Heavy Quarkonia Studies at LHCb

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(for the LHCb collaboration)

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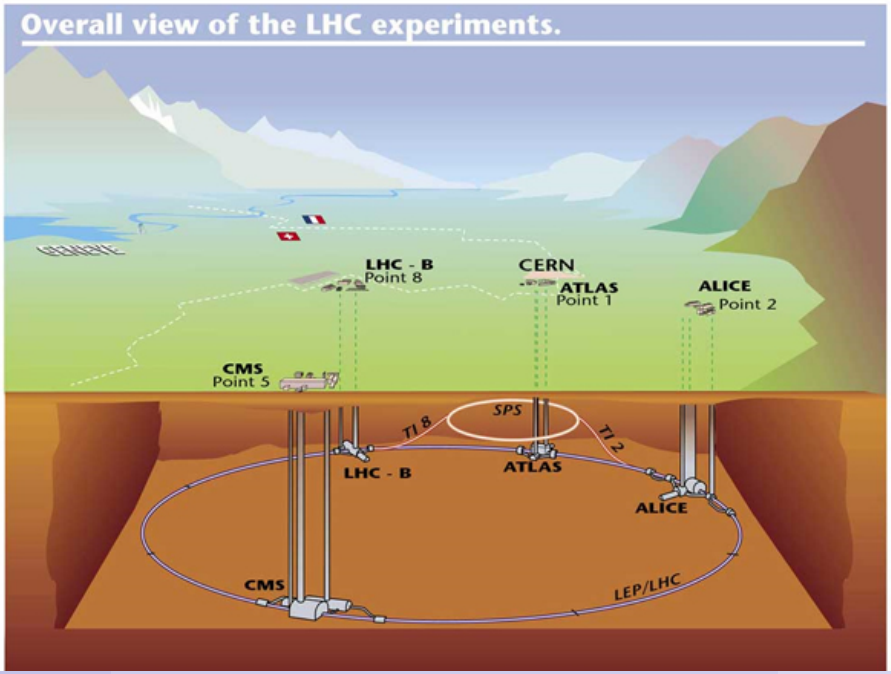
ReteQuarkonii Thematic Day @ IPN (Orsay), 09/02/2010

1. The LHC and LHCb experiment
2. Charmonium
   - J/ψ production
   - $\psi(2S)$, χ_c, $h_c(1P)$, $X(3872)$ and $Z(4430)^{\pm}$ studies
3. $B_c^{\pm}$
4. Bottomonium

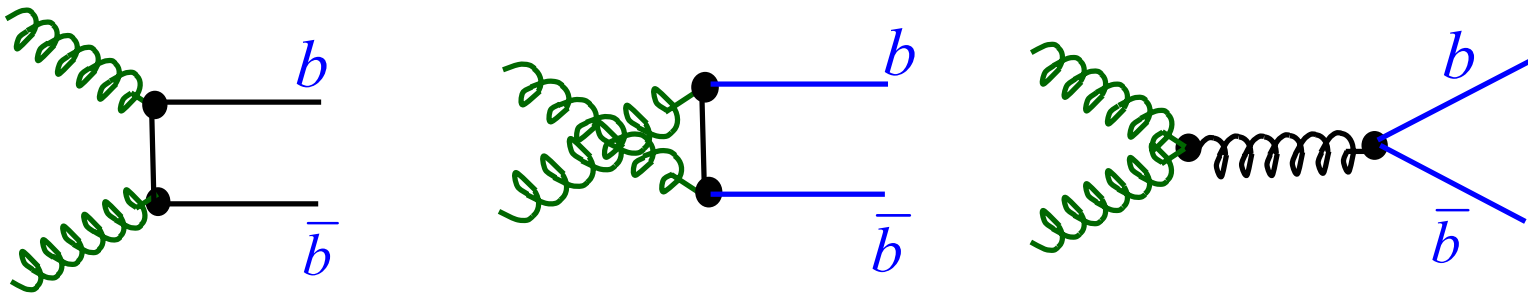
The Large Hadron Collider (LHC)

- The LHC experiments
  - ALICE: dedicated heavy-ion experiment
  - ATLAS and CMS: general purpose detectors
  - LHCb: dedicated *b*-physics experiment
  - LHCf and TOTEM Forward production of neutral particles & Total Cross Section, Elastic Scattering and Diffraction Dissociation
- The LHC status
  - 23/11/2009, first *pp* collision at $\sqrt{s}$ =900 GeV
  - 30/11/2009, 2 circulating *p*-beams, each at 1.18 TeV



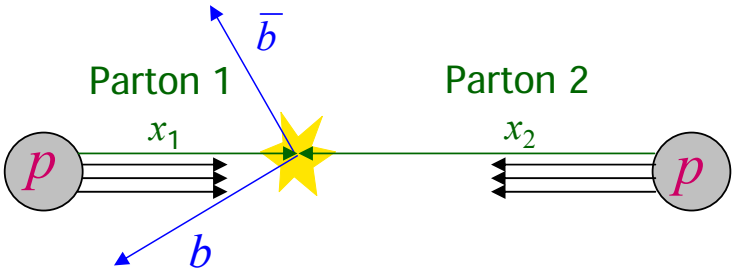
The b production at the LHC

- Correlated production of b and $\bar{b}$, $\sigma_{b\bar{b}} \sim 500\ \mu$b

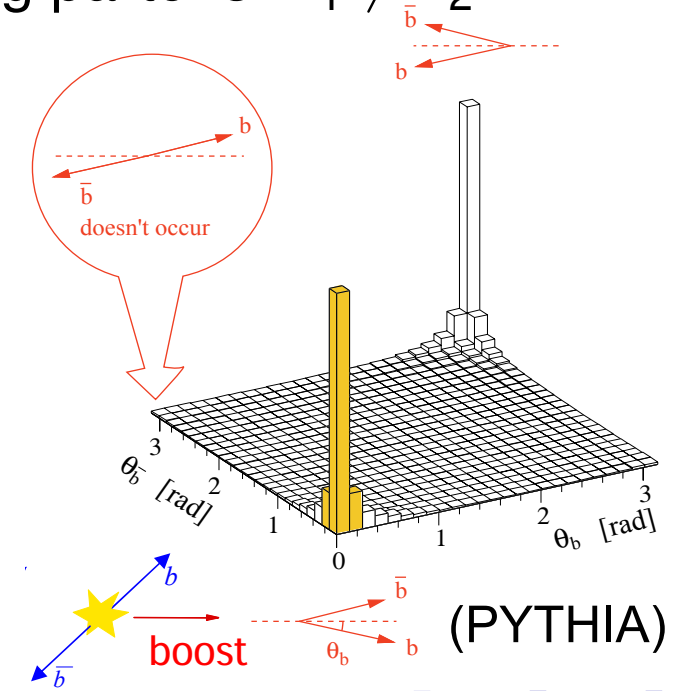


- Different momenta of the participating partons: $x_1 \neq x_2$

- b, $\bar{b}$ boosted and in same "cone"



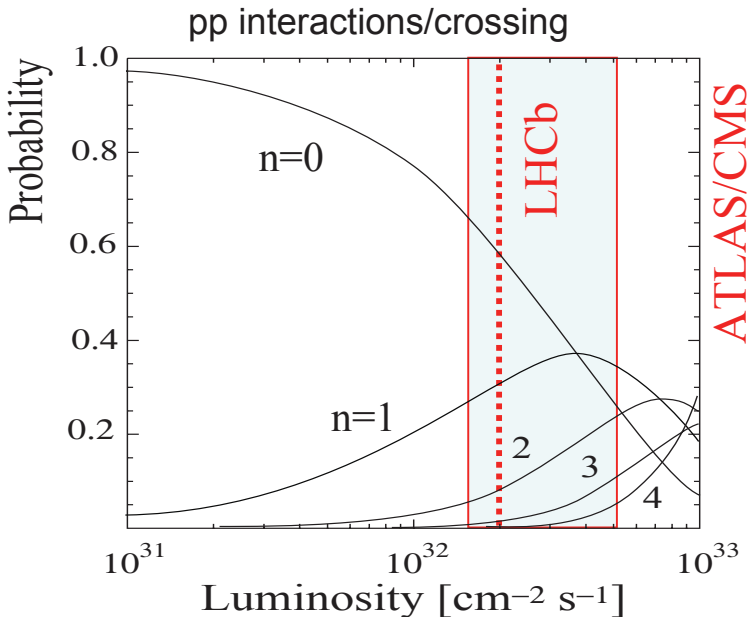
- $\Rightarrow$ Forward detector (NOT a fixed-target experiment!)



