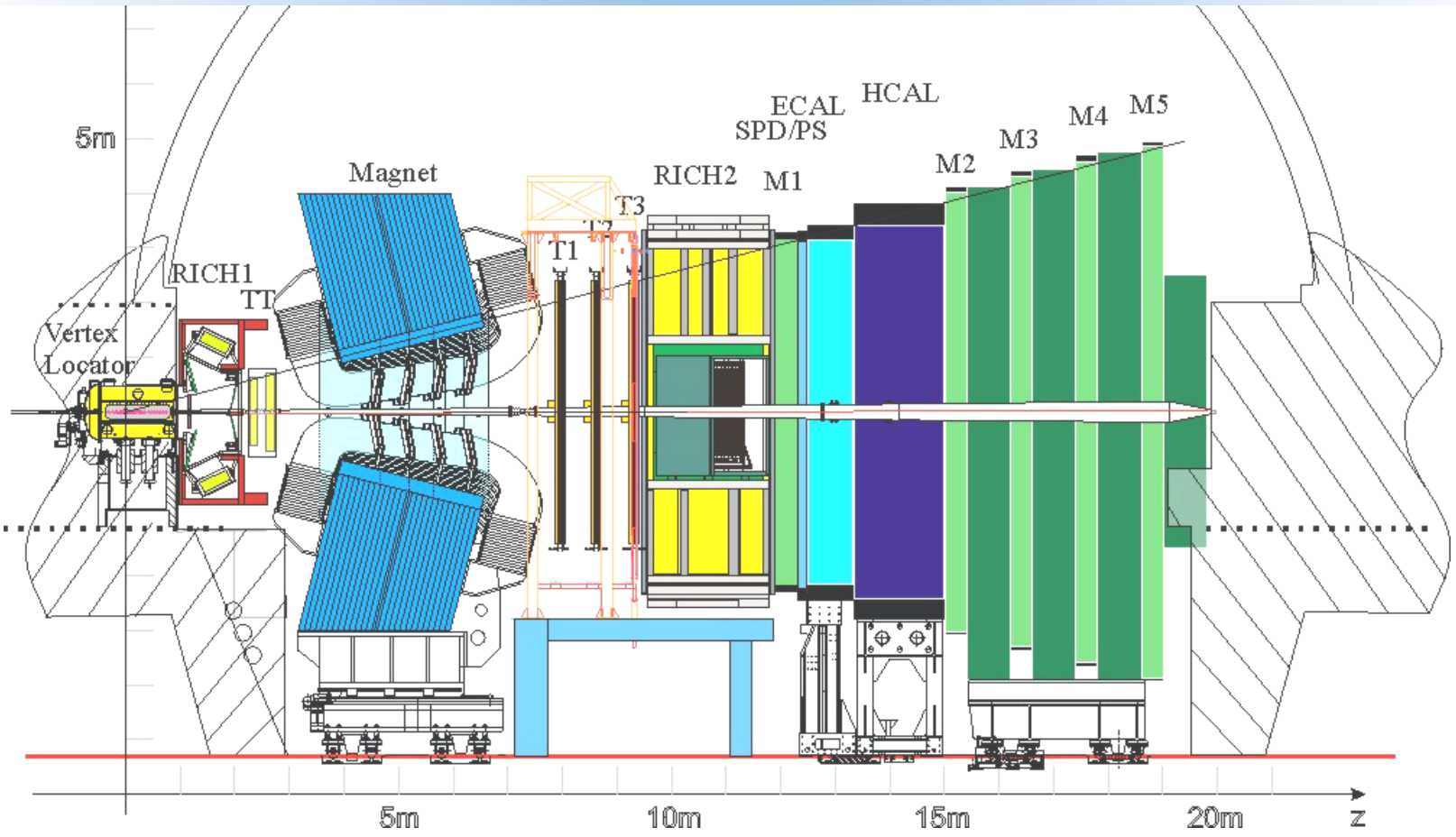
Quarkonium production studies at LHCb

Patrick Robbe, LAL Orsay, 20 May 2011

Outline

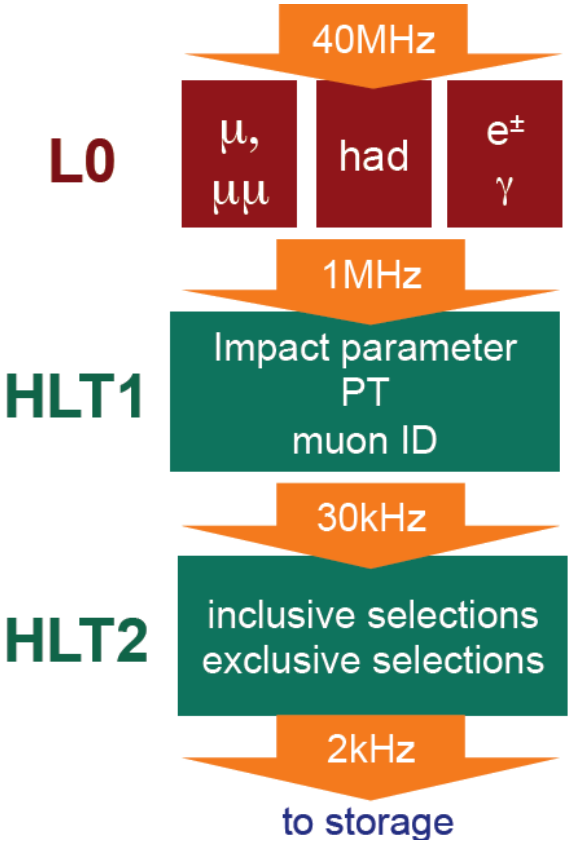
- The LHCb detector.
- Prompt J/ψ and J/ψ from *b* cross-section measurement with 5.2 pb^{-1} data.
- Double J/ψ observation.
- Exclusive J/ψ production.
- χ_c production.
- Υ production.

The LHCb Detector



- Acceptance: $1.9<\eta<4.9$ for charged tracks.

The LHCb Trigger

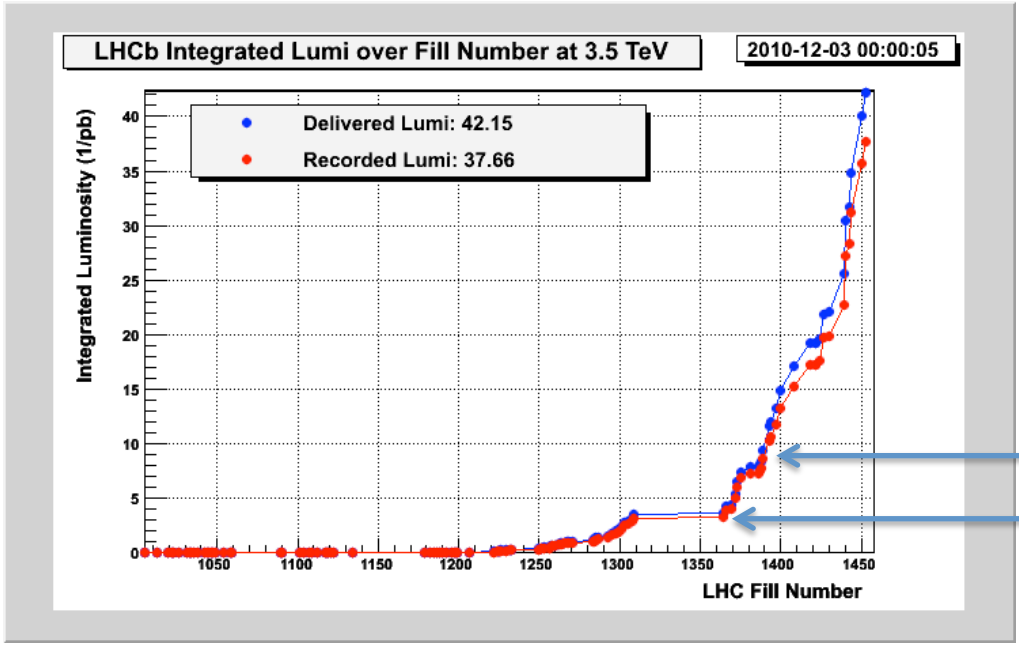


Level 0: Hardware triggers
From Muon system & calorimeters

High Level Trigger (HLT) 1: Software triggers
Add information from VELO and tracking stations to Level 0 information
Find primary vertices, etc.

HLT2: Software triggers
Use all of the detector information to make inclusive and exclusive selections

Data Taking



Data used in the J/ψ cross-section measurement

Full data sample ($37pb^{-1}$) is used for all other measurements.
Only record *pp* collisions (LHCb is off during ion runs)

J/ψ cross-section measurement

- Double differential cross-section measurement, as a function of the transverse momentum p_T and of the rapidity y:
  - 14 p_T bins, $p_T < 14$ GeV/c
  - 5 y bins, $2<y<4.5$
- Separately for:
  - Prompt J/ψ = direct J/ψ + J/ψ from χ_c and ψ(2S) feed-down,
  - J/ψ from b decays.
- Use (5.2±0.5) pb^{-1} of data collected end of September 2010 at LHCb, with two different trigger settings, with pp collisions at center-of-mass energy of 7 TeV:
  - 2.2 pb^{-1} with standard muon trigger,
  - 3 pb^{-1} with the lifetime unbiased muon trigger lines pre-scaled to cope with instantaneous luminosity increase.

Trigger and Selection

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 Trigger:	Single Muon:	Confirm L0 single Muon and p_T>1.8 GeV/c (Pre-scaled by 0.2 in 3pb^{-1} of data)
	Di-Muon:	Confirm L0 Di-Muon and $M_{\mu\mu}$>2.5 GeV/c^2
HLT2 Trigger:	Di-Muon:	$M_{\mu\mu}$>2.9 GeV/c^2

Global Event Cuts (GEC): reject events with very large multiplicities (93% efficiency)

Selection:

μ tracks:

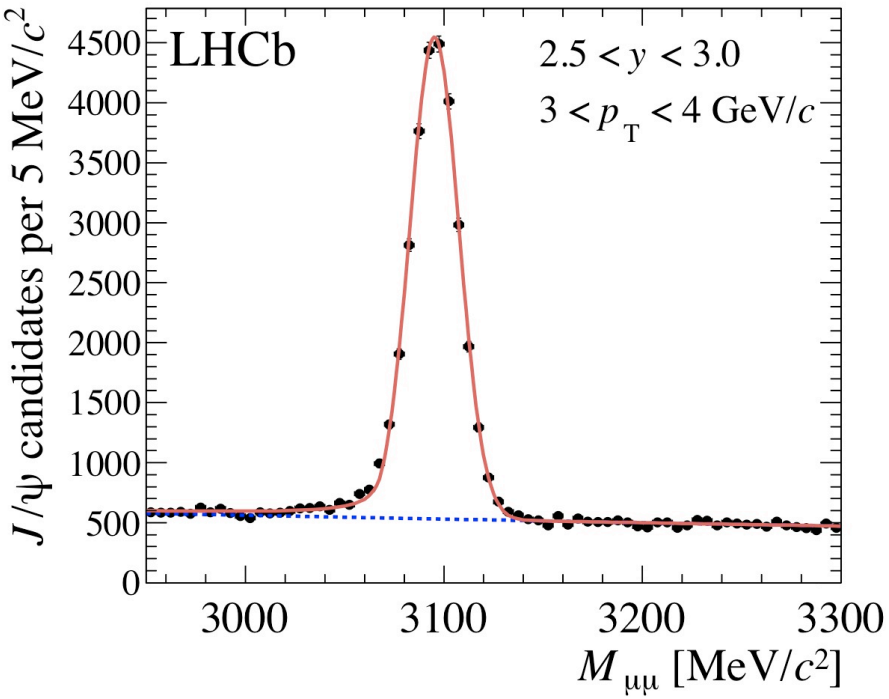
- well reconstructed tracks identified as muons in muon detector,
- p_T > 0.7 GeV/c,
- Track fit quality (χ^2/nDoF < 4).

