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Prompt J/Ψ and b→J/Ψ X production in pp-collisions at sqrt(s) = 7 TeV at LHCb

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- The LHCb detector
- New J/ψ productions cross sections results (prompt and from B decay)
- Future prospects

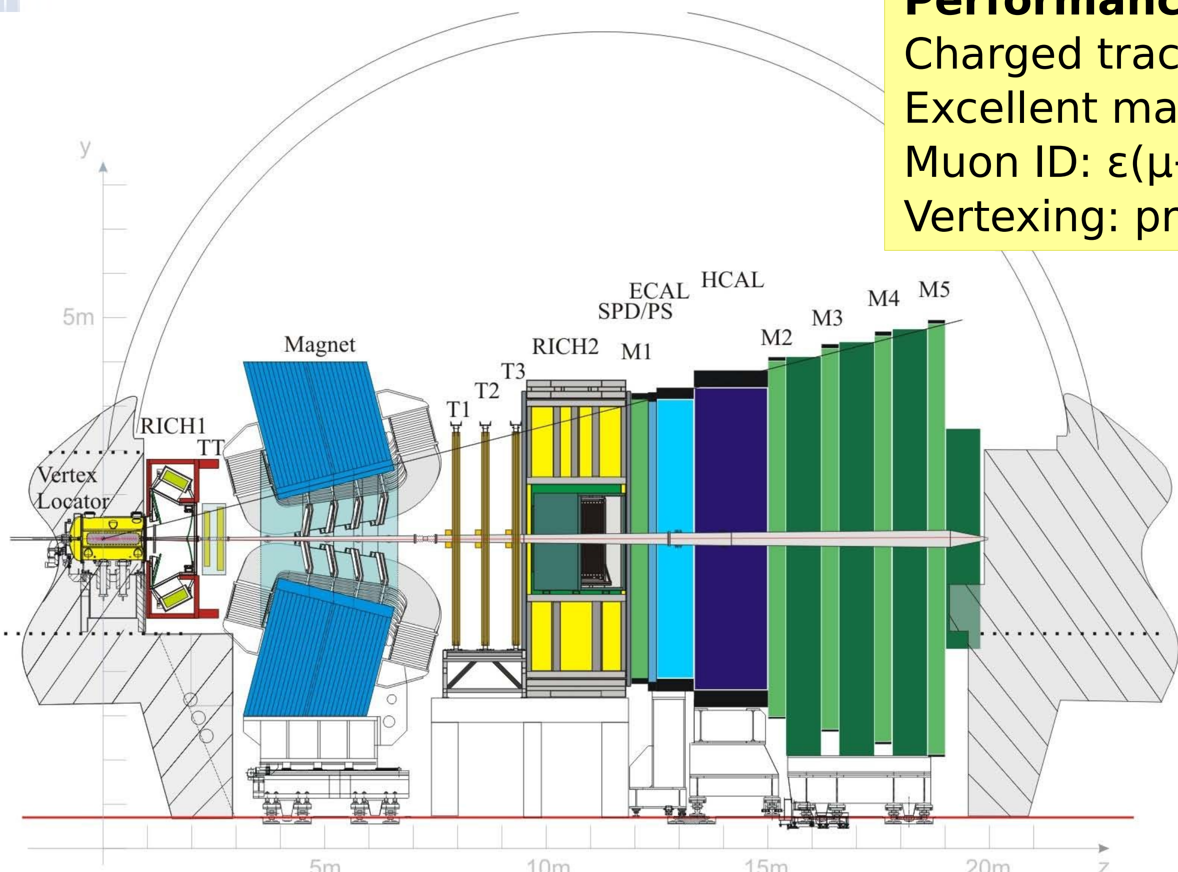
Physics motivation

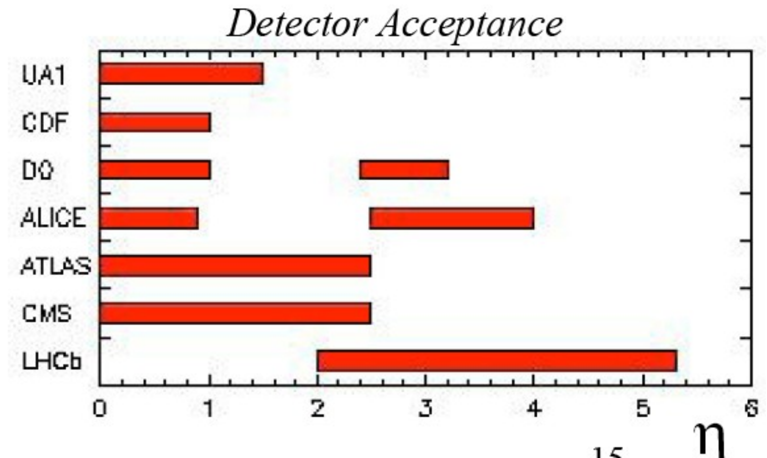
- **J/ψ produced in abundance at LHC:** enough statistics to study the production cross sections already with the first LHC data.
- **Measurement very important:**
  - J/ψ production mechanism not well understood, the color-octet model used to fit the CDF data doesn't describe the J/ψ polarization
  - b→ J/ψ X decays fundamental for the LHCb core physics program
- **3 main sources of J/ψ :**
  - direct production in pp collisions
  - feed down from heavier charmonium states (ψ(2S), $\chi_{c,...}$)
  - J/ψ from b-hadron decay chains

The LHCb detector

- Forward single arm spectrometer: large and correlated bb quark production in the forward region
- Coverage: 15-300 mrad
- Unique acceptance among the LHC experiments: can explore production properties in the forward region.

Performance numbers relevant to J/ψ analysis
Charged tracks Δp/p = 0.35 % - 0.55%
Excellent mass resolution
Muon ID: ε(μ→μ) = 94 %, mis-ID rate (π→μ) = 1-3 %
Vertexing: proper time resolution 30-50 fs





The J/ψ cross section

- Differential cross section $d^2\sigma/dp_t dy$ as a function of transverse momentum p_T and rapidity y
  - 14 bins in pt: $0 < p_T < 14$ GeV/c , 5 bins in y: $2 < y < 4.5$
- Two separate measurements:
  - prompt J/ψ: direct production in pp collisions or seed down from other charmonium states (ψ(2S), χ_c ...)
  - J/ψ from B decay
- Use (5.2±0.5) pb^{-1} of data collected at the end of September 2010 at LHCb, with pp collisions at center of mass energy of 7 TeV:
- Two different trigger conditions:
  - 2.2 pb^{-1} with HLT1 single muon line at full rate
  - 3 pb^{-1} with HLT1 single muon line pre-scaled (×0.2), to cope with instantaneous luminosity increase.

Trigger and selection

Trigger

L0	Single Muon	p_T>1.4 GeV/c
	Di-Muon	$p_{T,1}$>0.56 GeV/c, $p_{T,2}$>0.48 GeV/c
HLT1	Single Muon	Confirm L0 single Muon and p_T>1.8 GeV/c (Pre-scaled in Trigger 2 by 0.2)
	Di-Muon	Confirm L0 Di-Muon and Mμμ>2.5 GeV/c2
HLT2	Di-Muon	Mμμ>2.9 GeV/c2

