η_c PROMPT HADROPRODUCTION EXPERIMENTAL ASPECTS

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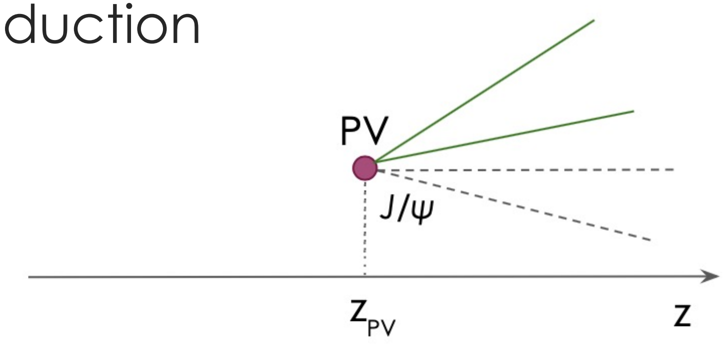
QCD Café

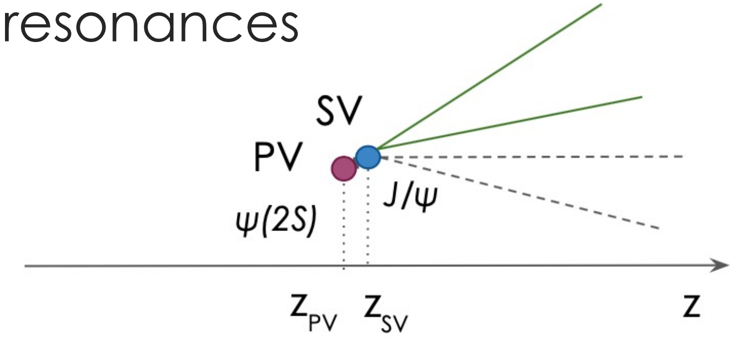
12/10/2021

CHARMONIUM PRODUCTION

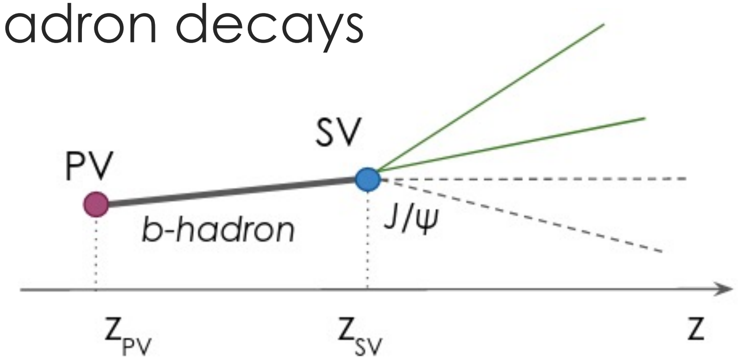
- **Sources of charmonium:**
  - prompt hadroproduction



  - decays of higher resonances



  - production in b-hadron decays



prompt production

distinguished via pseudo-proper decay time

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

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;

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

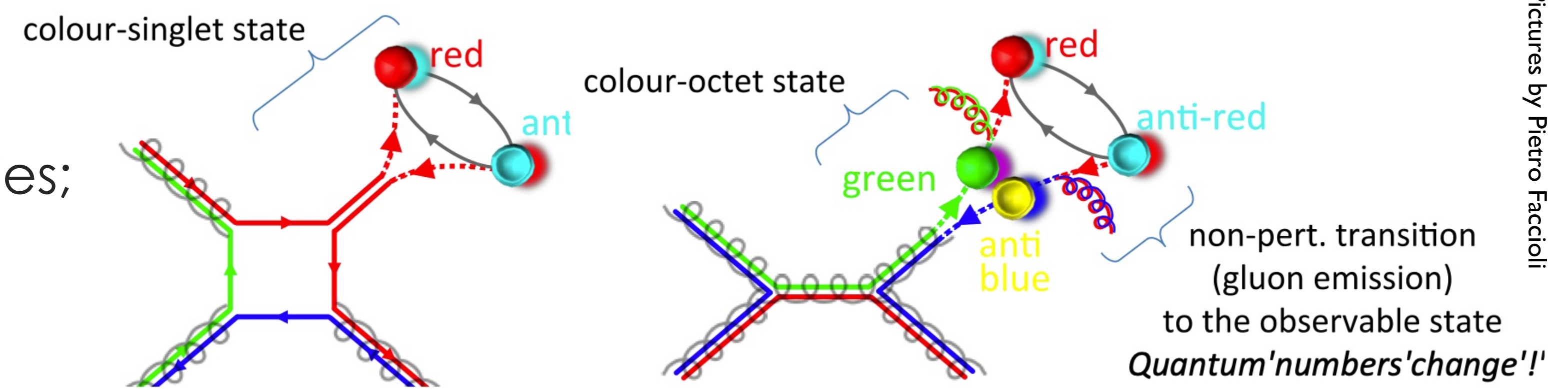
QUARKONIUM PRODUCTION IN NRQCD

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

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



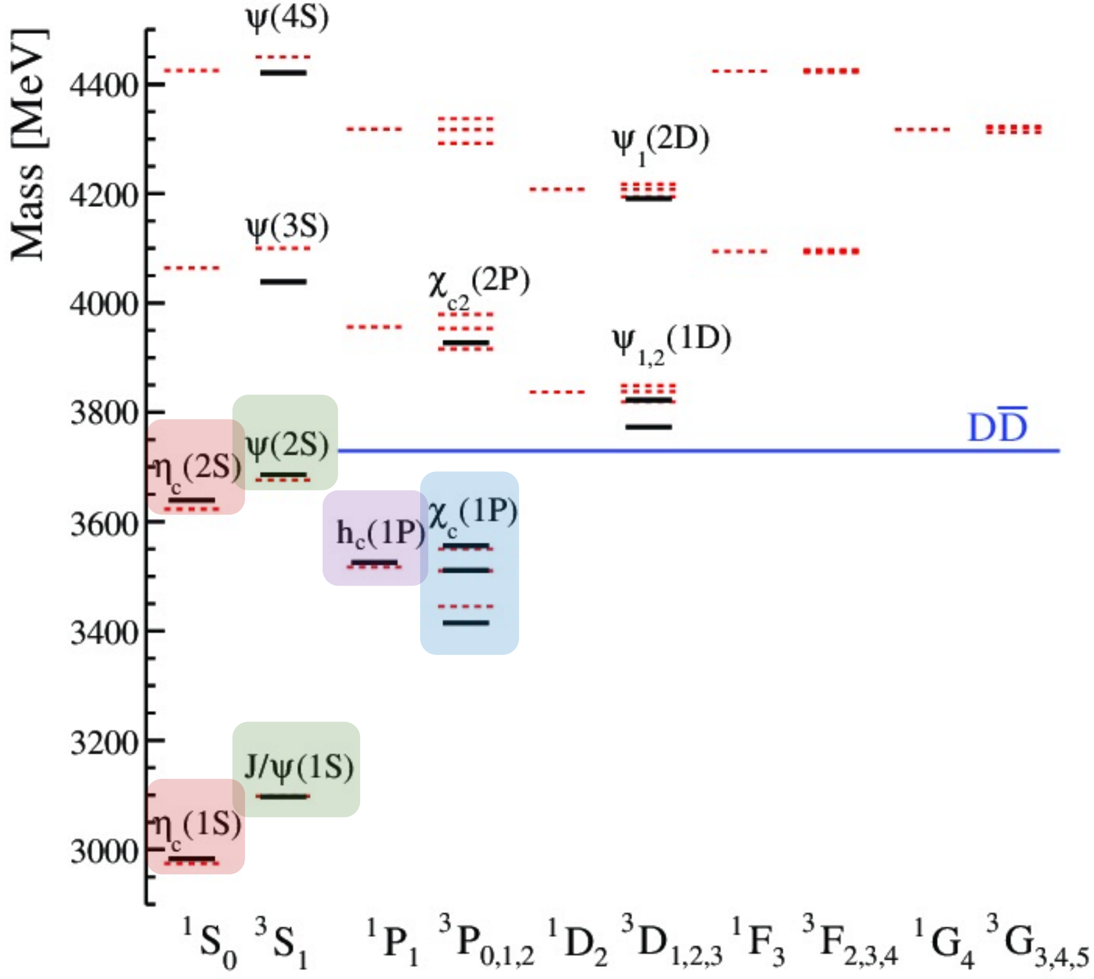
Pictures by Pietro Faccioli

- **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

CHARMONIUM SPECTROSCOPY

Rev.Mod.Phys 90 (2018) 015003

- Current status of charmonium spectrum



Final states:

$\mu^+\mu^-/e^+e^-$ or hadrons

$J/\psi\gamma$ or hadrons

hadrons

$\eta_c(1S)\gamma$ or hadrons

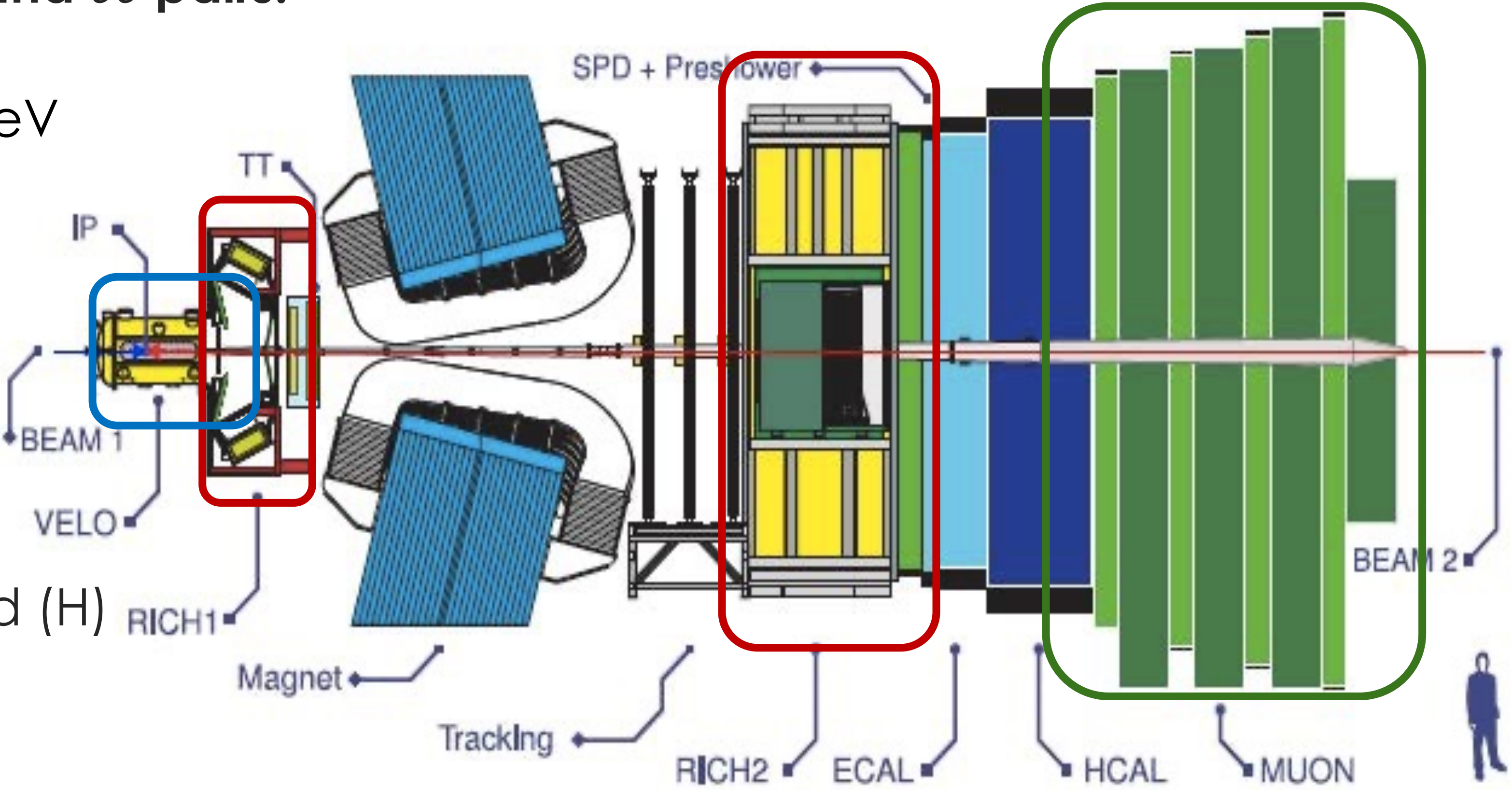
- **Hadronic final states allow to study different quarkonium states simultaneously**

