Heavy flavour results from ATLAS

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Introduction

Objectives of ATLAS Heavy Flavour (HF) physics programme:

- Test theoretical models for HF production within the Standard Model (SM)
- Search for new physics
  e.g. through rare decays and through new sources of CP violation in B-decays

Analyses presented here are:

- Inclusive electron and muon cross-sections from HF decays
- $J/\psi \to \mu\mu$ differential cross-section (inclusive, prompt and non-prompt)
- $\Upsilon(1s) \to \mu\mu$ differential cross-section
- Observation of $\chi_{c1}(1P)$ and $\chi_{c2}(1P)$ charmonium states
- Measurement of D meson production cross-sections
- Measurement of average B lifetime in $B \to J/\psi\ (\mu\mu)\ X$
- Observation and life time measurement of $B_d^0 \to J/\psi\ K^{*0}\ (K\,\pi)$ and $B_s^0 \to J/\psi\ \phi\ (K^+ K^-)$
- Observation of $B_d^0 \to J/\psi\ (\mu\mu)\ K_s^0\ (\pi^+\pi^-)$ and $\Lambda_b^0 \to J/\psi\ (\mu\mu)\ \Lambda^0\ (p^+\pi^-)$

Inclusive electron and muon cross-sections from HF decays

http://arxiv.org/abs/1109.0525

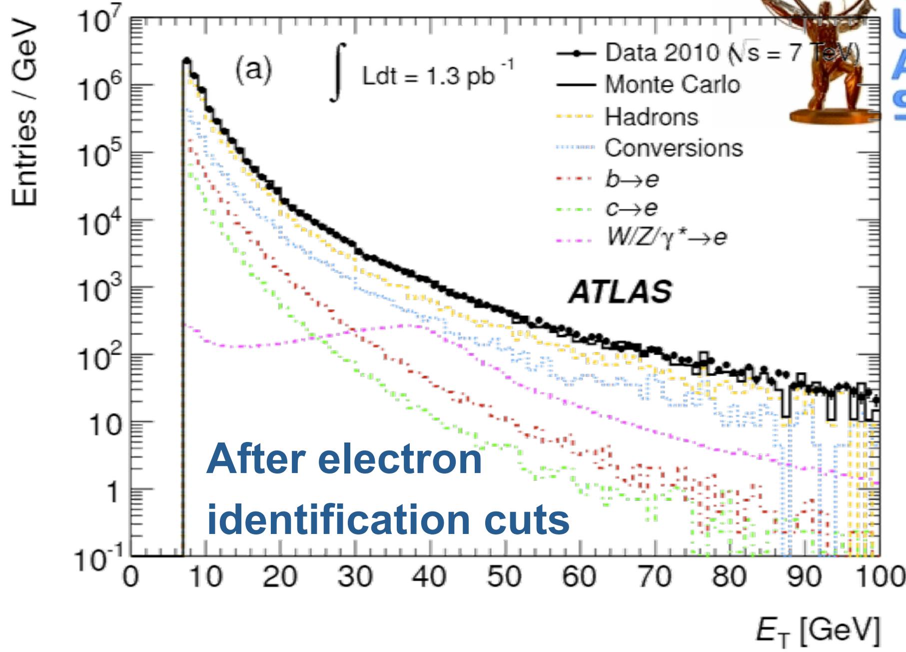
- Inclusive lepton spectra for p_T < 30GeV dominated by decays of HF hadrons (above 30GeV isolated electrons from W/Z/γ* with high identification efficiency dominate that channel)

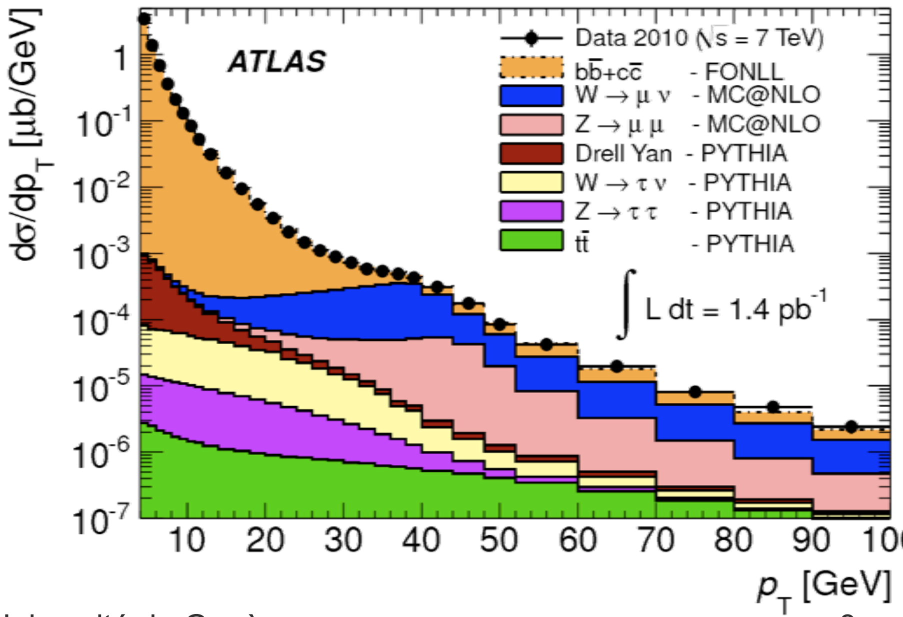
  - Extract electron signal from background of QCD fakes and conversions

  - Extract muon signal from background of QCD fakes and pion & kaon decays in flight

  - Subtract theoretical contribution from W/Z/γ* production

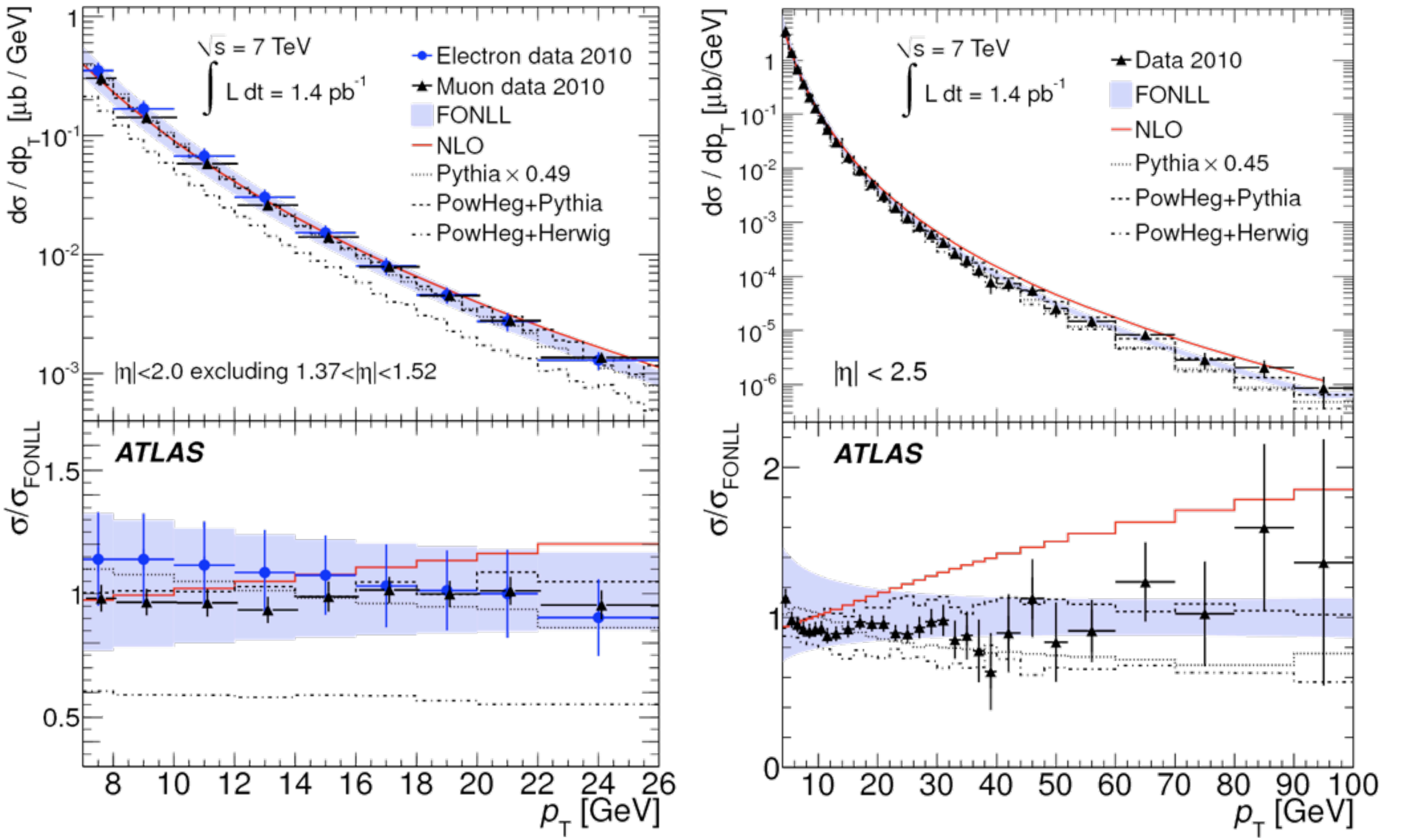
  => Obtain heavy flavour component





Inclusive electron and muon cross-sections from HF decays

- Good agreement with FONLL (Fixed Order NLO calculations with NLL resummation)
- In particular, high-p_T region of muon analysis shows sensitivity to NLL terms)



$J/\psi \rightarrow \mu\mu$ differential cross-section (inclusive, prompt, non-prompt)

http://arxiv.org/abs/1104.3038

Inclusive measurement

- Test theoretical models at higher p_T and wider rapidity ranges than previously studied (J/ψ with p_T = 1-70 GeV and within |y| < 2.4)

- J/ψ candidates reconstructed from opposite sign di-muon pairs with ID tracks fitted to common vertex, yield determined from fit to $\mu\mu$ invariant mass in p_T-y bins
- From reconstructed J/ψ candidates in p_T-y bin, true number obtained by applying weight:

