X(3872) and the search for its bottomonium counterpart at the LHC

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Outline

- Brief X(3872) history and theoretical status overview.

- Search for X(3872) bottomonium counterpart, X_b at CMS.

- Search for the X_b by ATLAS and study of the $\psi(2S)$ and X(3872) production.

- Determination of X(3872) quantum numbers at LHCb.

X(3872) history and theoretical status overview

- X(3872) was first discovered by Belle in 2003 in $B^{+,0} \to$ X(3872)$K^{+,0}$,

  X(3872) $\to \pi^+\pi^-$J/ψ, J/$\psi \to \ell^+\ell^-$ and soon confirmed by many experiments.

- The X(3872) state is narrow, has a mass very close to the $D^0\overline{D}^{*0}$ threshold and decays to ρ^0J/ψ and ωJ/ψ final states with comparable branching fractions, thus violating isospin symmetry $\to$ not a simple $c\bar{c}$ state.

- The structure of the state remains unclear, there are lots of theoretical developments in the area: tetraquark, molecular, and mixed models.

- Searches for the bottomonium counterpart are now very active.

- Previous and recent X(3872) analyses by CMS and LHCb:
  - **Eur. Phys. J. C (2012) 72: 1972**, LHCb, observation of X(3872) production.
  - **JHEP 04 (2013) 154**, CMS, measurement of the X(3872) production cross section.
  - **Nucl. Phys. B 886 (2014) 665-680**, LHCb, evidence for the decay X(3872)$\to\psi$(2S)γ.
  - **arXiv:1607.06446** (2016), LHCb, observation of η_c(2S)$\to$p$\bar{\text{p}}$ and search for X(3872)$\to$p$\bar{\text{p}}$ decays.

Search for the X_b at CMS
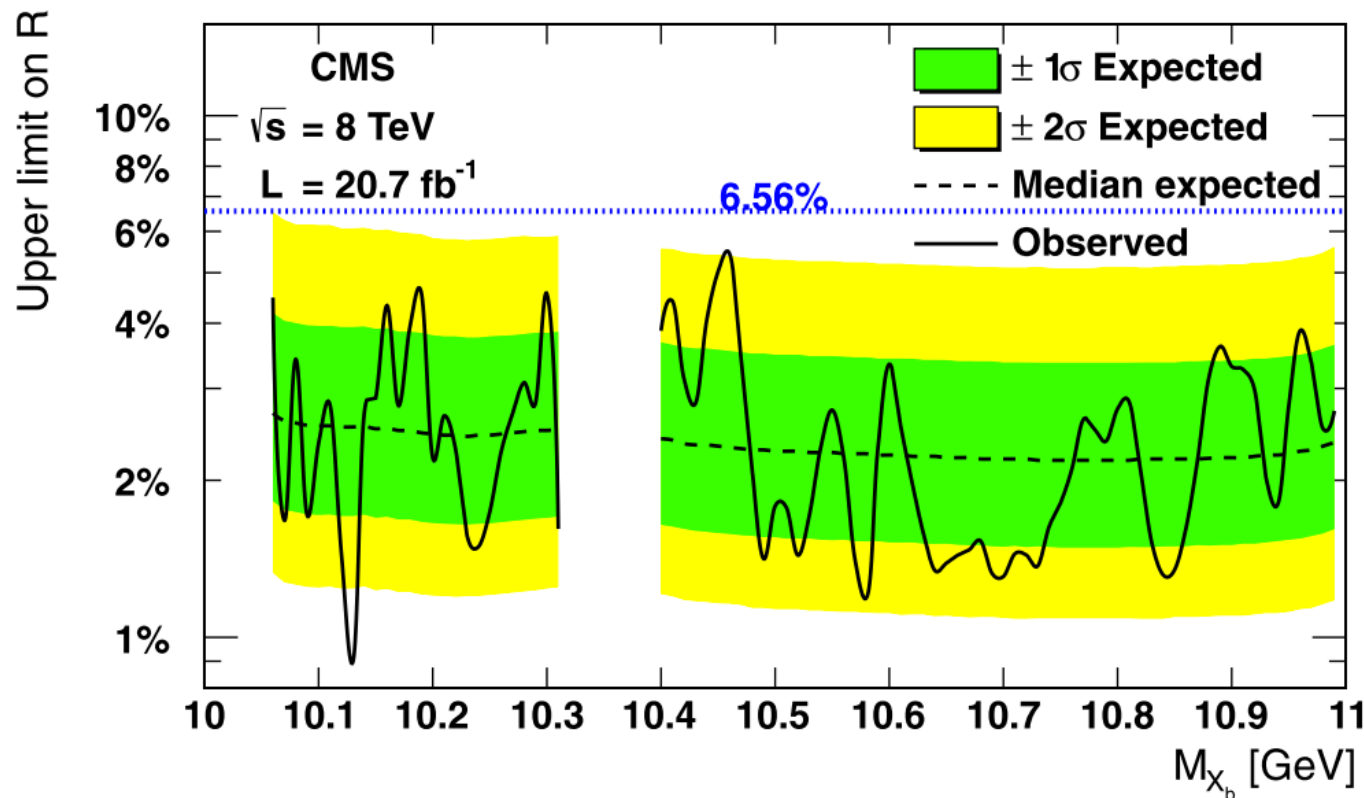
- **Phys. Lett. B 727 (2013), pp. 57–76**

- 20.7 fb^{-1} of 8 TeV CMS data.

- No evidence for X_b is observed.

$$R = \frac{\sigma(pp \to X_b)\, B(X_b \to \pi^+\pi^-\Upsilon(1S))}{\sigma(pp \to \Upsilon(2S))\, B(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))}$$

- Upper limits are set at the 95% confidence level on the ratio of the inclusive production cross sections times the branching fractions to $\Upsilon(1S)\pi^+\pi^-$ of the X_b and the $\Upsilon(2S)$. The upper limits on the ratio are in the range 0.9–5.4% for X_b masses between 10 and 11 GeV.

Search for the X_b and other hidden-beauty states at ATLAS (1)

- **Physics Letters B 740 (2015), pp. 199–217**

- 16.2 fb^{-1} of 8 TeV ATLAS data.

- Search in the decay channel $X_b \rightarrow \pi^+ \pi^- \Upsilon(1S)(\rightarrow \mu^+ \mu^-)$.

