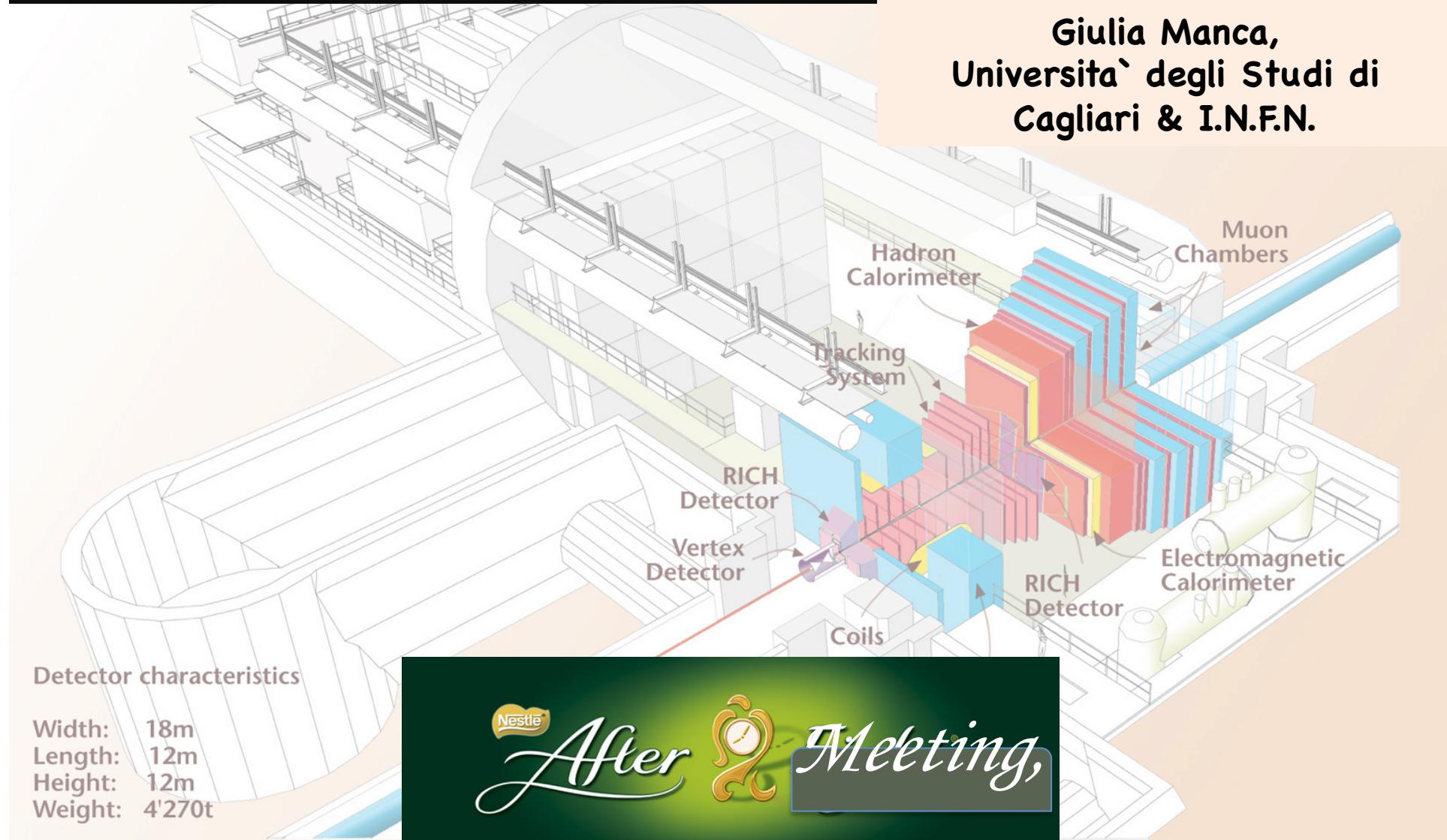


# Quarkonium Physics at LHCb: Present and Future

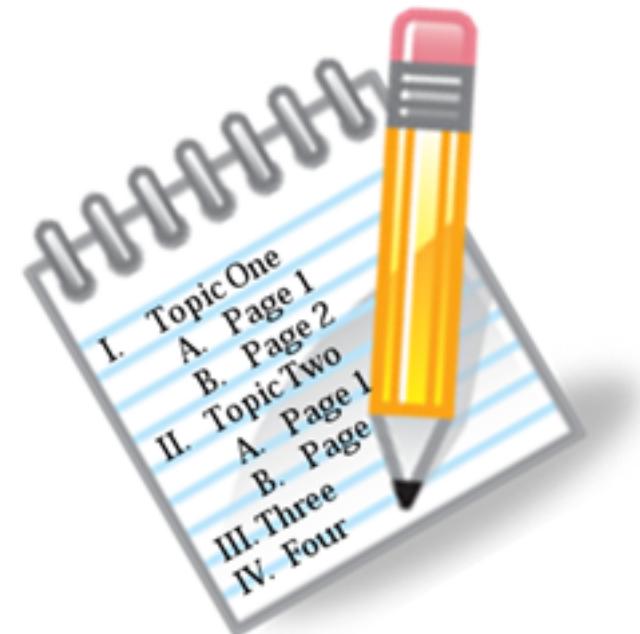
Giulia Manca,  
Universita` degli Studi di  
Cagliari & I.N.F.N.



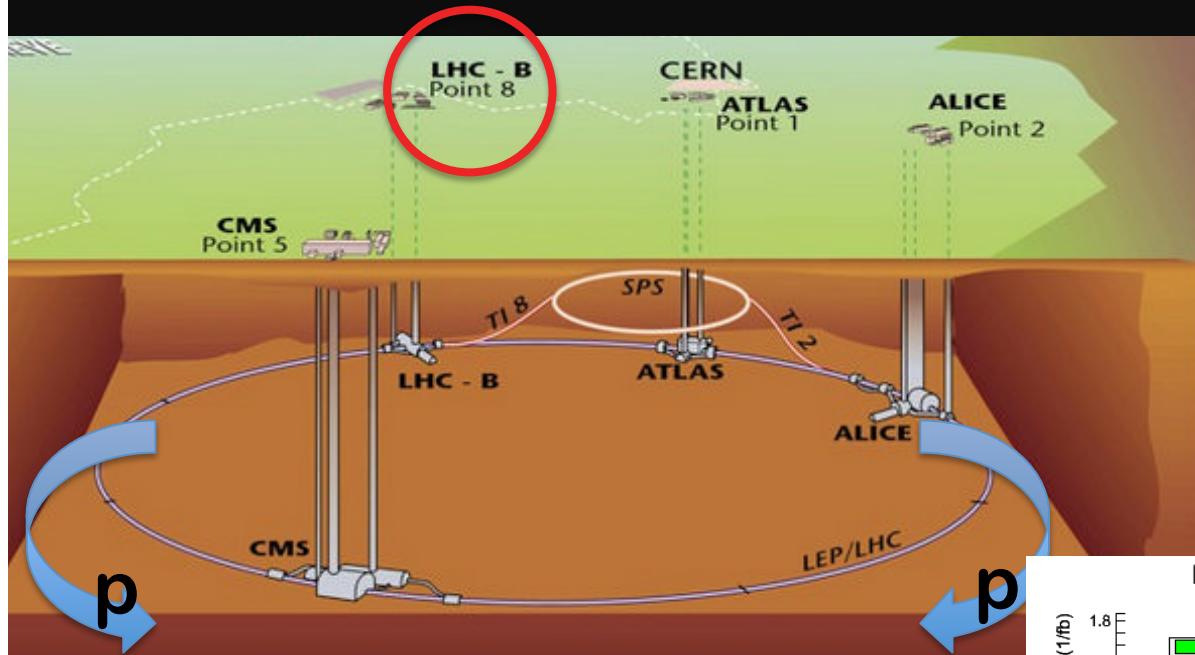
Grenoble (FR), 10<sup>th</sup> May 2012

# Outline

- Theory and motivation
- The LHCb Detector
- Selected quarkonia results
  - Now-ish
  - At the end of the run (2018)
  - For the upgrade
- Conclusions and outlook



# LHC and LHCb



2010-2011 :  $\sqrt{s} = 7 \text{ TeV}$

$L = 1-2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

2014 : (NOMINAL) :

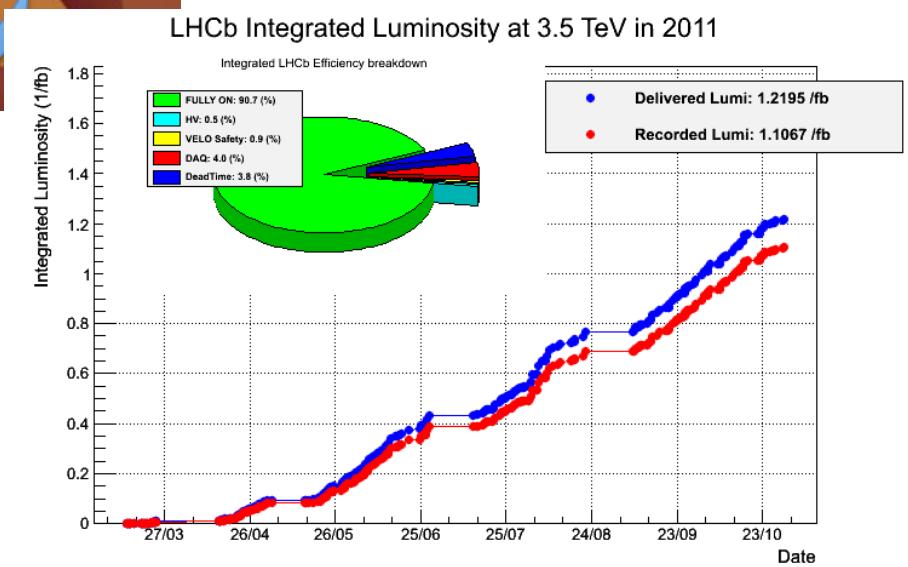
$\sqrt{s} = 14 \text{ TeV}$

$L \approx 4 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  (LHCb specific)

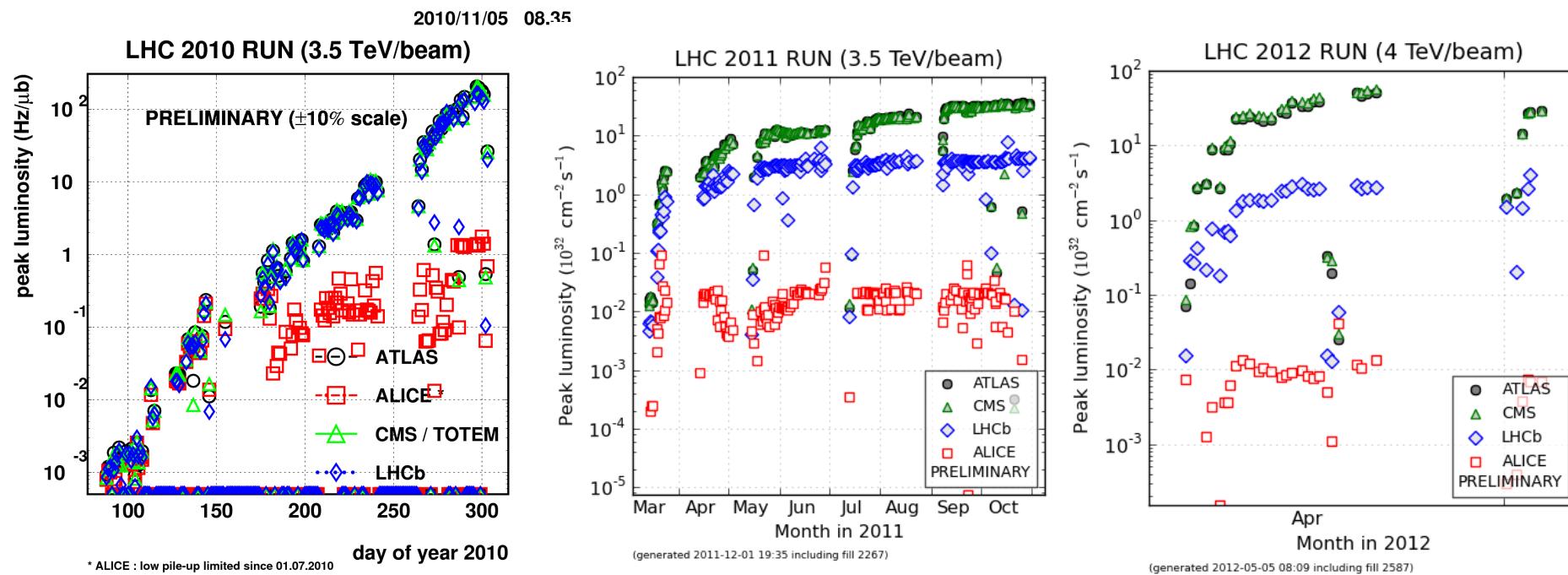
pp collider : NOW (2012) :

→ @  $\sqrt{s} = 8 \text{ TeV}$

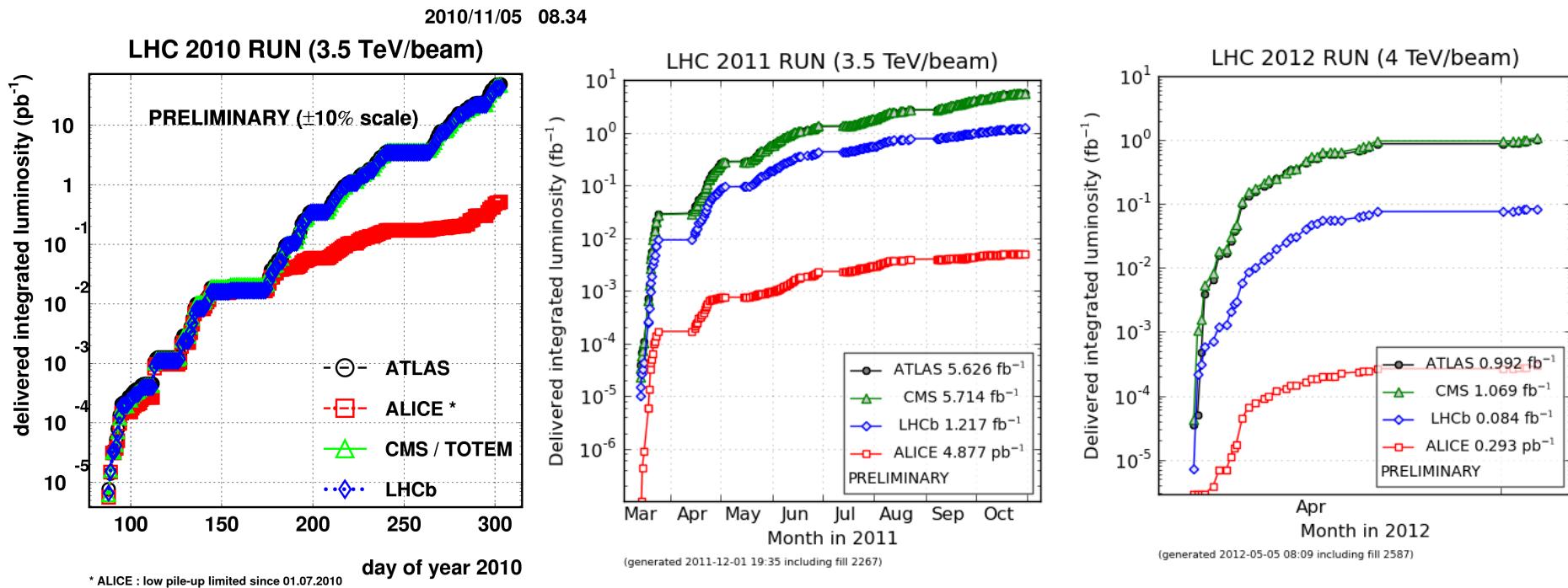
→  $L \approx 4 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$



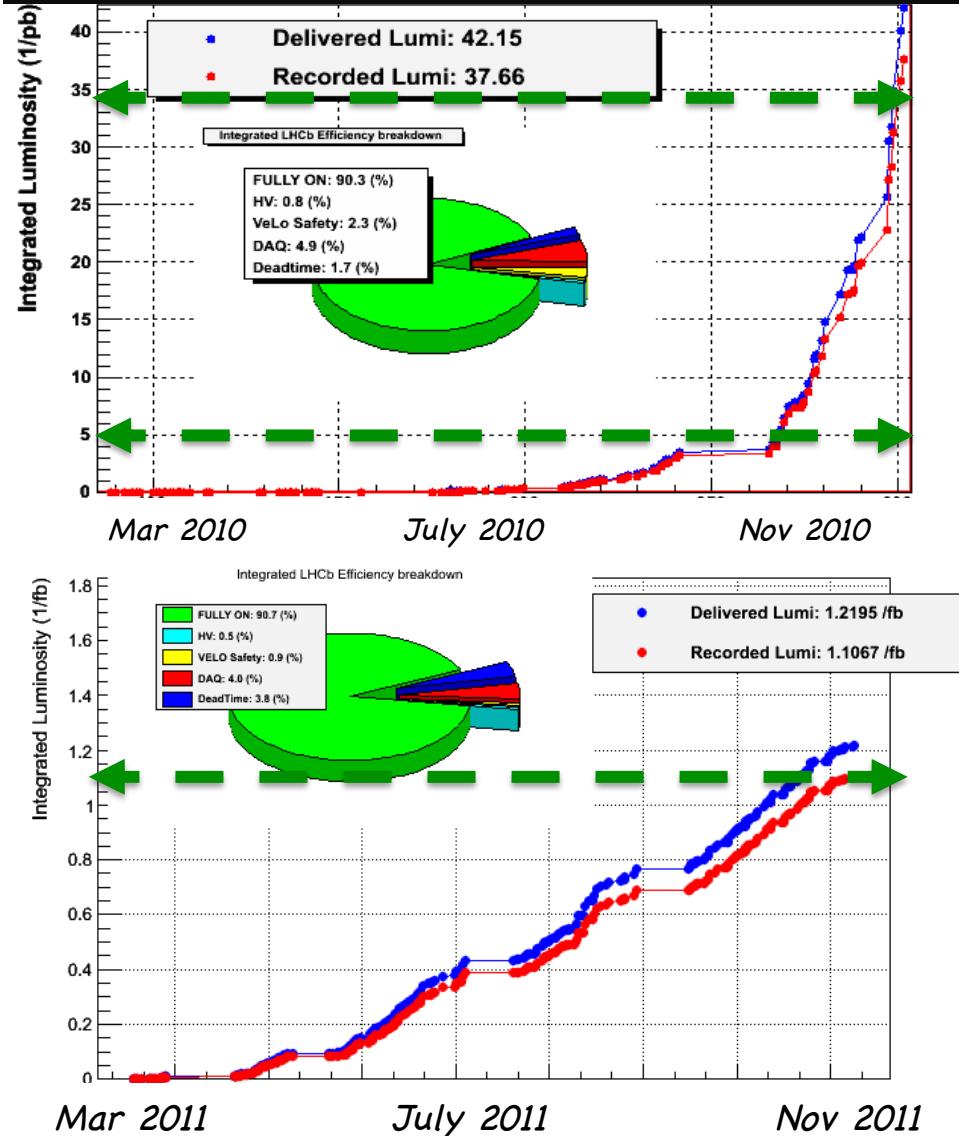
# Peak Luminosity



# Integrated Luminosity

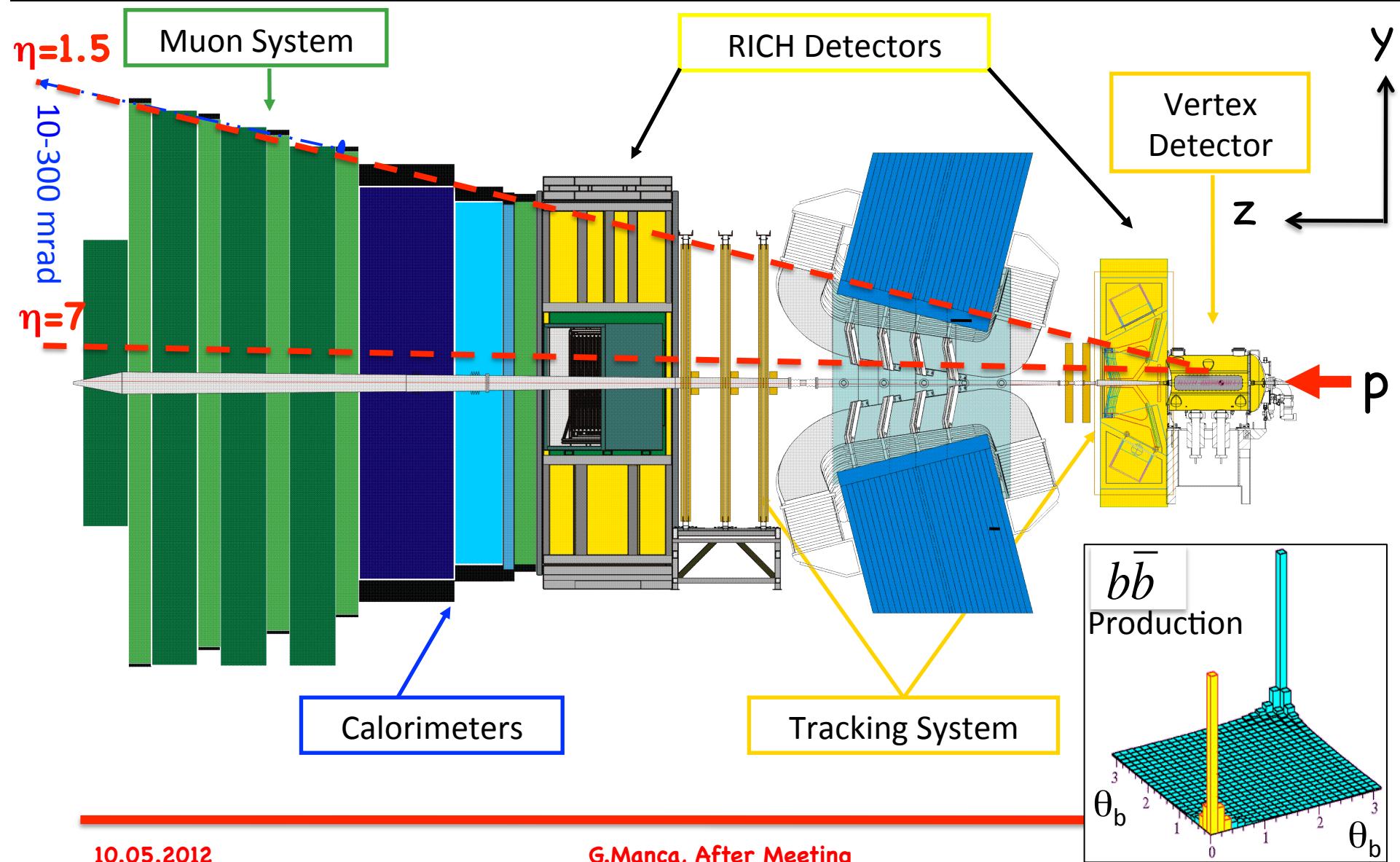


# Luminosity @ LHCb

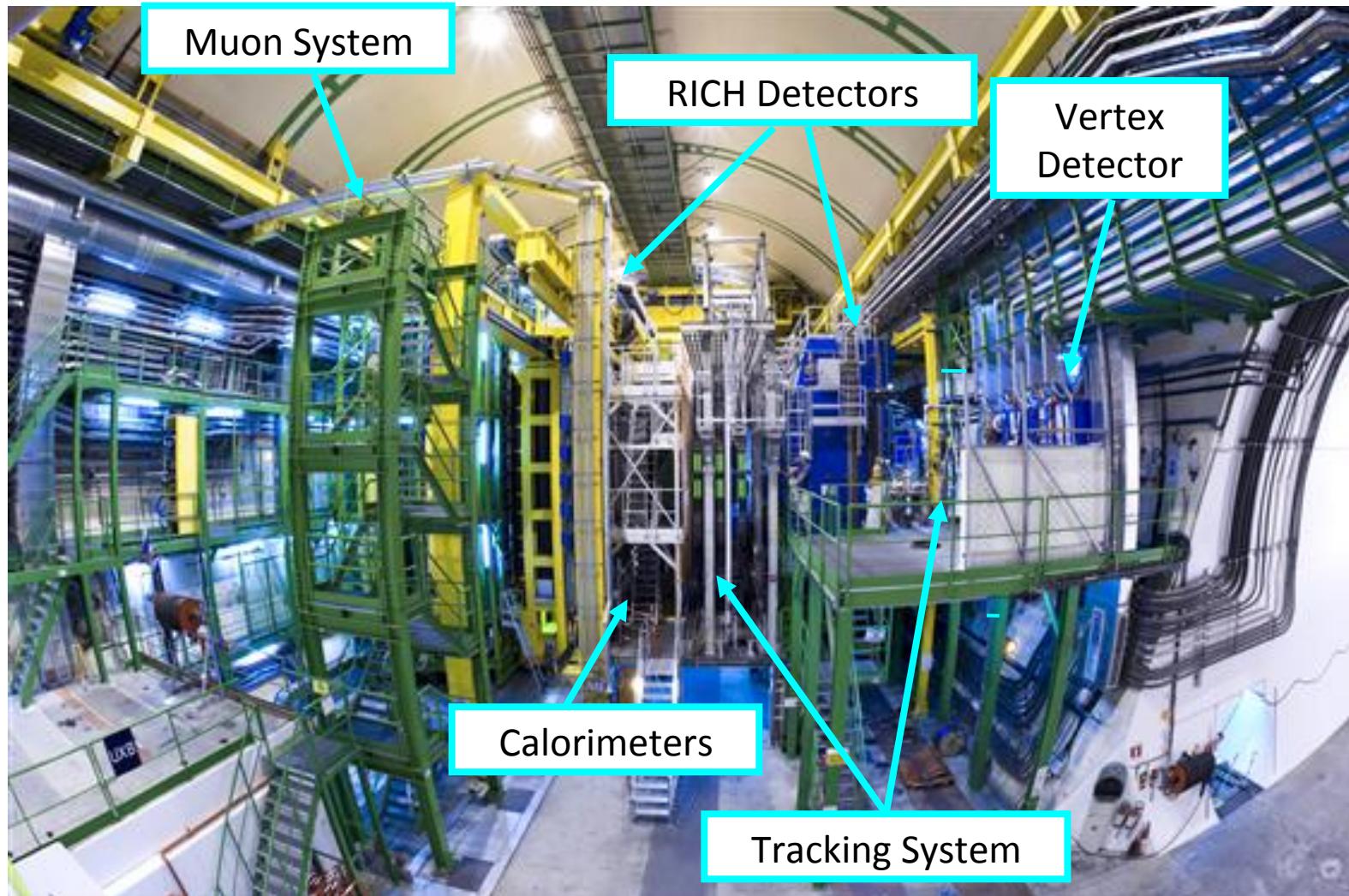


- LHC running very well!
- LHCb efficiency  $\approx 90\%$
- Collected more than  $1 \text{ fb}^{-1}$  in 2010–11
- Goal :
  - $1.5 \text{ fb}^{-1}$  (end of 2012)

