Onia Studies at LHCb

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On behalf of the LHCb collaboration

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Charm and bottom quark production at the LHC

Outlines:

- New Results from J/ψ Cross Section Measurement via $J/\psi \to \mu^+\mu^-$ with 5.2 pb^{-1} Data
- Prospects from other Onia Signals
- Conclusion

* Now at Syracuse University

New Results from J/ψ Cross Section Measurement

Data Sample

- $5.2\ pb^{-1}$ data to update the ICHEP results

	ICHEP Data ($14.2\ nb^{-1}$)	Current Analysis ($5.2\ pb^{-1}$)
p_T	[0-10] GeV/*c*, 10 bins	[0-14] GeV/*c*, 14 bins
y	[2.5,4], 1 bin	[2,4.5], 5 bins

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

- Collected in Sep-Oct 2010 with two trigger settings

Trigger 1: $(2.22\pm0.17)\ pb^{-1}$

Trigger 2: $(2.98\pm0.30)\ pb^{-1}$, with one muon line prescaled

Two different trigger efficiencies will be applied

In total: $5.20\pm0.52\ pb^{-1}$

Trigger and Selection Criteria

L0 Trigger	**Single Muon:**	**p_T>1.4 GeV/*c***
	Di-Muon:	**$p_{T,1}$>0.56 GeV/*c*, $p_{T,2}$>0.48 GeV/*c***
Hlt1 Trigger	**Single Muon:**	**Confirm L0 single Muon and p_T>1.8 GeV/*c* (Pre-scaled in Trigger 2 by 0.2)**
	Di-Muon:	**Confirm L0 Di-Muon and $M_{\mu\mu}$>2.5 GeV/c^2**
Hlt2 Trigger	**Di-Muon:**	**$M_{\mu\mu}$>2.9 GeV/c^2**

Only J/ψ that have fired the trigger will be considered

Selection Criteria

Both μ tracks:

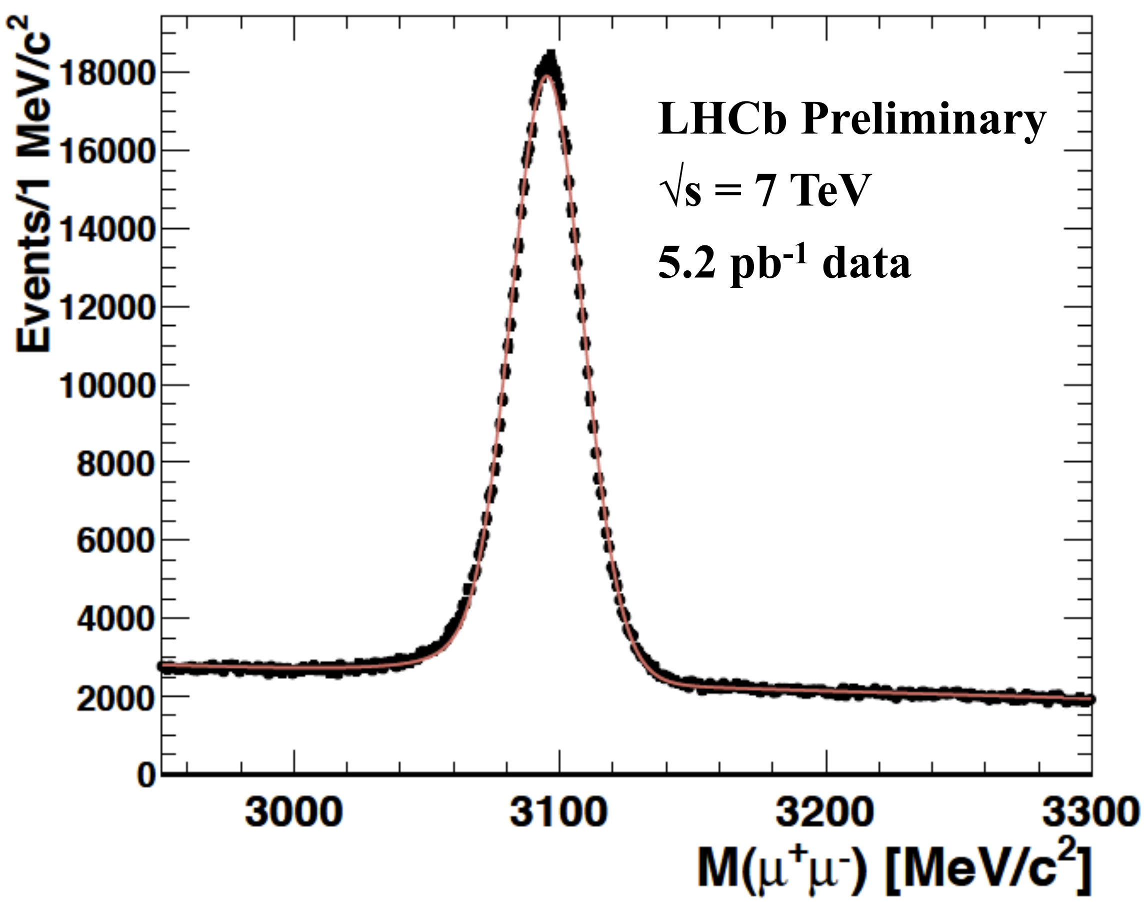
- **Well reconstructed tracks identified as muons**
- **p_T > 0.7 GeV/*c***
- **Track quality (χ^2/nDoF < 4)**

Reconstructed J/ψ:

- **Mass window: ±0.15 GeV/c^2**
- **vertex fit quality (p(χ^2)>0.5%)**

Event: At least one primary vertex (PV) for proper time calculation

J/ψ Yields



- ➢ Mass fit done in 14×5 bins with Crystal Ball function + exponential function
- ➢ Summing of fit results from 70 bins
- ➢ J/ψ: 564603±924 (ICHEP:2872±73)

$$f(m,\mu,\sigma,\alpha,n) = \begin{cases} \dfrac{\left(\frac{n}{|\alpha|}\right)^n e^{-\frac{1}{2}\alpha^2}}{\left(\frac{n}{|\alpha|} - |\alpha| - \frac{m-\mu}{\sigma}\right)^n} & \dfrac{m-\mu}{\sigma} < -|\alpha| \\ \exp\left(-\dfrac{1}{2}\left(\dfrac{m-\mu}{\sigma}\right)^2\right) & \dfrac{m-\mu}{\sigma} > -|\alpha|, \end{cases}$$

μ: J/ψ nominal mass
σ: mass resolution
α, n: CB parameters

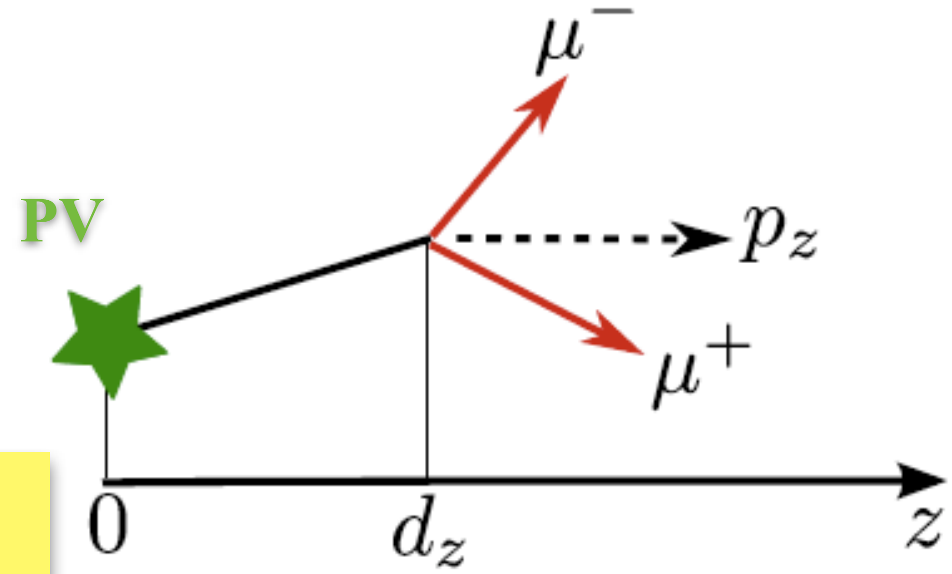
Cross section measurement strategy:

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

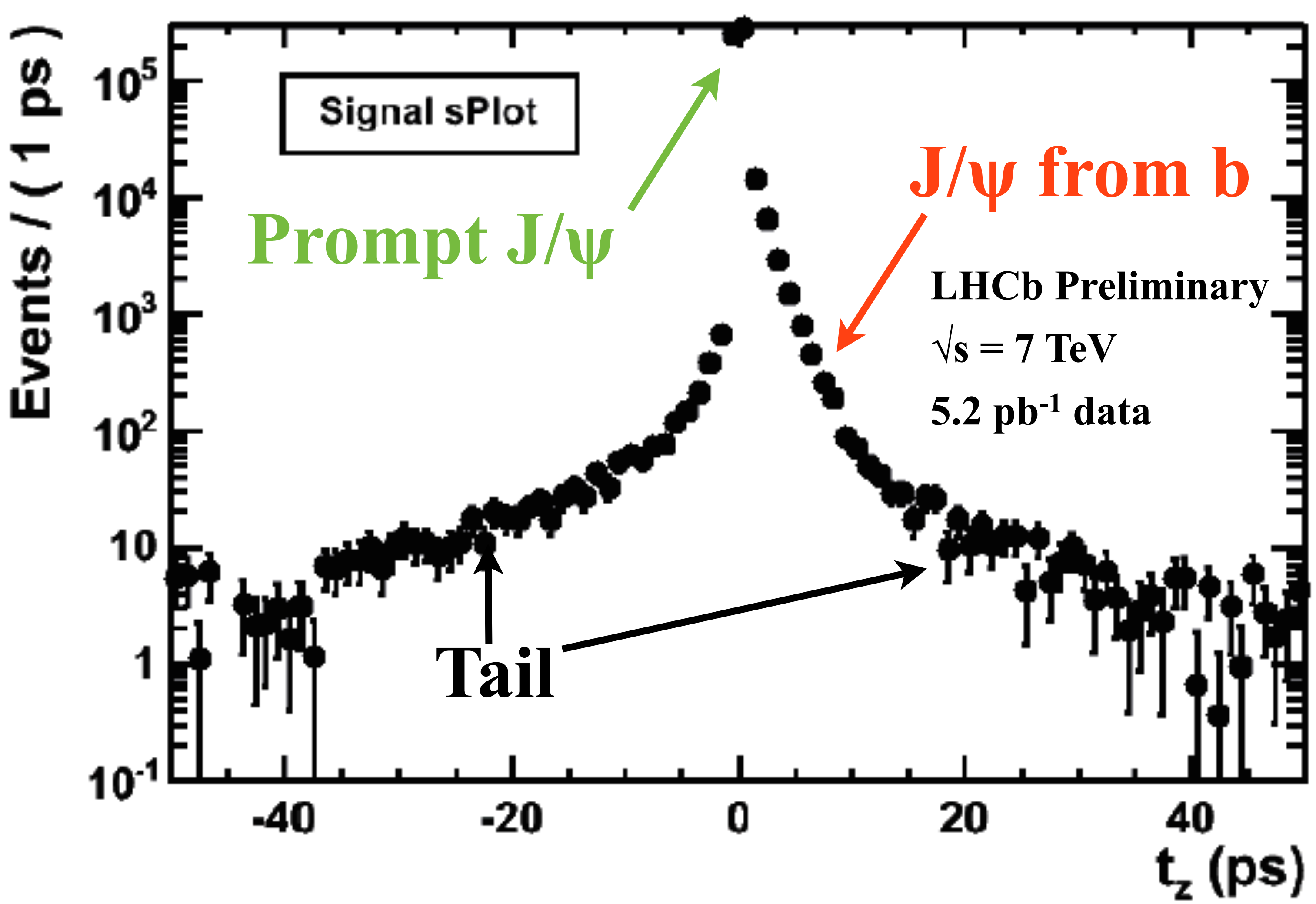
- N : Number of observed signal (prompt J/ψ and J/ψ from b)
- $\mathcal{L}$: Integrated luminosity (5.2 pb^{-1})
- ϵ_{tot} : Total efficiency for the channel (acceptance efficiency, reconstruction efficiency, trigger efficiency)
- $\mathcal{B}$: Branching ratio for the channel (Br($J/\psi \to \mu^+\mu^-$)= (5.94±0.06)%
- Δy : bin size (0.5)
- Δp_T : bin size (1 GeV/*c*)

Separation of Prompt and b Components

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



d_z: $Z_{J/\psi} - Z_{PV}$ where Z is the vertex position in axis-Z
p_z: J/ψ momentum in z direction
$M_{J/\psi}$: nominal J/ψ mass



Prompt J/ψ: centered around 0, parameterized as resolution function

J/ψ from b: parametrized as an exponential function convoluted with resolution function