- Analysis is performed in eight bins of rapidity, transverse momentum, and the angle (in the rest frame of the parent state) between the dipion system and the laboratory-frame momentum of the parent.
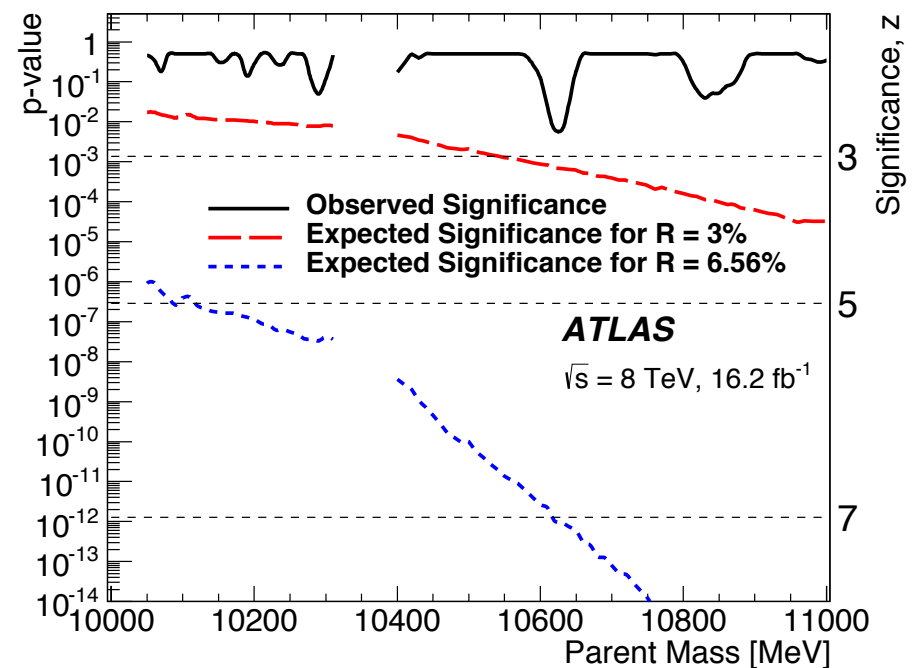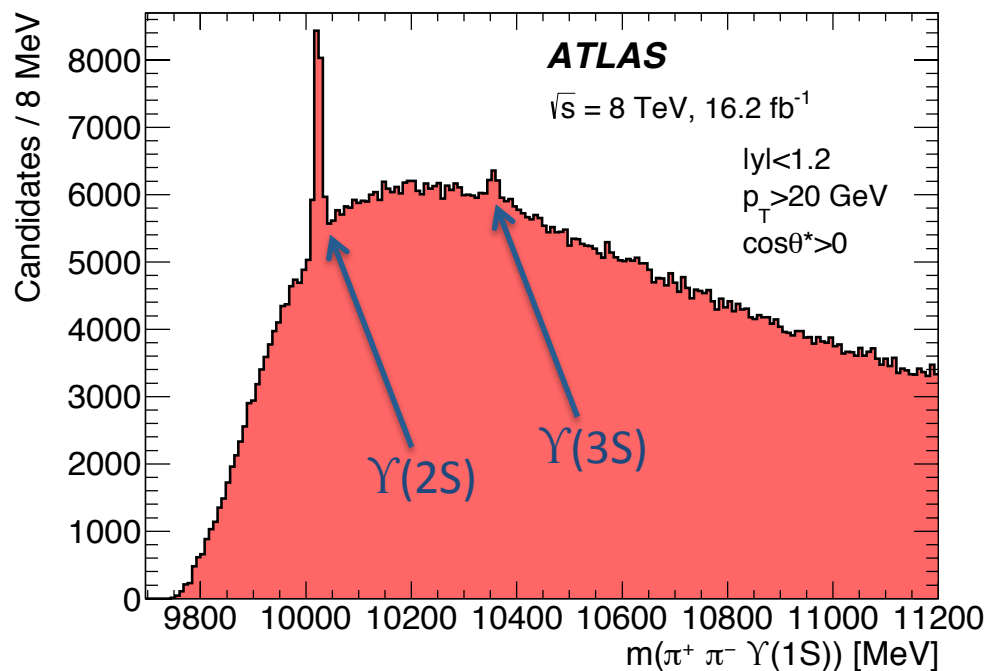
Search for the X_b and other hidden-beauty states at ATLAS (2)

(a) (b) (c)
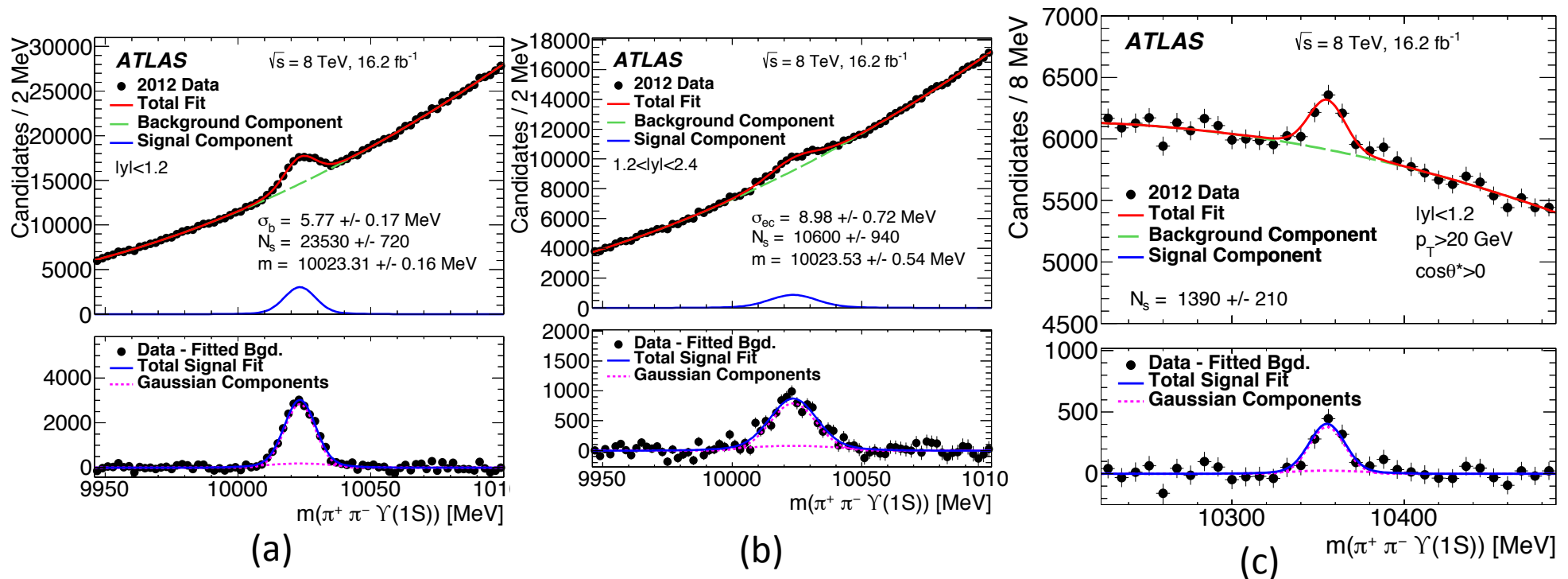
- The signal shape, distribution of signal among analysis bins, and efficiency, are first calibrated on the $\Upsilon(2S)$ peak in data → that it turns out only one parameter: the division of signal between barrel and endcap that needs to be adjusted.

