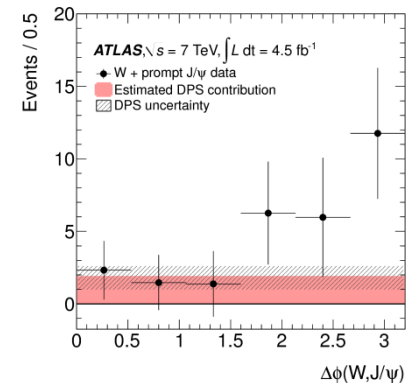
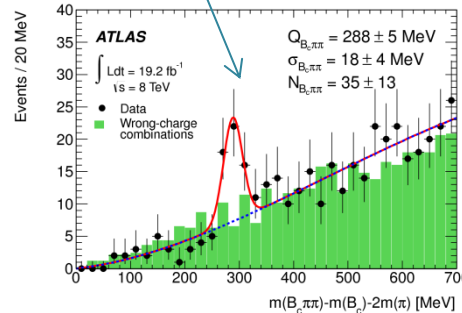
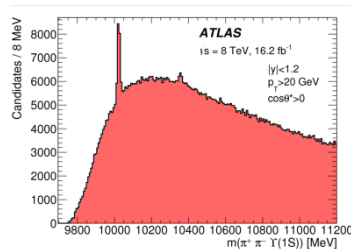
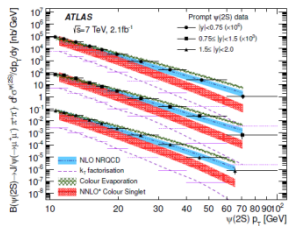
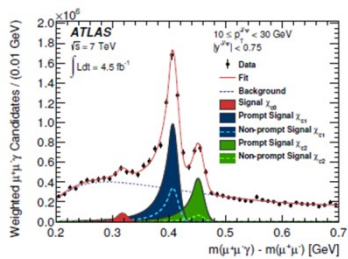


Heavy quark measurements with ATLAS

Julie Kirk
Rutherford Appleton Laboratory, STFC
on behalf of the ATLAS collaboration

Will concentrate on recent measurements:

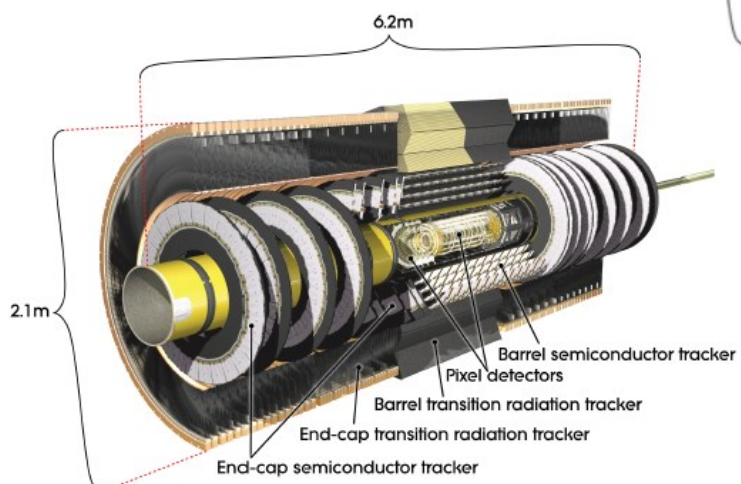
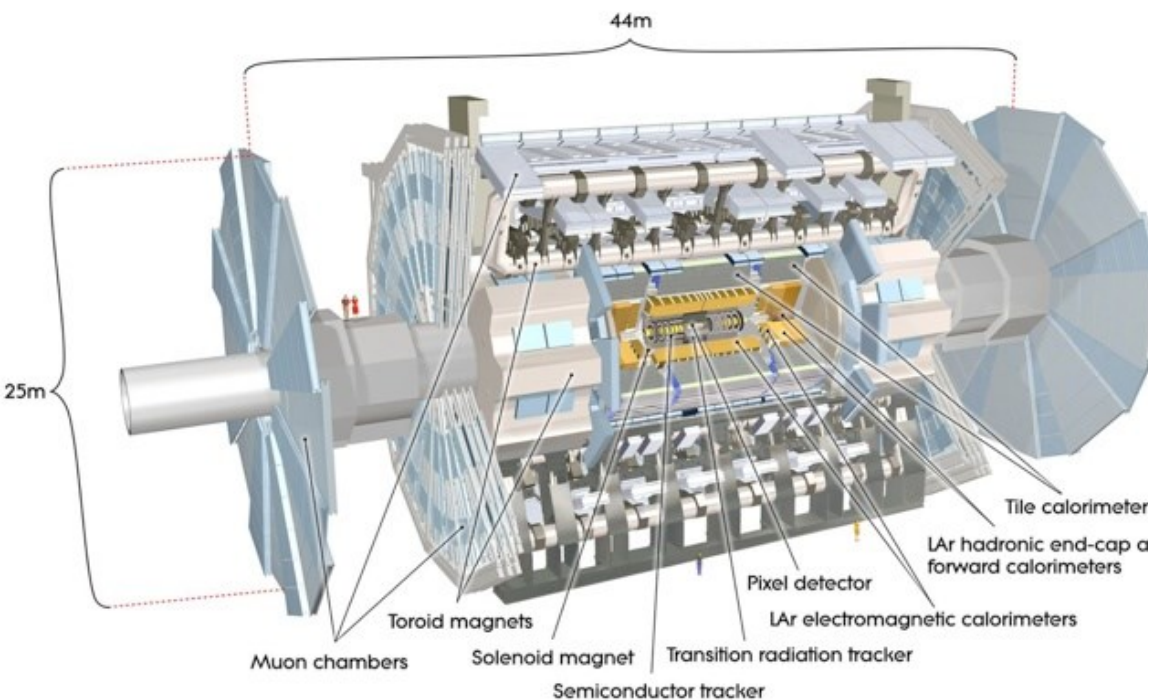
- Charmonium results
- Associated vector boson with J/ψ
- Observation of Excited B_c meson
- Search for X_b



ATLAS experiment



For B physics measurements require **excellent tracking** capabilities and **muon identification**



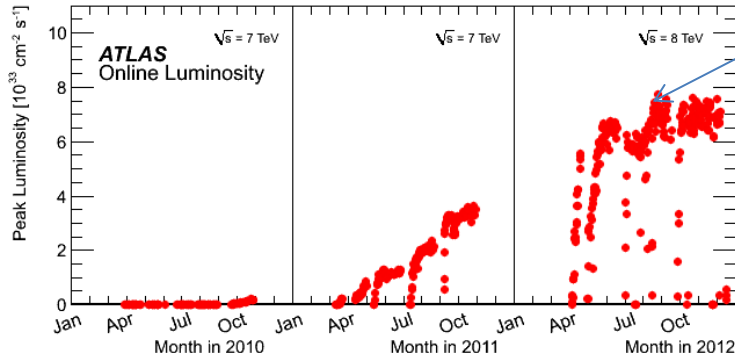
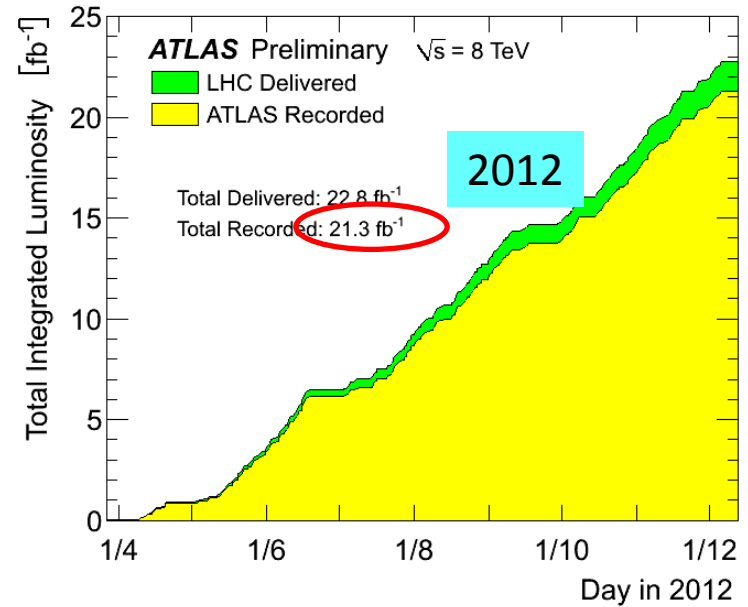
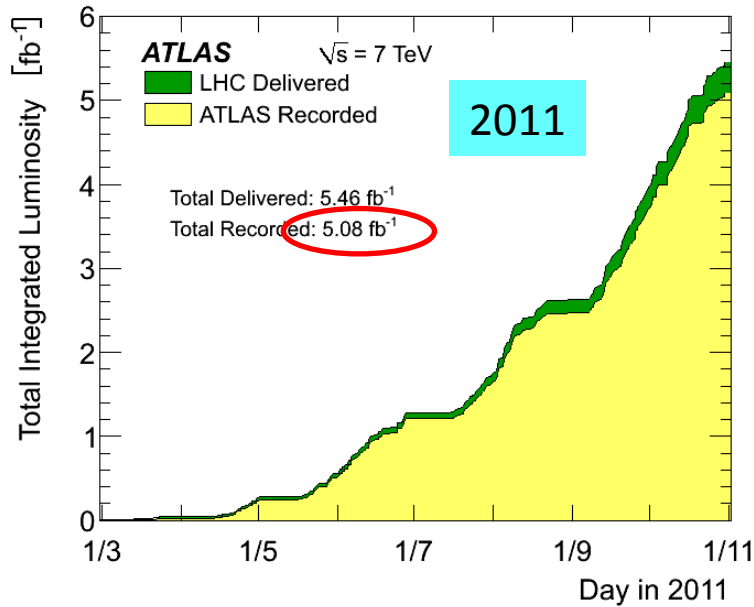
• Inner Detector

