Measurements of $\psi(2S)$ and $X(3872) \to J/\psi\,\pi^+\pi^-$ with the ATLAS detector

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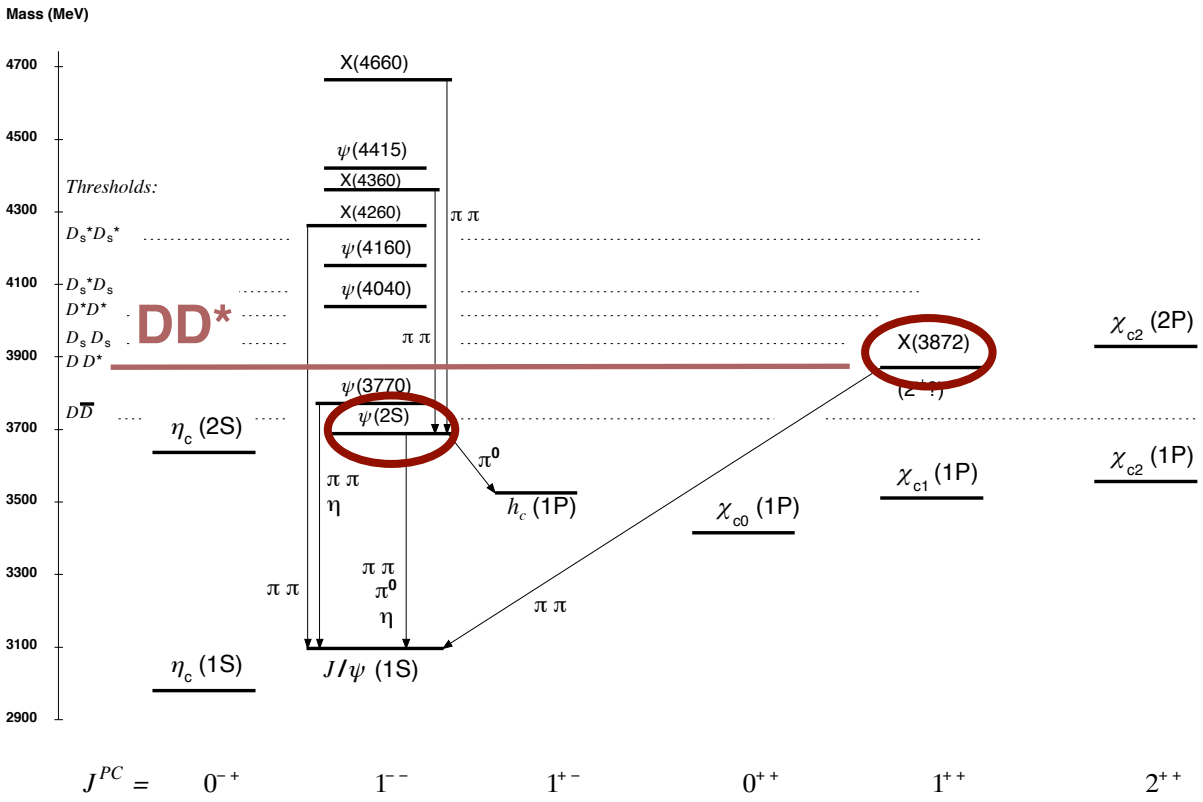
History of X(3872):

- Discovered by the Belle collaboration in 2003
  (Phys. Rev. Lett. 91, 262001 (2003))
- Soon after confirmed by other experiments - including CDF who constrained possible quantum numbers J^{PC}
  (Phys. Rev. Lett. 93, 072001 (2004))
- LHCb made first observation at LHC and confirmed quantum numbers to be 1^{++} (Phys. Rev. D 92, 011102 (2015))
- Peak seen by ATLAS while measuring $\psi(2S)$ at $\sqrt{s} = 7$ TeV, in the $J/\psi\,\pi^+\pi^-$ decay channel (JHEP 09 (2014) 079)
- Analysis of $\sqrt{s} = 8$ TeV ATLAS data presented (JHEP 01 (2017) 117)

What is X(3872)?

Properties:

- M(X(3872)): 3871.69 ± 0.17 MeV
- Close to the $D^0\bar{D}^{*0}$ threshold - initially hypothesised to be a $D^0\bar{D}^{*0}$ molecule with very small binding energy



- CMS $\sigma(X(3872))$ measurement found the predictions of this model to be overestimated compared to observations (JHEP 04(2013) 154)
- Current interpretation is that the state is a mixed $\chi_{c1}(2P) - D^0\bar{D}^{*0}$ state, where the $X(3872)$ is produced predominantly through its $\chi_{c1}(2P)$ component

Searching for $X(3872)(\psi(2S)) \rightarrow J/\psi\,\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$ decays

μ cuts:

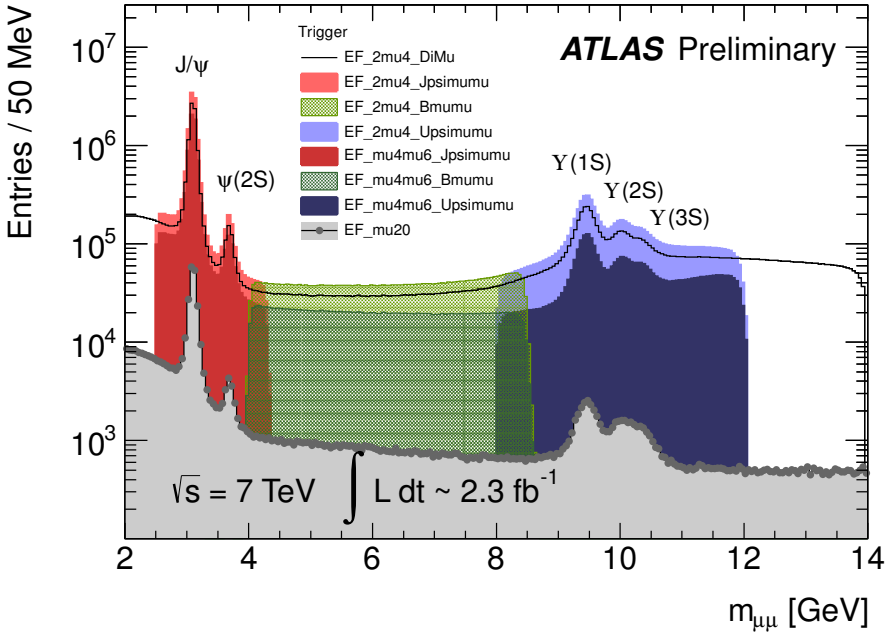
- Opposite sign muons
- Quality cuts, $p_T > 4$ GeV, $|\eta| < 2.3$
- Good trigger object matching ($\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.01$)