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,

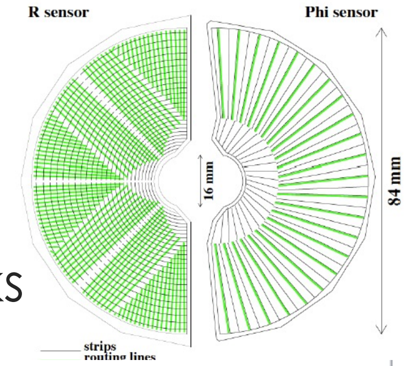
  ~4% of solid angle,

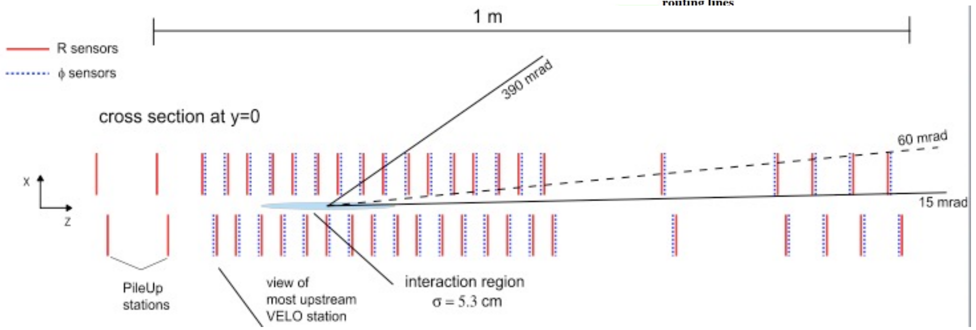
  but **~40% of heavy quarkonium (HQ) production x-section**
- **Forward peaked HQ production** at the LHC, second *b* in acceptance once the first *b* is in

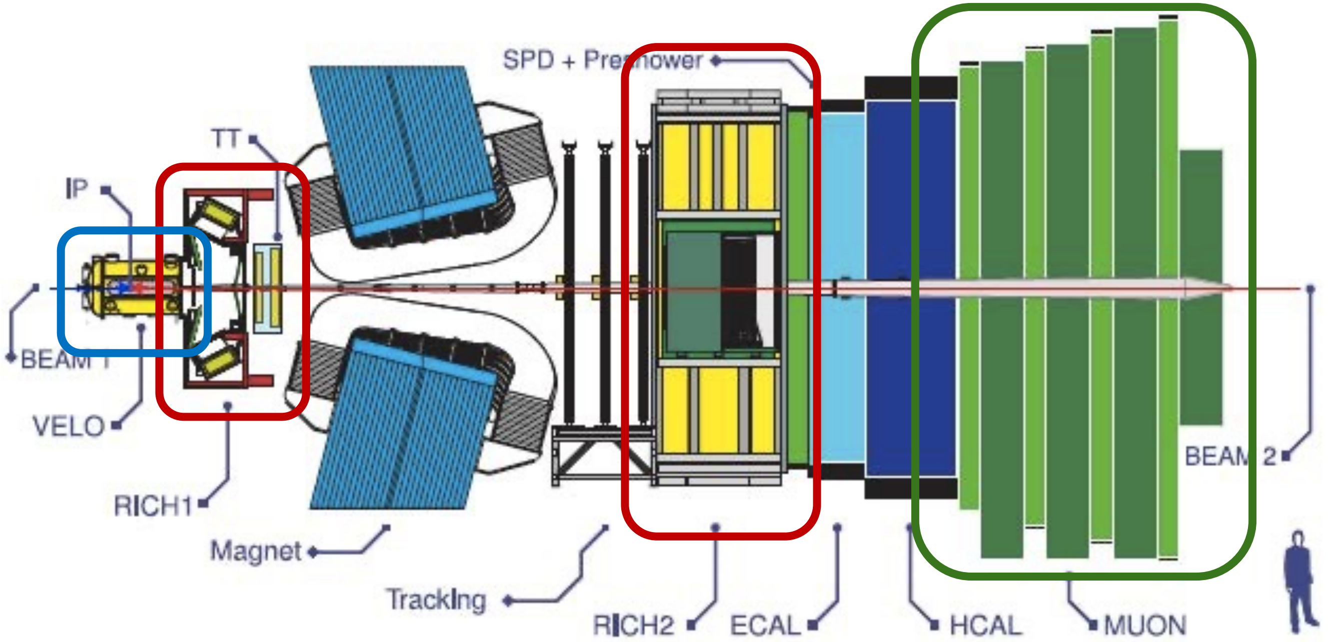
 JINST 9(2014) P09007

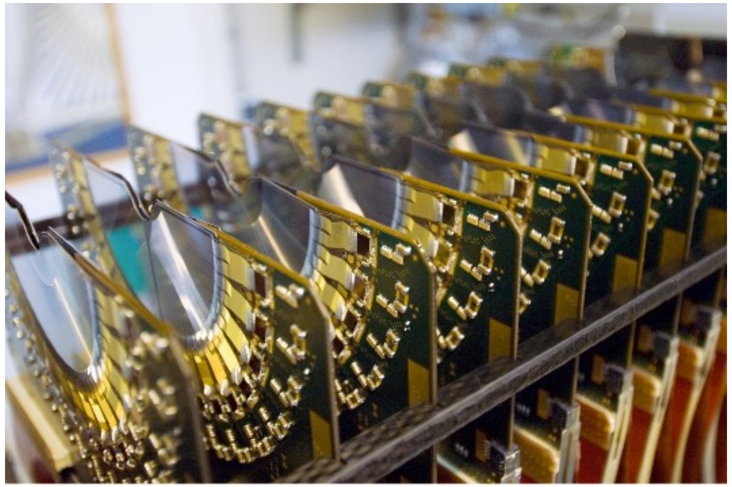
Vertex reconstruction VELO

- **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







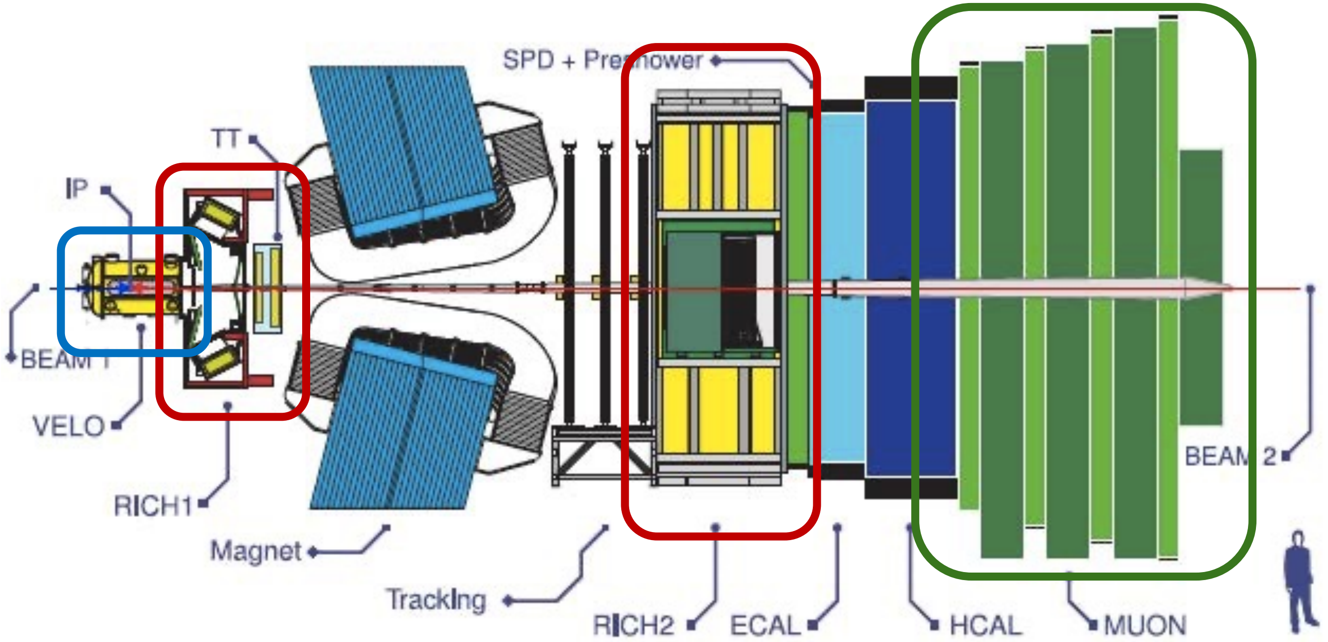


KEY LHCb SYSTEMS FOR PRODUCTION MEASUREMENTS

EPJC 73(2013) 2431
JINST 8 P02022

Particle identification

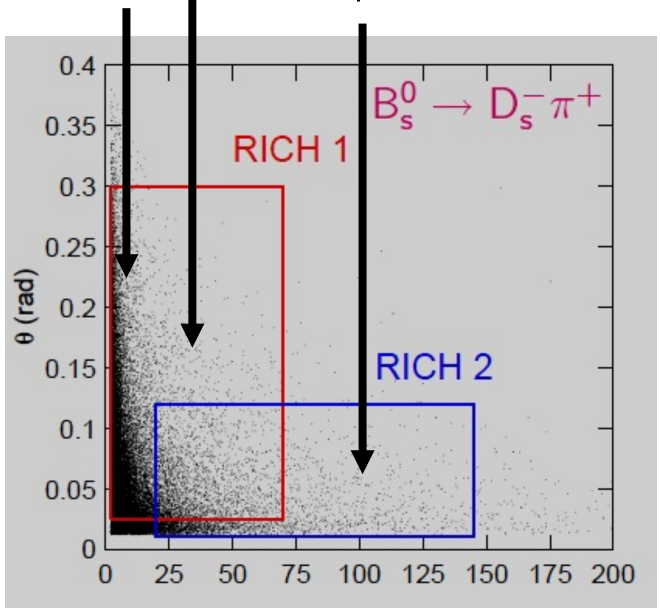
- **2 Ring Imaging Cherenkov Detectors (RICH)**: 3 Radiators covering p_T range 1.5-100 GeV/c
- **Muon detector** – triggering muons and measuring muon momenta
- Particle ID efficiency:
  - $K^{\pm}$ ID ~ 95 % for ~ 5 % $\pi \to K$ mis-id probability
  - $\mu^{\pm}$ ID ~ 97 % for 1-3 % $\pi \to \mu$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



