B-Physics Studies with the ATLAS Detector

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on behalf of the ATLAS Collaboration

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Outline

Beauty Production

- **Charmonium** and **Bottomonium** production via observation of J/ψ, Υ
  - inclusive J/ψ cross-section
    - J/ψ from B-hadron decays (non-prompt): **$\sigma(pp \to B\,X \to J/\psi\,X)$**
    - direct J/ψ (prompt): **$\sigma(pp \to J/\psi\,X)$**

    published in Nucl.Lett.B705 (2011) 9-27 arXiv:1106.5325v1 [hep-ex]
  - inclusive Υ cross-section: **$\sigma(pp \to \Upsilon\,X)$**

    published in Nucl.Phys. B850 (2011) 387-444 arXiv:1104.3038 [hep-ex]
- **b and $b\bar{b}$** production via b-tagging of jets

  submitted to EPJC arXiv:1109.6833v1 [hep-ex]

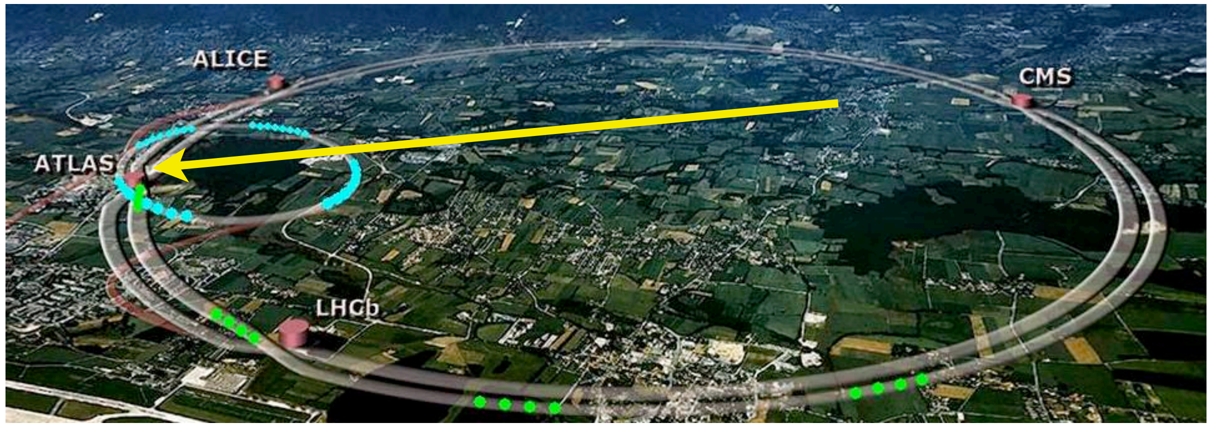
Beauty Properties

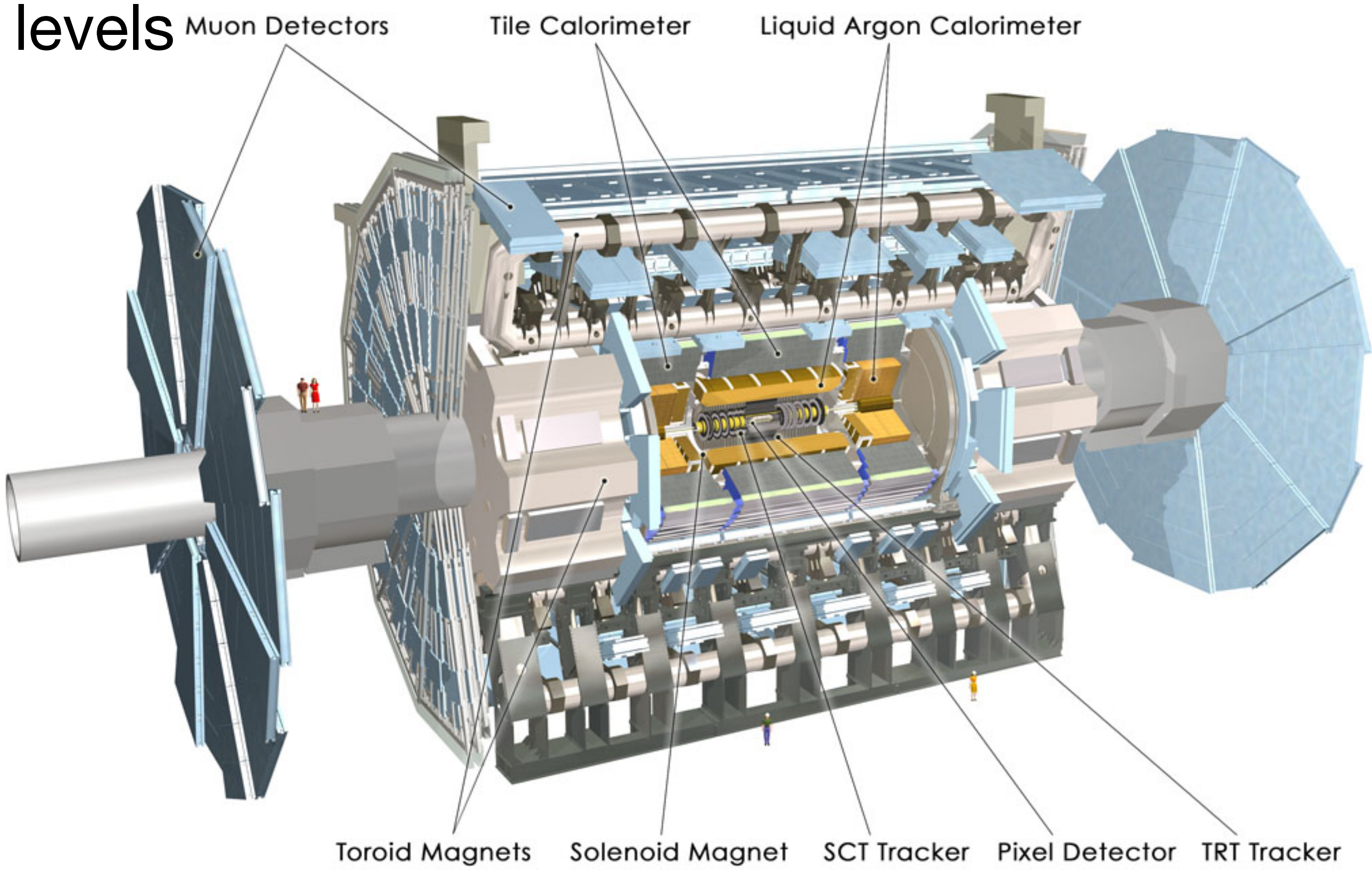
- **B-hadron** properties via measurement of exclusive B-lifetimes

  reported in ATLAS-CONF-2011-145, ATLAS-CONF-2011-092
- **CP violation**: via study of the exclusive decay $B_s \to J/\psi\,\varphi$
- **Beyond the Standard Model**: via the search for $B_s \to \mu^+\mu^-$

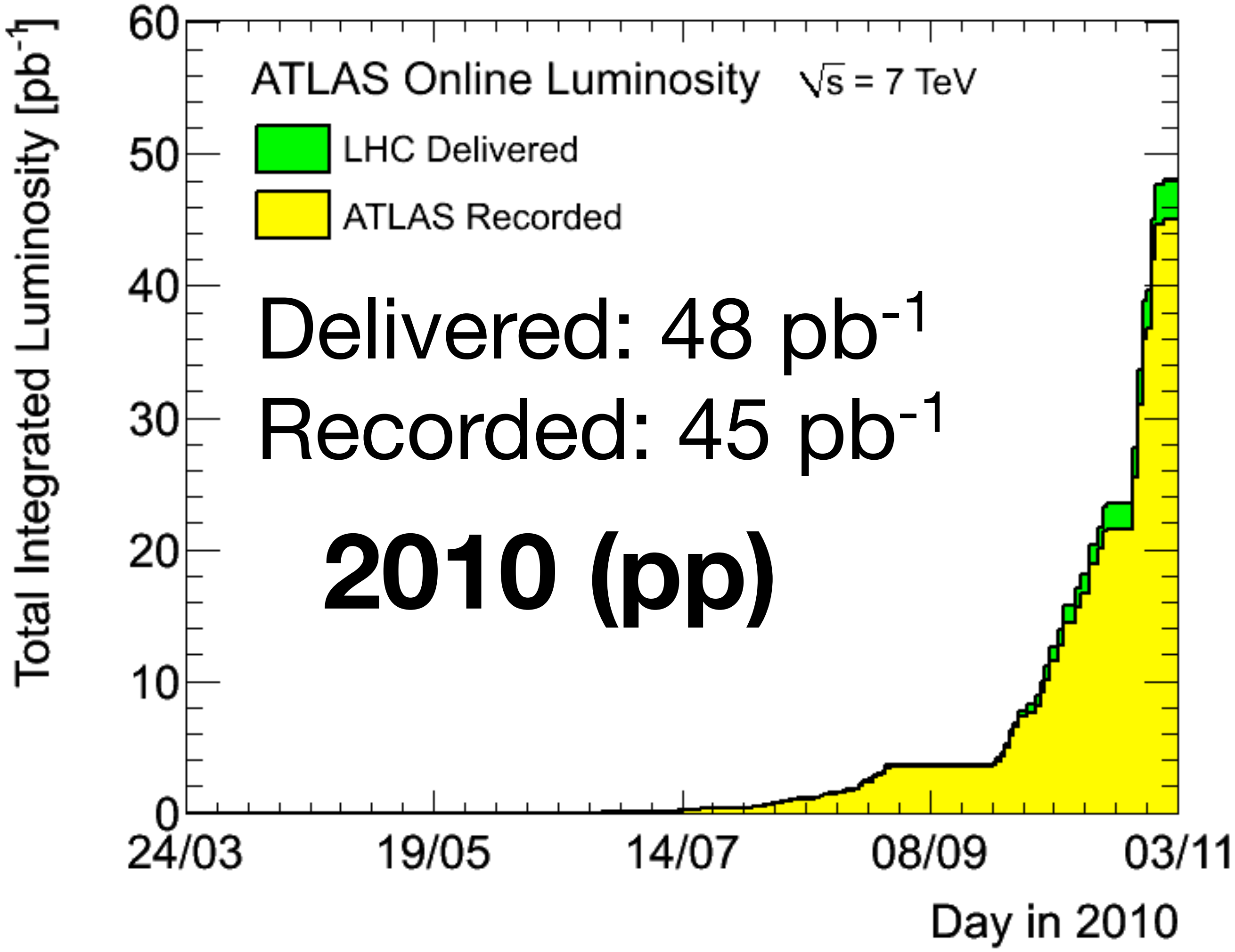
The ATLAS Experiment at the LHC

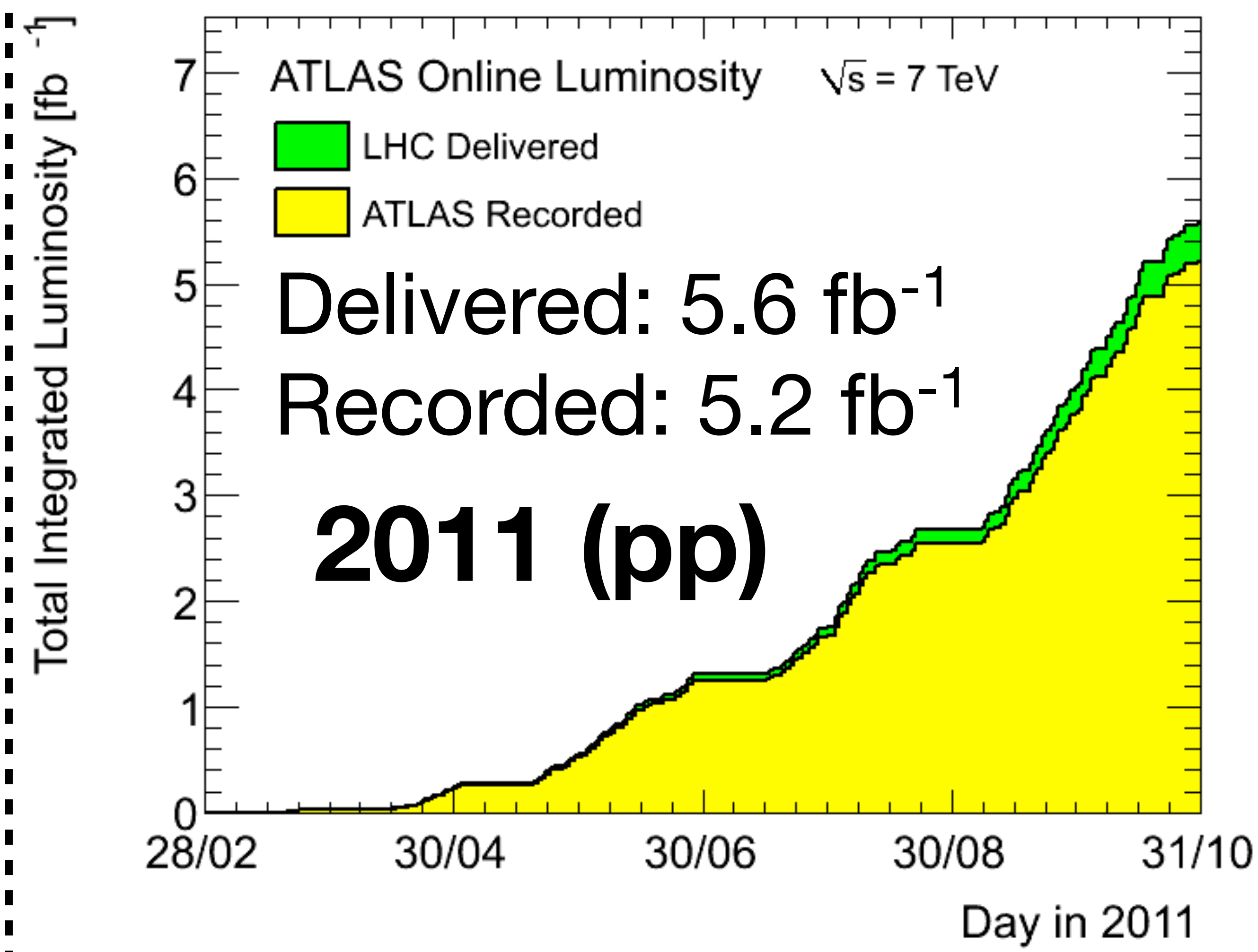
- ATLAS is a general purpose detector designed for p-p (and Pb-Pb) collisions at the LHC
- Optimized for high-p_T discovery of physics up to 10^{34} $cm^{-2}s^{-1}$ of instantaneous luminosity
- Acceptance in pseudo-rapidity (η) up to 2.5 for Inner Detector, up to 2.7 for Muon Spectrometer
- Good muon momentum resolution provided by Inner Detector combined with Muon Spectrometer measurement
- Highly selective trigger system in 3 levels
- LHC p-p run for 2011 finished, after operating at 7 TeV more than 5 fb^{-1} accumulated
- Dedicated B-Physics program





