Recent Results from ATLAS on Heavy Flavour and Vector Boson Physics

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ATLAS

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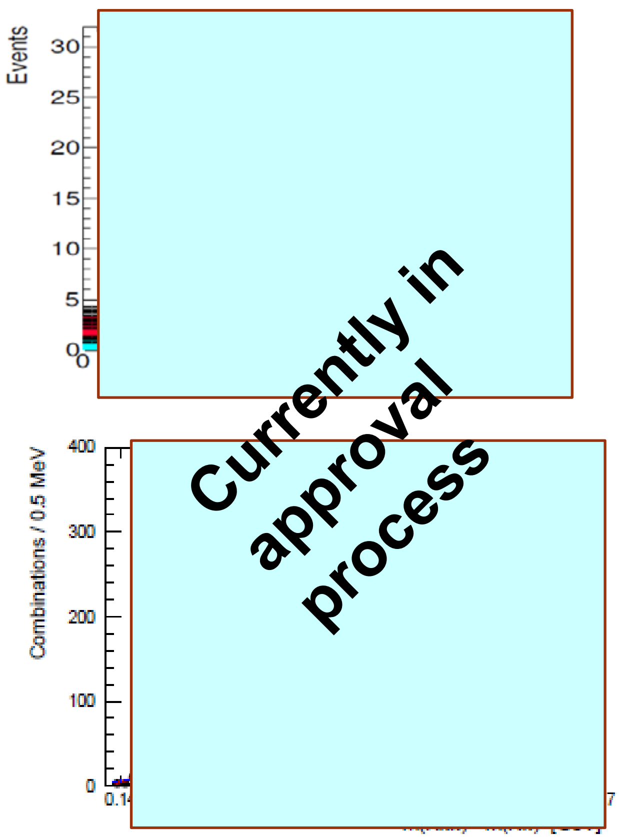
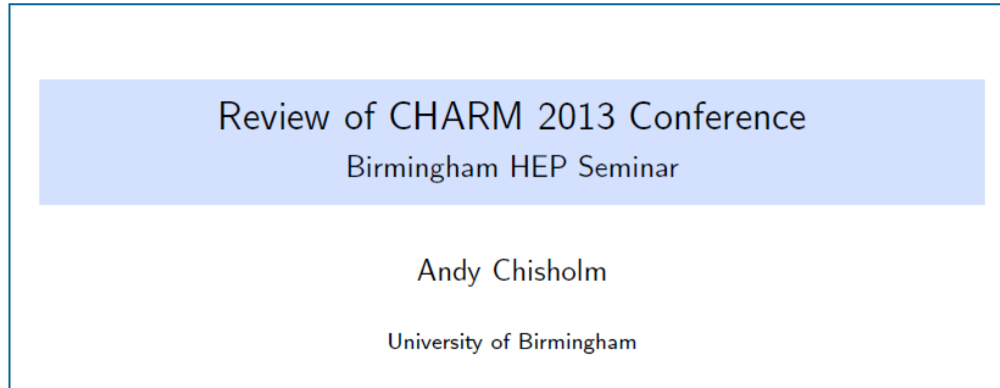
THE ROYAL SOCIETY

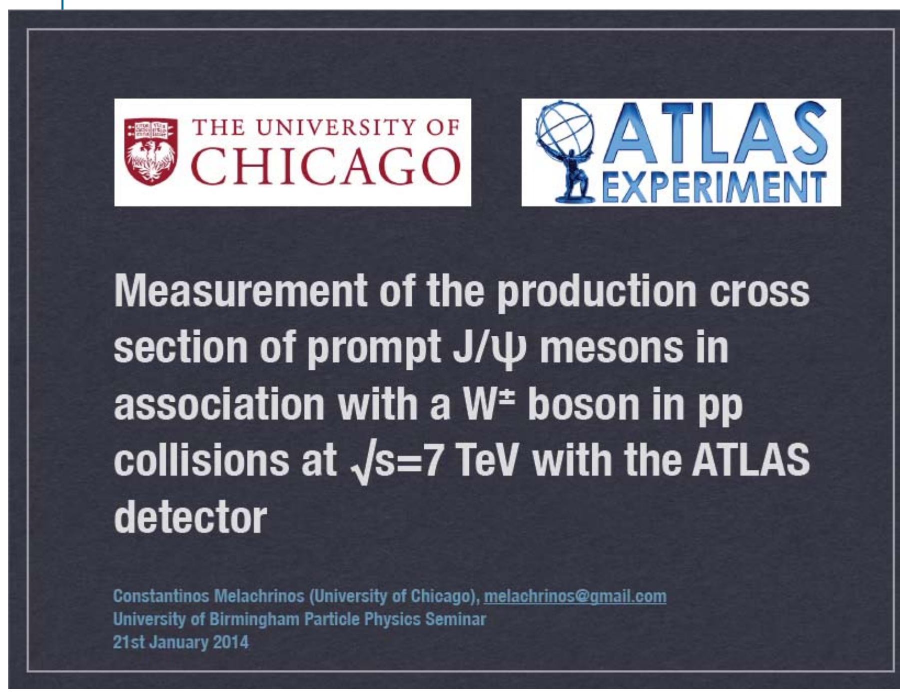
Plans for the seminar

1) My own (recent) ATLAS measurements:



2) Other related analyses, but:





3) Other ATLAS physics, but:

SEARCH FOR THE MAGNETIC MONOPOLE AT ATLAS

Graviton searches using the ATLAS detector

PROBING THE HIGGS PROPERTIES AT ATLAS

Searches for long-lived, massive particles with the ATLAS detector

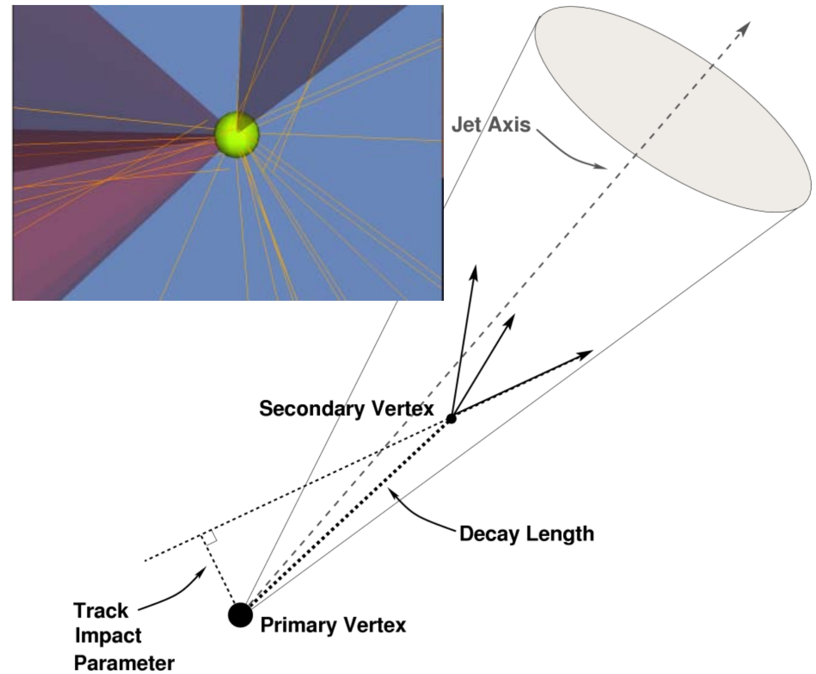
Peaky blinders: searches for $t\bar{t}$ resonances

→Updated plan for the seminar

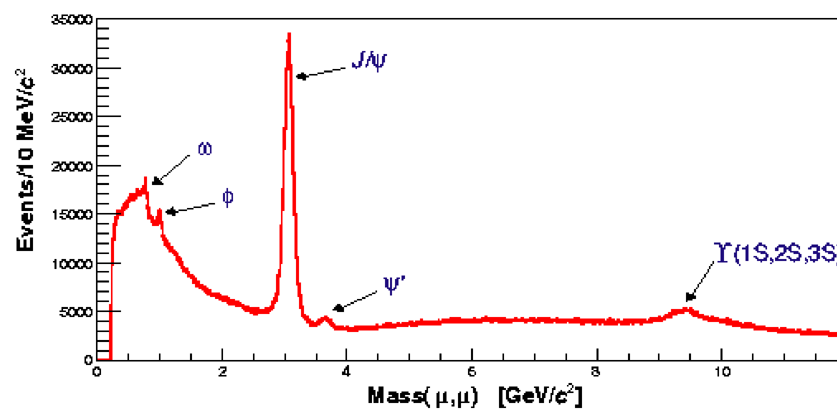
- An assortment of recent ATLAS heavy flavour results
- Some overlap with previous seminars
- Not everyone will have heard those / been awake / remember anything…

Heavy flavour physics in ATLAS

- Many methods developed for b-jet and c-jet tagging in ATLAS
  - Particularly important for Standard Model processes, e.g. top, Higgs, flavour-tagged analyses
  - Also for heavy flavour cross-sections and related measurements
    - I will cover one of those today

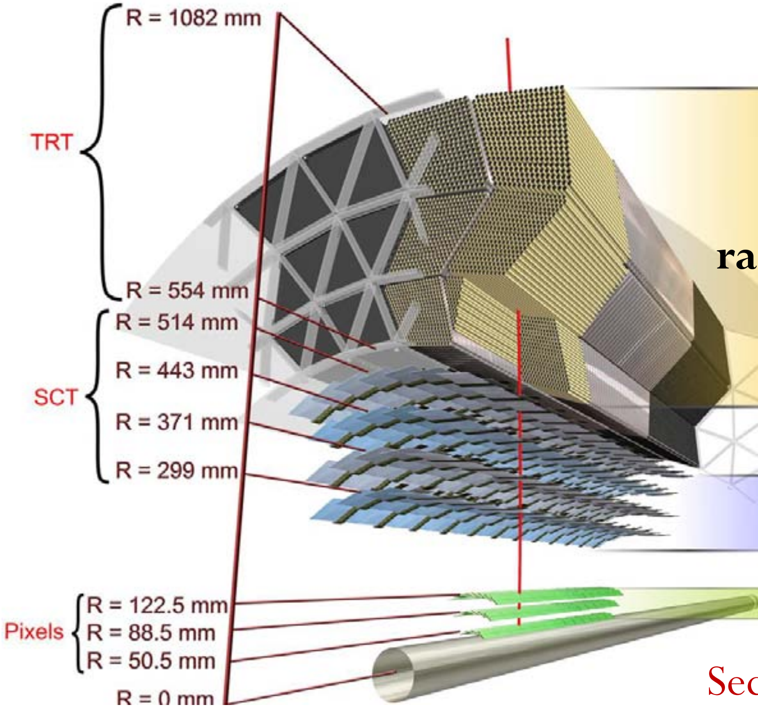


- Majority of ATLAS heavy flavour results involve quarkonium (J/ψ, Υ)
  - Use muon decays
  - Easy for reconstruction and triggering



The ATLAS detector for b,c physics

Inner detector



Transition radiation tracker
Particle ID, pattern recognition

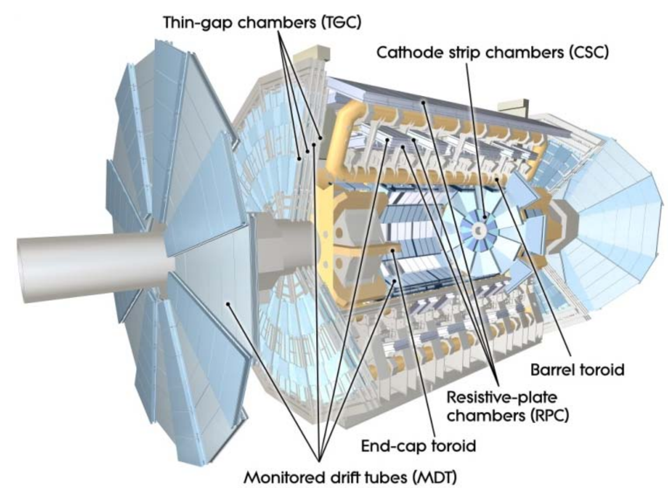
Silicon strips
Momenta

Silicon pixels
Secondary vertices

- Covers $|\eta|<2.5$
- Solenoidal B-field, 2T

Muon system

- Precise tracking chambers and trigger chambers
- $|\eta|<2.7$
- Toroidal B-field, ~0.5T



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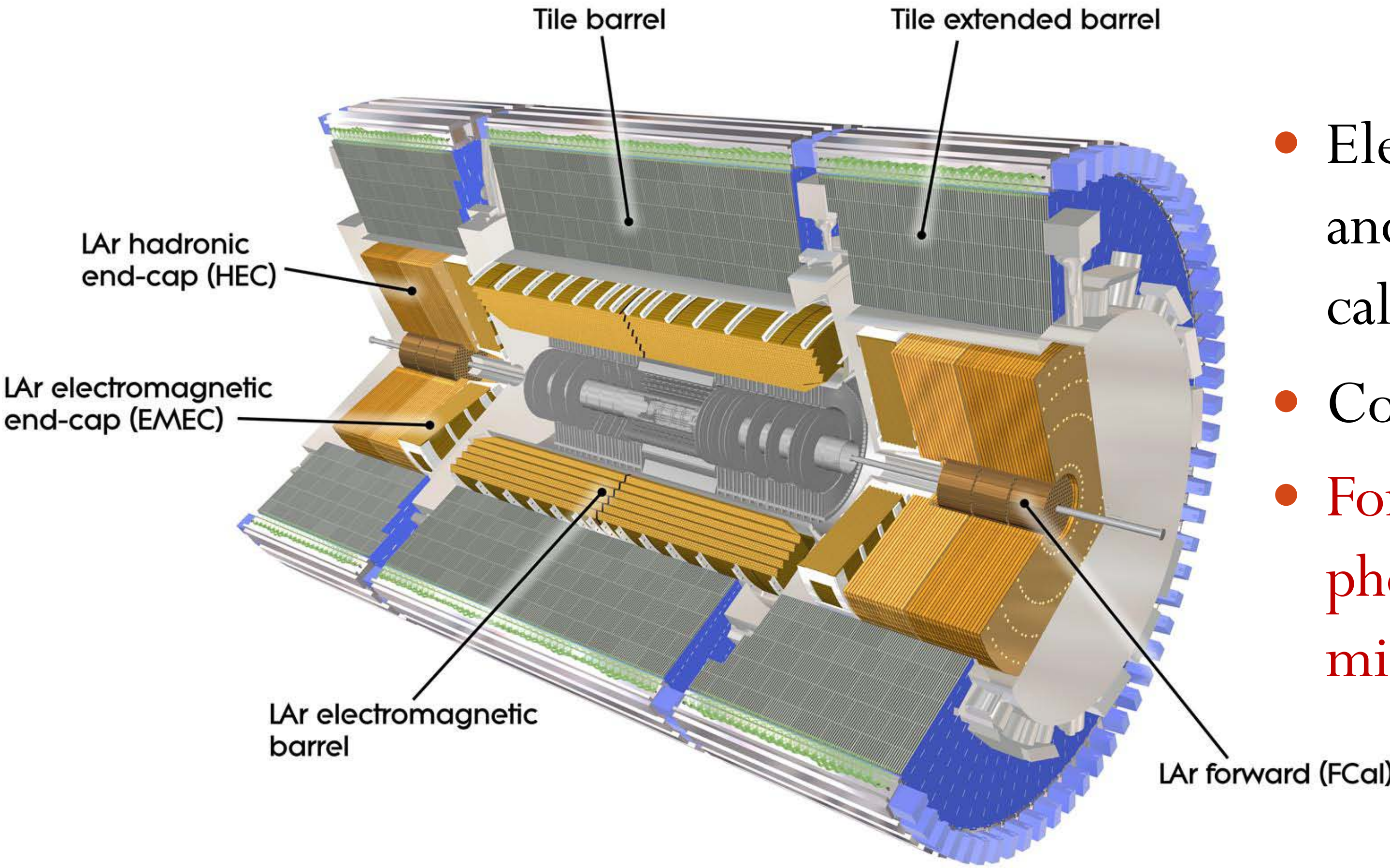
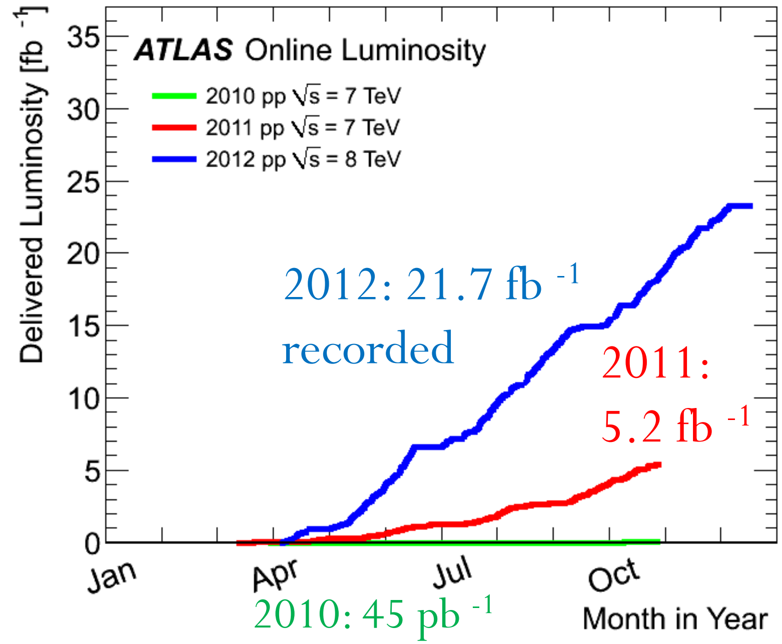
Calorimeters

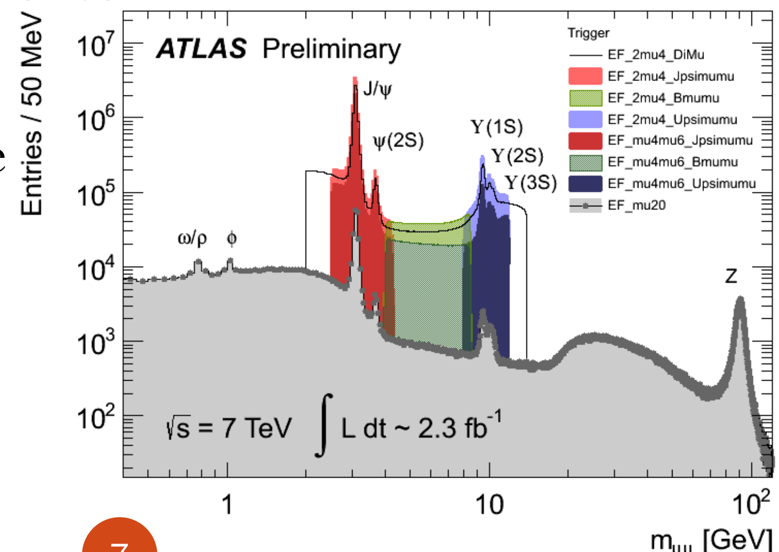


- Electromagnetic and hadronic calorimeters
- Covers $|\eta|<4.9$
- For jets, electrons, photons and missing E_T