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

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

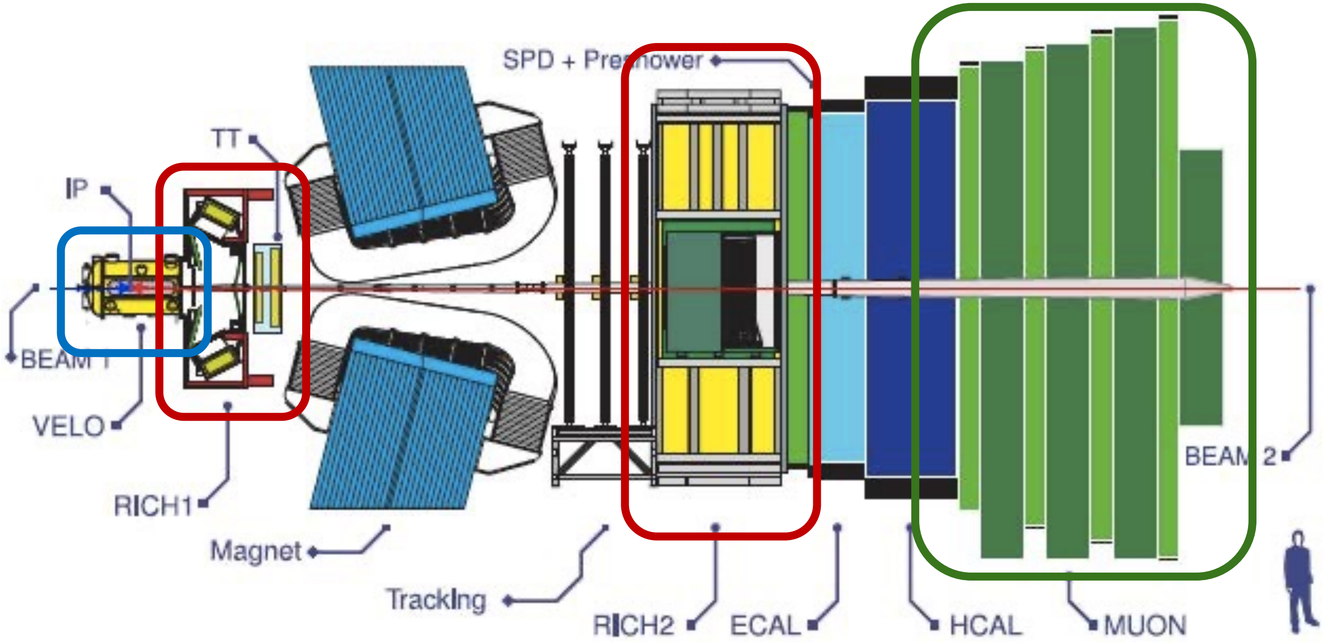
CF_4:
n=1.0005
up to ~100 GeV/c

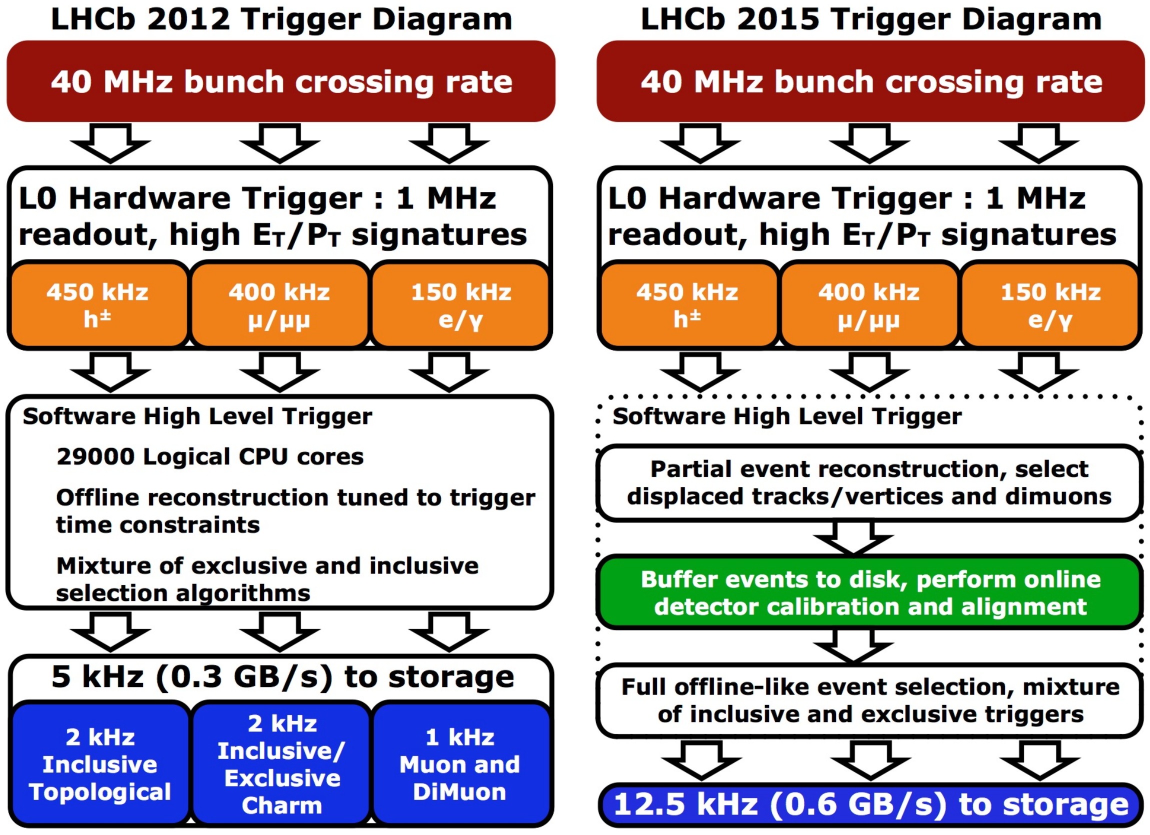


KEY LHCb SYSTEMS FOR PRODUCTION MEASUREMENTS [JINST 14 (2019) P04013]

Trigger

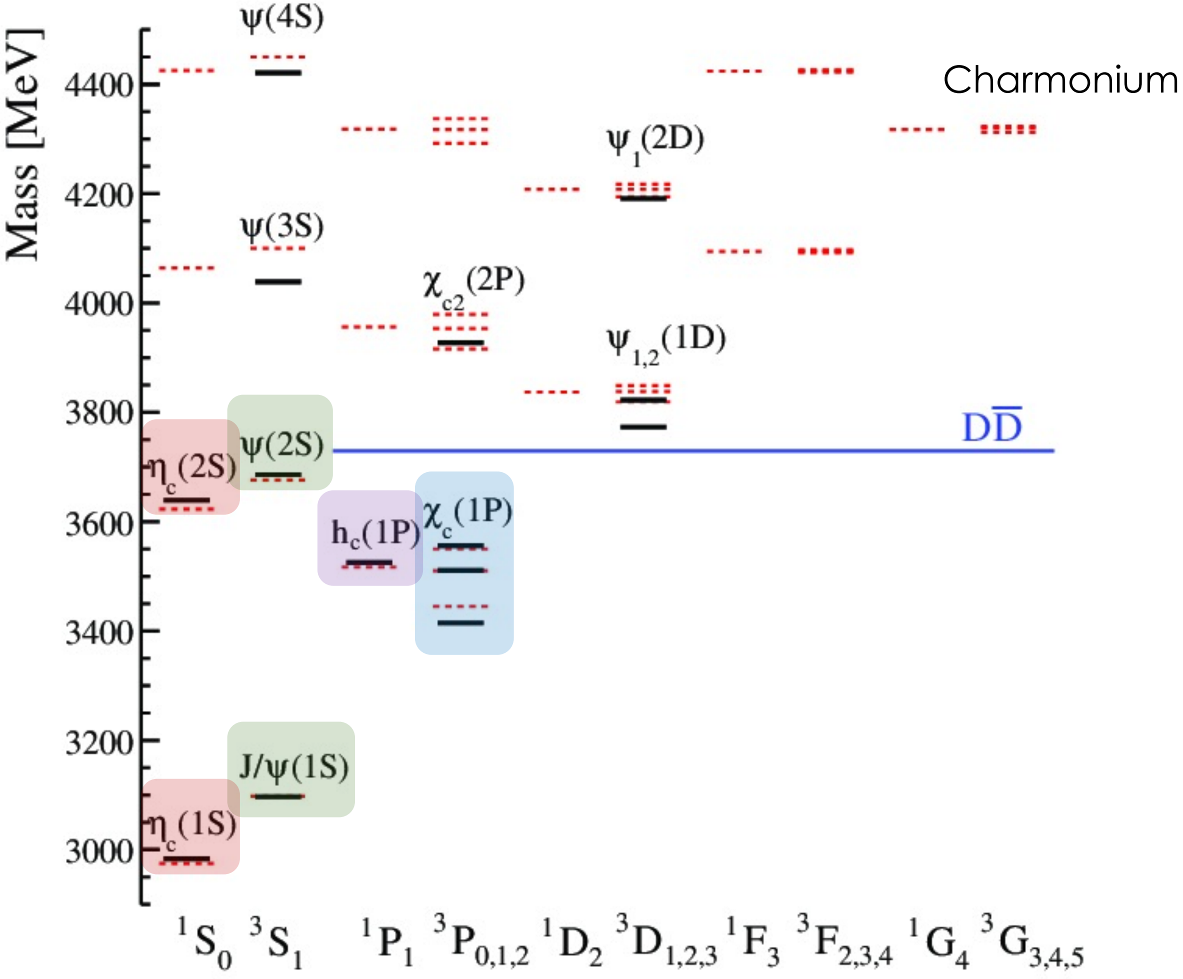
- **Two-level** trigger system
- LHCb detector designed to **trigger on decay products of *b* or c hadrons**: moderate p_T physics
- Trigger efficiency:
  - ~ 90 % for dimuon channels
  - ~ 30 % for multi-body hadronic final states





CHARMONIUM SPECTROSCOPY: LHCb PROGRESS

- Current status of quarkonium spectrum



Final states:

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 …

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

???

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

J/ψ AND ψ(2S) PRODUCTION

- Production measurement via $l^{+}l$ final state
- Cross-section determination in bin[p_T,y]

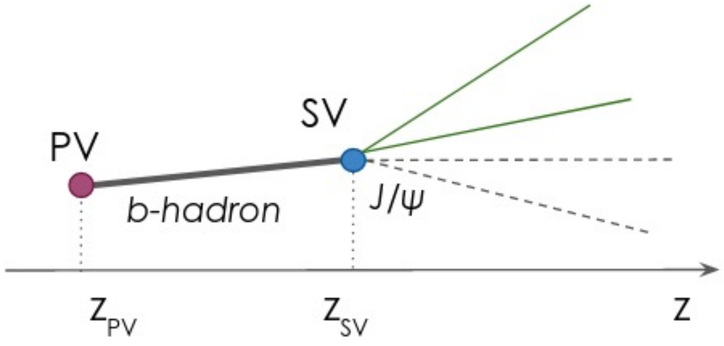
$$\frac{d^2\sigma}{dy dp_T} = \frac{\boxed{N(\psi \to l^+l^-)}}{\boxed{\mathcal{L}} \times \boxed{\varepsilon} \times \mathcal{B}(\psi \to l^+l^-) \times \boxed{\Delta y \times \Delta p_T}}$$

- integrated luminosity
- total efficiency
- number of signal candidates in the given (p_T, y) bin
- bin width

- **Prompt** and ***b*-decay production of charmonium**

distinguished via pseudo-proper decay time:

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

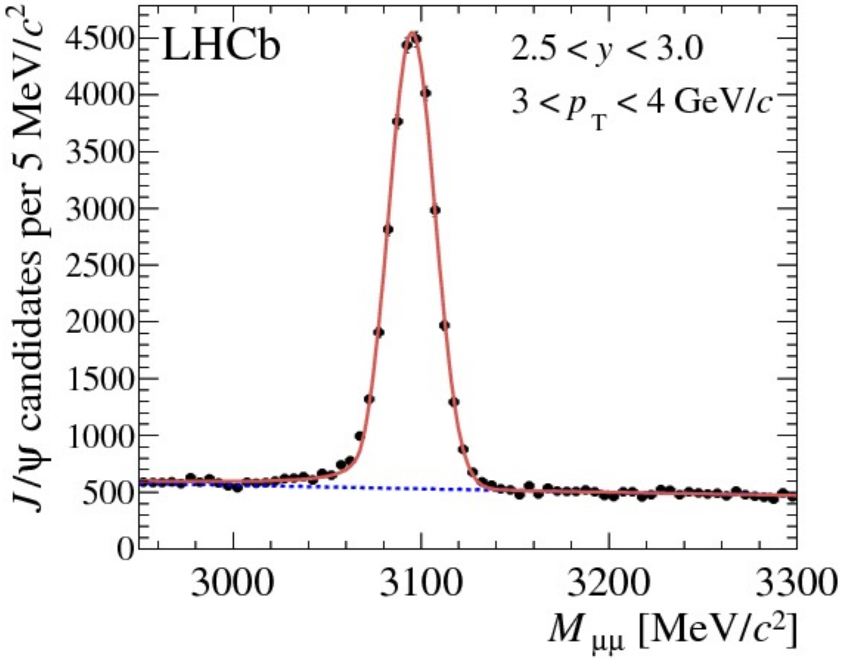


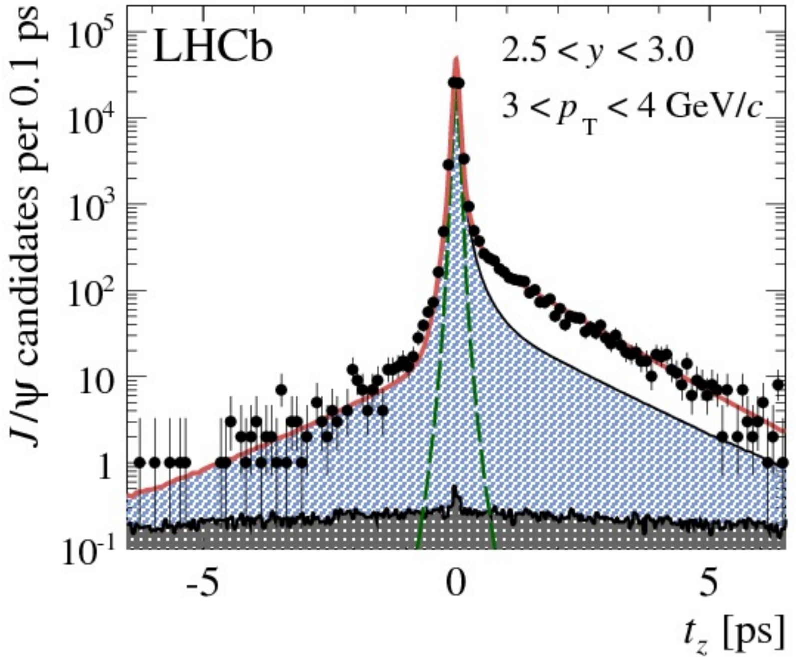
- **Full kinematic range cross-section**

COMBINED MASS-LIFETIME FITS

[Eur. Phys. J. C 71(2011) 1645]

- **Prompt** and **b-decay production** distinguished via decay time value: $\boldsymbol{t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{\mu\mu}}$





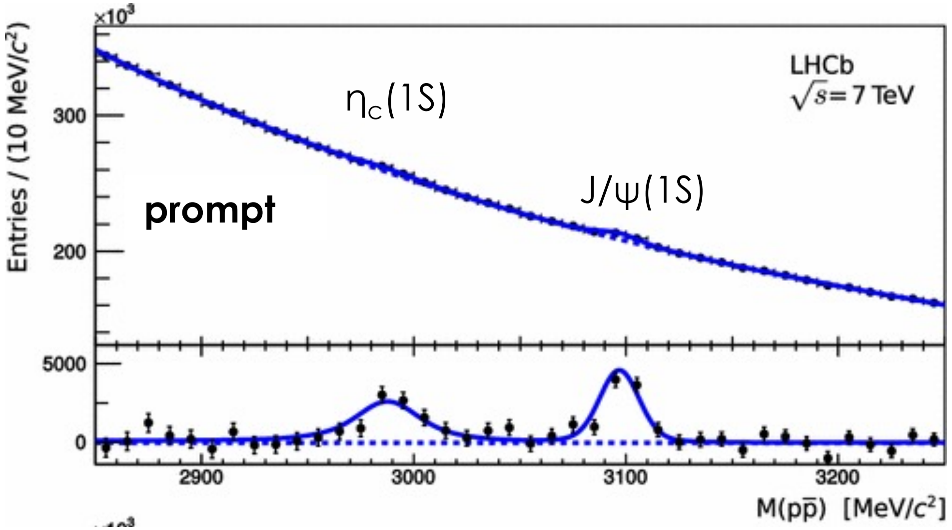
- Unbinned maximum likelihood fit in bins of **[p_T, y]** to $M_{\mu^+\mu^-}$ and t_z
- **Relatively low background =>**

