LOW X 2012

Paphos, Cyprus, Jun 27-30, 2012

Measurements of J/ψ and ϒ Production in ATLAS

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CERN

ATLAS EXPERIMENT http://atlas.ch

Introduction and Outline

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- Non Conclusive coherent theoretical picture of J/ψ and ϒ hadro-production
- LHC gives the opportunity for studying the quarkonium and b-production in a new regime at high transverse momenta and in a wider rapidity range than before

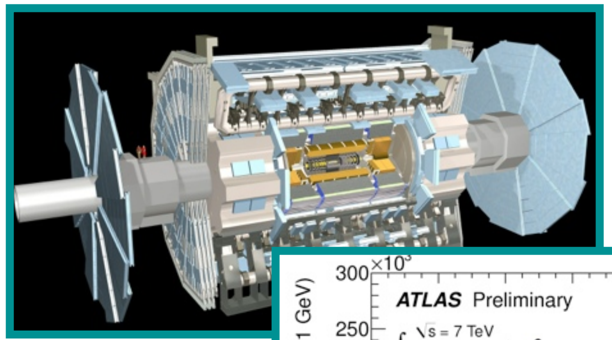
In this talk:

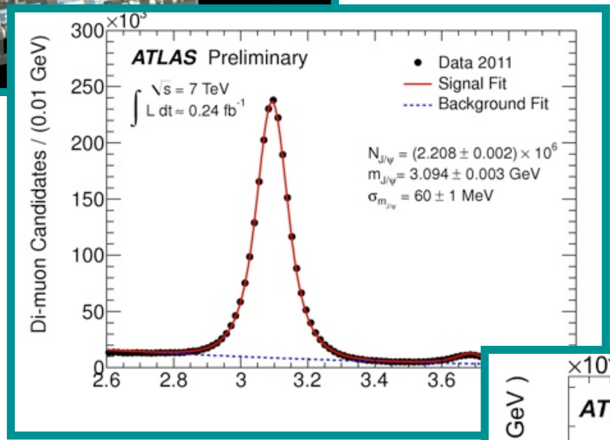
- Overview of the ATLAS Detector
  - Data Taking
  - Muon Spectrometer and Inner Detector
  - Trigger System
- J/ψ Production in ATLAS

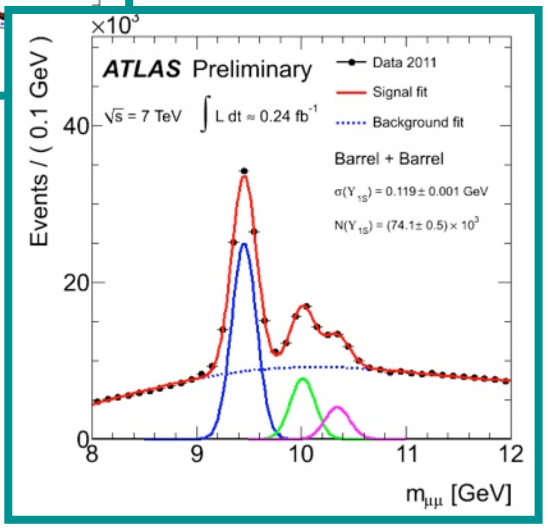
  Nucl.Phys. B850 (2011) 387-444 e-Print: arXiv:1104.3038 [hep-ex] (*)

  - Inclusive Cross Section
  - B-Fraction
  - Non-Prompt Cross Section
  - Prompt Cross Section
- ϒ Production in ATLAS

  Phys. Lett. B705 (2011) 9 e-Print: arXiv:1106.5325 [hep-ex] (*)
- Summary and Future Plans







(*) These results were obtained using ATLAS 2010 data corresponding to an integrated luminosity of 2.2 pb^{-1}(J/ψ) and 1.13 pb^{-1} (ϒ)

LHC/ATLAS Data Taking Performance

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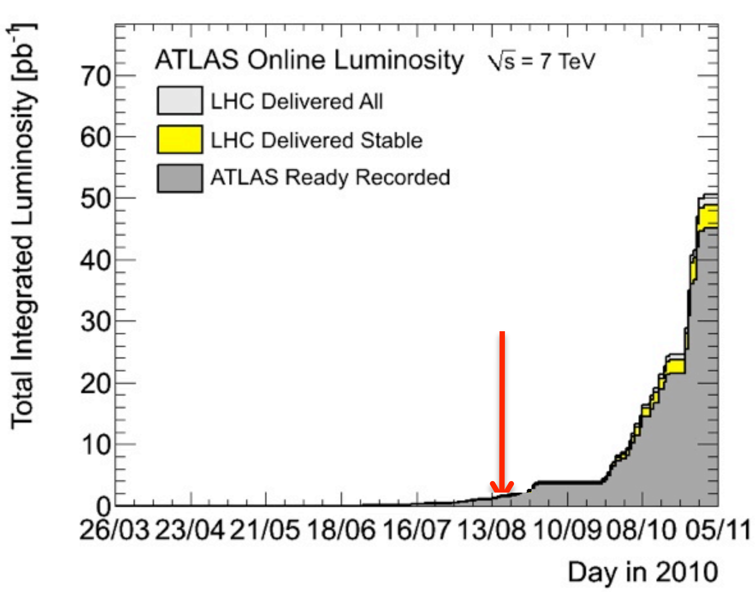
- LHC Peak luminosity ~6.76×10^{33} $cm^{-2}s^{-1}$ (June 2012)
- ATLAS data taking efficiency > 94%
- All subsystem operational fraction of channels > 96%
- Similar performances in 2011 and 2010

$\sqrt{s}$ = 8 TeV

(2012 Data Taking)

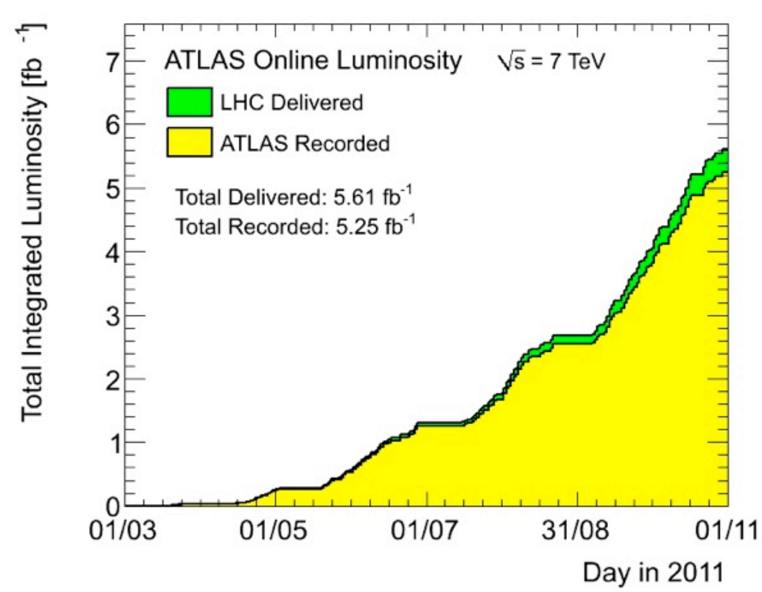
- Events collected for this analysis from Single Muon trigger thresholds
- Di-muon triggers exploited in more recent analysis for really high luminosity periods



Low-p_T triggers :

Single muon : 0, 4, 6 GeV

Dimuon : (4, 4), (4, 6) ... GeV



Low-p_T triggers :

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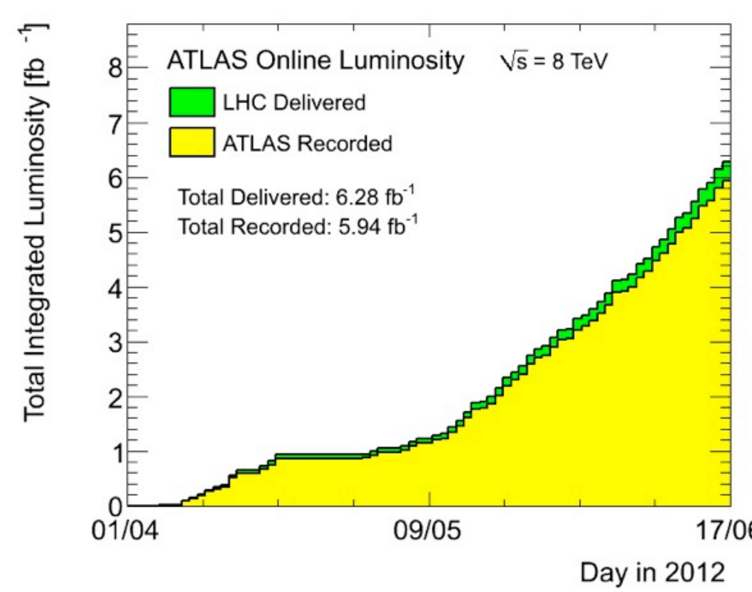
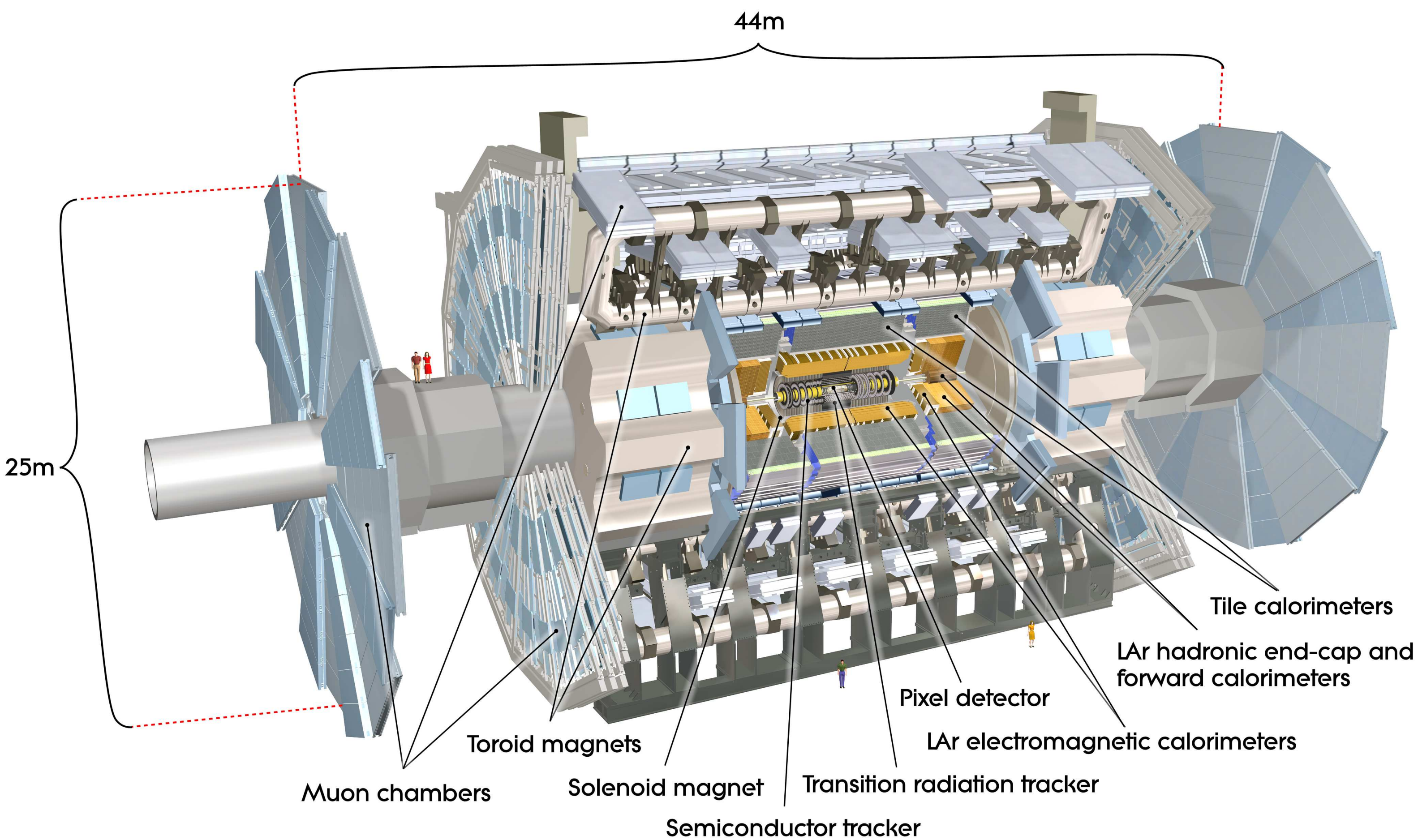


