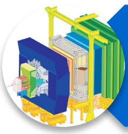
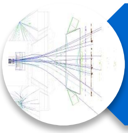
ÉCOLE DE PHYSIQUE des HOUCHES

Winter Workshop on Recent QCD Advances at the LHC
Les Houches, February 13th - 18th, 2011

Prompt J/ψ and b→J/ψ X production in pp-collisions at √s = 7 TeV at LHCb


The LHCb detector


New J/ψ production cross section results (prompt and from B decay)

Future prospects

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on behalf of the LHCb collaboration

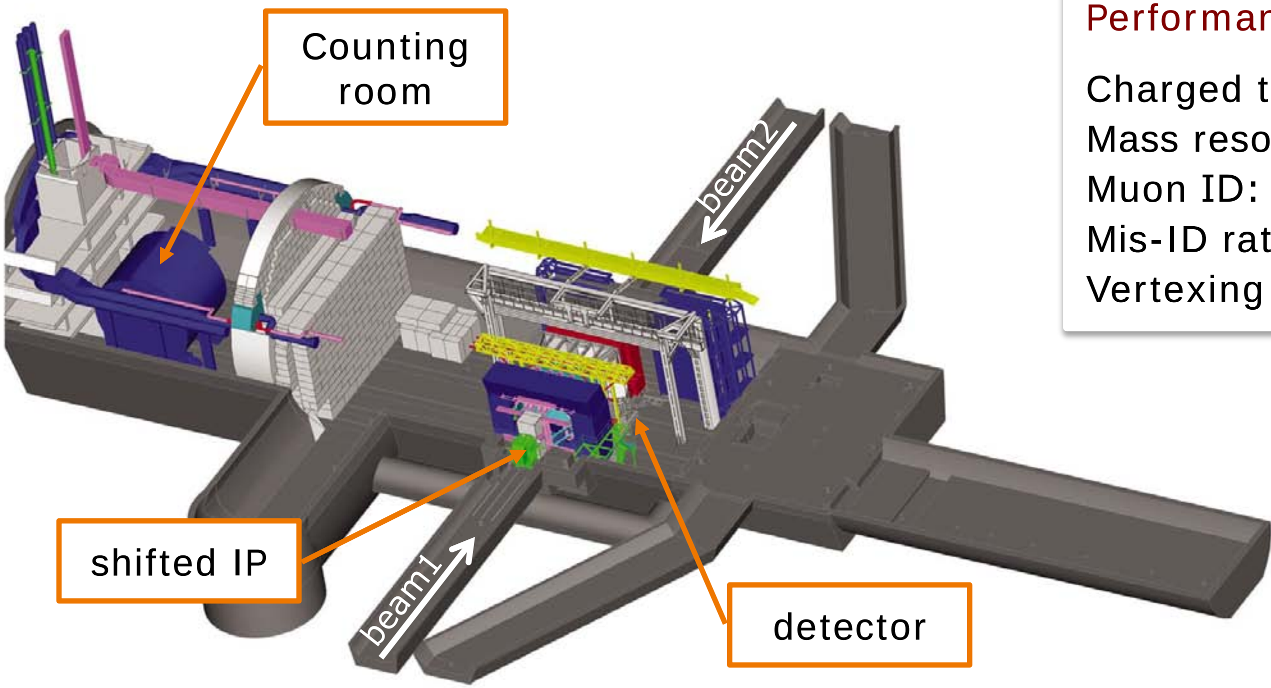
Physics motivation

- 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 does not 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

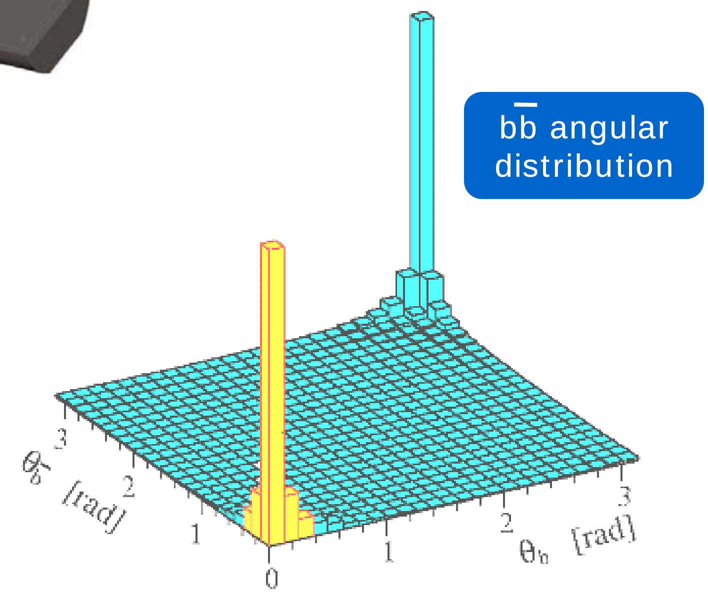


Performances relevant to J/ψ analysis

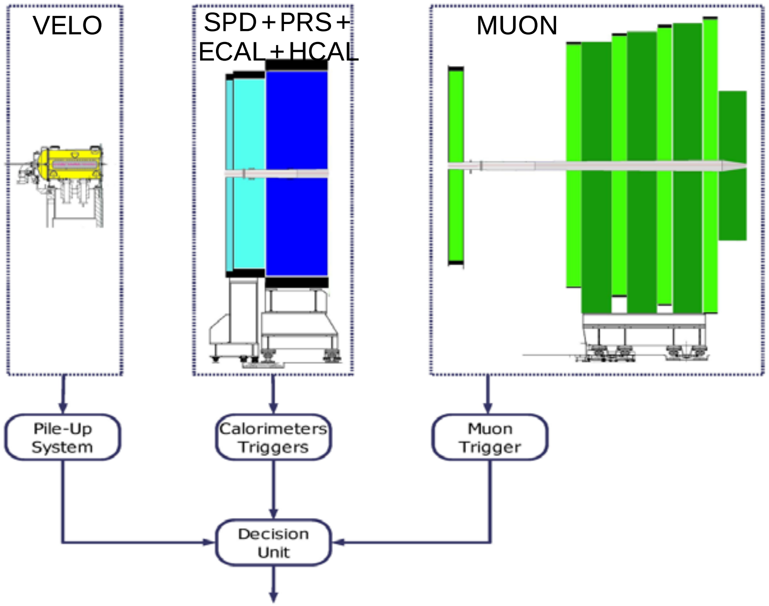
Charged tracks $\Delta p/p$	0.35 -0.55%
Mass resolution	15 MeV/c^2
Muon ID: $\varepsilon(\mu\rightarrow\mu)$	94%
Mis-ID rate $(\pi\rightarrow\mu)$	1-3 %
Vertexing: proper time res.	30-50 fs