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

$\mathcal{A}$ = detector acceptance

NB: depends on unknown spin alignment of J/ψ

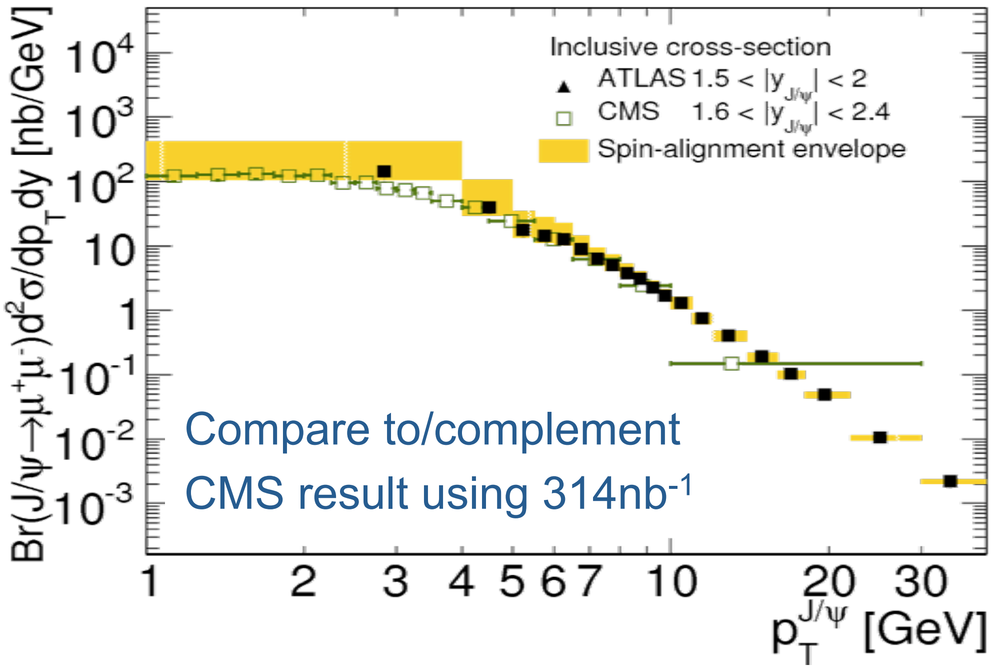
=>take envelope of max variation

$\mathcal{M}$ = bin migration correction

ε_{trk} = ID tracking efficiency

ε_{μ} = muon reconstruction efficiency w.r.t. ε_{trk} (tag & probe, also $Z \rightarrow \mu\mu$)

$\varepsilon_{\text{trig}}$ = trigger efficiency



Compare to/complement CMS result using 314nb^{-1}

$J/\psi \rightarrow \mu\mu$ differential cross-section (inclusive, prompt, non-prompt)

Prompt and non-prompt components

Inclusive measurement = sum of prompt and non-prompt components:

- **Prompt** = direct prod'n from hard interaction + feed-down from heavier states
- **Non-prompt** = via decay of B-hadron (*non-prompt fraction* = f_B)

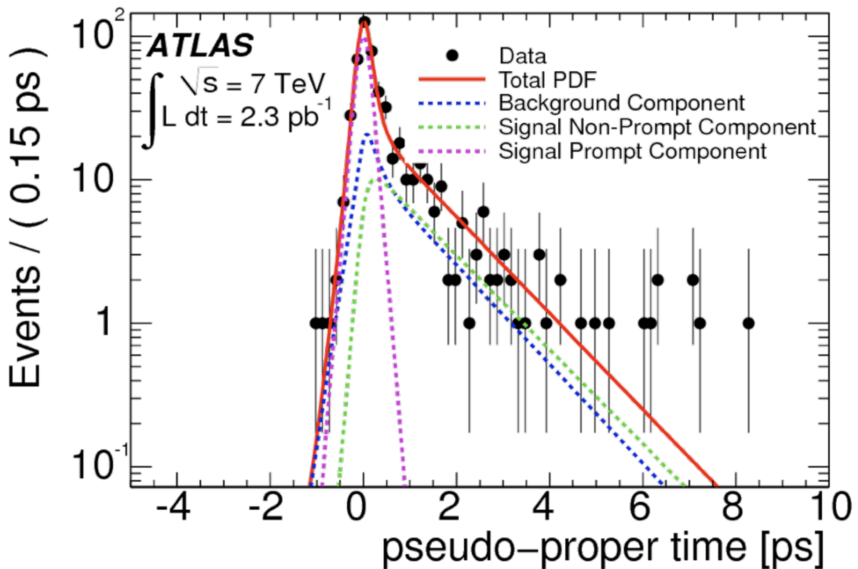
Non-prompt component identified by transverse displacement of J/ψ decay vertex, L_{xy}

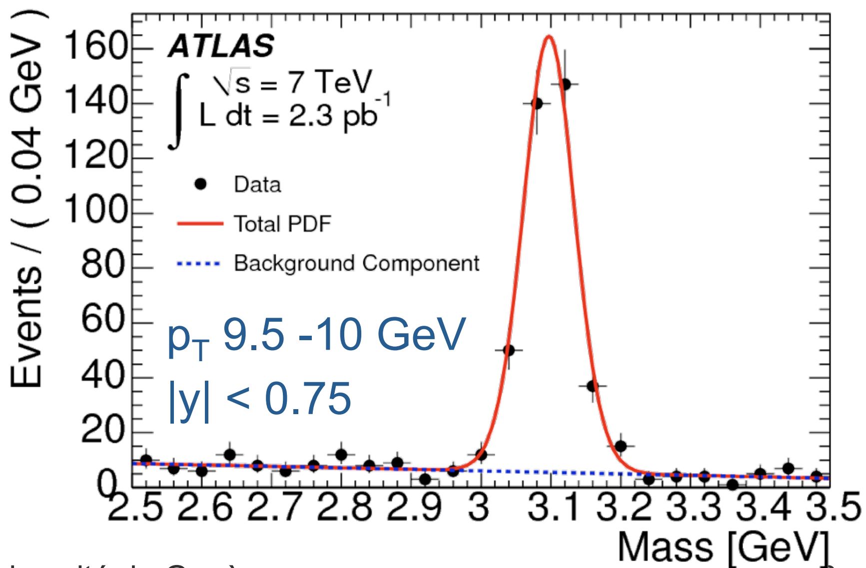
L_{xy} related to decay time of B hadron by $t = \frac{L_{xy} m_B}{p_T^B}$

As B hadron not reconstructed, construct pseudo proper time $\tau = \frac{L_{xy}\, m_{\mathrm{PDG}}^{J/\psi}}{p_T^{J/\psi}}$

Simultaneously fit mass & pseudo-proper time in (p_T, y) bins to find signal, J/ψ mass & f_B

(Sidebands of mass constrain background in the lifetime)





$J/\psi \rightarrow \mu\mu$ differential cross-section (inclusive, prompt,non-prompt)

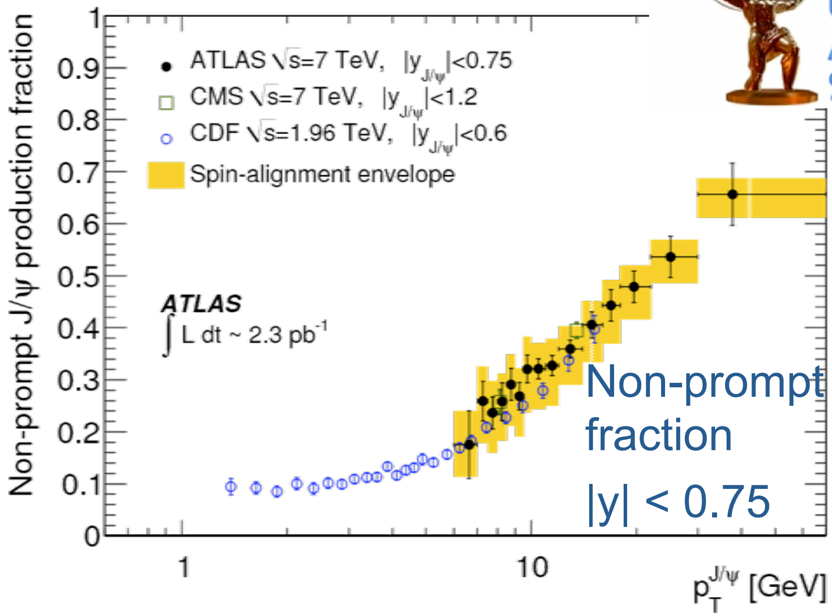
Non-prompt fraction compared to CMS & CDF:

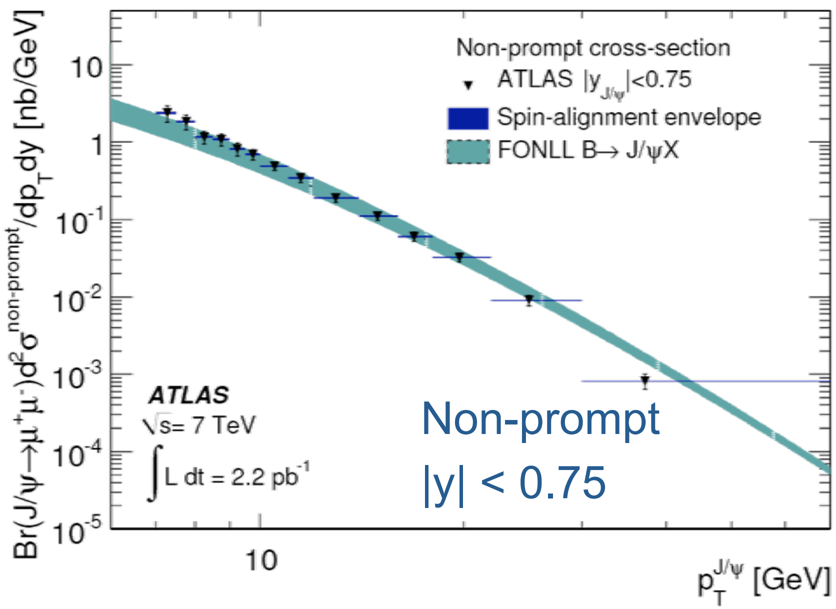
- f_B rises rapidly for J/ψ $p_T >$ 7GeV; little y dependence
- no strong dependence on collision energy

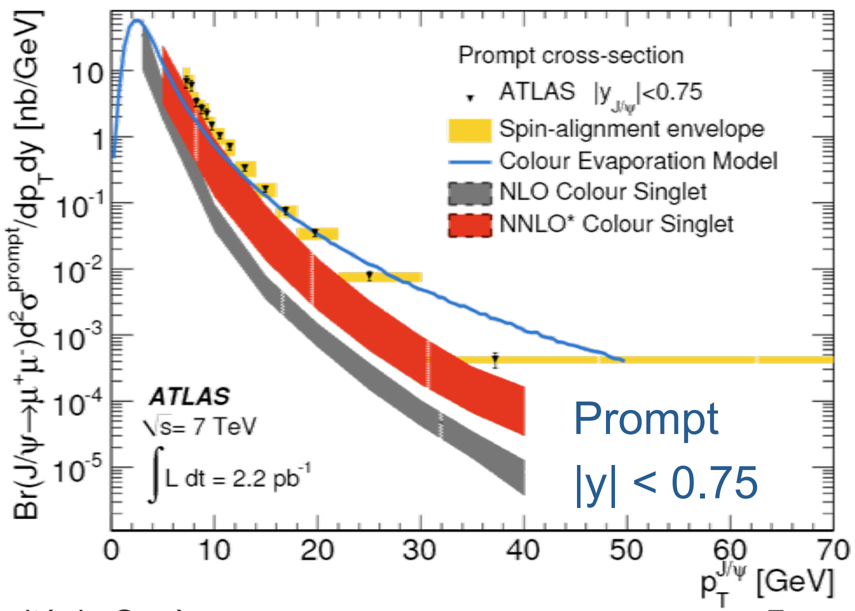
Non-prompt cross-section agrees with FONLL

