Quarkonium results from LHCb

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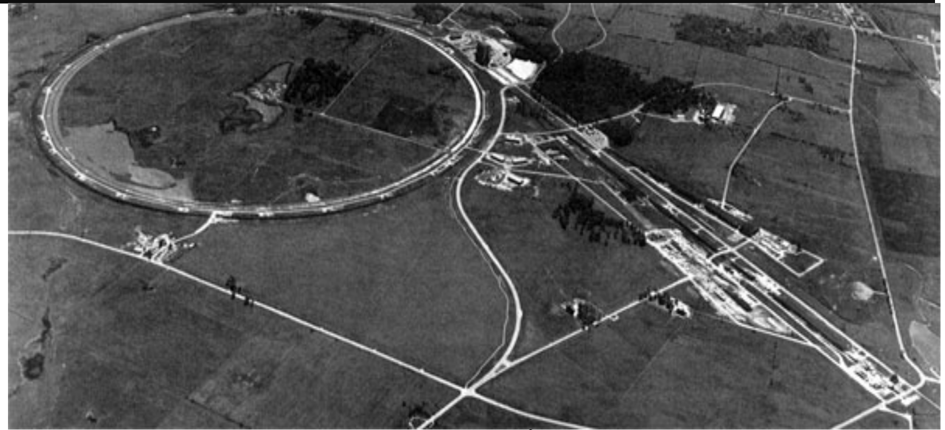
CPPM Seminar, 4th April 2011

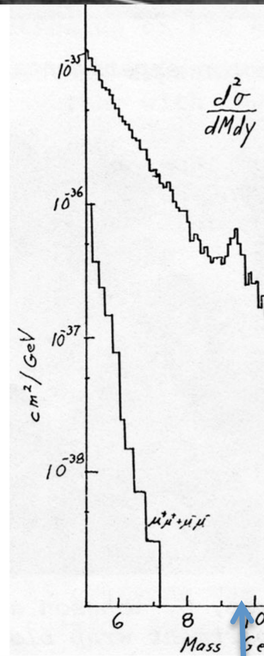
Outline

- ➡ 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 quarkonium 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 quarkonium central player for detector and software calibration





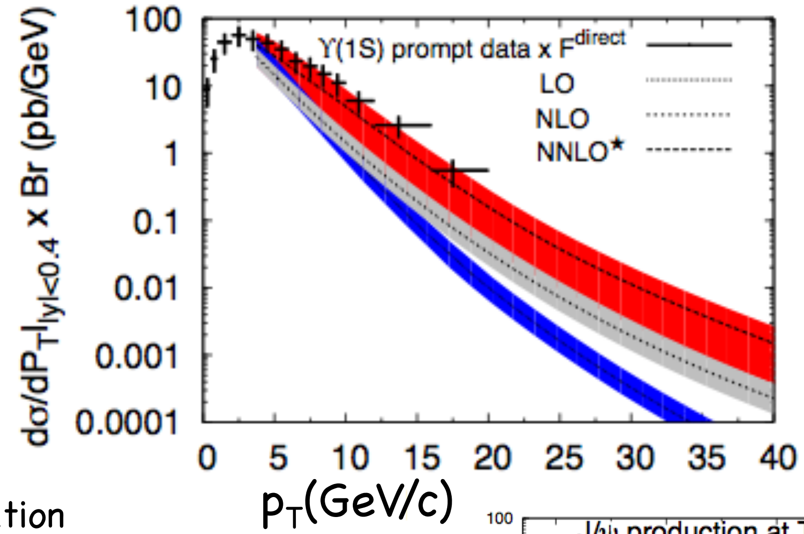
Fermilab, Summer 1977

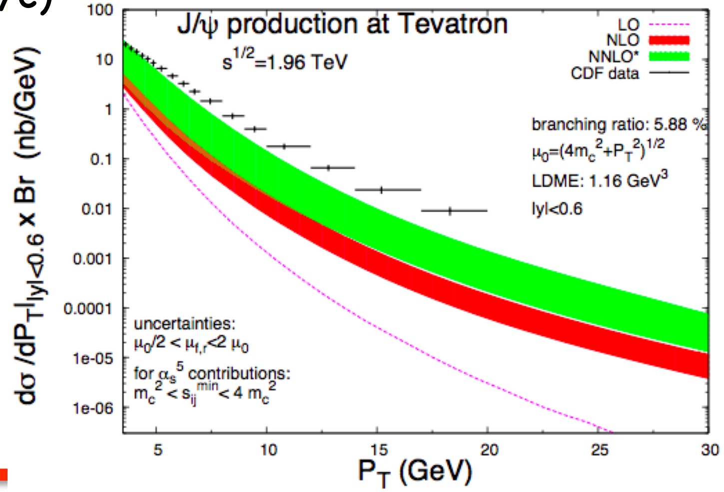
M=9.46 GeV/c^2

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

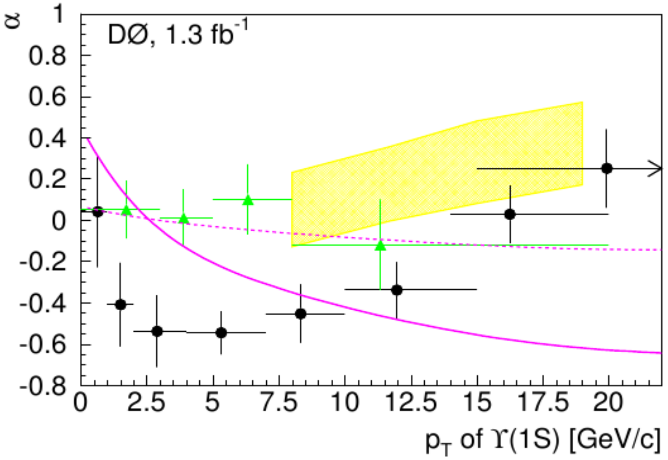




J/ψ & Υ cross section crucial milestone in understanding detector and first step to B cross section measurement

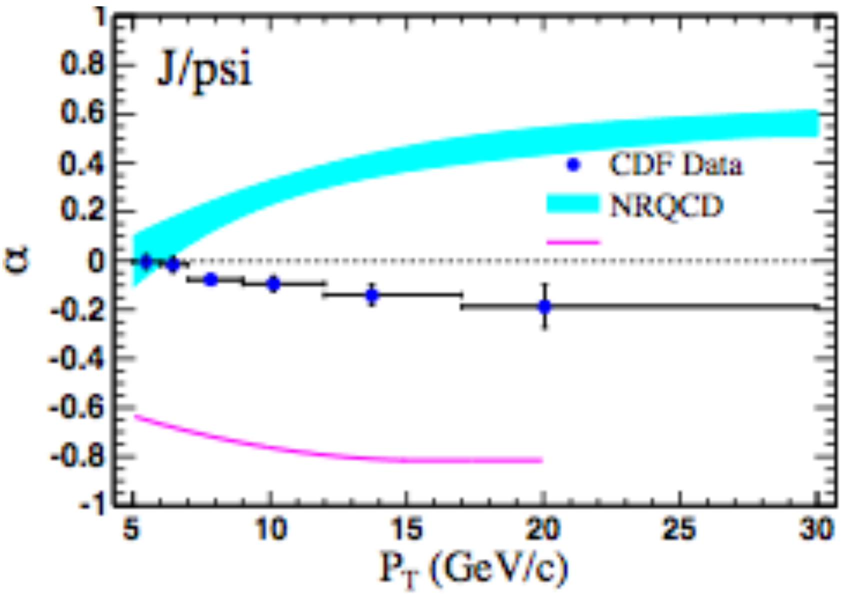
Polarisation measurement

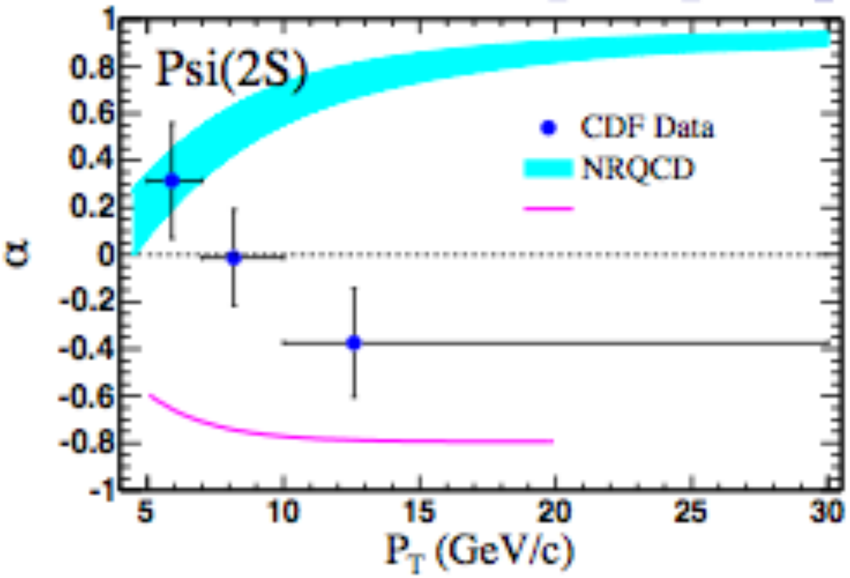
$\Upsilon(1S)$ Polarization:



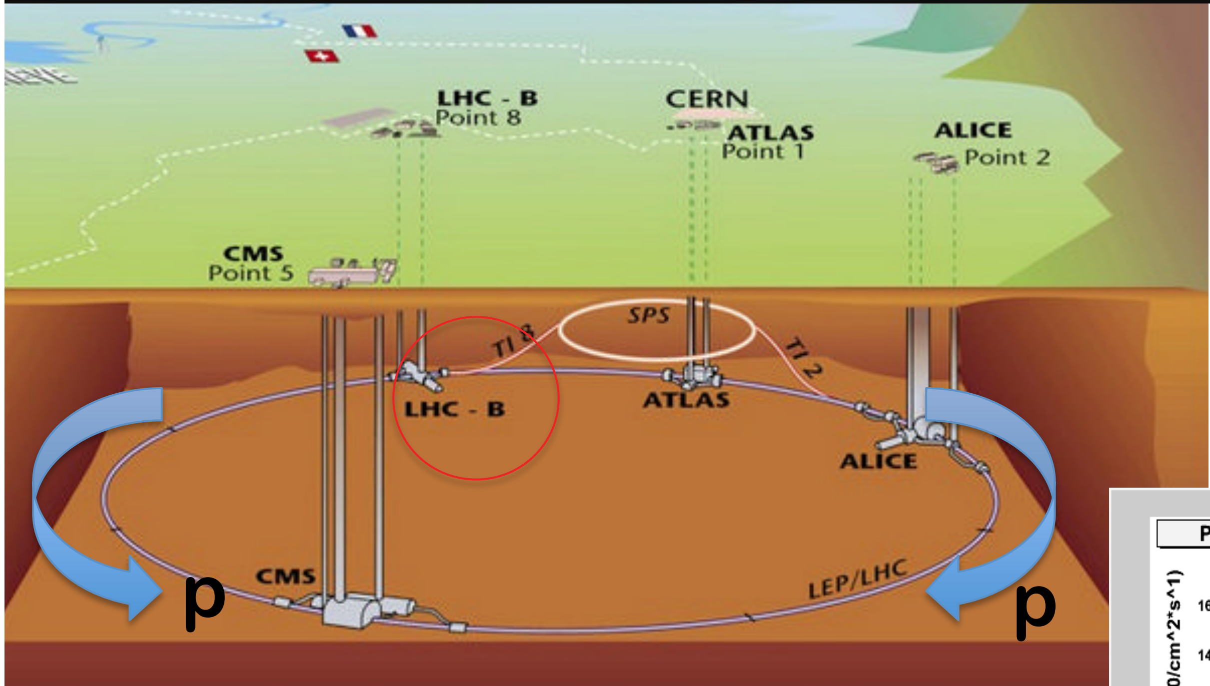
- In the Y(1S) case, the D0 results (black) are incompatible with the CDF results (green)
- The CDF results are compatible with the NRQCD predictions (yellow)
- The D0 results are marginally incompatible with NRQCD predictions
- The curves are the limiting case of the kT factorization predictions
- For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

CDF, PRL 99: 132001, 2007



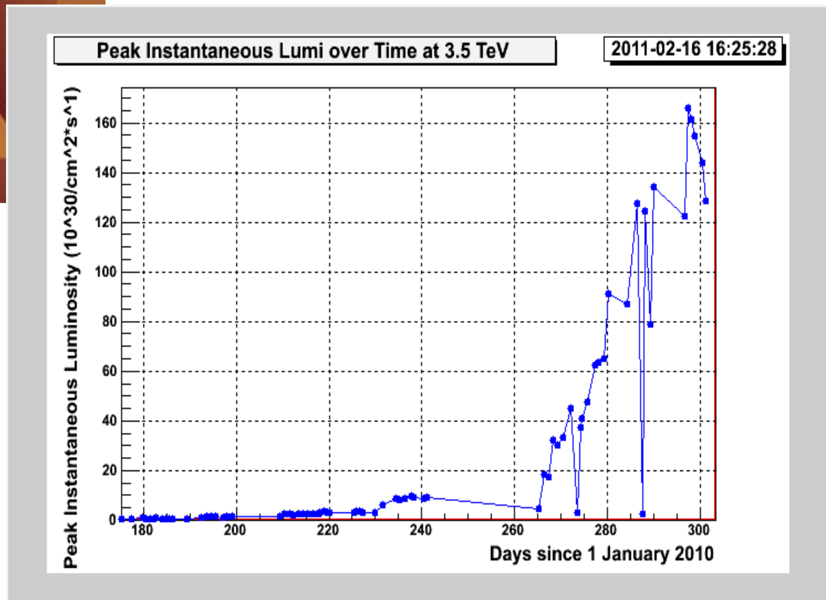


CERN and the LHC



pp collider : NOW :

- ➡ @ $\sqrt{s}$ = 7 TeV
- ➡ L ≈ 1-2·10^{32} cm^{-2} s^{-1}

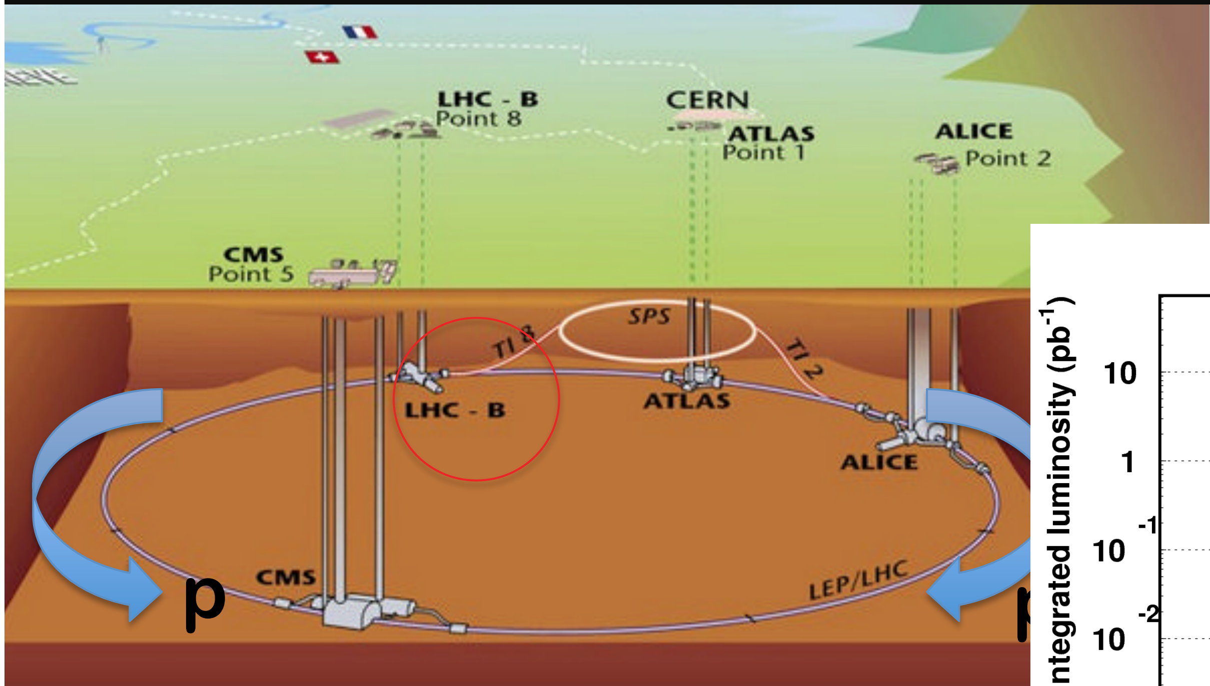


NOMINAL (2011) :

$\sqrt{s}$ =14 TeV

L = 2·10^{32} cm^{-2} s^{-1} (LHCb specific)

CERN and the LHC



pp collider : NOW :

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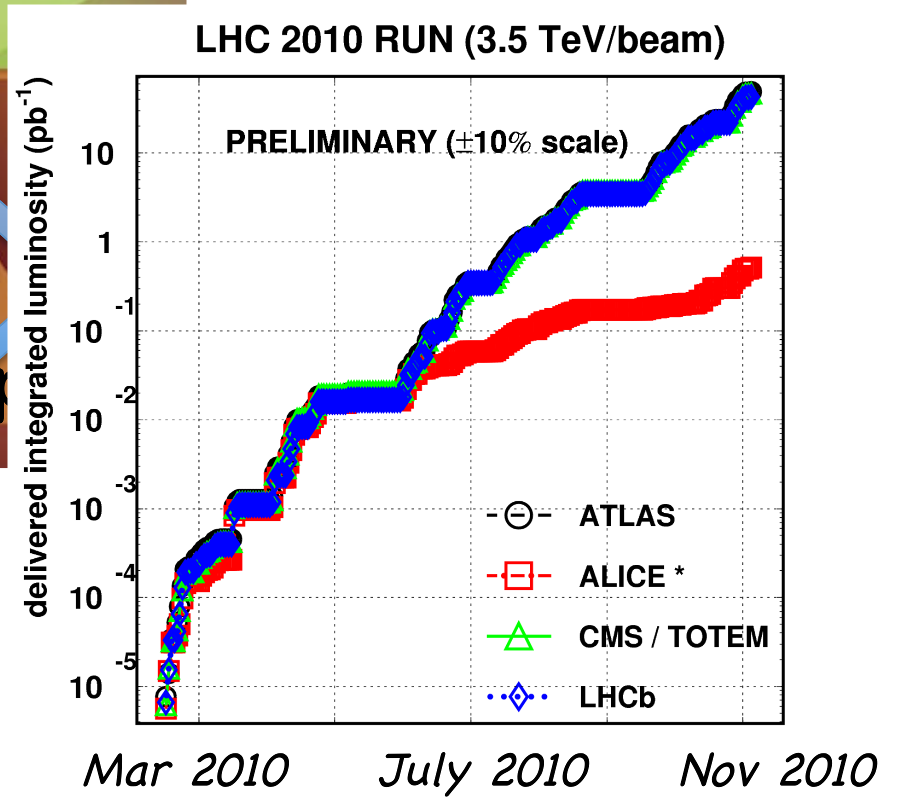

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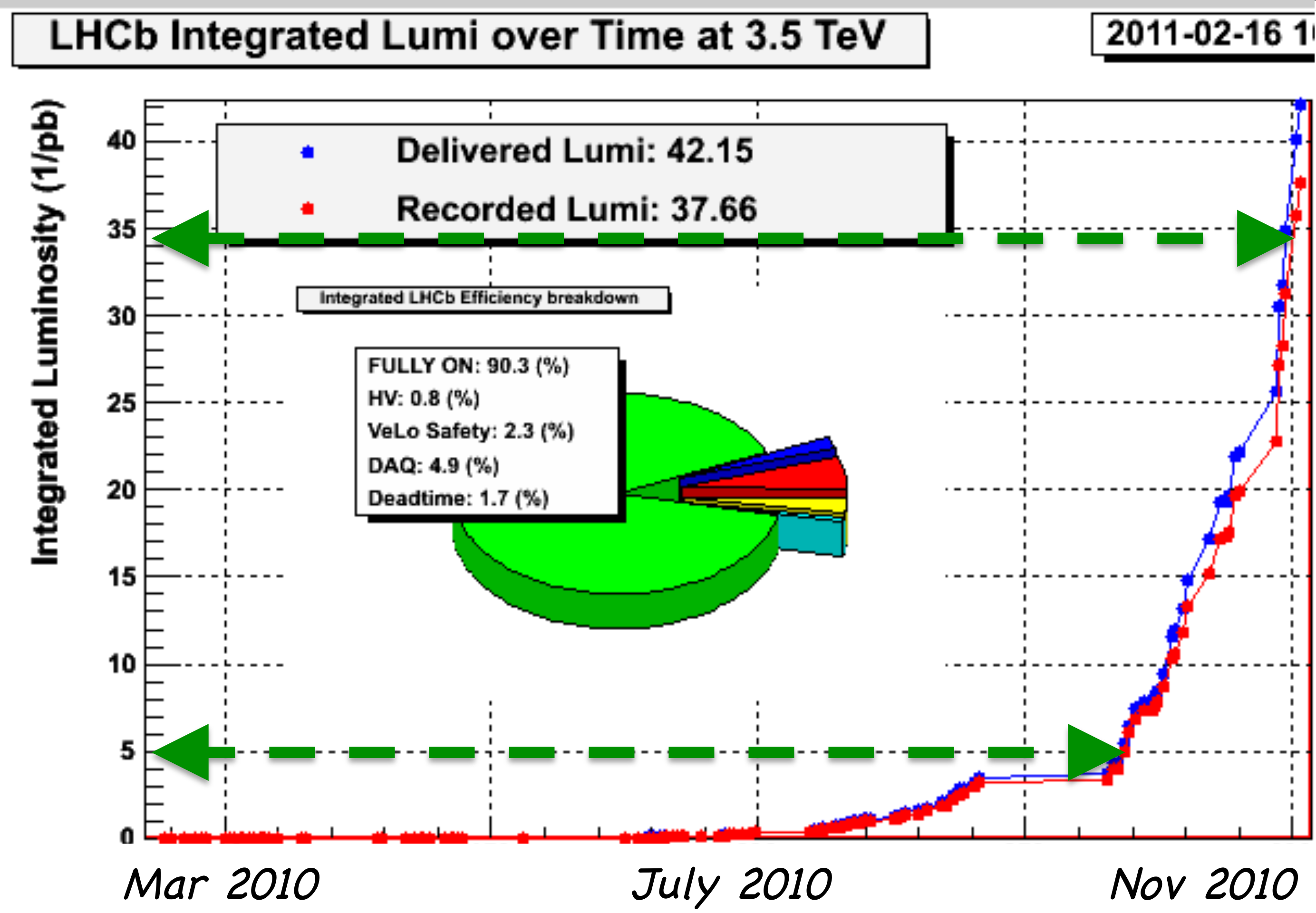
Luminosity @ LHCb



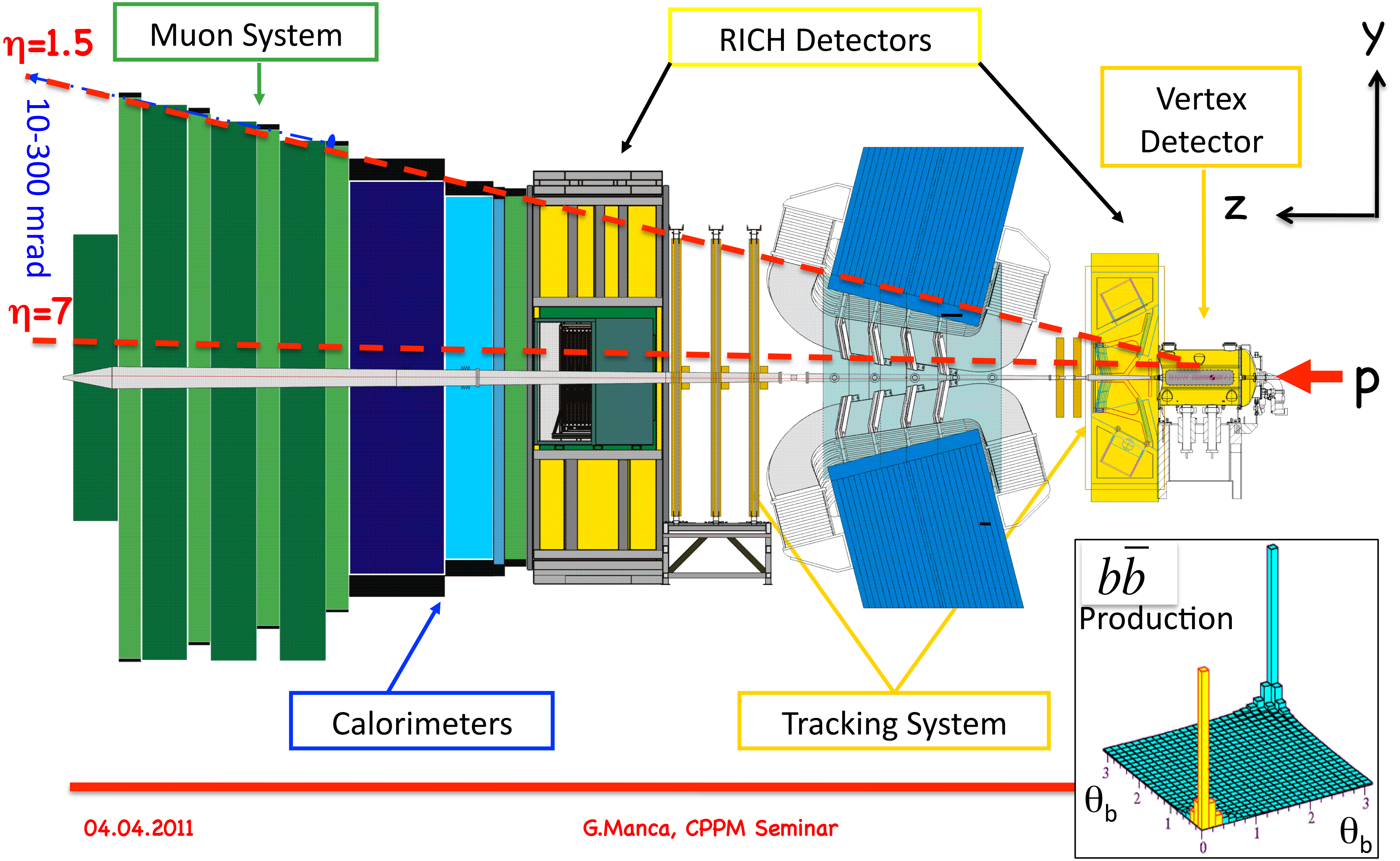
- LHC running very well!
- LHCb efficiency ≈90%
- These analyses :

  L ≈ 5-35 pb^{-1} (±10%)

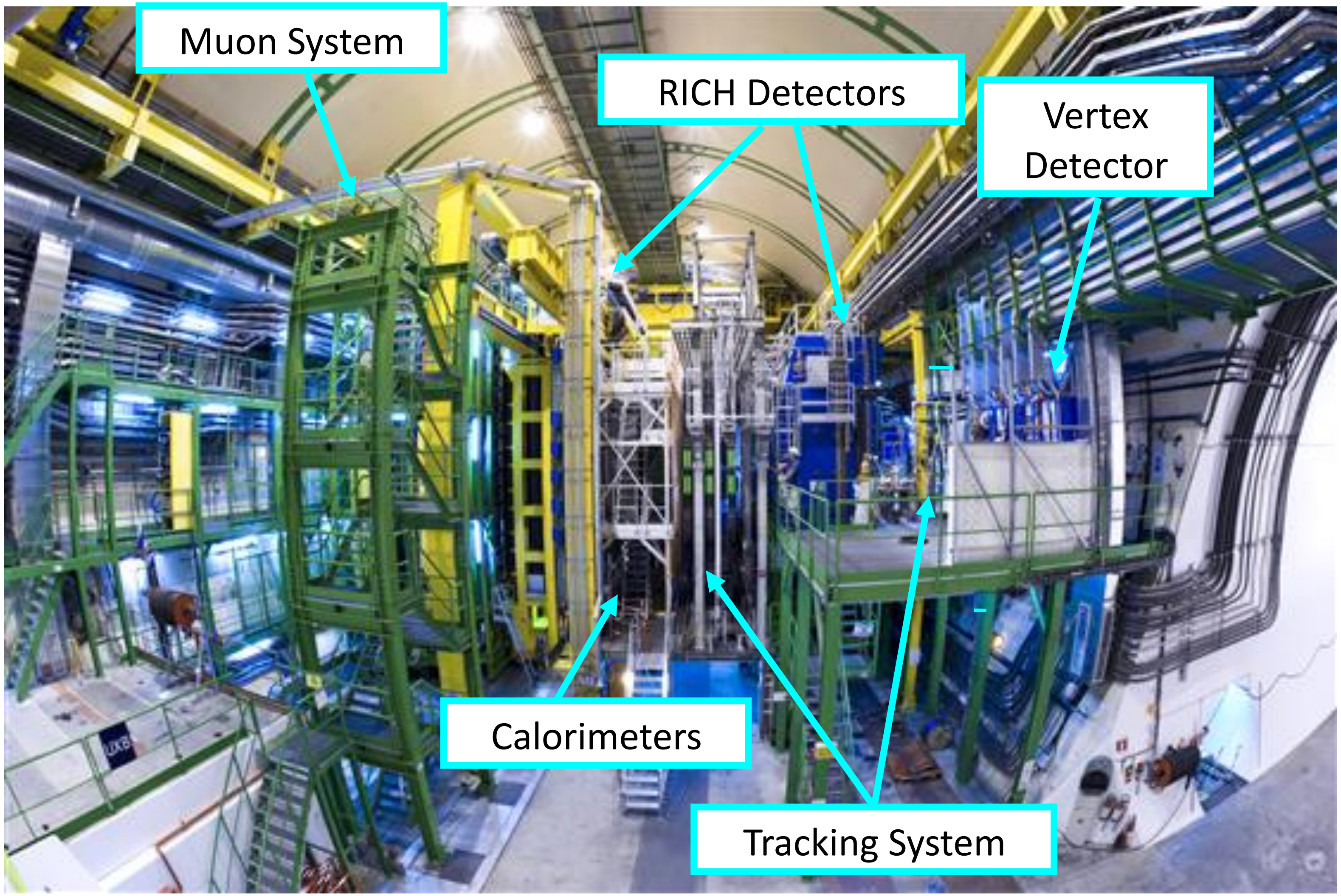
Goal :

- 1 fb^{-1} (end of 2011)

