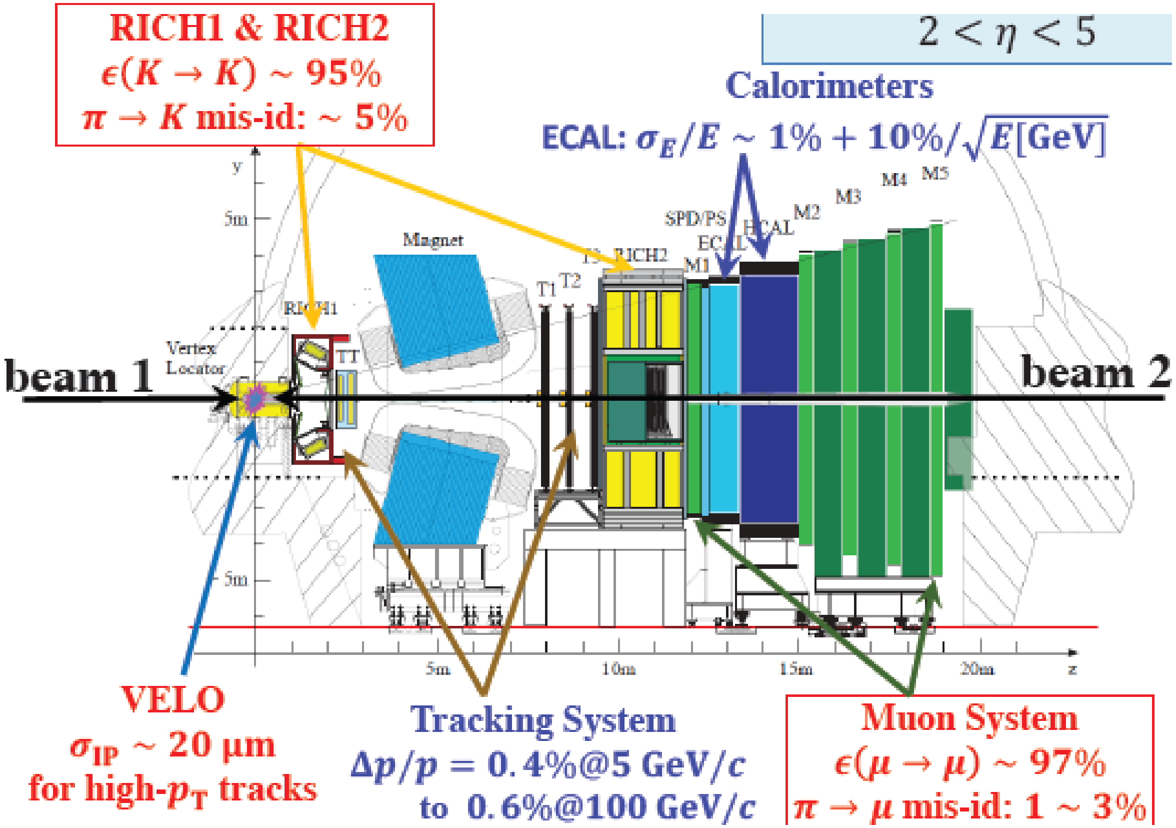
Heavy flavour production and spectroscopy at LHCb

Edwige Tournefier

On behalf of the LHCb collaboration

XXV Rencontres de Blois 2013

LHCb



LHCb recorded:

- pp collisions at
  - $\sqrt{s}$=7 TeV (1fb^{-1}, 2011)
  - $\sqrt{s}$=8 TeV (2fb^{-1}, 2012)
  - $\sqrt{s}$=2.76 TeV (71nb^{-1},2011)
- p-Pb collisions (2nb^{-1},2013)

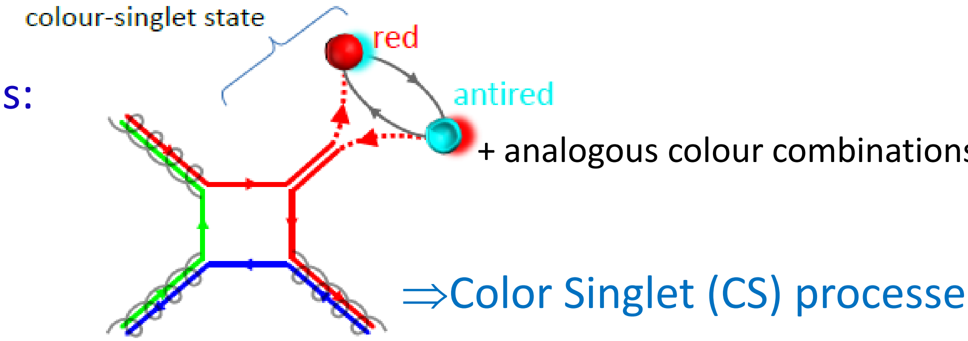
- Precise primary and secondary vertex reconstruction
- Excellent momentum, decay time resolution
- Good particule identification

Heavy flavour production: quarkonium

Quarkonia production provides a powerfull test of our understanding of strong interaction

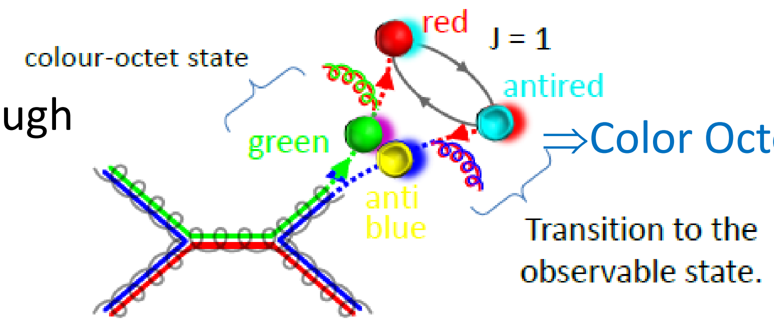
Quarkonia (cc, bb) production mechanisms:

1- Quarkonia produced directly as observable colour-neutral QQ-bar pair (Colour Singlet mechanism)



⇒Color Singlet (CS) processes

2-Coloured Q-Qbar are produced which then evolve to the observable state through soft gluon radiation (Colour Octet mechanism)



⇒Color Octet (CO) processes

⇒CSM (CS processes only)

⇒NRQCD model (CS + CO processes)

Thanks to Faccioli

⇒ Avalaible models fail to explain all the quarkonia measurements: production of prompt J/ψ, ψ(2S), ϒ, χ and their polarisation

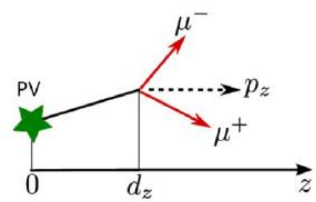
J/ψ and ϒ production

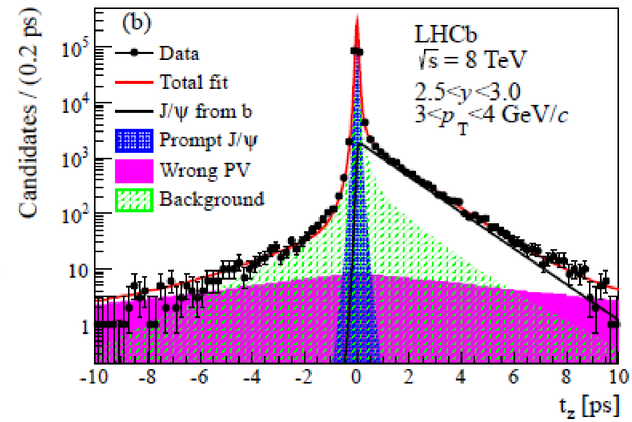
arXiv:1304.6977

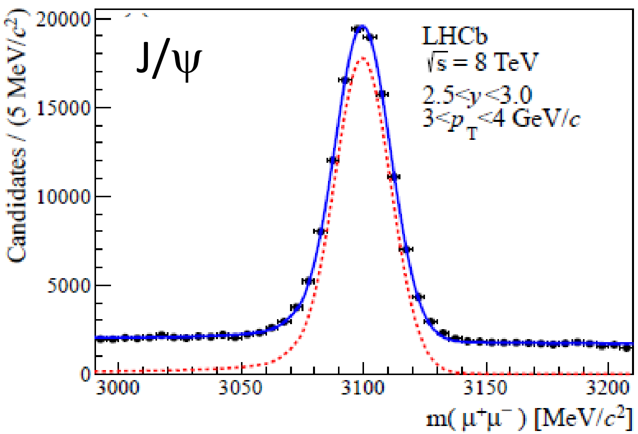
Measure prompt J/ψ and ϒ production cross section as a function of p_T and y at $\sqrt{s}$=8TeV

- J/ψ yields extracted with a 2D fit in each (p_T, y) bin
  - pseudo decay time
  - m($\mu^+\mu^-$)

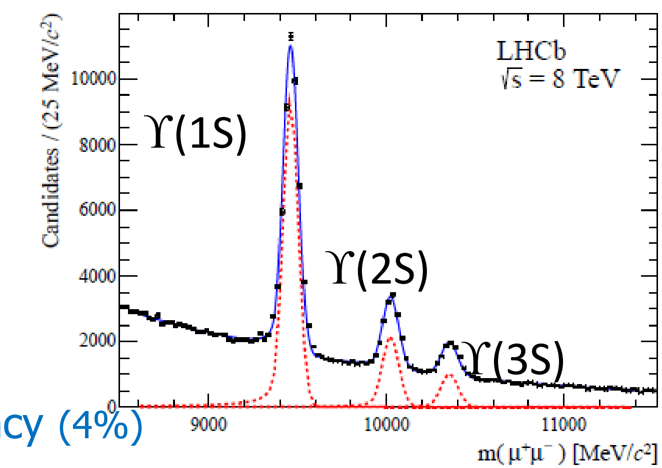
$$t_z = \frac{(z_{J/\psi} - z_{\rm PV}) \times M_{J/\psi}}{p_z}$$







