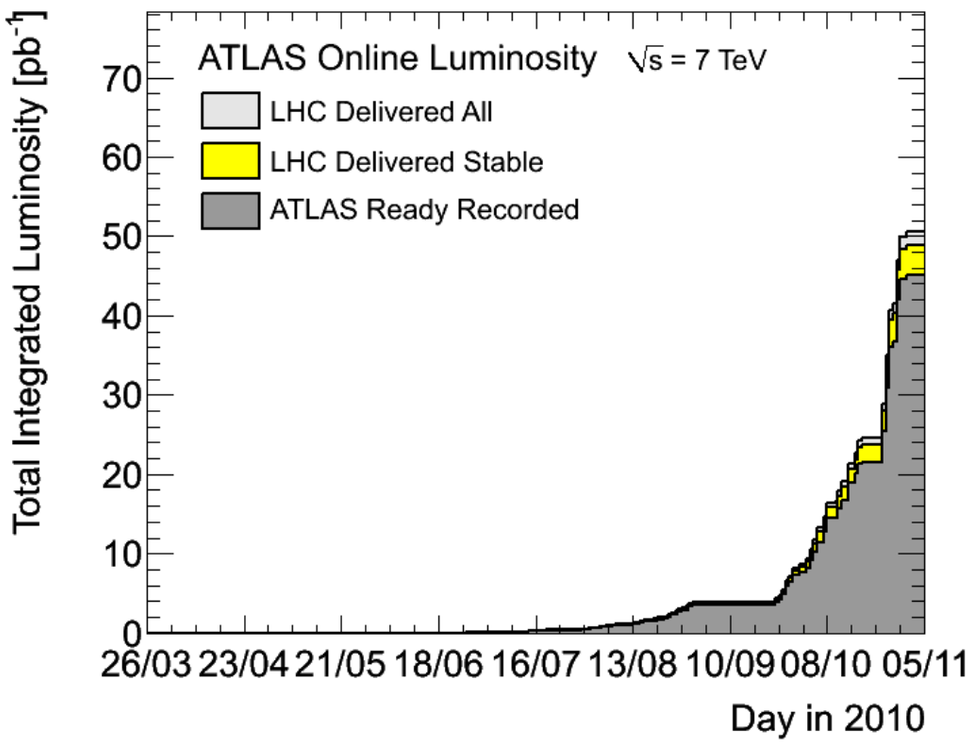
# Heavy Flavour Physics at ATLAS

Roger Jones
Lancaster University

On behalf of the ATLAS Collaboration

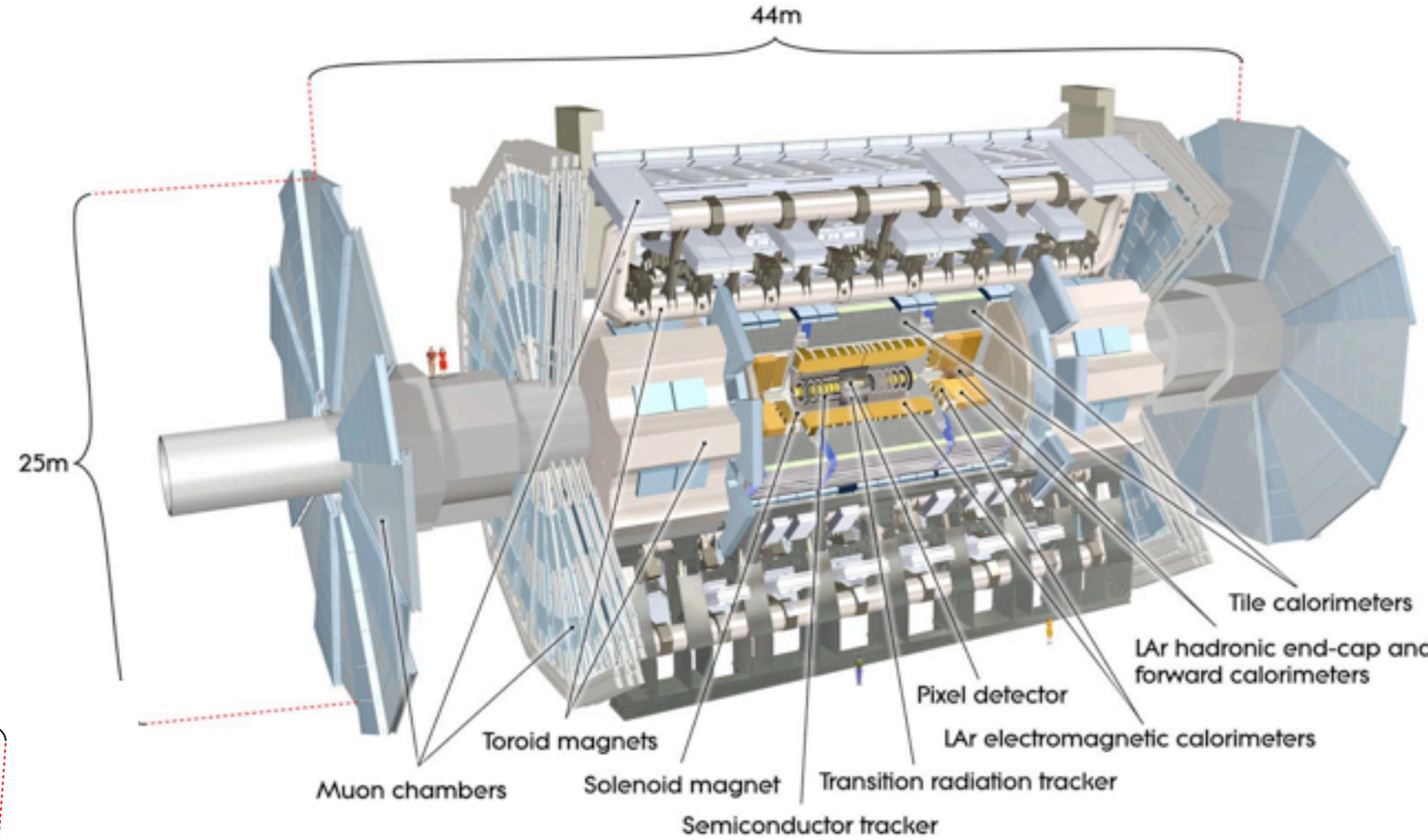

# Outline

- The ATLAS detector
- Observation of Charmonium, Upsilon & charm states
  - ATL-COM-PHY- 2010-034, ATLAS-CONF-2011-017
- Inclusive differential cross-section of J/ψ production
- Measurement of the fraction of non-prompt J/ψ decays, & prompt & non-prompt cross sections
  - Submitted Nuc. Phys. B
- Exclusive B-meson decays
  - ATLAS-CONF-2010-098
- Summary and Outlook

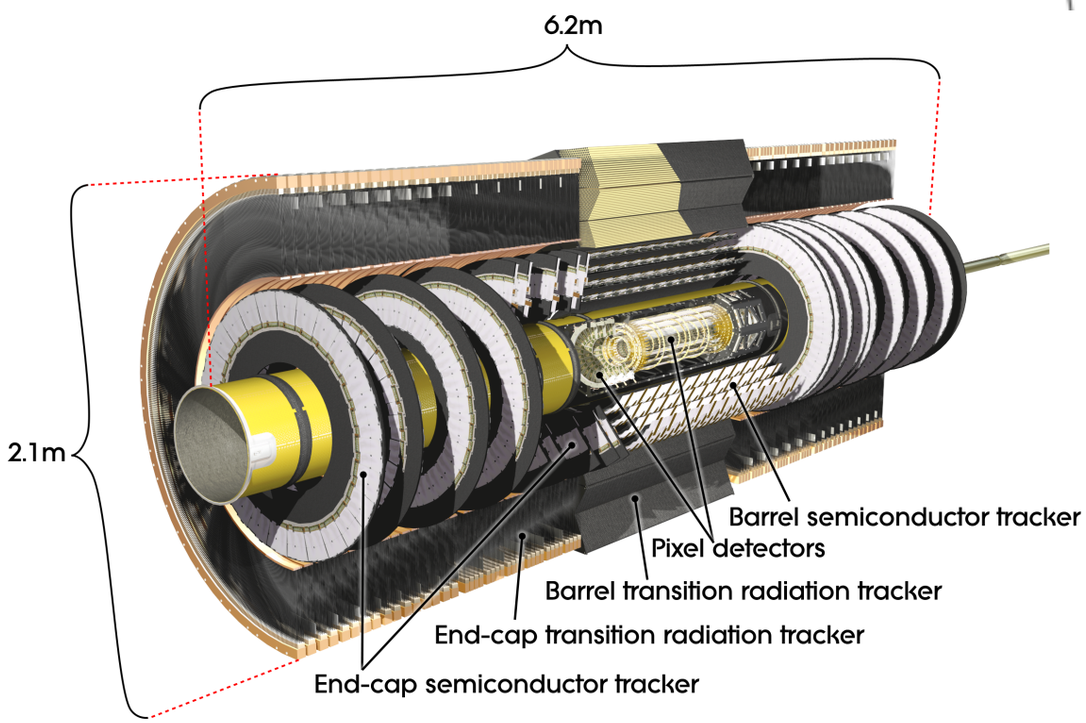


# The ATLAS Detector

- For B-physics measurements, requirement on excellent tracking capabilities and muon identification available with the ATLAS detector.



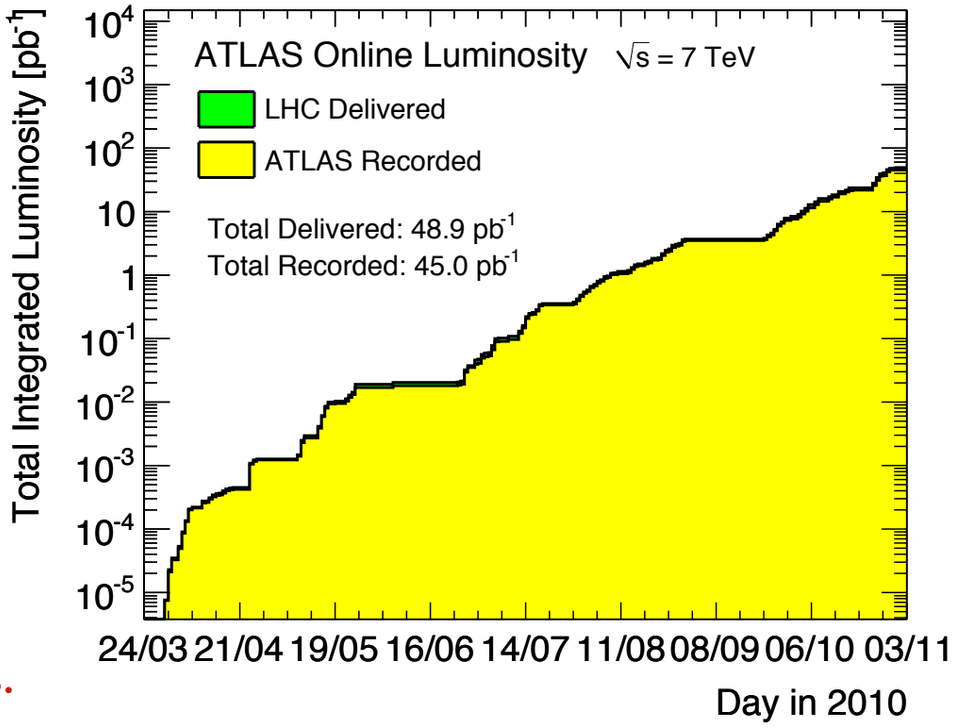

- **Inner Detector**
  - $|\eta|<2.5$,
  - Solenoid B=2T
  - Si Pixels,
  - Si strips,
  - Transition Radiation Tracker (TRT)
  - $\sigma/p_T \sim 3.4\times10\text{-}4\ p_T + 0.015$ for ($|\eta|<1.5$)
  - Used for Tracking and Vertexing:
  - Precise momentum and lifetime measurements

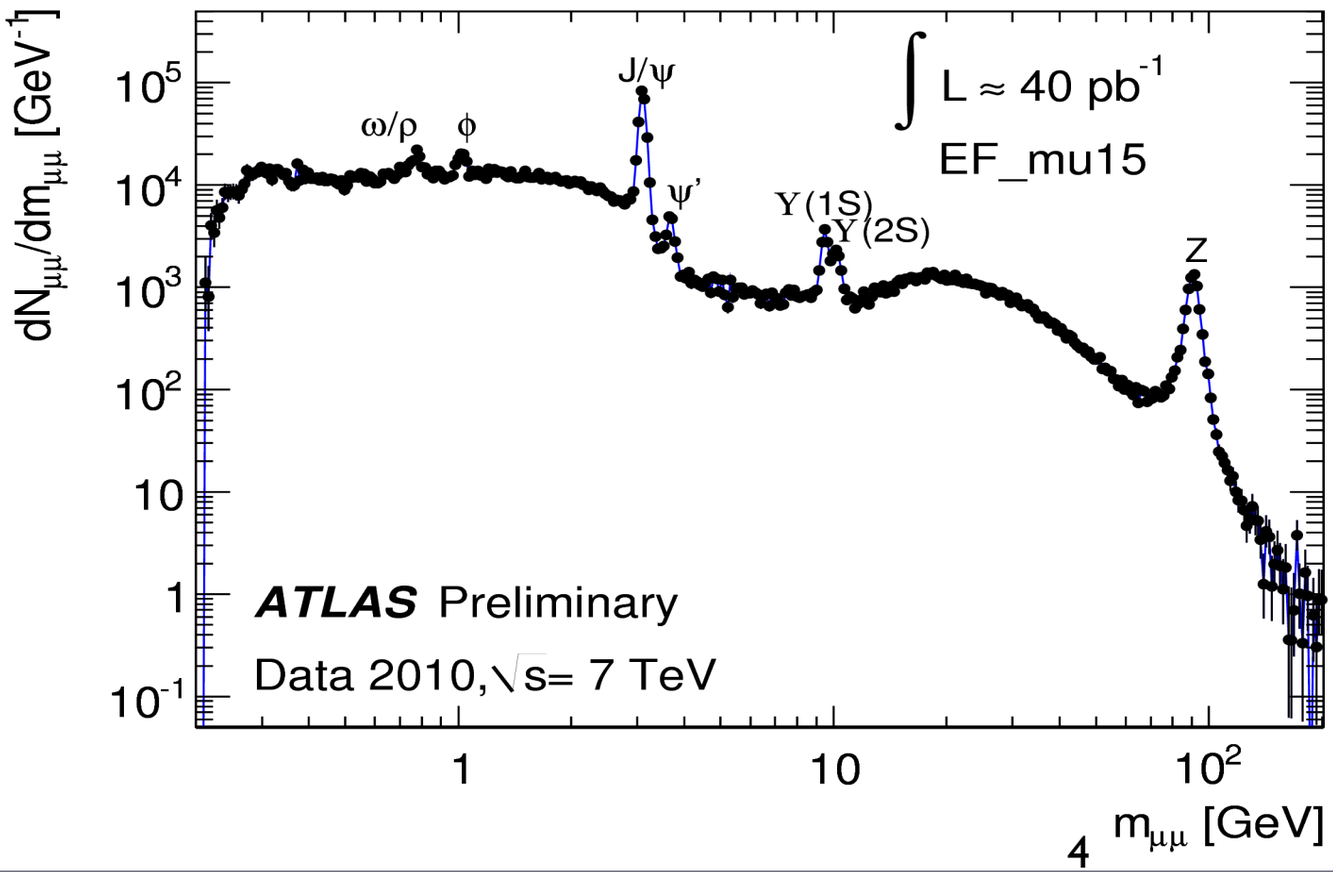



- **Muon Spectrometer**
  - $|\eta|<2.7$
  - Toroid B-Field, average ~0.5T
  - Muon Momentum resolution $\sigma/p< 10\%$ up to ~ 1 TeV

# Muon Trigger and Performance

- Muon identification is key to many B-physics analyses:
  - Clean trigger signature.
- Ever increasing instantaneous luminosity requires prescales & use of number of triggers to maximise statistics.
  - (0, 4, 6 GeV $p_T$ thresholds), single and di-muon triggers.
- Early period of data-taking essential to study, as access to low-pt region.
  - Later periods with higher instantaneous luminosities need higher threshold triggers & individual trigger studies.
- Di-muon invariant mass distribution from ρ to Z from all good-quality recorded 2010 7 TeV pp collision data passing a $p_T$ >15 GeV muon trigger.

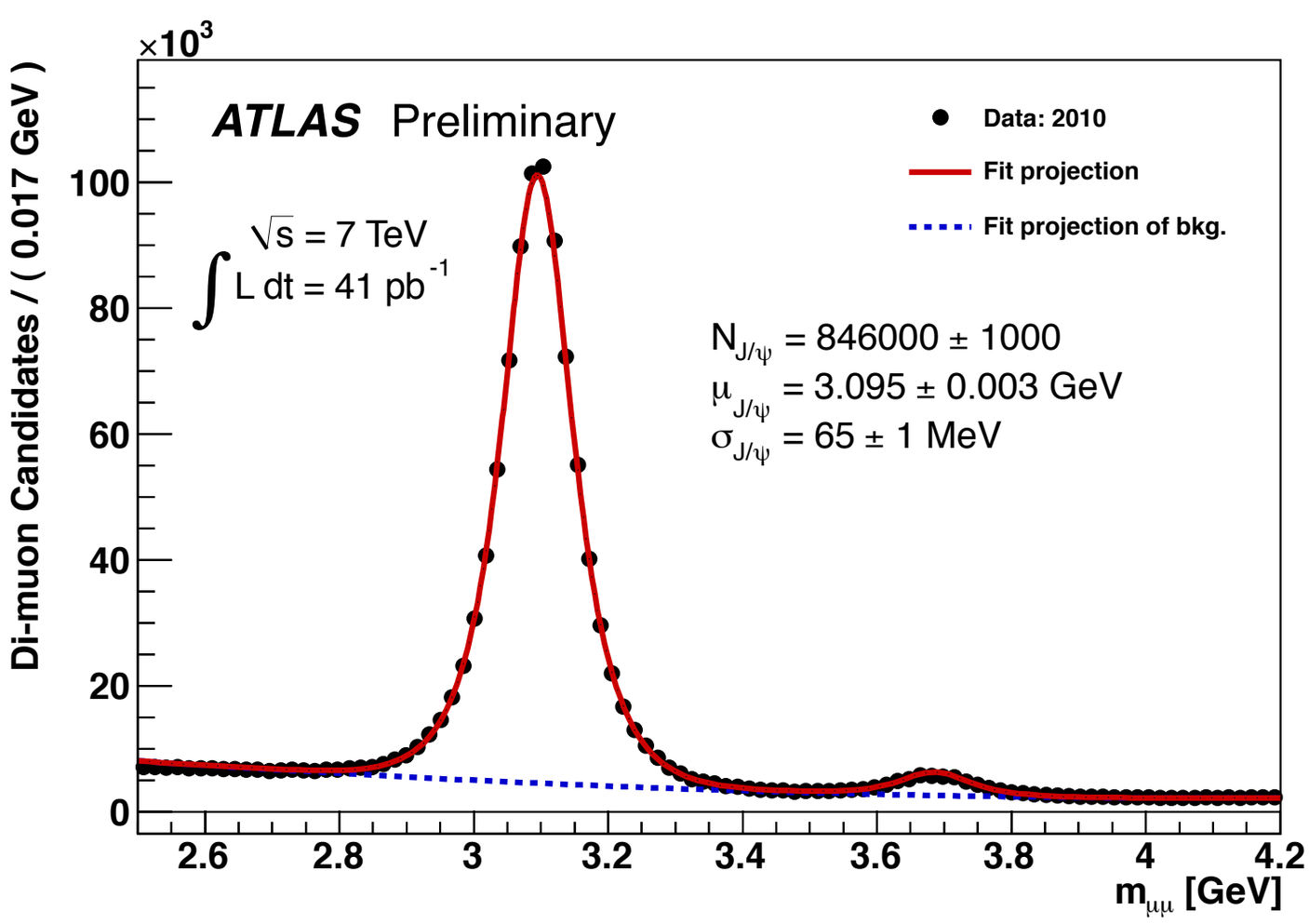



One muon $p_T$ >15 GeV, other $p_T$ > 2.5 GeV

# Charmonium Observations

- Key signatures of B-meson decays go through Charmonium states.
  - e.g. $B_d \rightarrow J/\psi(\mu\mu)Ks$ , $B_s \rightarrow J/\psi(\mu\mu)\Phi$;
- J/ψ also a 'standard candle' in commissioning and studying detector performance.
- ψ and ϒ QCD production needs to be understood
- Invariant mass distribution of J/ψ and ψ(2S) from all recorded pp 7 TeV, 2010 data passing a suite of muon-based triggers.

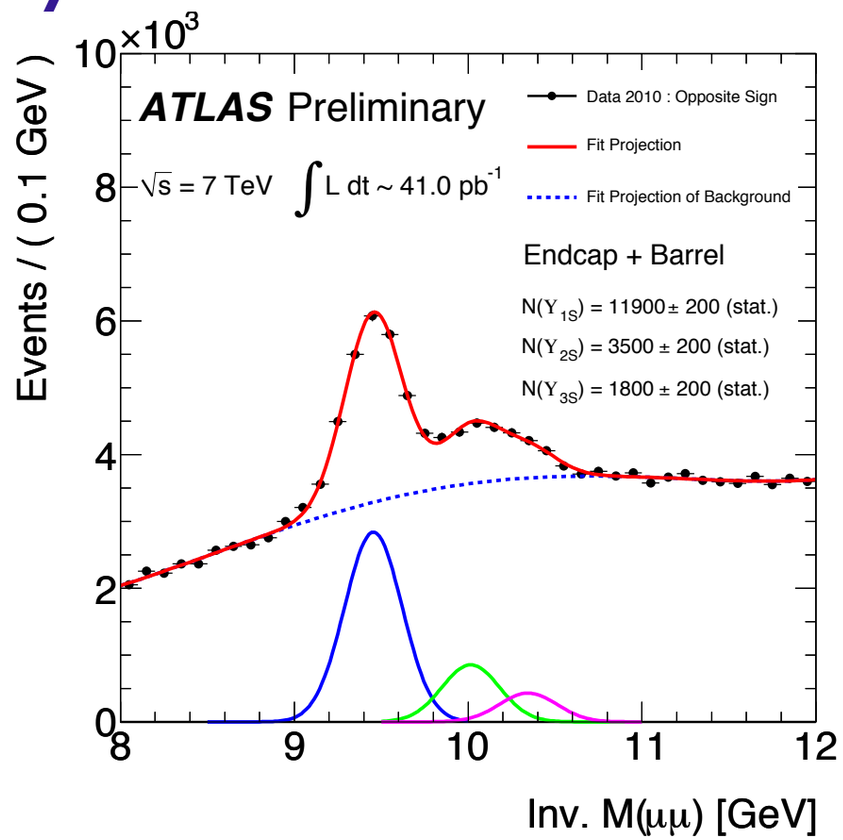


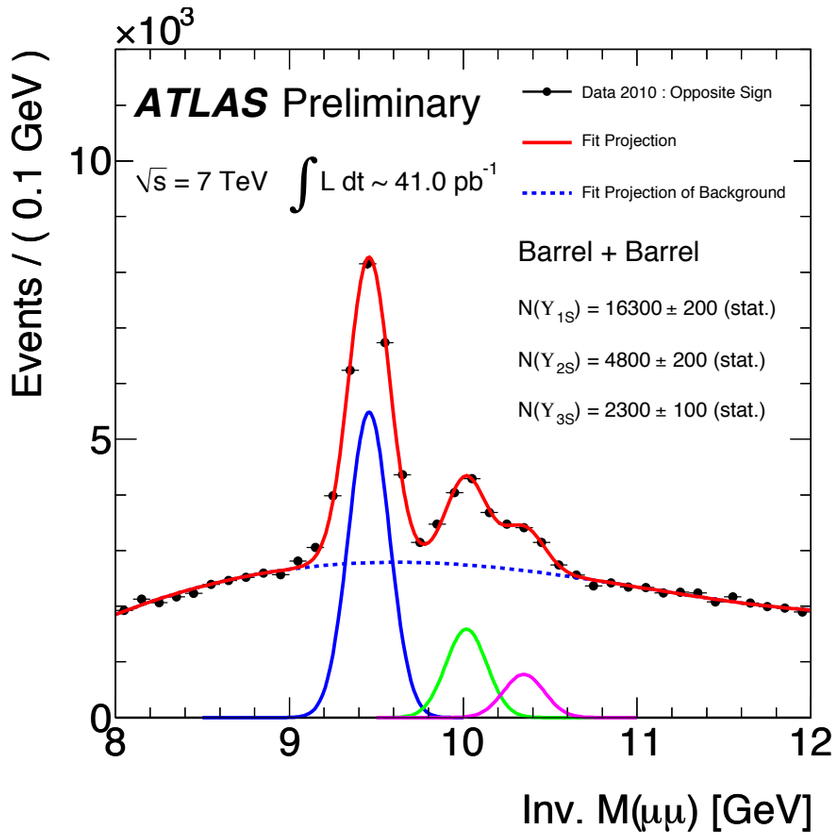

One muon $p_T$ >4 GeV,
other $p_T$ > 2.5 GeV

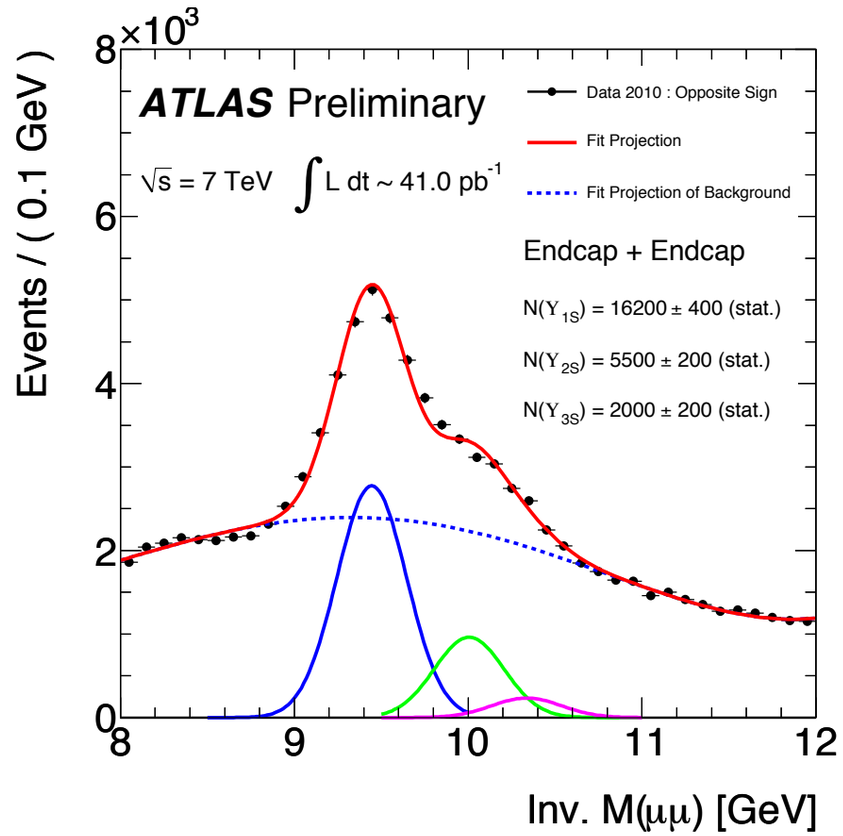
- Mass position in good agreement with PDG expectations:
- M(J/ψ) = 3095 ± 3 (syst.) MeV
- $M_{PDG}$ = 3096.916 ± 0.011 MeV

# Observation of Upsilon System

- Observation of the three Upsilon resonances separated into detector regions of muons in:
  - Barrel – Barrel, Endcap – Barrel and Endcap – Endcap.
- Full 2010 pp data passing single- or di-muon triggers, increasing $p_T$ thresholds with increasing instantaneous luminosity.
- Muons were required to have $p_T$ > (2.5, 4) GeV and energy > 3 GeV, and to be reconstructed within a pseudo-rapidity < 2.5.
- Extended maximum likelihood fit performed using three single Gaussians with common sigma and fixed mass-differences ΔM.
- Resolution in barrel region is clearer.
- Similar event yields in each
- Masses stable in each combination
  - Cross-section measurement in progress.

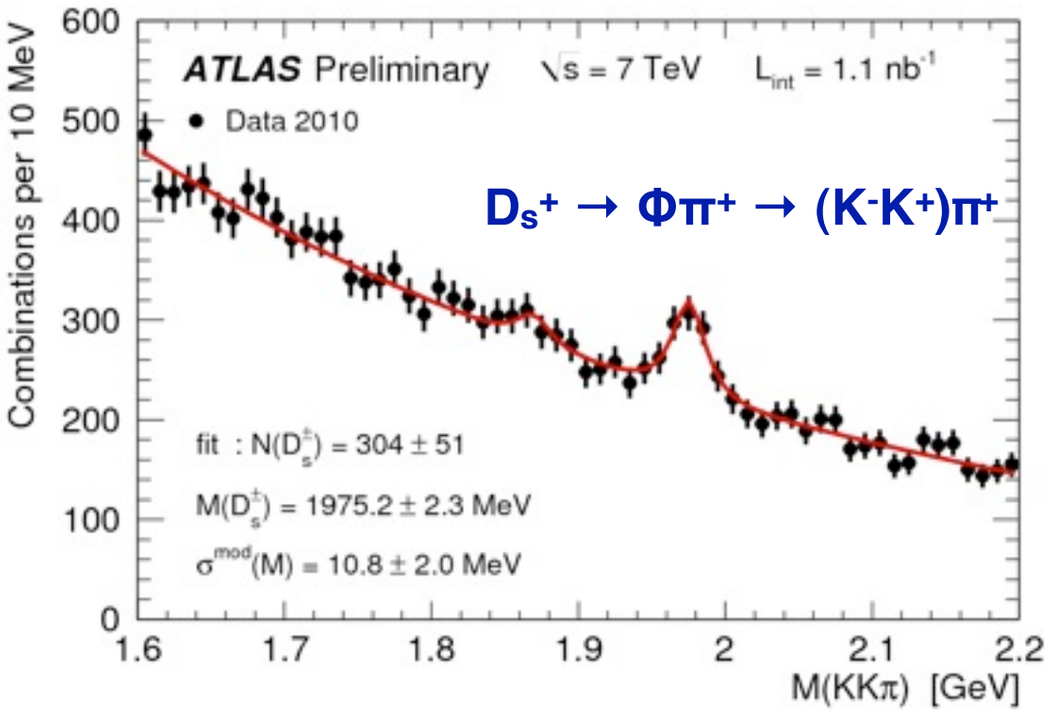


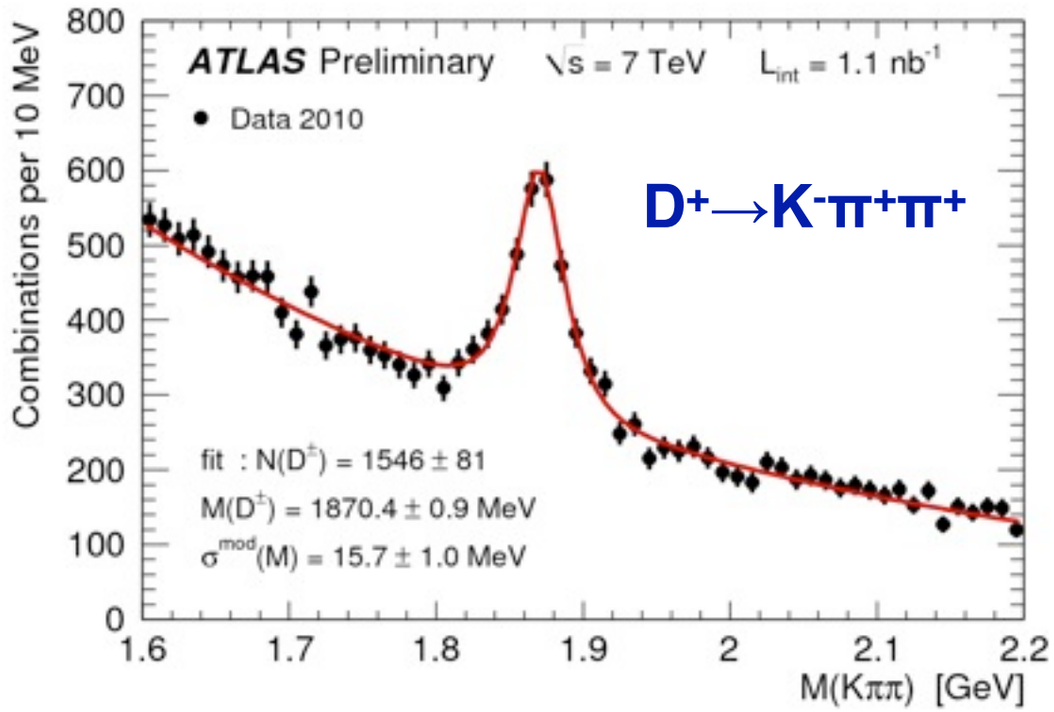



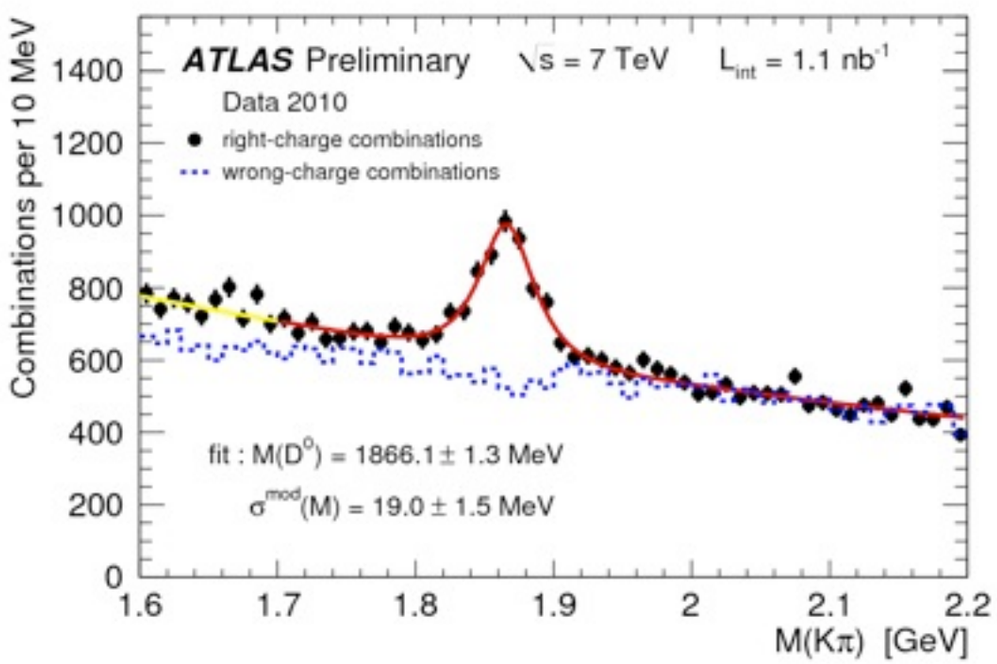
# D Mesons

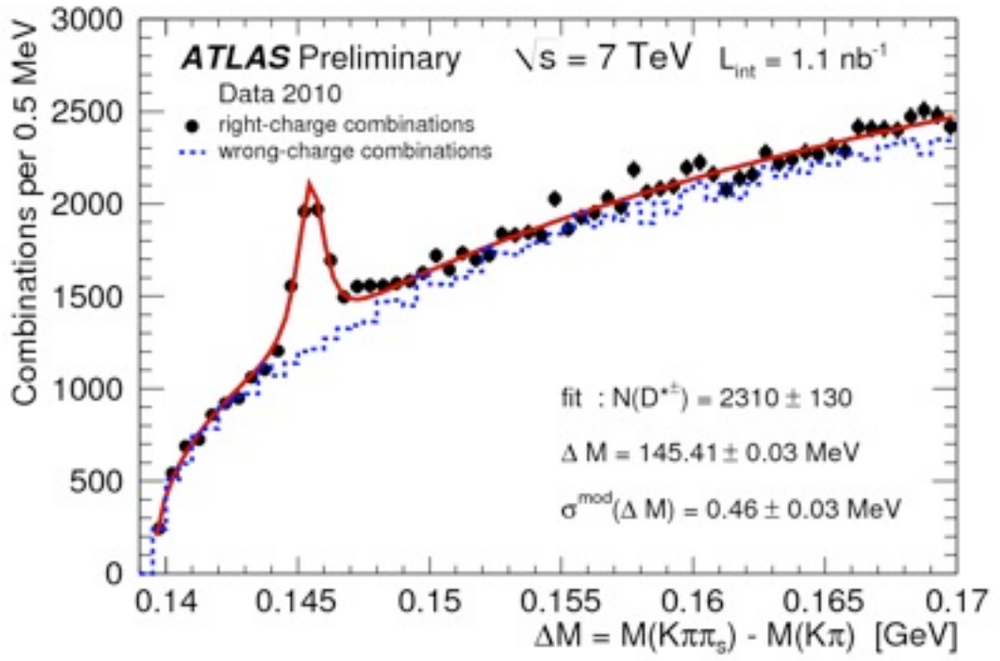
- ATLAS is also measuring production of charm mesons



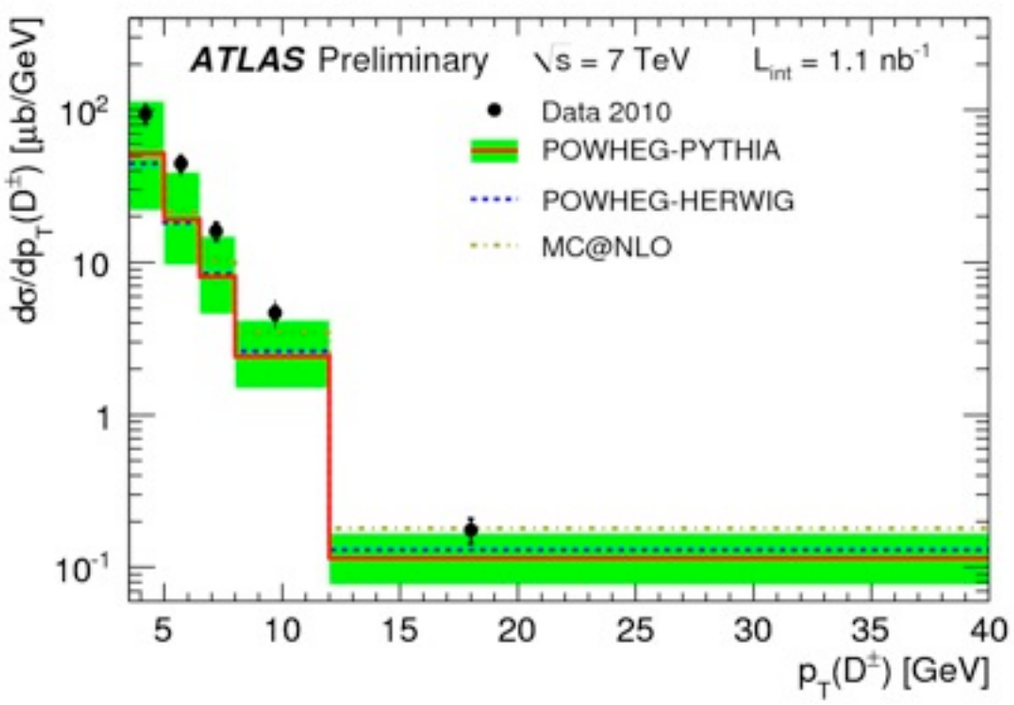

**$D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+)\pi^+$**



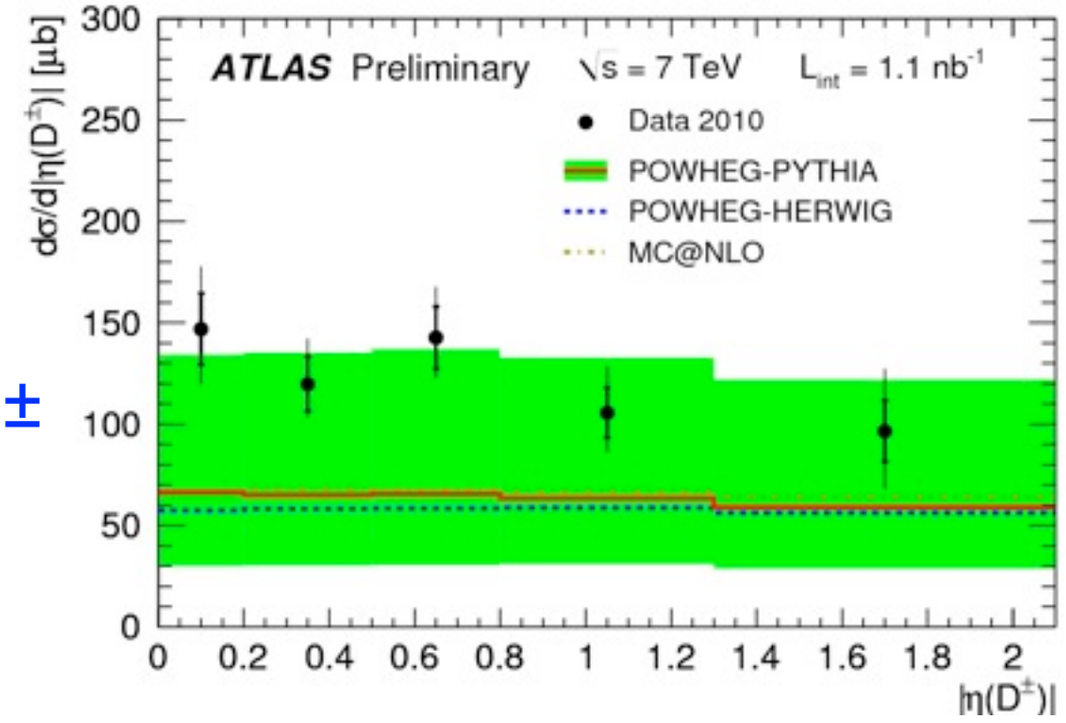



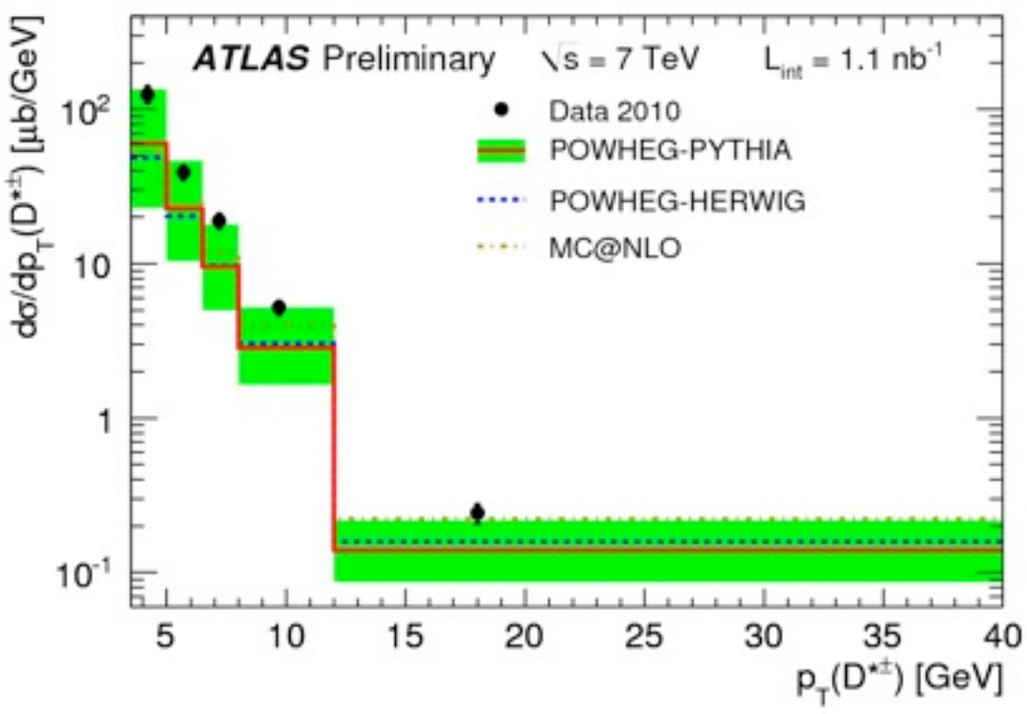
# Differential Cross-sections extracted

- Differential cross-sections with pT and η seem to be above predictions

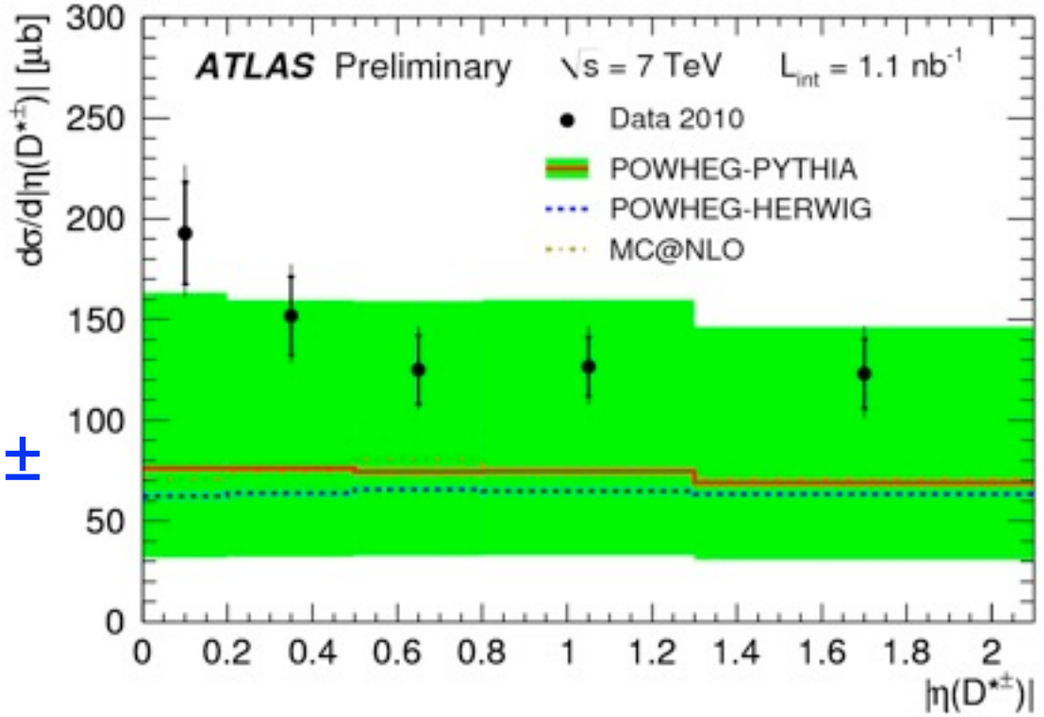



D±




D*±



# J/ψ Differential Cross-Section

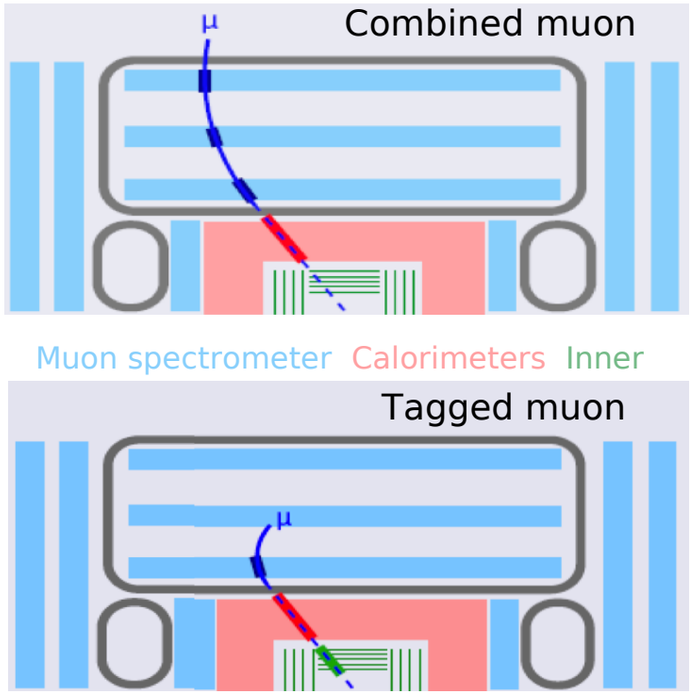
- ATLAS measurement of the inclusive J/ψ differential cross-section in bins of rapidity (y) and $p_T$ using single muon triggers
- Uses data collected between April and August of 2010.
  - Important inputs to measurement from:
    - Theoretical uncertainties from spin-alignment, possible strong effect on detector acceptance - not (yet) measured at LHC.
    - Efficiency determinations for trigger and muon reconstruction
      - Reconstruction efficiencies from data
      - Trigger efficiencies in fine bins from MC, bins weighted with match data.
- Measured the fraction of non-prompt production cross-section as a function J/ψ $p_T$,y.

$$f_B \equiv \frac{d\sigma(pp \to B + X \to J/\psi\, X')}{d\sigma(pp \xrightarrow{\text{Inclusive}} J/\psi\, X'')}$$

  - Direct production and feed-down from higher mass charmonium states.
  - Non-prompt J/ψ's produced in the decay of long-lived B-hadrons.
  - Many uncertainties cancel in the fraction,
    - Makes a suitable measurement for early data analysis.
- Differential prompt and non-prompt cross-sections also extracted

# Candidate Selection

- Trigger:
  - Differential cross-section
    - Required events passing a minimum-bias trigger, with a muon signature at the High-Level Trigger (HLT)
    - Gives access to low-$p_T$ candidates; high prescales applied at later periods
    - Luminosity used corresponds to 2.27 $pb^{-1}$.
  - Fraction measurement
    - Either the above trigger, or a single-muon trigger,
    - Increased statistics, more so in higher-$p_T$ regions.
    - Luminosity recorded corresponds to 2.44 $pb^{-1}$.




- Offline reconstruction
  - Require two muons using the tracker & the muon system, with at least one reconstructed in the muon system and then matched to an ID track.
  - Each muon required to have momentum > 3 GeV, pseudo-rapidity < 2.5.
  - Vertex fit is made using the oppositely-charged associated Inner-detector tracks.
- Main contribution to background is from "fakes", decays in flight and muons from heavy-flavour decays.

# Event Weighting

- From fits to data, extract the yields of J/ψ in each $p_T$ and y region:
- To go from yields to cross-section:
  - Need to correct for detector acceptance, reconstruction and trigger efficiencies:
    - Event weighting procedure:

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

Kinematic acceptance

Resolution migration

Track recon efficiency

Single muon offline efficiencies

Trigger efficiency

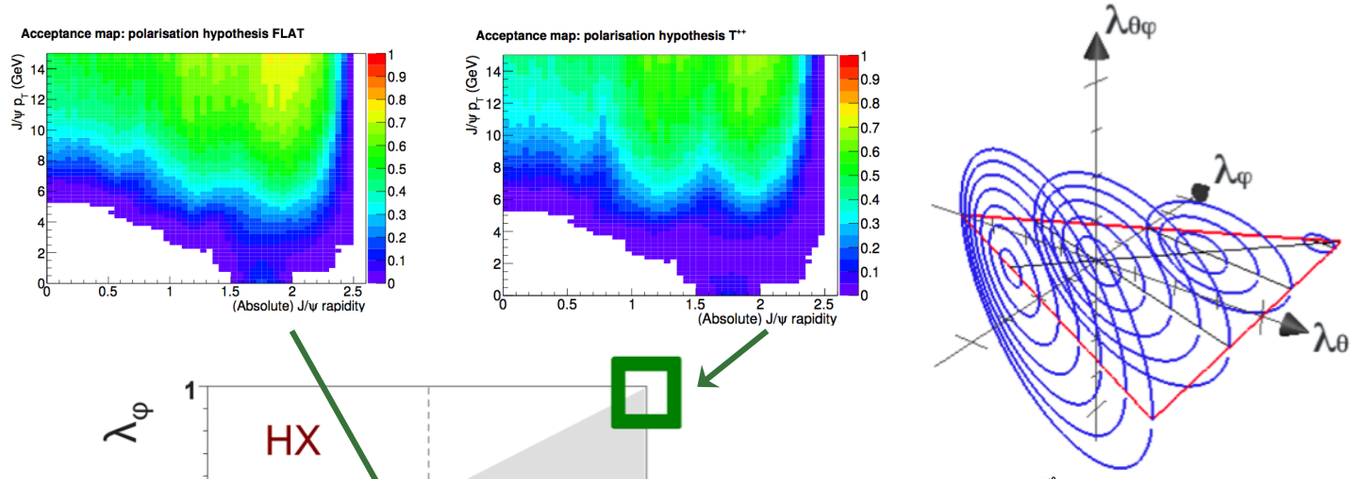
$$\mathcal{E}_{\text{trig}} = 1 - \left(1 - \mathcal{E}^+_{\text{trig}}(p_T^+, \eta^+)\right) \cdot \left(1 - \mathcal{E}^-_{\text{trig}}(p_T^-, \eta^-)\right)$$

- Weight is applied to each candidate passing the event selection.
- Trigger efficiency extracted from data for each "Combined" and "Tagged" muon type and each trigger condition; uses a data 'tag & probe' method combined with MC for finer binning.
- Efficiency to reconstruct muons in the detector determined from data using a 'tag and probe' method.

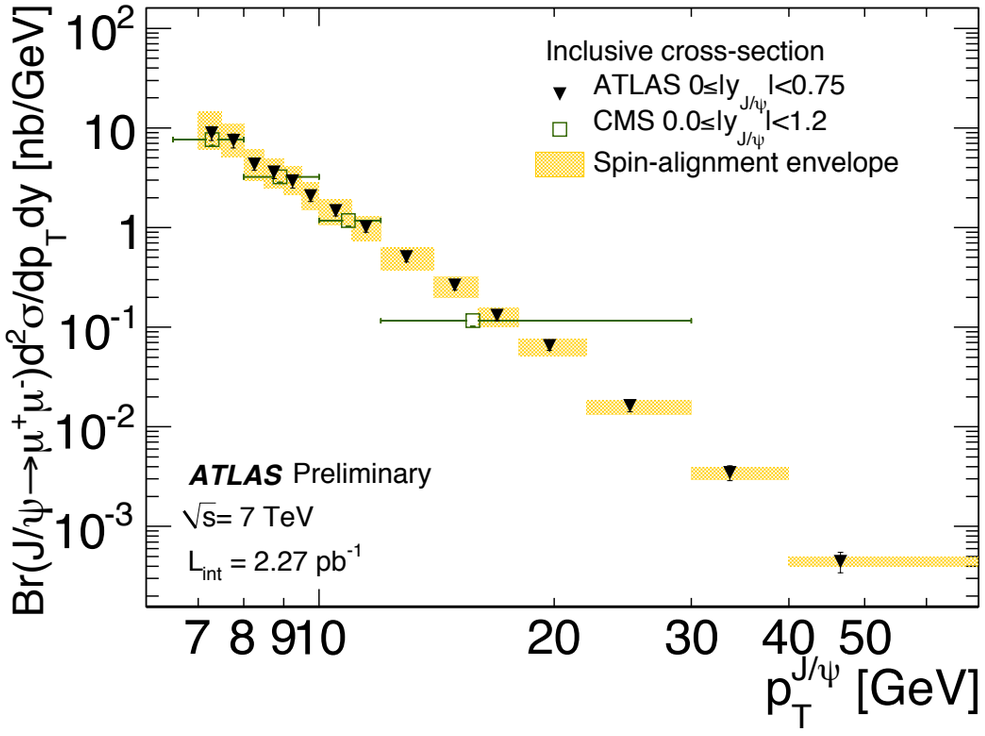
- Detector Acceptance depends strongly on the spin alignment, or polarisation of the J/ψ
  - not (yet) measured under LHC conditions and will be an important future measurement.
- Take 5 working points:
  - Covers maximum acceptance variations; applied as systematic uncertainty in final measurement.

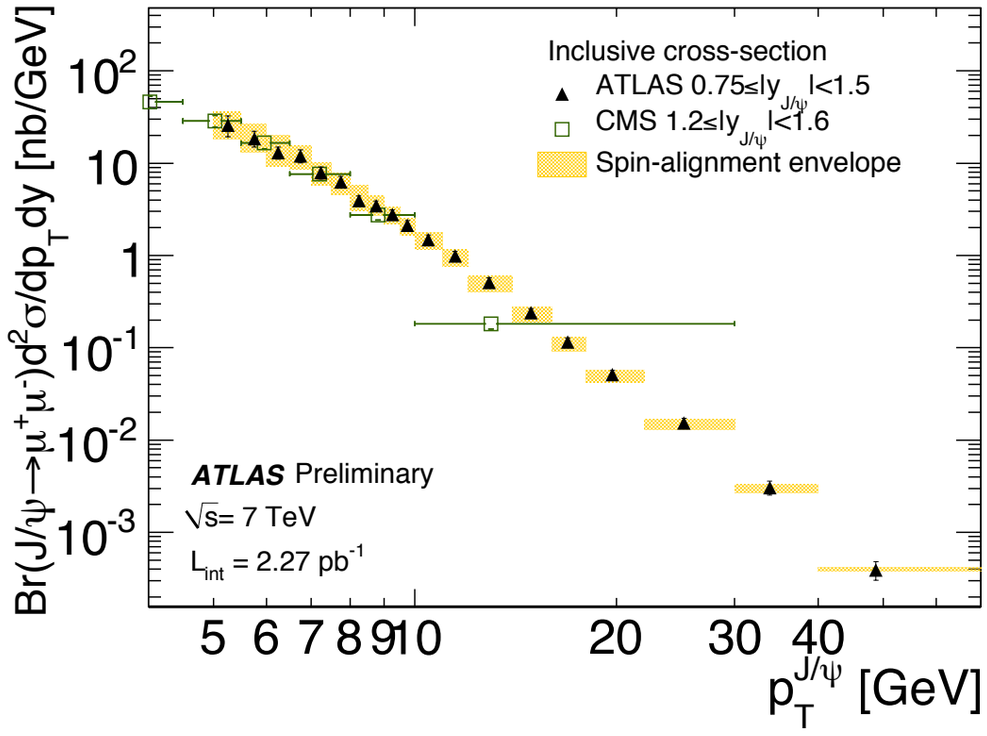
$$\frac{dN}{d\Omega} = 1 + \lambda_{\theta^\star}\cos^2\theta^\star + \lambda_{\phi^\star}\sin^2\theta^\star\cos 2\phi^\star + \lambda_{\theta^\star\phi^\star}\sin 2\theta^\star\cos\phi^\star$$

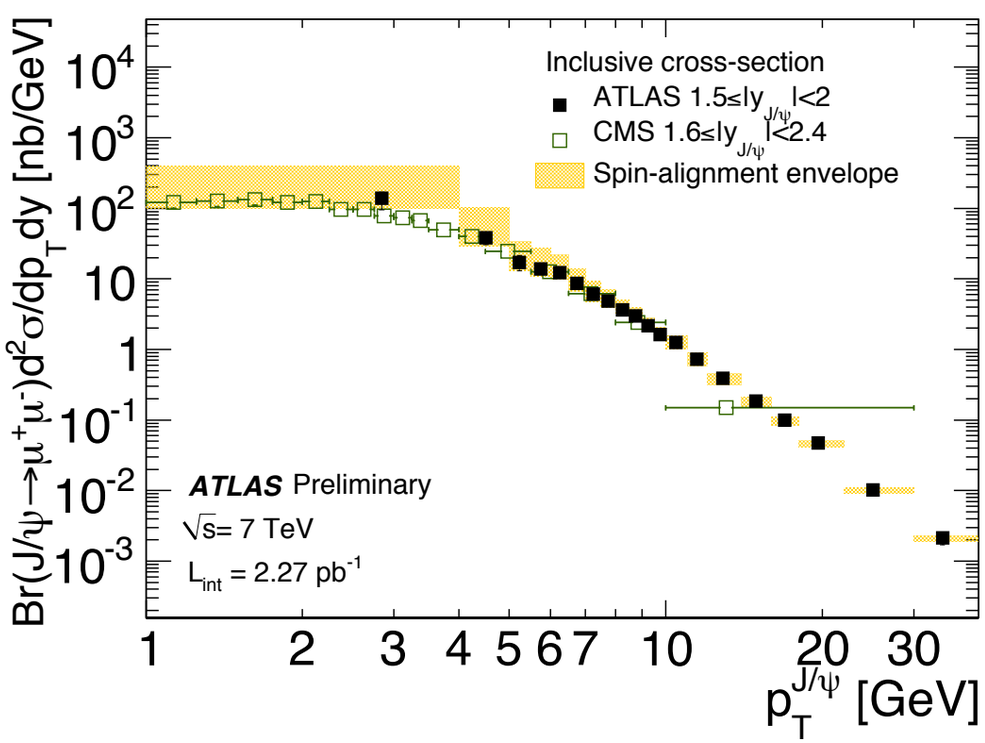
$$\frac{1-3|a_0|^2}{1+|a_0|^2} \qquad \frac{2Re\,a^*_{+1}a_{-1}}{1+|a_0|^2} \qquad \frac{\sqrt{2}Re\,[a^*_0(a_{+1}-a_{-1})]}{1+|a_0|^2}$$

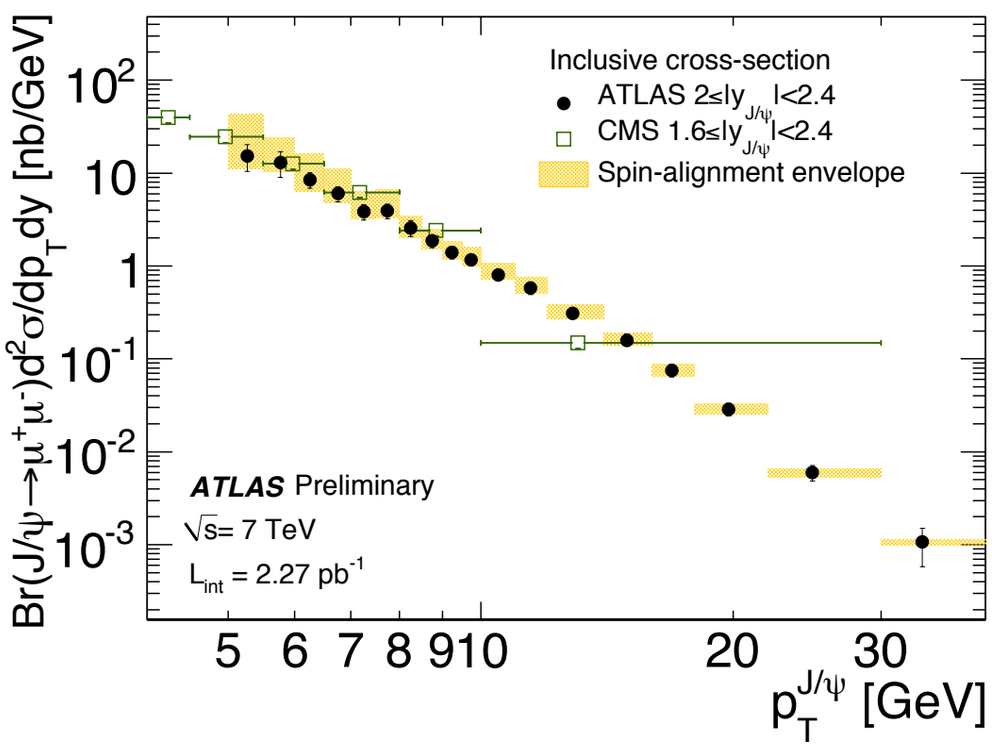


# Inclusive Differential Cross-Section




- Central points from "Flat" spin-alignment hypothesis, Yellow is envelope of all hypotheses.
- Good agreement with CMS, generally reduced uncertainties

# Non-Prompt Fraction Measurement

- Decays to J/ψ can proceed via various mechanisms:
  - Direct processes, e.g. from prompt production and decays of heavier charmonium ($\chi_c$) states:
    - Decays occur at production point in detector.
  - From B-hadron decays to J/ψ, many of which occur away from the production point of the interaction in the detector.

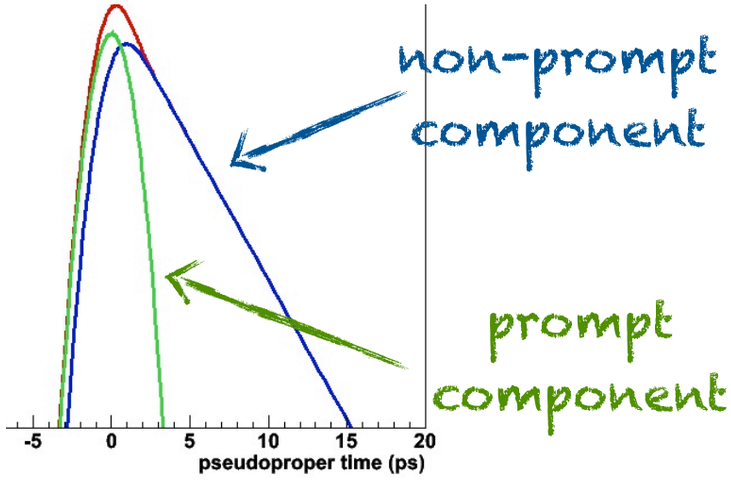
xy displacement of candidate from PV

Invariant mass of candidate

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

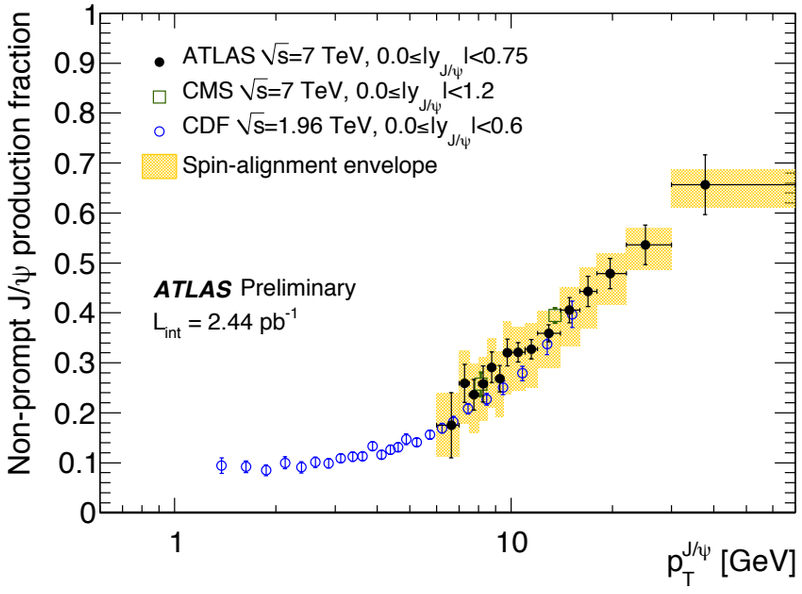
$p_T$ of candidate

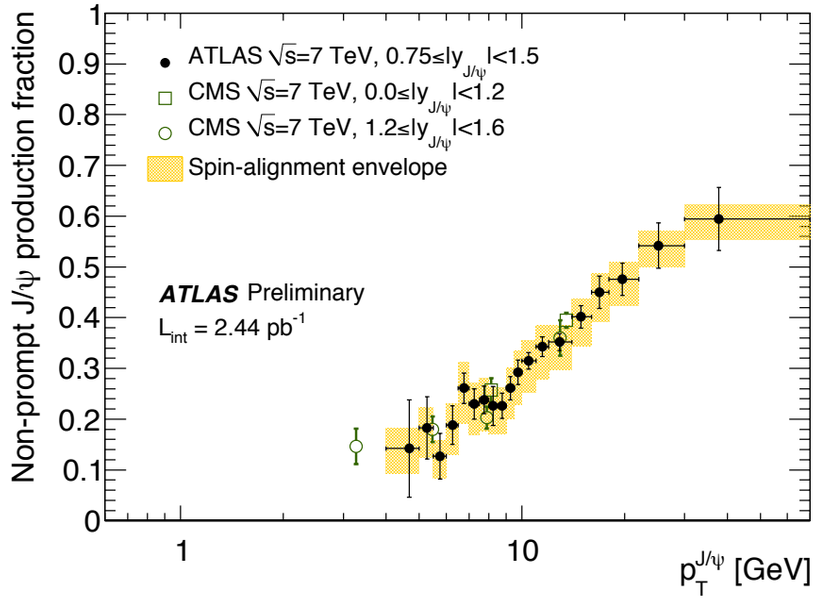
- Pseudo-proper lifetime discriminates between "prompt" & "non-prompt" decays.
- Simultaneous maximum likelihood fit performed to mass and lifetime distributions to extract ratio in many bins of J/ψ y, $p_T$.

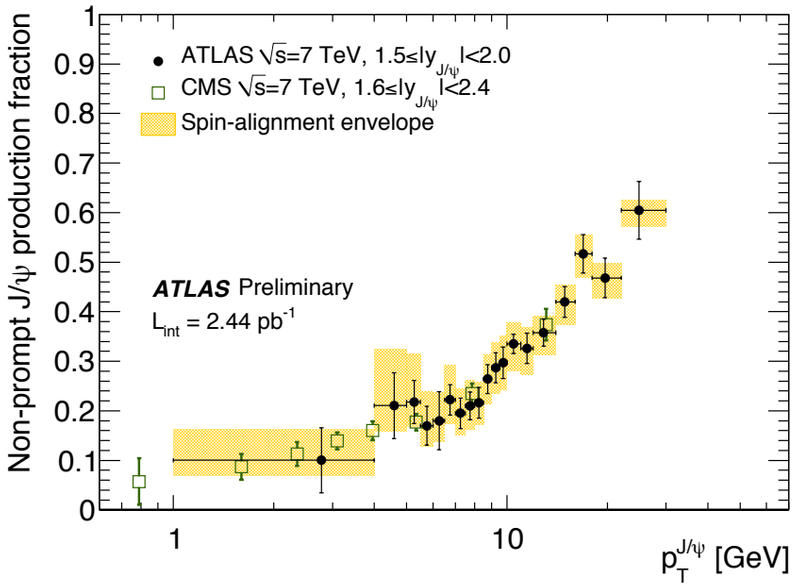


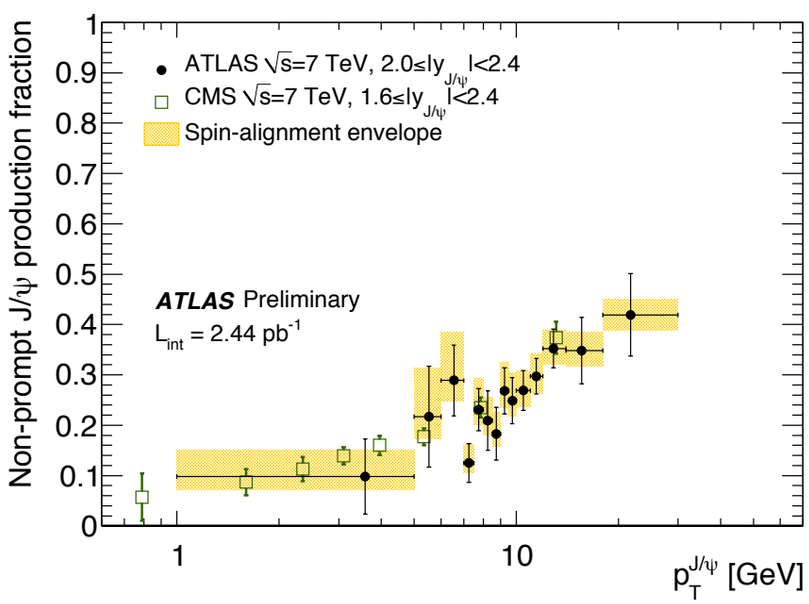
# Non-Prompt Fraction

- Non-prompt fraction as a function of J/ψ transverse momentum for each of the rapidity regions.



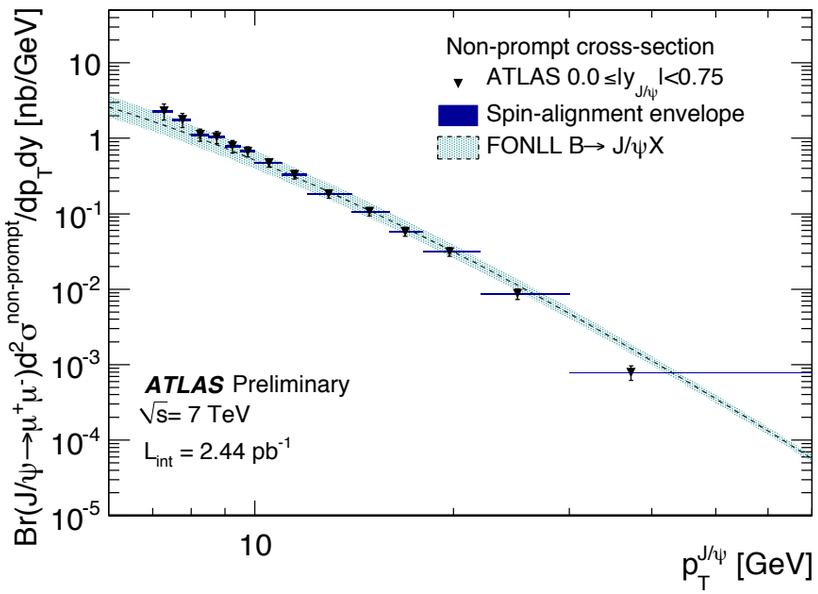



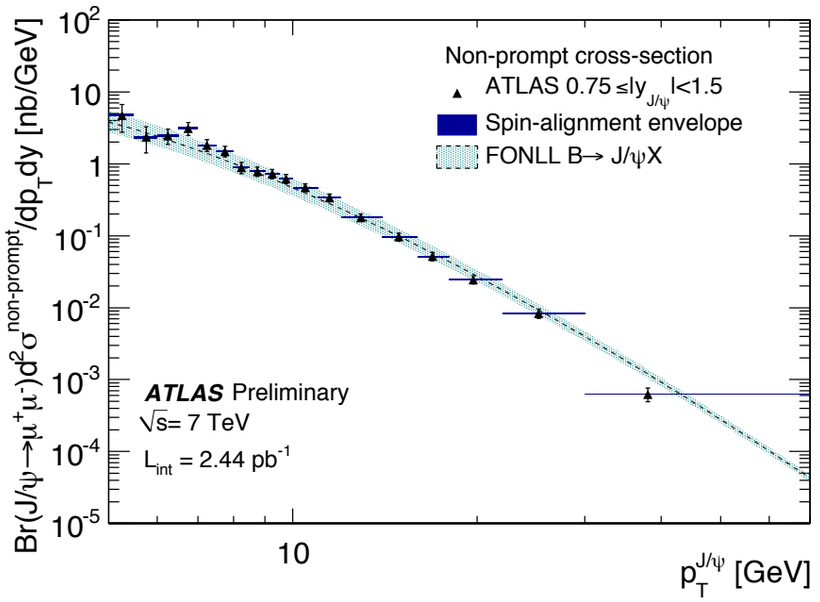



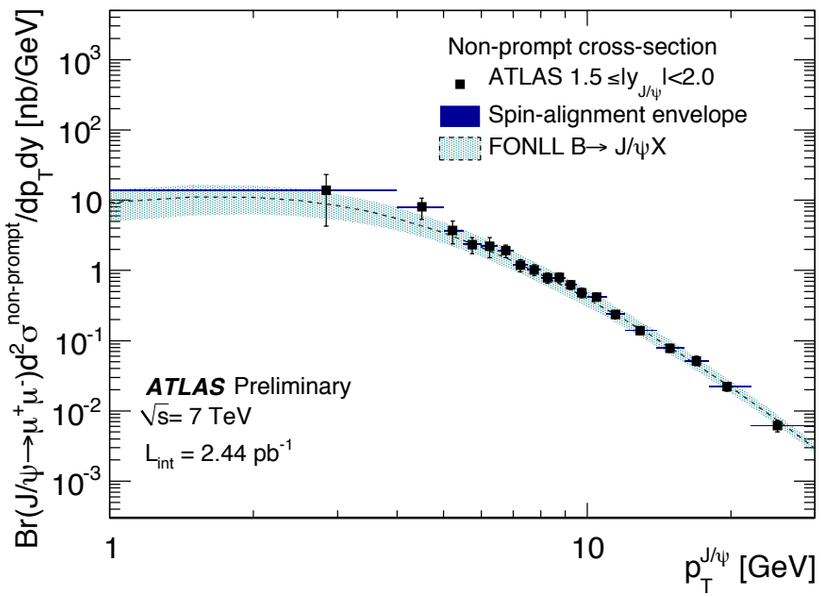

- Agreement is good compared to other experiments.

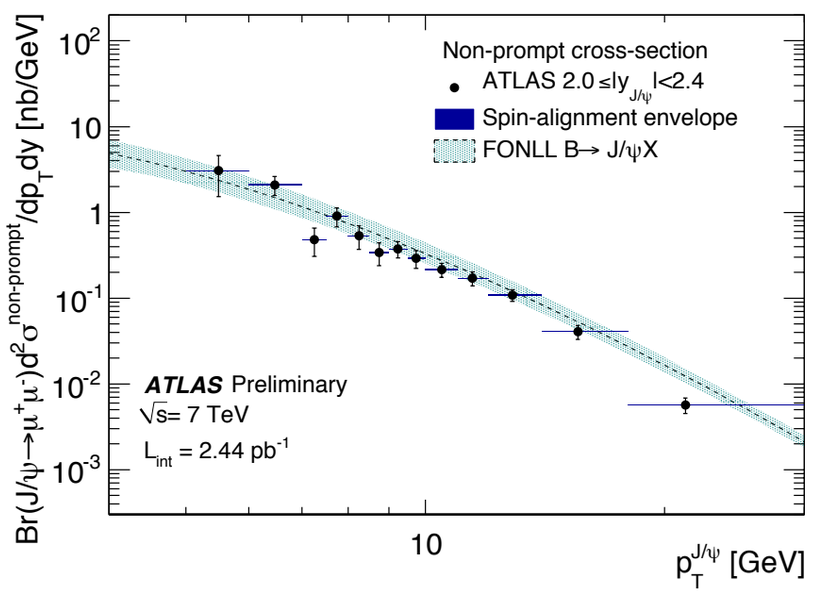
# Non-Prompt Cross-Section

- Corrected non-prompt cross-section as a function of J/ψ transverse momentum for each of the rapidity regions.



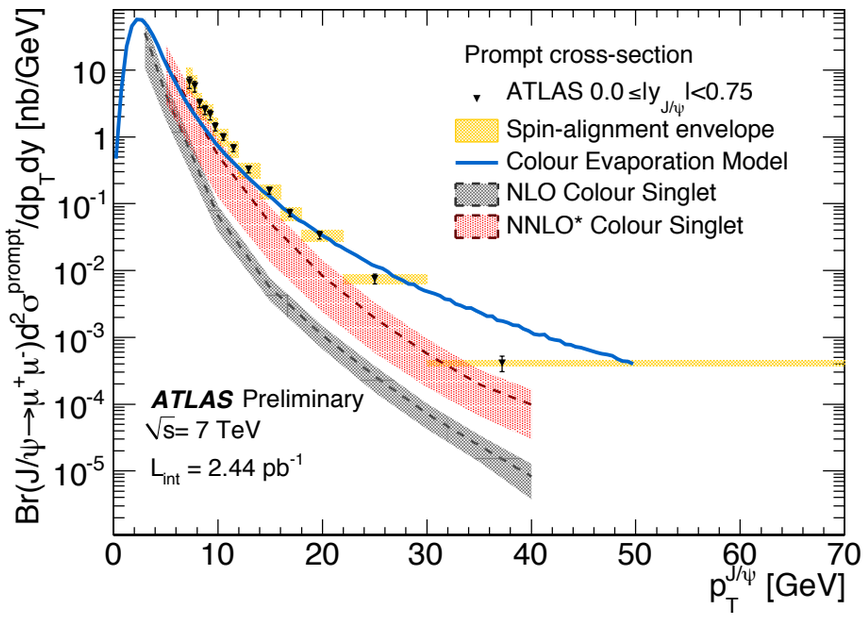



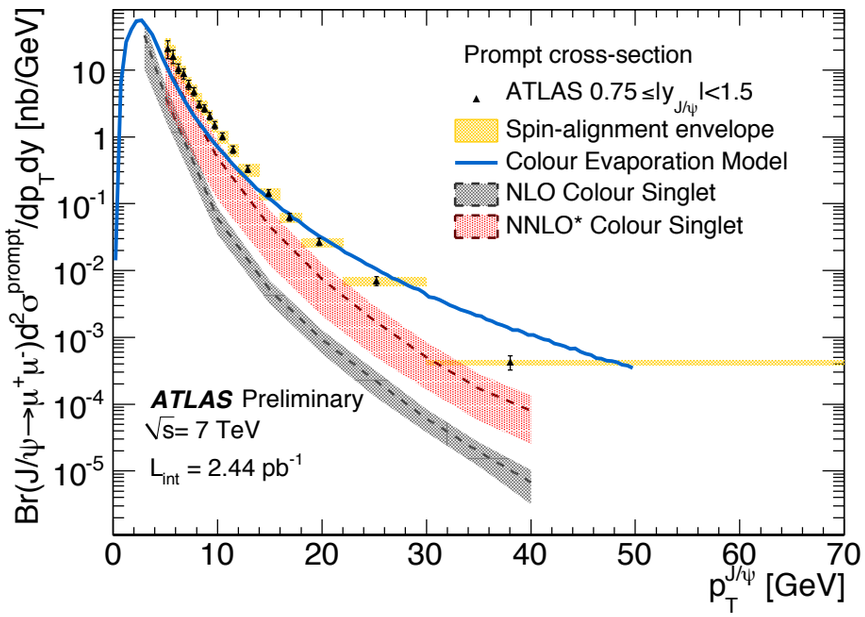

- Agreement is good with predictions.

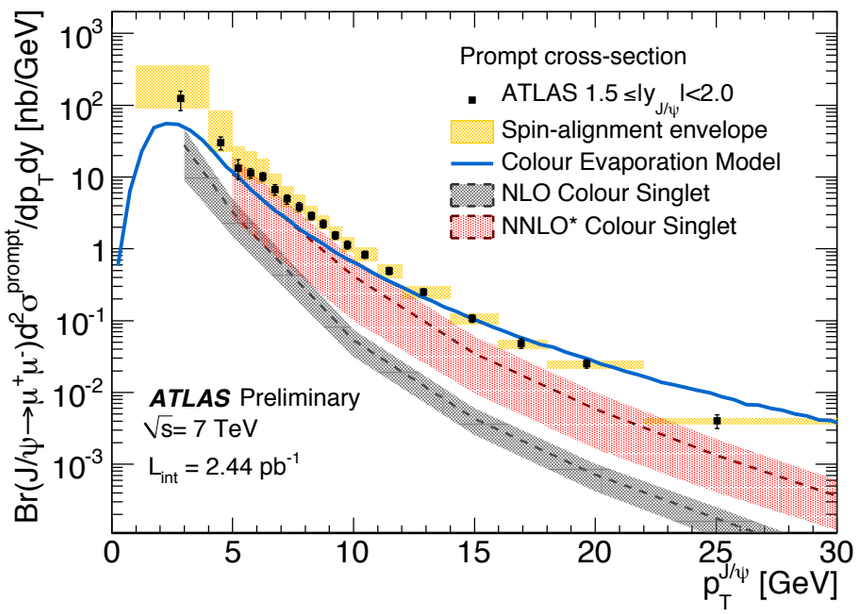
FONLL v1.3.2 (+CTEQ6.6):
M. Cacciari, M. Greco and P. Nason, JHEP **9805** (1998) 007, arXiv:hep-ph/9803400;
M. Cacciari, M. Greco and P. Nason, JHEP **0103** (2001) 006, arXiv:hep-ph/0102134.

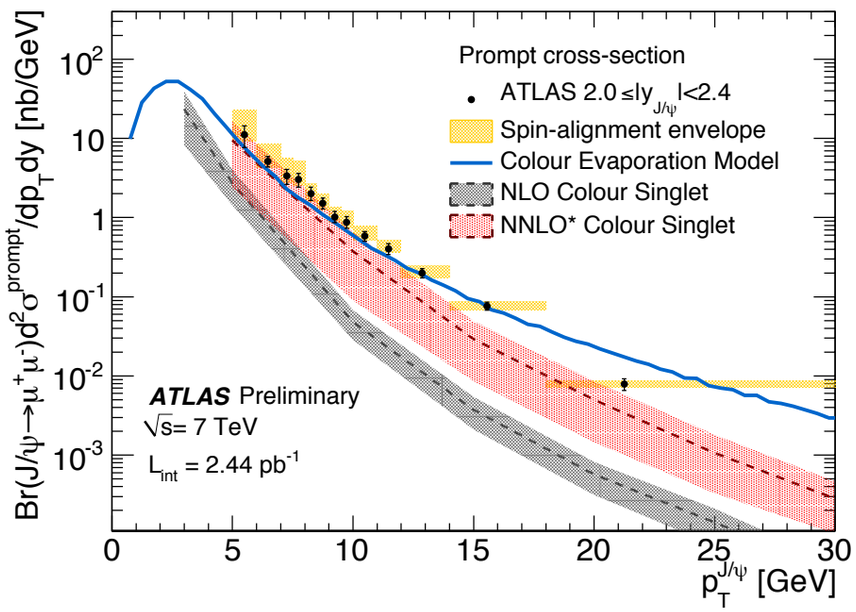
# Prompt Cross-Section

- Corrected prompt cross-section as a function of J/ψ transverse momentum for each of the rapidity regions.



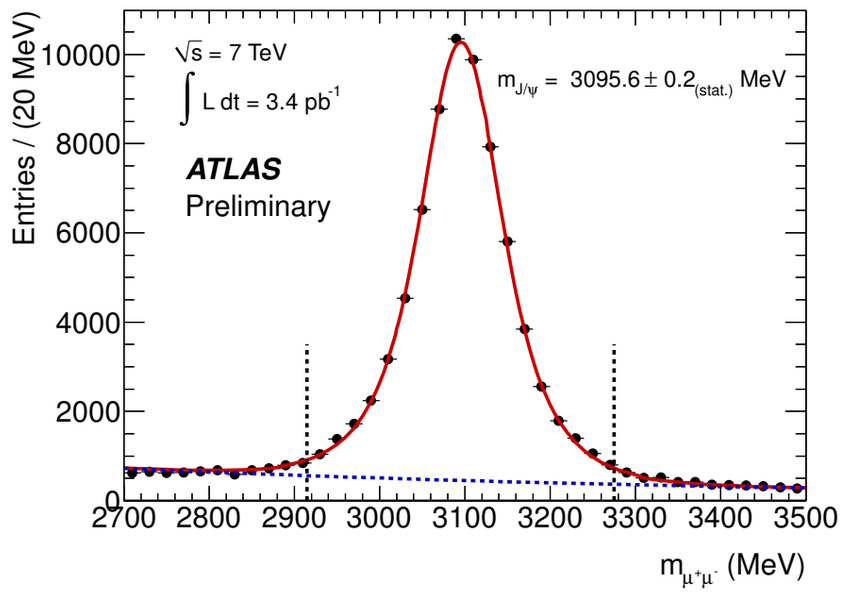



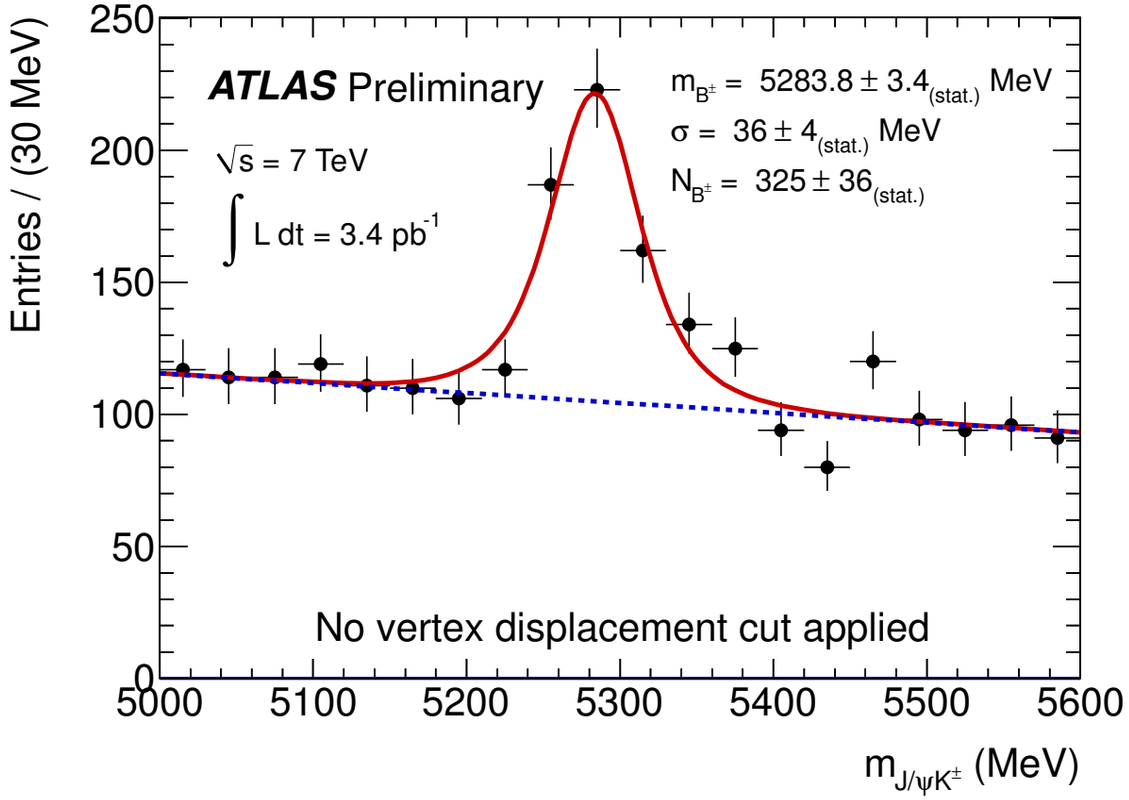

- Predictions from three theoretical models are overlaid.
- Agreement is in general good, with some discrepancy at high $p_T$.
- Important area of future study to provide improvements of understanding in J/ψ production.

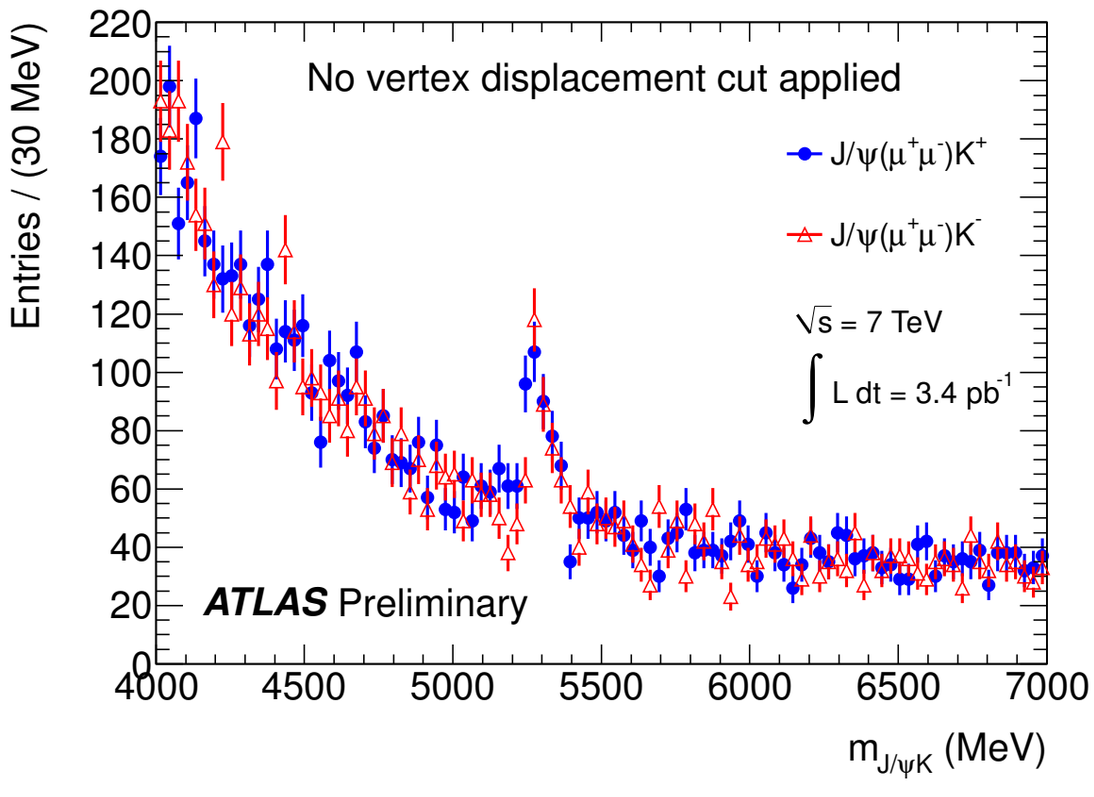
# Observations of B mesons – $B^{\pm} \rightarrow J/\psi(\mu\mu)K^{\pm}$

- Observation in ATLAS of the decay $B^{\pm} \rightarrow J/\psi(\mu\mu)K^{\pm}$
  - Reference channel for other B decay measurements
  - Cross-section imminent
- Data taken from June to August 2010, using single- and di-muon triggers.
- J/ψ candidates selected with additional track
  - assigned mass of Kaon.




- Mass constraint is applied to J/ψ → μμ system and fitted to common vertex with 'kaon'.

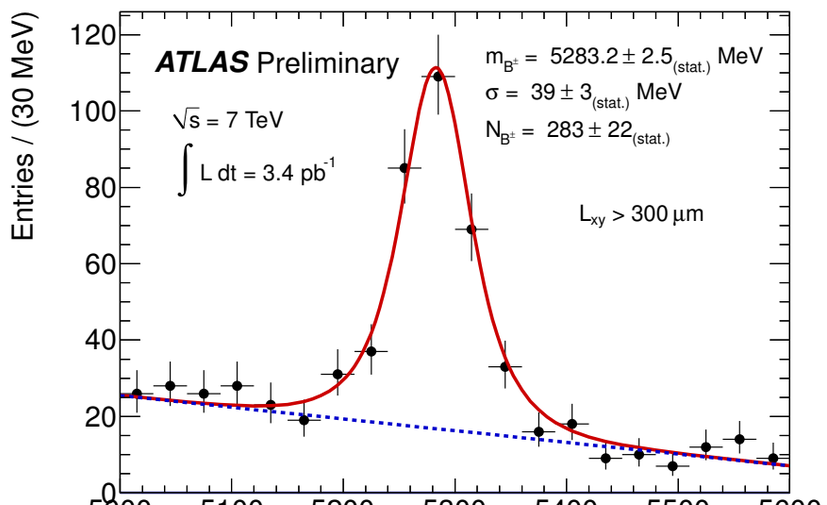


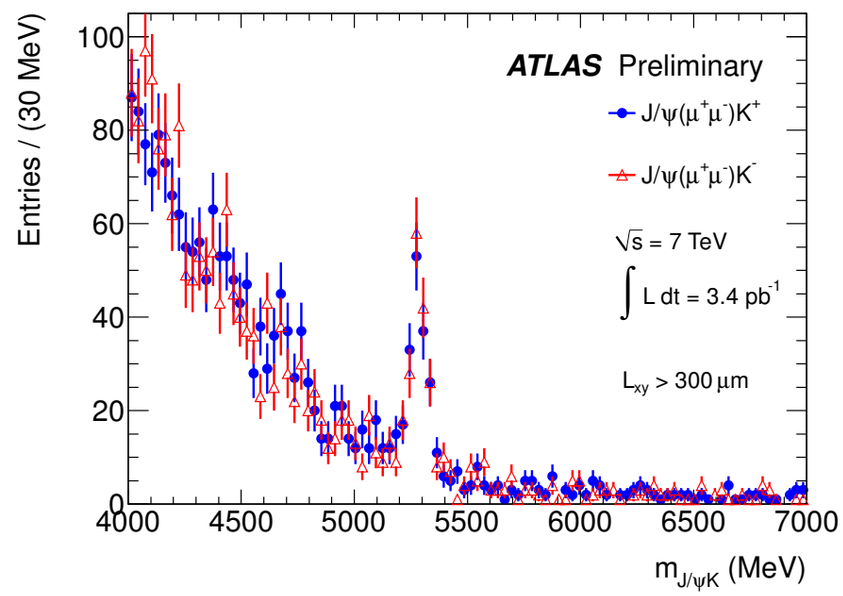




- Signal yield of 325 ± 36 candidates from 3.4 pb$^{-1}$ data.

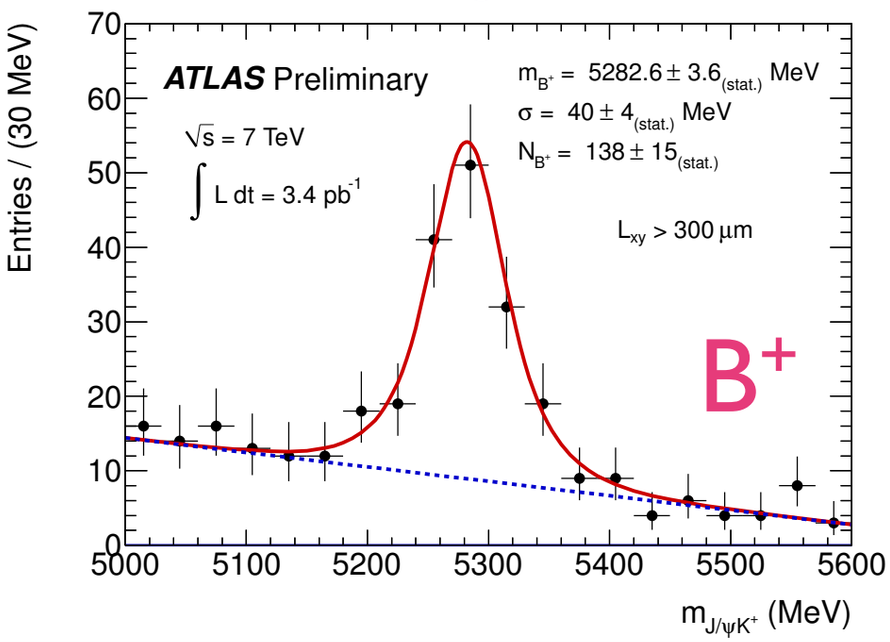
# $B^{\pm} \rightarrow J/\psi(\mu\mu)K^{\pm}$

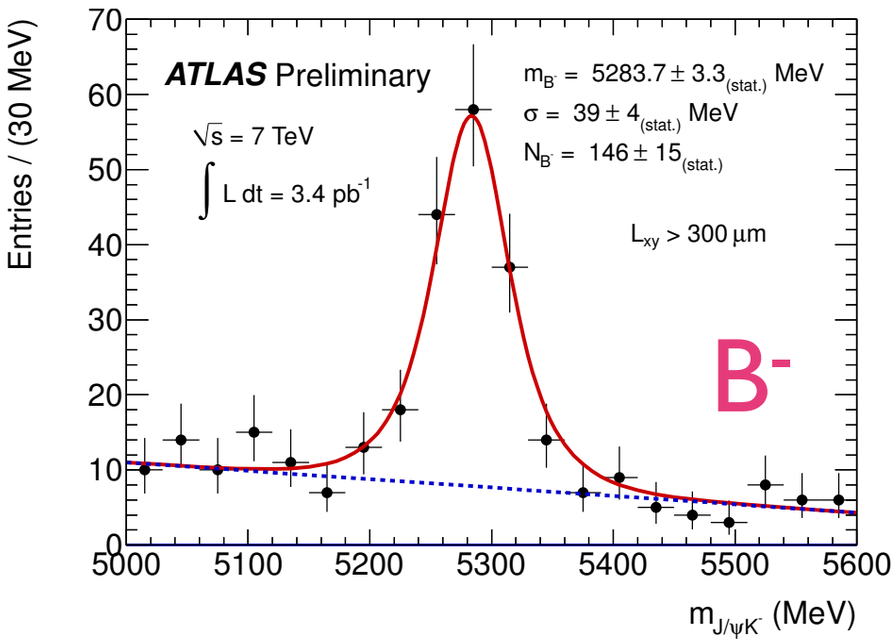
- Further reduction in background contamination can be achieved with a cut on the transverse decay length: $L_{xy} > 0.3$ mm
- Factor of 6 reduction in background with ~13% loss of signal.




- Mass (5283 ± 2.5 MeV) is compatible with PDG value: 5279.17 ± 0.29 MeV.
- Positive and Negative states are observed with consistent fitted parameters.



# Summary and Outlook

- First year of data-taking has been highly successful.
  - Observation of J/ψ and ψ(2S).
  - Observation of the three Upsilon states.
  - D meson states observed and cross section extracted
- $B^{\pm} \rightarrow J/\psi(\mu\mu)K^{\pm}$ observed, $B_d \rightarrow J/\psi(\mu\mu)K^{*0}$, $B_s \rightarrow J/\psi(\mu\mu)\phi$ imminent
- Measurement performed of J/ψ differential cross-section
  - plus fraction of non-prompt to inclusive decays, prompt and non-prompt differential cross-sections.

*https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults*

- Short and longer term plans include
  - Exclusive decays $B_c \rightarrow J/\psi(\mu\mu)\pi$,
  - Continue preparations for searches on rare decays such as $B_s \rightarrow \mu\mu$ and studies into CP violation.
- Updates of current results using full dataset and many more measurements in progress.
- 2011 and beyond promises bring many more exciting results.