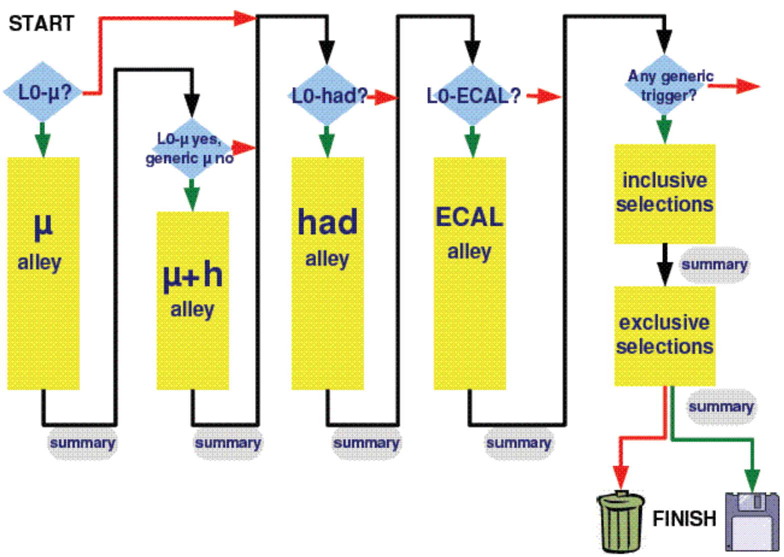
Single-arm forward spectrometer, dedicated to B-physics:

- □ $\mathcal{L} = 2\times10^{32}$ cm^{-2}s^{-1} → 10^{12} $b\bar{b}$/year
- □ Acceptance 10-250 mrad (V) / 10-300 mrad (H)
  → $1.6 < \eta < 4.9$ (unique @ LHC)
- □ Useful σ_{bb}(14 TeV) for LHCb is 230 μb



Trigger & Selection





Trigger

- L0 trigger:
  - 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 and p_T > 1.8 GeV/c
  - Di-Muon: confirm L0 and $M_{\mu\mu}$ > 2.5 GeV/c^2
- HLT2:
  - Di-Muon: $M_{\mu\mu}$ > 2.9 GeV/c^2

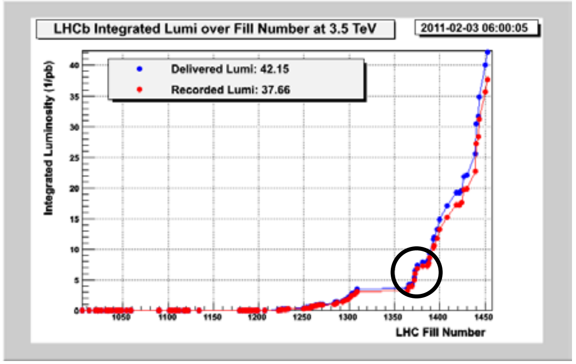
Offline Selection

- Muon track well reconstructed and identified as muon
- Both muons p_T > 0.7 GeV/c
- Muon track fit quality: χ^2/nDoF < 4
- J/ψ mass window: 150 MeV/c^2
- J/ψ vertex fit quality: P(χ^2)>0.5%.

Data and objectives

Data

- Use (5.2 ± 0.5) pb^{-1} of data collected at the end of September 2010 at LHCb, with pp collisions at $\sqrt{s}$ = 7 TeV, in two different trigger conditions:
  - 2.2 pb^{-1} with HLT1 single muon line at full rate.
  - 3.0 pb^{-1} with HLT1 single muon line pre-scaled (x 0.2), to cope with instantaneous luminosity increase.



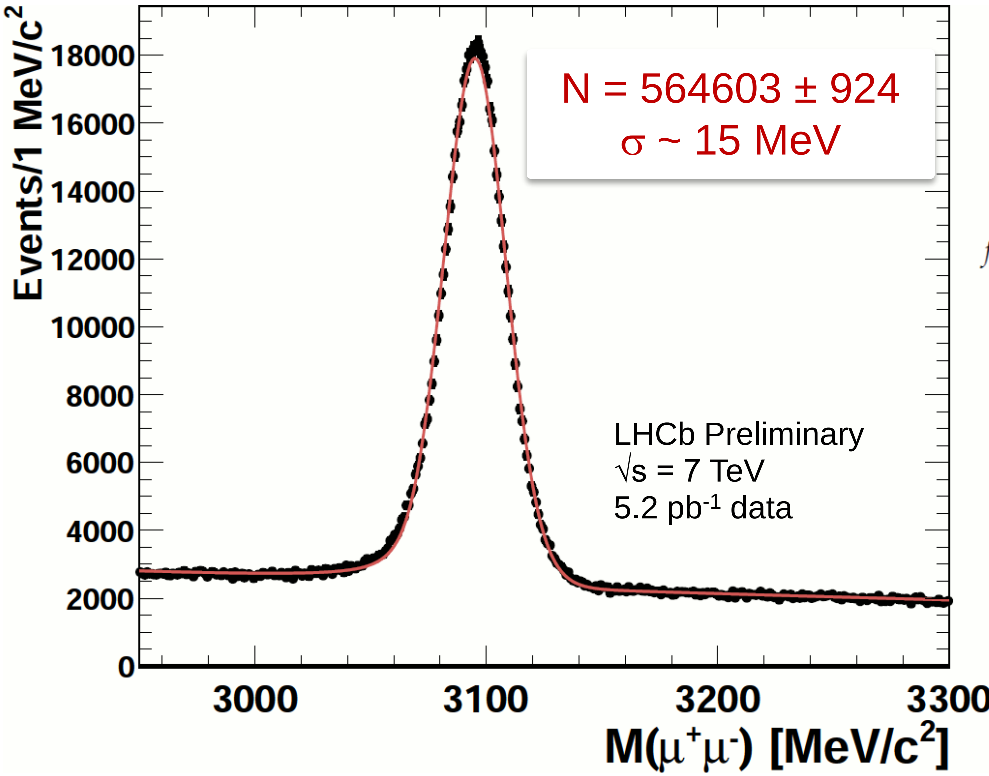
Goal

- Measure the differential cross section $d^2\sigma/dp_T dy$ as a function of the transverse momentum p_T and the rapidity y:

  14 bins in p_T $0 < p_T < 14$ GeV/c
  5 bins in y $2 < y < 4.5$

- Perform 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

J/ψ sample



Crystal Ball function

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

Invariant Mass Fit

- A Crystal Ball function for the signal to take the radiative tail into account.
- A negative exponential for the background.
- Same fit procedure for each bin of p_T and y.

The J/ψ cross section

$$\frac{d^2\sigma}{dy dp_T} = \frac{N_{J/\psi \to \mu^+\mu^-}}{L \times \varepsilon_{tot} \times BR_{J/\psi \to \mu^+\mu^-} \times \Delta y \times \Delta p_T}$$

→ N is the number of observed decays in a certain p_T and y bin

→ L is the total integrated luminosity (5.2 pb^{-1})

→ ε_{tot} is the total efficiency (acceptance × trigger × reconstruction × ...)