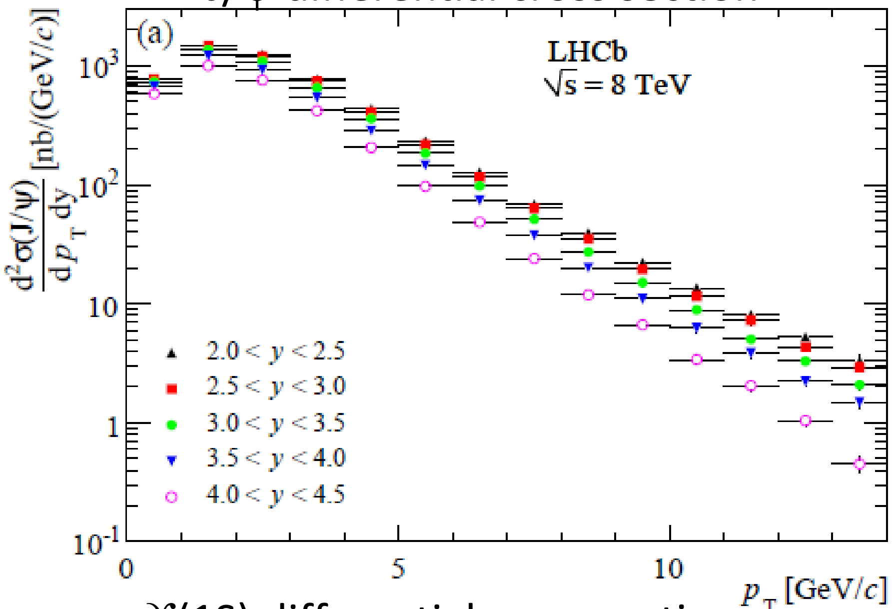
  - J/ψ from b cross section is also measured



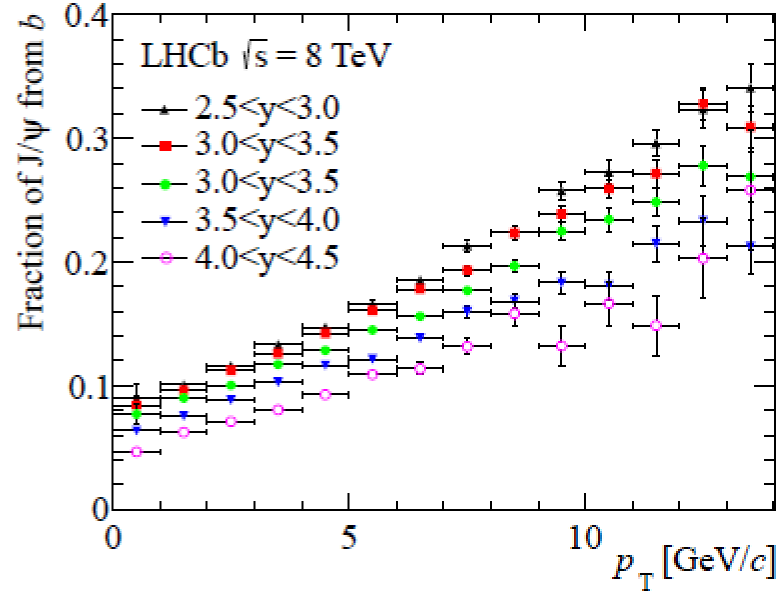
- J/ψ and ϒ assumed unpolarised
  - as measured by ALICE[1], CMS[2] and LHCb[3] (refs on slide18)
- Systematic dominated by luminosity (5%) and trigger efficiency (4%)

J/ψ and Υ production: results

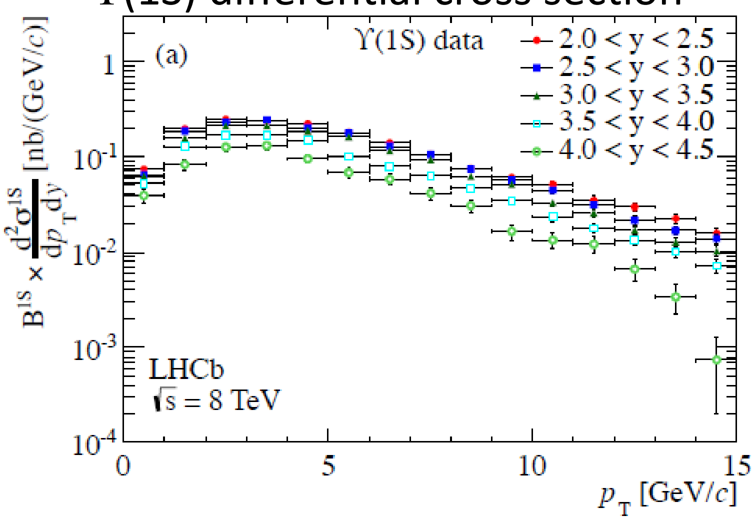
J/ψ differential cross section



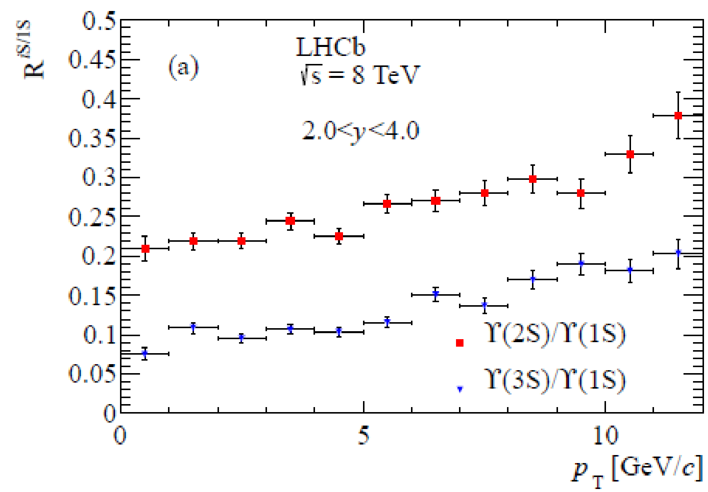
Fraction of J/ψ from b



Υ(1S) differential cross section

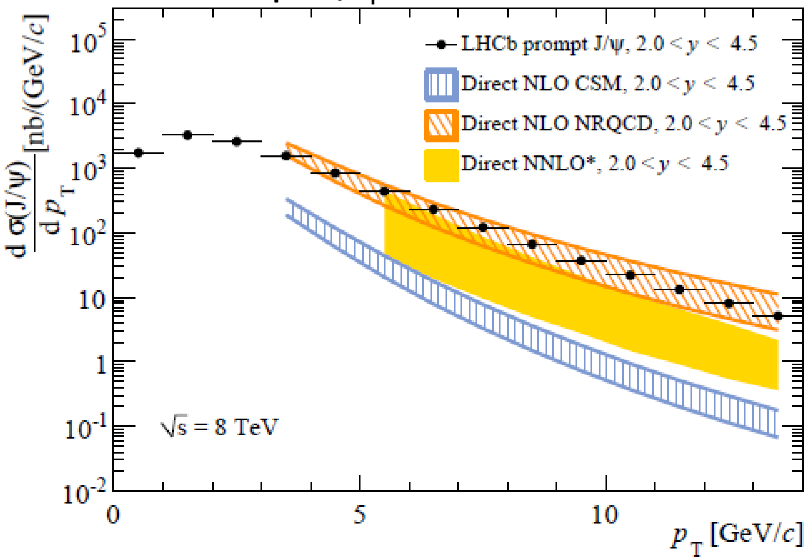


Ratio of Υ cross sections



J/ψ and ϒ production: comparison to theory

Prompt J/ψ cross section



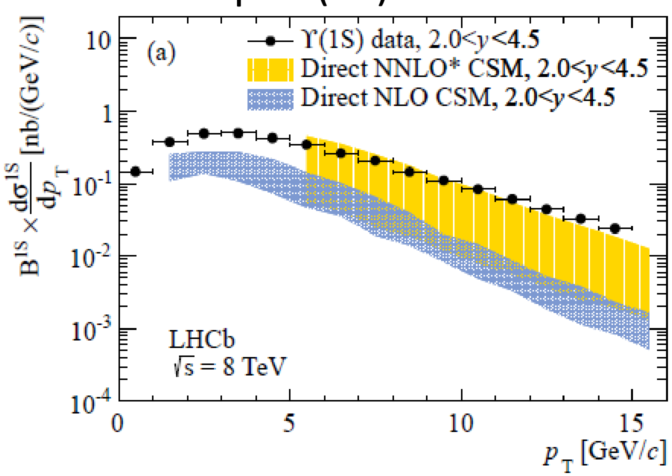
J/ψ

- Feedback from ψ(2S) and χ_c not included in theory (~30% in total Phys. Lett. B718 (2012)431)
- Reasonable agreement with NLO NRQCD and NNLO* CSM

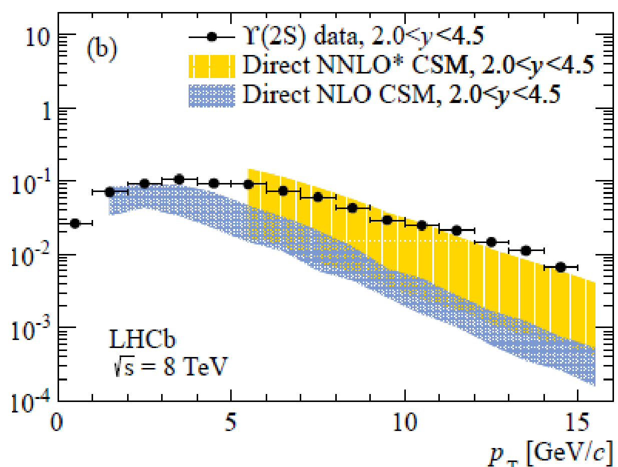
ϒ

- Feeddown from χ_b not included in theory (~20% for χ_b(1P)→ ϒ (1S)γ JHEP 11(2012)31)
- NNLO needed to describe the measurements

