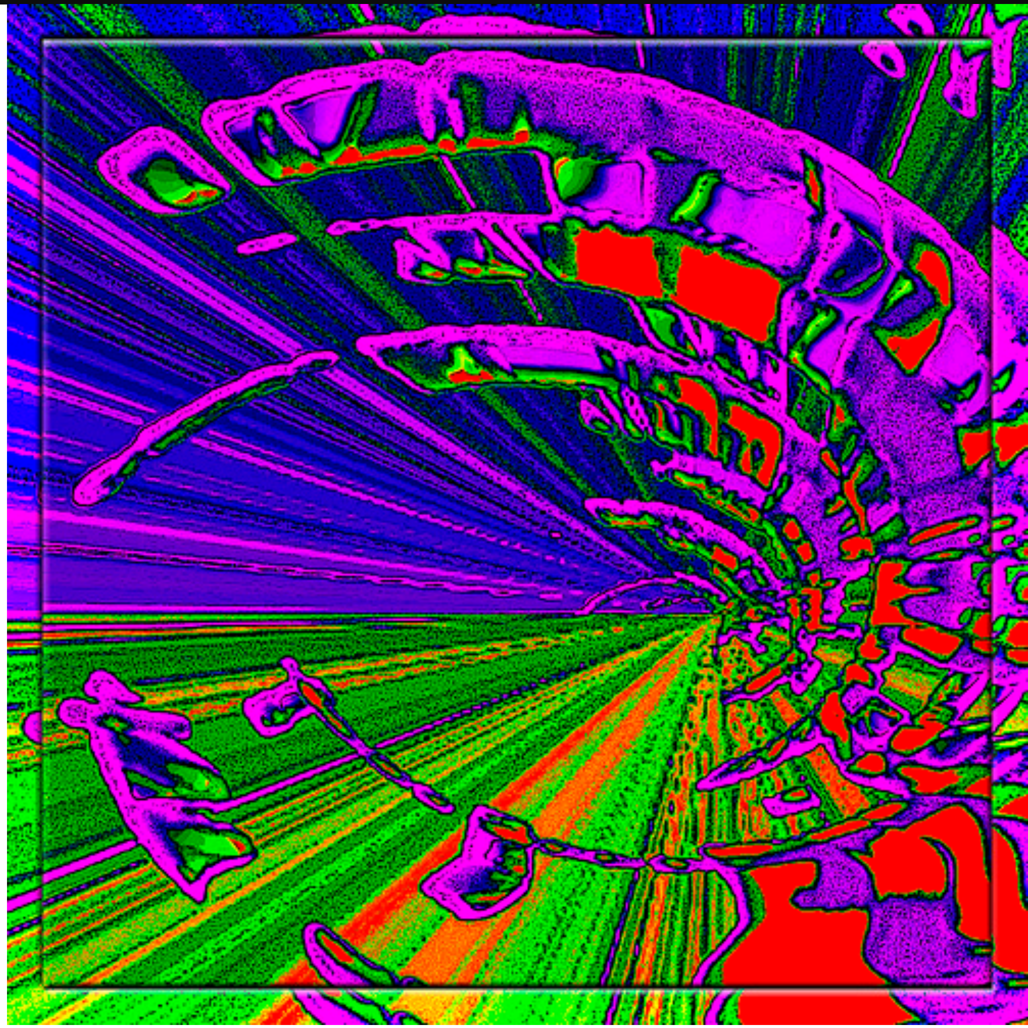
Quarkonium results at LHCb



Quarkonium Carrot

The Carrotinians - Exhibit Catalog. Item - JP=0– give or take about 1.5 GeV/c2 (aka 11)

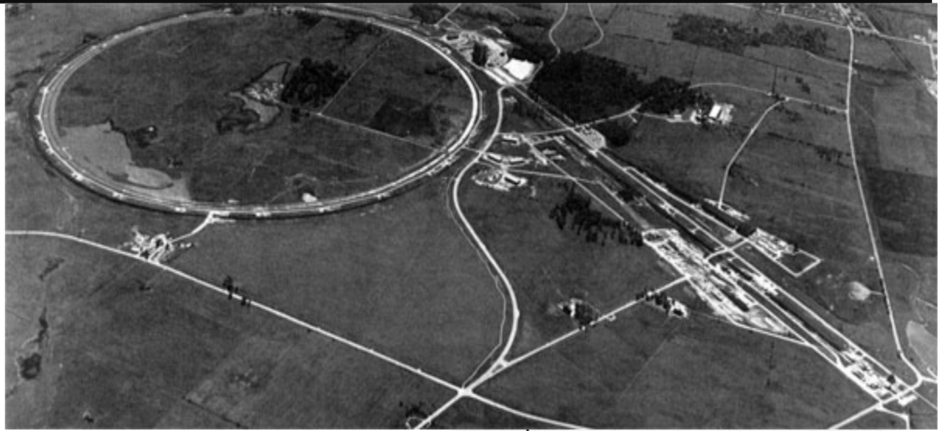
Giulia Manca, LPNHE Seminar, 17th March 2011

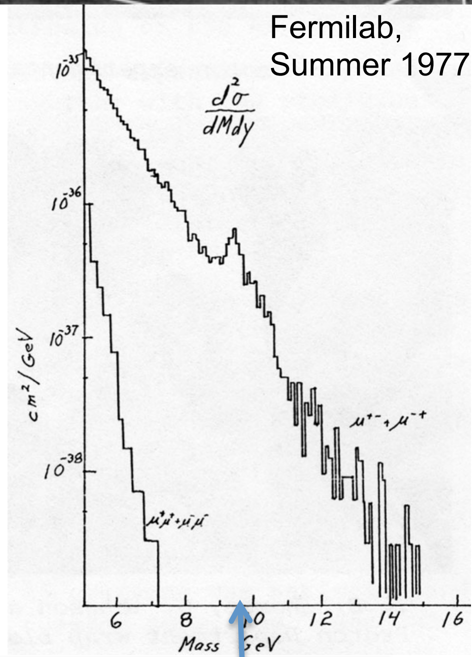
Outline

- ➡ Theory and motivation
- ➡ The LHC and LHCb
- ➡ Selected quarkonia results
  - J/ψ cross section
  - double J/ψ cross section
  - Υ cross section
- ➡ Conclusions and outlook

Introduction

- ➡Many quarkonia states discovered ~30 years ago
- ➡Nevertheless the production mechanism is not fully understood
- ➡Expected large cross-sections at LHC ->among first measurements
- ➡High rates make quarkonia central player for detector and software calibration

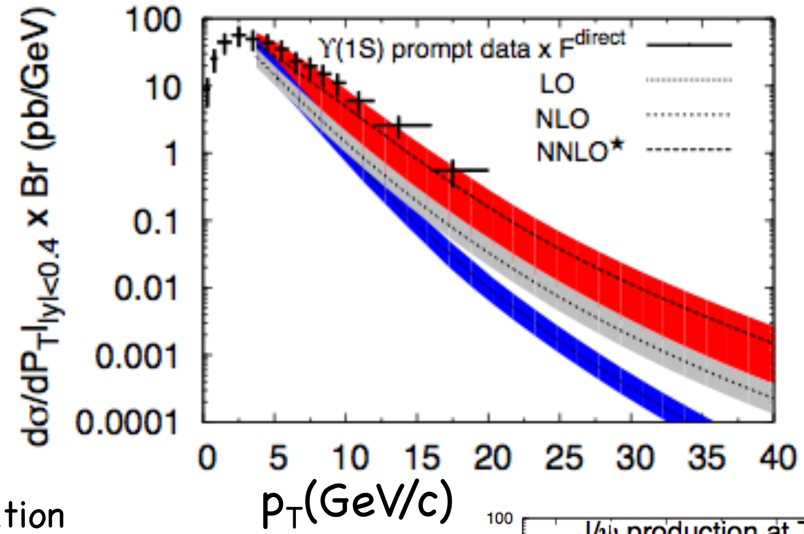


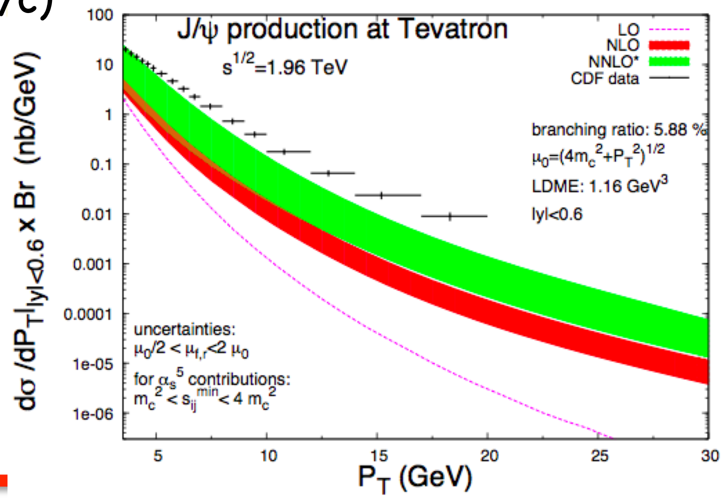


Motivations

J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007
P.Artoisenet, J.P.L, F.Maltoni, PLB 653:60,2007
P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, Phys. Rev. Lett. 101, 152001 (2008)

- The production mechanism in pp collisions still unclear
- Several models around :
  - Started with Color singlet(CSM)
    - Undershoots the data, no polarisation prdiction
  - Extendend to color octet (COM) mechanisms
    - Better agreement for cross-section, predicts TRANSVERSE polarisation, not confirmed by experiments
  - NLO CSM describes cross-section and allows LONGITUDINAL polarisation
  - Other models such as color evaporation model (CEM), kt factorization, soft color interaction model cannot describe the data or make predictions
- New data from LHC experiments will help to resolve this issue

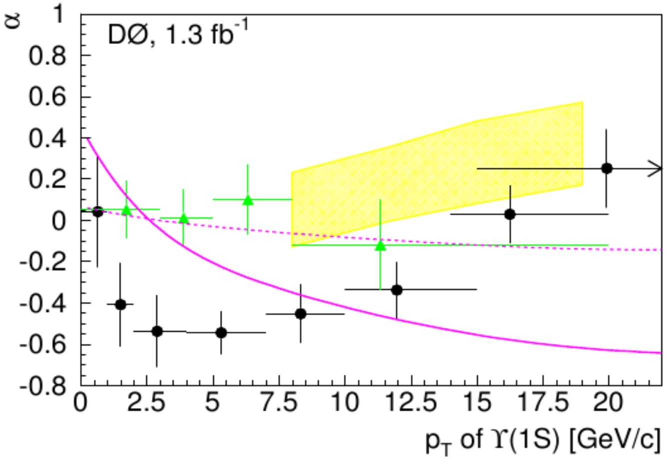




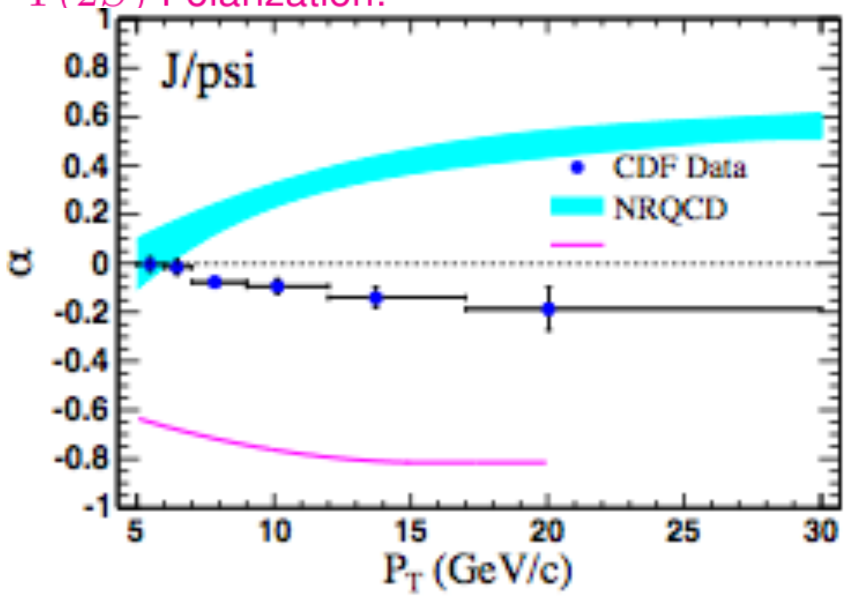
J/ψ & ϒ cross section crucial milestone in understanding detector and first step to B cross section measurement

Polarisation measurement

$\Upsilon(1S)$ Polarization:

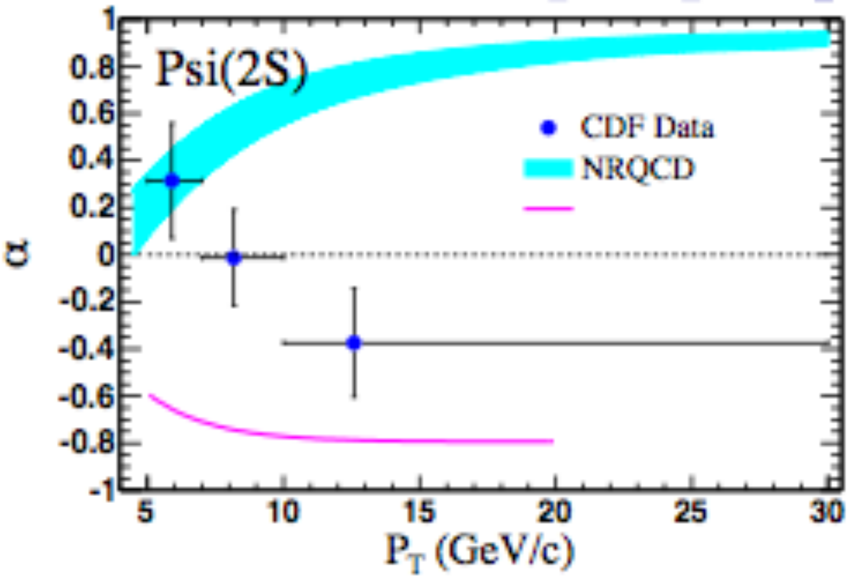


$\Upsilon(2S)$ Polarization:

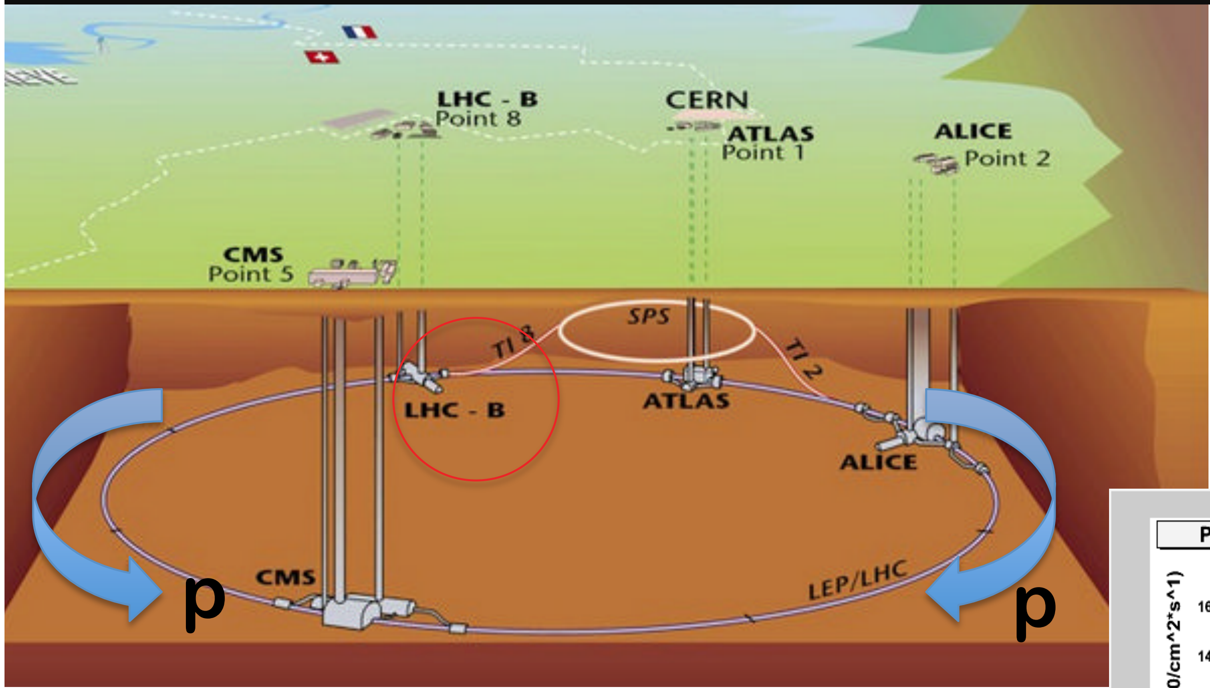


- In the Y(1S) case, the D0 results (black) are incompatible with the CDF results (green)
- The CDF results are compatible with the NRQCD predictions (yellow)
- The D0 results are marginally incompatible with NRQCD predictions
- The curves are the limiting case of the kT factorization predictions
- For J/psi and Psi(2s) the NRQCD and the data disagree.

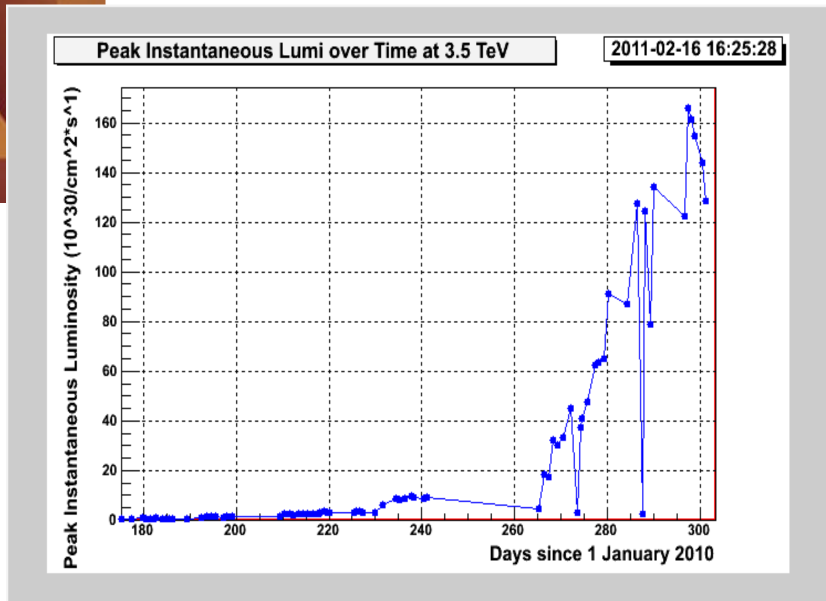
CDF, PRL 99: 132001, 2007



CERN and the LHC



pp collider : NOW :
- ➡ @ $\sqrt{s}$ = 7 TeV
- ➡ L ≈ $1\text{-}2\cdot10^{31}$ cm^{-2} s^{-1}

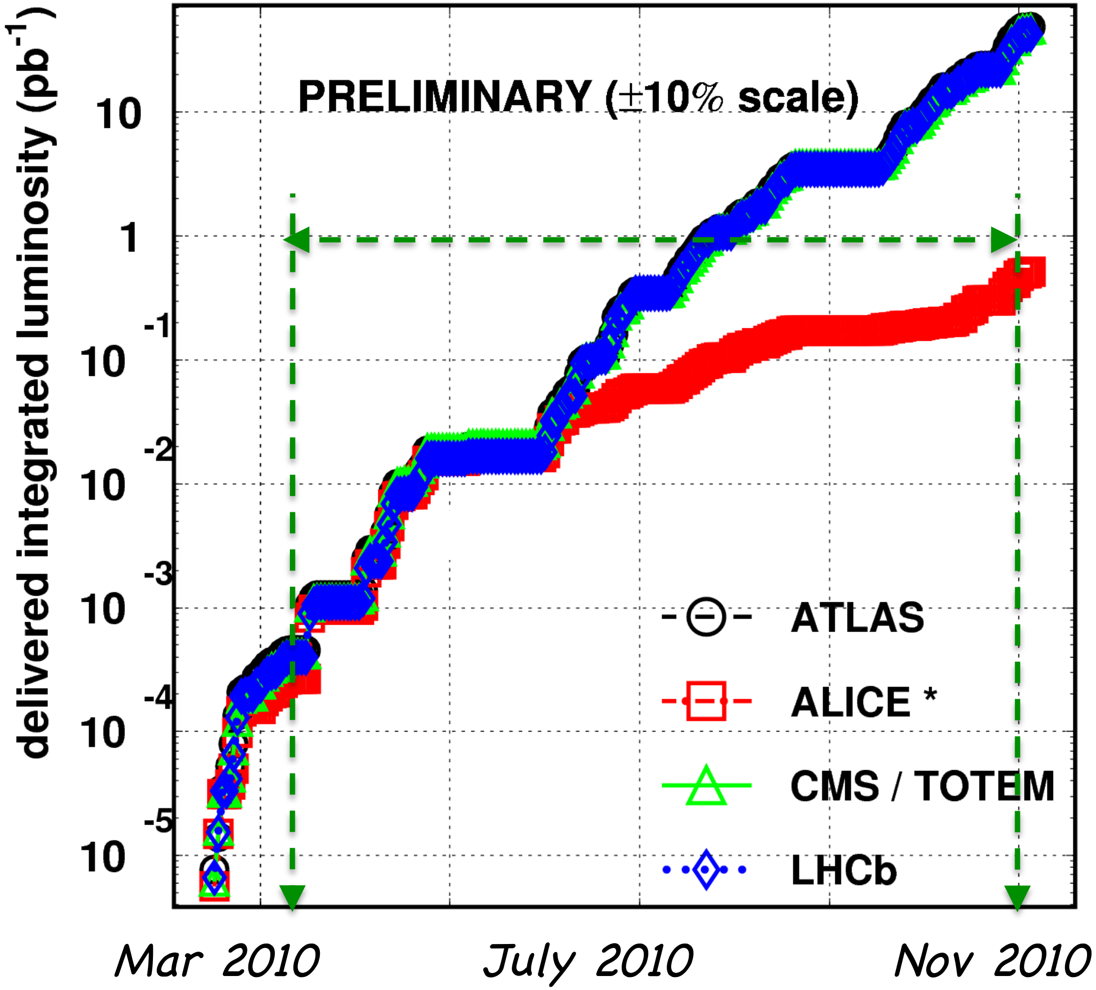


NOMINAL (2011) :

$\sqrt{s}$ =14 TeV

L = $2\cdot10^{32}$ cm^{-2} s^{-1} (LHCb specific)

Luminosity



* ALICE : low pile-up limited since 01.07.2010

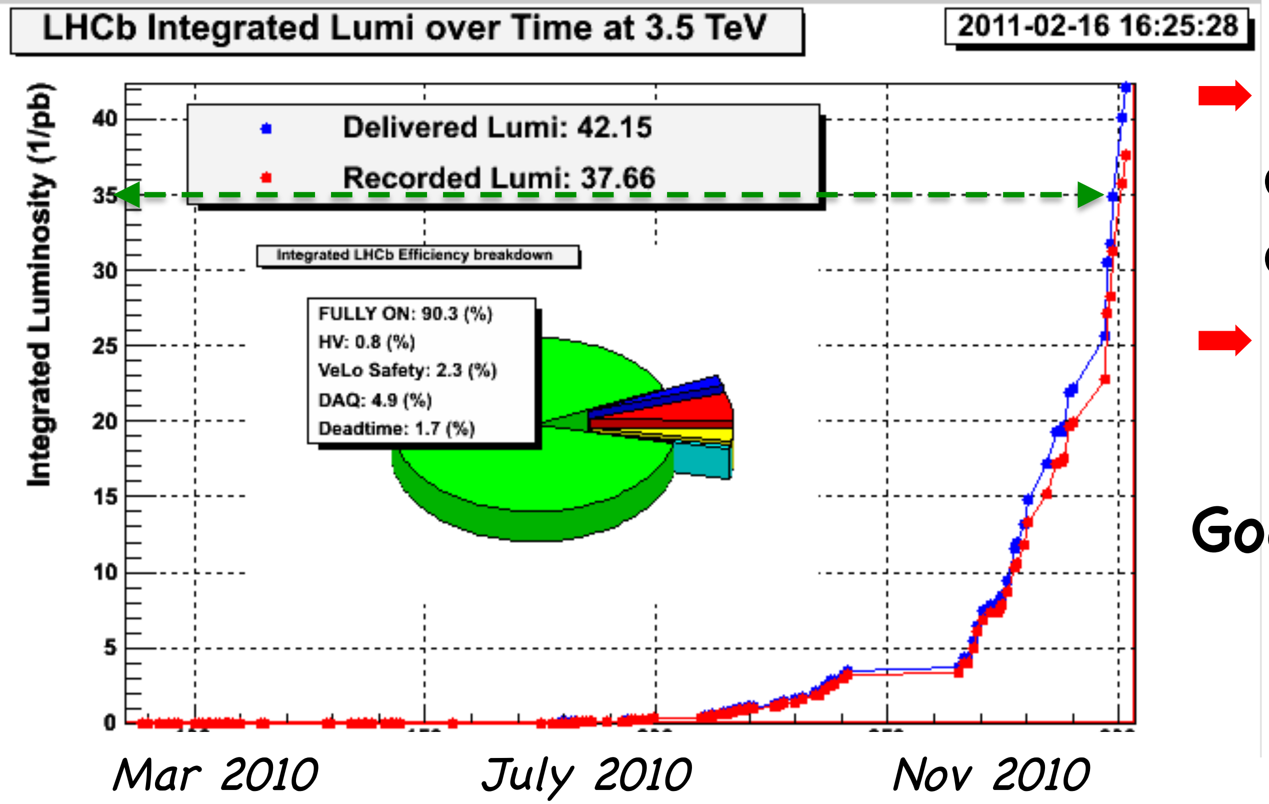
- ➡ LHC running well, all experiments have an efficiency ≈90%
- ➡ These analyses :

  $L \approx 35\ pb^{-1}$ (±10%)

Goals :

- 100 pb^{-1} (end of 2010)
- 1 fb^{-1} (end of 2011)

