



STUDY OF CHARMONIUM PRODUCTION AT LHCb

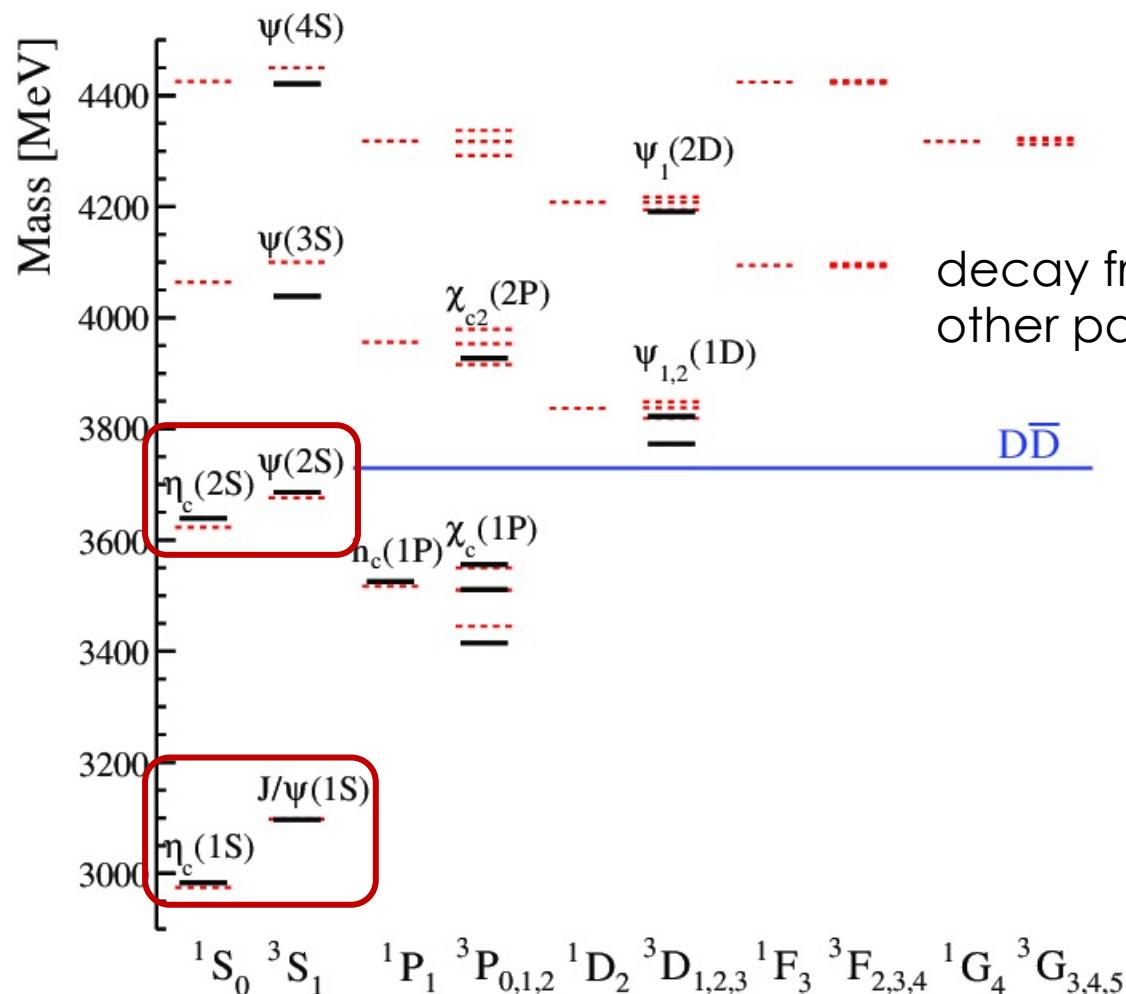
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on behalf of the LHCb Collaboration

Quarkonia as Tools

March 22, 2021

CHARMONIUM SPECTROSCOPY



- **Sources of charmonium:**

- prompt hadroproduction
- decays of higher resonances
- production in b-hadron decays

decay in
collision vertex

decay from
other particles

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 different 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;

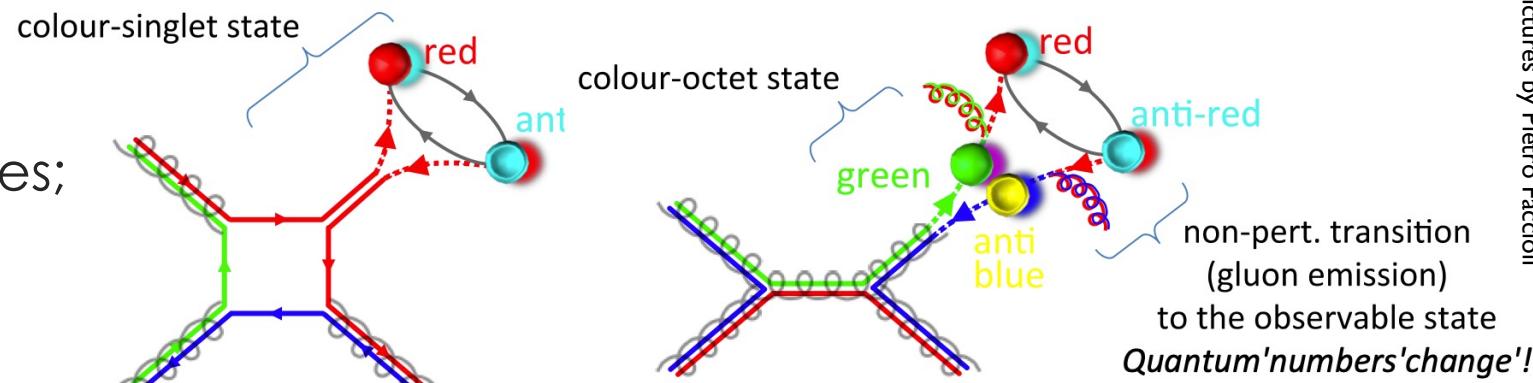
CHARMONIUM PRODUCTION IN NRQCD

- 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 (LDME),
non-perturbative part

- Both **CS** and **CO states** are allowed with varying probabilities;
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

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

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

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

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

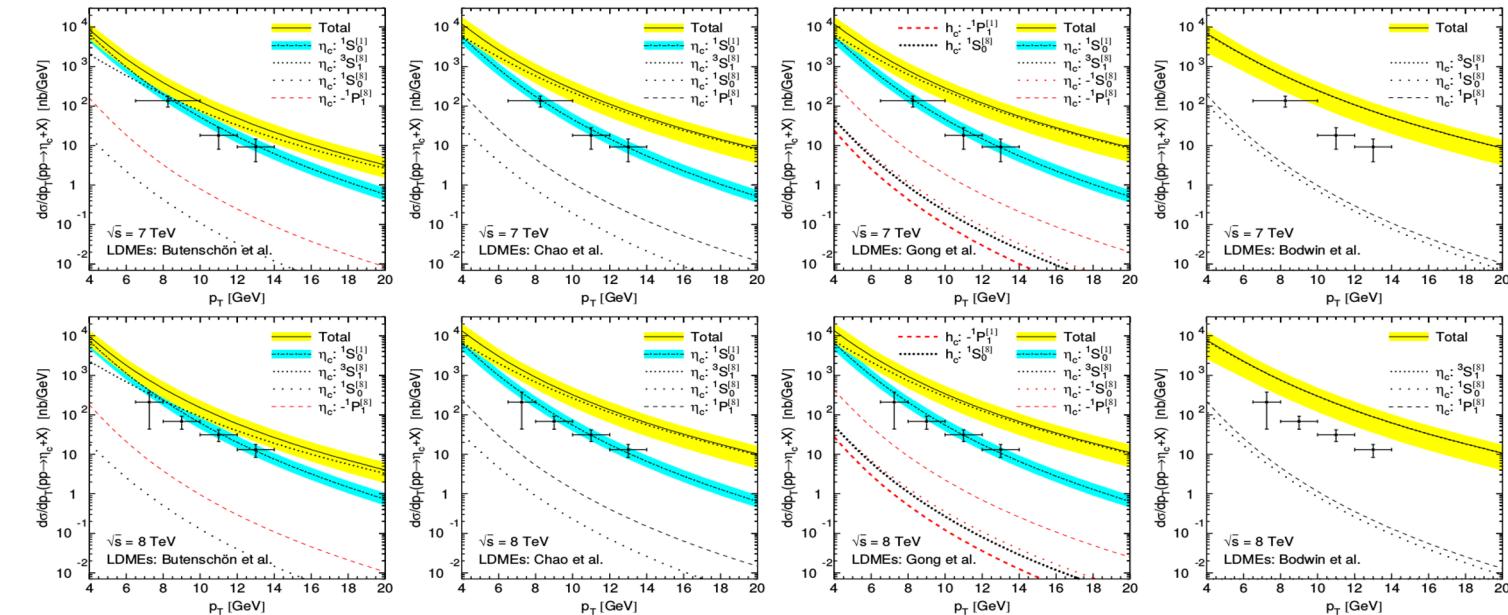
- Direct projection to LHCb data
- **LHCb data saturated by CS contribution**, tension in simultaneous description of η_c production and J/ψ production and polarization
- **Following progress in theory:**

→ [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](#)