- $|\eta| < 2.5$,
- Solenoid $B = 2T$
- Si Pixels,
- Si strips,
- Transition Radiation Tracker (TRT)
- $\sigma/p_T \sim 3.4 \times 10^{-4} p_T + 0.015$ for $(|\eta| < 1.5)$
- Used for Tracking and Vertexing:
- Precision momentum and lifetime measurements

• Muon Spectrometer

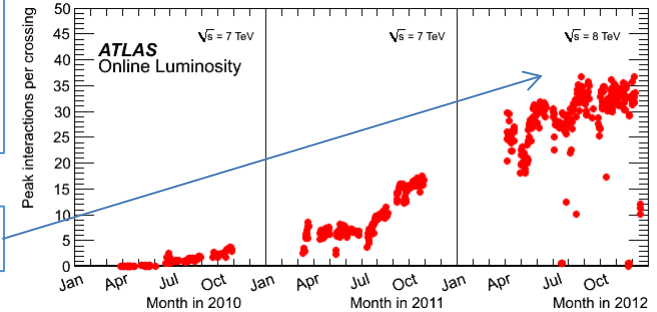
- $|\eta| < 2.7$
- Toroid B-Field, average $\sim 0.5T$
- Muon Momentum resolution $\sigma/p < 10\%$ up to $\sim 1 TeV$

ATLAS data sample



Peak instantaneous luminosity:
 $\sim 7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

Pileup of almost 40



ATLAS B-physics programme and trigger strategy



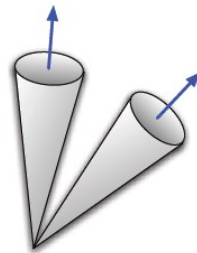
ATLAS is a general purpose detector – main focus is on high p_T discovery physics but also has a very strong dedicated B physics programme.

B-physics programme concentrates on low p_T di-muon signatures:

- Onia studies ($J/\psi \rightarrow \mu^+\mu^-$, $\Upsilon \rightarrow \mu^+\mu^-$, etc.)
- $B \rightarrow J/\psi(\mu\mu)X$, search for new states, mixing and CP violation studies
- Rare and semi-rare B decays $B \rightarrow \mu\mu(X)$

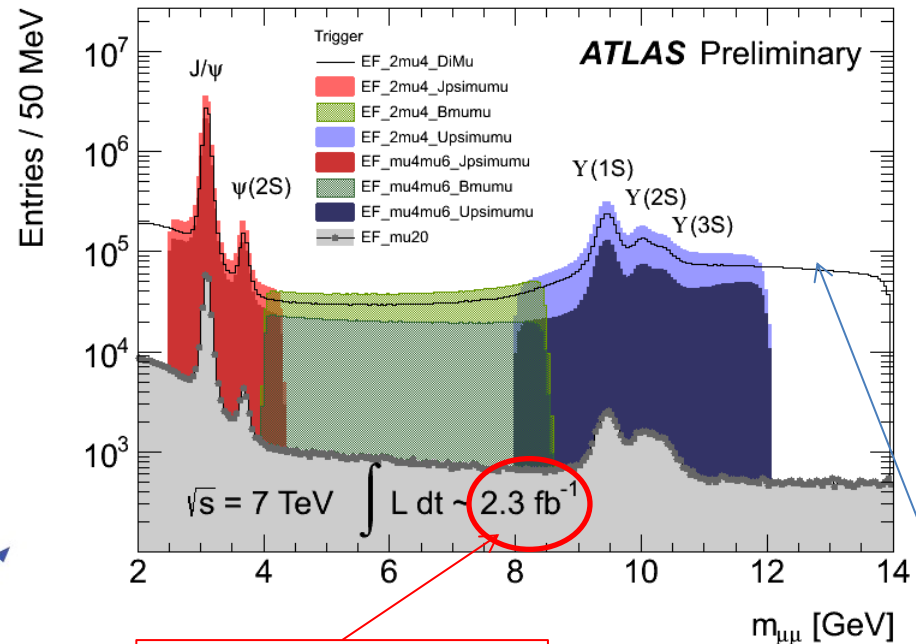
Trigger on low p_T (4,6 GeV) di-muon

- 2 muons at Level1
- Confirmed in High Level Trigger
- Then require vertex fit and mass cuts



- Maintained low p_T triggers in 2012 by introducing “Barrel” and “Barrel-only” triggers.

- **Large samples of events recorded for the B-physics programme**



About 50% of total 2011 data sample

“DiMu” prescaled in latter part of 2011 data-taking

Trigger	Mass window	No. of events (M)
2mu4_DiMu	1.4 – 14 GeV	27
2mu4_Jpsimumu	2.5 – 4.3 GeV	14
2mu4_Bmumu	4 – 8.5 GeV	3.7
2mu4_Upsimumu	8 – 12 GeV	9.1

Quarkonium Production

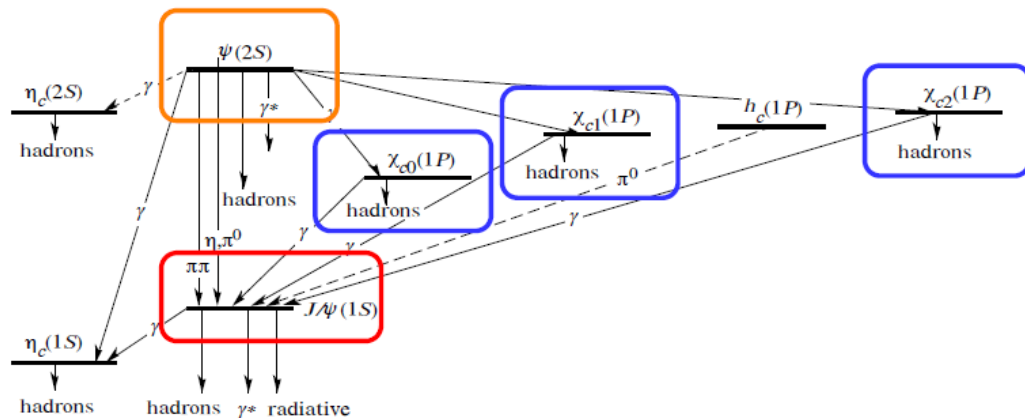


Quarkonium production gives unique window on QCD

Experimental input from LHC experiments necessary to inform future direction of theory

Several new studies:

- $\chi_c \rightarrow J/\psi \gamma$
([JHEP 1407 \(2014\) 154](#))
- $\psi(2s) \rightarrow J/\psi \pi^+ \pi^-$
([JHEP 1409 \(2014\) 79](#))



Common J/ψ selection:

- $p_T(\mu^+, \mu^-) > 4 \text{ GeV}$
- Muons must be trigger-matched
- $\chi^2 / \text{n.d.f.} (J/\psi) < 15$

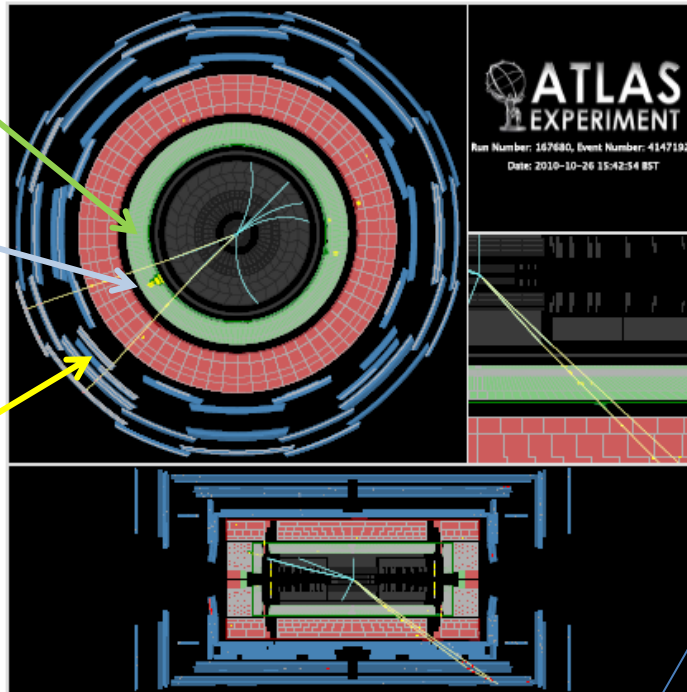
Not covered here:

- $J/\psi \rightarrow \mu\mu$ ([Nucl. Phys. B850 \(2011\) 387](#))
- $\Upsilon \rightarrow \mu\mu$ ([Phys. Rev. D87 \(2013\) 052004](#))

Charmonium: $\chi_c \rightarrow J/\psi \gamma$



Candidate $\chi_{c1} \rightarrow J/\psi \gamma \rightarrow \mu^+ \mu^- \gamma$ decay in ATLAS