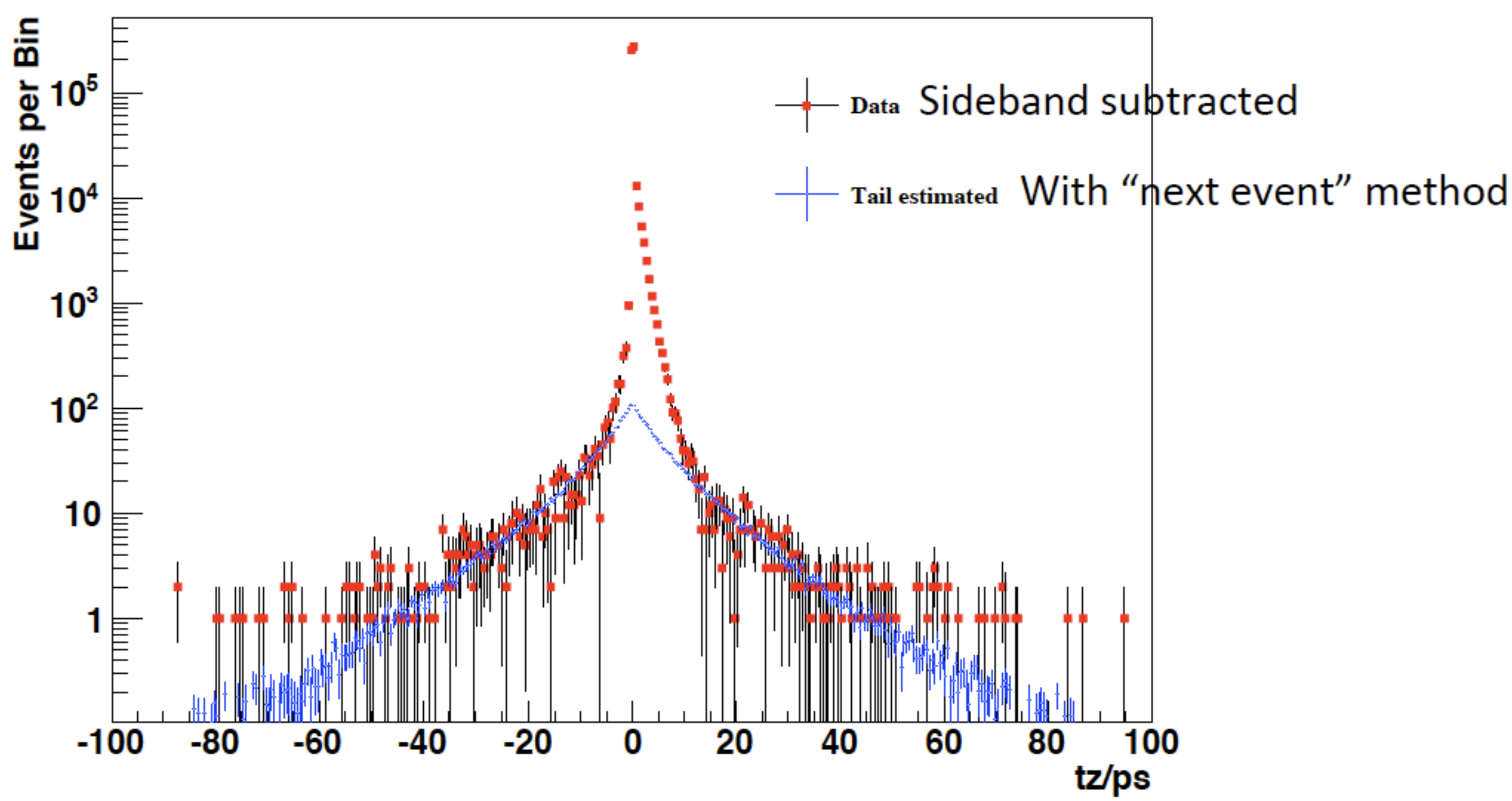
Tail Component

➢ Origin of the tail are signal J/ψ associated with wrong primary vertex, because:

- The correct primary vertex is not reconstructed
- Another primary vertex is reconstructed close to the correct one (the reconstructed and unreconstructed primary vertex are correlated, this is included in resolution function)

➢ The shape of the tail distribution is determined directly from data, using the next event method: Simulate an uncorrelated primary vertex using one of the following events in the J/ψ event list

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



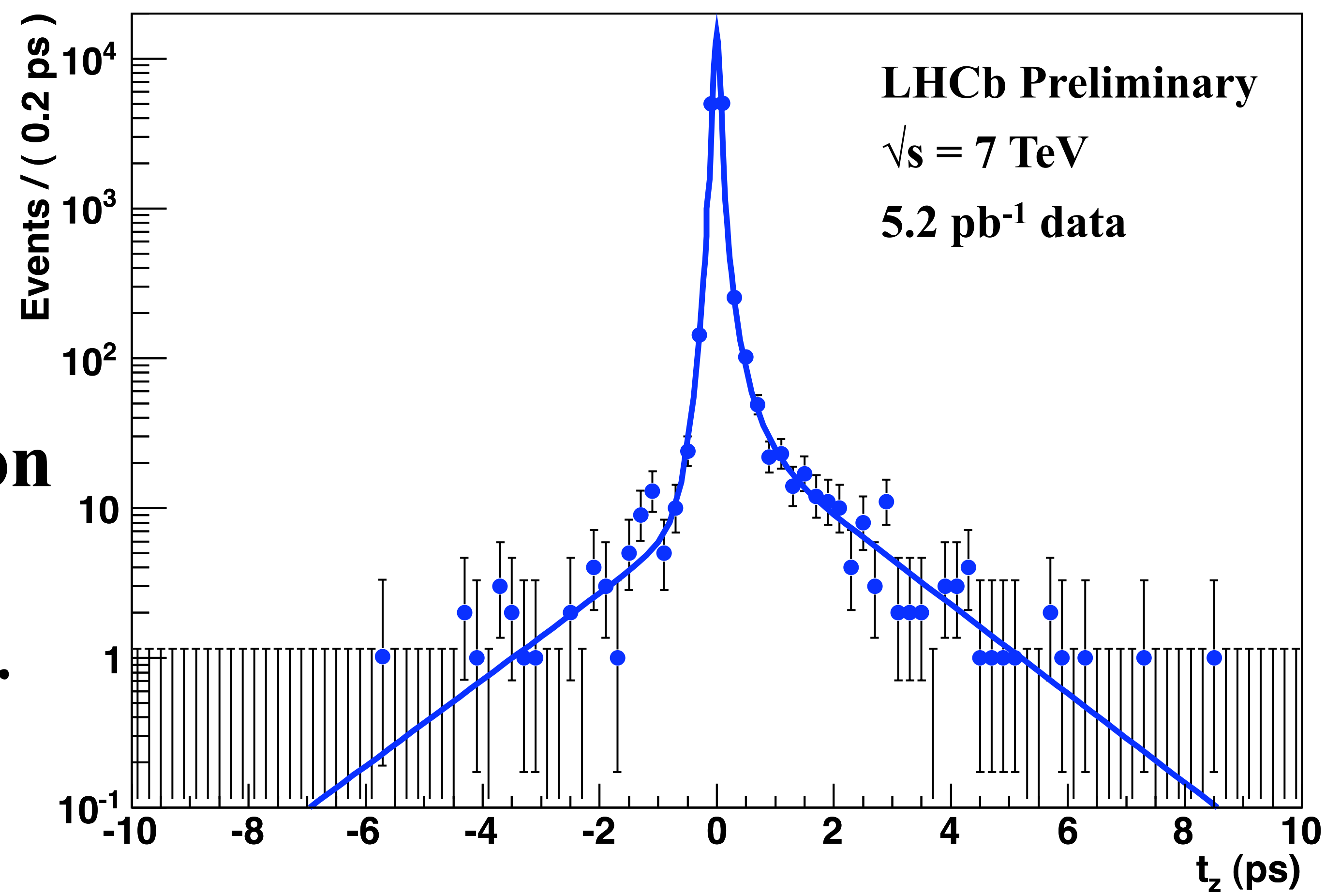
Combined Fit Function

➢ Combined fit over mass and t_z with per-event error

$$\text{Fit Function} = n_{J/\psi} F_{J/\psi}(t_z) G_{J/\psi}(m) + n_{\text{bkg}} F_{\text{bkg}}(t_z) G_{\text{bkg}}(m)$$

$$F_{\text{bkg}}(t_z) = \Big[(1-f_1-f_2-f_3-f_4)\delta(t_z) + \theta(t_z)\left(f_1\frac{e^{-t_z/\tau_1}}{\tau_1} + f_2\frac{e^{-t_z/\tau_2}}{\tau_2}\right) + \theta(-t_z)\left(f_3\frac{e^{-t_z/\tau_3}}{\tau_3}\right) + f_4\frac{e^{-|t_z|/\tau_4}}{2\tau_4}\Big] \otimes \left(\frac{\beta'}{\sqrt{2\pi}s'_1\sigma}e^{-\frac{(t_z-\mu'_0)^2}{2s'^2_1\sigma^2}} + \frac{1-\beta'}{\sqrt{2\pi}s'_2\sigma}e^{-\frac{(t_z-\mu'_0)^2}{2s'^2_2\sigma^2}}\right)$$

Sideband: [2.95,3.0]∪[3.2,3.25] GeV/c^2



Bin: p_T in [3,4] GeV/c
y in [2.5,3]

χ^2/nDoF = 0.51

➢ Long lifetime part due to association of tracks from b decays

➢ Number of parameters reduced for low statistics case

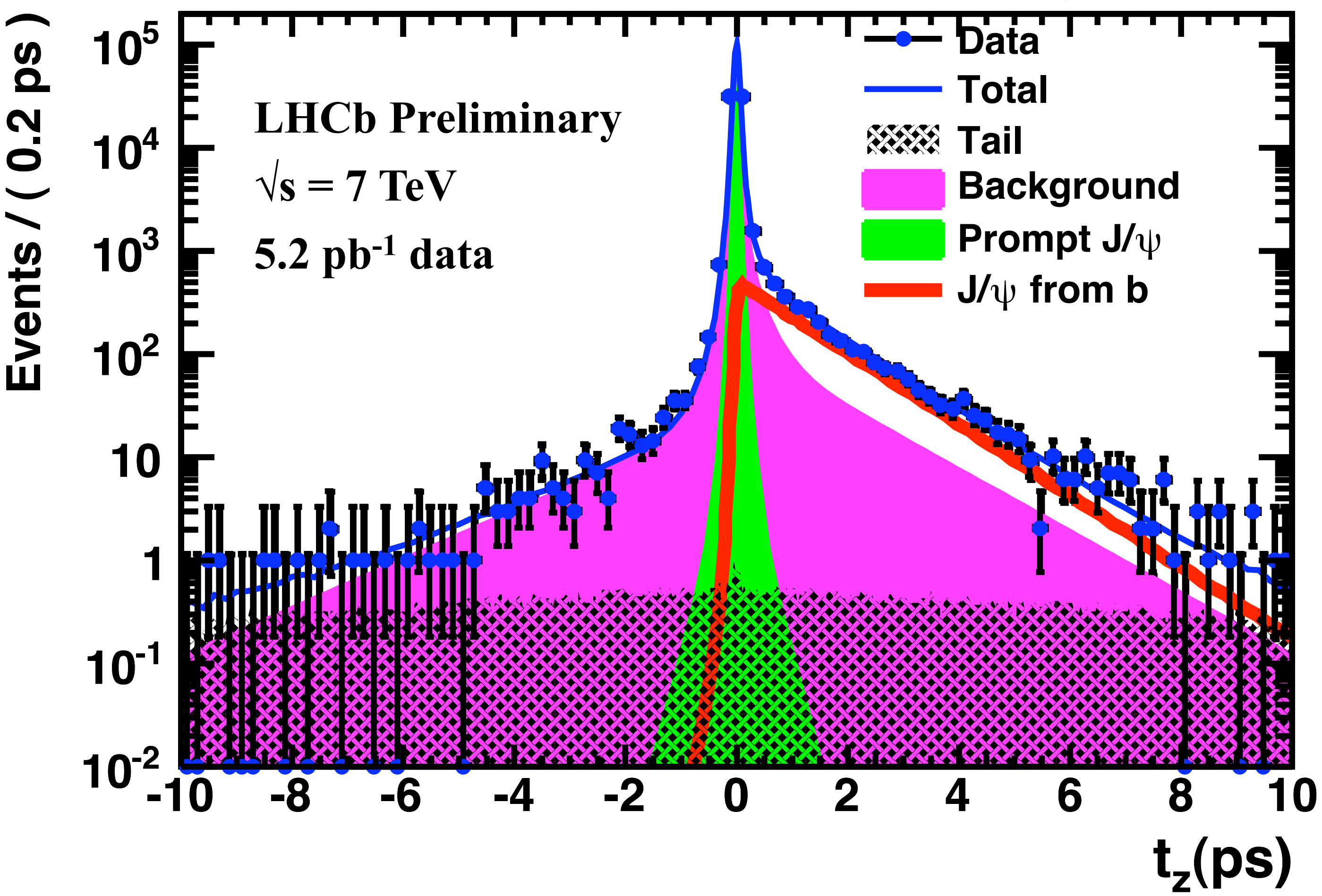
➢ Background parameters are fixed once obtained from fit to the sidebands t_z dsitribution

Combined Fit Function

➢ Combined fit over mass and t_z with per-event error

$$\text{Fit Function} = n_{J/\psi} F_{J/\psi}(t_z) G_{J/\psi}(m) + n_{\text{bkg}} F_{\text{bkg}}(t_z) G_{\text{bkg}}(m)$$

Bin: p_T in [3,4] GeV/c
y in [2.5,3]



χ^2/nDoF = 0.79

Prompt J/ψ: $n_p \delta(t_z) \otimes \text{Resolution}$

J/ψ from b: $\dfrac{n_b e^{-t_z/\tau}}{\tau} \otimes \text{Resolution}$

$$\text{Resolution} = \frac{\beta}{\sqrt{2\pi} s_1 \sigma} e^{-\frac{(t_z-\mu_0)^2}{2s_1^2\sigma^2}} + \frac{1-\beta}{\sqrt{2\pi} s_2 \sigma} e^{-\frac{(t_z-\mu_0)^2}{2s_2^2\sigma^2}}$$

