ATLAS results on charmonium production in Pb-Pb and pp collisions at the LHC

Alessandro Cerri (CERN) for the ATLAS collaboration

Introduction

Outline of this talk:

pp collisions at 7 TeV

- Motivation
- Inclusive, prompt and non-prompt J/ψ production
- Upsilon(1S) production

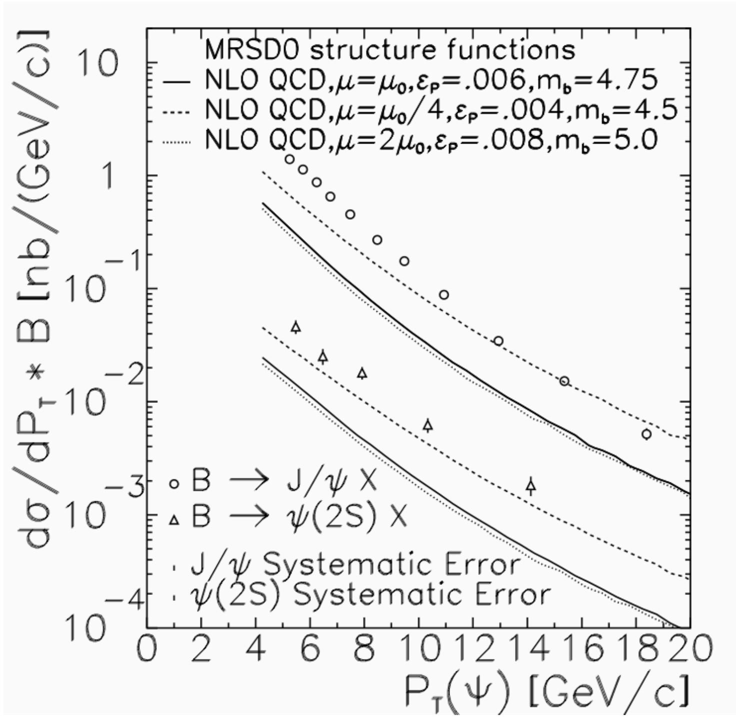
PbPb collisions at 2.76 TeV

- Motivation
- J/ψ suppression as a function of centrality
- Studies of Z

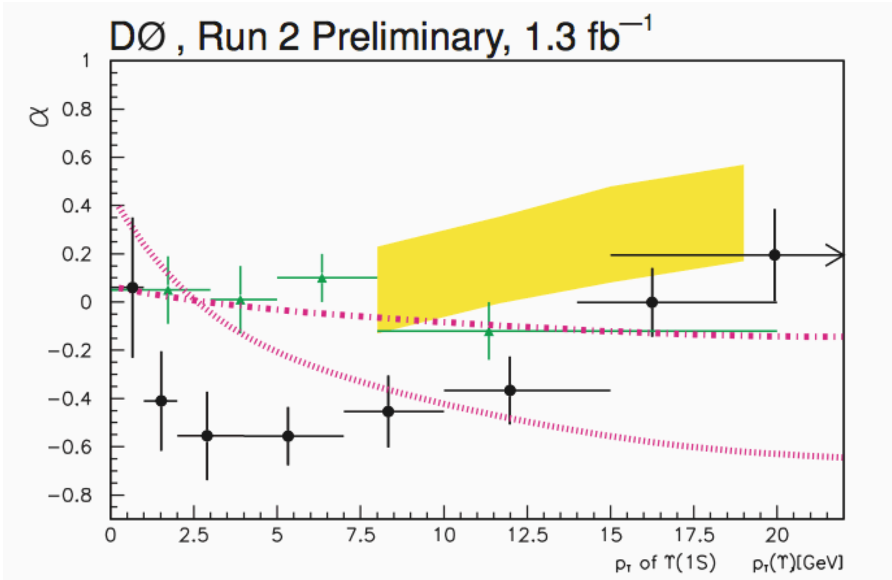
Conclusions

Motivations

- No unified mechanism exists to consistently explain the heavy quarkonium production and spin-alignment in e+e-, hadron and heavy-ion colliders
- J/Ψ & Υ production measurements provide constraint to physics models



F. Abe et al., The CDF Collaboration, Phys. Rev. Lett. 79, 572 (1997)

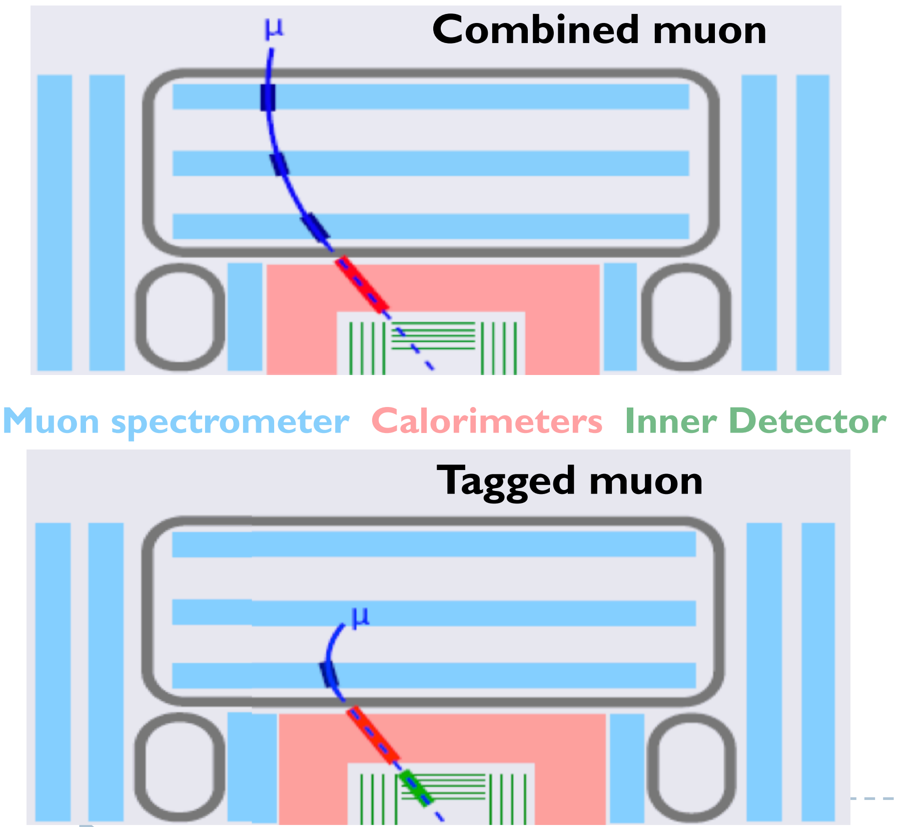


Phys. Rev.Lett.101, 182004 (2008)[D0] Phys. Rev. Lett. 88, 161802 (2002)[CDF] (actual figure from preliminary D0 note online)

Measuring J/ψ in pp: candidate selection

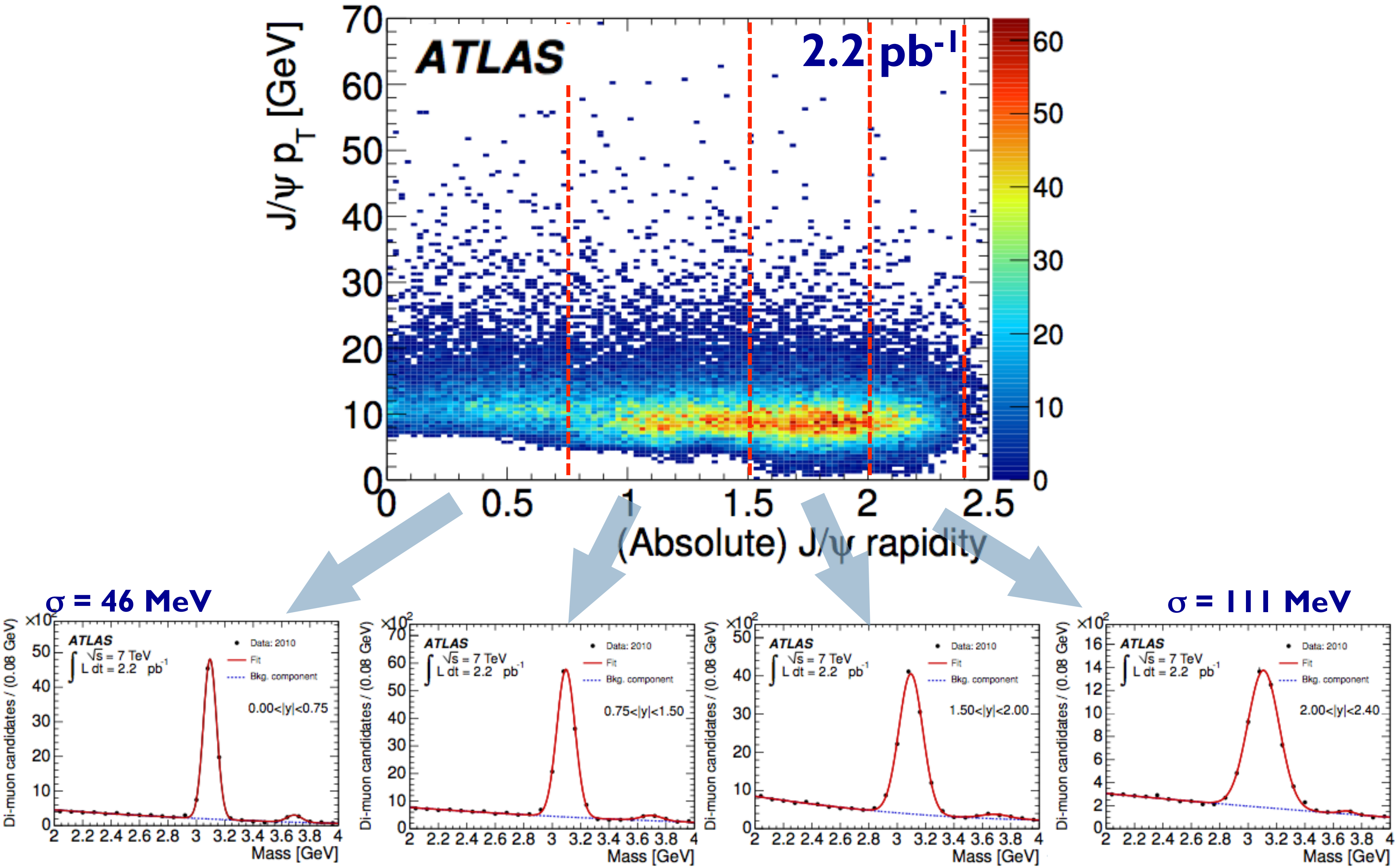
Muons associated to J/ψ candidate may be:

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



- 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



Measurement of inclusive cross-section

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

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

Bin migration

ID reco efficiency (per muon track)

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

Detector acceptance

Reconstruction efficiency

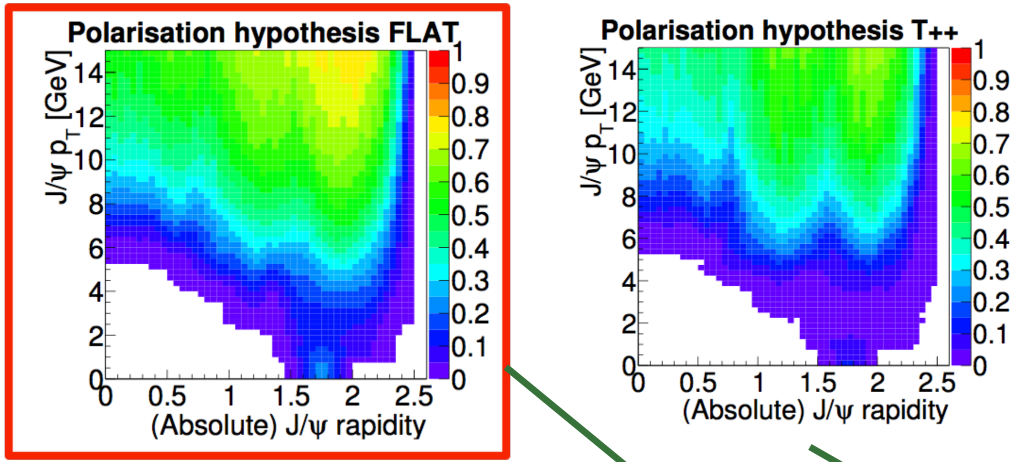
Trigger efficiency

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

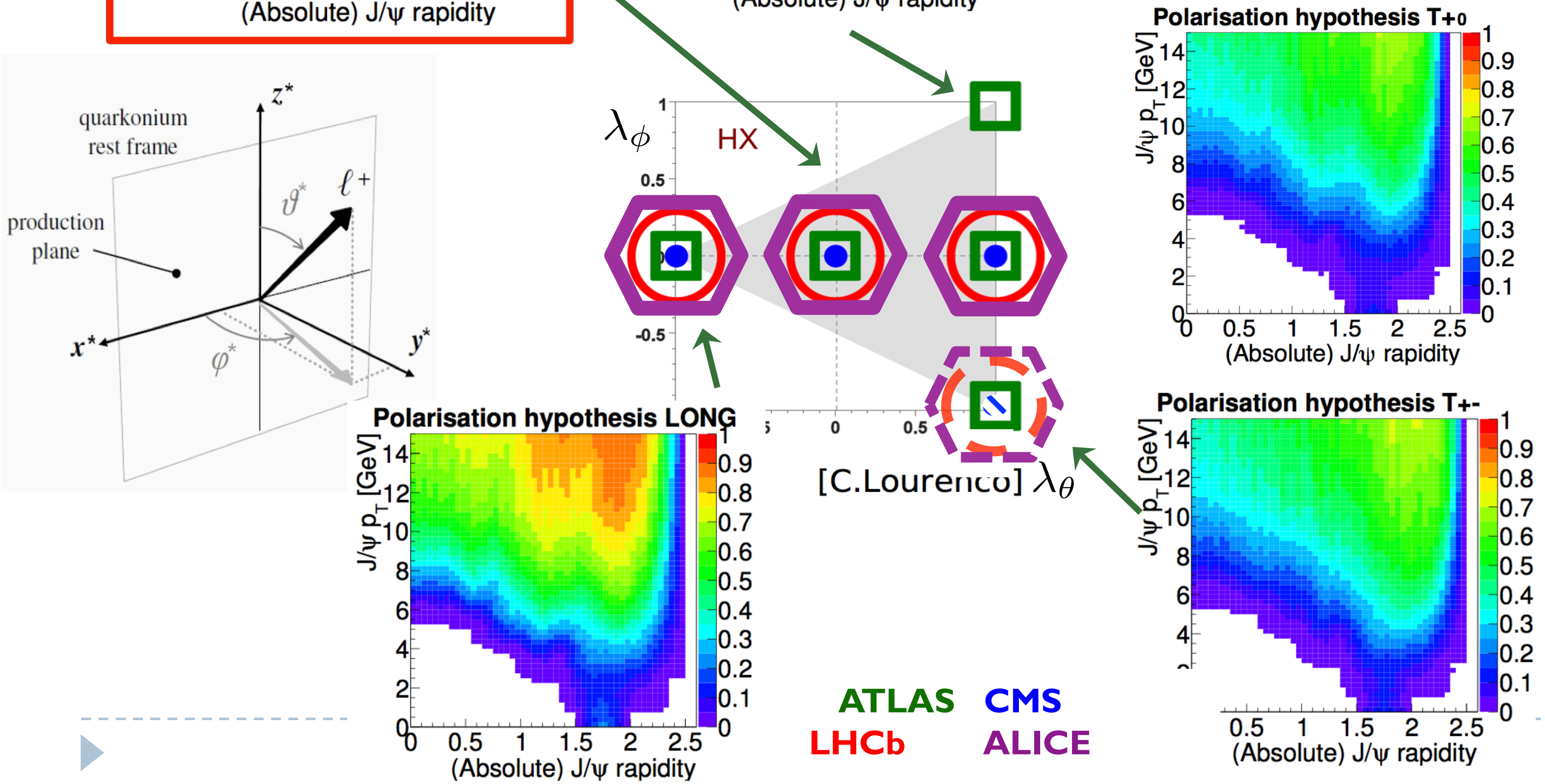
$$\frac{d^2\sigma(J/\psi)}{dp_T dy} \cdot Br(J/\psi \to \mu^+\mu^-) = \frac{N^{J/\psi}_{corr}}{\mathcal{L} \cdot \Delta p_T \Delta y}$$

Spin-alignment and acceptance corrections



Model-dependent on spin-alignment state

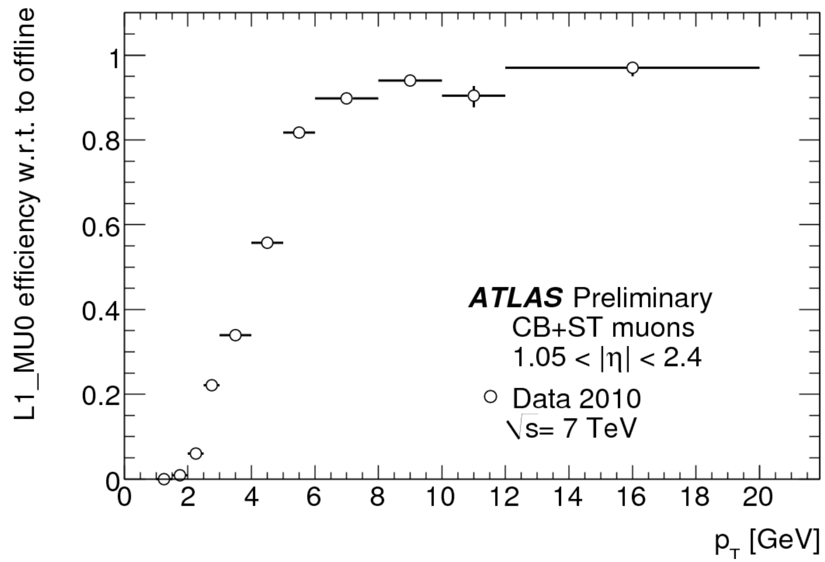
Possible differences between prompt and non-prompt J/ψ spin-alignment



J/ψ efficiency corrections

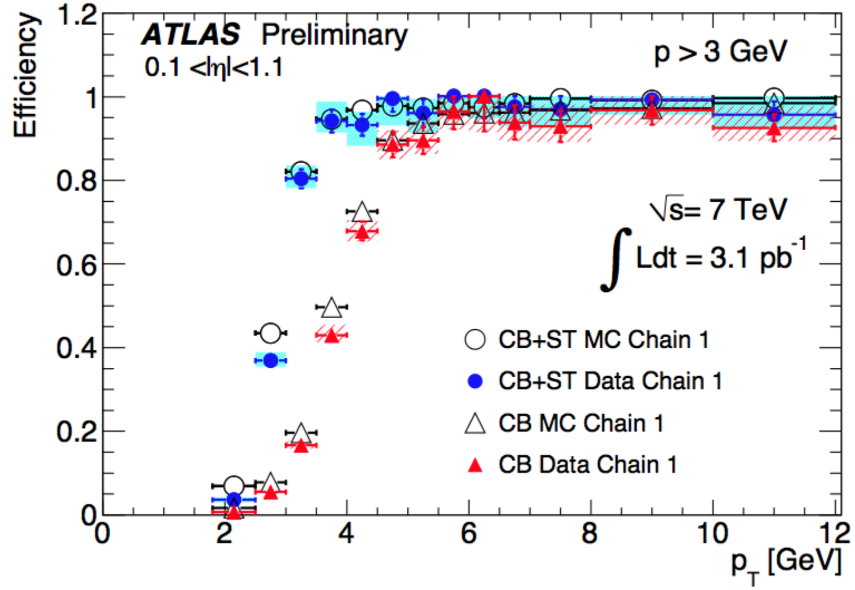
Single muon trigger efficiency

- 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/ψ→μμ at low p_T supported by Z→μμ measurements at higher p_T for improved plateau precision
- Regions with efficiency < 20% excluded from analysis