# THE LHCb DETECTOR



# THE LHCb DETECTOR



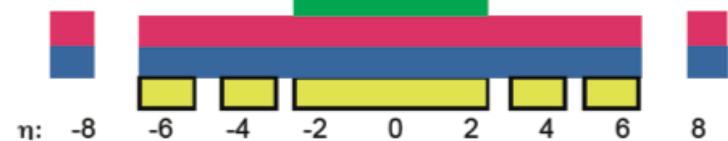
# Rapidity Range



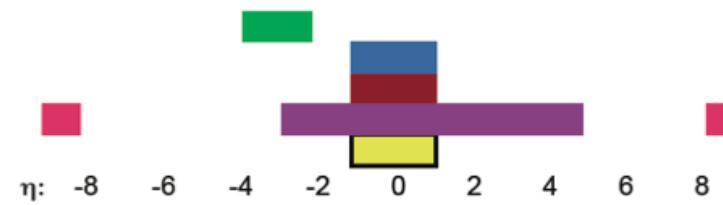
LHCb



ATLAS



CMS

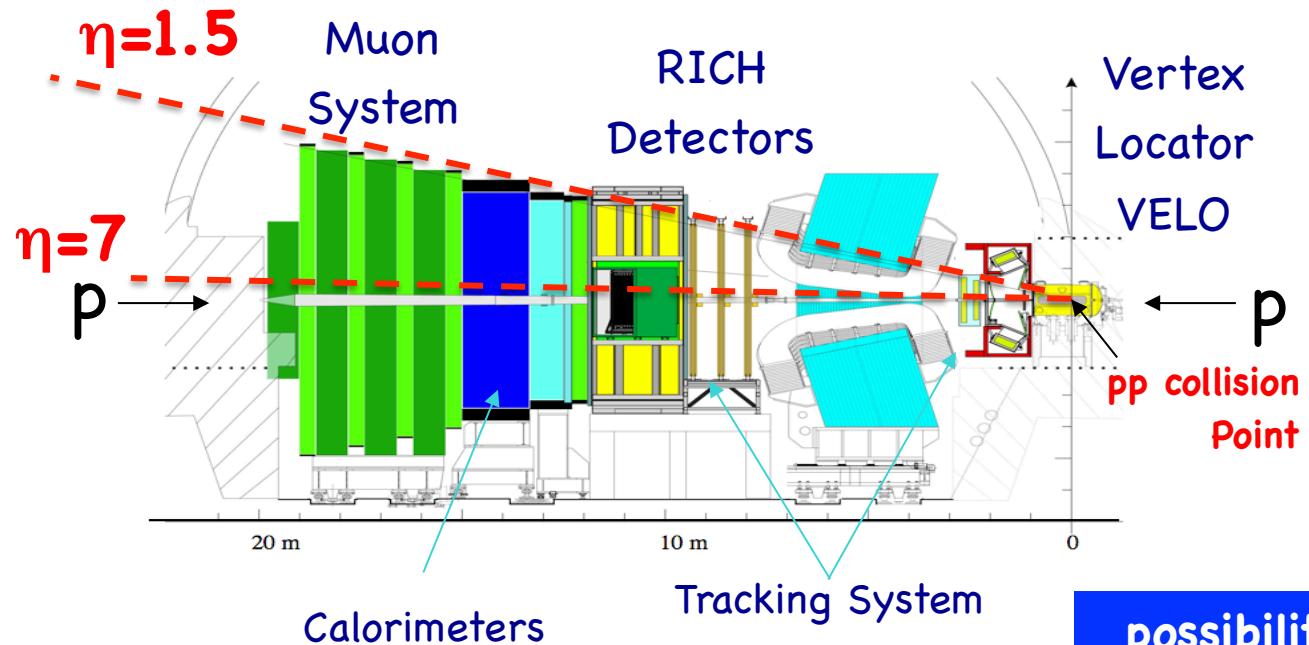


ALICE

tracking, ECAL, HCAL, counters lumi, muon, hadron PID

# The LHCb detector

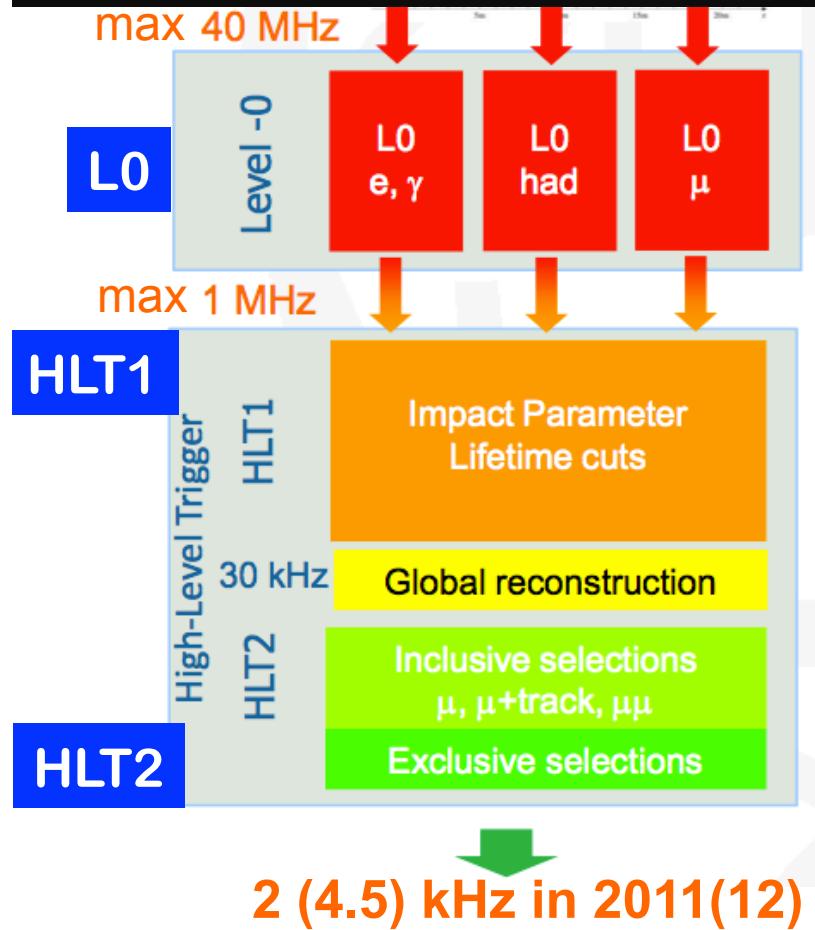
Angular  
acceptance :  
 $10 < \theta < 300$  mrad



Trigger : three levels, dominantly software

possibility  
to reverse  
field  
polarity to  
check for  
detector

# LHCb Trigger



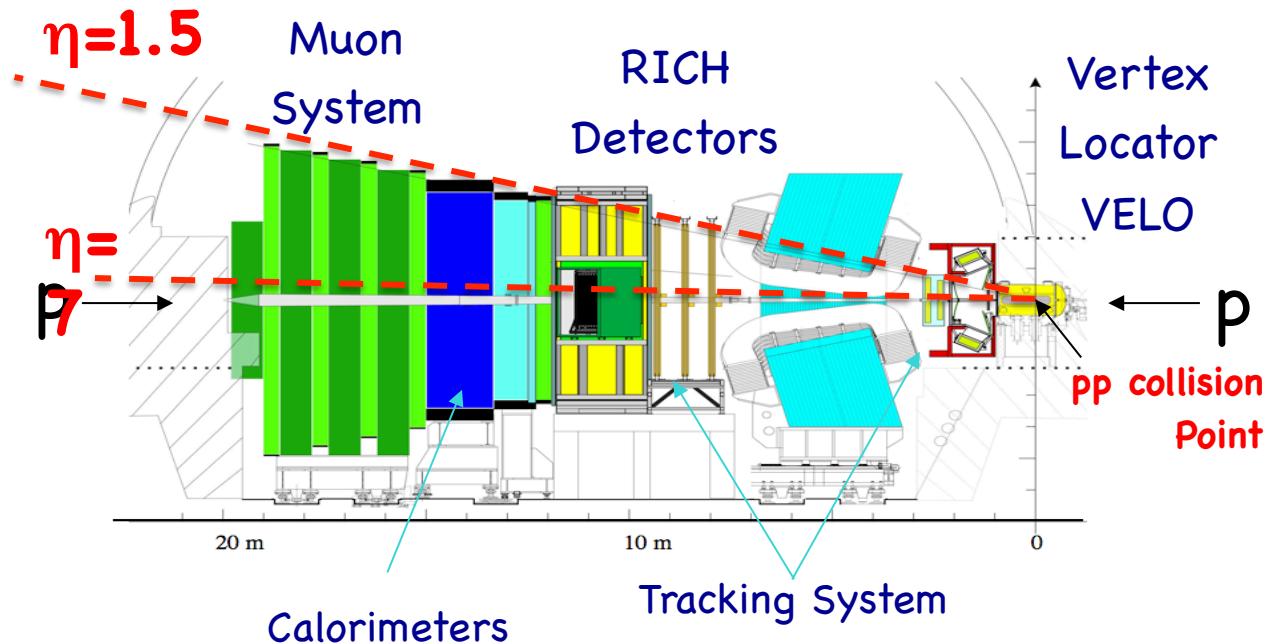
Muon Lines	
<b>L0</b>	Single- $\mu$ : $p_T > 1.4 \text{ GeV}/c$ $\mu\mu$ : $p_{T1} > 0.48 \text{ GeV}/c$ $p_{T2} > 0.56 \text{ GeV}/c$
<b>HLT1</b>	single- $\mu$ : $p_T > 1.8 \text{ GeV}/c$ , di- $\mu$ : $M_{\mu\mu} > 2.5 \text{ GeV}/c^2$
<b>HLT2</b>	Several dimuon lines with $p_T$ or $M_{\mu\mu}$ cuts

+ Global Event Cuts for events with high multiplicity

- Half of the bandwidth given to the muon lines
- $p_T$  cuts on muon lines kept very low
- Trigger rather stable during the whole period

# The LHCb detector

Angular acceptance :  
 $10 < \theta < 300$  mrad



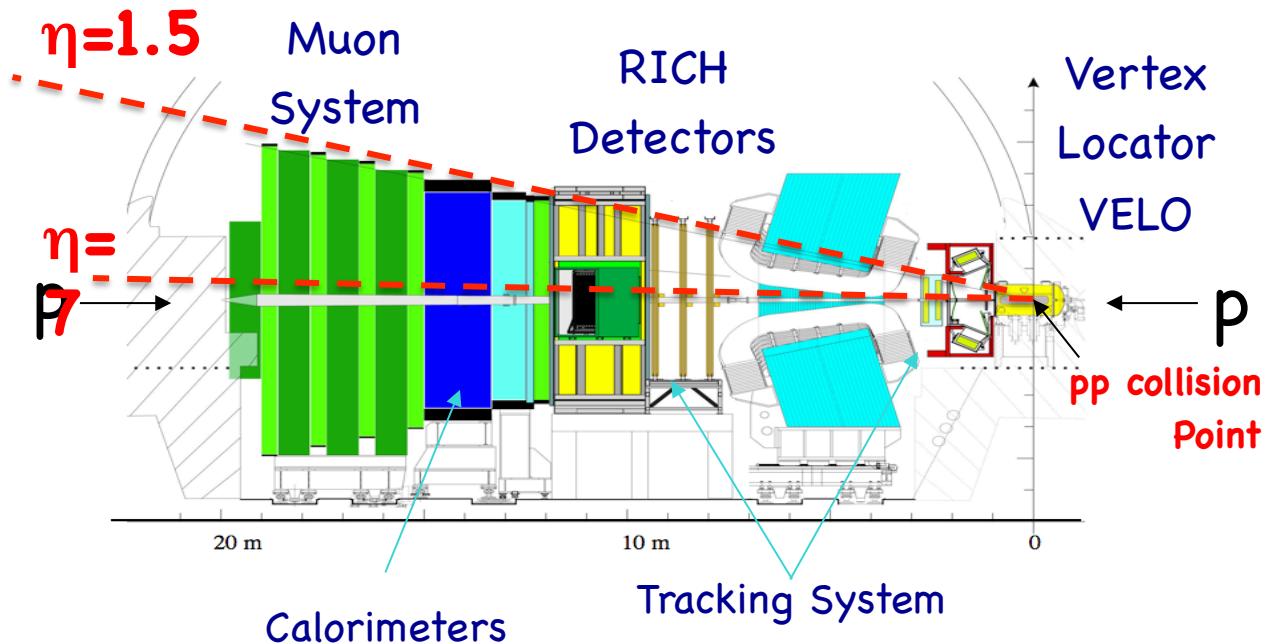
**Trigger** : three levels, dominantly software

- Performance numbers relevant to quarkonium analyses:
  - Charged tracks  $\Delta p/p = 0.35\% - 0.55\%$ ,  $\sigma(m) = 10-25 \text{ MeV}/c^2$
  - ECAL  $\sigma(E)/E = 10\% (E/\text{GeV})^{-1/2} \oplus 1\%$
  - Muon ID:  $\epsilon(\mu \rightarrow \mu) = 97\%$ , mis-ID rate ( $\pi \rightarrow \mu$ ) = 1-3 %
  - Vertexing: proper time resolution 30-50 fs

possibility  
to reverse  
field  
polarity to  
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detector

# The LHCb detector

Angular acceptance :  
 $10 < \theta < 300$  mrad



Trigger : three levels, dominantly software

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possibility  
to reverse  
field  
polarity to  
check for  
detector

# The LHCb Upgrade

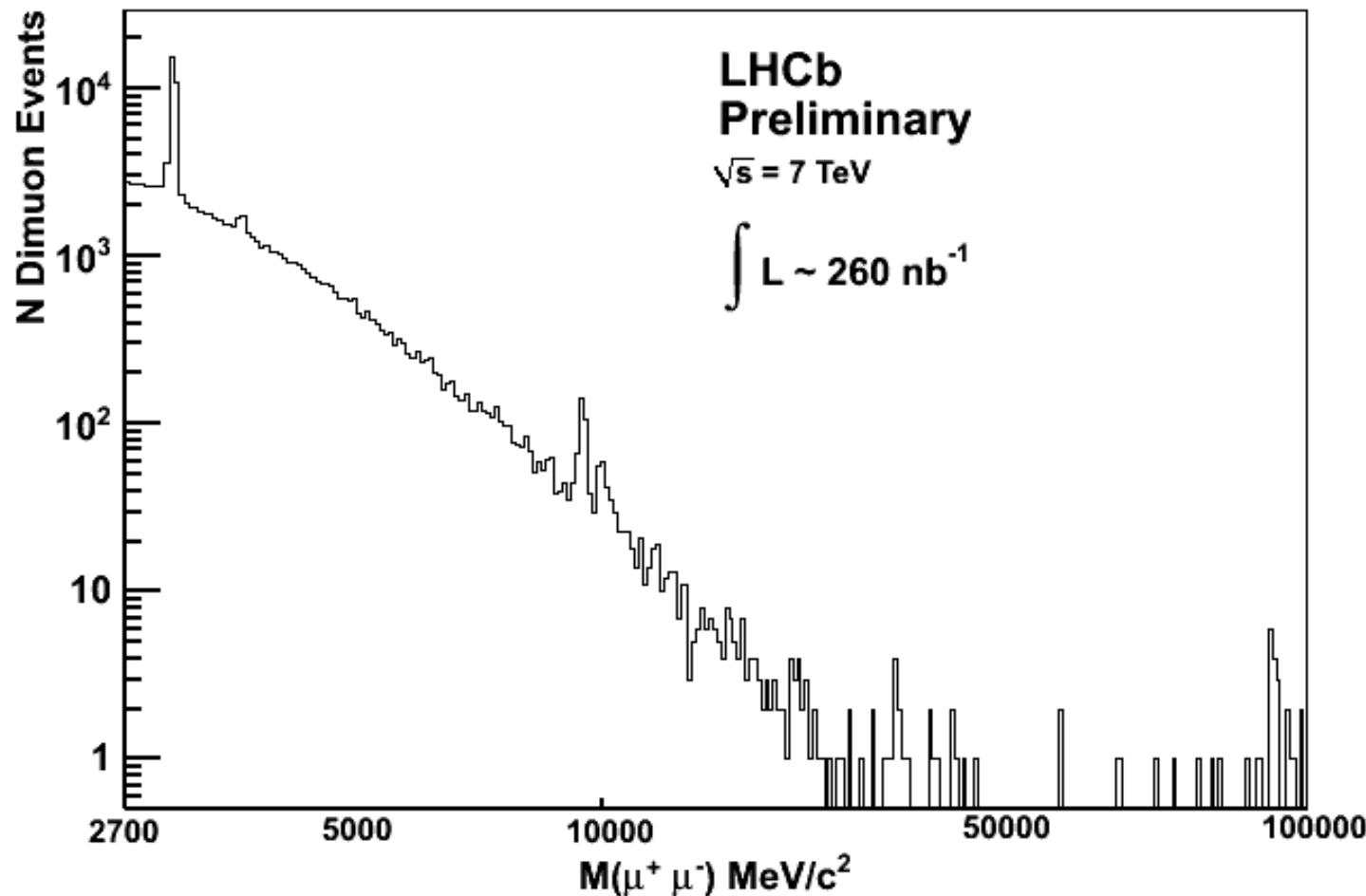
- LHC will stop in 2013 to restart in 2018 with “upgraded” detector
- Running conditions in 2018:
  - $\sqrt{s} = 14 \text{ TeV}$ , 40 MHz output,  $\mathcal{L}=1\cdot10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Minimal upgrade of those detectors not designed for these conditions:
  - New Trigger -> especially Hadronic will be revisited
  - New tracker (in place of IT)
  - New Velo (exploring if same or different technology)
- GOAL:  $50 \text{ fb}^{-1}$  in 10 yrs

# Quarkonium in the upgrade era

## → Rich quarkonium program!

- Expected  $\approx 300\text{-}500k$  double  $J/\psi$  and many more double quarkonium modes should open up
  - Definite proof of Double Parton Scattering ?
- Able to see signals in  $pp$  mode (e.g.  $\eta_b$ ) with improved hadronic triggers, maybe also  $Y(4S)$  ?
- Increase in luminosity allows to explore exotic (and not) spectroscopy
- Any interesting idea is welcome!

# Dimuon Resonances



# What we have done so far

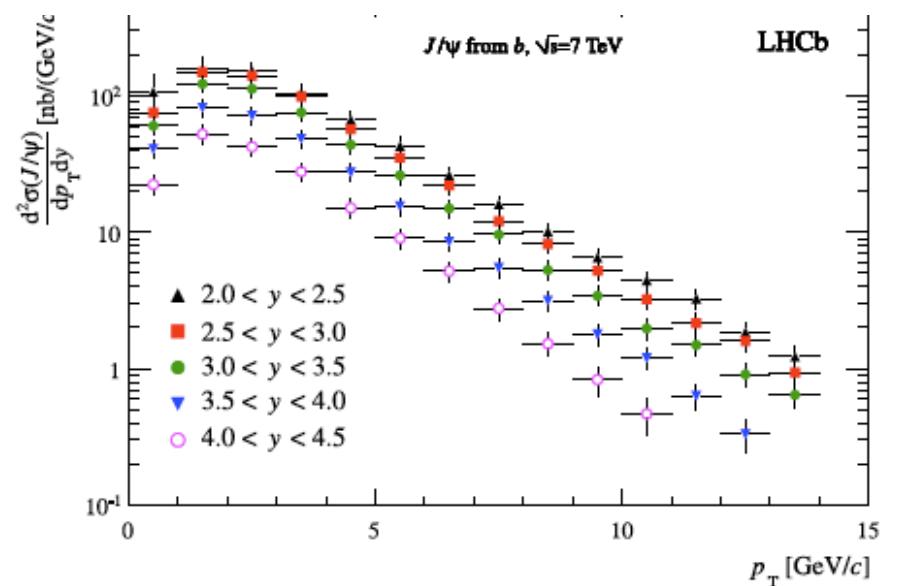
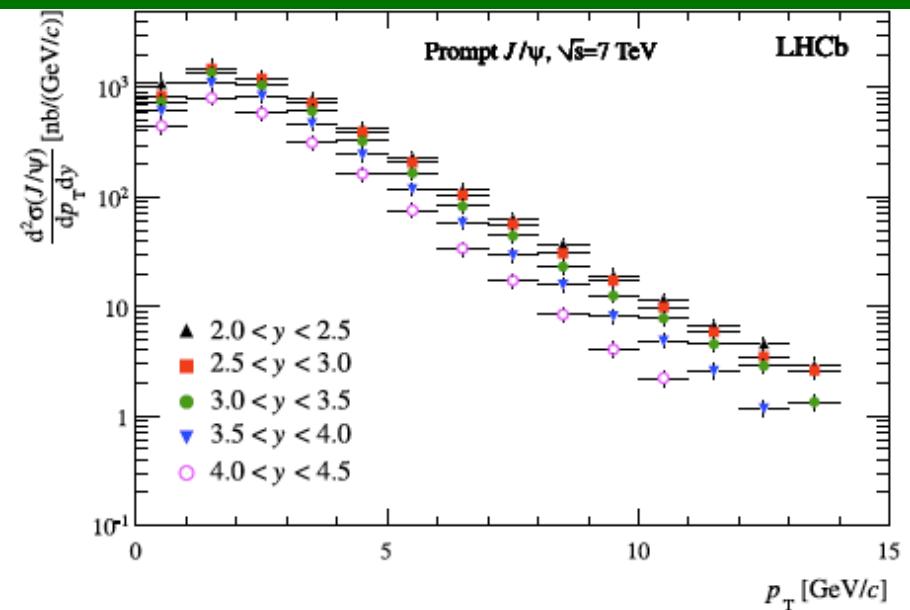
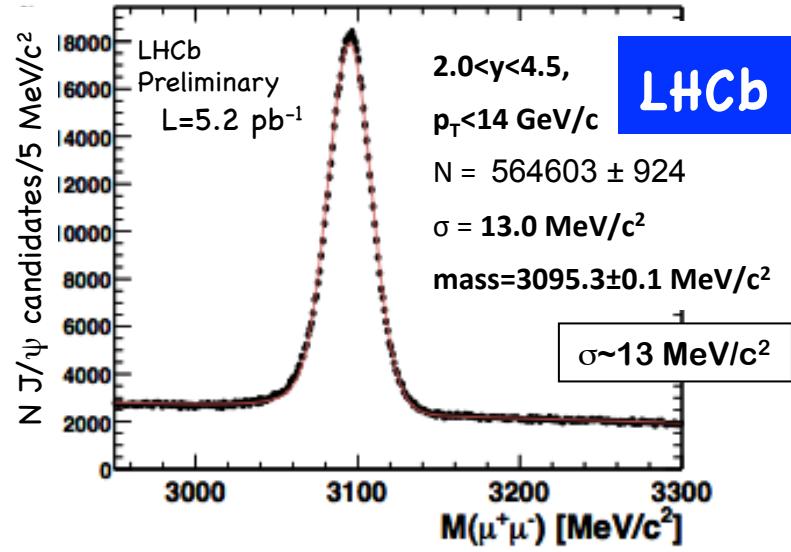