Tail: with next event method

Background: from sidebands

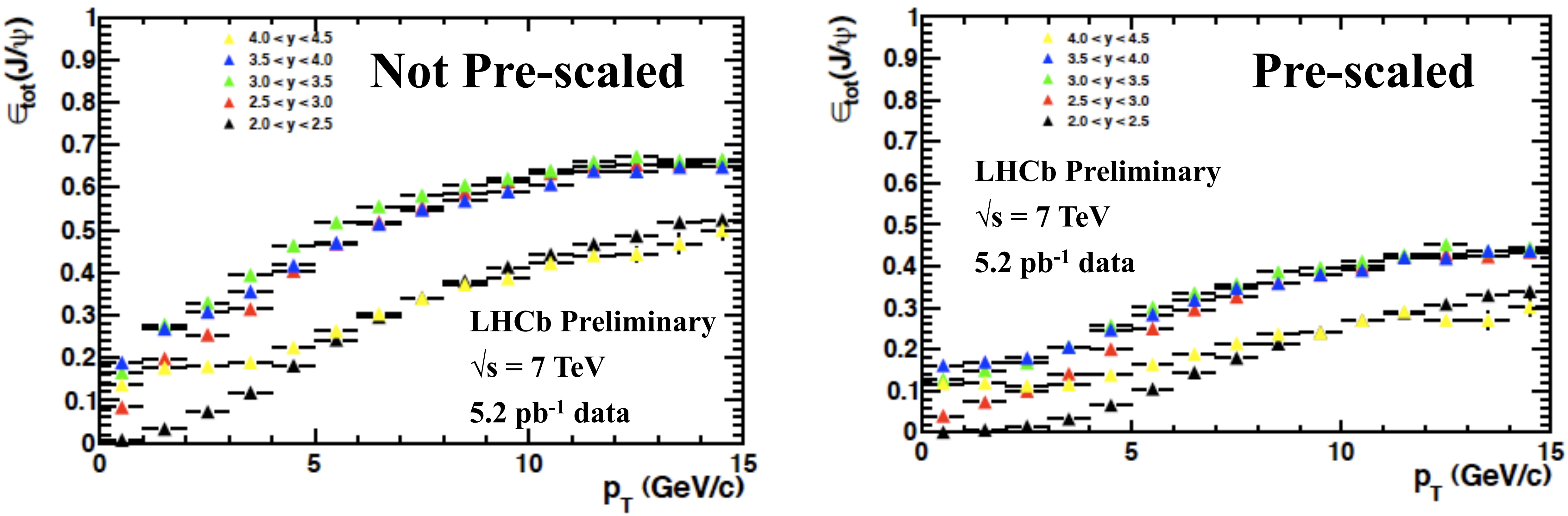
$$n_p = 22740 \pm 180, \; n_b = 3310 \pm 66$$

Efficiency (1)

➢ Obtained from Monte Carlo inclusive J/ψ sample generated with conditions and software as close as possible to the analyzed sample

➢ Efficiencies agreed with the one obtained from data

➢ Efficiencies from prompt and b components assumed to be the same for a given p_T and y bin (checked)



Total Efficiency

Systematics

Quantity	Systematic error	Comment
Trigger	1.7% to 4.5%	Bin dependent
GEC	2 %	Correlated between bins
Muon identification	2.5%	Correlated between bins
Tracking efficiency	8%	Correlated between bins
Track χ^2	1%	Correlated between bins
Vertexing	1%	Correlated between bins
Mass fits	1%	Correlated between bins
Bin size	0.1% to 15%	Bin dependent
Inter-bin cross-feed	0.5%	Correlated between bins (not applied to the total cross-section)
Radiative tail	1%	Correlated between bins
$\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$	1%	Correlated between bins
Luminosity	10%	Correlated between bins
t_z fits	3.6%	Correlated between bins
GEC efficiency of B events	2%	Applies only to J/ψ from b cross-sections
b hadronization fractions	2%	Applies only to extrapolations of $b\bar{b}$ cross-sections
$\mathcal{B}(b \rightarrow J/\psi X)$	9%	Applies only to extrapolations of $b\bar{b}$ cross-sections

➢ **Uncertainties from tracking efficiency, Muon identification and trigger will be updated with more data**

➢ **Besides, there are complications due to unknown polarization**

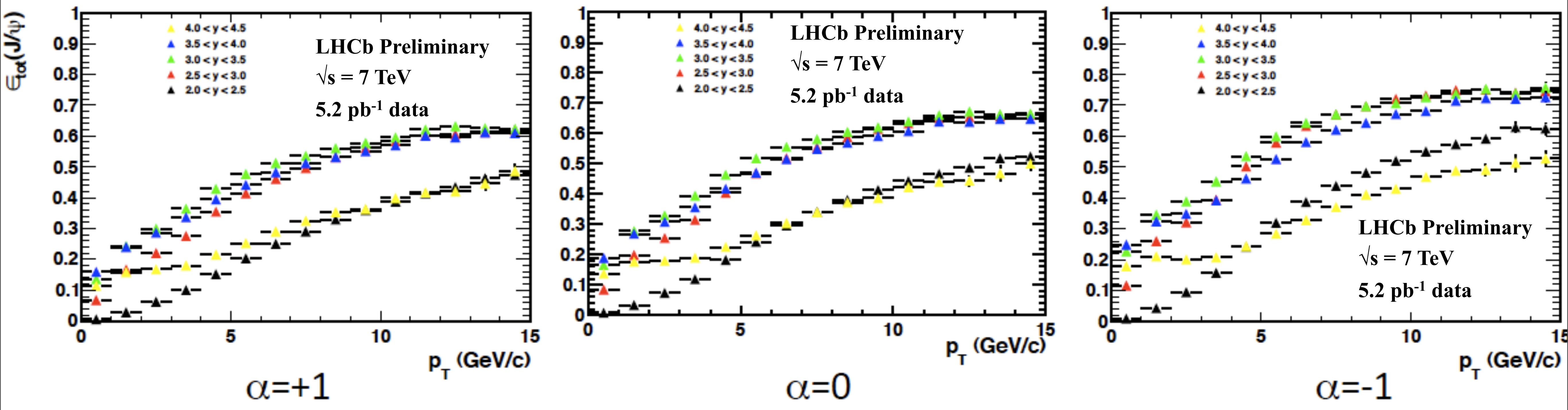
Polarization Effect

➢ Polarization affects a lot the detection efficiencies

➢ In LHCb simulation, J/ψ is not polarized. Different polarization scenarios obtained by weighting unpolarized sample

➢ Study performed in helicity frame without azimuthal dependence in 3 extreme cases

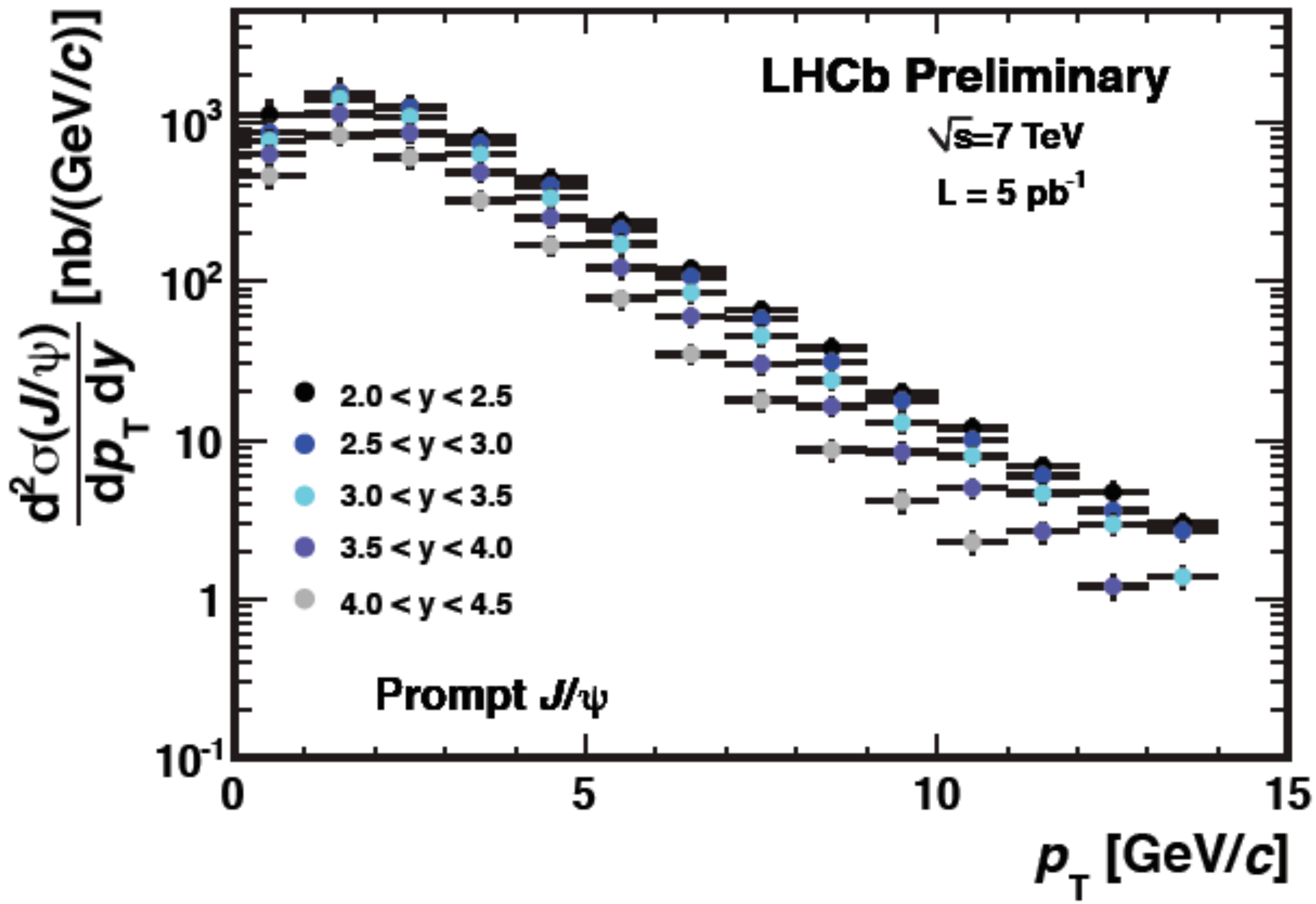
$$\frac{dN}{d\cos\theta} = \frac{1+\alpha\cos^2\theta}{2+2\times\alpha/3}$$



➢ Differences between 3% to 30% depending on bins

➢ Quote results in the above three scenarios for prompt J/ψ

Results: Prompt J/ψ (unpolarized Scenario)



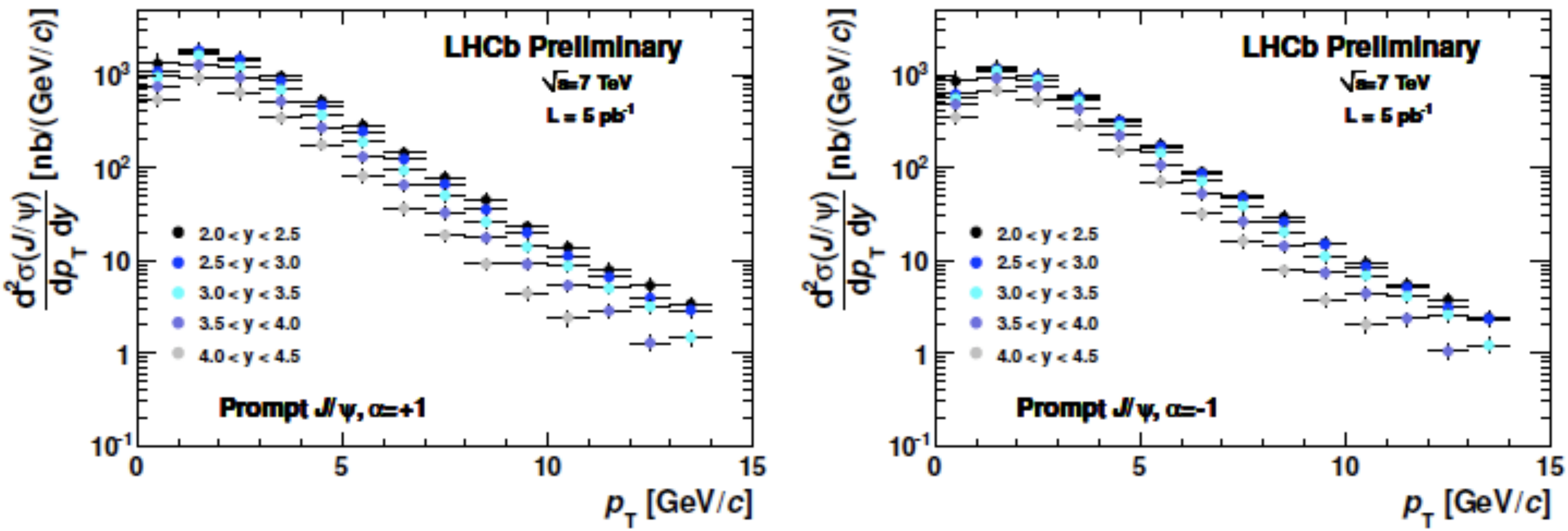
➢ **Integrated cross section**

stat. sys. polar

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

All the numerical results are in backup slides

Results: Prompt J/ψ (polarized scenarios)