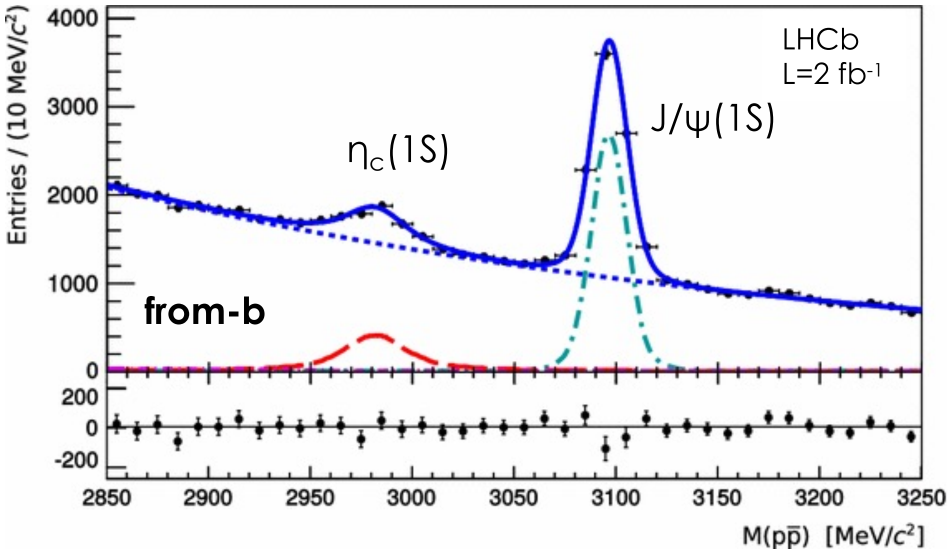
	$N(J/\psi)/N(bkg)$
b-decays	$>1\text{x}10^{-2}$
prompt	**$>1\text{x}10^{-1}$**

$\eta_c(1S)$ 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 =>**

	$N(J/\psi)/N(bkg)$	$N(\eta_c)/N(bkg)$
b-decays	$<8\times10^{-2}$	$<3\times10^{-2}$
prompt	$<4\times10^{-4}$	**$<4\times10^{-4}$**

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

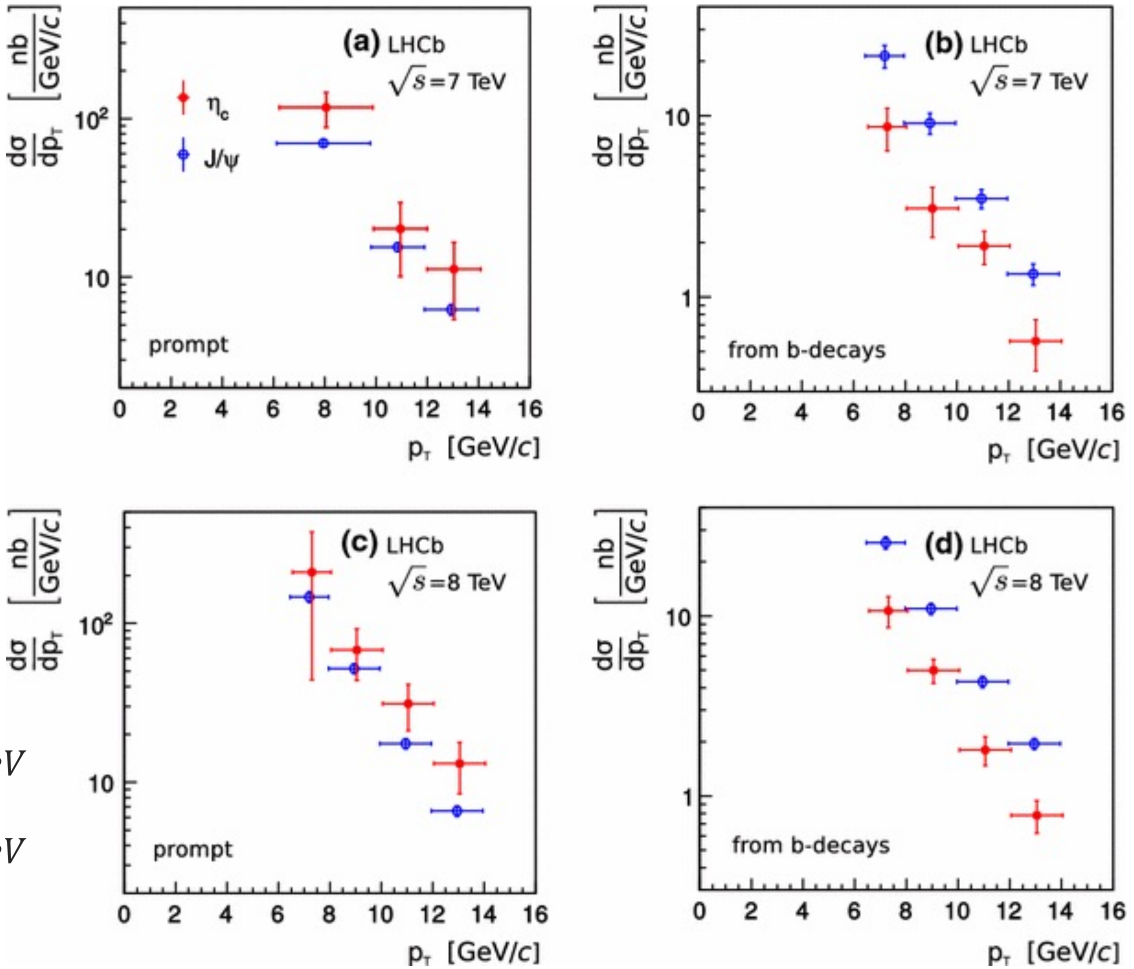
- Measurement of **p_T-differential production cross-sections**, experimental precision is worse than theoretical one
- **Strong impact on theory models**: contrary to theory expectations, $\eta_C(1S)$ prompt production entirely described by CS contribution
- **$\eta_c(1S)$ production:**

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

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

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

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



η_c PRODUCTION AT THE LHC

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

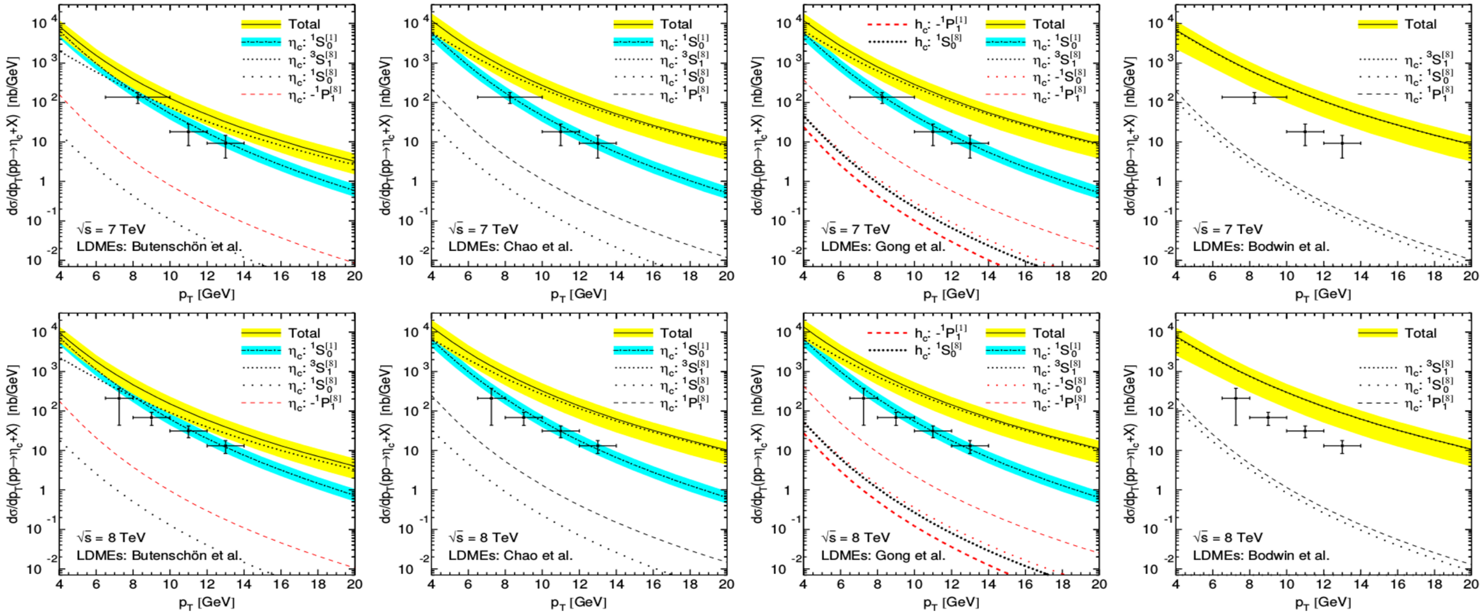
- **η_c(1S) LDMEs** determined

  from known HQSS relation for J/ψ

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

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

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



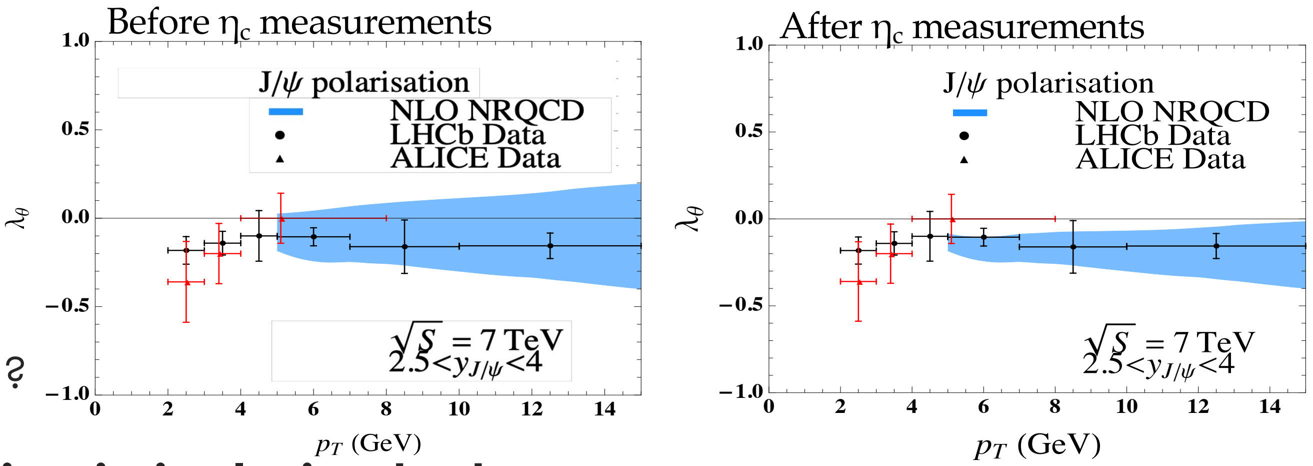
- Direct projection to LHCb data
- **LHCb data saturated by CS contribution**
- Tension in simultaneous description of η_c production and J/ψ production and polarization?
- **Recent progress in theory**:
  - Phys.Rev.Lett. 114(2015), 092005
  - Phys.Rev.Lett. 114(2015), 092006
  - Eur.Phys.J.C 75(2015) 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

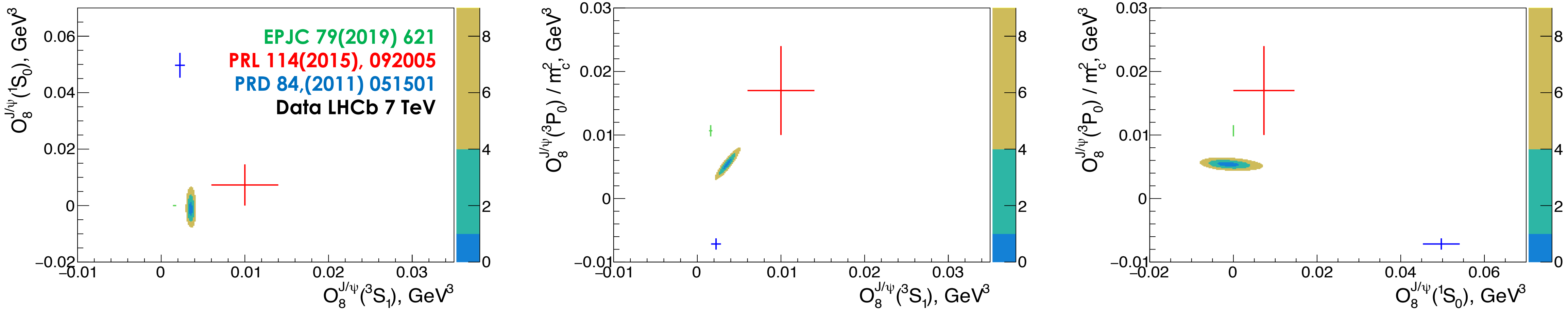
[PRL 114(2015), 092005](#)
[arXiv:1910.08796](#)

- 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](#)

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

- Cross-section determination:

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

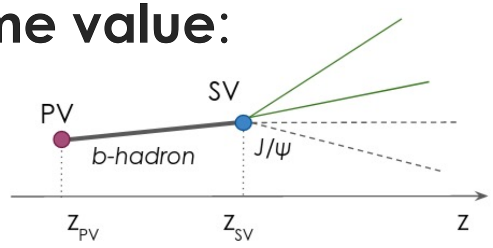
$$\frac{\mathcal{B}_{b\to\eta_c X}}{\mathcal{B}_{b\to J/\psi X}} = \boxed{\frac{N^b_{\eta_c}}{N^b_{J/\psi}}} \times \boxed{\frac{\mathcal{B}_{J/\psi\to p\bar{p}}}{\mathcal{B}_{\eta_c\to p\bar{p}}}} \times \boxed{\frac{\epsilon_{J/\psi\to p\bar{p}}}{\epsilon_{\eta_c\to p\bar{p}}}}$$