What we plan to do by ≈2013 in pp

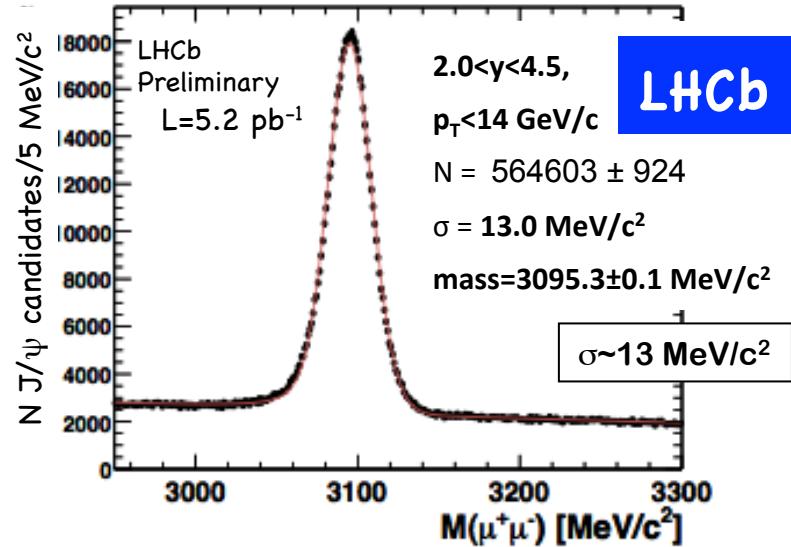
What we plan to do ...AFTER ;)

What we plan to do with pPb

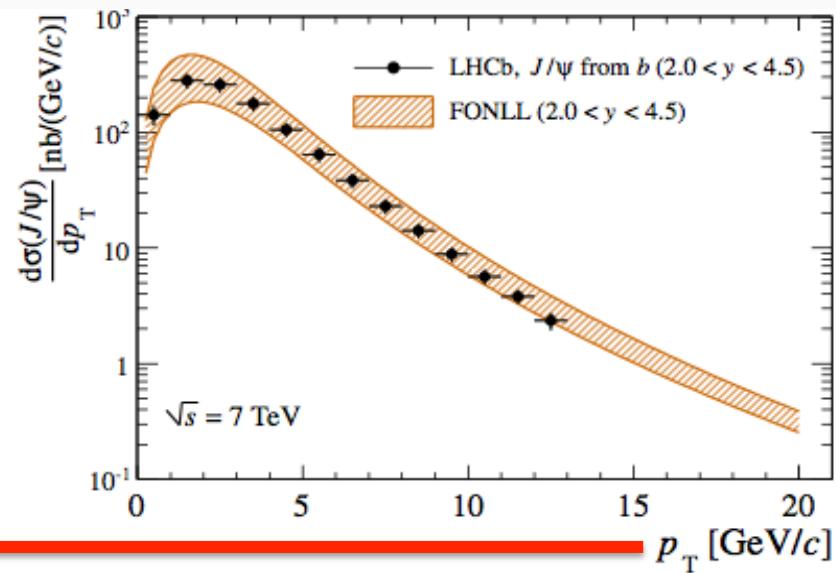
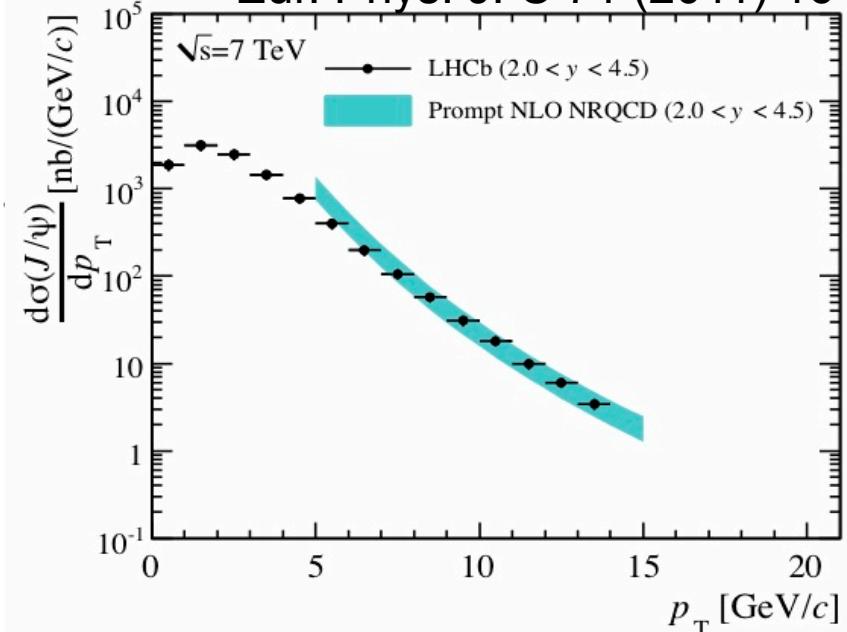
# $\text{J}/\psi \rightarrow \mu\mu$ cross-section



# $\text{J}/\psi \rightarrow \mu\mu$ cross-section



Eur. Phys. J. C 71 (2011) 1645



- L=5 pb<sup>-1</sup> : plenty!
- Good agreement with theory and other experiments
- Main systematic: polarisation

To do: measure polarisation and update cross-section

# J/ $\psi$ in the immediate future

- Measure the cross section at 2.76 and 8 TeV
- Measure the polarisation at 7 TeV

# J/ $\psi$ in the intermediate(pPb) future

- Measure the cross section at 2.76 and 8 TeV
- Measure the polarisation at 7 TeV
- Measure the cross section with pPb data, and other quantities (polarisation ?)

# J/ $\psi$ in the long-term future

- Measure the cross section at 2.76 and 8 TeV
- Measure the polarisation at 7 TeV
- Measure the cross section with pPb data, and other quantities (polarisation ?)
- Remeasure cross section and polarisation at 14 TeV
- Concentrate on J/y + charmonium, open charm, bottomonium...

# Double J/ψ Production

Phys. Lett. B 707 (2012) 52–59

→ First analysis of charmonium +?

$J/\psi\rho^0$ ,  $J/\psi\omega^0$ ,  $J/\psi\phi$ ,  $Y\psi$ , ...

→ Interesting for :

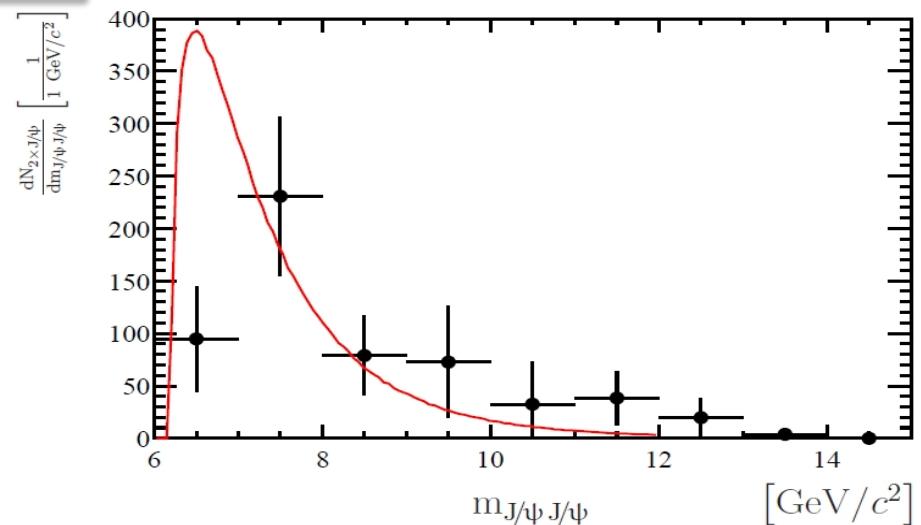
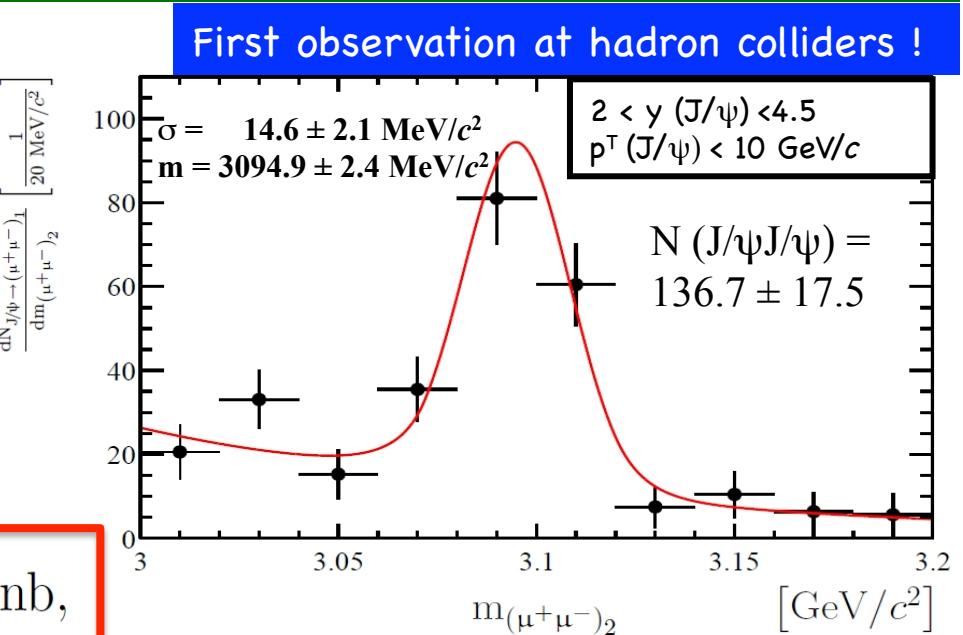
- Test of QCD: sensitive to CSM vs. COM and Double Parton Scattering (DPS)
- Possible smoking gun of tetraquark observation

$$\sigma^{J/\psi J/\psi} = 5.6 \pm 1.1 \pm 0.5 \pm 0.9|_{\text{tr}} \pm 0.6|_{\mathcal{L}} \text{ nb},$$

Theory (direct only)\* :

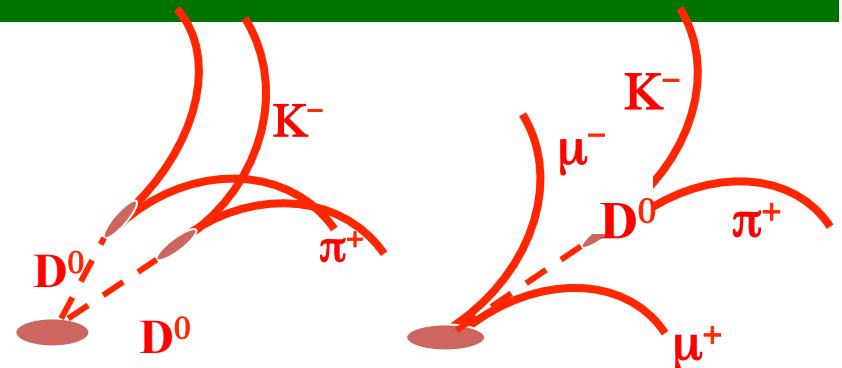
$$\sigma^{J/\psi J/\psi} (2 < y^{J/\psi} < 4.5) = 4.34 - 4.15 \text{ nb},$$

\* A.V.Berezhnou et al., arXiv:1101.5881



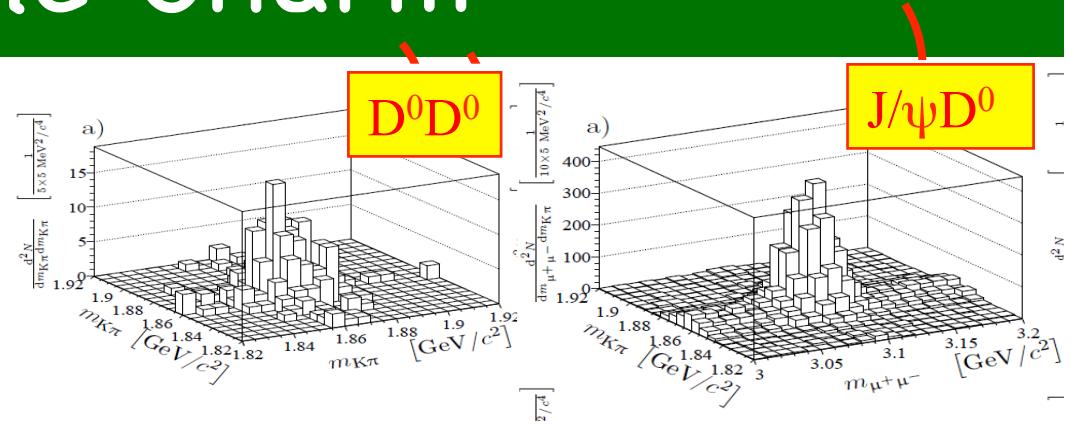
# Double Charm

→  $J/\psi C$  &  $CC\bar{c}$  measured @ LHCb  
in channels : 4  $J/\psi C$ , 6  $CC$ , 7  $\bar{C}C$



# Double Charm

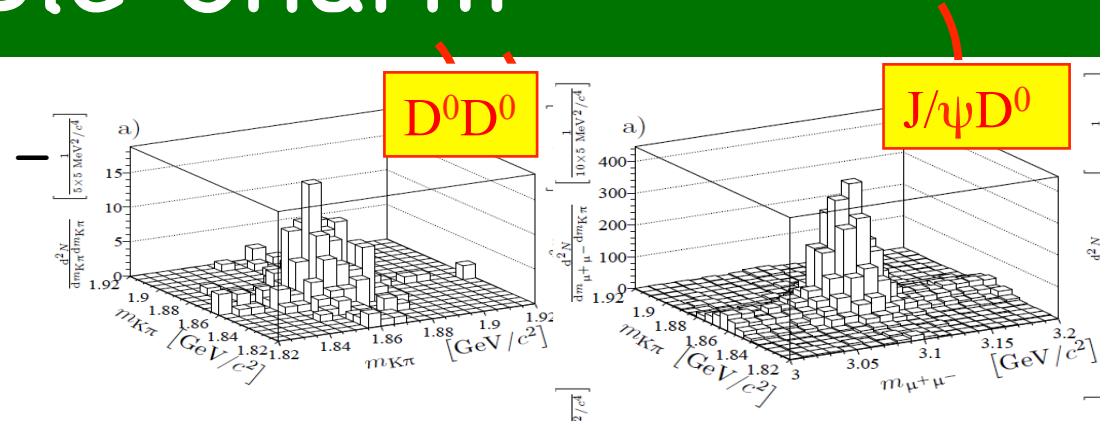
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→  $J/\psi C$  &  $CC\bar{c}$  measured  
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 $J/\psi C$ , 6  $CC$ , 7  $\bar{C}C$

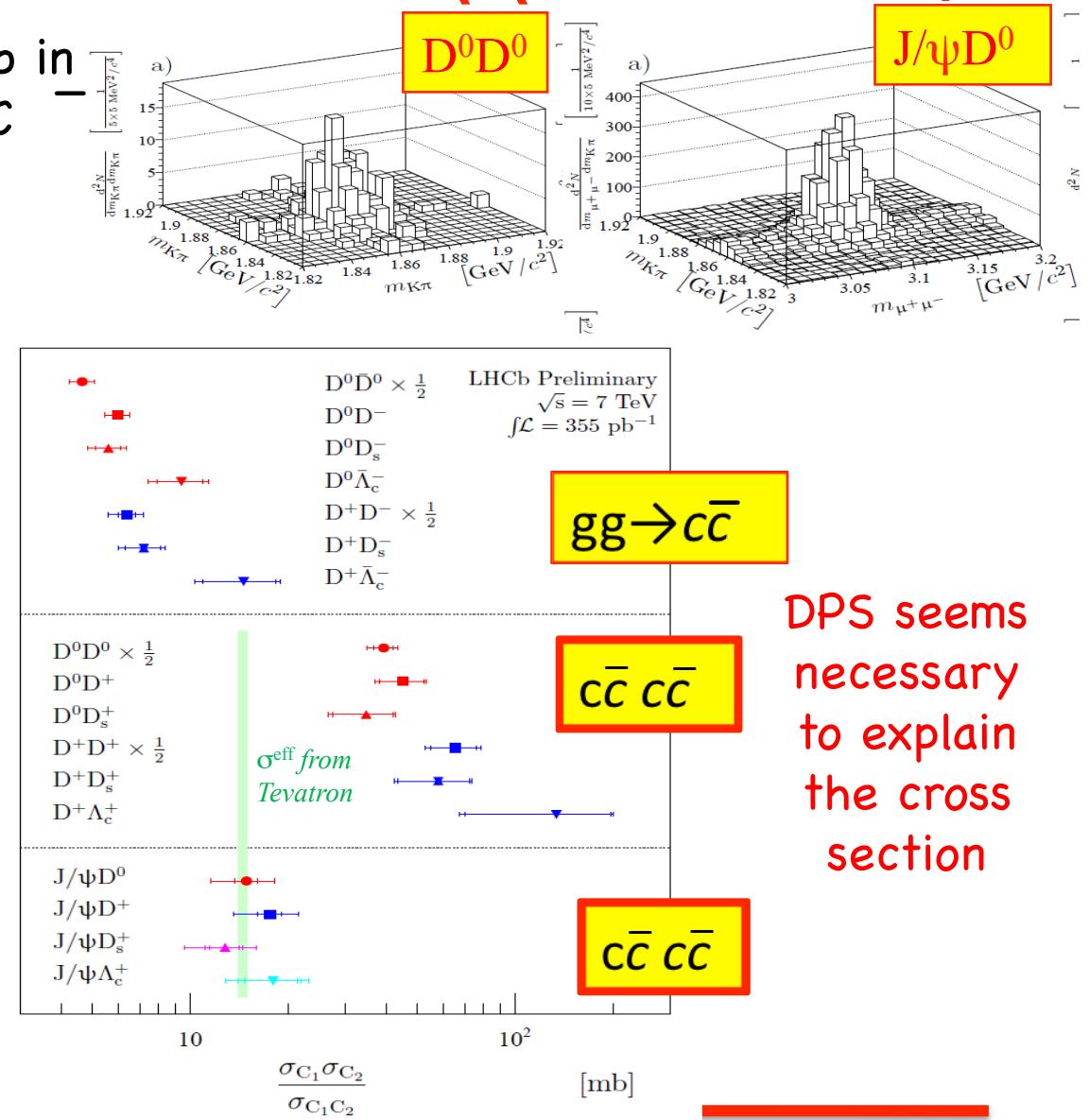
Mode	yield
$J/\psi D^0$	$4875 \pm 86$
$J/\psi D^+$	$3323 \pm 71$
$J/\psi D_s^+$	$328 \pm 22$
$J/\psi \Lambda_c^+$	$116 \pm 14$
$D^0 D^0$	$1087 \pm 37$
$D^0 \bar{D}^0$	$10080 \pm 105$
$D^0 D^+$	$1177 \pm 39$
$D^0 D^-$	$11224 \pm 112$
$D^0 D_s^+$	$111 \pm 12$
$D^0 D_s^-$	$859 \pm 31$
$D^0 \Lambda_c^+$	$41 \pm 8$
$D^0 \bar{\Lambda}_c^-$	$308 \pm 19$
$D^+ D^+$	$249 \pm 19$
$D^+ D^-$	$3236 \pm 61$
$D^+ D_s^+$	$52 \pm 9$
$D^+ D_s^-$	$419 \pm 22$
$D^+ \Lambda_c^+$	$21 \pm 5$
$D^+ \bar{\Lambda}_c^-$	$137 \pm 14$



# Double Charm

$\text{J}/\psi C$  &  $CC\bar{c}$  measured @ LHCb in channels : 4  $\text{J}/\psi C$ , 6  $CC$ , 7  $C\bar{c}$

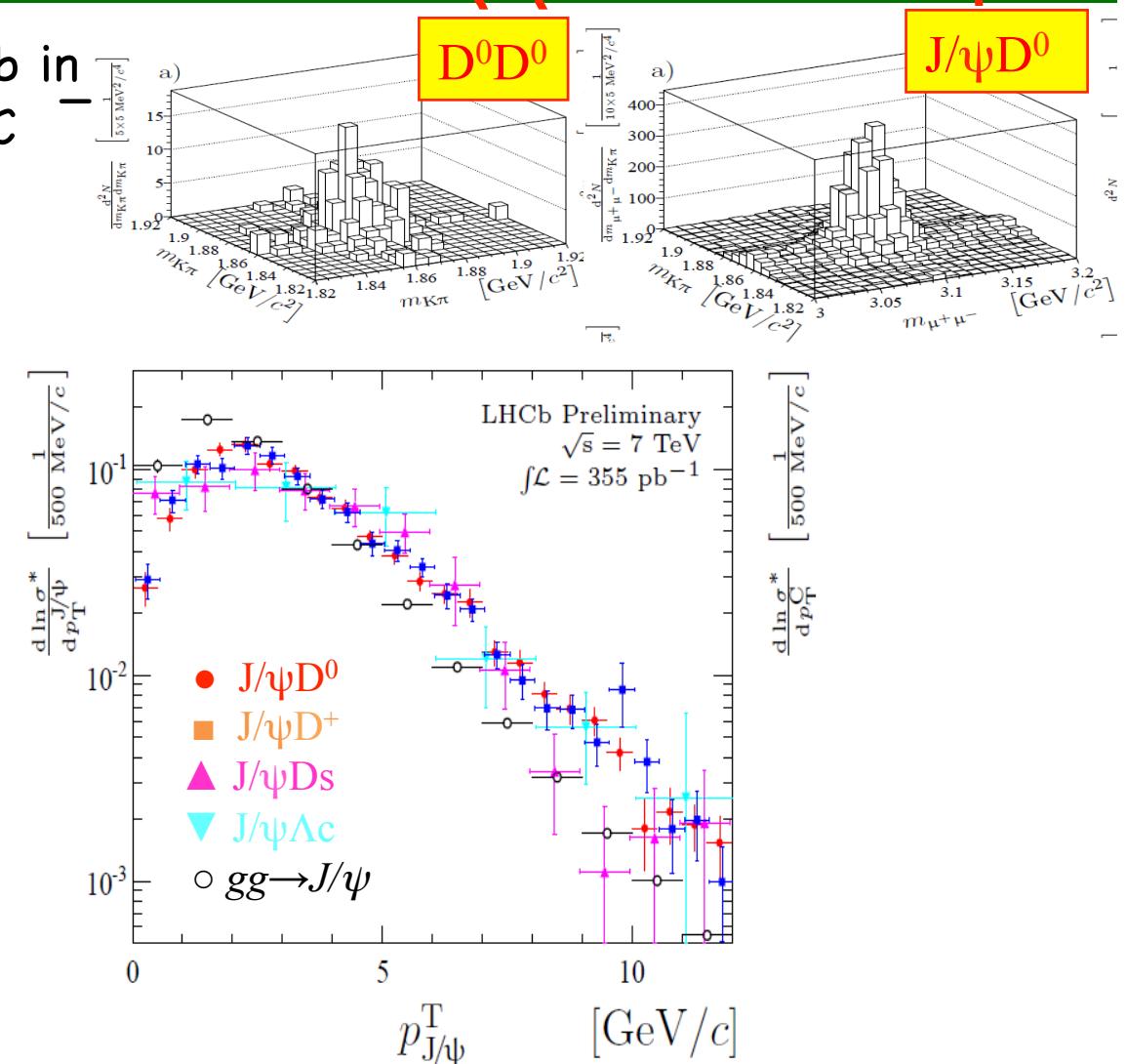
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# Double Charm

$J/\psi C$  &  $CC\bar{c}$  measured @ LHCb in  
channels : 4  $J/\psi C$ , 6  $CC$ , 7  $\bar{C}C$

Mode	yield
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...many more channels to explore!!