For the prompt cross-section

- CEM prediction too low & diverges at high p_T
- NNLO* calculations in Colour Singlet Model much better than NLO, still some discrepancy







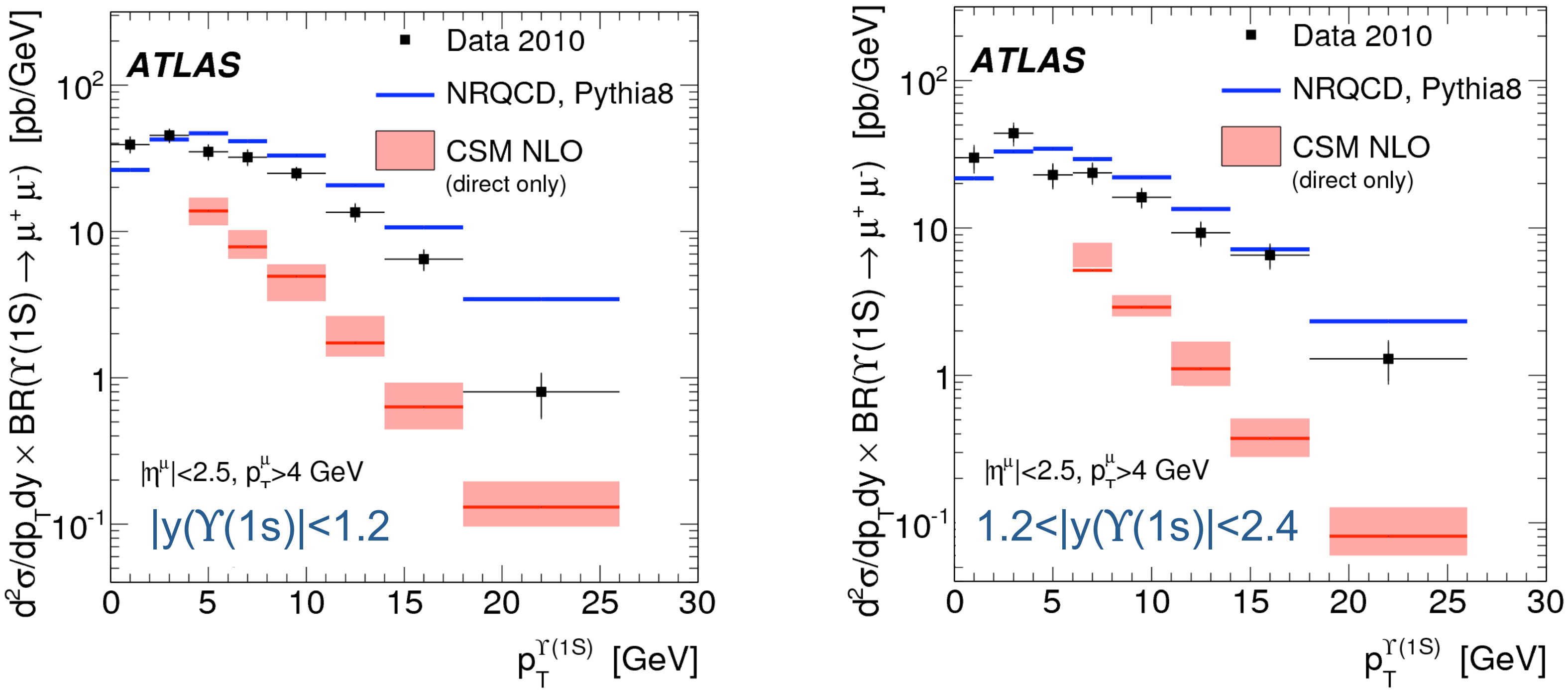
Υ(1s) → $\mu\mu$ differential cross-section

http://arxiv.org/abs/1106.5325

- Measure fiducial cross-section for muons with p_T > 4GeV and $|\eta| < 2.5$

$\Rightarrow$ Avoid uncertainties on acceptance from the unknown spin alignment

- True number of Υ candidates obtained by applying data-derived weights to account for muon trigger & reconstruction efficiency, then a likelihood fit to di-muon mass in p_T-y bins
- Overall uncertainty dominated by statistics (1.13pb^{-1})



- Non-Relativistic QCD framework predicts overall cross-section, different p_T dependence
- Color Singlet Model NLO calculation (in MCFM) significantly under estimates data (though does not include feed-down from higher mass states)

Observation of χ_{c1} (1P) and χ_{c2}(1P) charmonium states

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-136/

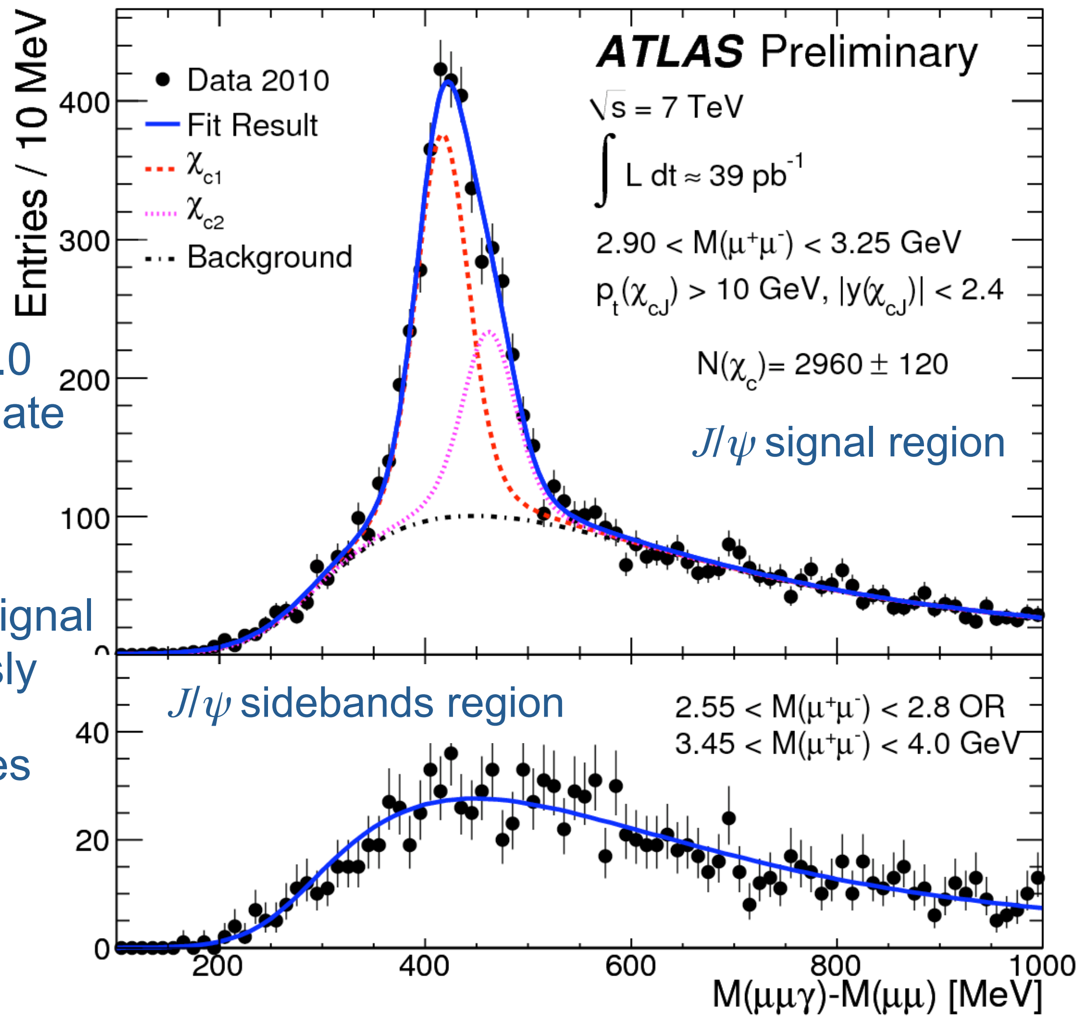
- $\chi_{c1/2}$ states reconstructed through decay mode $\chi \rightarrow J/\psi\,\gamma$ with $J/\psi \rightarrow \mu\mu$

NB: up to 40% of J/ψ inclusive cross-section comes from this process

Validate signal extraction for later cross section measurement:

- Reconstruct χ_c candidates with p_T > 10GeV in |y|< 2.4
- Select opposite charge muons with invariant mass in range 2.55-4.0 GeV with associated photon candidate (require small opening angle to reduce combinatorial background)
- Fit to $\Delta M = M(\mu\mu\gamma) - M(\mu\mu)$ in J/ψ signal region and sidebands simultaneously