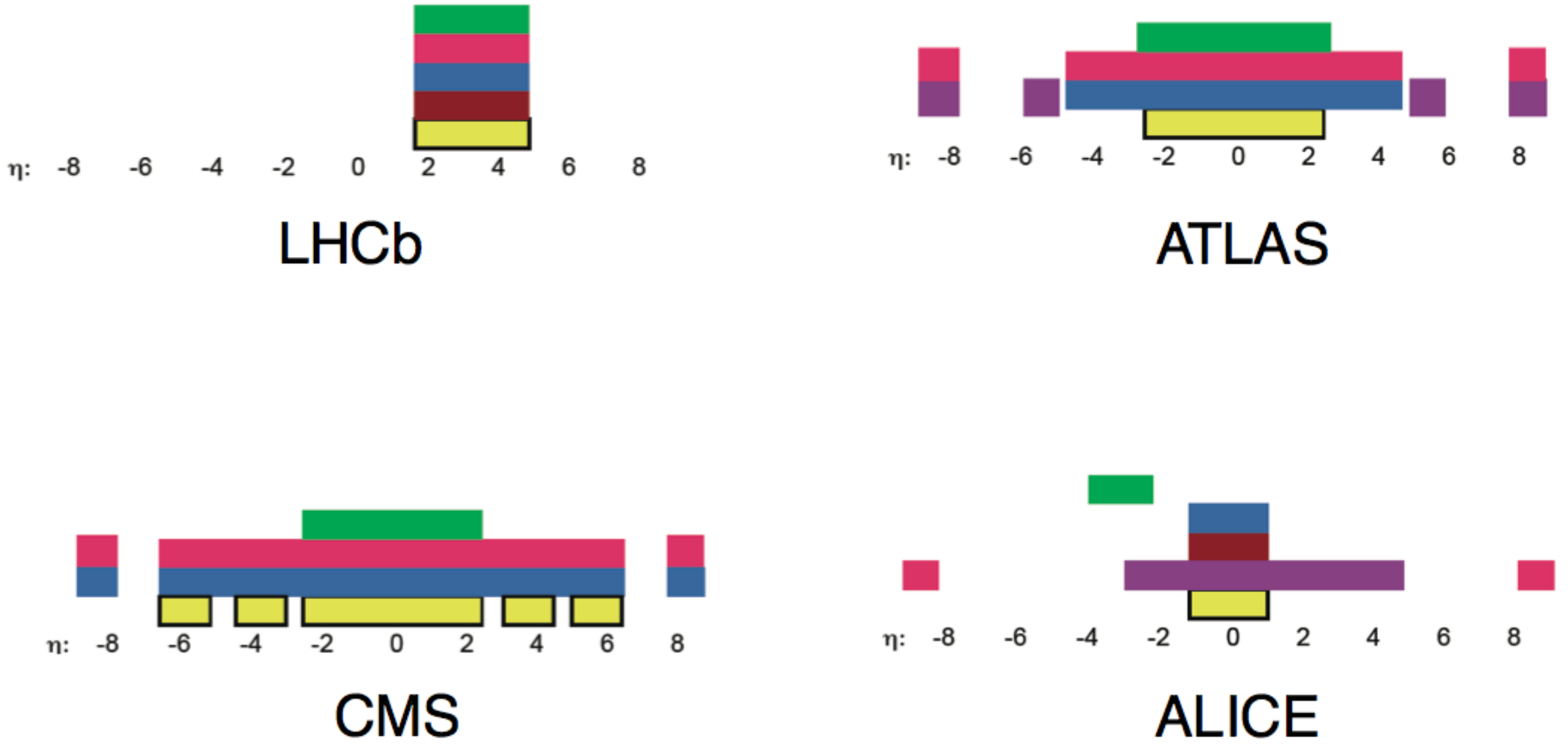
The LHCb detector



The LHCb detector



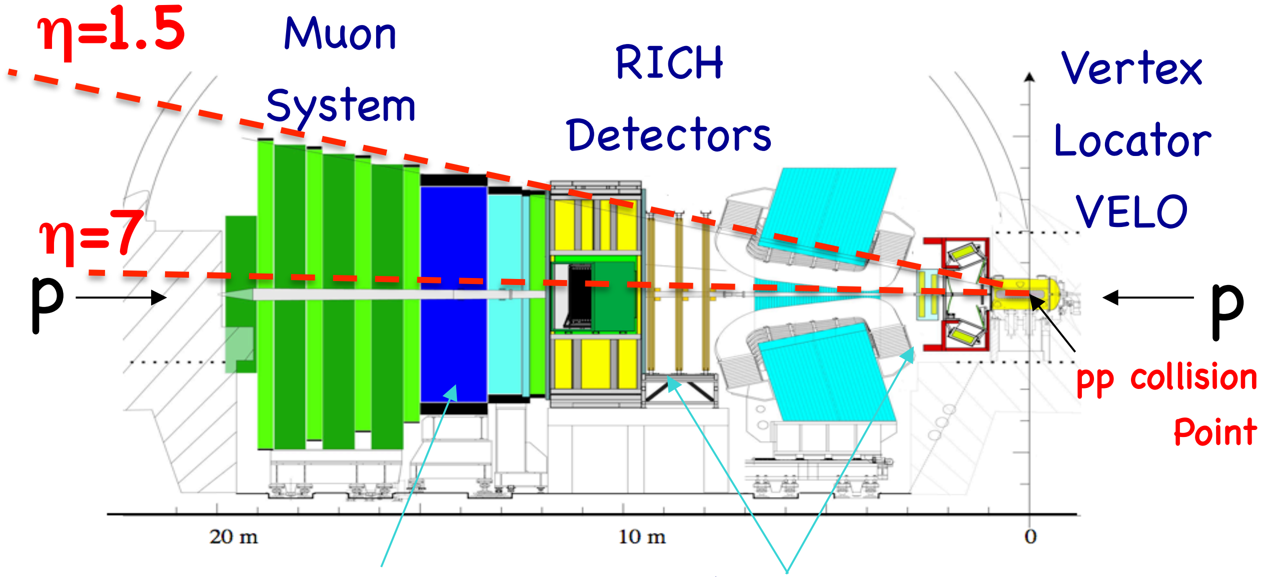
Rapidity Range



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

The LHCb detector

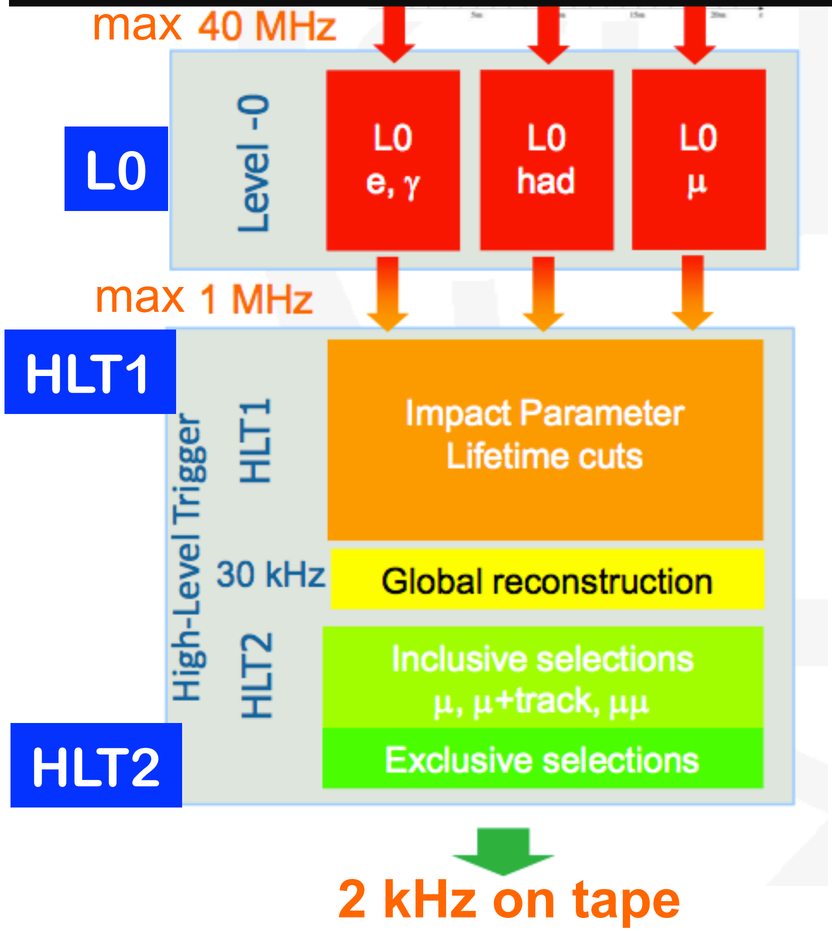
Angular acceptance :
10<θ<300 mrad



Trigger : three levels, dominantly software

possibility to reverse field polarity to check for detector asymmetries

LHCb Trigger



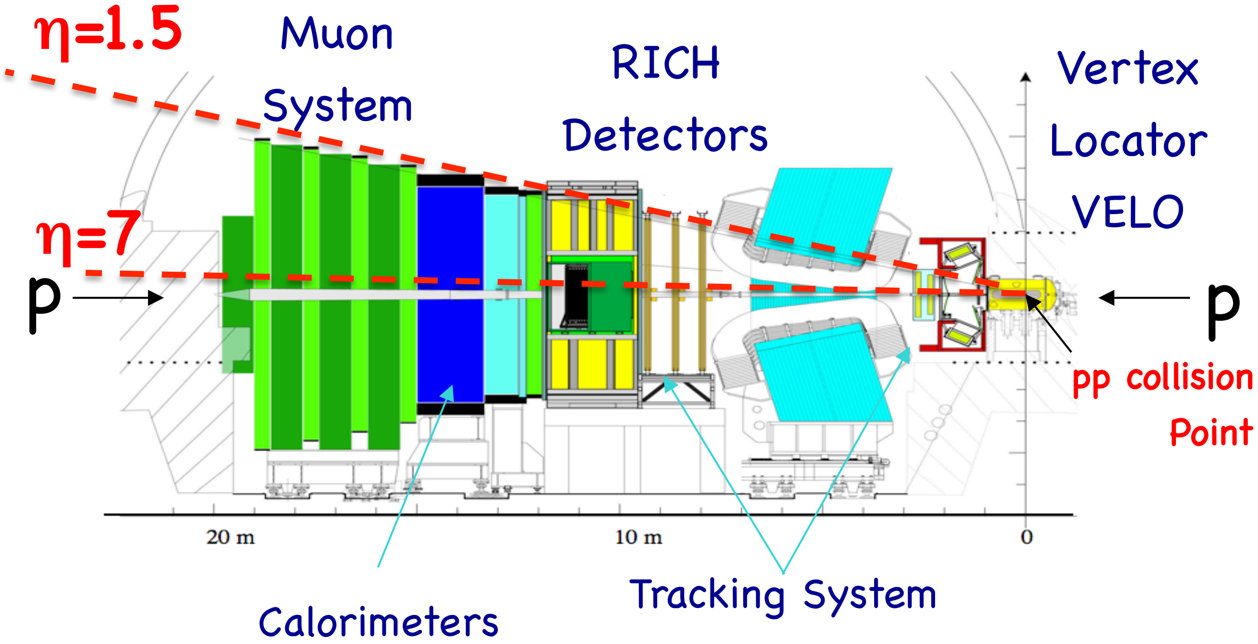
	Muon Lines
L0	Single- μ: **p_T> 1.4 GeV/c** μμ: **p_{T1}>0.48 GeV/c** **p_{T2}>0.56 GeV/c**
HLT1	single-μ: p_T>1.8 GeV/c, di-μ: $M_{\mu\mu}$>2.5 GeV/c^2
HLT2	Several dimuon lines with p_T or $M_{\mu\mu}$ cuts

+ Global Event Cuts for events with high multiplicity

- Half of the bandwidth (~1 kHz) 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 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

possibility to reverse field polarity to check for detector asymmetries

The LHCb detector

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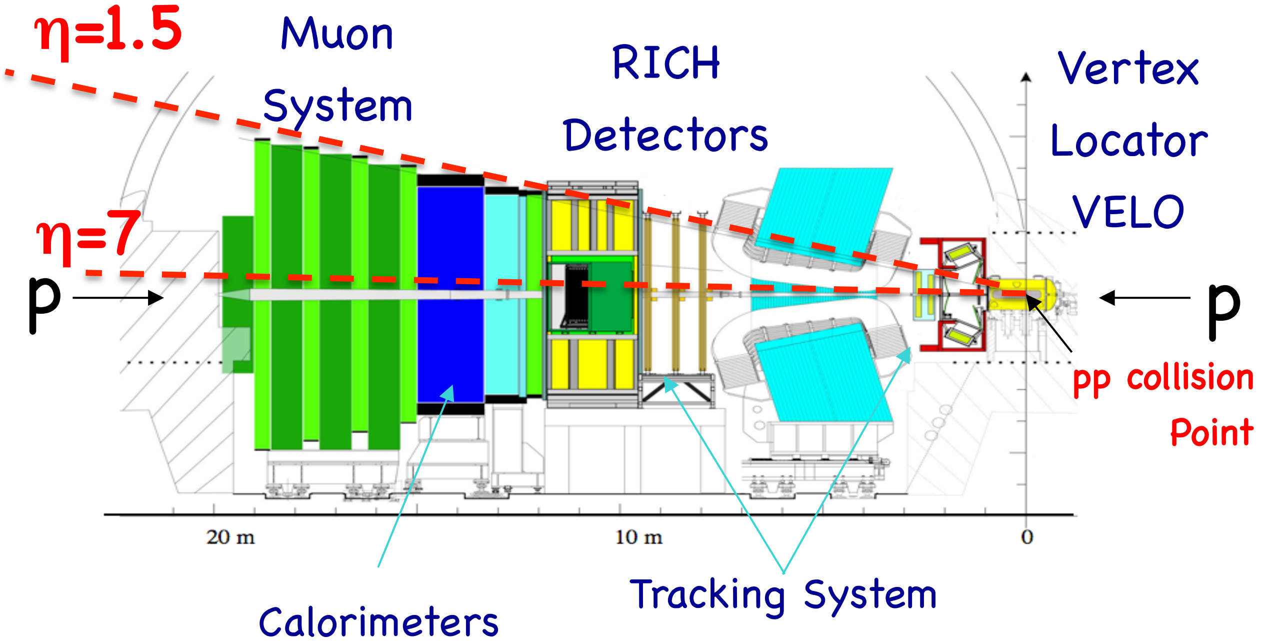

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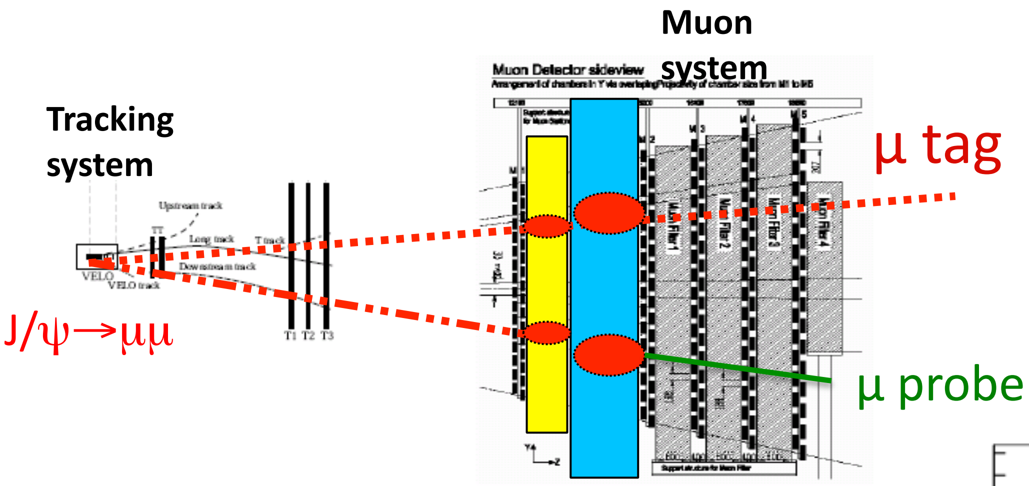
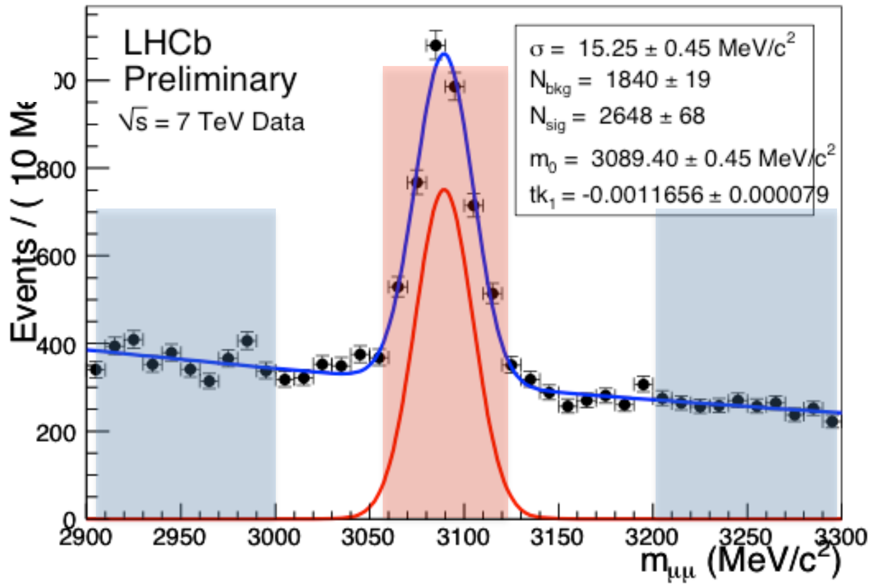
Muon Detector Performance



Tag: IsMuon,pt>1.5GeV,p>6GeV
Probe: MIP cuts, 1 hit M2

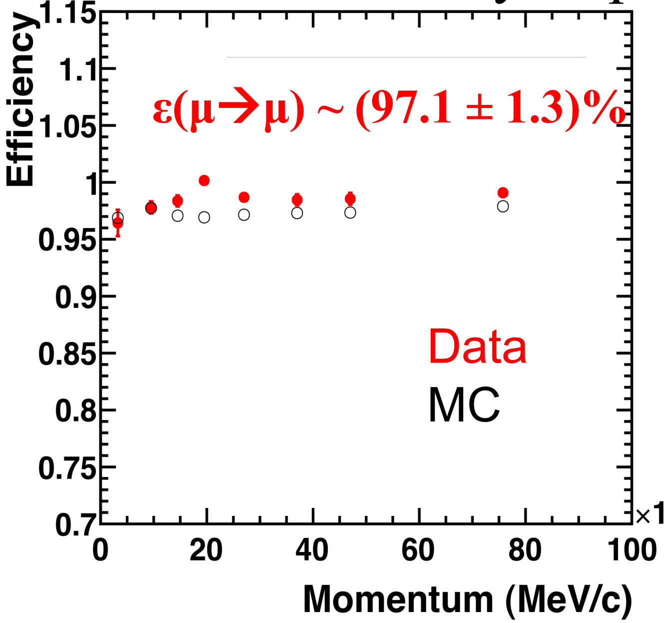
→ε(μ) = 97.1 ± 1.3 %



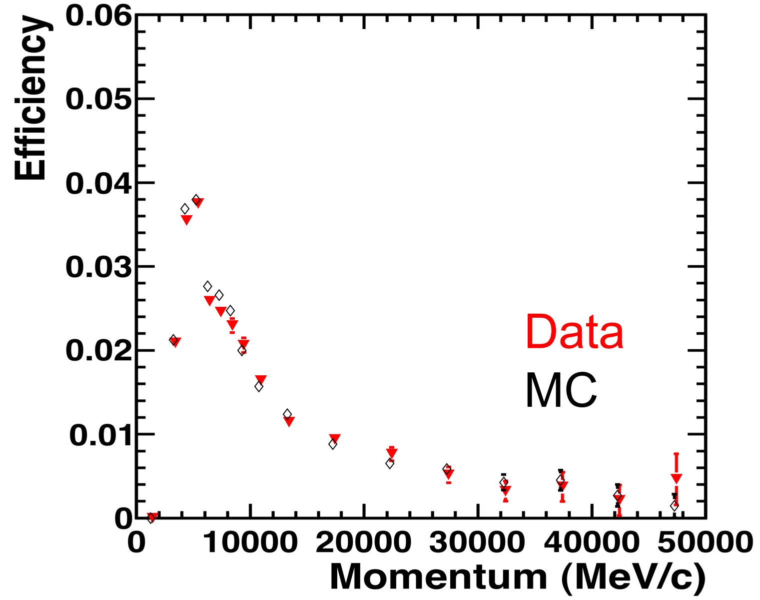
Muon Identification

Performance measured with pure samples of $J/\psi \rightarrow \mu\mu$, $K_s \rightarrow \pi\pi$, $\varphi \rightarrow KK$, $\Lambda \rightarrow p\,\pi$

MuonID efficiency vs p



π →μ misidentification rate vs p



Cross Section Measurement Strategy

For a generic resonance A:

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

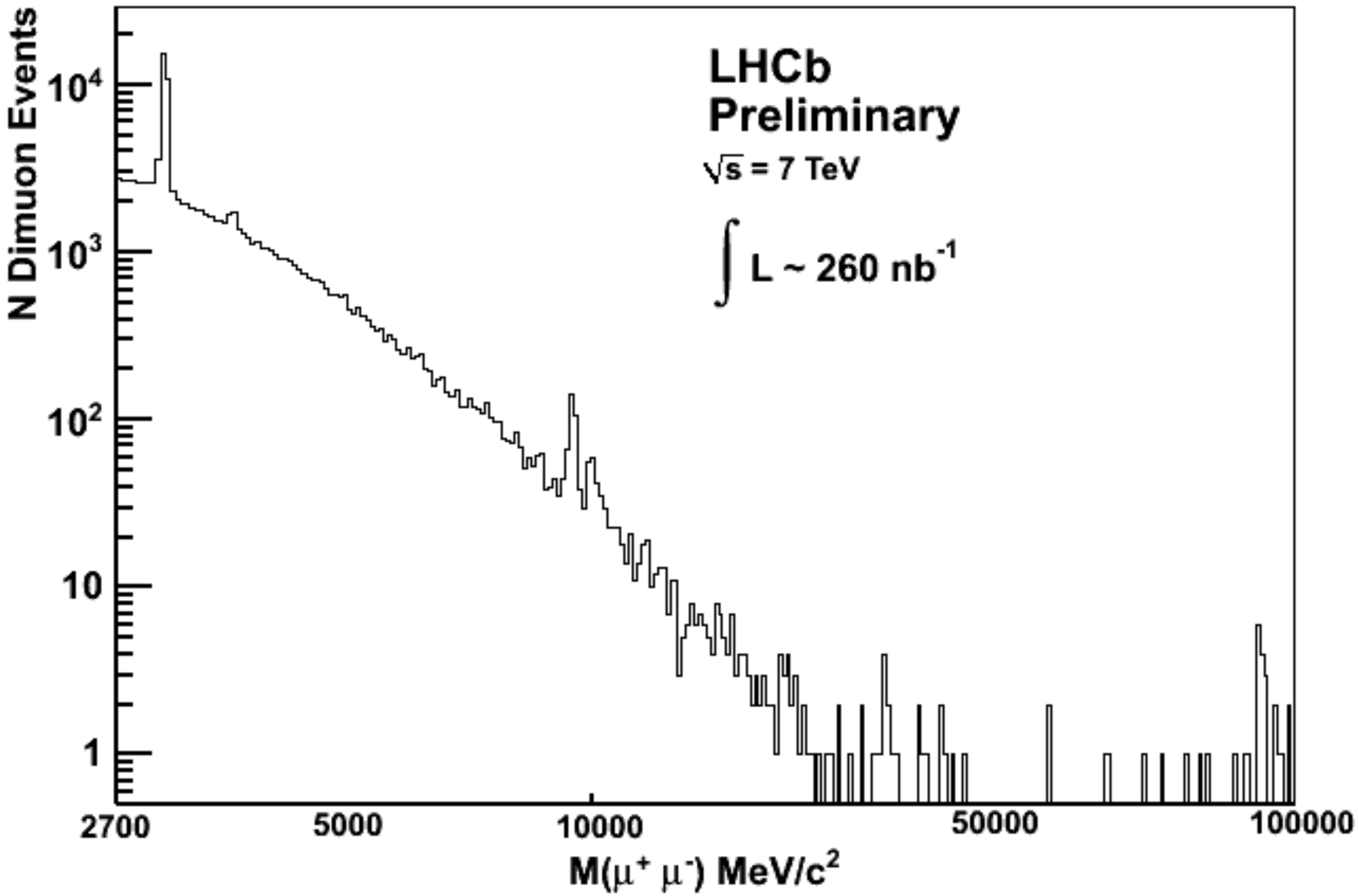
a) N^{fit} = number of events in the mass peak in each p_T bin, corrected for acceptance and efficiency

b)
c) } ε_{tot} = total efficiency
d)

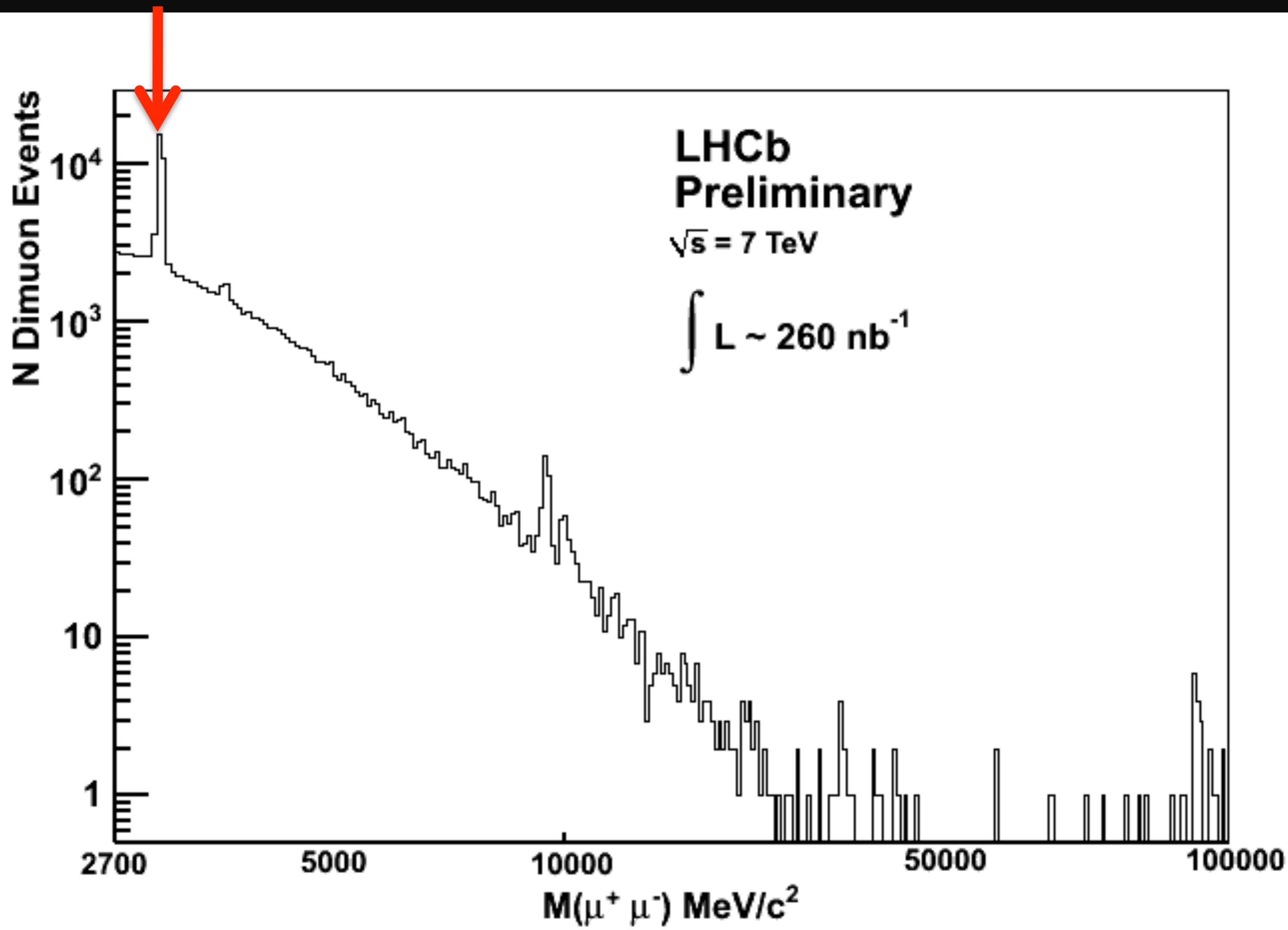
e) Δpt, Δy = bins of p_T and y

f) $\int Ldt$ = integrated luminosity

Dimuon Resonances

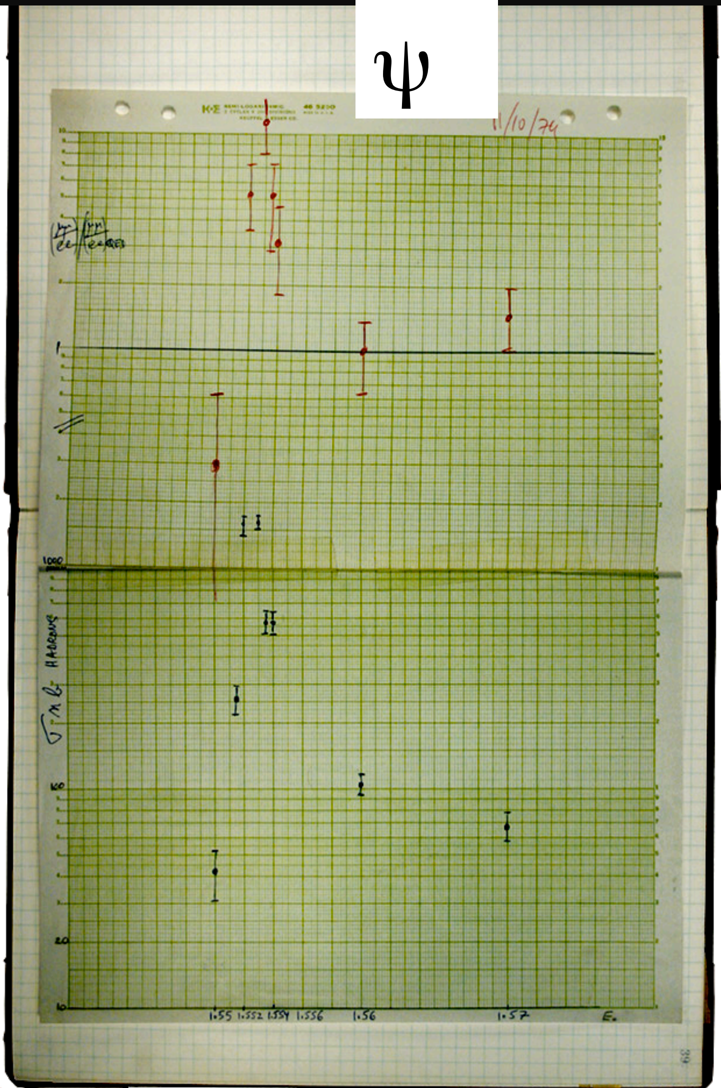


Dimuon Resonances



J/ψ Production

ψ



J

PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

one with approximate-
d with a lead convert-
n planes ($2\times A_0$, $3\times A$,
chambers rotated ap-
:t to each other to re-
To further reduce the
ambers at high rate,
izontal hodoscope
chambers A and B.
C (1 m×1 m) there
iss counters of 3 ra-
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ther reject hadrons
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s $\Delta\theta=\pm 1°$, $\Delta\varphi=\pm 2°$,
trometer enables us
n from 1 to 5 GeV in

e-of-flight spectrum
in the mass region
peak of 1.5-nsec width
us to reject the acci-
nstruction between the
in we have a clear-

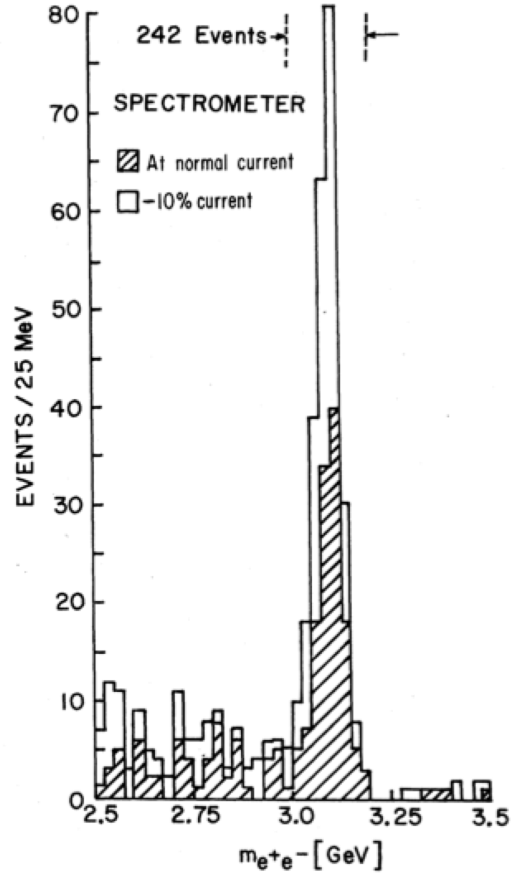
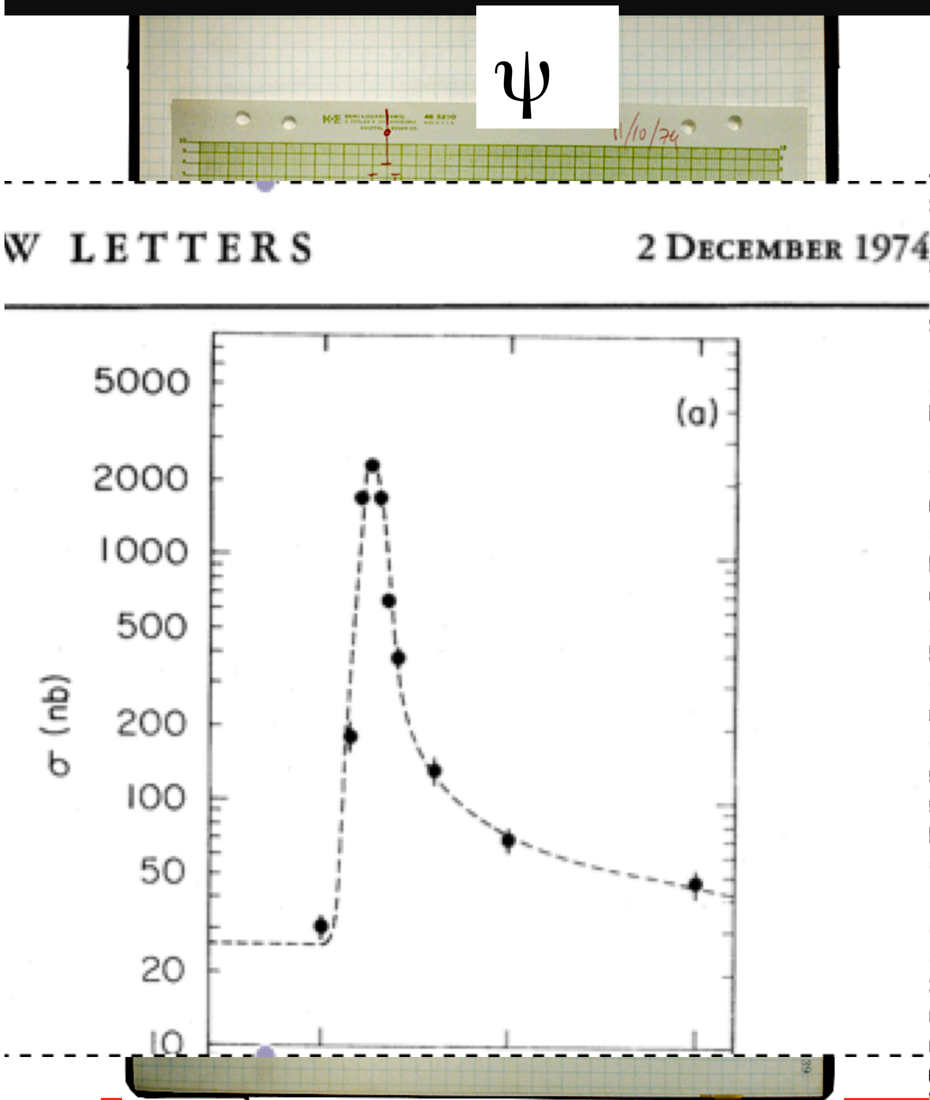


FIG. 2. Mass spectrum showing the existence of J.

