Heavy flavors production and spectroscopy at LHCb

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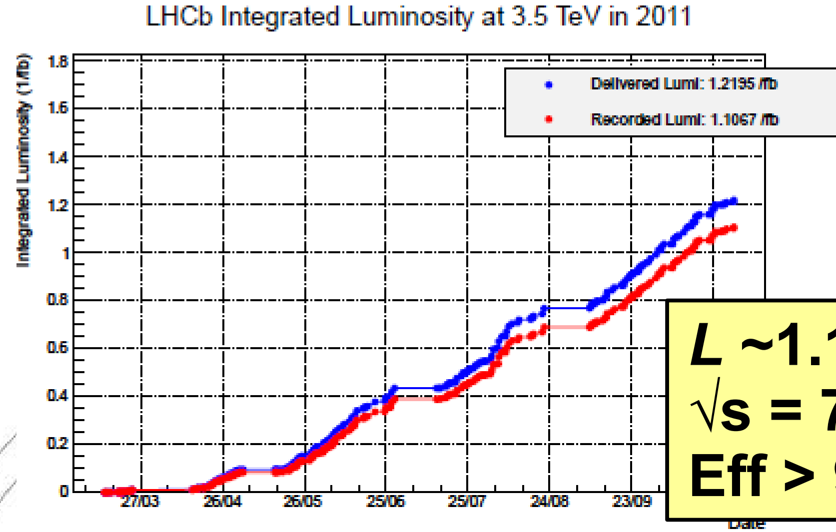
Hadron Collider Physics Symposium, HCP2011
November 14th – 18th, Paris, France

Outline

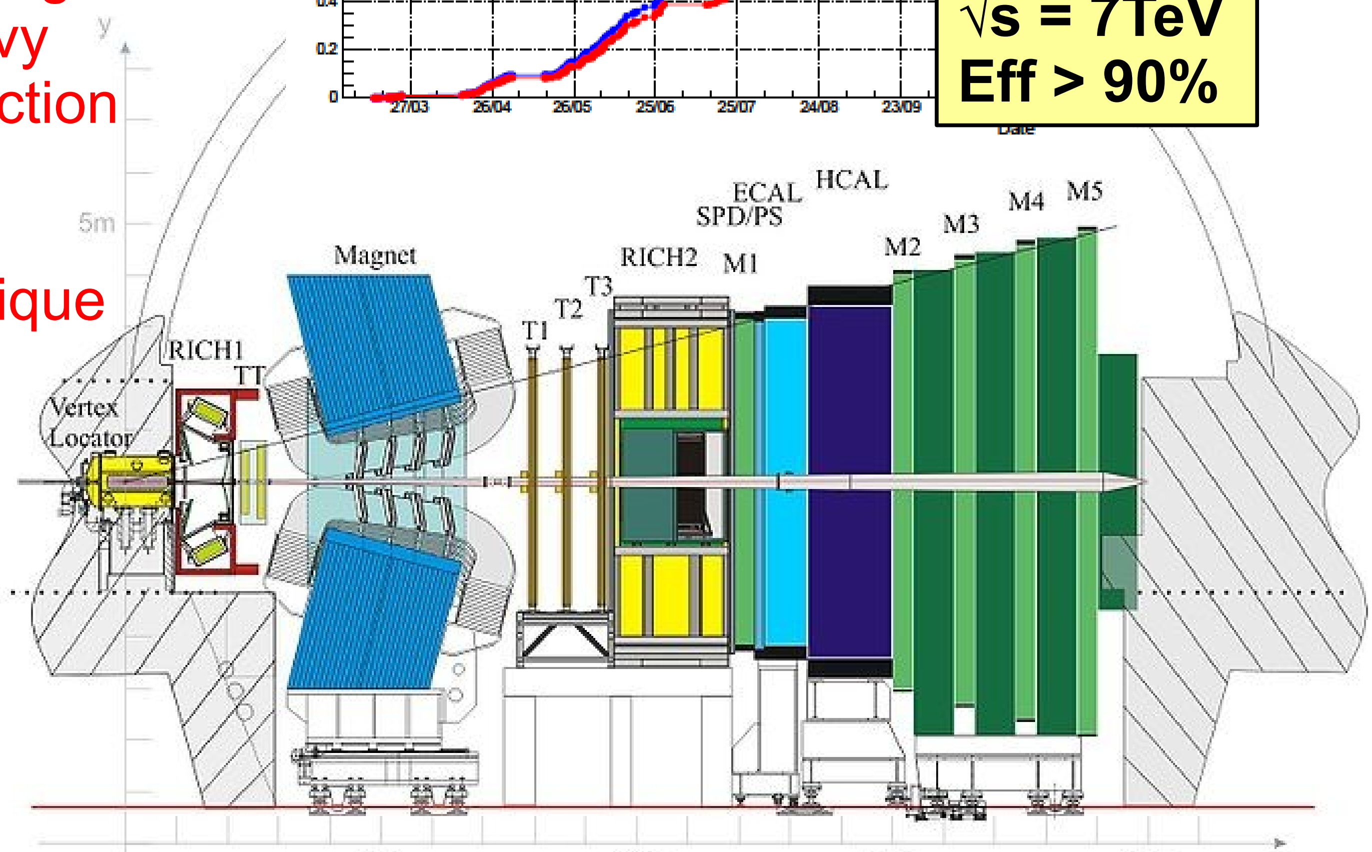
- **LHCb detector and dataset**
- **Heavy flavor production**. Cross section measurements
  - Prompt charm: 2/nb (2010 data) LHCb-CONF-2010-013
  - D^0 production asymmetry: 37/pb (2010 data) LHCb-CONF-2011-023
  - J/ψ:5.2/pb (2010 data) Eur.Phys.J.C71:1645,2011
  - **Double J/ψ**:37.5/pb (2010 data) arXiv:1109.0963v1. Submitted to Phys.Lett.B
  - $\psi(2S)$: 35/pb (2010 data) LHCb-CONF-2011-026
  - **χ_c ratios**: 35.6/pb (2010 data) LHCb-CONF-2011-020
  - **Charged B**: 34.6/pb (2010 data) LHCb-CONF-2011-033
  - **$\Upsilon(1S)$:** 32.4/pb (2010 data) LHCb-CONF-2011-016
- **Heavy flavor spectroscopy**
  - **$D_{(s)J}$ spectroscopy**: 320/pb (2011 data) Preliminary
  - **$B_{(s)J}$ spectroscopy**: 326/pb (2011 data) LHCb-CONF-2011-053
  - **X(3872) mass:** 35/pb (2010) LHCb-CONF-2011-021
  - **Ω_b and Ξ_b mass:** 576/pb (2011 data) LHCb-CONF-2011-060 (to appear)
- **Conclusions**

LHCb detector and dataset

- Optimized for the strongly forward peaked heavy quark production at LHC
- Covers ~4% of the solid angle but captures ~40% of heavy quark production cross-section
- Single-arm forward spectrometer, covers a unique rapidity range: $1.9<\eta<4.9$
- Great tracking, vertexing and PID performance
- Excellent machine for B and charm physics



L ~1.1/fb
$\sqrt{s}$ = 7TeV
Eff > 90%



More info have a look at M.John's talk on Monday

Heavy flavor production at LHCb

Measurement of heavy quark production cross sections in LHC, probes the spectrum and dynamics of partons of the colliding hadrons.

Heavy quarkonium remains as a challenging problem for the understanding of QCD.

$pp \rightarrow q\underline{q}$ LO gluon-gluon interactions (pQCD).

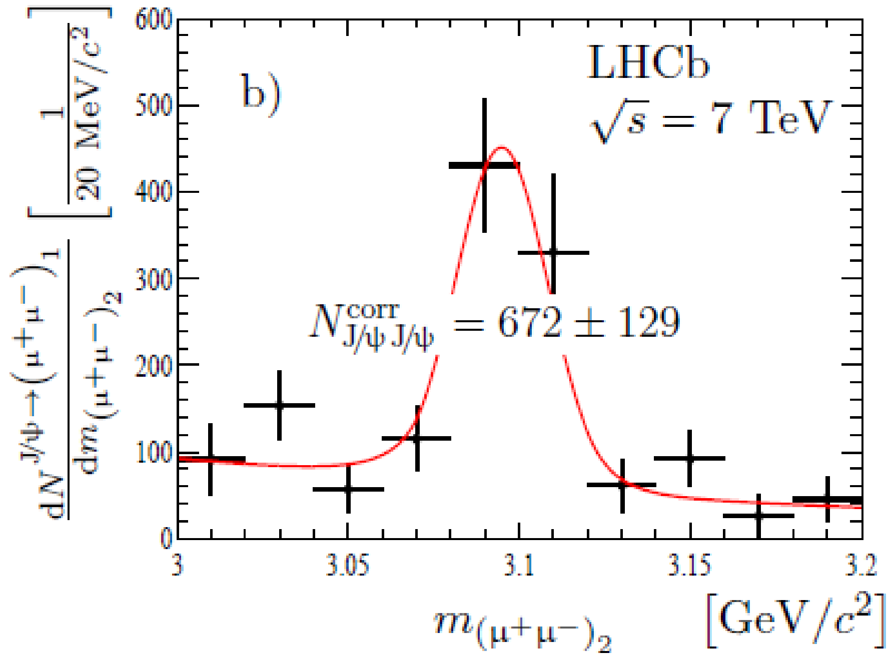
Quarkonium formation through NLO NRQCD: CS (Color Singlet) + CO (Color Octet) evolving via exchange of soft gluons.

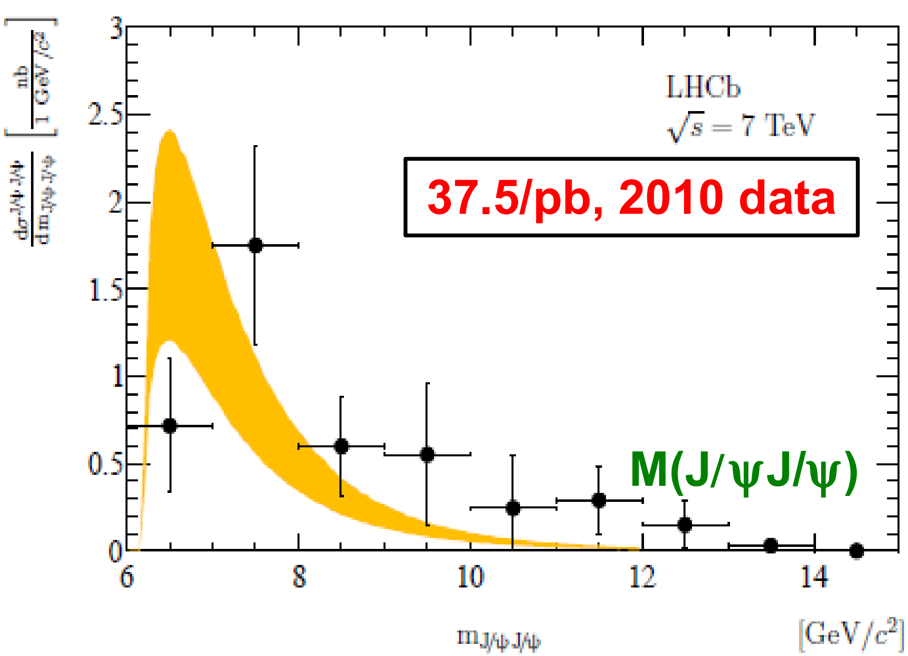
Fixed-order next to leading log (FONLL) for b-quark fragmentation and hadronization

$$\frac{d^2\sigma(X)}{dp_T d\eta} = \frac{N(X \rightarrow f)}{\mathcal{L} \times \epsilon \times \mathcal{B}(X \rightarrow f) \times \Delta p_T \times \Delta\eta}$$

