



# STUDY OF CHARMONIUM PRODUCTION VIA $p\bar{p}$ DECAY AT THE LHCb EXPERIMENT

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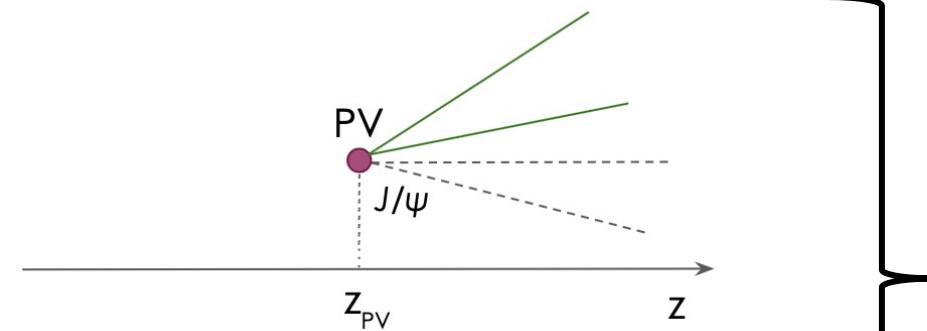
GDR-InF

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# CHARMONIUM PRODUCTION

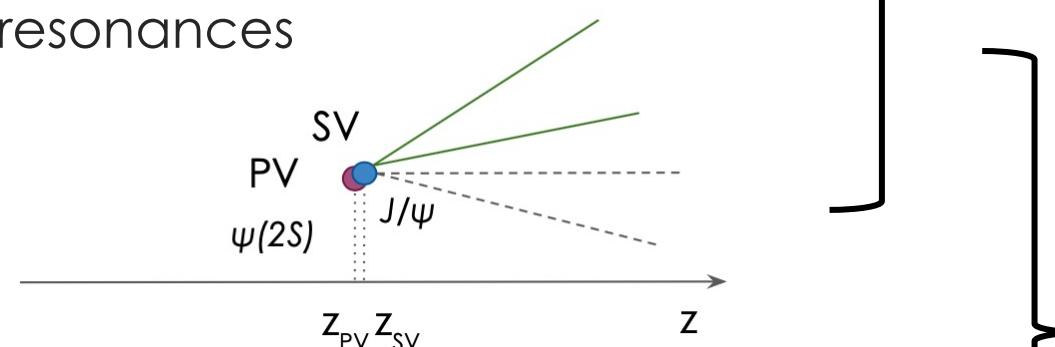
- Sources of charmonium:

- prompt hadroproduction



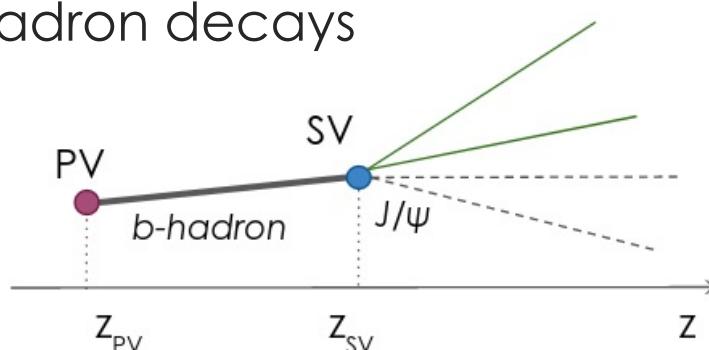
prompt production

- decays of higher resonances



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

- production in b-hadron decays



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;

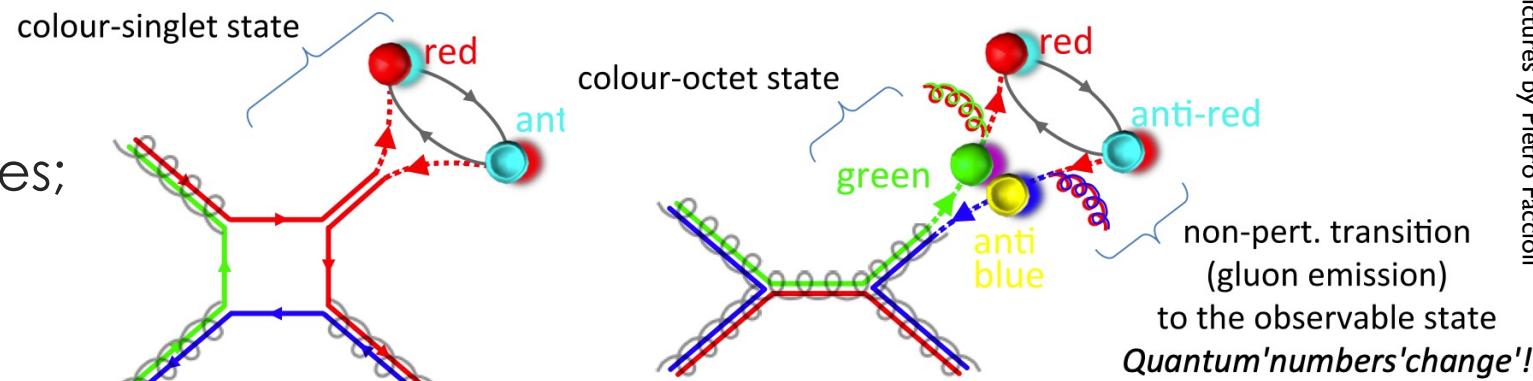
# QUARKONIUM PRODUCTION IN NRQCD

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

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

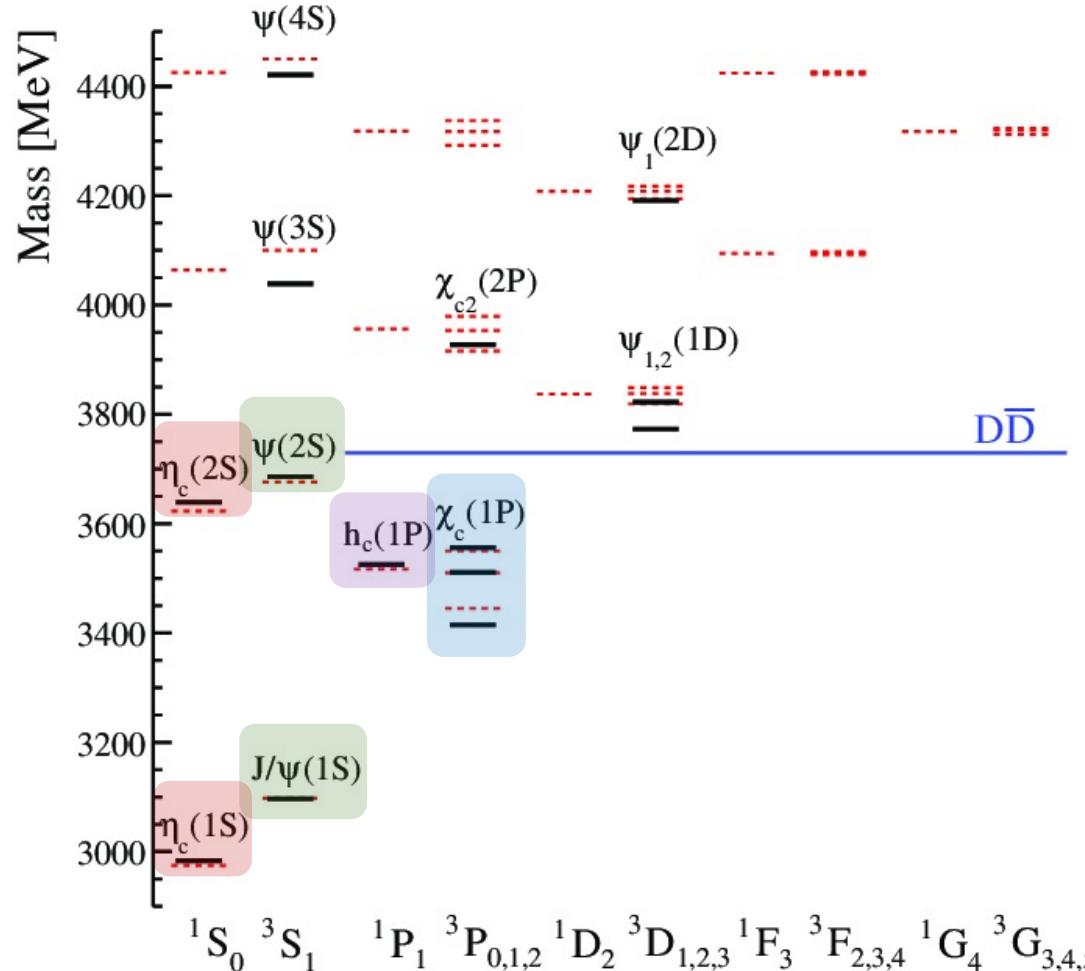
**Long distance matrix elements (LDMEs),**  
non-perturbative part

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



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

- Current status of charmonium spectrum



Final states:

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

$J/\psi\gamma$  or hadrons

hadrons

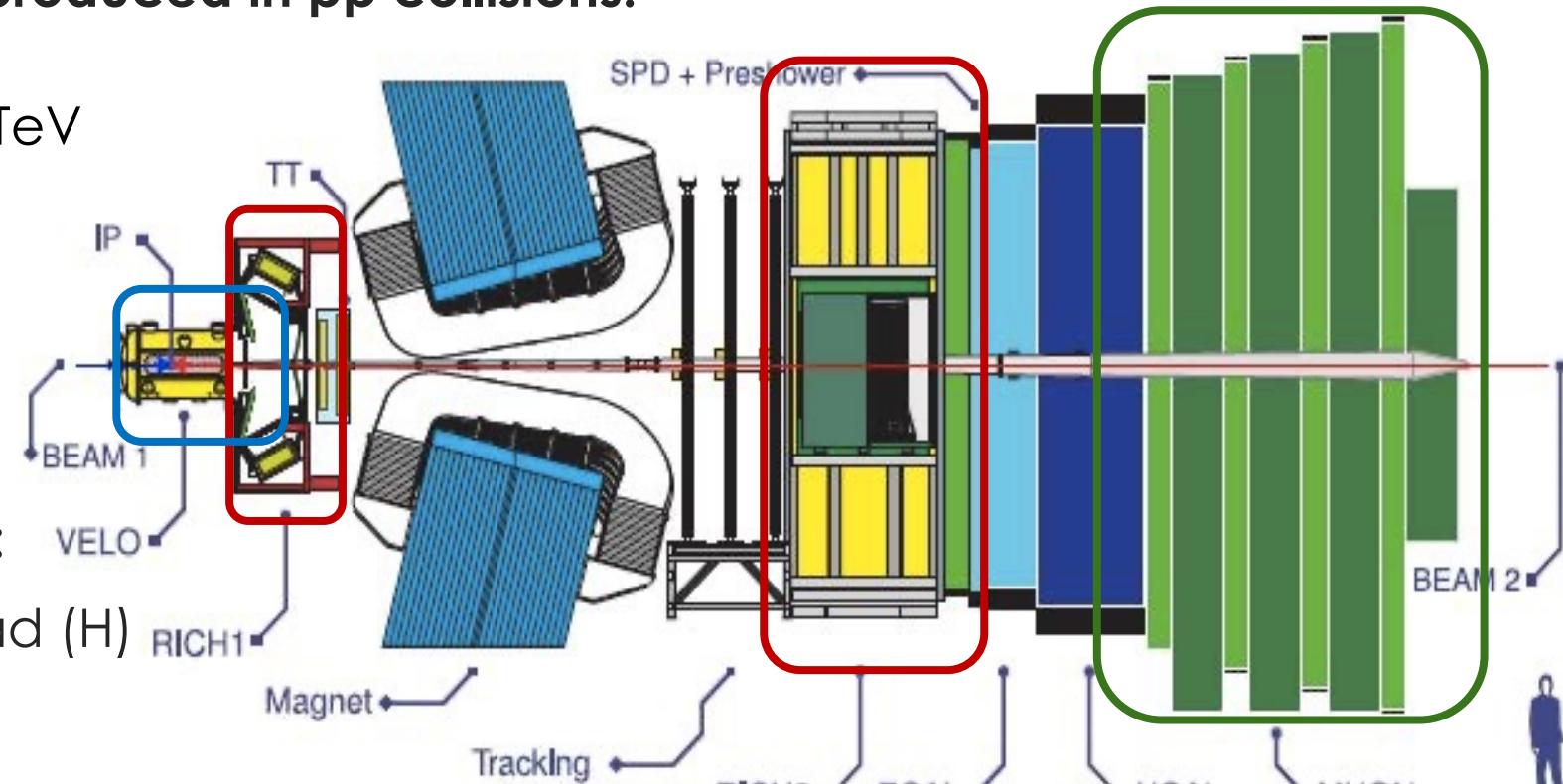
$\eta_c(1S)\gamma$  or hadrons

- Hadronic final states allow to study different quarkonium states simultaneously

- Large number of  $b\bar{b}$  and  $c\bar{c}$  pairs produced in pp collisions:

- $\sigma_{b\bar{b}} \sim 0.5$  mb
- $\sigma_{c\bar{c}} \sim 3.0$  mb

in LHCb @  $\sqrt{s} = 13$  TeV



- Single-arm forward spectrometer:

10-250 mrad (V), 10-300 mrad (H)