J/ψ Production



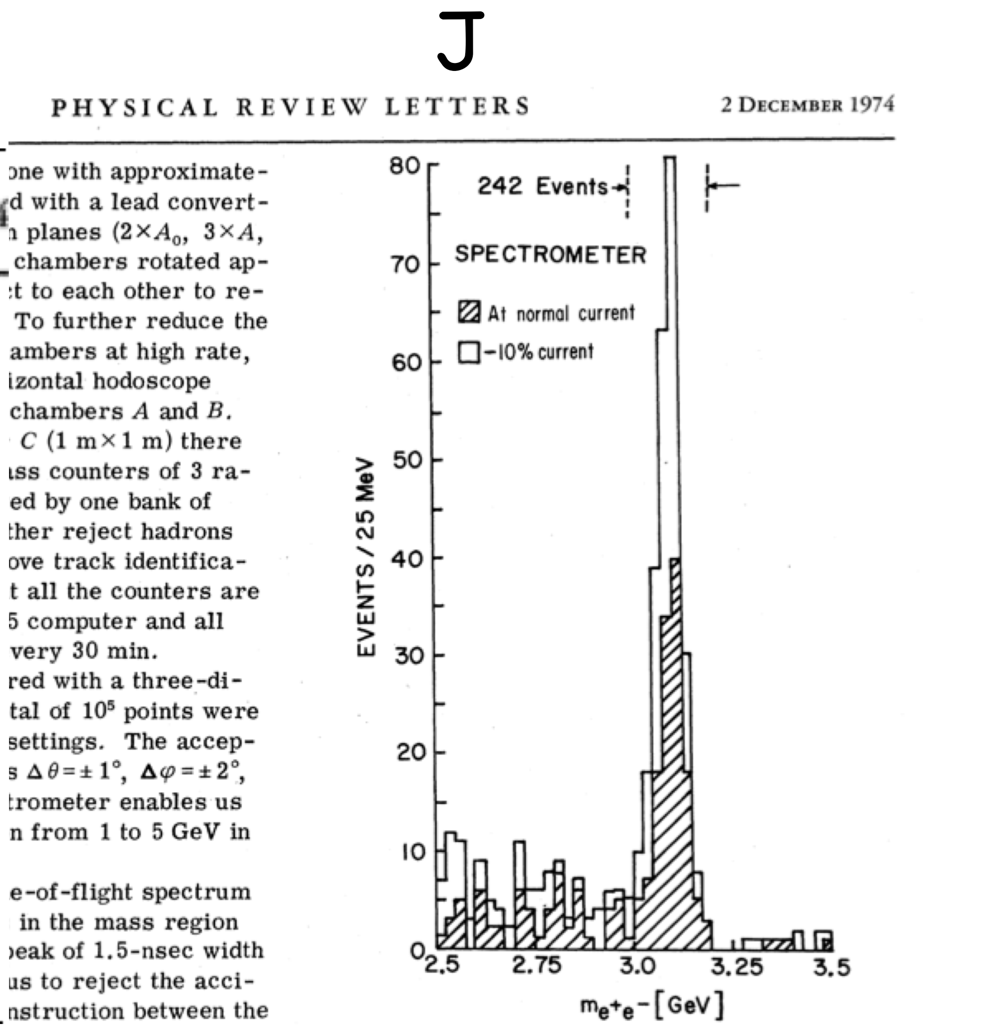
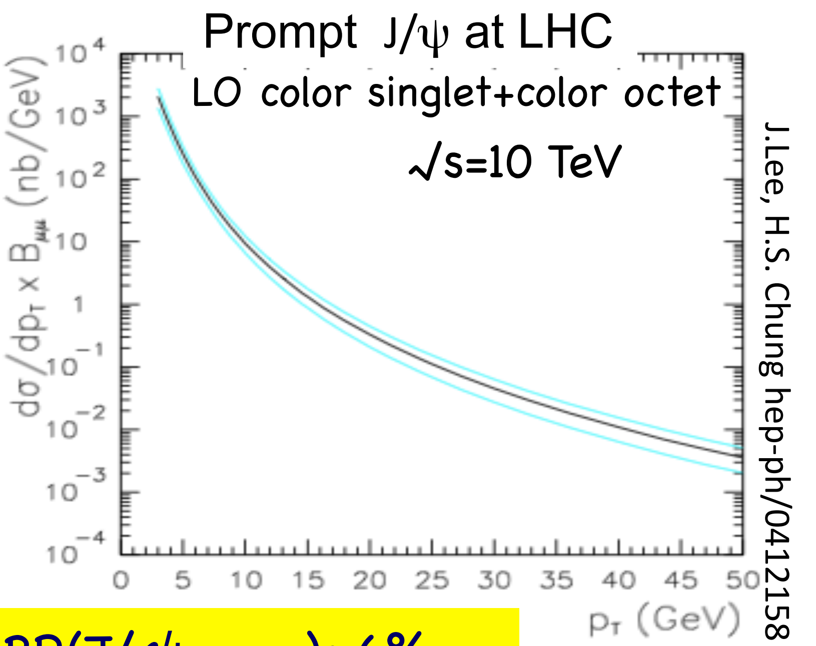


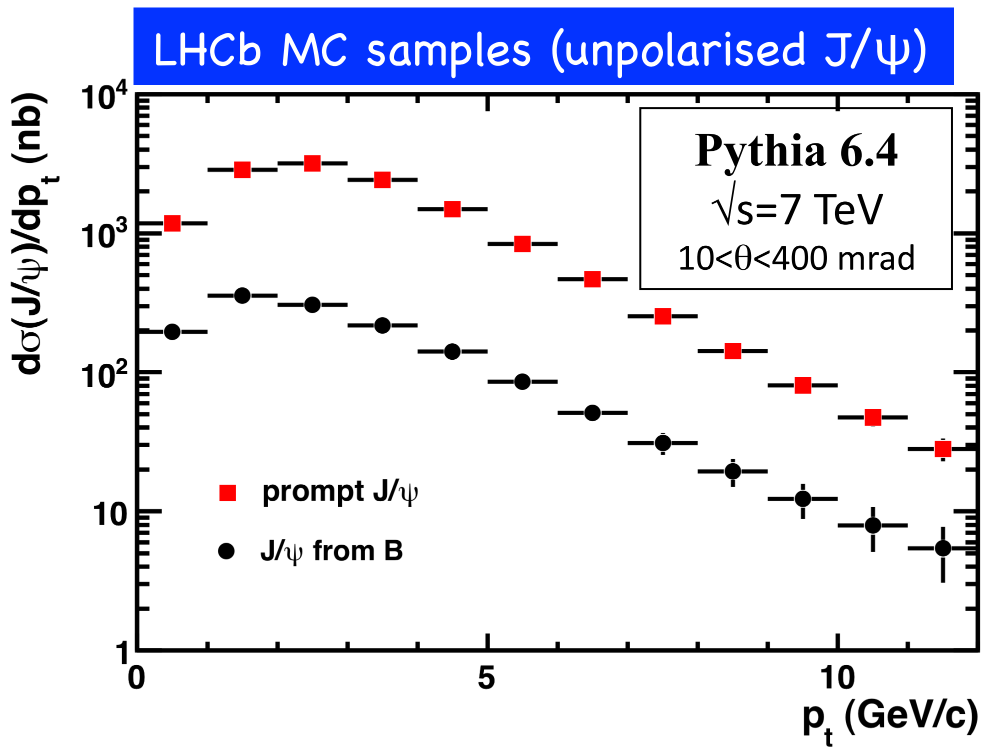
FIG. 2. Mass spectrum showing the existence of J.

J/ψ Production at pp

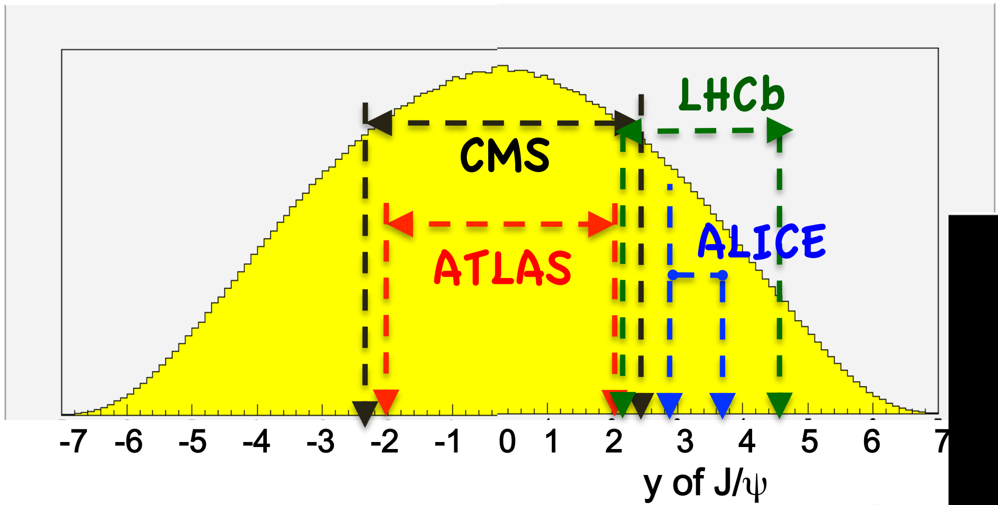
1st step	2nd step	3rd step	Production type
$pp \to c\bar{c}, b\bar{b} + X$	$c\bar{c} \to J/\psi + X$		Prompt,direct
	$c\bar{c} \to \chi_{c1}, \chi_{c2} + X$	$\chi_c \to J/\psi + \gamma$	Prompt,indirect
	$b\bar{b} \to B + X$	$B \to J/\psi + X$	Delayed,indirect



BR(J/ $\psi \to \mu\mu$)≈6%

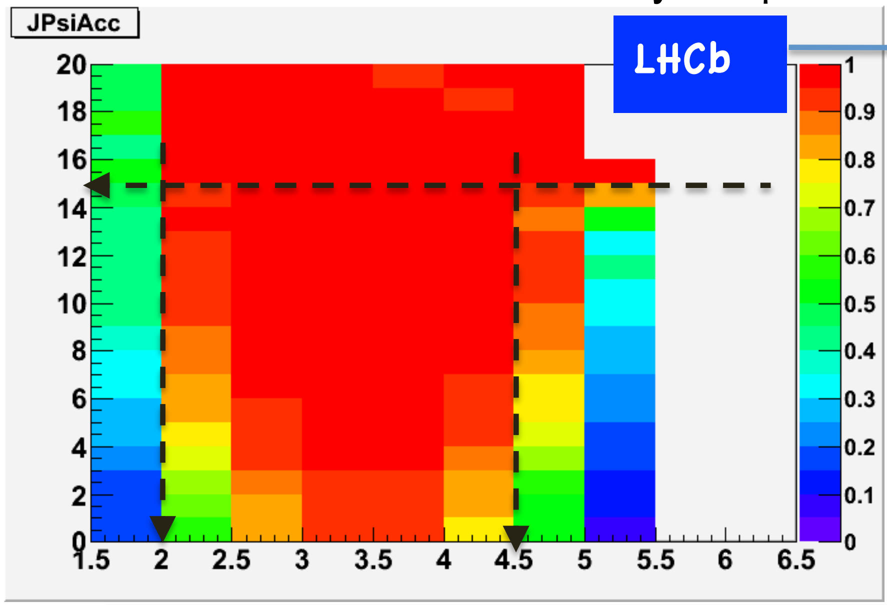


J/ψ→μμ Acceptance

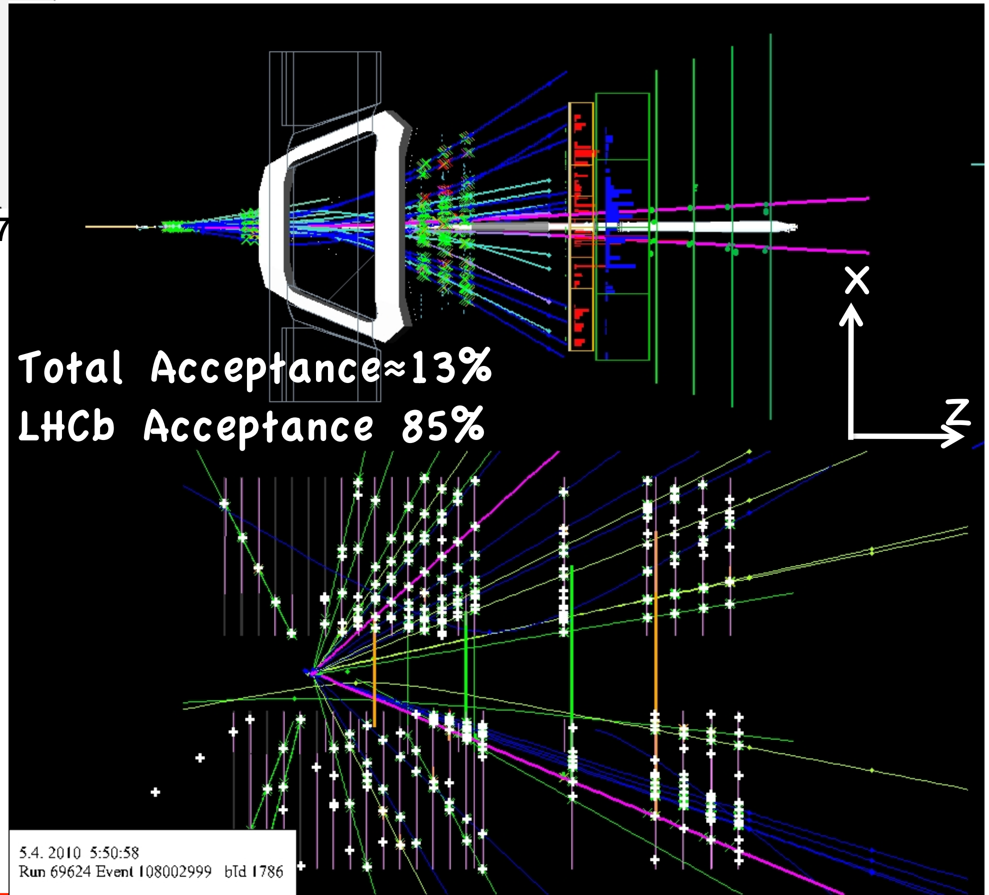


CMS → Total Acceptance≈20%
CMS 85%

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



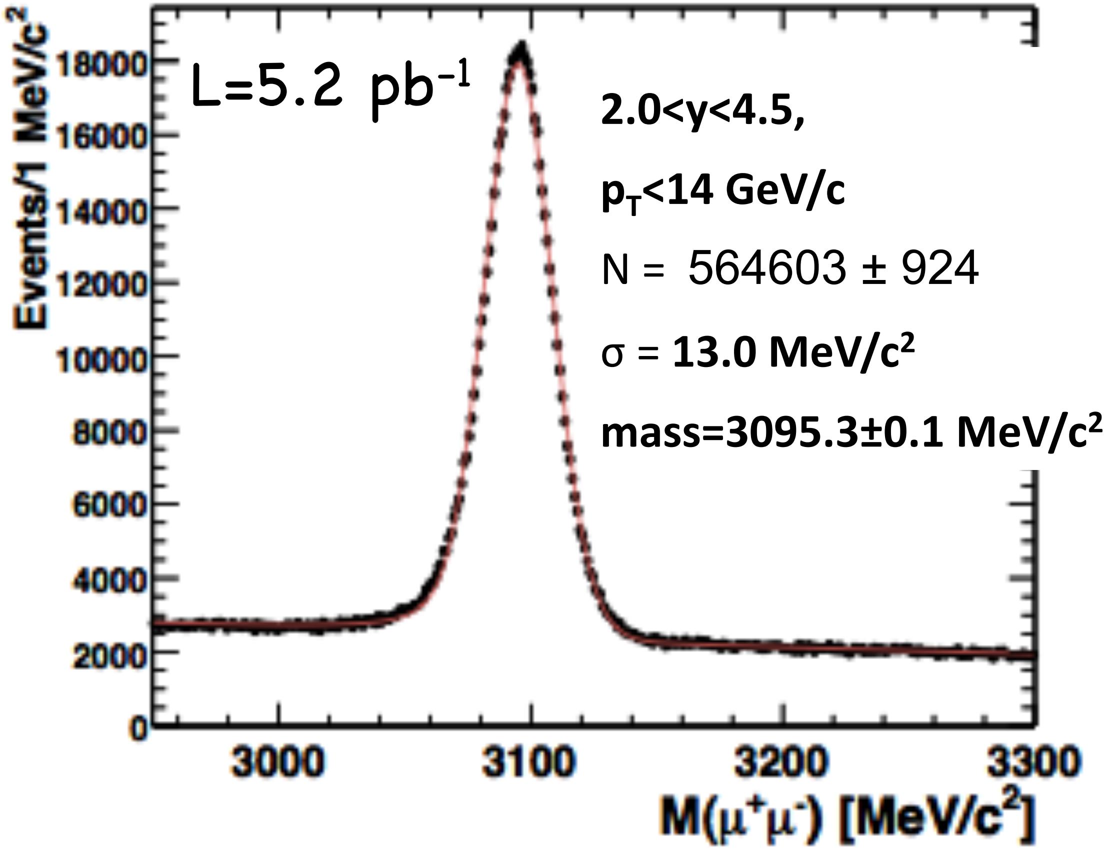
LHCb →

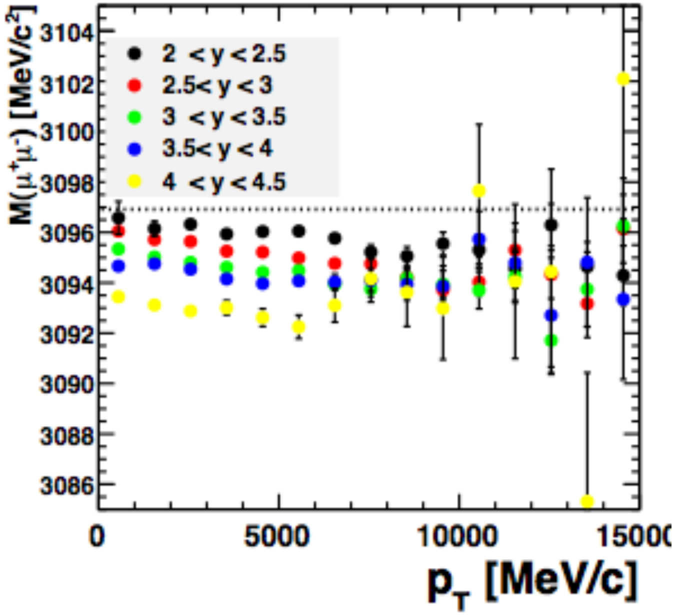


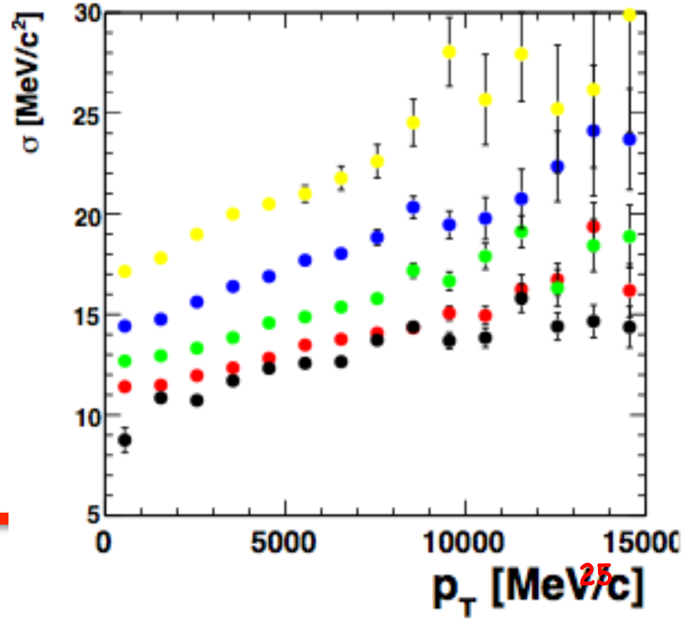
Total Acceptance≈13%
LHCb Acceptance 85%

J/ψ→μμ mass distribution

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

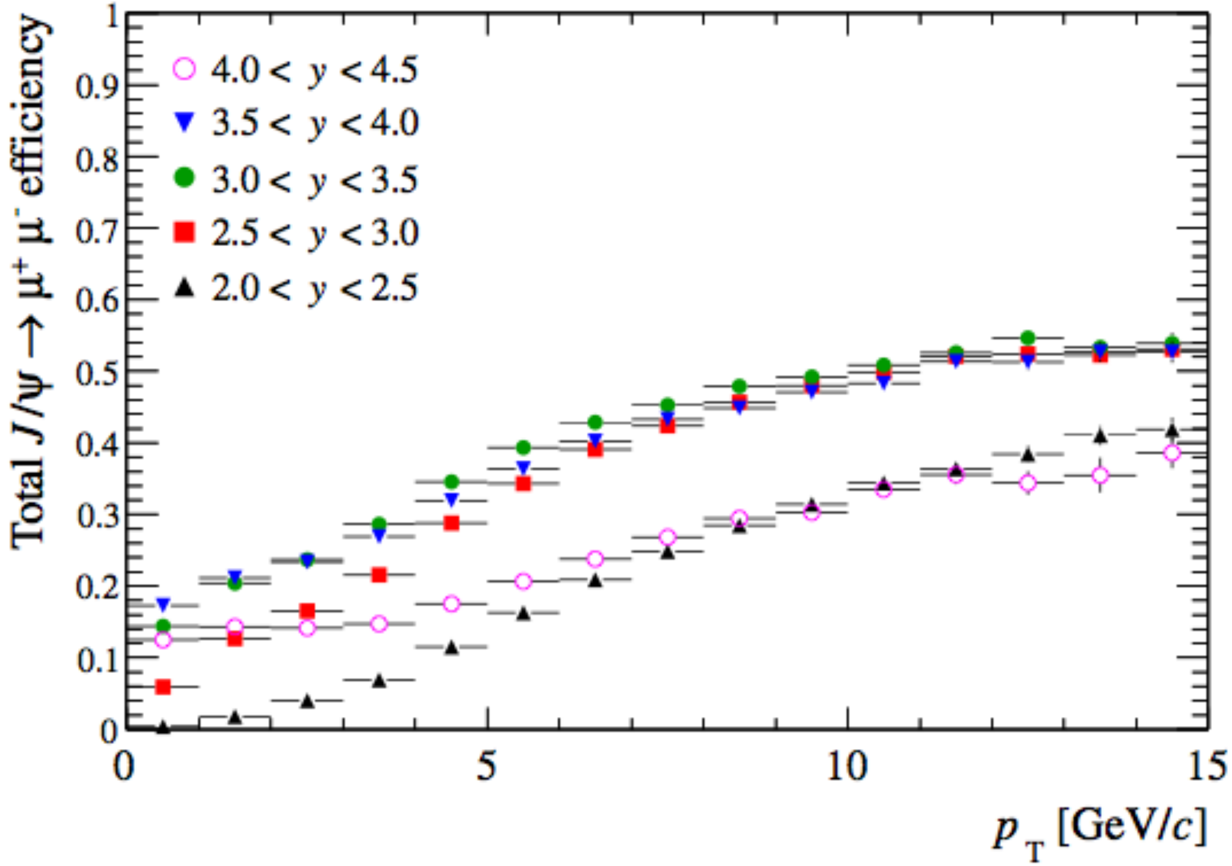




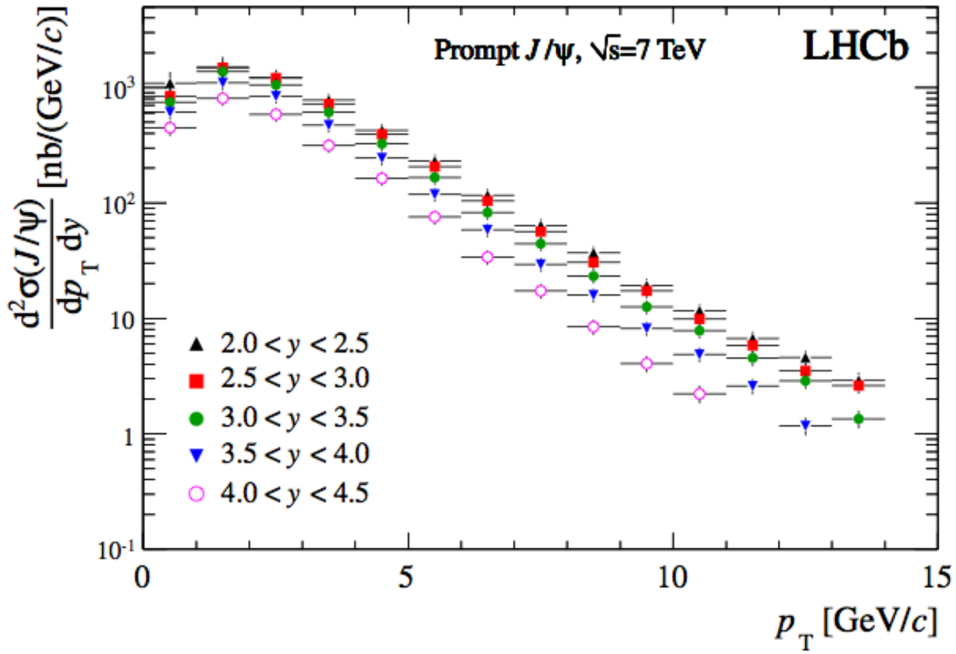


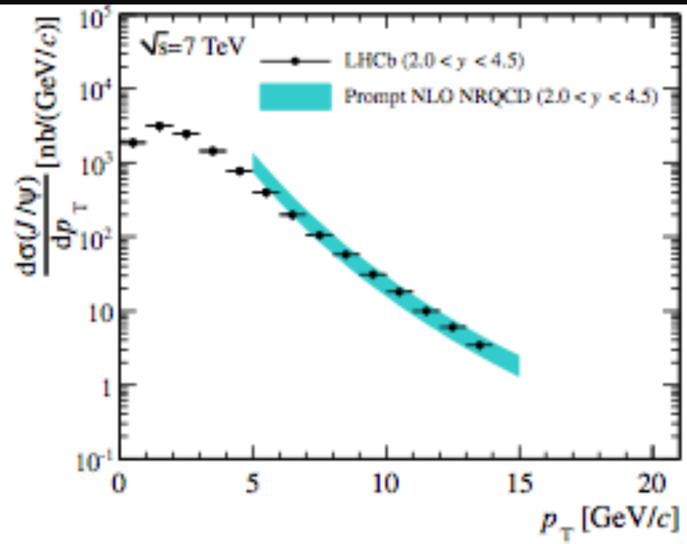
J/ψ Efficiency

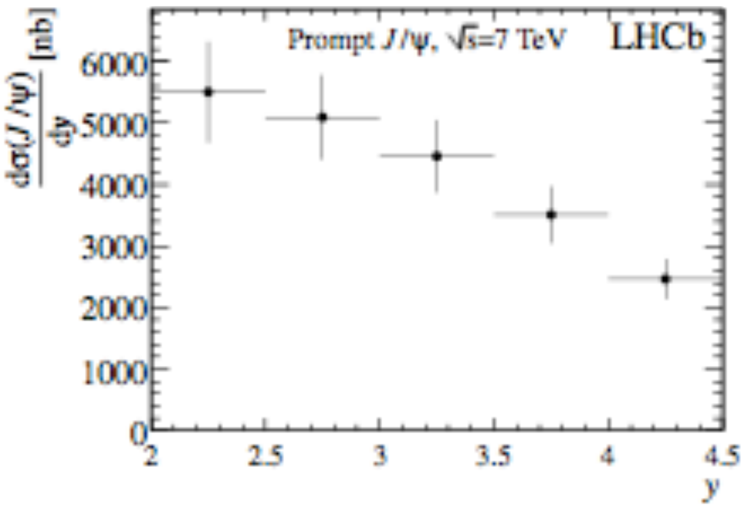
➡ Total efficiency, includes geometric acceptance, trigger and reconstruction and identification



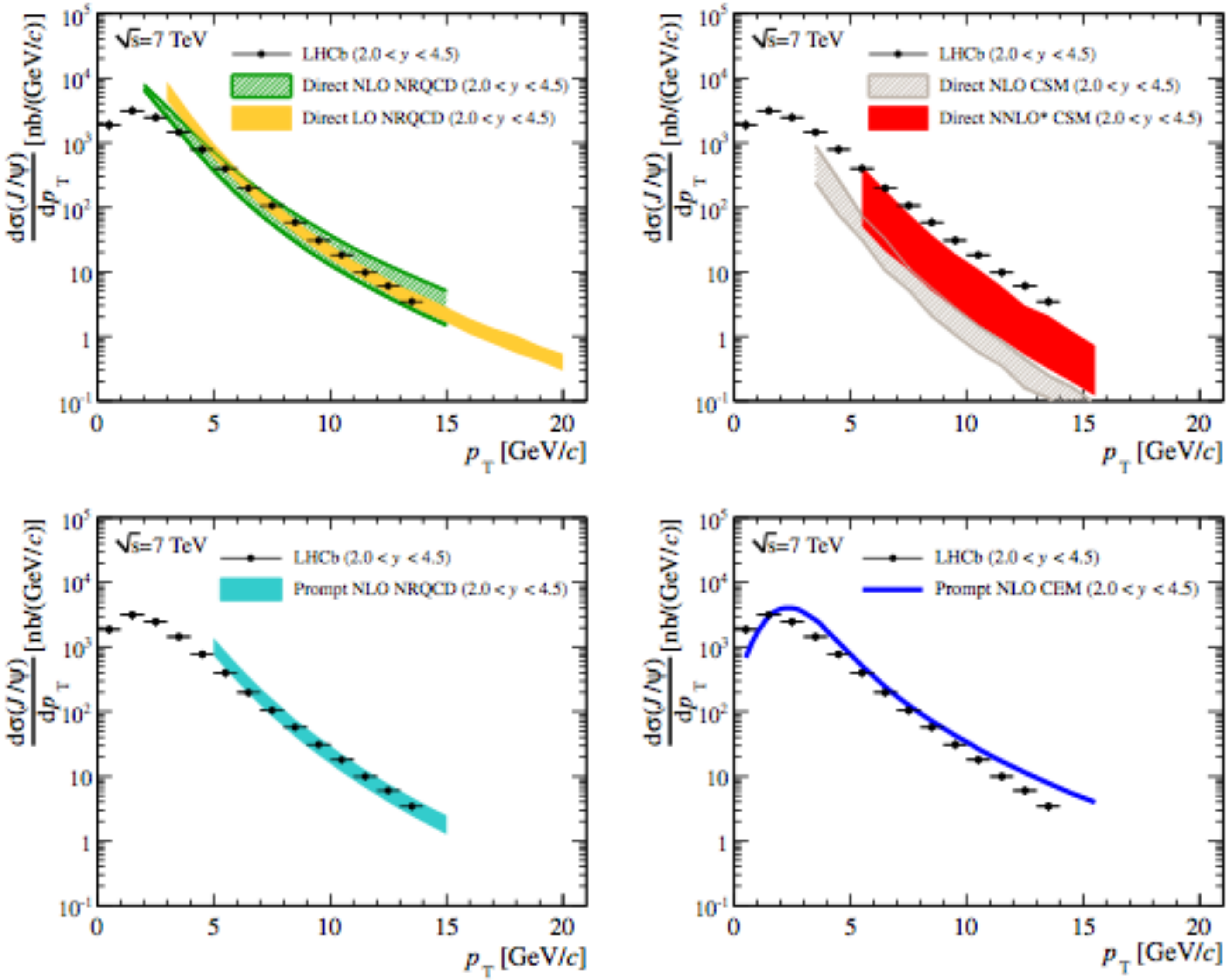
Prompt cross section measurement





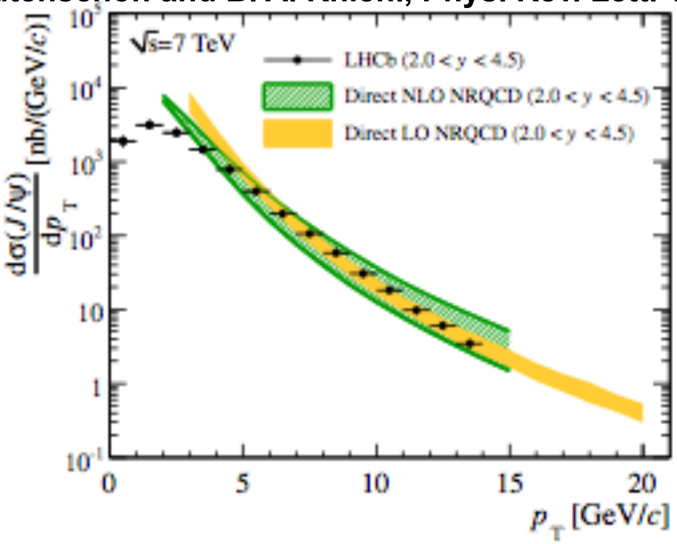


Comparison with theory

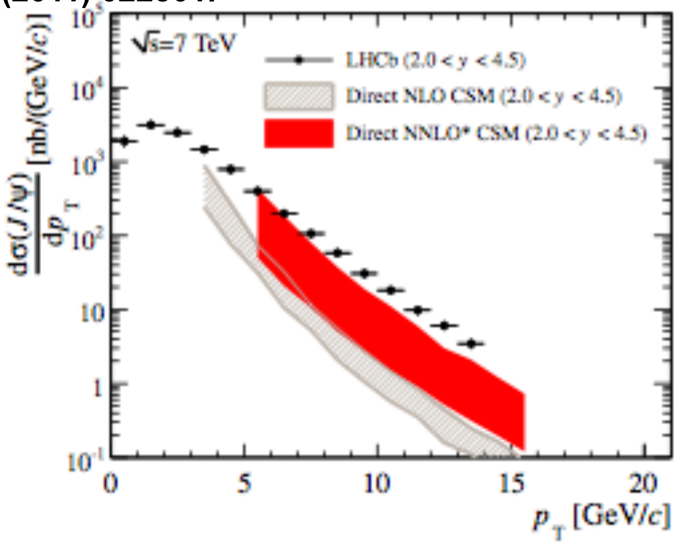


Comparison with theory

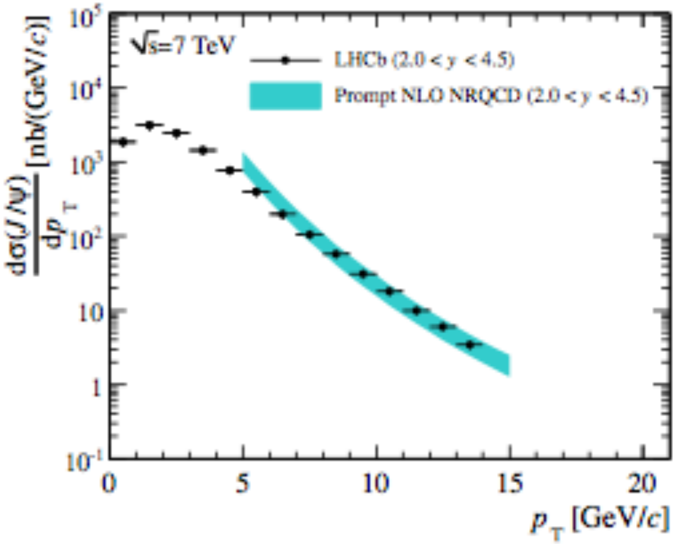
P. Artoisenet, PoS ICHEP 2010 (2010) 192.
M. Butenschön and B. A. Kniehl, Phys. Rev. Lett. 106 (2011) 022301.