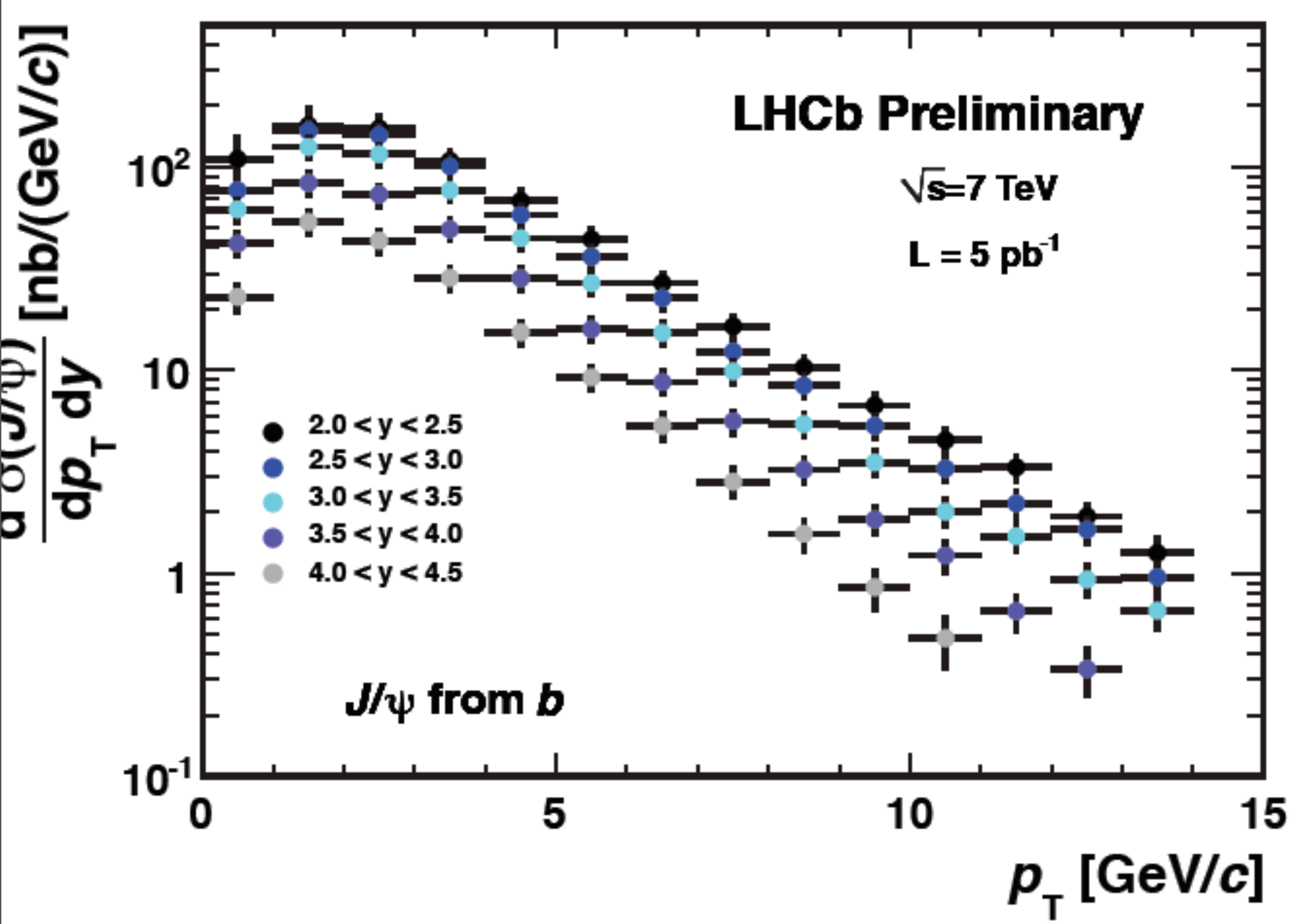


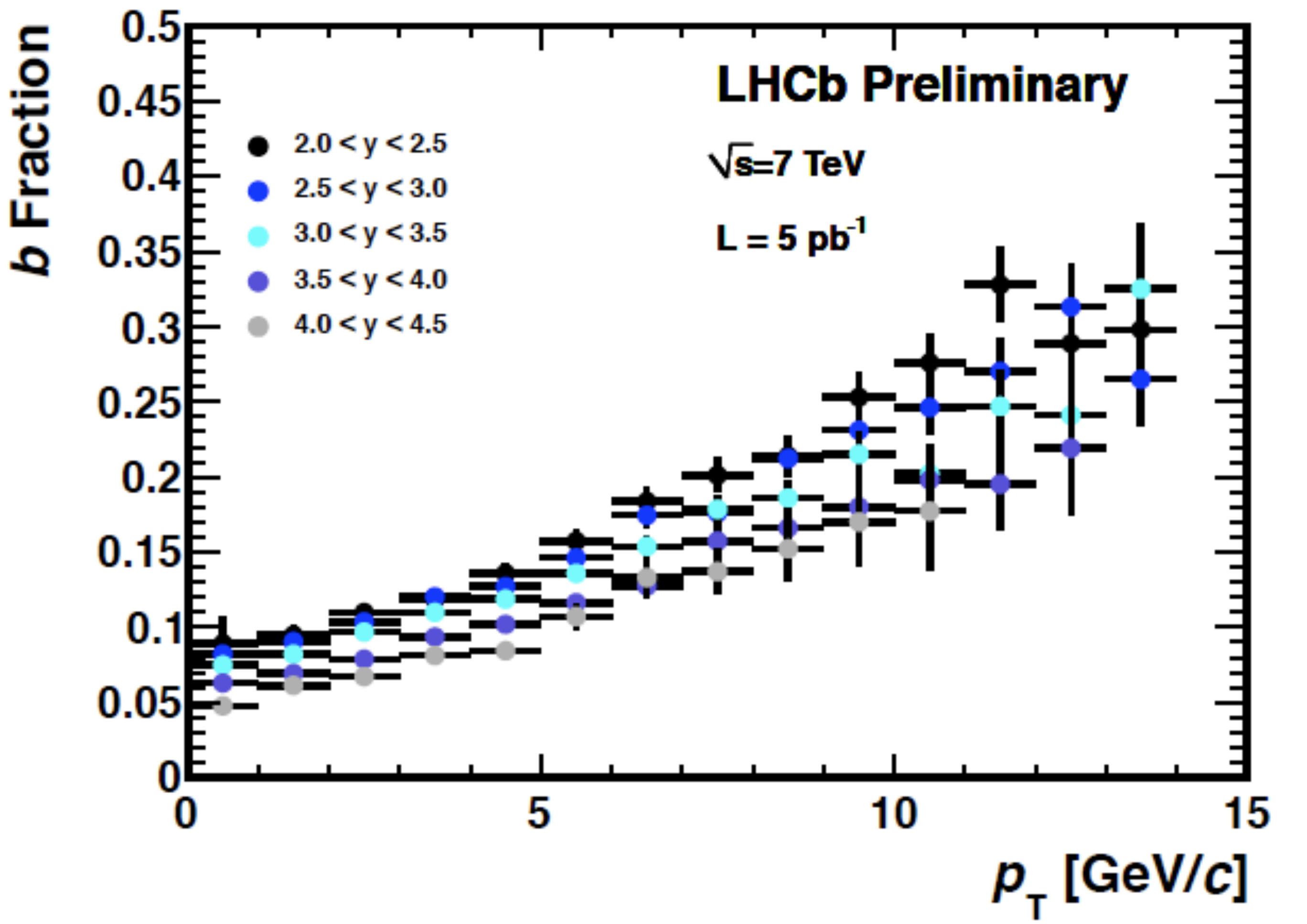
α=+1 α=-1

To be noted:

Prompt J/ψ polarization will be measured latter with data collected this year in bins of p_T and y

Results: J/ψ from b





- **Integrated cross section**

stat. sys.

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

- **Extrapolation to $b\bar{b}$ cross section in 4π via Pythia 6.4 with LEP branching ratio: Br(b→J/ψ+X) = (1.16±0.1)%**

$$\sigma(pp \to b\bar{b}X) = 295 \pm 4 \pm 48\ \mu\text{b}$$

(LHCb published results with b→D^0μνX: $\sigma(pp \to b\bar{b}X) = 284 \pm 20 \pm 49\ \mu\text{b}$ **)**

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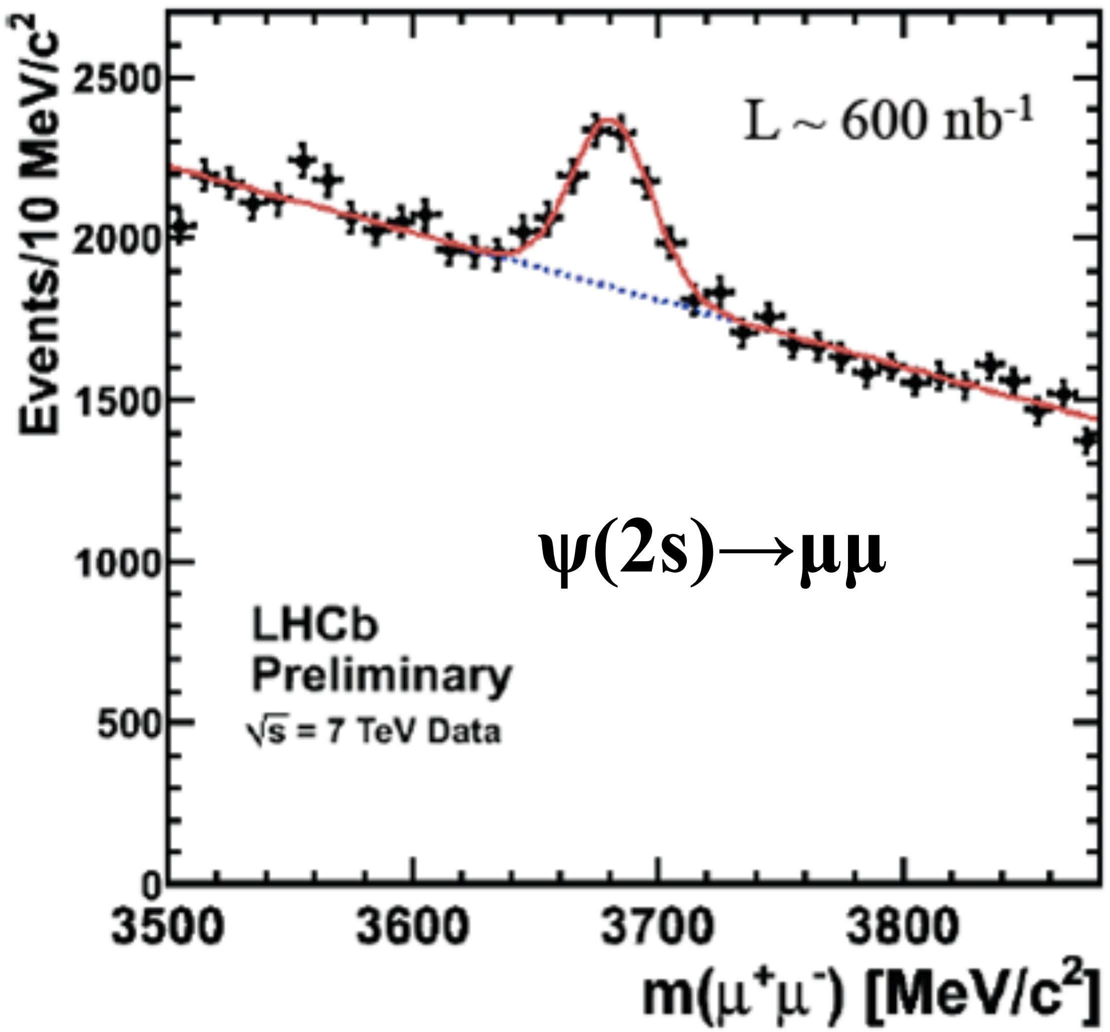
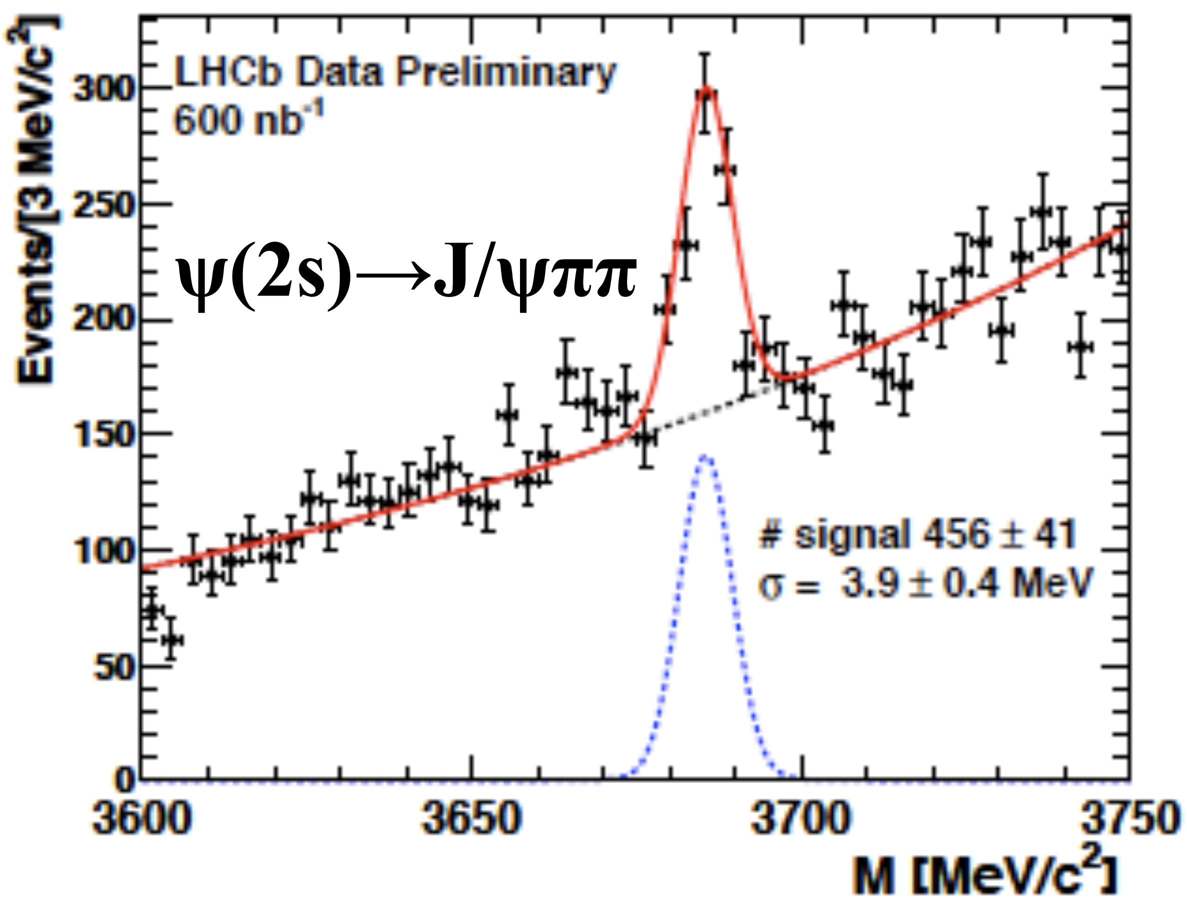
Ongoing Onia Studies (1)

- $\psi(2S)$: currently two channels under study
  - $\psi(2S)\to\mu\mu$: cross sections will be measured for prompt and b components in bins of p_T and y
  - $\psi(2S)\to J/\psi\pi\pi$: control channel for $X(3872)\to J/\psi\pi\pi$