Performance

- Most analyses presented today use 2011 data; 2012 analyses in preparation
- Events predominantly selected in muon or di-muon decay channels (e.g. J/ψ or Υ)
- Single-muon triggers supplemented by di-muon triggers:
  - invariant mass windows in the regions of the J/ψ, B and Υ
  - largely unprescaled





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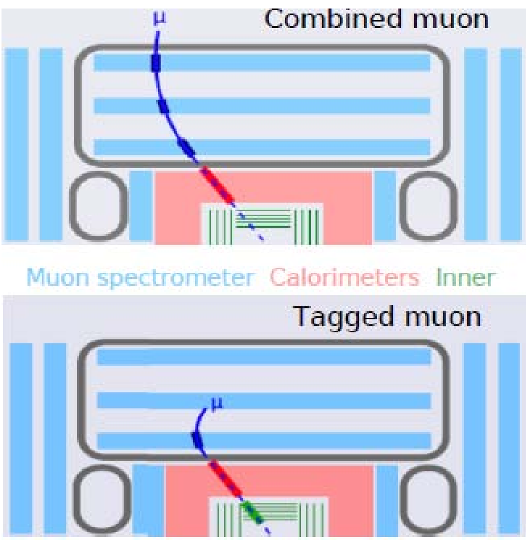
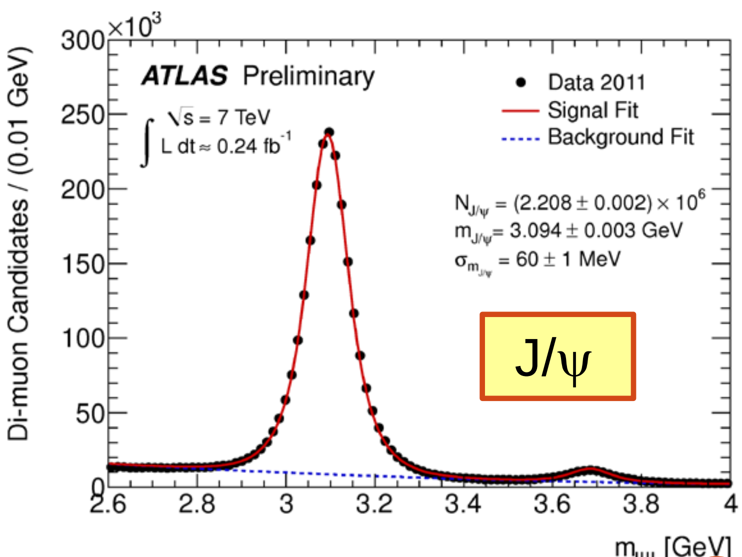
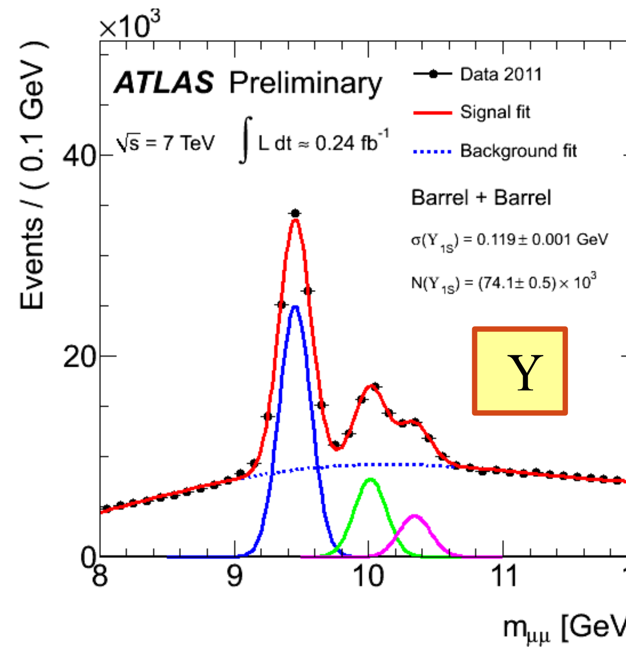
Muon and quarkonium reconstruction

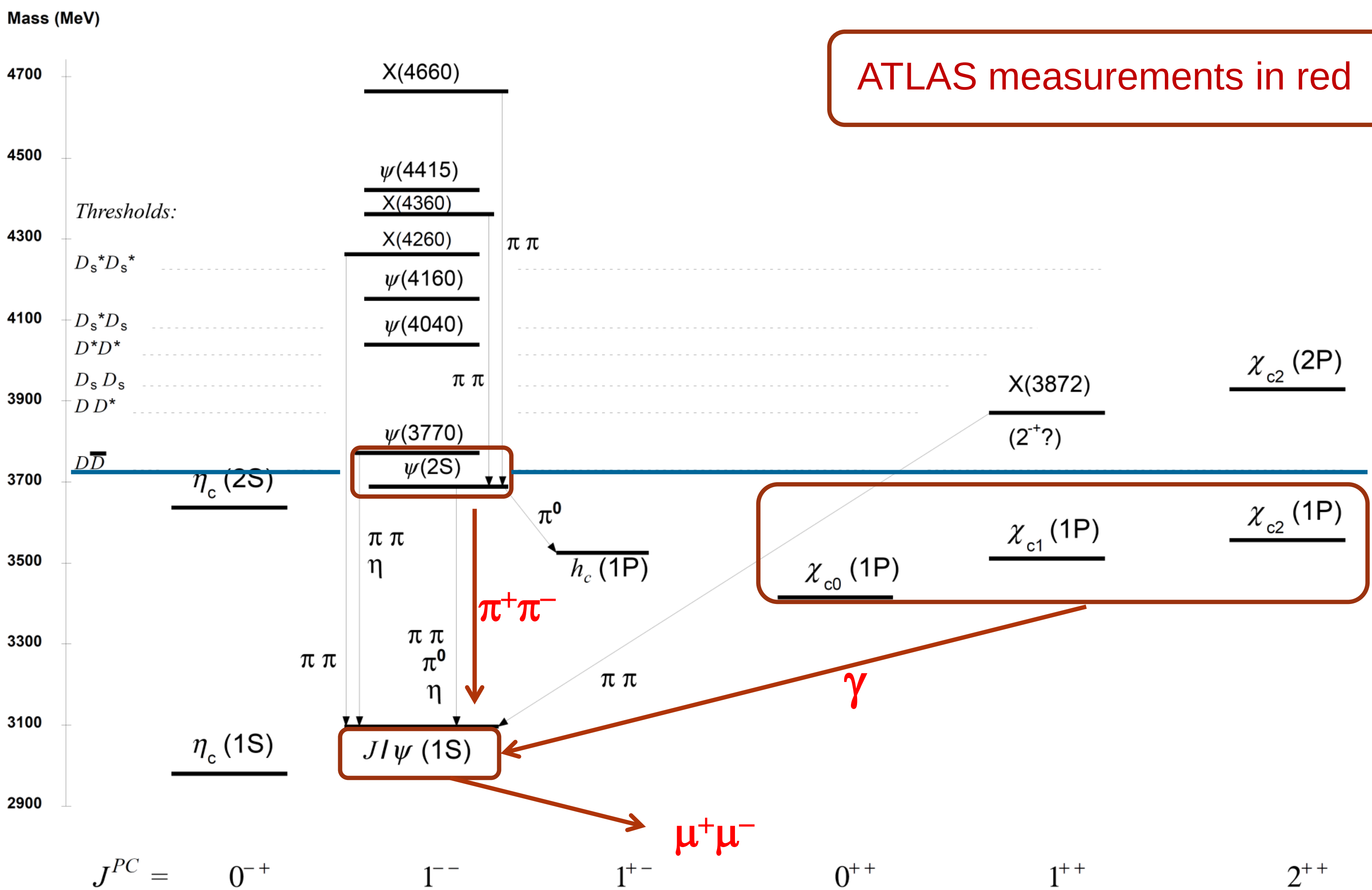


- Muon reconstruction
  - Combined muons: match inner detector and muon tracks
  - Tagged muons: match inner detector tracks to muon segments (low p_T)
- Require ≥ 1 combined muon for J/ψ, 2 for Υ

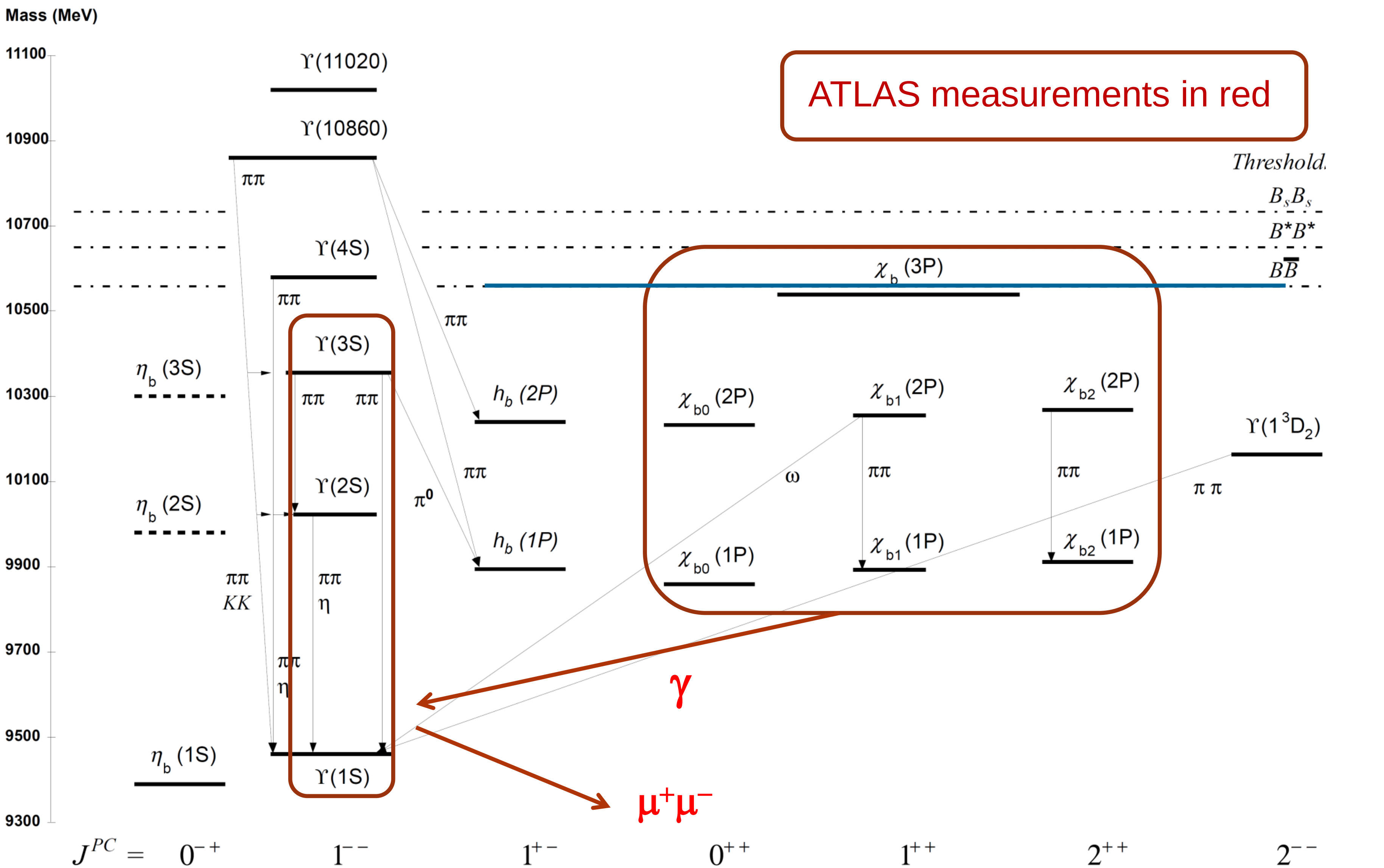




Charmonium spectroscopy $(c\bar{c})$



Bottomonium spectroscopy $(b\bar{b})$



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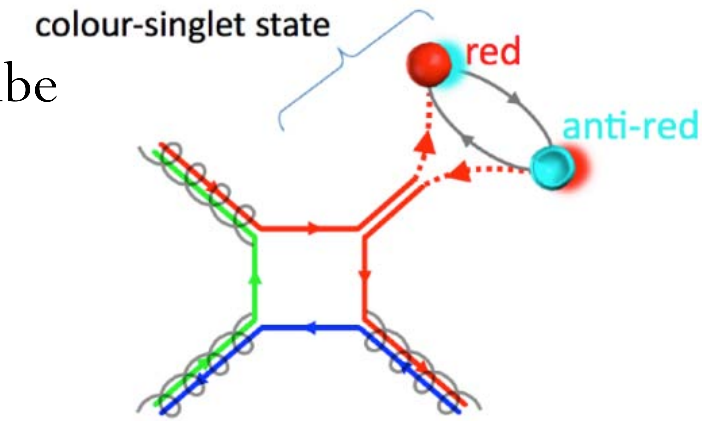
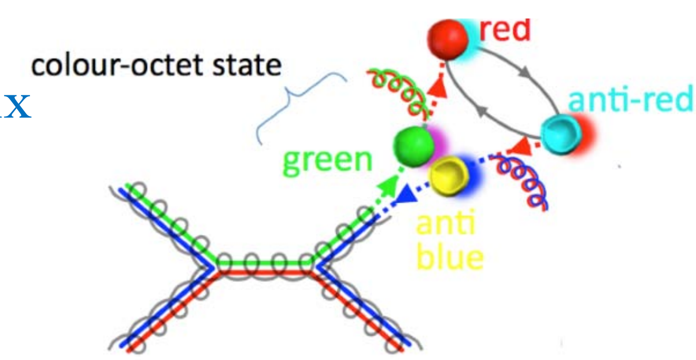
Quarkonium production

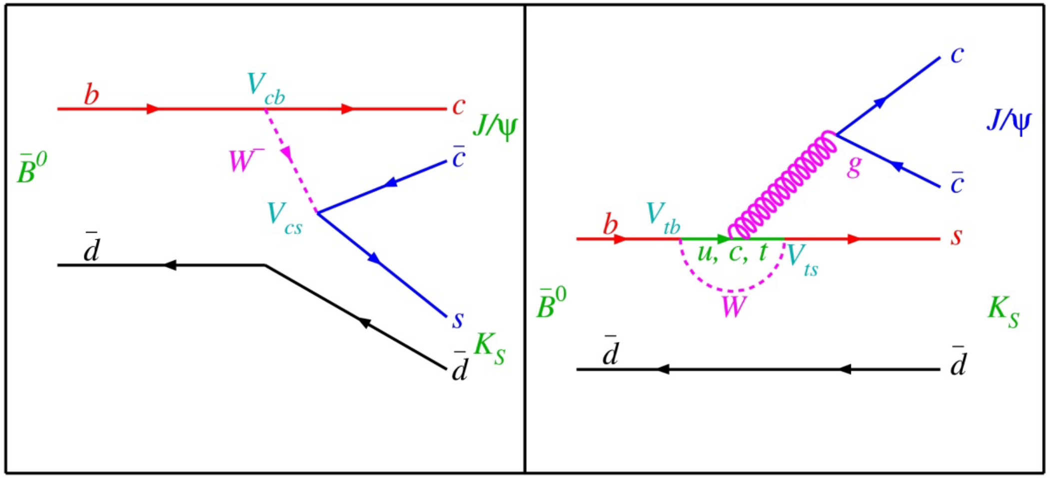
- Production mechanism for quarkonium states not fully understood
- Colour singlet (CS) mechanism cannot describe all measurements
- Colour octet (CO) model
  - Initial coloured state decays into a singlet quarkonium bound state
- Non-Relativistic QCD (NRQCD) includes CO+CS+non-perturbative effects, with matrix elements tuned to data
- Quarkonium production at the LHC offers
  - Numerous tests of perturbative QCD in a new energy regime
  - Higher transverse momenta
  - A wider rapidity range





Classifying quarkonia

- Prompt: Produced directly in the pp interaction or produced through feed-down decays from higher charmonium states (no displaced decay vertex)
- Non-prompt: Produced in the decay chains of b-hadrons (decay vertex can be displaced from primary pp vertex)



e.g. $B \rightarrow J/\psi\ K_s$

Ian Brock

Quarkonium measurements

Introduction: inclusive J/ψ

$\psi(2S)$

χ_c

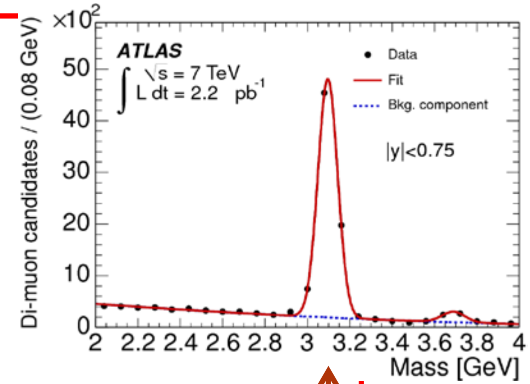
$\Upsilon(nS)$

Other measurements

Inclusive J/ψ cross-section: method

Nucl. Phys. B 850 (2011) 387

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

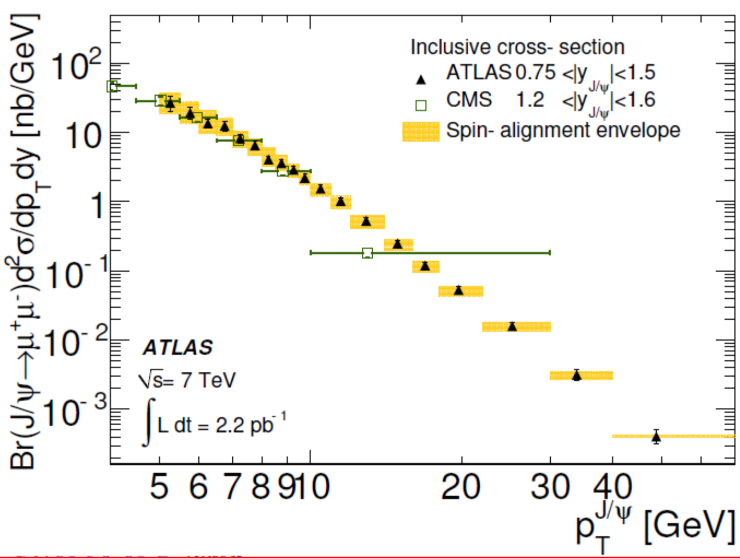


$$N_{\mathrm{corr}}=\Sigma w^{-1}\cdot N_{\mathrm{reco}}$$

Event weight: $w^{-1}=A\cdot M\cdot\epsilon^2_{\mathrm{trk}}\cdot\epsilon^+_\mu(p^+_T,\eta^+)\cdot\epsilon^-_\mu(p^-_T,\eta^-)\cdot\epsilon_{\mathrm{trig}}$

- Detector Acceptance: with generator level MC
- Bin migration correction: due to finite detector resolution
- Reconstruction efficiencies: with tag-and-probe method using data
- Trigger efficiency: determined from MC and reweighted to data

