Production of Quarkonium States at ATLAS

DIS2013, Marseille

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(on behalf of the ATLAS Collaboration)

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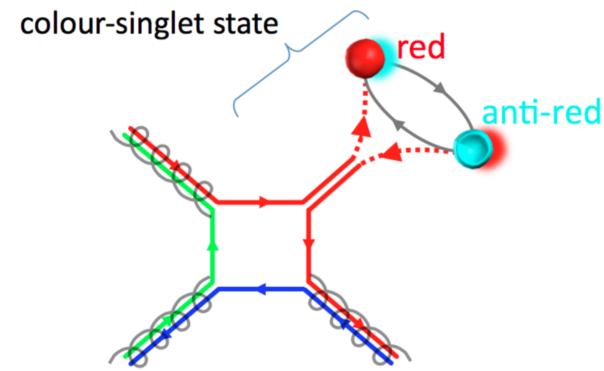
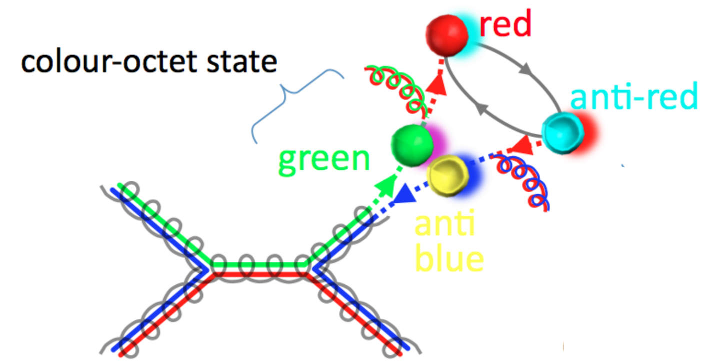
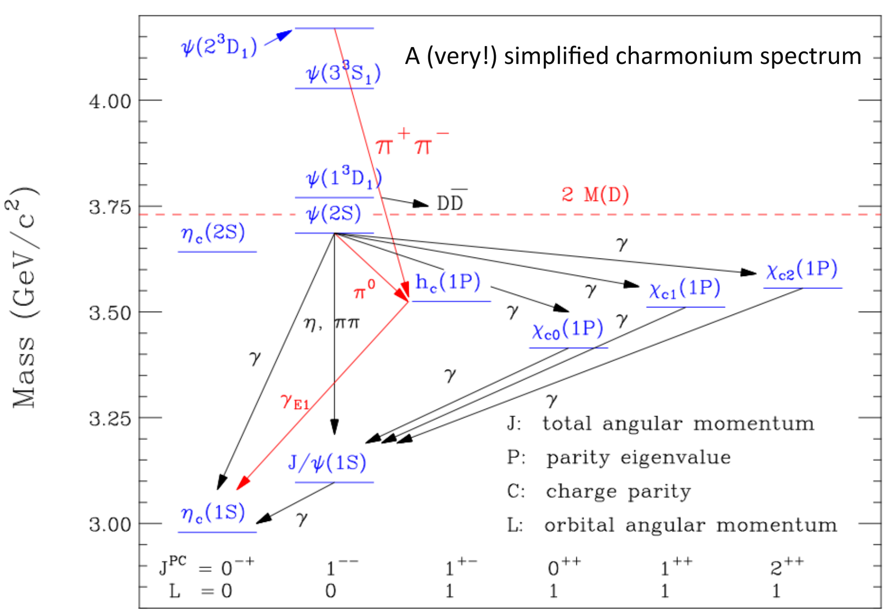
Quarkonium production

Naïvely a 'simple' system: a quark and anti-quark of same flavour in a bound state

- Quarkonia are probes of hadron formation, production not yet understood
- Long history of disagreement between theory and experiment
- Complex "ecosystem" to study – requires careful investigation of many nuanced effects







Tests of QCD calculations at the perturbative/non-perturbative boundary

Standard candles for Heavy Ion physics, B-meson production, searches

With yields at the LHC, can explore new observables, detailed effects…

Results in this presentation

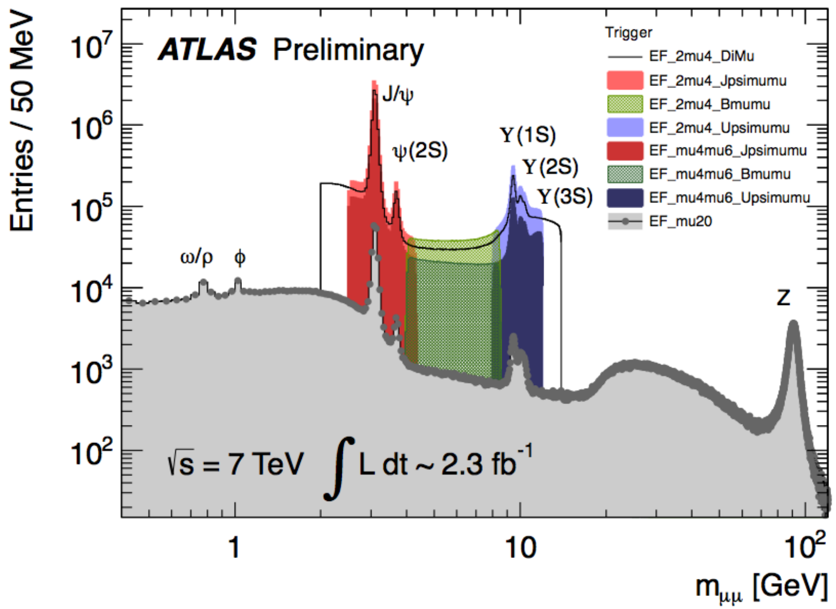
Today I will focus on two recent results on quarkonium from ATLAS:

- **Inclusive Upsilon(1,2,3S)→μμ production**
  (and briefly discuss the discovery of the χ_{bJ}(3P) and implications its implications)
  arXiv:1211.7255 [hep-ex], Phys.Rev D87 (2013) 052004
  http://hepdata.cedar.ac.uk/view/ins1204994

- **Observation and measurement of W+prompt J/ψ production**
  New result for this conference!
  ATLAS-CONF-2013-042, paper in preparation
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-042

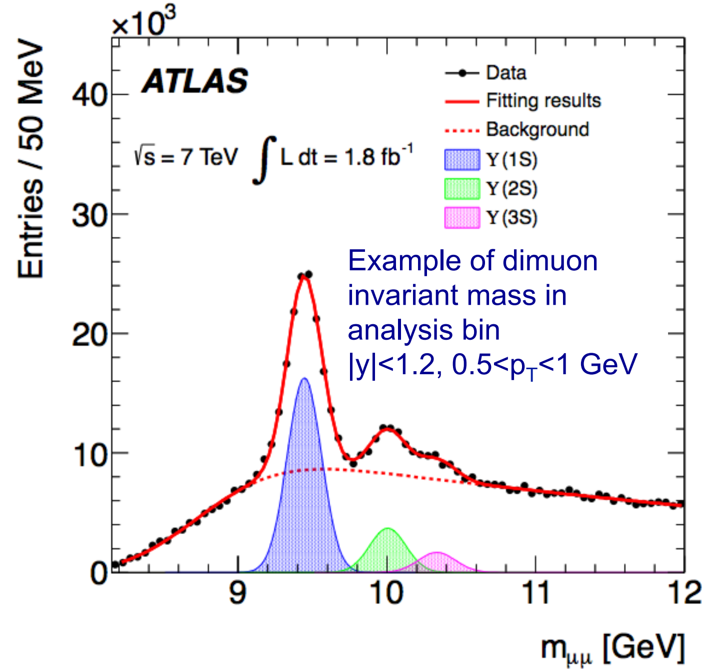
Υ(nS) production cross-sections

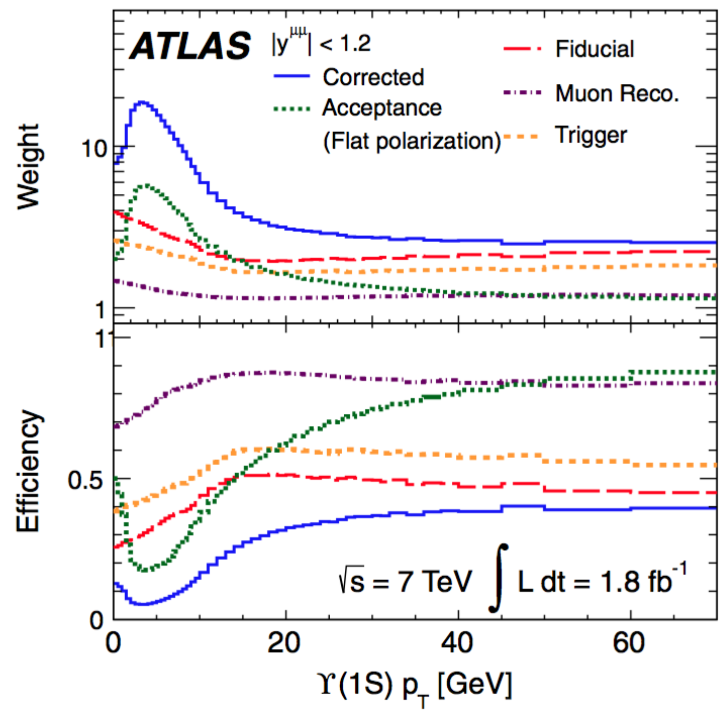
Υ(1S), Υ(2S), Υ(3S) states reconstructed in dimuon final state using ~1.8 fb^{-1} 7 TeV data using specialised low p_T di-muon trigger



Determine yields from fits to dimuon invariant mass spectra in 50×2 and 1×45 Upsilon p_T×rapidity intervals

Per-event corrections for detector efficiencies and acceptances to extract production cross-sections

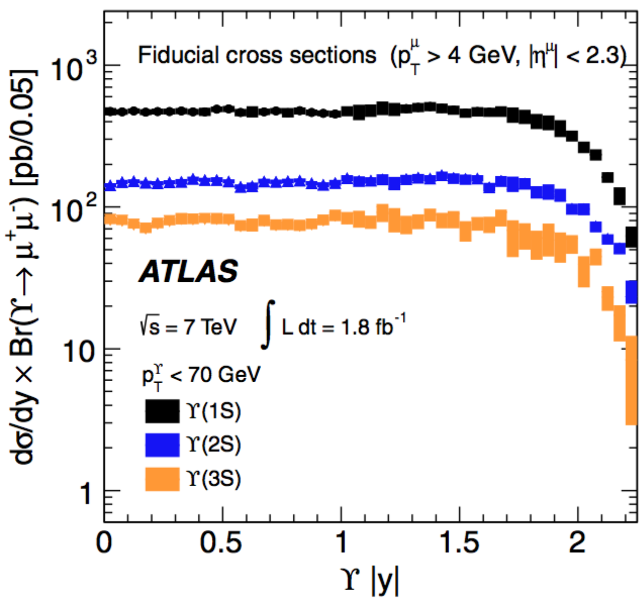




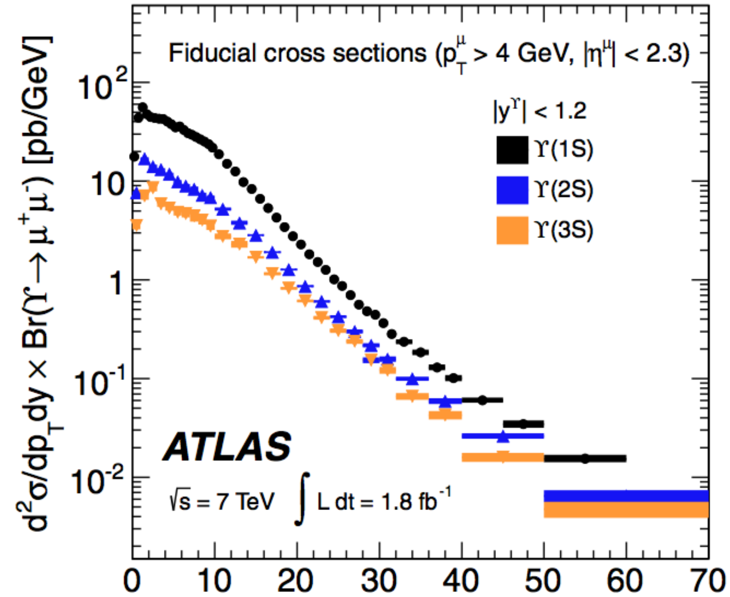
ϒ(nS) fiducial production cross-section results

