J/ψ production at the LHC with ATLAS

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on behalf of the ATLAS Collaboration
LowX 2011, Santiago de Compostela, Spain

Introduction

- This is a presentation of the ATLAS measurements of J/ψ production in 7 TeV pp collisions
  - Prompt fraction
  - Inclusive, prompt and non-prompt differential production cross sections
    - Compared with colour evaporation and colour singlet models
  - Raw tabulated results: http://hepdata.cedar.ac.uk/View/9035664
  - **2.2pb^{-1}** 2010 data
- All measurements are made using the di-muon decays of the J/ψ

Motivation: Can LHC quarkonia act as low x probes?

J/ψ:

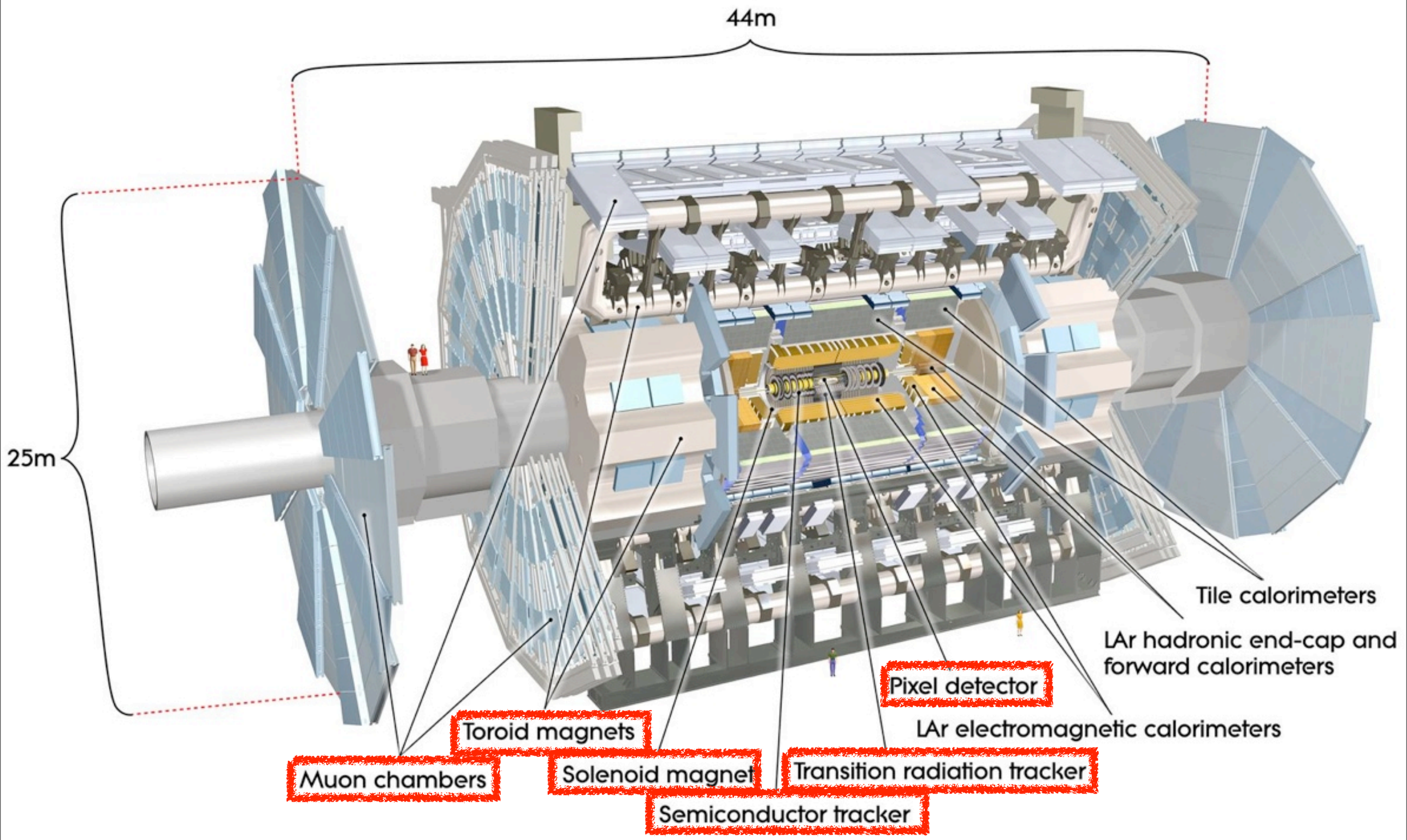
- At the TeVatron
  - $\sqrt{\hat{s}} \approx 3.5\mathrm{GeV} \qquad \sqrt{s} \approx 2\mathrm{TeV}$
  - CDF: $y \approx 0 \rightarrow x_{1,2} \approx 1.8\times10^{-3}$
  - D0: $-1.6 \lesssim y \lesssim 1.6 \rightarrow x_{1,2} \approx (0.36 - 8.9)\times10^{-3}$

Well below the "safe" range for which the PDFs are well established (10^{-3})

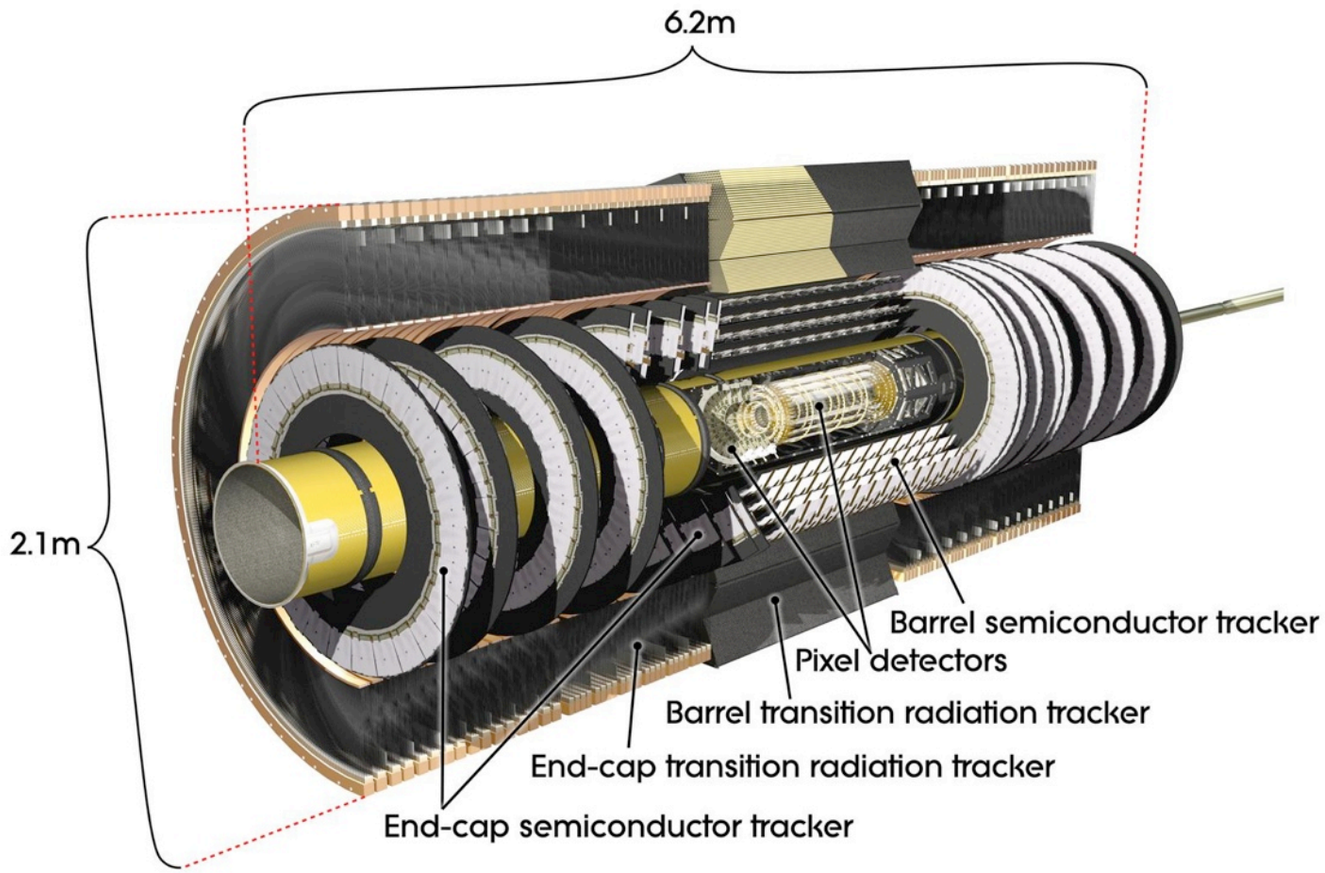
- At the LHC
  - $\sqrt{\hat{s}} \approx 3.5\mathrm{GeV} \qquad \sqrt{s} \approx 7\mathrm{TeV}$
  - ATLAS/CMS: $-2.4 \lesssim y \lesssim 2.4 \rightarrow x_1 \approx (0.04 - 6.0)\times10^{-3}$; $x_2 \approx (6.0 - 0.04)\times10^{-3}$
  - LHCb: $-2 \lesssim y \lesssim 5 \rightarrow x_1 \approx (4 - 80)\times10^{-3}$; $x_2 \approx (0.07\text{-}0.003)\times10^{-3}$

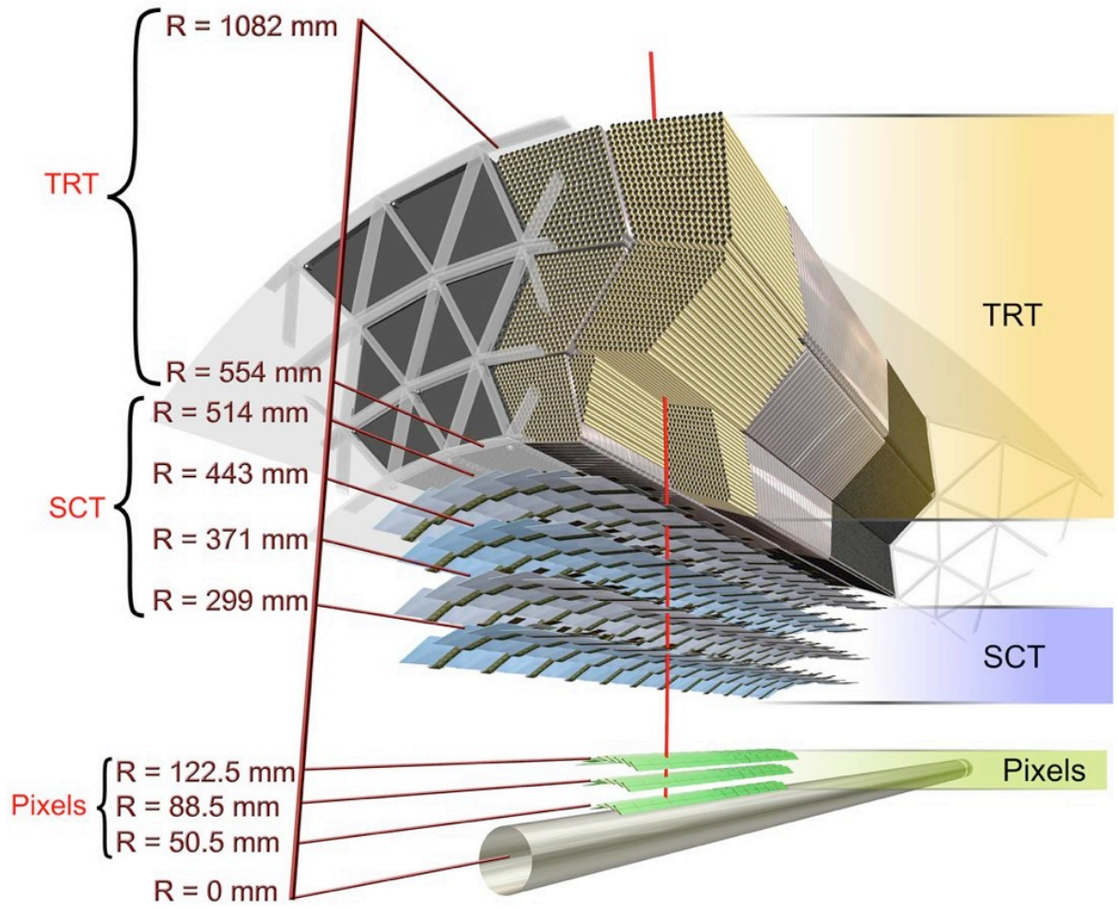
From the overview for the proceedings of QUARKONIUM 2010:
Three Days Of Quarkonium Production in pp and pA Collisions, 29-31 July 2010, Palaiseau, France

The ATLAS detector



The ATLAS detector: inner detector

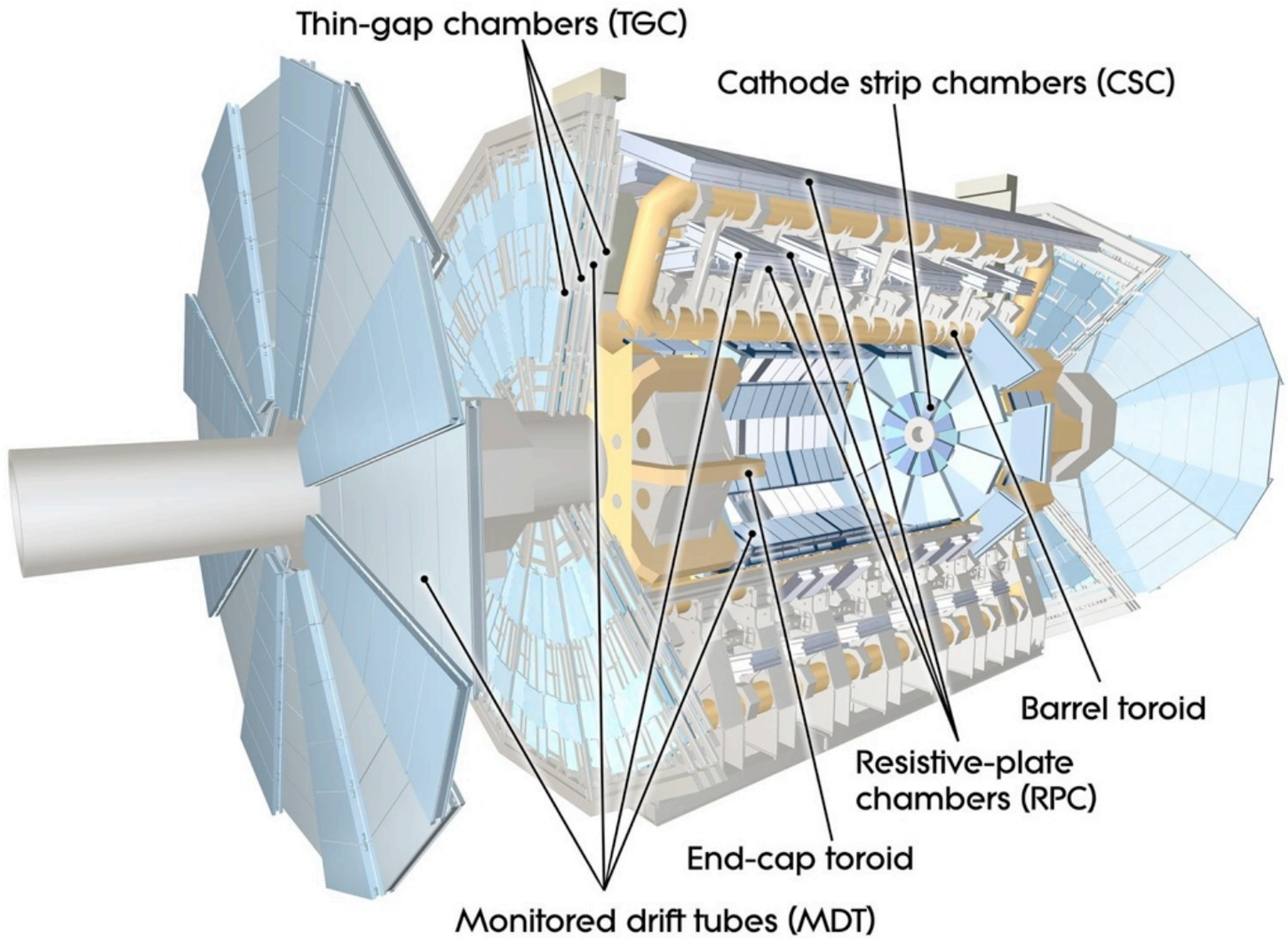




- 2T magnetic field, coverage $|\eta| < 2.5$
- Momentum scale: ~0.1% at low energy, ~1% up to ~100 GeV
- Momentum resolution: $\sigma/p_T = 3.8 \times 10^{-4}\ (\mathrm{GeV}) \oplus 0.015$
- Primary vertex resolution: ~30 μm transverse, ~50 μm longitudinal

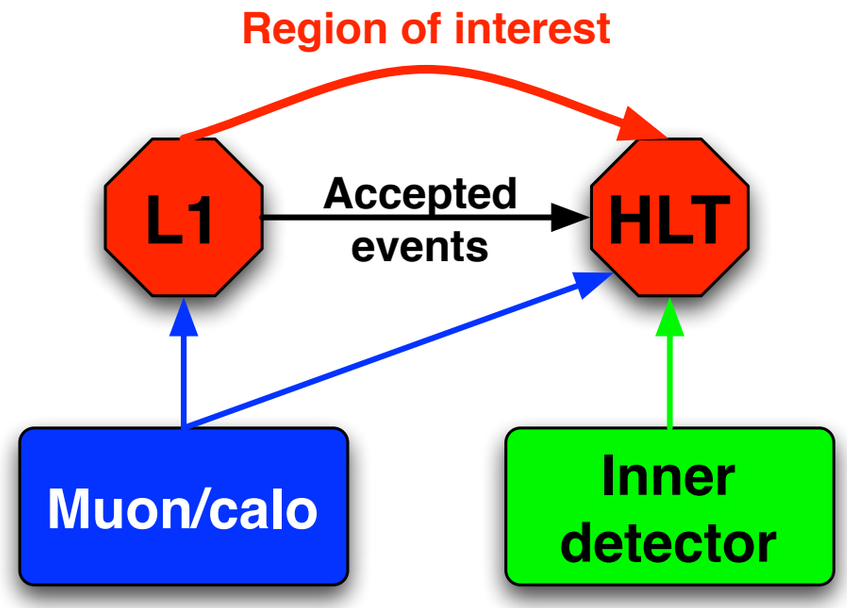
The ATLAS detector: muon spectrometer

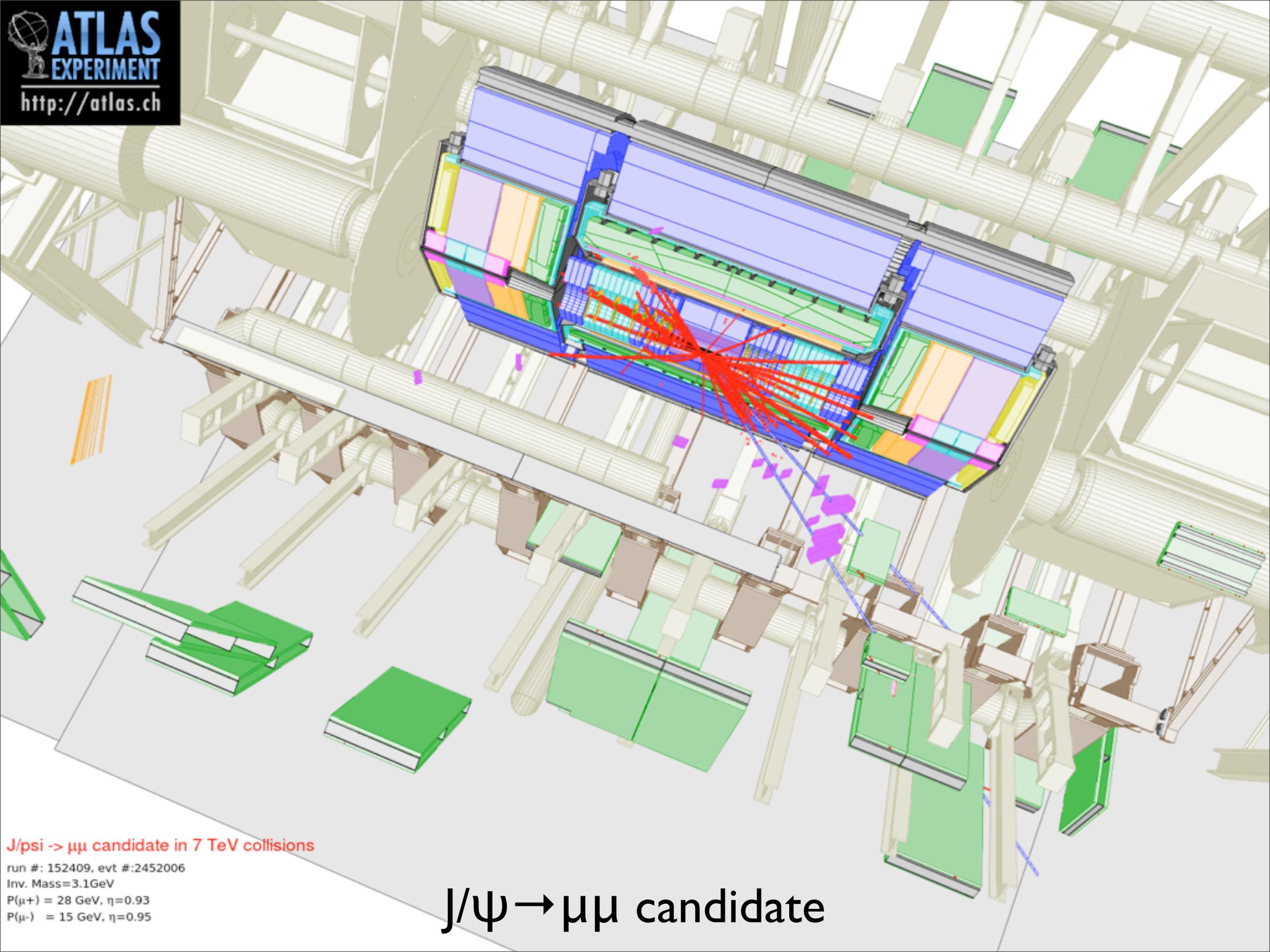
- Coverage $|\eta| < 2.7$
- Average field 0.5T
- Momentum resolution <10% for muons with energy < 1 TeV
  - Note the muons in these analyses are ~10-100 GeV
- Essential in this analysis for both trigger and offline muon identification