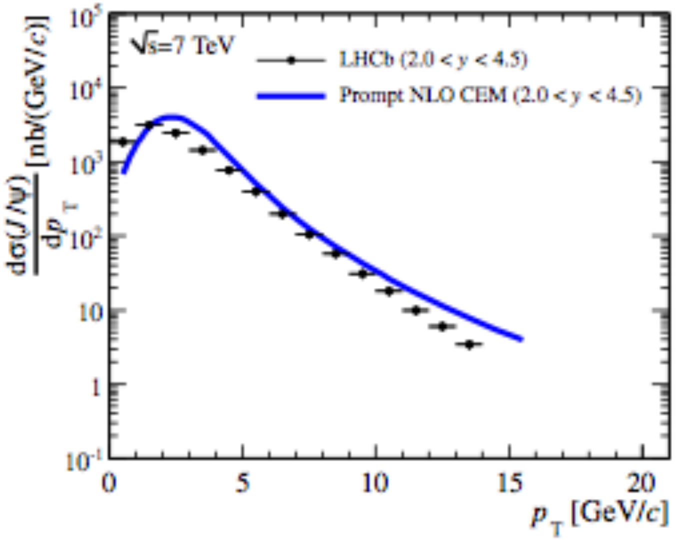


J.-P. Lansberg, Eur. Phys. J. C 61 (2009) 693



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

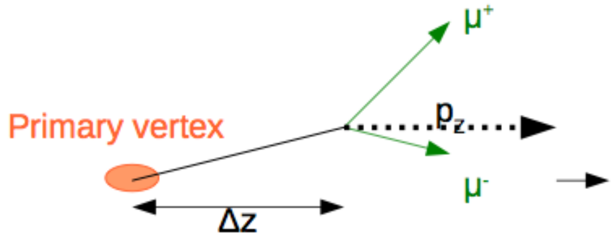




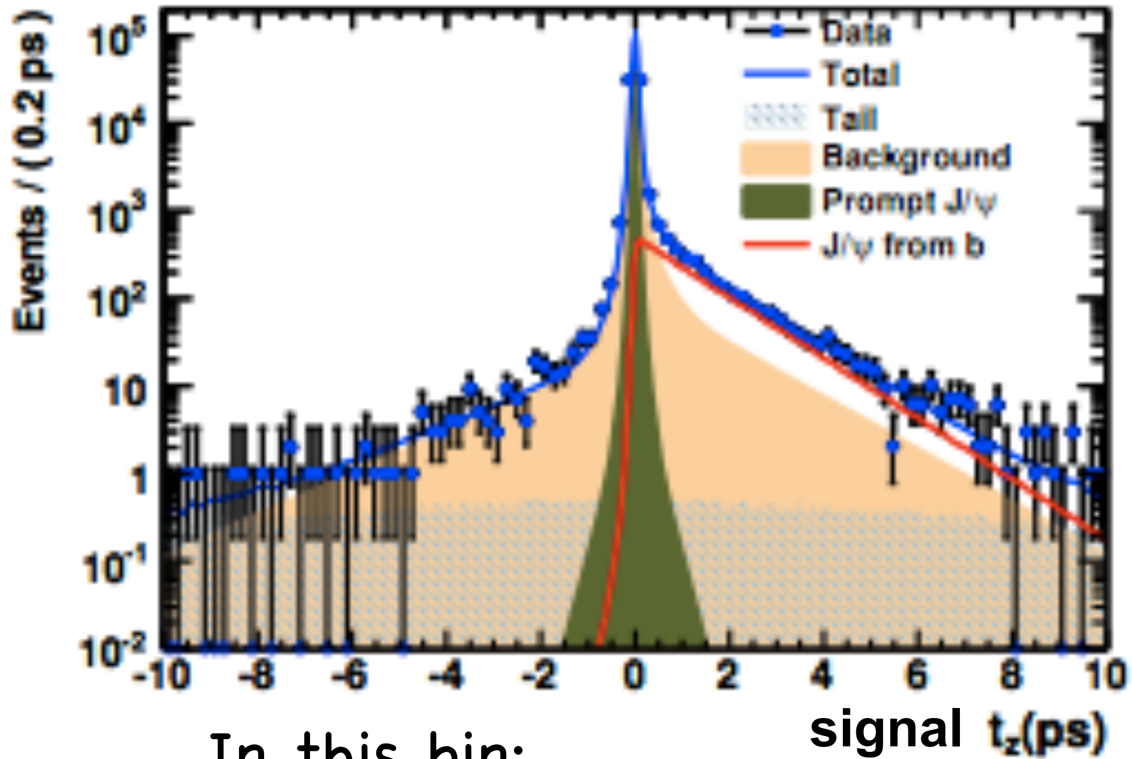
A. D. Frawley, T. Ullrich and R. Vogt, Phys. Rep. 462 (2008) 125.

J/ψ pseudo-proper time

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



3<pT<4 GeV/c, 2.5<y<3.0

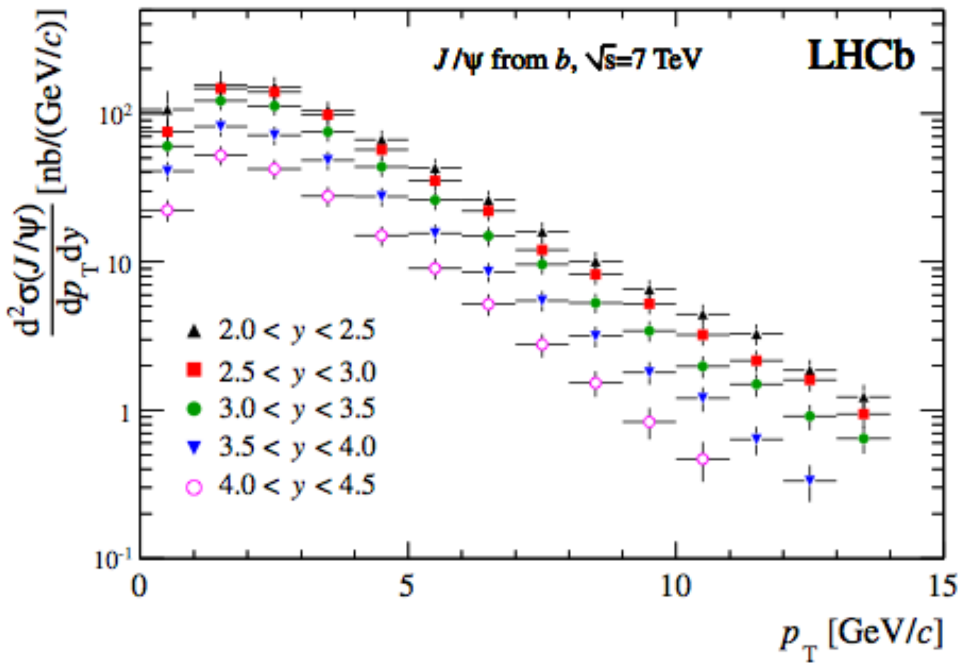


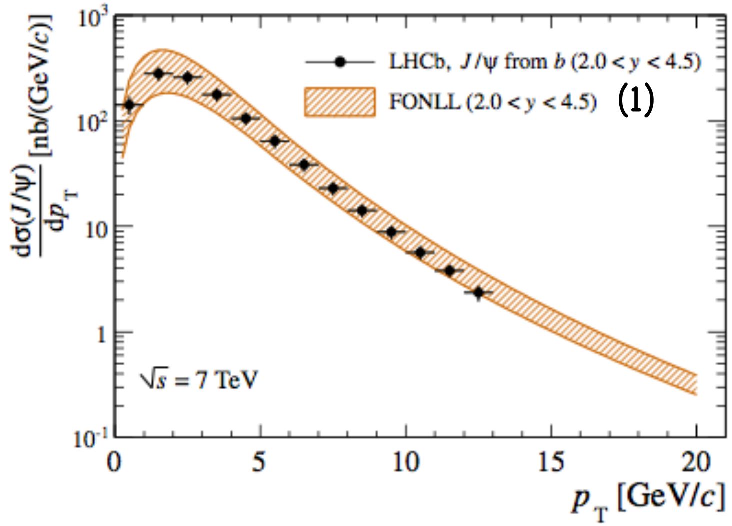
➡ t_z used to separate J/ψ prompt from J/ψ from B

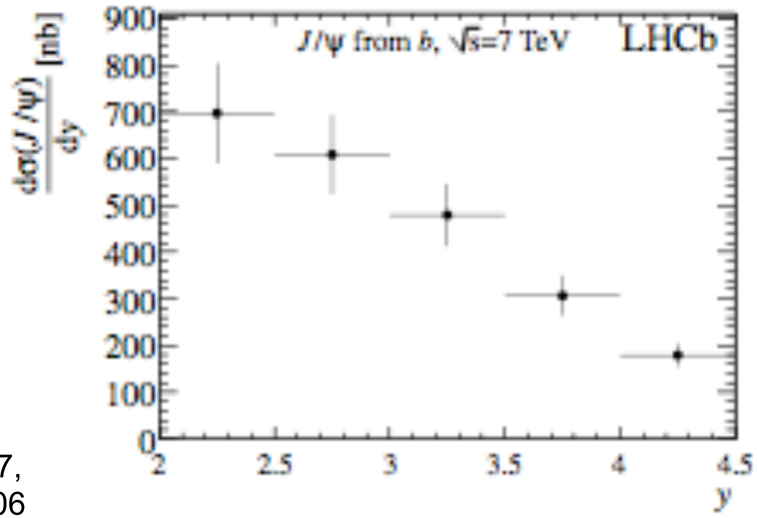
In this bin:

t_z resolution = 53 fs

J/ψ from B cross-section

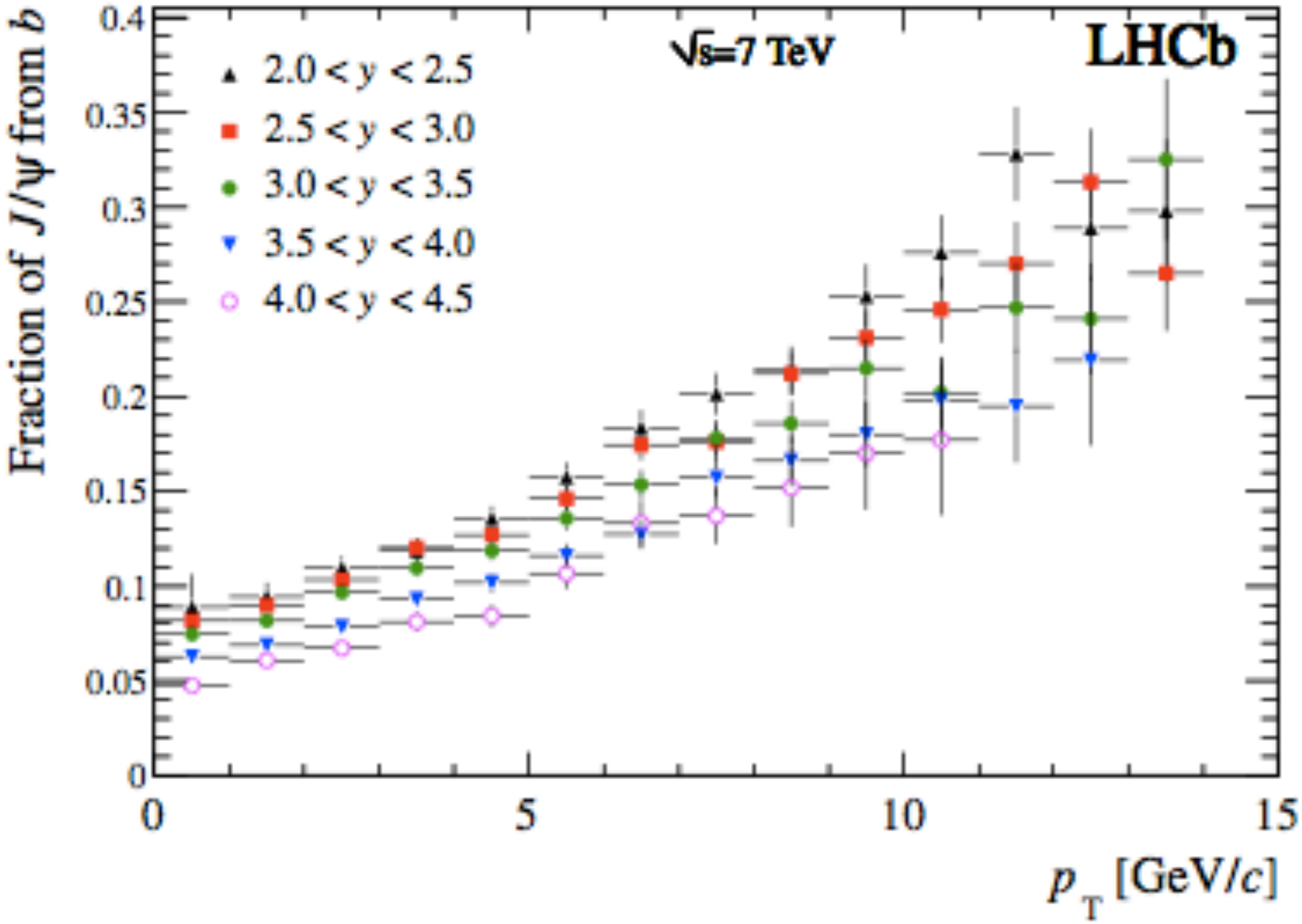




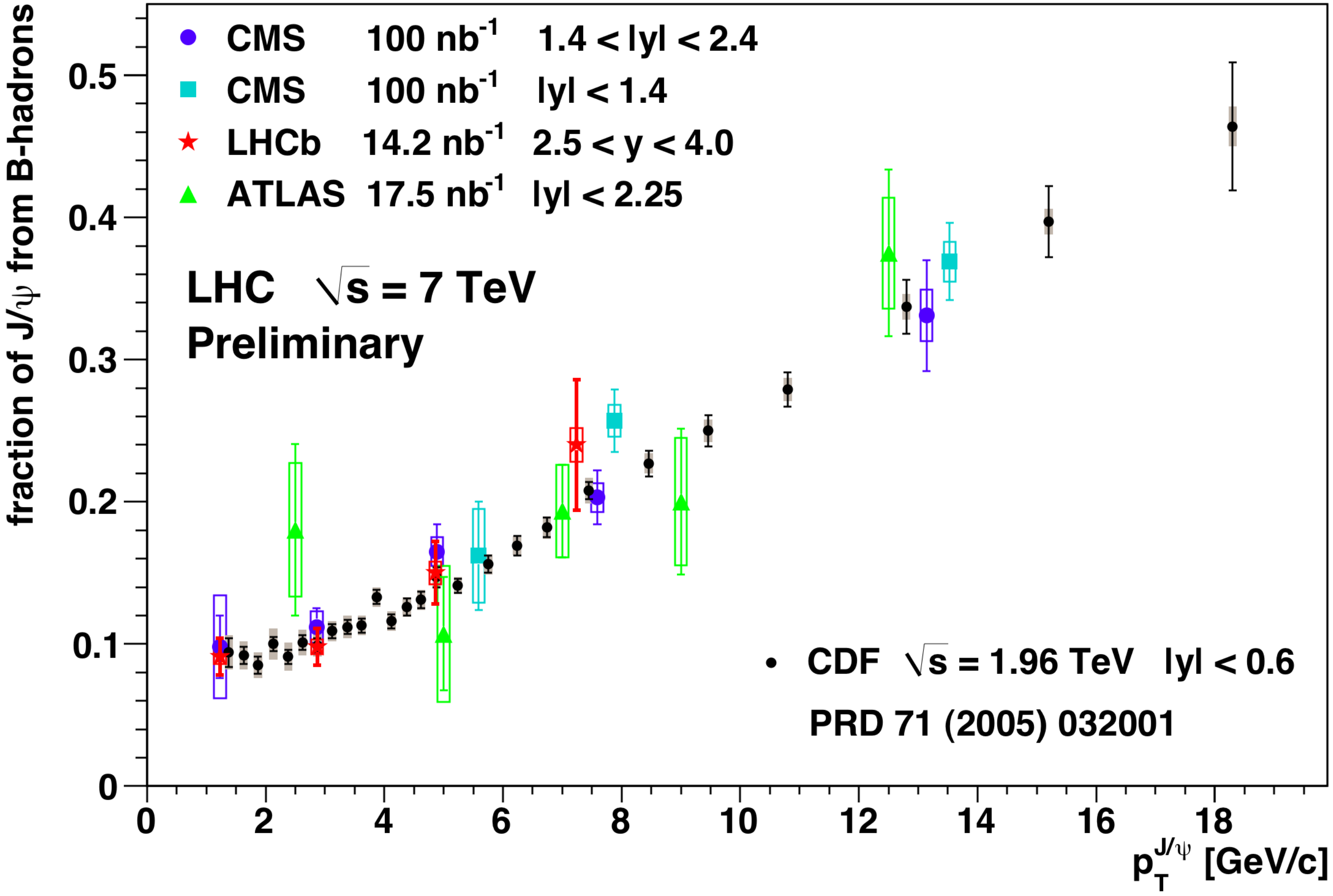


M. Cacciari, M. Greco and P. Nason, J. High Energy Phys. 9805 (1998) 007,
M. Cacciari, S. Frixione and P. Nason,J. High Energy Phys. 0103 (2001) 006

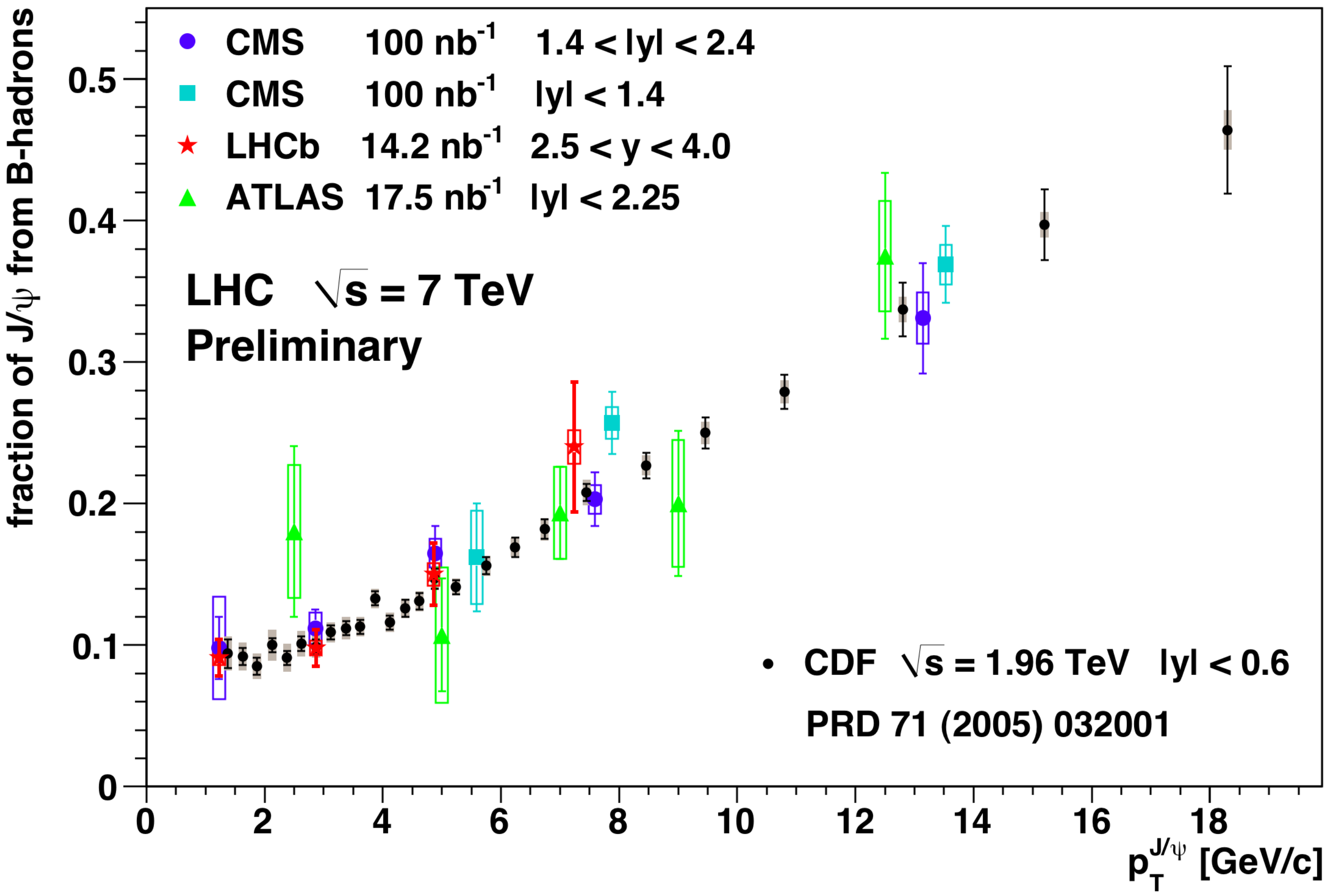
Fraction from B



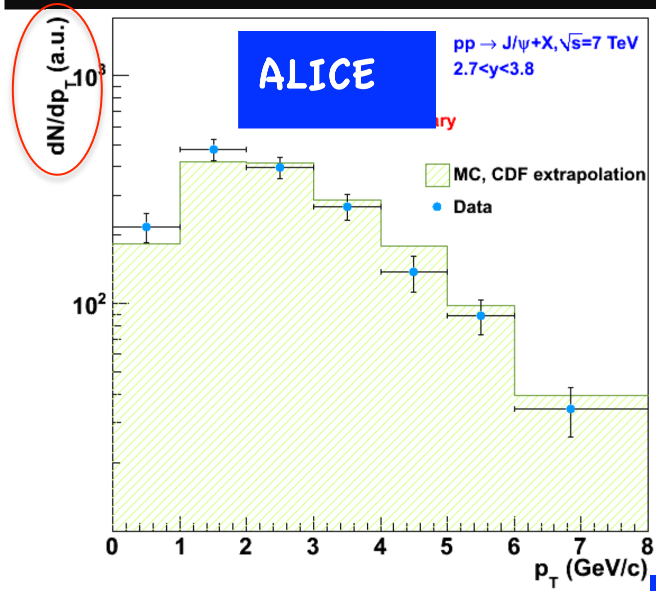
Fraction from B: Comparison with other experiments

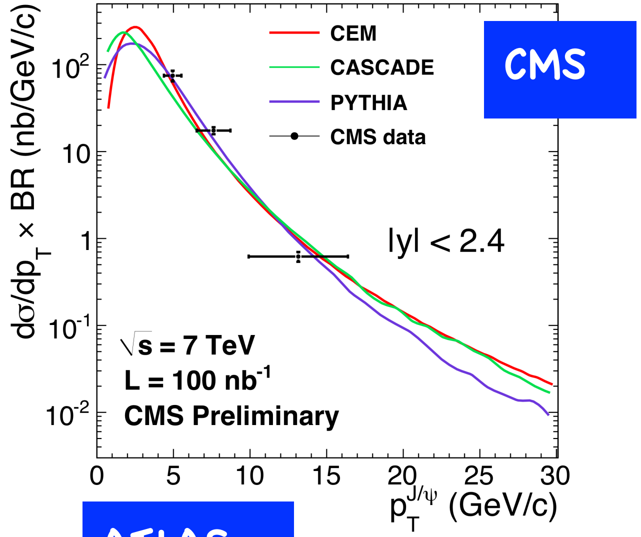


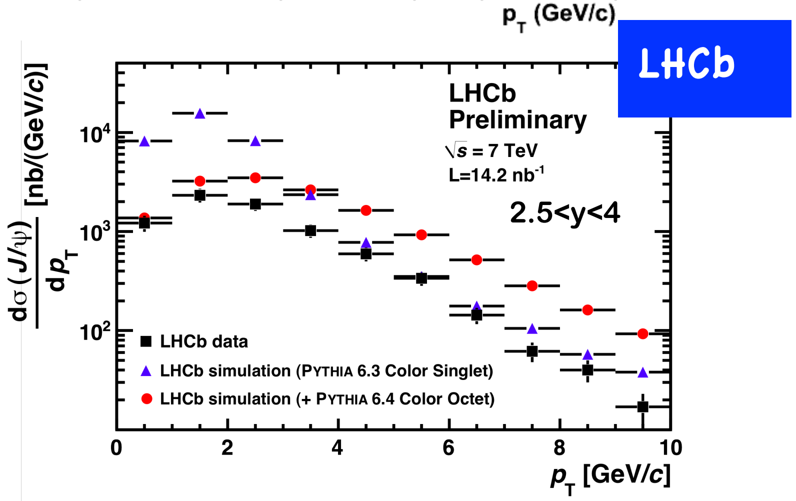
Fraction from B: Comparison with other experiments

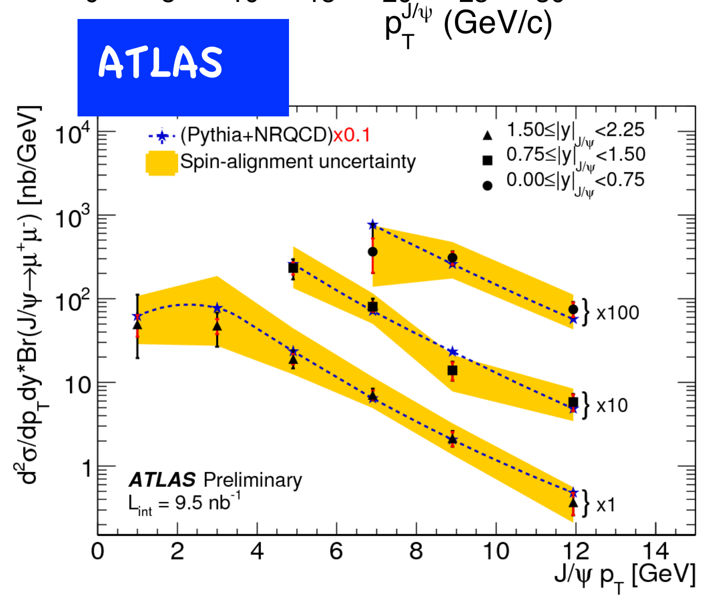


Inclusive cross section measurements

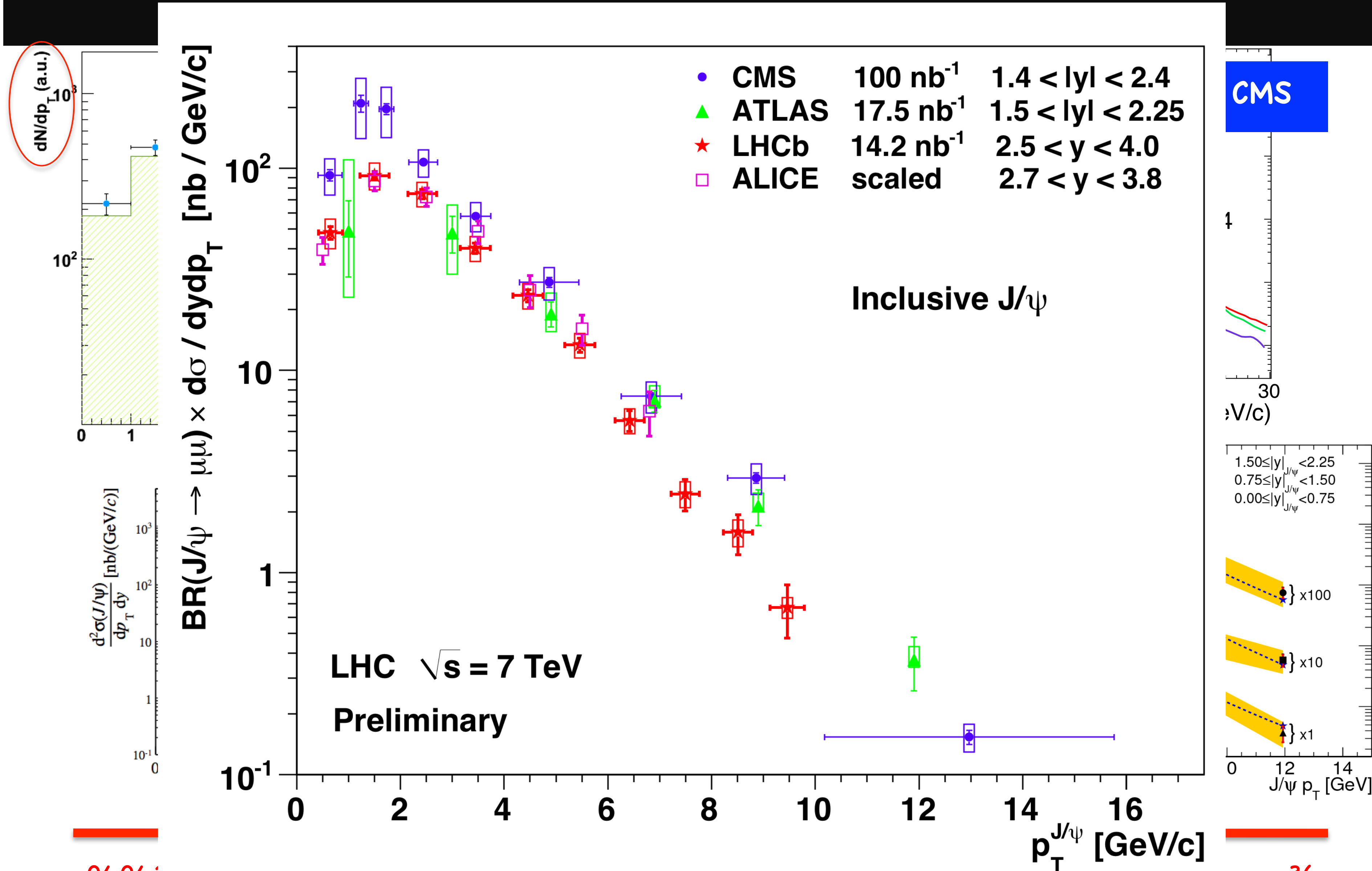








Inclusive cross section measurements



Integrated Cross-section Results

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

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

Using the LHCb acceptance from Pythia, we extrapolated :

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

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

$\alpha_{4\pi}^{FONLL} = 5.21$

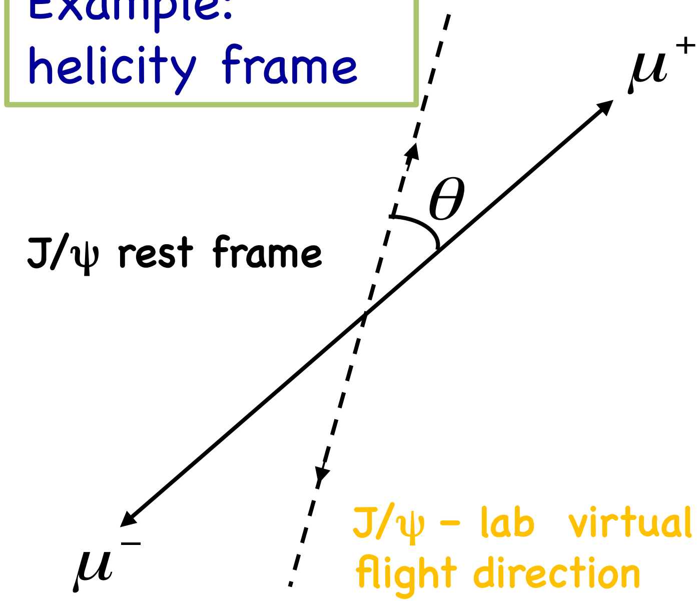
$Br(b \to J/\psi X) = (1.2 \pm 0.1)\%$

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

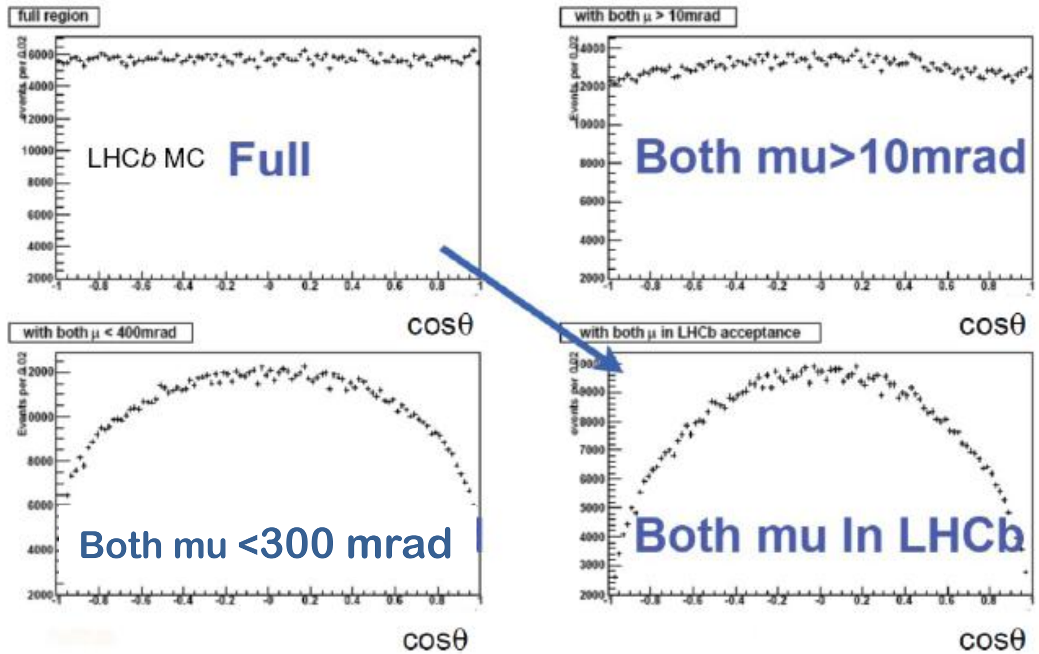
Influence of J/ψ Polarisation

- Detector acceptance as a function of helicity angle cosθ

Example:
helicity frame



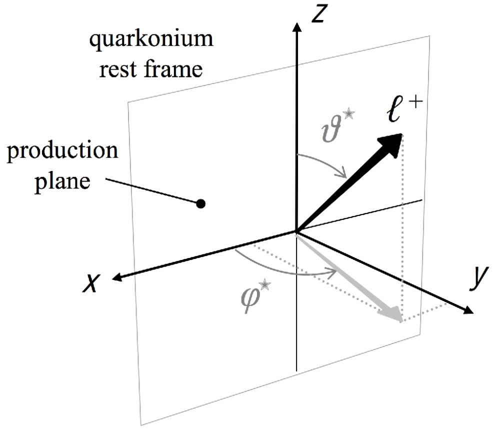
MC with no polarisation:LHCb



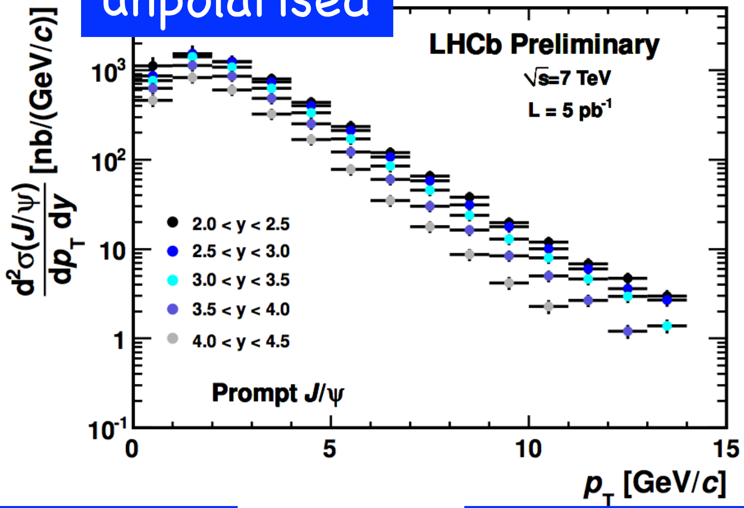
➡ acceptance generates an artificial polarisation
→ large influence of polarisation on measurement