High-p_T Dimuon triggers :

(4, 6), (6, 10) (10, 10) ... GeV

ATLAS Detector



Inner detector ($|\eta|< 2.5$):

- Silicon pixel and strip, Transition Radiation Tracker (TRT) $\sigma/p_T \approx 5\cdot10^{-4} p_T \oplus 0.001$
- 2T Solenoidal field

Calorimeters ($|\eta|<5$):

- EM : Pb-LAr $\sigma/E \approx 10\%/\sqrt{E(GeV)} \oplus 0.7\%$
- HADRONIC: Iron Scintillator Tiles $\sigma/E \approx 50\%/\sqrt{E(GeV)} \oplus 3\%$
- Forward (FCal) :$3.2<|\eta|<5$

Muon Spectrometer ($|\eta|< 2.7$):

- Trigger chambers: Resistive Plate Chambers (RPC) & Thin Gap Chambers (TGC) - $\sigma_t \sim$ ns
- 0.5 T Toroidal field
- Coordinate Measurements Chambers: Monitored Drift Tubes (MDT) & Cathode Strip Chambers (CSC) $\sigma/p_T \approx 10\%$ (for $p_T = 1$ TeV/c)

ATLAS Trigger System

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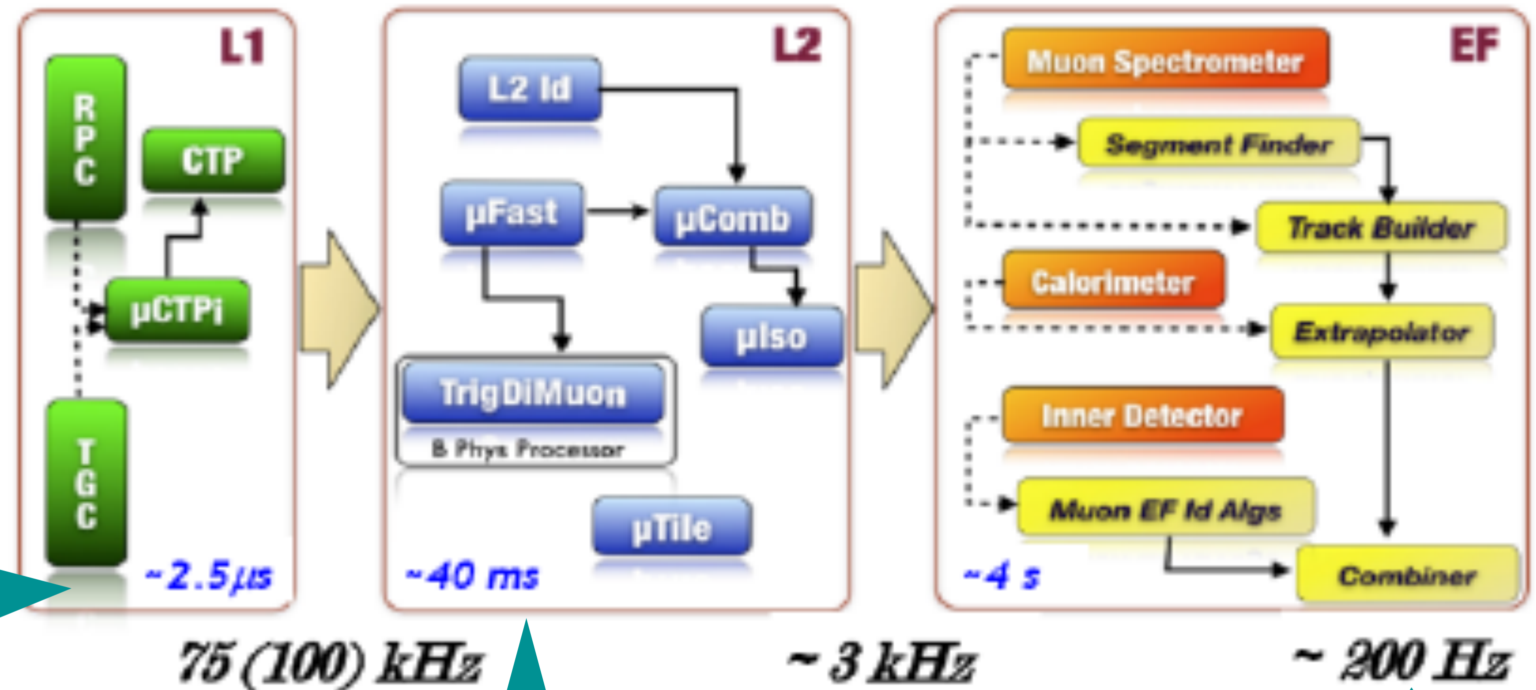
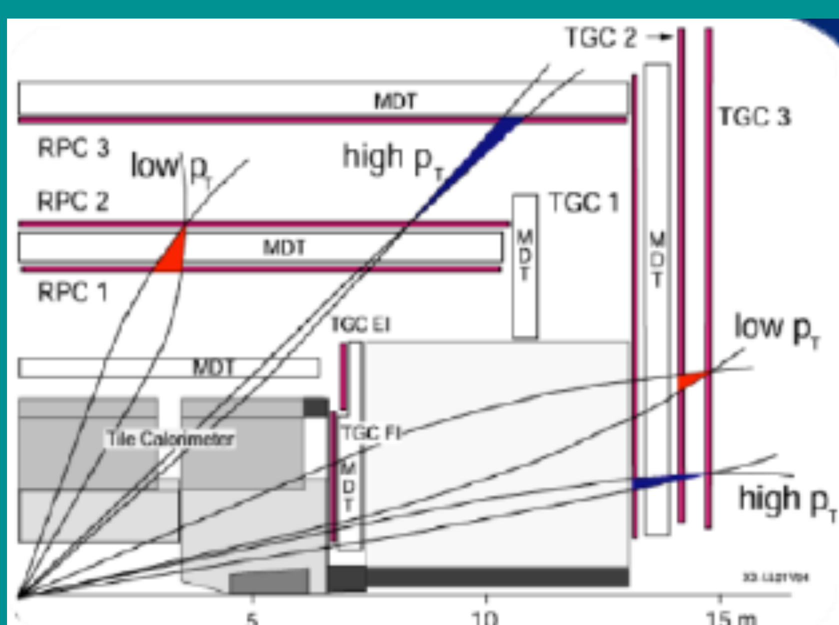
Three levels reduce LHC interaction rate of ~1 GHz to ~200Hz:

- **Level1 (L1)**, hardware-based
- High Level Trigger (HLT), software based:
  - **Level2(L2)**
  - **Event Filter (EF)**



Level 1 (L1)

- Hardware (RPC+TGC)
- 'Prompt' muons from interaction point (IP), p_T > threshold
- RoI (Region of Interest) id :p_T, η, φ



Level 2 (L2)

- RoIs in parallel,
- Several algorithms:
  1. 'Fast' Muon Spectrometer(MS), 'Stand Alone'
  2. 'Combined' reconstruction
  3. Isolation

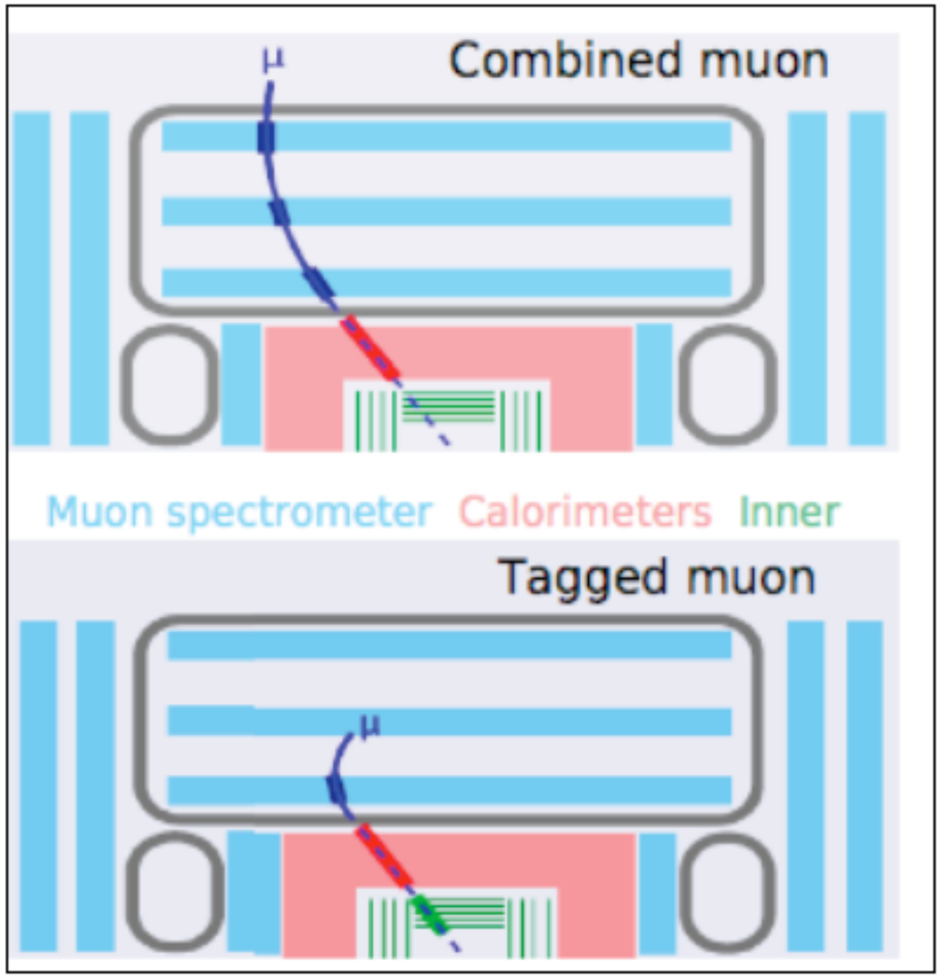
Event Filter (EF)

- Full event data available
- 'Offline' reconstruction adapted to the 'on-line' environment
- Two main strategies:
  1. Inside-Out (ID->MS)
     Outside-In (MS ->ID)
  2. Combined reconstruction

Event Selection

A “muon-based” analysis

- Primary vertex with >2 tracks
- OS di-muon events
  - p > 3.0 GeV, p_T> 1.0 GeV (4 GeV, ϒ)
  - $|\eta| < 2.5$
  - Track quality cuts
    - # Pixel Hits ≥ 1
    - # SCT Hits ≥ 6
  - ϒ prompt production : |d0|< 150 mm and |z0|sinθ < 1.5 mm [impact parameters with respect to the event vertex in the transverse/longitudinal direction]
- Require at least one muon to be Combined
- Require at least one muon to have triggered the event