Reconstructed J/ψ:

- mass window: 0.15 GeV/c^2,
- vertex fit quality ($p(\chi^2)$>0.5%).

Event: at least one reconstructed Primary Vertex (PV): to compute proper-time

J/ψ Sample



Mass resolution: 12.3 ± 0.1 MeV/c²

Mean mass: 3095.3 ± 0.1 MeV/c²
(stat error only)

Crystal Ball function:

$$f_{CB}(x;\mu,\sigma_M,\alpha,n) = \begin{cases} \frac{\left(\frac{n}{|\alpha|}\right)^n e^{-\frac{1}{2}\alpha^2}}{\left(\frac{n}{|\alpha|} - |\alpha| - \frac{x-\mu}{\sigma_M}\right)^n} & \frac{x-\mu}{\sigma_M} < -|\alpha| \\ \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma_M}\right)^2\right) & \frac{x-\mu}{\sigma_M} > -|\alpha| \end{cases}$$

Each mass distributions obtained in the 70 bins are fit with:

- A Crystal Ball function for the ***signal*** to take the radiative tail into account,
- An exponential function for the ***background***.
- Summing over all bins: ~500 000 signal J/ψ.

Cross-section Measurement

- Computed as:

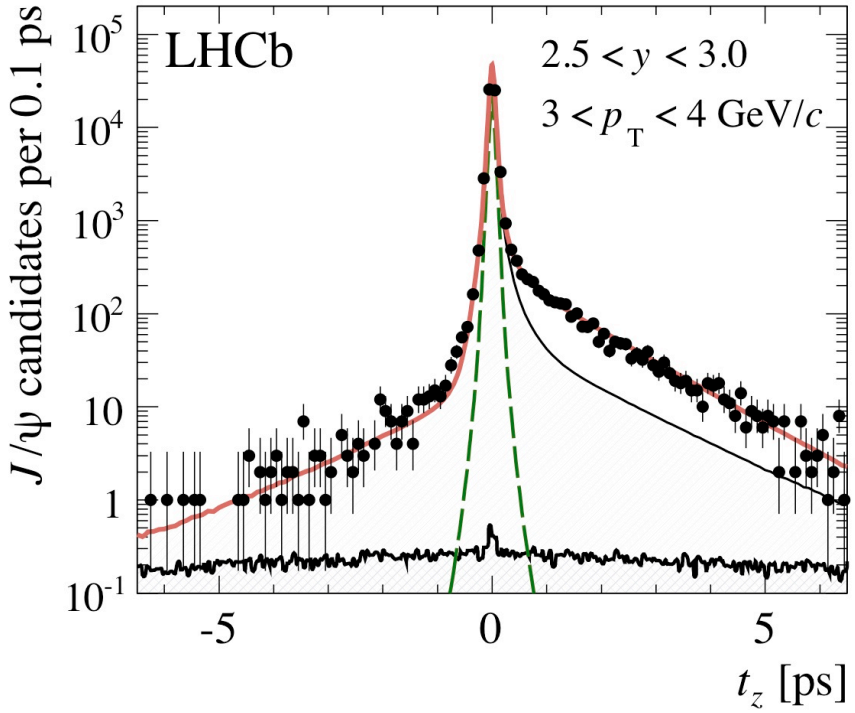
$$\frac{d^2\sigma}{dy dp_T} = \frac{N(J/\psi \to \mu^+\mu^-)}{\mathcal{L} \times \epsilon_{tot} \times \mathcal{B}(J/\psi \to \mu^+\mu^-) \times \Delta y \times \Delta p_T}$$

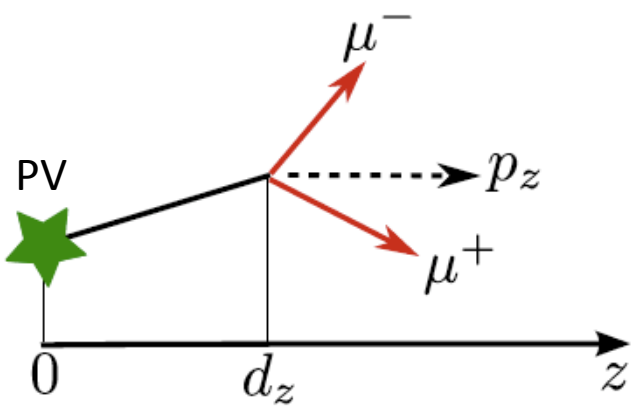
- With:
  - $N(J/\psi \to \mu^+\mu^-)$: number of reconstructed signal events, separately prompt and from *b*.
  - L: integrated luminosity (5.2 pb^{-1})
  - ε_{tot}: total detection efficiency, including acceptance, reconstruction, selection and trigger efficiencies.
  - $B(J/\psi \to \mu^+\mu^-)$: (5.94 ± 0.06) %
  - $\Delta y = 0.5$, $\Delta p_T = 1$: bin sizes.

Separation prompt J/ψ / J/ψ from *b*

- Fraction of J/ψ from *b* is given by fit of t_z, also in bins of p_T:

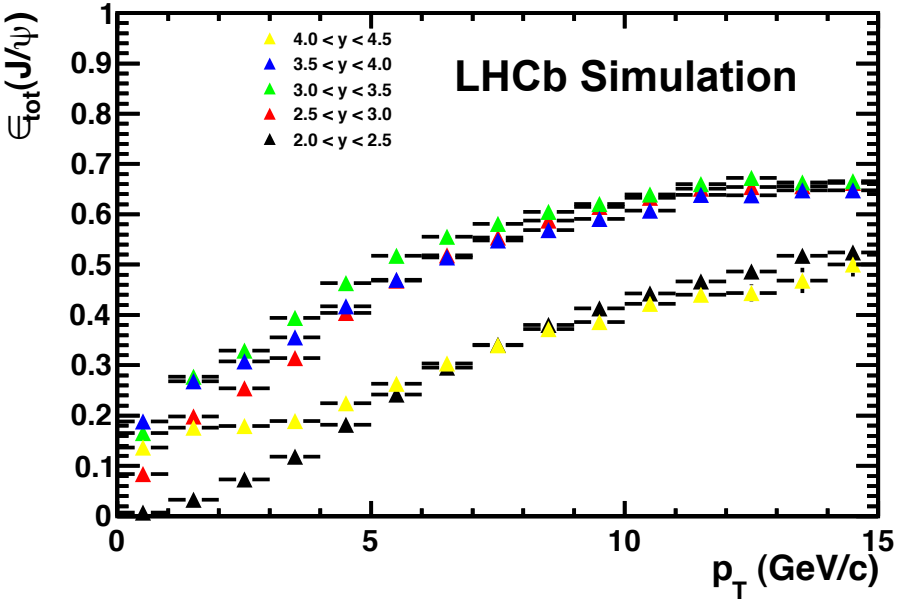
$$t_z(J/\psi) = \frac{\left(z_{J/\psi} - z_{PV}\right) \times M_{J/\psi}}{p_z}$$



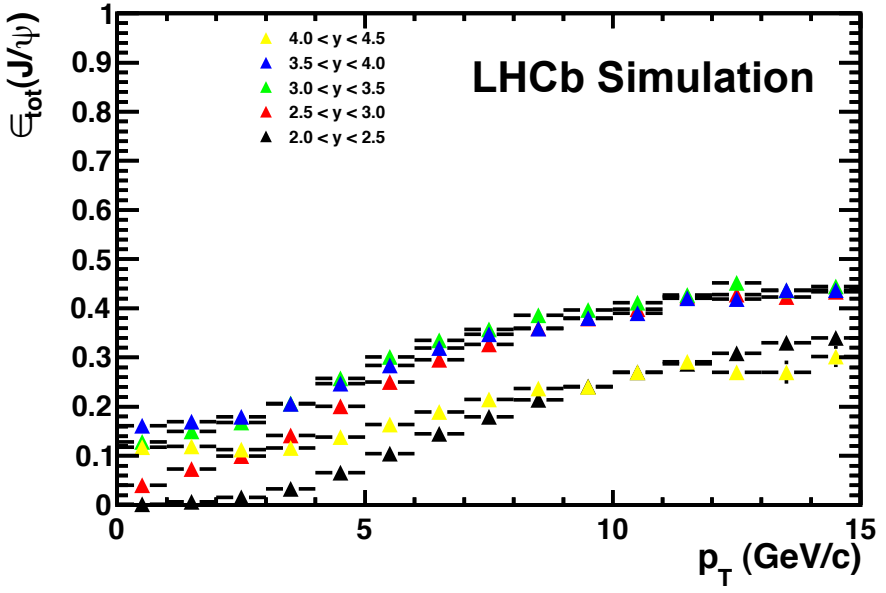


Efficiencies

- Efficiencies are computed from Monte Carlo and are extensively checked on data, with control samples.
- Efficiencies are checked in Monte Carlo to be equal for prompt J/ψ and J/ψ from *b* in each (p_T,y) bin. Small differences are treated as systematic uncertainties.



unprescaled trigger



prescaled trigger

Systematics

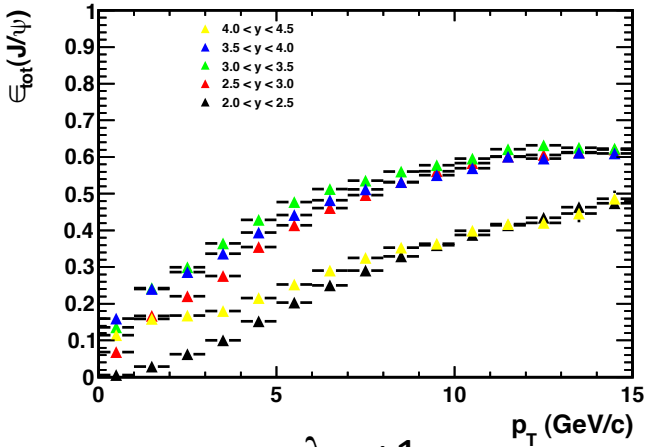
Source of systematic uncertainties considered:

Source	Systematic uncertainty (%)
Correlated between bins	
Inter-bin cross-feed	0.5
Mass fits	1.0
Radiative tail	1.0
Muon identification	1.1
Tracking efficiency	8.0
Track χ^2	1.0
Vertexing	0.8
GEC	2.0
$\mathscr{B}(J/\psi \to \mu^+\mu^-)$	1.0
Luminosity	10.0
Uncorrelated between bins	
Bin size	0.1 to 15.0
Trigger	1.7 to 4.5
Applied only to J/ψ from b cross-sections, correlated between bins	
GEC efficiency on B events	2.0
t_z fits	3.6
Applied only to the extrapolation of the $b\bar{b}$ cross-section	
b hadronisation fractions	2.0
$\mathscr{B}(b \to J/\psi X)$	9.0

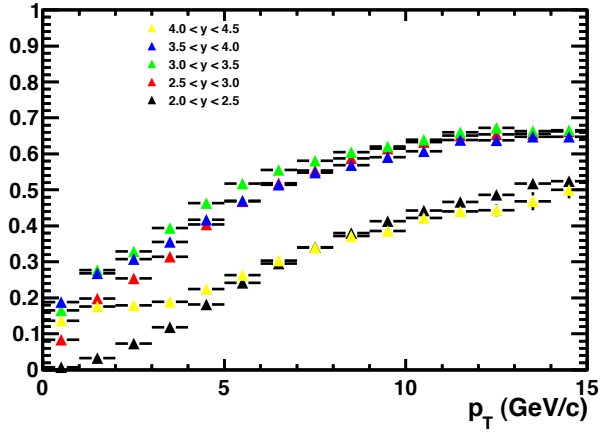
Polarization

- J/ψ are not polarized in the LHCb simulation.
- 3 extreme polarization cases studied, in the helicity frame where the angular distribution of J/ψ muons is:

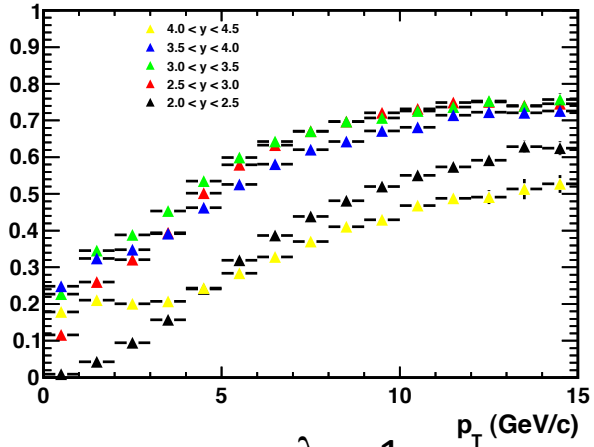
$$\frac{d^2N}{d\cos\theta\, d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi} \sin 2\theta \cos\phi + \lambda_\phi \sin^2\theta \cos 2\phi$$



λ_θ=+1



λ_θ=0

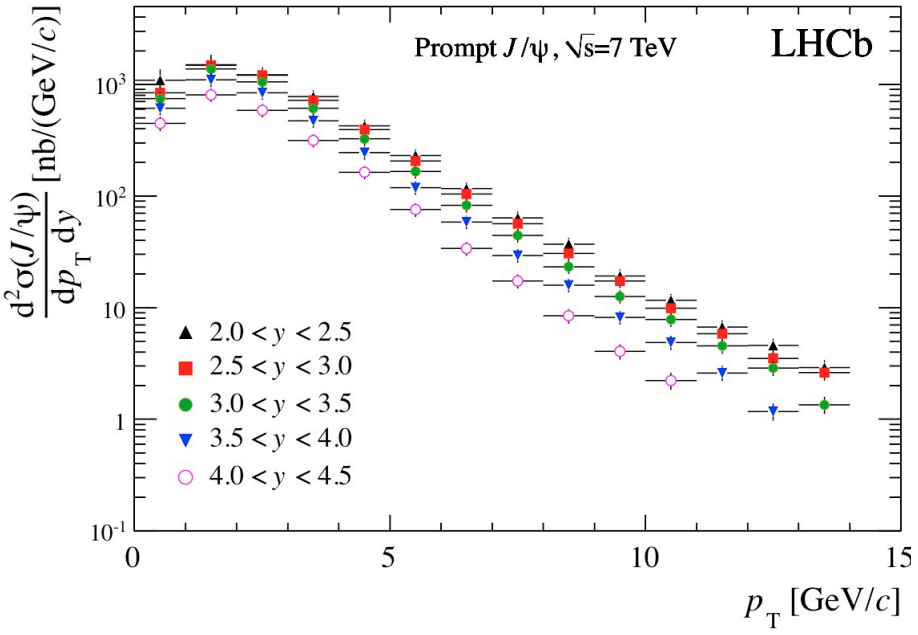


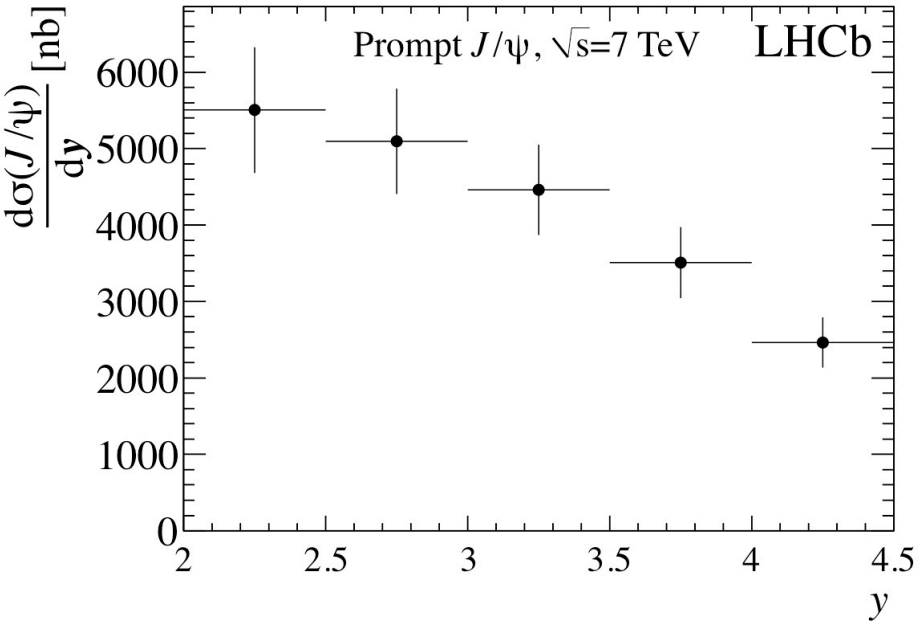
λ_θ=-1

- Differences between 3% and 30% depending on the bin: quote 3 different results of the prompt J/ψ cross-section, one for each polarization case (λ_θ and λ_θ equal to 0).
- Also studied effect of ϕ dependance: gives up to 25% larger difference in the high rapidity bin.
- Polarization measurement under progress.

Results: prompt J/ψ cross-section

Unpolarized J/ψ



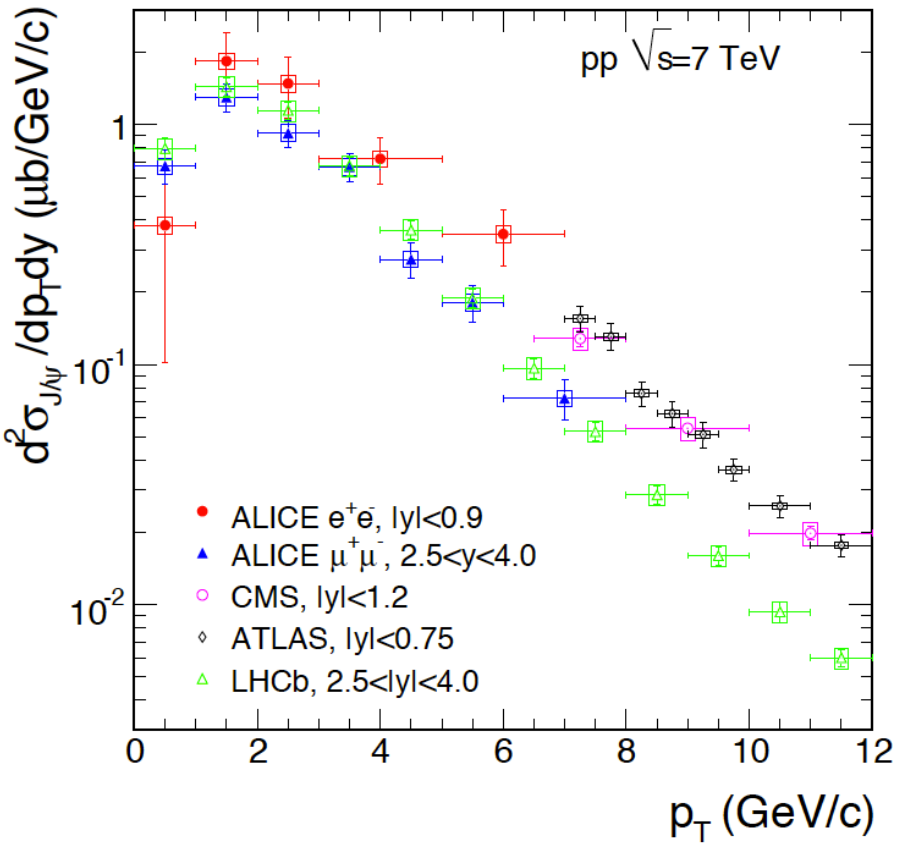


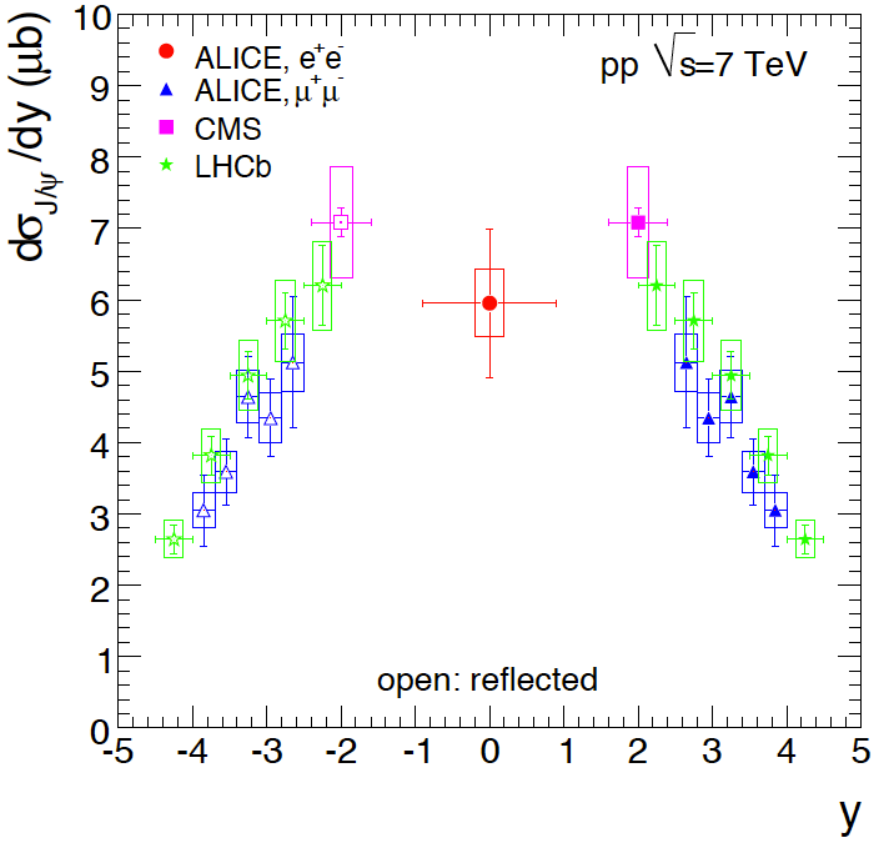
- Integrated over the acceptance:

$$\sigma\,(\text{prompt } J/\psi, p_T < 14\ \text{GeV}/c, 2.0 < y < 4.5) = 10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20}\ \mu\text{b}$$