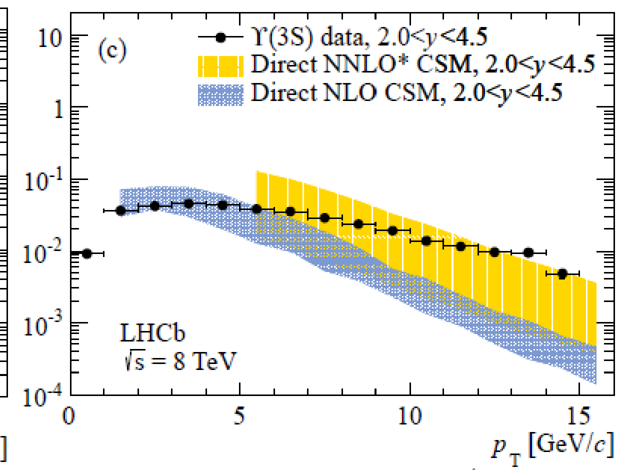
Prompt ϒ(1S) cross section



Prompt ϒ(2S) cross section



Prompt ϒ(3S) cross section



χ_{cJ}(1P) production

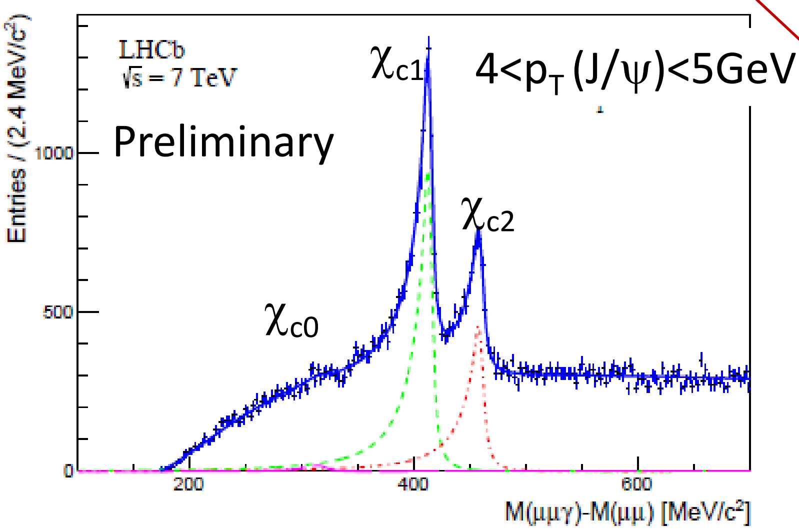
LHCb-PAPER-2013-028

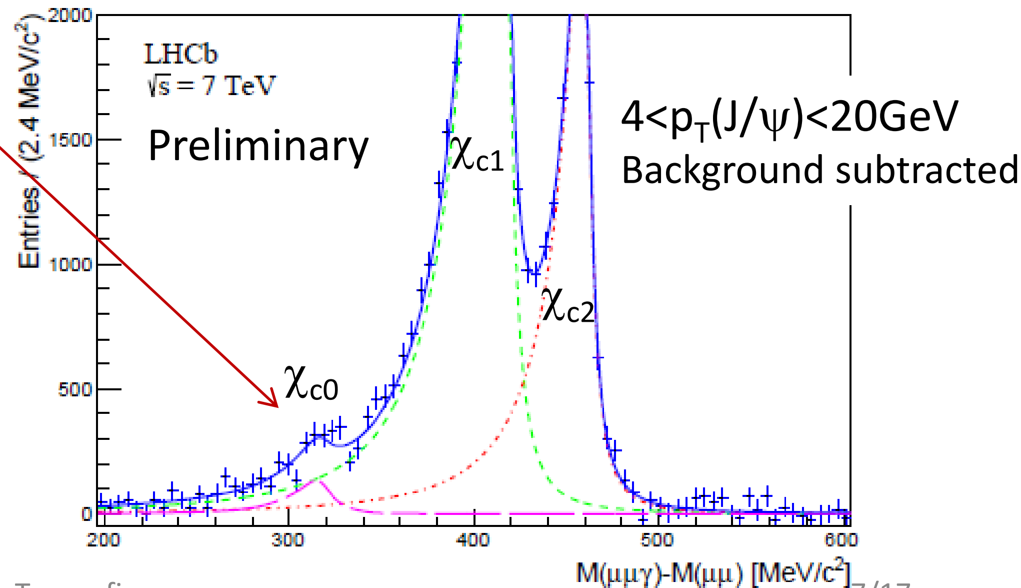
Measurement of the χ_{cJ}(1P) relative production rate (J=1,2) as a function of p_T

- Uses the decay $\chi_c \to J/\psi_{(\to\mu\mu)}\gamma$ where the photon converts into the detector
  - χ_{c1} and χ_{c2} peaks well separated thanks to the use of $\gamma \to ee$
- First measurement using converted photons in LHCb
- Converted photon efficiency checked using $\pi^0 \to \gamma\gamma(_{\to ee})$
- Systematic dominated by $\gamma_{\to ee}$ efficiency and fitting procedure

- χ_{c0} observed with 4.4σ statistical significance for $4<p_T(J/\psi)<20$GeV

- Resolution ~ 4 MeV/c2

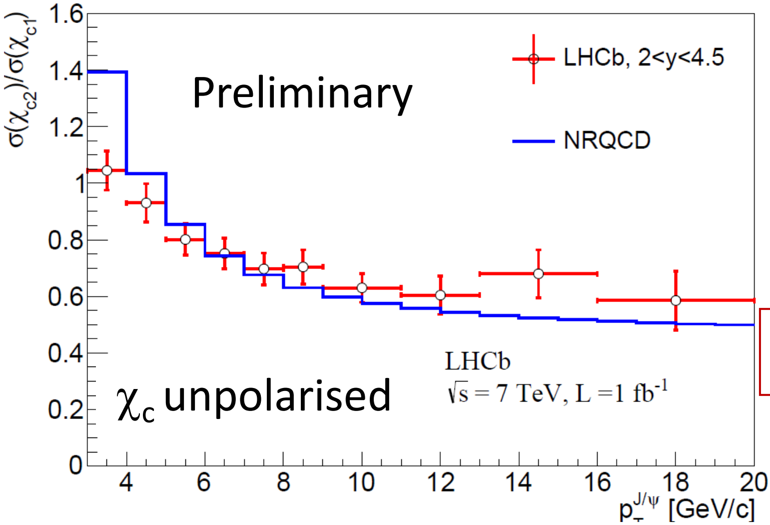




NEW !

χ_{cJ}(1P) production: results

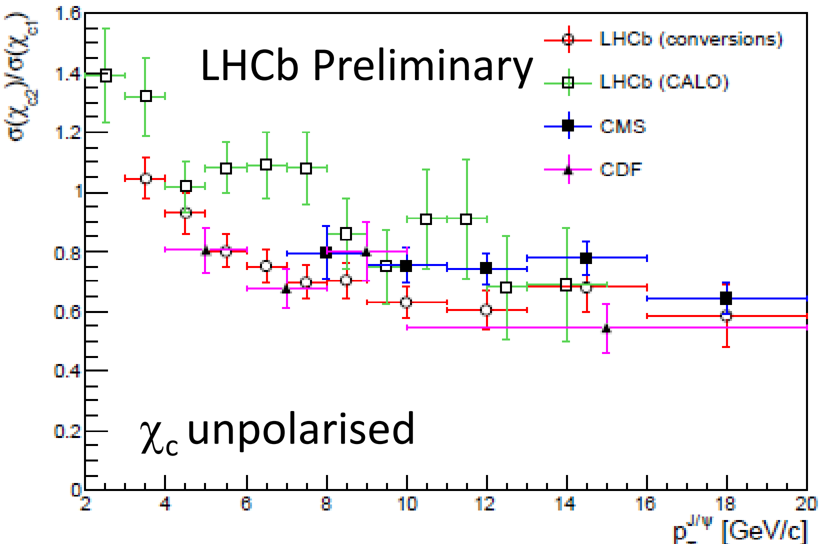
LHCb-PAPER-2013-028

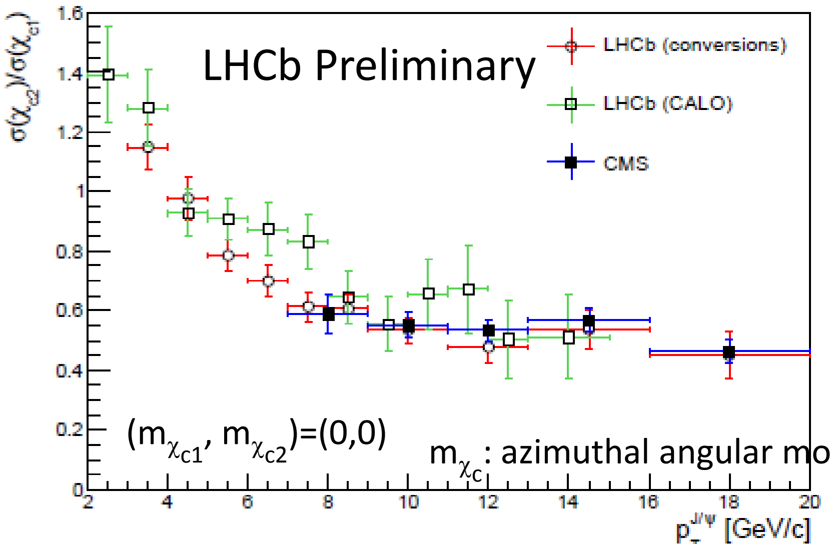


- NRQCD prediction from arxiv:1305.2389
- In agreement and more precise than previous measurements by LHCb non converted photons [5], CMS [6], CDF [7]
- First observation of χ_{c0} at hadron collider
  - ratio of cross-sections for $4<p_T(J/\psi)<20$GeV:

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.30(\text{stat}) \pm 0.26(\text{syst}) \pm 0.16(p_T\,\text{model}) \pm 0.08(\mathcal{B})$$

  - theory prediction [8]: 0.6 to 0.4 in this p_T range

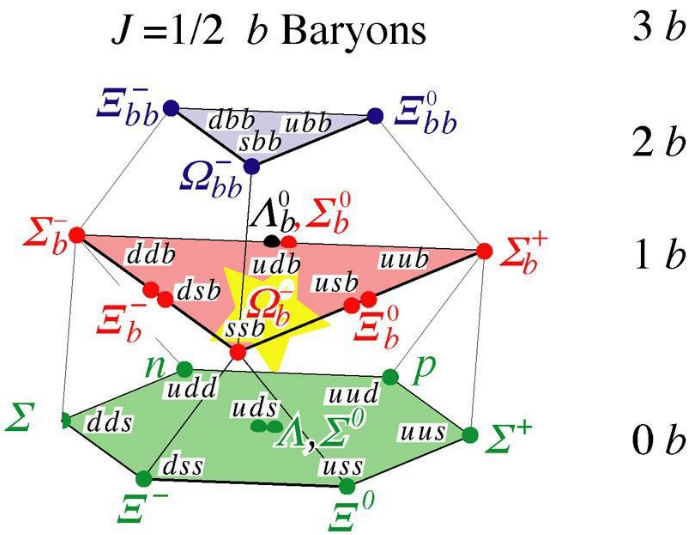




m_{χ_c}: azimuthal angular momentum

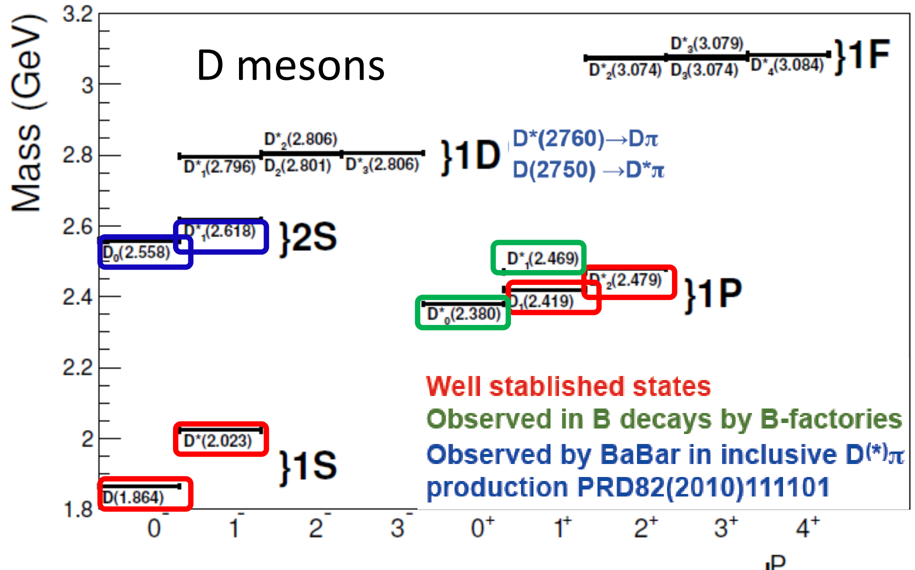
Spectroscopy

Spectroscopy provides a test of QCD models:
different predictions of masses, lifetimes, decay properties



- Many predicted states not yet observed or poorly measured
- Precise knowledge of masses is needed to shed light on some of the XYZ states:
  - loosely bound meson molecules (DD, BB)  have mass just below the DD/BB thresholds.