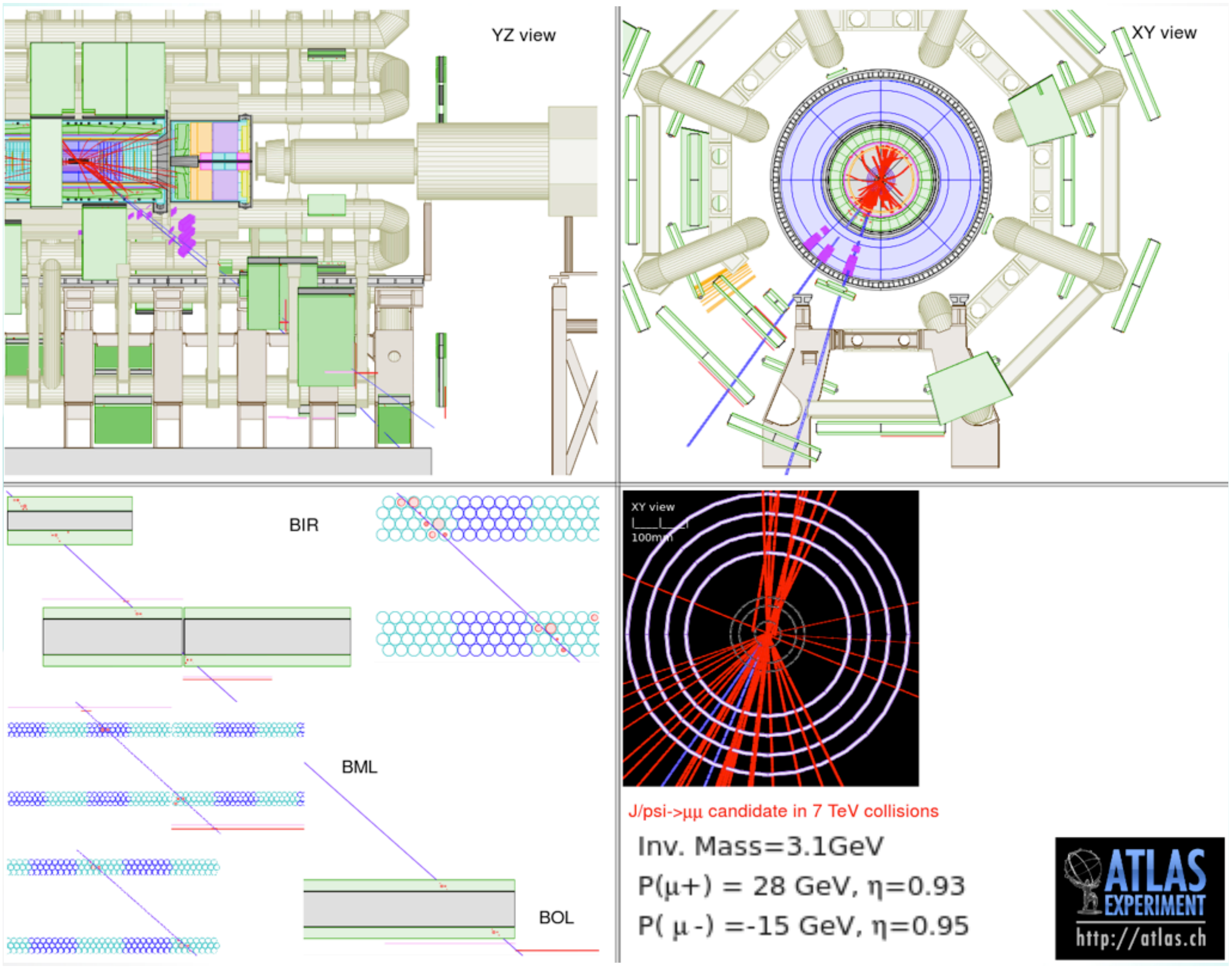


2 classes of muons :

Combined: full track segments in both the muon spectrometer and the inner detector

Tagged: full track segment in the inner detector associated with at least 1 hit in the muon system

$J/\psi \rightarrow \mu^+\mu^-$ Candidate



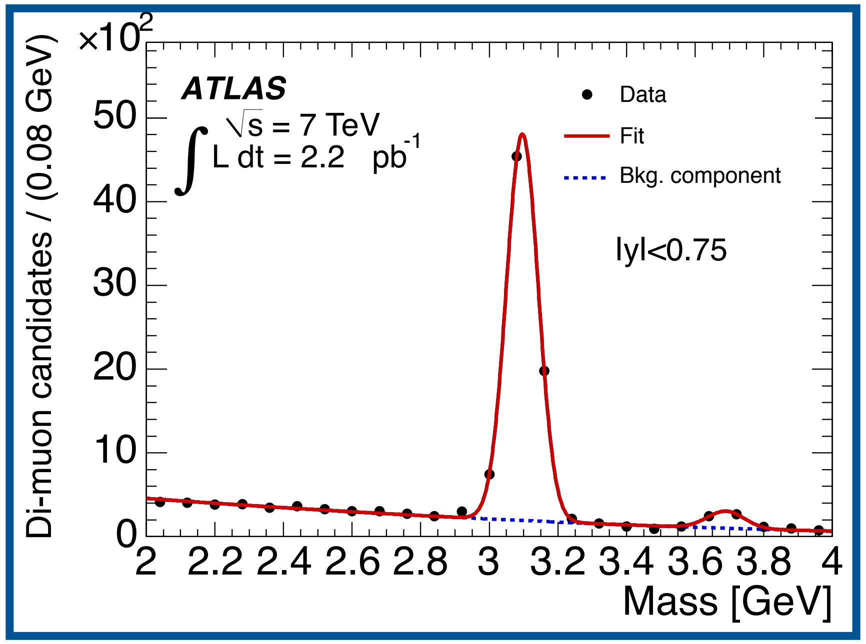
Inclusive $J/\psi \to \mu^+\mu^-$ Differential Production Cross-Section

- Select Di-muon candidates
- Divide into p_T and rapidity slices
- Correct efficiencies per candidate
  $\Rightarrow$ Per-Event Weight applied

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

acceptance ($\mathcal{A}$); bin migration ($\mathcal{M}$); ID track efficiency ($\mathcal{E}^2_{\text{trk}}$); Muon reconstruction efficiency (charge dependent) ($\mathcal{E}^\pm_\mu$); trigger efficiency ($\mathcal{E}_{\text{trig}}$)

- Extract weighted yield $\Rightarrow$ Mass Fit



- Calculate the inclusive cross-section

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

$$N^{corr.}_{obs.} = \sum_i w_i N^i_{obs}$$

Acceptance

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- Probability that $J/\psi(p_T,\eta)$ decays into muons which fall in the detector active region
- Calculated using generator-level Monte Carlo
- Function of the not known J/ψ spin alignment, so enters as a theoretical uncertainty
- Five extreme cases that lead to the biggest variation of acceptance within the kinematics of the ATLAS detector

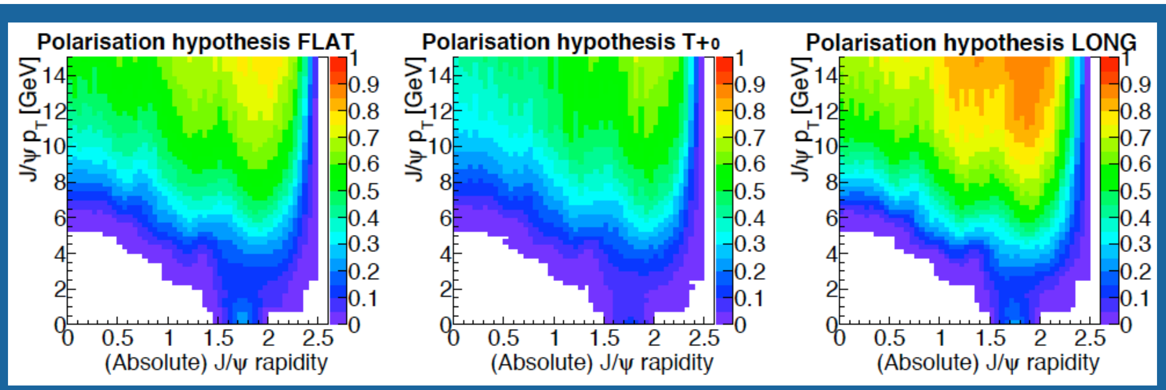
The cross section measurement is repeated for all the possible five configuration to provide an envelope of maximum variation

For Non-Flat distributions :

Re-weighting the Flat distribution in truth level

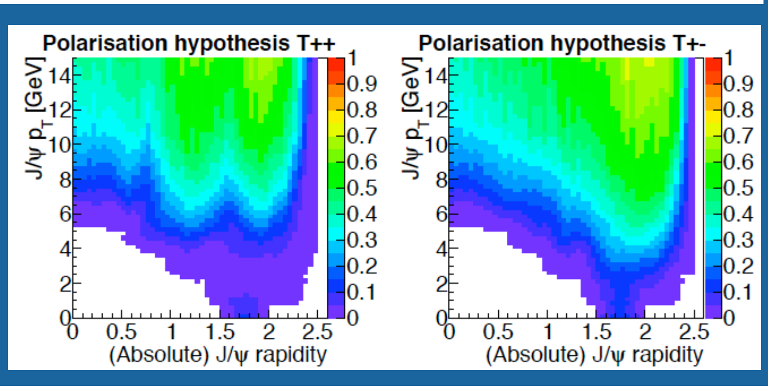
$$\frac{d^2N}{d\cos\theta^\star d\phi^\star} \propto 1 + \lambda_\theta \cos^2\theta^\star + \lambda_\phi \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta\phi} \sin 2\theta^\star \cos\phi^\star$$

- Flat: $\lambda_\theta = \lambda_\varphi = \lambda_{\theta\varphi} = 0$
- Longitudinal: $\lambda_\theta = -1$, $\lambda_\varphi = \lambda_{\theta\varphi} = 0$
- 1st Transverse: $\lambda_\theta = +1, \lambda_\varphi = \lambda_{\theta\varphi} = 0$
- 2nd Transverse: $\lambda_\theta = +1, \lambda_\varphi = +1, \lambda_{\theta\varphi} = 0$
- 3rd Transverse: $\lambda_\theta = +1, \lambda_\varphi = -1, \lambda_{\theta\varphi} = 0$



P. Faccioli et al., Eur. Phys. J. C (2010) 69: 657-673Introduction polarisation working points (arXiv : 1006.2738)

S. Palestini, Phys. Rev. D 83 (2011) 031503(R) : "Angular distribution and rotations of frame in vector meson decays into lepton pairs" (arXiv:1012.2485)



Signal Extraction

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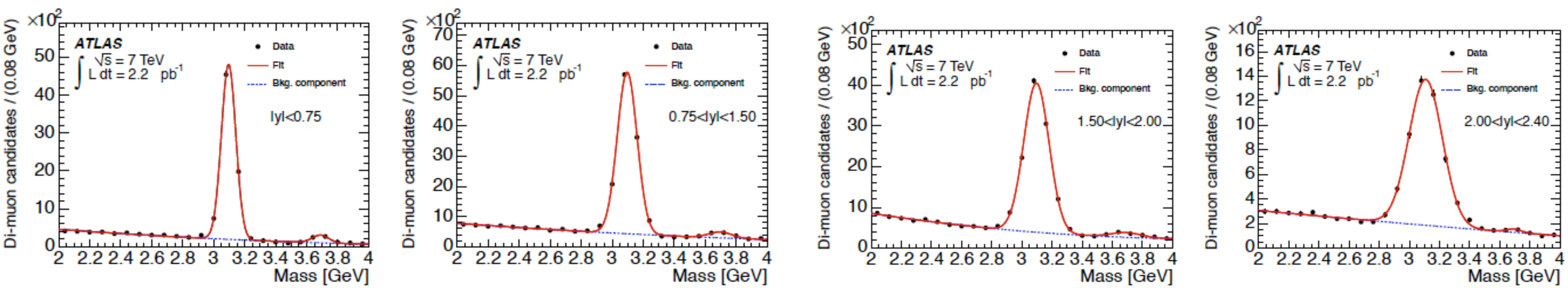
Efficiency corrections

- Trigger : evaluated with Monte Carlo to obtain a fine granularity, and then corrected by data (tag and probe, charge dependent)
- Reconstruction
  - muon : evaluated with data (tag and probe) using J/ψ for lower p_T muons and Z at higher p_T
  - ID : constant efficiency for muon tracks of 99.5 ± 0.5 %