# Double Charm & others...

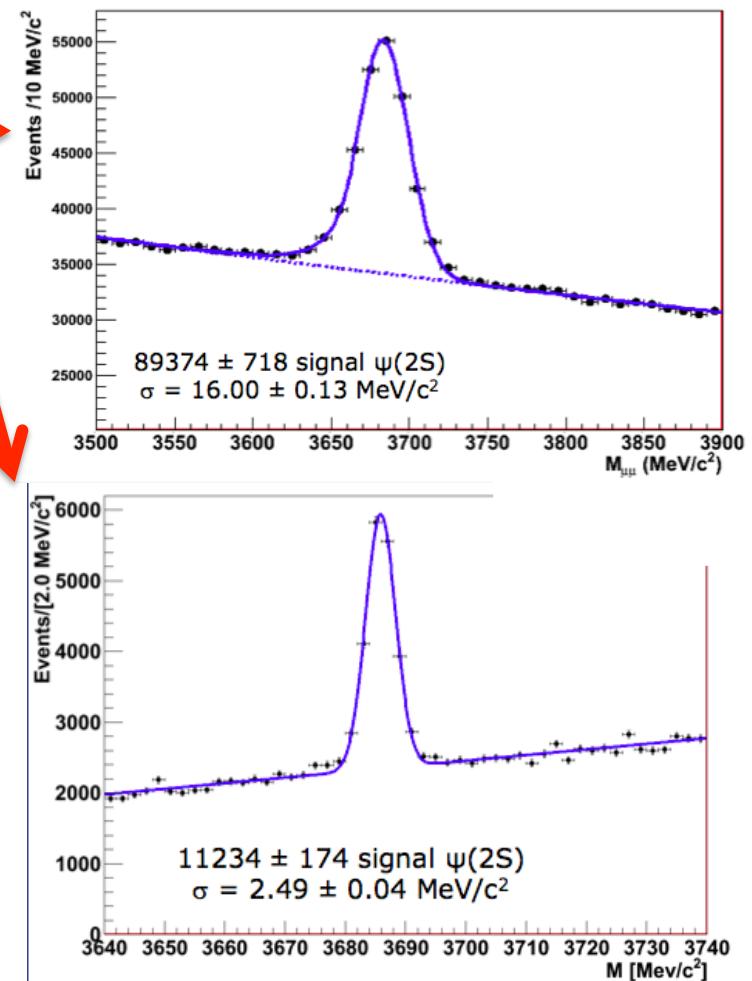
- We should be able to measure the double J/psi differential cross section with 2011 and 2012 data.
- Same for J/psi+open charm or double open charm
- End of run/Upgrade:
  - More double modes feasible with more luminosity and better trigger and higher cross sections: J/psi+psi2s, J/psi Upsilon, UpsilonUpsilon...

# LHCb : $\psi(2S)$ Production

Exploited in two modes

- $\psi(2S) \rightarrow \mu^+\mu^-$  [BR= $7.7 \pm 0.8 \times 10^{-3}$ ] 
- $\psi(2S) \rightarrow J/\psi(\mu^+\mu^-) \pi^+\pi^-$  [BR= $19.9 \pm 0.3 \times 10^{-3}$ ] 

Cross section in bins  $0 < p_T < 12$  GeV/c,  $2 < y < 4.5$

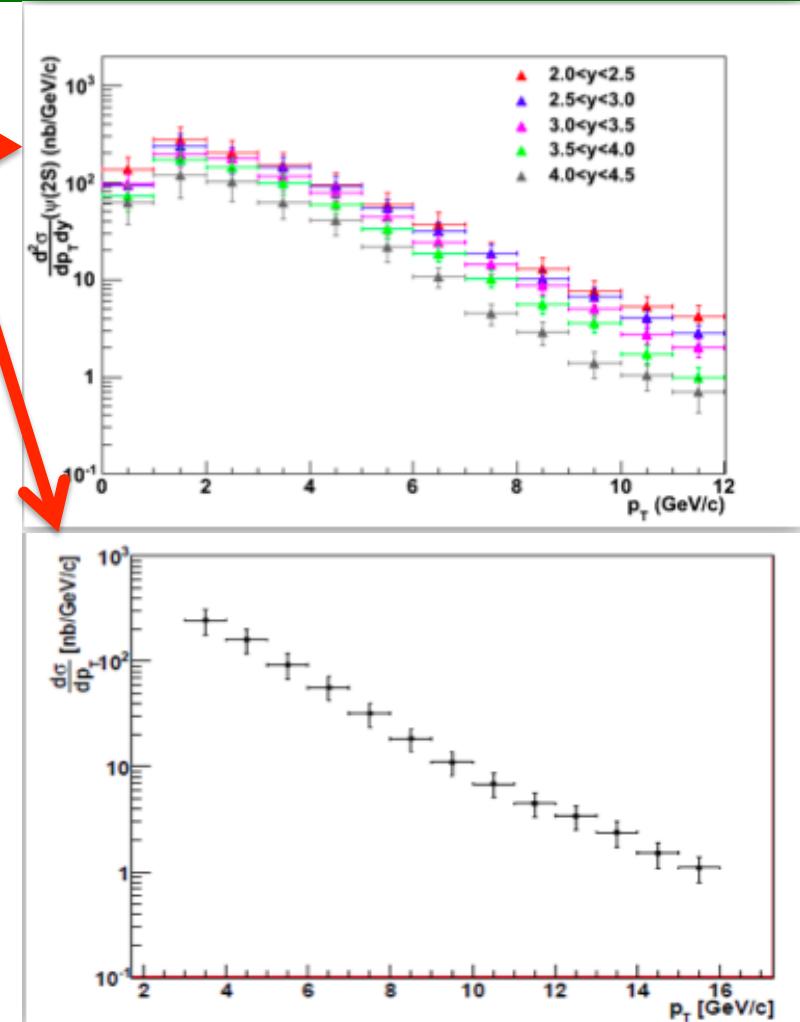


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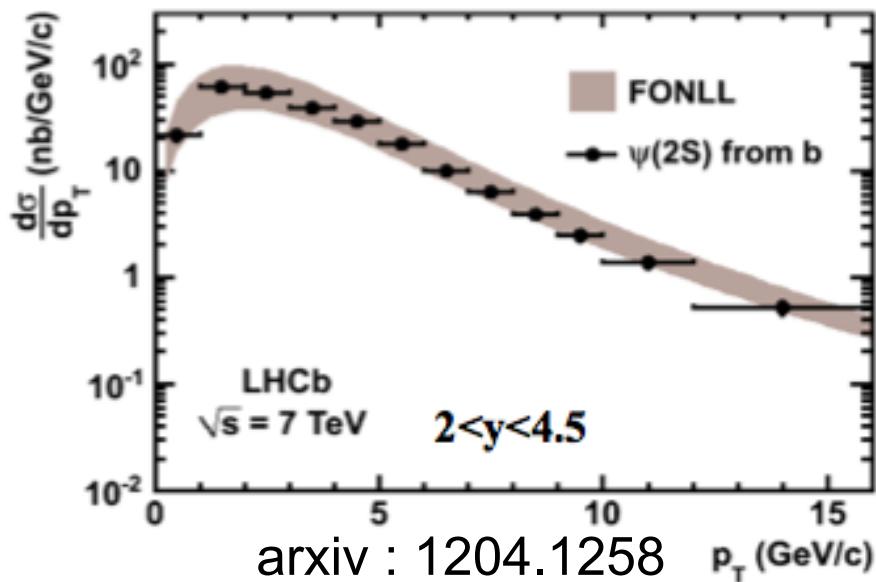


# $\psi(2S)$ Production

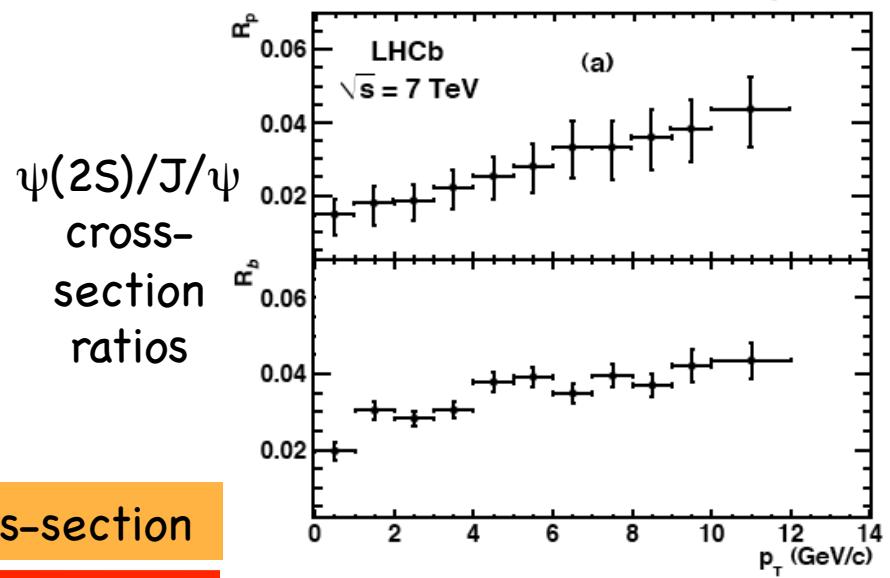
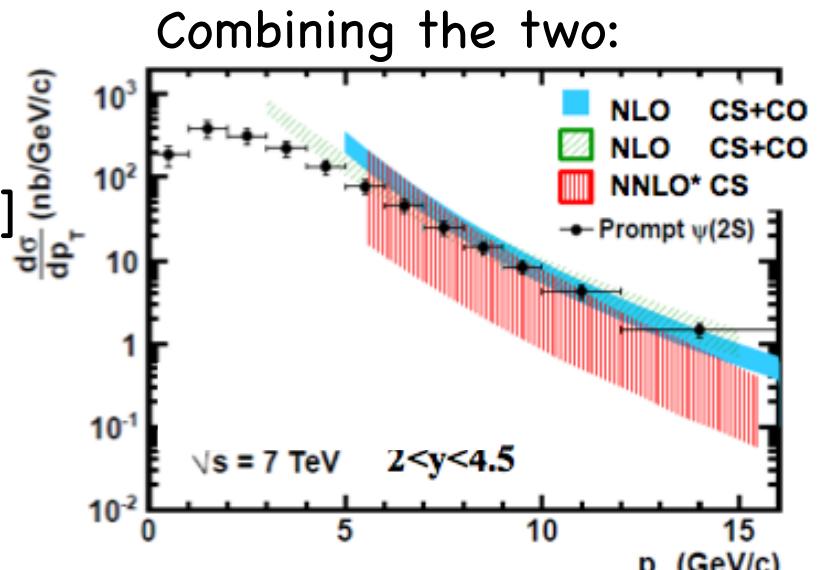
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To do: measure polarisation and update cross-section



arXiv:1202.1080

arXiv:1204.1462

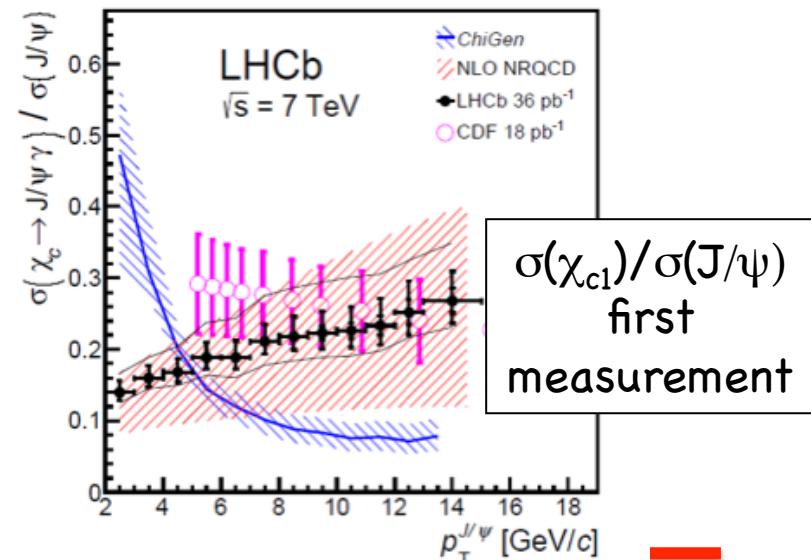
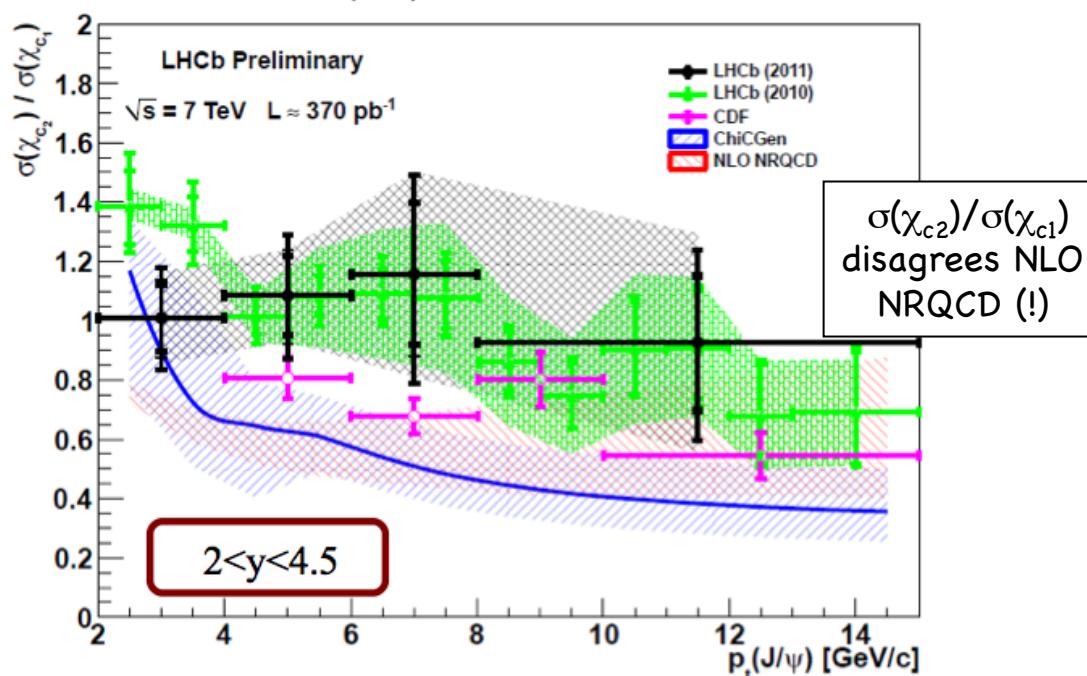
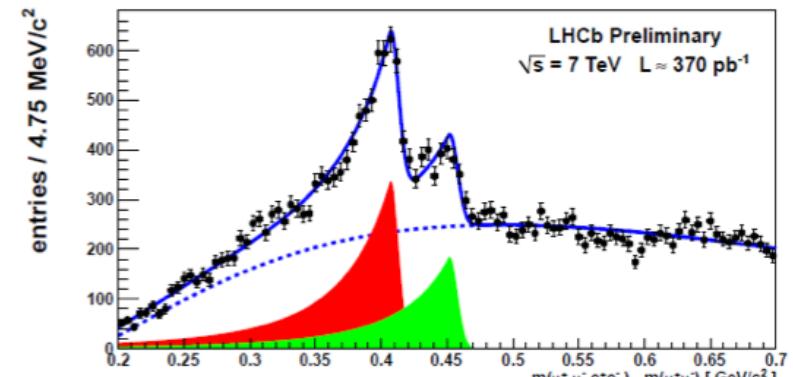
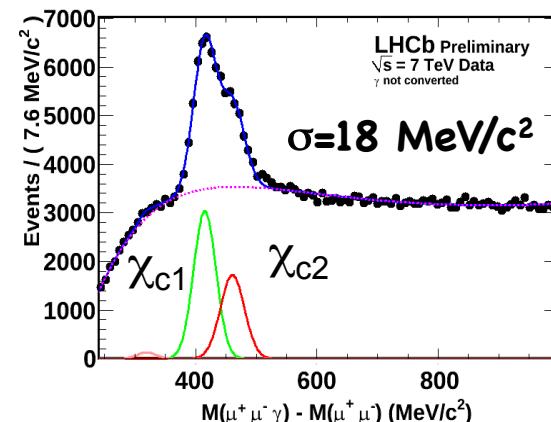
# Production of $\chi_c$

- Decays in  $J/\psi + \gamma$ ->low  $p_T$ : challenge!!
- Analyses use photons reconstructed in the calo or converted (tracker)

CDF: PRL 98 (2007) 232001

ChiCGen: <http://projects.hepforge.org/superchic/chigen.html>

NRQCD: PR D83 (2011) 111503

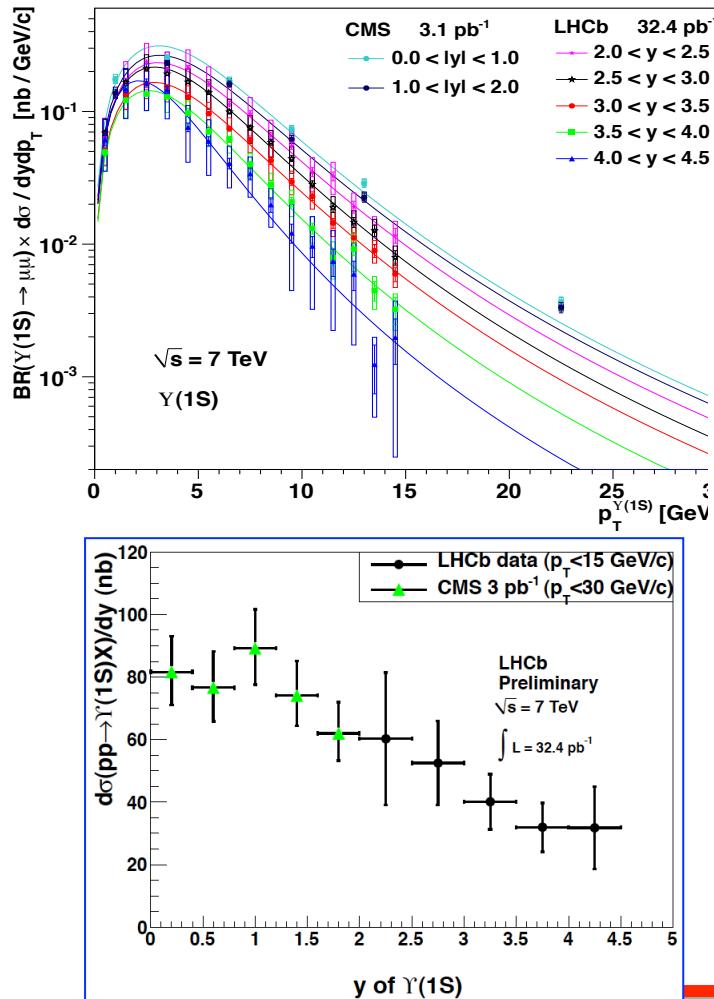


# $\chi_c$ Physics

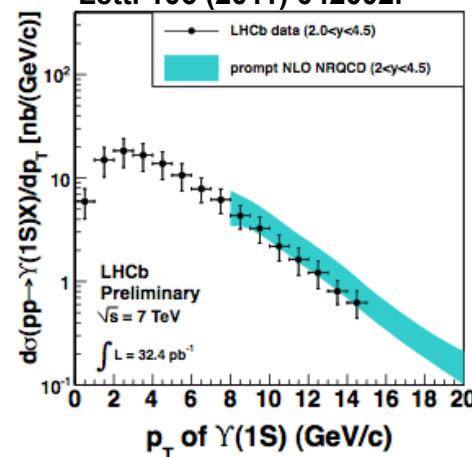
- ▶ Publish chic with conversion with full dataset
- ▶ Use all data to distinguish among different spin states ?

# Upsilon family

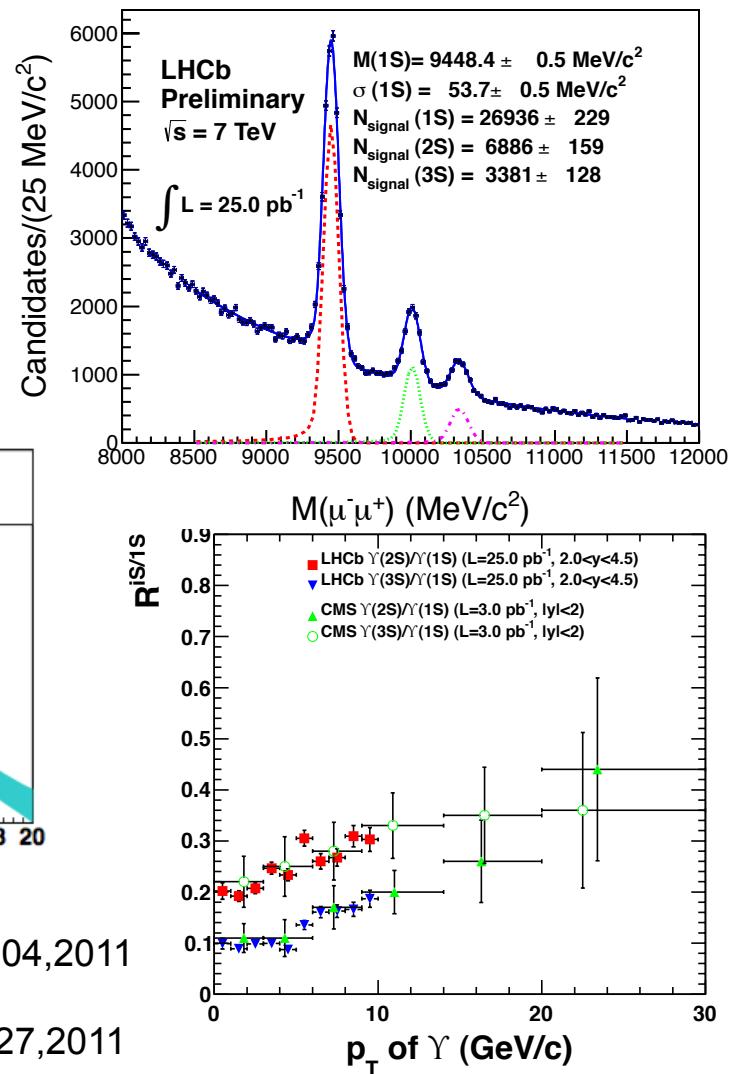
- Three states decaying into  $\mu\mu$
- Cross sections in  $p_T$ -y bins



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



CMS: Phys. Rev. D83:112004, 2011  
LHCb: arXiv:1202.6579  
ATLAS: Phys. Lett. B705:9-27, 2011



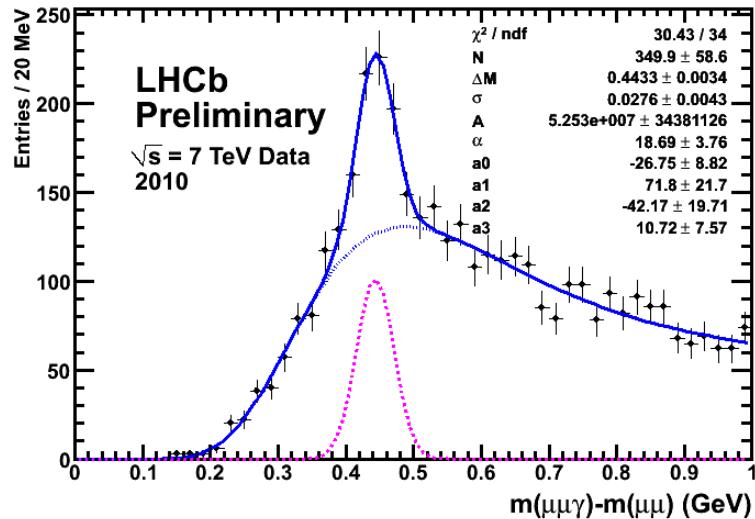
# Upsilon : the immediate future

- Update the cross section measurements with 2011 dataset and remeasure @ 8 TeV
- Measure the polarisation for all three states and update the cross sections
- Double upsilon production, exotic states, more exotic states...

# Upsilon : the long-term future

- Update the cross section measurements with 2011 dataset and remeasure @ 8 TeV
- Measure the polarisation for all three states and update the cross sections
- Double upsilon production, exotic states, more exotic states...

# $\chi_b$ Physics

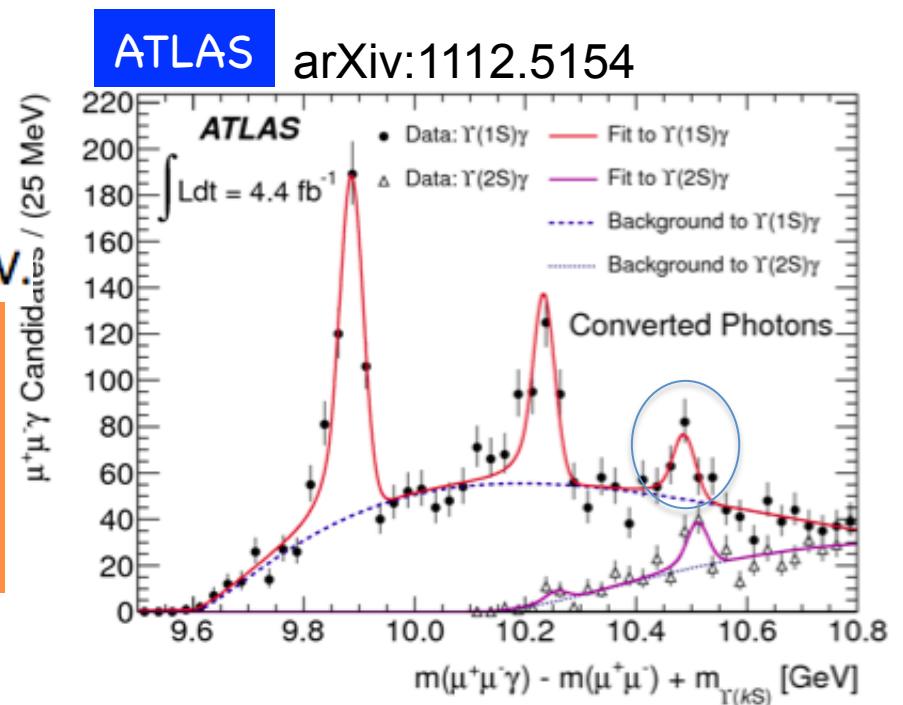


→ LHCb observed b states in 2010 data ( $37 \text{ pb}^{-1}$ ) with  $\gamma$  in the calo. Measurement of  $\chi_b$  ratios on the way!