Detector readiness and data sample





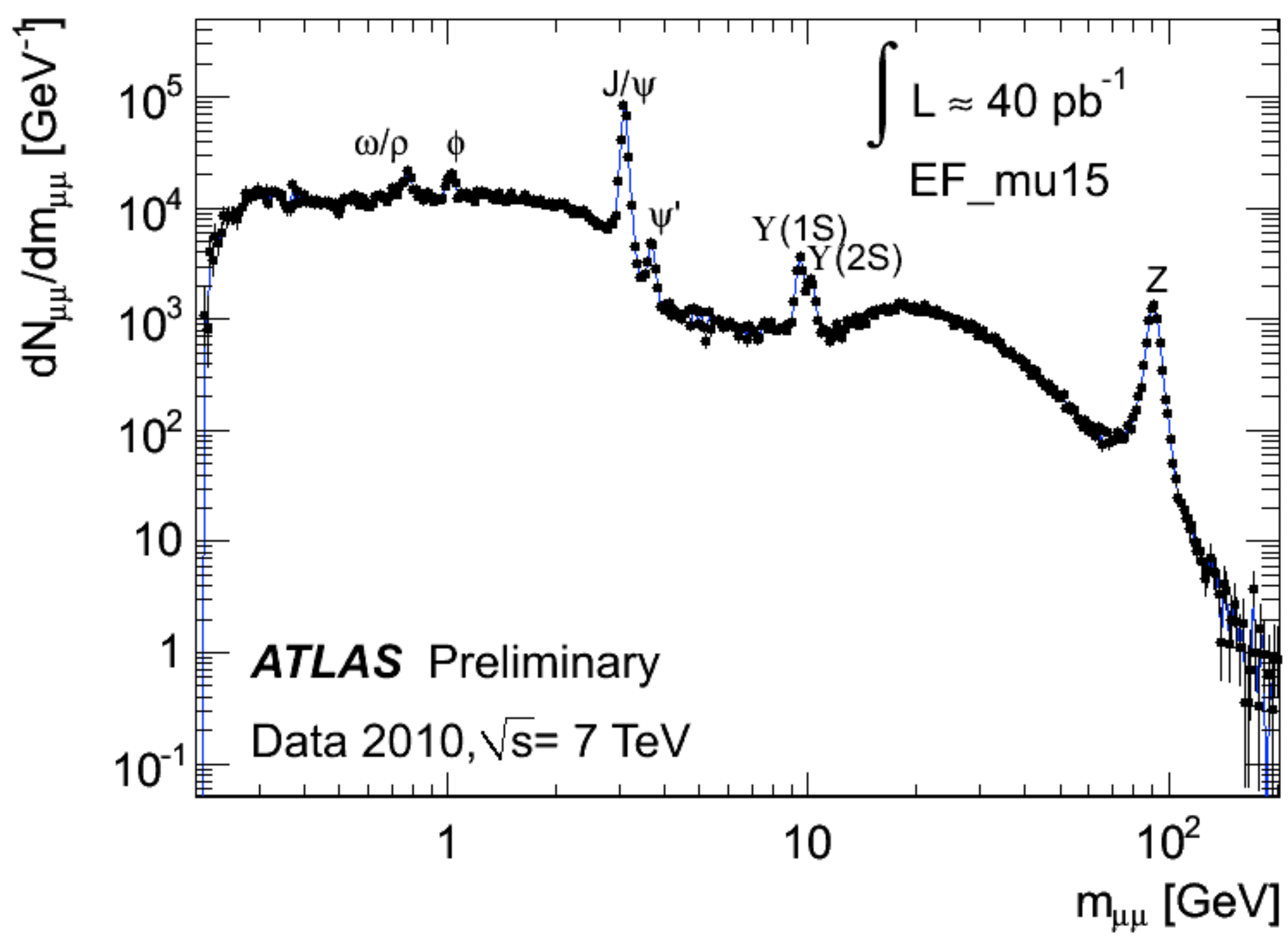
- Shown results shown were obtained from 2010 data only
- Luminosity uncertainty at 3.4%

- More interesting results expected from 2011 data analysis
- Luminosity uncertainty at 3.7%
- Peak: 3.65×10^{33} cm^{-2}s^{-1}

B-Physics Strategy

- Exploit the ability of the Muon Spectrometer to reconstruct muons with good efficiency
- Single muon triggers are effective for the low luminosity run period
- B-hadrons of low-p_T can still be reached with di-muon triggers

  - Di-muon decays of J/ψ and Υ provide a clean signature to trigger events
  - Focus on $B \to J/\psi$ exclusive decays
  - Extend discovery potential with $B \to \mu^+\mu^-$



Charm and Beauty production at hadron colliders

- **Motivation:**
  - LHC provides the chance to test pertubative (p-)QCD calculations for quarkonium and b-production at a new energy regime, higher transverse momenta and in wider rapidity range than before
  - Production mechanisms for quarkonium states (**J/ψ**, **Υ**) not clearly understood
    - Cross-section and spin-alignment measurements are needed to test existing models
    - Tevatron experiments have not provided consistent or conclusive results
  - b-jet production is an important ingredient to understand processes which represent backgrounds in searches for new physics

Charm and Beauty production via observed J/ψ

- At the LHC, J/ψ can produced:
  - **promptly** from pp collisions (or from decays of higher charmonium states like χ_c, ψ(2S))
  - indirectly from B-hadron decays (**non-prompt**)
- Measurement of inclusive J/ψ production: σ(**pp→J/ψ X**)*inclusive*
- Measurement of fraction of non-prompt J/ψ (**pp→B X'→J/ψ X"**):

$$f_B = \frac{d\sigma\left(pp \to B + X' \to J/\psi + X''\right)}{d\sigma\left(pp \to J/\psi + X\right)_{inclusive}}$$

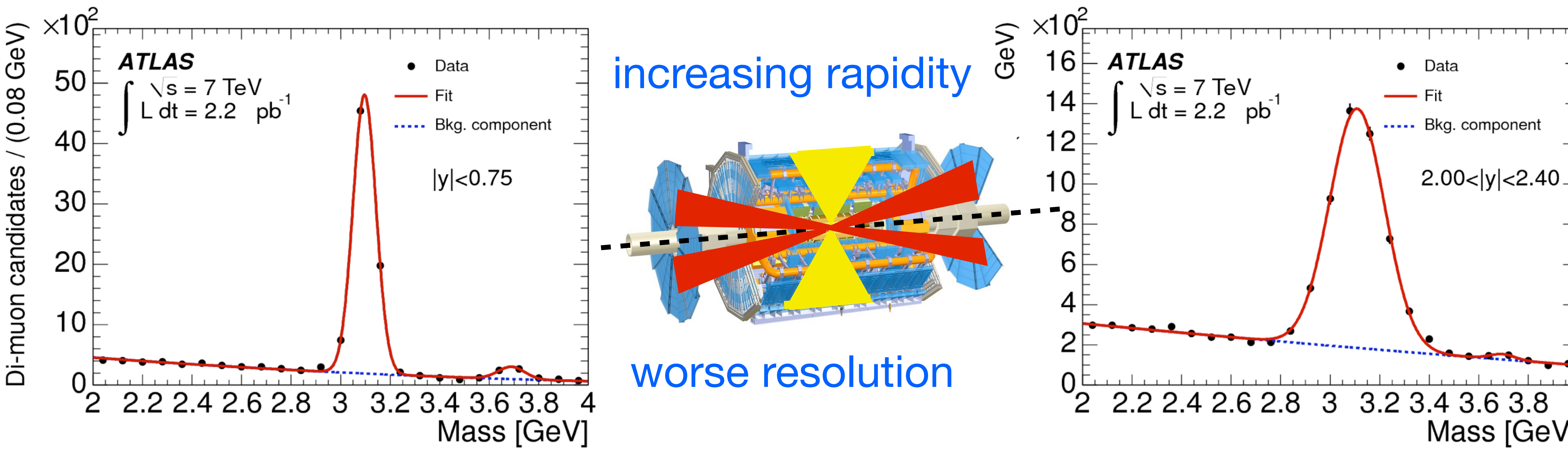
- From the two measurements, the cross-sections of *prompt* and *non-prompt* J/ψ production are extracted:

$$\sigma\left(pp \to J/\psi + X\right)_{prompt}$$

$$\sigma\left(pp \to B + X' \to J/\psi + X''\right)$$

Inclusive J/ψ production

- Trigger on single muons with p_T>4 GeV, reconstruct all muons with |p|>3 GeV
- Report results in four regions of rapidity |y|: (0,0.75) , (0.75,1.5) , (1.5,2.) , (2.,2.4)



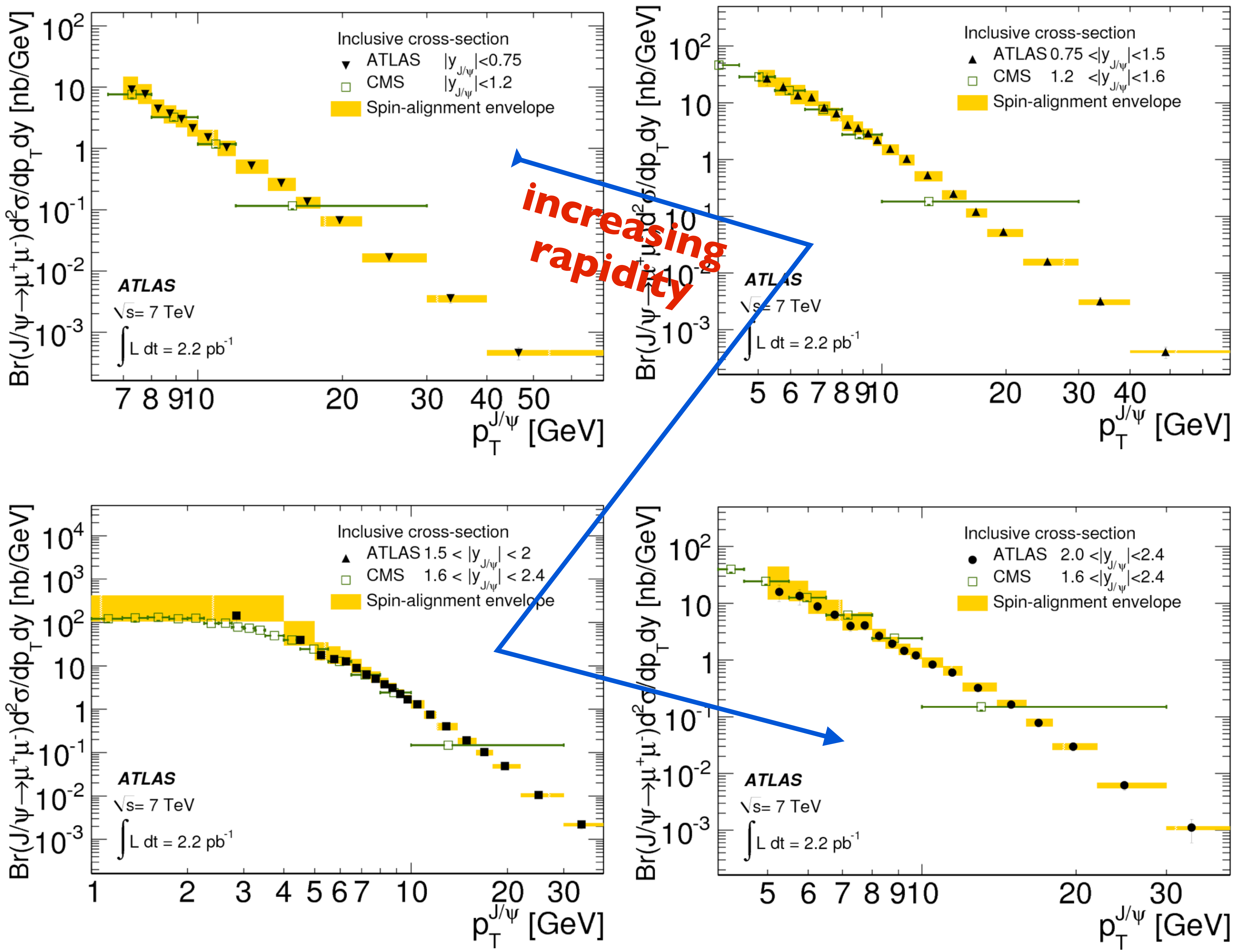
- Apply corrections to di-muon events for acceptance and efficiency
- Highest systematic from unknown spin alignment; different hypotheses create ‘envelope’ on the measured cross-section (shown with yellow band in subsequent plots)