The inclusive production cross-section is determined in bins of J/ψ p_T and y



- Obtain weighted yields in each slice using a binned χ^2 fit to the corrected mass distribution
- Single Gaussian for the signal and linear background
- ψ(2S) included in the fit but yield not extracted

Systematic Uncertainties

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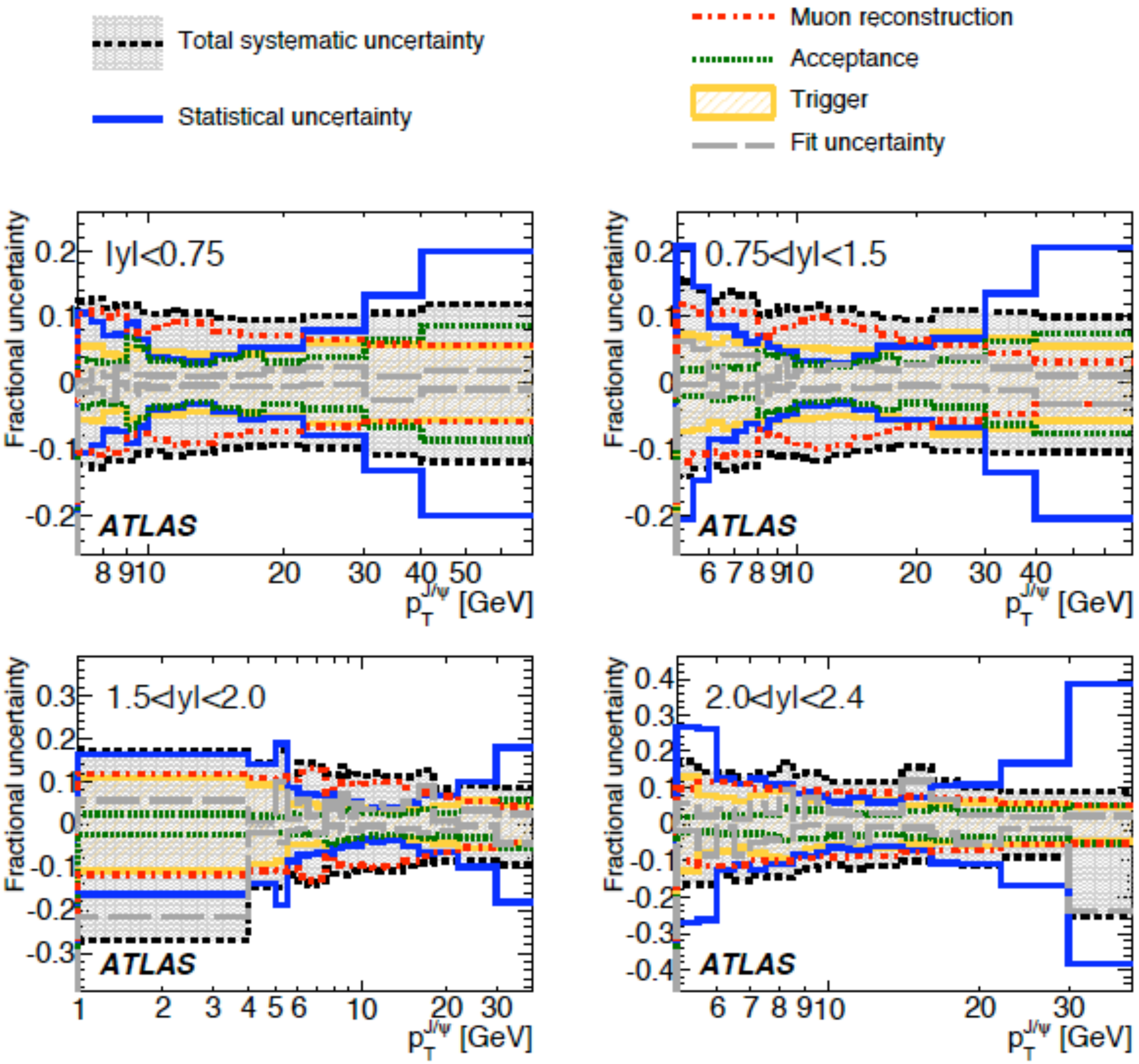
- Muon reconstruction and trigger : 5 – 10 %
- Luminosity : 3.4%
- Acceptance : 1-2%
- Bin Migration
  - low p_T and y ⇒ 0.1%
  - high p_T and y ⇒ 3%
- Fit Procedure: 1-3%



spin alignment not shown

Inclusive $J/\psi \rightarrow \mu^+\mu^-$ Differential Production Cross-Section in Rapidity Bins

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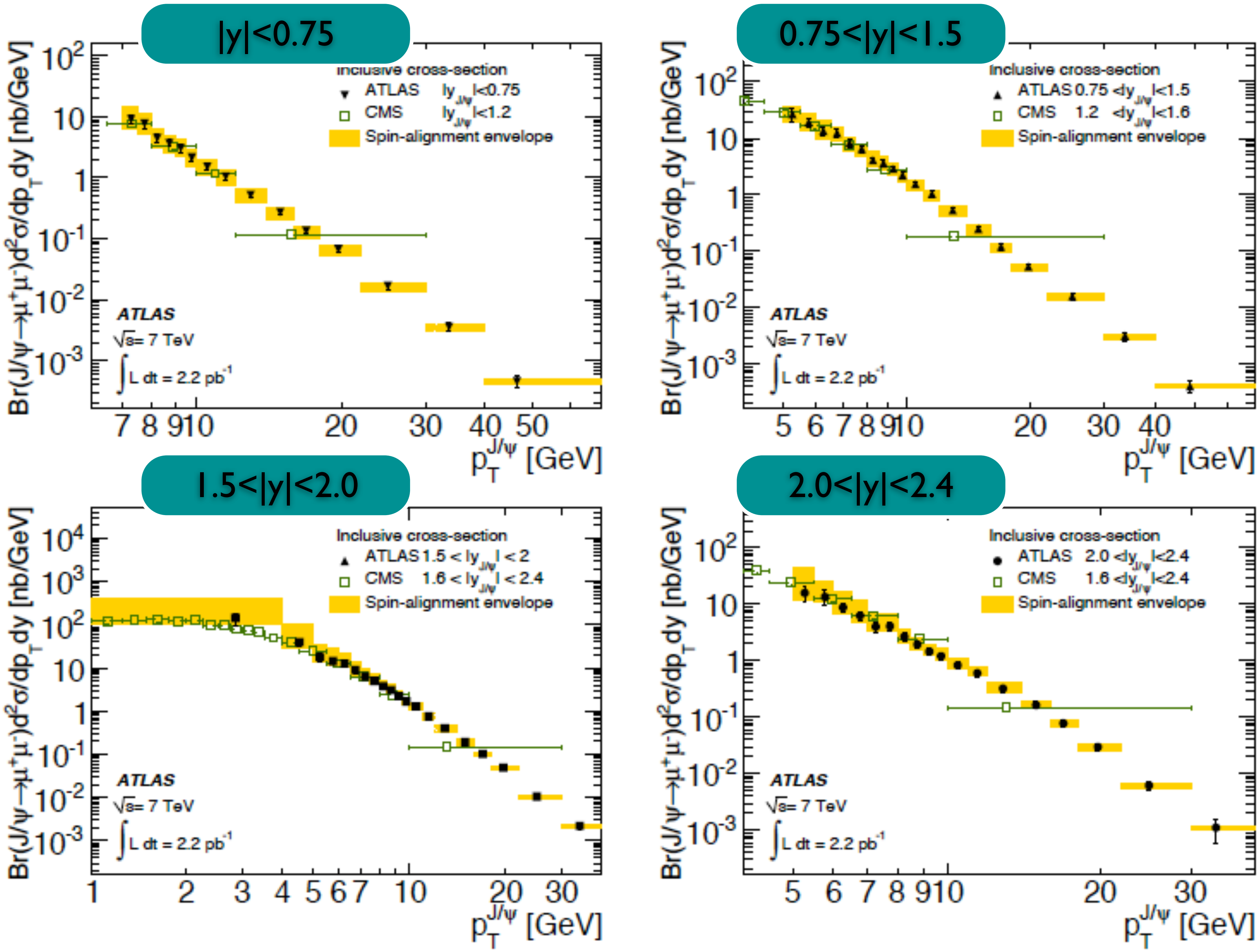
Compared to CMS(*) for similar rapidity ranges.

Good agreement, provide complementary measurements at low (CMS) and high (ATLAS) p_T

[V. Khachatryan et al., Eur.Phys.J. C71 (2011) 1575, arXiv:1011.4193 [hep-ex]]



(*) CMS has published more data on J/ψ and $\psi(2S)$, (arXiv:1111.1557, submitted to the Journal of High Energy Physics).

Their reach in p_T, and statistical errors are better than their previous analysis.

Fully consistent with the ATLAS results

Non-Prompt Fraction f_B

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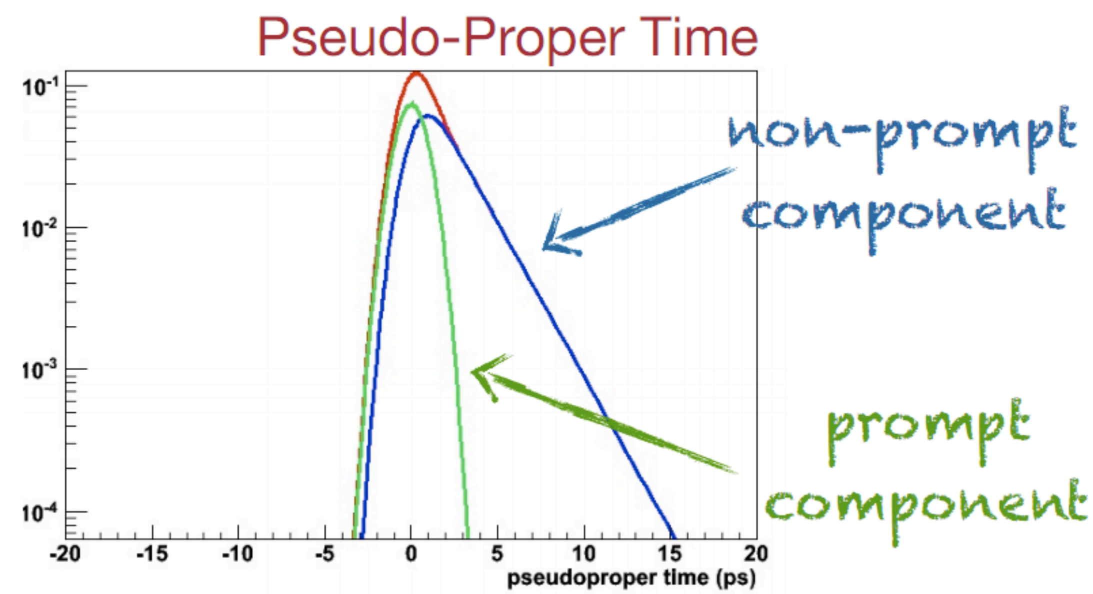
It is possible to distinguish J/ψ from prompt production and decays of heavier charmonium states from the J/ψ produced in B-hadron decays (non-prompt production)

Discriminant: measured distances between the primary vertices and corresponding J/ψ decay vertices

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



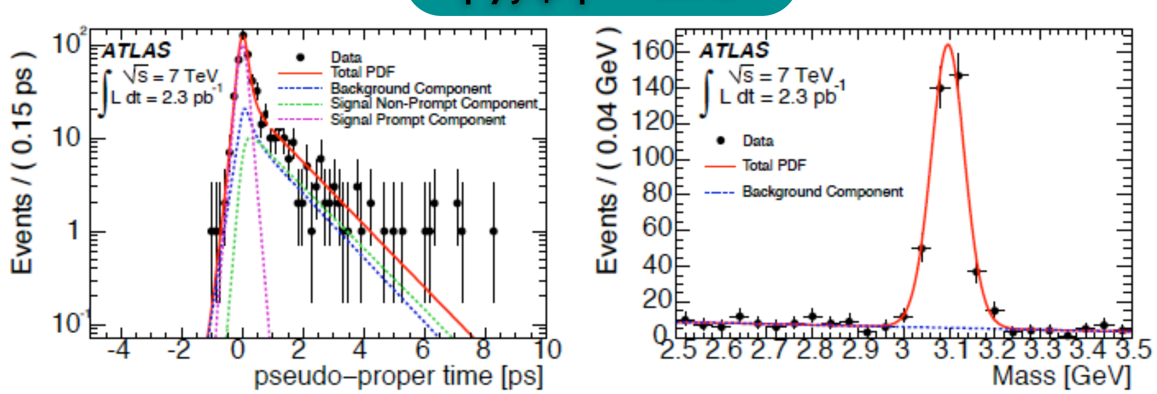
Observable: Pseudo-Proper Lifetime

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

Lxy is the displacement of the J/ψ vertex in the transverse plane.