Luminosity @ LHCb



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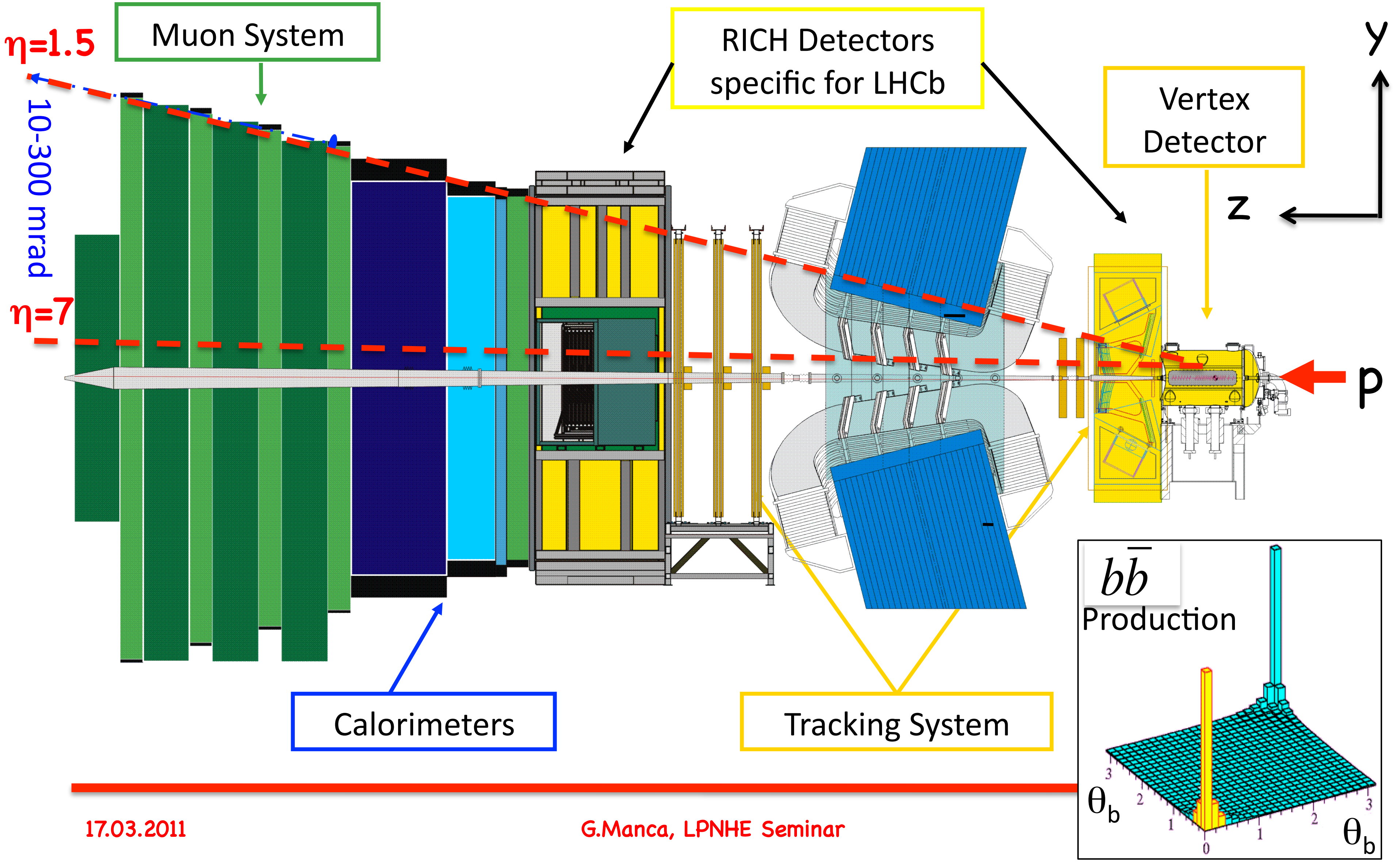
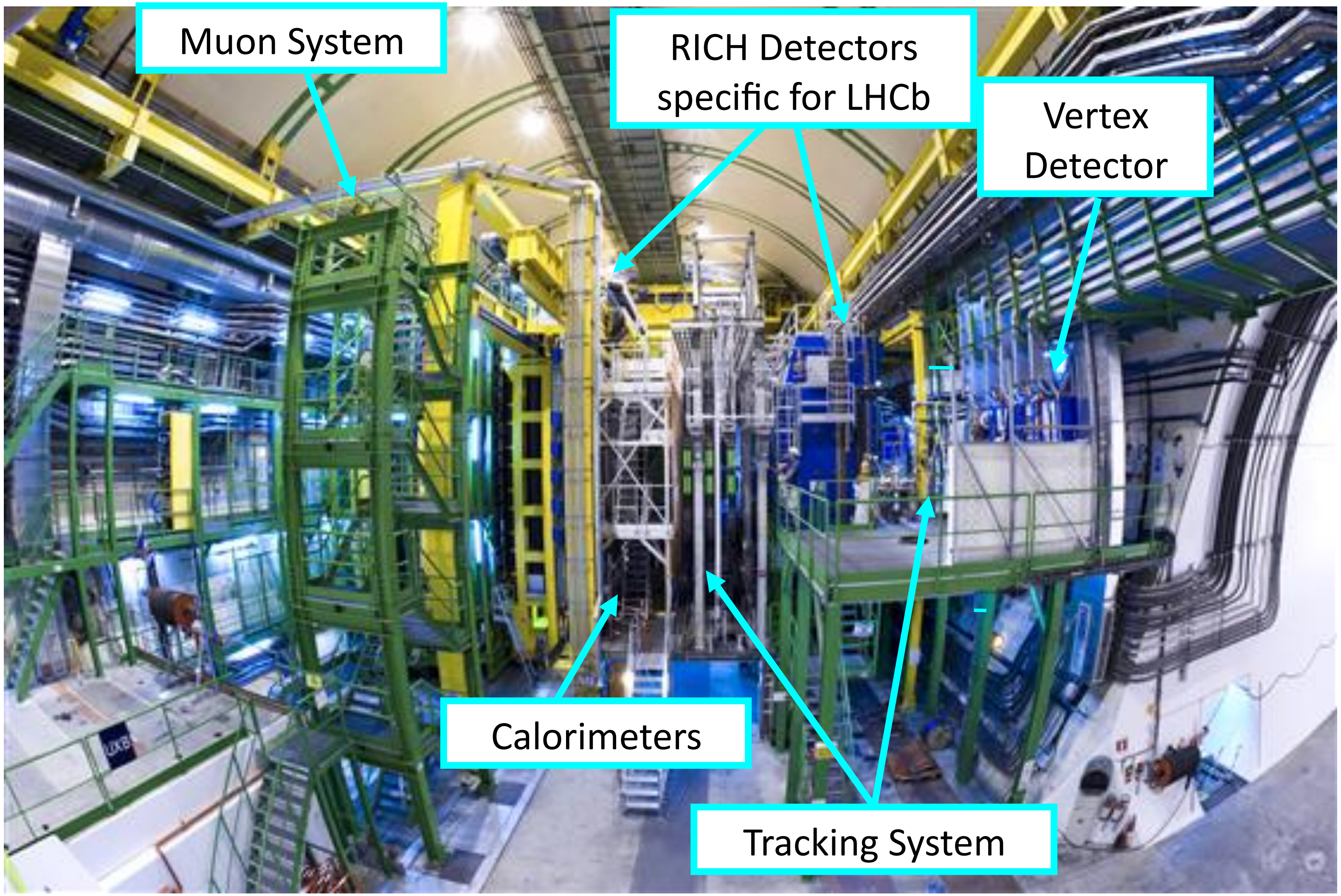
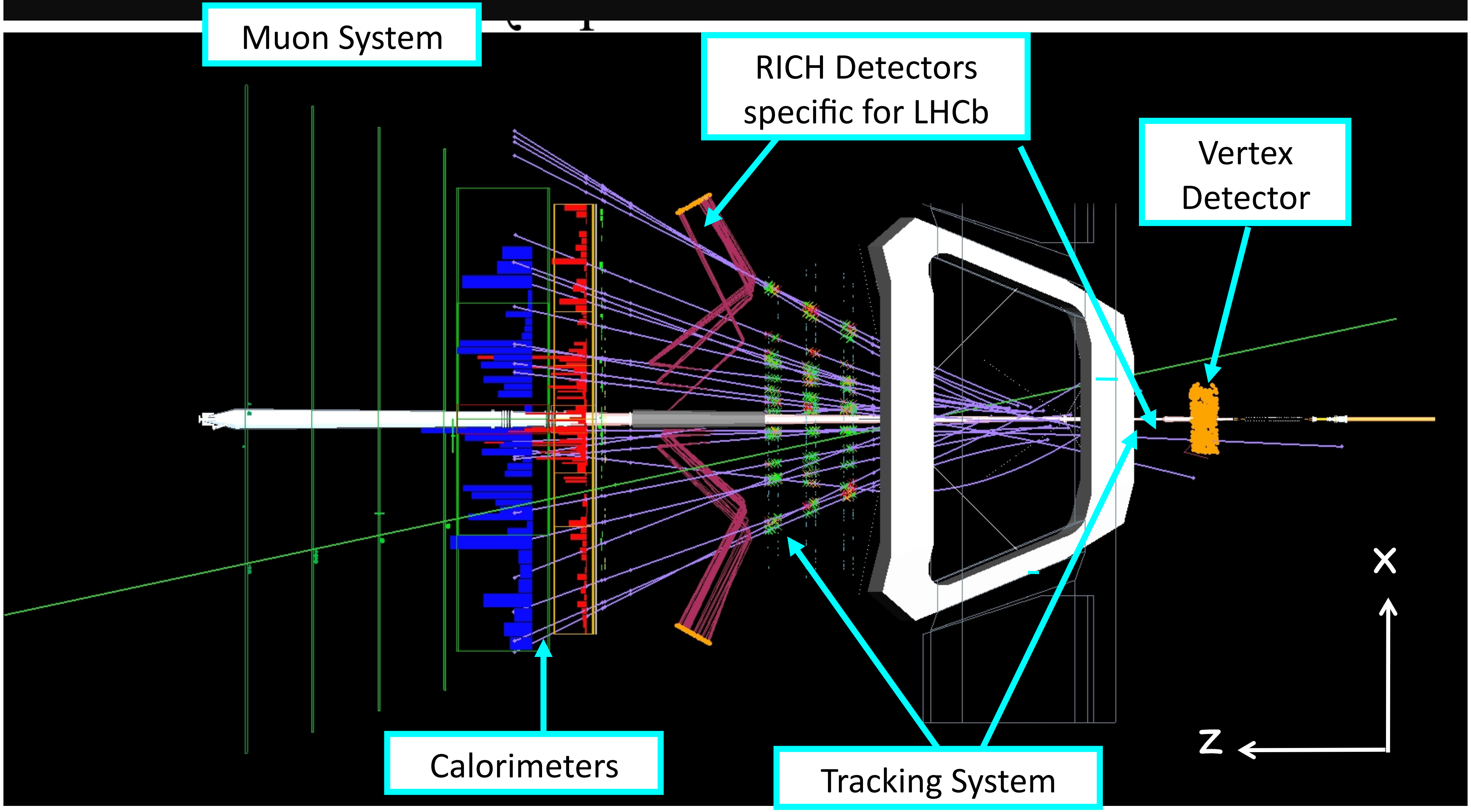
THE LHCb DETECTOR



The LHCb detector

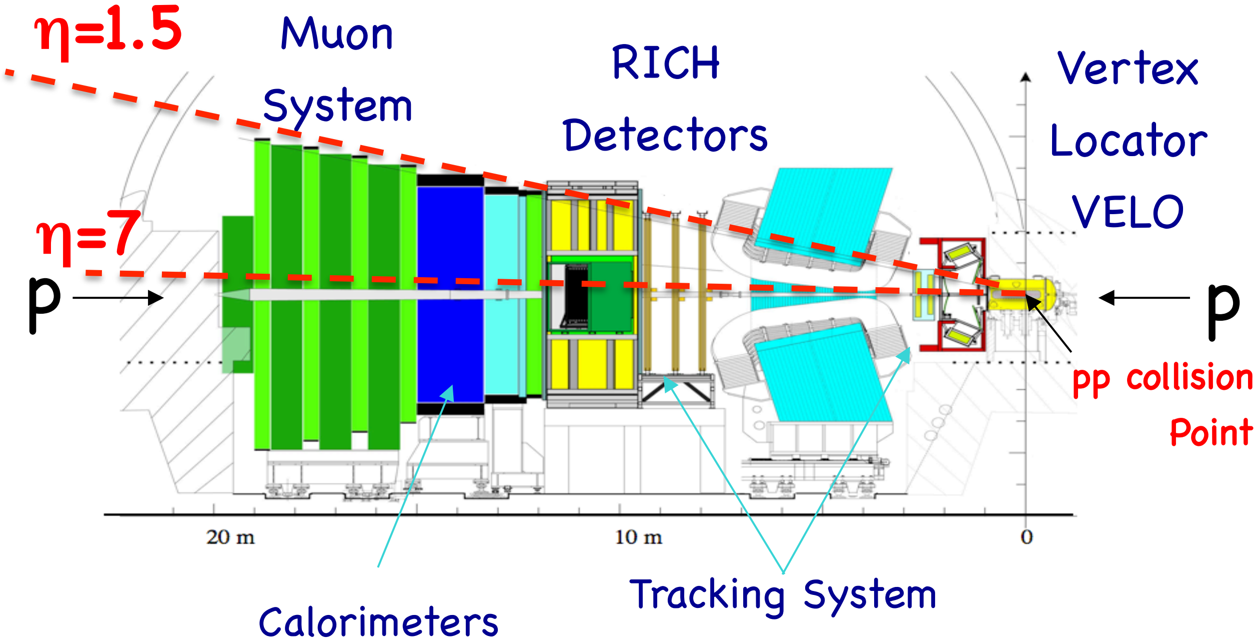


The LHCb detector



The LHCb detector

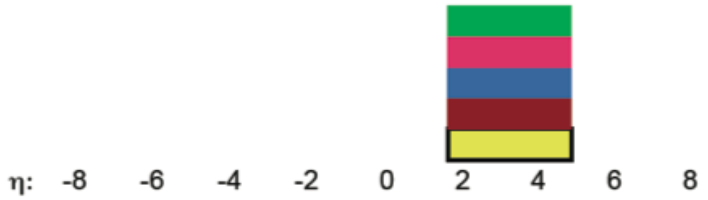
Angular acceptance : 10<θ<300 mrad



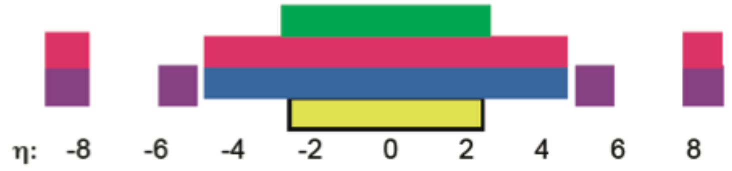
- Performance numbers relevant to quarkonium analyses:
  - Charged tracks $\Delta p/p$ = 0.35 % - 0.55%, $\sigma(m)$=10-25 MeV/c^2
  - ECAL $\sigma(E)/E$= 10% $(E/GeV)^{-1/2} \oplus$ 1 %
  - Muon ID: $\varepsilon(\mu \rightarrow \mu)$ = 97%, mis-ID rate $(\pi \rightarrow \mu)$ = 1-3 %
  - Vertexing: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

possibility to reverse field polarity to check for detector asymmetries

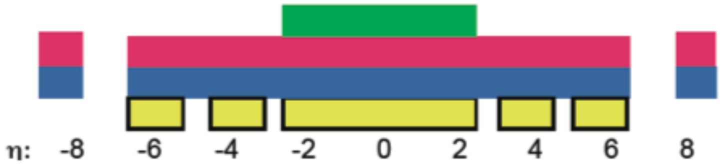
Rapidity Range



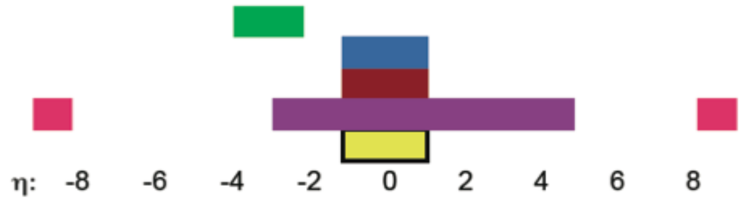
LHCb



ATLAS



CMS



ALICE

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

Cross Section Measurement Strategy

For a generic resonance A:

$$\left.\frac{d\sigma(pp \to A)}{dp_T\,dy}\right|_{2.0<y<4.5} Br(A \to \mu^+\mu^-) = \frac{N^{fit}{}_A(p_T, y; \varepsilon_{tot})}{\int L dt \cdot \Delta p_T \cdot \Delta y}$$

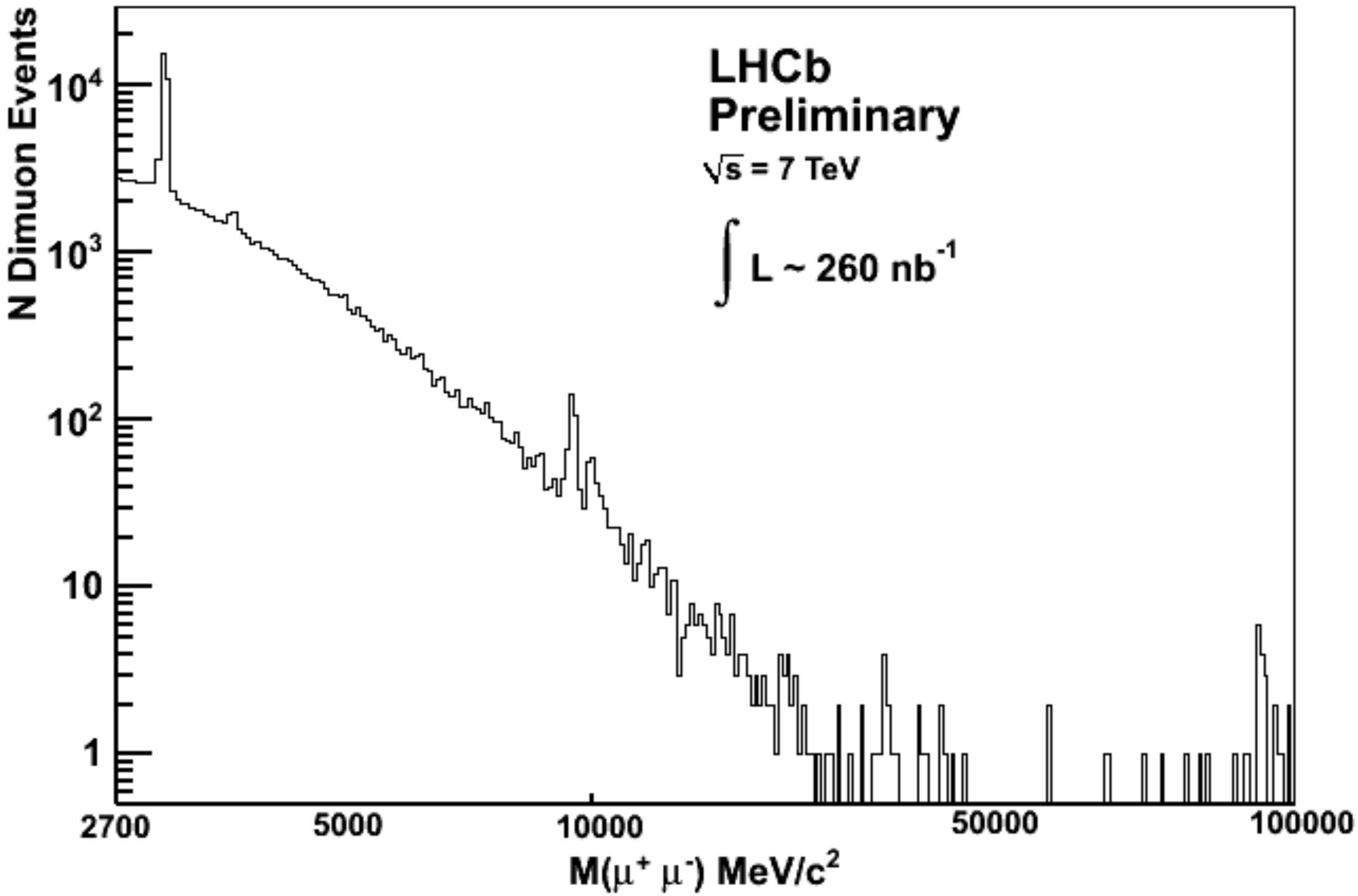
a) N^{fit} = number of events in the mass peak in each p_T bin, corrected for acceptance and efficiency

b), c), d) ε_{tot} = total efficiency

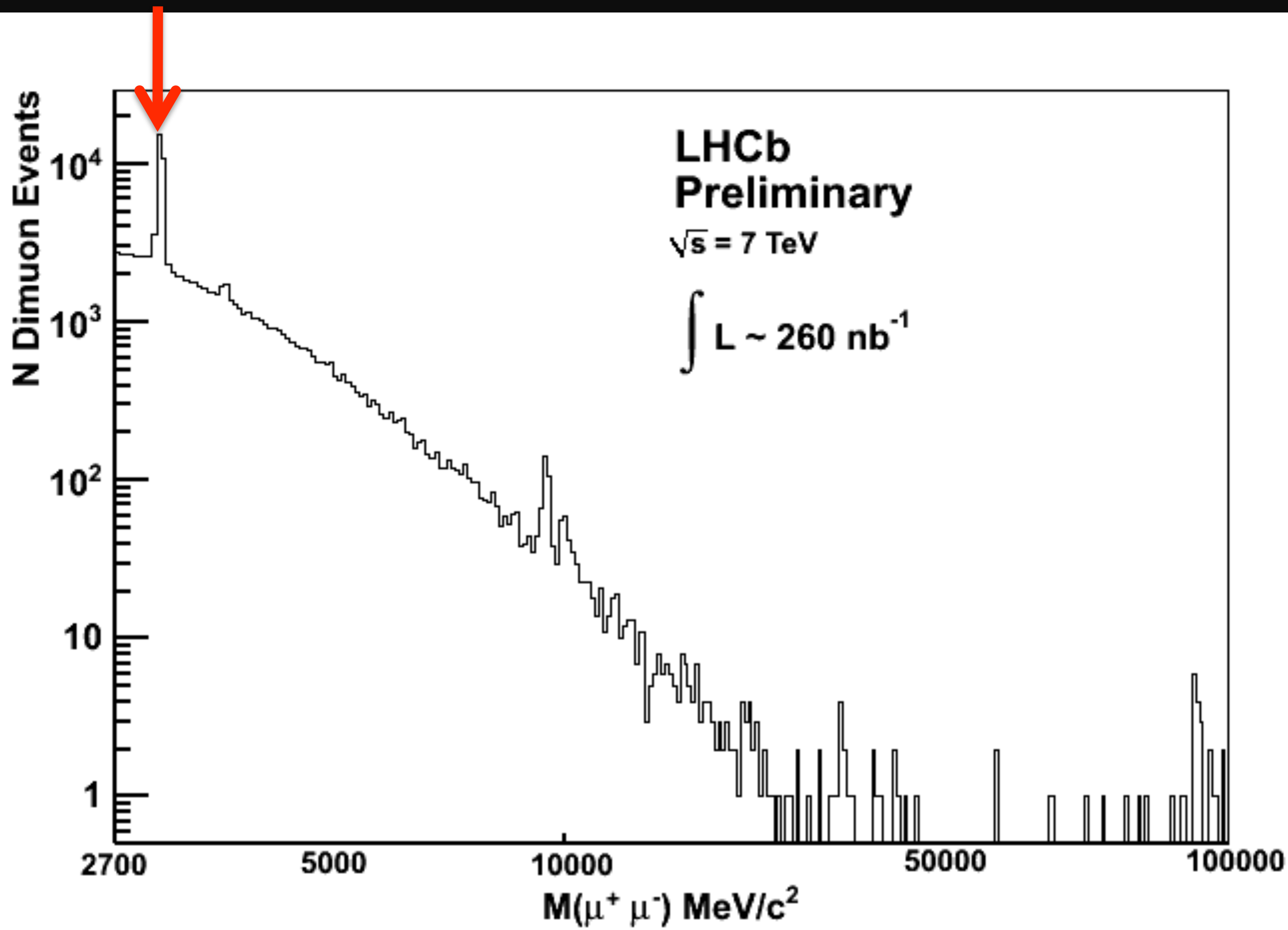
e) Δpt, Δy = bins of p_T and y

f) $\int$Ldt = integrated luminosity

Dimuon Resonances

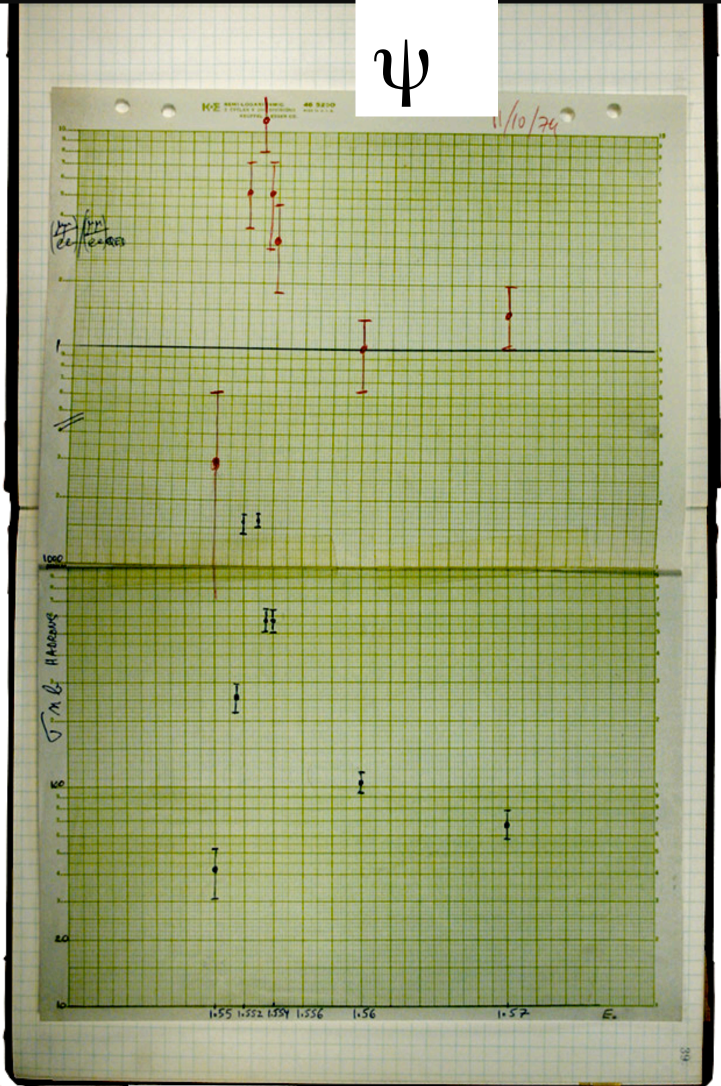


Dimuon Resonances



J/ψ Production

ψ



J

PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

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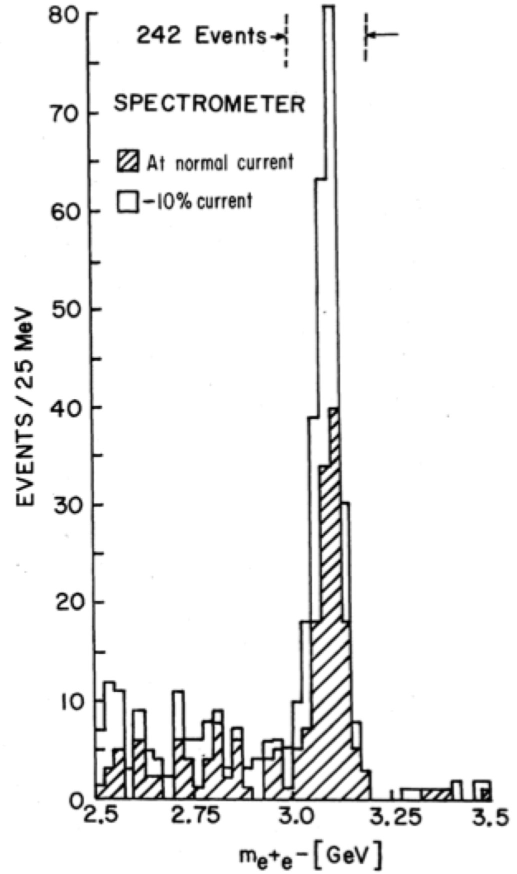
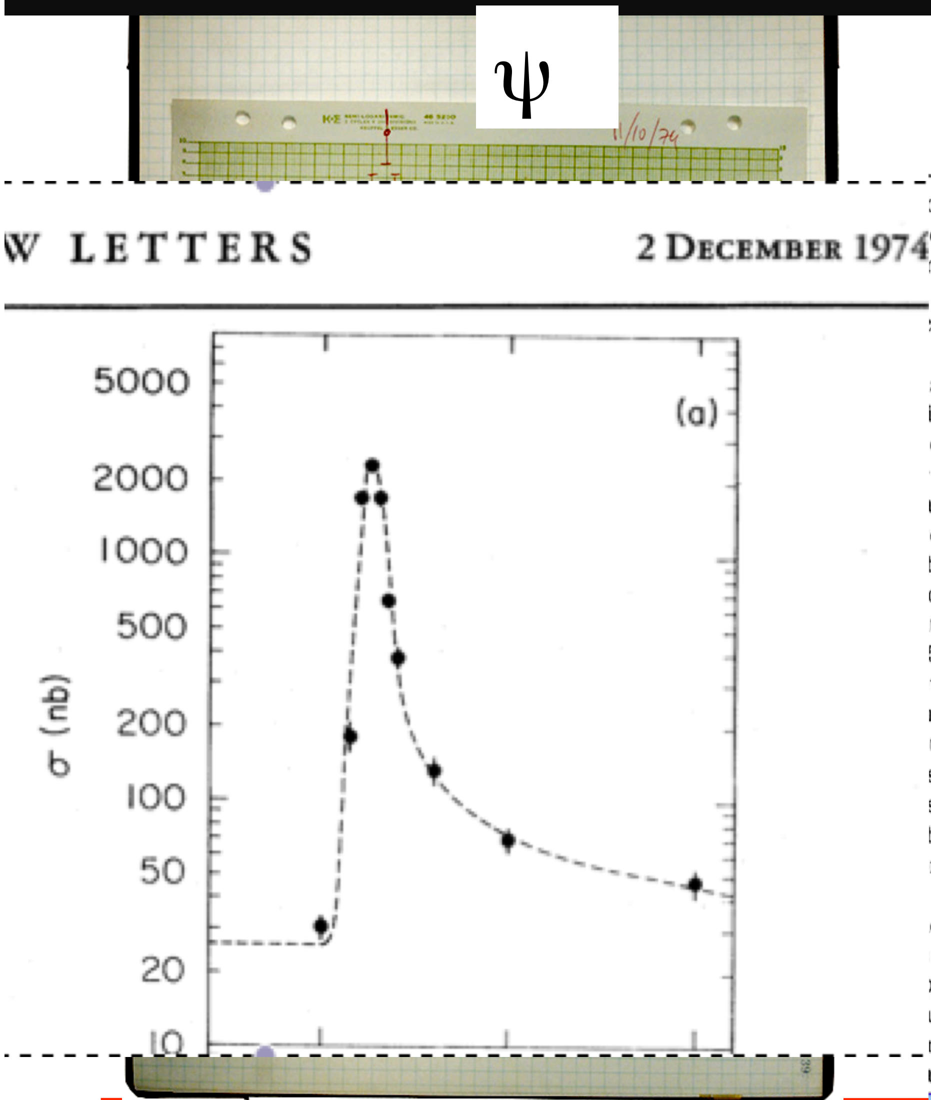


FIG. 2. Mass spectrum showing the existence of J.