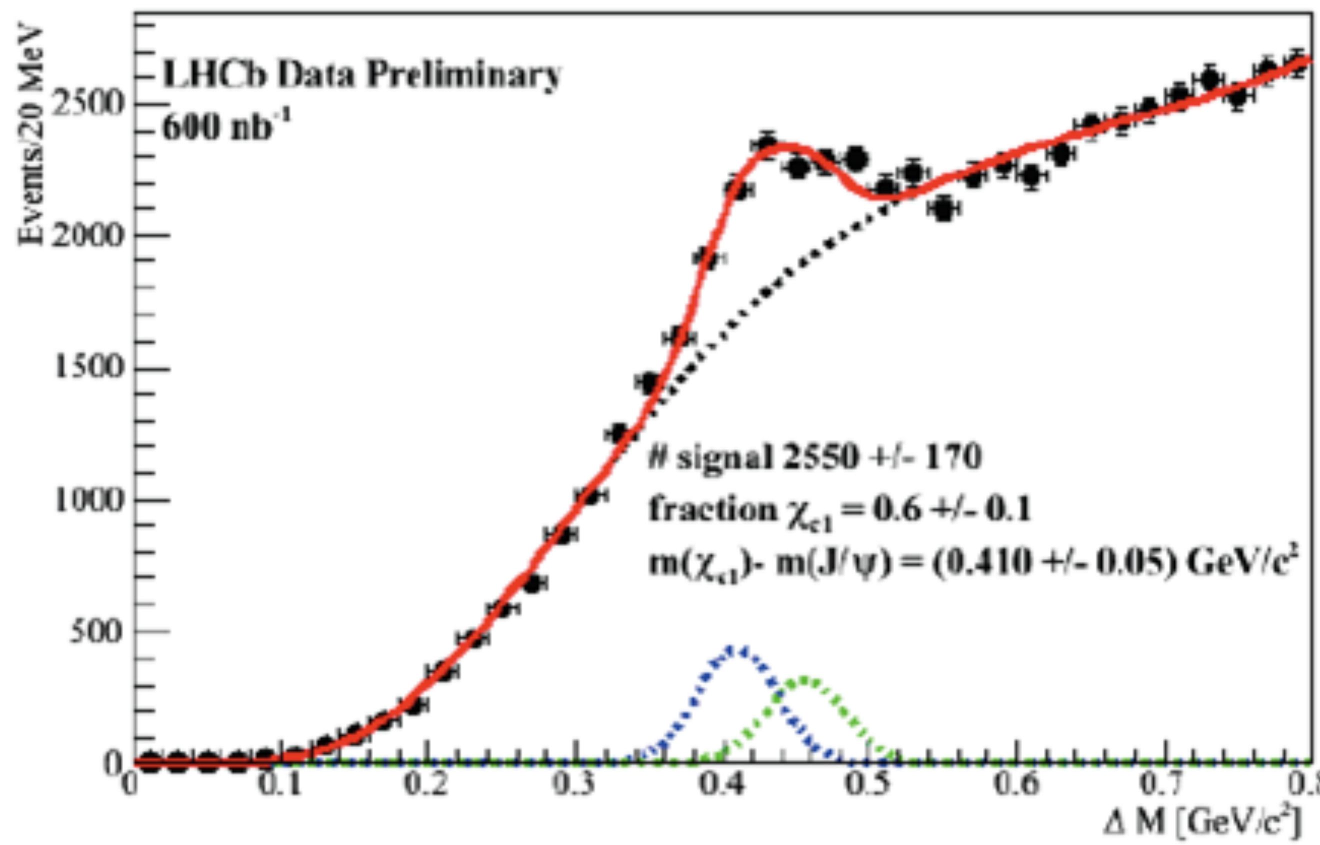
Studies given here and below will be performed with full data set collected during 2010 (~37pb^{-1})

Ongoing Onia Studies (2)

$\chi_c \rightarrow J/\psi\gamma$

- ➢ $\chi_{c1,2}$ are important sources of prompt J/ψ production:~30% feed down contribution

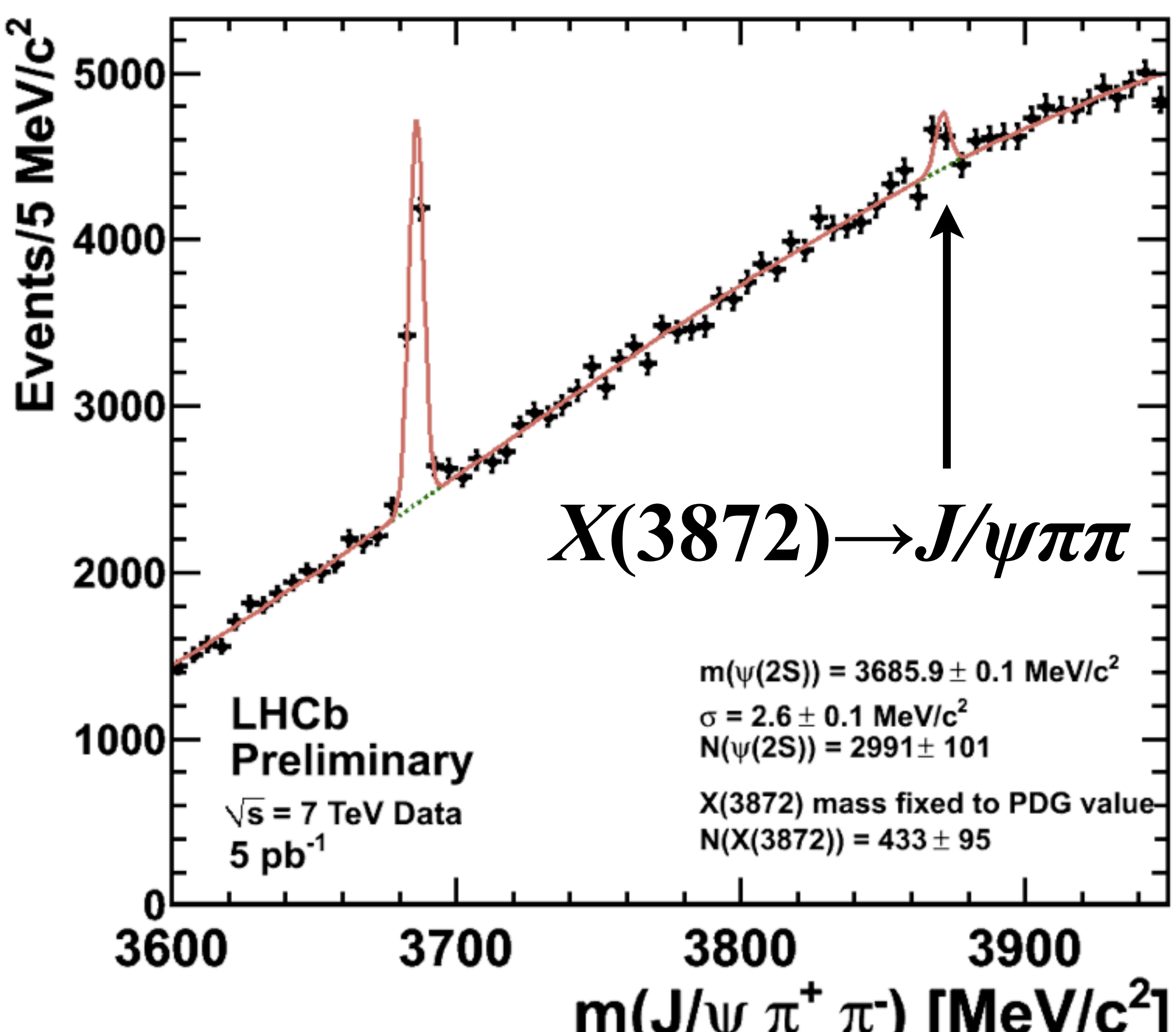
- ➢ Their production ratios with respect to J/ψ will be measured in bins of p_T

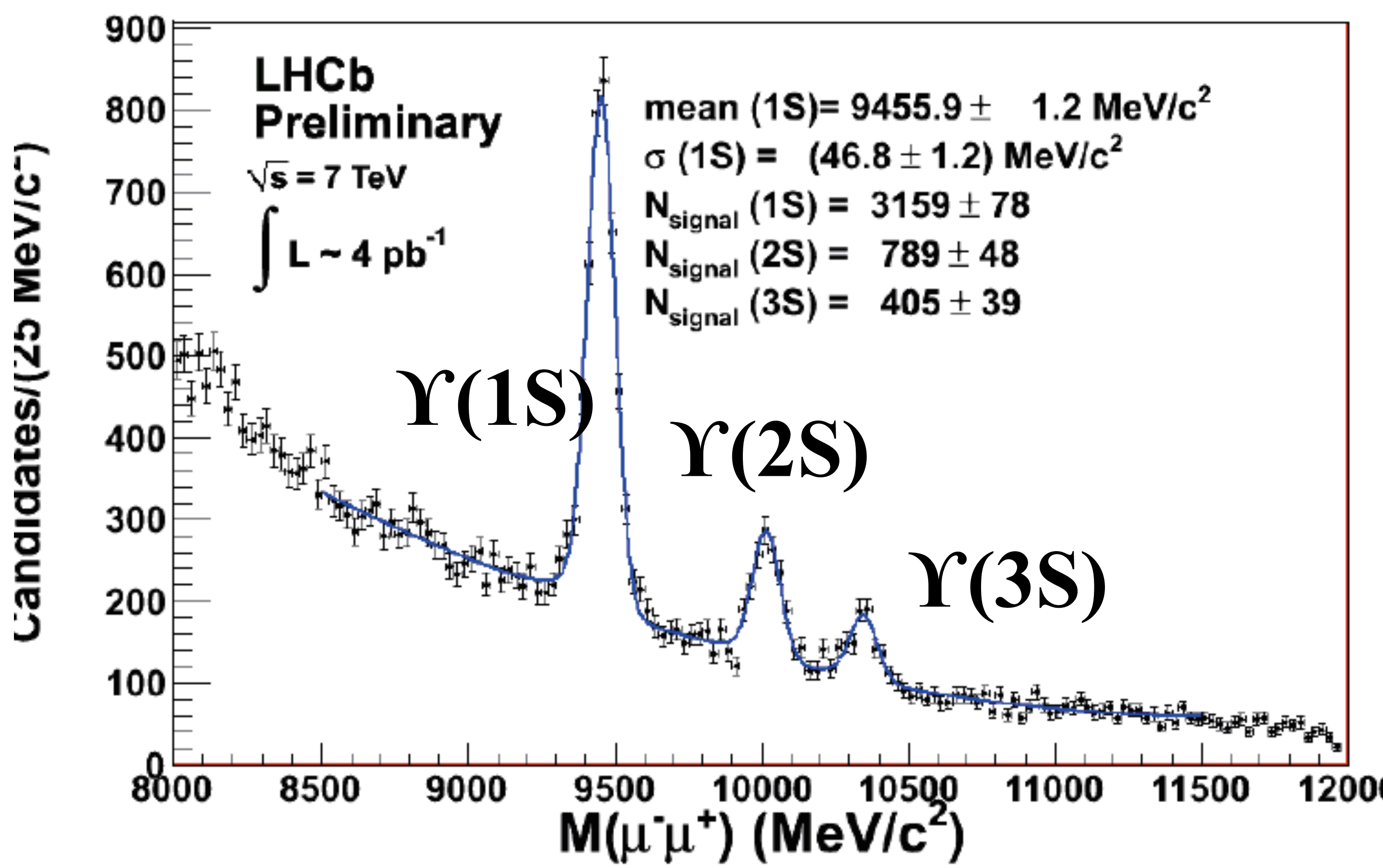


Ongoing Onia Studies (3)

- $X(3872) \to J/\psi\pi\pi$:
  - **433±95 signals observed with 5 pb^{-1}**
  - **Properties (mass, cross section, *etc*) will be measured**

- **Υ Studies**
  - **Cross section and polarization will be measured with $\Upsilon \to \mu\mu$ in bins of p_T and y for $\Upsilon(1S)$,$\Upsilon(2S)$,$\Upsilon(3S)$**





Conclusion

- ➢ **New Results with 5.2 pb^{-1} data for both prompt J/ψ and J/ψ from b cross section are given in 14 bins in p_T and 5 bins in y**
- ➢ **Integrated cross section for prompt J/ψ:**

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

- ➢ **Integrated cross section for J/ψ from b:**

$$\sigma\,(J/\psi \text{ from } b,\, p_{\mathrm{T}} < 14\ \mathrm{GeV}/c,\, 2 < y < 4.5) \;=\; 1.16 \pm 0.01 \pm 0.17\ \mu\mathrm{b}$$

and $b\bar{b}$ cross section in 4π (extrapolation based on Pythia):

$$\sigma(pp \to b\bar{b}X) = 295 \pm 4 \pm 48\ \mu\mathrm{b}$$

- ➢ **LHCb has a very rich onia program**

Results in Tables: Bin y∈ [2,2.5]

Prompt J/ψ

$2.0 < y < 2.5$ p_T (GeV/c)	0 − 1	1 − 2	2 − 3	3 − 4	4 − 5	5 − 6	6 − 7	7 − 8
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))	1117.4	1531.8	1255.0	796.3	434.9	235.5	119.2	65.2
stat. error (nb)	72.0	38.6	20.8	11.0	6.0	3.6	2.2	1.5
cor. syst. error (nb)	155.0	212.5	174.1	110.5	60.3	32.7	16.5	9.1
uncor. syst. error (nb)	231.5	289.4	112.2	45.0	22.5	12.3	6.2	3.1
total error (nb)	287.8	361.1	208.2	119.8	64.7	35.1	17.8	9.7
p_T (GeV/c)		8 − 9	9 − 10	10 − 11	11 − 12	12 − 13	13 − 14	14 − 15
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))		38.0	19.7	11.9	6.8	4.7	3.0	
stat. error (nb)		1.0	0.7	0.5	0.4	0.3	0.3	
cor. syst. error (nb)		5.3	2.7	1.7	0.9	0.7	0.4	
uncor. syst. error (nb)		1.0	0.5	0.3	0.2	0.2	0.1	
total error (nb)		5.5	2.9	1.8	1.0	0.7	0.5	

Results in Tables: Bin y∈ [2.5,3]

