Heavy quarkonium physics in ATLAS

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Outline of this talk:

Models of prompt production of quarkonium -- theory

ATLAS results on pp collisions at 7 TeV

- Inclusive, prompt and non-prompt J/ψ production (in some detail)
- Upsilon(1S) production
- Observation of χ_c
- Observation of some exclusive B decays

ATLAS results on PbPb collisions at 2.76 TeV

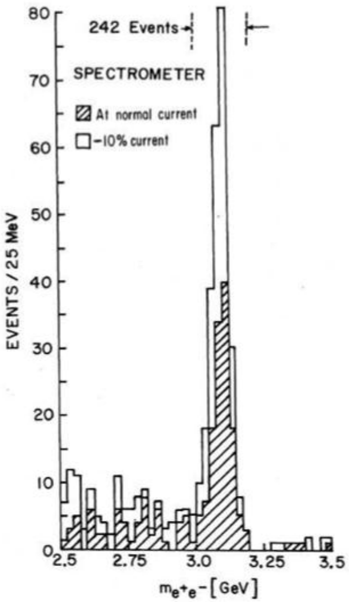
- J/ψ suppression as a function of centrality

Conclusions and plans

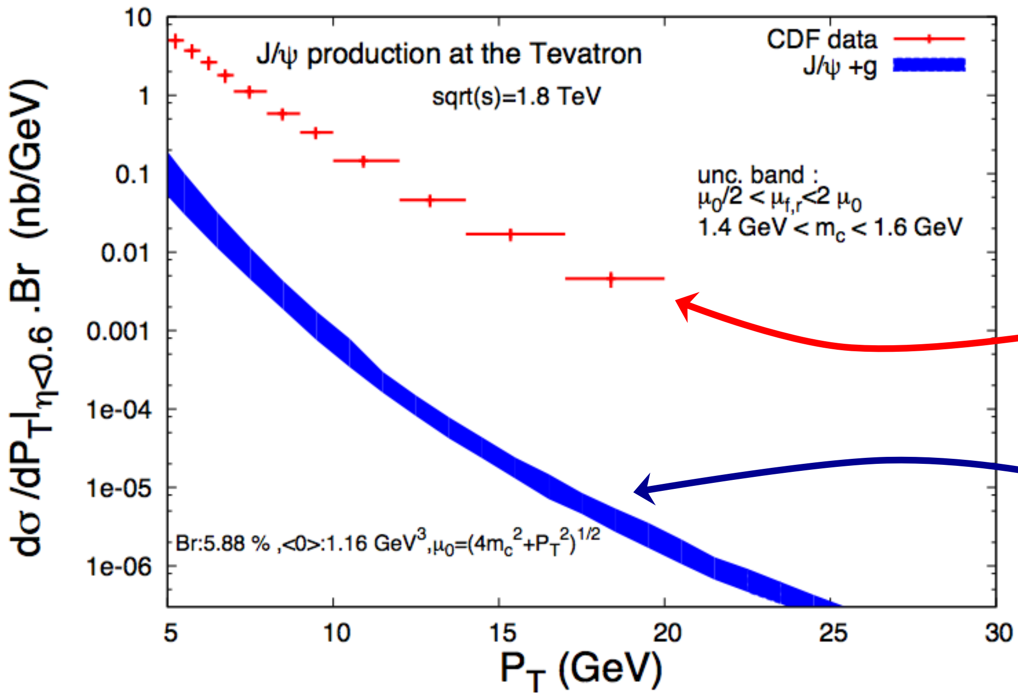
First, a little bit of theory…

Background to J/ψ production

We have experimentally observed J/ψ production in colliders since 1974, so why are we still interested?



Despite being a 'known' resonance the production mechanisms are still far from understood!



Measurement of J/ψ production from CDF

State of theory as of early 90's (LO calculation) "Color Singlet Model"

The Color Singlet Model @ LO

Color Singlet Model assumes:

Factorisation theorem:

decompose quarkonium formation into:

1)Creation of two on-shell heavy quarks

Typical scale makes this perturbative

2)Binding into physical meson

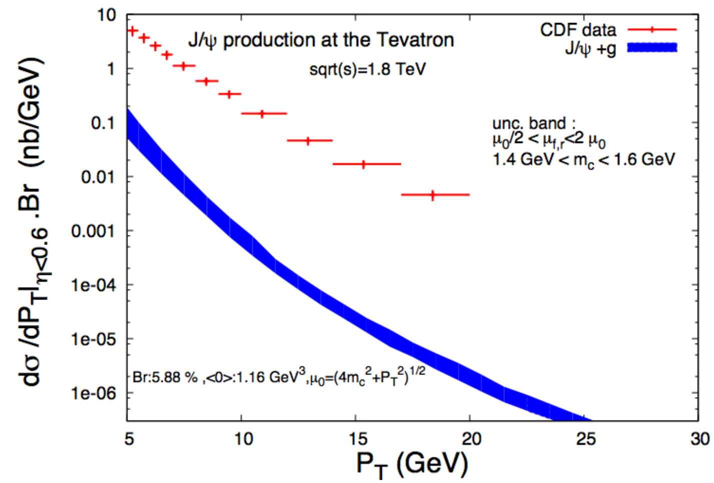
Non-perturbative QCD

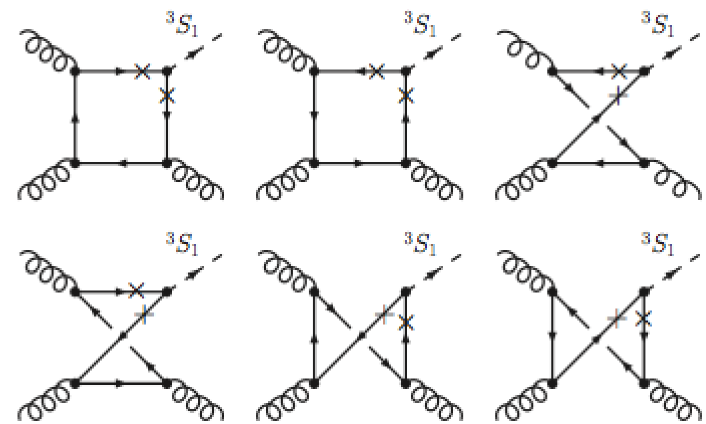
Static approximation:

Heavy quarks have small velocity *v* in meson, so can be treated as at rest relative J/ψ (double power expansion in α_s and *v*)

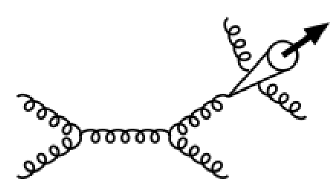
Quantum number conservation in binding:

Assume color & spin preserved in binding – implies states *produced* in color singlet state





colour-singlet fragmentation: $g + g \to [c\bar{c}[^3S_1^{(1)}] + gg] + g$



$+ \ldots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$

Extending the model: singlet → octet

Experimental evidence had shown the Color Singlet Model at the time was not able to describe the data
Unable to describe p_T dependence or normalisation

Theoretically, was understood there were missing contributions
Model had IR divergences in P-wave states that could not be reconciled
Understanding of NLO contributions and p_T scaling of diagrams suggested model was too strict and significant contributions were being ignored

Should the pair be perturbatively produced in a color singlet state?

Why can't it non-perturbatively evolve into singlet physical state during formation (emission of soft gluons)?

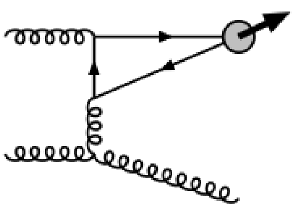
Loosening of the colour/spin conservation constraint led to
Color Octet Mechanism based on Non-Relativistic QCD (NRQCD)

Color Octet Mechanism / NRQCD

Color octet model solves a number of problems:

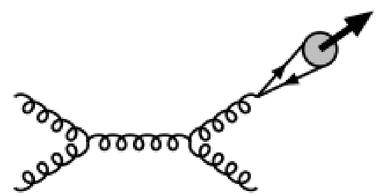
Adds additional diagrams = more rate
(e.g., quarkonia can be produced via single gluon):

colour-octet t-channel gluon exchange: $g+g \to c\bar{c}[{}^1S_0^{(8)}, {}^3P_J^{(8)}] + g$



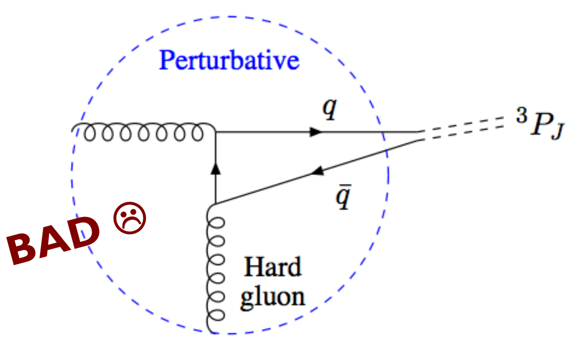
$+ \dots \qquad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

colour-octet fragmentation: $g+g \to c\bar{c}[{}^3S_1^{(8)}] + g$

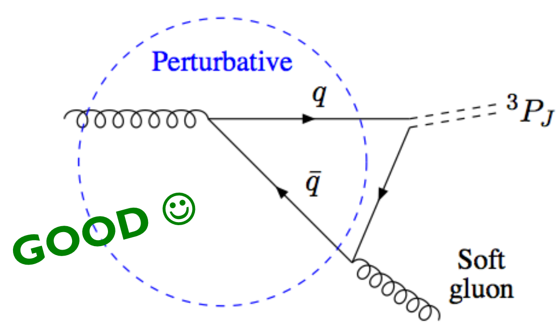


$+ \dots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

Cancels IR divergences in singlet contributions:



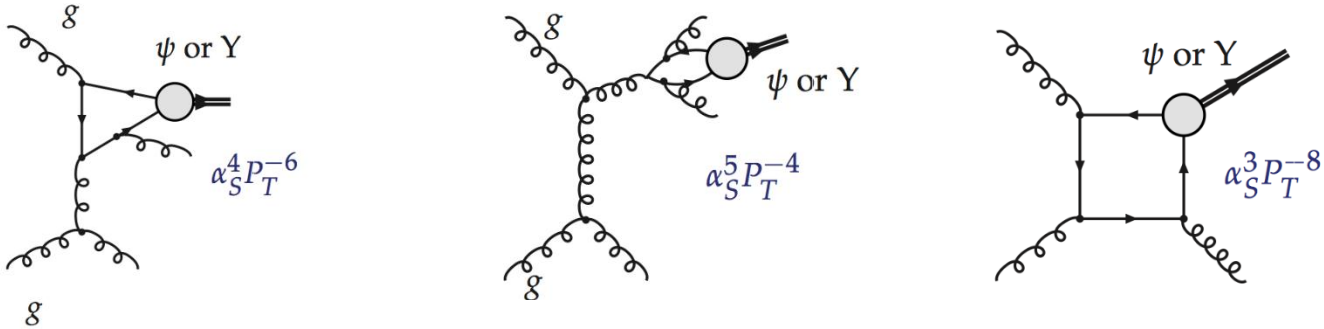
${}^3P_J(\mathbf{1})$ production in CSM

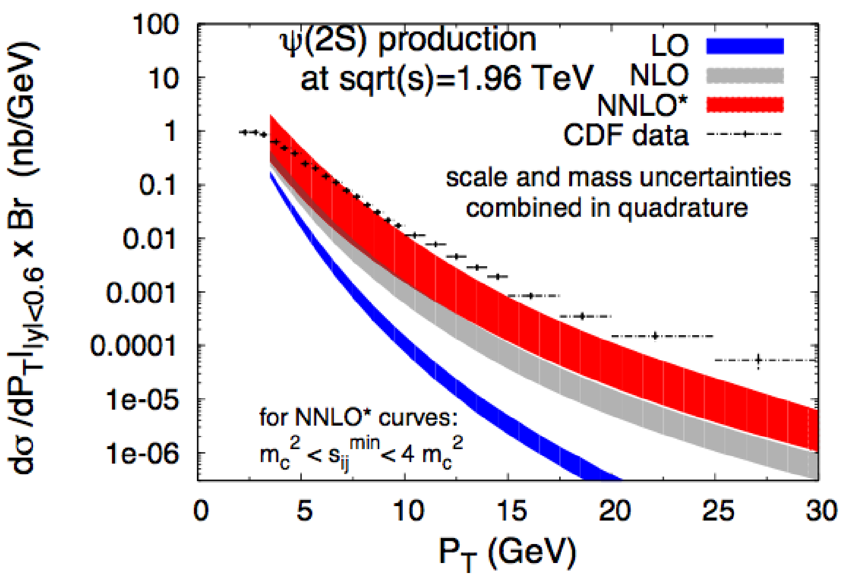


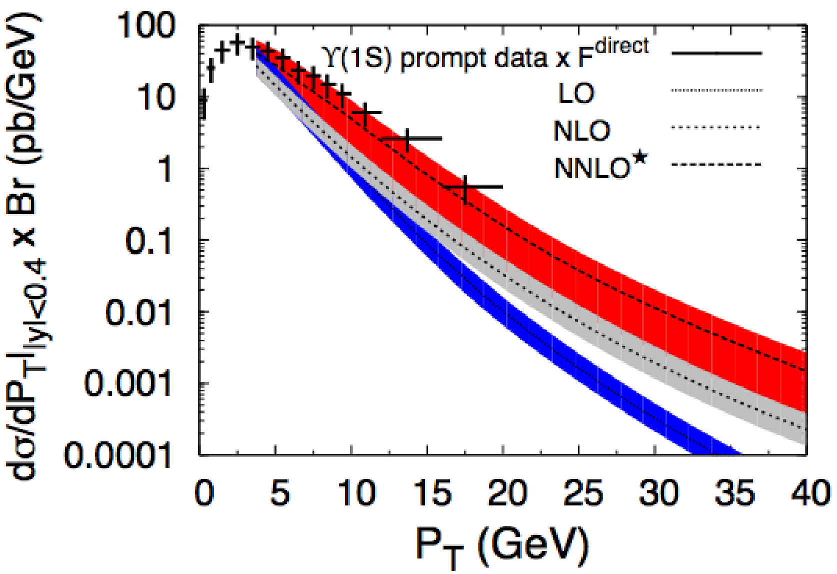
${}^3S_1(\mathbf{8})$ to ${}^3P_J(\mathbf{1})$ production in NRQCD

In the past couple of years, advances have allowed NNLO* predictions in the Color Singlet Model: show contributions to be (very) large!

Good agreement with CDF data: now testing predictions at ATLAS







Colour Evaporation Model

One more model, which assumes that once a ccbar pair is produced, even coloured, within certain invariant mass range, the colour somehow “evaporates” and the physical quarkomium states are produced.

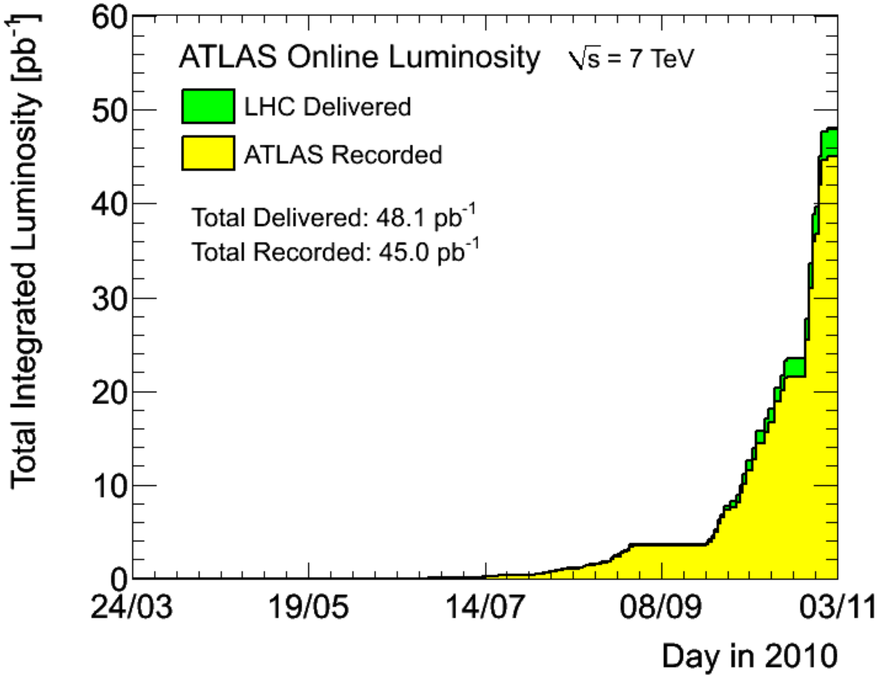
The mass range is usually taken between the two thresholds: for a pair of c-quarks and a pair of D mesons.

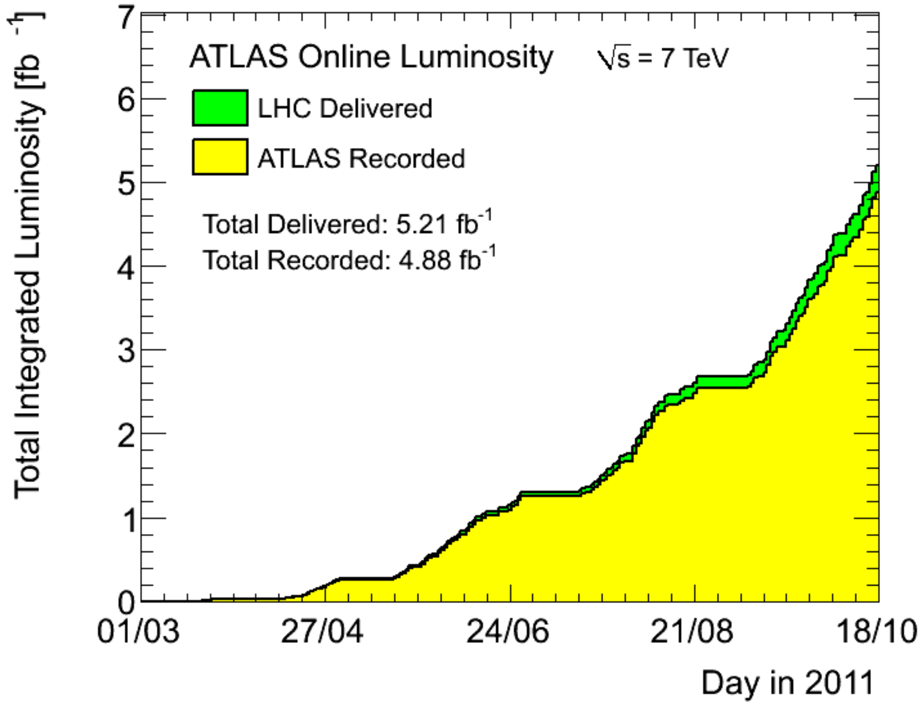
The integrated cross section is then split between the nine quarkonium states.