Offline selection

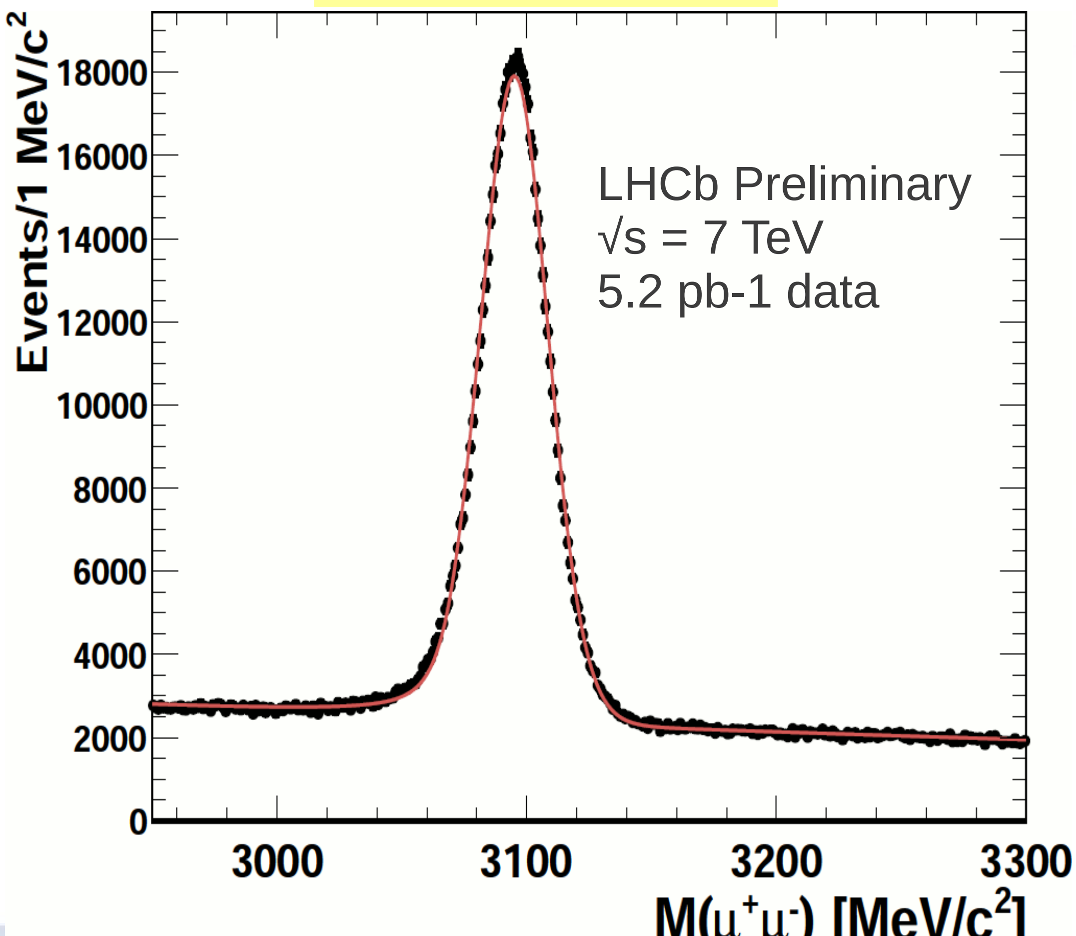
- Muon track well reconstructed and identified as muon
- Muon p_T > 0.7 GeV/c
- Muon track fit quality: χ^2/nDoF < 4
- J/ψ mass window: 0.15 GeV/c^2,
- J/ψ vertex fit quality: P(χ^2)>0.5%.

J/ψ invariant mass fit

- To take into account of the radiative tail, a **Crystal Ball** function is used to fit the signal
- Combinatorial background reasonably fit with a negative exponential
- Excellent mass resolution (~ 15 MeV/c^2 depending on bin)
- Same plot has been done for each bin of p_T and y to evaluate the number of J/ψ in each bin

$$f_{CB}(x; M, \sigma, a, n) = \begin{cases} \dfrac{\left(\frac{n}{|a|}\right)^n e^{-\frac{1}{2}a^2}}{\left(\frac{n}{|a|} - |a| - \frac{x-M}{\sigma}\right)^n} & \dfrac{x-M}{\sigma} < -|a| \\ \exp\left(-\dfrac{1}{2}\left(\dfrac{x-M}{\sigma}\right)^2\right) & \dfrac{x-M}{\sigma} > -|a|. \end{cases}$$

N = 564603 ± 924



J/ψ cross section evaluation

$$\frac{d^2\sigma}{dy\,dp_T} = \frac{N\left(J/\psi \to \mu^+\mu^-\right)}{\mathcal{L} \times \epsilon_{tot} \times \mathcal{B}\left(J/\psi \to \mu^+\mu^-\right) \times \Delta y \times \Delta p_T}$$

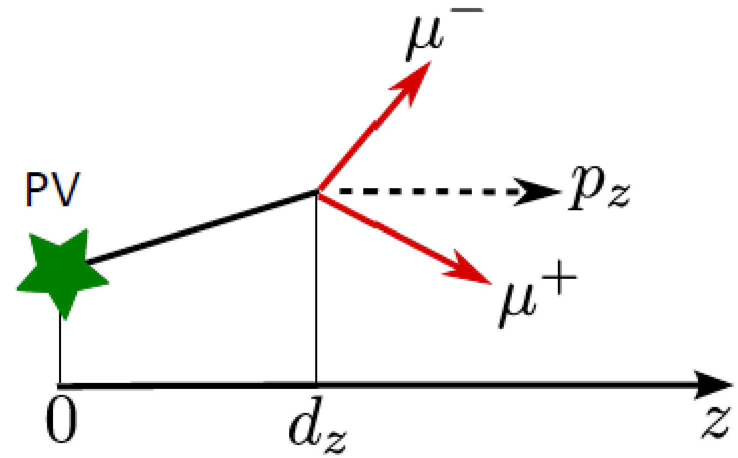
where....

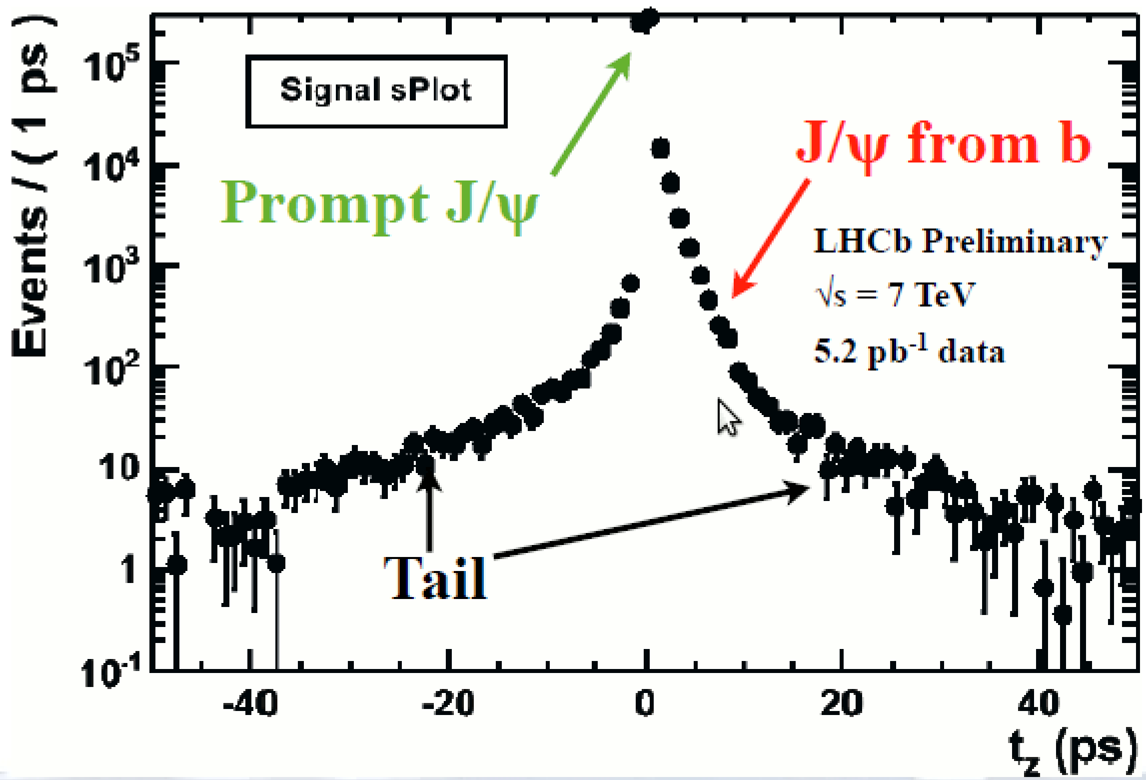
- **$N(J/\psi \to \mu^+ \mu^-)$** is the number of observed decays in a certain p_T and y bin
- $\mathcal{L}$ is the total integrated luminosity (5.2 pb-1)
- **ε_{tot}** is the total efficiency, containing acceptance, trigger, reconstruction etc...
- **$B(J/\psi \to \mu^+ \mu^-)$** is the $J/\psi \to \mu^+ \mu^-$ branching ratio: (5.94 ± 0.06)%
- **Δy=0.5, Δp_T=1 MeV/c** are the bin sizes