Prompt J/ψ

$2.5 < y < 3.0$ p_T (GeV/c)	$0-1$	$1-2$	$2-3$	$3-4$	$4-5$	$5-6$	$6-7$	$7-8$
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))	864.6	1526.6	1243.7	736.6	402.0	211.5	106.9	57.9
stat. error (nb)	13.0	12.7	9.3	5.8	3.4	2.2	1.5	1.1
cor. syst. error (nb)	120.0	211.8	172.5	102.2	55.8	29.3	14.8	8.0
uncor. syst. error (nb)	135.8	40.3	24.7	18.4	12.1	7.9	4.1	2.8
total error (nb)	181.7	216.0	174.5	104.0	57.2	30.5	15.5	8.6
p_T (GeV/c)		$8-9$	$9-10$	$10-11$	$11-12$	$12-13$	$13-14$	$14-15$
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))		31.3	17.8	10.1	6.0	3.6	2.7	
stat. error (nb)		0.7	0.5	0.4	0.3	0.2	0.2	
cor. syst. error (nb)		4.3	2.5	1.4	0.8	0.5	0.4	
uncor. syst. error (nb)		0.3	0.2	0.1	0.1	0.1	0.1	
total error (nb)		4.4	2.5	1.5	0.9	0.6	0.4	

Results in Tables: Bin y∈ [3,3.5]

Prompt J/ψ

$3.0 < y < 3.5$ p_T (GeV/c)	0 – 1	1 – 2	2 – 3	3 – 4	4 – 5	5 – 6	6 – 7	7 – 8
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))	767.3	1410.2	1079.2	626.5	332.8	170.7	84.4	45.5
stat. error (nb)	7.2	8.6	6.8	4.6	2.8	2.0	1.3	0.9
cor. syst. error (nb)	106.5	195.7	149.7	86.9	46.2	23.7	11.7	6.3
uncor. syst. error (nb)	46.6	27.1	19.3	13.9	9.3	5.4	3.1	1.5
total error (nb)	116.4	197.7	151.1	88.1	47.2	24.4	12.2	6.6
p_T (GeV/c)		8 – 9	9 – 10	10 – 11	11 – 12	12 – 13	13 – 14	14 – 15
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))		23.8	12.9	8.0	4.6	2.9	1.4	
stat. error (nb)		0.6	0.5	0.4	0.3	0.2	0.2	
cor. syst. error (nb)		3.3	1.8	1.1	0.6	0.4	0.2	
uncor. syst. error (nb)		0.2	0.1	0.1	0.1	0.0	0.0	
total error (nb)		3.4	1.8	1.2	0.7	0.5	0.2	

Results in Tables: Bin y∈ [3.5,4]

Prompt J/ψ

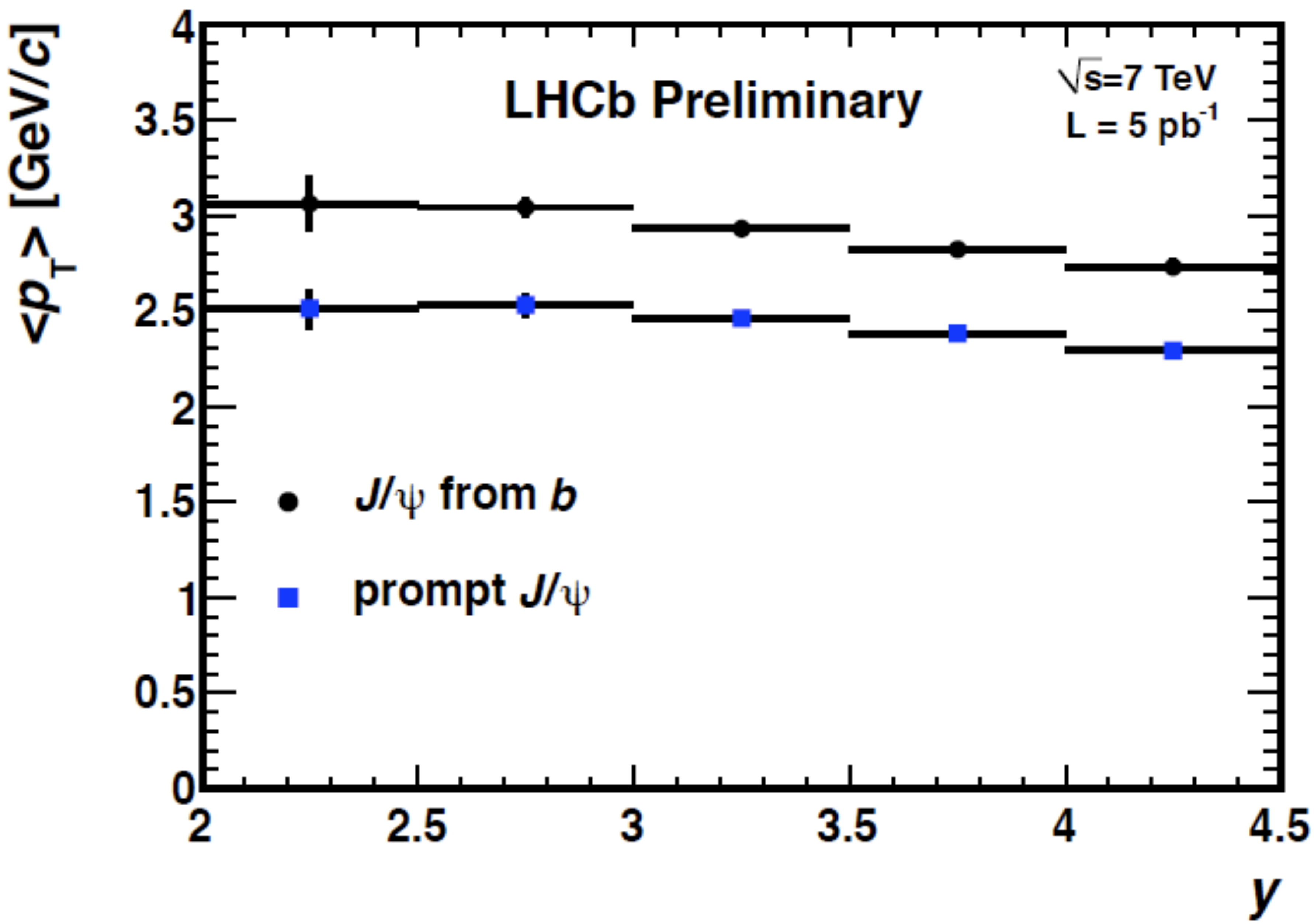
$3.5 < y < 4.0$ p_T (GeV/c)	0 – 1	1 – 2	2 – 3	3 – 4	4 – 5	5 – 6	6 – 7	7 – 8
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))	629.0	1127.8	859.4	482.6	250.3	121.5	60.1	30.1
stat. error (nb)	5.7	6.9	6.0	3.9	2.6	1.6	1.1	0.7
cor. syst. error (nb)	87.3	156.5	119.2	67.0	34.7	16.9	8.3	4.2
uncor. syst. error (nb)	23.1	23.3	19.4	13.3	7.7	5.2	2.0	1.0
total error (nb)	90.4	158.3	121.0	68.4	35.7	17.7	8.6	4.4
p_T (GeV/c)		8 – 9	9 – 10	10 – 11	11 – 12	12 – 13	13 – 14	14 – 15
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))		16.3	8.4	5.0	2.7	1.2		
stat. error (nb)		0.5	0.4	0.3	0.2	0.1		
cor. syst. error (nb)		2.3	1.2	0.7	0.4	0.2		
uncor. syst. error (nb)		0.2	0.1	0.1	0.1	0.0		
total error (nb)		2.3	1.2	0.8	0.4	0.2		

Results in Tables: Bin y∈ [4,4.5]

Prompt J/ψ

$4.0 < y < 4.5$ p_T (GeV/c)	0 – 1	1 – 2	2 – 3	3 – 4	4 – 5	5 – 6	6 – 7	7 – 8
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))	458.3	826.8	602.2	322.5	167.2	77.5	34.7	17.8
stat. error (nb)	5.6	6.8	5.9	4.3	2.8	1.7	1.1	0.7
cor. syst. error (nb)	63.6	114.7	83.6	44.7	23.2	10.7	4.8	2.5
uncor. syst. error (nb)	28.3	28.2	23.0	14.3	6.5	2.9	1.5	0.8
total error (nb)	69.8	118.3	86.9	47.2	24.2	11.3	5.2	2.7
p_T (GeV/c)		8 – 9	9 – 10	10 – 11	11 – 12	12 – 13	13 – 14	14 – 15
$\frac{d^2\sigma}{dp_T dy}$ (nb/(GeV/c))		8.7	4.2	2.3				
stat. error (nb)		0.5	0.3	0.2				
cor. syst. error (nb)		1.2	0.6	0.3				
uncor. syst. error (nb)		0.4	0.2	0.1				
total error (nb)		1.3	0.7	0.4				

Results: Mean p_T



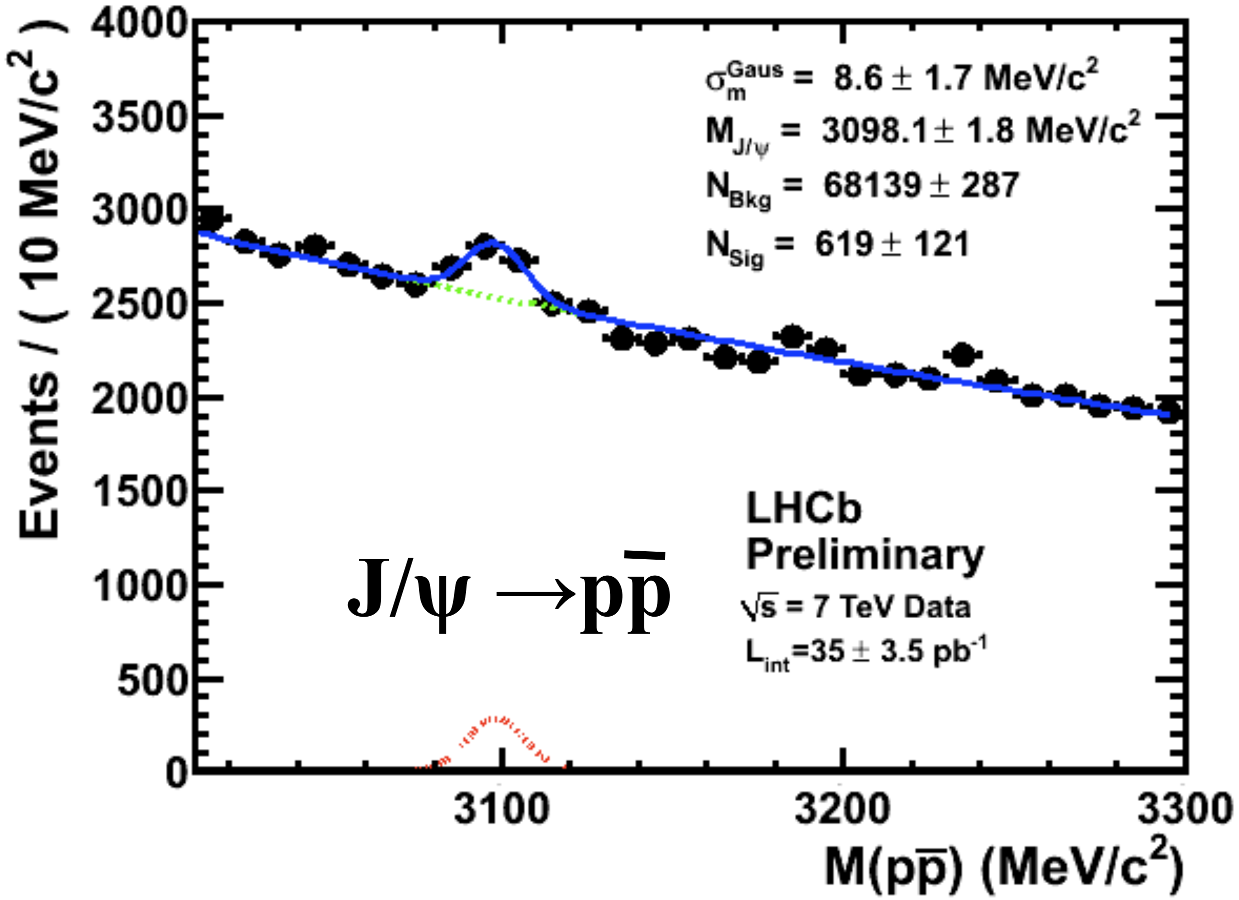
➢ **Obtained by interpolating the measured cross-section with a cubic B-spline function**

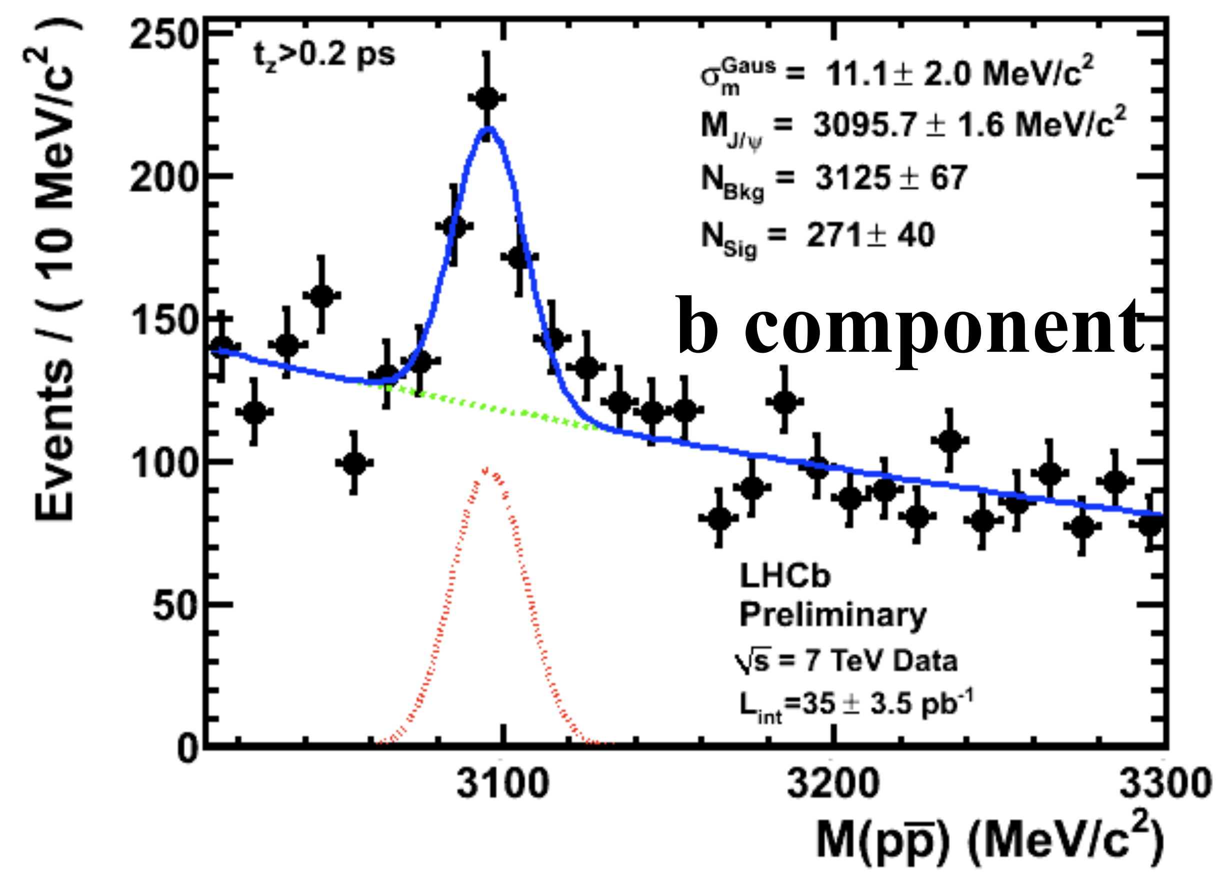
➢ **J/ψ from b: Mean p_T 20% higher than prompt J/ψ**