Trigger scheme

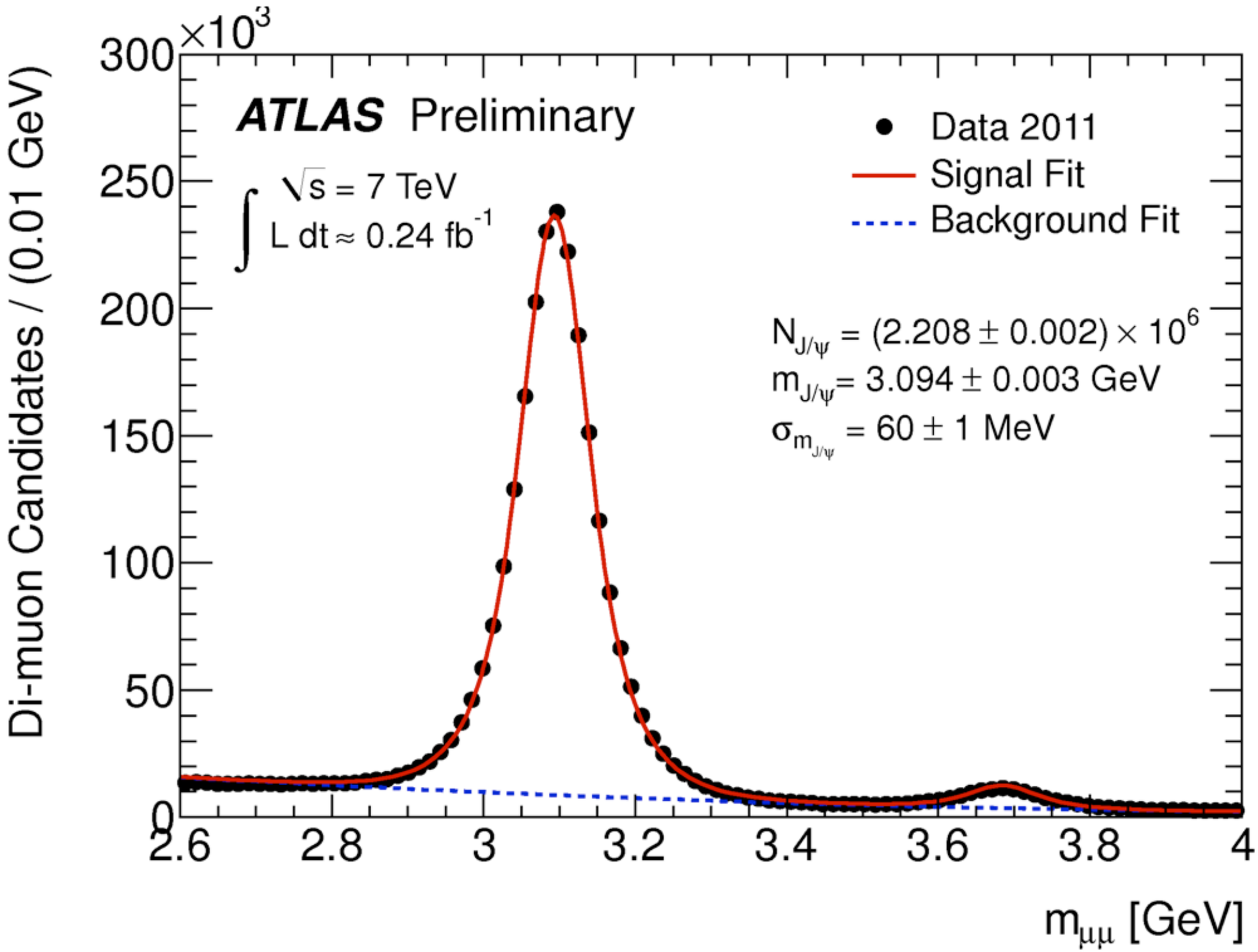
- Quarkonia measurements in ATLAS use muon triggers exclusively
- 1st level (L1) muon trigger decision involves formation of one or more "regions of interest" (RoI) around the objects firing the trigger
  - The HLT only processes information in these regions
- The analyses presented here use a single region of interest
  - Any event containing a muon which passes the L1 and HLT cuts is accepted



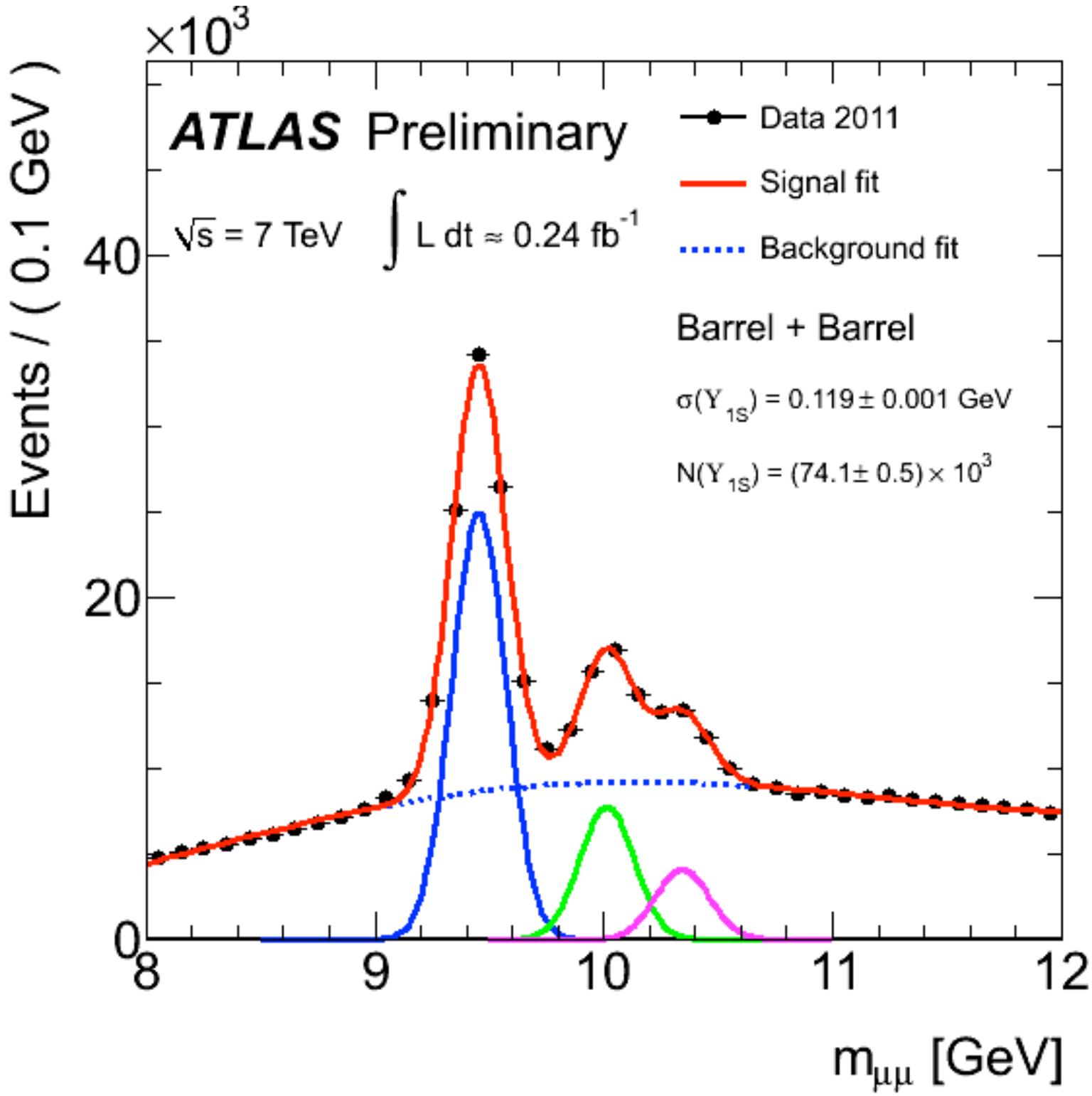


J/ψ→μμ candidate

J/ψ with 2011 data set



ϒ with 2011 data set



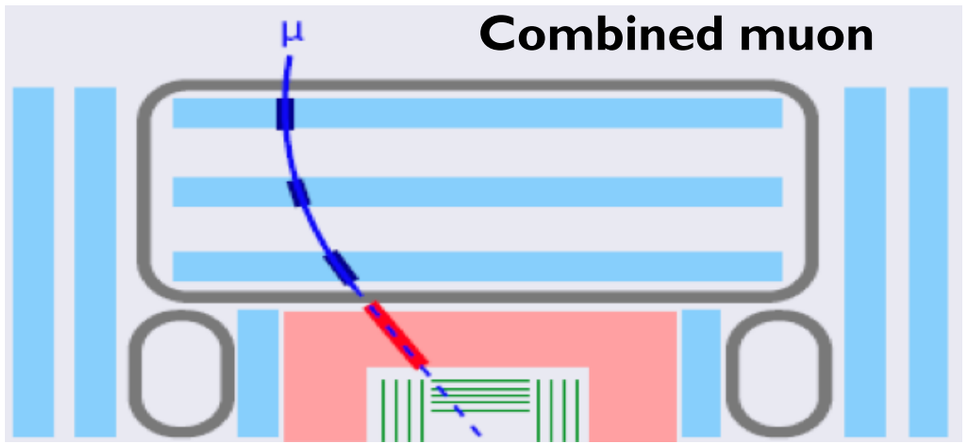
J/ψ candidate selection: trigger and offline

Trigger selection

- Single μ RoI with >0, 4, 6 GeV threshold depending on data taking period
- Also 10 GeV and minimum bias trigger for fraction measurements

Offline selection

- $\mu^+\mu^-$ with associated inner detector tracks; tracks must have 1 pixel hit and 6 SCT hits
- $p_T(\mu) > 1$ GeV; $p(\mu) > 3$ GeV
- Primary vertex must exist and must have been built with >2 tracks.
- One of the muons must be *combined*
- One of the muons must have fired the single muon trigger

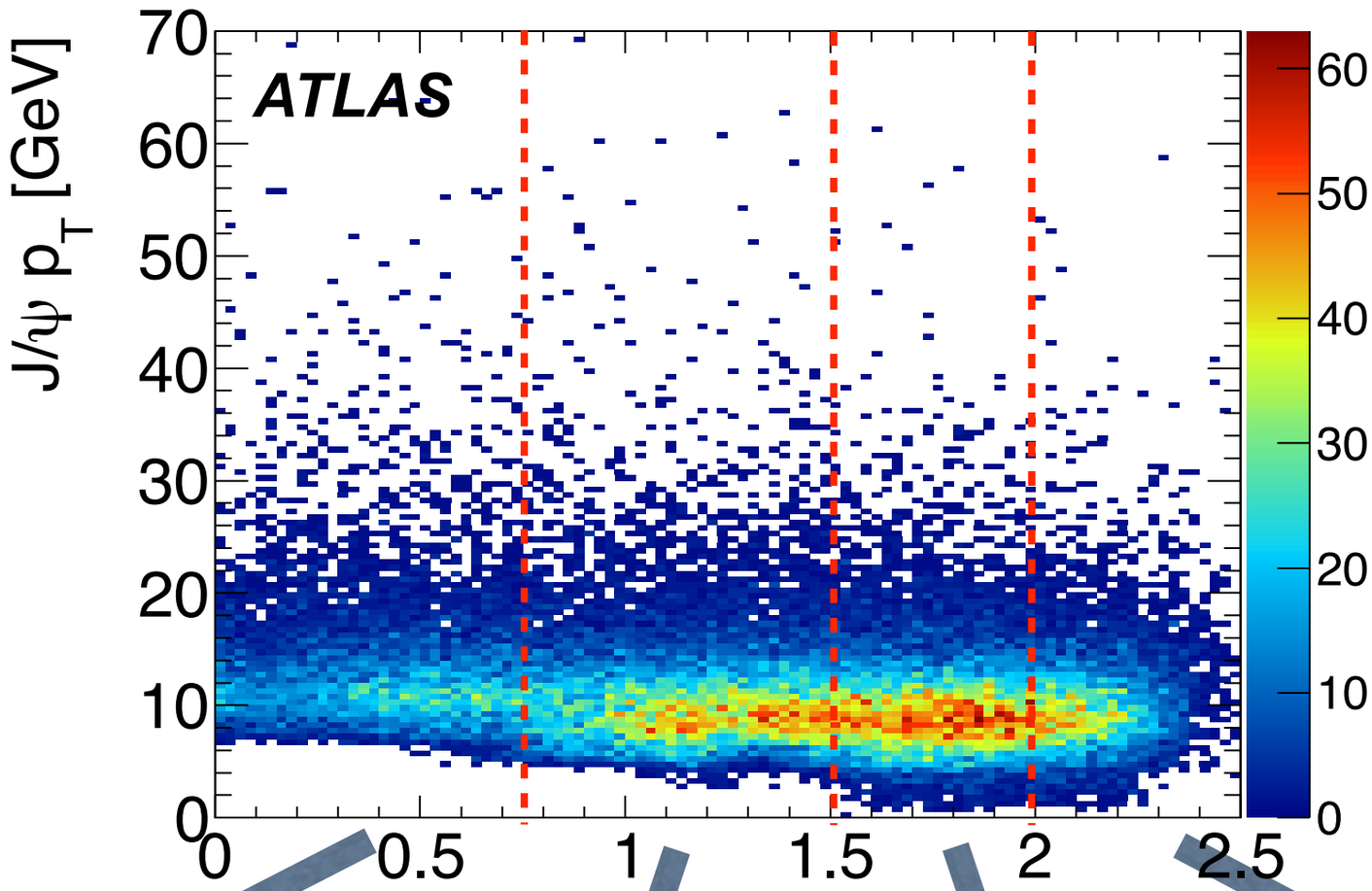


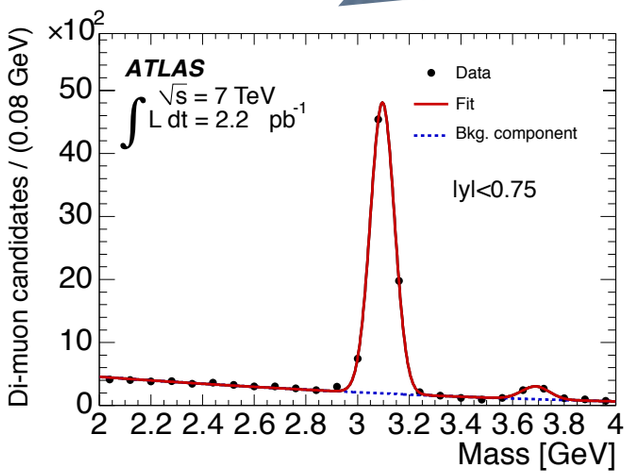
Combined (full Muon Spectometer & Inner Detector track measurement with fit between the two)

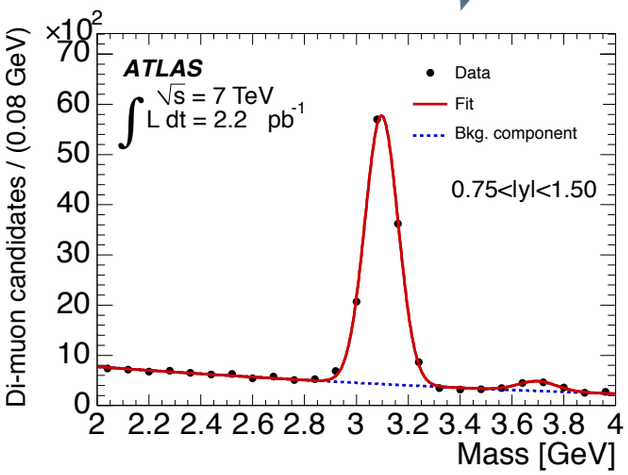
Tagged (Inner Detector measurement associated to at least one hit in Muon Spectrometer)

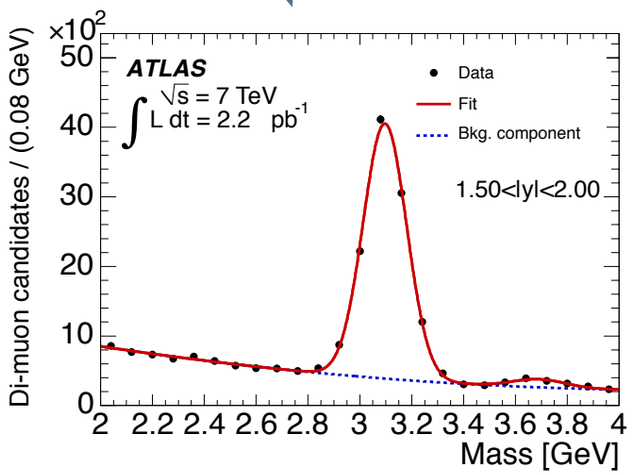
J/ψ sample before corrections

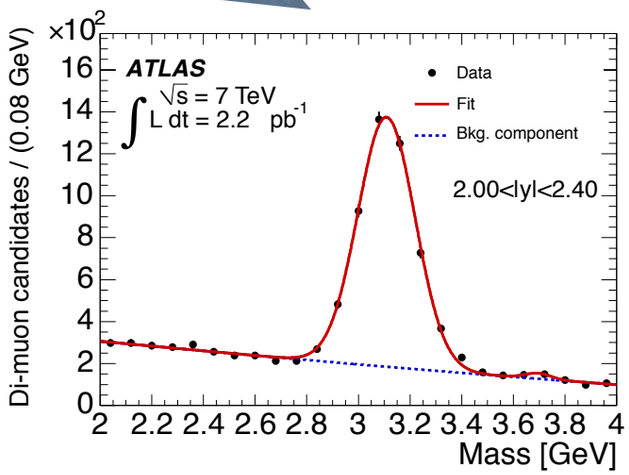
$2.2pb^{-1}$











Cross section measurement: basics

Collect candidates → Divide into pT and y slices → Obtain correction weights **per candidate** → Obtain weighted yield in each slice → Inclusive differential cross section

Weight applied to *i*th candidate

$$w_i$$

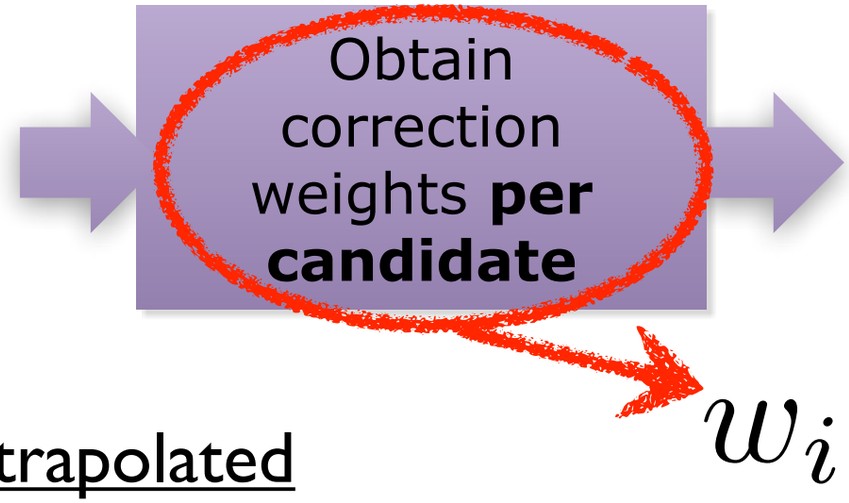
Corrected number of candidates in a given slice

$$N_{corr} = \sum_i w_i^{-1} \, N_{reco}$$

Inclusive differential cross section

$$\frac{d^2\sigma\left(X\right)}{dp_T dy} \cdot Br\left(X \to \mu\mu\right) = \frac{N_{corr}}{\mathcal{L} \cdot \Delta p_T \Delta y}$$

Correction weights



J/ψ measurement is extrapolated

Bin migration **Muon reconstruction efficiency**

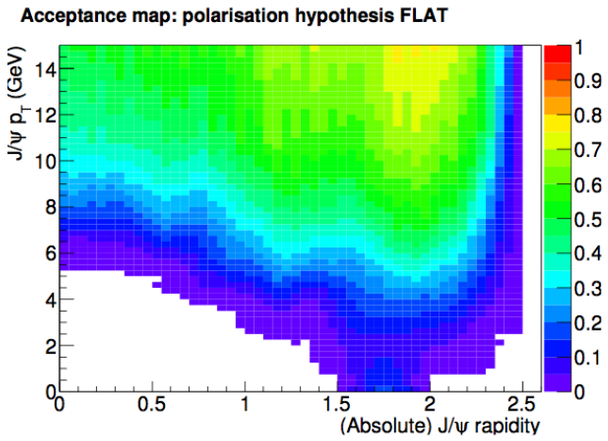
$$w^{-1} = \boxed{\mathcal{A}} \cdot \boxed{\mathcal{M}} \cdot \boxed{\epsilon_{trk}^2} \cdot \boxed{\epsilon_\mu^+\left(p_T^+, \eta^+\right) \cdot \epsilon_\mu^-\left(p_T^-, \eta^-\right)} \cdot \boxed{\epsilon_{trig}}$$

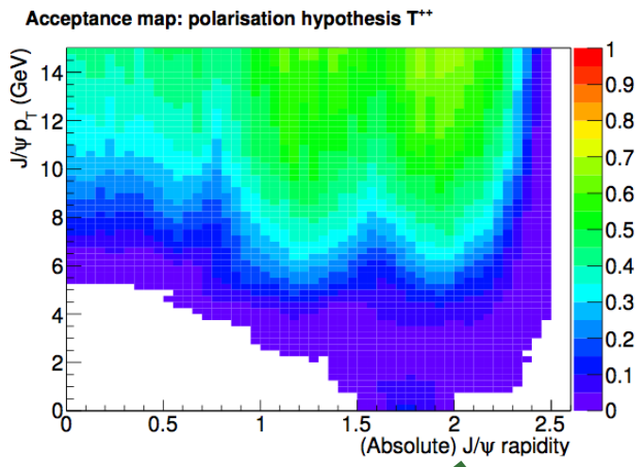
Acceptance **Muon ID track efficiency** **Trigger efficiency**

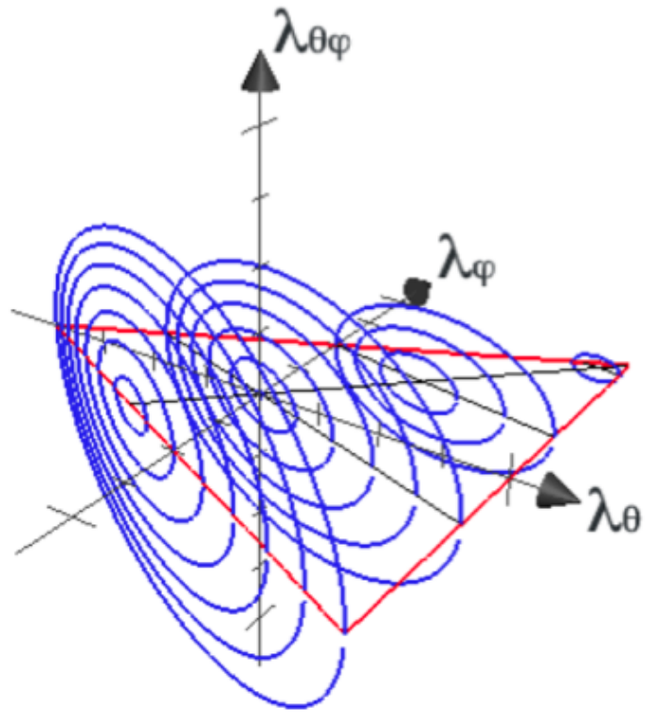
probability that a given J/ψ(p_T,η) decays into muons which fall in the detector acceptance. This is a function of the J/ψ spin alignment, which is not known, so this enters the measurement as a theoretical uncertainty