The model has very few free parameters, and despite (or maybe thanks to) its extreme simplicity works surprisingly well up to (including) Tevatron energies.

…and now – some experimental data

Integrated luminosity so far



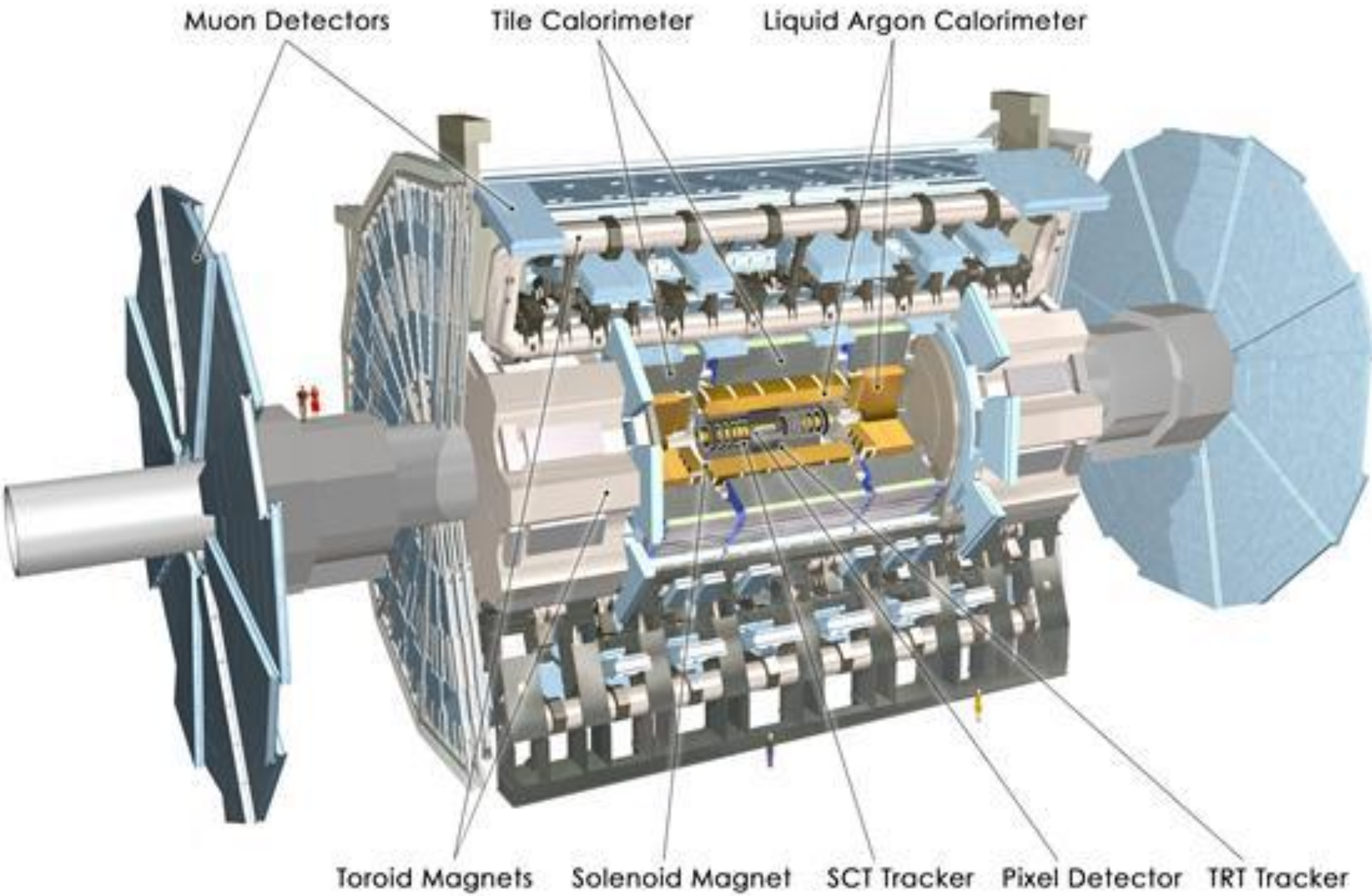


The analyses presented below use a tiny fraction of the accumulated integrated luminosity – around 2 pb-1, i.e. up to August 2010.

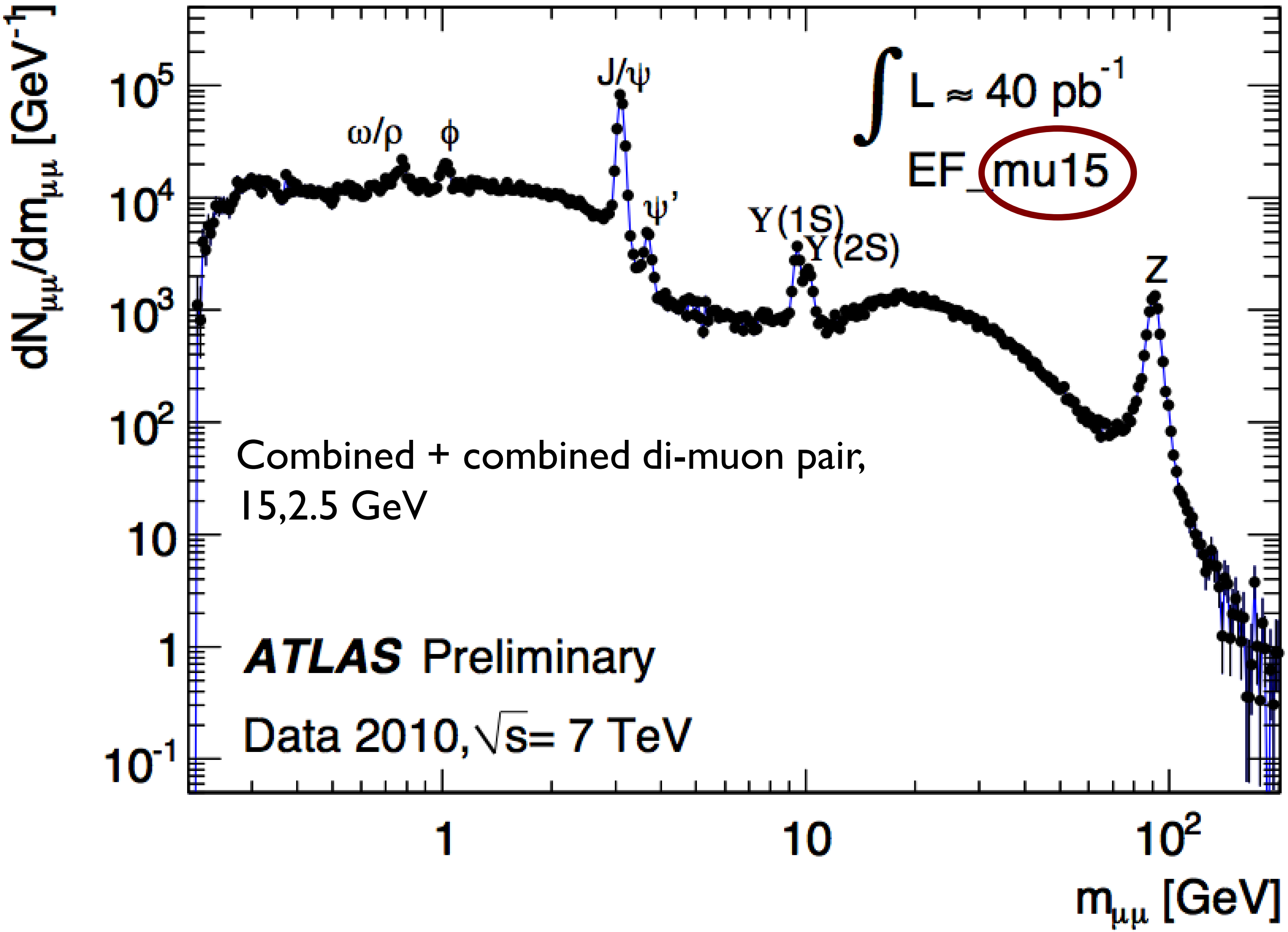
Since then, muon trigger pT thresholds have increased

We have many more Jpsis now – but all at hight pT

Atlas detector



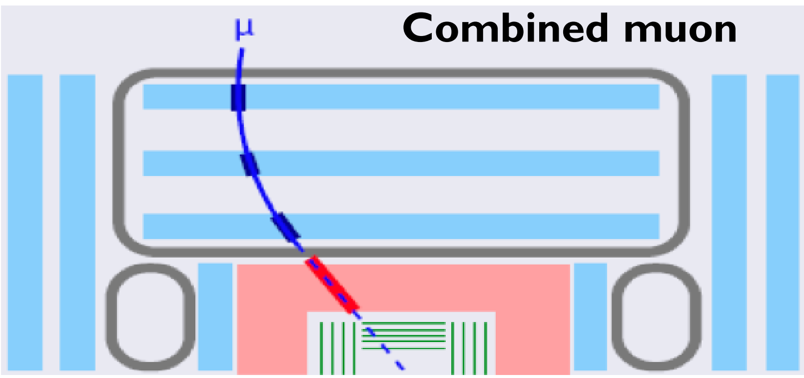
Di-muon invariant mass distribution (40 pb^{-1})



Measuring J/ψ in pp: candidate selection

Muons associated to J/ψ candidate may be:

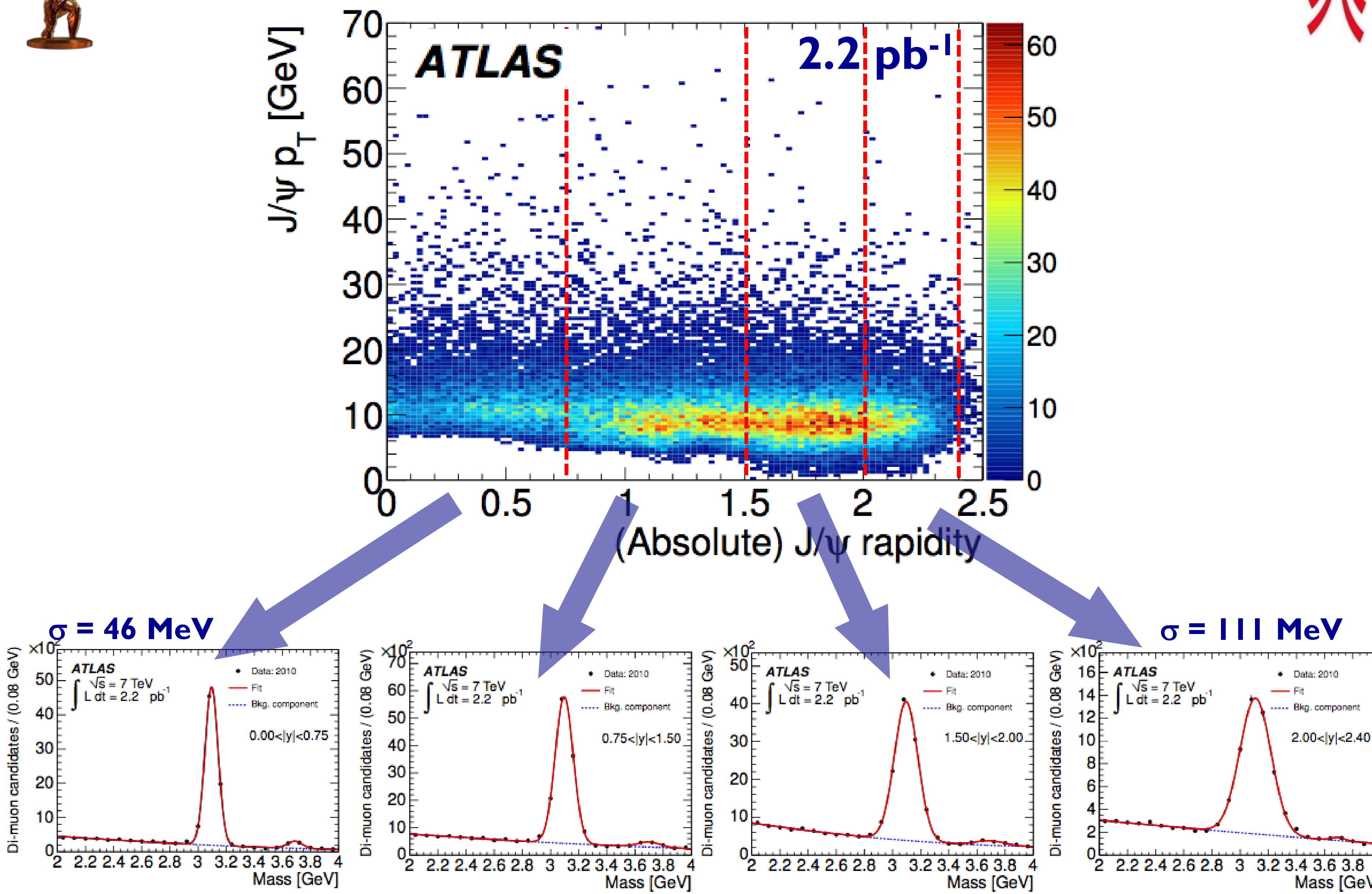
- **Combined** (full Muon Spectrometer & Inner Detector track measurement with fit between the two)
- **Tagged** (Inner Detector measurement associated to at least one segment in Muon Spectrometer)



Muon spectrometer Calorimeters Inner Detector

- Tagged increases chance of fake muon signature, so require at least one of muons in pair to be combined
- At least one muon in pair must have been the object that fired the trigger:
  - ~0 GeV, 4 GeV and 6 GeV P_T thresholds as instantaneous luminosity increased.
  - Dimuon triggers in late 2010, 2011data
- Muons must have p>3 GeV, p_T>1 GeV, $|\eta|$<2.5, pixel hits >0, silicon hits>5

J/ψ candidate selection



Basic strategy of inclusive cross-section analysis method is:

Reconstruct J/ψ candidates in p_T-y bins

Correct **candidate-by-candidate** for efficiency, bin migrations, acceptances

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

Bin migration

ID reco efficiency
(per muon track)

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

Detector acceptance

Reconstruction efficiency

Trigger efficiency

Fit resultant weighted yields to derive signal component $N_{corr} \rightarrow N^{J/\psi}_{corr}$

Extract resultant cross-section from $N^{J/\psi}_{corr}$ in given analysis bin

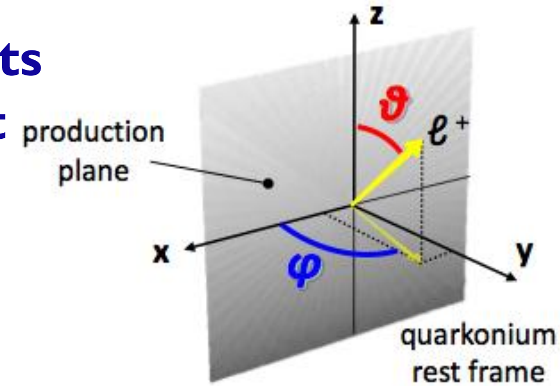
$$\frac{d^2\sigma(J/\psi)}{dp_T dy} \cdot Br(J/\psi \rightarrow \mu^+\mu^-) = \frac{N^{J/\psi}_{corr}}{\mathcal{L} \cdot \Delta p_T \Delta y}$$

Spin-alignment working points

Acceptance: probability that J/ψ survives muon cuts

We know acceptance can vary with spin-alignment

State has generalised angular decay distribution:



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

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

$$\lambda_{\theta^\star} = \frac{1-3|a_0|^2}{1+|a_0|^2} \qquad \lambda_{\phi^\star} = \frac{2Re\,a^*_{+1}a_{-1}}{1+|a_0|^2} \qquad \lambda_{\theta^\star\phi^\star} = \frac{\sqrt{2}Re\left[a^*_0(a_{+1}-a_{-1})\right]}{1+|a_0|^2}$$

Before we can explicitly measure spin-alignment, we work with five specific working points that provide an envelope for expectation.