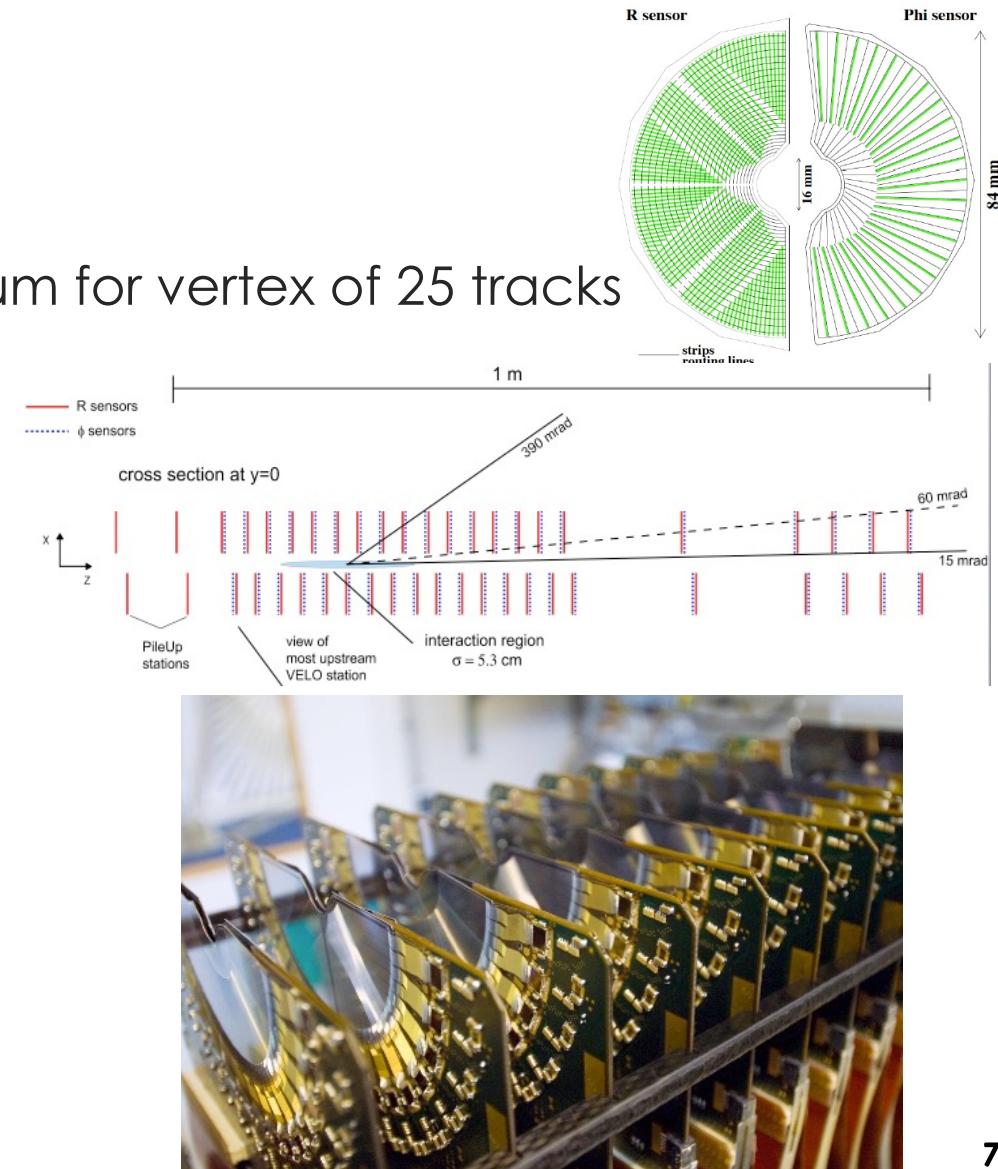
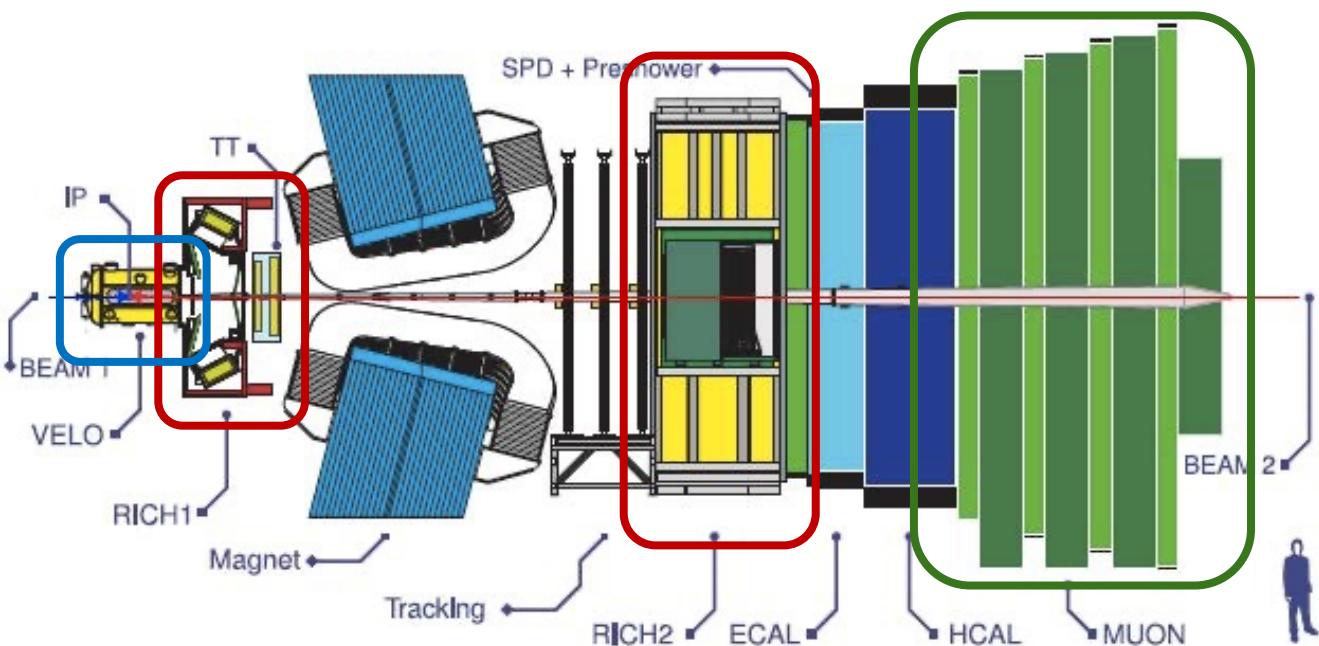
- Forward region  $2.0 < \eta < 5.0$ ,  
~4% of solid angle,

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

## Vertex reconstruction **VELO**

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



## Particle identification

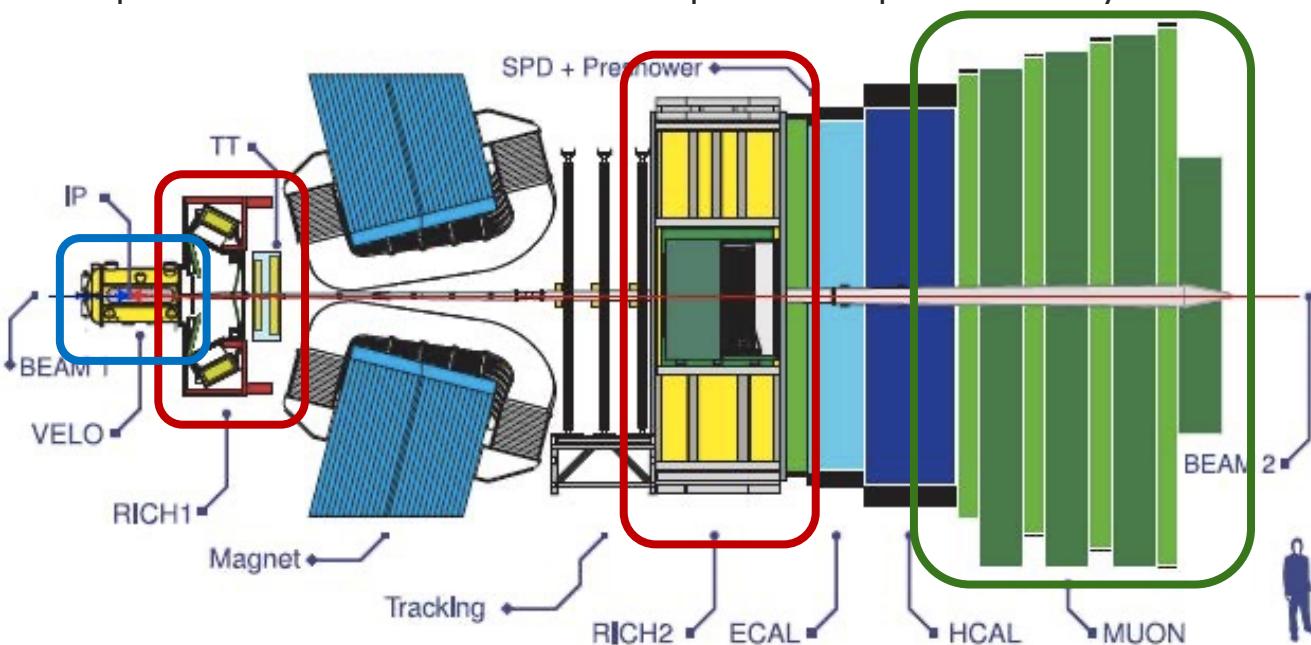
- **2 Ring Imaging Cherenkov Detectors (RICH):**

3 radiators covering momentum range 1.5-100 GeV/c

- **Muon detector:** triggering muons and measuring muon momenta

- Particle ID efficiency:

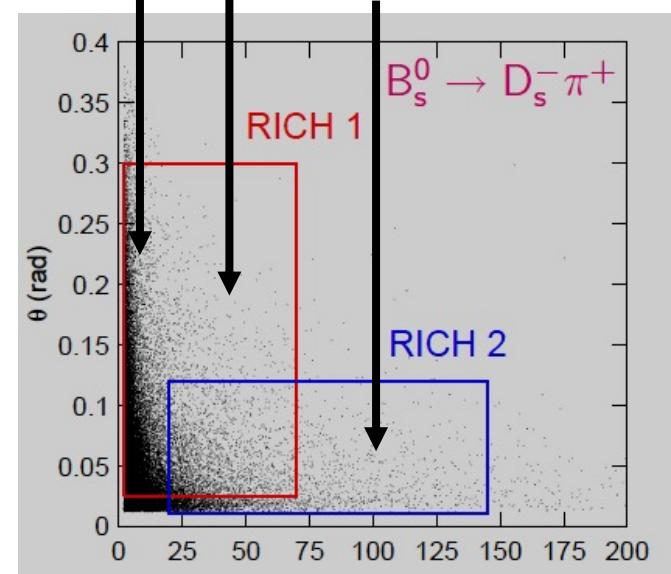
- $K^\pm$  ID ~ 95 % for ~ 5 %  $\pi \rightarrow K$  mis-id probability
- $\mu^\pm$  ID ~ 97 % for 1-3 %  $\pi \rightarrow \mu$  mis-id probability



**C<sub>4</sub>F<sub>10</sub>:**  
 $n=1.0014$   
 up to ~70 GeV/c

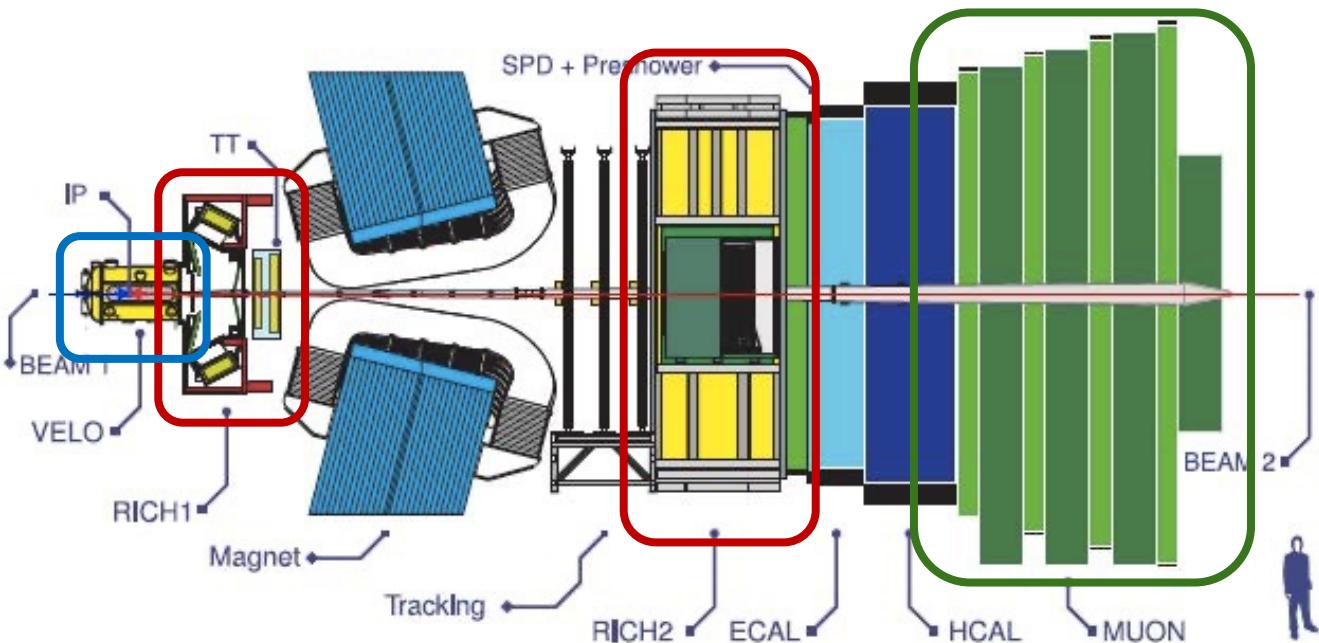
**Silica Aerogel (Run I):**  
 $n=1.03$   
 1.5-10 GeV/c

**CF<sub>4</sub>:**  
 $n=1.0005$   
 up to ~100 GeV/c



## 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



LHCb 2012 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high  $E_T/P_T$  signatures450 kHz  $h^\pm$ 400 kHz  $\mu/\mu\mu$ 150 kHz  $e/\gamma$ 

Software High Level Trigger

29000 Logical CPU cores  
Offline reconstruction tuned to trigger time constraints  
Mixture of exclusive and inclusive selection algorithms

5 kHz (0.3 GB/s) to storage

2 kHz Inclusive Topological

2 kHz Inclusive/Exclusive Charm

1 kHz Muon and DiMuon

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high  $E_T/P_T$  signatures450 kHz  $h^\pm$ 400 kHz  $\mu/\mu\mu$ 150 kHz  $e/\gamma$ 