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

Different polarisation scenarios



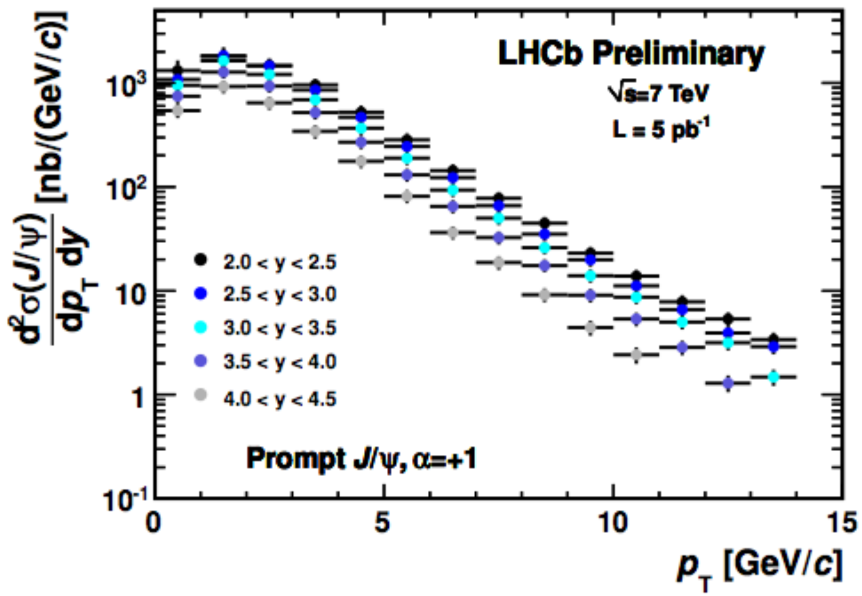
unpolarised



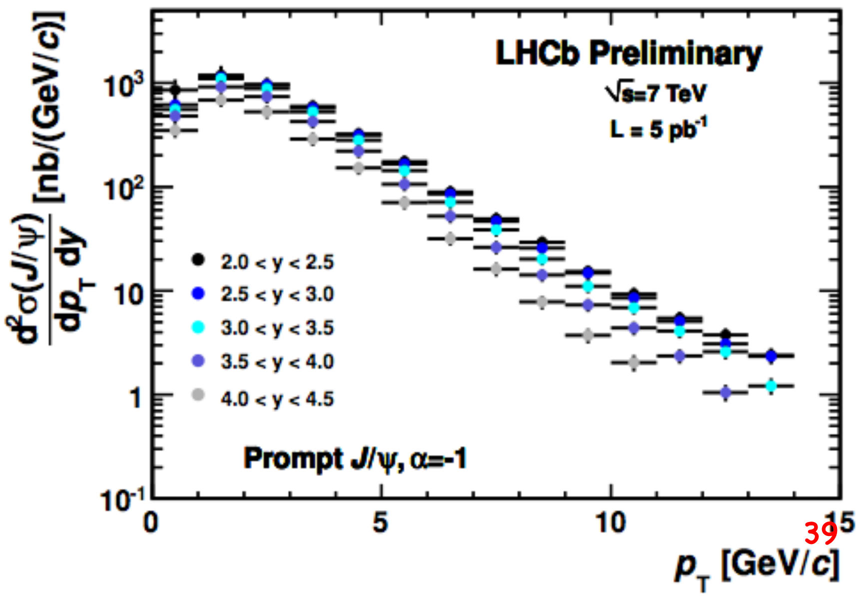
$\alpha = (\sigma T - 2\sigma L)/(\sigma T + 2\sigma L)$
With σT /L cross sections for production of transverse and longitudinal polarised

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

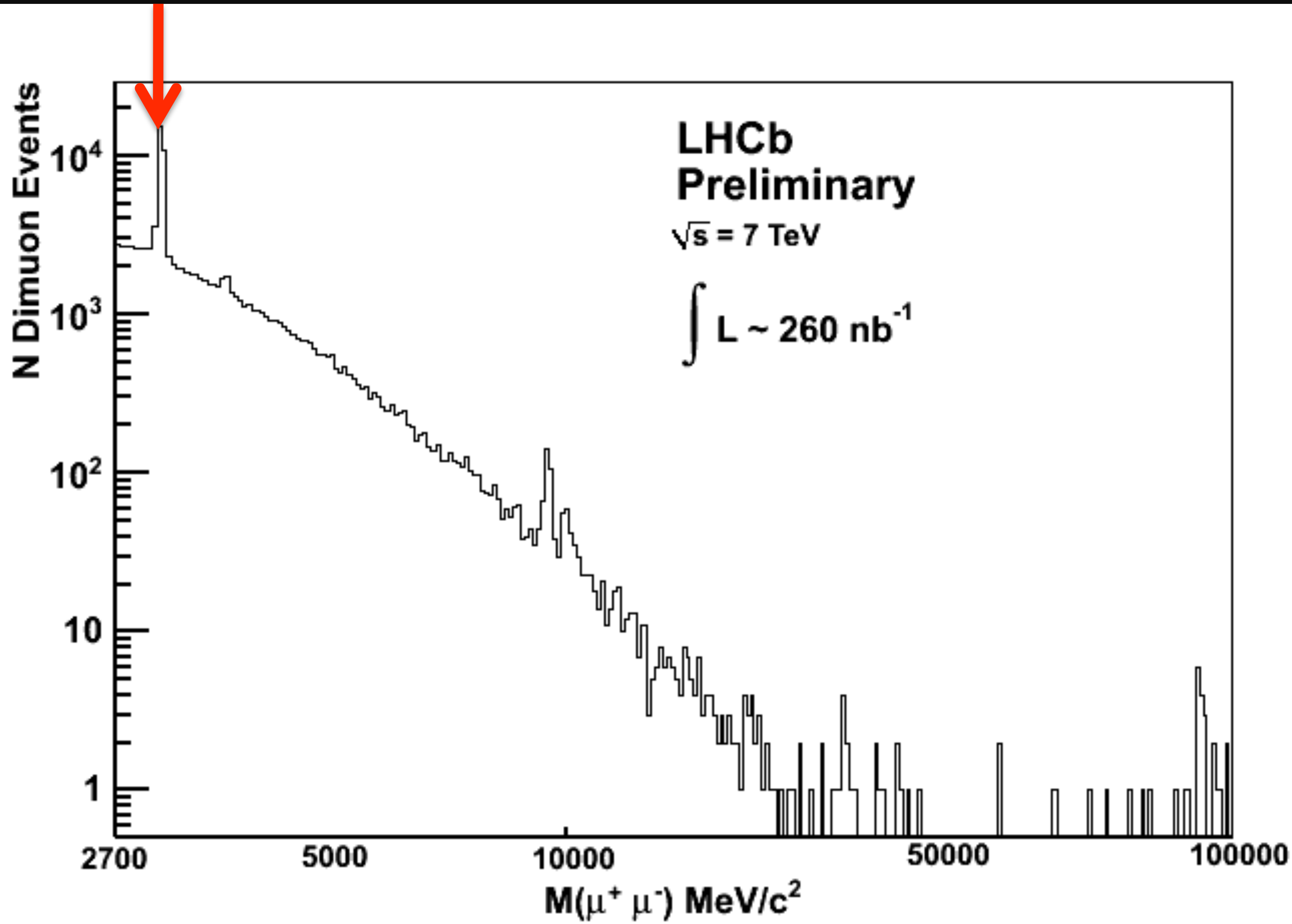
Fully transversly polarised



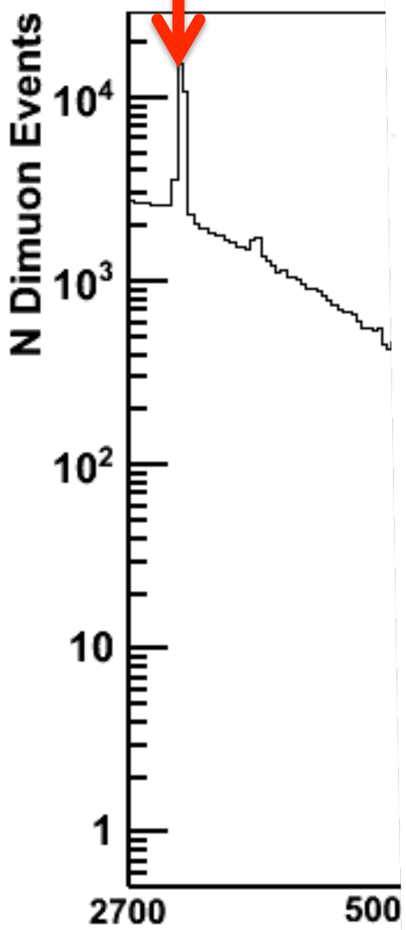
Fully longitudinally polarised



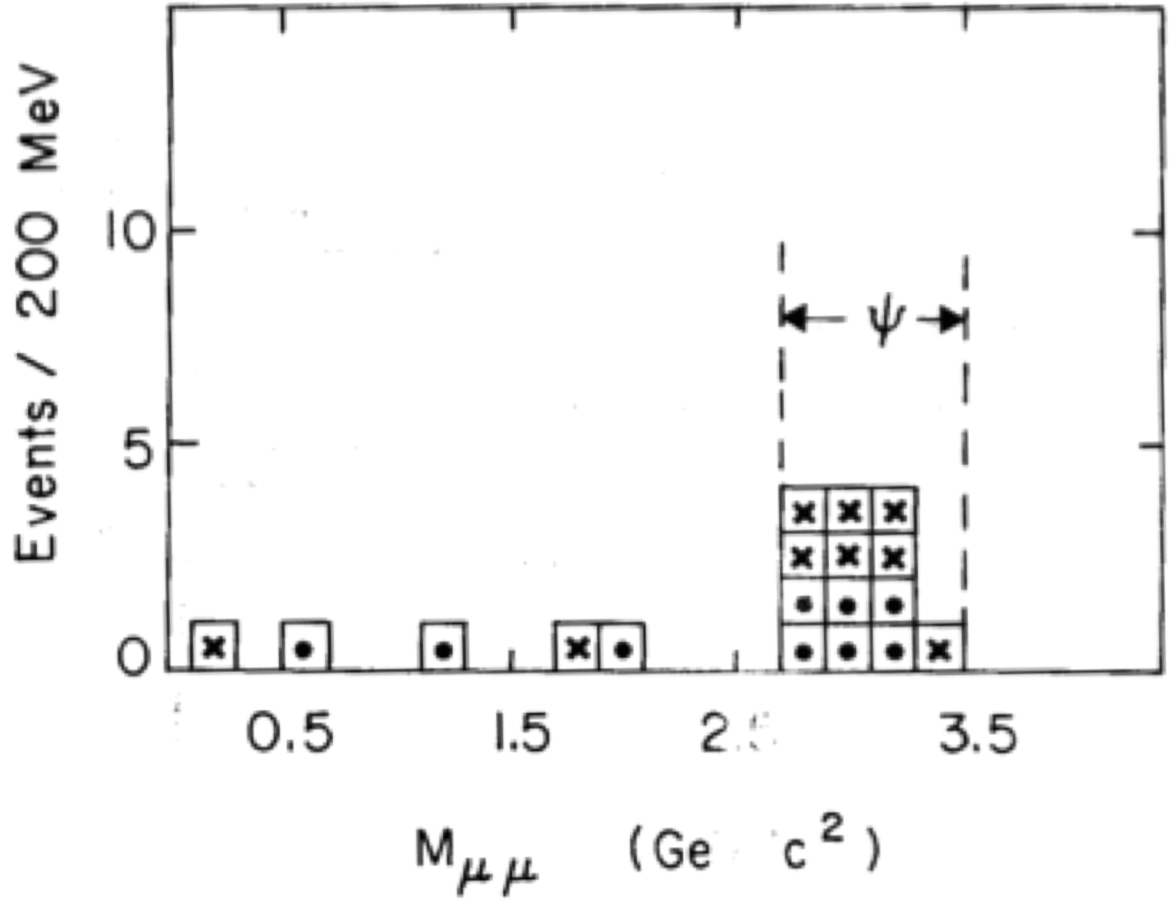
Double J/ψ production



Double J/ψ production



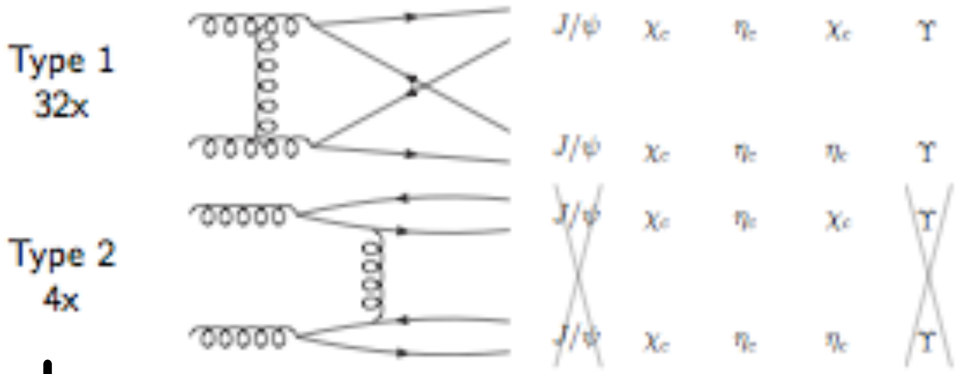
J. Badier et al. (NA3 Collaboration),
Phys. Lett. 114B (1982) 457. , Phys. Lett. 158B (1985) 85.



Motivations

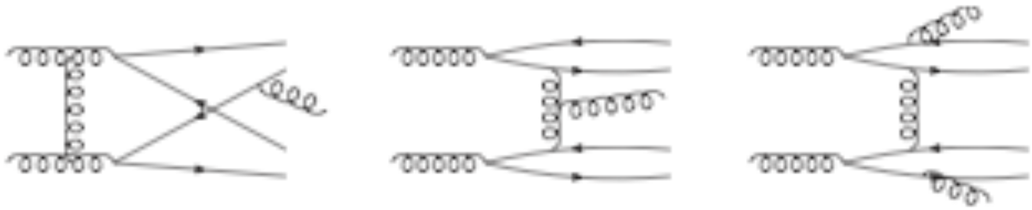
➡ Many new resonances in charmonium+V

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



➡ Interesting for:

- Test of QCD: sensitive to CSM vs. COM

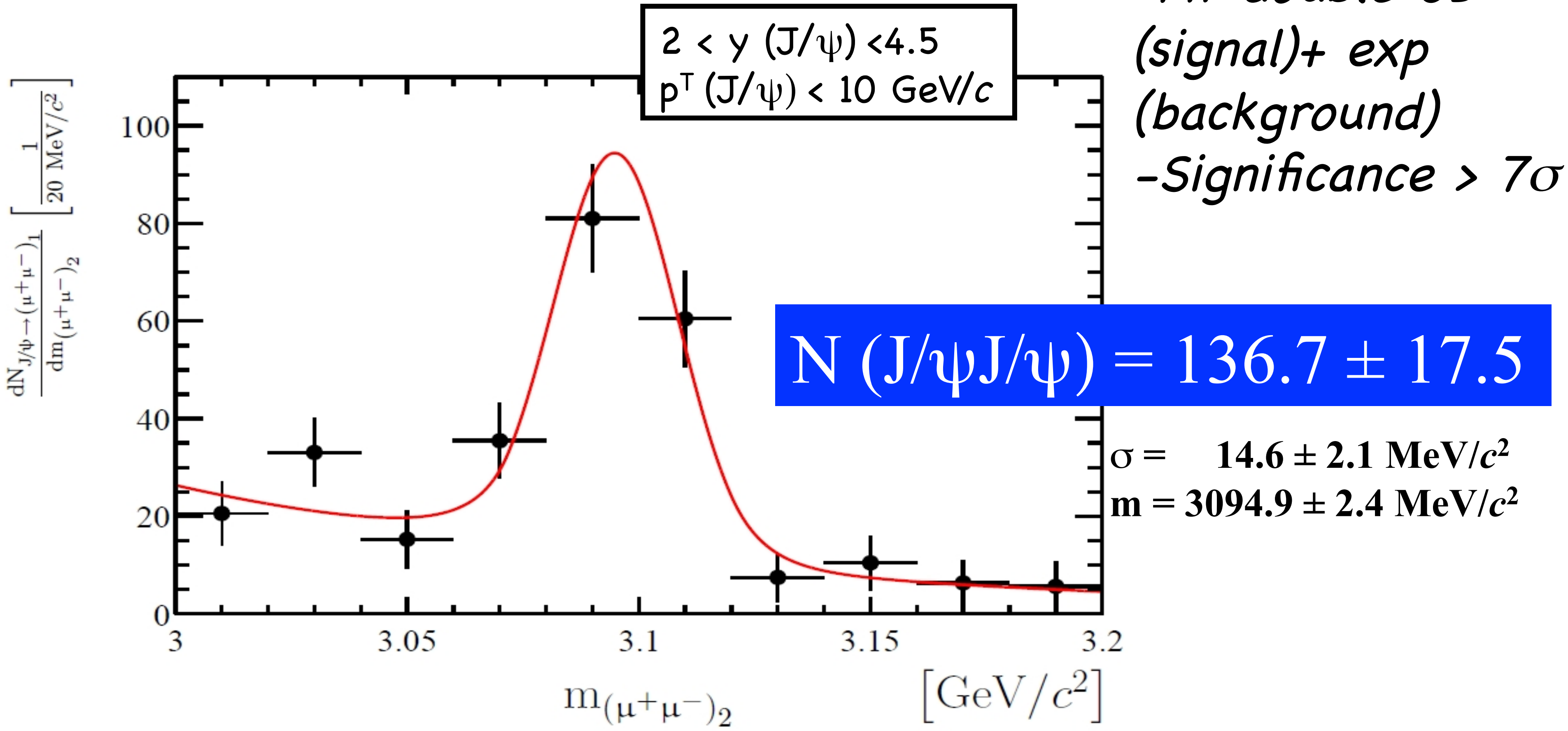


Type 1 Type 2 Type 3

- Possible hint of tetraquark production

Signal

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

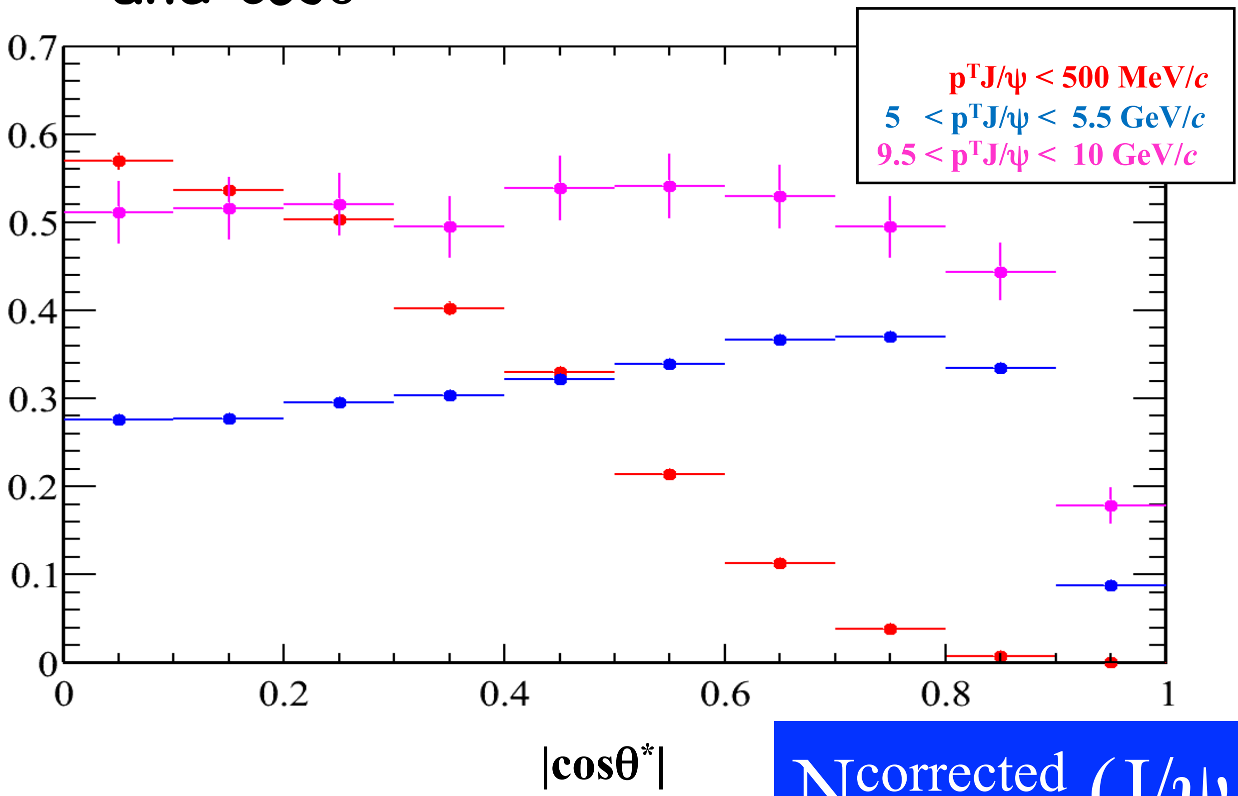


-Fit=double CB (signal)+ exp (background)

-Significance > 7σ

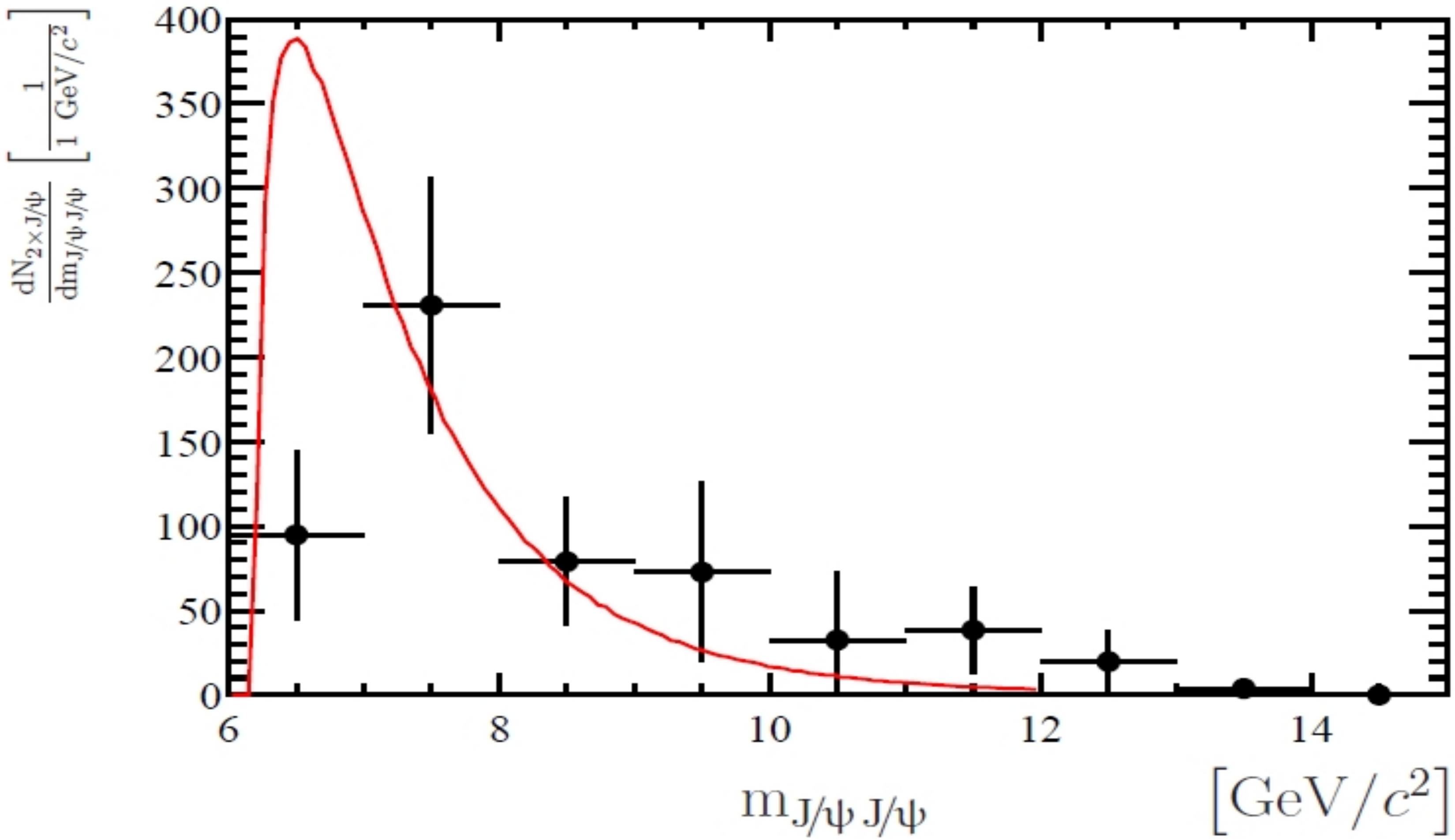
Efficiency

- ➡ Each event : weight $w=\varepsilon^{-1}$, with $\varepsilon=\varepsilon_{rec} x \varepsilon_{trig}$ x acceptance
- ➡ Assume factorisation : $\varepsilon_{J/\psi J/\psi} = \varepsilon_{J/\psi} x \varepsilon_{J/\psi}$, 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/ψ) <4.5
p^T (J/ψ) < 10 GeV/*c*

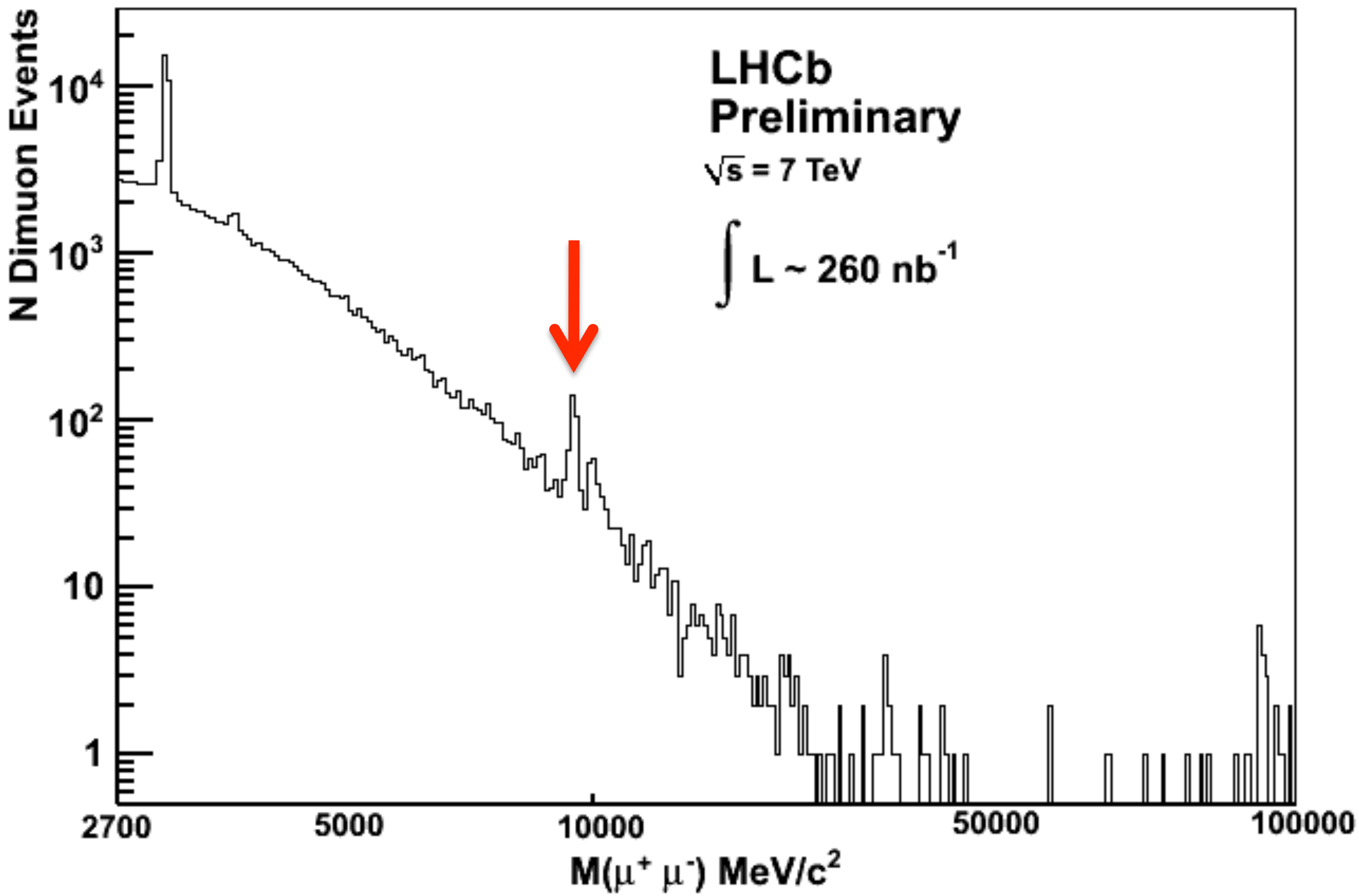
$$\sigma^{J/\psi\, J/\psi} = 5.6 \pm 1.1 \pm 0.5 \pm 0.9|_{\mathrm{tr}} \pm 0.6|_{\mathcal{L}} \ \mathrm{nb},$$

To be compared with theoretical prediction (direct only)

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

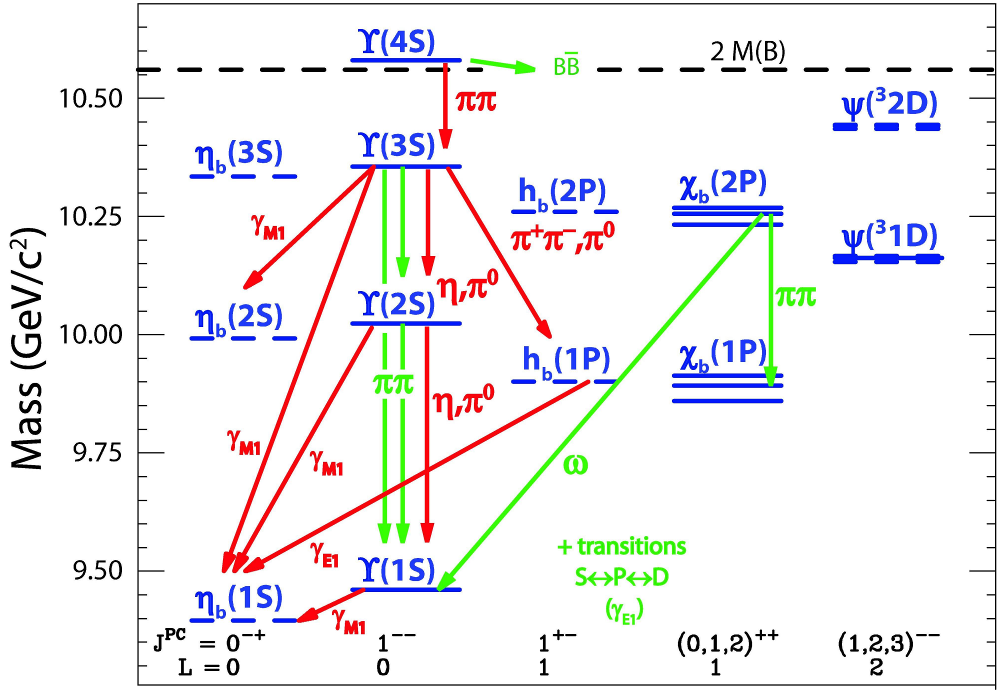
A.V.Berezhnouy, A.K. Likhoded, A.V.Luchinsky, A.A. Novoselov, arXiv:1101.5881

Υ production



Three for the price of one!