FLAT (unphysical, but default in Pythia)

$$\lambda_{\theta^\star} = \lambda_{\phi^\star} = \lambda_{\theta^\star\phi^\star} = 0$$

TRPM

$$a_0 = 0, \quad a_{+1} = -a_{-1}$$

LONG

$$\lambda_{\theta^\star} = -1$$

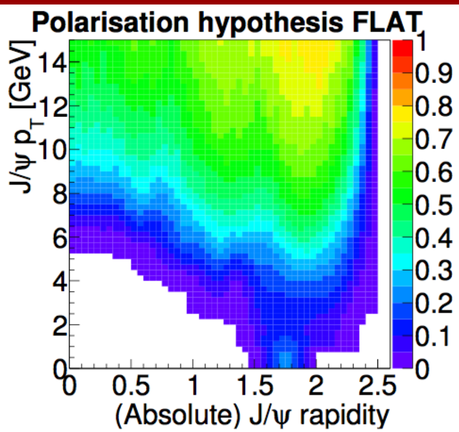
TRP0

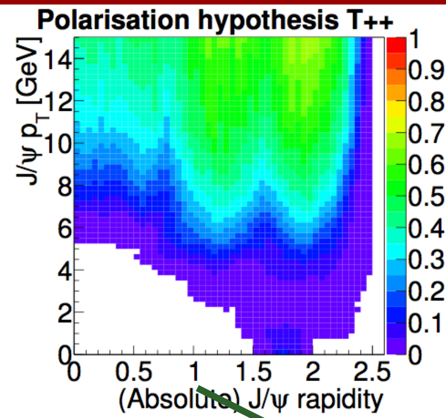
$$\lambda_{\theta^\star} = +1$$

TRPP

$$a_0 = 0, \quad a_{+1} = +a_{-1}$$

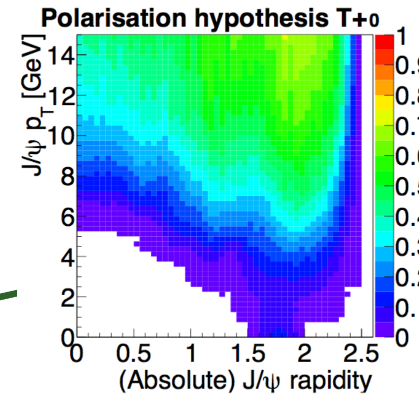
Spin-alignment and acceptance corrections

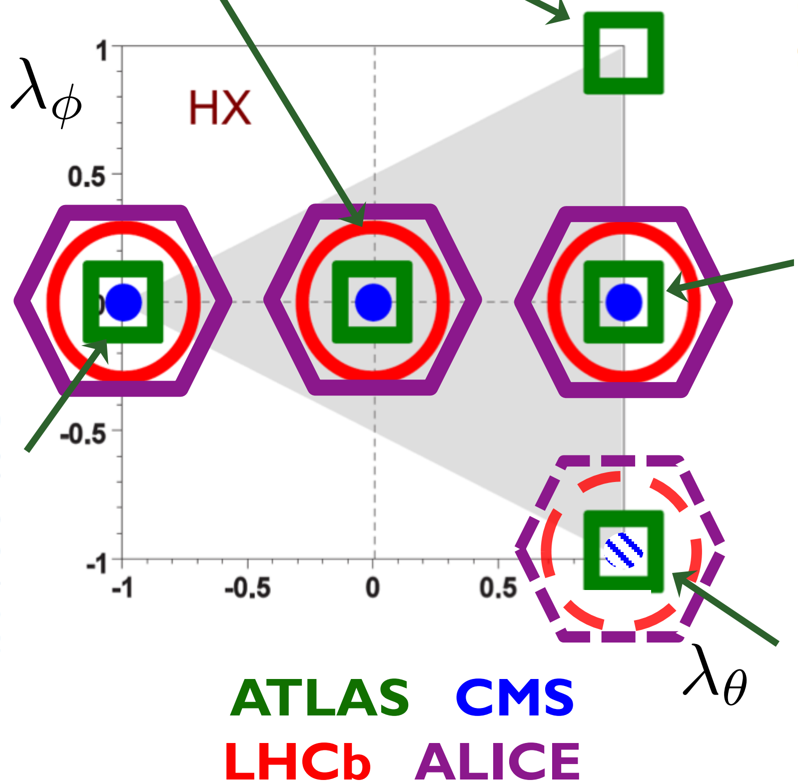


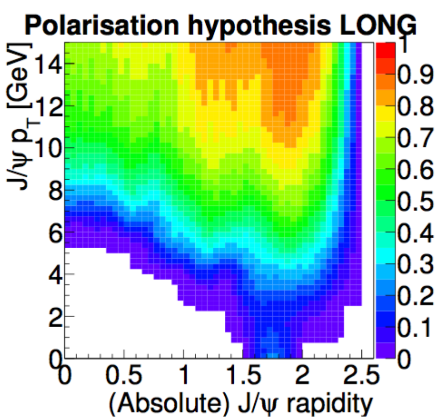


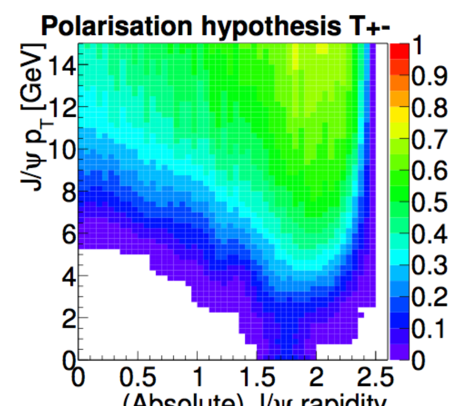
Model-dependent on spin-alignment state

Possible differences between prompt and non-prompt J/ψ spin-alignment



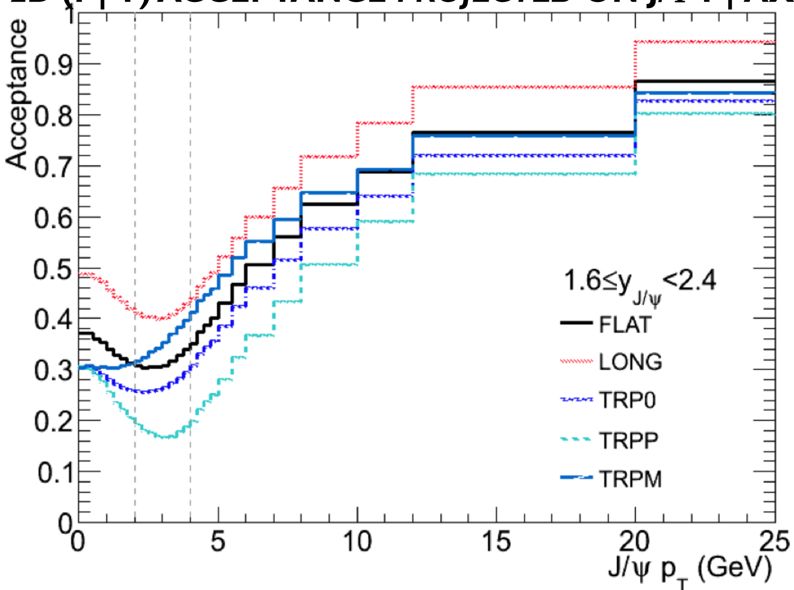






Acceptance effects on onia: ϕ^* angle

2D (P_T-Y) ACCEPTANCE *PROJECTED* ON J/Ψ P_T AXIS



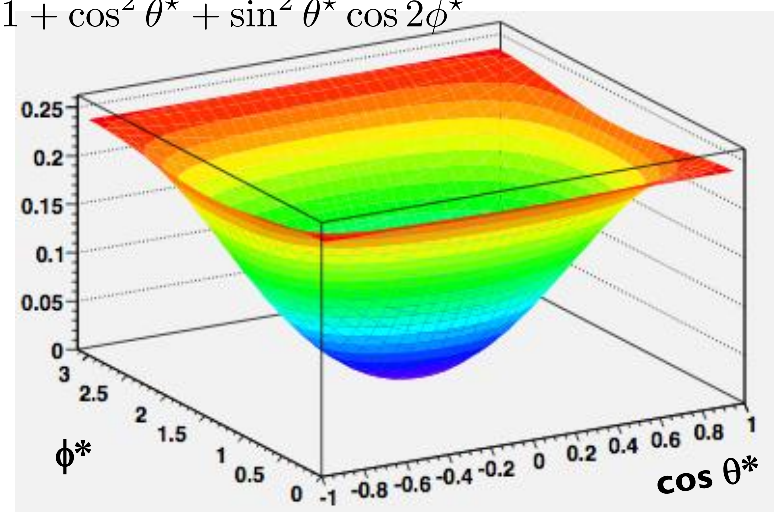
Acceptance in azimuthal angle dependent on angle between J/ψ production and decay plane

Non-trivial influence of ϕ^* acceptance on produced J/ψ, particularly at low p_T

Integrating over ϕ^* (as was/is done at e.g. Tevatron) safe only if have flat acceptance in that variable, else cos θ^* dependence and average acceptance in given bin *will* be incorrect!

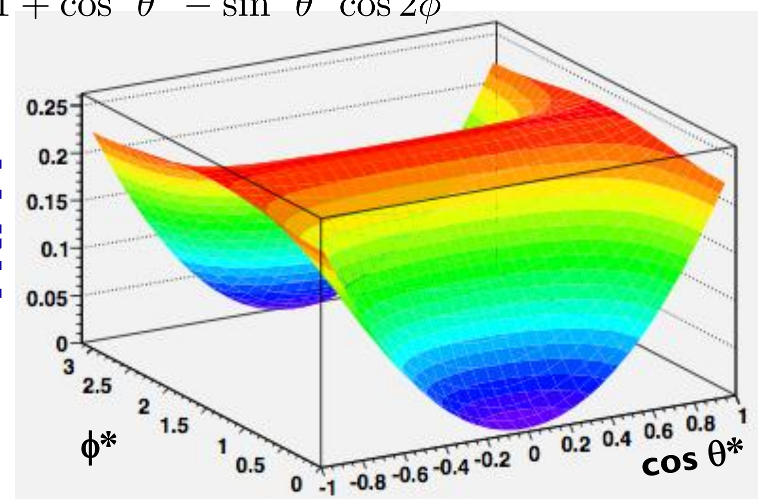
$$\frac{dN}{d\Omega} = 1 + \cos^2\theta^\star + \sin^2\theta^\star \cos 2\phi^\star$$

TRPP



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

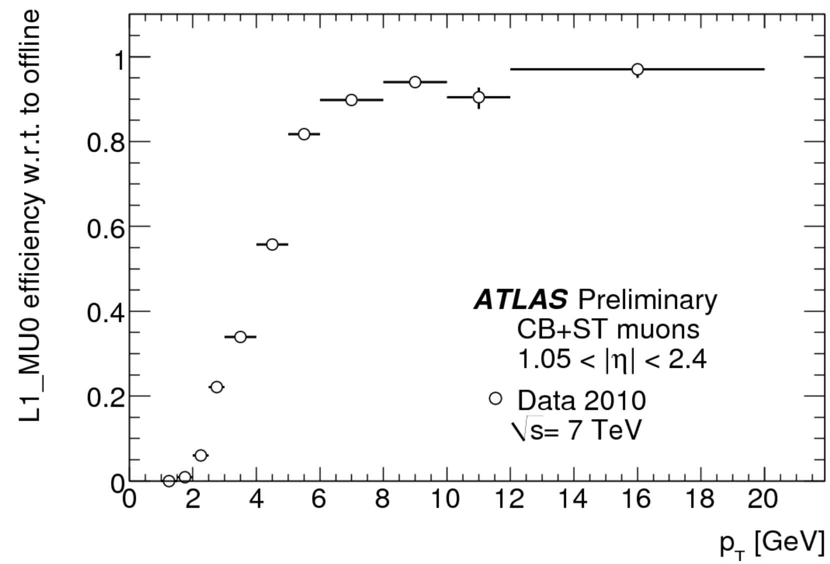
TRPM



J/ψ efficiency corrections

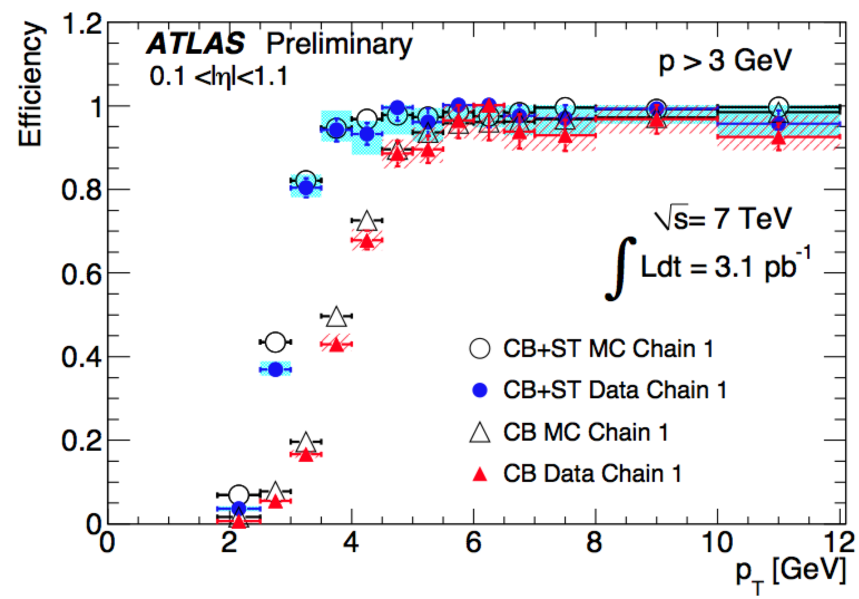
Single muon trigger efficiency

- Evaluated with Monte Carlo to obtain fine granularity, corrected with Tag & Probe data measurement
- Efficiencies reach plateau of 80—100% at around 6—8 GeV (pseudo-rapidity dependent)



Offline reconstruction efficiency

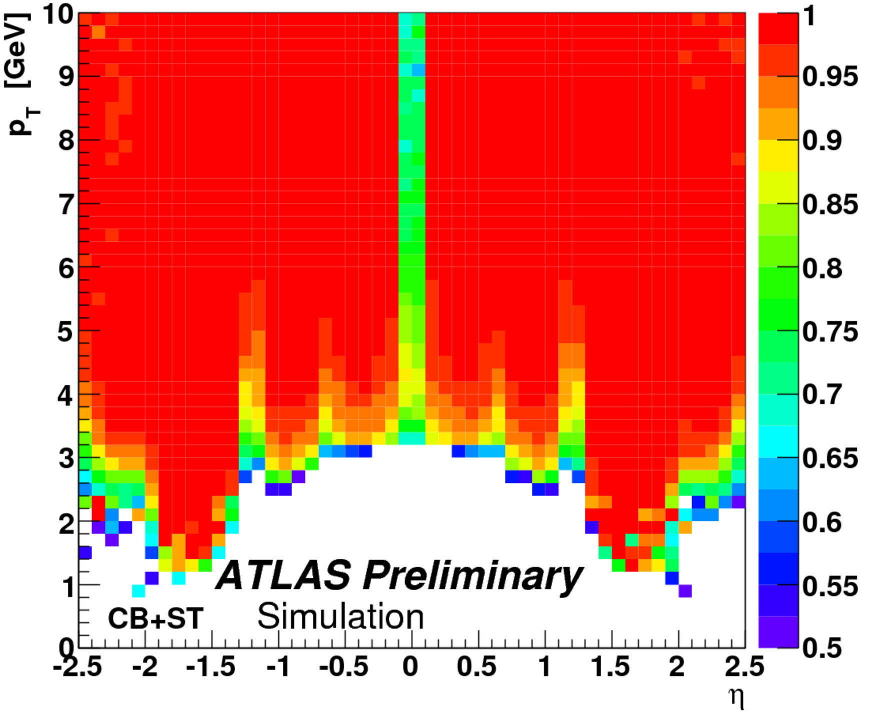
- Evaluated with data (Tag & Probe) using $J/\psi\rightarrow\mu\mu$ at low p_T supported by $Z\rightarrow\mu\mu$ measurements at higher p_T for improved plateau precision
- Regions with efficiency < 20% excluded from analysis

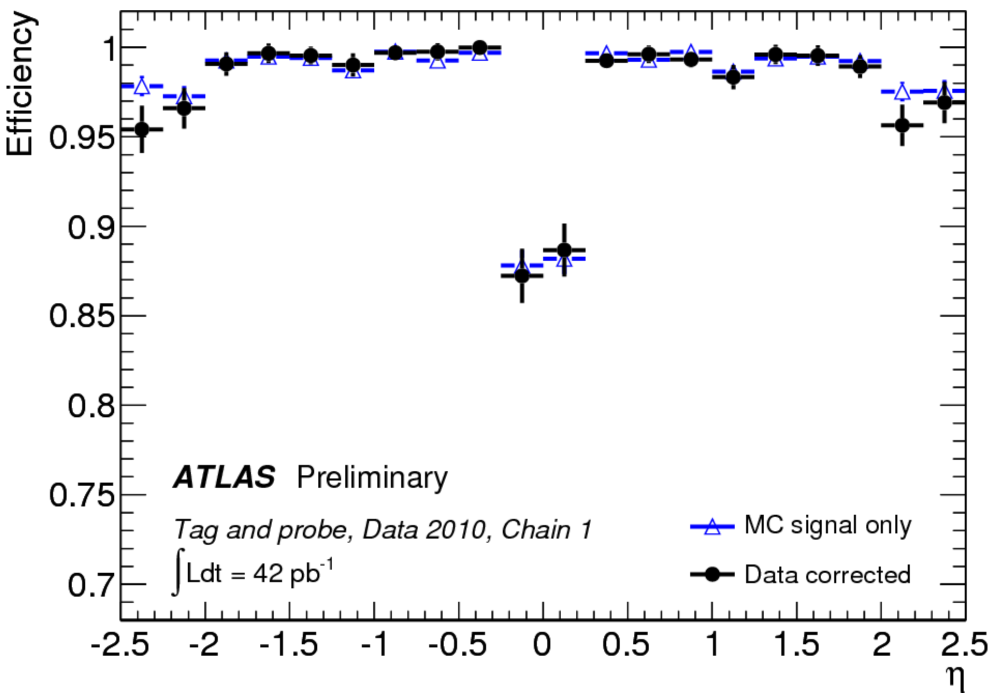


ID track reconstruction efficiency

- Essentially constant (within uncertainties) at 99.5%±0.5% for muon tracks

Muon reco. efficiencies for quarkonia





Reconstruction efficiency for low p_T from J/ψ decays (MC)

Reconstruction efficiency at high p_T from $Z \rightarrow \mu\mu$ data

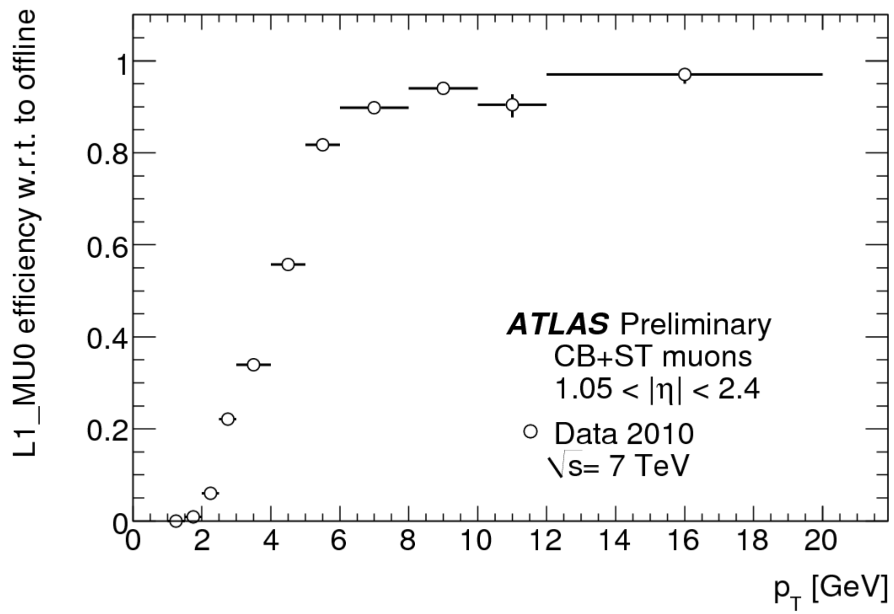
Muon trigger efficiencies for quarkonia

Trigger efficiency maps derived from hybrid scheme of finely-binned Monte Carlo (needed to remove biases) reweighted using Tag & Probe data from J/ψ (low p_T) and Z (high p_T) decays