- After this, the simultaneous fit to the 8 bins is validated on the $\Upsilon(3S)$.

- Both the expected overall yield and the division among bins are reproduced well.

# Search for the X_b and other hidden-beauty states at ATLAS (3)
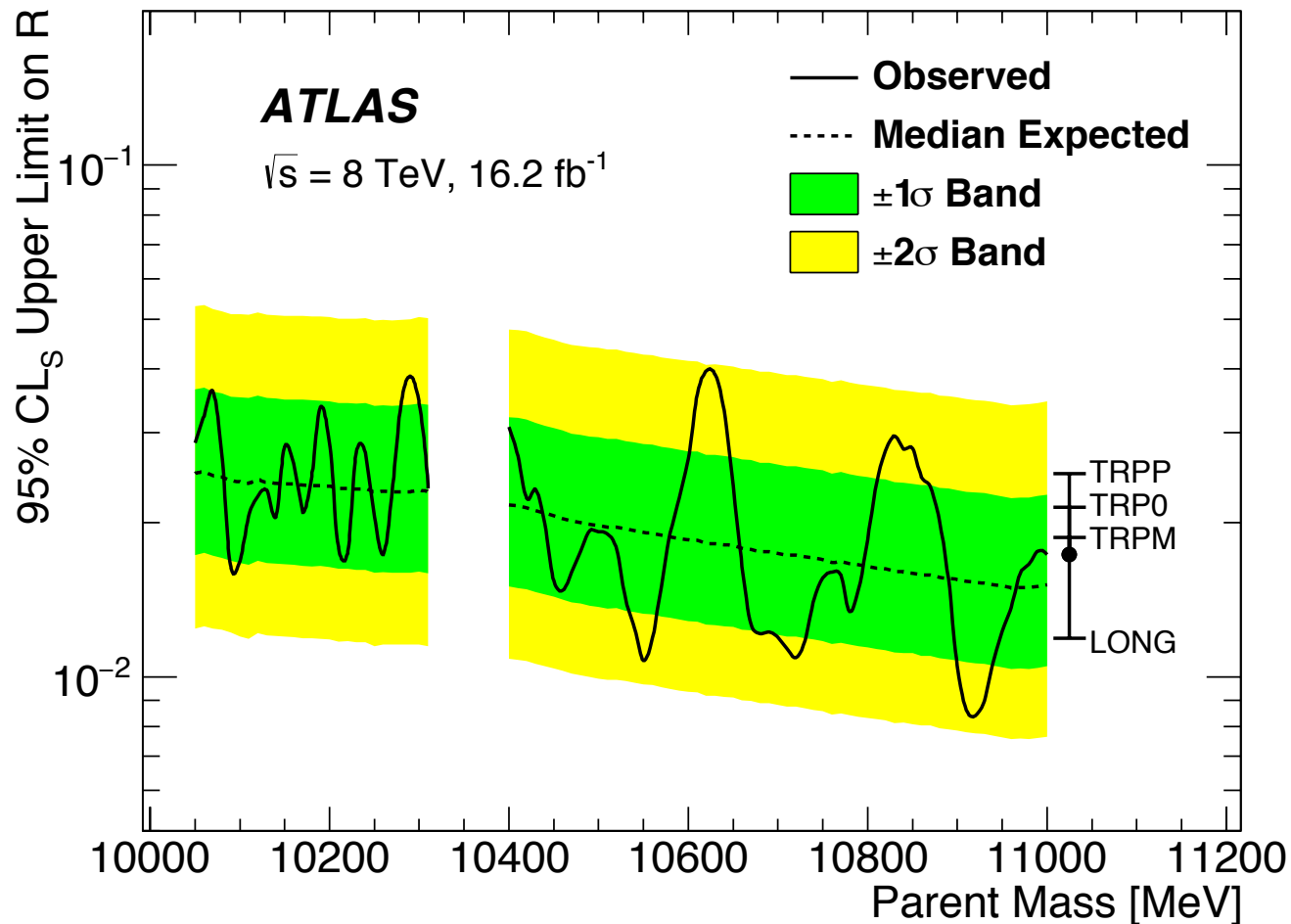
- The bar on the right shows typical shifts under alternative X_b spin-alignment scenarios.

- Upper limits are recalculated under longitudinal ('LONG') and three transverse ('TRPP', 'TRP0', 'TRPM') spin-alignment scenarios.

- No evidence for new narrow states is found for masses 10.05–10.31 GeV and 10.40–11.00 GeV.

- Upper limits are also set on the ratio
  $R = [\sigma(pp \rightarrow X_b)\, B(X_b \rightarrow \pi^+\pi^-\Upsilon(1S))]\, /$
  $[\sigma(pp \rightarrow \Upsilon(2S))\, B(\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S))],$
  with results ranging from 0.8% to 4.0% depending on the X_b mass.

Production measurements of ψ(2S) and X(3872) at ATLAS (1)

- **ATLAS-CONF-2016-028**

- Decay mode: $J/\psi\,\pi^+\pi^-$, 11.4 fb^{-1} of 8 TeV ATLAS data.

- Rapidity range $|y|<0.75$, p_T range of $J/\psi\,\pi^+\pi^- = (10-70)$ GeV.

