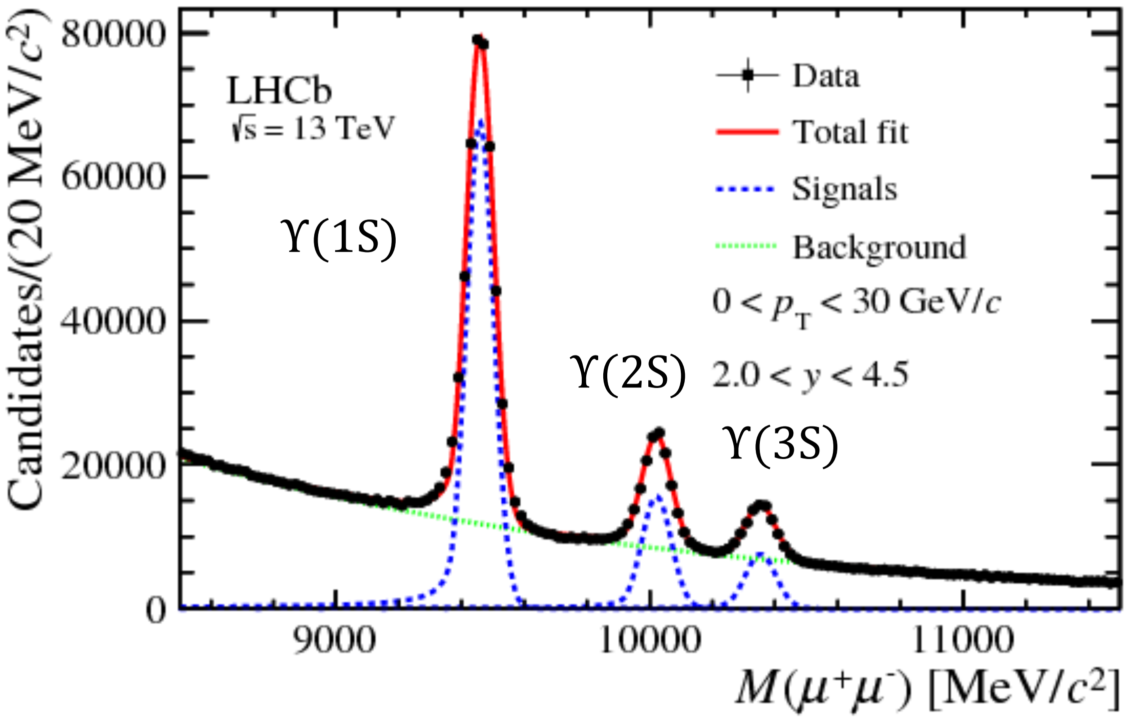
Υ(nS) PRODUCTION AT √s=13 TeV

JHEP07 (2018) 134
JHEP05 (2019) 076

- Cross-section determination

  in bin[p_T,y] as a function of p_T($0 < p_T < 30$GeV/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
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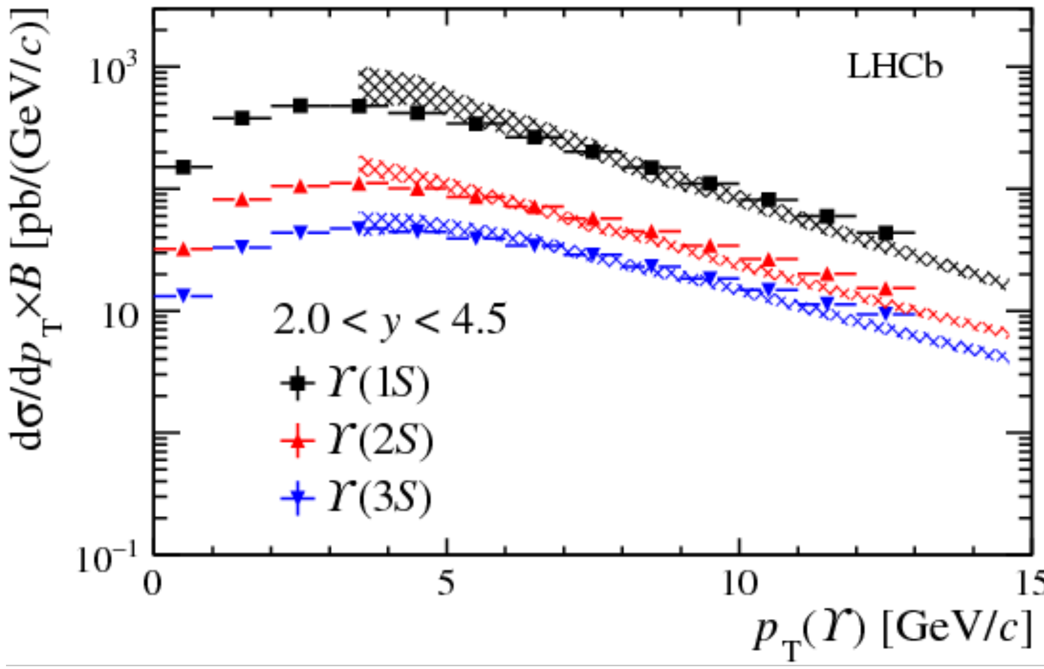