Double J/ψ production

arXiv:1109.0963v1. Submitted to Phys.Lett.B





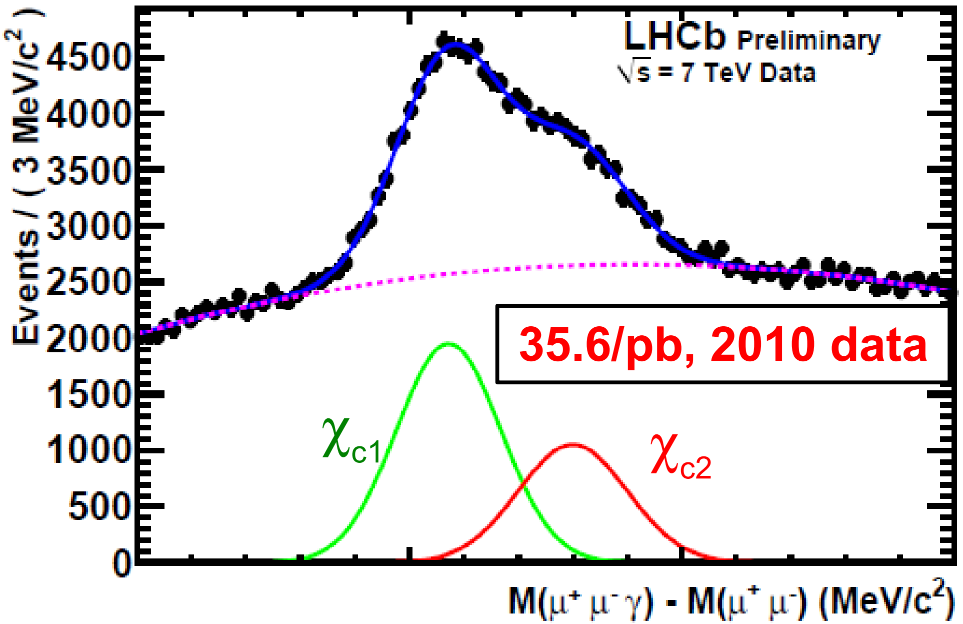
- Quarkonia production in NRQCD depends on the CS and CO (for high p_T) matrix elements.
- Theoretical calculations of LO production of CS-states predicts σ(pp→J/ψJ/ψ)=4nb at √s=7TeV (J.Phys.G37 075019(2010), arXiv:1101.5881), in the LHCb rapidity range. Accounts for ψ(2S) feed-down and prompt J/ψ.

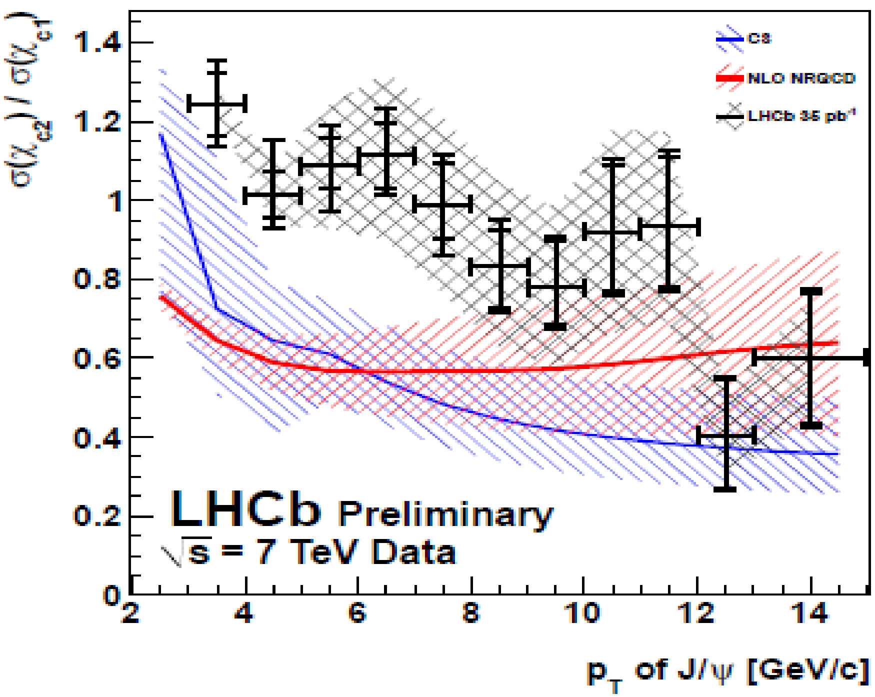
- $J/\psi \to \mu^+\mu^-$, $p_T(\mu)$>0.65GeV, all tracks consistent with the same PV and muon ID applied.
- Signal described with a double-sided Crystall Ball.
- Efficiency corrected: particle ID, trigger and reconstruction.
- Systematic effects
  - Polarization, trigger efficiency

$$\boxed{\sigma^{J/\psi\, J/\psi} = 5.1 \pm 1.0 \pm 1.1\ \mathrm{nb}}$$

χ_c cross-section ratio

LHCB-CONF-2011-020





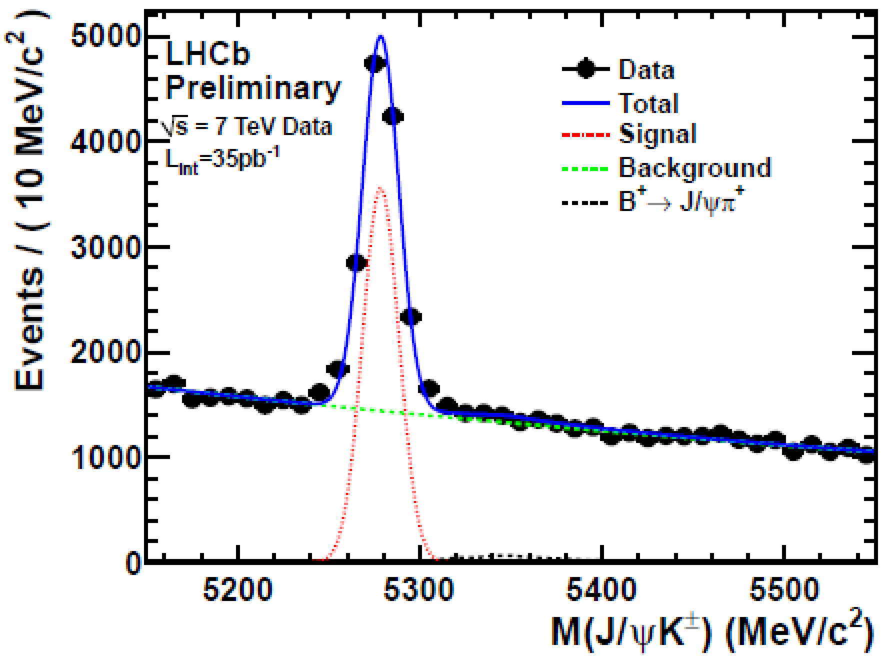
- P-wave χ_{cJ} important since it contributes to J/ψ production via radiative decays. $\chi_{cJ} \rightarrow J/\psi(\mu^+\mu^-)\gamma$
- Measurement of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ as a function of the $p_T(J/\psi)$
- Photons identified using a CL likelihood with information from the calorimeter and tracking (converted and not converted)
  - p_T>650MeV, p>5GeV.
  - J/ψ pseudo-proper time strategy to remove χ_{cJ} from B decays
- Unknown χ_c and J/ψ polarization accounted for in the efficiency.
- Larger systematic effect from χ_c branching ratios

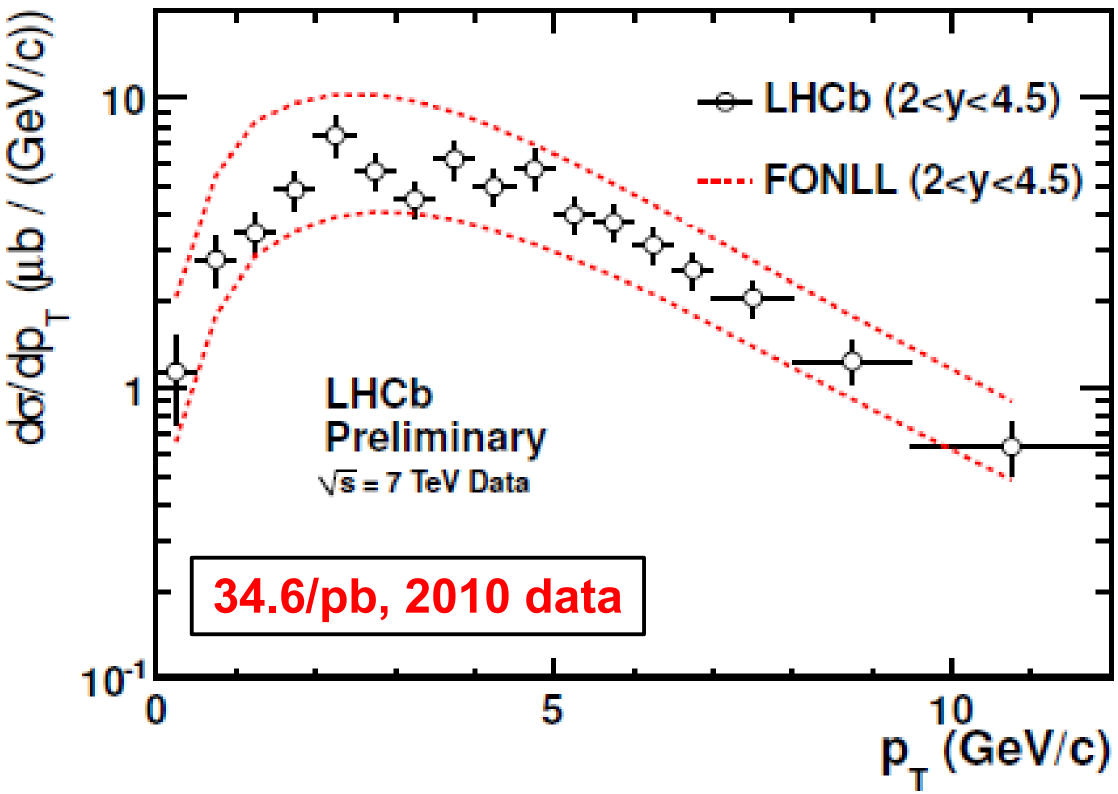
$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \cdot \frac{\epsilon^{\chi_{c1}}_{J/\psi}\epsilon^{\chi_{c1}}_{\gamma}\epsilon^{\chi_{c1}}_{sel}}{\epsilon^{\chi_{c2}}_{J/\psi}\epsilon^{\chi_{c2}}_{\gamma}\epsilon^{\chi_{c2}}_{sel}} \cdot \frac{B(\chi_{c1} \rightarrow J/\psi\gamma)}{B(\chi_{c2} \rightarrow J/\psi\gamma)}$$

$B^{\pm}$ production

LHCB-CONF-2011-033

- Reconstruction of $B^{\pm} \to J/\psi(\mu^+\mu^-)K^{\pm}$.
  - $p_T(\mu)>0.7$GeV, $p_T(K)>0.5$GeV. Good vertex quality
  - ~8800 signal events with a ~10MeV mass resolution