J/ψ cuts:

- $\chi^2_{\mu\mu\,vtx} < 200$, $p_T > 8$ GeV & $|y| < 2.3$
- $|\,m(J/\psi) - m(J/\psi)_{PDG}| < 120$ MeV

π cuts:

- Opposite sign, $p_T > 600$ MeV, $|\eta| < 2.4$



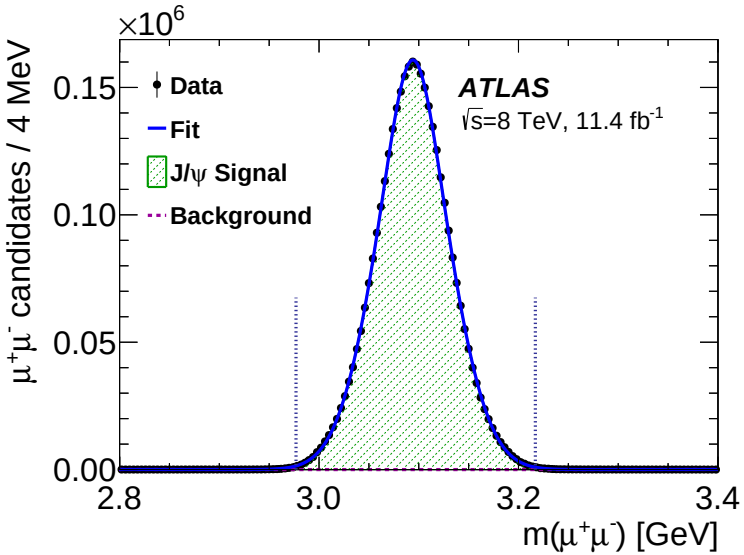
Dedicated di-muon triggers for quarkonium $\mathcal{Q} \rightarrow \mu^+\mu^-$ decays

Di-muon trigger with 4 GeV p_T threshold on each muon
Effective integrated luminosity 11.4 fb^{-1} at 8 TeV

Event selection

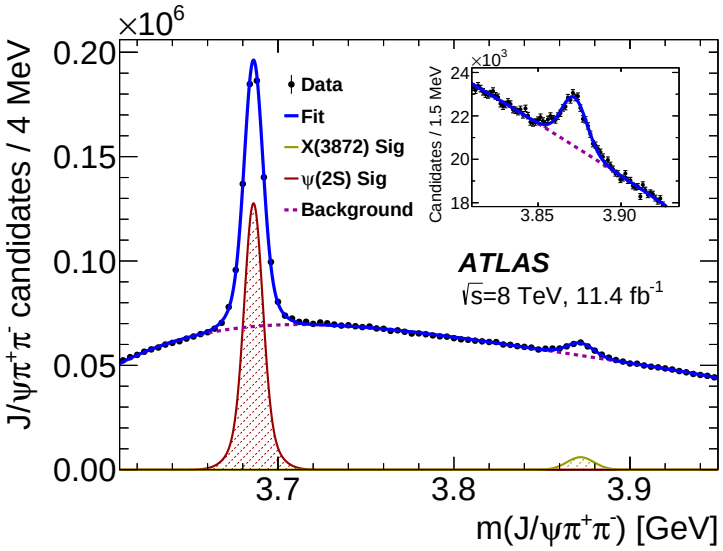
$J/\psi\pi^+\pi^-$ background suppression cuts:

- $P(\chi^2_{J/\psi\pi\pi}) > 4\%$
- Opening angle $\Delta R(J/\psi, \pi^+) < 0.5$ and $\Delta R(J/\psi, \pi^-) < 0.5$
- Q = m($J/\psi\pi^+\pi^-$) - m(J/ψ)$_{PDG}$ - m($\pi^+\pi^-$) $<$ 300 MeV



Constrained vertex fit on each $\mu^+\mu^-\pi^+\pi^-$ candidate:

- Di-muon with (2.8 $<$ m$_{\mu\mu}$ $<$ 3.4) GeV fitted to a common vertex
- Di-muon mass constrained to the J/ψ mass
- Pion mass hypothesis used for the other two tracks



370k $\psi(2S)$; 30k X(3872)

Analysis method - overview

Analysis performed for:

- $|y| < 0.75$ of the $J/\psi\pi^+\pi^-$ system, for optimal tracking resolution
- p_T divided into 5 bins
- Effective pseudo-proper lifetime, τ, separated into 4 bins, where $\tau = \frac{L_{xy} m}{p_T}$ with $L_{xy} = \frac{\vec{L}\cdot\vec{p}_T}{p_T}$

Each $J/\psi\pi^+\pi^-$ candidate in data weighted for acceptance, reconstruction and trigger efficiency

For each p_T and lifetime bin:

- Minimum χ^2 fit in the $J/\psi\pi^+\pi^-$ invariant mass to determine ψ(2S) and X(3872) signal yields

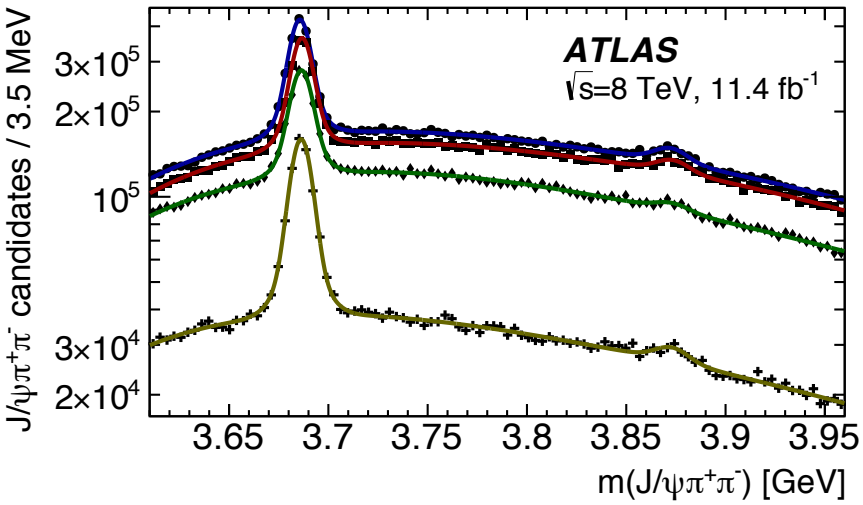
For each p_T bin:

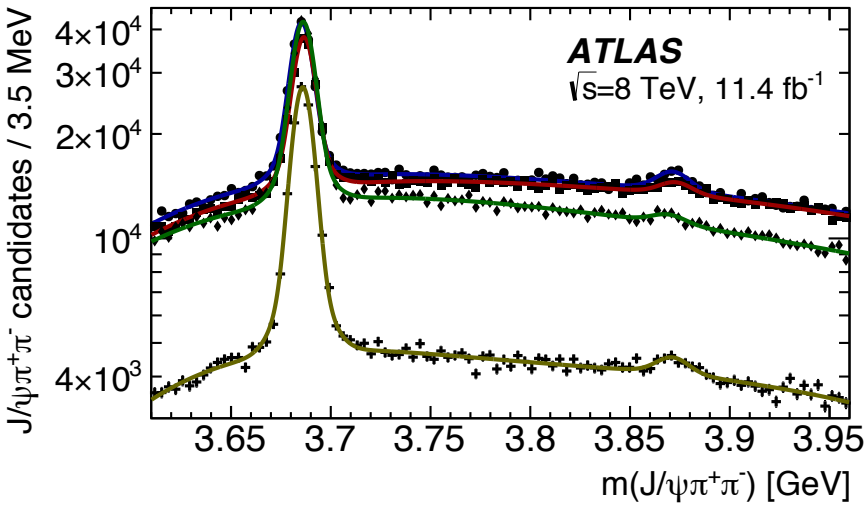
- Yields in individual lifetime windows are subsequently fitted
- Determines lifetime dependence and hence separates the signal into prompt and non-prompt components

The lifetime fits are performed separately for ψ(2S) and X(3872)

Mass fits: double-Gaussian signal peaks on a smooth background

- Fraction of narrow Gaussian shared between $\psi(2S)$ and X(3872)
- Resolution parameters linked by $\sigma_X = \kappa\sigma_\psi$
- Values of fraction and κ determined from global fits





- Corrected yields of $\psi(2S)$ and X(3872) determined in each lifetime window for each p_T bin
- Can be used directly for total production cross section
- Need lifetime analysis to separate prompt and non-prompt

Lifetime fits - definitions

Lifetime fit probability distribution function:

- $F^i(\tau) = (1 - f^i_{NP}) F^i_P(\tau) + f^i_{NP} F^i_{NP}(\tau)$

Non-prompt fraction f^i_{NP}:

- Measured in each p_T bin, separately for i $= \psi$(2S), X(3872)

Prompt signal F^i_P:

- Described by a lifetime resolution function determined from the data

Non-prompt signal F^i_{NP}:

- Usual assumption – a single one-sided exponential convoluted with the resolution function, with a single "effective pseudo-proper lifetime" fitted to the data (single-lifetime fit, 1L)

Single lifetime fit - results

Assumption: non-prompt ψ(2S) and X(3872) are produced from the same admixture of parent b-hadrons:

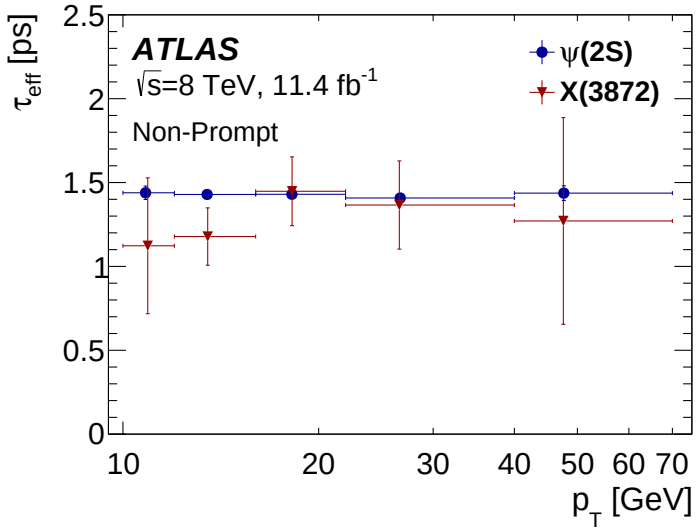
- Implies same lifetimes for ψ(2S) and X(3872) in each p_T bin
- p_T spectra of ψ(2S) and X(3872) linked through kinematics

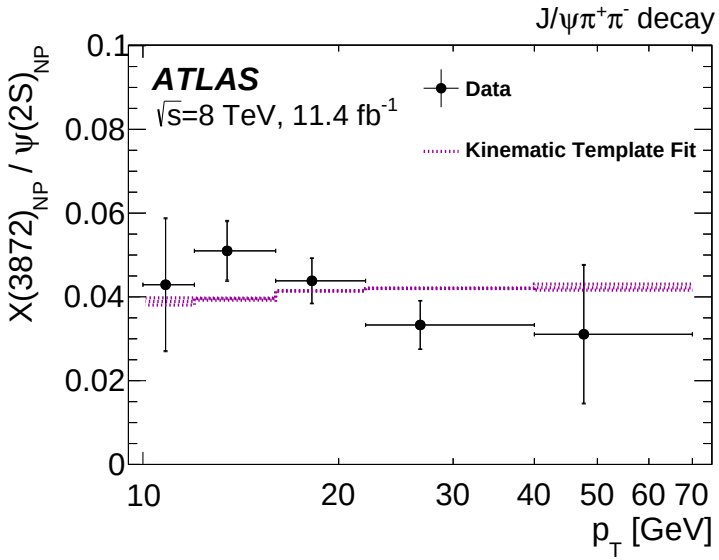
Effective lifetimes:

- ψ(2S) - independent of p_T
- X(3872) - possibly slightly shorter in low p_T bins

Non-prompt X(3872):ψ(2S) ratio

- Fit to kinematic template





$$R_B^{1L} = \frac{Br(B\to X(3872))Br(X(3872)\to J/\psi\pi^+\pi^-)}{Br(B\to\psi(2S))Br(\psi(2S)\to J/\psi\pi^+\pi^-)} = (3.95 \pm 0.32(stat) \pm 0.08(sys))\%$$

Two-lifetime fits

Alternative lifetime model: two-lifetime fit

$$F^i_{NP}(\tau) = (1 - f^i_{SL})F_{LL}(\tau) + f^i_{SL}F_{SL}(\tau)$$

- Non-prompt component presented as a sum of short-lived (SL) and long-lived (LL)
- Two single-sided exponentials smeared with the same resolution function
- f_{SL} is a fraction of SL within non-prompt - supposedly from B_c decays
- Statistical power of data does not allow determination of two free lifetimes
- The two lifetimes fixed, the fraction of SL contribution left free in the fit

Fixing the two lifetimes:

- τ depends on parent's lifetime and decay kinematics — $\tau(\Lambda_b) = 1.451 \pm 0.013$ ps
- τ_{LL} determined from fits to $\psi(2S)$, allowing for some SL contribution — $\boldsymbol{\tau_{LL} = 1.45 \pm 0.05}$ **ps**
- τ_{SL} obtained from simulation varying B_c decay mode — $\tau(B_c) = 0.507 \pm 0.009$ ps
- Both varied within shown limits during systematic studies — $\boldsymbol{\tau_{SL} = 0.40 \pm 0.05}$ **ps**

Two-lifetime fit results quoted from now on, unless stated otherwise

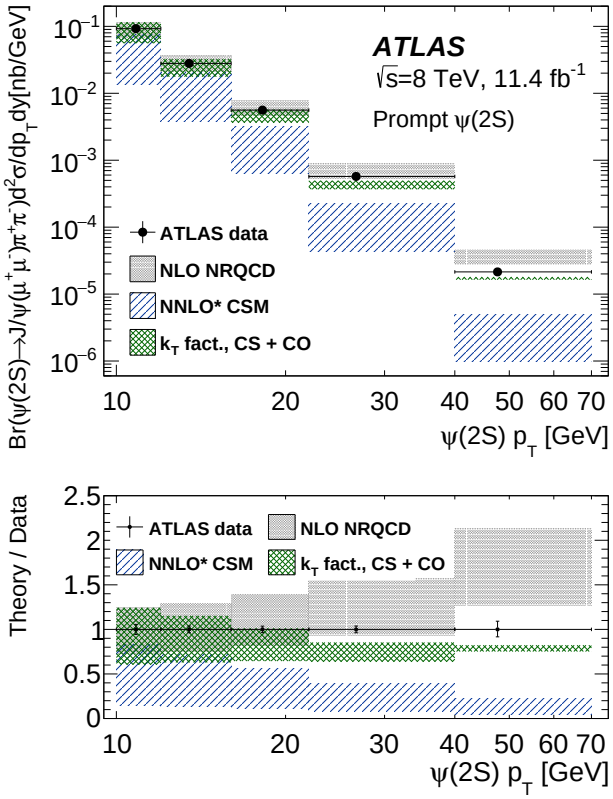
$\psi(2S)$ cross sections

Prompt:

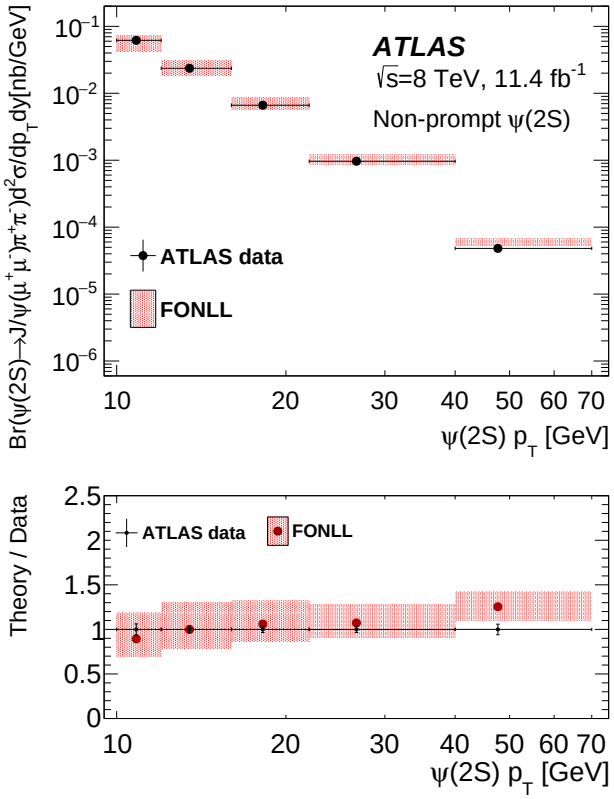
- NLO NRQCD with LDMEs fitted to Tevatron data models the data reasonably
- CSM NNLO* close at low p_T, deviates at high p_T

Non-prompt:

- FONLL describes data well



Prompt $\sigma \times Br$ vs. Pt

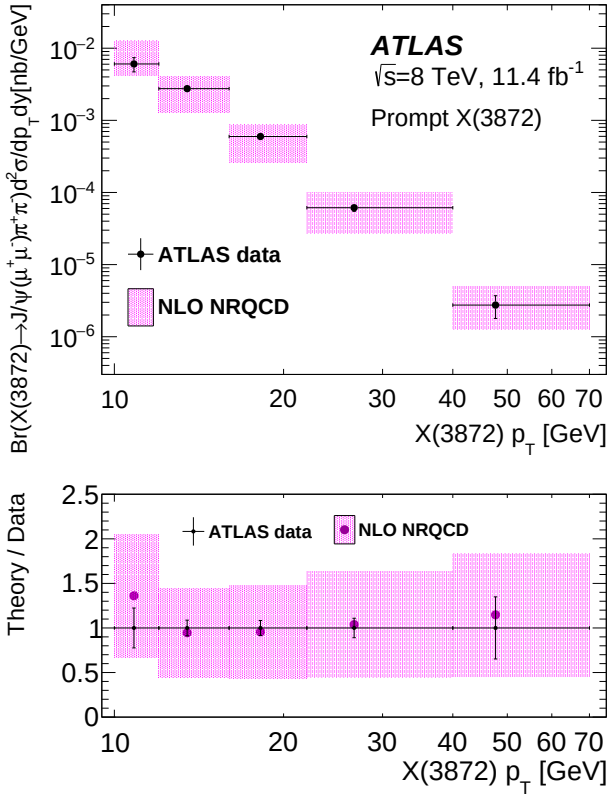


Non-prompt $\sigma \times Br$ vs. Pt

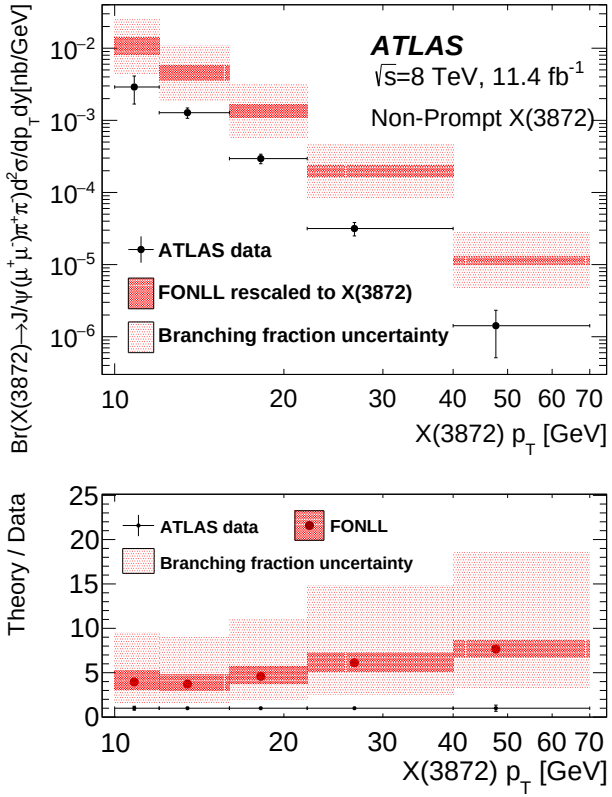
X(3872) cross sections

Prompt: described well by NLO NRQCD

- Assumes X(3872) is a mixture of $\chi_{c1}(2P) - D^0\bar{D}^{*0}$
- $\chi_{c1}(2P)$ coupling assumed responsible for production
- Parameters fitted to CMS data
- **CMS and ATLAS consistent**



Prompt $\sigma \times Br$ vs. Pt



Non-prompt $\sigma \times Br$ vs. Pt

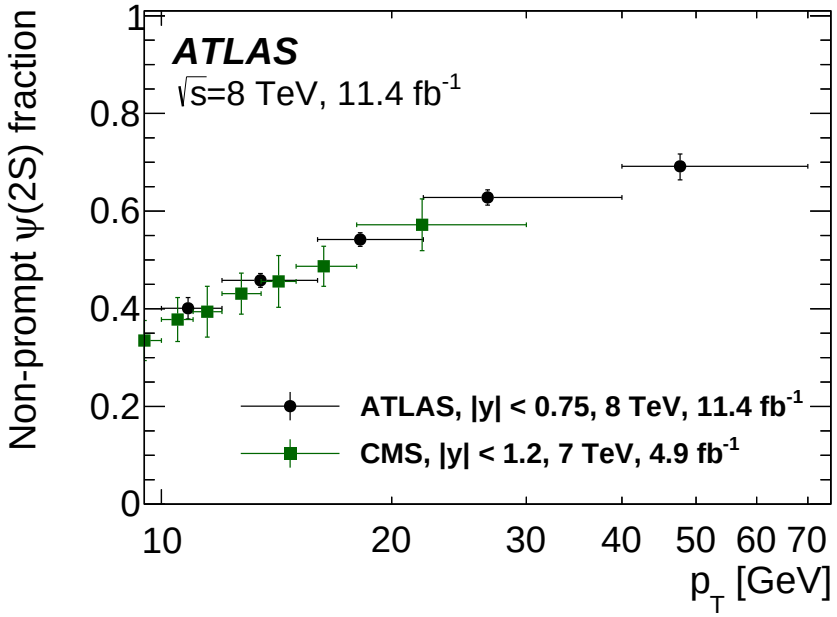
Non-prompt:

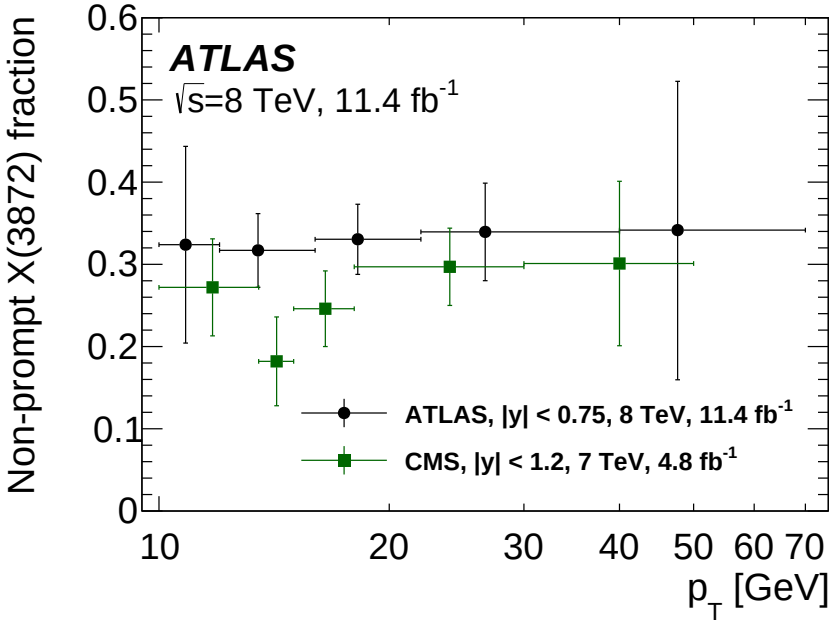
- Recalculate FONLL from $\psi(2S)$ - overshoots the data, increasing with p_T
- BR not measured - used estimate from Artoisenet, Braaten based on Tevatron data (Phys. Rev. D81 (2010) 114018)
- $R_B = 18 \pm 8\%$