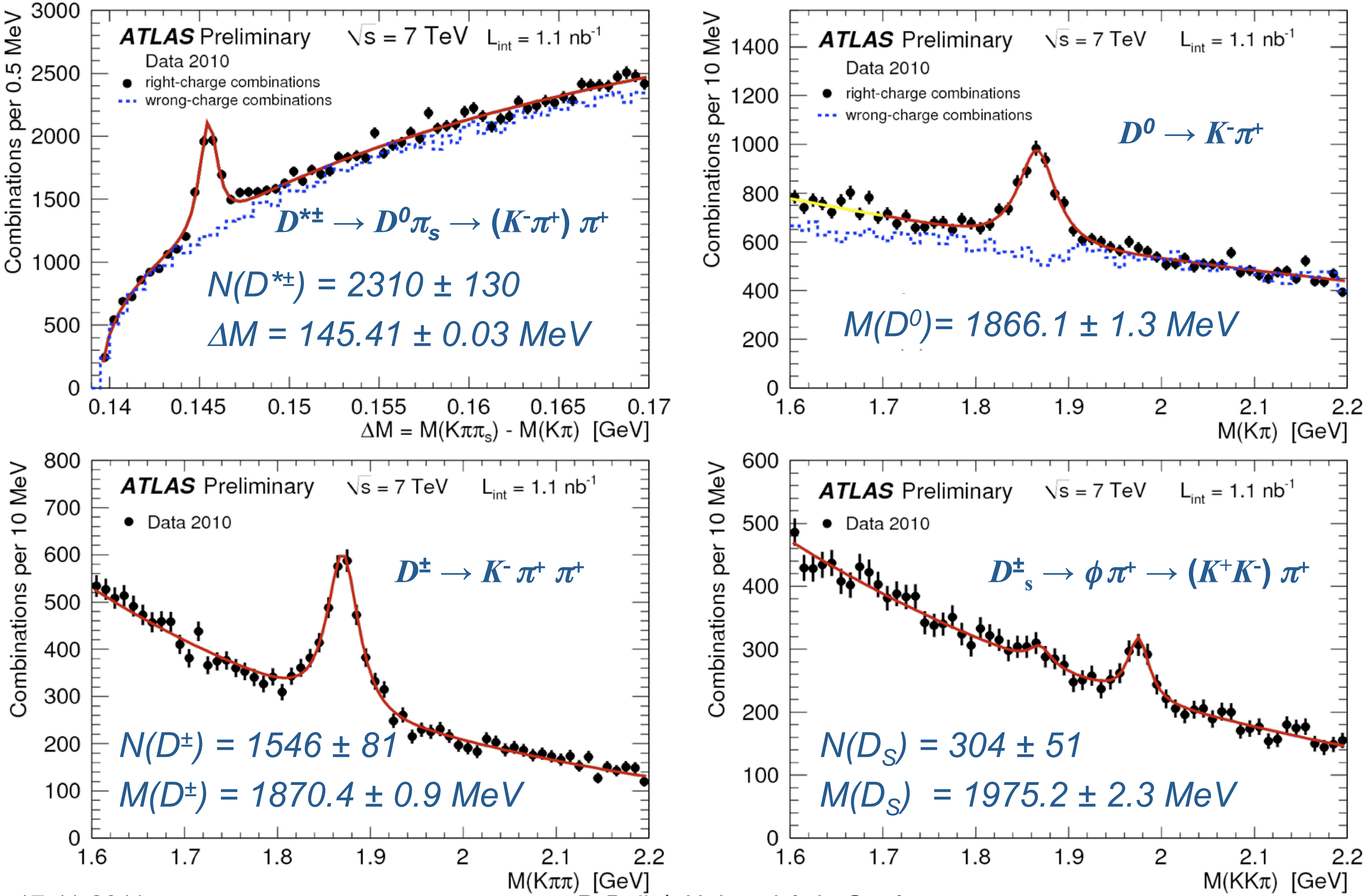
⇒ Yields 2960 ± 120 (stat) candidates



Measurement of D meson production cross-sections

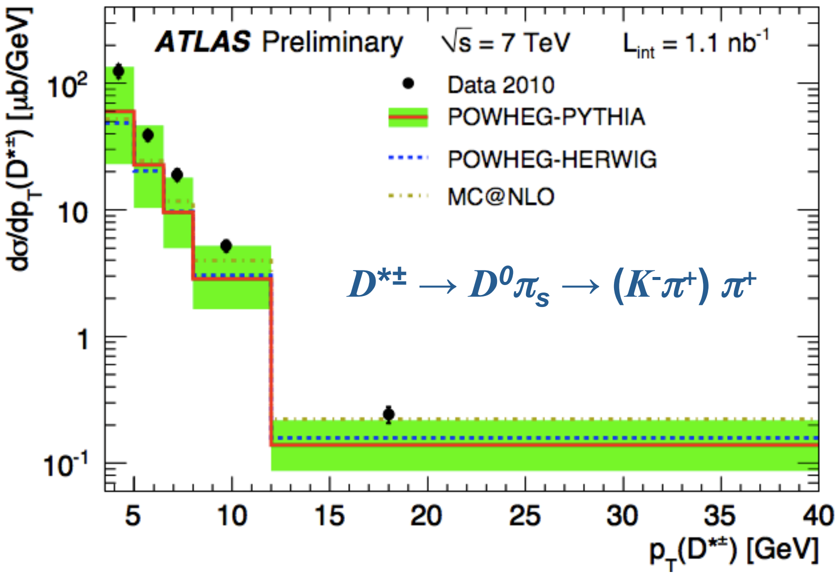
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-017/

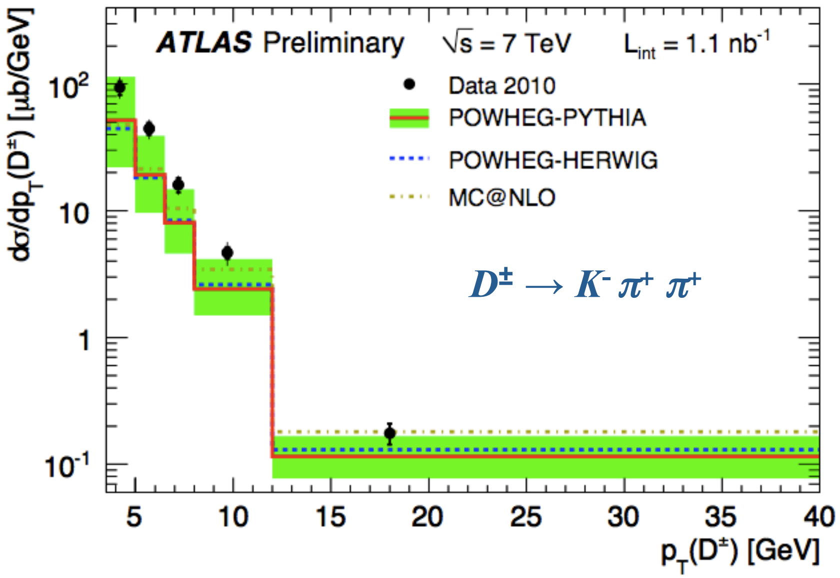
- $D^{*\pm}$, $D^{\pm}$, $D^{\pm}_{s}$ charmed mesons reconstructed for p_T > 3.5GeV and |y|< 2.1
- Use ID tracks and extract masses & yields with fits to M or ΔM distributions



Measurement of D meson production cross-sections

- D^* and $D^{\pm}$ cross-sections measured as fn. of p_T and y for p_T > 3.5GeV, |y|< 2.1
- Efficiency and acceptance taken from MC





- NLO QCD predictions (from POWHEG or MC@NLO) consistent with data

NB: Contribution from B-hadron production to *visible* cross-section subtracted and result extrapolated to obtain *total* charm hadronisation cross-section

Can then also calculate two fragmentation ratios for charged charmed mesons:

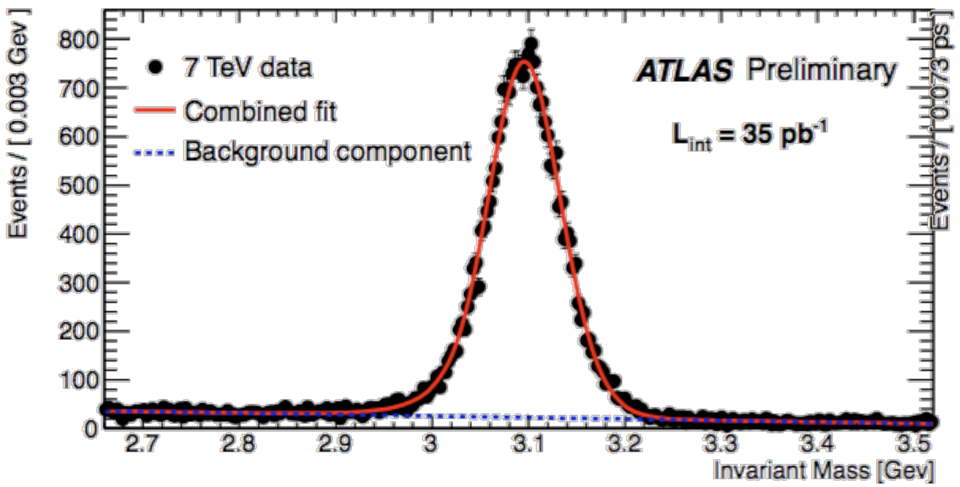
- strangeness suppression factor (fraction of $D^{\pm}_s$)
- fraction of D mesons produced in vector state ($D^{*\pm}$)

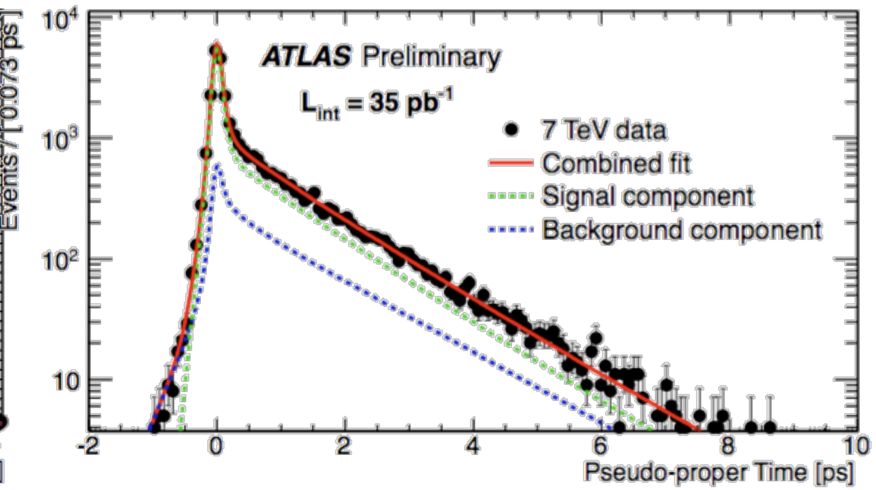
} Agreement with LEP results seen

Measurement of average B lifetime in $B \rightarrow J/\psi\,(\mu\mu)\,X$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-145/

- Precise measurement of B-hadron lifetimes tests predictions of Heavy Quark Effective Theory (HQET). (Predicts lifetime ratios between different species to ~1%)
- Measure average lifetime $<\tau_b>$ of admixture of B-hadrons decaying to final states including J/ψ: demonstrates method for future measurements in exclusive channels.
- As in J/ψ non-prompt cross-section measurement, use pseudo-proper time (PPT) to extract the fraction of J/ψs arising from B-hadron production
- To extract real decay time from fit, convolve PPT PDF with a correction factor (“F-factor”)
- Extract $<\tau_b>$ with simultaneous fit to mass and PPT. (Mass fit reduces combinatorial bkg)





Agreement with Tevatron : $<\tau_b> = 1.489 \pm 0.016\,(\text{stat}) \pm 0.043\,(\text{syst})\,\text{ps}$

e.g. current detector misalignment uncertainty

Observation and life time measurement of $B_d^0 \rightarrow J/\psi K^{*0} (K\pi)$ & $B_s^0 \rightarrow J/\psi \phi (K^+K^-)$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-050/
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-092/

- $B_s^0 \rightarrow J/\psi \phi$: allows measurement of B_s^0 mixing phase responsible for CP violation: SM prediction for CP asymmetry is small: any sizable effect = *new physics*

- Will also measure width difference $\Delta\Gamma_s$ between light (B_s^L) & heavy (B_s^H) eigenstates