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

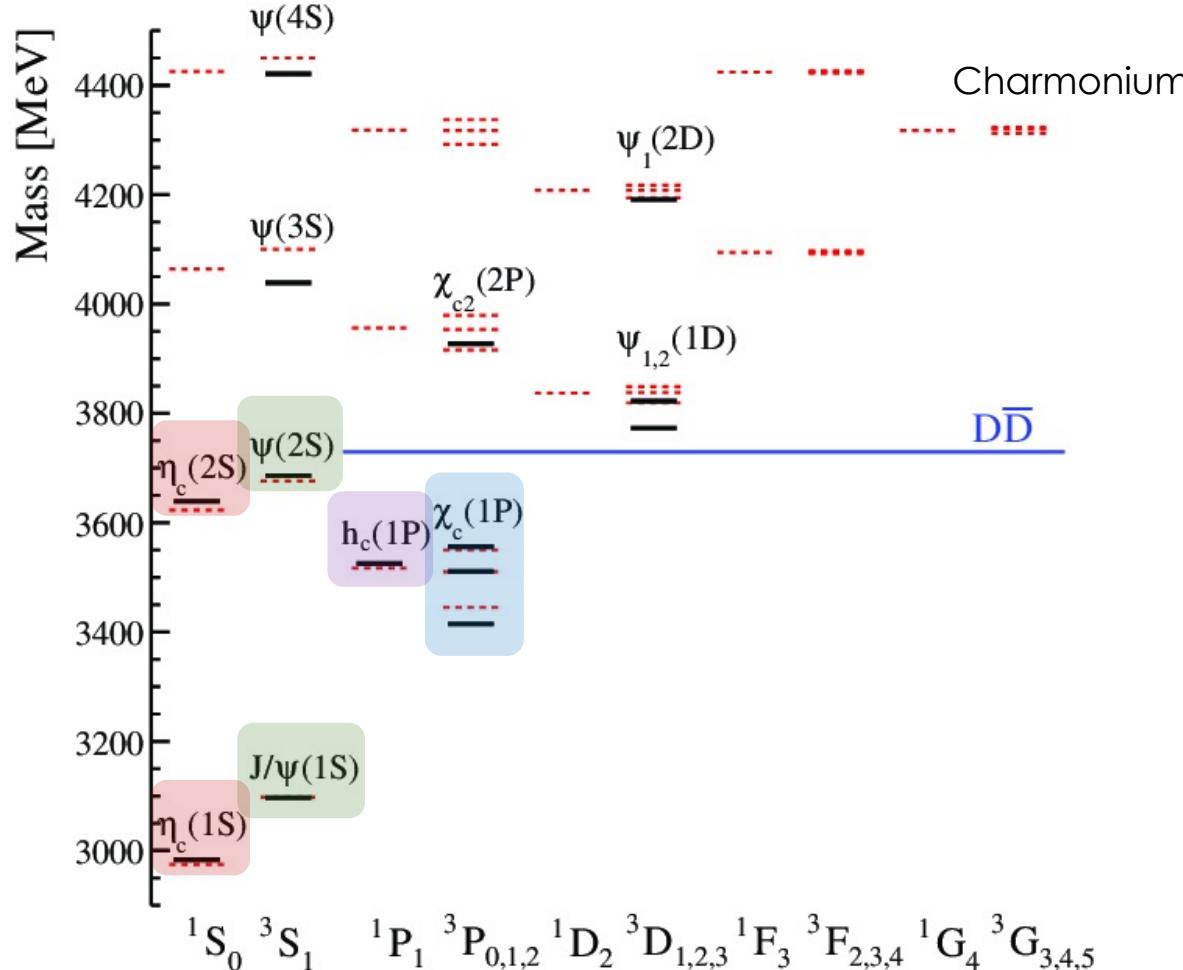
Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

# CHARMONIUM SPECTROSCOPY: LHCb PROGRESS

- Current status of quarkonium spectrum



Final states:

**J/ $\psi$**  and  **$\psi(2S)$**  prompt, b-decays production and polarization measured via  $\mu\mu$   
7, 8 and 13 TeV: [JHEP 10\(2015\) 172](#), [EPJC 80\(2020\) 185](#) ...

**$\chi_c$**  prompt production measured via **J/ $\psi$**   
7 TeV: [JHEP 10\(2013\) 115](#), [PLB 714\(2012\) 215-223](#)

**$\chi_c$**  and  **$\eta_c(2S)$**  b-decays production measured via  **$\phi\phi$** ,  
7 and 8 TeV: [EPJC 77\(2017\) 609](#)  
 **$\eta_c(1S)$**  prompt and b-decays production measured via **pp**  
7, 8 and 13 TeV: [EPJC 75\(2015\) 311](#), [EPJC 80\(2020\) 191](#)

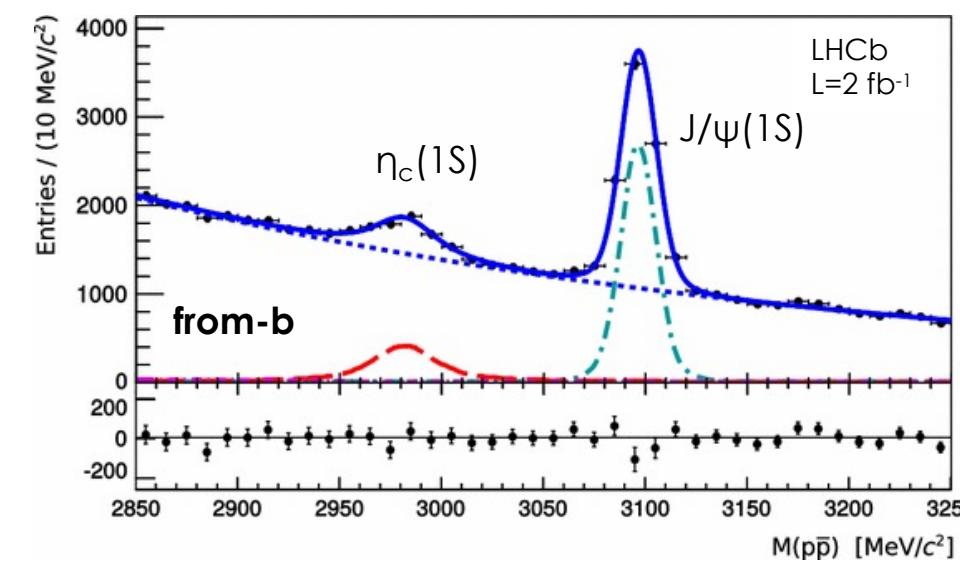
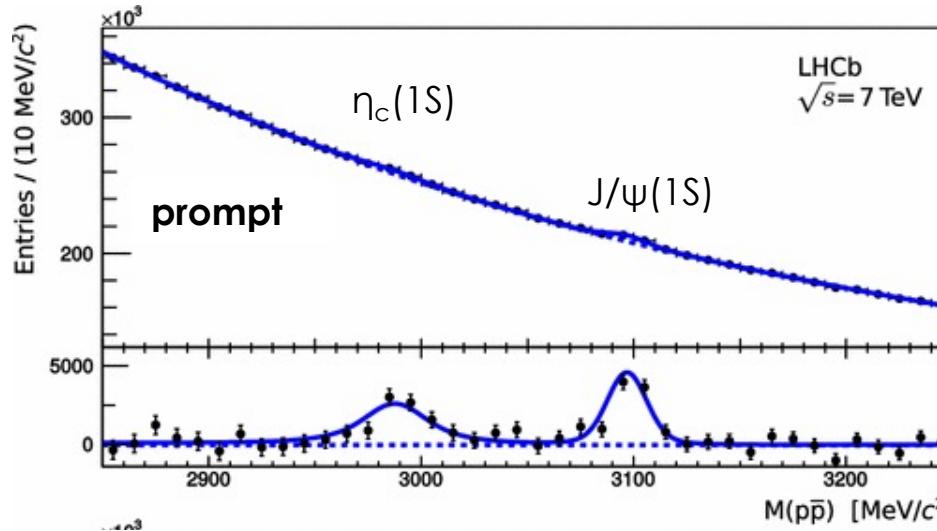
???

- Hadronic final states allow to study different quarkonium states simultaneously

- **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**

# $\eta_c(1S)$ 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

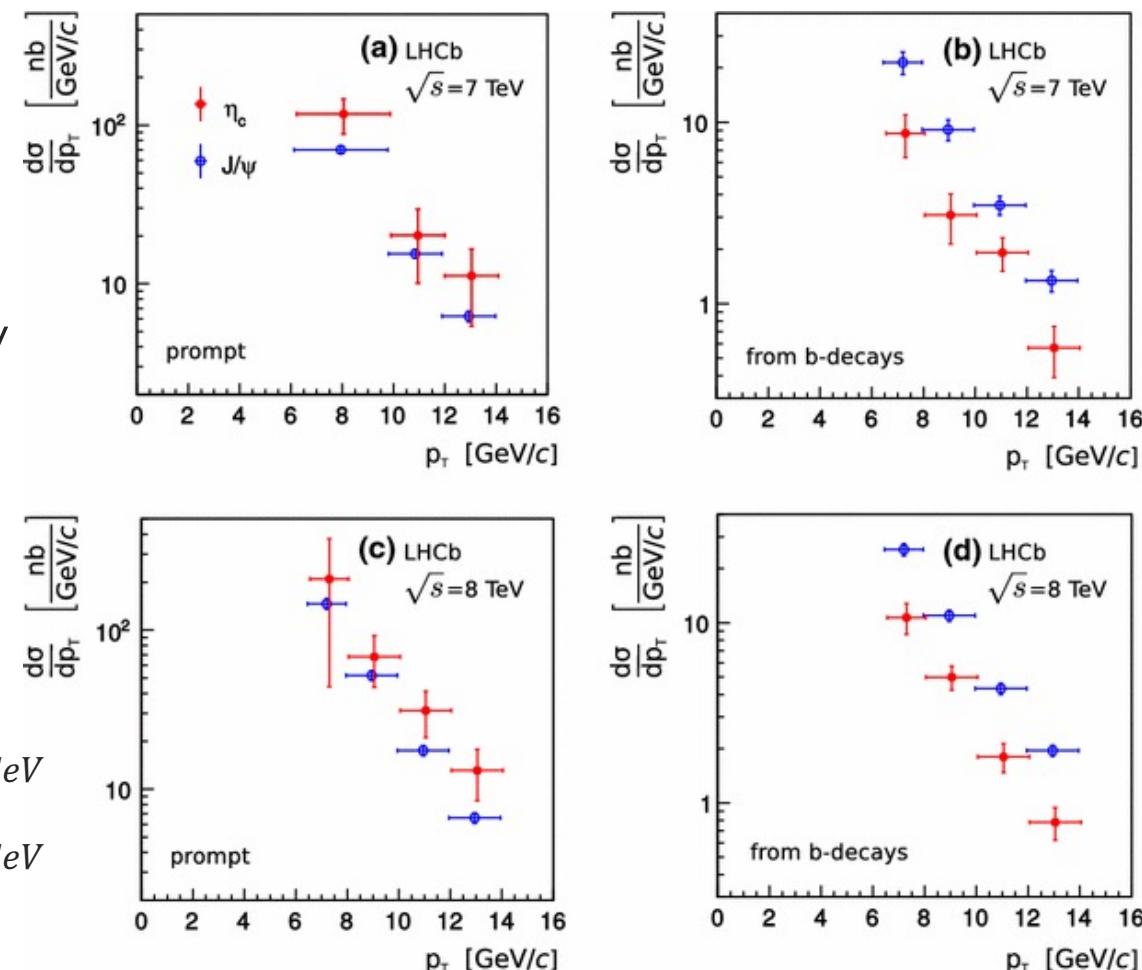
## $\eta_c(1S)$ production:

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

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

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

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



# $\eta_c$ 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  $J/\psi$

$$\langle \mathcal{O}_{1,8}^{\eta_c}(1S_0) \rangle = \frac{1}{3} \langle \mathcal{O}_8^{J/\psi}(3S_1) \rangle$$

$$\langle \mathcal{O}_8^{\eta_c}(3S_1) \rangle = \langle \mathcal{O}_8^{J/\psi}(1S_0) \rangle$$

$$\langle \mathcal{O}_8^{\eta_c}(1P_1) \rangle = 3 \langle \mathcal{O}_8^{J/\psi}(3P_0) \rangle$$

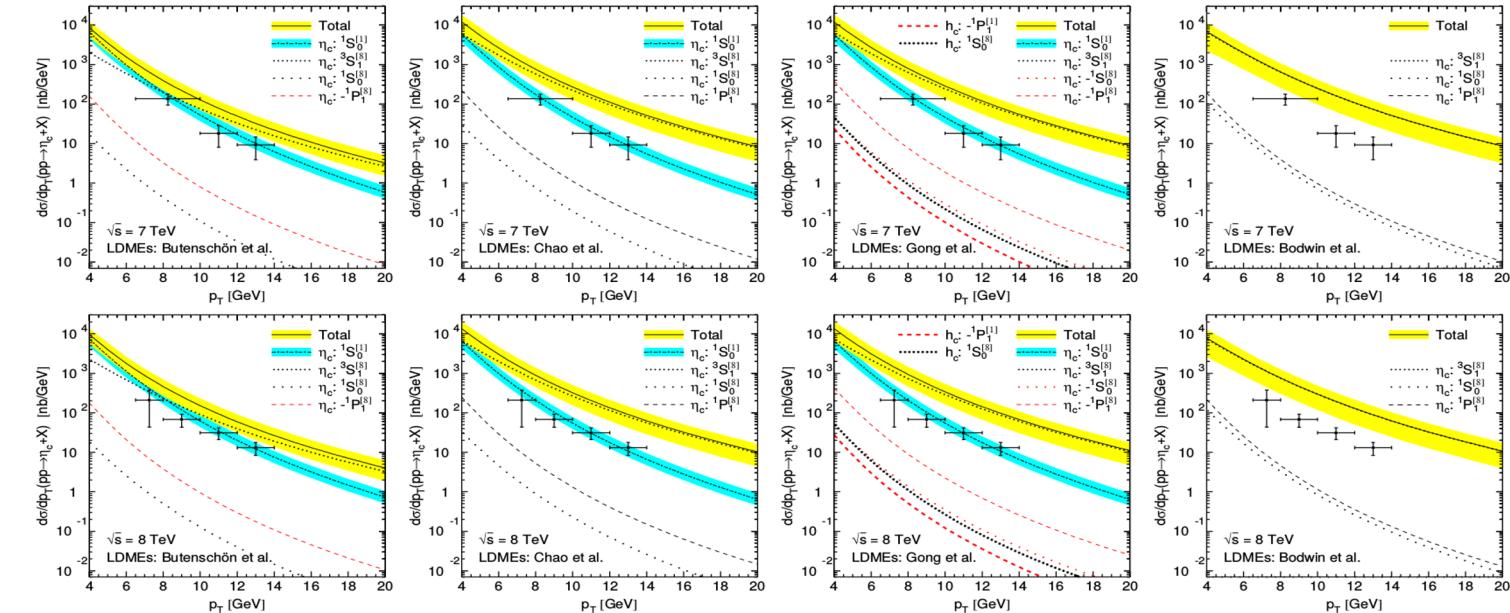
- Direct projection to LHCb data
- **LHCb data saturated by CS contribution**
- Tension in simultaneous description of  $\eta_c$  production and  $J/\psi$  production and polarization?
- **Recent progress in theory:**

→ [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](#)