Non-prompt fraction

ψ(2S): non-prompt fraction

- Grows with p_T
- Little dependence on energy
- Agrees well with CMS at 7 TeV



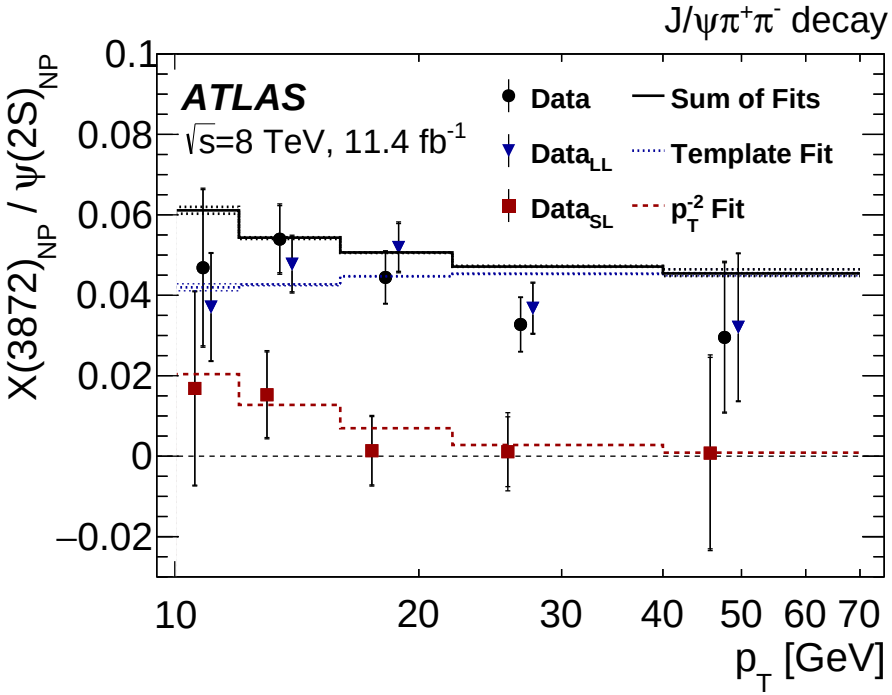


X(3872): non-prompt fraction

- No visible p_T dependence
- Consistent with CMS result within errors

Ratio of non-prompt X(3872):ψ(2S)

- Long-lived part fitted to kinematic template
- Short-lived part: non-fragmentation contributions dominate at low p_T (Berezhnoy, arXiv:1309.1979) - fit with $A.p_T^{-2}$



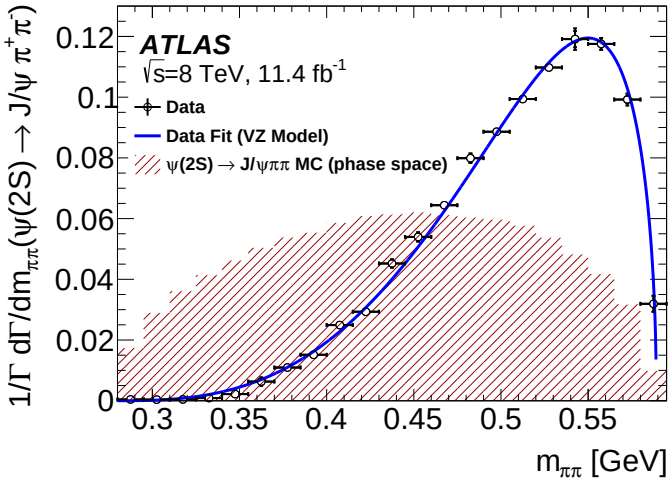
- $R_B^{2L} = (3.57 \pm 0.33(stat) \pm 0.11(sys))\%$
- Integrate the fits to determine the fraction of non-prompt X(3872) that is short-lived for $p_T > 10$ GeV

$$\frac{\sigma(pp \to B_c) Br(B_c \to X(3872))}{\sigma(pp \to \text{non-prompt } X(3872))} = (25 \pm 13(stat) \pm 2(sys) \pm 5(spin))\%$$

Measured invariant mass distributions of the di-pion system in the decays of ψ(2S) and X(3872) into $J/\psi\pi^+\pi^-$

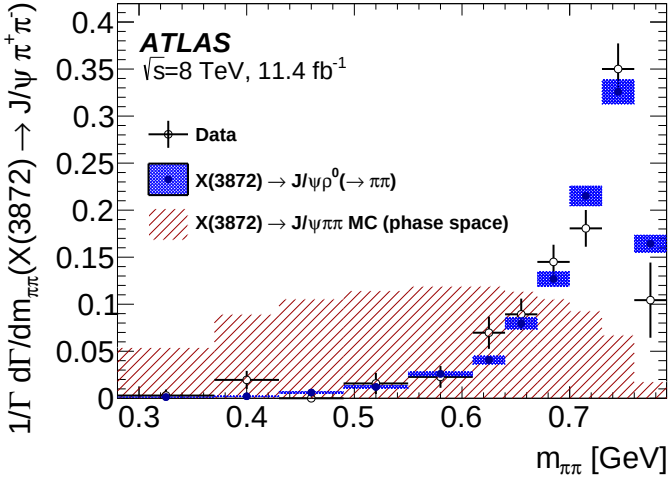
In $\psi(2S) \to J/\psi\pi^+\pi^-$ decays:

- Di-pion mass distribution peaks at high masses
- Fit to Voloshin-Zakharov function
  - $\frac{1}{\Gamma}\frac{d\Gamma}{dm_{\pi\pi}} \propto (m_{\pi\pi}^2 - \lambda m_\pi^2)^2 \times$ PS
- Found $\lambda = 4.16 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$
- In agreement with previous measurements



In X(3872) $\to J/\psi\pi^+\pi^-$ decays:

- Di-pion mass distribution has an even sharper peak at high masses
- In agreement with simulation where the dipion system is produced via ρ^0 meson decay
- Also in agreement with previous observations