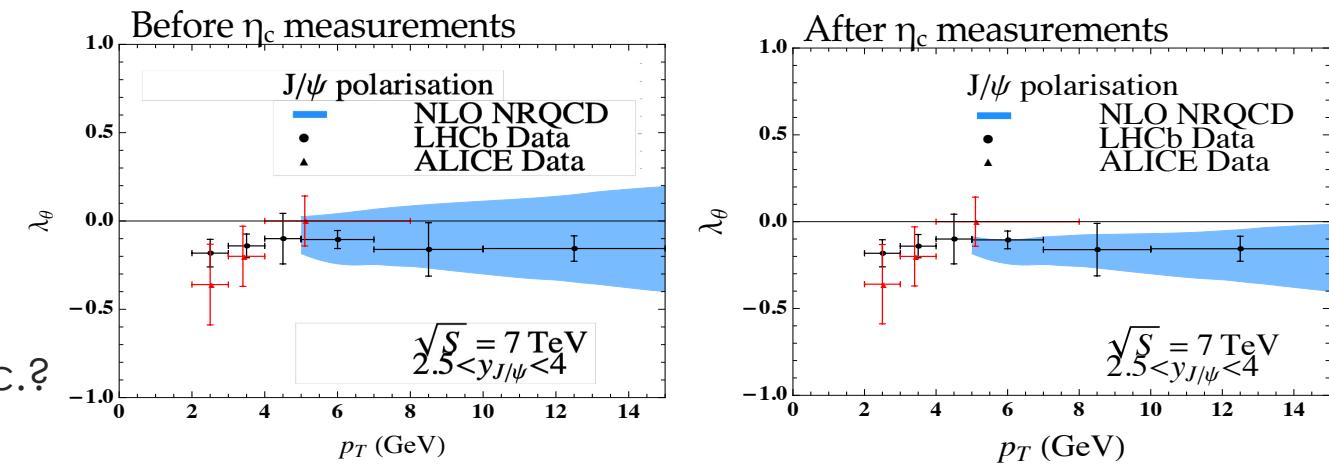
→ [Phys.Rev.Lett. 110\(2013\) 042002](#)

→ [Phys.Rev.D 93 \(2016\) 034041](#)

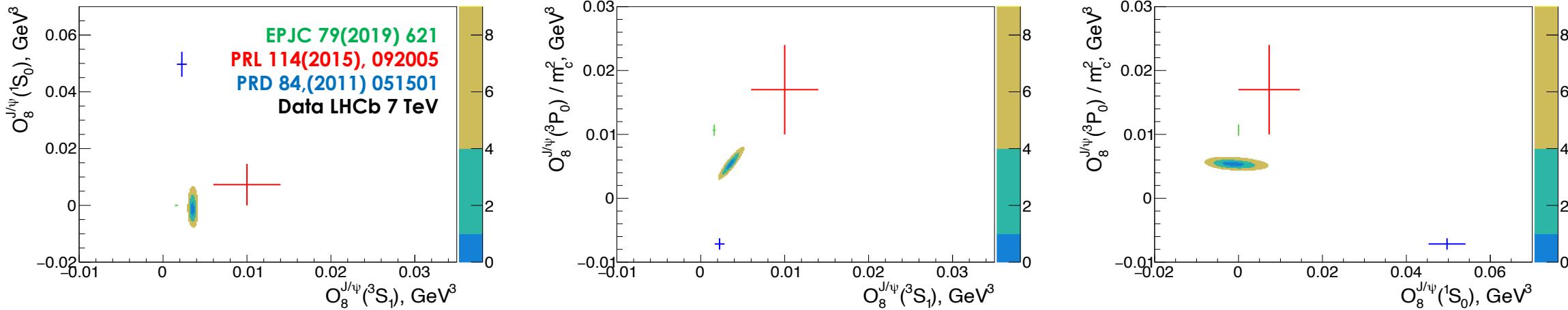
- η_c production @ $\sqrt{s}=7$ and 8 TeV sets new constraint on J/ ψ polarization

Outcome:

- Impressive progress
- Tension with CDF data
- Two large CO contributions cancel each other \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 clean test of NRQCD [Phys.Lett.B 786 \(2018\) 342-346](#)

- LHC provides large number of $b\bar{b}$ and $c\bar{c}$ pairs:

- $\sigma_{b\bar{b}} \sim 0.5$ mb in LHCb @ $\sqrt{s} = 13$ TeV
- $\sigma_{c\bar{c}} \sim 3.0$ mb

- 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**

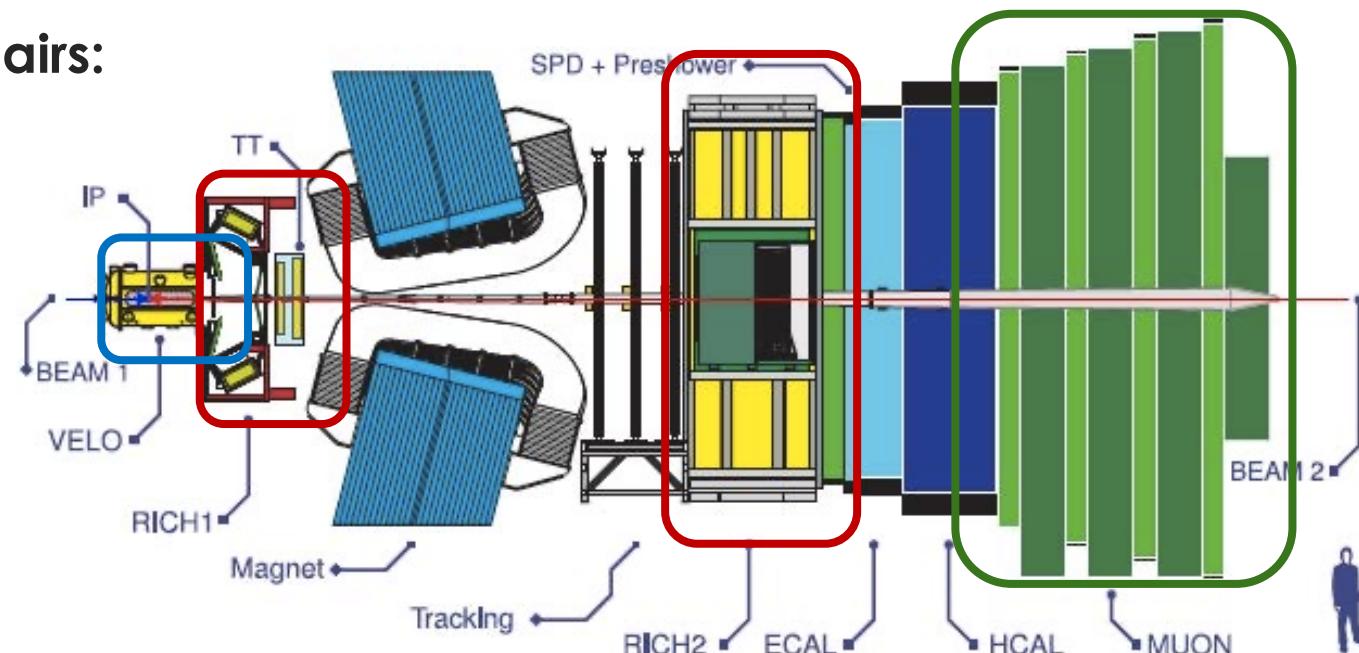
- Forward peaked HQ production at the LHC, second b in acceptance once the first b is in

- Key detector systems for production measurement:

- Vertex reconstruction with **VELO**

- Particle identification with **2 Ring Imaging Cherenkov Detectors (RICH)** and **Muon detector**

- Trigger



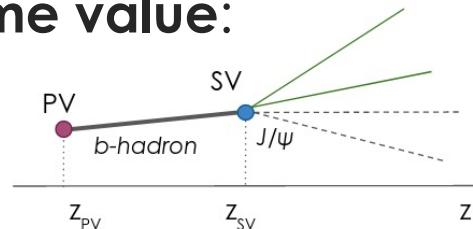
- Cross-section determination:

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

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

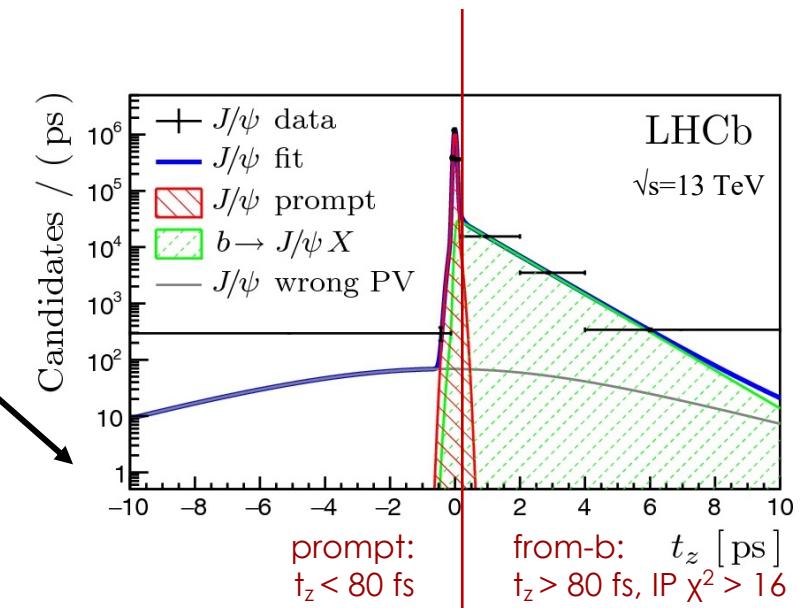
- Extracted from DATA
- Calculated from PDG:
 $\mathcal{B}_{J/\psi \rightarrow p\bar{p}} = (2.120 \pm 0.029) \times 10^{-3}$
 $\mathcal{B}_{\eta_c(1S) \rightarrow p\bar{p}} = (1.45 \pm 0.14) \times 10^{-3}$
- From Simulation

