Heavy Quarkonia Production in ATLAS

14th January 2013

Heavy Flavor Workshop @ LBNL

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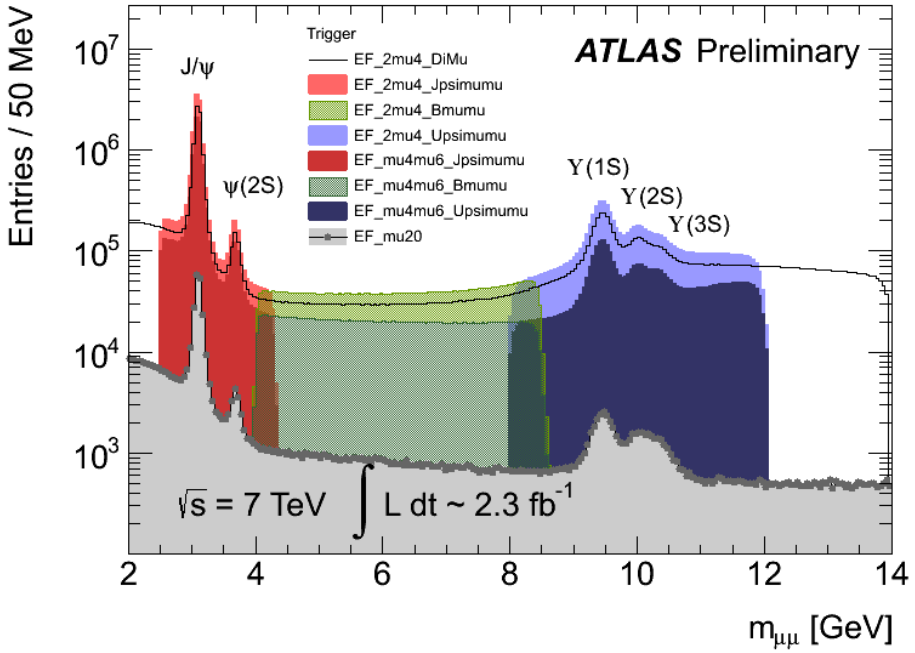
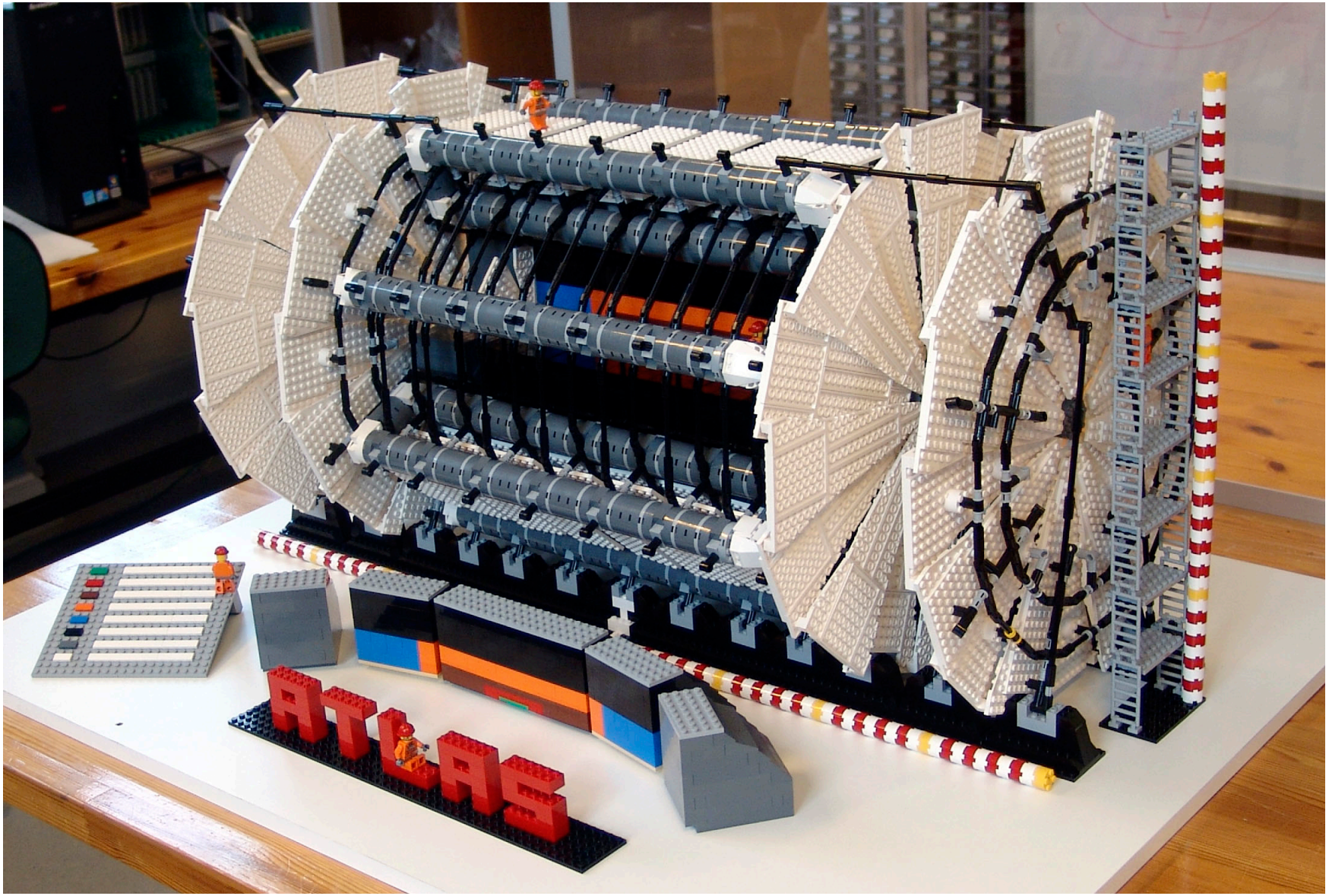
On Behalf of the ATLAS Collaboration

Outline

- Quick Overview of the ATLAS Detector
- J/ψ Production
  - Inclusive cross-sections / B-Fractions
  - Prompt / Non-prompt cross-sections
- ϒ(nS) Production
  - Fiducial / Corrected cross-sections
  - ϒ(2,3S) / ϒ(1S) Ratios
- χ_b(3P) Observation
- Summary & Future Plans

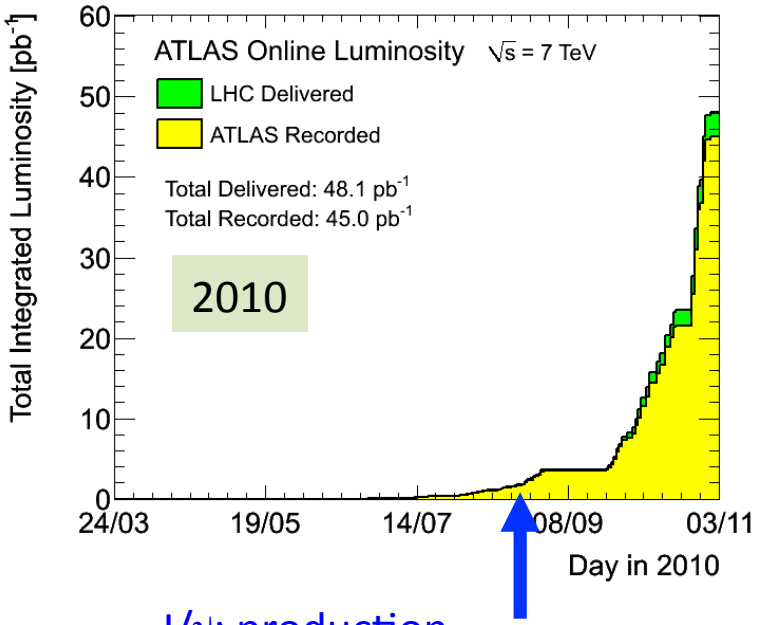


The ATLAS Detector



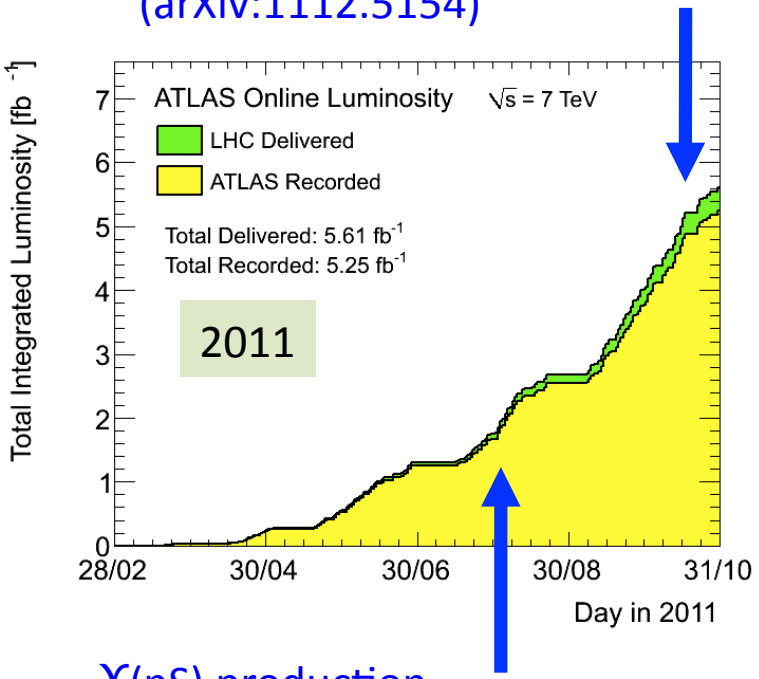
Data-Taking in ATLAS

- ATLAS is running perfectly, and collected:
  - ~45 pb^{-1} in 2010 with 7 TeV
  - ~5 fb^{-1} in 2011 with 7 TeV
  - ~20 fb^{-1} in 2012 with 8 TeV



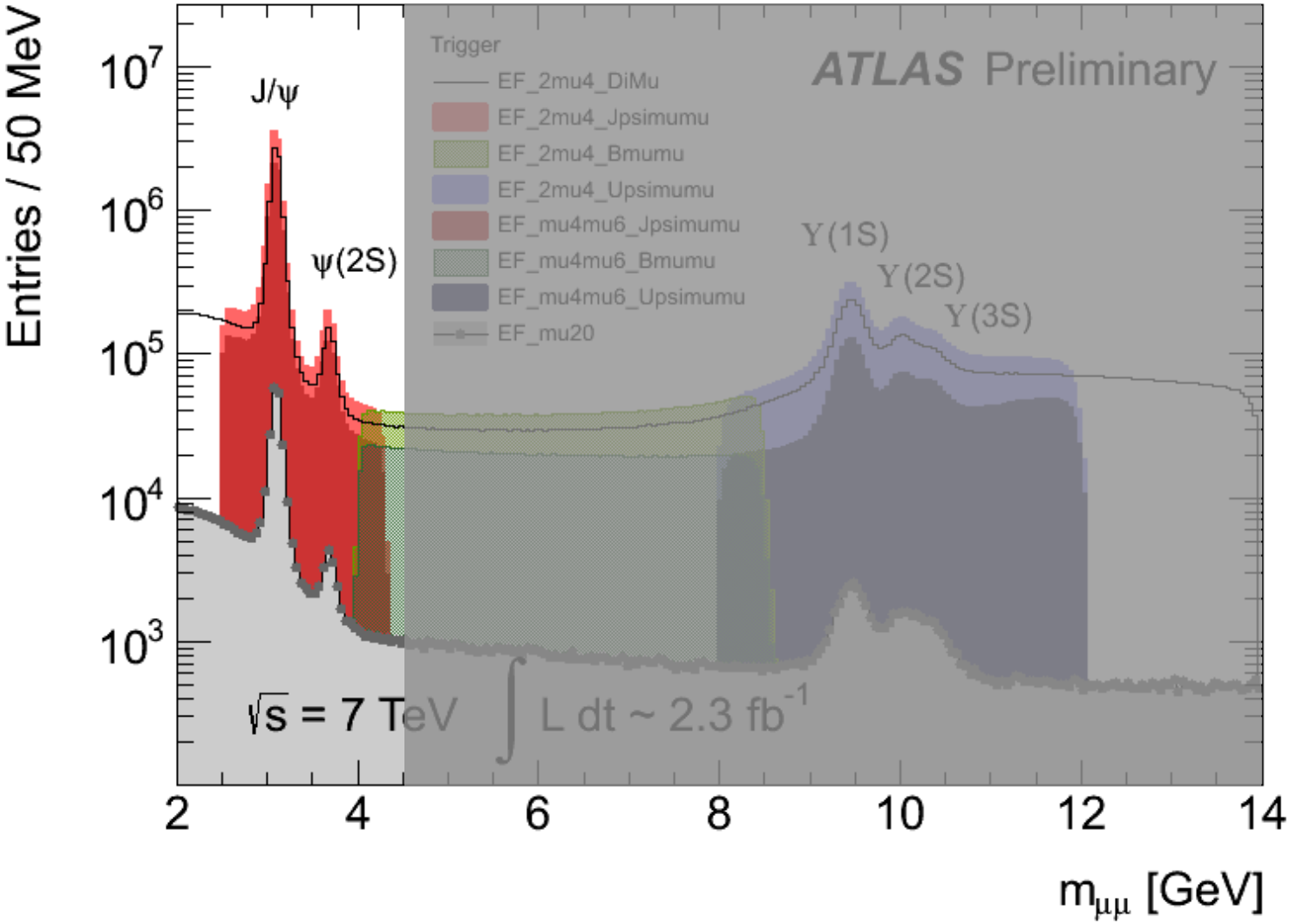
J/ψ production
Nucl. Phys. **B 850** (2011) 387-444
(arXiv:1104.3038)

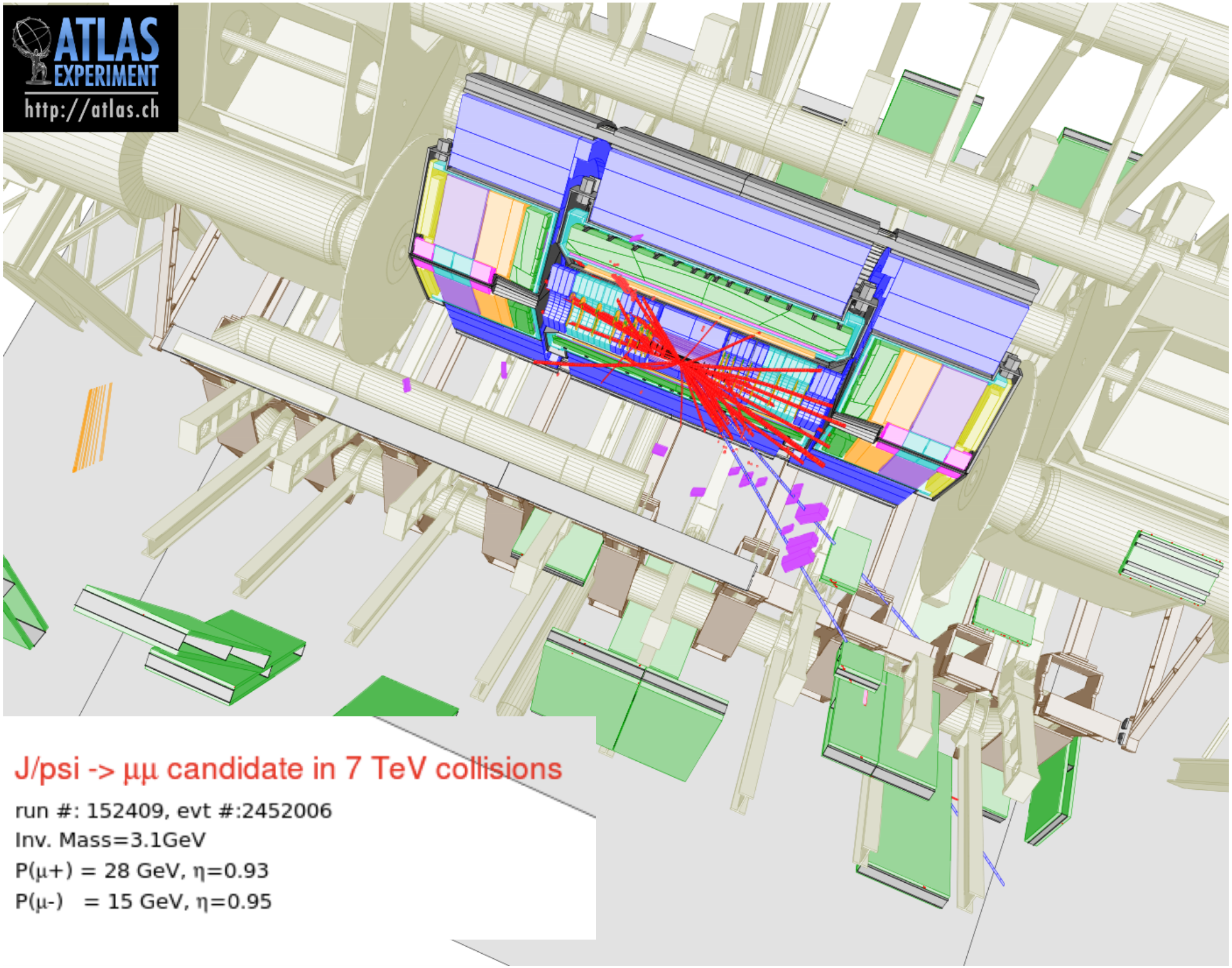
χ_b(3P) observation
Phys. Rev. Lett. **108** (2012) 152001
(arXiv:1112.5154)



Υ(nS) production
arXiv:1211.7255 (submitted to PRD)

J/ψ Production




ATLAS
EXPERIMENT
http://atlas.ch
J/psi -> μμ candidate in 7 TeV collisions
run #: 152409, evt #:2452006
Inv. Mass=3.1GeV
P(μ+) = 28 GeV, η=0.93
P(μ-) = 15 GeV, η=0.95

Analysis Strategy

- Select Di-muon candidates
- Divide into p_T and rapidity slices
- Correct efficiencies per candidate

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

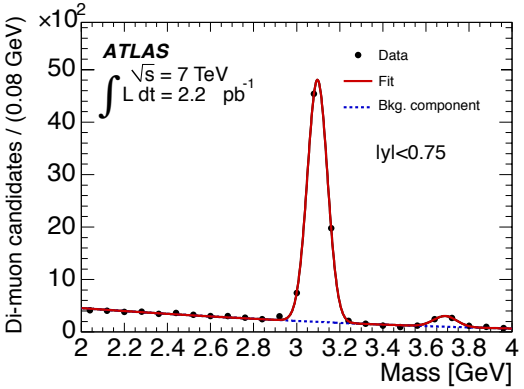
Detector Acceptance | Reconstruction Efficiency | Trigger Efficiency

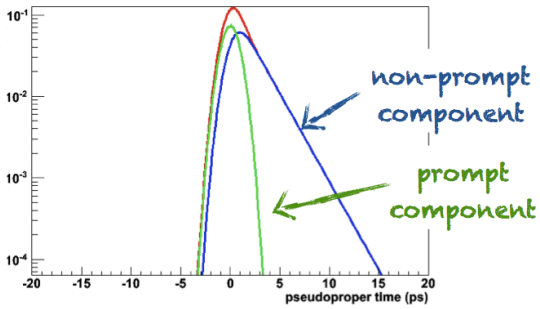
$$N_{obs.}^{corr.} = \sum_i w_i N_{obs.}^i$$

- Extract weighted yield
  - Mass fits
- Calculate the inclusive cross-sections

$$\frac{d^2\sigma(J/\psi)}{dp_T dy} \cdot Br(J/\psi \to \mu^+\mu^-) = \frac{N_{corr}^{J/\psi}}{\mathcal{L} \cdot \Delta p_T \Delta y}$$

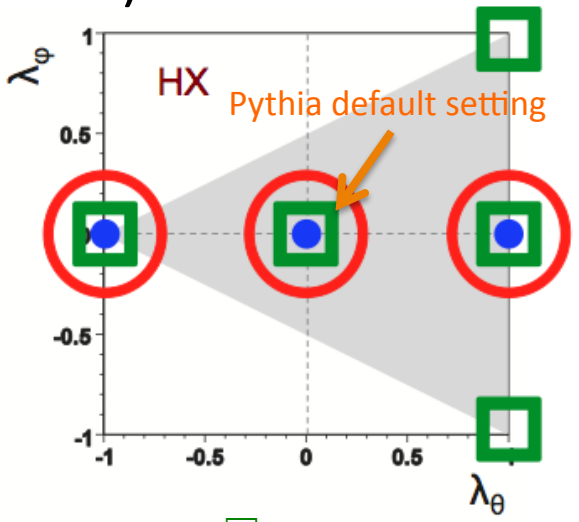
- Determine non-prompt fractions
  - Fit mass and life-time simultaneously
- Calculate non-prompt/prompt cross-sections