- Trigger and tracking the largest contribution to systematics, enclosed on the efficiency term.
- FONLL uncertainty includes uncertainty on the b-quark mass, renormalization/factorization scales and PDF uncertainty

$$\boxed{\sigma(B^{\pm}, y \in [2, 4.5]) = 37.1 \pm 1.9\,(\mathrm{stat.}) \pm 5.3\,(\mathrm{syst.})\,\mu\mathrm{b}}$$

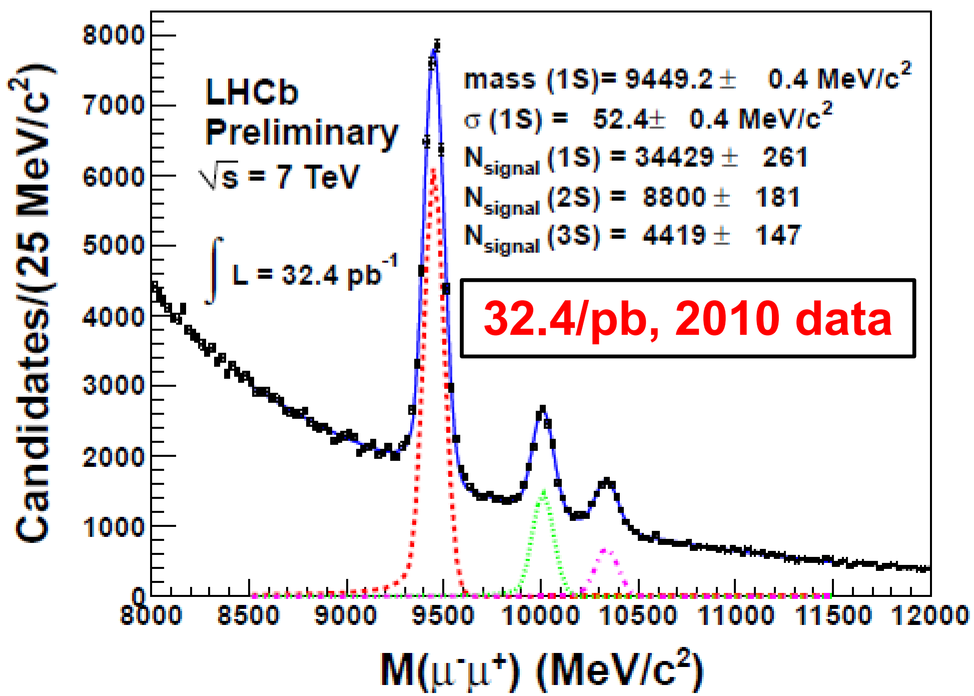
Υ(1S) production

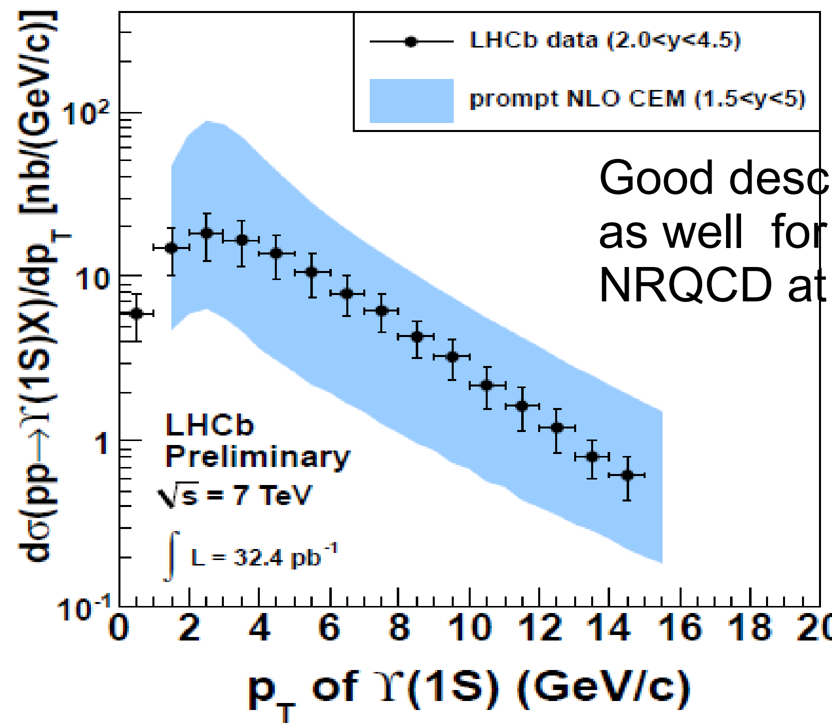
LHCB-CONF-2011-016

- Υ(1S) production at LHCb
  - Prompt production
  - Feed-down from heavier bottomonium χ_{b0}, χ_{b1}, χ_{b2} and excited Υ.
- Υ(1S)→ $\mu^+\mu^-$ reconstruction
  - Track quality, p_T>1GeV, Υ(1S) vertex.
- Fits to the M($\mu^+\mu^-$) repeated for 15x5 bins in p_T and η.
- Efficiency variation only in the helicity frame ignoring the azymuthal component

$$\frac{dN}{d\cos\theta} = \frac{1+\alpha\cos^2\theta}{2+2\alpha/3}$$

$$\boxed{\sigma(pp \to \Upsilon(1S)X;\, p_T(\Upsilon(1S)) < 15\ \mathrm{GeV}/c;\, 2 < y(\Upsilon(1S)) < 4.5) = 108.3 \pm 0.7\,^{+30.9}_{-25.8}\ \mathrm{nb}}$$





Good description as well for NLO NRQCD at high p_T

Heavy flavor spectroscopy at LHCb

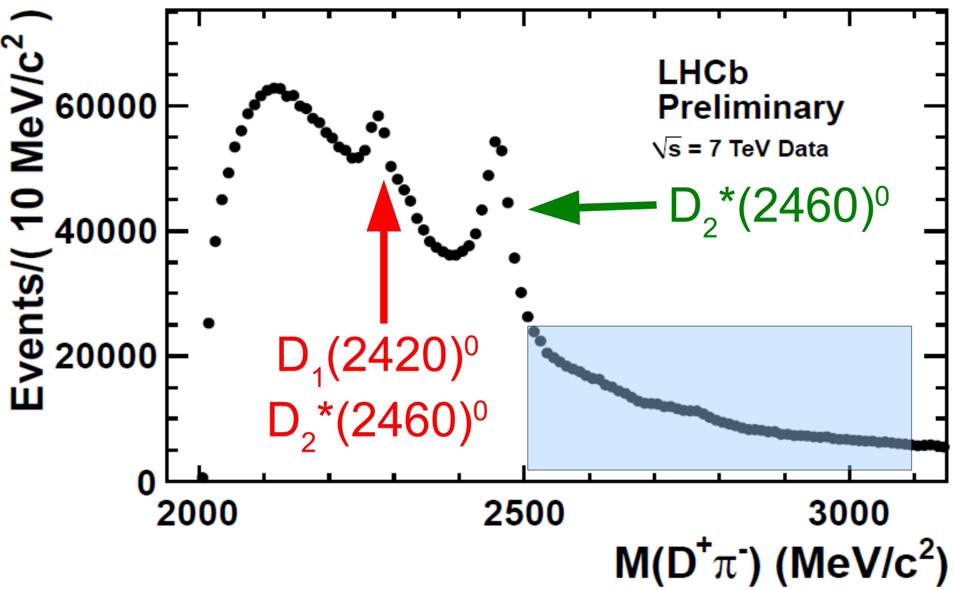
A large variety of high mass charmed and bottom states are awaiting to be found and many others with their properties still to be determined.

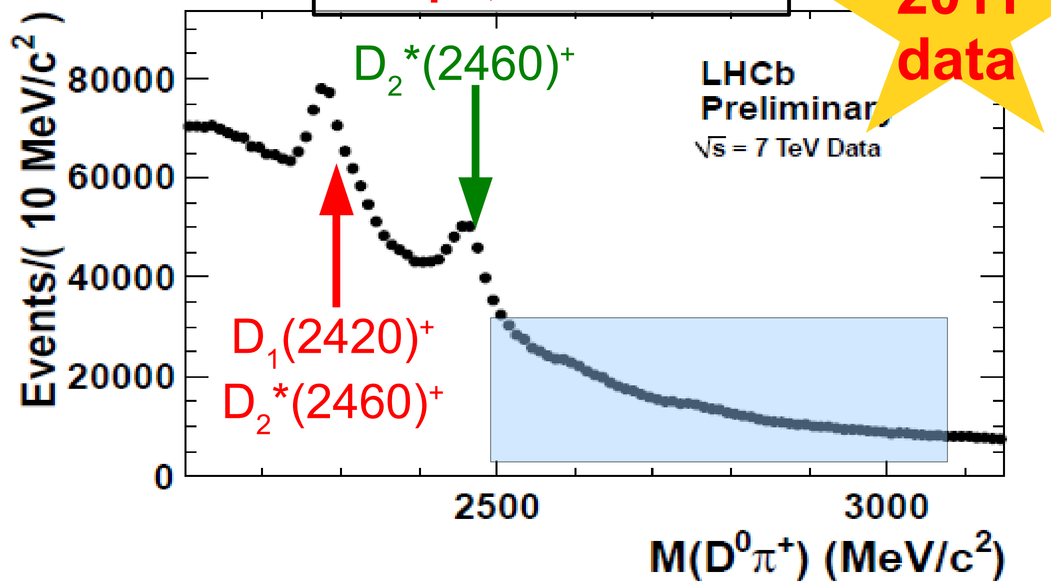
Spectra for high mass mesons predicted using QCD potentials and chiral model. Experimental approach often difficult since background levels are very high in inclusive production.