Fit signal + background in many p_T, y bins



- Result with 2.2 pb^{-1}
- Example of one rapidity bin (4 in total)
- ■: variation due to 5 extreme spin alignment scenarios
- Agreement with CMS

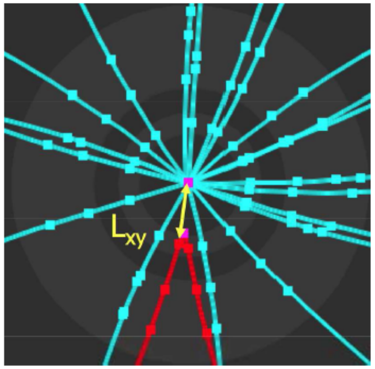
T. Matsushita (Kobe)
PLHC2012

Prompt and non-prompt J/ψ: method

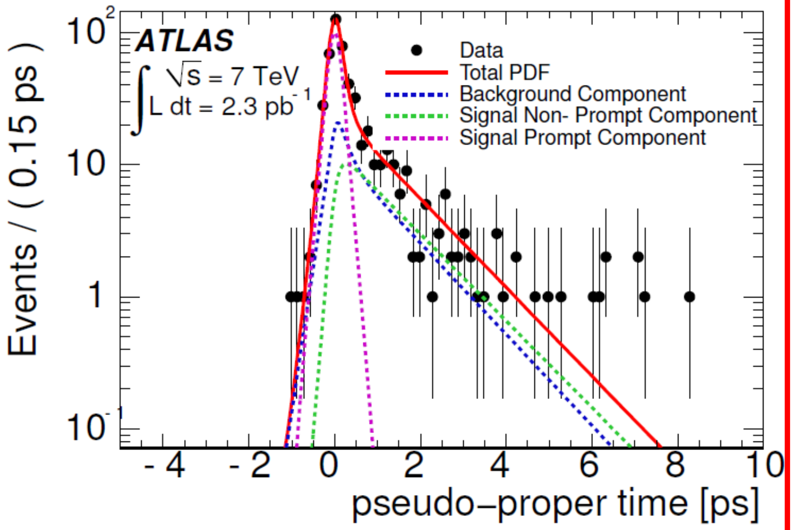
pseudo-proper time

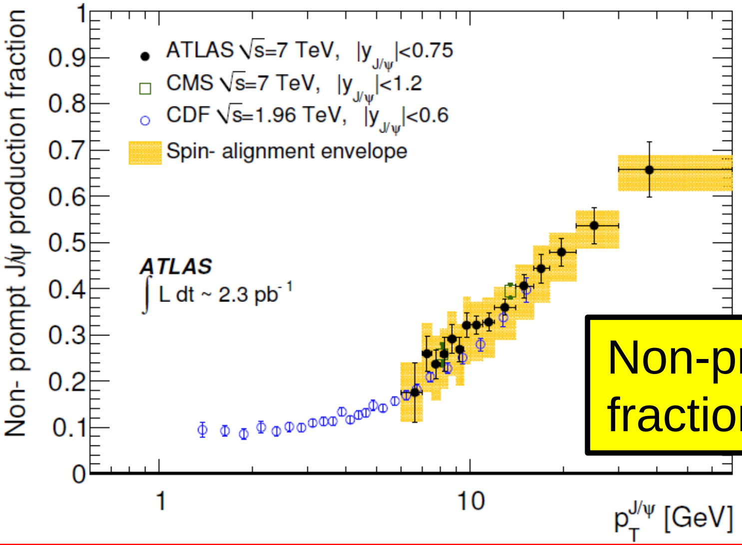
$$\tau = \frac{L_{xy} \cdot m(J/\psi)}{p_T(J/\psi)}$$

- x-y displacement of J/ψ from PV
- Invariant mass of J/ψ
- p_T of J/ψ



- Prompt J/ψ have $\sim$ zero τ while non-prompt J/ψ have positive τ
- Simultaneous fit to mass and τ
- Good agreement with CDF
- Fraction is p_T dependent





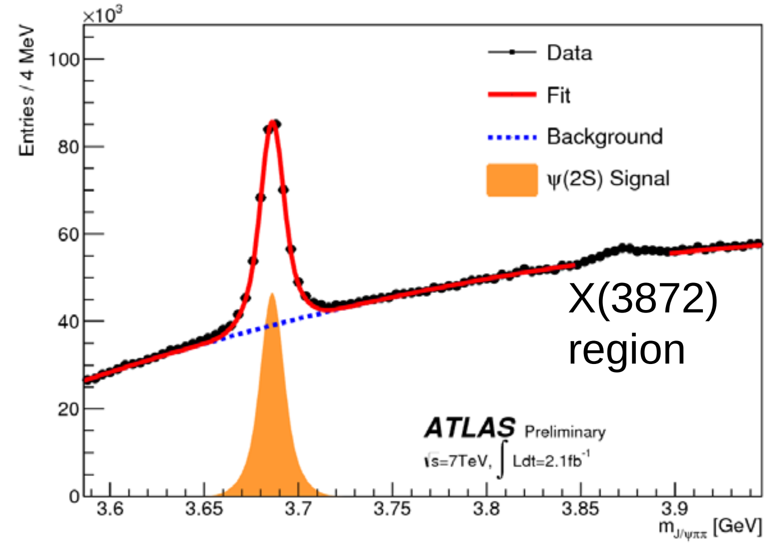
Non-prompt fraction

T. Matsushita (Kobe)
PLHC2012

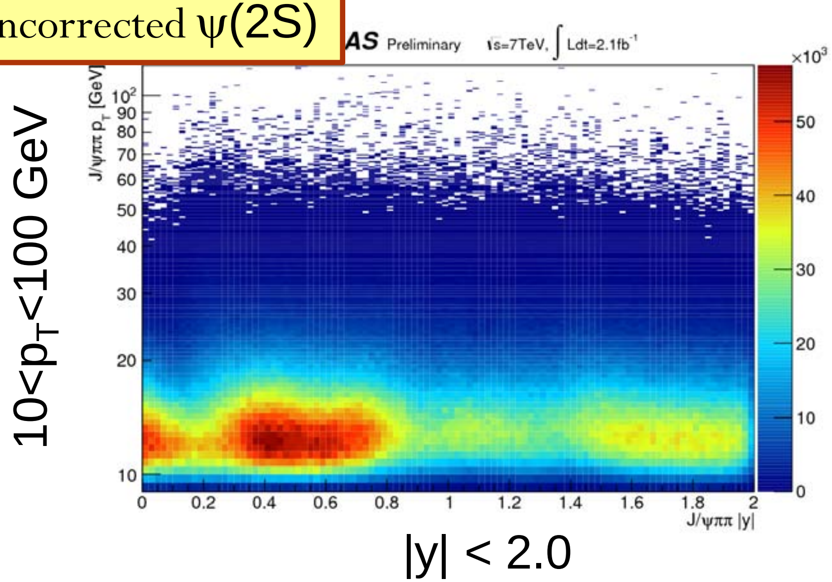
ATLAS-CONF-2013-094

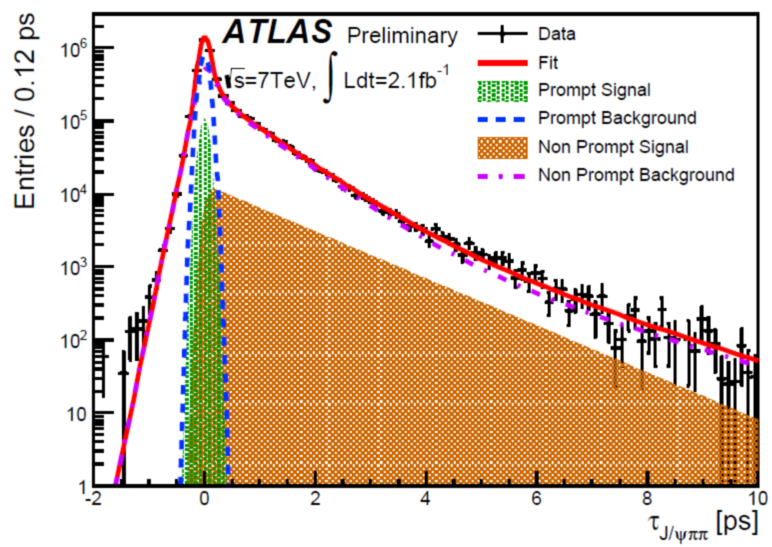
ψ(2S) measurement

- Measured in $\psi(2S) \rightarrow J/\psi\ \pi\pi$ mode
- 2.1 fb^{-1} at 7 TeV
- No significant feed-down from higher charmonium states
- Additional pion efficiency and acceptance corrections



Uncorrected ψ(2S)





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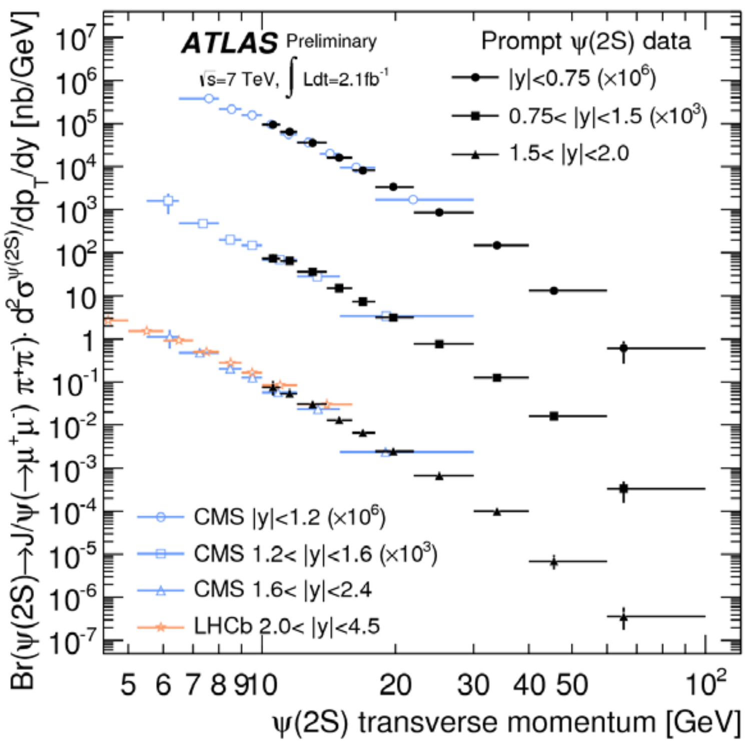
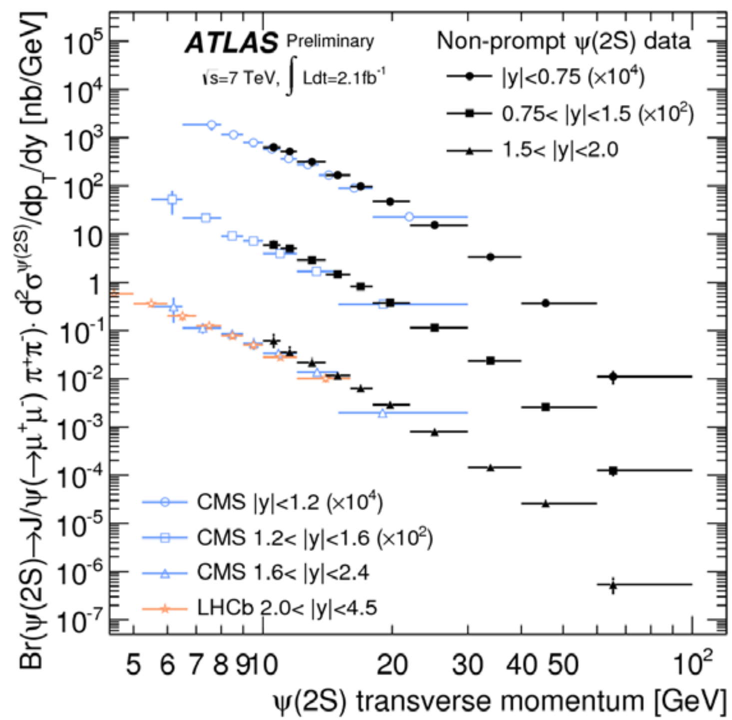
ψ(2S) cross-section compared to other results

Prompt cross-section



Non-prompt cross-section

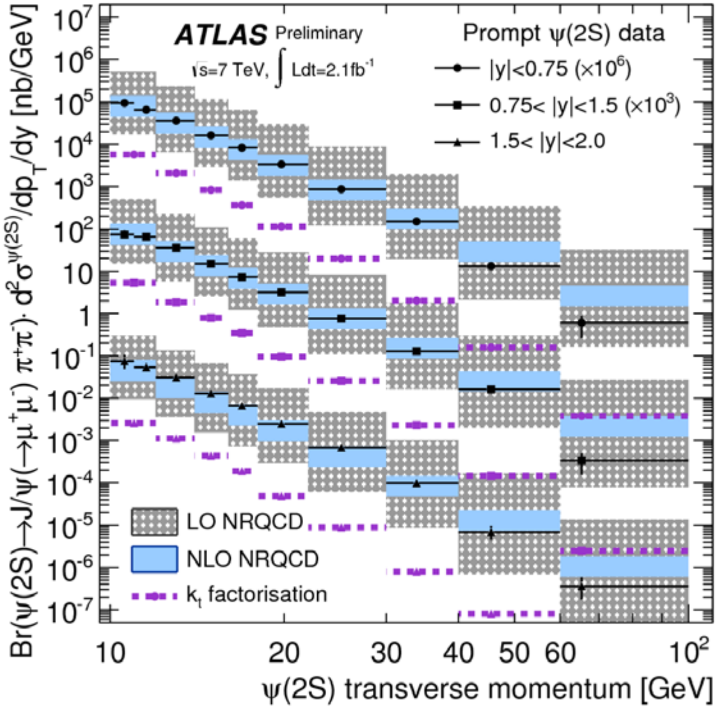


- Agree well with other LHC results
- p_T range extended

Spin-alignment of ψ(2S) was assumed to be isotropic for central results. Variations for a number of extreme spin-alignment scenarios detailed separately.

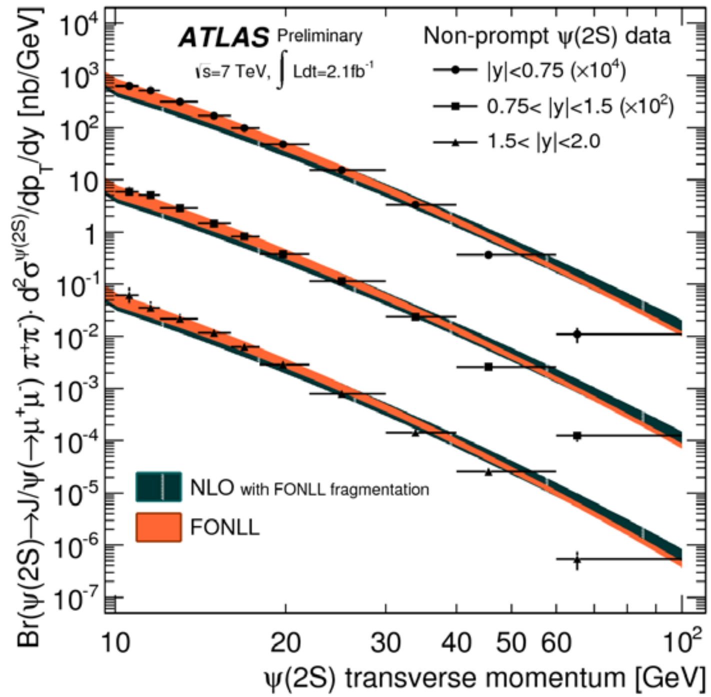
ψ(2S) cross-section compared to theory

Prompt cross-section



- (N)LO NRQCD in good agreement, except for highest p_T
- Matrix element retuning possible
- k_T factorisation underestimates data
  - (parton-level colour singlet+k_T-dependent parton distributions)

Non-prompt cross-section

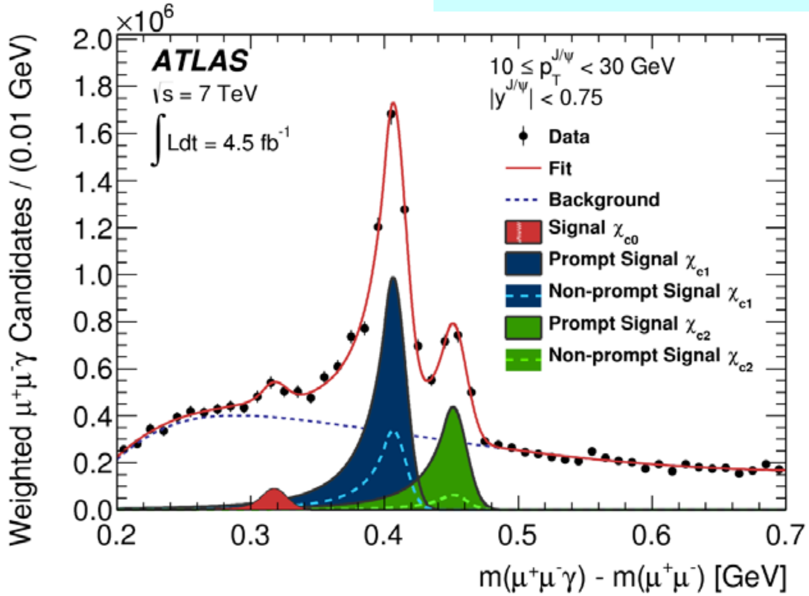


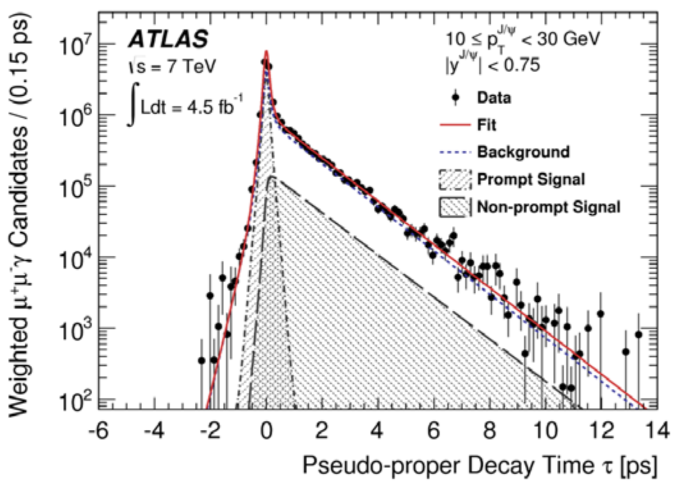
- NLO and FONLL (Fixed Order Next-to-Leading Logarithm) have a harder p_T spectrum than data
- FONLL: b-hadron production spectrum $\otimes$ momentum distribution of the ψ(2S)