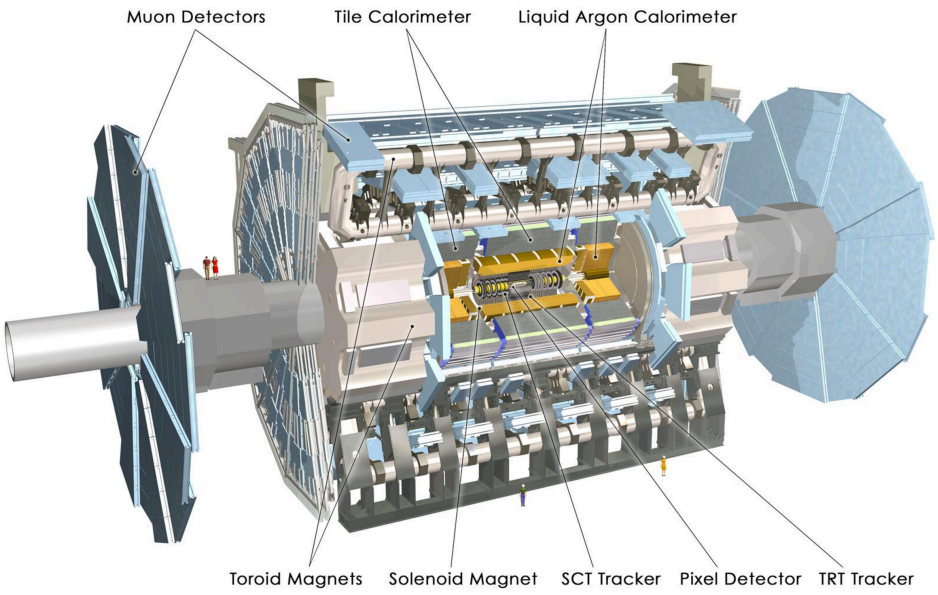


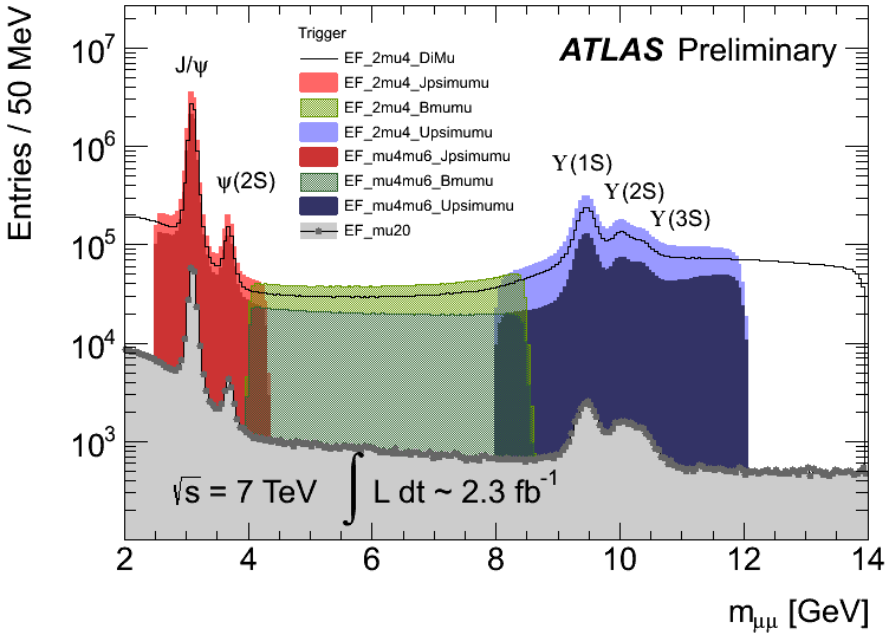
Summary

- Differential cross sections are measured for the prompt and non-prompt production of the X(3872) and ψ(2S) charmonium states in the decay mode $J/\psi\,\pi^+\pi^-$
- Two models of lifetime dependence of the non-prompt production are considered: a single and two lifetime component model
- Two-lifetime fit obtains:
  - A ratio of X(3872) and ψ(2S) branching fractions: $\boldsymbol{R_B^{2L} = (3.57 \pm 0.33(stat) \pm 0.11(sys))\%}$
  - The fraction of short-lived non-prompt component in X(3872) production: $\boldsymbol{\frac{\sigma(pp\to B_c)Br(B_c\to X(3872))}{\sigma(pp\to \text{non-prompt } X(3872))} = (25 \pm 13(stat) \pm 2(sys) \pm 5(spin))\%}$

Backup

ATLAS Detector





General purpose detector

Dedicated di-muon triggers for quarkonium

$\mathcal{Q} \to \mu^+\mu^-$ **decays**

- **Muon Spectrometer (MS):** Triggering $|\eta| < 2.4$ and Precision Tracking $|\eta| < 2.7$
- **Inner Detector (ID):** Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT) $|\eta| < 2.5$
- **LAr EM Calorimeter:** Highly granular + longitudinally segmented (3-4 layers)
- **Resolution in $m_{\mu^+\mu^-}$:** Around 50 MeV at J/ψ and 150 MeV at $\Upsilon(nS)$

Systematics

Differential cross sections

Source of uncertainty	$\psi(2S)$[%] Min	Med	Max	$X(3872)$[%] Min	Med	Max
Statistical	0.9	1.4	5.4	7.3	9.9	63
Trigger eff.	1.0	1.3	2.5	1.1	1.3	2.6
Muon tracking	2.0	2.0	2.0	2.0	2.0	2.0
Muon reconstruction eff.	0.2	0.2	0.3	0.2	0.2	0.4
Pion reconstruction eff.	2.5	2.5	2.5	2.5	2.5	2.5
Bkgd suppression req.	0.8	0.8	3.0	2.0	3.0	6.0
Mass fit model variation	0.6	0.8	1.2	0.9	1.6	2.6
Short-lifetime variation	0.1	0.2	0.3	0.2	0.7	1.7
Long-lifetime variation	0.6	1.0	1.2	0.3	0.6	0.9
Lifetime resolution model	0.4	1.5	4.0	0.6	2.6	3.4
Total systematic	3.5	3.6	6.4	4.1	4.9	7.5
(2L-fit − 1L-fit) / 2L-fit (prompt)	−0.1	−0.4	−0.6	−0.3	−0.5	−3.4
(2L-fit − 1L-fit) / 2L-fit (non-prompt)	+0.1	+0.4	+0.7	+0.1	+1.4	+9.8

