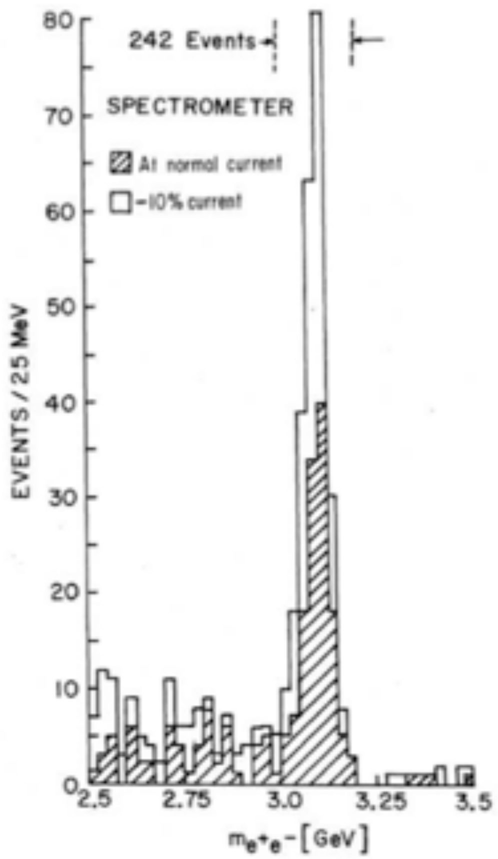
Production of Heavy Quarkonium States at the LHC with the ATLAS Experiment

James Walder
Lancaster University

On behalf of the ATLAS Collaboration

Heavy Quarkonium Physics

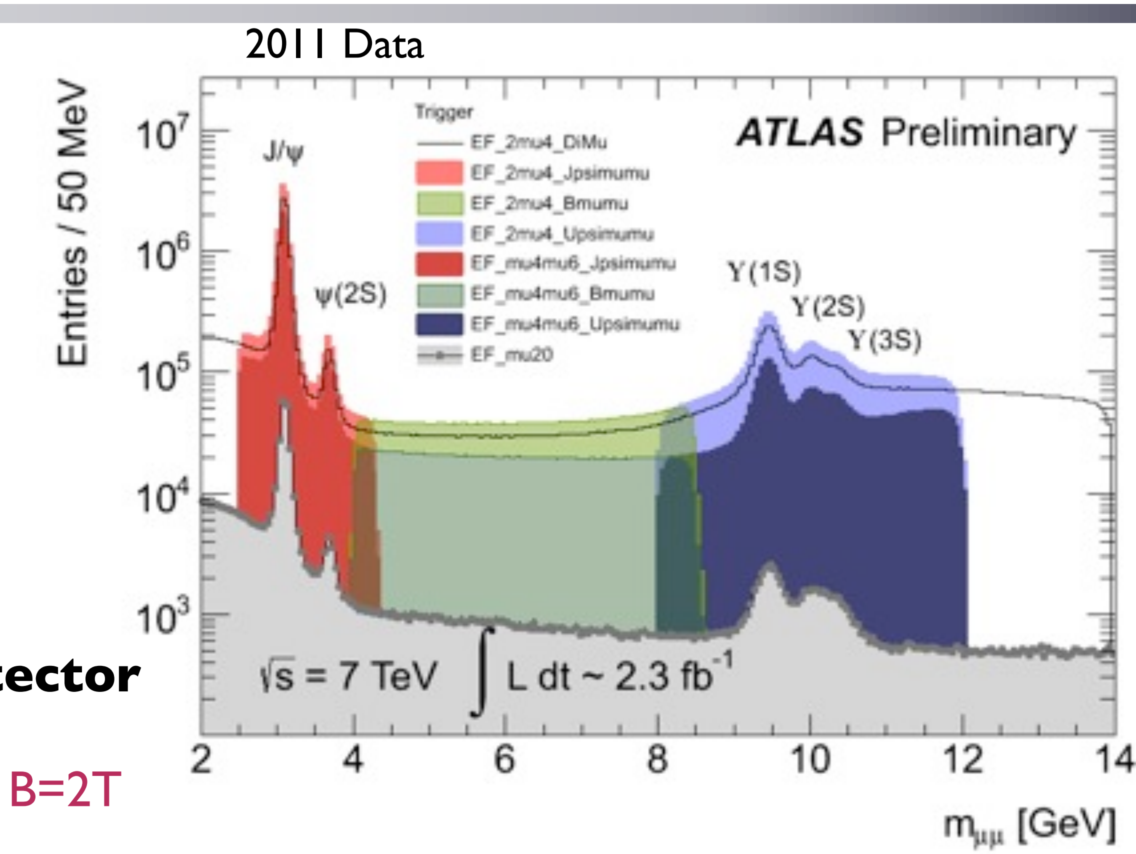
- Heavy Quarkonium, the bound state of b or c quark anti-quark pair, continues to challenge our understanding of QCD near to strong decay threshold
  - J/ψ observed in 1974,
  - Despite being a “known” resonance its production mechanisms still uncertain.

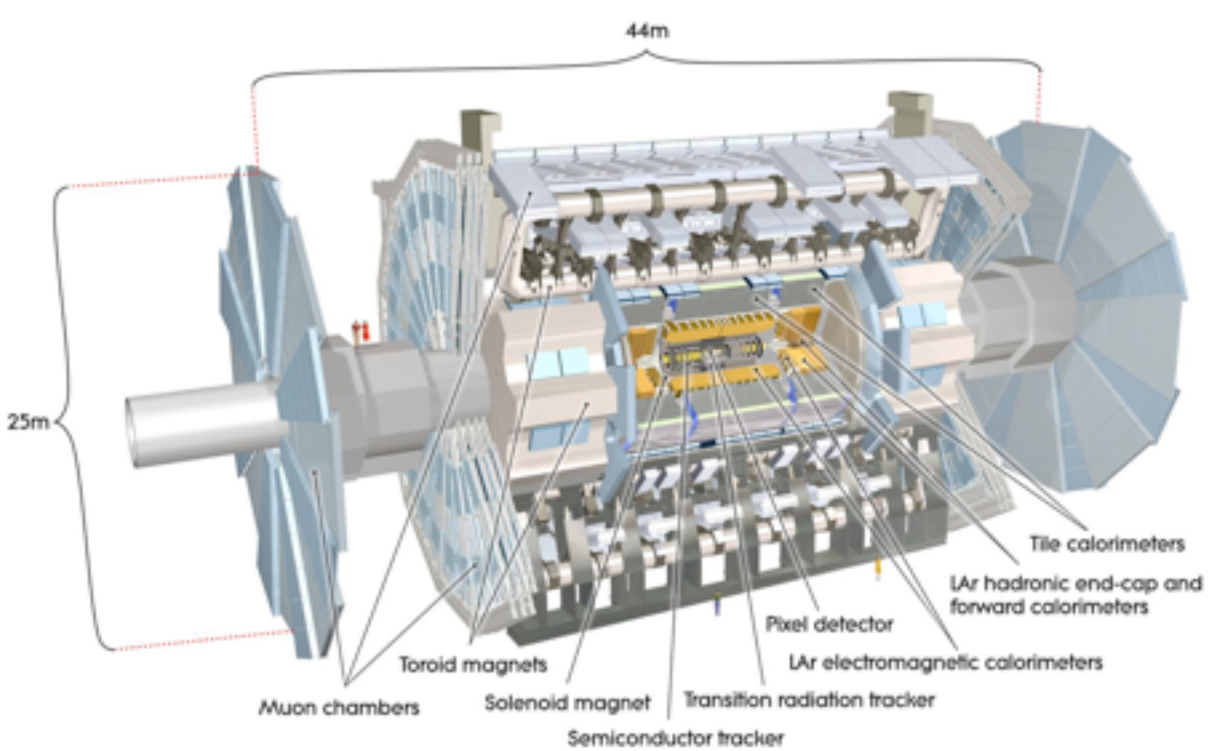


- Onia production occurs through:
  - Prompt production -
    - Direct production,
    - Feed-down from higher quarkonium states.
  - Non-prompt production -
    - From decays of B hadrons (only charmonium).
- LHC era extends reach of the hadro-production of quarkonium to new energy regime.
- ATLAS presents results on J/ψ and Υ production cross-sections, and observation of the $\chi_{c/b}$ system.

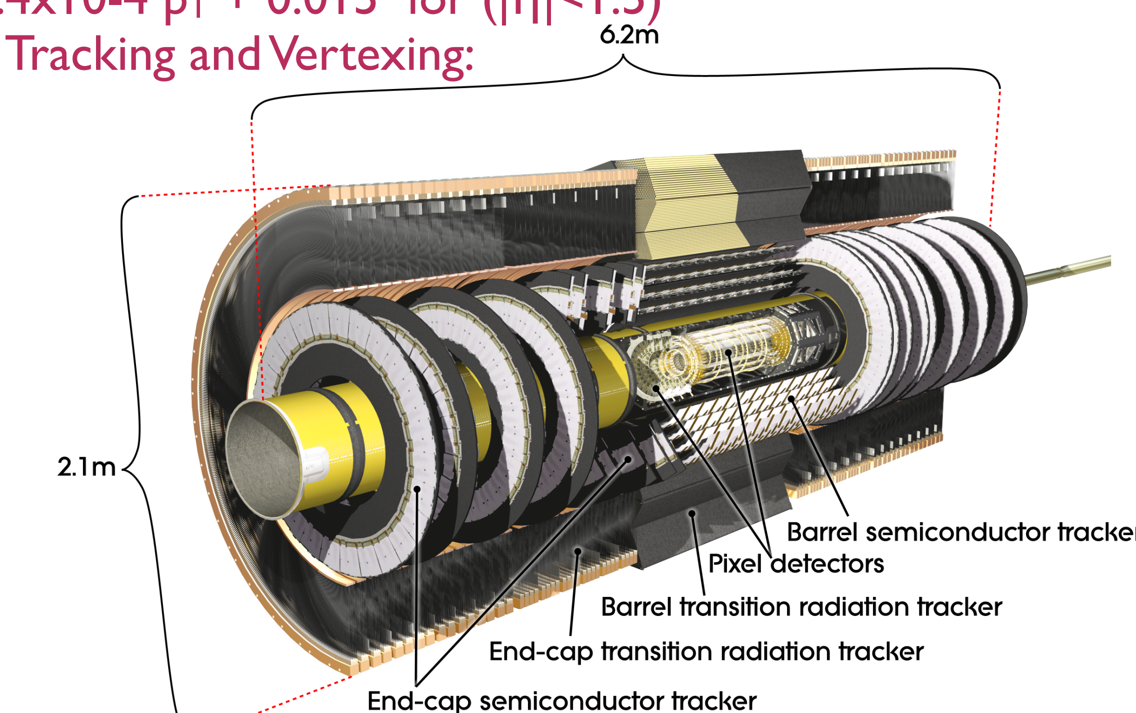
The ATLAS Detector

- Data selection begins with optimised suite of single and di-muon triggers:
  - 3-level system: 40 MHz to *O*(200) Hz
- Muon ID from Muon Spectrometer
- Inner Detector provides precision momentum and lifetime measurements





- **Inner Detector**
  - $|\eta|<2.5$,
  - Solenoid B=2T
  - Si Pixels,
  - Si strips,
  - Transition Radiation Tracker (TRT)
  - $\sigma/p_T \sim 3.4\text{x}10\text{-}4\ p_T + 0.015$ for ($|\eta|<1.5$)
  - Used for Tracking and Vertexing:



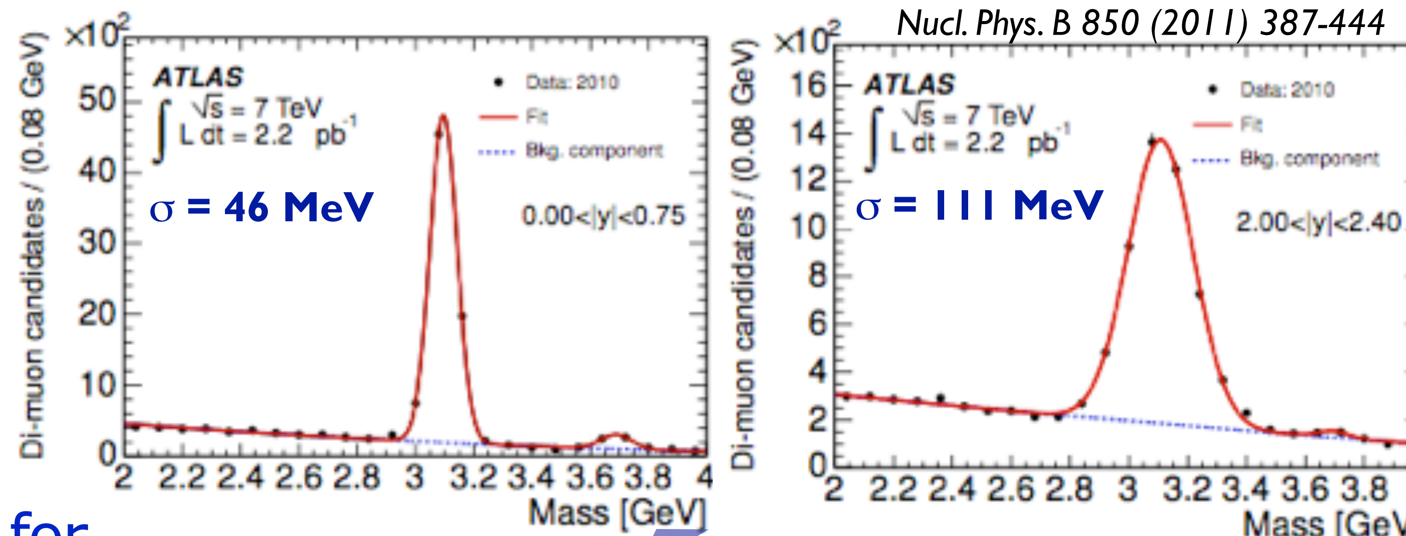
- **Muon Spectrometer**
  - $|\eta|<2.7$
  - Toroid B-Field, average ~0.5T
  - Muon Momentum resolution $\sigma/p <$ 10% up to ~ 1 TeV

J/ψ : Measurement of the differential Inclusive, Prompt and Non-Prompt Cross-Section

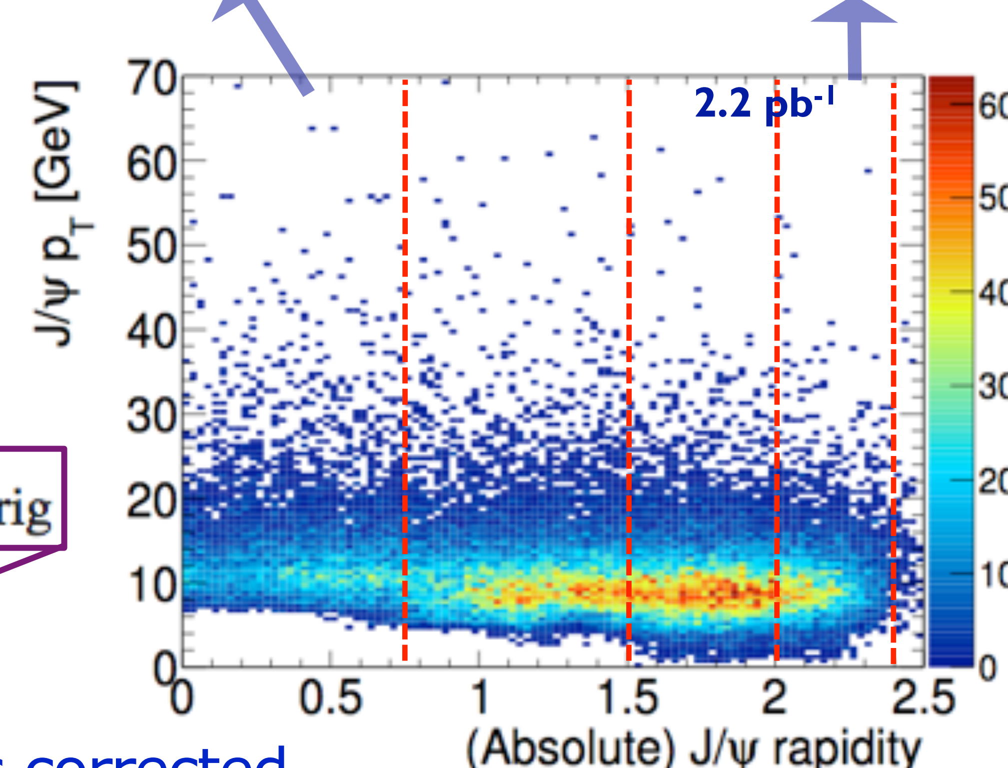
LANCASTER UNIVERSITY

- J/ψ candidates identified through di-muon decays:
  - Experimentally clean; BR ~ 6%
- Separate events in to bins of pT-rapidity for differential analysis

Nucl. Phys. B 850 (2011) 387-444



- Per-candidate weights applied to correct for detector inefficiencies from:
  - Muon reconstruction and trigger efficiencies,
  - Detector acceptance.



$$w^{-1} = \mathcal{A} \cdot \mathcal{M} \cdot \mathcal{E}^2_{\mathrm{trk}} \cdot \mathcal{E}^+{}_{\mu}(p_T^+, \eta^+) \cdot \mathcal{E}^-{}_{\mu}(p_T^-, \eta^-) \cdot \mathcal{E}_{\mathrm{trig}}$$

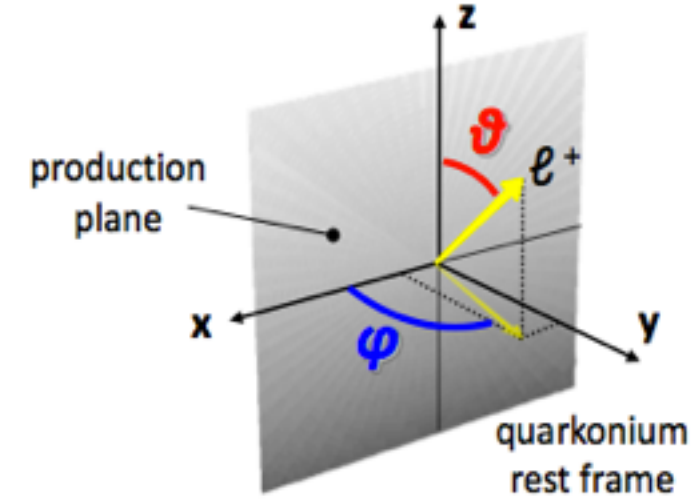
- $\mathcal{A}$: Detector acceptance
- $\mathcal{M}$: Bin migration
- $\mathcal{E}^2_{\mathrm{trk}}$: ID reco efficiency (per muon track)
- $\mathcal{E}^+{}_{\mu}(p_T^+, \eta^+) \cdot \mathcal{E}^-{}_{\mu}(p_T^-, \eta^-)$: Reconstruction efficiency
- $\mathcal{E}_{\mathrm{trig}}$: Trigger efficiency

- Binned χ^2 fit to weighted mass-distributions determines corrected yields in each bin.
  - Extract differential inclusive cross-section:
    - $$\frac{d^2\sigma(J/\psi)}{dp_T dy} \cdot Br(J/\psi \to \mu^+\mu^-) = \frac{N^{J/\psi}_{corr}}{\mathcal{L} \cdot \Delta p_T \Delta y}$$

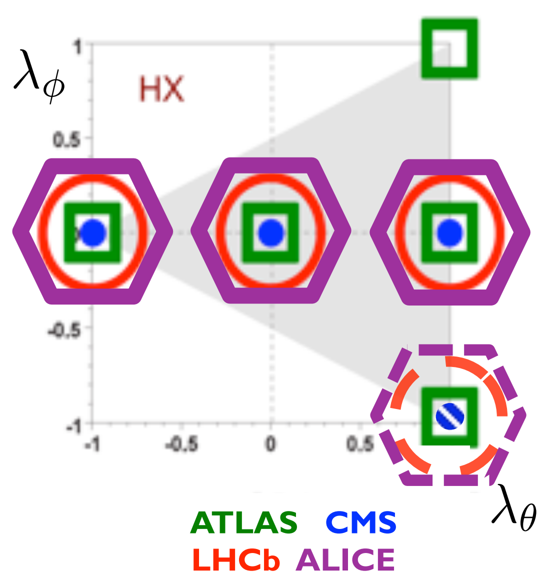
J/ψ : Spin-Alignment

- Acceptance: probability that J/ψ survives muon cuts
  - However, acceptance depends on spin-alignment,
    - Not yet well-measured under LHC conditions.

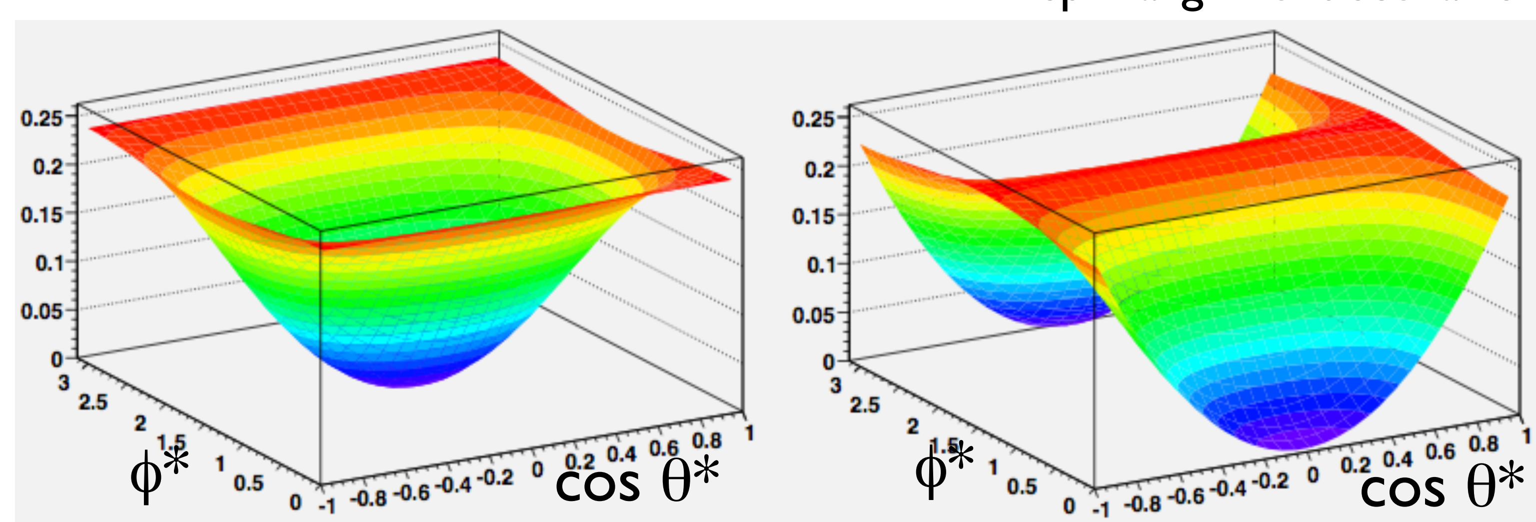
$$\frac{dN}{d\Omega} = 1 + \lambda_{\theta^\star} \cos^2\theta^\star + \lambda_{\phi^\star} \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta^\star\phi^\star} \sin 2\theta^\star \cos\phi^\star$$



- Isotropic distribution taken as central assumption
  - $\lambda_{\theta^\star} = \lambda_{\phi^\star} = \lambda_{\theta^\star\phi^\star} = 0$ (non-physical / pythia default)
- Take five specific working-point scenarios
  - Use as envelope of additional uncertainty on central value.
- Relative uncertainty between different scenarios reduces at higher-pT.



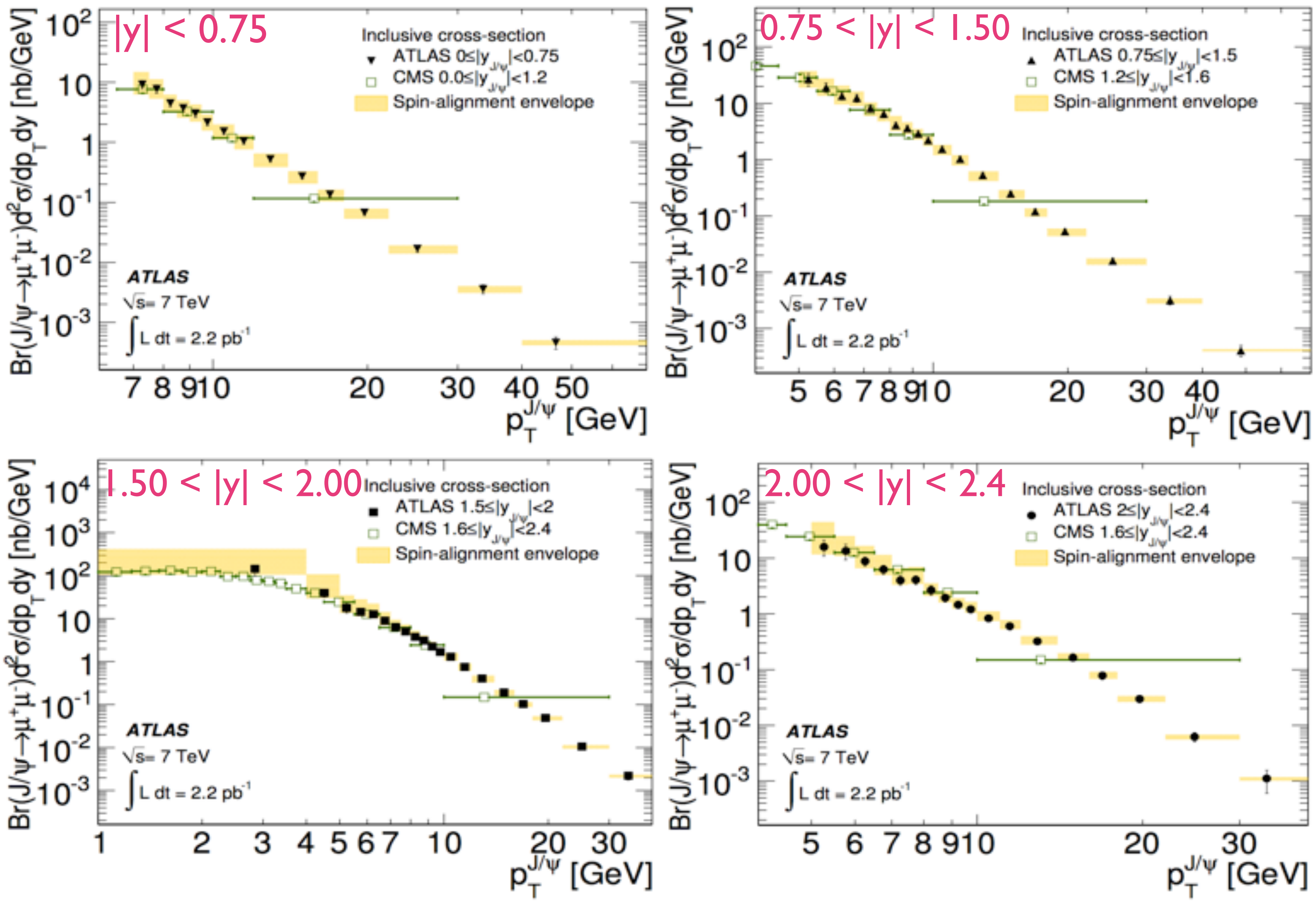
Possible extreme transverse spin-alignment scenario



V. Kartvelishvili

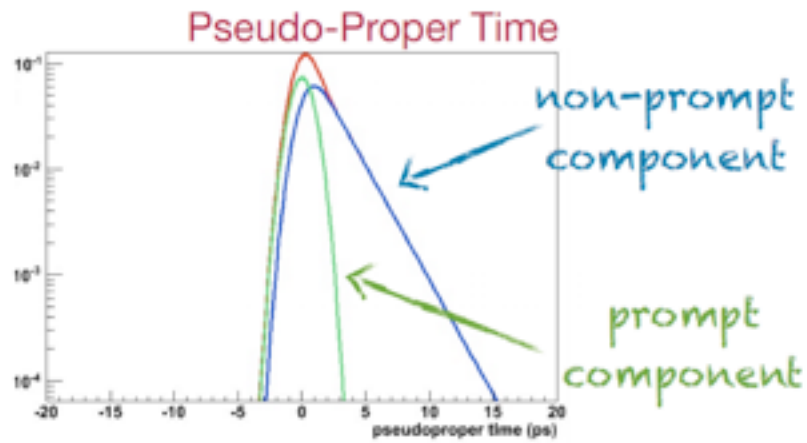
J/ψ: Inclusive Cross-section

- Good agreement between experiments.
  (including updated CMS results (not shown)- JHEP 02 (2012) 011)



J/ψ: Non-prompt Fraction

- Discriminate between prompt and non-prompt components from 2-d mass-lifetime fit.



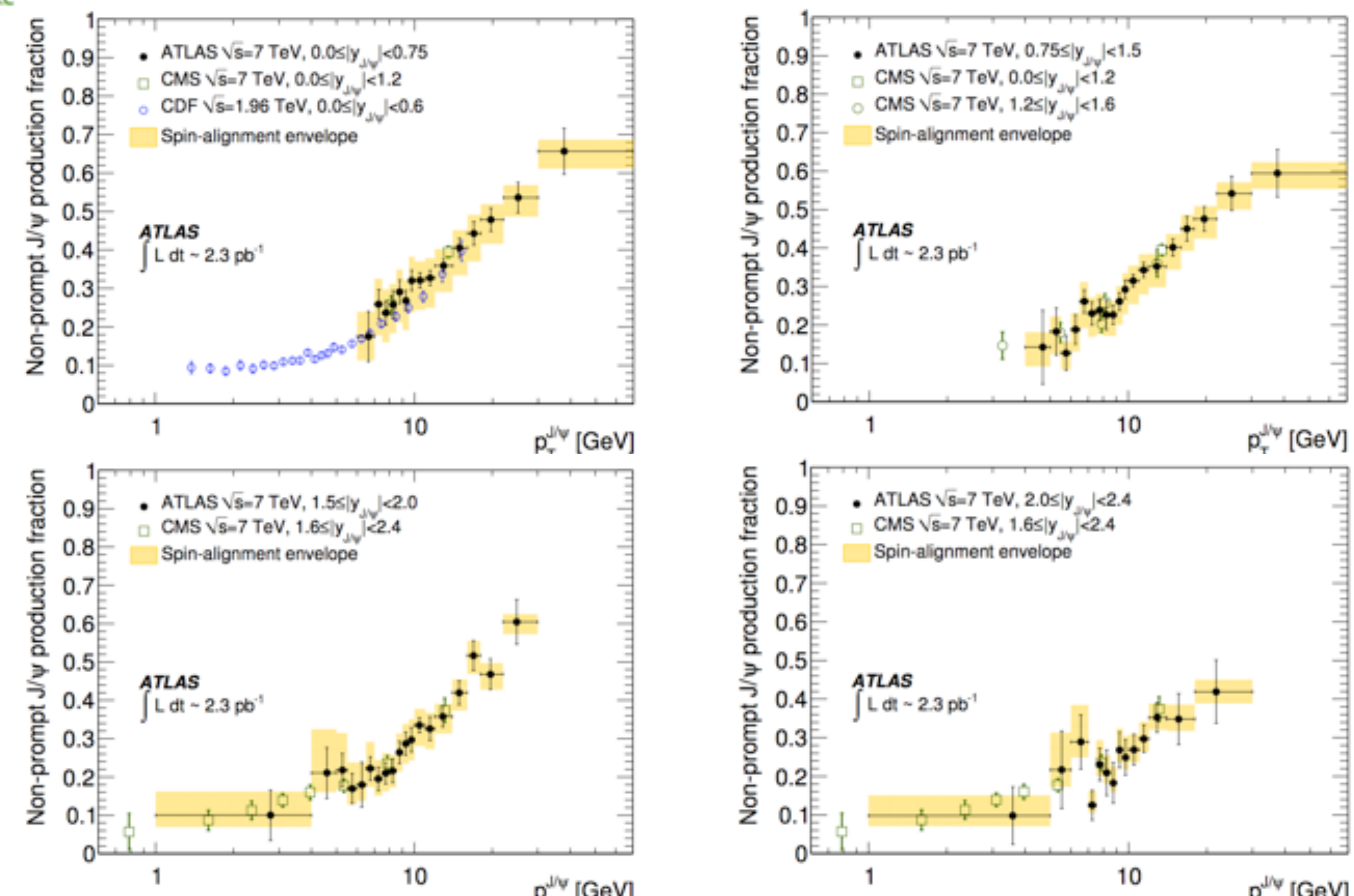
xy displacement of candidate from PV

Invariant mass of candidate

$$\tau = \frac{L_{xy}\, m(J/\psi)}{p_T(J/\psi)}$$

p_T of candidate

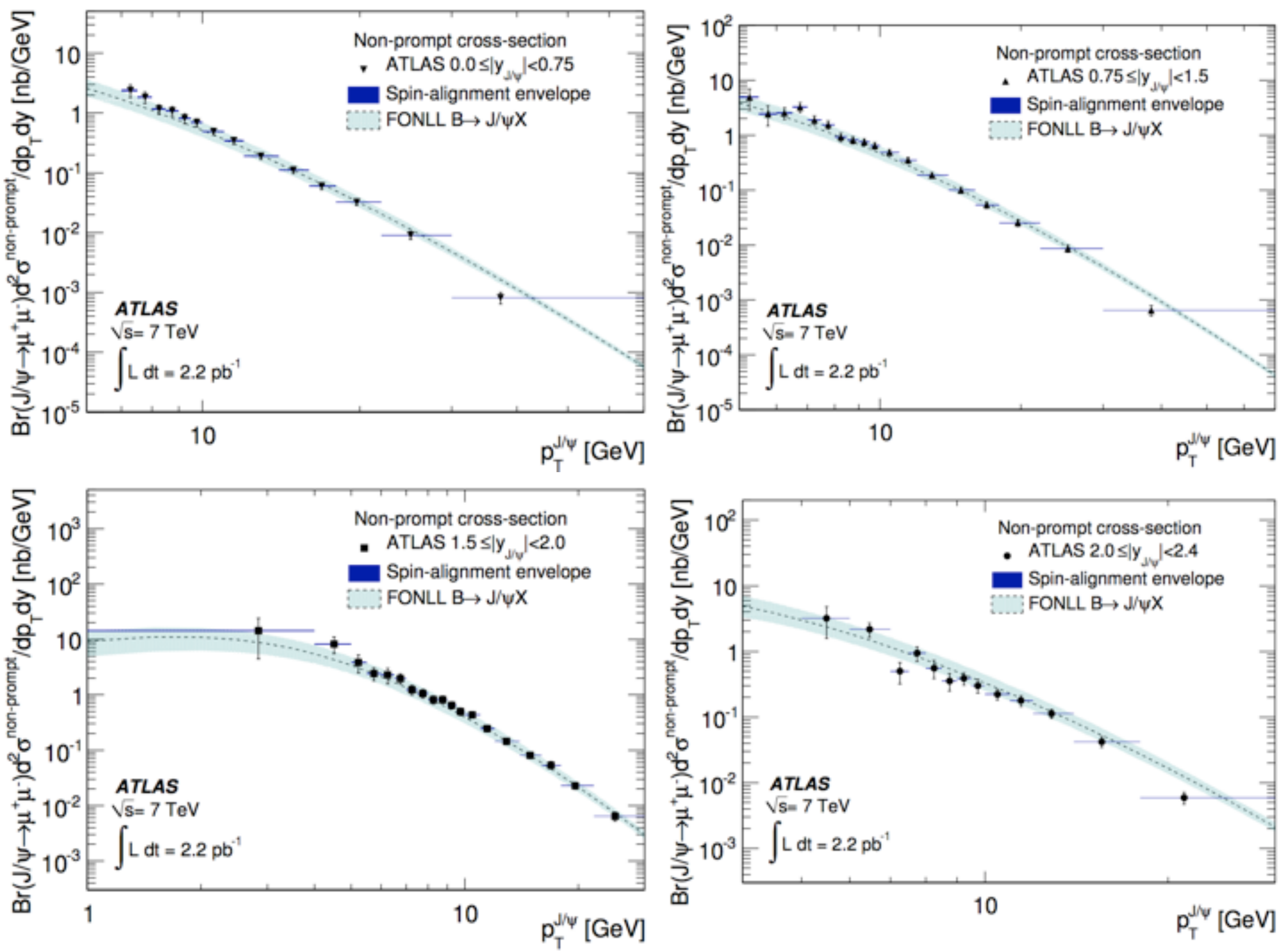
- Synergy between CDF and CMS measurements:
  - No strong dependence with centre-of-mass energy, or pp vs p$\bar{p}$.



- (also compatible with updated CMS results - not shown - JHEP 02 (2012) 011)

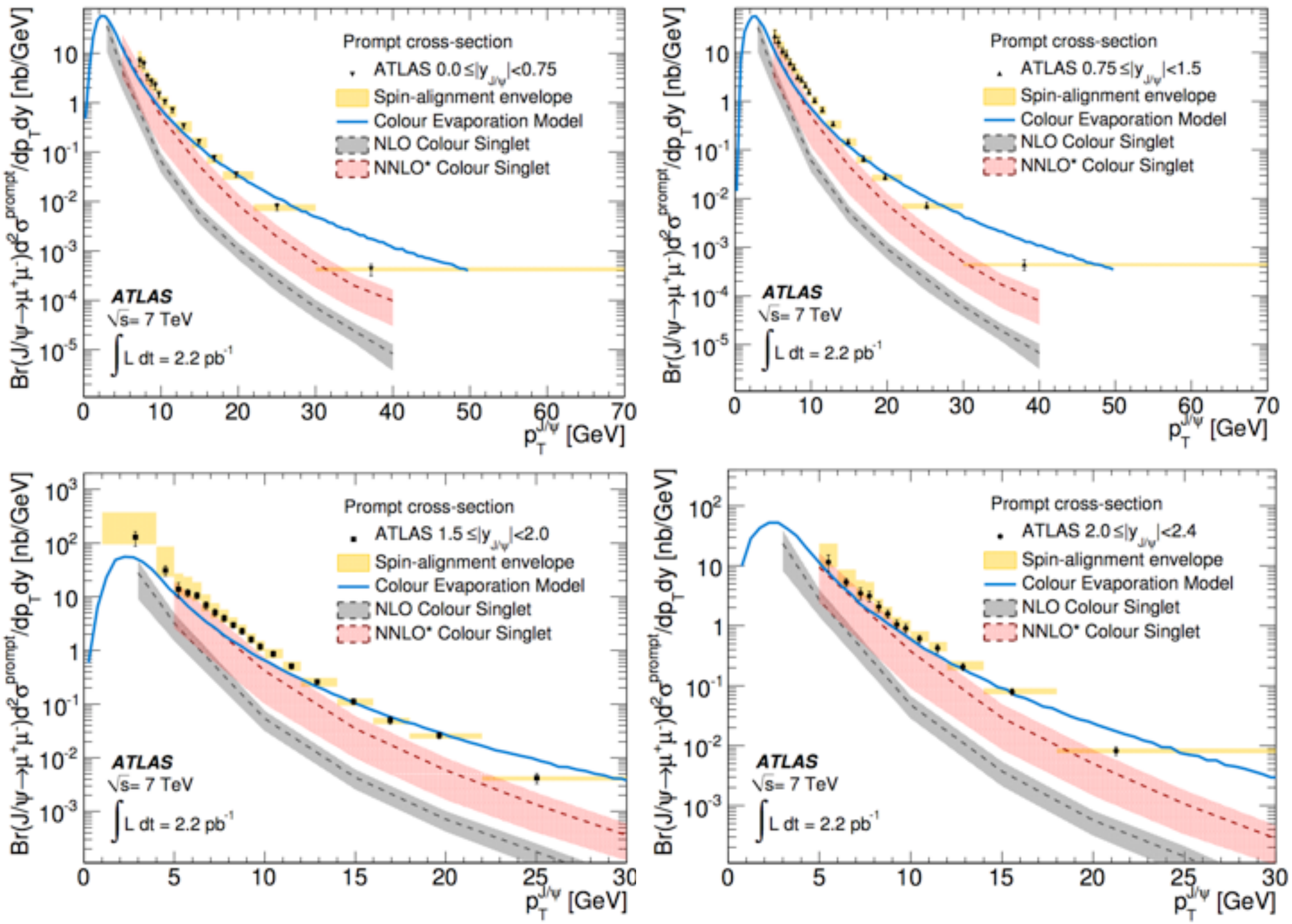
J/ψ: Non-prompt Cross-section

- Non-prompt cross-section agrees well with FONLL predictions



J/ψ: Prompt Cross-section

- Contributions from NNLO* compare better than NLO.
- CEM shape not quite in agreement.

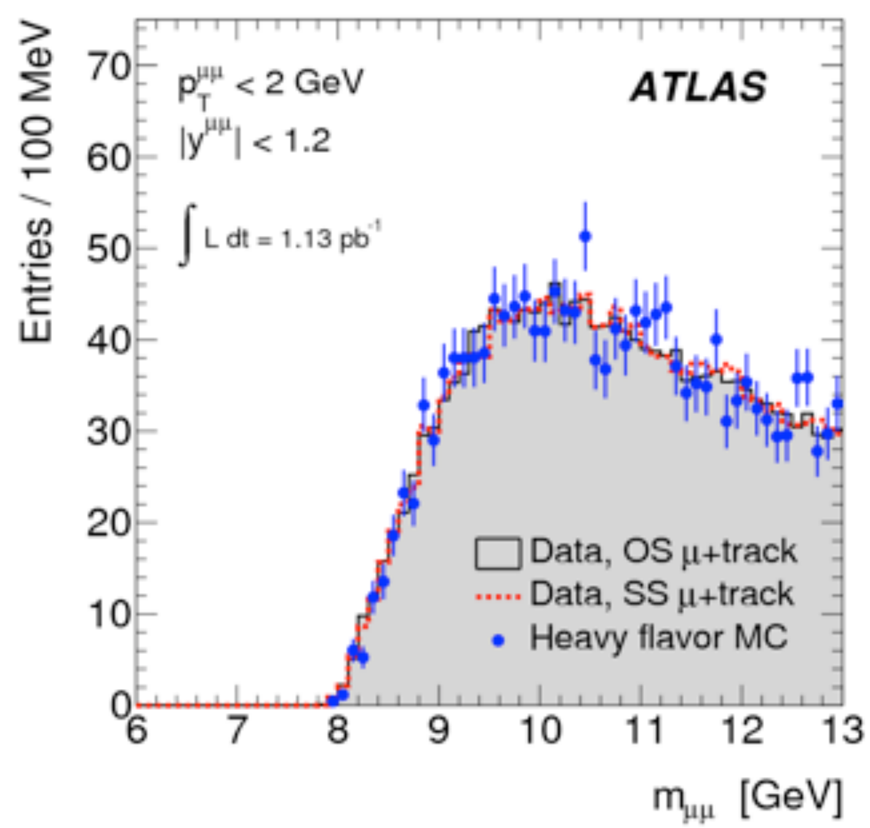


Upsilon: Fiducial Cross-section

- Measurement of differential production cross-section of $\Upsilon(1S)$ in p_T & rapidity.
- Similar procedure as for J/ψ for weight correction
  - Candidate selection: 4 GeV p_T on both muons within $|\eta|<2.5$
- Likelihood fit to $\Upsilon(1,2,3S)$ and background templates

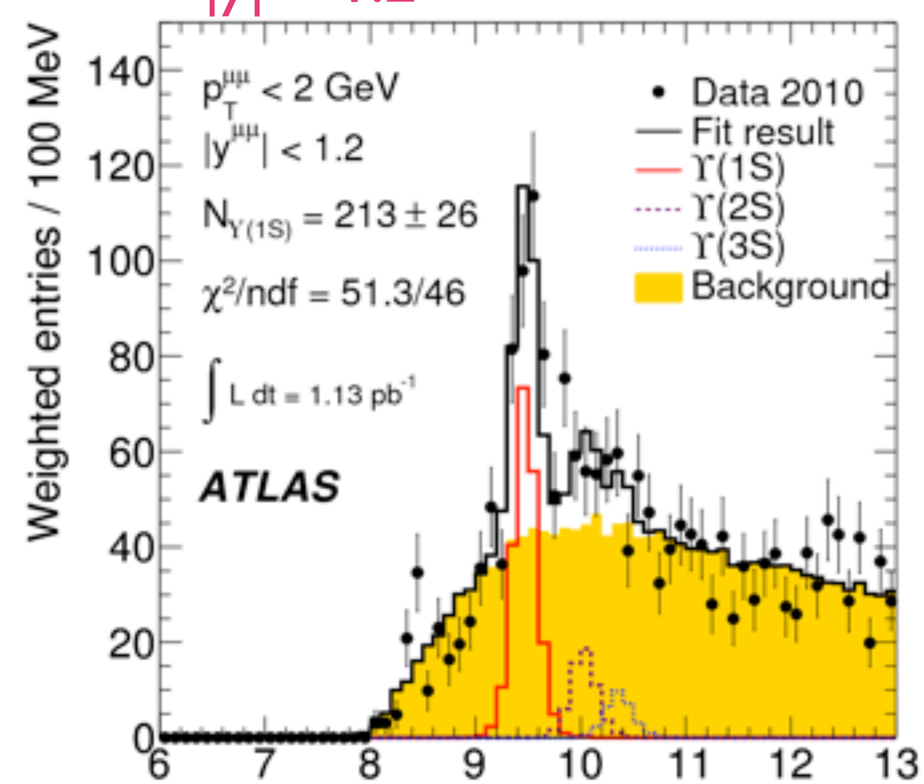
Backgrounds more significant than in J/ψ, larger and more complex!

Use OS/SS μ+trk data and HF MC to model

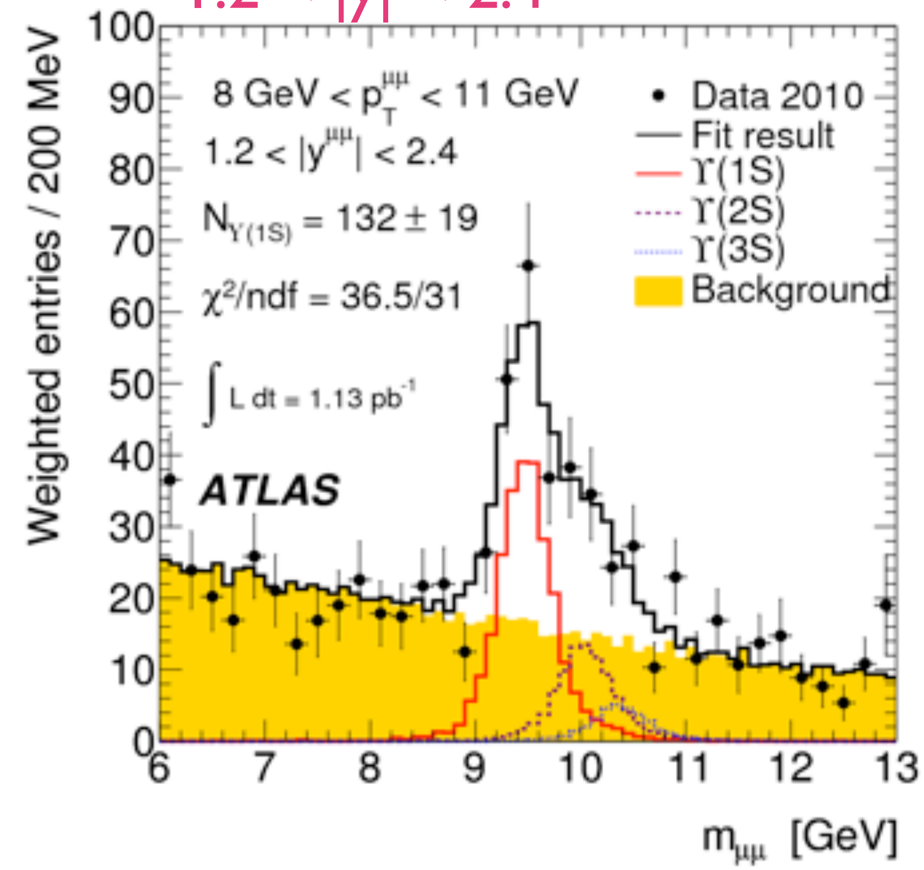


|y| < 1.2

Phys.Lett. B705 (2011) 9-27

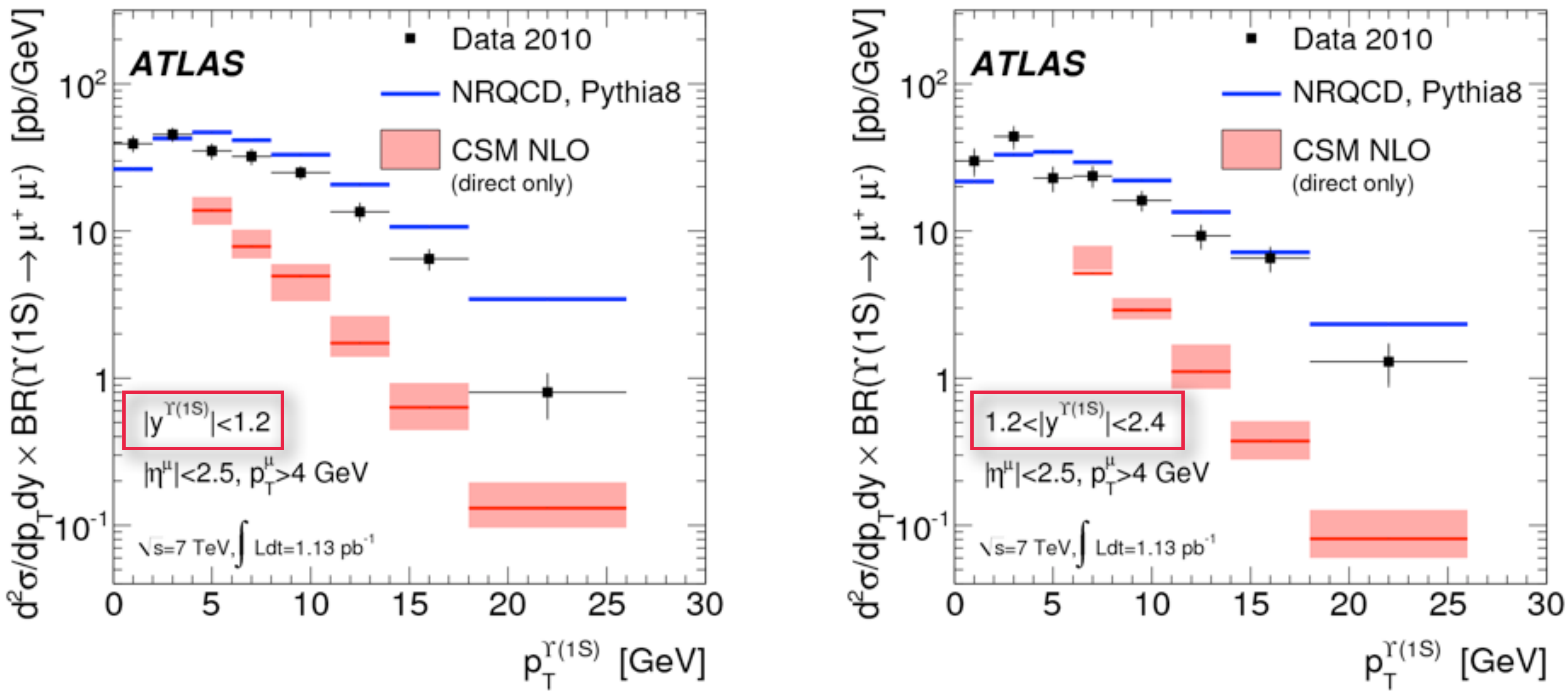


1.2 < |y| < 2.4



ϒ : Fiducial Cross-section Results

- Results are not corrected for acceptance step:
  - defined within muon kinematics (p_T > 4 GeV, |η|<2.5) –
  - removes spin-alignment uncertainty!

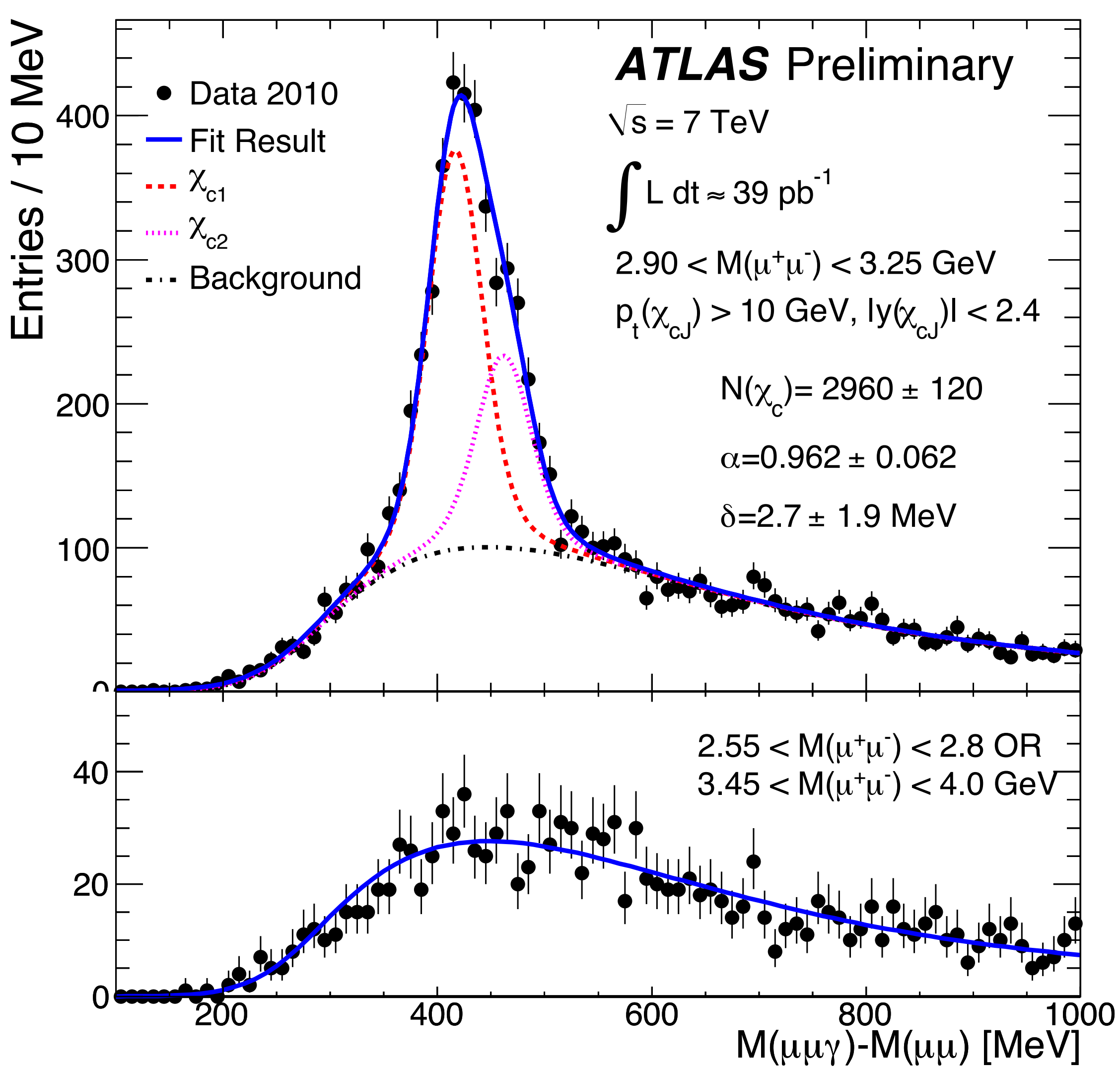


- Colour Singlet Model prediction is low, but contains no feed down from higher order states (NLO only)
- NRQCD shows closer agreement (within ~2x), although shape is not matched.

Spectroscopy: χ states

- Contribution to S-wave charm(bottom)-onium states through feed-down of the P-wave χ_c and χ_b states considerable (~ 1/3)
  - Measurement of these feed-down processes key in overall understanding of quarkonium production
- Experimentally, observe χ_c through its radiative decays to J/ψ.
  - Challenge of reconstructing soft-photon through calorimetry or tracking (via conversions to electron pairs).
- Construct the Mass difference:
  - $\Delta m = m(\mu\mu\gamma) - m(\mu\mu)$
    - Effectively removes contribution of the di-muon resolution.
- χ_c observation using photons identified in electromagnetic calorimeter.
  - Background shape determined from di-muon sideband region.
  - χ_{c0} contribution neglected - small branching fraction through radiative decays.

(ATLAS-CONF-2011-136)



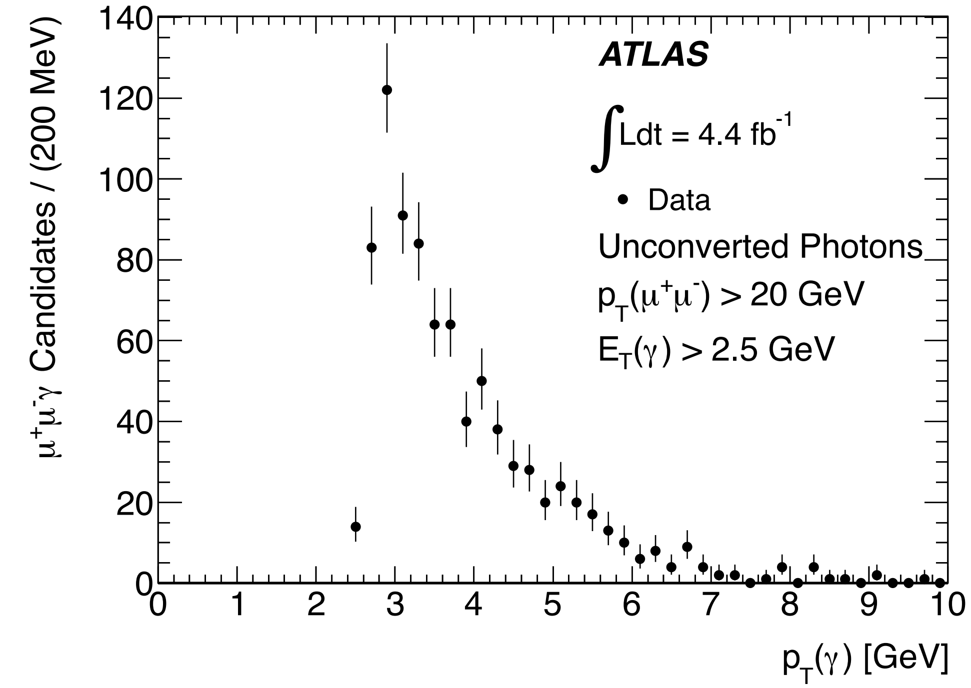
Observation of χ_b system

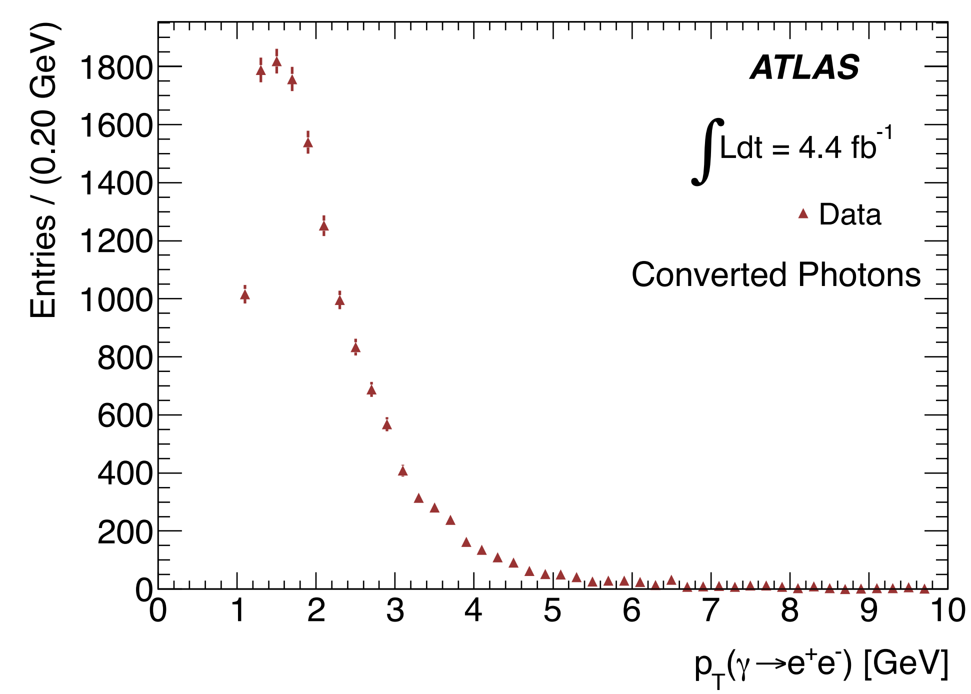
Phys. Rev. Lett. 108 (2012) 152001

- Observation of χ_b system similar to χ_c :
  - Observed through radiative decays to upsilons.
- Upsilons identified through di-muon decay.

- Data from 2011 at 7 TeV, corresponds to 4.4 fb^{-1}.
  - Events required to pass a suite of single or di-muon triggers.

- Photons identified through both:
  - Calorimetric measurement:
    - High efficiency
    - Threshold reconstruction energy 2.5 GeV.
  - Tracking-based through conversions ($\gamma \rightarrow e^+e^-$ in silicon layer of the inner detector)
    - Small probability(conversion) x reco. eff.
    - Lower threshold p_T >1 GeV.
- Photons not compatible with originating from di-muon vertex rejected.

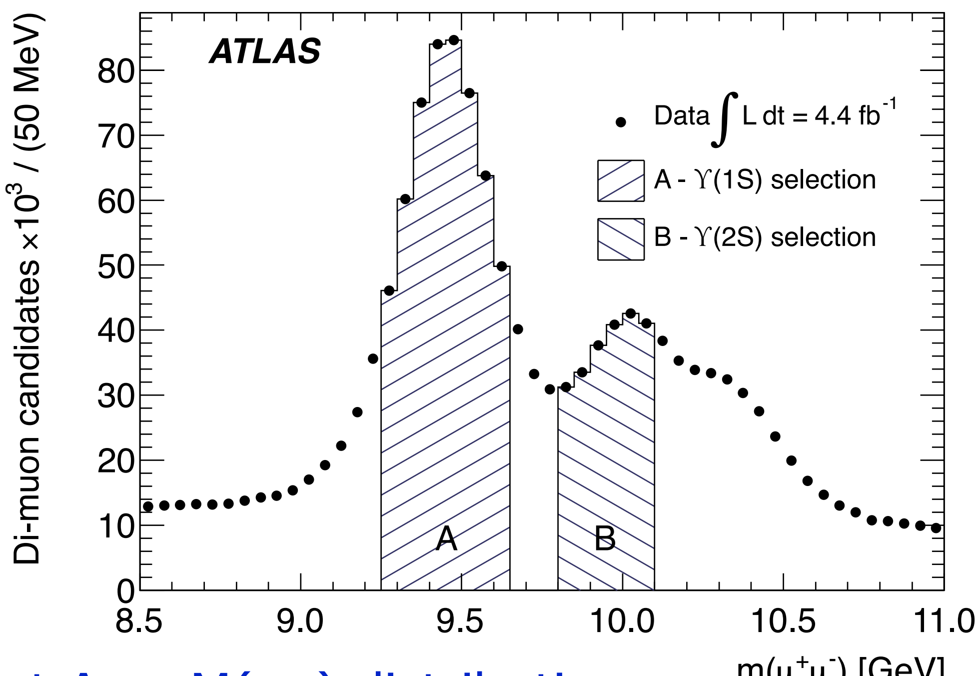




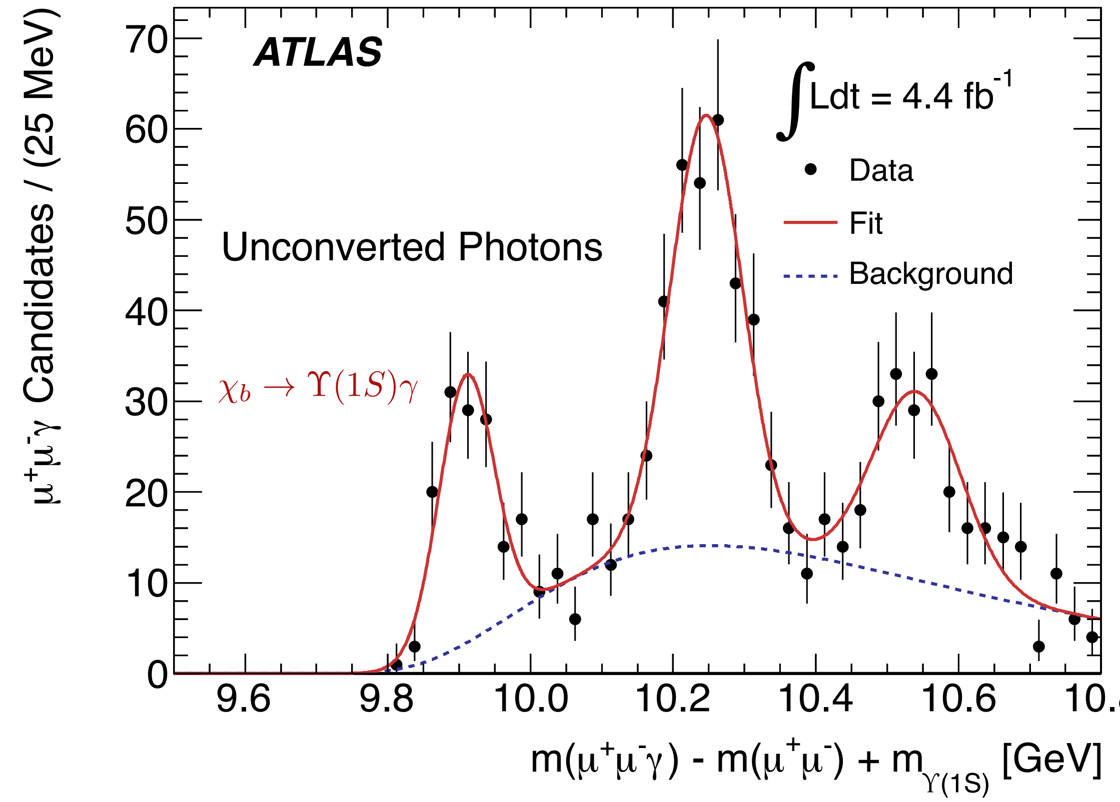
Observation of $\chi_b(3P)$

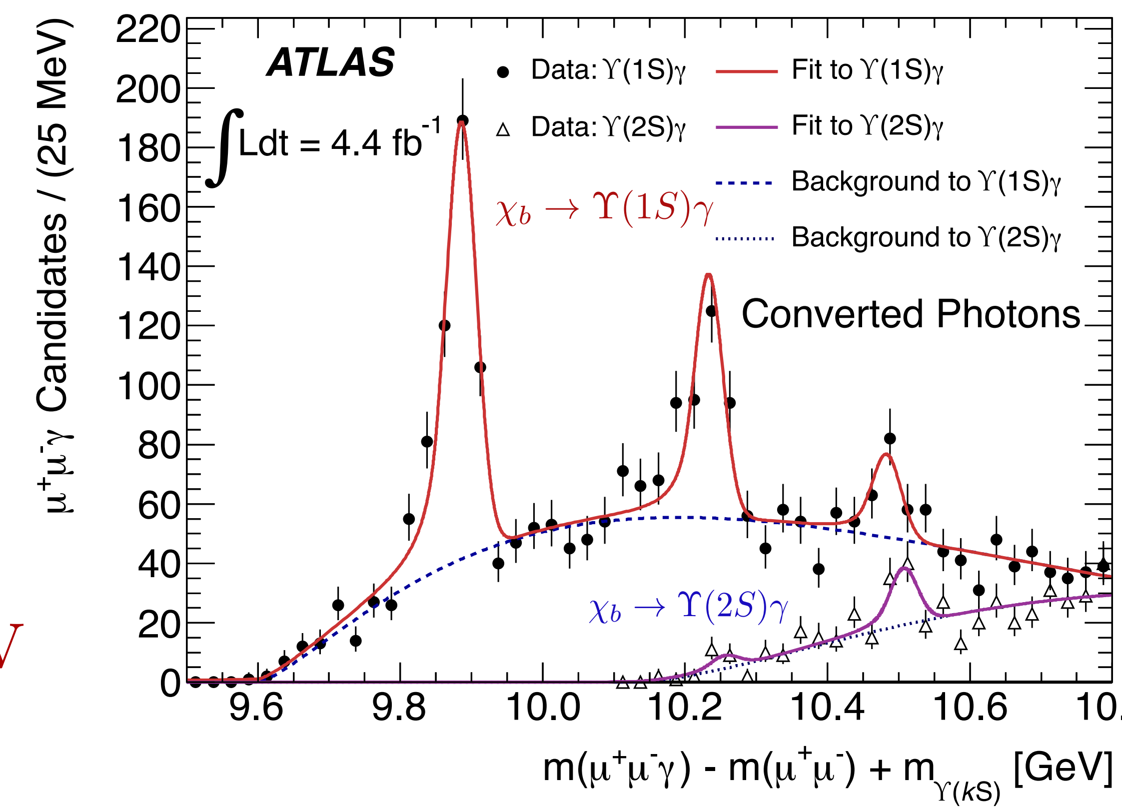
LANCASTER UNIVERSITY

- Di-muon candidates selected around $\Upsilon(1S)$ and $\Upsilon(2S)$:
  - Photon p_T too soft in $\Upsilon(2S)$ transitions to be observed through unconverted photons.
  - Also true for the expected transitions to $\Upsilon(3S)$ (calorimetry and conversions).



- Plot Δm+M(μμ) distribution:
  - $\chi_b(1P)$ and $\chi_b(2P)$ observed.
  - **First observation of new χ_b state.**
  - Interpreted as $\chi_b(3P)$.
- Mass barycentre is estimated to be (using conversions):
  - $M(3P) = 10.530 \pm 0.005\,(\mathrm{stat.}) \pm 0.009\,(\mathrm{syst.})$ GeV
- Hyperfine structure to be resolved.





