



# Heavy Flavour Physics at ATLAS

---

Vivek Jain, Indiana University  
(for the ATLAS Collaboration)

**New Data from the Energy Frontier,  
Aspen, Feb. 16, 2011**

# Outline

## ■ Introduction

- ❑ Heavy Flavour Physics Program
- ❑ ATLAS detector

## ■ Results - [\(available at this link\)](#)

- ❑ Quarkonia –  $J/\psi$ , Upsilon
- ❑ B physics – Exclusive signals
- ❑ Charm physics – Exclusive signals

## ■ Future Plans

## ■ Summary

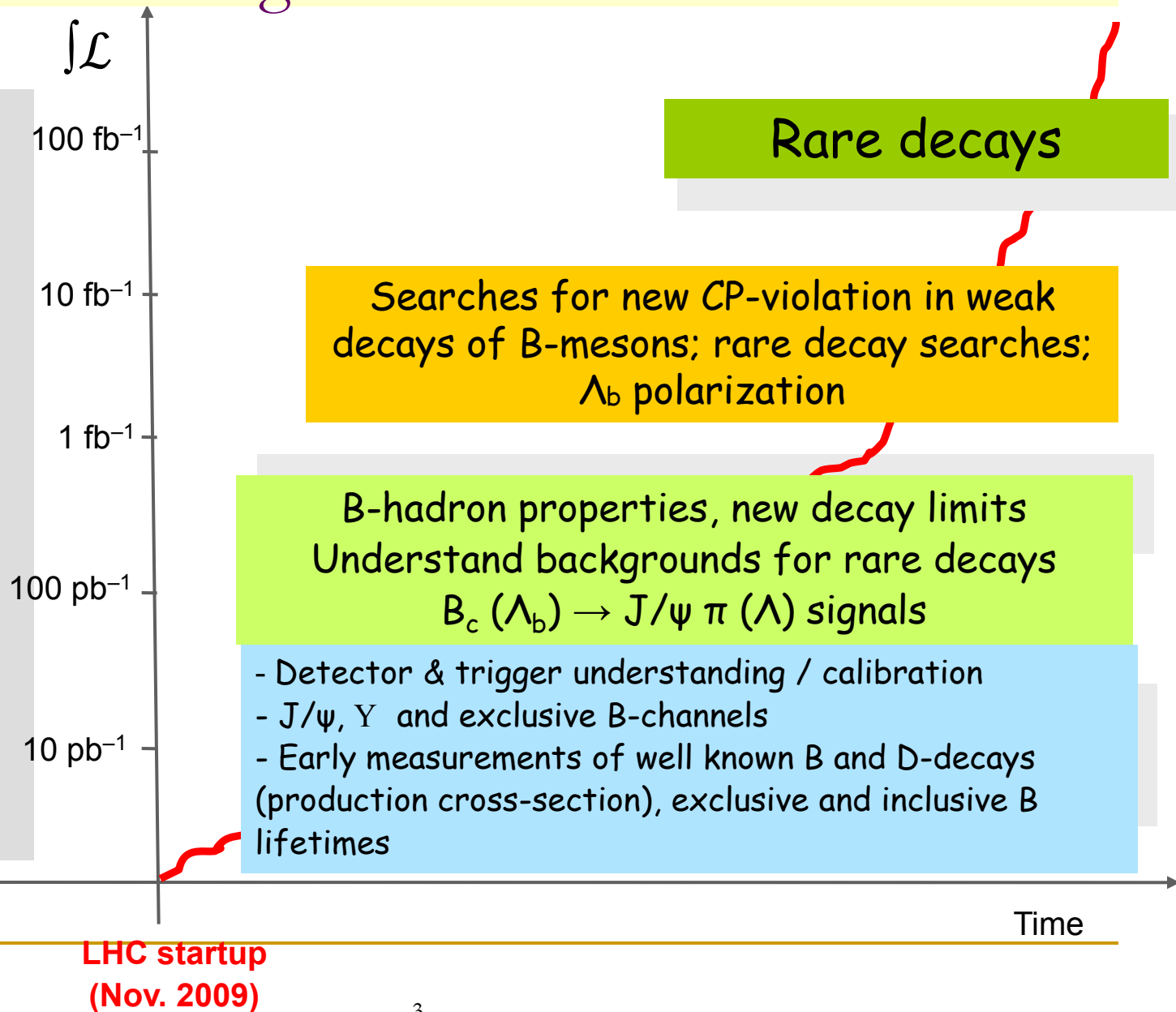
# Heavy Flavour Program at ATLAS

## Key elements for B-Physics searches:

Efficient low pt muon trigger

Very good

- Muon coverage
- Track momentum resolution
- Mass resolution
- Vertex resolution
- Well understood MC



Muon Spectrometer ( $|\eta| < 2.7$ ) : air-core toroids with gas-based muon chambers  
Muon trigger and measurement with momentum resolution  $< 10\%$  up to  $E_\mu \sim 1$  TeV

Length :  $\sim 46$  m  
Radius :  $\sim 12$  m  
Weight :  $\sim 7000$  tons  
 $\sim 10^8$  electronic channels  
3000 km of cables

3-level trigger  
reducing the rate  
from 40 MHz to  
 $\sim 200$  Hz

Inner Detector ( $|\eta| < 2.5$ ,  $B=2$ T):  
Si Pixels, Si strips, Transition  
Radiation detector (straws)  
Precise tracking and vertexing,  
 $e/\pi$  separation  
Momentum resolution:  
 $\sigma/p_T \sim 3.8 \times 10^{-4} p_T (\text{GeV}) \oplus 0.015$

Muon Detectors

Tile Calorimeter

Liquid Argon Calorimeter

Toroid Magnets

Solenoid Magnet

SCT Tracker

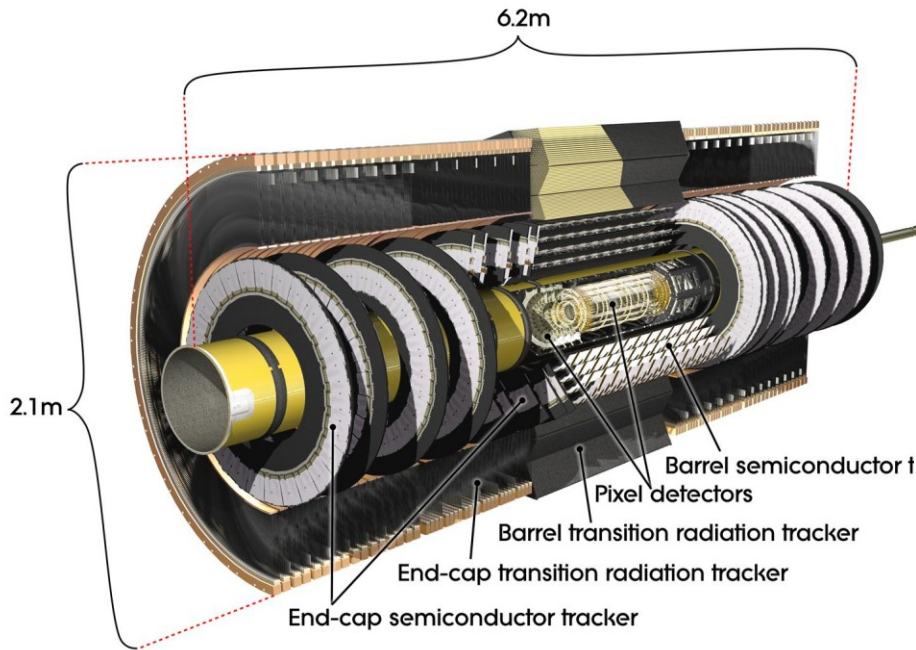
Pixel Detector

TRT Tracker

EM calorimeter: Pb-LAr Accordion  
 $e/\gamma$  trigger, identification and measurement  
E-resolution:  $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ( $|\eta| < 5$ ): segmentation, hermeticity  
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)  
Trigger and measurement of jets and missing  $E_T$   
E-resolution:  $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

# Inner Detector



ID contains 3 sub-detectors (resolutions)

Pixel detector: 10/115  $\mu\text{m}$  in  $R\phi/z$

Silicon strip detector: 17/580  $\mu\text{m}$

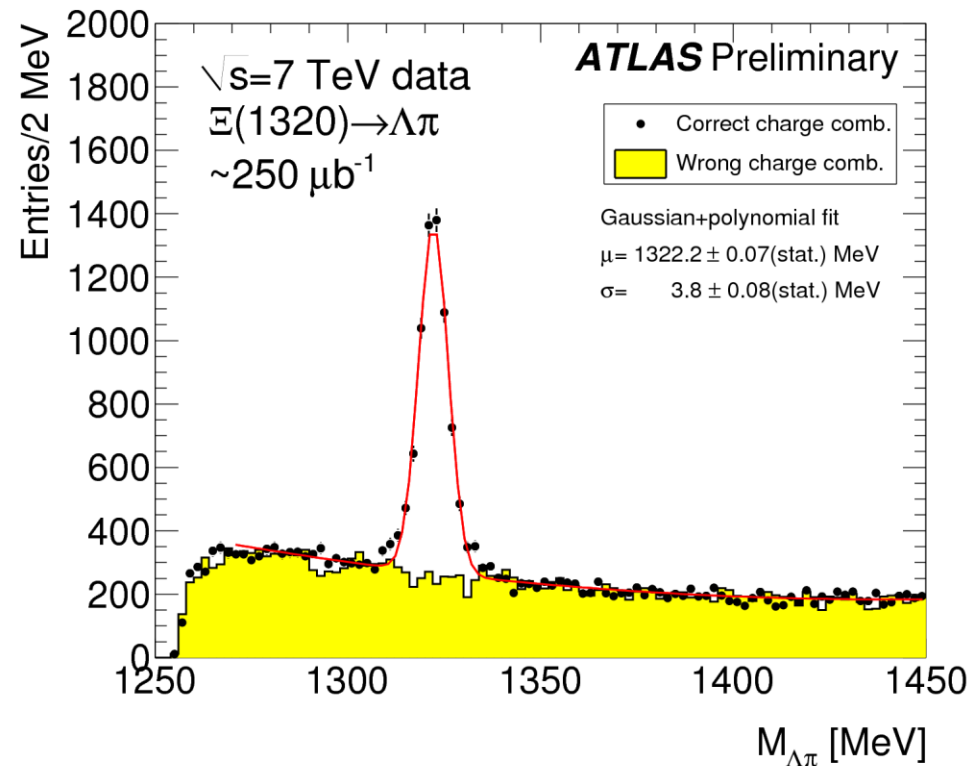
Transition radiation tracker: 130  $\mu\text{m}$   $R\phi$   
2 T solenoidal magnetic field

Coverage:  $|\eta| < 2.5$  (2.0 for TRT)

Accurate track & vertex reco.

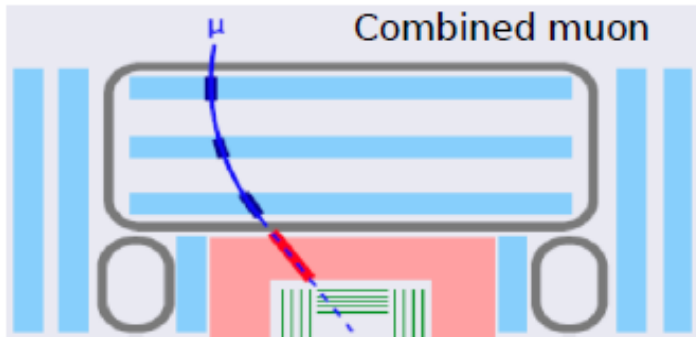
Resolution goal:

$$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$$

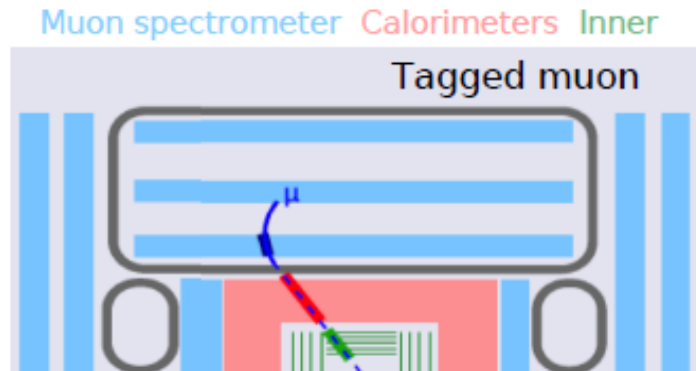


# Muon Reconstruction

In selection of  $J/\psi$  candidates we consider two types of muon:



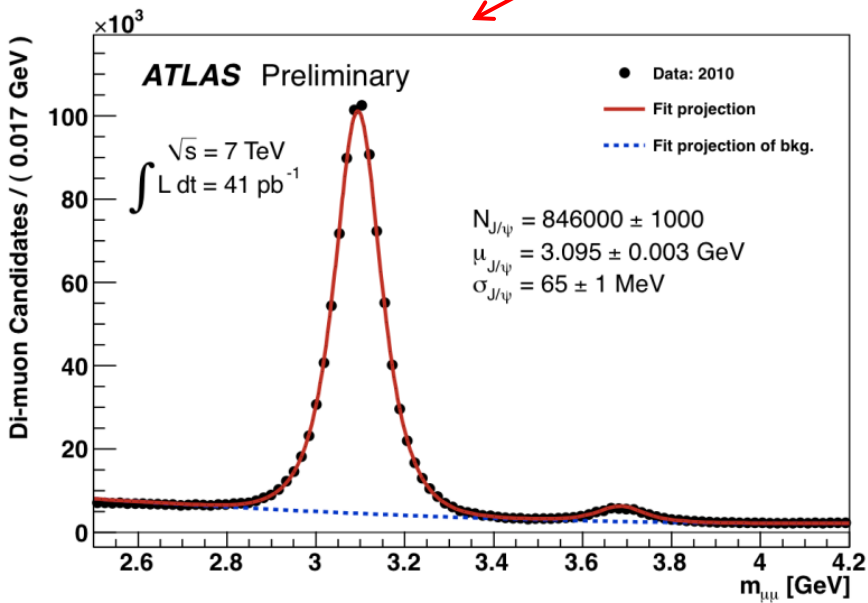
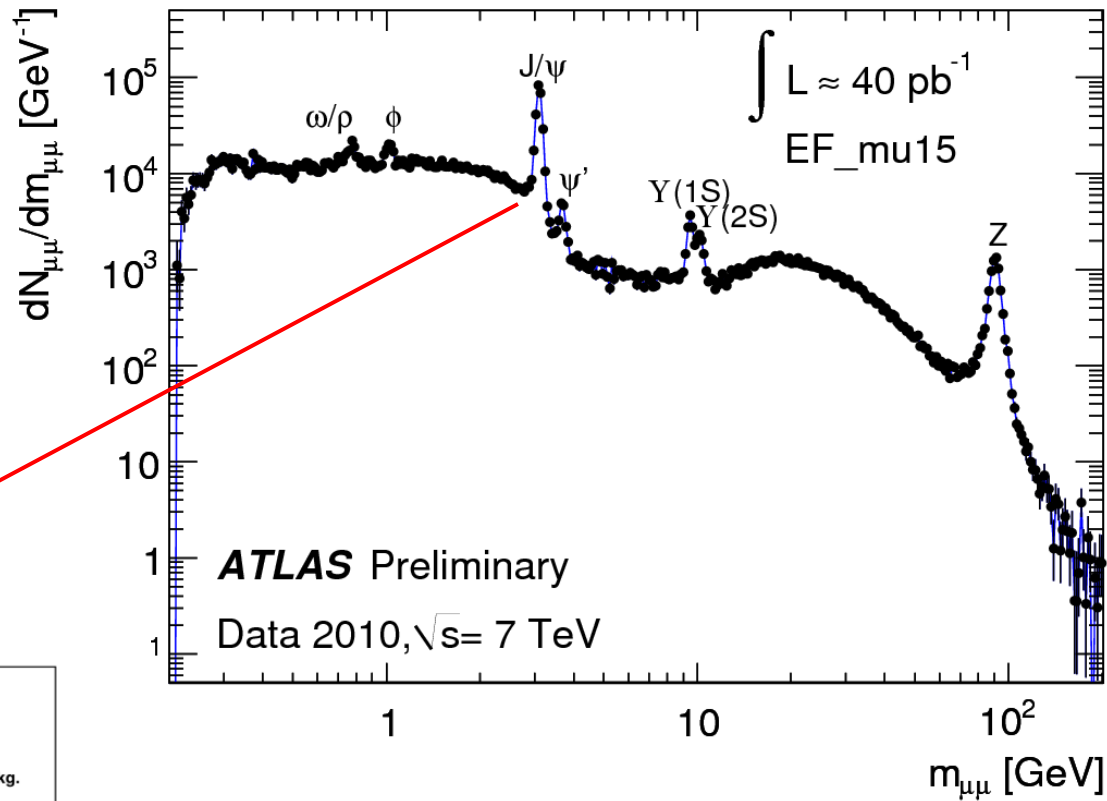
**Combined** muons have an ID track matched to a MS track and refitted through the detector to give the best measurement. At least one muon in a pair must be combined.



**Tagged** muons are ID tracks matched to muon segments when extrapolated to the MS. Such muons generally have low momentum.

Can reconstruct muons with  $P_t > 1$  GeV

# Dimuon mass

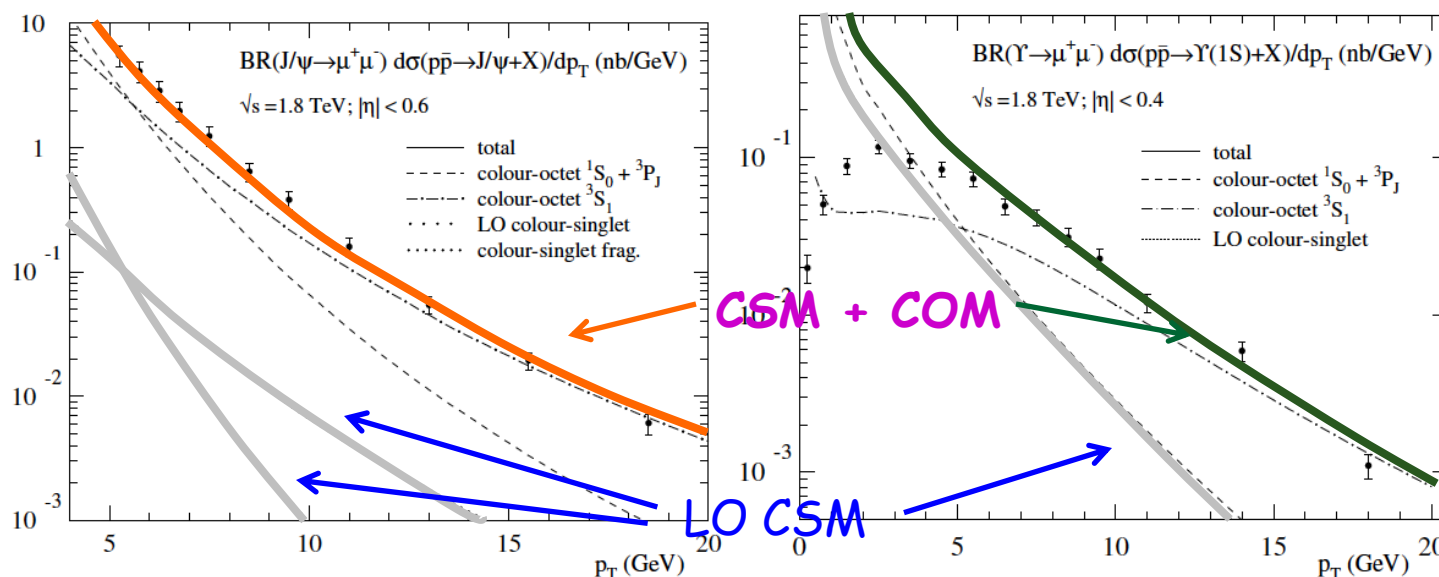


Many different triggers

# B physics triggers

- Triggers used for analyses ranged from those seeded by Minimum bias at L1 ( $J/\psi$  diff. x-section), Single muon at L1 to dimuon triggers.
  - Dimuon triggers pick up  $J/\psi$  (both prompt and from B's), Upsilon,  $B \rightarrow \mu\mu$  (X)
    - Seeded by a single muon at L1 or a dimuon at L1.  
Refinement at higher trigger levels
- In future, e.g.,  $L \sim 10^{33}$ , we will still have the dimuon triggers, although the ones seeded by a single muon at L1 may pick up a prescale.

- Historically Quarkonium Production & Polarization not understood
- Some popular models on the market :
  - Color Singlet Model (CSM) - LO calculation badly underestimated experiment
  - Color Octet Mechanism (COM) ( $\equiv$ NRQCD) - Gave shape but no absolute prediction
  - ...



$J/\psi$

$Y(1s)$

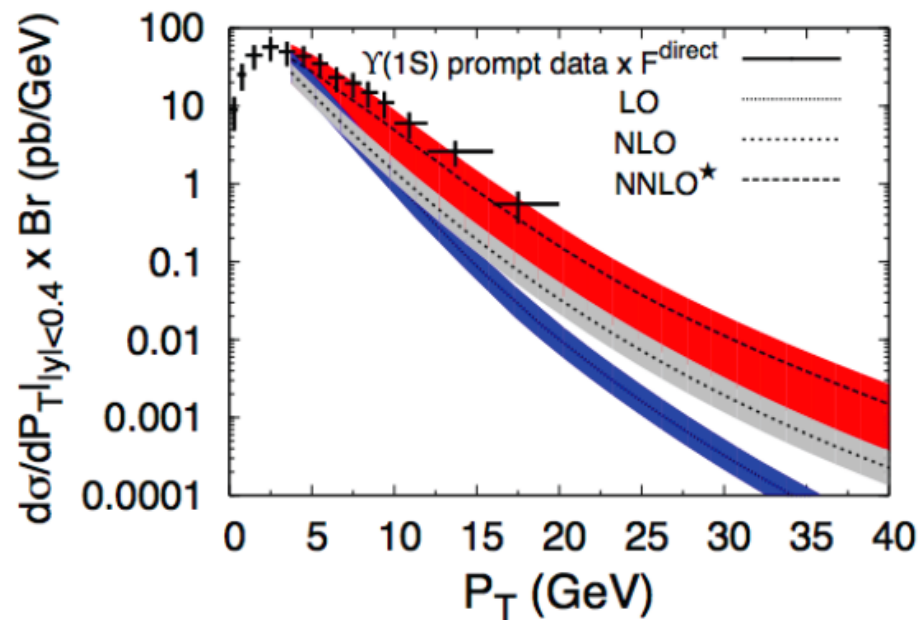
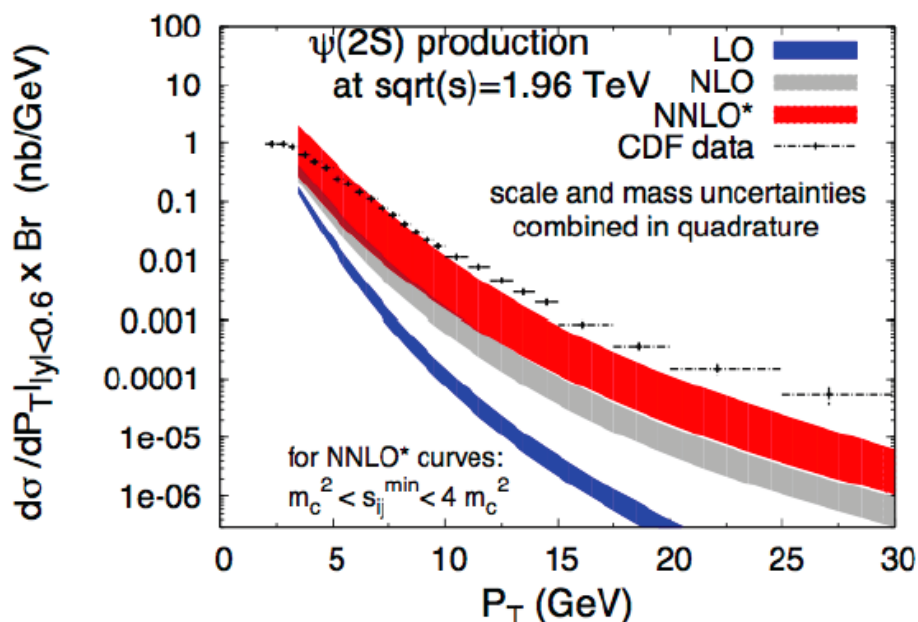
- Recently, theorists started to calculate the NNLO\* contribution in Color Singlet Model

- Very large!