Separation of prompt J/ψ and J/ψ from b

To distinguish prompt J/ψ from b → J/ψ decays, we use the pseudo-proper time t_z

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





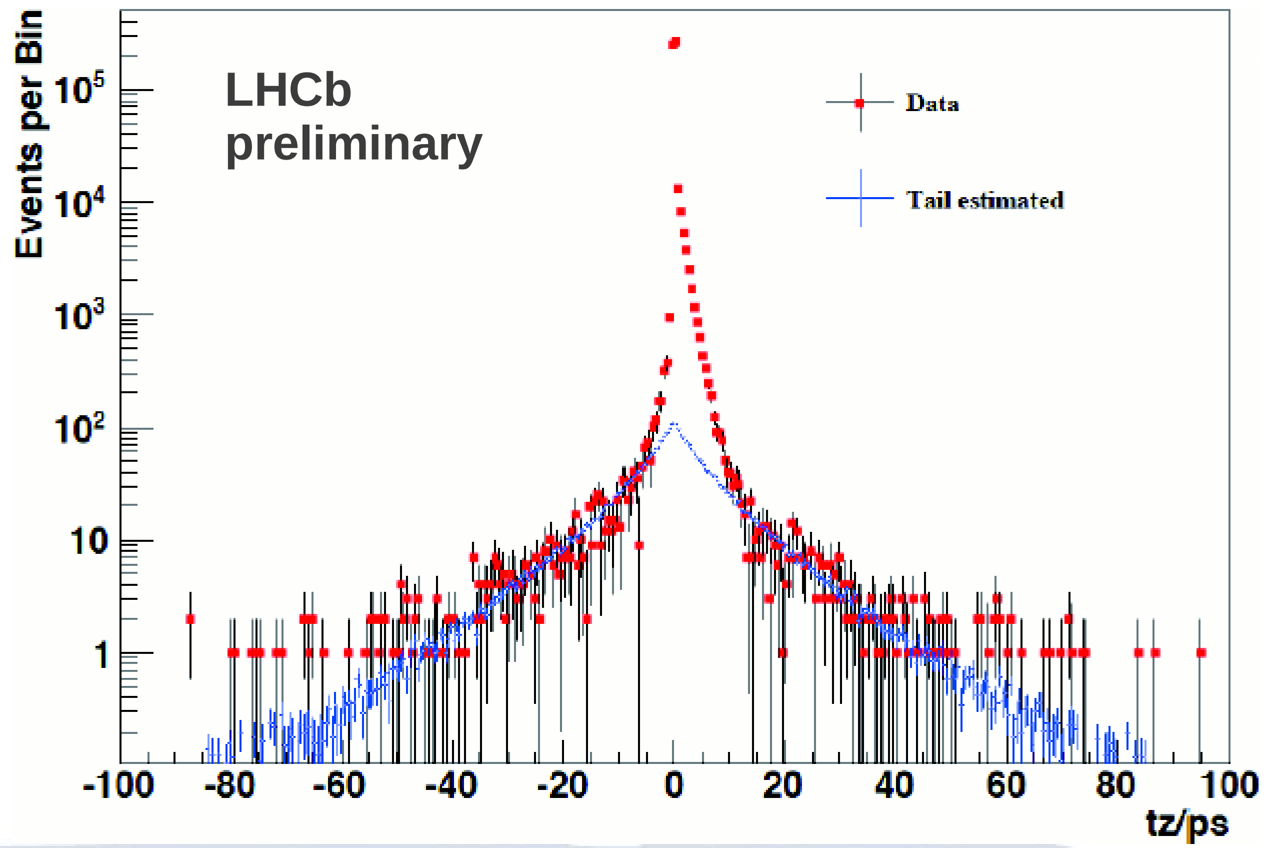
t_z tail

The very long symmetric tails (up to 40 ps) are due to a wrong primary vertex (PV) association. The shape of this tails is determined directly from data considering the PV of the next event, so completely uncorrelated (simulating a wrong association)

$$t_z^{\text{next}}(J/\psi) = \frac{\left(z_{J/\psi} - z_{\text{PV}}^{\text{next}}\right) \times M_{J/\psi}}{p_z}$$

- Data, side-bands subtracted
- “next event” method tail simulation

The “next event” method reproduces the tails very well



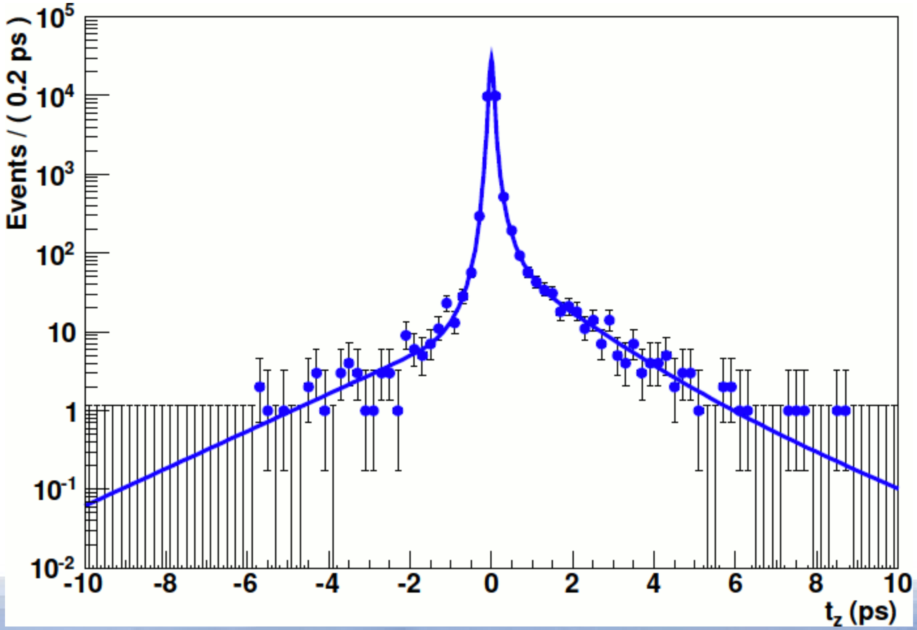
t_z signal and background functions

To fit the t_z distribution we used the following function:

Signal: $$f_{\mathrm{signal}}(t_z; f_p, f_b, \tau_b) = f_p \delta(t_z) + f_b \frac{e^{-t_z/\tau_b}}{\tau_b} + (1 - f_b - f_p) f_{\mathrm{tail}}(t_z)$$

Prompt J/ψ (delta) + J/ψ from B (negative exponential) + t_z tail, all convolved with a resolution function (double Gaussian)