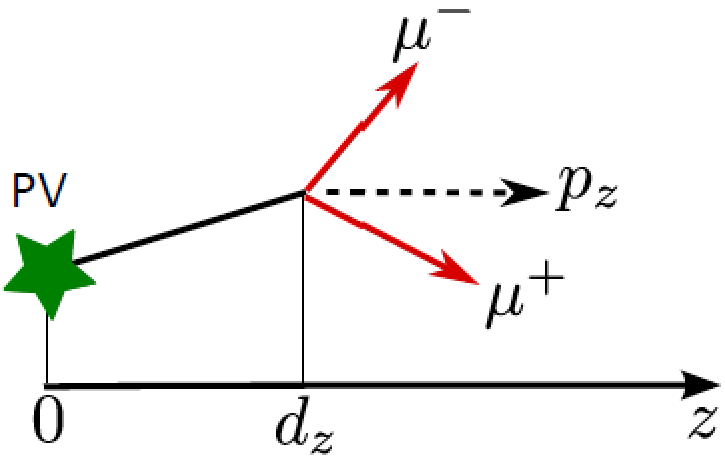
→ BR is the $J/\psi \to \mu^+ \mu^-$ branching ratio: (5.94 ± 0.06)%

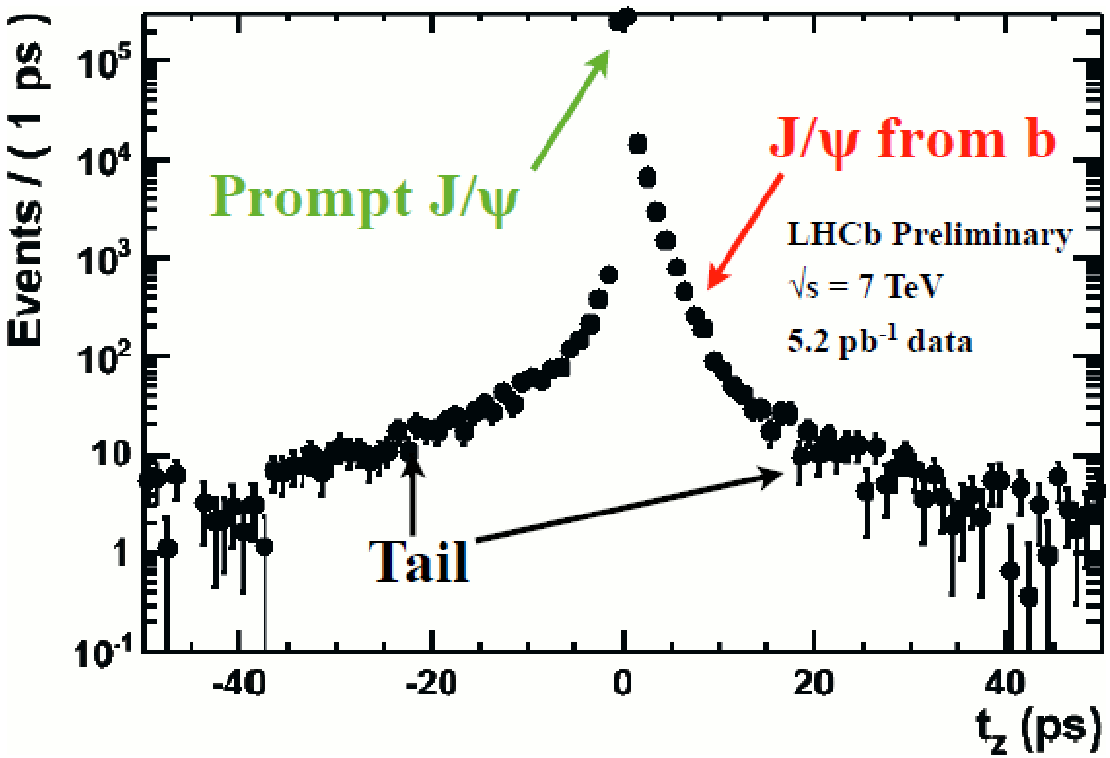
→ $\Delta y = 0.5$, $\Delta p_T = 1$ GeV/c are the bin sizes

Prompt J/ψ and J/ψ from b

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

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



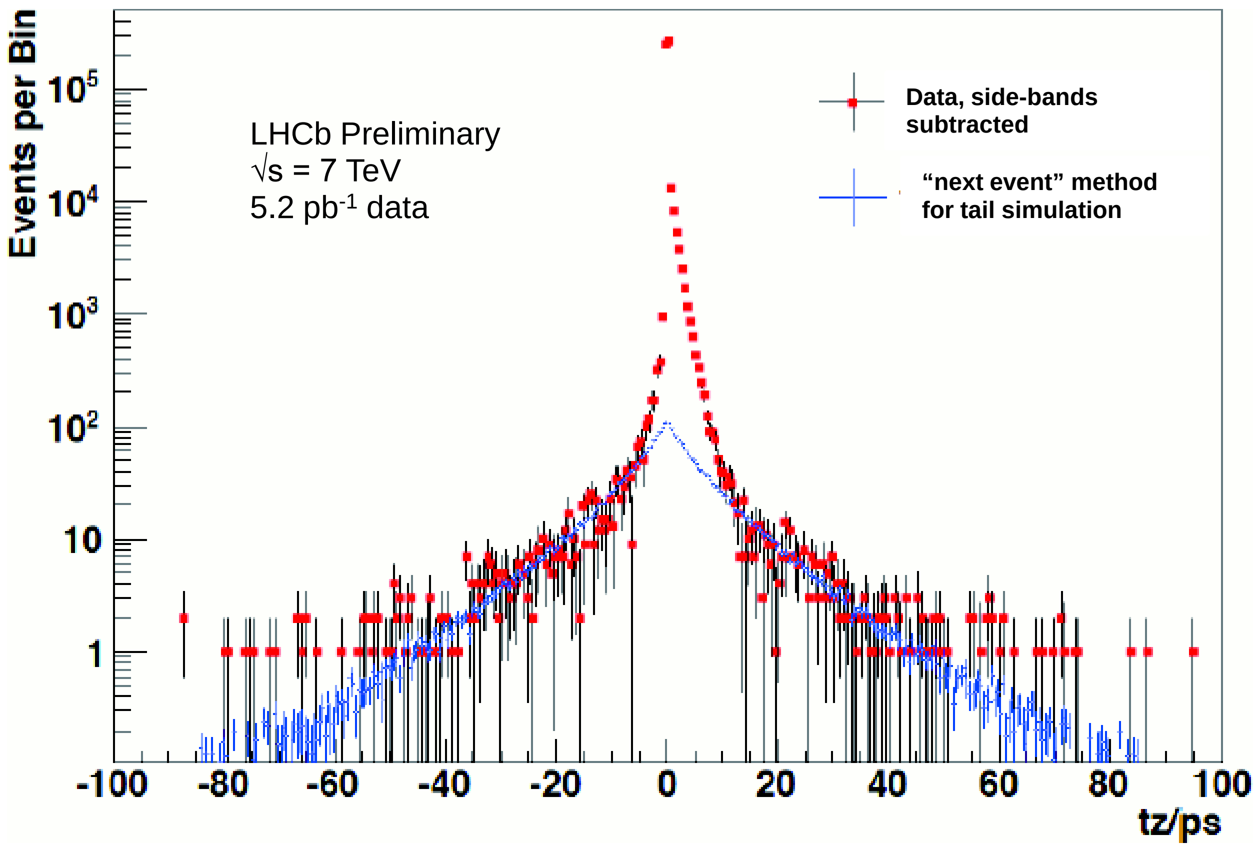


t_z tail

The very long symmetric tails (up to 40 ps) are due to a wrong PV association.
The shape of this tails is determined directly from data by simulating a wrong association (next event PV → uncorrelated PV).