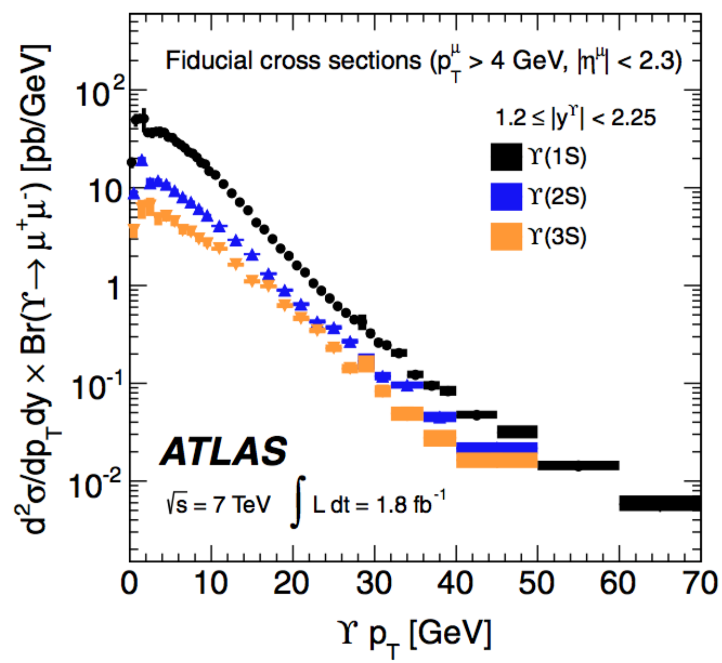
Measurement in fiducial phase space:
$p_T(\mu)>4$ GeV, $|\eta(\mu)|<2.3$, $|y(\Upsilon)|<2.25$

- Precise measurements δ~5%, with largest p_T reach for quarkonia
- Free from theoretical uncertainties
- Useful for modeling of backgrounds, MC tuning but hard to compare to theoretical predictions

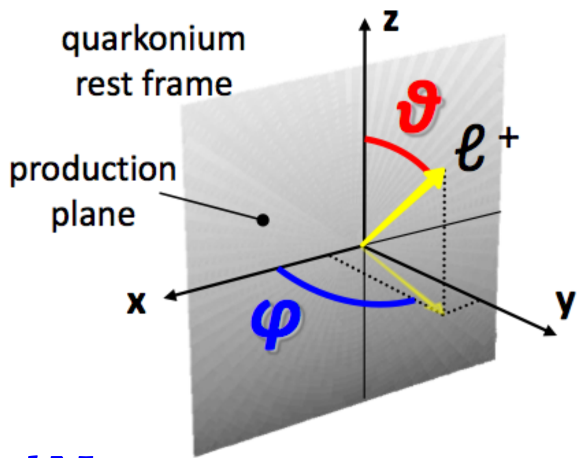


State	Integrated fiducial cross sections $p_T^\mu > 4$ GeV, $\lvert\eta^\mu\rvert < 2.3$ $\sigma_{\text{fid}}(pp \to \Upsilon) \times \text{Br}(\Upsilon \to \mu^+\mu^-)$ Range: $p_T^\Upsilon < 70$ GeV, $\lvert y^\Upsilon\rvert < 2.25$
$\Upsilon(1S)$	1.890 ± 0.007 ± 0.095 ± 0.074 nb
$\Upsilon(2S)$	0.601 ± 0.003 ± 0.040 ± 0.023 nb
$\Upsilon(3S)$	0.304 ± 0.003 ± 0.021 ± 0.012 nb





Spin-alignment and acceptance corrections

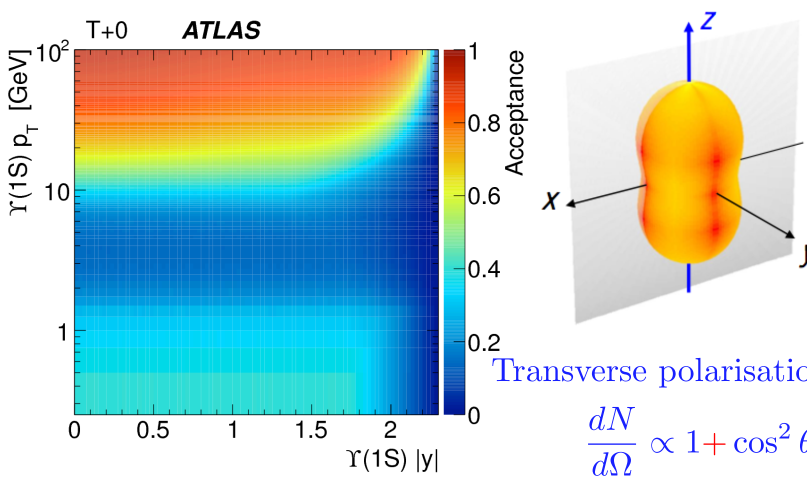


Higher order theoretical calculations/models cannot make cuts on final state particles

Correct data for muon fiducial acceptance cuts

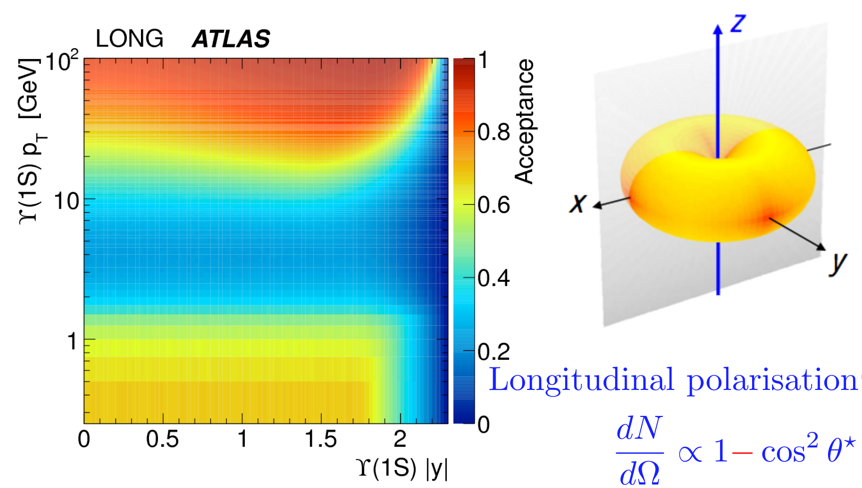
Acceptance depends on spin-alignment / angular distributions of muons in the decay

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



Transverse polarisation

$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta^\star$$



Longitudinal polarisation

$$\frac{dN}{d\Omega} \propto 1 - \cos^2\theta^\star$$

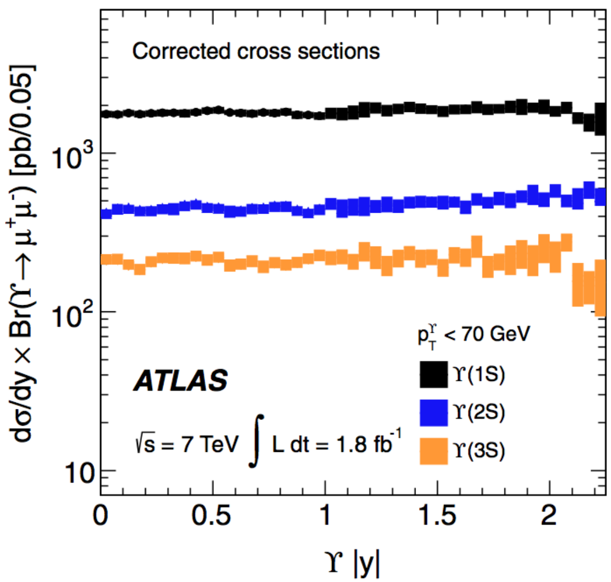
Two extremes shown here, but any quantum-mechanically allowed set of λ_i are possible

ϒ(nS) corrected production cross-section results

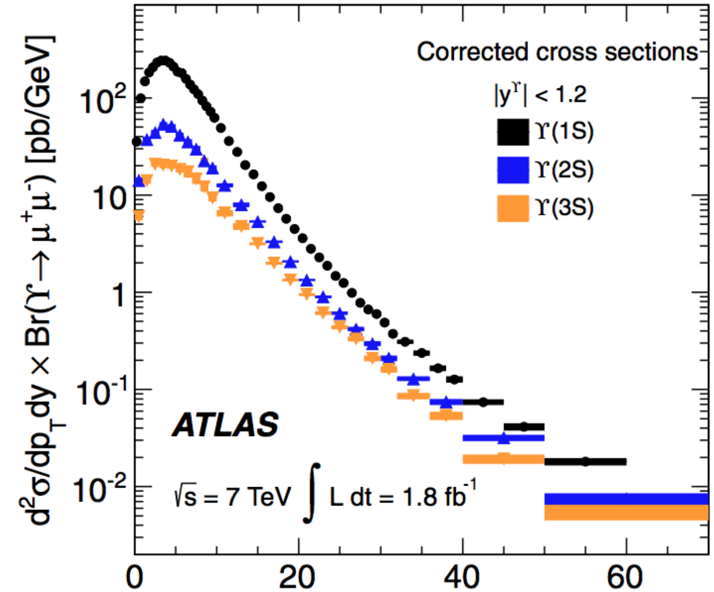
Acceptance-corrected production cross-sections can be compared with theory.

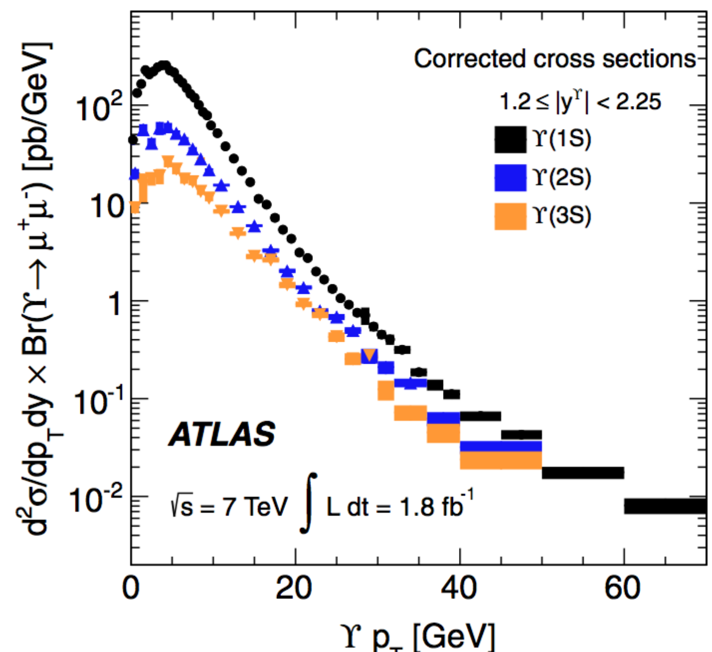
Phase space: $|y(\Upsilon)|<2.25$, $p_T(\Upsilon)<70$ GeV

Results shown here for isotropic muon angular distributions



State	Integrated corrected cross sections $\sigma(pp \to \Upsilon) \times Br(\Upsilon \to \mu^+\mu^-)$ Range: $p_T^\Upsilon < 70$ GeV, $|y^\Upsilon| < 2.25$
$\Upsilon(1S)$	$8.01 \pm 0.02 \pm 0.36 \pm 0.31$ nb
$\Upsilon(2S)$	$2.05 \pm 0.01 \pm 0.12 \pm 0.08$ nb
$\Upsilon(3S)$	$0.92 \pm 0.01 \pm 0.07 \pm 0.04$ nb