- Good agreement with CDF data

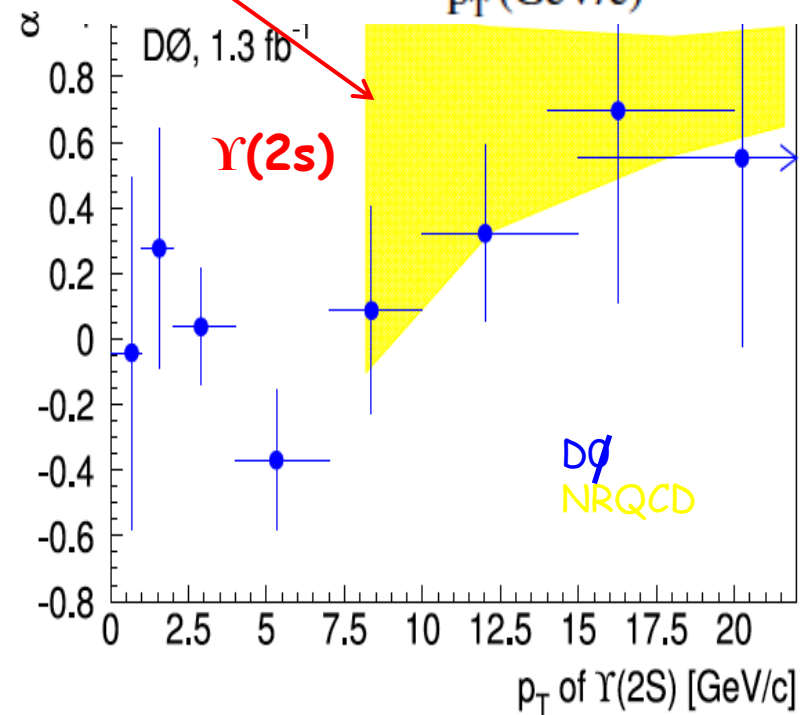
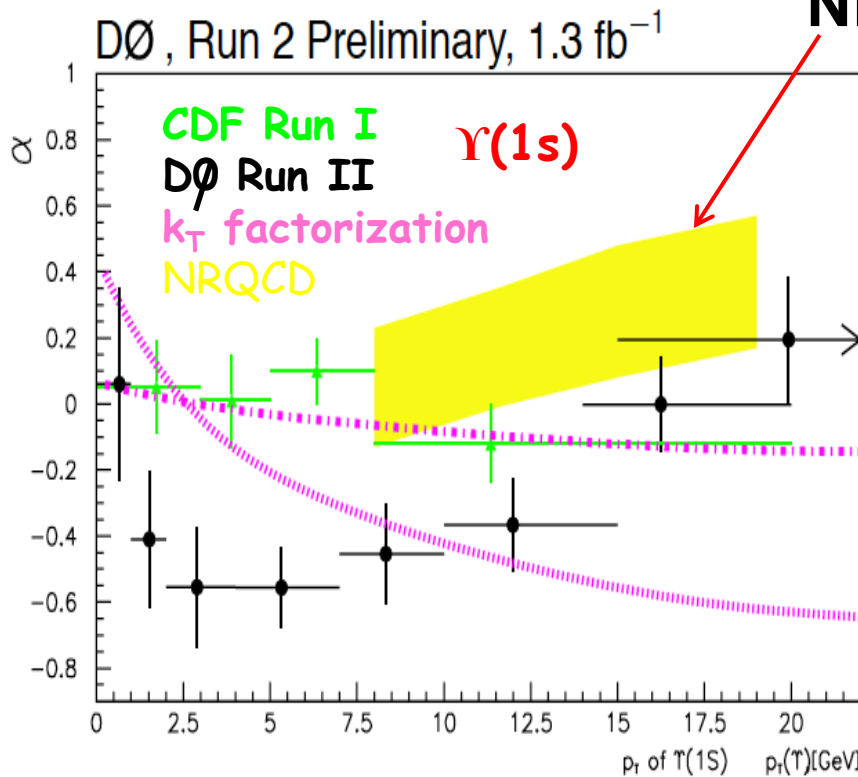
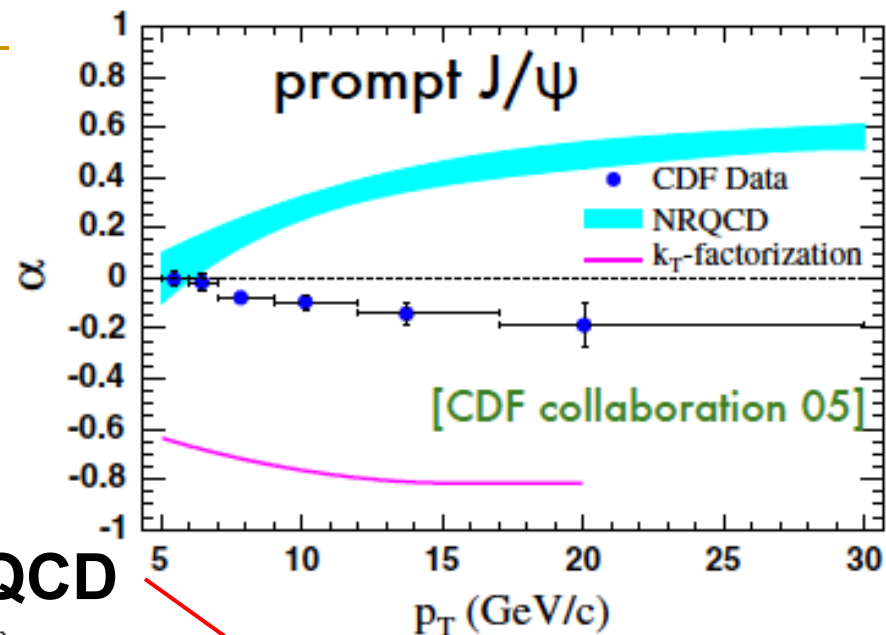
J.P. Lansberg arXiv:0811.4005

- \* Note: Not full NNLO calculation, currently, only real contribution up to  $\alpha_s^5$  (NLO yield + contributions from  $pp \rightarrow Q + jjj$ )



# Onia Polarization

- Situation is equally confusing
- Tevatron experiments disagree with each other and with Theory



# $J/\psi \rightarrow \mu\mu$ differential cross-section & Ratio of prompt to non-prompt $J/\psi$

- $J/\psi$  are also produced in B decays, so we need to account for those
  - For now, compare measured cross-section with MC, which includes both sources. Also includes feed-downs
  - **In the pipeline - Double differential  $(p_T, y)$  x-section; Prompt Cross-section in  $(p_T, y)$  bins**
- Use  $9.5 \text{ nb}^{-1}$  for differential cross-section
- Ratio of prompt/non-prompt  $J/\psi$  with  $17.5 \text{ nb}^{-1}$

# J/ψ Production Cross Section

- Get true yield of J/ψ candidates from the observed yield, by applying an event-by-event “weight”

$$w^{-1} = \underbrace{\mathcal{A}(p_T, y, \lambda_i)}_{\text{Detector Acceptance}} \times \underbrace{\mathcal{E}_\mu(\vec{p}_1) \times \mathcal{E}_\mu(\vec{p}_2)}_{\text{Reconstruction Efficiency}} \times \underbrace{\mathcal{E}_{\text{trig}}(\vec{p}_1, \vec{p}_2)}_{\text{Trigger Efficiency}}$$

## □ Detector Acceptance :

- Probability for both muons to be in the detector fiducial volume (generator level MC)

## □ Reconstruction efficiency :

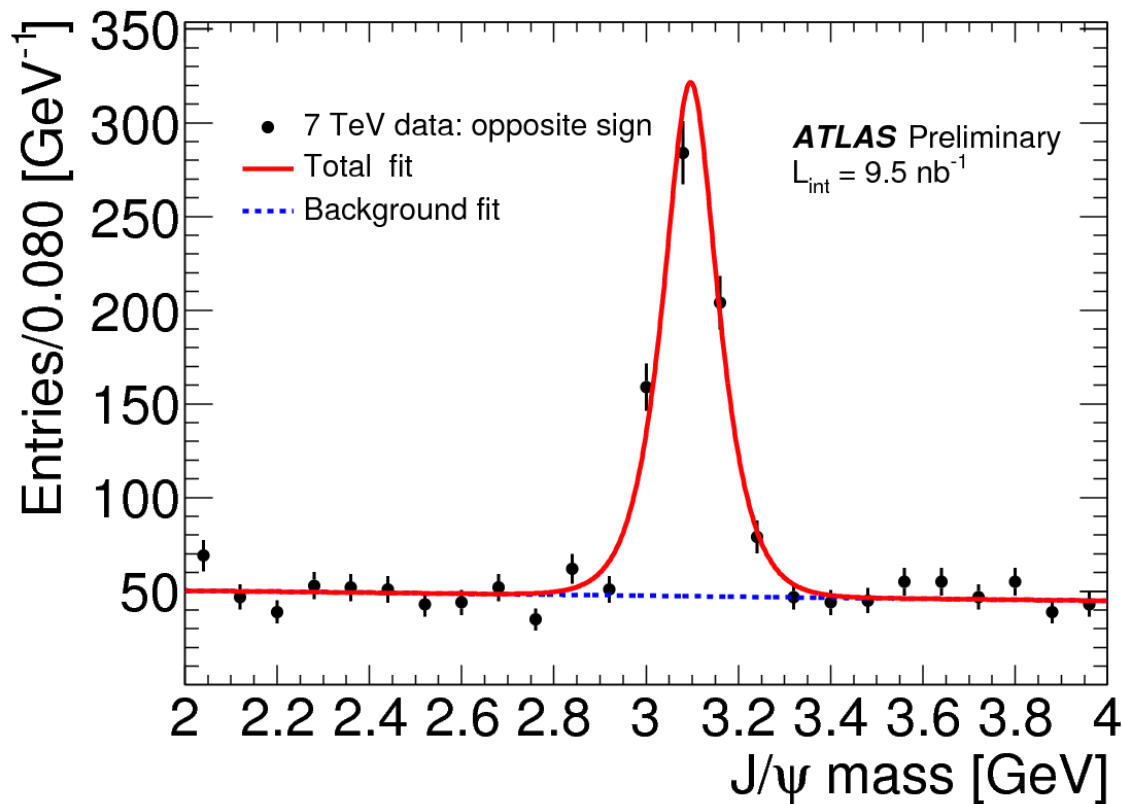
- Estimated from prompt J/ψ MC and validated with data.  
 $|\eta(\mu)| < 2.5, P(\mu) > 3.5 \text{ GeV}$

## □ Trigger efficiency :

- Relative to offline calculated using minimum bias data

# Fitting Mechanism

- Use Unbinned Maximum Likelihood Fit to extract number of  $J/\psi$  candidates



Sample used in analysis

**$N = 710 \pm 34$**

**$\text{Mass} = 3.096 \pm 0.003 \text{ GeV}$**

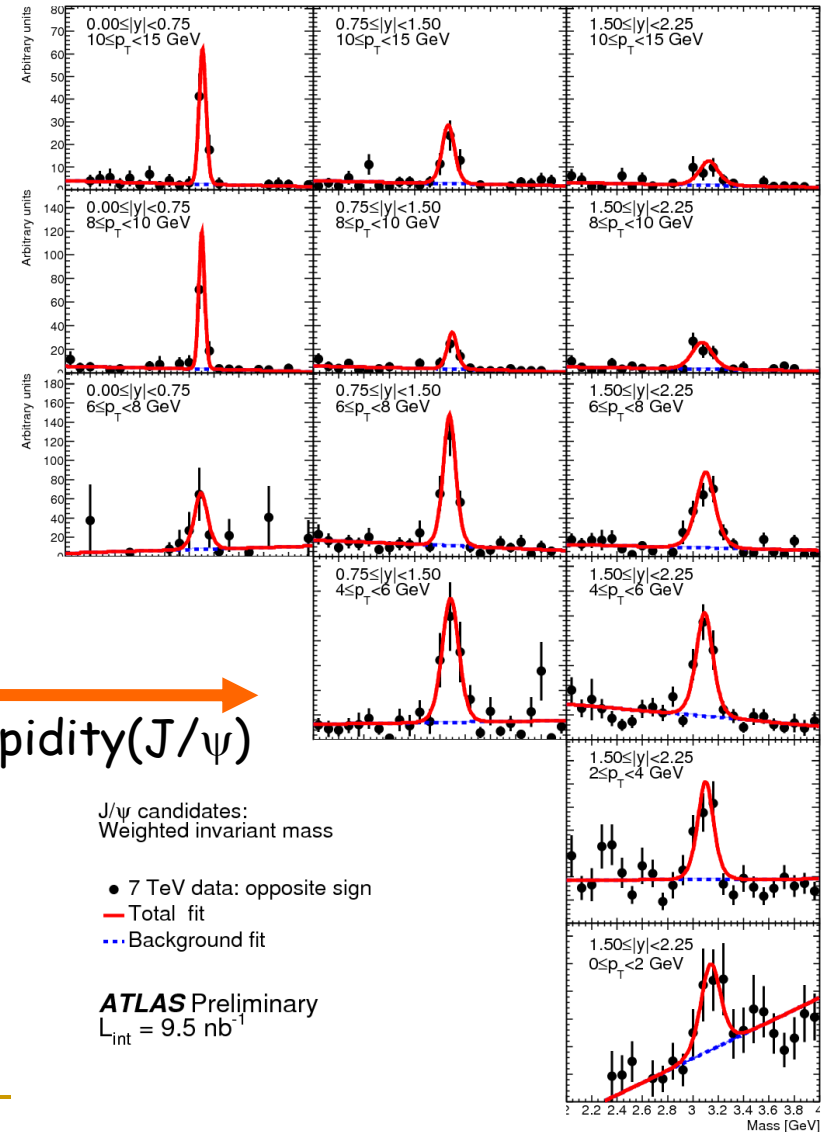
**$\text{Width} = 70 \pm 3 \text{ MeV}$**

# Final Fitting Results


- Correct  $J/\psi$  yield by event weight
- For display only. Weighted Yields

$p_T(J/\psi)$

rapidity( $J/\psi$ )



# Systematic Uncertainties

- Acceptance :
  - Biggest effect is the unknown spin-alignment 
- Single muon reconstruction and Trigger efficiency :
  - From minimum bias Monte Carlo, validated by Data with proper uncertainty (mainly the systematic at low pT turn on curve)
- Muon selection :
  - Compare the results between different combinations