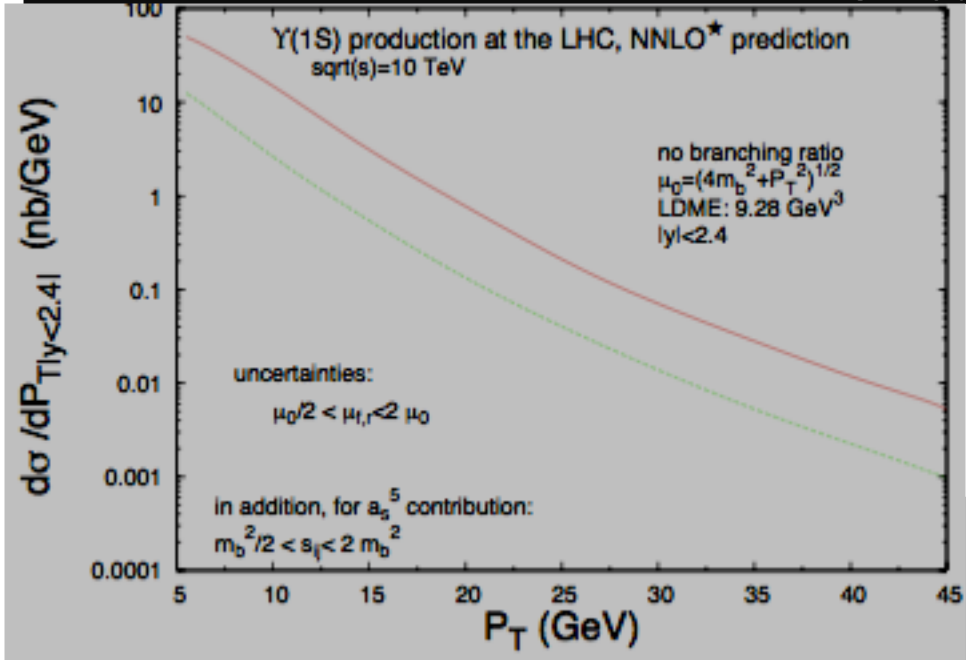
1st step	2nd step	3rd step	Prod. type
	$b\bar{b} \to \Upsilon(nS)$	–	Prompt,Direct
$pp \to b\bar{b} + X$	$b\bar{b} \to \chi_b$	$\chi_b \to \Upsilon(nS) + \gamma$	Prompt,Indirect
	$b\bar{b} \to \Upsilon(n'S)$	$\Upsilon(n'S) \to \Upsilon(nS) + X$	Prompt,Indirect



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

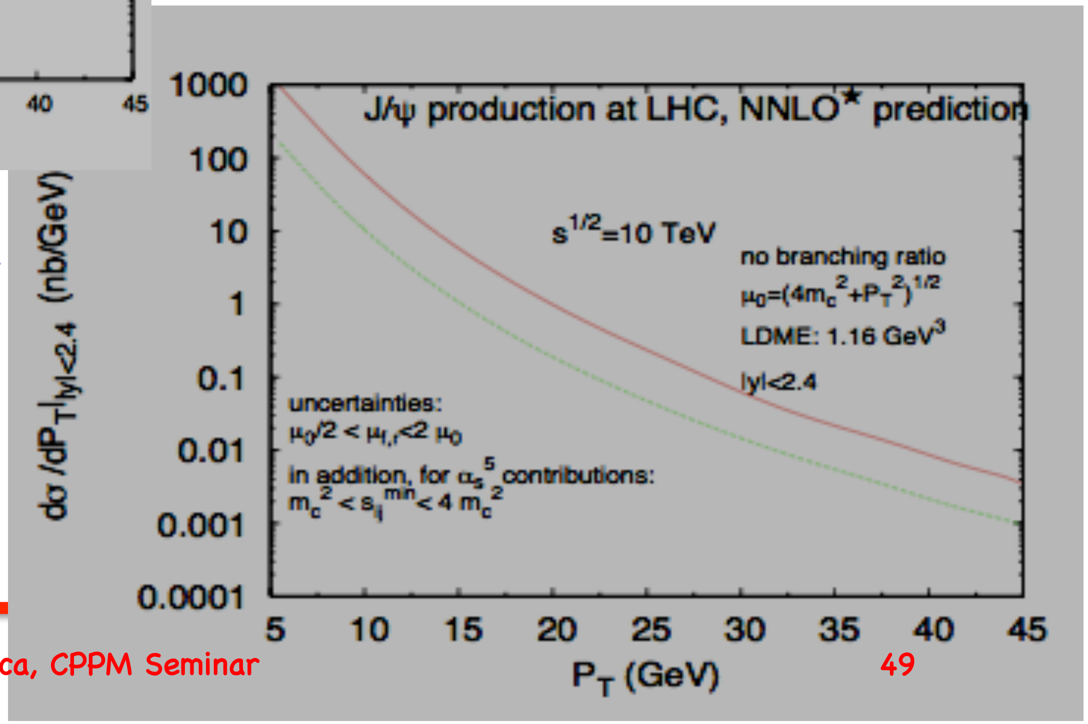
G.Bodwin, talk at Berkeley workshop May'09



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

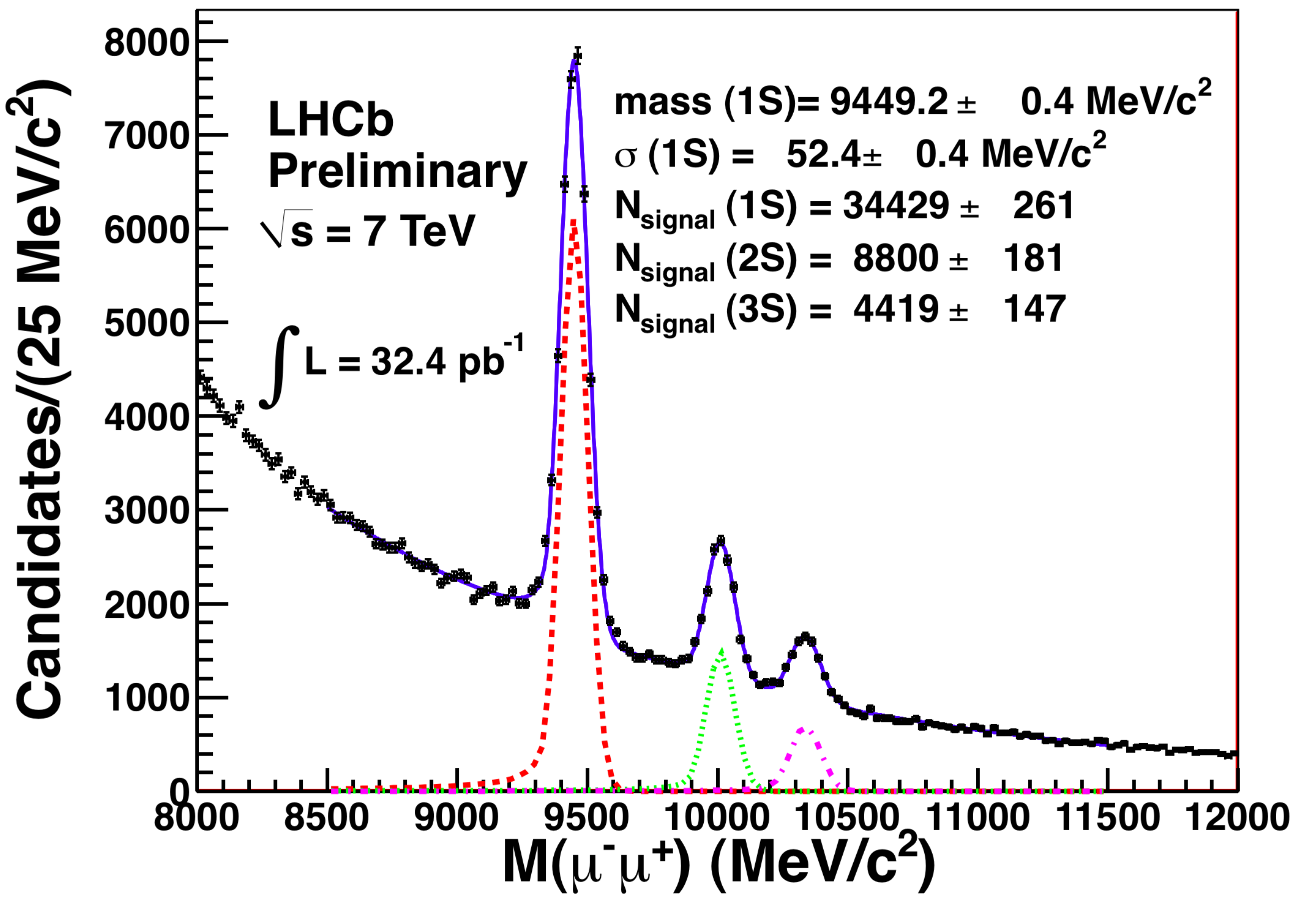
Caveats:

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 background. Fixed (α=2,n=1) and width (2S,3S) to scale with the masses.

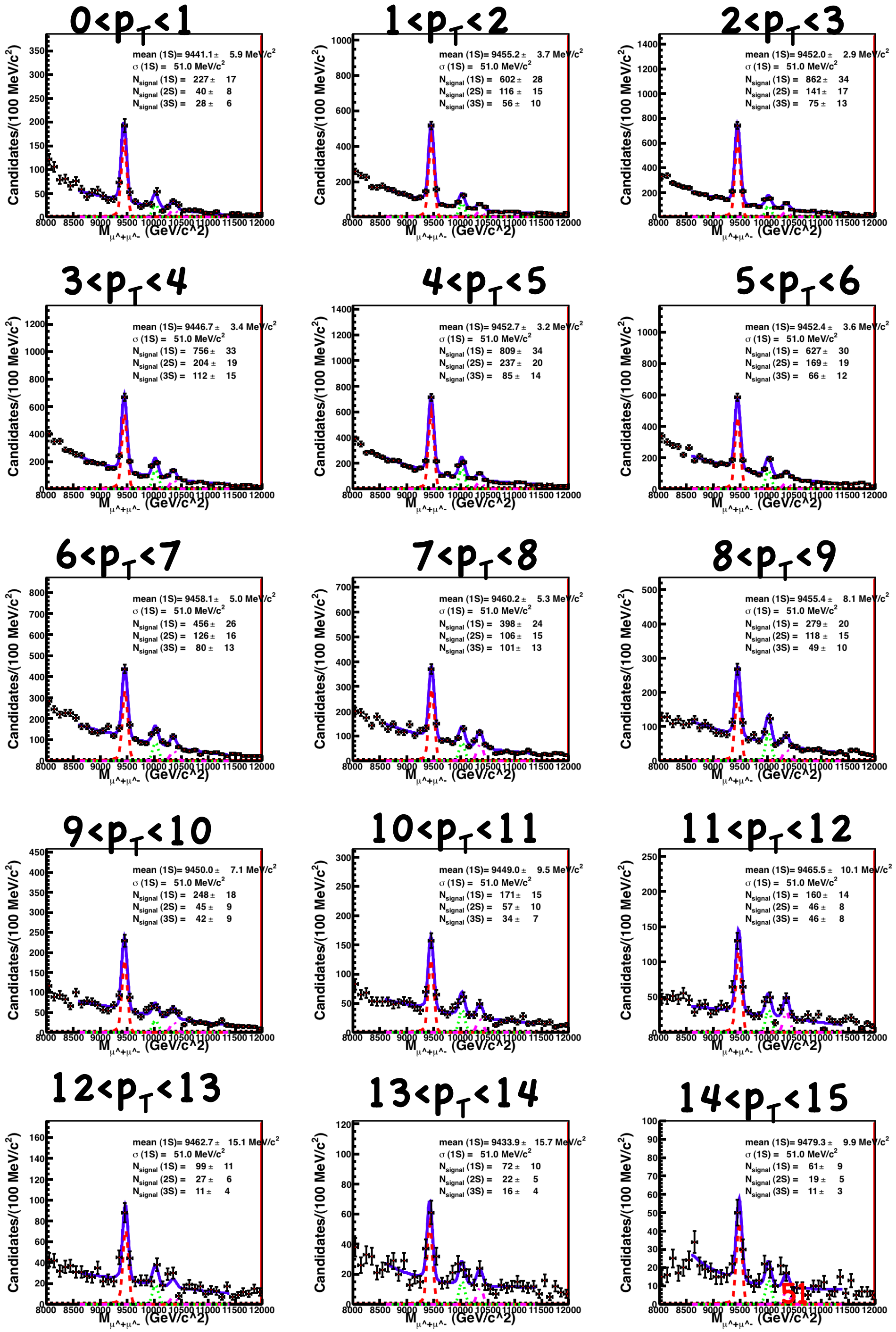


Same function used on individual bin fits

Number of Υ (1S) candidates

- N^{fit} : extracted from Crystal Ball (CB) part of the fit with CB+ exponential.
- Fix width and masses
- Only Υ(1s) considered.

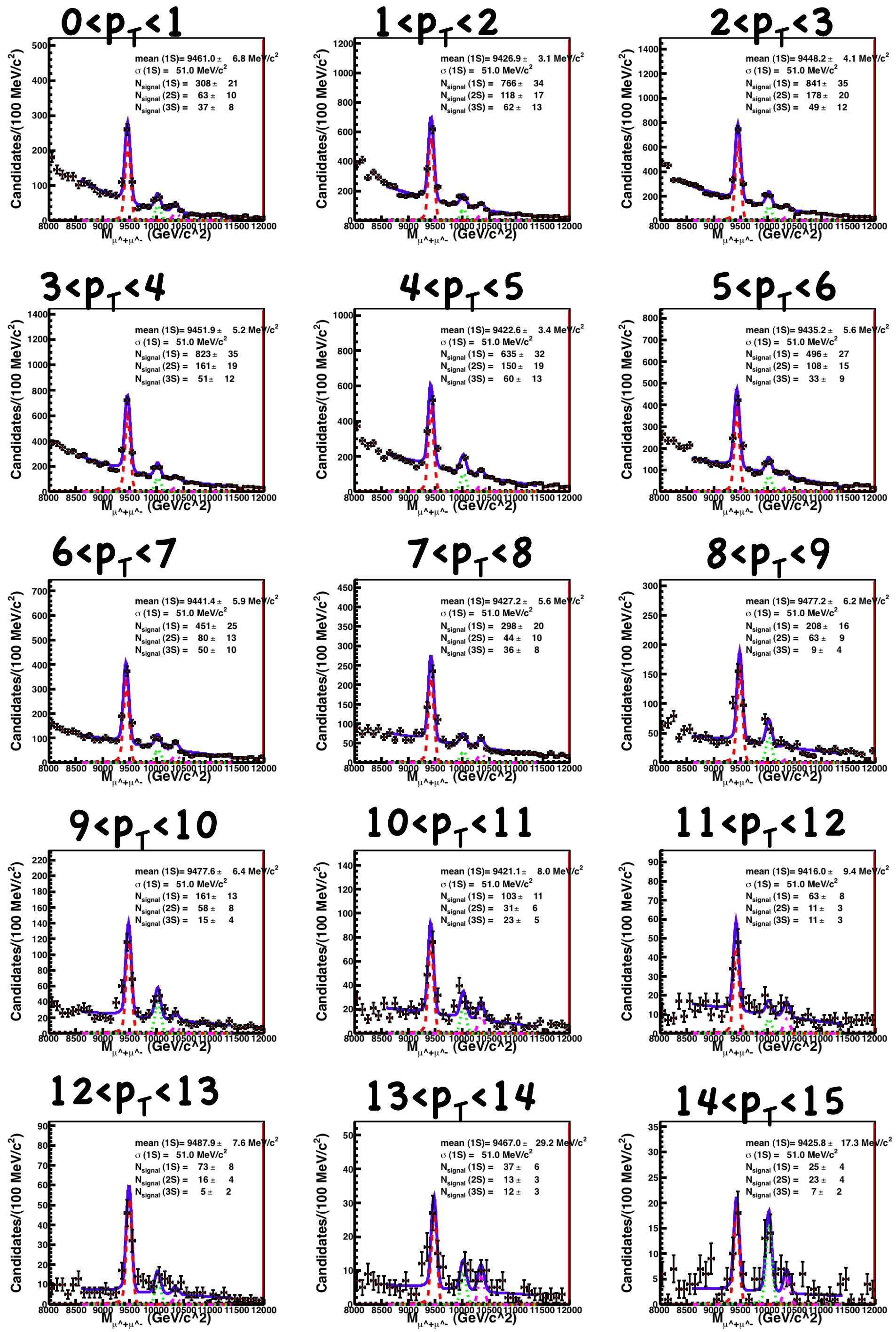
  - 2.0 < y < 2.5



Number of Υ (1S) candidates

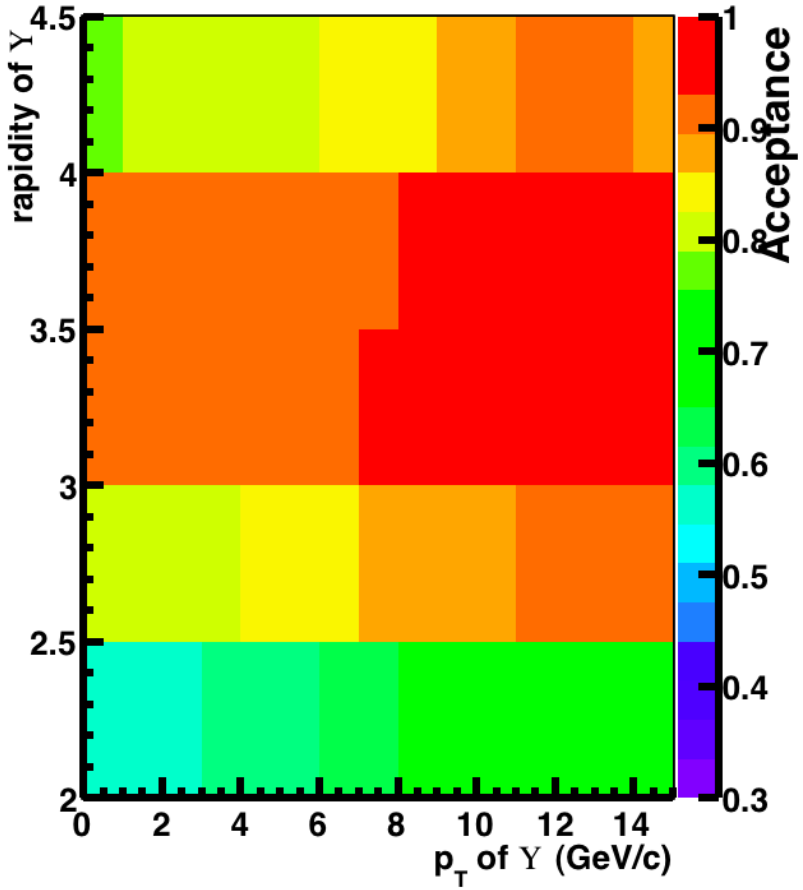
- N^{fit} : extracted from Crystal Ball (CB) part of the fit with CB +exponential.
- Fix width,m2S,m3S to 50 MeV.
- Only Υ(1s) considered.

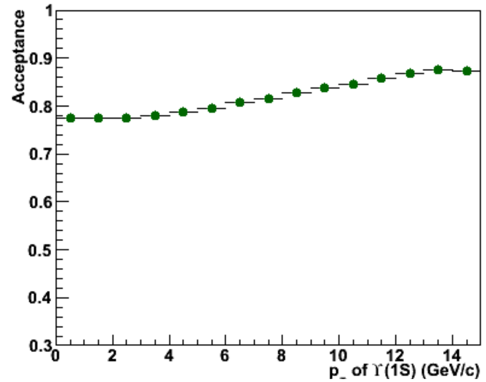
  - 3.5 < y < 4.0

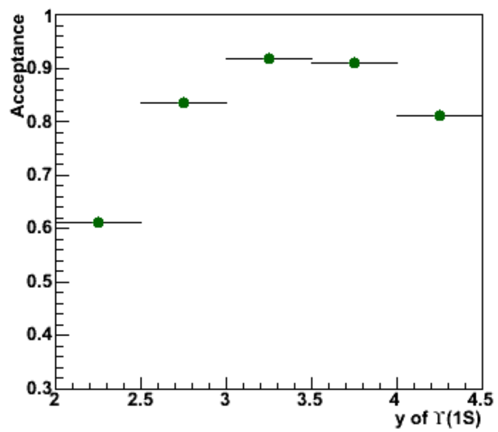


Acceptance

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

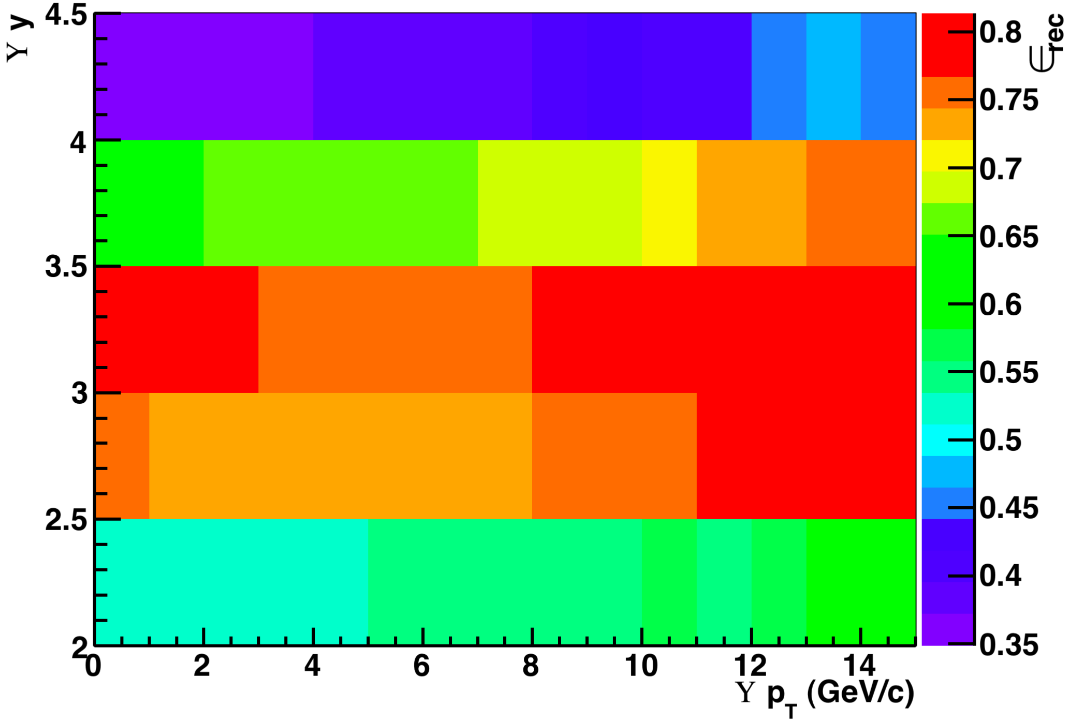


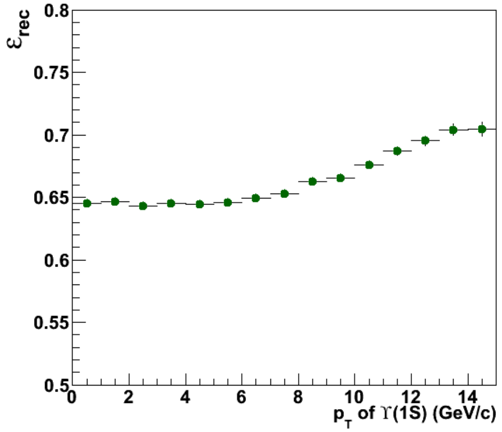


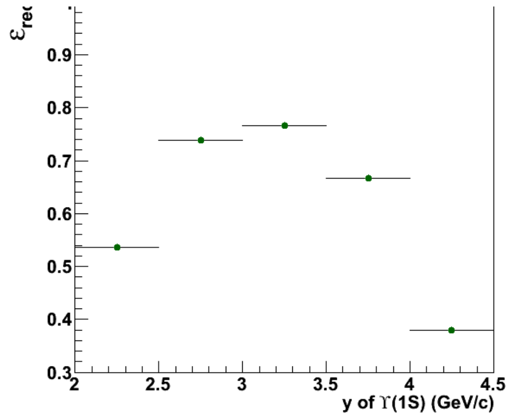


Reconstruction Efficiency

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

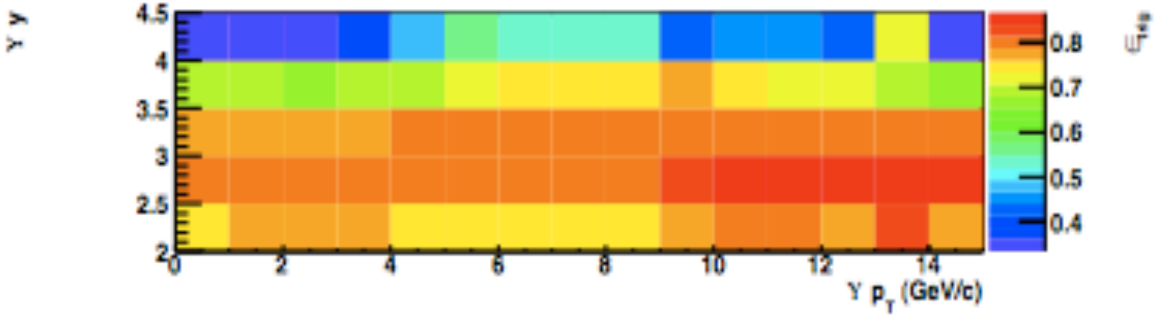


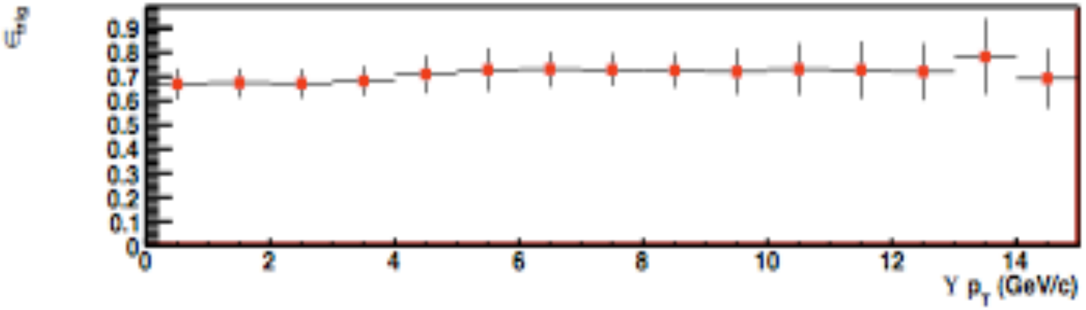


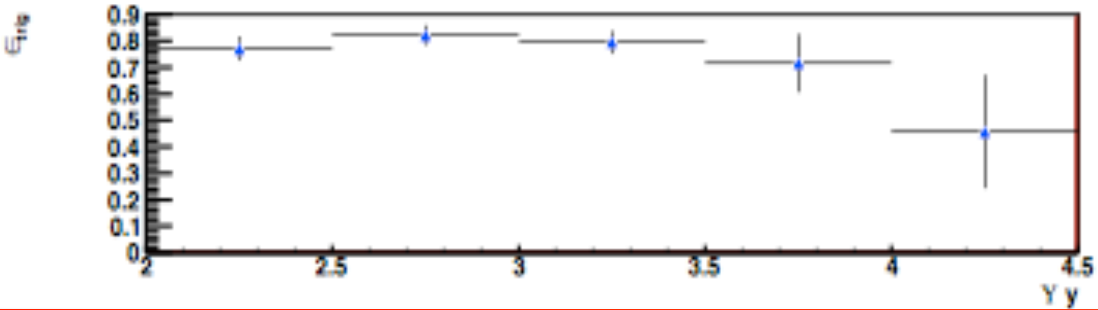


Trigger Efficiency

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



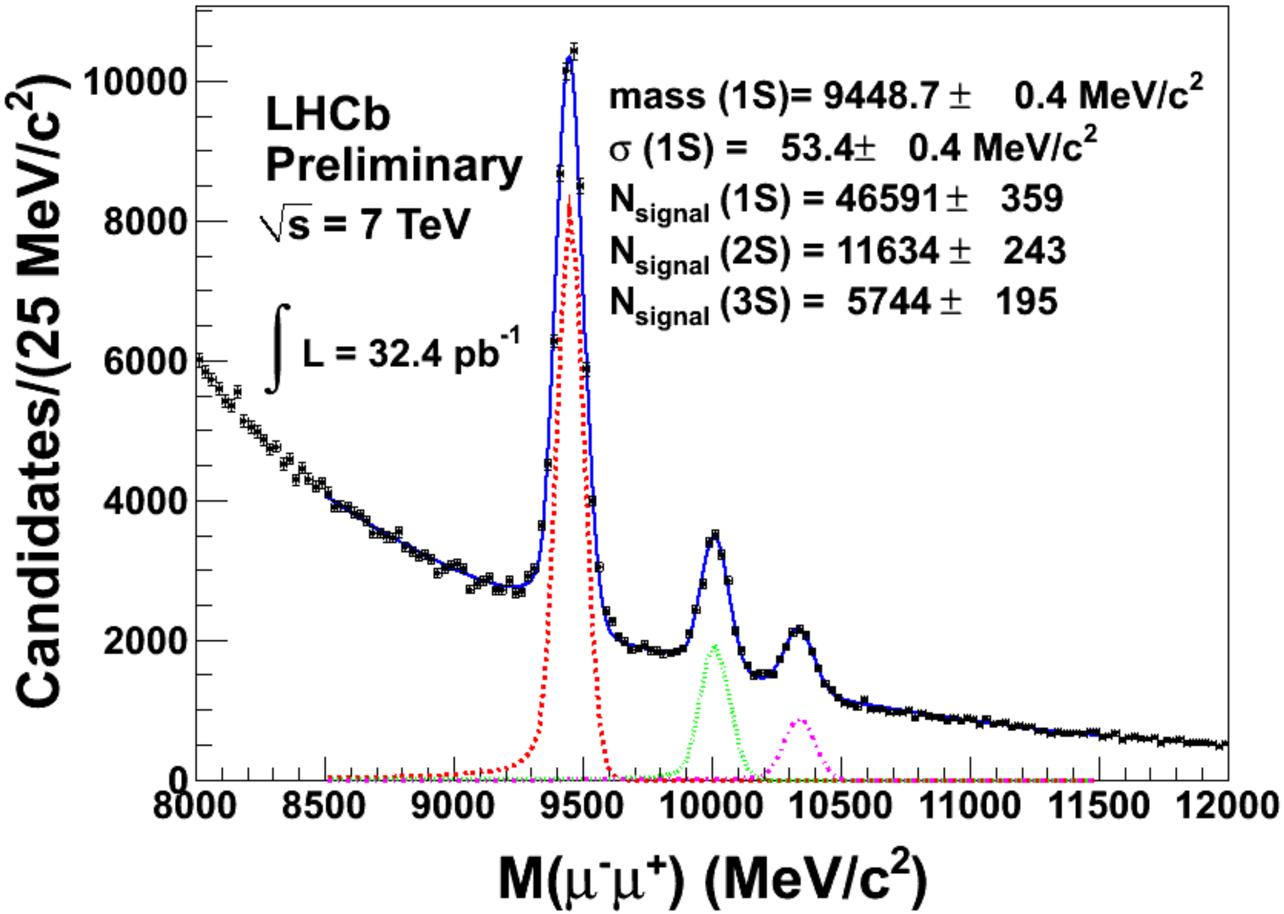




- ➡ Efficiency measured in the J/ψ sample f(sum pt muons, mean y), applied as a weight to each event

Scaled number of Υ(1S) candidates

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



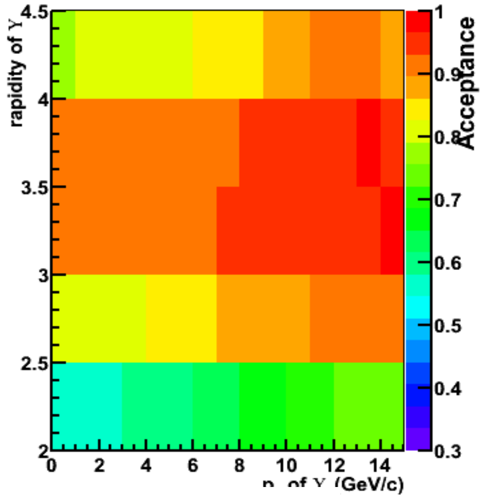
Scaled for the trigger efficiency

Systematic Uncertainties

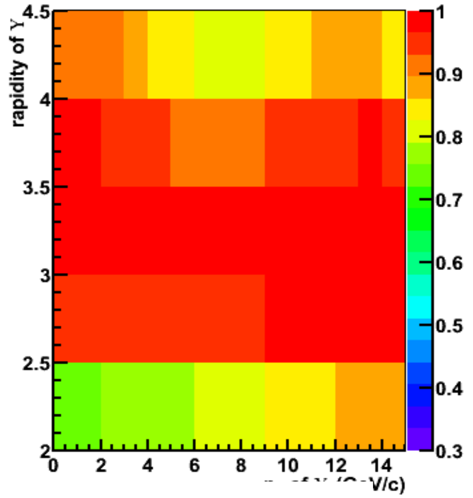
SOURCE	METHOD	VALUE	COMMENTS
luminosity	see section 3.2.2	10%	correlated among bins
ϵ^{trig} calculation	difference MC-MC truth	2-67%	correlated among bins
polarisation on A	extreme polarisation scenarios	0-33%	correlated among bins
polarisation on ϵ^{rec}	extreme polarisation scenarios	0-21%	correlated among bins
choice of fit function	different function	1%	correlated among bins
unknown p_T spectrum	p_T spectrum distribution	1%	correlated among bins[2]
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
ϵ^{muonID}	tag and probe [20]	1.1%	correlated among bins

Polarisation effect on A

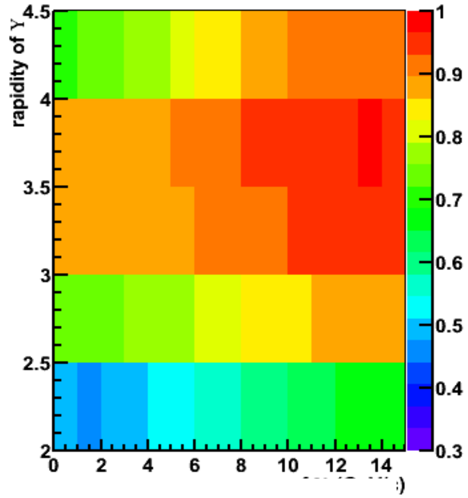
Calculated reweighting the MC unpolarised events assuming α=±1