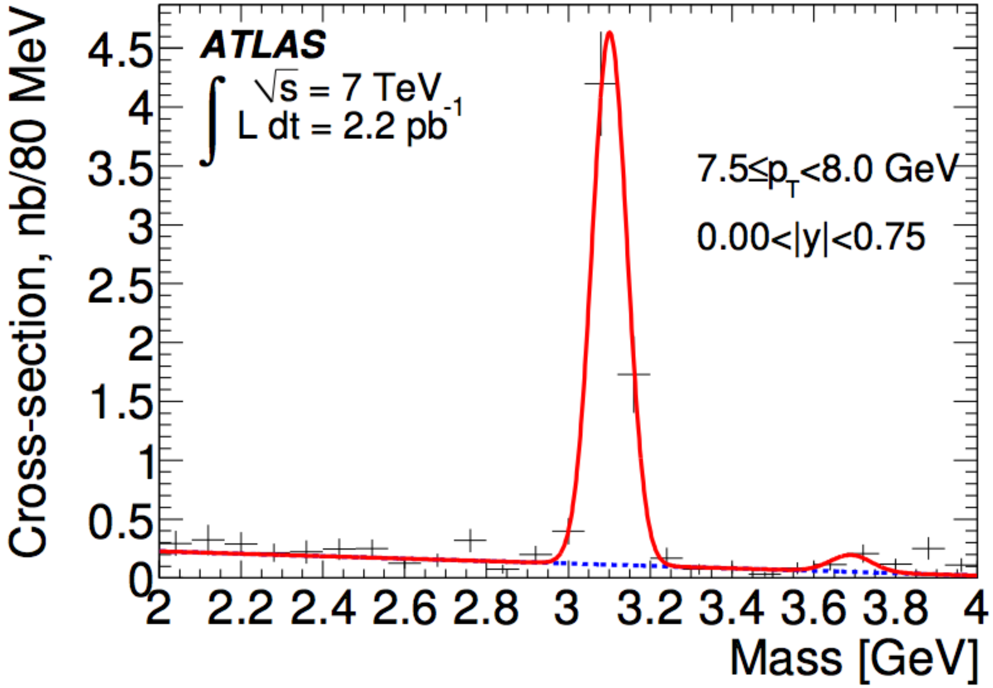
ID track reconstruction efficiency

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

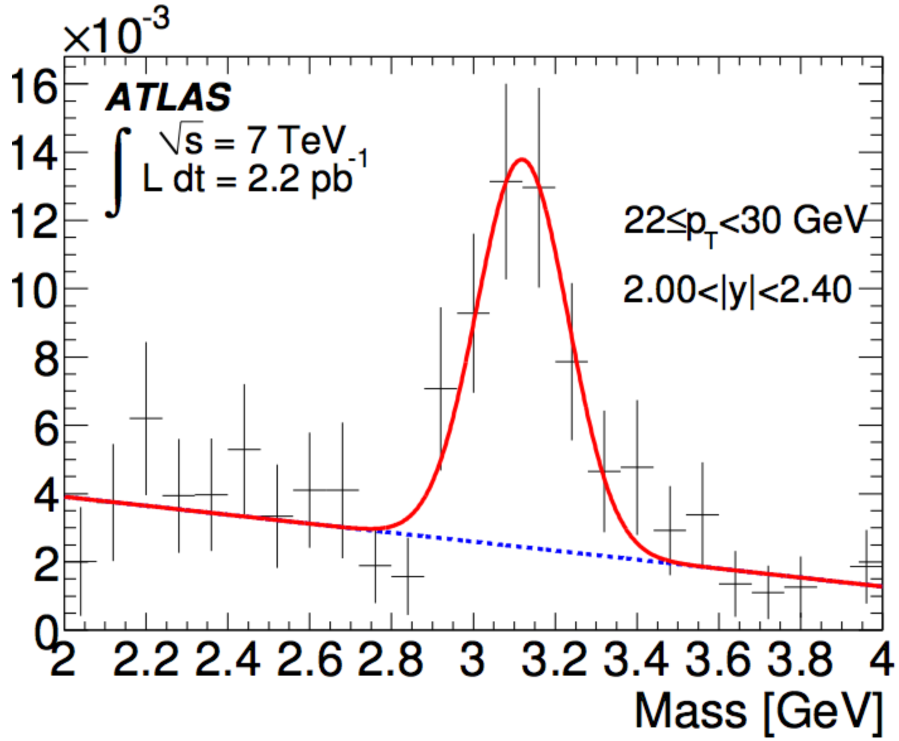
Weighted fits and cross-section extraction

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
- ψ(2S) included in fit, but yields not extracted at this time



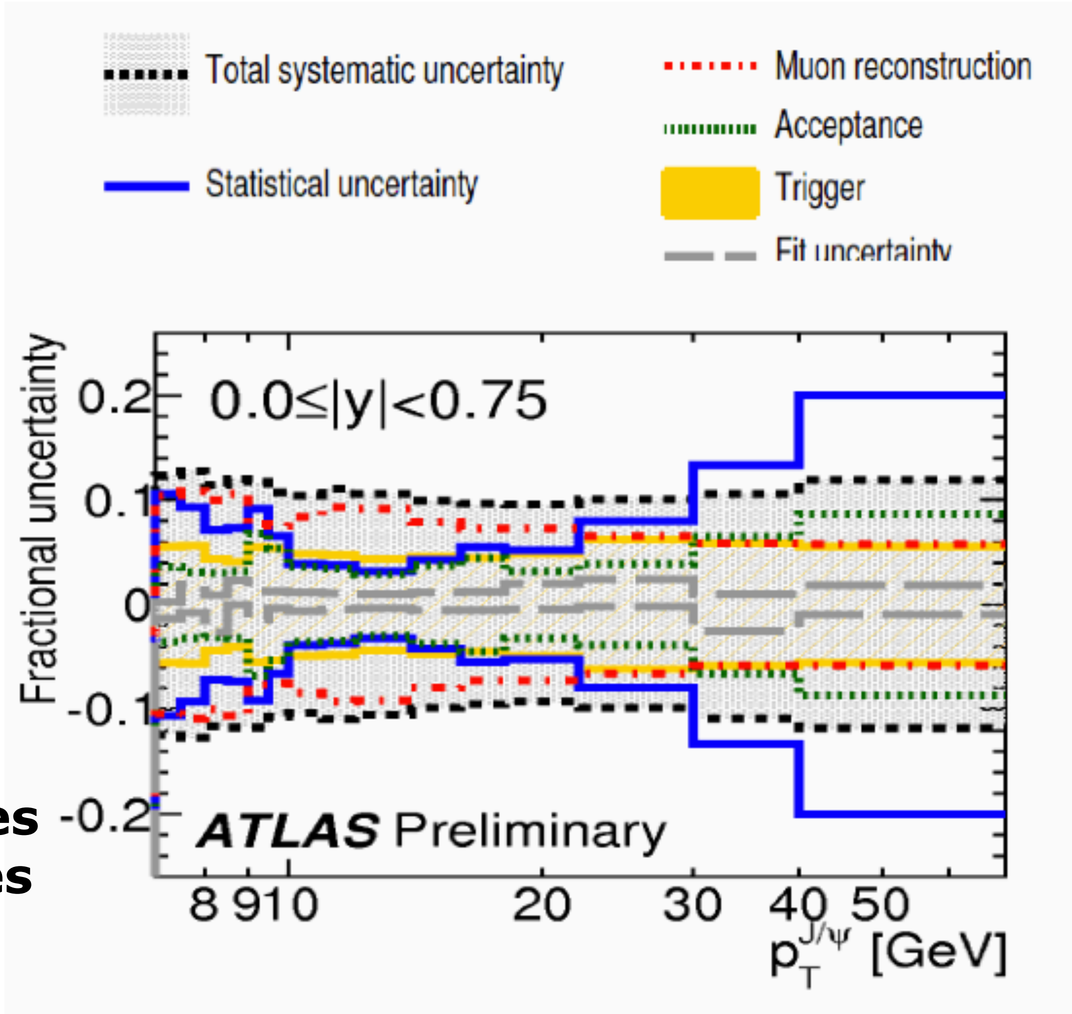
low p_T, central rapidity

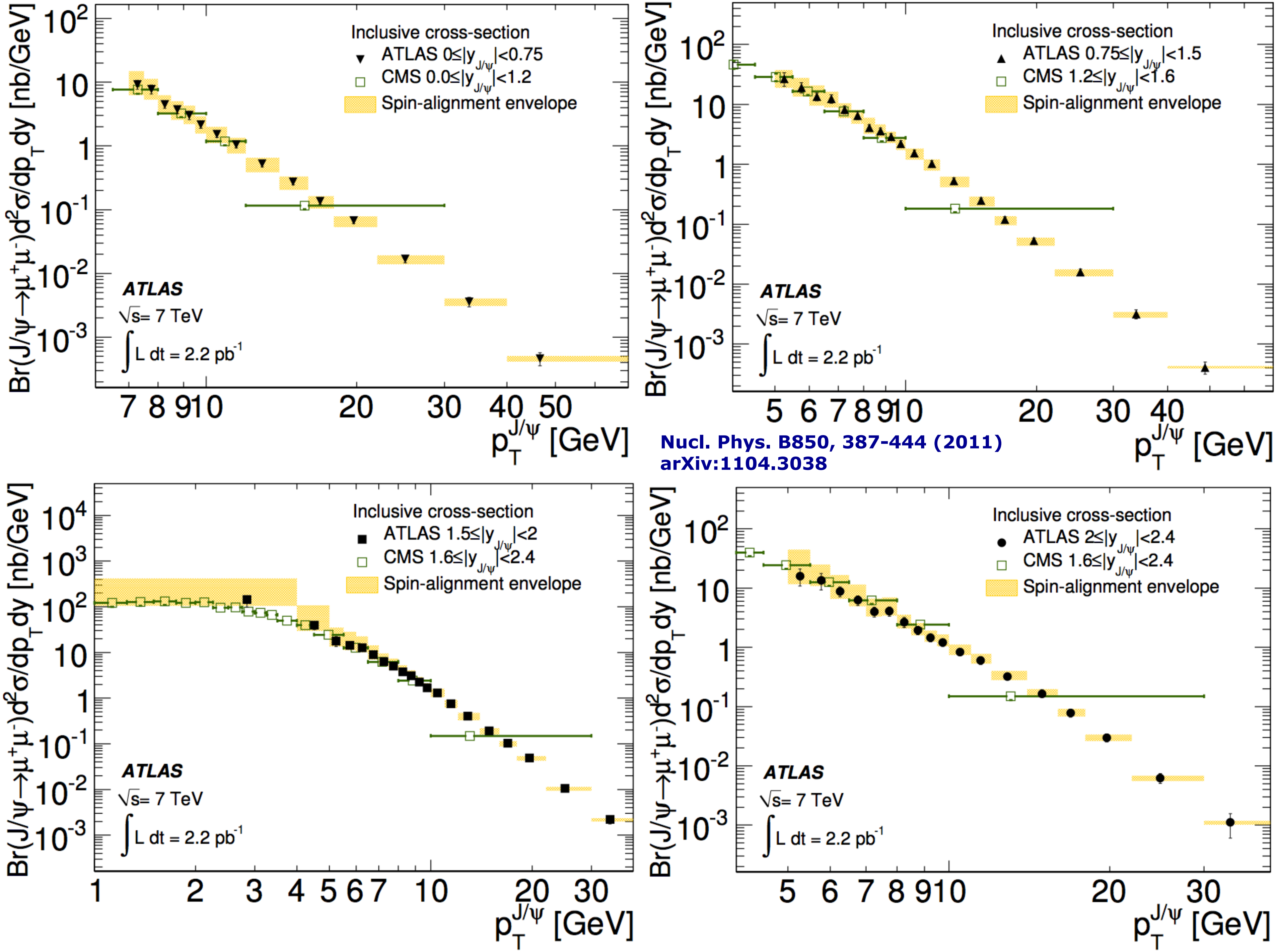


high p_T, forward rapidity

Systematic uncertainties

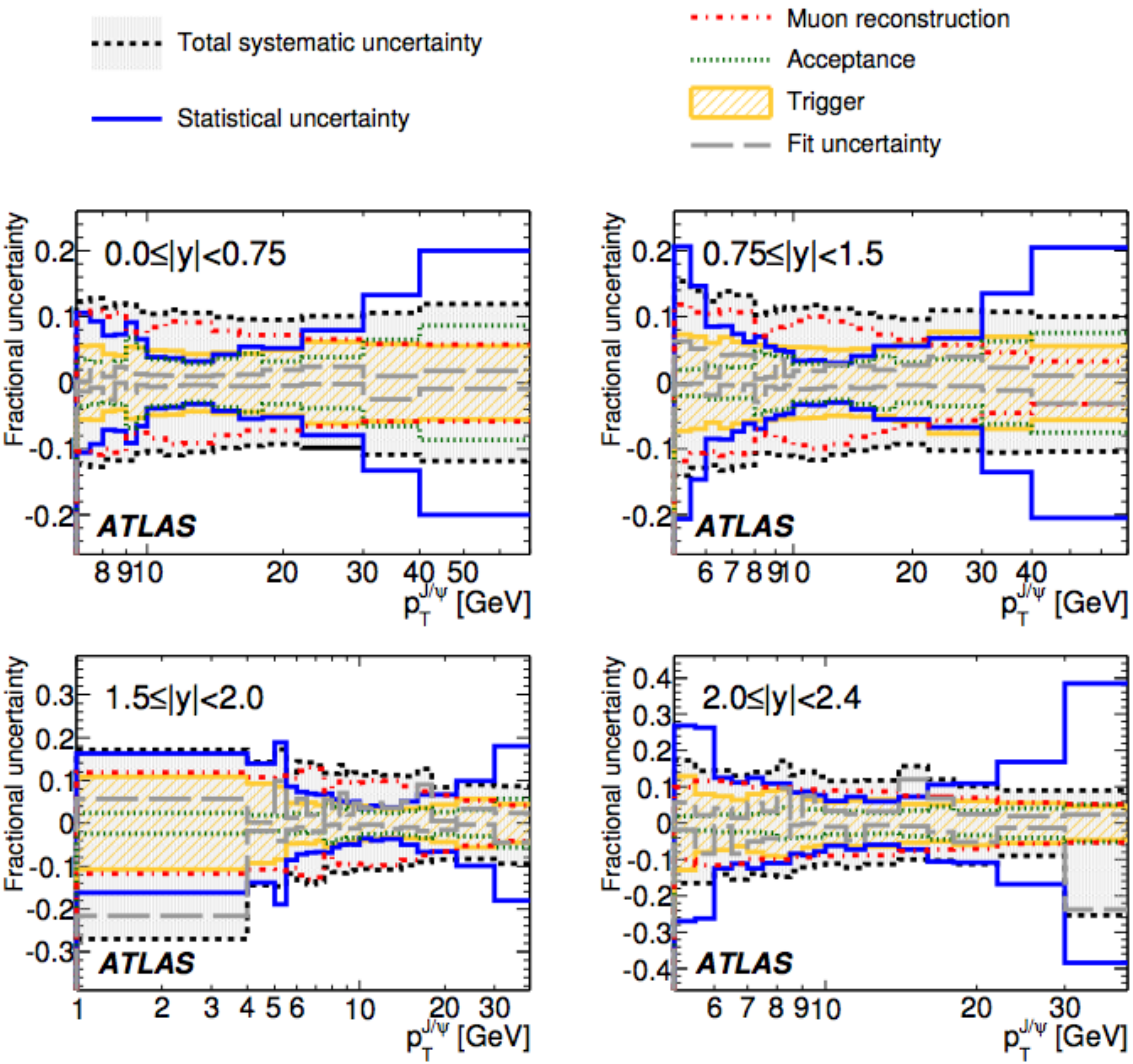
- Muon Reconstruction
- Muon/ID efficiency
- Acceptance
  - Bin Migration
  - Vertexing
  - Trigger
  - Fit uncertainty
- Total
  - Above
  - Luminosity (3.4%)
  - MC model dependence
  - Final State Radiation
  - Spin-alignment envelopes are separate uncertainties (5~200%)





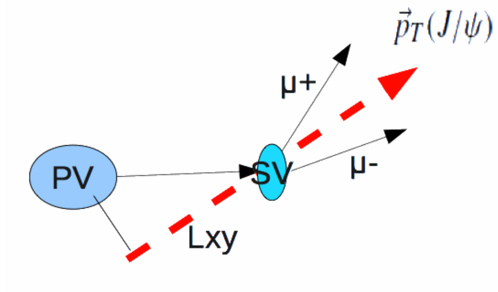
Nucl. Phys. B850, 387-444 (2011)
arXiv:1104.3038