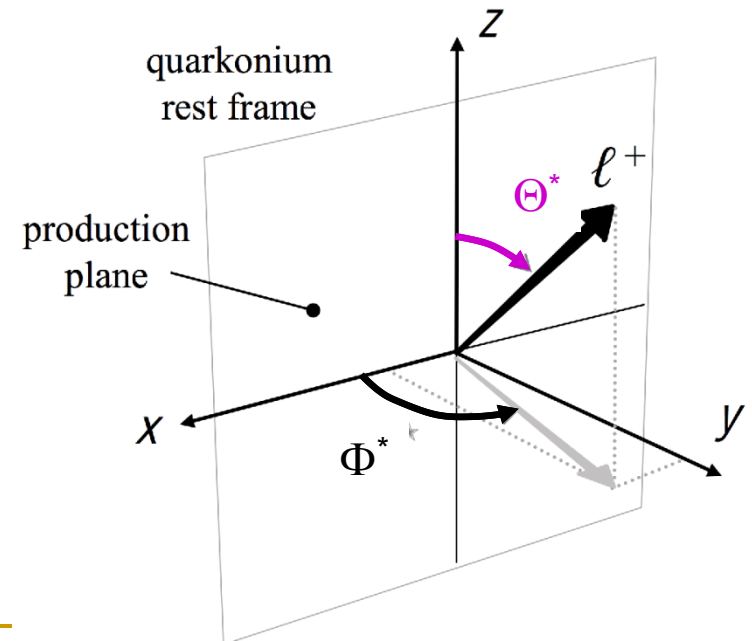
# J/ψ spin-alignment

- Acceptance depends on the **as yet unknown** angular distribution of the decaying particle (spin-alignment of J/ψ) by the formula

P. Faccioli et al. arXiv:1006.2738

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

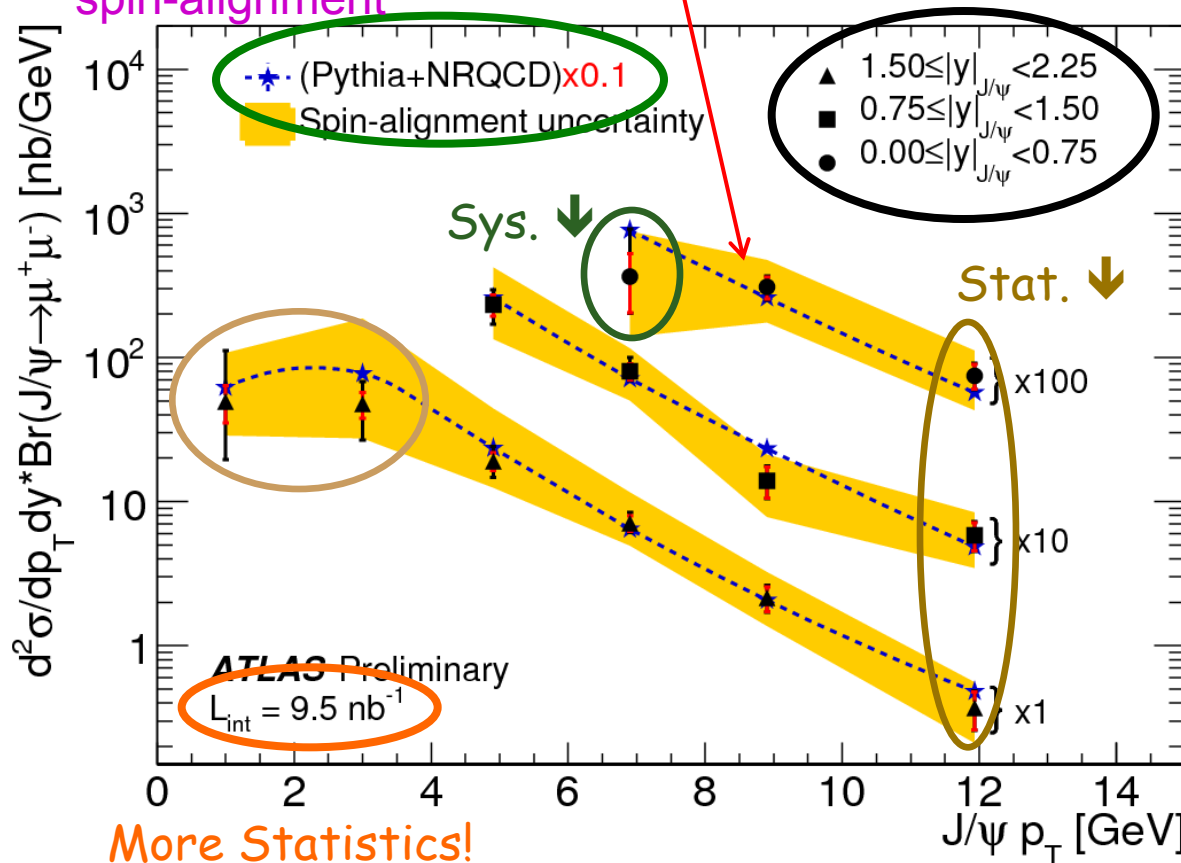
- $\theta^*$  : between  $\mu^+$  in J/ψ rest frame & J/ψ momentum in lab
- $\phi^*$  : between J/ψ prod & decay planes in lab
- **Use 5 different configurations, obtain systematic uncertainty:**
  - e.g.,  $\lambda_\theta = -1$ ,  $\lambda_\phi = \lambda_{\theta\phi} = 0$



# Results and future improvements

Yellow bands are the systematic uncertainty from not knowing the spin-alignment

Finer rapidity bins



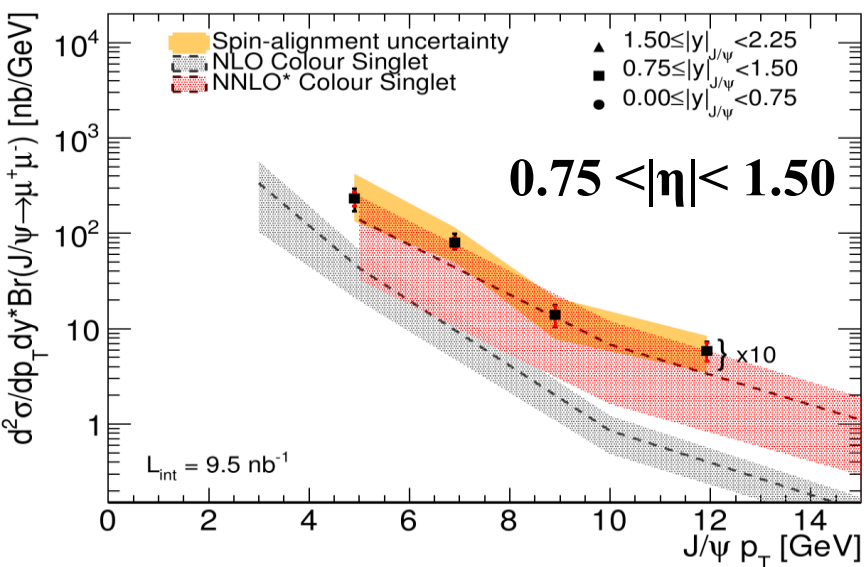
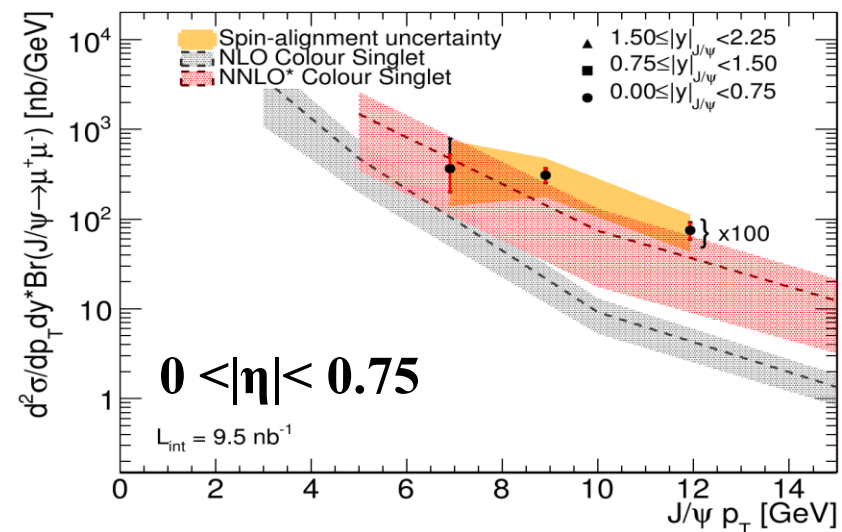
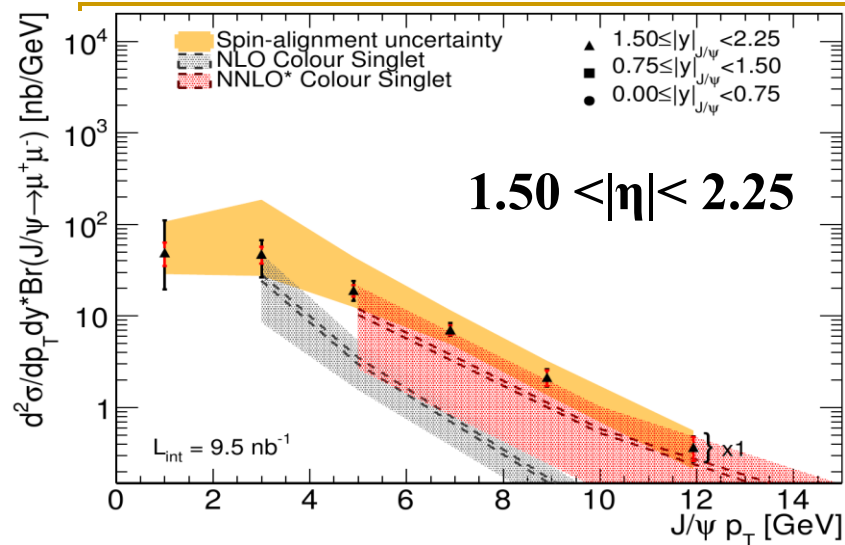
\* Trigger Matching

\* Data-driven offline and trigger efficiencies

Extend to higher  $p_T(J/\psi)$



Central value is for *inclusive*  $J/\psi$  for 'flat' polarisation hypothesis (Red: statistical error)



- Only for direct vector quarkonium production (**Lansberg, PRL 101 (2008) 152001**)
- In order to be compared to inclusive ATLAS data, needs correcting for:
  - feeddown from  $\chi_c$ -states
  - non-prompt contribution from  $B \rightarrow J/\psi X$  decays
- Corrections made using Tevatron measurements

# Ratio of non-prompt to prompt $J/\psi$ cross section

- ◆ non-prompt: from decay of B-hadrons.
- ◆ prompt from direct & feed-down from other charmonium states

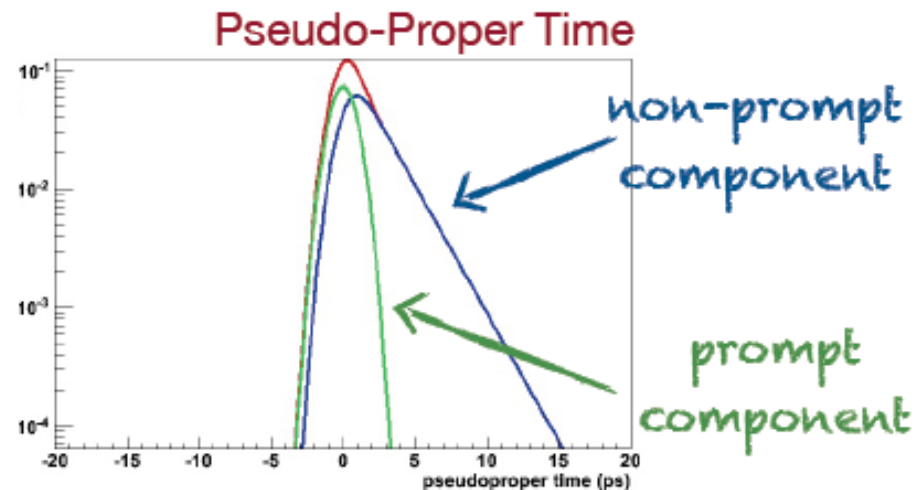
$$F = \frac{pp \rightarrow b\bar{b}X \rightarrow J/\psi X'}{pp \rightarrow J/\psi X''}$$