Υ(nS) production cross-sections and theory

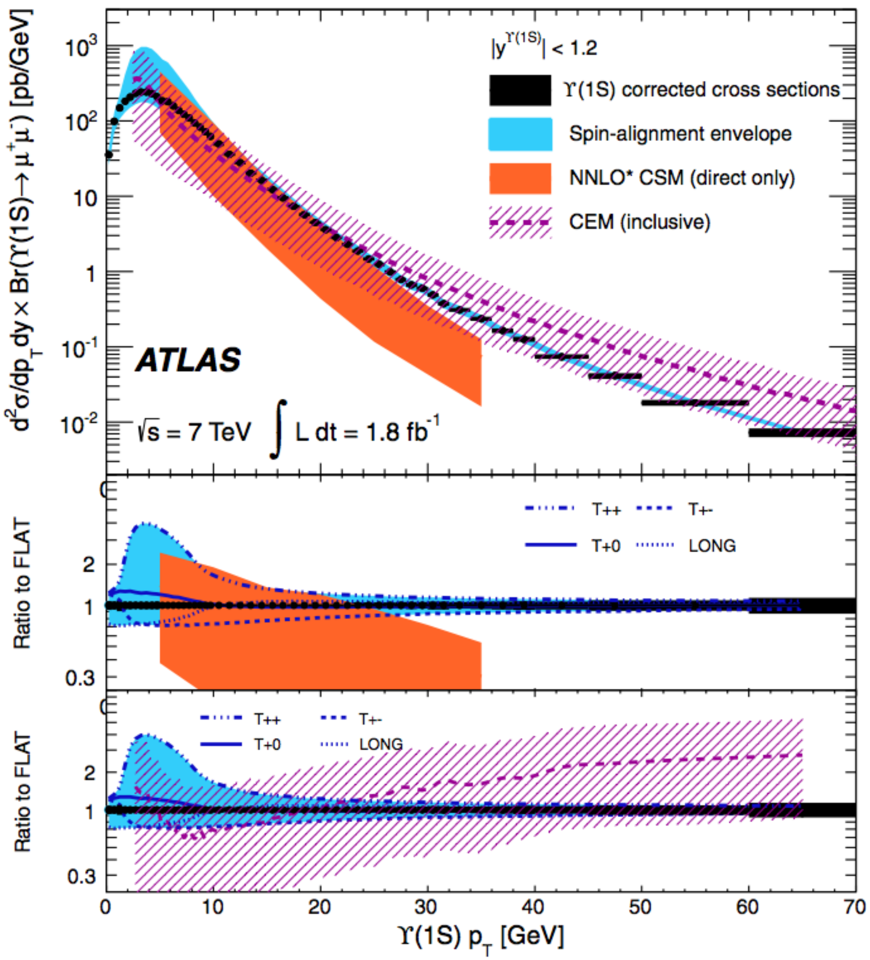
Spin-alignment envelope on data shown by blue band – dominant uncertainties at low p_T

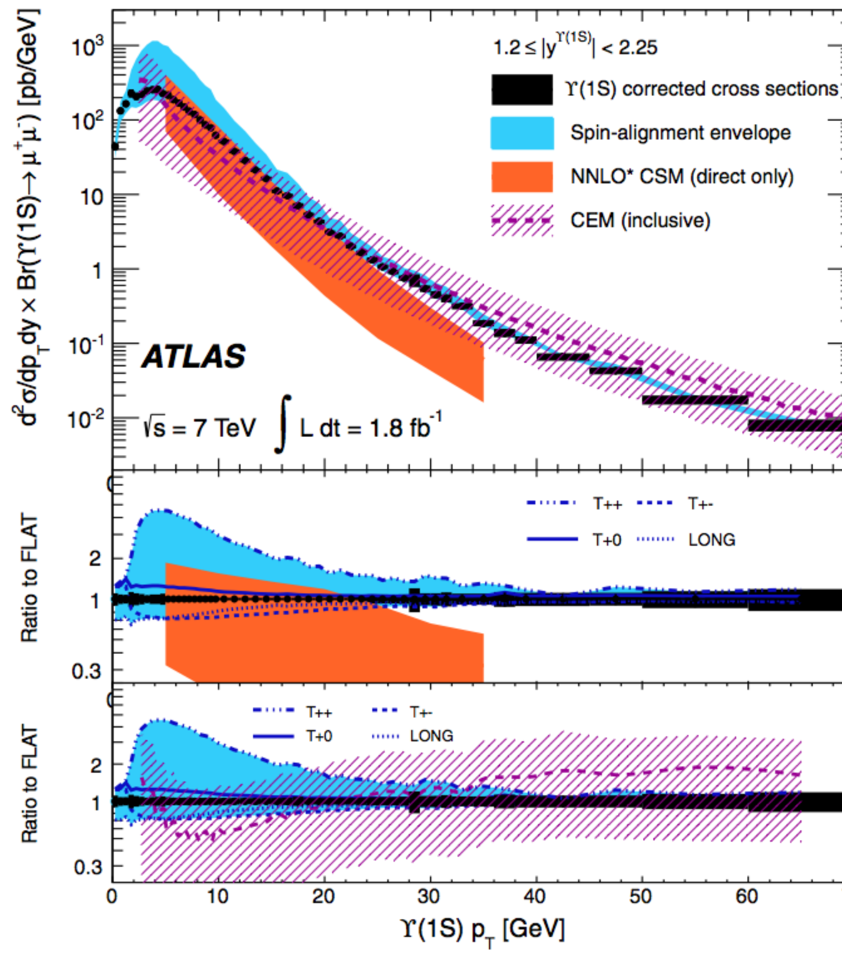
High p_T data largely free of spin-alignment uncertainty: a precision laboratory!

Theory comparisons:

- pQCD NNLO* Colour Singlet Model predictions
- Phenomenologically-driven Colour Evaporation Model

Both have problems describing the shape and normalisation of data



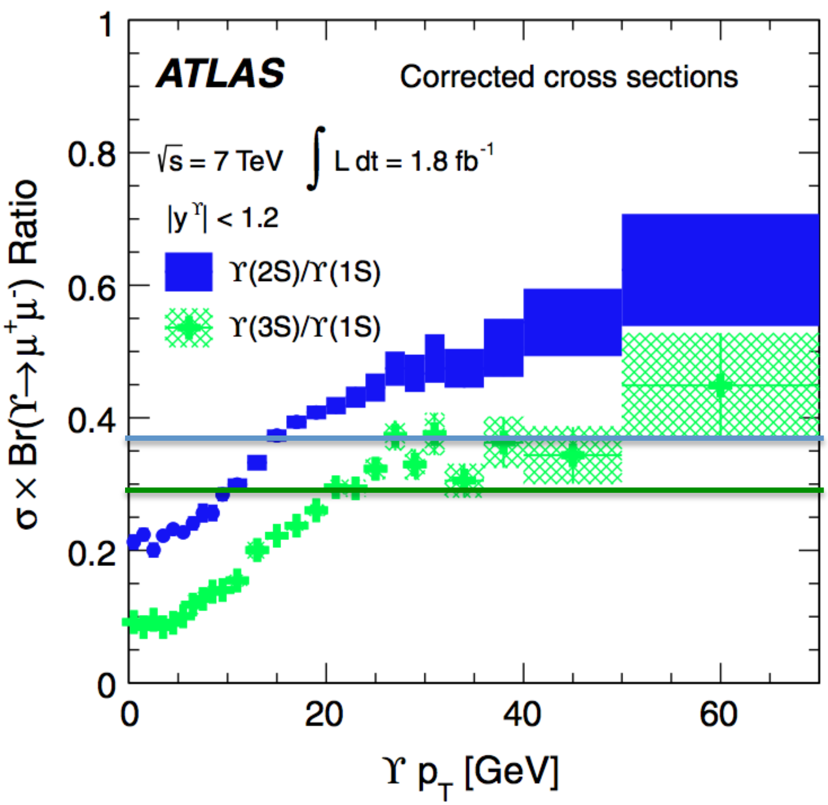


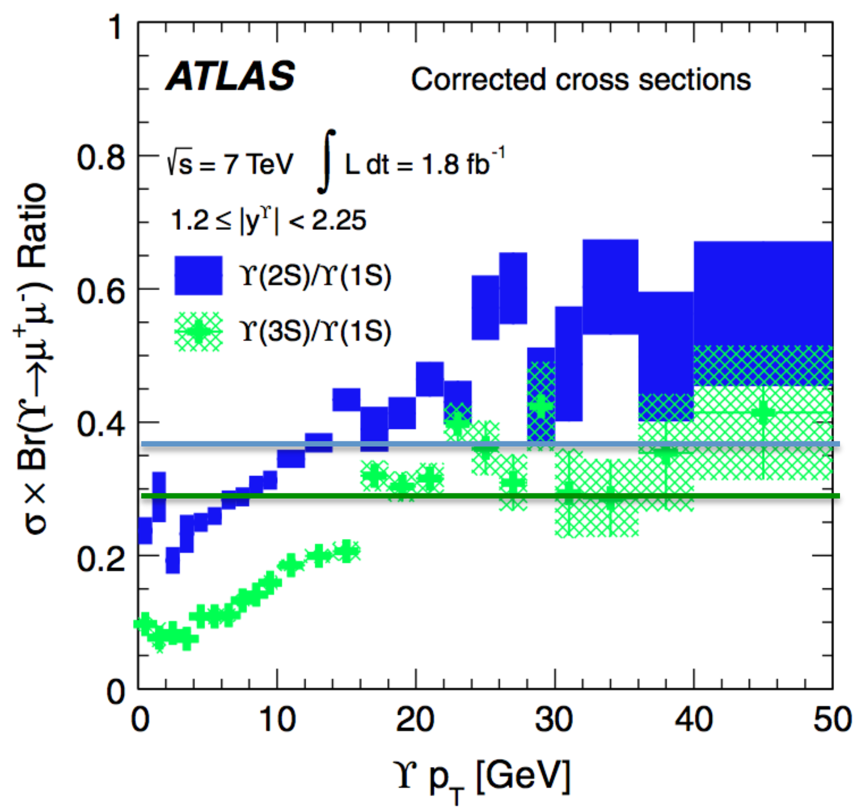
$\Upsilon(nS):\Upsilon(1S)$ production cross-section ratios

Production cross-section ratios measured as a function of Upsilon p_T

Experimental uncertainties reduced through systematic cancellations – precise measurement!

- Observe strong dependencies with p_T not encapsulated by theory calculations (horizontal lines)
- Sensitive to $\chi_{bJ}(nP)$ production cross-sections
- Low p_T data in agreement with measurements by CMS
- Observing plateau behaviour for the first time at high p_T