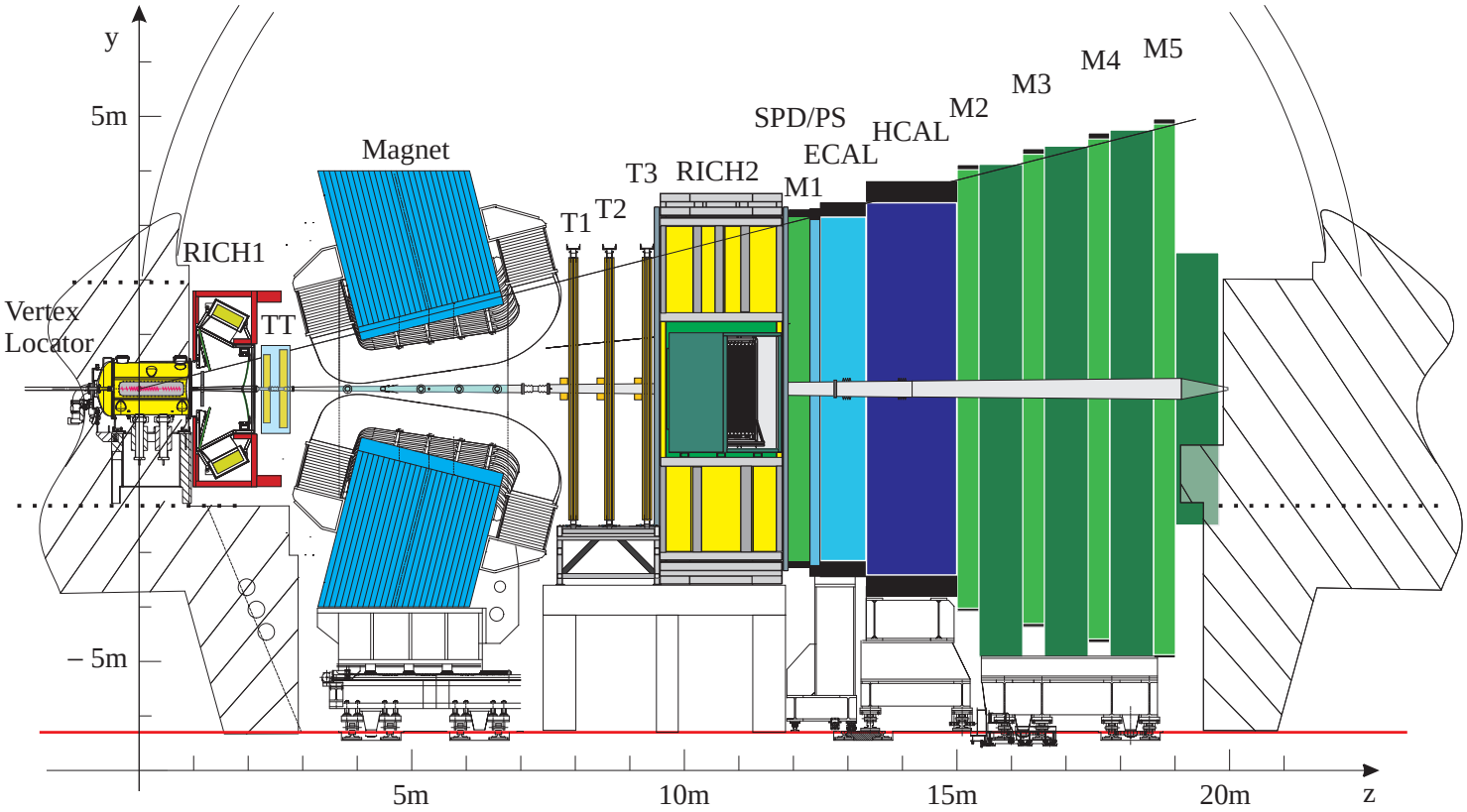
The pileup and the LHCb luminosity

- Pileup
  - Inelastic pp interactions in a bunch crossing are Poisson-distributed with mean $n_{pp} = \frac{\sigma_{pp}^{\text{inel}} \cdot L}{\nu_{\text{bx}}}$

    $\sigma_{pp}^{\text{inel}}$ = 80 mb for $\sqrt{s} = 14$ TeV; L - instantaneous luminosity; ν_{bx} - bunch crossing rate
- ATLAS/CMS
  - Nominal $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$, $n_{pp} = 25$
- LHCb
  - Low luminosity: $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ by not focusing the beam as much as ATLAS/CMS, $n_{pp} = 0.7$
  - $\sim 10^{12}$ $b\bar{b}$ per year (10^7 s)
- Startup phase
  - Lower $\sqrt{s}$, low L and very low ν_{bx} $\Rightarrow$ significant pileup
  - similar L_{int} to each experiment



The LHCb detector



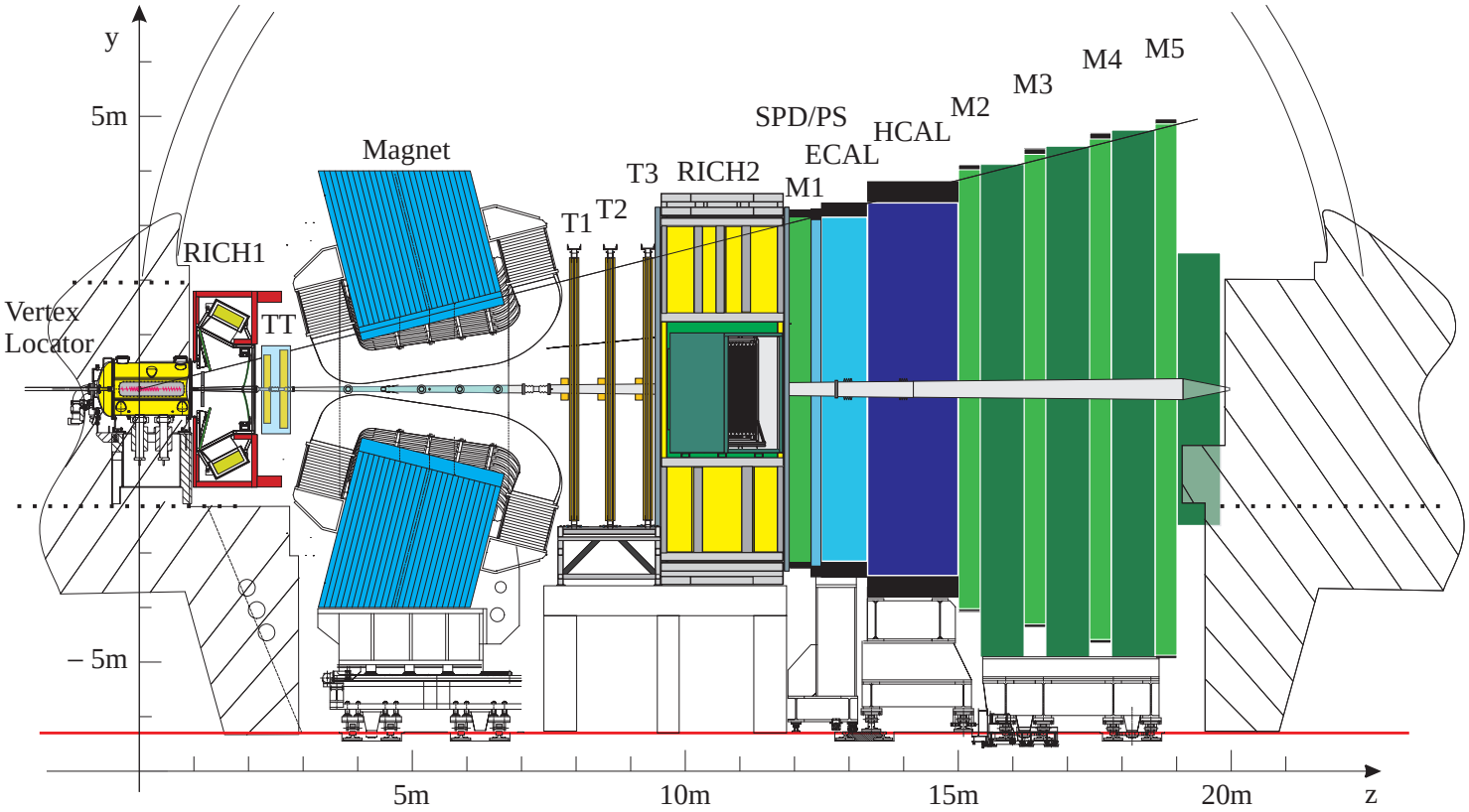
Geometry acceptance (15 - 300) mrad; $1.9 < \eta < 4.9$

Vertex Locator $\sigma_{PV,x/y} \sim 10\ \mu m$, $\sigma_{PV,z} \sim 60\ \mu m$; $\sigma_L \sim 250\ \mu m$

Magnet Warm magnet, ~ 4 Tm.