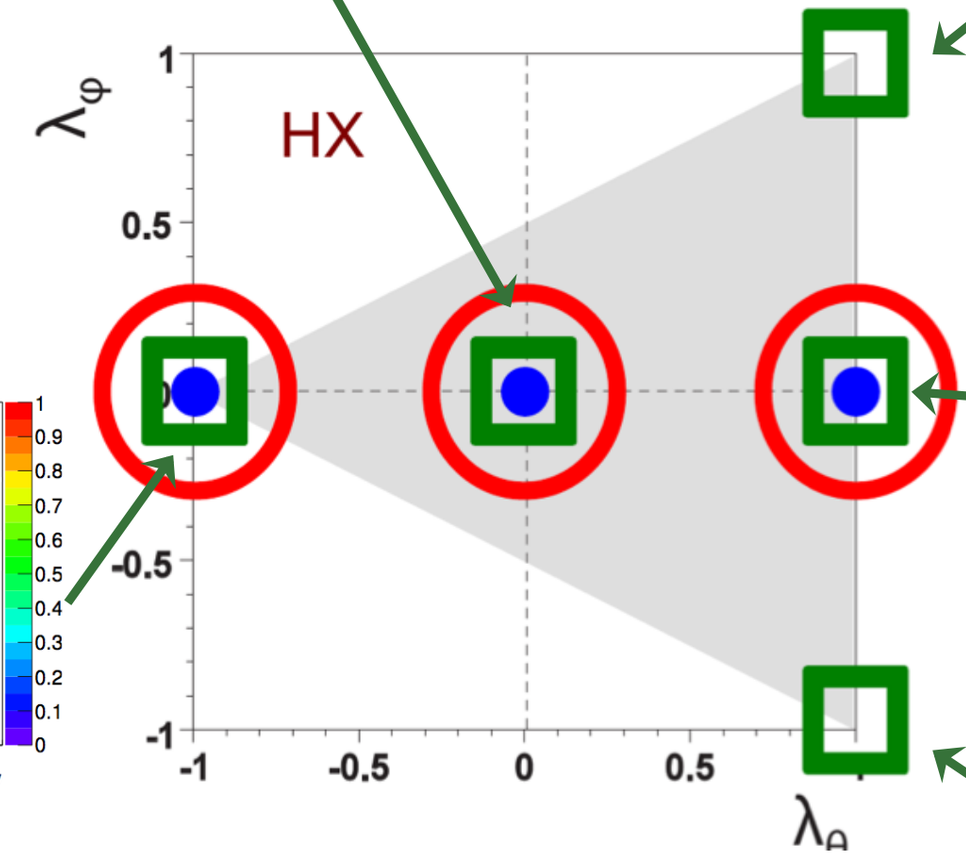
Acceptance corrections

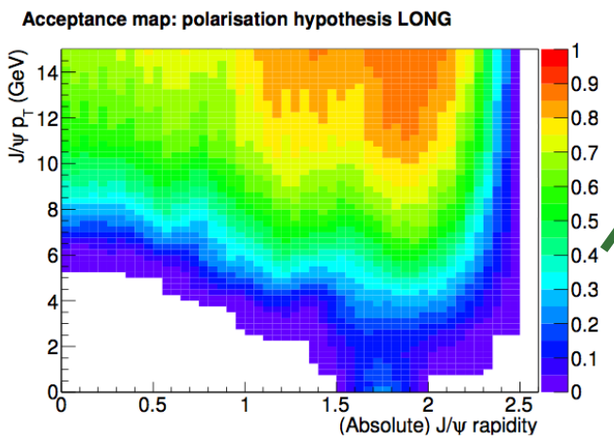
Five spin alignment working points are established with separate acceptance maps. These are used to provide a theoretical uncertainty around the results

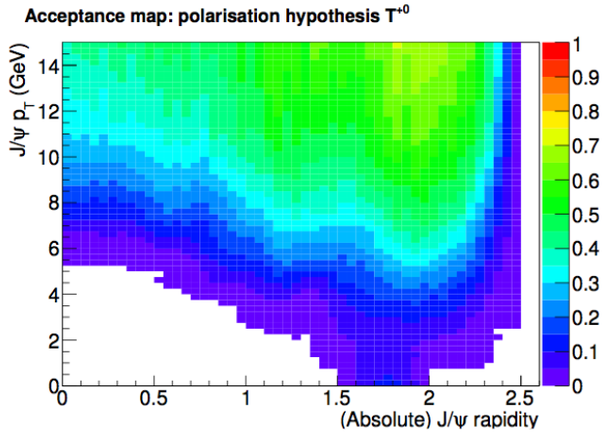


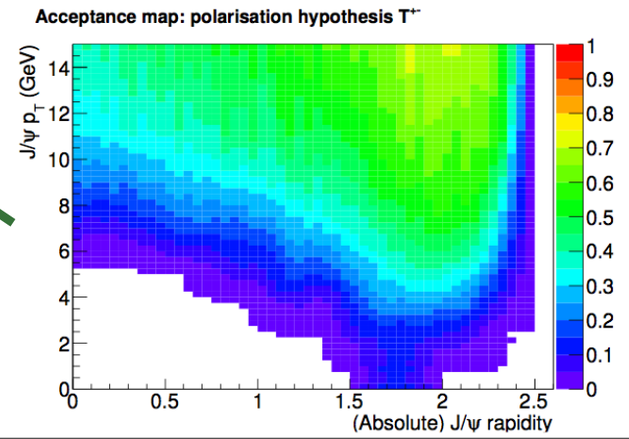








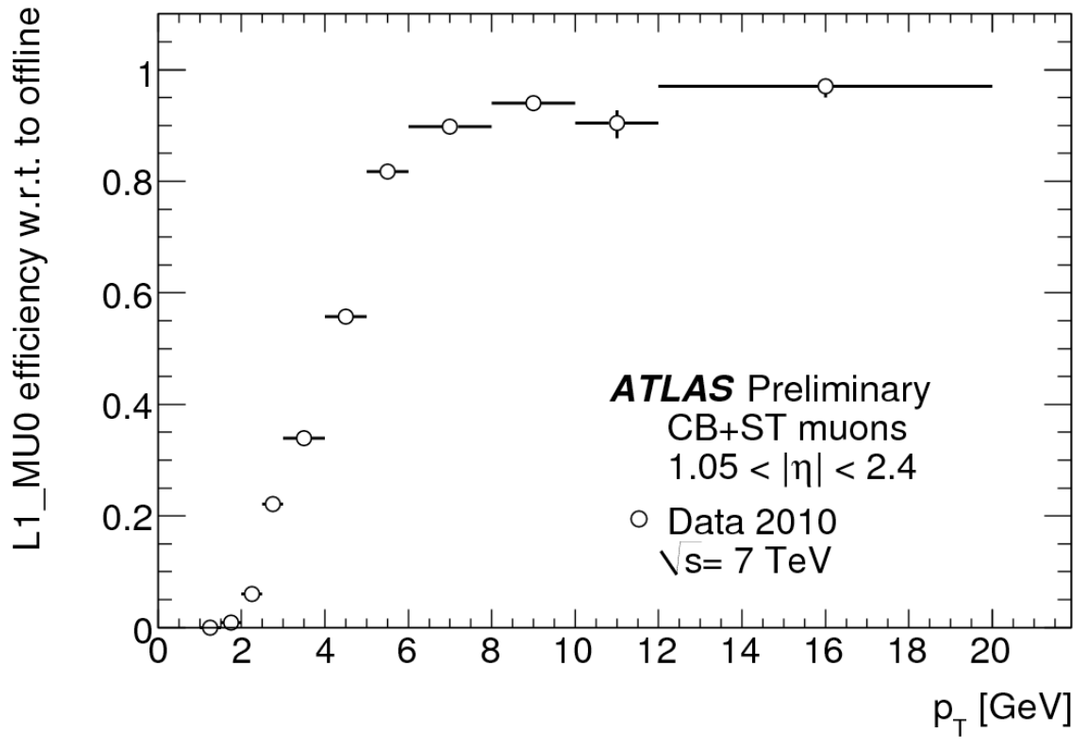




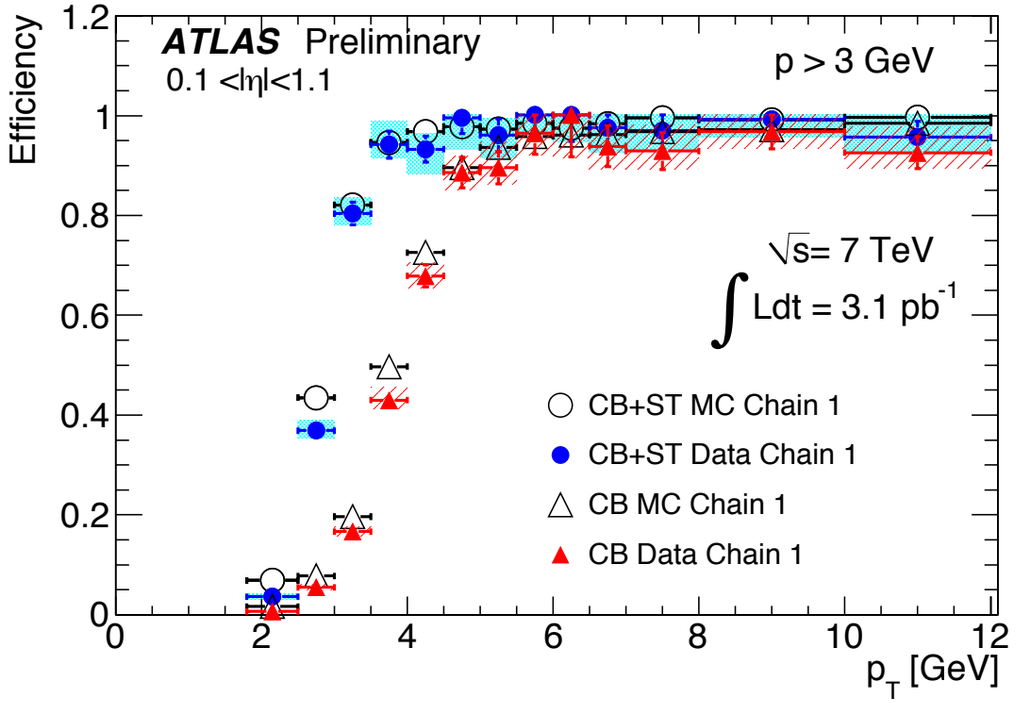
ATLAS CMS LHCb

Efficiency corrections

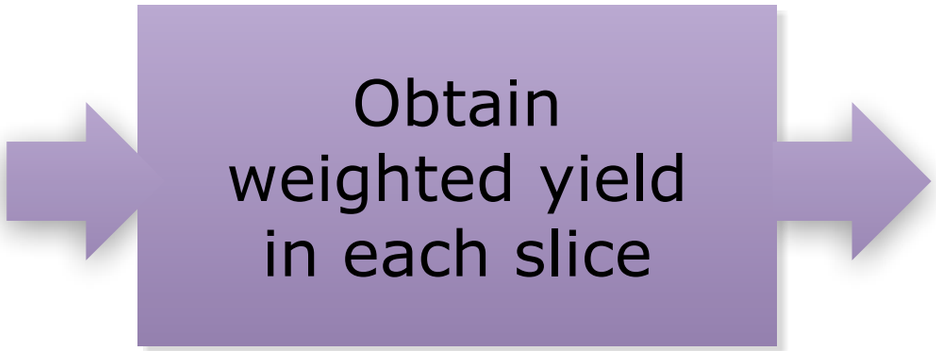
- Single-muon trigger efficiency
  - Evaluated with Monte Carlo to obtain a fine granularity, and then corrected by data (tag and probe)
  - Efficiencies reach a plateau of 80-100% at around 6-8 GeV (depends on η)



- Offline muon reconstruction efficiency
  - Evaluated with data (tag and probe) using J/ψ for lower p_T muons and Z at higher p_T
  - Regions with efficiency < ~20% not used
- ID track reconstruction efficiency
  - Essentially constant efficiency for muon tracks of 99.5 ± 0.5 %

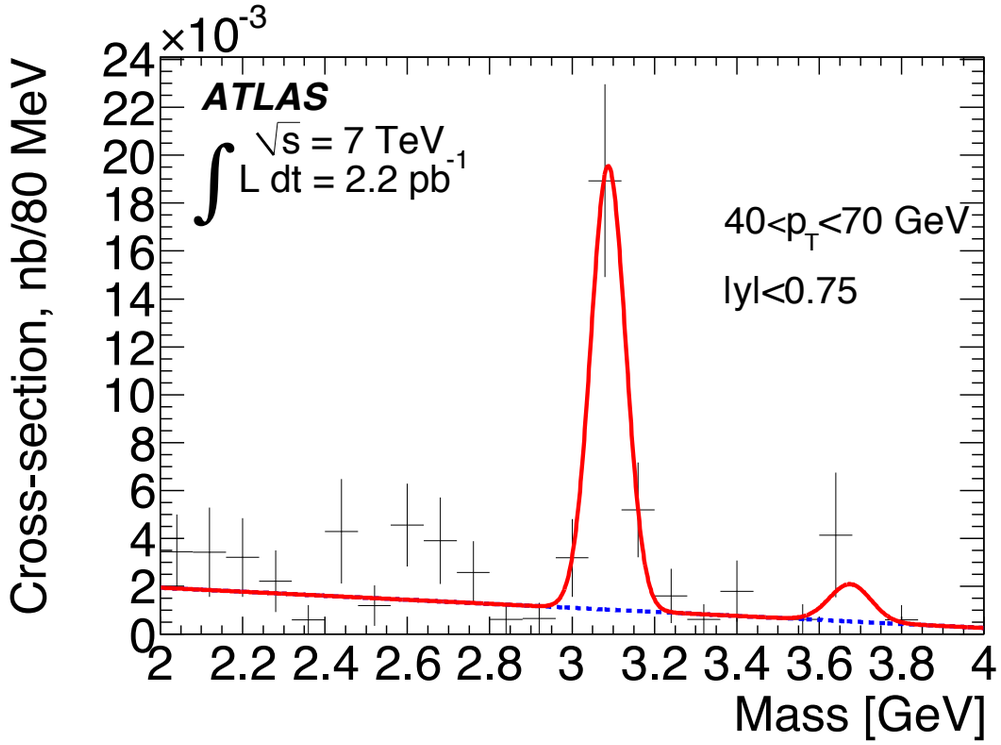


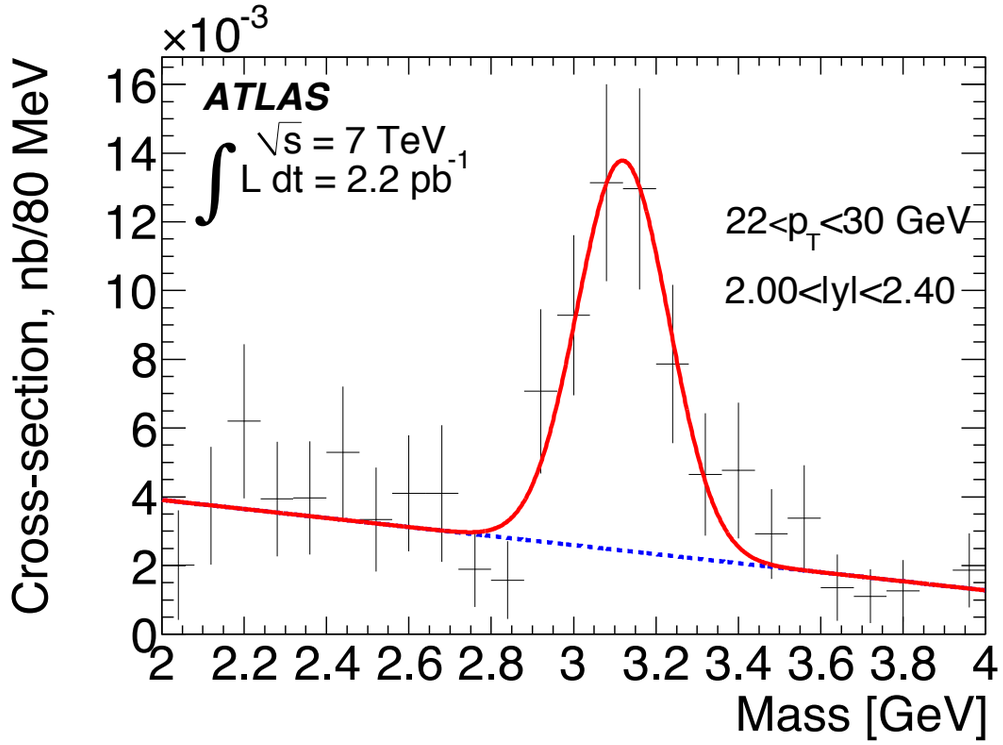
Signal yield extraction

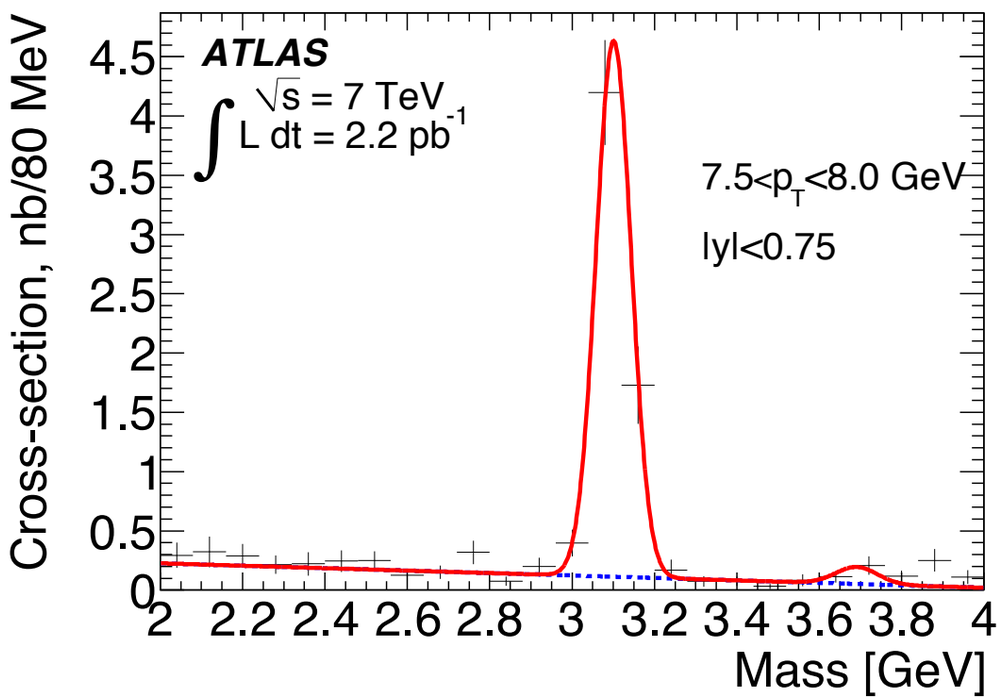


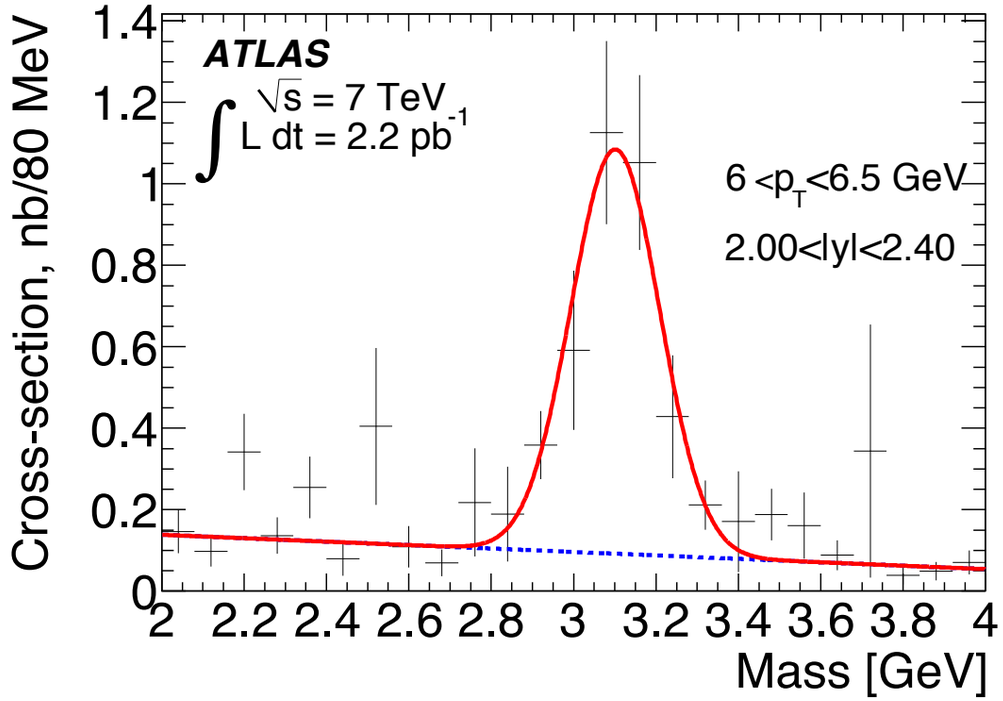
- Binned χ^2 fit to the corrected mass distribution
- Single Gaussian for the signal (since the slices are so fine) and linear background
- $\psi(2S)$ included in the fit but yield not extracted