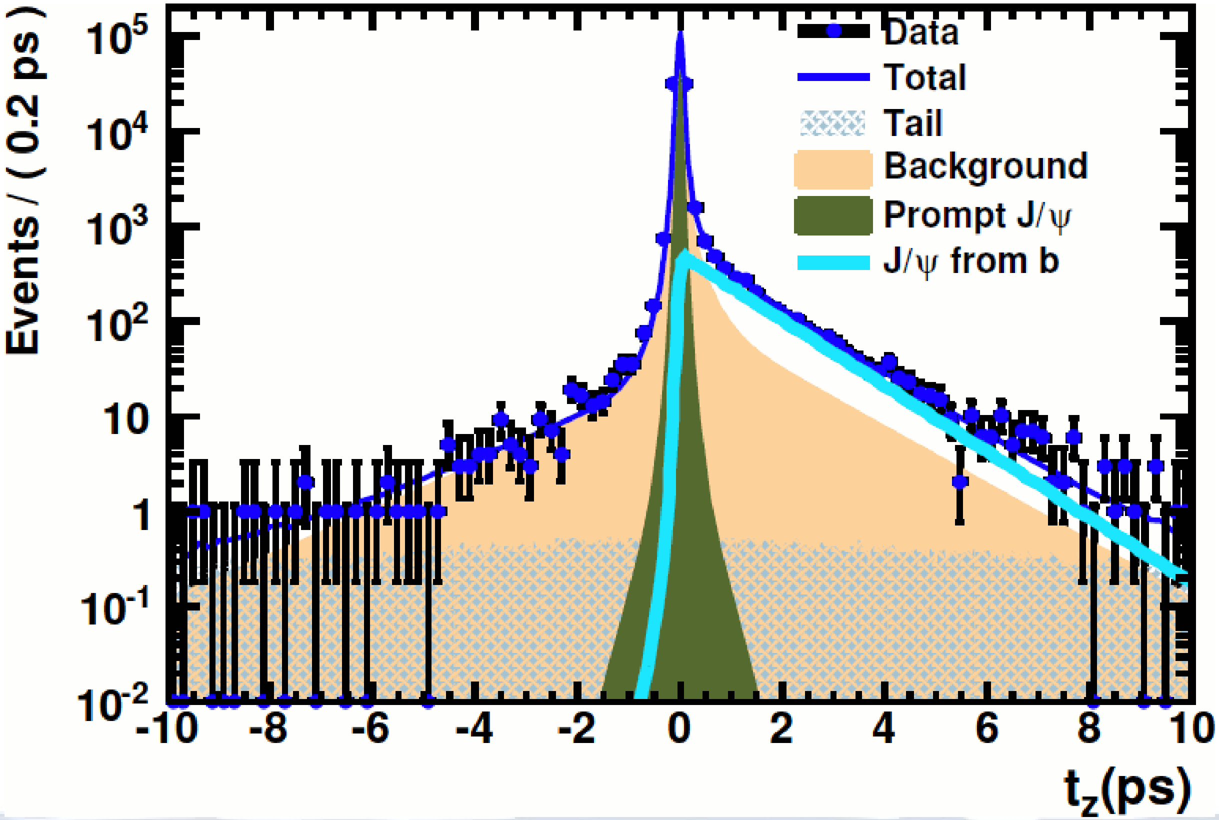
Background: Background contribution to the t_z distribution is parameterized with an empirical function, which is the sum of a delta function and five exponentials (three for positive t_z and two for negative t_z, the negative and positive exponentials), convolved with the sum of two Gaussian functions (the choice of the background function is motivated by the shape of the t_z distribution seen in the J/ψ mass sidebands).



t_z fit

A combined fit in t_z and mass is performed in every p_T and y bin to extract the number of prompt J/ψ and J/ψ from B decay

t_z distribution with the fit result superimposed for the bin: 3 GeV/c < p_T < 4 GeV/c, 2.5 < y < 3.



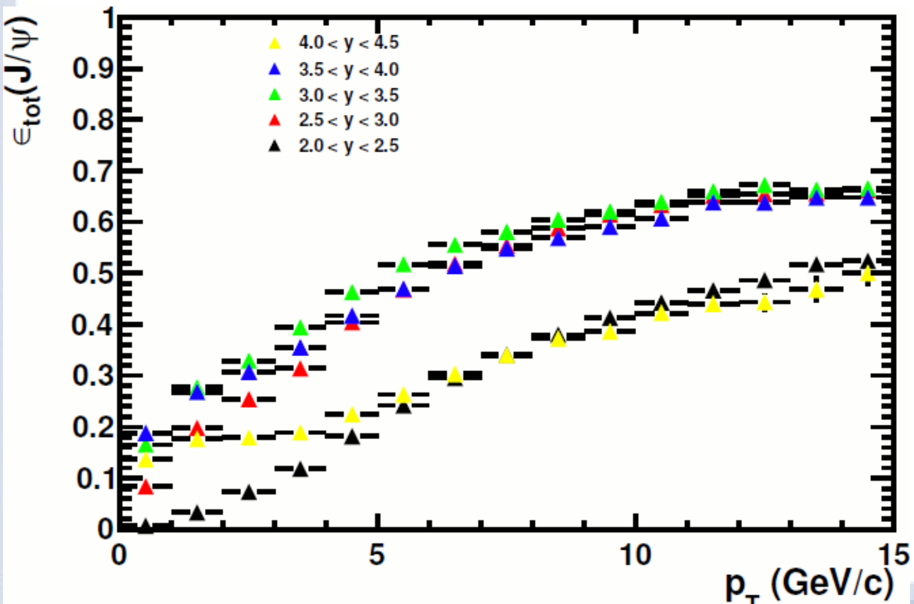
Efficiency evaluation

- A sample of fully simulated inclusive J/ψ is used to estimate the total efficiency ε_{tot} in each bin of p_T and rapidity. The total efficiency includes the geometrical acceptance ε_{acc}, the detection, reconstruction and selection efficiency combined in an efficiency term ε_{rec} and the trigger efficiency ε_{tri}:

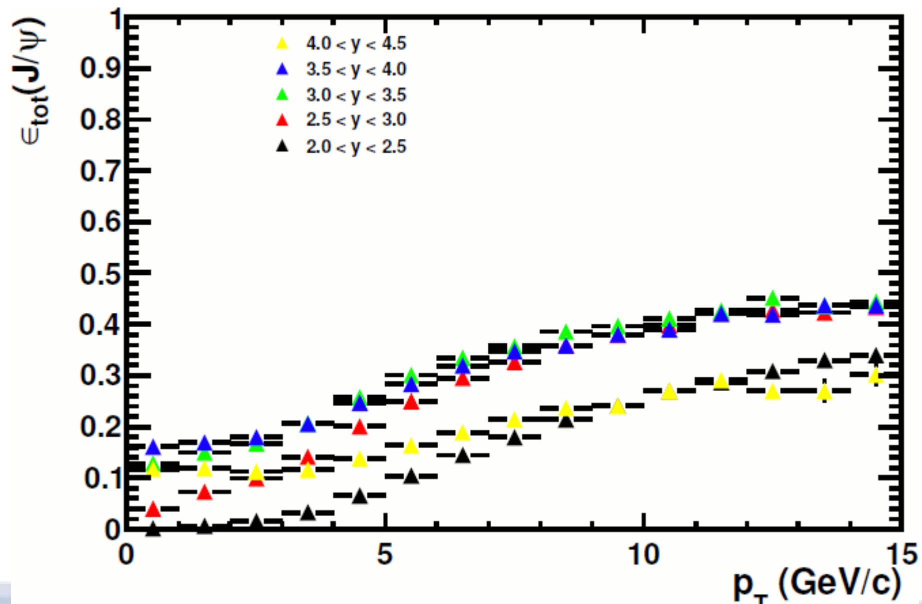
$$\epsilon_{\mathrm{tot}} = \epsilon_{\mathrm{acc}} \times \epsilon_{\mathrm{rec}} \times \epsilon_{\mathrm{tri}}$$

- Efficiencies are computed from Monte Carlo and are extensively checked on data, with control samples. Prompt J/ψ and J/ψ from B result to have the same efficiency (small differences are treated as systematic uncertainties)