Acceptance

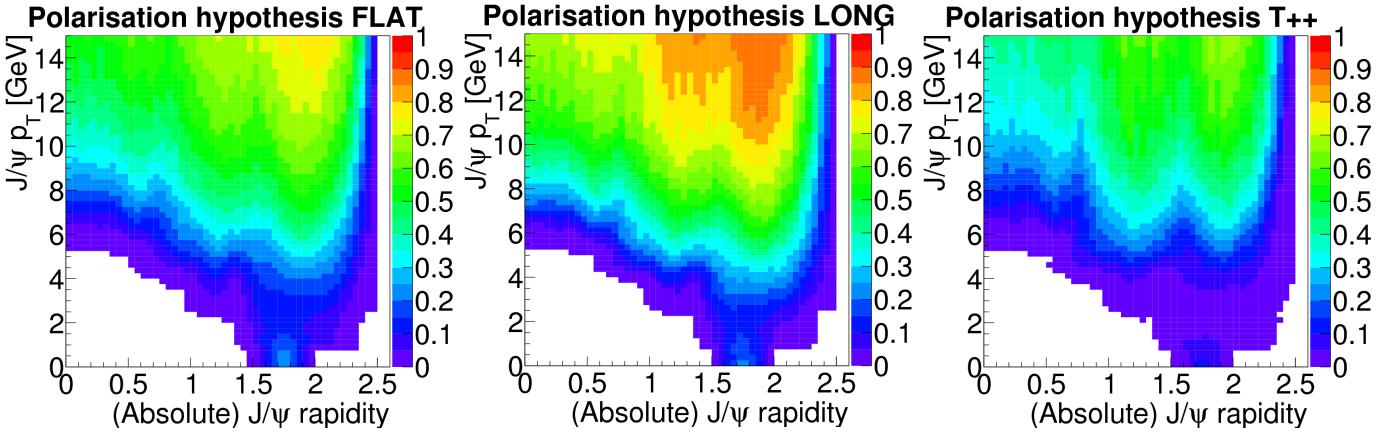
- Five spin-alignment scenarios (in Helicity frame):
  - Flat : $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$
  - Longitudinal : $\lambda_\theta = -1,\ \lambda_\phi = \lambda_{\theta\phi} = 0$
  - 1st Transverse : $\lambda_\theta = +1, \lambda_\phi = \lambda_{\theta\phi} = 0$
  - 2nd Transverse : $\lambda_\theta = +1, \lambda_\phi = +1, \lambda_{\theta\phi} = 0$
  - 3rd Transverse : $\lambda_\theta = +1, \lambda_\phi = -1, \lambda_{\theta\phi} = 0$



ATLAS
CMS
LHCb

- For Non-Flat distributions :
  - Re-weighting the Flat distribution in truth level

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



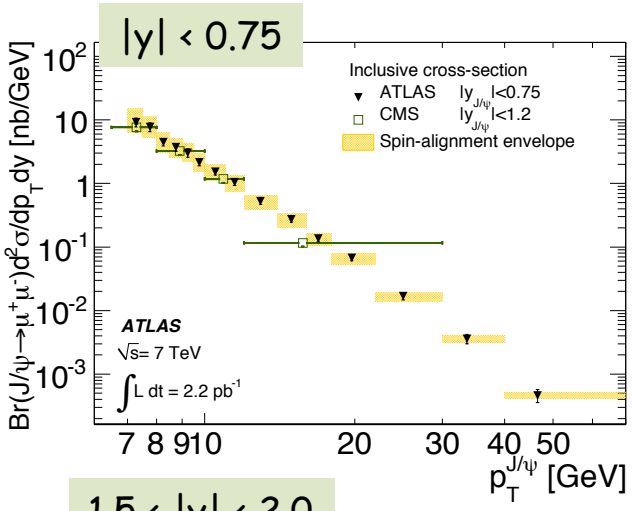
P. Faccioli et al., Eur. Phys. J. C (2010) 69: 657-673Introduction polarisation working points (arXiv : 1006.2738)

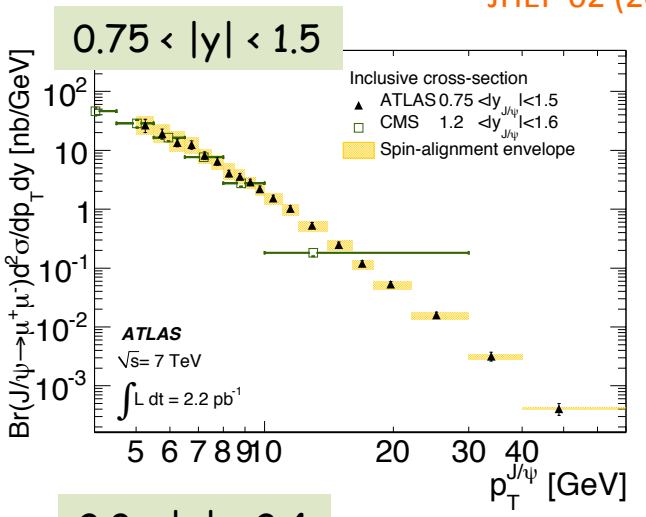
S. Palestini, Phys. Rev. D 83 (2011) 031503(R) : "Angular distribution and rotations of frame in vector meson decays into lepton pairs" (arXiv:1012.2485)

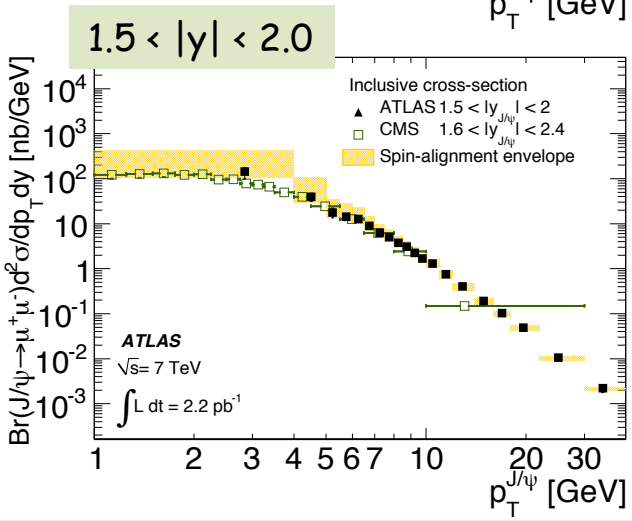
Inclusive J/ψ Cross-Sections

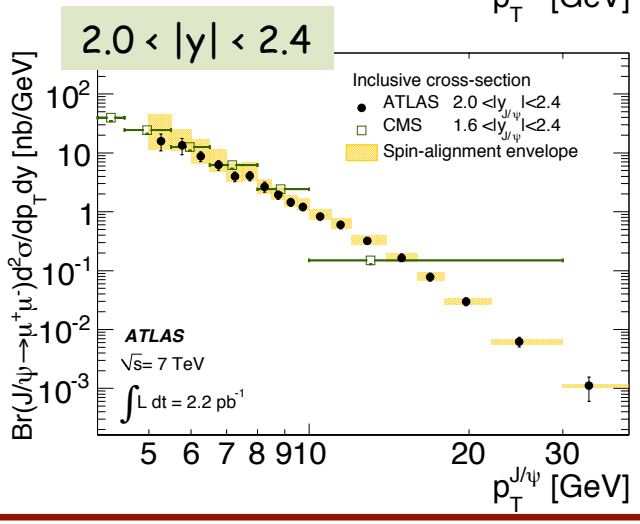
- Reach to high-p_T region, precise measurements
- Good agreements with CMS results (green points)

CMS new results:
JHEP 02 (2012) 011



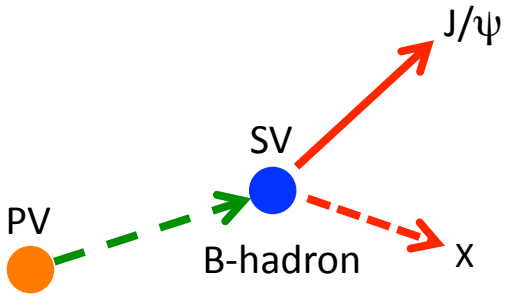






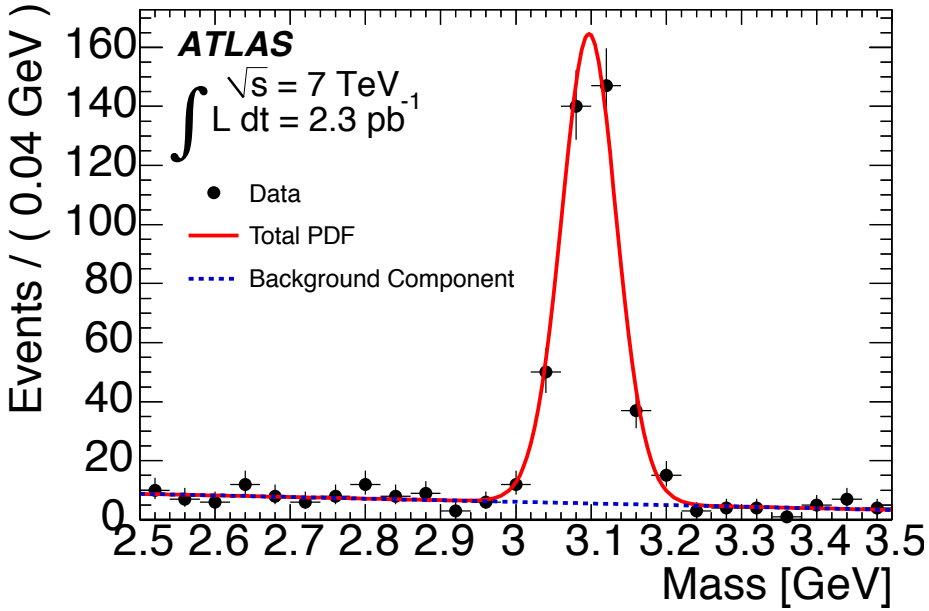
Determine Non-prompt Fractions

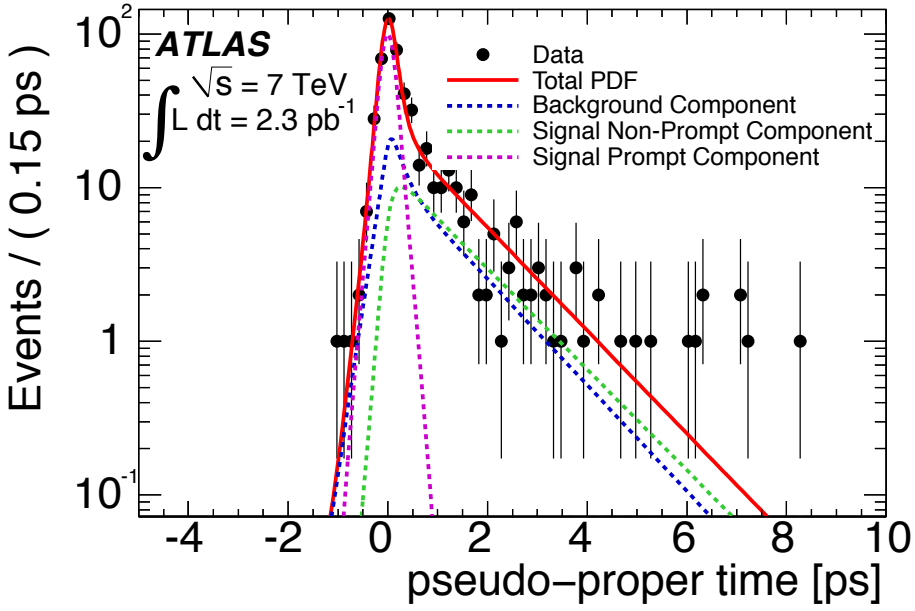
- Use unbinned Maximum Likelihood Fit to extract mass and life-time simultaneously



Pseudo-proper time: $\tau = \frac{L_{xy}\, m_{\mathrm{PDG}}^{J/\psi}}{p_T^{J/\psi}}$.

Lxy: the displacement of the J/ψ vertex in the transverse plane

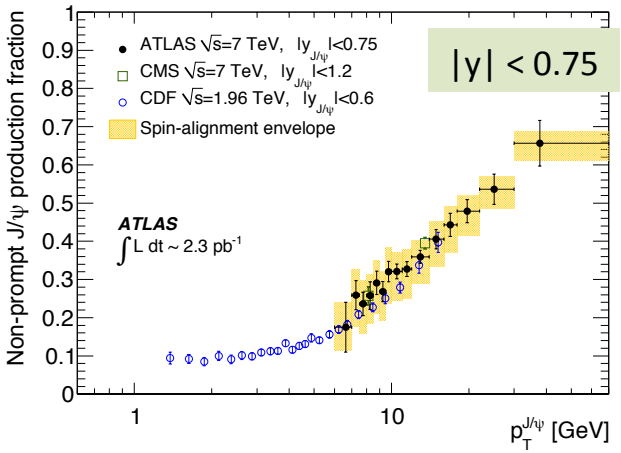


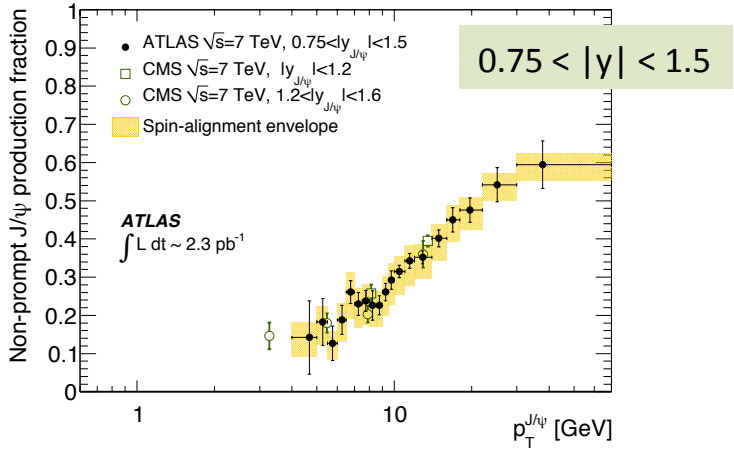


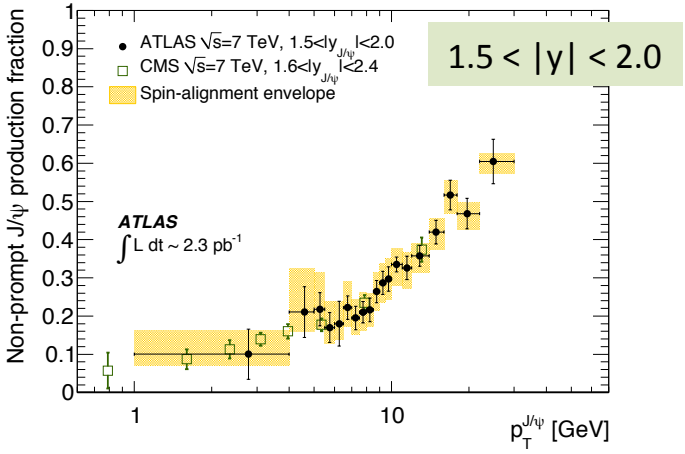
B-Fractions

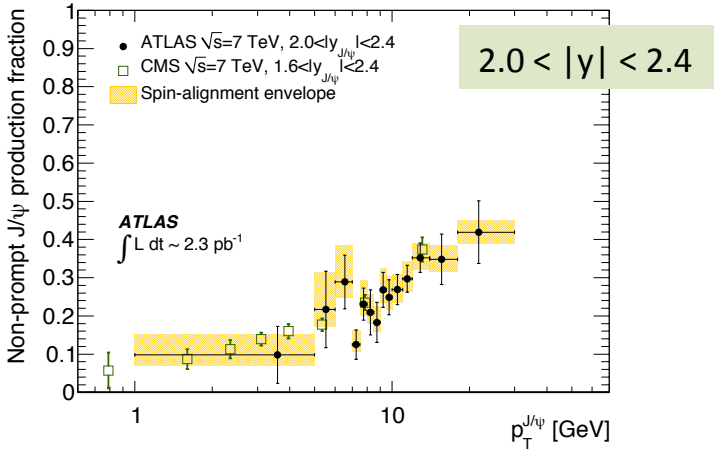
- Good agreements with CDF (blue) and CMS (box)

➔ Small dependence on $p\bar{p}$ v.s. pp and 1.96 v.s. 7 TeV





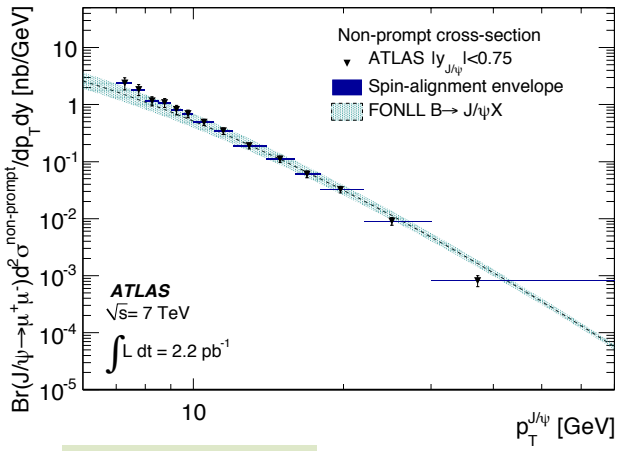




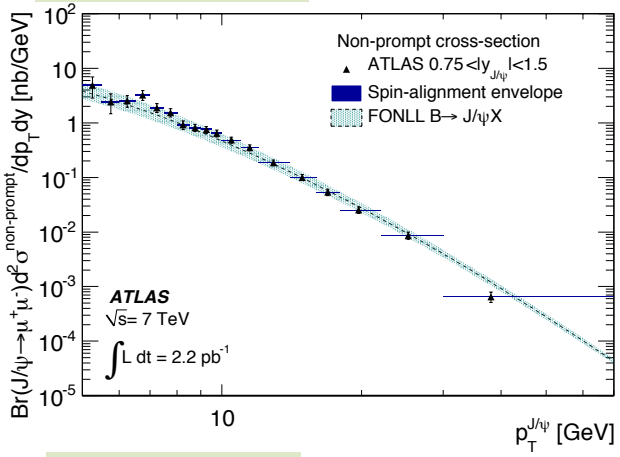
Non-prompt J/ψ Cross-sections

- Good agreement with FONLL predictions

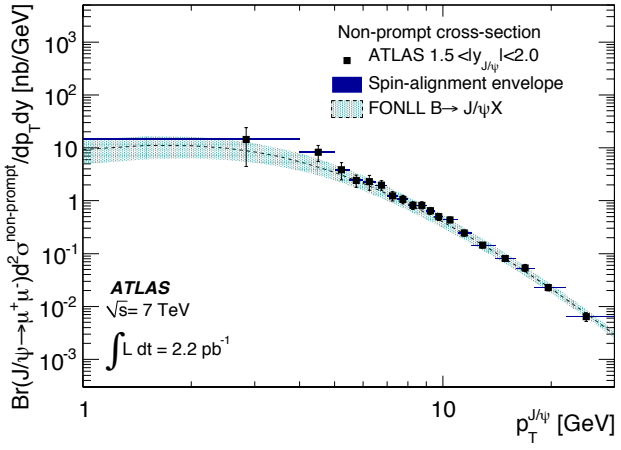
|y| < 0.75



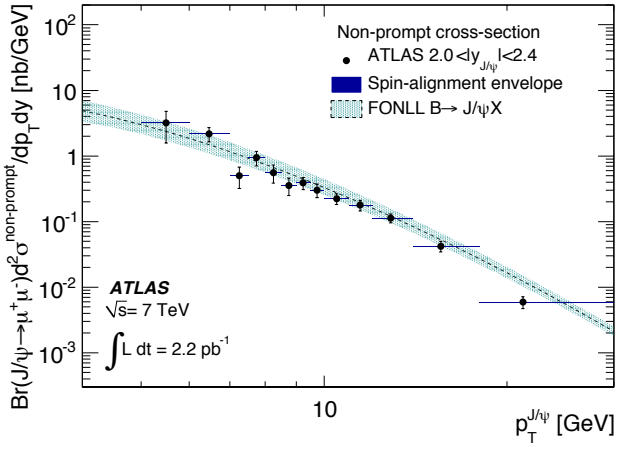
0.75 < |y| < 1.5



1.5 < |y| < 2.0

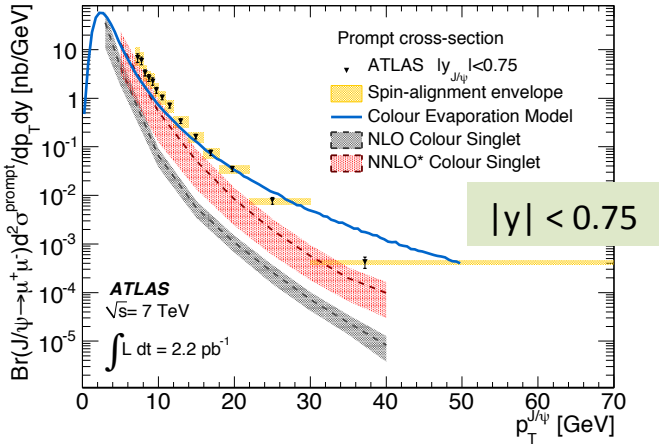


2.0 < |y| < 2.4

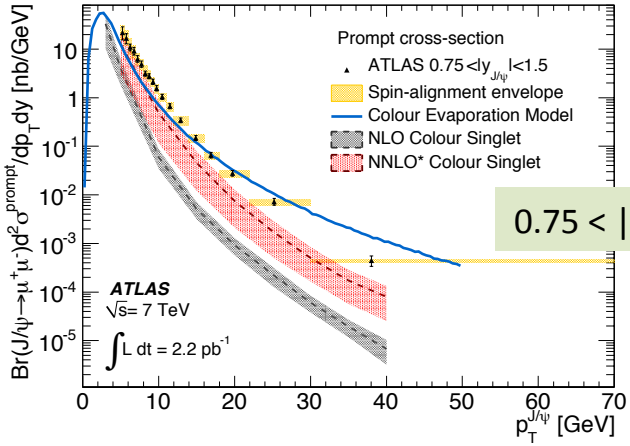


Prompt J/ψ Cross-sections

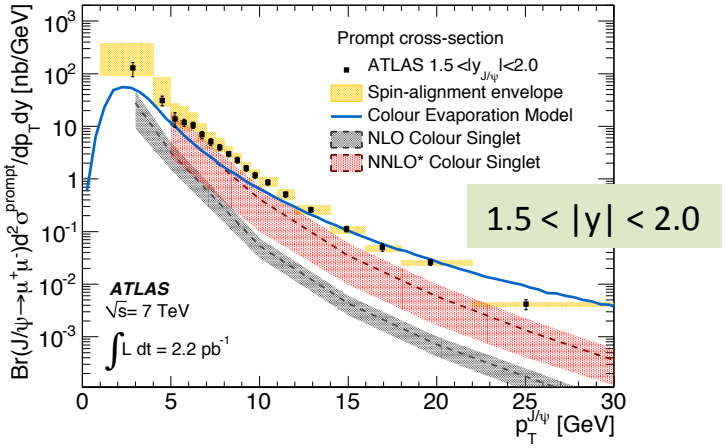
- NNLO* CSM : better than NLO, but still underestimate…
- Color Evaporation Model : seem to be pulling away from the data at high-p_T region