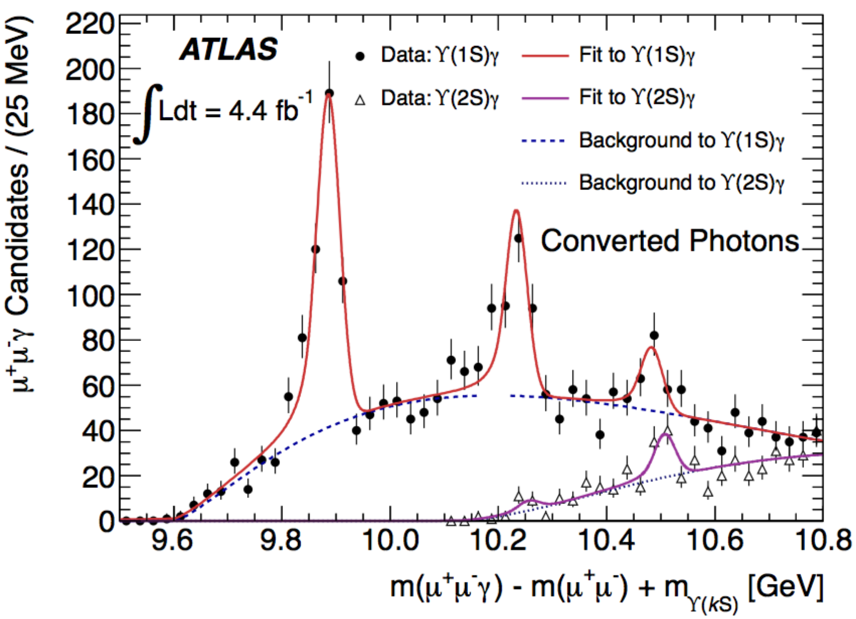


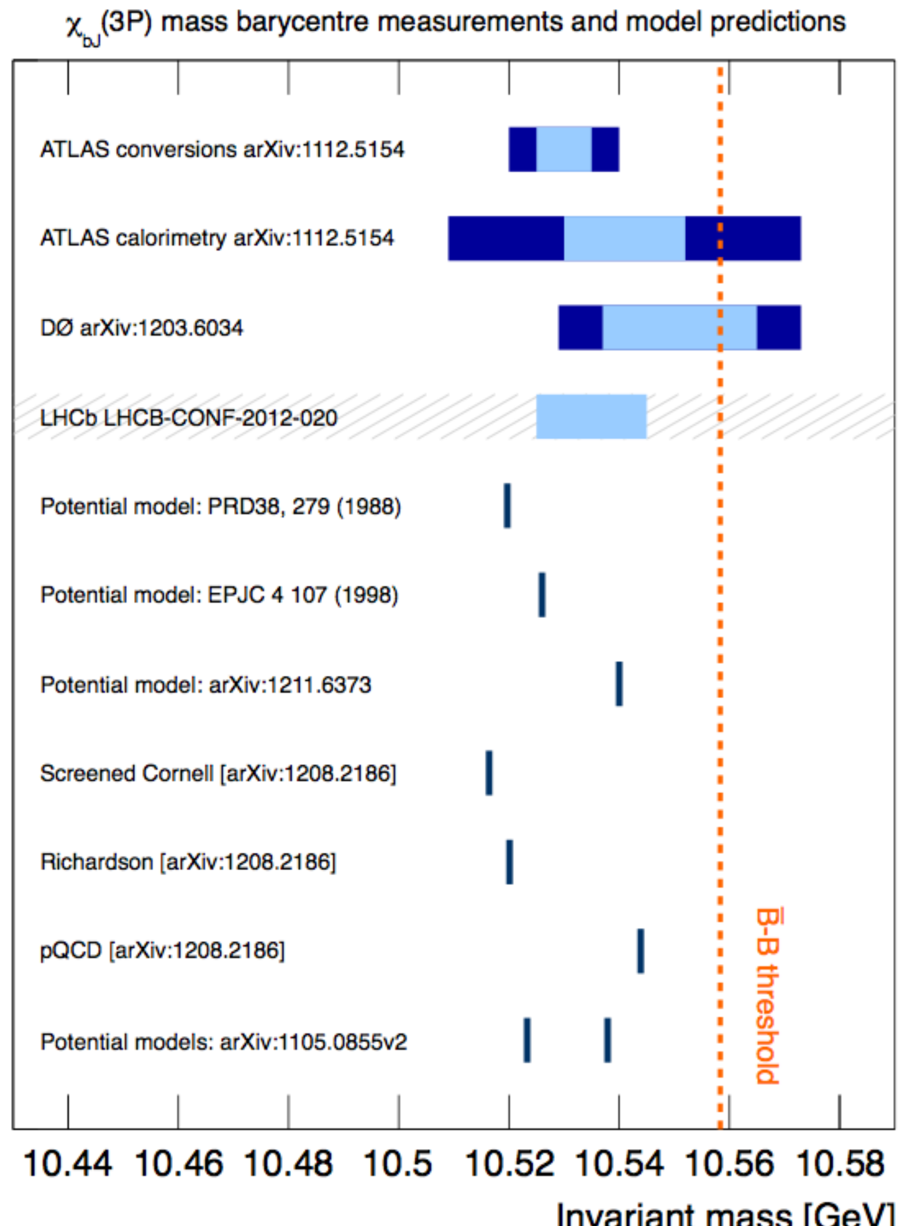


Observation of the χ_{bJ}(3P) bottomonium state

Production of χ_{bJ}(3P) observed for the first time through radiative transitions to ϒ(1S) and ϒ(2S) in two independent analysis channels

Observation and mass measurement verified by DØ and LHCb,
light blue: statistical, dark blue statistical+systematic
[No quoted systematic for LHCb observation]





Implications of the χ_{bJ}(3P) observation

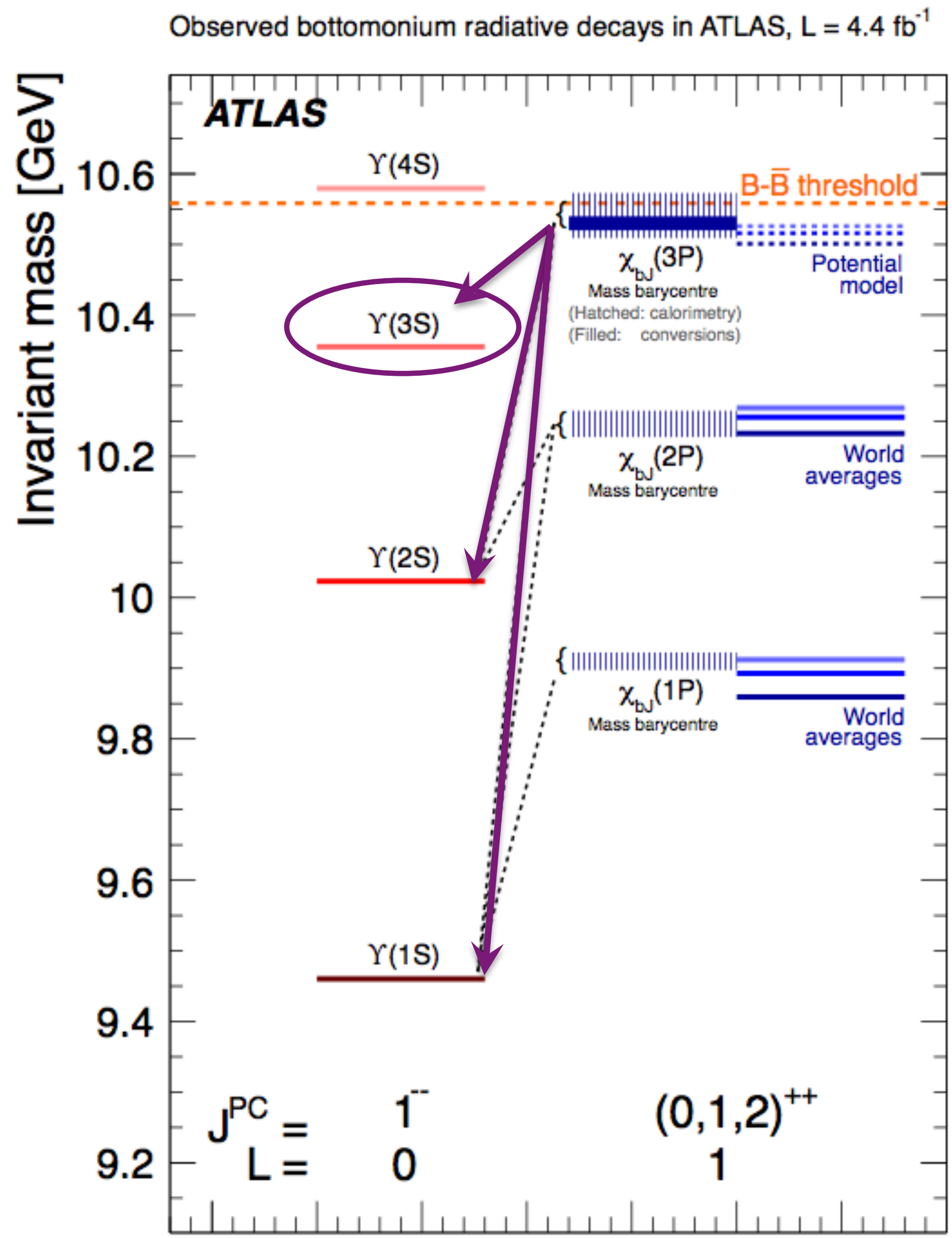
Verified a new source of feed-down to inclusive Upsilon production

ϒ(3S) previously expected to be free from significant feed-down contributions

- χ_{bJ}(3P) decays to ϒ(3S) kinematically allowed! [not observed at ATLAS directly due to phase space and statistics limitations]
- Polarisation of ϒ(3S) can **no longer be a clean probe** of direct quarkonium production

Recent theory calculations now take into account modification to observables due to the χ_{bJ}(3P)

Implication:
Only remaining clean laboratory for direct quarkonium production is the ψ(2S)!



Associated W boson + prompt J/ψ production

Using 4.6 fb^{-1} of 2011 7 TeV data, search for associated production of a W boson and *prompt* J/ψ production for first time

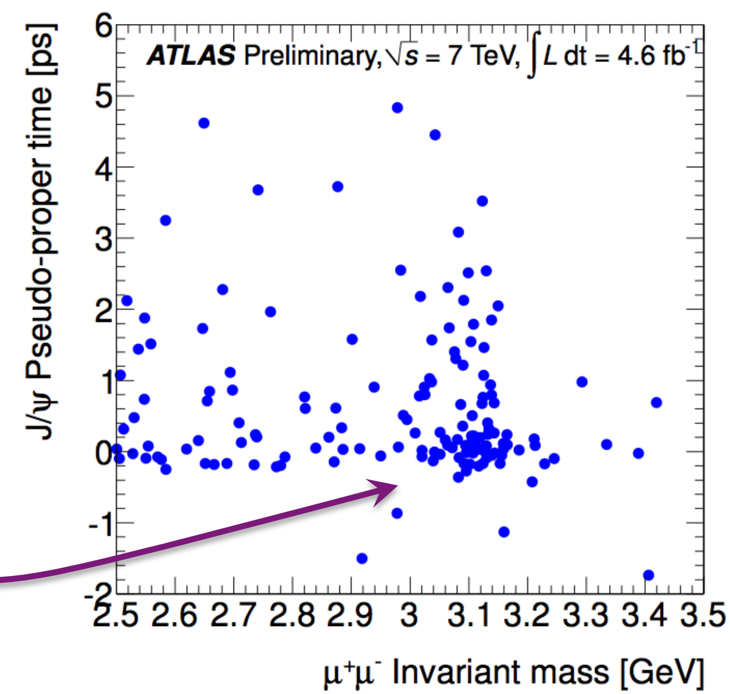
Probes new production modes of quarkonium, new dominant contributions to test theoretical predictions (and Color Octet vs. Colour Singlet modes).

Study W(→μν)+J/ψ(→μμ) decay mode, using single high p_T muon trigger
- W boson: $p_T(\mu)>25$ GeV, $|\eta(\mu)|<2.4$, MET>20 GeV, $m_T(W)>40$ GeV
- J/ψ candidate: $p_T(\mu^\pm)>2.5(3.5)$ GeV, $|\eta(\mu)|>1.3(<1.3)$, $|y(J/\psi)|<2.1$

Background contributions assessed from:
- Pileup (multiple pp collisions in bunch crossing), Z+jets, top pair production, W+b-quark, B_c→J/ψ+μν+X, heavy quark jets.

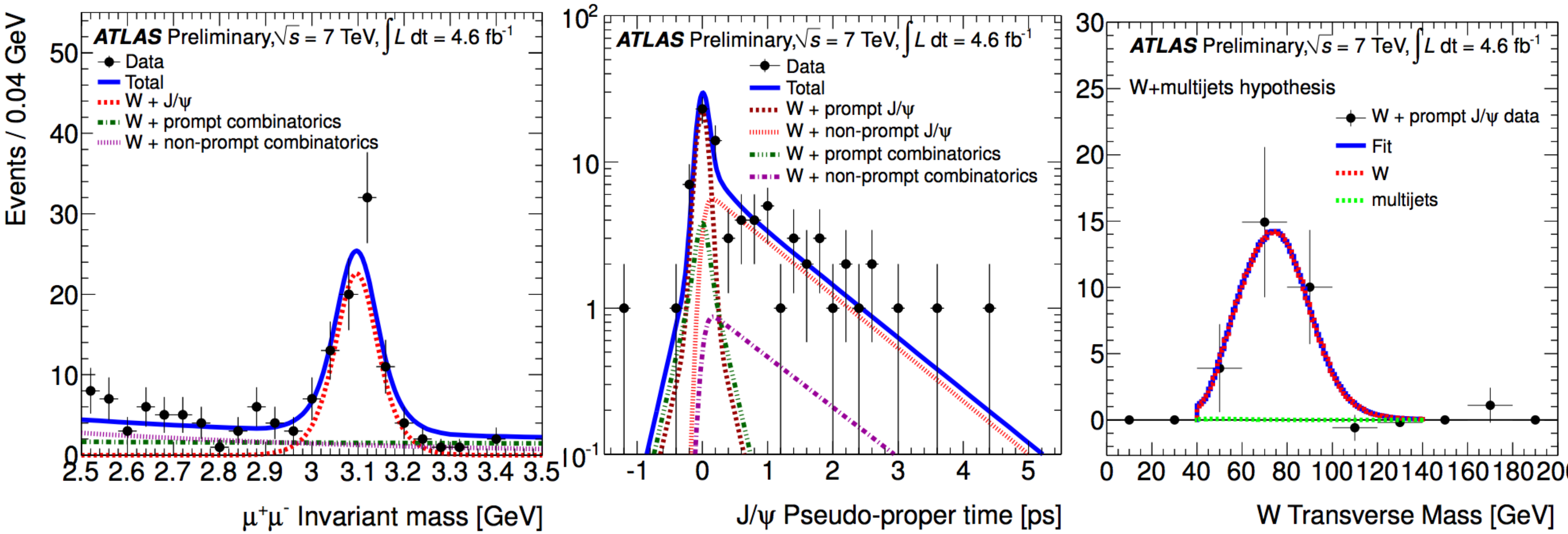
Double Parton Scattering considered part of the signal, in the first instance