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

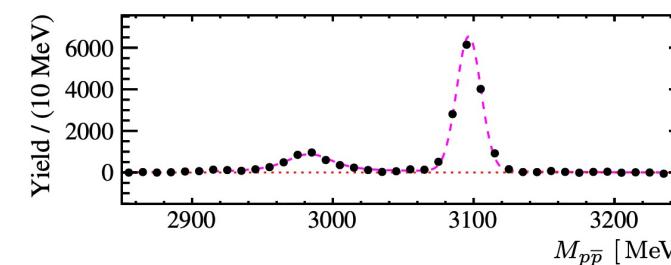
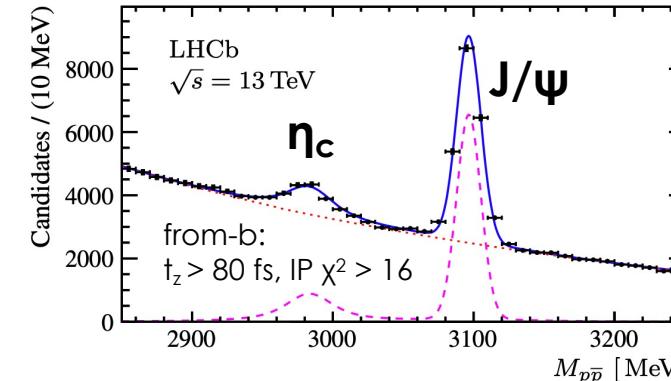
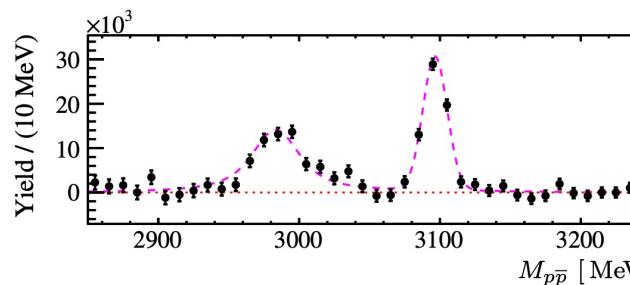
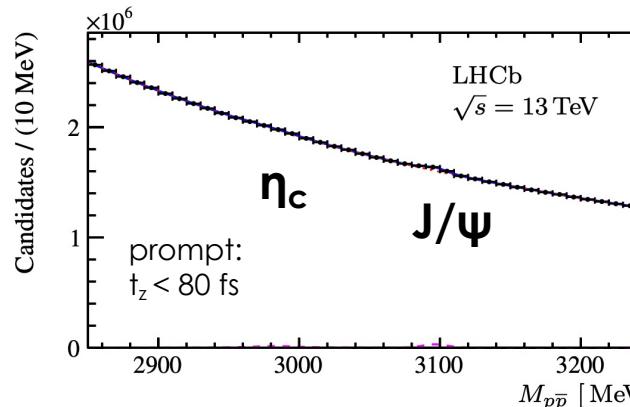


$$t_z = \frac{z_{SV} - z_{PV}}{p_z} M_{p\bar{p}}$$

- 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 η_c mass up to date:

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

- Relative charmonium yields:

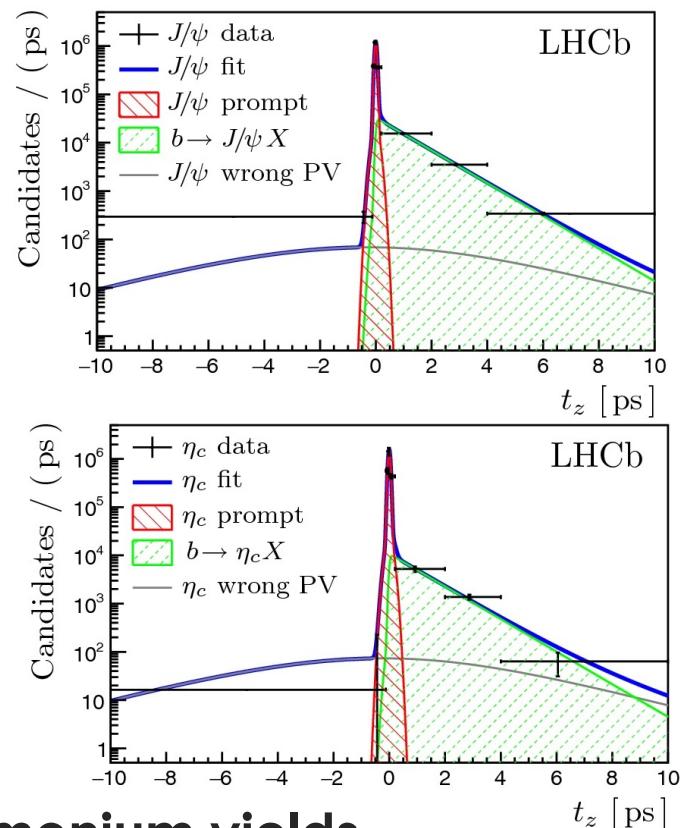
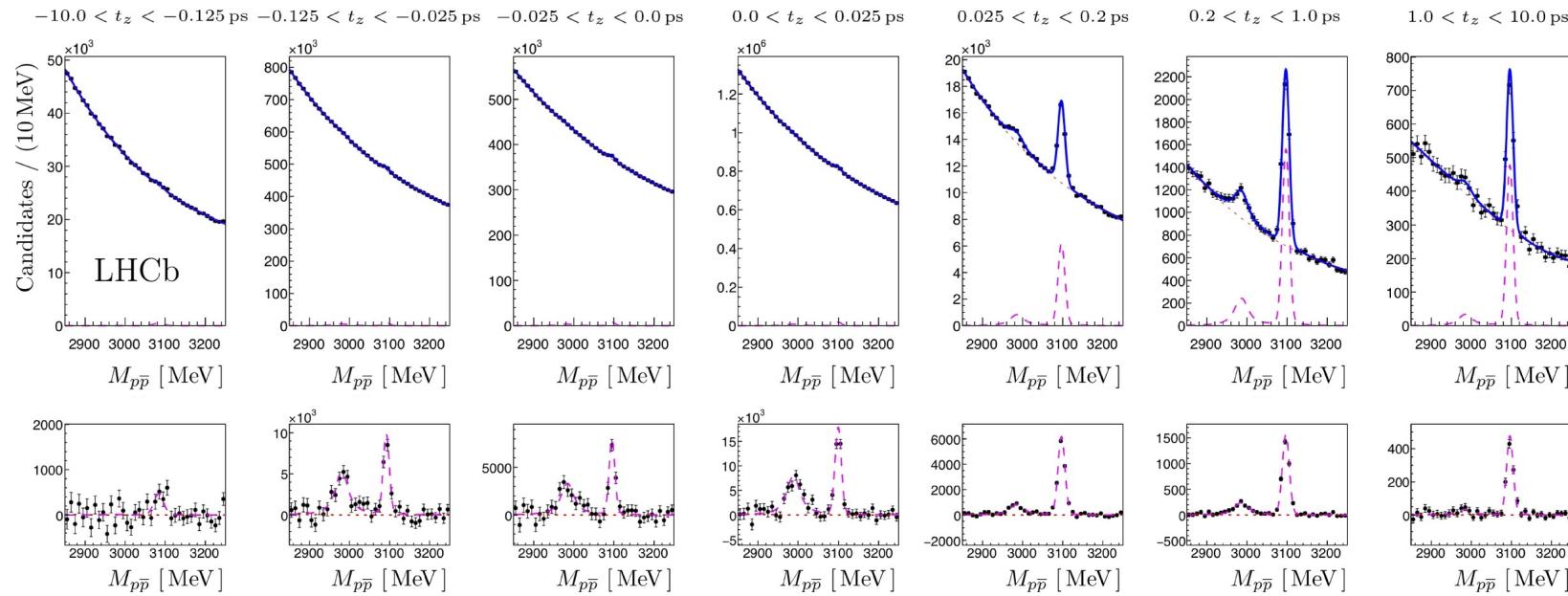
$$6.5 < p_T < 14.0 \text{ GeV}/c, 2.0 < y < 4.5$$

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

- Cross-feed probabilities:

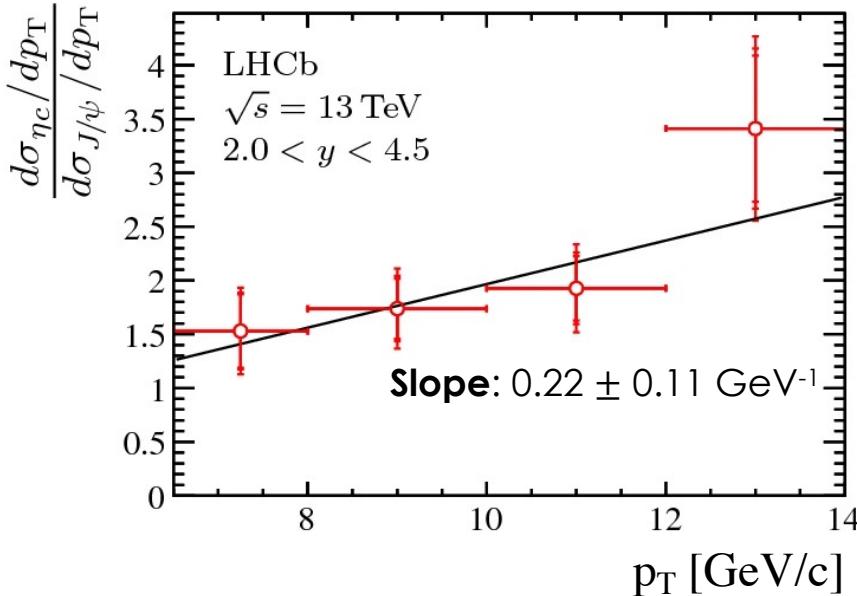
$$\begin{aligned} \rightarrow \varepsilon^{\text{prompt} \rightarrow \text{prompt}} &= 0.965 \pm 0.021 \\ \rightarrow \varepsilon^{\text{prompt} \rightarrow \text{from-b}} &= 0.0002 \pm 0.0001 \\ \rightarrow \varepsilon^{\text{from-b} \rightarrow \text{prompt}} &= 0.066 \pm 0.005 \\ \rightarrow \varepsilon^{\text{from-b}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