- MC simulation is used for studies of selection and reconstruction efficiencies.
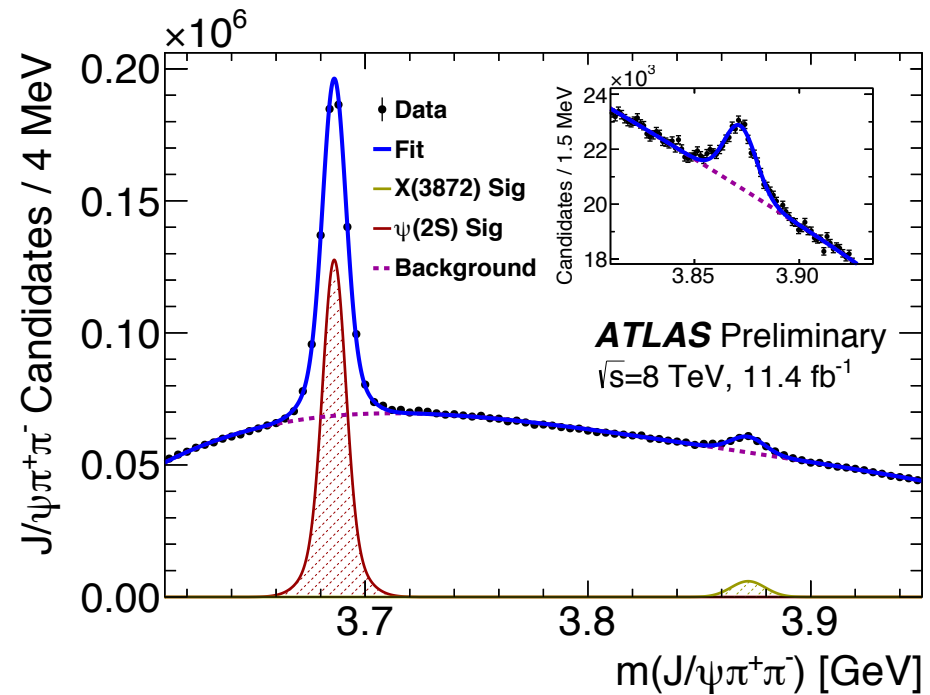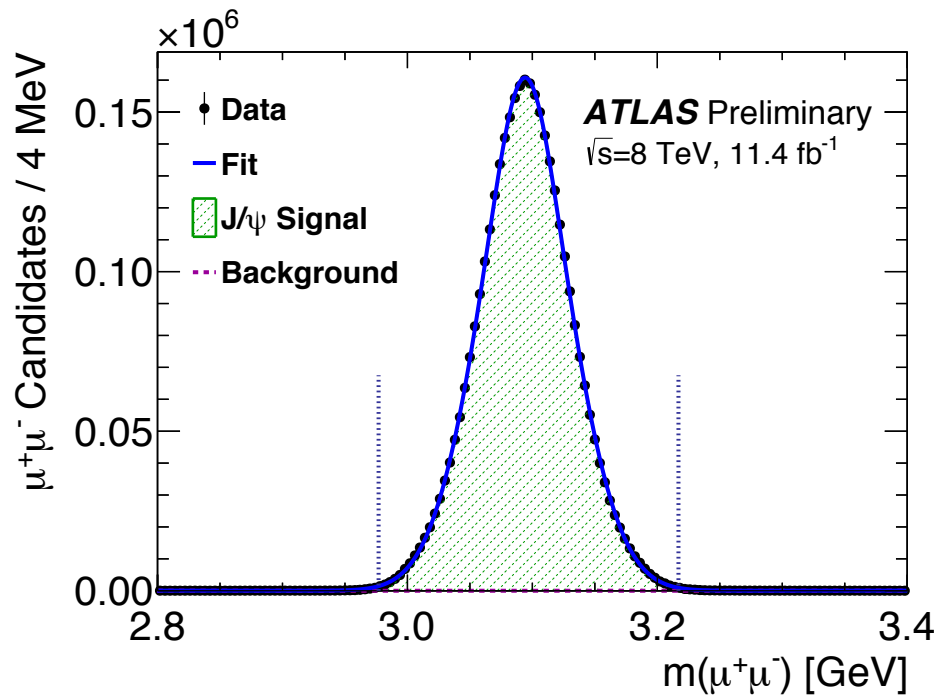
Production measurements of ψ(2S) and X(3872) at ATLAS (2)

- The production cross sections of the ψ(2S) and X(3872) states are measured in five bins of J/ψπ$^+$π$^-$ p_T, with bin boundaries
  - (10, 12, 16, 22, 40, 70) GeV.

- The cross sections measured are obtained under the assumption of
  - no spin alignment, but
  - appropriate sets of correction factors for a number of extreme spin alignment scenarios are calculated and presented in the Appendix of the corresponding Conference Note.

- In order to separate prompt production of the ψ(2S) and X(3872) states and the non-prompt production from the decays of long-lived particles such as b-hadrons, the data sample in each p_T bin was divided into intervals of pseudo-proper lifetime τ=L$_{xy}$m/p_T.

- Four intervals of τ(J/ψπ$^+$π$^-$) were defined:
  - −0.3 ps < τ < 0.025 ps
  - 0.025 ps < τ < 0.3 ps
  - 0.3 ps < τ < 1.5 ps
  - 1.5 ps < τ < 15.0 ps

Production measurements of ψ(2S) and X(3872) at ATLAS (3)

- Measured effective pseudo-proper lifetimes for non-prompt X(3872) and ψ(2S), and the ratio of non-prompt X(3872) and ψ(2S) production.
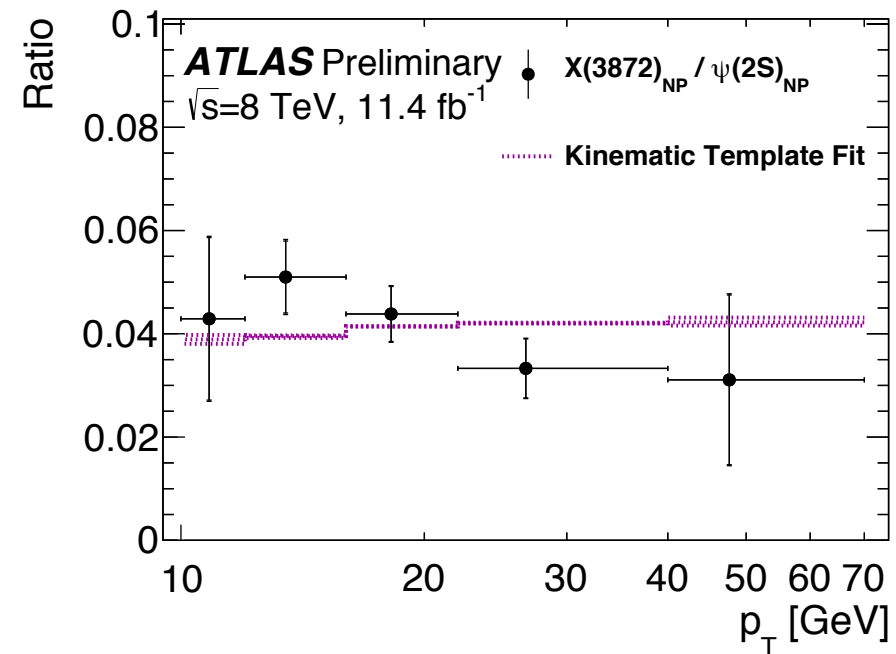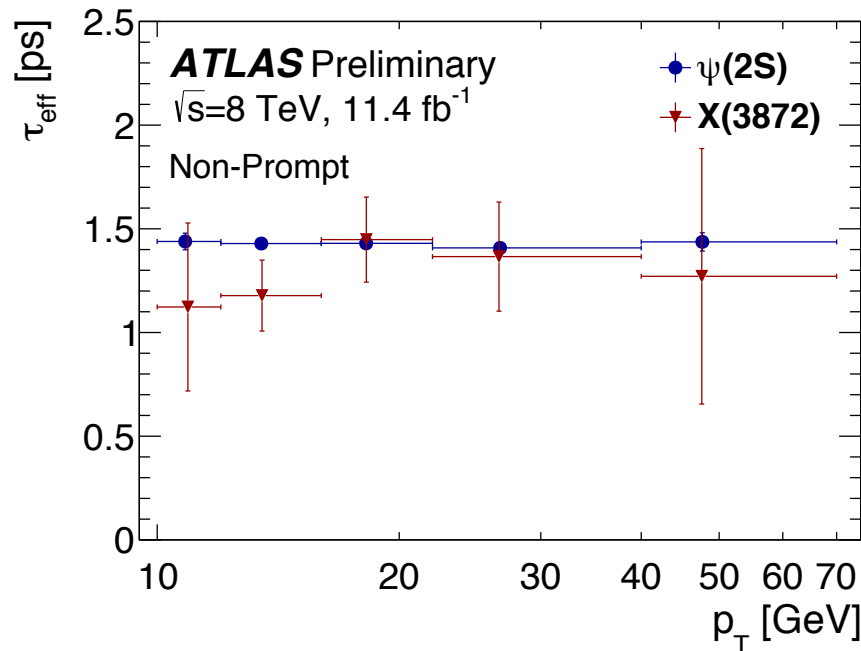
- Kinematic template fit was calculated as a ratio of the simulated p_T distributions of non-prompt X(3872) and non-prompt ψ(2S), assuming that the same mix of the parent b-hadrons contributes for both signals.
- The shape of the template reflects the kinematics of the decay of a b-hadron into ψ(2S) or X(3872), with the width of the band showing the range of variation for extreme values of the invariant mass of the recoiling hadronic system.