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

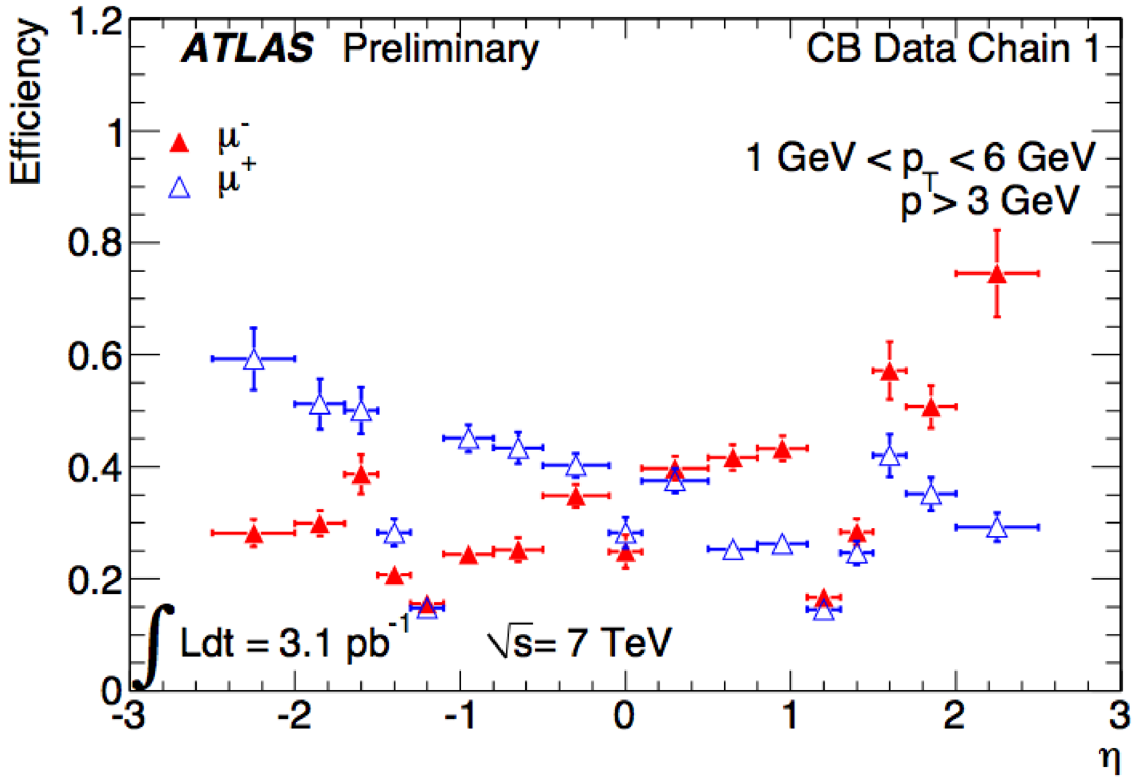
- Significant charge dependence observed (and corrected for)
- Muon turn-on thresholds needed accurate handling
- Fine granularity needed to properly model features (even at high p_T)

Efficiencies plateau at around 80-100% *dependent on pseudorapidity*



Charge-dependence of muon reco./trigger

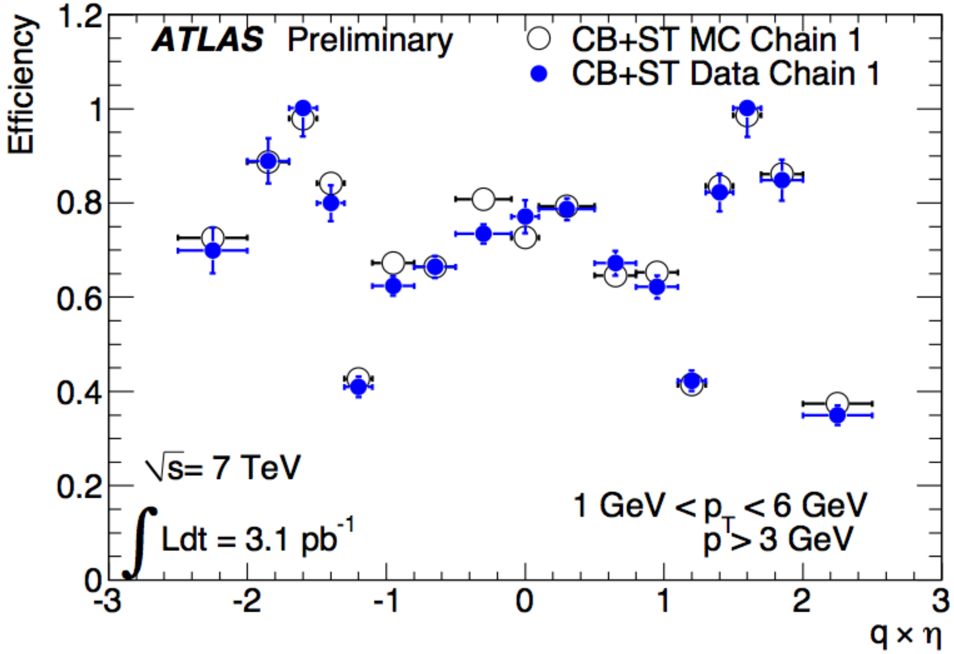
Due to the toroidal magnetic field of the ATLAS Muon Spectrometer, muons with positive (negative) charge are bent towards larger (smaller) η.



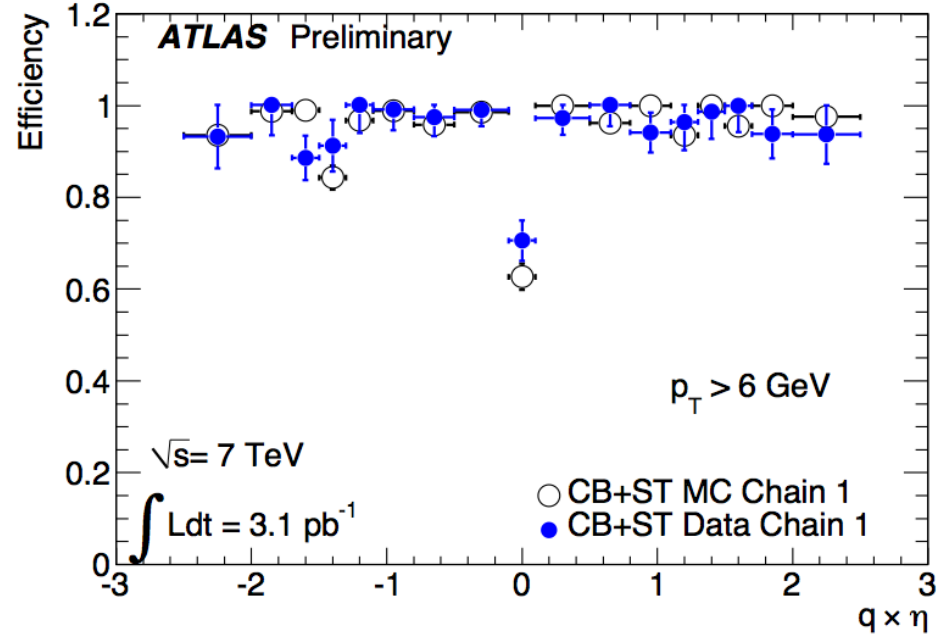
Introduces a charge dependence of the muon reconstruction/trigger efficiencies, particularly relevant at very large $|\eta|$, where muons of one charge may be bent outside the detector geometrical acceptance, and at low p_T, where muons of one charge may be bent back before reaching spectrometer stations

Charge-dependence of muon reco./trigger

Reconstruction efficiency of Combined (CB) + Tagged (ST) muons as a function of charge*pseudorapidity in MC and data



LOW P_T

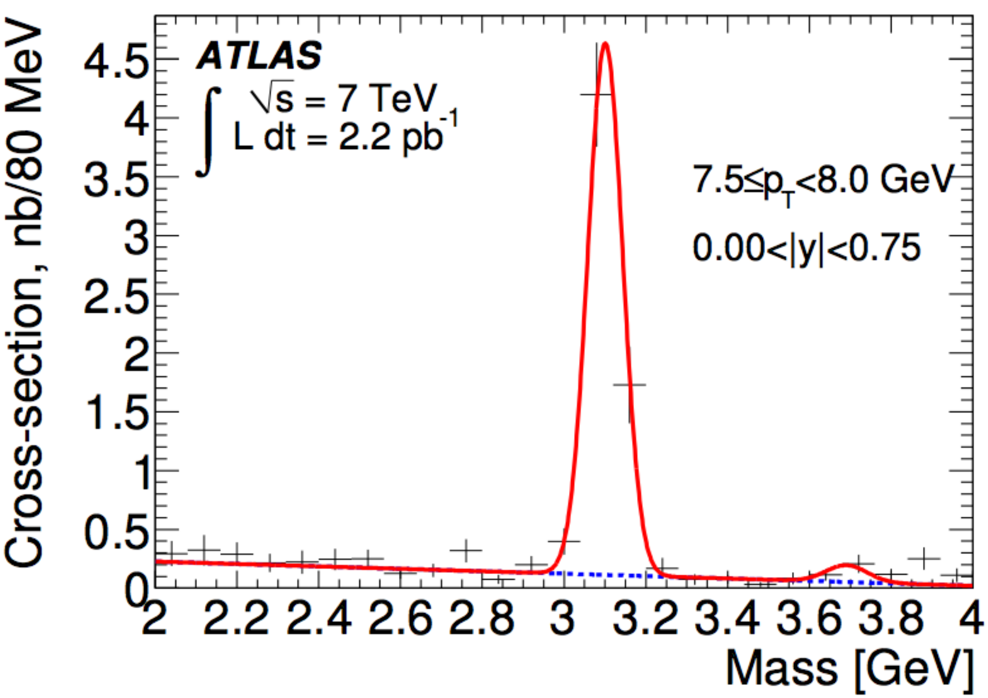


HIGH P_T

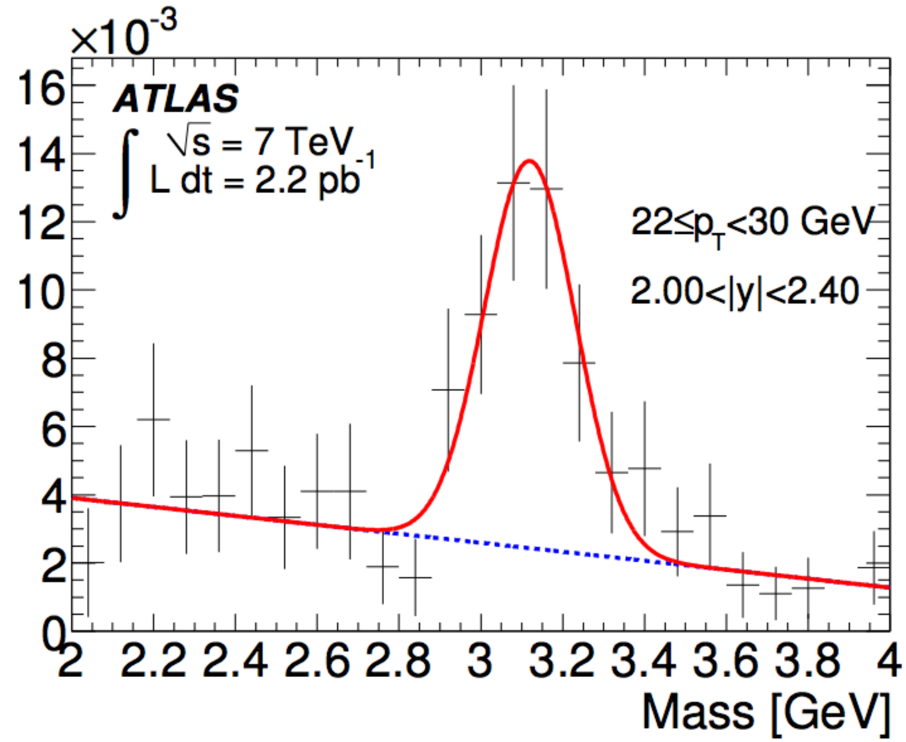
Weighted fits and cross-section extraction

For inclusive cross-section measurement, a binned χ^2 fit was used

- Was found to give stable unbiased weighted fit results w.r.t unbinned maximum likelihood fits once restricted to fine p_T—y slices as in this analysis
- $\psi(2S)$ included in fit, but yields not extracted at this time

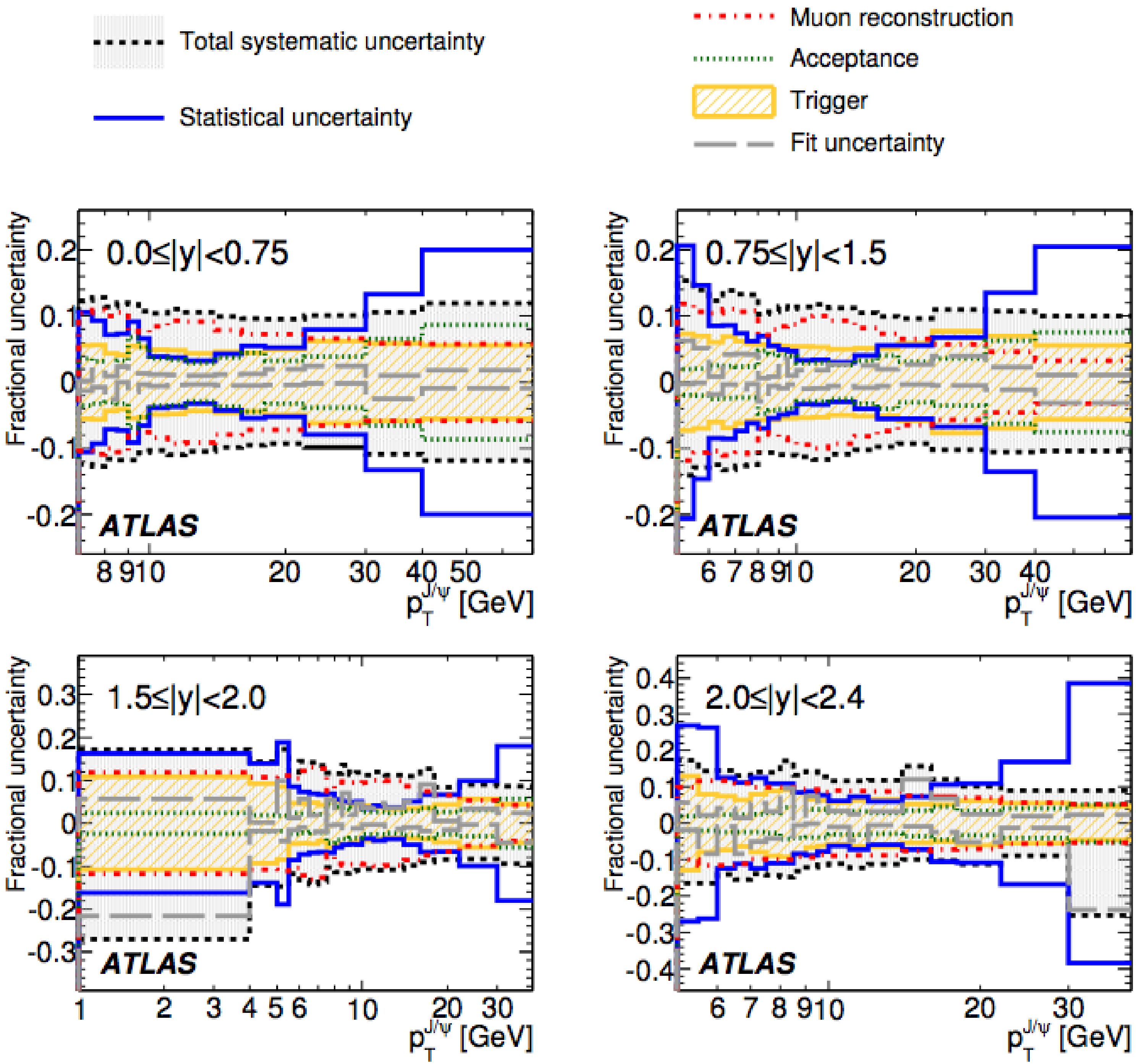


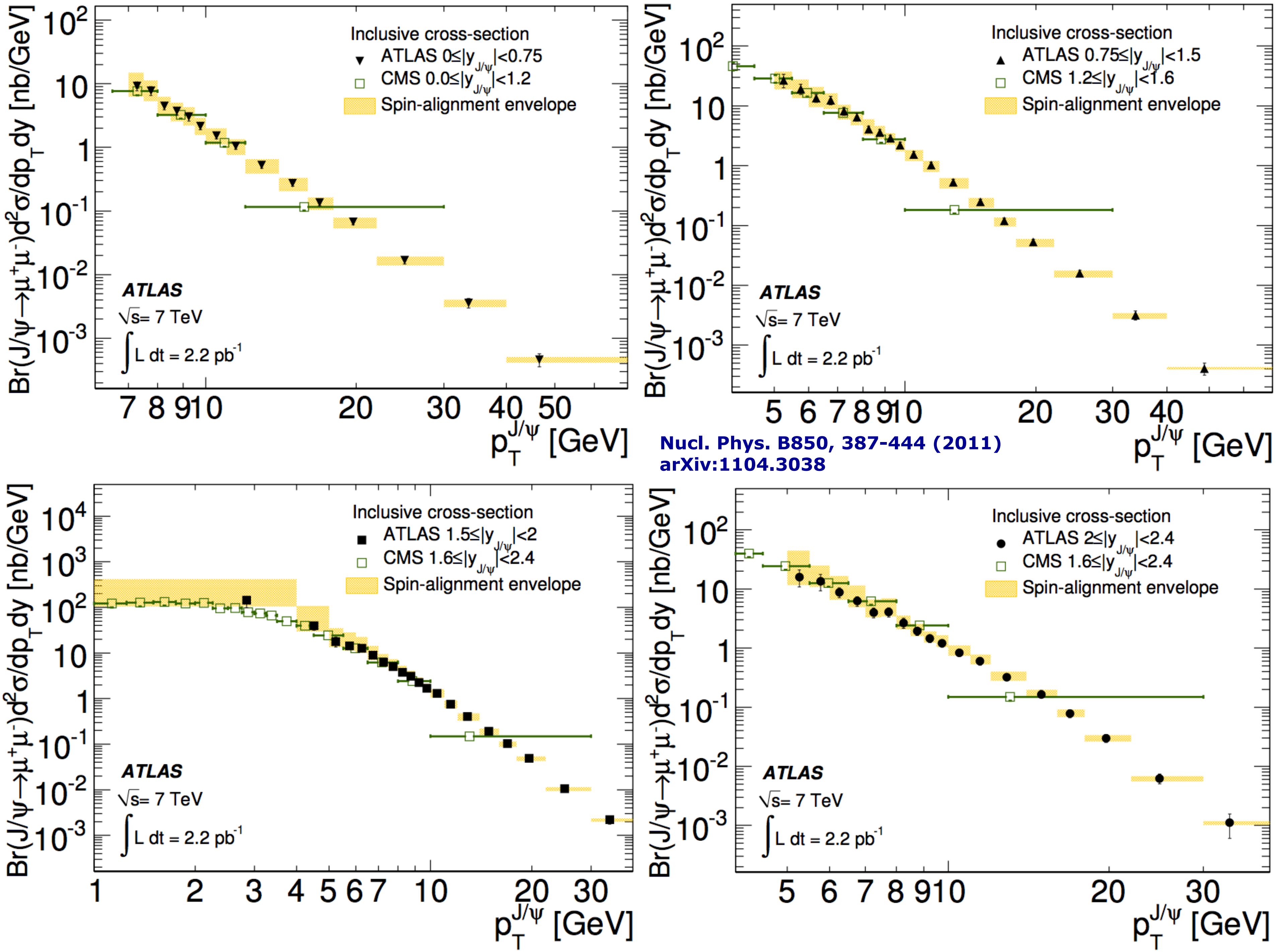
LOW P_T, CENTRAL RAPIDITY



HIGH P_T, FORWARD RAPIDITY

Sources of systematic uncertainty, and total uncertainties in each analysis bin





Nucl. Phys. B850, 387-444 (2011)
arXiv:1104.3038

Measurement of non-prompt fraction

Simultaneous unbinned maximum likelihood fit on invariant mass and pseudo-proper time distribution (used as discriminant for prompt/non-prompt J/ψ) to determine fraction in p_T—y bins