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

The *next event* method reproduces the tails very well.



t_z signal and background functions

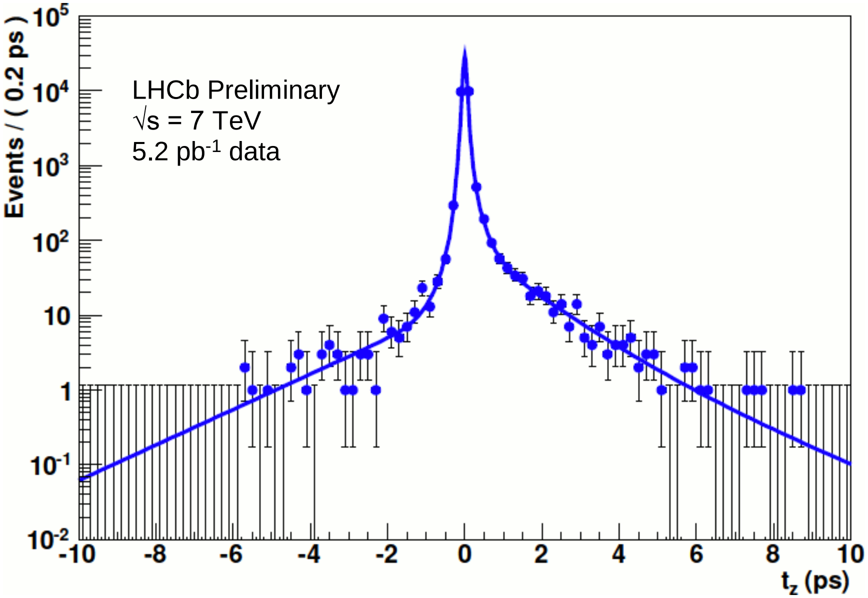
To fit the t_z distribution we used the following function:

Signal:

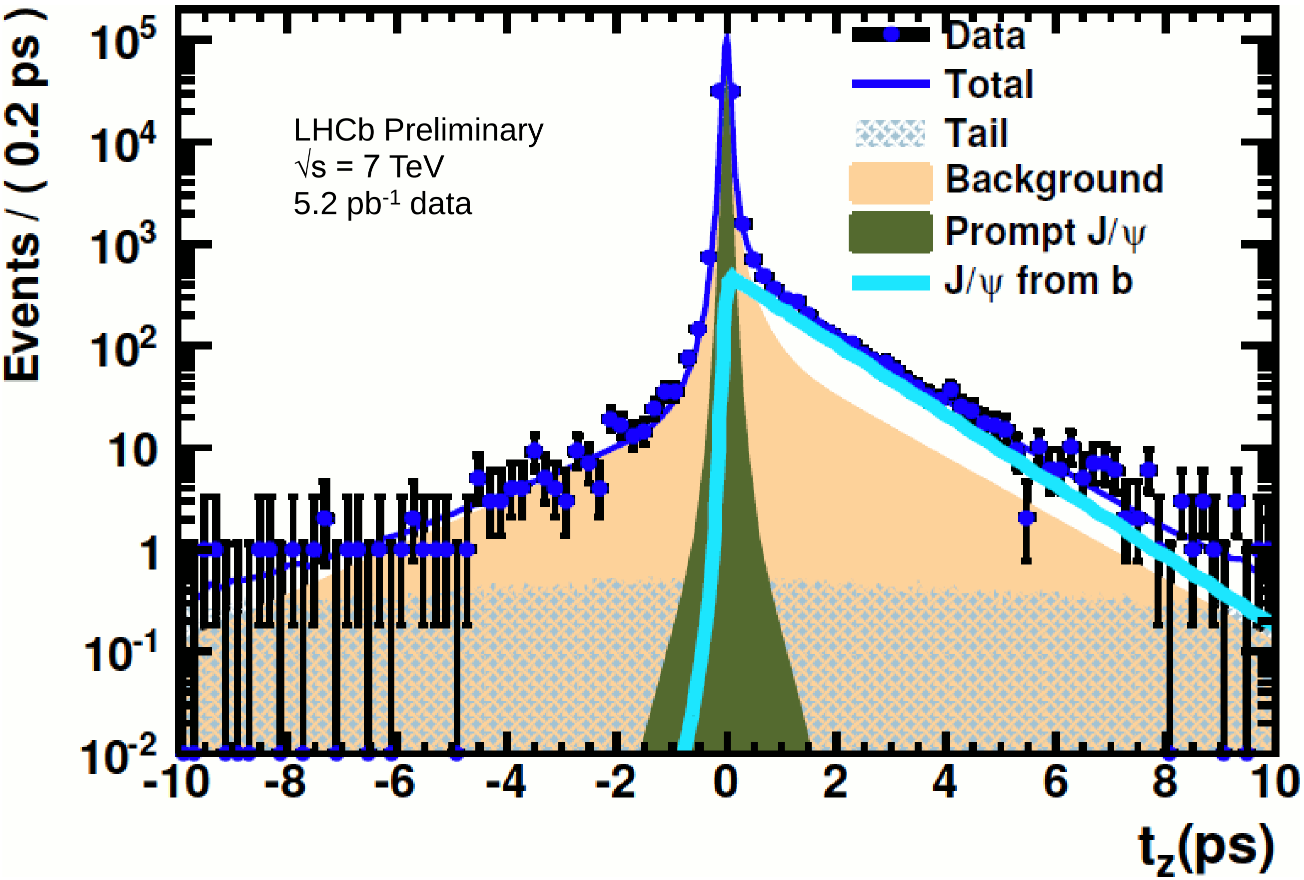
$$f_{signal}(t_z; f_p, f_b, \tau_b) = f_p \delta(t_z) + f_b \frac{e^{-t_z/\tau_b}}{\tau_b} + (1 - f_b - f_p) f_{tail}(t_z)$$

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 negative exponentials for positive t_z and two positive exponentials for negative t_z), 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).



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 of J/ψ from B decay.



Example of a fit result for the bin:
3 GeV/c < p_T < 4 GeV/c,
2.5 < y < 3.