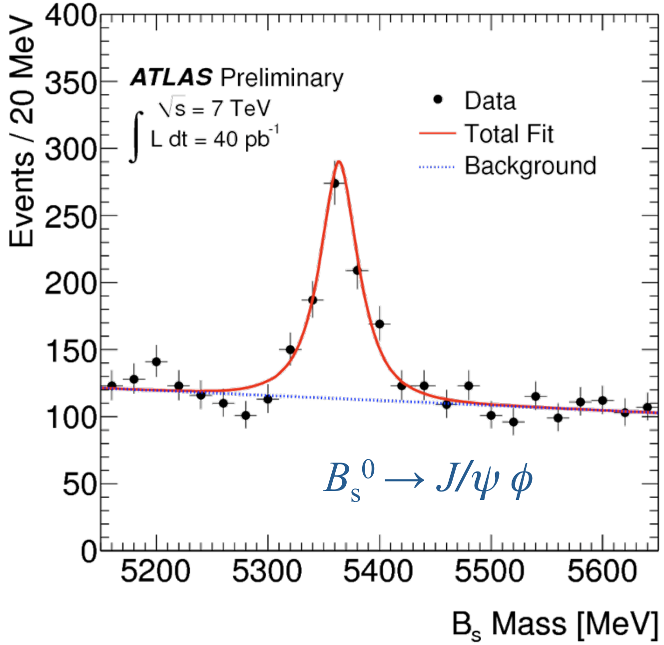
$\Rightarrow B_d^0 \rightarrow J/\psi K^{*0}$ represents a higher statistics testing ground

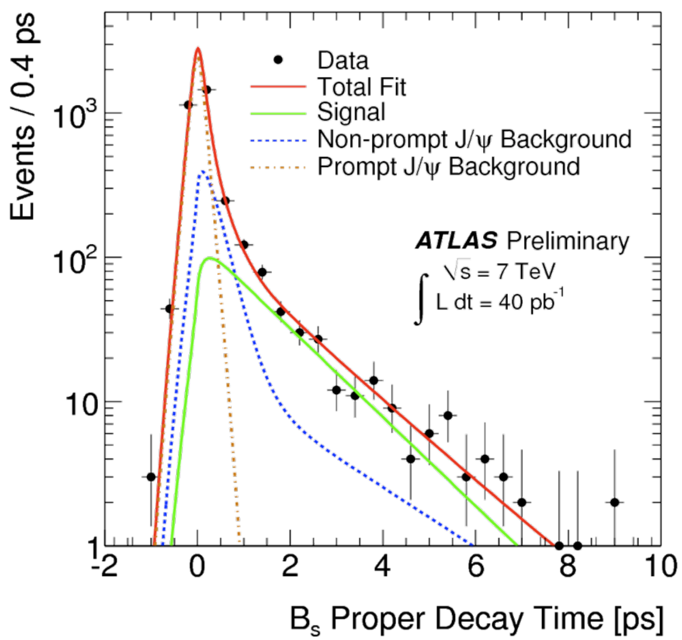
- Since B meson is reconstructed, can calculate its proper decay time: $\tau = \dfrac{L_{xy} M_B}{p_T(B)}$

Simultaneous fit to invariant mass & proper decay time

$\Rightarrow$ Extract signal, B-mass & lifetime

	N_{sig}
B_d^0	2750 ± 90
B_s^0	463 ± 26
	m_B MeV
B_d^0	5279.0 ± 0.8
B_s^0	5363.7 ± 1.2





Lifetimes agree with world average => confirms validity of method

Observation of $B_d^0 \rightarrow J/\psi\,(\mu\mu)\,K_s^0\,(\pi^+\pi^-)$ & $\Lambda_b^0 \rightarrow J/\psi\,(\mu\mu)\,\Lambda^0\,(p^+\pi^-)$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-105/

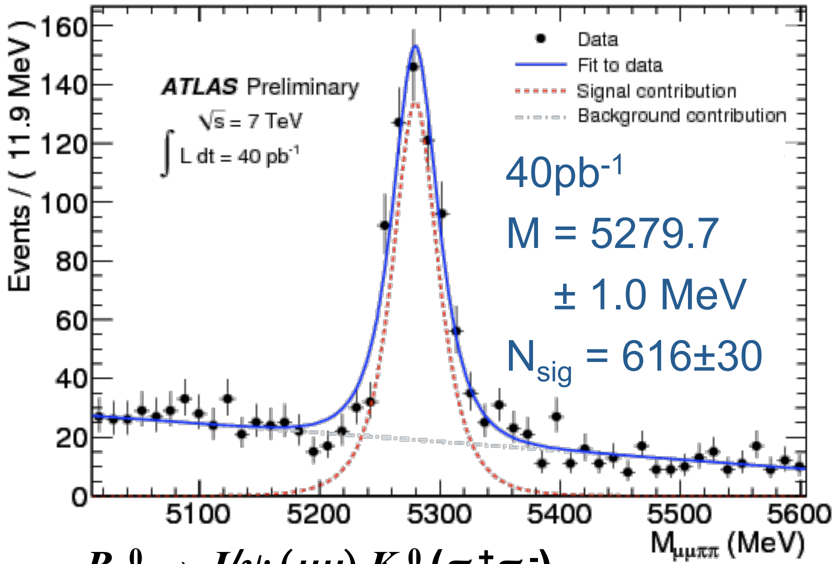
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-124/

- Large experimental uncertainty on Λ_b^0 lifetime, lifetime ratio predicted by HQET
- Possibility to measure Λ_b^0 transverse polarisation
- Asymmetry of B_d^0 and $\bar{B}_d^0$ decay rates to $J/\psi\,(\mu\mu)\,K_s^0$ proportional to sin2β

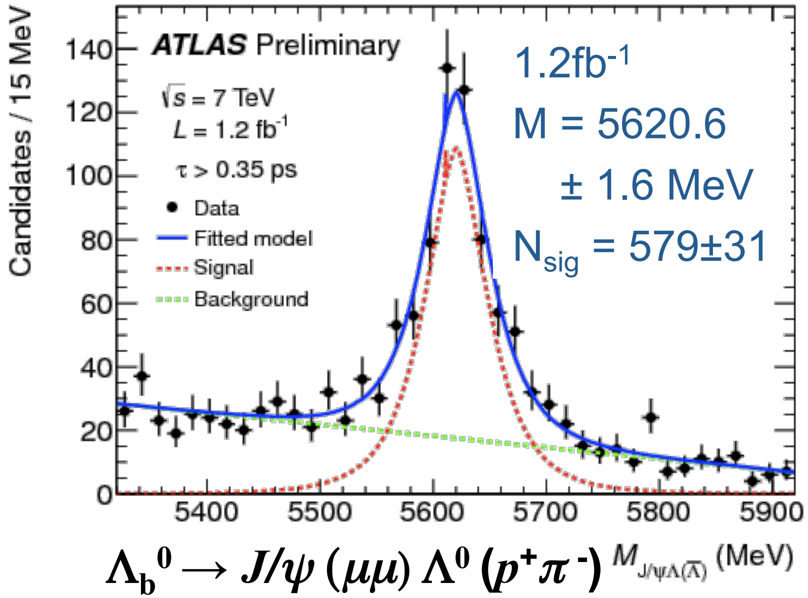
Decays have same topology: demonstrate of signal extraction for future studies:

- Decay has cascade character since K_s^0 or Λ^0 create a displaced tertiary vertex
- Reconstruct K_s^0 or Λ^0 from opposite sign ID tracks and fit to common vtx with J/ψ muons
- Reduce prompt J/ψ background with min. requirement on proper time of B_d^0 or Λ_b^0
- Extract mass and number of signal events from likelihood fit to mass distribution

⇒ Fitted masses consistent with world average



$B_d^0 \rightarrow J/\psi\,(\mu\mu)\,K_s^0\,(\pi^+\pi^-)$



$\Lambda_b^0 \rightarrow J/\psi\,(\mu\mu)\,\Lambda^0\,(p^+\pi^-)$

Conclusions

- Presented the results of three papers and seven conference notes from 2011

- Many interesting measurements already made, of cross-sections and masses and lifetimes of various HF states:
  - thanks to excellent performance of ATLAS trigger, muon and tracking systems
  - confirming SM results and constraining theoretical models at LHC energies
    - extending beyond reach of Tevatron in e.g.
      - sensitivity to NLL terms in inclusive lepton spectra
      - p_T range of J/ψ cross-section measurement
  - demonstration of methods and capabilities for future measurements

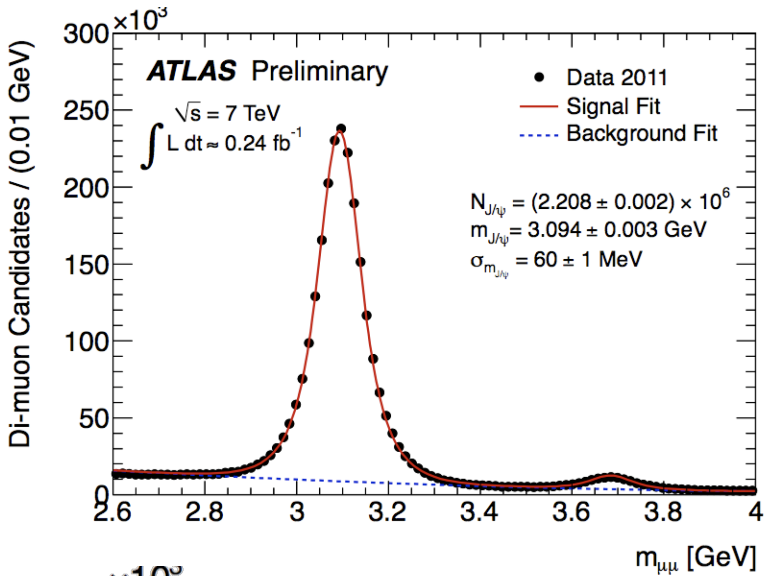
$\Rightarrow$ Rich programme planned with 2011 dataset including CP violation and rare decays

BACKUP SLIDES

Quarkonia plots

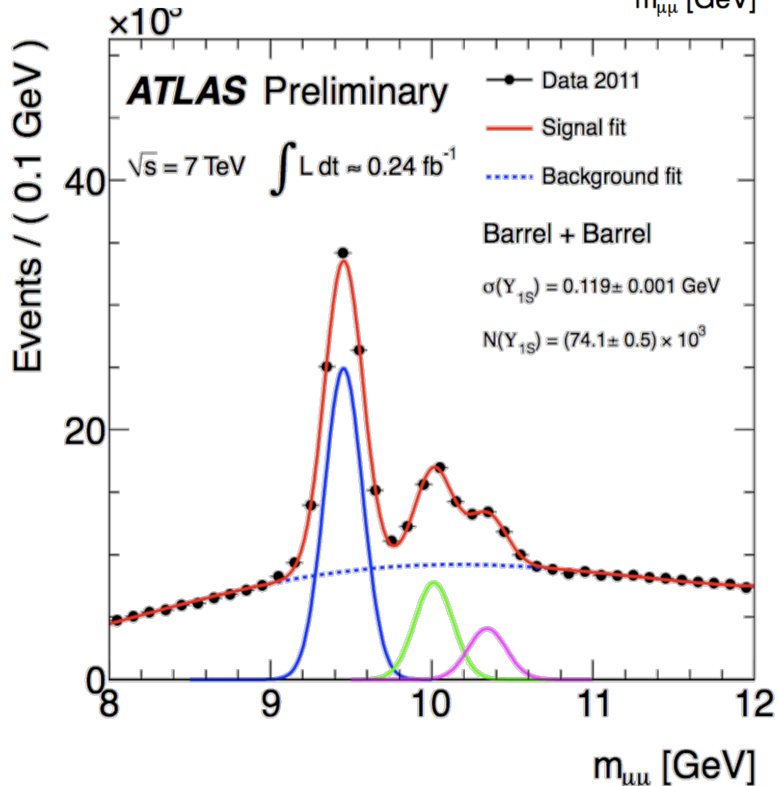
J/ψ→μμ and ψ(2s)→μμ candidates:

- All oppositely charged di-muon pairs passing vertexing
- Events fire a variety of di-muon triggers, with one or two muons at L1 confirmed at HLT
- Pair of muons required to have a minimum pT of (2.5, 4) GeV. At least one high-quality ("combined") muon is required in each pair.