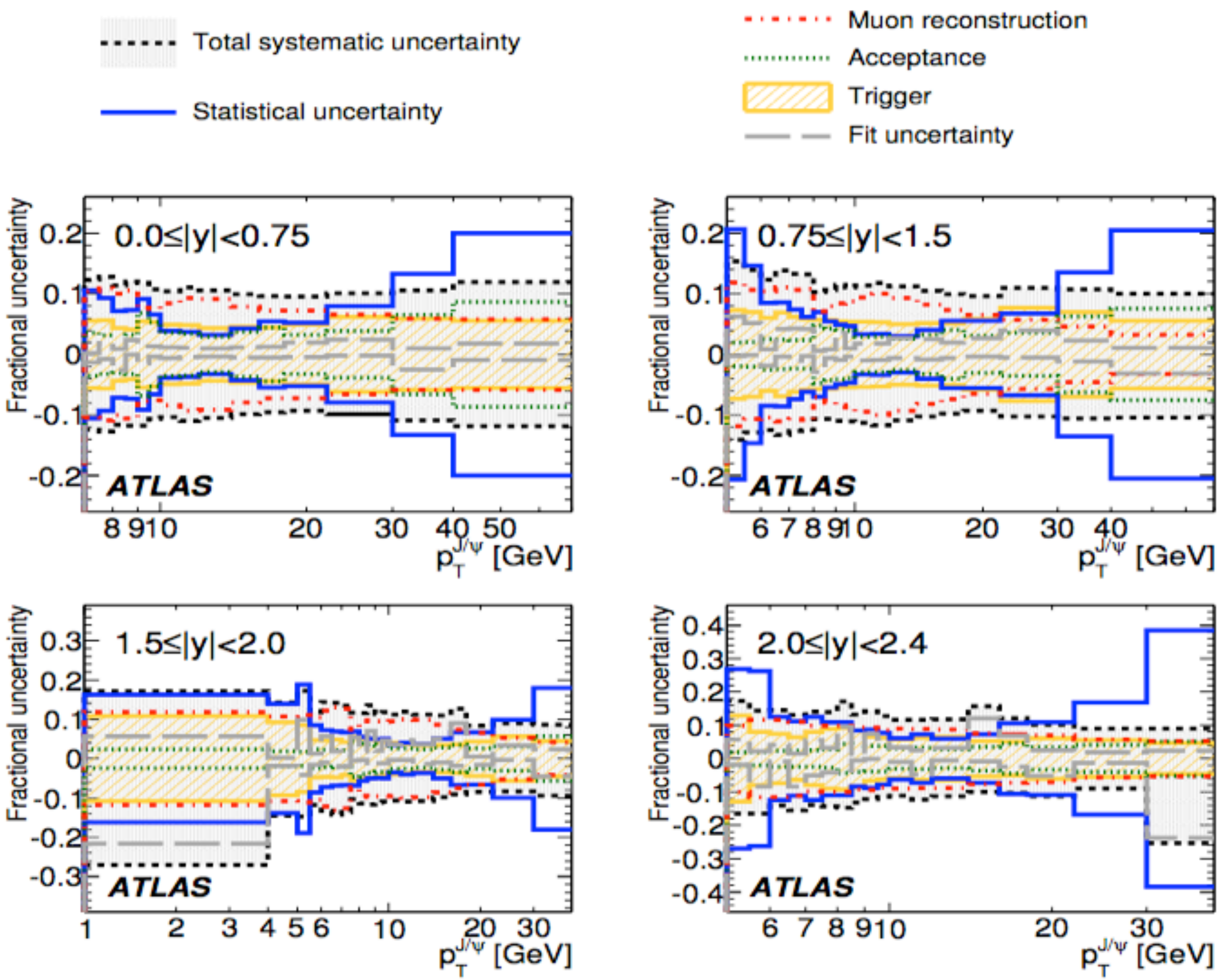
Conclusions

- Heavy Quarkonium continues to challenge current understanding:
  - Data and theory gap reducing.
- ATLAS has measured:
  - J/ψ inclusive, prompt and non-prompt differential cross-sections.
  - $\Upsilon(1S)$ fiducial differential cross-section.
- χ_c observed through radiative decays to J/ψ .
- $\chi_b(1P)$ and $\chi_b(2P)$ observed through radiative decays to $\Upsilon(1S)$.
- First observation of $\chi_b(3P)$ state decaying to $\Upsilon(1S)$ and $\Upsilon(2S)$:
  - Each of the $\Upsilon(1,2,3S)$ states now subject to feed-down contributions.
- **Prompt production of $\psi(2S)$, only state not contaminated by feed-down.**
- Synergy across LHC experiments exploring low-pT and extending into highest pT ranges across rapidities.
- Spin-alignment measurement will reduce a dominant source of uncertainty.
- These results, and forthcoming ATLAS measurements of:
  - $\Upsilon(1,2,3S)$, and $\psi(2S)(\rightarrow \mu\mu \text{ and } \rightarrow \mu\mu\pi\pi)$ production cross-sections,
  - $\psi(2S)$ to J/ψ production ratios, di-onia production and cross-sections of $\chi_{b/c}$ systems,
- will provide important input on the underlying mechanisms of Heavy Quarkonium near the strong decay threshold.

Backup

J/ψ: Sources of Uncertainties

- Sources of systematic uncertainty, and total uncertainties in each analysis bin (excluding spin-alignment)

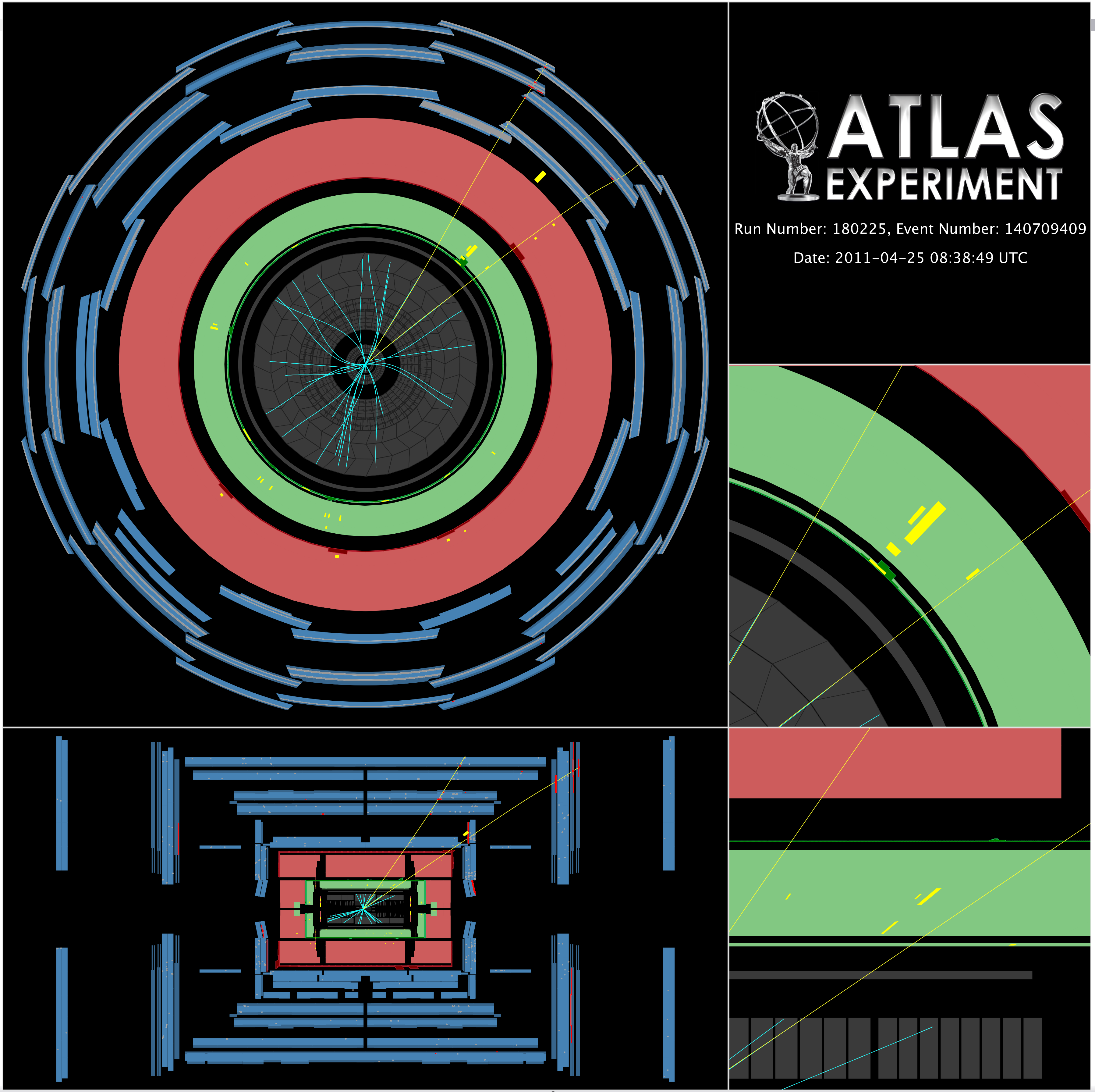


χ_b Event Selection

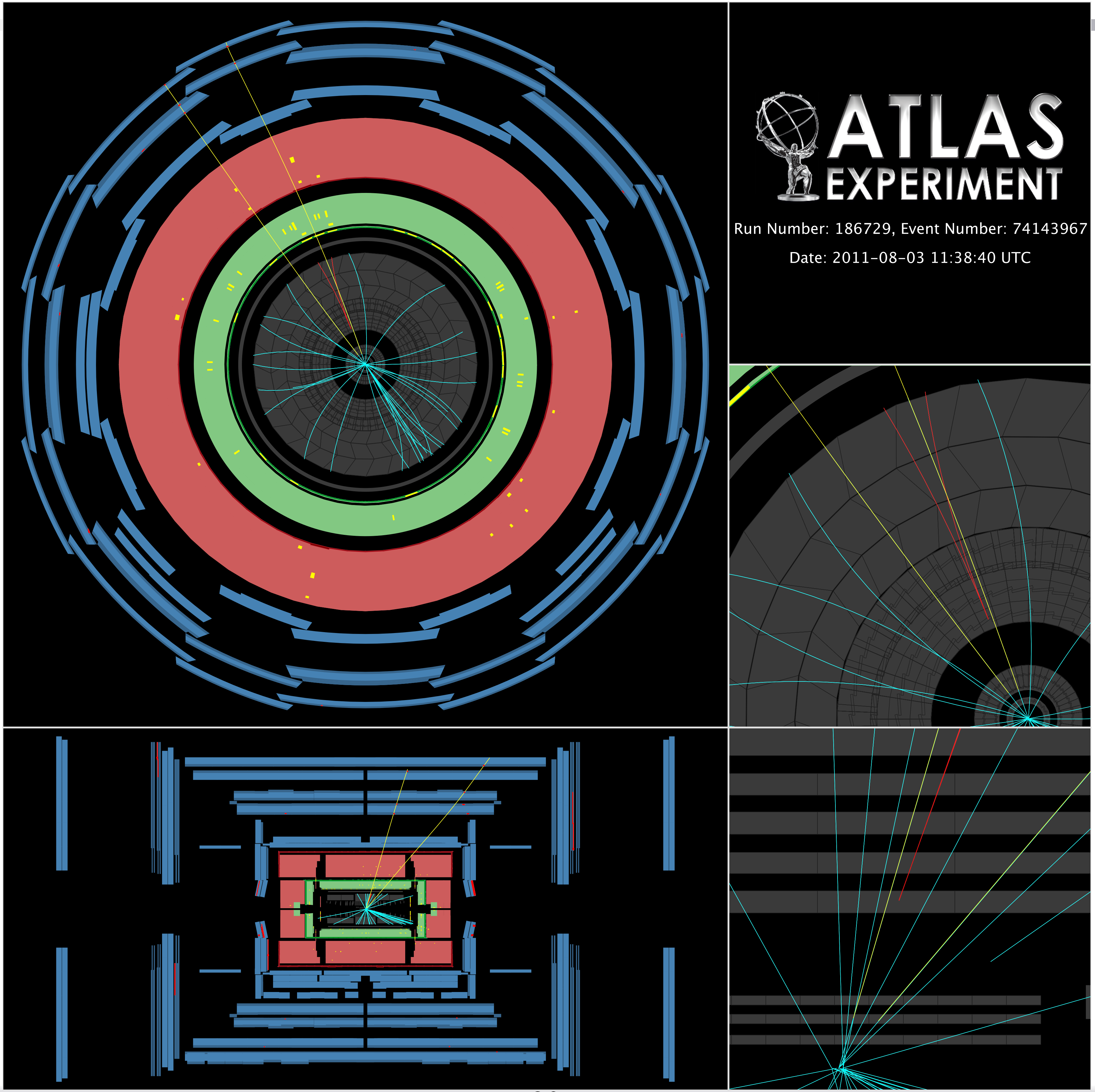
LANCASTER UNIVERSITY

- $p_T(\mu)>4$ GeV
- $|\eta| < 2.3$
- Muons identified using muon spectrometer
  - Track parameters from inner detector
- Oppositely-charged di-muon pairs forming a good vertex compatible with Upsilon mass.
- $p_T(\mu\mu)>12$ GeV (conversion)
- $p_T(\mu\mu)>20$ GeV (calorimetry)
- $|y|<2.0$
- **Photons identified through calorimetry:**
  - $E_T(\gamma) > 2.5$ GeV
  - $|\eta(\gamma)|<2.37$
  - Correction applied to photon to point back to $\mu\mu$-vertex
- **Photons identified through conversions:**
  - $p_T(\gamma) > 1$ GeV, $p_T(e)>0.5$ GeV
  - $|\eta(\gamma)|<2.5$
  - Radius of Conversion > 40 mm, P(conv) > 0.01
  - Unsigned Impact Parameter (3D) cut < 2mm to reject photons not compatible with Upsilon vertex.