Inclusive J/ψ production

ATLAS

polarization uncertainty

CMS

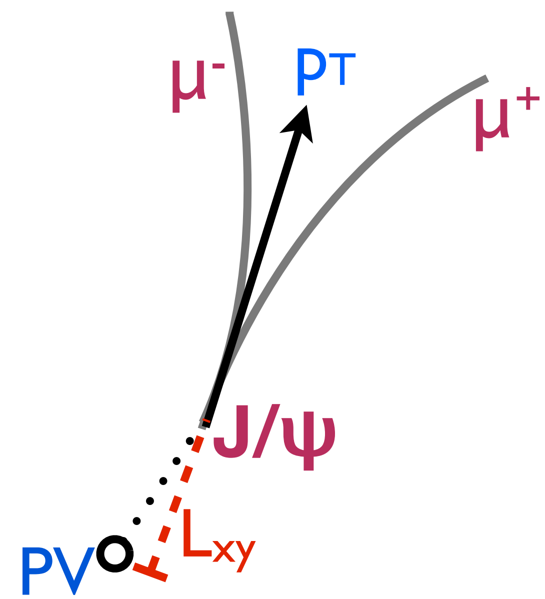


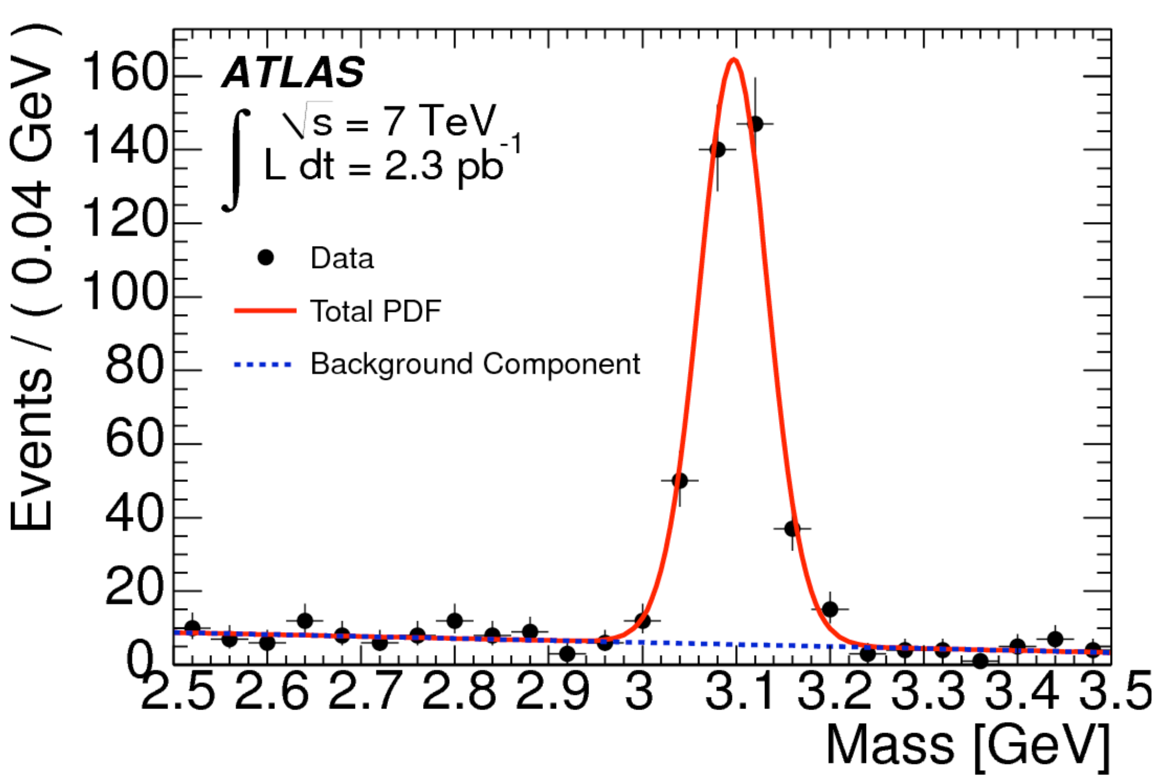
Fraction of J/ψ from B-hadron decays

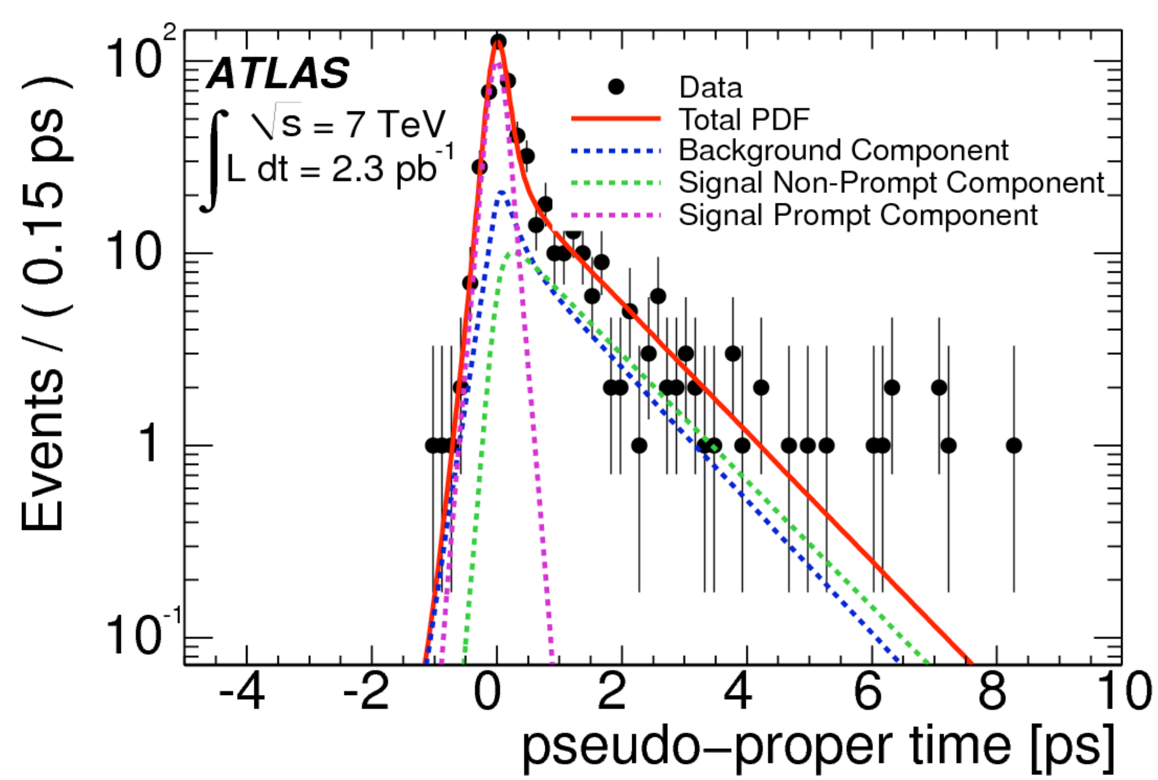
- Fraction is extracted by fitting simultaneously mass and pseudo-proper decay time of J/ψ candidates

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

distance of J/ψ decay vertex from primary vertex projected on p_T







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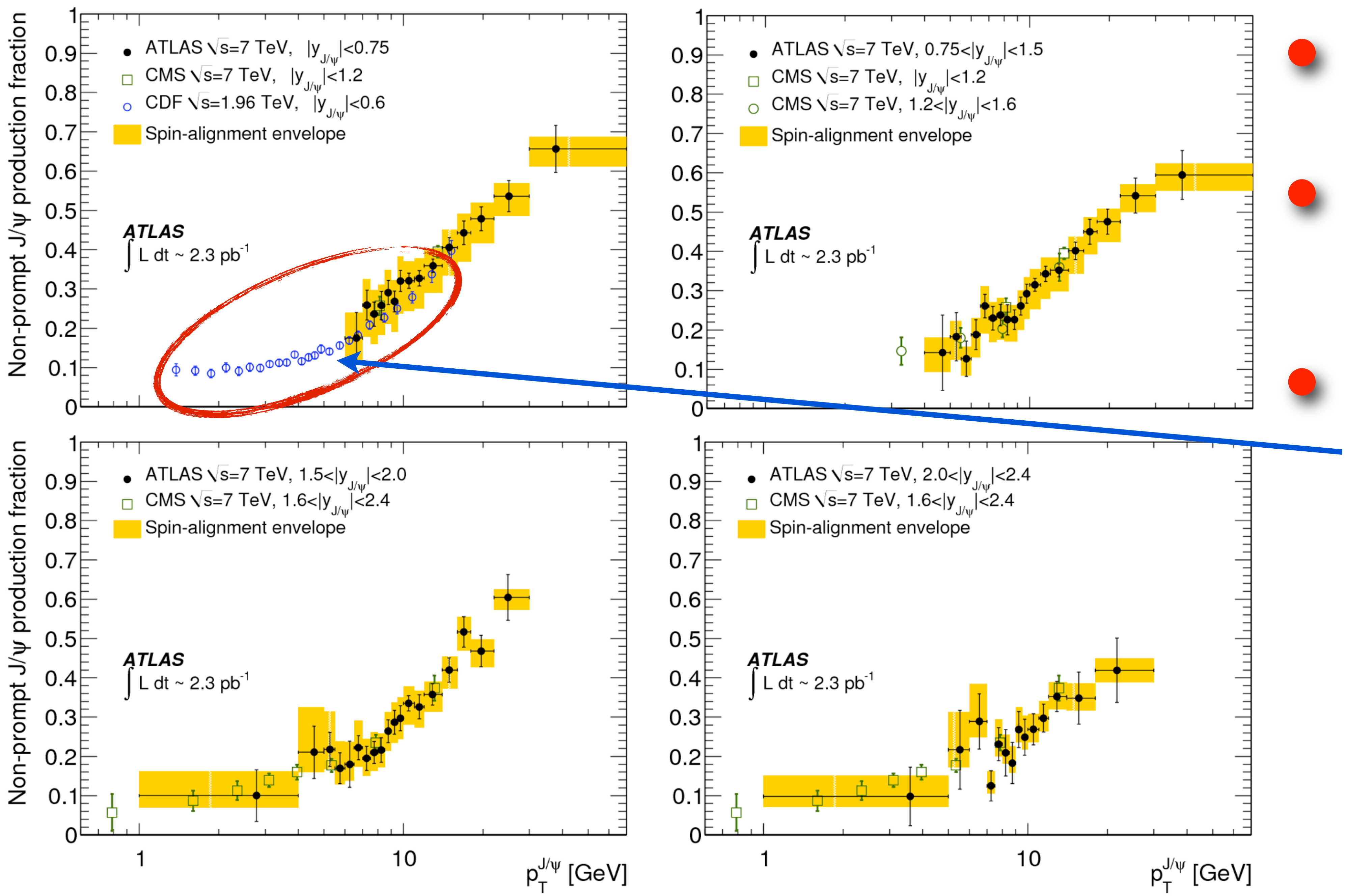


- Strong p_T dependence
- Agreement with CMS, extending p_T coverage
- Agreement with CDF, no dependence on collision energy

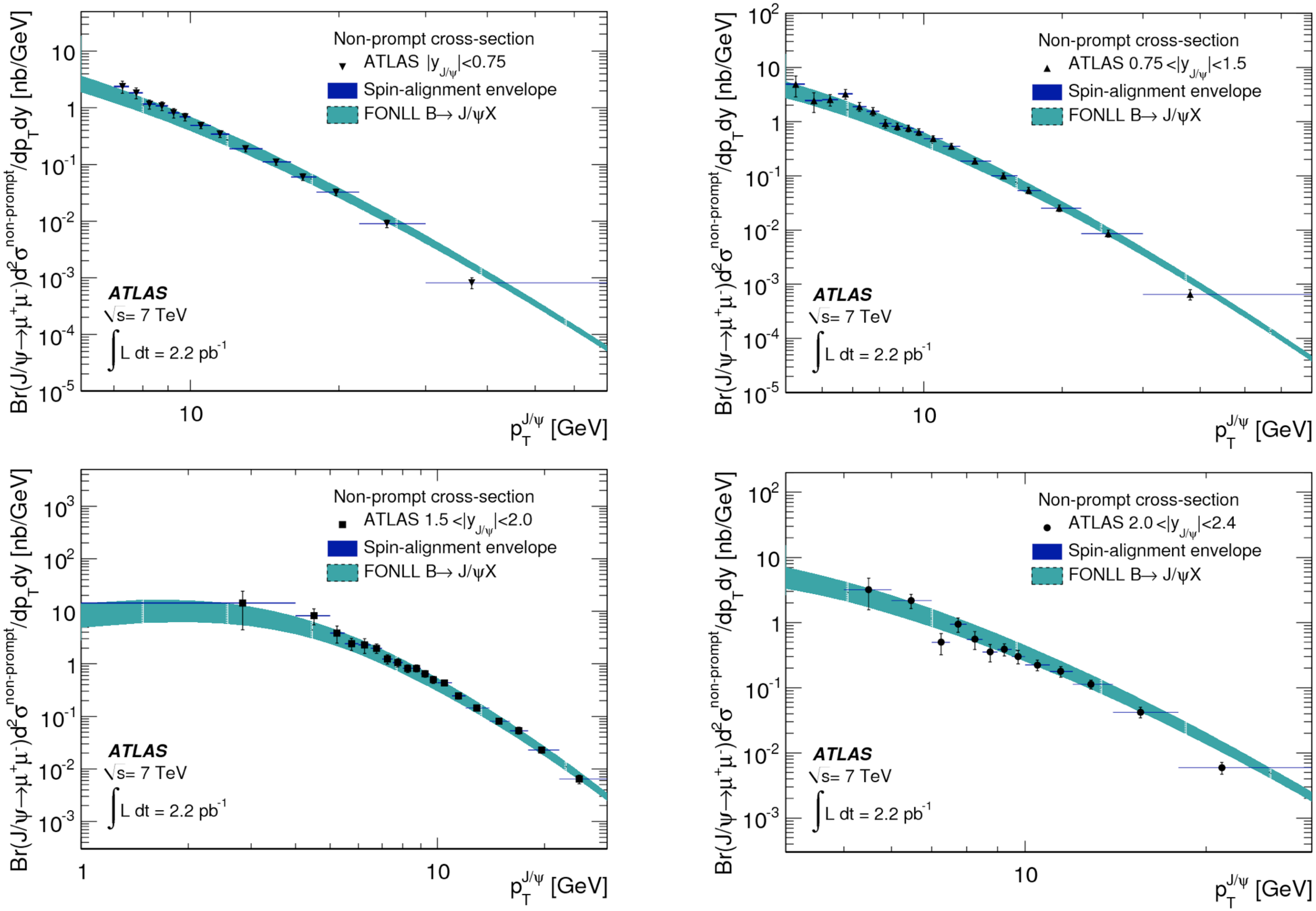
ATLAS
CMS
CDF

Cross-section of non-prompt J/ψ

- Good agreement with theory (Fixed Order Next-to-Leading Logarithm, FONLL)

ATLAS

theoretical uncertainty



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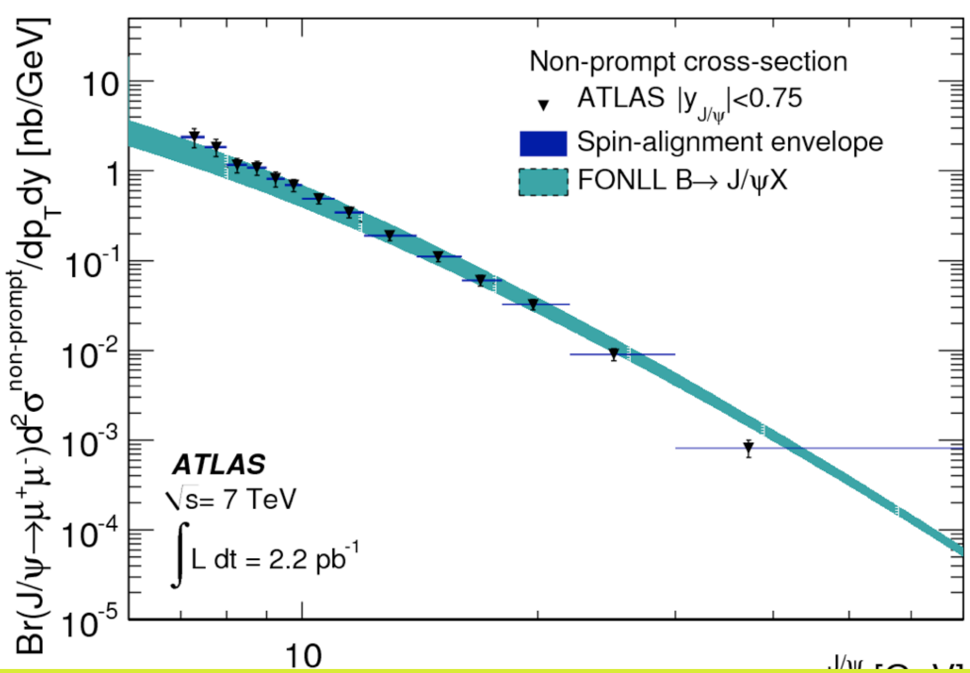
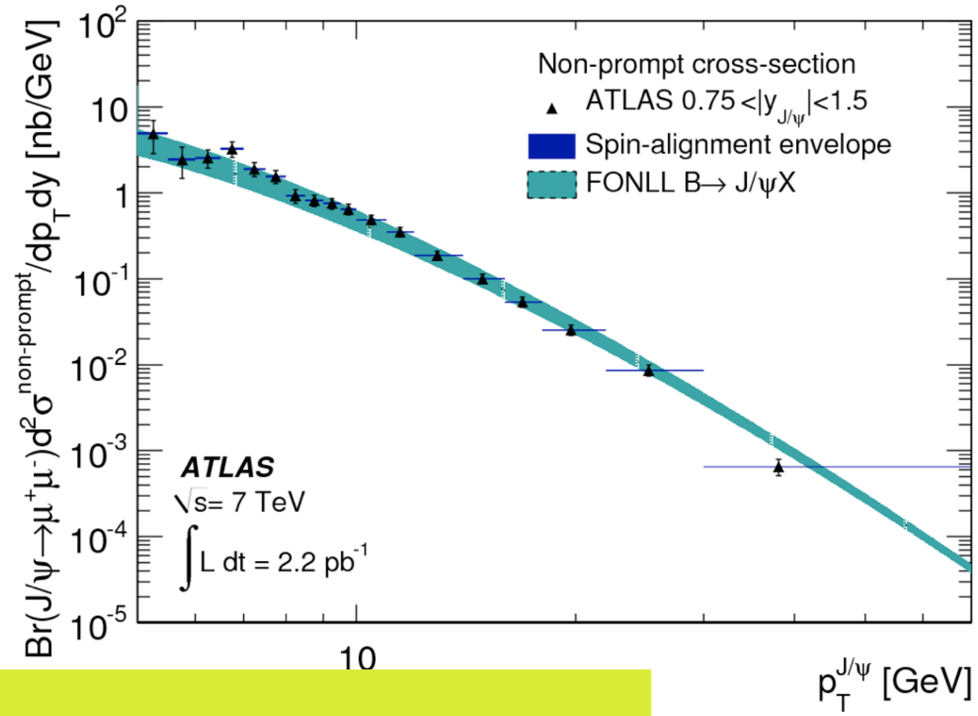
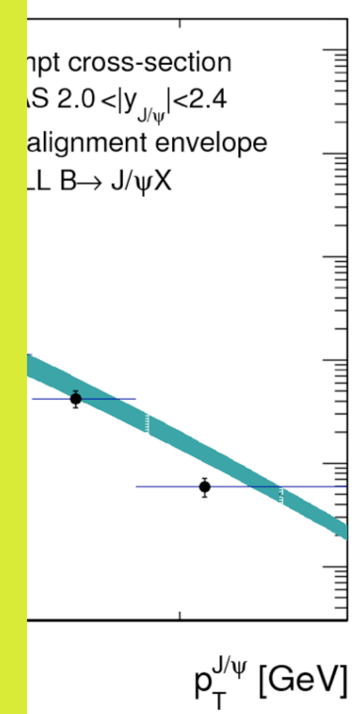