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



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

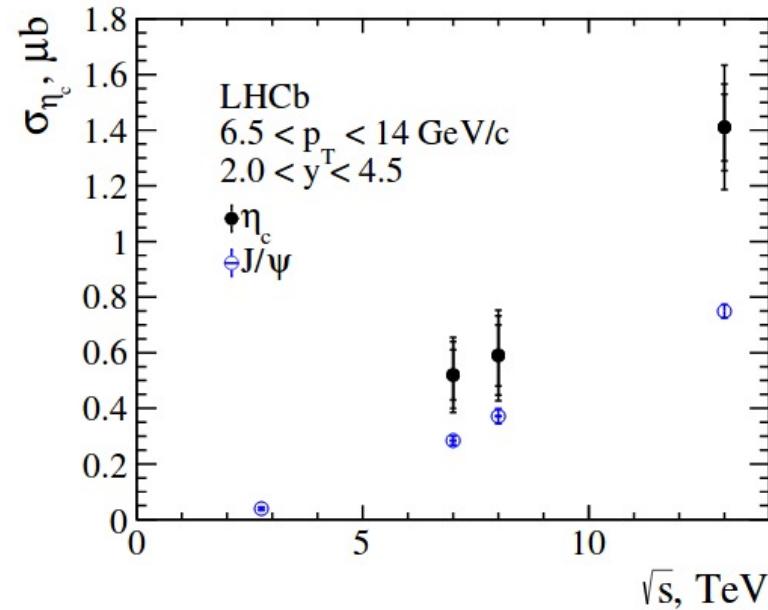
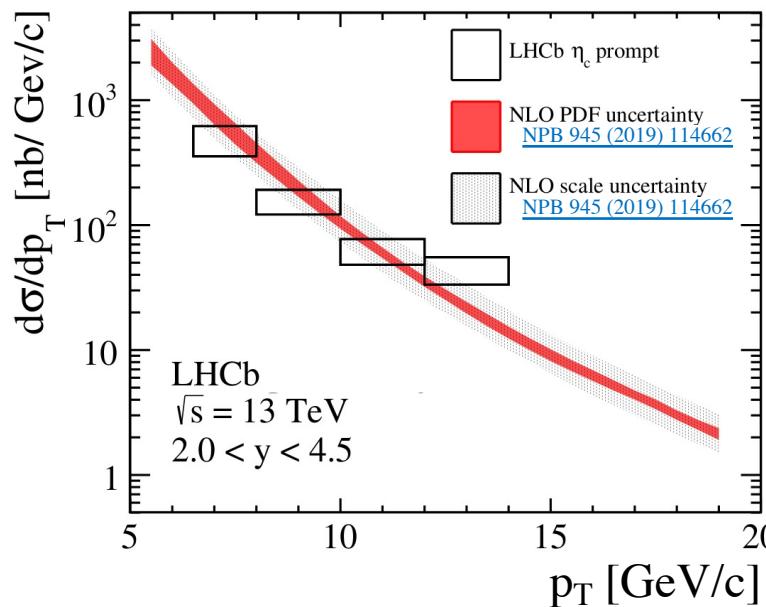
- Relative η_c to J/ ψ p_T -differential production cross-sections



- Relative $\eta_c(1S)$ to J/ ψ 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**
- 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 $\sqrt{s}=13 \text{ TeV}$:

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

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

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

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

- Cross-section determination

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

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

- integrated luminosity

- total efficiency

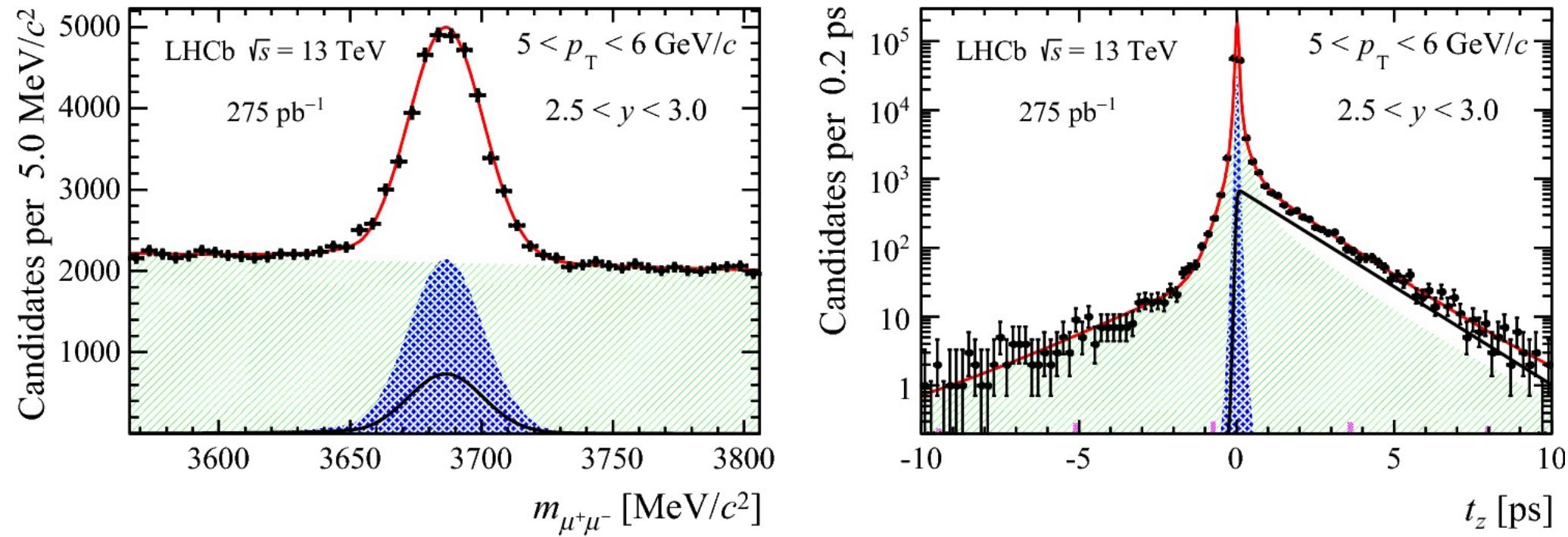
- the phase space factor to correct dielectron channel

- number of signal candidates in the given (p_T, y) bin

- bin width

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

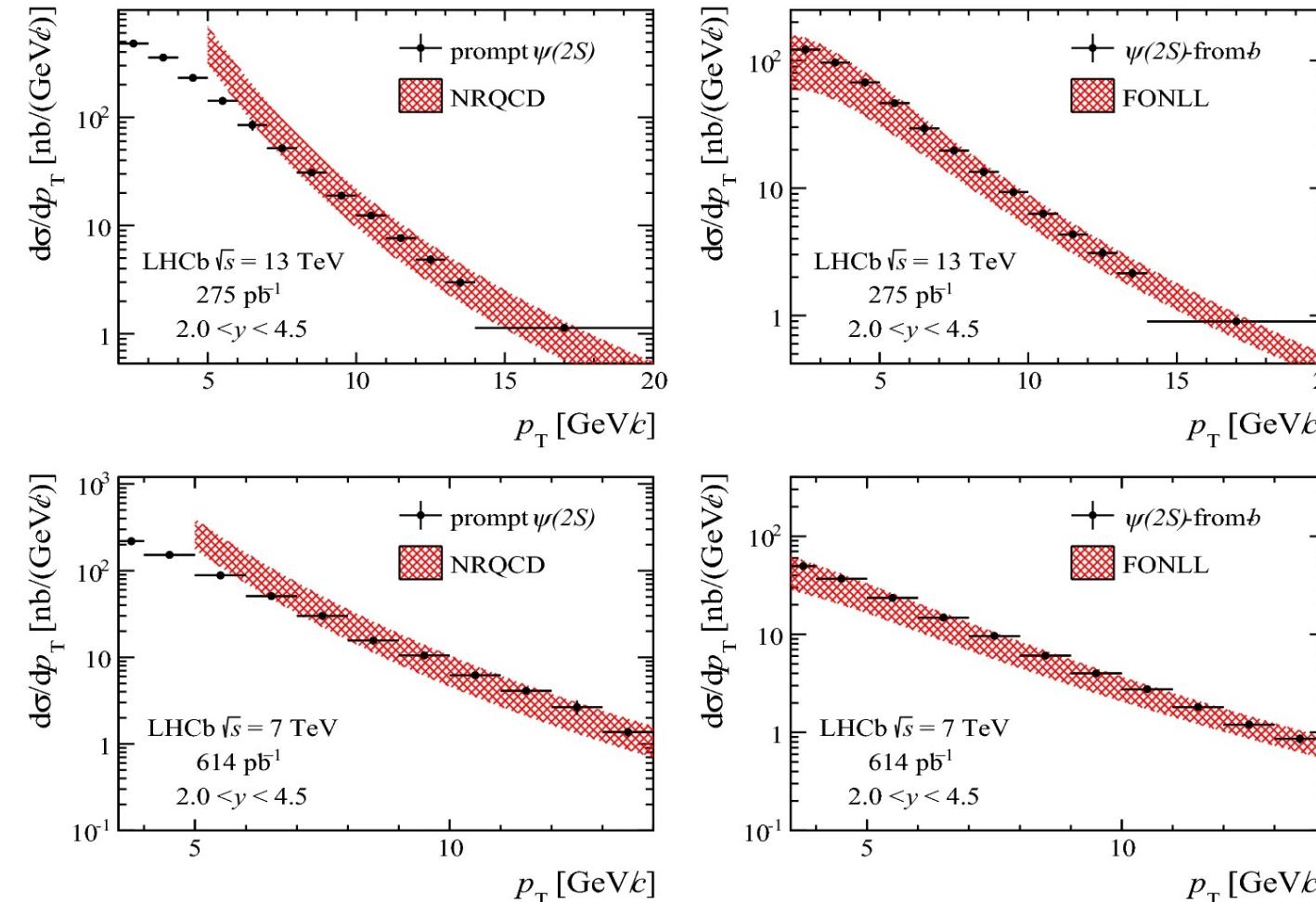
- Prompt** and **b-decay production** distinguished via **combined mass-lifetime fits**
- Full kinematic range cross-section**