⇒ b- and c- hadrons spectroscopy
  - Precise mass measurements
  - Determinationof quantum numbers



- LHCb measurements presented here:
  - Excited D and $B_{(s)}$ mesons
  - X(3872) quantum numbers
  - b-baryons (Ω_b,Ξ_b,Λ_b)mass measurement
  - B_c mass measurement

NEW !

LHCb-PAPER-2013-026

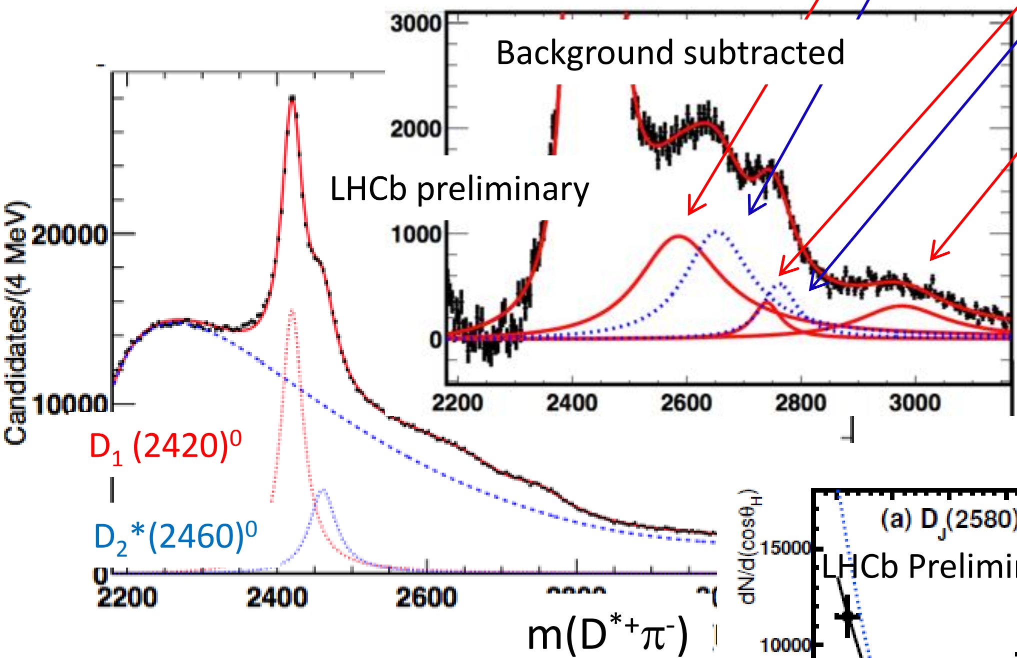
Excited D mesons

- Search for D_J states decaying to $D^0\pi^+$, $D^+\pi^-$, $D^{*+}\pi^-$

$\Rightarrow$ States found in the high mass tail: $D_J^*(2650)$, $D_J^*(2760)$

$D_J(2580)^0$, $D_J(2740)^0$, $D_J(3000)^0$ $\leftarrow$ new state!

$\Rightarrow$ Confirms the states observed by BaBar



Study of the spin-parity:

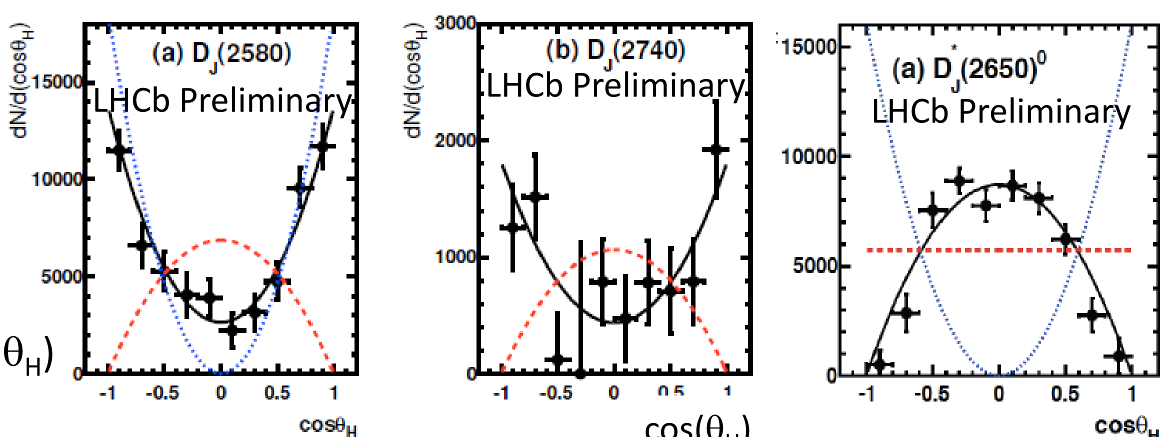
Analysis in bins of $\cos(\theta_H)$ (π^- helicity angle)

$\Rightarrow$Unnatural parity confirmed for $D_J(2580)^0$, $D_J(2740)^0$, suggested for $D_J(3000)^0$

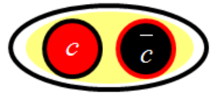
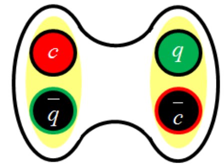
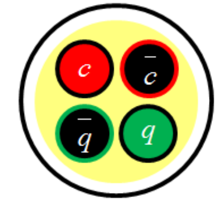
$\Rightarrow$ Natural parity confirmed for $D_J^*(2650)$,$D_J^*(2760$

Unnatural parity: $J^P=0^-,1^+,2^-,\ldots \Rightarrow \sin^2(\theta_H)$

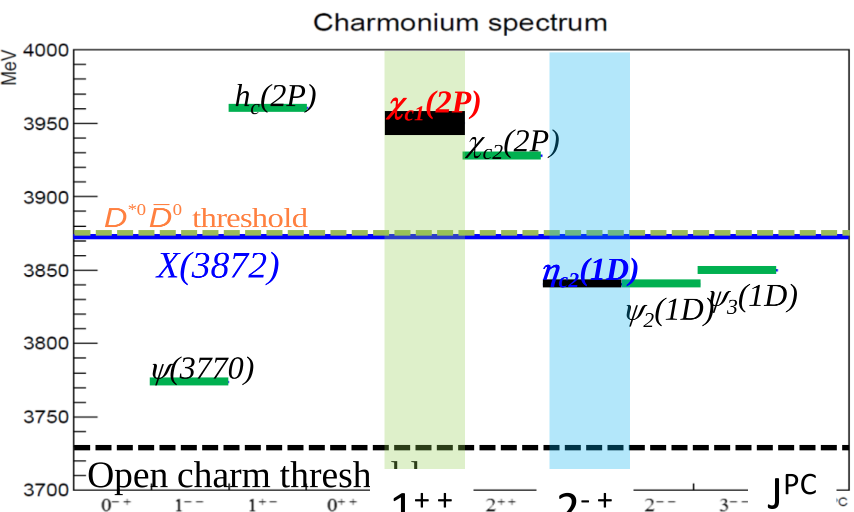
Natural parity: $J^P=0^+,1^-,2^+,\ldots \Rightarrow 1+h\cos^2(\theta_H)$

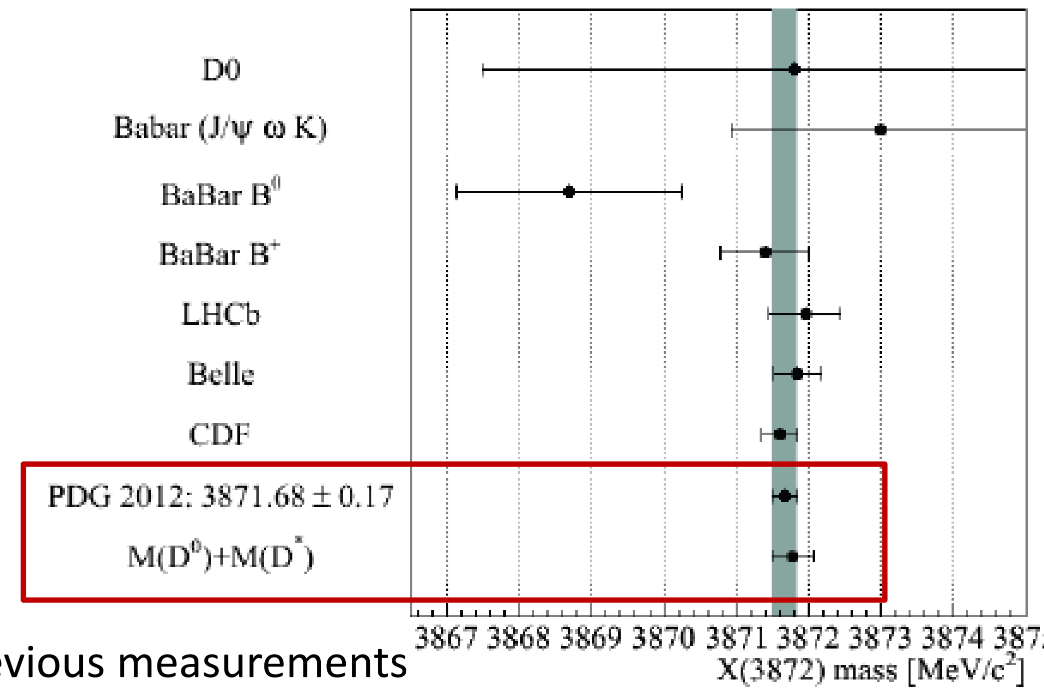


The X(3872)

- X(3872) discovered by BELLE in 2003 but nature is still unclear: conventional charmonium  ,DD* molecule  ,tetraquark  ?