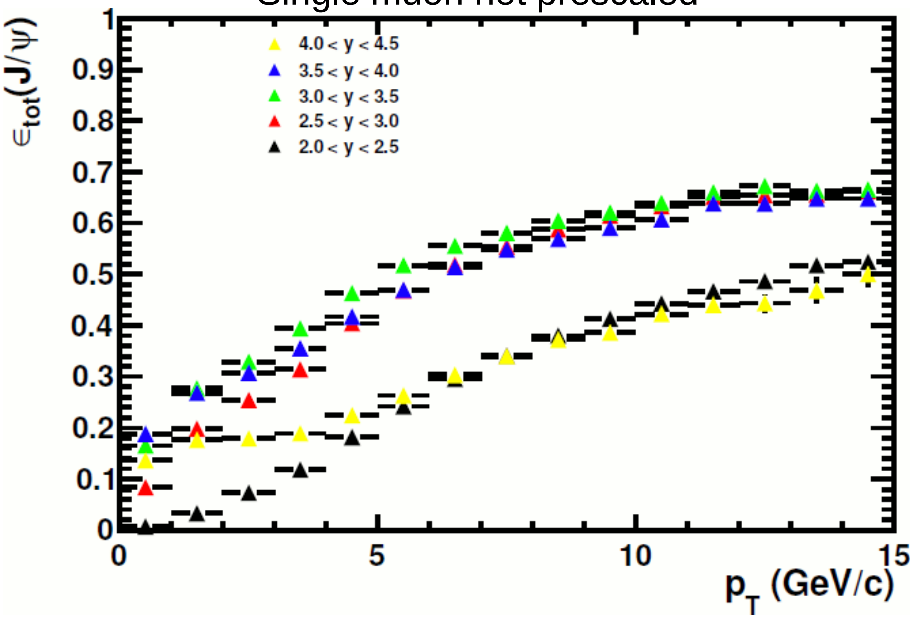
Efficiency

- 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_{trg} :

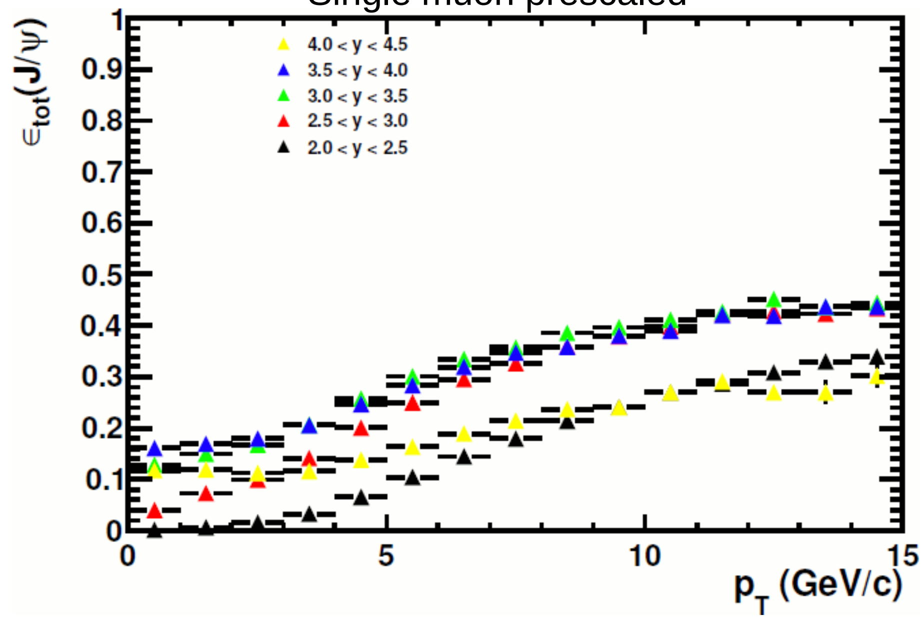
$$\varepsilon_{tot} = \varepsilon_{acc} \times \varepsilon_{rec} \times \varepsilon_{trg}$$

- 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 candidates were removed (Trigger Independent of Signal, TIS)

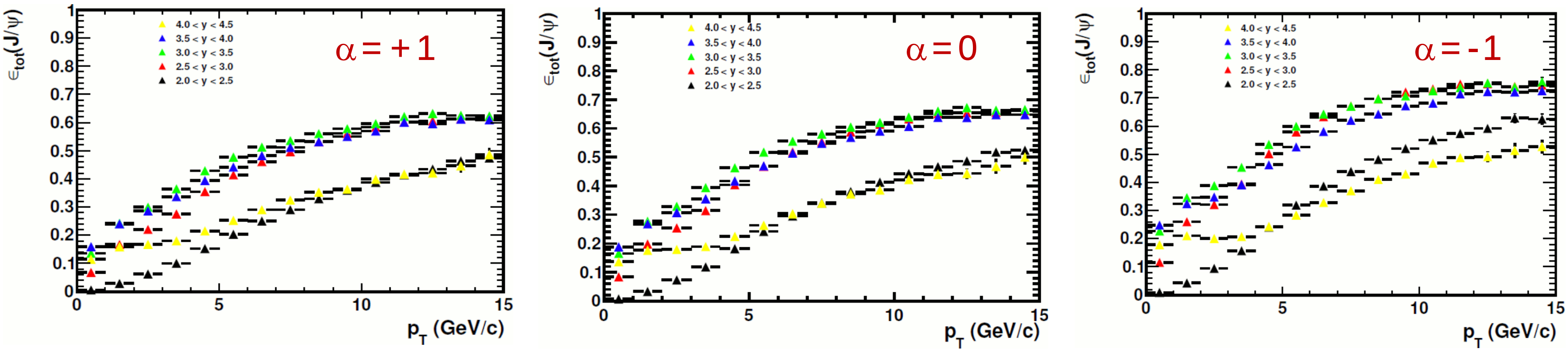
Quantity	Systematic error	Comment
Trigger	1.7% to 4.5%	Bin dependent
GEC	2 %	Correlated between bins
Muon identification	2.5%	Correlated between bins
Tracking efficiency	8%	Correlated between bins
Track χ^2	1%	Correlated between bins
Vertexing	1%	Correlated between bins
Mass fits	1%	Correlated between 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):