Muon 1

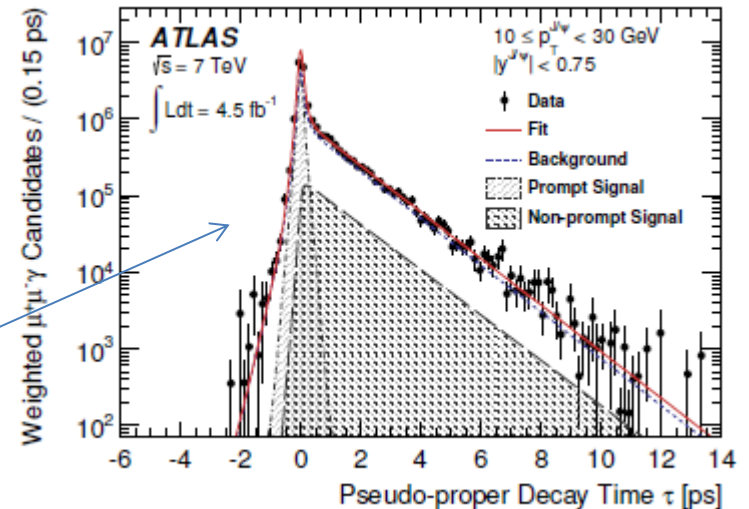
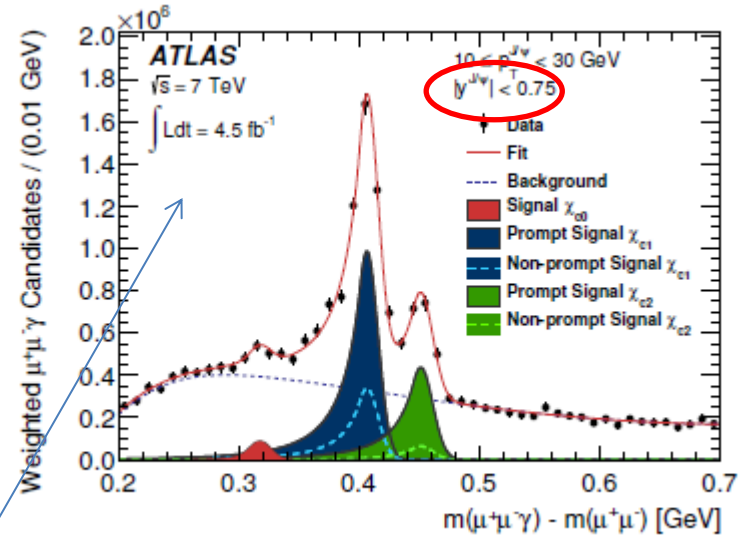
Photon
(typically ~ 1 GeV)

Muon 2

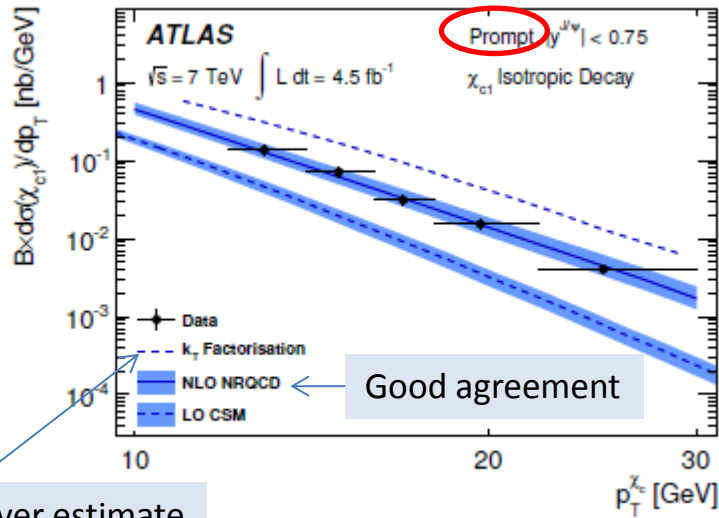
Prompt and non-prompt are separated using 2D unbinned maximum likelihood fit to mass and pseudo-proper decay time (τ) distributions

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

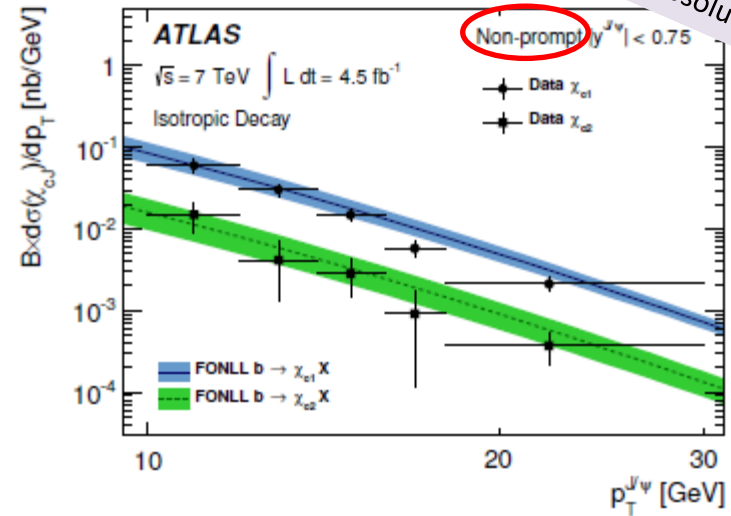
xy displacement of candidate from PV Invariant mass of candidate
pr of candidate



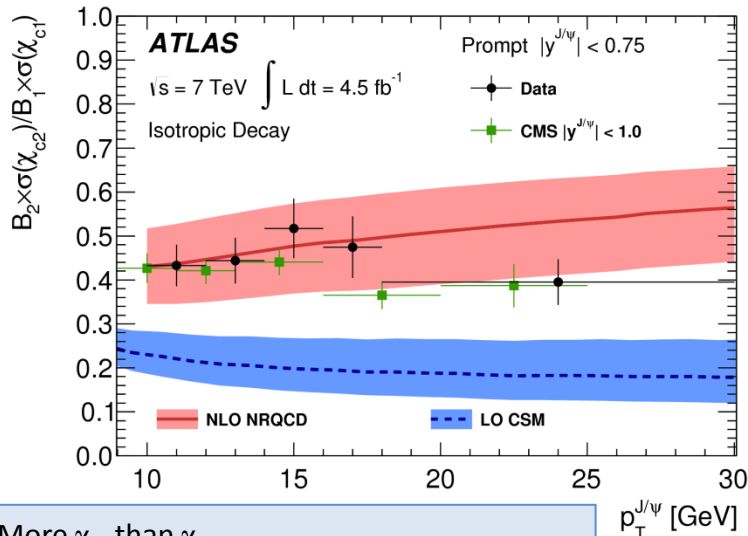
Charmonium: $\chi_c \rightarrow J/\psi \gamma$



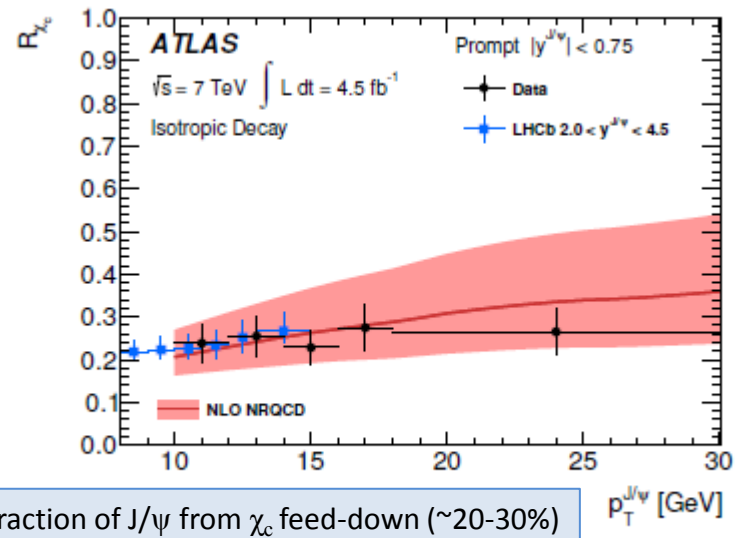
over estimate



First absolute cross-sections



More χ_{c1} than χ_{c2}
 NLO NRQCD describes ratio well at low p_T
 possible discrepancy at higher p_T



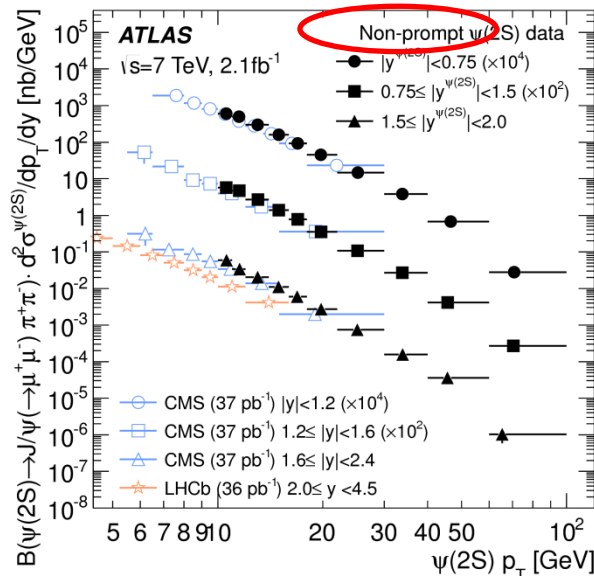
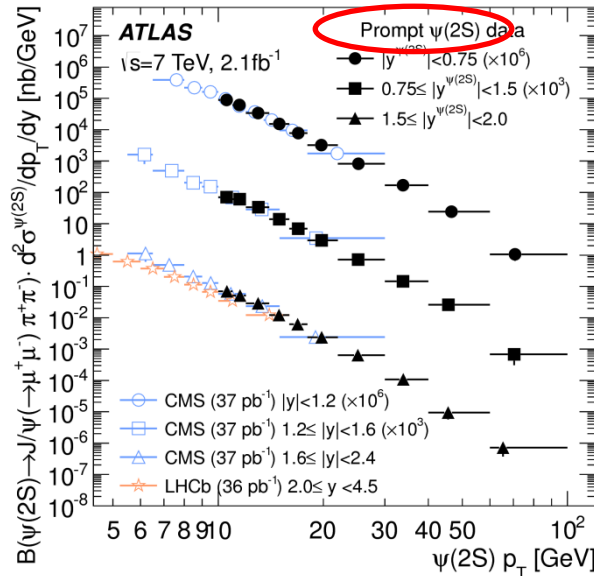
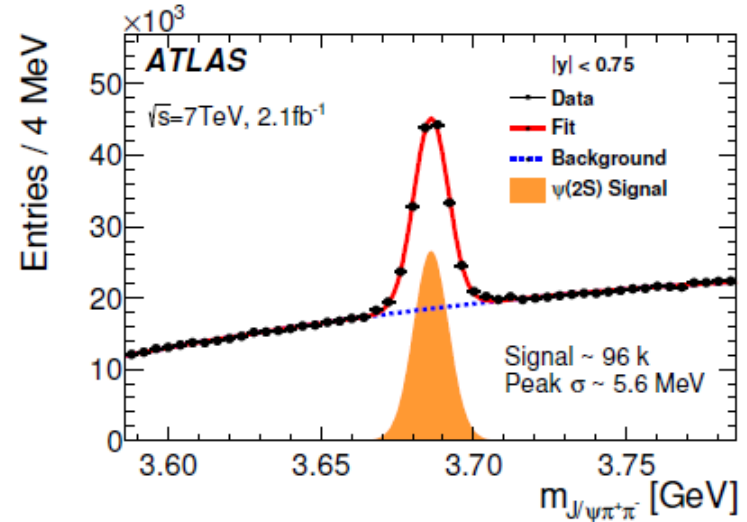
Fraction of J/ψ from χ_c feed-down ($\sim 20\text{-}30\%$)