- Extracted from DATA
- Calculated from PDG:

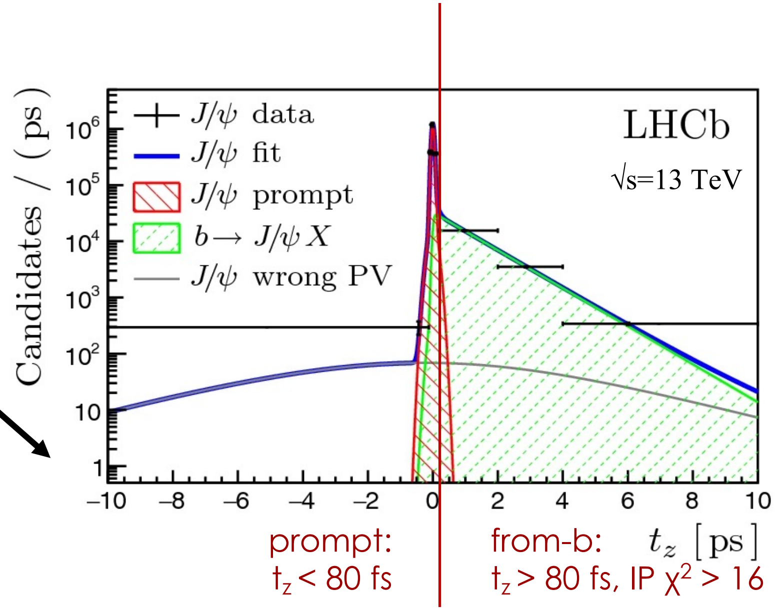
$$\mathcal{B}_{J/\psi\to p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3}$$
$$\mathcal{B}_{\eta_c(1S)\to p\bar{p}} = (1.45 \pm 0.14) \times 10^{-3}$$

- From Simulation

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



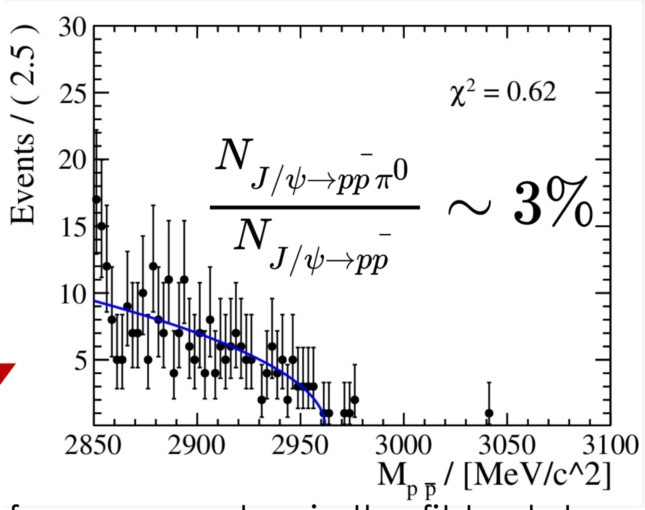
$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$$



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

MASS SIGNAL AND BKG. PARAMETRIZATION

- **Signal:**
  - J/ψ: DG(σ_n, σ_w, f_n) x δ(m(J/ψ))
  - η_c: DG(σ_n, σ_w, f_n) x RBW(m(η_c))
- **Background:**
  - J/ψ→ppπ^0 contribution $\sqrt{M_{J/\psi} - M_{\pi^0} - M_{p\bar{p}}}$, $M_{p\bar{p}} < (M_{J/\psi} - M_{\pi^0})$
  - Combinatorial: exp x pol(2)



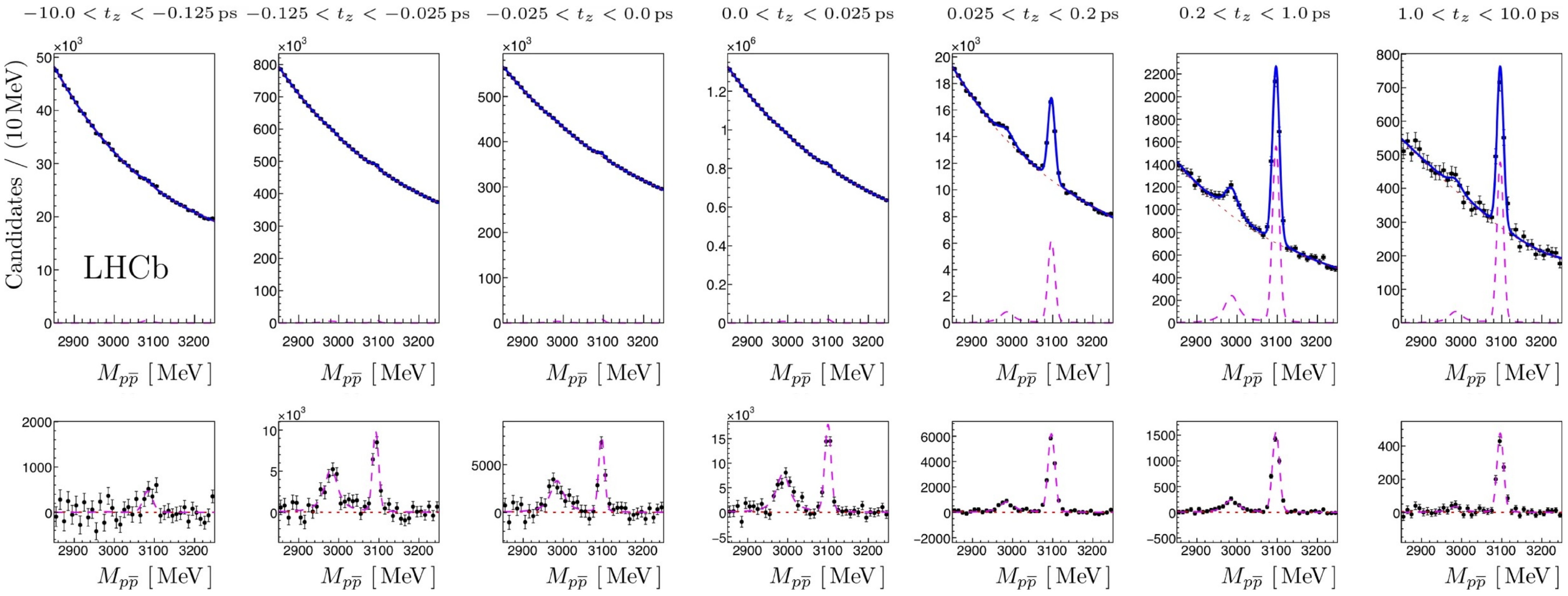
No free parameters in the fit to data.
Yield is bound to yield of J/ψ->pp

Parameter	
σ_n/σ_w	fixed from MC
f_n	fixed from MC
$\sigma_{\eta_c}/\sigma_{J/\psi}$	fixed from MC
σ_{η_c}	common free parameter, linear slope of p_T-dependence extracted from MC
$m_{J/\psi} - m_{\eta_c}$	common free parameter for all fits in bins of t_z and p_T
$m_{J/\psi}$	common free parameter for all fits in bins of t_z and p_T
Γ_{η_c}	fixed world average from Ref. [41] (31.8 MeV/c^2)
$\Delta m_{(t_z)}$	fixed from MC in each t_z bin
$\alpha_{(t_z)}$	fixed from MC in each t_z bin

t_Z-FIT TECHNIQUE

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

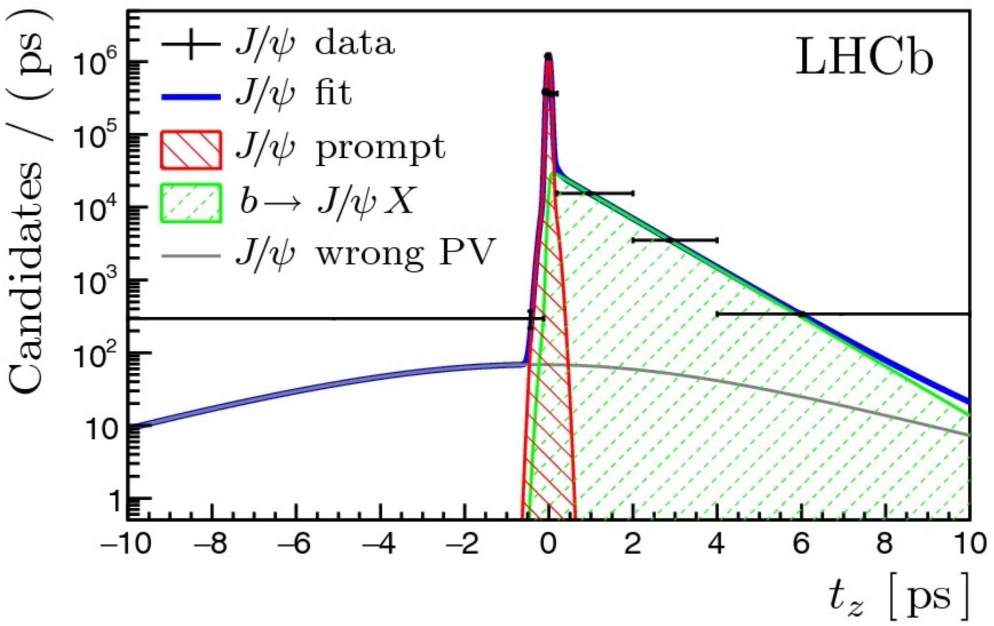
$6.5 < p_T < 14$ GeV, $2.0 < y < 4.5$

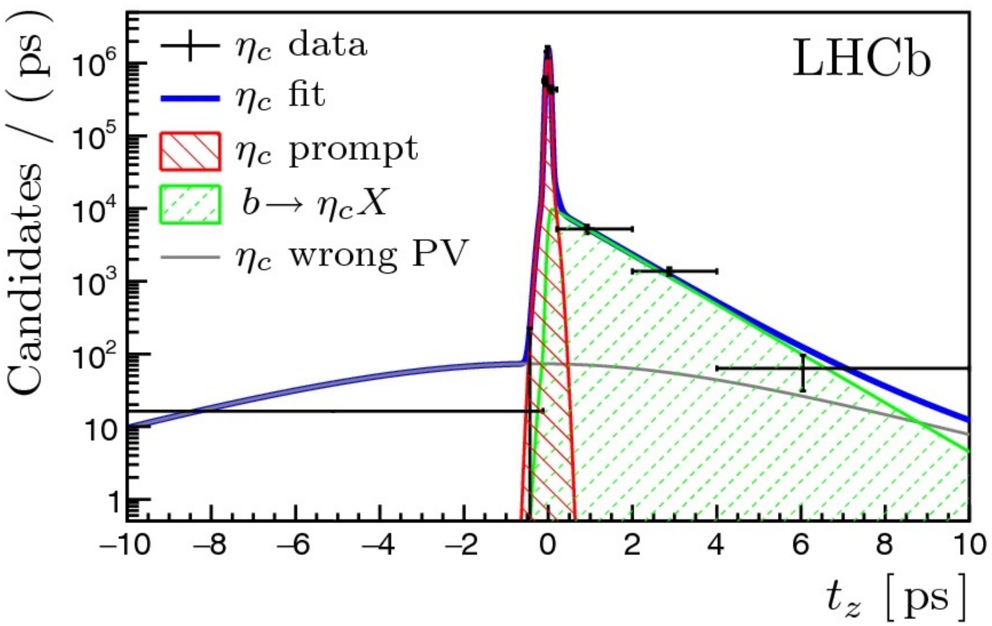


- Simultaneous likelihood **fit to $M_{p\bar{p}}$** in bins of **$[p_T, t_z]$ to extract charmonium yields**
- η_c mass correction applied in bins of t_z

t_Z-FIT TECHNIQUE

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





$$F^{\eta_c}(t_z) = \left(\boxed{N_p\delta(t_z)} + \boxed{\frac{N_b}{\tau_b}\exp -t_z/\tau_b}\right) * \boxed{DG(\mu, S_{J/\psi}, S_n/S_w, \beta)} + \boxed{N_t f_{tail}(t_z)}$$