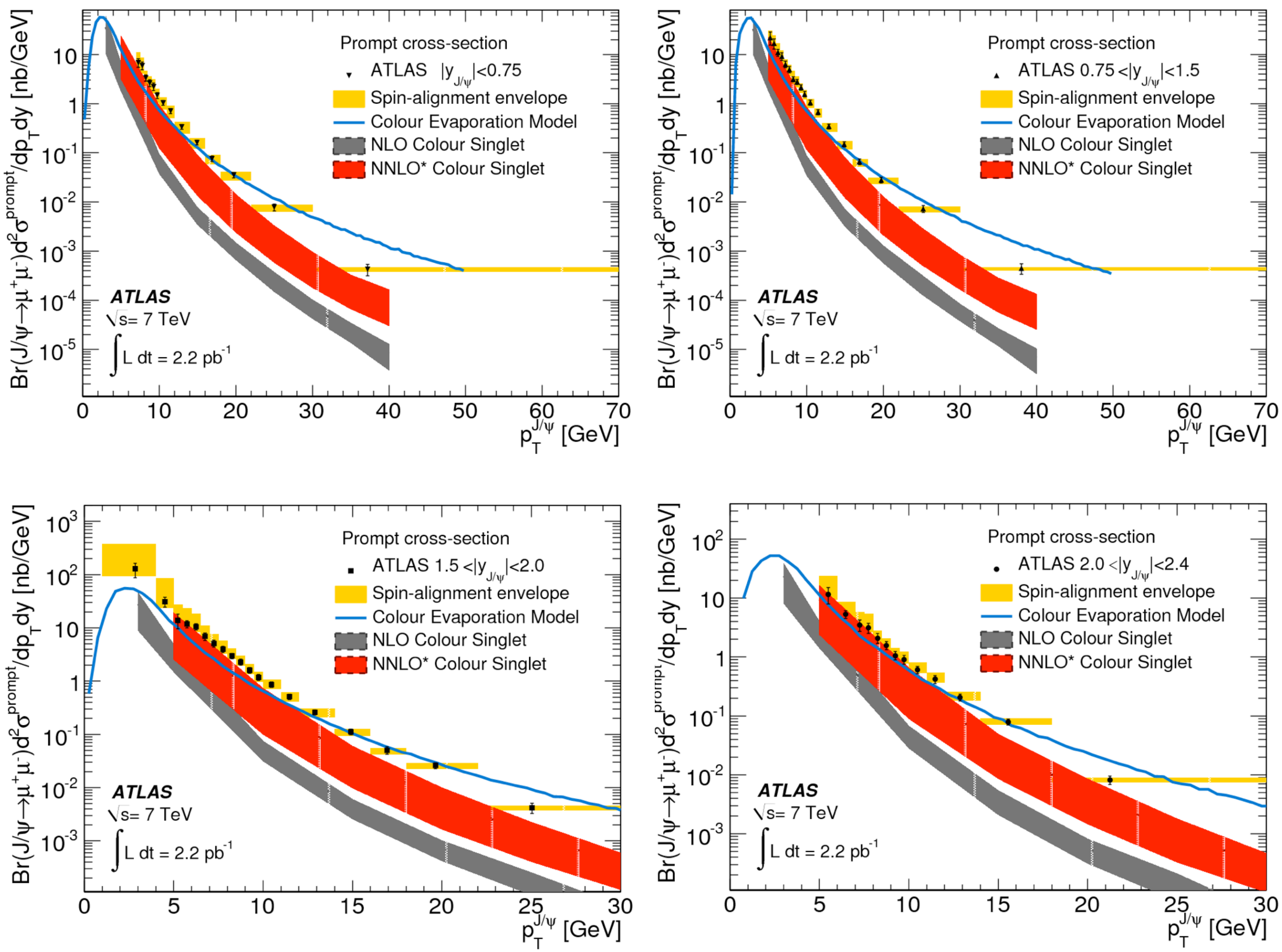
$$Br(J/\psi \to \mu^+\mu^-)\sigma(pp \to B + X \to J/\psi X; |y_{J/\psi}| < 2.4, p_T^{J/\psi} > 7\ \text{GeV}) = 23.0 \pm 0.6\ (\text{stat.}) \pm 2.8 (\text{syst.}) \pm 0.2\ (\text{spin}) \pm 0.8\ (\text{lumi.})\ \text{nb}$$

- *13% measurement*

$$Br(J/\psi \to \mu^+\mu^-)\sigma(pp \to B + X \to J/\psi X; 1.5 < |y_{J/\psi}| < 2, p_T^{J/\psi} > 1\ \text{GeV}) = 61 \pm 24\ (\text{stat.}) \pm 19\ (\text{syst.}) \pm 1\ (\text{spin}) \pm 2\ (\text{lumi.})\ \text{nb}$$

Cross-section of prompt J/ψ

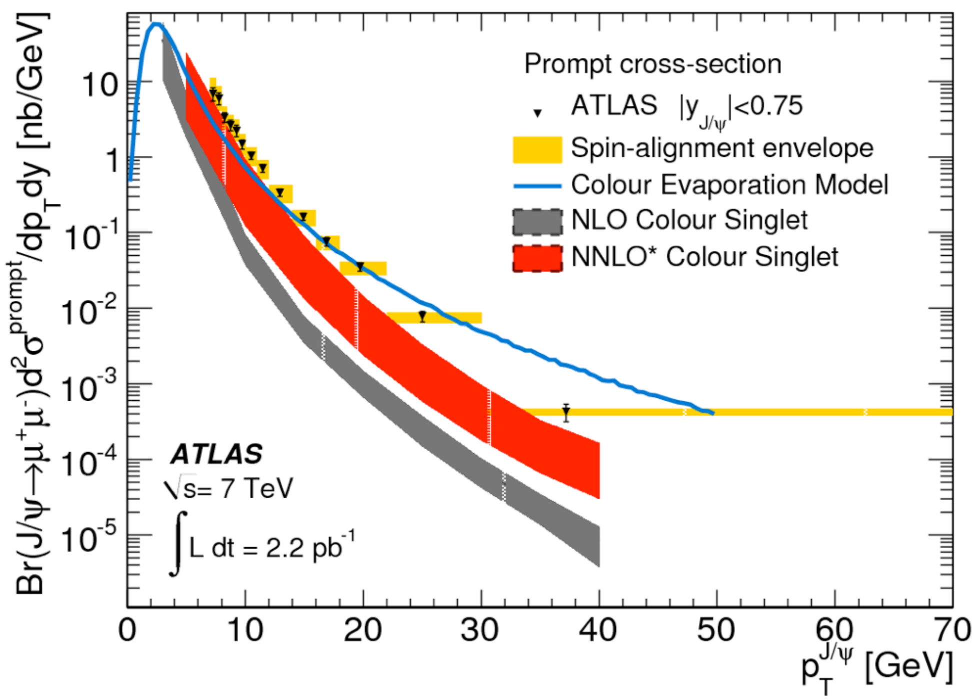
- Great theoretical interest in this measurement

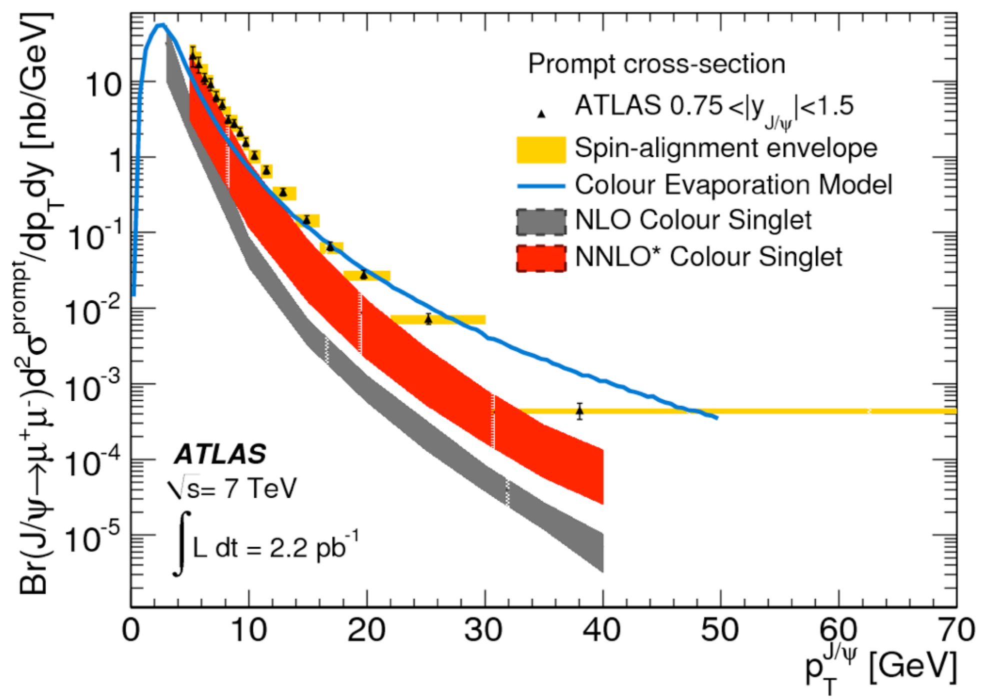


- Colour Evaporation Model (**CEM**) is not describing shape
- Colour Singlet Model (CSM) is low in absolute scale for NLO but good in shape
- CSM NNLO* calculation is significantly improved

Cross-section of prompt J/ψ

- Great theoretical interest in this measurement





- Colour Evaporation Model (**CEM**) is not describing shape
- Colour Singlet Model (CSM) is low in absolute scale for NLO but good in shape
- CSM NNLO* calculation is significantly improved

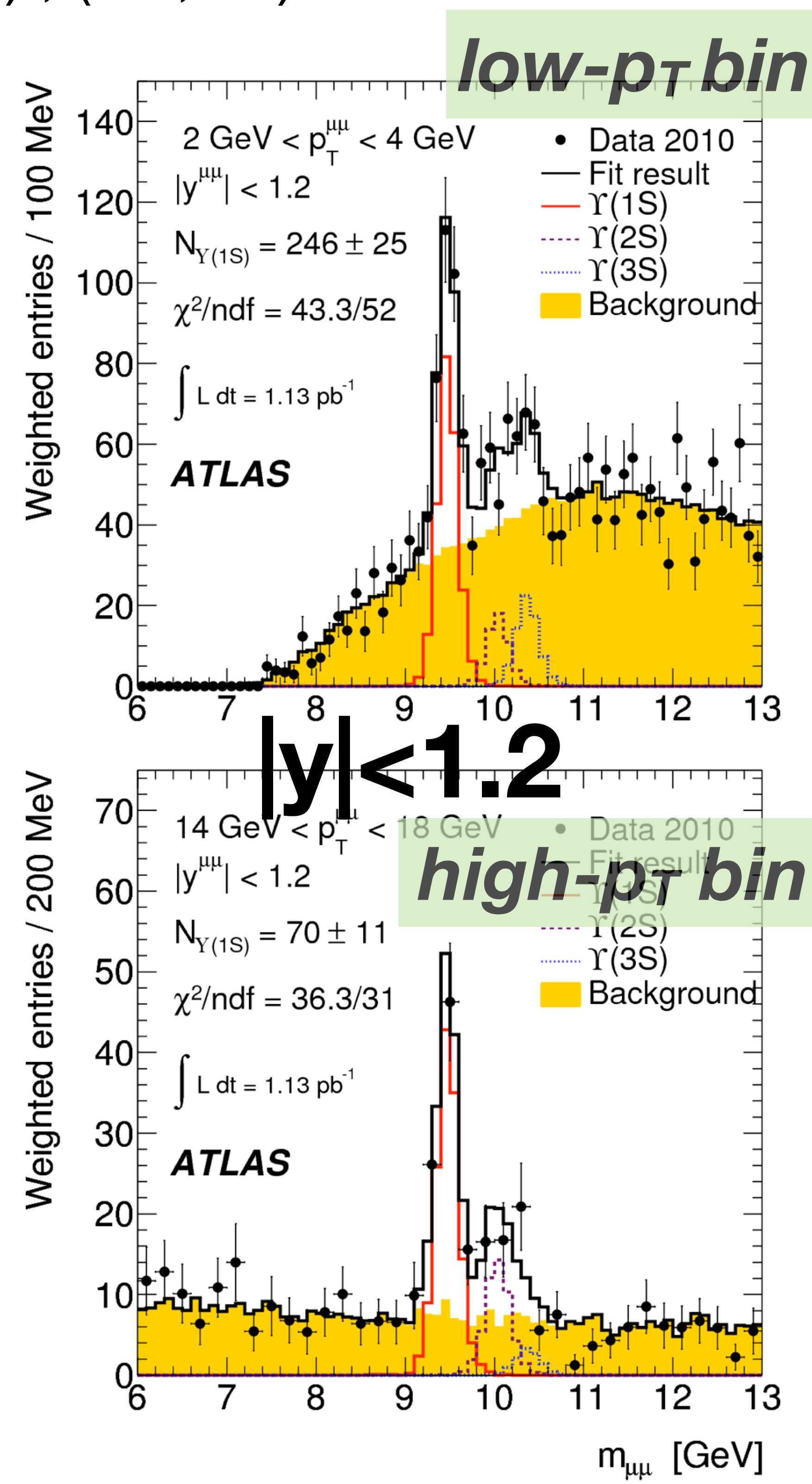
$$Br(J/\psi \to \mu^+\mu^-)\sigma(pp \to \text{prompt } J/\psi X; |y| < 2.4, p_T > 7\text{ GeV})$$
$$= 59 \pm 1\text{ (stat.)} \pm 8\text{(syst.)} \pm {}^{9}_{6}\text{ (spin)} \pm 2\text{ (lumi.) nb}$$

- *21% measurement*

$$Br(J/\psi \to \mu^+\mu^-)\sigma(pp \to \text{prompt } J/\psi X; 1.5 < |y| < 2, p_T > 1\text{ GeV})$$
$$= 450 \pm 70\text{ (stat.)} \pm^{90}_{110}\text{ (syst.)} \pm {}^{740}_{110}\text{ (spin)} \pm 20\text{ (lumi.) nb}$$

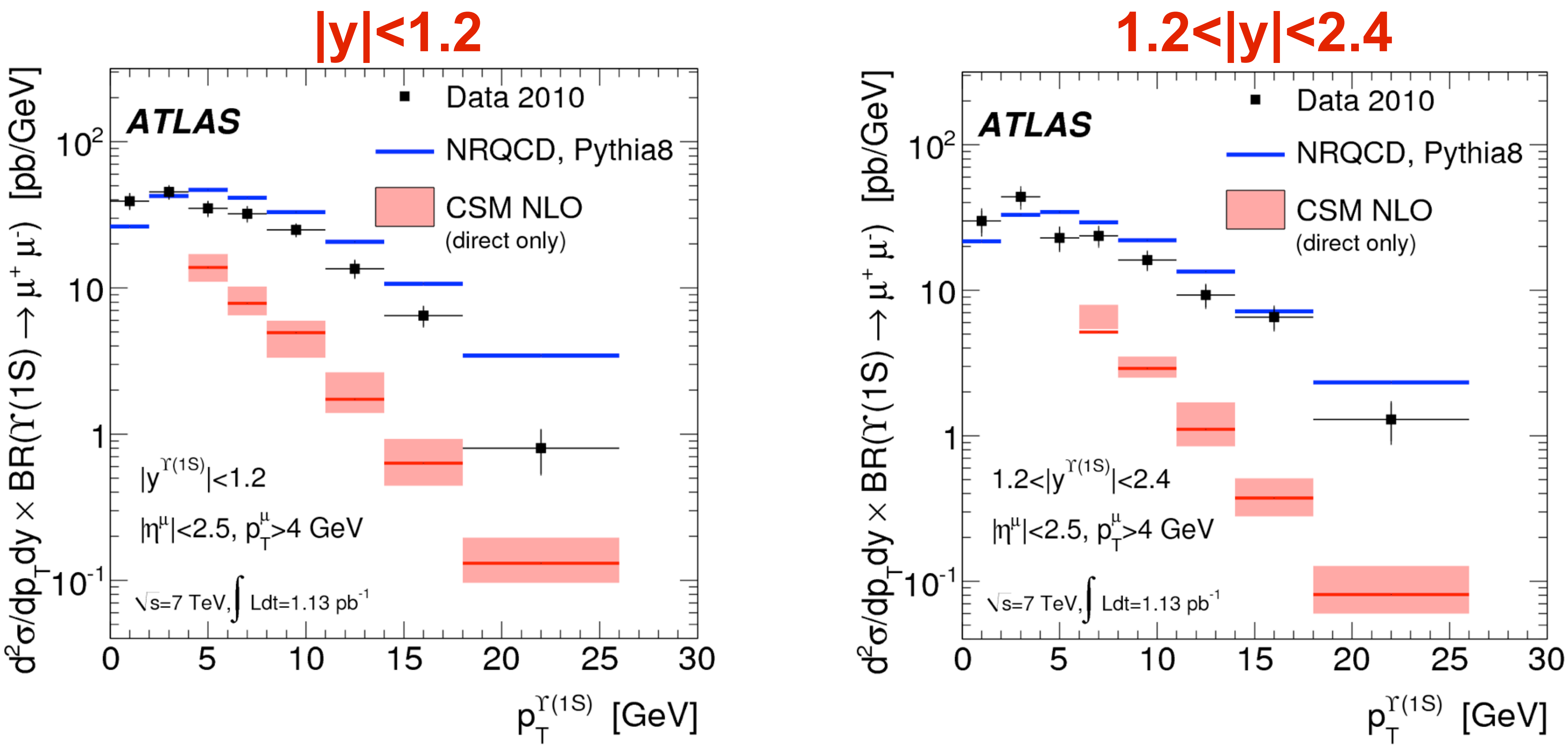
Υ production cross-section

- Report results in two regions of rapidity |y|: (0,1.2) , (1.2,2.4)
- Only yield of Υ(1S) is extracted
- Background fit using templates from data (muon+track, oppositely signed)
- Di-muon events are being corrected for acceptance and efficiency
- “High”-p_T (>4 GeV) muons required, in this phase space uncertainty from unknown Υ spin-alignment is negligible