→ Finer resolution possible if using converted photons (end of the run)

ATLAS discovered  $\chi_b(3P)$  in  $\Upsilon(1S)$  gamma  
 Mass =  $10.530 \pm 0.05 \text{ (stat.)} \pm 0.009 \text{ (syst.) GeV}$

- Confirm the observation and measure masses, cross sections...
- Measure the ratio of  $\Upsilon$  from  $\chi_b$ , to be fed into the cross section predictions
- Rare decays

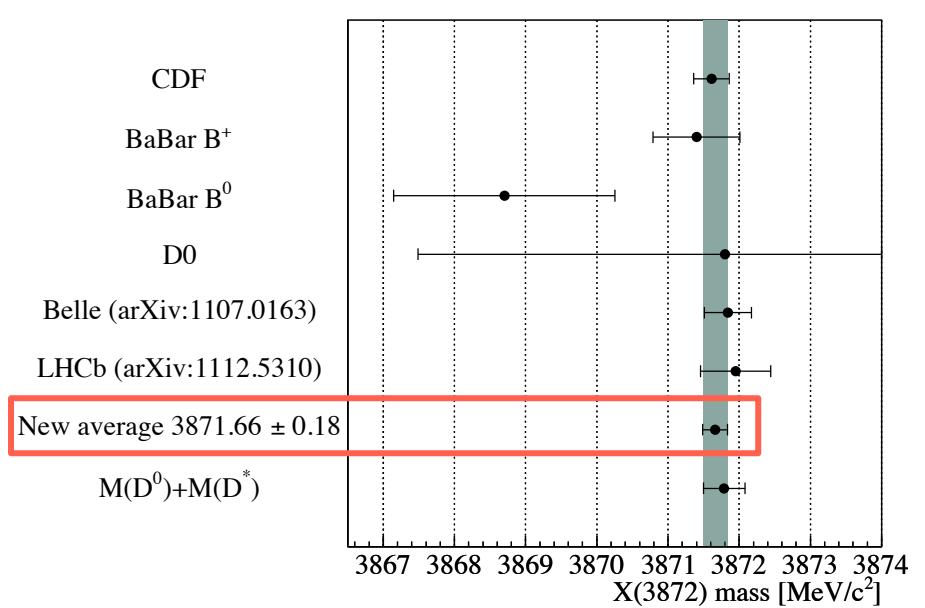
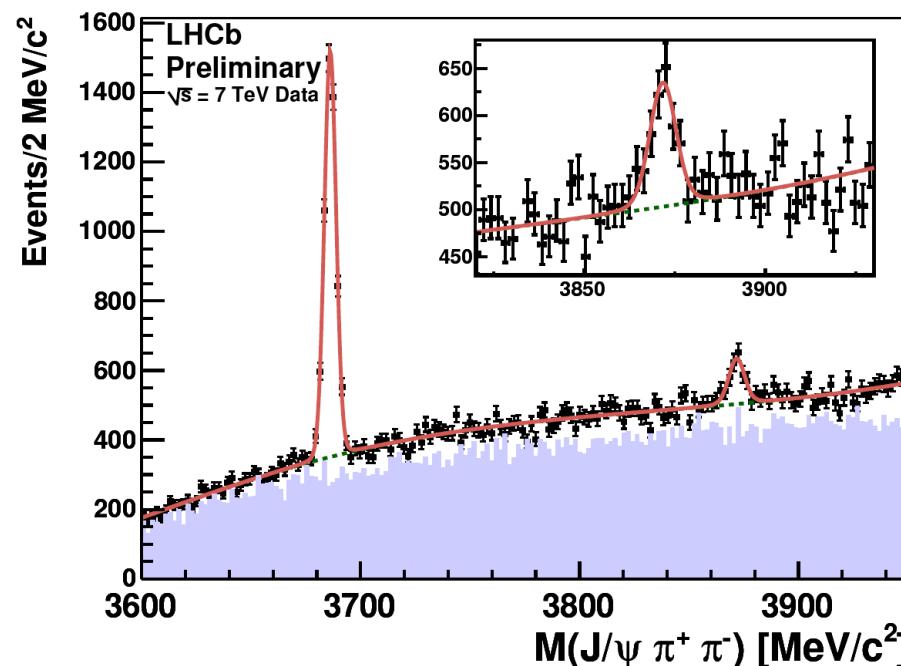


# X(3872)

- First observation of  $X \rightarrow J/\psi \pi\pi$  at LHC !!
- Measured mass and cross section

$$\boxed{M_{X(3872)} = 3871.95 \pm 0.48 \text{ (stat)} \pm 0.12 \text{ (syst)} \text{ MeV/c}^2}$$

$$\boxed{\sigma_{X(3872)} B_{J/\psi \pi^+ \pi^-} = 4.7 \pm 1.1 \text{ (stat)} \pm 0.7 \text{ (syst)} \text{ nb}}$$



# X(3872) : the future

- Precision measurement of the mass, cross sections
- Measurement of the quantum numbers
- Studies of from B decays

# Exotic and “Rare” Spectroscopy

► Search for not observed yet states

- Expected :  $\eta_c$  ,  $\eta_b$  in hadronic channels
- Need confirmation :  $Z(4430)$  ,  $Z_b(10880)$
- Never observed before :  ${}^3D_2$  , ?

# p-Pb collisions : setup

*From M.Schmeling*

→ two configurations for proton-nucleus collisions:  $pA \neq Ap$

- $pp$  minimum bias interactions:
  - up to 0.3 % average occupancy in silicon detectors
  - up to 3 % average occupancy in Outer Tracker
- tracking algorithms break down at
  - Silicon Strip detectors:  $\sim 10\%$
  - Outer Tracker:  $\sim 30\%$

- For pPb collisions ( $A=208$ ), occupancies increased by  $A^{1/3} \approx 6$ 
  - > single interactions should be OK at LHCb.
- Pile up does not seem to be a problem

# p-Pb collisions : Physics? *From M.Schmeling*

→ LHCb is able to contribute to pp and pA physics:

- soft QCD measurements
  - particle multiplicities and production ratios
  - strangeness production ( $V^0, \phi, K^*, \dots$ ) and  $\Lambda$ -polarization
  - energy flow and underlying event measurements
- $J/\psi$ -related measurements
  - production cross sections of charmonium states
  - polarization studies
- “advanced” topics
  - low mass DY and in general physics probing low-x
  - inclusive photon production
  - open charm,  $\Upsilon$ -production,  $b$ -cross-section, ...

Important benchmark for pp & pA studies – about 20k events expected, 30x more with dedicated trigger

# pPb run : Concerns

*From M.Schmeling*

## → *trigger issues*

- low luminosity up to  $10^{27} \text{ cm}^{-2}\text{s}^{-1}$ : record all inelastic events
- high luminosity:  $J/\psi$  (di-)muon trigger
- maybe high- $p_T$  photon trigger
  - concern: saturation of ECAL electronics
  - calorimeter occupancies maybe too large for physics

## → *computing issues*

- 10 – 20% more data than currently foreseen
  - need for planning and probably extra resources

## → *VELO issues*

- Single-Event-Latchup (SEL) in electronics
  - safeguard by low thresholds for trip-current

# pPb Summary

From M.Schmelling

- LHCb detector expected to be able to handle pPb collisions
  - occupancies and high-Z background OK
  - need simulation studies to understand detector performance
- rich physics program interpolating between pp and AA
- many puzzles in studies of ...
  - inclusive particle production (multiplicities)
  - strangeness production
  - baryon number transport and baryon suppression
- large potential for  $J/\psi$  measurements
- more studies needed for low- $x$  physics and isolated photons
- large rapidity coverage when combining pA and Ap running

Strong support from the collaboration for running in pPb;  
However, experiment was not designed with this in mind,  
potential damage and limited resources to be kept in mind

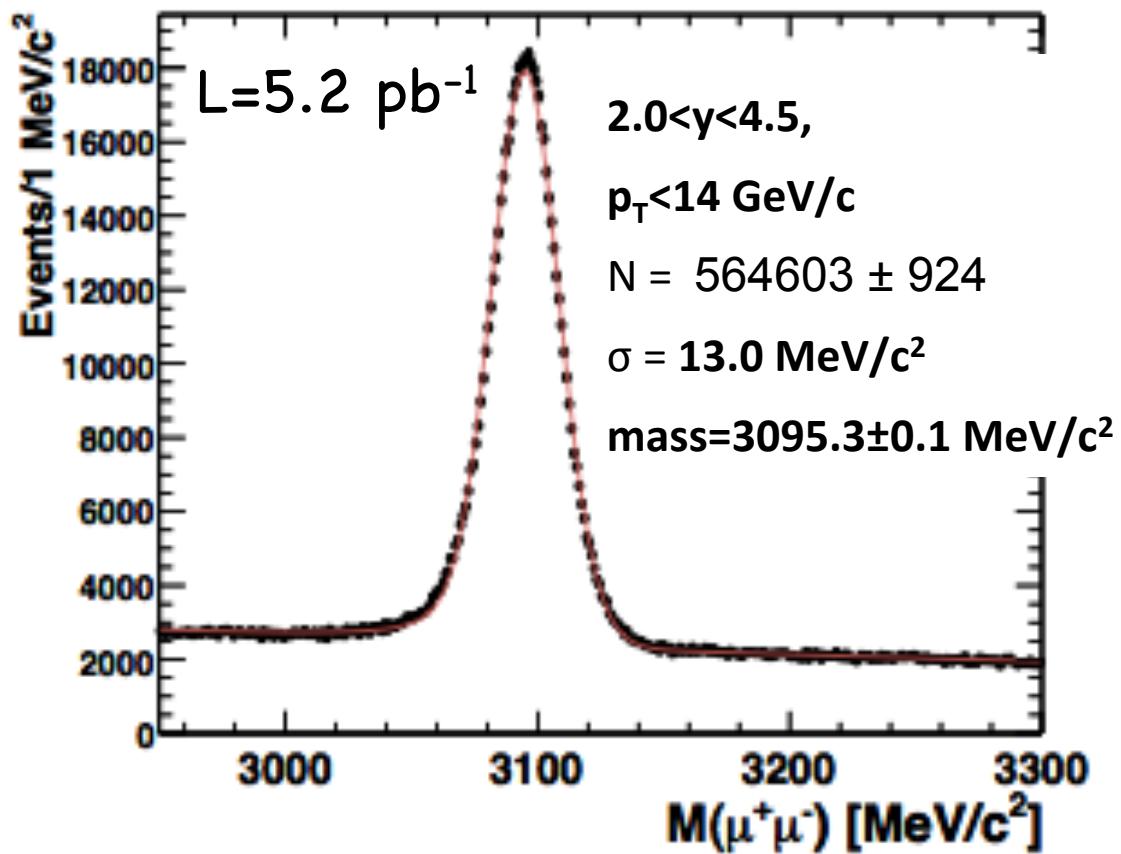
# Conclusions and Outlook

- LHCb produced very many interesting results in Quarkonium physics, many more in the pipeline!
- Very rich program to explore in medium ( $\sim 2\text{fb}^{-1}$ ) and long ( $\sim 50 \text{ fb}^{-1}$ ) term
- Ready to take data with p-Pb interactions, J/psi and Upsilon natural candidates

# Back up

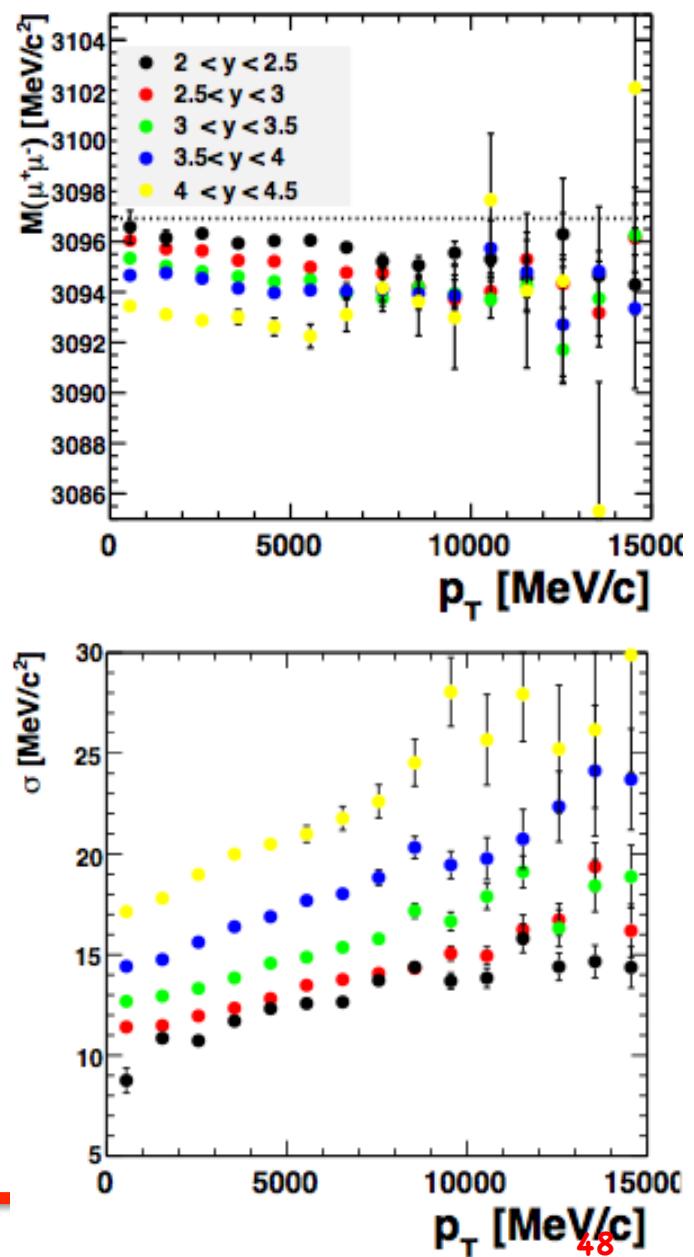
# J/ $\psi$ $\rightarrow\mu\mu$ mass distribution

Fit performed using a Crystal Ball function (signal) + exponential for the background, in each pt-y bin



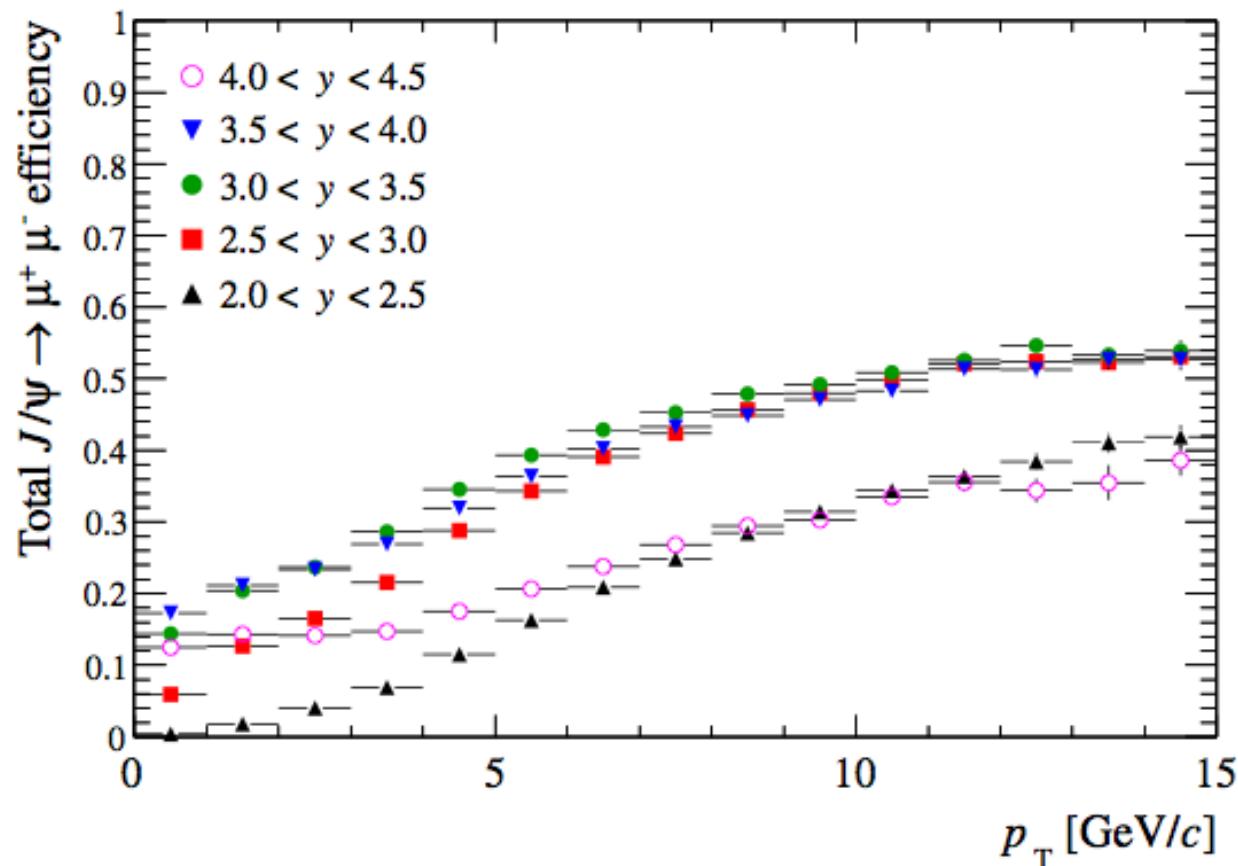
10.05.2012

G.Manca, After Meeting

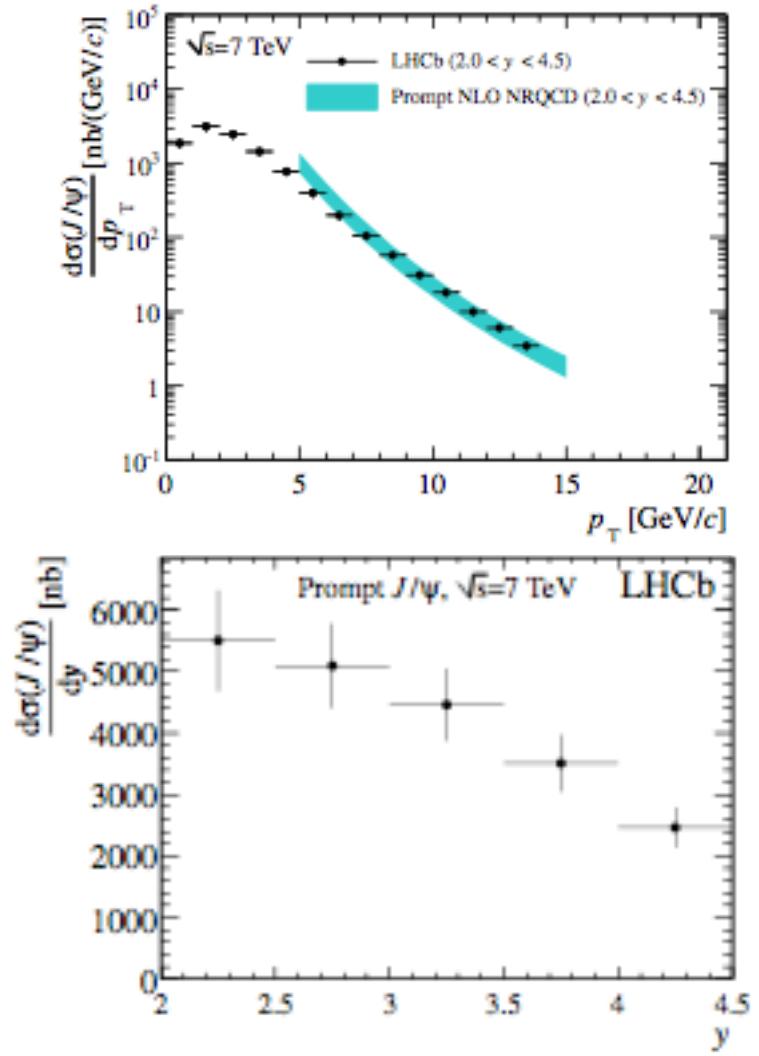
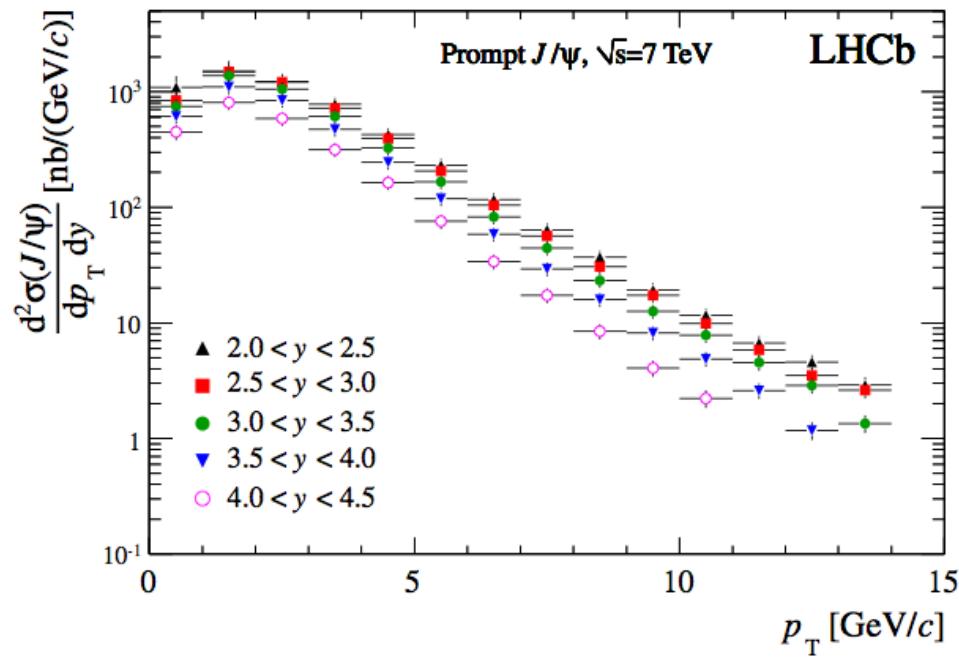


# J/ $\psi$ Efficiency

- Total efficiency, includes geometric acceptance, trigger and reconstruction and identification



# Prompt cross section measurement

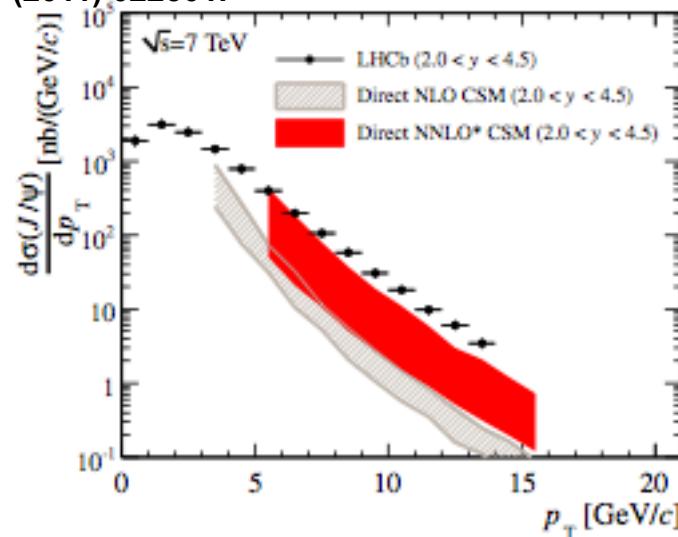
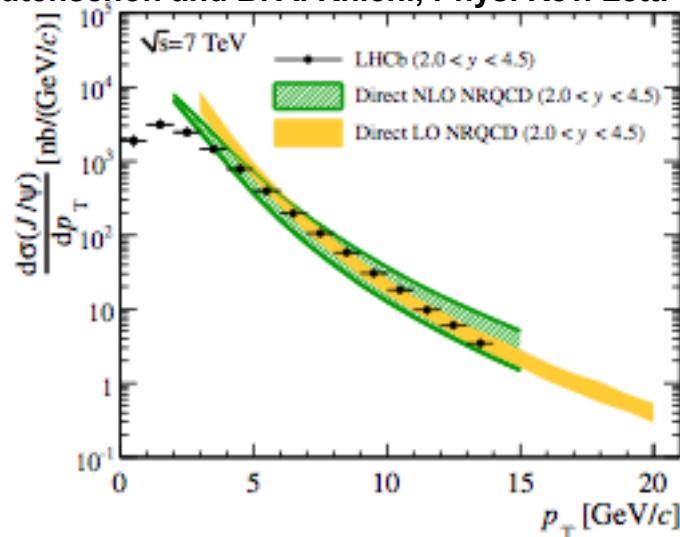


# Comparison with theory

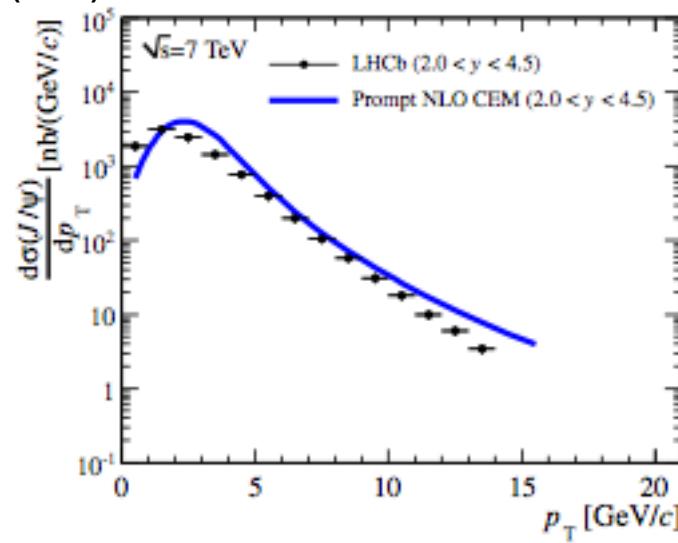
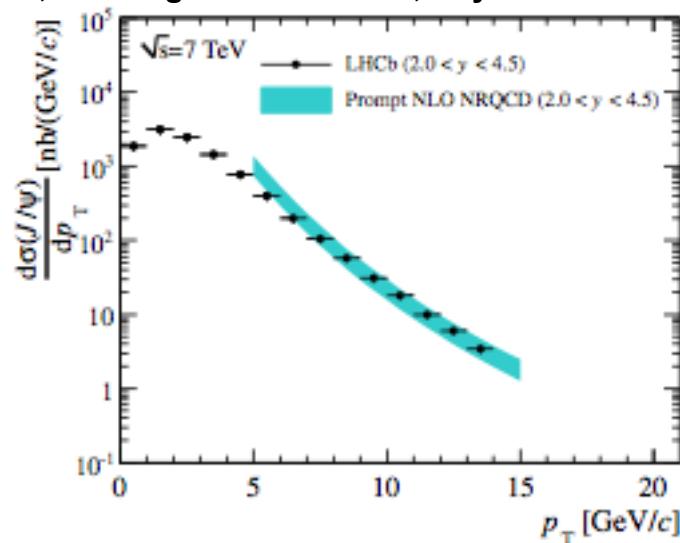
P. Artoisenet, PoS ICHEP 2010 (2010) 192.

