Quarkonium at LHCb

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On behalf of LHCb

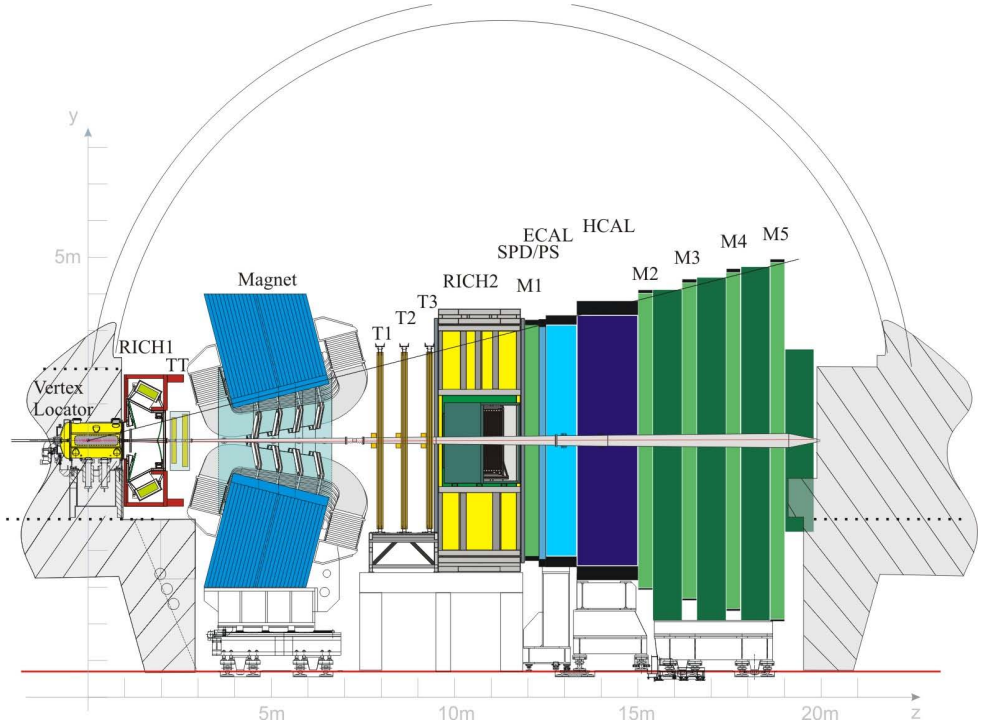
ReteQuarkonii workshop, Nantes, 25/10/2010

Outline:

- The LHCb experiment
- J/ψ production cross-section
- Future measurements
  - J/ψ production cross-section and polarization
  - $\psi(2S)$
  - $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$
  - χ_c
  - $X(3872)$
- Conclusion

The LHCb experiment:

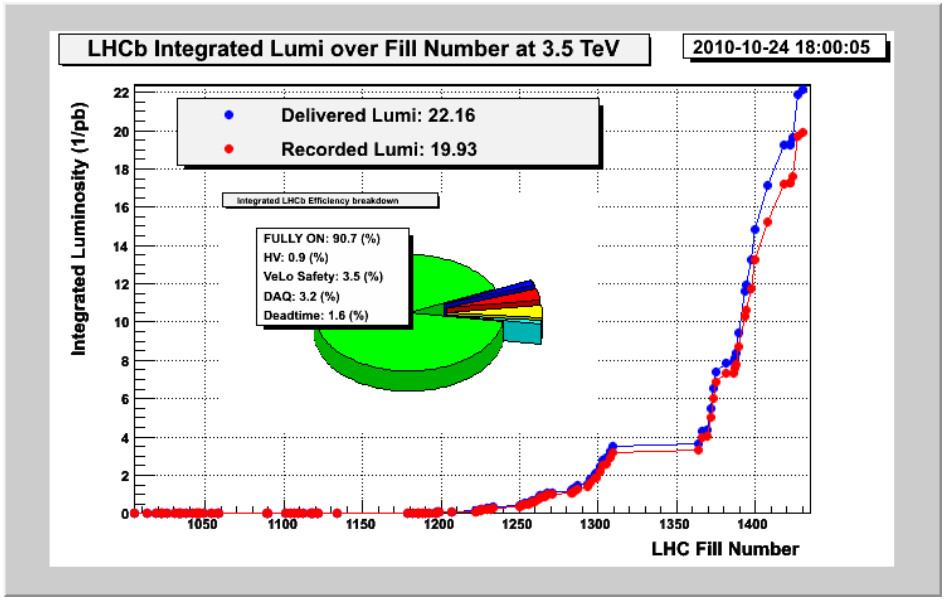
- Forward single arm spectrometer: large and correlated $b\bar{b}$ quark production in the forward region
- Coverage : 15-300 mrad



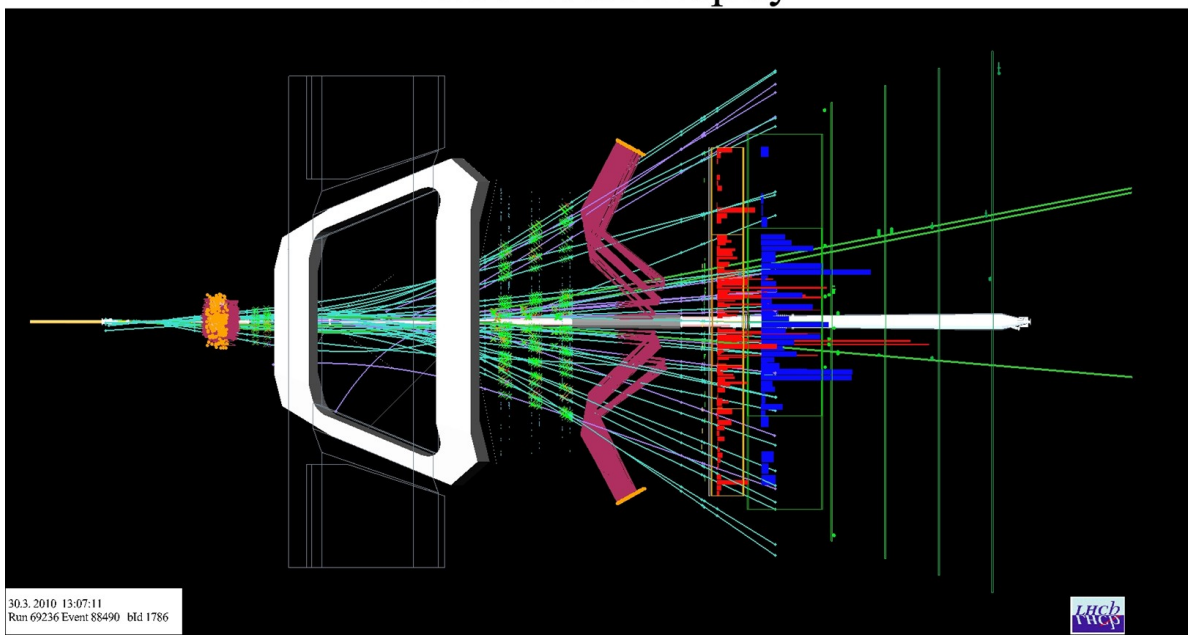
- Mainly dedicated to b-physics:
  - **CP violation** studies, measurement of the CKM mass mixing matrix parameters
  - **Rare decays**: e.g. $B_s \to \mu\mu$ decay channel studies, may reveal physics beyond the Standard Model
  - **Flavour physics**: J/ψ, $\psi(2S)$ production and polarization, X, Y, Z spectroscopy...

Status:

- LHCb is in good shape:
  - 19.93 pb^{-1} of data at $\sqrt{s} = 7$ TeV have been recorded
  - $\sim 90\%$ of the delivered luminosity has been recorded