Y production cross-section

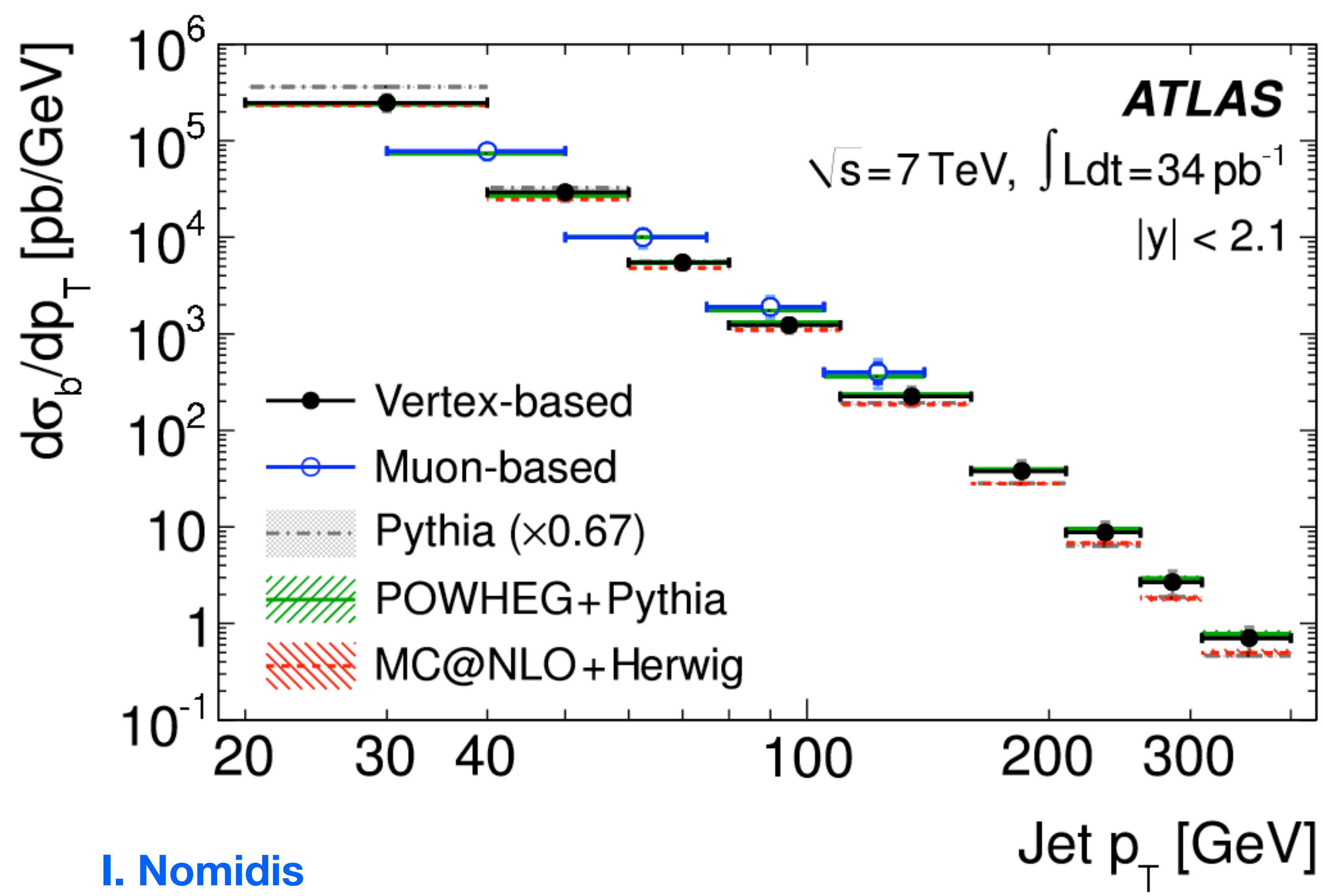
- Uncertainty of measurement is 10-15% at low p_T, 35% at high p_T
- PYTHIA8 implementation of Non-Relativistic (NR) QCD gives reasonable predictions, p_T dependance is not well described
- CSM NLO prediction is low **but** refers only to direct production; higher order corrections and/or addition of feed-down from higher order states needed



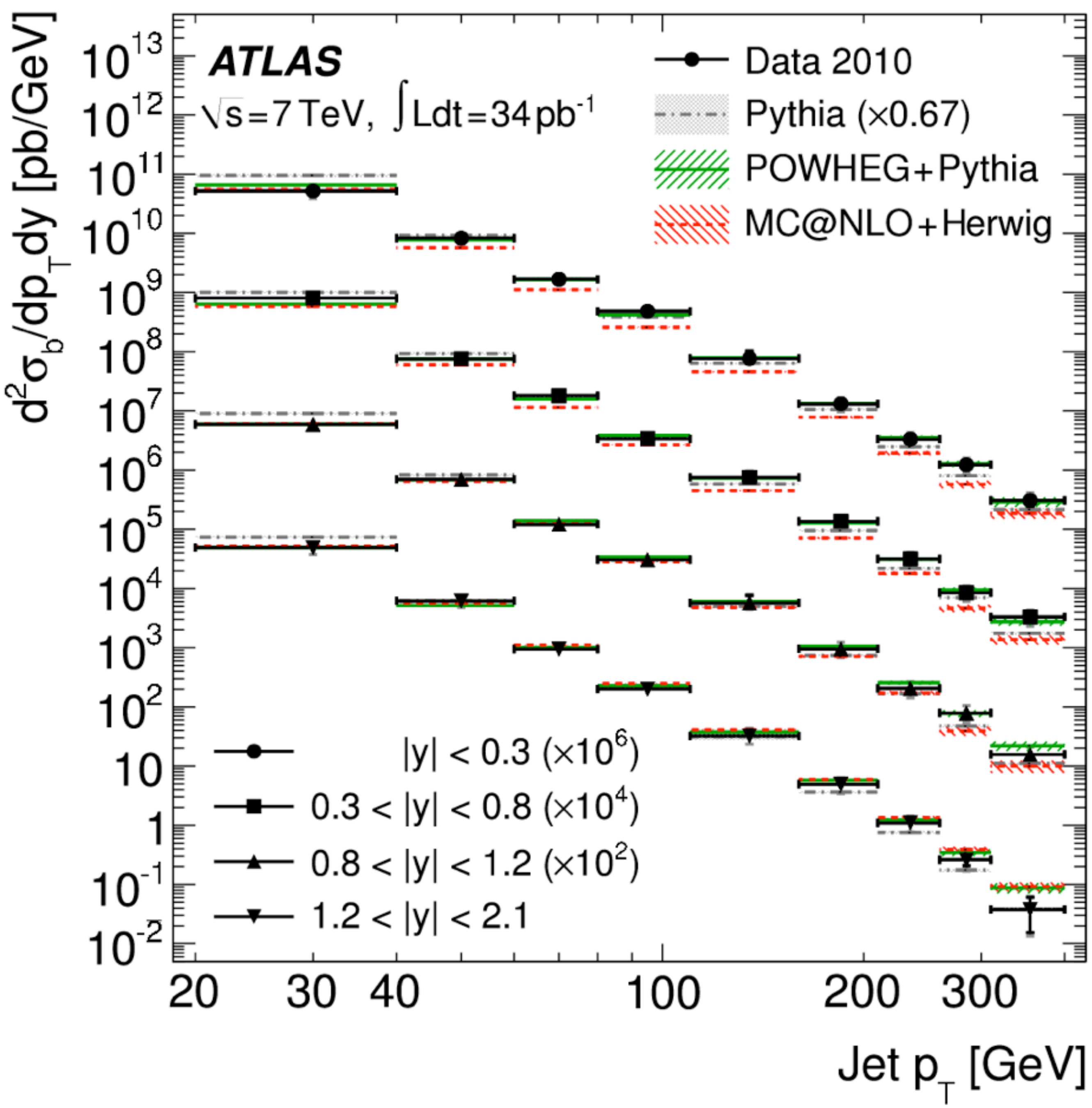
Inclusive b cross-section by b-tagged jets

- b-jets are 3.5-5% of all jets
- Two methods for b-tagging
  - Search for ***displaced vertex***, calculating the invariant mass of associated tracks
  - Search for ***muon*** inside jet, could be from B semi-leptonic decay ($B \rightarrow \mu\ \nu\ X$), calculating the muon p_T w.r.t. the jet axis
- The two tagging approaches are consistent

See ATLAS talk of A.Favareto (Wednesday) for b-tagging performance



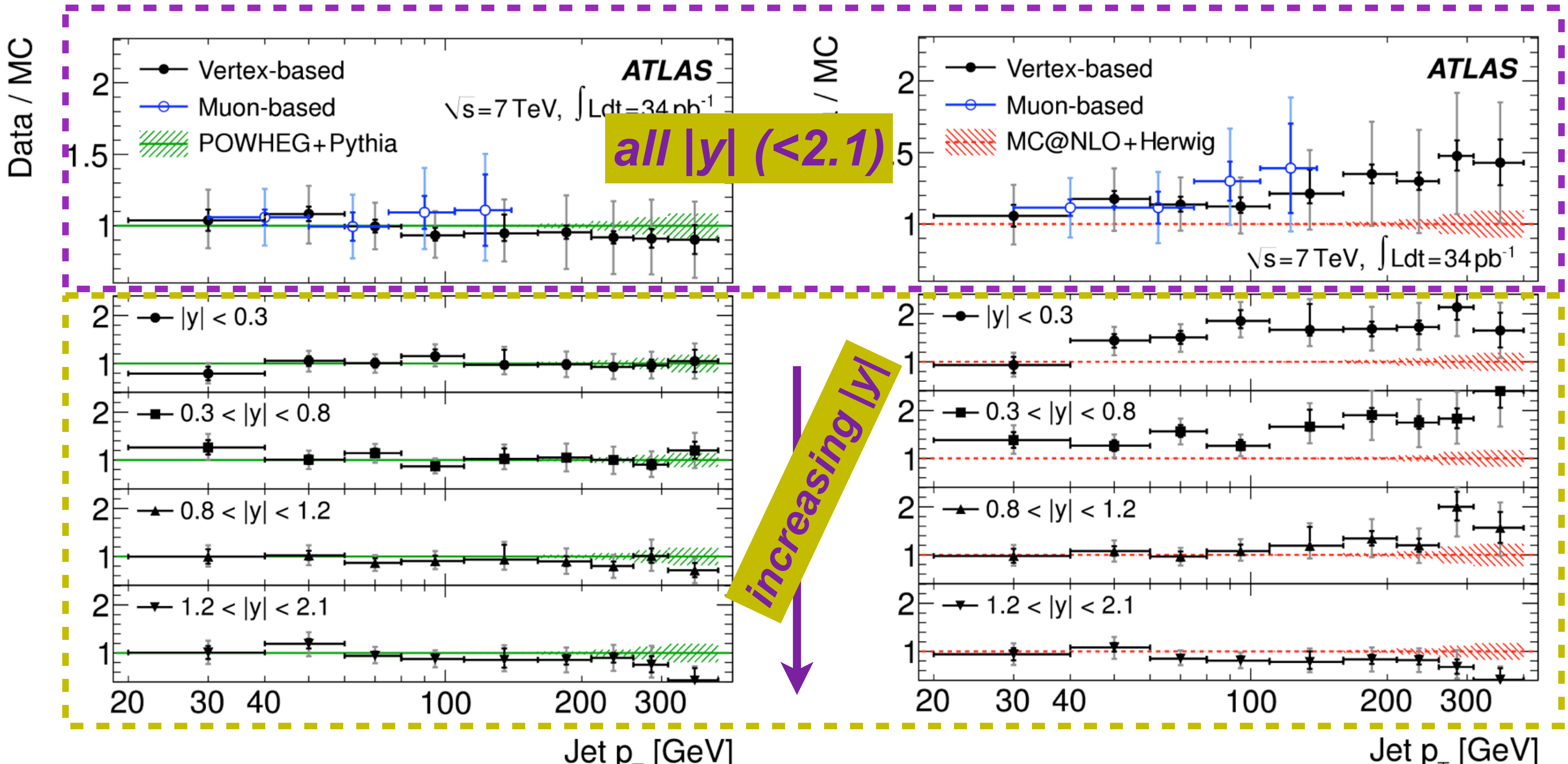
Inclusive b-jet cross-section vs y, p_T



- Results in four rapidity regions
- **Pythia** (LO) is higher by factor of 1.5 but shape is fine
- Both **PowHeg** and **MC@NLO** predictions are in reasonable agreement with data