Single muon not prescaled



Single muon prescaled



Systematic effects

- A large number of systematic uncertainties have been studied in details on data and MC (trigger, global cuts, track chi2, vertexing, global fit)
  - The systematic uncertainty associated with the trigger efficiency is evaluated by comparing data with simulation. Trigger efficiency in data uses a trigger unbiased event sample, i.e., a sample in which the event would still be triggered if the J/Ψ candidate were removed (Trigger Independent of Signal, TIS)

Quantity	Systematic error	Comment
Trigger	1.7% to 4.5%	Bin dependent
GEC	2 %	Correlated between bins
Muon identification	2.5%	Correlated between bins
Tracking efficiency	8%	Correlated between bins
Track χ^2	1%	Correlated between bins
Vertexing	1%	Correlated between bins
Mass fits	1%	Correlated between bins
Bin size	0.1% to 15%	Bin dependent
Inter-bin cross-feed	0.5%	Correlated between bins (not applied to the total cross-section)
Radiative tail	1%	Correlated between bins
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	1%	Correlated between bins
Luminosity	10%	Correlated between bins
t_z fits	3.6%	Correlated between bins
GEC efficiency of B events	2%	Applies only to J/ψ from b cross-sections
b hadronization fractions	2%	Applies only to extrapolations of $b\bar{b}$ cross-sections
$\mathcal{B}(b \to J/\psi X)$	9%	Applies only to extrapolations of $b\bar{b}$ cross-sections

Polarization effect

- The efficiency is evaluated from a Monte Carlo simulation in which the J/Ψ is produced unpolarized. However, studies show that both longitudinal and transverse J/Ψ polarization may lead to very different efficiencies.

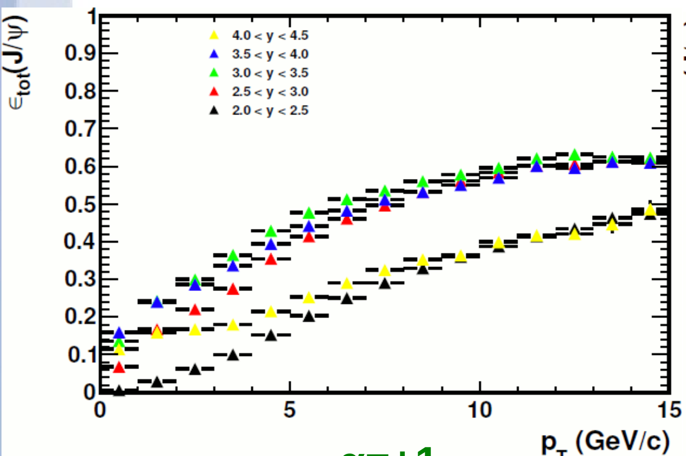
- 3 extreme polarization cases have been studied, in the helicity frame, where the angular distribution of J/Ψ muons is (integrating over the azimuthal angle φ):

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

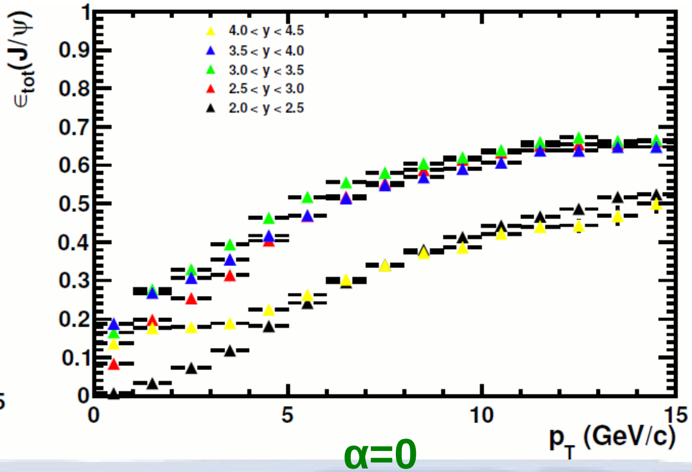
α: polarization
θ*: polar angle

- The plots indicate that the polarization significantly affects the acceptance and reconstruction efficiencies (up to 30%) and that the effect depends on p_T and y.
  Therefore, waiting for a polarization measurement, the prompt J/Ψ cross-section will be given separately for the three polarizations

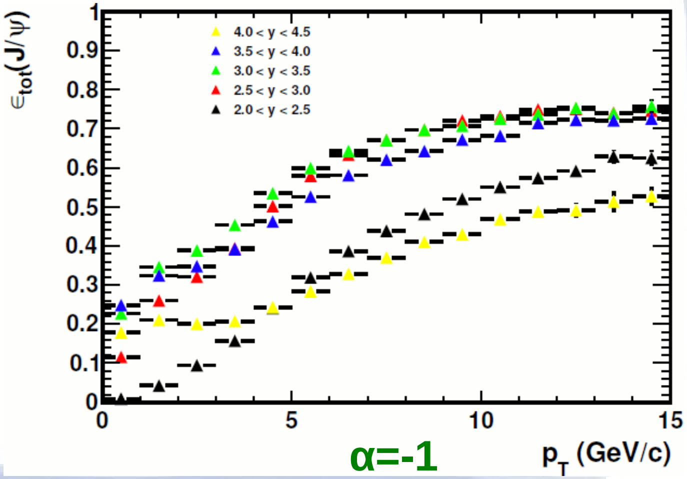
Single muon trigger not prescaled



α=+1



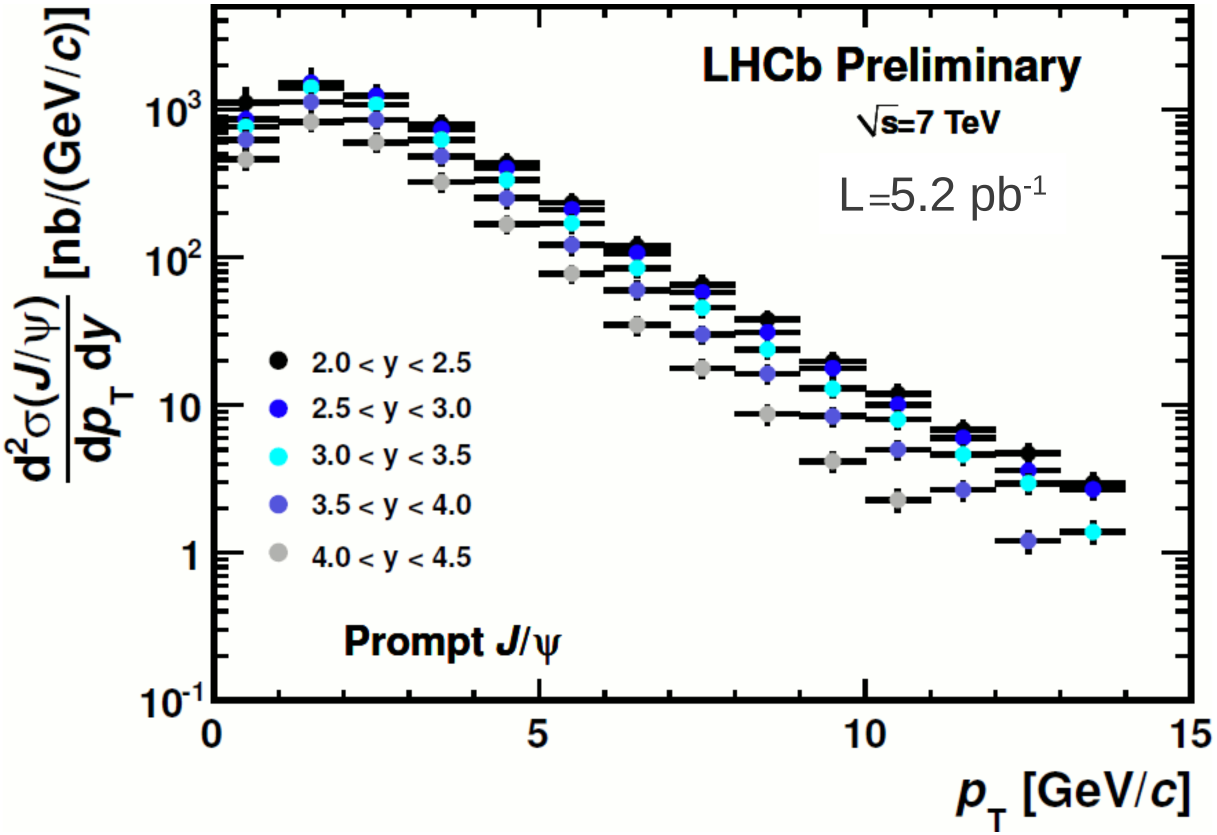
α=0



α=-1

Results: Prompt J/ψ cross section

Differential cross-section for prompt J/ψ in data as a function of p_T in bins of y , assuming that prompt J/ψ are produced unpolarized.