Fractions

Source of uncertainty	Absolute uncertainty [%] $f_{\rm NP}^{\psi}$ Min	Med	Max	$f_{\rm NP}^{X}$ Min	Med	Max	$f_{\rm SL}^{X}$ Min	Med	Max
Statistical	0.4	0.5	1.4	4.2	5.8	17.8	16.4	25.8	63
Trigger eff.	0.1	0.1	0.3	0.1	0.1	0.4	0.0	0.1	0.1
Muon tracking eff.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Muon reconstruction eff.	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1
Pion reconstruction eff.	0.4	0.5	0.7	0.3	0.3	0.4	0.0	0.3	0.4
Bkgd suppression req.	0.8	1.1	1.4	0.6	0.7	0.7	0.1	0.1	0.7
Mass fit model variation	0.1	0.1	0.2	0.2	0.6	1.8	1.0	1.3	2.4
Lifetime resolution variation	0.2	0.7	1.7	0.4	1.0	2.9	1.8	3.6	12.1
Short-lifetime variation	0.0	0.1	0.1	0.1	0.4	0.8	0.3	0.7	2.8
Long-lifetime variation	0.3	0.4	0.4	0.2	0.2	0.3	3.3	4.0	4.4
Total systematic	1.3	1.5	2.4	1.0	1.4	3.6	4.1	4.9	13.5
(2L-fit − 1L-fit) / 2L-fit	+0.4	+0.6	+0.9	+0.9	+3.1	+9.1	–	–	–

- Typically, for X(3872) errors are statistically dominated
- For ψ(2S) statistical and systematic errors are similar in size
- Last row shows relative differences between single- and double-lifetime fits, mostly quite small

Acceptance and efficiency corrections

- Corrections for acceptance, trigger efficiency, muon and pion reconstruction efficiencies are applied on a per-event basis.
- Per-event weight is factorised: $w = (\mathcal{A} \cdot \epsilon_{trig} \cdot \epsilon_{reco}^{\pi\pi} \cdot \epsilon_{reco}^{\mu\mu})^{-1}$
- $\mathcal{A}$ Acceptance: probability that the daughter muons and pions fall within the fiducial region: $p_T(\mu) > 4$ GeV, $\eta(\mu) < 2.3$, $p_T(\pi) > 0.6$ GeV, $\eta(\pi) < 2.4$
- The acceptance maps were calculated using high statistics generator-level simulations, with small detector-level corrections applied later
- ϵ_{trig} Trigger efficiency: obtained using data-driven tag-and-probe method (Eur. Phys. J. C 76 (2016) 283)
- $\epsilon_{reco}^{\mu\mu}$ Muon reconstruction efficiency: obtained using data-driven tag-and-probe method.
- $\epsilon_{reco}^{\pi\pi}$ Pion reconstruction efficiency: map built using Monte Carlo simulations (JHEP 1409 (2014) 079)

Di-pion mass distributions

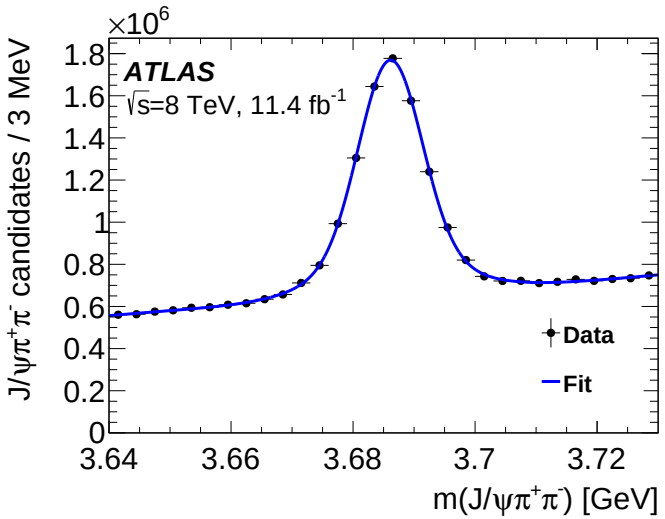
Measured invariant mass distributions of the di-pion system in the decays of ψ(2S) and X(3872) into $J/\psi\pi^+\pi^-$

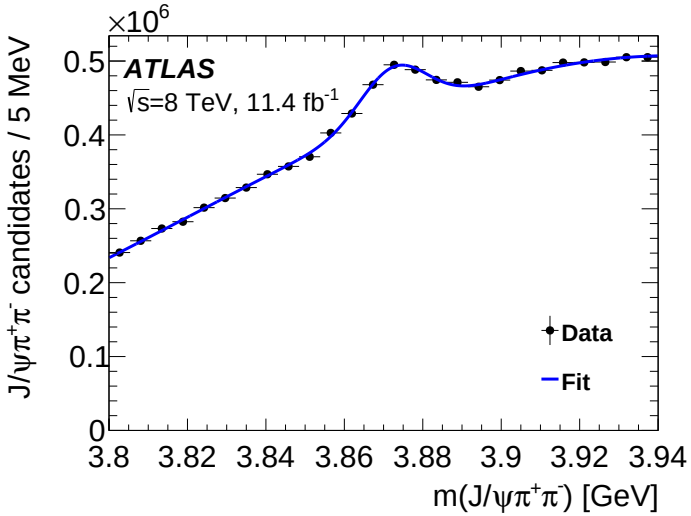
- Removed potentially biasing selection cuts
- Added cuts on lifetime significance and $p_T > 12$ GeV to reduce combinatorial background

Fitted $J/\psi\pi^+\pi^-$ invariant mass distributions, corrected for acceptance and efficiency, with a double-Gaussian signal and a smooth background

$$f(m) = G_{12}(m) + N_{bkg}\left(\frac{m-p_0}{m_0-p_0}\right)^{p1} e^{-p_2(m-p_0)-p_3(m-p_0)^2}$$

Repeated fits for narrow bins of di-pion mass Kinematically allowed di-pion mass range divided into 21 bins for ψ(2S), 11 bins for X(3872)





Full di-pion mass range