Inclusive b-jet cross-section vs p_T, data vs MC

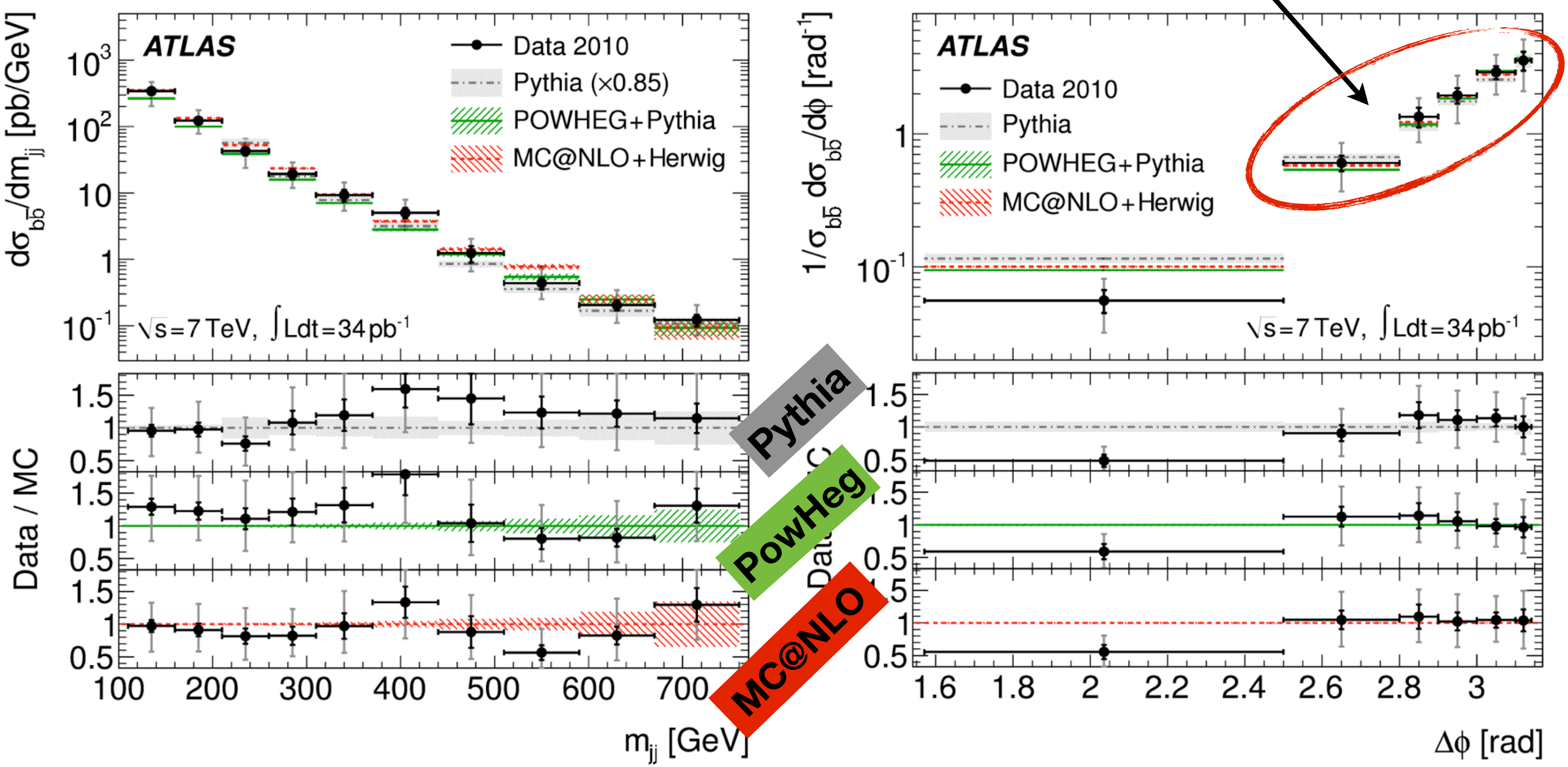
- The two b-tagging approaches are consistent (compared at the full y-acceptance)
- PowHeg+Pythia predictions are good in all rapidity regions
- MC@NLO predicts different behaviour at high-p_T (partly due to Herwig, possibly)



Inclusive $b\bar{b}$ di-jet cross-section vs inv.mass, $\Delta\varphi$

- **correlations in $b\bar{b}$ production**

- *di-jet mass*: All theory predictions compatible with measured cross-sections
- *di-jet azimuthal angle*: enhanced back-to-back behaviour is well reproduced by all generators

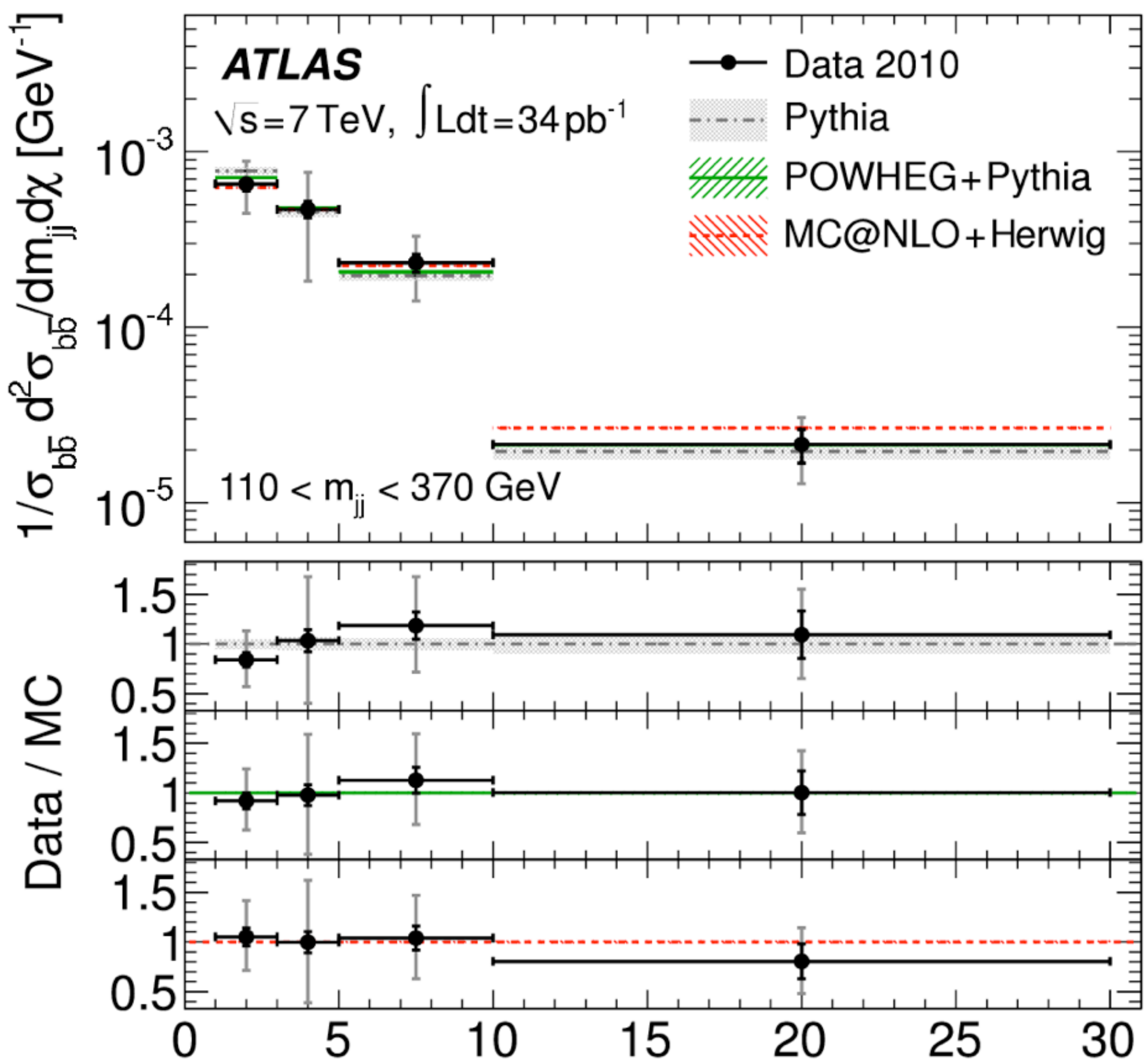


Inclusive $b\bar{b}$ di-jet cross-section vs χ

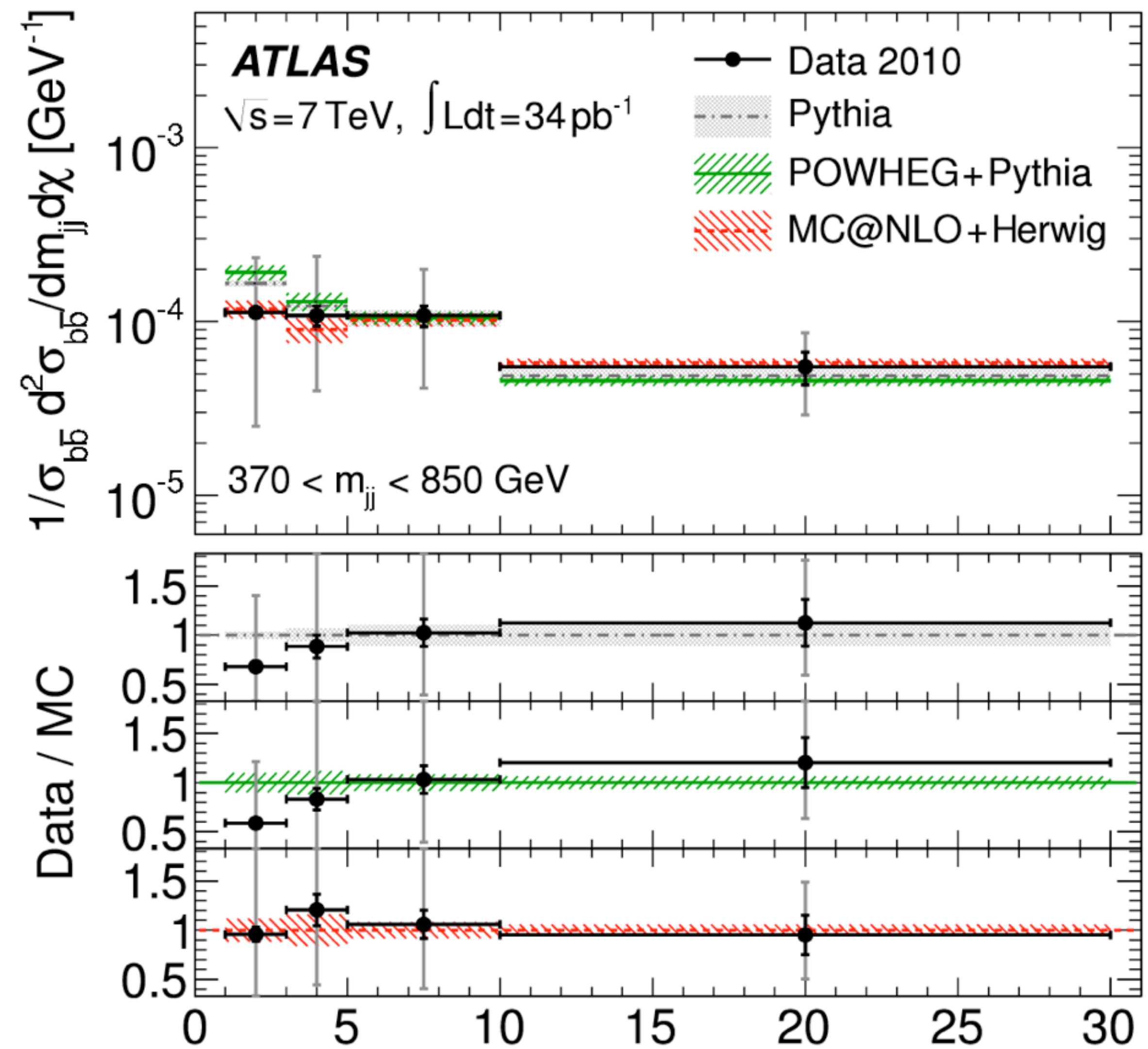
$$\chi = \exp(|y_1| - |y_2|)$$

- **correlations in $b\bar{b}$ production**

- *di-jet χ*: Cross-section obtained in two di-jet mass bins; in quite good agreement with both Pythia and NLO predictions but dominated by systematic uncertainties



low-mass bin



high-mass bin

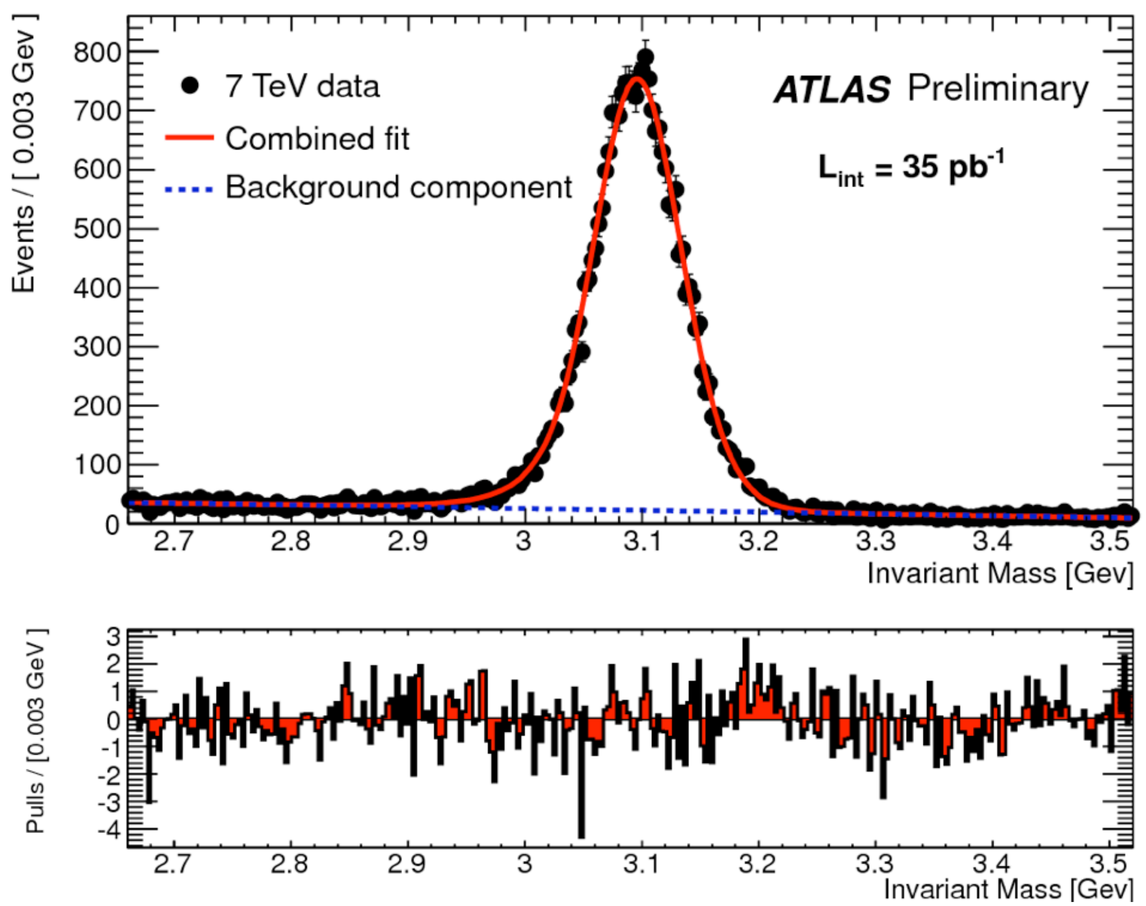
B-hadron lifetimes

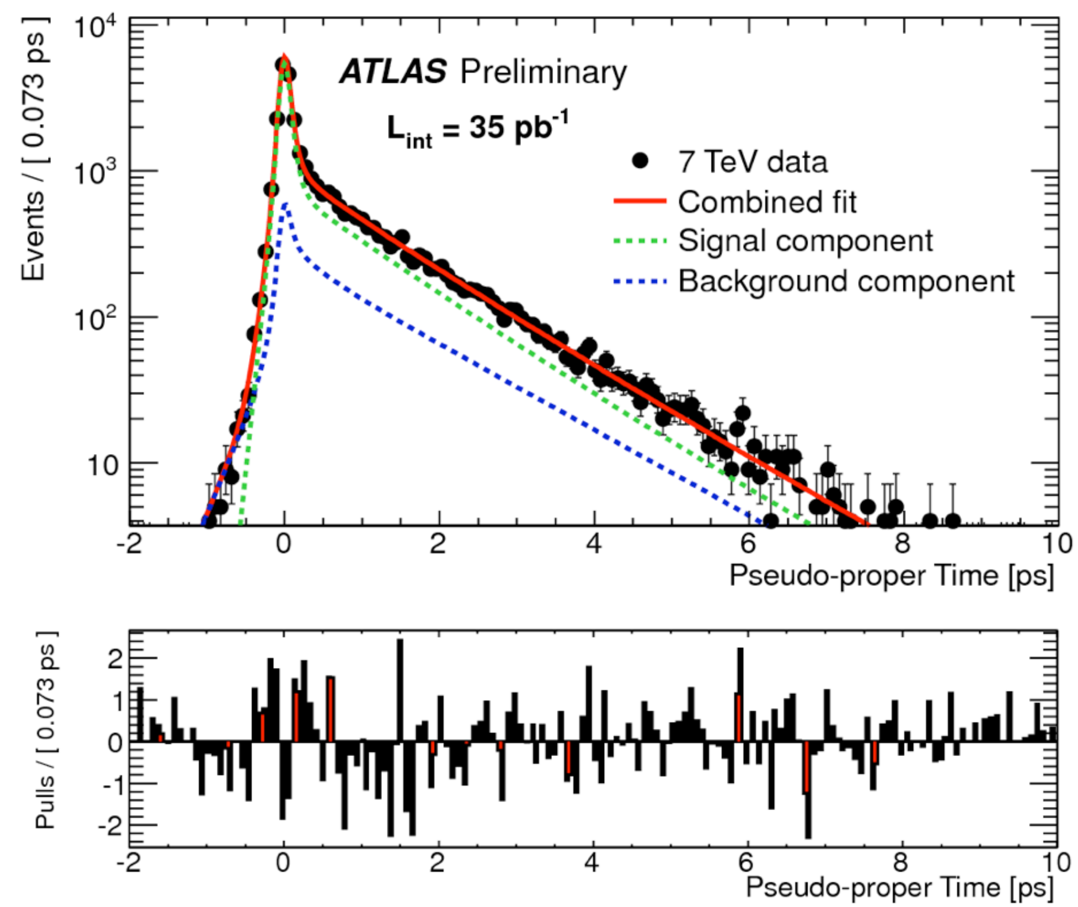
- **Motivation:**
    - Test theoretical predictions of Heavy Quark Expansion Theory (HQET)
    - Precise measurements of lifetime ratios of different B-hadron species
    - Measurement of lifetime difference $\Delta\Gamma_s$ in the B_s system (double lifetime)