J/ψ Production

ψ



J

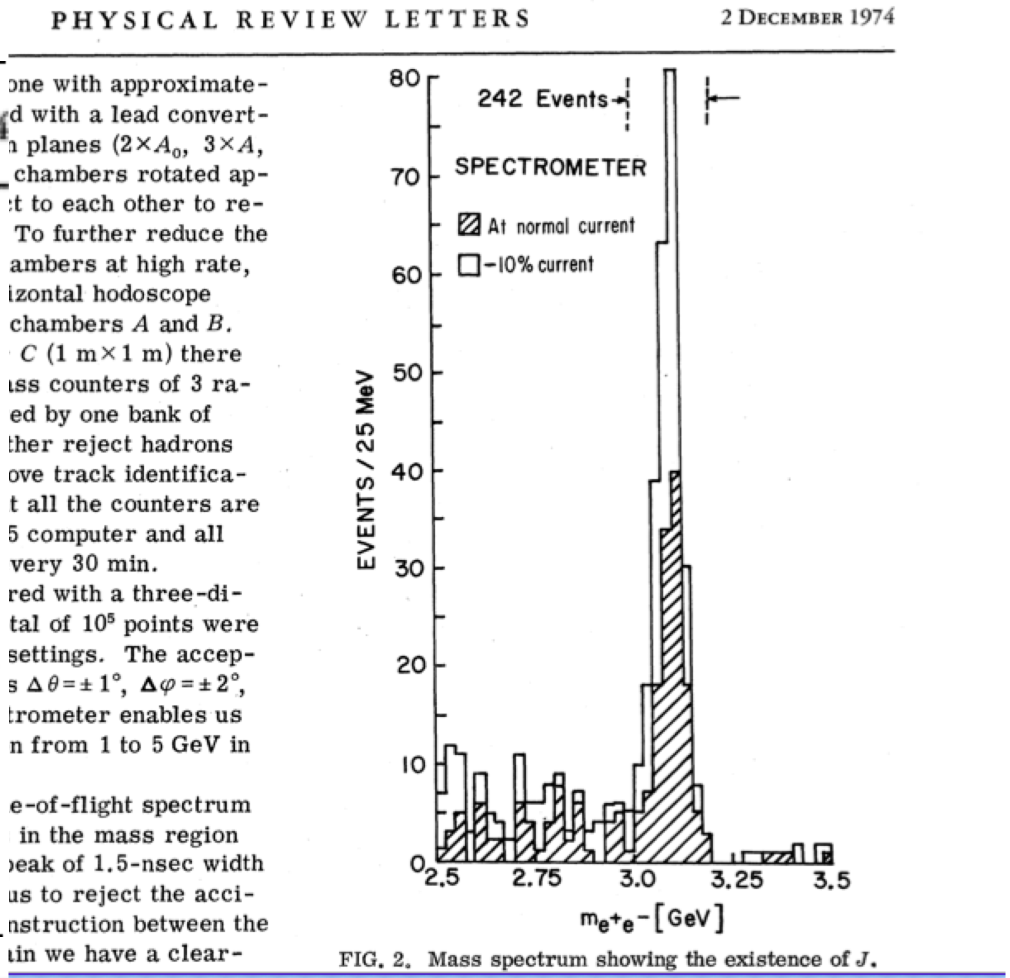

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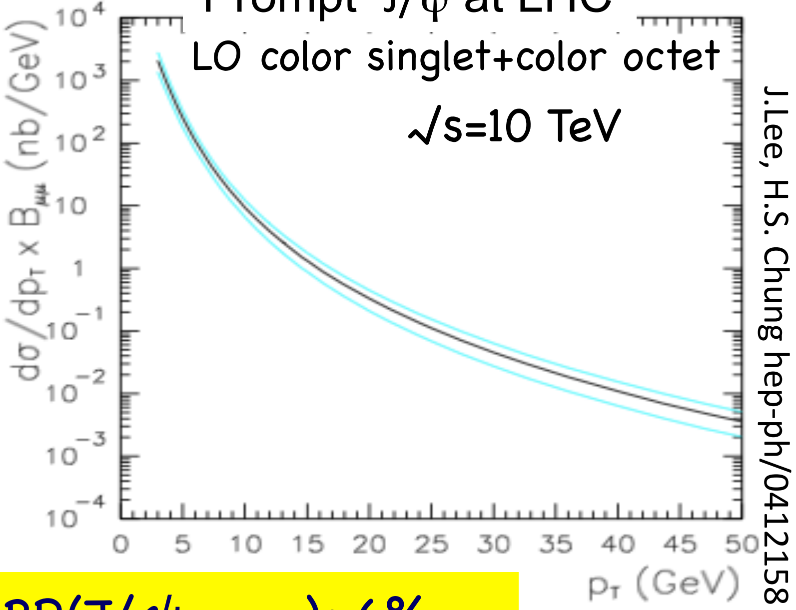
FIG. 2. Mass spectrum showing the existence of J.

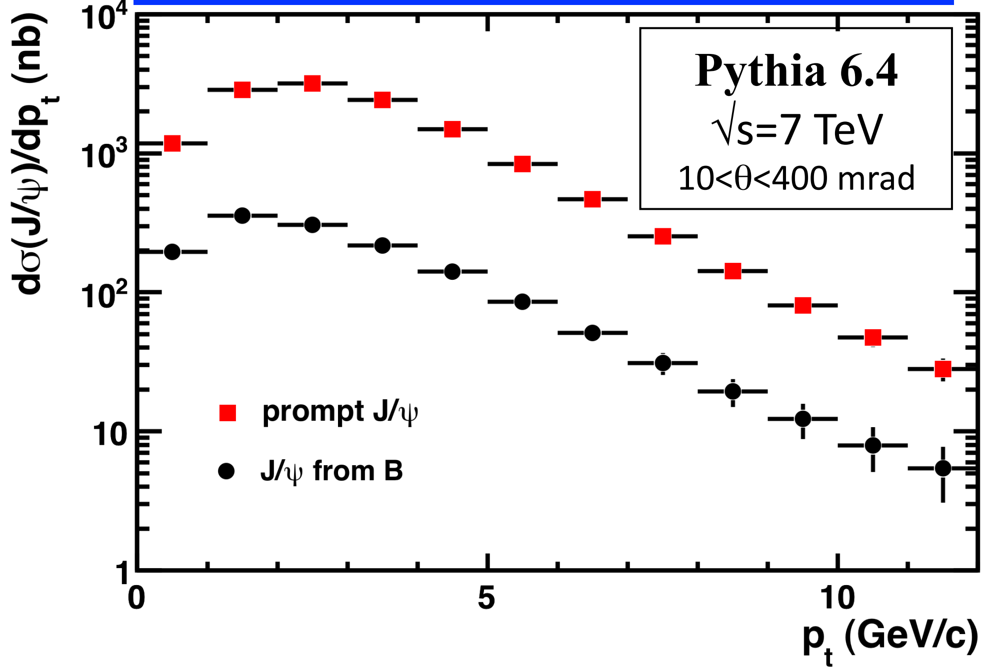
J/ψ Production at pp

1st step	2nd step	3rd step	Production type
$pp \rightarrow c\bar{c}, b\bar{b} + X$	$c\bar{c} \rightarrow J/\psi + X$		Prompt,direct
	$c\bar{c} \rightarrow \chi_{c1}, \chi_{c2} + X$	$\chi_c \rightarrow J/\psi + \gamma$	Prompt,indirect
	$b\bar{b} \rightarrow B + X$	$B \rightarrow J/\psi + X$	Delayed,indirect

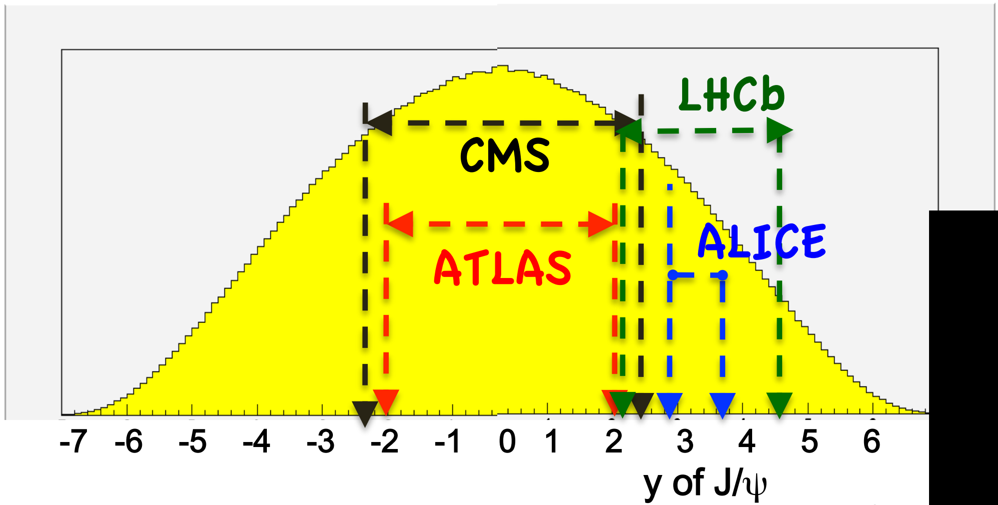


BR(J/ $\psi \rightarrow \mu\mu$)≈6%

LHCb MC samples (unpolarised J/ψ)

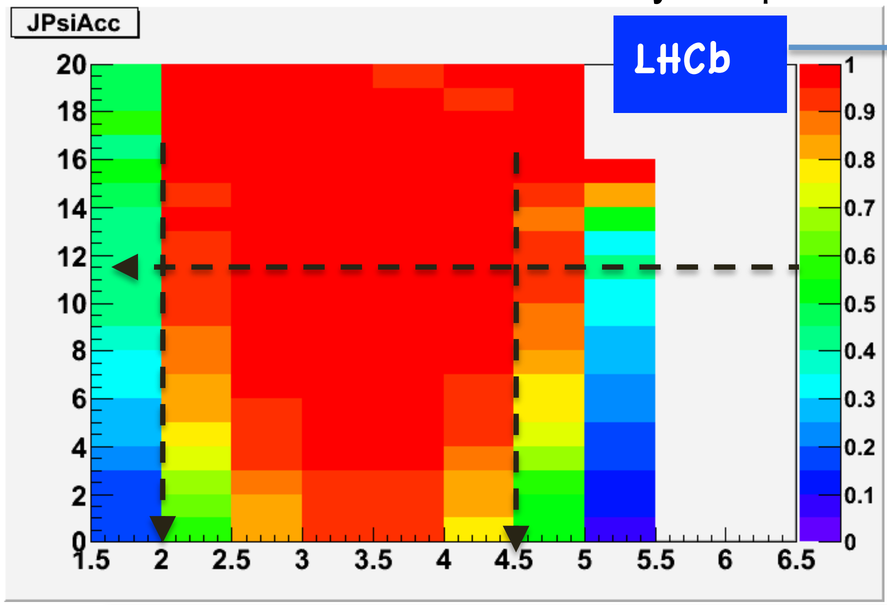


J/ψ Acceptance

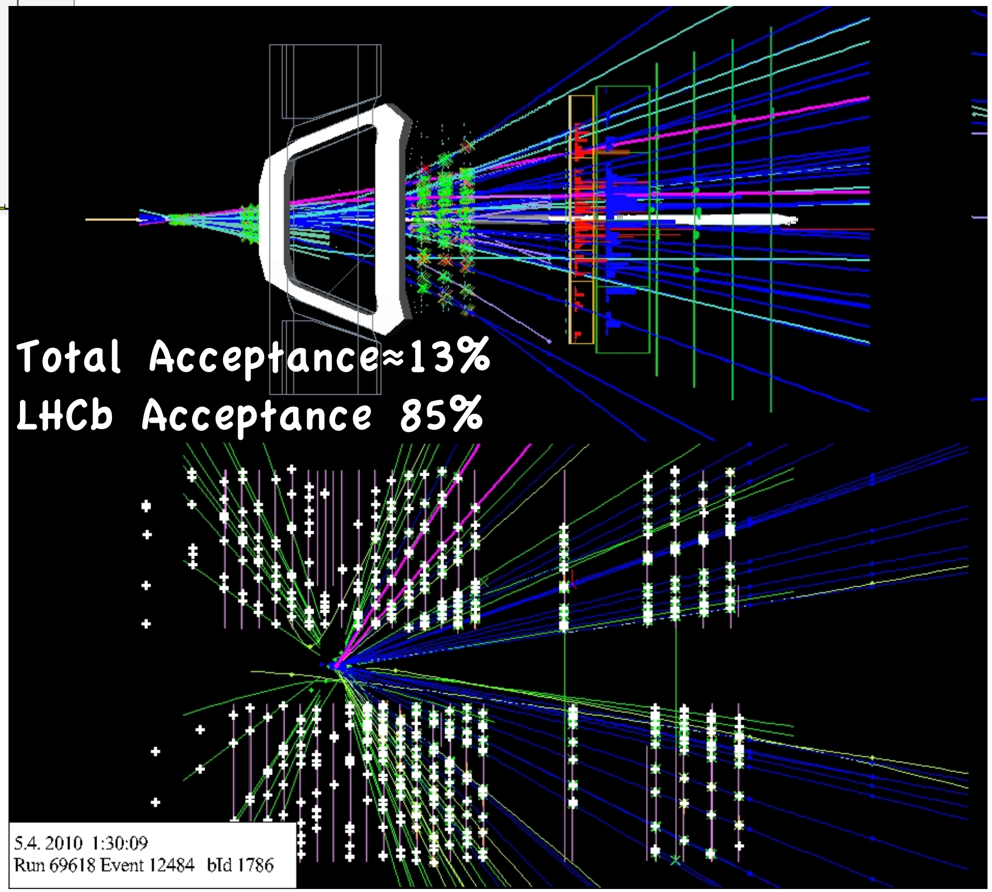


CMS → Total Acceptance≈20%
CMS 85%

ATLAS → Total Acceptance≈2-8%
ATLAS Acceptance 80%

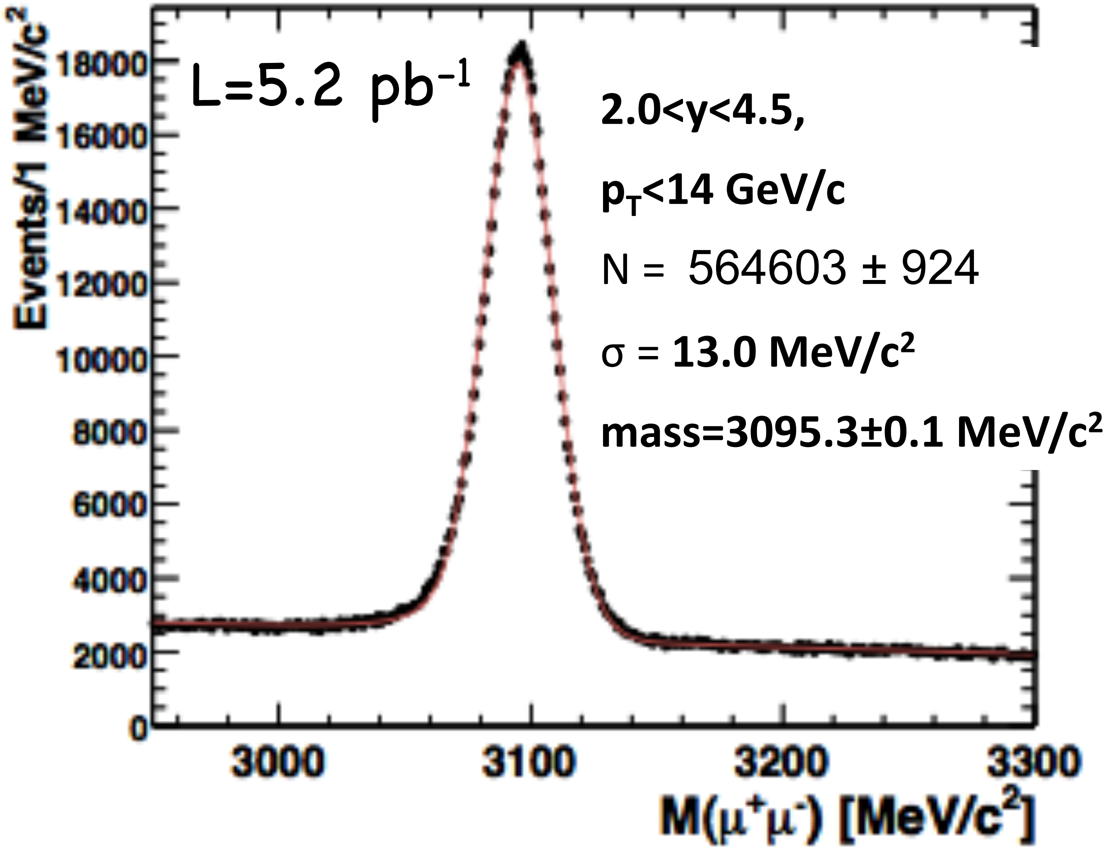


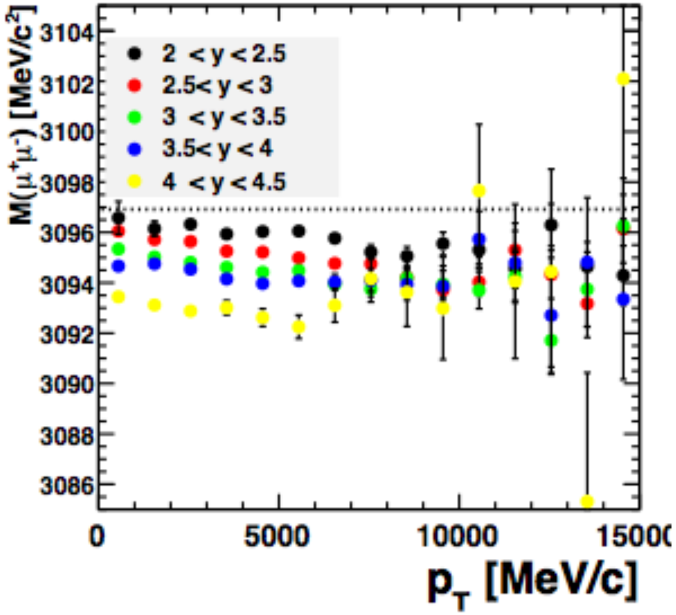
LHCb → Total Acceptance≈13%
LHCb Acceptance 85%

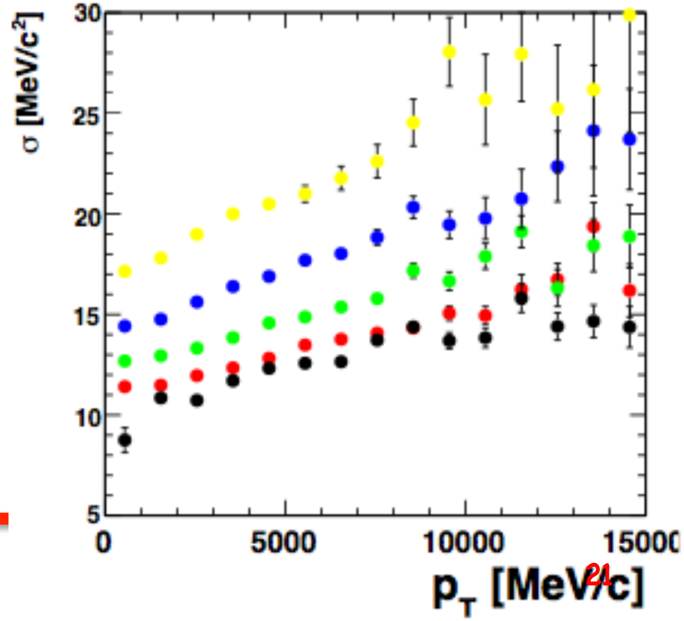


J/ψ→μμ mass distribution

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

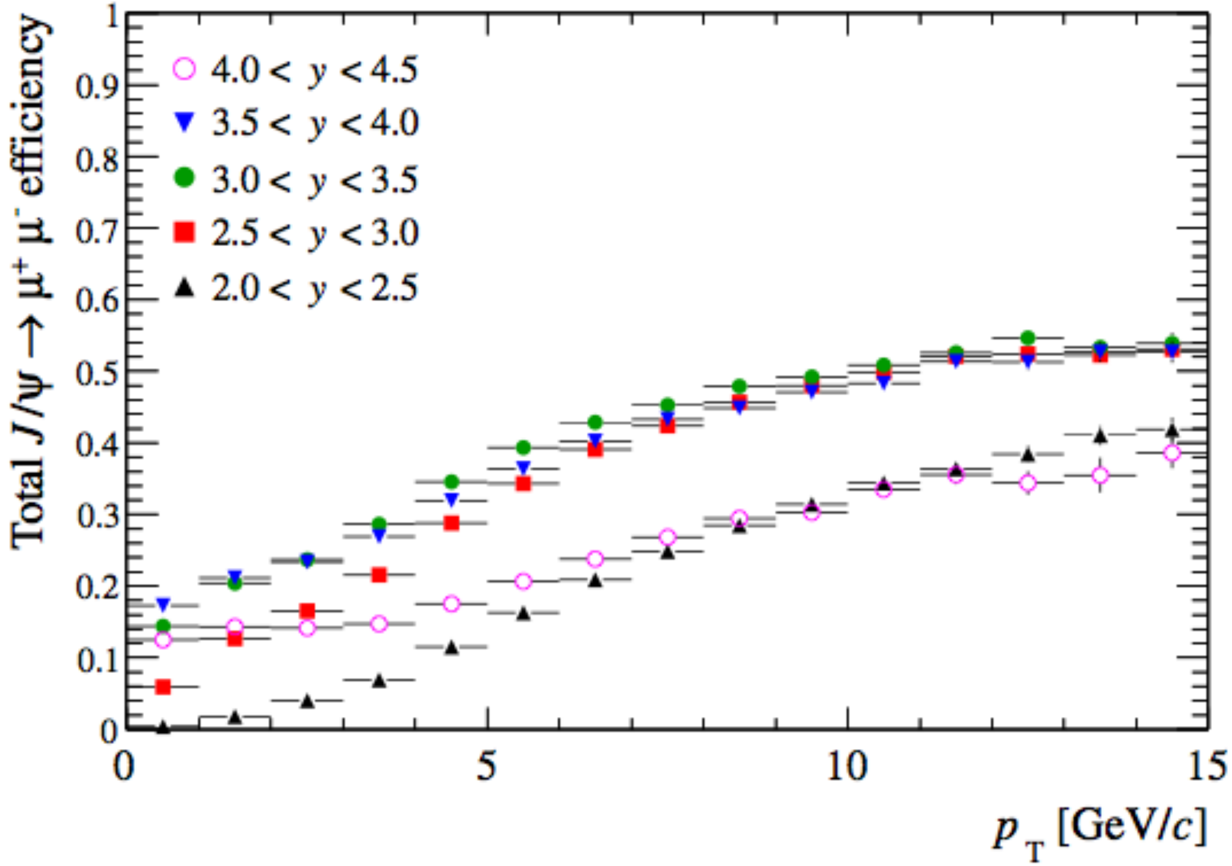




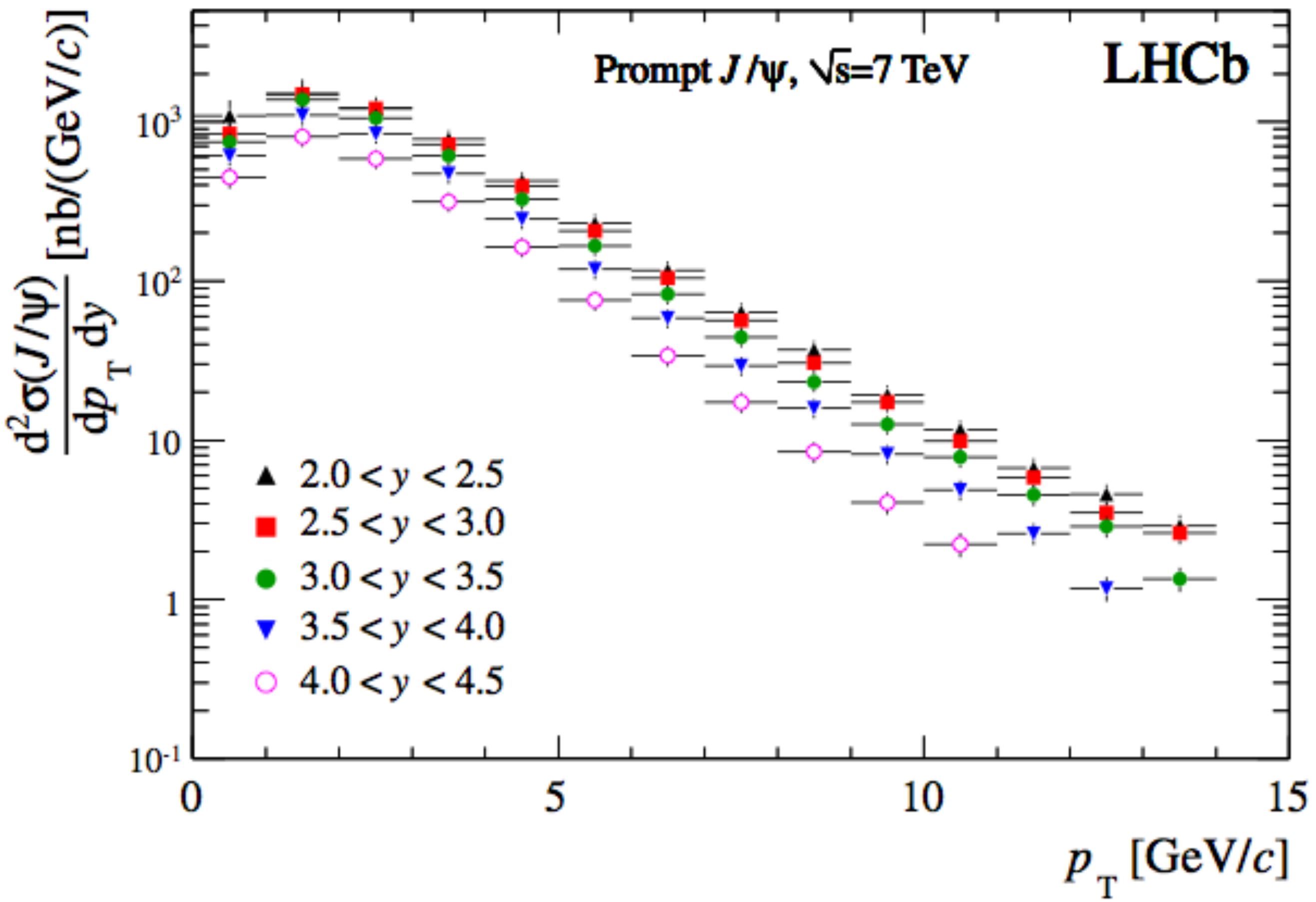


J/ψ Efficiency

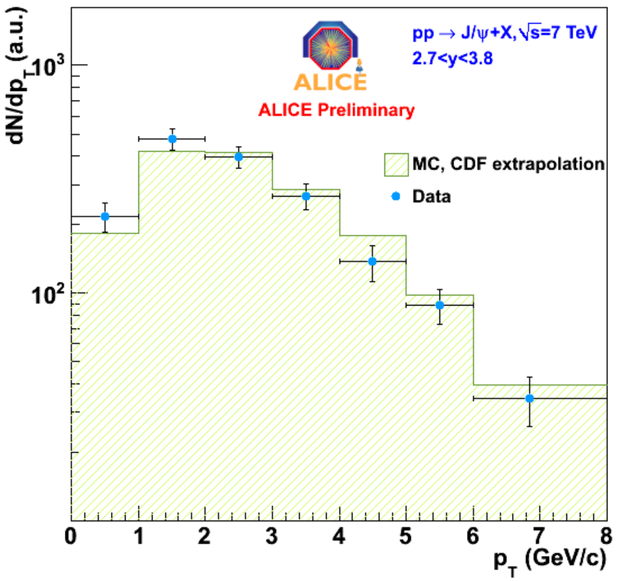
➡ Total efficiency, includes geometric acceptance, trigger and reconstruction and identification