Ongoing Onia Studies (1)

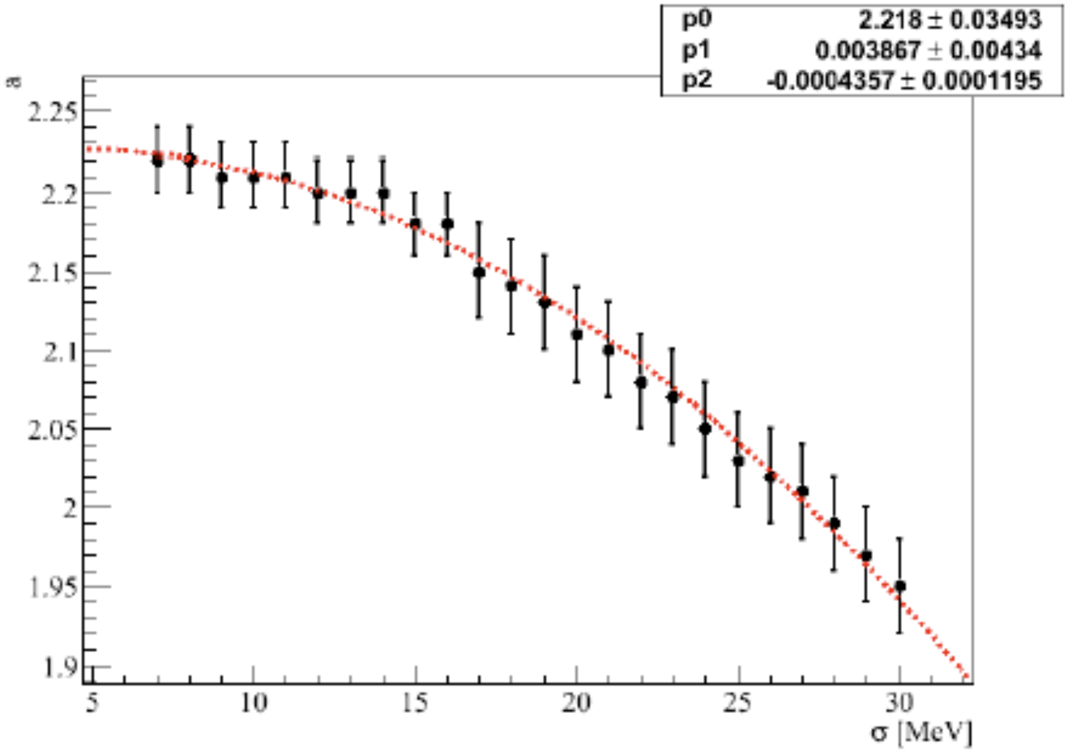
- J/ψ polarization measurement
  - Full angular momentum study in bins of p_T and y

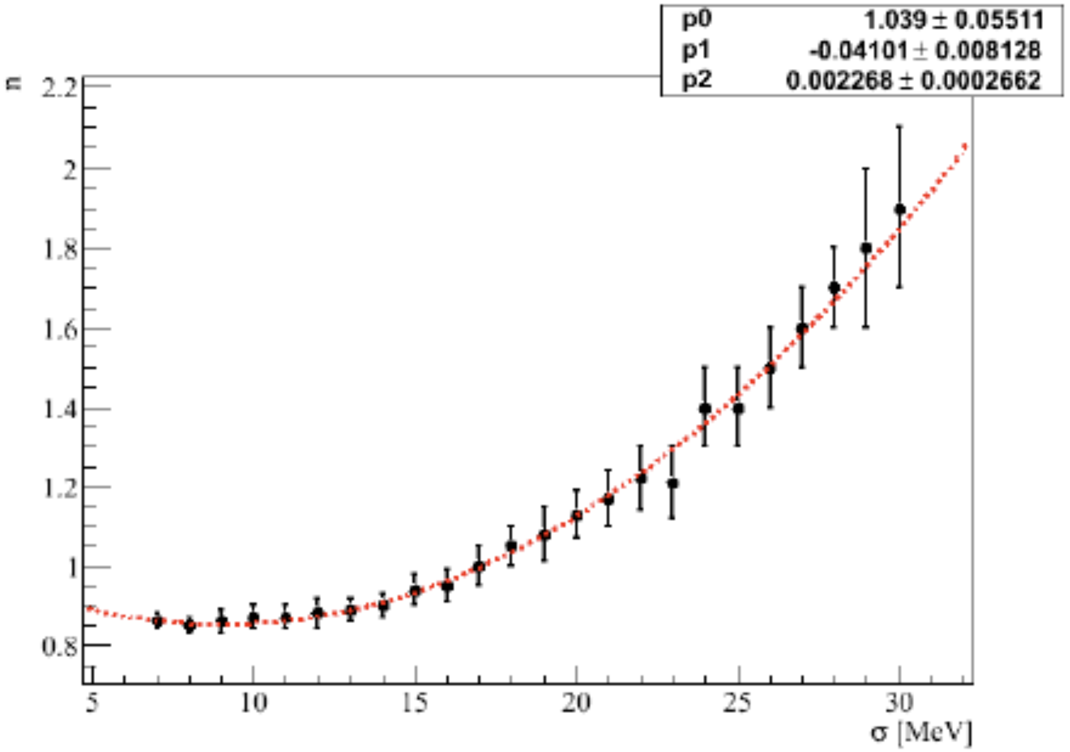
- charmonium→$p\bar{p}$: Study simultaneously different charmonium states (h_c,χ_c.....) decaying to $p\bar{p}$