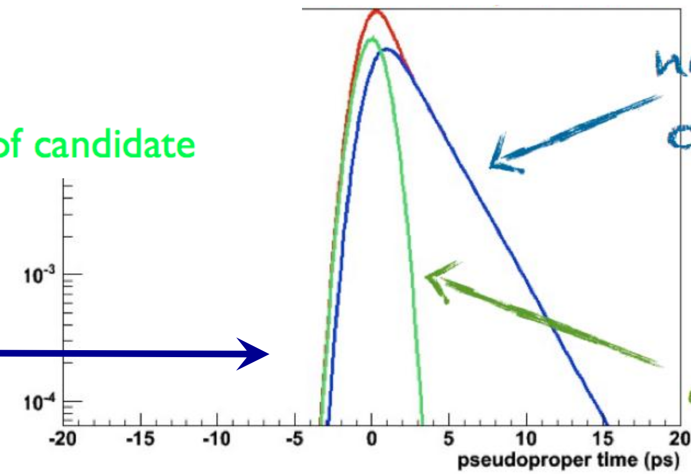
xy displacement of candidate from PV

Invariant mass of candidate

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

p_T of candidate

Pseudo-proper time τ discriminant

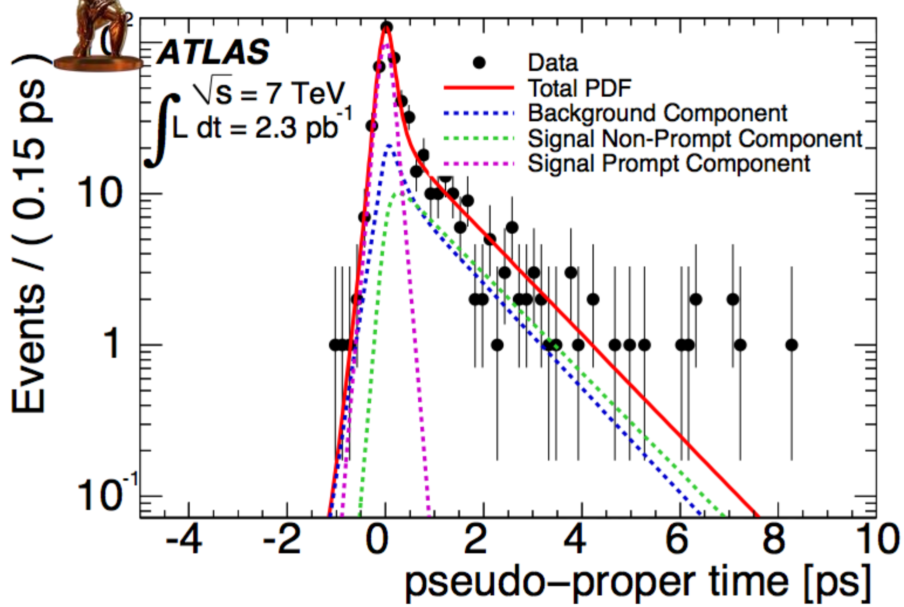


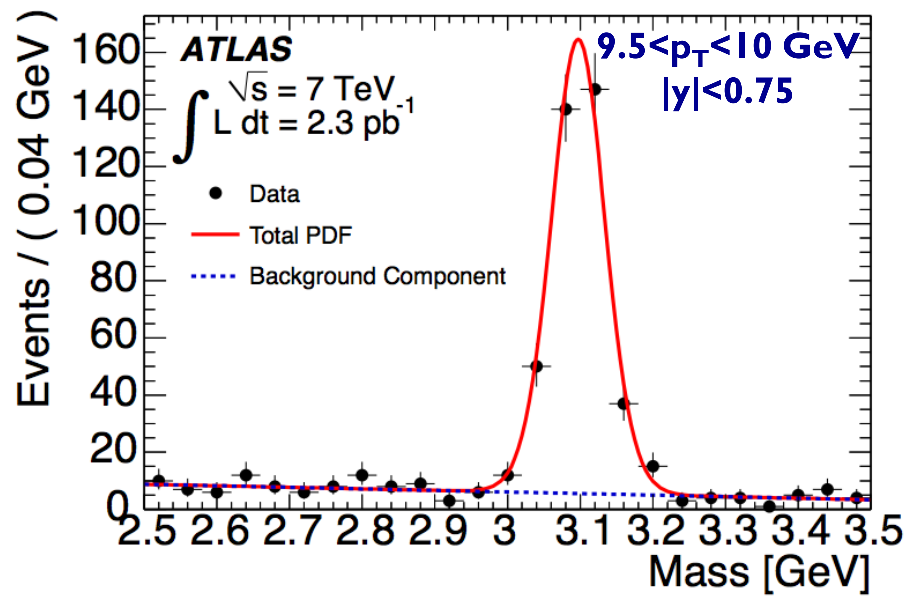
non-prompt component

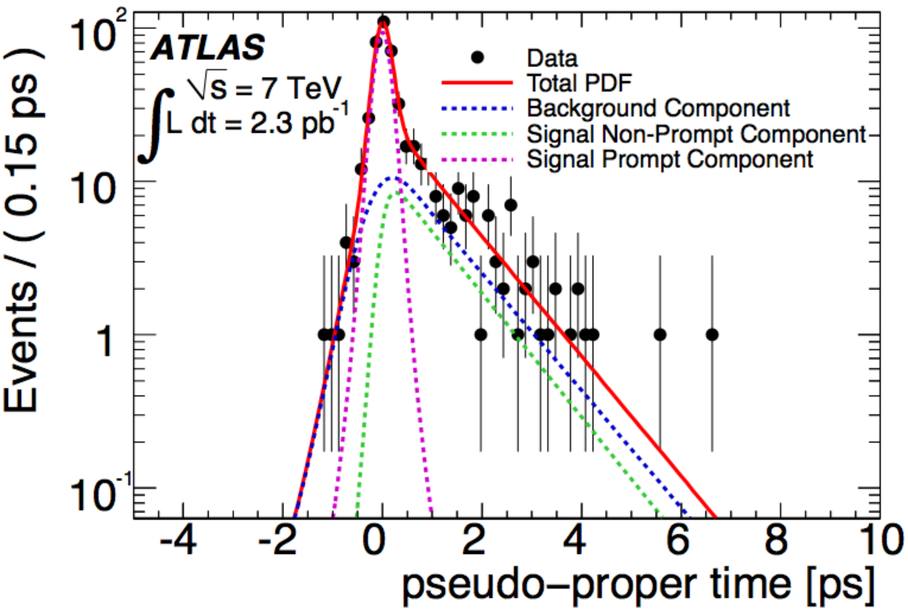
prompt component

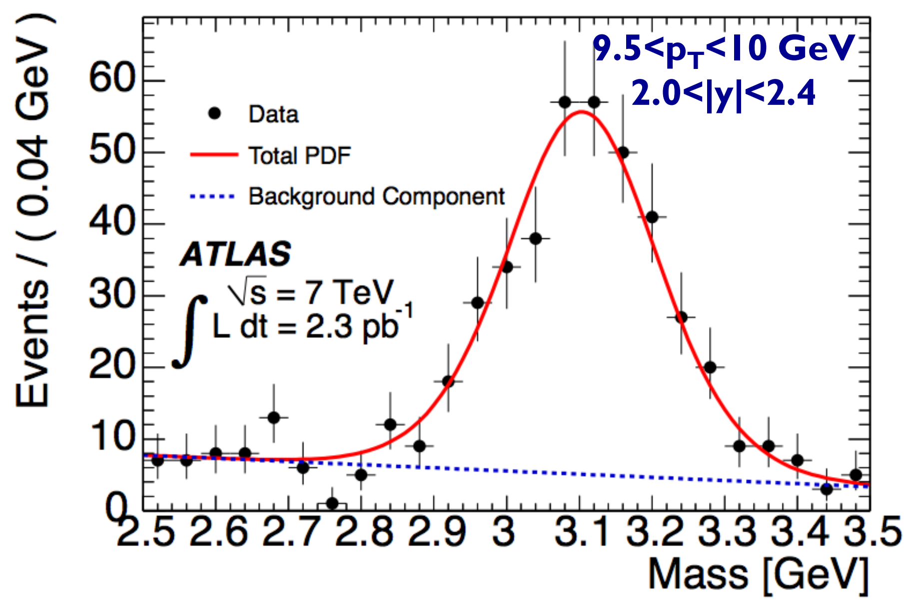
Further combine inclusive cross-section and corrected non-prompt fraction to extract prompt and non-prompt differential cross-sections

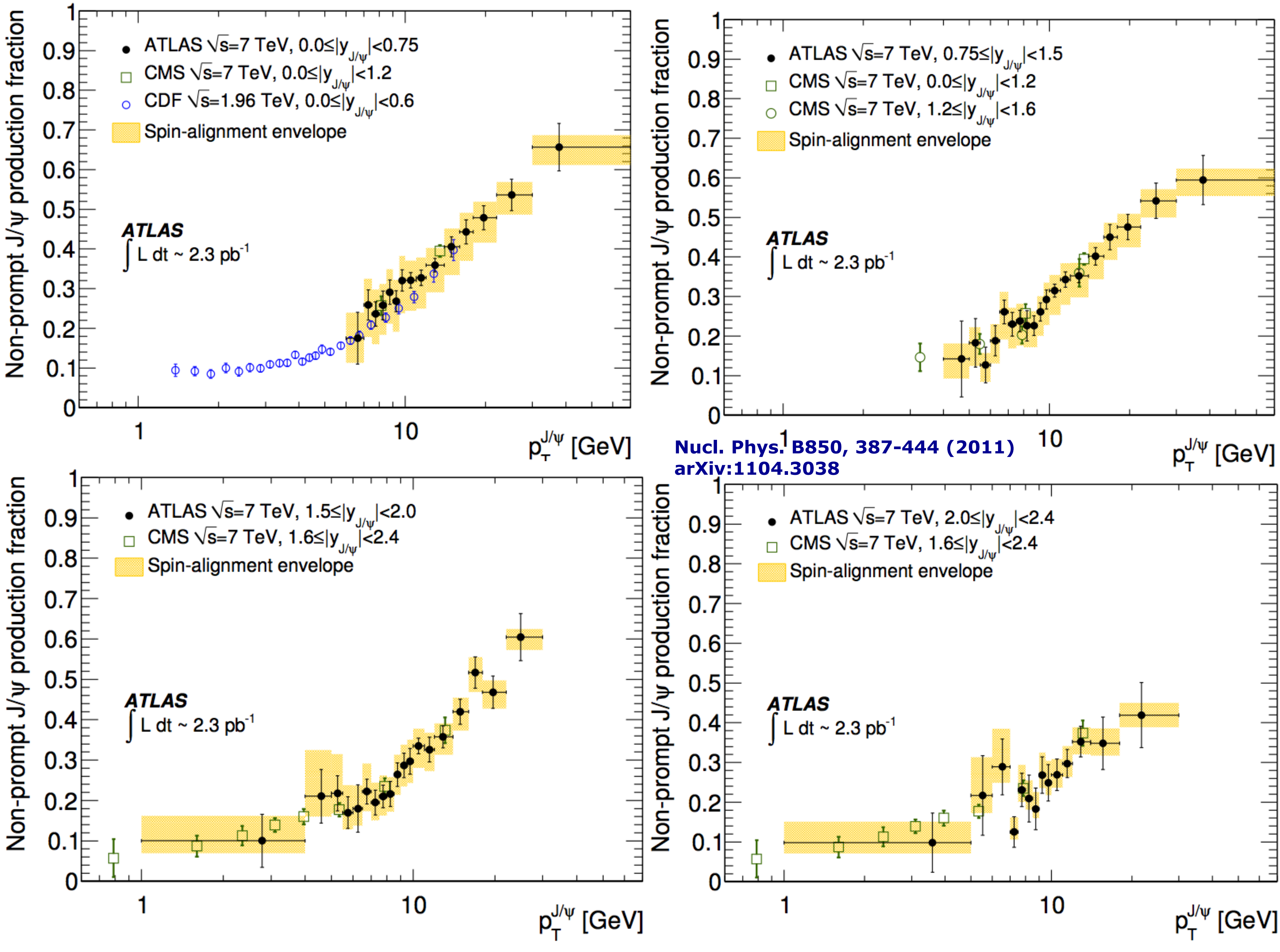
Simultaneous mass/lifetime fit projections

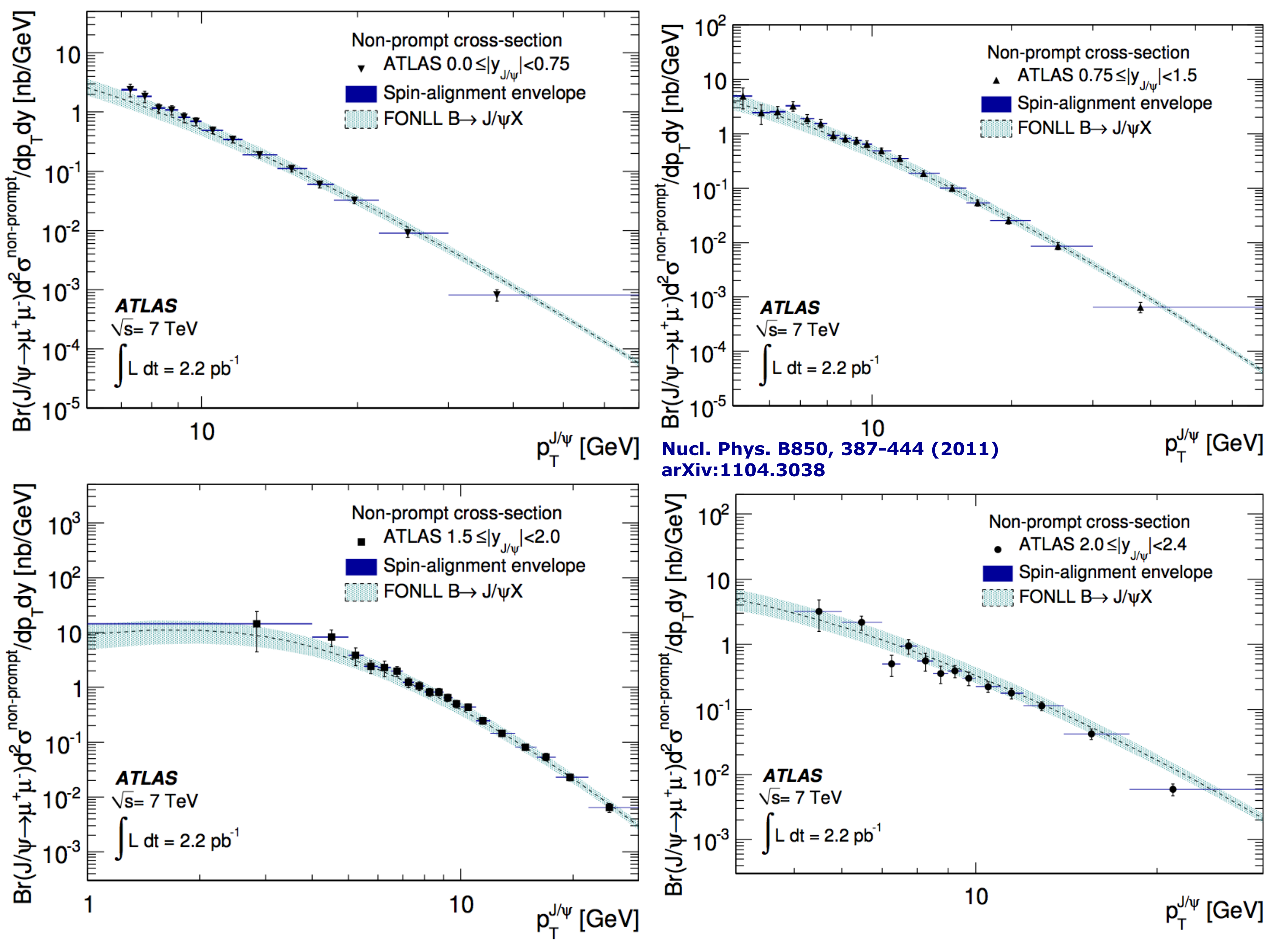









ATLAS √s=7 TeV, 0.0≤|y_J/ψ|<0.75
CMS √s=7 TeV, 0.0≤|y_J/ψ|<1.2
CDF √s=1.96 TeV, 0.0≤|y_J/ψ|<0.6
Spin-alignment envelope
ATLAS
∫L dt ~ 2.3 pb^-1
Non-prompt J/ψ production fraction
p_T^J/ψ [GeV]
ATLAS √s=7 TeV, 0.75≤|y_J/ψ|<1.5
CMS √s=7 TeV, 0.0≤|y_J/ψ|<1.2
CMS √s=7 TeV, 1.2≤|y_J/ψ|<1.6
Spin-alignment envelope
ATLAS √s=7 TeV, 1.5≤|y_J/ψ|<2.0
CMS √s=7 TeV, 1.6≤|y_J/ψ|<2.4
Spin-alignment envelope
ATLAS √s=7 TeV, 2.0≤|y_J/ψ|<2.4
CMS √s=7 TeV, 1.6≤|y_J/ψ|<2.4
Spin-alignment envelope
Nucl. Phys. B850, 387-444 (2011)
arXiv:1104.3038