- **Prompt $\psi(2S)$ and $\psi(2S)$ 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



$\psi(2S)$ production in LHCb:

- $\sqrt{s}=13 \text{ TeV}$

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

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

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

- $\sqrt{s}=7 \text{ TeV}$:

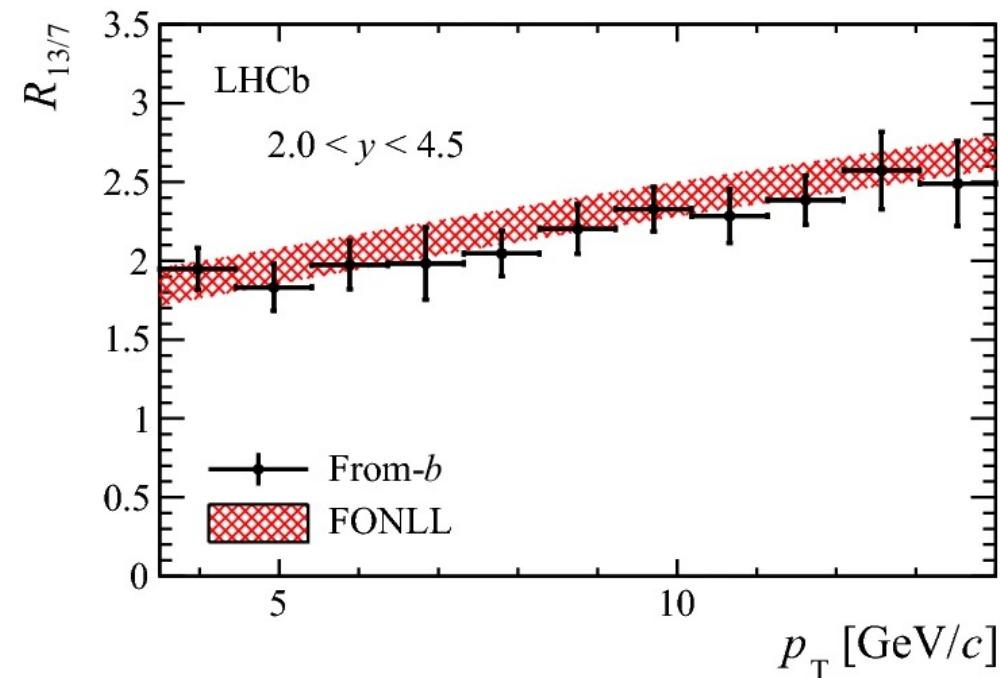
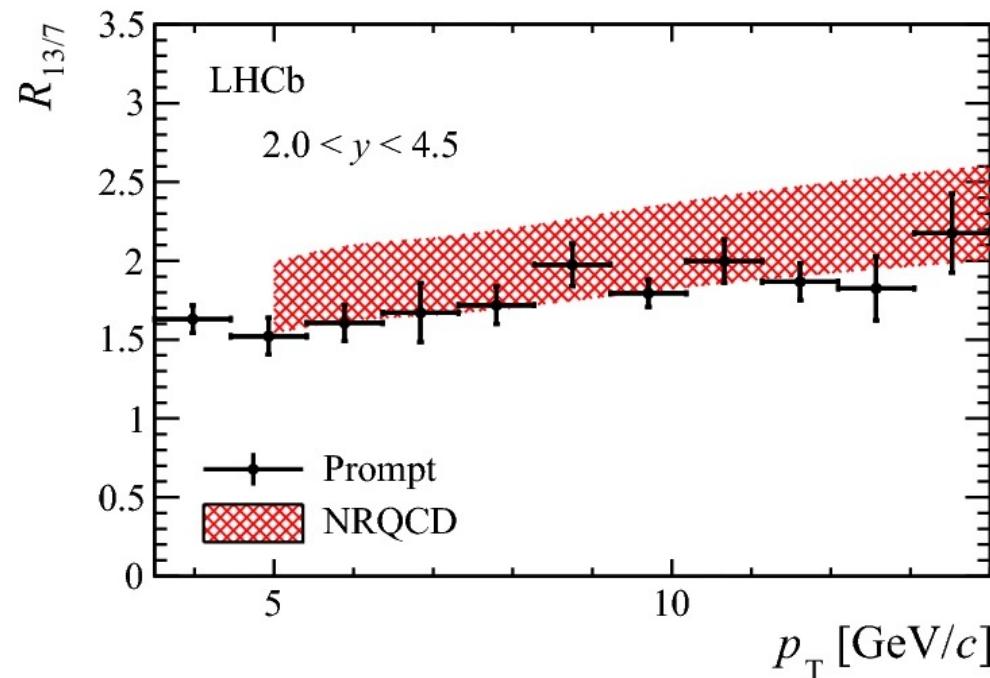
$3.5 < p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5,$

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

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

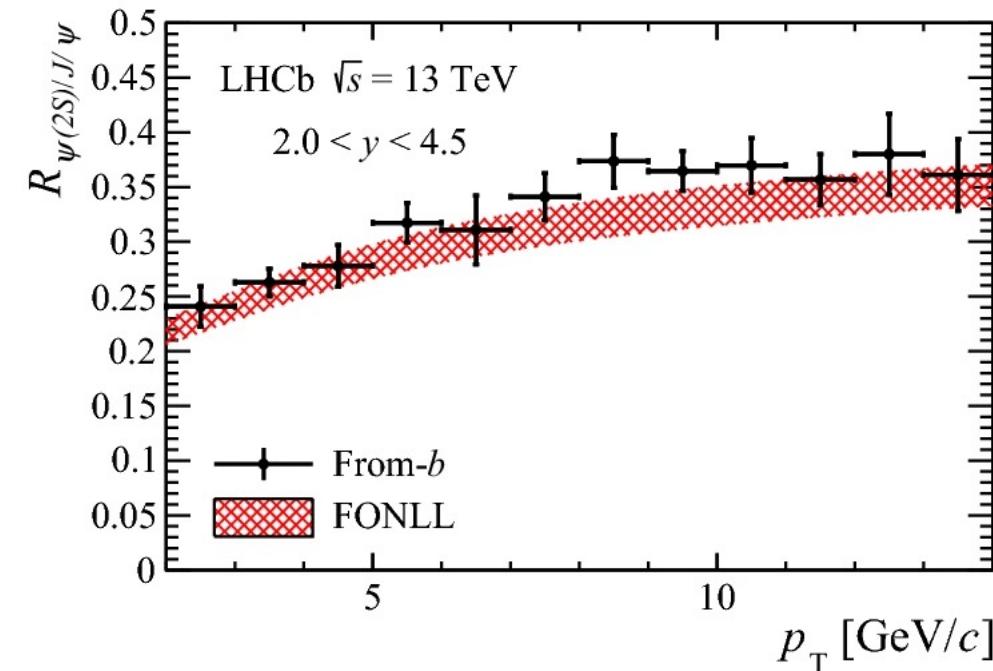
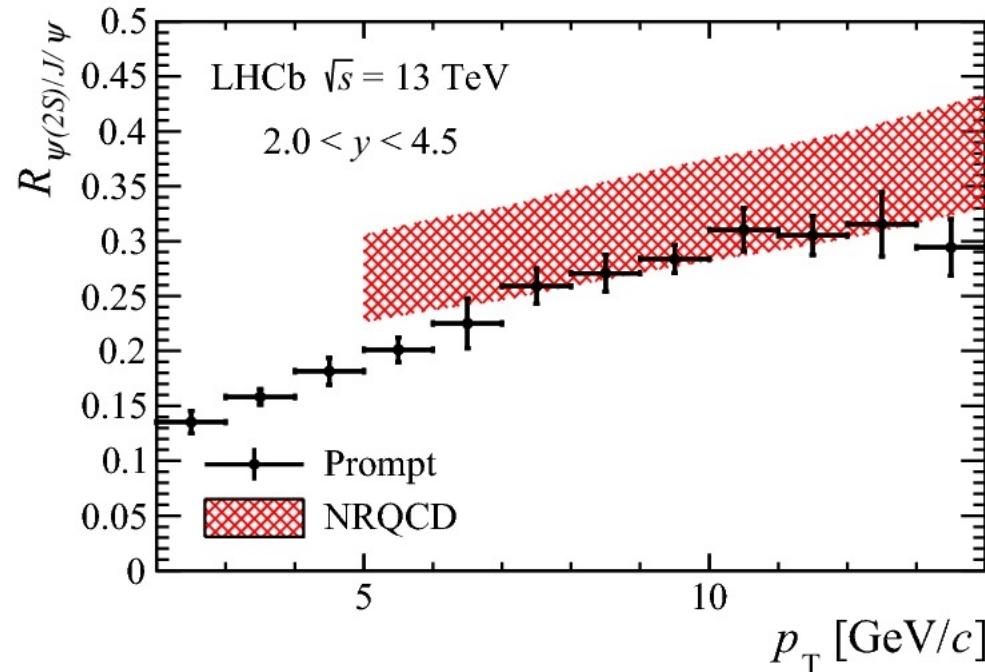
- Reasonable agreement between NRQCD and data for $p_T > 7 \text{ GeV}/c$
- Good agreement for FONLL