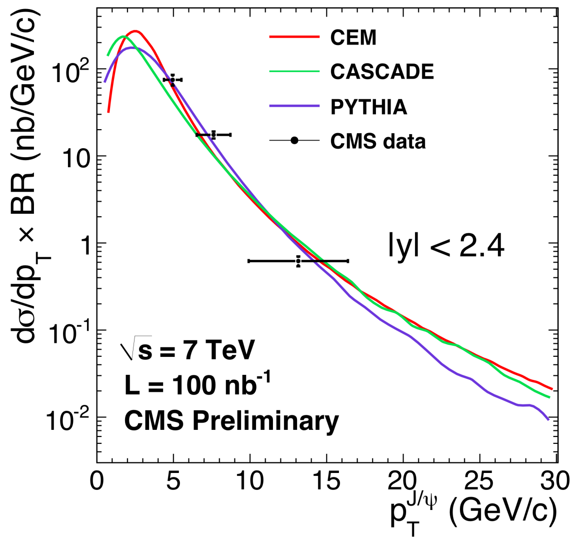


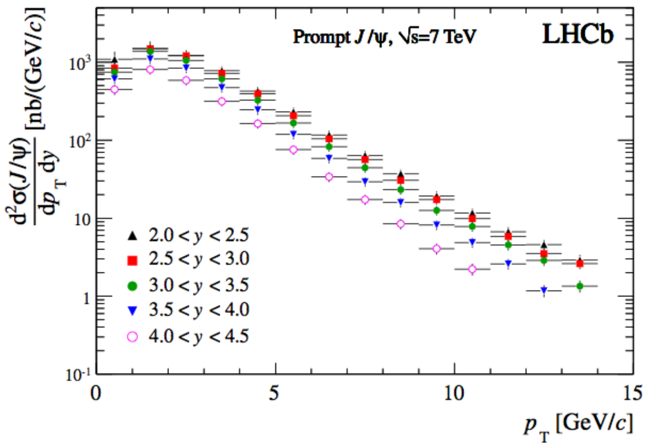
Prompt cross section measurement

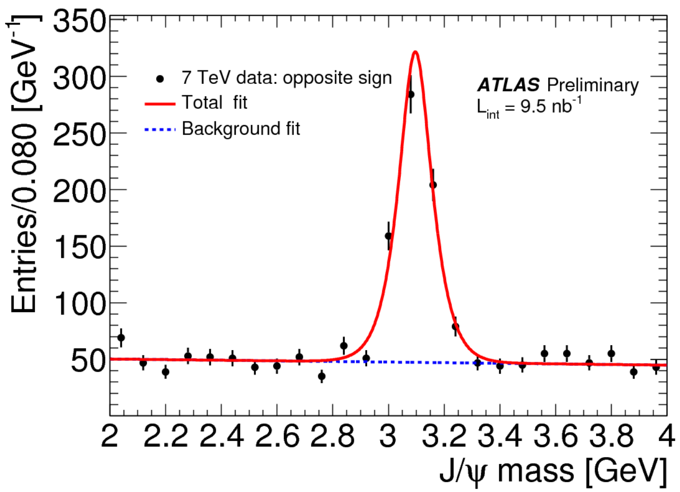


Comparison with other experiments

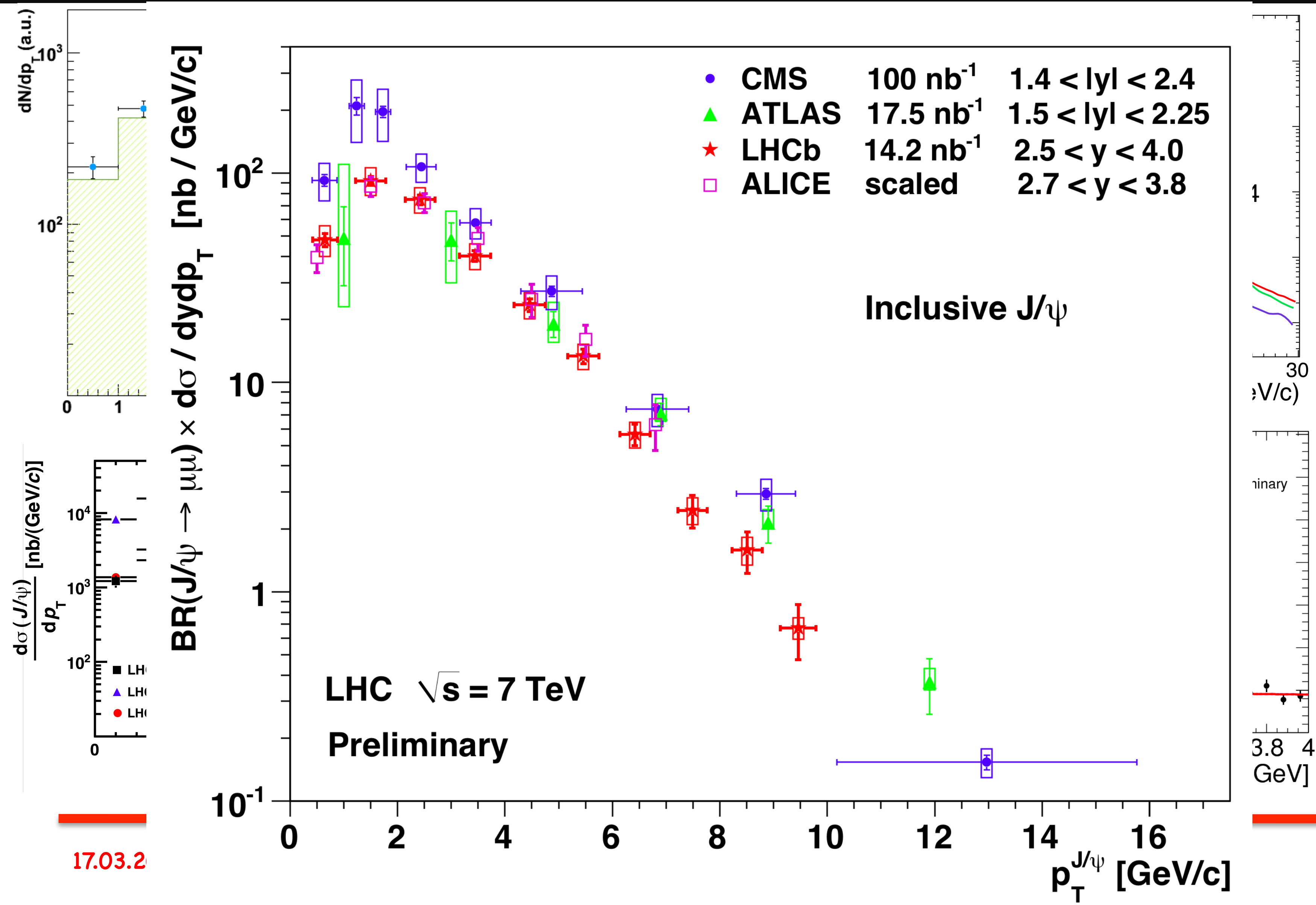




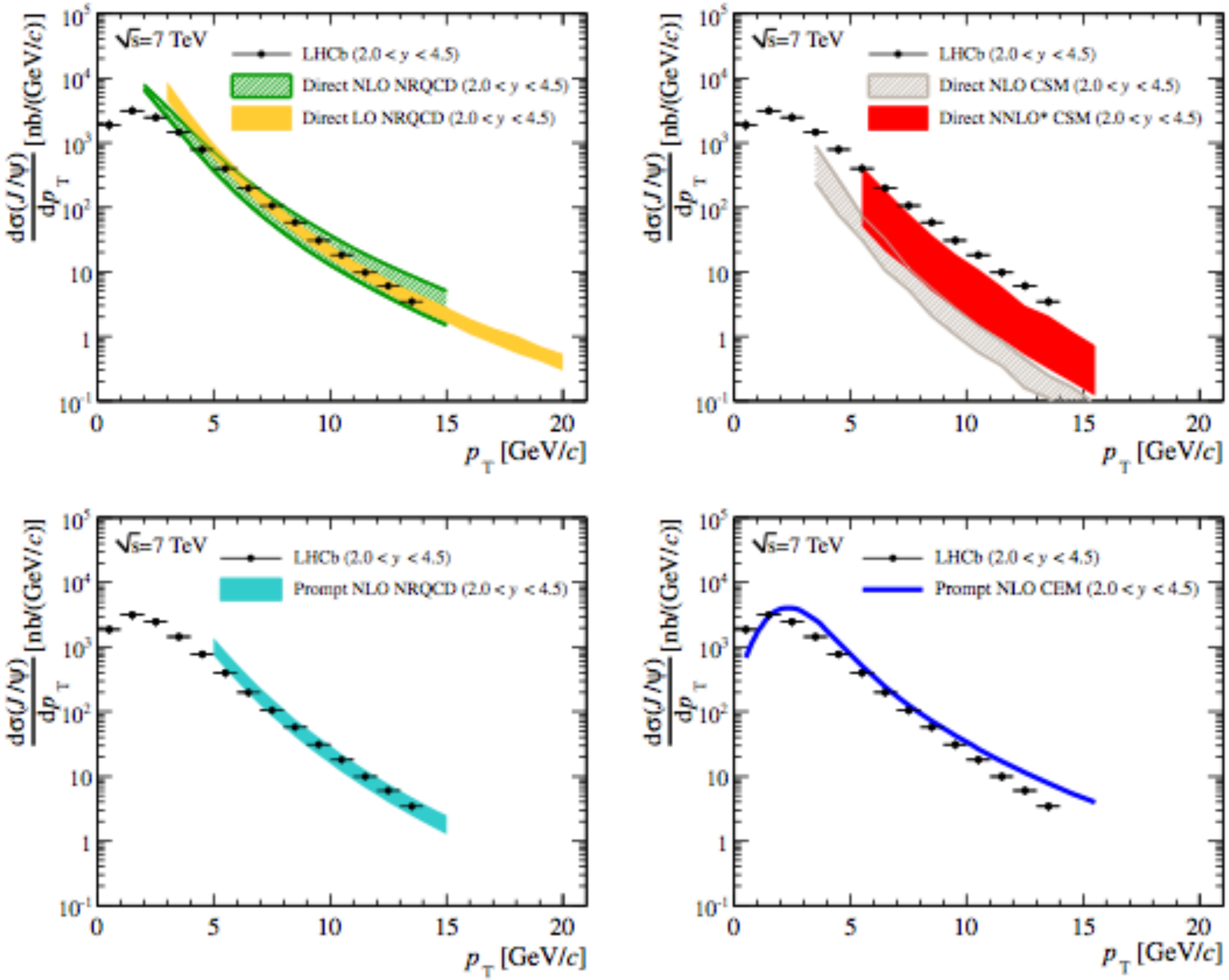




Comparison with other experiments

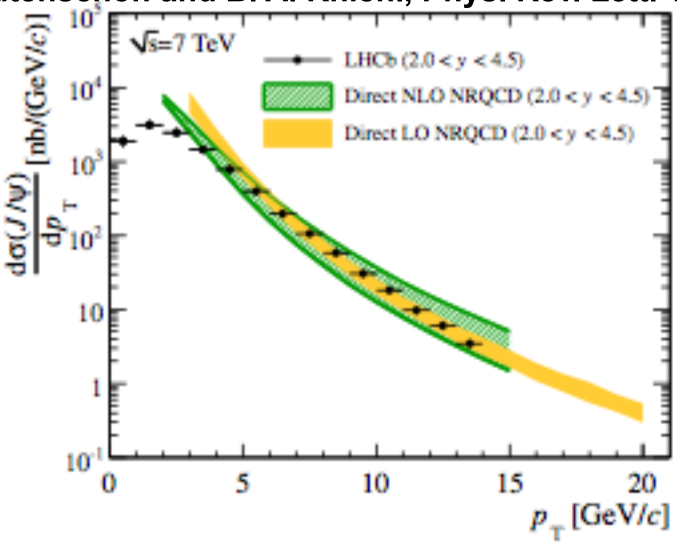


Comparison with theory

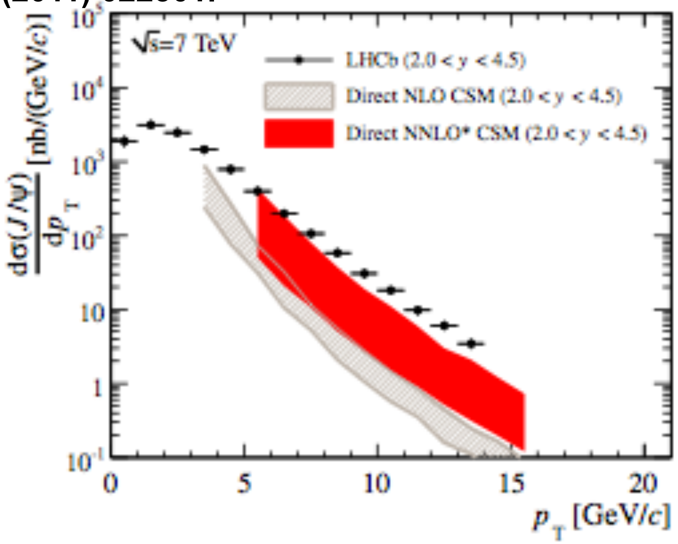


Comparison with theory

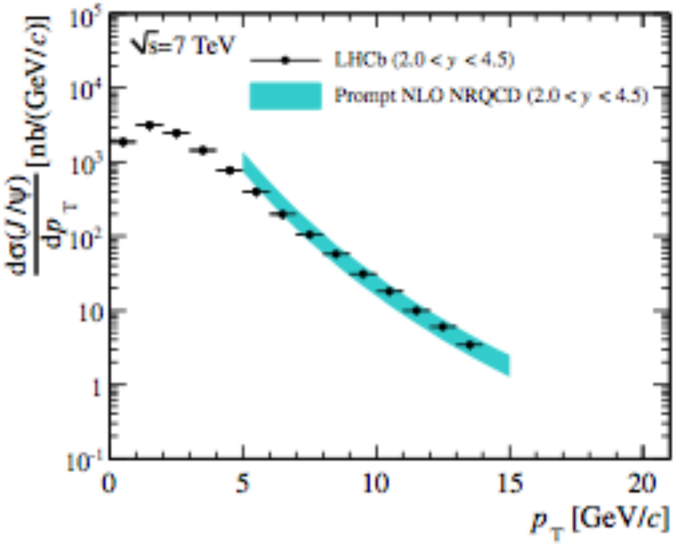
P. Artoisenet, PoS ICHEP 2010 (2010) 192.
M. Butenschön and B. A. Kniehl, Phys. Rev. Lett. 106 (2011) 022301.

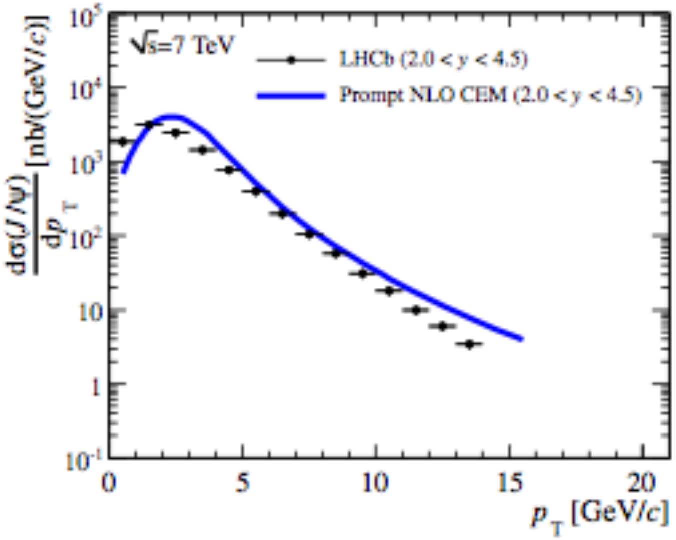


J.-P. Lansberg, Eur. Phys. J. C 61 (2009) 693



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

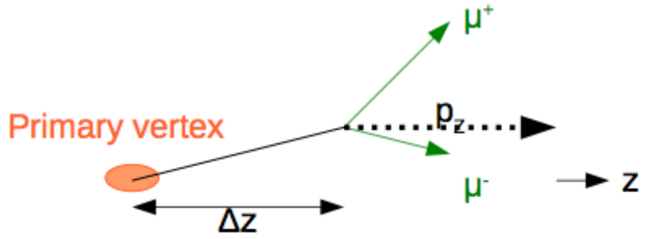


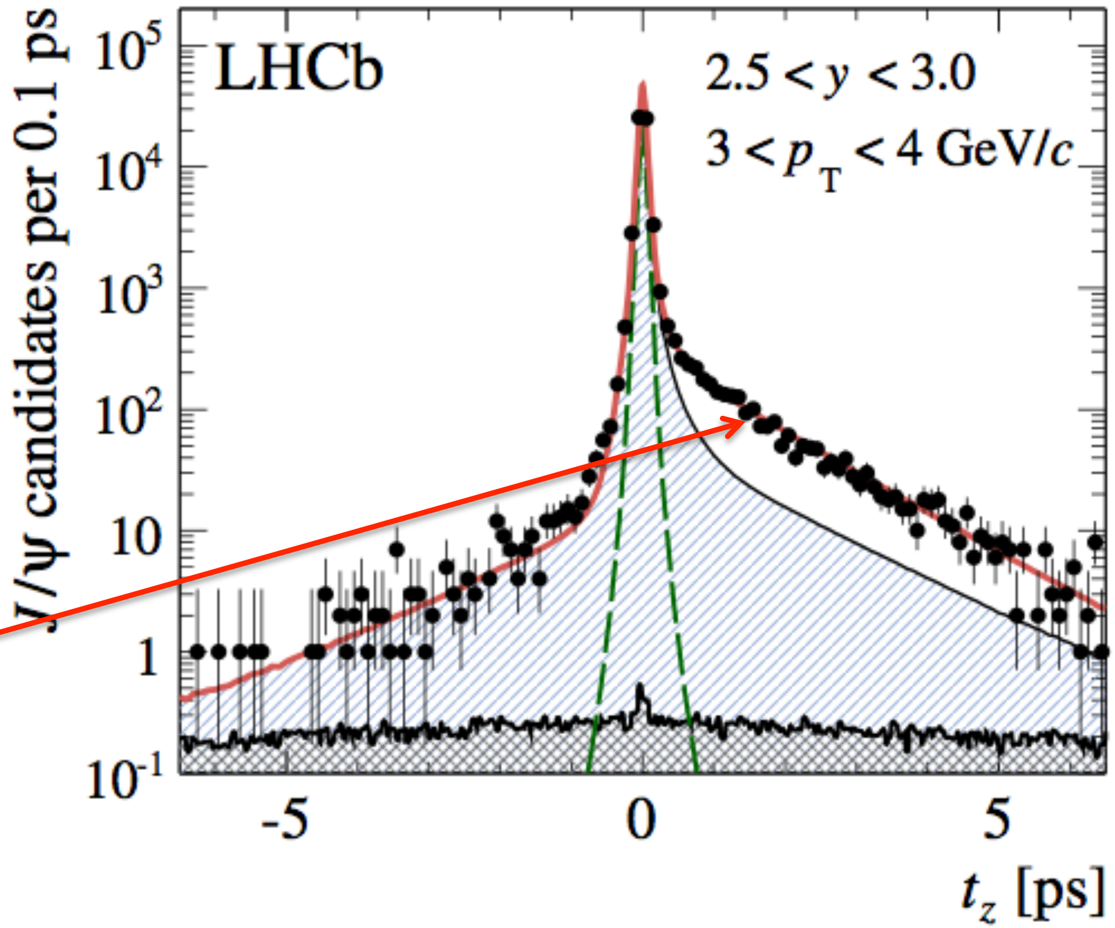


A. D. Frawley, T. Ullrich and R. Vogt, Phys. Rep. 462 (2008) 125.

J/ψ proper time/decay length

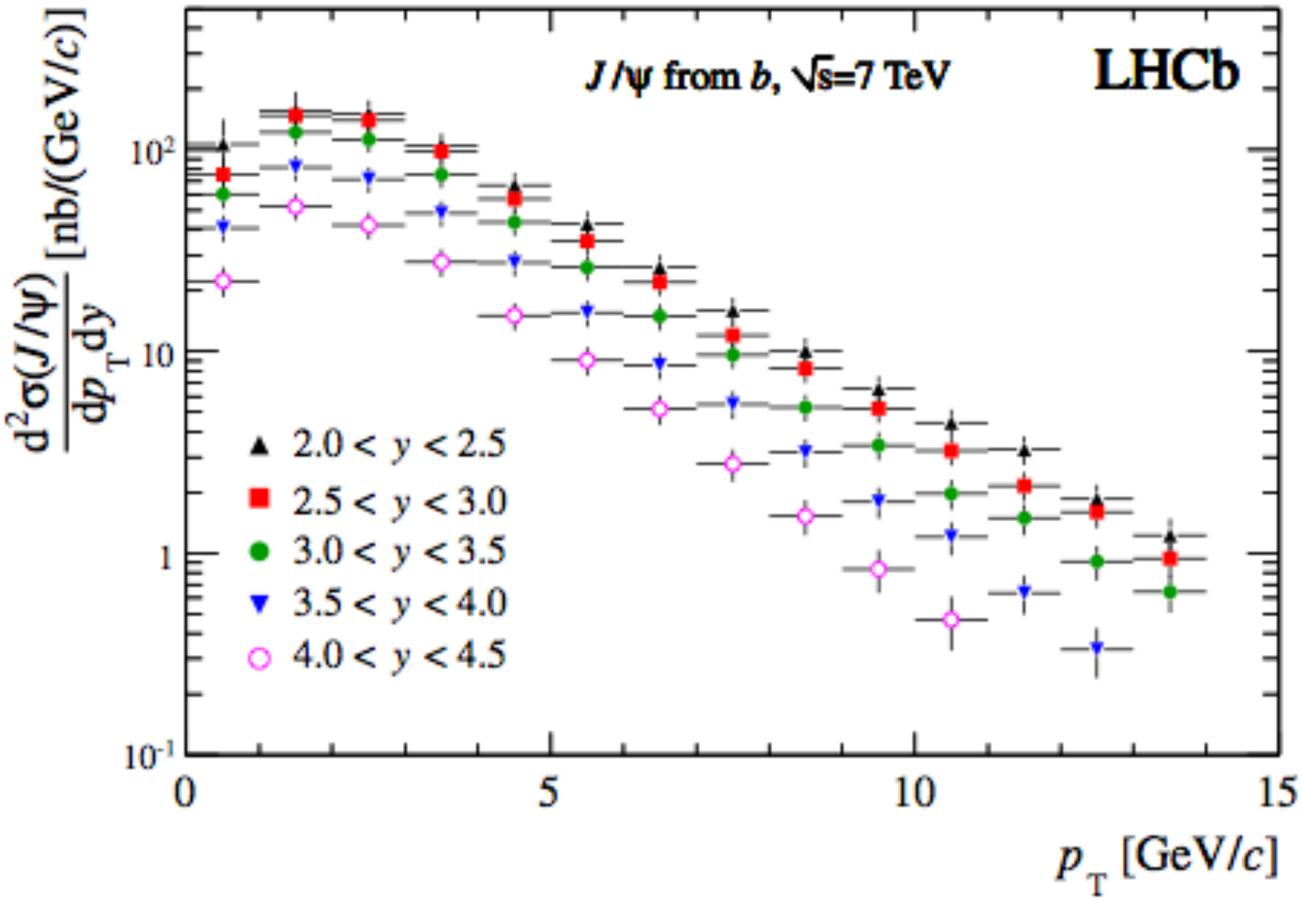
$t_z = \Delta z / p_z * M_{J/\psi}$



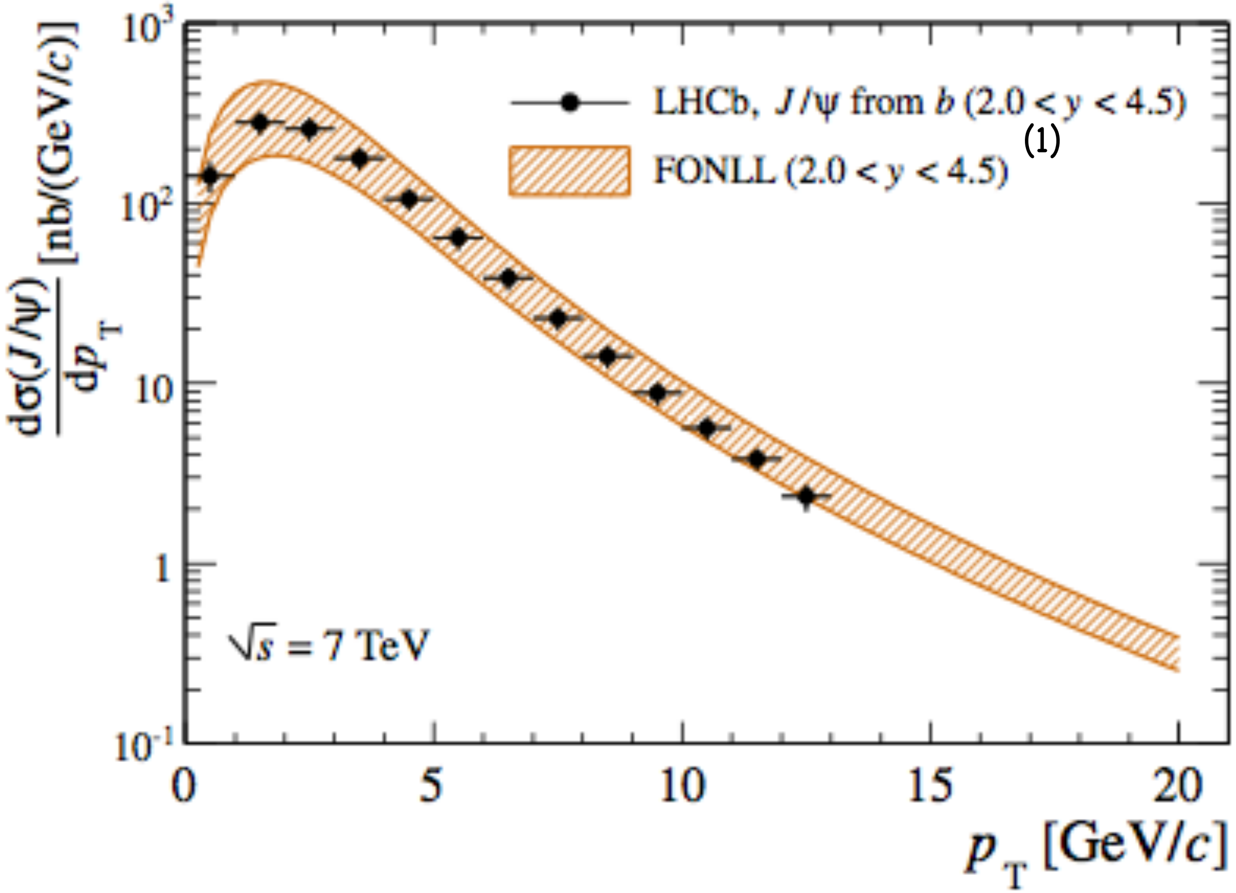


- t_z used to separate J/ψ prompt from J/ψ from B

J/ψ from B cross-section



Comparison with theory



(1) 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

Integrated Cross-section Results

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

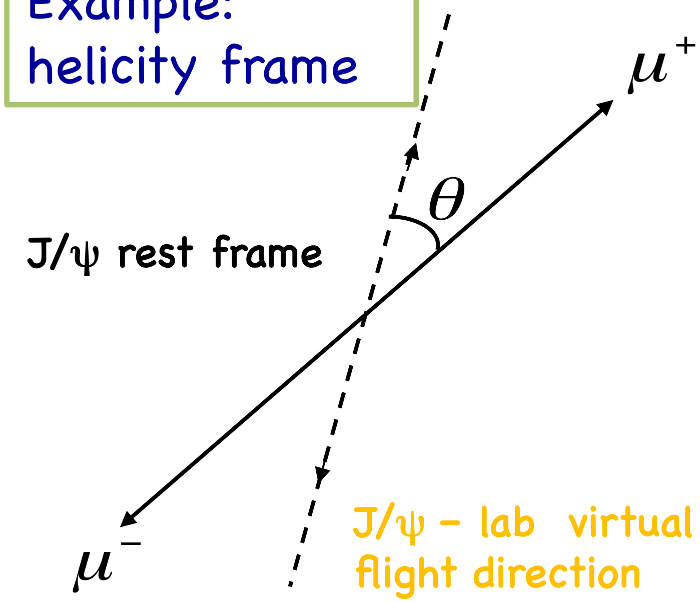
$$\sigma(J/\psi \text{ from } b, p_T < 14\,\text{GeV}/c, 2.0 < y < 4.5) = 1.14 \pm 0.01 \pm 0.16\,\mu\text{b},$$