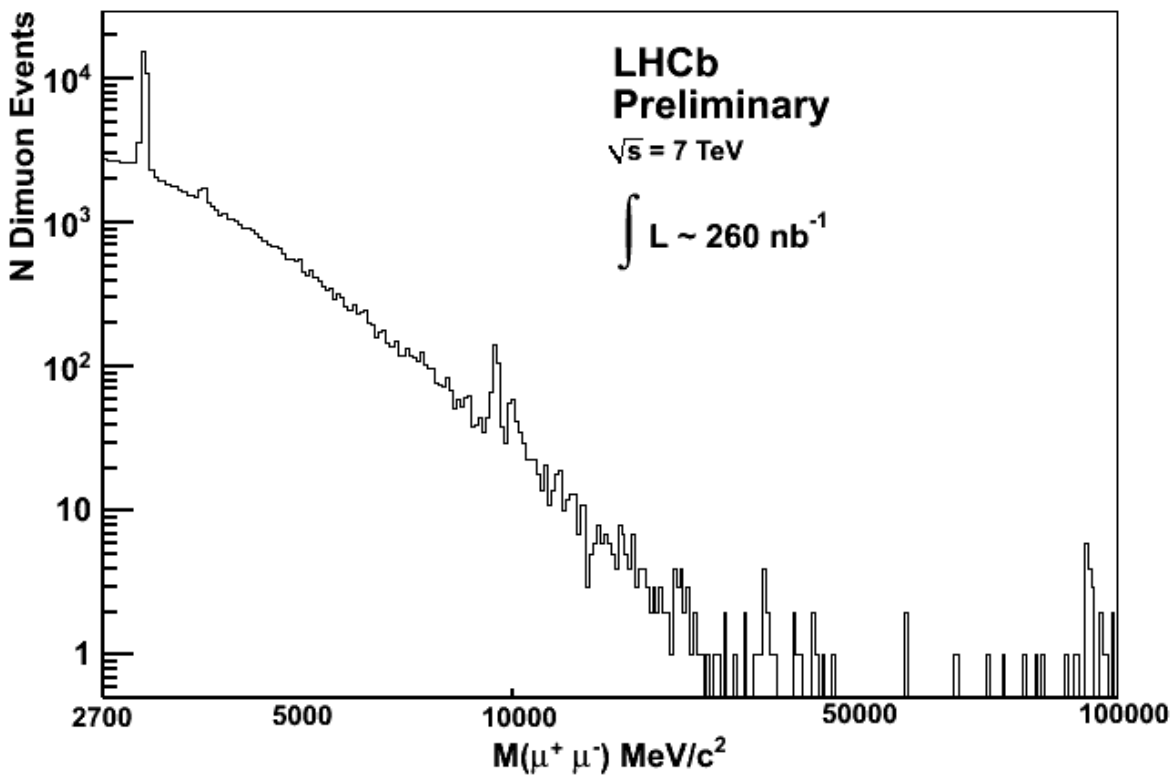
LHCb Event Display



Event at $\sqrt{s} = 7$ TeV, March 2010

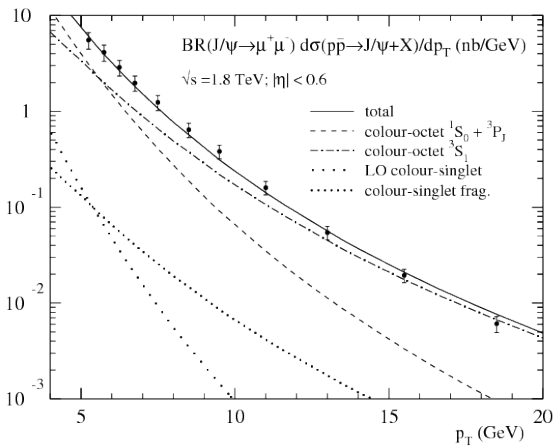
J/ψ production cross-section:

- Many J/ψ are produced at LHCb, from three different sources:
  - Prompt J/ψ:
    - Direct production in pp collisions
    - Feed down from other charmonium states ($\psi(2S)$, χ_c...)
  - J/ψ from b:
    - Decays from b-hadrons

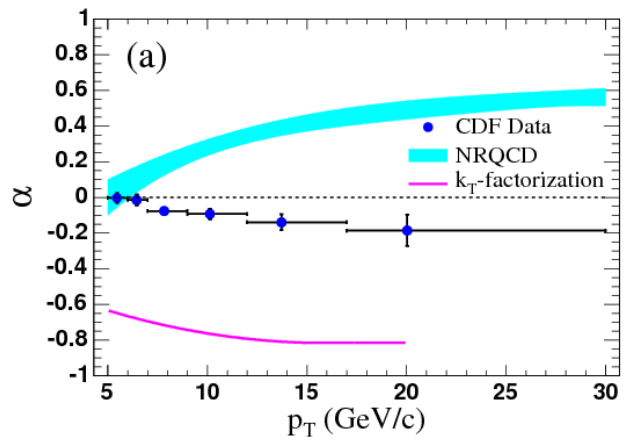


J/ψ production cross-section:

- The J/ψ production cross-section is an important measurement:
  - The prompt cross-section is not well understood: the color-octet model used to fit CDF results does not decribe the J/ψ polarization
  - LHCb will measure new region of the transverse momentum (p_T) and rapidity (y) phase space (high y and low p_T)
  - $b \to J/\psi X$ or di-muon studies are very important modes for LHCb's physics program



Colour-singlet and colour-octet contributions to direct J/ψ production at the Tevatron compared to experimental data from CDF; Krämer (2001), arXiv:hep-ph/0106120



Prompt J/ψ polarization as a function of p_T; CDF collaboration (2007), arXiv:0704.063

Selection:

- Trigger:
  - Level 0 trigger (L0): require one muon, with $p_T(\mu) > 320$ MeV/c
  - High Level Trigger (HLT): confirms the L0 muon and add a $p_T > 1.3$ GeV/c cut or a second muon with $M_{\mu\mu} > 2500$ MeV/c^2
- For the offline selection, we require two muons:
  - With opposite charges
  - Fully reconstructed tracks (Velo + Tracker)
  - Identified by the muon system (hits in the muon stations)
  - At least one primary vertex
  - A good common vertex
  - $p_T(\mu) > 700$ Mev/c

J/ψ production cross-section:

- The cross section as been measured as a function of p_T for ICHEP with a 14.2 nb^{-1} data sample with low pile up conditions (CERN-LHCb-CONF-2010-010)
- Production cross-section for prompt J/ψ and J/ψ from b:

$$\sigma = \frac{N(J/\psi \to \mu\mu)}{L \times \epsilon \times B(J/\psi \to \mu\mu)}$$

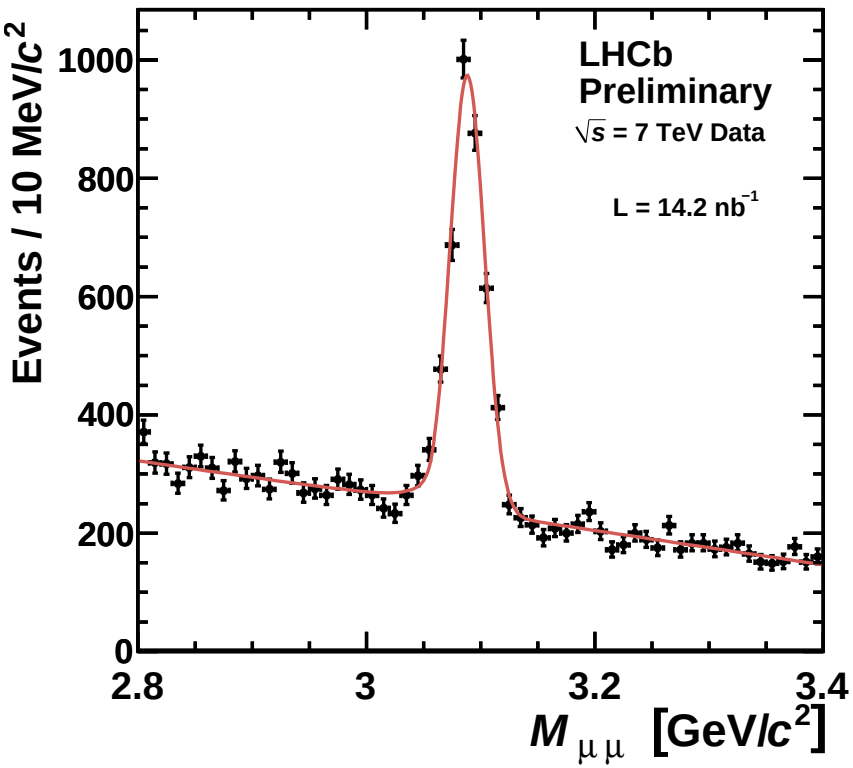
  - N: number of observed $J/\psi \to \mu\mu$
  - $\epsilon = \epsilon_{acc} \times \epsilon_{rec} \times \epsilon_{trig}$: J/ψ detection efficiencies, taken from Monte Carlo simulations
  - $B(J/\psi \to \mu\mu) = (5.93 \pm 0.06) \times 10^{-2}$, the $J/\psi \to \mu\mu$ branching fraction.
- This leads to the measurement, for $p_T < 10$ Gev/c (10 bins) and $2.5 < y < 4$ (1 bin), of:
  - σ(inclusive J/ψ)
  - $\sigma(b \to J/\psi)$

J/ψ invariant mass fit:

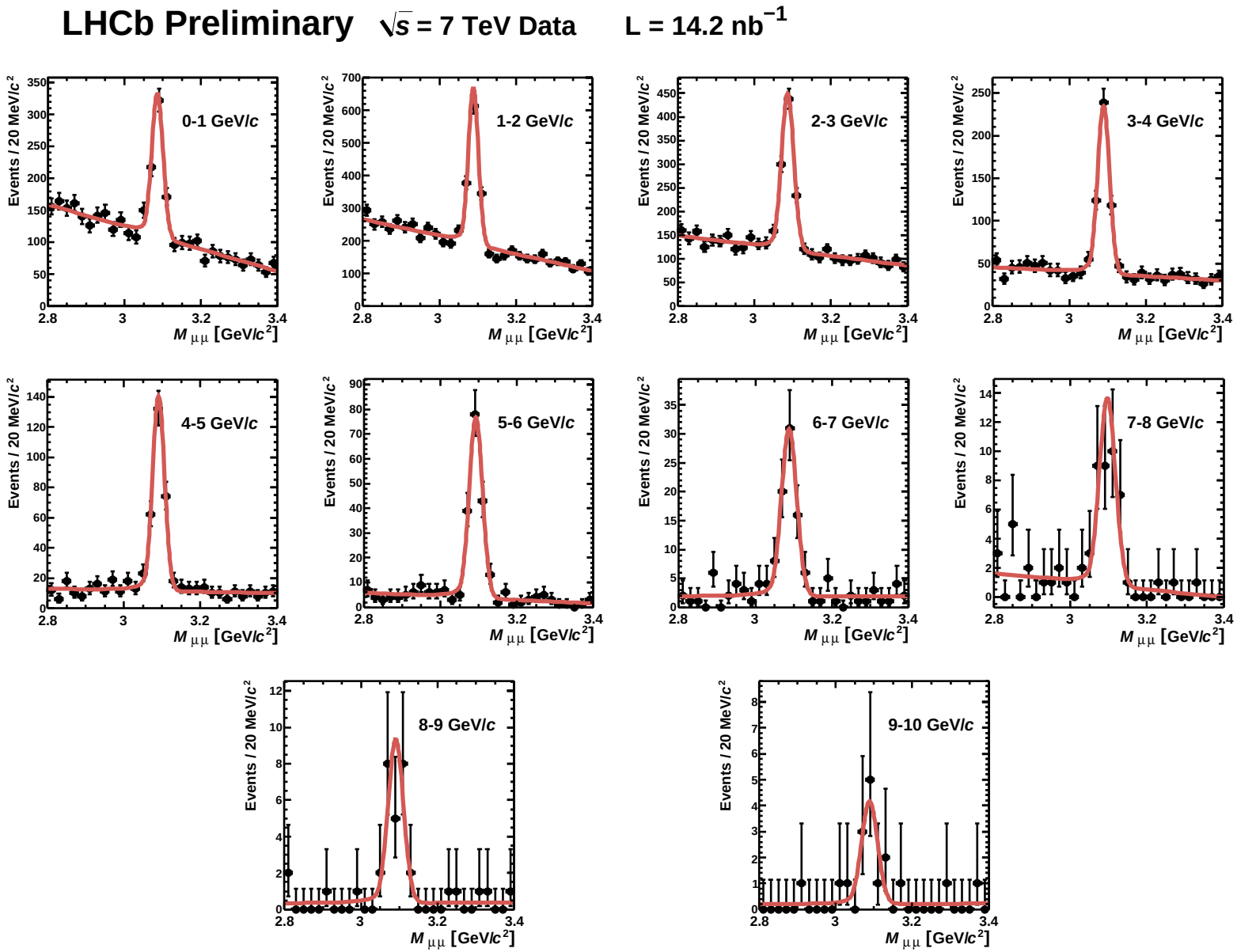
- Crystall Ball function for the signal and a first order polynomial for background:

$$f(x;\mu,\sigma_{\mathrm{M}},\alpha,n) = \begin{cases} \dfrac{\left(\frac{n}{|\alpha|}\right)^n e^{-\frac{1}{2}\alpha^2}}{\left(\frac{n}{|\alpha|} - |\alpha| - \frac{x-\mu}{\sigma_{\mathrm{M}}}\right)^n} & \dfrac{x-\mu}{\sigma_{\mathrm{M}}} < -|\alpha| \\ \exp\left(-\dfrac{1}{2}\left(\dfrac{x-\mu}{\sigma_{\mathrm{M}}}\right)^2\right) & \dfrac{x-\mu}{\sigma_{\mathrm{M}}} > -|\alpha| \end{cases}$$

- Fit results:
  - $m = 3088 \pm 0.4$ MeV$/c^2$
  - $\sigma = 15.0 \pm 0.4$ MeV$/c^2$
  - $N_{sig} = 2872 \pm 73$
  - $S/B = 1.3$ (in a 3σ mass window around the fitted J/ψ mass)



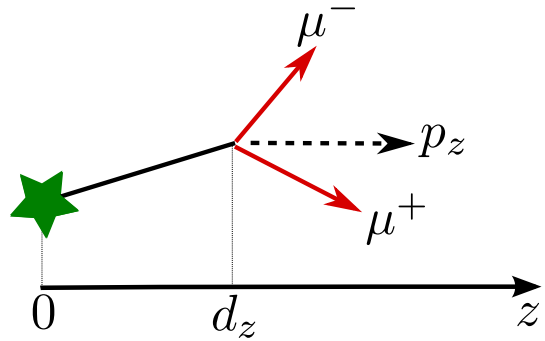
Mass fit in p_T bins:



Distinction between prompt J/ψ and J/ψ from b:

To distinguish prompt J/ψ from $b \to J/\psi$ decays, we use the pseudo-proper time t_z:

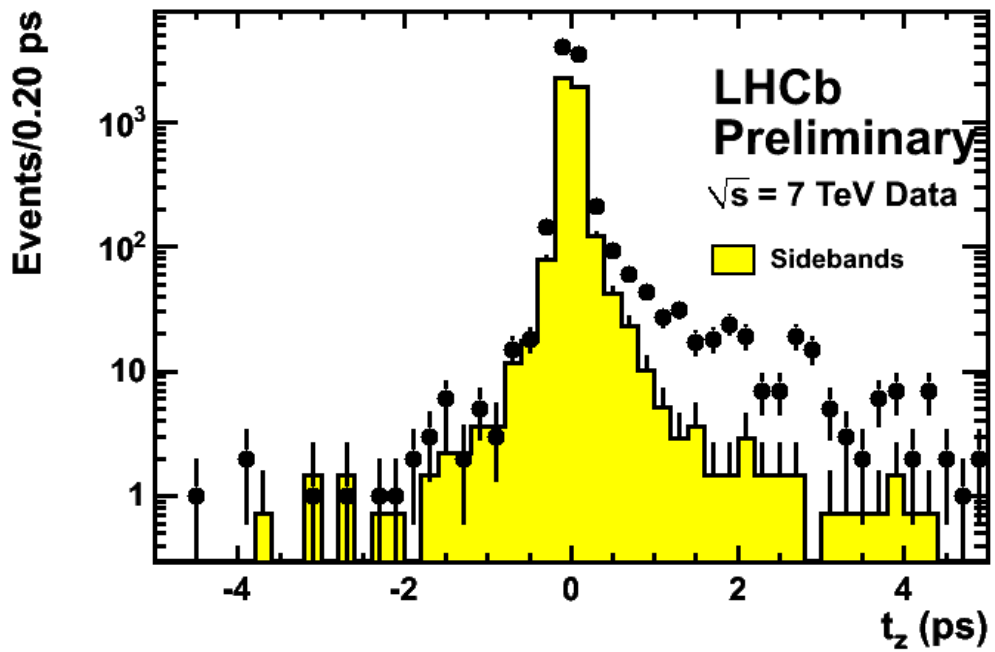
$$t_z(J/\psi) = \frac{d_z \times M_{J/\psi}}{p_z}$$



d_z: distance between primary and secondary vertex along z-axis

p_z: J/ψ momentum along z-axis

- Non-J/ψ combinatorial background:
  - Obtained from upper mass sidebands
    ($M_{J/\psi} \in [3150 - 3500]$ MeV/c^2)
  - Asymmetric tails (include tracks from secondary vertices)
- J/ψ signal:
  - Peak is prompt J/ψ
  - Exponential component from $b \to J/\psi$

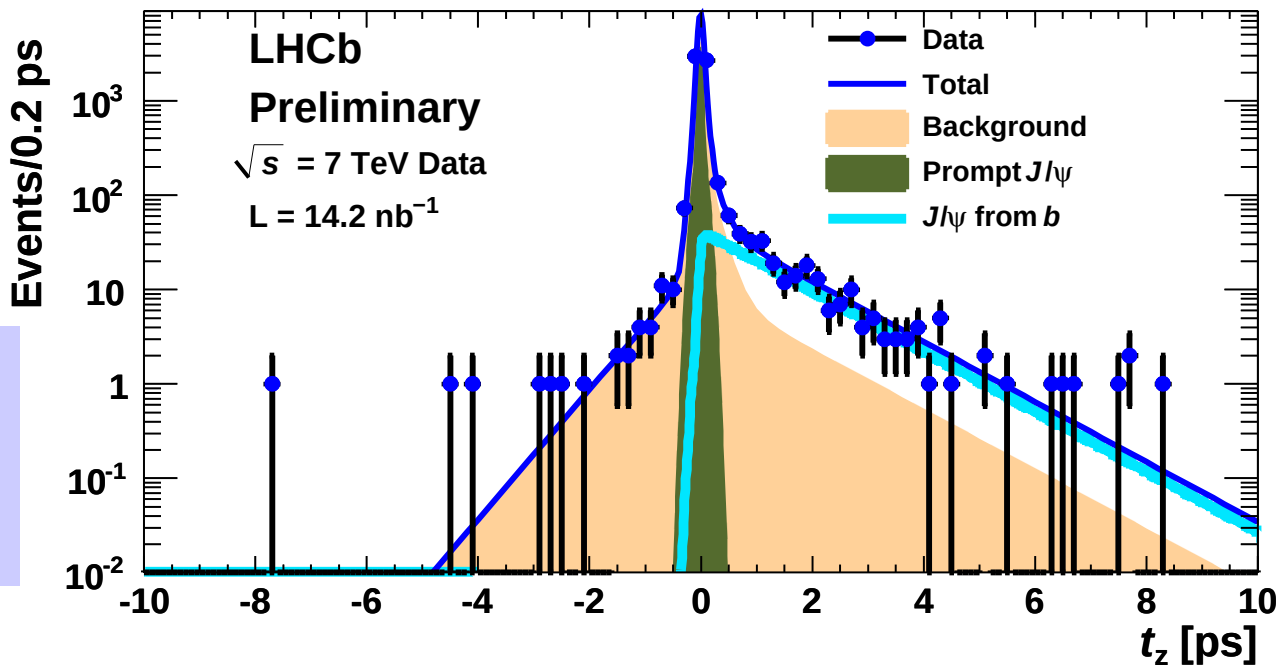


Fit results:

- Sidebands and signal distributions are fitted to extract the fraction f_b of J/ψ from b
- The fit is done on the full data sample
- n_p and n_b: number of prompt J/ψ and J/ψ from b.
- τ_b: pseudo b lifetime.