Measurement of χ_{c1} and χ_{c2} production

arXiv:1404.7035, sub. to JHEP 29/04/14

- Using 4.5 fb-1 at 7 TeV (2011)
- P-wave states of the charmonium system: triplet $\chi_{cJ}(1P)$, with J=0,1,2
  - Complementary to S-wave J/ψ and $\psi(2S)$
  - Radiative decays into $J/\psi\ \gamma$
  - Photon reconstructed from $\gamma \rightarrow e^+e^-$ conversions in inner tracking detectors
- Large branching fractions for J=1,2
- Yield of χ_{c0} is too low for reliable measurement
- Additional photon efficiency corrections





Fit to separate prompt and non-prompt

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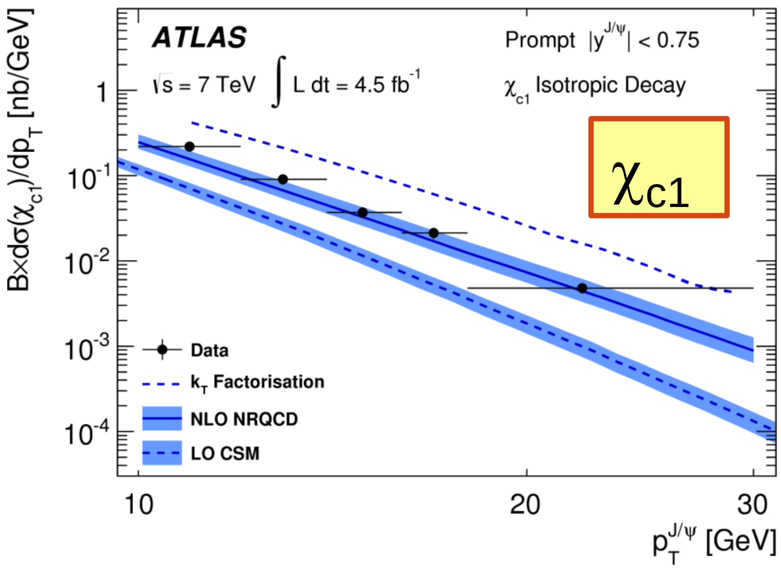
$\chi_{c1,2}$ prompt cross-section

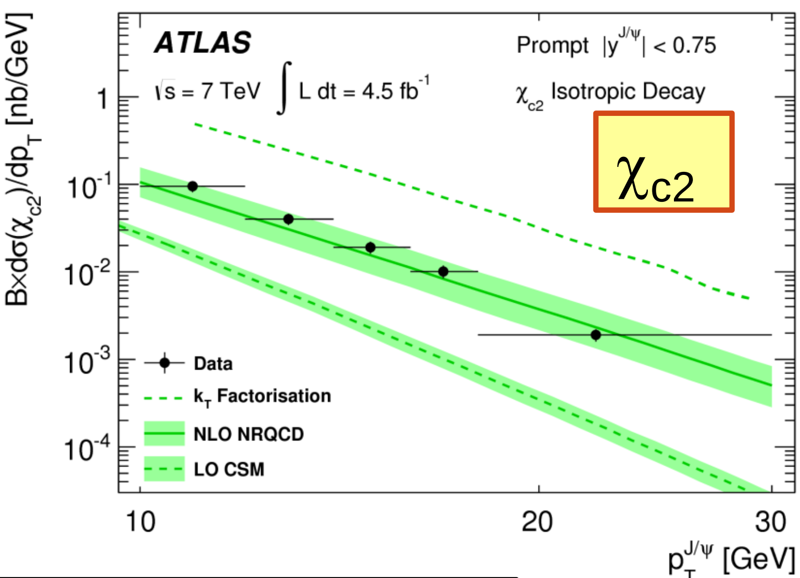
- Measured for $|y_{J/\psi}|<0.75$ as function of $p_T^{J/\psi}$ and $p_T^{\chi c}$
- Compare to the predictions of
  - NLO NRQCD: matrix elements from experimental data

    Good agreement
  - LO colour singlet +potential model

    Low: higher orders important?
  - k_T factorisation: colour singlet + longitudinal/transverse gluon distribution

    Overestimates data



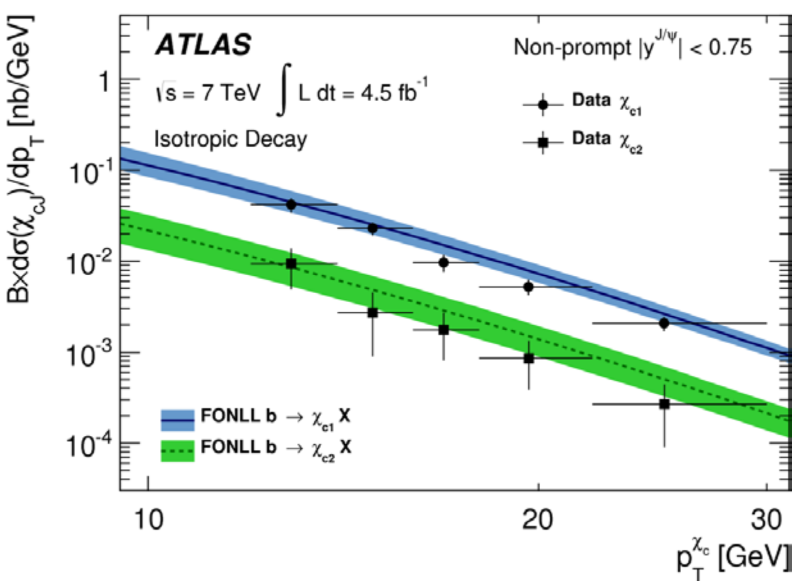


Plots for isotropic decay angular distributions (unpolarised)

$\chi_{c1,2}$ non-prompt cross-section and ratios

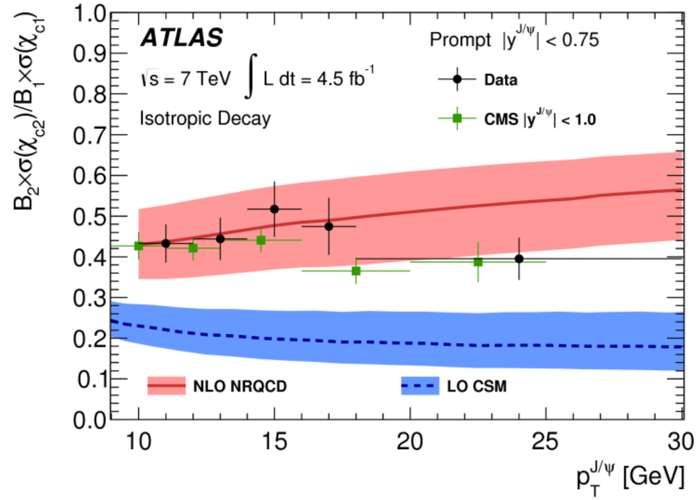
Non-prompt cross-section

- First measurement at LHC
- Fixed-order next-to-leading log (FONLL) describes data
- FONLL: b-hadron production combined with momentum distributions of χ_{c1} and χ_{c2}



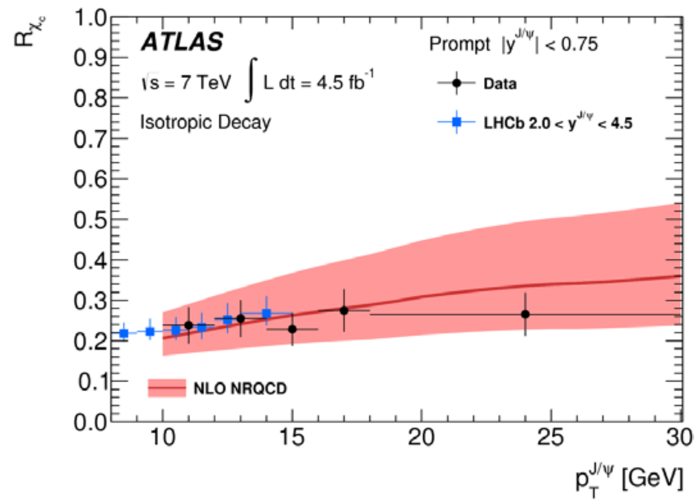
Plots for isotropic decay angular distributions (unpolarised)

Prompt χ_{c2}/χ_{c1}



- Sensitive to possible colour octet contributions, NLO NRQCD in good agreement (esp. low p_T)

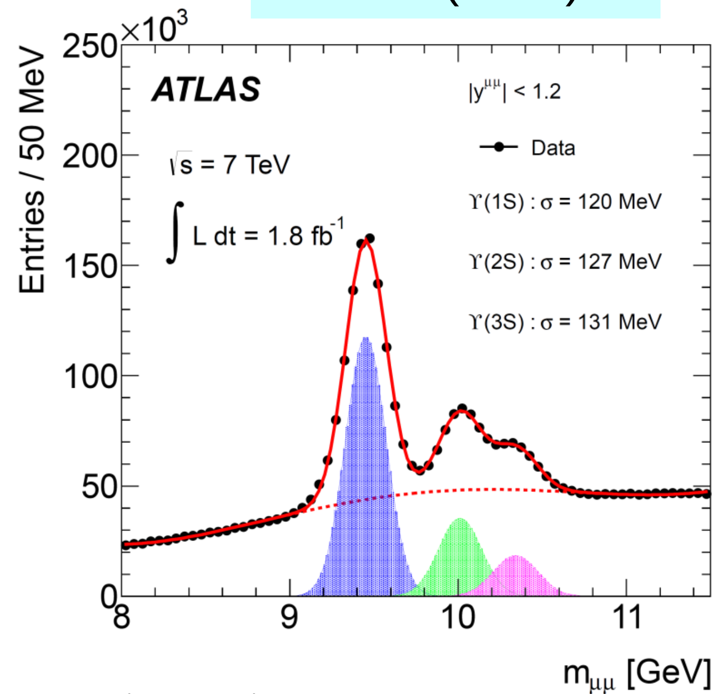
χ_c feed-down fraction



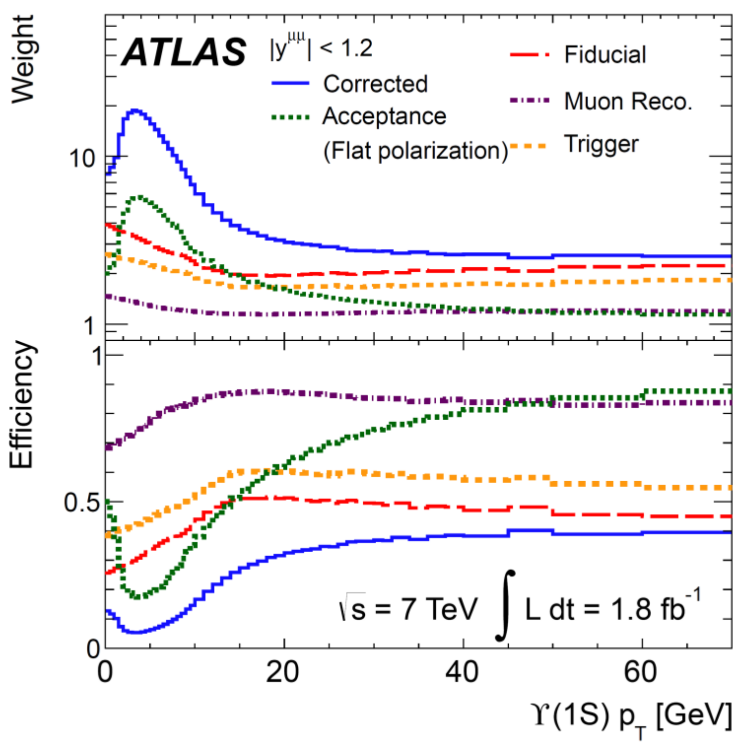
- 20-30% of prompt J/ψ originate from χ_c

Bottomonium: $\Upsilon(nS)$

Phys. Rev. D 87, 052004 (2013)

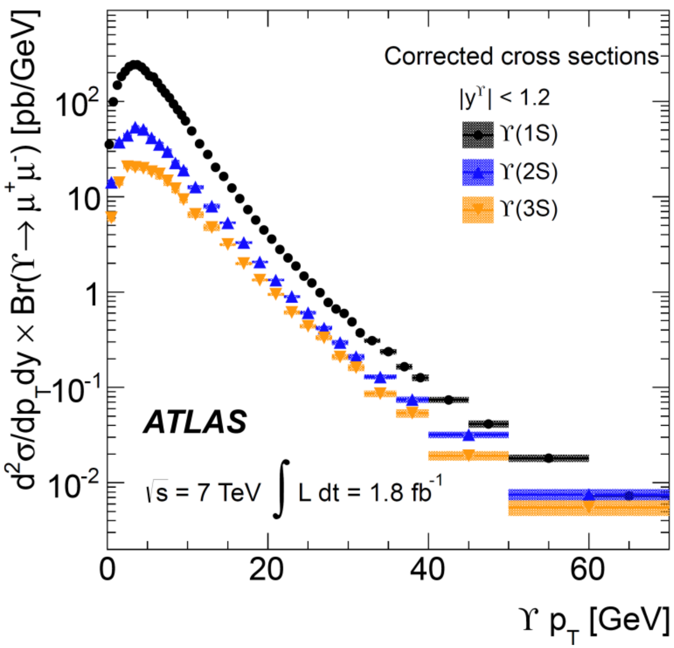


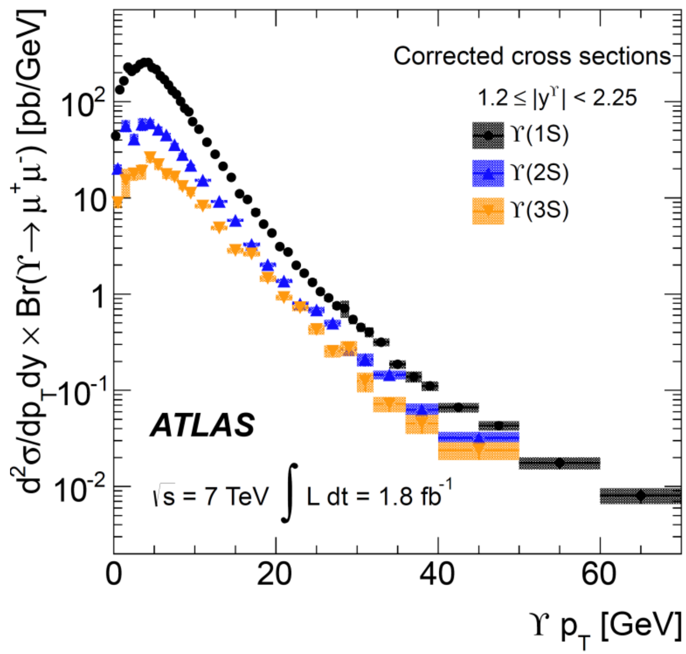
- Earlier result on $\Upsilon(1S)$ fiducial cross-section: Phys.Lett.B 705 (2011) 9
- Updated: $\Upsilon(nS)$, n=1,3 using 1.8 fb^{-1} at 7 TeV



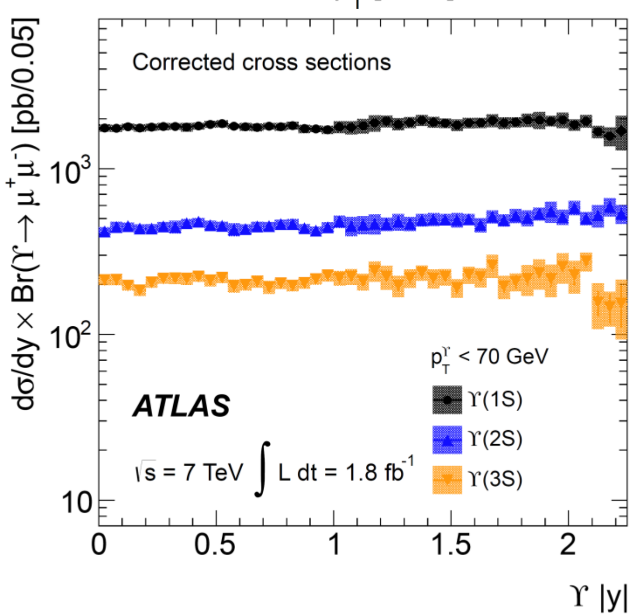
- Fit dimuon invariant mass spectra in finely binned p_T and rapidity intervals
- Correct each event for detector efficiencies and acceptances: extract production cross-sections

Υ(nS) Corrected differential cross-sections





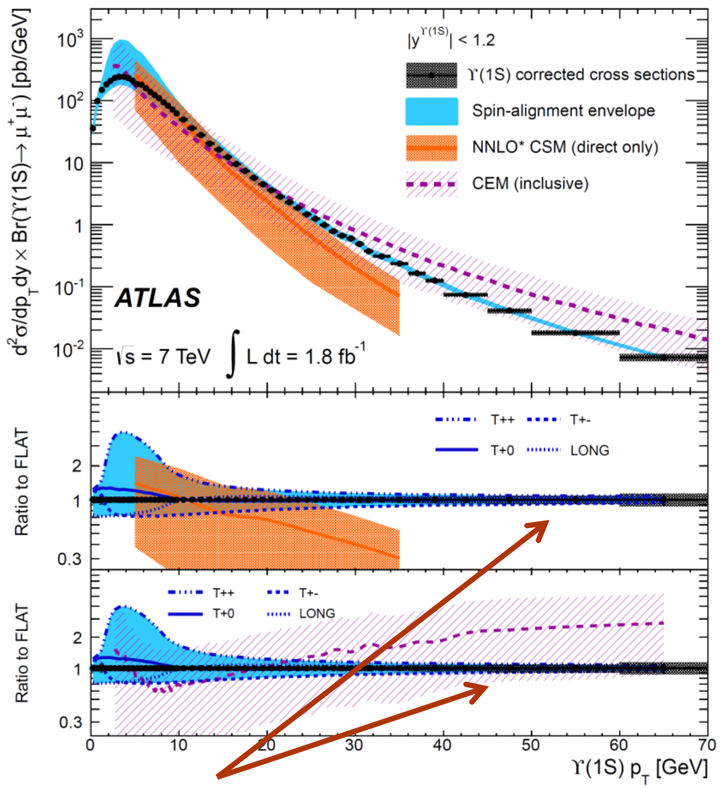
- Corrected for muon fiducial acceptance cuts
- $|y(Y)|<2.25$, $p_T(Y)<70$ GeV