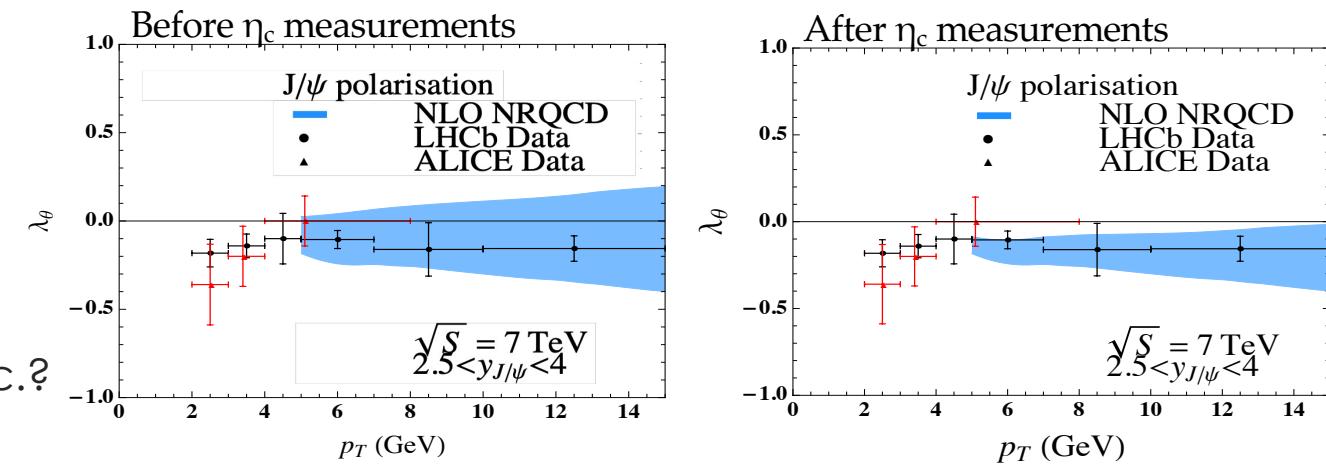
→ [Phys.Rev.Lett. 110\(2013\) 042002](#)

→ [Phys.Rev.D 93 \(2016\) 034041](#)

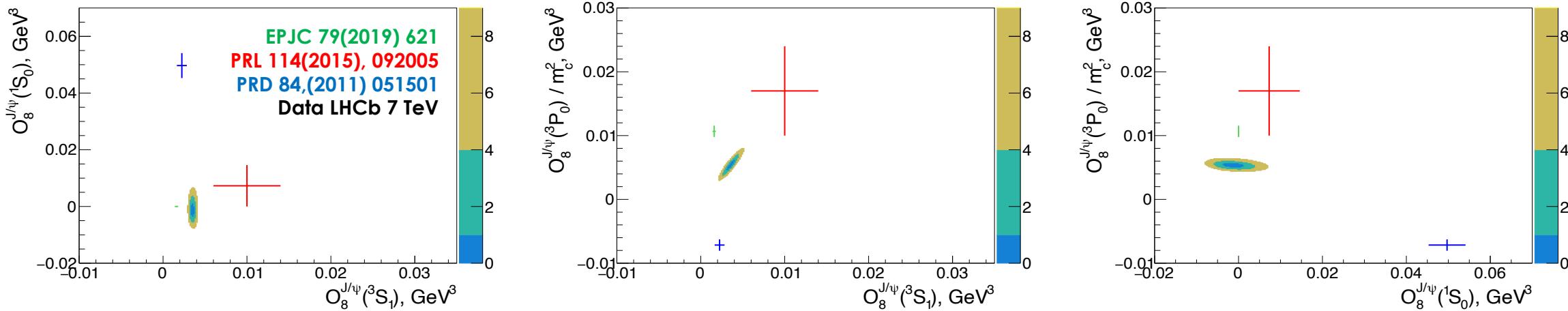
- $\eta_c$  production @  $\sqrt{s}=7$  and 8 TeV sets new constraint on J/ $\psi$  polarization

- **Outcome:**

- Impressive progress
- Tension with CDF data
- Two large CO contributions cancel each other  $\Rightarrow$   
 $\Rightarrow$  hierarchy problem  $\Rightarrow$  Soft Gluon Fragmentation, etc.?



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



- Same links for  $\eta_c(2S)$  and  $\psi(2S)$  are expected  $\Rightarrow$  powerful test of NRQCD [Phys.Lett.B 786 \(2018\) 342-346](#)

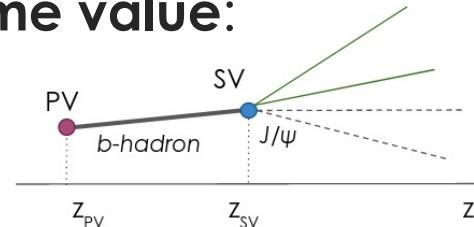
- Cross-section determination:

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

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

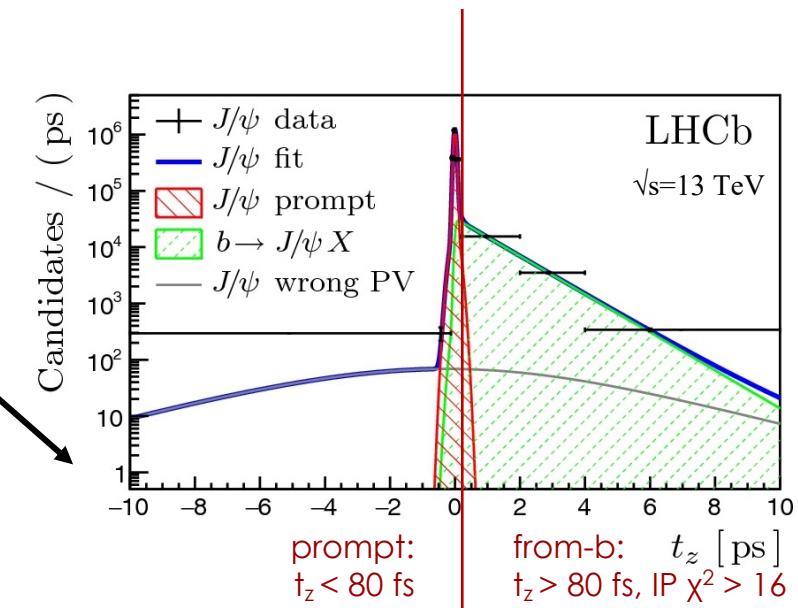
- Extracted from DATA
- Calculated from PDG:  
 $\mathcal{B}_{J/\psi \rightarrow p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3}$   
 $\mathcal{B}_{\eta_c(1S) \rightarrow p\bar{p}} = (1.45 \pm 0.14) \times 10^{-3}$
- From Simulation

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

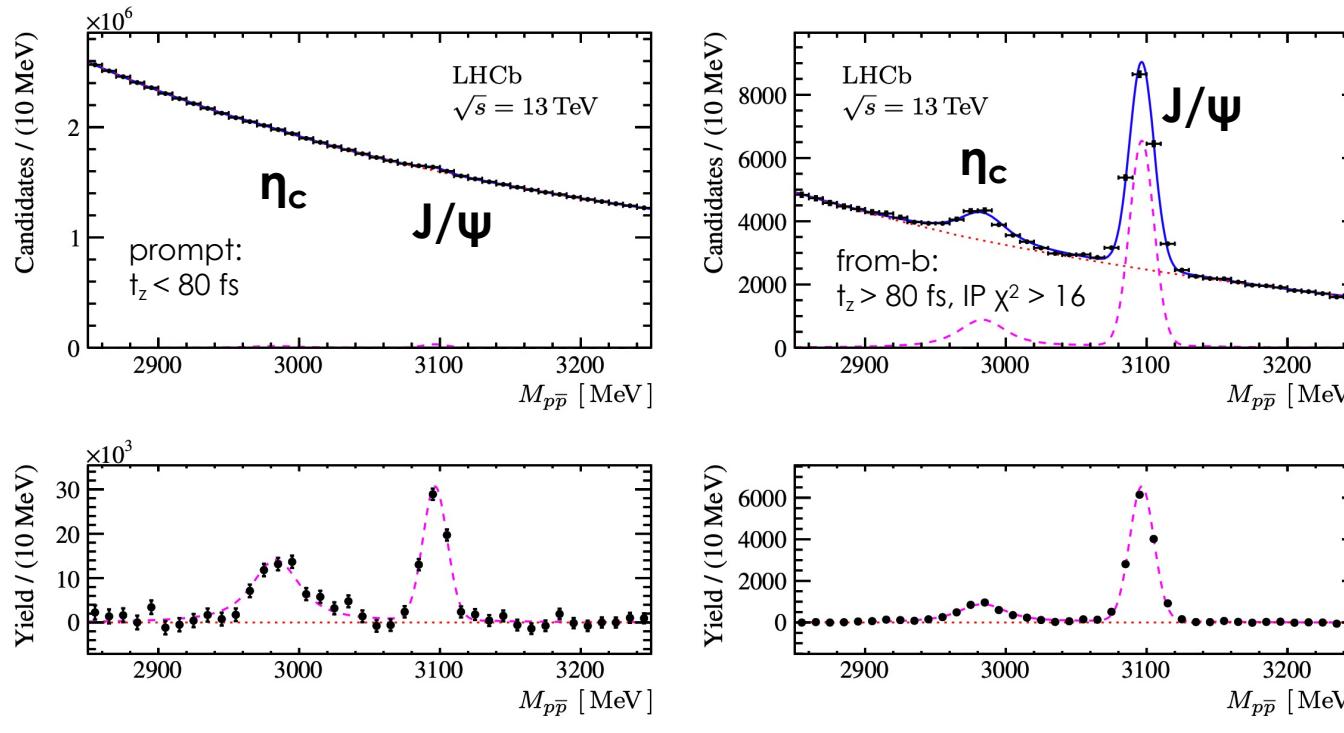


$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$$

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



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



- The most precise determination of  $\eta_c$  mass up to date:

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

- Relative charmonium yields:

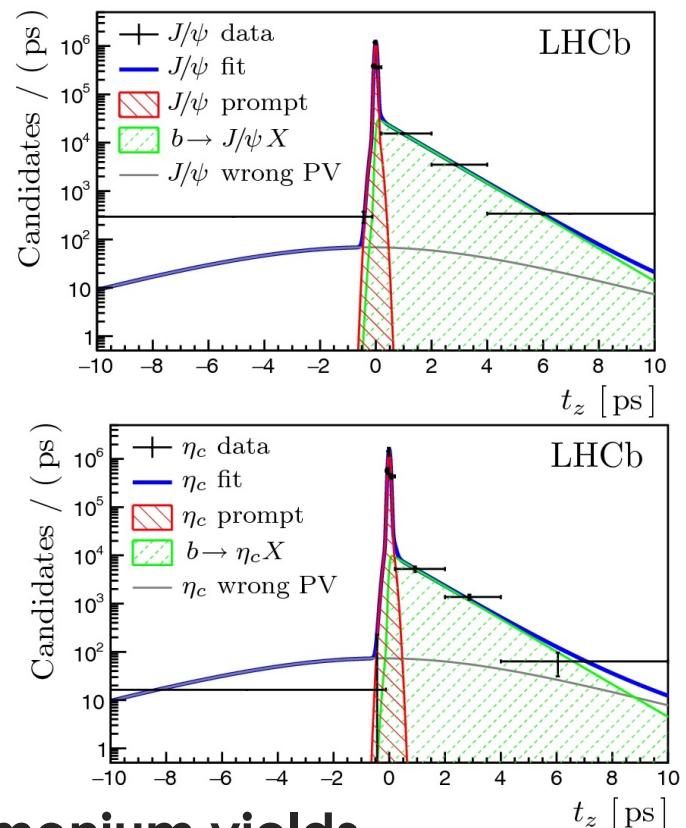
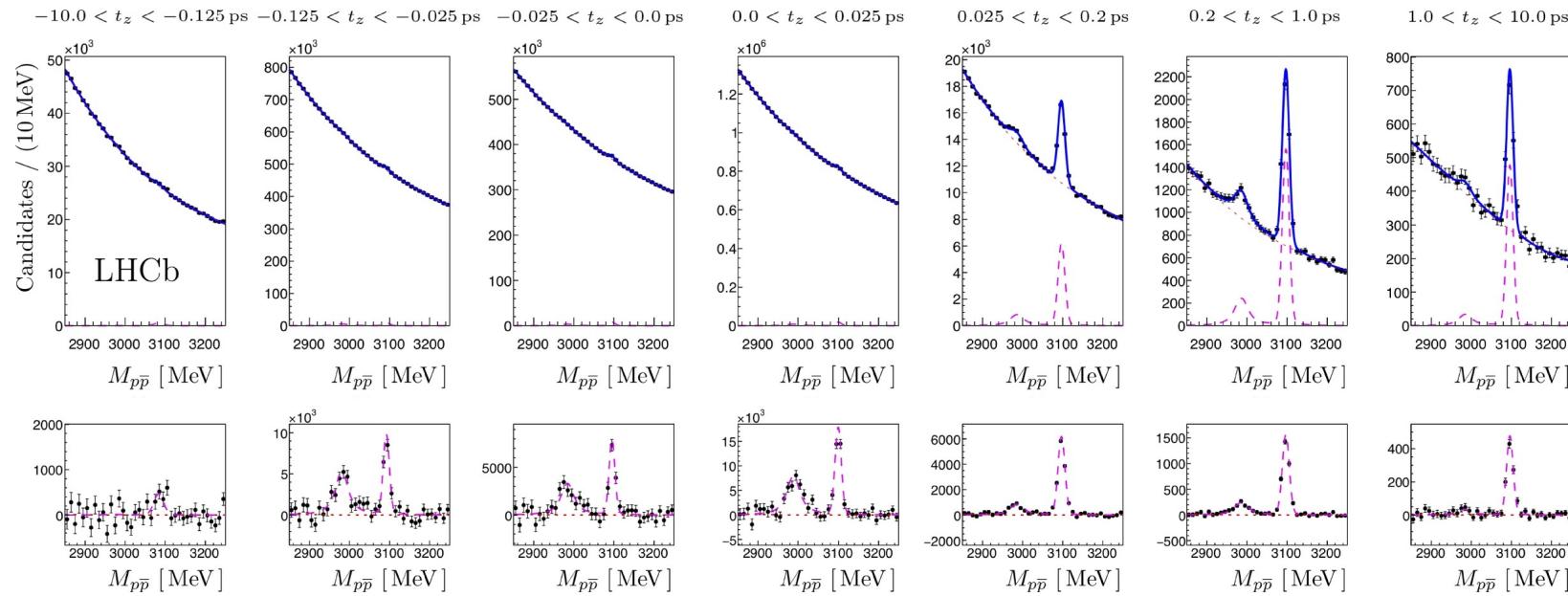
$$6.5 < p_T < 14.0 \text{ GeV}/c, 2.0 < y < 4.5$$