Υ(1s,2s,3s)→μμ candidates

- All oppositely charged di-muon where both muons are detected in the barrel (|η|<1.05)
- Events fire a variety of di-muon triggers, with one or two muons at L1 confirmed at HLT
- Pair of muons required to have a minimum pT of (4, 4) GeV. At least one high-quality ("combined") muon is required in each pair.
- The separations of the three peaks are fixed using the PDG masses but the absolute position on the invariant mass scale is a free parameter of the fit.

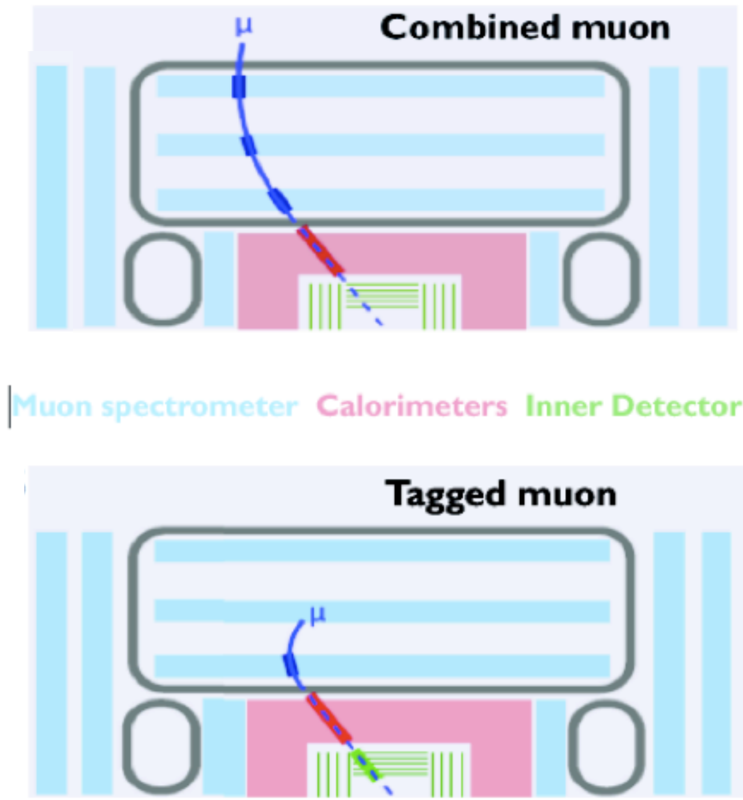


Muon triggering and reconstruction

Trigger

3 trigger levels: L1 (hardware) + HLT (L2 + EF)

- At low luminosity (early data) use L1 Minimum Bias Trigger Scintillators (MBTS) trigger with confirmation of muon at EF
- Subsequent data periods used L1 Muon trigger (hits in RPCs and TGCs)
- As luminosity increased, L1 Muon trigger seeds HLT with increasing p_T cuts (4, 6… GeV)
- Also dimuon triggers with J/ψ mass cut at EF



Reconstruction

Three categories of muons:

- Standalone MS tracks: based entirely on MS
- Combined muons: statistical combination of ID and MS tracks
- Tagged muons: MS track *segments* matched to ID tracks

$J/\psi \rightarrow \mu\mu$ differential cross-section (inclusive, prompt, non-prompt)

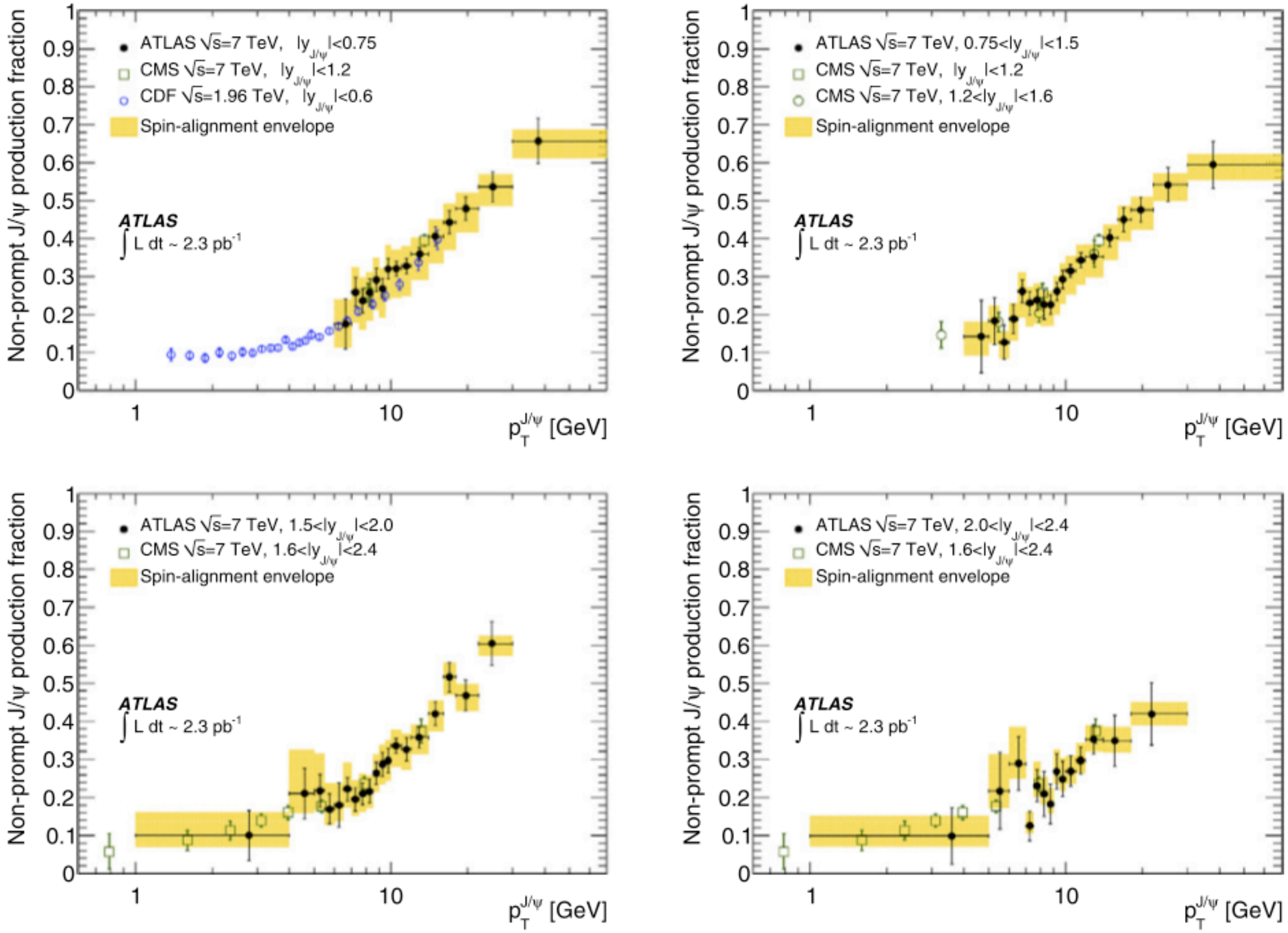
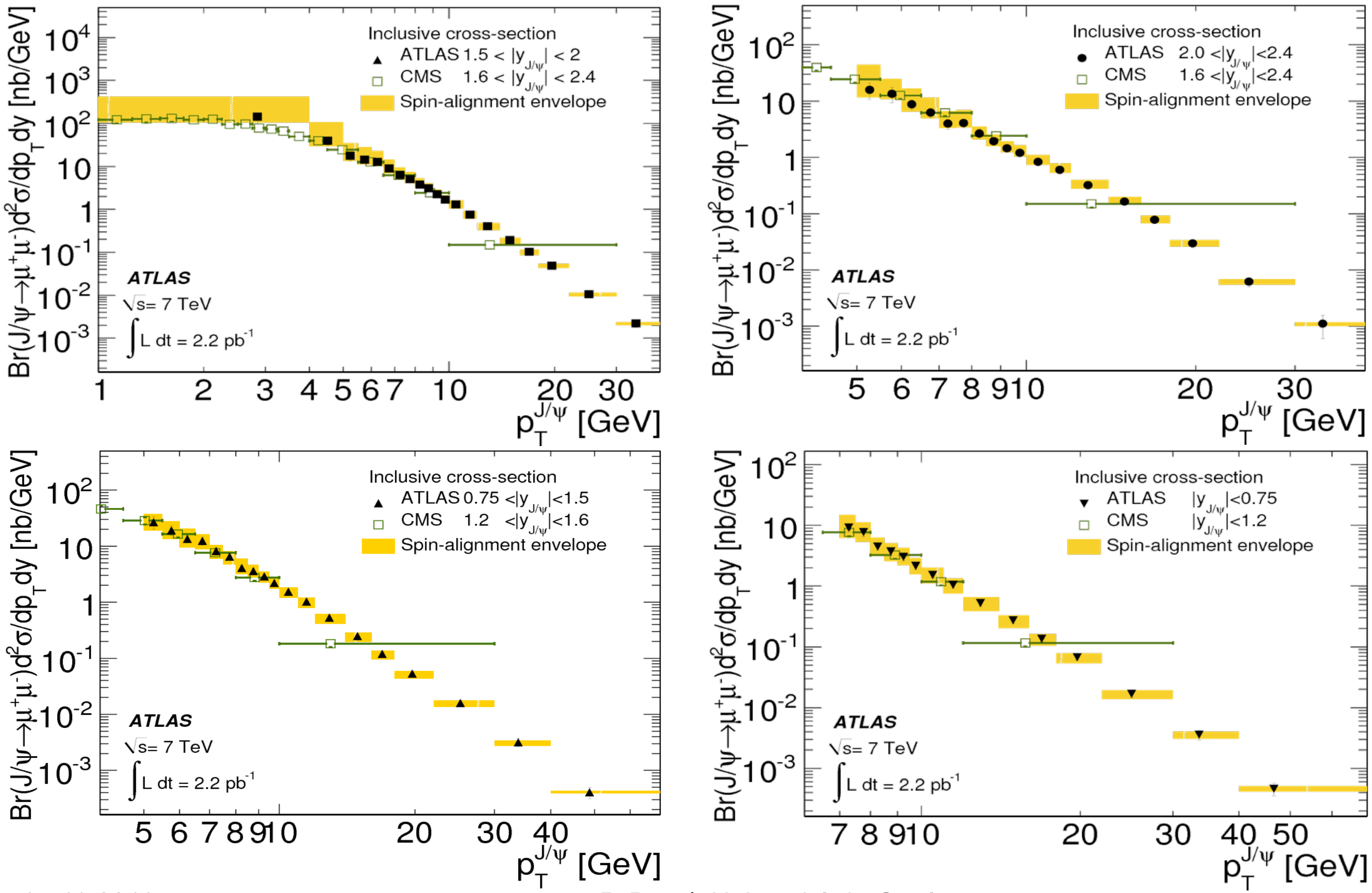


Fig. 9. J/ψ non-prompt to inclusive fractions as a function of J/ψ transverse momentum. Overlaid is a band representing the variation of the result under various spin-alignment scenarios (see text) representing a theoretical uncertainty on the prompt and non-prompt J/ψ components. The equivalent results from CMS [3] and CDF [4] are included.