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

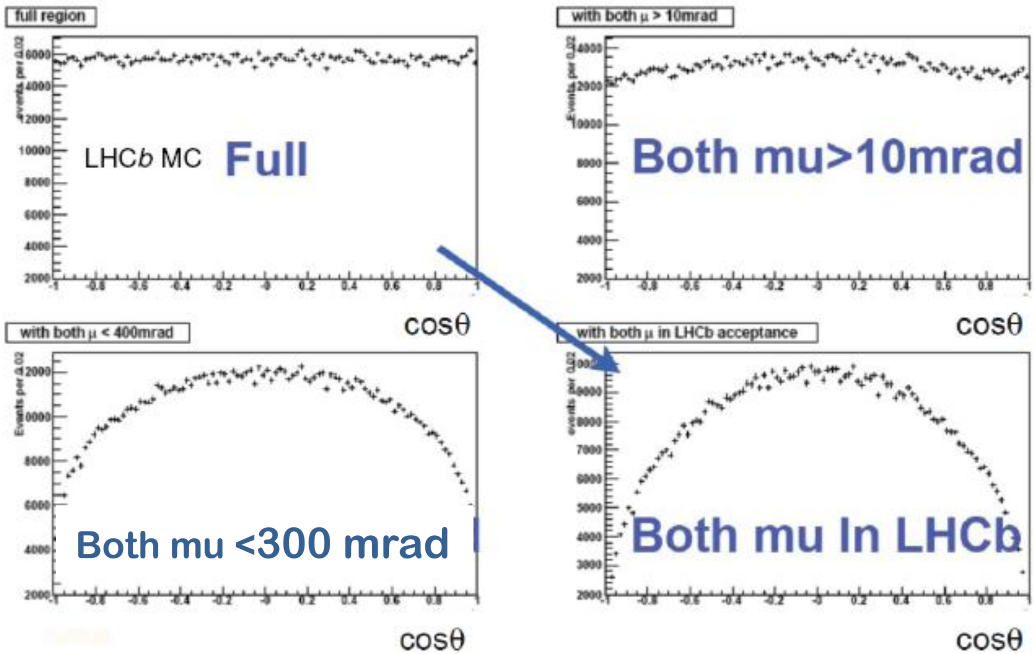
Influence of J/ψ Polarisation

- Detector acceptance as a function of helicity angle cosθ

Example:
helicity frame



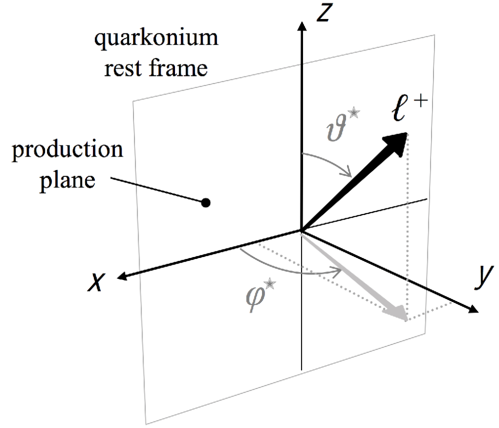
MC with no polarisation:LHCb

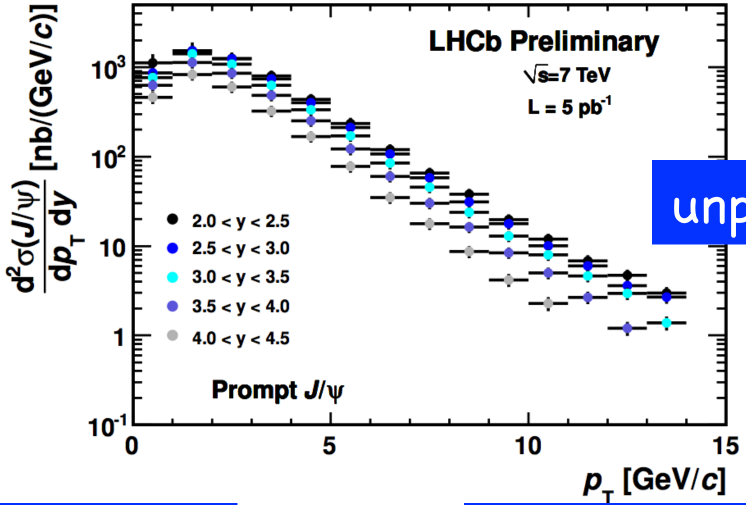


➡ acceptance generates an artificial polarisation
→ large influence of polarisation on measurement

➡ First step: Treat polarisation as systematic error; here, present results in three different polarisation scenarios

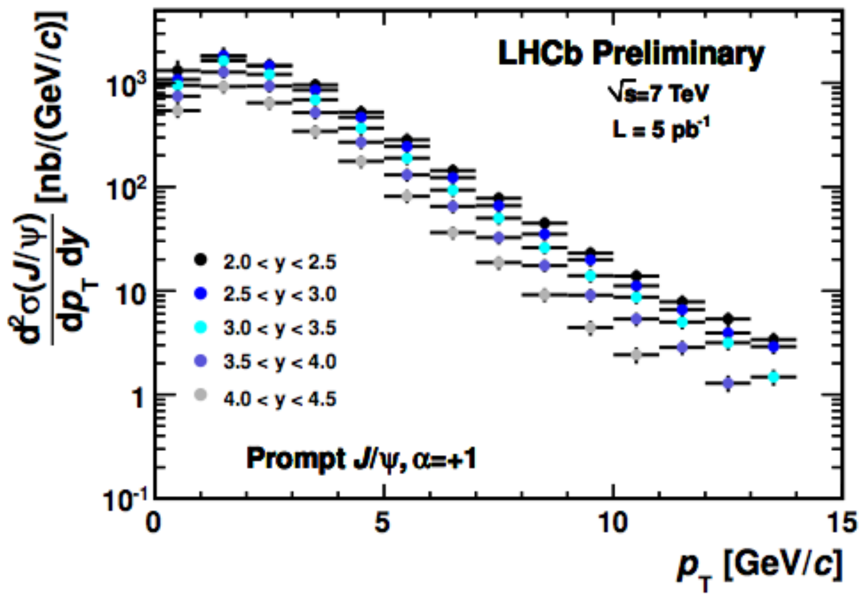
Different polarisation scenarios



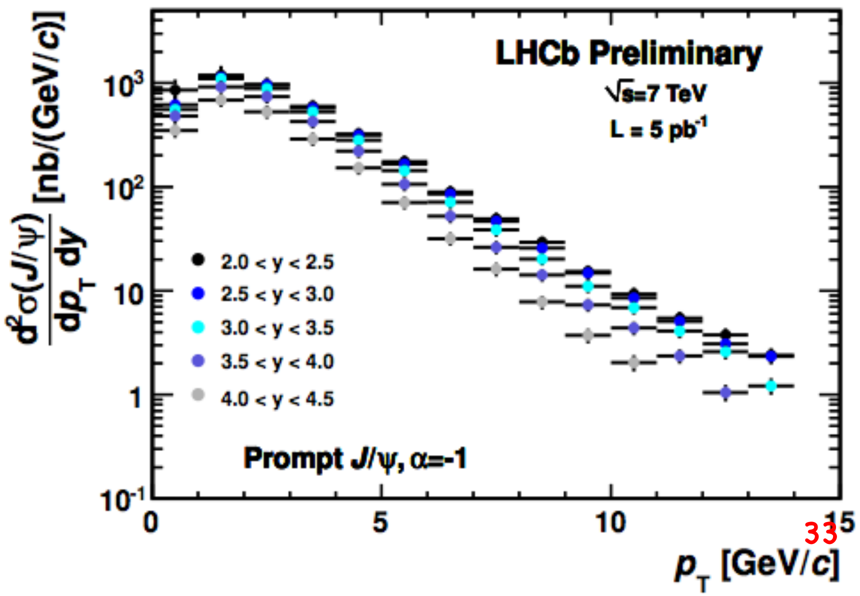


unpolarised

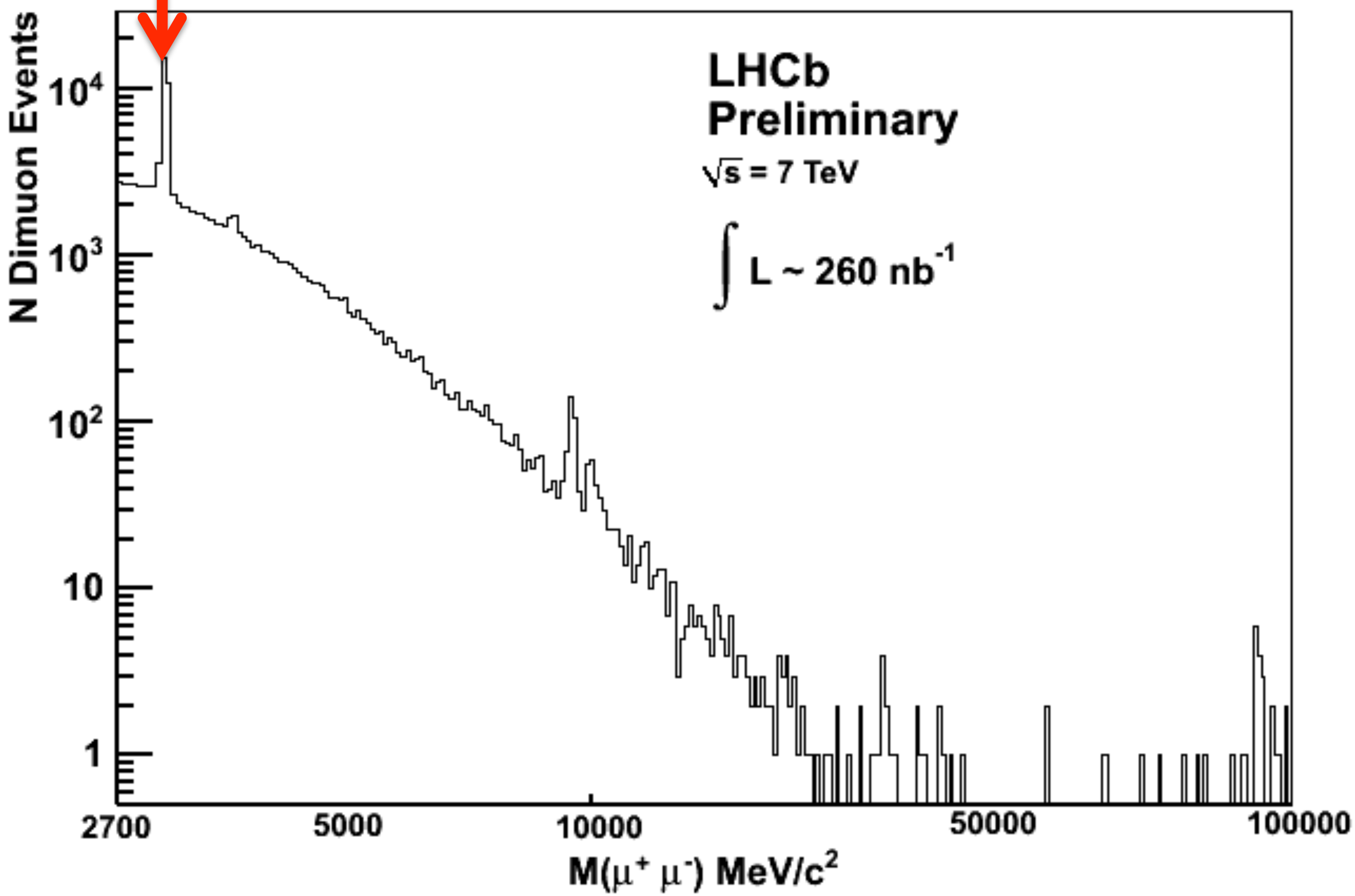
Fully transversly polarised



Fully longitudinally polarised

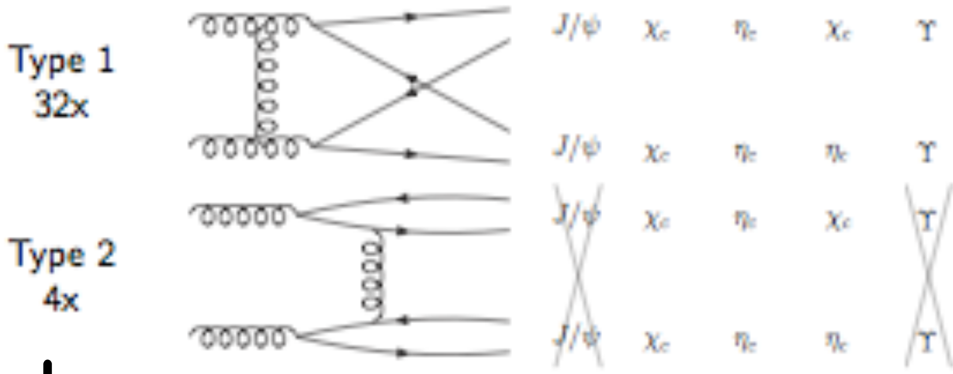


Double J/ψ production

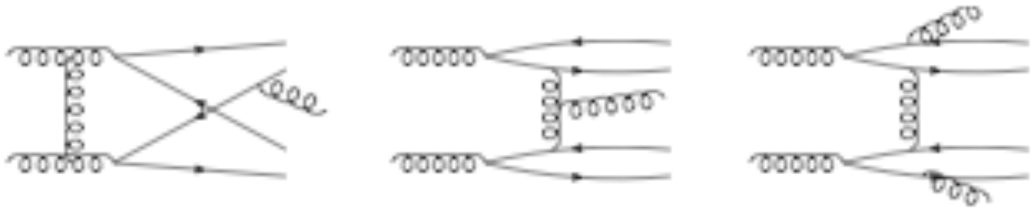


Motivations

- ➡ 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

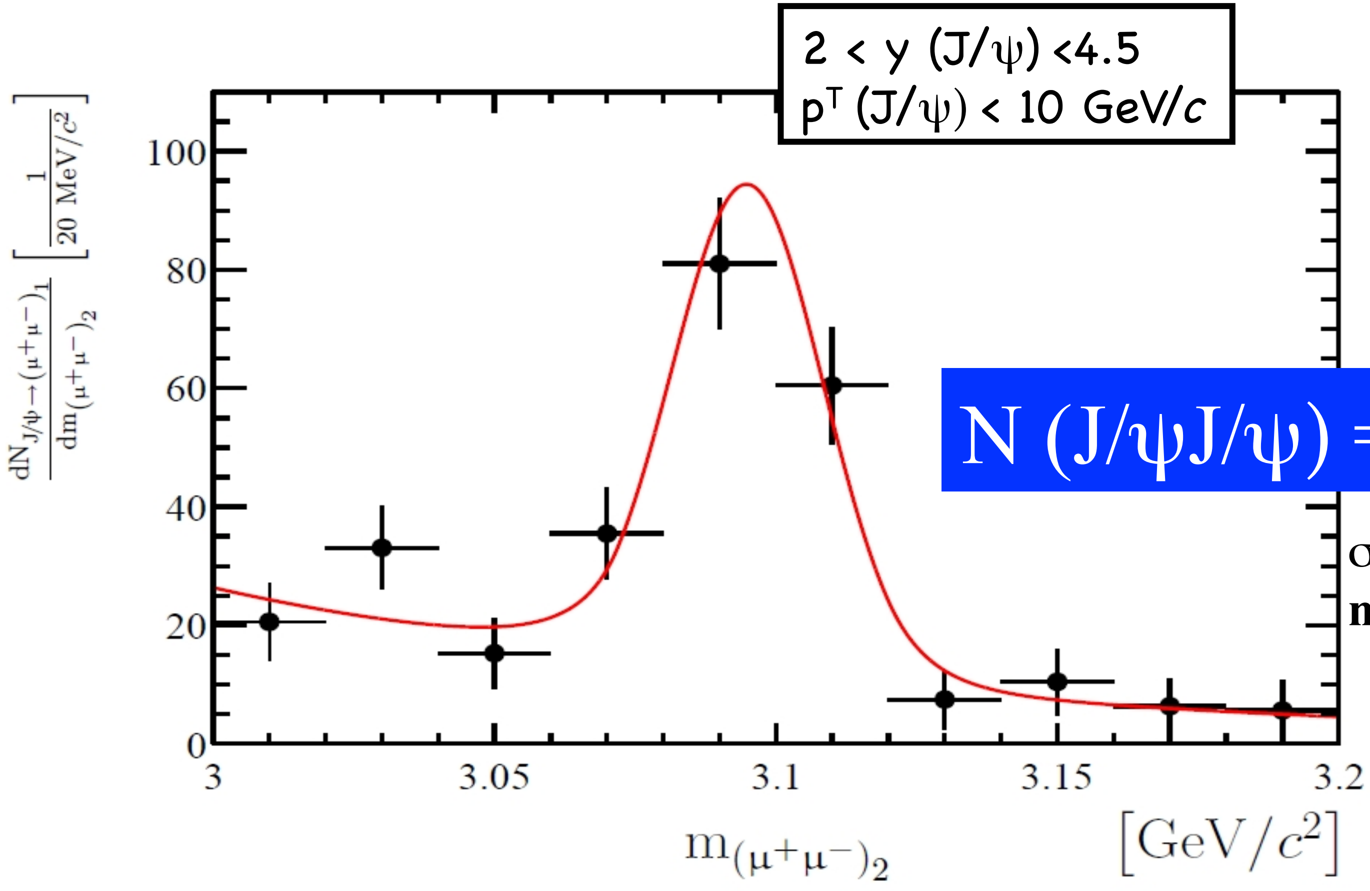


Type 1 Type 2 Type 3

  - Possible hint of tetraquark production

Signal

➡ Number of J/ψ events in bins of mass of the other J/ψ



-Fit=double CB (signal)+ exp (background)

-Significance > 7σ

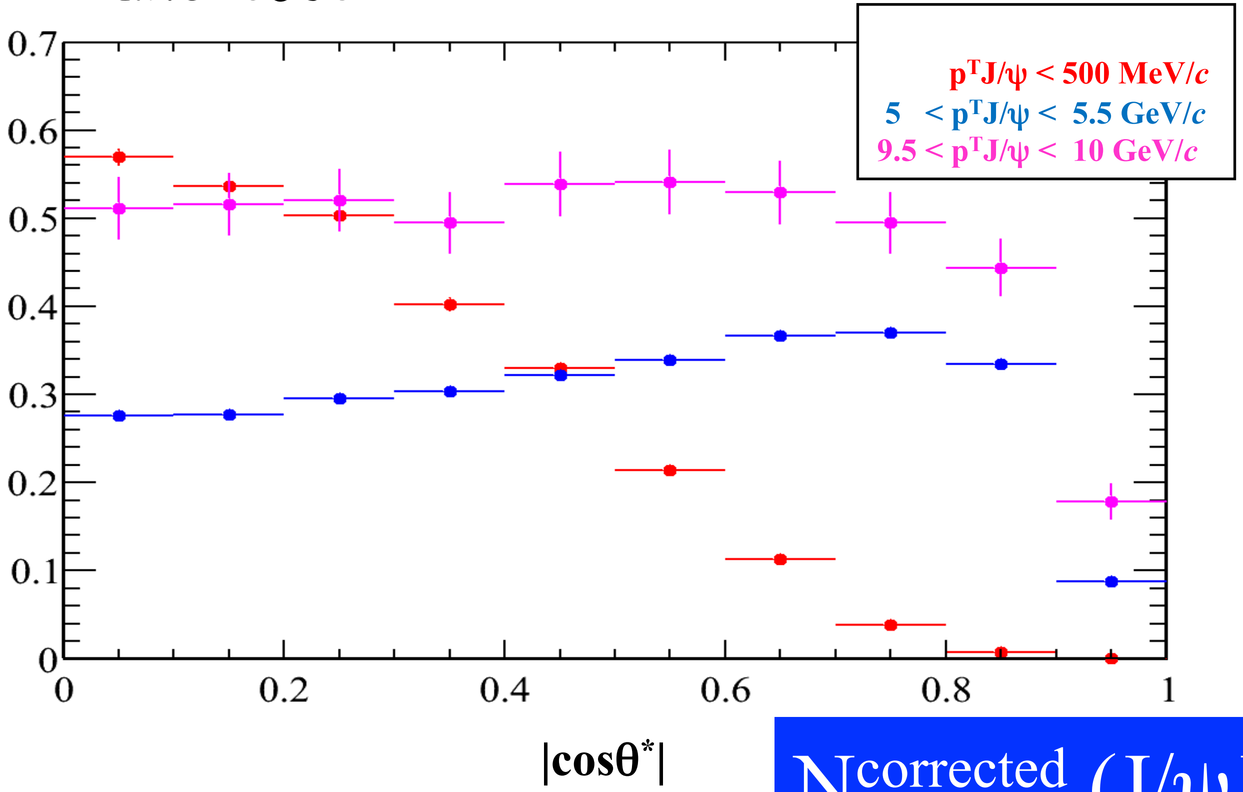
$N\ (J/\psi J/\psi) = 136.7 \pm 17.5$

σ = 14.6 ± 2.1 MeV/c^2

m = 3094.9 ± 2.4 MeV/c^2

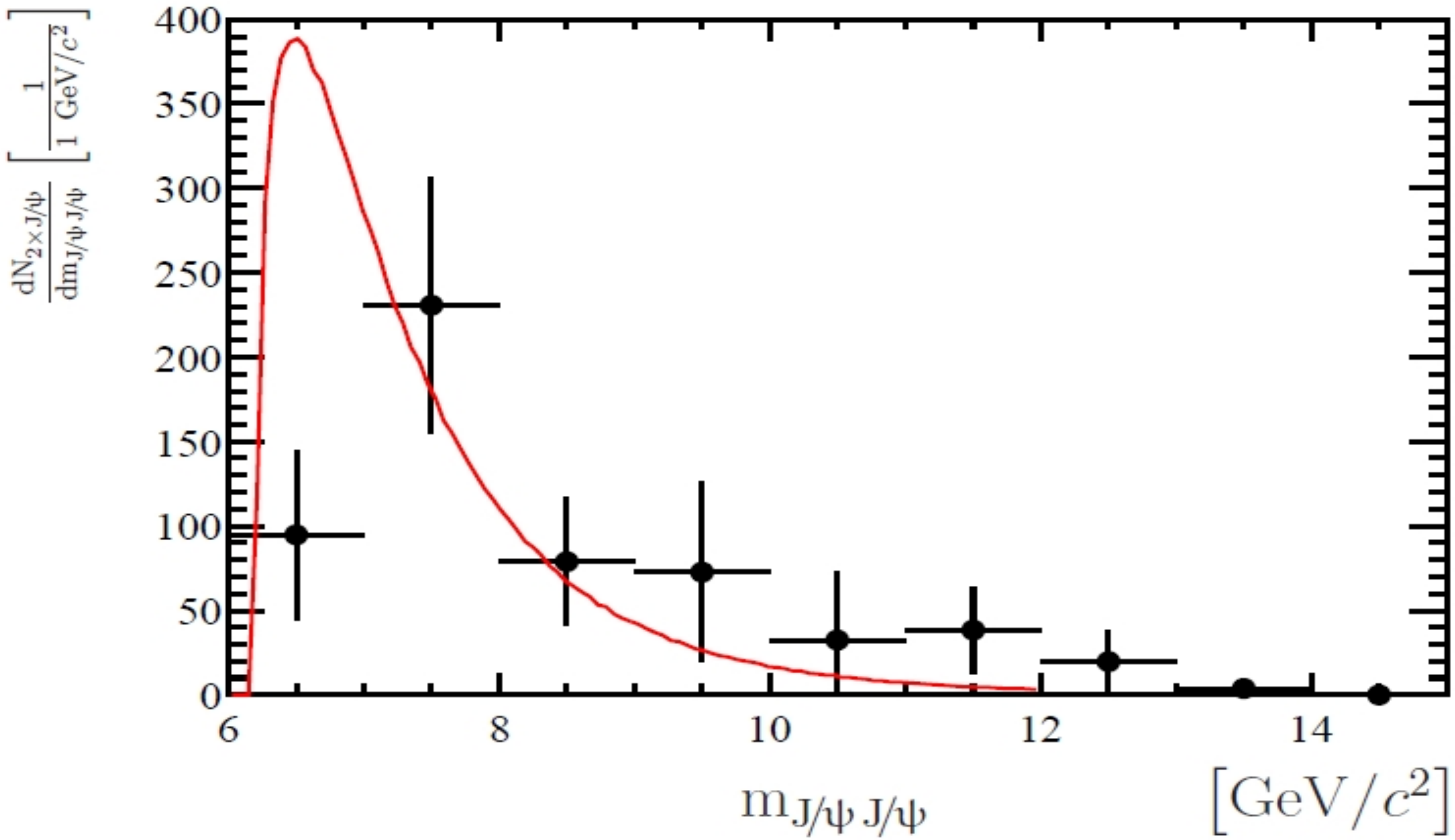
Efficiency

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



$$N^{corrected}(J/\psi J/\psi) = 700 \pm 133$$

J/ψ J/ψ Invariant Mass



Results

$$\sigma^{J/\psi\, J/\psi} = \frac{1}{\mathcal{L} \times \mathcal{B}^2_{\mu^+\mu^-}} \times N^{corr}_{J/\psi\, J/\psi}$$

J/ψ Signal window
$2 < y\ (J/\psi) < 4.5$
$p^T\ (J/\psi) < 10$ GeV/c

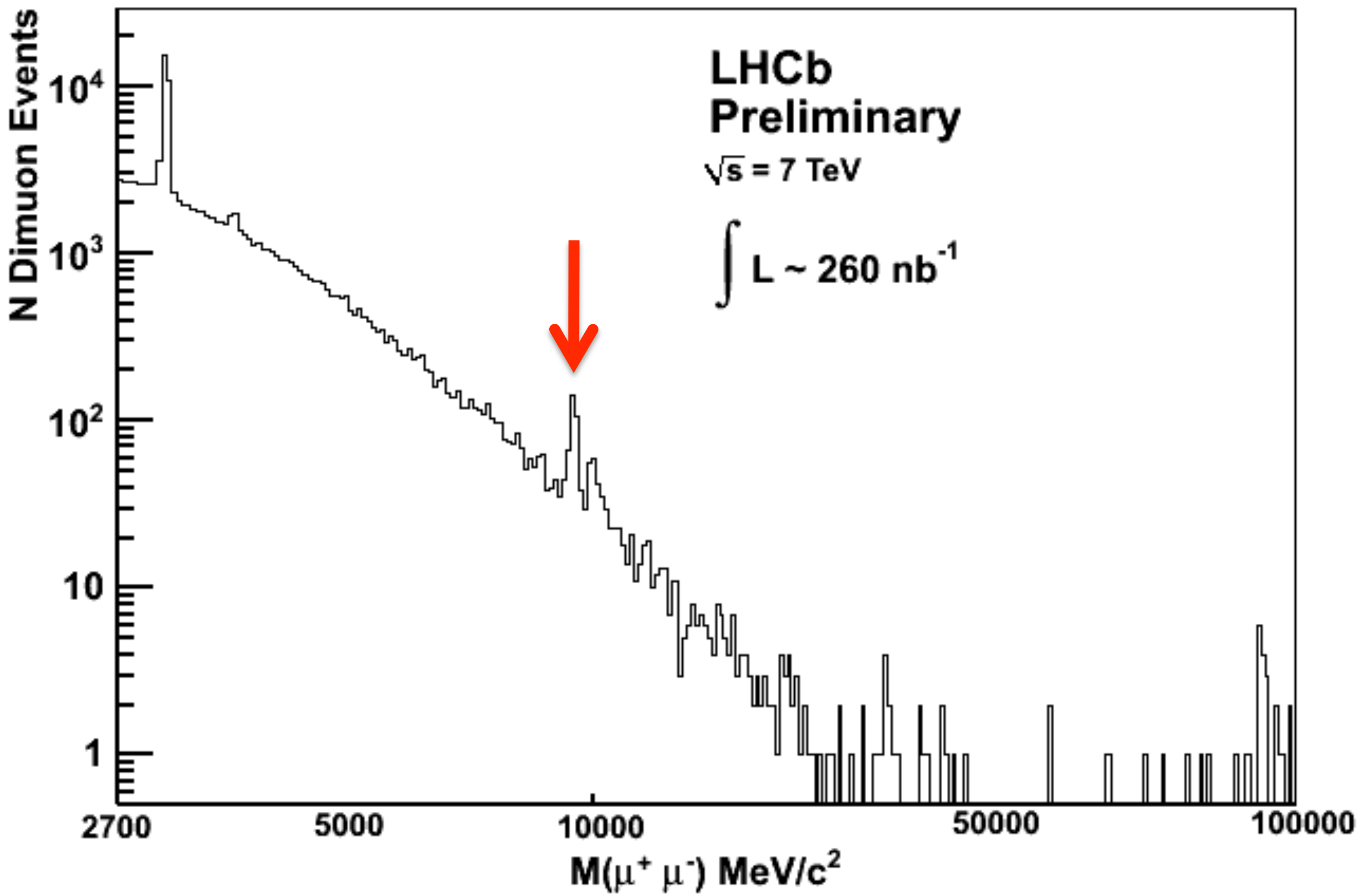
$$\sigma^{J/\psi\, J/\psi} = 5.6 \pm 1.1 \pm 0.5 \pm 0.9|_{tr} \pm 0.6|_{\mathcal{L}}\ \text{nb},$$

To be compared with theoretical prediction (direct only)

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

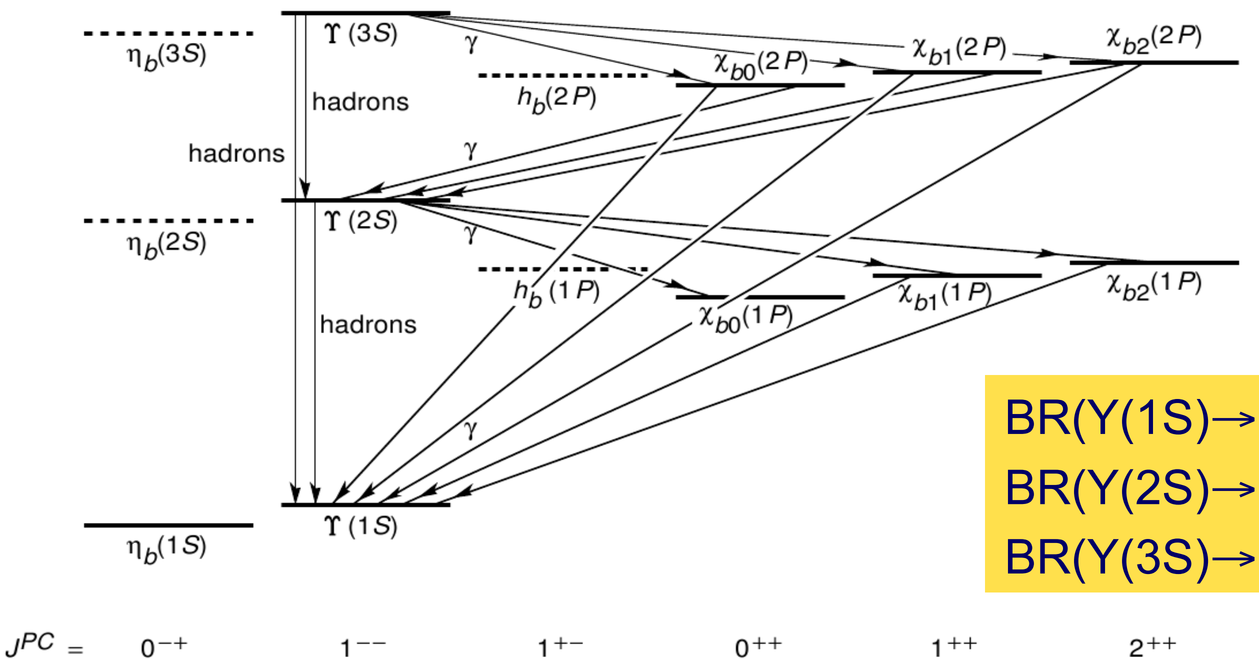
A.V.Berezhnouy, A.K. Likhoded, A.V.Luchinsky, A.A. Novoselov, arXiv:1101.5881

Υ production



Three for the price of one!