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



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



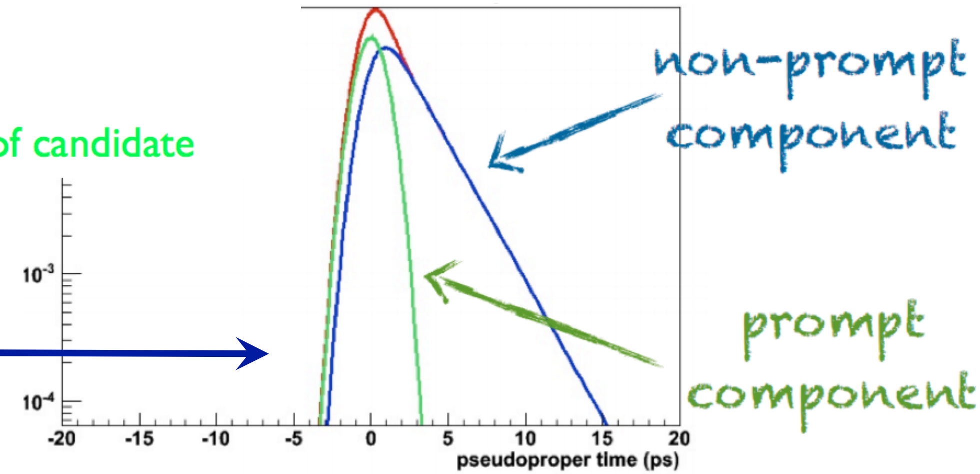
xy displacement of candidate from PV

Invariant mass of candidate

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

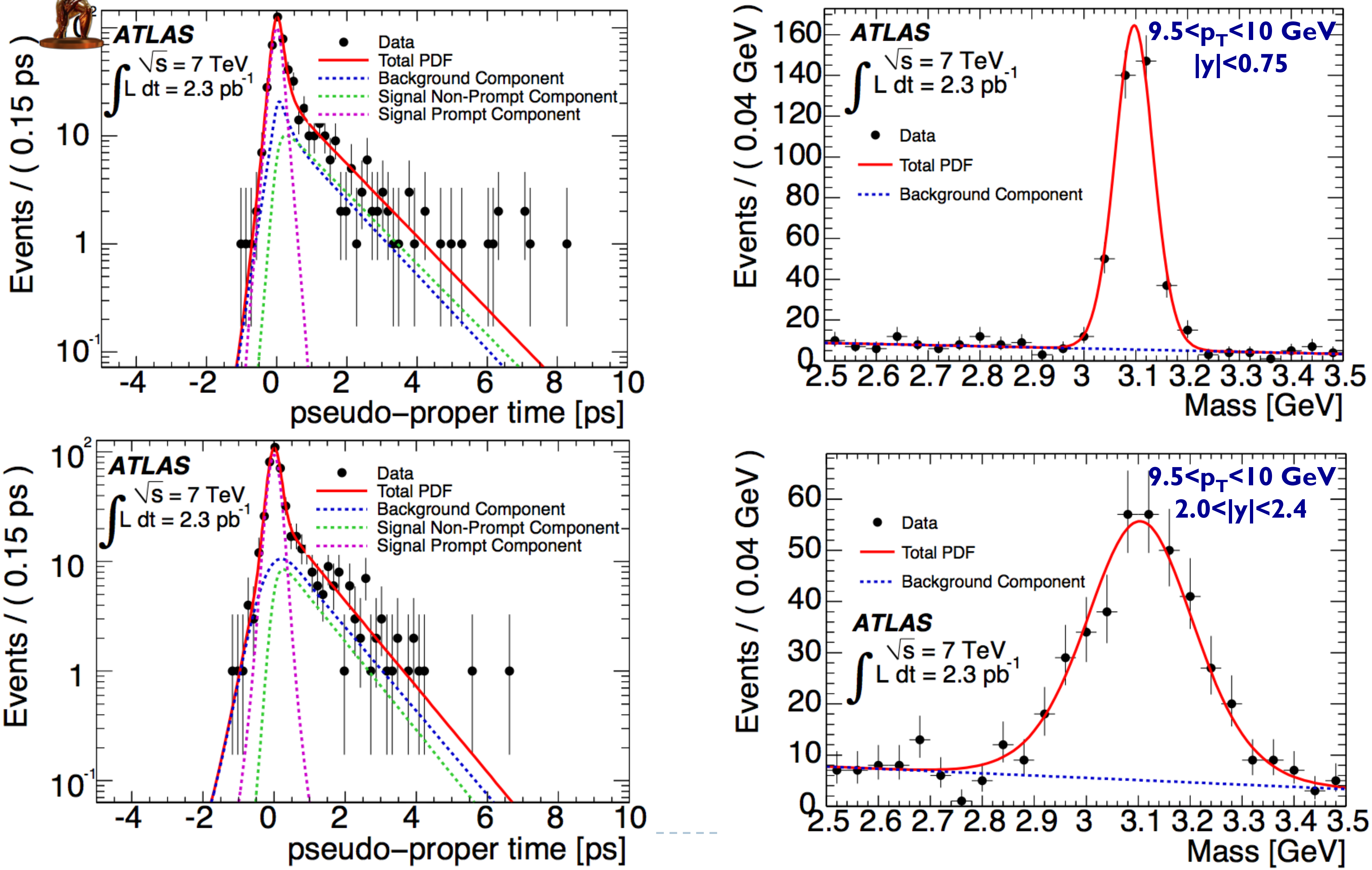
p_T of candidate

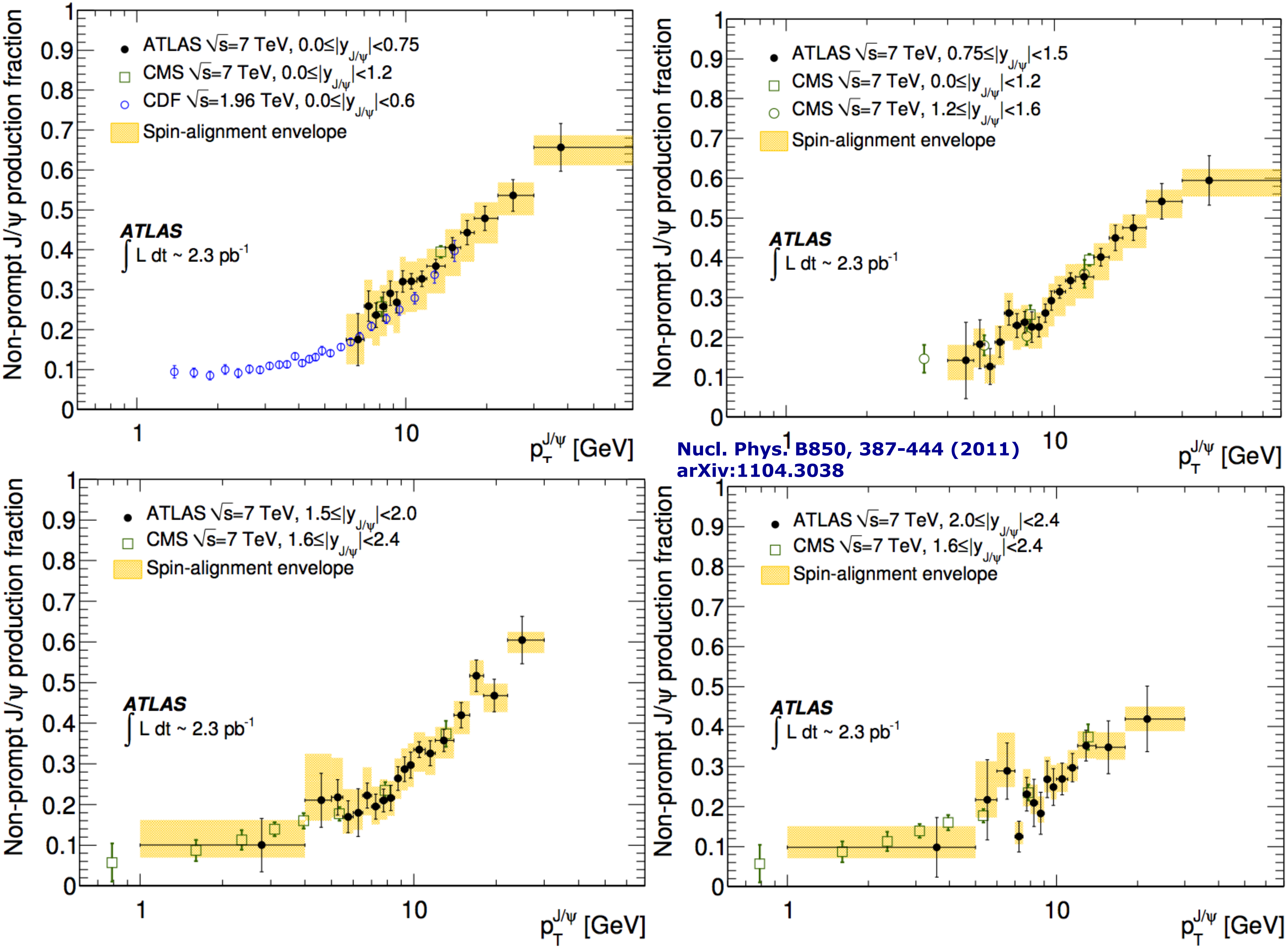
Pseudo-proper time τ discriminant



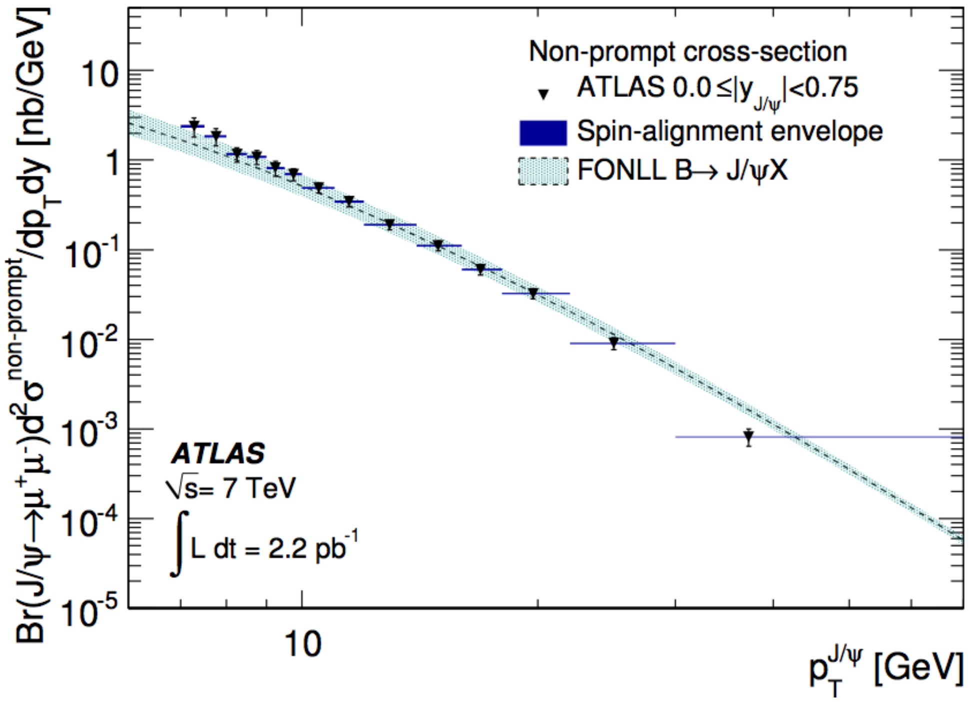
Further combine inclusive cross-section and corrected non-prompt fraction to extract prompt and non-prompt differential cross-sections

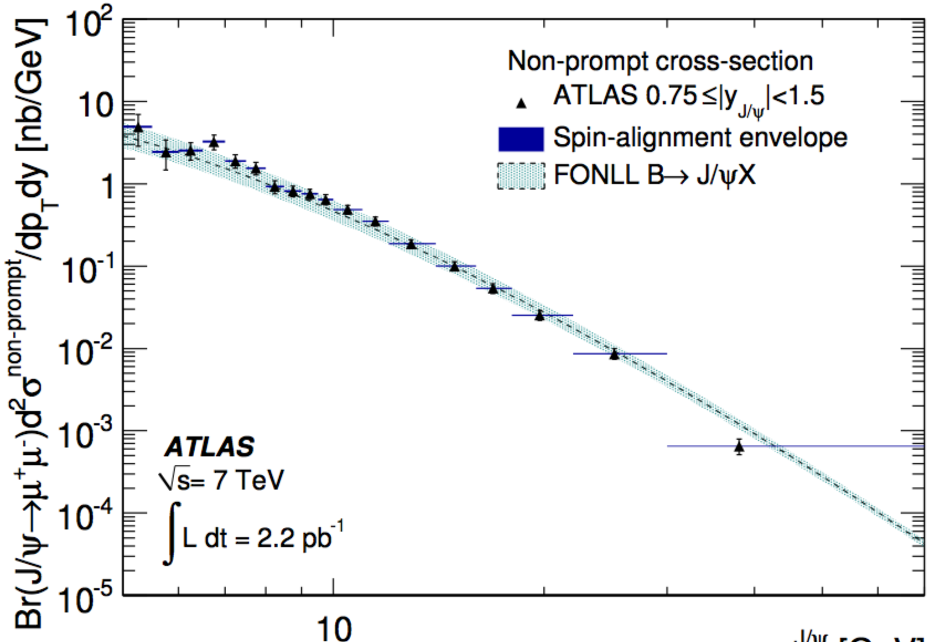
Simultaneous mass/lifetime fit projections



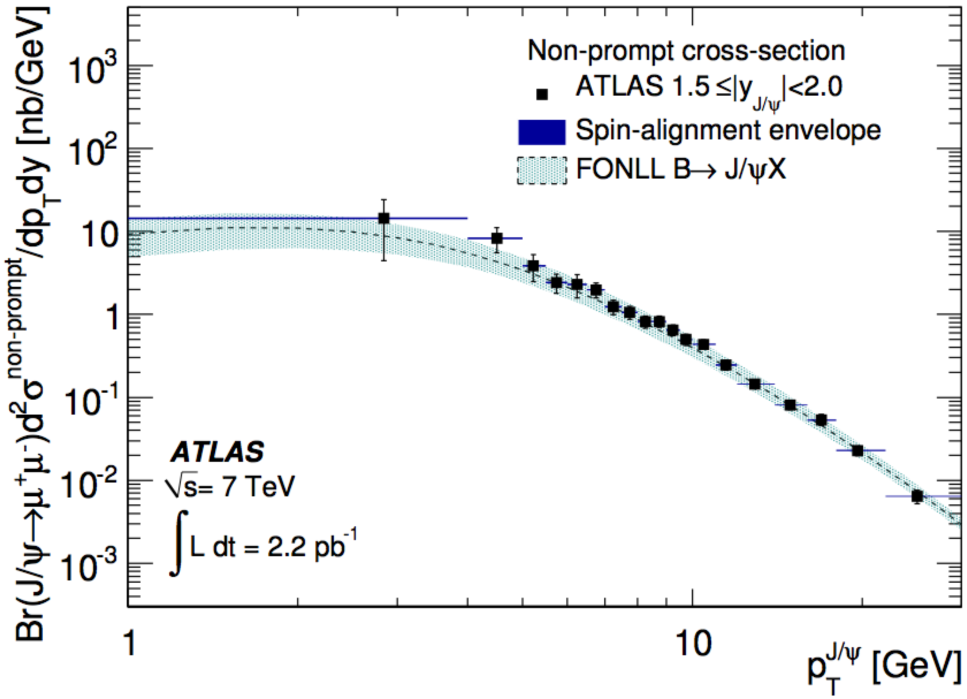


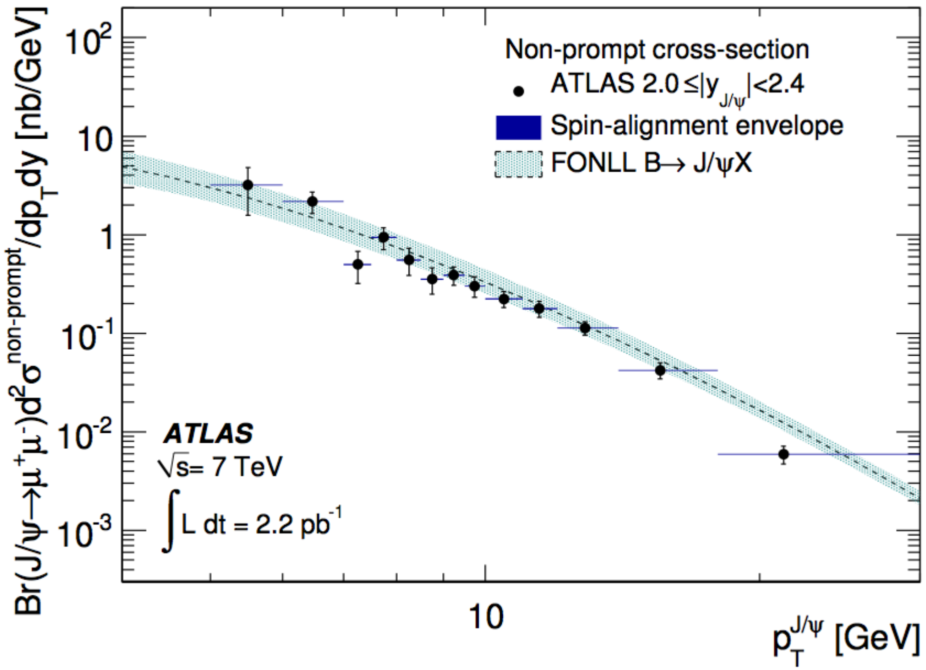
Nucl. Phys. B850, 387-444 (2011)
arXiv:1104.3038





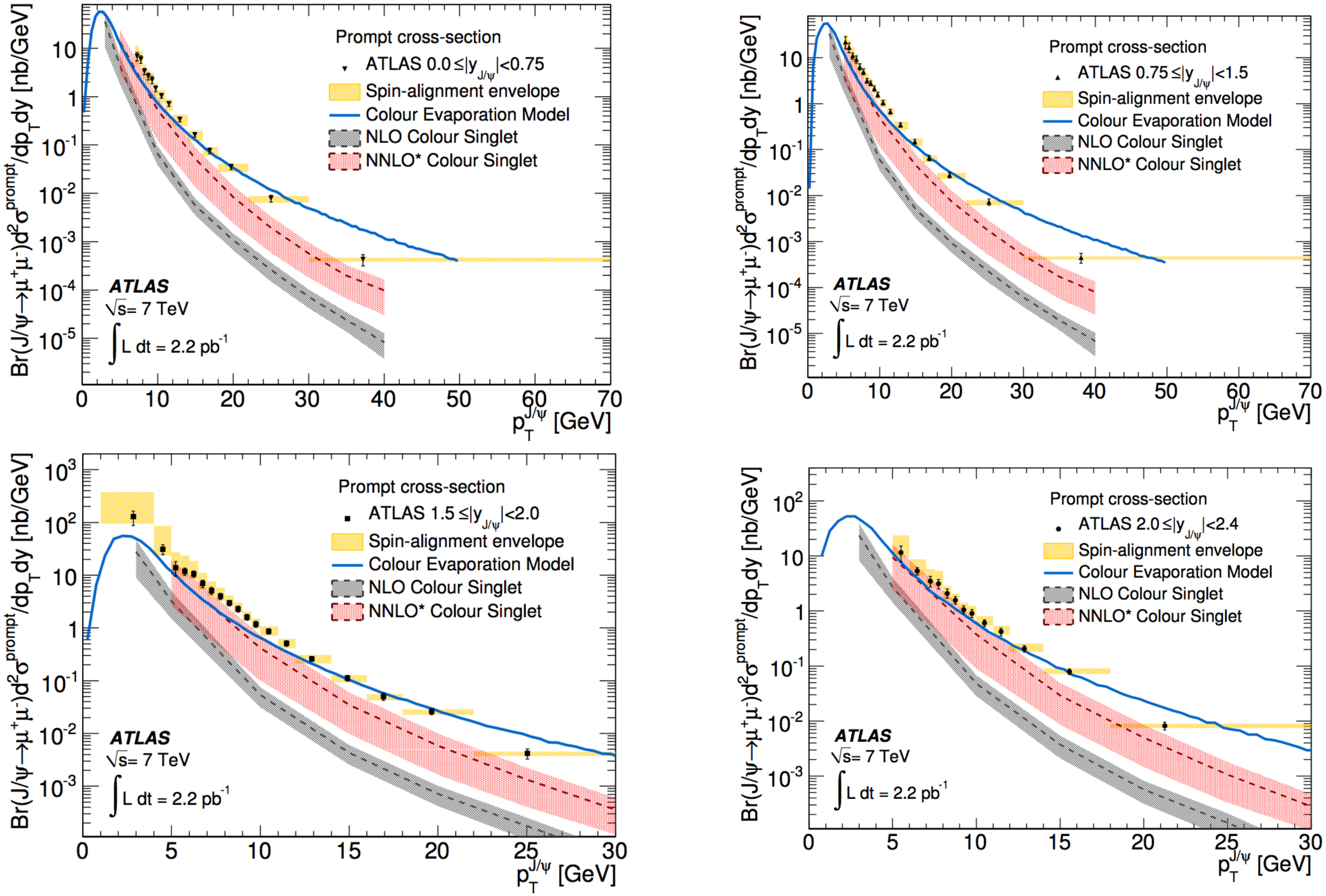
Nucl. Phys. B850, 387-444 (2011)
arXiv:1104.3038





Prompt cross-section

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



Comparisons include J/ψ feed-down from higher states

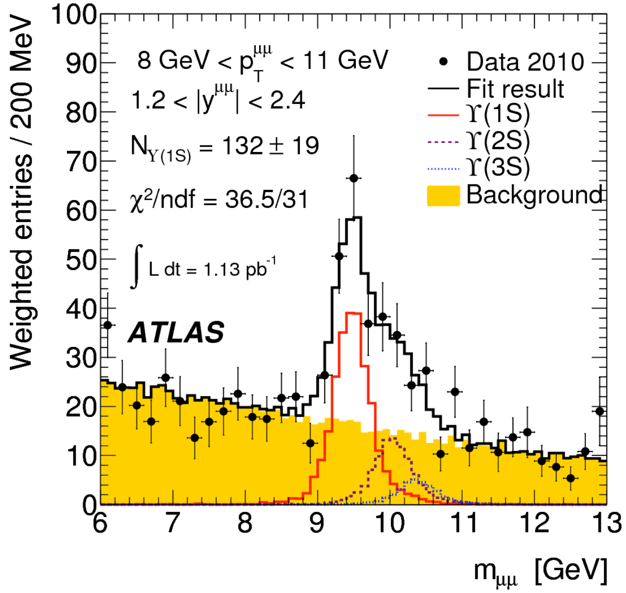
Theoretical predictions have issues to describe both shapes and normalization