Yield extraction example







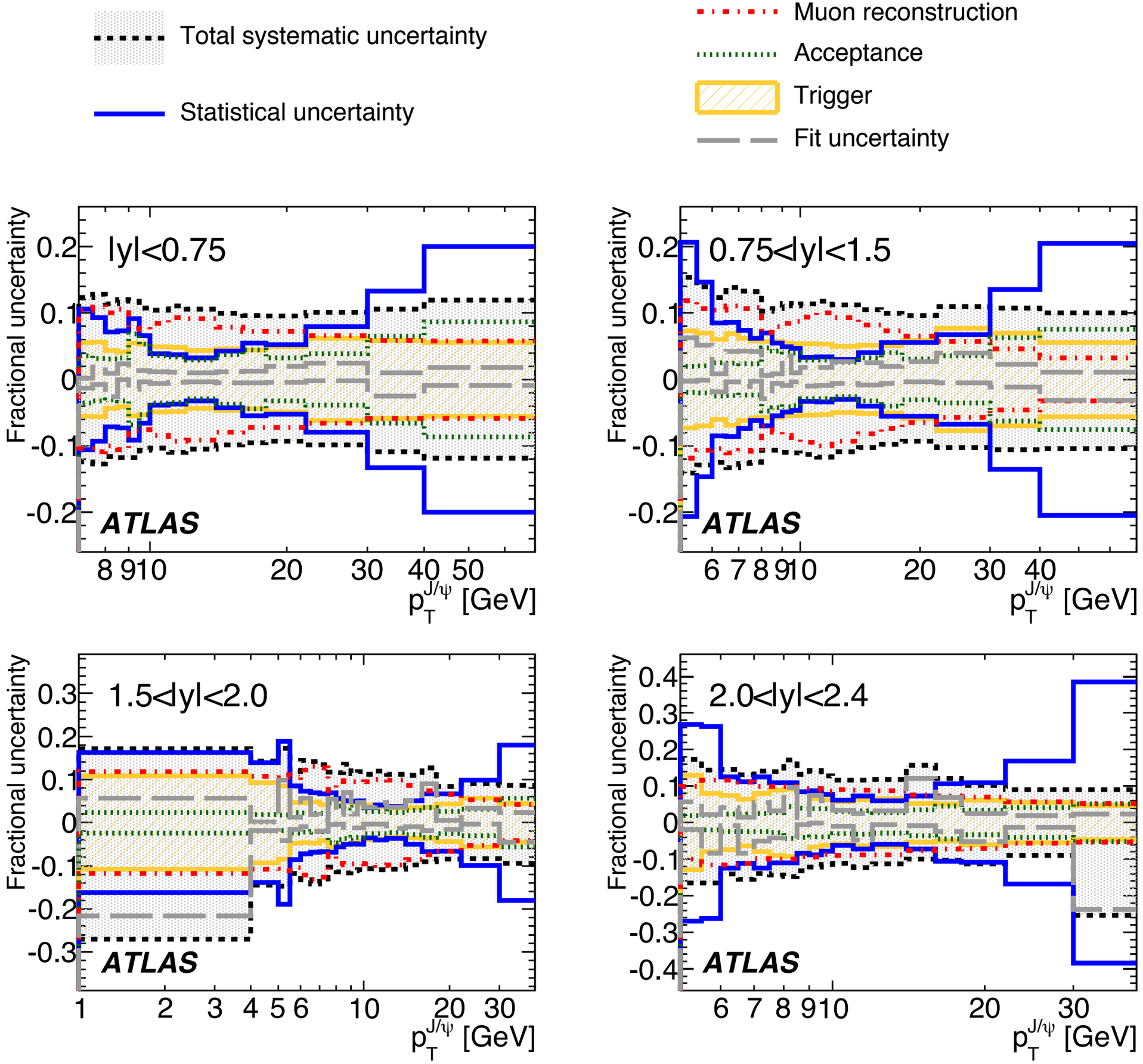


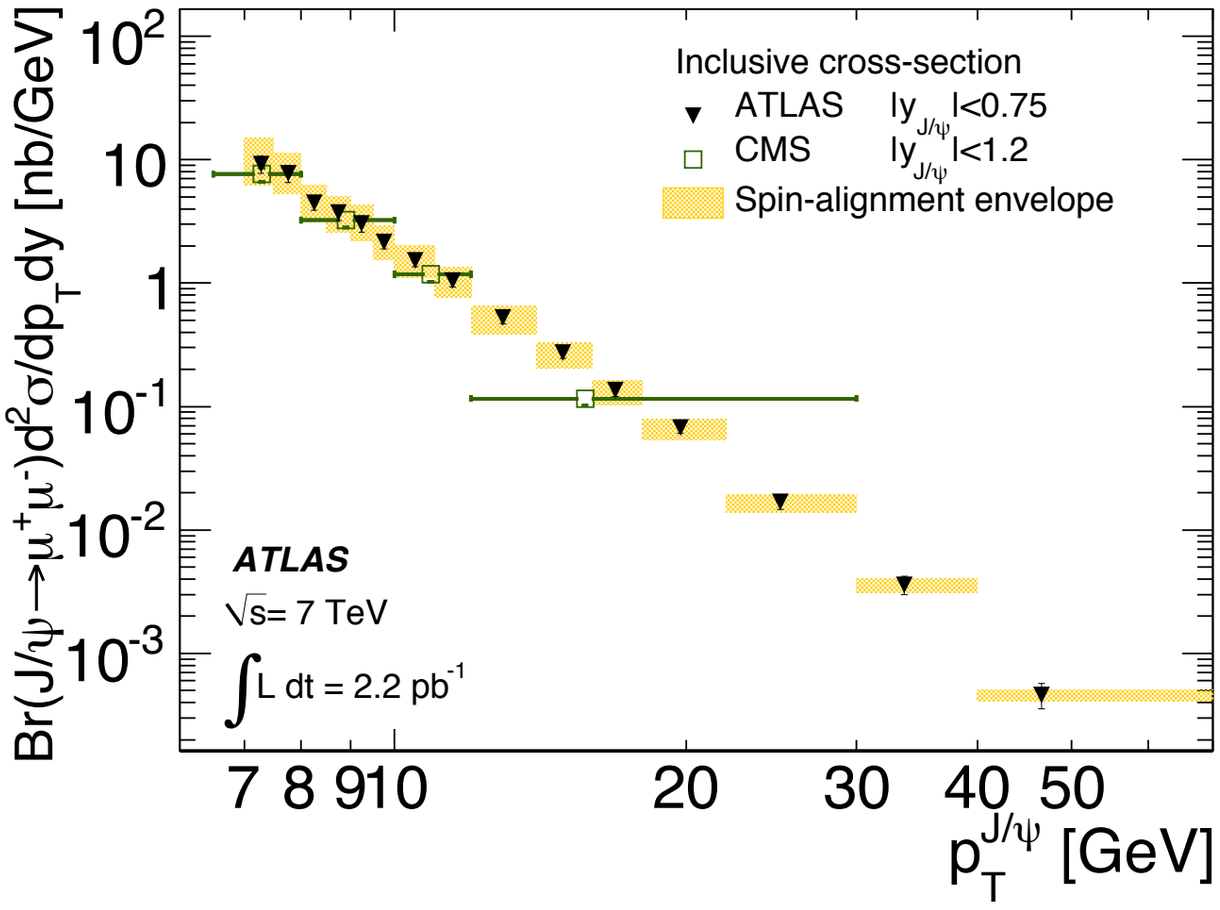
Sources of systematic uncertainty

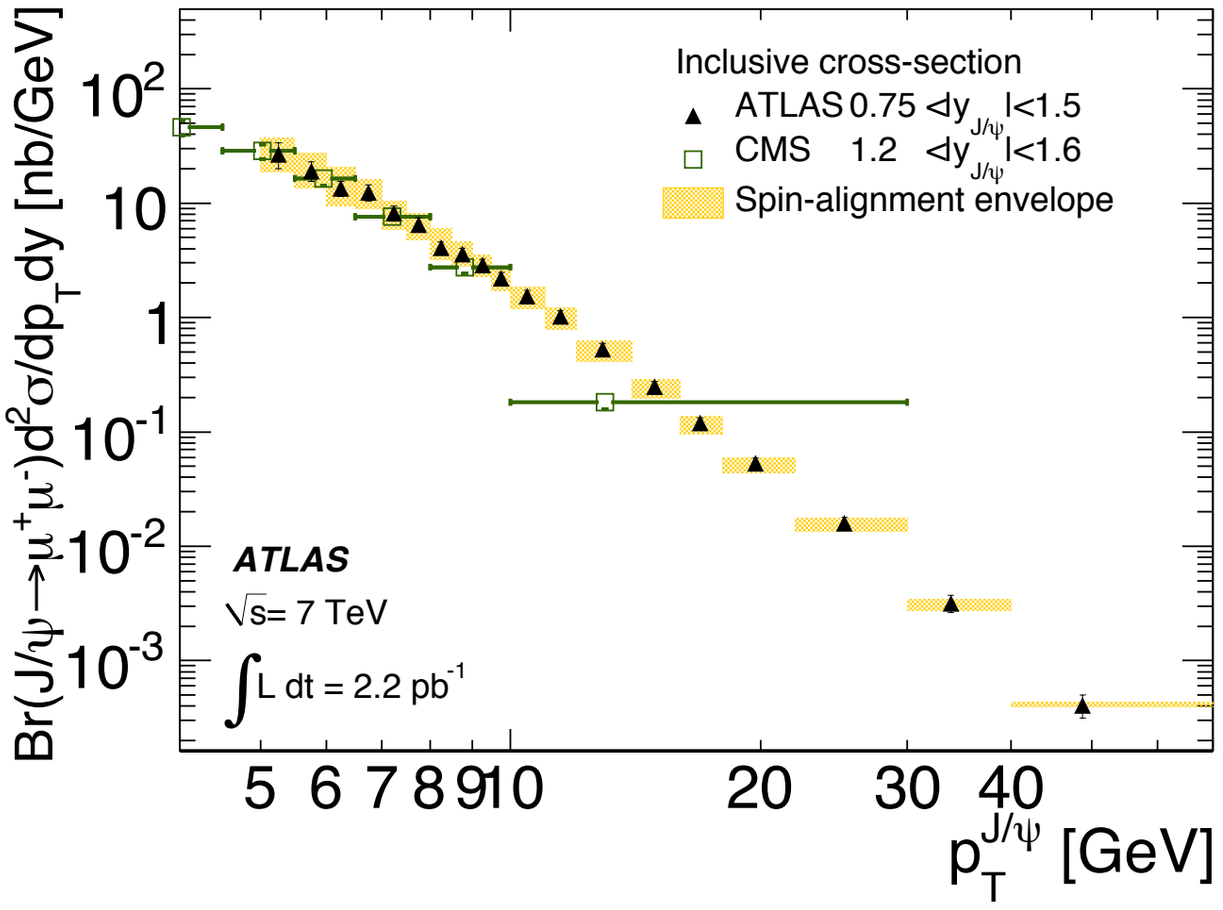
- Luminosity
- Muon reconstruction/trigger efficiencies, ID track reconstruction efficiency
- Fit models
- Acceptance
  - Bin migration
  - Limited statistics
  - Differences in prompt/non-prompt spectra
  - Final-state radiation
- Vertexing efficiency

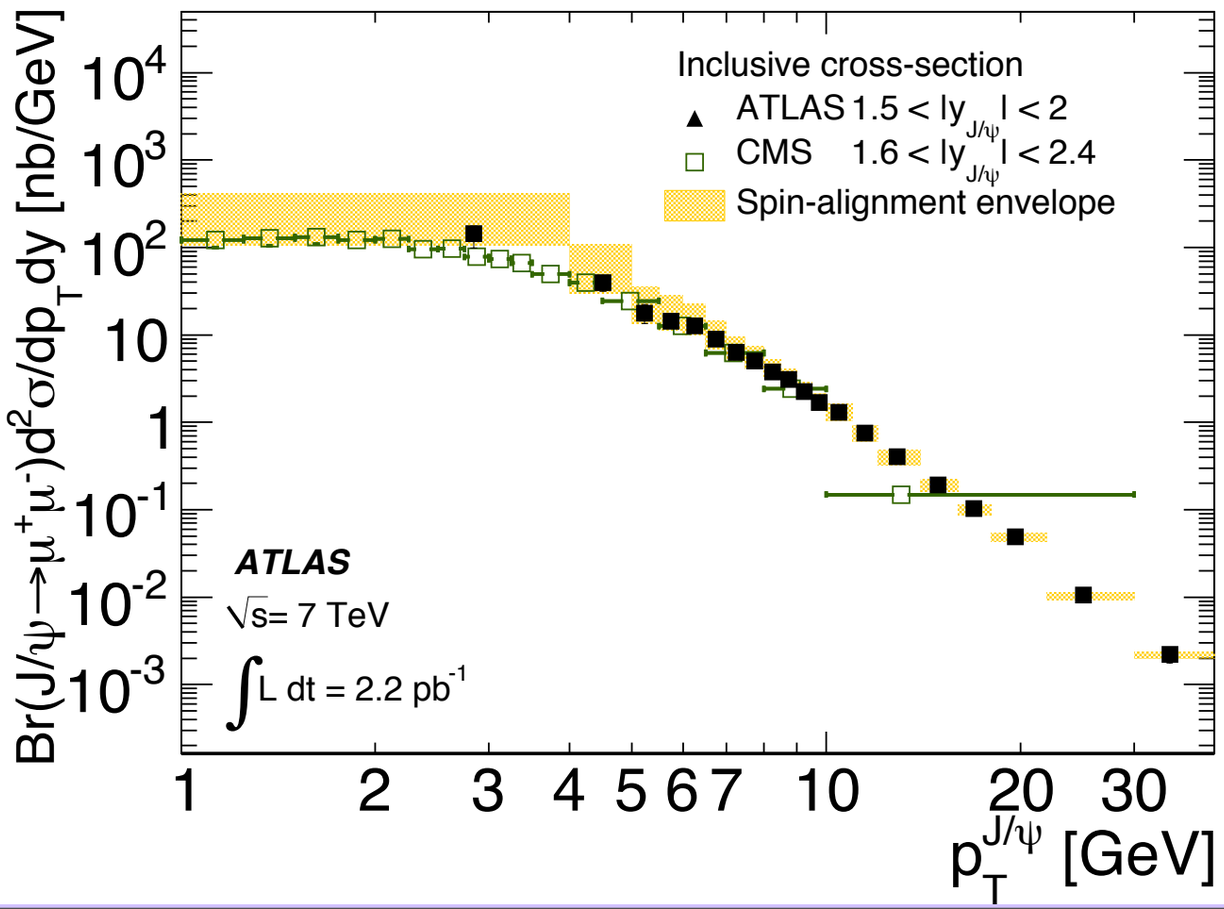
Summary of uncertainties

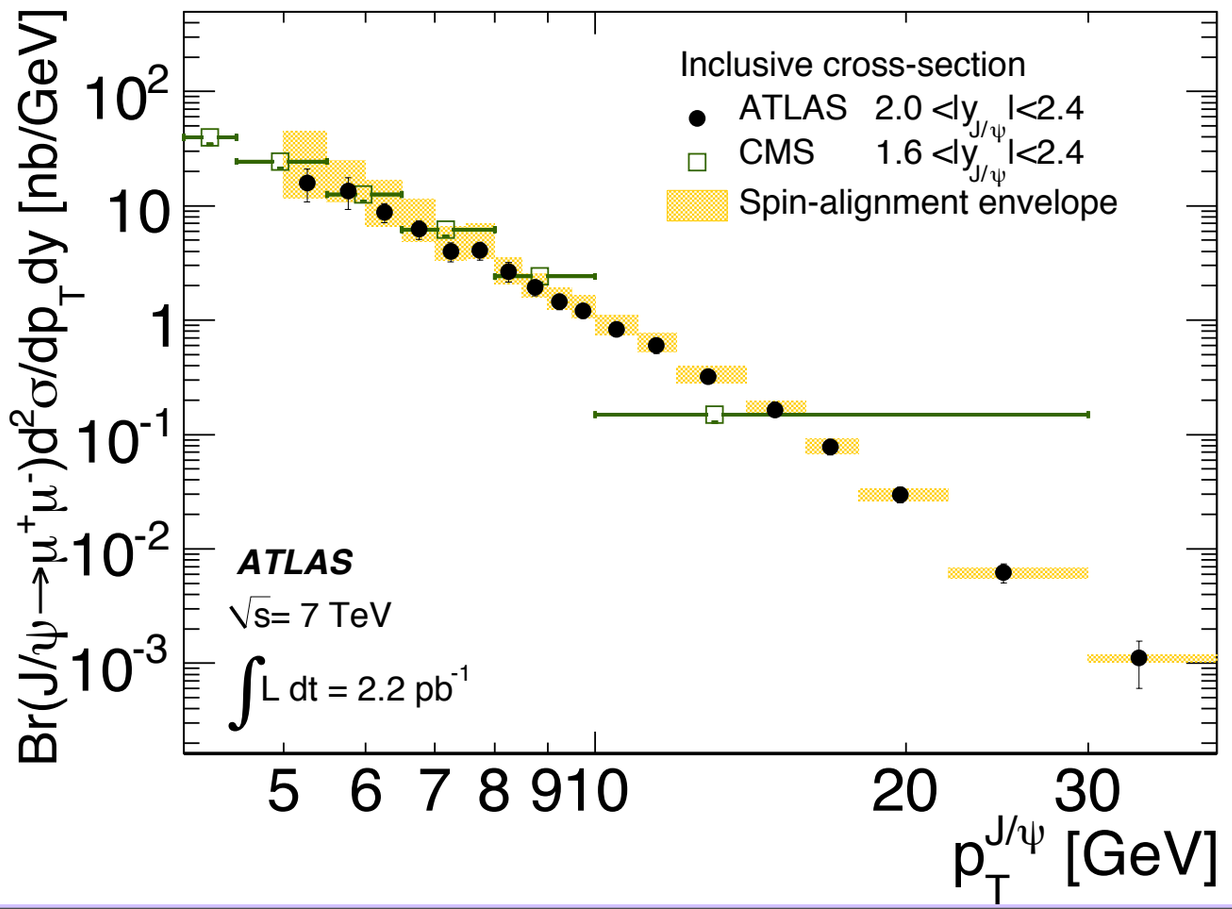
excluding spin alignment




Inclusive cross-section
ATLAS |y_J/ψ|<0.75
CMS |y_J/ψ|<1.2
Spin-alignment envelope
ATLAS
√s= 7 TeV
∫L dt = 2.2 pb-1
Br(J/ψ→μ+μ-)d2σ/dpTdy [nb/GeV]
pTJ/ψ [GeV]


Inclusive cross-section
ATLAS 0.75 <|y_J/ψ|<1.5
CMS 1.2 <|y_J/ψ|<1.6
Spin-alignment envelope
ATLAS
√s= 7 TeV
∫L dt = 2.2 pb-1
Br(J/ψ→μ+μ-)d2σ/dpTdy [nb/GeV]
pTJ/ψ [GeV]


Inclusive cross-section
ATLAS 1.5 < |y_J/ψ| < 2
CMS 1.6 < |y_J/ψ| < 2.4
Spin-alignment envelope
ATLAS
√s= 7 TeV
∫L dt = 2.2 pb-1
Br(J/ψ→μ+μ-)d2σ/dpTdy [nb/GeV]
pTJ/ψ [GeV]

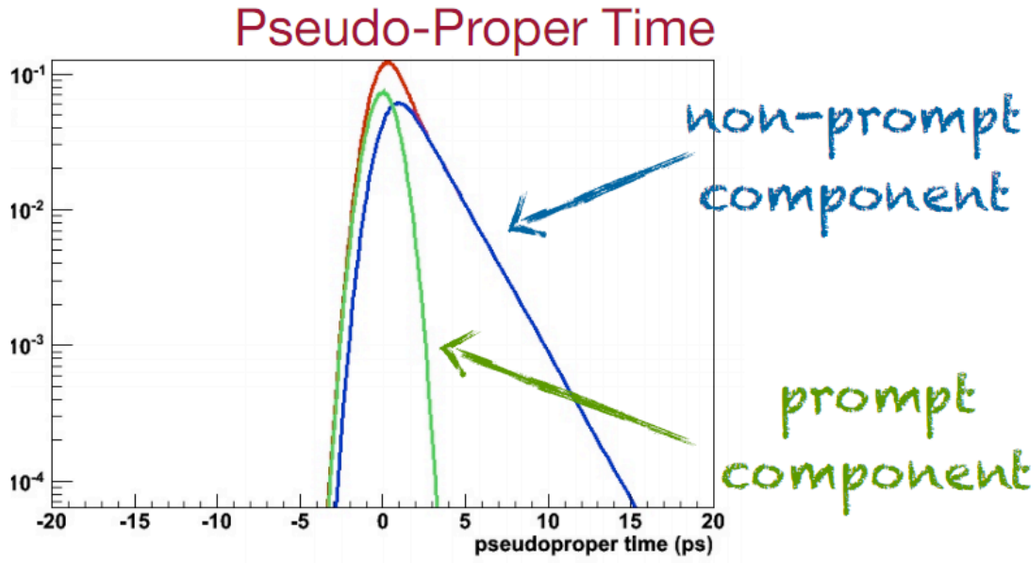

Inclusive cross-section
ATLAS 2.0 <|y_J/ψ|<2.4
CMS 1.6 <|y_J/ψ|<2.4
Spin-alignment envelope
ATLAS
√s= 7 TeV
∫L dt = 2.2 pb-1
Br(J/ψ→μ+μ-)d2σ/dpTdy [nb/GeV]
pTJ/ψ [GeV]

Non-prompt fraction

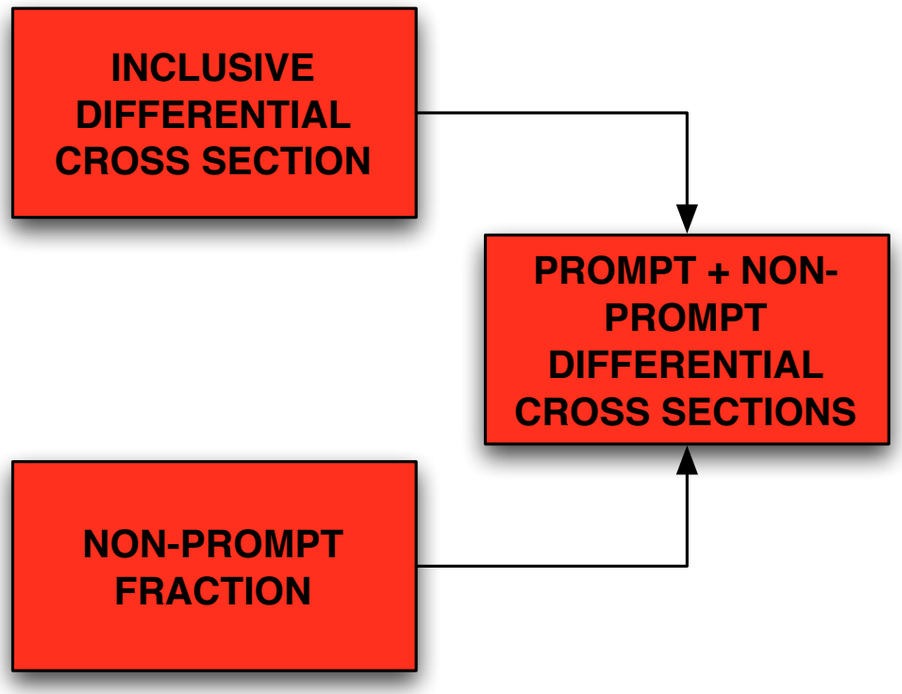
- Need to separate out the component of J/ψ from non-prompt sources in order to access the prompt cross section
- Discriminating variable: pseudo-proper lifetime