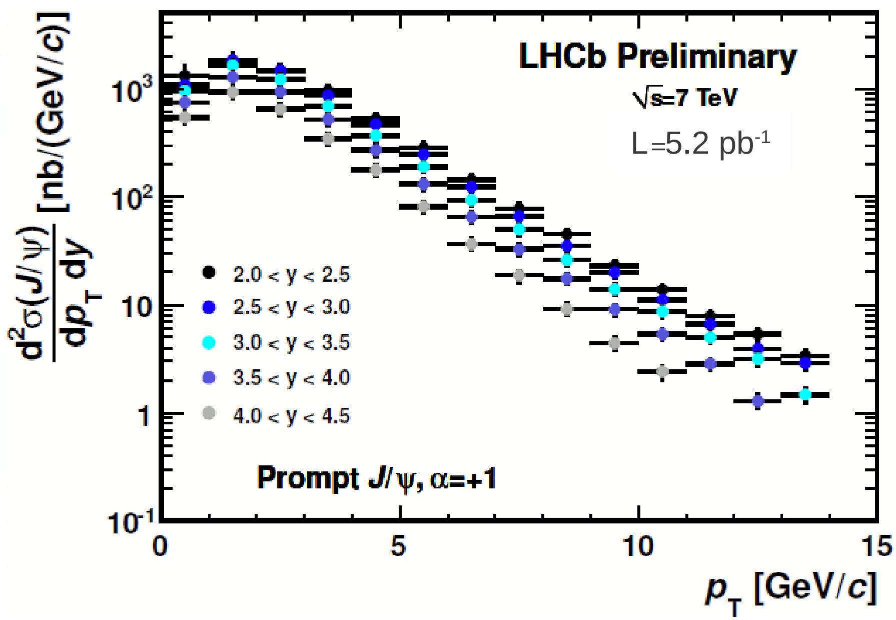
The integrated cross-section for prompt J/ψ production in the defined acceptance, summing over all bins of the analysis, is:

$$\sigma\,(\text{prompt } J/\psi,\, p_{\mathrm{T}} < 14\ \mathrm{GeV}/c,\, 2 < y < 4.5) \;=\; 10.8 \pm 0.05 \pm 1.51^{+1.69}_{-2.25}\ \mu\mathrm{b},$$

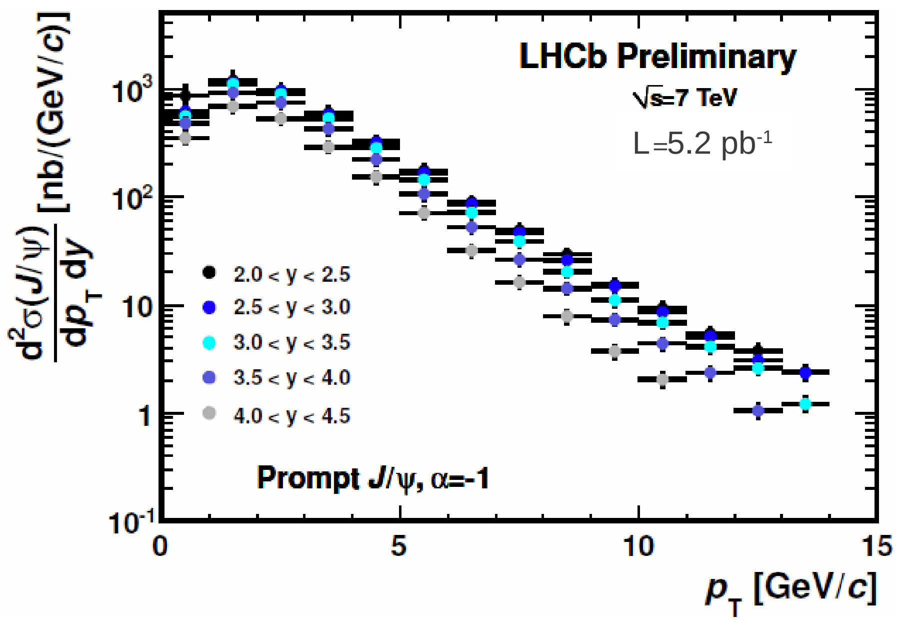
Results: Prompt J/ψ cross section

- Differential cross-section for prompt J/ψ in data as a function of p_T in bins of y, for the two extreme polarization cases.

longitudinal, α=+1



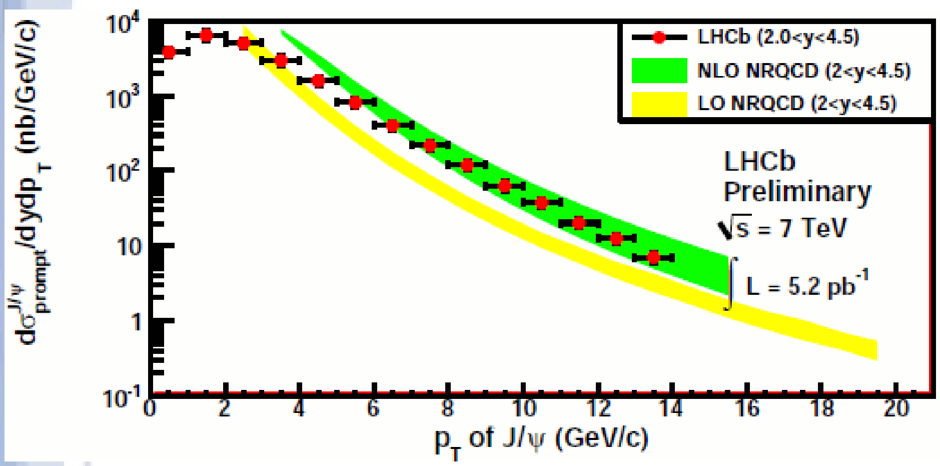
transverse α=-1,

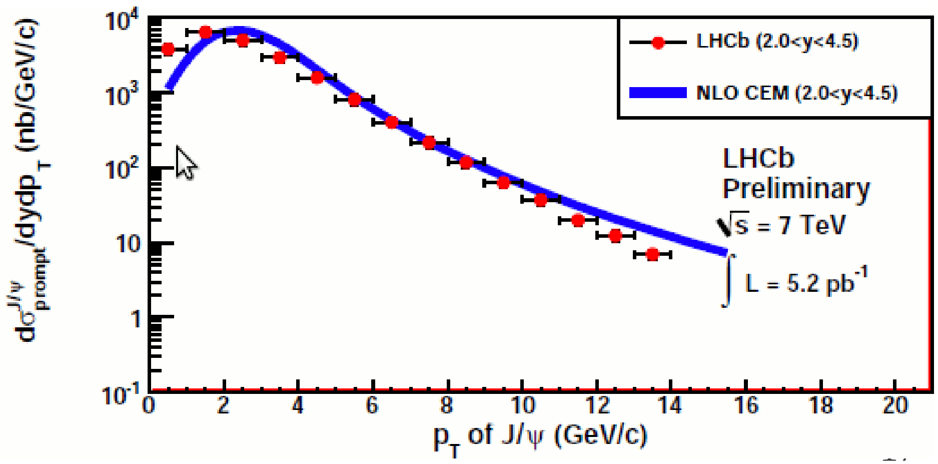


Comparison with theoretical models

- A comparison with three different models is proposed.
  - LO and NLO NRQCD (Non Relativistic QCD summing color Singlet and color Octet)
  - NLO CEM (Color Evaporation Model)