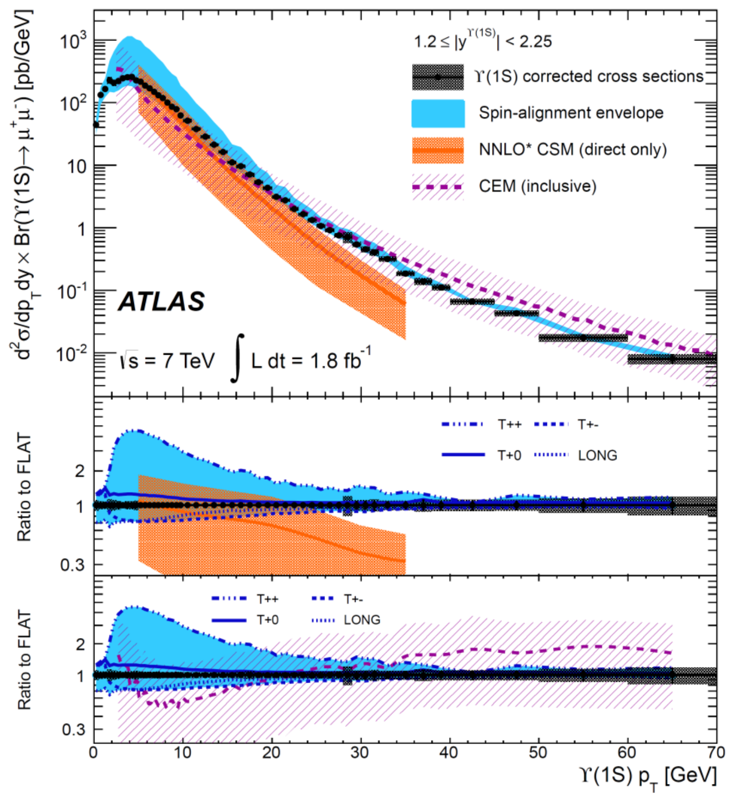


- Acceptance depends on spin-alignment, i.e. angular distributions of muons
- Shown here for unpolarised (isotropic) muon angular distributions

Comparison with theory: Υ(1S)

- Compare differential cross-sections with models:
  - NNLO* Colour Singlet Model (direct Υ production only)
  - Phenomenological Colour Evaporation Model (inclusive)





Models fail to describe shape & normalisation of data

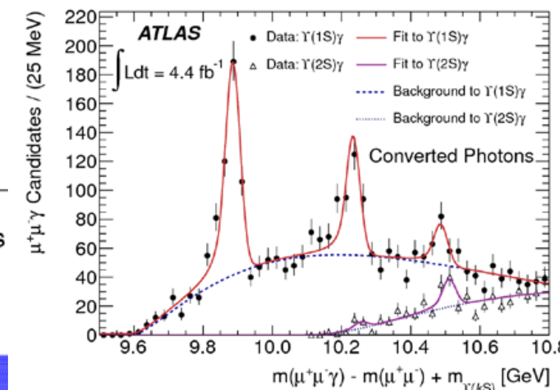
Better at p_T<20 GeV (Tevatron region), new contributions at high p_T not accounted for by CSM

Also for Υ(2S,3S)

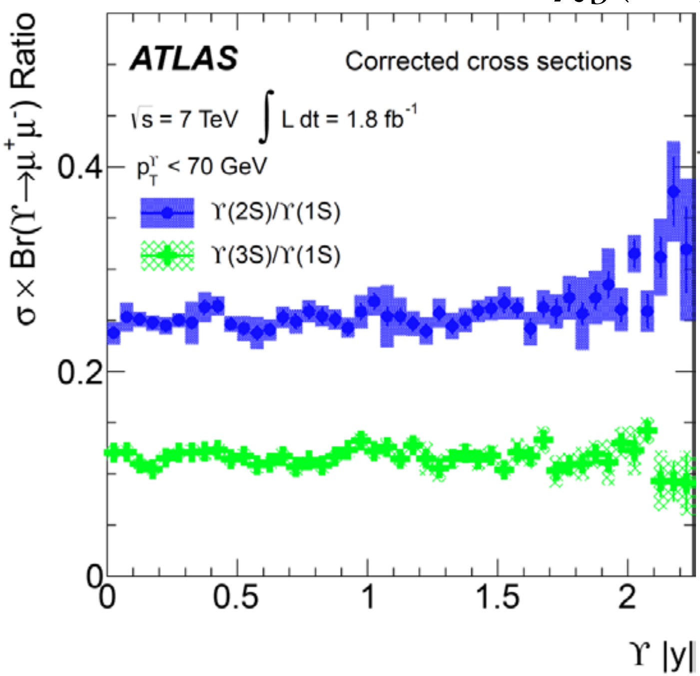
Note: high p_T has **negligible spin-alignment uncertainty**→very precise measurements

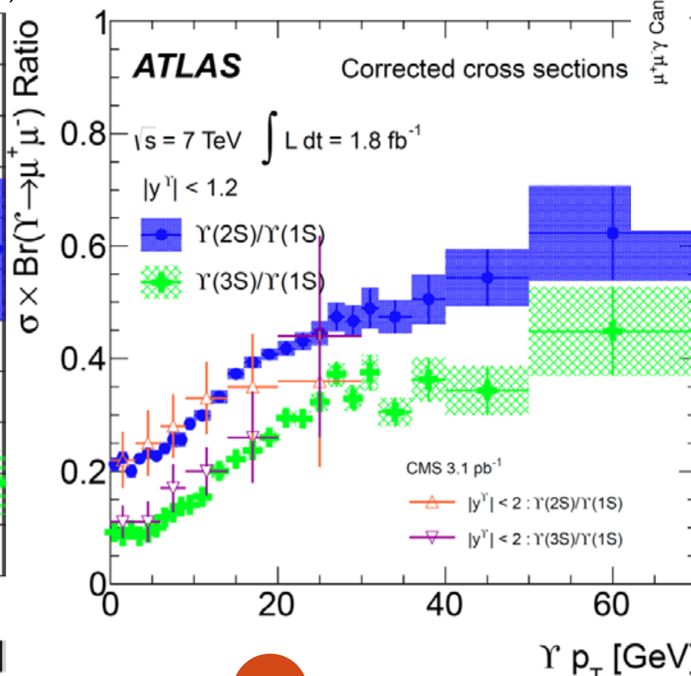
Υ(3S)/Υ(1S) and Υ(2S)/Υ(1S)

- Production ratios sensitive to feed-down contributions
- Rise in production rates of higher Υ states as function of p_T (c.f. CMS)
- Indication of saturation at 30-40 GeV: direct production dominates over decays of excited states?



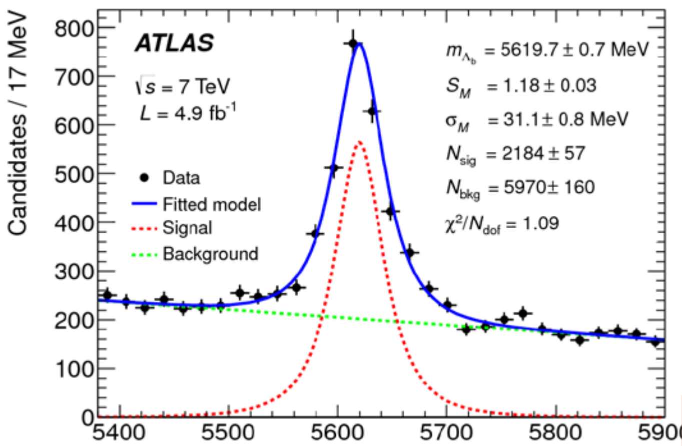
- Ratio sensitive to $\chi_b(nP)$ contributions

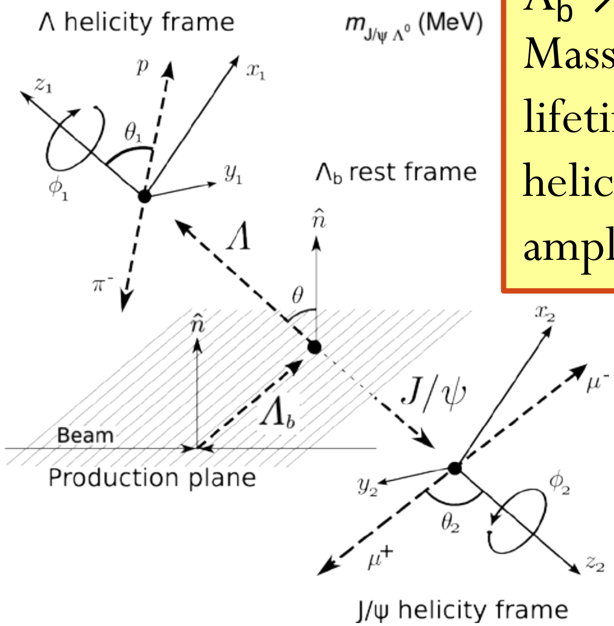




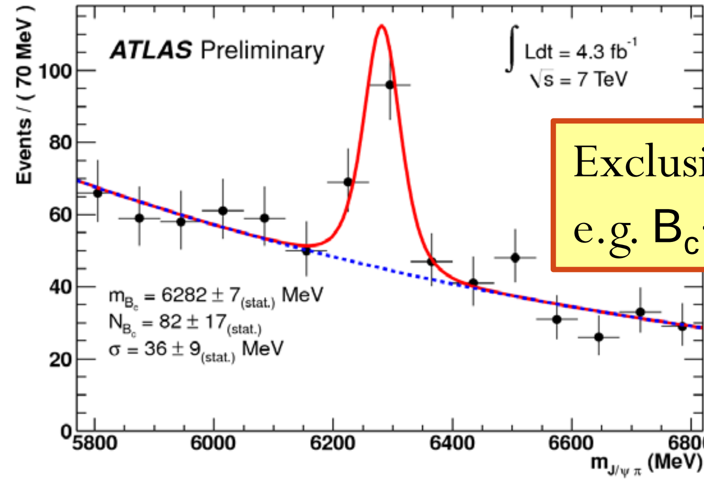
Other measurements involving quarkonium decays

- A few examples

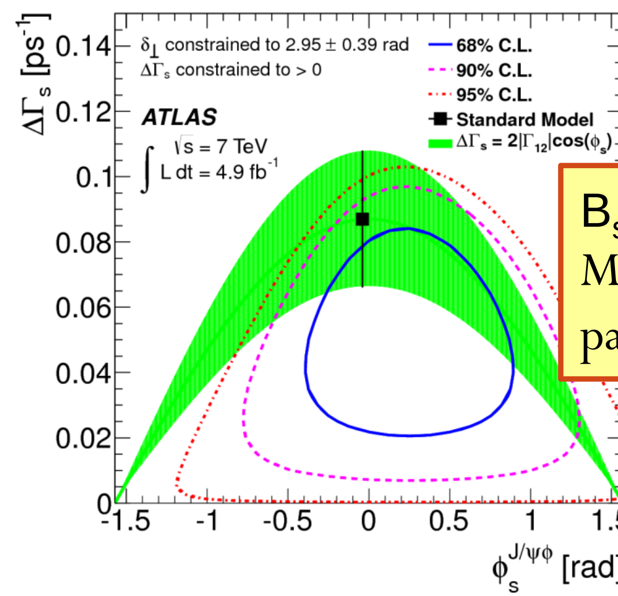




$\Lambda_b \to J/\psi\ \Lambda$
Mass, lifetime and helicity amplitudes



Exclusive decays
e.g. $B_c \to J/\psi\ \pi$



$B_s \to J/\psi\ \phi$
Mixing parameters

Heavy flavour cross-sections

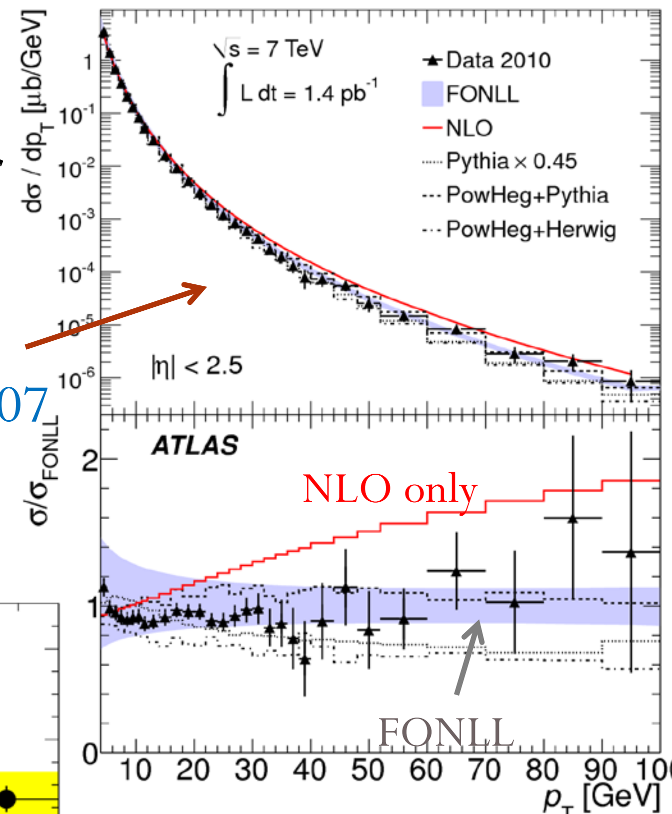
Overview

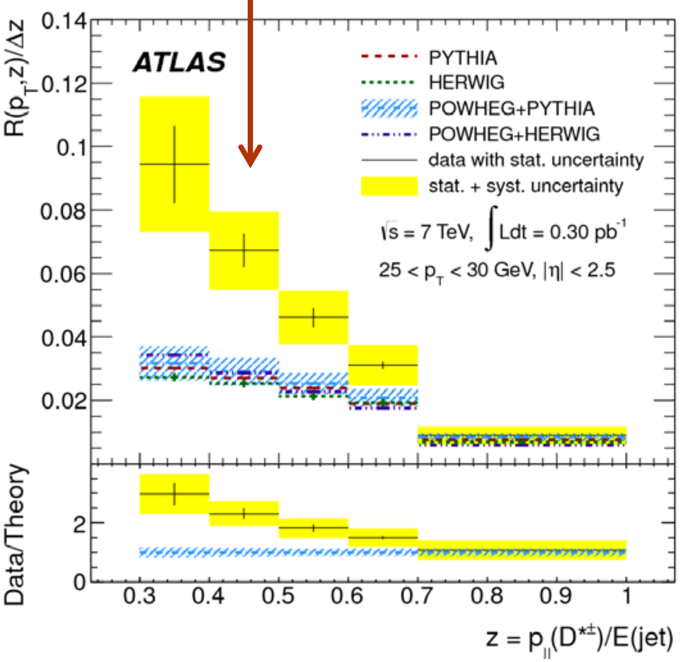
B^+ cross-section

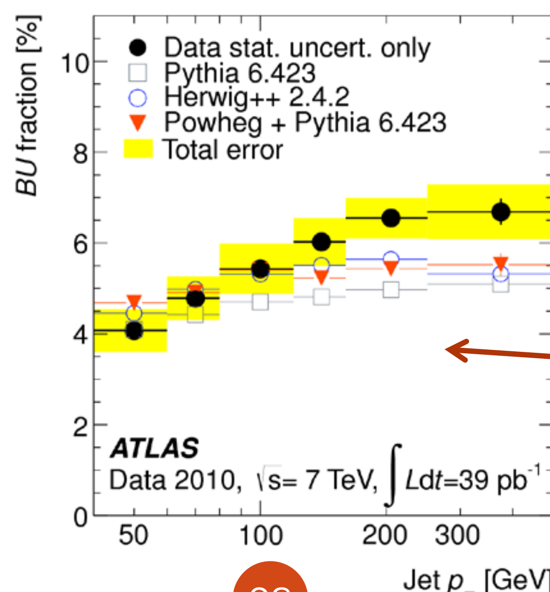
Earlier heavy flavour production measurements

- $D^{(*)}$ meson production cross sections
  ATLAS-CONF-2011-017
- Inclusive and dijet cross-sections of b-jets
  Eur.Phys.J.C 71 (2011) 1846
- $D^{*+/-}$ production in jets
  Phys. Rev. D85 (2012) 052005

- Inclusive production of electrons and muons (b/c cross section)
  Phys.Lett.B 707 (2012) 438





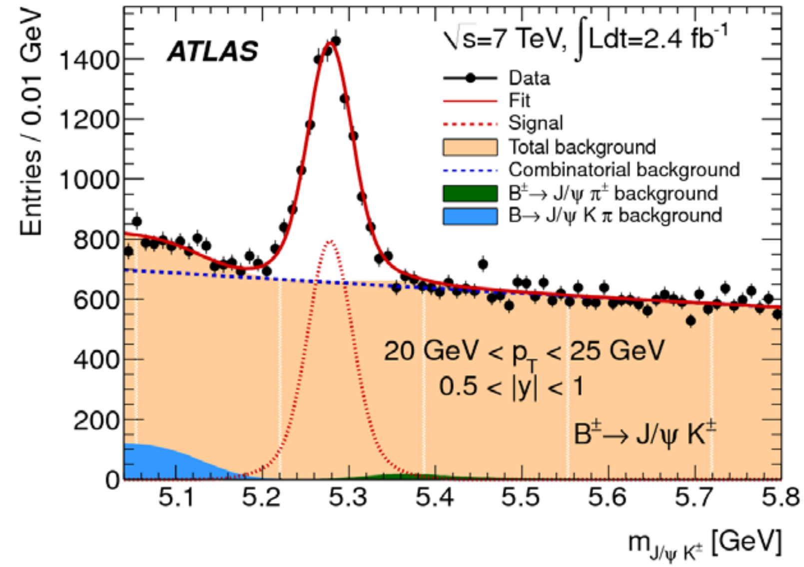


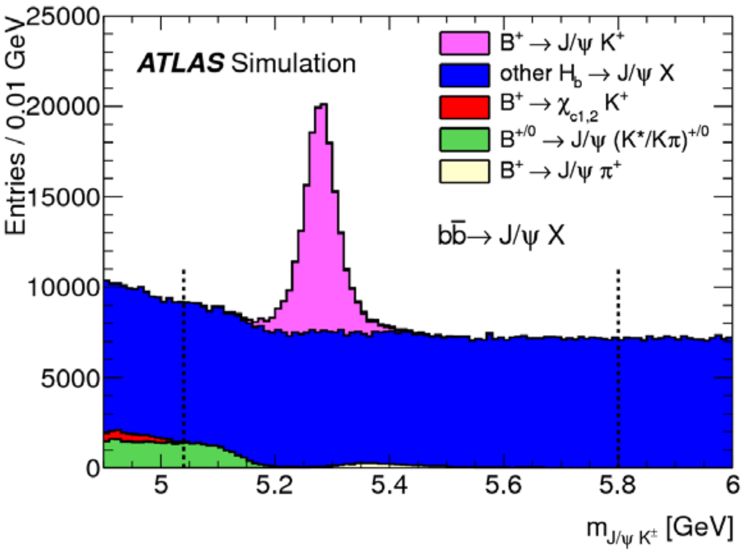
- Flavour composition of dijet events
  Eur. Phys. J. C (2013) 73:2301

B^+ cross-section

JHEP 10 (2013) 042

- 2.4 fb^{-1} data at 7 TeV; select $B^+ \rightarrow J/\psi\, K^+$
- Start from J/ψ candidates in mass window [2.7,3.5] GeV
- Fit to common vertex with additional charged track of $p_T > 1$ GeV
- Retain $B^\pm$ candidates with $p_T > 9$ GeV and $|\eta| < 2.3$





- Resonant backgrounds $J/\psi\,\pi$, $J/\psi\, K\pi$
- Combinatorial background J/ψ+X
- Extract differential cross-section:

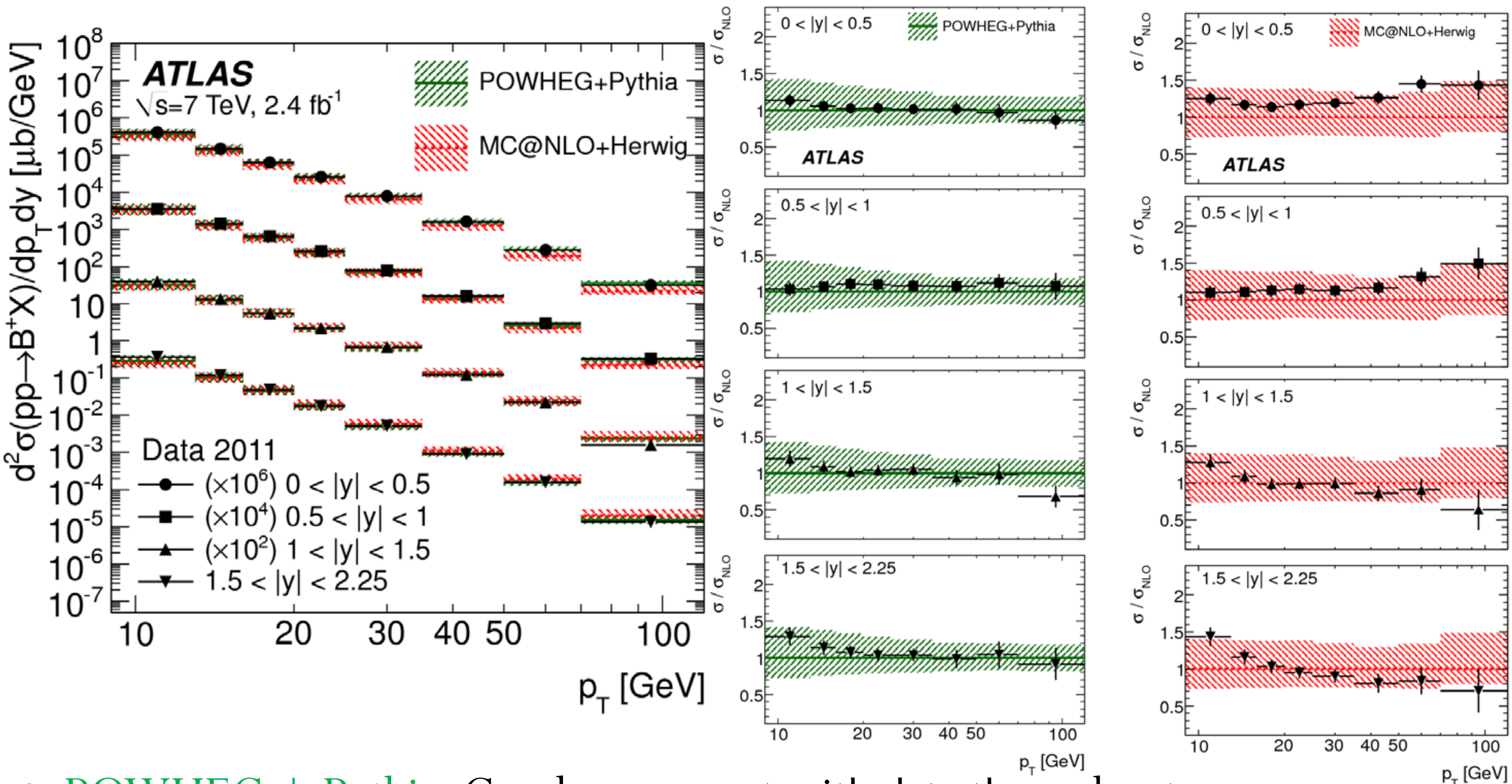
$$\frac{\mathrm{d}^2\sigma(pp \to B^+X)}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} \cdot \mathscr{B} = \frac{N^{B^+}}{\mathscr{L} \cdot \Delta p_\mathrm{T} \cdot \Delta y}$$

$$N^{B^+} = \frac{1}{A} \frac{N^{B^\pm}_\mathrm{reco}}{\varepsilon^{B^+} + \varepsilon^{B^-}}$$

Luminosity
Branching ratio
Acceptance, efficiencies

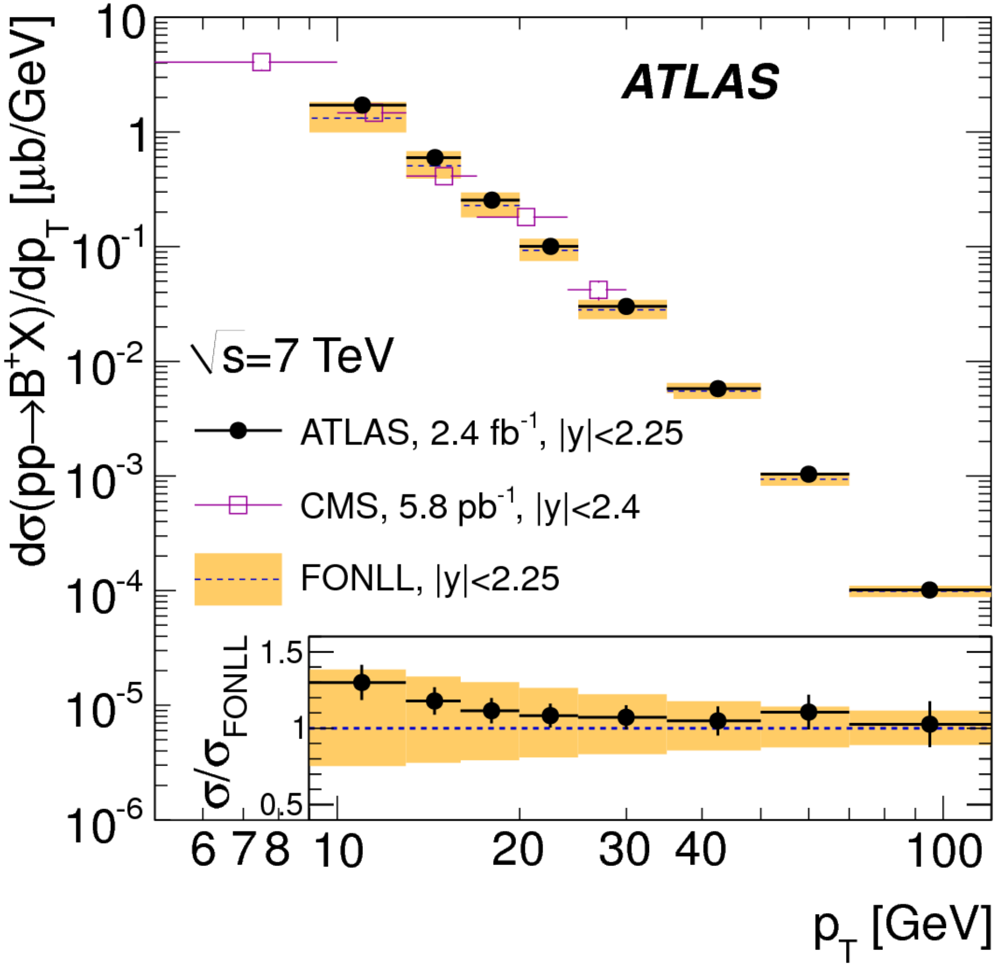
Miriam Watson

B^+ double differential cross-section



- POWHEG + Pythia: Good agreement with data throughout
- MC@NLO+Herwig: lower cross-section at low p_T, softer p_T spectrum for $|y|<1$; harder for $|y|>1$

B^+ cross-section vs. p_T



- Comparison with CMS and FONLL prediction with
$$f_{\bar{b}\rightarrow B^+} = 0.401 \pm 0.008$$
- FONLL (Fixed-Order-Next-to-Leading-Logarithm) describes dependence in p_T and rapidity
- Theoretical uncertainties from scale and b-quark mass

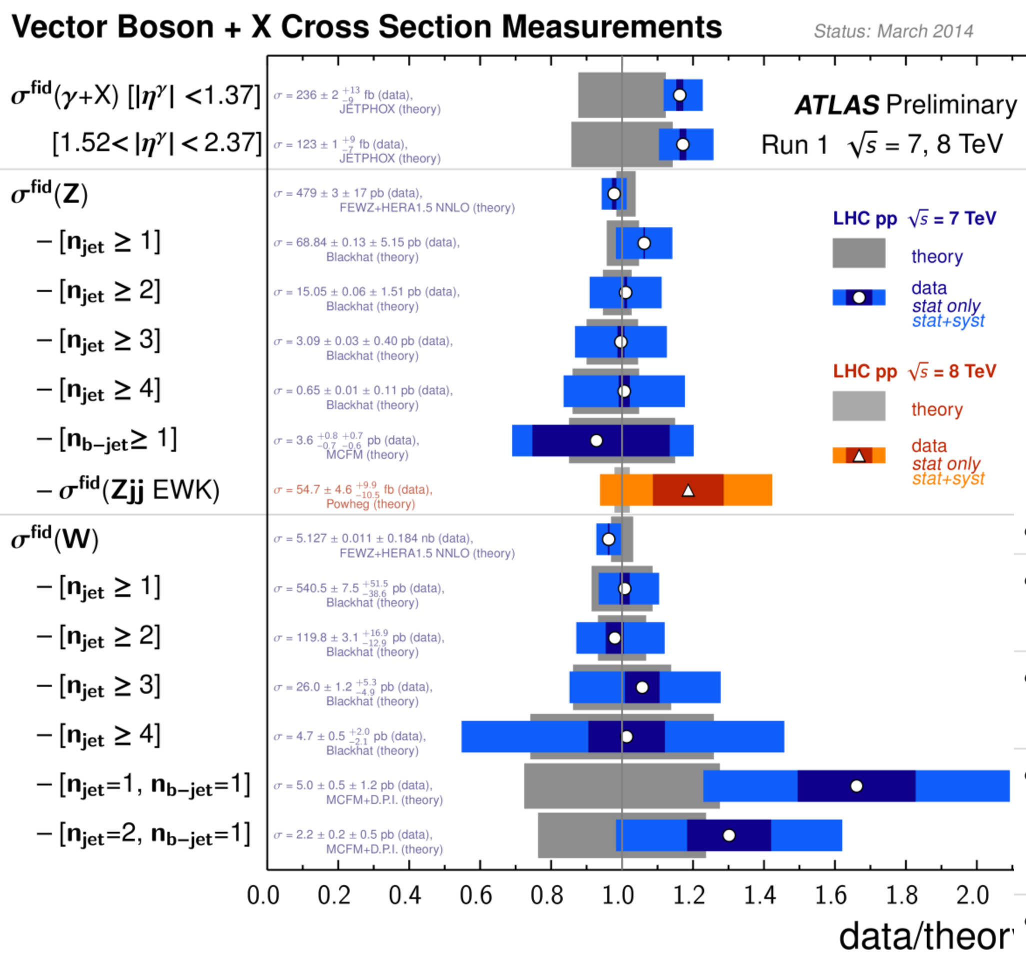
$$\boxed{\sigma(pp \rightarrow B^+X) = 10.6 \pm 0.3\ (\text{stat.}) \pm 0.7\ (\text{syst.}) \pm 0.2\ (\text{lumi.}) \pm 0.4\ (\mathscr{B})\ \mu\text{b}}$$

Heavy flavour with vector bosons

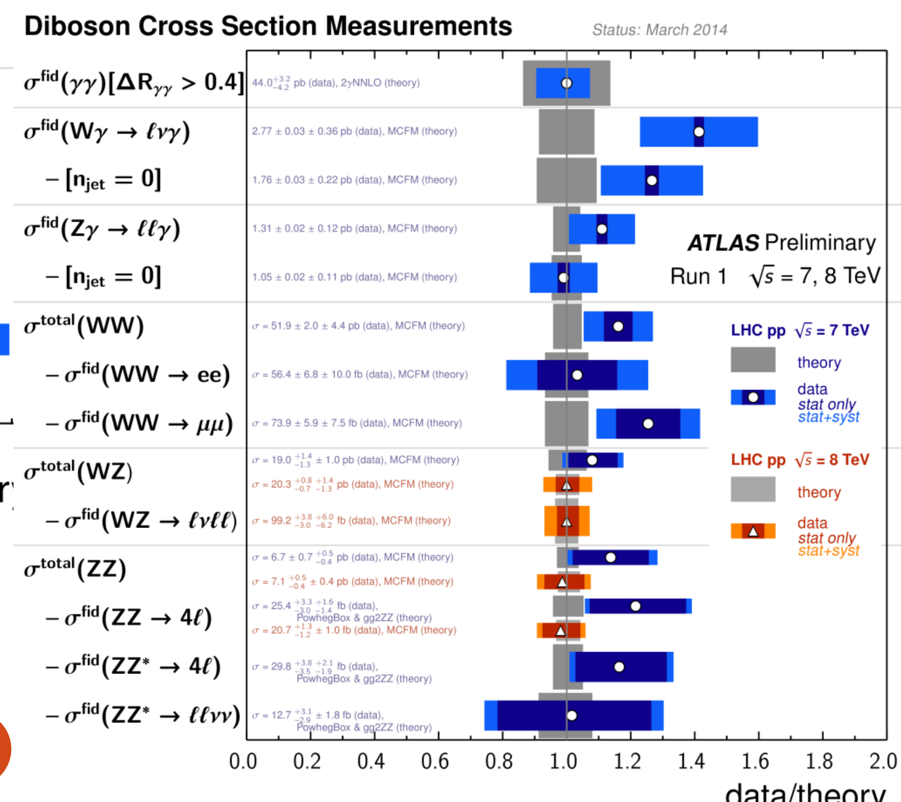
W + prompt J/ψ

W + charm

ATLAS vector boson measurements



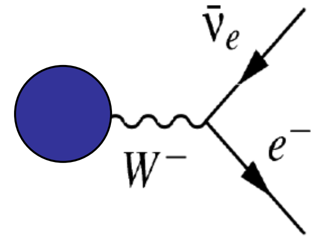
See also Schott+Dunford
http://arxiv.org/abs/1405.1160
"Review of single vector boson production"

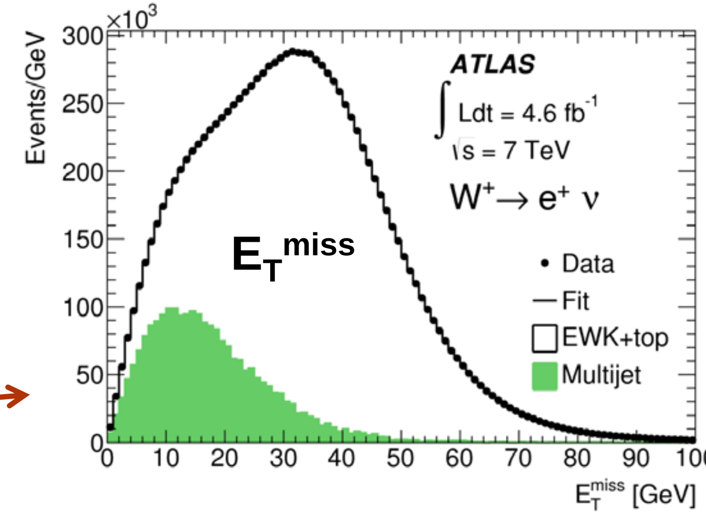


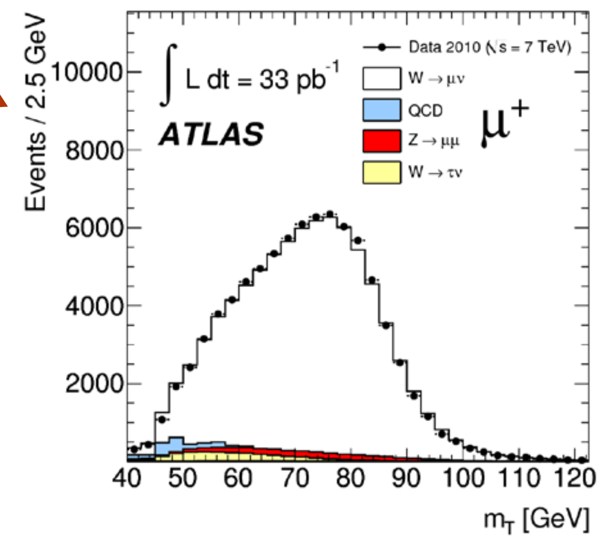
- Will concentrate on W+J/ψ and W+c today

W candidates

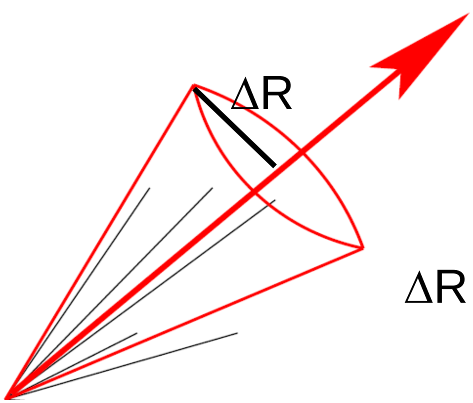
- Selected in W→ eν, μν modes
- General selection:
  - Single lepton trigger
  - p_T, |η| cuts on lepton
  - Significant missing E_T
  - Significant transverse mass, M_T
  - Isolated lepton: check track or cluster activity in a cone around the lepton to remove leptons in jets







$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1-\cos\Delta\phi_{e,miss}}$$

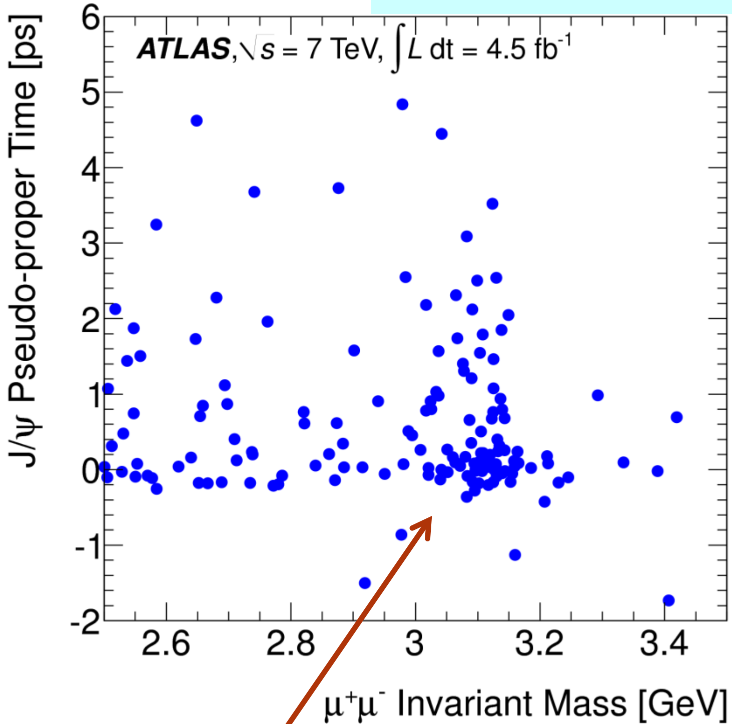


$\Delta R = \sqrt{\Delta\eta^2+\Delta\phi^2}$

W+prompt J/ψ measurement

arXiv:1401.2831, JHEP 04 (2014) 172

- Search for associated production of W(→μν) and prompt J/ψ (→μμ)
- Probes quarkonium production mechanism
- Sensitive to multiple parton interactions
- Use 4.6 fb^{-1} at 7 TeV (2011)
- Include double parton scattering (DPS) in signal, and estimate contribution