Color Evaporation Model: Phys. Rept. 462 (2008) 125, Phys. Lett. B 91 (1980) 253

Color Singlet Model: Phys. Rev. D 81 (2010), Eur. Phys. J. C 61 (2009) 693

Upsilon fiducial cross-section

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

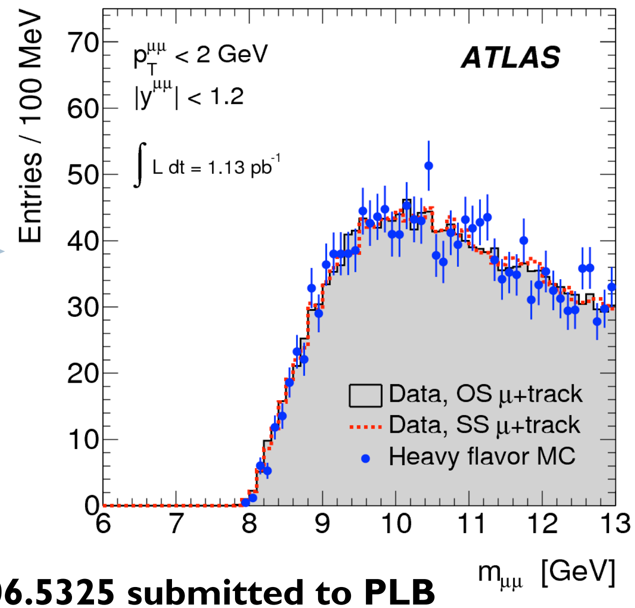


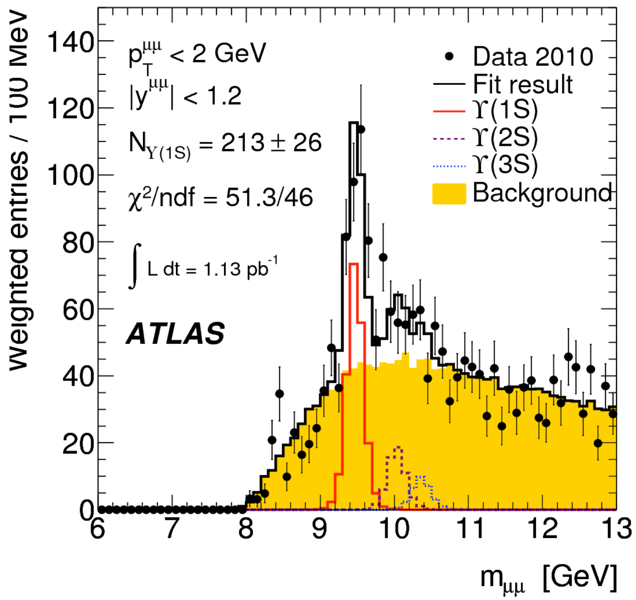
Similar procedure as for J/ψ for weight correction

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

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

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



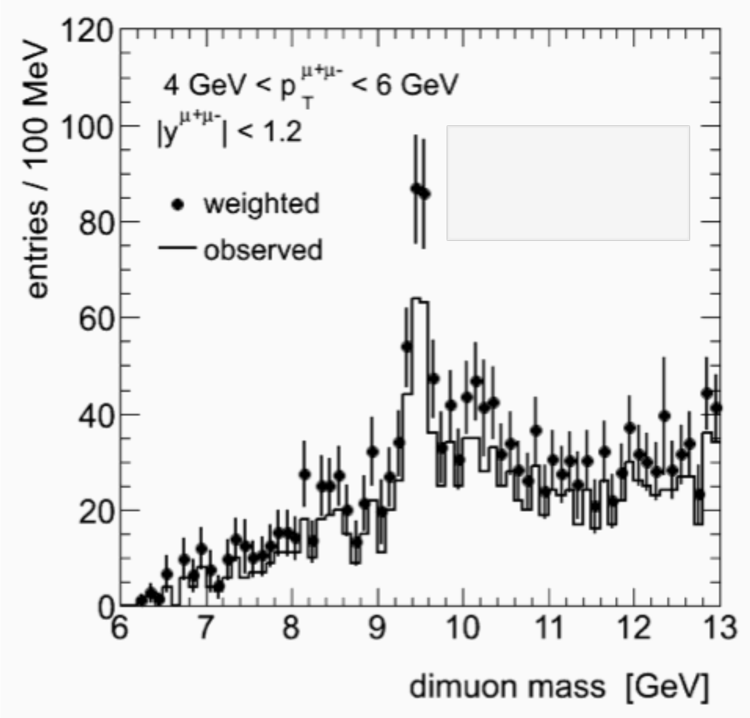


Use OS/SS μ+trk data and HF MC to model

arXiv:1106.5325 submitted to PLB

Upsilon cross-section

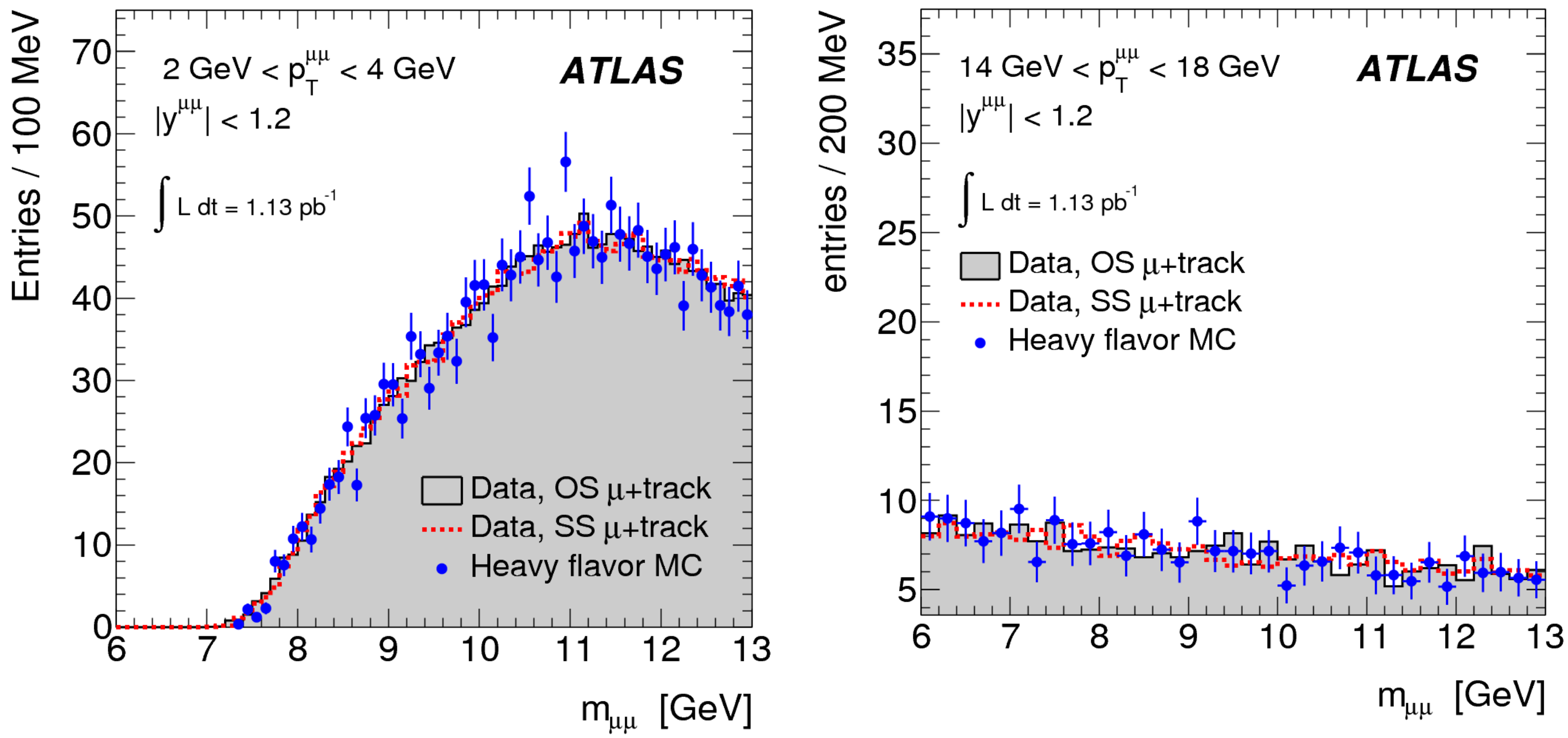
Measurement based on 1.13 pb^{-1} of data, using a **single muon** trigger



Every event is reweighted by the inverse of the event efficiency: $weight^{-1} = \varepsilon_{total} = \varepsilon_{trigger} \times \varepsilon_{muon\ reco} \times \varepsilon_{tracking}$

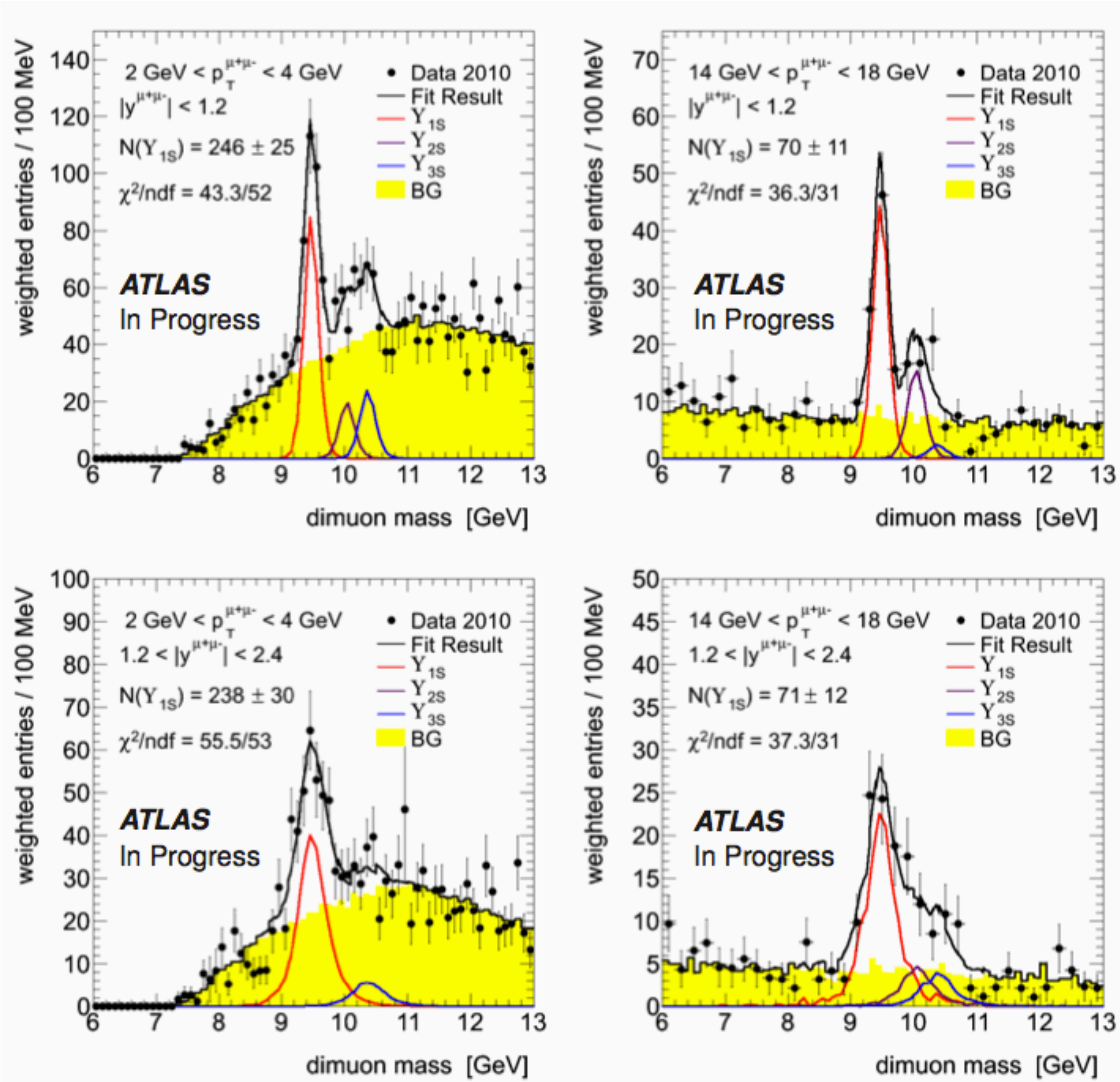
Efficiencies are derived from data-driven methods (e.g. J/ψ tag and probe)

Background modeling



- Muon pT cuts are only slightly less than $M_{\Upsilon(1S)}/2$
- BG is strongly sculpted and varies rapidly as a function of $\mu^+\mu^-$ mass
- We model the BG shape by selecting on
  - **opposite sign (OS) μ+track in data**
  - SS μ+track in data
  - $\mu^+\mu^-$ in heavy flavor MC

Upsilon cross-section: fit of di-muon invariant mass

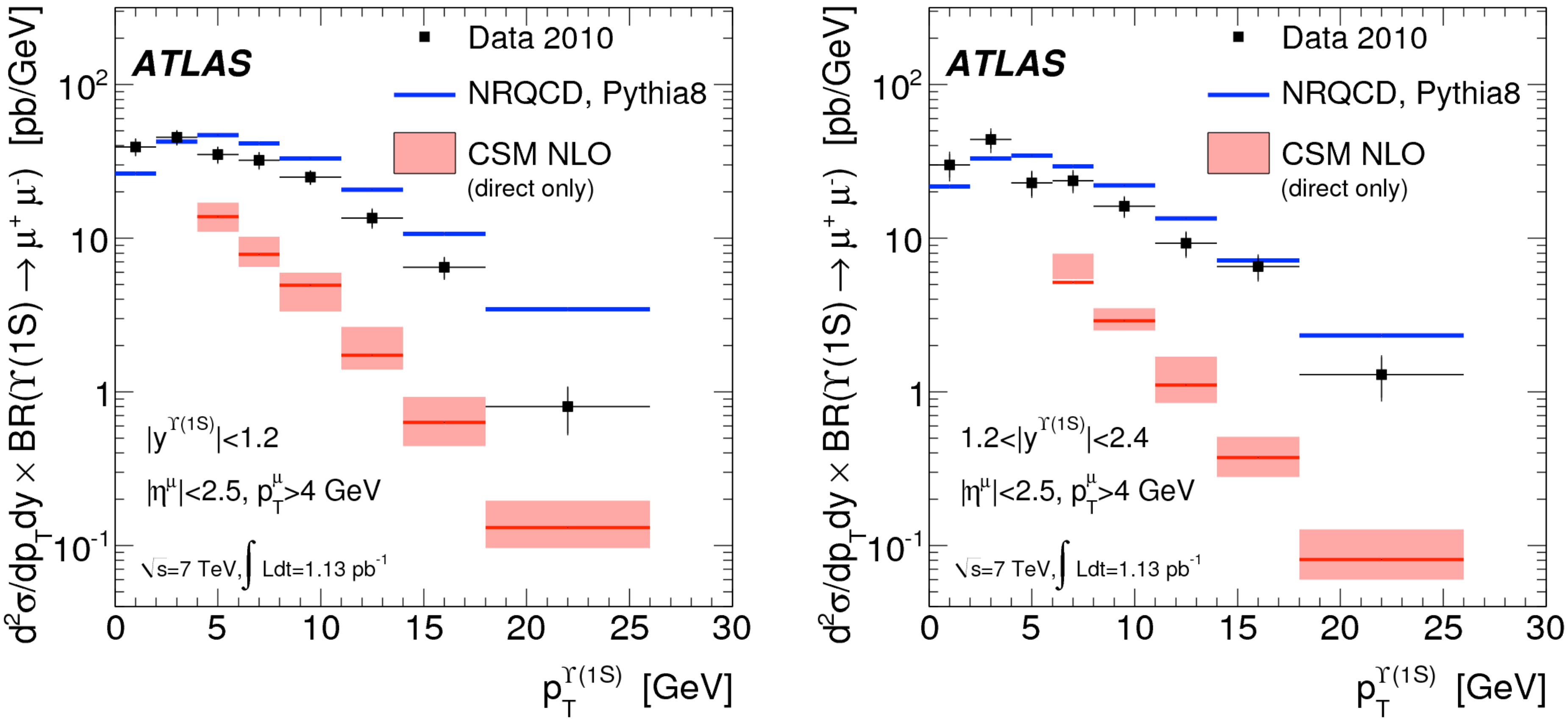


- Unbinned extended maximum likelihood fit for 4 parameters: N_{1S}, N_{2S}, N_{3S}, N_{BG}
- Background PDF from OS μ+track templates
- Signal PDF from simulation templates
- Resolution determined from studies of J/ψ and Z peaks as well as cosmics and fixed in fit.

Upsilon cross-section results

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!



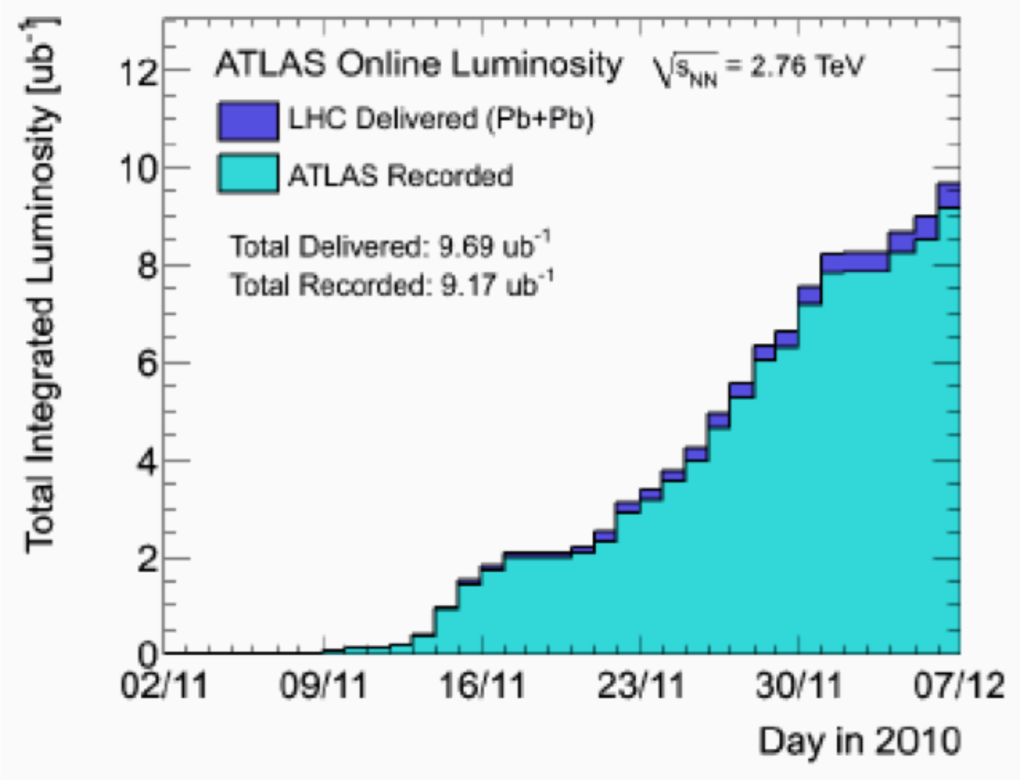
- Systematic uncertainties in central bins dominated by BG shape; 2-6%
- In forward bins, BG and signal shape uncertainties each about ~8%
- Upsilon(1,2,3S) fiducial/inclusive differential cross-sections coming soon…

The 2010 ATLAS Heavy Ions run

- **LHC 2010 Pb-Pb collisions**
  - Luminosity in Pb-Pb CollisionsCenter-of-mass energy: √s = 2.76 TeV per nucleon
  - 9.17 μb-1 of Pb-Pb data collected by ATLAS → data taking efficiency > 95%

- **Samples used**
  - Measurements use ~5 μb^{-1}
  - Trigger used: Minimum Bias Trigger Scintillators ~100% efficienct
  - MC sample: Pythia J/ψ (W, Z) p-p @2.76 TeV overlaid with Hijing MC

Luminosity integrated in 2010 by ATLAS for Pb-Pb collisions



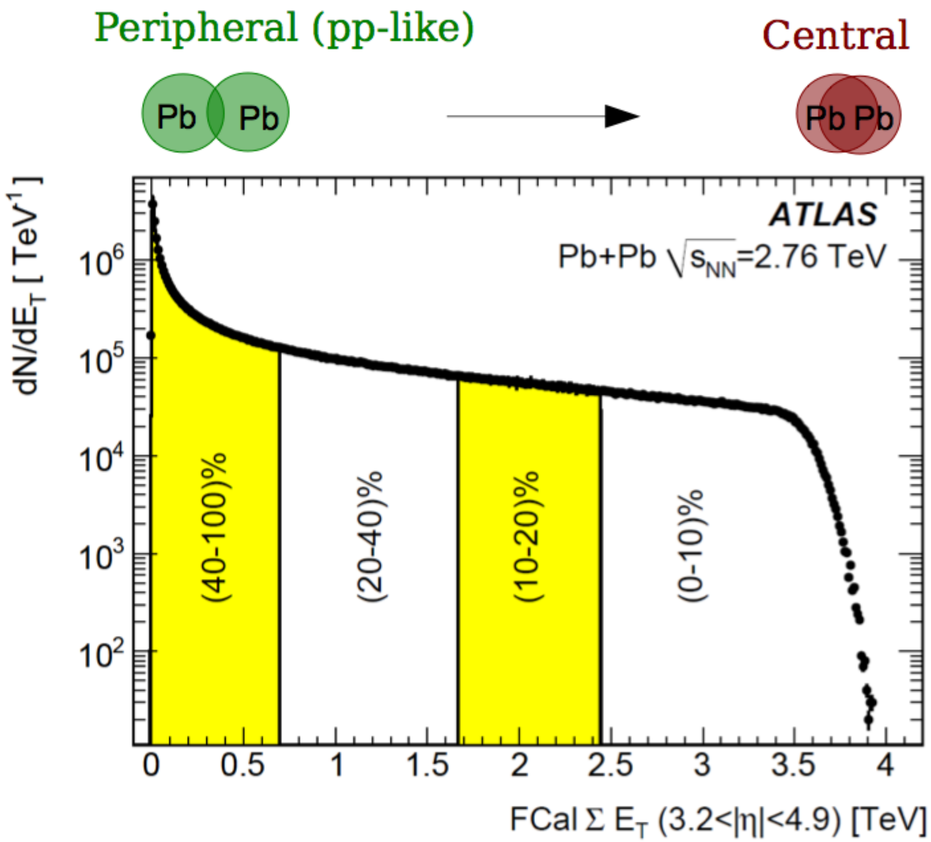
J/ψ (and Z, and W) in heavy ion collisions