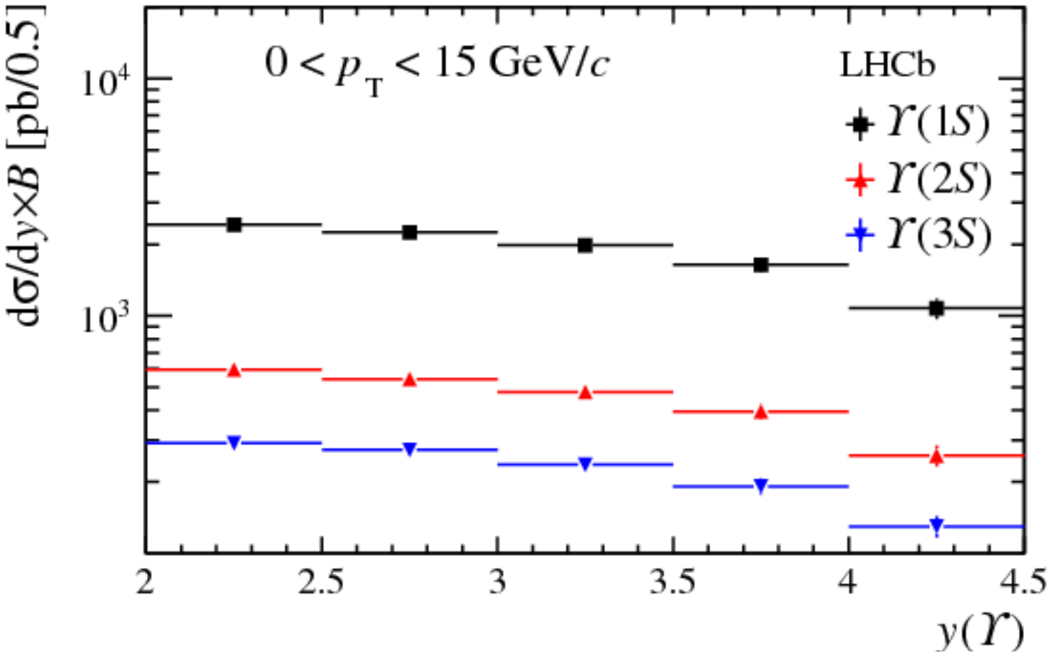




- Double differential production cross-section measured in range $0 < p_T < 30$ GeV/c and $2.0 < y < 4.5$
- **Good agreement between NRQCD and data** at high p_T for all states

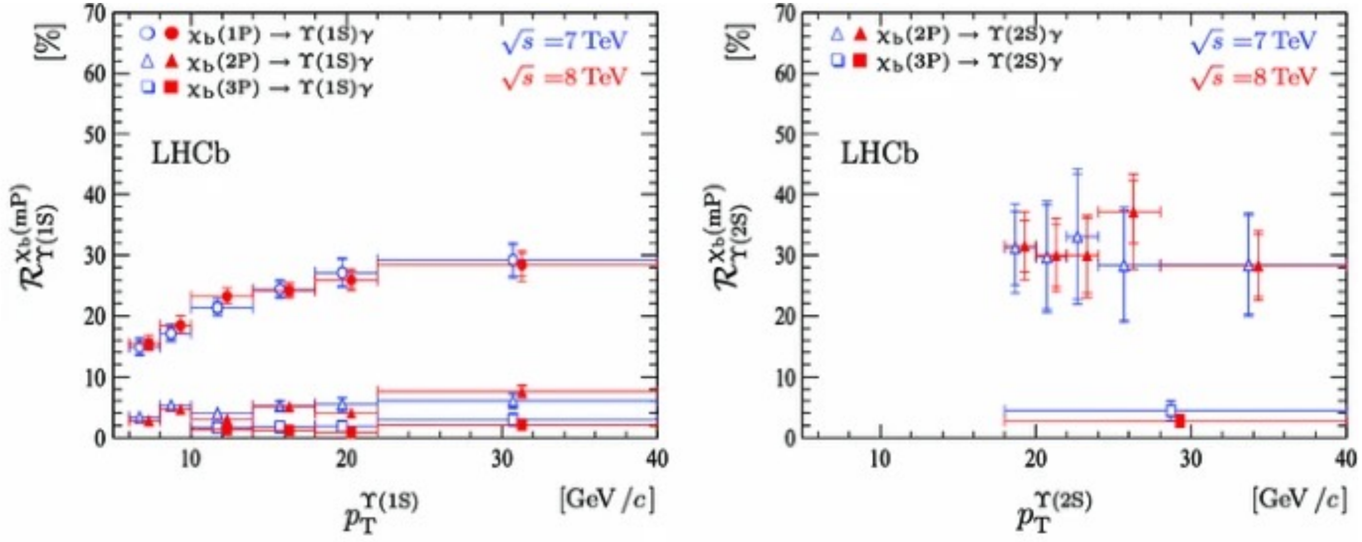
χ_b PRODUCTION AT $\sqrt{s}$=7 AND 8 TeV