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

- Cross-feed probabilities:

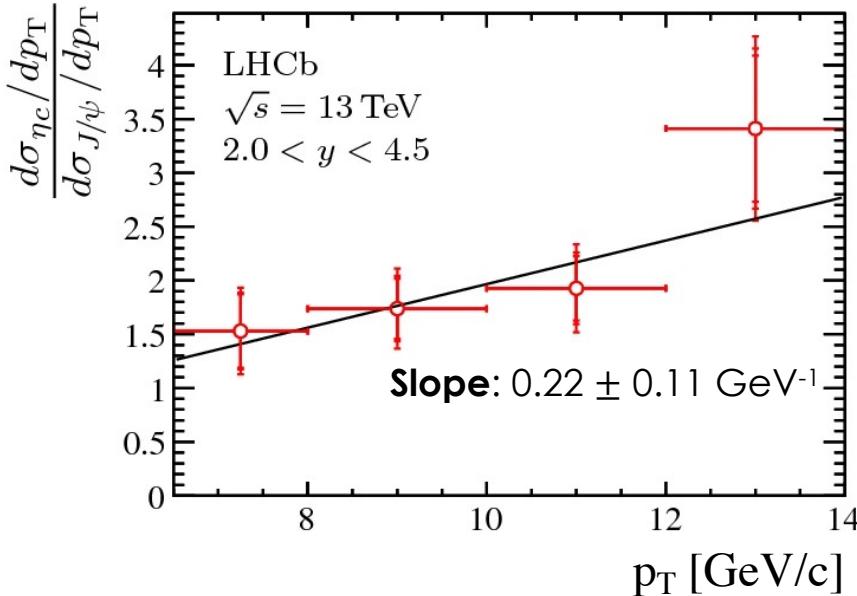
$$\begin{aligned} \rightarrow \varepsilon^{prompt \rightarrow prompt} &= 0.965 \pm 0.021 \\ \rightarrow \varepsilon^{prompt \rightarrow from-b} &= 0.0002 \pm 0.0001 \\ \rightarrow \varepsilon^{from-b \rightarrow prompt} &= 0.066 \pm 0.005 \\ \rightarrow \varepsilon^{from-b \rightarrow from-b} &= 0.689 \pm 0.022 \end{aligned}$$

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



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

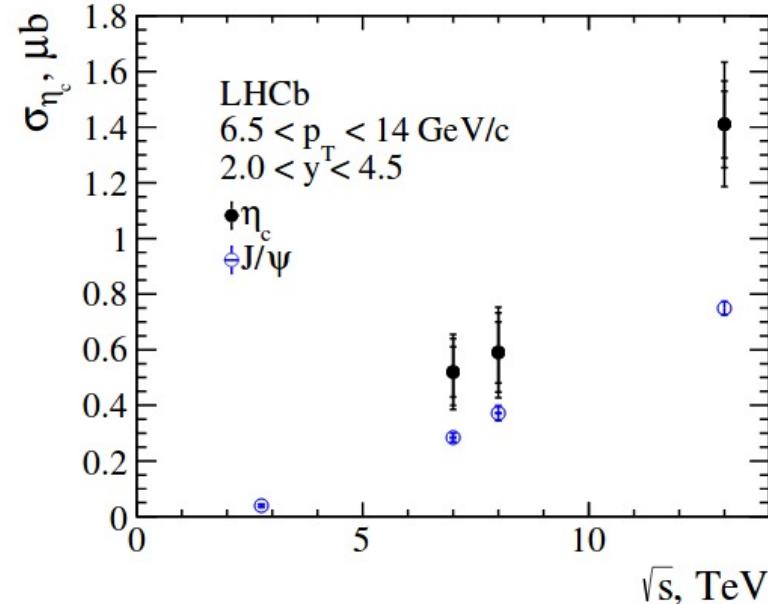
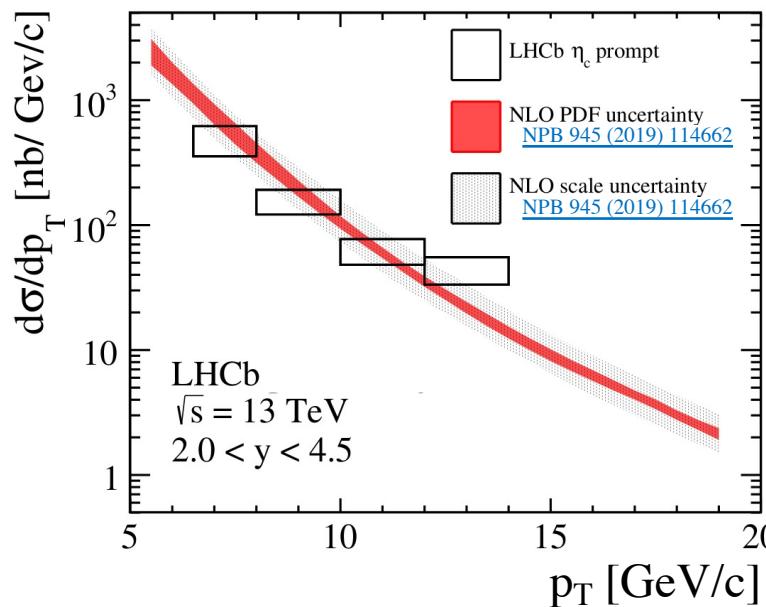
- Relative  $\eta_c$  to J/ $\psi$   $p_T$ -differential production cross-sections



- Relative  $\eta_c(1S)$  to J/ $\psi$  production** in LHCb at  $\sqrt{s}=13 \text{ TeV}$   
 $6.5 < p_T < 14.0 \text{ GeV}/c, 2.0 < y < 4.5$   
 $\sigma_{\eta_c}^{prompt} / \sigma_{J/\psi}^{prompt} = 1.69 \pm 0.15_{stat} \pm 0.10_{syst} \pm 0.18_{\mathcal{B}_{c\bar{c} \rightarrow p\bar{p}}} \mu b$   
 $\mathcal{B}_{b \rightarrow \eta_c X} / \mathcal{B}_{b \rightarrow J/\psi X} = 0.48 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.05_{\mathcal{B}_{c\bar{c} \rightarrow p\bar{p}}}$

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

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



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

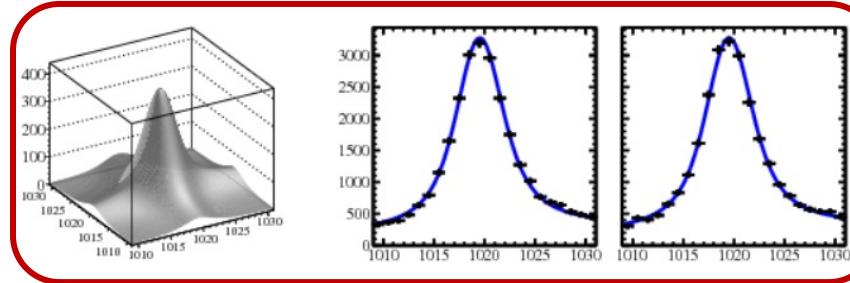
$6.5 < p_T < 14.0$  GeV/c,  $2.0 < y < 4.5$

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

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

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

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



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

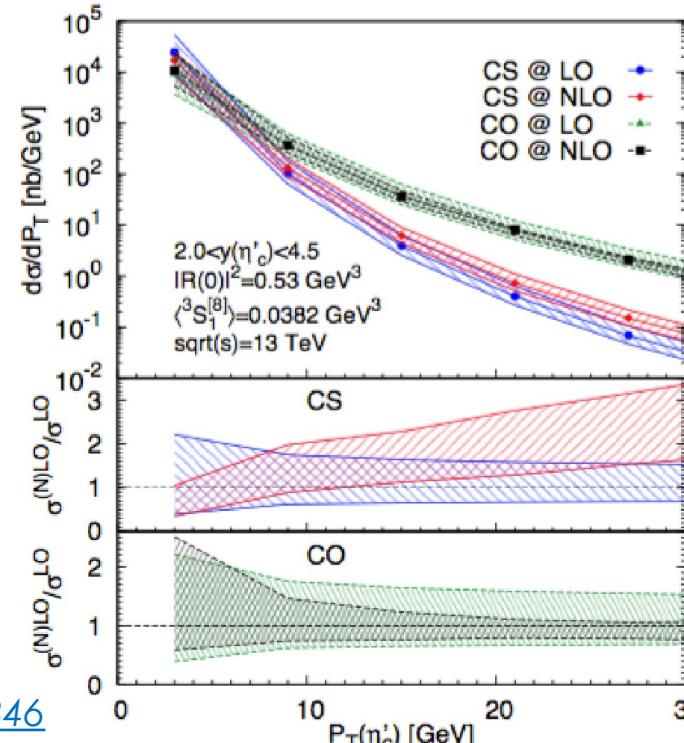
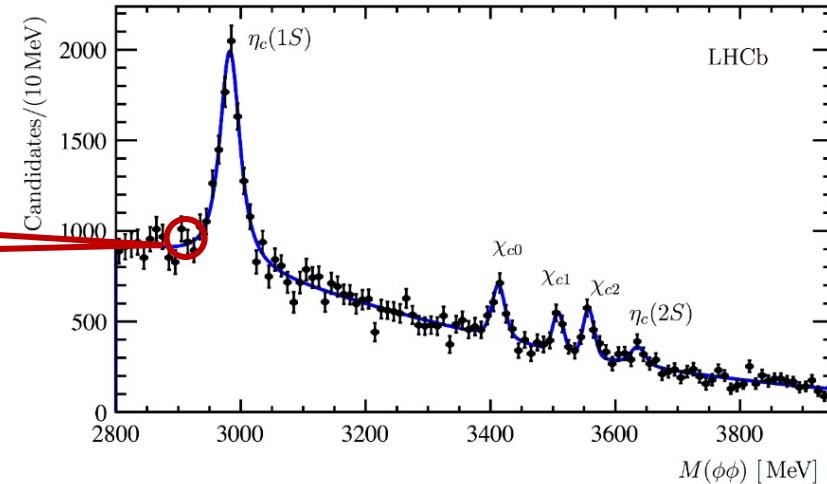
first evidence for  $\eta_c(2S) \rightarrow \phi\phi$

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

- Important to measure  $\eta_c(2S)$  hadroproduction:

- theory prediction  $\Rightarrow$
- dedicated LHCb trigger in 2018

- Prompt  $\eta_c(1S)$  production measurement?



## SUMMARY

- **$\eta_c(1S)$  hadroproduction** is precisely 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 in b-decays
- **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

# FIT PARAMETRIZATION

Parameter	
$\sigma_n/\sigma_w$	fixed from MC
$f_n$	fixed from MC
$\sigma_{\eta_c}/\sigma_{J/\psi}$	fixed from MC
$\sigma_{\eta_c}$	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 $p_T$
$\Gamma_{\eta_c}$	fixed world average from Ref. [41] (31.8 MeV/c <sup>2</sup> )
$\Delta m_{(t_z)}$	fixed from MC in each $t_z$ bin
$\alpha_{(t_z)}$	fixed from MC in each $t_z$ bin

After selection	$N(J/\psi)/N(bkg)$	$N(\eta_c)/N(bkg)$
b-decays	<8x10 <sup>-2</sup>	<3x10 <sup>-2</sup>
<b>prompt</b>	<4x10 <sup>-4</sup>	<b>&lt;4x10<sup>-4</sup></b>

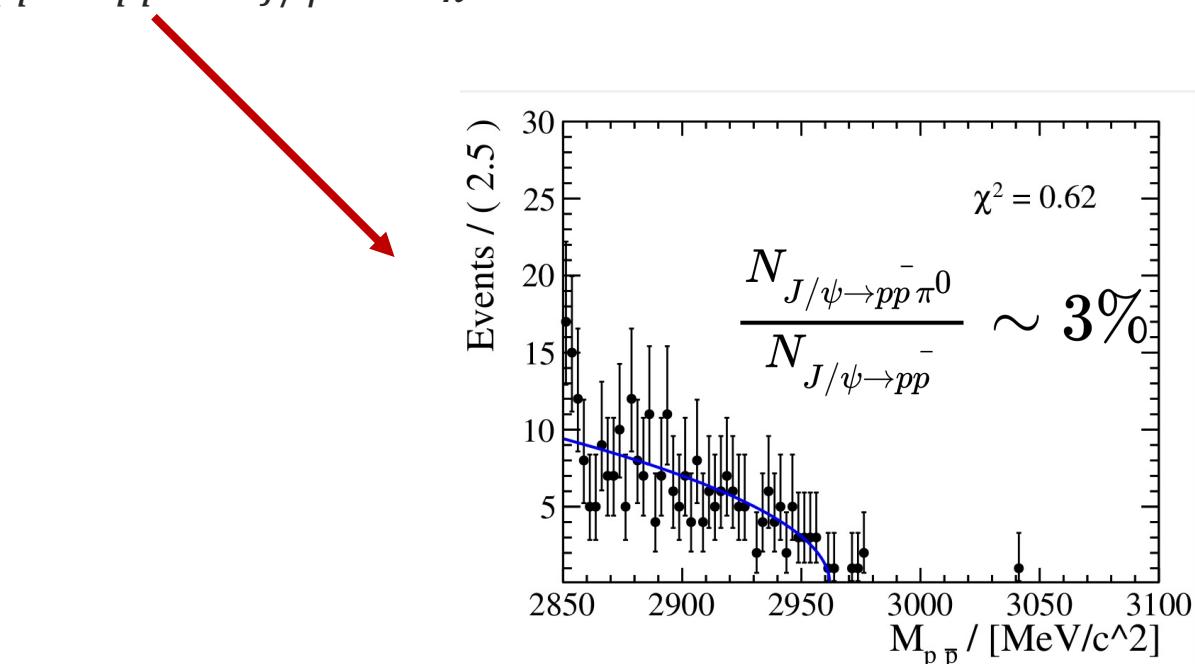
# MASS SIGNAL AND BKG. PARAMETRIZATION

- **Signal:**

- $J/\psi$ :  $DG(\sigma_n, \sigma_w, f_n) \times \delta(m(J/\psi))$
- $\eta_c$ :  $DG(\sigma_n, \sigma_w, f_n) \times RBW(m(\eta_c))$