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}

Centrality: characterized 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 in HI: analysis approach

centrality bin

most peripheral centrality bin

normalized mean number of binary collisions

$R_{coll} = N_{coll,c}/N_{coll,40-80}$

$$R_c = \frac{N_c^{corr}(J/\Psi \to \mu^+\mu^-)}{N_{40-80\%}^{corr}(J/\Psi \to \mu^+\mu^-) \cdot R_{coll}}$$

$N_c^{corr} = N_c^{meas}/(\varepsilon(J/\psi)_c \times W_c)$

reconstruction efficiency

centrality bin width

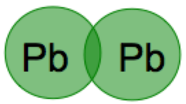
- No attempt to compare with p-p results
- Normalization on most peripheral bin

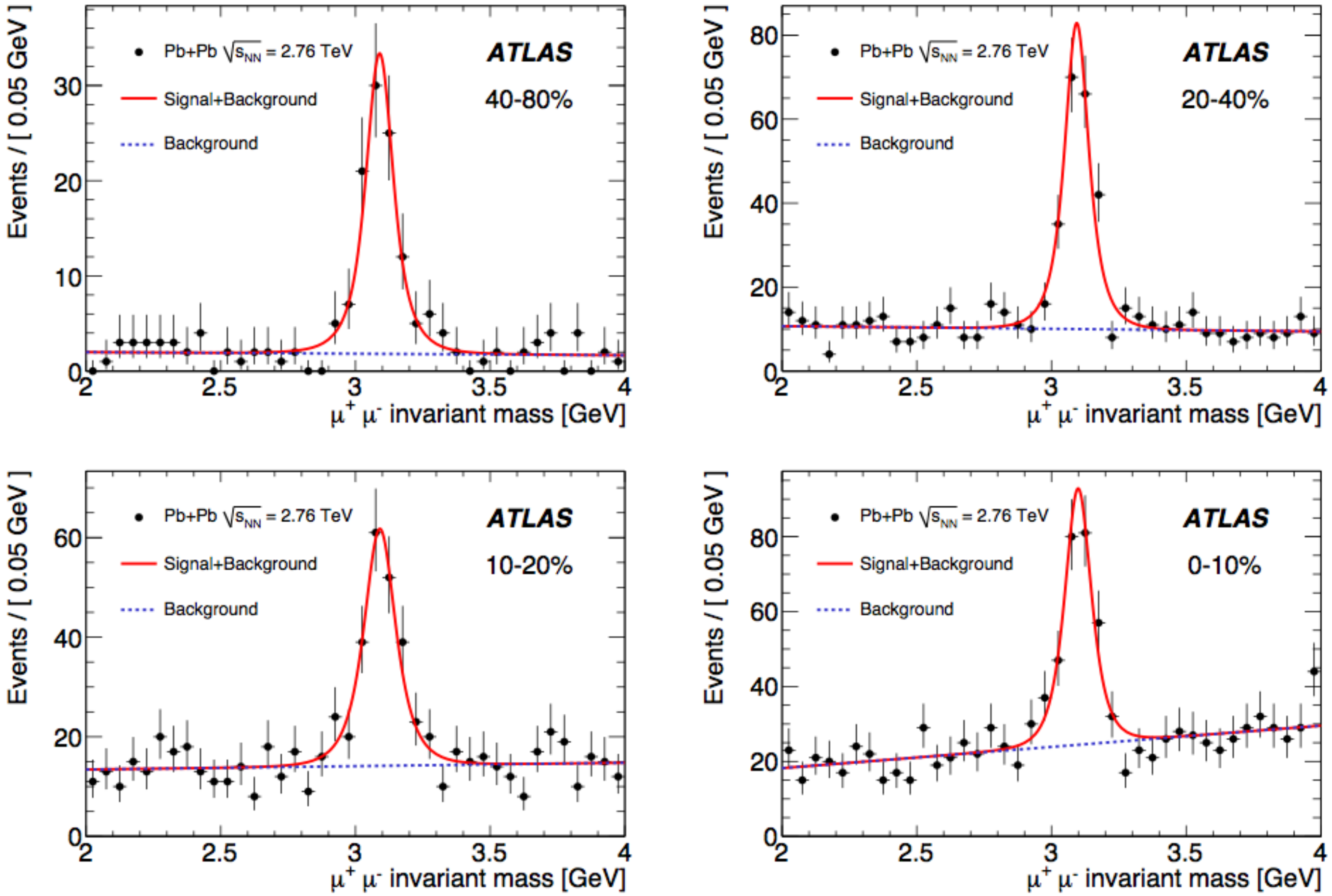
J/ψ reconstruction in heavy ions

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

Systematics: efficiency vs centrality

- Trigger+reconstruction efficiency ε= 98%
- Small centrality dependence for Combined Muons
  - ~3-4% drop from inner detector tracks reconstruction
  - As expected: central events have higher occupancy in the ID but not in the muon chambers
- We use this efficiency variation to correct our raw yield

Efficiency correction in centrality bins:

- 0-10%: 0.93 ± 0.01
- 10-20%: 0.91 ± 0.02
- 20-40%: 0.97 ± 0.01
- 40-80%: 1

→ all normalized on peripheral bin

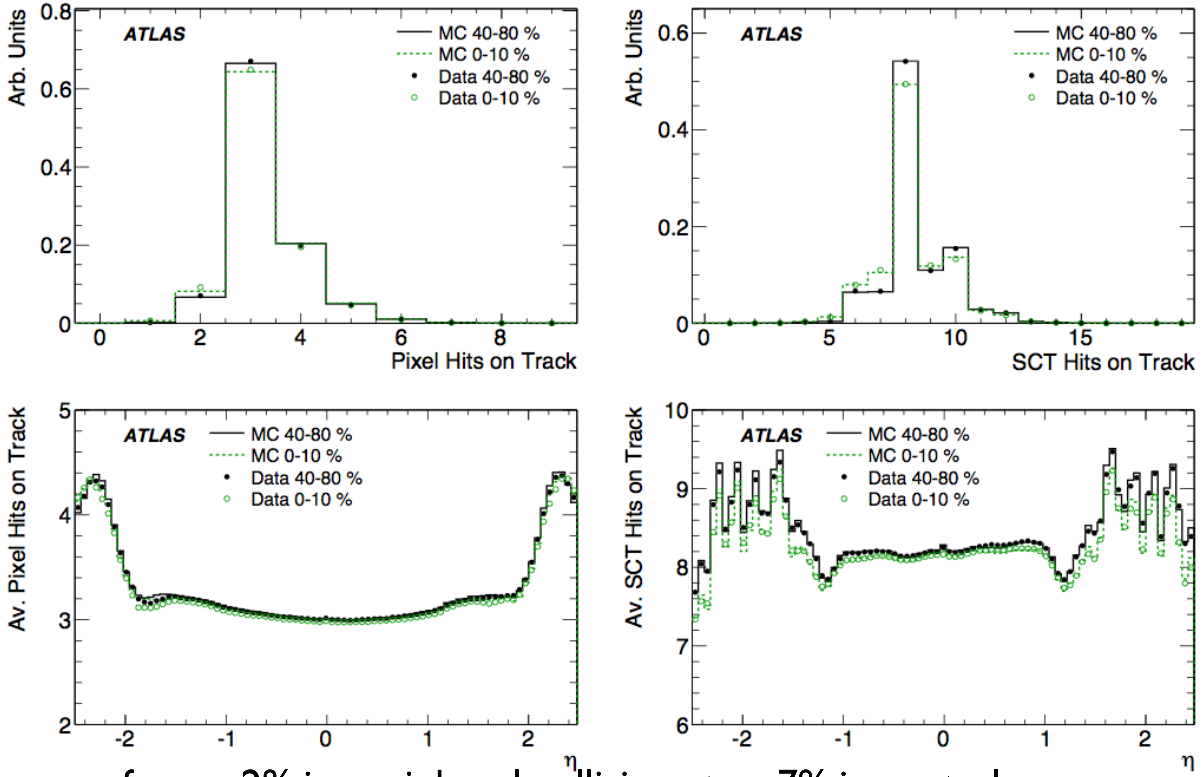
Systematics: MC reliability

Largest efficiency dependence on centrality comes from ID occupancy effects

Systematic effects studied comparing basic track quantities in MC and data versus centrality bins

Fraction of tracks with :

- less than 2 hits in Pixel detector,
- less than 6 hits in Semi-Conductor Tracker (SCT),
- with hole in SCT,
- with hole in innermost Pixel layer

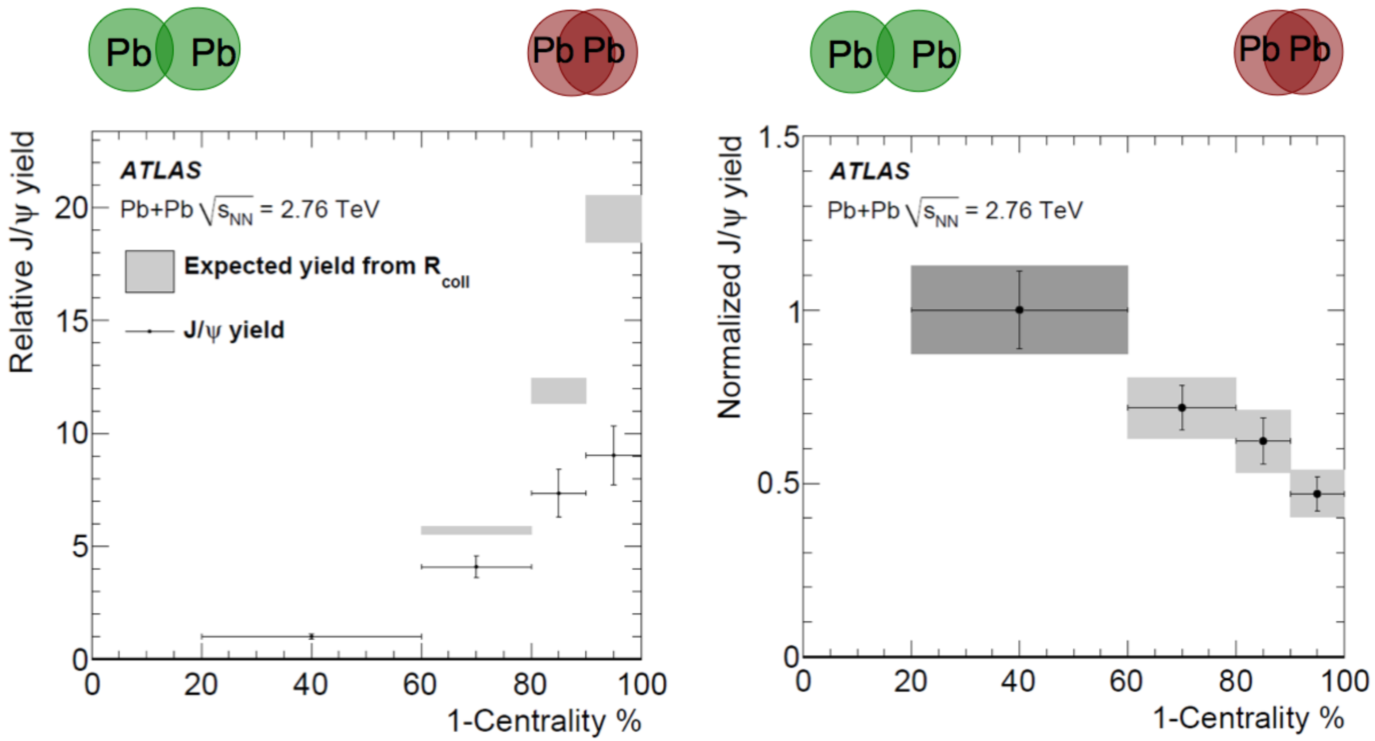


Uncertainty ranges from ~2% in peripheral collisions to ~7% in central

arXiv:1012.5419 [hep-ex]
Phys. Lett. B697:294 (2011)

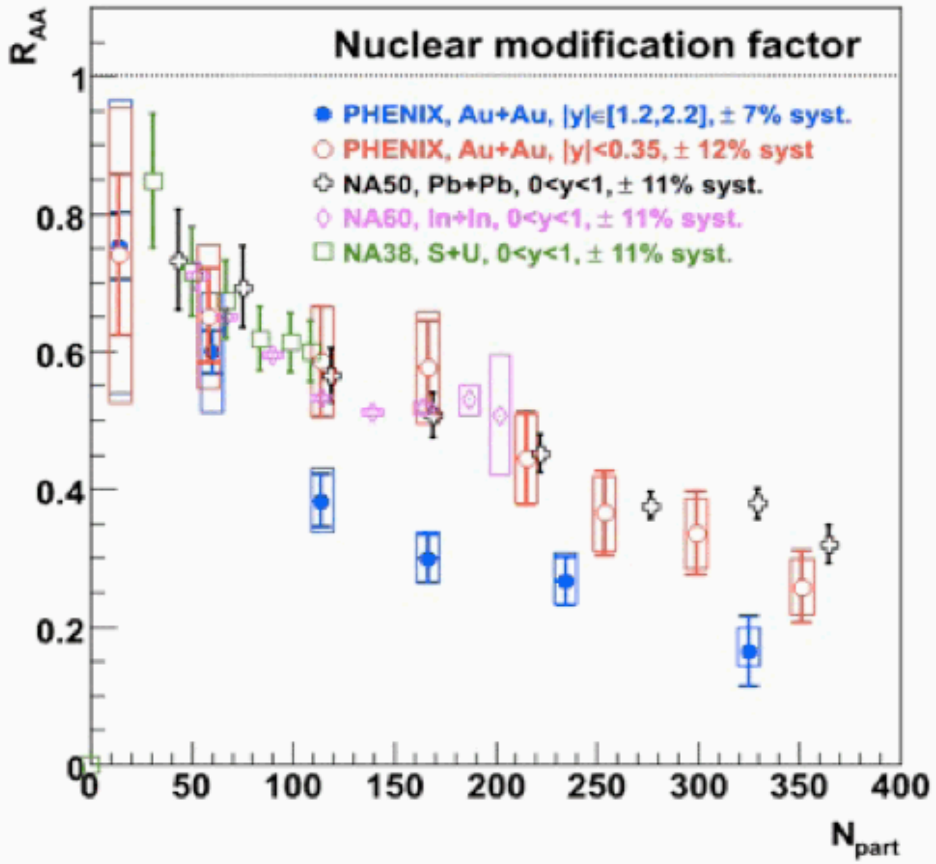
J/ψ suppression

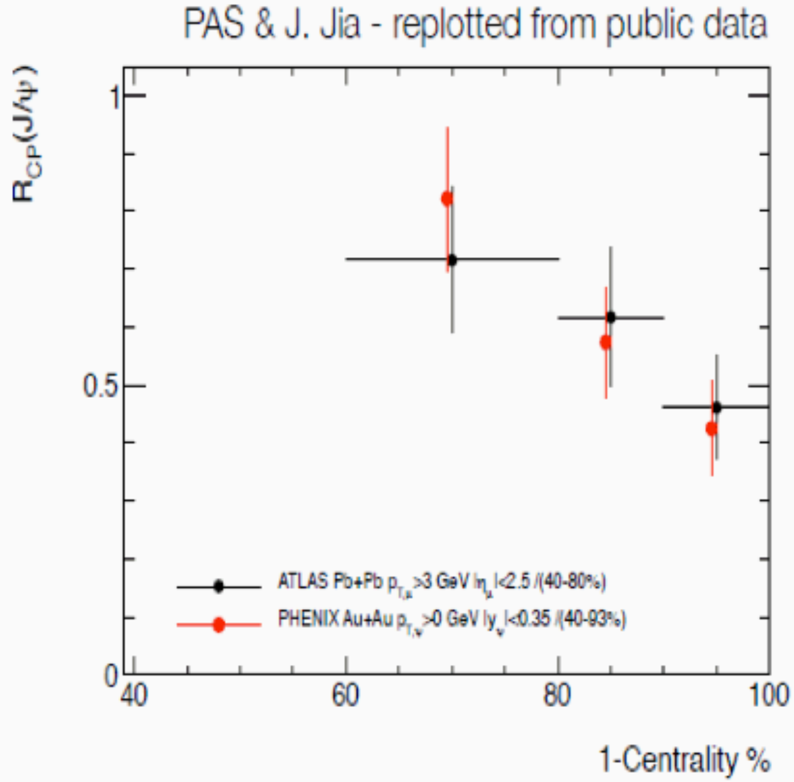
Experimental acceptance: p_T>3 GeV, |η|<2.5 [includes both prompt/non-prompt J/ψ]



- Significant decrease of the ratio is observed as a function of centrality
- Qualitatively same effect as the one seen by NA50 and PHENIX at very different center-of-mass energies
- Main systematics: J/ψ reconstruction efficiency ~2.3-6.8%, signal extraction ~5.2-6.8%, Rcoll estimate ~3.2-5.3%

Comparison with RHIC





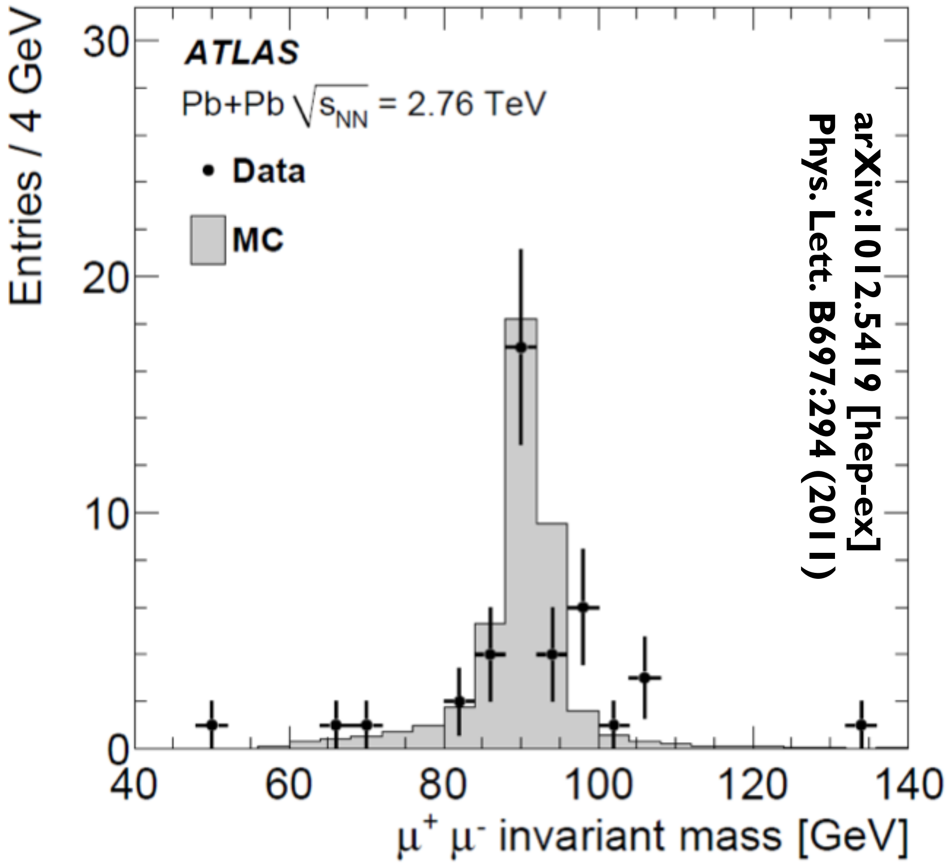
Attempt to replot PHENIX data vs Centrality [P.Steinberg, J.Jia] suggests suppression is energy-independent