Nucl. Phys. B850, 387-444 (2011)
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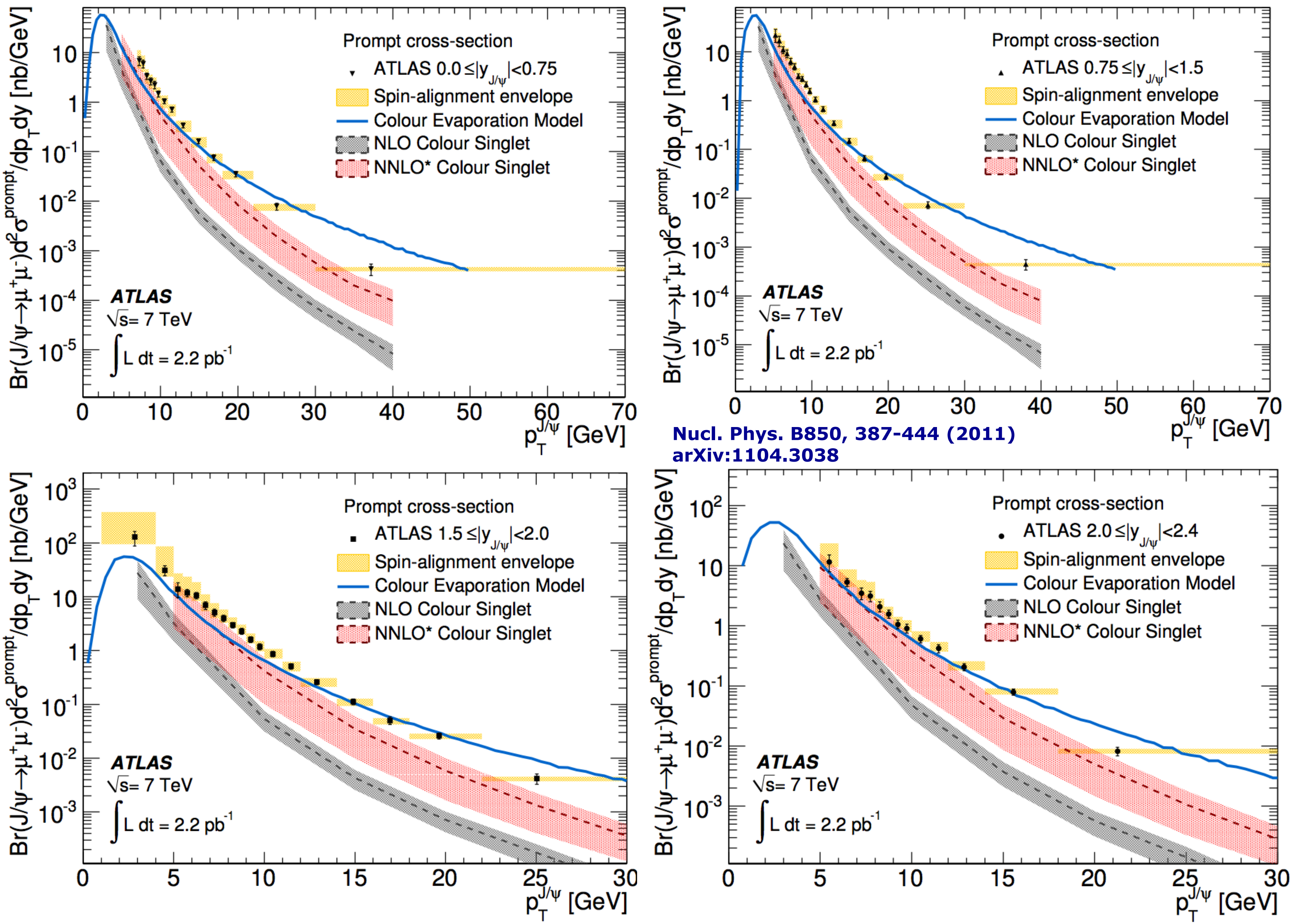


Nucl. Phys. B850, 387-444 (2011)
arXiv:1104.3038

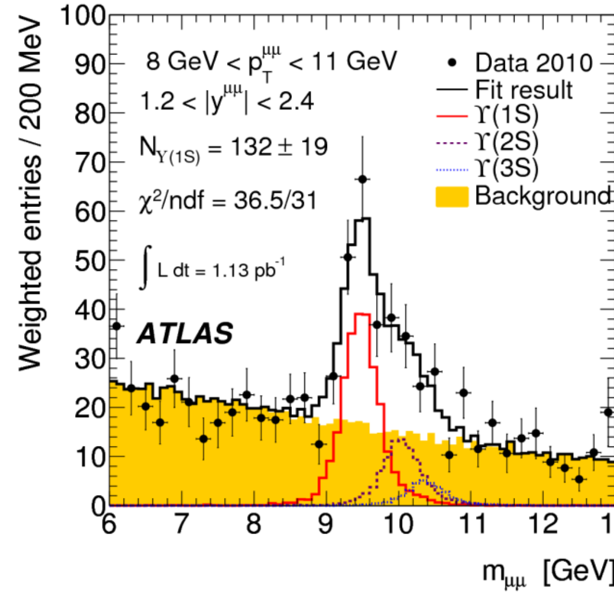
Upsilon fiducial cross-section

Measurement of differential production cross-section of Upsilon(1S) in p_T & y

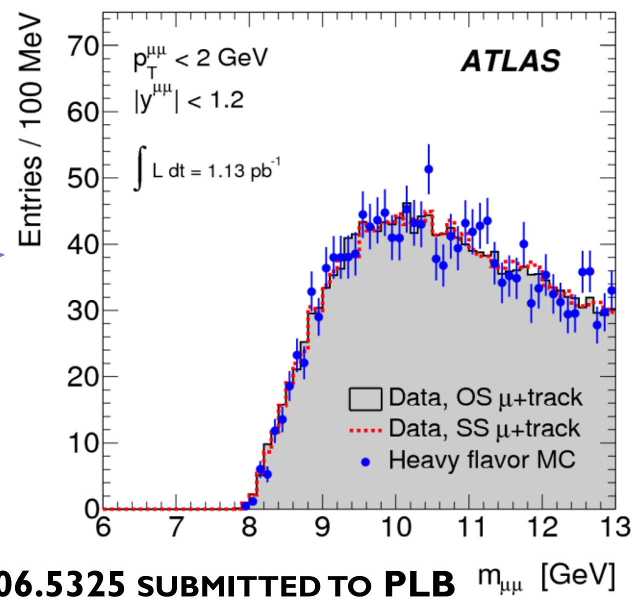
Similar procedure as for J/ψ for weight correction

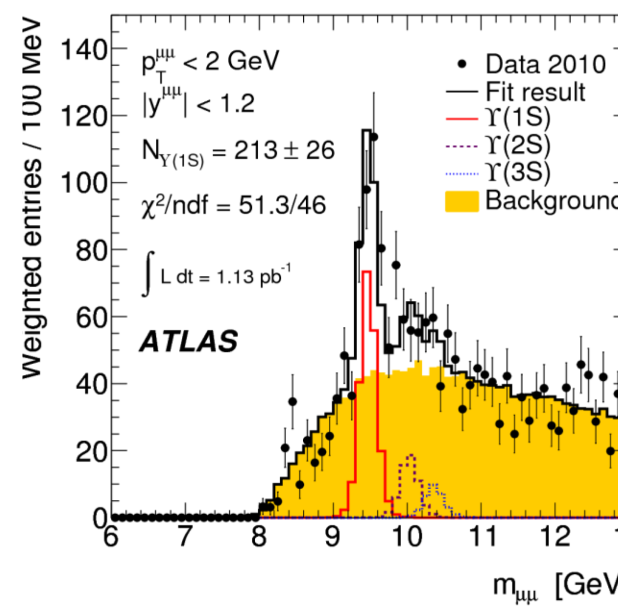
Candidate selection: 4 GeV p_T on both muons (|η|<2.5)

Likelihood fit to U(1,2,3S) and background templates



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

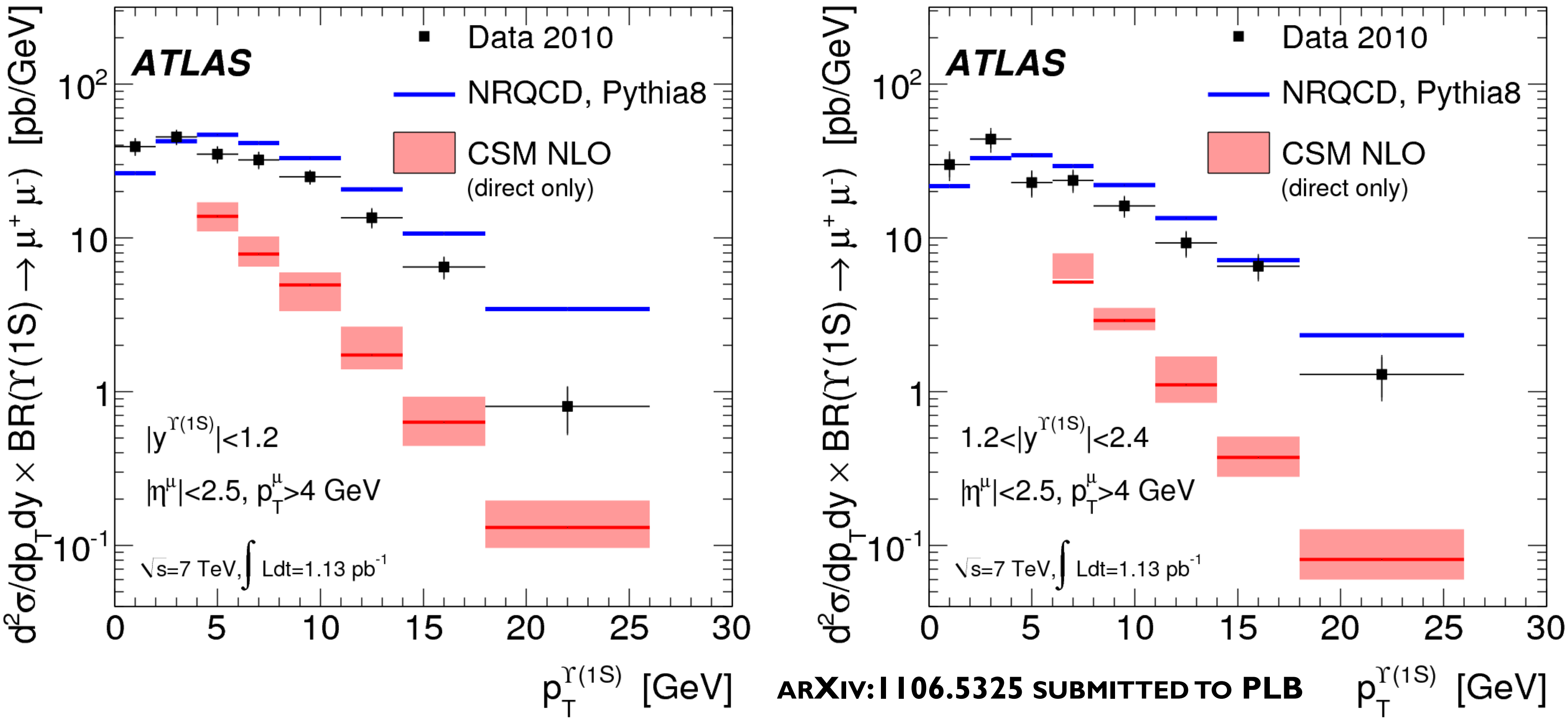




Use OS/SS μ+trk data and HF MC to model

ARXIV:1106.5325 SUBMITTED TO PLB

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



ARXIV:1106.5325 SUBMITTED TO PLB

Upsilon(1,2,3S) fiducial/inclusive differential cross-sections coming soon…

Exclusive B production in pp: B^0_d/B^0_s

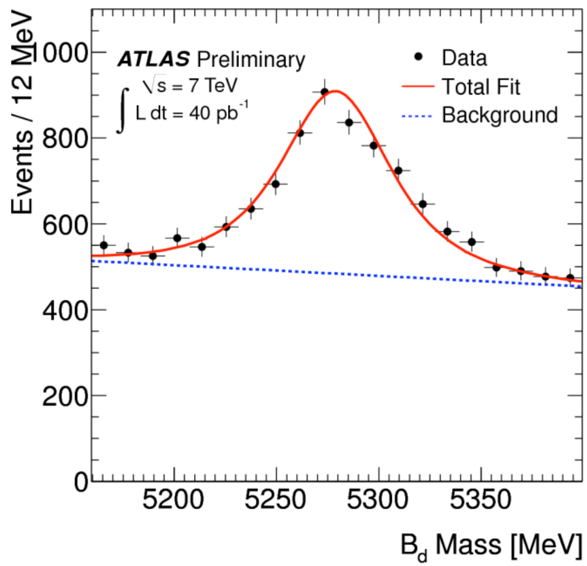
$B^0_d \to J/\psi(\mu\mu)K^{0*}$

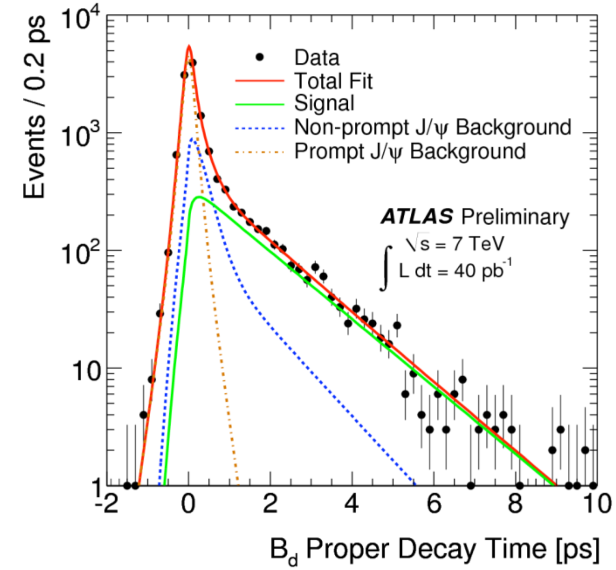
Kaon candidate built from tracks of $p_T(trk)>0.5$ GeV, $p_T(K)>2.5$ GeV

Constrained vertex fit

Lifetime: $1.51 \pm 0.04_{stat} \pm 0.04_{syst}$ ps

[**PDG:** 1.525 ± 0.009 ps]





ATLAS-CONF-2011-092

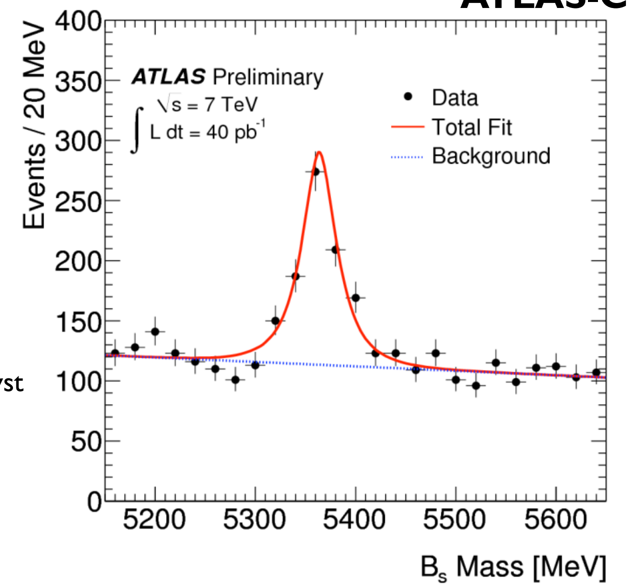
$B^0_s \to J/\psi(\mu\mu)\phi(KK)$

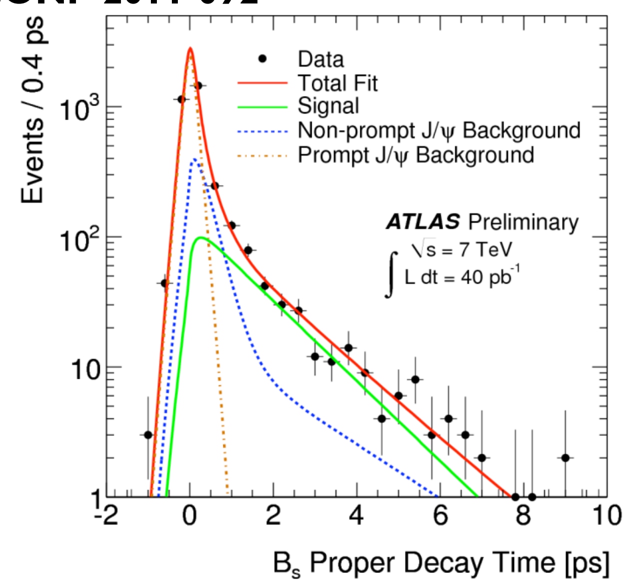
Phi candidate from kaons $p_T(K)>1$ GeV

Constrained vertex fit

Lifetime: $1.41 \pm 0.08_{stat} \pm 0.05_{syst}$ ps

[**PDG:** 1.472 ± 0.026 ps]