$J/\psi \rightarrow \mu\mu$ differential cross-section (inclusive, prompt, non-prompt)

- Inclusive cross-sections in 4 rapidity bins compared to CMS result (using 314nb^{-1})
- Spin alignment envelope main theoretical uncertainty
- Muon trigger and reconstruction main experimental uncertainties



$J/\psi \rightarrow \mu\mu$ differential cross-section (inclusive, prompt, non-prompt)

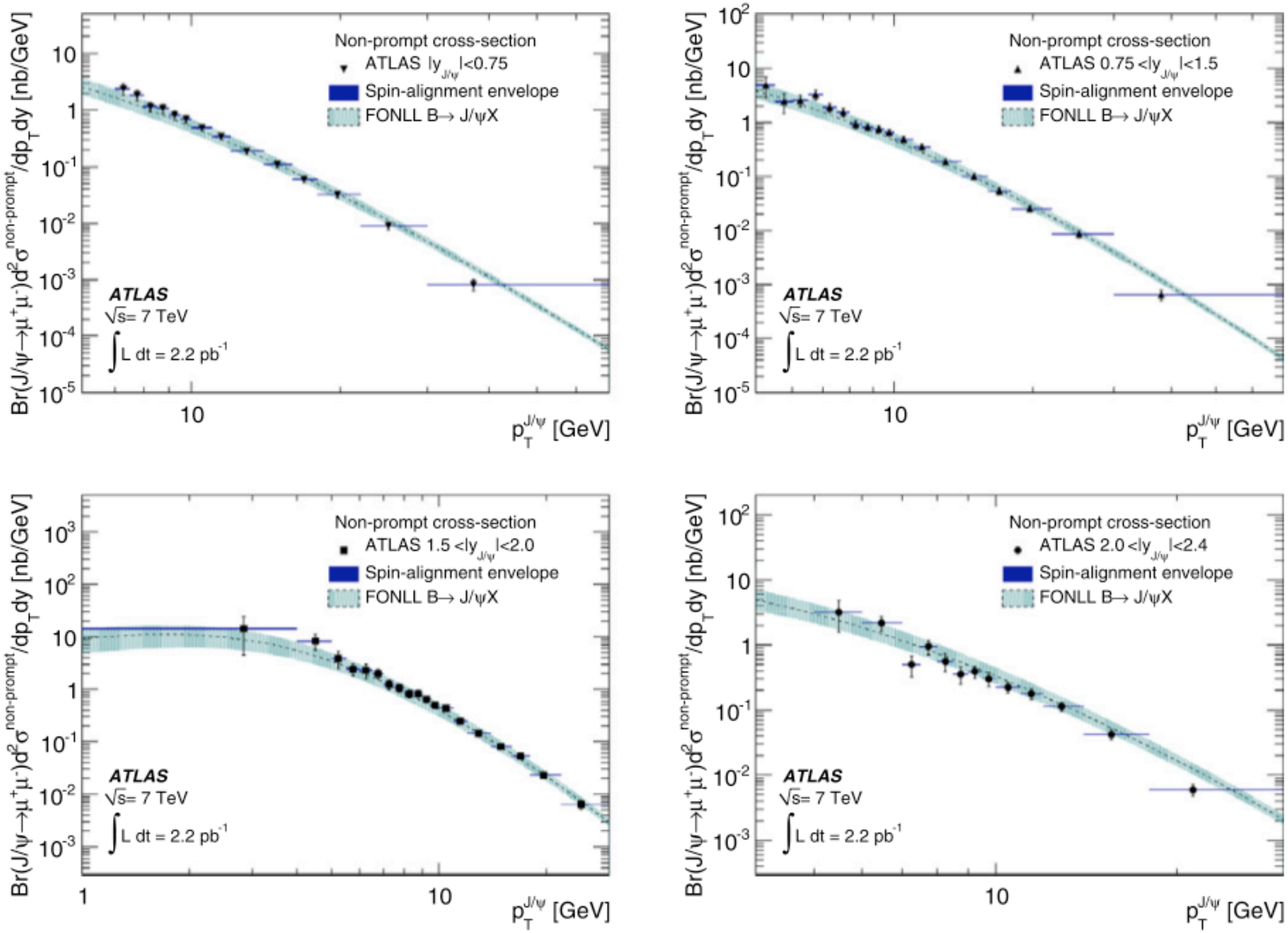


Fig. 10. Non-prompt J/ψ production cross-section as a function of J/ψ transverse momentum, compared to predictions from FONLL theory. Overlaid is a band representing the variation of the result under spin-alignment variation on the non-prompt J/ψ component as described in the text. The central value assumes an isotropic polarisation for both prompt and non-prompt components. The luminosity uncertainty (3.4%) is not shown.

$J/\psi \rightarrow \mu\mu$ differential cross-section (inclusive, prompt, non-prompt)

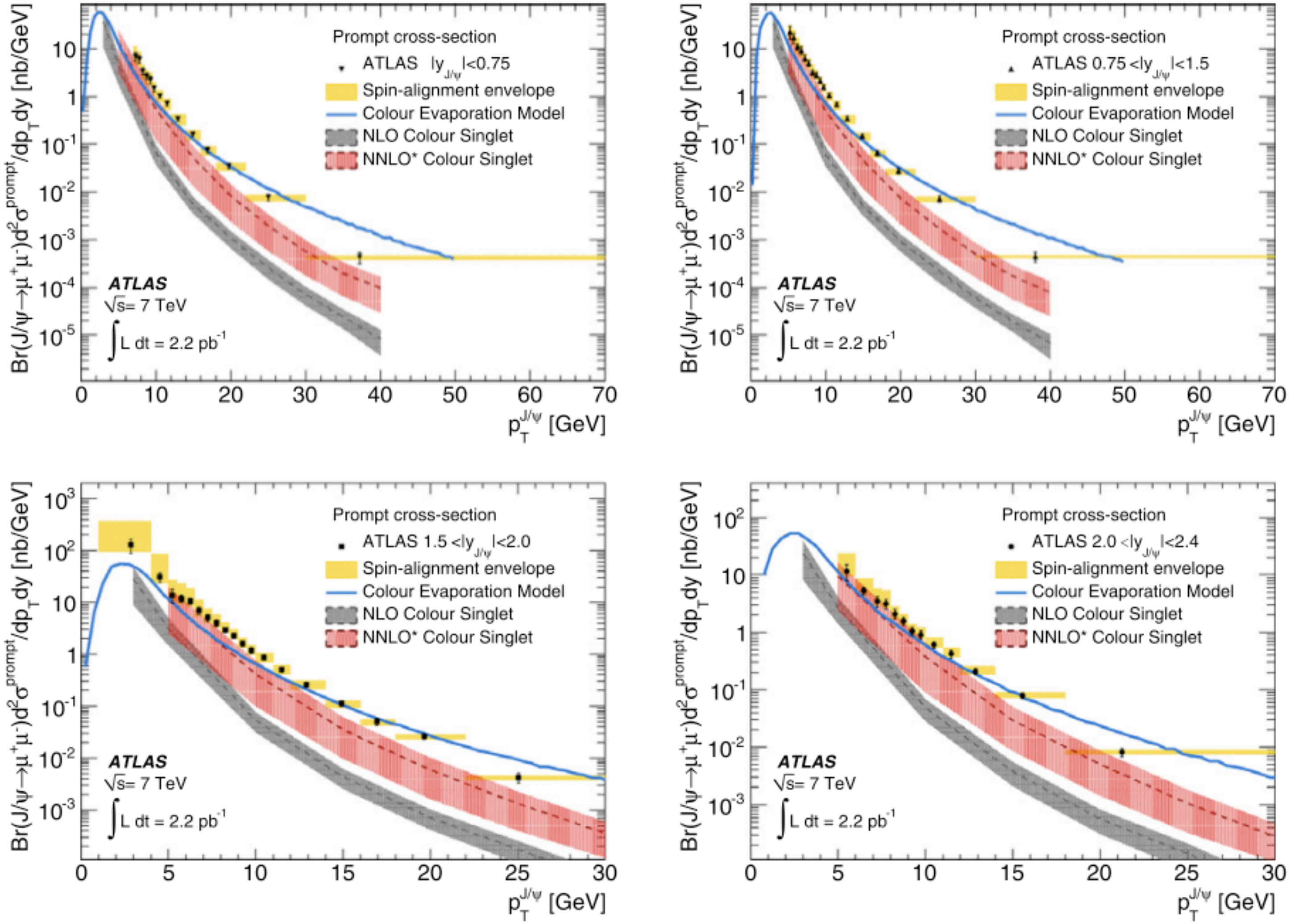


Fig. 11. Prompt J/ψ production cross-section as a function of J/ψ transverse momentum in the four rapidity bins. Overlaid is a band representing the variation of the result under various spin-alignment scenarios (see text) representing a theoretical uncertainty on the prompt component. Predictions from NLO and NNLO* calculations, and the Colour Evaporation Model are overlaid. The luminosity uncertainty (3.4%) is not shown.