Tracking system (TT, T1-T3) $\Delta p/p$: 0.35%-0.55%, σ_m:12-25 MeV/c^2

The LHCb detector (cont.)



RICH1 & RICH2 $\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$

Muon system (M1-M5) $\varepsilon(\mu \to \mu) \sim 94\%$, mis-ID rate $(\pi \to \mu) \sim 3\%$

ECAL $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)

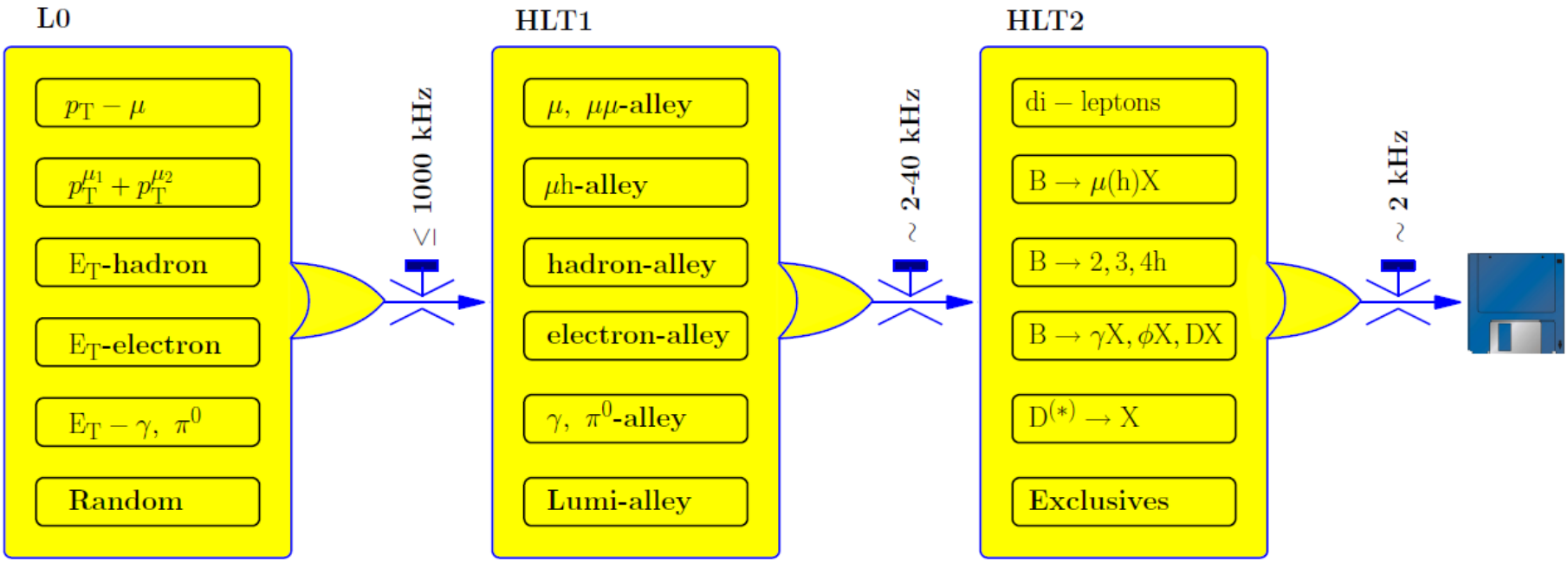
HCAL $\sigma_E/E = (69 \pm 5)\%/\sqrt{E} \oplus (9 \pm 2)\%$ (E in GeV)

The LHCb trigger system

- Level-0 Trigger (Hardware)
  - High p_T μ, e, γ, hadron candidates

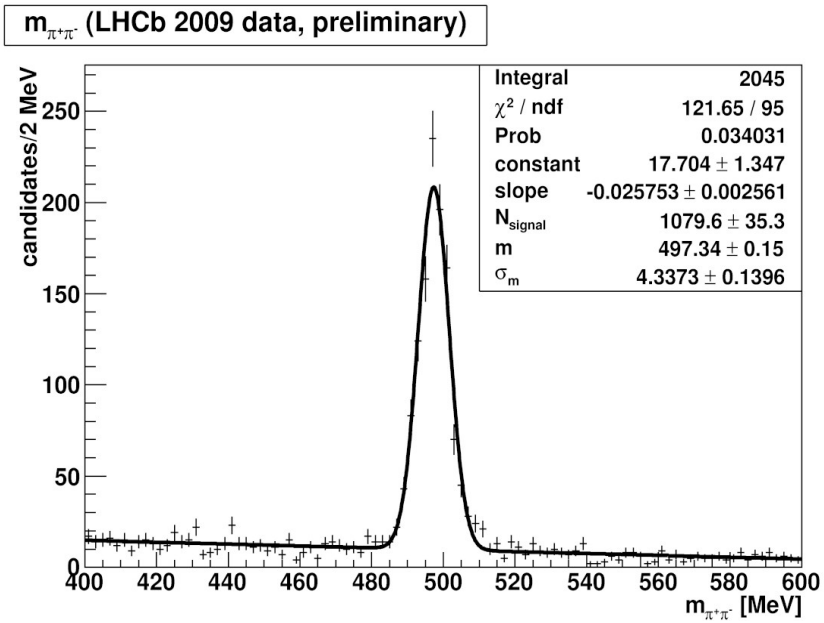
	had	μ	$\mu\mu$	$e^{\pm}$	γ	π^0
p_T>(GeV)	3.5	1	$\sum > 1.5$	2.6	2.3	4.5

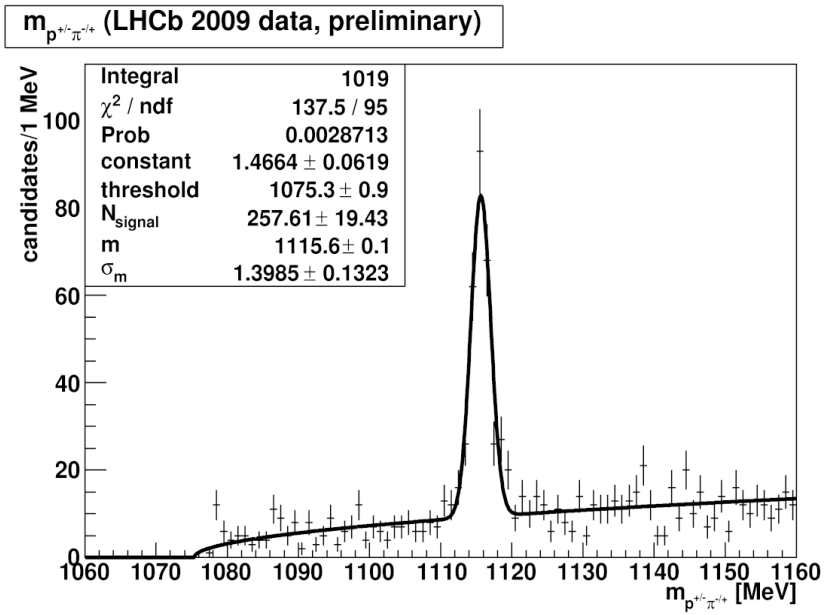
  - Efficiency: Muon (90%), Electromagnetic (70%), Hadronic (50%)
- High Level Trigger (Software)
  - HLT1: Check L0 candidate with more complete info, add impact parameters and lifetime cuts
  - HLT2: Global event reconstruction + selections (inclusive or exclusive)
  - Efficiency: Muon (80%), Electromagnetic (60%), Hadronic (80%)



The LHCb status

- The LHCb detector is fully installed. First data at $\sqrt{s}$ =900 GeV recorded, analysis ongoing.
- Very preliminary K^0_S and Λ mass distributions, real data!





$$M_{K^0_S} = 497.3 \pm 0.2(\text{stat.})\ \text{MeV}/c^2$$
$$\sigma_m = 4.3 \pm 0.1(\text{stat.})\ \text{MeV}/c^2$$
$$M^{\text{PDG}}_{K^0_S} = 497.7\ \text{MeV}/c^2$$