- $n_p = 2527 \pm 74$
- $n_b = 316 \pm 24$
- $\tau_b = 1.35 \pm 0.10$ ps

$$f_b = \frac{n_b}{n_b + n_p} = (11.1 \pm 0.8)\%$$



Efficiencies ϵ:

- Acceptance efficiency:

$$\epsilon_{acc} = \frac{J/\psi \text{ with both } \mu \text{ in LHCb}}{\text{generated } J/\psi \to \mu\mu}$$

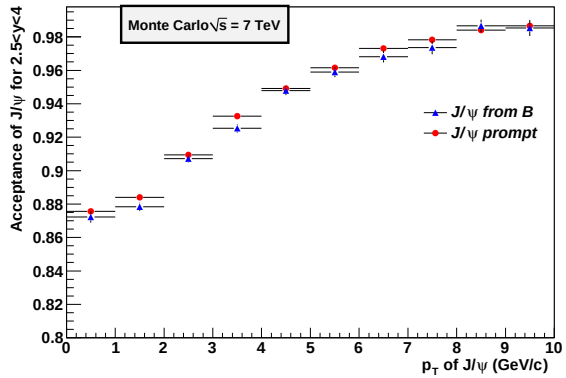
- Reconstruction efficiency:

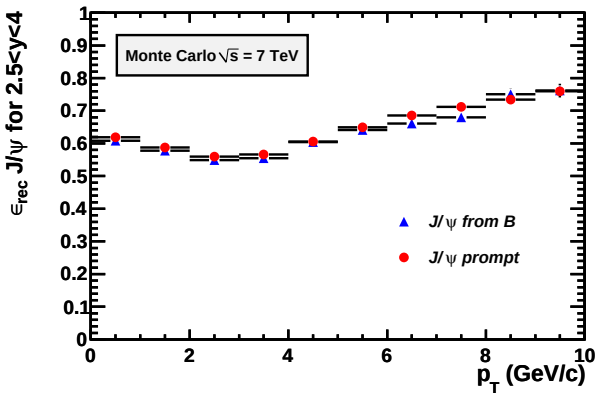
$$\epsilon_{rec} = \frac{\text{reconstructed } J/\psi}{J/\psi \text{ with both } \mu \text{ in LHCb}}$$

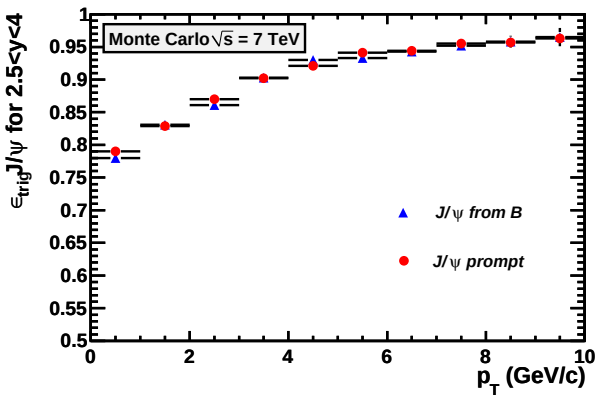
- Trigger efficiency:

$$\epsilon_{trig} = \frac{\text{triggered } J/\psi}{\text{reconstructed } J/\psi}$$

All efficiencies for prompt J/ψ and $b \to J/\psi$ are the same within 1% in each p_T bin

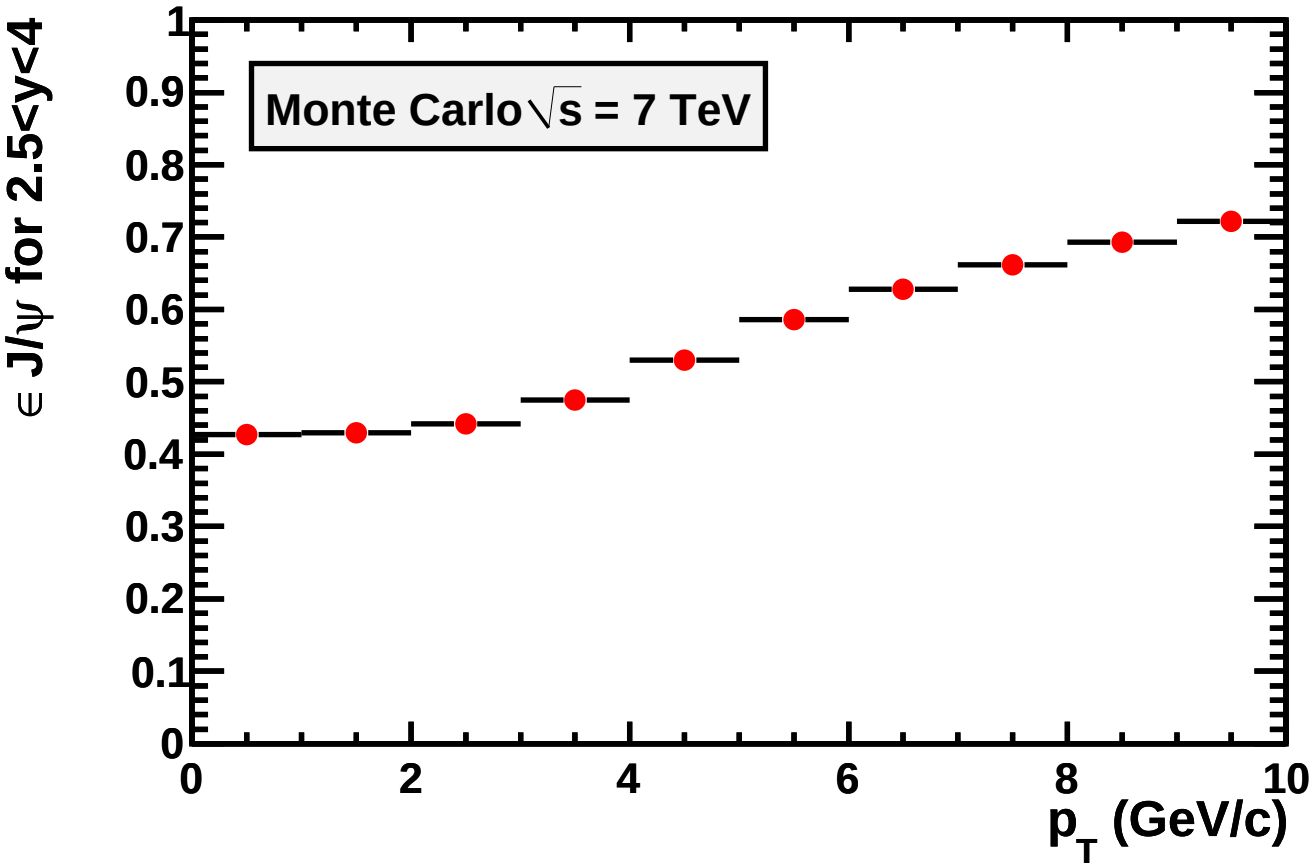






Total efficiency:

- $\epsilon_{tot} = \epsilon_{acc} \times \epsilon_{rec} \times \epsilon_{trig}$



J/ψ polarization:

The angular distribution depends of the polarization:

$$\frac{dN}{d\cos\theta} = \frac{1+\alpha\cos^2\theta}{2+2\alpha/3}, \text{ where } \alpha = \begin{cases} +1 & \text{fully transverse} \\ -1 & \text{fully longitudinal} \\ 0 & \text{no polarization} \end{cases}$$

θ is the angle between the direction of the μ^+ momentum in the J/ψ centre-of-mass frame and the direction of the J/ψ momentum in the laboratory frame

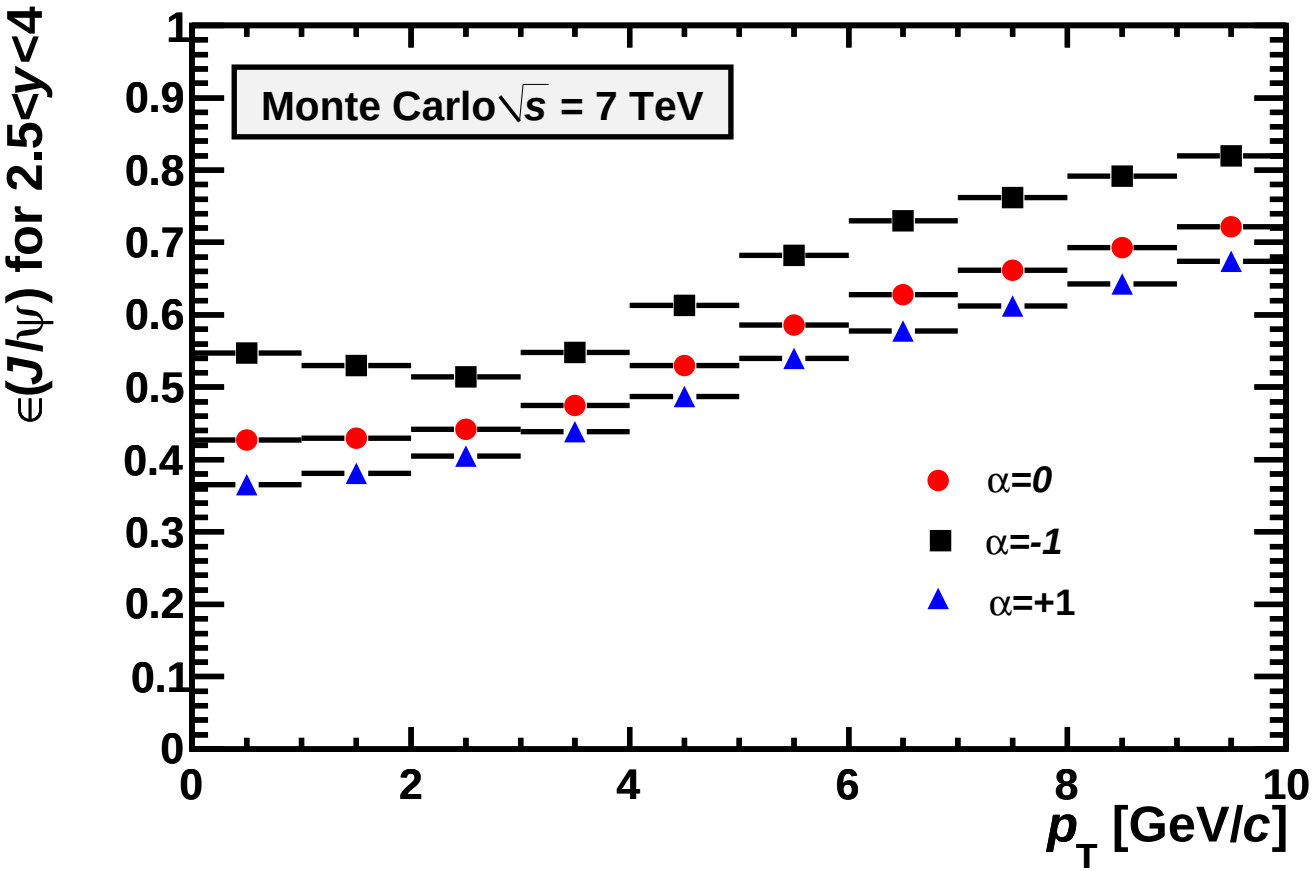
- Polarization affect the acceptance up to 20% depending on the p_T, y bin.