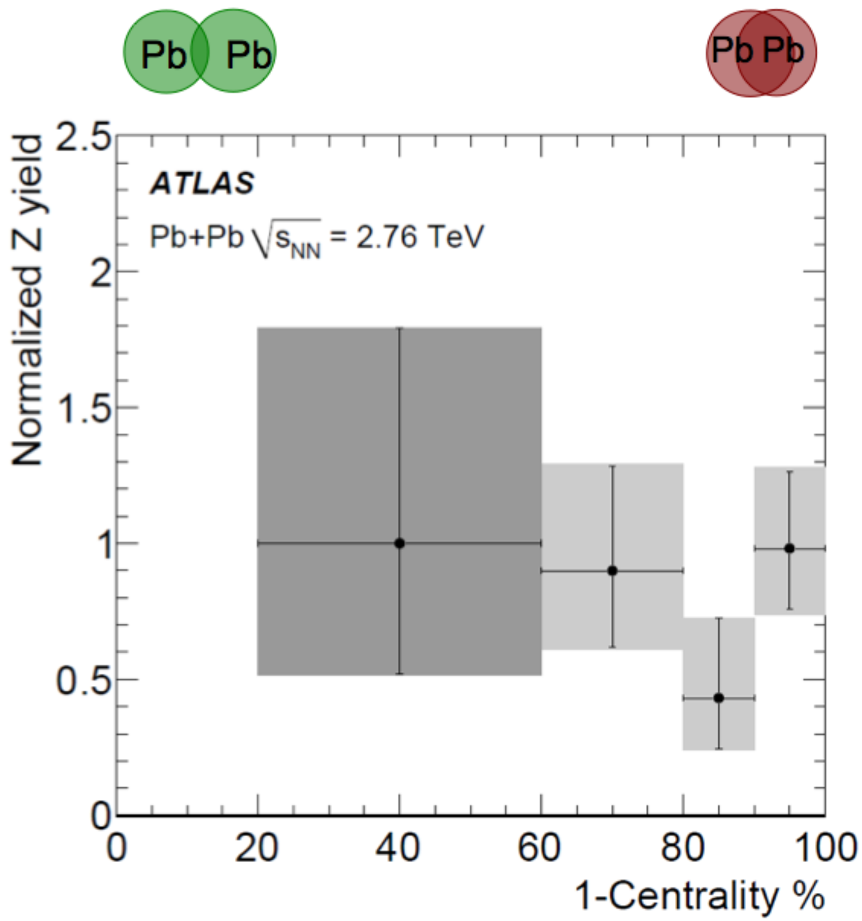
R_{CP} analysis: Z → μμ

Analysis repeated with Z→μμ 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





Have presented a variety of measurements from ATLAS in pp/PbPb:

Quarkonia and heavy flavour production in pp collisions @ 7 TeV

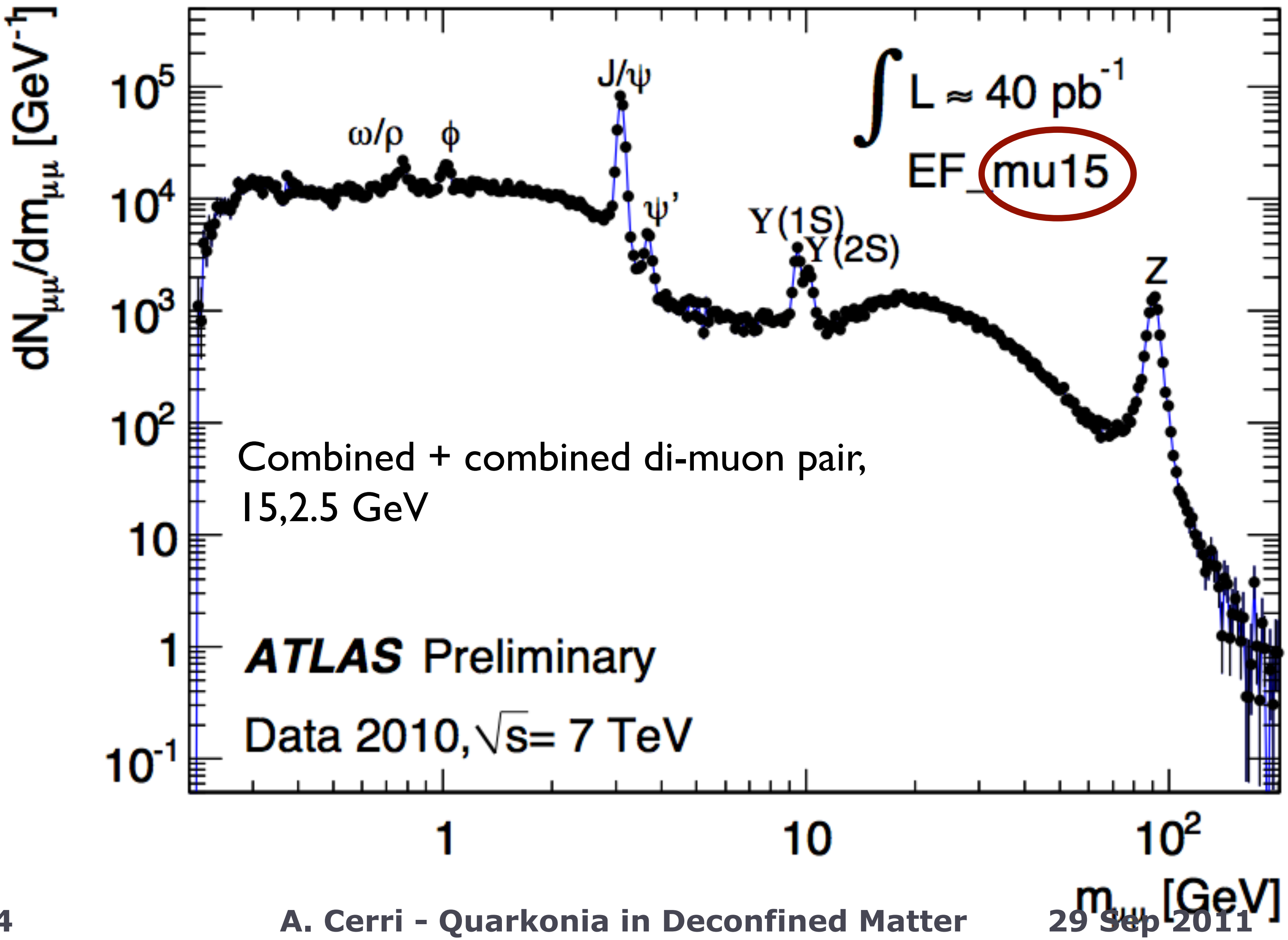
- Prompt quarkonia continue to provoke questions in pp collisions
  - and how does effect of spin-alignment impact PbPb results?
- Non-prompt J/ψ in good agreement with FONLL, within scale uncertainties
- Have 2.76 TeV pp results for various observables as benchmarks for PbPb runs

Studies of suppression of J/ψ, Z in PbPb collisions @ 2.76 TeV/nucleon

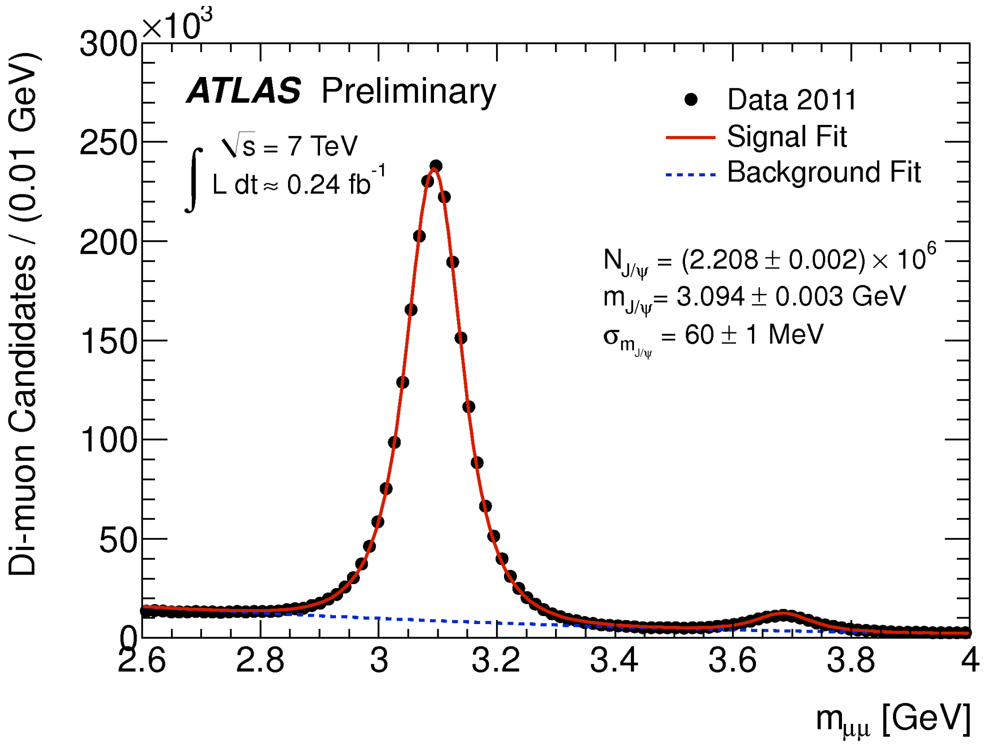
- We observe an anomalous suppression of the J/ψ yield that increases with centrality
- Centrality suppression is consistent with PHENIX Au+Au collision

Expect many more results in quarkonia/electroweak results in pp/PbPb from ATLAS in the near future!

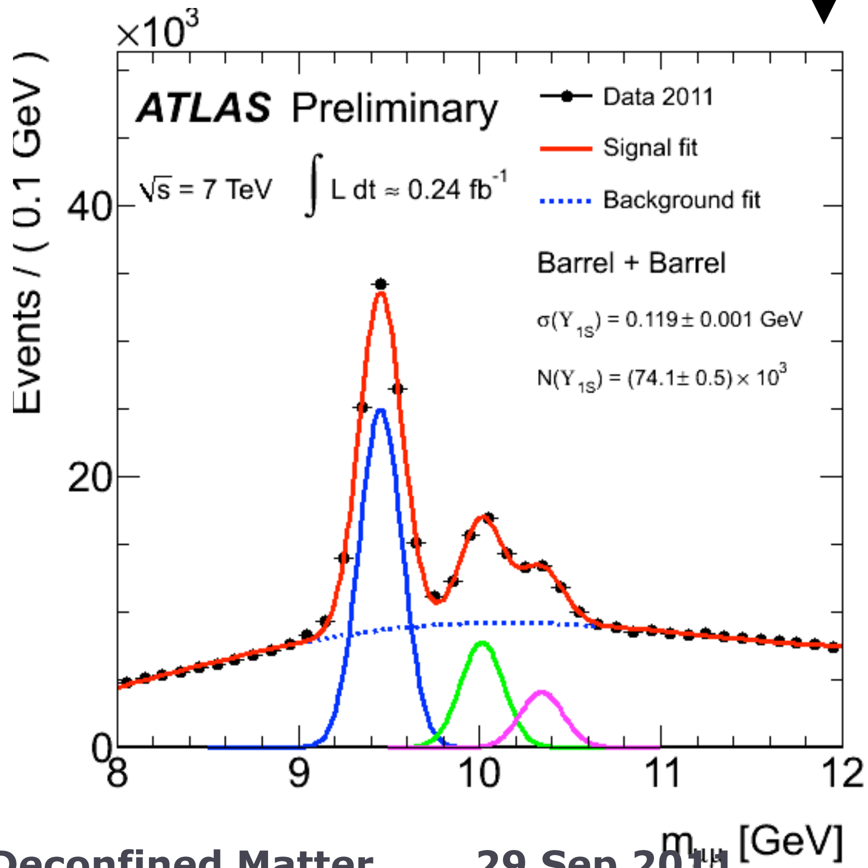
Additional slides



$dN_{\mu\mu}/dm_{\mu\mu}$ [GeV^{-1}]
$\int L \approx 40\ pb^{-1}$
EF_mu15
J/ψ
ω/ρ
φ
ψ'
Υ(1S)
Υ(2S)
Z
Combined + combined di-muon pair,
15,2.5 GeV
ATLAS Preliminary
Data 2010, $\sqrt{s}$= 7 TeV
$m_{\mu\mu}$ [GeV]



Muons in *barrel* (|η|<1.05) only



At least one combined muon in muon pair

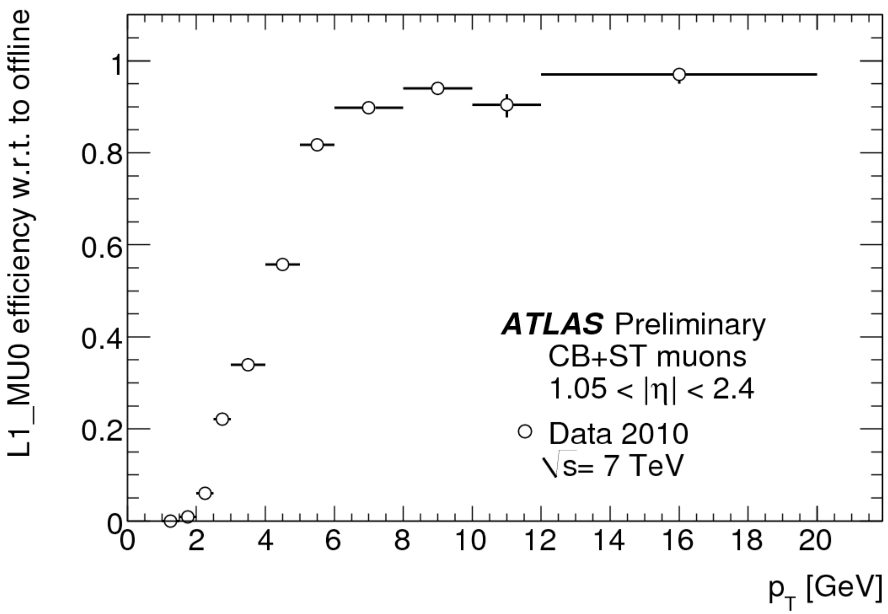
J/ψ: 4, 2.5 GeV muon p_T thresholds
U(nS): 4, 4 GeV muon p_T thresholds

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

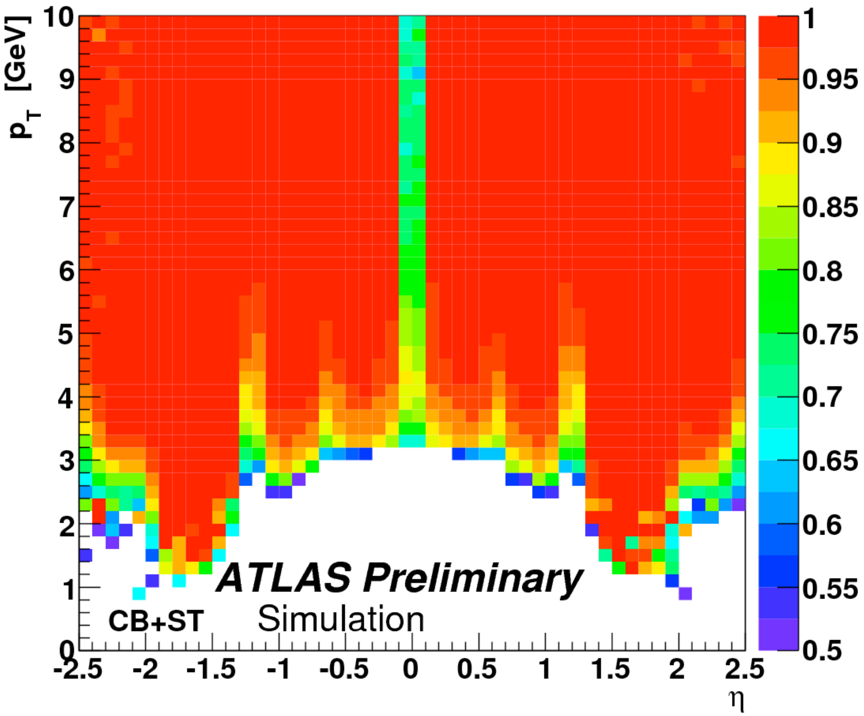
$$\mathcal{E}_{\text{trig}} = 1 - \left(1 - \mathcal{E}^{+}_{\text{trig}}(p_T^{+}, \eta^{+})\right) \cdot \left(1 - \mathcal{E}^{-}_{\text{trig}}(p_T^{-}, \eta^{-})\right)$$

- 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)

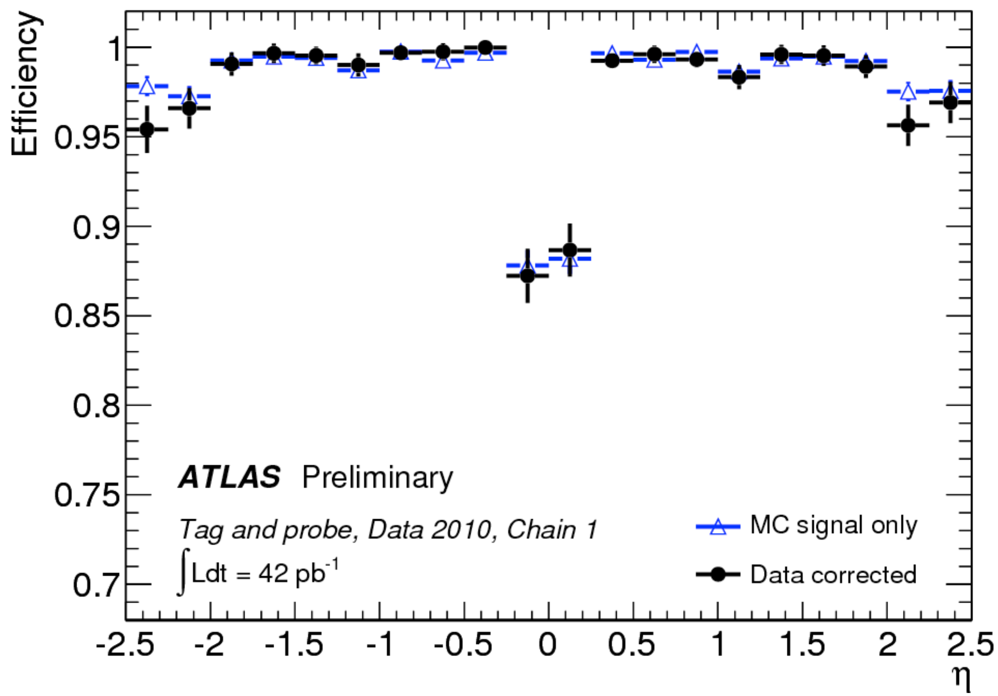
Efficiencies plateau at around 80-100% *dependent on pseudorapidity*



Reconstruction efficiency maps derived from Tag & Probe data from J/ψ supported by $Z \to \mu\mu$ derived data at higher p_T for improved precision in plateau region: exclude areas of low efficiency (<20%)