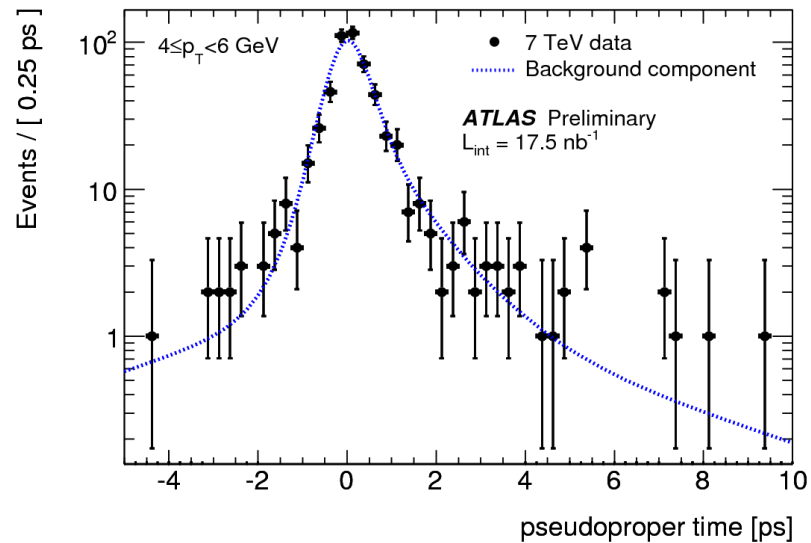
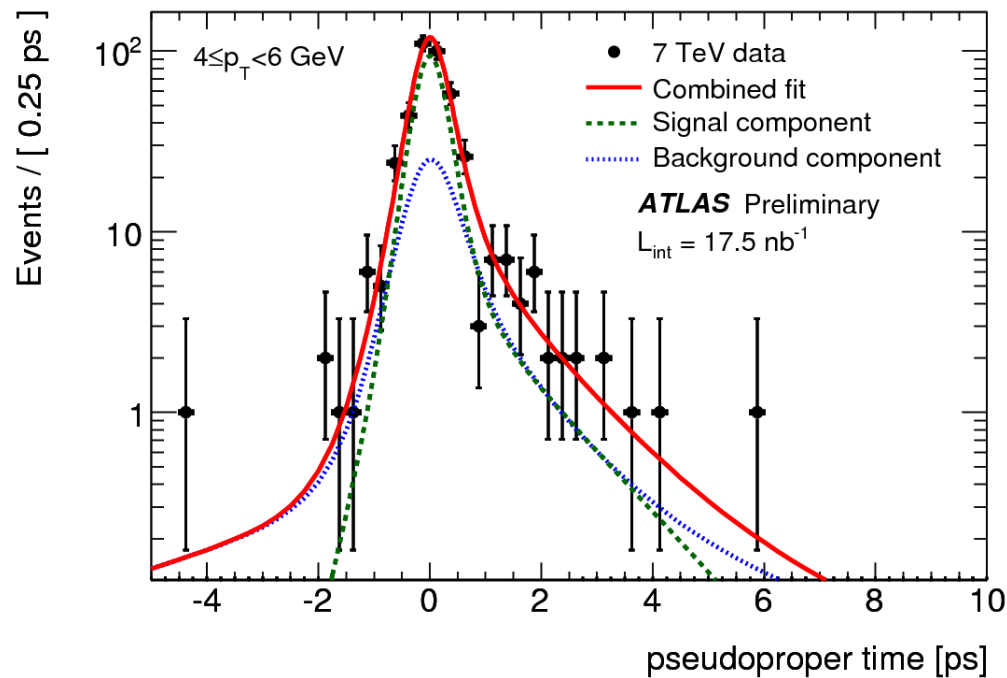
- ◆ Discriminating variable is the pseudo-proper time:

$$\tau = L_T M^{\mu\mu} / P_T^{\mu\mu}$$

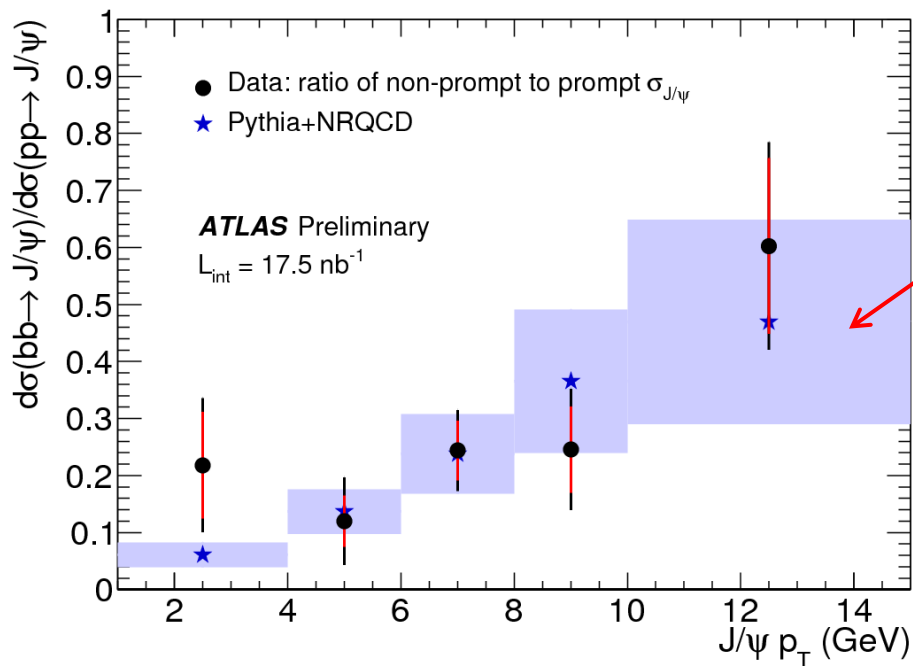
$$\simeq L_T M^B / P_T^B \propto e^{-\tau/\tau(B)}$$

$L_T \rightarrow$  decay length wrt the primary vertex in the xy projection





Background component from  
 $J/\psi$  sideband region



Large statistical error due to  
small MC samples of  $bb \rightarrow J/\psi X$

# Upsilon Observation

- Using ~290 nb<sup>-1</sup> 2010 ATLAS data

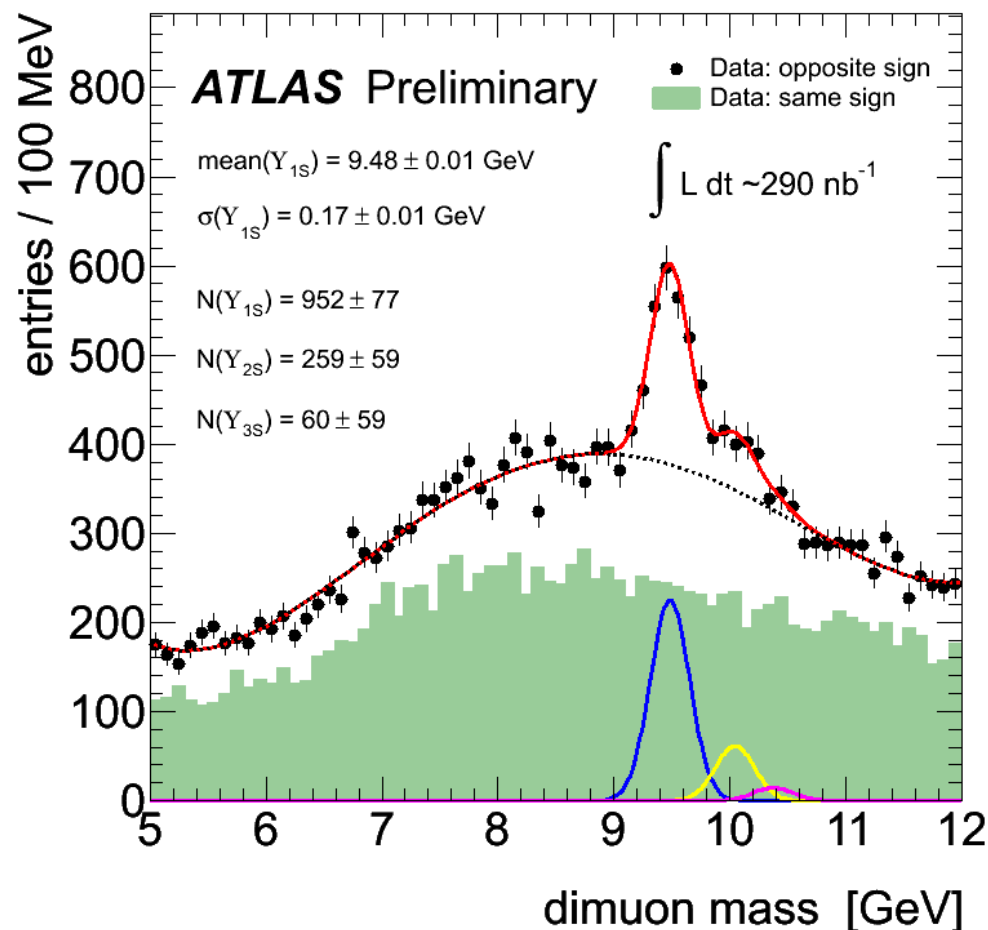
Cross-section measurements  
are in the pipeline

- Muon trigger as in  
J/ψ analysis

- Selection Criteria :

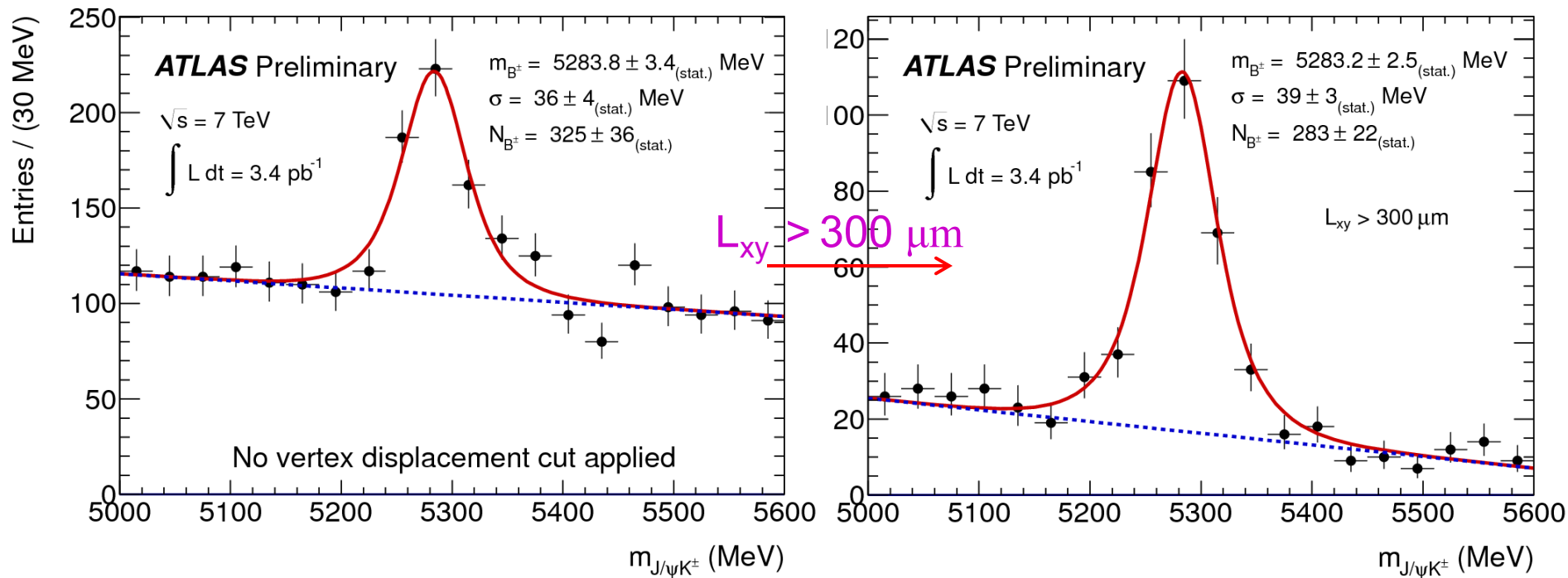
- Good primary vertex
- $pT(\mu_1, \mu_2) > 4, 2.5$  GeV
- $|\eta(\mu)| < 2.5$

- ~950  $Y(1S)$  candidates



# Exclusive B signals: $B^+ \rightarrow J/\psi K^+$

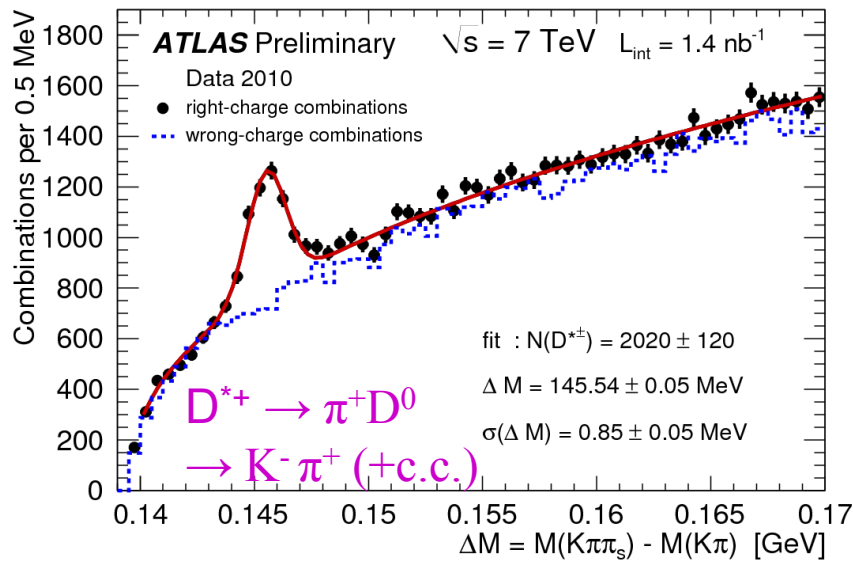
- Very useful for understanding reconstruction, flavour tagging algorithms that will be used for CP violation, studying rare decays