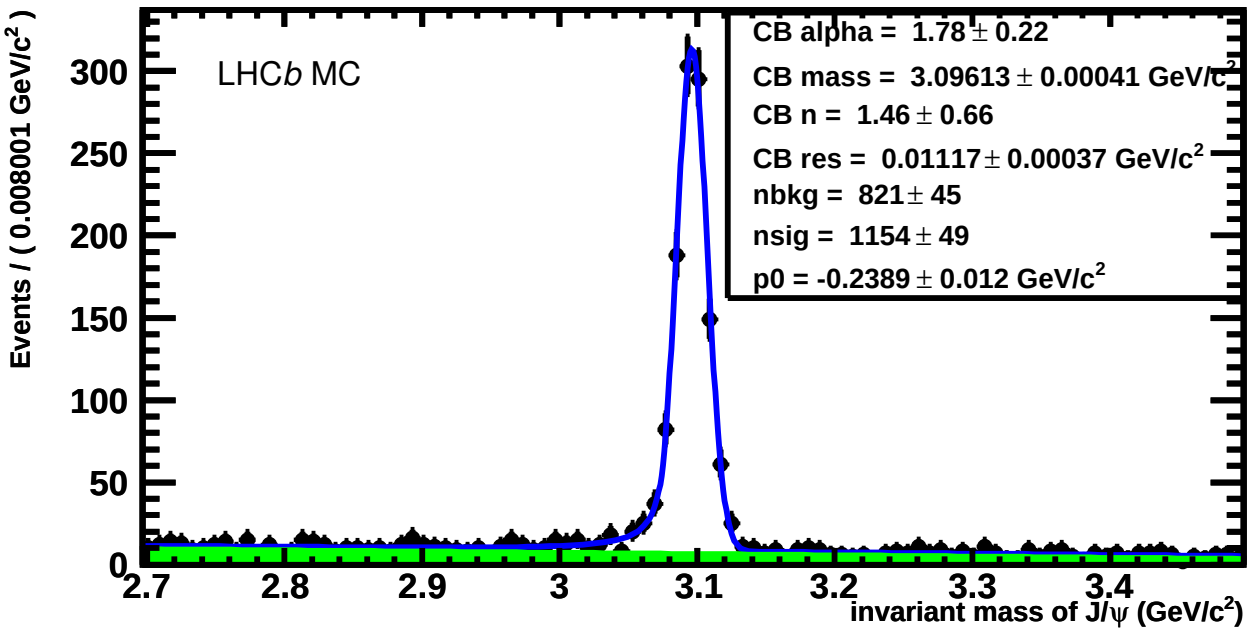
$$M_\Lambda = 1115.6 \pm 0.1(\text{stat.})\ \text{MeV}/c^2$$
$$\sigma_m = 1.4 \pm 0.1(\text{stat.})\ \text{MeV}/c^2$$
$$M^{\text{PDG}}_\Lambda = 1115.7\ \text{MeV}/c^2$$

J/ψ production: motivation

- The J/ψ was discovered more than 30 years ago, but we still do not understand the underlying production mechanism:
  - LO color octet mechanism (COM) can describe the p_T spectrum and cross section of the J/ψ produced at Tevatron, but can not explain the polarization, NLO doesn't help.
  - The other models, e.g., color evaporation model, k_T factorization, soft color interaction model can not describe the cross section and polarization simultaneously, either.
  - New measurements at the LHCb experiment (higher energy, special η coverage) will help resolve this issue.
- Large cross section and clear $J/\psi \to \mu^+\mu^-$ signal
  - J/ψ crucial for detector alignment, calibration, μ-ID and tracking efficiencies measurements, and so on.
  - The measurements of the cross sections of the prompt J/ψ and the J/ψ from b decays are important for later analysis in LHCb, e.g., absolute branching fraction measurements, assess event yields.

J/ψ selection

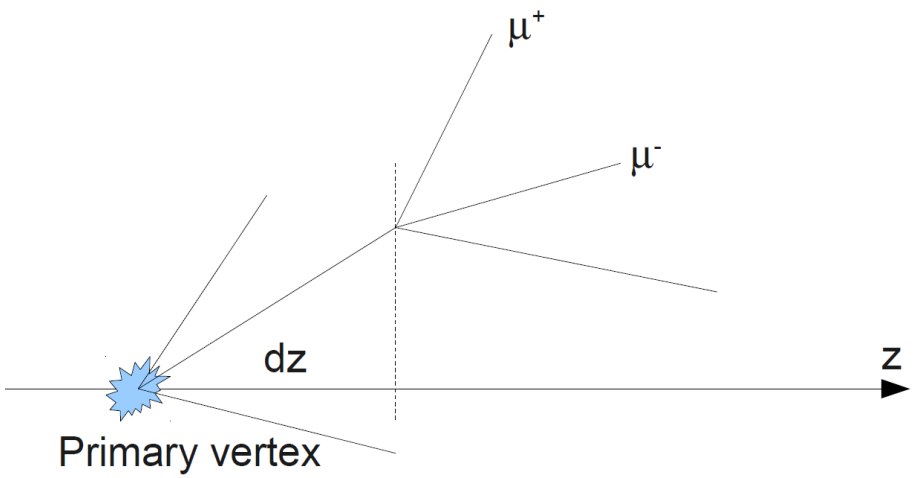
- Selection studied with the simulated minimum bias events
  - Loose μ ID selection, loose cuts on $p_{\mathrm{T}}(\mu^{\pm})$, μ^{+} and μ^{-} coming from a common vertex, at least one reconstructed primary vertex
- Expect about 2.8×10^{6} reconstructed J/ψ for 5 pb^{-1} of data at $\sqrt{s} = 7$ TeV
- Very good mass resolution: $\sim$11 MeV/c^2



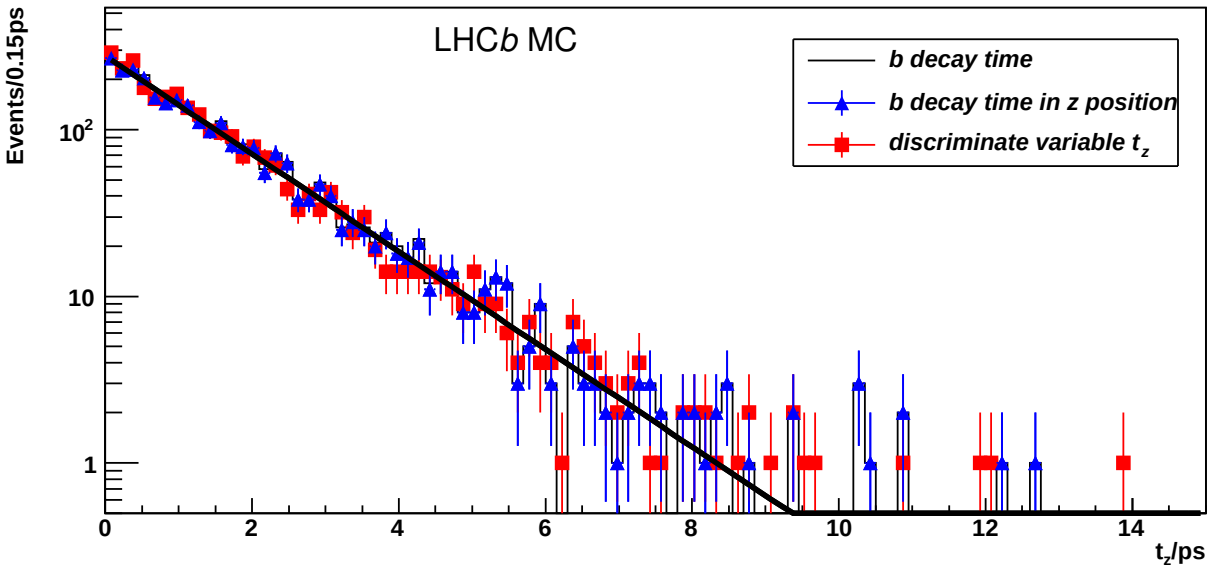
Separation of prompt J/ψ from $b \to J/\psi$