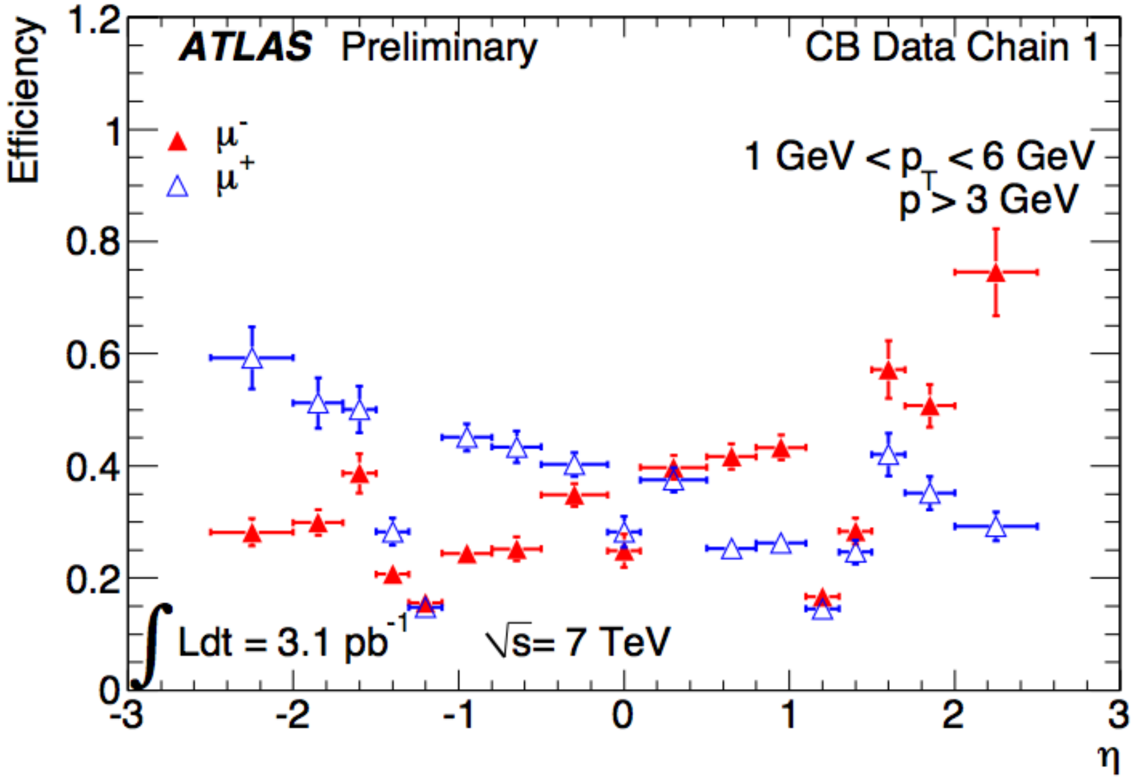


Reconstruction efficiency for low p_T from J/ψ decays (MC)



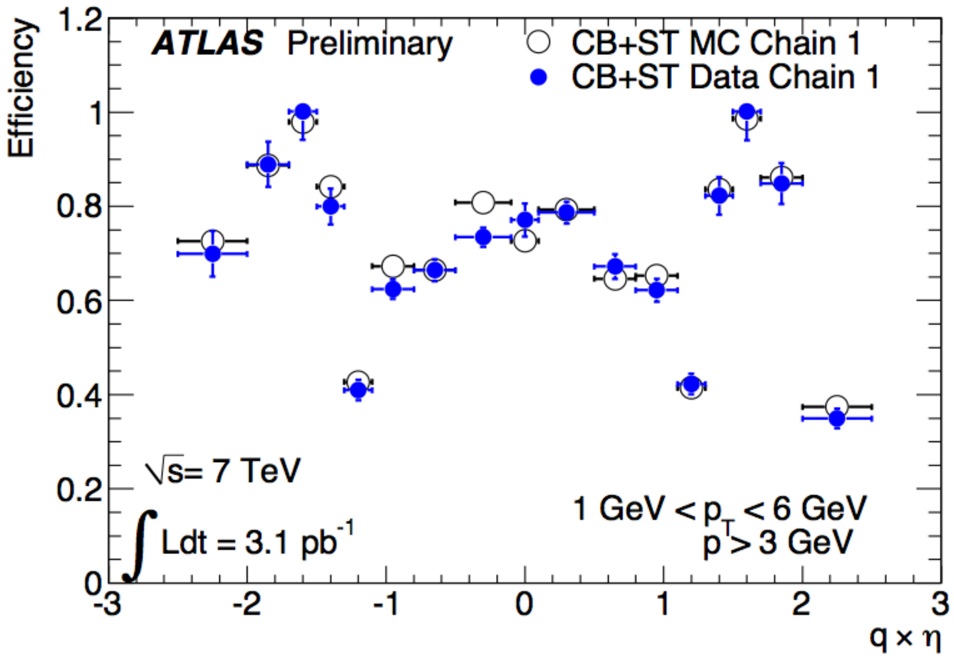
Reconstruction efficiency at high p_T from $Z \to \mu\mu$ data

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

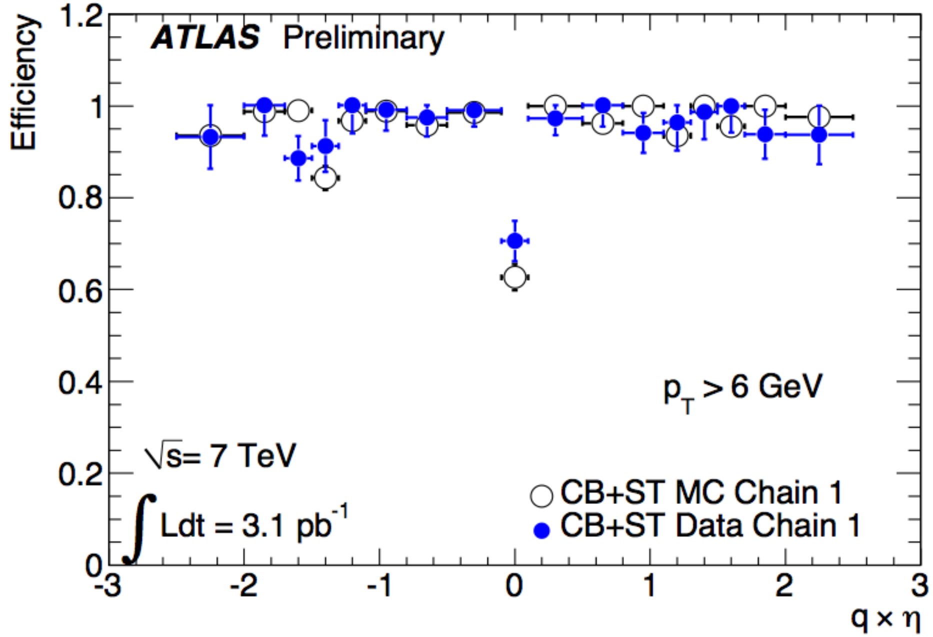


Introduces a charge dependence of the muon reconstruction/trigger efficiencies, particularly relevant at very large $|\eta|$, where muons of one charge may be bent outside the detector geometrical acceptance, and at low p_T, where muons of one charge may be bent back before reaching spectrometer stations

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



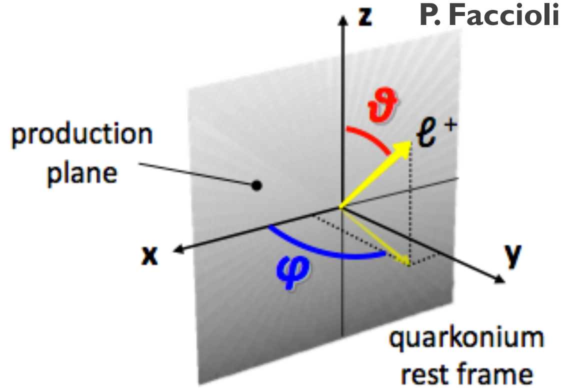
Low p_T



High p_T

We know acceptance can vary with spin-alignment

State has generalised angular decay distribution:



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

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

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

Before measure spin-alignment, we work with five specific working points that provide a maximal envelope for expectation →

FLAT (unphysical, but default in Pythia MC)

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

TRPM

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

LONG

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

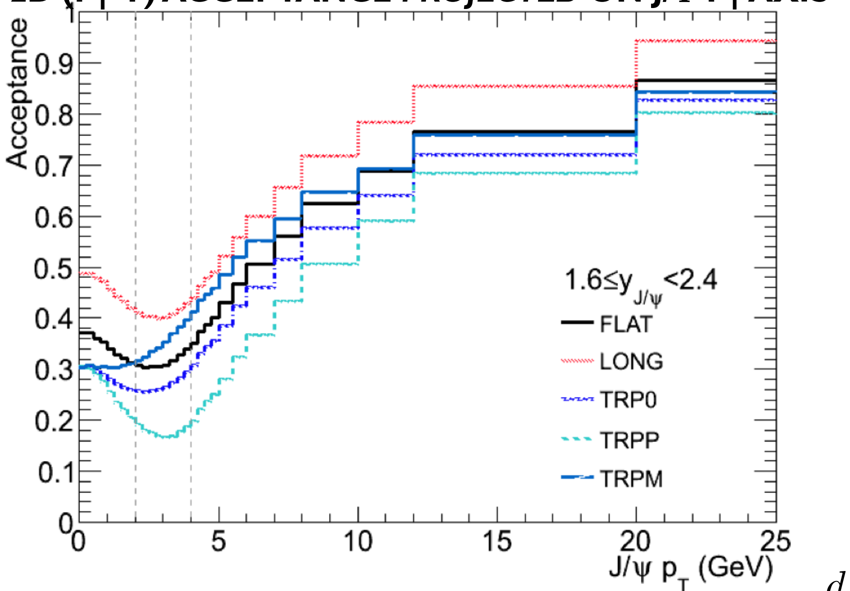
TRP0

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

TRPP

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

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



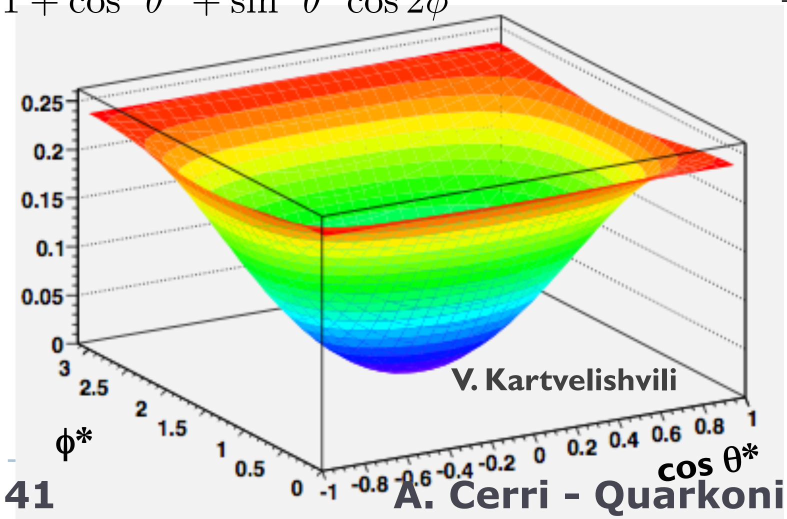
Acceptance in azimuthal angle dependent on angle between J/ψ production and decay plane

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!

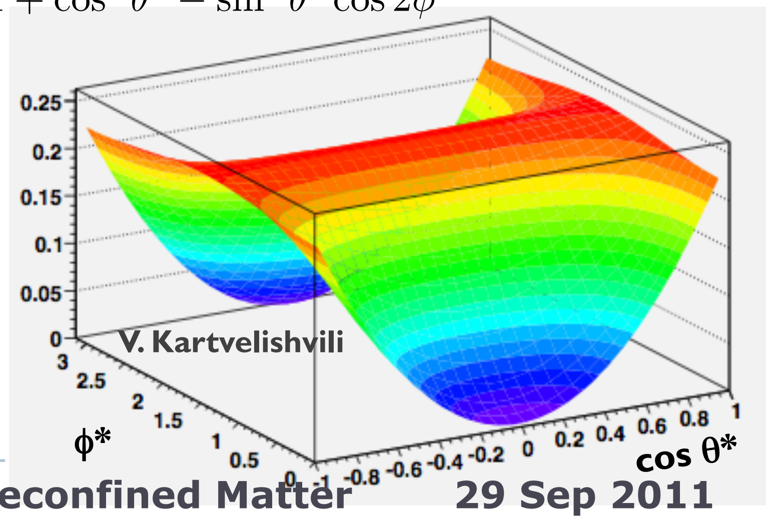
$$\frac{dN}{d\Omega} = 1 + \cos^2\theta^\star + \sin^2\theta^\star \cos 2\phi^\star$$

TRPP



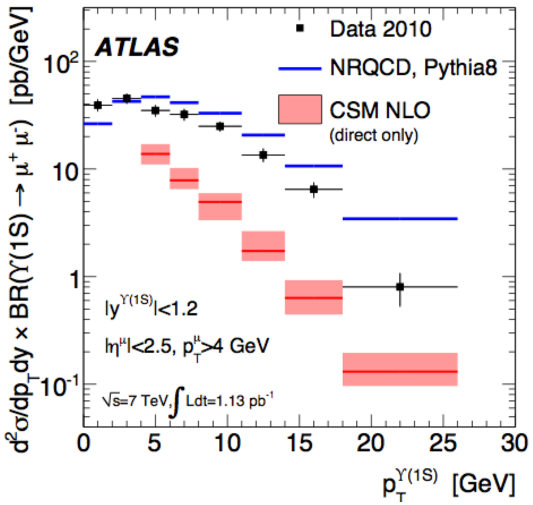
$$\frac{dN}{d\Omega} = 1 + \cos^2\theta^\star - \sin^2\theta^\star \cos 2\phi^\star$$

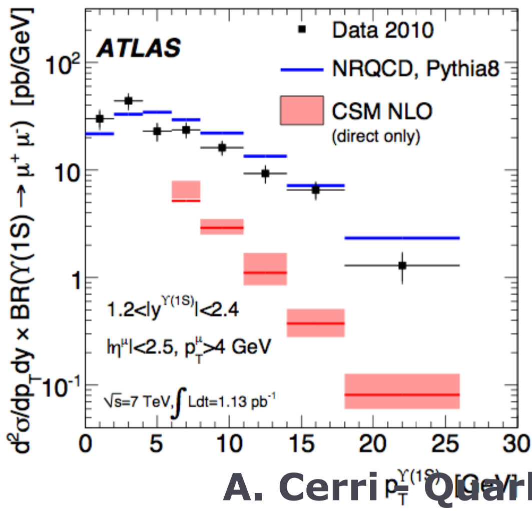
TRPM



Upsilon cross-section reported within fiducial cuts on muons of p_T>4 GeV, $|\eta|$<2.5, in two bins of Upsilon rapidity and eight bins of p_T

arXiv:1106.5325 submitted to PLB





$p_T^{\Upsilon(1S)}$ (GeV)	$N_{\Upsilon(1S)}$	$d^2\sigma/dp_T dy$ (pb/GeV)	δ_{stat} (%)	δ_{syst} (%)	δ_{tot} (%)
		$|y^{\Upsilon(1S)}| < 1.2$			
0 – 2	213	39.3	12	6	13
2 – 4	246	45.4	10	5	11
4 – 6	190	35.0	12	5	13
6 – 8	175	32.2	12	6	13
8 – 11	203	24.9	10	4	11
11 – 14	110	13.6	13	7	15
14 – 18	70	6.5	15	7	17
18 – 26	17	0.8	33	9	34
		$1.2 < |y^{\Upsilon(1S)}| < 2.4$			
0 – 2	163	30.0	17	13	22
2 – 4	238	43.8	13	13	18
4 – 6	124	22.9	18	9	20
6 – 8	129	23.7	15	9	17
8 – 11	132	16.2	14	7	16
11 – 14	75	9.3	18	9	20
14 – 18	71	6.5	17	10	20
18 – 26	28	1.3	29	15	33

The decay $D^{*\pm} \rightarrow D^0 \pi^\pm_s$ relies on ID track reconstruction and vertexing of the $D^0 \rightarrow K^- \pi^+$

Uses MBTS trigger > 99.5% efficient; track multiplicity independent

Combine two oppositely-charged tracks assign K/π mass hypothesis to each, and

$p_T(K,\pi) > 1.0$ GeV

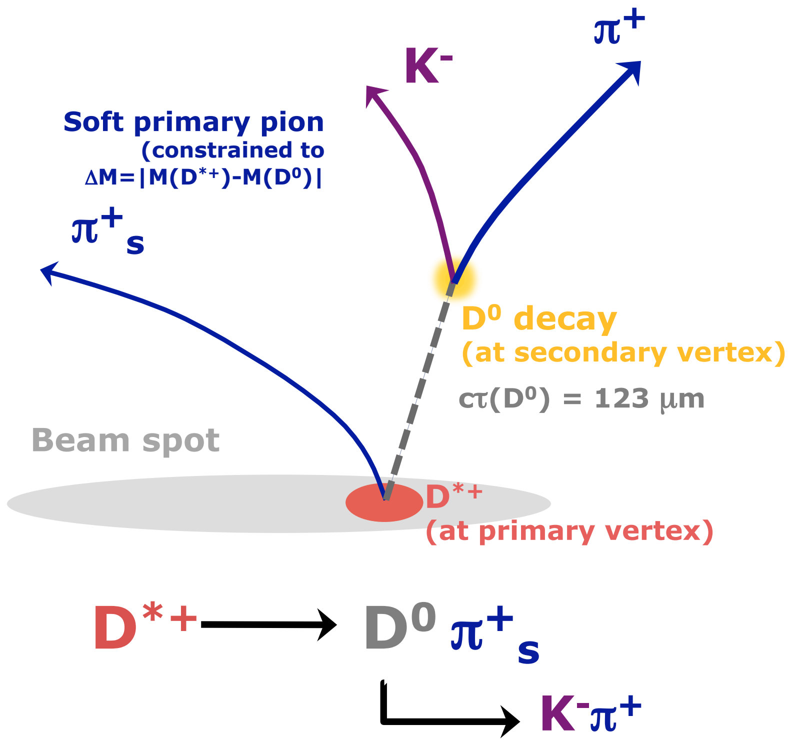
Third (soft) track added with pion mass, and

$p_T(\pi) > 0.25$ GeV

Build D^0 signal from $M(K\pi)$ for $D^{*\pm}$ candidates

Additional discrimination from mass difference $\Delta M = M(K\pi\pi_s) - M(K\pi)$

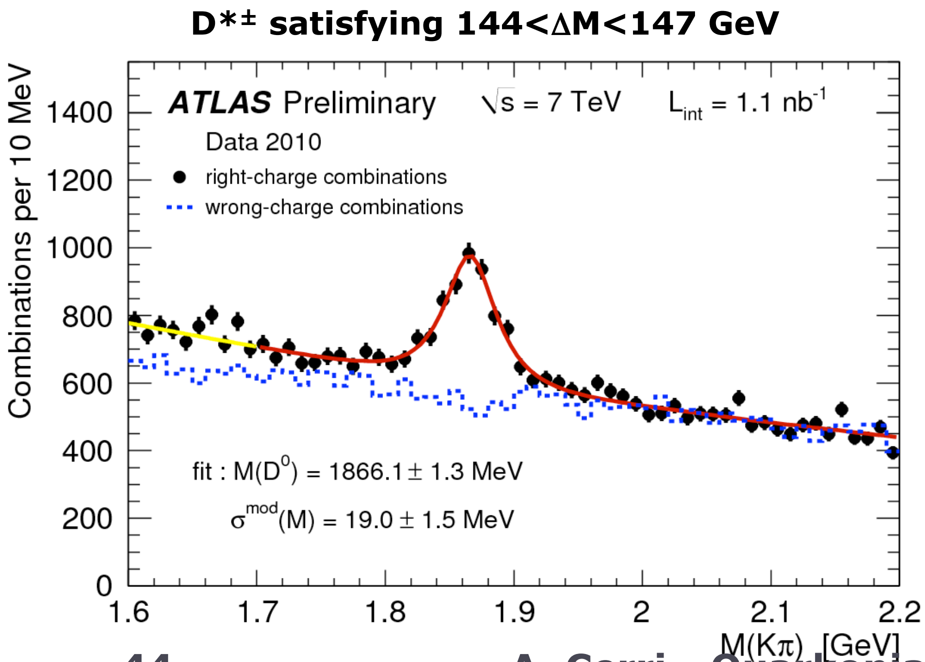
Use presence of secondary vertex and properties of hard process to guide cut selection to enhance signal