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



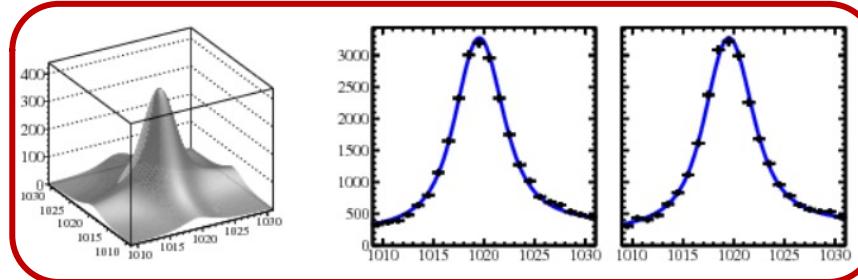
- Good agreement between NRQCD and data
- Good agreement for FONLL

- 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**

- 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 $\eta_c(2S) \rightarrow \phi\phi$

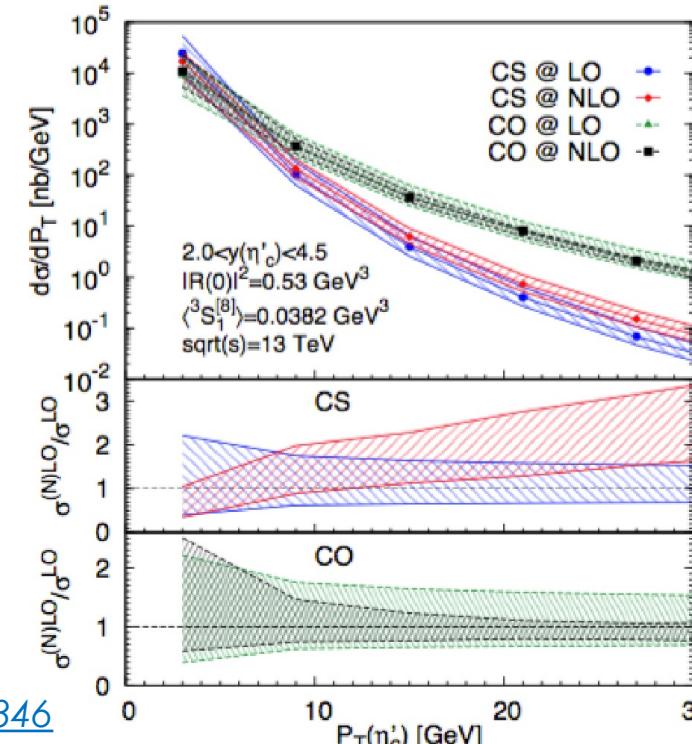
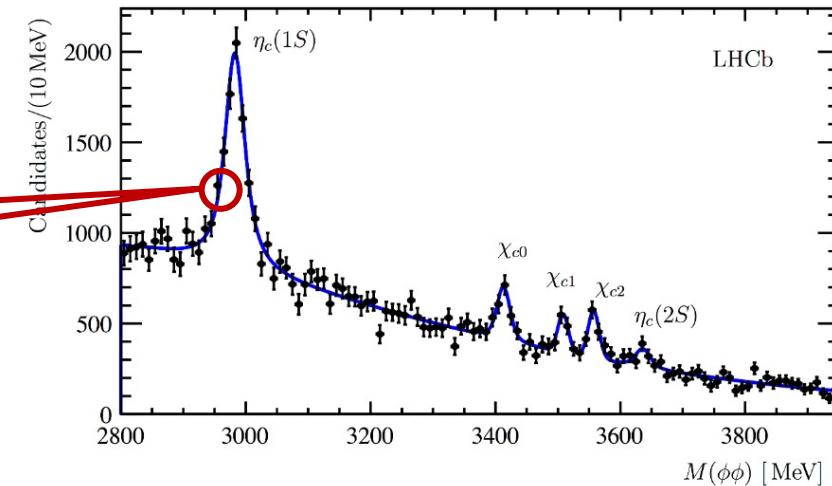
$$\frac{\mathcal{B}(b \rightarrow \eta_c(2S)X) \times \mathcal{B}(\eta_c(2S) \rightarrow \phi\phi)}{\mathcal{B}(b \rightarrow \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \rightarrow \phi\phi)} = 0.040 \pm 0.011 \pm 0.004$$

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

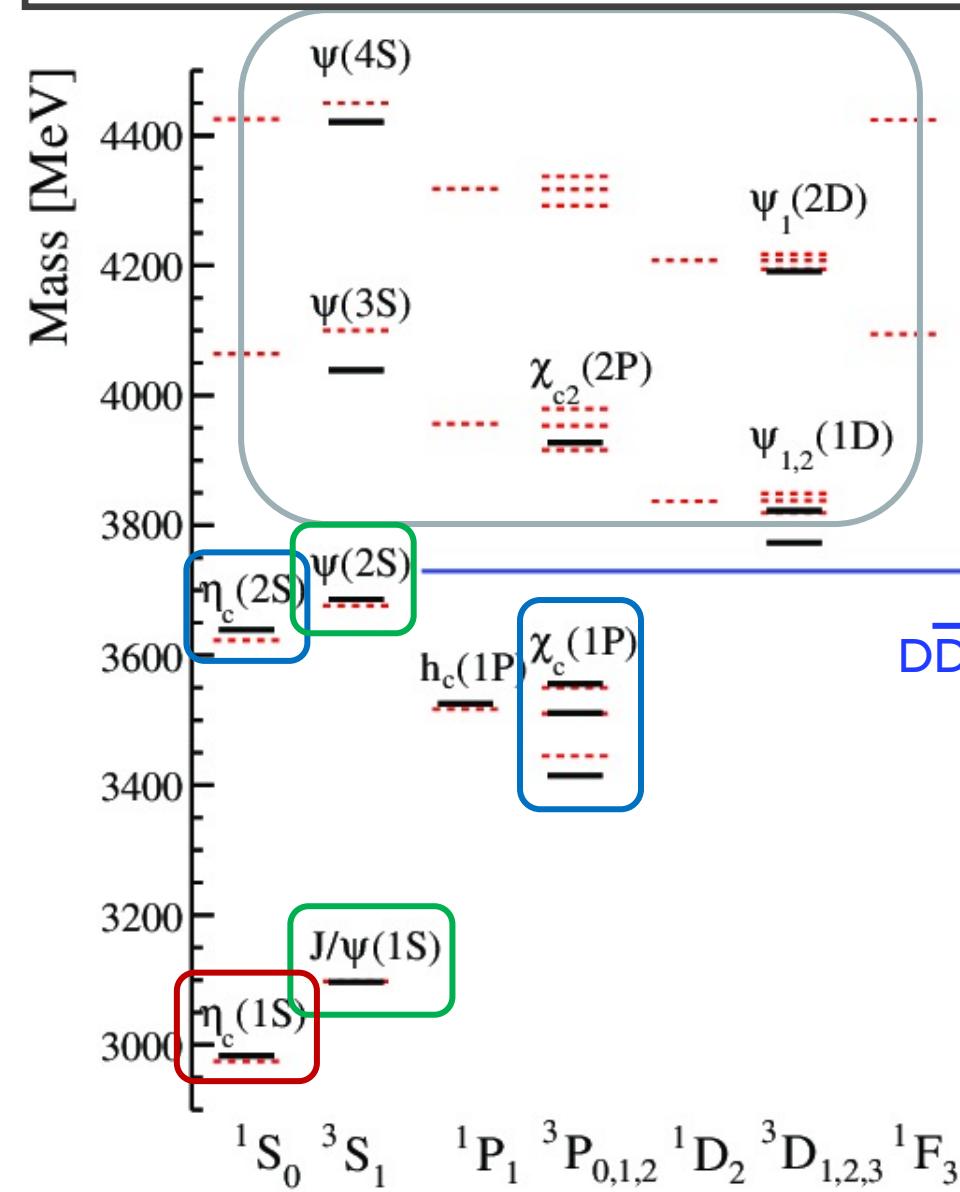
- theory prediction



- dedicated LHCb trigger in 2018**



CHARMONIUM SPECTROSCOPY: LHCb PROGRESS



- LHCb results allow to perform **powerful tests of QCD** via quarkonium production:
 - χ_c prompt production measured via $J/\psi\gamma$
7 TeV: [JHEP 10\(2013\) 115](#), [PLB 714\(2012\) 215-223](#)
 - χ_c and $\eta_c(2S)$ b-decays production measured via $\phi\phi$,
7 and 8 TeV: [EPJC 77\(2017\) 609](#)
 - J/ψ 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 ...](#)
 - $\eta_c(1S)$ prompt and b-decays production measured via pp
7, 8 and 13 TeV: [EPJC 75\(2015\) 311](#), [EPJC 80\(2020\) 191](#)
 - Non-conventional charmonium
- Prospects:**
 - h_c and $\eta_c(2S)$ prompt production
 - All states accessible via hadronic decays
→ study decays to $\Lambda\Lambda$, $\Lambda^*\Lambda^*$, $\Sigma\Sigma$, $\Xi\Xi$ final states