Uses J/ψ cross-section results

$\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$



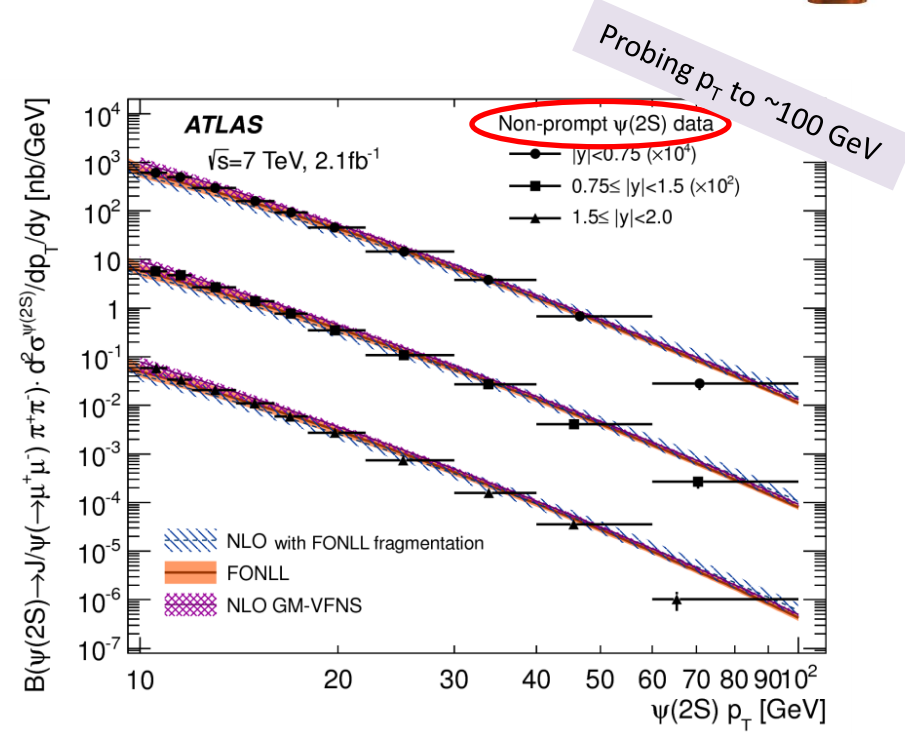
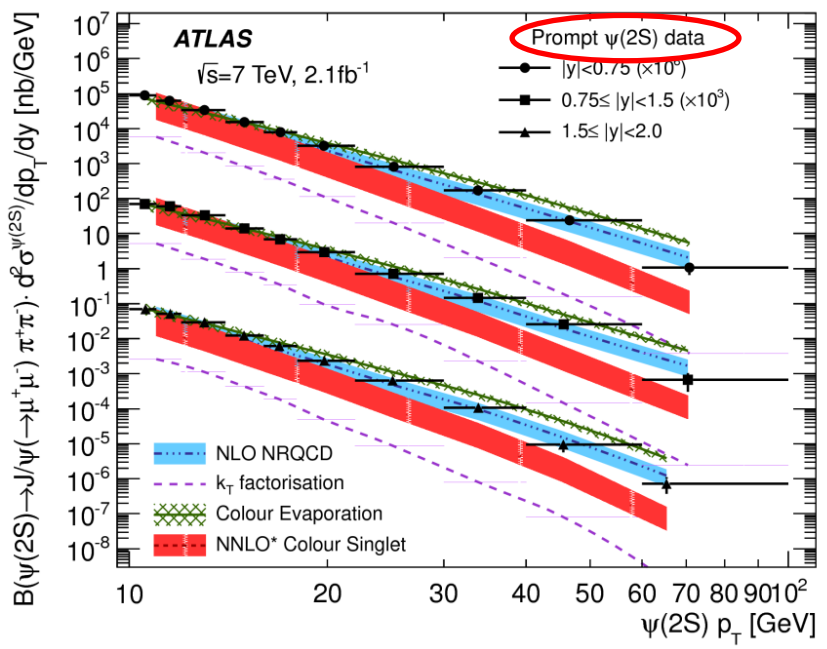
- Prompt $\psi(2S)$ not affected by significant feed-down. Good test of theoretical predictions.
- 4-track vertex fit (with $J/\psi \rightarrow \mu\mu$ mass constraint) gives good mass resolution.



Differential cross sections also available binned in $p_T(J/\psi)$

Good agreement with measurements from CMS and LHCb

$\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$



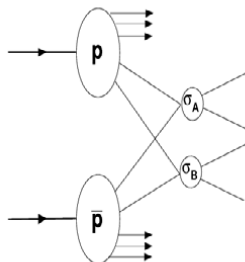
k_T factorisation under estimates $\psi(2s)$ production (correlated to over estimate of χ_c)
 NLO NRQCD provides best description

All predictions give good description of data.

Associated vector boson plus quarkonium production

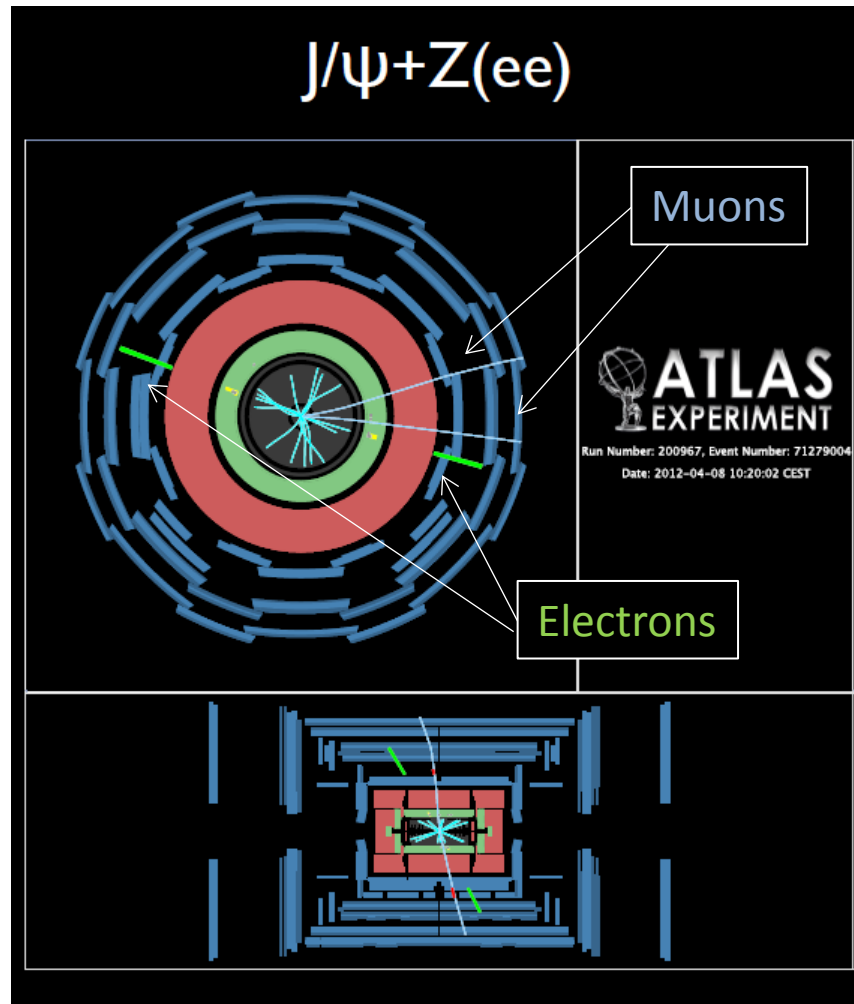
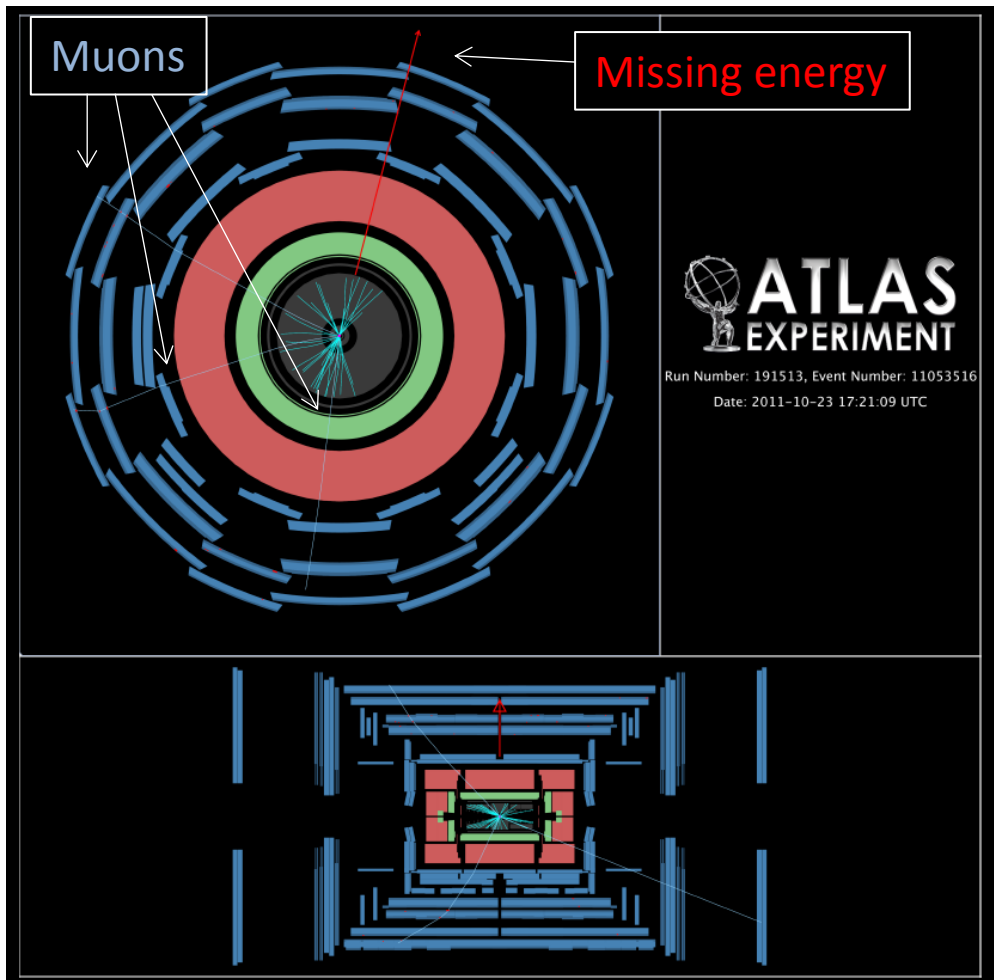