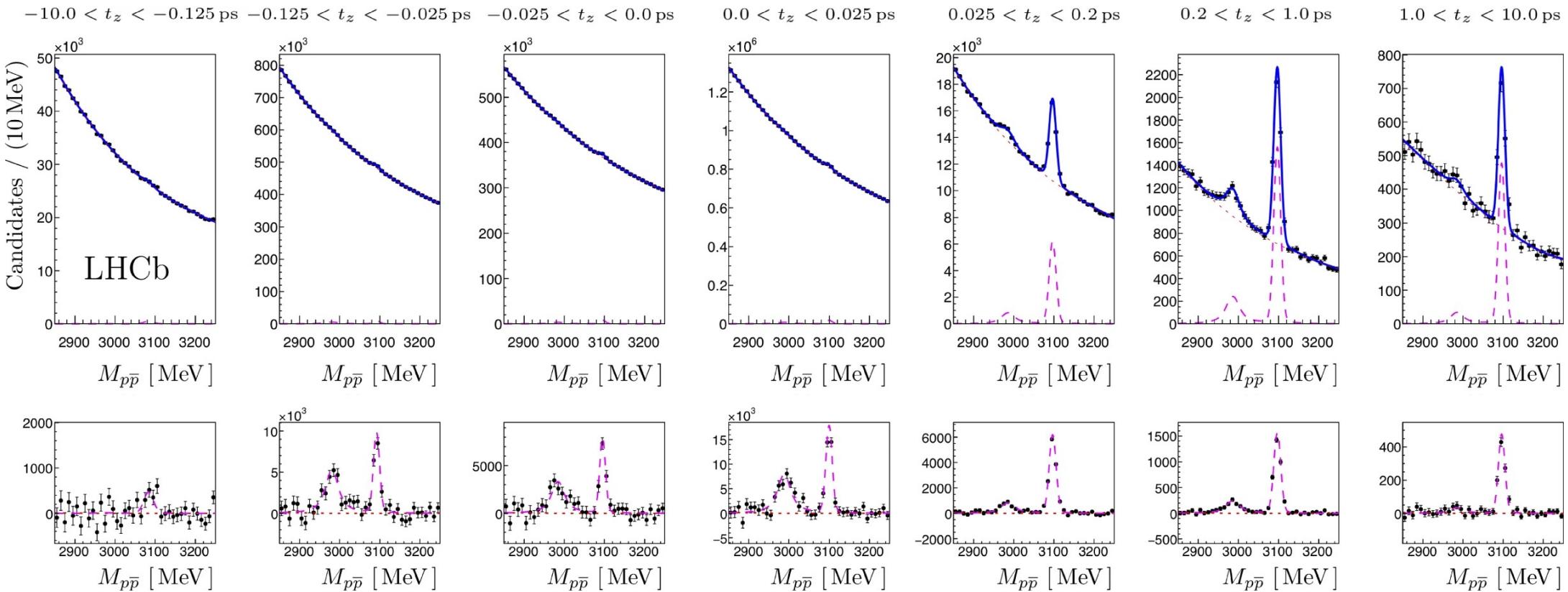
- **Background:**

- $J/\psi \rightarrow pp\pi^0$  contribution  $\sqrt{M_{J/\psi} - M_{\pi^0} - M_{p\bar{p}}}$ ,  $M_{p\bar{p}} < (M_{J/\psi} - M_{\pi^0})$
- Combinatorial:  $\exp \times \text{pol}(2)$



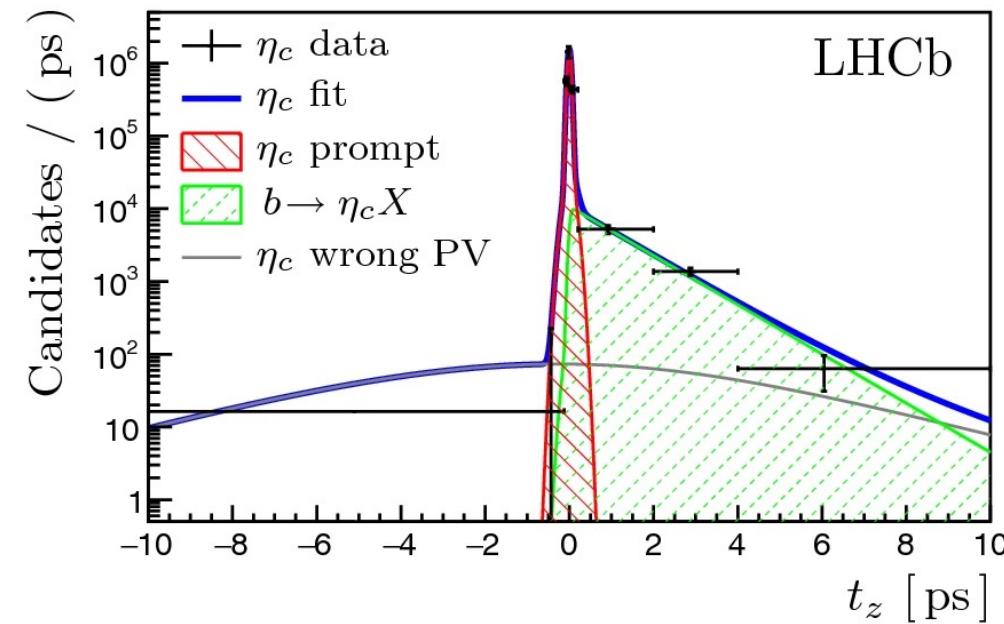
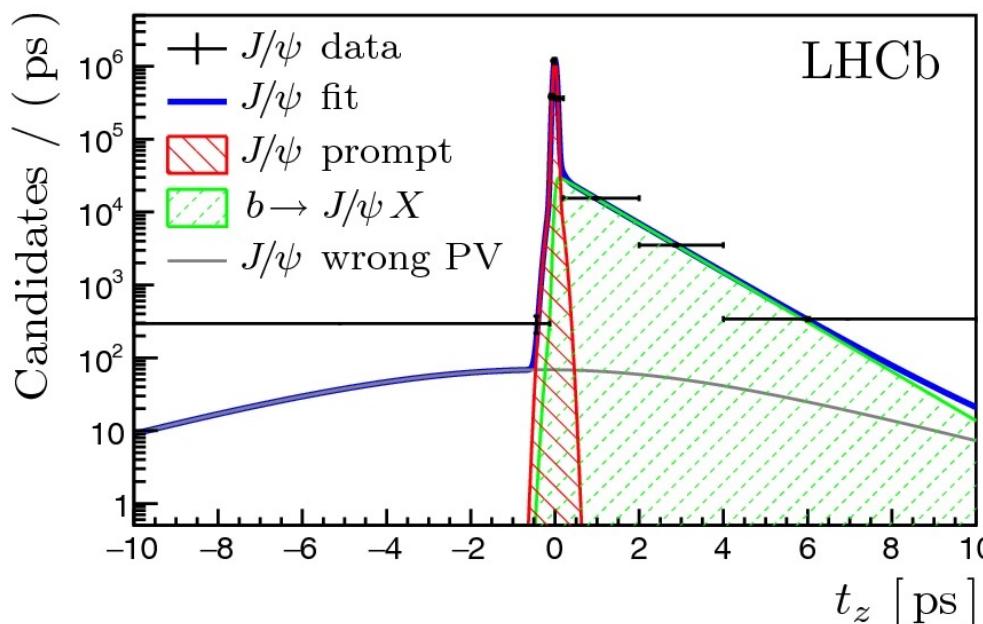
No free parameters in the fit to data.  
Yield is bound to yield of  $J/\psi \rightarrow pp$

$6.5 < p_T < 14 \text{ GeV}$ ,  $2.0 < y < 4.5$



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

$6.5 < p_T < 14 \text{ GeV}$ ,  $2.0 < y < 4.5$

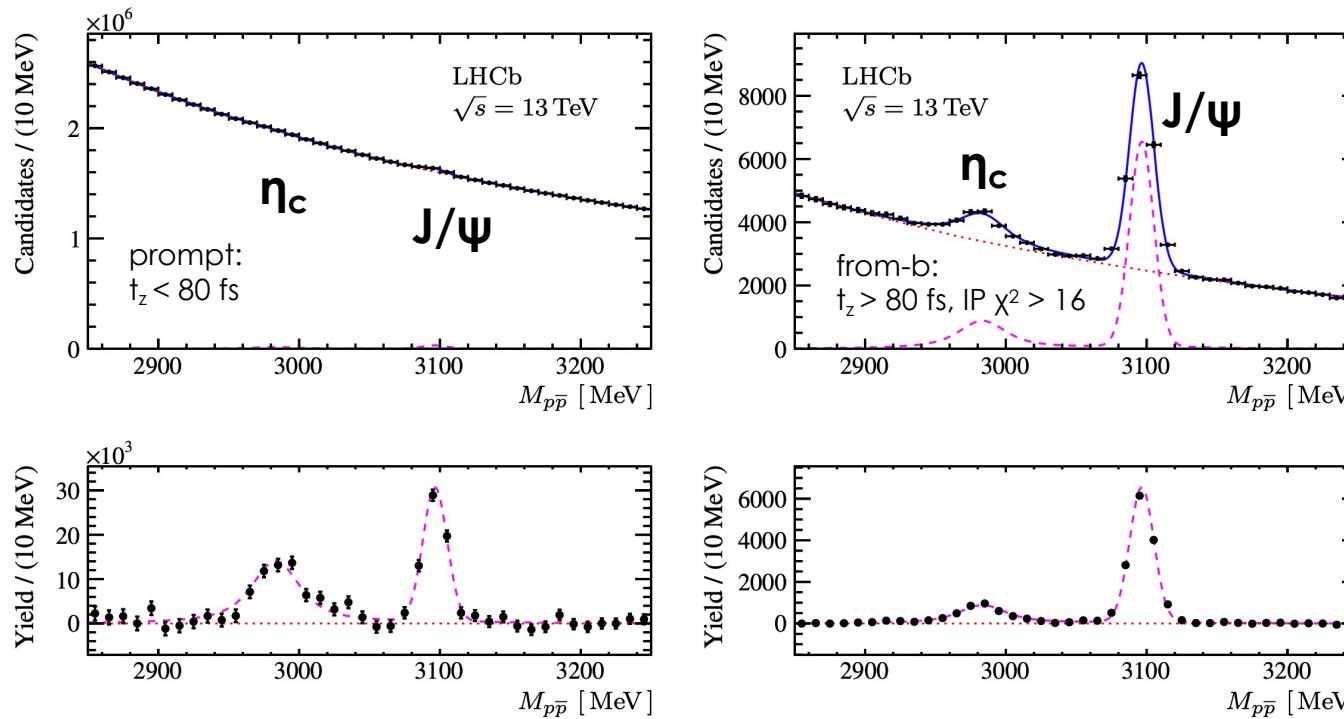


$$F^{\eta_c}(t_z) = [N_p \delta(t_z)] + \frac{N_b}{\tau_b} \exp -t_z/\tau_b * DG(\mu, S_{J/\psi}, S_n/S_w, \beta) + N_t f_{tail}(t_z)$$

prompt ccbar    
 ccbar from  $b$ -decays    
  $t_z$ -resolution    
 events with mismatched PV

- Simultaneous integral  $\chi^2$  fit to  $t_z$  in  $p_T$ -bins to separate prompt and from  $b$ -decays charmonium

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



- The most precise determination of  $\eta_c$  mass up to date:  
 $\Delta M_{J/\psi, \eta_c} = 113.0 \pm 0.7_{\text{stat}} \pm 0.1_{\text{syst}} \text{ MeV}$
- Result is consistent with  $t_z$ -fit technique

- Relative charmonium yields:

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

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

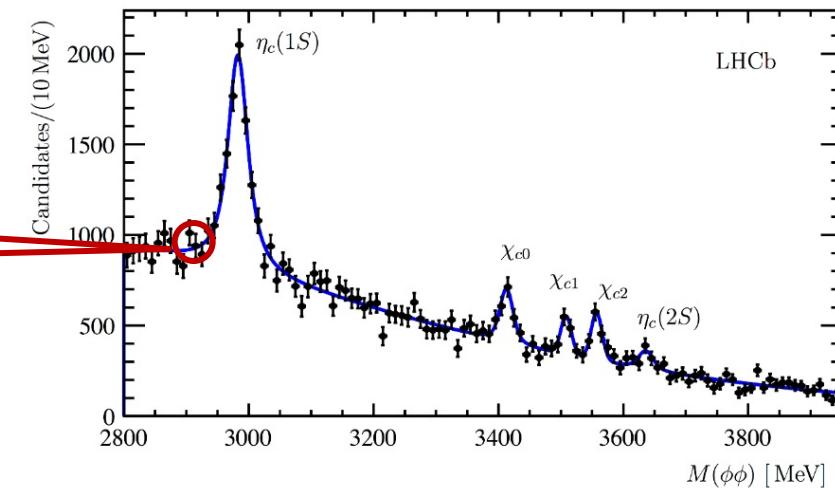
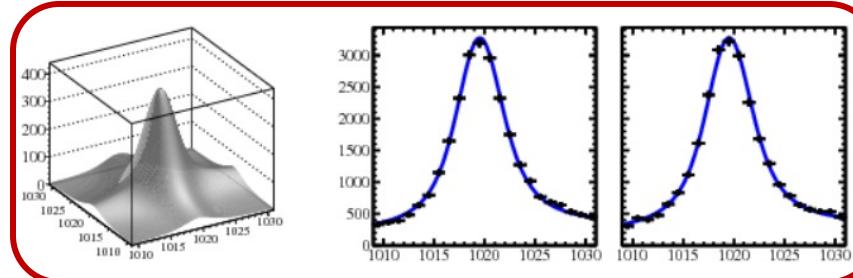
- Cross-feed probabilities:

$$\begin{aligned} \cdots \rightarrow \varepsilon^{\text{prompt} \rightarrow \text{prompt}} &= 0.965 \pm 0.021 \\ \cdots \rightarrow \varepsilon^{\text{prompt} \rightarrow \text{from-b}} &= 0.0002 \pm 0.0001 \\ \cdots \rightarrow \varepsilon^{\text{from-b} \rightarrow \text{prompt}} &= 0.066 \pm 0.005 \\ \cdots \rightarrow \varepsilon^{\text{from-b} \rightarrow \text{from-b}} &= 0.689 \pm 0.022 \end{aligned}$$