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

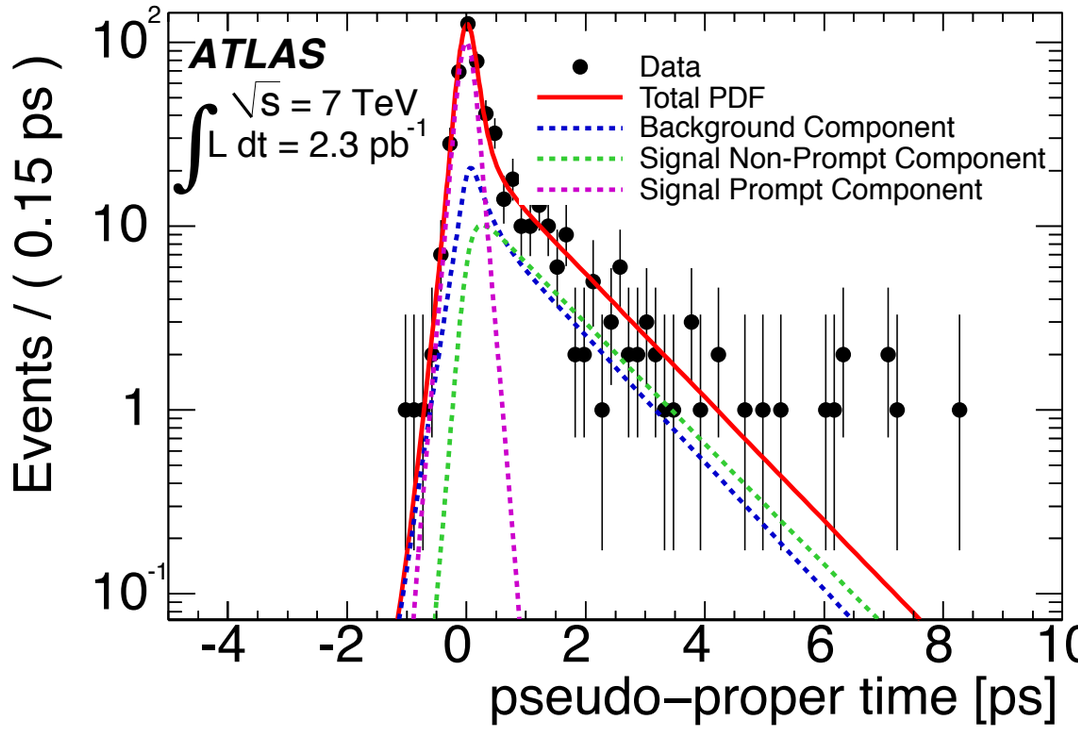
L_{xy} is the xy displacement of the candidate wrt the primary vertex and projected on its p_T

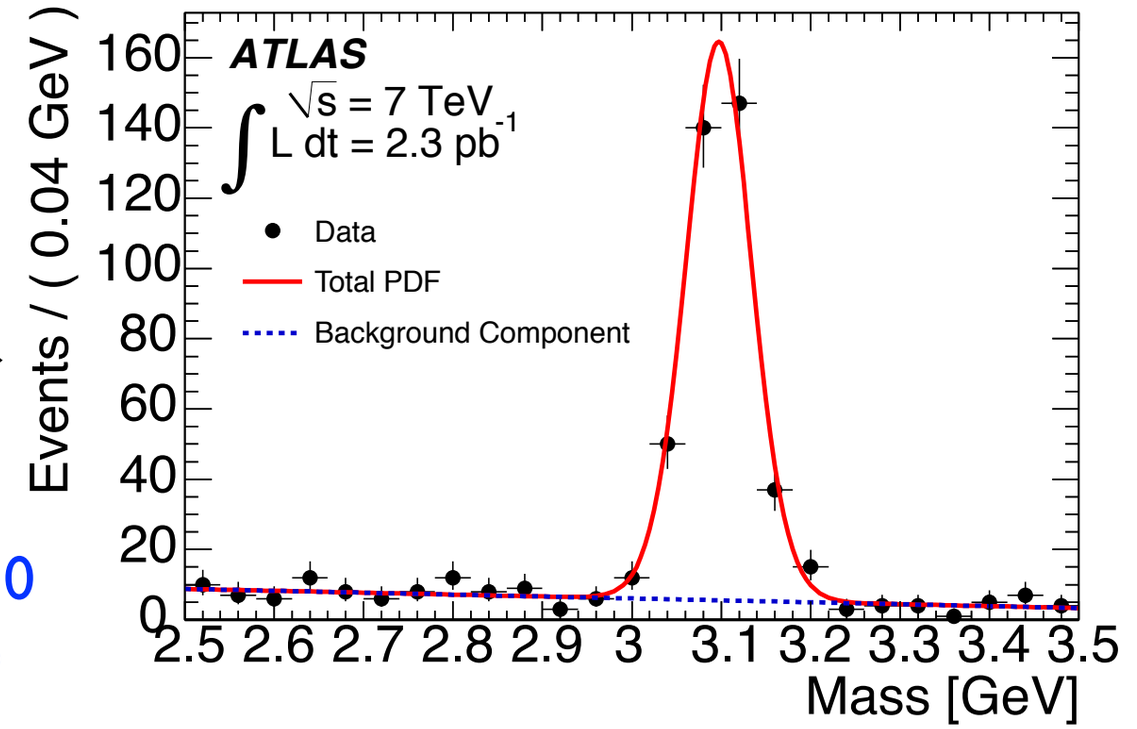


- Perform simultaneous invariant mass and pseudo-proper lifetime fits to extract the non-prompt fraction in each p_T-y slice
- Prompt and non-prompt cross sections can then be extracted by combining the inclusive cross section and the non-prompt fraction