- Huge LHC luminosities provide **quarkonia** samples produced in **association** with additional **objects**: other quarkonia, vector bosons, jets, top.....
- Two production mechanisms:
 - Single parton scattering (**SPS**) : objects from **same** diagrams
 - Double parton scattering (**DPS**) : objects from a **separate hard scatter** in same proton-proton collision



- Event by event these are indistinguishable. Try to find observables to disentangle them (expect differences in e.g. Δy and opening angle)
- Results for:
 - $J/\psi + W(\mu\nu)$ ([JHEP 04\(2014\) 172](#)).
 - $J/\psi + Z(\mu\mu \text{ or } ee)$ (Submitted to EPJC, [arXiv:1412:6428](#))

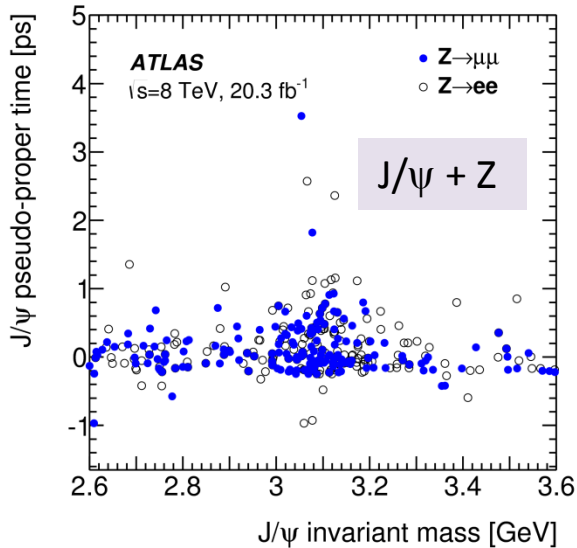
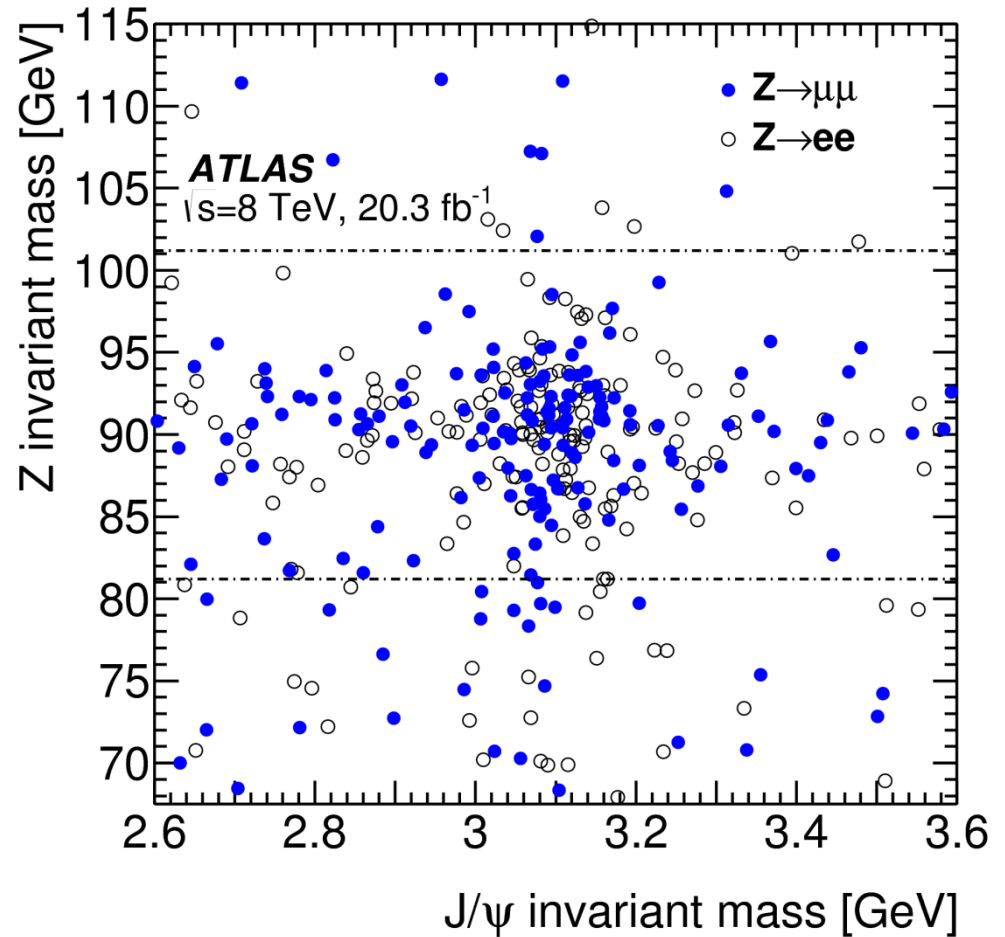
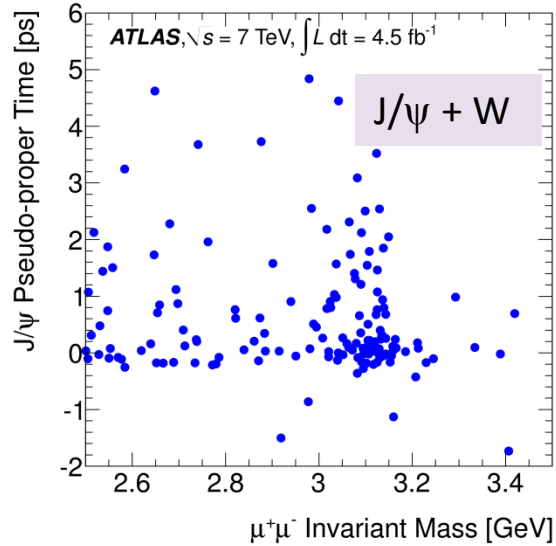
$J/\psi + W (\rightarrow \mu\nu)$



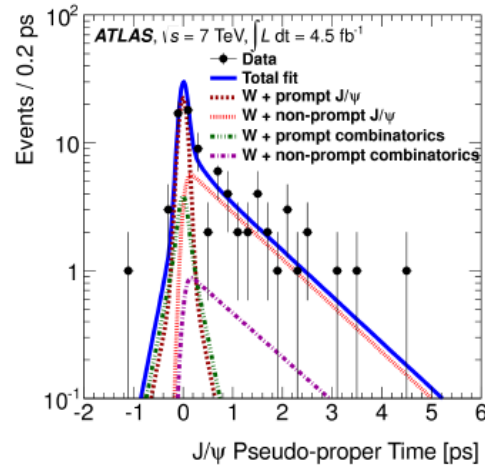
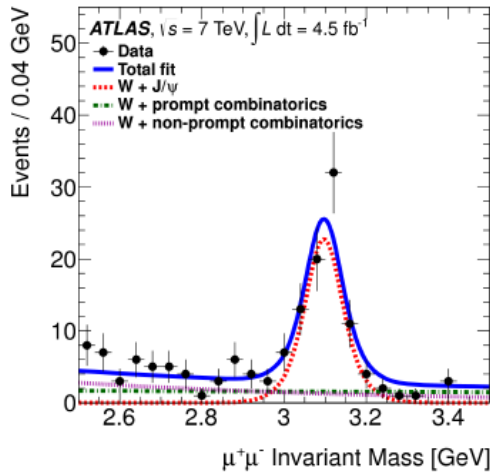
Event Selection:

- High p_T lepton with trigger-match
- J/ψ : leading muon $p_T > 4\text{GeV}$, $p_T(J/\psi) > 8.5\text{ GeV}$, $|\eta(J/\psi)| < 2.1$
- W : $p_T(\mu) > 25\text{GeV}$, $E_t^{\text{miss}} > 20\text{GeV}$, $m_T(W) > 40\text{GeV}$
- Z : $p_T(l/l) > 25$ (15) GeV , $m(Z) = \text{PDG}(m_Z) \pm 10\text{ GeV}$