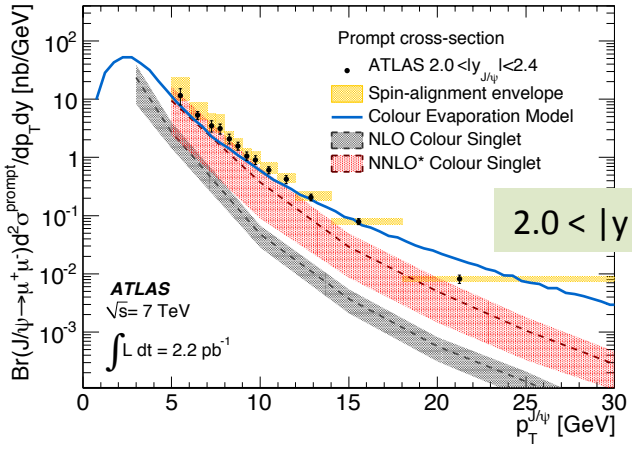
|y| < 0.75



0.75 < |y| < 1.5

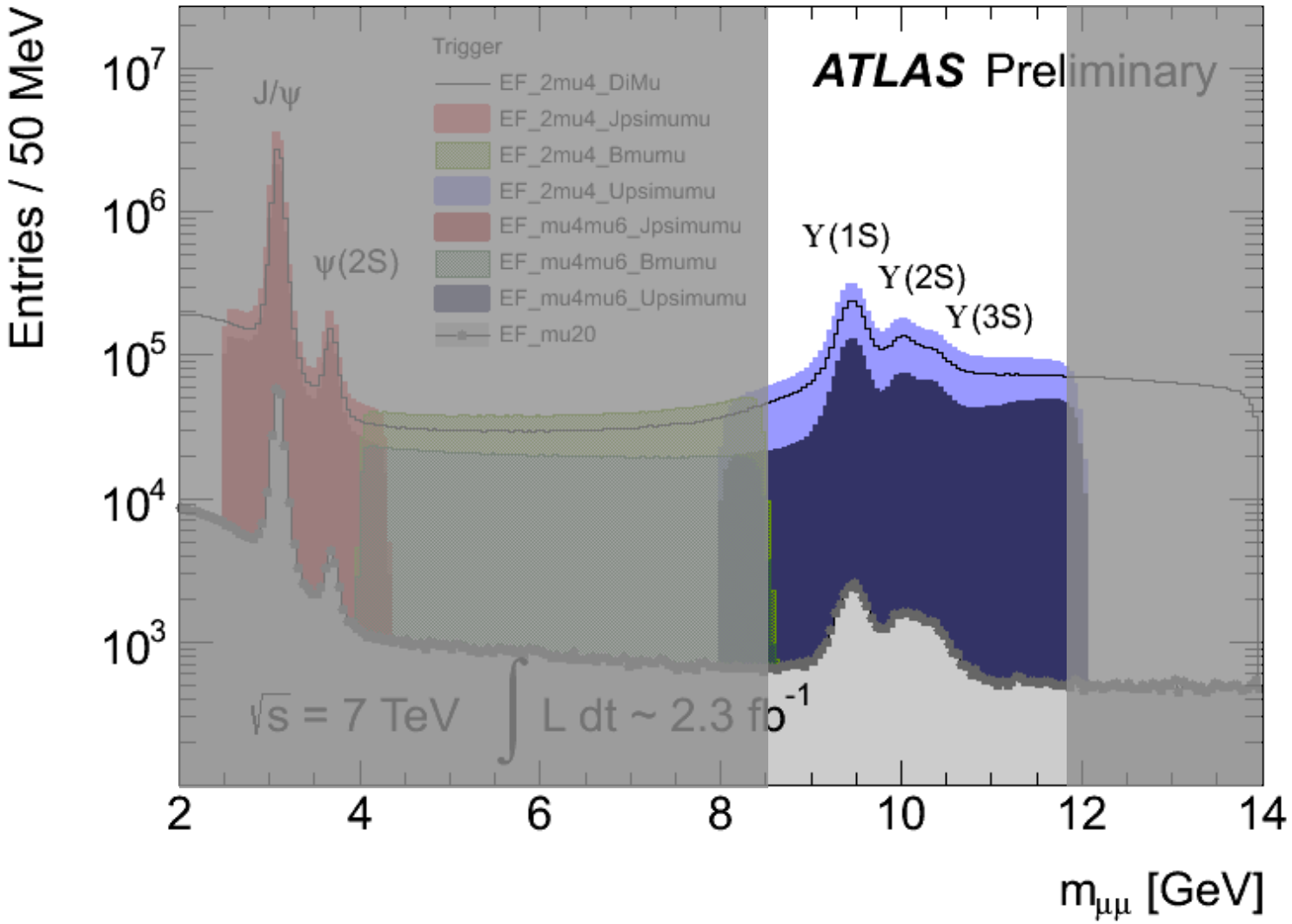


1.5 < |y| < 2.0



2.0 < |y| < 2.4

Υ(nS) Production



Υ(nS) Cross-sections

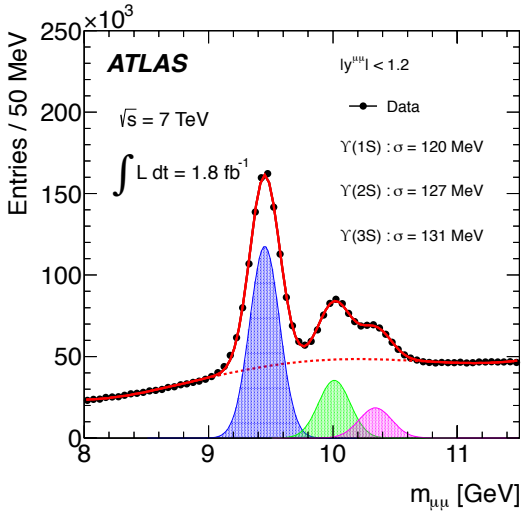
- Measure the Υ(1,2,3S) differential cross-section
  - Fiducial cross-section

    ➔ only correct reco. and trig. efficiencies: restricted phase space

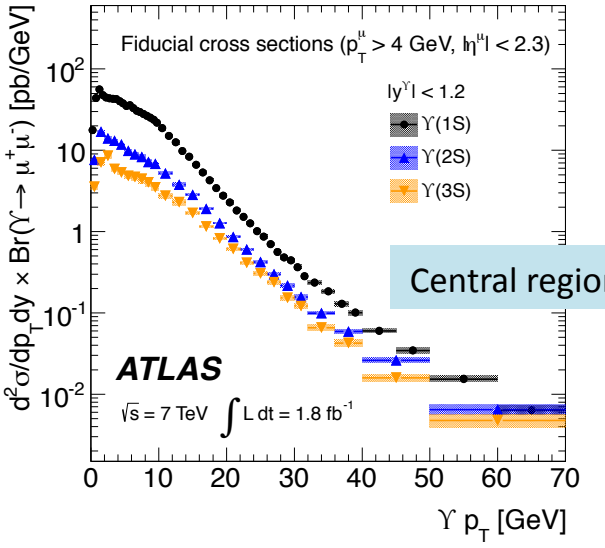
    (Note: smaller uncertainty from measurement, but most of theory groups are not able to provide the predictions beyond NLO necessary to describe bottomnium production)
  - Corrected cross-section

    ➔ also correct Υ kinematic acceptance: full phase space

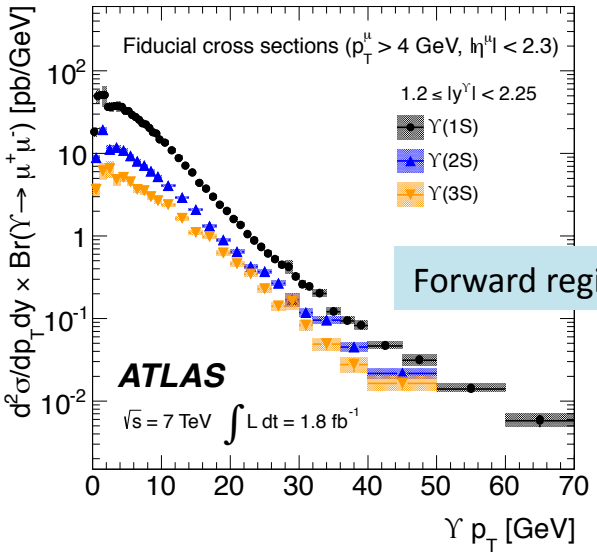
    (Note : bigger uncertainty from measurement, but able to do the direct comparison to the predictions)
  - Ratios: $\sigma^{\Upsilon(2S)}/\sigma^{\Upsilon(1S)}$ and $\sigma^{\Upsilon(3S)}/\sigma^{\Upsilon(1S)}$



Υ(nS) Fiducial Cross-sections



Central region



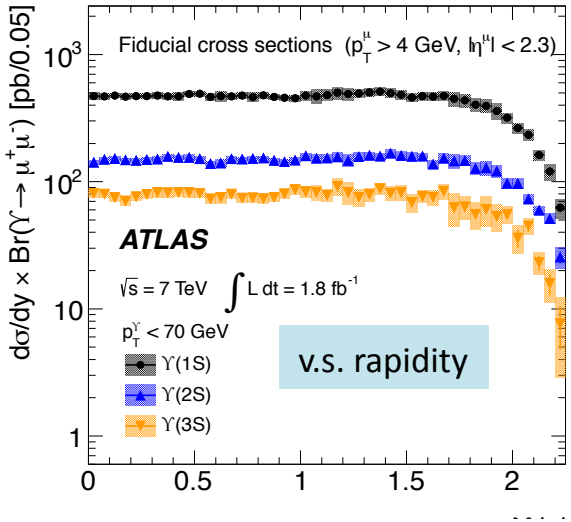
Forward region

$$w^{-1} = \mathcal{A}(p_T, y, \lambda_i) \times \mathcal{E}_\mu(\vec{p}_1) \times \mathcal{E}_\mu(\vec{p}_2) \times \mathcal{E}_{\rm trig}(\vec{p}_1, \vec{p}_2)$$

Detector Acceptance

Reconstruction Efficiency

Trigger Efficiency



v.s. rapidity

Integrated fiducial cross sections $p_T^\mu > 4\,\text{GeV}, \lvert\eta^\mu\rvert < 2.3$	
State	$\sigma_{\rm fid}(pp \to \Upsilon) \times \text{Br}(\Upsilon \to \mu^+\mu^-)$ Range: $p_T^\Upsilon < 70\,\text{GeV}, \lvert y^\Upsilon\rvert < 2.25$
$\Upsilon(1S)$	$1.890 \pm 0.007 \pm 0.095 \pm 0.074$ nb
$\Upsilon(2S)$	$0.601 \pm 0.003 \pm 0.040 \pm 0.023$ nb
$\Upsilon(3S)$	$0.304 \pm 0.003 \pm 0.021 \pm 0.012$ nb

Υ(1S) Corrected Cross-sections

Blue : Spin-alignment envelope

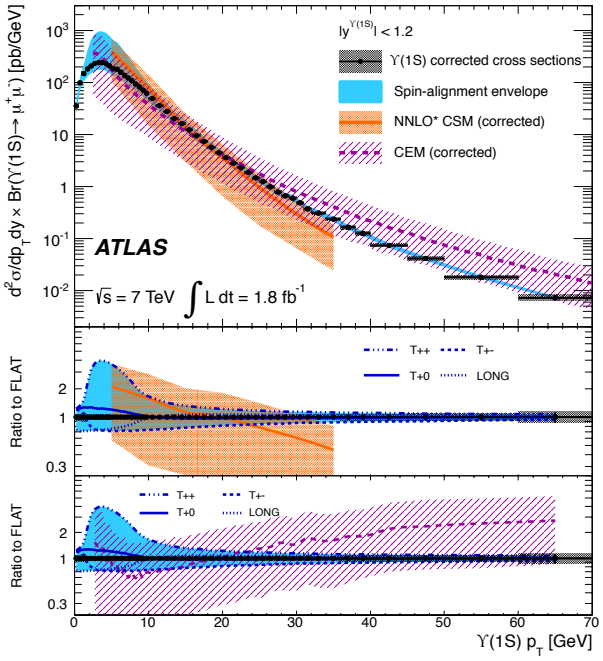
Orange : NNLO* Color Singlet

➔ good agreement in the moderate p_T region, but slightly underestimates at high p_T

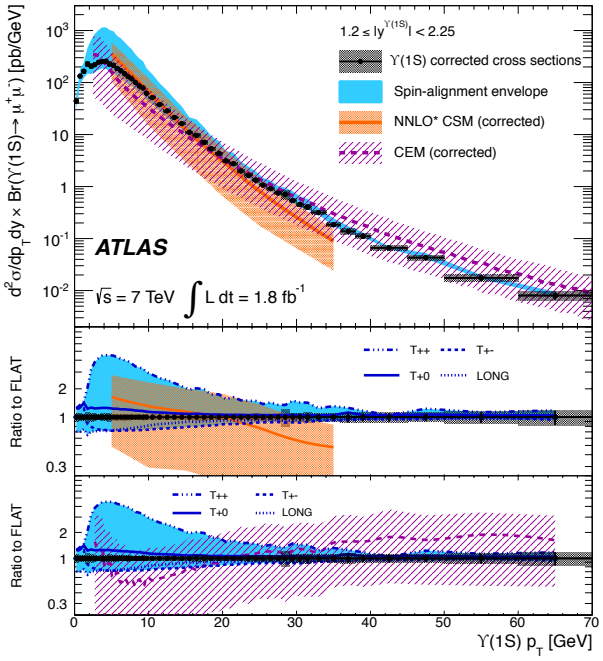
Purple : Color Evaporation Model

➔ better agreement at high p_T , but underestimates at lower p_T

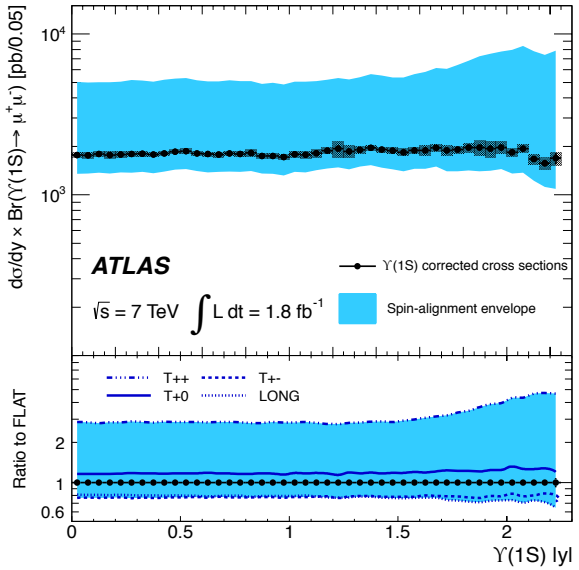
Central region



Forward region



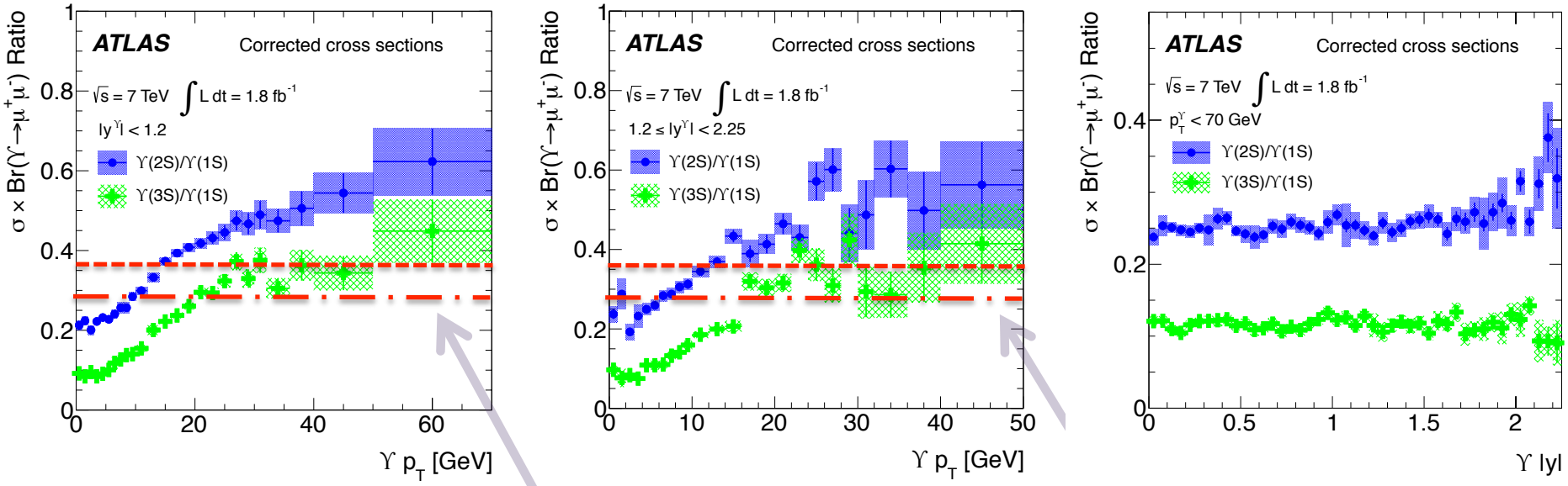
v.s. rapidity



*Note: similar results for Υ(2S) and Υ(3S) are shown in the backup slides

Υ(nS) / Υ(1S) Ratios

- General formula : $R(\frac{\sigma_{nS}}{\sigma_{1S}}) = \frac{N_{nS}^{corr.}}{N_{1S}^{corr.}}$
  - ➔ Systematic uncertainty reduced
- The predictions from the NNLO* CSM:
  - Υ(2S)/Υ(1S) ~ 36%
  - Υ(3S)/Υ(1S) ~ 29%



Reach the kinematic region where Υ(1S) is dominant!

χ_b(nP) Production

LHC reports discovery of its first new particle

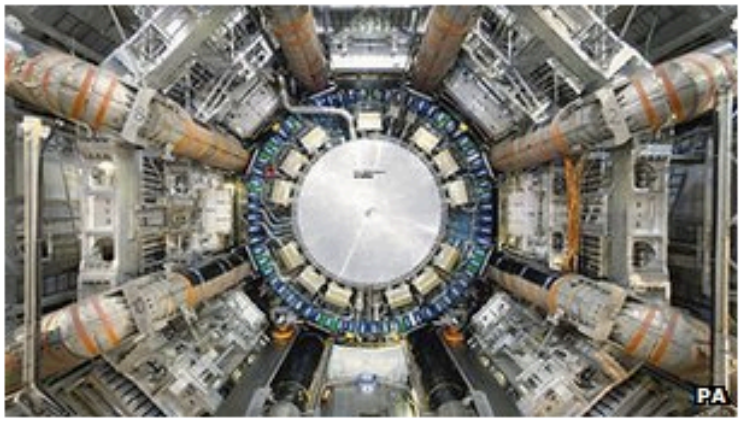
2011 Dec. 22

By Jonathan Amos
Science correspondent, BBC News

The Large Hadron Collider (LHC) on the Franco-Swiss border has made its first clear observation of a new particle since opening in 2009.

It is called Chi_b (3P) and will help scientists understand better the forces that hold matter together.

The as-yet unpublished discovery is **reported on the Arxiv pre-print server**.

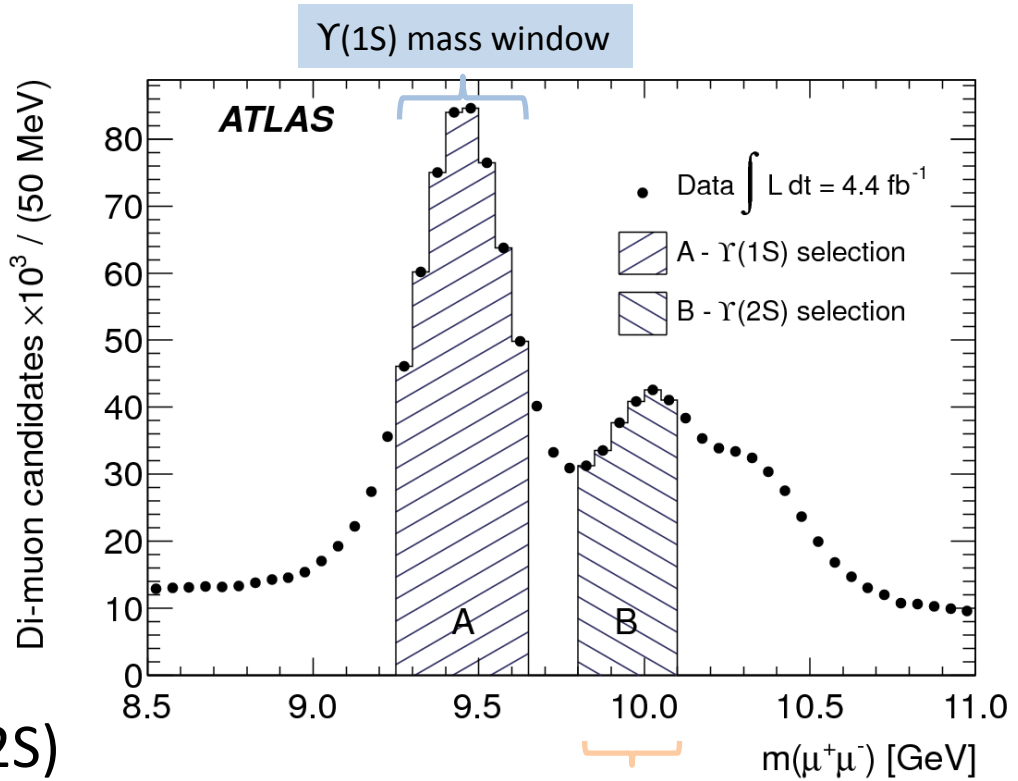


The LHC has been built to investigate the fundamental building blocks of nature

$\chi_b(3P)$ Observation

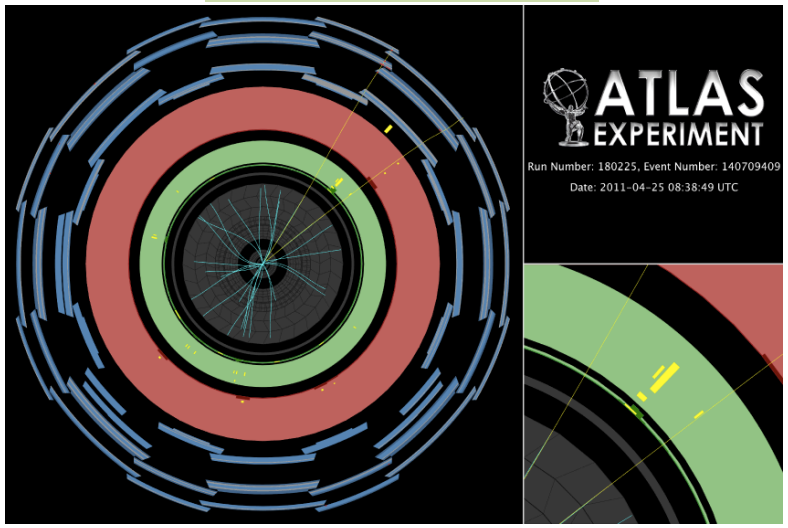
- $\chi_b(1P)$ and $\chi_b(2P)$ have been discovered many years ago, but not $\chi_b(3P)$ with a predicted mass ~10.52 GeV.
- We used [$\Upsilon(1,2S) \rightarrow \mu^+\mu^-$] γ to reconstruct $\chi_b(nP)$ states
- Photons :
  - Unconverted photons
    (Calorimetry photon)
    Pure EM Calorimeter signal
  - Converted photons
    Two opposite charged
    ID tracks interacting at a
    conversion vertex
- To reduce the di-muon mass resolution from $\Upsilon(1,2S)$

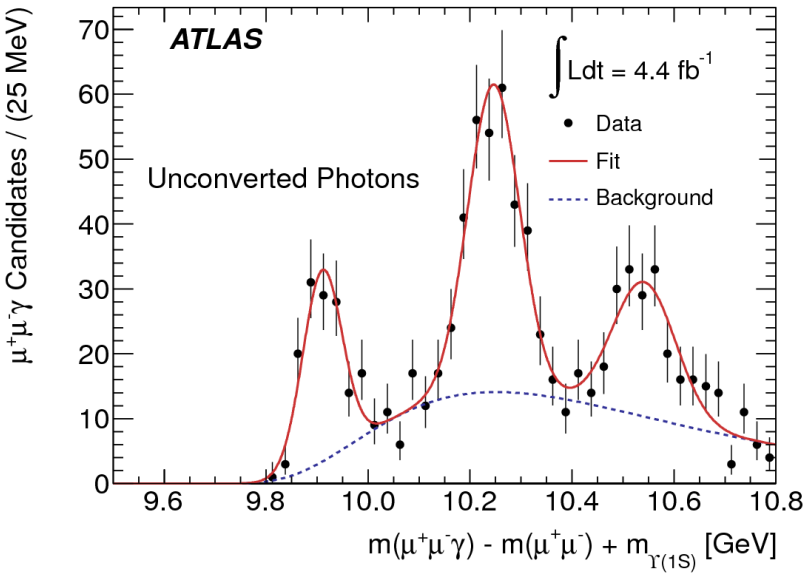
  → $\tilde{m}_k = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-) + m_{\Upsilon(kS)}$



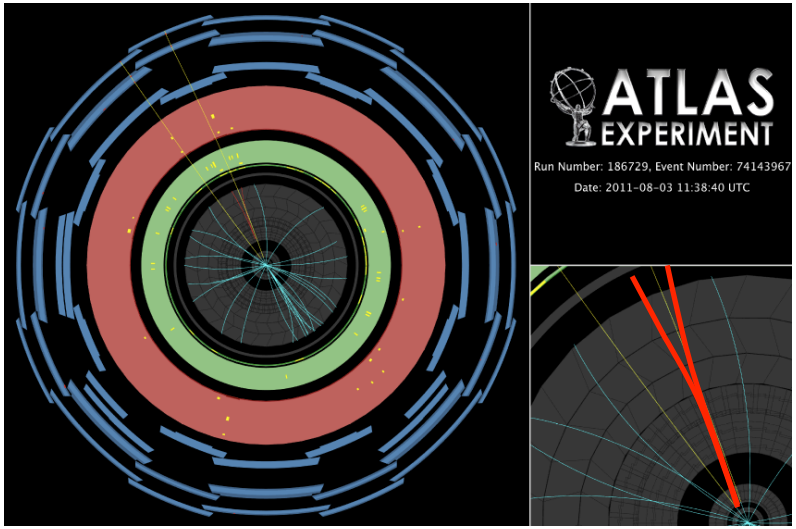
$\chi_b(3P)$ Observation

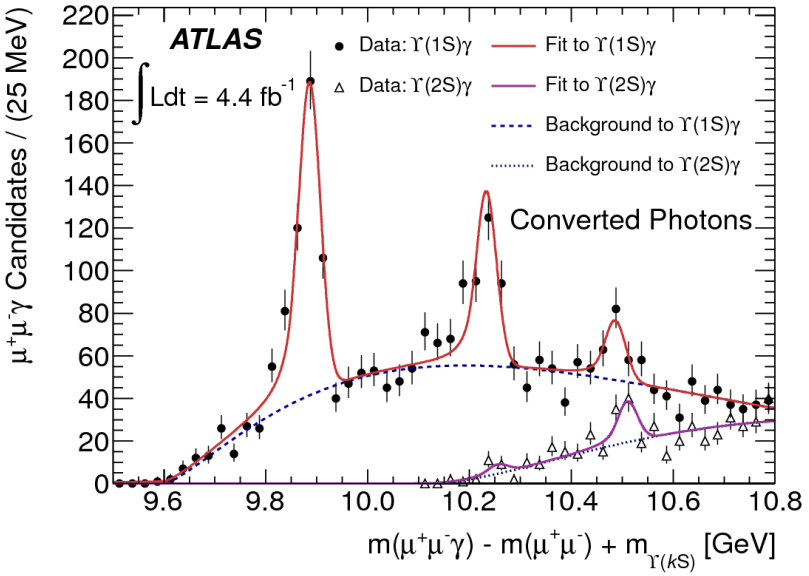
Calorimetry Photons



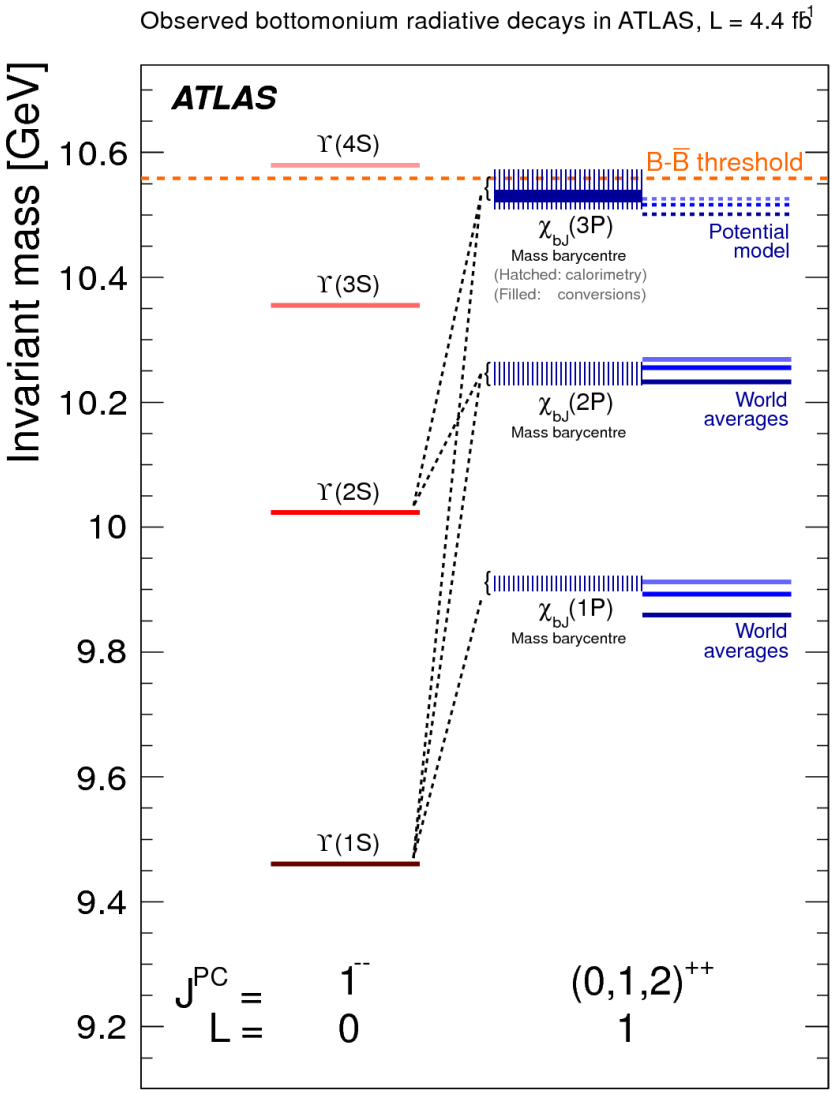


Converted Photons





χ_b(3P) Observation



- New χ_b(3P) state is discovered

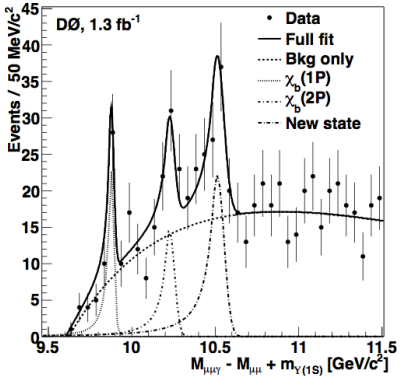
➔Mass is consistent with the prediction (potential model)

Unconverted photon:

$$\overline{m}_3 = 10.541 \pm 0.011\ (\text{stat.}) \pm 0.030\ (\text{syst.})\ \text{GeV}$$

Converted photon:

$$\overline{m}_3 = 10.530 \pm 0.005\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{GeV}$$



D0 confirmed this new state (arXiv:1203.6034)

m = $10.551 \pm 0.014(\text{stat.}) \pm 0.017(\text{syst.})\ \text{GeV}/c^2$

LHCb also confirmed (LHCb-CONF-2012-020)

m = 10.535 ± 0.010 (stat.) GeV

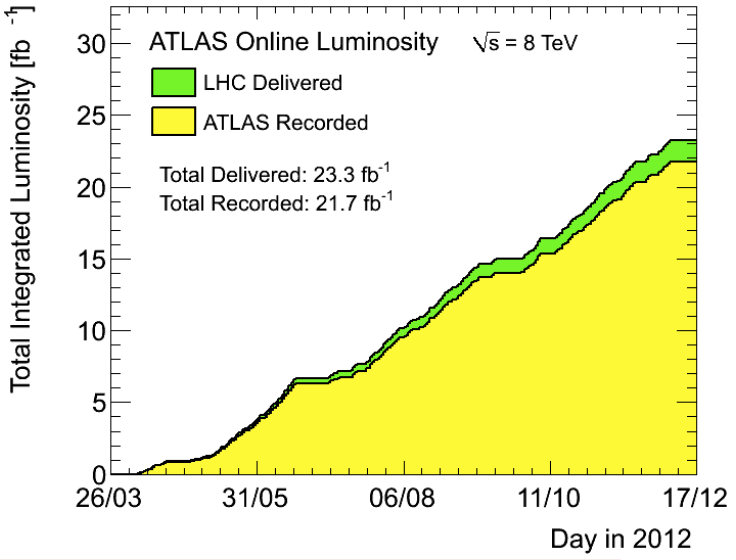
Summary

- ATLAS has excellent Inner Detector, Muon Spectrometer and trigger system to study heavy quarkonium physics
  - Prompt and non-prompt J/ψ production cross-sections have good agreements with other experiments and predictions
  - Fiducial and corrected Υ(nS) production cross-sections are showed in details in low-p_T region and explored to high-p_T
  - The first new particle in LHC observed : χ_b(3P)
- With ~20 fb^{-1} data collected in 2012, we are looking forward to have more interesting results from ATLAS

  W/Z + J/ψ, ψ(2S)→ μμ, J/ψ polarization

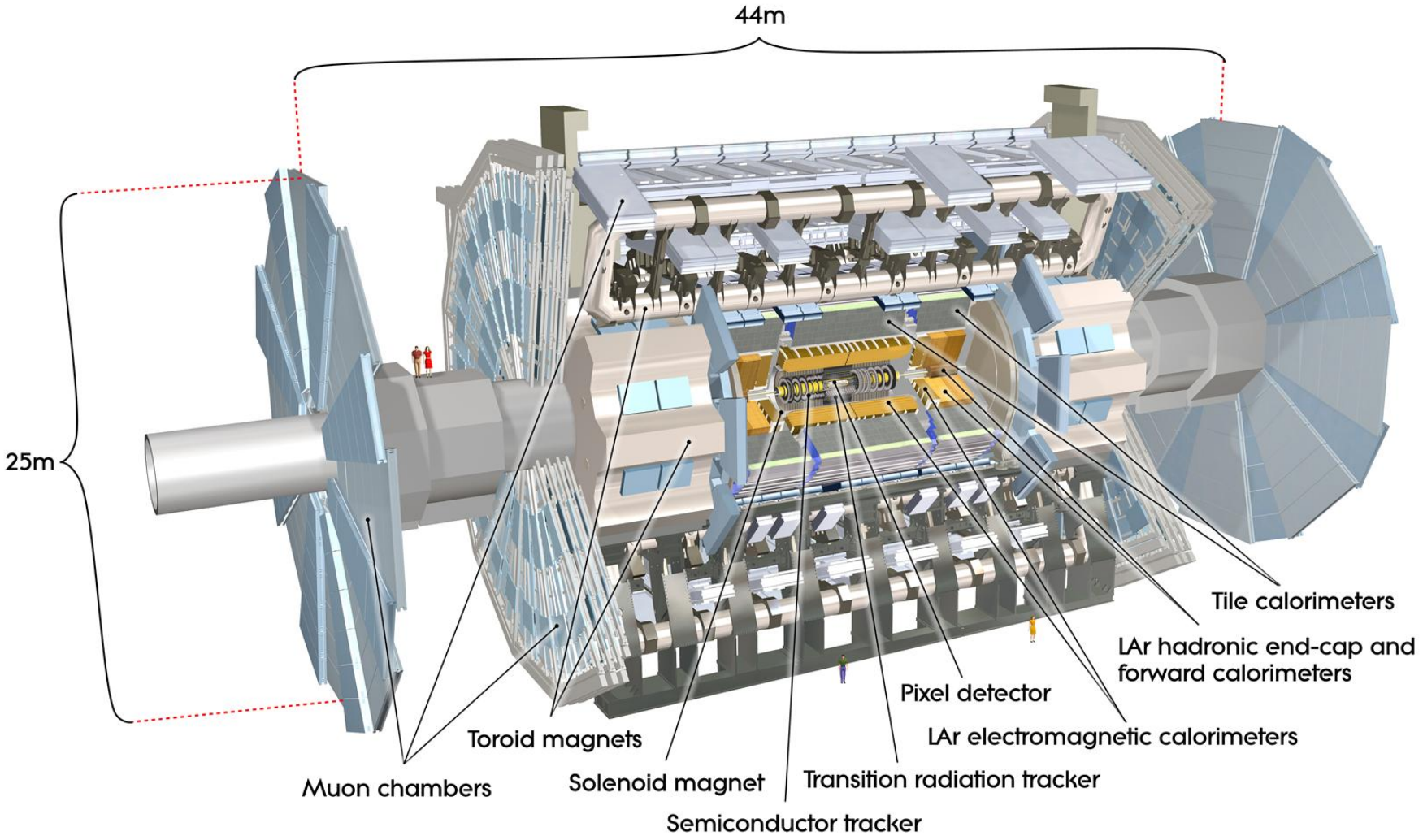
  X(3872)/ψ(2S) → J/ψ + π, χ_b(nP) x-section, exotic search in Υ + π + π

  …

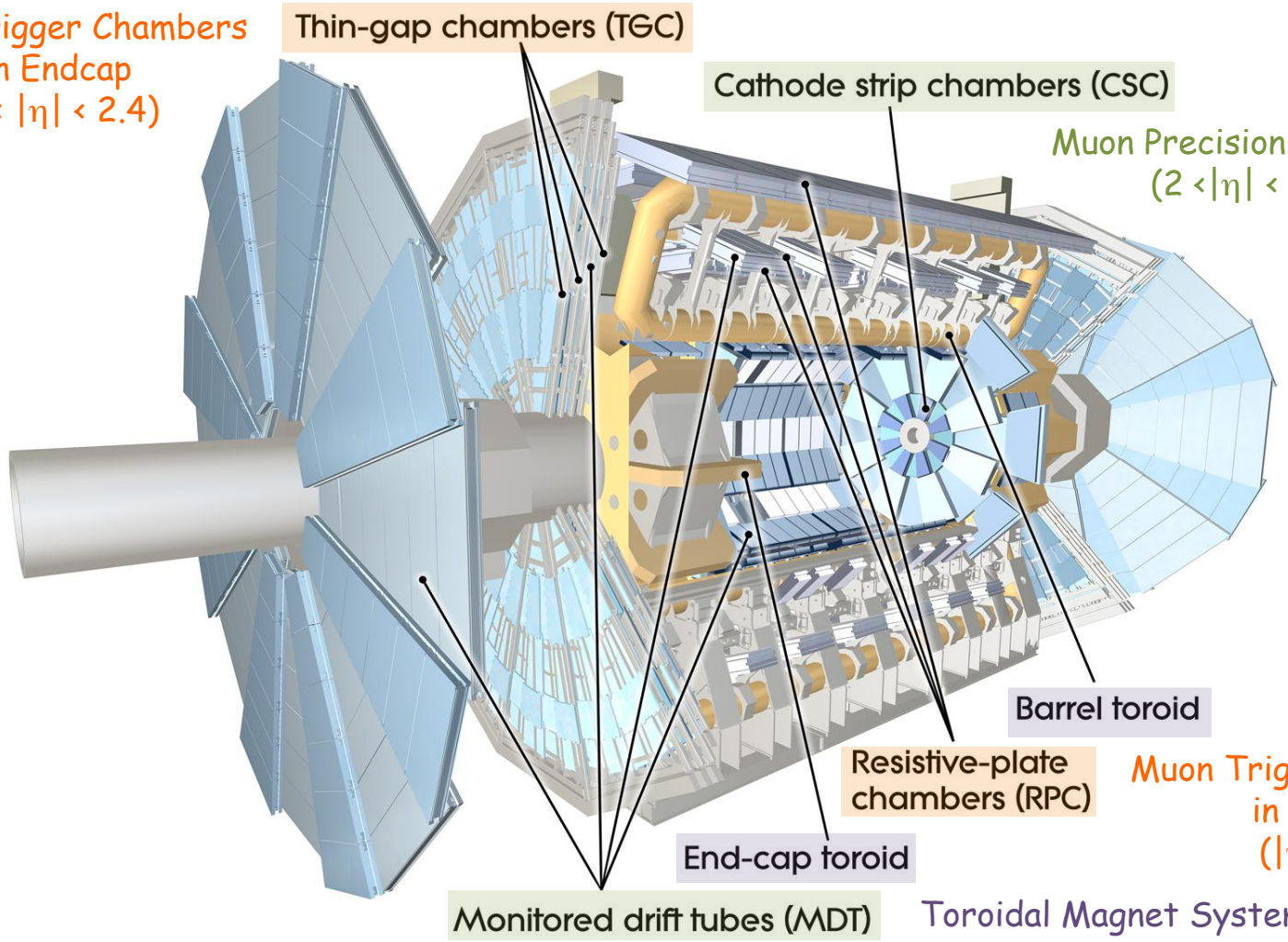


Backup Slides

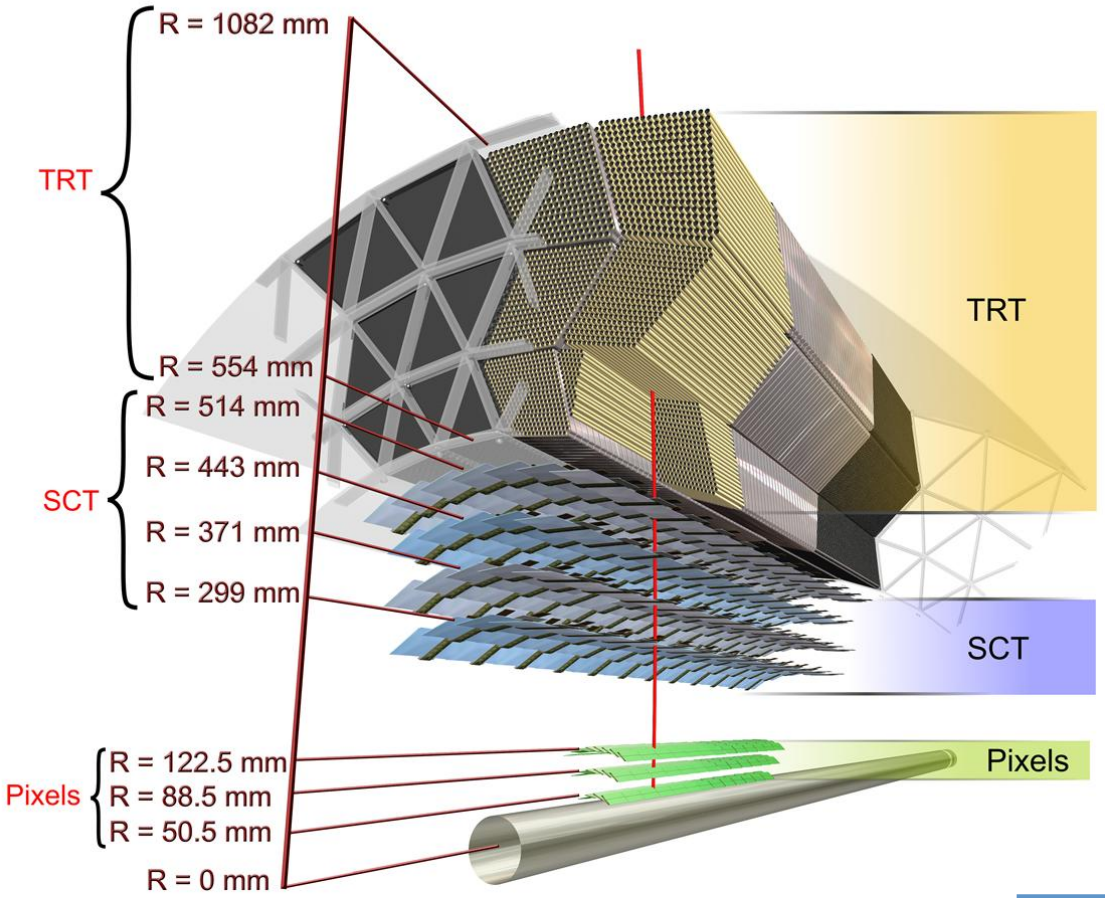
ATLAS Overview



Muon Spectrometer



Inner Detector



- In General :
  - Coverage : $|\eta| < 2.5$
  - Solenoid B field = 2 Tesla
  - Relative p_T resolution 0.035% x p_T [GeV] + 1.5%

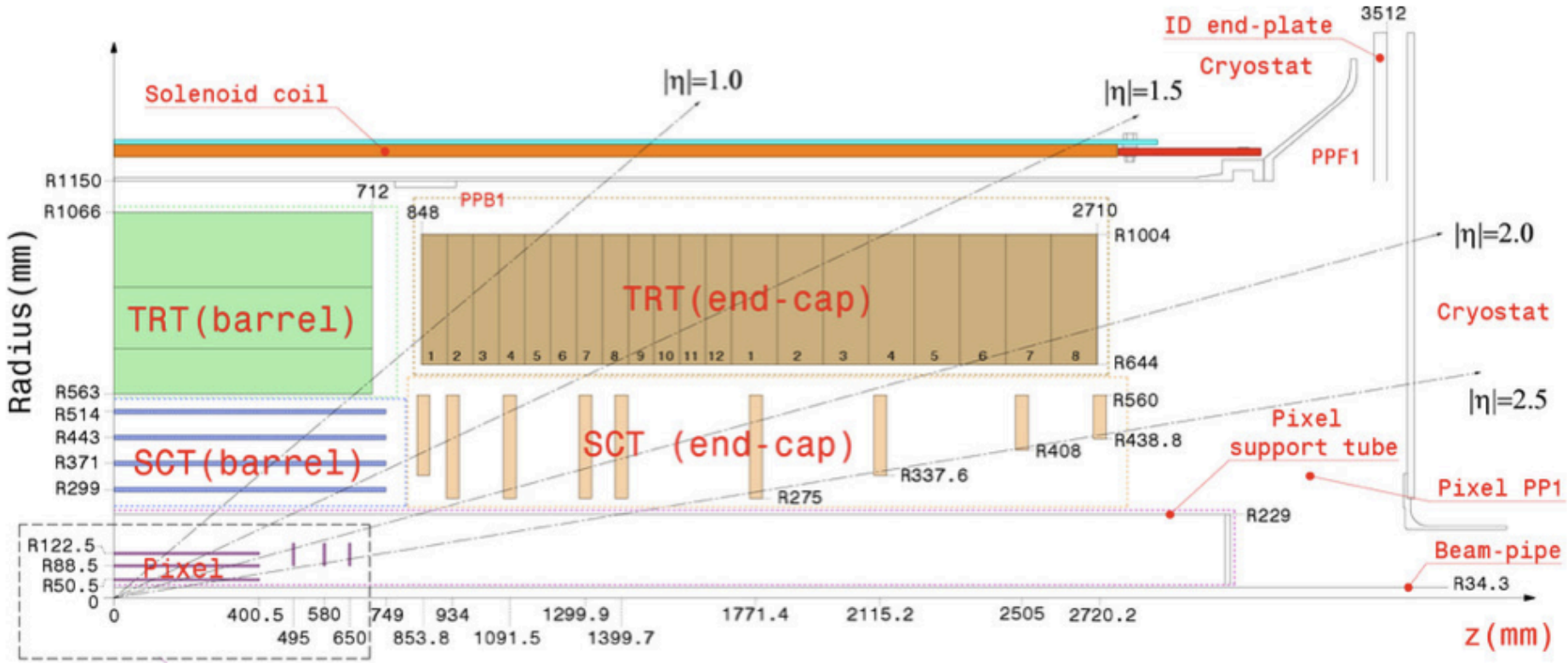
Transition Radiation Tracker
$|\eta| < 2.0$

Semiconductor Tracker
$|\eta| < 2.5$

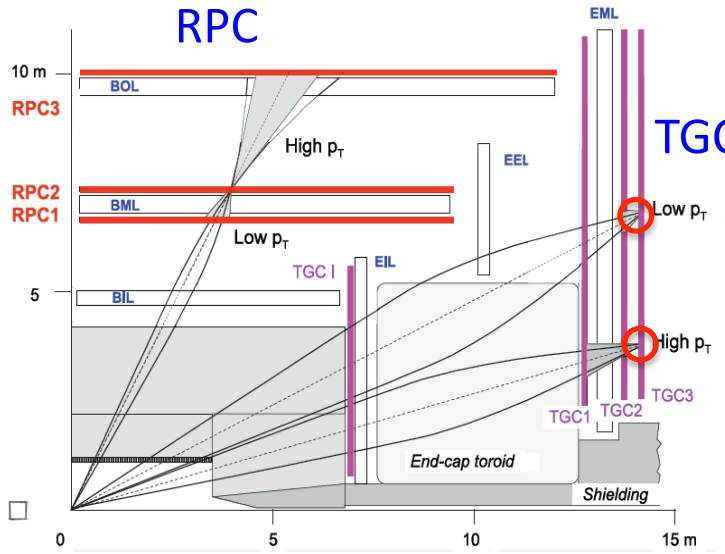
Pixel Detectors $|\eta| < 2.5$

	$J/\psi \rightarrow \mu\mu$	$\Upsilon \rightarrow \mu\mu$
Detector Resolution	~ 50 MeV	~ 160 MeV

Inner Detector

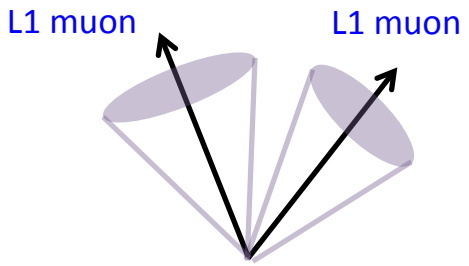


(Muon) Trigger System



ATLAS also can trigger on Di-muon events

- Two RoIs
- Quality cuts on muon pair
- Invariant mass cut



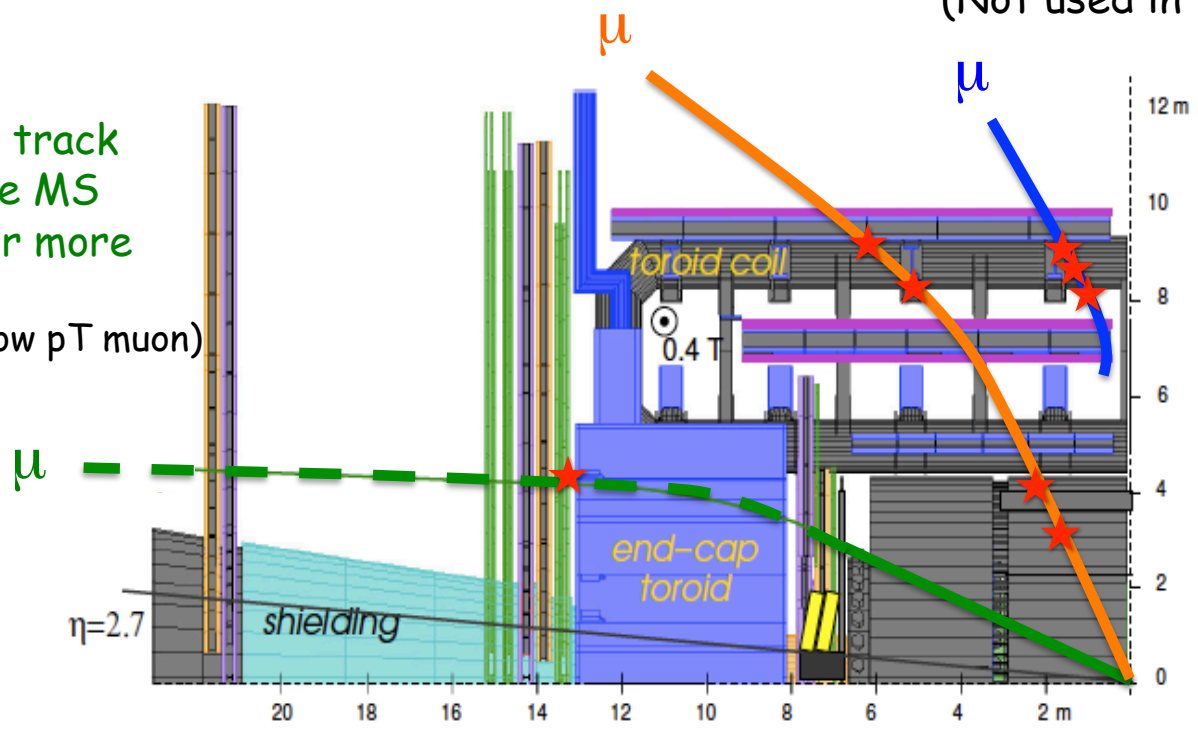
- Level 1 :
  - Hardware-based, online
  - Look for coincidence hits in muon trigger chambers (RPC, TGC)
  - Create regions of interest (RoI)
- Level 2 :
  - Software-based, offline
  - Refine L1 candidate with precision hits from MDT and combine with ID
- Event Filter :
  - Software-based, offline
  - Use the offline precision algorithms to reconstruct muon candidates

Muon Candidates

Combined Muon :
Standalone Muon extrapolated to Inner Detector with good fit
(Best quality muon)

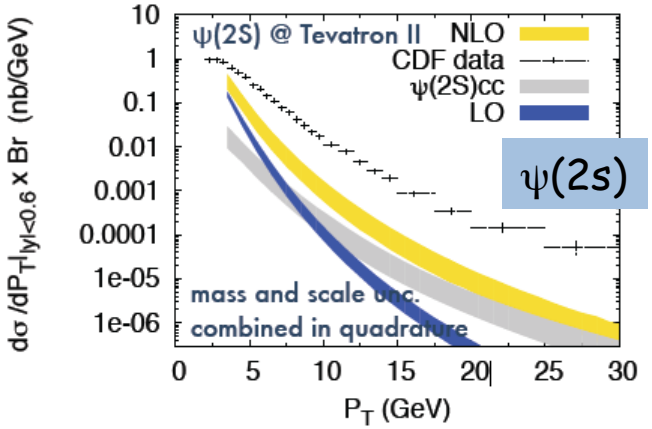
Standalone Muon :
A track fitted by only Muon Segments in the Muon Spectrometer
(Not used in the analysis)

Tagged Muon :
An Inner Detector track extrapolated to the MS and match to one or more Muon Segments
(high efficiency for low pT muon)

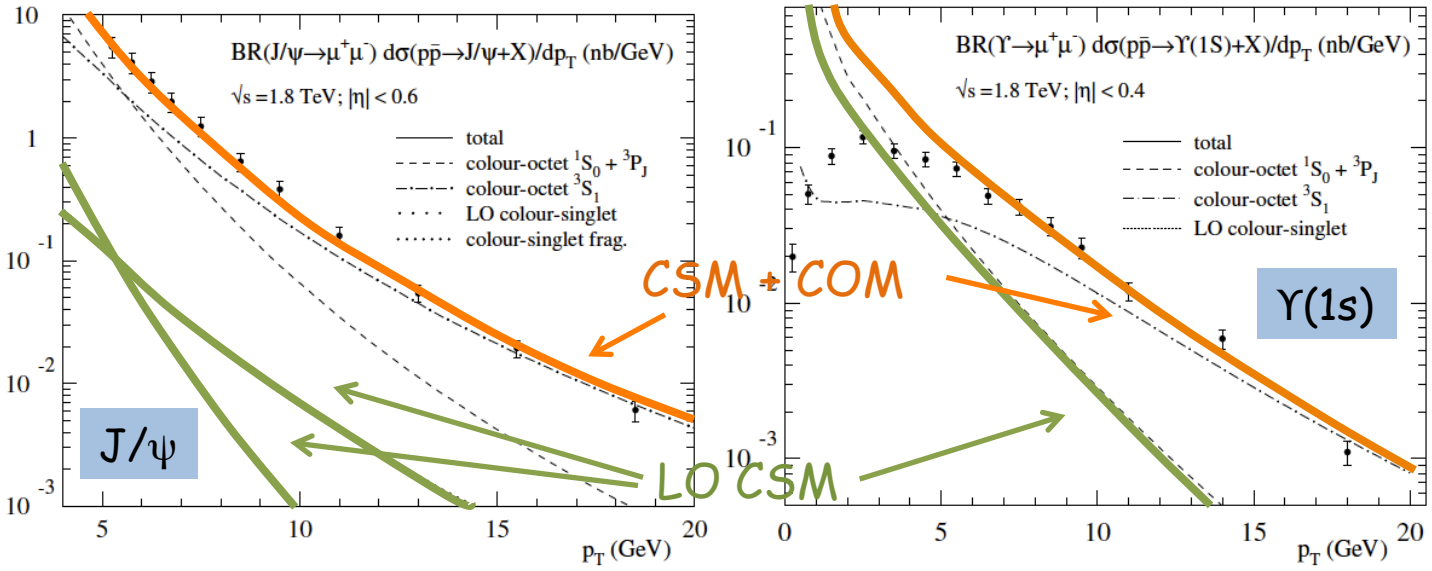


Physics Motivation

- Historically physicists tried to understand the quarkonium production mechanism and polarization
- Some popular models in the market :
  - Color Singlet Model (CSM)
  - Color Octet Mechanism (COM) / NRQCD
  - Color Evaporation Model
  - k_T factorization
  - …

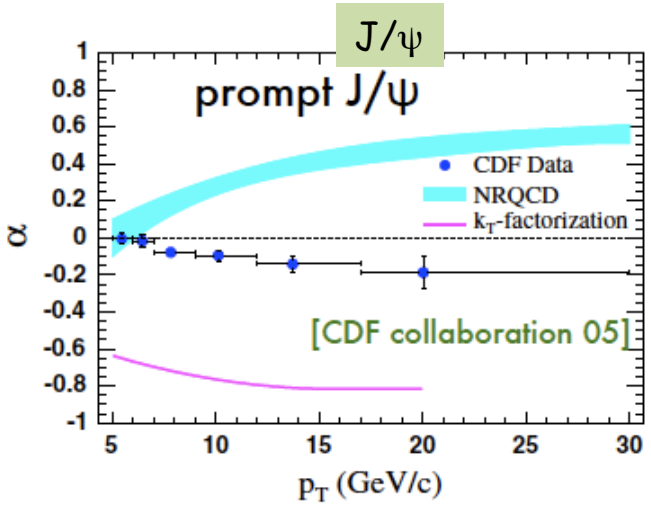


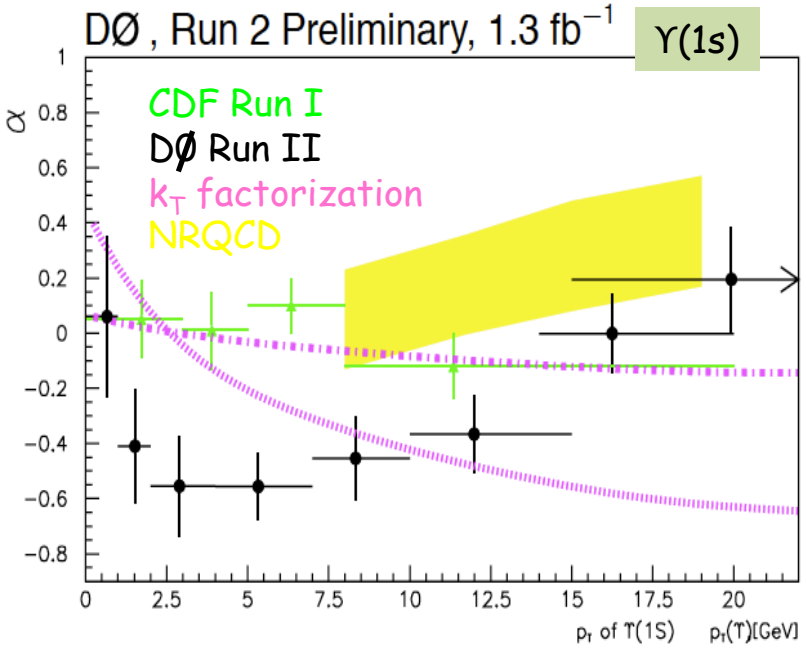
Tevatron Results

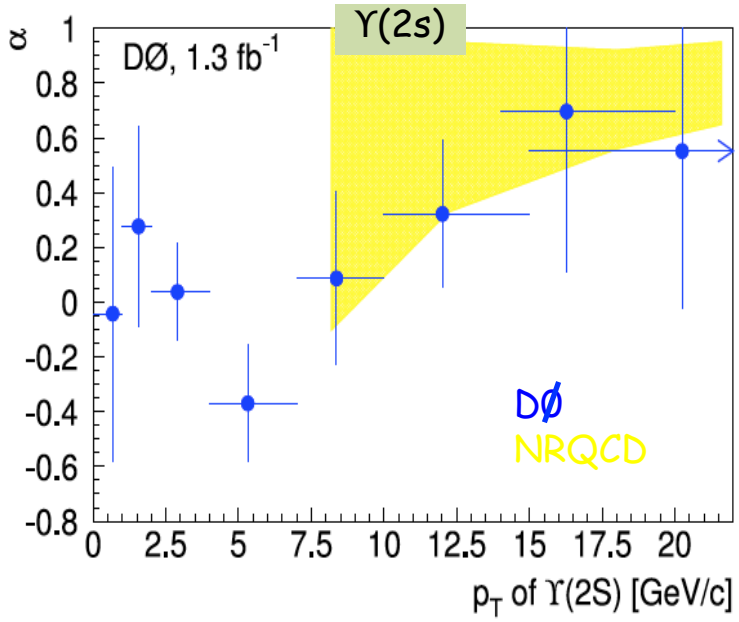


Polarization of Quarkonium

- Recent Tevatron results shows the discrepancy between "data and theoretical prediction" and even "CDF and D0 results"
  - ➔ challenged the previous statements





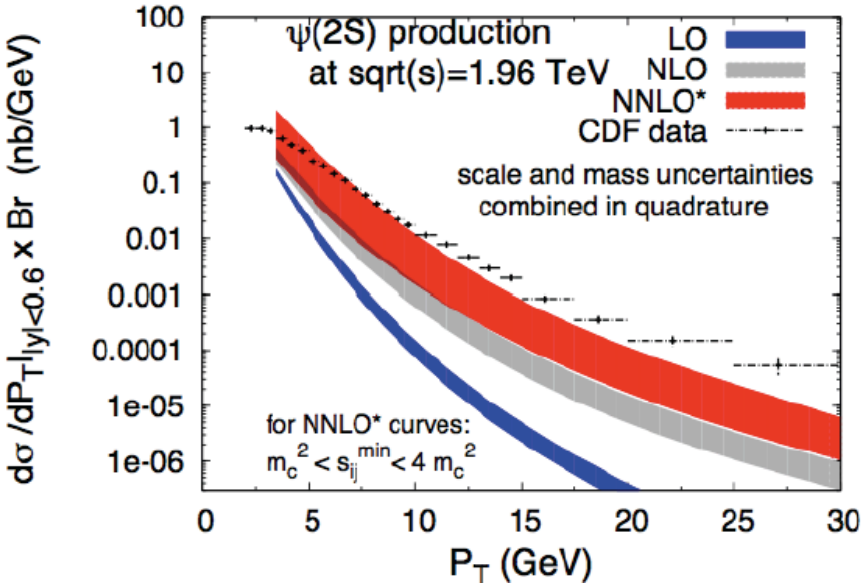


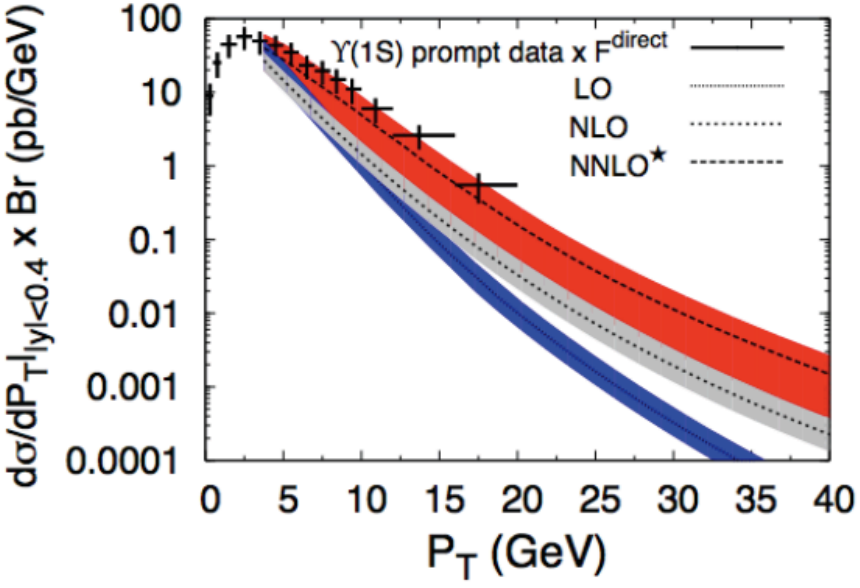
Higher Order Calculation

- In the past few years, theorists started to calculate the NNLO* contribution in Color Singlet Model

  J.P. Lansberg arXiv:0811.4005

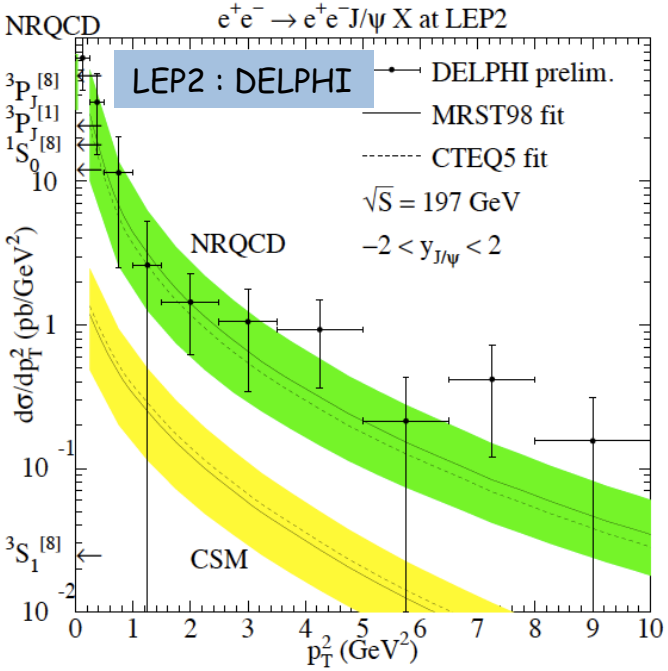
  ➔ Very large!
- Good agreement with CDF data, how about ATLAS?
- Note : NNLO* is not full NNLO calculation, currently only real contribution up to α_s^5 has been calculated (corresponds to sum of the NLO yield and contributions from pp → Q + jjj)

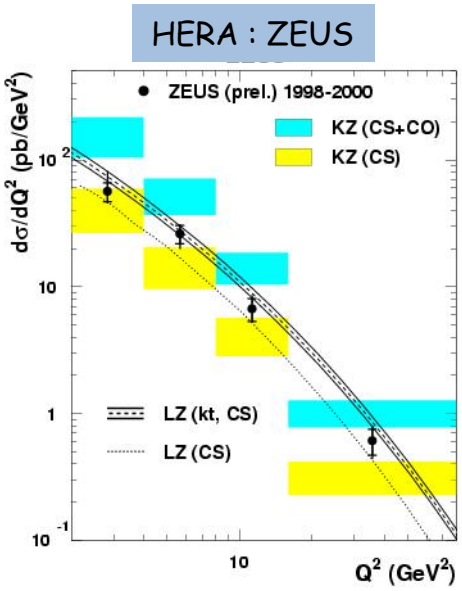


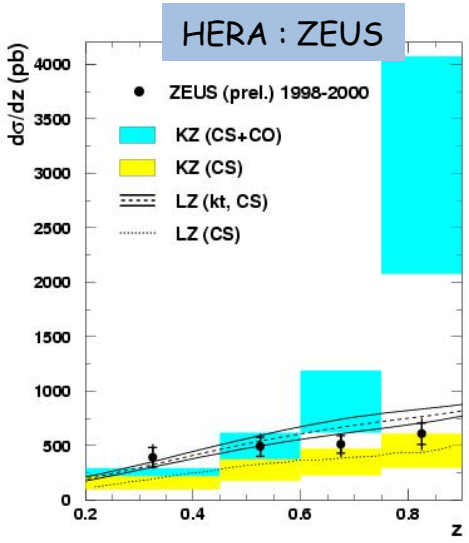


Other Experiments

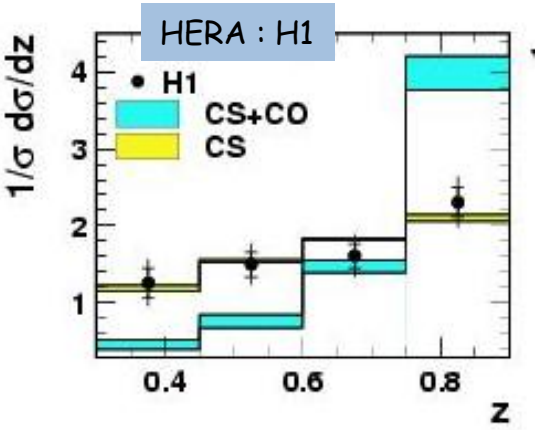
- Other measurements
  - DELPHI at LEP2 (ee collision)
  - ZEUS and H1 experiments at HERA (ep collision)
- Shapes favored the combined CSM + COM, but the model uncertainties are large





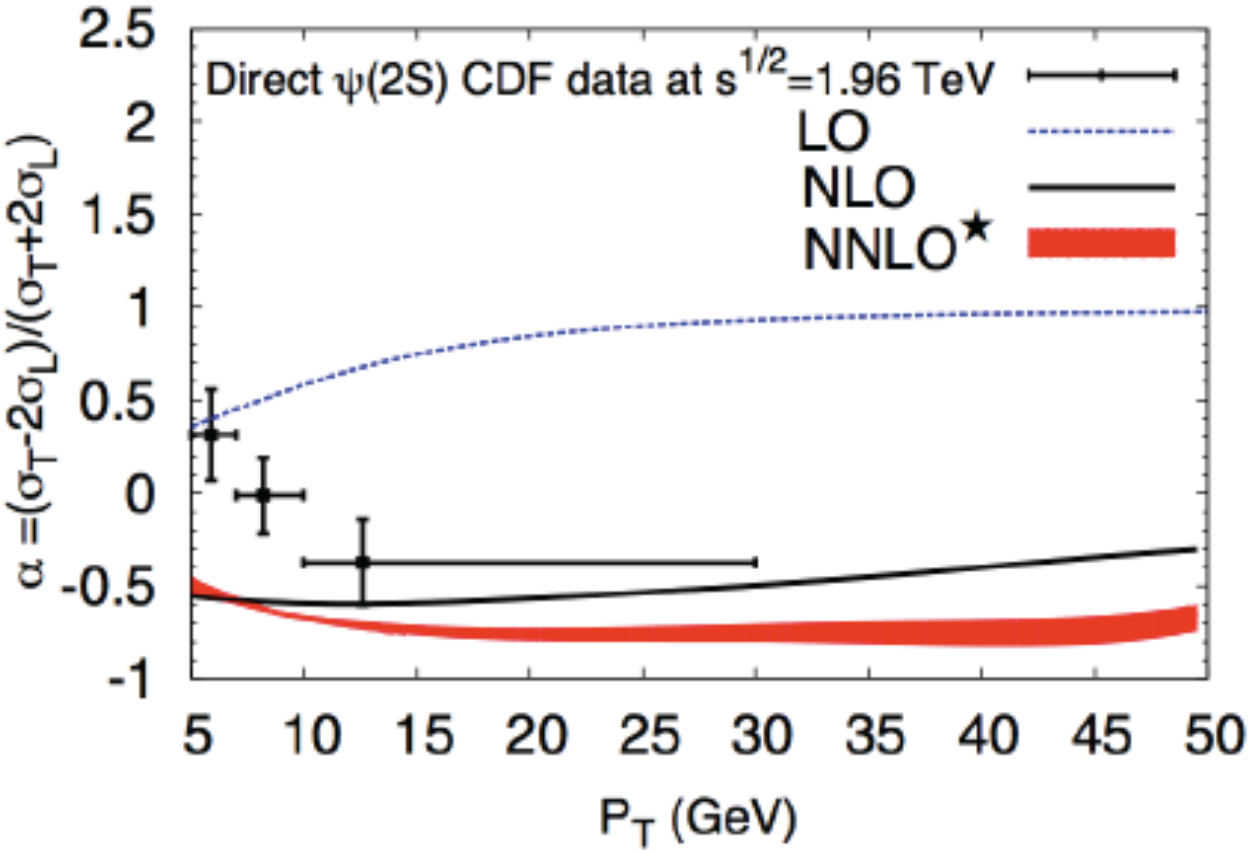


$$z = \frac{(E - p_z)_{J/\psi}}{(E - p_z)_{\text{hadrons}}}$$



Higher order calculation

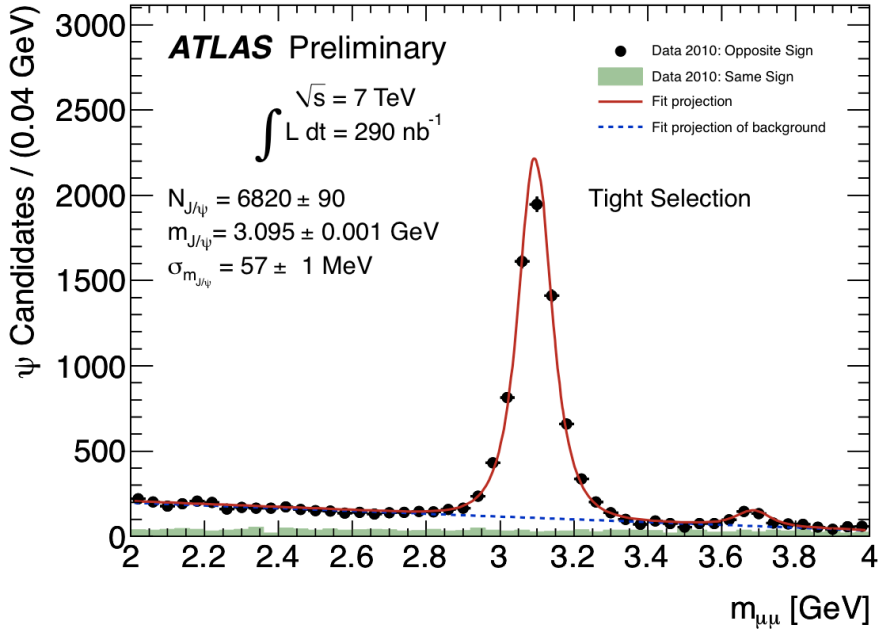
- Polarization in NNLO* prediction



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 :
    - Observation :
      - $pT(\mu_1) > 4$ GeV
      - $pT(\mu_2) > 2.5$ GeV
    - Cross Section Measurement :
      - $P(\mu) > 3.5$ GeV
- Trigger Configurations :
  - Muon hardware level 1 trigger or minimum bias trigger with confirmation at MS

J/ψ and ψ(2s)Observation in ATLAS with 290 nb^{-1} Data



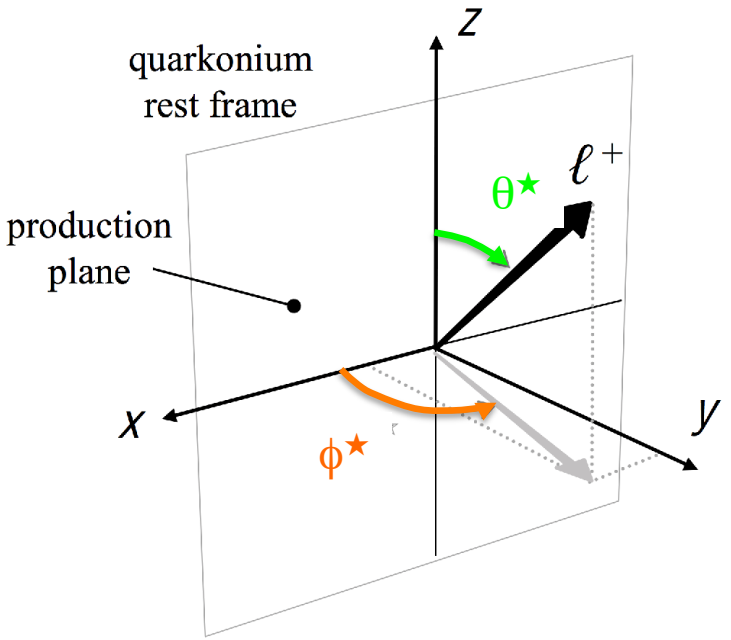
J/ψ Spin-Alignment

- Acceptance plays an crucial rule in fully inclusive cross section measurement
- Acceptance depends on the angular distribution of the decaying particle (spin-alignment of J/ψ) by the formula

P. Faccioli et al. arXiv:1006.2738

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

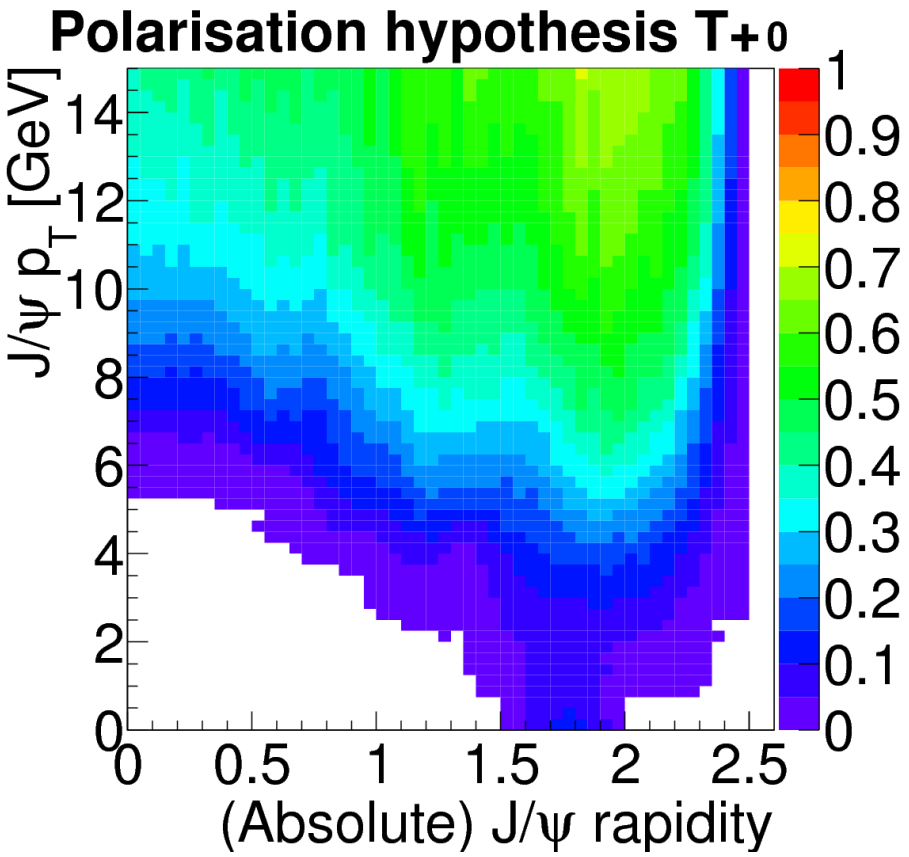
- $\theta^\star$: angle between μ^+ momentum in the J/ψ rest frame and J/ψ momemtum
- $\phi^\star$: angle between J/ψ production and decay plan in lab frame

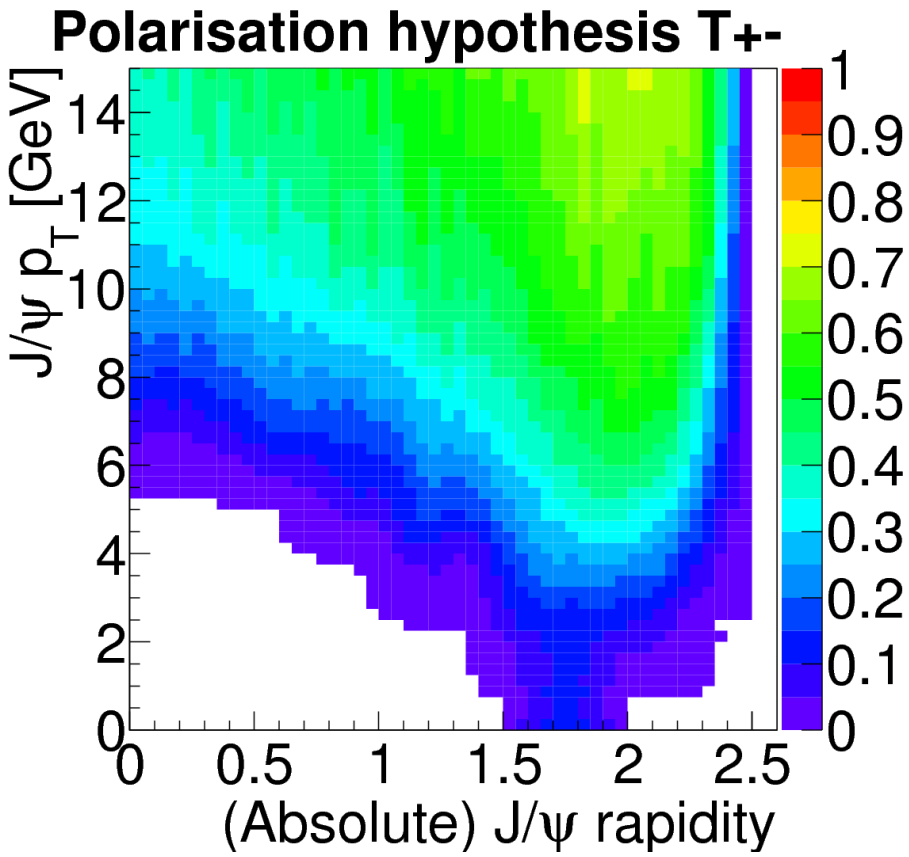


- Spin-alignment has not been measured, so it's still an open question

➔ Systematic uncertainty in the measurement

J/ψ Spin-Alignment





Acceptance and Data Binning

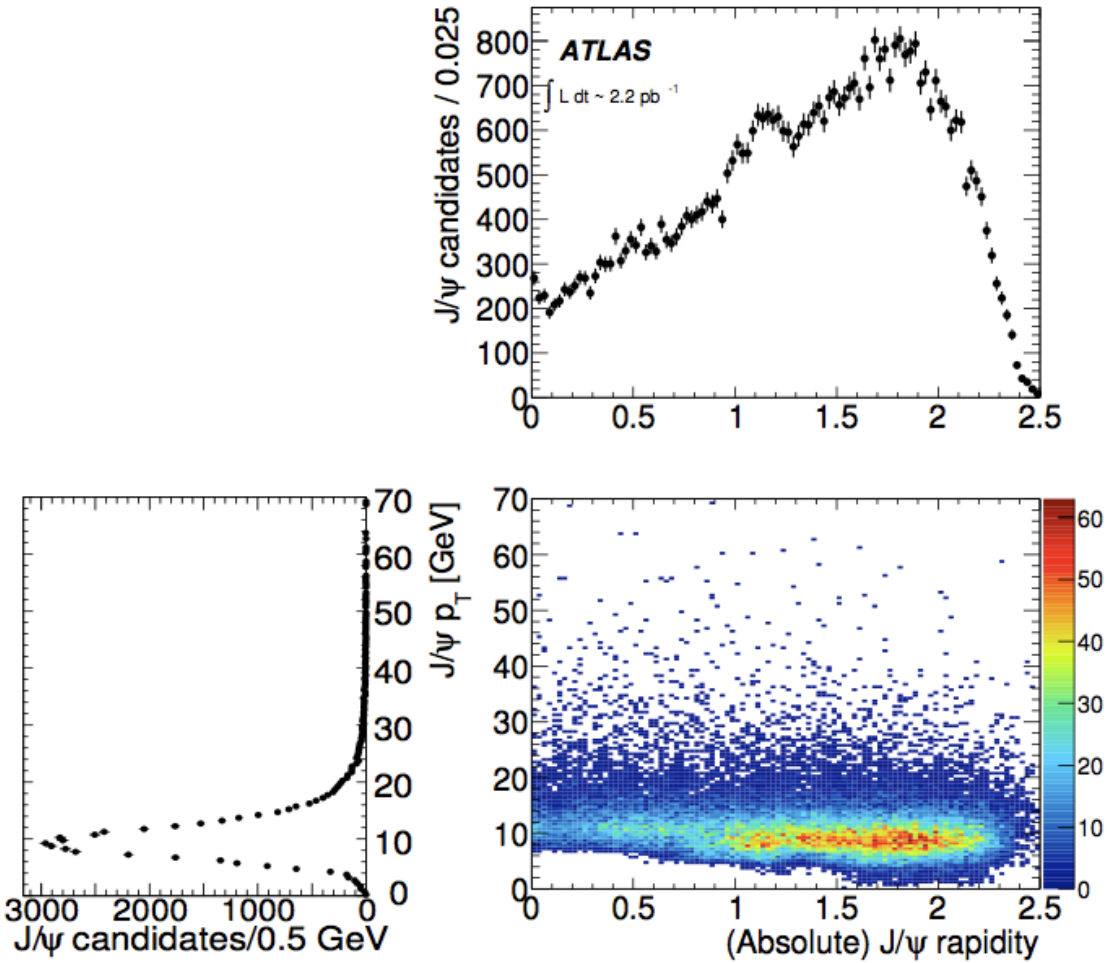
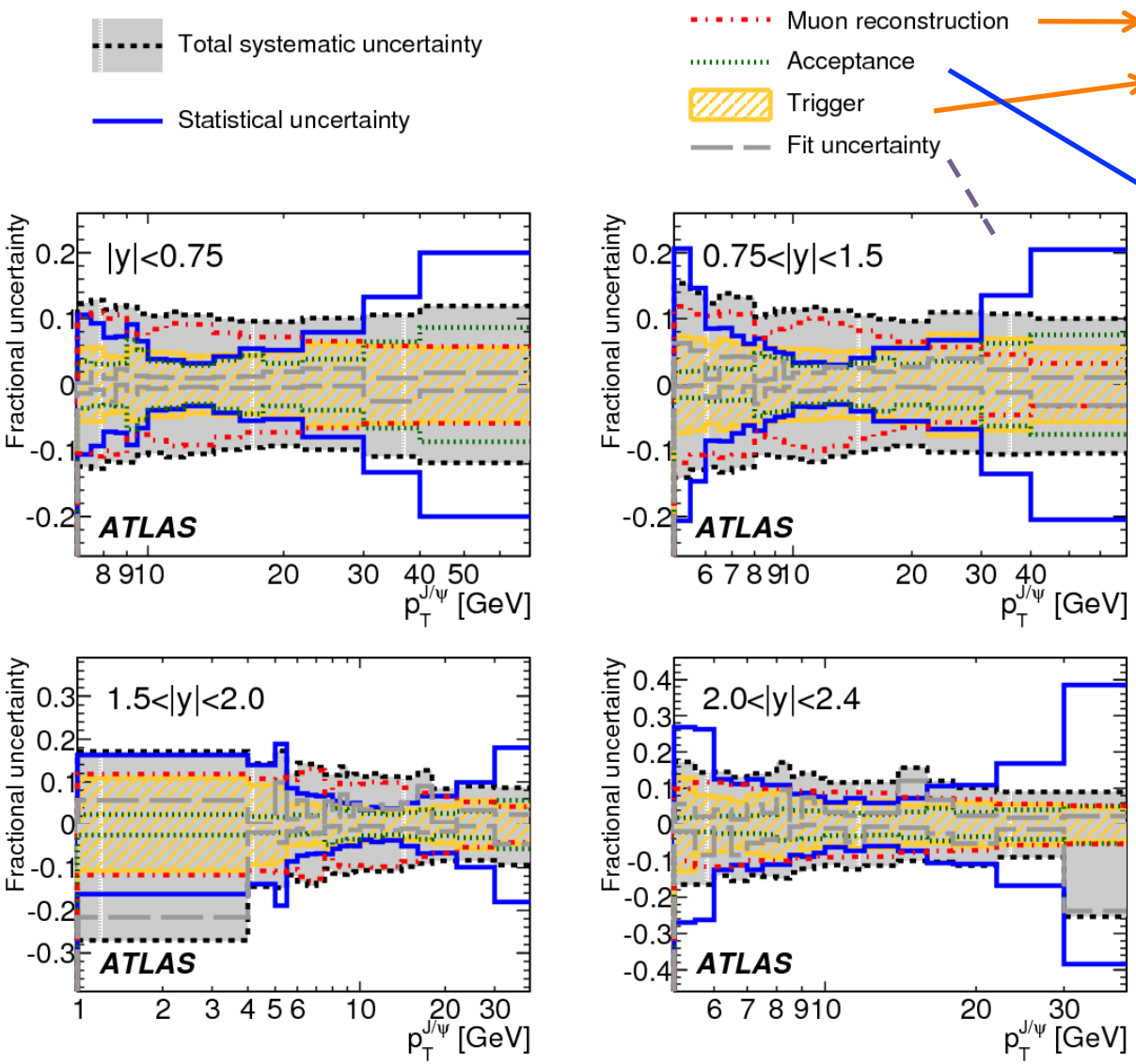


Figure 3: Distribution of reconstructed J/ψ candidate yields (in the invariant mass interval $2.7 \leq m_{J/\psi} < 3.5$ GeV) as a function of J/ψ p_T and rapidity.

Uncertainties



Dominate by statistical uncertainty from data-driven method

Consider several possible sources :

- MC statistics
- Kinematic
- Bin migration
- FSR

- Try other signal and background models
- Pseudo-experiments to deal with statistical fluctuation

3.4% for luminosity

Determine Non-prompt Fractions

- Unbinned Maximum Likelihood Fit is used to extract the J/ψ mass and the number of J/ψ candidates
- Likelihood function :

$$L = \prod_{i=1}^{N} \left[f_{\rm sig} P_{\rm sig}(\tau, \delta_\tau) F_{\rm sig}(m_{\mu\mu}, \delta_m) + (1 - f_{\rm sig}) P_{\rm bkg}(\tau, \delta_\tau) F_{\rm bkg}(m_{\mu\mu}) \right]$$

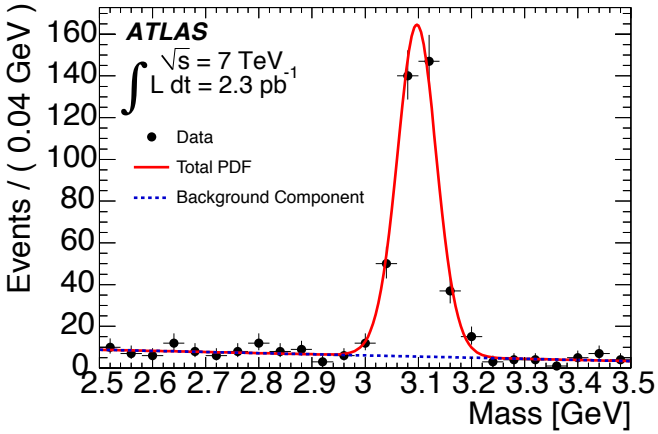
$$P_{\rm sig}(\tau, \delta_\tau) = f_B P_B(\tau, \delta_\tau) + (1 - f_B) P_P(\tau, \delta_\tau),$$

  - Signal PDF (Gaussian distribution) :

$$F_{\rm sig}(m_{\mu\mu}, \delta_m) \equiv \frac{1}{\sqrt{2\pi}\, S\, \delta_m} e^{\frac{-(m_{\mu\mu} - m_{J/\psi})^2}{2(S \cdot \delta_m)^2}}$$

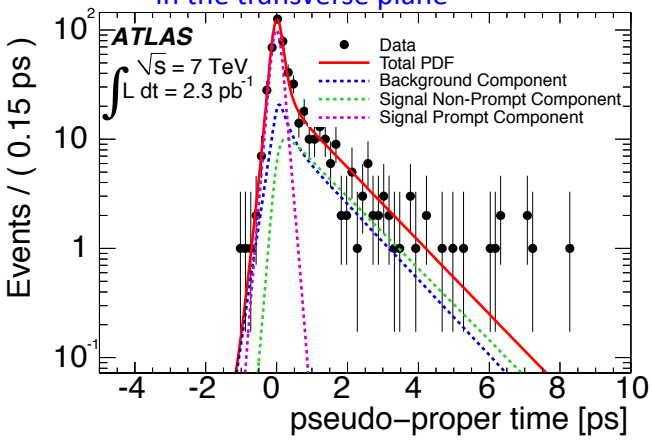
  - Background PDF (linear distribution) : simple linear function

  - Free parameters :
    - δ_m : mass error for each candidate
    - S : scaling factor for the mass resolution



Pseudo-proper time: $\tau = \frac{L_{xy}\, m_{\rm PDG}^{J/\psi}}{p_T^{J/\psi}}$.

Lxy: the displacement of the J/ψ vertex in the transverse plane



J/ψ Production Cross Section

- Apply the "weight" event by event to get the true number of J/ψ candidates :

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

Detector Acceptance | Reconstruction Efficiency | Trigger Efficiency

  - Detector Acceptance :
    - Defined as the probability of both muons from J/ψ in the detector fiducial volume
    - Estimated from Monte Carlo generator-level
  - Reconstruction efficiency :
    - Defined in the muon fiducial volume
    - Estimated from prompt J/ψ Monte Carlo sample and validated with the efficiency from data
  - Trigger efficiency :
    - Relative to the offline reconstruction was calculated using minimum bias data

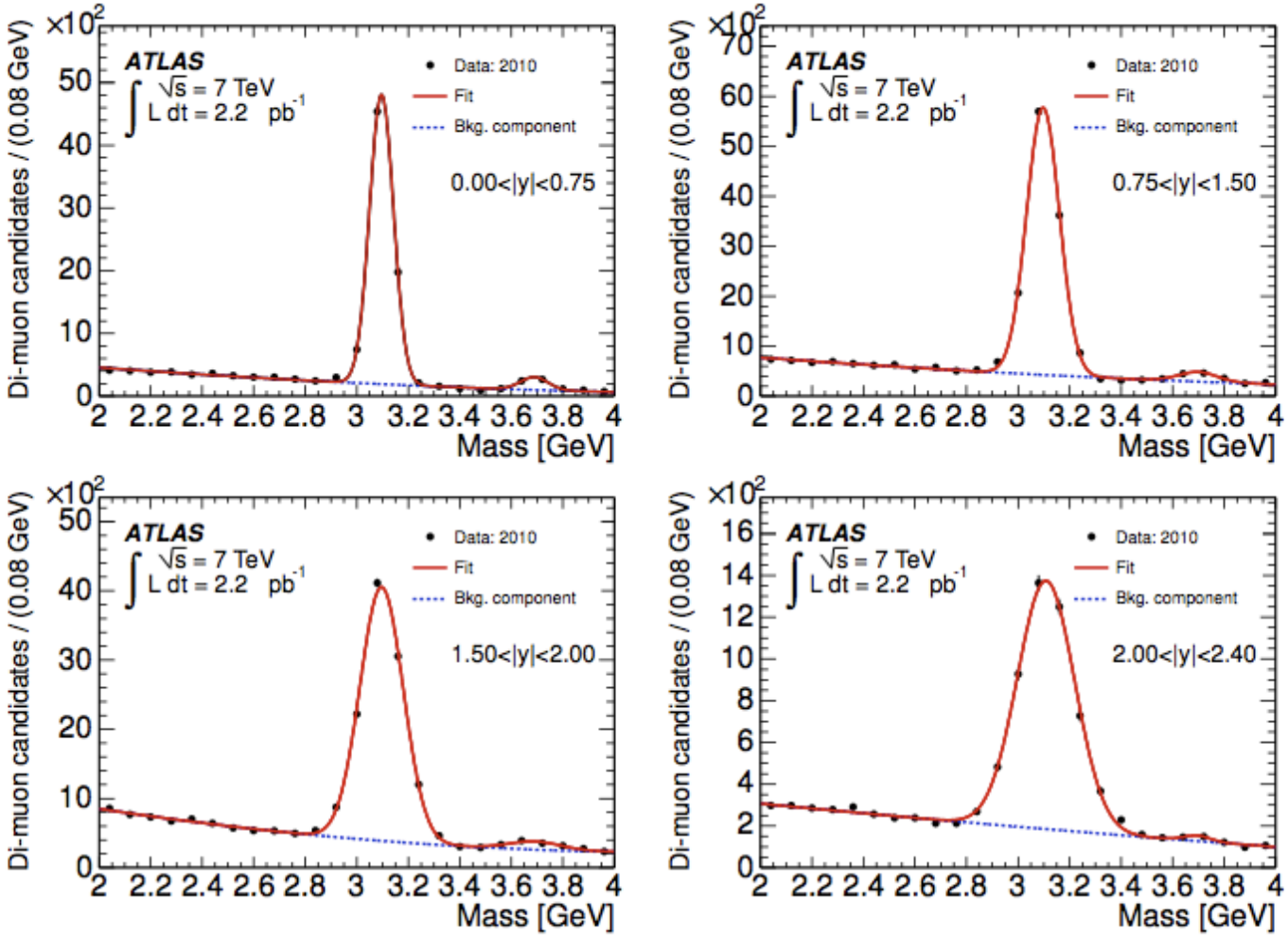


Figure 4: Invariant mass distributions of reconstructed $J/\psi \to \mu^+\mu^-$ candidates used in the cross-section analysis, corresponding to an integrated luminosity of 2.2 pb^{-1}. The points are data, and the uncertainties indicated are statistical only. The solid lines are the result of the fit described in the text.

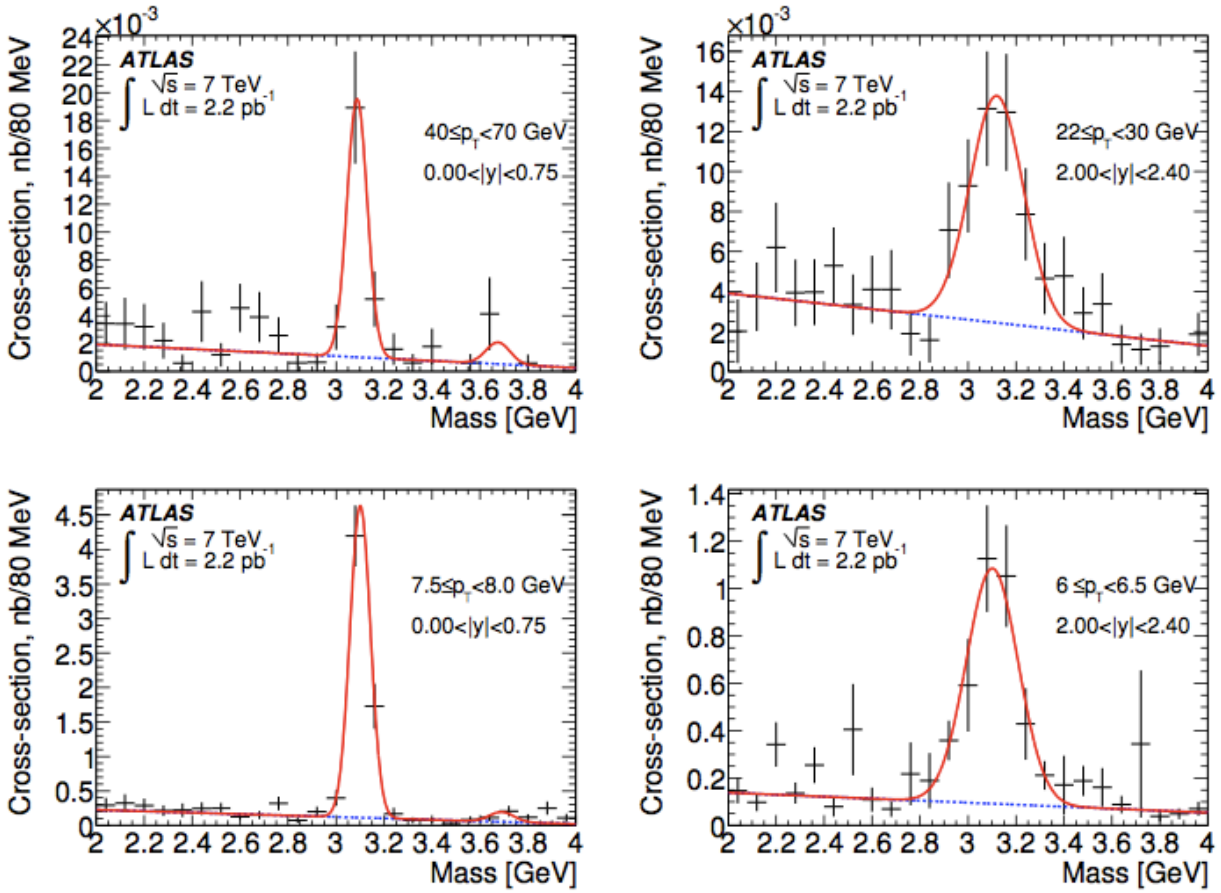


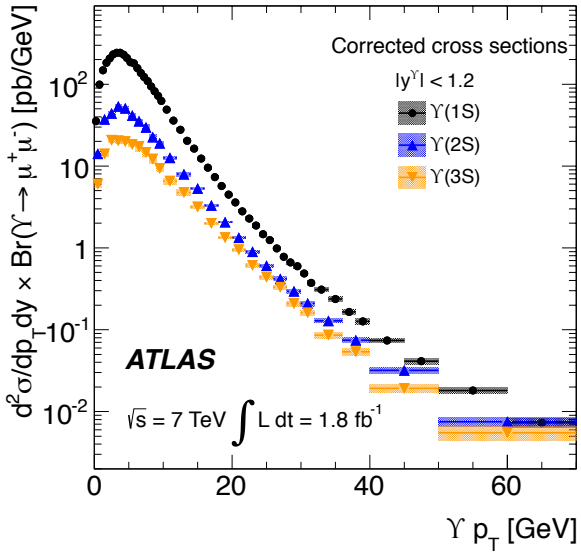
Figure 5: Acceptance- and efficiency-corrected invariant di-muon mass distributions scaled by integrated luminosity for selected bins in J/ψ rapidity and transverse momentum. Low- and high- p_T bins are shown here for the central and forward rapidity ranges, to represent the complete sample. Statistical uncertainties and systematic uncertainties due to efficiency and acceptance corrections are shown, combined in quadrature.

Data-taking in 2011

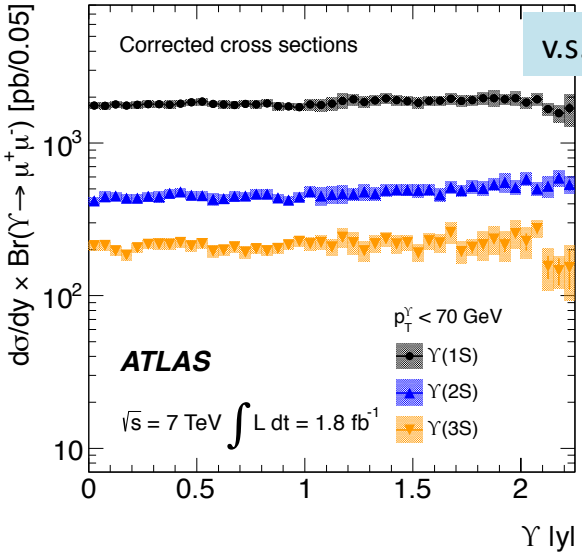
Trigger	Total events (M)
EF_2mu4_DiMu	27
EF_mu4mu6_DiMu	11
EF_2mu4_Jpsimumu	14
EF_mu4mu6_Jpsimumu	8.4
EF_2mu4_Bmumu	3.7
EF_mu4mu6_Bmumu	1.9
EF_2mu4_Upsimumu	9.1
EF_mu4mu6_Upsimumu	3.9
EF_mu20	2.1

Υ(nS) Corrected Cross-sections

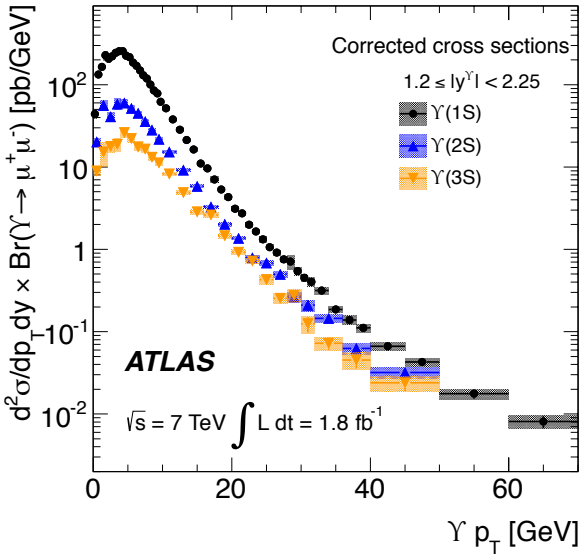
Central region



v.s. rapidity



Forward region



Integrated corrected cross sections	
State	$\sigma(pp \to \Upsilon) \times \mathrm{Br}(\Upsilon \to \mu^+\mu^-)$ Range: $p_{\mathrm{T}}^{\Upsilon} < 70\,\mathrm{GeV}$, $\lvert y^{\Upsilon} \rvert < 2.25$
$\Upsilon(1S)$	$8.01 \pm 0.02 \pm 0.36 \pm 0.31$ nb
$\Upsilon(2S)$	$2.05 \pm 0.01 \pm 0.12 \pm 0.08$ nb
$\Upsilon(3S)$	$0.92 \pm 0.01 \pm 0.07 \pm 0.04$ nb

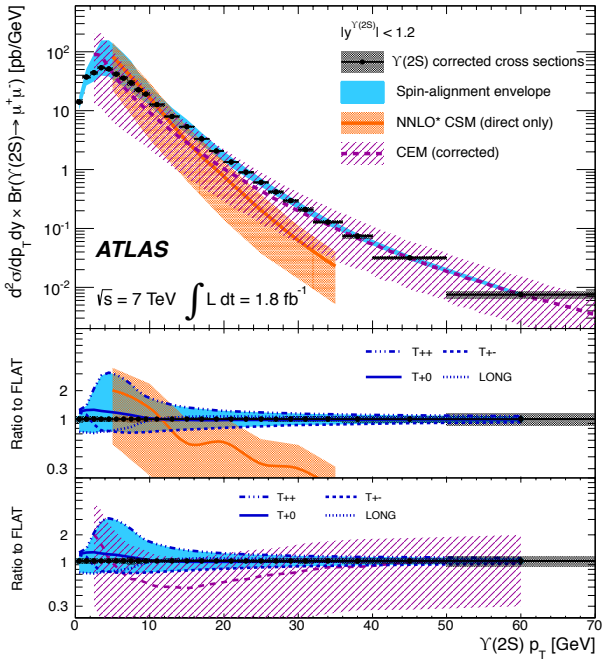
Υ(2S) Corrected Cross-sections

Blue : Spin-alignment envelope

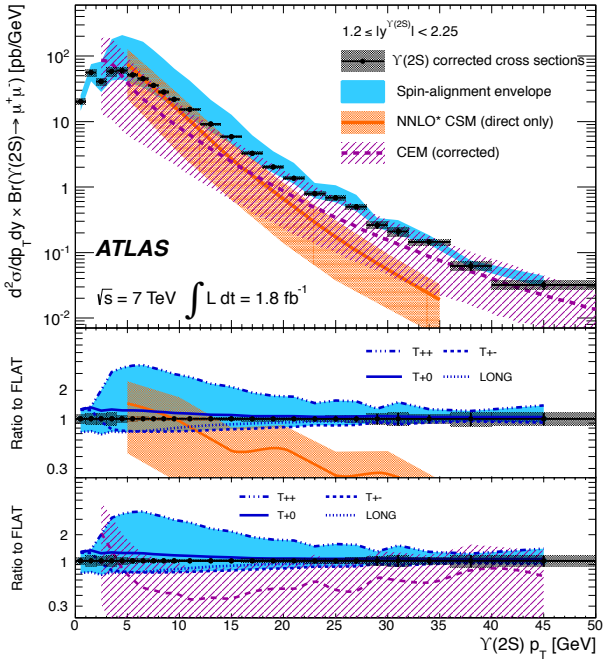
Orange : NNLO* Color Singlet

Purple : Color Evaporation Model

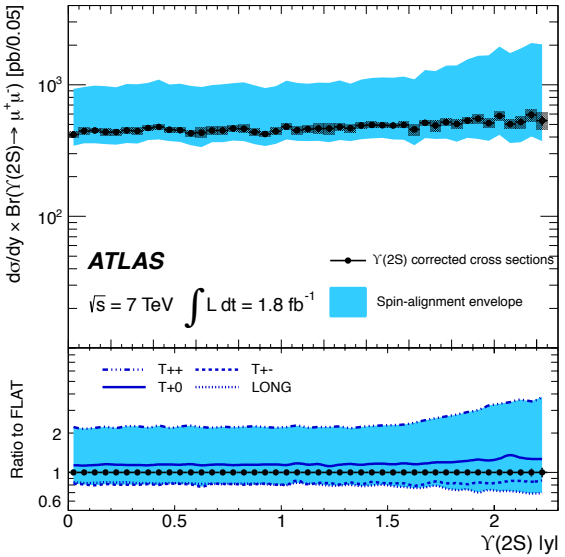
Central region



Forward region



v.s. rapidity



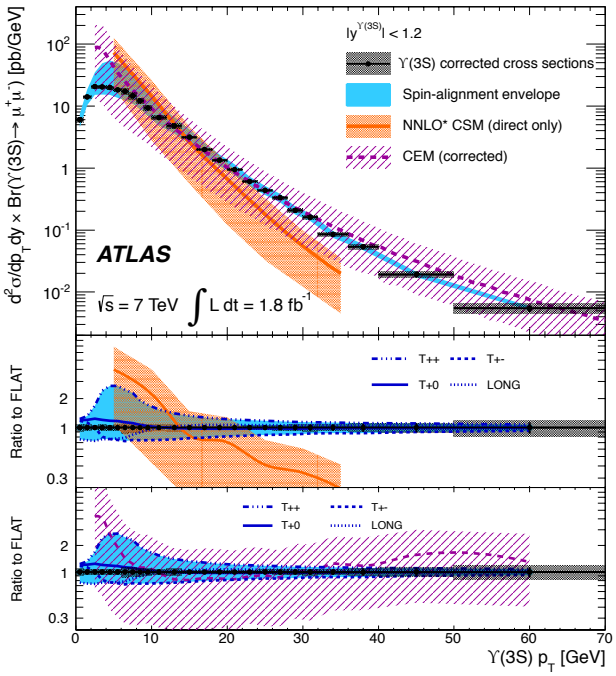
Υ(3S) Corrected Cross-sections

Blue : Spin-alignment envelope

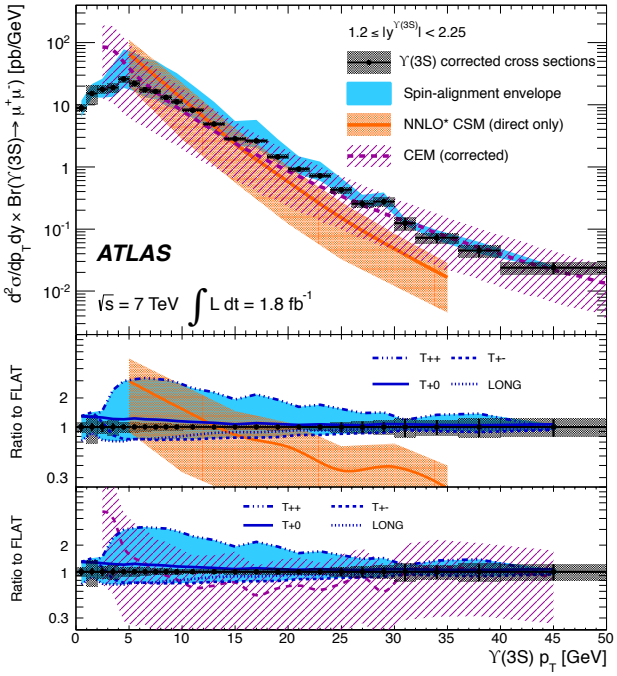
Orange : NNLO* Color Singlet

Purple : Color Evaporation Model

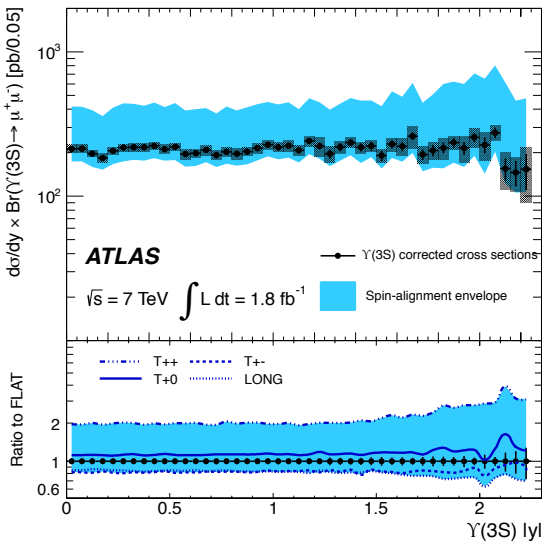
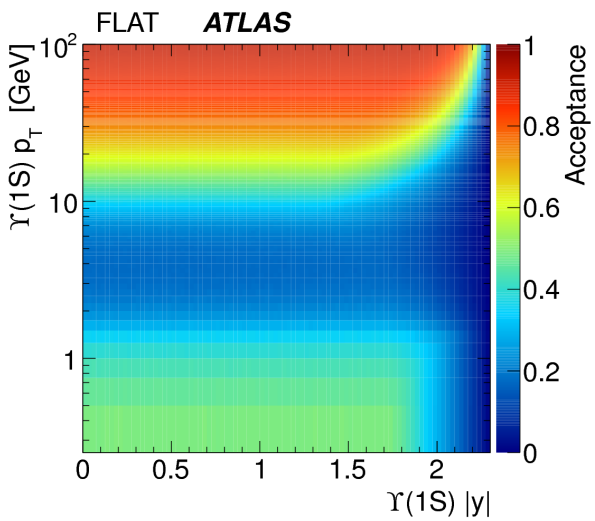
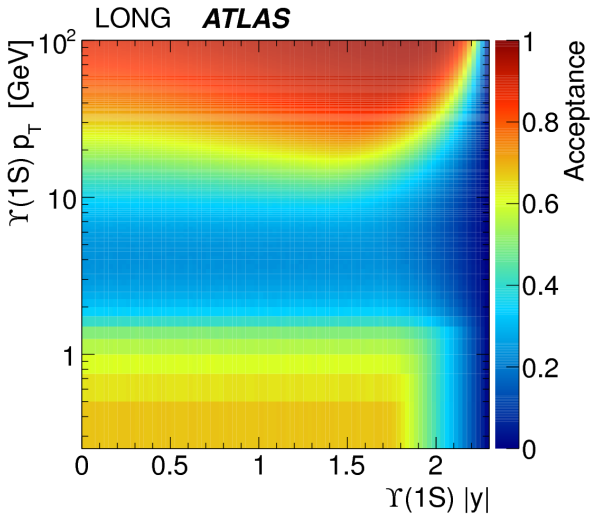
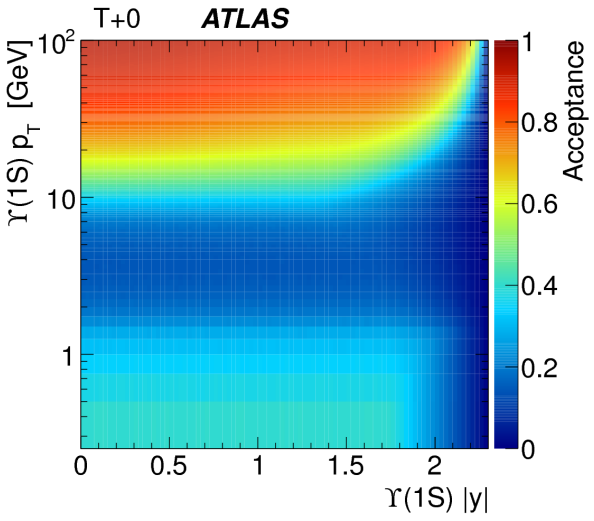
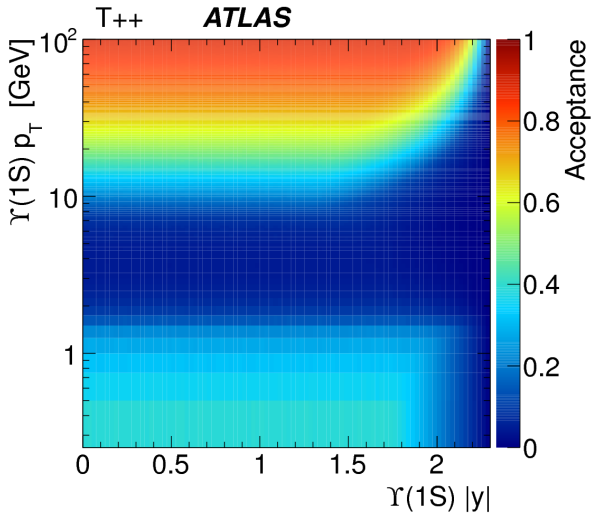
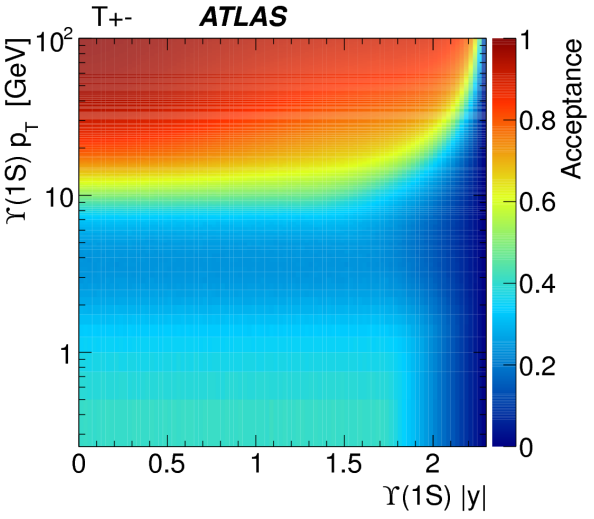
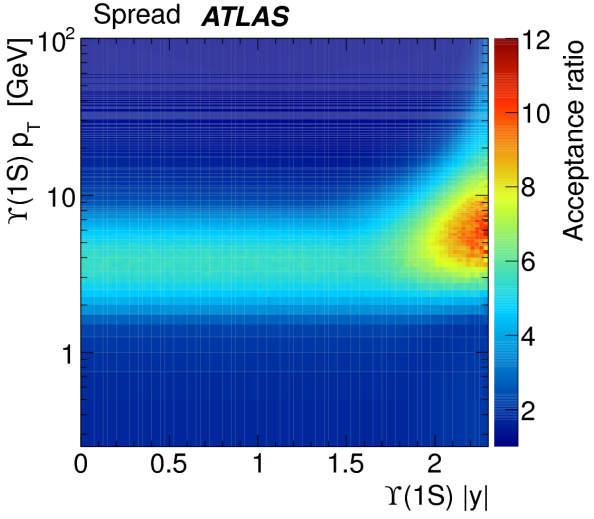
Central region



Forward region



v.s. rapidity



Υ(1S) Acceptance Maps