Onia production at ATLAS

Takashi Matsushita
on behalf of the ATLAS Collaboration

Kobe University

Takashi.Matsushita@cern.ch

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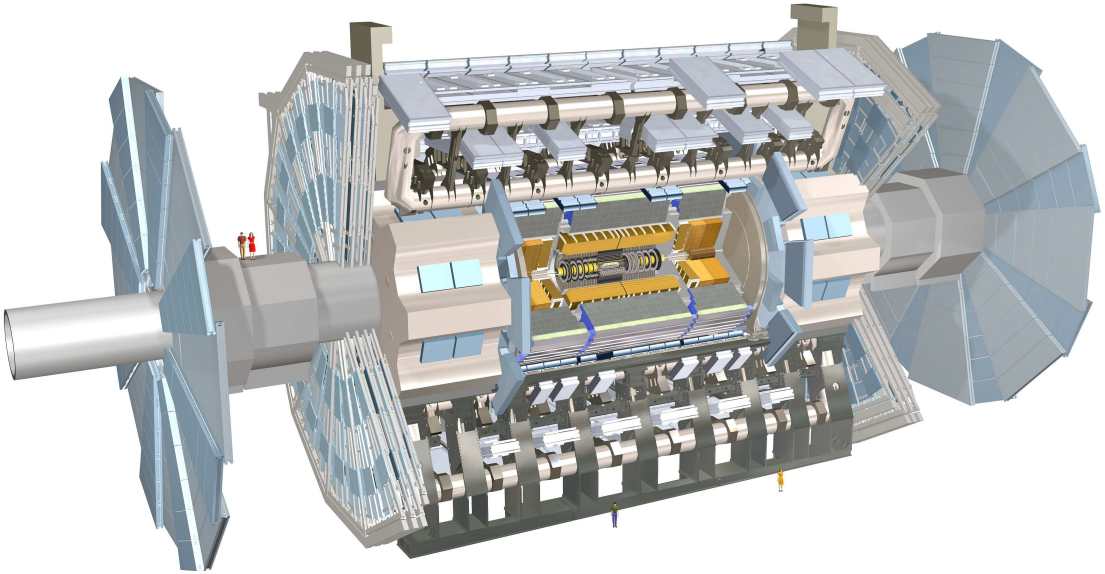
ATLAS detector

Inner detector

- $|\eta| < 2.5$, Solenoidal B-field $= 2$ T
- Silicon: pixels, strips
- Transition Radiation Tracker
- $\sigma(p_T)/p_T \sim 3.4\times10^{-4} p_T \oplus 0.015$

Muon spectrometer

- precision chambers $|\eta| < 2.7$
- trigger chambers $|\eta| < 2.4$
- Toroidal B-field, average ~ 0.5 T
- $\sigma(p_T)/p_T \sim 10\%\ p_T$ for 1 TeV track



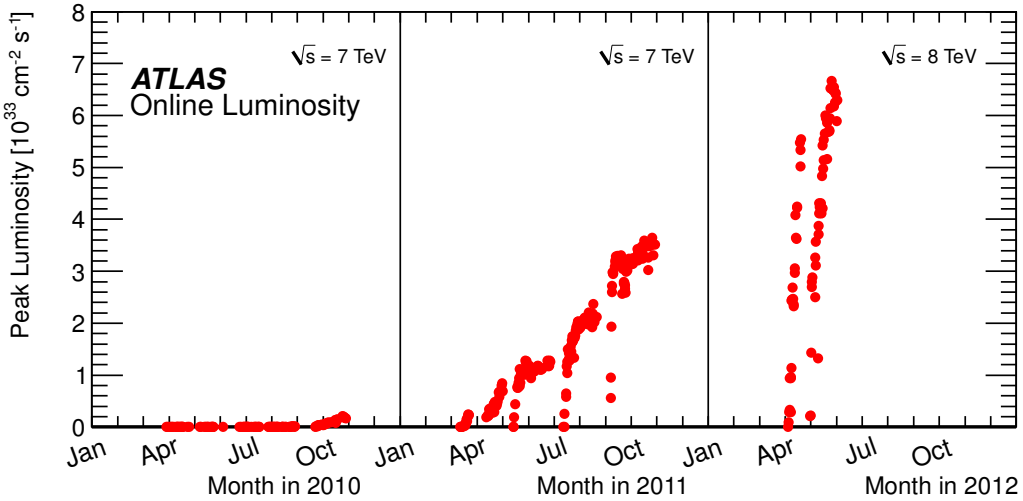
- length: 44 m
- height: 25 m
- weight: 7000 tons
- $\sim 10^8$ electronic channels

Three level trigger system

- Level 1: hardware trigger with muon and calorimeter information $\sim$75 kHz
- Level 2: software trigger to confirm level 1 trigger decision $\sim O(1)$ kHz
- Event Filter: event selection with more complex algorithm $\sim O(100)$ Hz

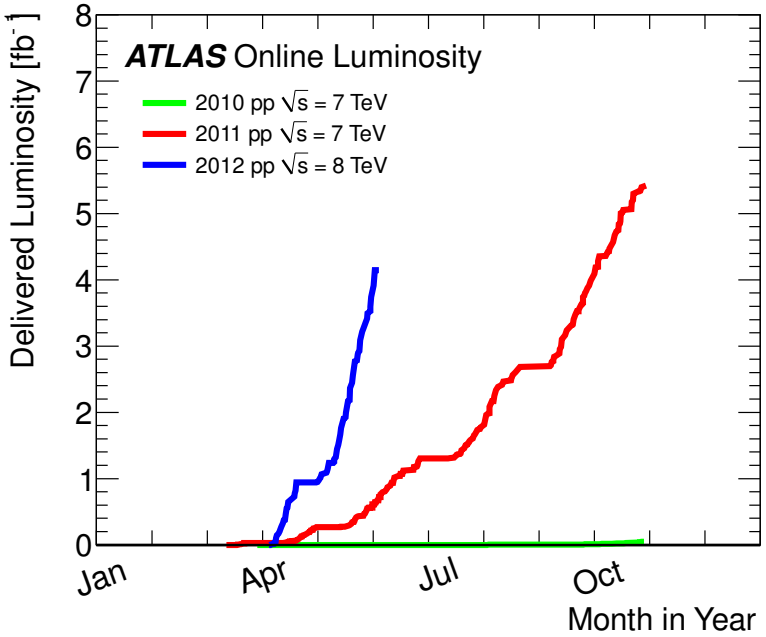
Data sample

- 2010: peak $\mathcal{L} = 2.1 \times 10^{32}$ cm^{-2}s^{-1}
- 2011: peak $\mathcal{L} = 3.7 \times 10^{33}$ cm^{-2}s^{-1}
- 2012: peak $\mathcal{L} = 6.7 \times 10^{33}$ cm^{-2}s^{-1}