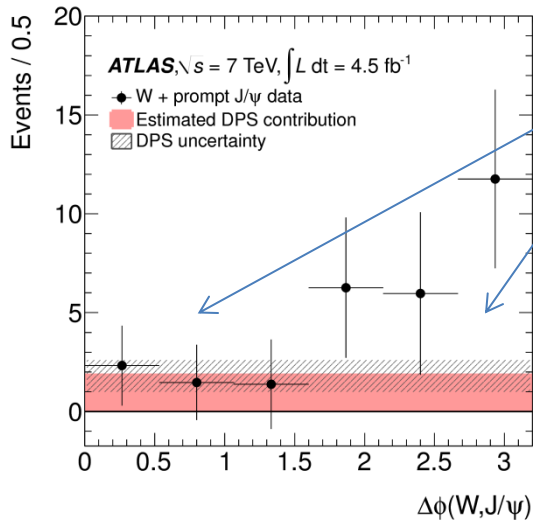
Candidates



J/ψ(prompt) + W

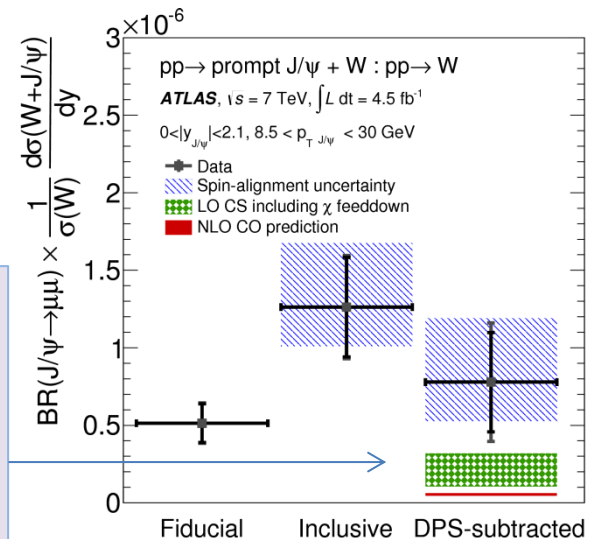


- Extract prompt signal from fit to J/ψ mass and pseudo-proper time.
- Observe 27 events with significance of 5.1σ

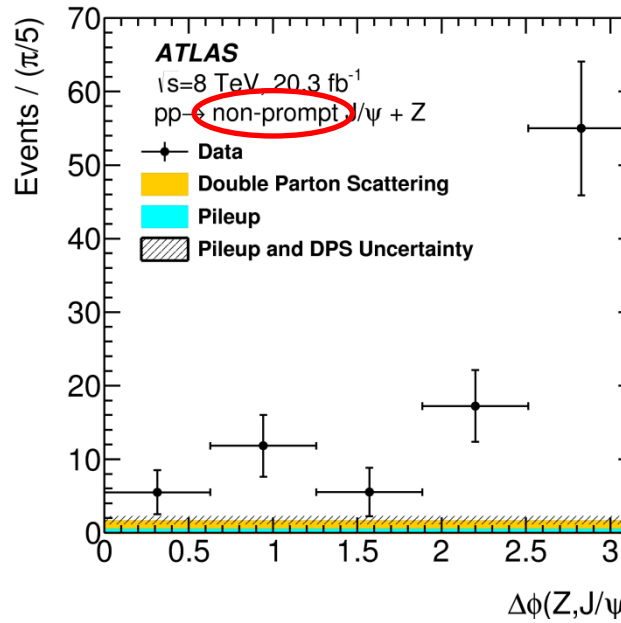
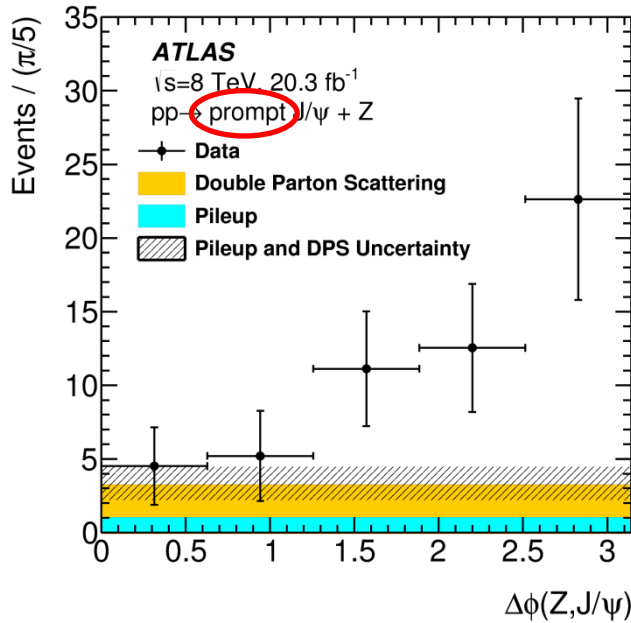


Expect DPS to be flat, SPS to peak at high $\Delta\phi$.

Ratio J/ψ+W to inclusive W cross-sections. Colour Singlet and Colour Octet models both compatible at 2σ

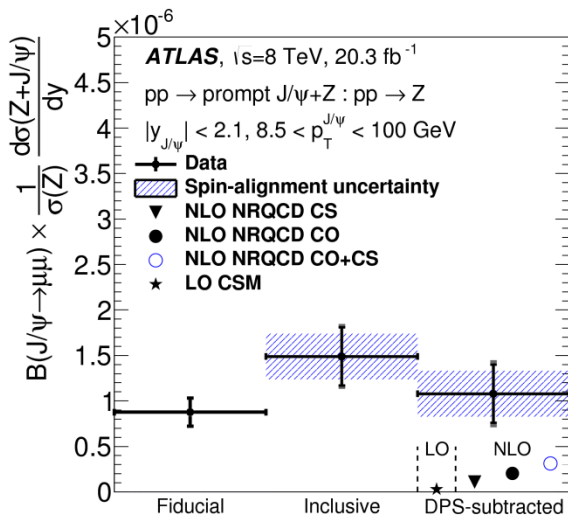


J/ψ + Z

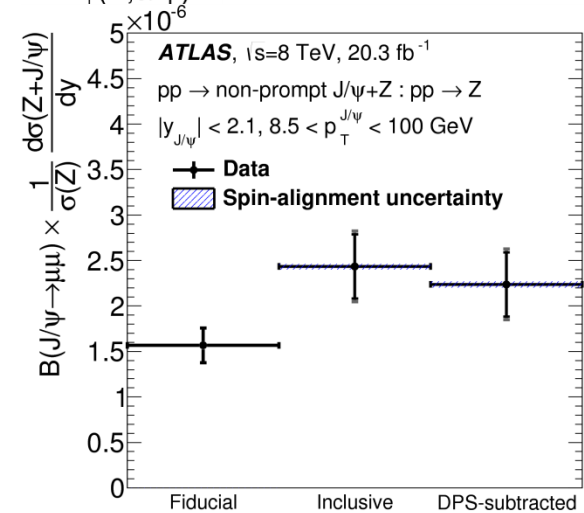


DPS band is determined from data assuming independent hard scatters.

Again observe rise at high $\Delta\phi$



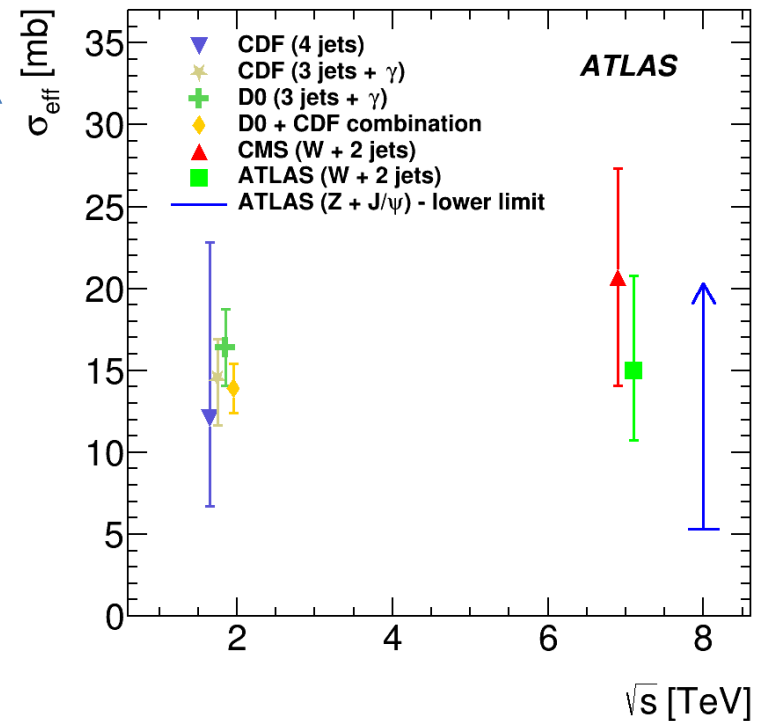
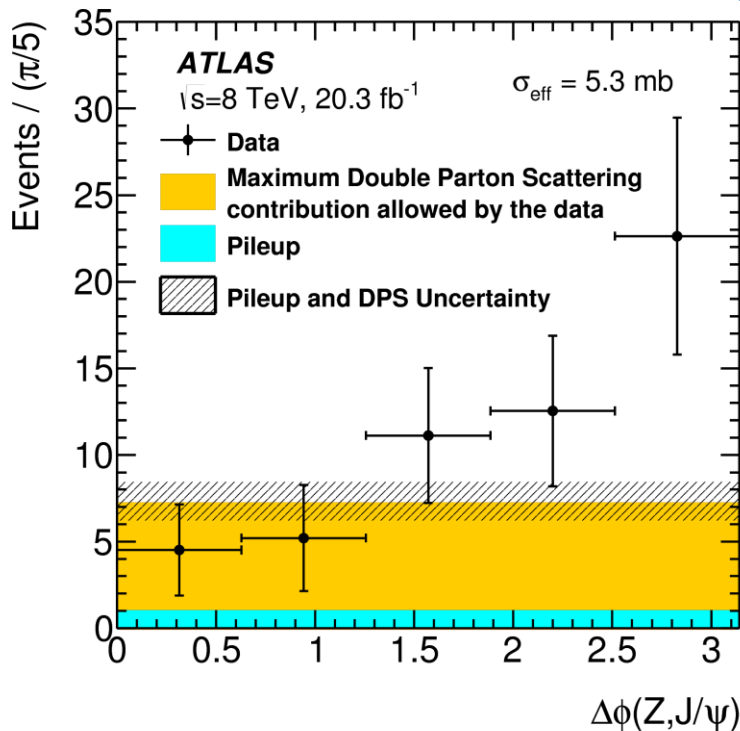
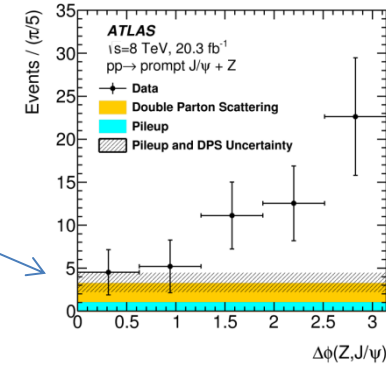
Models underestimate the SPS contribution (but no feed-down component)