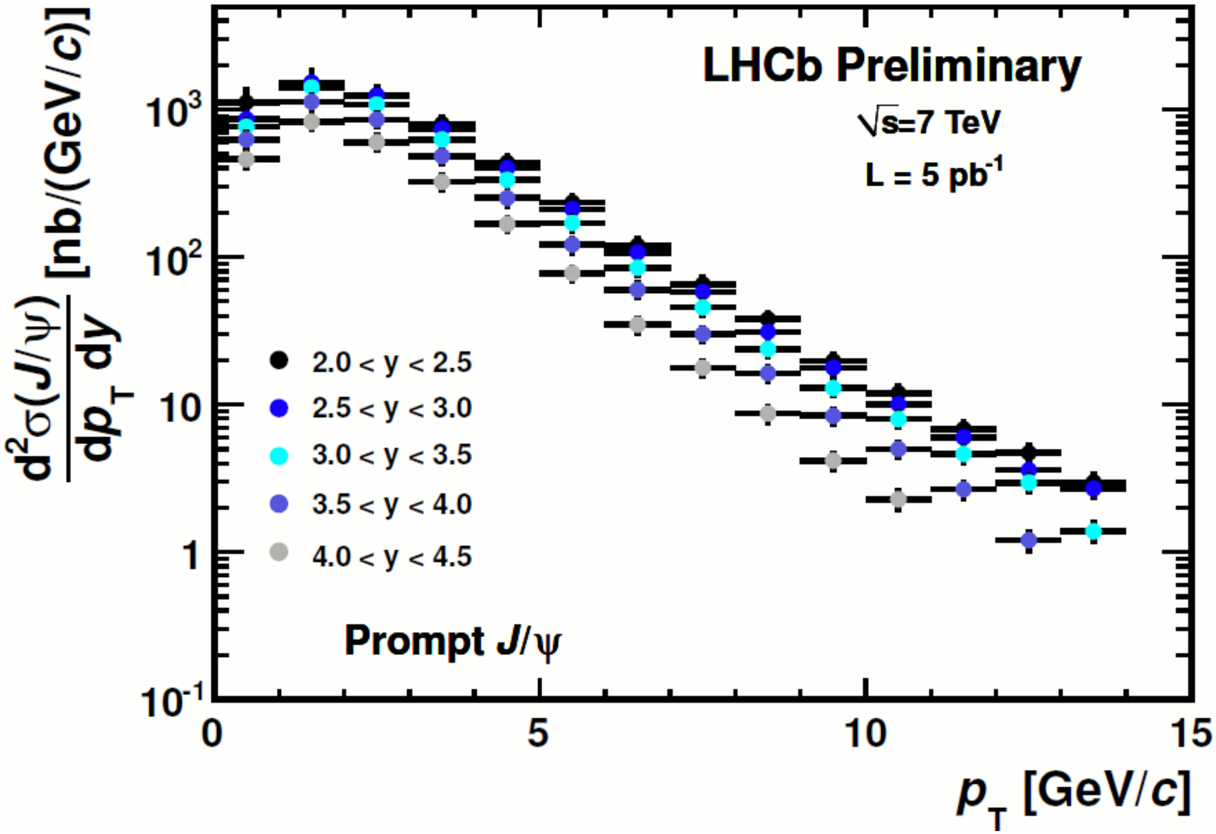
$$\frac{dN}{d\cos\theta} = \frac{1+\alpha\cos^2\theta}{2+2\times\alpha/3}$$



- 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.
  → the prompt J/Ψ cross-section will be given separately for the 3 polarizations.

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.

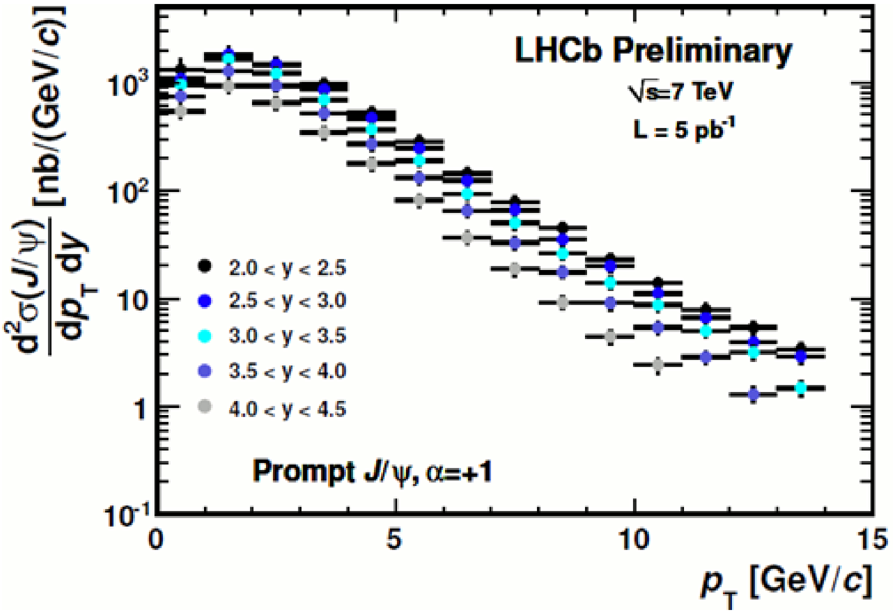


$$\sigma\left(prompt\ J/\psi, p_T < 14\ GeV/c, 2 < y < 4.5\right) = 10.8 \pm 0.05 \pm 1.51^{+1.69}_{-2.25}\ \mu b$$