prompt ccbar

ccbar from *b*-decays

t_z-resolution

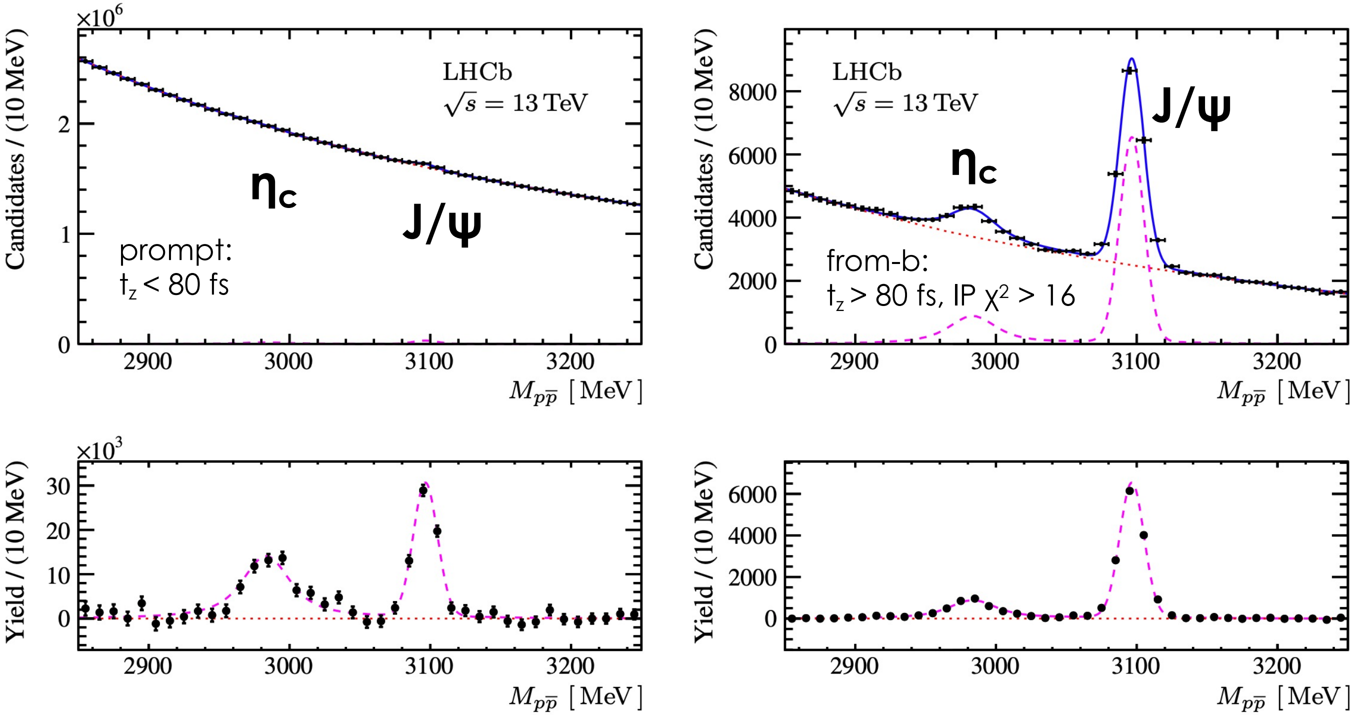
events with mismatched PV

- Simultaneous integral χ^2 **fit to t_z** in p_T-bins **to separate prompt** and **from *b*-decays charmonium**

t_Z-CUT TECHNIQUE

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

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



- Relative charmonium yields:

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

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

- 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:

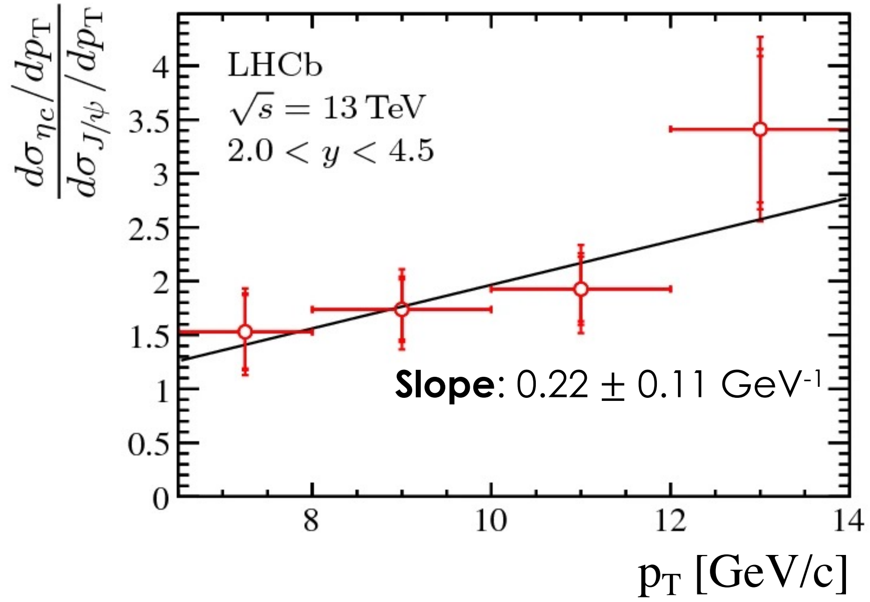
$$\Delta M_{J/\psi,\eta_c} = 113.0\ \pm 0.7_{stat} \pm 0.1_{syst} MeV$$

- Result is consistent with t_z-fit 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, $2.0 < y < 4.5$

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

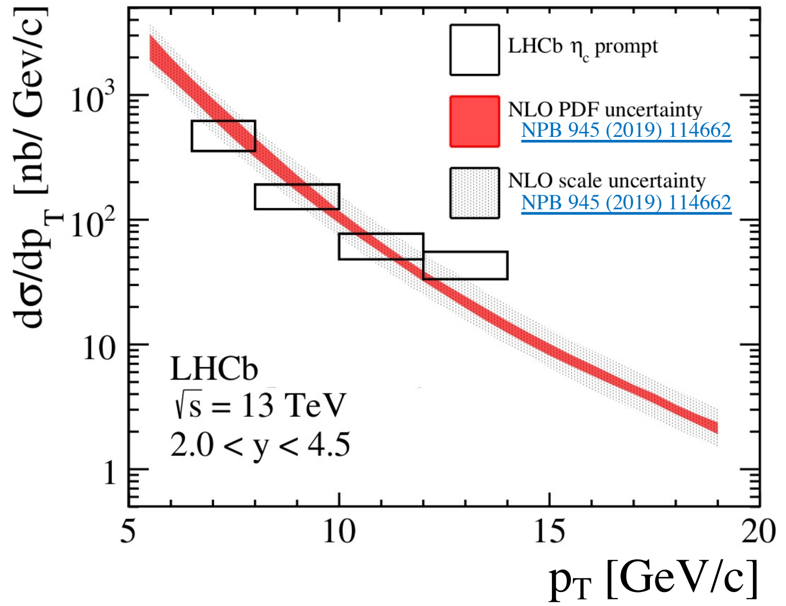
$$\mathfrak{B}_{b\to\eta_c X}/\mathfrak{B}_{b\to J/\psi X} = 0.48 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.05_{\mathfrak{B}_{c\bar{c}\to p\bar{p}}}$$

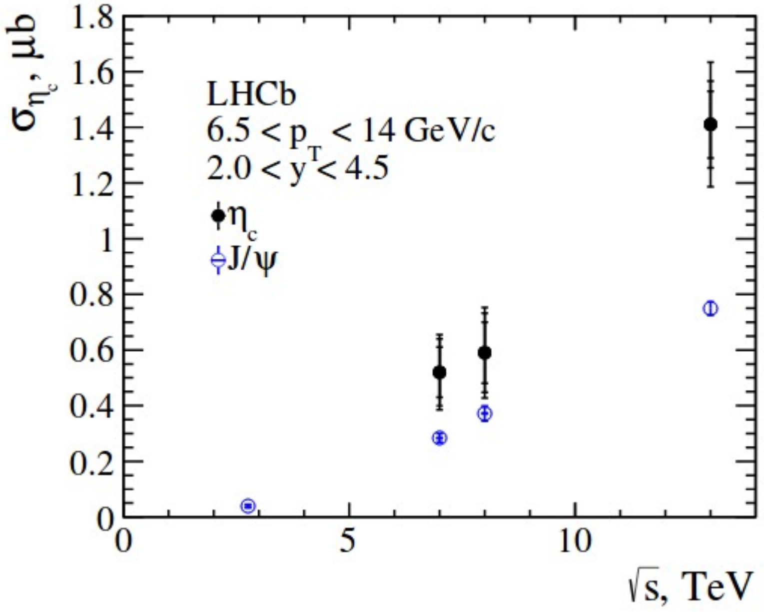
- Measurement in extended p_T is required
- **Larger slope** would indicate **possible CO contribution**
- **Interpretation of η_c(2S)/ψ(2S) much more clean** than of η_c(1S)/J/ψ due to absence of feed-down contributions

INTEGRATED AND DIFFERENTIAL CROSS-SECTIONS

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

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





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

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

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

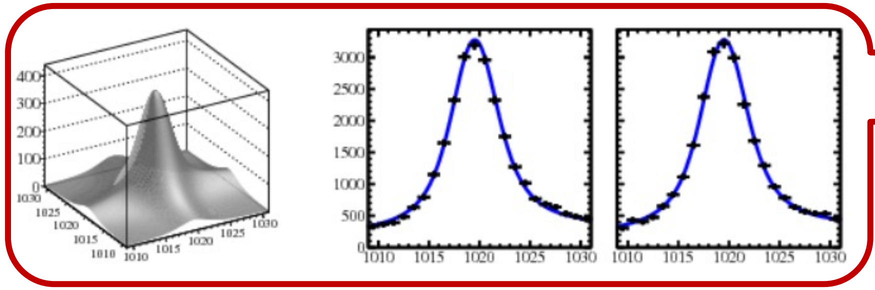
$$\mathfrak{B}_{b\to\eta_c X} = (5.51 \pm 0.32_{stat} \pm 0.29_{syst} \pm 0.77_{J/\psi})\times 10^{-3}$$

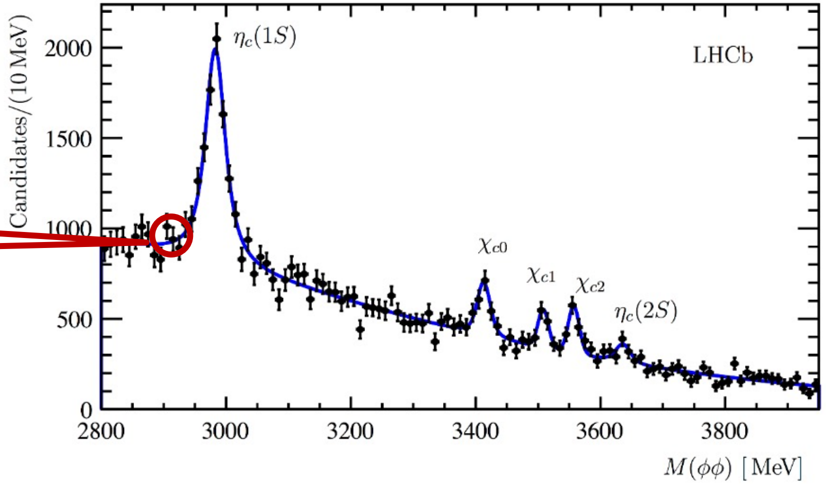
- **$\eta_c(1S)$ production can be described by CS contribution only**

η_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

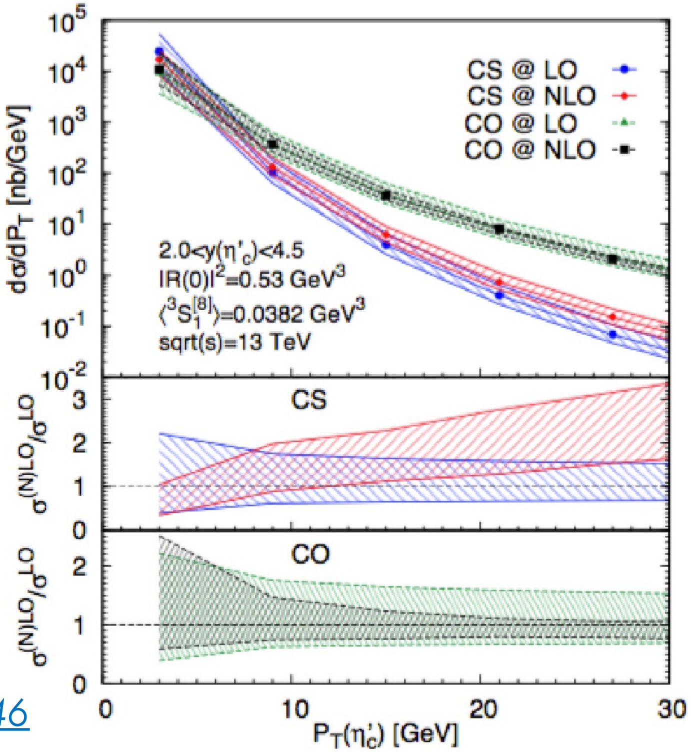




- First measurement of $\eta_c(2S)$ production in b-decays; first evidence for $\eta_c(2S) \to \phi\phi$

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

- **Important to measure $\eta_c(2S)$ hadroproduction**:
  - theory prediction ⇒
  - **dedicated LHCb trigger in 2018**
- **Prompt $\eta_c(1S)$ production measurement?**



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

SUMMARY

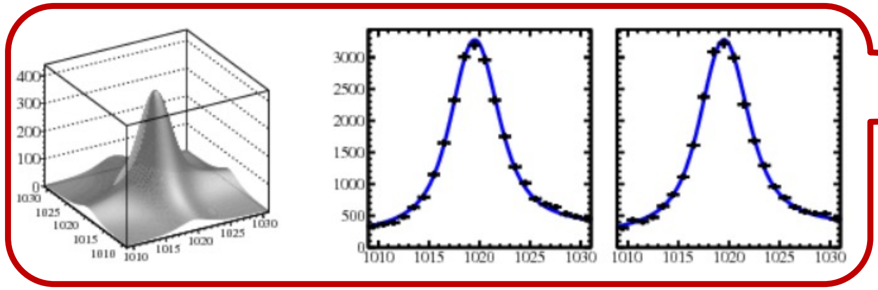
- **$\eta_c(1S)$ hadroproduction** can be measured using **only hadronic decays**
  - challenging background conditions
- **Current progress**:
  - prompt $\eta_c(1S)$ measured at 7, 8 and 13 TeV via pp
  - $\eta_c(1S)$ production from b-decays measured via $\phi\phi$
  - first evidence of $\eta_c(2S)$ production
- **LHCb results allow to perform powerful tests of QCD and constrain theory**
  - $\eta_c(1S)$ prompt production measurement constrains CO LDMEs
- **Prospects for future study:**
  - **$\eta_c(1S)$** production in extended kinematic range
  - **$h_{c,b}$** 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