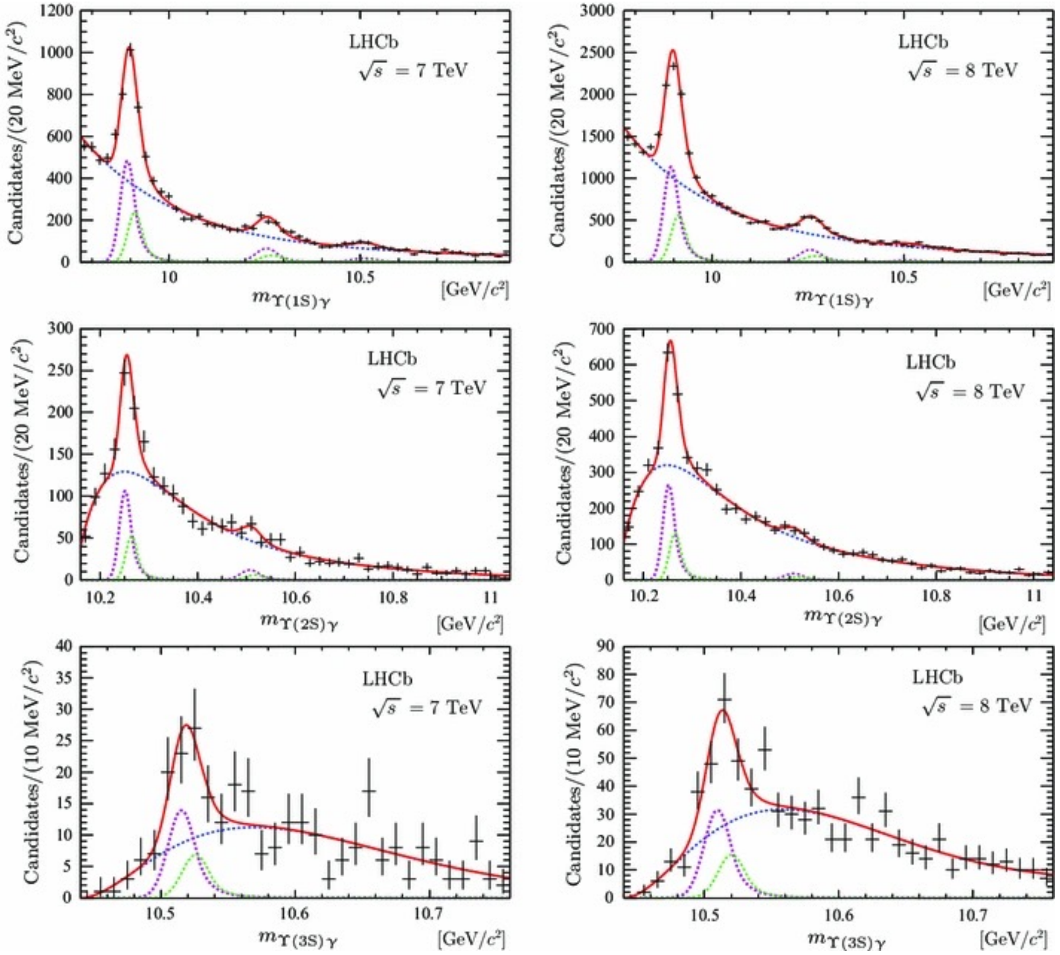
Eur.Phys.J.C 74(2014)10, 3092
JHEP10 (2014) 088

- 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

$b\bar{b}$ AND $c\bar{c}$ PAIR PRODUCTION

- **LHC provides large number of $b\bar{b}$ and $c\bar{c}$ pairs:**
  - ~5×10^{11} $b\bar{b}$ pairs
  - ~3×10^{12} $c\bar{c}$ pairs

  within LHCb acceptance per fb^{-1} @ $\sqrt{s}$ =13 TeV

  - $\sigma_{bb} \approx 250$ μb
  - $\sigma_{cc} \approx 20 \times \sigma_{bb}$

  within LHCb acceptance @ $\sqrt{s}$ =7 TeV