Simultaneous invariant mass and pseudoproper lifetime fits to extract the non-prompt fraction in each p_T-y slice

$|y_{J/\psi}| < 0.75$

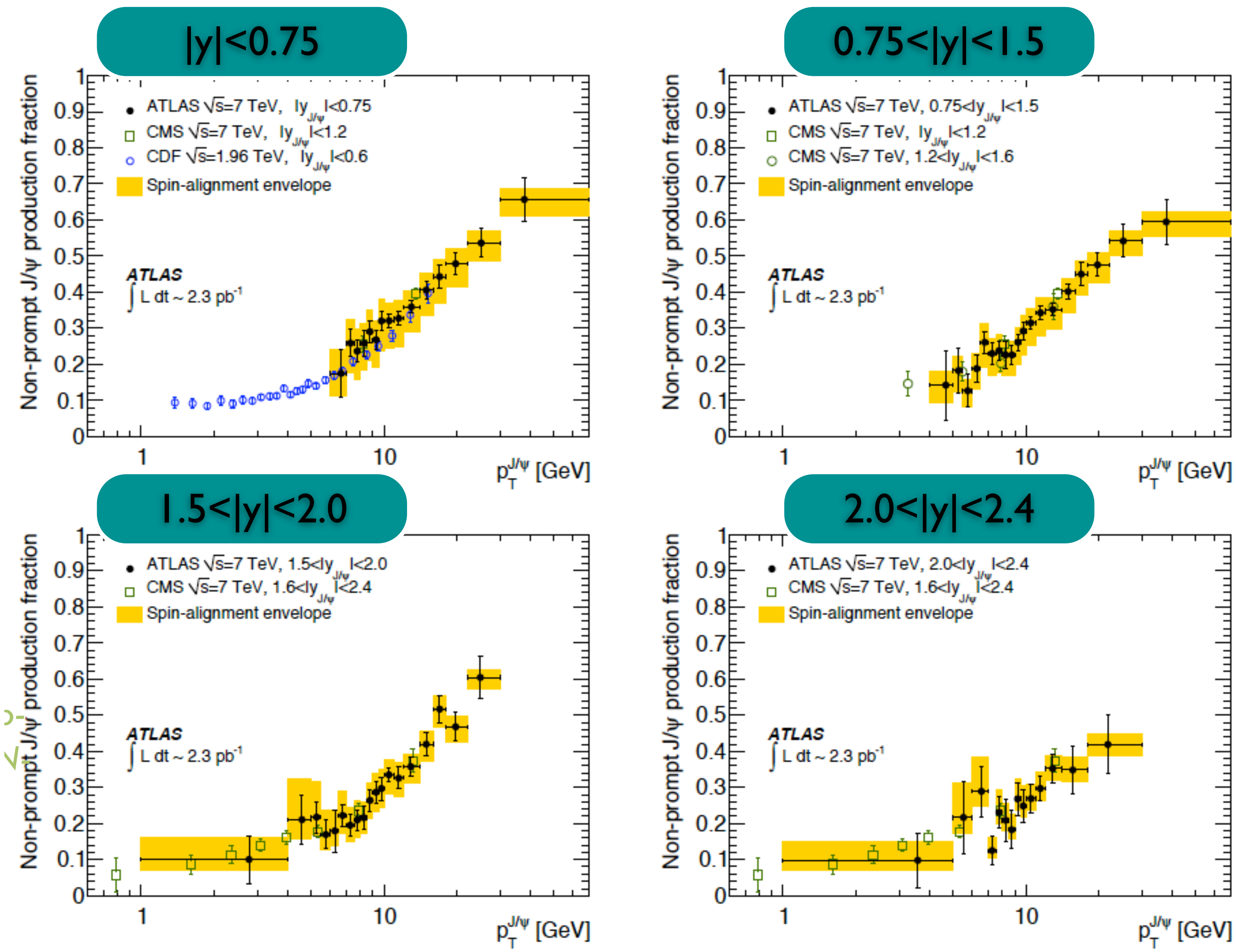


Non-Prompt Fraction Results

Good Agreement with:

- CMS [arXiv:1011.4193 [hep- ex], CMS-BPH-10-002, CERN-PH-EP-2010-04]
- CDF [Phys. Rev. D71 (2005) 032001, arXiv:hep-ex/ 0412071]

- No strong dependence on the center of mass energy
- Independent of production mechanism (pp v.s. ppbar)

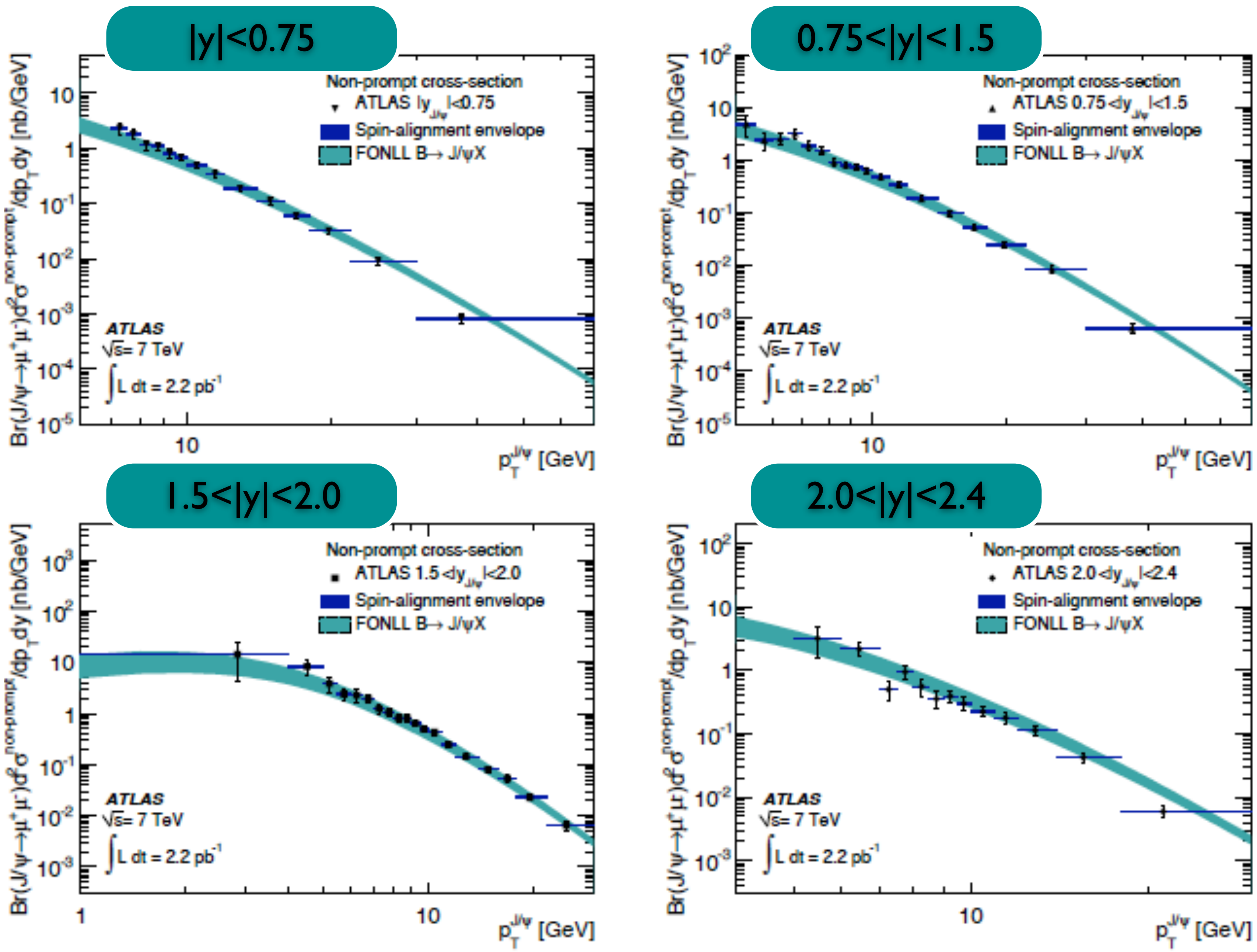


Prompt/non-prompt cross sections can be extracted by combining the inclusive cross section and the non-prompt fraction

Non-Prompt Cross Section

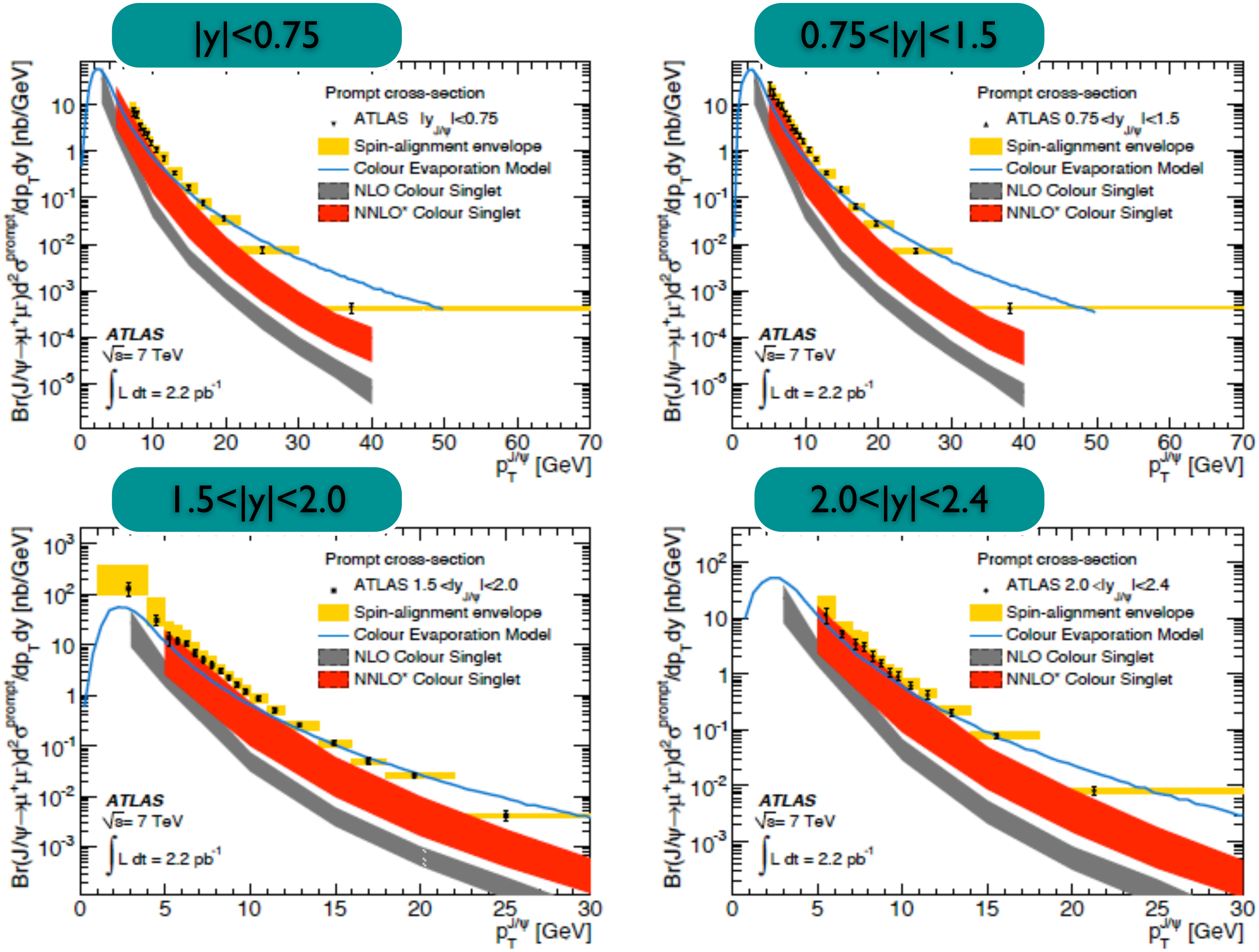
Good Agreement between Data and Fixed Order Next-to-Leading Logarithm (FONLL)