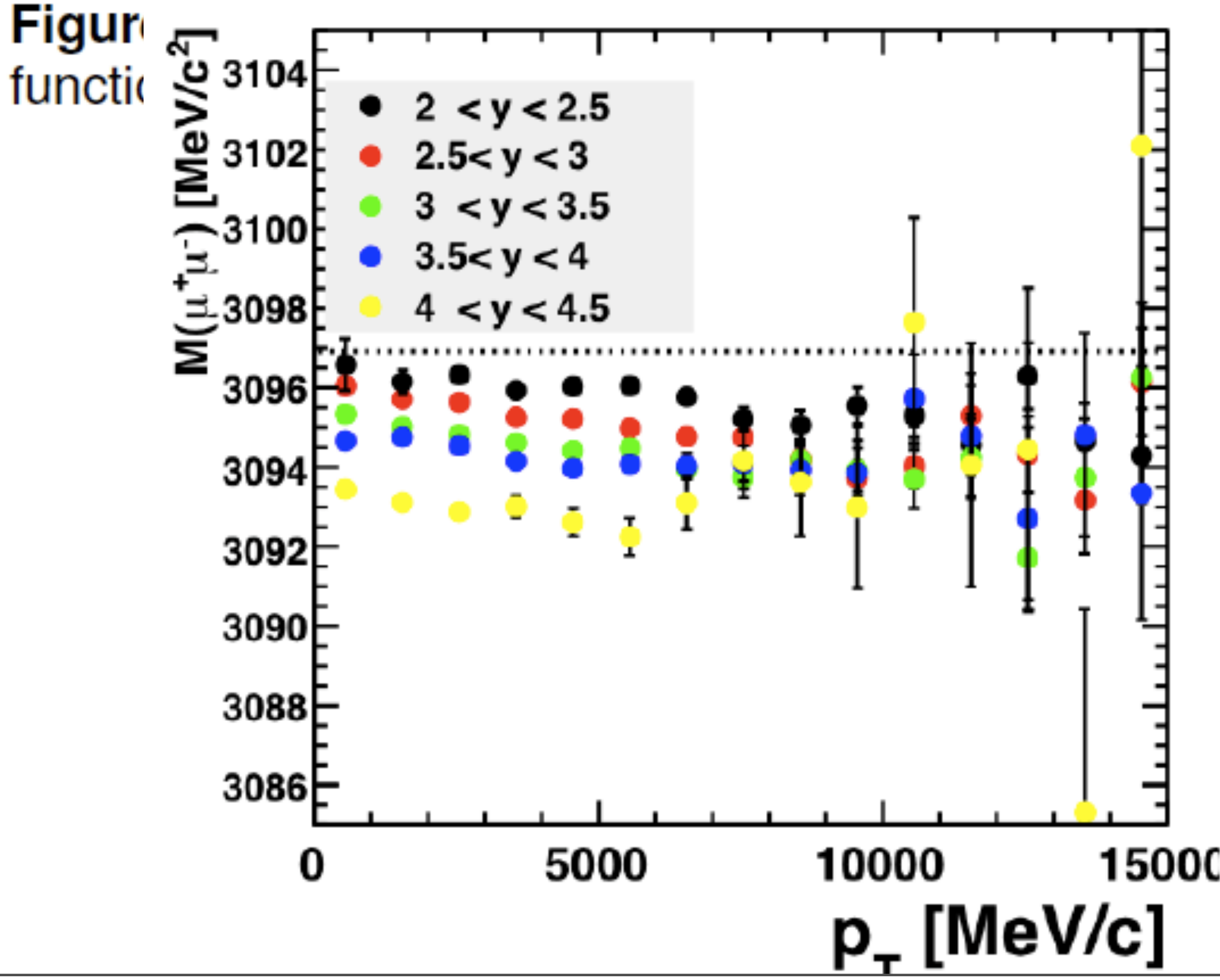


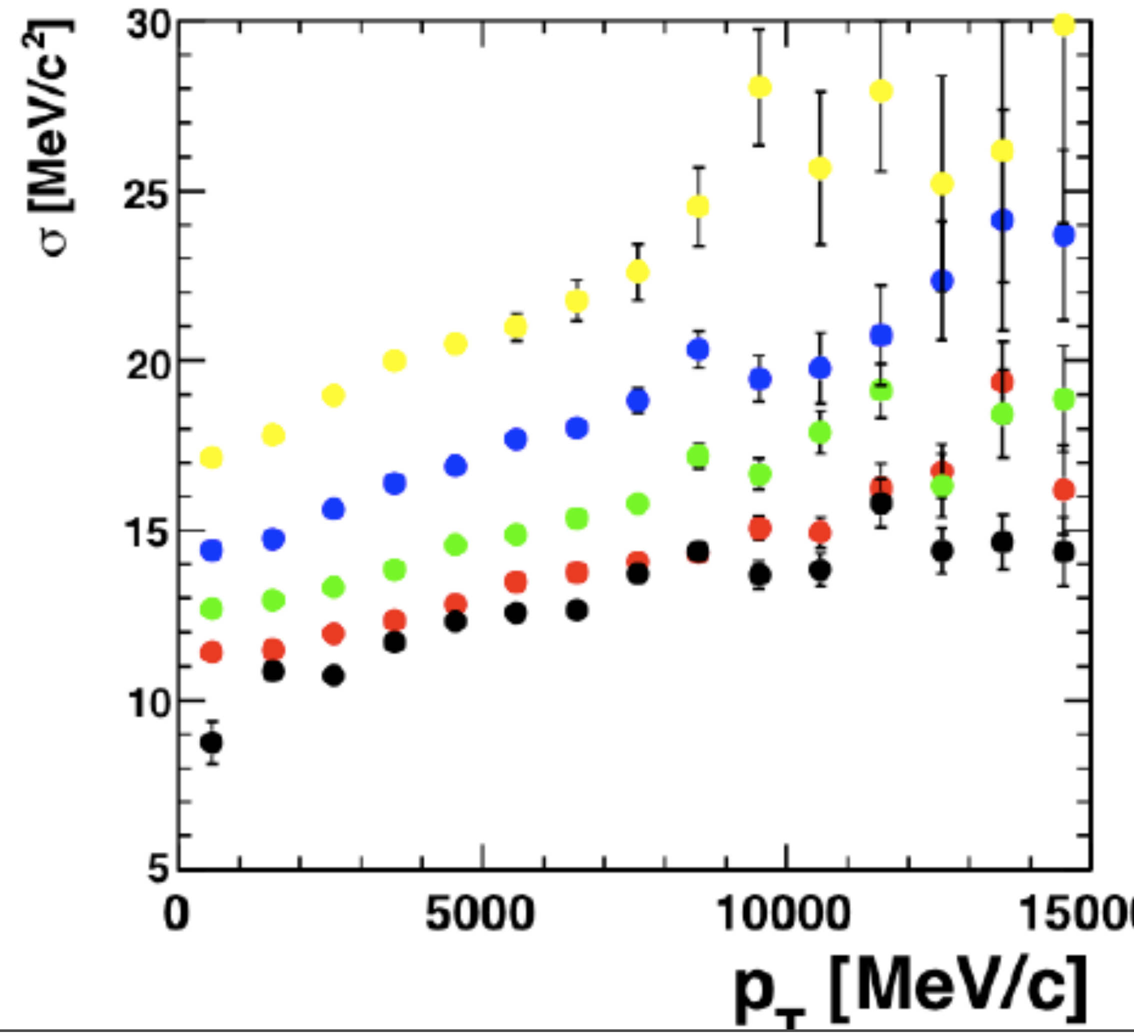


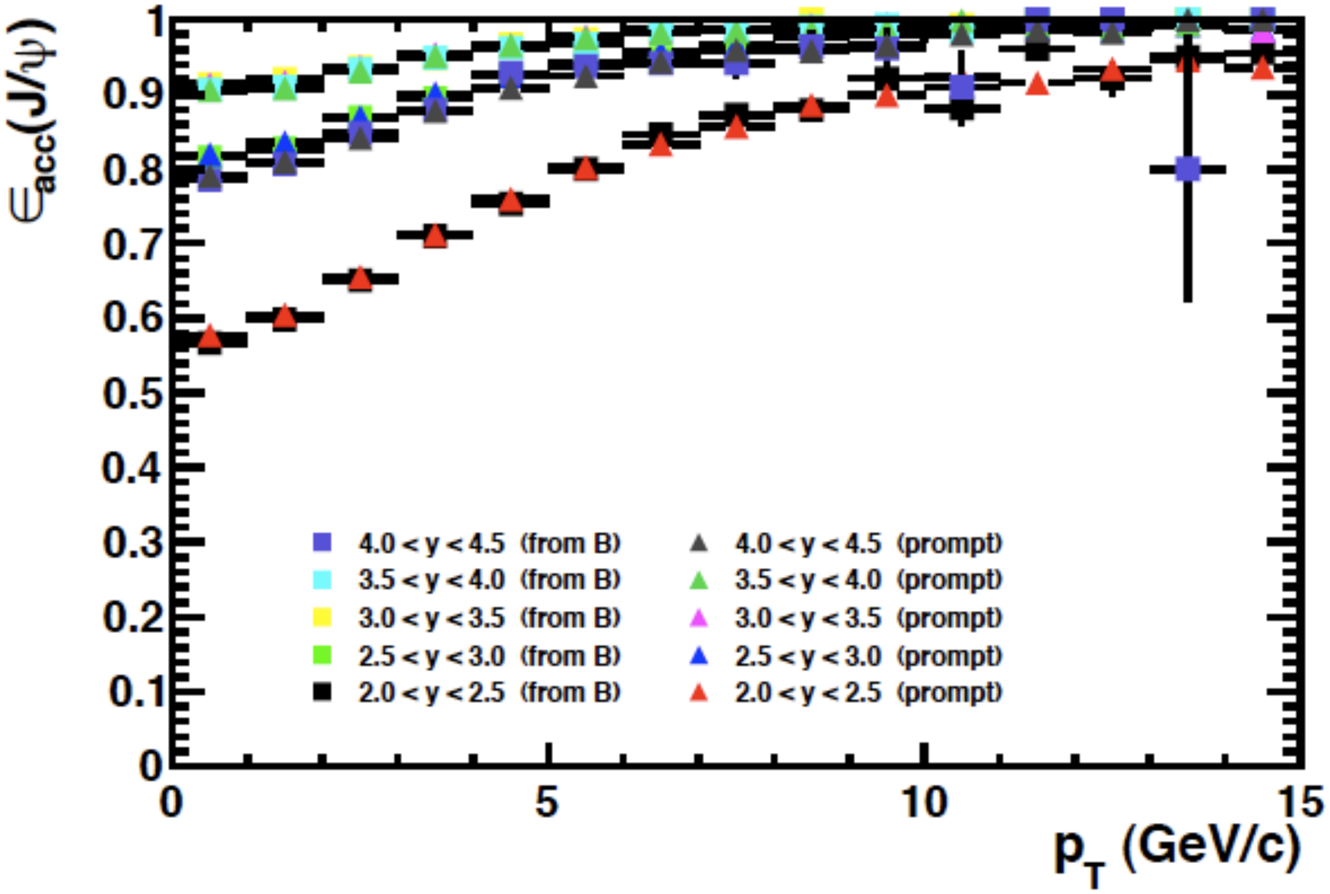
Methods for Mass Fit

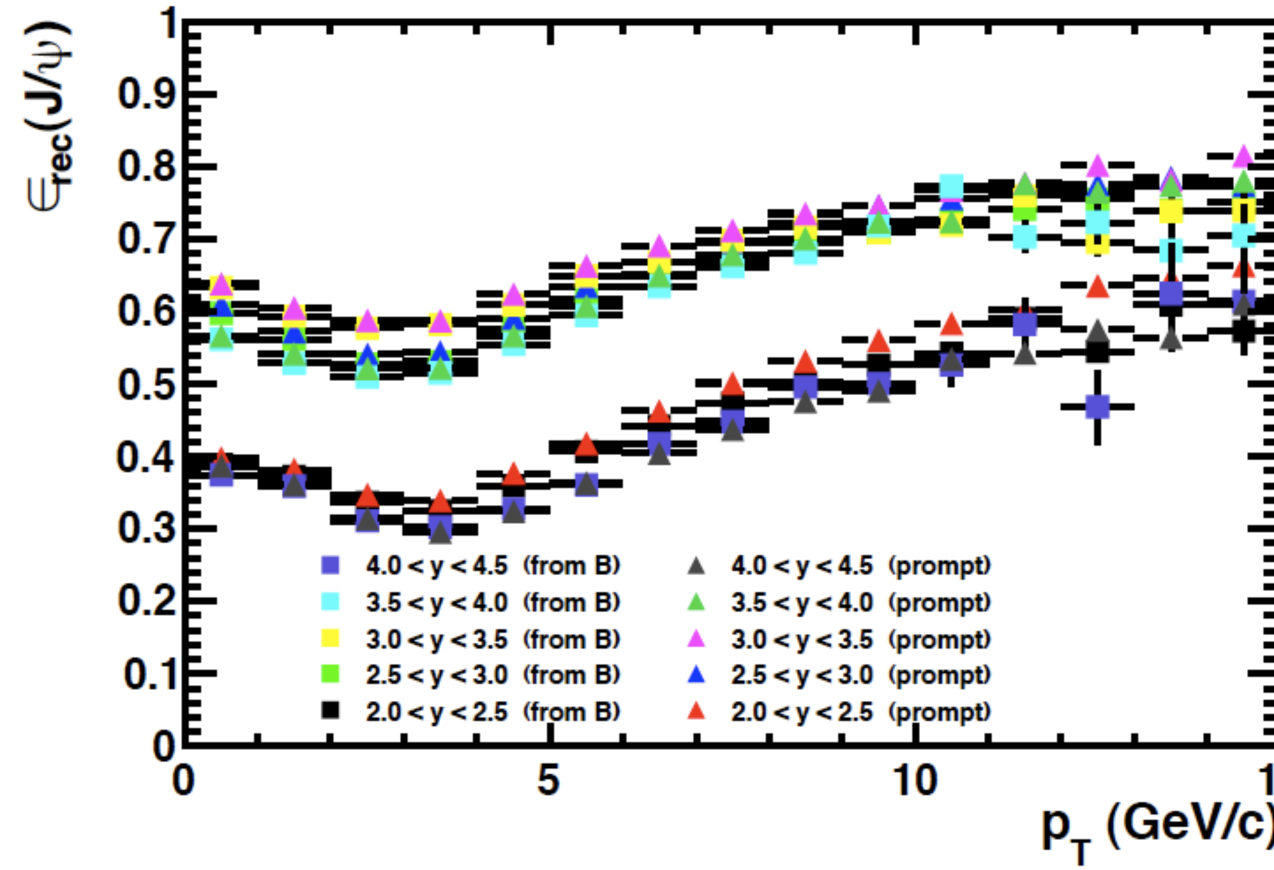






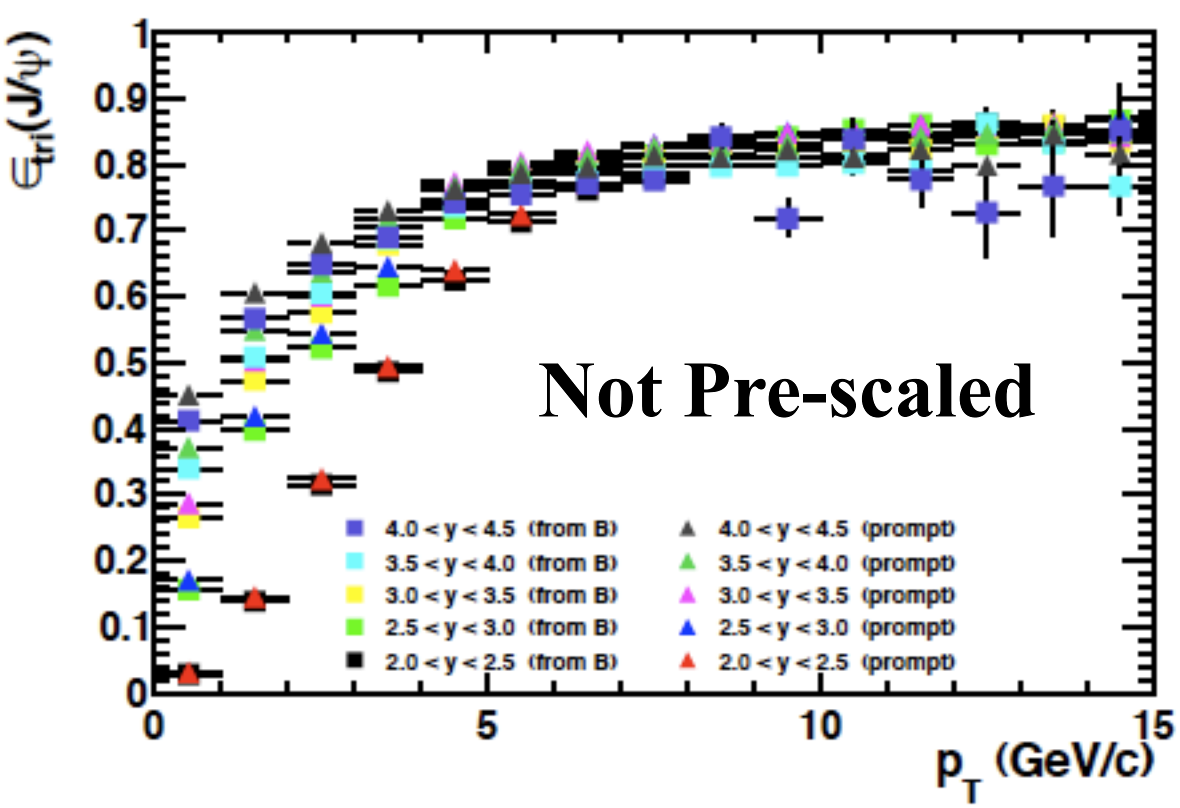


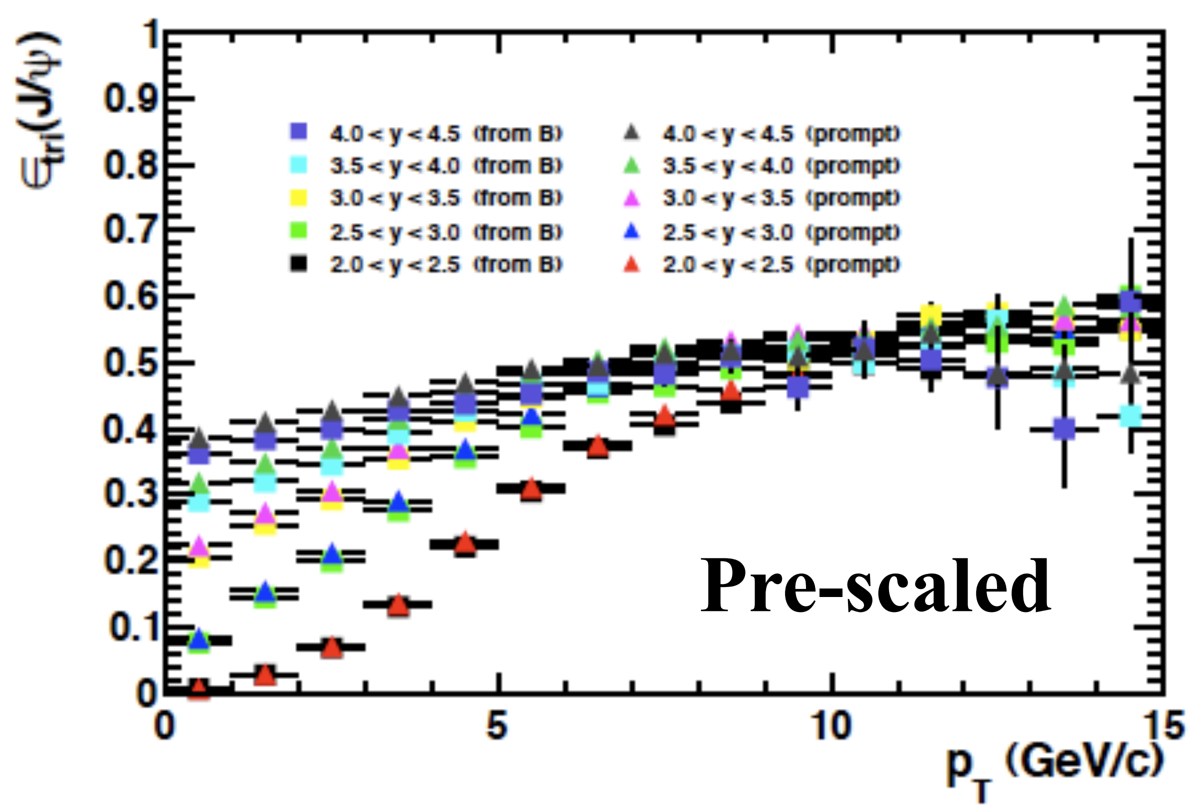




Acceptance Efficiency

Reconstruction Efficiency





Trigger Efficiency