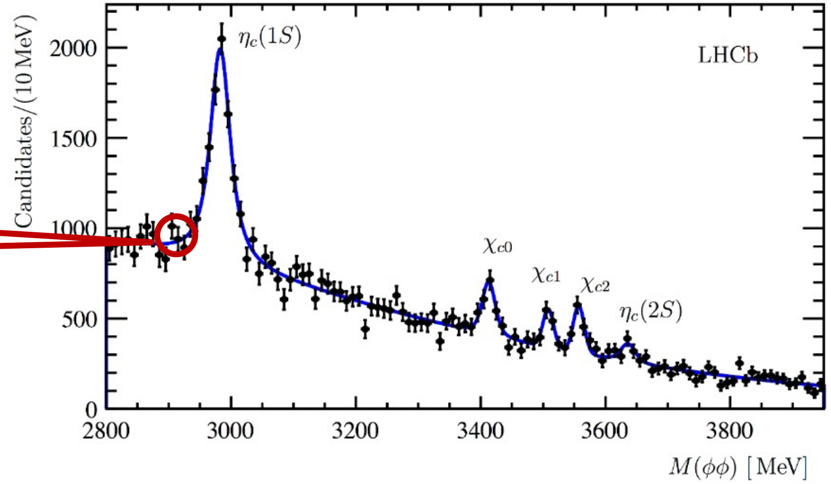
BACKUP

χ_c PRODUCTION IN *b*-DECAYS AT LHCb

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

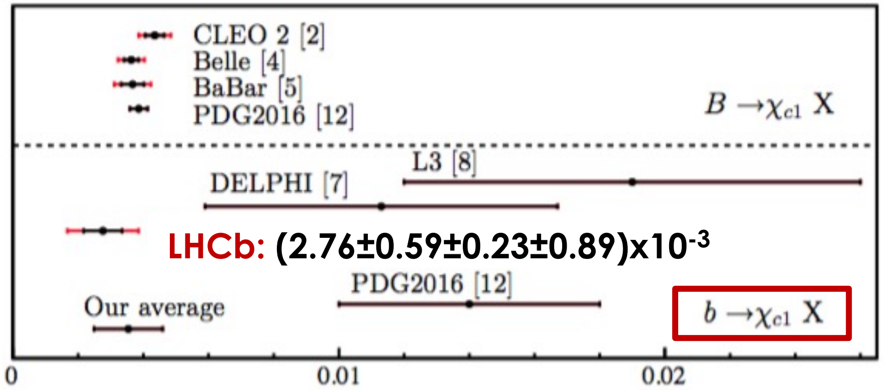
- Charmonium reconstructed via **decays to φφ**;
  true φφ combinations extracted using 2D fit technique

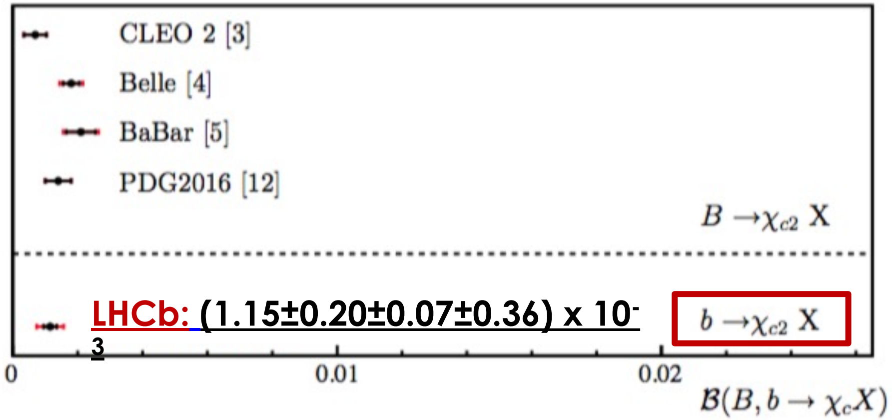




- **First measurement of χ_{c0}** production in b-decays:
  $\mathcal{B}(b \to \chi_{c0} X) = (3.02 \pm 0.47_{stat} \pm 0.23_{syst} \pm 0.94_{\mathcal{B}}) \times 10^{-3}$

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

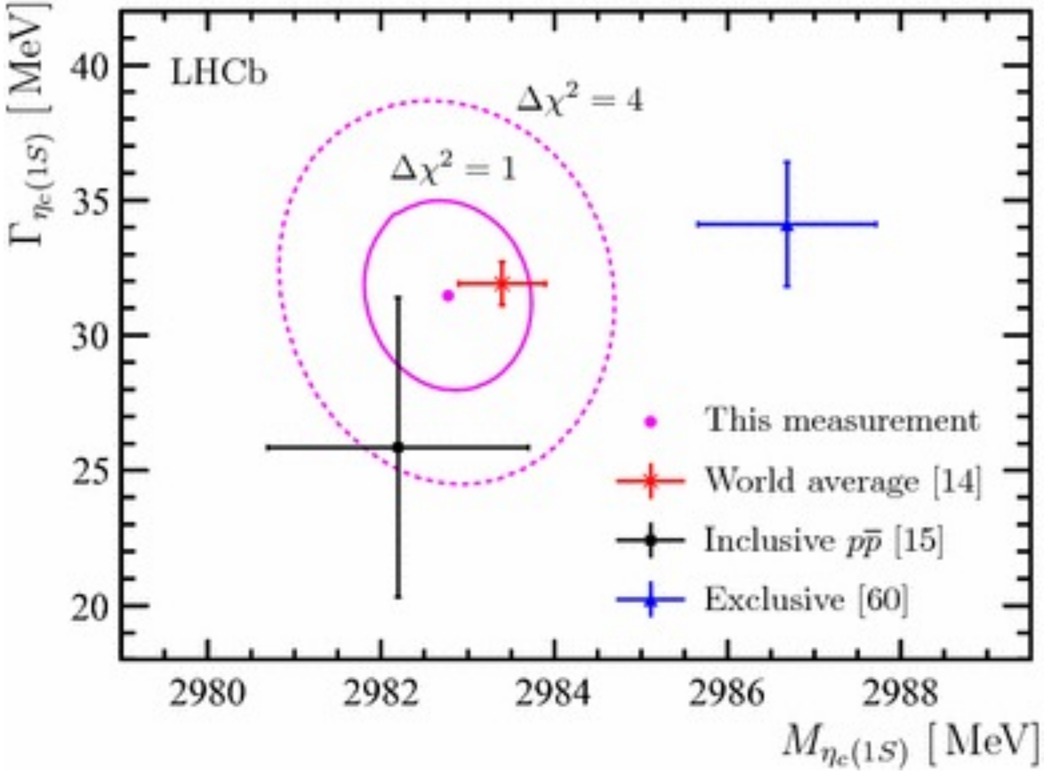




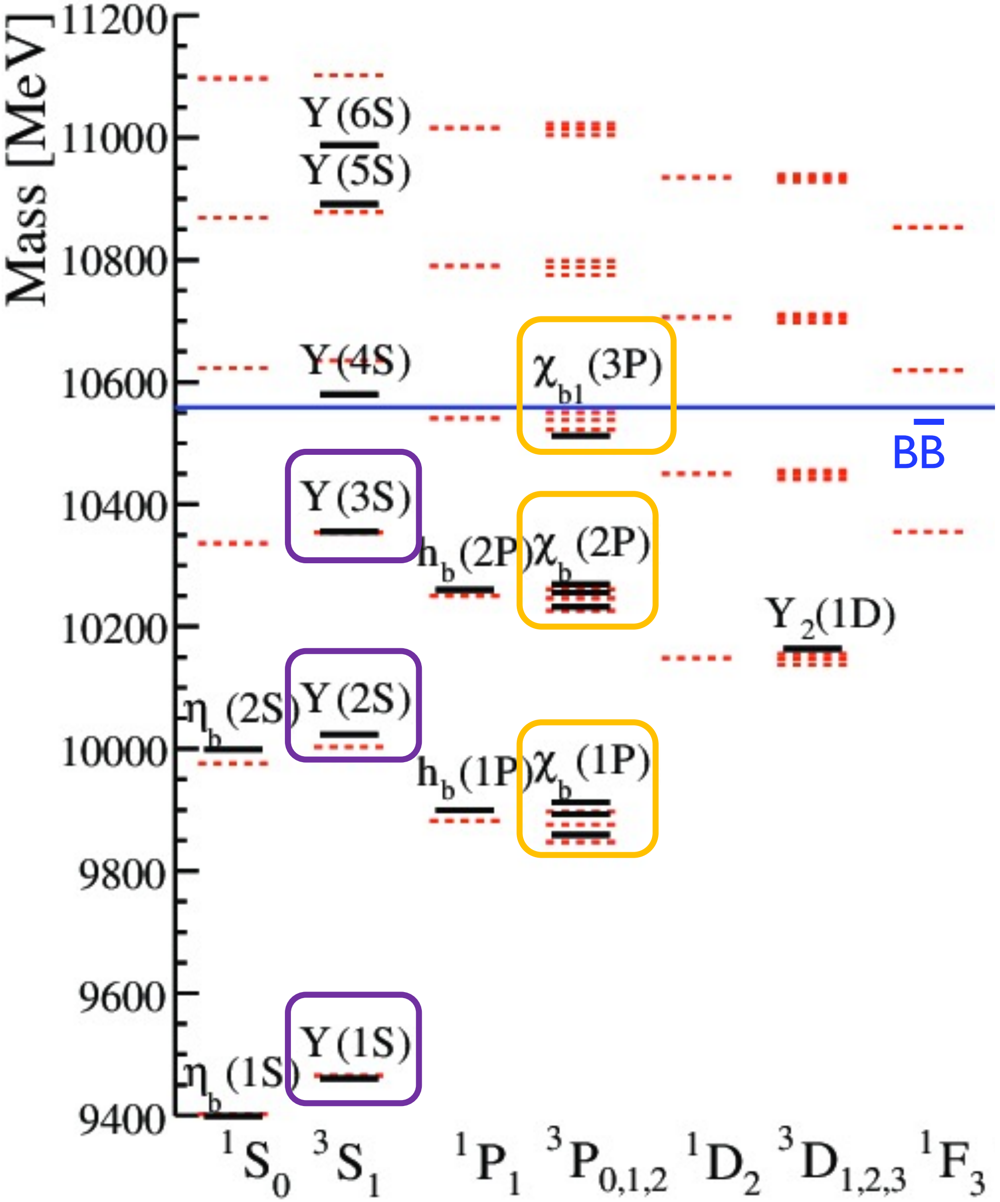
- **Promising channel to study χ_c polarizarion** [Phys.Rev.D 103 (2021) 9, 096006]

η_C MASS MEASUREMENT

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



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

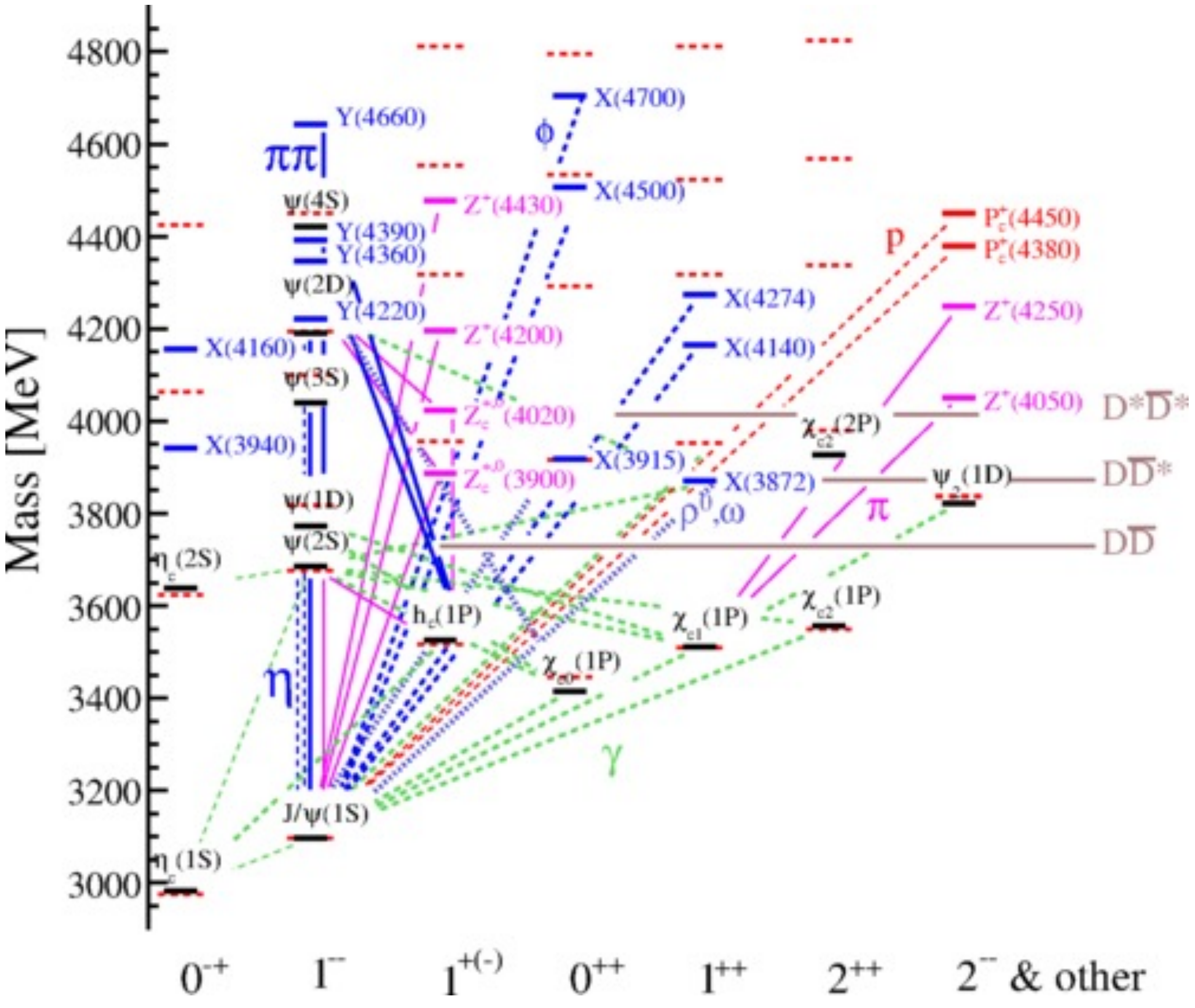
Prospects:

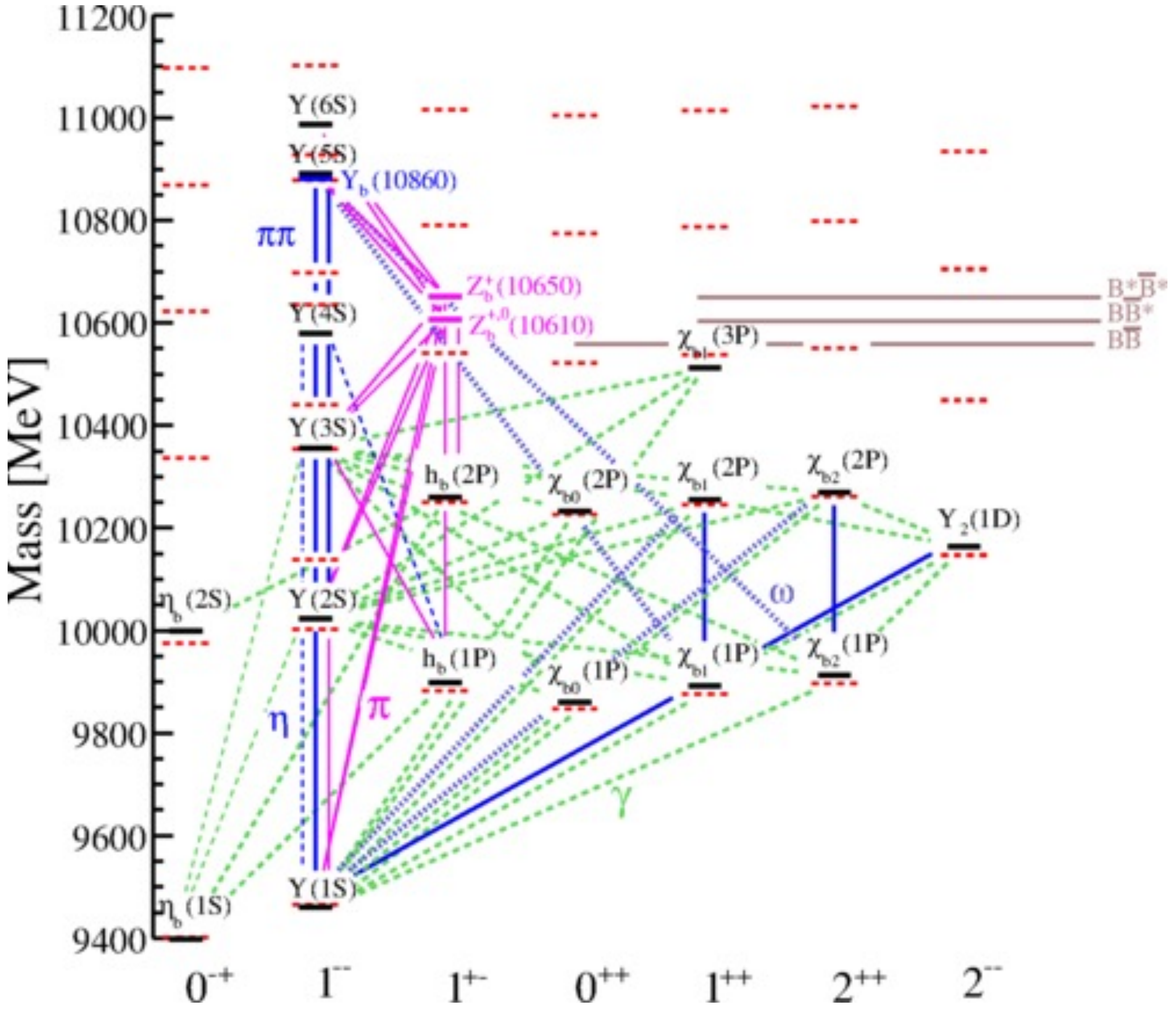
- h_b and η_b(1S) production

Rev.Mod.Phys 90 (2018) 015003

QUARKONIUM DECAYS

- Possible transitions between quarkonium states





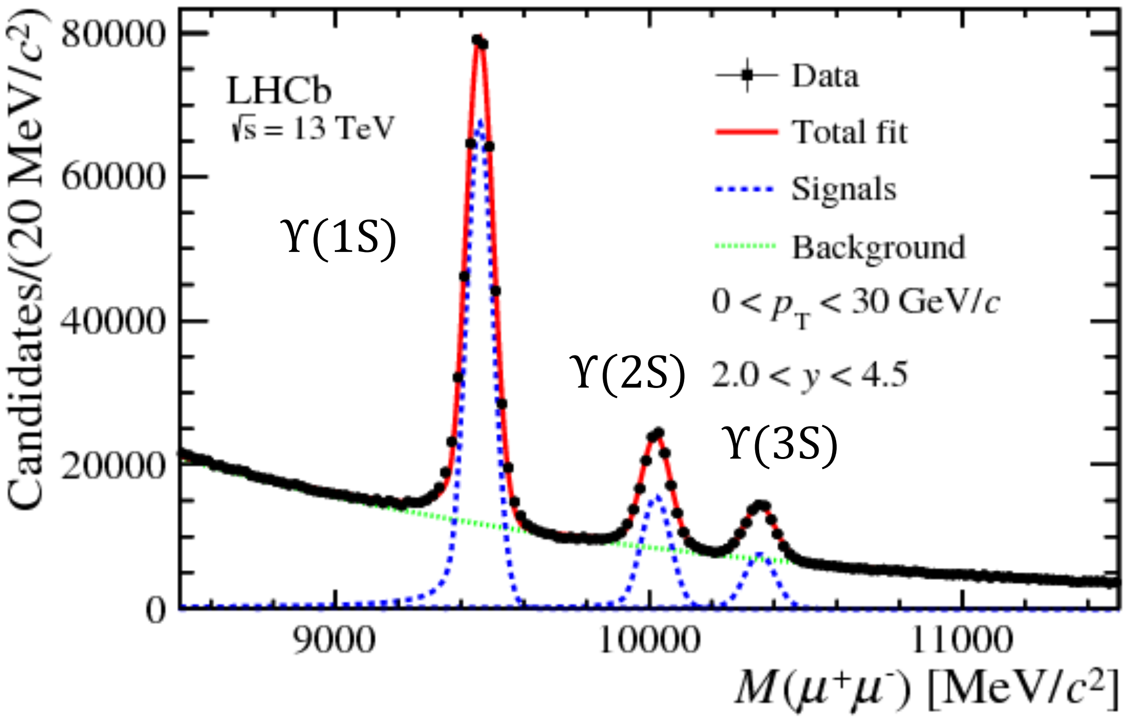
Υ(nS) PRODUCTION AT √s=13 TeV

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)

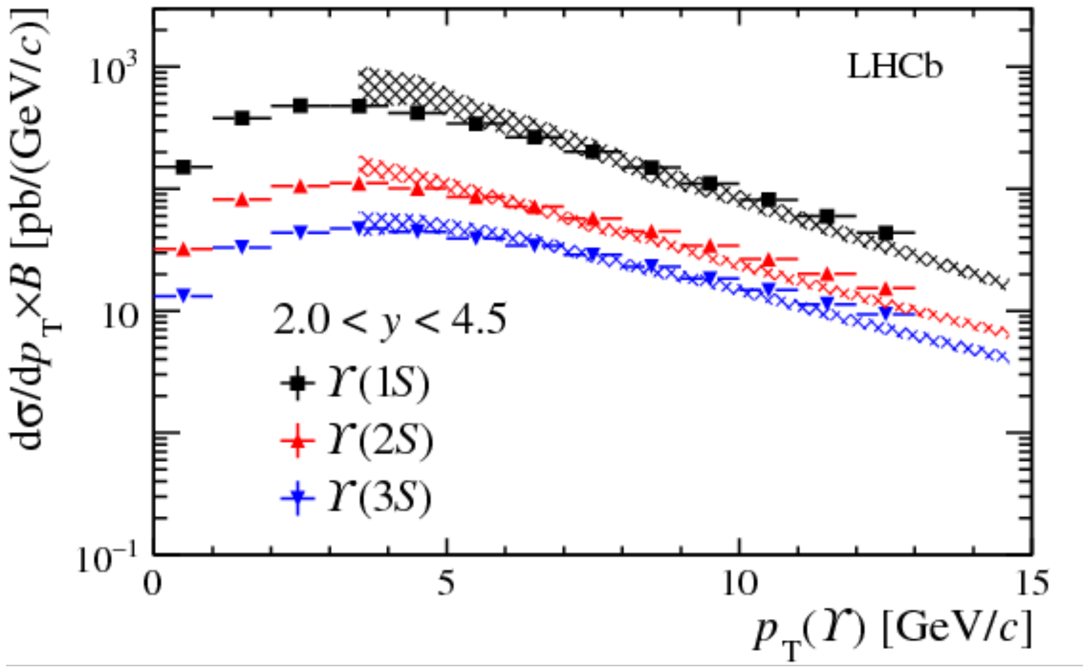
$$\frac{d^2\sigma}{dydp_T} = \frac{N(\Upsilon \to \mu^+\mu^-)}{\mathcal{L} \times \varepsilon_{tot} \times \mathcal{B}(\Upsilon \to \mu^+\mu^-) \times \Delta y \times \Delta p_T}$$

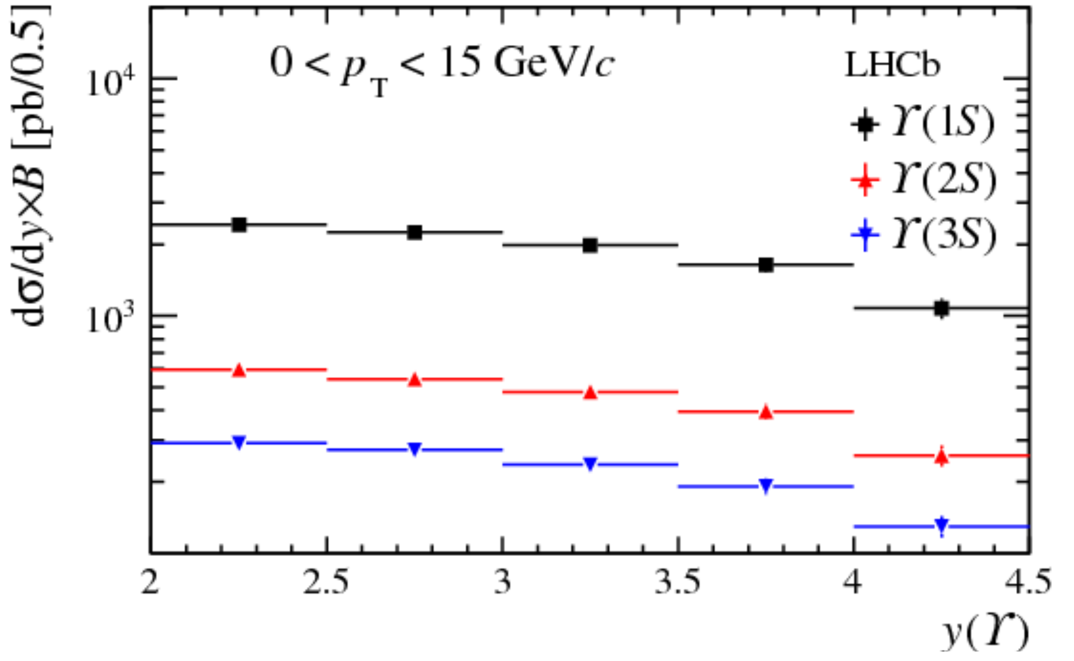


- Unbinned likelihood fit in bins of **[p_T, y]** to $M_{\mu\mu}$ **to extract Υ(nS) yields**

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