- Mass measurement:
  - if DD* molecule, it is loosely bound: $M(X)-[M(D)+M(D^*)] = -0.16 \pm 0.26$ MeV/c^2





- Quantum numbers:
  - $J^{PC}=1^{++}$ or 2^{-+} not excluded by previous measurements (CDF, Belle, BaBar)

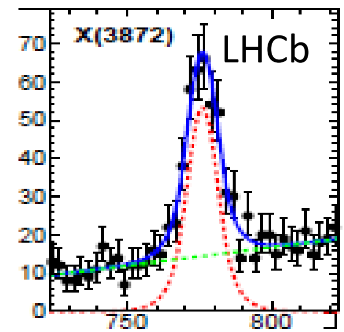
arXiv:1302.6269

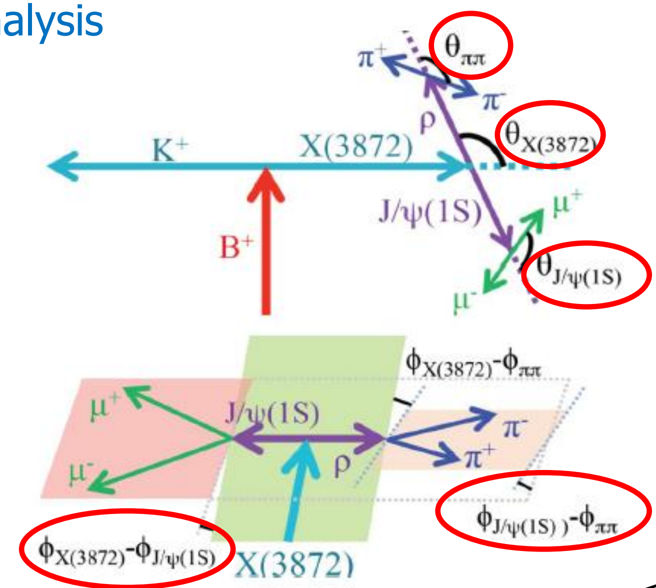
X(3872) quantum numbers

- X(3872) reconstructed from B decays
  - $B^+ \to X(3872)\, K^+$ and $X \to J/\psi_{(\to\mu\mu)}\pi^+\pi^-$
  - The angular correlations in the B^+ decay chain carry information on the J^{PC} of the X

$\Rightarrow$ 5D angular analysis

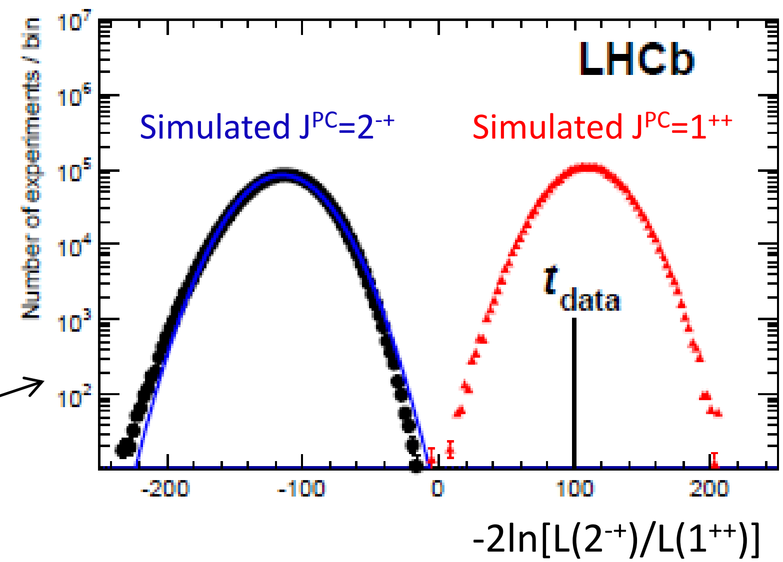
$N(B^+ \to X(3872)\, K^+) = 313 \pm 36$





- Likelihood ratio test to discriminate betwen $J^{PC}=1^{++}$ or 2^{-+}

$\Rightarrow$ 1^{++} favoured over 2^{-+} at more than 8σ

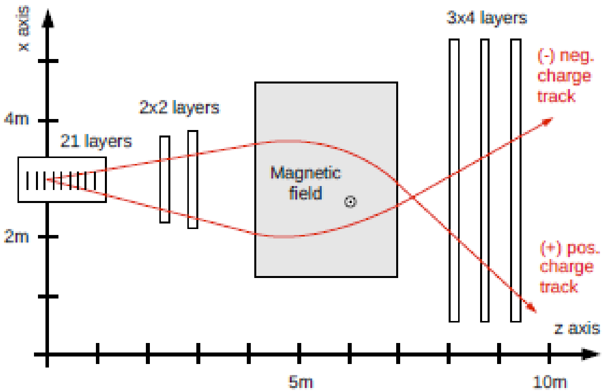


$\Rightarrow$ conventionnal η_{c2} state ruled out

Mass measurements at LHCb

Precise mass measurement require good momentum measurement

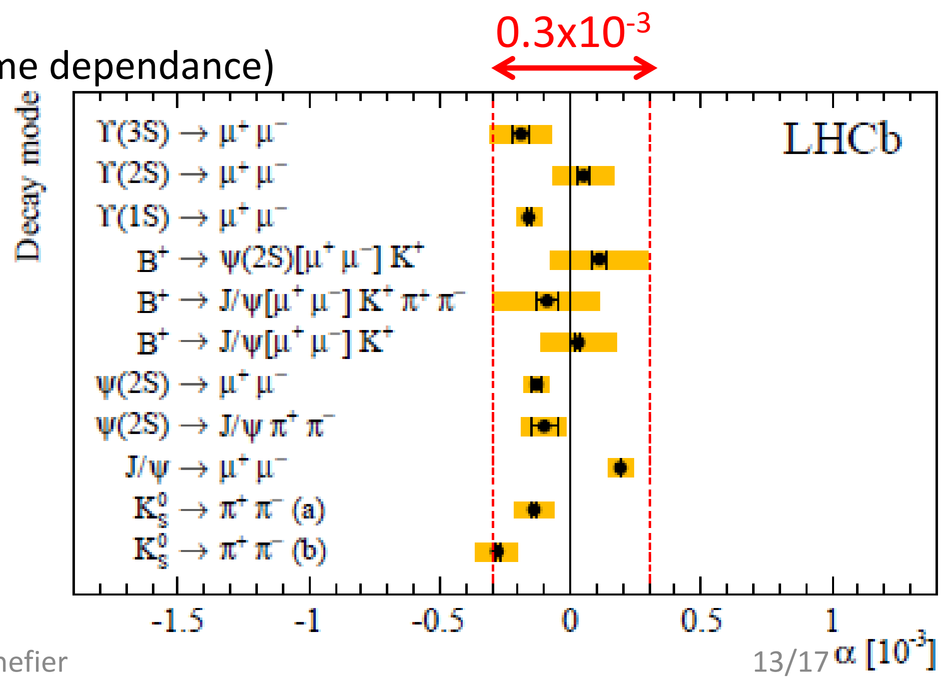
- Precise tracking devices:
  - $\Delta p/p \approx 0.5\%$
- Limitations:
  - Field map of 4Tm dipole magnet
  - Alignment of tracking stations



- Momentum scale calibration
  - Use $J/\psi \rightarrow \mu^+\mu^-$: relative momentum scale (time dependance)
  - Use high statistic $B^+ \rightarrow J/\psi K^+$

  $\Rightarrow$momentum calibration as a function of the

  K^+ track angles (using known J/ψ and B^+ mass)



- Residuals:
  - Estimate residuals using known resonances

  $\Rightarrow$ Error on momentum scale: $\alpha = \pm 0.3\times10^{-3}$

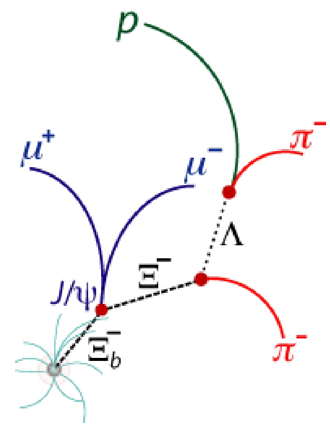
Phys. Rev. Lett. 110, 182001 (2013)

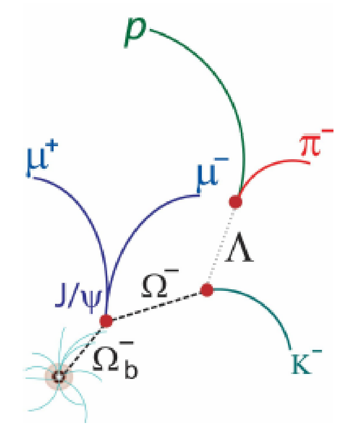
b-baryons: Ω_b, Ξ_b, Λ_b mass

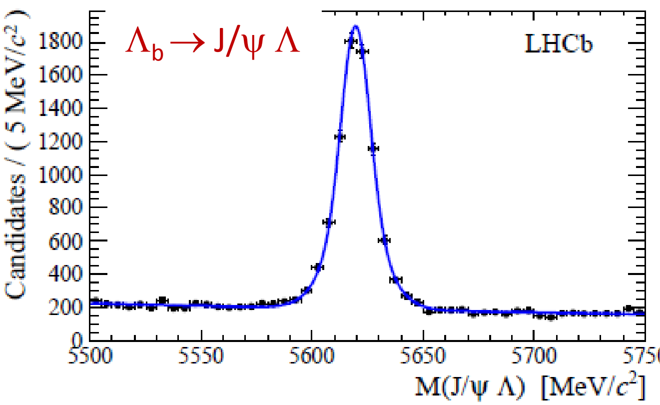
$\Xi^-_b \to J/\psi\ \Xi^-$, $\Omega^-_b \to J/\psi\ \Omega^-$, $\Lambda_b \to J/\psi\ \Lambda$,

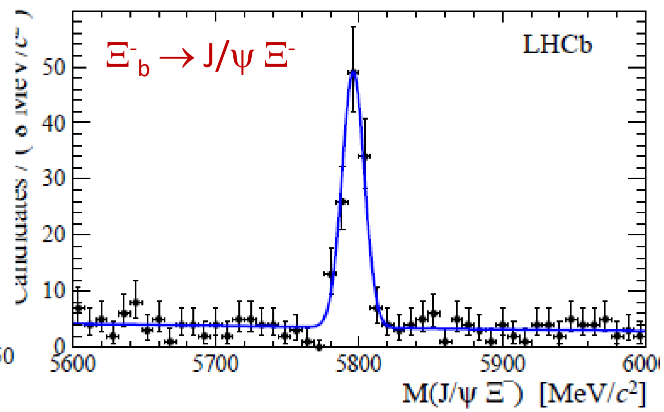
- Ω_b, Ξ_b selections almost identical
- Selection: take advanage of the decay topology
- Systematic dominated by momentum scale