Production measurements of ψ(2S) and X(3872) at ATLAS (4)

- The fit of the measured ratio to that template allows to determine the ratio of the average branching fractions:

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

- The somewhat falling trend shown on the right figure on the previous slide does not completely agree with the shape of the template, also possibly suggesting the presence of an additional contribution to the non-prompt X(3872) yield in the low-p_T bins.

- The short-lived component is understood to be due to B_c decays, and the value of the pseudo-proper-lifetime parameter of the short-lived component is based on the value expected for B_c.

- An alternative fit model hence was implemented in the analysis, which allows for two non-prompt contributions with distinctly different effective lifetimes.

$$R_B^{2L} = \frac{Br(B \to X(3872))Br(X(3872) \to J/\psi\pi^+\pi^-)}{Br(B \to \psi(2S))Br(\psi(2S) \to J/\psi\pi^+\pi^-)} = (3.57 \pm 0.33(\text{stat}) \pm 0.11(\text{sys}))\%$$

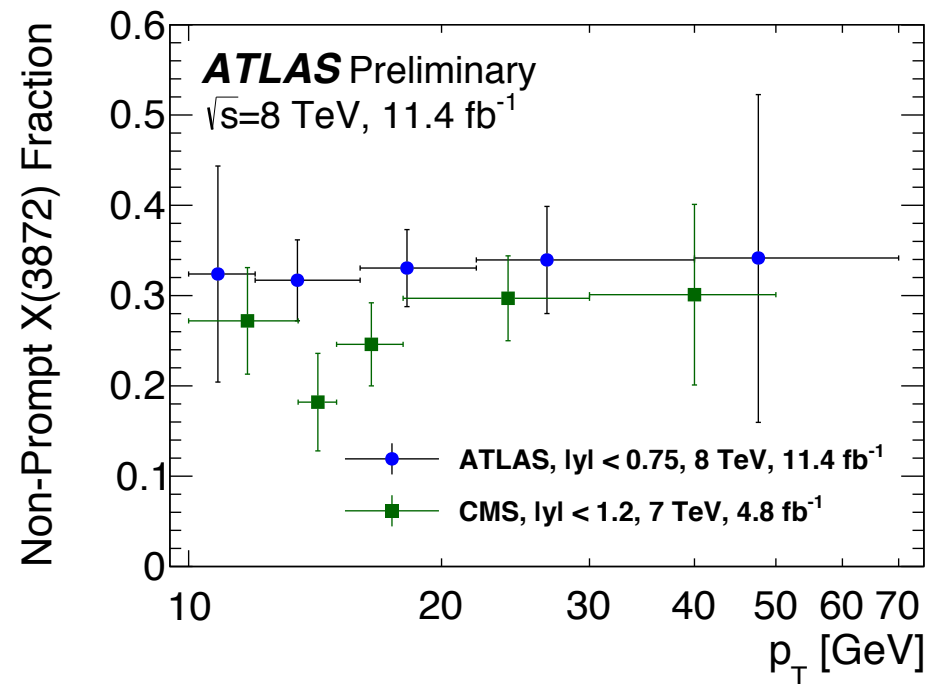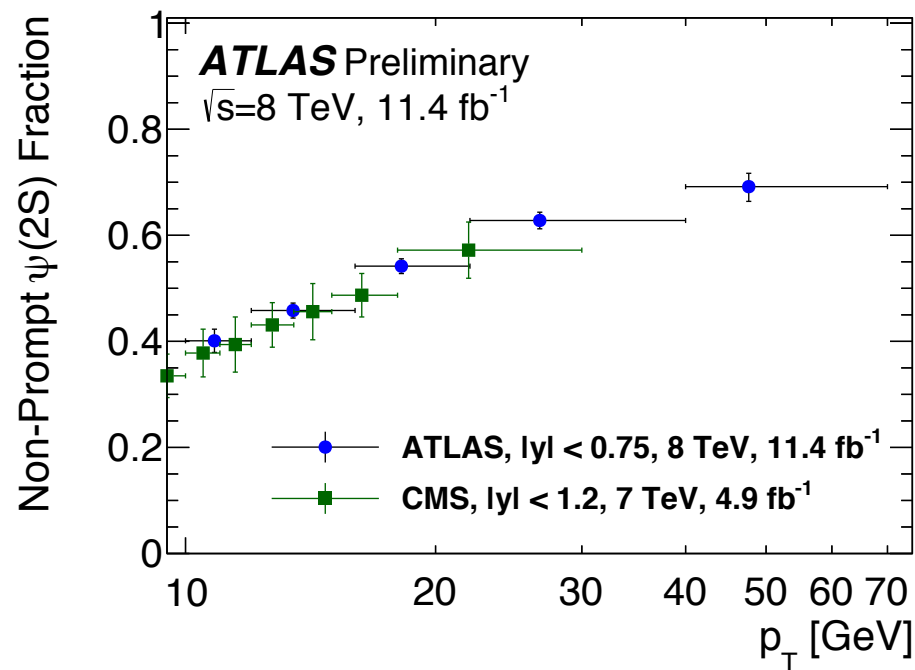# Production measurements of ψ(2S) and X(3872) at ATLAS (5)