LHC is performing better and better

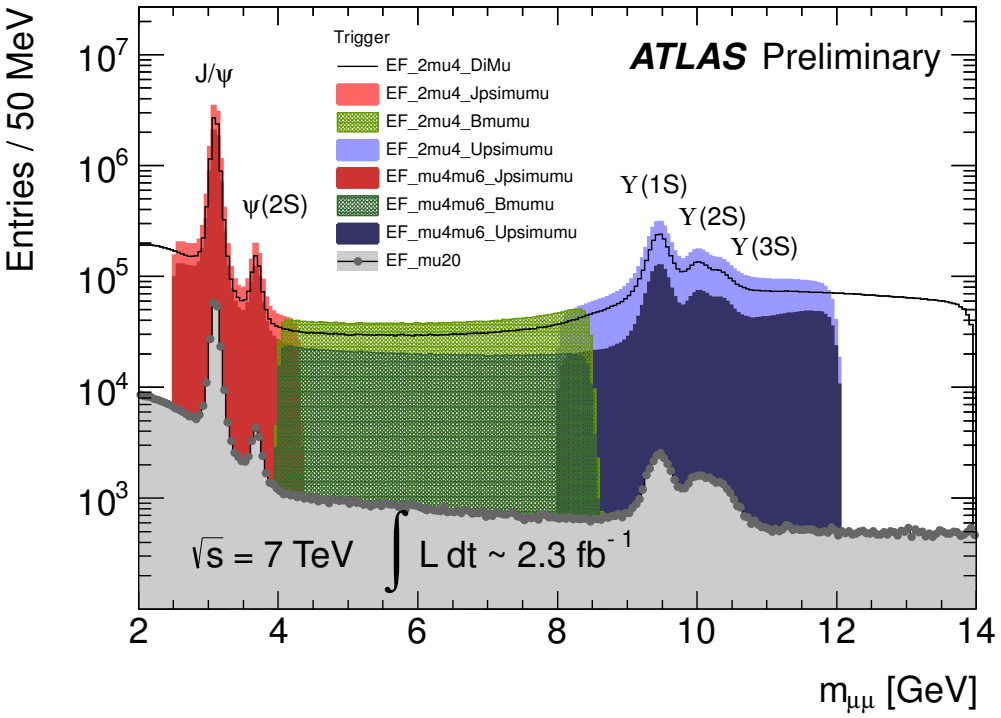
- 2010: $\int \mathcal{L}dt = 0.045$ fb^{-1} $\sqrt{s} = 7$ TeV
- 2011: $\int \mathcal{L}dt = 5.3$ fb^{-1} $\sqrt{s} = 7$ TeV
- 2012: $\int \mathcal{L}dt = 3.9$ fb^{-1} $\sqrt{s} = 8$ TeV



Plenty of data available

Di-muon triggers for B-physics programme

- ATLAS has a B-physics programme with low p_T dimuon signatures
  - Onia studies: $J/\psi \to \mu\mu, \Upsilon \to \mu\mu$
  - CP violation/mixing: $B_s \to J/\psi\phi$
  - Rare B decays: $B_s \to \mu\mu$
- Trigger on low p_T dimuon essential
  - 2 muons at Level 1 HW trigger
  - Confirmation with SW trigger
  - Performs vertex fit and mass cut
- "2mu4" triggers unprescaled in 2011
  - A large number of events recorded for the B-physics programme

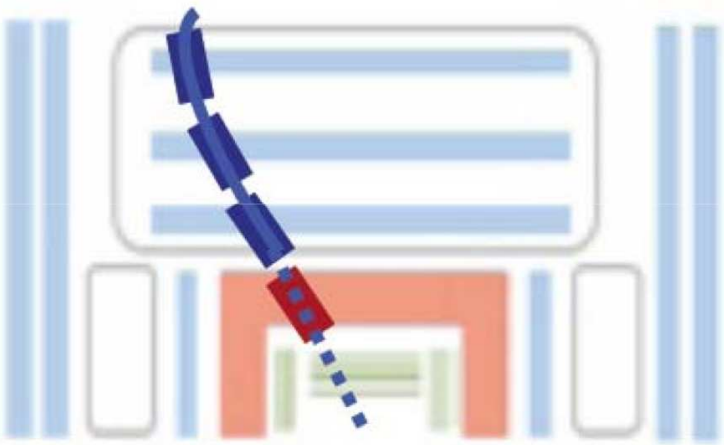


Trigger	Mass range	# of events
2mu4_Jpsimumu	2.5 – 4.3 GeV	14 M
2mu4_Upsimumu	8 – 12 GeV	9.1 M
2mu4_Bmumu	4 – 8.5 GeV	3.7 M