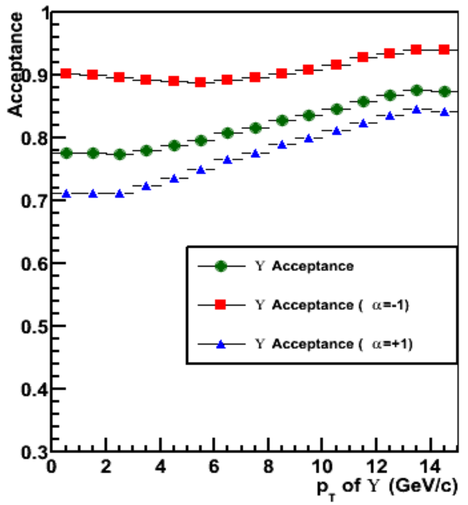
α= 0

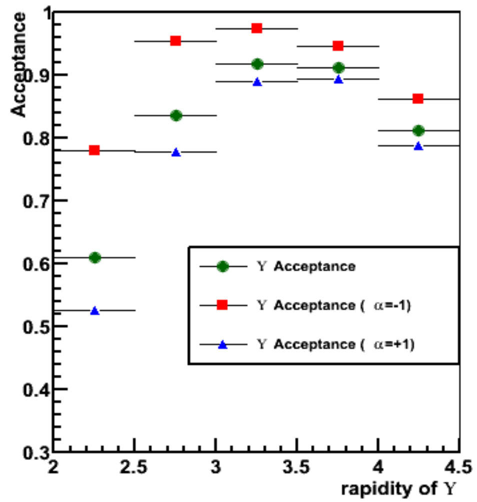


α= -1



α=+1



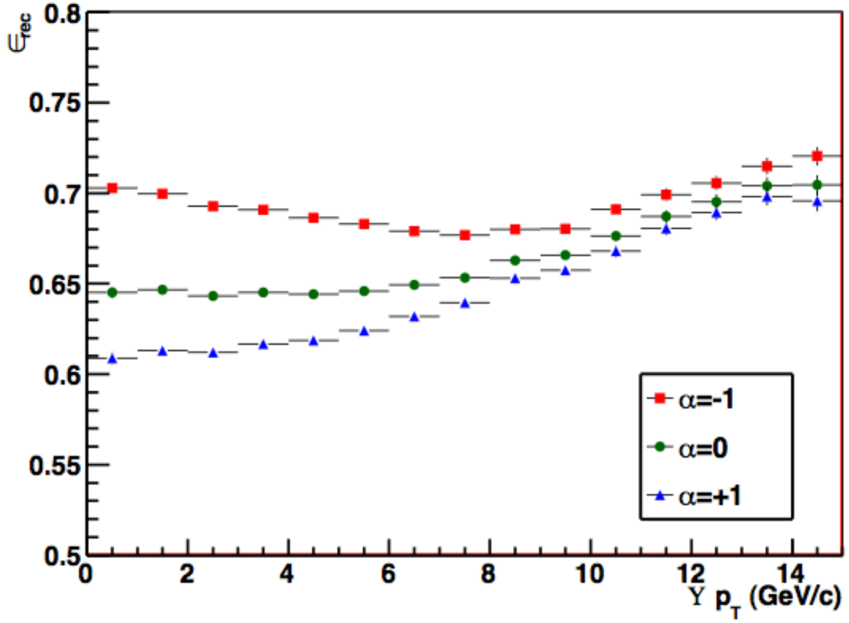


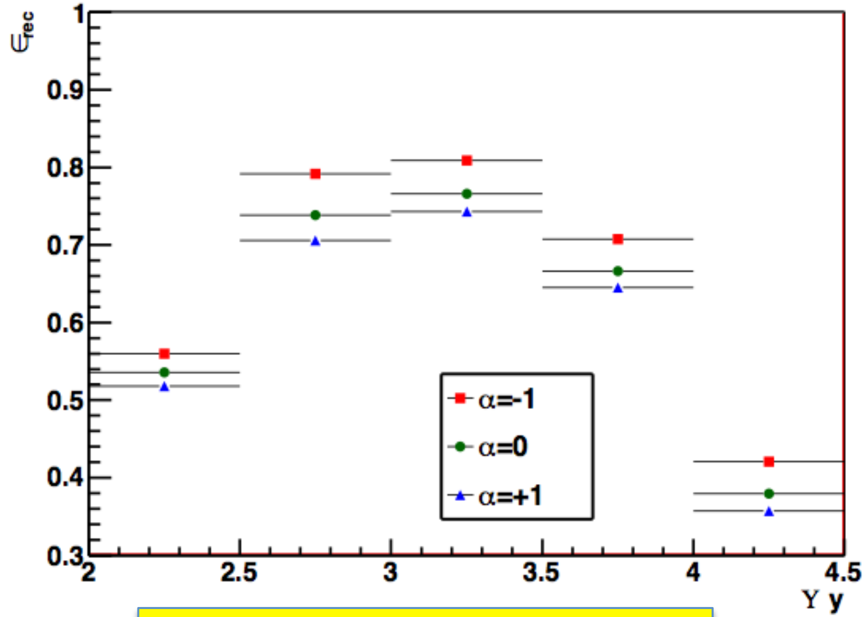
α = (σT −2σL)/(σT +2σL)
With σT /L cross sections for production of transverse and longitudinal polarised

α = −1 ->full longitudinal polarisation
α = +1 -> full transverse polarization,
α = 0 -> no polarisation

Polarisation effect on ε_{reco}

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

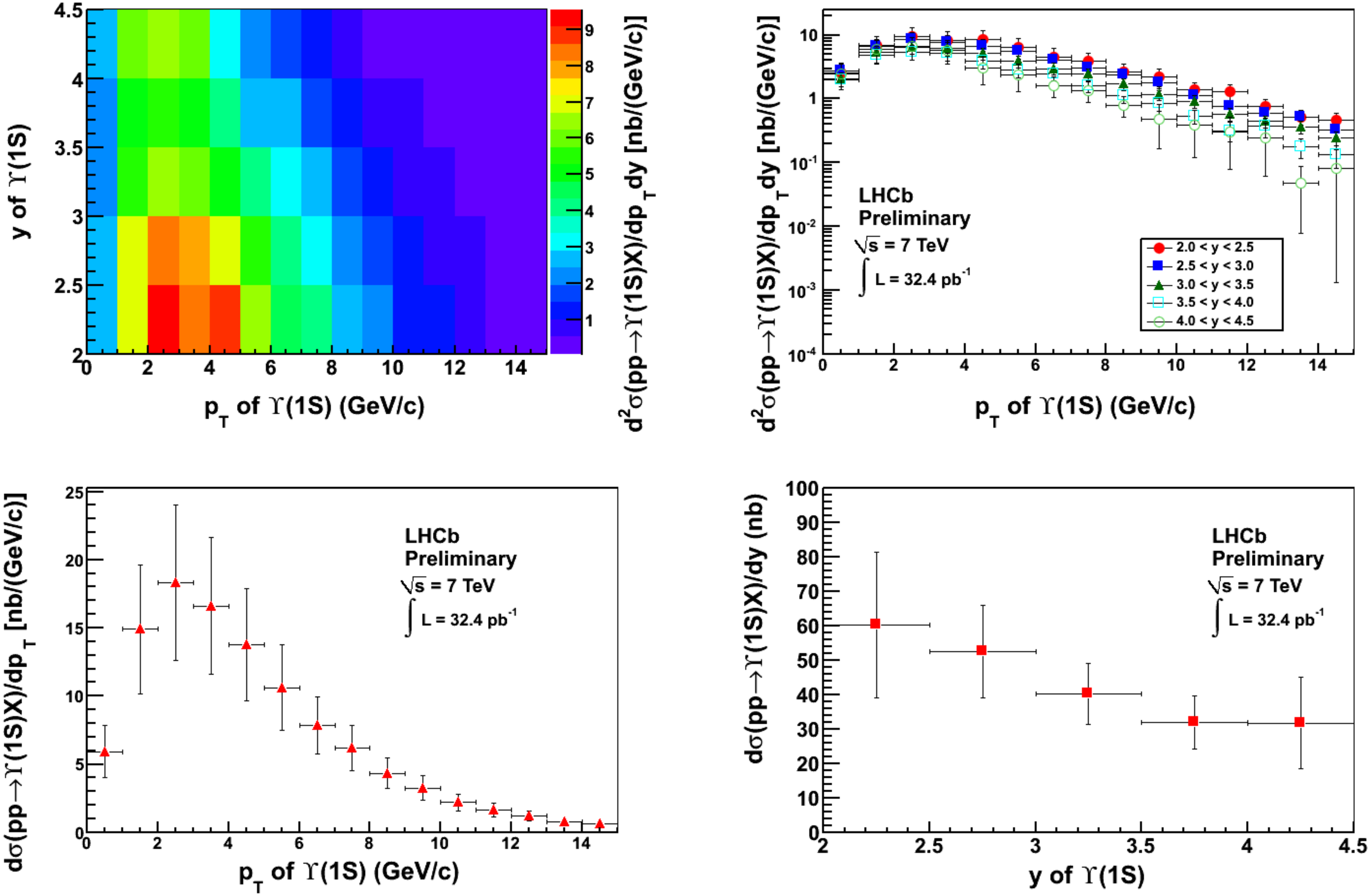




α = (σT −2σL)/(σT +2σL)
With σT /L cross sections
for production of transverse
and longitudinal polarised

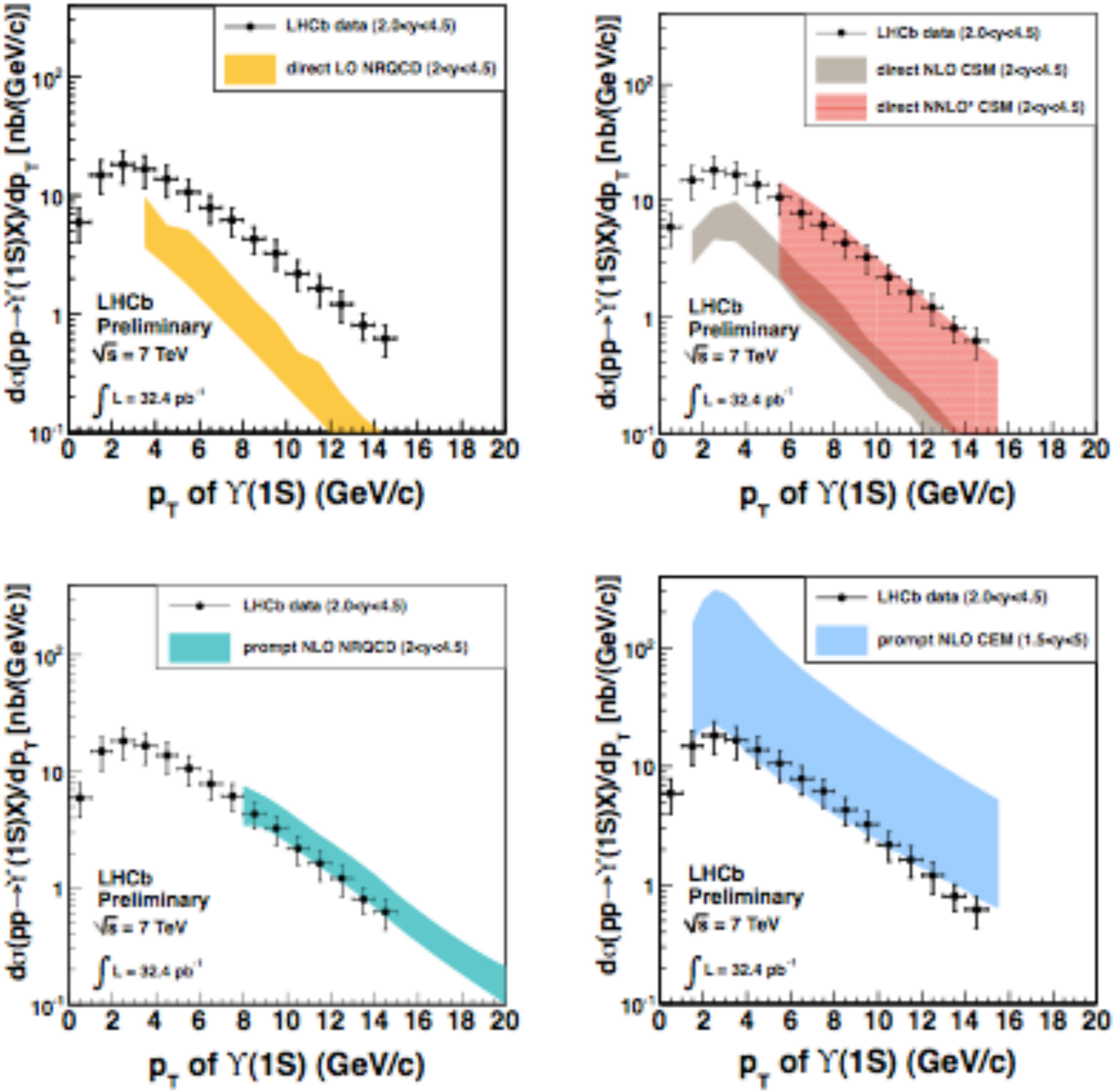
α = −1 ->full longitudinal polarisation
α = +1 -> full transverse polarization,
α = 0 -> no polarisation

Upsilon Cross Section

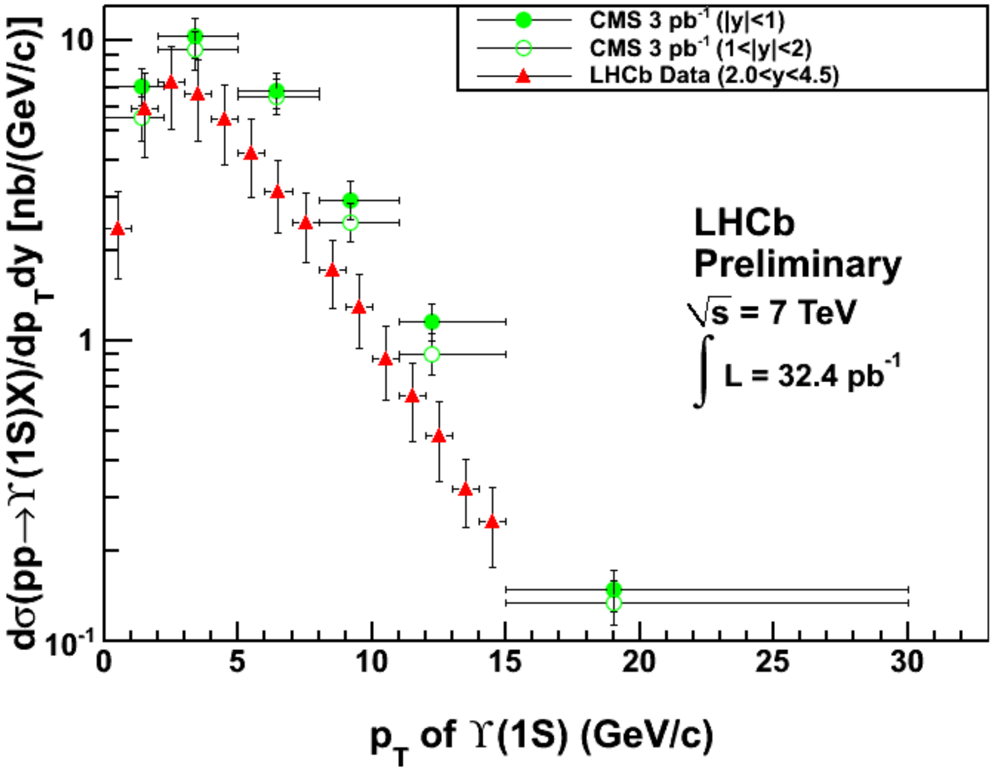


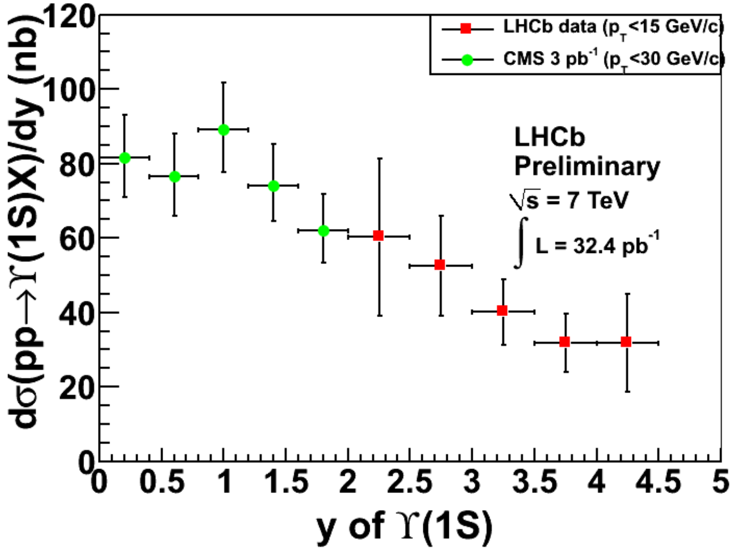
$$108.3 \pm 0.7(\text{stat})\,^{+18.8}_{-7.9}(\text{pola}) \pm 22.0(\text{osys}) \pm 10.8(\text{lumi})\ \text{nb} = 108.3 \pm 0.7(\text{stat})\,^{+30.9}_{-25.8}(\text{syst})\ \text{nb}$$

Comparison with Theory



Comparison with CMS

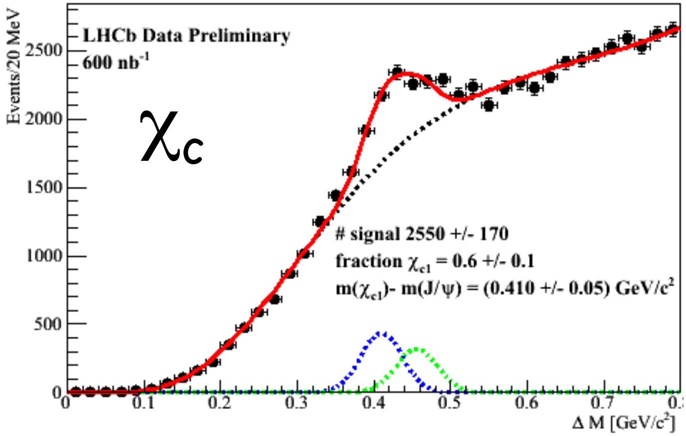




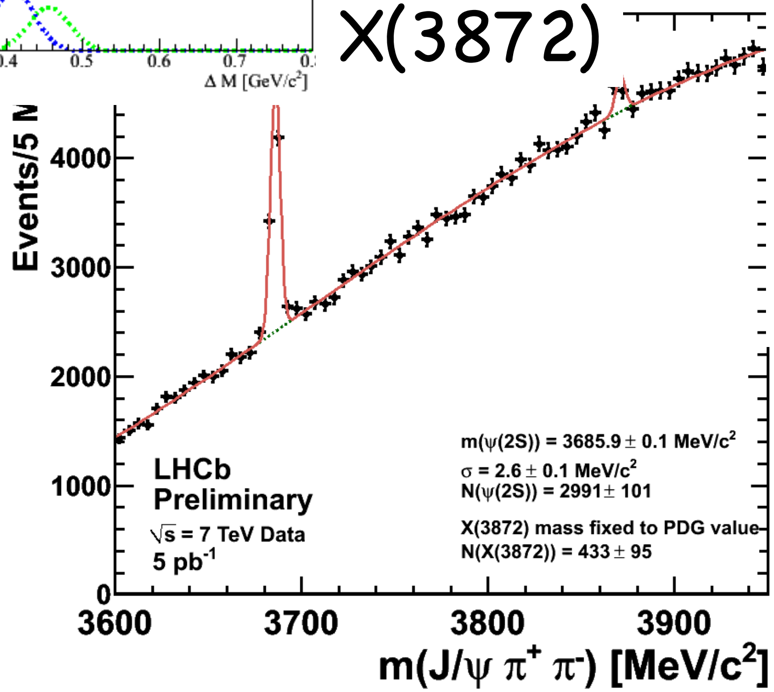
Conclusions

- 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 !

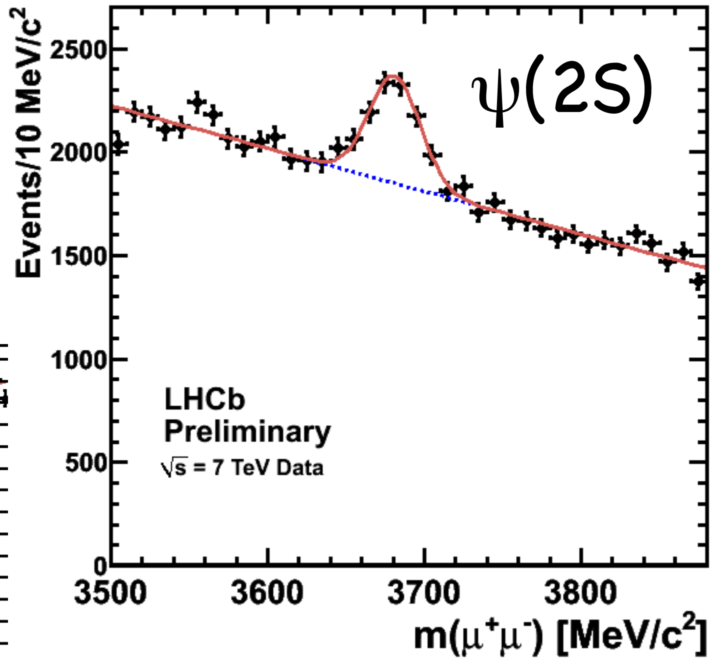
Next time…



LHCb Data Preliminary
600 nb^{-1}
χ_c
signal 2550 +/- 170
fraction χ_{c1} = 0.6 +/- 0.1
m(χ_{c1})- m(J/ψ) = (0.410 +/- 0.05) GeV/c^2
Events/20 MeV
Δ M [GeV/c^2]



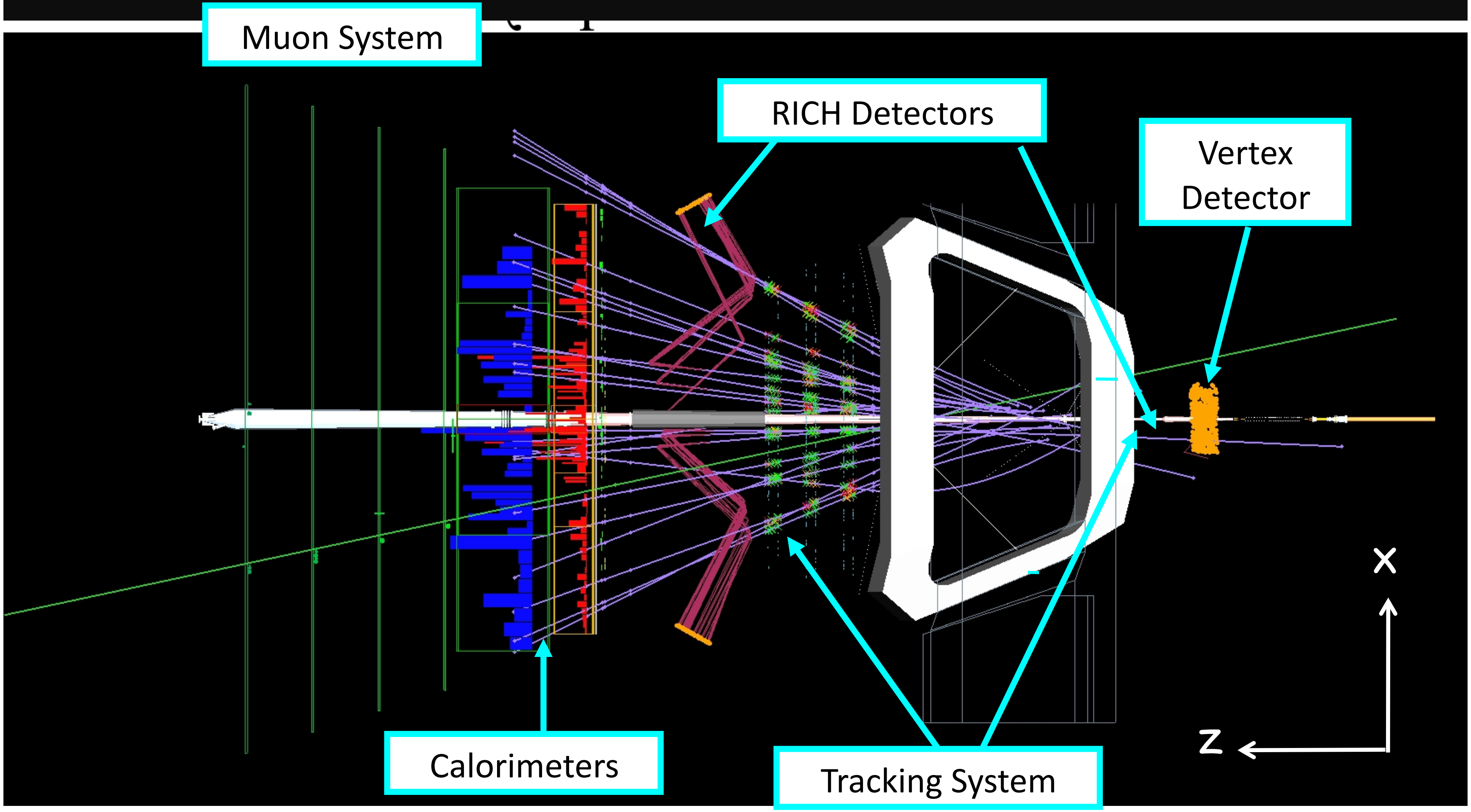
X(3872)
Events/5 MeV
LHCb
Preliminary
√s = 7 TeV Data
5 pb^{-1}
m(ψ(2S)) = 3685.9 ± 0.1 MeV/c^2
σ = 2.6 ± 0.1 MeV/c^2
N(ψ(2S)) = 2991 ± 101
X(3872) mass fixed to PDG value
N(X(3872)) = 433 ± 95
m(J/ψ π$^+$ π$^-$) [MeV/c^2]



ψ(2S)
Events/10 MeV/c^2
LHCb
Preliminary
√s = 7 TeV Data
m(μ$^+$μ$^-$) [MeV/c^2]

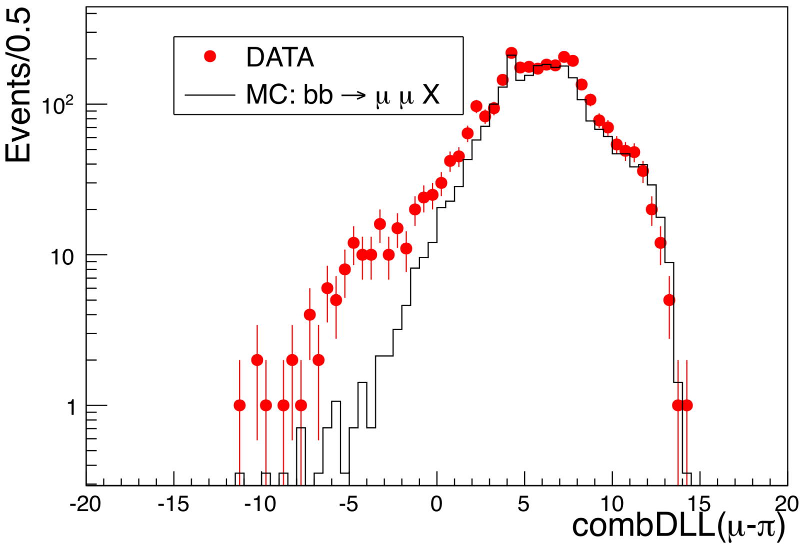
Back up

The LHCb detector

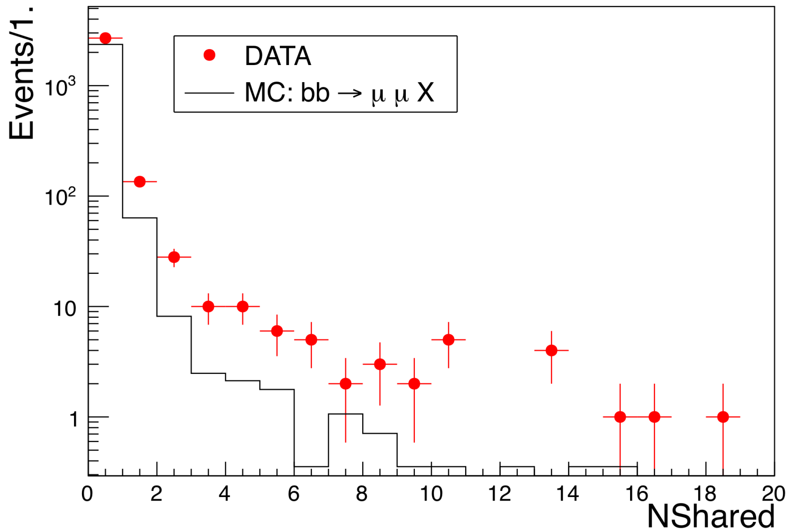


Muon Identification

MuonID Likelihood



Number of Muon Hits shared between tracks

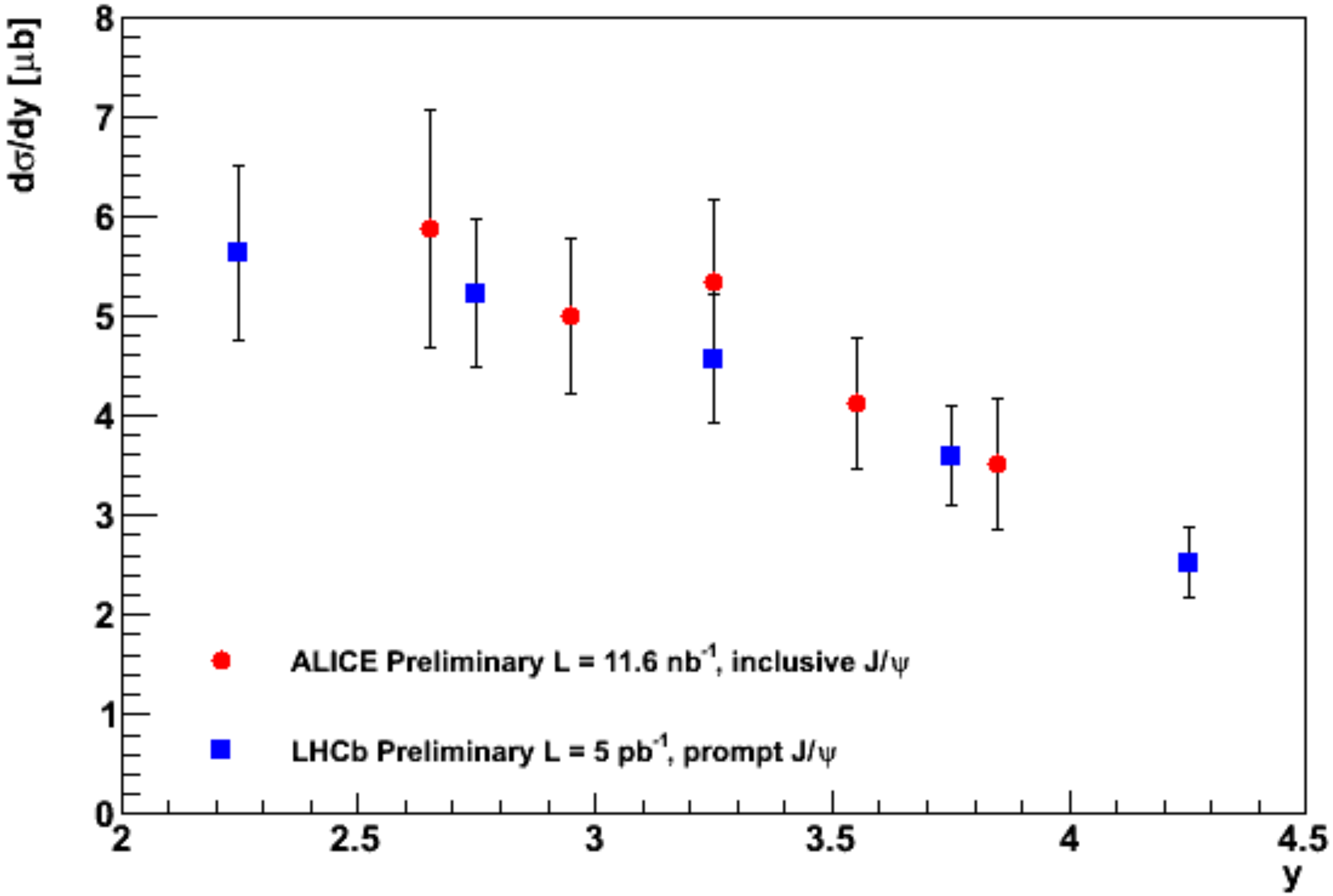


J/ψ integrated cross section measurements

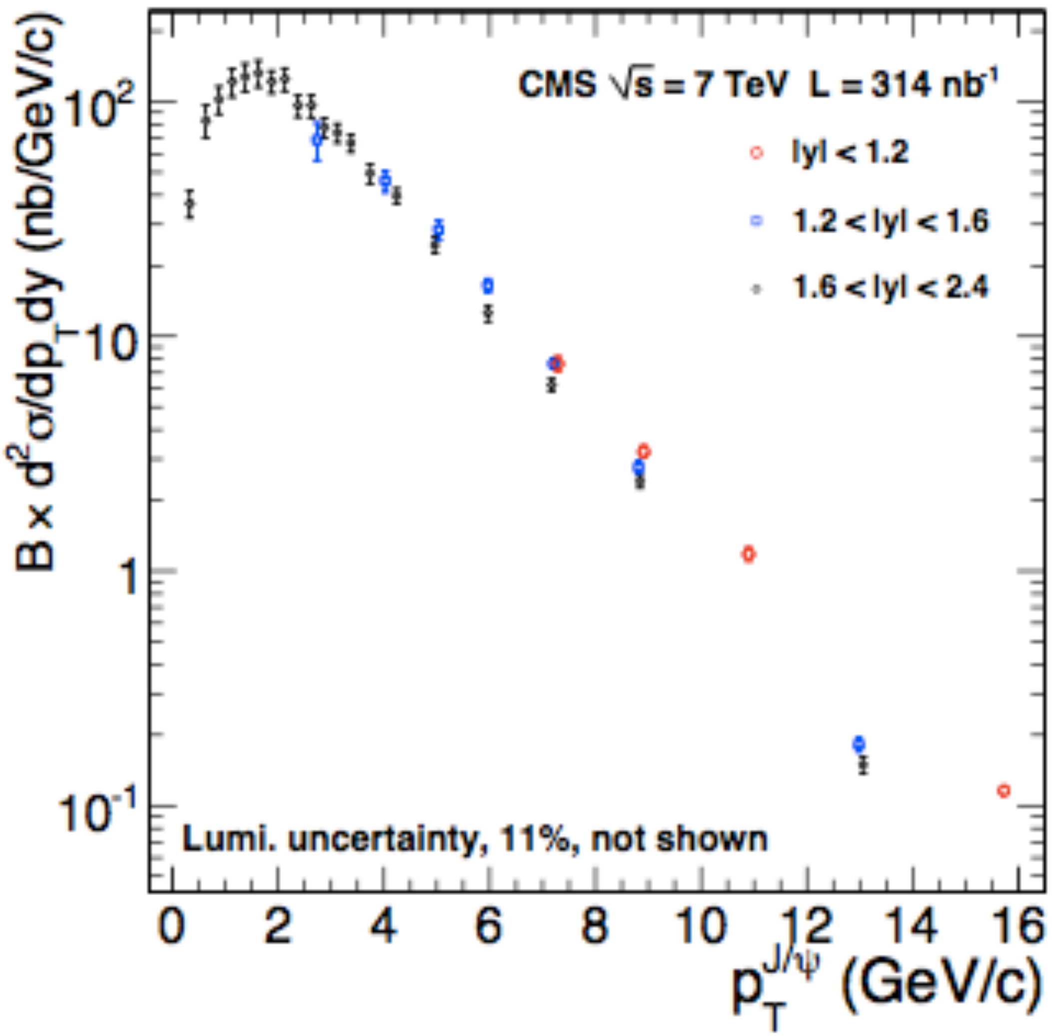
Experiment Range Luminosity	LHCb (in μb) pT<15 GeV, 2.0<y<4.5 14.2 pb^{-1}	5 pb^{-1}	CMS (in nb) 6.5(4)<pT<30 GeV, |y|<2.4 300(100) nb^{-1}	ATLAS (in nb) <y>~1.85 100 nb^{-1}
Inclusive J/ψ			289.1 ± 16.7 ± 60.1	250^{+130}_{-80}
Prompt J/ψ	7.65 ± 0.19 ± $1.10^{+0.87}_{-1.27}$	$10.52 \pm 0.04_{stat} \pm 1.40_{syst}{}^{+1.64}_{-2.20\ pol}$	70.9 ± 2.1± 3.0 ± 7.8 /BR=1195.6	
J/ψ from B	0.81 ± 0.06 ± 0.13	1.14±0.01±0.16	$26.0 \pm 1.4_{stat} \pm 1.6_{syst} \pm 2.9_{lum}$ /BR=438	
Total bb*	319 ± 24 ± 59	288 ± 4 ± 48		