Strong effect on the efficiency

- The cross-section is measured for 3 values of α; difference is quoted as a systematic error.

J/ψ polarization:

- $\epsilon_{tot} = \epsilon_{acc} \times \epsilon_{rec} \times \epsilon_{trig}$



The total efficiency depends on the assumed polarization!

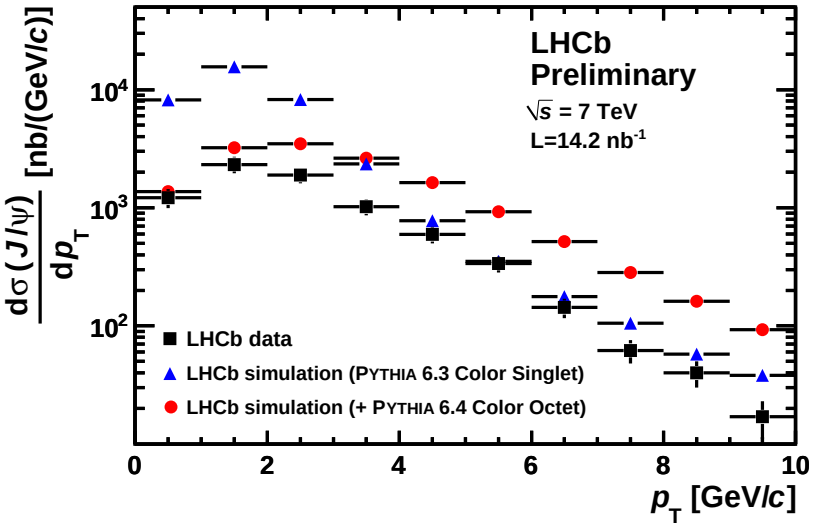
Systematics uncertainties:

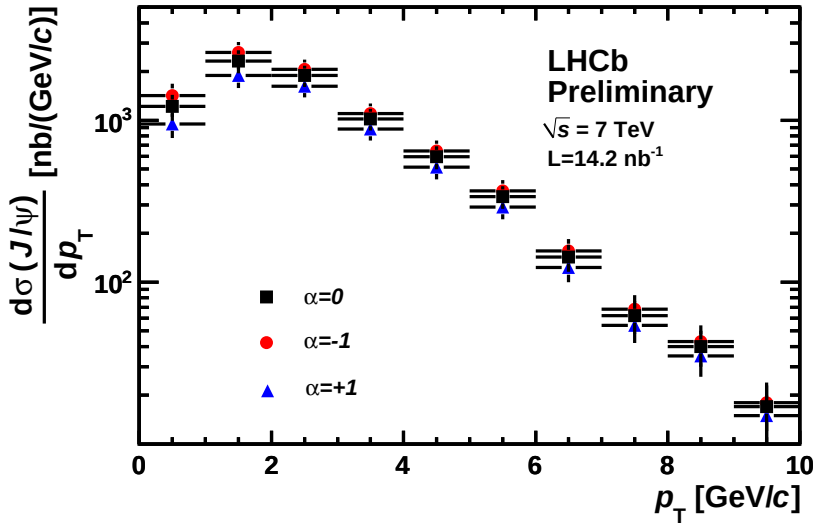
Quantity	Systematic error	Comment
Trigger	2.8 % to 9.4 %	Correlated between bins
Muon identification	2.5%	Correlated between bins
Tracking efficiency	8%	Correlated between bins
Track χ^2	2%	Correlated between bins
Vertexing	1%	Correlated between bins
Bin size	1.3% to 3.9%	Bin dependent
Inter-bin cross-feed	0.5%	Correlated between bins (not applied to the total cross-section)
Loss of events due to the radiative tail	1%	Correlated between bins
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	1%	Correlated between bins
Luminosity	10%	Correlated between bins
b momentum spectrum	4 %	Applies only to J/ψ from b cross-section
b hadronization fractions	2%	Applies only to extrapolations of $b\bar{b}$ cross-section.
$\mathcal{B}(b \to J/\psi X)$	9%	Applies only to extrapolations of $b\bar{b}$ cross-section

assuming non polarized J/ψ

- Main sources of systematic errors:
  - Differences between data and MC (trigger and tracking efficiencies)
  - Uncertainty on the integrated luminosity
  - Additional systematic uncertainties from f_b (fraction of $b \to J/\psi$) dependence on p_T

Results (1):





For $p_T < 10$ GeV/c and $2.5 < y < 4$:

- $\sigma(pp \to J/\psi X) = 7.63 \pm \underbrace{0.19}_{\text{statistical}} \pm \overbrace{1.10}^{\text{systematics}} \underbrace{{}^{+0.87}_{-1.27}}_{\text{polarization}}$ μb
- $\sigma(J/\psi \text{ from } b) = 0.81 \pm 0.06 \pm 0.13$ μb
- Measurements are shown with inclusive J/ψ cross-section obtained with 2 LHCb Pythia tunings used for Monte Carlo productions: LO Color Singlet and NRQCD, tuned to CDF data

Results (2):

- Extrapolation with Pythia 6.4 and EvtGen, of the total $b\bar{b}$ cross section:

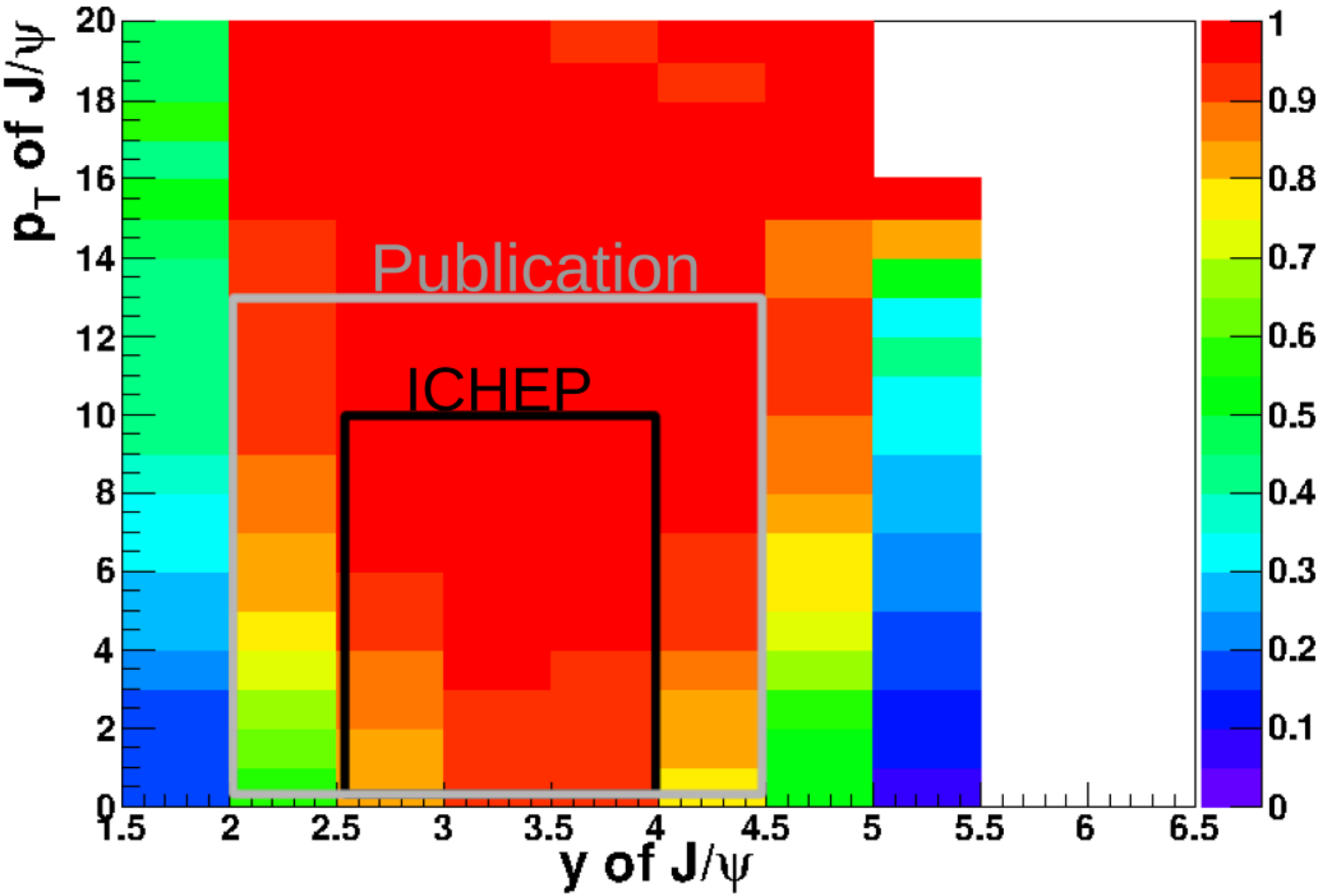
$$\sigma(pp \to b\bar{b}X) = 319 \pm 24 \pm 59 \ \mu\text{b}$$