- Validation of tracking and secondary vertex finding (resolution, alignment, calibration):
    - with lifetime measurement of inclusive $B \rightarrow J/\psi\ X$ decays
    - with lifetime measurement of exclusive B hadron decays

Average B-hadron lifetime

- ...with inclusive J/ψ sample, extract average B-lifetime from B→J/ψ X decays





- Result (in agreement with CDF measurement):
  $< \tau_B > = 1.489 \pm 0.016$ (stat.) ± 0.043 (syst.) ps
- Expectation from world averaged lifetimes and production fractions for different B-hadron species: $< \tau_{exp} > = f_u\tau_u + f_d\tau_d + f_s\tau_s + f_\Lambda\tau_\Lambda = 1.544 \pm 0.014$ ps
- Dominant systematics are background fit model and detector misalignment

B^0, B_s lifetime

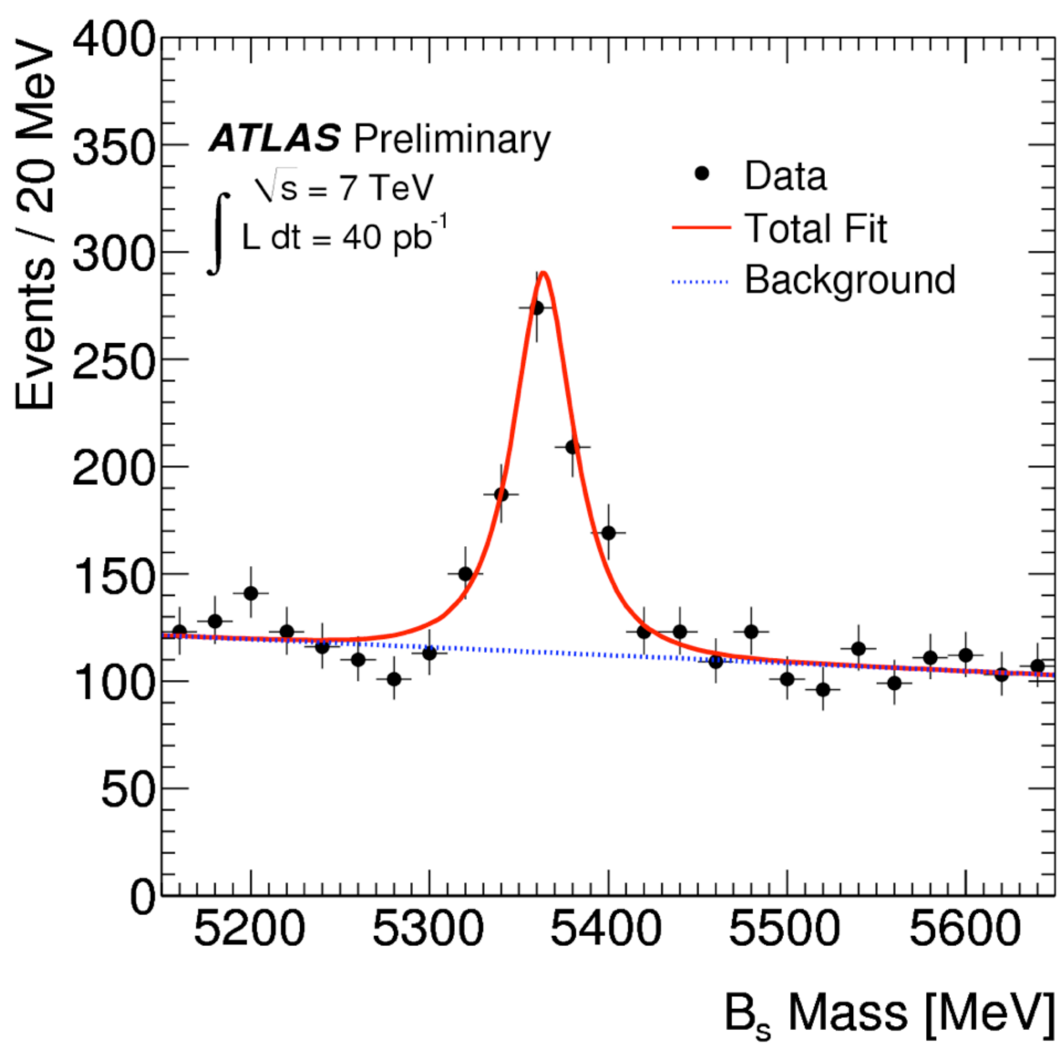
- in the exclusive channel $B^0 \to J/\psi\ K^*$ (~2750 signal events)

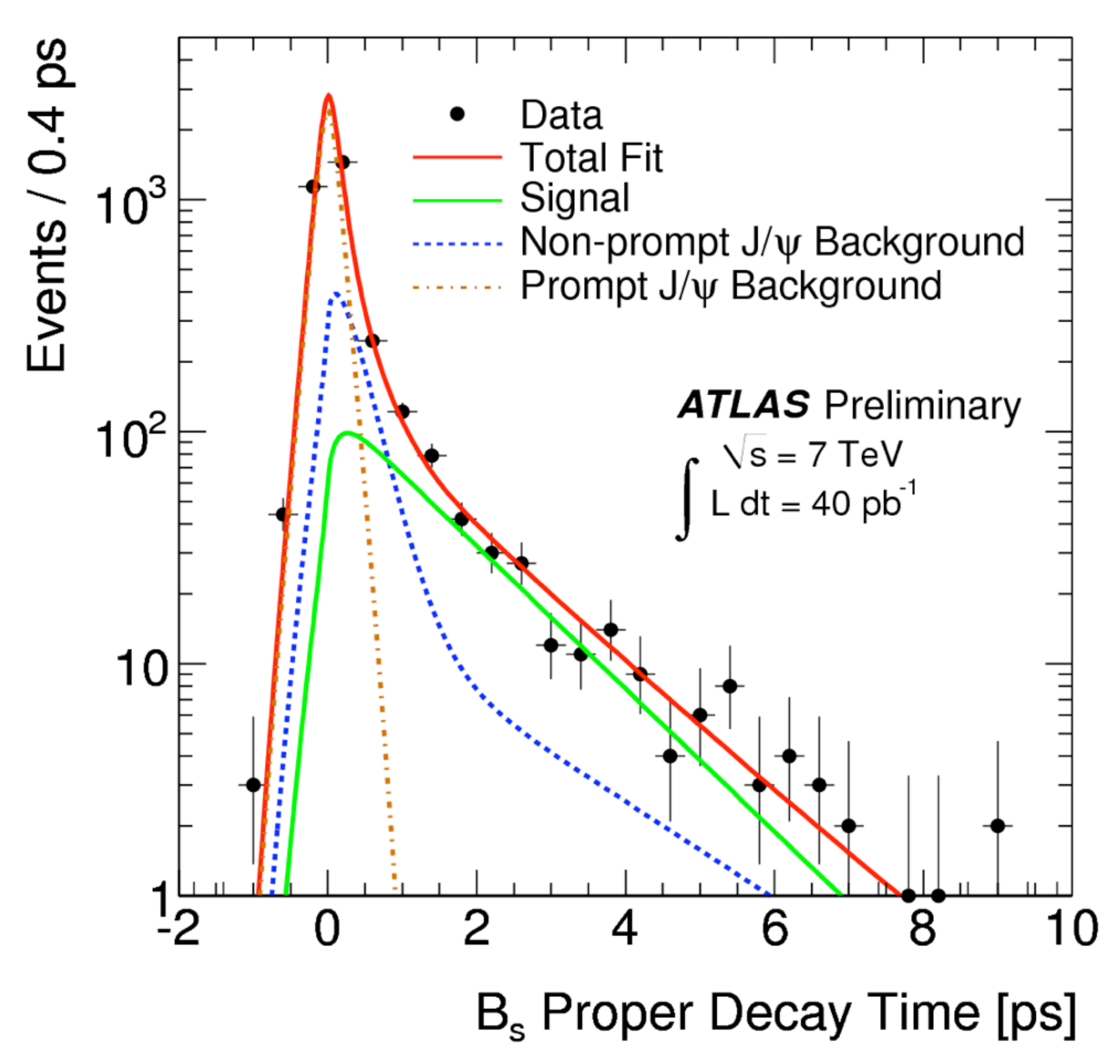
$$\tau_{Bd} = 1.51 \pm 0.04\ (\text{stat.}) \pm 0.04\ (\text{syst.})\ \text{ps}$$

- in the exclusive channel $B_s \to J/\psi\ \varphi$ (~463 signal events)

$$\tau_{Bs}\ (\text{single}) = 1.41 \pm 0.08\ (\text{stat.}) \pm 0.05\ (\text{syst.})\ \text{ps}$$

good agreement with world averaged values





B^0, B_s lifetime

- in the exclusive channel $B^0 \to J/\psi K^*$ (~2750 signal events)

  τ_{Bd} = 1.51 ± 0.04 (stat.) ± 0.04 (syst.) ps

- in the exclusive channel $B_s \to J/\psi \varphi$ (~463 signal events)

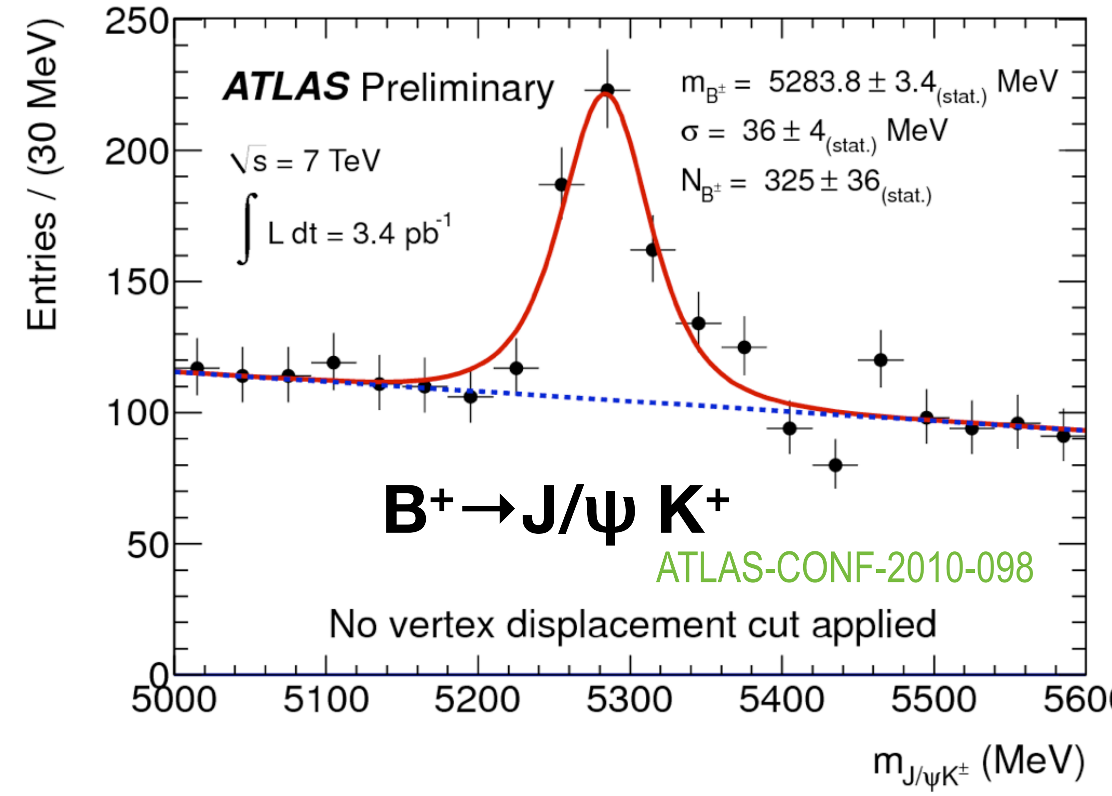
  τ_{Bs} (single) = 1.41 ± 0.08 (stat.) ± 0.05 (syst.) ps

good agreement with world averaged values

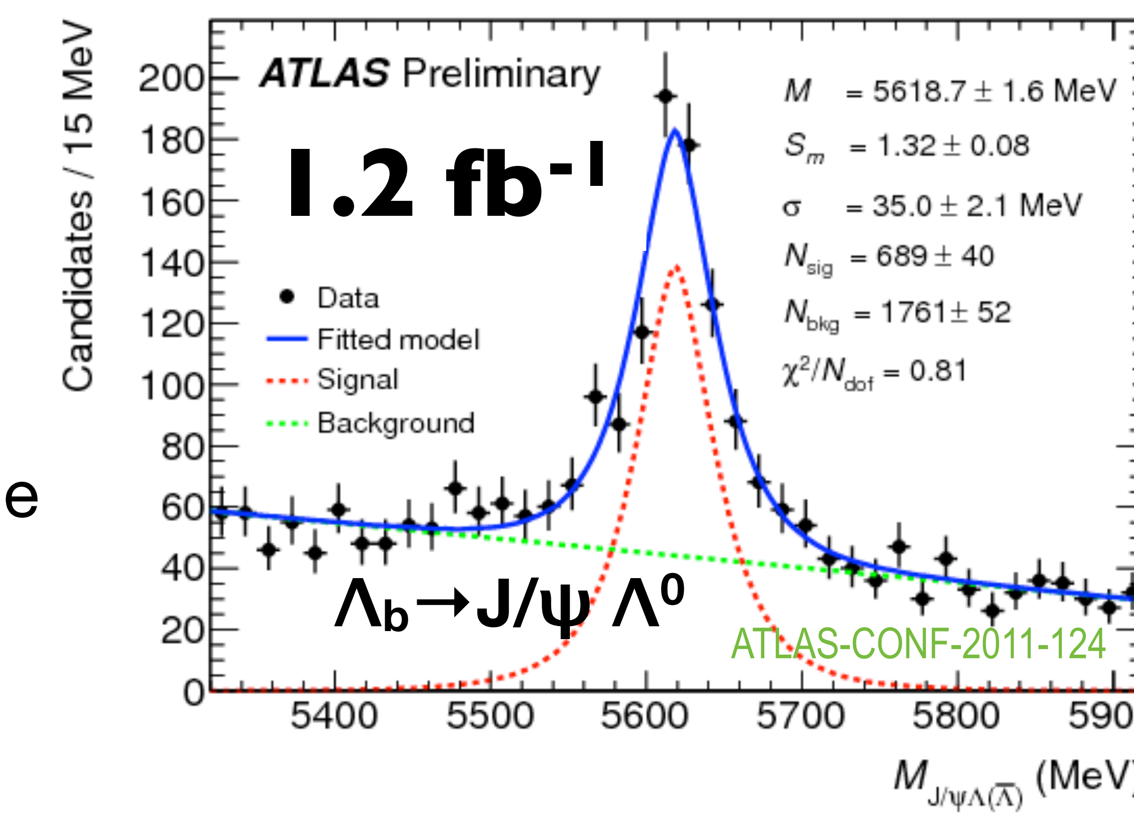
Source of systematics	Systematic uncertainty $\delta_{syst}(\tau_{B_d})$, ps	$\delta_{syst}(\tau_{B_s})$, ps
Modelling signal, background	0.01	0.01
Time uncertainty model	0.03	0.03
Mass window	0.01	0.02
Alignment	0.03	0.03
Total, quadratic sum	0.04	0.05