- Pseudo-lifetime t_z

$$t_z = \frac{dz}{p_z^{J/\psi}} m^{J/\psi}$$

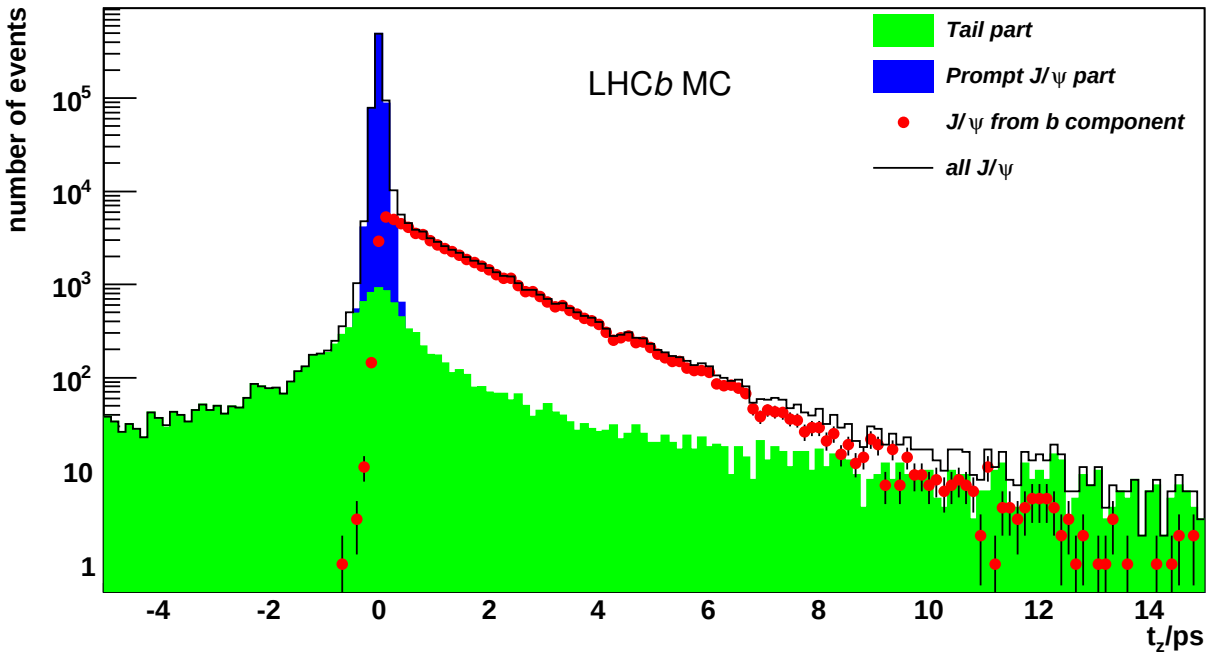


- Simple approximation of b lifetime



t_z distribution

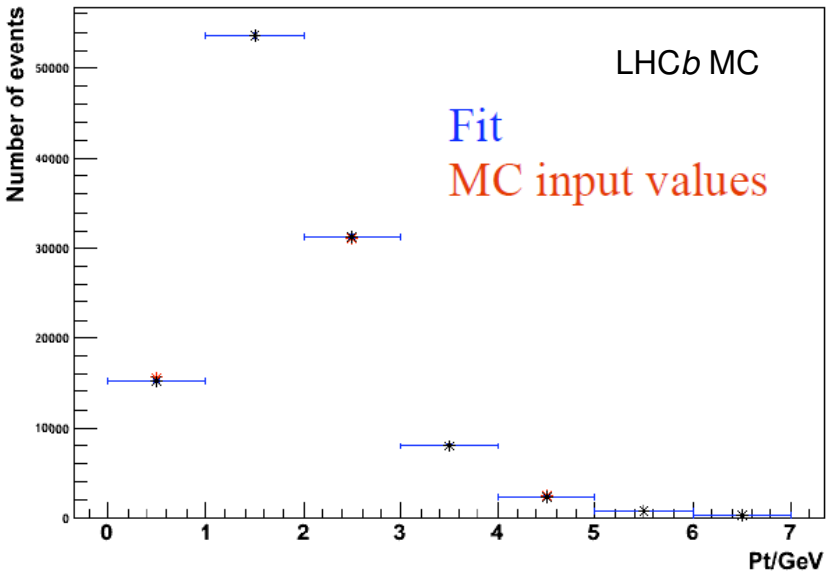
- t_z distribution has four components
  - Prompt J/ψ, peak at 0, Gaussian
  - J/ψ from b decays, Exponential convoluted with Gaussian
  - Background distribution, estimated from mass sidebands
  - Long tail due to association to wrong primary vertex, measured using the J/ψ vertex and the PV in different event



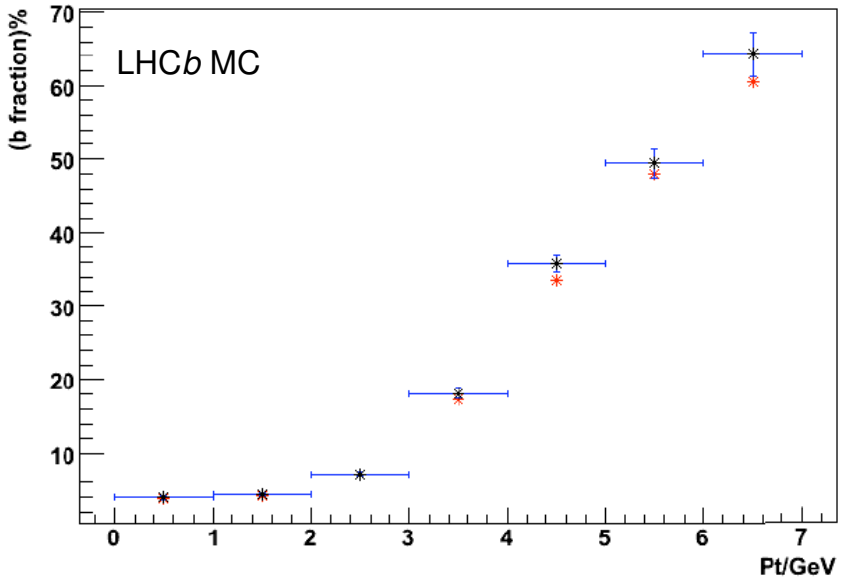
J/ψ cross section measurement

- Measurement in bins of p_{T} and η
  - 7 bins for p_{T} 0-7 GeV/c, 4 bins for η 3-5
- Combined mass and lifetime fit used to extract number of prompt J/ψ and J/ψ from b decays
- Tests of fitting procedure on sample corresponding to 0.145 pb^{-1} @ 14 TeV $\Rightarrow$ Good agreements between fit result and MC input

Only binning in p_{T}, because of small Monte Carlo statistics



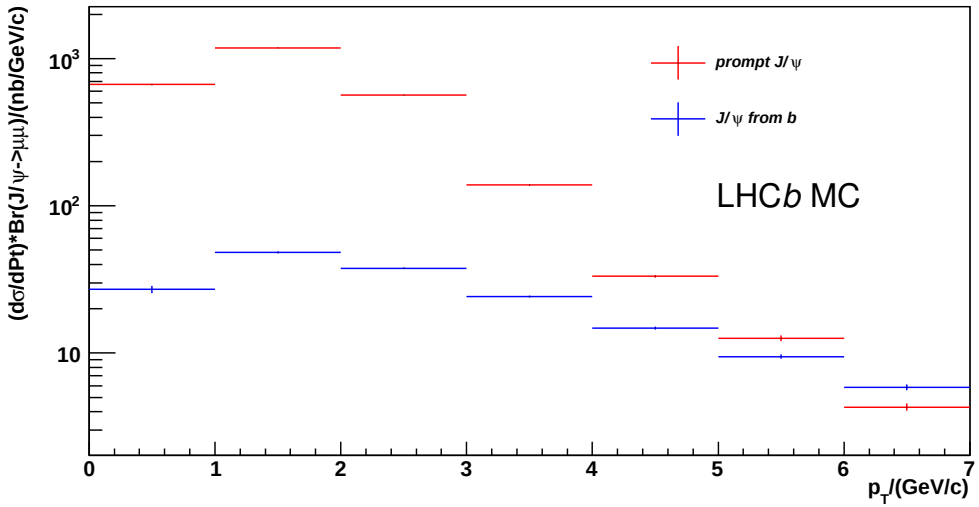
Number of prompt J/ψ



Fraction of J/ψ from b

J/ψ cross section measurement (cont.)