PDFs for mass and lifetime fits for J/ψ cross section analysis

Invariant mass PDFs

Signal PDF = Gaussian with mean value = J/ψ mass

Background PDF = second order polynomial

Pseudo-proper time PDFs

Signal PDF = sum of two terms, for prompt and non prompt decays:

- non prompt decays: exp. fn of pseudo lifetime convolved with a time resolution function
- prompt decays: time resolution function

Background = sum of long lived and prompt components

Free parameters are:

- fraction of signal J/ψ candidates
- J/ψ mass
- scale factor to account for mass resolution of fit
- fraction of J/ψ candidates from B decays (non–prompt fraction)
- pseudo proper lifetime of B hadron decays
- scale factor to account for time resolution of fit
- parameters of background PDFs

Observation and life time measurement of $B_d^0 \rightarrow J/\psi\, K^{*0}\, (K\,\pi)$ & $B_s^0 \rightarrow J/\psi\, \phi\, (K^+ K^-)$

	N_{sig}
B_d^0	2750 ± 90
B_s^0	463 ± 26

	m_B MeV
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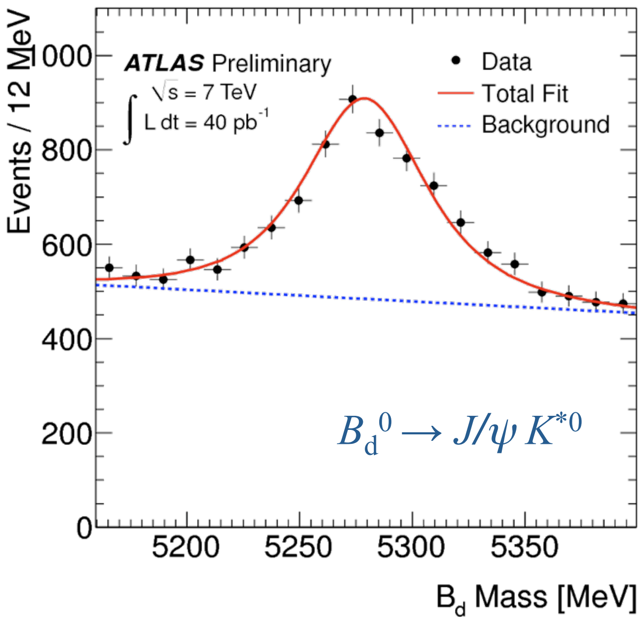
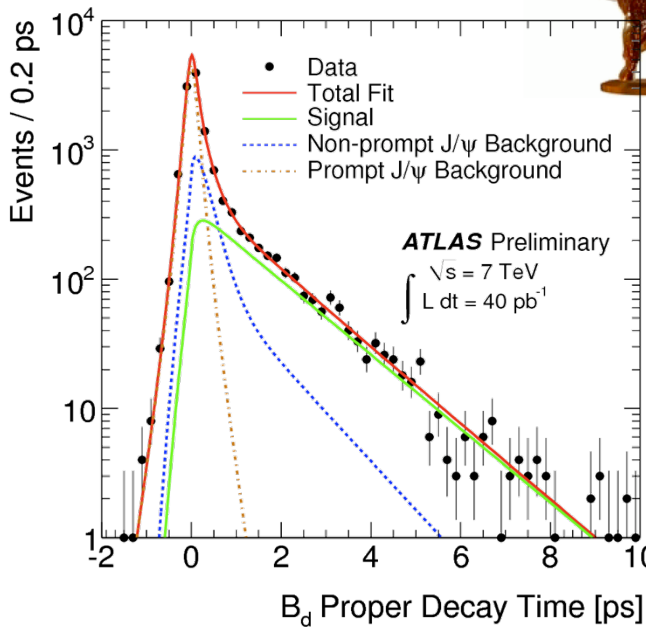




	τ_B, ps - ATLAS	τ_B, ps - PDG value
B_d^0	1.51 ± 0.04 (stat) ± 0.04 (syst)	1.525 ± 0.009
B_s^0	1.41 ± 0.08 (stat) ± 0.05 (syst)	1.472 ± 0.026

Inner Detector alignment and
proper decay time uncertainty

NB: single proper decay time PDF for B_s^0 (only 463 ± 26 candidates) so $\Delta\Gamma_s$ not measured

Correction factor (“F-factor”) for B-lifetime measurements

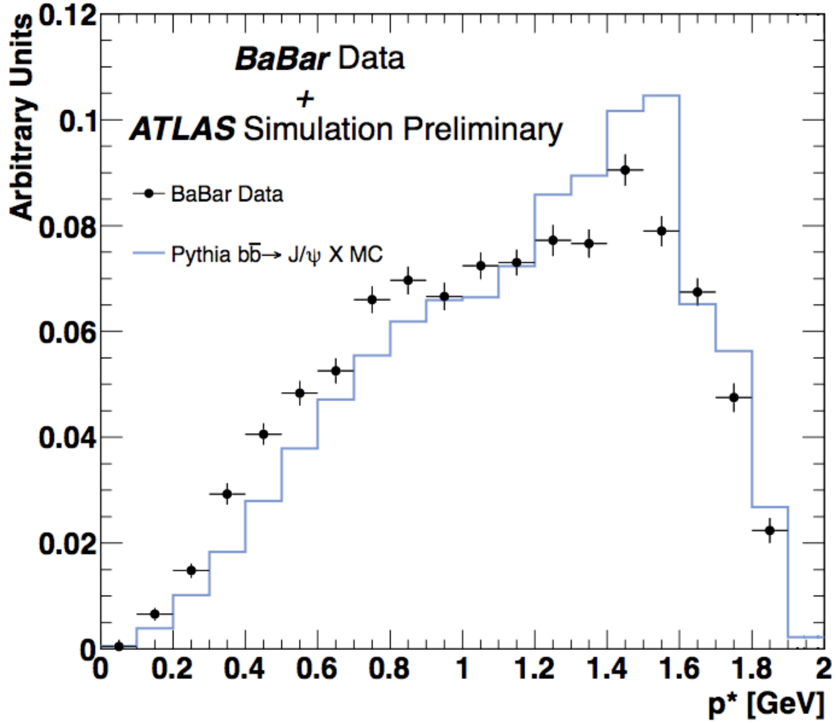
- Require a factor to correct psuedo-proper time to proper time
- Cannot be extracted from data since B-hadron decay not fully reconstructed
- F-factor from MC depends on the momenta of the B hadron and the J/ψ

$\Rightarrow$ J/ψ spectrum must be well described

To quantify discrepancy, truth spectra of $b^+b^- \rightarrow J/\psi$ X compared to measurements of BaBar at the Y(4S) resonance

$\Rightarrow$ plot momentum of J/ψ in Y(4S) rest frame (at SLAC, produced in 2-body decay of Y4s)

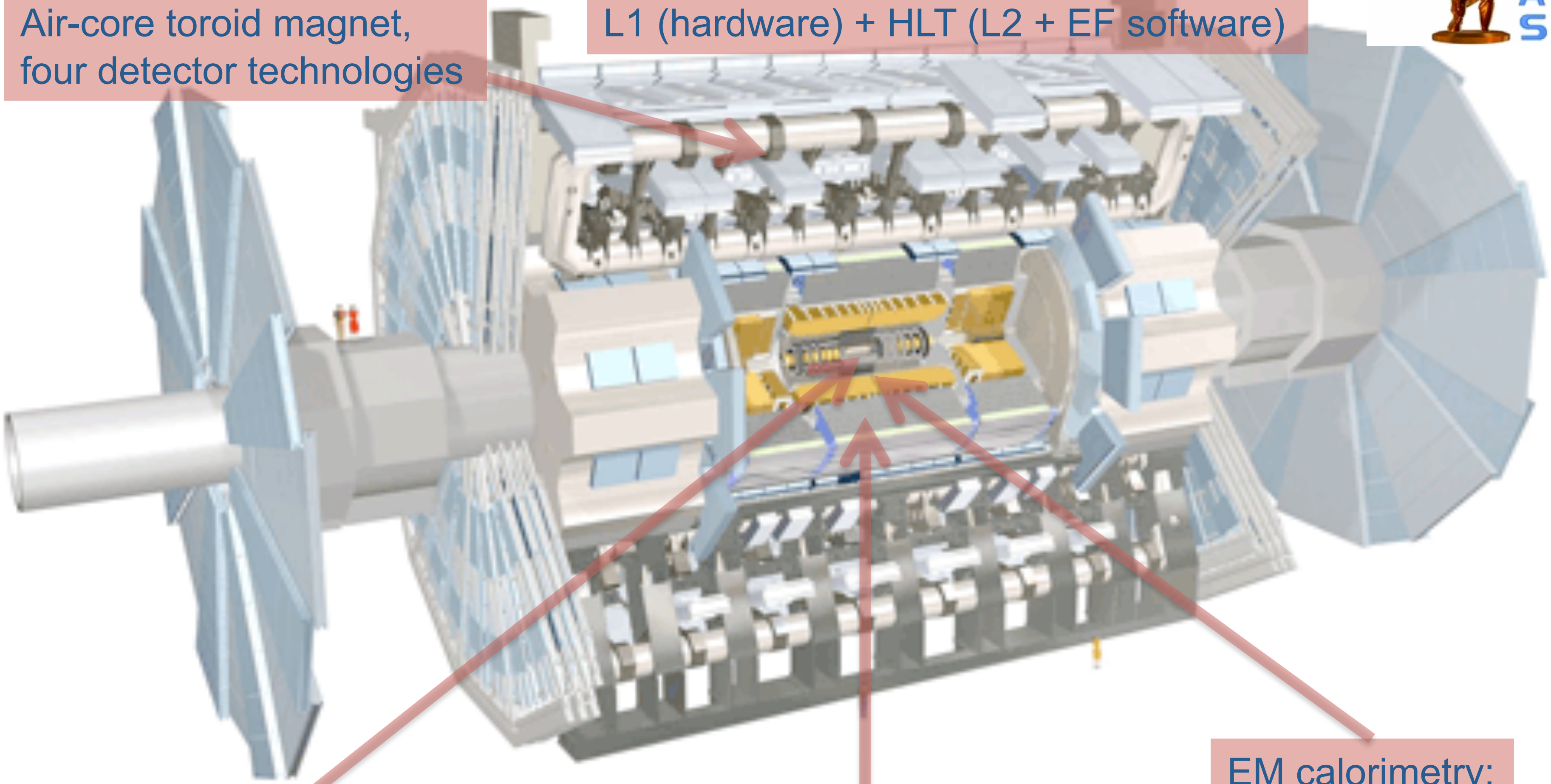
- Compare to truth after boosting J/ψ mesons into the rest frame of the Y(4S) in the MC simulation (even though there is no Y(4S))
- Highlights the need to improve the MC modelling (main shortcoming likely due to the fact that not all inclusive B-meson decays simulated)
- Empirical re- weighting of the MC sample performed by modifying decay branching ratios



ATLAS Detector Essentials

Muon Spectrometer (MS):
Air-core toroid magnet,
four detector technologies

Three level trigger system:
L1 (hardware) + HLT (L2 + EF software)



Inner Detector (ID):
Si Pixels+ Si strips (SCT) +
Transition Radiation Tracker (TRT)

HAD calorimetry:
Fi/scintillator tiles (central) + Cu/W-LAr (forward)

EM calorimetry:
Pb-LAr