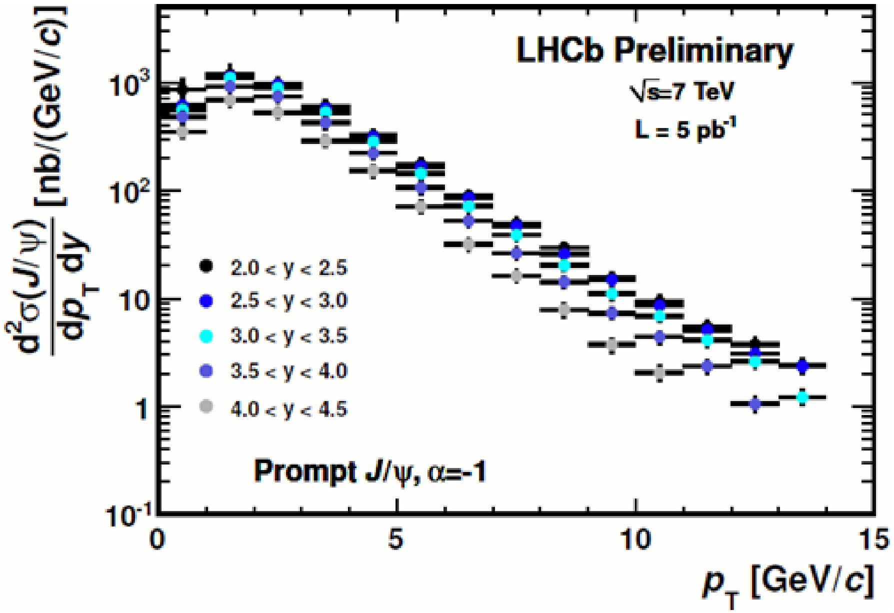
Results: Prompt J/ψ cross section

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



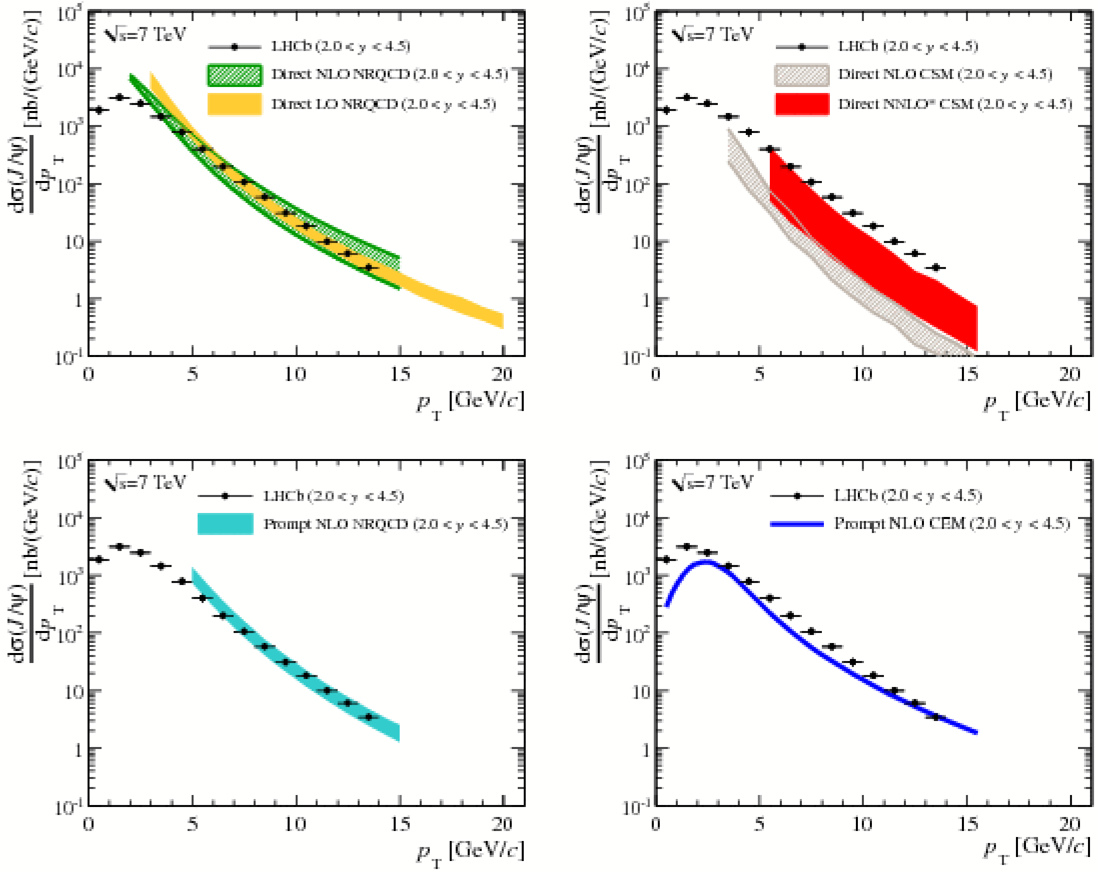
transverse α=-1



Comparison with theoretical models

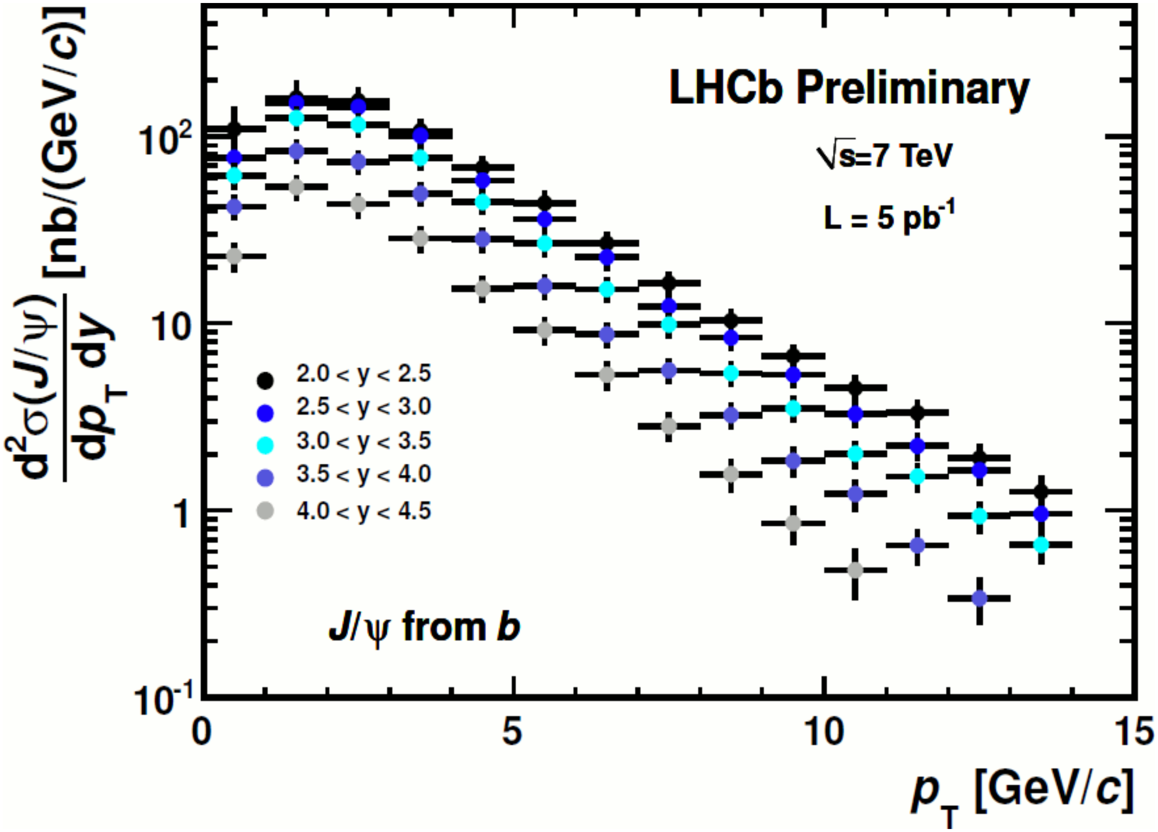
- A comparison with three different models is proposed.
  - → LO and NLO NRQCD (Non Relativistic QCD summing color Singlet and color Octet)
  - → NLO and NNLO CSM
  - → NLO CEM (Color Evaporation Model)

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

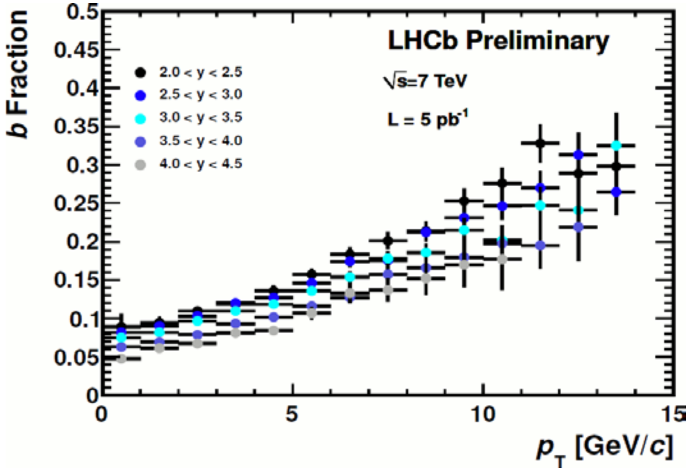


Results: J/ψ from B cross section

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.