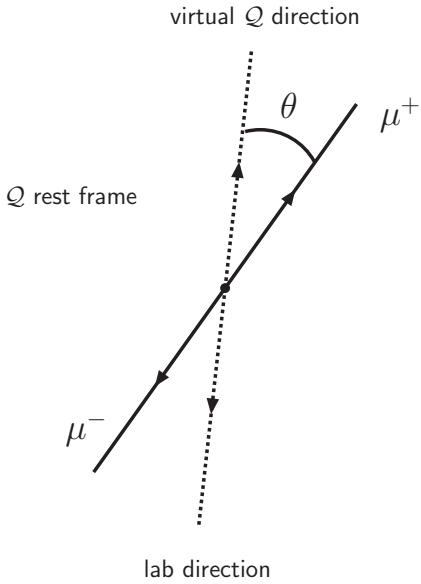
- Reconstruction, selection and trigger efficiencies required to obtain the cross sections, estimated using Monte Carlo

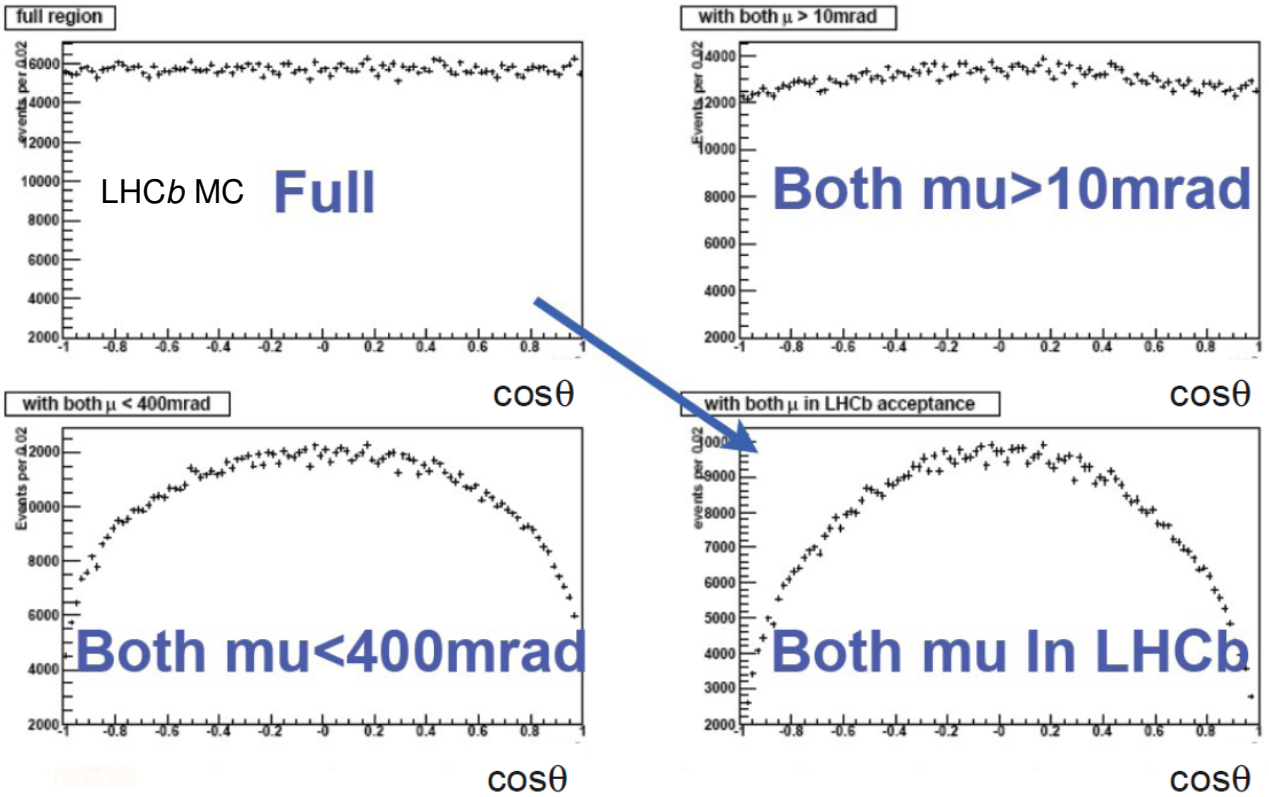


- Results (p_{T} in range 0-7 GeV, two μ in LHCb acceptance)
  - $\sigma(\text{prompt } J/\psi) \times \mathscr{B}(J/\psi \to \mu^+\mu^-) =$ $3104.2 \pm 2.2(\text{fit}) \pm 7.3(\text{efficiency})$ nb (input: 3102.0 nb)
  - $\sigma(J/\psi \text{ from } b) \times \mathscr{B}(J/\psi \to \mu^+\mu^-) =$ $233.6 \pm 1.7(\text{fit}) \pm 2.0(\text{efficiency})$ nb (input: 235.7 nb)

Systematics by J/ψ polarization

- Polarization, using helicity frame. Will also use Gottfried-Jackson (GJ) and Collins-Soper (CS) frames, as suggested.
  - $\frac{dN}{d\cos\theta} \propto 1 + \alpha\cos^2\theta$; ($\alpha = 1$, Transverse; $\alpha = -1$, Longitudinal)
- LHCb acceptance generates an artificial polarization





Systematics by J/ψ polarization (cont.)

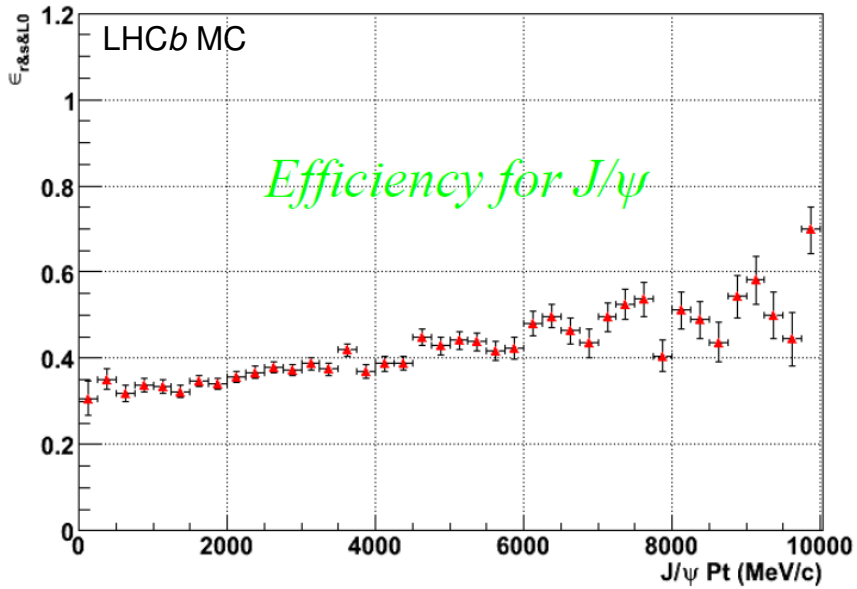
- Tevatron measurements disagree with theoretical predictions
  - Not possible to put correct polarization in Monte Carlo
- Systematic error up to 25% if ignoring polarization

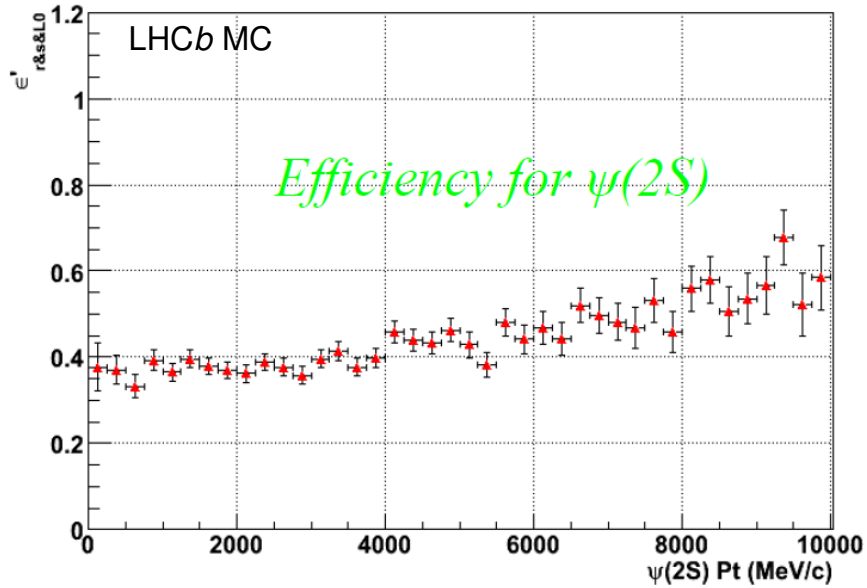
Input α	Input σ [nb]	Measured σ [nb] assuming $\alpha = 0$	Discrepancy
0	4340	4337.3 ± 7.7	—
+1 (T)	4909	4305.4 ± 7.7	-12%
-1 (L)	3518	4383.0 ± 7.9	+25%