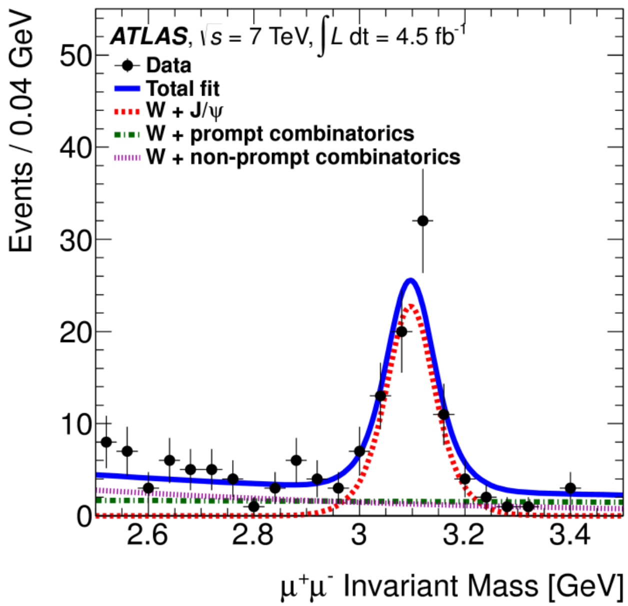


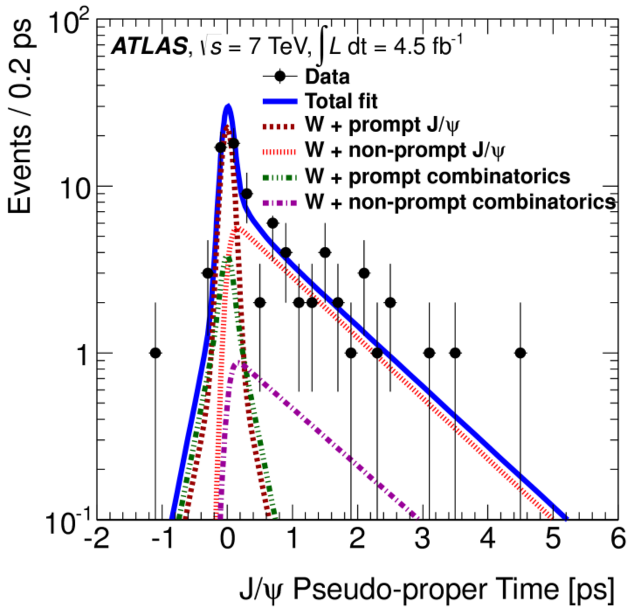
J/psi pseudo-proper time vs. mass

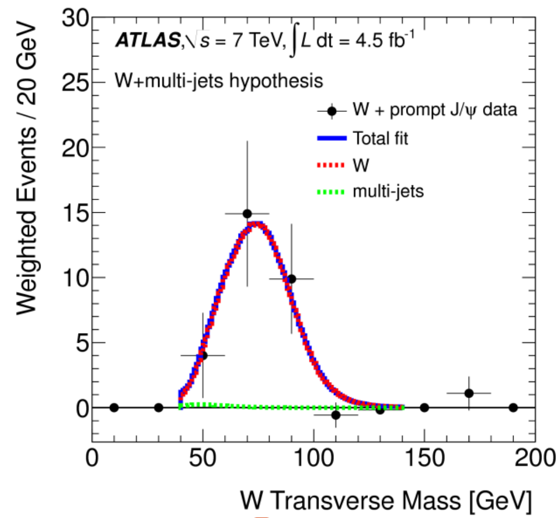
Events triggered on W muon (single lepton trigger)

Prompt J/ψ fits and W verification

- Unbinned maximum likelihood fit to J/ψ mass and pseudo-proper time → extract prompt signal
- Fit weighted $m_T(W)$ distribution for prompt candidates: W signal and multi-jet background
- Jet bkd. 0.1±4.6 events







Observe ~29 W+prompt J/ψ events

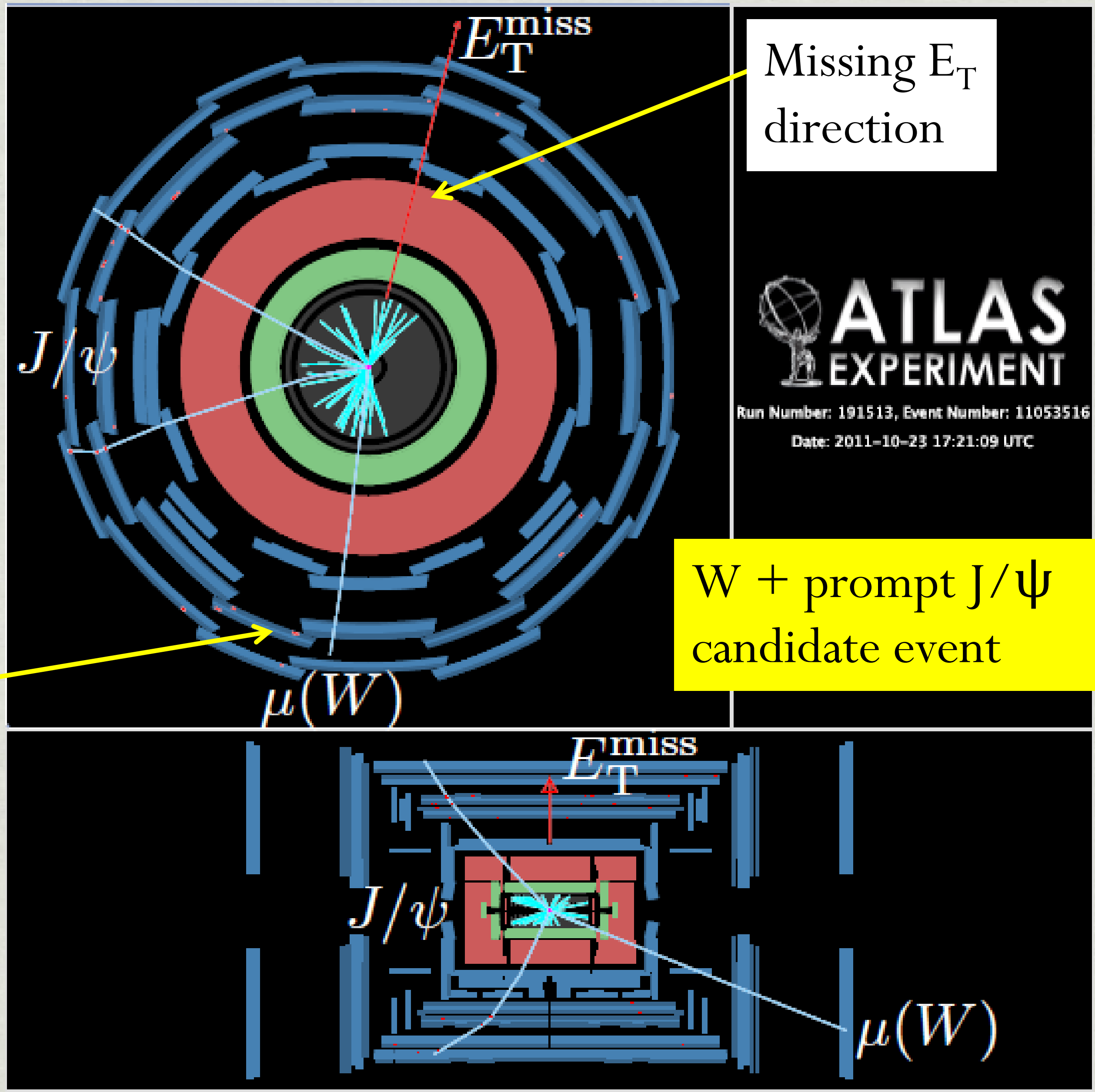
Background-only hypothesis rejected at 5.3σ level

Muons from J/ψ candidate

p_T (J/ψ) = 9.3 GeV, pseudo-proper time = 0.0 ps

Muon from W candidate

p_T (μ) = 39 GeV



Constantinos Melachrinos

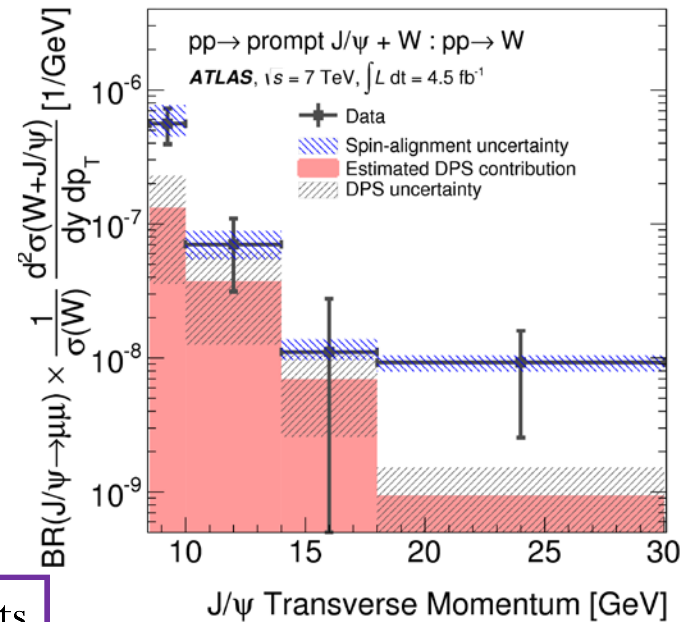
SPS and DPS contributions

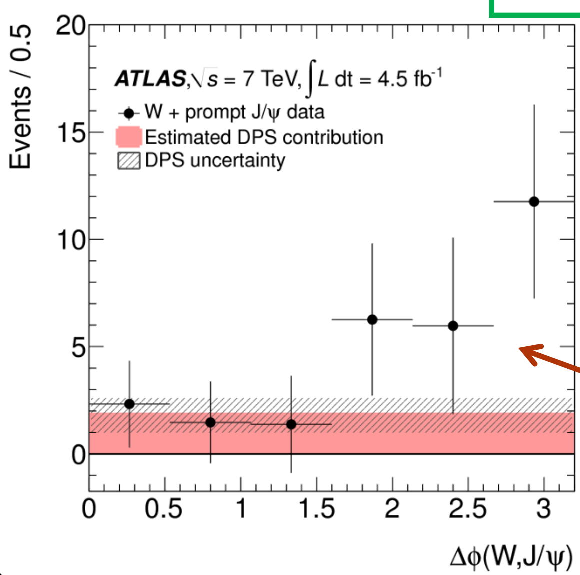
- Measure $(W^{\pm} + J/\psi)$ production cross-section relative to inclusive $W^{\pm}$ cross-section
- Estimate DPS contribution from:
  - $d\sigma(W+J/\psi) = d\sigma(W) \otimes d\sigma(J/\psi) \,/\, \sigma_{eff}$

Measured in this analysis

From ATLAS prompt J/ψ arXiv:1104.3038

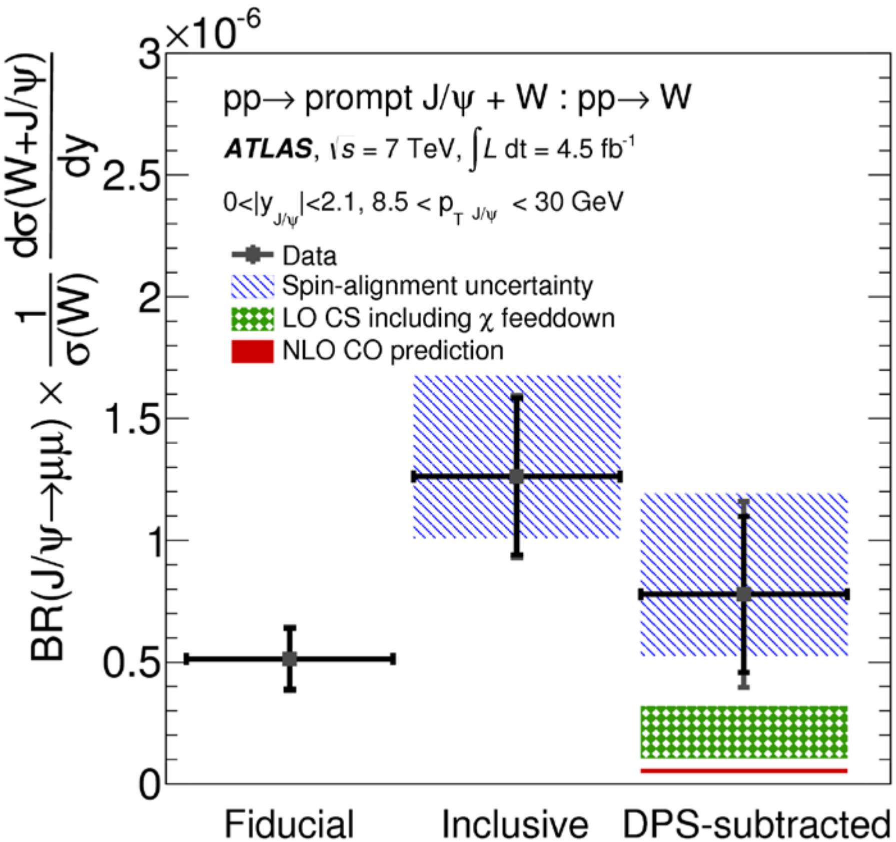
From ATLAS W+2jets arXiv:1301.6872





- Note: this is a phenomenological approximation
- DPS estimate ~40%
- Expect peak towards $\Delta\phi = \pi$ for SPS contribution

Prompt J/ψ+W compared to theory



CS: arXiv:1303.5327
CO:arXiv:1012.3798

- Summary of fiducial, corrected and DPS-subtracted cross-section ratios
- Colour singlet model (CS): LO, includes feed-down from ψ(2S) and χ_c
- Colour octet model (CO) : NLO
- Rate appears to be dominated by CS contributions (but could have large corrections to CO, or modified DPS formalism)
- Both compatible with measurement at 2σ

Heavy flavour with vector bosons

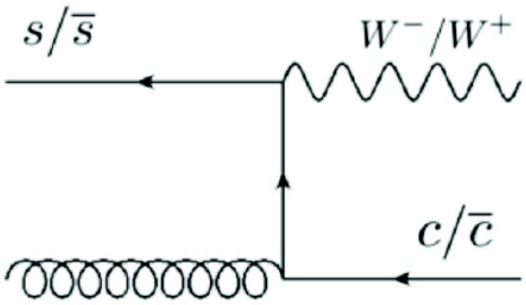
W + prompt J/ψ

W + charm

arXiv:1402.6263, sub. to JHEP

W + charm quarks

- **W boson + single charm quark** is produced in LO by quark-gluon scattering with a down-type quark (d, s, b).

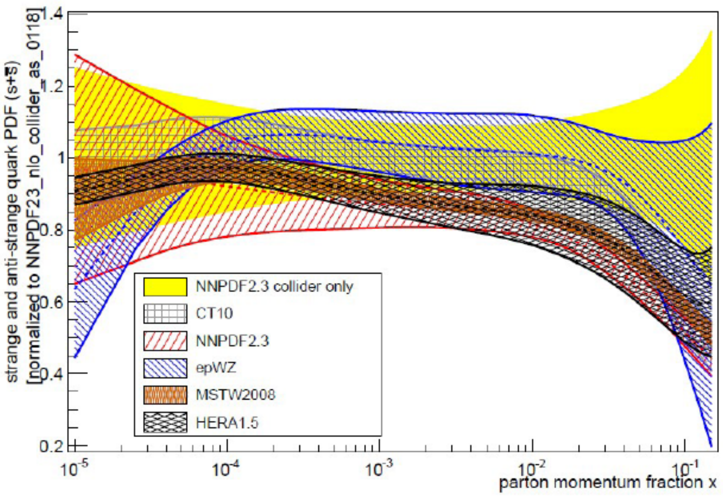


- Contribution of quark flavours determined by PDFs and by CKM Matrix (Vcd, Vcs and Vcb)

- At **LHC energy and M_W**:
  gs and g$\bar{s}$ initial states dominant, d-quark contributes about 10%

- **Directly sensitive to the s-quark PDF**

20% uncertainty on strange PDF

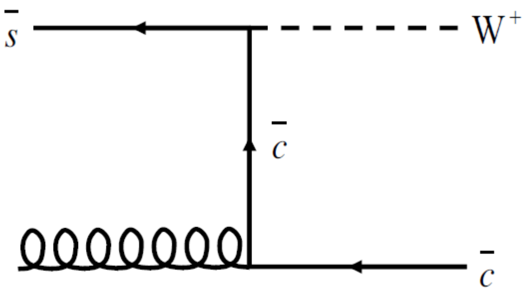


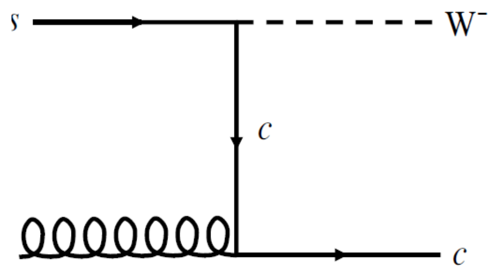
- Constrained only by neutrino-nucleon DIS, sensitive to the modeling of c-quark fragmentation and nuclear corrections

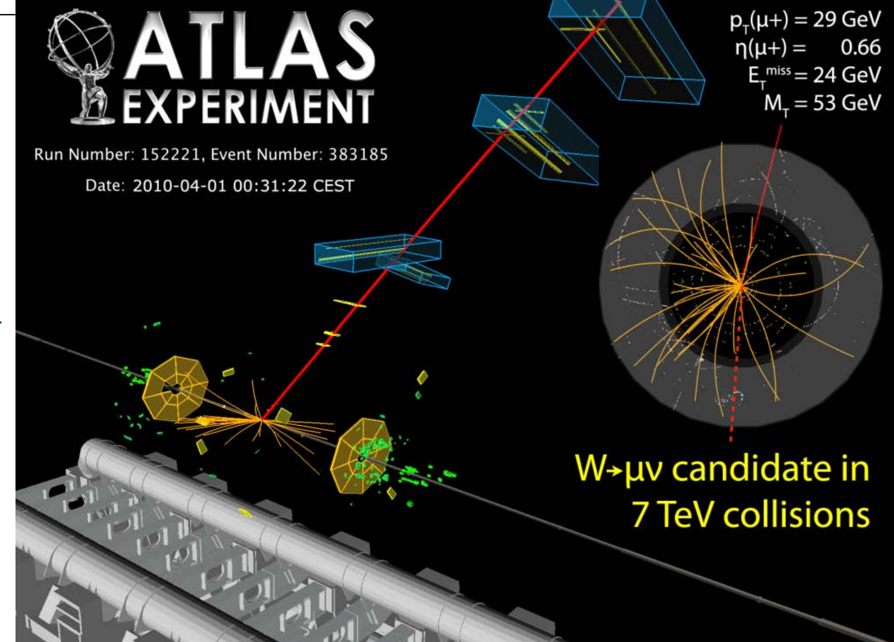
- **Some PDF analyses suggest s-quark sea is suppressed w/r to d-quark sea ATLAS W/Z analysis indicated SU(3) flavour symmetric sea**