BACKUP SLIDES

QUARKONIA PRODUCTION MECHANISMS

- **Production mechanisms:**

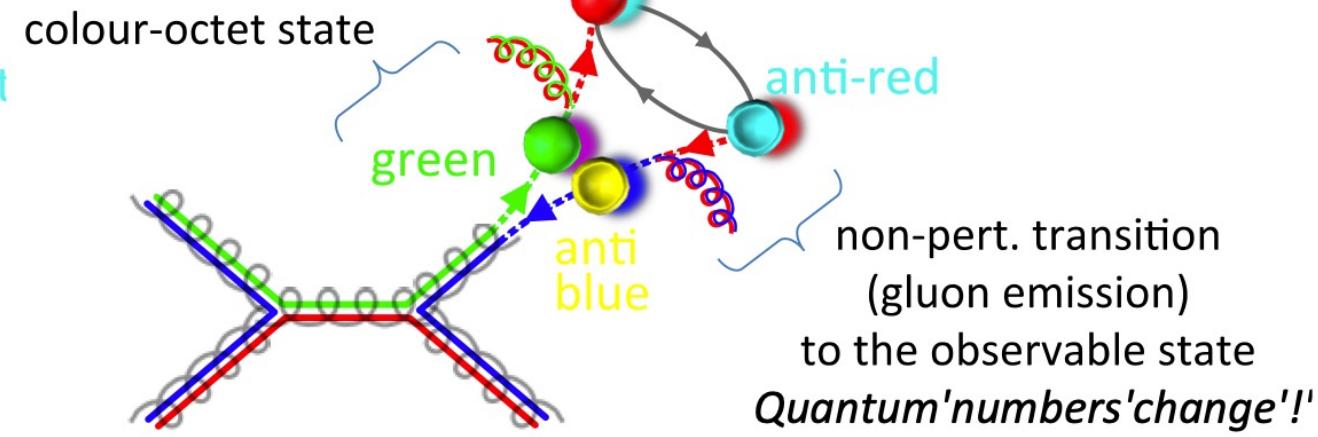
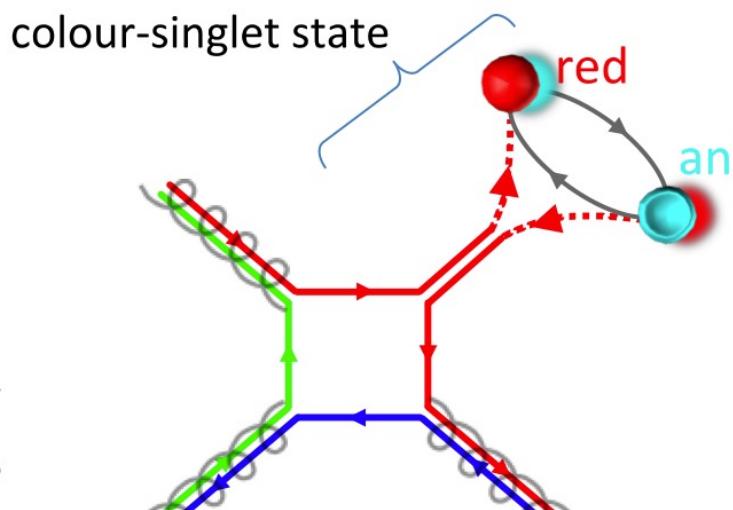
- Color Singlet (CS):

- 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

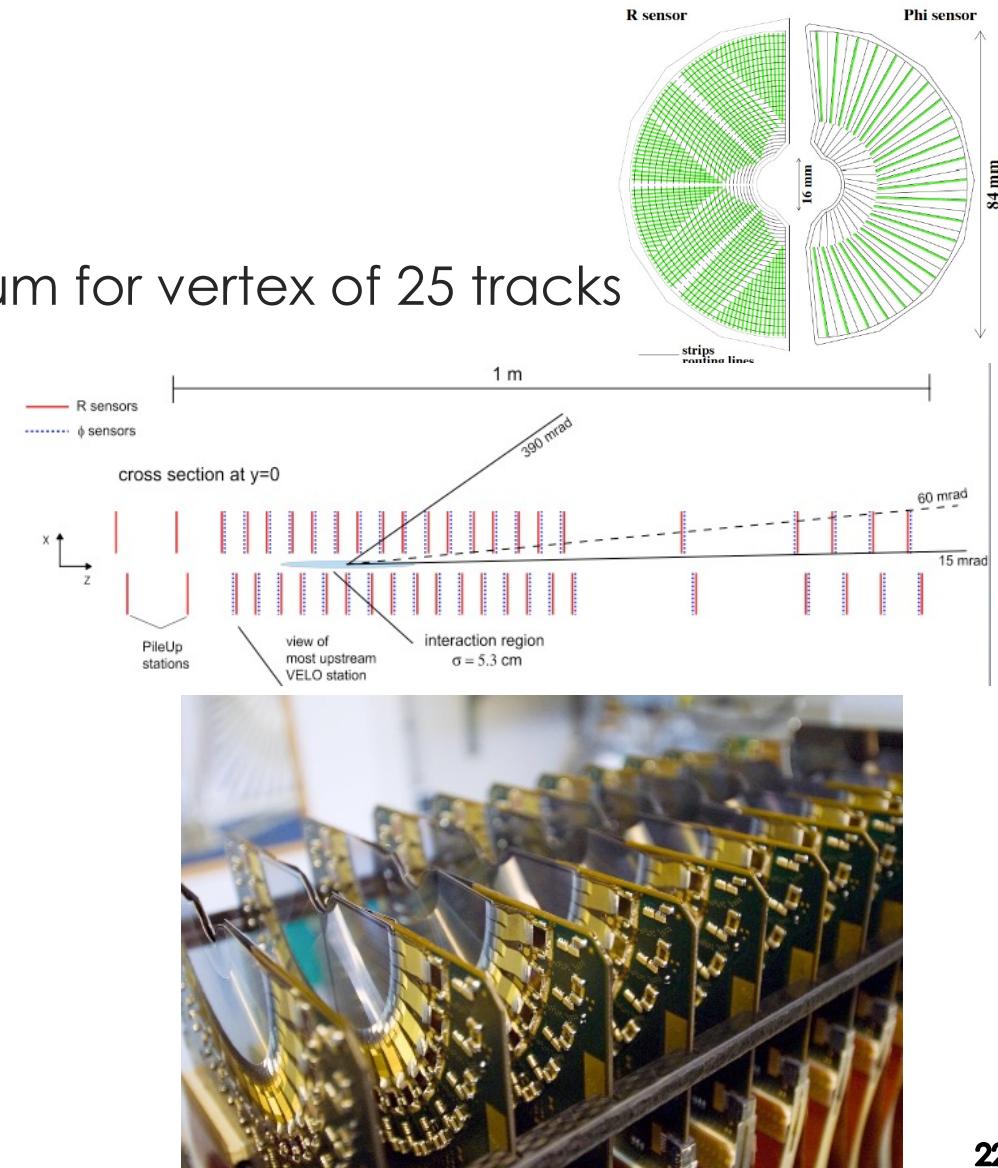
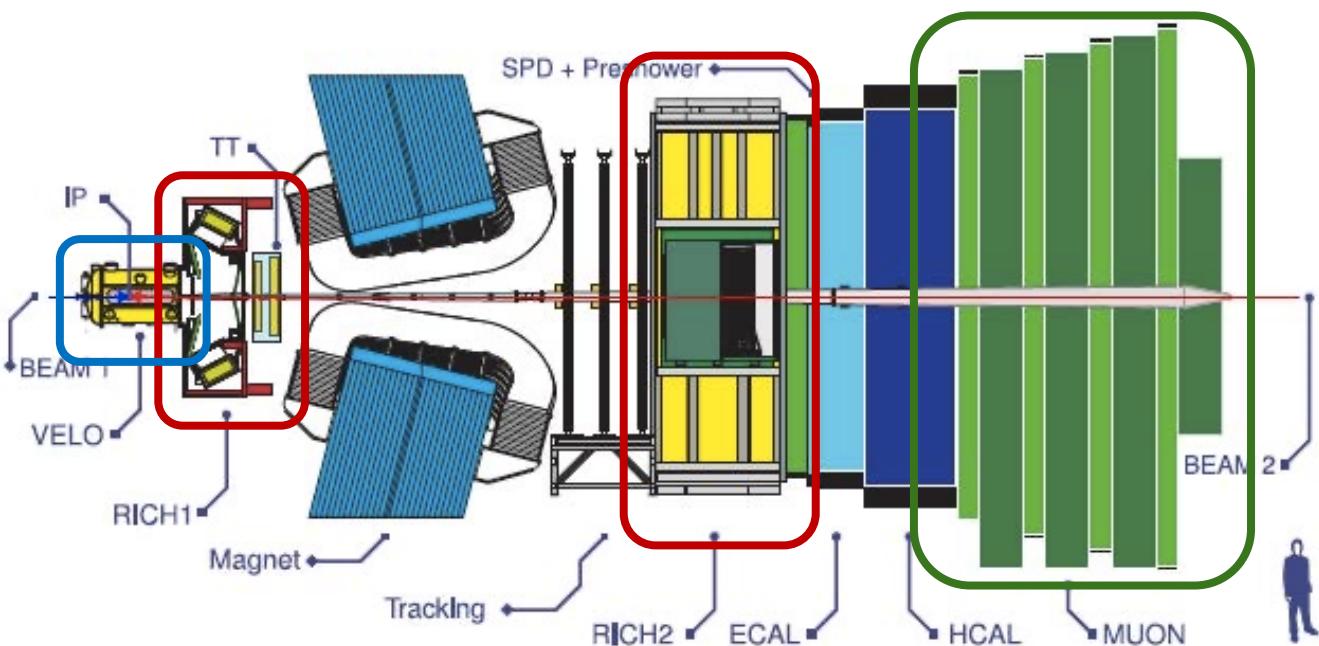
Figures by Pietro Faccioli