ATLAS now able to reconstruct $B^{\pm} \rightarrow J/\psi(\mu\mu)K^{\pm}$

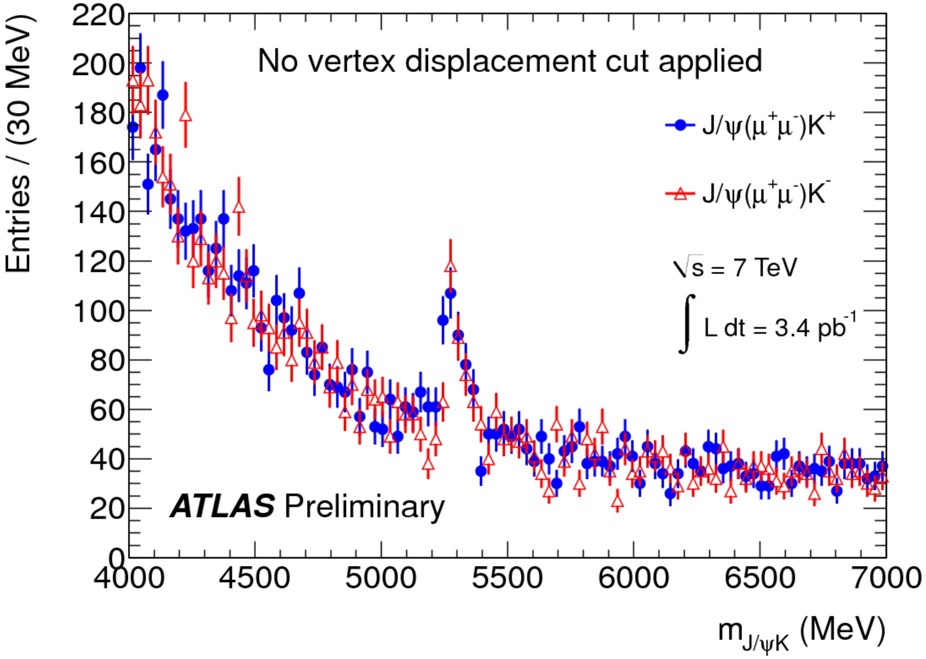
Candidates built from J/ψ candidate with 4, 2.5 GeV muon p_T cuts

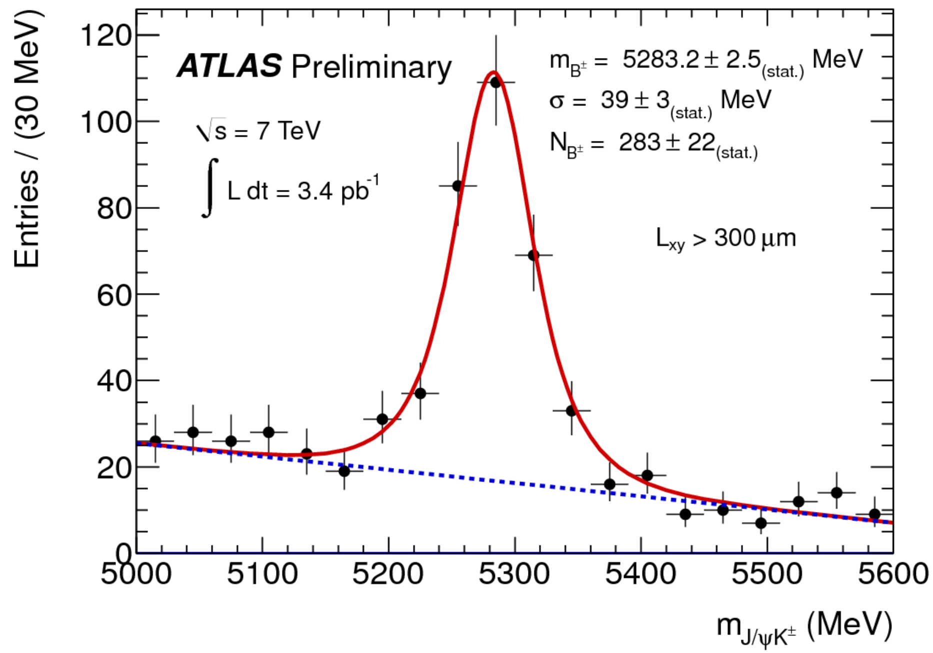
Constrained vertex fit of $\mu\mu K$ system, $p_T(\mu\mu K)$>10 GeV

Exploit displaced vertex of decay to improve signal/background:

B transverse decay length cut > 300 μm

Signal reduction 13%, consistent with MC, background reduced by factor of **six**





J/ψ (and W, and Z) in heavy ion collisions

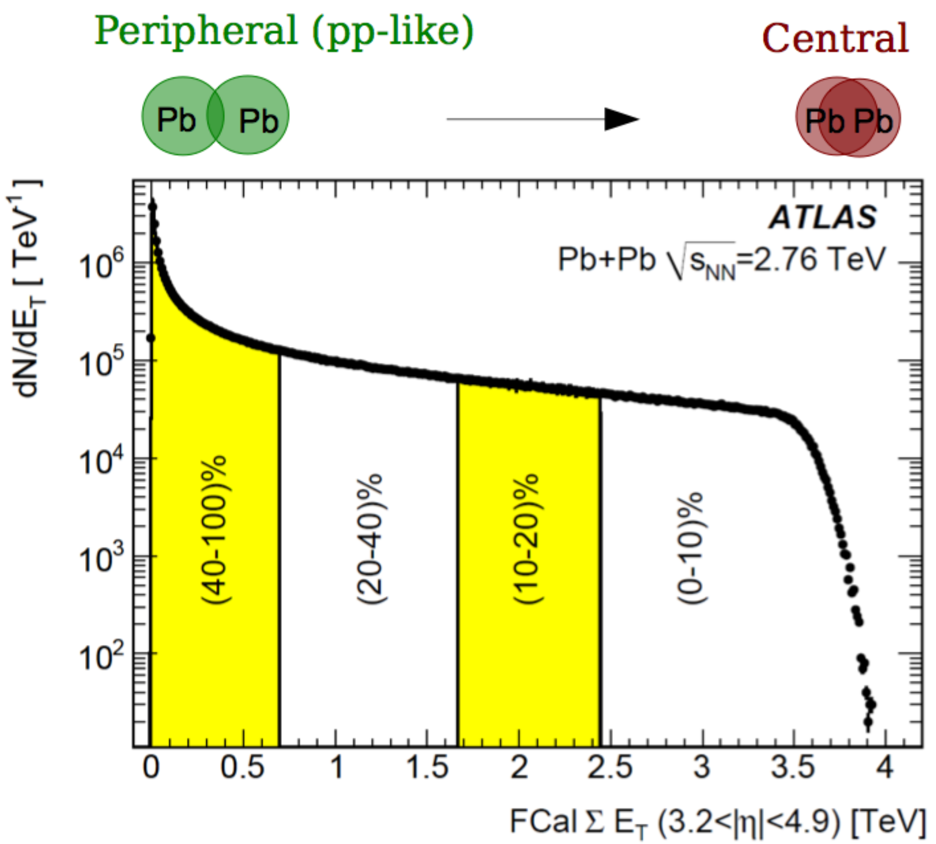
ATLAS has performed studies on J/ψ, W and Z with 2010 PbPb data

In each heavy ion collision, have N_{coll} binary collisions between N_{part} particles
Any yield measurement in heavy ions must be normalised to N_{coll}

Trigger: Minimum Bias Trigger

Centrality: characterised by percentage of total cross-section using the forward calorimeter transverse energy sum:
ΣET (3.2 < |η| < 4.9)

- Estimate of N_{coll} is performed using Glauber MC simulation
- Exclude 80-100% range due to uncertainty in determination of N_{coll}

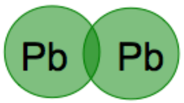


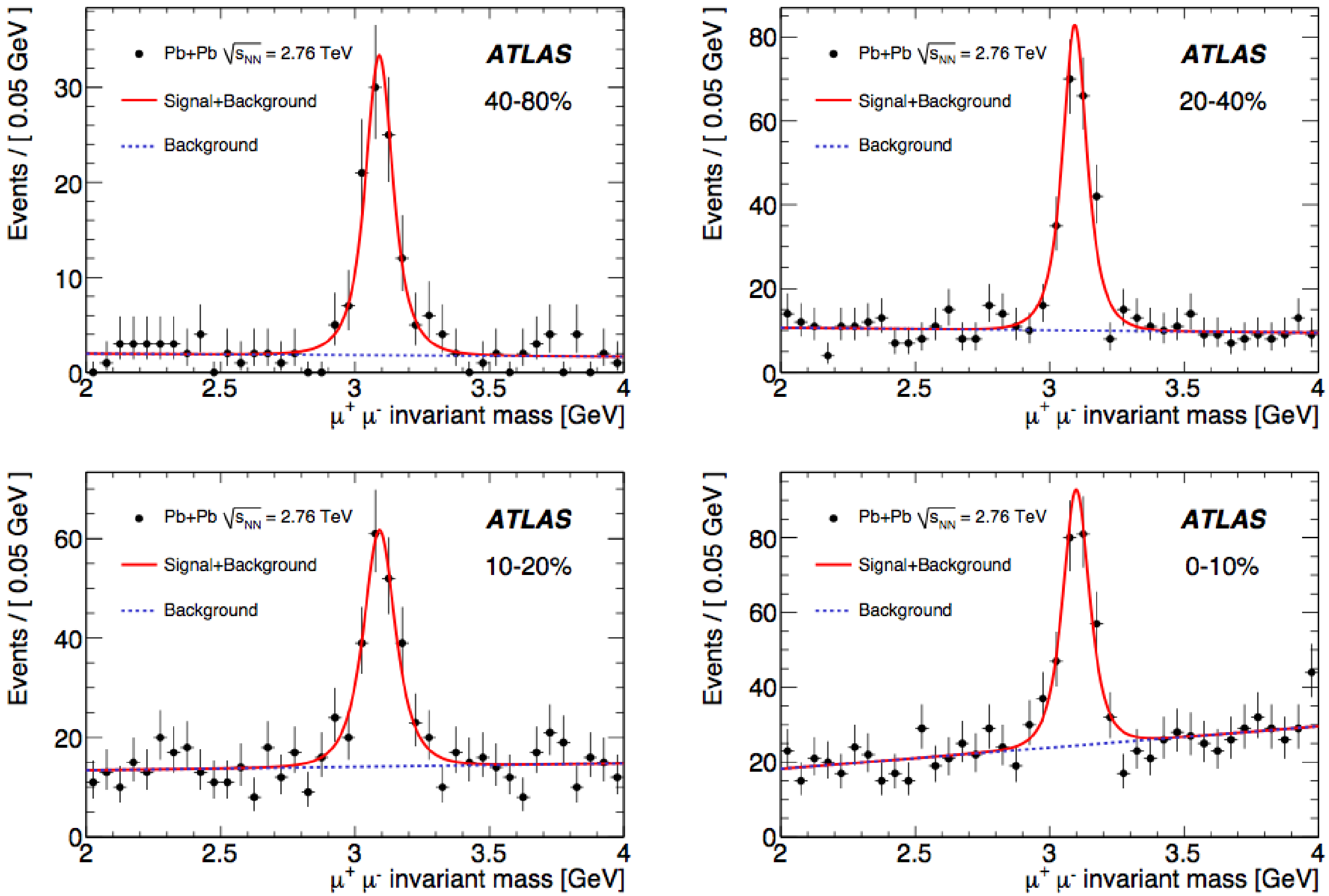
J/ψ reconstruction in heavy ions

J/ψ candidates identified from two combined muons; p_T>3 GeV, |η|<2.5
(reduces centrality dependence of track reconstruction to ~4%)

- Sideband subtraction method to extract signal yield, cross-check with UBML fit
- Systematic uncertainties assigned from reconstruction efficiency & signal extraction

Peripheral (pp-like)





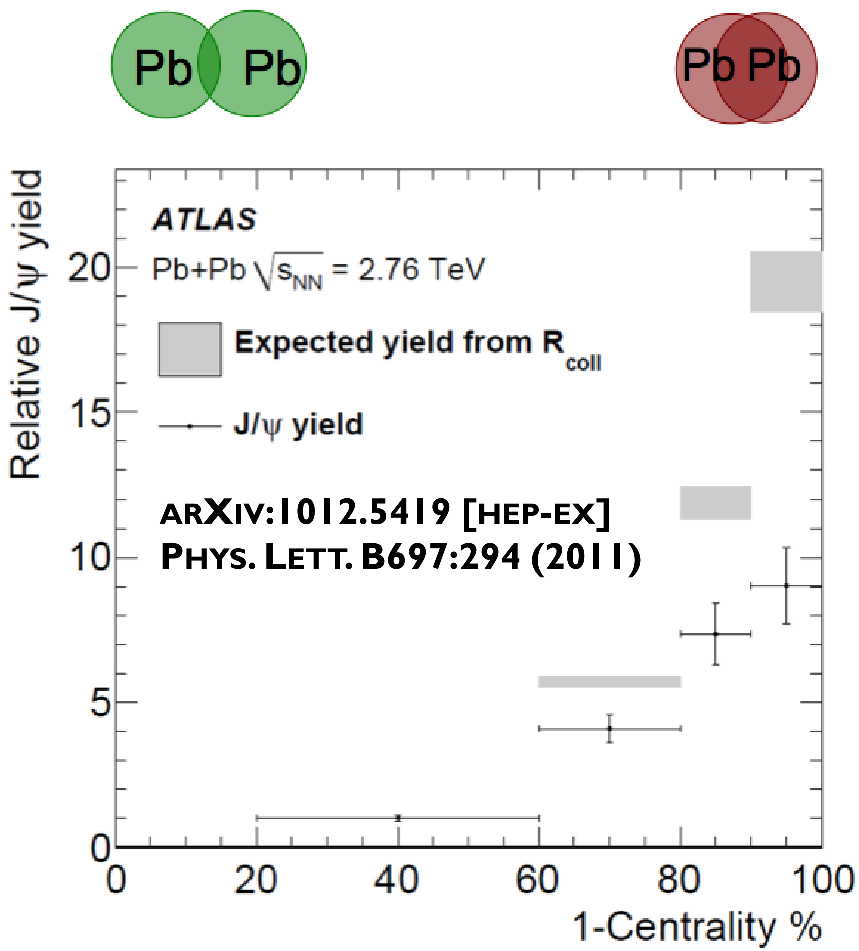
Central

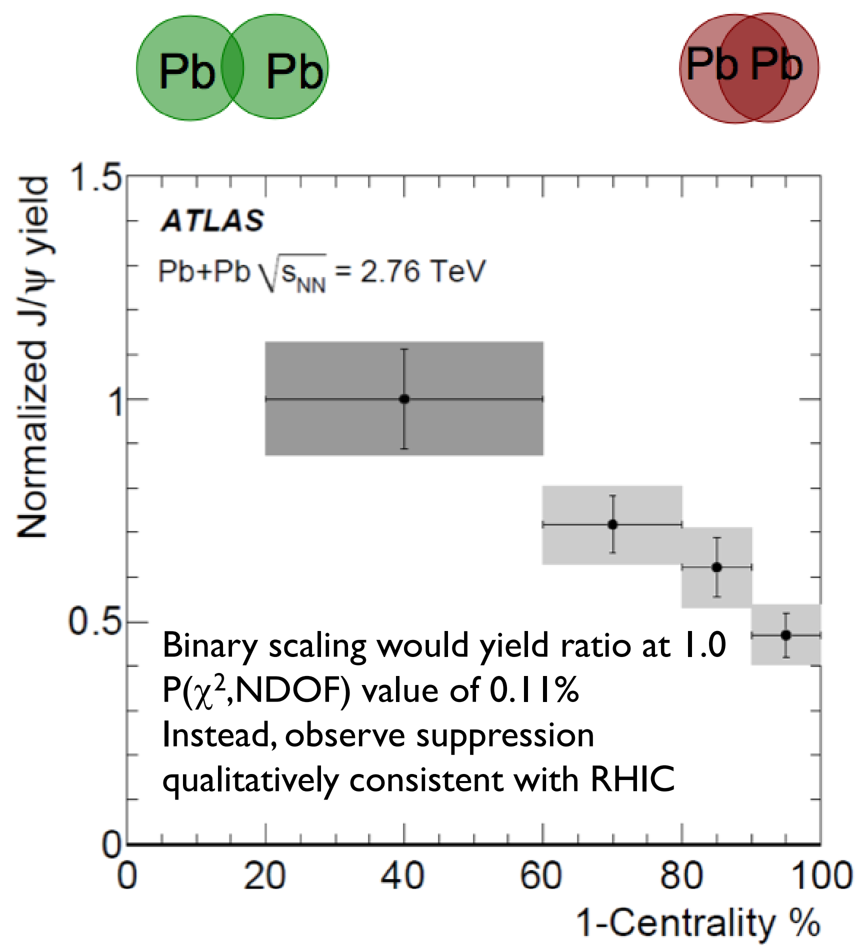
J/ψ suppression

Relative J/ψ yield normalised to most peripheral bin

Compare to $R_{coll} = N_{coll}[\text{central}]/N_{coll}\,[40–80\%]$

Experimental acceptance: $p_T>3$ GeV, $|\eta|<2.5$ [includes both prompt/non-prompt J/ψ]