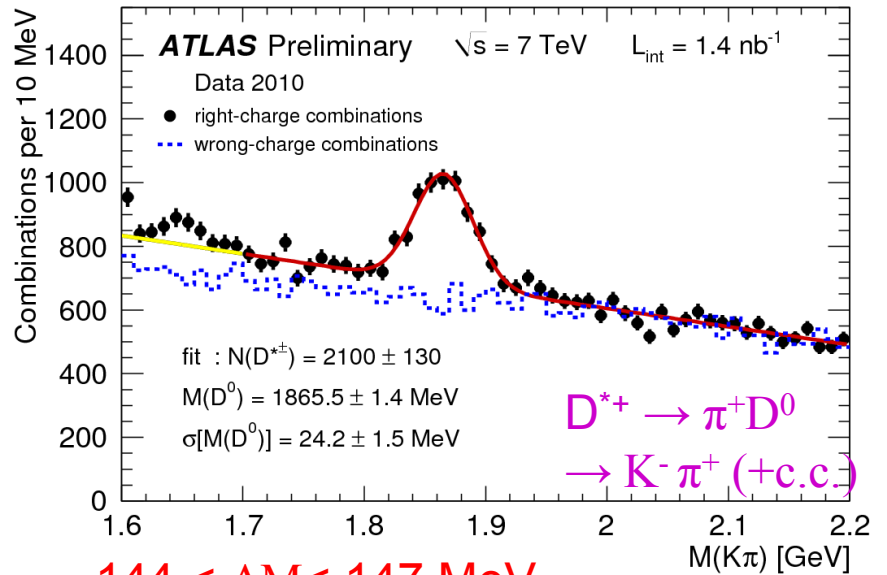
13% loss of signal due to  $L_{xy}$  cut agrees with MC predictions

# Exclusive $D^{(*)}$ signals

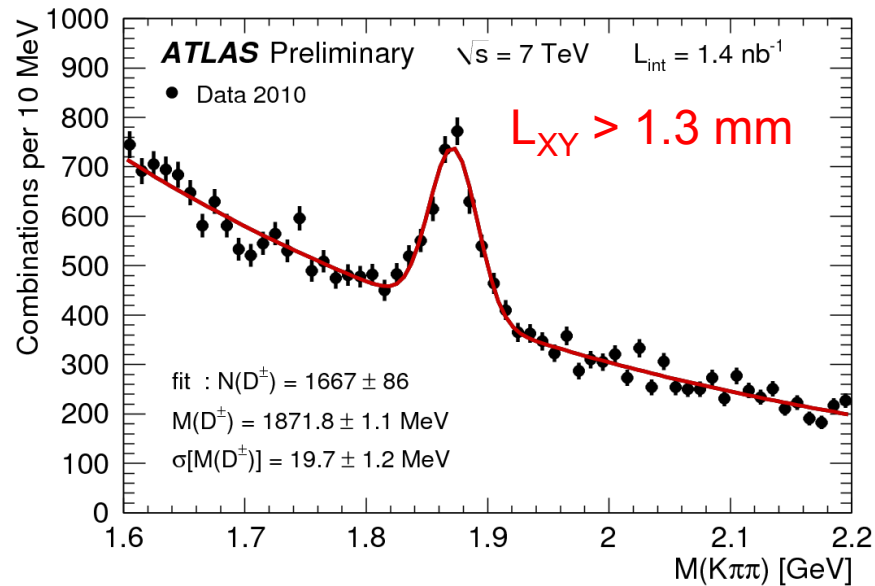
- A good testing ground for QCD predictions for heavy flavour production
  - Cross-section measurements are in the pipeline
  - Selected using minimum bias trigger
- Test reconstruction, vertexing algorithms
  - Width of mass distributions in data agree with MC
- Exclusive signals can also be used to understand tracking efficiency
  - $D \rightarrow K3\pi / D \rightarrow K\pi$  is well-known (PDG:  $2.08 \pm 0.05$ ).
  - Compare our result with PDG. In the pipeline



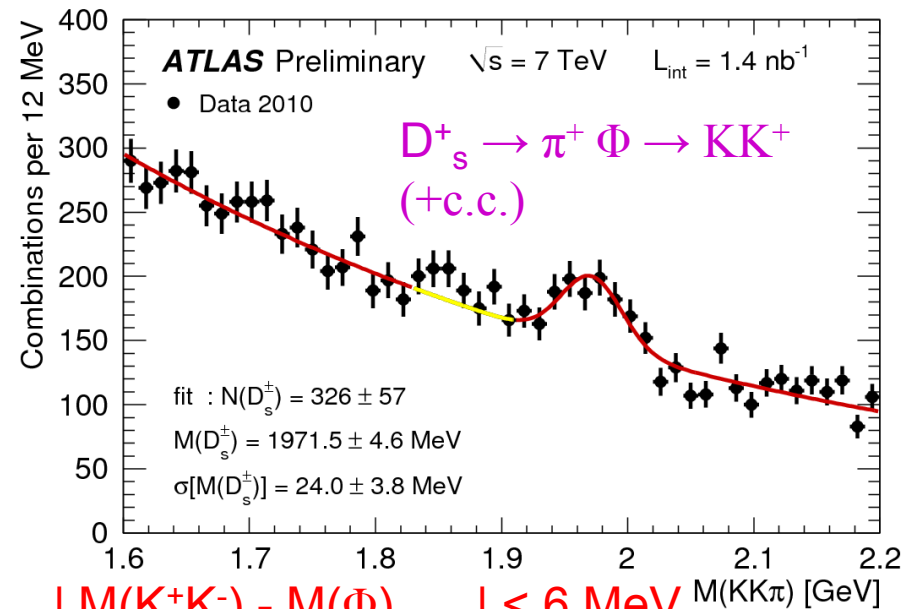
$1.83 < M(K\pi) < 1.90 \text{ GeV}$



$144 < \Delta M < 147 \text{ MeV}$



$D^+ \rightarrow K^- \pi^+ \pi^+ (+c.c.)$



$|M(K^+ K^-) - M(\Phi)_{\text{PDG}}| < 6 \text{ MeV}$

No particle ID used here

# Future Plans

## ■ Quarkonia

- Polarization analysis on 2010 data in progress
- $\psi'$  (prompt), Upsilon cross-section, polarization
- Search for various X, Y, Z states in progress

## ■ Open charm and beauty studies

- Cross-sections (also in association with quarkonia),  $\Lambda_b$  polarization, Exclusive & Inclusive B lifetimes,  $B_c$ ...

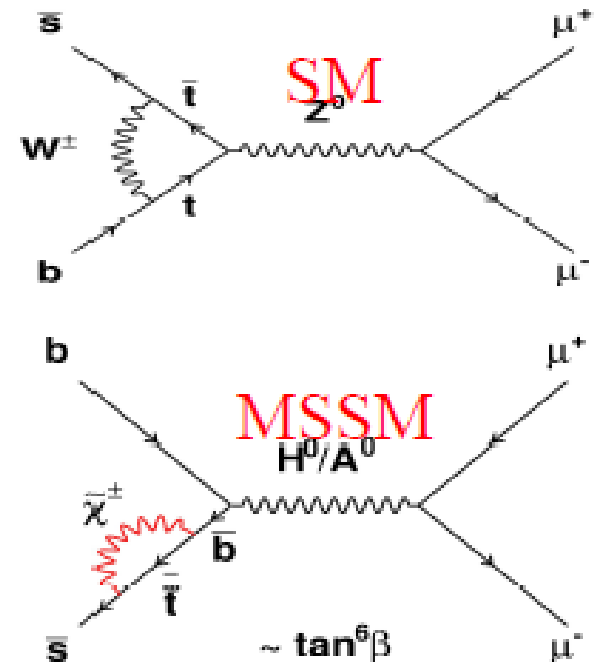
## ■ Rare decays – Need datasets $\sim \text{few fb}^{-1}$

- $B_s \rightarrow J/\psi \Phi$  – lifetimes, helicity amplitudes

- 
- Additional sources of CP violation

# $B_s \rightarrow \mu\mu$

- Rate in SM:  $(3.42 \pm 0.52) \cdot 10^{-9}$
- Current PDG (90% CL) Limit:  
 $< 4.7 \cdot 10^{-8}$
- Good mode to search for SUSY with large  $\tan\beta$
- Studies are on-going
- Can continue search in high Luminosity era
  - Triggers will probably need to be modified



# Summary

- B physics program at ATLAS is starting to produce results
  - See benchmark modes, initial physics results
    - $J/\psi$  cross-section, Upsilon observation, Exclusive B and Charm meson signals
  - Early stages
    - Understanding issues relating to reconstruction, trigger, etc.
- Exciting times lie ahead

---

# Extra stuff

# Muon Spectrometer

## ■ Precision tracking chambers and trigger chambers

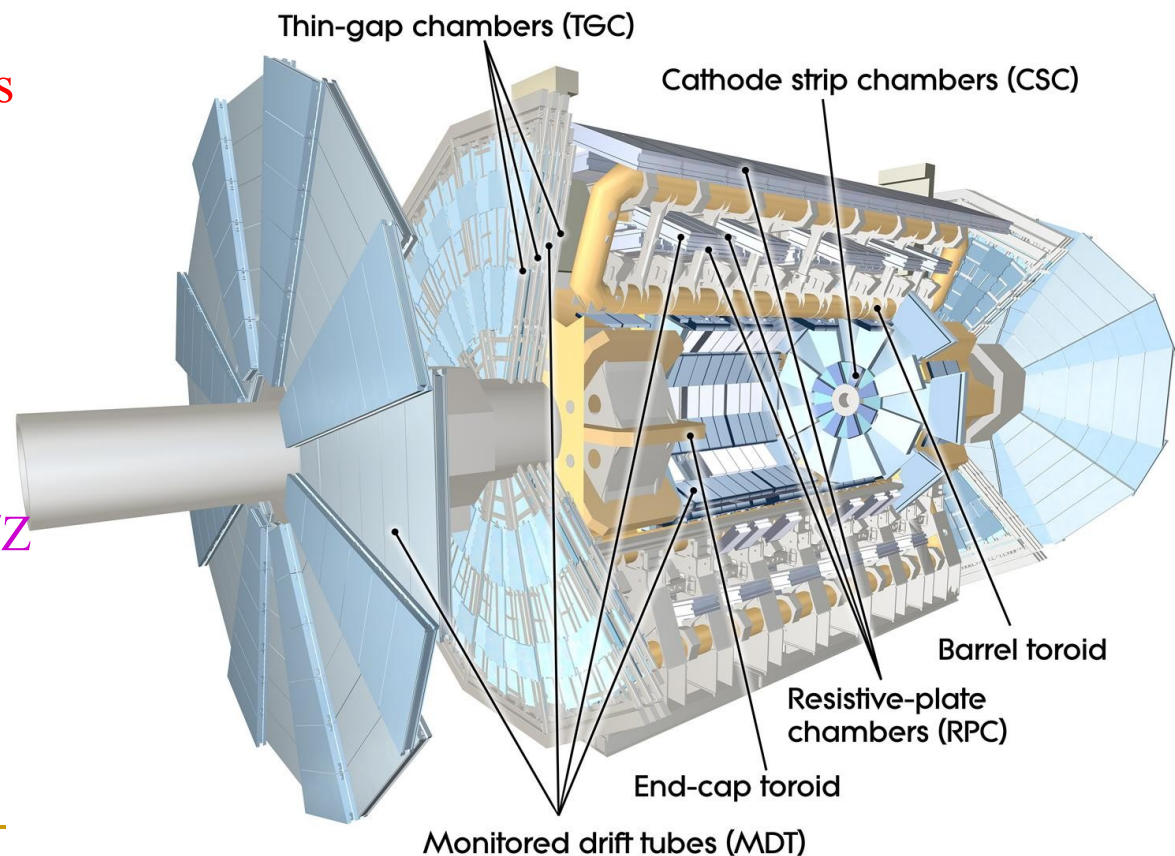
- Monitored drift tubes
- Cathode drift chambers
- Thin-gap chambers
- Resistive plate chambers