(stat) (syst) (polar)

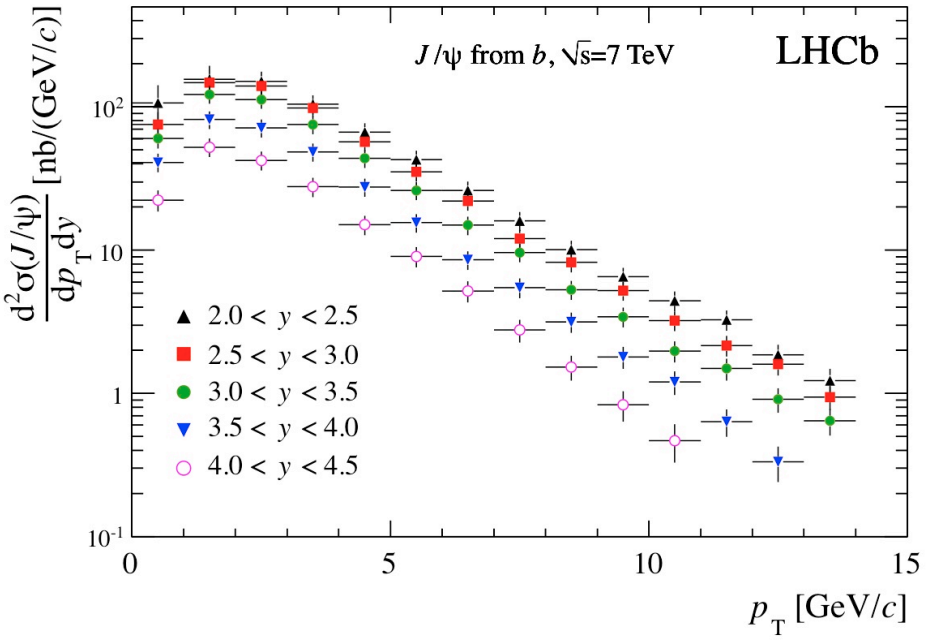
prompt J/ψ: comparison with other LHC experiments

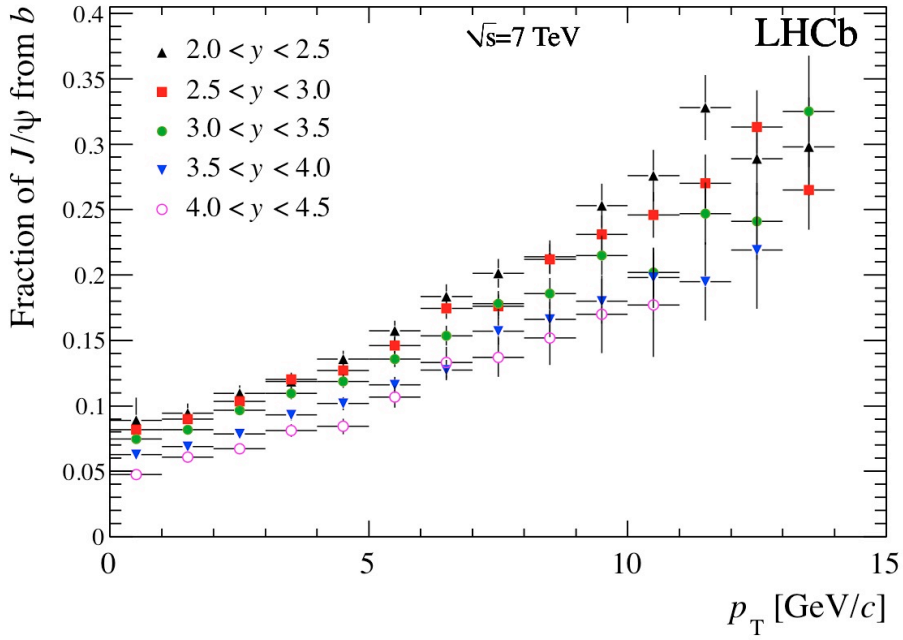




From ALICE Collaboration, K. Aamodt et al., arXiv:1105.0380 [hep-ex]

Results: J/ψ from *b* cross-section





- Integrated over the acceptance:

$$\sigma(J/\psi \text{ from } b,\ p_T < 14\ \text{GeV}/c,\ 2.0 < y < 4.5) = 1.14 \pm 0.01 \pm 0.16\ \mu\text{b}$$

Results: $b\bar{b}$ cross-section

- From the J/ψ from *b* cross-section, extrapolate to the total $b\bar{b}$ cross-section in 4π:

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

- $\alpha_{4\pi}$: extrapolation factor computed from PYTHIA 6.4, no uncertainty associated to it, equal to 5.88.
- B($b \to J/\psi$ X)=(1.16±0.1)%: measured at LEP, with 9% uncertainty.
- With Tevatron measured hadronization fractions, we estimate B($b \to J/\psi$ X)=(1.08±0.05)%: assign 2% uncertainty due to hadronization fractions.
- **Result**:

$$\sigma(pp \to b\bar{b}X) = 288 \pm 4 \pm 48\ \mu\mathrm{b}$$

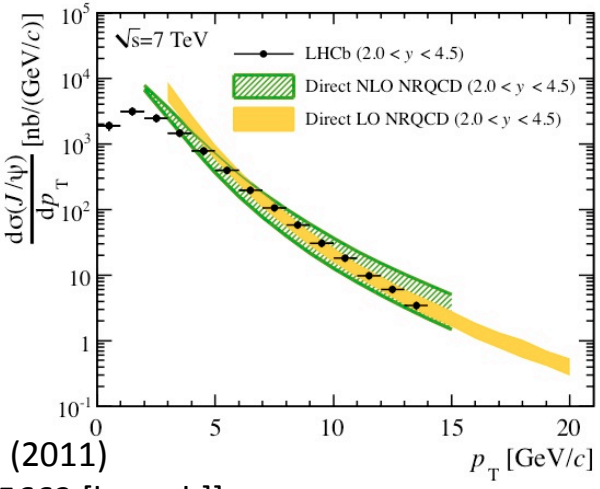
- LHCb published value from $b \to D^0\mu\nu$X (Phys.Lett.B694 (2010) 209)

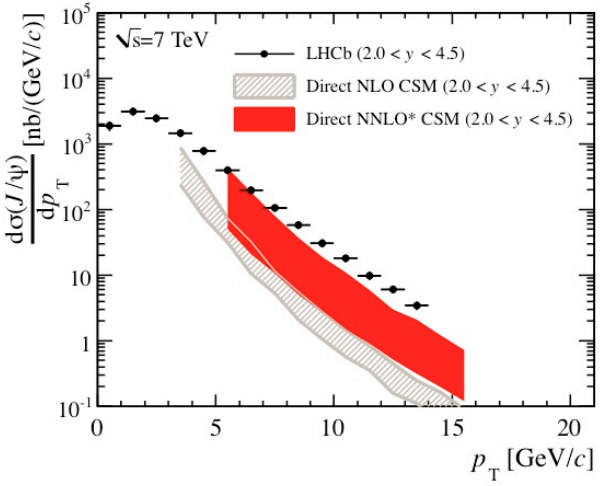
$$\sigma(pp \to b\bar{b}X) = 284 \pm 20 \pm 49\ \mu\mathrm{b}\,.$$

Prompt J/ψ comparison with theory

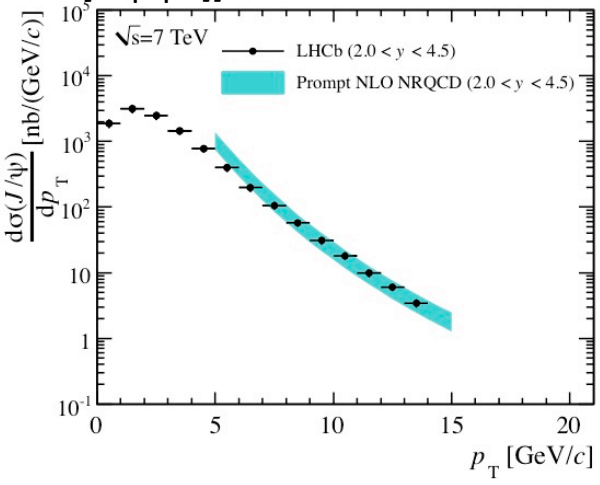
P. Artoisenet
[PoS ICHEP 2010 (2010) 192]

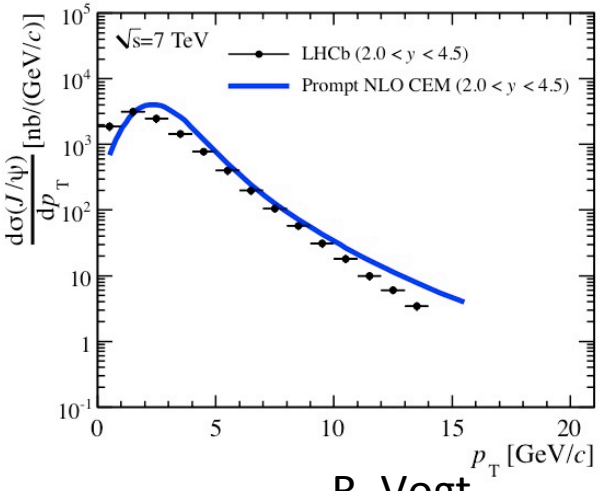
M. Butenschön and B. Kniehl
[Phys. Rev. Lett. 106 (2011) 022301, arXiv:1009.5662 [hep-ph]]





J.-P. Lansberg
[Eur. Phys. J. C 61 (2009) 693, arXiv:0811.4005 [hep-ph]]