All J/ψ candidate events in mass and lifetime



Extraction of W+prompt J/ψ signal from background

Unbinned maximum likelihood fit to J/ψ mass and lifetime, extract prompt component from data – background-only hypothesis rejected at 5.3σ level



Yields from two-dimensional fit

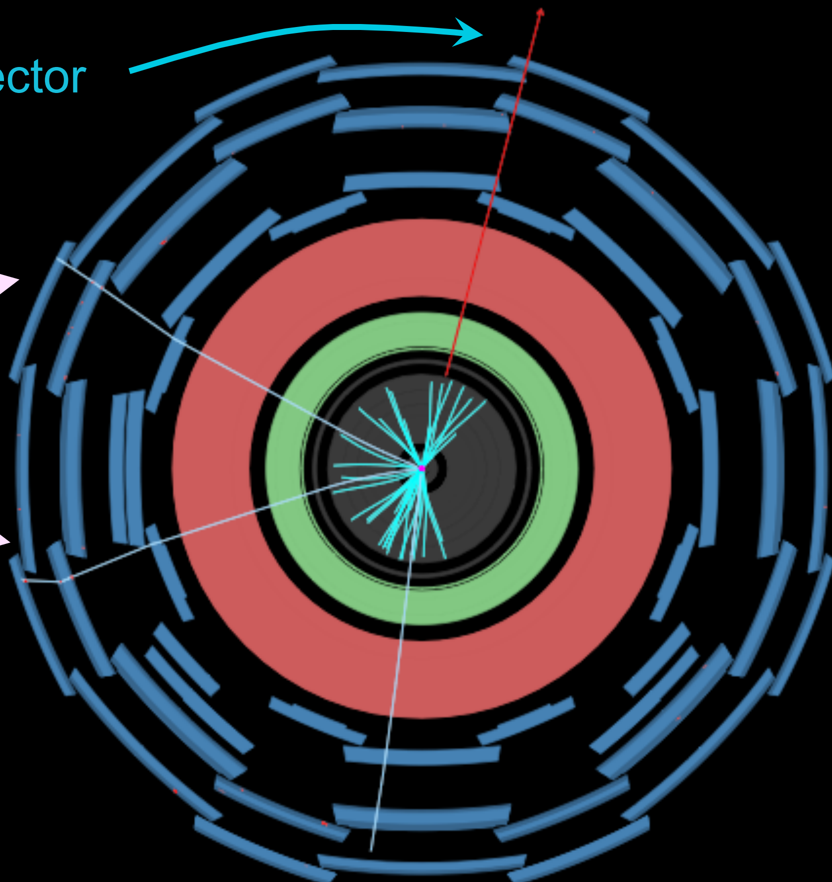
Process	Barrel	Endcap	Total
Prompt J/ψ	$10.0^{+4.7}_{-4.0}$	$19.2^{+5.8}_{-5.1}$	$29.2^{+7.5}_{-6.5}$
Non-prompt J/ψ	$27.9^{+6.5}_{-5.8}$	$13.9^{+5.3}_{-4.5}$	$41.8^{+8.4}_{-7.3}$
Prompt background	$20.4^{+5.9}_{-5.1}$	$18.8^{+6.3}_{-5.3}$	$39.2^{+8.6}_{-7.3}$
Non-prompt background	$19.8^{+5.8}_{-4.9}$	$19.2^{+6.1}_{-5.1}$	$39.0^{+8.4}_{-7.1}$
p-value	1.5×10^{-3}	1.4×10^{-6}	4.4×10^{-8}
Significance	3.0	4.7	5.3

Multijet contribution to W boson signal determined to be 0.1±4.6 events from signal+multijet template fit to transverse mass

Contribution from pileup assessed to be 1.8±0.2 events

Expected Z+jets contribution reduced to zero with invariant mass veto

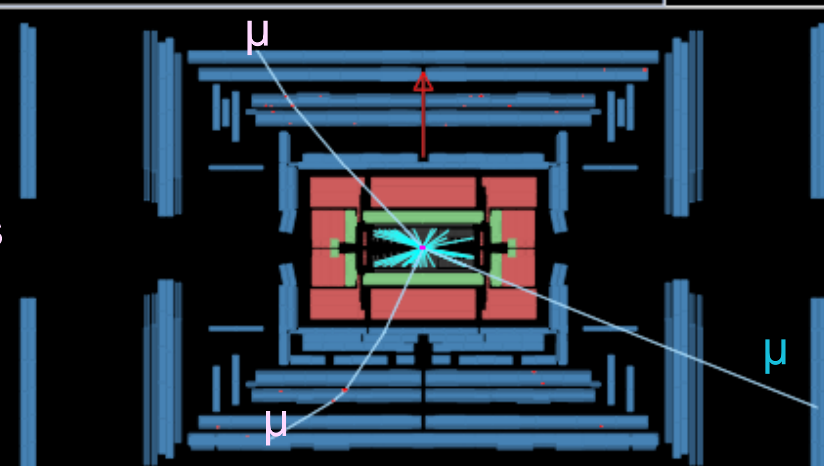
W + prompt J/ψ candidate event



ATLAS EXPERIMENT

Run Number: 191513, Event Number: 11053516

Date: 2011-10-23 17:21:09 UTC

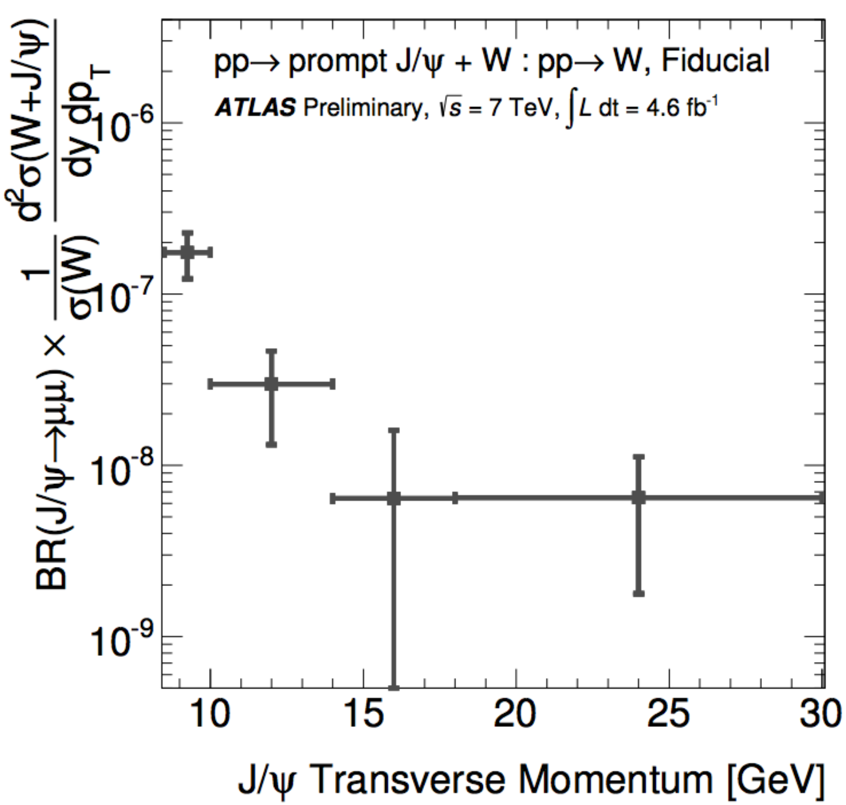


J/ψ candidate p_T = 9.3 GeV
Pseudo proper time = 0.0 ps

W boson p_T = 39 GeV

Measurement of fiducial W+prompt J/ψ cross-section

Unbinned maximum likelihood fit to J/ψ mass and lifetime and background determination repeated in four bins of J/ψ p_T



After applying corrections for detector effects and efficiencies:

measure fiducial cross-section of associated W+prompt J/ψ production as a function of J/ψ p_T

Normalise results to inclusive W production cross-section measured in same phase space for systematic uncertainty reduction

Inverting lifetime requirement to measure W+non-prompt J/ψ production:

estimate of W+b cross-section consistent with ATLAS direct measurements and NLO pQCD

Corrected results and double parton scattering

Correct fiducial cross-section for muon acceptance from J/ψ decay to compare with theory (as for Upsilon analysis described earlier)

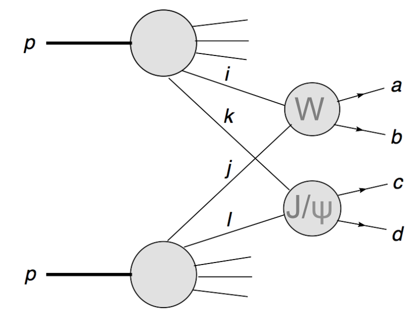
Double Parton Scattering can contribute to signal. Estimate using the following standard/simple ansatz:

Measured directly in this analysis

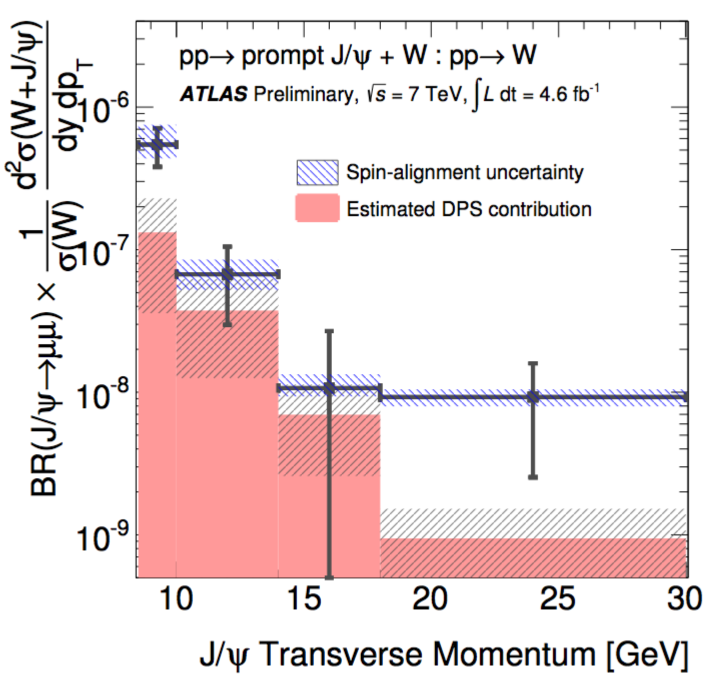
From ATLAS measurement prompt J/ψ arXiv:1104.3038

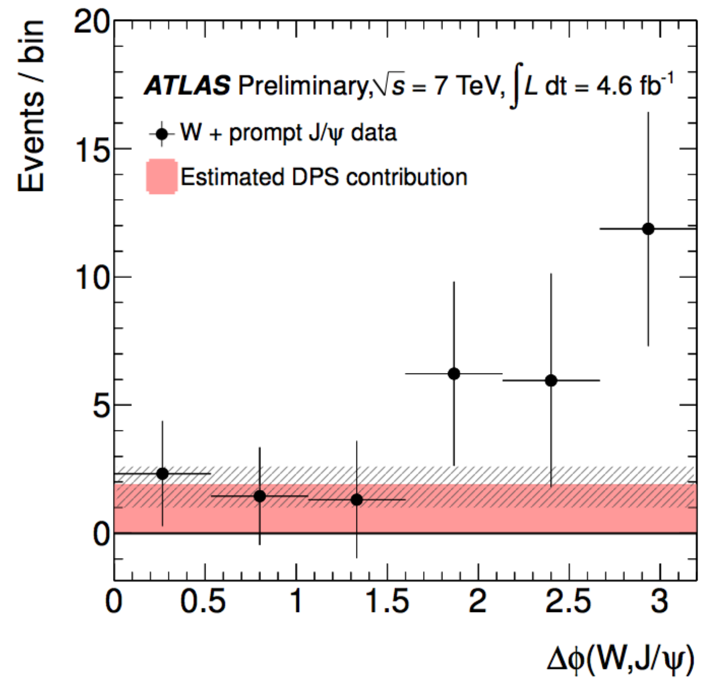
$$d\sigma_{W+J/\psi} = \frac{d\sigma_W \otimes d\sigma_{J/\psi}}{\sigma_{\text{eff}}}$$