More measurements to be published

- B-hadron cross-section in exclusive decays
- **Motivation:**
  - Test NLO QCD
  - Reference to the rare decay $B_s \to \mu^+\mu^-$



- Lifetime, helicity, polarization of Λ_b
- **Motivation:**
  - B_d/Λ_b lifetime ratio measurement is important to HQET and pQCD predictions
  - Possibility of measuring helicity amplitude and transverse polarization for the first time



More measurements to be published

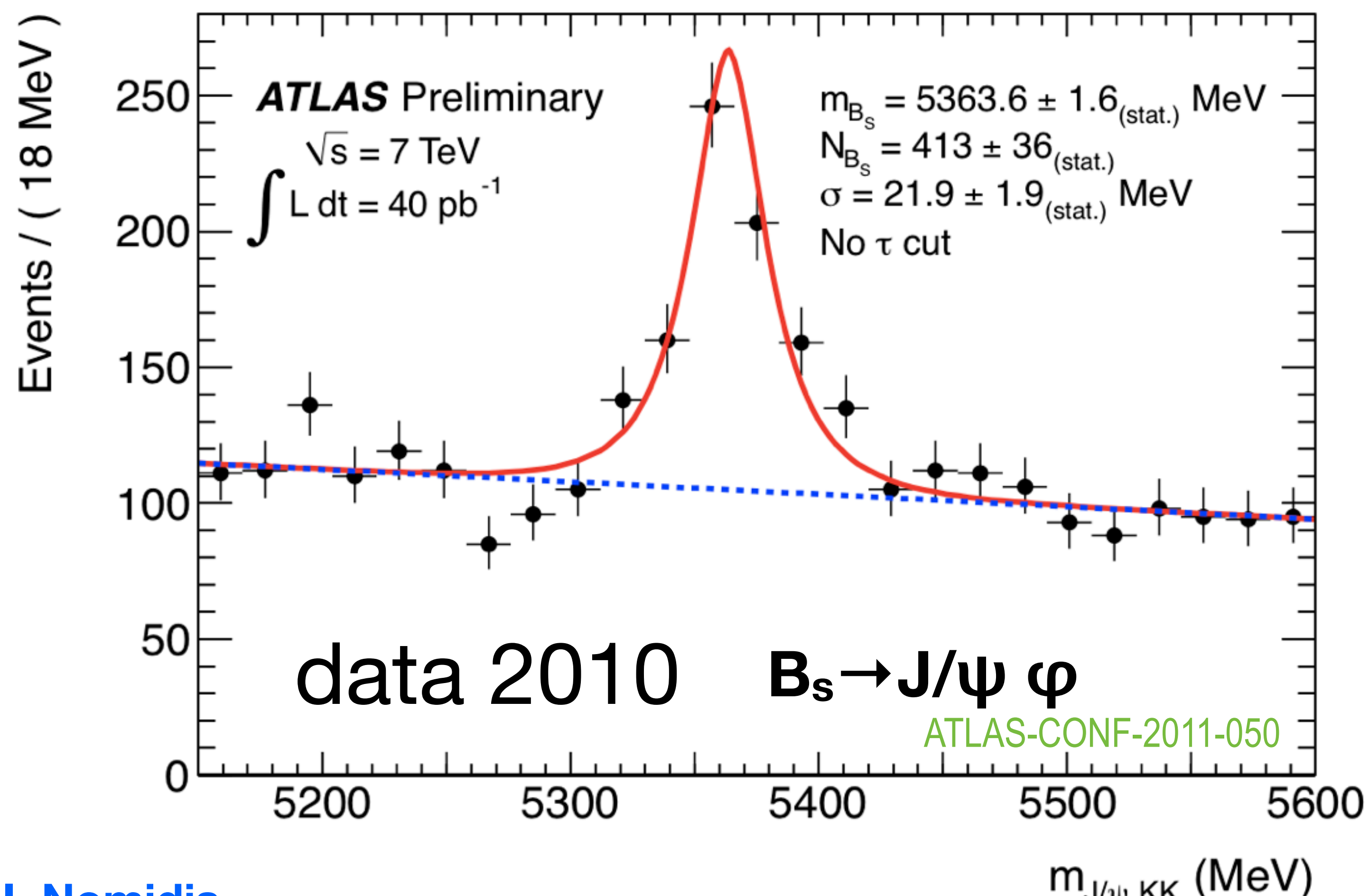
- Search for $B_s \rightarrow \mu^+\mu^-$
- **Motivation:**
  - Process mediated by Flavour Changing Neutral Current (FCNC), forbidden in the Standard Model at tree level (CKM suppressed)
  - Expected BR in the Standard Model is tiny: $BR(B_s \rightarrow \mu\mu) = (3.2 \pm 0.2) \times 10^{-9}$ (A.J.Buras et al. JHEP 1010:009, 2010)
  - ATLAS result eagerly awaited
    - CDF, 7 fb^{-1}: $BR(B_s \rightarrow \mu\mu) < 4.0 \times 10^{-8}$ @95% C.L. Phys. Rev. Lett. 107, 191801 (2011)

      $BR(B_s \rightarrow \mu\mu) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$ @95% C.L.
    - LHCb, 37 pb^{-1}: $BR(B_s \rightarrow \mu\mu) < 5.6 \times 10^{-8}$ @95% C.L. Physics Letter B 699 (2011) 330-340

      UPDATE 300 pb^{-1}: $BR(B_s \rightarrow \mu\mu) < 1.6 \times 10^{-8}$ @95% C.L. LHCb-CONF-2011-037
    - CMS, 1.14 fb^{-1}: $BR(B_s \rightarrow \mu\mu) < 1.9 \times 10^{-8}$ @95% C.L. Phys. Rev. Lett. 107 (2011) 191802

More measurements to be published

- CP violation in $B_s \to J/\psi\ \varphi$
- **Motivation:**
  - Two mass eigenstates (CP^+ and CP^-) with different lifetimes, distinguished by angular analysis
  - Clean extraction of the CP violating phase φ_s
  - Standard Model predicts small value for this phase
  - New physics can contribute largely to this phase



More measurements to be published

- **Pursue measurements in more channels:**

- $B^0 \rightarrow J/\psi\ K_s$
  - This channel allows clean extraction of the CP violating phase φ_s
  - Same topology with $\Lambda_b \rightarrow J/\psi\ \Lambda^0$

- $B_c^\pm \rightarrow J/\psi\ \pi^\pm$
  - $B_c^\pm$ relative production ($B_c/B^\pm$), mass, lifetime

- $pp \rightarrow J/\psi\ J/\psi\ X$
  - Double-onia production as test to pQCD
  - Background to $\chi_b \rightarrow J/\psi\ J/\psi$

Summary

- ATLAS studies *beauty production* via:
  - observation of J/ψ and Υ mesons (published cross-sections)
  - b-jets (submitted b and and $b\bar{b}$ cross-sections for publication)
- Measurements support current NLO predictions quite well
- Room for improvement in theoretical predictions for prompt J/ψ and inclusive Υ production

- ATLAS studies *B-hadron properties* by measuring B-lifetimes
- Inclusive and exclusive lifetimes in agreement with world averaged values
- Looking forward to measuring B_s double lifetime and CP violation in $B_s \to J/\psi\ \varphi$

- ATLAS searches for $B_s \to \mu^+\mu^-$
- Looking forward to discovery or to push the limit down for BR($B_s \to \mu^+\mu^-$)

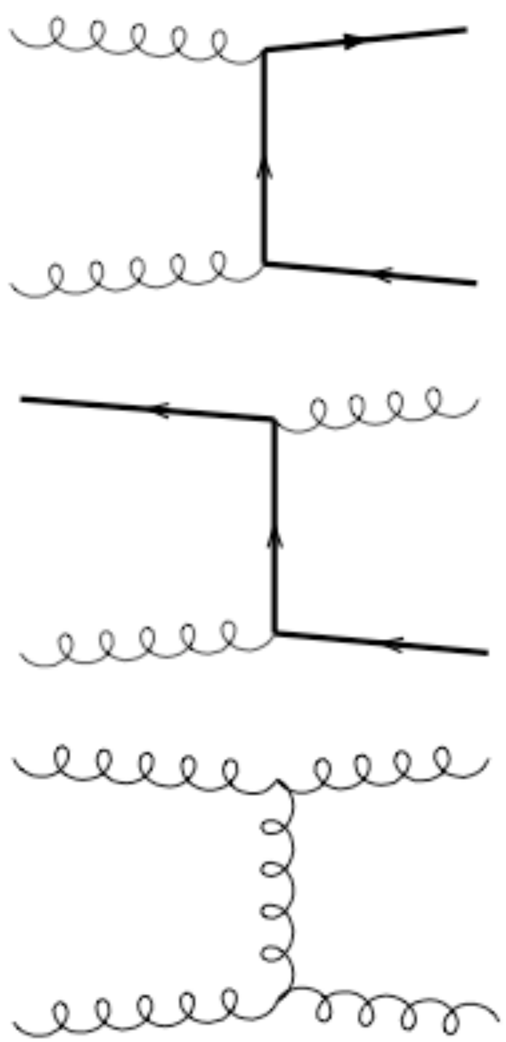
Backup

Models for prompt J/ψ production

- Colour Evaporation Model (CEM) gives a decent description of Tevatron and LHC data; although the p_T shape is not described at low and high p_T, it is quite adequate given the simplicity of this model
  - *The exchange of soft gluons is assumed to randomise the colour state, implying a probability 1/9 that a $c\bar{c}$ pair is colour singlet and produces charmonium if its mass is below the threshold for open charm production, $m_{c\bar{c}} < 2m_D$. The fraction of a specific charmonium state i, relative to all charmonia, is given by a non-perturbative parameter ρ_i*
- Colour Octet Model (COM) could describe the p_T shape at Tevatron but was problematic at explaining polarization
  - *$Q\bar{Q}$ pairs can be produced at short distances in CO ($^1S_0^{[8]}$, $^3S_1^{[8]}$, $^3P_J^{[8]}$) states and subsequently evolve into physical quarkonia by non-perturbative emission of soft gluons*
- Colour Singlet Model (CSM) at NLO enhances cross-section at high p_T and resolves polarization of J/ψ; it gets low in absolute scale when compared to data, but improves significantly at NNLO* calculation
  - *CSM assumes that colour and spin of the $Q\bar{Q}$ pair do not change during binding*
  - *At NNLO*, only tree-level diagrams at this order are considered and an infrared cut-off is imposed to control soft and collinear divergences*

$b\bar{b}$ production at LHC

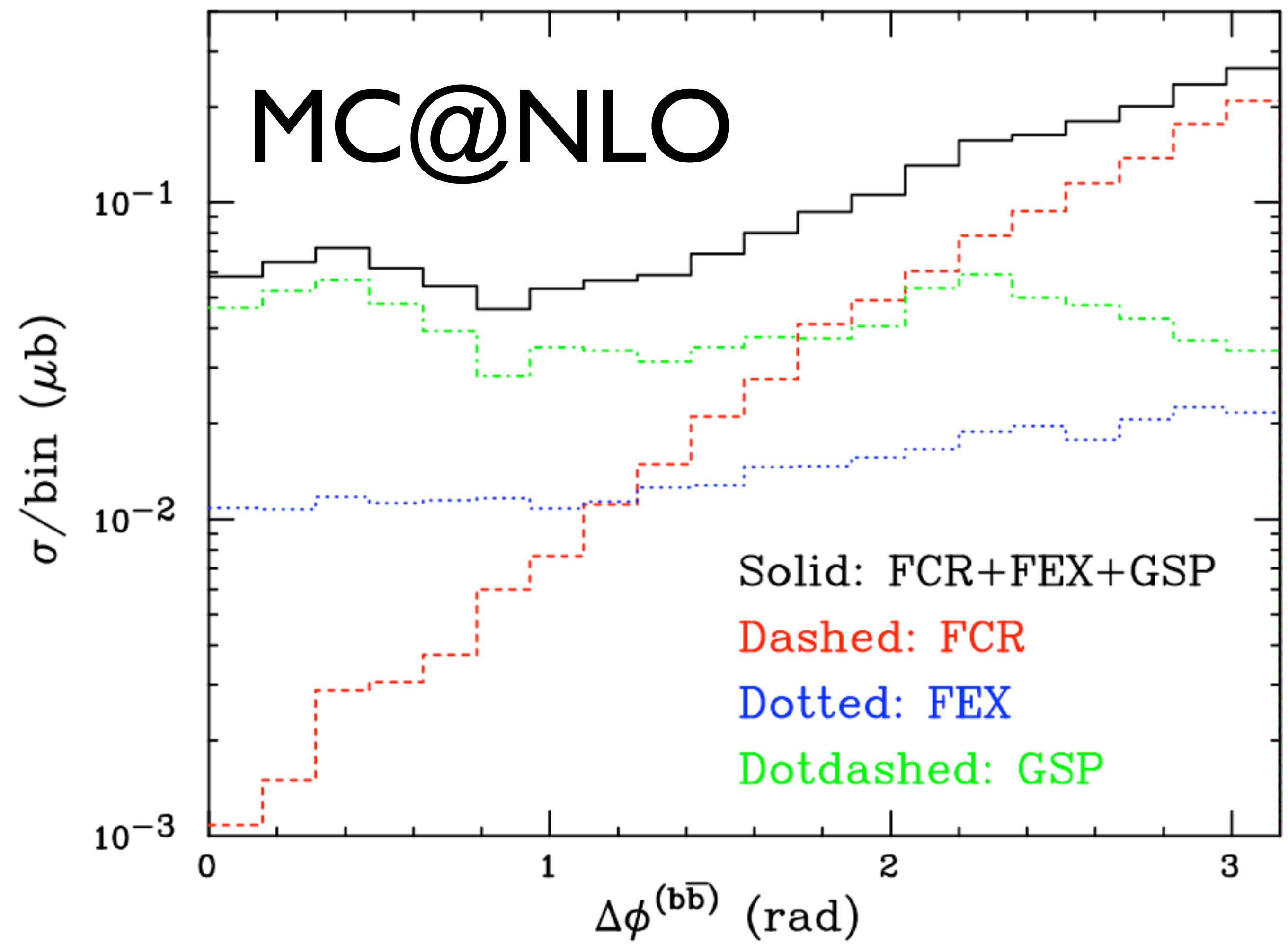
- **correlations in $b\bar{b}$ production**



Flavour Creation

Flavour Excitation

Gluon Splitting



- Mixing of FCR, FEX and GSP is dictated by QCD, needs to be implemented in the NLO MC in order to describe the kinematics and rate of bb-production

Inclusive b and $b\bar{b}$ cross-section systematics

Syst. uncertainty	Inclusive b-jet	$b\bar{b}$-dijet	Muon-based
Jet energy scale	10–20%	10–20%	15–20%
b-tagging efficiency	5–20%	30–50%	–
b-jet purity fit	3–8%	20–30%	8–18%
Luminosity	3.4%	3.4%	3.4%
Other sources	2%	2%	3%

Average B-hadron lifetime

- ...with inclusive J/ψ sample, extract average B-lifetime from B→J/ψ X decays

what is measured: $\tau = \dfrac{L_{xy} m(J/\psi)}{p_T(J/\psi)}$ — F-factor from MC → ***what is needed:*** $\tau = \dfrac{L_{xy} m(B)}{p_T(B)}$

- MC is weighted to match BaBar data
    - BaBar data in Υ(4S) frame, smearing from boost from B to Υ(4S) frame added