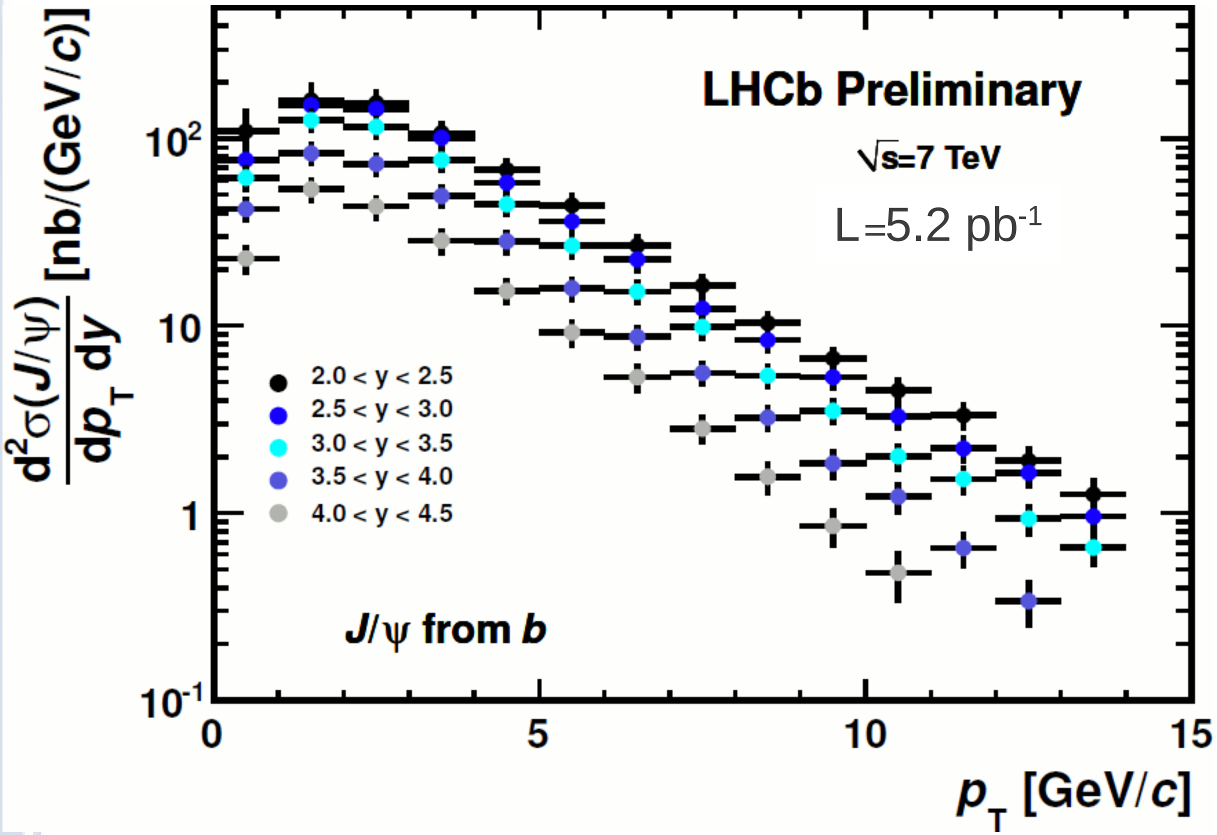
- The NLO NRQCD model seems to fit data reasonably well in the high pT region, though the uncertainty is much large and there is a clear problem at low pT.



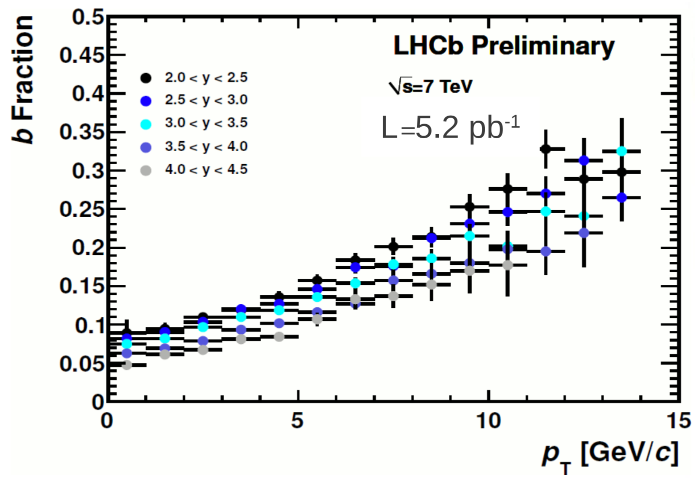


Results: J/ψ from B cross section

Differential cross-section for J/ψ from B decay
as a function of p_T in bins of y



Fraction of J/ψ from b, as a function of p_T, in bins of rapidity



The integrated cross-section in the defined acceptance, summing over all bins of the analysis, is:

$$\sigma\,(J/\psi \text{ from } b,\, p_T < 14\ \text{GeV}/c,\, 2 < y < 4.5)\ =\ 1.16 \pm 0.01 \pm 0.17\ \mu\text{b},$$

Cross section extrapolation

Using the LHCb Monte Carlo simulation based on PYTHIA 6.4, the measurement is extrapolated to the full angular acceptance.

$$\sigma(pp \to b\bar{b}X) = \alpha_{4\pi} \frac{\sigma\left(J/\psi \text{ from } b,\ p_{\mathrm{T}} < 14\ \mathrm{GeV}/c,\ 2 < y < 4.5\right)}{2\mathcal{B}(b \to J/\psi X)}$$

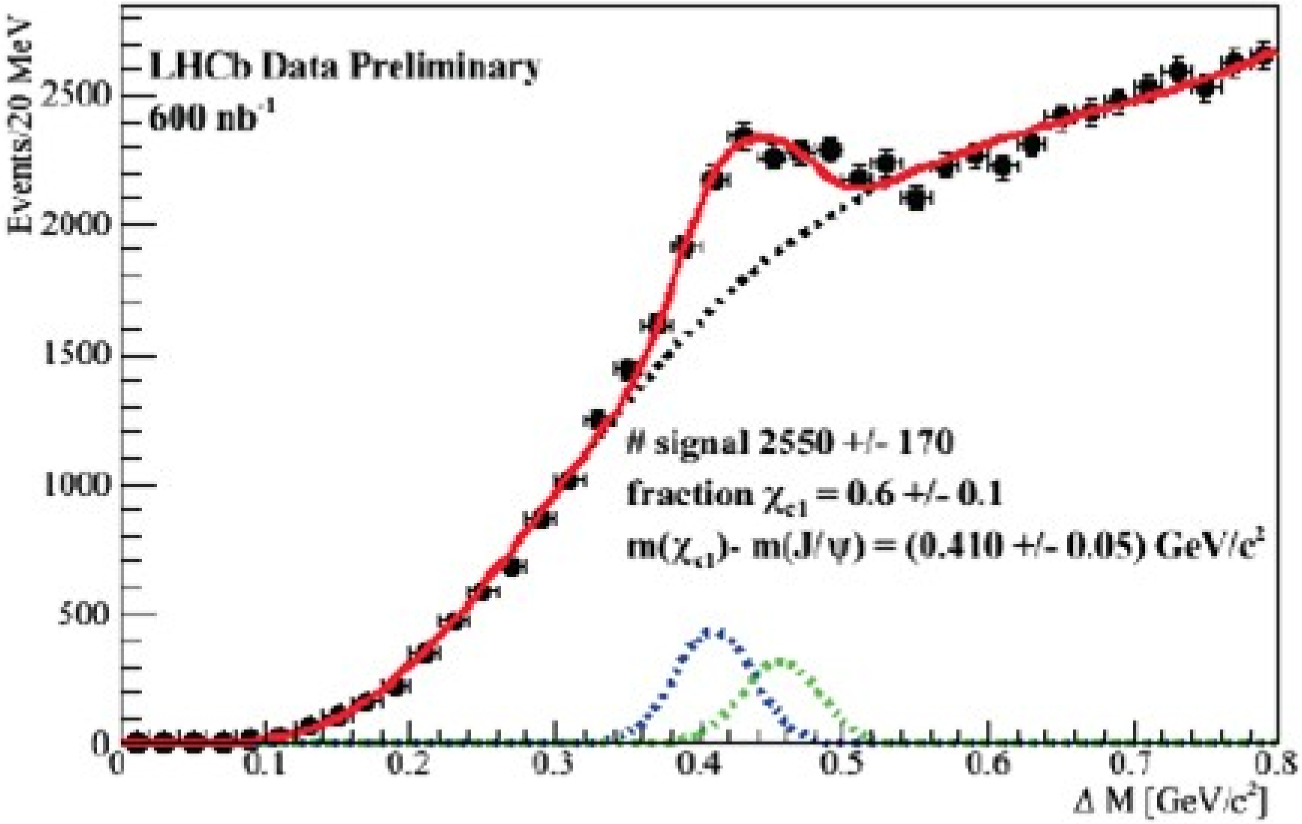
where $\alpha_{4\pi} = 5.88$ is the ratio of J/ψ from b events in the full range over the number of events in the region $2 < y < 4.5$. The results is:

$$\sigma(pp \to b\bar{b}X) = 295 \pm 4 \pm 48\,\mu\mathrm{b}$$

- First uncertainty is statistical and the second one systematic.
- The systematic uncertainty includes the uncertainties on the b fractions (2%) and on B(b → J/Ψ X). No additional uncertainty is assigned to the extrapolation factor $\alpha_{4\pi}$ estimated from the simulation.
- The above result is in excellent agreement with that obtained from b decays into $D^0\mu\nu X$ [Phys.Lett.B694 (2010) 209]: σ(pp → bb X) = 284 ± 20 ± 49 μb.

Prospects for future measurements

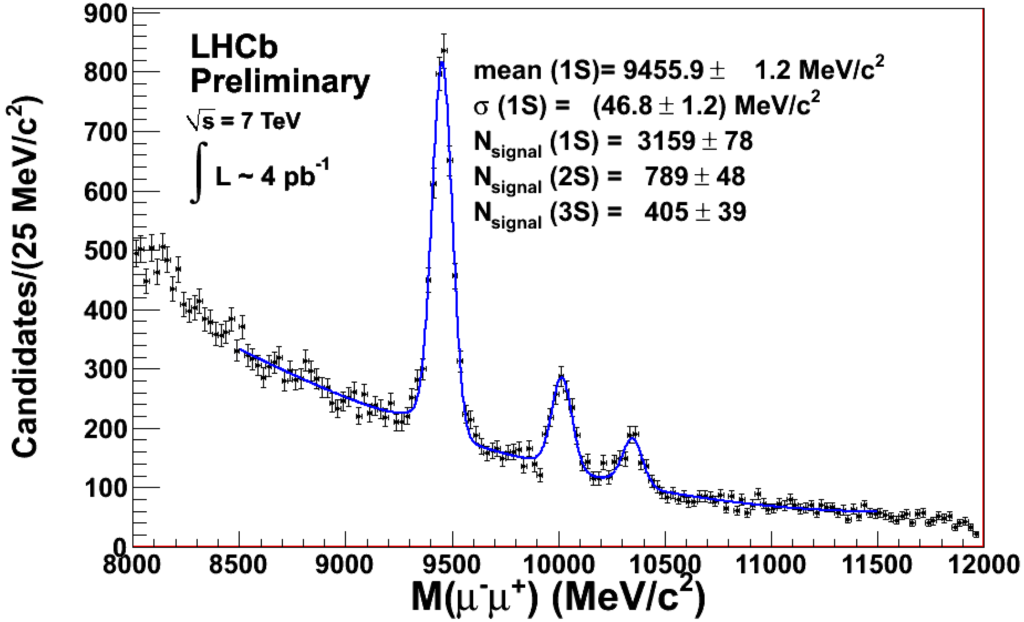
- **Polarization**: with full data sample, possible (ongoing analysis) to measure polarization of prompt J/ψ, in bins of p_T and y.
- **Measurement of χ_{c1}** cross-section will be possible (will also allow to know proportion of J/ψ from feed-down)



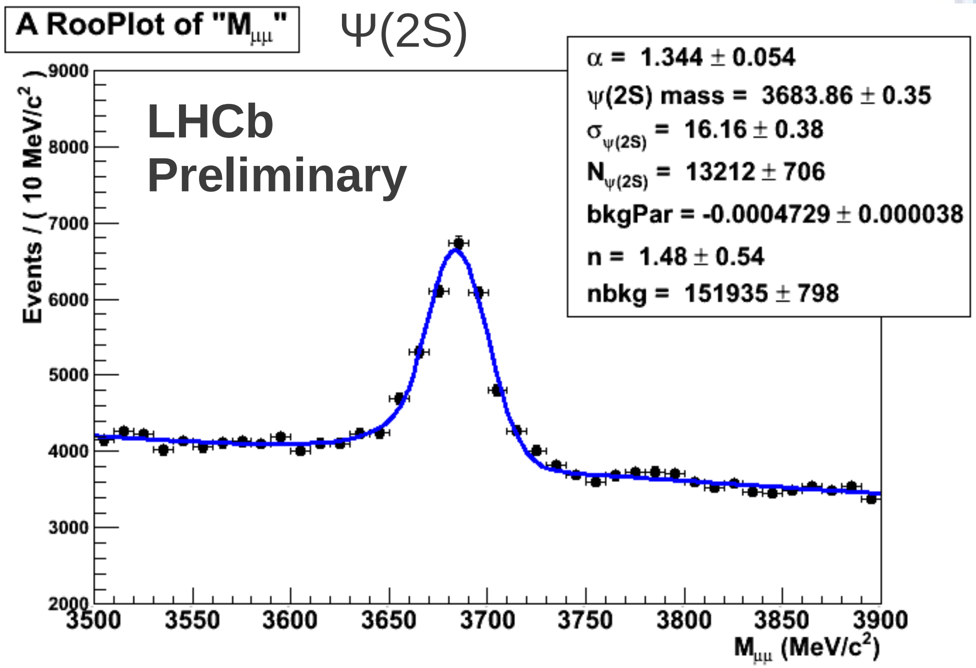
Prospects for future measurements

- Using the $\mu^+ \mu^-$ decay channel, with the full data sample, LHCb will also measure other quarkonium states ψ(2S), Υ(1S), Υ(2S), Υ(3S)

Υ(1S), Υ(2S), Υ(3S)



Ψ(2S)



Conclusions

- New measurements of the J/Ψ cross sections (prompt and from B decays) have been presented, with 5.2 pb^{-1} of data at the LHCb experiment.
- Cross sections have been measured as a function of p_T and y, extending the range of the first measurement presented
  - ICHEP 2010: 14.2 nb-1 with only 10 p_T bins and no bins in rapidity
  - Actual measurement 5.2 pb-1
  - Full statistics analysis (37 pb-1) ongoing
- Large uncertainty is due to unknown J/Ψ polarization: measurement of the polarization is ongoing to address this issue.
- Measurement of Ψ(2S) and Y(1S), Y(2S), Y(3S) cross sections will allow to provide a complete picture of quarkonium production in the forward rapidity region.