K. T. Chao et al.
[Phys. Rev. Lett. 106 (2011) 042002, arXiv:1009.3655 [hep-ph]]

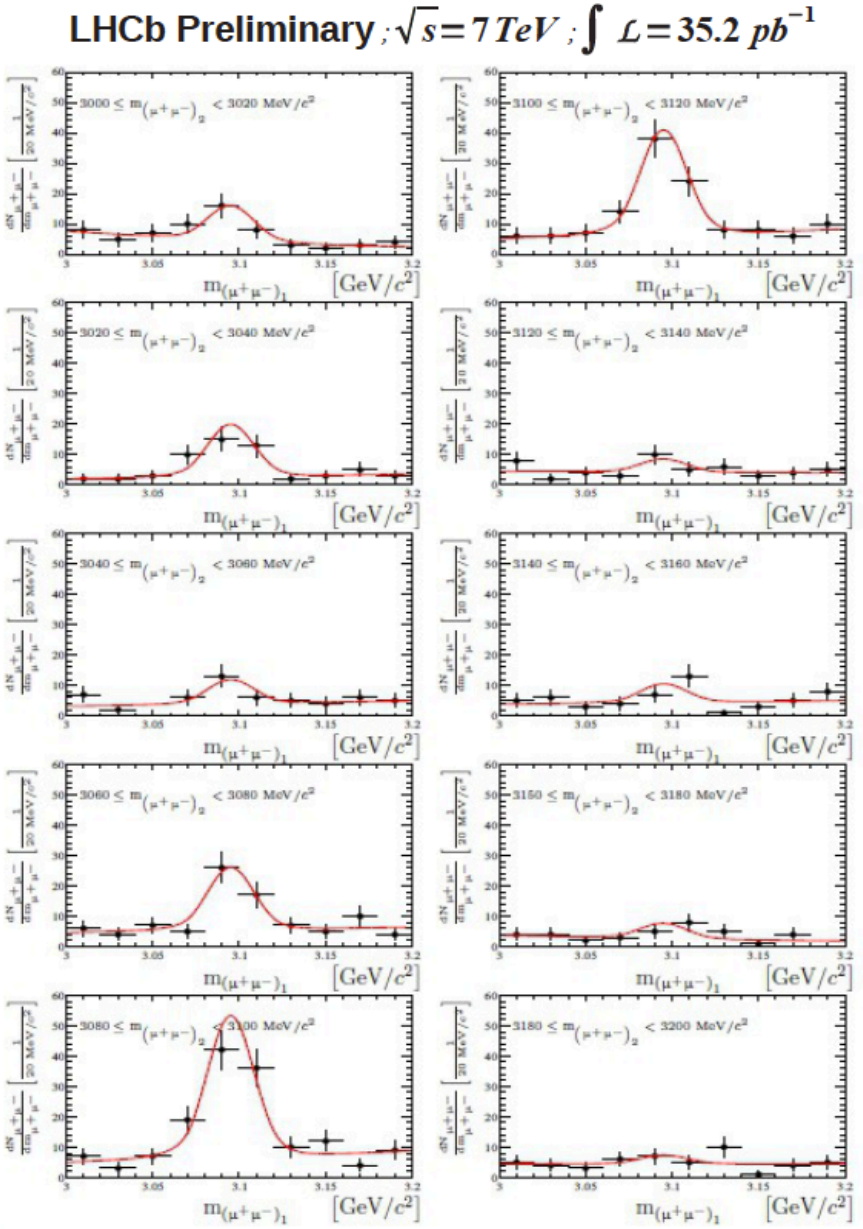
R. Vogt
[Phys. Rep. 462 (2008) 125, arXiv:0806.1013 [nucl-ex]]

Double J/ψ production observation

- Observed in NA3 (π-platinum) in 1982.
- Theoretical predictions [A.V. Berezhnoy et al., arXiv:1101.5881]
  - In 4π : $\sigma_{J/\psi,J/\psi}$ = 24.5 nb
  - In LHCb acceptance (2<*y*<4.5) : $\sigma_{J/\psi,J/\psi}$ = 4.34 – 4.15 nb
- Analysis performed in the range
  - 2<*y*<4.5
  - p_T<10 GeV/*c*
  - With the full 2010 dataset.

Selection

- 4 muons from the same vertex,
- Fit $M(\mu^+\mu^-)_1$ in bins of $M(\mu^+\mu^-)_2$, with:
  - Double Crystal Ball for the signal (with tail parameters fixed from the simulation and mass and width from the single J/ψ sample),
  - Exponential for the background.

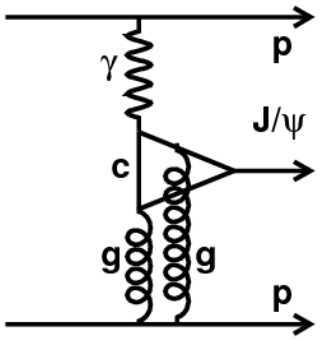


Results

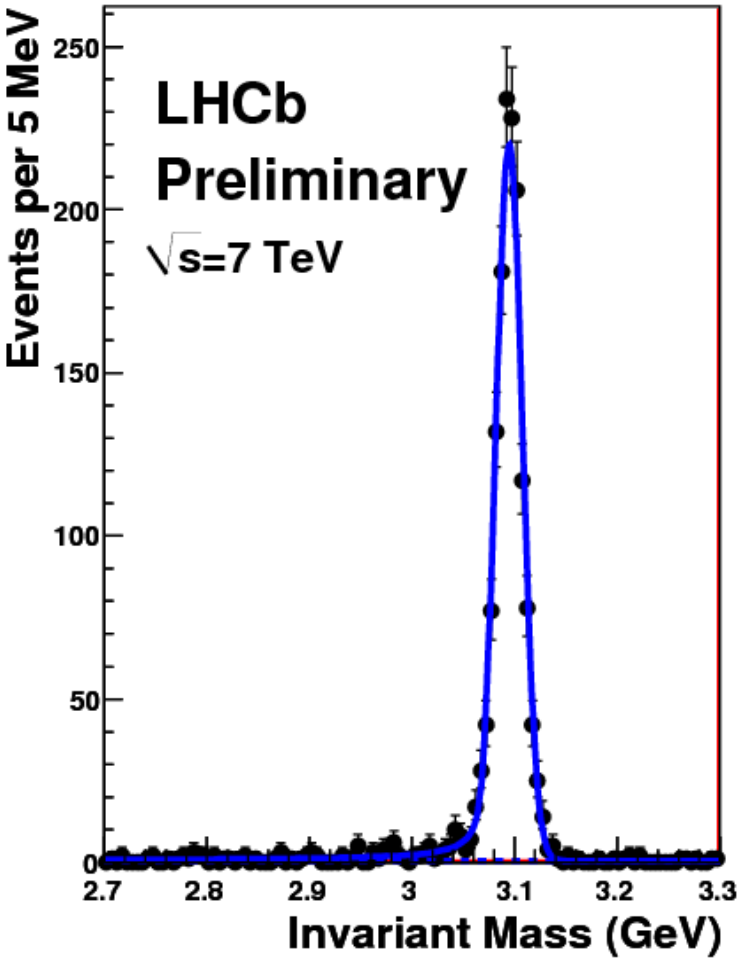
$$\sigma^{J/\psi\,J/\psi} = \frac{1}{\mathcal{L} \times \mathcal{B}^2_{\mu^+\mu^-}} \times N^{corr}_{J/\psi\,J/\psi} = 5.6 \pm 1.1 \pm 0.5 \pm 0.9\ (\text{tracking}) \pm 0.6\ (\text{lumi})\ \text{nb}$$

Exclusive J/ψ production

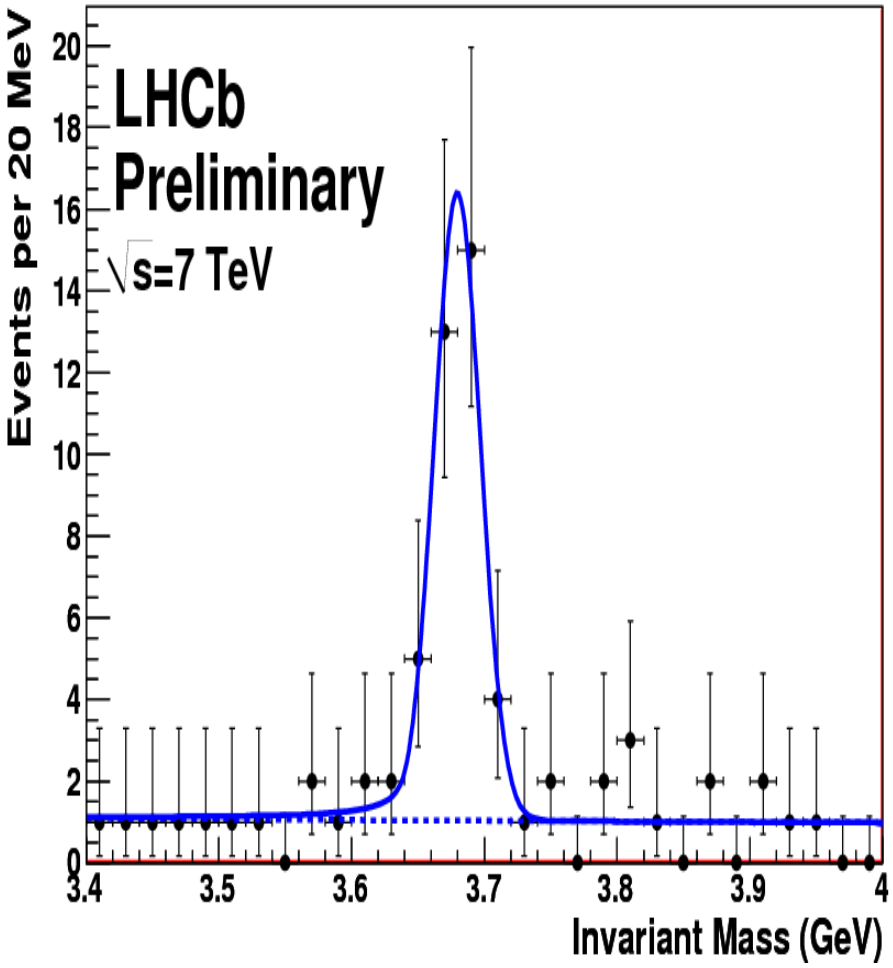
- Production of 1 J/ψ and nothing else: possible if one colour-less object is exchanged.
- Unambiguous evidence of pomeron, search for odderon.
- Selection:
  - No backward tracks (gap of 2 units of rapidity)
  - Only 2 forward muons.
  - $p_T(\mu\mu)<900$ MeV/c
  - No photons



Exclusive J/ψ mass spectrum



J/ψ



ψ (2S)