From ATLAS measurement W+2jets arXiv:1301.6872

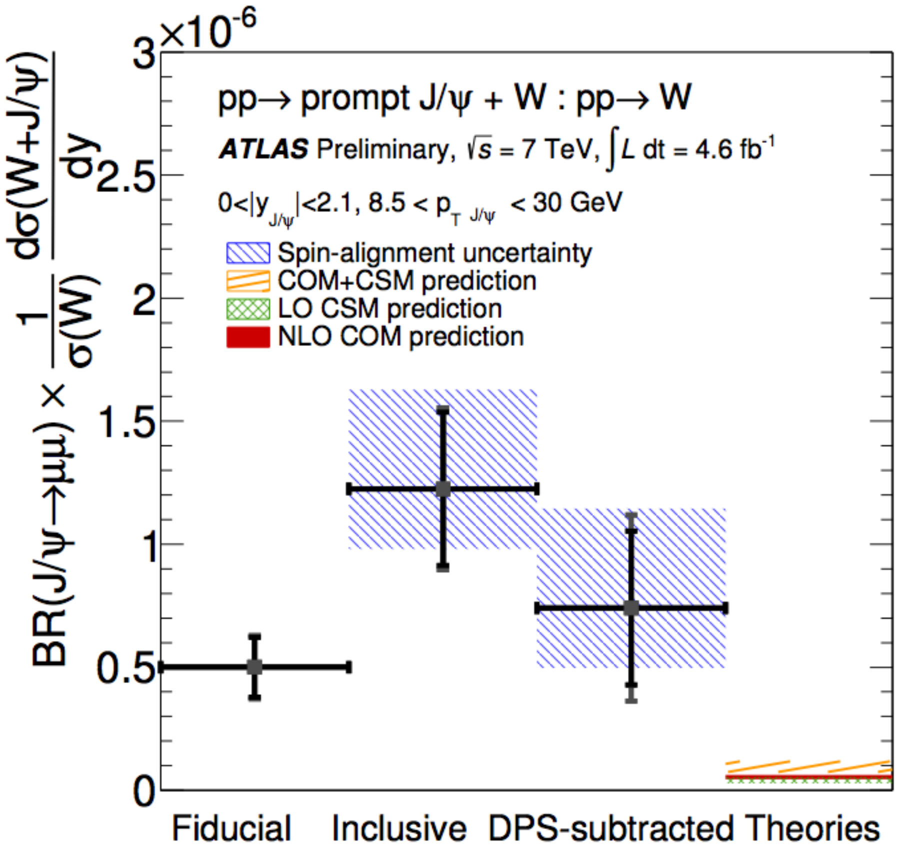


Both single and double parton scattering components observed in the data (f_{DPS}≈40%)



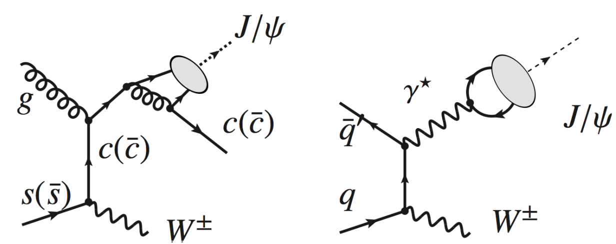


Production cross-section of W boson + prompt J/ψ



Present total cross-sections of inclusive W+prompt J/ψ production ***before and after*** estimation of double parton scattering component

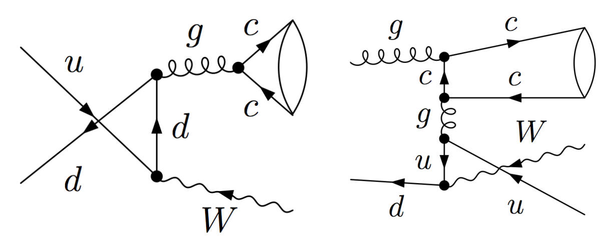
Compare DPS-subtracted to latest theoretical predictions
Data approximately an order of magnitude above predictions



LO CSM (SINGLET) arXiv:1303.5327

Accounting for the deficit:

- Large higher order corrections to theory
- Strongly transverse J/ψ spin-alignment in this production mode?
- Indication of breakdown of DPS σ_{eff} ansatz / factorisation, or NRQCD universality?
- Intrinsic charm contributions?



NLO COM (OCTET) arXiv:1304.4670

Summary

Measurement of ϒ(nS) production at the LHC

- Tests of pQCD calculations phenomenological models; entering unexplored regimes
- Indirect sensitivity to P-wave χ_{bJ}(nP) feed-down dynamics in cross-section ratios
- χ_{bJ}(3P) observation limitations on ϒ(3S) as a probe of direct quarkonium production

More exclusive ϒ(nS) and χ_{bJ}(nP) studies with spin-alignment, associated production, angular correlations and other new observables need to be explored to get a full picture

First observation (5.3σ) and measurement of associated W +prompt J/ψ production

New probe of quarkonium production:
Rates larger than theory predictions allow scope for interpretations:
are higher order corrections needed? CSM or COM? NRQCD universality?
Intrinsic charm? Seeing a breakdown of simple σ_{eff} DPS model / factorisation?

Novel double parton scattering study environment:
Further ongoing studies at 8 TeV in W/Z+onia and in double quarkonium production will allow us to make more concrete statements on double parton scattering

More studies needed, but more results from ATLAS coming soon!
(happily)

Thank you!

Upsilon production: arXiv:1211.7255; Phys.Rev D87 (2013) 052004

χ_{bJ}(3P) observation: arXiv:1112.5154; Phys.Rev.Lett. 108 (2012) 152001

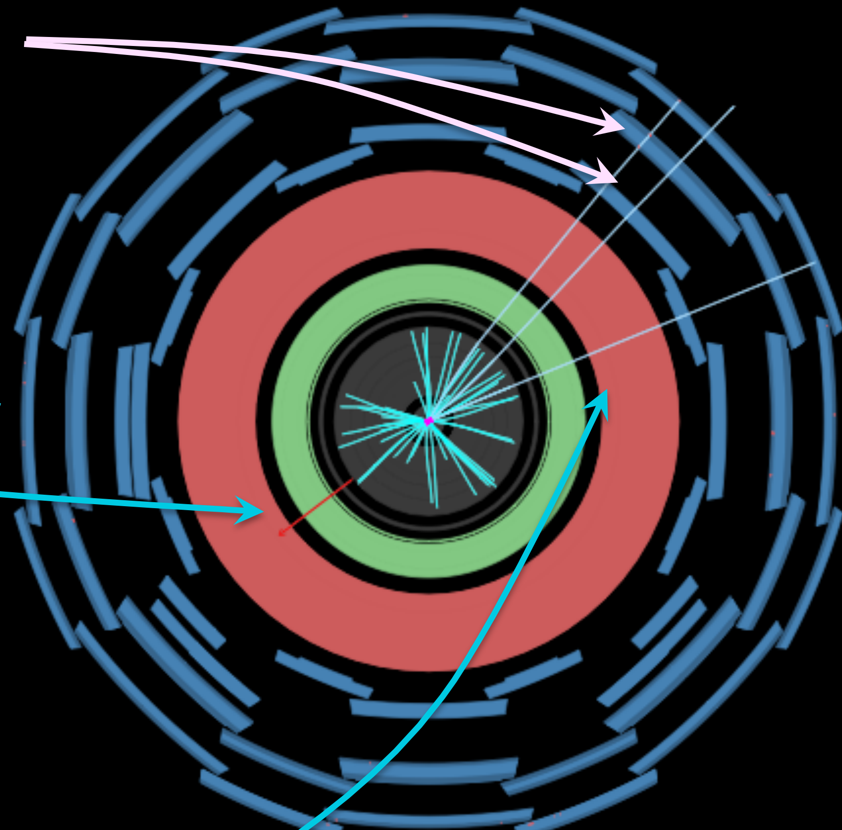
W+prompt J/ψ: ATLAS-CONF-2013-042

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-042

ATLAS B-Physics public results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

Additional Material

W + prompt J/ψ candidate event



ATLAS EXPERIMENT

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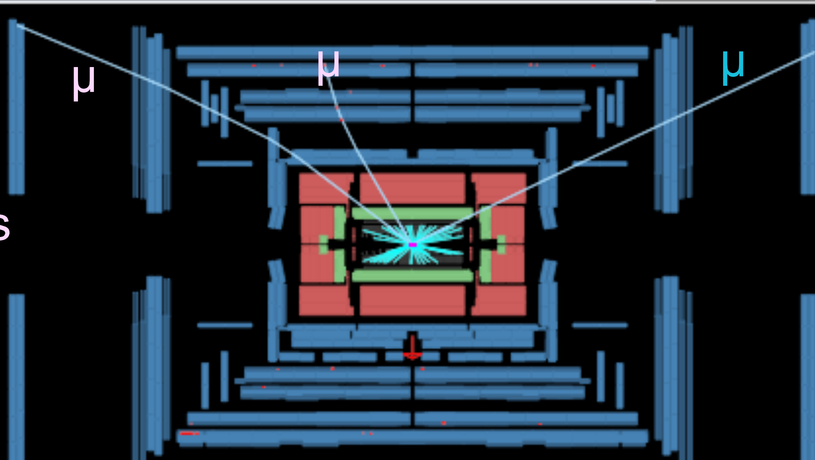
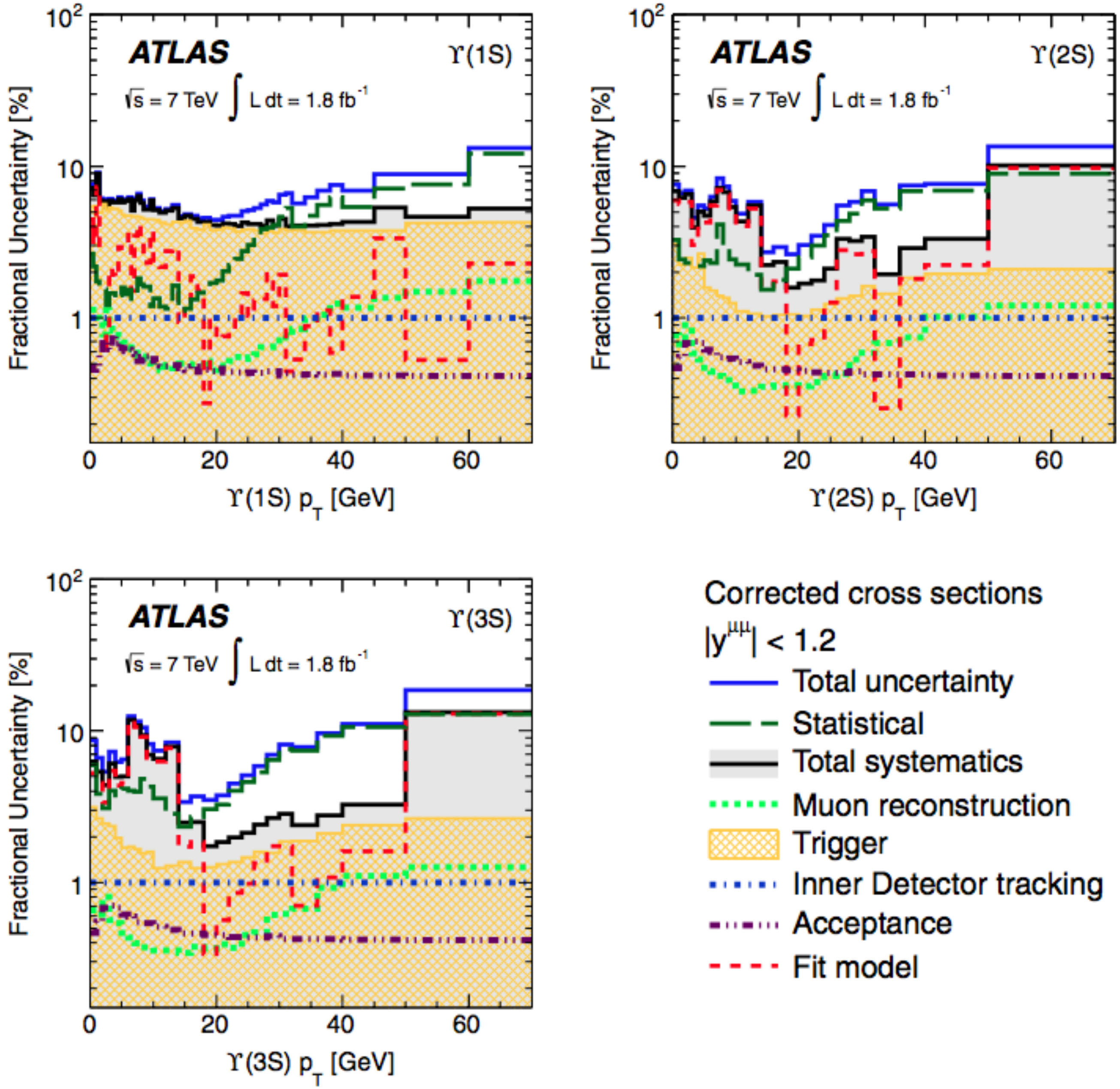
Date: 2011-09-16 18:30:08 UTC