- b-flavoured measured cross-sections is consistent with theoretical predictions and other LHCb measurement ($\sigma(pp \to b\bar{b}X)$ from $b \to D_0\mu\nu X$, arXiv:1009.2731).
- See Alexandr Kozlinskiy's talk on open heavy flavour for more details (Thursday at 9:40).

J/ψ production cross-section: prospects

- A new cross-section measurement, as a function of y ($2 < y < 4.5$; 5 bins) and p_T ($p_T < 13$ MeV/c; 13 bins), will be done with $\sim$5 pb^{-1} of data collected in september 2010 for a publication
  - running with higher pile-up than nominal LHCb conditions since July. Require adaptation of settings (trigger, fits...)
  - the fraction f_B of number of $b \to J/\psi$ will be measured in each bin
  - systematics uncertainties will be reduced
- The prompt J/ψ and $b \to J/\psi$ polarizations will be measured in bins of p_T and y

Phase spaces:

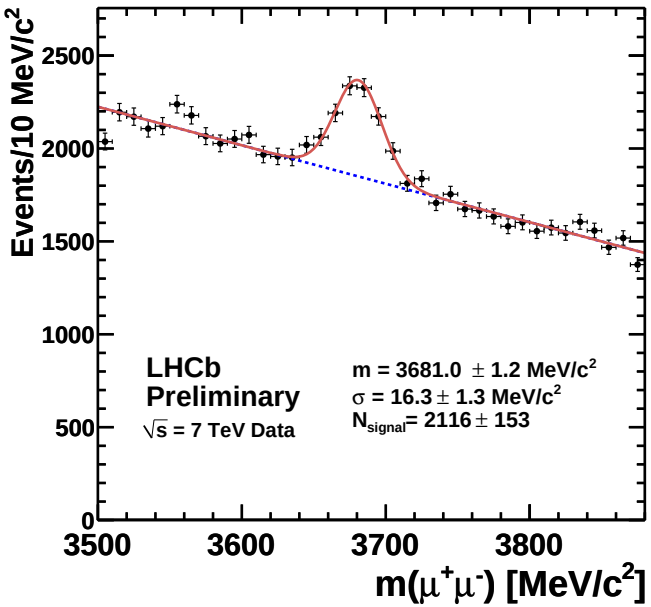


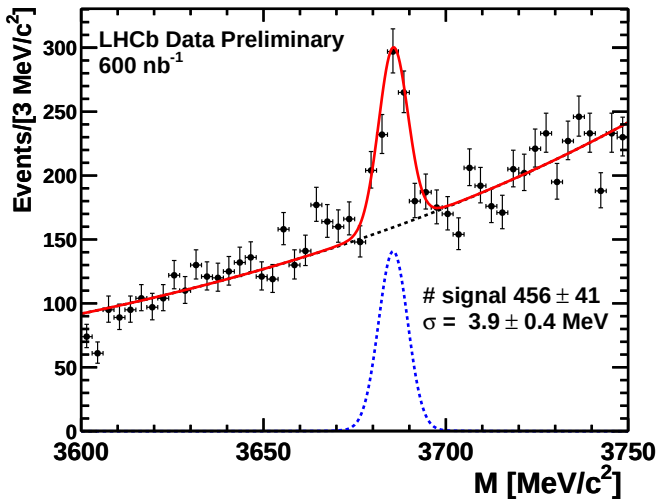
A larger phase space will be studied in the publication

$\psi(2S)$:

- Two different channels are studied:

$$\psi(2S) \to \mu\mu \text{ and } \psi(2S) \to J/\psi\pi\pi$$

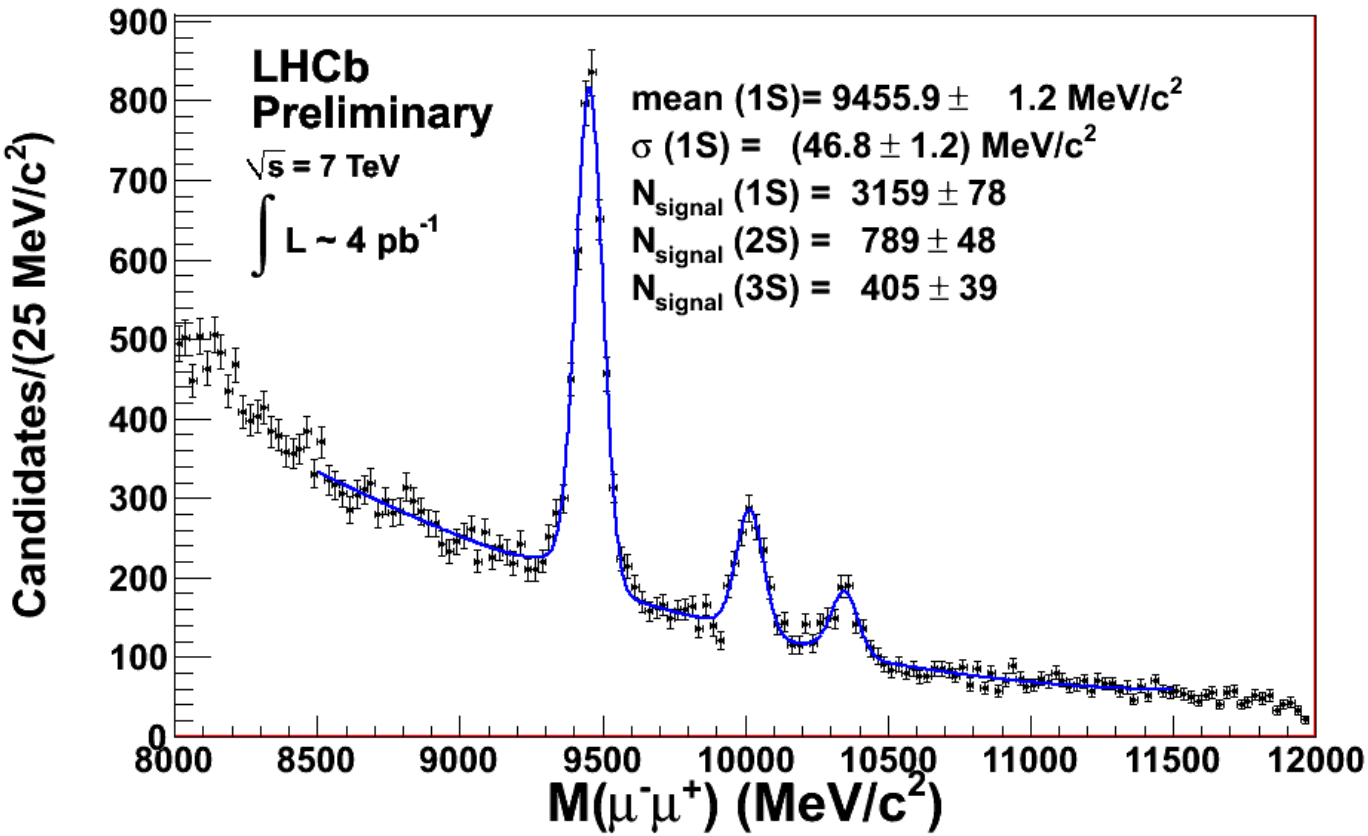




- $\psi(2S)$ suffers less from heavier charmonium feed down than J/ψ. The production cross-section is easier to interpret.
- When enough statistics will be available, the polarization and the production cross-section in bins of p_T and y will be measured for both prompt $\psi(2S)$ and $b \to \psi(2S)$

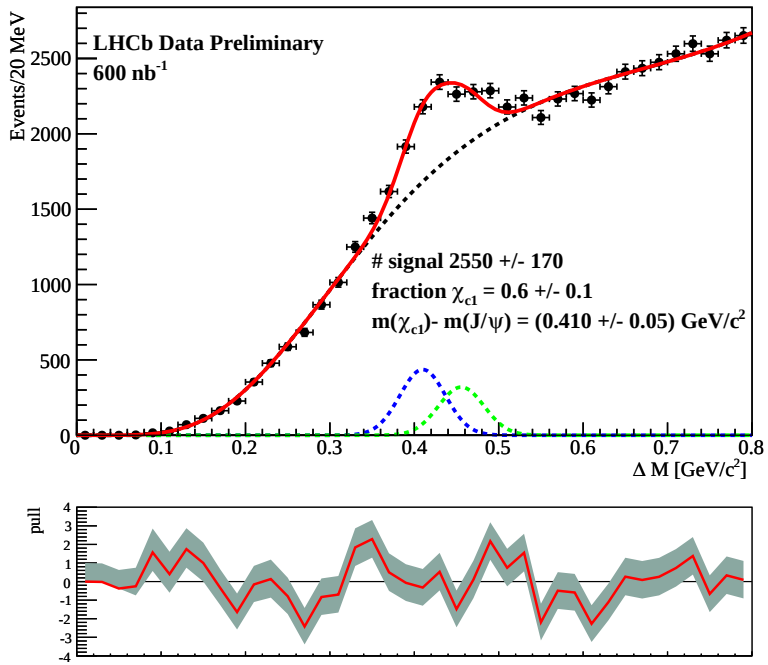
$\Upsilon \to \mu\mu$:

- The three states are well separated
- The production cross-section in bins of p_T and y will be measured for winter conferences
- A polarization measurement will also be made



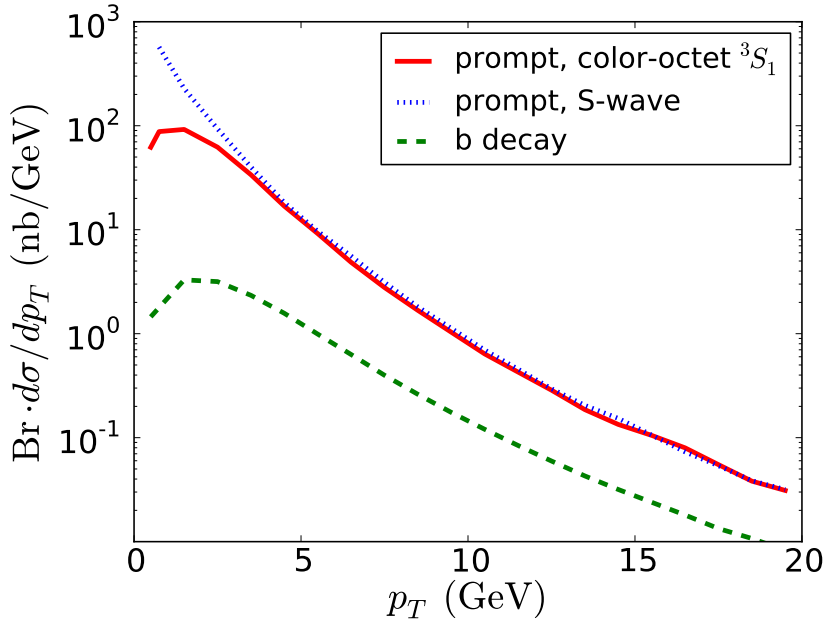
$\chi_c \to J/\psi\gamma$:

- χ_{c1} and χ_{c2} are two important sources of J/ψ: $\sim 30\%$ of J/ψ are feed down from χ_c
- To interpret correctly the J/ψ production cross-section, $\sigma(\chi_{c1}) + \sigma(\chi_{c2})/\sigma(J/\psi)$ will be measured in bins of p_T



$X(3872) \to J/\psi\pi\pi$:

- ~ 290 signal events are expected from $B^{\pm} \to XK^{\pm}$ meson decay for $L = 1$ fb^{-1} (from a 2008 Monte Carlo analysis).
- Prompt production signal is expected to be more important than the b-decay production.



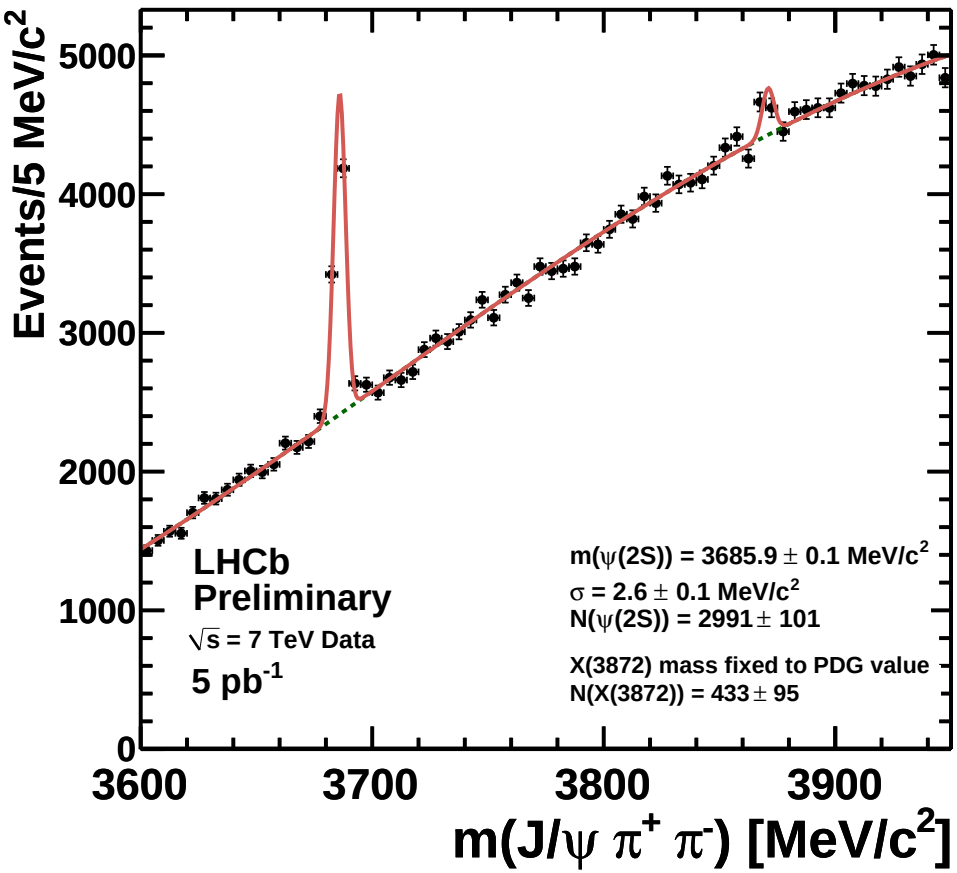
Theoretical $X \to J/\psi\pi\pi$ cross-sectionin pp collisions at $\sqrt{s} = 7$ TeV. P. Artoisenet et al. arXiv:0911.2016v1.

$X(3872) \to J/\psi\pi\pi$:

- $X(3872)$ mass is fixed to PDG value:

  $M_{X(3872)} = 3871.56 \pm 0.2$ MeV/c^2

- The mass will be the first measurement to be done when a $O(0.1)$ MeV/c^2 statistical uncertainty will be obtained



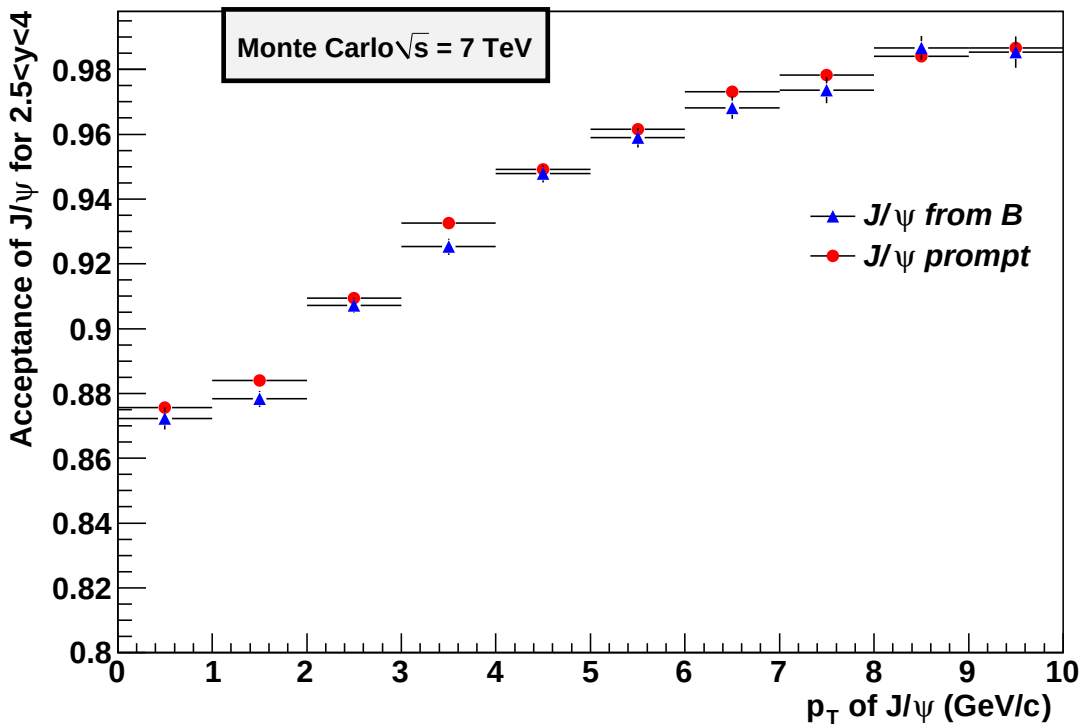
Conclusion:

- LHCb quarkonia physics program is rich and promising
- Preliminary measurement of the J/ψ differential production cross-section performed with first 14.2 nb^{-1}
- A new analysis with a larger data sample is being done
- Exciting results are expected for $\psi(2S)$, Υ, χ_c and $X(3872)$ at the winter conferences

BACKUP SLIDES

BACKUP; Detector acceptance ϵ_{acc}:

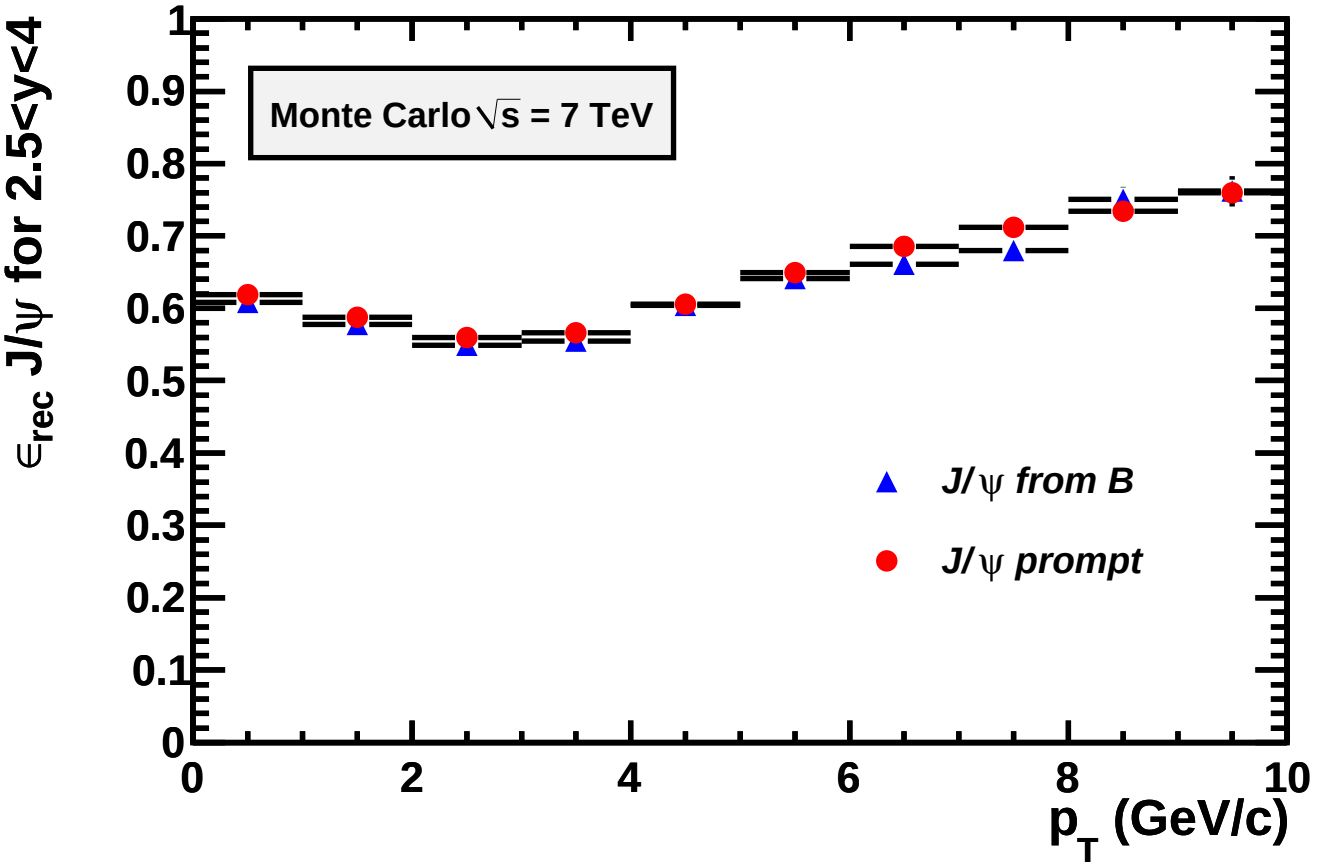
- $\epsilon_{acc} = \frac{J/\psi \text{ with both } \mu \text{ in LHCb}}{\text{generated } J/\psi \to \mu\mu}$ (i.e. the momentum direction of each muon is required to be in [10, 400]mrad before the magnet)
- Extracted from Monte Carlo.



Acceptance for prompt J/ψ and $b \to J/\psi$ are the same within 1%

BACKUP; Reconstruction efficiency ϵ_{rec}:

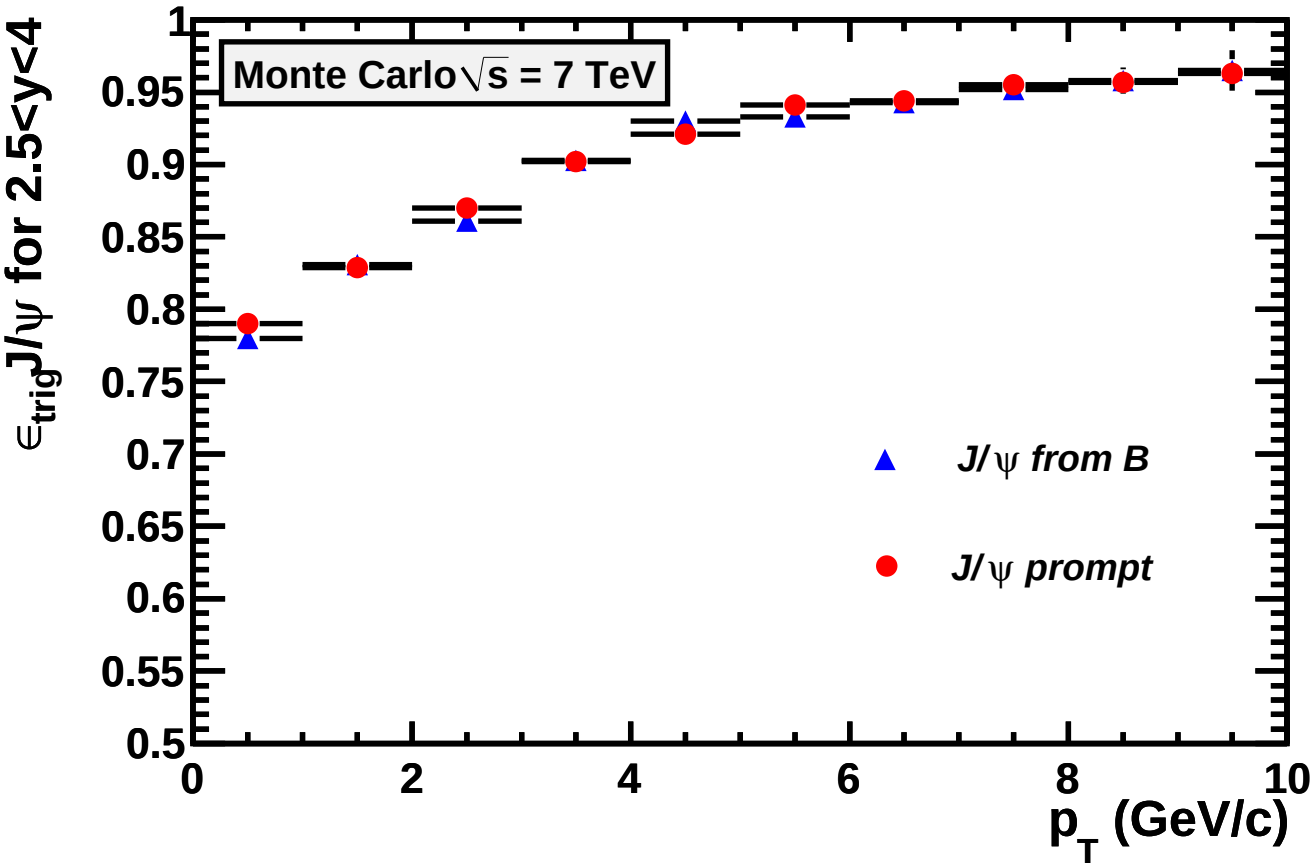
- $\epsilon_{rec} = \frac{\text{reconstructed } J/\psi}{J/\psi \text{ with both } \mu \text{ in LHCb}}$



Reconstruction efficiencies for prompt J/ψ and $b \to J/\psi$ are the same within 1% in each p_T bin

BACKUP; Trigger efficiency ϵ_{trig}:

- $\epsilon_{trig} = \frac{\text{triggered } J/\psi}{\text{reconstructed } J/\psi}$



Trigger efficiency (L0 $\times$ HLT1) is the same for prompt J/ψ and $b \to J/\psi$

BACKUP; $B^{\pm} \to (X(3872) \to (J/\psi \to \mu\mu)\pi\pi)K^{\pm}$ signal:

- $X(3872)$ signal from b mesons decay yield after 18 month of running:

$$N_{phys} = L_{int} \times 2 \times \sigma_{b\bar{b}} \times f_{B^{\pm}} \times BR^{sig}_{vis} \times \epsilon^{sig}_{tot} \approx 290 \text{ events}$$

  - $L_{int} = 1\text{fb}^{-1}$ the integrated luminosity expected after 18 months.
  - $\sigma_{b\bar{b}} = 319$ μb the measured $b\bar{b}$ production cross section in pp collisions at $\sqrt{s} = 7\text{TeV}$.
  - $f_{B^{\pm}} = 39.9$ % is the fraction of b quarks that hadronize to a $B^{\pm}$ meson.
  - $BR^{sig}_{vis} = BR(B^{\pm} \to (X(3872) \to (J/\psi \to \mu\mu)\pi\pi)K^{\pm}) = 6.76 \times 10^{-7}$ is the visible decay branching fraction.
  - $\epsilon^{sig}_{tot} = 0.17$ % is the total reconstruction efficiency (from Monte Carlo analysis).

Backup; J/ψ event: