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

Wednesday, 16 March 2011
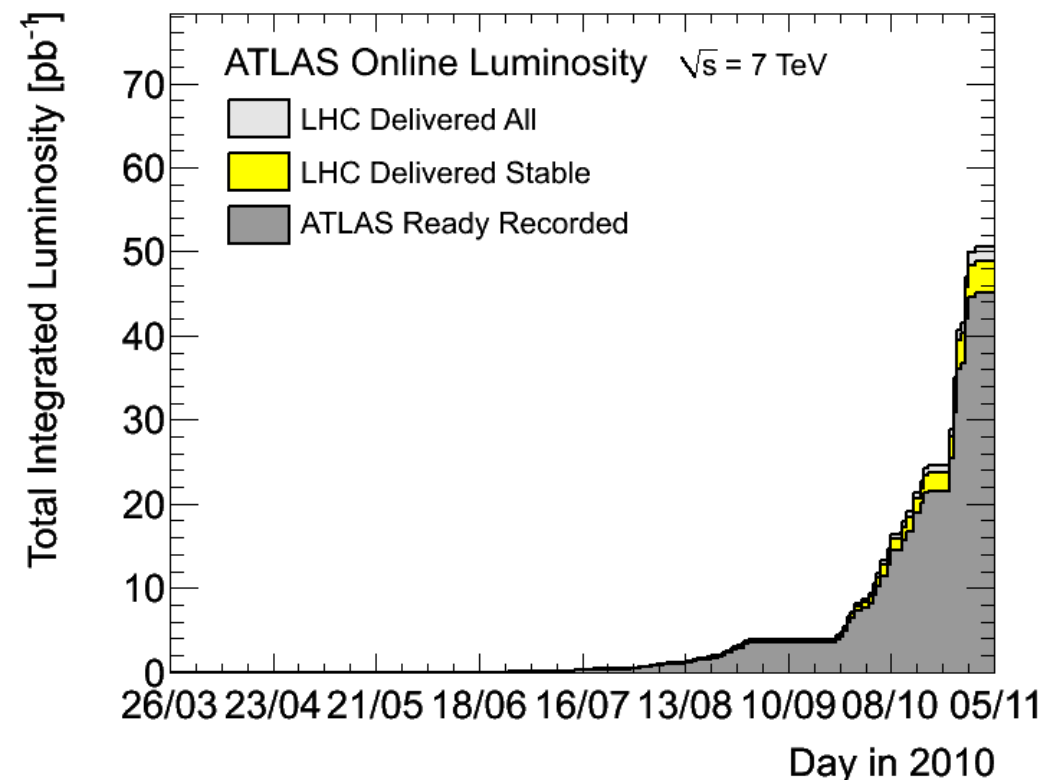
The ATLAS Detector

- 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)
  - $\sigma/p_T \sim 3.4 \times 10\text{-}4\ p_T + 0.015$ for $(|\eta|<1.5)$
  - Used for Tracking and Vertexing:
 - Precise momentum and lifetime measurements
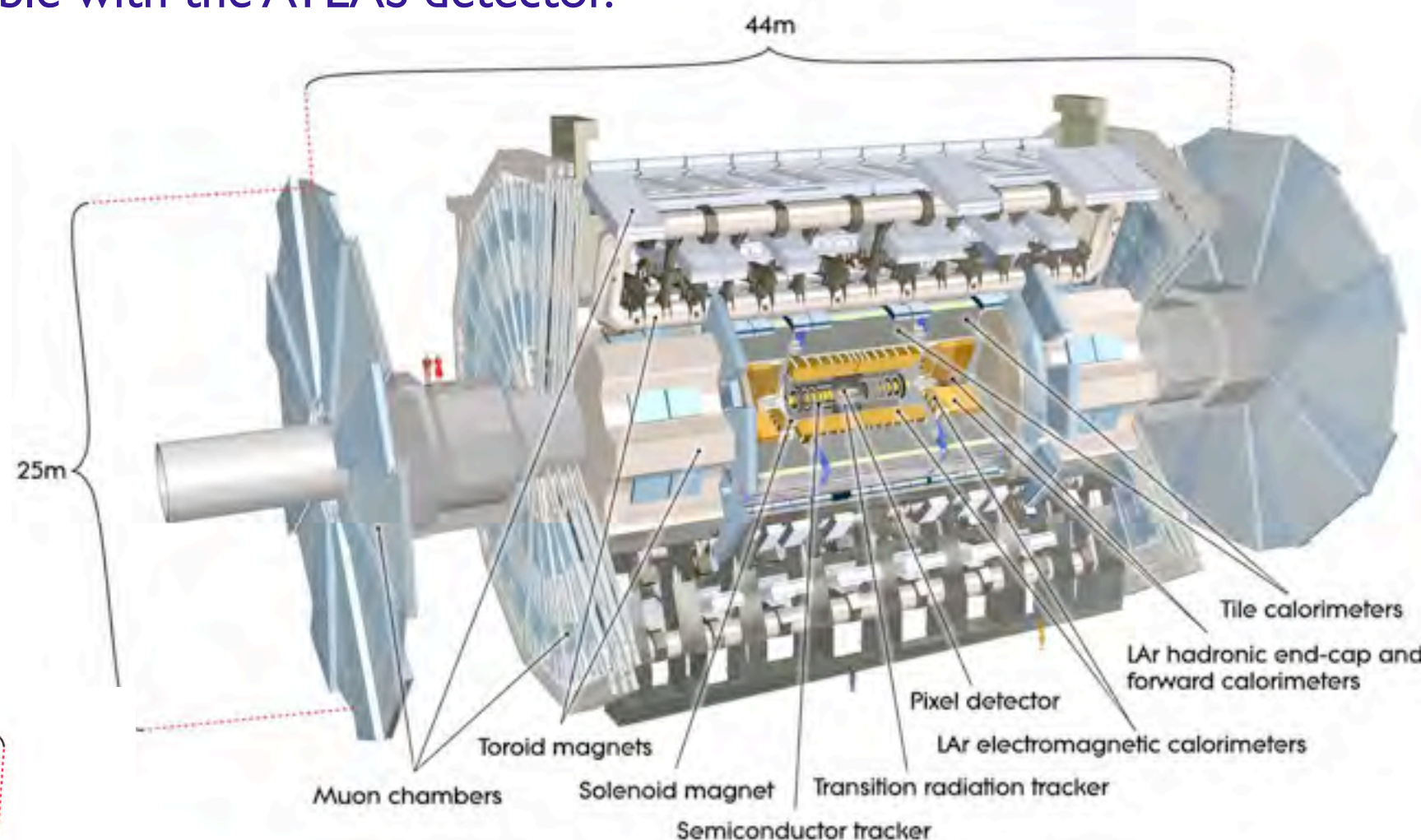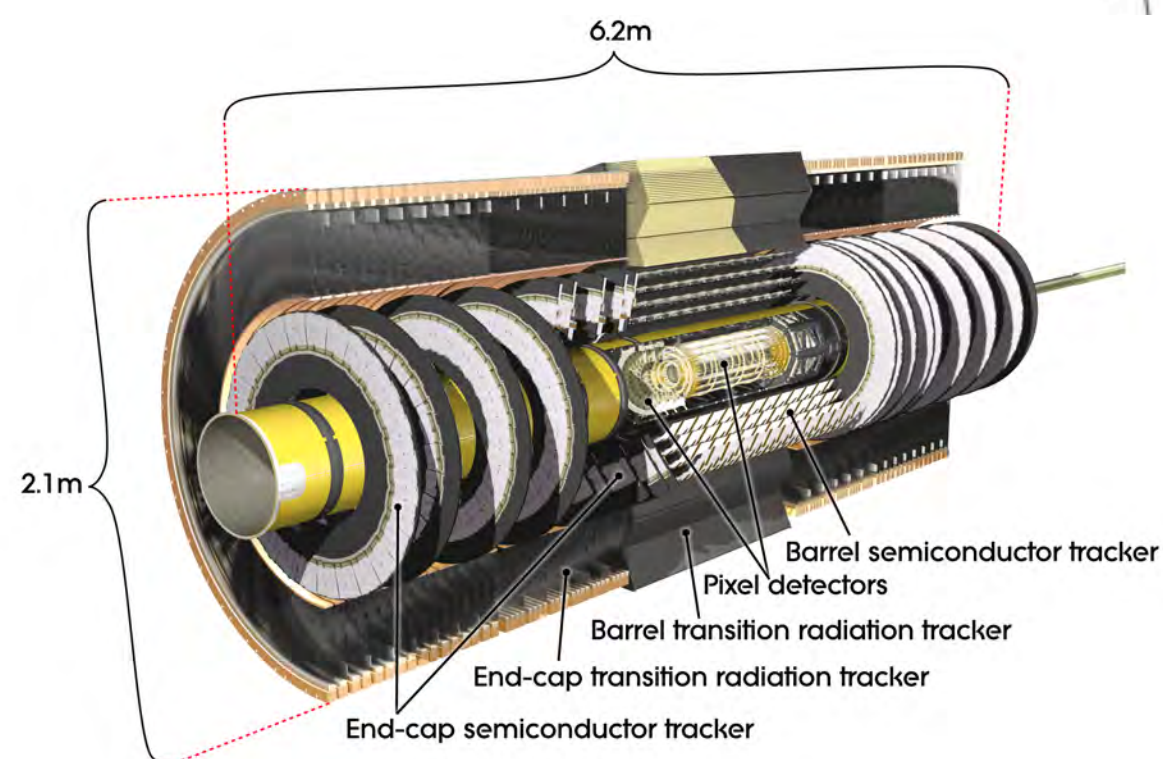
- **Muon Spectrometer**
  - $|\eta|<2.7$
  - Toroid B-Field, average ~0.5T
  - Muon Momentum resolution $\sigma/p< 10\%$ up to ~ 1 TeV

Wednesday, 16 March 2011
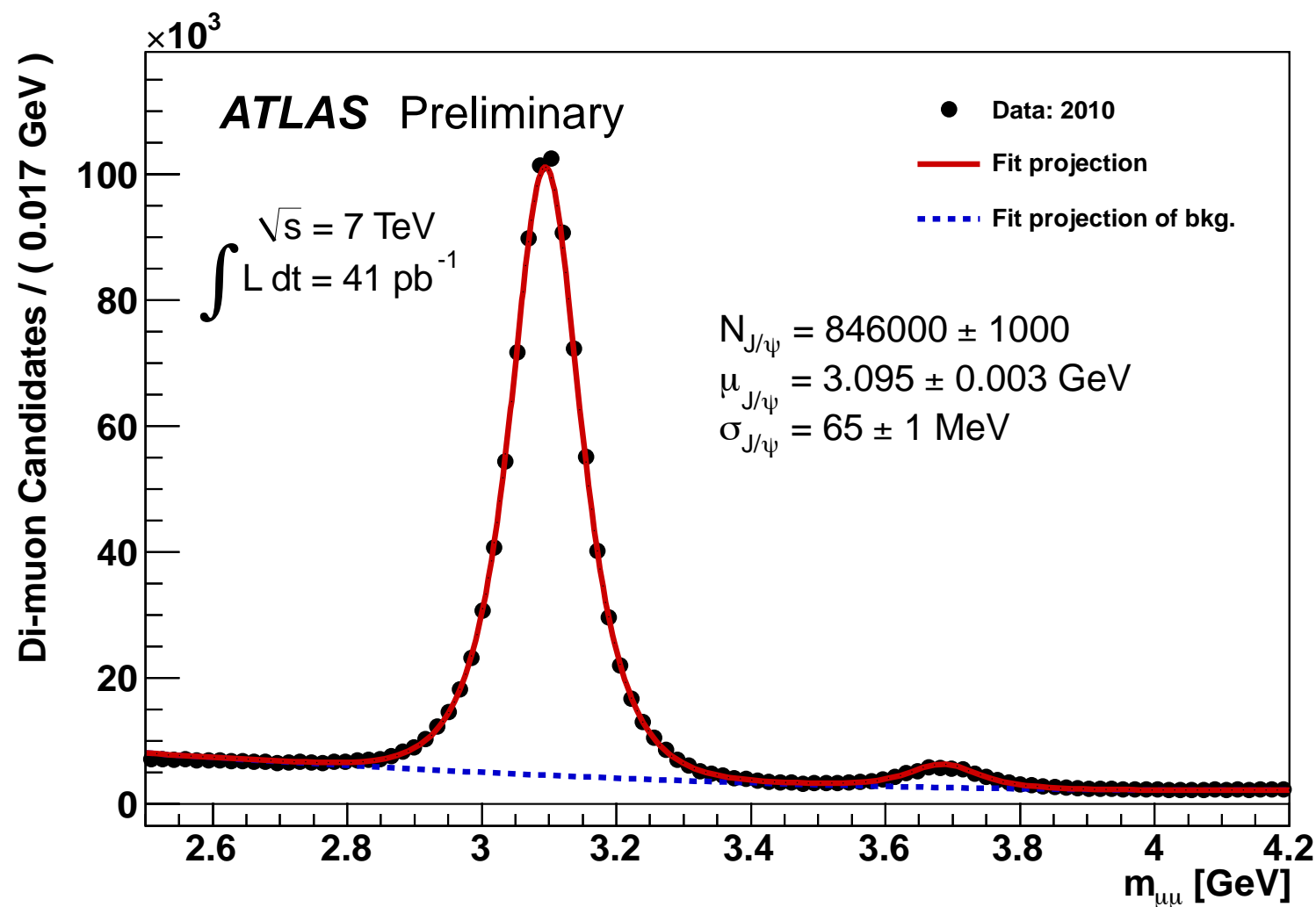
Muon Trigger and Performance

- Muon identification is key to many B-physics analyses:

  - Clean trigger signature.

- Ever increasing instantaneous luminosity requires 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.
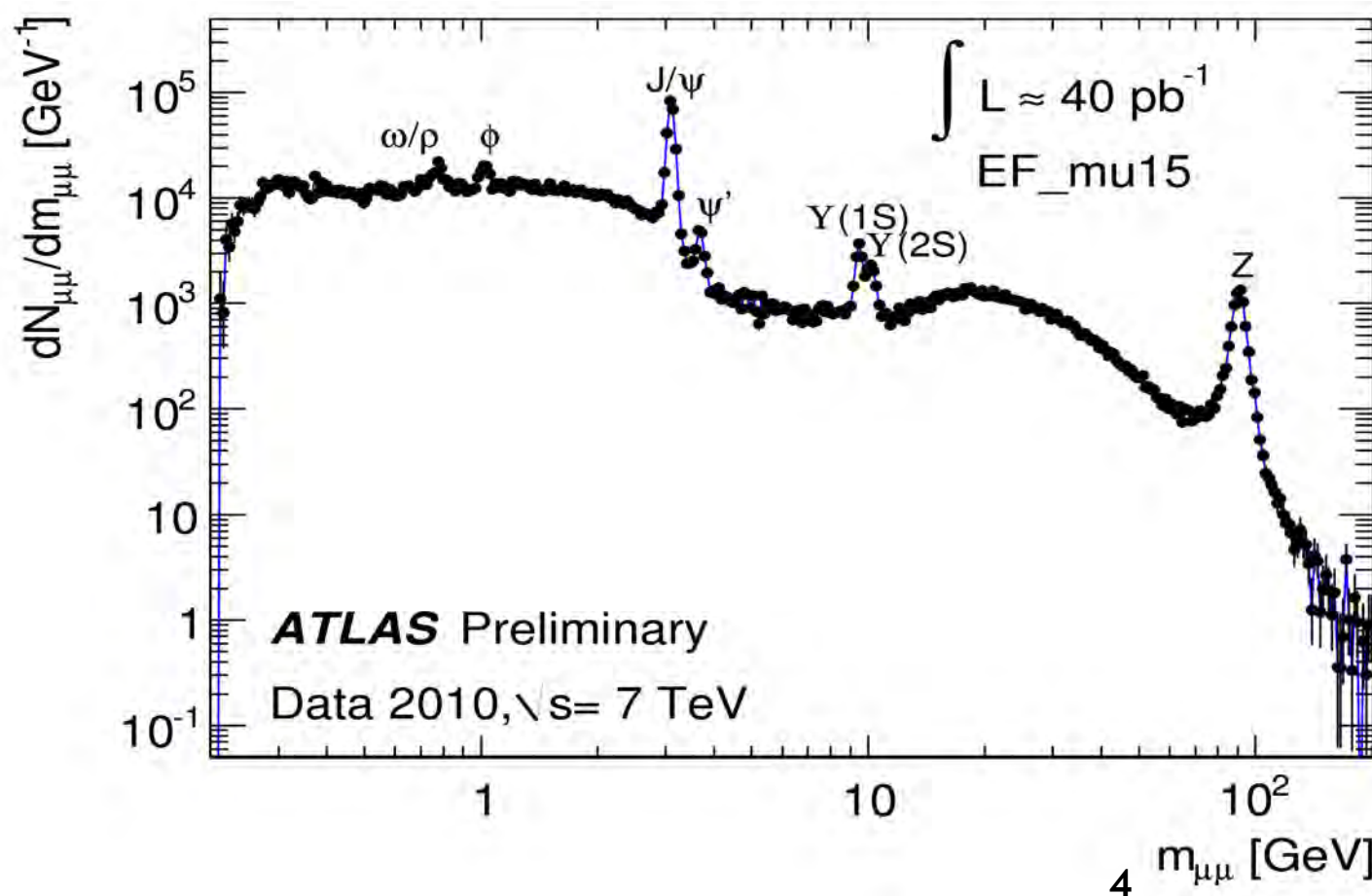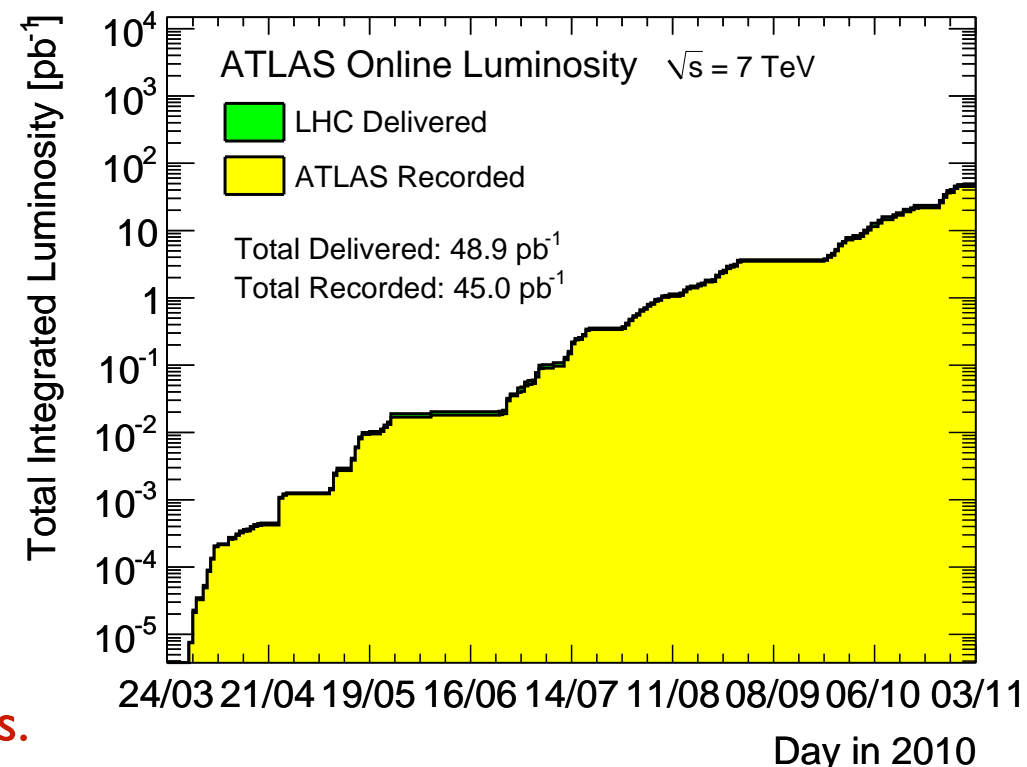
One muon p_T >15 GeV, other p_T > 2.5 GeV

Roger Jones

Wednesday, 16 March 2011

Charmonium Observations

- Key signatures of B-meson decays go through Charmonium states.
  - e.g. $B_d \rightarrow J/\psi(\mu\mu)K_s$, $B_s \rightarrow J/\psi(\mu\mu)\Phi$;

- 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 $\psi(2S)$ from all recorded pp 7 TeV, 2010 data passing a suite of muon-based triggers.
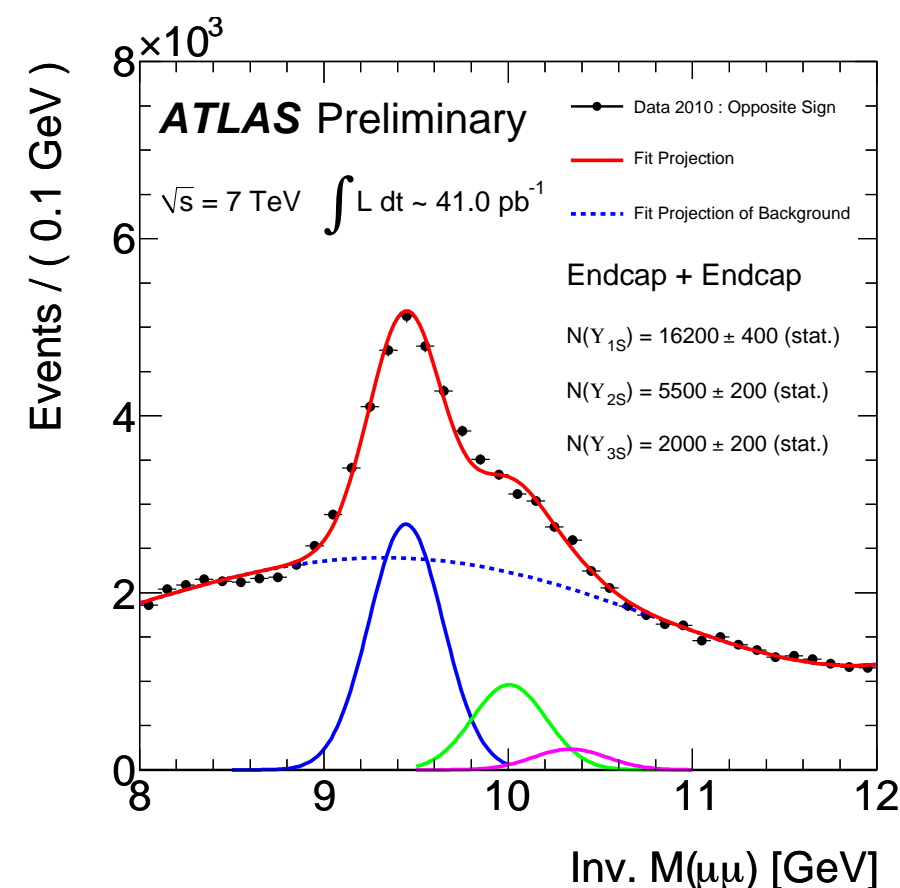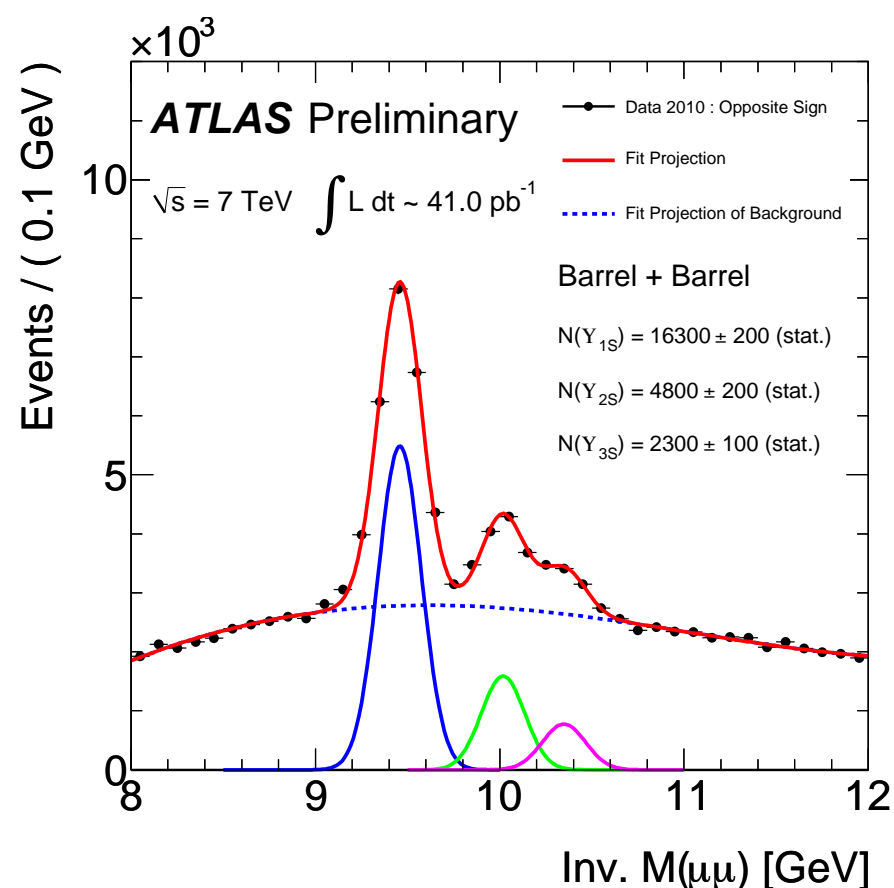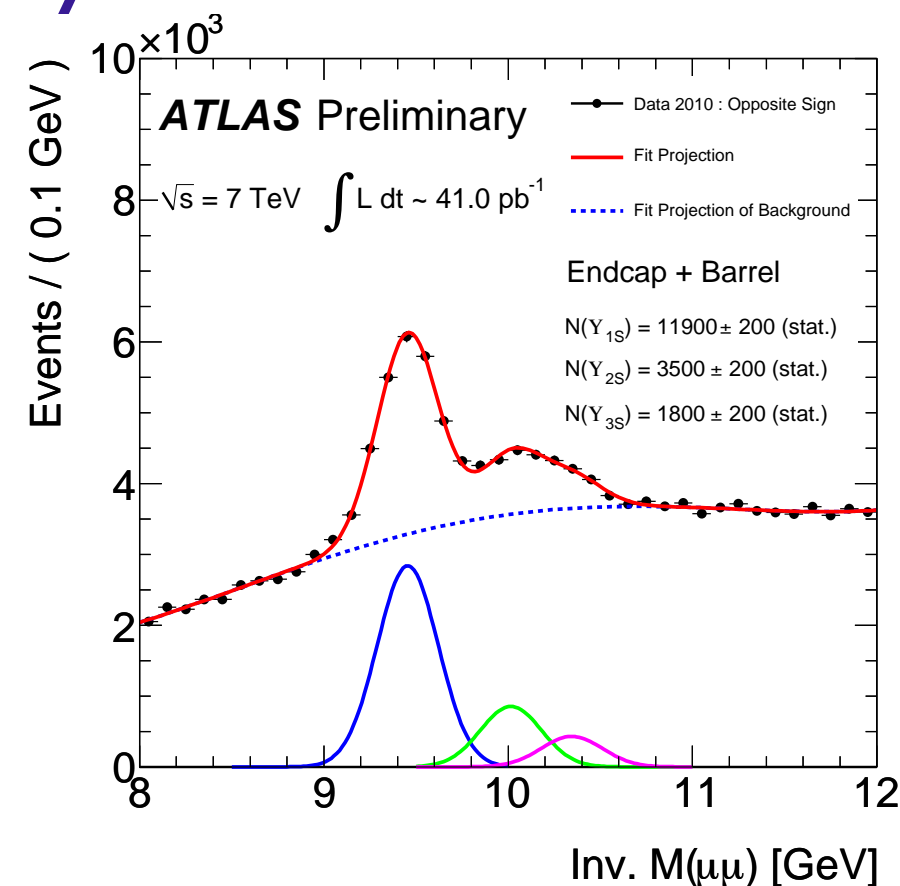

ATLAS Preliminary

Data: 2010

Fit projection

Fit projection of bkg.

$\sqrt{s} = 7$ TeV

$\int L\, dt = 41$ pb^{-1}

$N_{J/\psi} = 846000 \pm 1000$

$\mu_{J/\psi} = 3.095 \pm 0.003$ GeV

$\sigma_{J/\psi} = 65 \pm 1$ MeV

Di-muon Candidates / (0.017 GeV)

$m_{\mu\mu}$ [GeV]

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

- Mass position in good agreement with PDG expectations:

- $M(J/\psi) = 3095 \pm 3$ (syst.) MeV
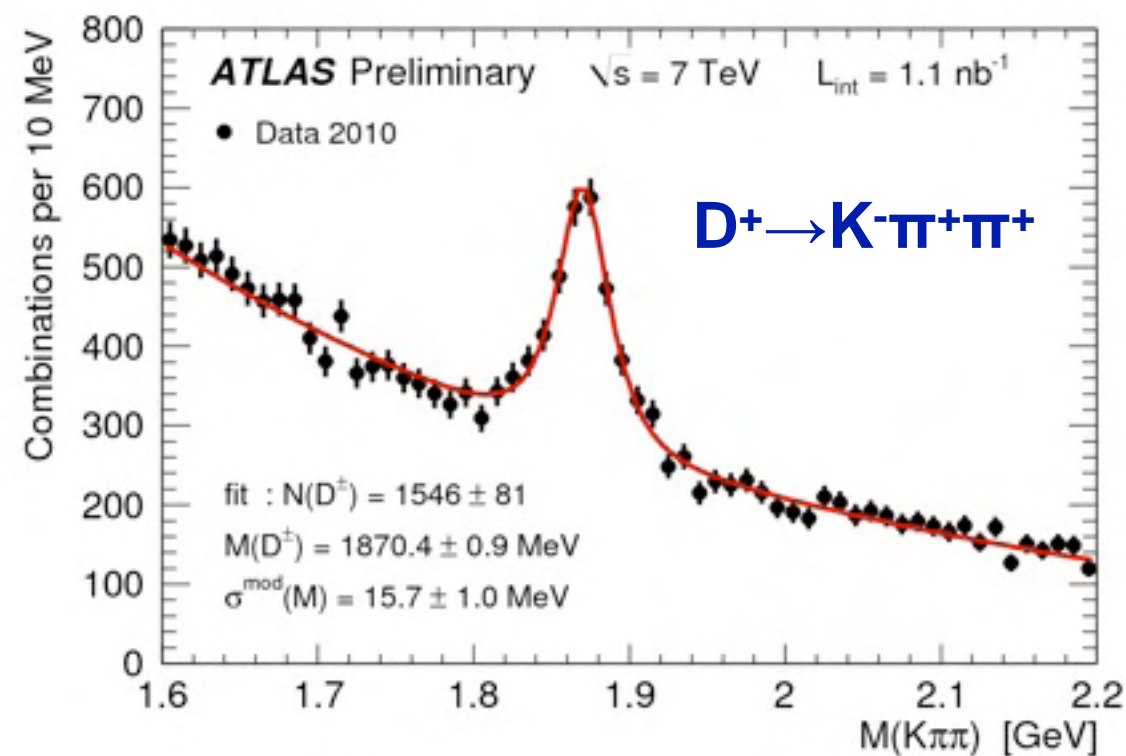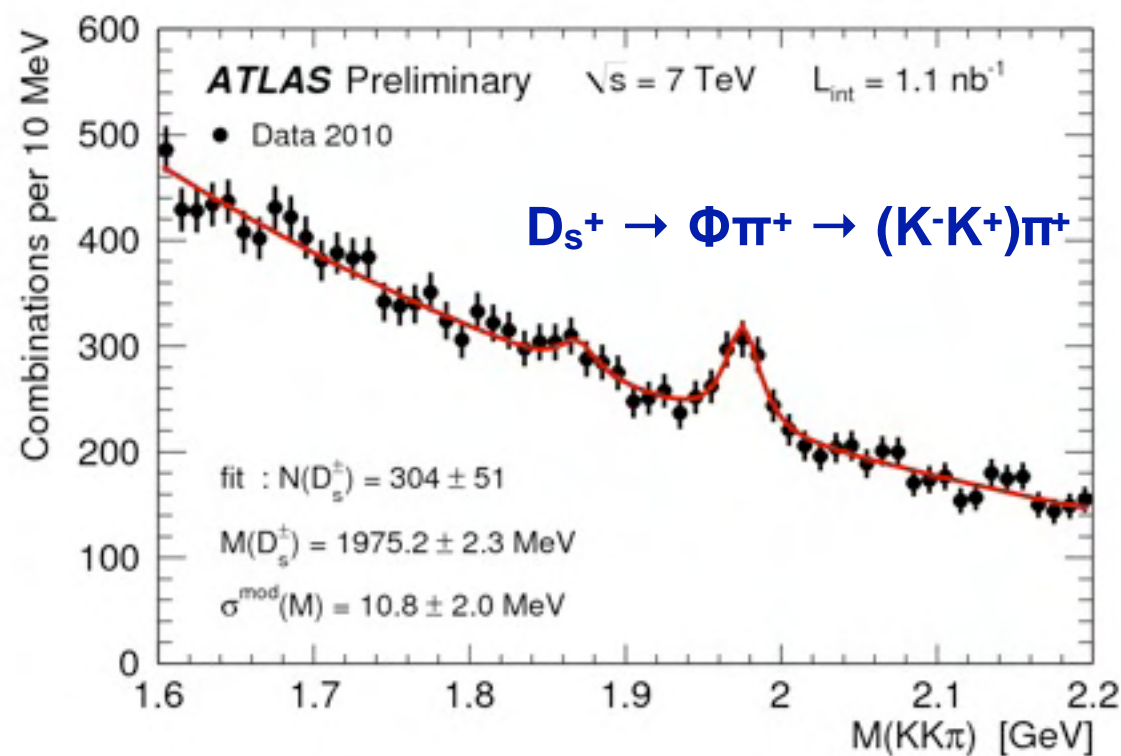
- $M_{PDG} = 3096.916 \pm 0.011$ MeV

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.

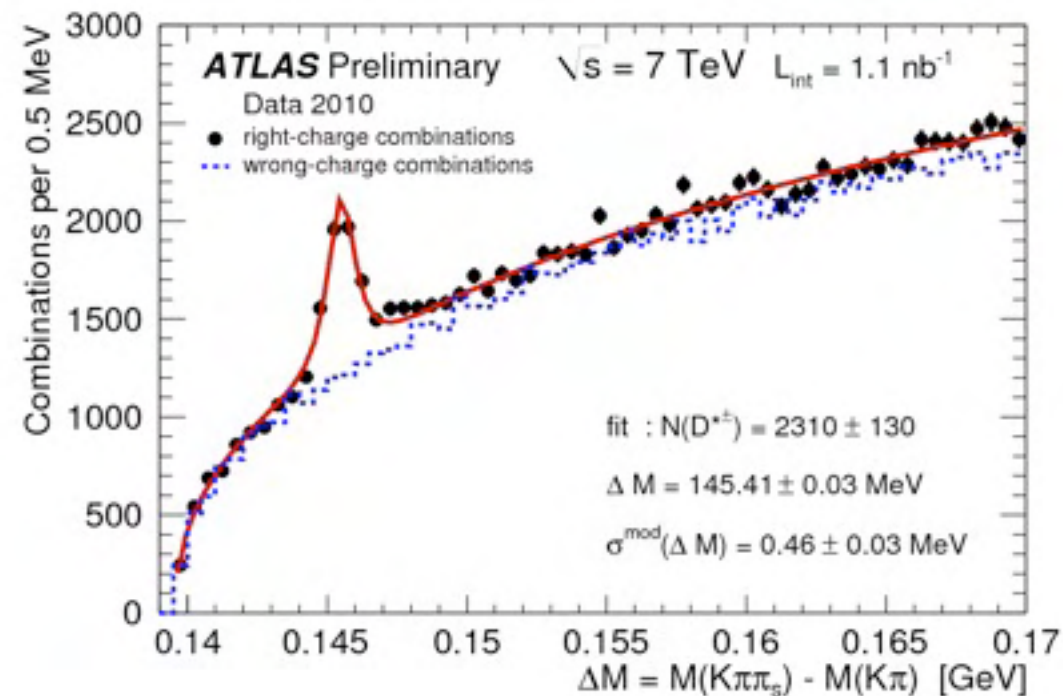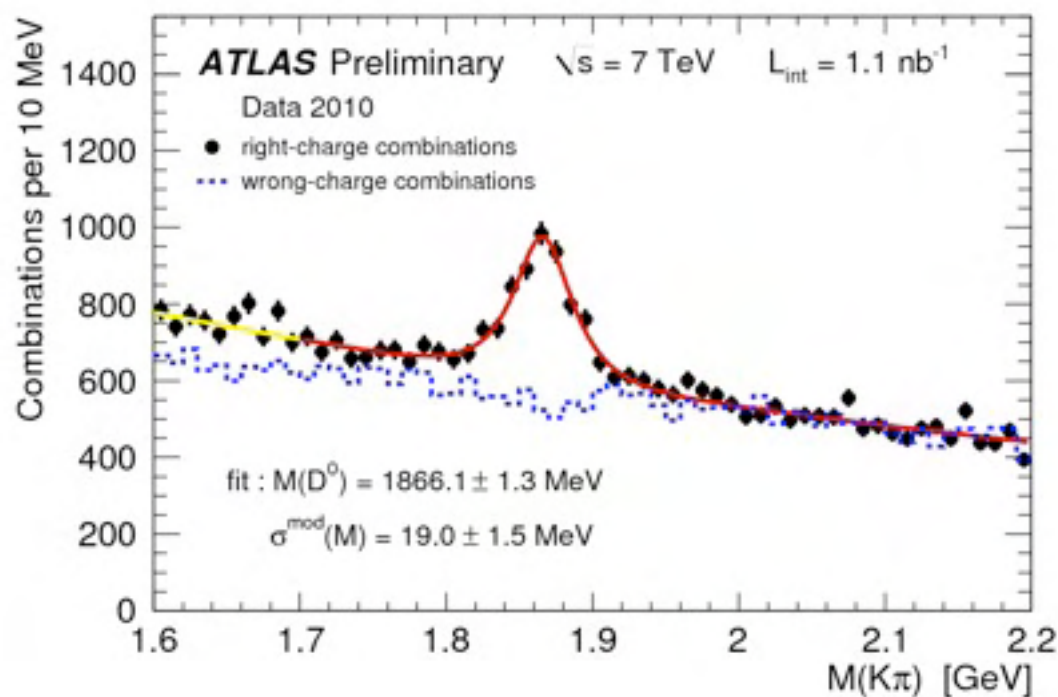 - Cross-section measurement in progress.

ATLAS Preliminary
$\sqrt{s}$ = 7 TeV $\int L\, dt$ ~ 41.0 pb^{-1}

Endcap + Barrel
$N(Y_{1S})$ = 11900 ± 200 (stat.)
$N(Y_{2S})$ = 3500 ± 200 (stat.)
$N(Y_{3S})$ = 1800 ± 200 (stat.)

Data 2010 : Opposite Sign
Fit Projection
Fit Projection of Background

Inv. M(μμ) [GeV]

ATLAS Preliminary
$\sqrt{s}$ = 7 TeV $\int L\, dt$ ~ 41.0 pb^{-1}

Barrel + Barrel
$N(Y_{1S})$ = 16300 ± 200 (stat.)
$N(Y_{2S})$ = 4800 ± 200 (stat.)
$N(Y_{3S})$ = 2300 ± 100 (stat.)

Data 2010 : Opposite Sign
Fit Projection
Fit Projection of Background

Inv. M(μμ) [GeV]

ATLAS Preliminary
$\sqrt{s}$ = 7 TeV $\int L\, dt$ ~ 41.0 pb^{-1}

Endcap + Endcap
$N(Y_{1S})$ = 16200 ± 400 (stat.)
$N(Y_{2S})$ = 5500 ± 200 (stat.)
$N(Y_{3S})$ = 2000 ± 200 (stat.)

Data 2010 : Opposite Sign
Fit Projection
Fit Projection of Background

Inv. M(μμ) [GeV]

Wednesday, 16 March 2011

D Mesons

- ATLAS is also measuring production of charm mesons

$D_s^+ \rightarrow \Phi\pi^+ \rightarrow (K^-K^+)\pi^+$

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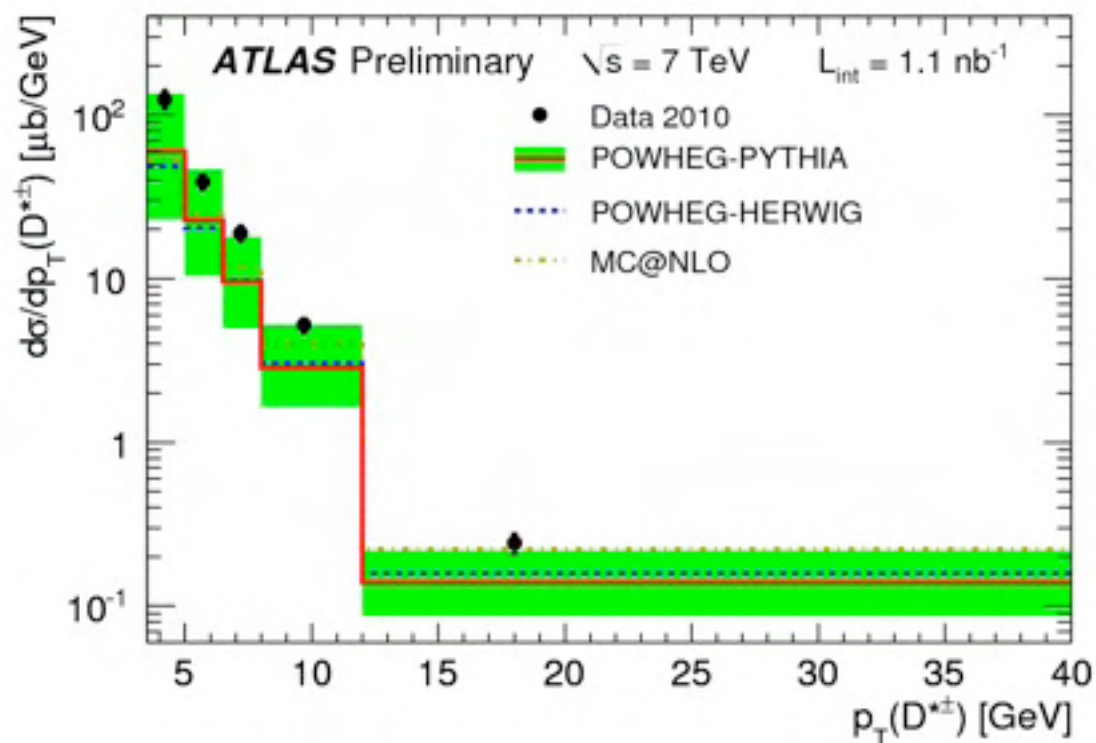
$D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+)\pi^+$

Wednesday, 16 March 2011

Differential Cross-sections extracted

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

Wednesday, 16 March 2011
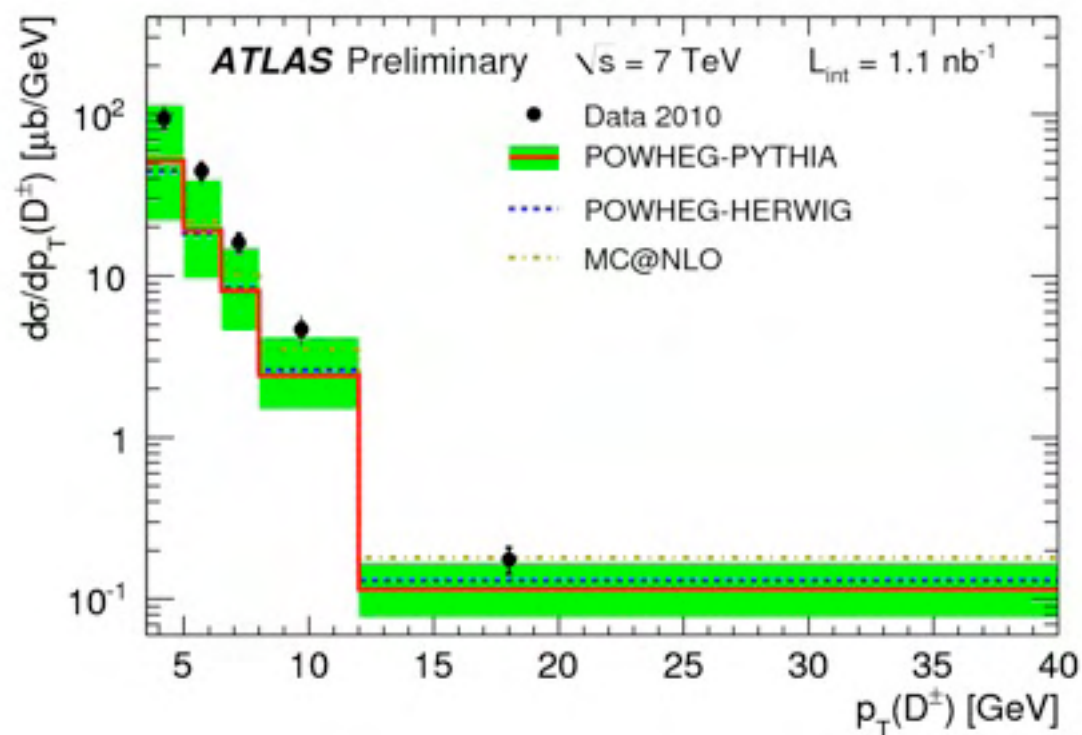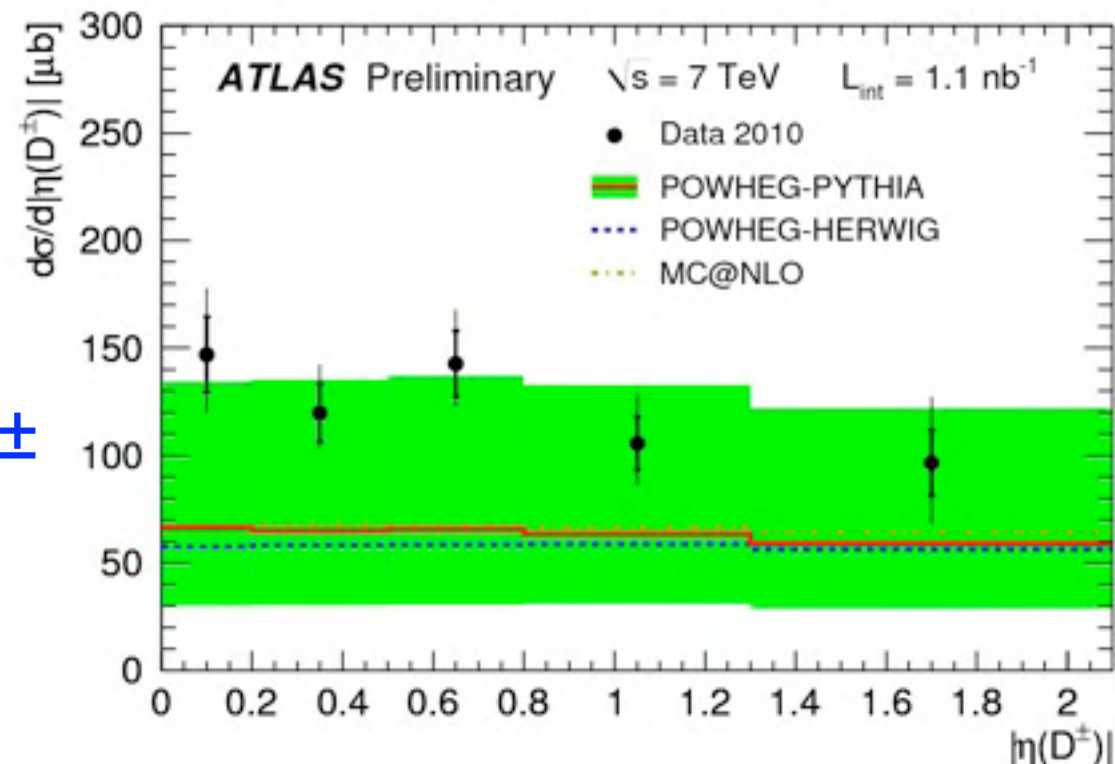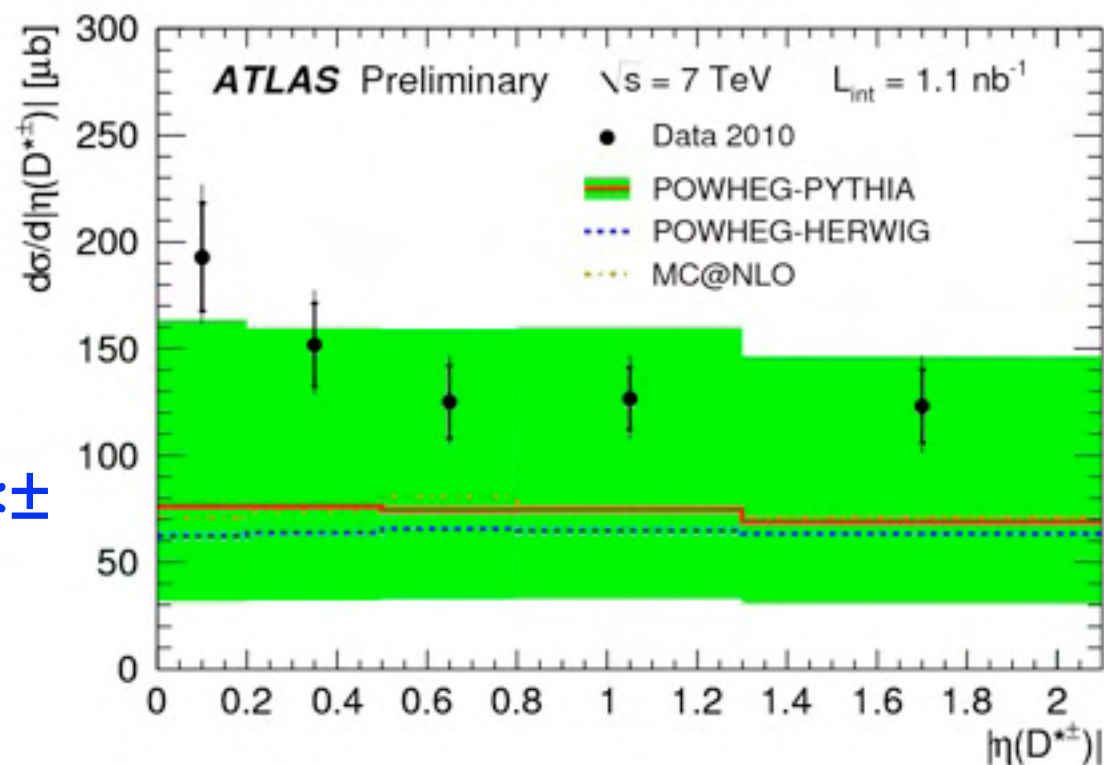
J/ψ Differential Cross-Section

- 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.

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

  - 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

LANCASTER
UNIVERSITY

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}.

Combined muon

Muon spectrometer   Calorimeters   Inner

Tagged muon

- 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.
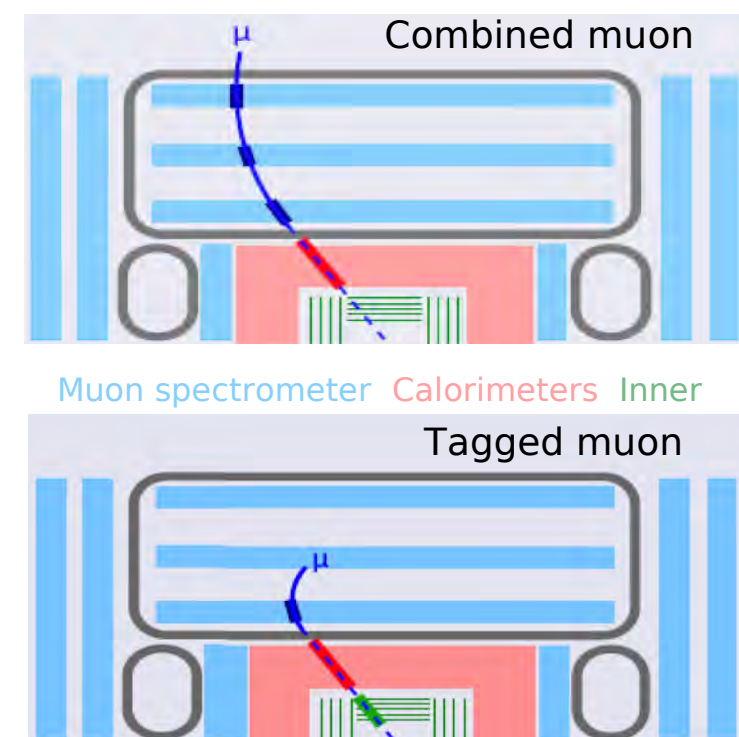
Event Weighting

- 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.

LANCASTER
UNIVERSITY

Wednesday, 16 March 2011

- 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.

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

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

**ATLAS** **CMS** **LHCb**
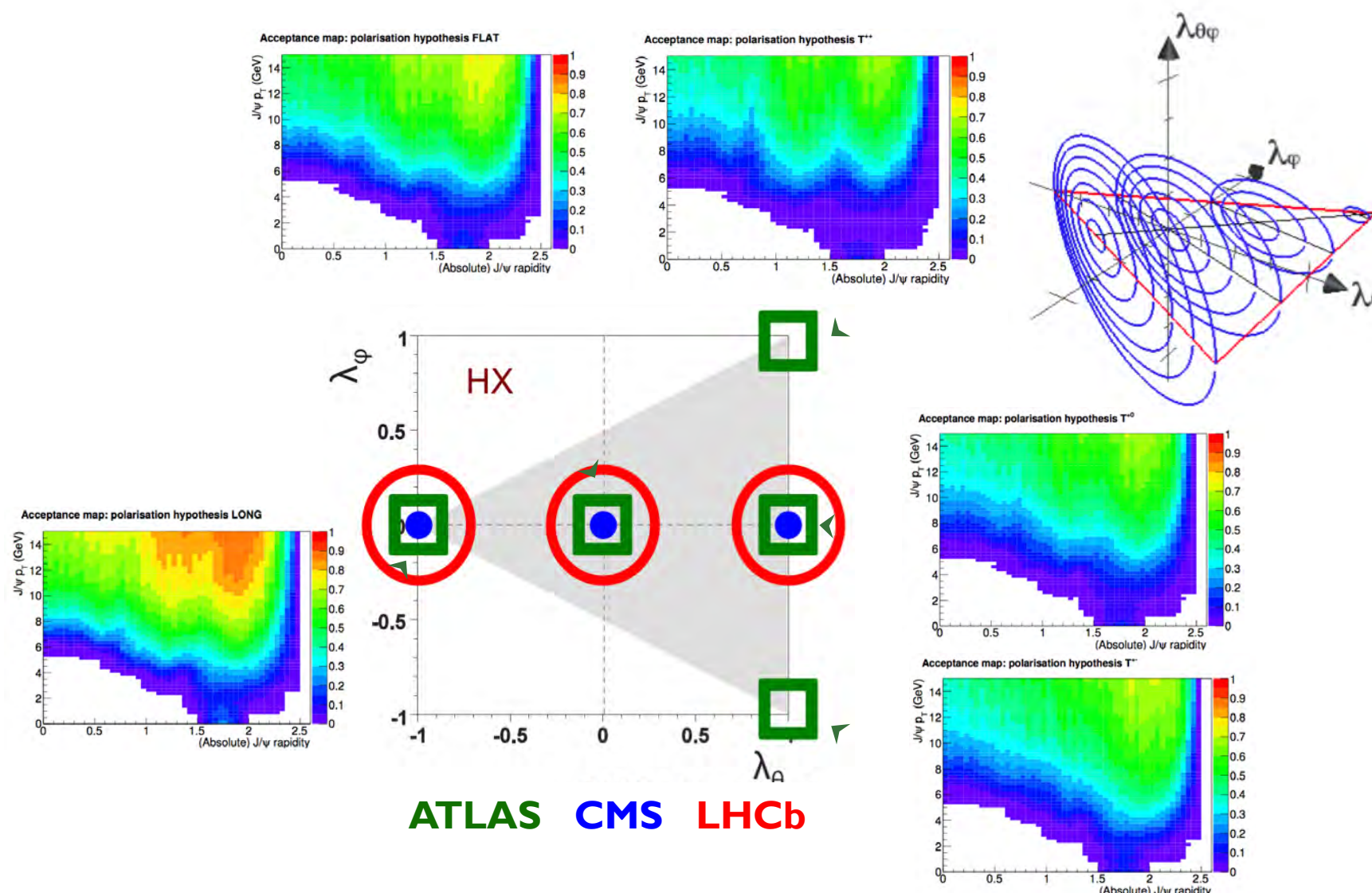
Inclusive Differential Cross-Section
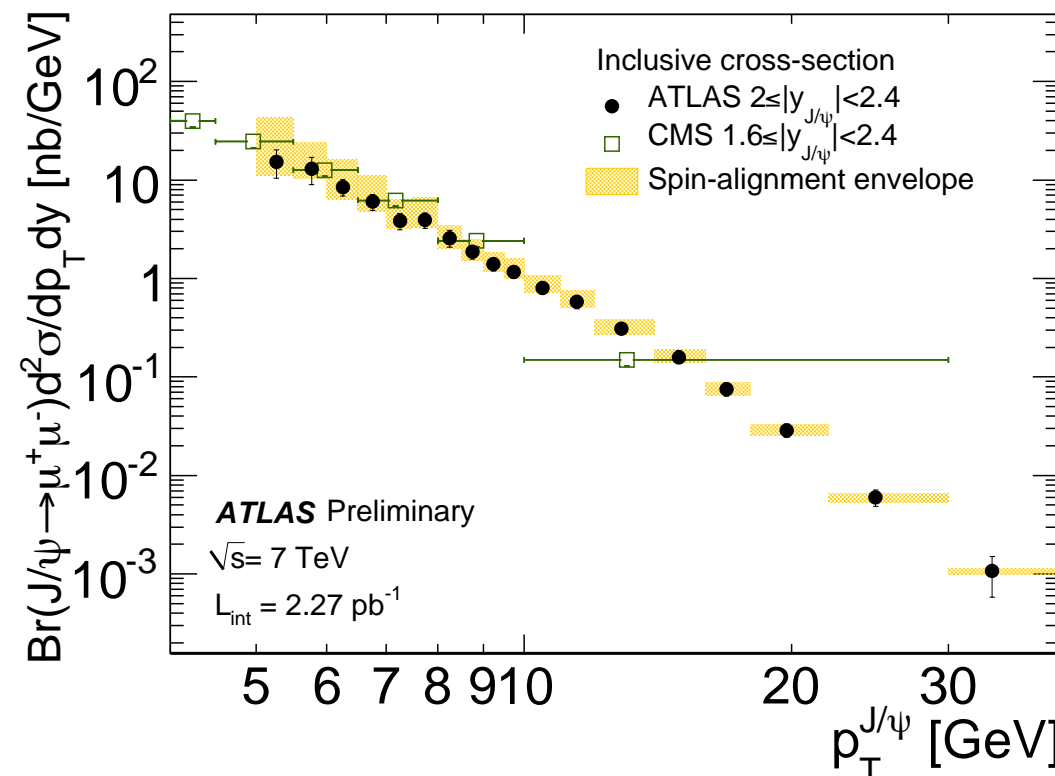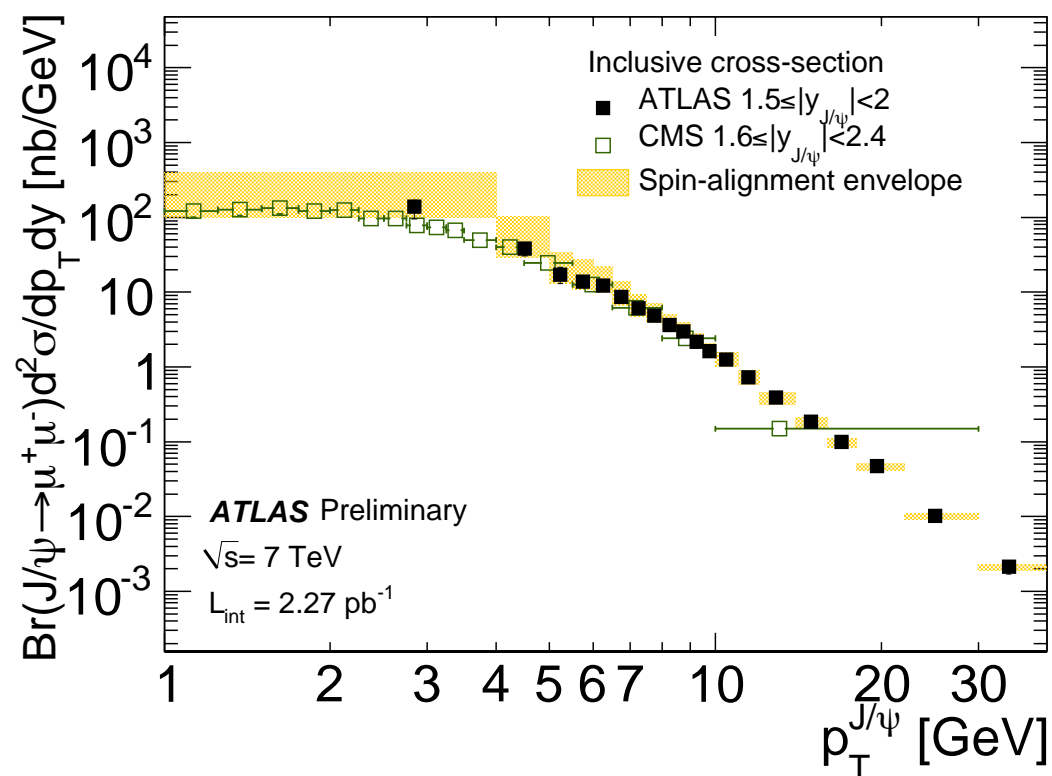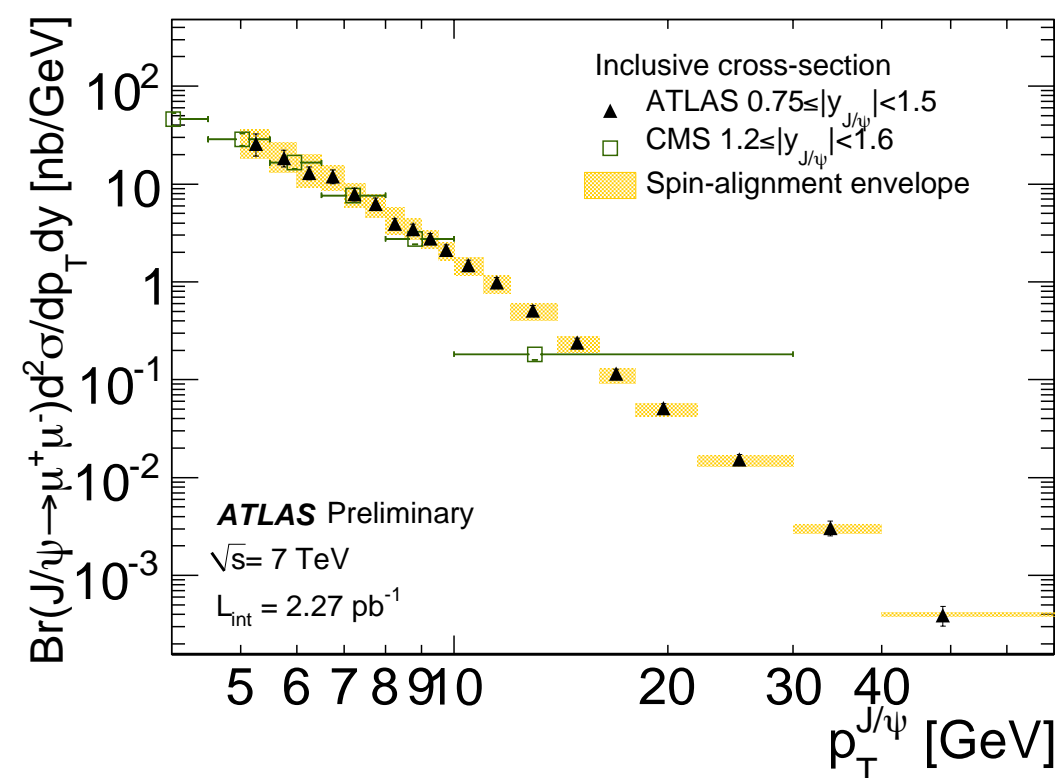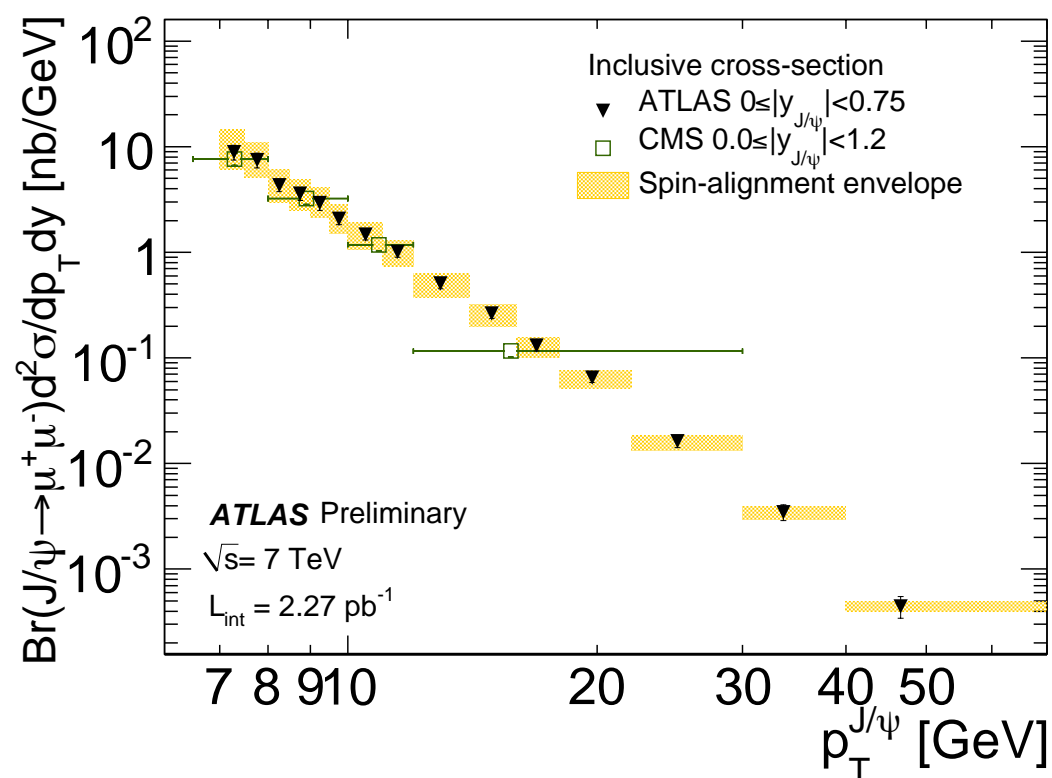
- Central points from "Flat" spin-alignment hypothesis, Yellow is envelope of all hypotheses.

- Good agreement with CMS, generally reduced uncertainties

Wednesday, 16 March 2011

Non-Prompt Fraction Measurement

- Decays to J/ψ can proceed via various mechanisms:

  - Direct proc... m prompt production and decays of heavier charmonium (χ_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.

Prompt to Non-Prompt J/ψ Production Cross-Section Ratio

$$R = \frac{d\sigma(pp \to b\bar{b}X \to J/\psi X)}{d\sigma(pp \to J/\psi X)}$$

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

xy displacement of candidate from PV

Invariant mass of candidate

p_T of candidate

- Pseudo-proper lifetime discriminates between "prompt" & "non-prompt" decays.

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

- Simultaneous maximum likelihood fit performed to <u>mass</u> and <u>lifetime</u> distributions to extract ratio in many bins of J/ψ y, p_T.

non-prompt component

prompt component

pseudoproper time (ps)

Wednesday, 16 March 2011
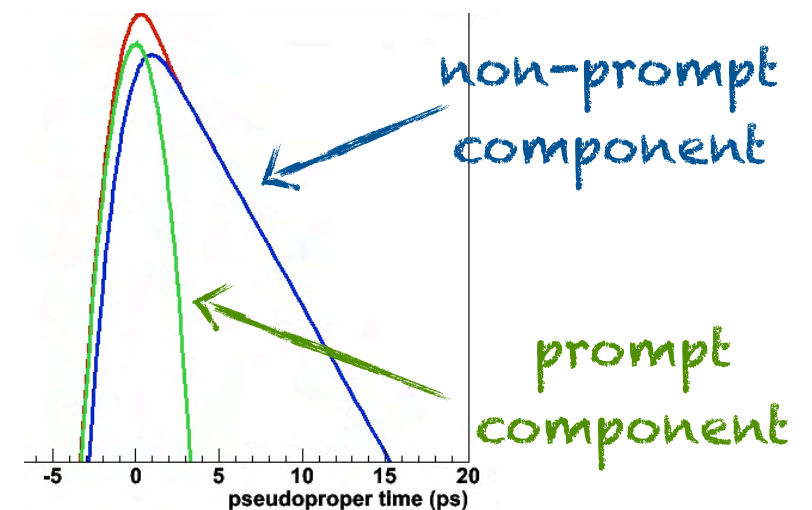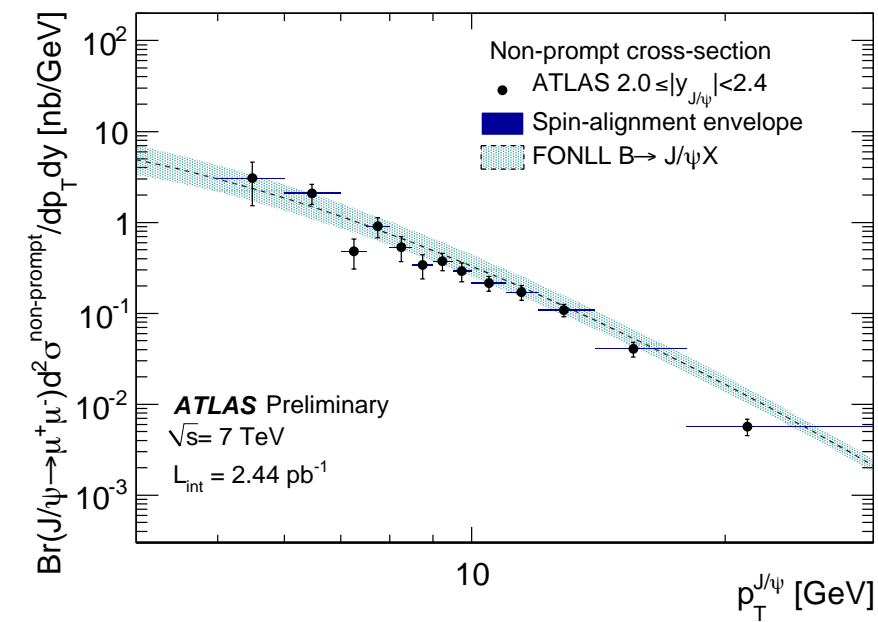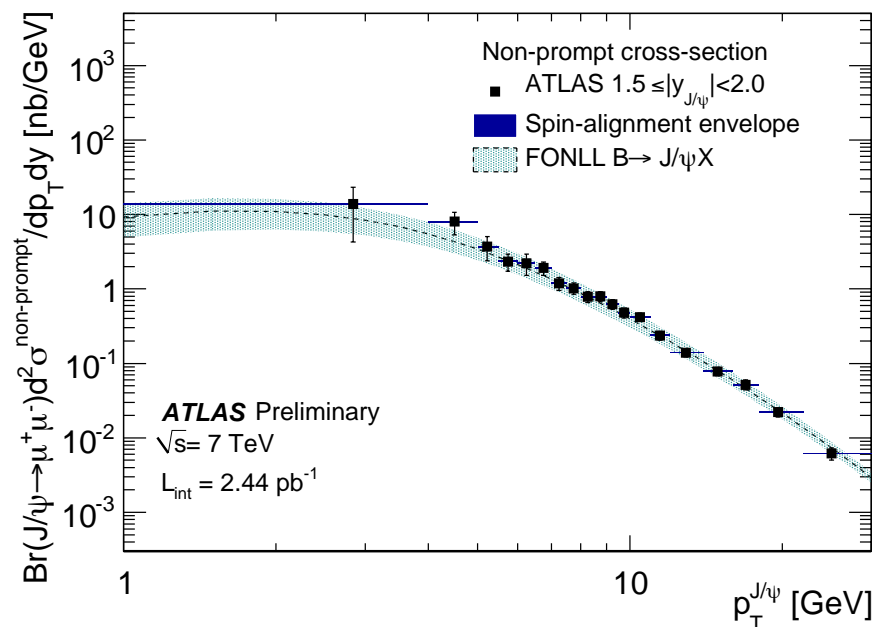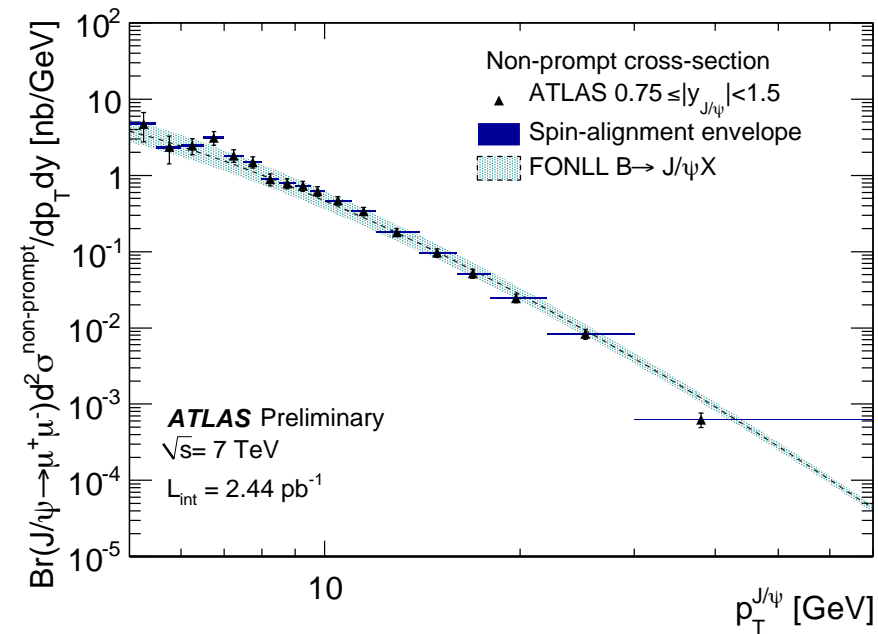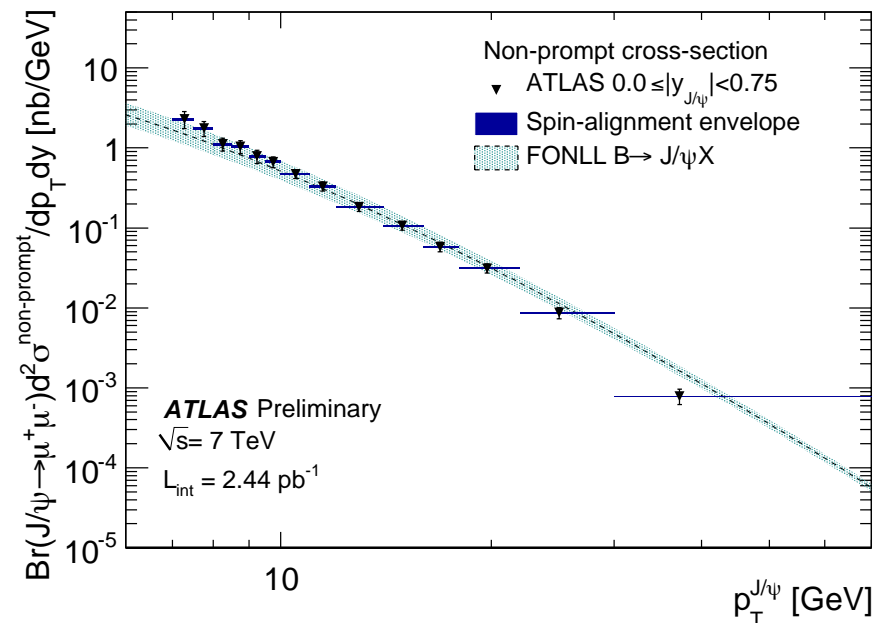
Non-Prompt Fraction

- Non-prompt fraction as a function of J/Ψ transverse momentum for each of the rapidity regions.
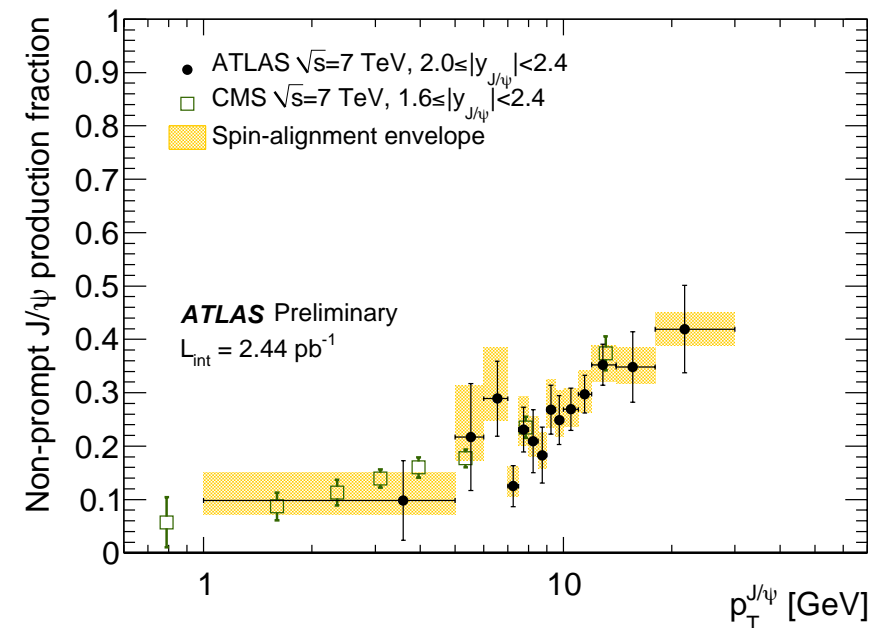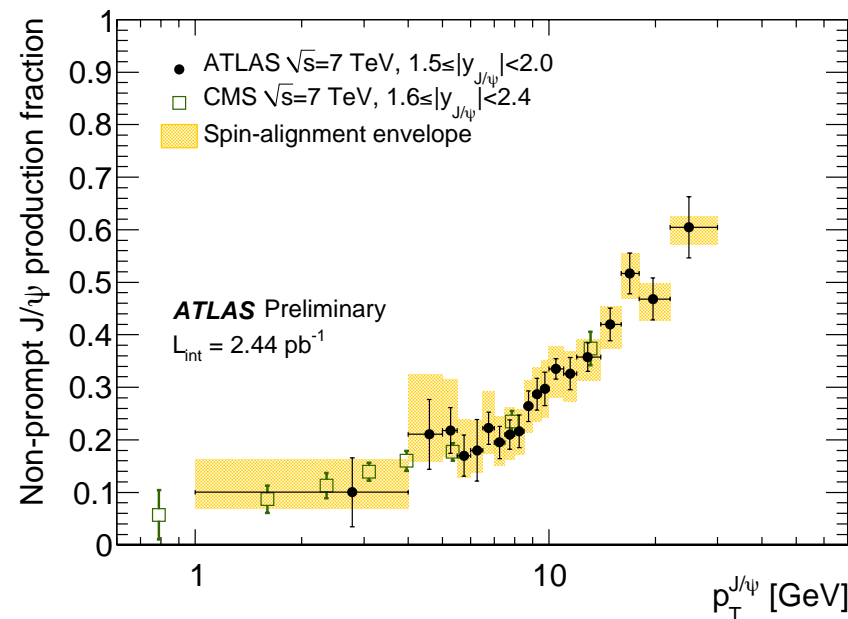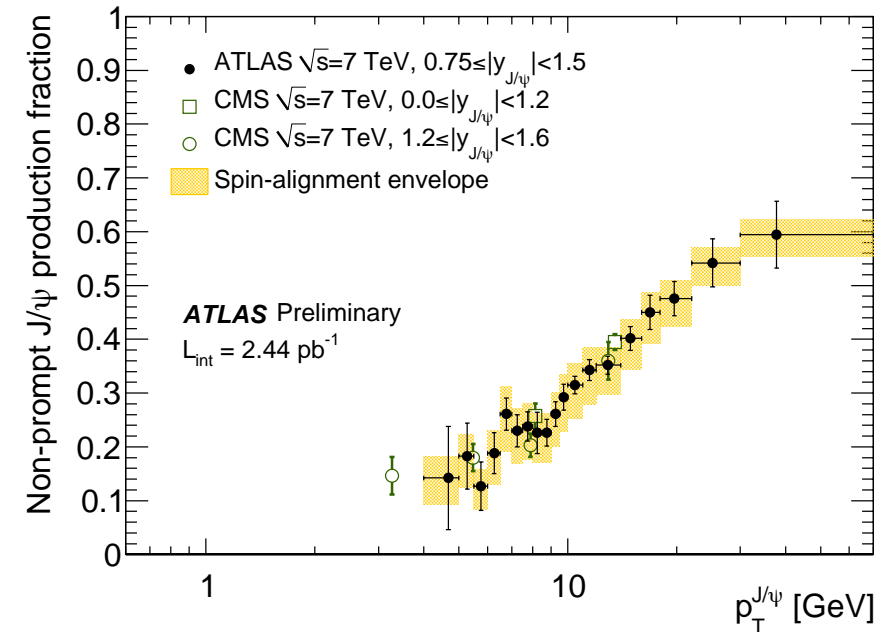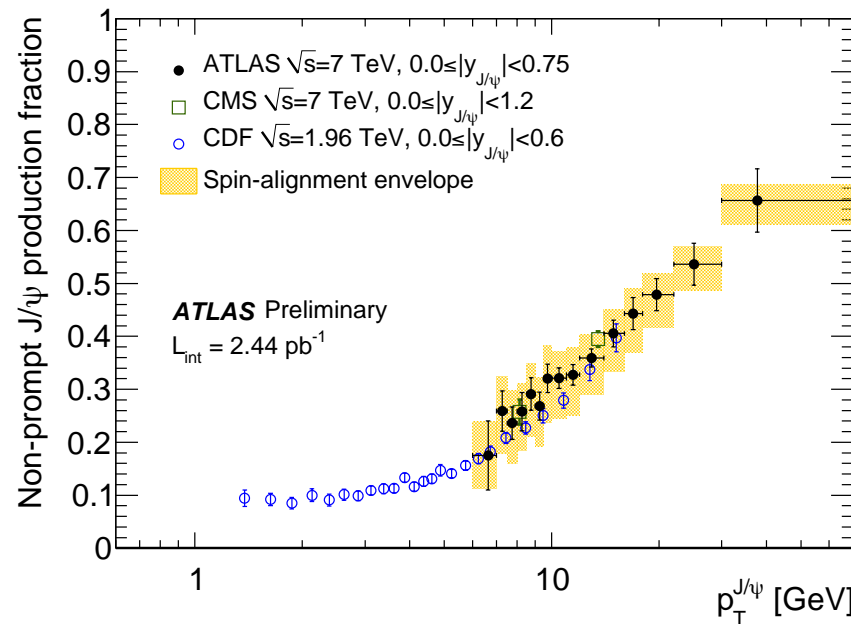
- Agreement is good compared to other experiments.