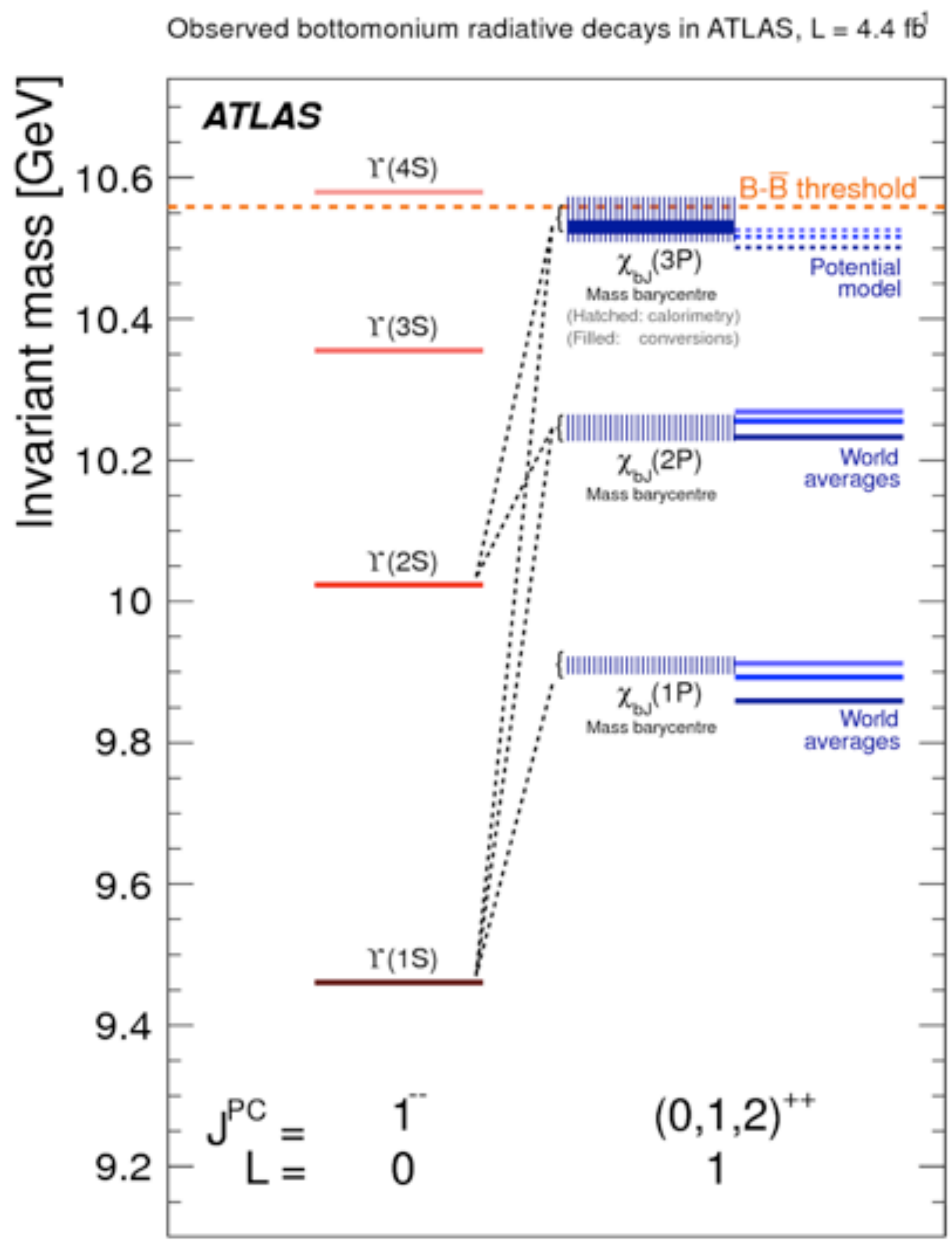
$\chi_b(3P)$ Calorimetry Candidate



$\chi_b(3P)$ Conversion Candidate

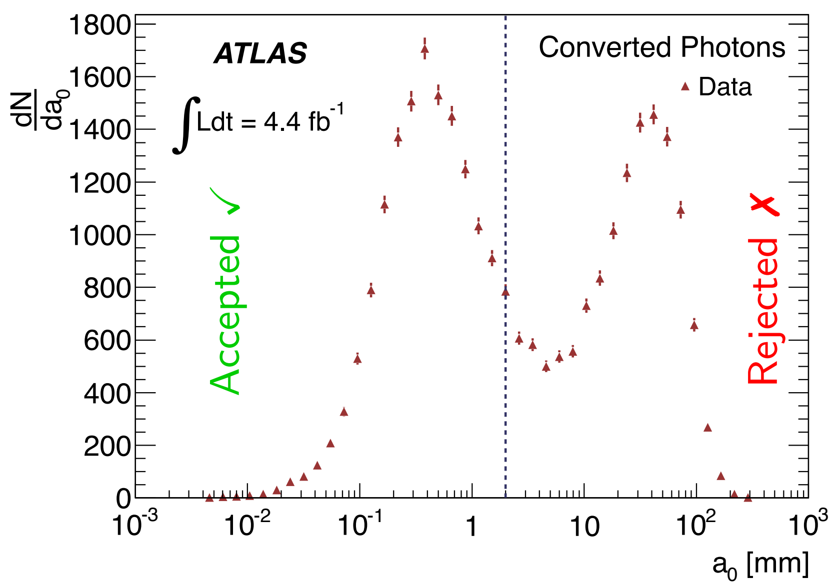


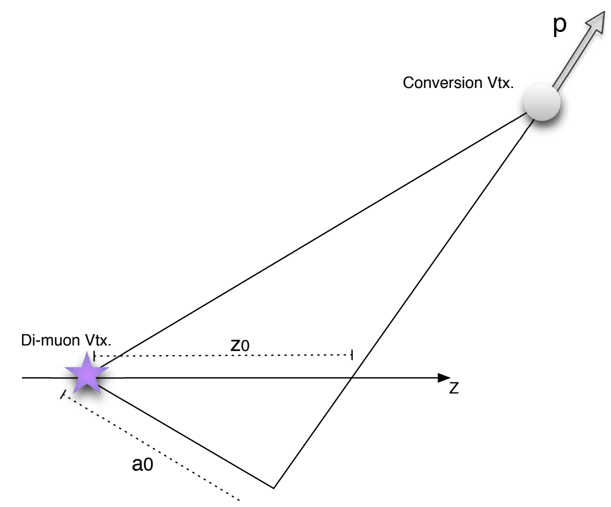
Bottomonium Spectroscopy through radiative decays in ATLAS



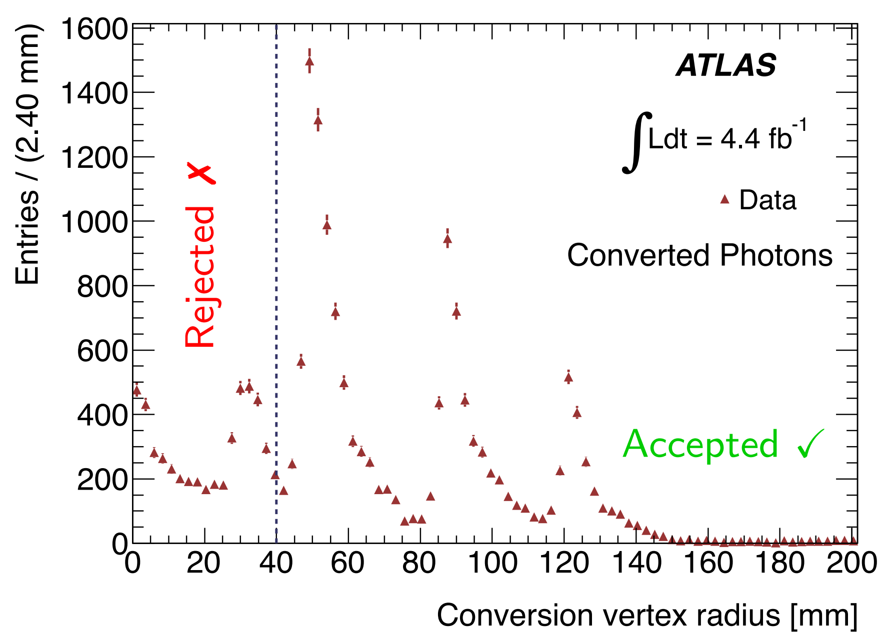
Selections

The 3D impact parameter of the converted photon with respect to the di-muon vertex, a_0, is a powerful variable which can be used to select photons associated with the di-muon vertex:





- $a_0 < 2$ mm is required to **reject photon combinatorics not compatible with having originated from the di-muon vertex**
- The χ^2 probability of the conversion vertex fit is required to be greater than 0.01



A. Chisholm

Systematics: Unconverted

An extended unbinned maximum likelihood fit is performed to the $m\left(\mu^+\mu^-\gamma\right) - m\left(\mu^+\mu^-\right) + m^{PDG}_{\Upsilon(1S)}$ distribution to extract an estimate of the $\chi_b(3P)$ mass barycentre:

Fit Model

- **Signal:** Single Gaussian for each $\chi_b(nP)$ peak, each with a free mean value and width
- **Background:** Described by $\exp\left(A \cdot (\Delta M) + B \cdot (\Delta M)^{-2}\right)$ where A and B are free parameters

Assigned Systematic Uncertainties

- Unconverted photon energy scale uncertainty (estimated at $\pm 2\%$ of the ΔM position)
- Modelling of the background distribution (estimated from refitting with various alternative models)

	Fitted Mass (MeV)
$\chi_b(1P)$	9910 ± 6 (stat.) ± 11 (syst.)
$\chi_b(2P)$	10246 ± 5 (stat.) ± 18 (syst.)
$\chi_b(3P)$	10541 ± 11 (stat.) ± 30 (syst.)

The statistical significance of third signal remains greater than 6σ with each systematic variation

A. Chisholm

Systematics: Converted

Fit Model:

- As the $J = 0$ branching fraction is significantly smaller than for $J = 1, 2$ its contribution can be neglected
- The $\chi_b(nP)$ state is therefore modelled by **two Crystal Ball (CB)** functions to describe the low-mass Bremsstrahlung tail
- For $n = 1, 2$, the masses of the individual J=1,2 states are fixed to the known PDG values, and for n=3 the hyperfine splitting is fixed to the theoretically predicted value of 12 MeV
- The relative normalisations of the J=1 and J=2 components are fixed to be equal
- A free parameter λ, common to all the peaks, accounts for additional energy losses and appears in the form $\overline{\Delta m} \cdot \lambda$
- The background is modelled by $(\Delta m - q_0)^{\alpha} \cdot \exp\{(\Delta m - q_0) \cdot \beta\}$

Assigned Systematic Uncertainties:

- Vary relative $J = 1, 2$ signal normalisation by ± 0.25 (or left free in fit): ± 5 MeV
- Alternative signal and background models: ± 5 MeV
- Decoupled fits to the $\Upsilon(1S)$ and $\Upsilon(2S)$ distributions: ± 5 MeV
- Individually releasing constraints to the PDG values for the $\chi_b(1P)$ and $\chi_b(2P)$ masses: ± 3 MeV

A. Chisholm