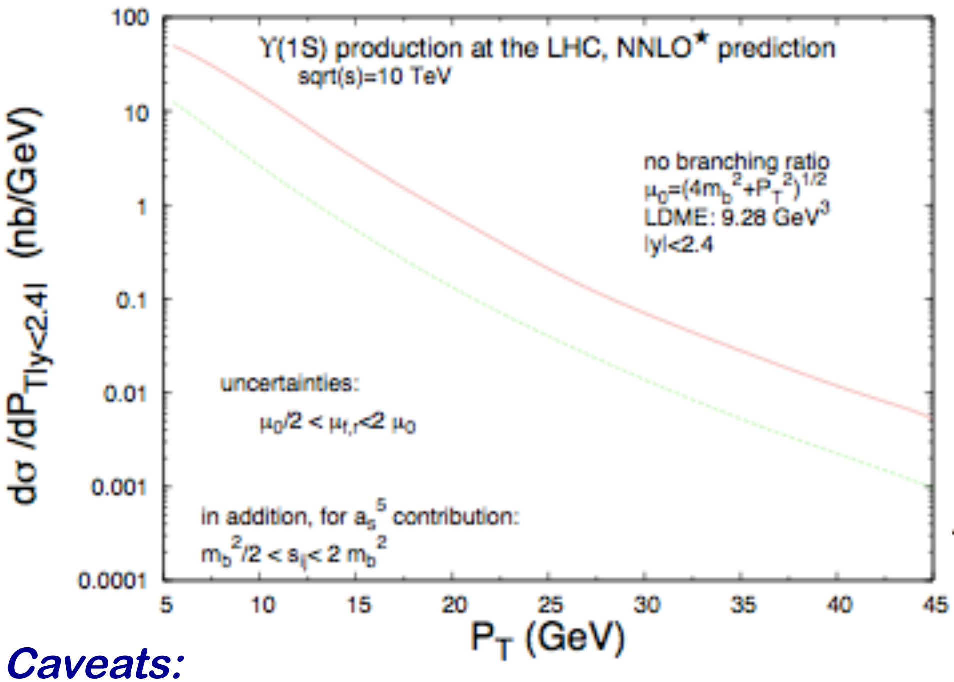
1st step	2nd step	3rd step	Prod. type
	$b\bar{b} \to \Upsilon(nS)$	–	Prompt,Direct
$pp \to b\bar{b} + X$	$b\bar{b} \to \chi_b$	$\chi_b \to \Upsilon(nS) + \gamma$	Prompt,Indirect
	$b\bar{b} \to \Upsilon(n'S)$	$\Upsilon(n'S) \to \Upsilon(nS) + X$	Prompt,Indirect



BR(Y(1S)→μμ)=(2.48±0.05)%
BR(Y(2S)→μμ)=(1.93±0.17)%
BR(Y(3S)→μμ)=(2.18±0.21)%

Υ cross section

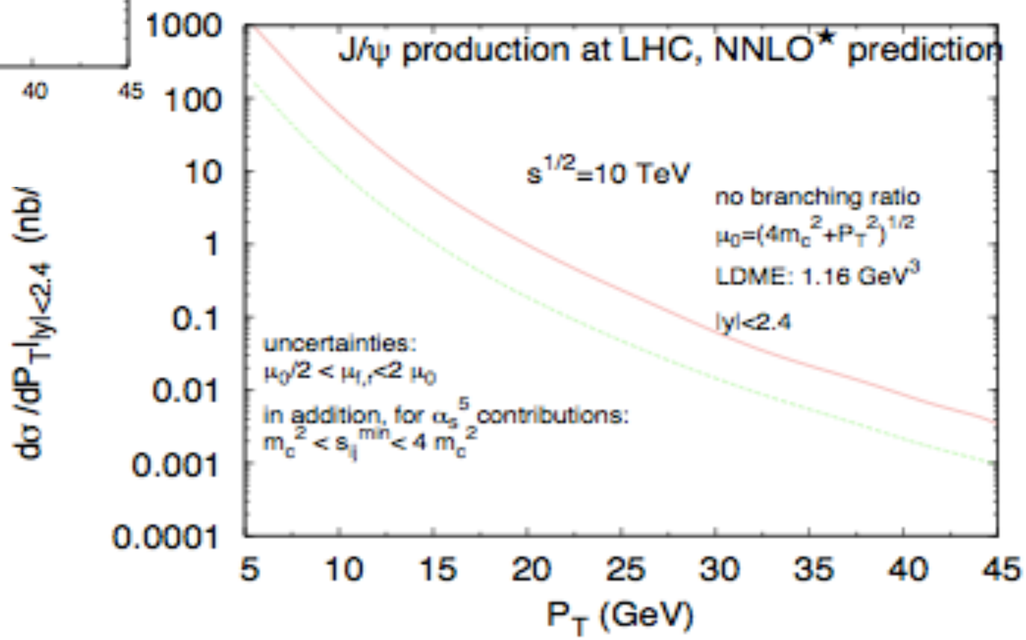
G.Bodwin, talk at Berkeley workshop May



Υ rate ~ 1/100 J/ψ rate
LHC rate ~ 50 Tevatron rate

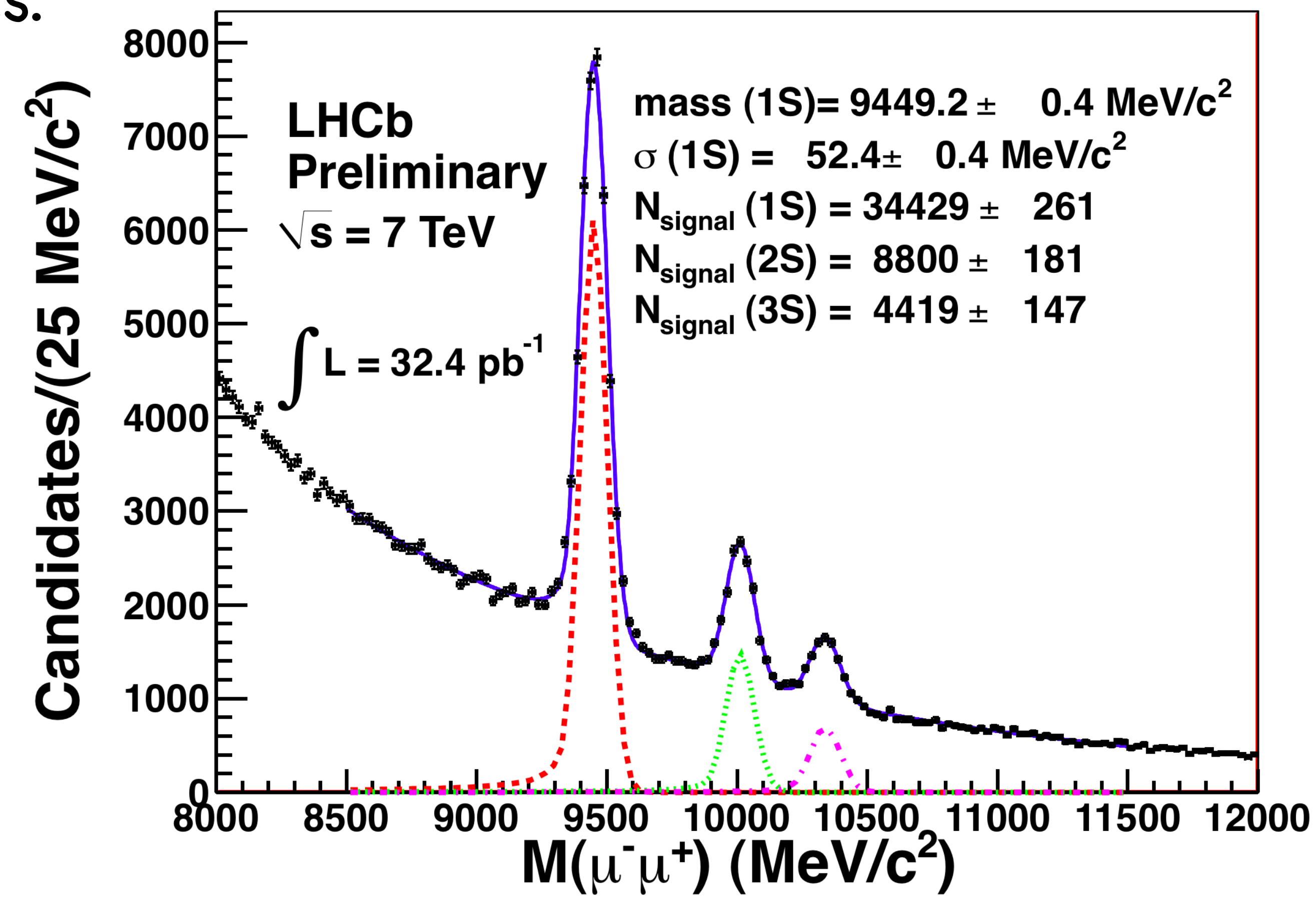
Caveats:

1. These plots only include the color-singlet contributions ➔lower limit
2. Branching ratios not included
3. Our energies lower than 5 GeV ➔more events
4. Rapidity range different (but flat y)
5. 10 TeV!



Number of Υ(1S) candidates

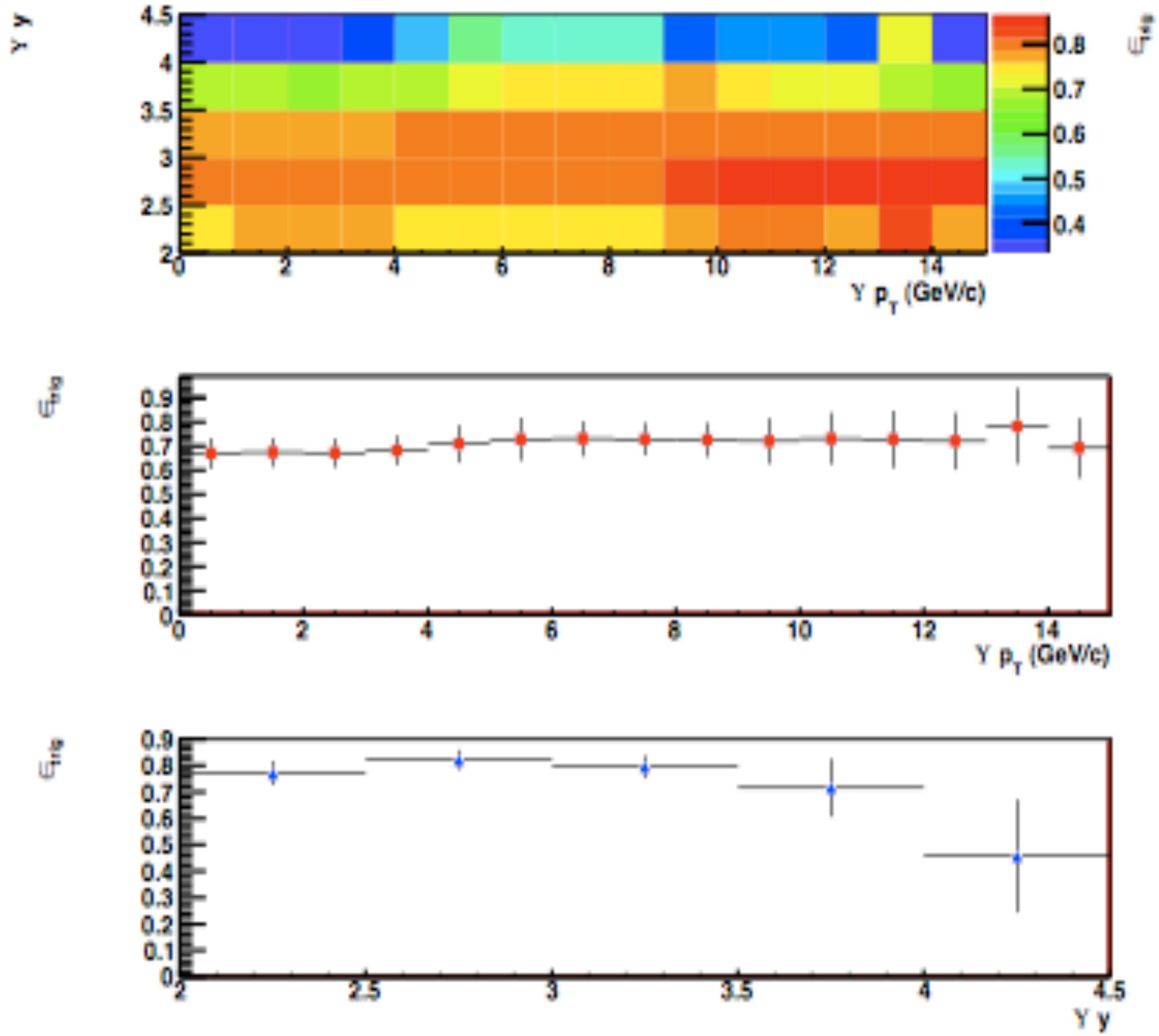
- N^{fit} : function=3 Crystal Balls(CB)+exponential for the background. Fixed (α=2,n=1) and width (2S,3S) to scale with the masses.



Same function used on individual bin fits

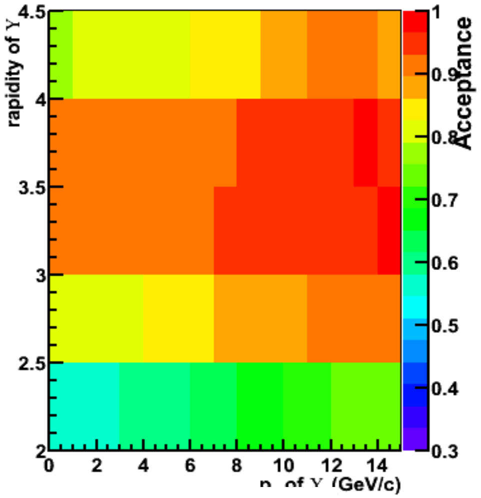
Trigger Efficiency

➡ Scaled number of candidates and effect as a function of ϒ pT and y

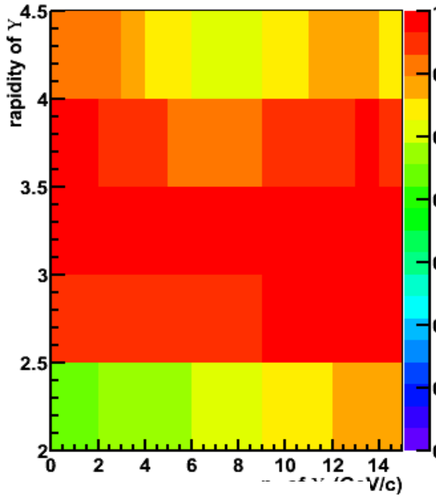


Polarisation effect on A

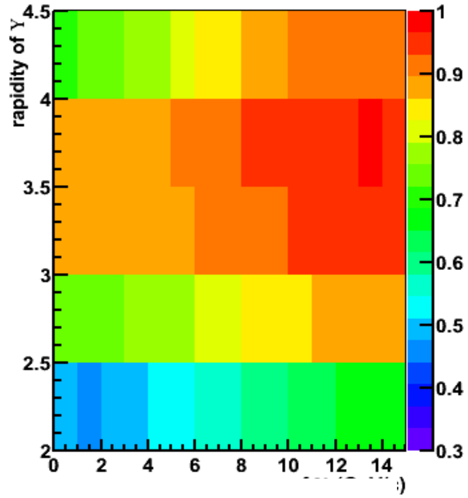
Calculated reweighting the MC unpolarised events assuming $\alpha=\pm1$



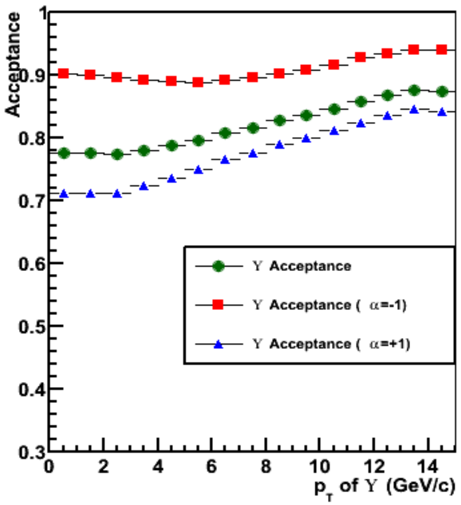
α= 0

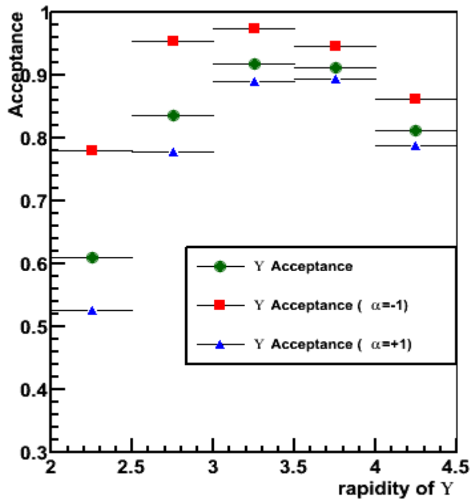


α= -1



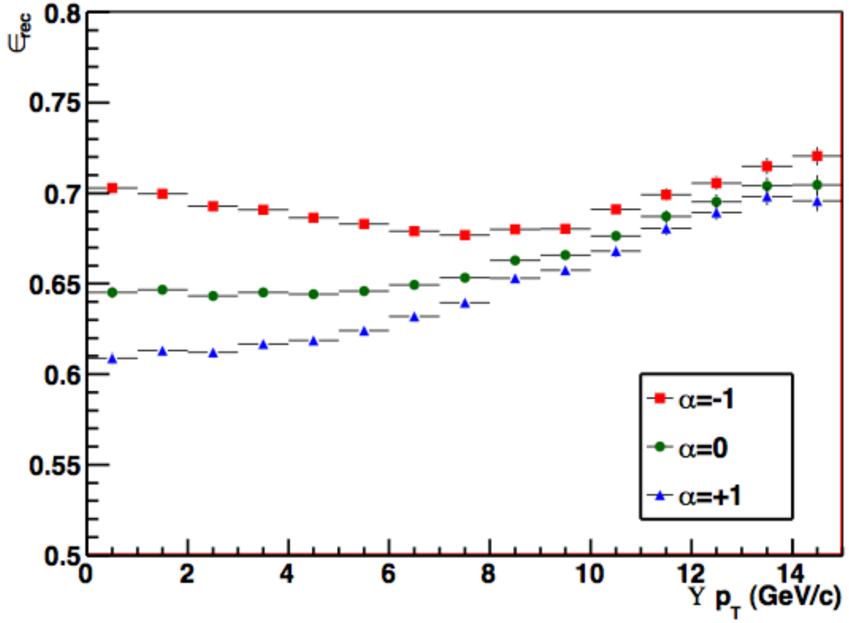
α=+1

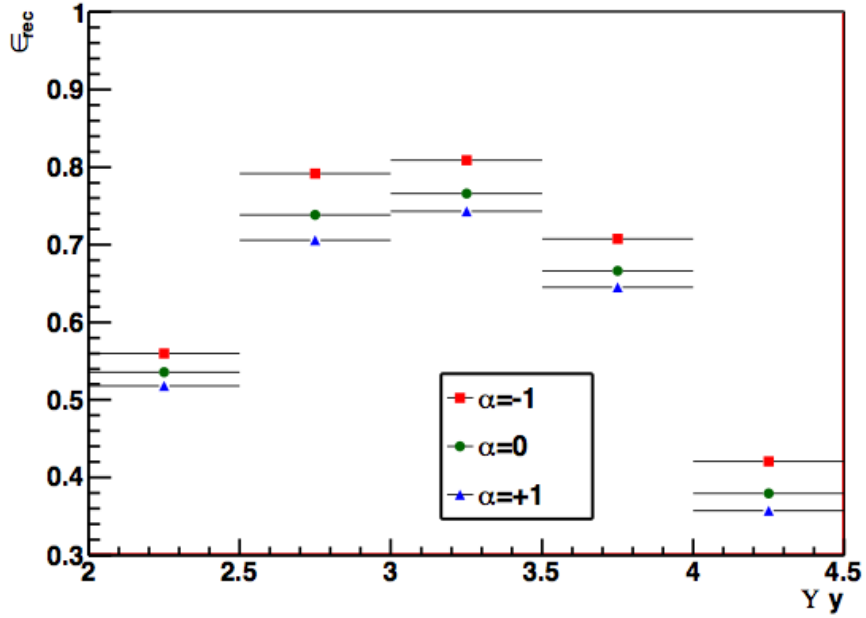




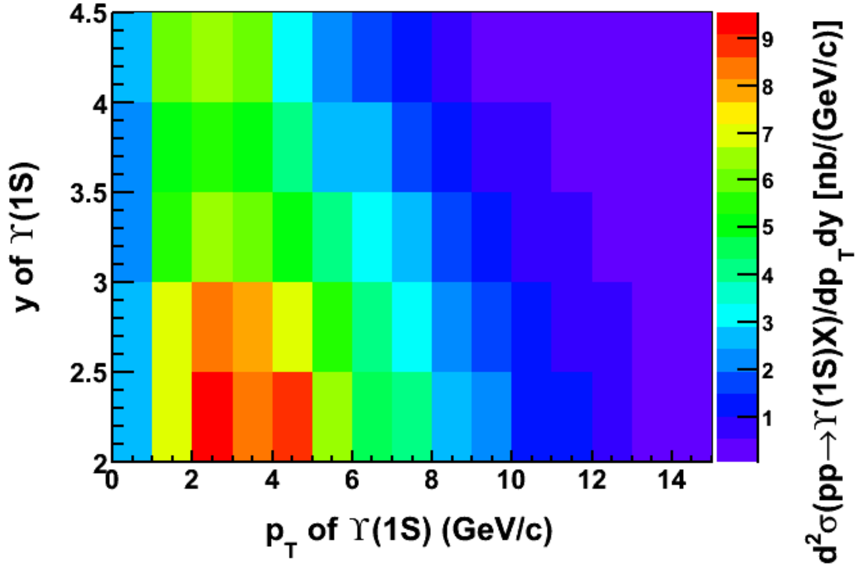
Polarisation effect on ε_{reco}

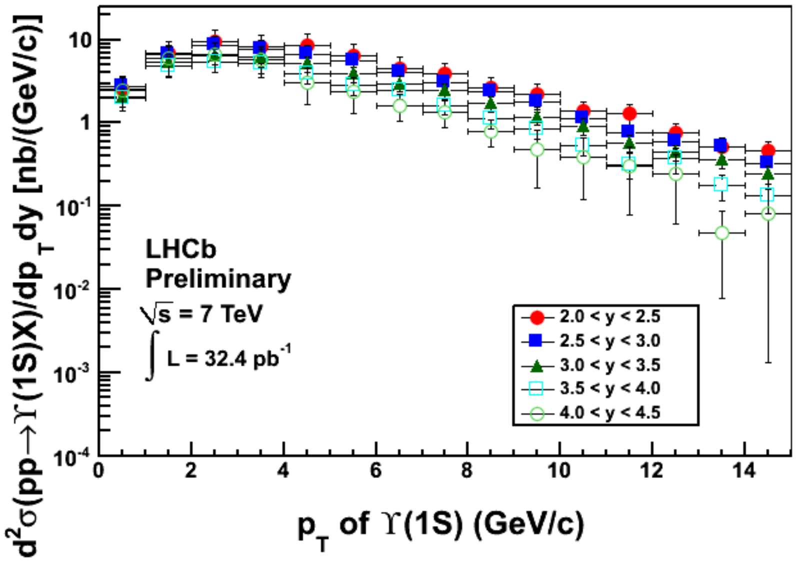
➡ Calculated reweighting the MC unpolarised events assuming $\alpha=\pm1$