[M. Cacciari, M. Greco and P. Nason, JHEP 9805 (1998) 007, arXiv:hep-ph/9803400; JHEP 0103 (2001) 006, arXiv:hep- ph/0102134]



Prompt Cross-Section

- NNLO* Color Singlet Model (CSM) : better than NLO, but still underestimate... *arXiv:1006.2750 [hep-ph]; Phys. Rev. D81 (2010) 051502; Eur. Phys. J. C 61 (2009) 693, arXiv:0811.4005 [hep-ph].*
- Color Evaporation Model (CEM) prediction is generally lower and diverges in shape from measured data, showing disagreement in the extended p_T range probed in this measurement *Phys. Rept. 462 (2008) 125, arXiv: 0806.1013 [nucl-ex]; Phys. Lett. B 91 (1980) 253; Z. Phys. C 6 (1980) 169*



NNLO* is not full NNLO calculation, currently only real contribution up to α_s^5 has been calculated (corresponds to sum of the NLO yield and contributions from $pp \rightarrow Q + jjj$)

Υ Cross-Section

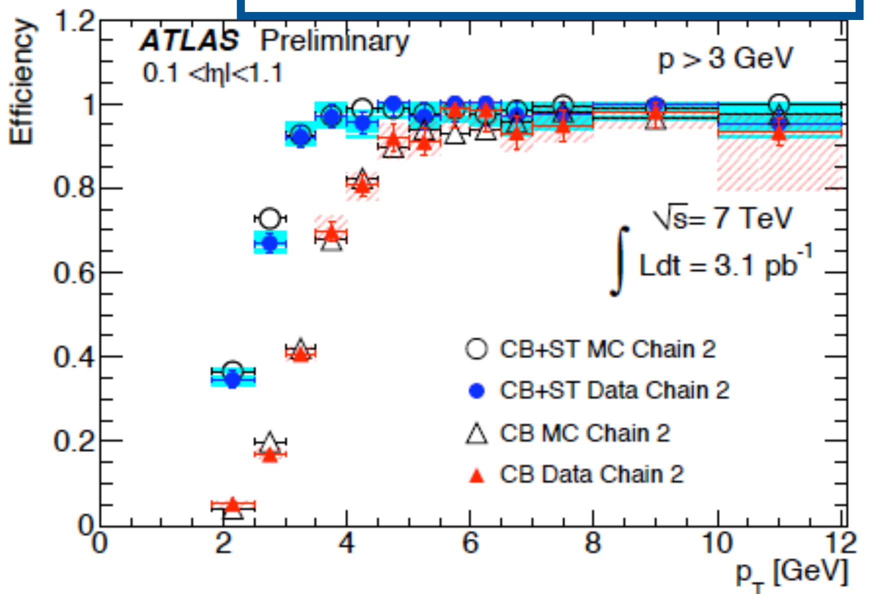
- Measurement within fiducial cuts
  - $p_T > 4$ GeV, $|\eta|<2.5$
  - no uncertainties due to the spin alignment

$$\frac{d^2\sigma}{dp_T dy} \times BR(\Upsilon(1S) \to \mu^+\mu^-) = \frac{N^*_{\Upsilon(1S)}}{\int \mathcal{L} dt \times \Delta p_T \times \Delta y},$$

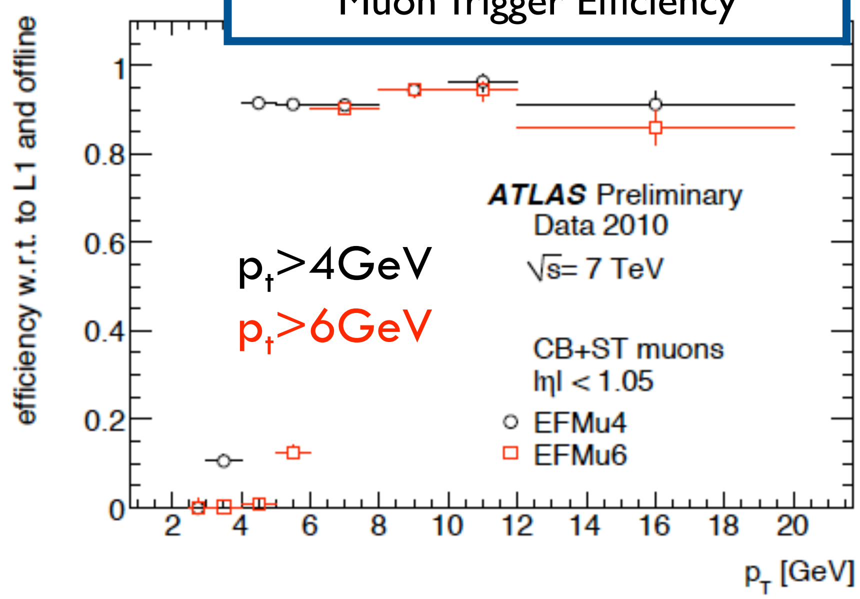
(*)corrected

- Unbinned maximum likelihood fit to the di-muon mass distribution after correcting for the efficiency per event
  - Muon reconstruction efficiency (using J/ψ decays)
  - Muon trigger efficiency (using J/ψ decays)
  - Tracking efficiency
  - Efficiency of impact parameter selection
- All efficiency factors are determined directly from the data

Muon Reconstruction Efficiency



Muon Trigger Efficiency



Υ yields and background determination

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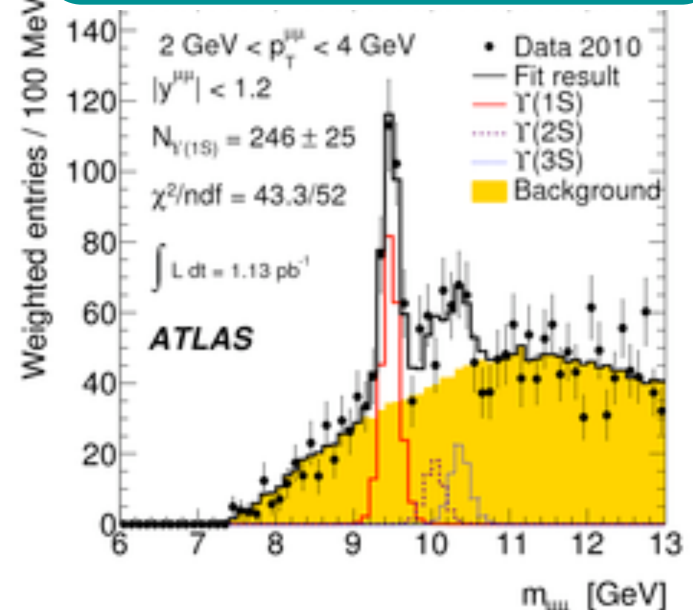
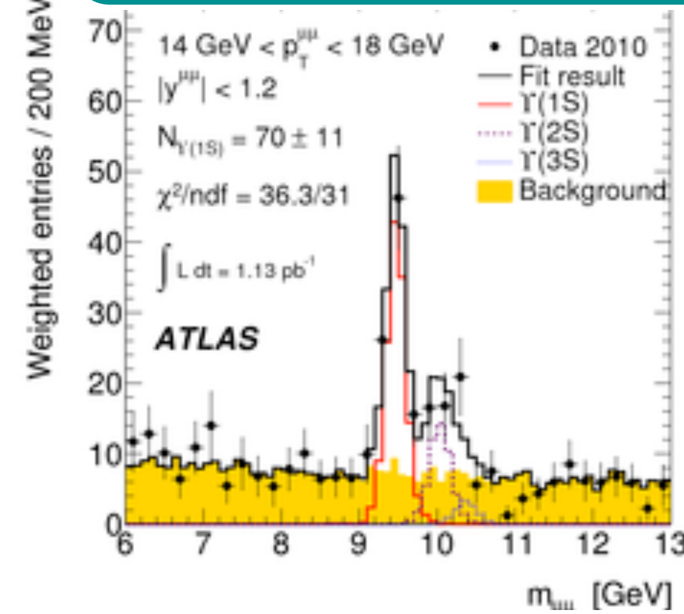
- background depends on the kinematic bin
- Υ(1S) is not well separated from Υ(2S) and Υ(3S)
- Signal Model: templates from MC
  - Independent for each resonance peak
  - Adjust resolution to reflect data
  - Separation of mass peaks fixed to world average
- Background model from data
  - Template generated from μ + oppositely signed track

    same track quality and kinematic selection applied
  - Alternative templates (μ+SS track, MC bbbar) give results in agreement (systematic uncert.)
- 4 parameters are fitted independently in each kinematic bin: $N_{\Upsilon(1S)}$, $N_{\Upsilon(2S)}$, $N_{\Upsilon(3S)}$, N_{bkg}

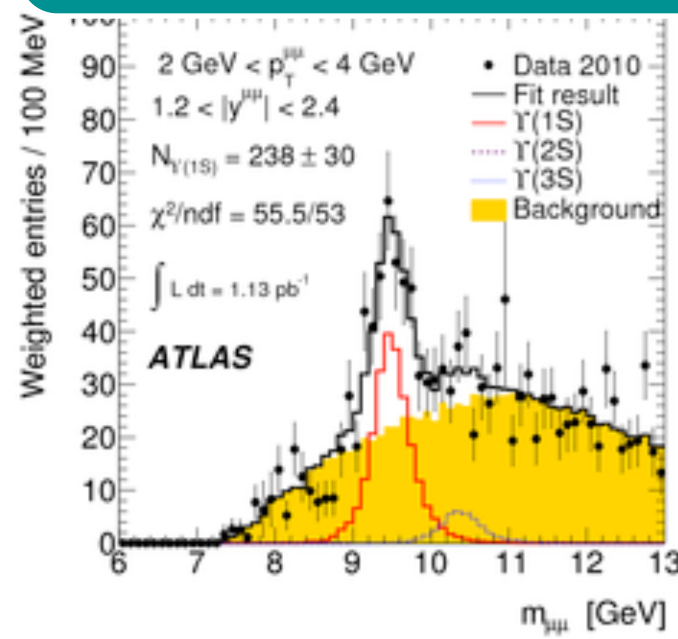
|y|<1.2 && 2 GeV < | p$^{\mu\mu}$ | < 4 GeV



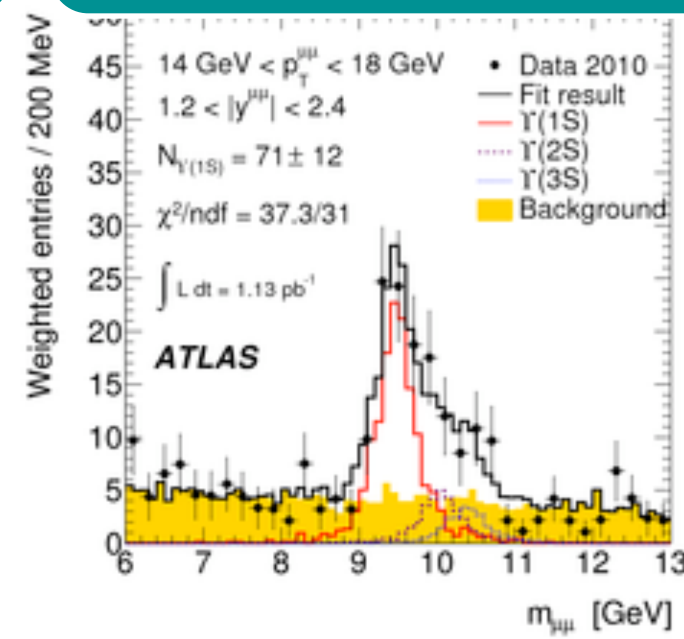
|y|<1.2 && 14 GeV < | p$^{\mu\mu}$ | < 18 GeV