M. Butenschön and B. A. Kniehl, Phys. Rev. Lett. 106 (2011) 022301.

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



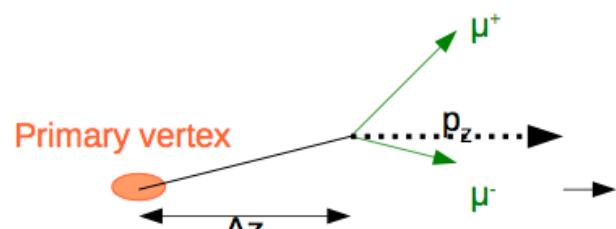
Y. Q. Ma, K. Wang and K. T. Chao, Phys. Rev. Lett. 106 (2011) 042002.



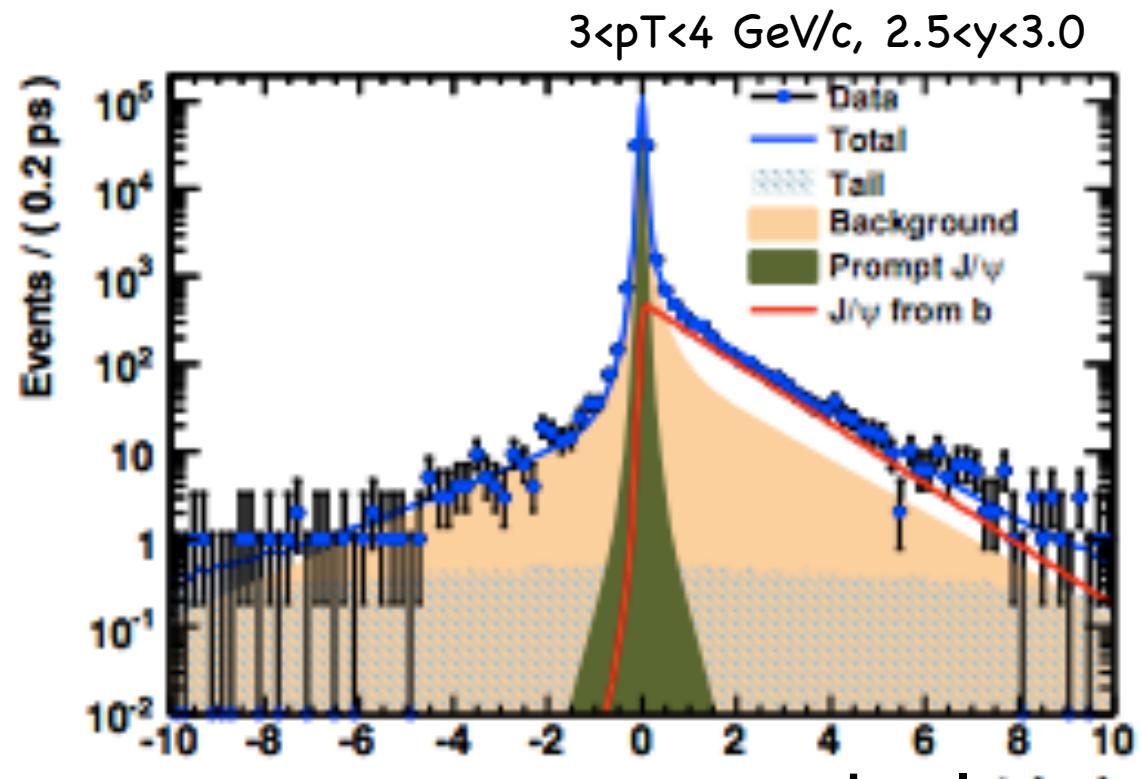
A. D. Frawley, T. Ullrich  
and R. Vogt, Phys. Rep.  
462 (2008) 125.

# J/ $\psi$ pseudo-proper time

$$t_z = \Delta z / p_z * M_{J/\psi}$$



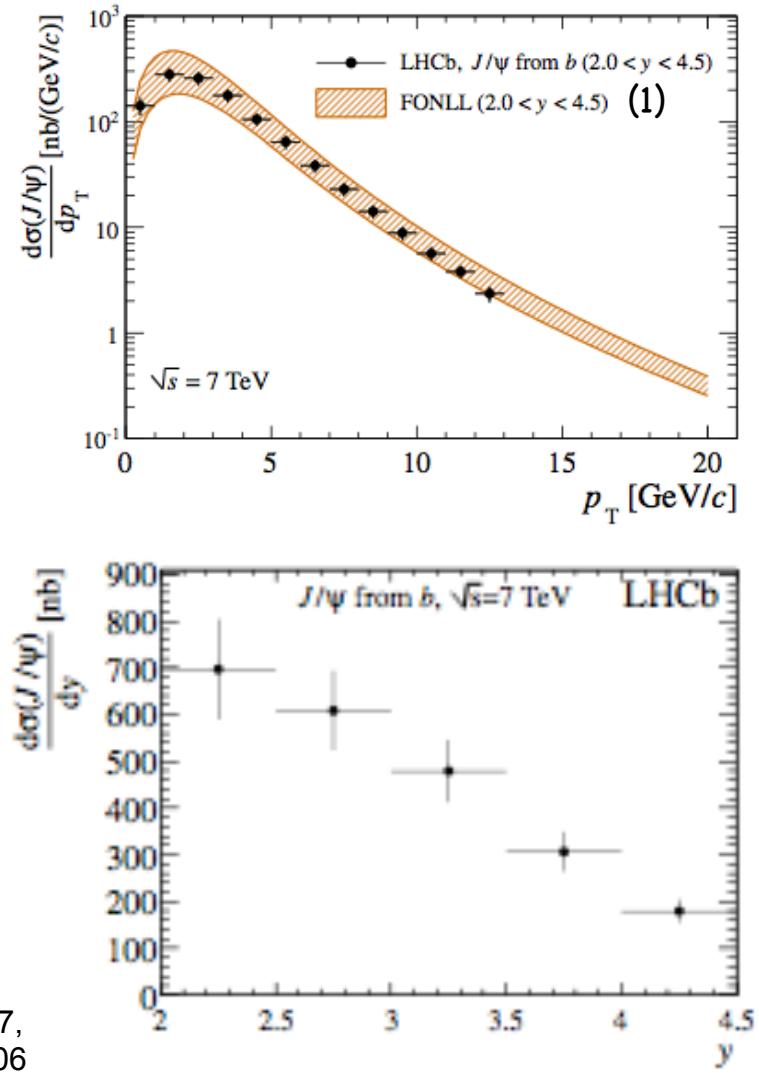
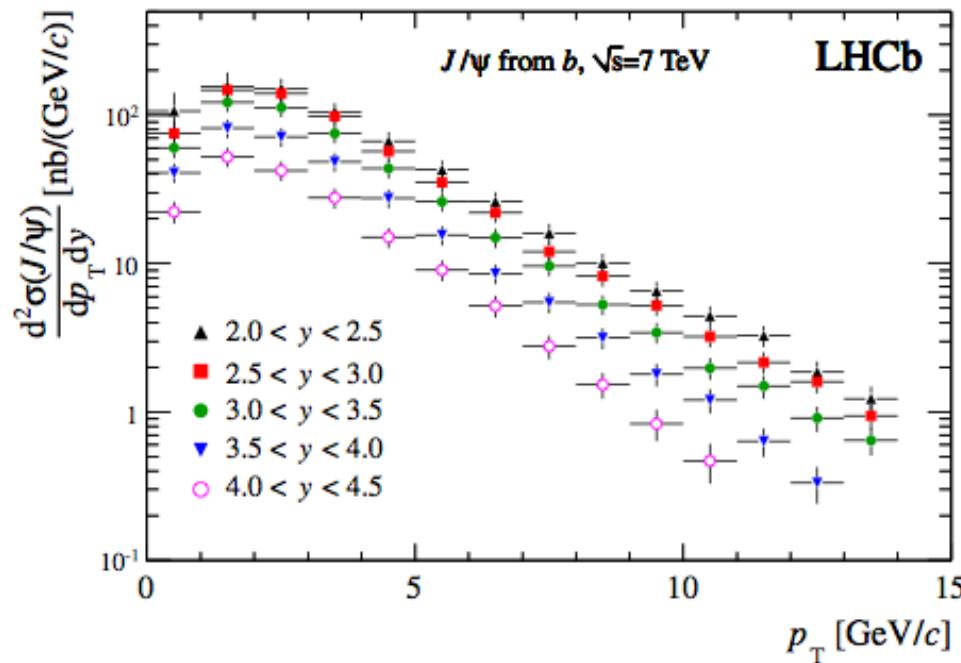
→  $t_z$  used to separate J/ $\psi$  prompt from J/ $\psi$  from B



In this bin:

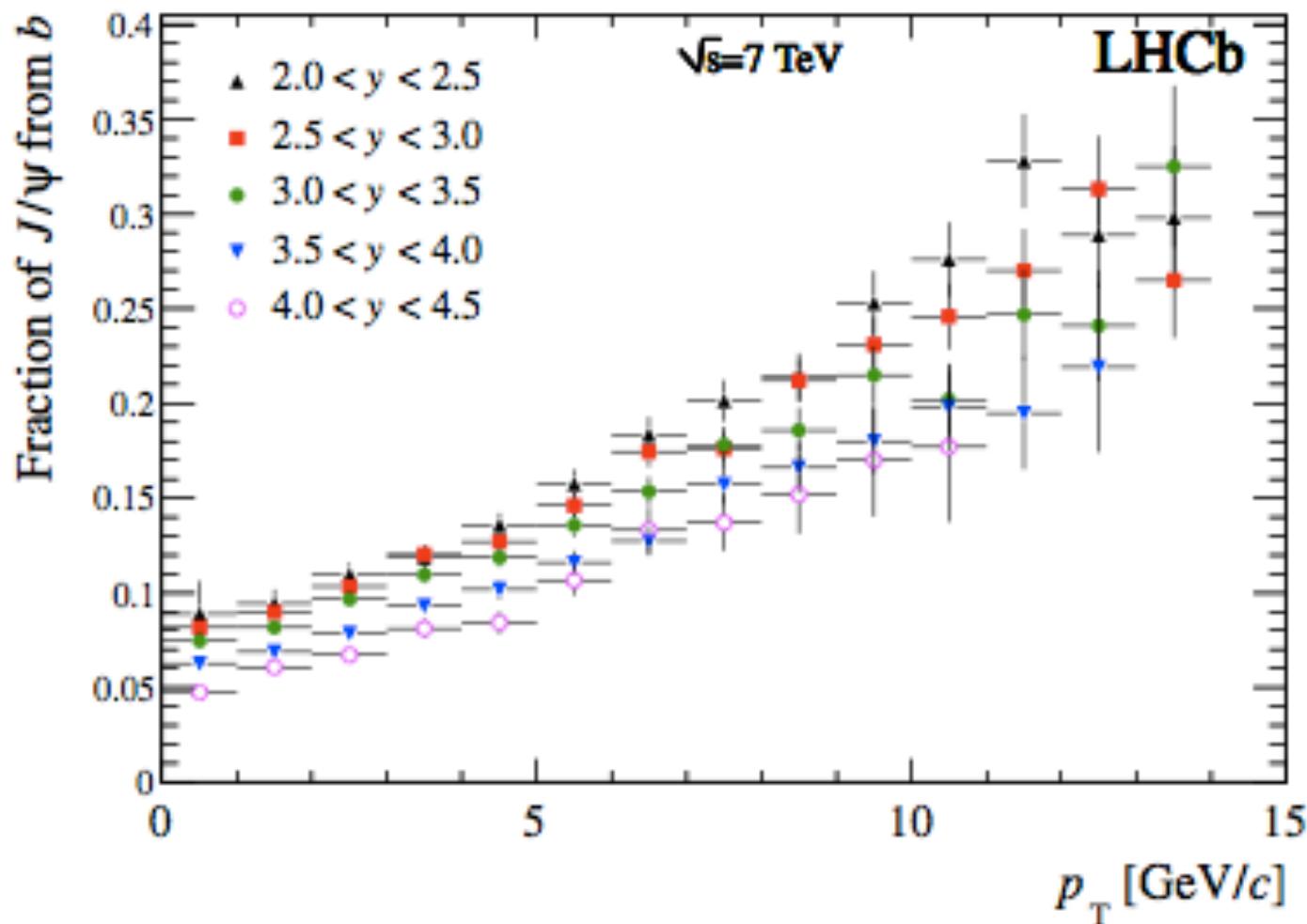
$t_z$  resolution = 53 fs

# J/ $\psi$ from B cross-section

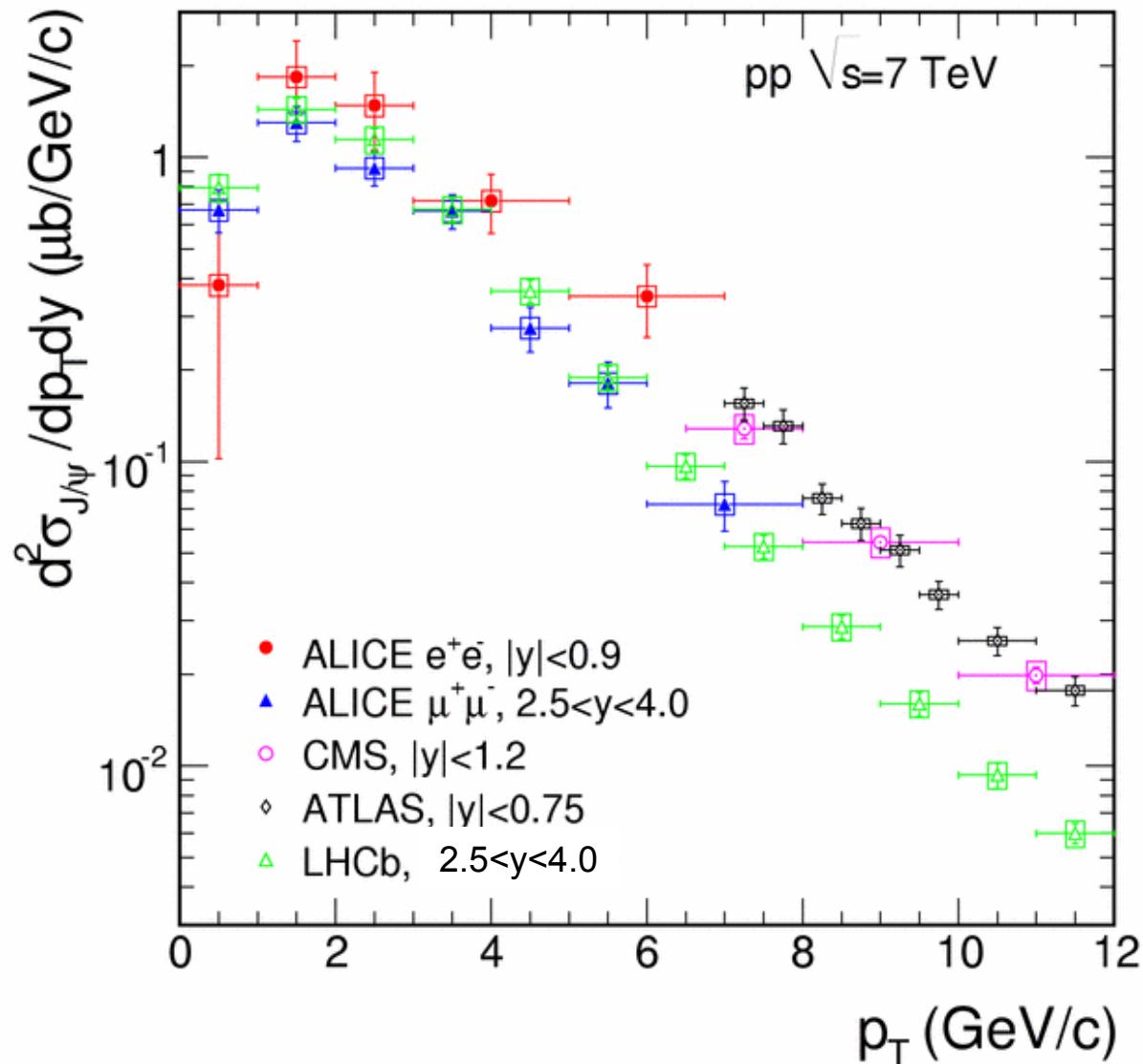


M. Cacciari, M. Greco and P. Nason, J. High Energy Phys. 9805 (1998) 007,  
 M. Cacciari, S. Frixione and P. Nason, J. High Energy Phys. 0103 (2001) 006

# Fraction from $B$



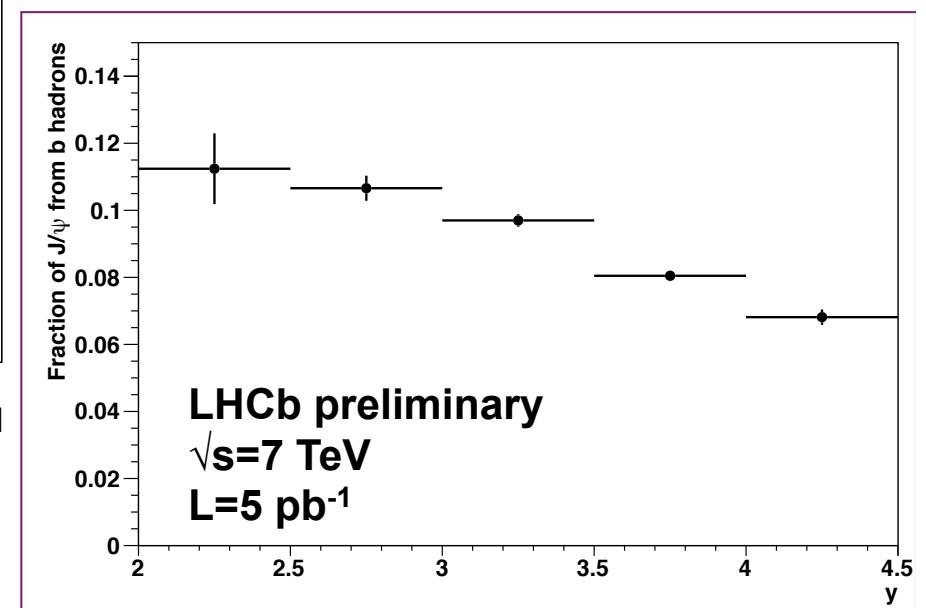
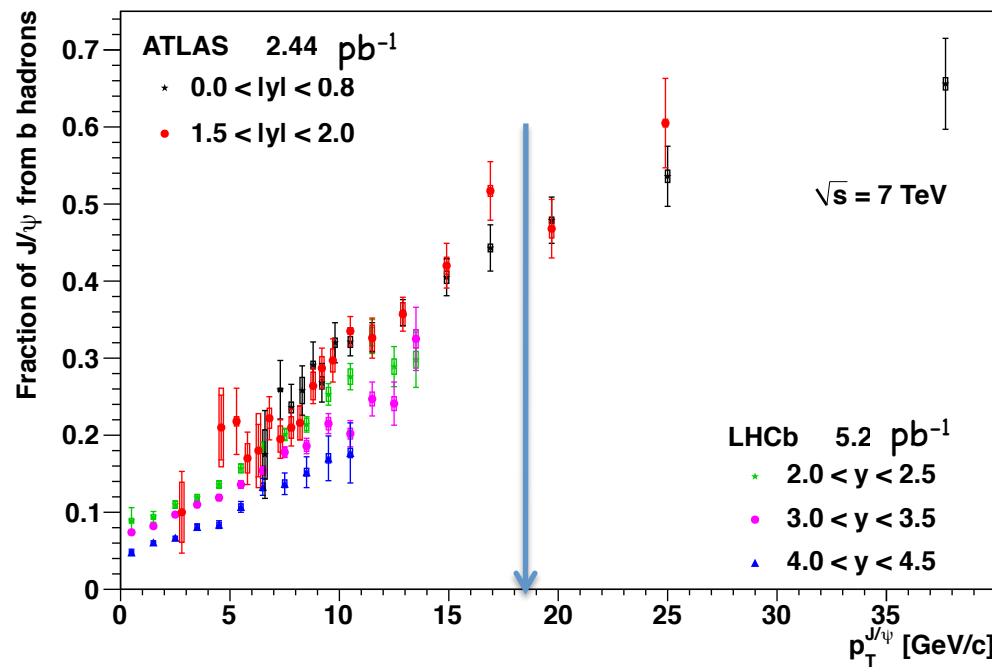
# J/ $\psi$ : comparison with other experiments



# Fraction of $J/\psi$ from $B$

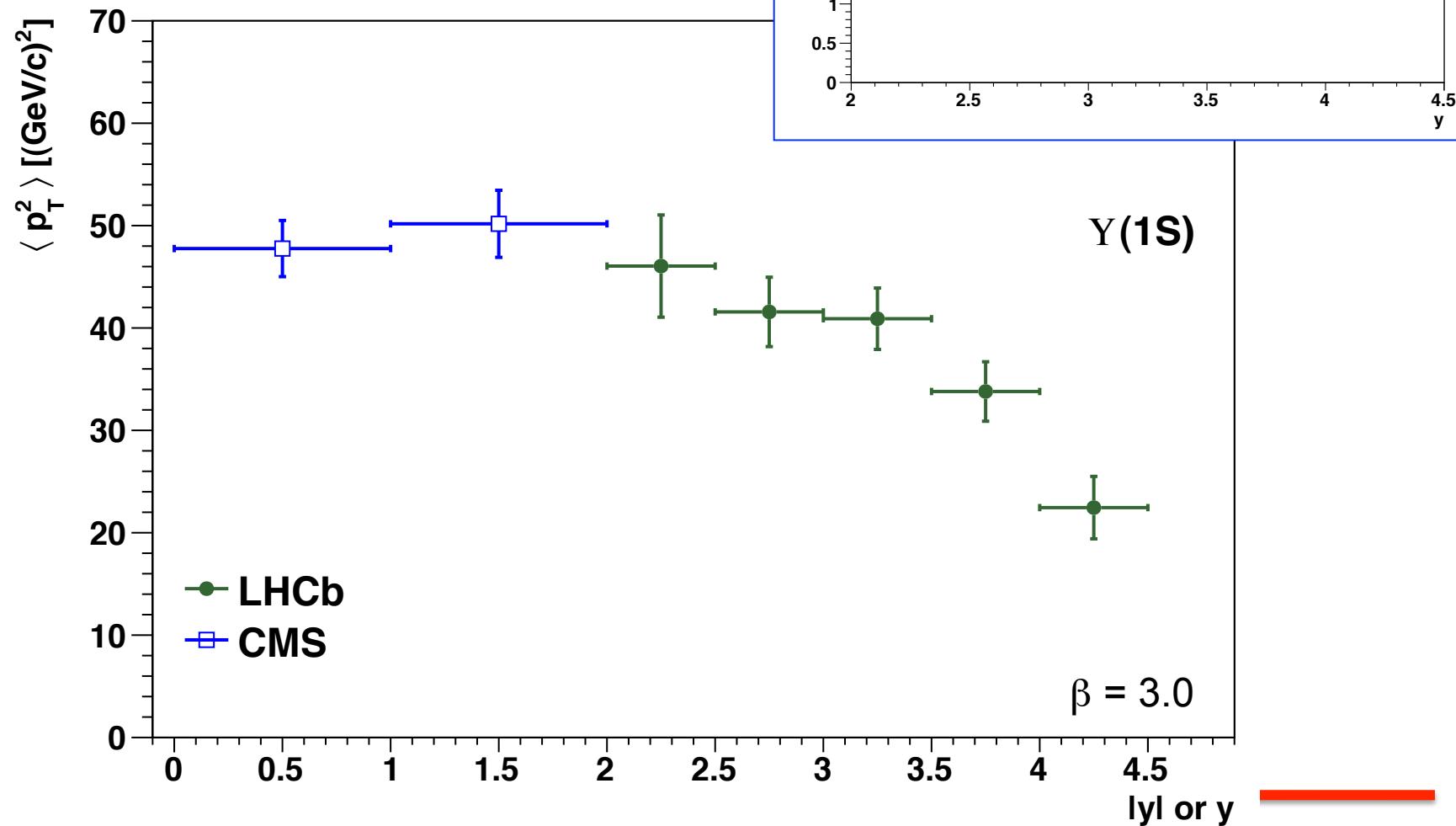
→ Spring 2011 :