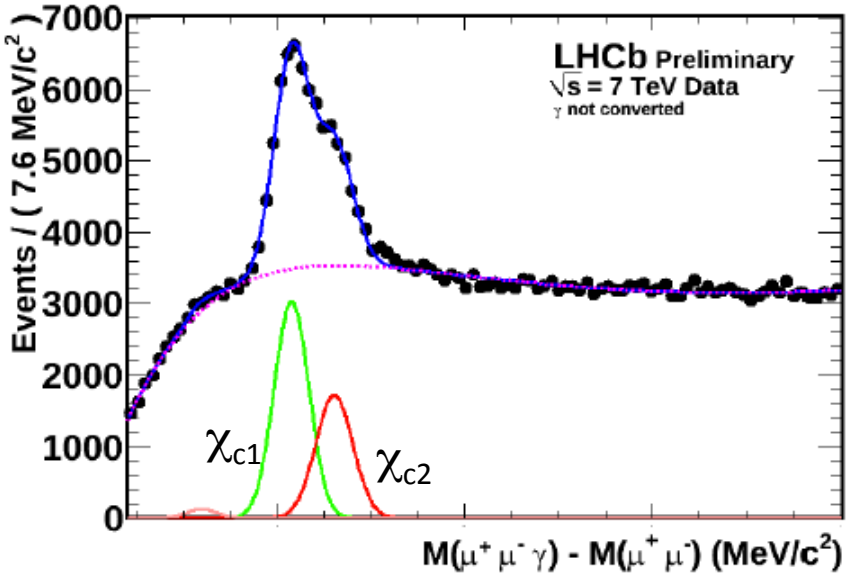
Exclusive J/ψ cross-section

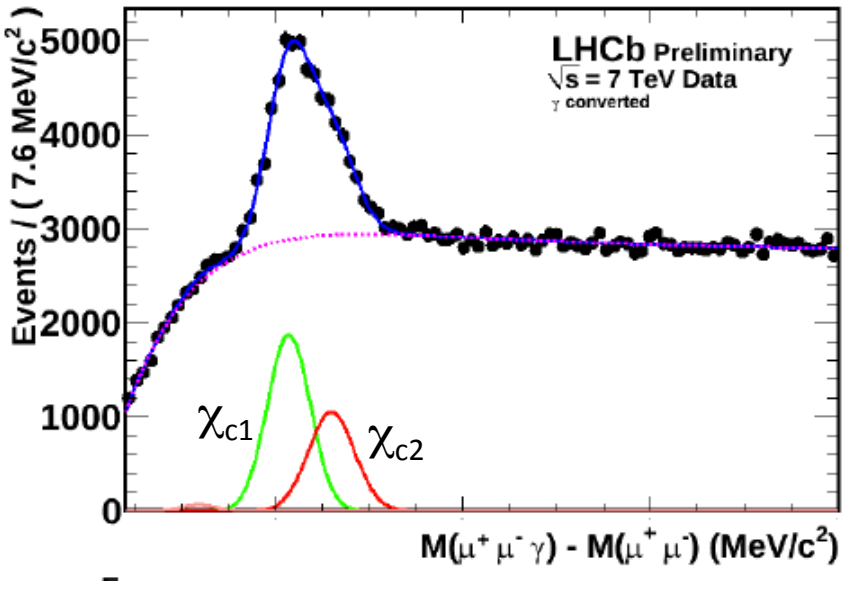
- $\sigma(J/\psi \rightarrow \mu^+\mu^-, 2<\eta(\mu^+),\eta(\mu^-)<4.5) = 474 \pm 12 \pm 45 \pm 92$ pb
- $\sigma(\psi(2S) \rightarrow \mu^+\mu^-, 2<\eta(\mu^+),\eta(\mu^-)<4.5) = 12.2 \pm 1.8 \pm 1.2 \pm 2.4$ pb
- $\sigma(\psi(2S))/\sigma(J/\psi) = 0.20 \pm 0.03$
  - CDF: $\sigma(\psi(2S))/\sigma(J/\psi) = 0.14 \pm 0.09$
  - HERA: $\sigma(\psi(2S))/\sigma(J/\psi) = 0.166 \pm 0.012$
  - Theory predictions:
    - $\sigma(J/\psi \rightarrow \mu^+\mu^-, 2<\eta(\mu^+),\eta(\mu^-)<4.5)$
      - Starlight (Klein and Nystrand): 292 pb
      - SuperChic (Harland-Lang, Khoze, Ryskin, Stirlin): 330 pb
      - Motyka and Watt: 330 pb
      - Schafer and Szczurek: 710 pb
    - $\sigma(\psi(2S) \rightarrow \mu^+\mu^-, 2<\eta(\mu^+),\eta(\mu^-)<4.5)$
      - Starlight (Klein and Nystrand): 6 pb
      - Schafer and Szczurek: 17 pb

χ_c production

- Very important measurement to know better the J/ψ production: allows to extract the feed-down J/ψ production.
- χ_c are reconstructed in the decay mode $\chi_c \rightarrow$ J/ψ γ, where the photon is reconstructed in the electromagnetic calorimeter.
- First results obtained for the measurement of the ratio: $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in bins of J/ψ p_T, between 3 and 15 GeV/*c*.
- Absolute cross-section measurements foreseen for the summer.

χ_c mass fits

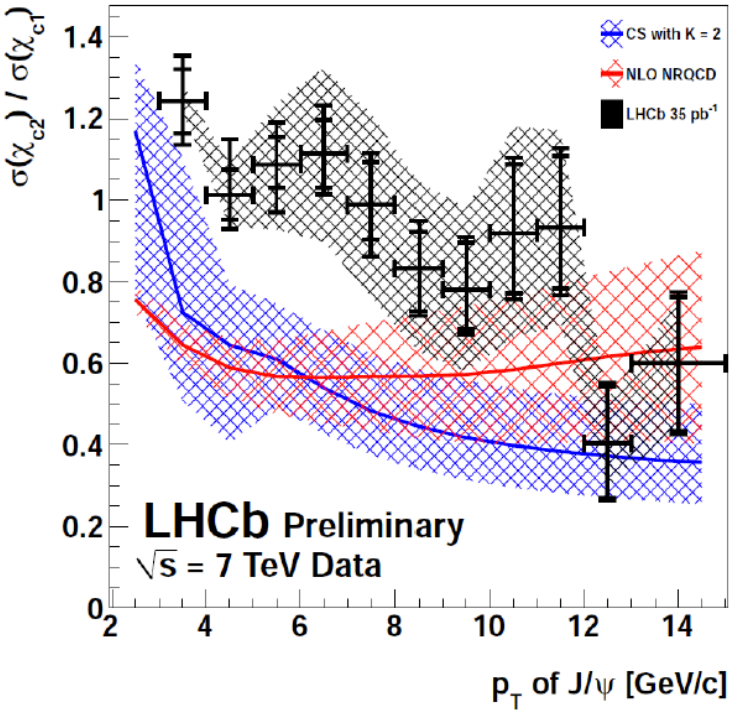




- Data sample separated between converted and unconverted γ (after the magnet: both cases give a single cluster in the ECAL but have different resolutions)
- Only prompt χ_c, χ_c from B decays are rejected using the t_z of the J/ψ.
- Number of χ_c candidates extracted from fits to the $\Delta M = M(J/\psi\ \gamma)-M(J/\psi)$ distributions, in bins of p_T of 1 GeV/c width.
- Resolutions controlled from π^0.

χ_c production cross-section ratios

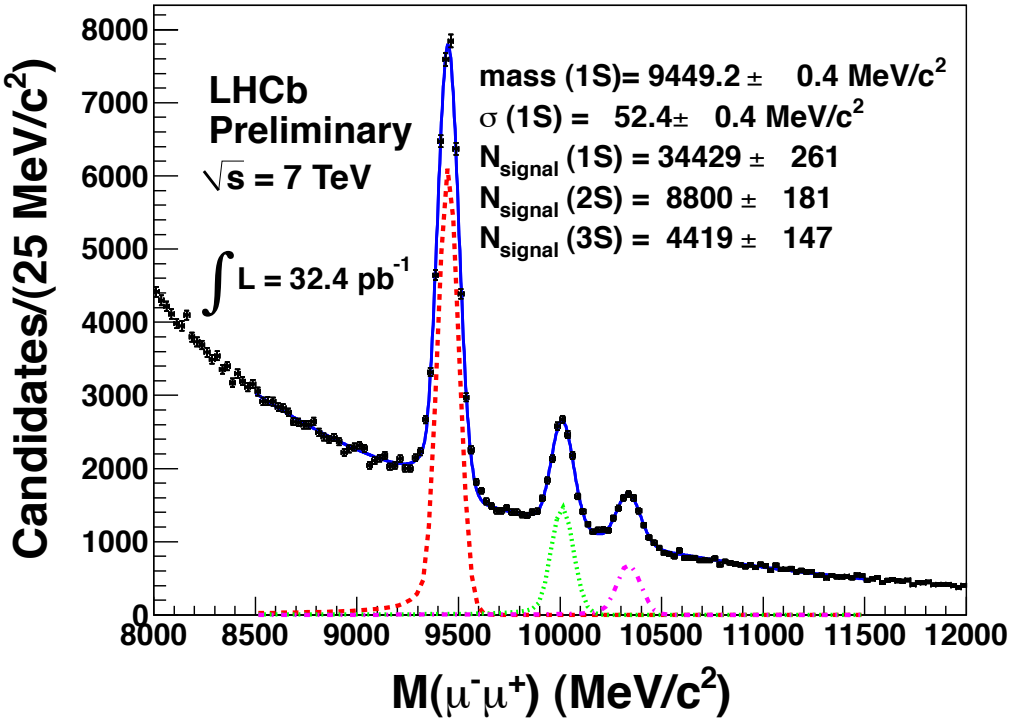
- Signal yields are corrected with efficiency from MC.
- Large effect of unknown polarization of the χ_c.
- Main systematics from the modelization of the background shapes and from BR($\chi_c \rightarrow J/\psi\ \gamma$).



- LHCb data, with statistical error, total error and variation due to polarization
- LO Color Singlet model (L. Harlang-Land)
- NLO NRQCD (KT Chao, arXiv: 1002.3987 [hep-ph])

Υ(1S) production

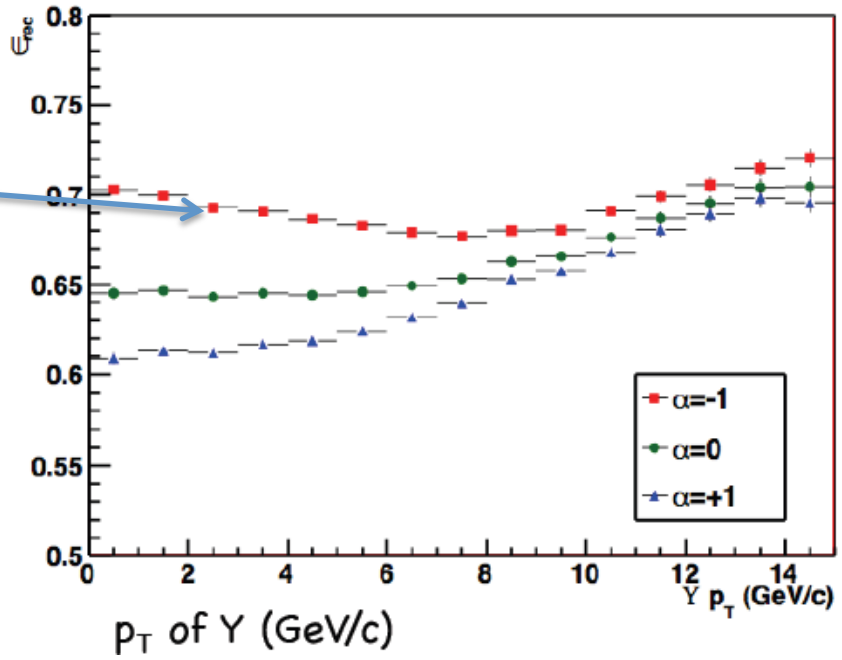
- Only prompt production, with feed-down from χ_b or Υ(nS), that will also be studied in the future.
- Very similar selection and method as J/ψ measurement.
- Resolutions allow to separate the 3 states.