- Ratio of cross section times branching fraction between X(3872) and ψ(2S) for prompt (left) and non-prompt (right) production. For the non-prompt production, the total ratio is separated into short-lived and long-lived components for the X(3872).
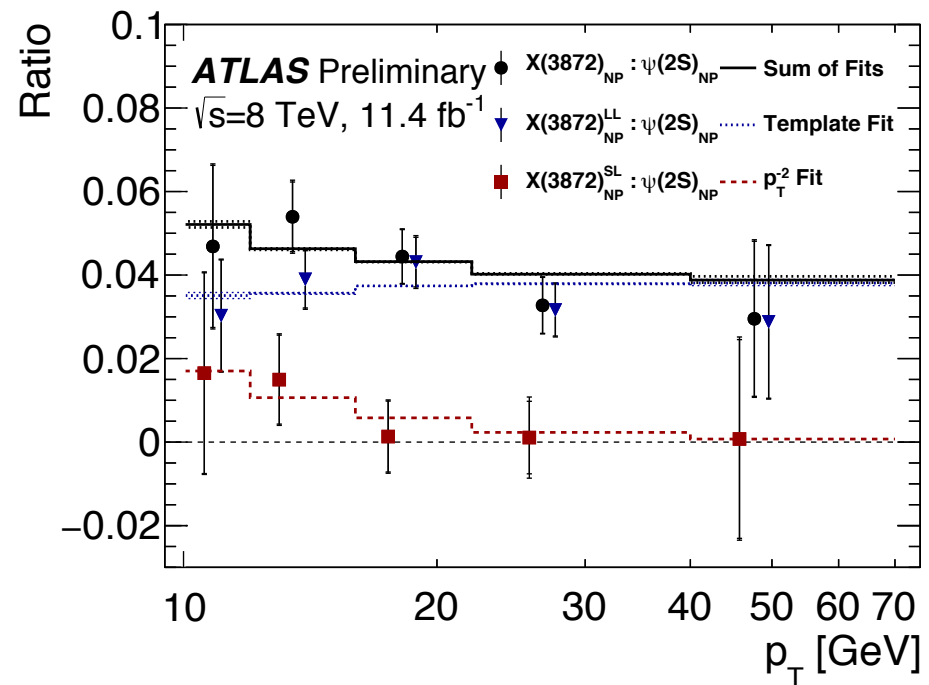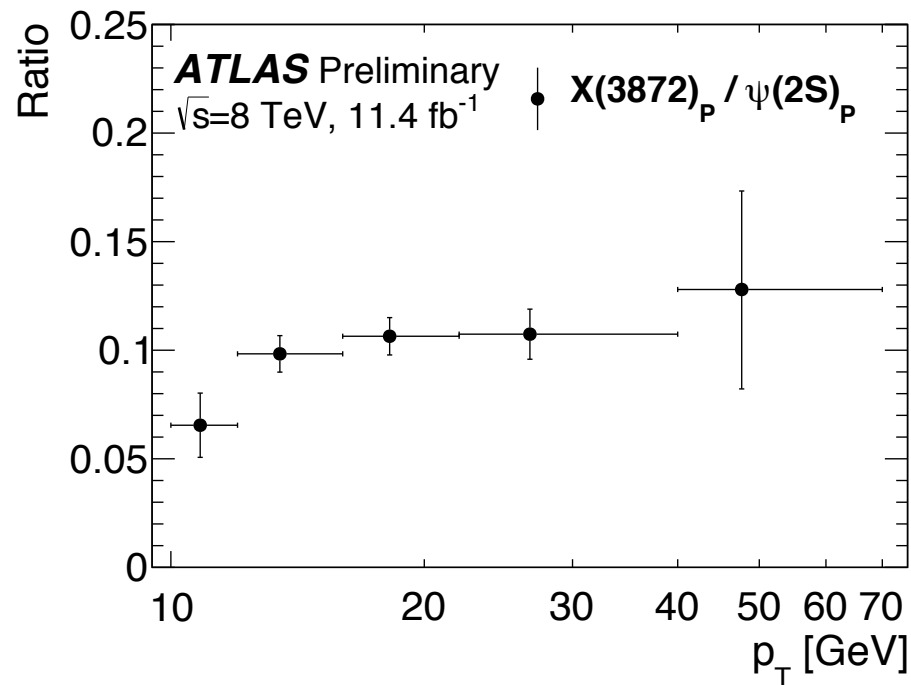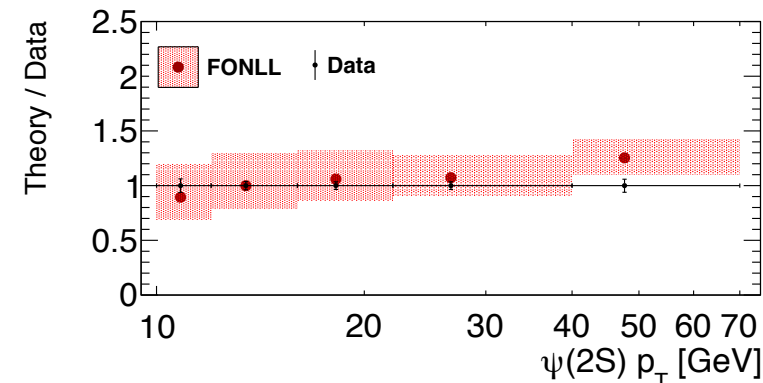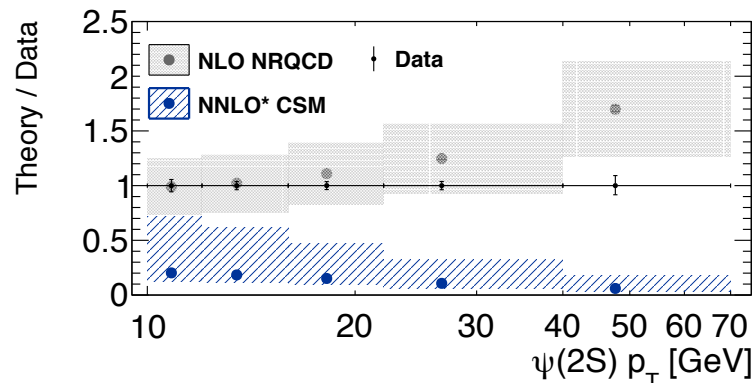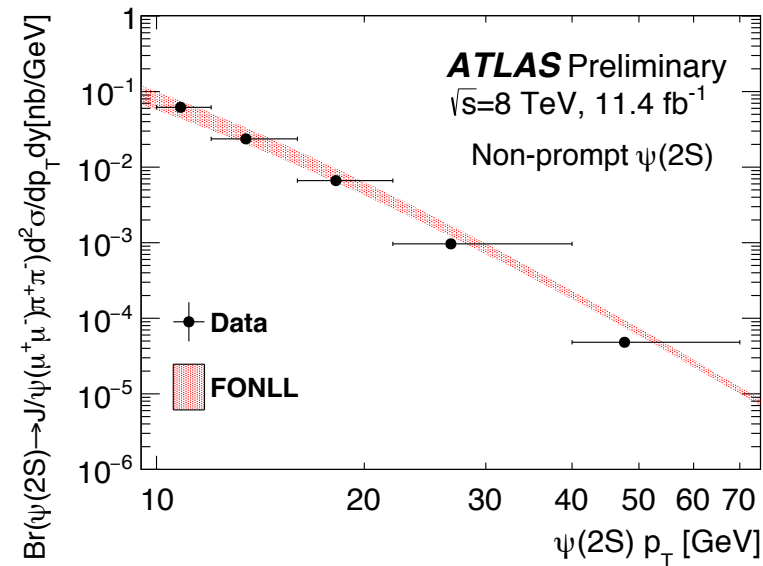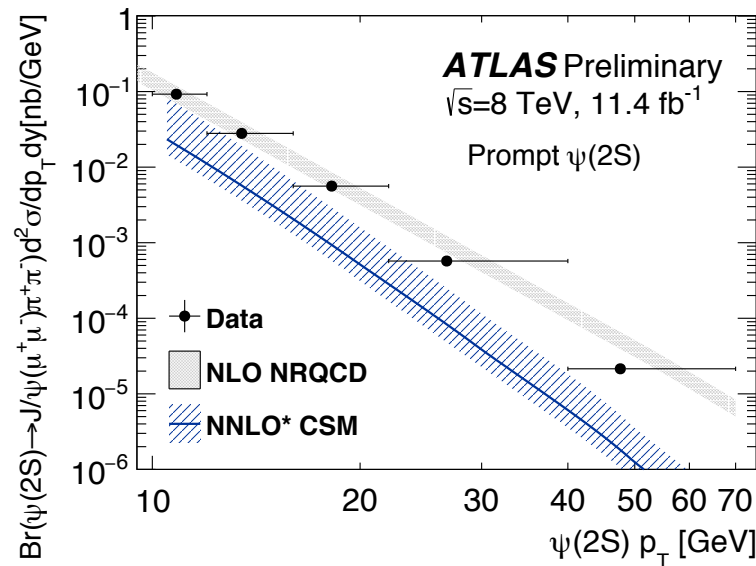
Production measurements of ψ(2S) and X(3872) at ATLAS (6)