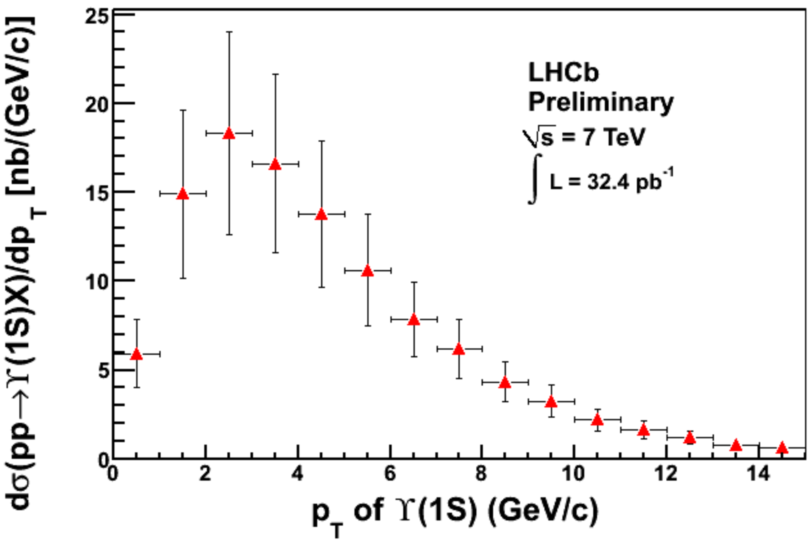


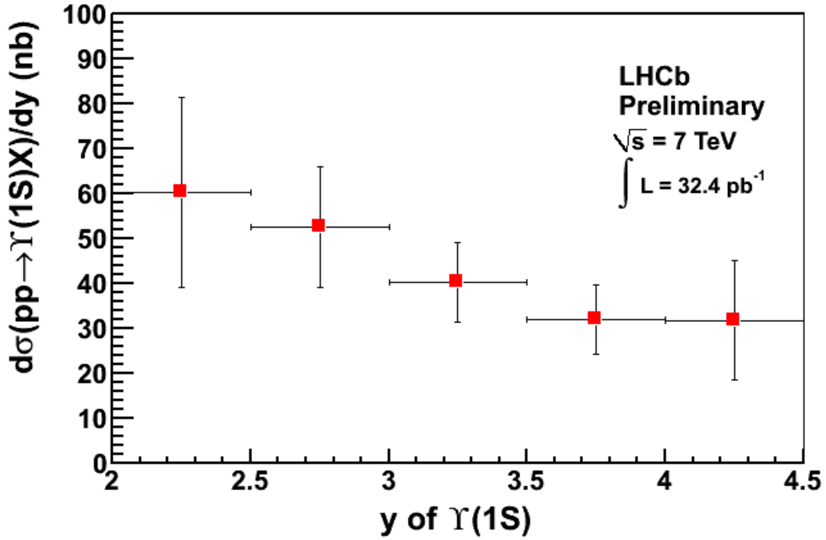


Upsilon Cross Section



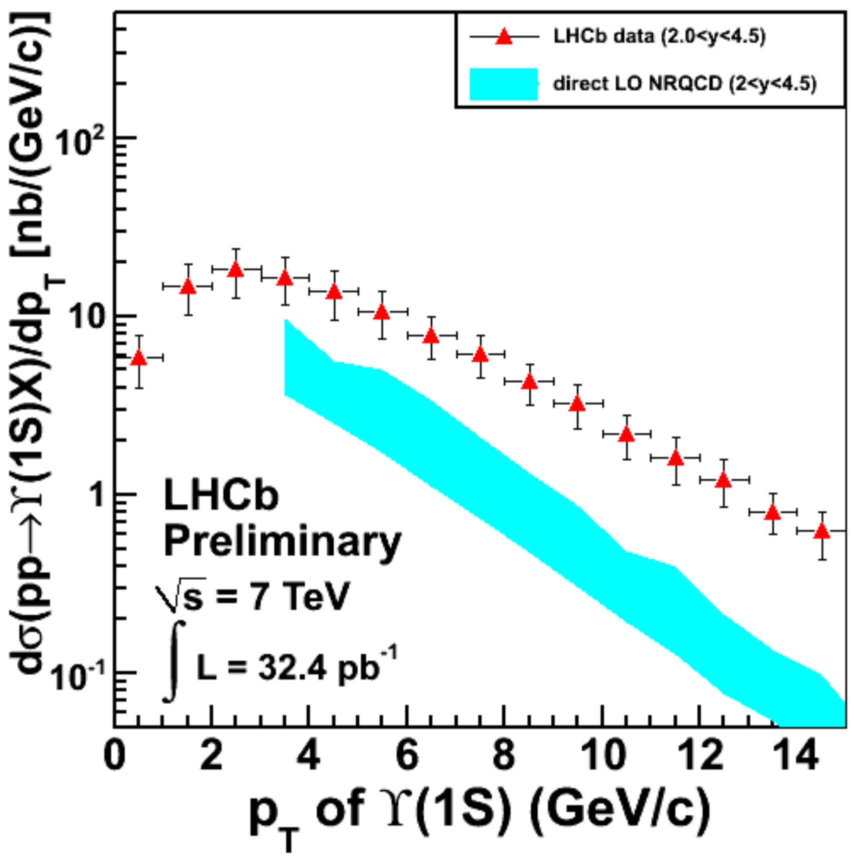


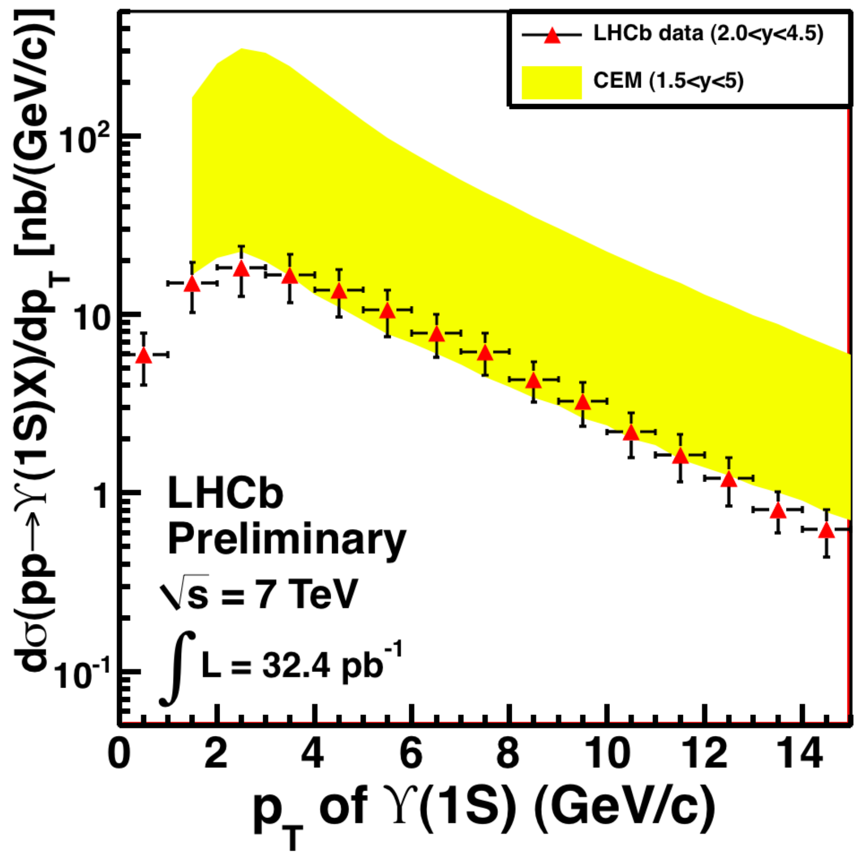




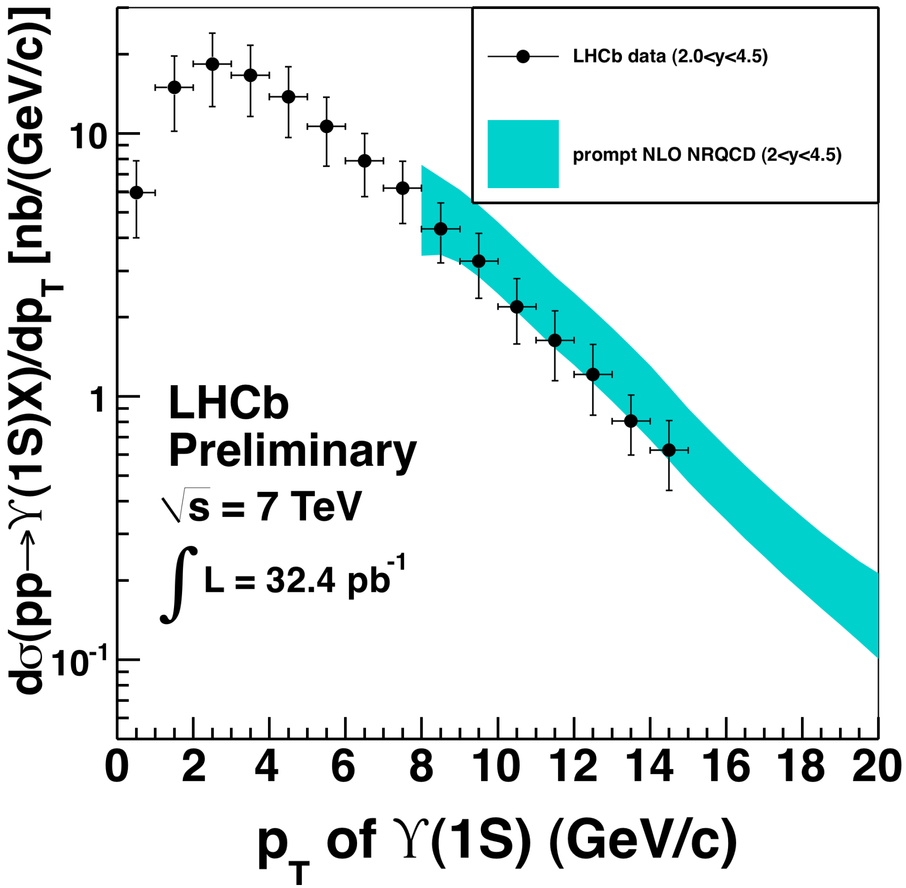
$$108.3 \pm 0.7(\text{stat})\ ^{+18.8}_{-7.9}(\text{pola}) \pm 22.0(\text{osys}) \pm 10.8(\text{lumi})\ \text{nb} = 108.3 \pm 0.7(\text{stat})\ ^{+30.9}_{-25.8}(\text{syst})$$

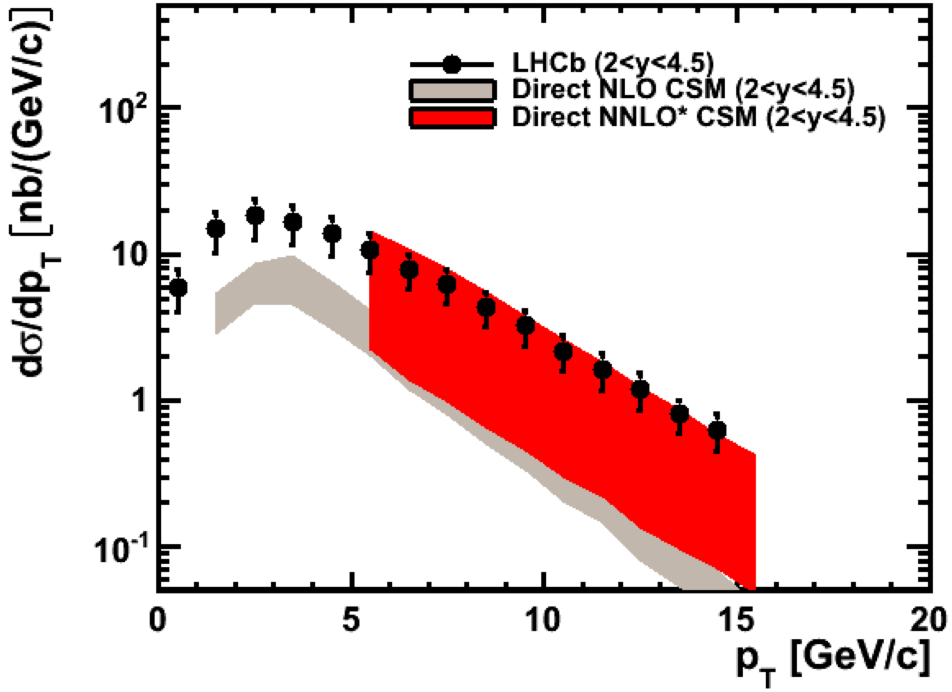
Comparison with Theory



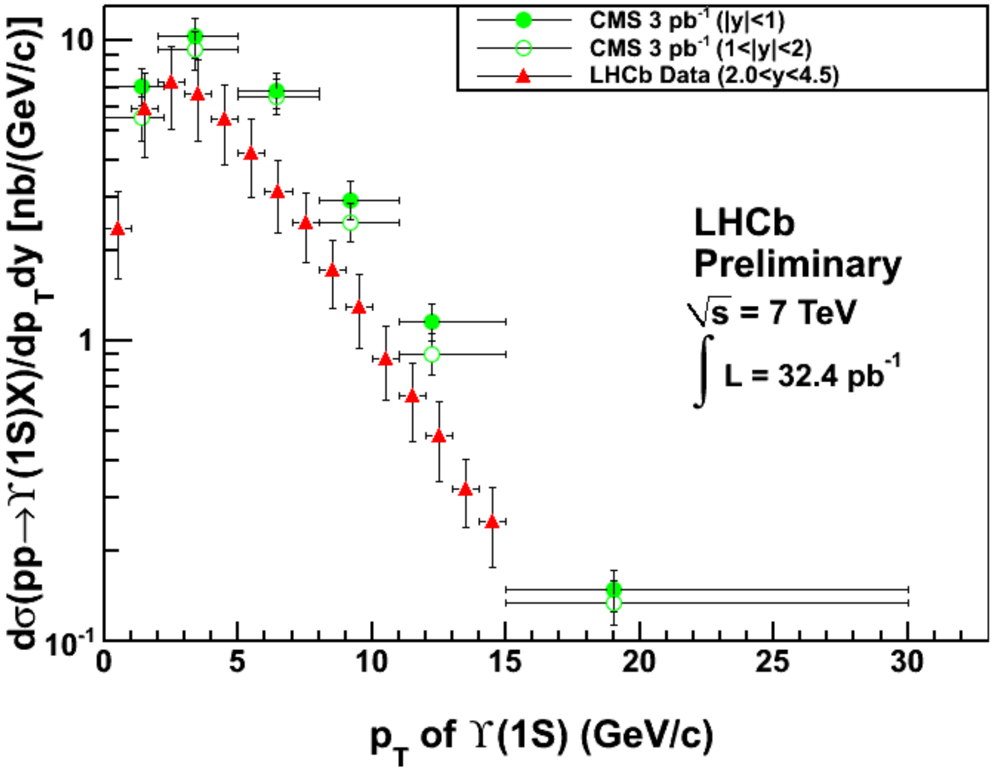


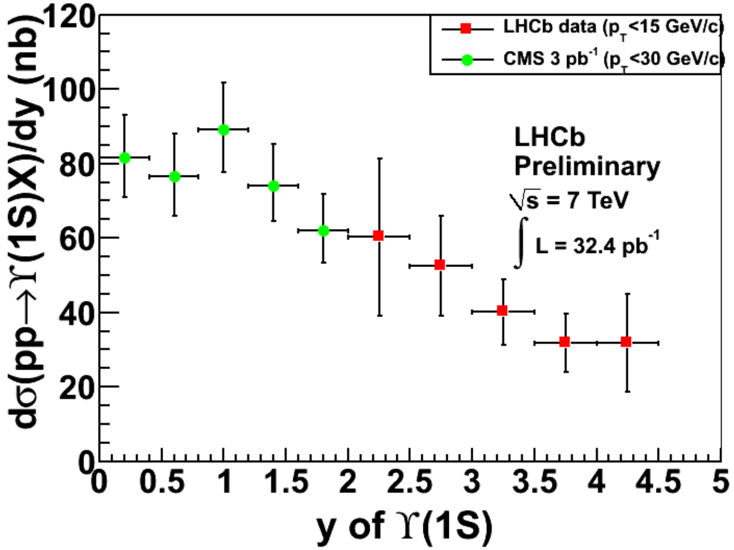
Comparison with Theory





Comparison with CMS

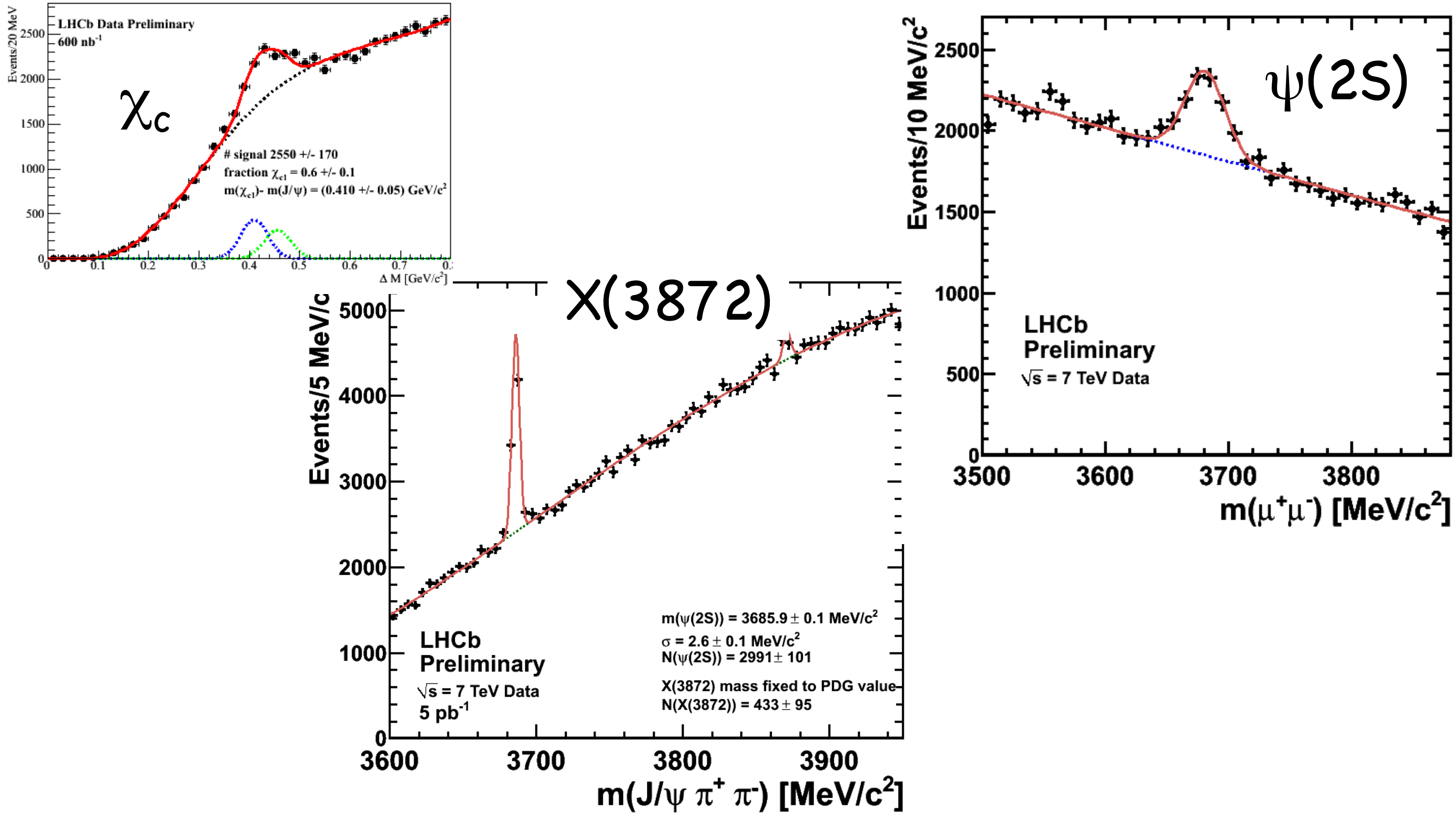




Conclusions

- Quarkonium physics at LHCb is producing nice results – starts to probe new regime!
- J/ψ, Υ polarisation, χ_c,$\psi(2S)$ cross section, X(3872) mass measurements on the way
- Many more interesting results just round the corner-stay tuned !

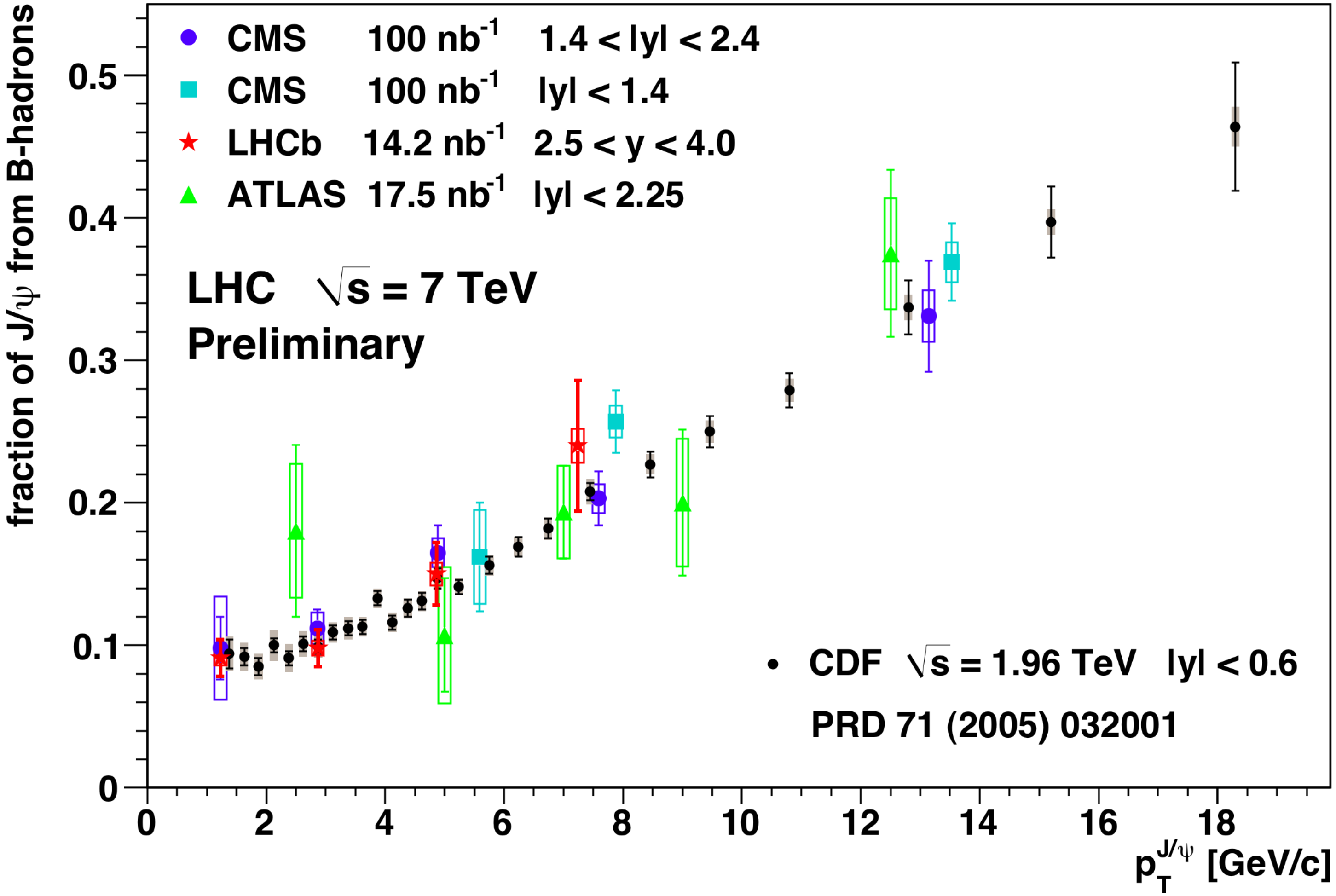
Next time...



χc
LHCb Data Preliminary
600 nb-1
signal 2550 +/- 170
fraction χc1 = 0.6 +/- 0.1
m(χc1)- m(J/ψ) = (0.410 +/- 0.05) GeV/c2
Events/20 MeV
Δ M [GeV/c2]
X(3872)
LHCb
Preliminary
√s = 7 TeV Data
5 pb-1
m(ψ(2S)) = 3685.9 ± 0.1 MeV/c2
σ = 2.6 ± 0.1 MeV/c2
N(ψ(2S)) = 2991 ± 101
X(3872) mass fixed to PDG value
N(X(3872)) = 433 ± 95
Events/5 MeV/c
m(J/ψ π+ π-) [MeV/c2]
ψ(2S)
LHCb
Preliminary
√s = 7 TeV Data
Events/10 MeV/c2
m(μ+μ-) [MeV/c2]

Back up

Fraction from B: Comparison with other experiments

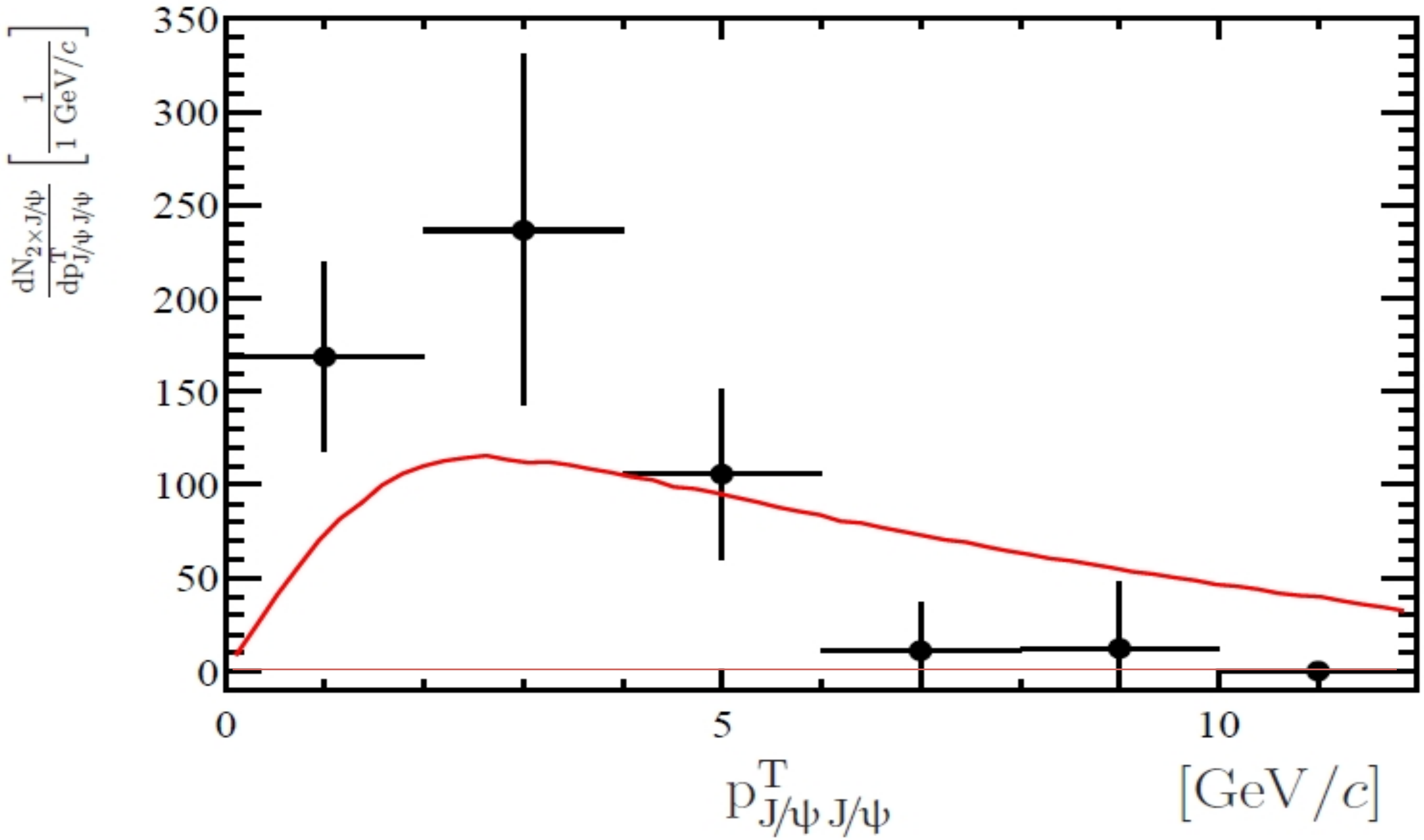


J/ψ integrated cross section measurements

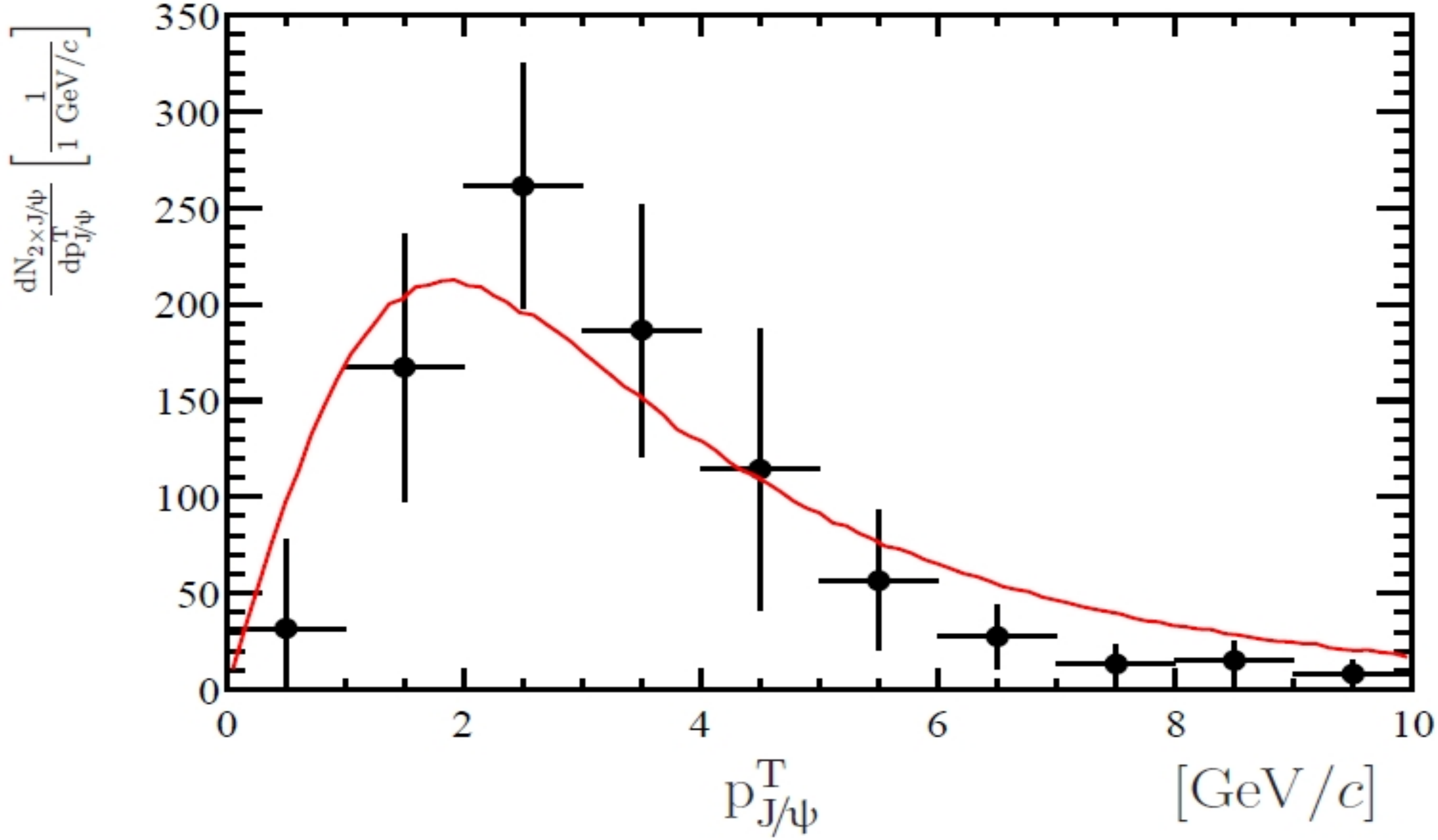
Experiment Range Luminosity	LHCb (in μb) pT<10 GeV, 2.5<y<4 14.2 pb^{-1}	 5 pb^{-1}	CMS (in nb) 4<pT<30 GeV, |y|<2.4 100 nb^{-1}	ATLAS (in nb) <y>~1.85 100 nb^{-1}
Inclusive J/ψ	$7.65 \pm 0.19 \pm 1.10^{+0.87}_{-1.27}$	$10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20}$	$289.1 \pm 16.7 \pm 60.1$	250^{+130}_{-80}
J/ψ from B	$0.81 \pm 0.06 \pm 0.13$	$1.14 \pm 0.01 \pm 0.16$	$56.1 \pm 5.5 \pm 7.2$	
Total bb*	$319 \pm 24 \pm 59$	$288 \pm 4 \pm 48$		