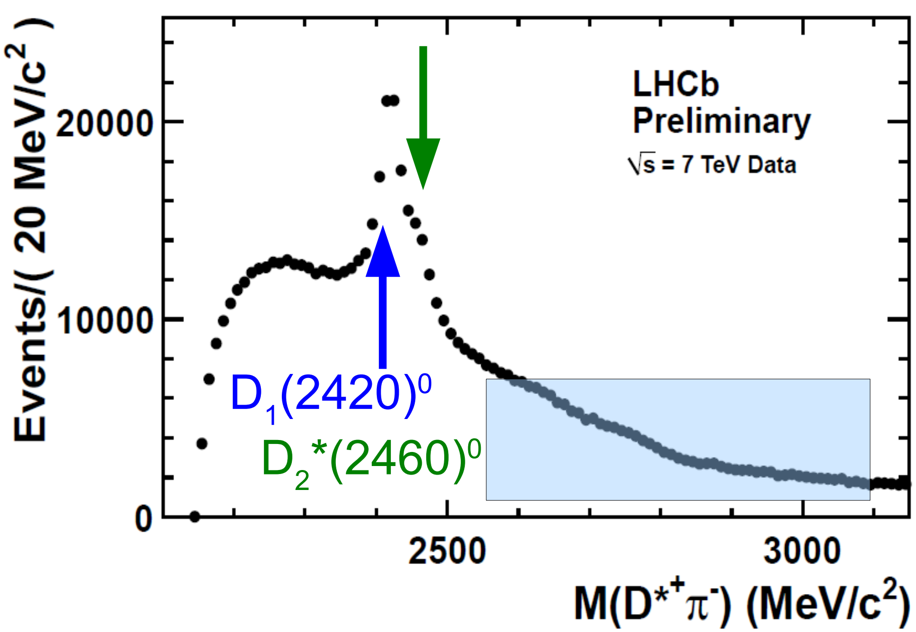
D_J spectroscopy

320/pb, 2011 data

2011 data

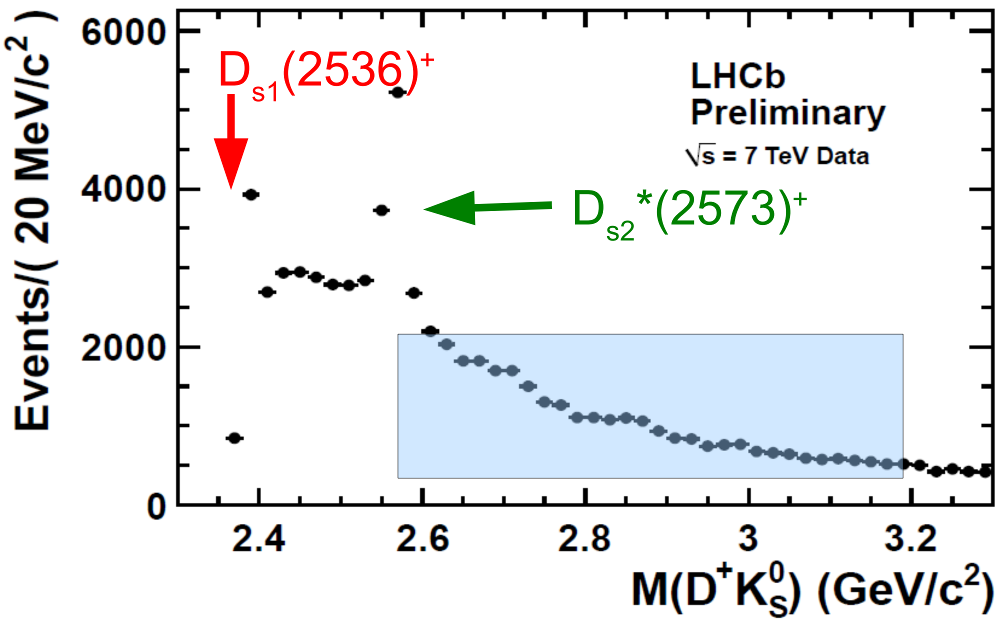


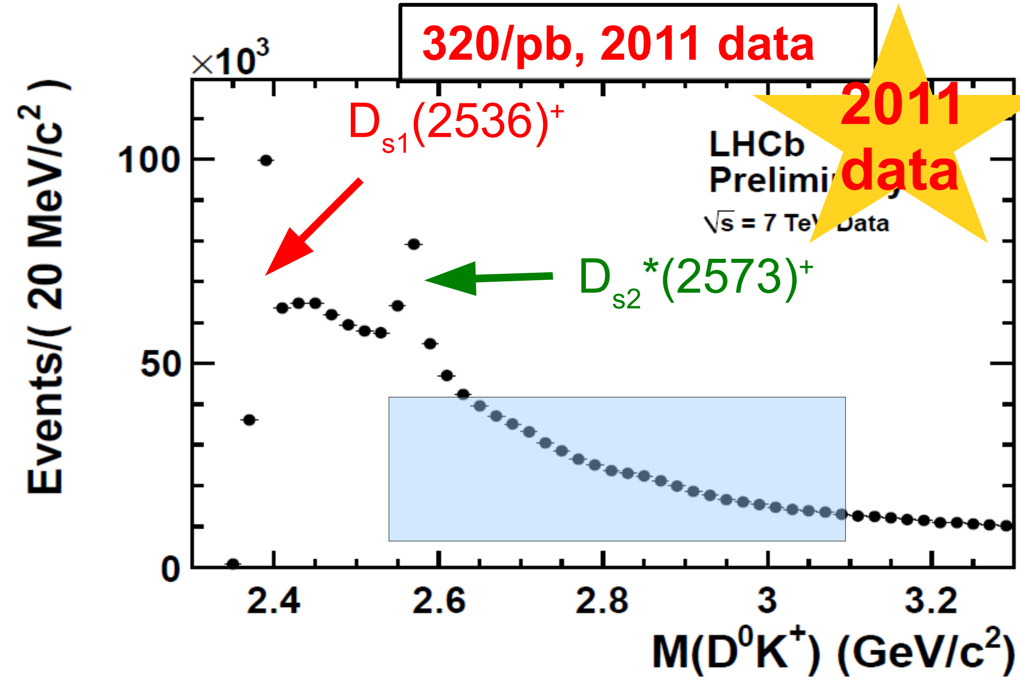




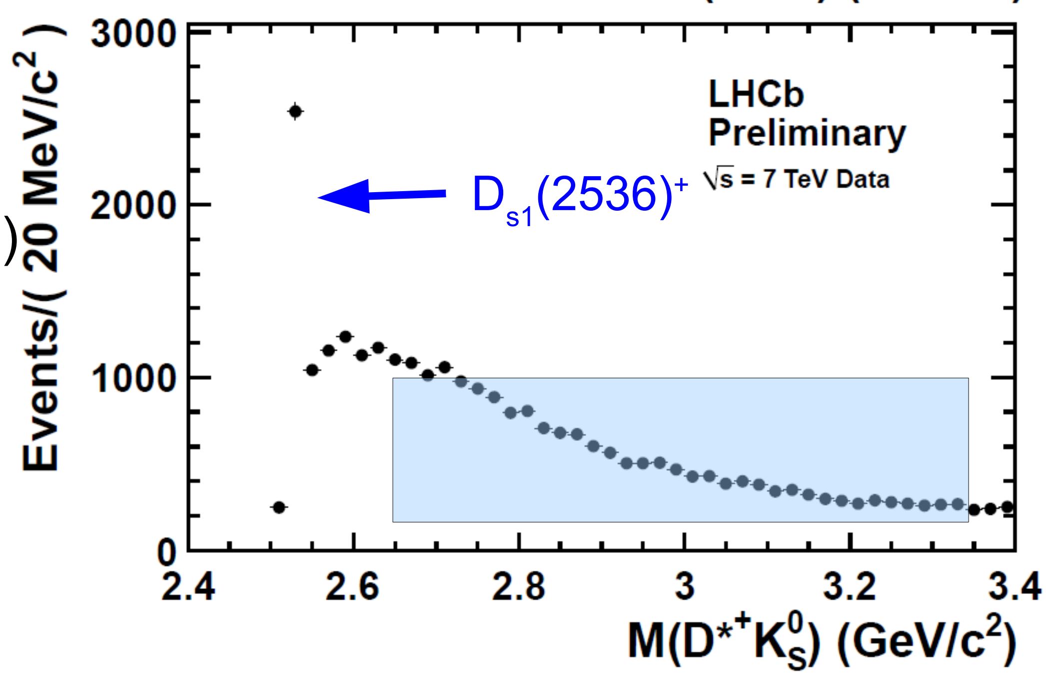
- Feed-down states $D_J \rightarrow D^*\pi(D^* \rightarrow D\gamma, D\pi^0)$
- BaBar has observed PRD82, 11101(2010) the broad states
  - **$D^*(2600)^{0/+}$, $D^*(2710)^{0/+}$, $D(2550)^0$, $D(2750)^0$**
- LHCb is investigating the region of interest to confirm the existence of the states claimed by BaBar

D_{sJ} spectroscopy





- Feed-down states $D_{sJ} \to D^*K(D^* \to D\gamma, D\pi^0)$
- BaBar has observed PRD80, 092003(2009) the broad states
  - **$D_{s1}^*(2710)^+$, $D_{sJ}^*(2860)^+$, $D_{sJ}(3040)^+$**
- LHCb is investigating the region of interest to confirm the existence of the states claimed by BaBar