- Measured non-prompt fractions for ψ(2S) (left) and X(3872) (right) production, compared to CMS results at √s = 7 TeV.

Production measurements of ψ(2S) and X(3872) at ATLAS (7)

- The measured differential cross section (times the product of the relevant branching fractions) for prompt production of ψ(2S) is presented on the left, and the non-prompt production is presented on the right. Compared to NLO NRQCD, NNLO* CSM and FONLL.
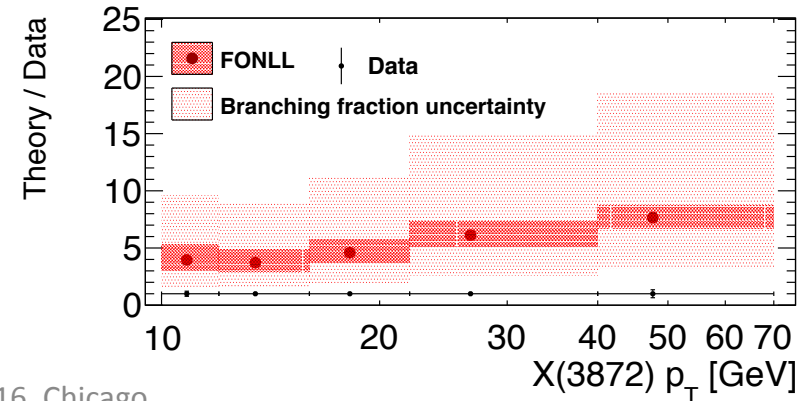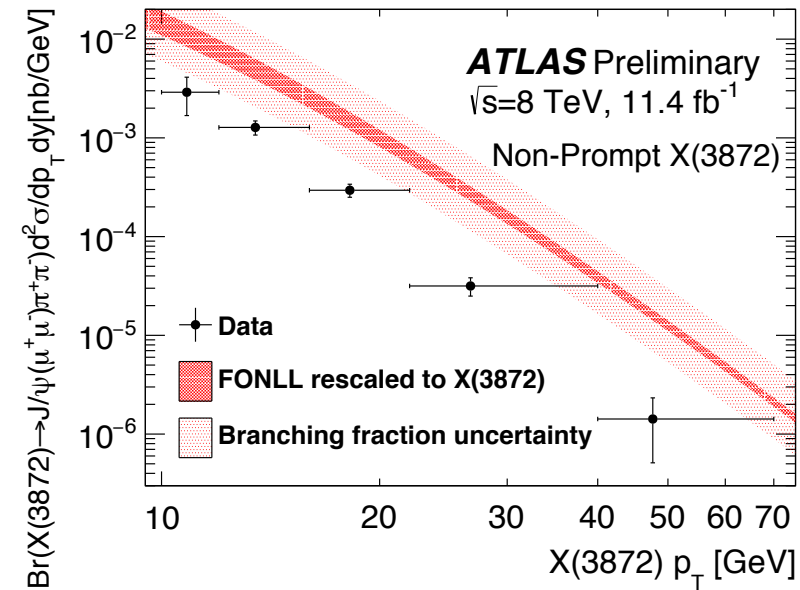
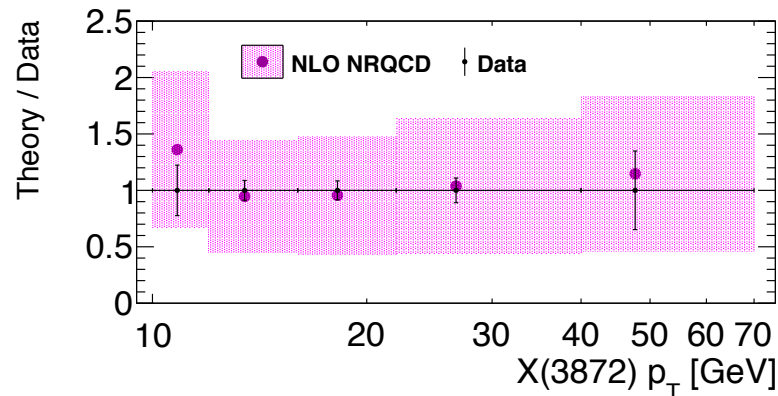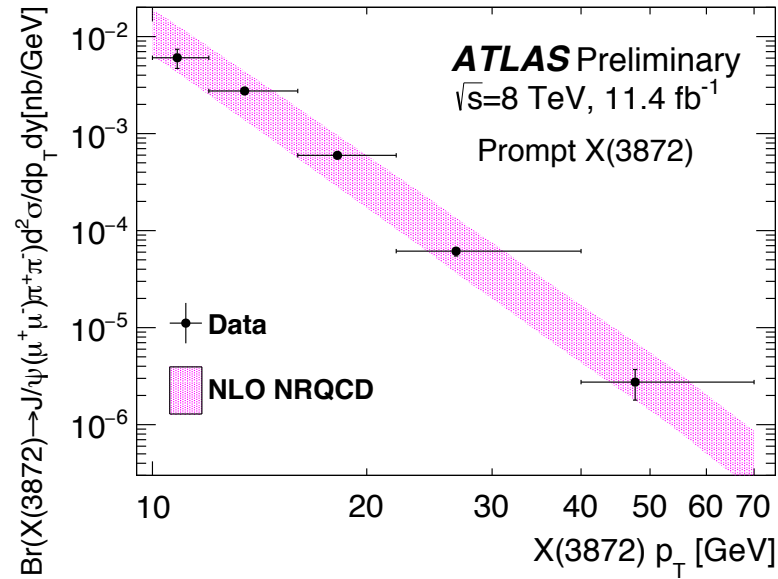# Production measurements of ψ(2S) and X(3872) at ATLAS (8)