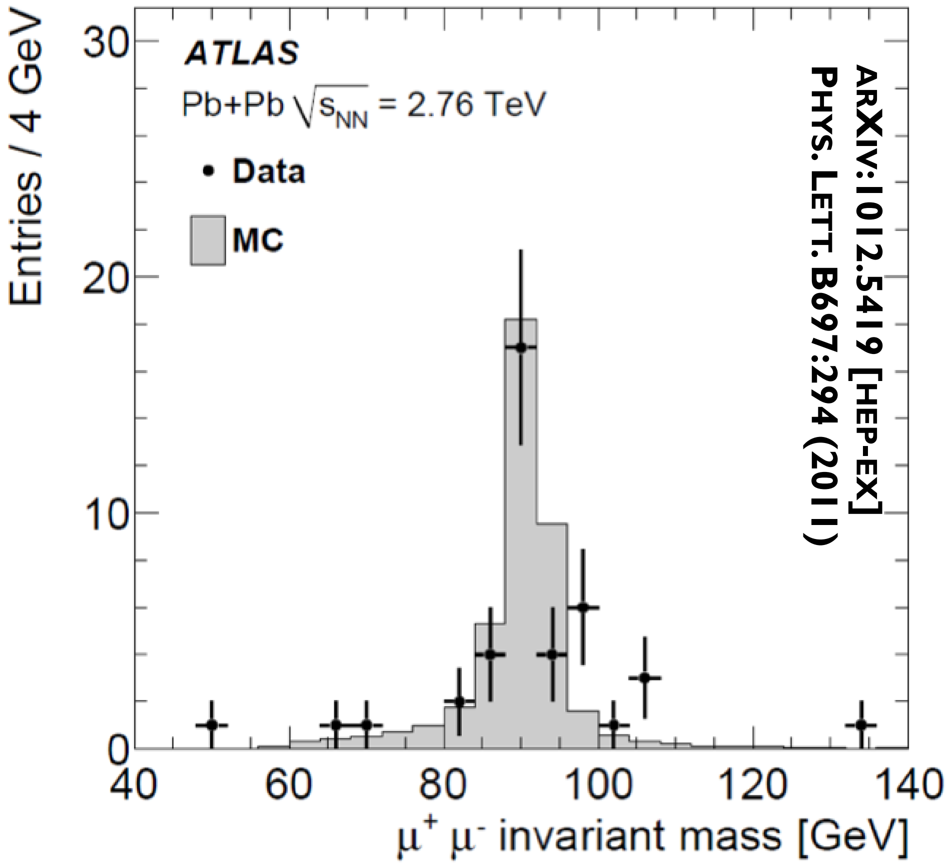


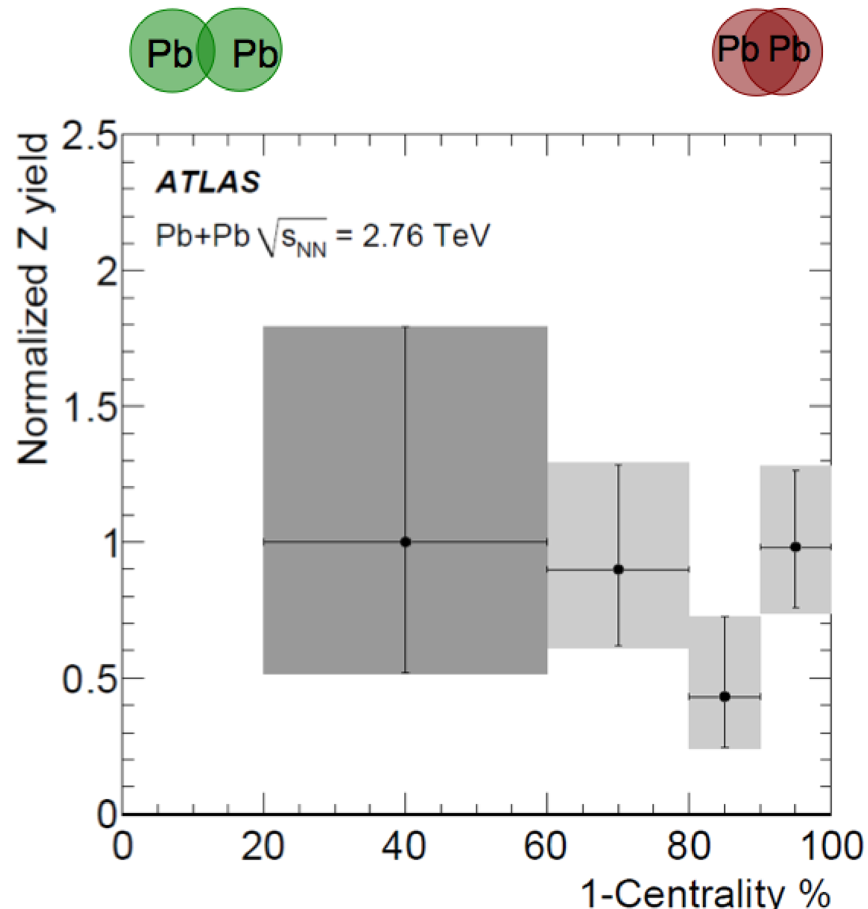
R_{CP} analysis: $Z \to \mu\mu$

Analysis repeated with $Z \to \mu\mu$ decays ($p_T(\mu)$>20 GeV)

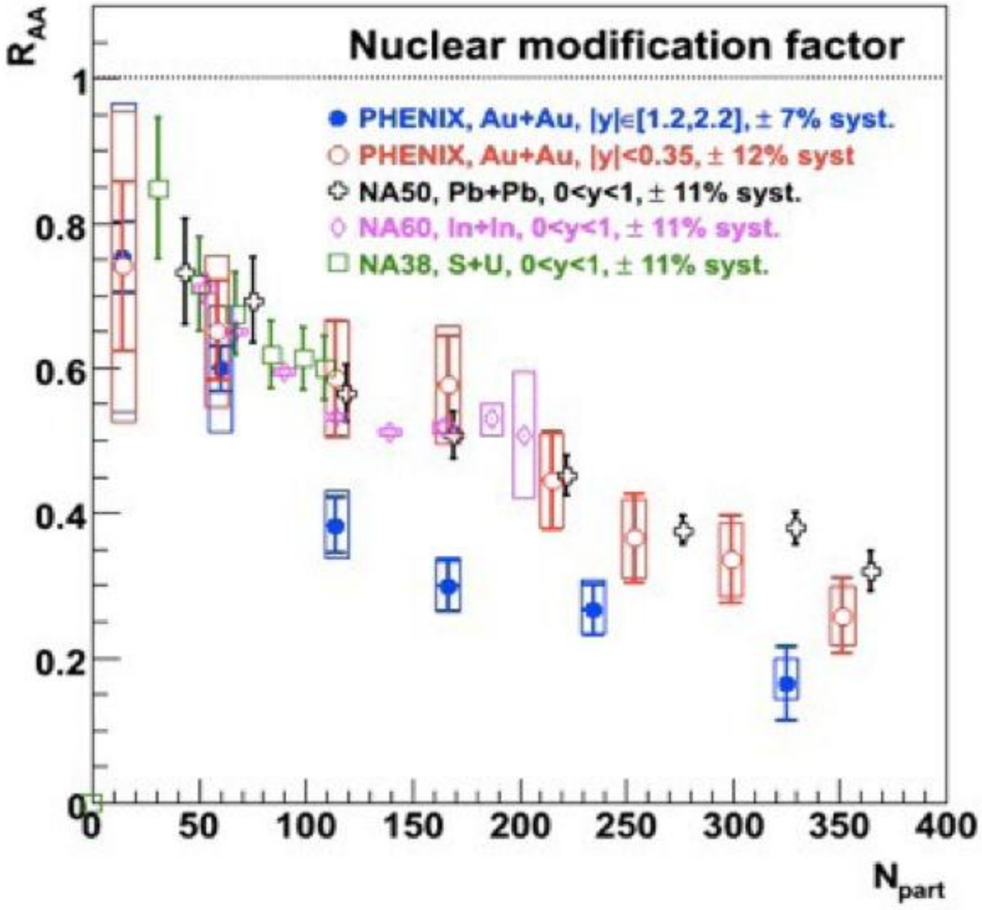
Relative Z boson yield found to be compatible with a linear scaling with binary collisions

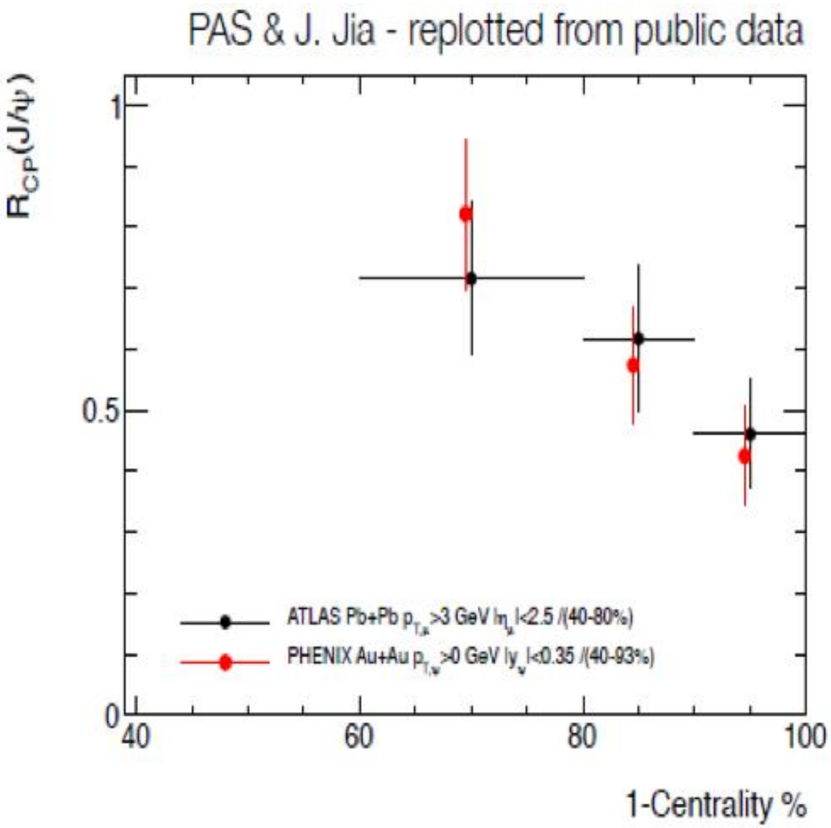
Low statistics (38 Z candidates) precludes any definite conclusions



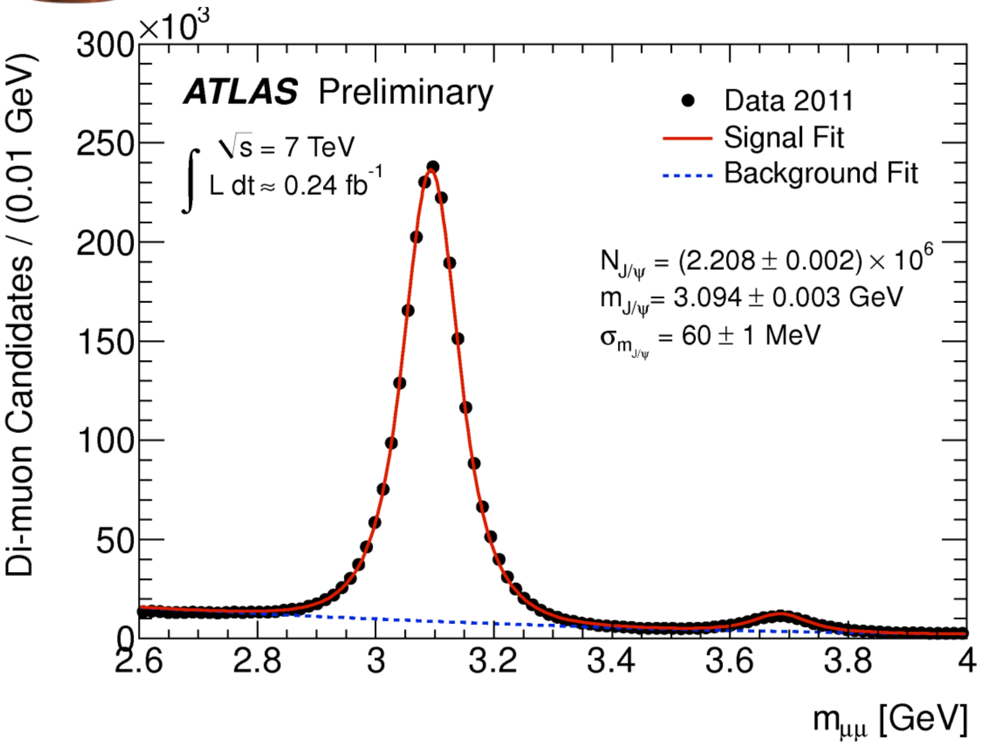


J/ψ HI suppression: comparison with RHIC



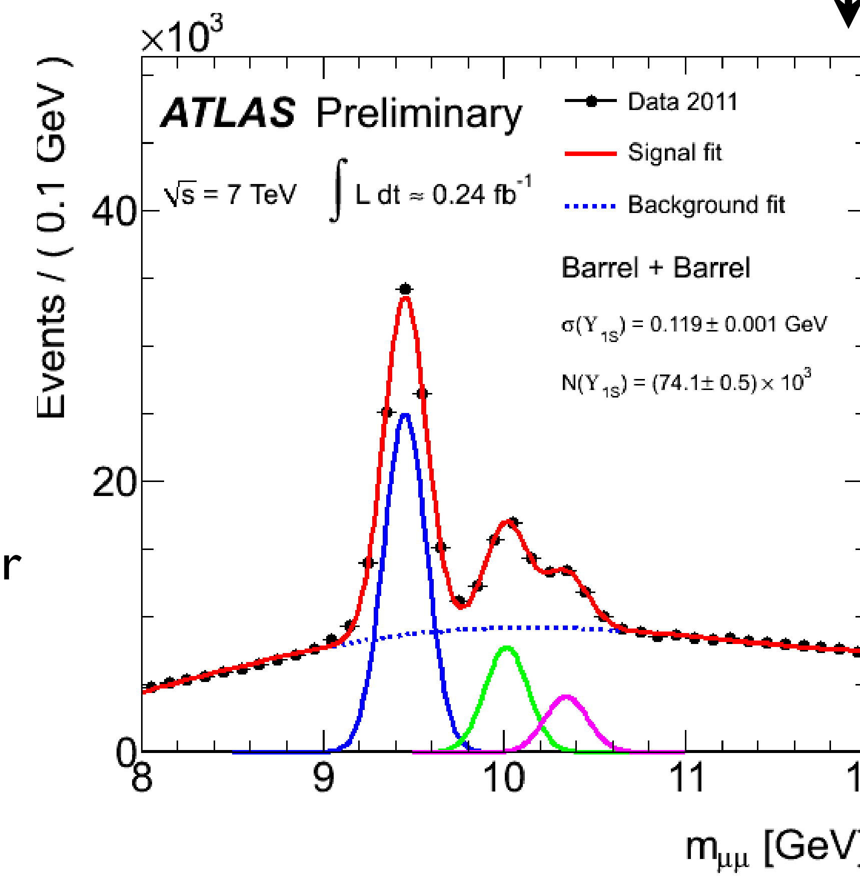


Attempt to replot PHENIX data vs Centrality [P.Steinberg, J.Jia] suggest suppression is energy-independent



At least one combined muon in muon pair

Muons in *barrel* ($|\eta|<1.05$) only



J/ψ: 4, 2.5 GeV muon p_T thresholds

Υ(nS): 4, 4 GeV muon p_T thresholds

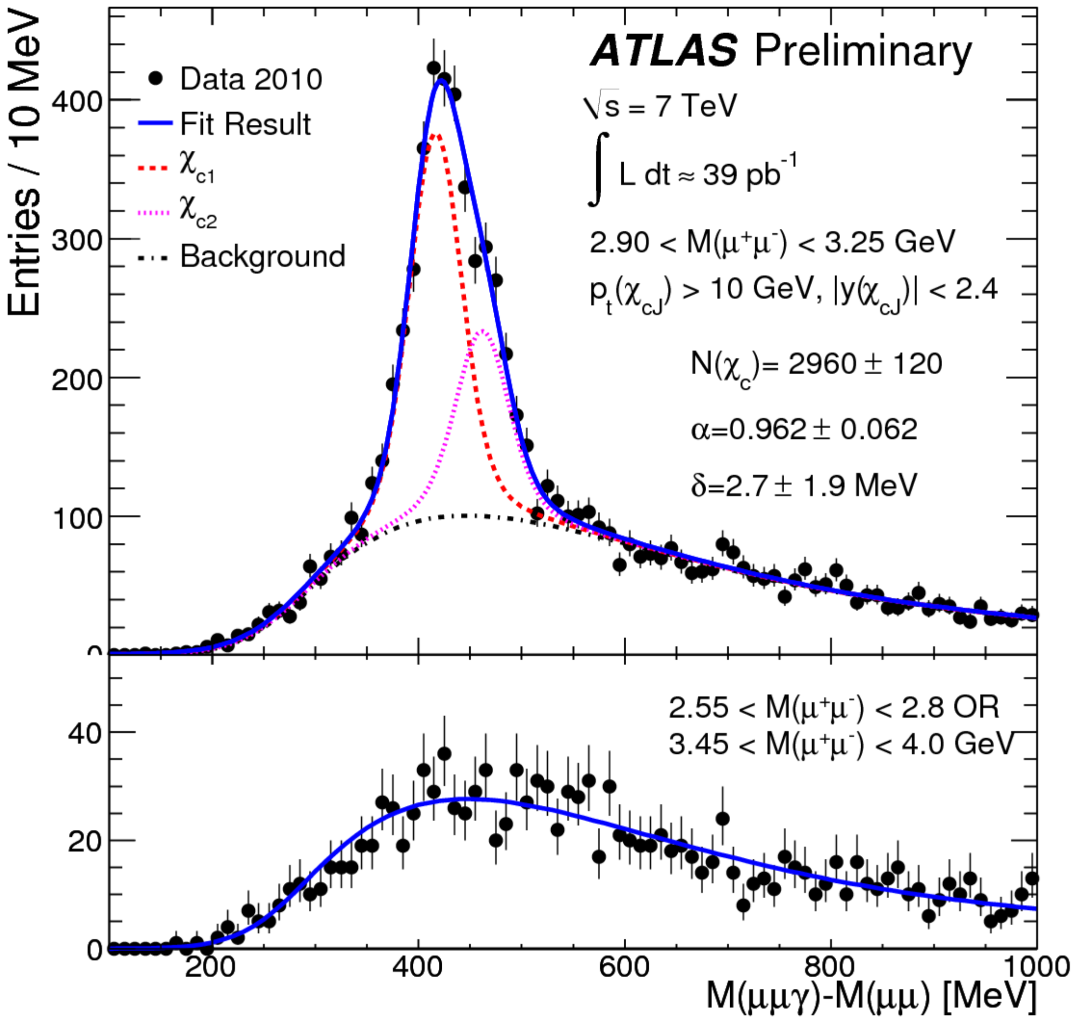
Observation of χ_c states

X_c decays observed into J/ψ + γ

Photons reconstructed in ECal

Peak(s) in mass difference

Analysis in progress using photon conversions (better resolution, but lower efficiency)



Summary and plans

Presented a number of quarkonium measurements from ATLAS:

- Cross section, separately for prompt and non-prompt contributions
- Reaching highest pT so far
- Prompt quarkonia continue to provoke questions in pp collisions
- Non-prompt J/ψ in good agreement with FONLL, within scale uncertainties
- Υ cross section measured within fiducial acceptance cuts
- J/ψ suppression with centrality of heavy ion collisions

Plans for the near future (quarkonium-related):

- Measurement of the cross section of $\psi(2S)$
- Measurement of the production of χ_c (and χ_b ?) states
- Measurement of J/ψ spin-alignment
- Measurement of Υ cross section and spin alignment
- Measurement of Quarkonium production at 2.76 TeV, and also in p-Pb collisons as reference for PbPb