Kristin Lohwasser

Measurement overview



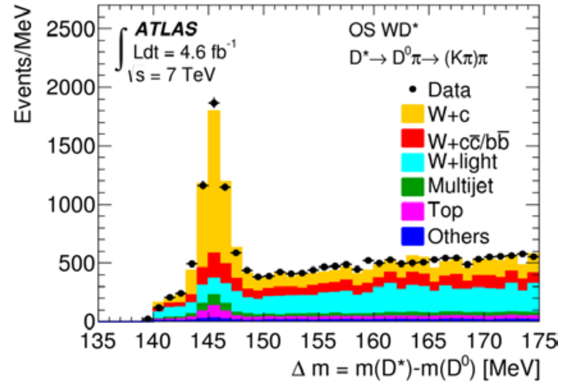


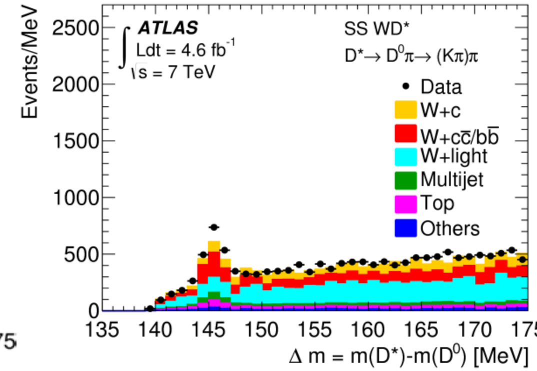


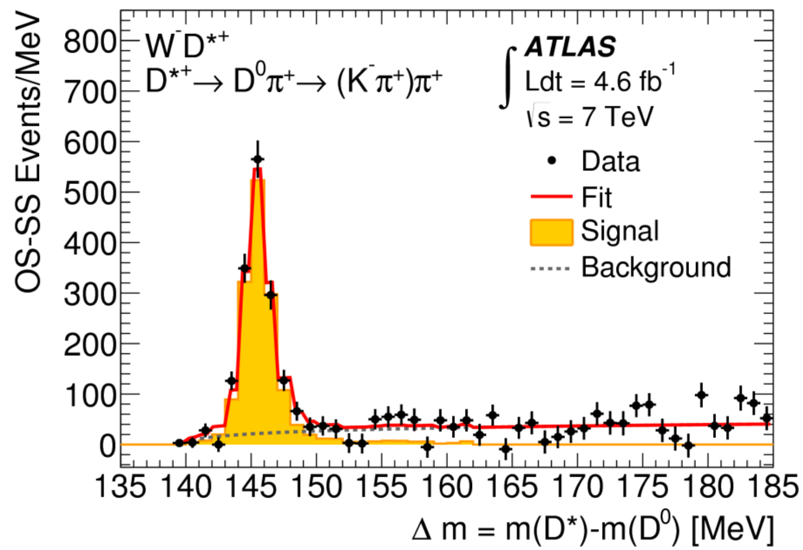
- 4.6 fb^{-1} of data collected in 2011 at $\sqrt{s}$ = 7TeV
- W boson selected via muon or electron decays
- Charm is tagged using either:
  - Semi-leptonic decays inside a jet (soft muons)
  - D(*) decays
- Charge correlation between W boson and charm quark
  - Signal has opposite sign (OS)
  - Most backgrounds are charge symmetric (SS)
- OS-SS enables isolation of the W + c final state from W + $c\bar{c}, b\bar{b}$

W + D analysis

- Select samples of $W^{\mp} + D^{\pm}$ and $W^{\mp} + D^{*\pm}$ by reconstructing $D^{(*)\pm}$ decays in the inner detector:
  - $D^- \rightarrow K^+\pi^-\pi^-$
  - $D^{*+} \rightarrow D^0\pi+$ with
    - $D^0 \rightarrow K^-\pi^+$
    - $D^0 \rightarrow K^-\pi^+\pi^0$
    - $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$
- Form OS-SS distributions of $m(K\pi\pi)$ for $D^{\pm}$ and $\Delta m = m(D^*) - m(D^0)$ and fit

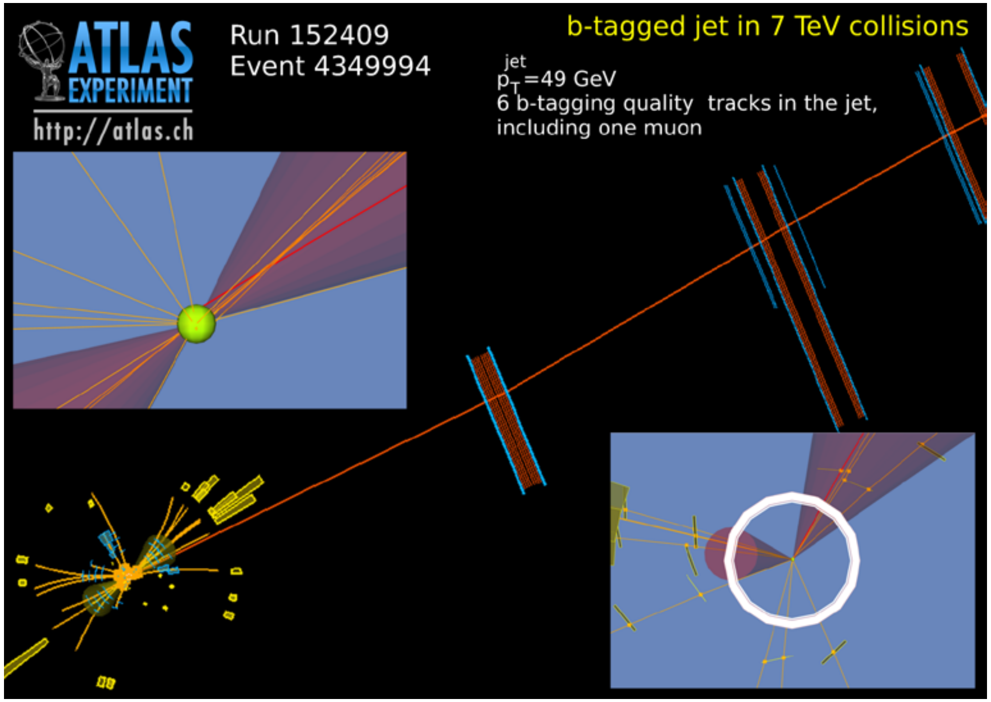


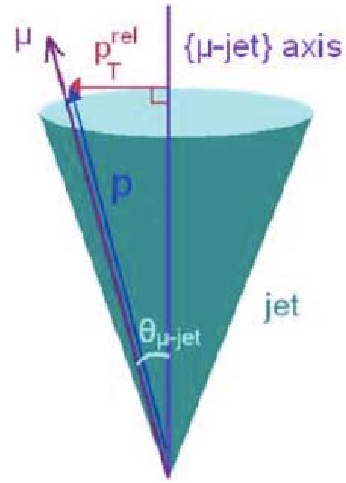


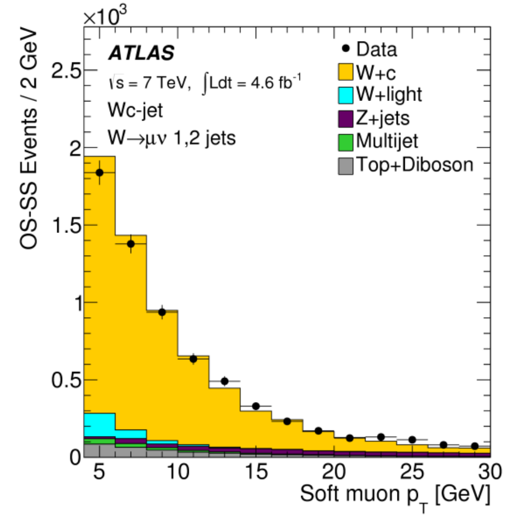


W+light jets background: functional form
Data-driven correction for peaking heavy flavour background

W + c-jet analysis







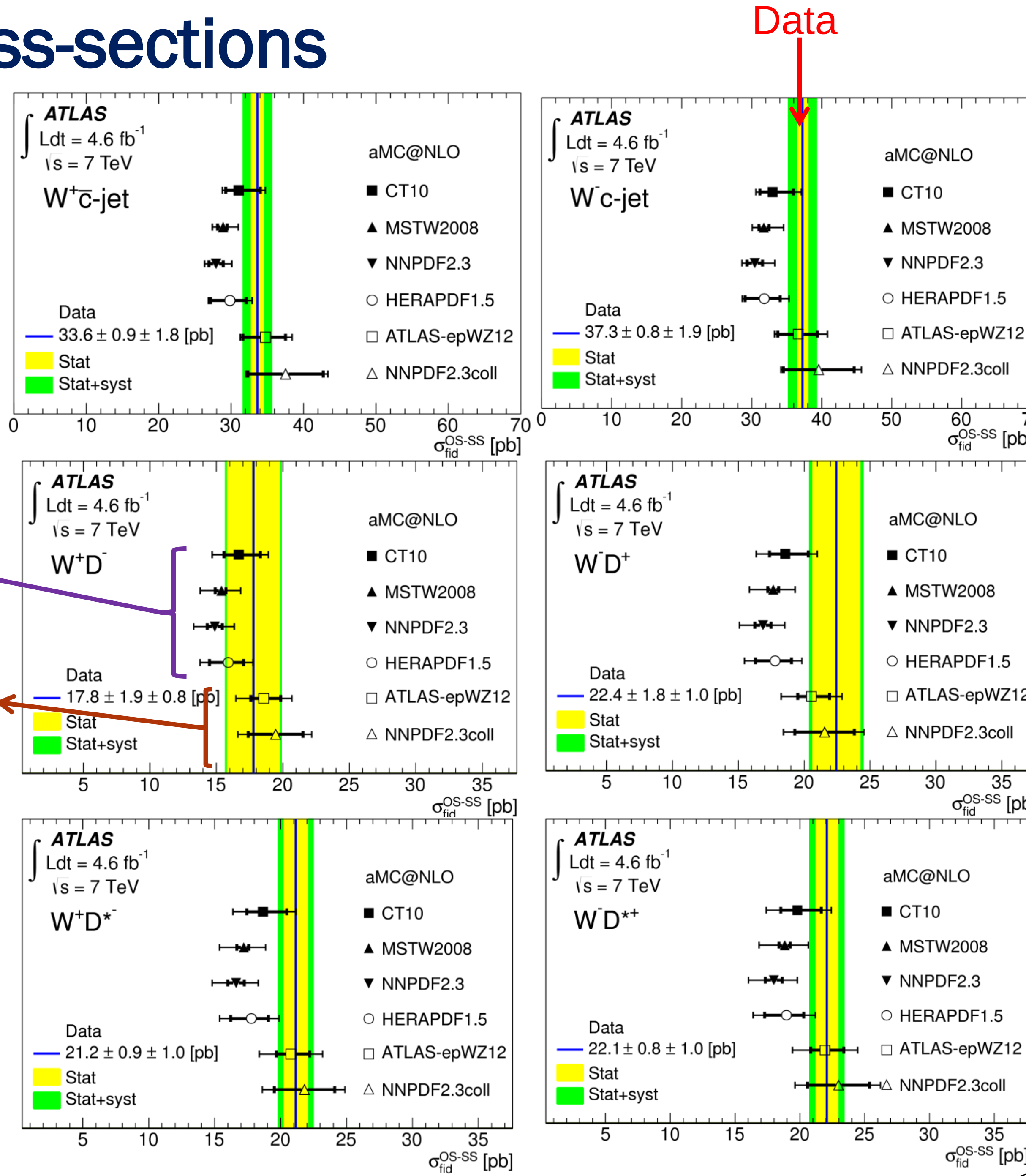
- Select a sample of jets containing soft muons
  - Anti-k_t jets, R=0.4
  - Muons $\Delta R < 0.5$ from jet axis, p_T>4 GeV
- Discriminate using muon momentum relative to jet axis, p_T^{rel}

Fiducial W+c cross-sections

- Compare fiducial cross-sections with aMC@NLO plus various PDF sets
- Predicted values vary by ~25%

s-quark suppressed cf. d-quark

s-quark ~ d-quark

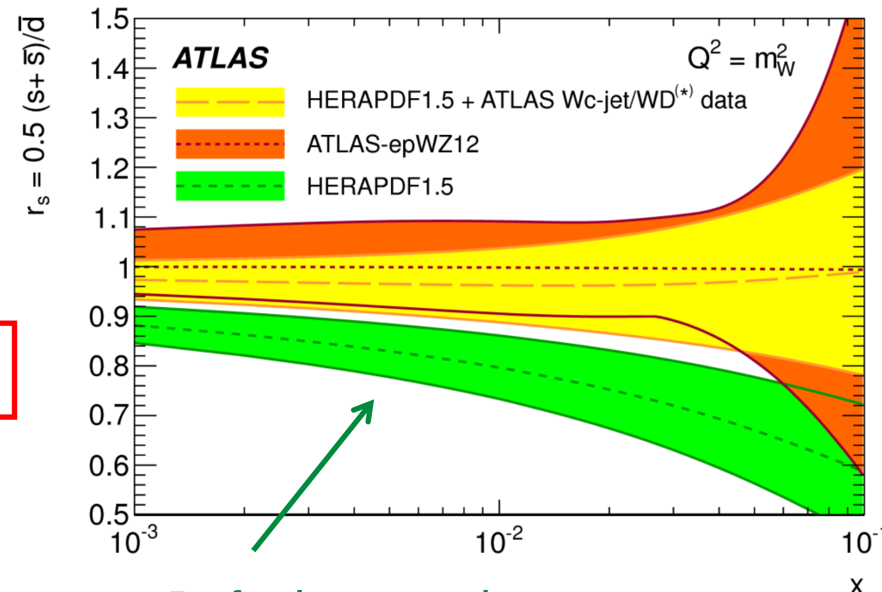


- Data consistent with wide range of predictions
- Favour symmetric light-quark sea at x~0.01

Ratio of strange-to-down sea quarks

- Ratio of strange to down sea quarks is regulated in HERA PDF by a single parameter (PDF eigenvector: f_s)
- Free fit of strange to down sea content of proton in ATLAS data (within this model)

$$r_s \equiv 0.5(s+\bar{s})/\bar{d} = f_s/(1-f_s) = 0.96^{+0.16}_{-0.18}{}^{+0.21}_{-0.24}$$



Default: s-quark suppressed cf. d-quark

- Results compatible with the ATLAS-epWZPDF which includes ATLAS W/Z data
- Consistent with SU(3) flavour symmetry in the proton

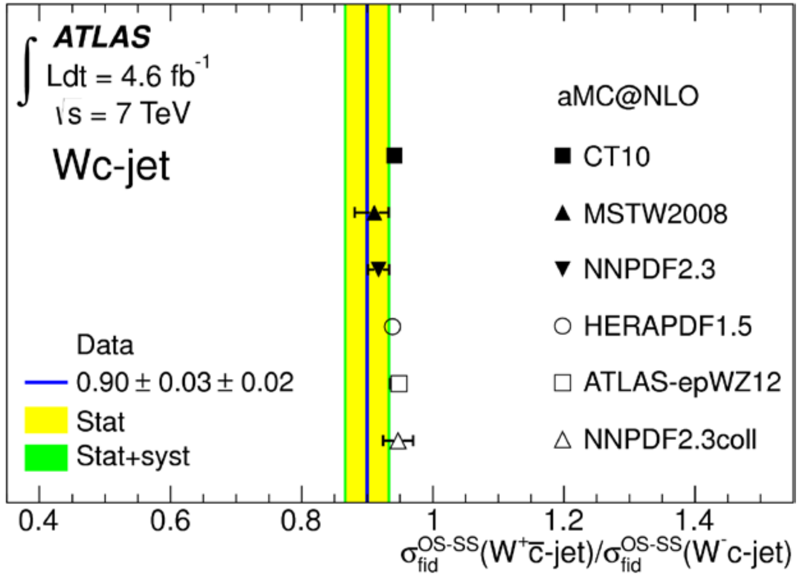
Cross-section ratio +/-

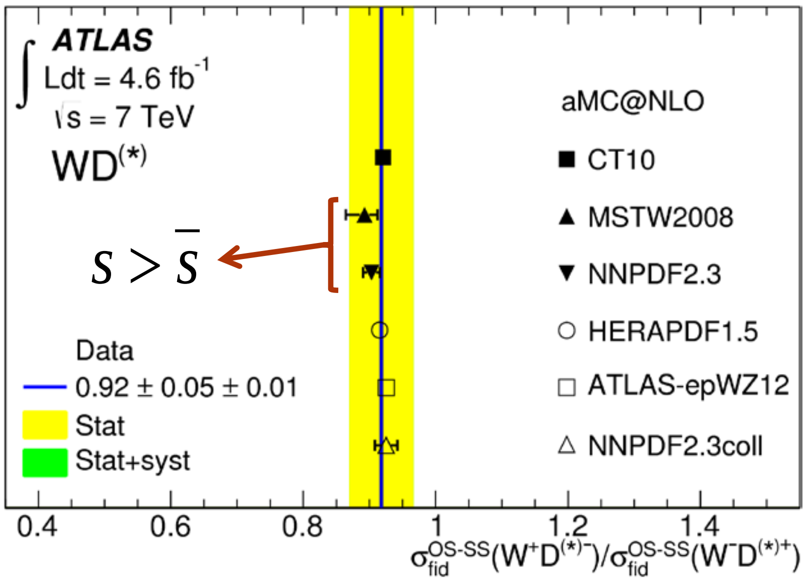
$$R_c^{\pm} = \frac{W^+ + \bar{c}}{W^- + c}$$

- Ratio W^+/W^- is smaller than 1 due to valence down contribution
- Deviation of predicted value might be due to strange sea asymmetry $s:\bar{s}$
- Take CT10 prediction (no asymmetry)⟶ estimate of sensitivity

$$\boxed{A_{s\bar{s}} = (2 \pm 3)\%}$$

- W+c analysis is dominated by statistical uncertainties: 2012 data will help





Summary

Full details of ATLAS heavy flavour results at https://twiki.cern.ch/twiki/bin/view/AtlasPublic

- Many interesting results from the first years of ATLAS
  - Heavy flavour production measurements
    - Absolute cross-section measurements
    - Detailed comparisons with NLO and NLO+NLL predictions
    - Associated production of W + charm quarks: probes s-quark PDFs
  - Quarkonium physics
    - Production of charmonium and bottomonium; comparison with theory
    - First observation of associated W+ prompt J/ψ
    - Confronting data with colour-singlet, -octet and -evaporation models
    - Future vector boson+onia measurements will provide input to multiple parton scattering studies
- Updates and new analyses with more data are in progress