- new data from Atlas show some saturation at high  $p_T$
- LHCb shows decreasing trend at forward rapidity



# $\Upsilon$ : $p_T$ shape vs. rapidity

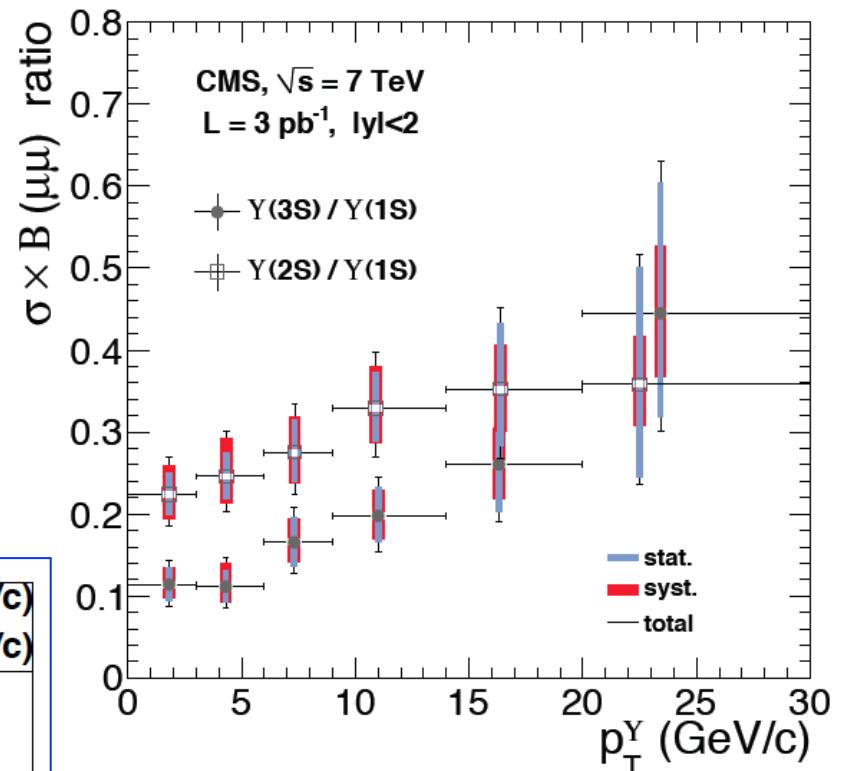
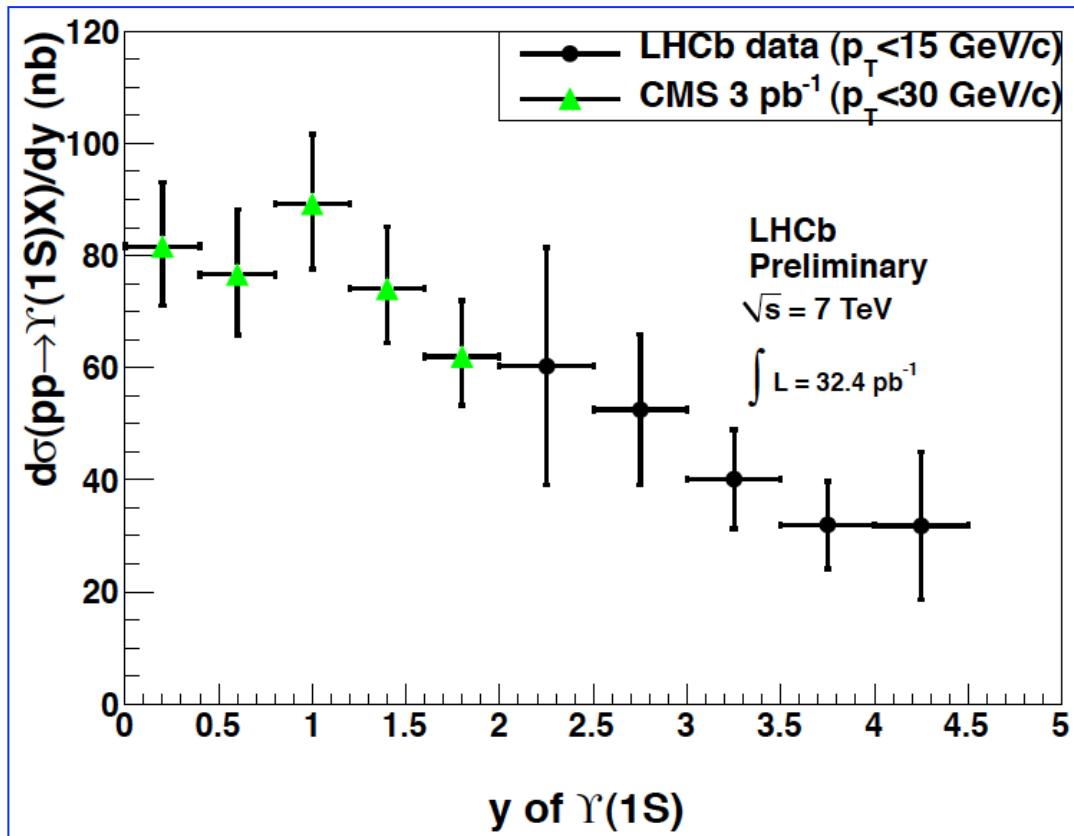
Also in the case of the  $\Upsilon(1S)$  we see that  $\beta$  is essentially independent of rapidity



# $\Upsilon$ : rapidity and 2S, 3S data

Good compatibility between LHCb and CMS for the  $d\sigma/dy$  1S production cross section

Heavier 2S and 3S states have flatter  $d\sigma/dp_T$



# Integrated J/ψ → μμ cross section measurements

Experiment Range Luminosity	LHCb (in $\mu\text{b}$ ) $p_T < 15 \text{ GeV}$ , $2.0 < y < 4.5$ $5.2 \text{ pb}^{-1}$	CMS (in nb) $6.5 < p_T < 30 \text{ GeV}$ , $ y  < 2.4$ $312 \text{ nb}^{-1}$	ATLAS (in nb) $ y  < 2.4, p_T > 7 \text{ GeV}$ $1.5 <  y  < 2, p_T > 1 \text{ GeV}$ $2.2 \text{ pb}^{-1}$	ALICE(in $\mu\text{b}$ ) $2.5 < y < 4.0,$ $0 < p_T < 12 \text{ GeV}$ $13.3 \text{ nb}^{-1}$
Inclusive J/ψ		$97.5 \pm 1.5 \pm 3.4 \pm 10.7$ (lum)	$81.1 \pm 1 \pm 10^{+25}_{-20} \pm 3$ $510 \pm 70 + 84 - 123 + 919 - 134 \pm 17$	$6.31 \pm 0.25 \pm 0.80^{+0.95}_{-1.9}$ <sub>6</sub>
Prompt J/ψ	$10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20}$	$70.9 \pm 2.1 \text{ (stat)} \pm 3.0 \text{ (syst)} \pm 7.8 \text{ (lum.)}$	$59 \pm 1 \pm 8 + 9 - 6 \pm 2$ $450 \pm 67 + 85 - 114 + 741 - 105 \pm 15$	
J/ψ from B	$1.14 \pm 0.01 \pm 0.16$	$26.0 \pm 1.4 \text{ (stat)} \pm 1.6 \text{ (syst)} \pm 2.9 \text{ (lum.)}$	$23.0 \pm 0.6 \pm 2.8 \pm 0.2 \pm 0.8$ $61 \pm 24 \pm 19 \pm 1 \pm 2$	
Total bb*	$288 \pm 4 \pm 48$			

\* Extrapolating to the LHCb acceptance using Pythia 6.4

Uncertainties : First stat, second syst, third spin, fourth lum

# LHCb : $\Upsilon(1S)$ Systematic Uncertainties

SOURCE	METHOD	VALUE	COMMENTS
luminosity	see section 3.2.2	10%	correlated among bins
$\epsilon^{trig}$ calculation	difference MC-MC truth	2-67%	correlated among bins
polarisation on A	extreme polarisation scenarios	0-33%	correlated among bins
polarisation on $\epsilon^{rec}$	extreme polarisation scenarios	0-21%	correlated among bins
choice of fit function	different function	1%	correlated among bins
unknown $p_T$ spectrum	$p_T$ spectrum distribution	1%	correlated among bins <sup>2</sup>
GEC	statistical uncertainty of data	2%	correlated among bins
$\epsilon^{trackquality}$	difference data-MC	0.5% per track	correlated among bins
$\epsilon^{track-finding}$	difference data-MC	4% per track	correlated among bins
vertexing	difference data-MC	1%	correlated among bins
$\epsilon^{muonID}$	tag and probe [20]	1.1%	correlated among bins

# LHCb X Mass Measurement

## Signal Modeling

- Vary fit range
- Vary natural width from 0 – 2.6 MeV
- Embed MC in same-sign background and check for bias from background fit model

## Calibration

- Vary momentum scale by  $\pm 0.1$  per mille [quoted uncertainty]
- Parameterize residual  $\eta$  bias and make dependent scale factor
- Vary amount of material by 10 %

## Alignment

- Drop TT hits and repeat procedure
- Scale track slopes in velo by per mille

Source of uncertainty	Value [ $MeV/c^2$ ]
<b>Mass fitting:</b> Natural width	0.02
Background model	0.02
Fit range	0.01
<b>Momentum calibration:</b> Average momentum scale	0.05
$\eta$ dependence of momentum scale	0.03
<b>Detector description:</b> Energy loss correction	0.05
<b>Detector alignment:</b> Tracking stations (TT information)	0.05
Vertex detector (track slopes)	0.01
Quadratic sum	0.10

# LHCb : Chic ratio syst (I)

Four types of systematics

- Systematics coming from the fit
  - From fixed parameters: s1, si/s1, mi-m1
  - From background shape: fit range,  $\chi_{c0}$  in the fit
- Systematics from efficiencies
  - Error from Monte Carlo statistic
- Systematics from MC fit
  - Uncertainty from the difference in percentage between generated and reconstructed  $N(\chi_{c2})/N(\chi_{c1})$ . Due to wrong MC photon association.
- Systematic From the  $\text{Br}(\chi_c(1,2) \rightarrow J/\psi \gamma)$ 
  - Correlated systematic
- Evaluation of all the systematics for results in converted and not converted samples
- Combination of the results with the statistical errors
- Combination of the uncorrelated systematics
- Evaluation of the correlated systematic using the combined results

# LHCb Chic ratio : syst (II)

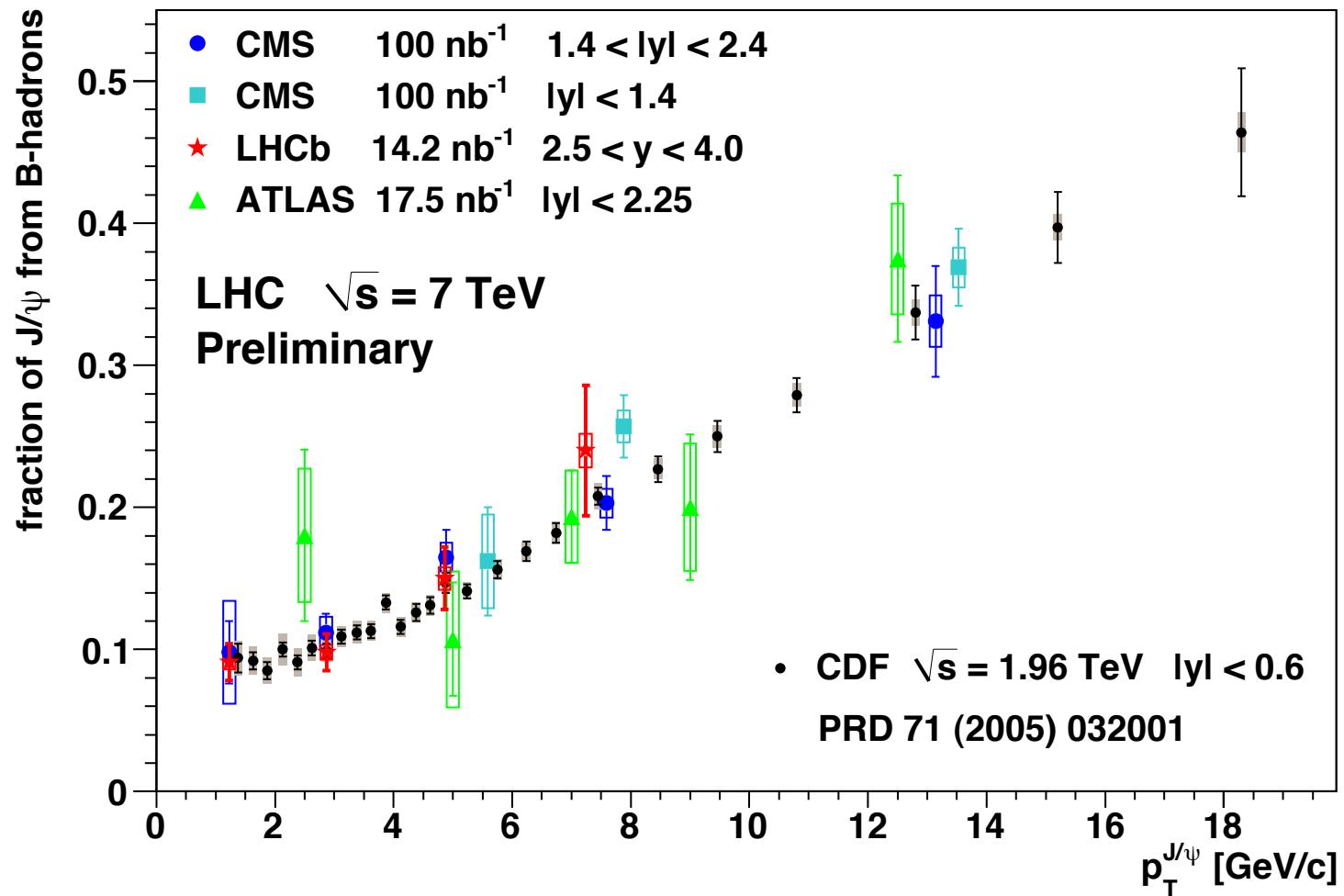
$\gamma$  not converted

$p_T^{J/\Psi}$ (GeV/c )	2 – 3	3 – 4	4 – 5
$Br(\chi_c \rightarrow J/\psi\gamma)$	–	+0.070 –0.070	+0.070 –0.053
Efficiencies	–	+0.012 –0.011	+0.015 –0.011
Systematics from fit	–	+0.040 –0.040	+0.029 –0.033
$p_T^{J/\Psi}$ (GeV/c )	5 – 6	6 – 7	7 – 8
$Br(\chi_c \rightarrow J/\psi\gamma)$	+0.070 –0.061	+0.079 –0.061	+0.061 –0.053
Efficiencies	+0.015 –0.013	+0.021 –0.019	+0.021 –0.020
Systematics from fit	+0.029 –0.033	+0.043 –0.036	+0.029 –0.033
$p_T^{J/\Psi}$ (GeV/c )	8 – 9	9 – 10	10 – 11
$Br(\chi_c \rightarrow J/\psi\gamma)$	+0.061 –0.044	+0.061 –0.044	+0.070 –0.061
Efficiencies	+0.025 –0.024	+0.034 –0.032	+0.058 –0.053
Systematics from fit	+0.027 –0.024	+0.024 –0.029	+0.027 –0.036
$p_T^{J/\Psi}$ (GeV/c )	11 – 12	12 – 13	13 – 15
$Br(\chi_c \rightarrow J/\psi\gamma)$	+0.061 –0.035	+0.017 –0.018	+0.044 –0.035
Efficiencies	+0.053 –0.046	+0.026 –0.023	+0.055 –0.052
Systematics from fit	+0.020 –0.020	+0.022 –0.013	+0.022 –0.043

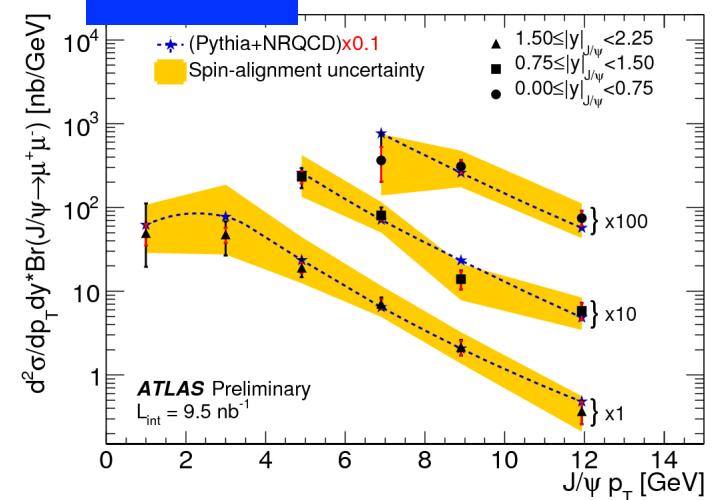
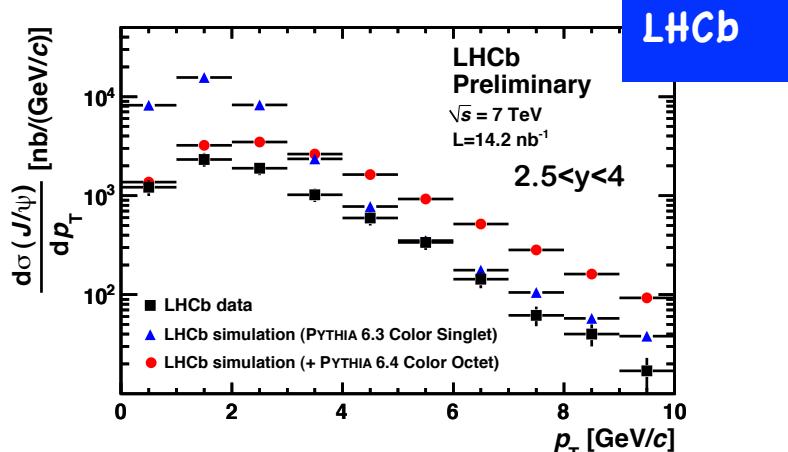
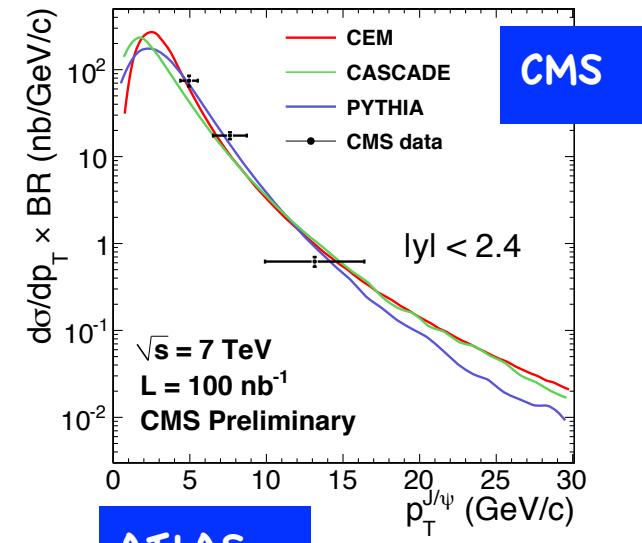
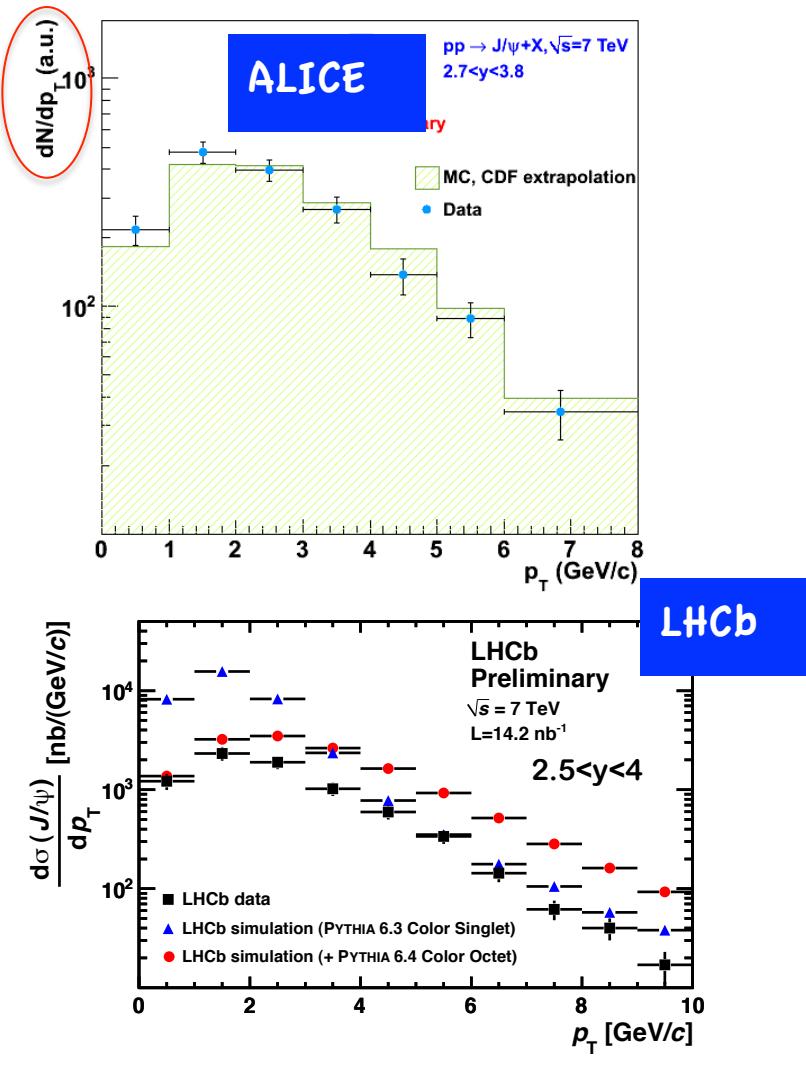
$\gamma$  converted

$p_T^{J/\Psi}$ (GeV/c )	2 – 3	3 – 4	4 – 5
$Br(\chi_c \rightarrow J/\psi\gamma)$	–	+0.105 –0.079	+0.061 –0.044
Efficiencies	–	+0.024 –0.022	+0.018 –0.013
Systematics from fit	–	+0.066 –0.089	+0.045 –0.045
$p_T^{J/\Psi}$ (GeV/c )	5 – 6	6 – 7	7 – 8
$Br(\chi_c \rightarrow J/\psi\gamma)$	+0.061 –0.053	+0.053 –0.053	+0.070 –0.053
Efficiencies	+0.018 –0.019	+0.021 –0.018	+0.032 –0.031
Systematics from fit	+0.045 –0.038	+0.036 –0.040	+0.052 –0.087
$p_T^{J/\Psi}$ (GeV/c )	8 – 9	9 – 10	10 – 11
$Br(\chi_c \rightarrow J/\psi\gamma)$	+0.044 –0.035	+0.044 –0.017	+0.035 –0.026
Efficiencies	+0.028 –0.028	+0.029 –0.025	+0.040 –0.036
Systematics from fit	+0.047 –0.052	+0.040 –0.047	+0.029 –0.036
$p_T^{J/\Psi}$ (GeV/c )	11 – 12	12 – 13	13 – 15
$Br(\chi_c \rightarrow J/\psi\gamma)$	+0.087 –0.061	+0.053 –0.035	+0.026 –0.026
Efficiencies	+0.125 –0.098	+0.091 –0.078	+0.055 –0.050
Systematics from fit	+0.158 –0.045	+0.029 –0.024	+0.038 –0.070