* Extrapolating to the LHCb acceptance using Pythia 6.4

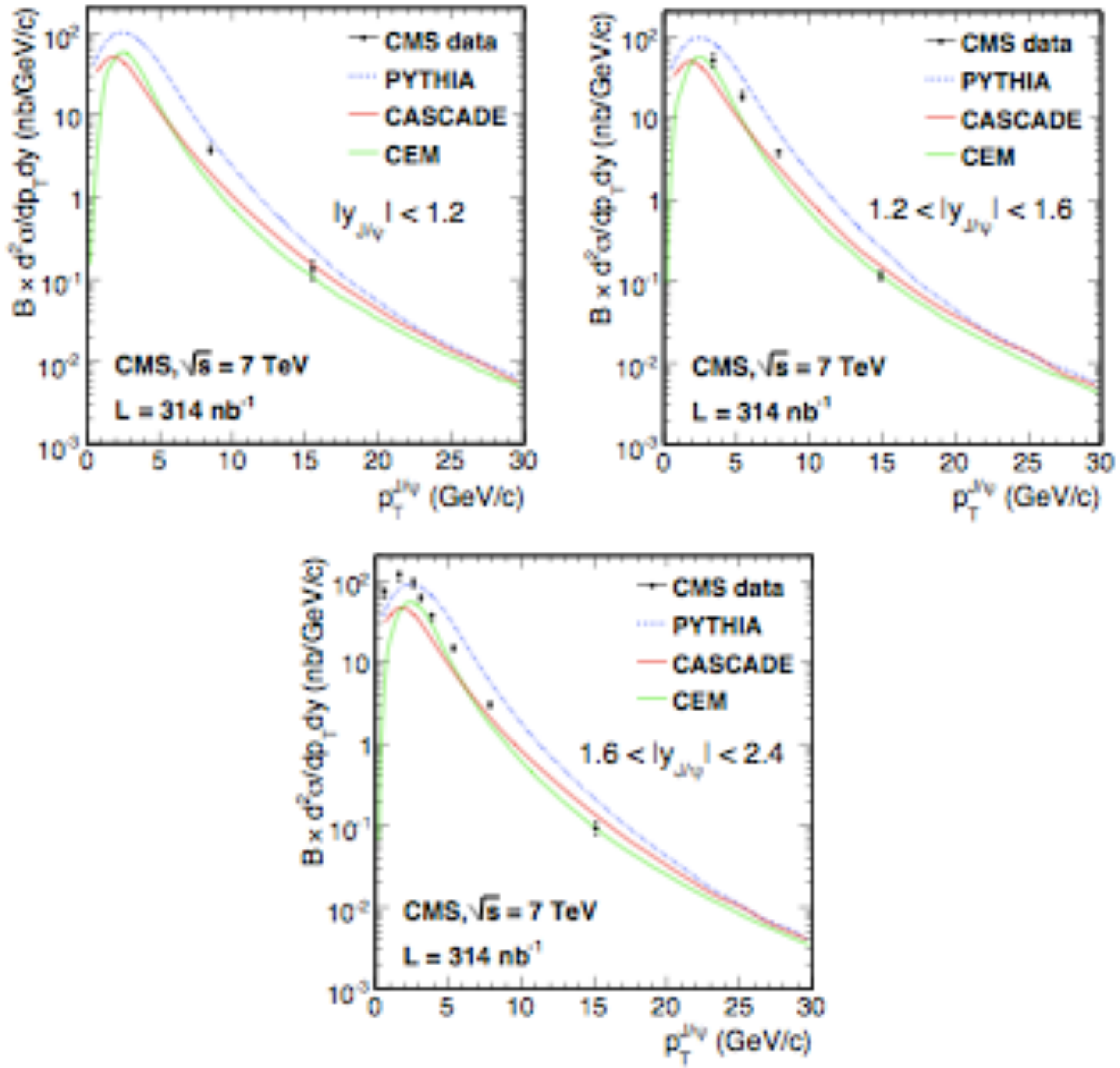
Alice updated J/psi



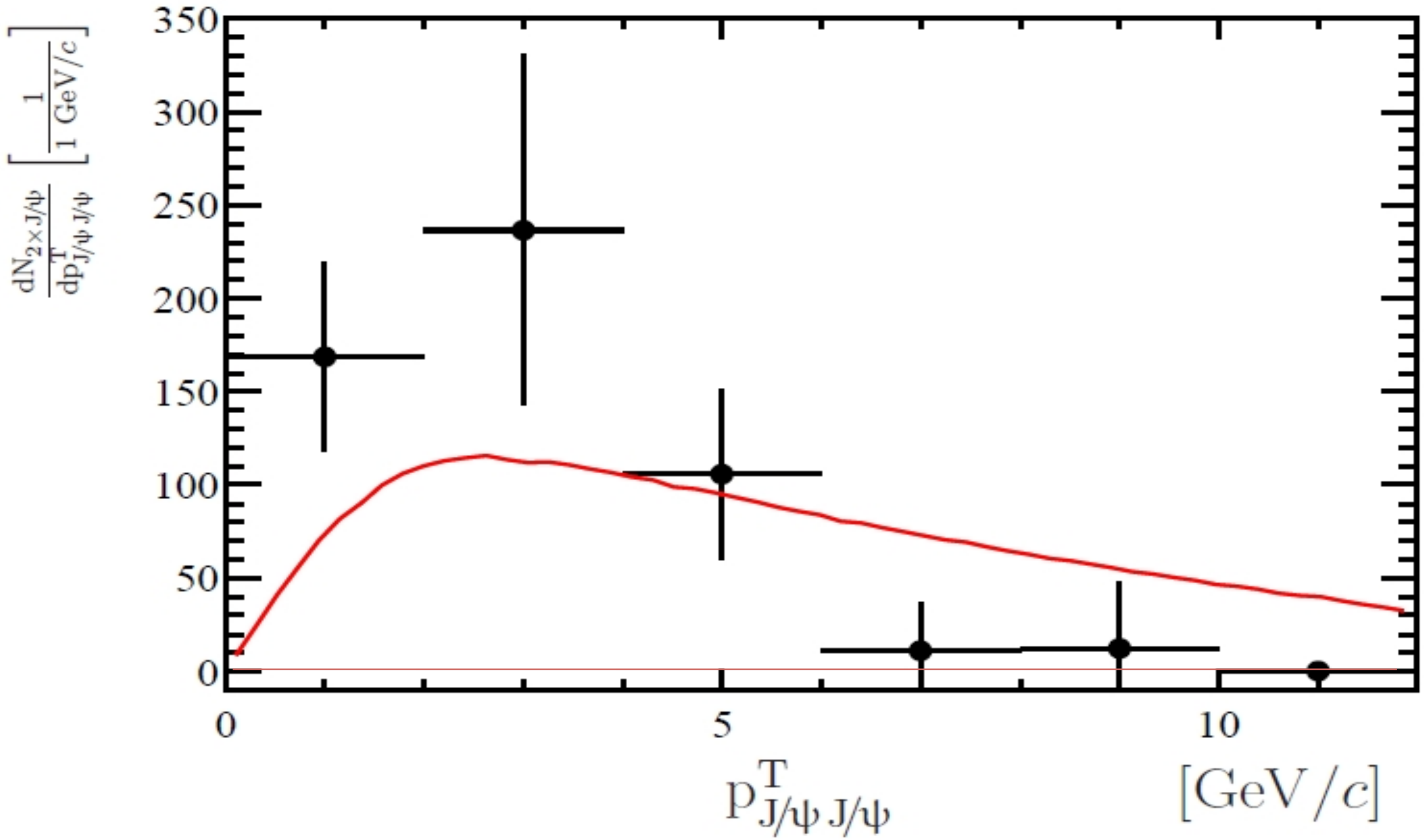
CMS Updated J/psi



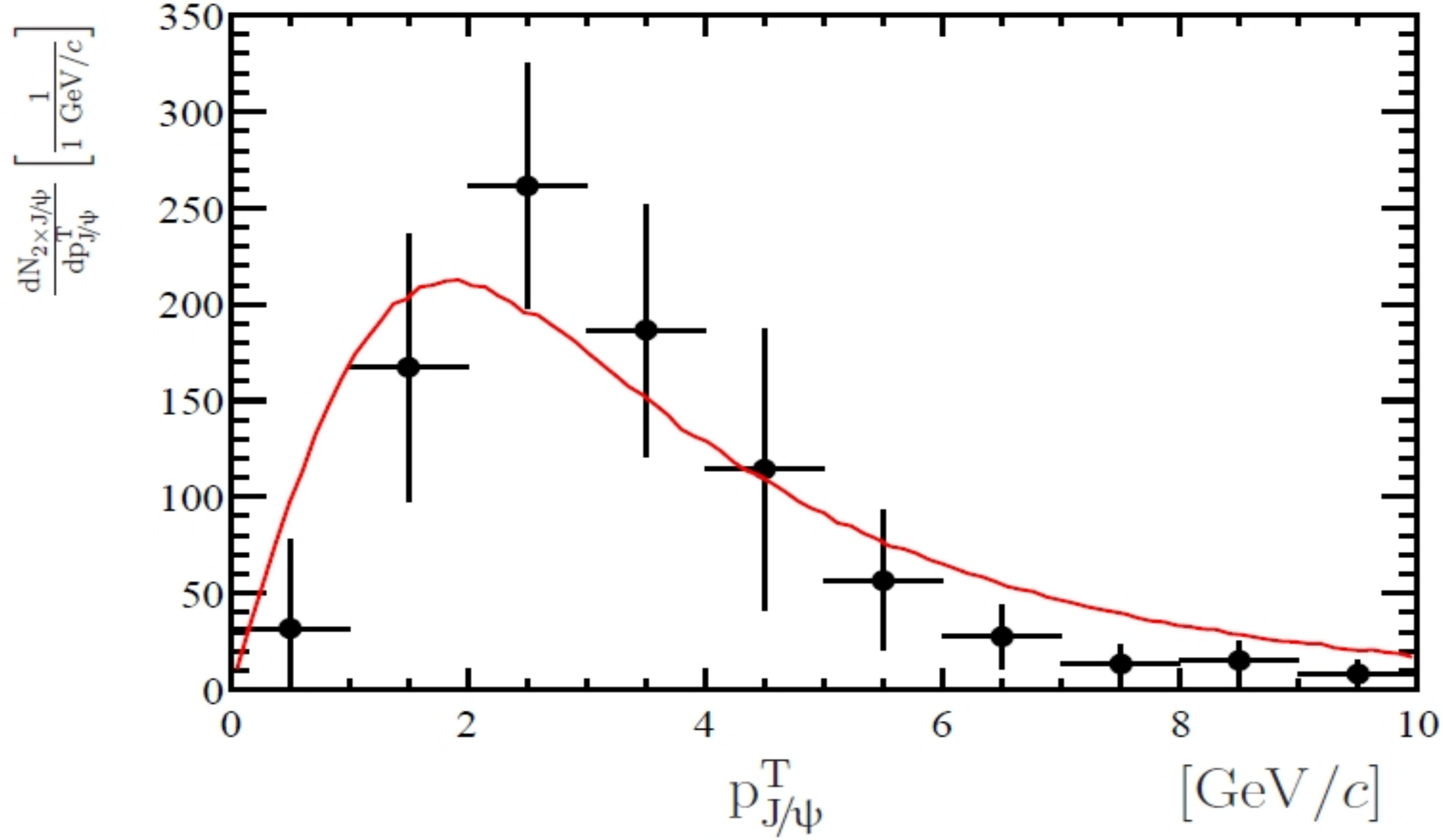
CMS Updated J/psi



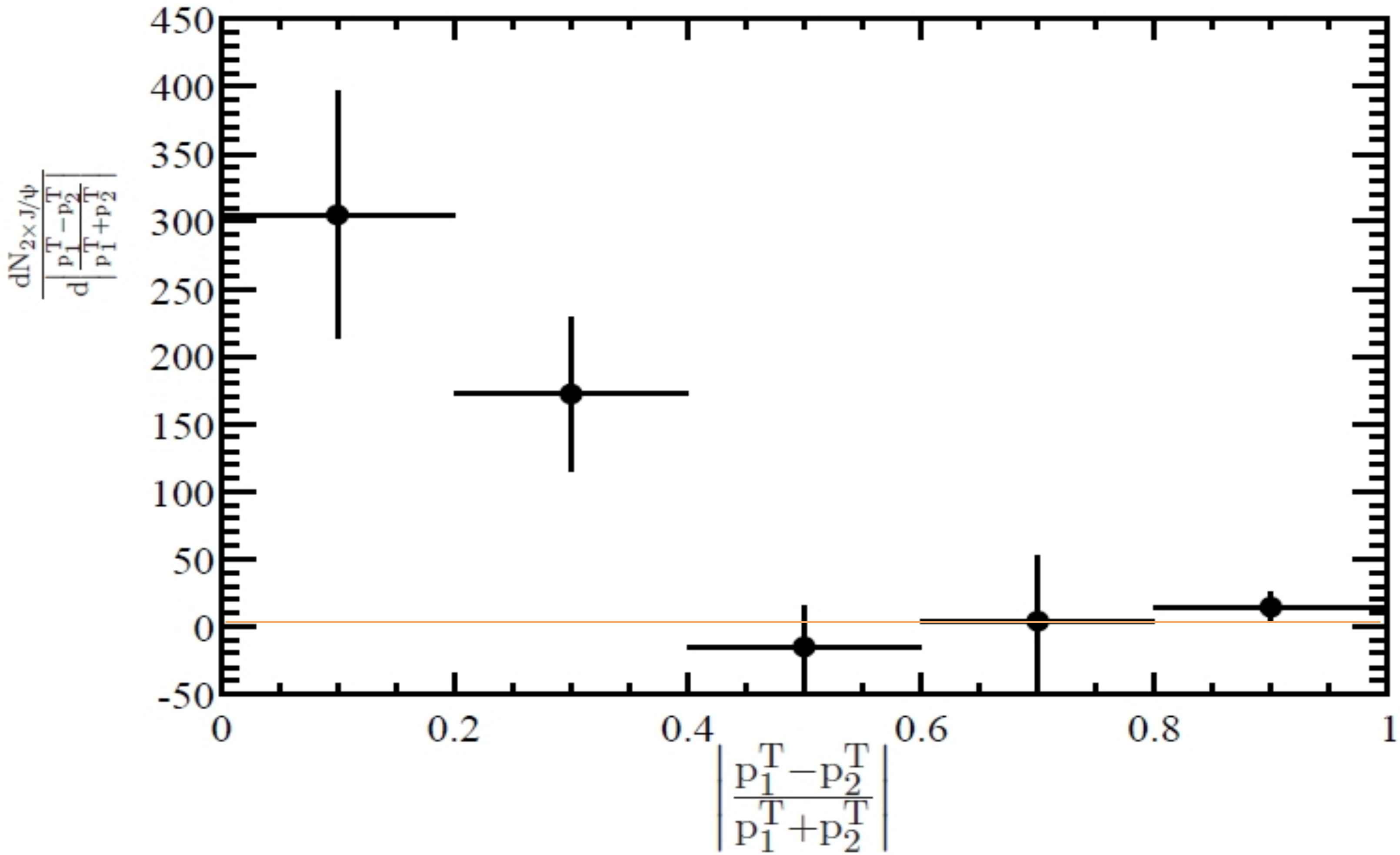
Efficiency corrected $p^T_{J/\psi J/\psi}$



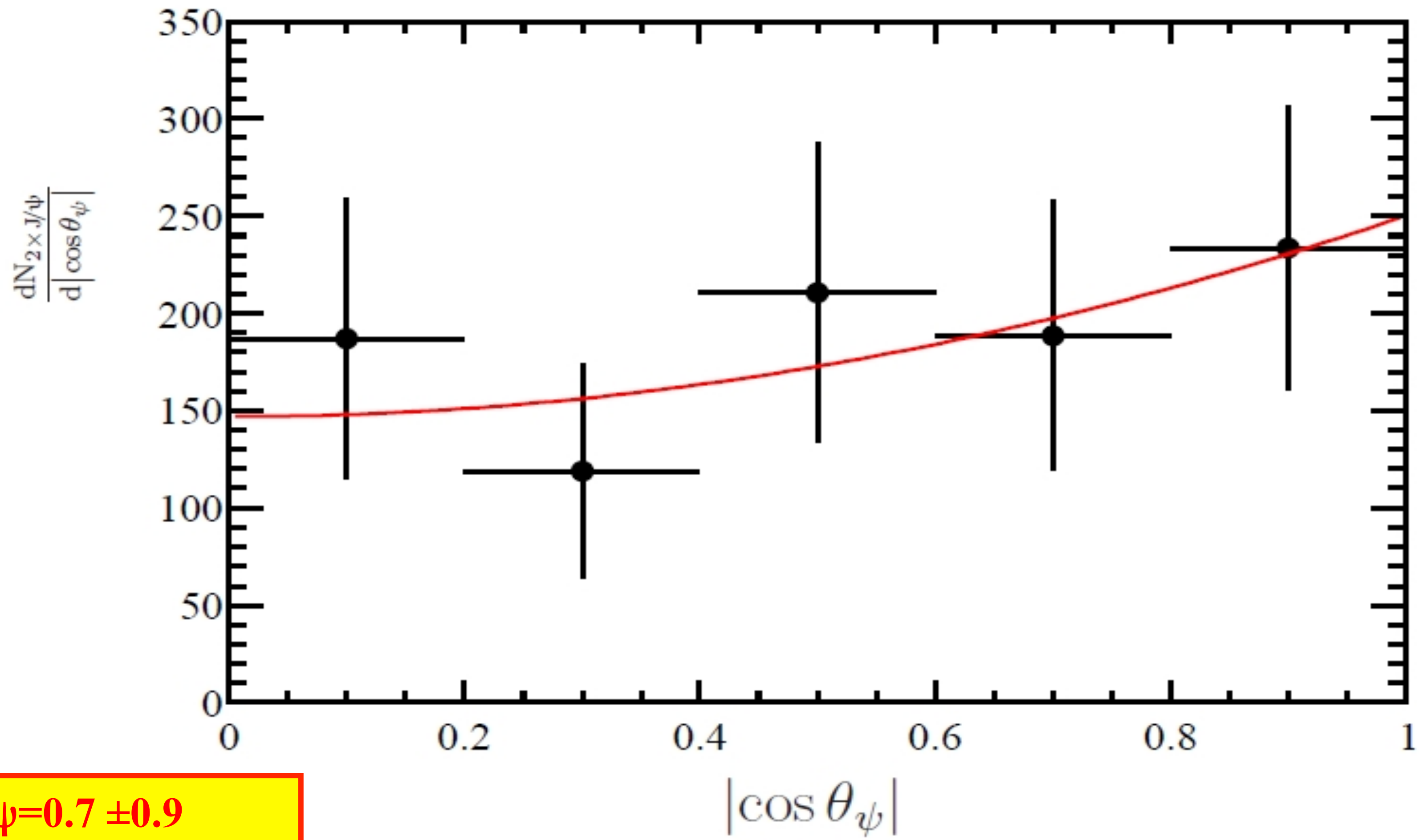
Efficiency corrected $p^T_{J/\psi}$ from $2\times J/\psi$



Efficiency corrected p^T-asymmetry

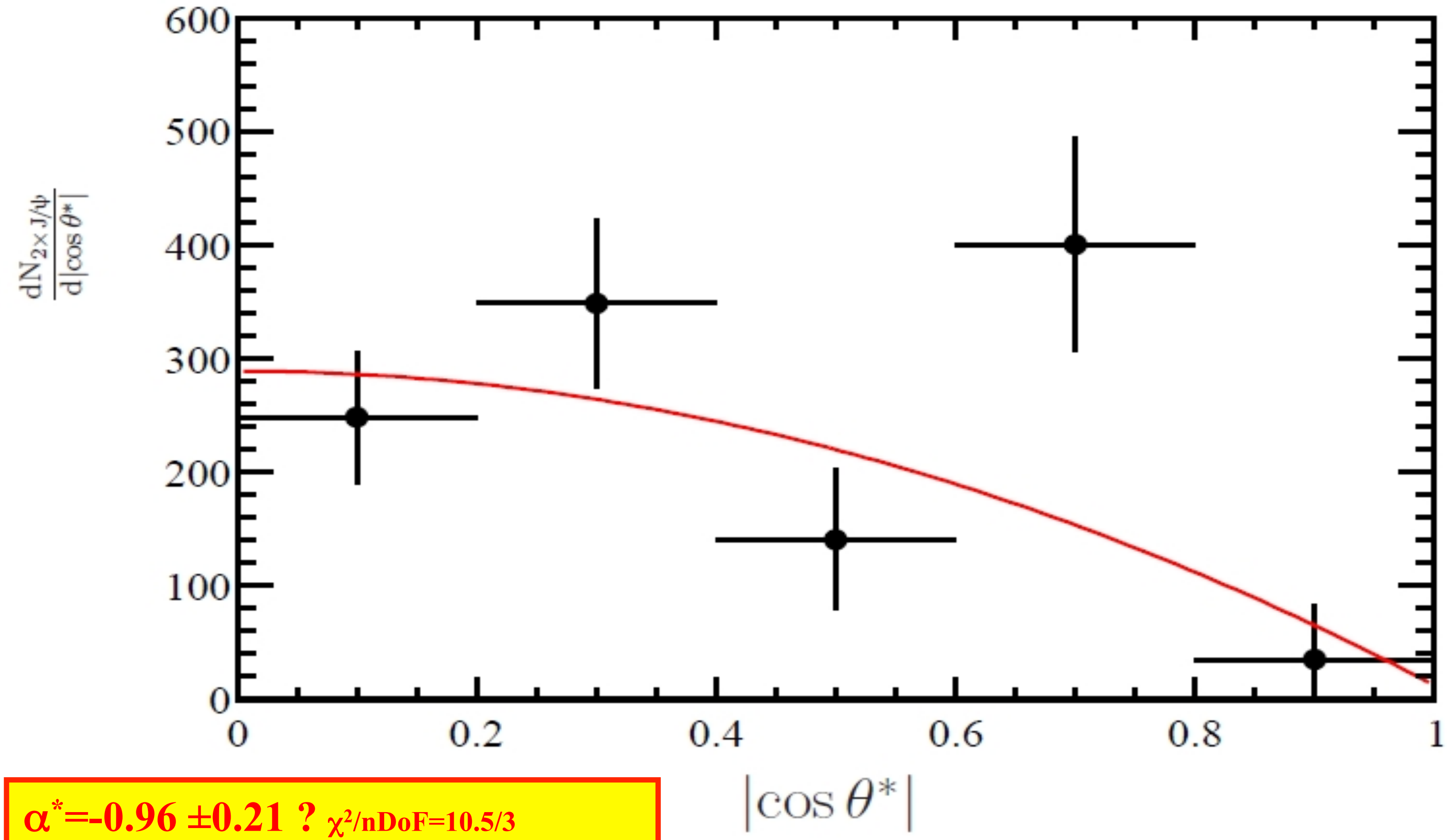


J/ψ polarization: $\cos\theta_\psi$



$\alpha\psi = 0.7 \pm 0.9$

J/ψ polarization: cosθ*

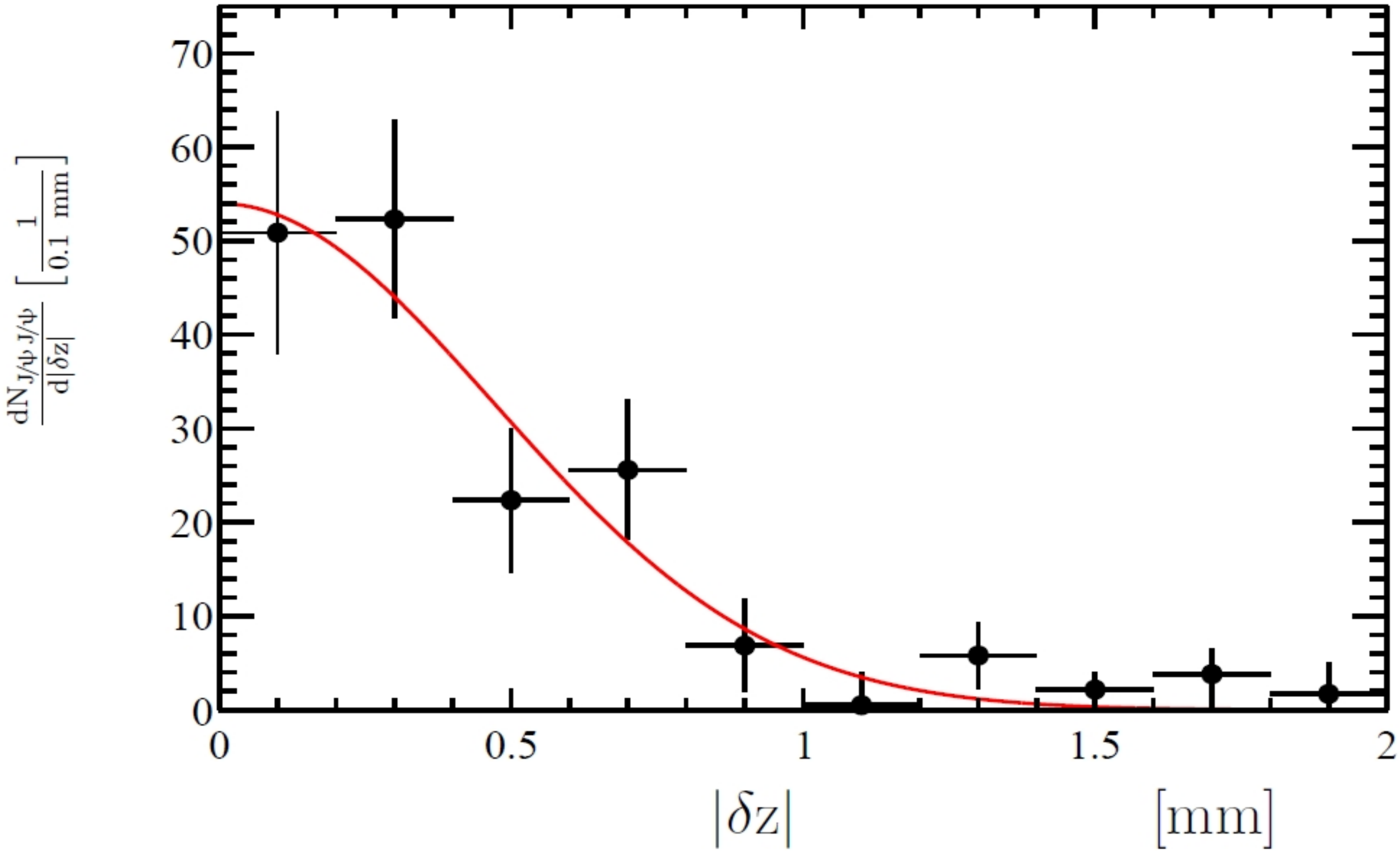


α^*=-0.96 ±0.21 ? χ^2/nDoF=10.5/3

Pileup: J/ψJ/ψ versus J/ψ+J/ψ

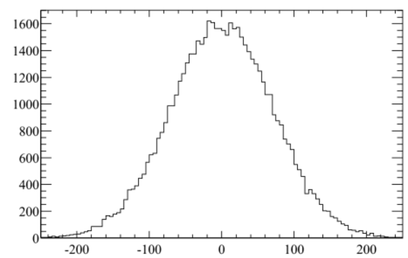
- How to prove that it is *NOT* pileup?
  - Monte Carlo
  - Look for data:
    - Distance between J/ψ vertices
    - Track in PV: ×2 larger for pileup
    - PV-multiplicity: -1 for pileup
    - Wide range $\chi^2_{DTF}/nDoF$ scan

J/ψJ/ψ distance

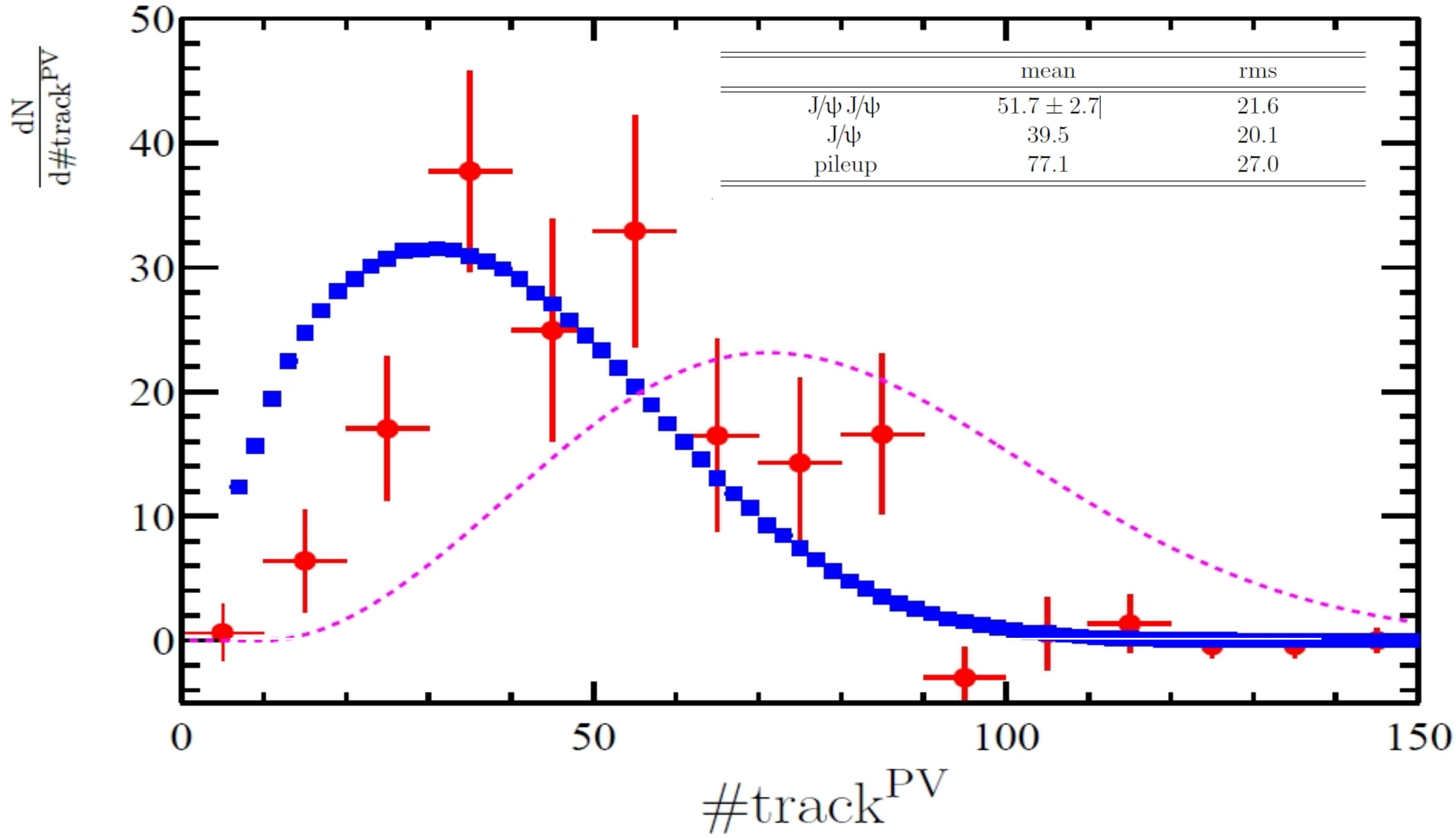


J/ψJ/ψ distance

- $\sigma^{|\delta z|} = 470 \pm 62\ \mu m$
- 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



	mean	rms
J/ψ J/ψ	51.7 ± 2.7	21.6
J/ψ	39.5	20.1
pileup	77.1	27.0

dN/d#track^PV
#track^PV
0
50
100
150
10
20
30
40

a) Number of Υ(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