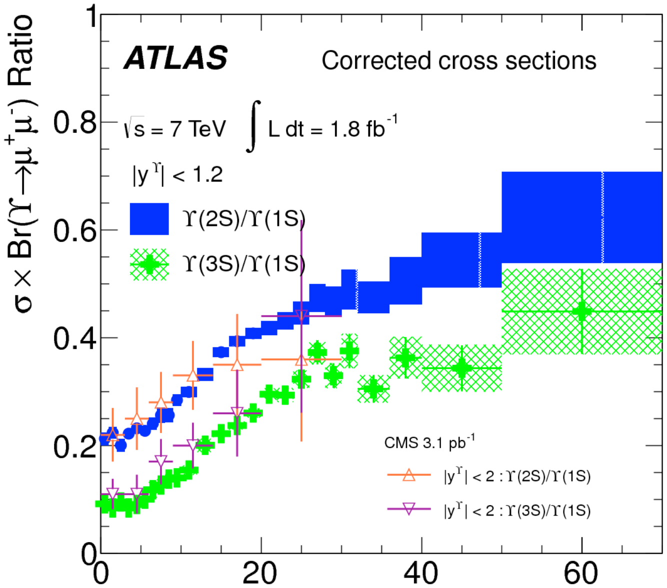
J/ψ candidate p_T = 9.4 GeV
Pseudo proper time = -0.1 ps

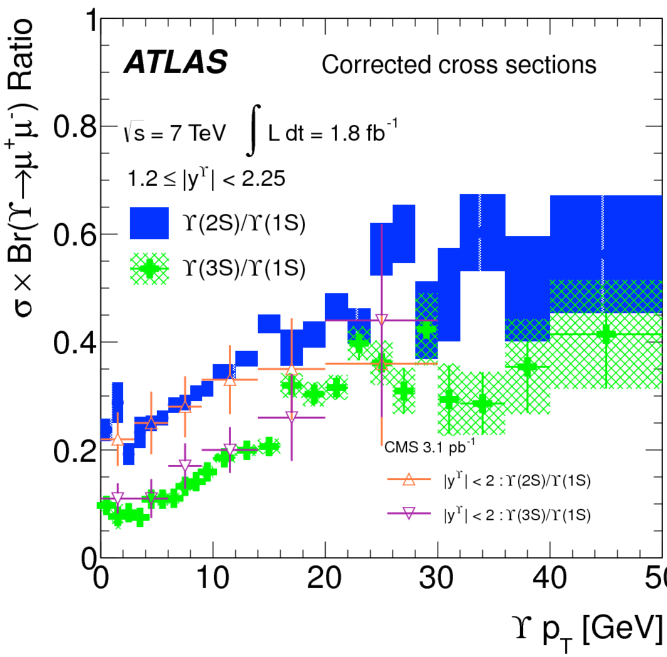
W boson p_T = 42 GeV

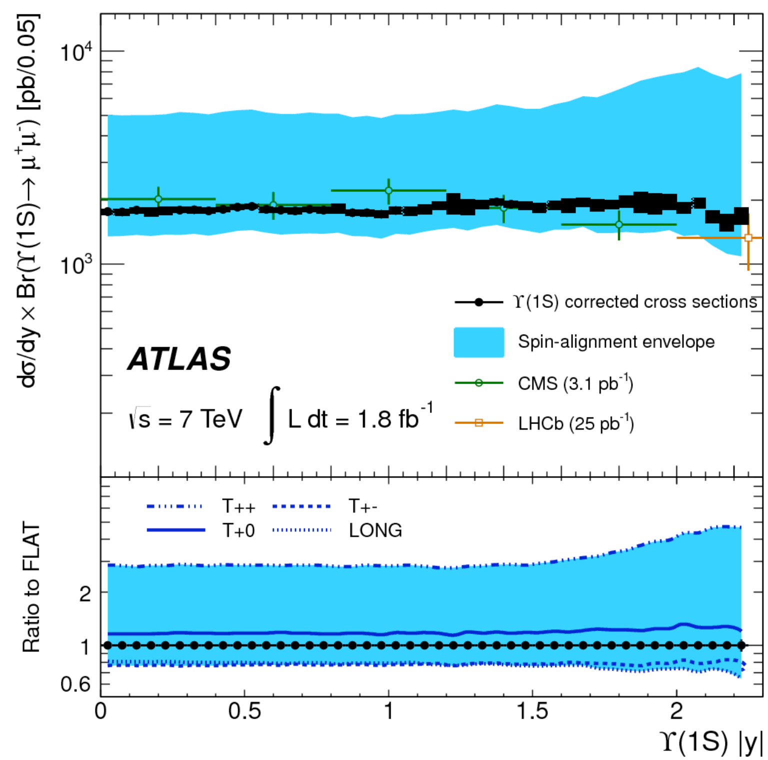
Upsilon production: experimental uncertainties



Upsilon in comparison to CMS/LHCb



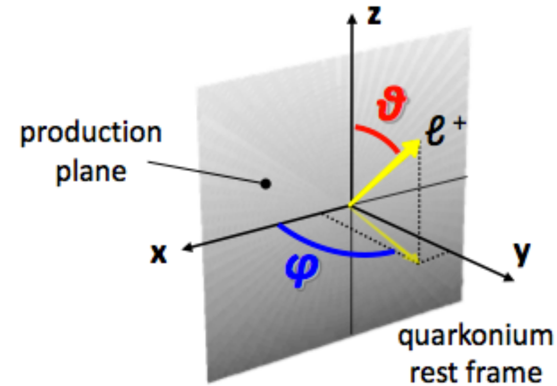




Spin-alignment working points at ATLAS

We know acceptance can vary with spin-alignment

State has generalised angular decay distribution:



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

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

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

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

FLAT (unphysical, except as the result of a particular admixture of polarised exclusive processes)

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

T(ransverse)**+-**

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

LONG(itudinal)

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

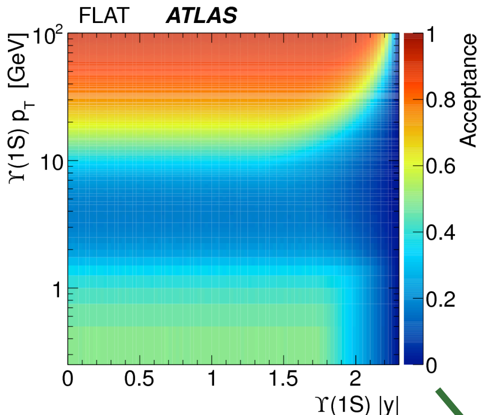
T(ransverse)**+0**

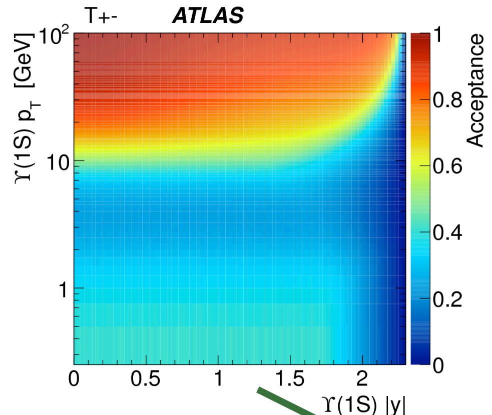
$$\lambda_{\theta^\star} = +1$$

T(ransverse)**++**

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

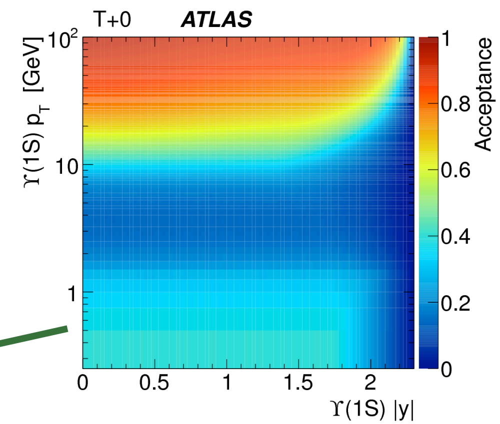
Spin-alignment and acceptance corrections

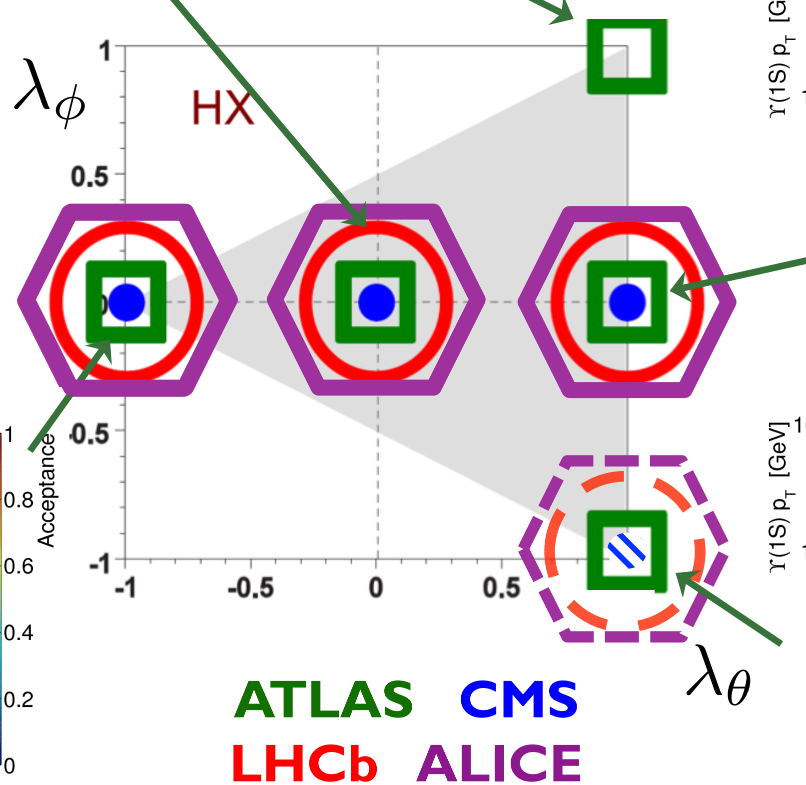


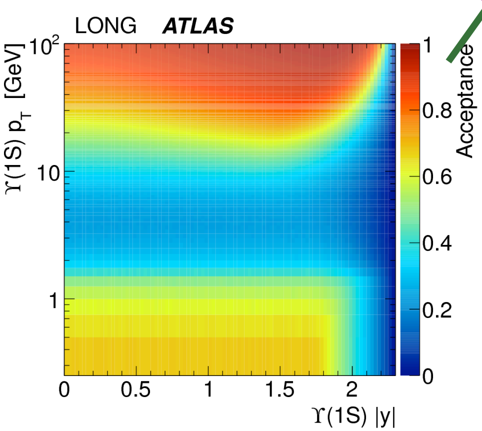


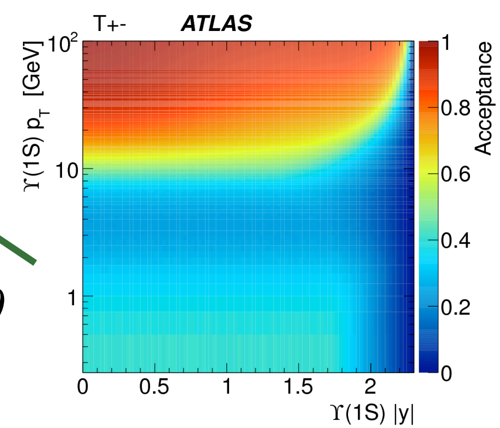
Acceptance maps correct efficiency-corrected fiducial measurements for muon kinematic acceptance