Wednesday, 16 March 2011

Non-Prompt Cross-Section

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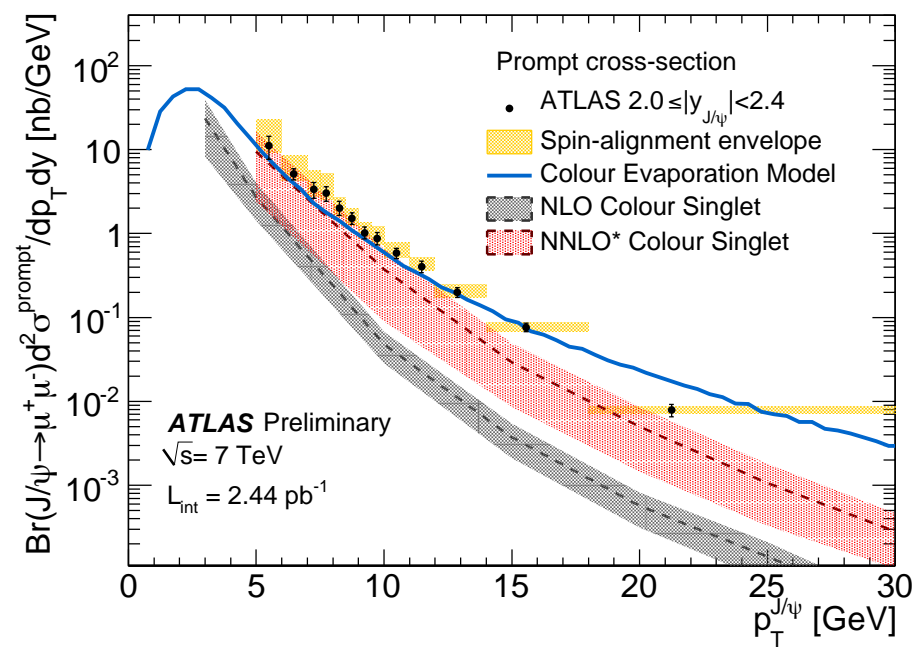

- Agreement is good with predictions.

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.

Wednesday, 16 March 2011

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.
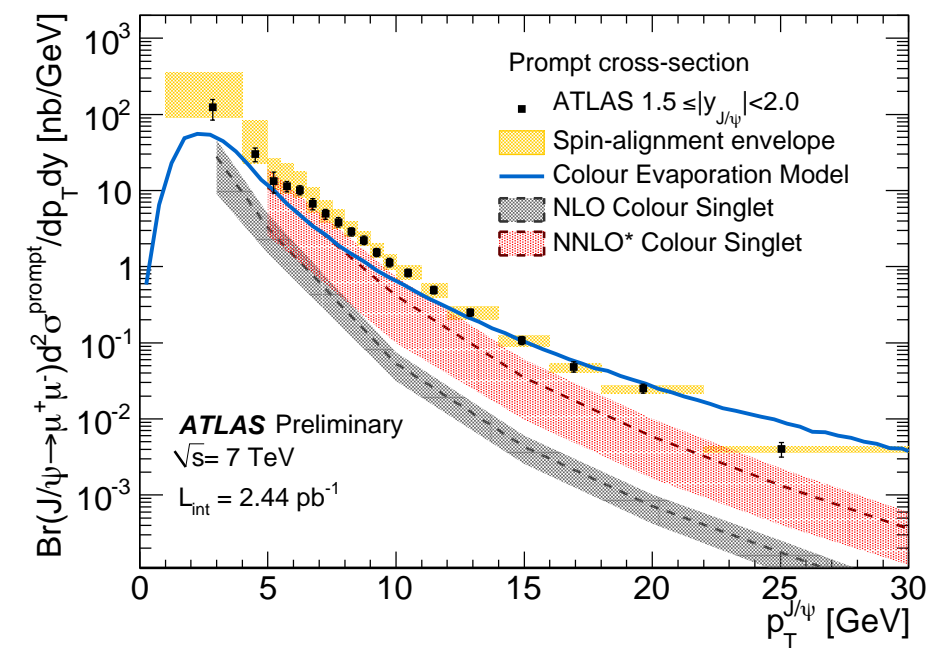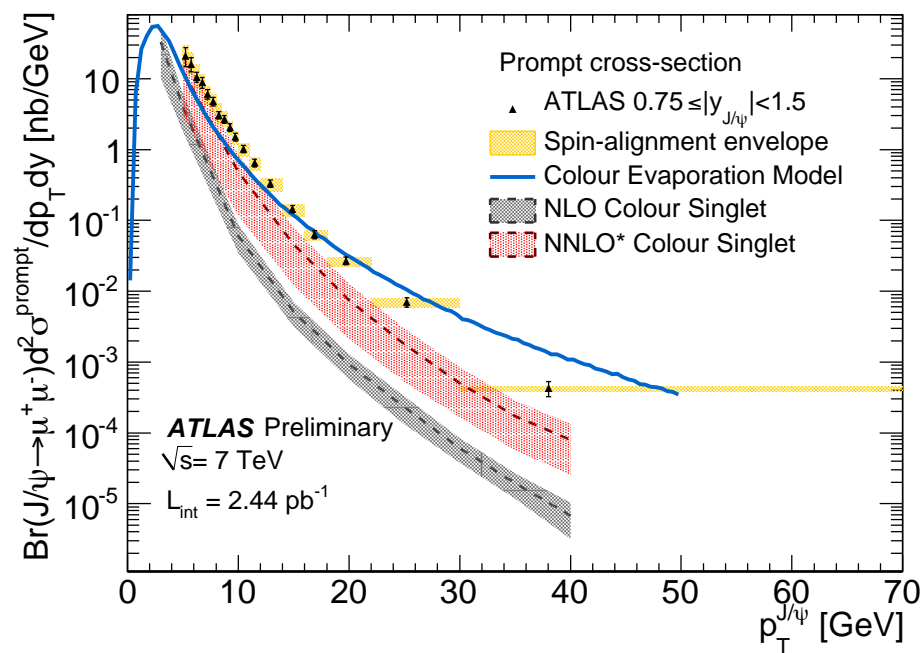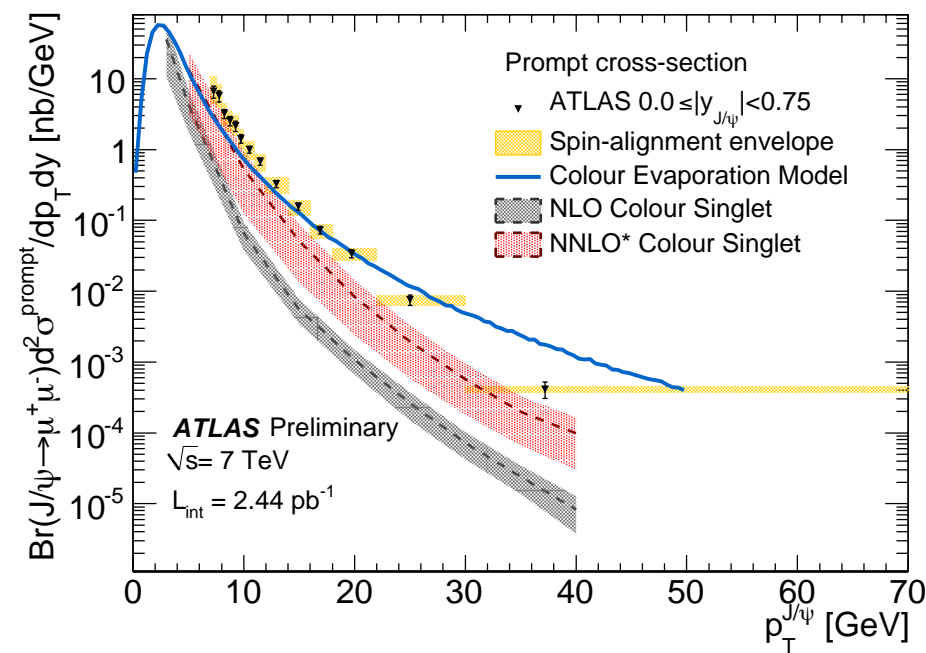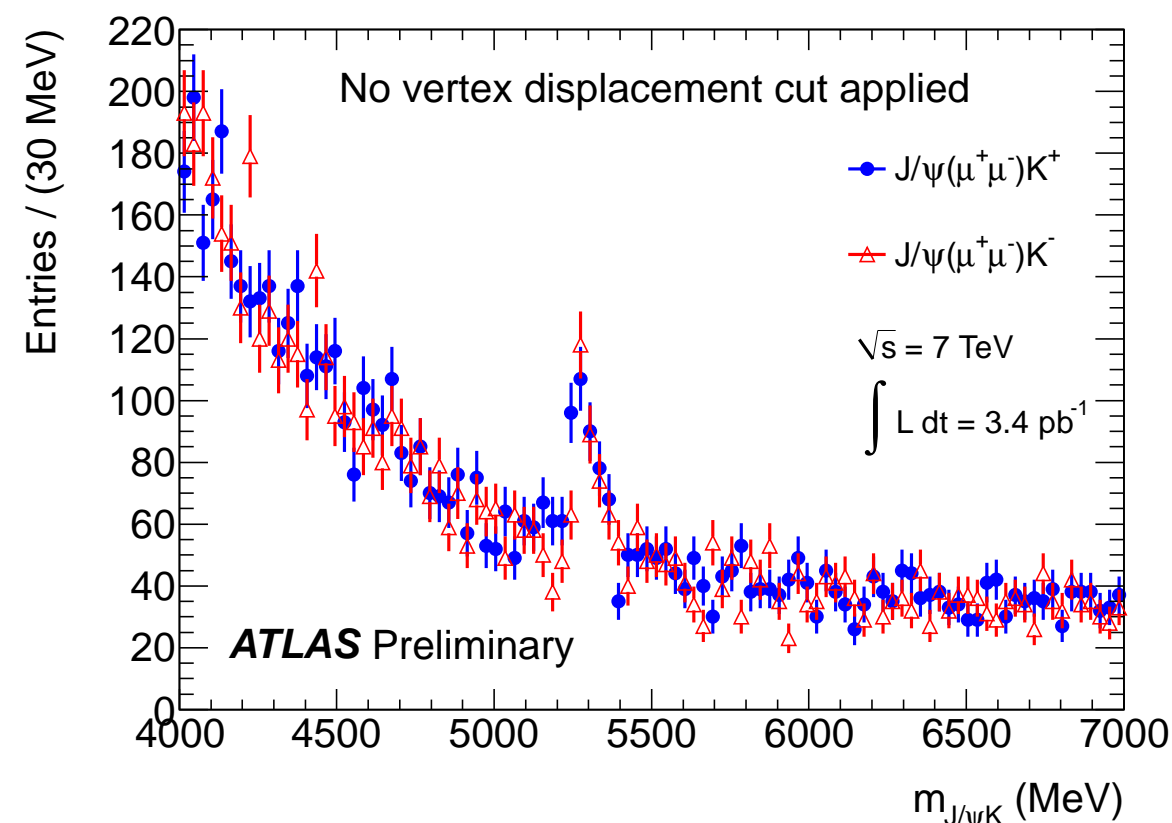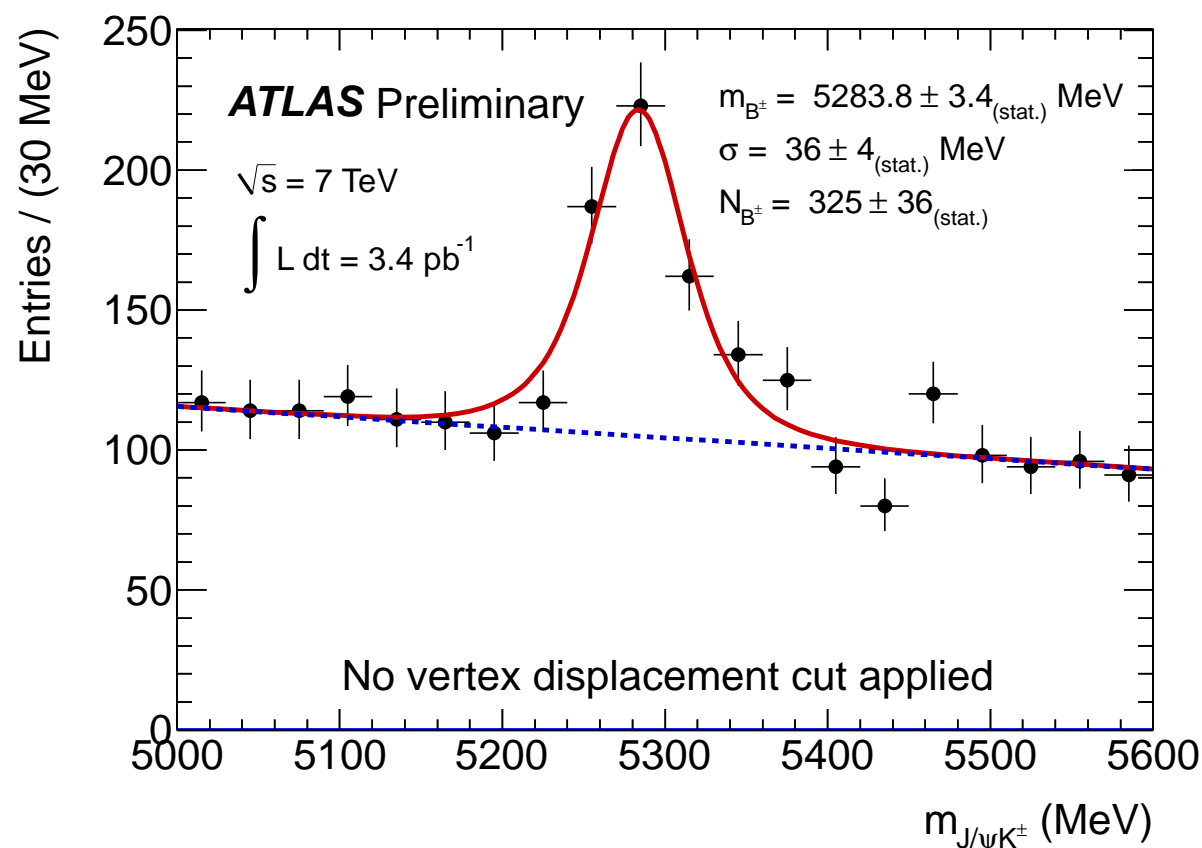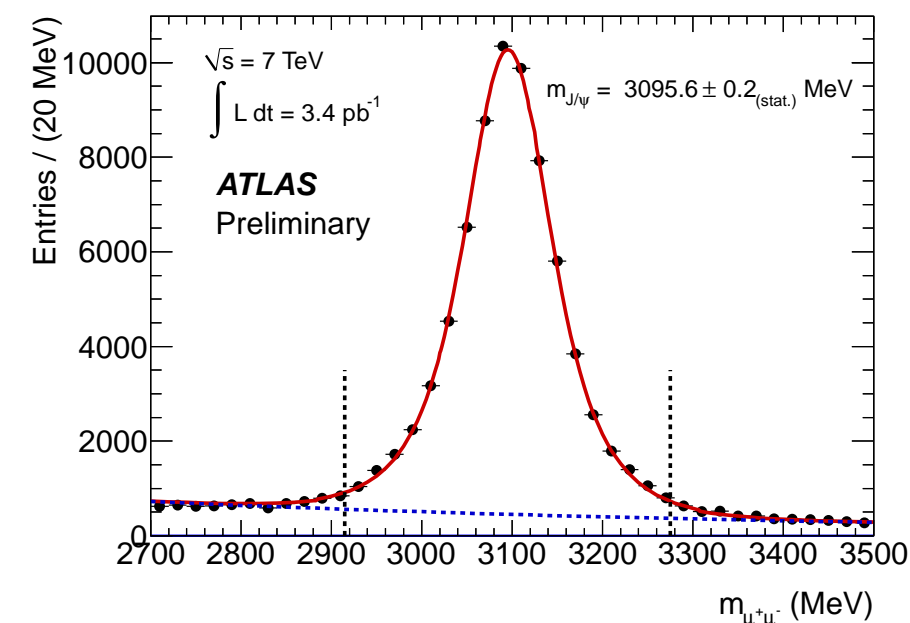
- Agreement is in general good, with some discrepancy at high p$_T$.