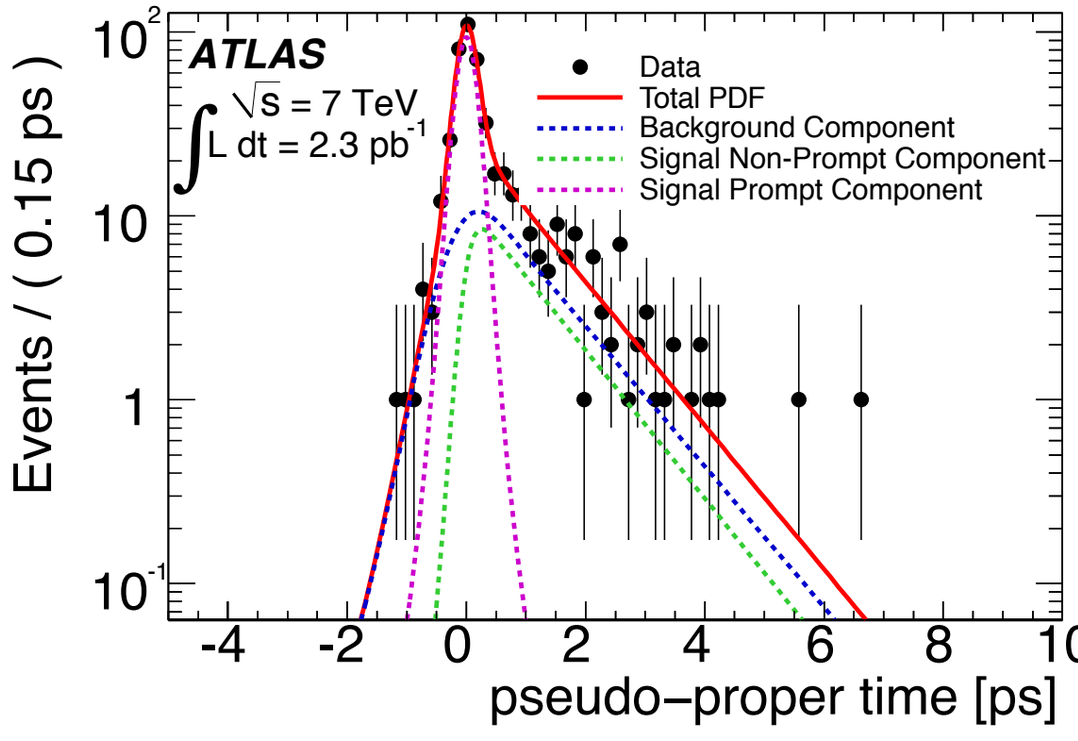


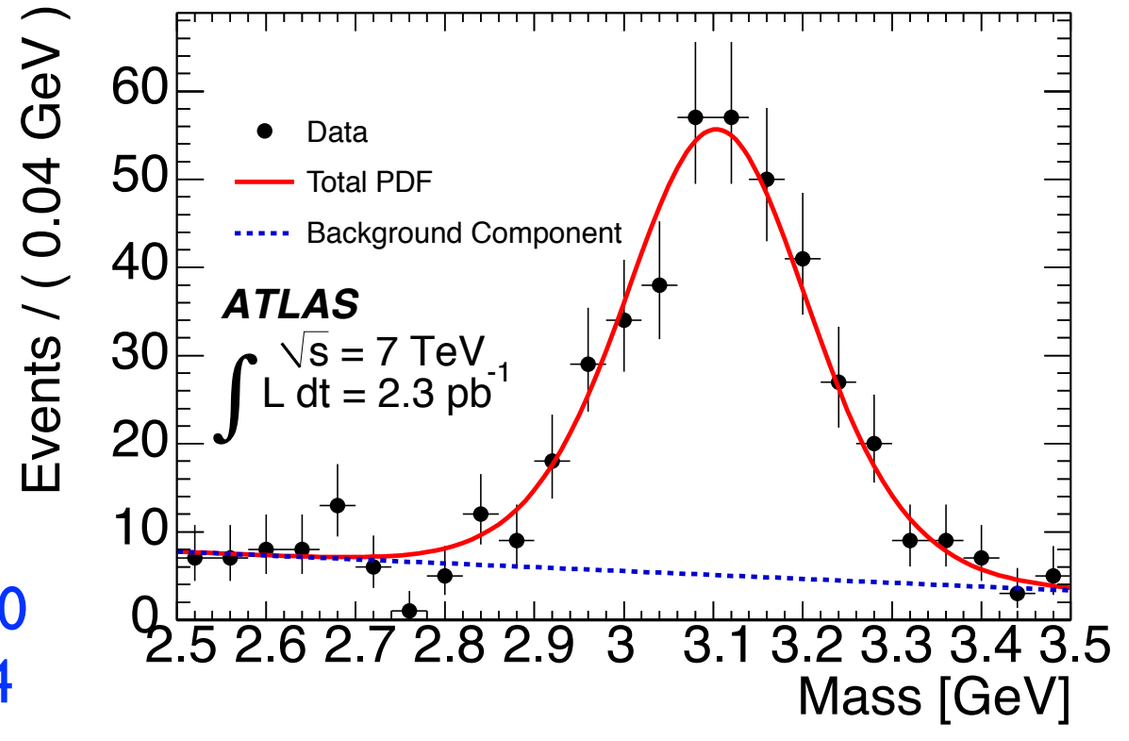
Non-prompt fraction fit example





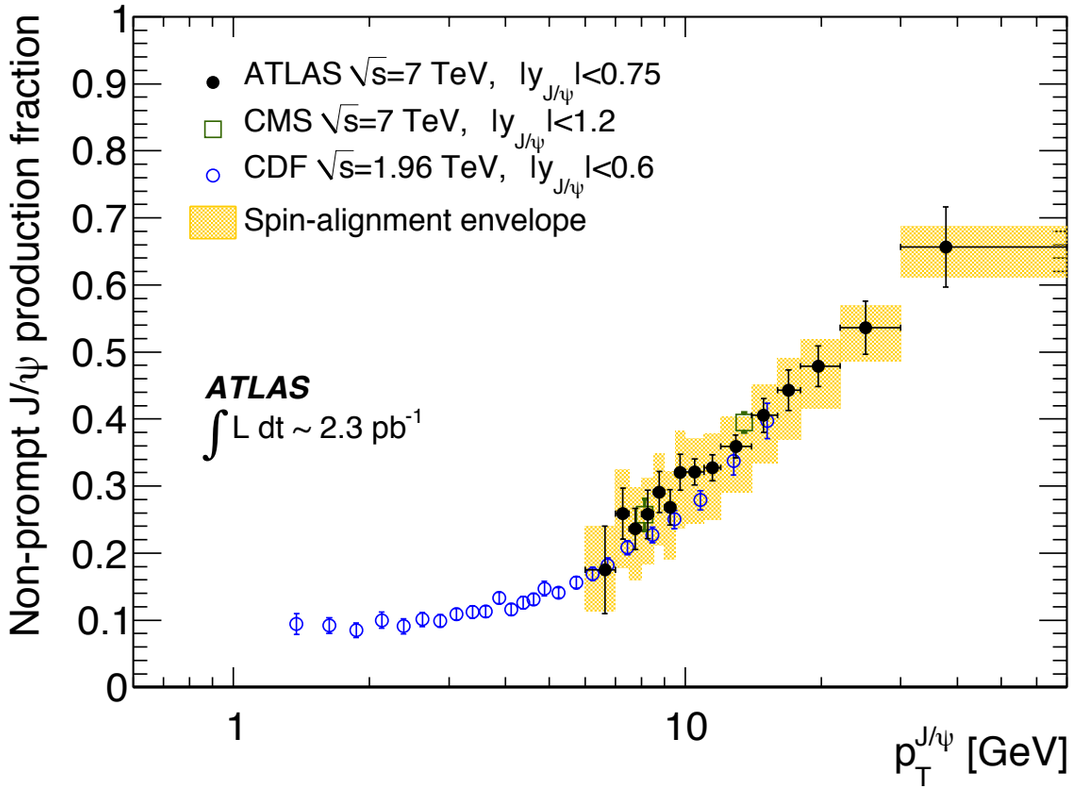
9.5<p_T<10
|y|<0.75

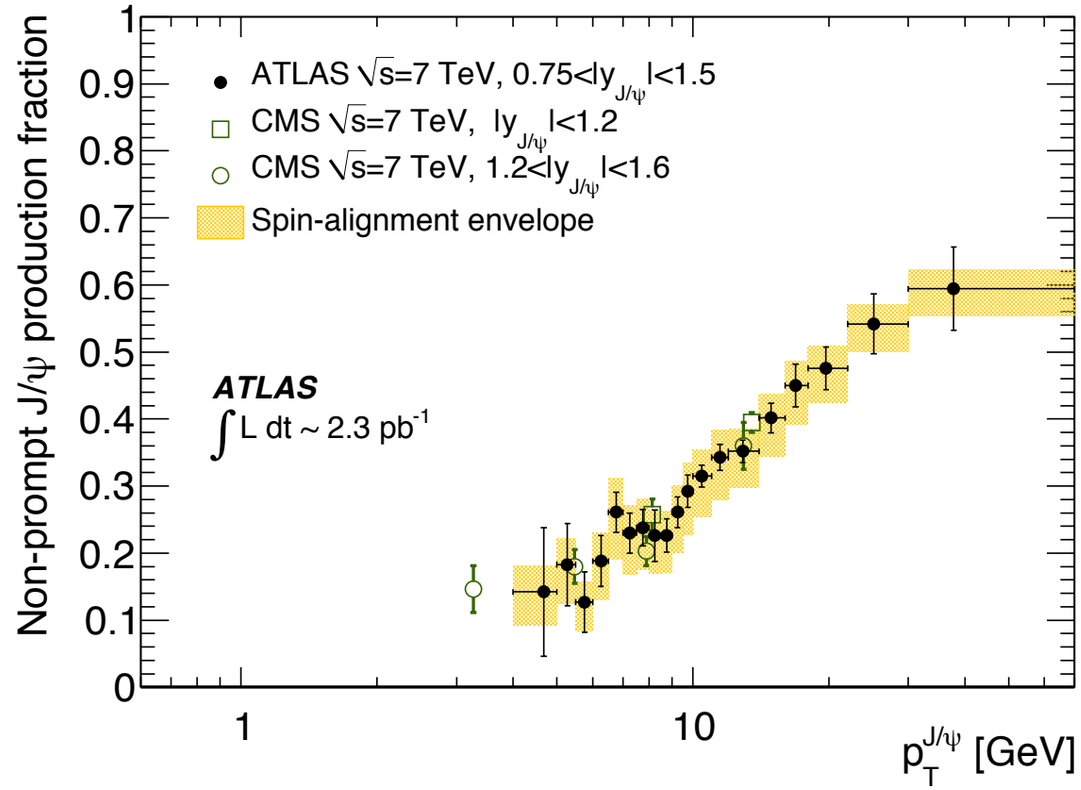


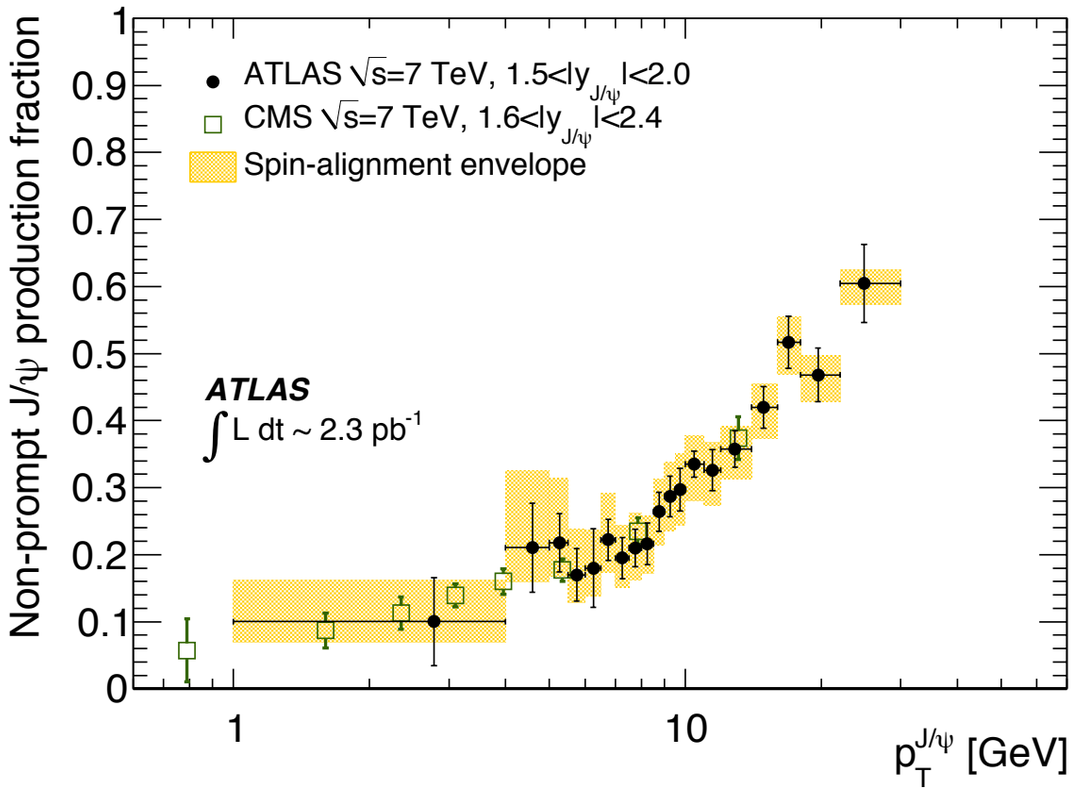


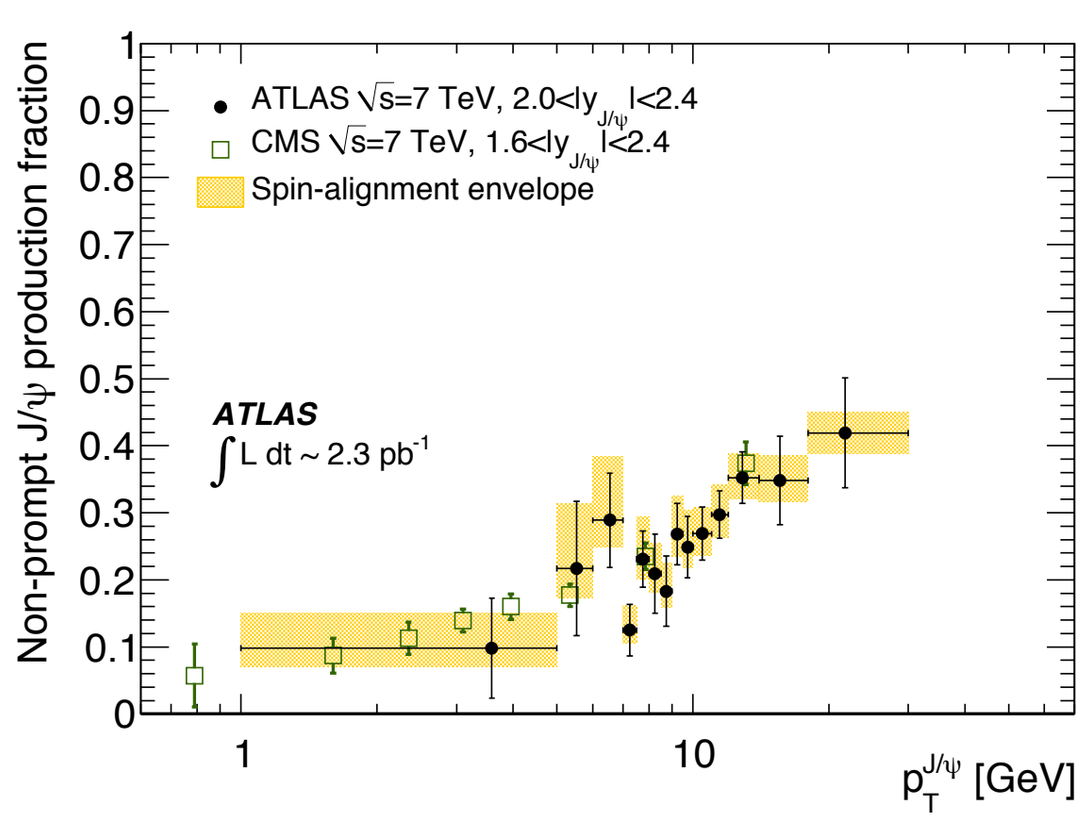
9.5<p_T<10
2<|y|<2.4

Non-prompt fraction results

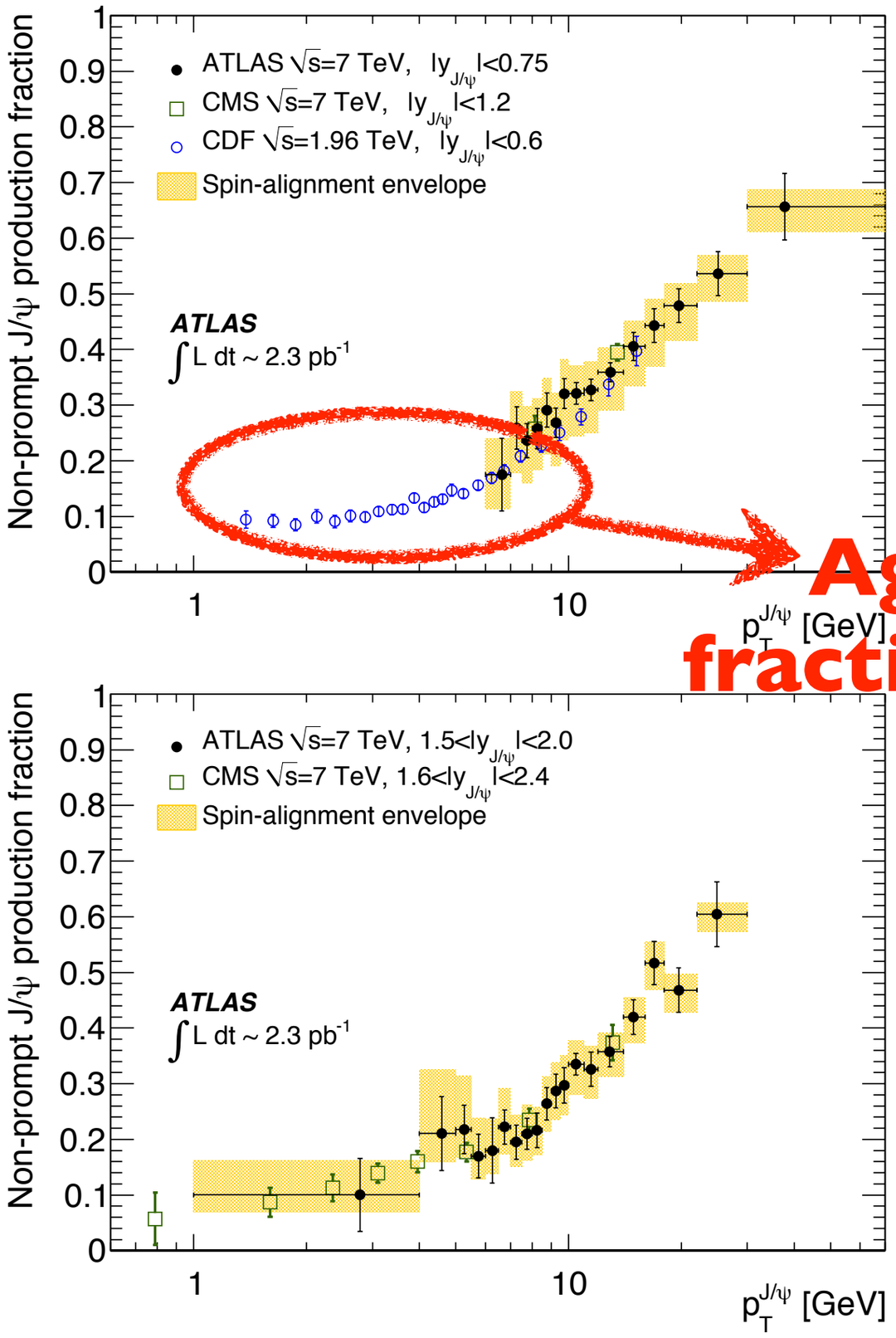


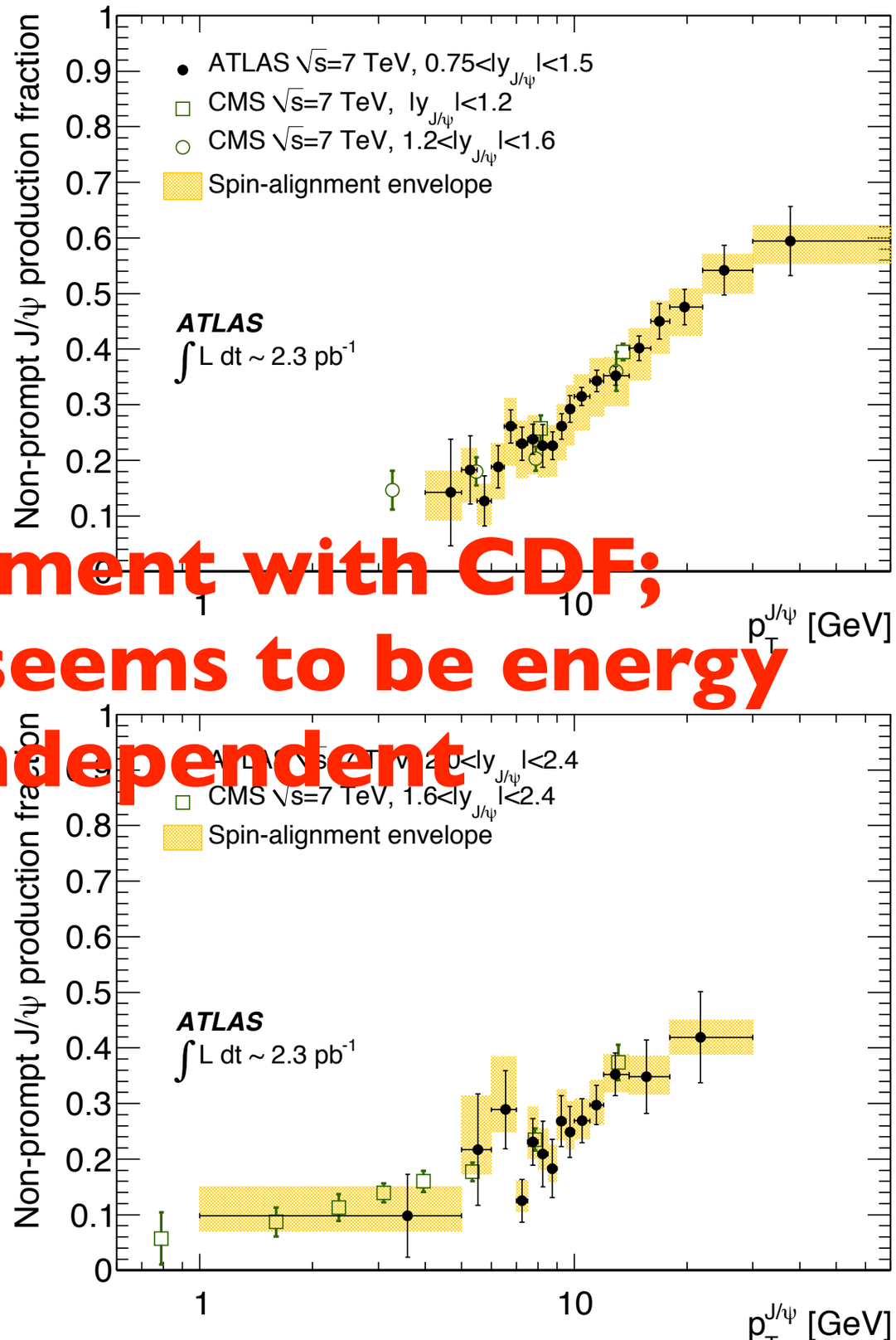






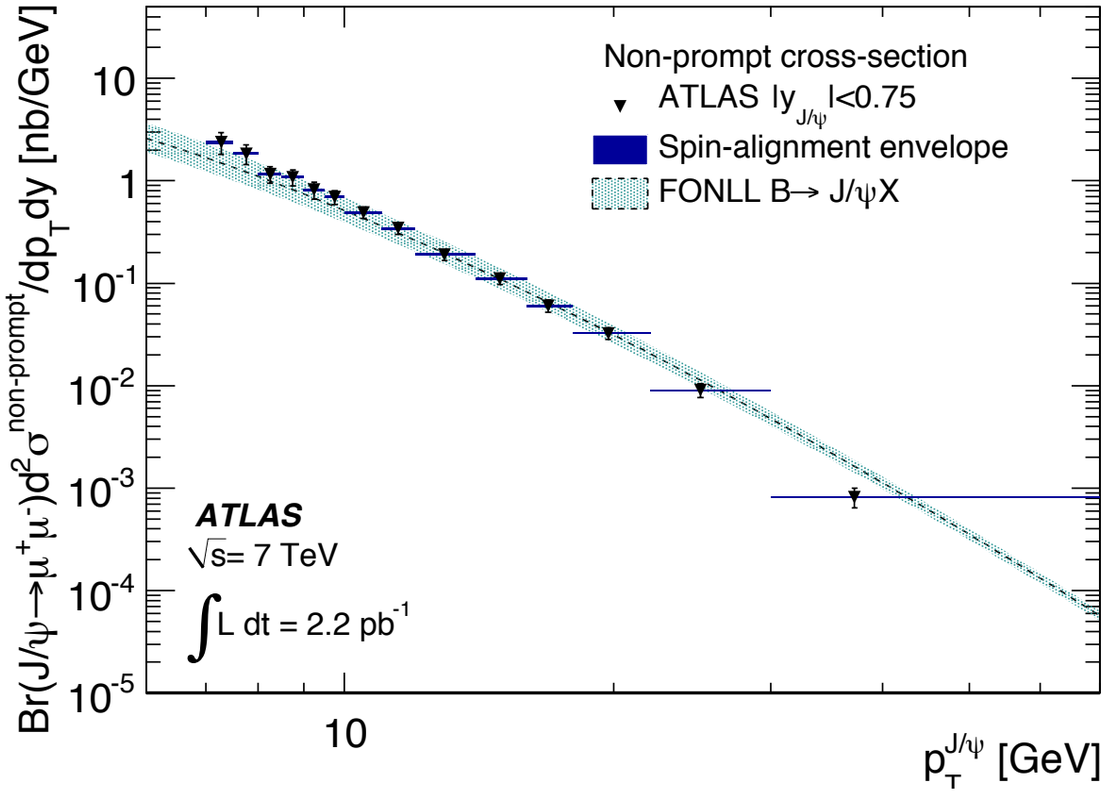
Non-prompt fraction results

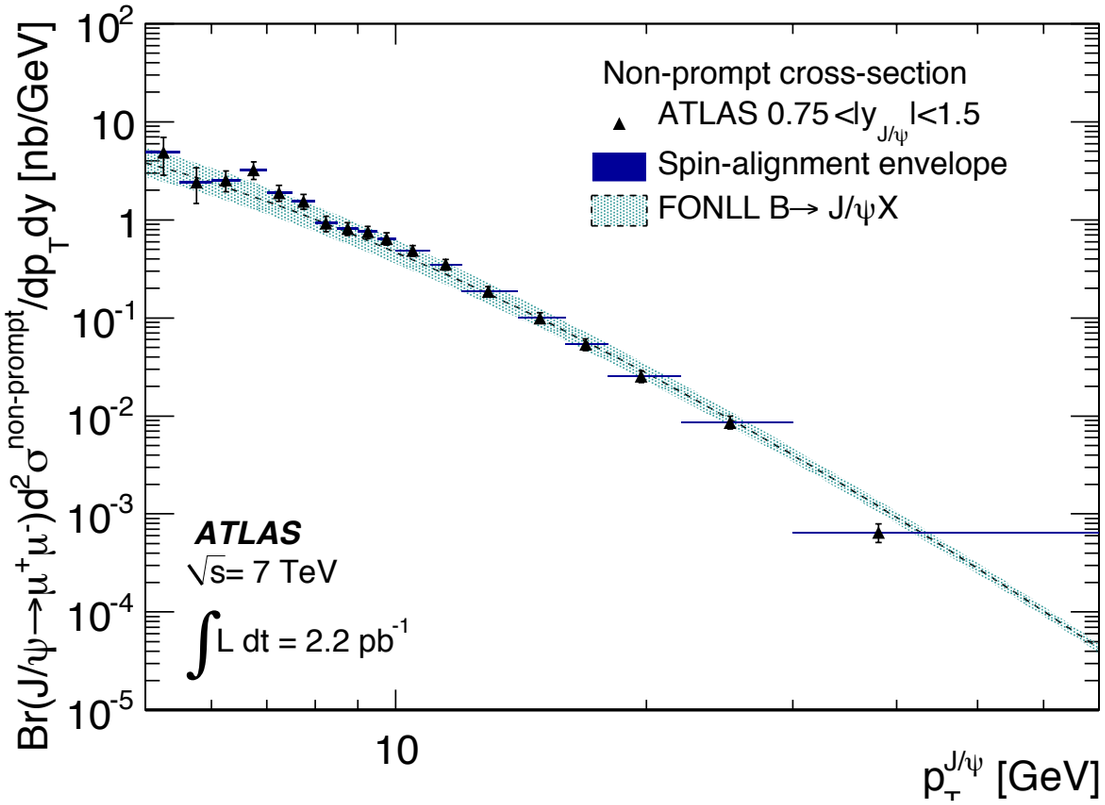


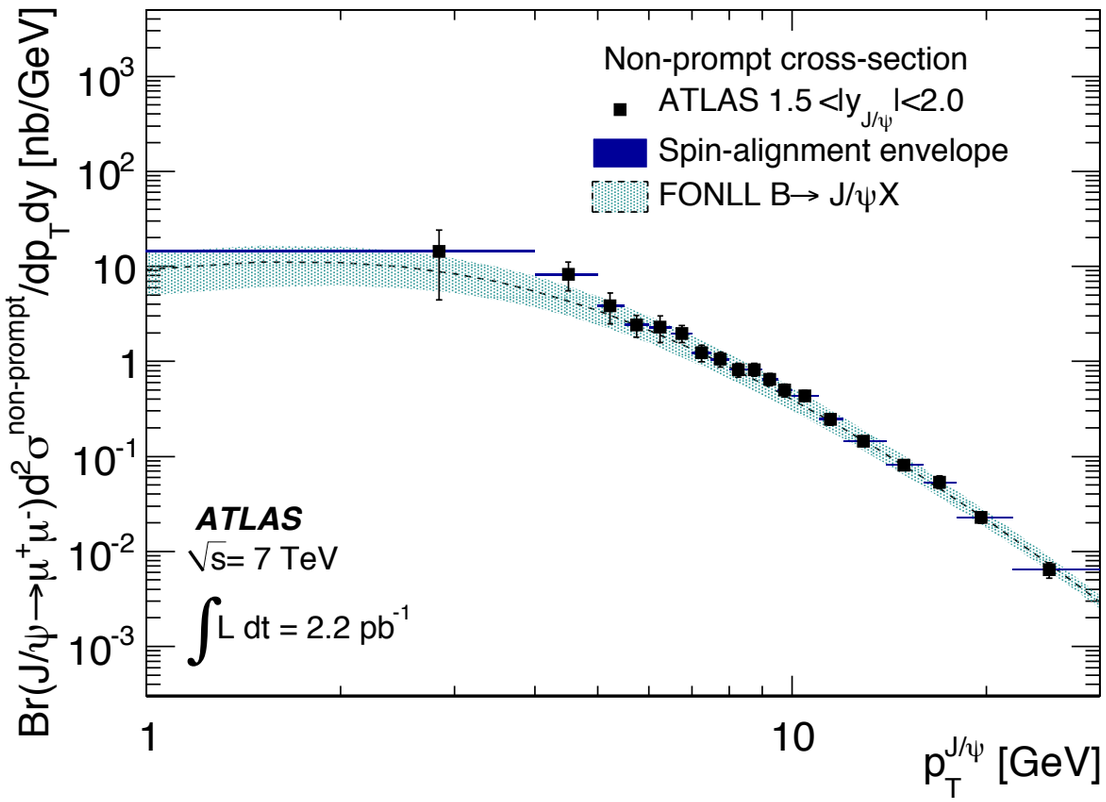


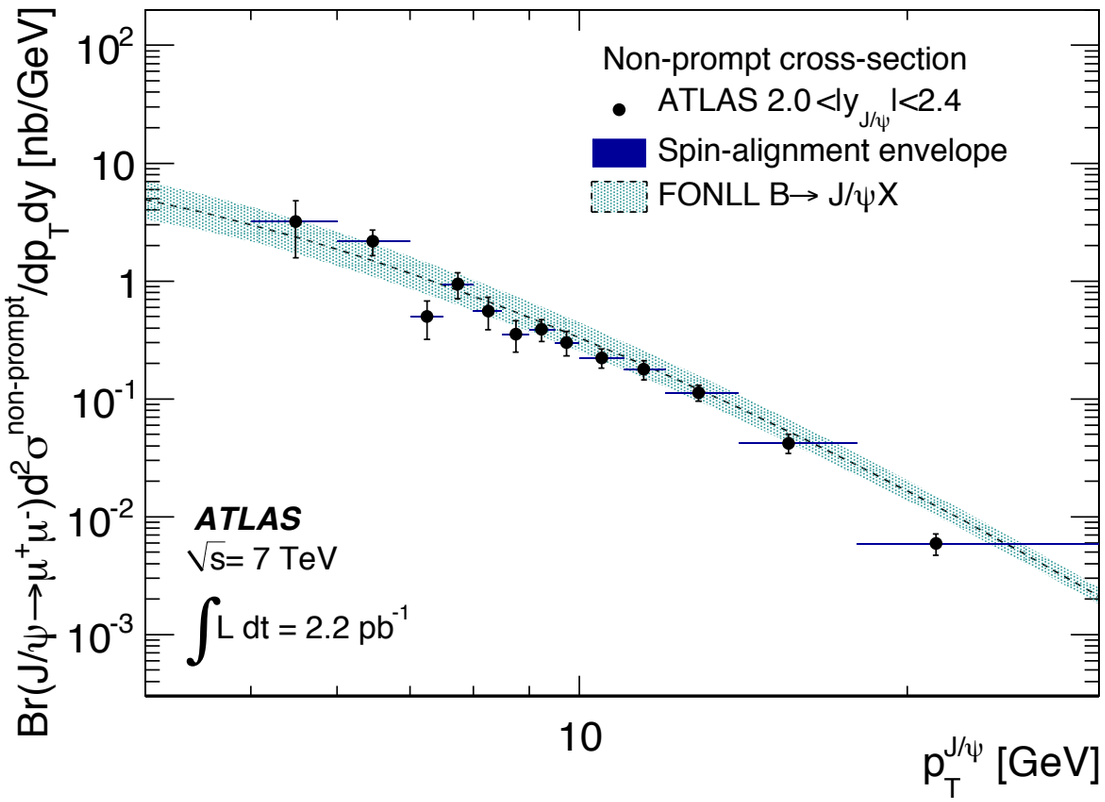
Agreement with CDF; fraction seems to be energy independent