J/ψ + Z



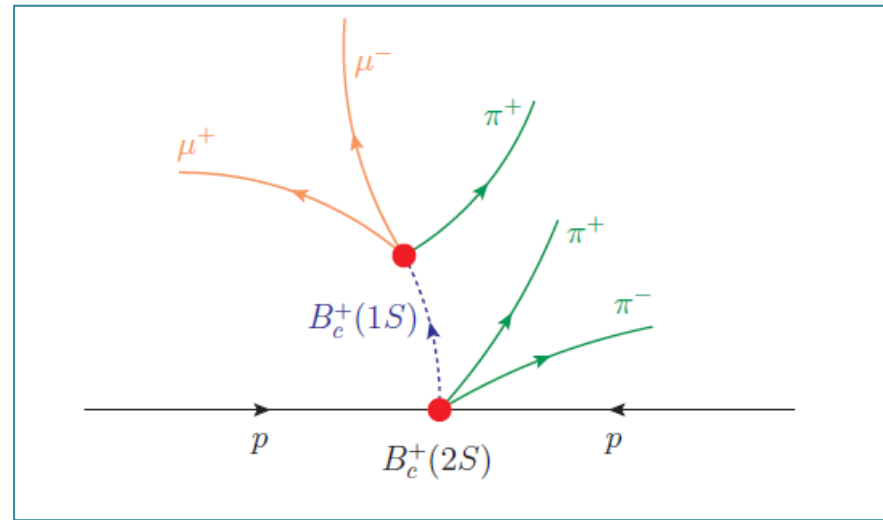
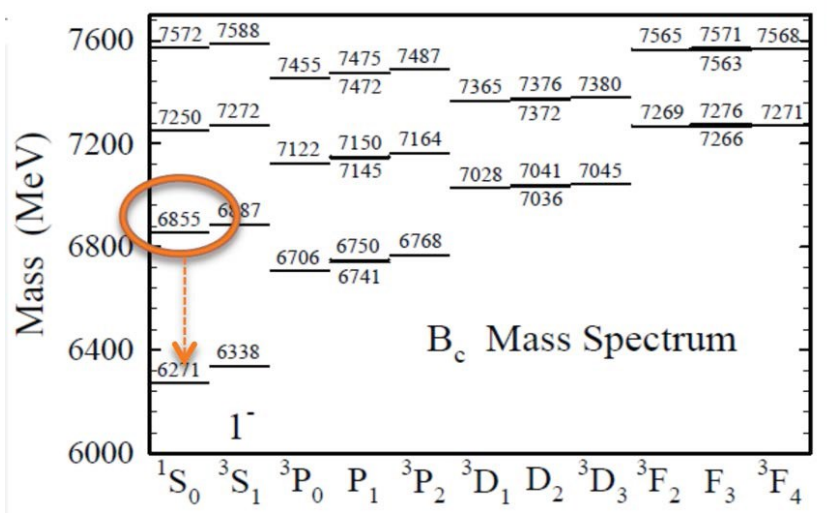
- Assuming first bin here is due to DPS
- Can set upper limit on DPS contribution
- Gives a lower limit on σ_{eff}



Search for $B_c^+(2S)$ excited states



- Spectrum and properties of B_c^+ predicted by theory (NRQCD and lattice calculations)
- No excited states of B_c^+ observed previously.
- Cannot distinguish $2S_0$ and $2S_1$ (miss soft gamma & mass resolution)
- Search for cascade decay of $B_c^+(2S)$ to $B_c^+(1S)$ and two pions where $B_c^+(1S) \rightarrow J/\psi\pi^+$.
- [Phys. Rev. Lett. 113\(2014\) 212004](#)



Event selection



J/ψ selection:

- $p_T()$ > 4,6 GeV
- $\chi^2 / \text{n.d.f. (J/}\psi) < 15$
- mass (J/ψ) within $\pm 3\sigma$ of nominal

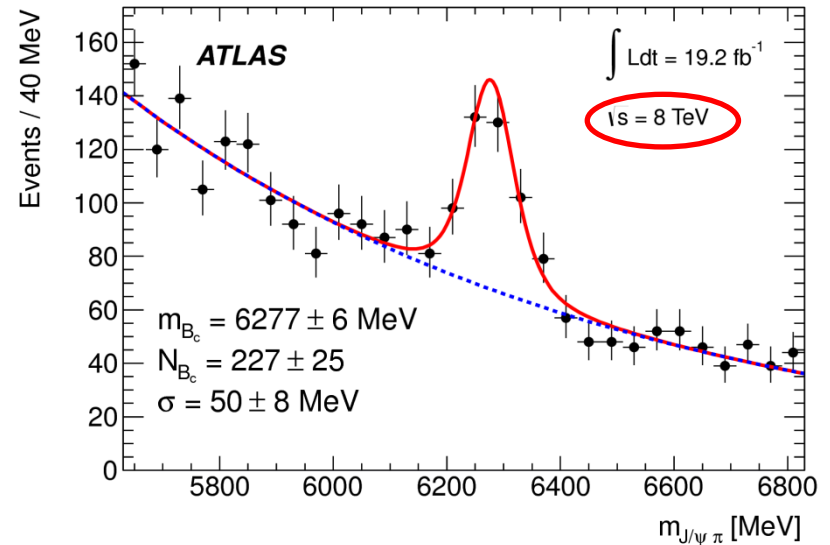
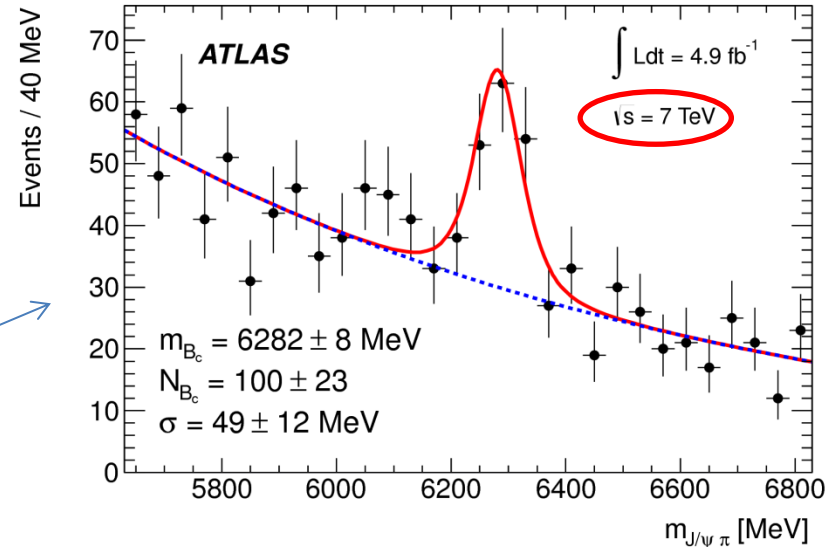
$B_c^+(1S)$ selection:

- $\chi^2 / \text{n.d.f. (} B_c^+) < 2.0 (1.5)^*$
- $p_T(B_c^+) > 15 (18) \text{ GeV}$
- transverse impact parameter sig. of pion > 5 (4.5)

$B_c^+(2S)$ selection:

- $B_c^+(1S)$ candidates with mass within $\pm 3\sigma$ of fitted mass
- $p_T(\pi^+, \pi^-) > 400 \text{ MeV}$
- If several $B_c^+(2S)$ candidates, choose one with best χ^2