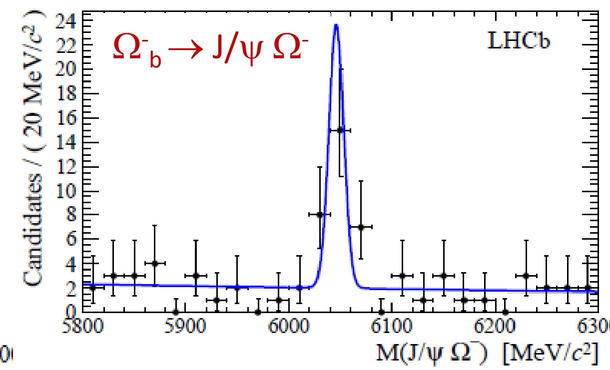
$\Rightarrow$ World's most precise measurements

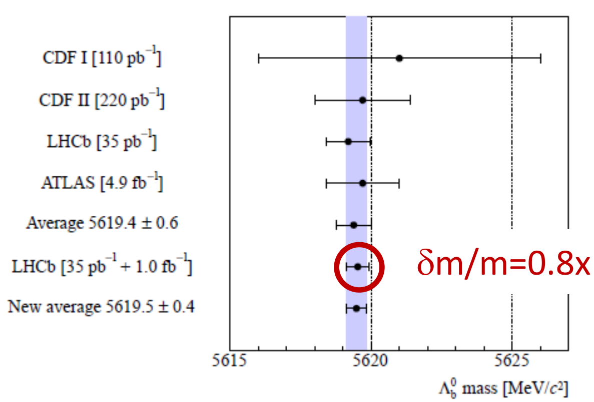




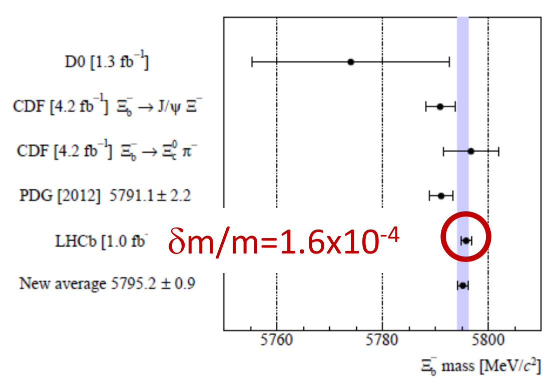




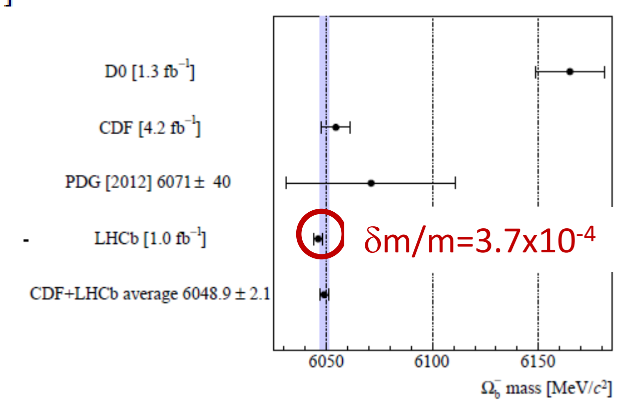




$\delta m/m = 0.8 \times 10^{-4}$



$\delta m/m = 1.6 \times 10^{-4}$

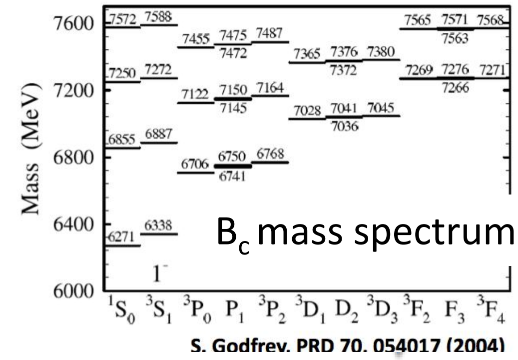


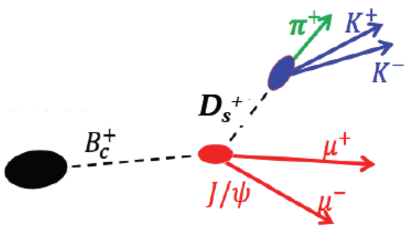
$\delta m/m = 3.7 \times 10^{-4}$

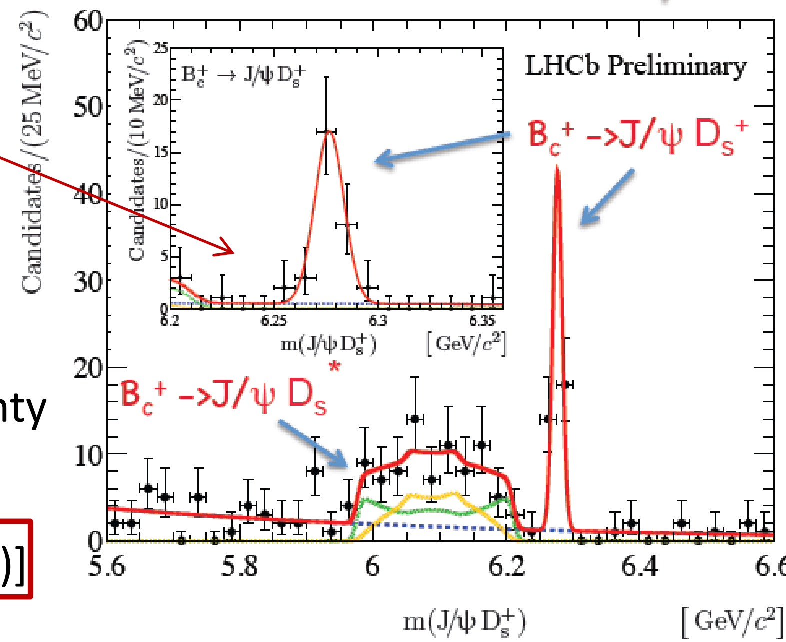
LHCb-PAPER-2013-010

B_c mass

- B_c is largely unexplored
- It is a unique meson with 2 open heavy flavours
- First observation in 1998 by CDF
- At LHCb: first observation of $B^+_c \to J/\psi\ D_s^{+(*)}$







Based on 2011+2012 data sample (3fb-1)

$\Rightarrow$ $m(B_c^+) = 6276.28 \pm 1.44_{stat} \pm 0.36_{syst}$ MeV/c^2

Most precise single measurement of the B_c mass

Systematic dominated by momentum scale uncertainty and D_s mass

using $m(D_s^+) = [m(D^0)] + [m(D^0)-m(D^+)] - [m(D^+) - m(D_s^+)]$

Measured by LHCb: arXiv:1304.6865

$\Rightarrow m(B_c^+)-m(D_s^+) = 4307.97 \pm 1.44_{stat} \pm 0.11_{syst}$ MeV/c^2

[Phys. Rev. Lett. 110 (2013) 151803]

Excited $B_{(s)}$ mesons

Search for B_{sJ} mesons in their decay: $B_{sJ} \to B^{+(*)}K^-$

- Reconstruct B^+ in a variety of decays: $B^+ \to J/\psi K^+$, $D0(K^+\pi^-)\pi^+$, $D0(K^+\pi^-)\pi^+\pi^-\pi^+$, … and combine it with a K-

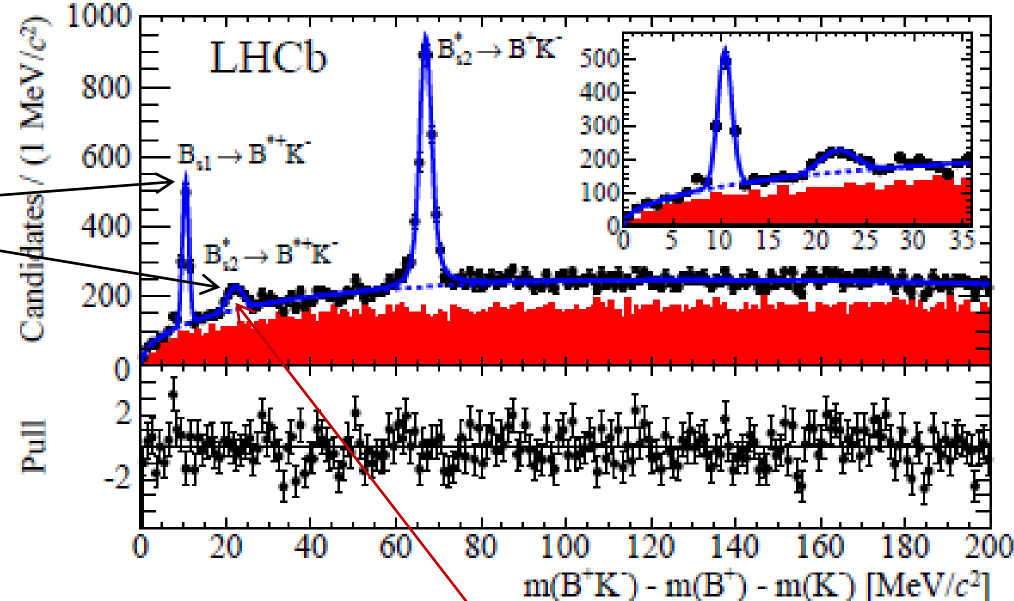
$$m(B^*_{s2}) = 5839.99 \pm 0.05 \pm 0.11 \pm 0.17\ \mathrm{MeV}/c^2,$$

- Partially reconstructed decays:
  - $B^*_s \to B^{+*}(\to B^+\gamma)\, K^-$
  - Mass difference between

$B^{*+}K^-$ and B^+K^- peaks = $m(B^*)$-$m(B)$

$\Rightarrow$ Best measurement of $m(B^*)$-$m(B)$

$$m(B^{*+}) - m(B^+) = 45.01 \pm 0.30 \pm 0.23\ \mathrm{MeV}/c^2$$



First observation of $B^*_{s2} \to B^{+*}(\to B^+\gamma)\, K^-$

$\Rightarrow$ Precise $m(B^{*+})$ used to understand if the Z_b states reported by Belle could be $B^{(*)}B^{(*)}$ molecules?

if so, should be just below $B^{(*)}\, B^{(*)}$ threshold

- $Z_b(10610)^+$ is 3.69±2.05 MeV/c above BB^* threshold
- $Z_b(10650)^+$ is 3.68±1.71 MeV/c above B^*B^* threshold

Summary and outlook

LHCb has a rich program in heavy flavour production and spectroscopy

- Quarkonium production cross section measurements
- Precise mass measurements of b- and c- baryons (starting to explore B_c meson!)
- Search for new (exotic) states
- Determination quantum numbers of new states