Non-prompt cross section

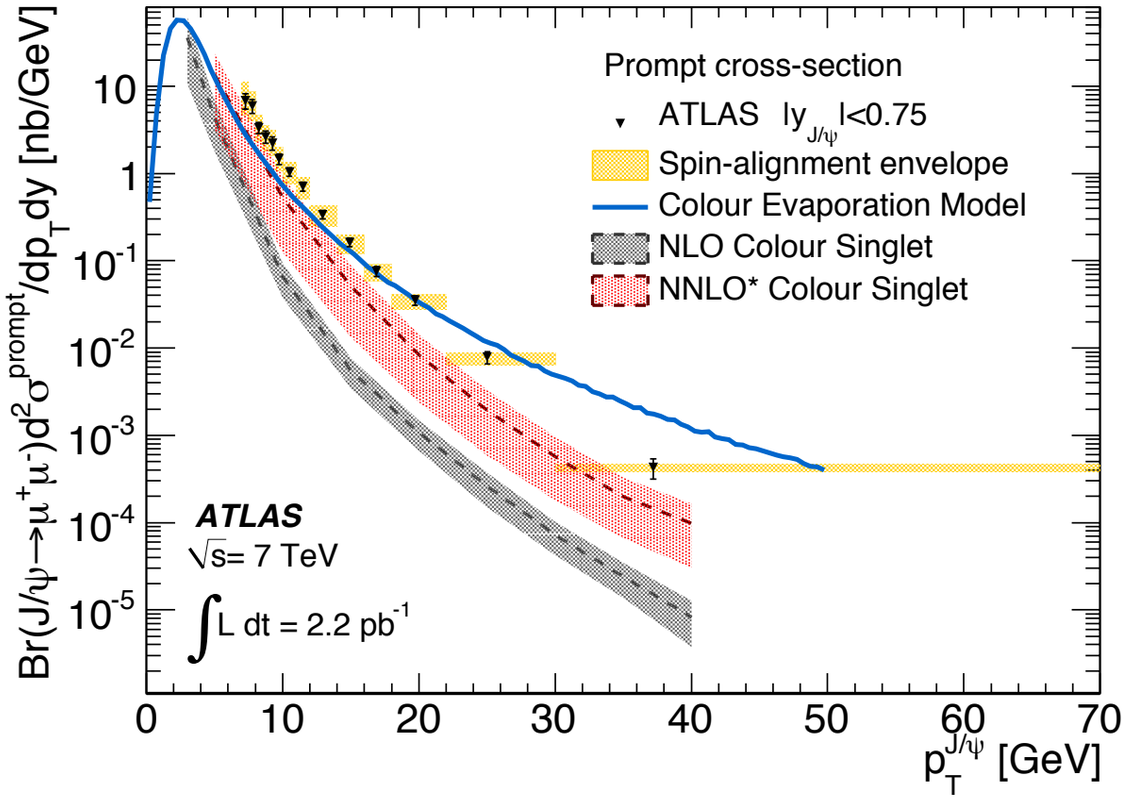


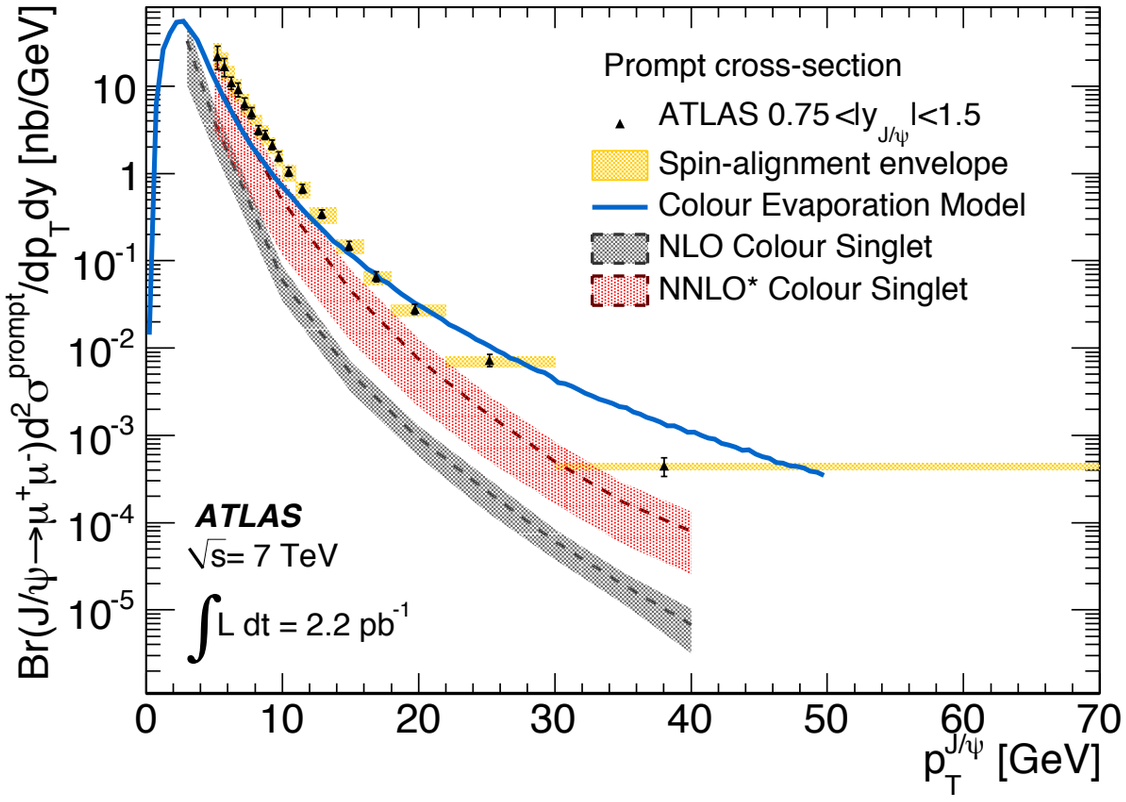


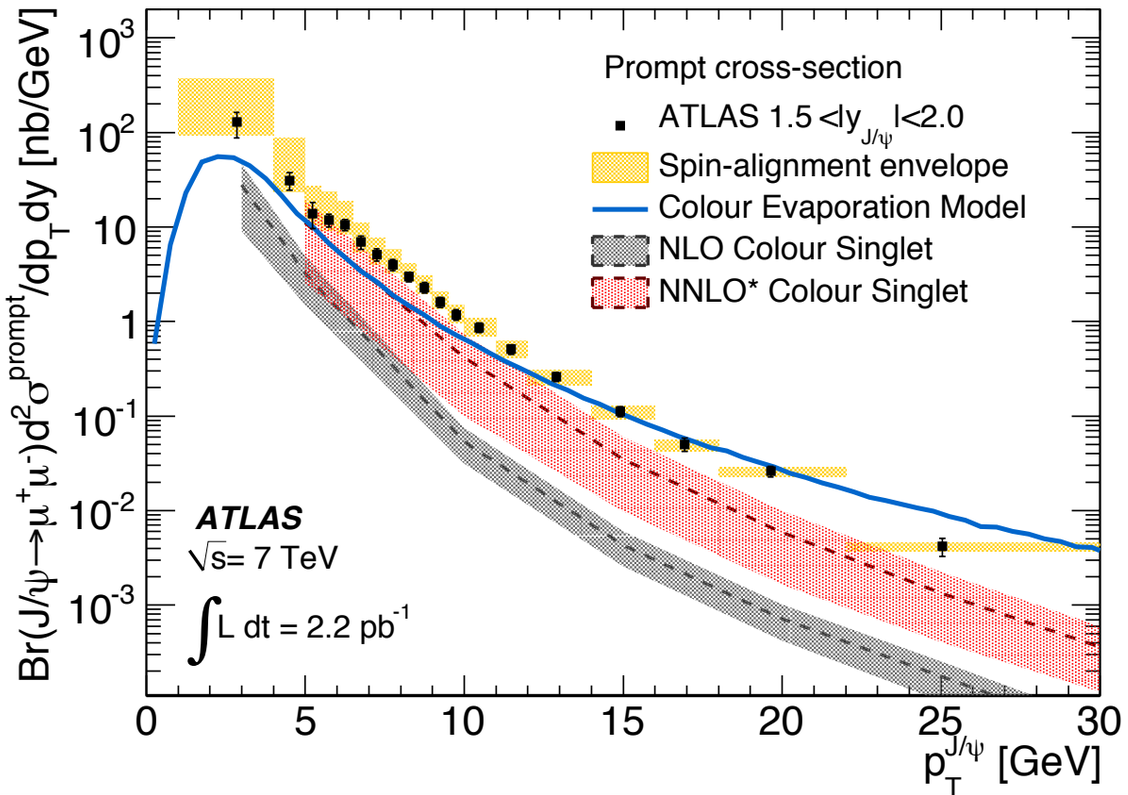


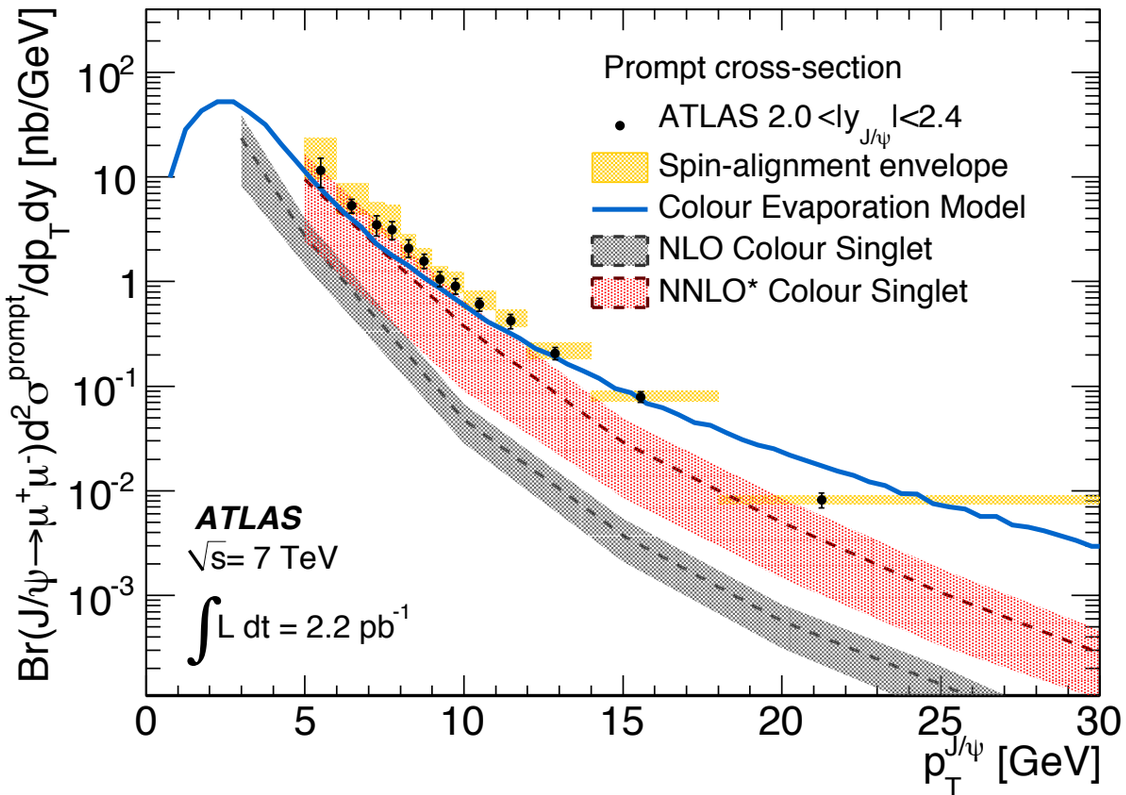


Prompt cross section

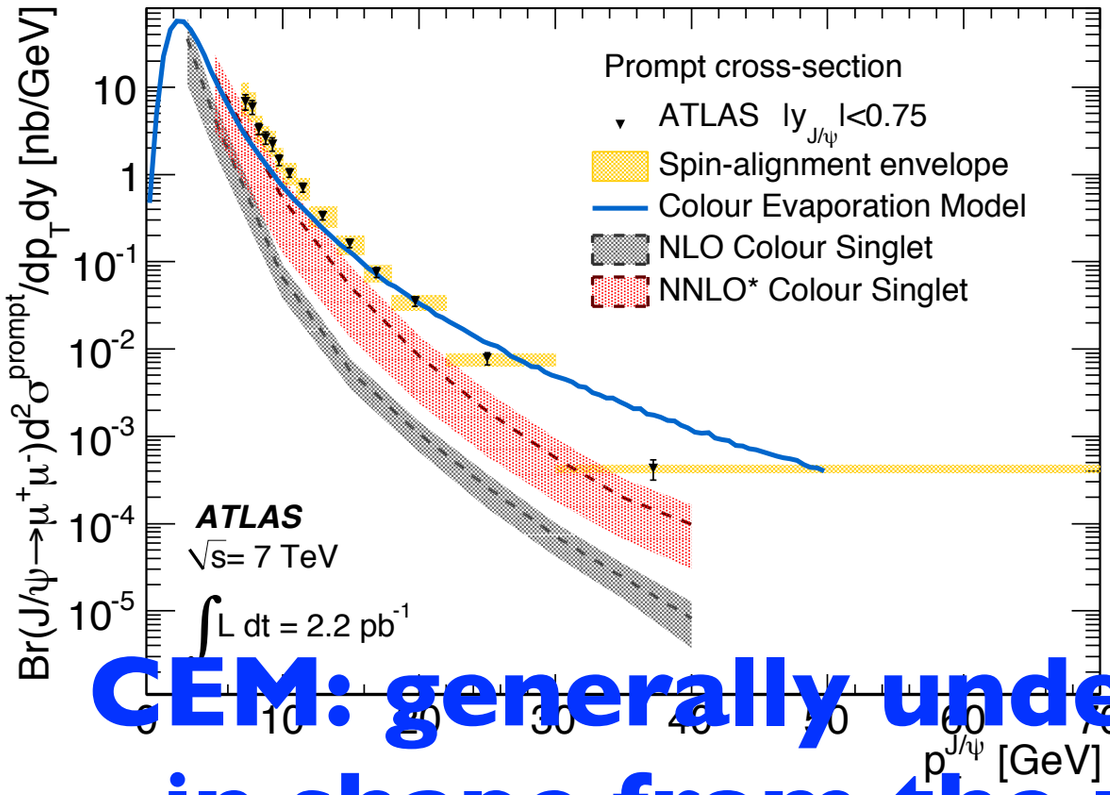


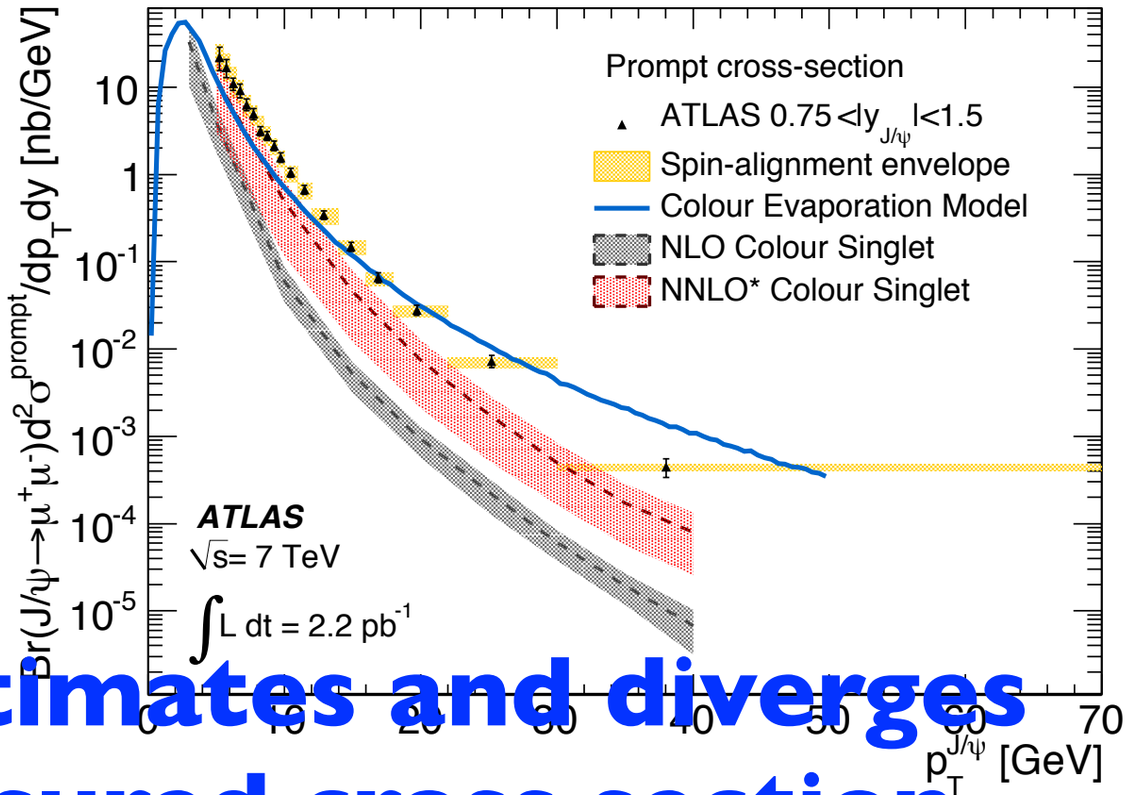




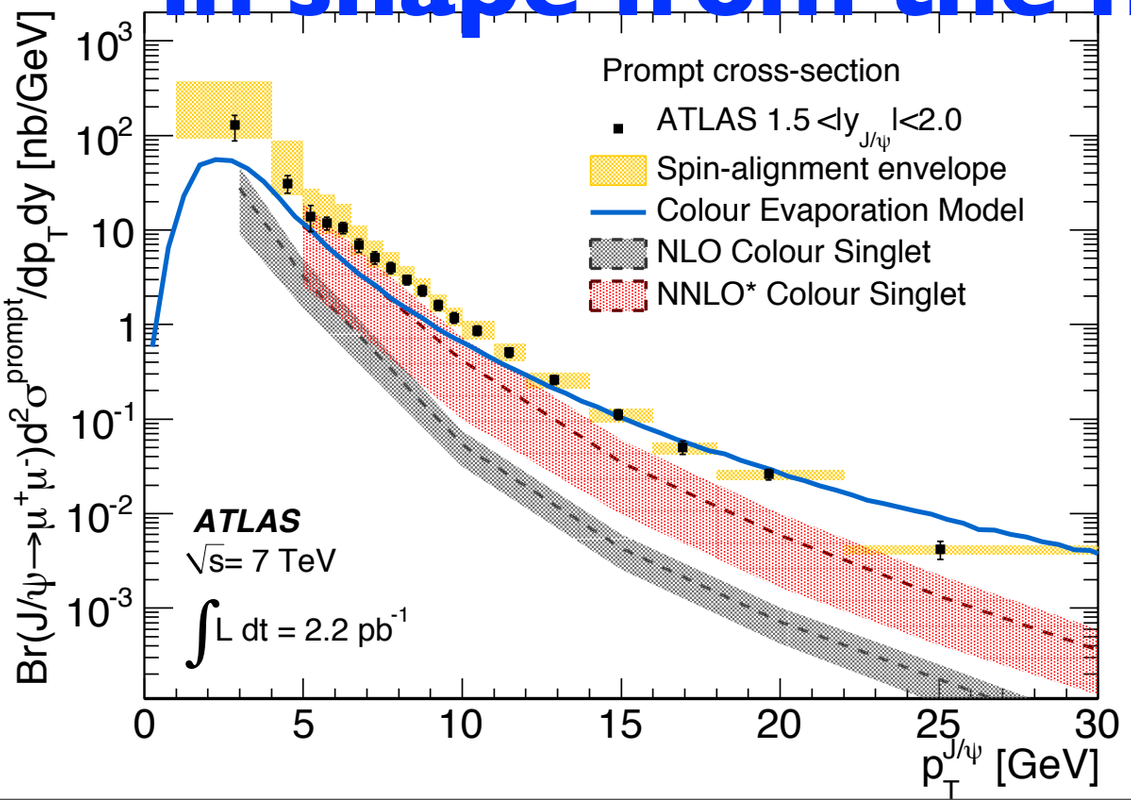


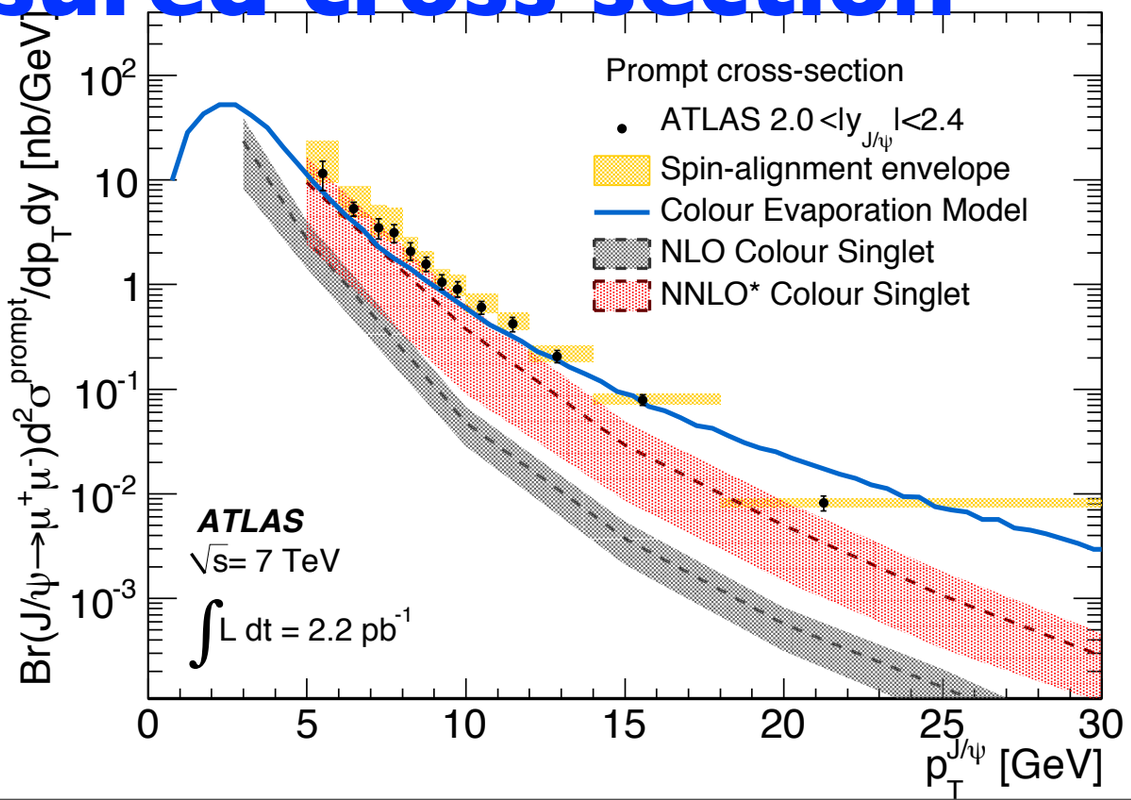
Prompt cross section



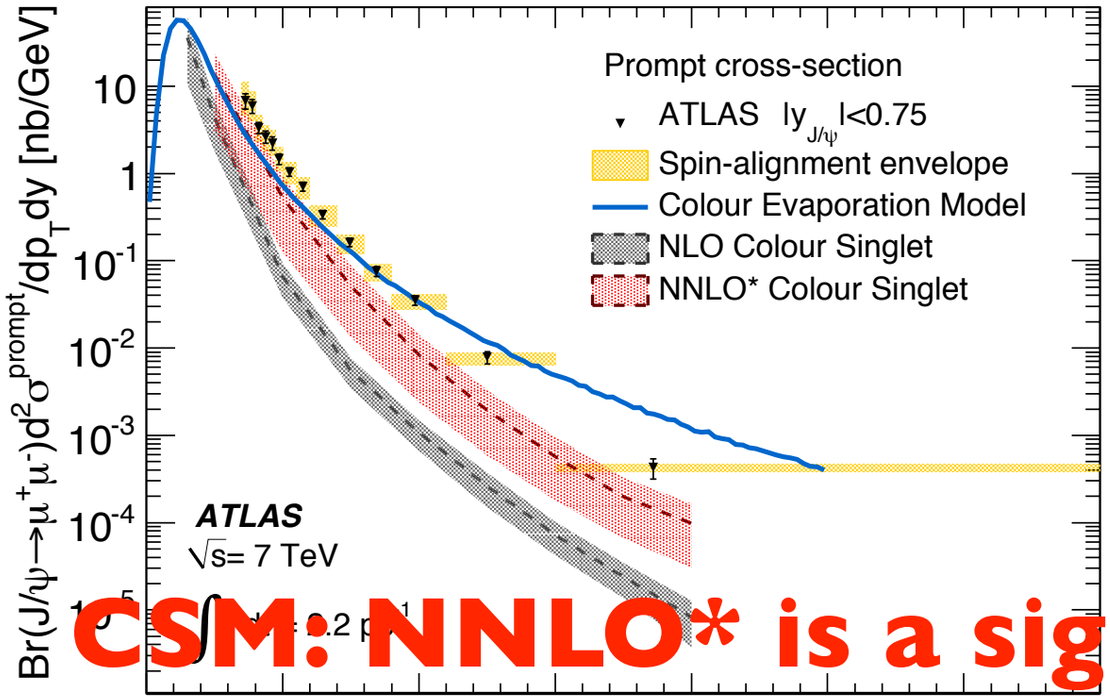


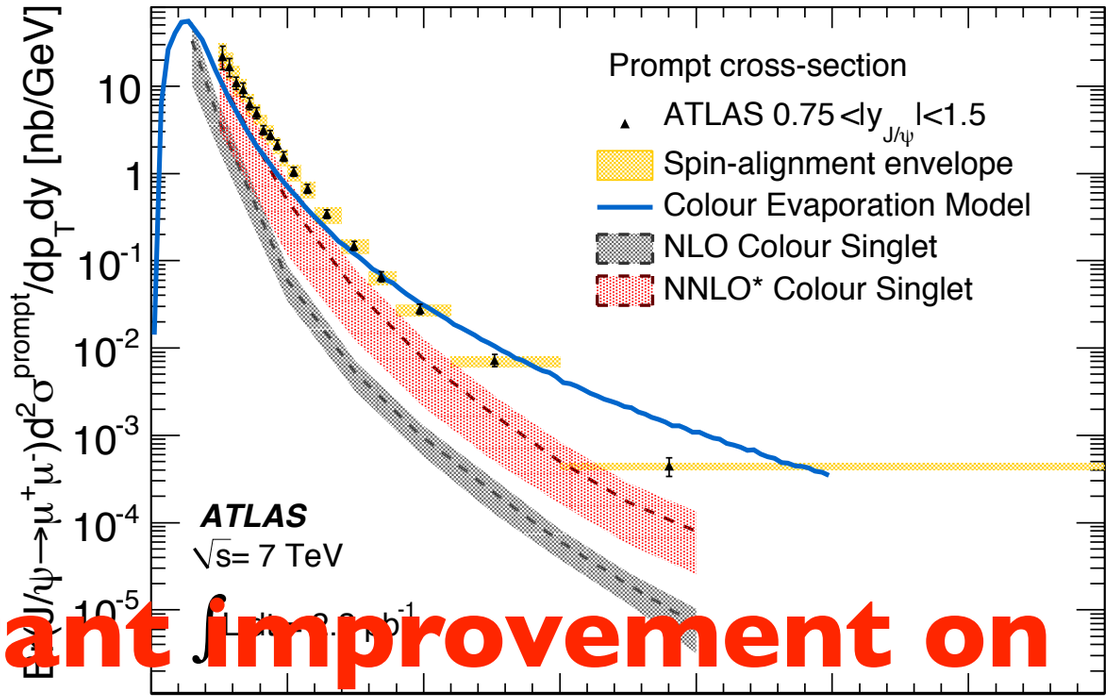
CEM: generally underestimates and diverges in shape from the measured cross section