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

Cross section extrapolation

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

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

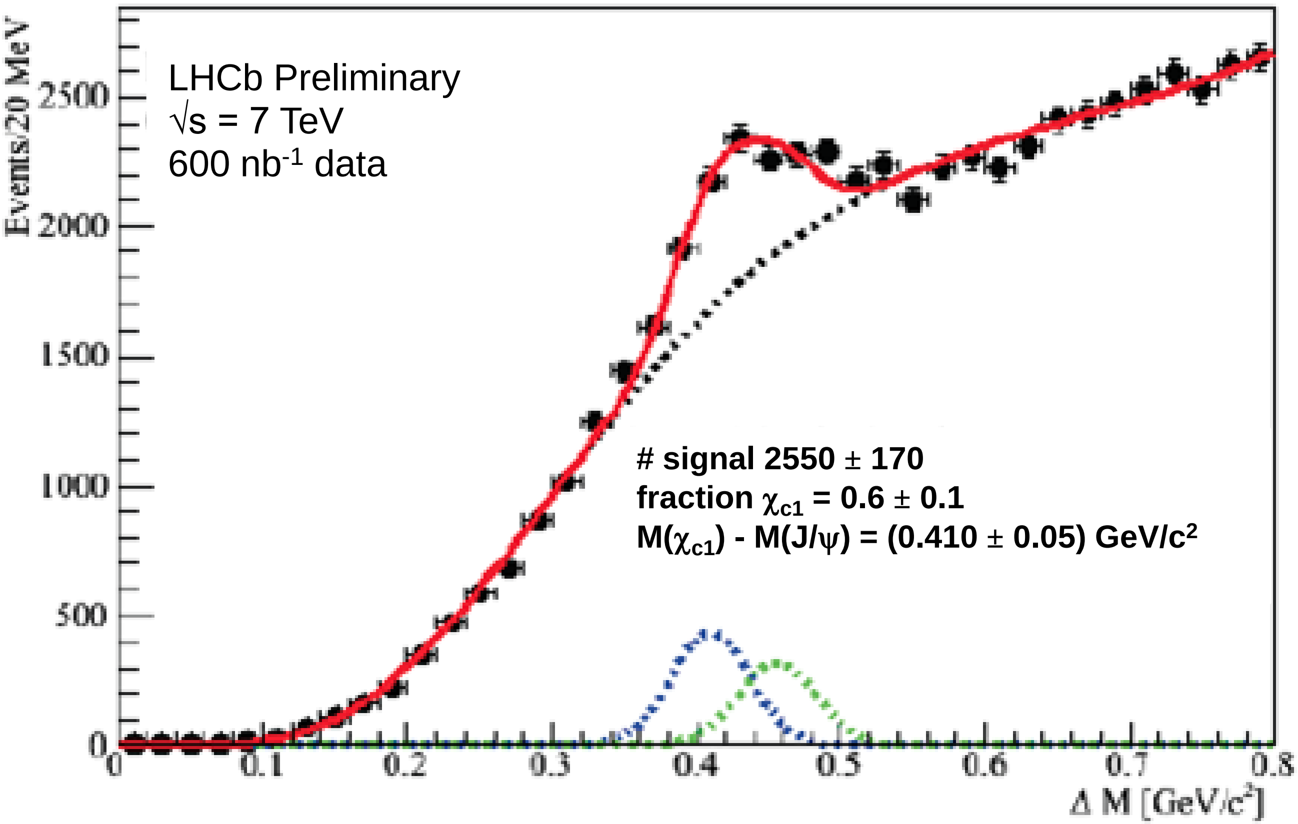
where where $\alpha_{4\pi}$ = 5.88 is the ratio of J/ψ from b events in the full range over the number of events in the region 2 < y < 4.5. The results is:

$\sigma(pp \to bbX) = 295 \pm 4\ (stat) \pm 48\ (sys)\ \mu b$

- The systematic uncertainty includes the uncertainties on the b fractions (2%) and on *Br(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*]: $\sigma(pp \to bb\ X) = 284 \pm 20 \pm 49\ \mu b$.

Prospects for future measurements

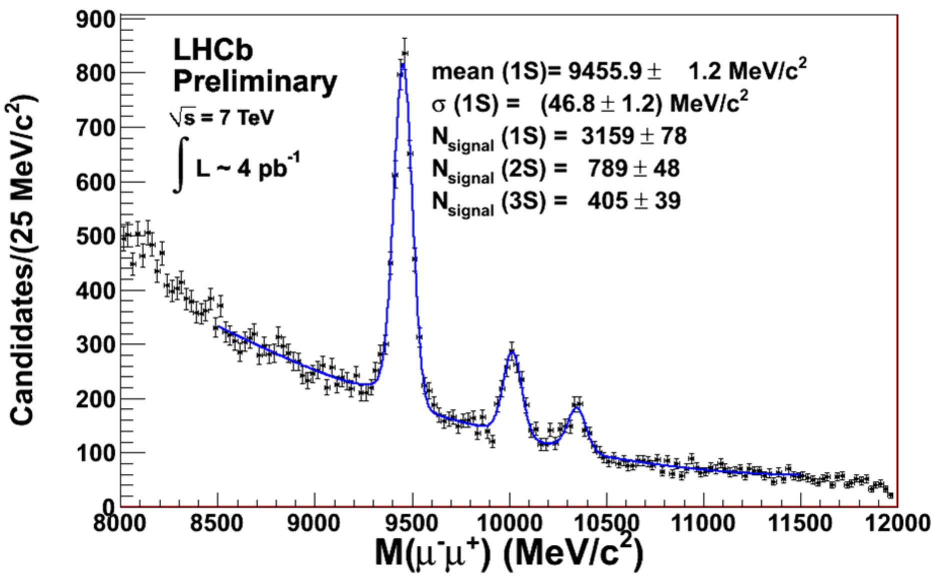
- **Polarization**: with full data sample, possible (ongoing analysis) to measure the polarization of prompt J/ψ, in bins of p_T and y.
- **Measurement of χ_c** cross-section will be possible (will also allow to know proportion of J/ψ from feed-down).



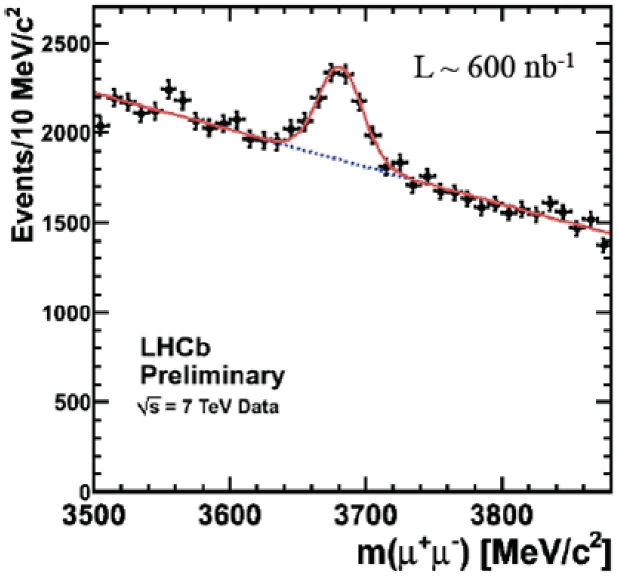
Prospects for future measurements

Using the μ⁺ μ⁻ 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 Υ(1S), Υ(2S), Υ(3S) cross sections will allow to provide a complete picture of quarkonium production in the forward rapidity region.