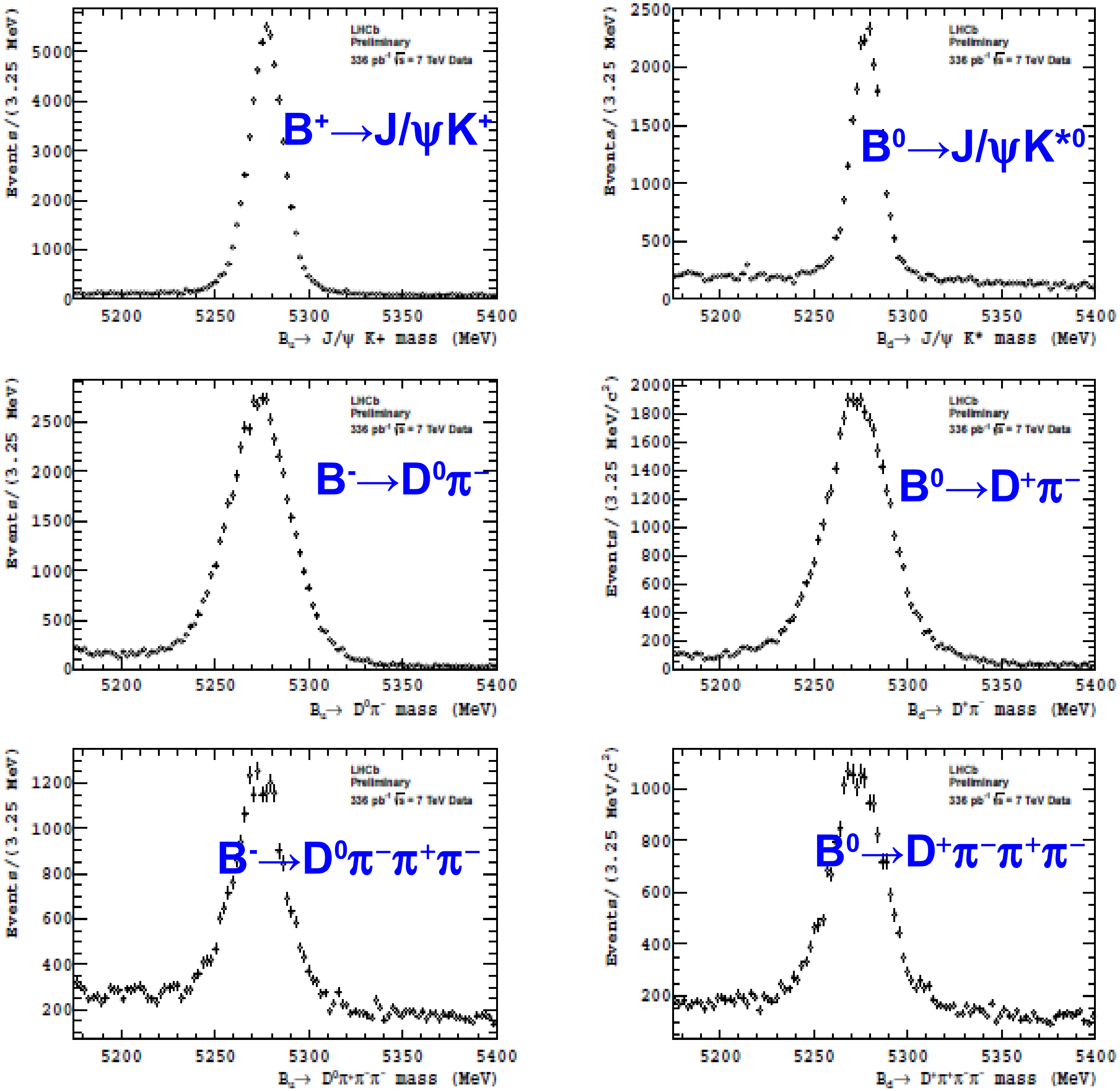


$B_{(s)J}$ spectroscopy

LHCB-CONF-2011-053

336/pb, 2011 data

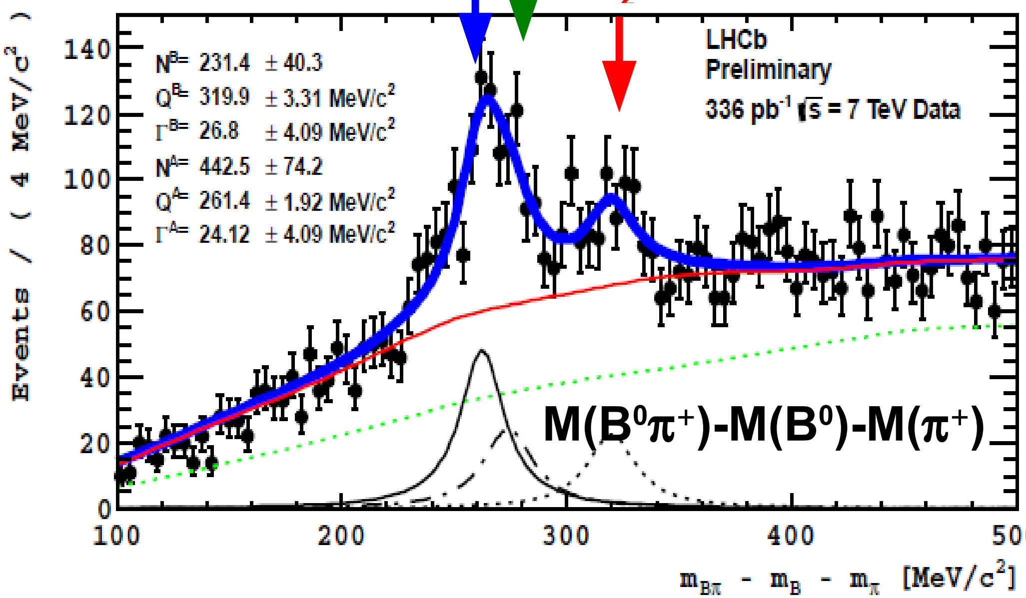
2011 data



- B-mesons properties are predicted from HQET in the limit of infinite b-quark mass
- Reconstruction of Bh and B*(Bγ)h decay modes. Soft photon is not reconstructed
  - $J/\psi \to \mu^+\mu^-$
  - $D^0 \to K^-\pi^+$
  - $D^+ \to K^-\pi^+\pi^+$
  - $K^{*0}(892) \to K^+\pi^-$
  - Particle ID and track quality constraints applied to all tracks.
  - $B_{(s)}$** required p_T>5GeV and good vertex quality
- Fits to Q=M(Bh)-M(B)-M(h) are performed

$B_2^{*0} \rightarrow B^{*+}\pi^-$

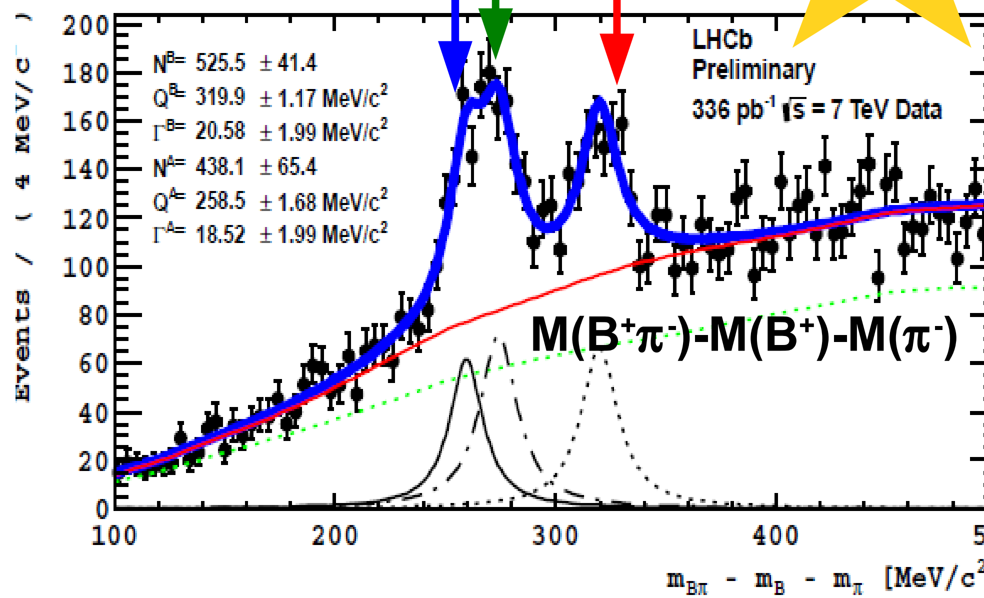
$B_1^0 \rightarrow B^{*+}\pi^-$ $B_2^{*0} \rightarrow B^+\pi^-$



$B_2^{*+} \rightarrow B^{*0}\pi^+$

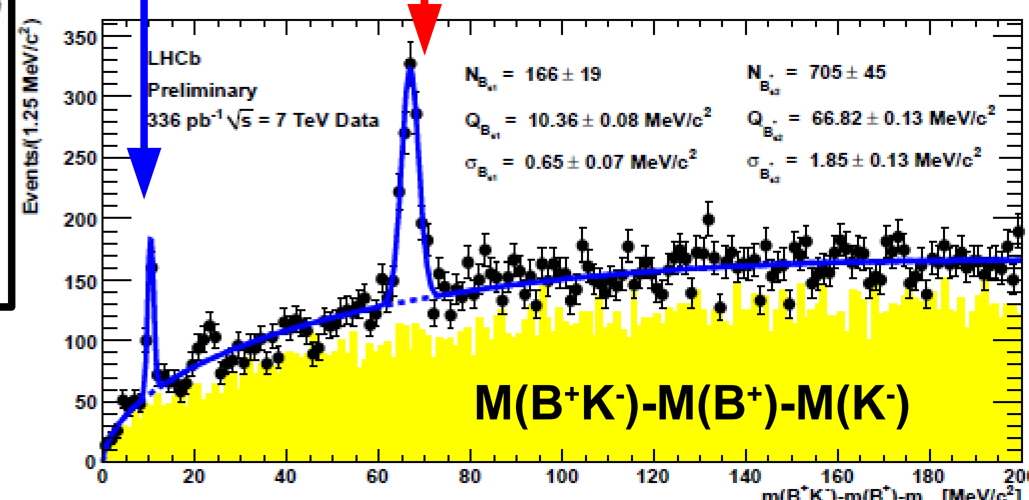
$B_1^+ \rightarrow B^{*0}\pi^+$ $B_2^{*+} \rightarrow B^0\pi^+$

2011 data



$$M_{B^0_{s1}} = (5828.99 \pm 0.08_{\rm stat} \pm 0.13_{\rm syst} \pm 0.45^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,,$$
$$M_{B^{*0}_{s2}} = (5839.67 \pm 0.13_{\rm stat} \pm 0.17_{\rm syst} \pm 0.29^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,,$$
$$M_{B^0_1} = (5724.1 \pm 1.7_{\rm stat} \pm 2.0_{\rm syst} \pm 0.5^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,,$$
$$M_{B^+_1} = (5726.3 \pm 1.9_{\rm stat} \pm 3.0_{\rm syst} \pm 0.5^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,,$$
$$M_{B^{*0}_2} = (5738.6 \pm 1.2_{\rm stat} \pm 1.2_{\rm syst} \pm 0.3^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,,$$
$$M_{B^{*+}_2} = (5739.0 \pm 3.3_{\rm stat} \pm 1.6_{\rm syst} \pm 0.3^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,,$$