- Not shown here:
  - pA run results for J/psi production (LHCb-CONF-2013-008)
  - Λ_b* observation (Phys.Rev.Lett.109(2012)172003)
  - Λ_b polarisation (arXiv:1302.5578, accepted by Physics Letters B)
  - Study of D_{sJ} spectroscopy (JHEP 10 (2012)151)

- More to come:
  - Most results based on only 1/3 of the data (2011)
  - Quarkonia polarisation measurements (LHCb-PAPER-2013-008 in preparation)

References

J/ψ and Υ production

- [1] ALICE, Phys. Rev. Lett 108 (2012) 082001
- [2] CMS, Phys. Rev. Lett. 110 (2013) 081802
- [3] LHCb LHCb-PAPER-2013-008 in preparation
- [4] LHCb Phys. Lett. B718 (2012)431

χ_c

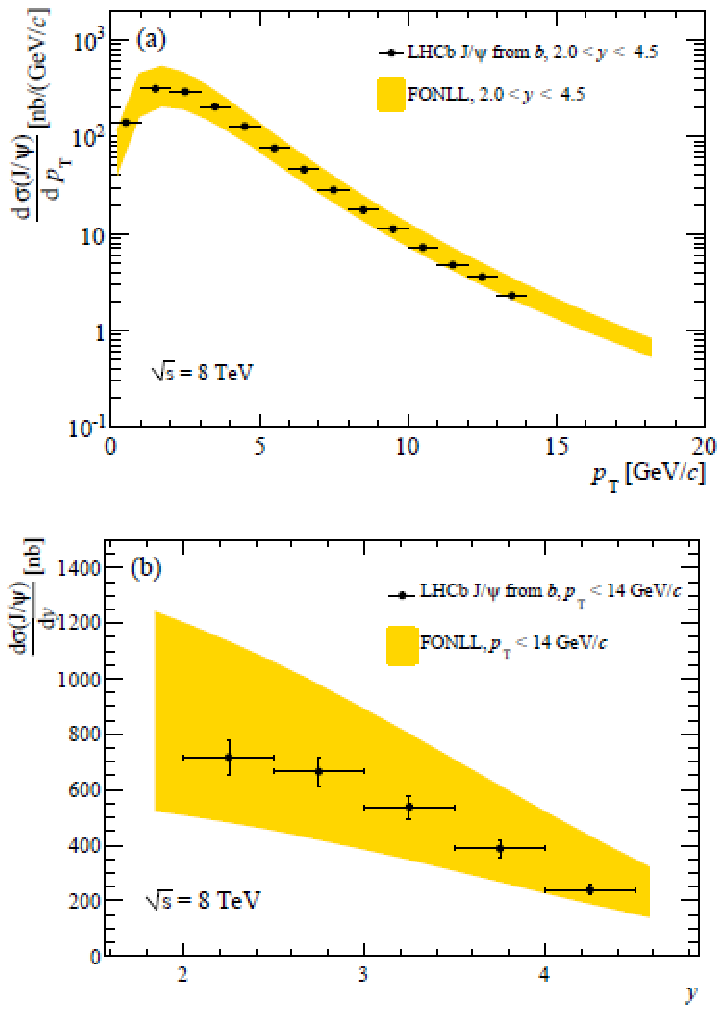
- [5] LHCb Phys. Lett.B714 (2012)215
- [6] CMS Eur. Phys. J. C72(2012)2251
- [7] CDF Phys.Let.B 98(2007)232001
- [8] Likhoded, Luchinsky, Poslavsky arxiv:1305.2389[hep-ph]

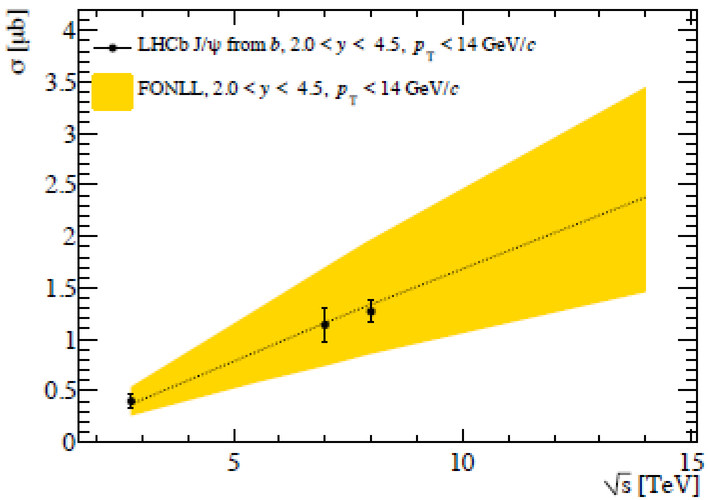
Exclusive J/psi and psi(2S) production

- [9] arXiv:1301.7084

Backup slides

J/psi from b production

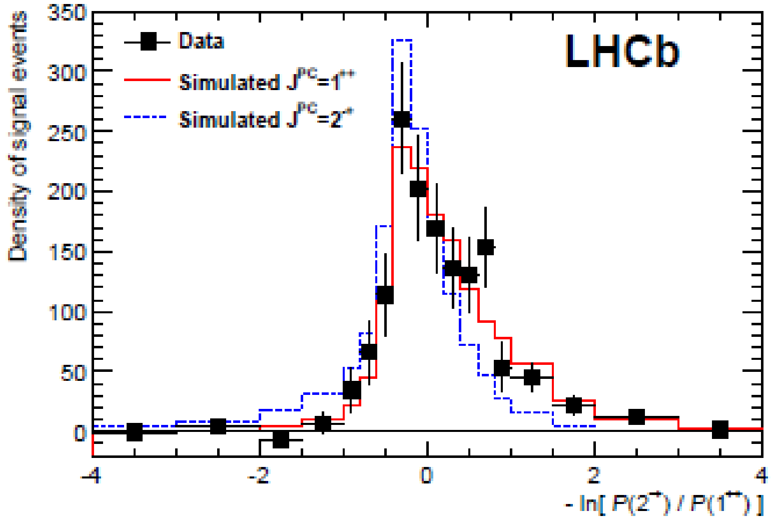


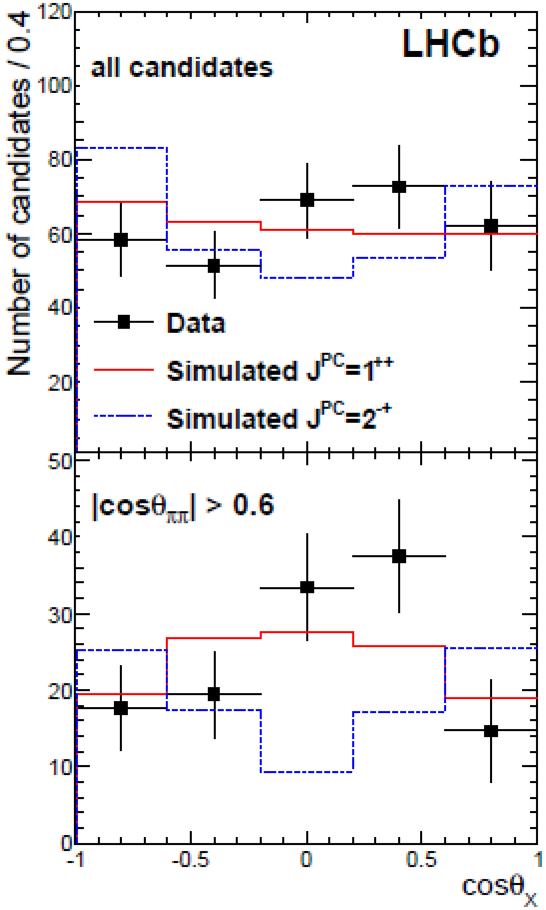


X(3872)

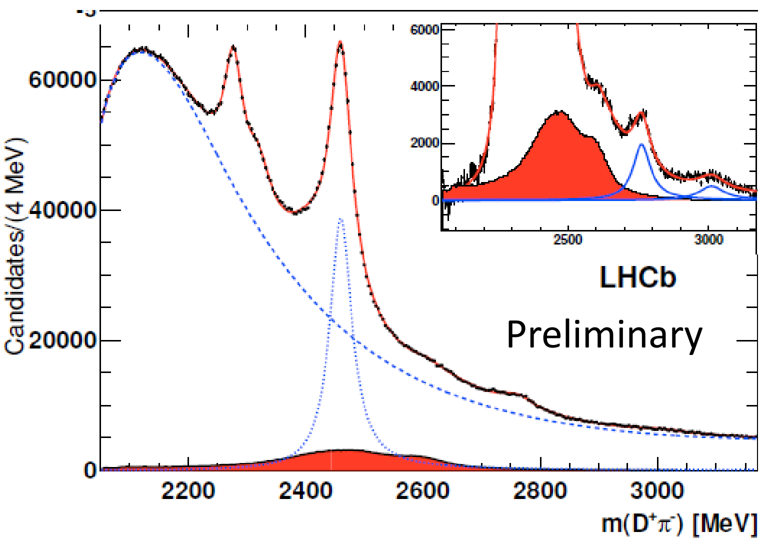
- Tests:
  - Shape

    - 1D distribution





D_J spectroscopy



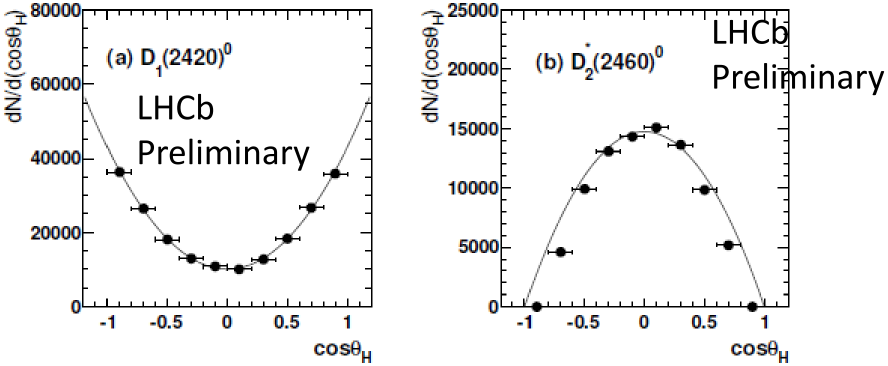


Figure 8: Distributions of (a) $D_1(2420)^0$ and (b) $D_2^*(2460)^0$ candidates as function of the helicity angle $\cos\theta_H$. The distributions are fitted with Unnatural and Natural Parity functions respectively.