1.2<|y|<2.4 && 2 GeV < | p$^{\mu\mu}$ | < 4 GeV



1.2<|y|<2.4 && 14 GeV < | p$^{\mu\mu}$ | < 18 GeV



Systematic Uncertainties

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- Luminosity calibration: 3.4%
- Muon reconstruction efficiency: 1%
- Muon trigger efficiency: 1%
- Efficiency of impact parameter selection: 1% - 3.5%
- bin migrations due to detector resolution and final state: 2%
- Fit model: 5%-10%
  - Signal
    - Pseudo-experiments with varied signal description
    - Mass scale (peak position & separation) & resolution
  - Background
    - Pseudo-experiments with varied templates:
      - same sign μ+track
      - bb, cc Monte Carlo

$\Upsilon(1S)$ Differential Cross-Section

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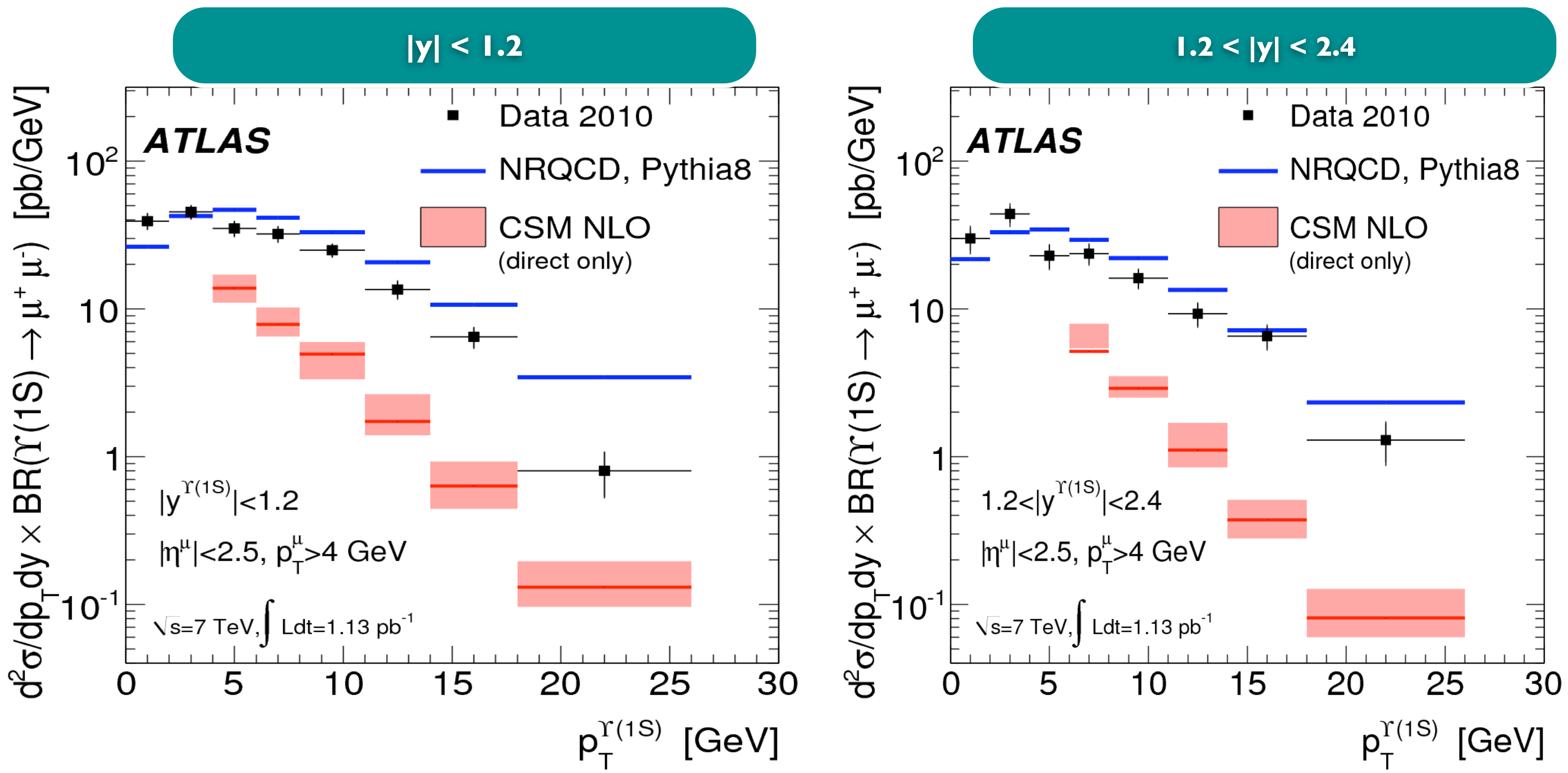
Comparison with:

- PYTHIA8/Non Relativistic QCD : different p_T dependence, but normalization is reasonable
- MCFM/Color Singlet Model NLO : cross section from data is higher
  - prediction does not include feed-down from higher mass states (factor ~2)
  - higher order corrections needed



uncertainty:

~ 10-15% at low p_T

~ 35% at high p_T dominated by the statistical precision of the data

Summary

- ATLAS has an excellent Inner Detector, Muon Spectrometer and trigger system to study heavy quarkonium physics
- 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
  - reasonable agreement of the fraction with CDF: no strong dependence on the center of mass energy
  - FONLL describes the non-prompt cross section well; prompt production is more problematic
- Measurement of $\Upsilon(1S)$ cross section in fiducial cuts
  - Two muons with $p_T > 4$ GeV and $|\eta| < 2.5$
- Both the J/ψ prompt component results and the $\Upsilon(1S)$ results suggest improvements of theoretical models needed

Future Plans

- Have already more than ~10 fb^{-1} with di-muon trigger from 2011 and 2012 data-taking
- J/ψ polarization

  $\psi(2S)$ cross-section, $\sigma(\psi(2S))/\sigma(J/\psi)$ (and polarization?)

  X(3872) cross-section

  Di-onia production: $J/\psi + J/\psi$, $J/\psi + \Upsilon$,...

  χ_c cross-sections

  Vector-boson associated production : $W+J/\psi$, $Z+J/\psi$

  More ...

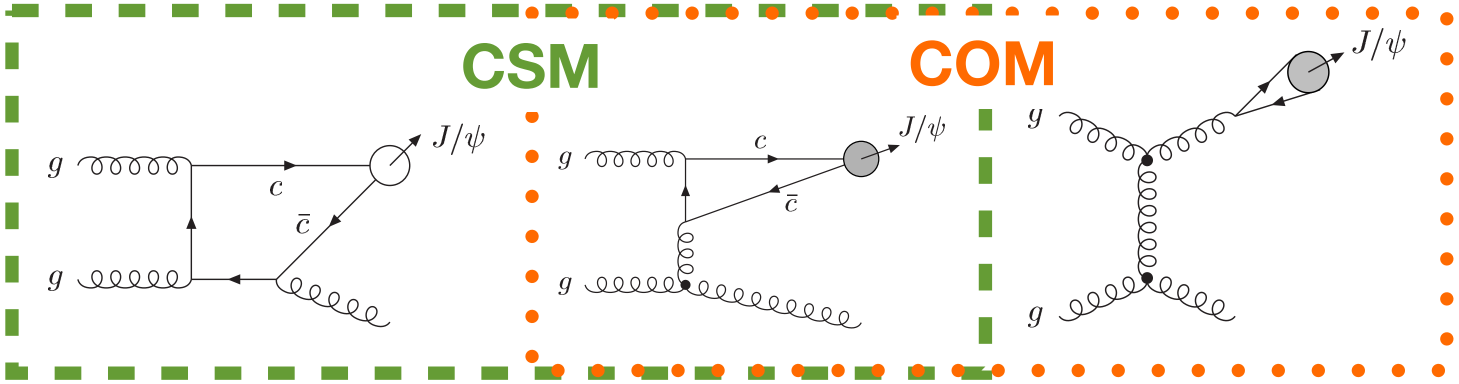
Stay Tuned...

Back-Up Slides

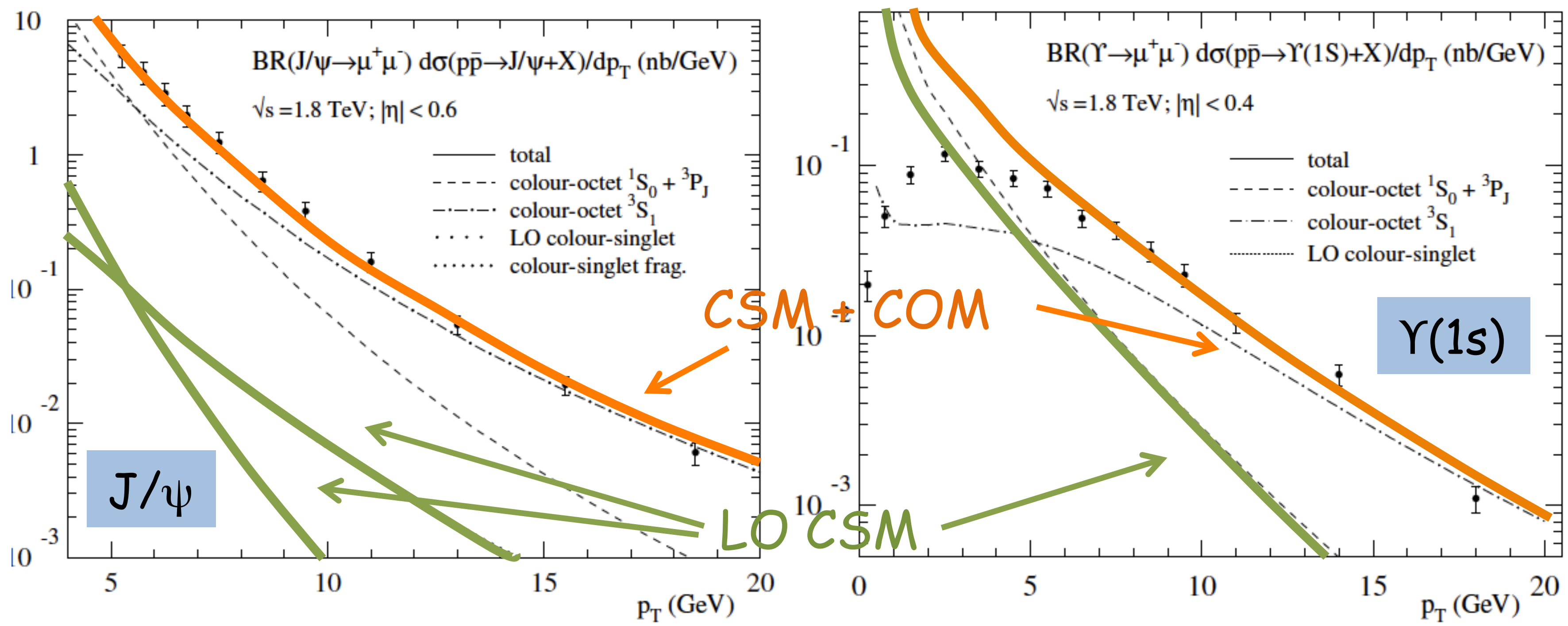
Focus on Physics Motivation

- Physicist are still trying to develop a coherent theoretical model for the heavy flavour hadro-production and polarisation
- Several models are available on the market:
  - Color Singlet Model (CSM)
  - Color Octet Model (COM) / NRQCD
  - Color Evaporation Model (CEM)
  - k_T factorization
  - ...