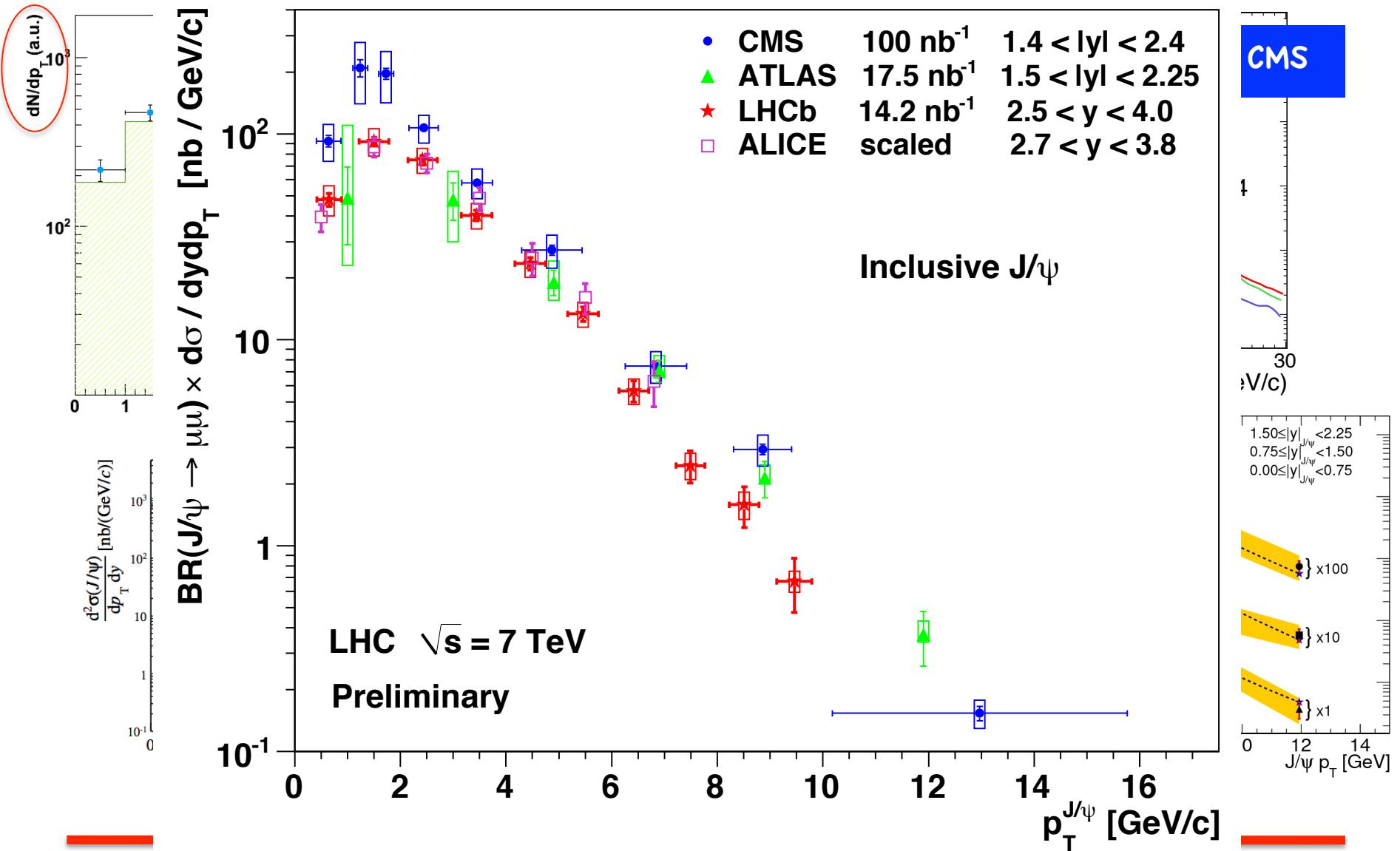
# Fraction from B: Comparison with other experiments



# Inclusive cross section measurements



# Inclusive cross section measurements



# Integrated Cross-section Results

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

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

Using the LHCb acceptance from Pythia, we extrapolated :

$$\sigma(pp \rightarrow b\bar{b}X) = \alpha_{4\pi} \frac{\sigma(J/\psi - \text{from} - b, p_T < 14 \text{GeV}/c, 2.0 < y < 4.5)}{2Br(b \rightarrow J/\psi X)}$$

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

$$\left. \begin{array}{l} \alpha_{4\pi}^{\text{FONLL}} = 5.21 \\ Br(b \rightarrow J/\psi X) = (1.2 \pm 0.1)\% \end{array} \right\}$$

In good agreement with:  $\sigma(pp \rightarrow b\bar{b}X) = 284 \pm 20 \pm 49 \mu\text{b}$   
measured in  $B \rightarrow D^0 \mu \nu X$  at LHCb

# Systematics on J/ $\psi$ cross section measurement

Source of systematic uncertainties considered:

*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 $\chi^2$	1.0
Vertexing	0.8
GEC	2.0
$\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$	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/ $\psi$  from b cross-sections, correlated between bins*

GEC efficiency on B events	2.0
$t_z$ fits	3.6

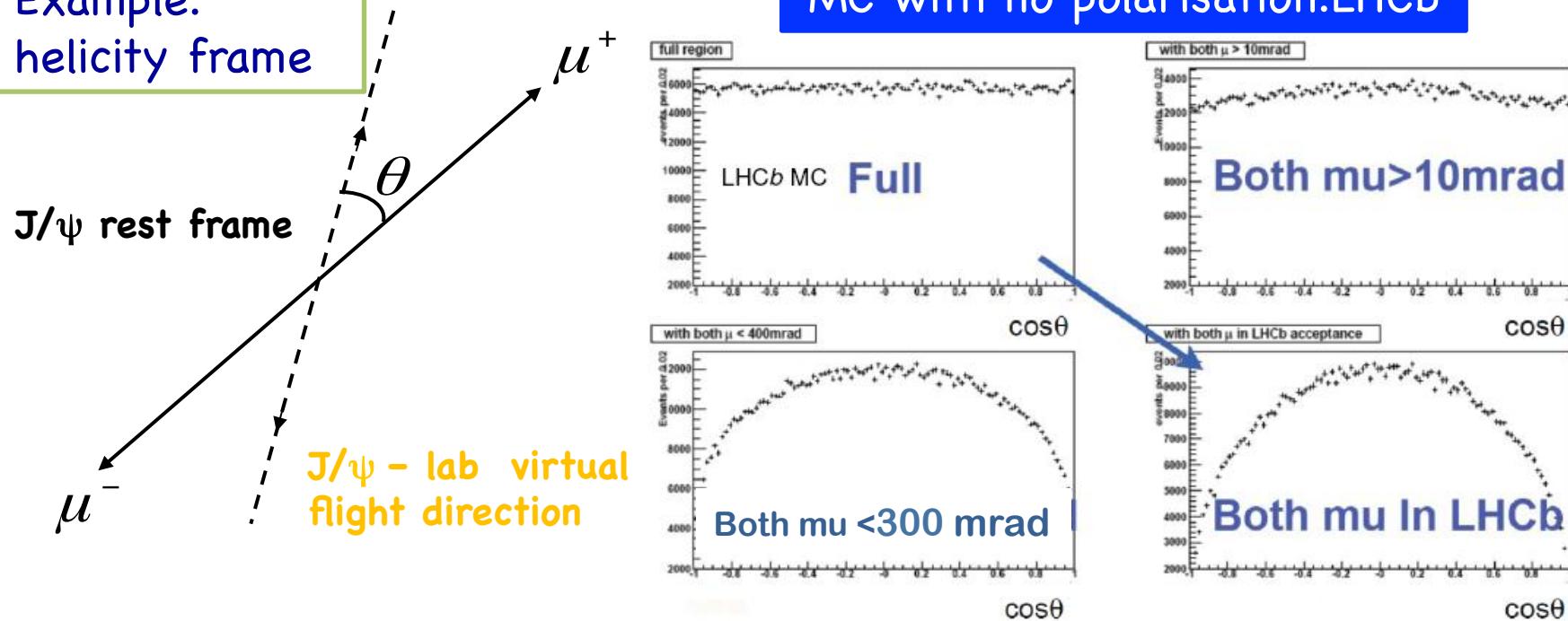
*Applied only to the extrapolation of the b $\bar{b}$  cross-section*

b hadronisation fractions	2.0
$\mathcal{B}(b \rightarrow J/\psi X)$	9.0

# Influence of J/ $\psi$ Polarisation

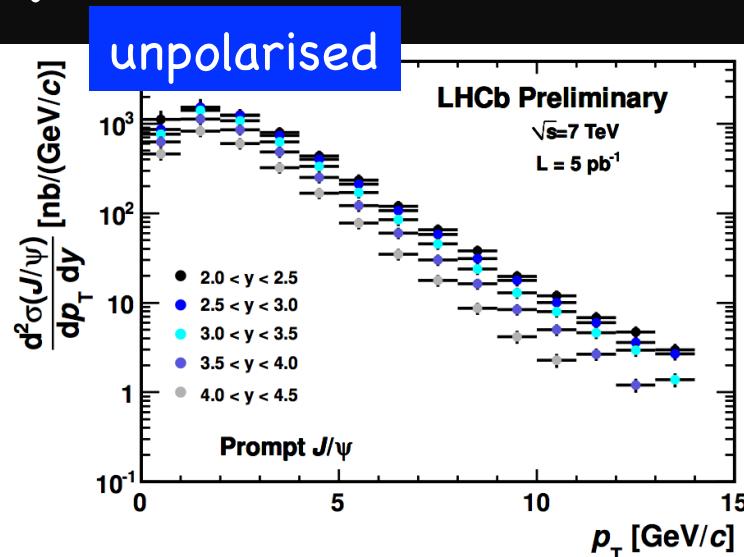
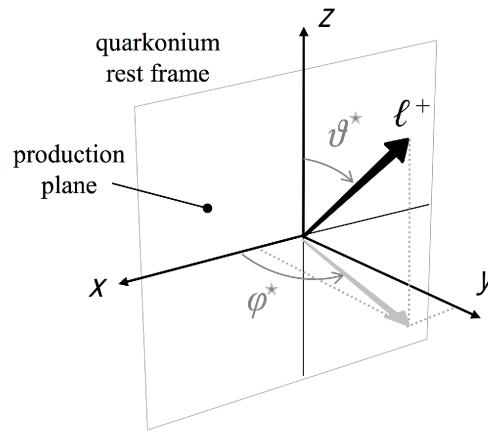
- Detector acceptance as a function of helicity angle  $\cos\theta$

Example:  
helicity frame



- acceptance generates an artificial polarisation  
→ large influence of polarisation on measurement
- First step: Treat polarisation as systematic error; here, present results in three different polarisation scenarios

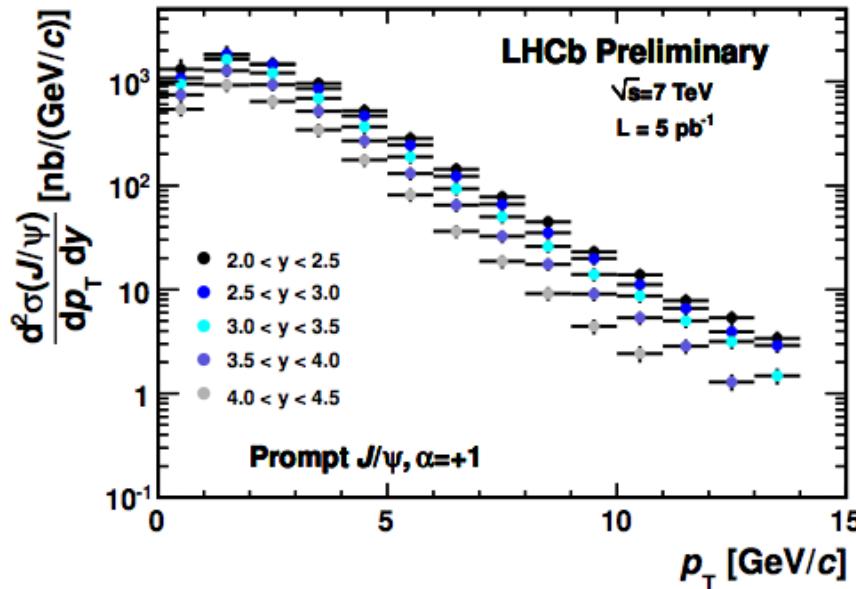
# Different polarisation scenarios



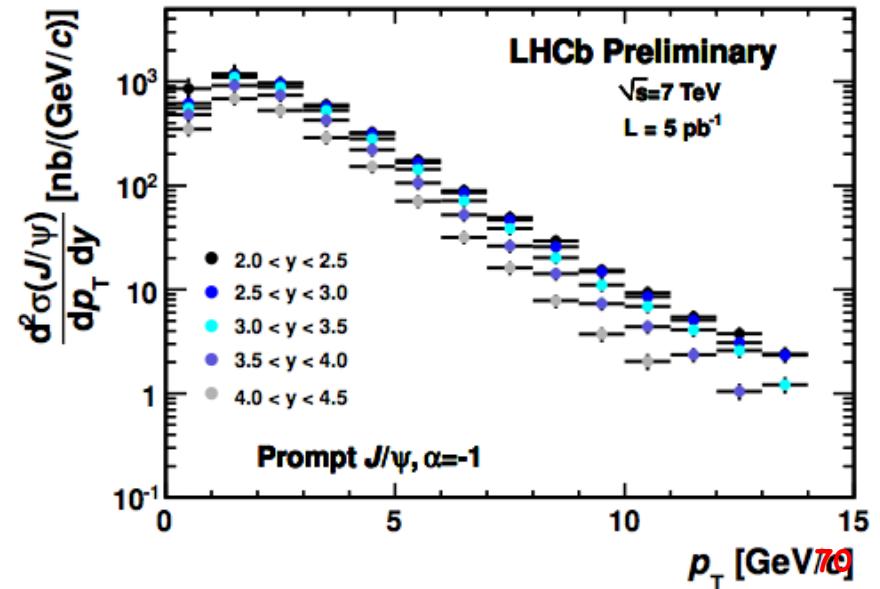
$\alpha = (\sigma_T - 2\sigma_L) / (\sigma_T + 2\sigma_L)$   
With  $\sigma_T / \sigma_L$  cross sections for production of transverse and longitudinal polarised

$\alpha = -1 \rightarrow$  full longitudinal polarisation  
 $\alpha = +1 \rightarrow$  full transverse polarization,  
 $\alpha = 0 \rightarrow$  no polarisation

Fully transversely polarised



Fully longitudinally polarised



# Motivations

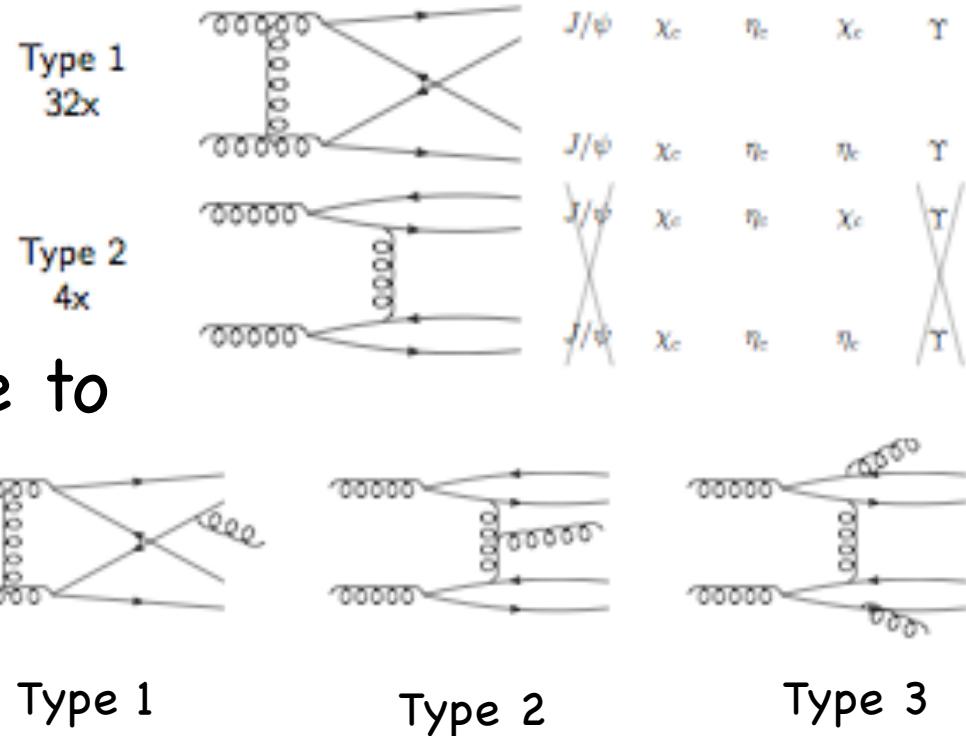
→ Many new resonances in charmonium+V

$J/\psi\rho^0$ ,  $J/\psi\omega^0$ ,  $J/\psi\phi$ ,  $\Upsilon\psi$ , ...

→ Interesting for:

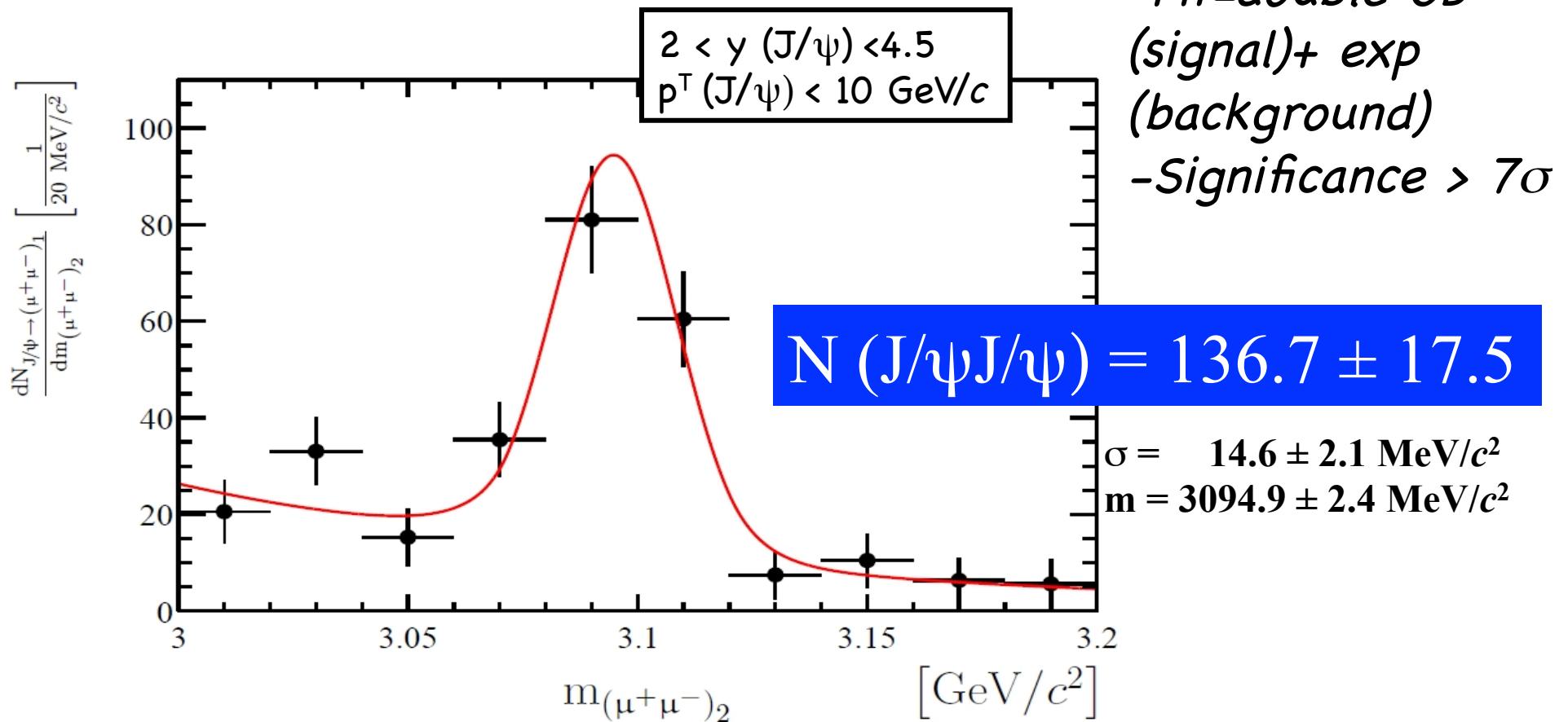
- Test of QCD: sensitive to CSM vs. COM

- Possible hint of tetraquark production



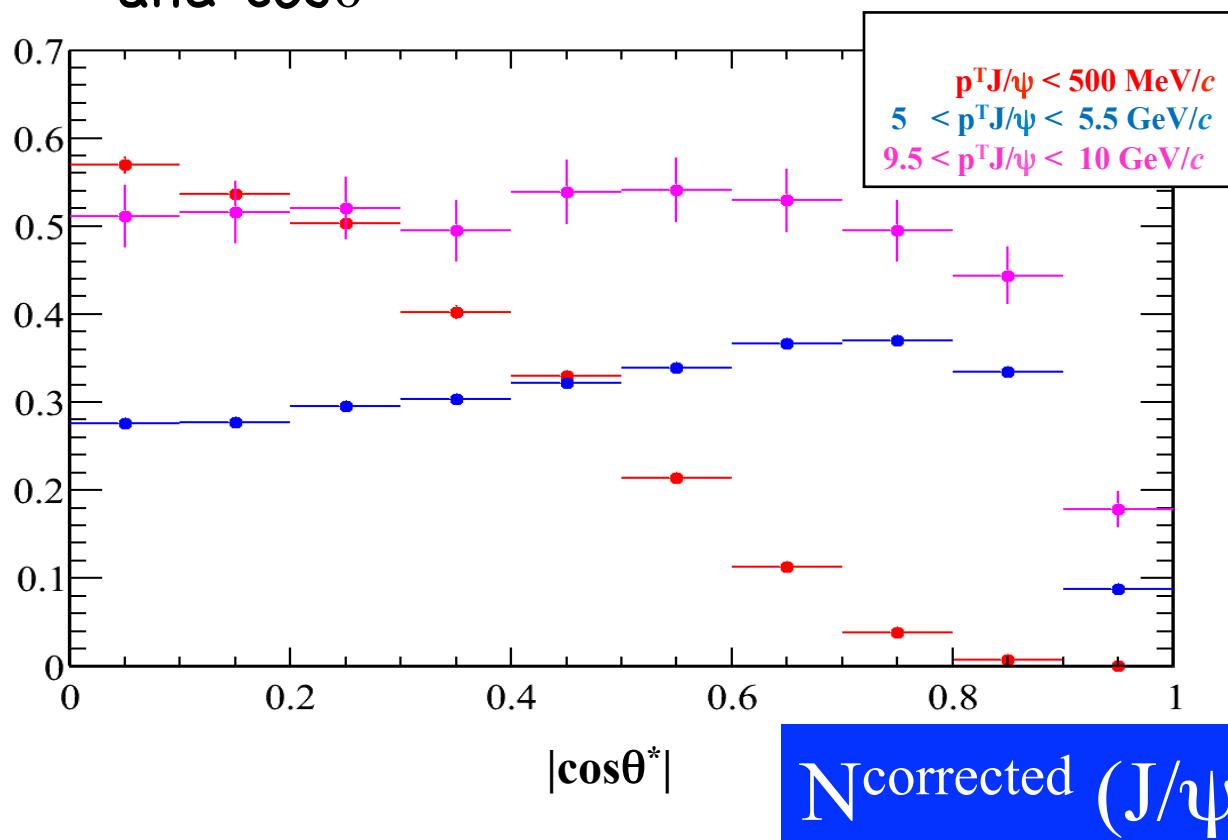
# Signal

→ Number of  $\text{J}/\psi$  events in bins of mass of the other  $\text{J}/\psi$



# Efficiency

- Each event : weight  $w = \varepsilon^{-1}$ , with  $\varepsilon = \varepsilon_{\text{rec}} \times \varepsilon_{\text{trig}} \times \text{acceptance}$
- Assume factorisation :  $\varepsilon_{J/\psi J/\psi} = \varepsilon_{J/\psi} \times \varepsilon_{J/\psi}$ ,  $\varepsilon$  binned vs.  $p_T$ ,  $y$  and  $\cos\theta^*$



$N_{\text{corrected}} (J/\psi J/\psi) = 700 \pm 133$

# J/ψ J/ψ Invariant Mass