$B_{s1}^0 \rightarrow B^{*+}K^-$ $B_{s2}^{*0} \rightarrow B^+K^-$ Know states

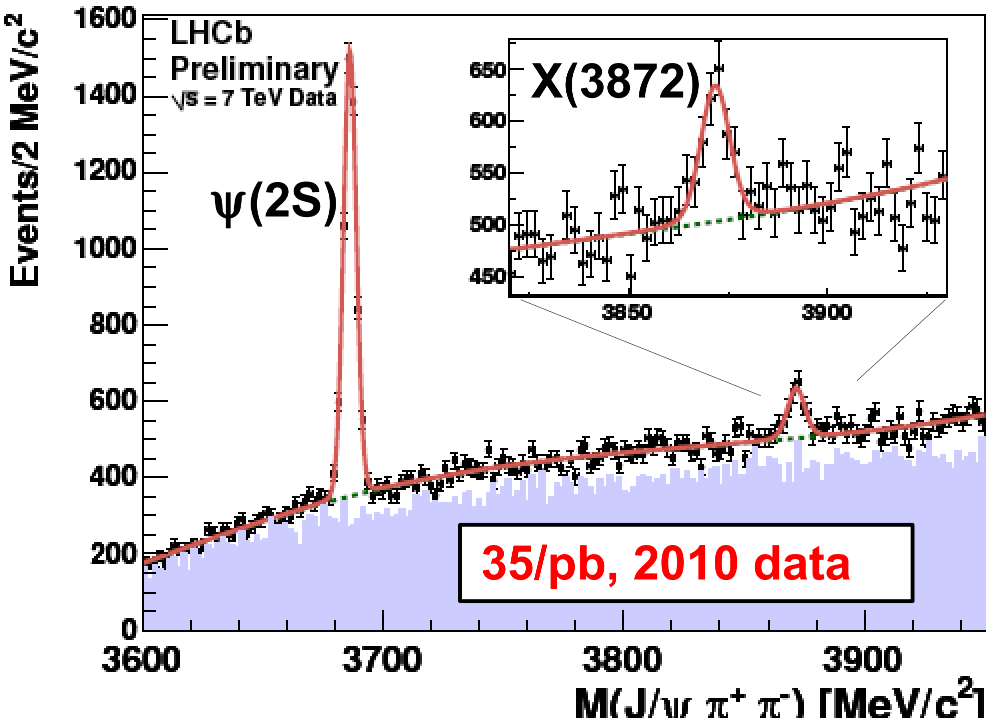


B_1^+ and B_2^{*+} first observation. Compatible with their isospin partners

X(3872) mass

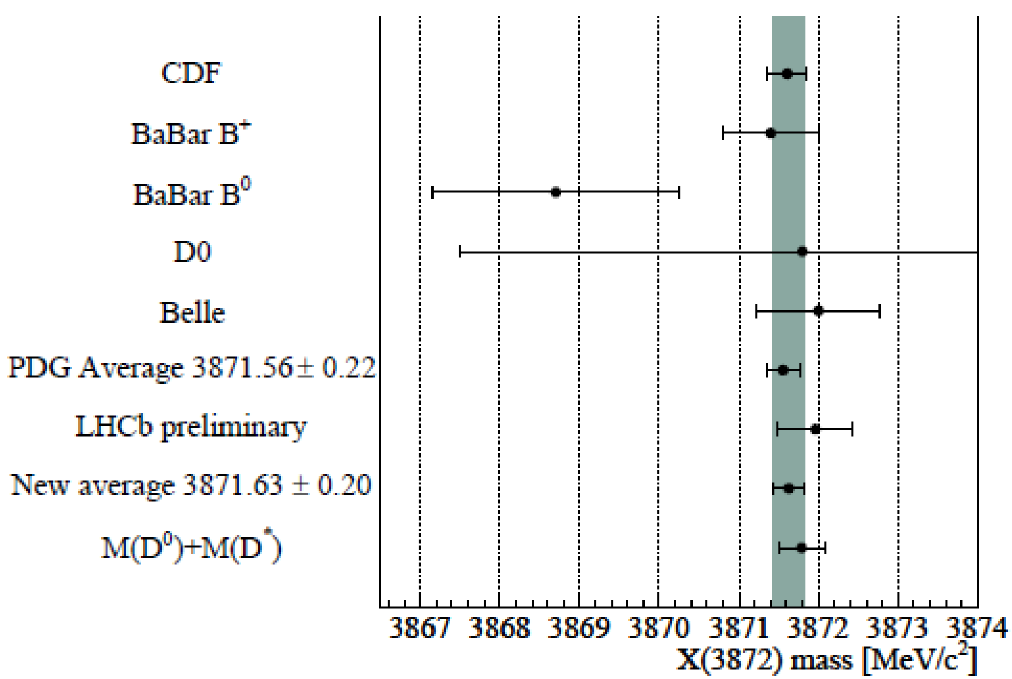
LHCB-CONF-2011-021

- Exotic meson, with $J^{PC} = 2^{-+}$ or 1^{++}. First of a large list of exotic structures, up to 4.7GeV
  - Charmonium state, $\eta_{c2}(1D)$ but mass inconsistency.
  - Near the thresohlod D*D, may it be a loosely bound molecule
  - Tetraquark state
- Reconstruction of $X(3872) \rightarrow J/\psi(\mu^+\mu^-)\pi^+\pi^-$ final state
- Momentum scale calibrated using $J/\psi \rightarrow \mu^+\mu^-$.
- X(3872) described using a BW function with fixed width.
- Background from wrong-sign pions combination



585±74 X(3872) events

$$M_{X(3872)} = 3871.96 \pm 0.46 \pm 0.10\ \mathrm{MeV}/c^2$$

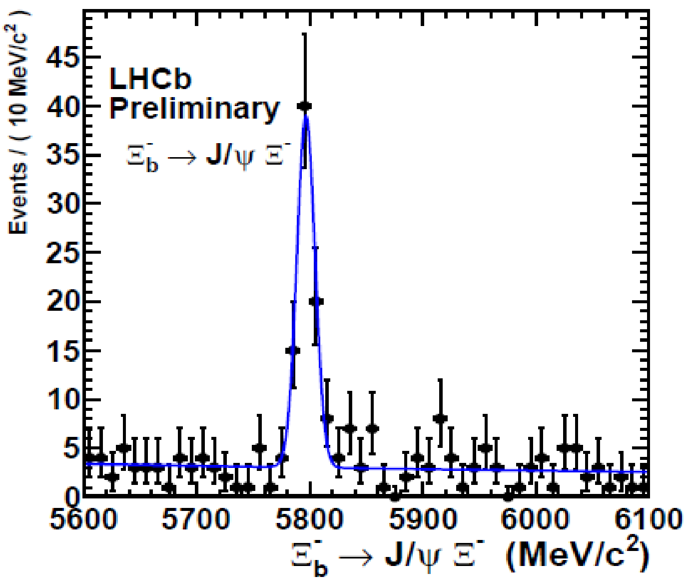


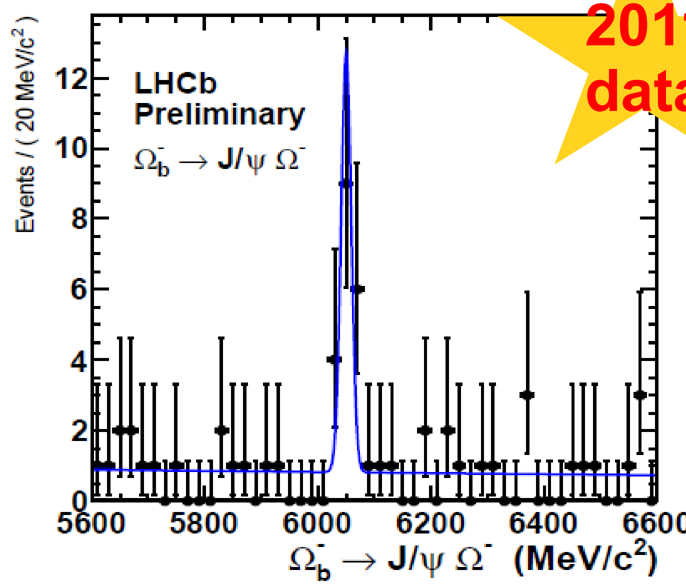
Ω_b and Ξ_b mass

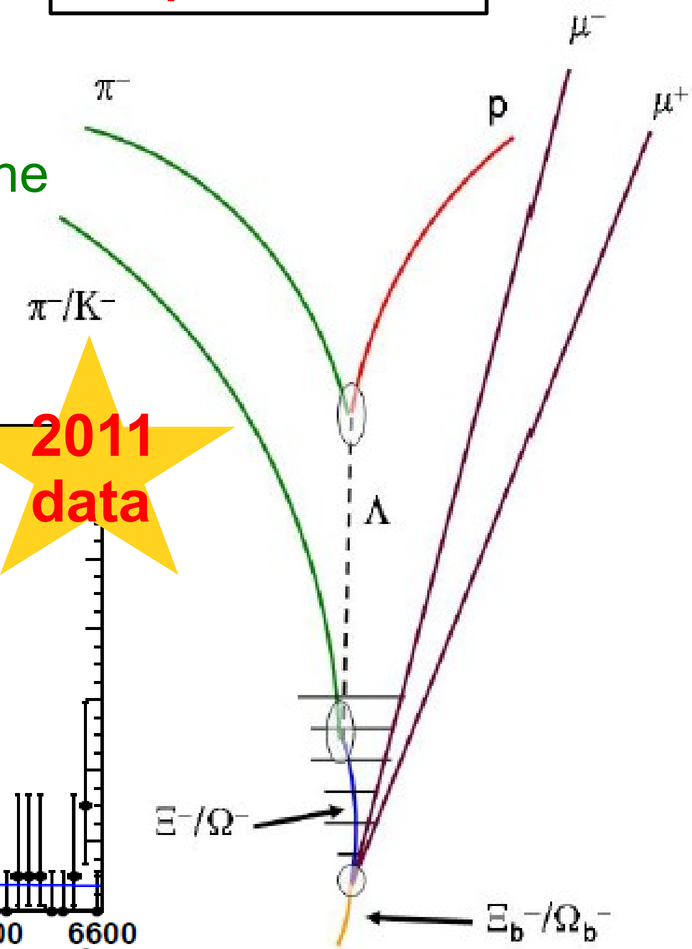
LHCB-CONF-2011-060 (to appear)

576/pb, 2011 data

- Reconstructed modes
  - $\Xi_b^- \to J/\psi(\mu^+\mu^-)\Xi^-(\Lambda(p\pi^-)\pi^-)$
  - $\Omega_b^- \to J/\psi(\mu^+\mu^-)\Omega^-(\Lambda(p\pi^-)K^-)$
- Decay time cuts useful given the particular topology of the decays
- Momentum scale calibration using B^+, B^0 and Λ_b decays largest systematic effect





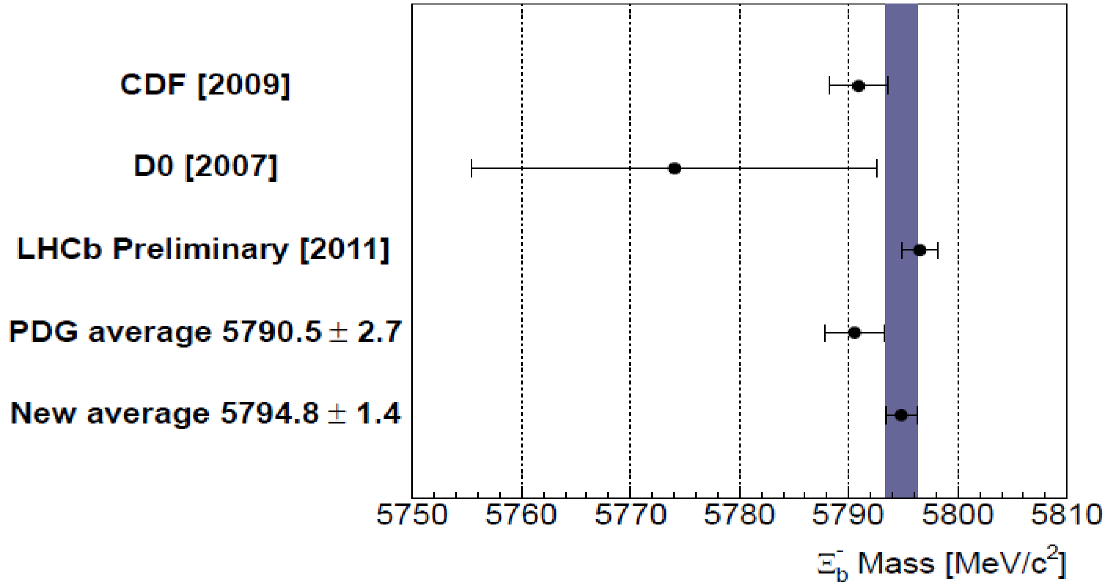


Decay mode	Yield	Mass (MeV/c^2)	Mass resolution (MeV/c^2)
$\Xi_b^- \to J/\psi\Xi^-$	72.2 ± 9.4	5796.5 ± 1.2	9.1(fixed)
$\Omega_b^- \to J/\psi\Omega^-$	$13.9^{+4.5}_{-3.8}$	6050.3 ± 4.5	9.5(fixed)

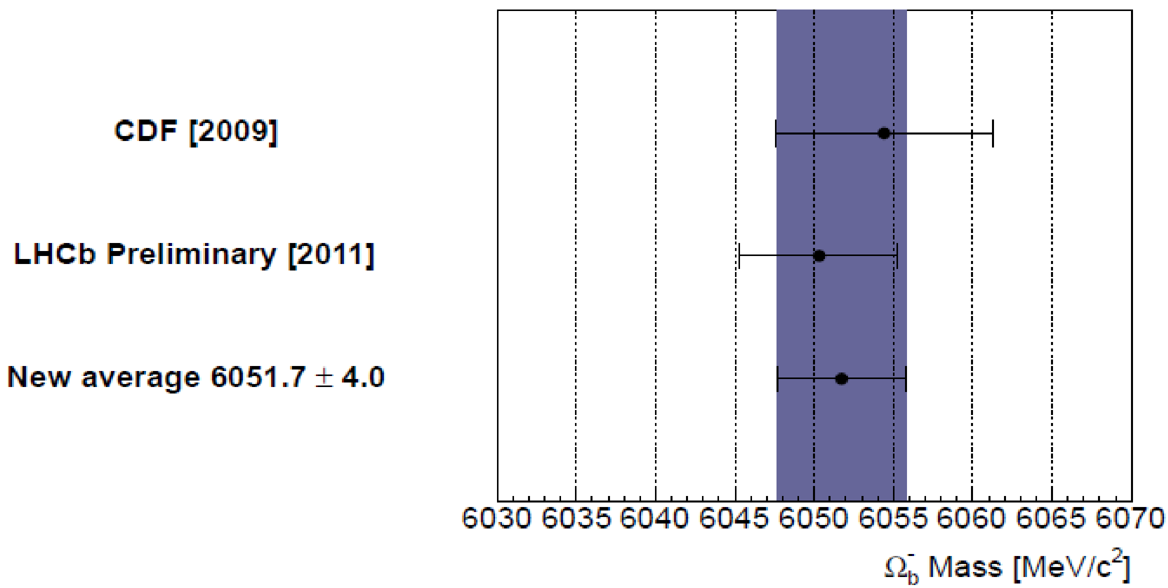
Mass Ξ_b^- : $5796.5 \pm 1.2 \pm 1.2\ \mathrm{MeV/c^2}$