## ■ $|\eta|$ coverage up to 2.7

## ■ Magnetic field produced by 3x8 air-core toroids

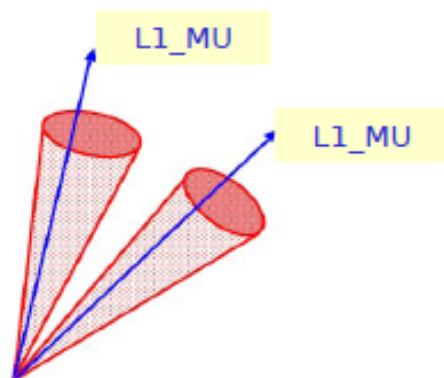
- Barrel/End Cap toroids
- Complex field map
- $B \sim 0.5T$ , but varies in R/Z
- Bend in barrel is in Z
- Bend in ECap is along R

$$\sigma_{p_T}/p_T = 10\% \text{ at } p_T = 1 \text{ TeV}^-$$



# B-Trigger Strategy

## Di-muon Trigger



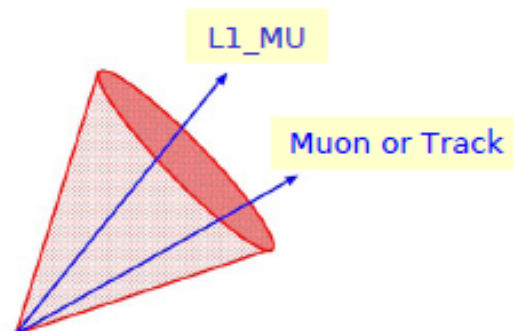
### Two L1 muons

confirm muon at L2

Tracking in small RoI

Mass & vertex cuts

## Single $\mu$ Trigger



### One L1 muon

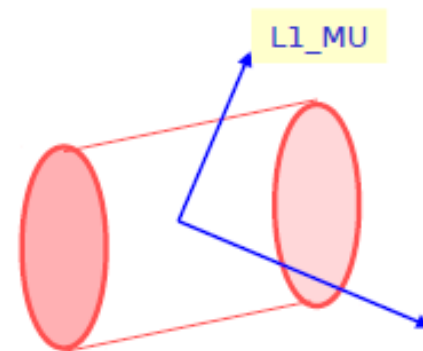
confirm muon at L2

Tracking in one large

RoI, search for the 2<sup>nd</sup> muon

Mass & vertex cuts

## FullScan Trigger



### One L1 muon

confirm muon at L2

Tracking in entire detector,  
search for the 2<sup>nd</sup> muon

Mass & vertex cuts

The lowest level 1 muon trigger threshold are **4 GeV, 6 GeV**

### ▪ Single L1 muon triggers:

- Use lowest muon pT threshold and FullScan(time consuming) to give highest efficiency at startup

### ▪ L1 di-muon triggers:

- Use lowest muon pT threshold (MU4)
- Reduce the background and will be needed at higher luminosity.

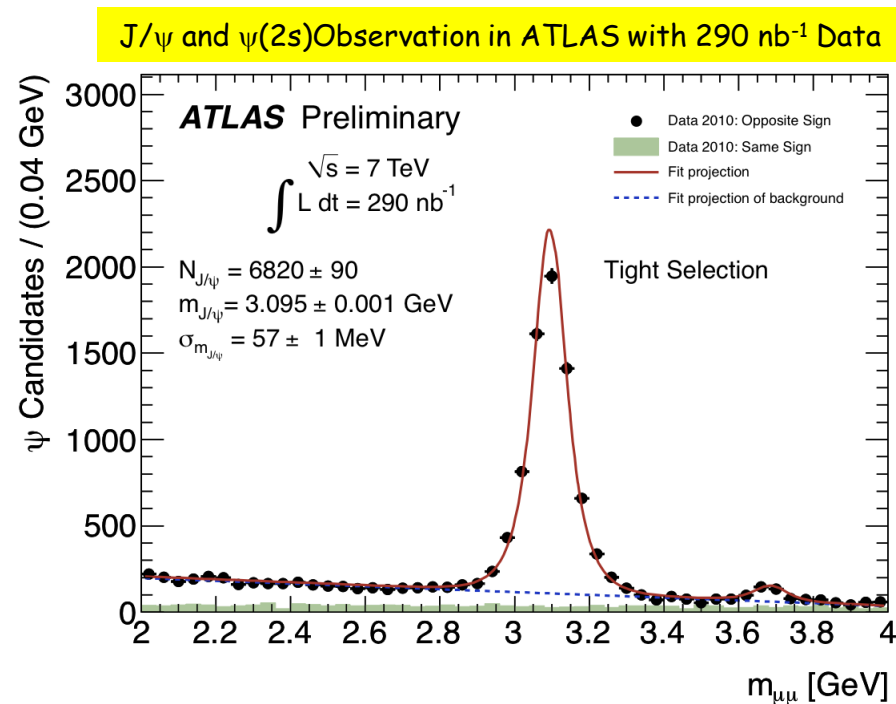
# J/ψ Analysis

## ■ Event Selection :

- At least ONE primary vertex which has 3 tracks associated (each of them has quality cuts, 6 SCT, 1 Pixel hits, to remove the badly measured muons)
- Opposite charge muon pairs with successful vertex fit
- ONE of the muon candidates needs to be “Combined Muon”
- $|\eta(\mu)| < 2.5$
- Momentum Cut :
  - Cross Section Measurement :
    - $P(\mu) > 3.5 \text{ GeV}, |\eta| < 2$
    - $P(\mu) > 8 \text{ GeV}, |\eta| > 2$

## ■ Trigger Configurations :

- Muon hardware level 1 trigger or minimum bias trigger with confirmation at MS



# Fitting Mechanism

- Unbinned Maximum Likelihood Fit is used to extract the  $J/\psi$  mass and the number of  $J/\psi$  candidates
- **Log- Likelihood function :**

$$\ln \mathcal{L} = \sum_{i=1}^N w_i \cdot \ln \left[ f_{\text{signal}}(m_{\mu\mu}^i) + f_{\text{bkg}}(m_{\mu\mu}^i) \right]$$

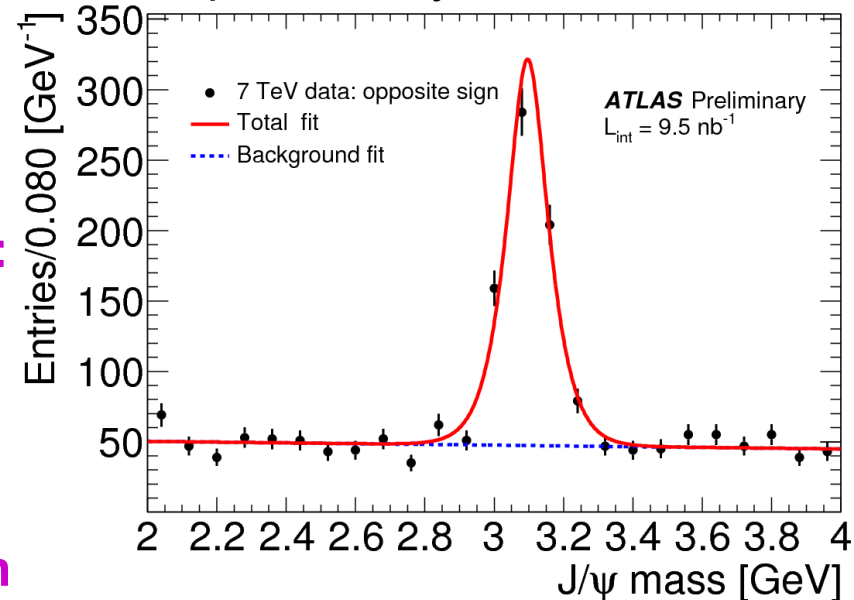
- **Signal PDF (Gaussian function) :**

$$f_{\text{signal}}(m_{\mu\mu}, \delta m_{\mu\mu}) \equiv a_0 \frac{1}{\sqrt{2\pi} S \delta m_{\mu\mu}} e^{\frac{-(m_{\mu\mu} - m_{J/\psi})^2}{2(S \delta m_{\mu\mu})^2}}$$

- **Background PDF: linear function**

\* Using event-by-event mass error

Reconstructed sample used as Input to analysis



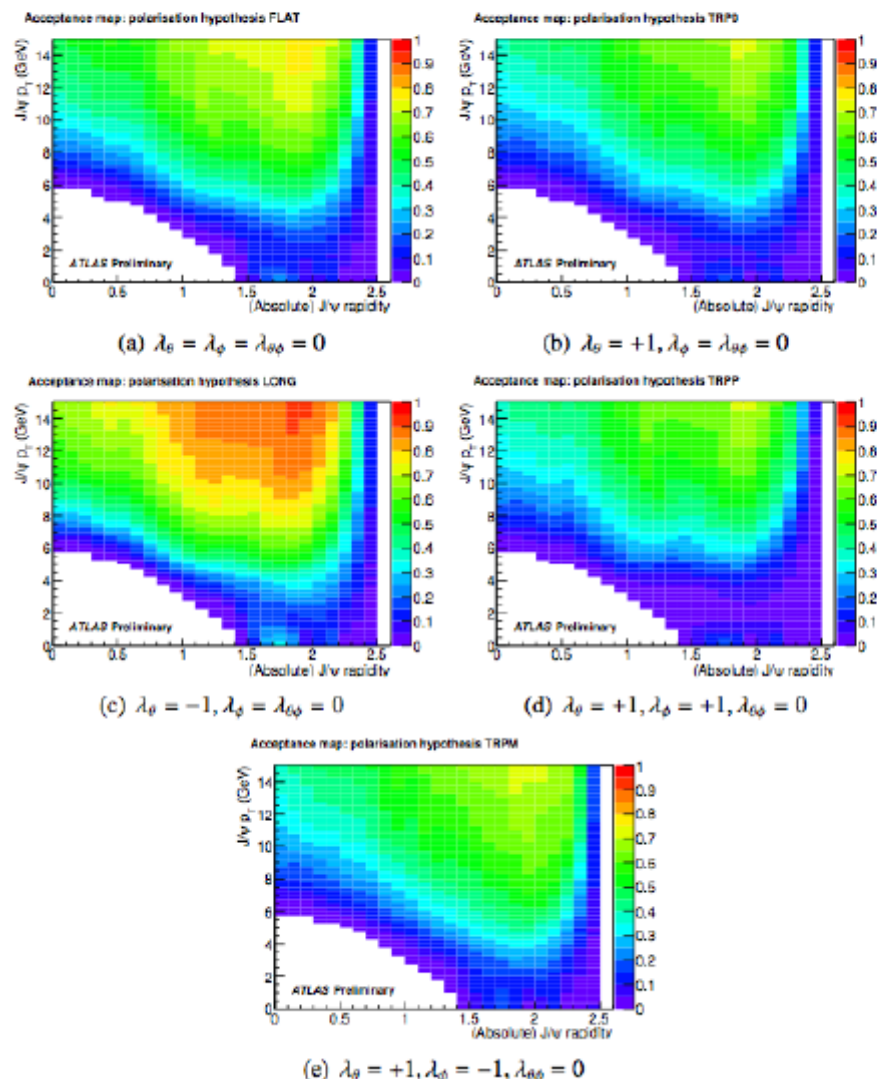
**$N = 592 \pm 30$**

**$\text{Mass} = 3.095 \pm 0.003 \text{ GeV}$**

**$\text{Width} = 71 \pm 4 \text{ MeV}$**

# Effect of spin-alignment uncertainty

Acceptance maps and weight factors for  $J/\psi$  at spin alignment working points



$p_T, \text{ GeV}$	FLAT	LONG	TRP0	TRPP	TRPM
$0 < y \leq 0.75$					
6 – 8	1.00	0.67	1.31	1.30	1.32
8 – 10	1.00	0.69	1.29	1.32	1.26
10 – 15	1.00	0.72	1.24	1.25	1.23
$0.75 < y \leq 1.5$					
4 – 6	1.00	0.69	1.29	1.55	1.15
6 – 8	1.00	0.72	1.25	1.29	1.22
8 – 10	1.00	0.74	1.21	1.22	1.20
10 – 15	1.00	0.77	1.18	1.18	1.18
$1.5 < y \leq 2.25$					
0 – 2	1.00	0.81	1.15	1.55	0.96
2 – 4	1.00	0.73	1.23	3.23	0.77
4 – 6	1.00	0.64	1.18	1.98	0.87
6 – 8	1.00	0.79	1.15	1.44	0.98
8 – 10	1.00	0.80	1.15	1.26	1.05
10 – 15	1.00	0.82	1.08	1.18	1.08