- Working on measuring polarization and cross section simultaneously

$\psi(2S)$

- $\psi(2S) \to \mu^+\mu^-$ similar to $J/\psi \to \mu^+\mu^-$, yield about 2-4% of the J/ψ yield, lower S/B (1-2), similar mass resolution: 13 MeV/c^2.
- Goal is to measure $\sigma(\psi(2S))/\sigma(J/\psi)$, as a function of p_T, with separation of prompt $\psi(2S)$ from non-prompt $\psi(2S)$.
- Early measurement (most systematics cancelled), with precision of about 10%: $\frac{\varepsilon_{\text{rec\&sel\&L0}}(\psi(2S))}{\varepsilon_{\text{rec\&sel\&L0}}(J/\psi)} = 1.01 \pm 0.07(\text{stat.})$

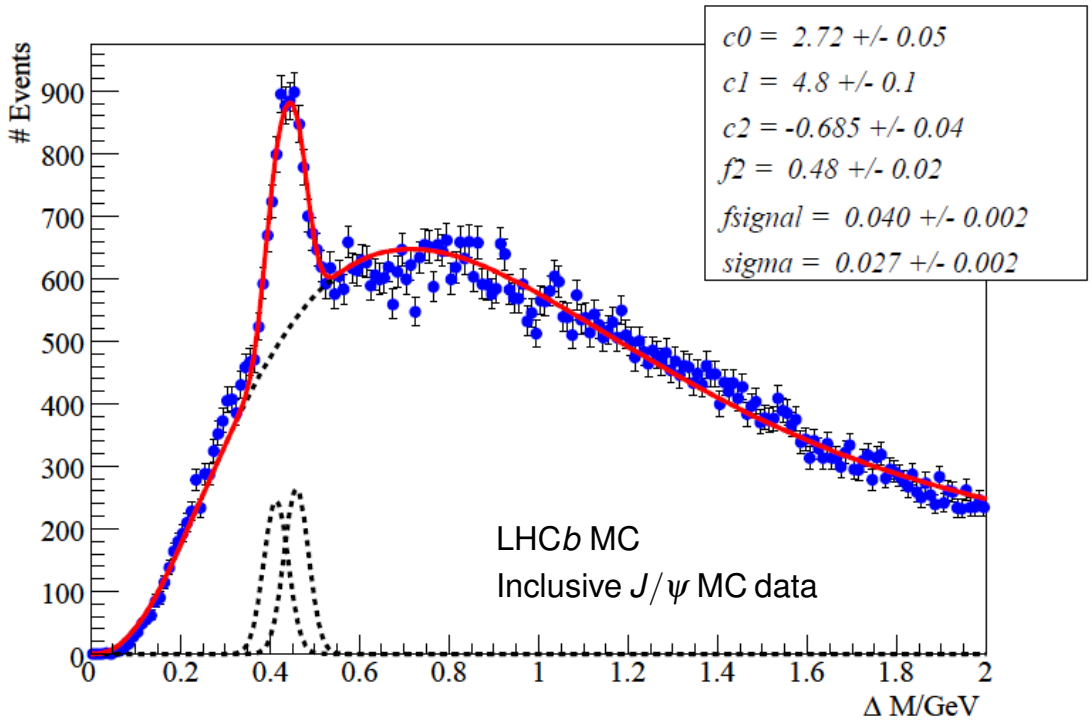




- Also complicated by the unknown polarization (systematics up to 22% on $\sigma(\psi(2S))/\sigma(J/\psi)$).

χ_c

- $\sim$ 30% of J/ψ come from $\chi_{c1,2} \to J/\psi\gamma$ [Tevatron measurements]. Important observables: fraction of J/ψ from $\chi_{c1,2}$, $R_{\chi_c} = \sigma(\chi_{c2})/\sigma(\chi_{c1})$
- J/ψ selection + $E_T(\gamma)$>500 MeV for $\chi_{c1,2} \to J/\psi\gamma$
- Plot $\Delta M = m(J/\psi\gamma) - m(J/\psi)$
  - Signal modelled as two Gaussians
  - Background: $P(\Delta M) = (\Delta M)^{c0} \cdot exp(-c1 \cdot \Delta M - c2 \cdot \Delta M^2)$
- $\sigma_m \sim 27$ MeV/c^2 [$M(\chi_{c2}) - M(\chi_{c1}) = 55$ MeV], some sensitivity to $\sigma(\chi_{c2})/\sigma(\chi_{c1})$



$h_c(1P)$

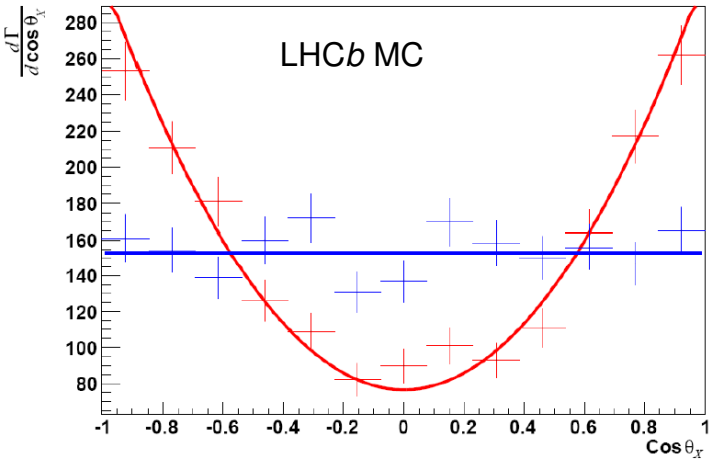
- Very limited experimental studies of the h_c decays.
  - Only $h_c \to \eta_c \gamma$ and $h_c \to 2(\pi^+\pi^-)\pi^0$ observed.
- At LHCb, $h_c \to \eta_c \gamma$ $(\eta_c \to \phi\phi)$ is difficult ($E_\gamma \sim 500$ MeV in the h_c rest frame)
  - will be covered in the nominal running
- Ongoing studies of hadronic channels, e.g., $h_c \to p\bar{p}$, $h_c \to \phi K^+ K^-$, $h_c \to \phi \pi^+ \pi^-$, ...
  - $h_c \to p\bar{p}$ probably accessible in 2010, improving trigger efficiency
- Simultaneous measurements of the $[J/\psi, \chi_{c0,1,2}, h_c] \to p\bar{p}$ ongoing:
  - Mass resolutions are about 10 MeV/c^2.
  - Will measure

$$\frac{\sigma(h_c) \times \mathscr{B}(h_c \to p\bar{p})}{\sigma(J/\psi) \times \mathscr{B}(J/\psi \to p\bar{p})}$$

    cross check from the measurements of $\frac{\sigma(\chi_{ci}) \times \mathscr{B}(\chi_{ci} \to p\bar{p})}{\sigma(J/\psi) \times \mathscr{B}(J/\psi \to p\bar{p})}$.
- Would be interesting to measure $\mathscr{B}(B^+ \to h_c K^+)$

$X(3872)$ and $Z(4430)^{\pm}$

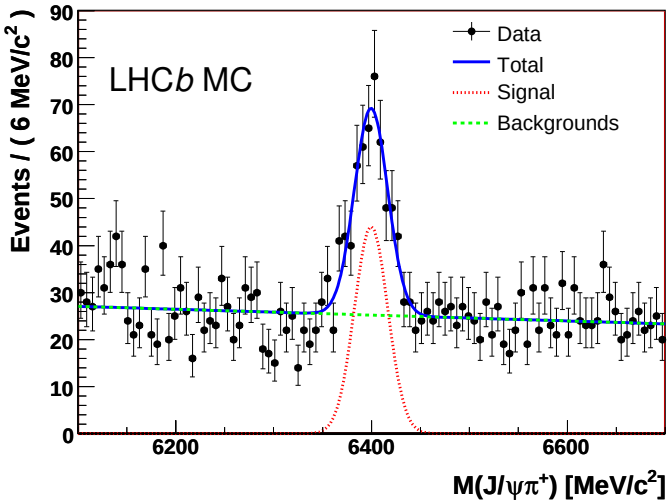
- At LHCb, large sample of prompt $X(3872) \to J/\psi\pi^+\pi^-$ (and the control channel $\psi(2S) \to J/\psi\pi^+\pi^-$) and $X(3872)$ from b decays make it possible to study $X(3872)$ systematically
  - About 1.8K $B^{\pm} \to X(3872)(\to J/\psi\pi^+\pi^-)K^{\pm}$ signal events can be selected from 2 fb^{-1} of data at $\sqrt{s}$ =14 TeV. Possible to disentangle unknown J^{PC}: $1^{++}/2^{-+}$



Expected distributions for 1^{++} and 2^{-+} hypotheses for 2 fb^{-1} of data. Generator level only, no detector simulation, no acceptance corrections yet!