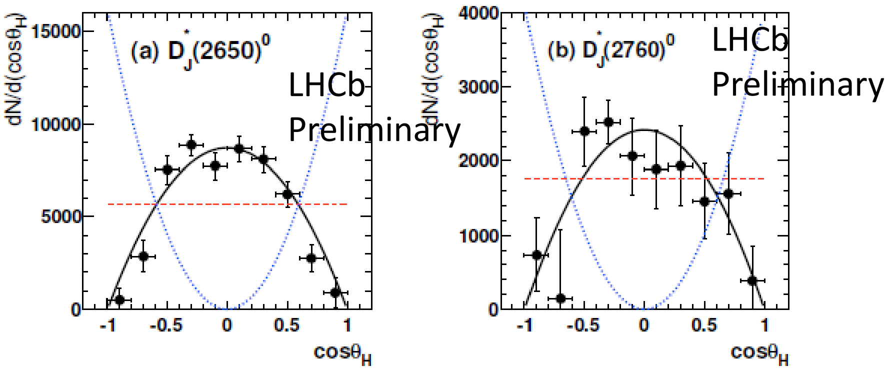


Figure 9: Distributions of (a) $D_J^*(2650)^0$ and (b) $D_J^*(2760)^0$ candidates as function of the helicity angle $\cos\theta_H$. The distributions are fitted with Natural Parity (black continuous), Unnatural Parity (red, dashed), $J^P = 0^-$ (blue, dotted).

D_J spectroscopy

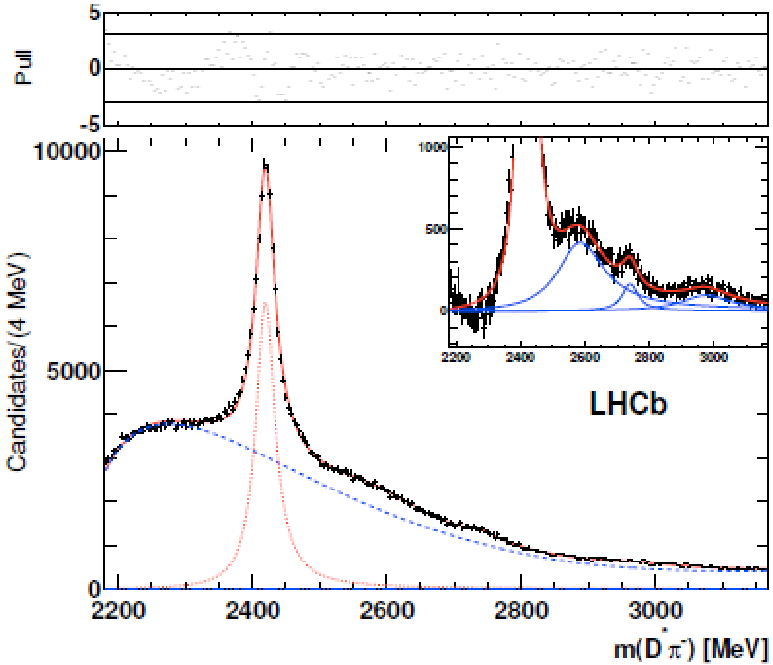


Figure 4: Fit to the $D^{*+}\pi^-$ mass spectrum, *Unnatural Parity Sample*. The dashed (blue) line shows the fitted background, the dotted (red) line shows the $D_1(2420)^0$ contribution. The inset shows the $D^{*+}\pi^-$ mass spectrum after subtracting the fitted background. The full line curves (blue) show the contributions from $D_J(2580)^0$, $D_J(2740)^0$, and $D_J(3000)^0$. The top window shows the Pull distribution where the horizontal lines evidence the $\pm 3\sigma$ limits. The *Pull* is defined as $Pull = (N_{data} - N_{fit})/\sqrt{N_{data}}$.

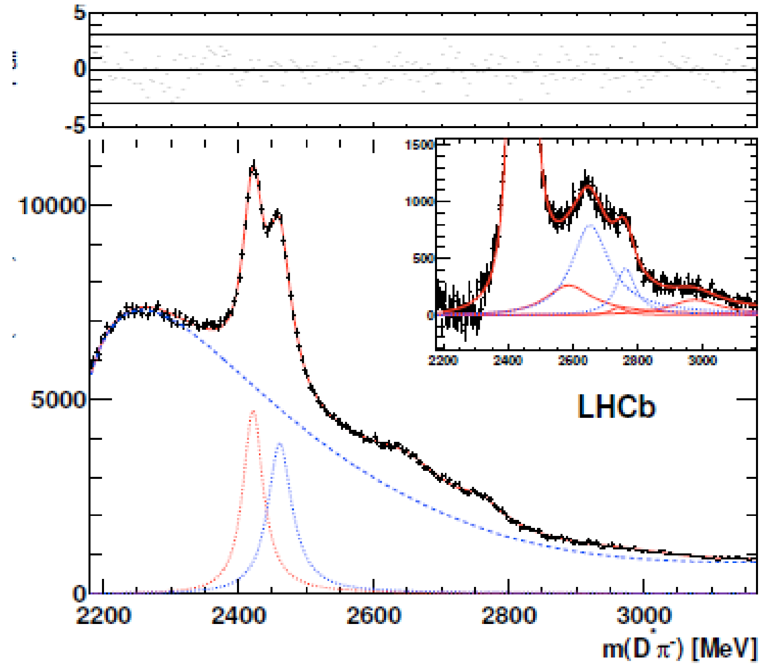


Figure 5: Fit to the *Enhanced Natural Parity Sample* $D^{*+}\pi^-$ mass spectrum. The dashed (blue) line shows the fitted background, the dotted lines shows the $D_1(2420)^0$ (red) and $D_2^*(2460)^0$ (blue) contributions. The inset shows the $D^{*+}\pi^-$ mass spectrum after subtracting the fitted background. The full line curves (red) show the contributions from $D_J(2580)^0$, $D_J(2740)^0$, and $D_J(3000)^0$. The dotted (blue) lines show the $D_J^*(2650)^0$ and $D_J^*(2760)^0$ contributions. The top window shows the Pull distribution where the horizontal lines evidence the $\pm 3\sigma$ limits.

Excited Bs mesons

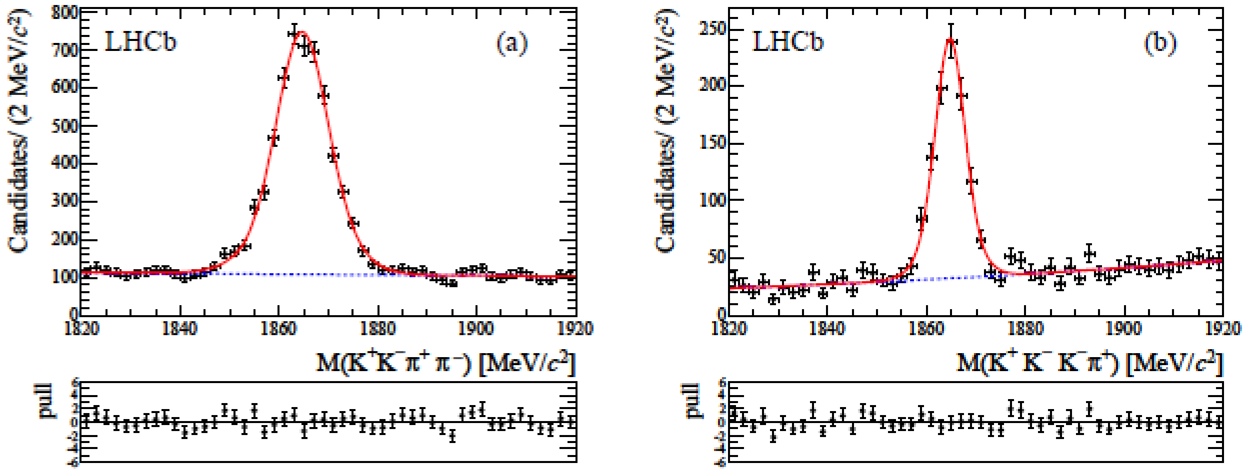
Table 2: Results of the fit to the mass difference distributions $m(B^+K^-) - m(B^+) - m(K^-)$. The first uncertainties are statistical and the second are systematic.

Parameter	Fit result	Best previous measurement
$m(B_{s1}) - m(B^{*+}) - m(K^-)$	$10.46 \pm 0.04 \pm 0.04$ MeV/c^2	$10.73 \pm 0.21 \pm 0.14$ MeV/c^2 [9]
$m(B_{s2}^*) - m(B^+) - m(K^-)$	$67.06 \pm 0.05 \pm 0.11$ MeV/c^2	$66.96 \pm 0.39 \pm 0.14$ MeV/c^2 [9]
$m(B^{*+}) - m(B^+)$	$45.01 \pm 0.30 \pm 0.23$ MeV/c^2	45.6 ± 0.8 MeV/c^2 [28]
$\Gamma(B_{s2}^*)$	$1.56 \pm 0.13 \pm 0.47$ MeV/c^2	
$\frac{\mathcal{B}(B_{s2}^* \to B^{*+}K^-)}{\mathcal{B}(B_{s2}^* \to B^+K^-)}$	$(9.3 \pm 1.3 \pm 1.2)\%$	
$\frac{\sigma(pp \to B_{s1}X)\mathcal{B}(B_{s1} \to B^{*+}K^-)}{\sigma(pp \to B_{s2}^*X)\mathcal{B}(B_{s2}^* \to B^+K^-)}$	$(23.2 \pm 1.4 \pm 1.3)\%$	
$N_{B_{s1} \to B^{*+}K^-}$	750 ± 36	
$N_{B_{s2}^* \to B^{*+}K^-}$	307 ± 46	
$N_{B_{s2}^* \to B^+K^-}$	3140 ± 100	

$$m(B^{*+}) = 5324.26 \pm 0.30 \pm 0.23 \pm 0.17 \text{ MeV}/c^2,$$
$$m(B_{s1}) = 5828.40 \pm 0.04 \pm 0.04 \pm 0.41 \text{ MeV}/c^2,$$
$$m(B_{s2}^*) = 5839.99 \pm 0.05 \pm 0.11 \pm 0.17 \text{ MeV}/c^2,$$

D masses

arXiv:1304.6865



$$
\begin{aligned}
M(D^0) &= 1864.75 \pm 0.15\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{MeV}/c^2, \\
M(D^+) - M(D^0) &= 4.76 \pm 0.12\,(\text{stat}) \pm 0.07\,(\text{syst})\ \text{MeV}/c^2, \\
M(D_s^+) - M(D^+) &= 98.68 \pm 0.03\,(\text{stat}) \pm 0.04\,(\text{syst})\ \text{MeV}/c^2.
\end{aligned}
$$

$$M(D_s^+) = 1968.19 \pm 0.20 \pm 0.14 \pm 0.08\,\text{MeV}/c^2,$$