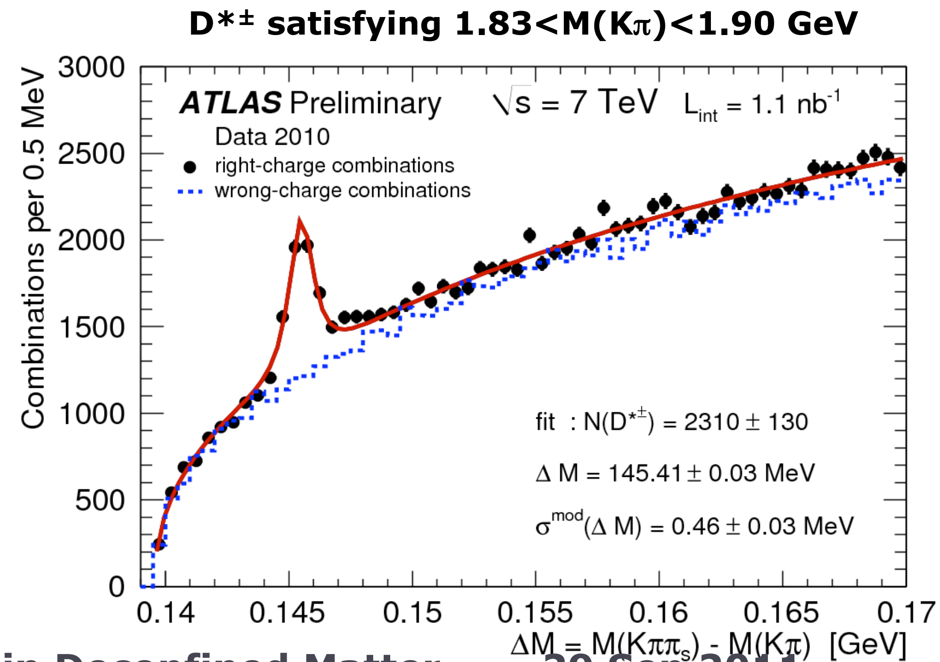


Approx. 2000 $D^{*\pm}$ in both M and ΔM peaks
Mass of D^0 compatible with PDG value

Not corrected for efficiency or detector effects

Secondary vertex fit χ^2<5
Transverse decay length>0 mm
$p_T(D^*)/\Sigma E_T$>0.02
$p_T(D^*)$>3.5 GeV, $p_T(K,\pi)$>1.0 GeV
$|\eta(D^*)|$<2.1





Similar strategy to D*:

combine two oppositely charged tracks, assign pion mass, **$p_T(\pi_1)>1.0$ GeV, $p_T(\pi_2)>0.8$ GeV**

Combine with third track with kaon mass

$p_T(K)>1.0$ GeV

Combinatorial background reduced with cut on angle between kaon in D^+ rest frame and D^+ momentum direction in lab frame

Suppression of D^{*+}:

require $M(K\pi\pi)-M(K\pi)>150$ MeV

Suppression of $D^+_s \rightarrow \phi(K^+K^-)\pi^+$:

require $|M(K^+K^-)-M(\phi)_{PDG}|>8$ MeV

~1550 candidates seen in clear peak

Mass in good agreement with PDG

Secondary vertex fit $\chi^2<6$

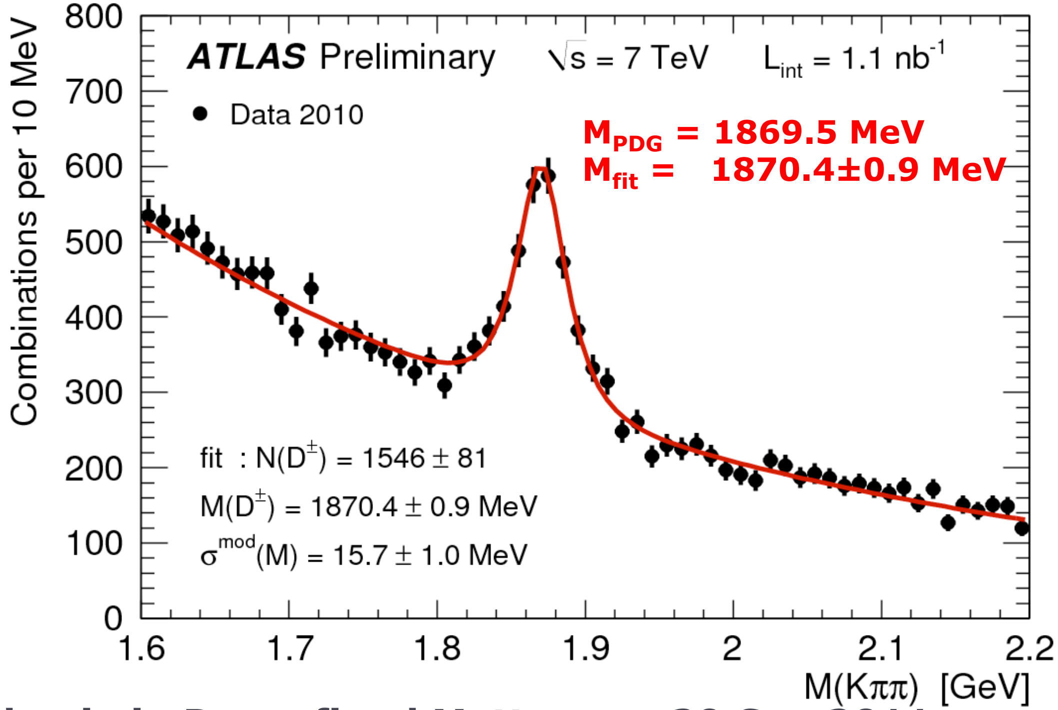
Transverse decay length>1.3 mm

$p_T(D+)/\Sigma E_T>0.02$

$p_T(D+)>3.5$ GeV

$|\eta(D+)|<2.1$

$\cos\theta^*(K)>-0.8$



$D^{\pm}_s \longrightarrow \phi\, \pi^+$

$\phi \longrightarrow K^+K^-$

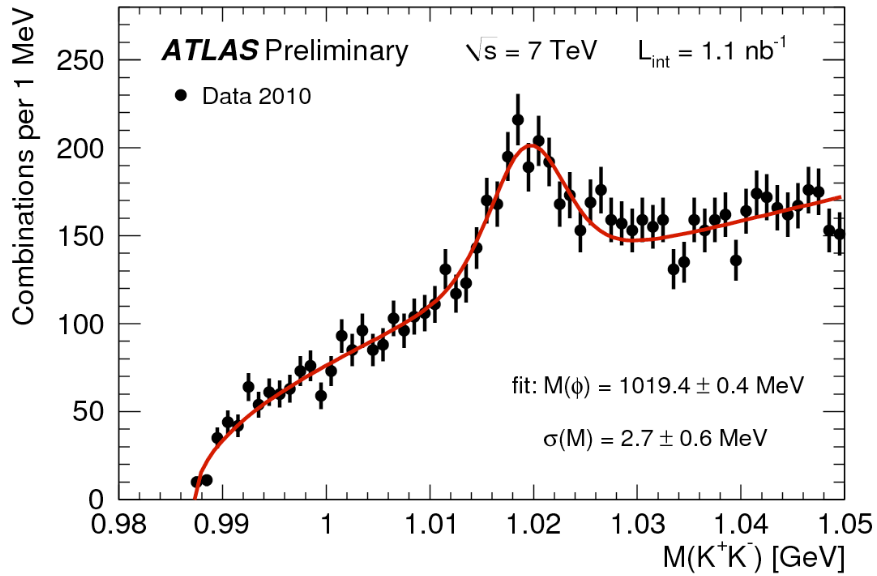
Secondary vertex fit χ^2<6
Transverse decay length>0.4 mm
$p_T(D^+_s)/\Sigma E_T$>0.04
$p_T(D^+_s)$>3.5 GeV
$|\eta(D^+_s)|$<2.1
$\cos\theta^*(\pi)$<0.4, $|\cos^3\theta'(K)|$>0.2

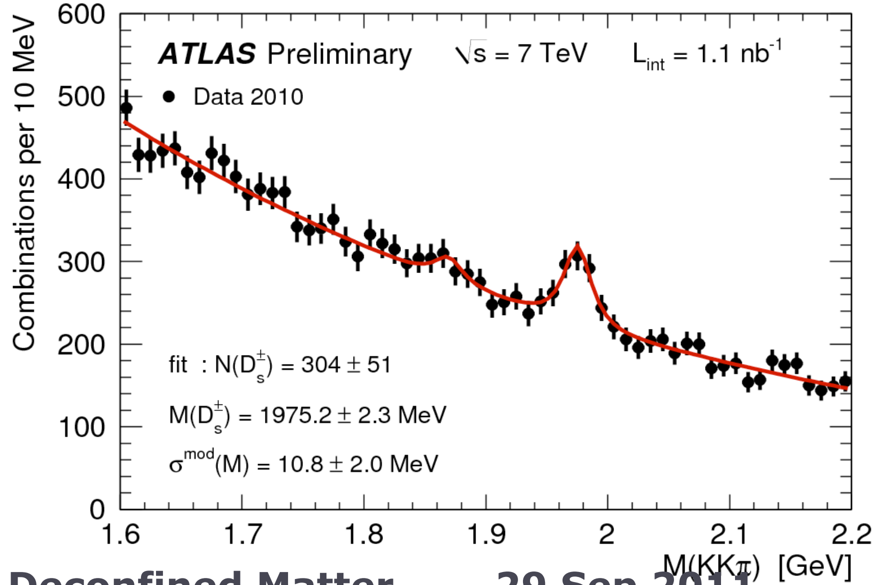
Again combine two oppositely charged tracks, assign kaon mass, **$p_T(K)$>0.7 GeV**

Consider good ϕ candidate if
$|M(KK)|$<6 MeV of PDG ϕ mass
ϕ peak clearly visible on M(KK) plot

Combine with third track (π hypothesis)
$p_T(\pi)$>0.8 GeV

326 $D^{\pm}_s$ candidates seen in $M(KK\pi)$ peak





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

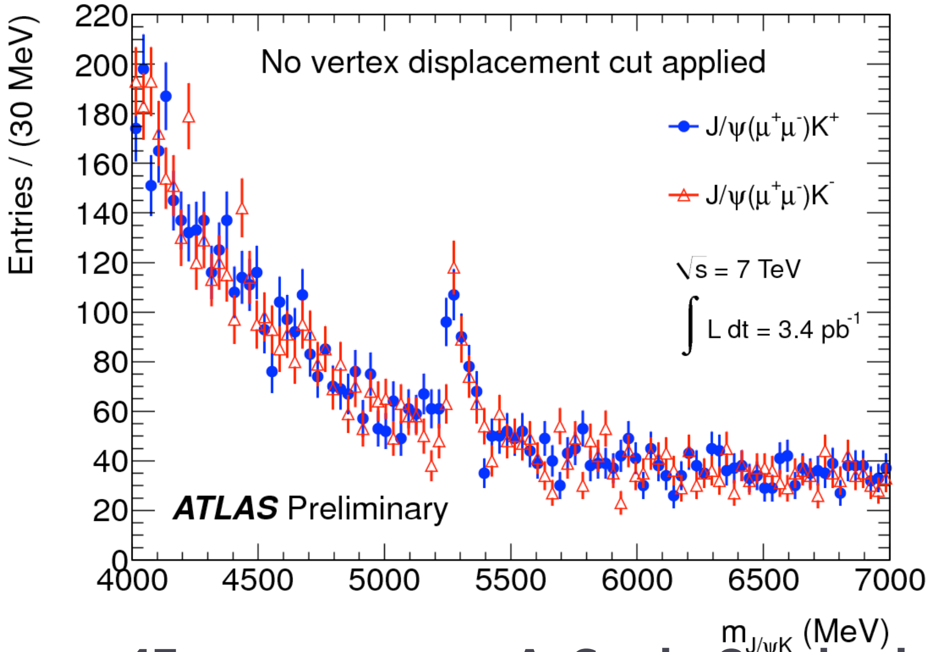
Candidates built from J/ψ candidate with 4, 2.5 GeV muon p_T cuts

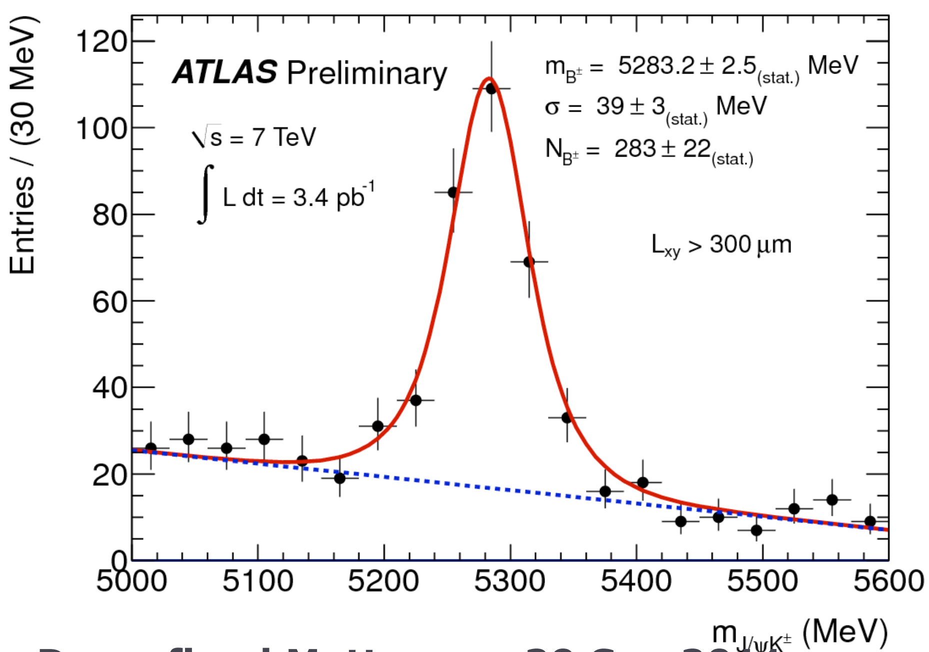
Constrained vertex fit of $\mu\mu K$ system, $p_T(\mu\mu K)>10$ GeV

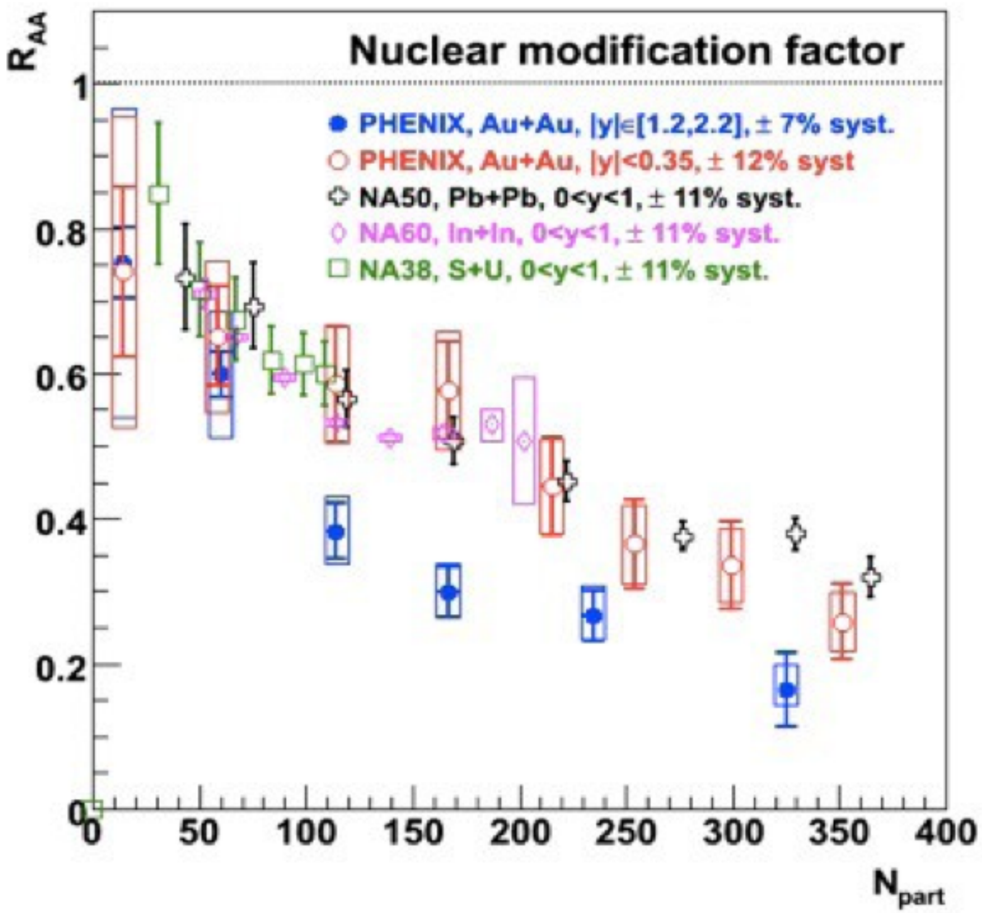
Exploit displaced vertex of decay to improve signal/background:

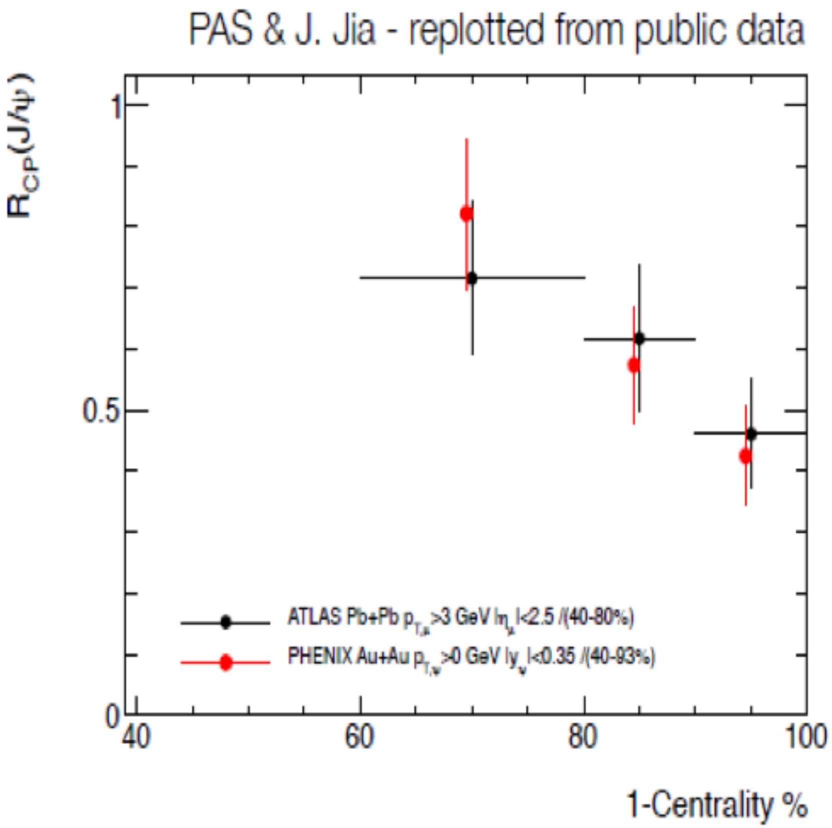
B transverse decay length cut > 300 μm

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









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

Corrected efficiency ratios for J/ψ and Z candidates from MC

Relative yields in all cases – normalise to most peripheral bin

Candidate acceptance on J/ψ: two muons have p_T>3 GeV in |η|<2.5

Centrality	$N^{meas}(J/\psi)$	$\epsilon(J/\psi)_c/$ $\epsilon(J/\psi)_{40-80}$	Systematic Uncertainty		
			Reco. eff.	Sig. extr.	Total
0-10%	190 ± 20	0.93 ± 0.01	6.8 %	5.2 %	8.6 %
10-20%	152 ± 16	0.91 ± 0.02	5.3 %	6.5 %	8.4 %
20-40%	180 ± 16	0.97 ± 0.01	3.3 %	6.8 %	7.5 %
40-80%	91 ± 10	1	2.3 %	5.6 %	6.1 %

Candidate acceptance on Z: two muons have p_T>20 GeV in |η|<2.5

Centrality	N(Z)	$\epsilon(Z)_c/\epsilon(Z)_{40-80}$
0-10%	19	0.99 ± 0.01
10-20%	5	0.97 ± 0.01
20-40%	10	0.98 ± 0.01
40-80%	4	1