Υ(1S): systematics

SOURCE	VALUE
luminosity	10%
ϵ^{trig} calculation	2-67%
polarisation on A	0-33%
polarisation on ϵ^{rec}	0-21%
choice of fit function	1%
unknown p_T spectrum	1%
GEC	2%
$\epsilon^{trackquality}$	0.5% per track
$\epsilon^{track-finding}$	4% per track
vertexing	1%
ϵ^{muonID}	1.1%

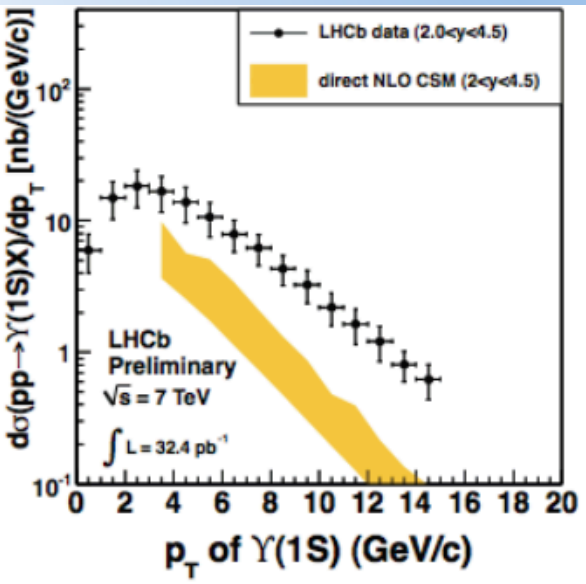
Reconstruction efficiencies for different polarizations.

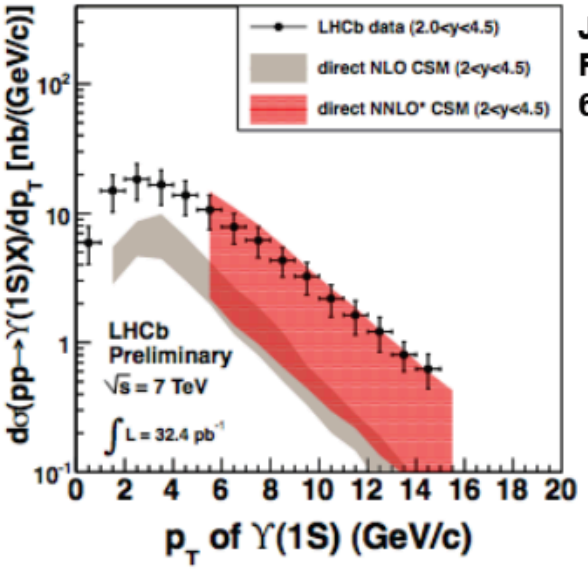


Here also, large uncertainties due to unknown polarization.

Υ(1S): results

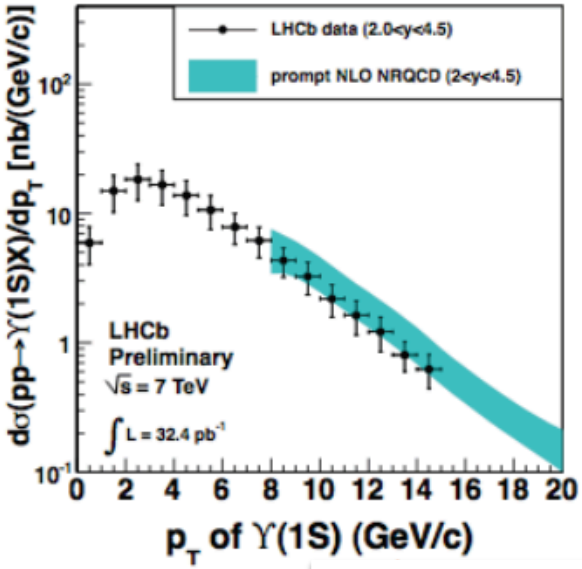
P. Artoisenet, PoS ICHEP 2010 (2010) 192.

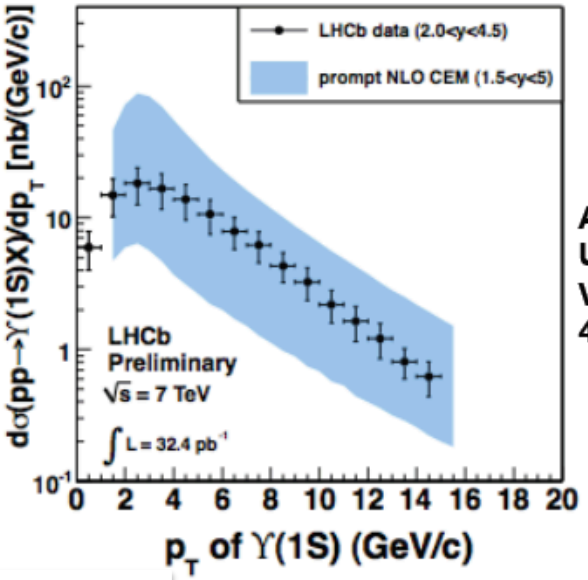




J.-P. Lansberg, Eur. Phys. J. C 61 (2009) 693

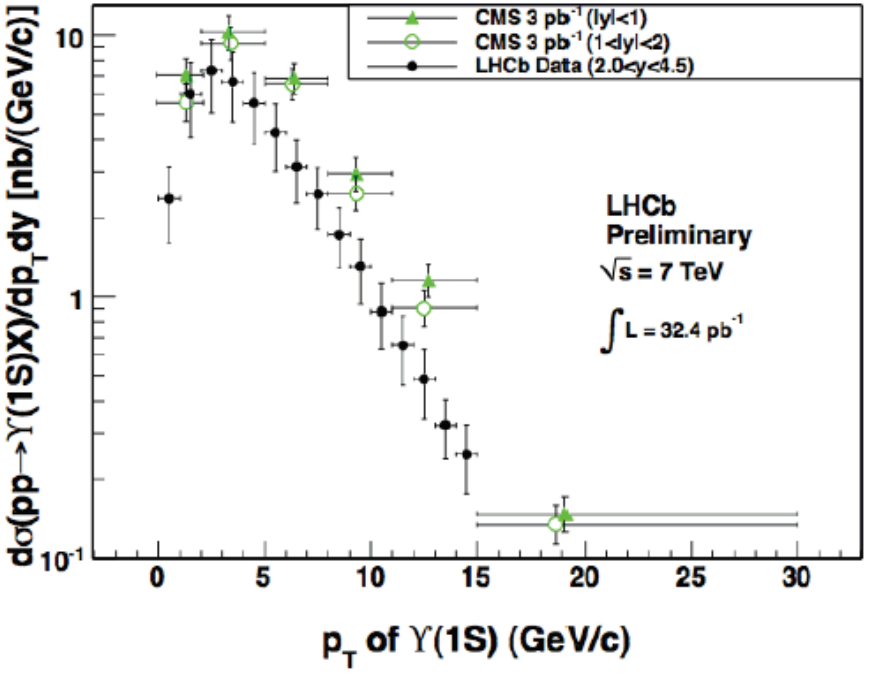
Y. Q. Ma, K. Wang and K. T. Chao, Phys. Rev. Lett. 106 (2011) 042002.