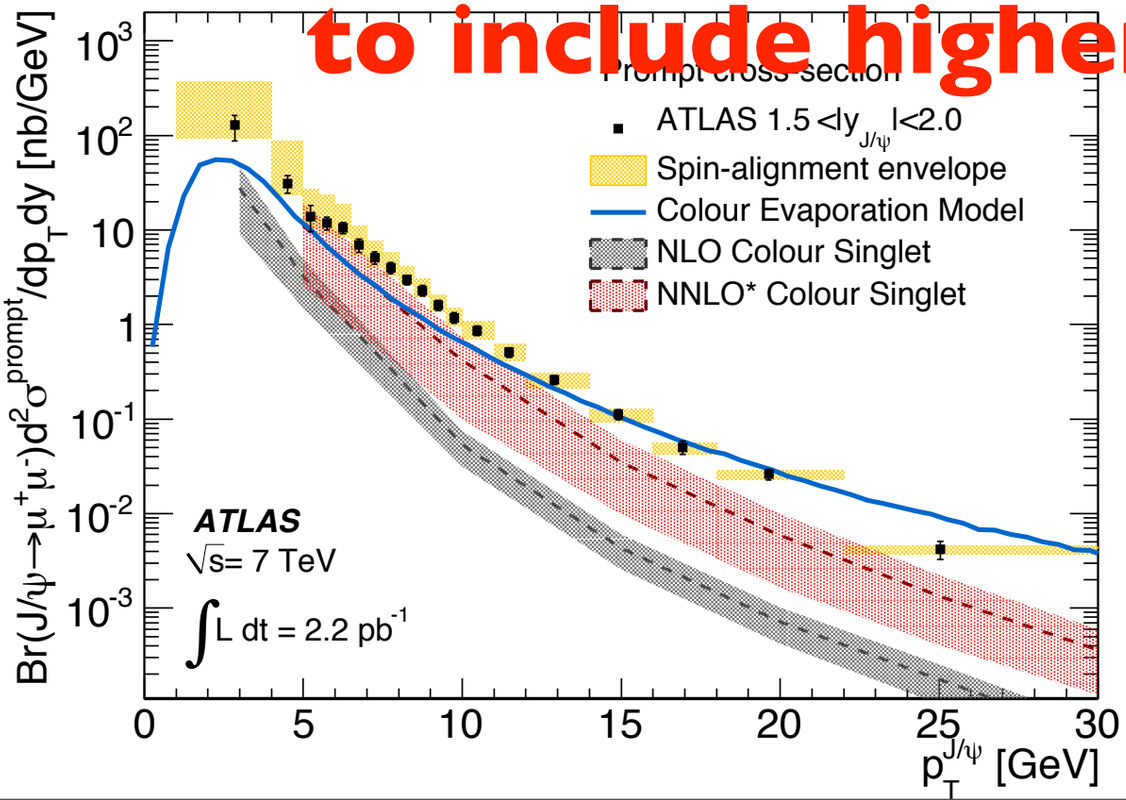


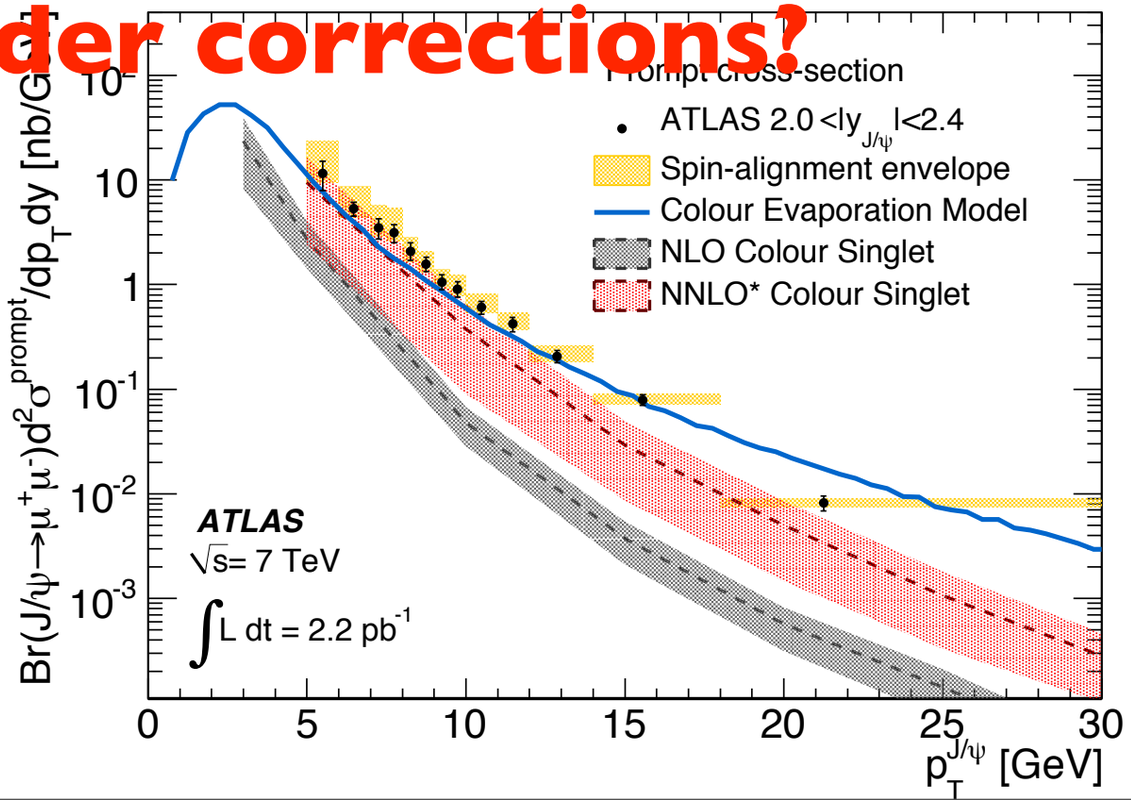
Prompt cross section





CSM: NNLO* is a significant improvement on NLO but still underestimating cross section; need to include higher order corrections?





Summary and next steps

- J/ψ inclusive cross section measured in four rapidity slices from p_T 1-70 GeV
  - Non-prompt fraction also measured allowing the derivation of the non-prompt and prompt cross sections separately
  - Measurements are in good agreement with CMS where there is overlap
  - ATLAS complements results from the other LHC experiments; together they cover p_T from 0-70 GeV and $0 < |y| < 5$ - plenty of input for theoretical models!
    - FONLL describes the non-prompt cross section well; prompt production is more problematic
- Many more measurements in preparation
  - Υ cross section (to be released shortly), J/ψ and Υ spin alignment, measurements at 2.76TeV, ψ(2s) production, χ_c production, double onia production.....
- Taken together the LHC experiments have already provided a set of quarkonia production measurements which span an impressive range of transverse momenta and rapidities

Supporting slides

More details on the models

- FONLL
  - FONLL 1.3.2 using CTEQ6.6 PDFs
  - Br(B→J/ψX)=0.0116
  - Uncertainty bands from: b-quark mass 4.75±0.25 GeV, renormalisation (μ_R) and factorisation (μ_F) scales, PDF uncertainties
- CEM
  - CTEQ6M PDFs, charm quark mass of 1.2 GeV, no uncertainty bands
  - include contributions from χc and ψ(2S) feed-down
- CSM
  - CTEQ6M PDFs, charm quark mass of 1.5 GeV
  - direct production only so corrections applied to enable the prediction to be directly applied to data: flat 10% for ψ(2S)→J/ψππ, 40% for radiative χc

References for models

- Colour evaporation model:
  - T. Ullrich, A. D. Frawley and R. Vogt, Phys. Rept. **462** (2008) 125, **arXiv:0806.1013[nucl-ex]**
  - V. D. Barger, W.Y. Keung and R. J. N. Phillips, Phys. Lett. B **91** (1980) 253 and Z. Phys. C **6** (1980) 169
- NLO/NNLO* colour singlet model:
  - J. Lansberg, **arXiv:1006.2750 [hep-ph]**;
  - S. J. Brodsky and J. P. Lansberg, Phys. Rev. D**81** (2010) 051502(R);
  - J. P. Lansberg, Eur. Phys. J. C **61** (2009) 693, **arXiv:0811.4005 [hep-ph]**
- Fixed order NLL: M.Cacciari, M.Greco and P. Nason, JHEP **9805** (1998) 007, **arXiv:hep-ph/9803400** and JHEP **0103** (2001) 006, **arXiv:hep-ph/0102134**.

Spin alignment working points

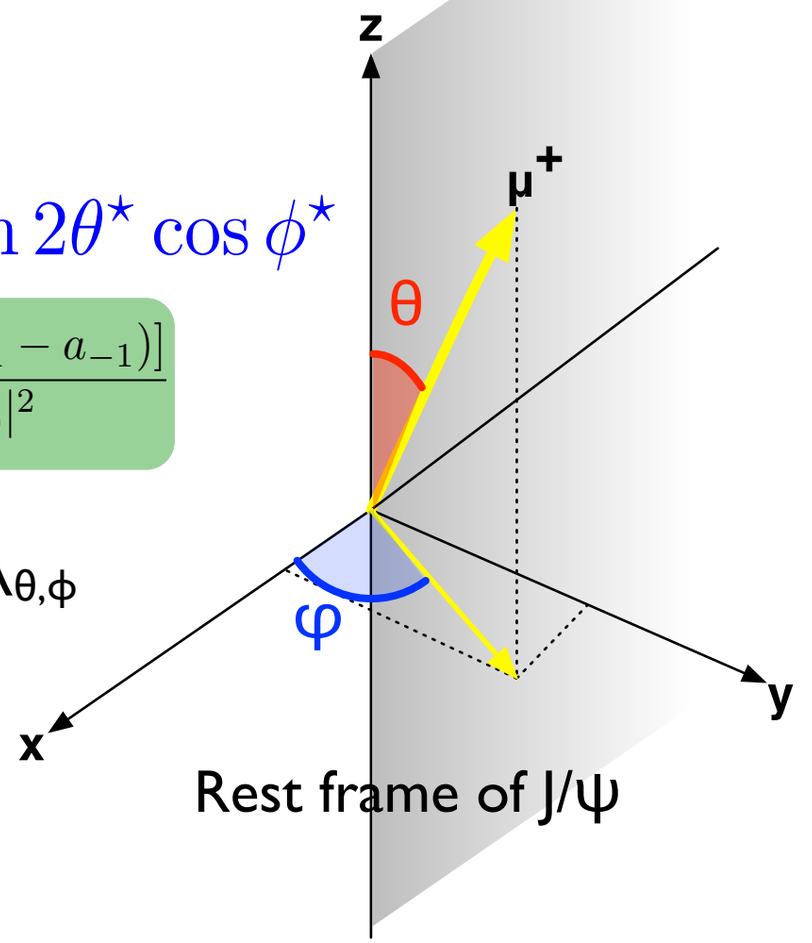
- Generalised description of vector state:

$$|\psi\rangle = a_{-1}|\mathbf{1,\text{-}1}\rangle + a_0|\mathbf{1,0}\rangle + a_{+1}|\mathbf{1,+1}\rangle$$

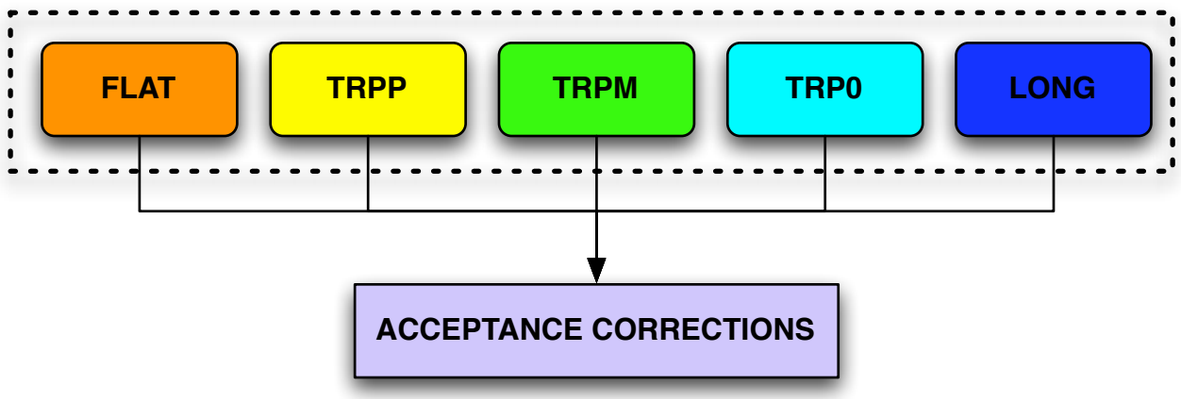
- Angular distribution:

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

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

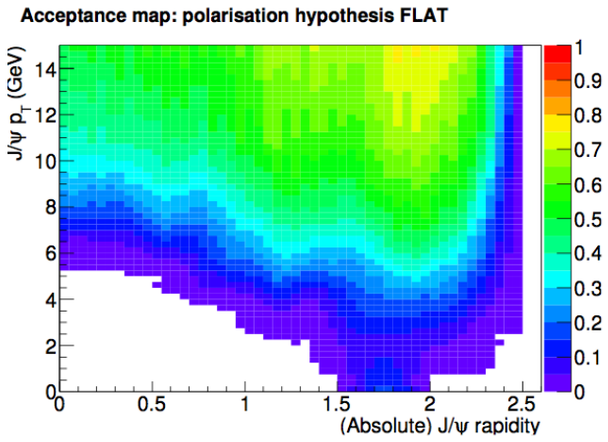


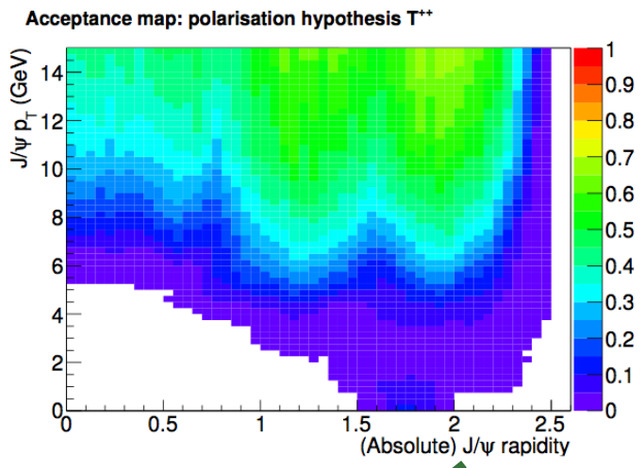
Five spin alignment models selected by choosing different values of $\lambda_{\theta,\phi}$ to provide working points for the acceptance maps

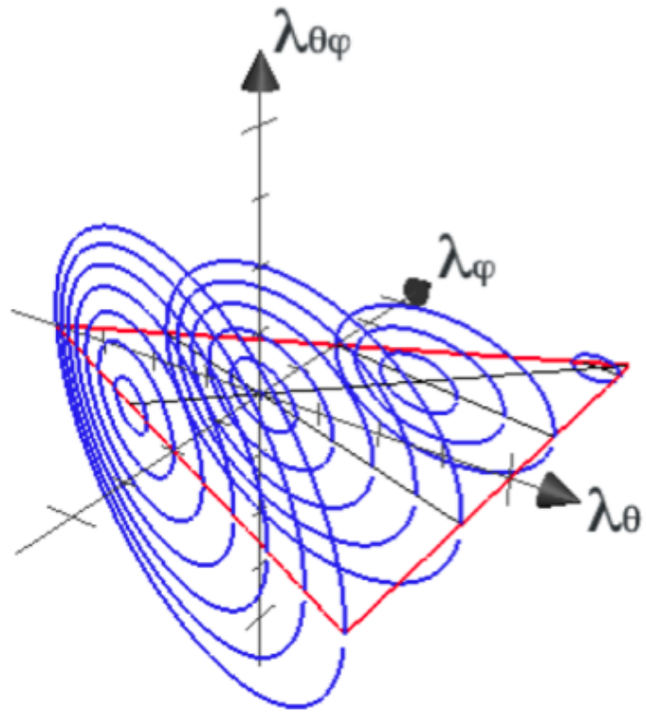


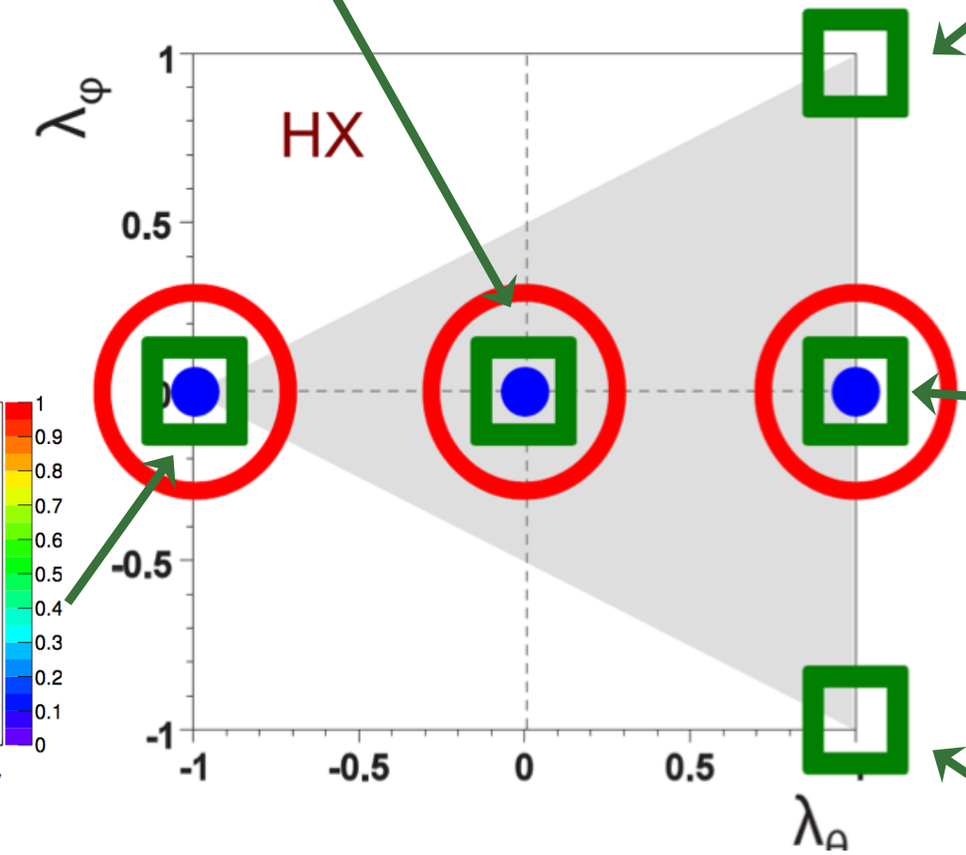
Acceptance corrections

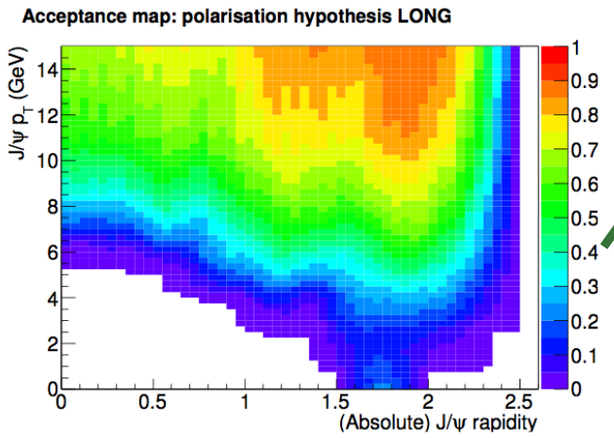
Five spin alignment working points are established with separate acceptance maps. These are used to provide a theoretical uncertainty around the results

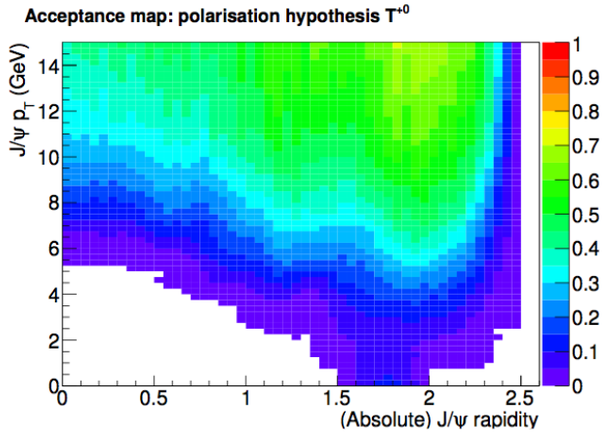


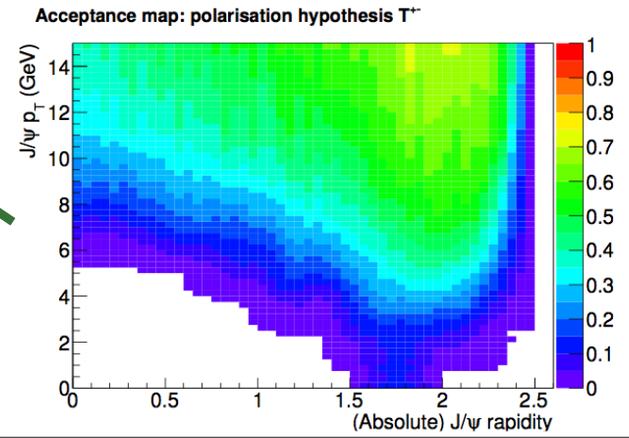












ATLAS CMS LHCb

J/ψ lifetime fitting models

Mass fit:

signal – gaussian with per-event error

background – Chebyshev polynomial

Lifetime fit:

signal – delta function plus exponential convoluted with gaussian with per-event error to account for resolution

background – symmetric positive/negative exponentials plus positive exponential convoluted with gaussian with per-event error for resolution

Offline reconstruction efficiency corrections