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

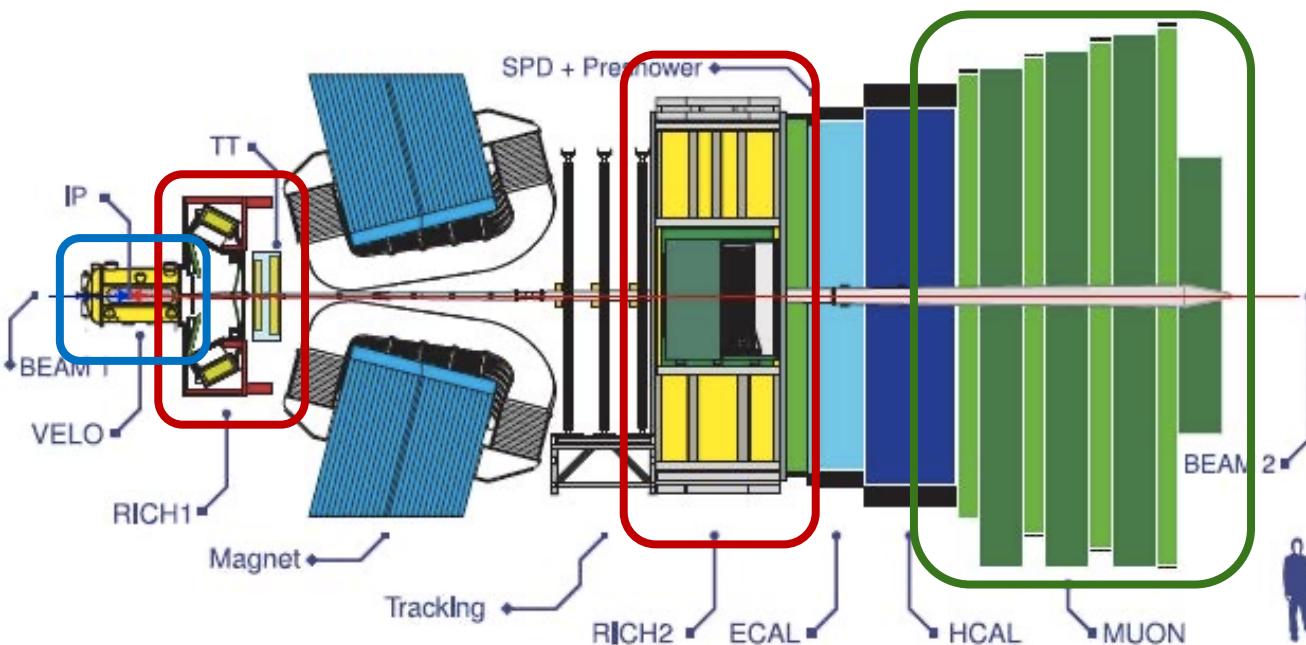
Vertex reconstruction **VELO**

- **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

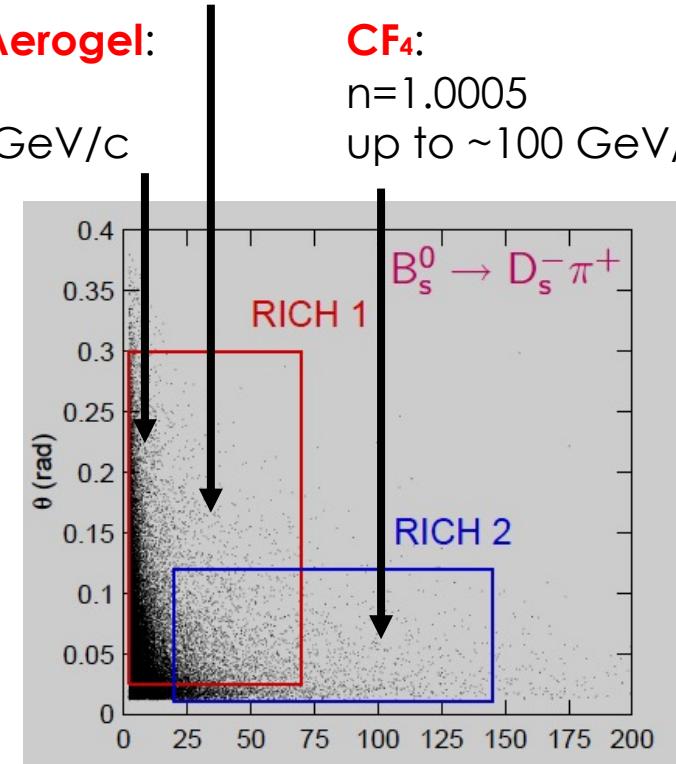
- **2 Ring Imaging Cherenkov Detectors (RICH)**: 3 Radiators covering p_T range 1.5-100 GeV/c
- **Muon detector** – triggering muons and measuring muon momenta
- Particle ID efficiency:
 - K^\pm ID ~ 95 % for ~ 5 % $\pi \rightarrow K$ mis-id probability
 - μ^\pm ID ~ 97 % for 1-3 % $\pi \rightarrow \mu$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



C₄F₁₀:
 $n=1.0014$
 up to ~70 GeV/c

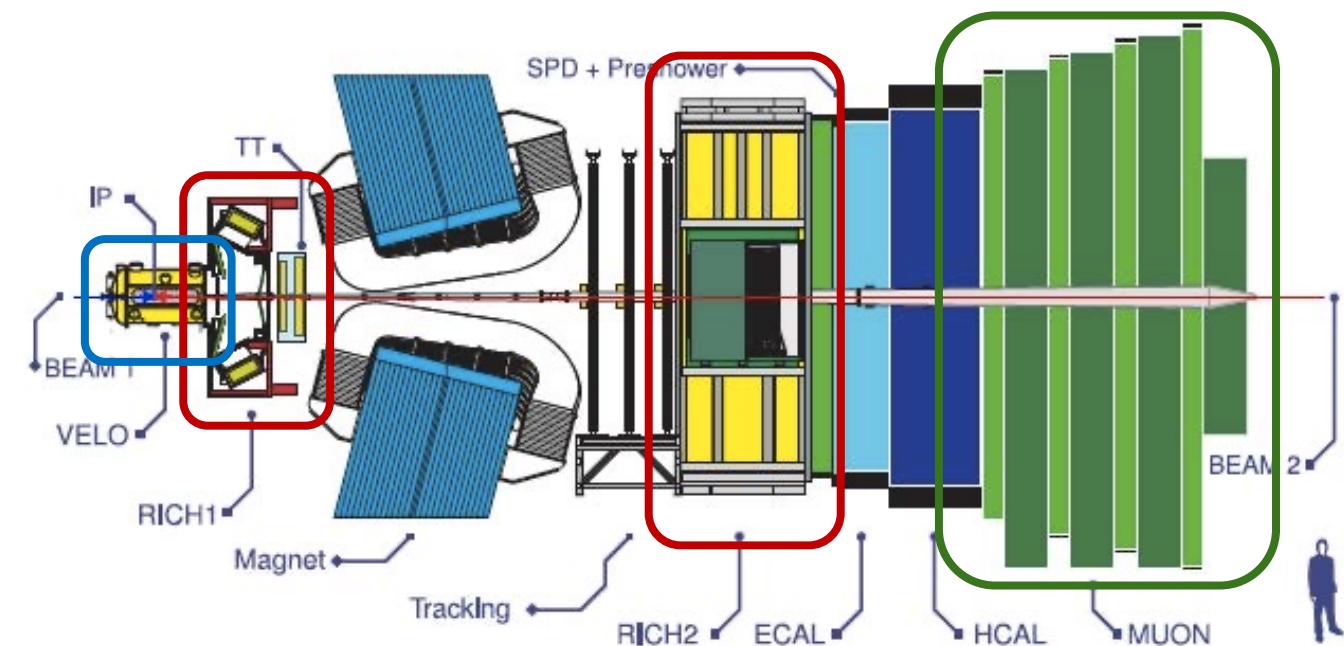
Silica Aerogel:
 $n=1.03$
 1.5-10 GeV/c

CF₄:
 $n=1.0005$
 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/γ

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/γ

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

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

- LHC provides large number of $b\bar{b}$ and $c\bar{c}$ pairs:

- $\sim 5 \times 10^{11} b\bar{b}$ pairs
- $\sim 3 \times 10^{12} c\bar{c}$ pairs

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

- $\sigma_{bb} \approx 250 \mu\text{b}$
- $\sigma_{cc} \approx 20 \times \sigma_{bb}$

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