2011 data

Best Ξ_b^- mass measurement up to date



Mass Ω_b^- : $6050.3 \pm 4.5 \pm 2.2\ \mathrm{MeV/c^2}$



6.7σ discrepancy from CDF+LHCb with DØ result (far to the right of the plot)

Conclusions

- We present some of the LHCb results on heavy flavors production and spectroscopy

- The collaboration is actively working in order to supersede the results with low statistics (2010 data), with measurements using the full 2011 data sample

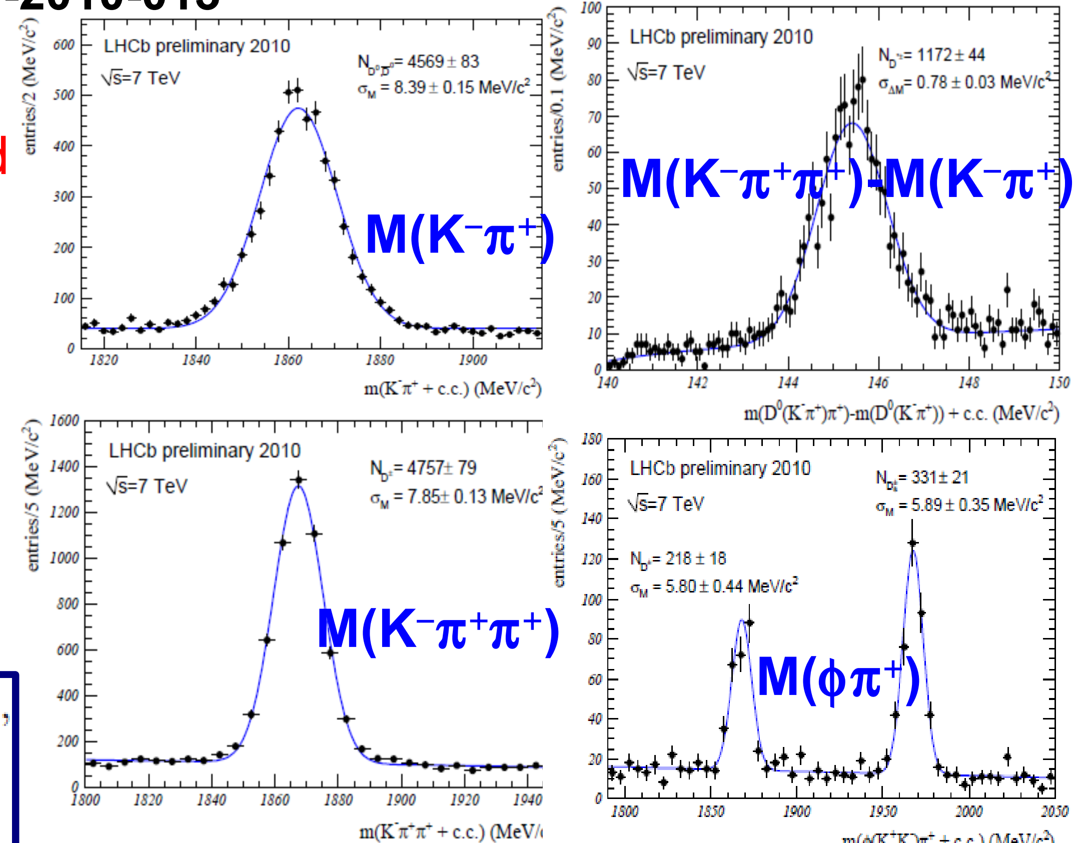
- LHCb is in a great position to perform precise and competitive measurements, and ready to explore the nature of the production and the spectra of states, in the heavy flavors sector

Backup slides

Prompt charm production

LHCB-CONF-2010-013

- Open charm cross section is a key input for estimate sensitivity for CPV, mixing and rare decays of charmed mesons
  - Prompt: Direct production and feed-down
  - Secondary: from B-hadron decays
- Considered $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^+ \to \phi\pi^+$, $D^{*+} \to D^0\pi^+$, $D_s^+ \to \phi\pi^+$.



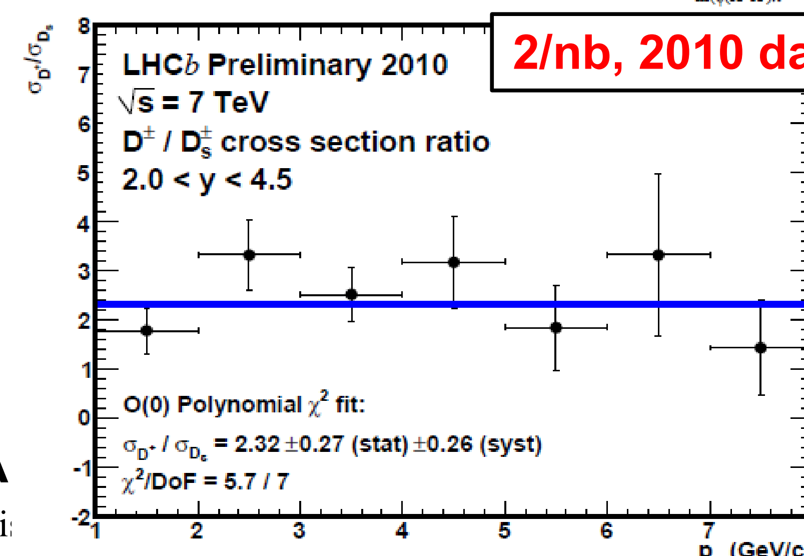
Integrated cross section in LHCb acceptance

$$\sigma(D^0) = 1488 \pm 41 \pm 34 \pm 174\,\mu\text{b} = 1488 \pm 182\,\mu\text{b},$$
$$\sigma(D^{*+}) = 676 \pm 64 \pm 21 \pm 119\,\mu\text{b} = 676 \pm 137\,\mu\text{b},$$
$$\sigma(D^+) = 717 \pm 39 \pm 26 \pm 98\,\mu\text{b} = 717 \pm 109\,\mu\text{b},$$
$$\sigma(D_s^+) = 194 \pm 23 \pm 16 \pm 26\,\mu\text{b} = 194 \pm 38\,\mu\text{b}.$$

Uncorrelated systematics: Selection, data MC comparison...

Correlated systematics: Lumi, tracking

2/nb, 2010 data



Integrated extrapolated cross section

$$\sigma(pp \to c\bar{c}X) = 6.10 \pm 0.93\,\text{mb}$$

All results in agreement with LHCb tune to PYTHIA

D^0 production asymmetry

LHCB-CONF-2011-023

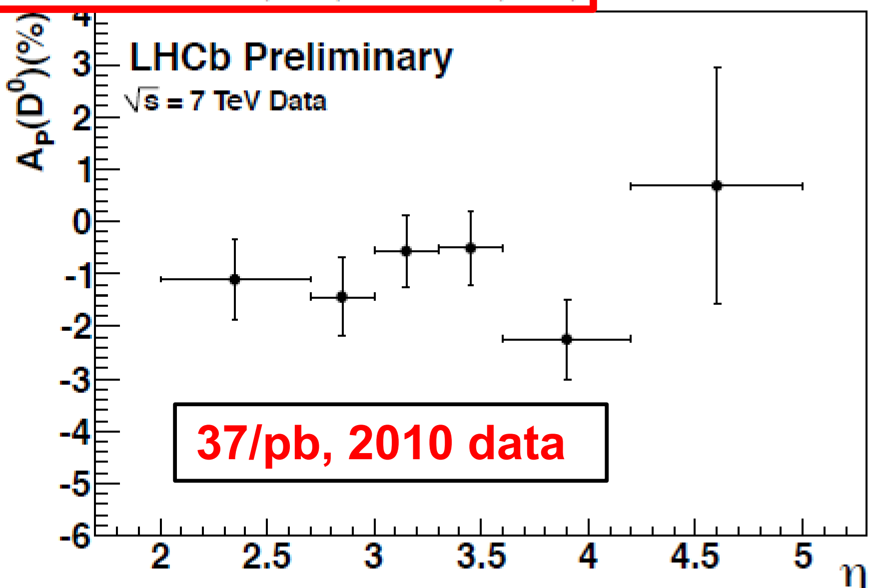
$$A_{\mathrm{RAW}}(f) \equiv \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})} \qquad A_{\mathrm{RAW}}(f)^* \equiv \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to D^0(f)\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \bar{D}^0(\bar{f})\pi^-)}$$

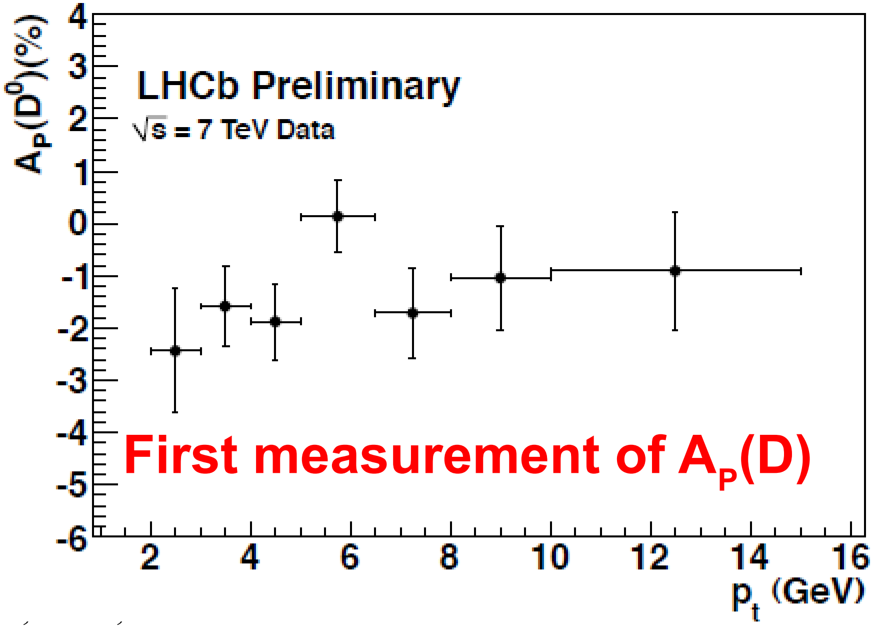
CP asymmetry (external inputs),
Production asymmetry
Production asymmetry is a key input in CPV measurements and QCD models.