Some Production Diagrams for J/ψ



Tevatron Results



Color Evaporation Model

First proposed in 1977 ⇒ Considerable phenomenological success

In the CEM, the cross section for production of a quarkonium state M is some fraction F_M of the cross section for producing QQbar pairs with invariant mass below the MMbar threshold, where M is the lowest-mass meson containing the heavy quark Q

QQbar production cross section with a cut on the pair mass

No constraints on the color or spin of the final state

"Color evaporation"

Produced QQbar pair neutralizes its color by interaction with the collision-induced color field

The additional energy needed to produce heavy-flavored hadrons when the partonic center-of-mass energy is less than $2m_M$, the heavy hadron threshold, is obtained nonperturbatively from the color field in the interaction region

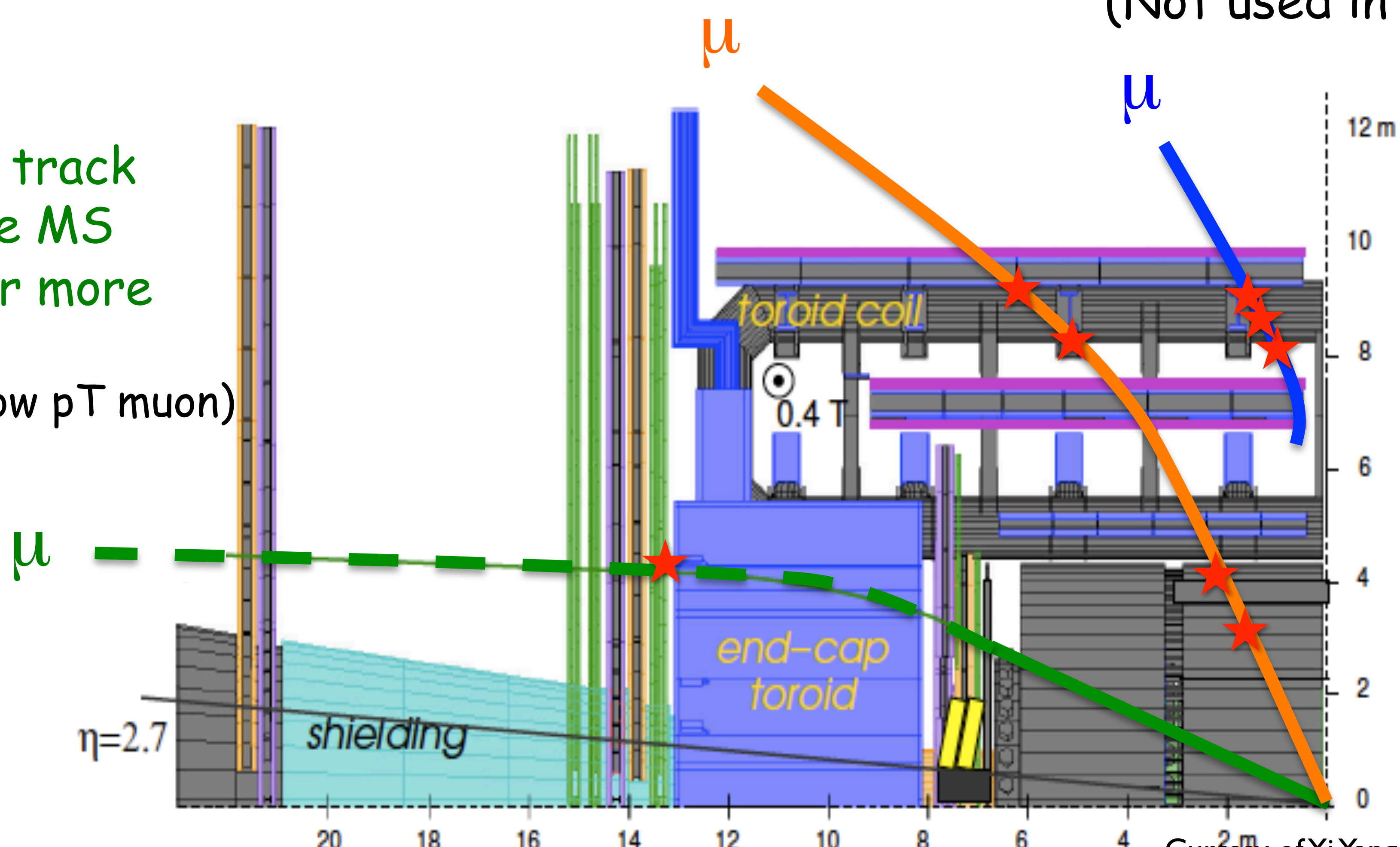
Fractions F_H are assumed to be universal so that, once they are determined by data, they can be used to predict the cross sections in other processes and in other kinematic regions.

ATLAS Muon Reconstruction

Combined Muon :
Standalone Muon extrapolated to Inner Detector with good fit
(Best quality muon)

Standalone Muon :
A track fitted by only Muon Segments in the Muon Spectrometer
(Not used in the analysis)

Tagged Muon :
An Inner Detector track extrapolated to the MS and match to one or more Muon Segments
(high efficiency for low pT muon)



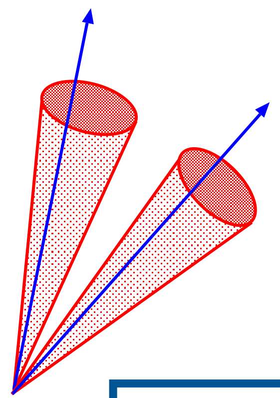
Curtesy of Yi Yang

ATLAS Di-muon Trigger for B-Physics

UNIVERSITÉ DE GENÈVE

In ATLAS we implemented two different dimuon trigger algorithms:

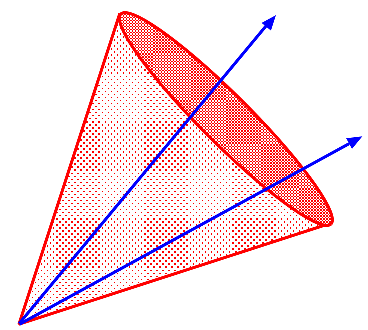
"Topological" - i. e. EF_2mu4_Jpsimumu



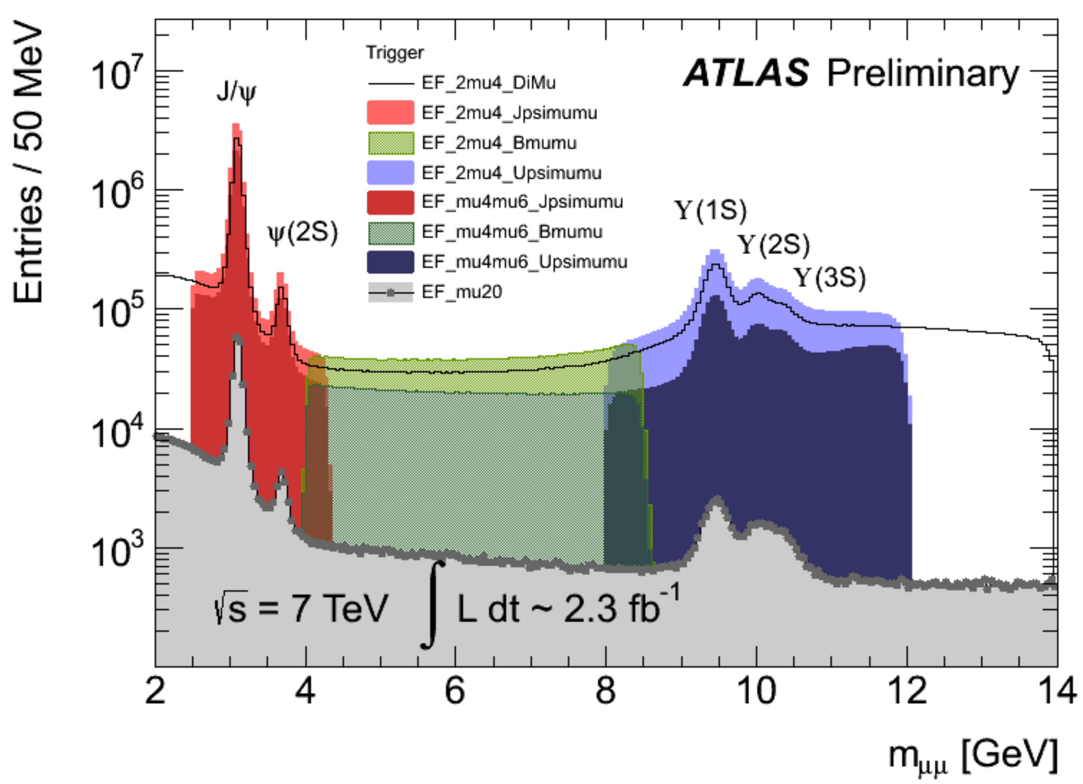
- 2 EF_mu4 required
- Invariant Mass cut [2.5-4.3] GeV
- Vertexing cut

Less acceptance for high-p_T J/ψ due to small ΔR separation between muons

L2 TrigDimu Based - i. e. EF_mu4_Jpsimumu



- L1_MU0 required
- OS ID tracks searched in Extended RoI ($\Delta\eta$<0.75 and $\Delta\varphi$<0.75)
- Invariant Mass cut >2.8 GeV on selected ID tracks
- Extrapolation at MS for "muon tag"
- Invariant Mass cut [2.5-4.3] GeV
- Vertexing cut
- Confirmed at EF level



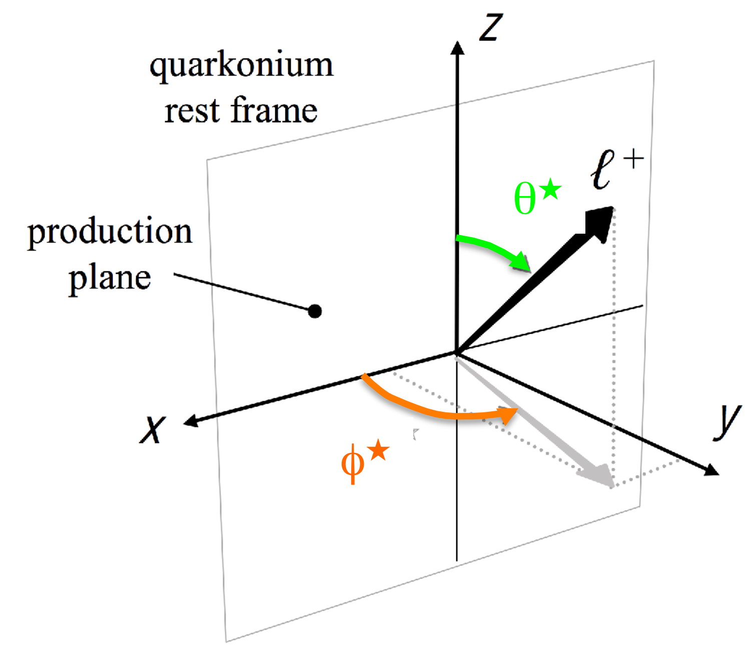
J/ψ Spin Alignment

Acceptance depends on the angular distribution of the decaying particle (spin-alignment of J/ψ) by the formula

P. Faccioli et al. arXiv:1006.2738

$$\frac{d^2N}{d\cos\theta^\star d\phi^\star} \propto 1 + \lambda_\theta \cos^2\theta^\star + \lambda_\phi \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta\phi} \sin 2\theta^\star \cos\phi^\star$$

- $\theta^\star$: angle between μ^+ momentum in the J/ψ rest frame and J/ψ momemtum
- $\varphi^\star$: angle between J/ψ production and decay plan in lab frame



Spin-alignment has not been measured, so it's still an open question

Systematic uncertainty in the measurement