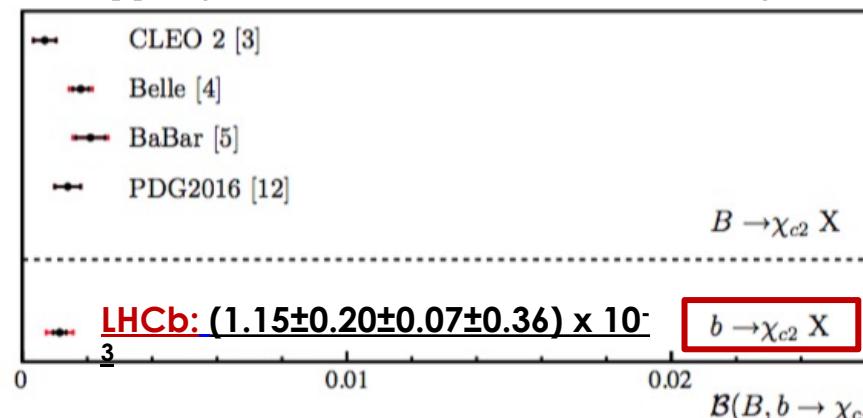
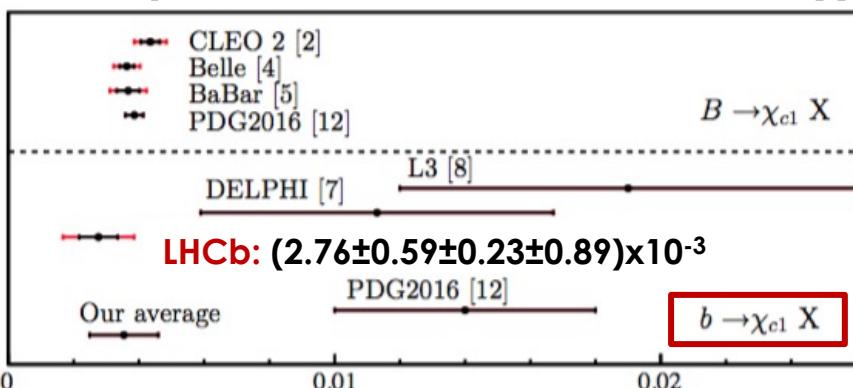
# $\chi_c$ PRODUCTION IN $b$ -DECAYS AT LHCb

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

- Charmonium reconstructed via **decays to  $\phi\phi$** :  
true  $\phi\phi$  combinations extracted using 2D fit technique



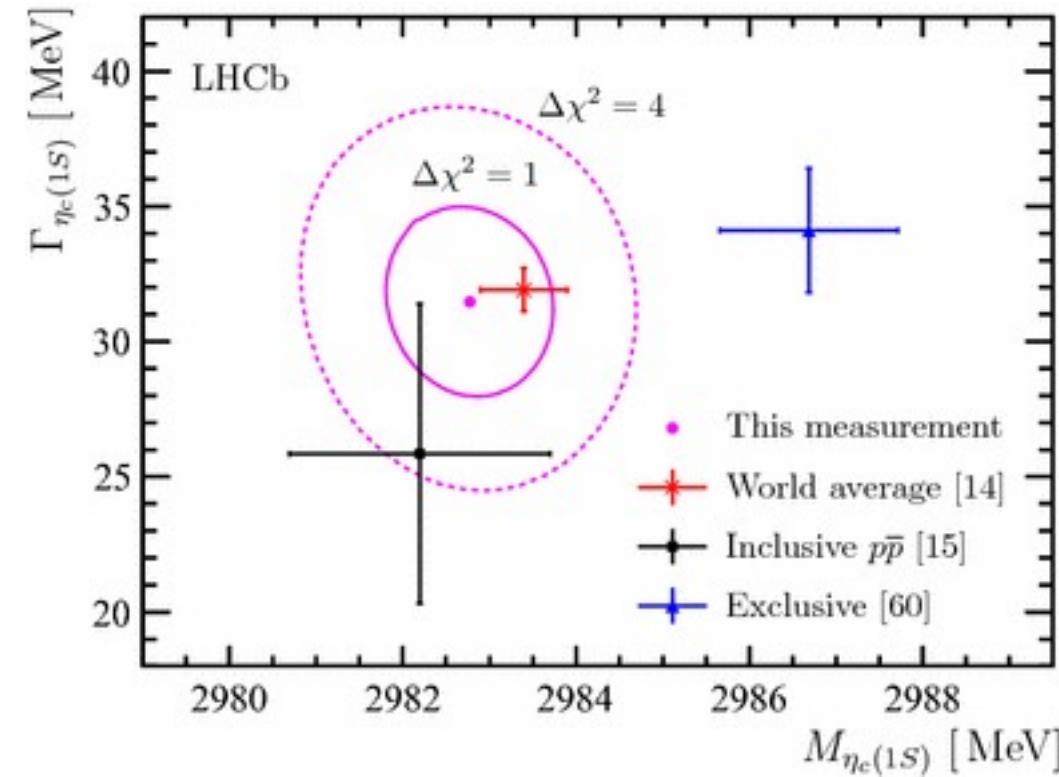
- First measurement of  $\chi_{c0}$  production in  $b$ -decays:**  
 $\mathcal{B}(b \rightarrow \chi_{c0} X) = (3.02 \pm 0.47_{stat} \pm 0.23_{syst} \pm 0.94_B) \times 10^{-3}$
- Most precise measurements** of  $\chi_{c1}$  and  $\chi_{c2}$  production in  $b$ -decays, consistent with B-factories



- Promising channel to study  $\chi_c$  polarization [[Phys.Rev.D 103 \(2021\) 9, 096006](#)]

# $\eta_c$ MASS MEASUREMENT

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



# J/ψ AND ψ(2S) PRODUCTION

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

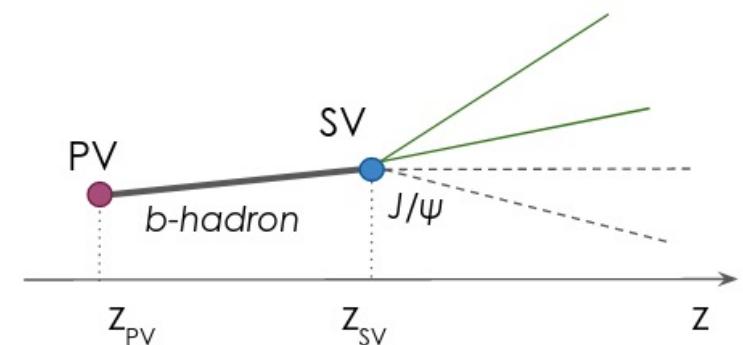
$$\frac{d^2\sigma}{dydp_T} = \mathcal{L} \times \varepsilon \times N(\psi \rightarrow l^+l^-) \times \mathcal{B}(\psi \rightarrow l^+l^-) \times \Delta y \times \Delta p_T$$

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

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

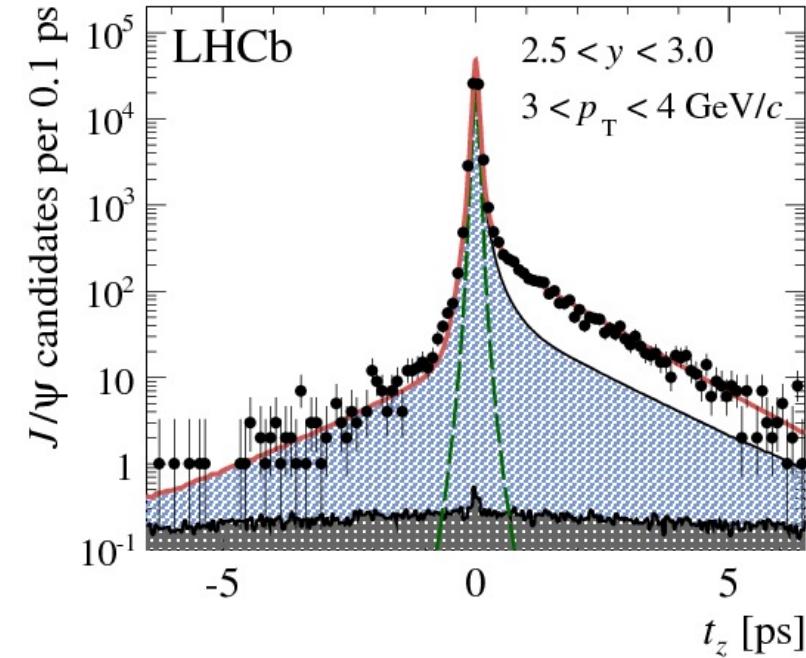
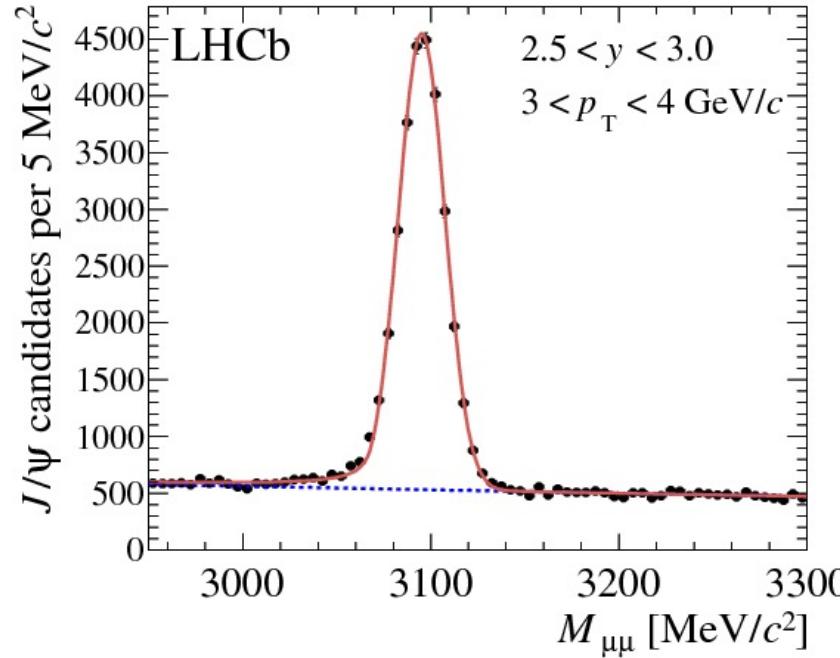
distinguished via pseudo-proper decay time:

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



- Full kinematic range cross-section**

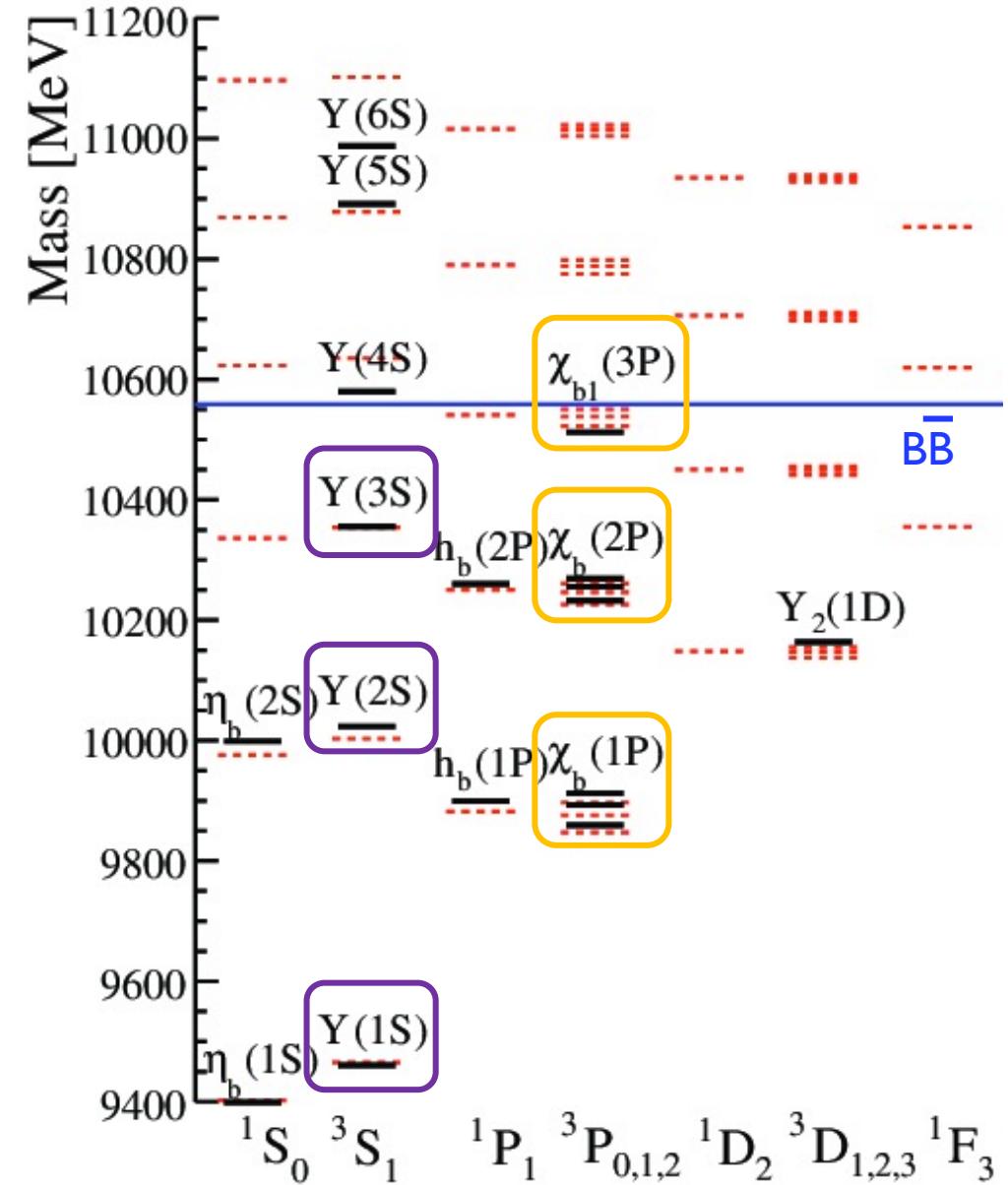
- Prompt and **b**-decay production distinguished via decay time value:  $t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{\mu\mu}$



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

	$N(J/\psi)/N(\text{bkg})$
b-decays	$>1\times10^{-2}$
prompt	$>1\times10^{-1}$

# BOTTOMONIUM SPECTROSCOPY: LHCb PROGRESS



**Y(nS)** production measured via  $\mu\mu$

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](#)

**Y(nS)** polarization measured via  $\mu\mu$

7 and 8 TeV: [JHEP 12\(2017\) 110](#)