$D^0 \to K^-\pi^+$ untagged
$D^{*+} \to D^0(K^-\pi^+, K^-K^+, \pi^-\pi^+)\pi^+$

$$A_{\mathrm{RAW}}(K^-\pi^+) - A_{\mathrm{RAW}}(K^-\pi^+)^* + A_{\mathrm{RAW}}(K^-K^+)^* = A_{\mathrm{P}}(D^0) + A_{CP}(K^-K^+)$$
$$A_{\mathrm{RAW}}(K^-\pi^+) - A_{\mathrm{RAW}}(K^-\pi^+)^* + A_{\mathrm{RAW}}(\pi^-\pi^+)^* = A_{\mathrm{P}}(D^0) + A_{CP}(\pi^-\pi^+)$$

$$\boxed{A_{\mathrm{P}}(D^0) = \frac{N_{\mathrm{P}}(D^0) - N_{\mathrm{P}}(\bar{D}^0)}{N_{\mathrm{P}}(D^0) + N_{\mathrm{P}}(\bar{D}^0)}} \qquad \boxed{A_P(D^0) = [-1.08 \pm 0.32(\mathrm{stat.}) \pm 0.12(\mathrm{sys.})]\ \%}$$



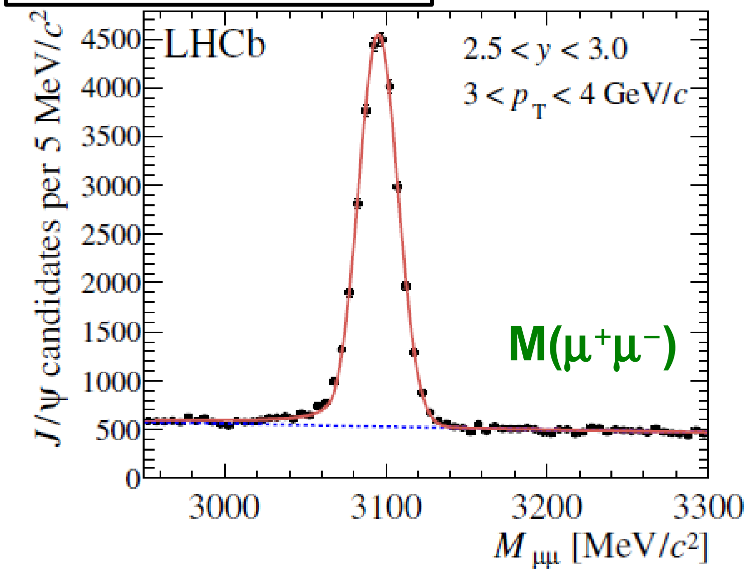


J/ψ production

Eur.Phys.J.C71:1645,2011

5.2/pb, 2010 data

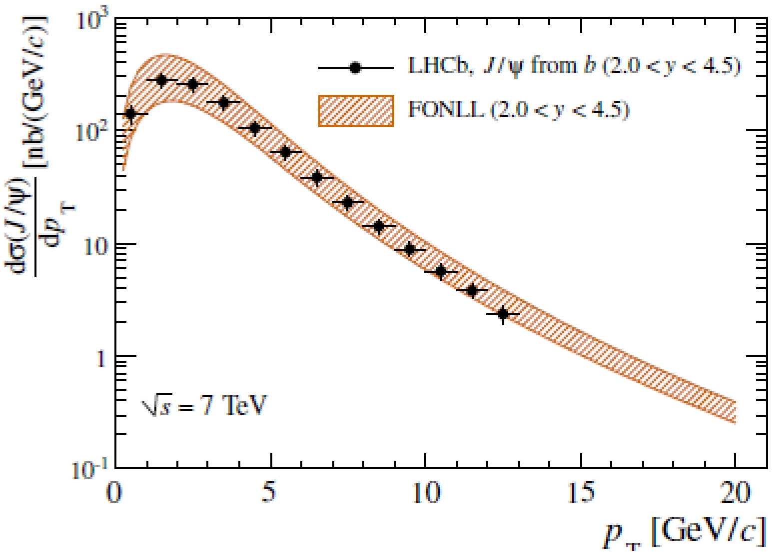
- J/ψ reconstructed into $\mu^+\mu^-$
  - Prompt production
    - From heavier prompt charmonium. Direct prompt J/ψ
  - From B decays. Separation using pseudo-proper time.



- Pseudo-proper time
  - Prompt: delta function
  - From B: decaying exponential
  - Tail from J/ψ with wrong PV association

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

- Differential cross section
  - Effects of the J/ψ polarization on the efficiency studied from MC.
  - Most important systematics effects: Tracking efficiency and luminosity.



- Prompt J/ψ in very good agreement with NLO NRQCD
- J/ψ from B, good agreement with FONLL

$$\sigma\,(\text{prompt } J/\psi, p_{\rm T} < 14~\text{GeV}/c, 2.0 < y < 4.5) = 10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20}~\mu\text{b}$$
$$\sigma\,(J/\psi \text{ from } b, p_{\rm T} < 14~\text{GeV}/c, 2.0 < y < 4.5) = 1.14 \pm 0.01 \pm 0.16~\mu\text{b}$$

$\psi(2S)$ production

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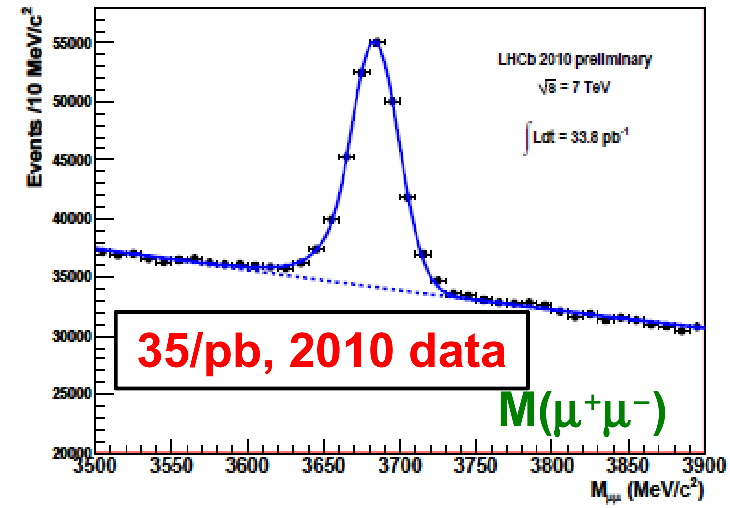
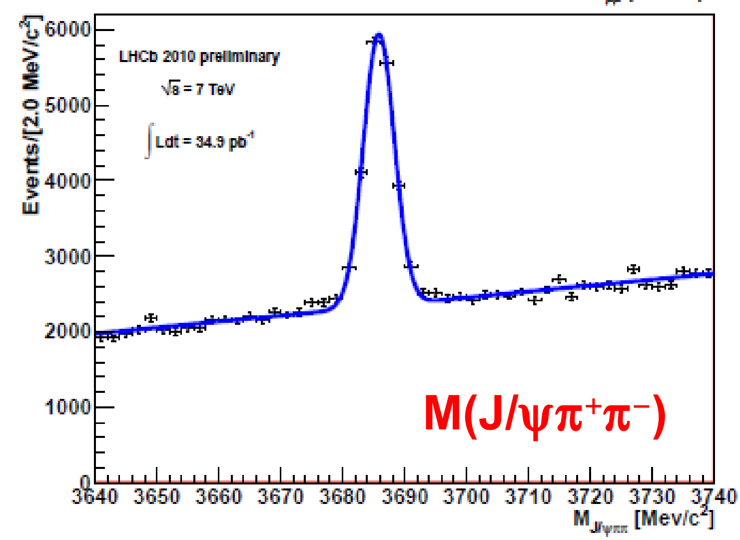
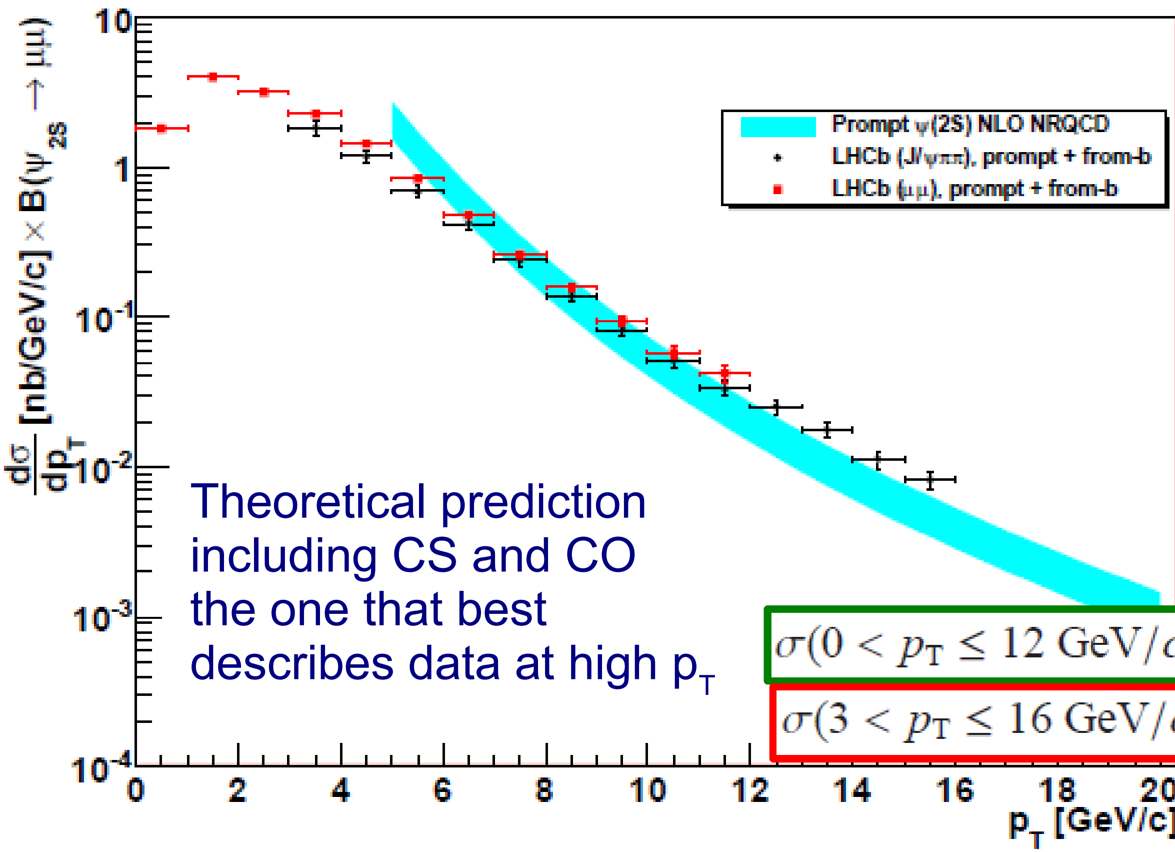
- No appreciable feed-down from higher charmonium states
  - Direct production and from b-hadron decay
- $\psi(2S)$ reconstructed in $\mu^+\mu^-$ and $J/\psi(\mu^+\mu^-)\pi^+\pi^-$
  - Particle ID, and vertex and track quality constraints
- Unknown polarization accounted for in the efficiency by using the helicity distribution. (largest systematic)







$$\sigma(0 < p_{\mathrm{T}} \leq 12\ \mathrm{GeV}/c, 2 < y \leq 4.5) = 1.88 \pm 0.02 \pm 0.31^{+0.25}_{-0.48}\ \mu\mathrm{b}$$

$$\sigma(3 < p_{\mathrm{T}} \leq 16\ \mathrm{GeV}/c, 2 < y \leq 4.5) = 0.62 \pm 0.04 \pm 0.12^{+0.07}_{-0.14}\ \mu\mathrm{b}$$