* Selection for 7TeV and (8TeV) data



$B_c^+(2S)$ observation

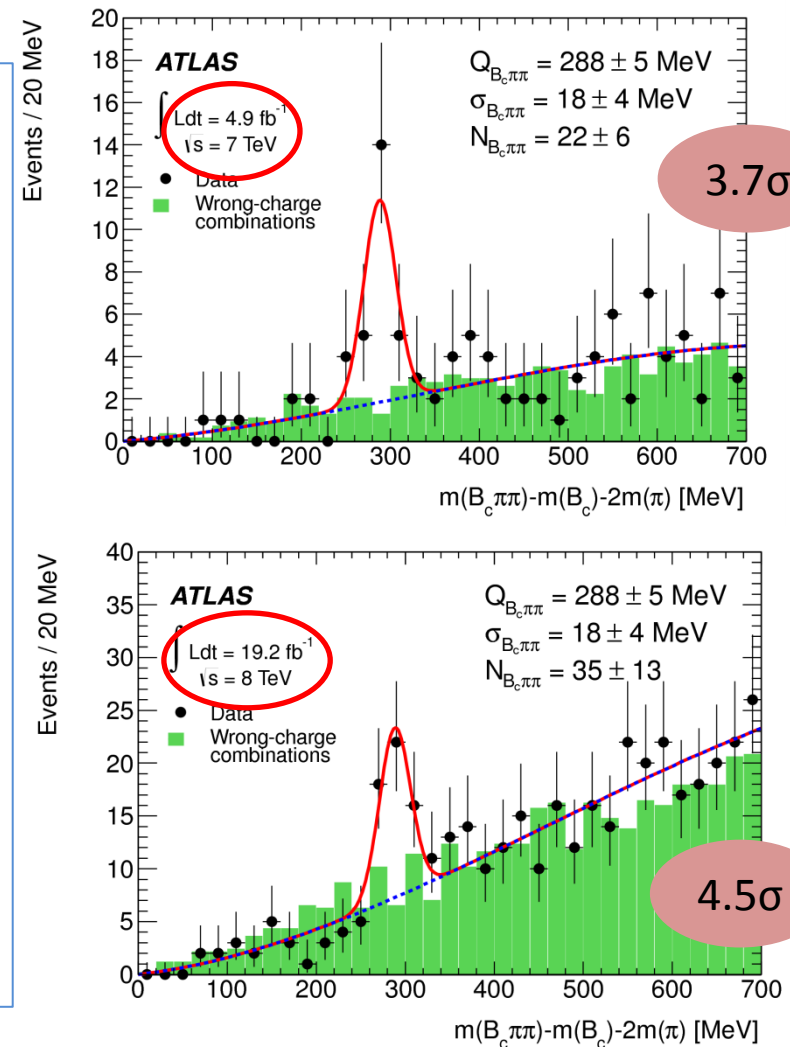


- Extended unbinned fit of Q-value distribution:

$$Q(B_c^+ \pi^+ \pi^-) = m(B_c^+ \pi^+ \pi^-) - m(B_c^+) - 2m(\pi^+)$$

- Signal: Gaussian
- Background: 3rd order polynomial
- Significance calculated using toy studies to account for “look elsewhere effect”
 - Combined significance is **5.2 σ**
- Mass = 6842 ± 4 (stat.) ± 5 (syst) MeV

consistent with predicted mass of $B_c^+(2S)$

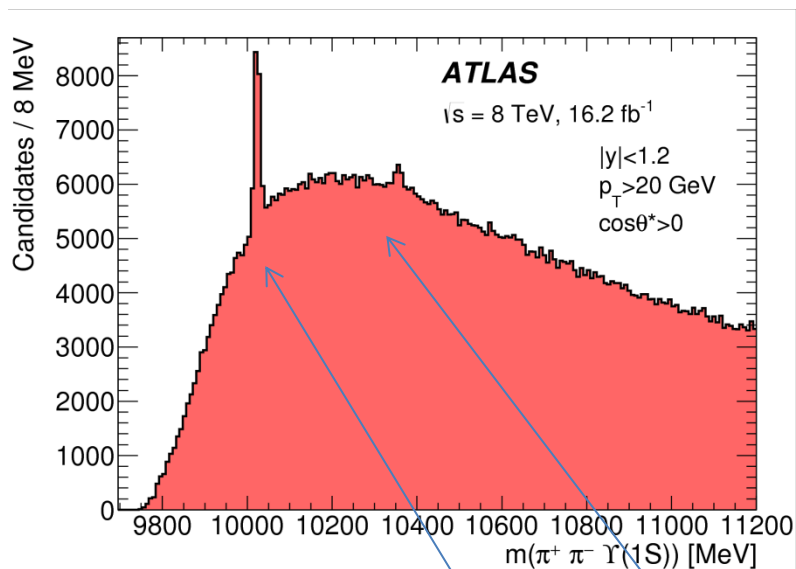


Search for X_b in $\pi^+\pi^-\Upsilon(1S)$

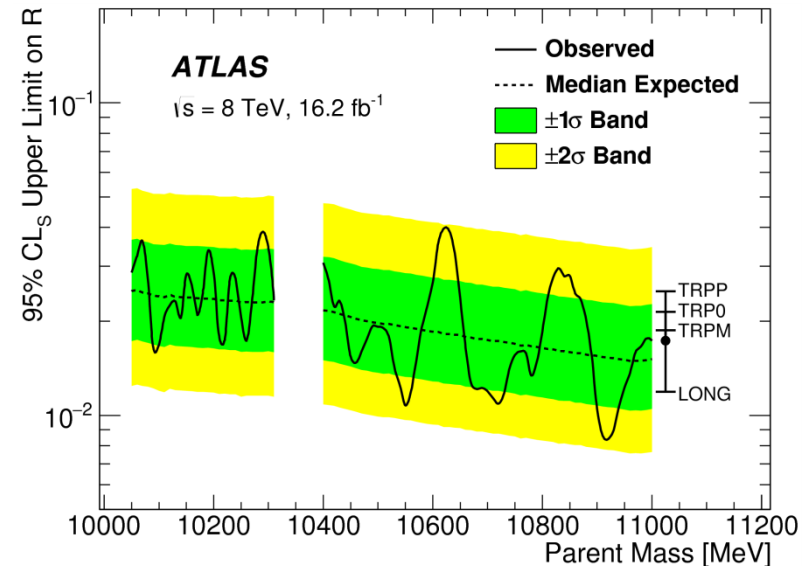


- Heavy-quark symmetry suggests existence of X_b analogous to the $X(3872)$ observed in $\pi^+\pi^-J/\psi$
- Predicted mass ~ 10.5 GeV
- Search in $\pi^+\pi^-\Upsilon(1S)$

[Phys. Lett. B740 \(2015\) 199](#)



Only observed peaks due to $\Upsilon(2S)$ and $\Upsilon(3S)$



- Scan 10-11 GeV in 10MeV steps (use $\Upsilon(2S)$ as reference)
- No signal found
- Limits \sim few %

Summary



ATLAS has collected a large di-muon sample during Run 1

Presented latest new heavy flavour results:

- $\chi_c \rightarrow J/\psi \gamma$
- $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$
- Observation of associated production of vector boson plus J/ψ
- $B_c^+(2S)$ observation
- Search for $X_b \rightarrow \pi^+ \pi^- \Upsilon(1S)$

Other results still in pipeline:

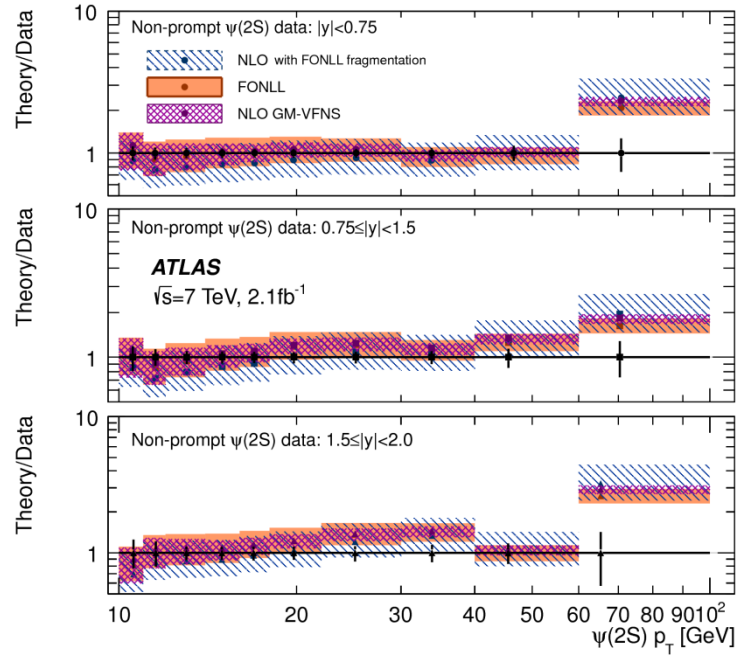
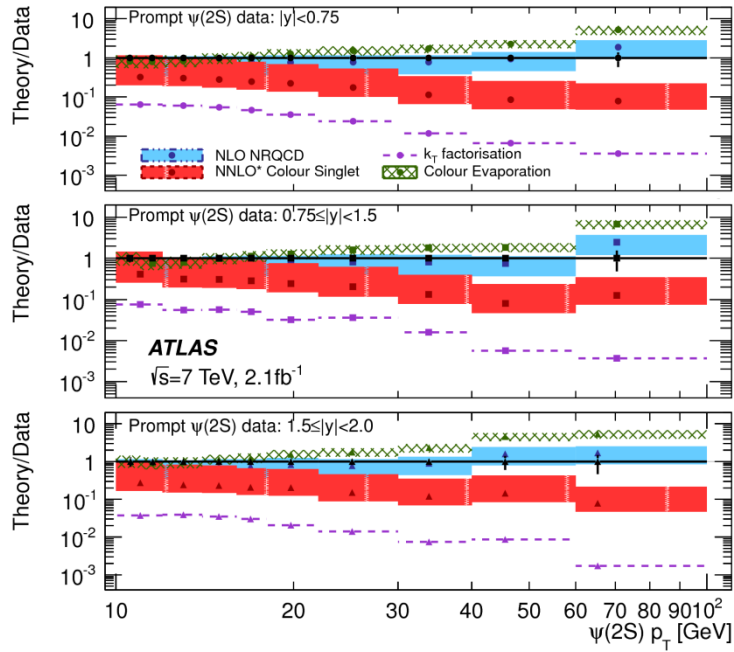
- B_s mixing (see talk by A.Wharton)
- $B \rightarrow \mu\mu$
-

Looking forward to much more data in Run 2!!

Backup



$\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$



J/ψ + Z : differential cross-sections