**χ<sub>b</sub>(nP)** production measured via  $Y(nS)\gamma$

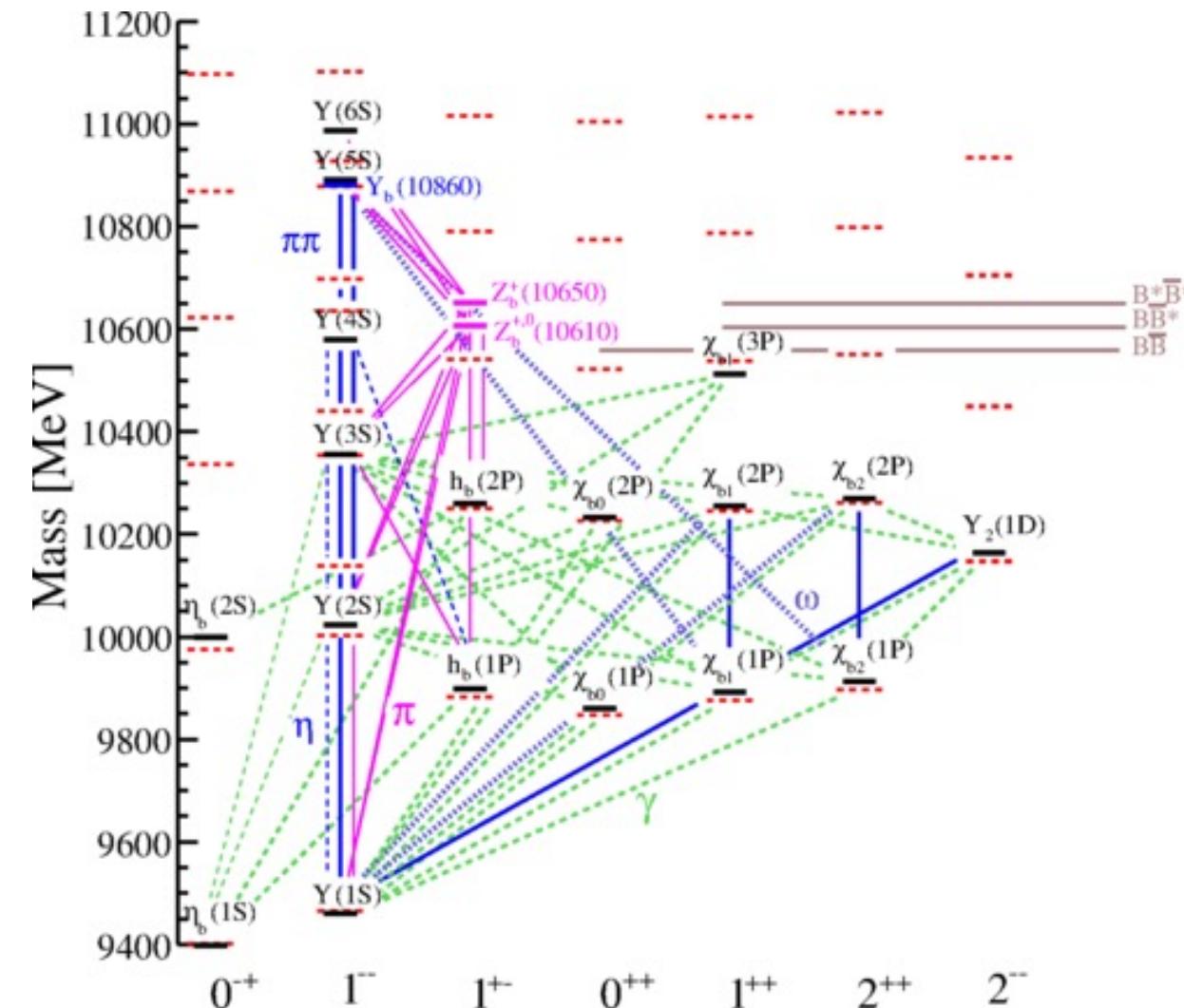
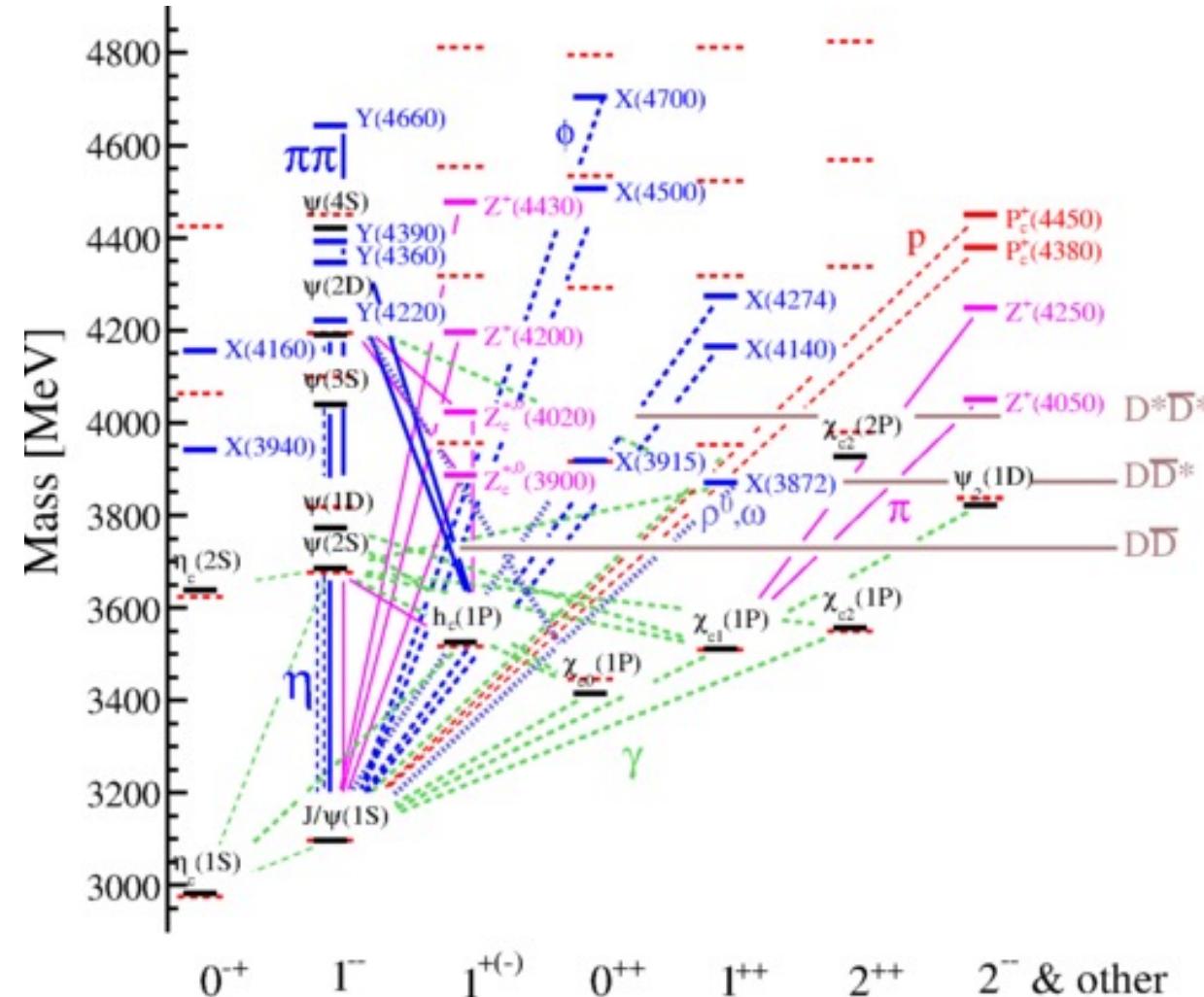
7 and 8 TeV: [Eur.Phys.J.C 74\(2014\) 3092](#)

## Prospects:

- h<sub>b</sub> and n<sub>b</sub>(1S) production

# QUARKONIUM DECAYS

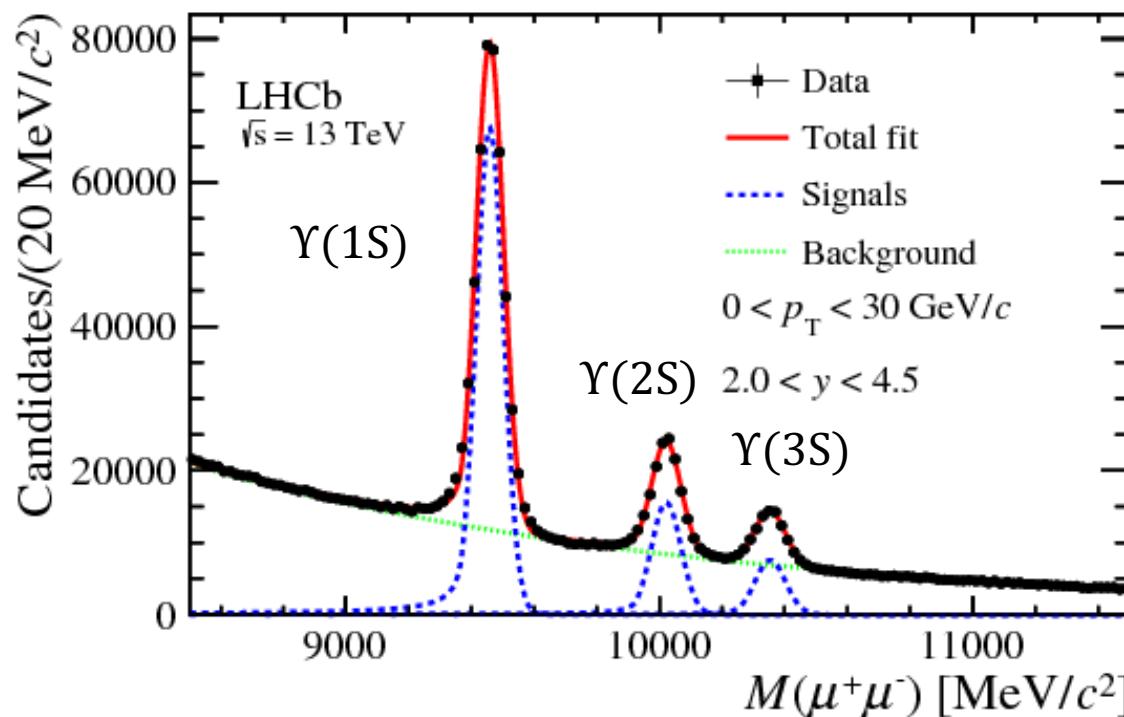
- Possible transitions between quarkonium states



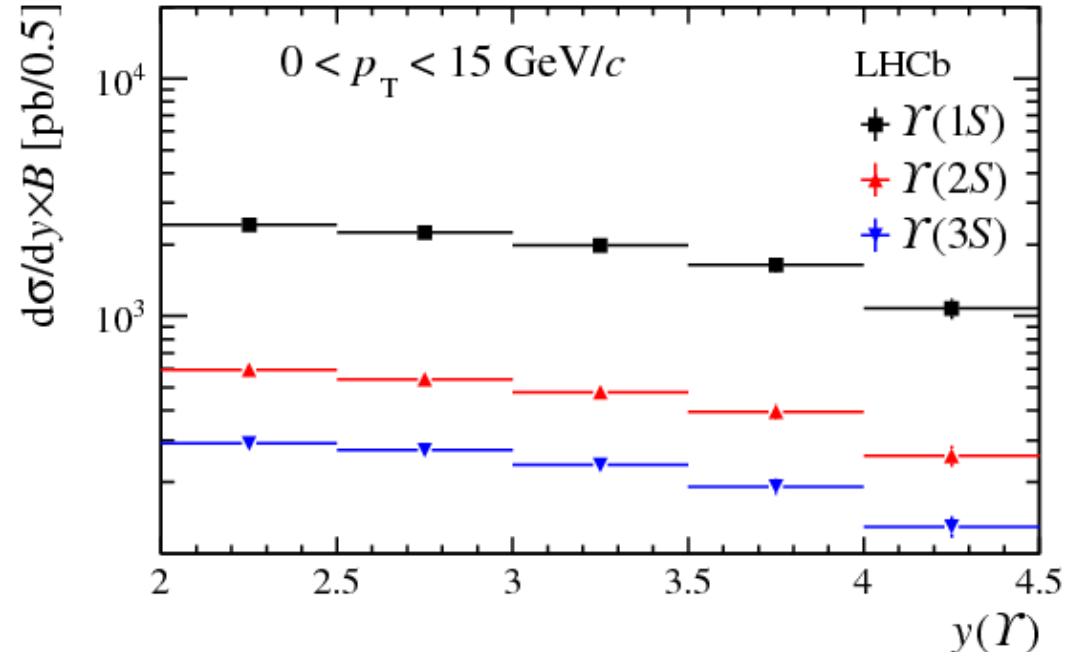
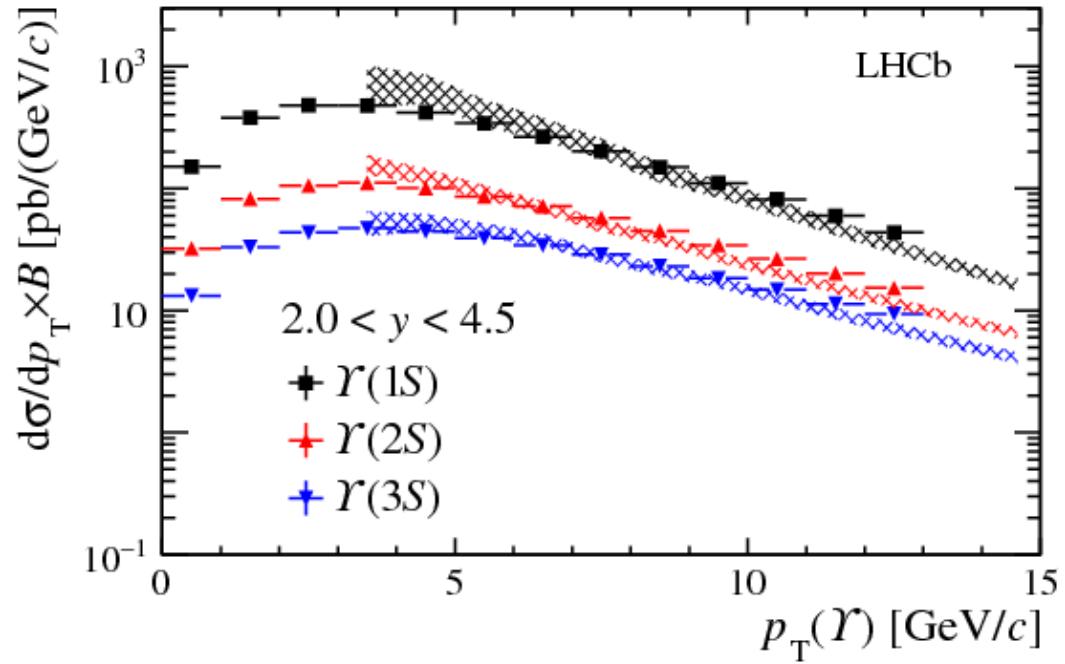
- Cross-section determination

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

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



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



- 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