# J/ψ Spin Alignment – cont.

## ■ Five spin alignment scenarios :

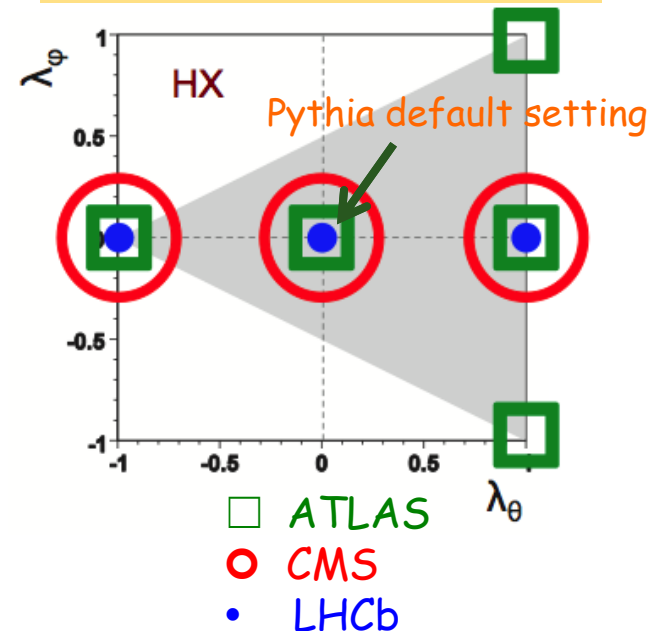
- ❑ Flat :  $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$
- ❑ Longitudinal :  $\lambda_\theta = -1, \lambda_\phi = \lambda_{\theta\phi} = 0$
- ❑ 1<sup>st</sup> Transverse :  $\lambda_\theta = +1, \lambda_\phi = \lambda_{\theta\phi} = 0$
- ❑ 2<sup>nd</sup> Transverse :  $\lambda_\theta = +1, \lambda_\phi = +1, \lambda_{\theta\phi} = 0$
- ❑ 3<sup>rd</sup> Transverse :  $\lambda_\theta = +1, \lambda_\phi = -1, \lambda_{\theta\phi} = 0$

## ■ For Non-Flat distributions :

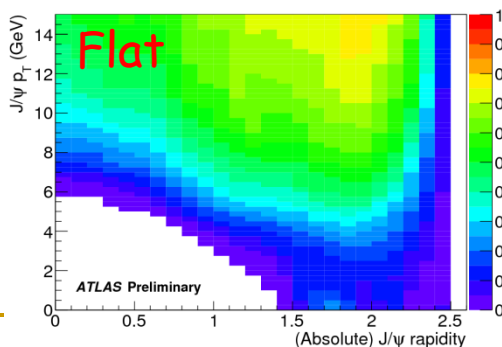
- ❑ Re-weighting the Flat distribution in truth level according to the formula in previous page

C. Lourenço

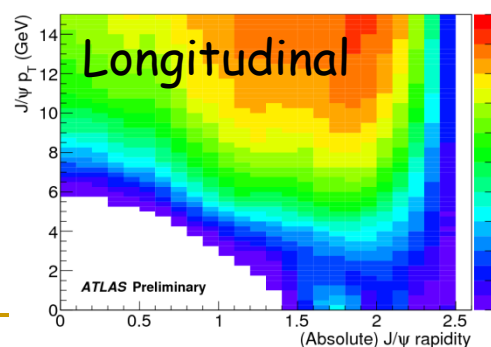
Introduction polarisation working points  
(arXiv : 1006.2738)



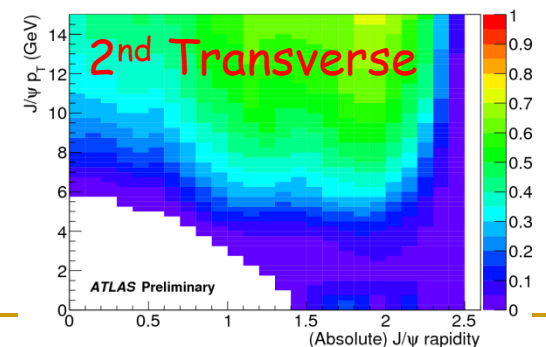
Acceptance map: polarisation hypothesis FLAT



Acceptance map: polarisation hypothesis LONG



Acceptance map: polarisation hypothesis TRPP



**Systematics-dominated @low  $p_T$ :**  
**Main systematics are from trigger and muon reconstruction**

**Will improve somewhat with more data, but will always be limited in this region of phase space**

**Comparable variation from spin-alignment uncertainty**

**Can only be reduced by direct measurement --- may take a while**

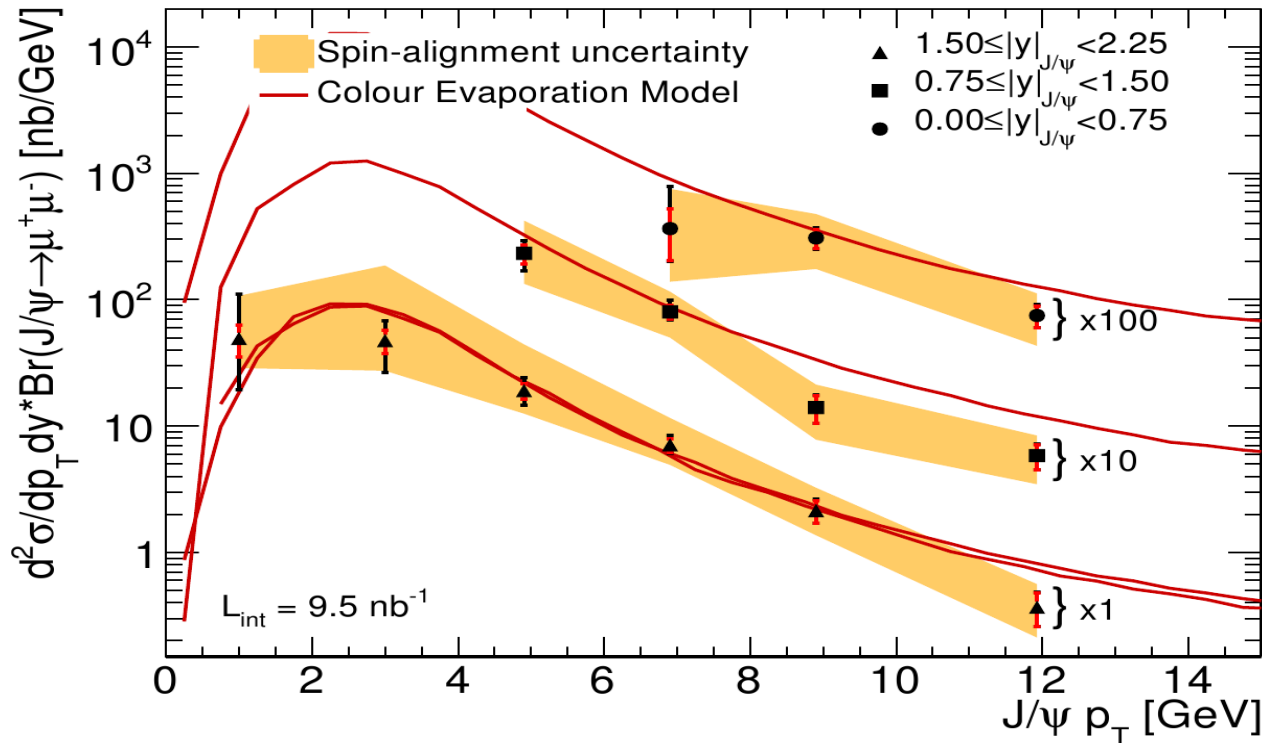
$p_T(J/\psi)$ GeV	Mean $p_T$ GeV	$\frac{d\sigma}{dp_T dy} \cdot \text{Br}[J/\psi \rightarrow \mu^+ \mu^-]$ (nb/GeV)	
$0.0 \leq  y  < 0.75$			
		Data	PYTHIA
6 – 8	6.9	$3.6 \pm 1.6$ (stat) $^{+3.9}_{-0.3}$ (syst) $^{+3.9}_{-2.3}$ (theory)	$76.5 \pm 1.5$
8 – 10	8.9	$3.08 \pm 0.66$ (stat) $^{+0.40}_{-0.22}$ (syst) $^{+1.7}_{-1.4}$ (theory)	$26 \pm 1$
10 – 15	11.9	$0.75 \pm 0.18$ (stat) $^{+0.11}_{-0.05}$ (syst) $^{+0.37}_{-0.32}$ (theory)	$5.7 \pm 0.3$
$0.75 \leq  y  < 1.50$			
		Data	PYTHIA
4 – 6	4.9	$23.2 \pm 4.0$ (stat) $^{+5.2}_{-4.9}$ (syst) $^{+18.9}_{-9.9}$ (theory)	$260 \pm 3$
6 – 8	6.9	$8.0 \pm 1.0$ (stat) $^{+1.9}_{-0.6}$ (syst) $^{+3.6}_{-3.0}$ (theory)	$72 \pm 2$
8 – 10	8.9	$1.40 \pm 0.34$ (stat) $^{+0.18}_{-0.09}$ (syst) $^{+0.73}_{-0.62}$ (theory)	$23.3 \pm 0.9$
10 – 15	11.9	$0.58 \pm 0.13$ (stat) $^{+0.06}_{-0.04}$ (syst) $^{+0.26}_{-0.24}$ (theory)	$4.9 \pm 0.3$
$1.50 \leq  y  < 2.25$			
		Data	PYTHIA
0 – 2	1.0	$49 \pm 20$ (stat) $^{+61}_{-26}$ (syst) $^{+58}_{-21}$ (theory)	$621 \pm 3$
2 – 4	3.0	$48 \pm 10$ (stat) $^{+18}_{-18}$ (syst) $^{+139}_{-20}$ (theory)	$773 \pm 3$
4 – 6	4.9	$19.1 \pm 2.7$ (stat) $^{+5.1}_{-3.5}$ (syst) $^{+25.1}_{-6.6}$ (theory)	$235 \pm 2$
6 – 8	6.9	$7.10 \pm 0.88$ (stat) $^{+1.32}_{-0.57}$ (syst) $^{+4.5}_{-2.2}$ (theory)	$64 \pm 1$
8 – 10	8.9	$2.14 \pm 0.43$ (stat) $^{+0.33}_{-0.10}$ (syst) $^{+1.1}_{-0.8}$ (theory)	$20.7 \pm 0.9$
10 – 15	11.9	$0.37 \pm 0.11$ (stat) $^{+0.06}_{-0.03}$ (syst) $^{+0.19}_{-0.16}$ (theory)	$4.8 \pm 0.3$

CEM: once a c-cbar pair is produced, creation of colour singlet bound states is governed by a suppression factor ([Phys.Rep.462\(2008\)125](#))

No extra parameters used to extrapolate from Tevatron, using CTEQ6M

Agreement with preliminary ATLAS data remarkably good at low pt

Will be very interesting to compare with higher statistics data (soon!)



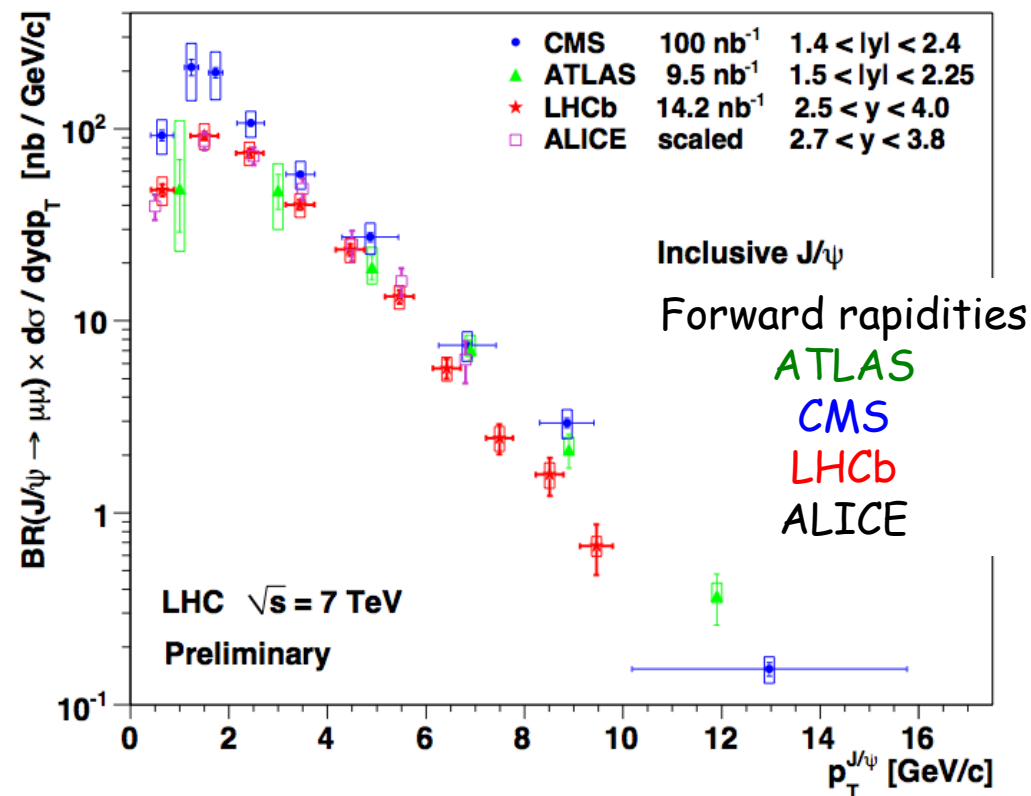
[R.Vogt]

# Compare to Other LHC experiments

(compilation by H. K. Woehri)

- Have good agreement with other experiments

\* LHCb, ALICE has further forward acceptance



Central rapidities  
ATLAS :  $0.75 < |y| < 1.5$   
ATLAS :  $|y| < 0.75$   
CMS :  $|y| < 1.5$