- Similar studies for $B^0 \to Z(4430)^{\pm}(\to \psi(2S)\pi^{\pm})K^{\mp}$
  - About 6.2K signal events can be selected from 2 fb^{-1} of data at $\sqrt{s}$ =14 TeV assuming $\mathcal{B}(B^0 \to Z(4430)^{\pm}K^{\mp}) \times \mathcal{B}(Z(4430)^{\pm} \to \psi(2S)\pi^{\pm}) = 4.1 \times 10^{-5}$
  - Possible to confirm the Belle discovery with about 100 pb^{-1} of data at $\sqrt{s} = 7$ TeV if the $Z(4430)^{\pm}$ exists

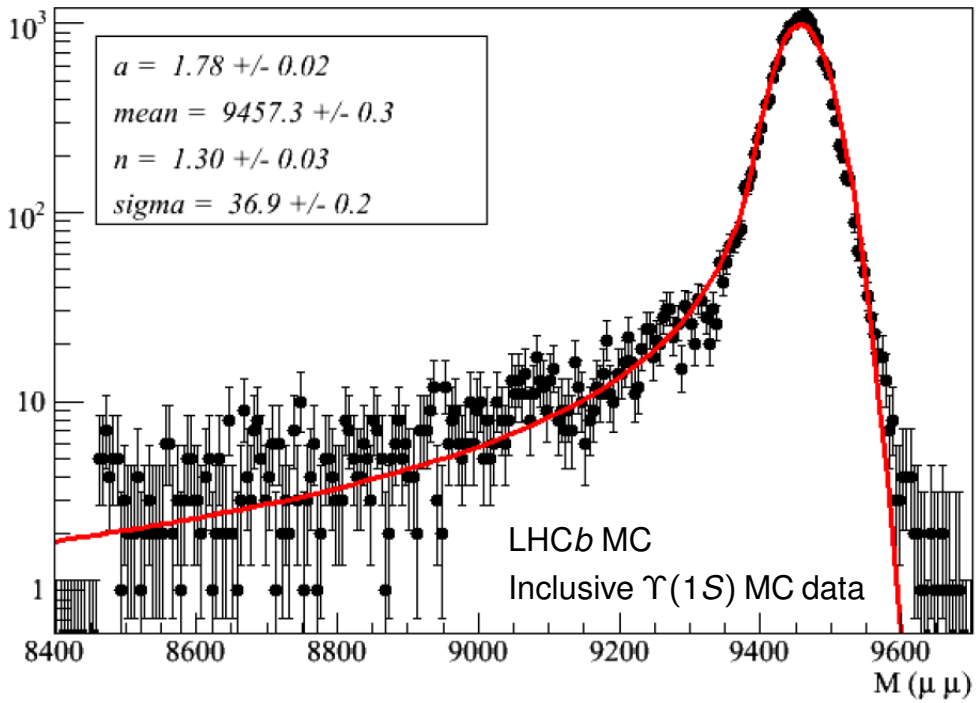
- $\sigma(B_c^+)_{\rm LHC}/\sigma(B_c^+)_{\rm Tevatron} \sim$ O(10)
- $B_c^{\pm} \to J/\psi(\mu^+\mu^-)\pi^{\pm}$
  - About 310 signal events can be selected from 1 fb^{-1} of data at $\sqrt{s} = 14$ TeV assuming $\sigma_{\rm tot}(B_c^{\pm}) = 0.4\ \mu$b and $\mathscr{B}(B_c^{\pm} \to J/\psi\pi^{\pm}) = 0.13\%$
  - Mass: ± 1.7 (stat.) MeV/c^2 (CDF: 2.9 (stat.) $\pm$ 2.5 (syst.) MeV/c^2)



  - Lifetime: ± 27 (stat.) fs. (D0: 38 (stat.) $\pm$ 32 (syst.) fs)
- $B_c^{\pm} \to J/\psi(\mu^+\mu^-)\mu^{\pm}X$
  - Signal yield one order of magnitude higher
  - Lifetime and production cross section measurements possible with 2010 data

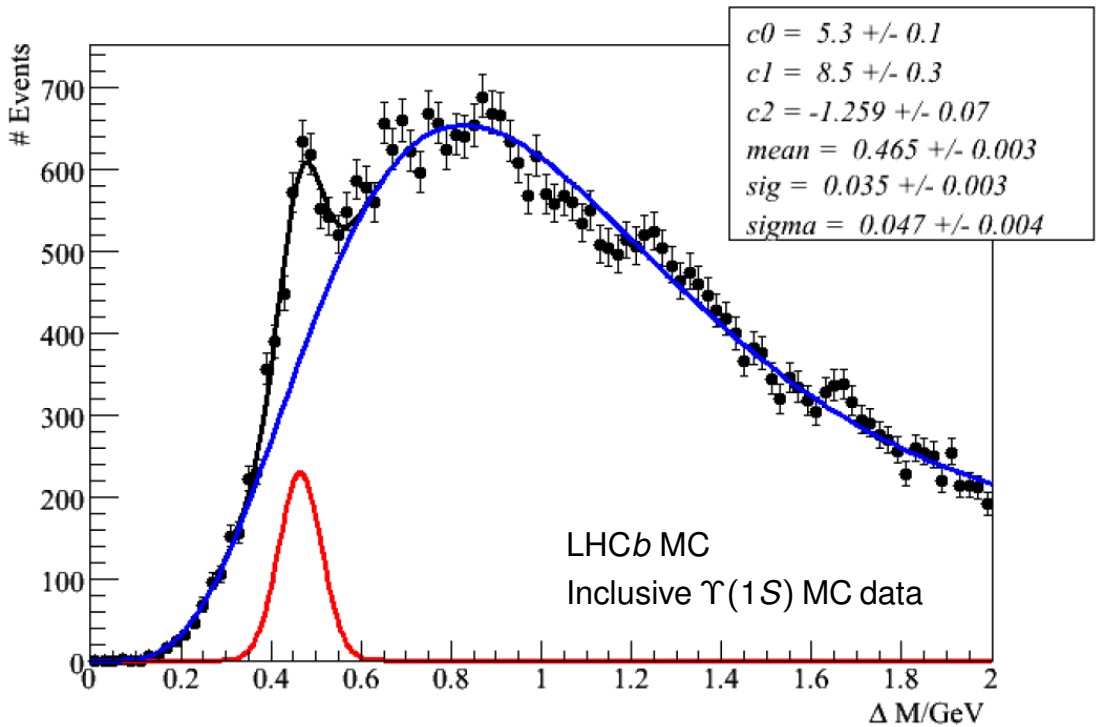
$\Upsilon(1S)$

- About 50% $\Upsilon(1S)$ produced directly, 40% $\Upsilon(1S)$ from the feed-down of $\chi_{b2}(1P)$
- $\Upsilon(1S) \rightarrow \mu^+\mu^-$ selection
  - Loose muon particle ID
  - $p_T(\mu) > 1.5$ GeV/c
- $\varepsilon(\mathrm{L0}) \sim 96\%$
- Mass resolution, about 37 MeV/c^2



$\chi_{b2}(1P)$

- About 40% of $\Upsilon(1S)$ is from the feed-down of $\chi_{b2}(1P) \rightarrow \Upsilon(1S)\gamma$.
- $\Upsilon(1S)$ selection + $E_{\mathrm{T}}(\gamma) > 500$ MeV
- Mass resolution: about 47 MeV/c^2.



Summary

- Many analysis of heavy quarkonia ongoing at the LHCb experiment.
- About 2.8M $J/\psi \to \mu^+\mu^-$ events can be selected from 5 pb^{-1} of data in the coming run ($\sqrt{s} = 7$ TeV), the production cross sections of prompt J/ψ and the J/ψ from b decays will be measured.
- Other studies will also be possible with 2010 data
  - $\psi(2S) \to \mu^+\mu^-$
  - $B^0 \to Z(4430)^{\pm}(\to \psi(2S)\pi^{\pm})K^{\mp}$
  - $B_c^{\pm} \to J/\psi\mu^{\pm}X$
  - $\Upsilon(1S) \to \mu^+\mu^-$
  - ...