* Extrapolating to the LHCb acceptance using Pythia 6.4

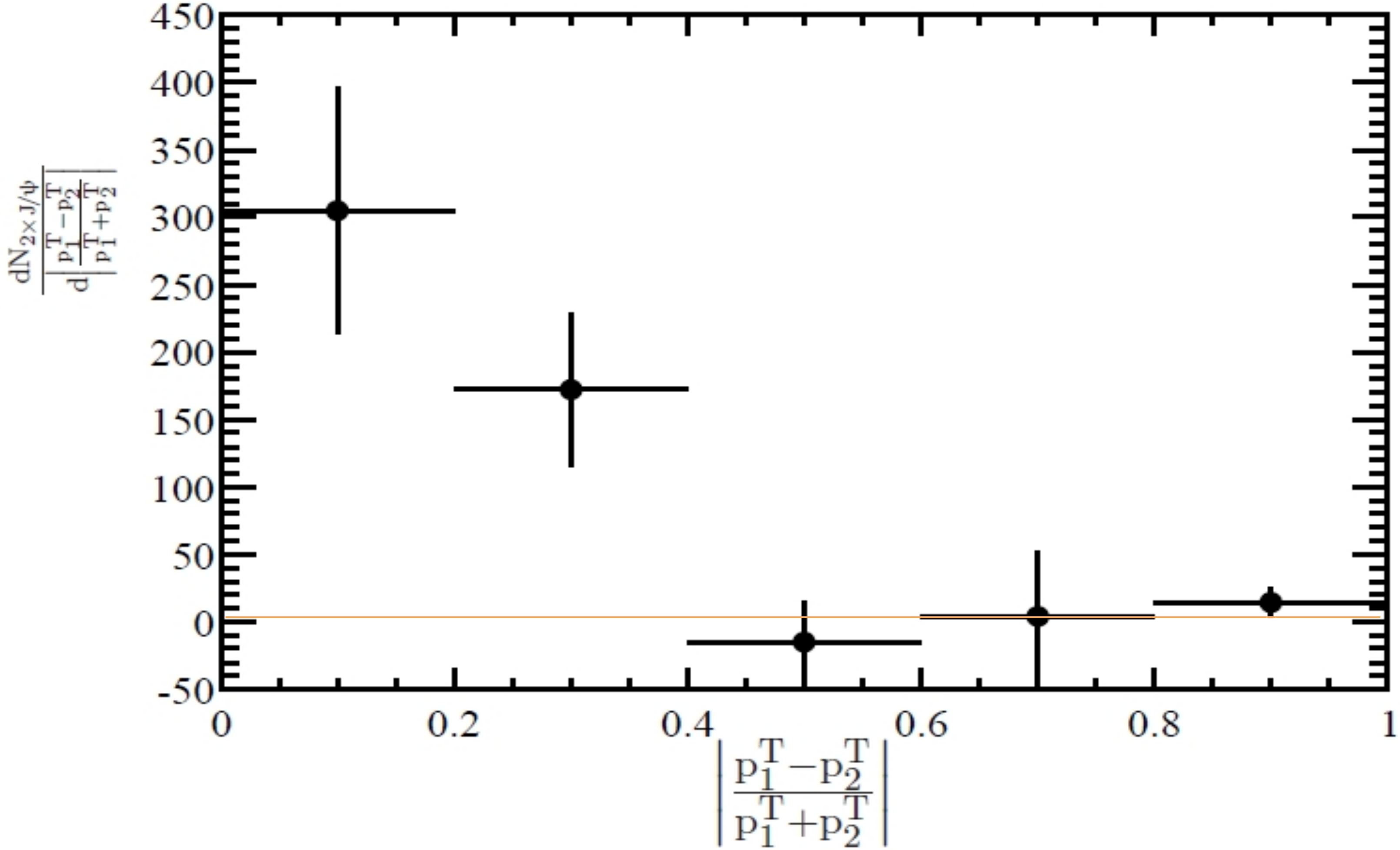
Efficiency corrected $p^T_{J/\psi J/\psi}$



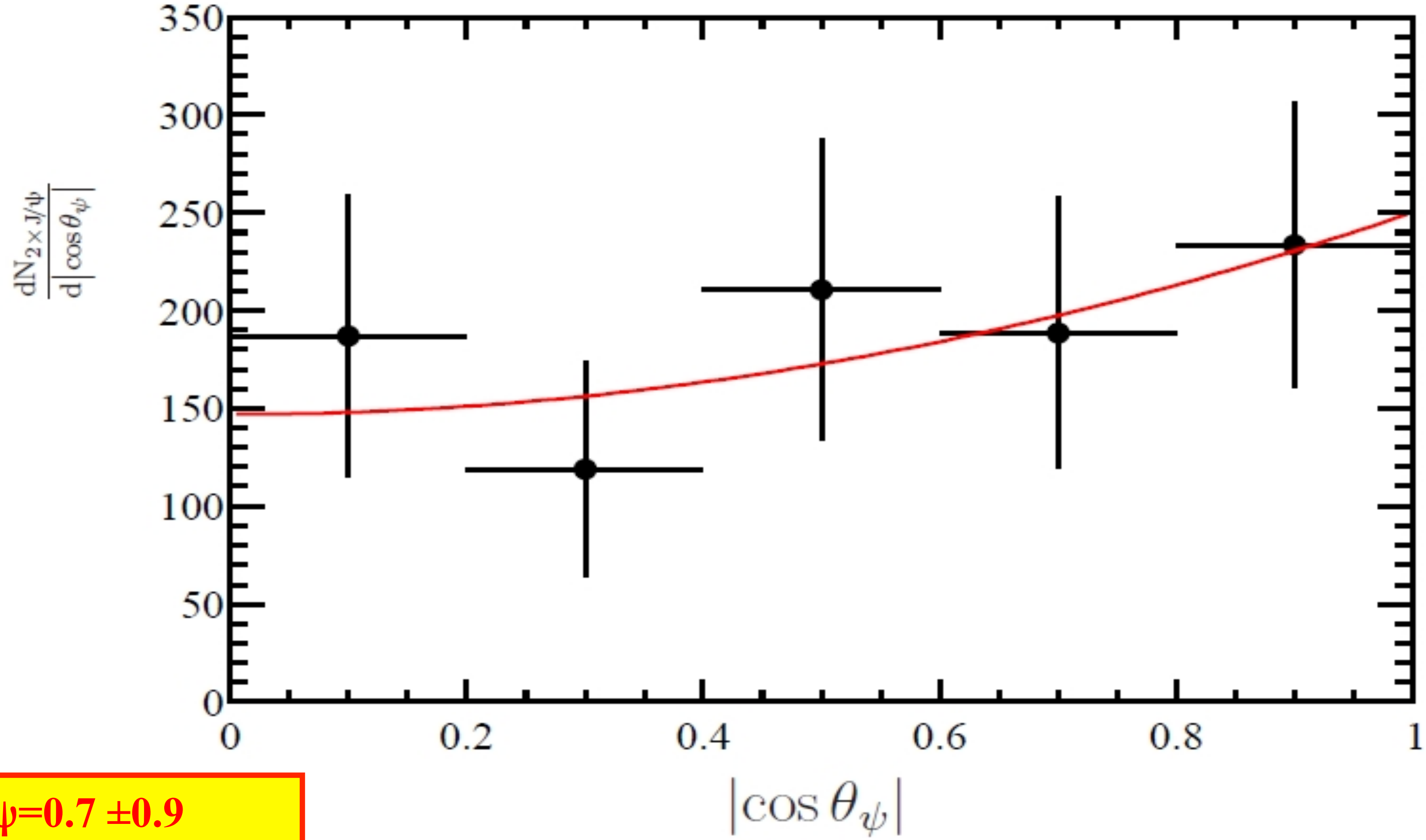
Efficiency corrected $p^T_{J/\psi}$ from $2\times J/\psi$



Efficiency corrected p^T-asymmetry

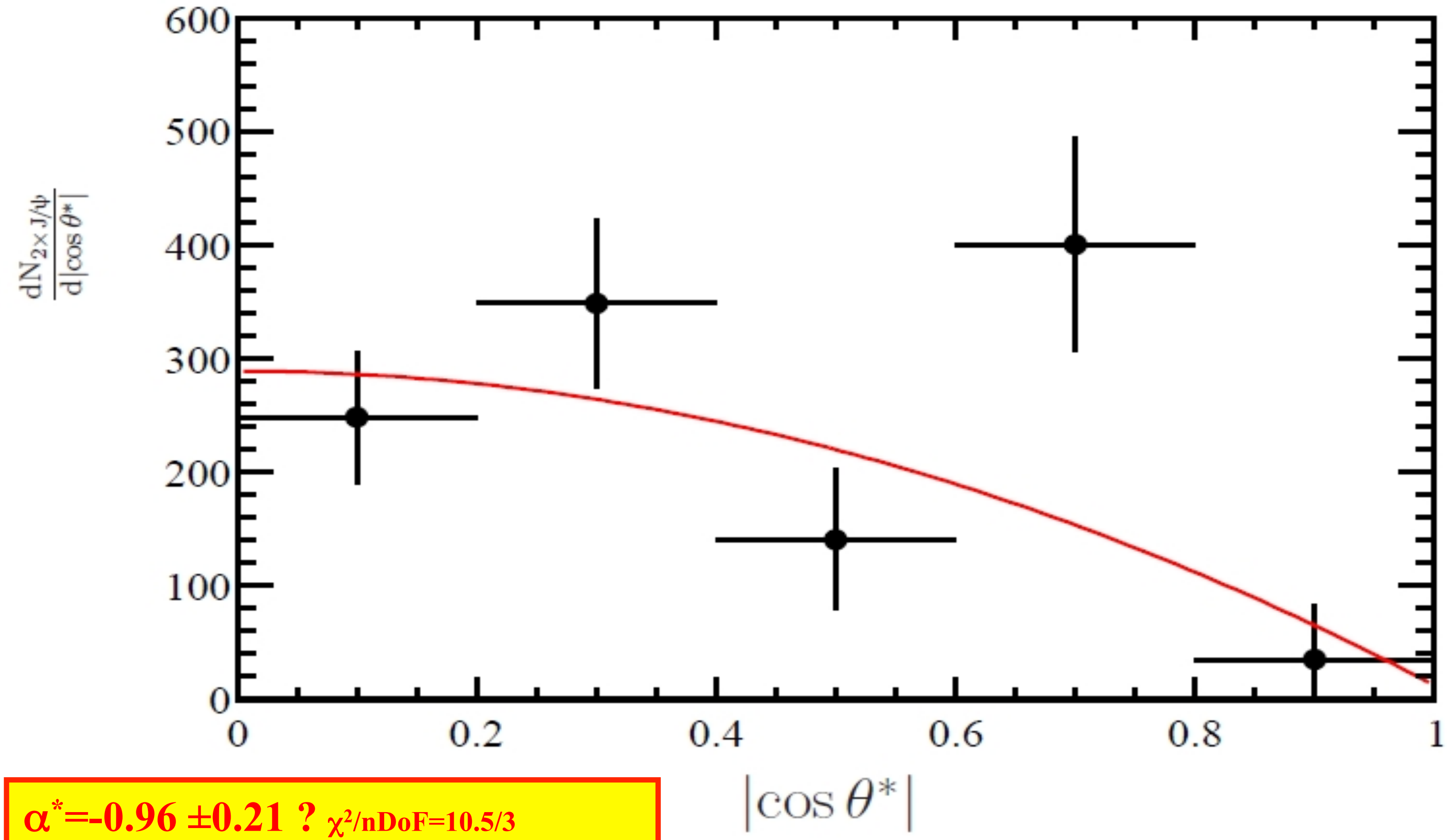


J/ψ polarization: $\cos\theta_\psi$



$\alpha\psi = 0.7 \pm 0.9$

J/ψ polarization: cosθ*



α^*=-0.96 ±0.21 ? χ^2/nDoF=10.5/3

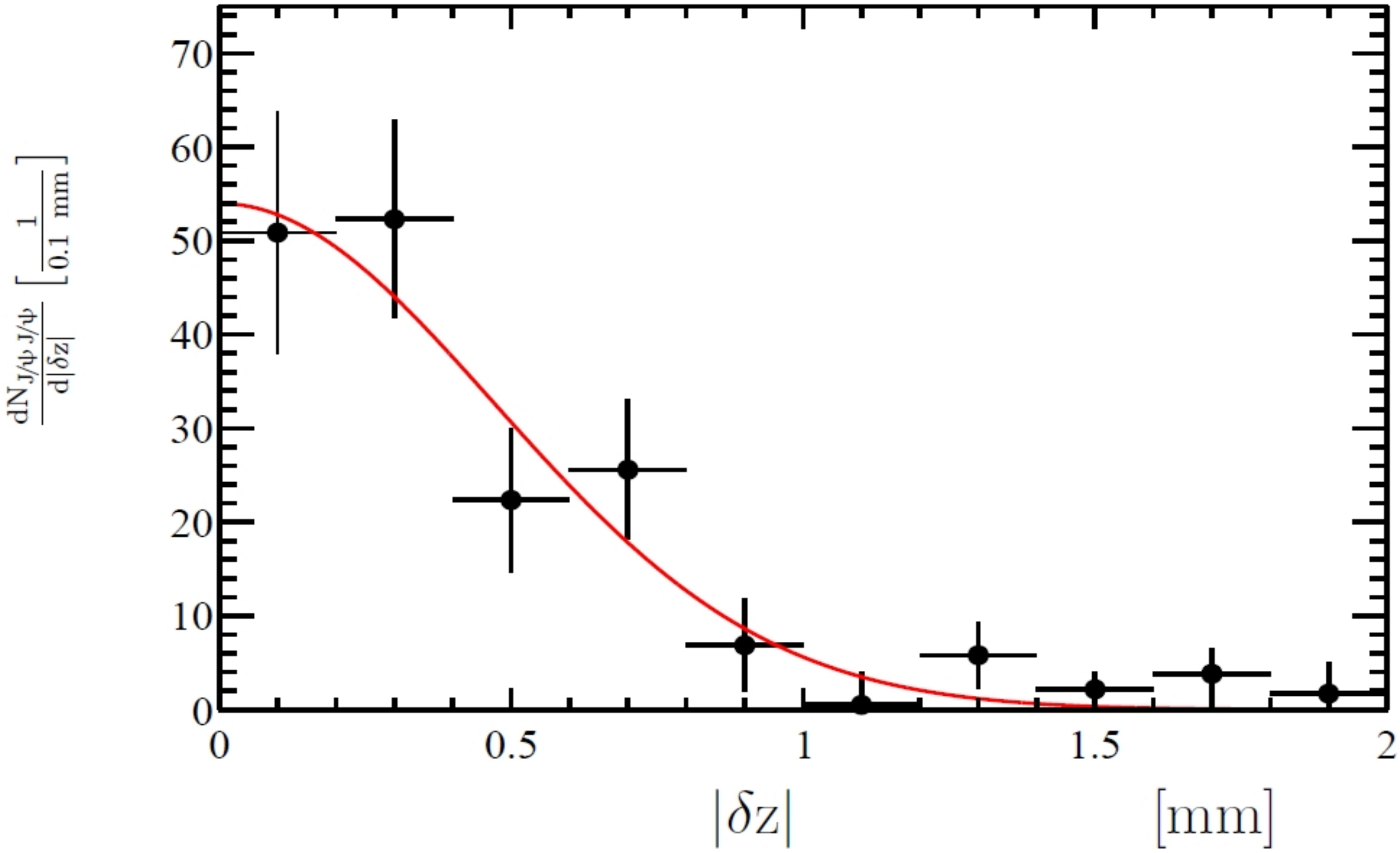
Pileup: $J/\psi J/\psi$ versus $J/\psi+J/\psi$

➡How to prove that it is *NOT* pileup?

- Monte Carlo

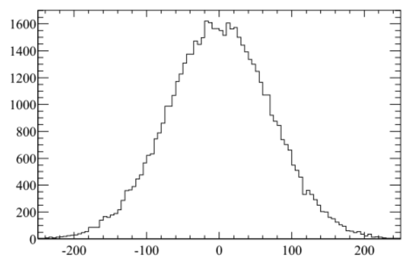
- Look for data:
  - ➢Distance between J/ψ vertices
  - ➢Track in PV: $\times 2$ larger for pileup
  - ➢PV-multiplicity: -1 for pileup
  - ➢Wide range $\chi^2_{DTF}/nDoF$ scan

J/ψJ/ψ distance

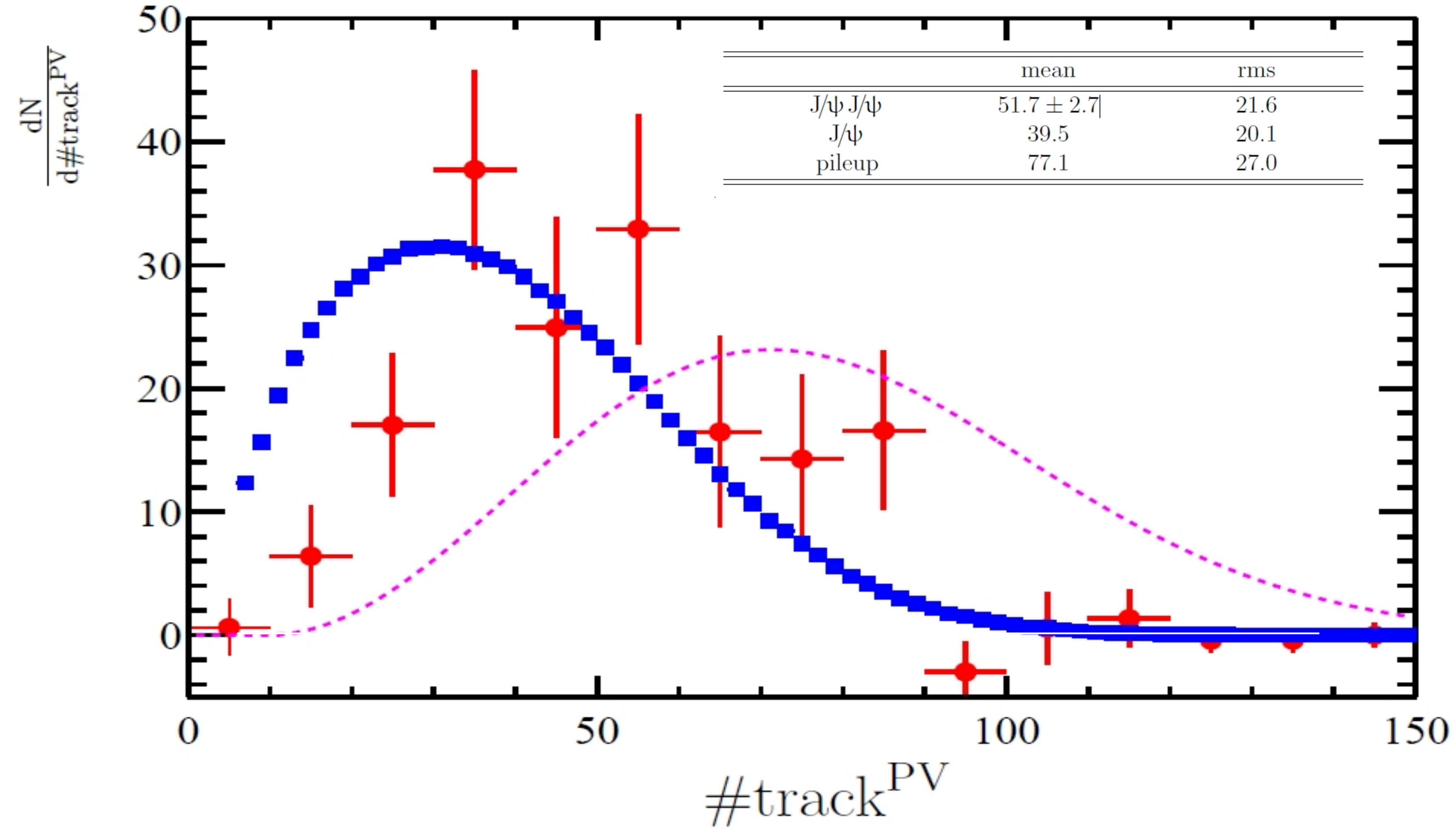


J/ψJ/ψ distance

- $\sigma^{|\delta z|} = 470 \pm 62\ \mu m$
- All signal is collected from 1.5/2mm
- Monte Carlo:
  - take events with J/y+J/y in inclusive J
    - Different pp-collisions!
  - signal window
  - correct for cross-section
  - [CONSERVATIVELY]: ~9.4 events in 2mm
  - apply trigger & reconstruction efficiency
    - <1.5 events



#tracks in PV



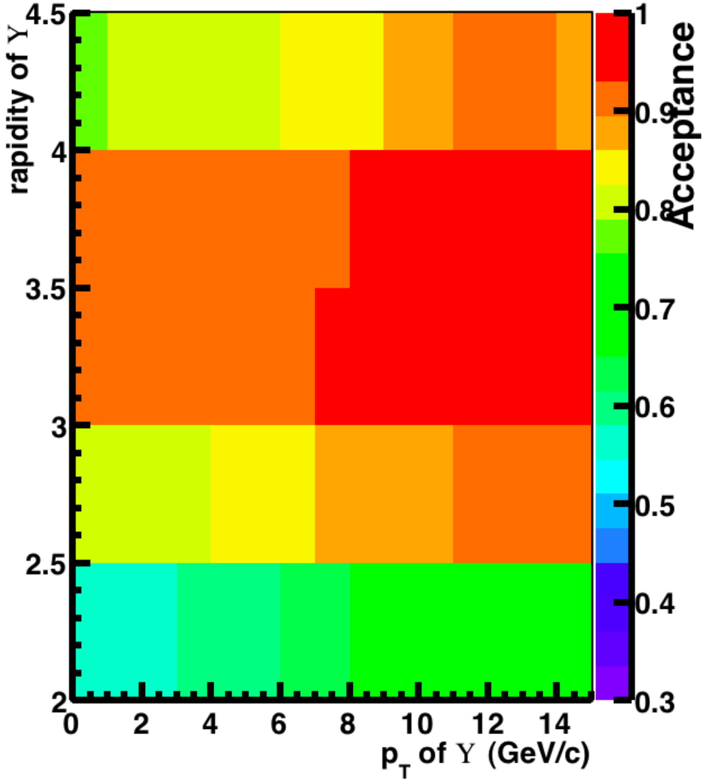
$\frac{dN}{d\#track^{PV}}$
50
40
30
20
10
0
0
50
100
150
$\#track^{PV}$
mean
rms
J/ψ J/ψ
51.7 ± 2.7
21.6
J/ψ
39.5
20.1
pileup
77.1
27.0

a) Number of $\Upsilon(1S)$ candidates

p_T (GeV/c)	2.0< y <2.5	2.5< y <3.0	3.0< y <3.5	3.5< y <4.0	4.0< y <4.5
0- 1	228 ± 15	516 ± 23	437 ± 21	308 ± 18	88 ± 9
1- 2	602 ± 25	1244 ± 35	1153 ± 34	766 ± 28	231 ± 15
2- 3	863 ± 29	1553 ± 39	1358 ± 37	841 ± 29	254 ± 16
3- 4	757 ± 28	1453 ± 38	1284 ± 36	824 ± 29	253 ± 16
4- 5	809 ± 28	1268 ± 36	1102 ± 33	636 ± 25	182 ± 14
5- 6	627 ± 25	1070 ± 33	845 ± 29	481 ± 22	157 ± 13
6- 7	457 ± 21	774 ± 28	651 ± 26	452 ± 21	110 ± 11
7- 8	398 ± 20	600 ± 24	546 ± 23	298 ± 17	91 ± 10
8- 9	279 ± 17	482 ± 22	392 ± 20	208 ± 14	57 ± 8
9-10	249 ± 16	379 ± 19	271 ± 16	162 ± 13	31 ± 6
10-11	171 ± 13	253 ± 16	214 ± 15	104 ± 10	27 ± 5
11-12	160 ± 13	176 ± 13	139 ± 12	64 ± 8	20 ± 4
12-13	100 ± 10	139 ± 12	108 ± 10	74 ± 9	16 ± 4
13-14	70 ± 8	123 ± 11	87 ± 9	37 ± 6	5 ± 2
14-15	61 ± 8	78 ± 9	60 ± 8	27 ± 5	5 ± 2

b) Acceptance

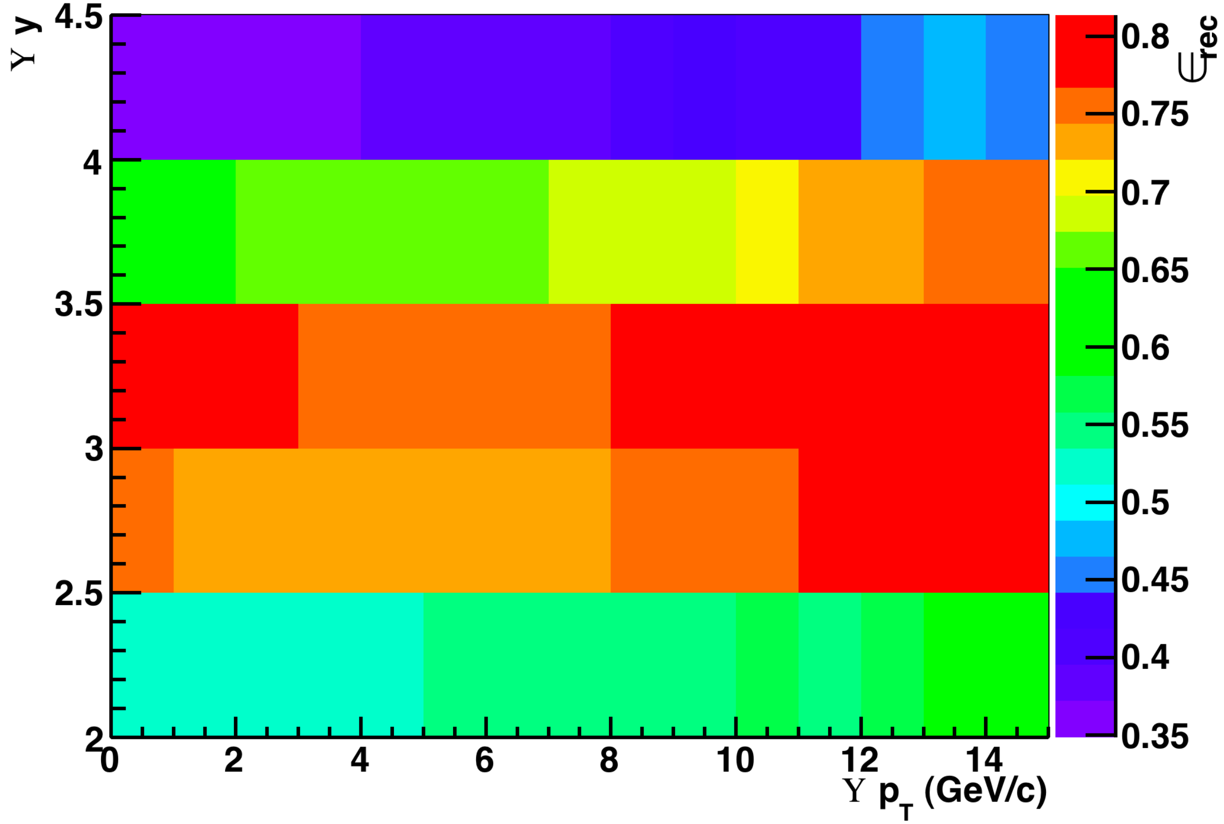
$$A = \text{acceptance of the LHCb geometry cut} = \frac{\text{Nevts gen with } \mu^+\mu^- \text{ in } 0<p_T<15, 2.0<y<4.5, 10<\theta<400\text{mrad}}{\text{Nevts generated with } \mu^+\mu^- \text{ in } 0<p_T<15, 2.0<y<4.5}$$



- Using gen-only samples without "DaughtersInLhcb" Cut (in the same way as for the J/ψ)
- More details on the method talk@J/ψ meeting on 26.05.2010 : http://indico.cern.ch/contributionDisplay.py?contribId=1&confId=95276

c) Reconstruction Efficiency

E_{rec} = efficiency for ϒ's to be detected, reconstructed and matched to MC $= \dfrac{\text{N ϒ's detected,reconstructed,matched MC in range}}{\text{N ϒ's generated in angular acceptance in range}}$



MC Matching efficiency and Tracking efficiency scale factor assumed 100% (as in Jpsi)