- 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 $J/\psi \rightarrow \mu\mu$ system and fitted to common vertex with 'kaon'.

$\sqrt{s} = 7$ TeV
$\int L\, dt = 3.4$ pb^{-1}

ATLAS Preliminary

$m_{J/\psi} = 3095.6 \pm 0.2_{(stat.)}$ MeV

ATLAS Preliminary

$\sqrt{s} = 7$ TeV
$\int L\, dt = 3.4$ pb^{-1}

$m_{B^{\pm}} = 5283.8 \pm 3.4_{(stat.)}$ MeV
$\sigma = 36 \pm 4_{(stat.)}$ MeV
$N_{B^{\pm}} = 325 \pm 36_{(stat.)}$

No vertex displacement cut applied

No vertex displacement cut applied

$J/\psi(\mu^+\mu^-)K^+$
$J/\psi(\mu^+\mu^-)K^-$

$\sqrt{s} = 7$ TeV
$\int L\, dt = 3.4$ pb^{-1}

ATLAS Preliminary

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

Wednesday, 16 March 2011

LANCASTER UNIVERSITY

B$^\pm \rightarrow$ J/Ψ(μμ)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.

ATLAS Preliminary
√s = 7 TeV
∫ L dt = 3.4 pb^{-1}
L$_{xy}$ > 300 μm
m$_{B^\pm}$ = 5283.2 ± 2.5$_{(stat.)}$ MeV
σ = 39 ± 3$_{(stat.)}$ MeV
N$_{B^\pm}$ = 283 ± 22$_{(stat.)}$

ATLAS Preliminary
J/ψ(μ$^+$μ$^-$)K$^+$
m$_{B^+}$ = 5282.6 ± 3.6$_{(stat.)}$ MeV
σ = 40 ± 4$_{(stat.)}$ MeV
N$_{B^+}$ = 138 ± 15$_{(stat.)}$
√s = 7 TeV
∫ L dt = 3.4 pb^{-1}
L$_{xy}$ > 300 μm
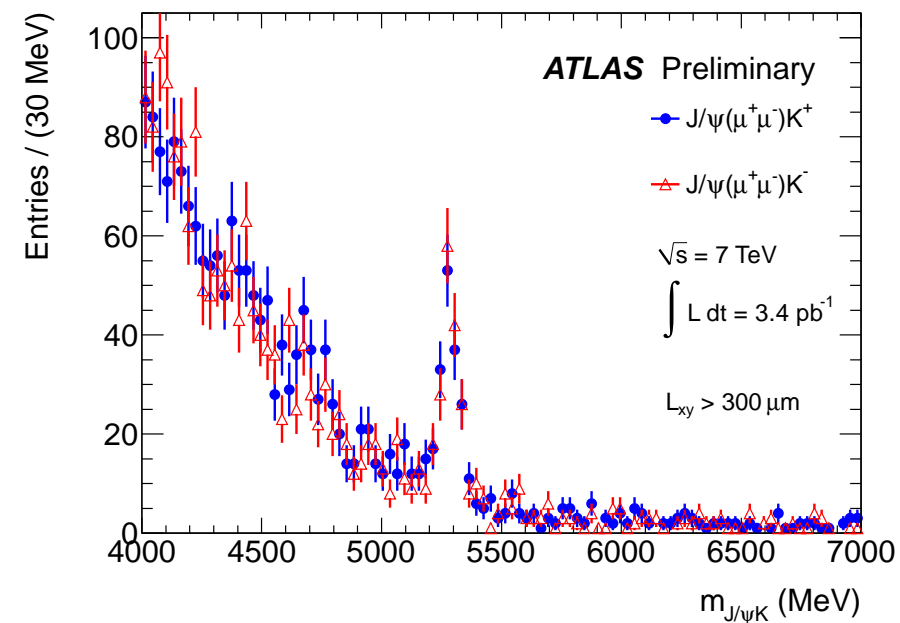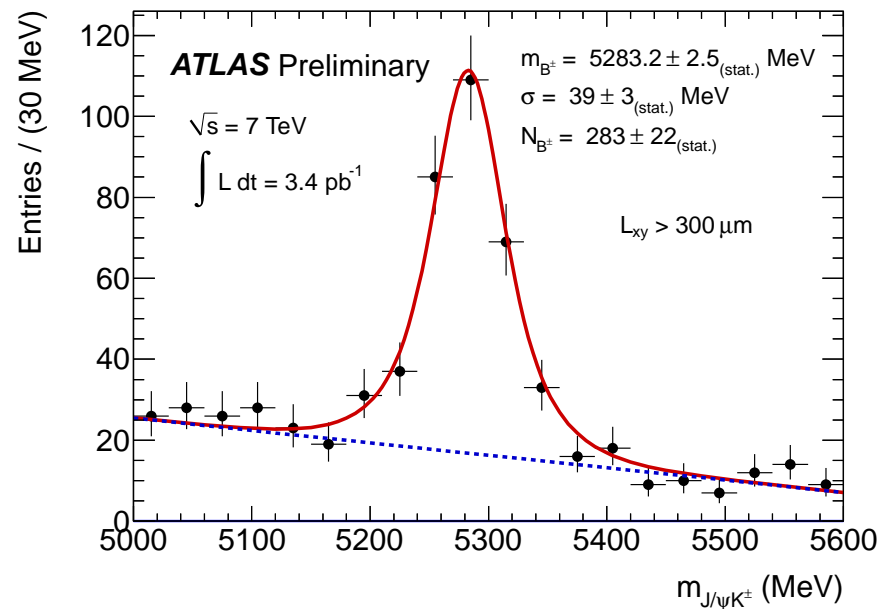
- Mass (5283 ± 2.5 MeV) is compatible with PDG value: 5279.17 ± 0.29 MeV.

- Positive and Negative states are observed with consistent fitted parameters.

ATLAS Preliminary
√s = 7 TeV
∫ L dt = 3.4 pb^{-1}
m$_{B^+}$ = 5282.6 ± 3.6$_{(stat.)}$ MeV
σ = 40 ± 4$_{(stat.)}$ MeV
N$_{B^+}$ = 138 ± 15$_{(stat.)}$
L$_{xy}$ > 300 μm
B$^+$

ATLAS Preliminary
√s = 7 TeV
∫ L dt = 3.4 pb^{-1}
m$_{B^-}$ = 5283.7 ± 3.3$_{(stat.)}$ MeV
σ = 39 ± 4$_{(stat.)}$ MeV
N$_{B^-}$ = 146 ± 15$_{(stat.)}$
L$_{xy}$ > 300 μm
B$^-$

Wednesday, 16 March 2011
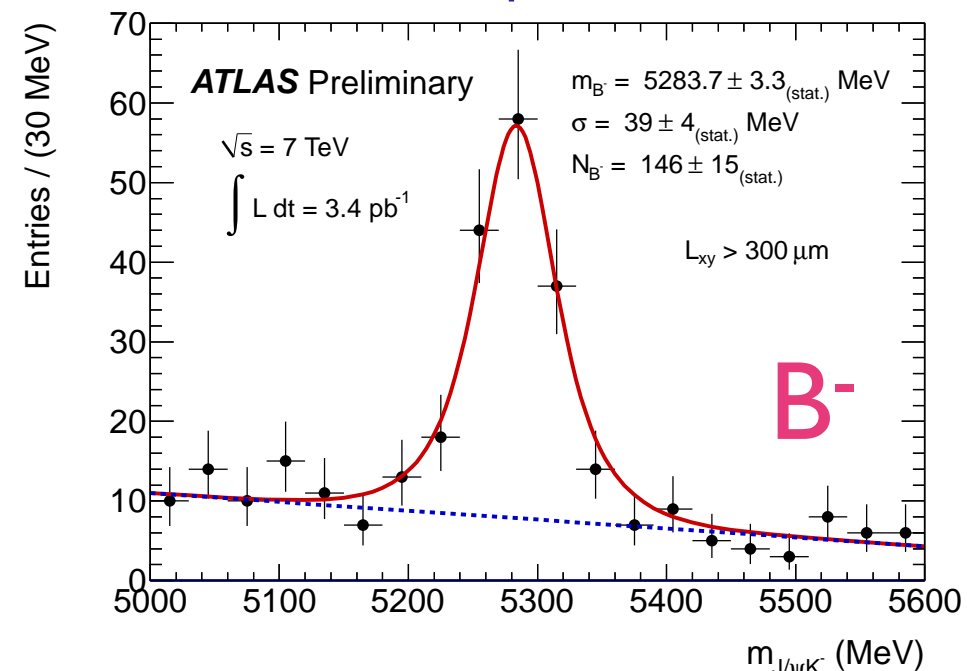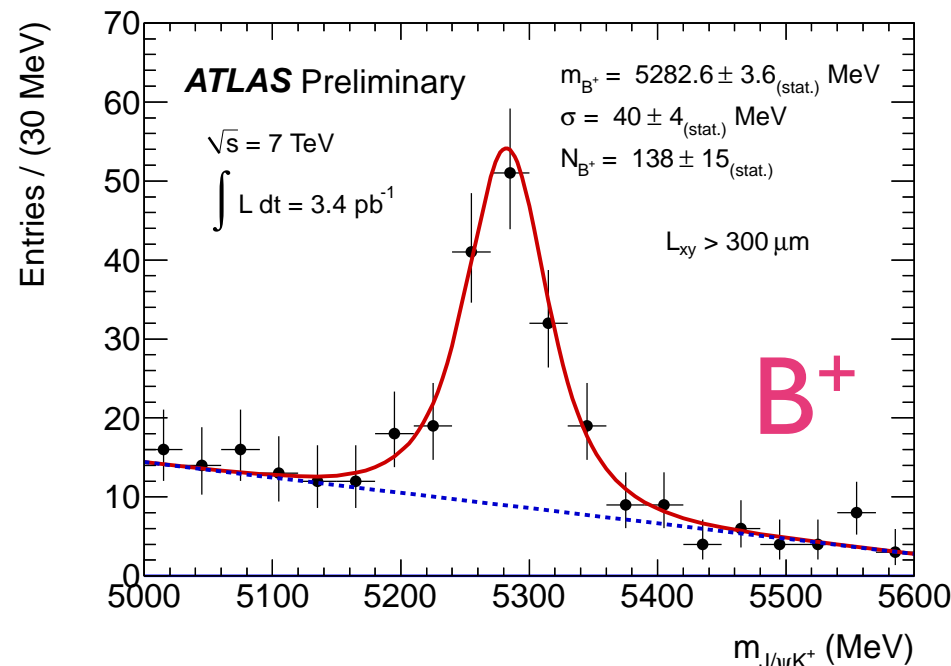
Summary and Outlook

- First year of data-taking has been highly successful.

  - Observation of J/ψ and $\psi(2S)$.

  - Observation of the three Upsilon states.

  - D meson states observed and cross section extracted

- $B^{\pm} \to J/\psi(\mu\mu)K^{\pm}$ observed, $B_d \to J/\psi(\mu\mu)K^{*0}$, $B_s \to J/\psi(\mu\mu)\phi$ 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 $B_c \to J/\psi(\mu\mu)\pi$,

  - Continue preparations for searches on rare decays such as $B_s \to \mu\mu$ 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.

Wednesday, 16 March 2011

LANCASTER
UNIVERSITY