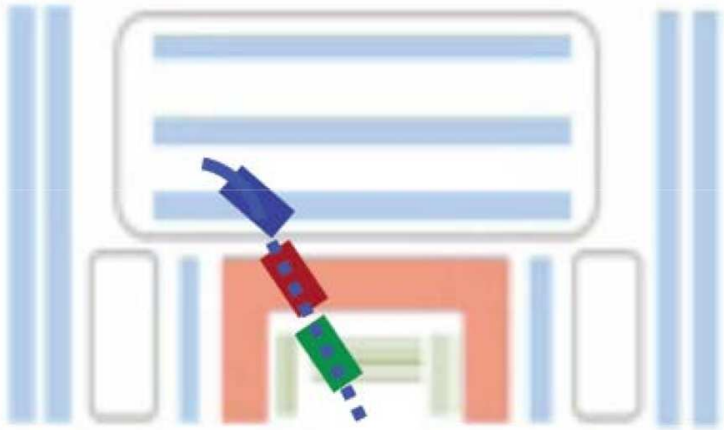
figure and numbers with 2.3 fb^{-1}

Muon reconstruction

Combined muon

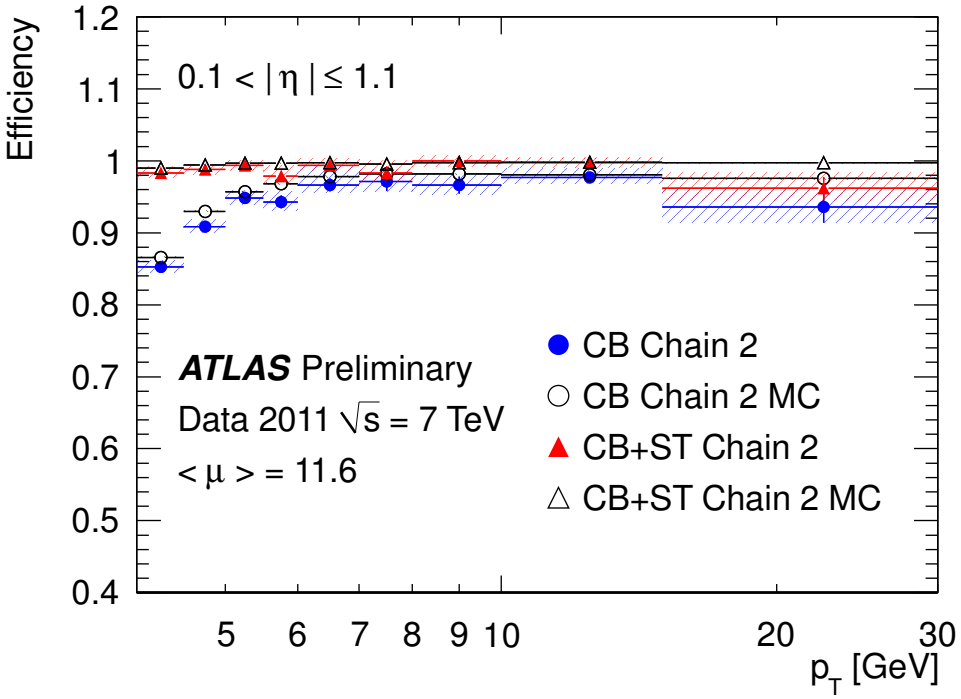


Tagged muon



muon spectrometer | calorimeter | inner detector

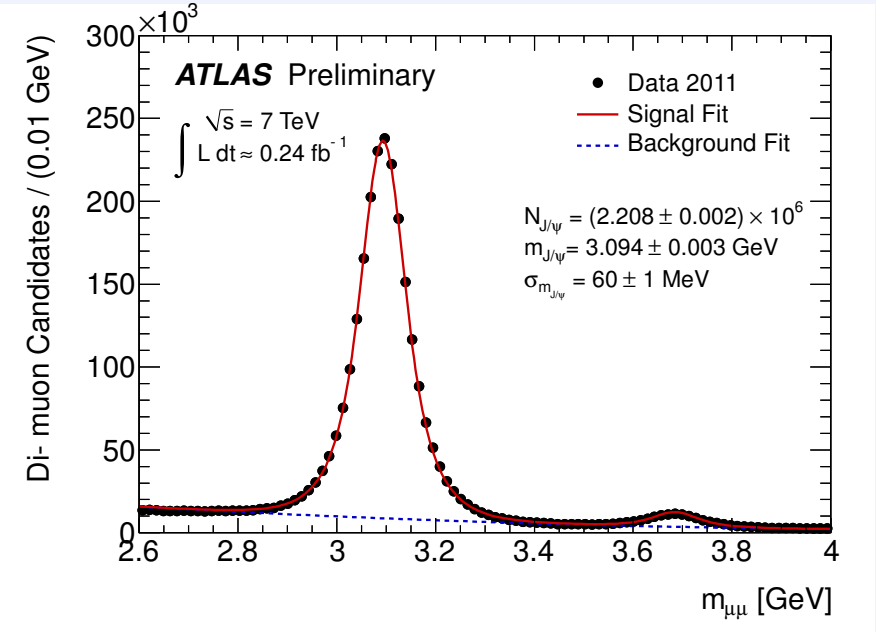
- **Combined**: Muon Spectrometer and Inner Detector track
- **Tagged**: Inner Detector track matched with Muon Spectrometer segment



- Reconstruction efficiency in low-p_T region well described by simulation

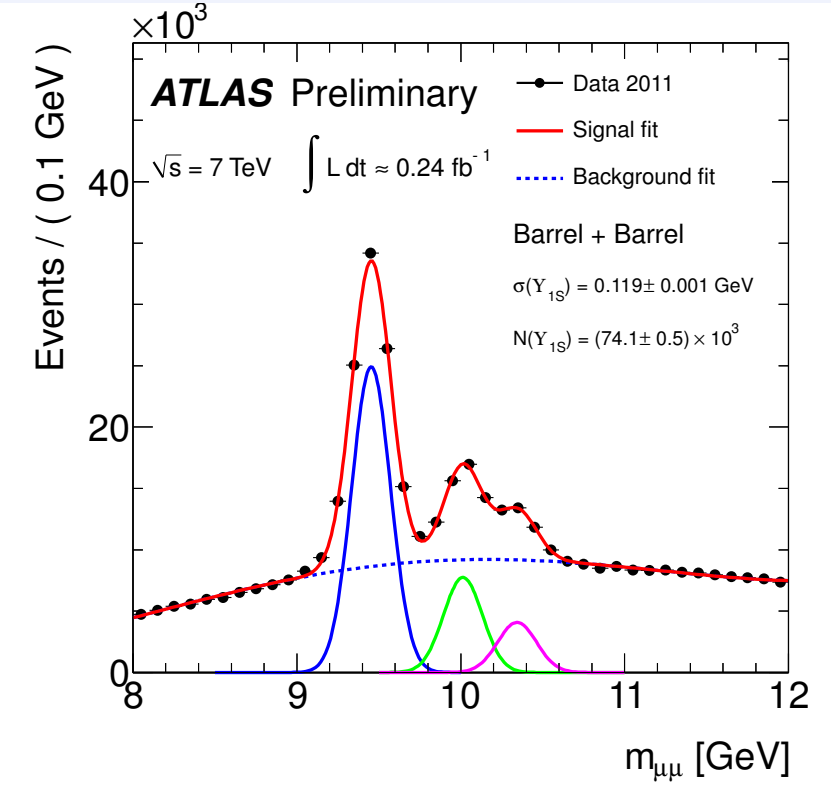
Quarkonia

Charmonium



- J/ψ and $\psi(2S)$ candidates
- Key signatures of B-meson decays through charmonium states; e.g. $B_{d(s)} \to J/\psi\ K(\phi)$
- $\sim$ 2.2 millions J/ψ with 240 pb^{-1}

Bottomonium

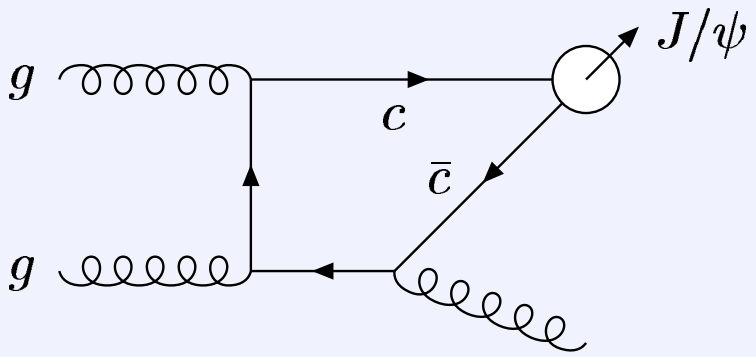


- Three Upsilon states observed in the barrel region
- $\sim$ 74 thousands $\Upsilon(1S)$ with 240 pb^{-1}

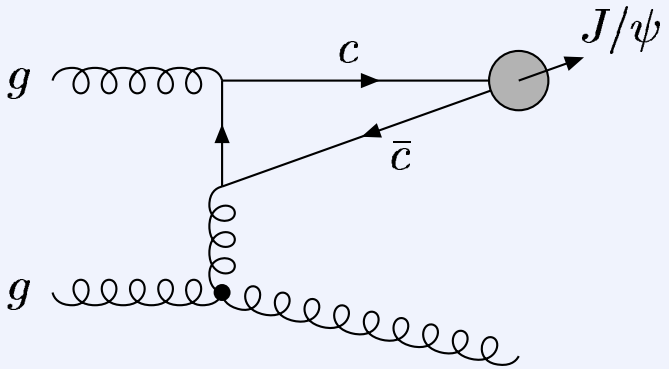
Quarkonium physics

- J/ψ and Υ production at the LHC offers
  - Test of perturbative QCD at new energy regime
    - Higher transverse momentum
    - Wider rapidity range
  - Production mechanism for quarkonium states not fully understood

colour singlet



colour octet



$J/\psi \to \mu\mu$

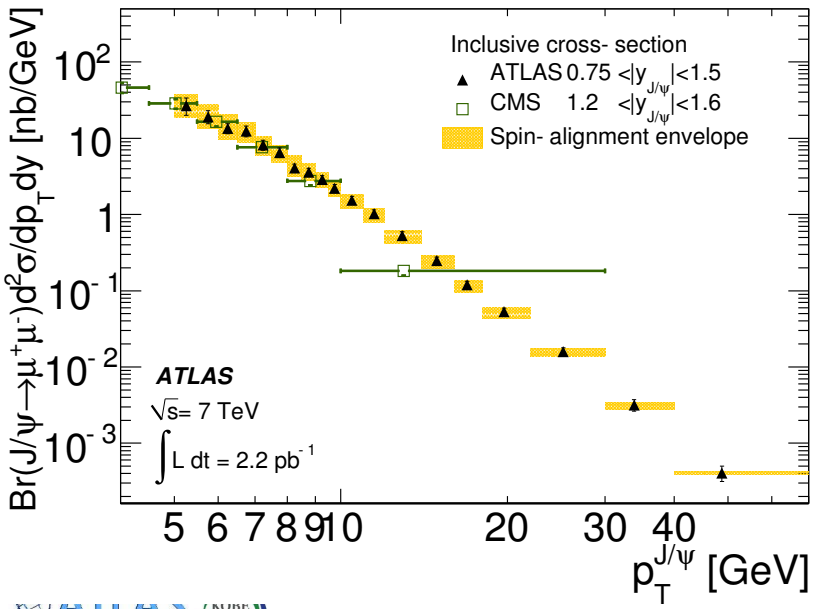
Inclusive cross-section

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

$N_{\text{corr}} = \Sigma w^{-1} \cdot N_{\text{reco}}$

Event weight: $w^{-1} = A \cdot M \cdot \epsilon^2_{\text{trk}} \cdot \epsilon^+_\mu(p^+_T, \eta^+) \cdot \epsilon^-_\mu(p^-_T, \eta^-) \cdot \epsilon_{\text{trig}}$

- Detector Acceptance: with generator level MC
- Bin migration correction: due to finite detector resolution
- Reconstruction efficiencies: with tag-and-probe method using data
- Trigger efficiency: determined from MC and reweighted to data



- Result with 2.2 pb^{-1}
- Example of one rapidity bin (4 in total)
- ■: variation due to 5 extreme spin alignment scenarios
- Agreement with CMS

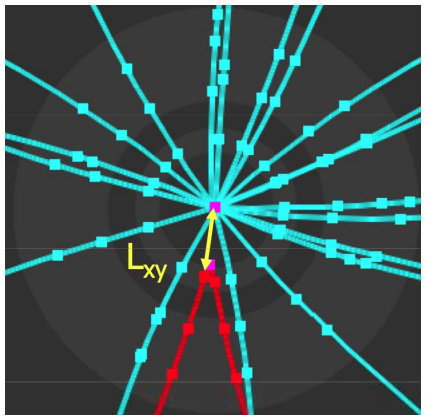
$J/\psi \to \mu\mu$

Measurement of non-prompt fraction

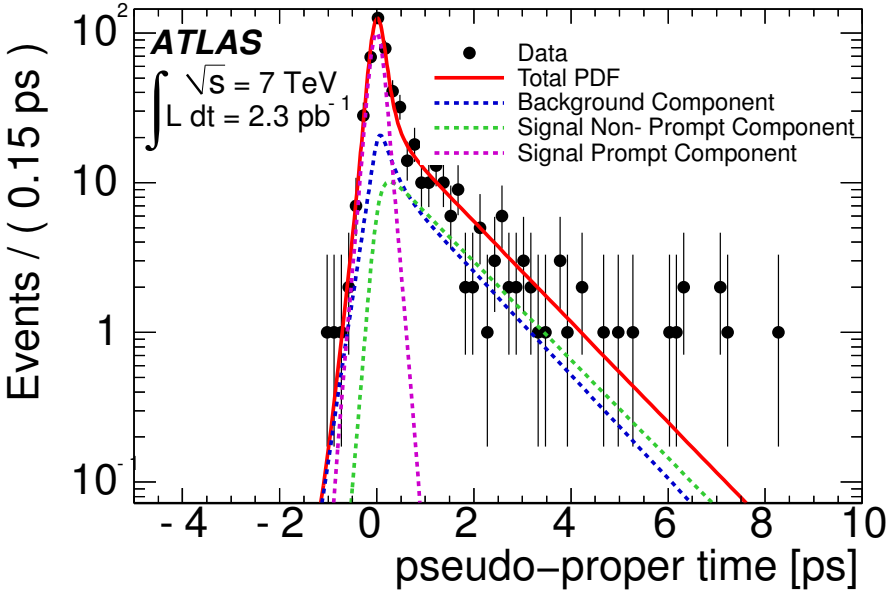
pseudo-proper time

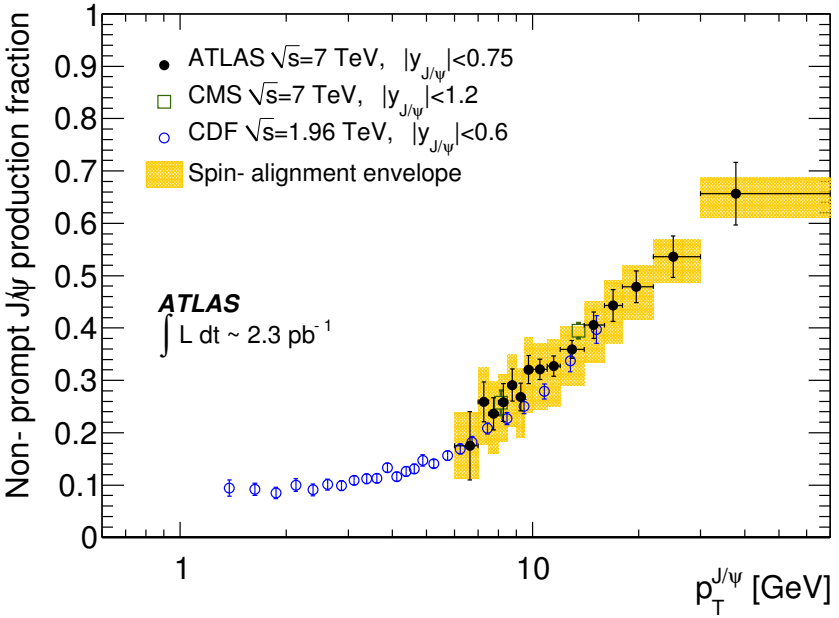
$$\tau = \frac{L_{xy} \cdot m(J/\psi)}{p_T(J/\psi)}$$

- x-y displacement of J/ψ from PV
- Invariant mass of J/ψ
- p_T of J/ψ



- Prompt J/ψ have $\sim$ zero τ while non-prompt J/ψ have positive τ
- Simultaneous fit to mass and τ
- Good agreement with CDF
- Fraction is p_T dependent

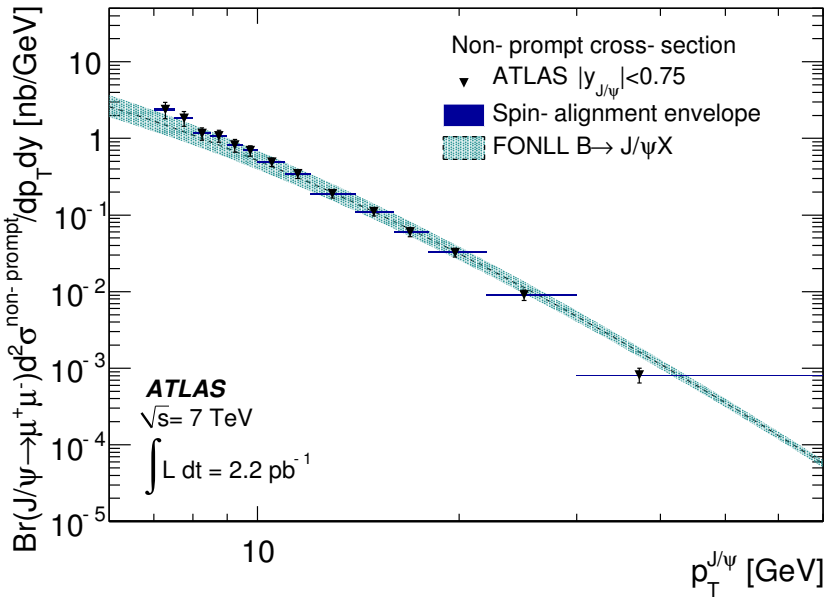




$J/\psi \to \mu\mu$

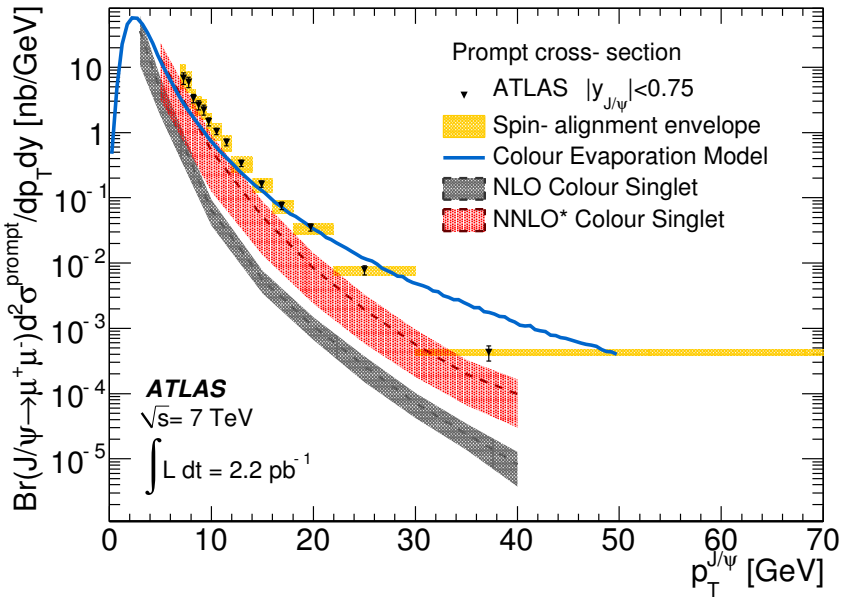
Measurement of non-prompt/prompt J/ψ cross-section

Non-prompt J/ψ cross-section



- Good agreement with prediction by FONLL (Fixed Order Next to Leading Log)

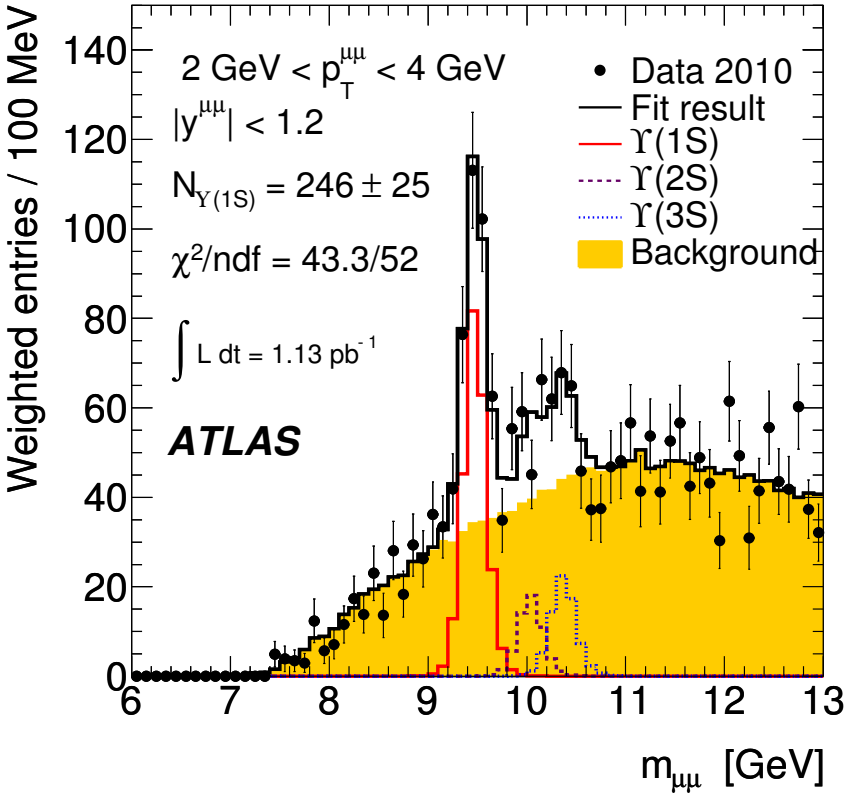
Prompt J/ψ cross-section

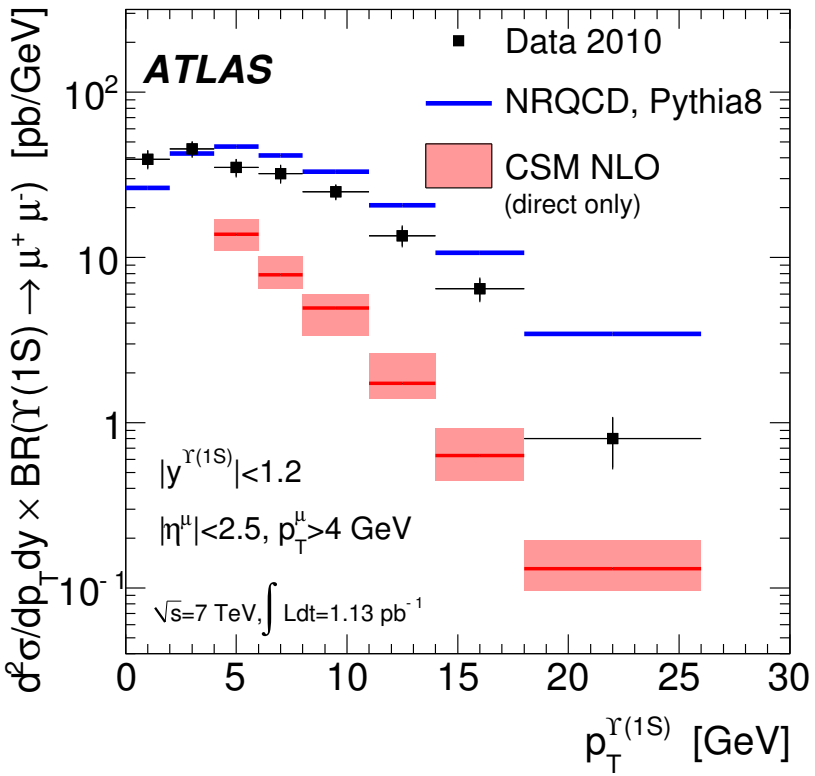


- CEM is not describing shape
- NLO CSM is low but describing shape
- NNLO* CSM describe the data better

$\Upsilon \to \mu\mu$

cross-section





- Result with 1.1 pb^{-1}
- Number of Υ(1S) events from fit

- Implementation of NRQCD in Pythia is higher (lower) than data at high (low) p_T
- CSM prediction at NLO underestimates the data. Feed-down from excited states can only account for up to a factor of two increases in predictions. NNLO corrections need to be large, or leaves more room for colour octet contributions.

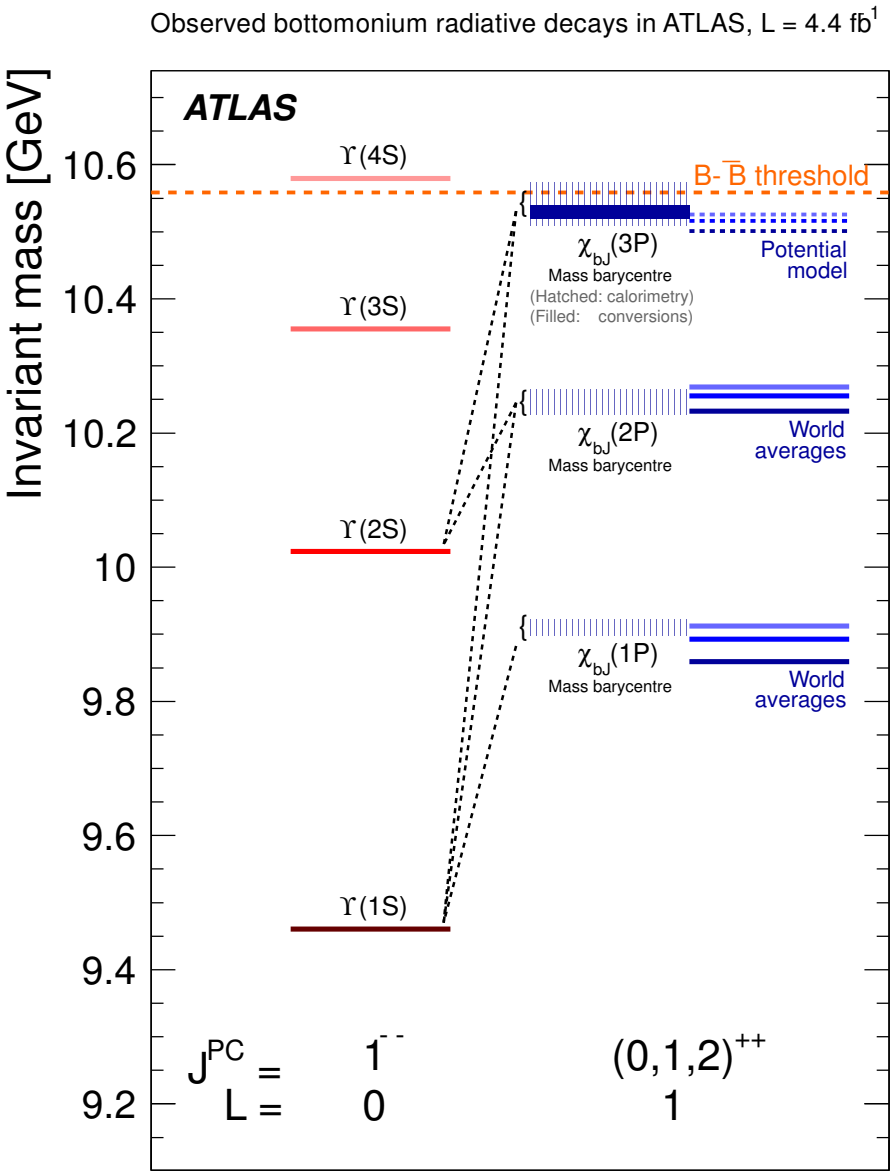
Observation of χ_b(3P)

- χ_c and χ_b represent spin triplet (S=1) P-wave (L=1) states of charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) spectra.

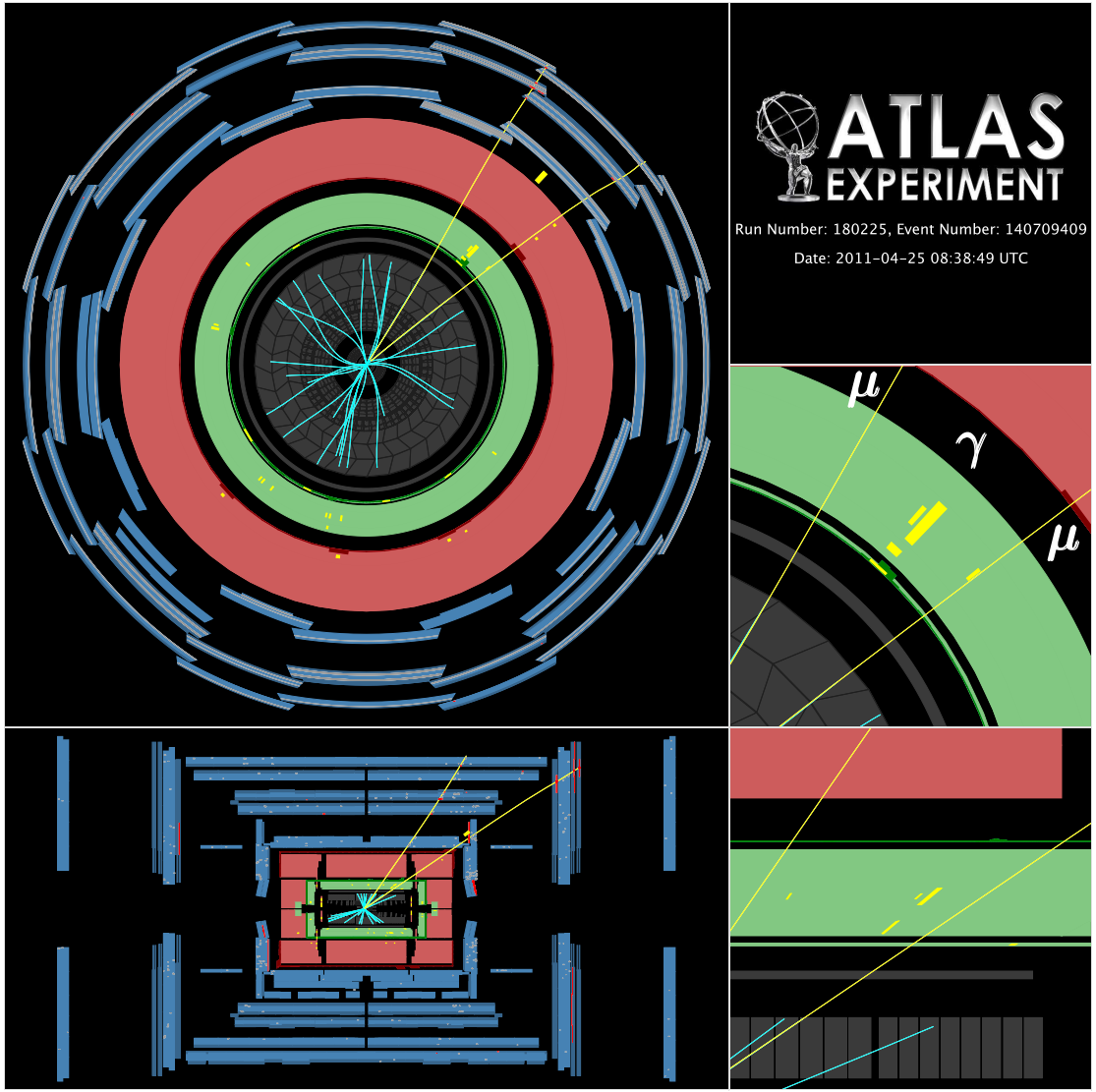
- The χ represents a triplet of states with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$
- Branching fractions for the radiative decays $\chi_b \to \Upsilon\gamma$ are large $O(10\%)$

- χ_b(1P) and χ_b(2P) already observed
- χ_b(3P) also predicted below $B\bar{B}$ threshold.

- Search for χ_b(3P) states in $\chi_b \to \Upsilon\gamma$ decays has been performed. Photon reconstructed either directly in the calorimeter or through conversion to e^+e^-.



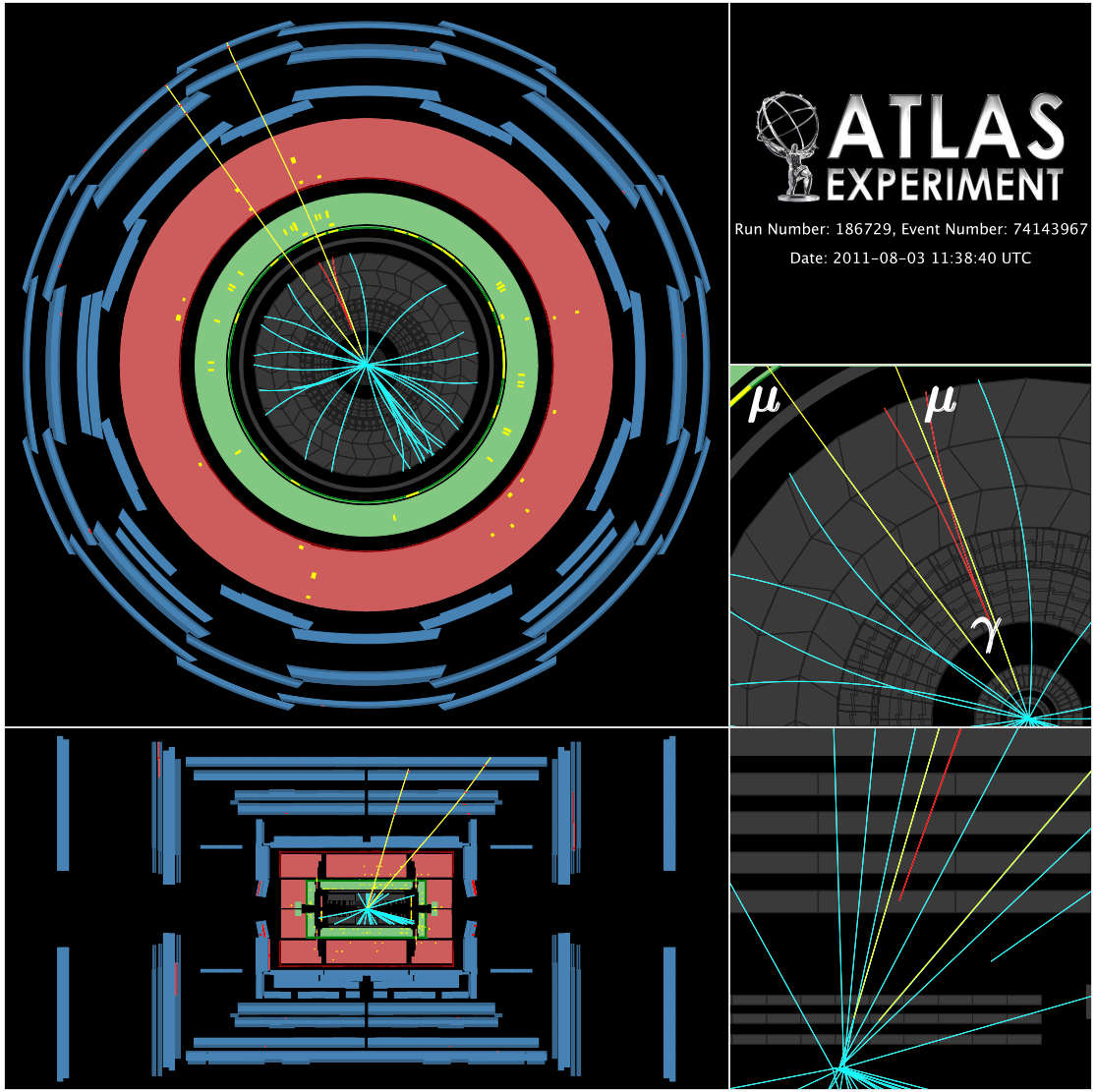
χ_b(3P) candidate



- $\mu\mu$ + unconverted γ

- $m(\mu\mu\gamma) - m(\mu\mu) + m(\Upsilon(1S)) = 10.54$ GeV

χ_b(3P) candidate

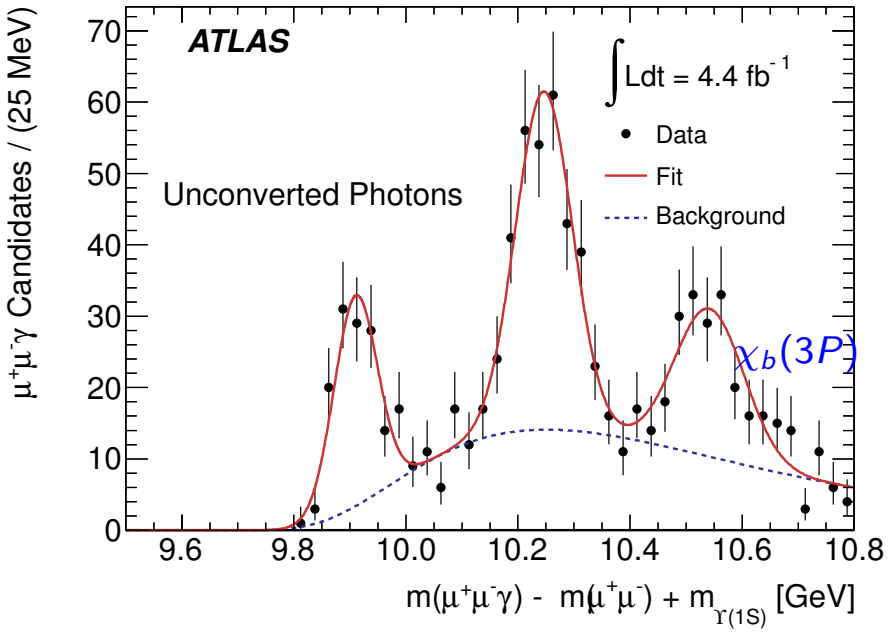


- $\mu\mu$ + converted γ

- $m(\mu\mu\gamma) - m(\mu\mu) + m(\Upsilon(1S)) = 10.54$ GeV

Observation of $\chi_b(3P)$

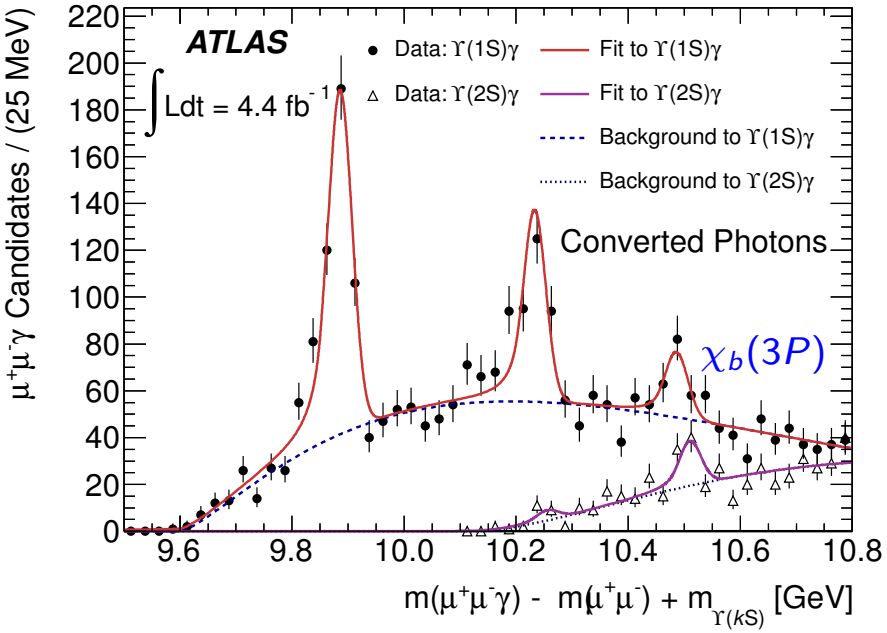
Unconverted photons



$m(\chi_b(3P))$

10.541 $\pm$ 0.011 (stat.) $\pm$ 0.030 (syst.) GeV

Converted photons



$m(\chi_b(3P))$

10.530 $\pm$ 0.005 (stat.) $\pm$ 0.009 (syst.) GeV

These distributions are not corrected for detector efficiencies or acceptances.

- Statistical significance of $> 6\ \sigma$ in each channel
- Spin-averaged potential model prediction: 10.525 GeV

Observation by $D\emptyset$: `http://arxiv.org/abs/arXiv:1203.6034`

$m_{D\emptyset}(\chi_b(3\mathrm{P})) = 10.551 \pm 0.014$ (stat.) $\pm$ 0.017 (syst.) GeV

Summary and outlook

- ATLAS has performed measurements of Onia production
  - J/ψ cross-sections
    - agreement with CDF/CMS
    - non-prompt fraction increases as p_T of J/ψ increases
    - Colour Singlet Model at NNLO improves agreement with measured prompt cross-sections compared to NLO
  - Υ cross-sections
    - NRQCD does not describe shape
    - Colour Singlet Model is describing shape but lower than data
      No feed down from higher order states are included
  - Observation of new state χ_b(3P)
    - measured mass agrees well with prediction of 10.525 GeV

- ATLAS has collected a large number of di-muon sample in 2011, many new results will follow
  - Quarkonia
    - J/ψ spin alignment
    - cross-sections and ratio of Υ(1S,2S,3S)
    - ψ(2S) cross-sections and ratio to J/ψ
    - Studies of double-quarkonium production
    - Onia $\rightarrow \pi\pi$