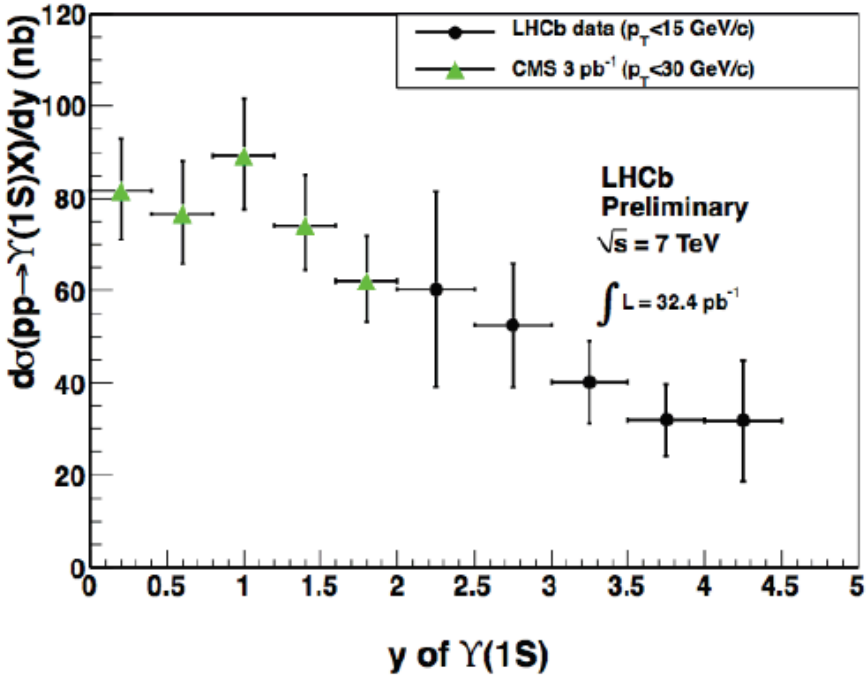




A. D. Frawley, T. Ullrich and R. Vogt, Phys. Rep. 462 (2008) 125.

Υ(1S): comparison with CMS

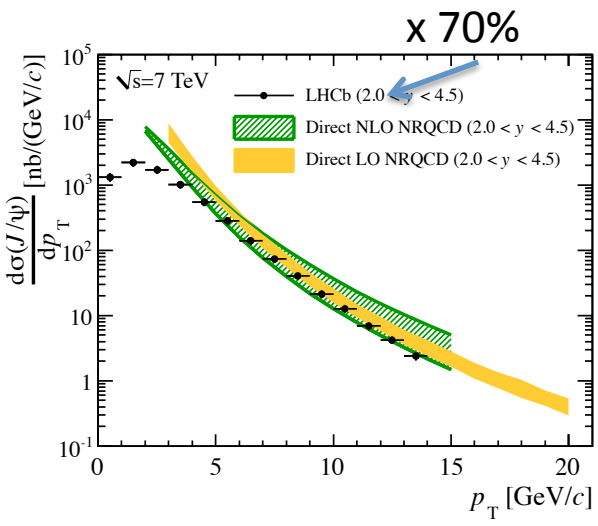


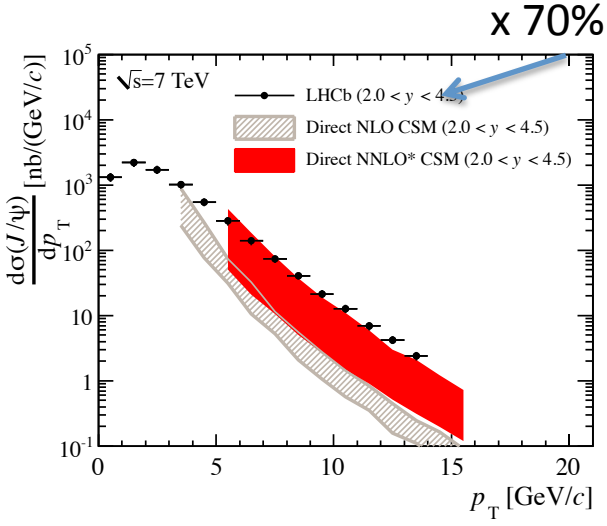


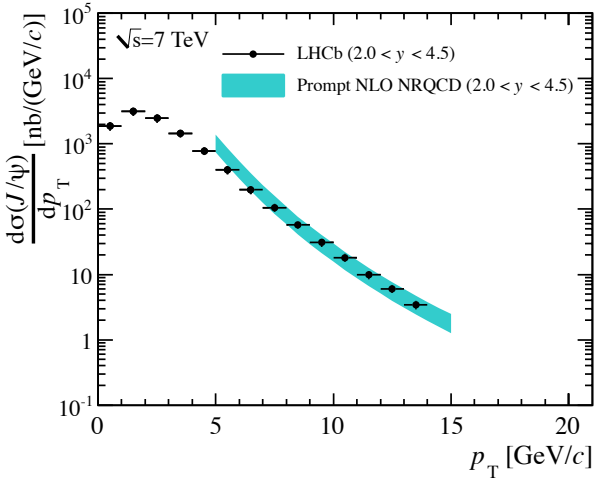
Conclusions

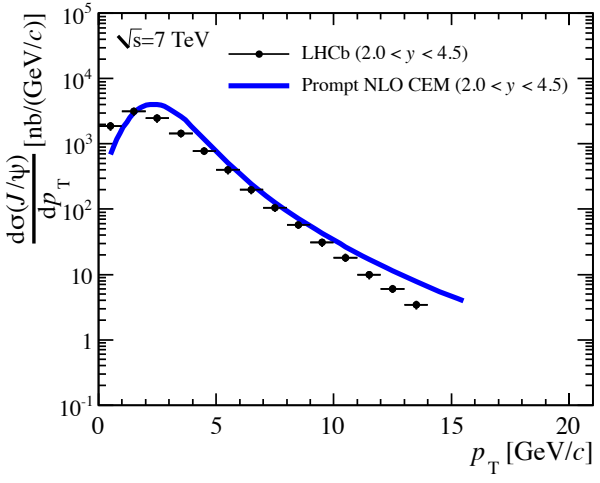
- J/ψ cross-section measurement at LHCb with 5 pb^{-1} of data, as a function of p_T and y, [arXiv:1103.0423], Eur. Phys. J. C **71** (2011) 1645.
- Large uncertainties due to unknown J/ψ polarization: future polarization measurement will address this issue.
- Observation of double J/ψ production in hadronic collisions [LHCb-CONF-2011-009].
- Observation of central exclusive production of J/ψ [LHCb-CONF-2011-022].
- χ_{c1} and χ_{c2} production measurements [LHCb-CONF-2011-020].
- Υ production [LHCb-CONF-2011-016]
- New results soon on ψ(2S), Υ(2S) and Υ(3S) production

Comparison with theory

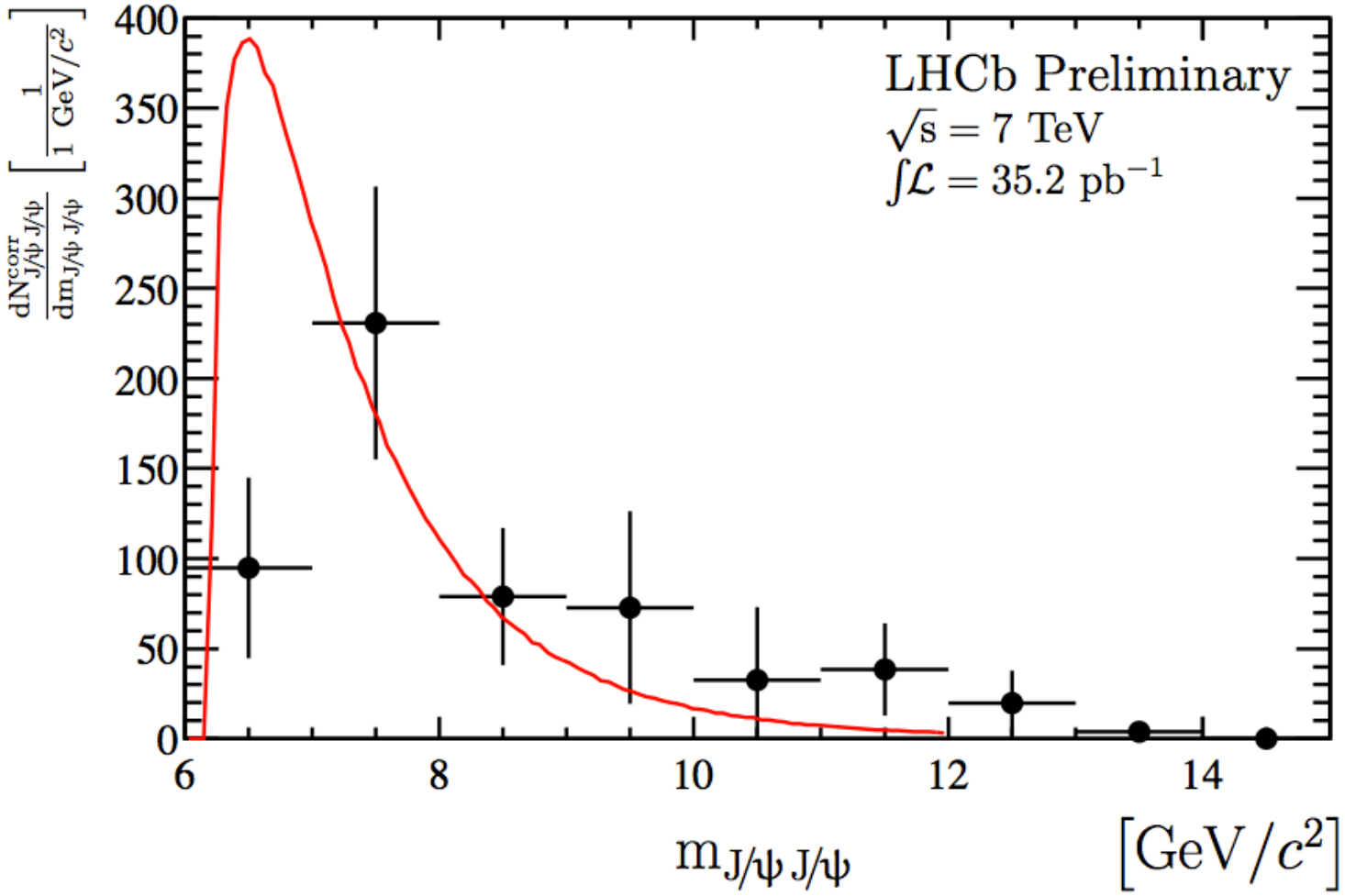




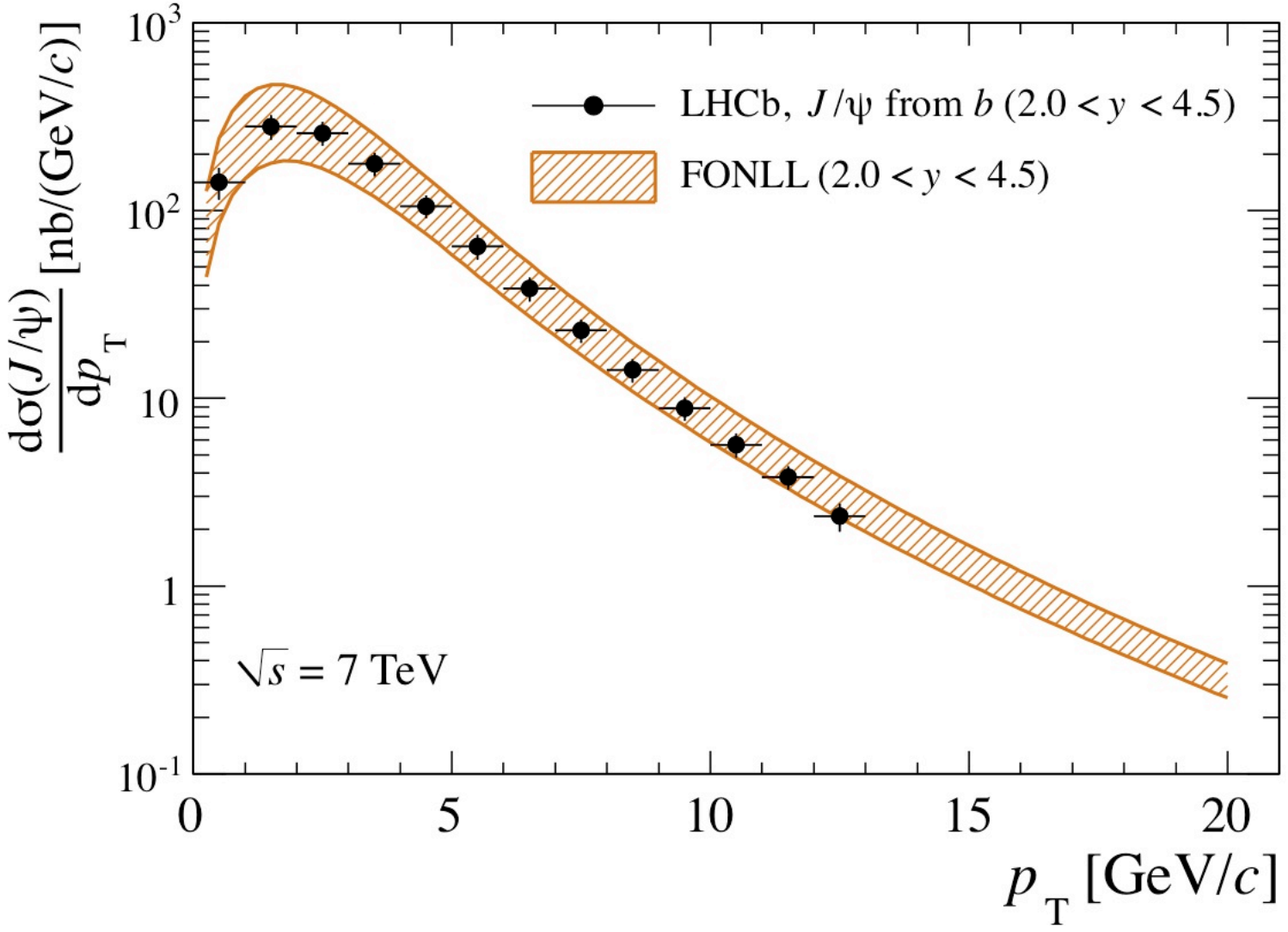




M(J/ψ J/ψ)


LHCb Preliminary
$\sqrt{s} = 7$ TeV
$\int \mathcal{L} = 35.2\ \mathrm{pb}^{-1}$
$\frac{dN^{corr}_{J/\psi\,J/\psi}}{dm_{J/\psi\,J/\psi}} \left[\frac{1}{1\ \mathrm{GeV}/c^2}\right]$
$m_{J/\psi\,J/\psi}$ $[\mathrm{GeV}/c^2]$
0
50
100
150
200
250
300
350
400
6
8
10
12
14

J/ψ from *b* comparison with theory



M. Cacciari