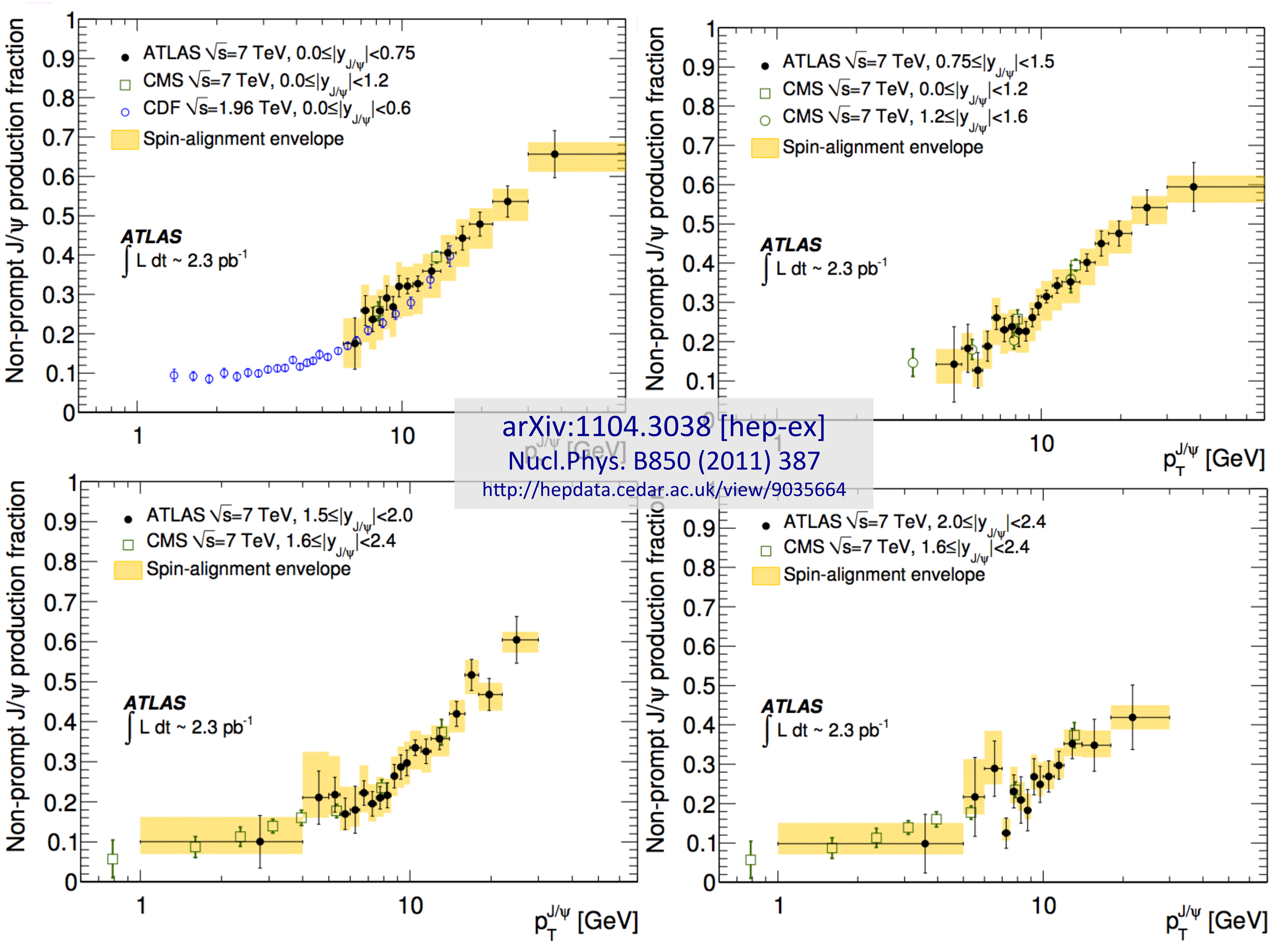
Corrections dependent on quarkonium spin-alignment state
Υ(1S) example shown here











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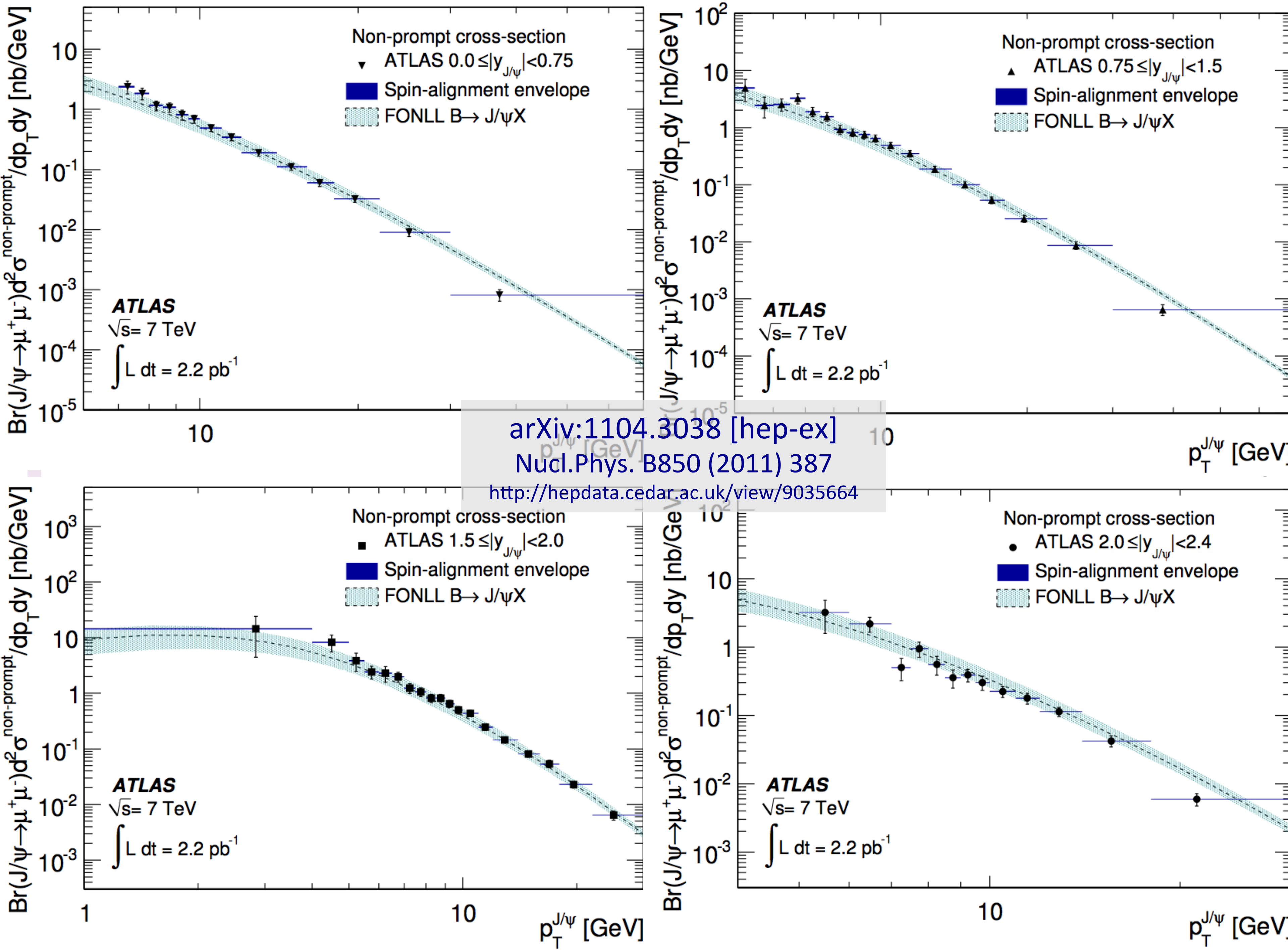
http://hepdata.cedar.ac.uk/view/9035664



arXiv:1104.3038 [hep-ex]
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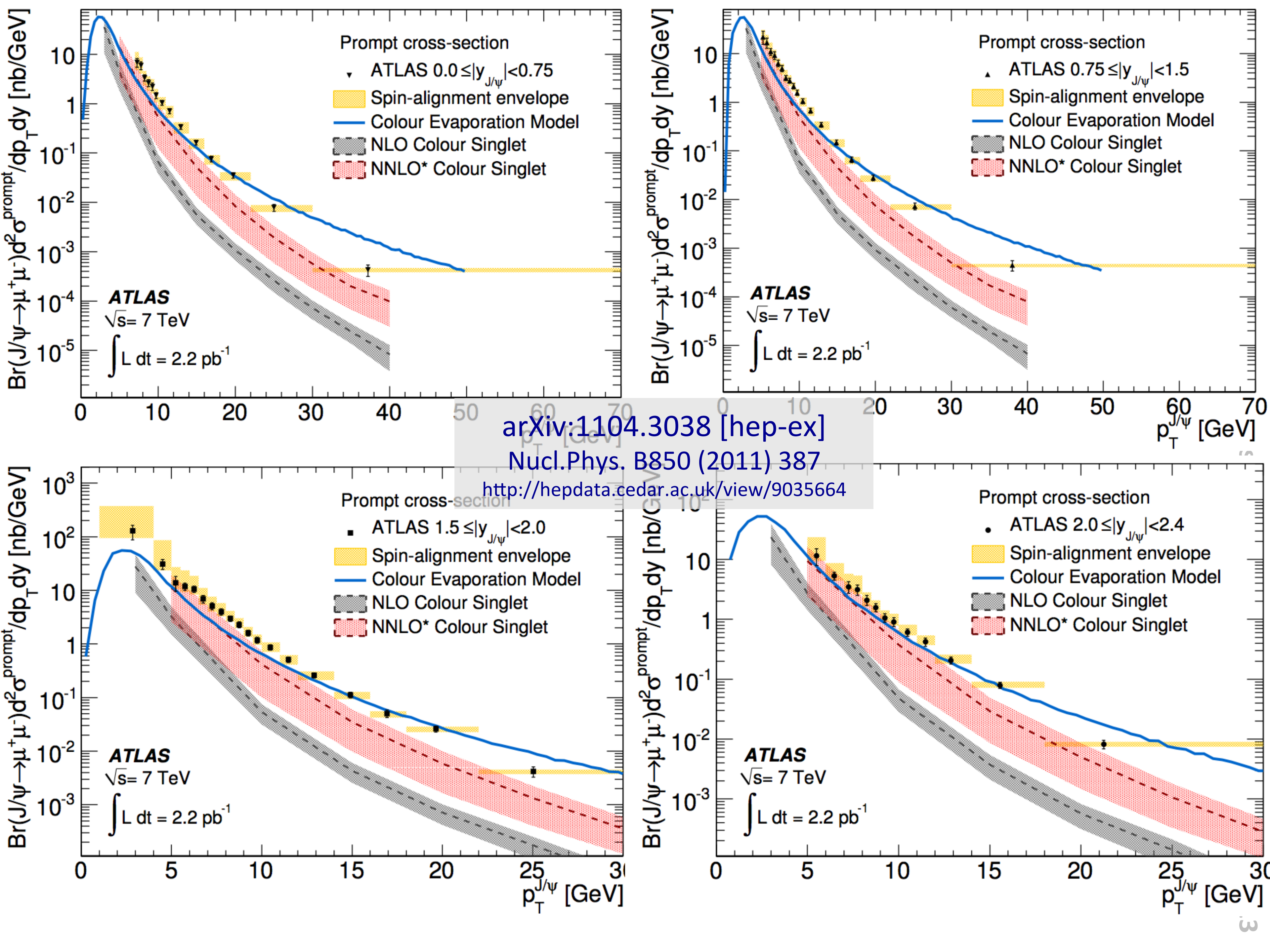

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