- The measured differential cross section (times the product of the relevant branching fractions) for prompt production of X(3872) is presented on the left, and the non-prompt production is presented on the right. The X(3872) is modeled as a mixture of a $\chi_{c1}(2P)$ and a $\bar{D}^0 D^{*0}$ molecular state.

Production measurements of ψ(2S) and X(3872) at ATLAS (9)

- The above is used to determine the fraction of non-prompt X(3872) from short-lived sources, integrated over the p_T range (p_T > 10 GeV) covered in the analysis:

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

- The invariant mass distributions of the di-pion system in ψ(2S) → J/ψπ⁺π⁻ and X(3872) → J/ψπ⁺π⁻ decays are also measured. The results do not favour a phase space distribution in either decay, and favour X(3872) → J/ψρ⁰ .

X(3872) quantum numbers determination at LHCb (1)

- **Phys. Rev. D 92, 011102 (2015)**

- Brief history and foreword

  - Early constraints on the quantum numbers – CDF's 2005 angular analysis restricted the options to 1^{++} and 2^{-+}; also using the dipion mass distribution.

    - **Measurement of the Dipion Mass Spectrum in X(3872) -> J/ψππ**.

  - In 2011 these numbers are confirmed by Belle.

  - LHCb's 2013 full angular analysis finally settled on 1^{++}, but that analysis assumed that the lowest orbital angular momentum process dominated the decay.

    - **Phys. Rev. Lett. 110 (2013) 222001**.

  - The new analysis presented below removes that assumption.

X(3872) quantum numbers determination at LHCb (2)

- 3.0 fb^{-1} of 7 and 8 TeV LHCb data.

- $B^+ \to X(3872)K^+$, with $X(3872) \to \rho^0 J/\psi$, $\rho^0 \to \pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$.

- The fit yields 1011 ± 38 signal events over the background of 1468 ± 44 in the ΔM range of (725–825) MeV. The X(3872) mass resolution is 2.8 MeV.

- The signal purity is 80% within 2.5σ around the peak.
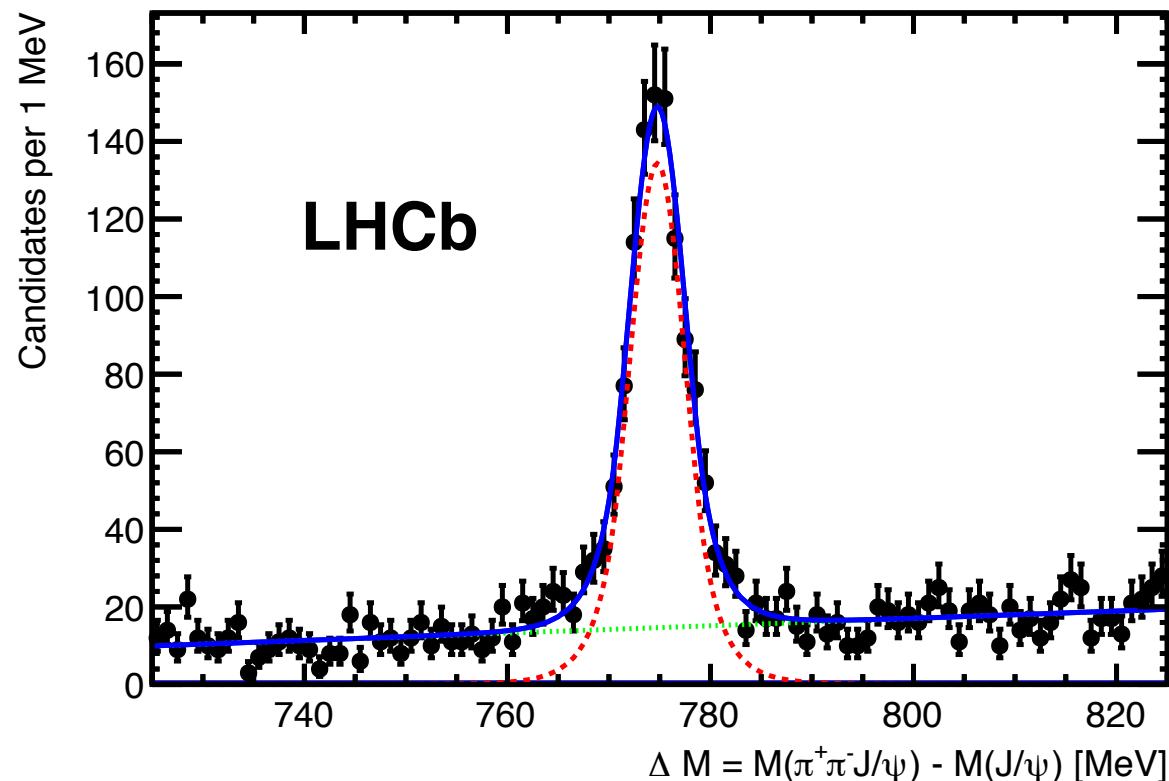
X(3872) quantum numbers determination at LHCb (3)

- The probability density function P for each J^{PC} hypothesis, J_X, is defined in the five-dimensional angular space
  - $\Omega \equiv (\cos\theta_X, \cos\theta_\rho, \Delta\phi_{X,\rho}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$, where
  - θ_X, θ_ρ and $\theta_{J/\psi}$ are the helicity angles in X(3872), ρ_0 and J/ψ decays, respectively, and
  - $\Delta\phi_{X,\rho}$, $\Delta\phi X,_{J/\psi}$ are the angles between the decay planes of the X(3872) particle and of its decay products.

- The quantity P is the normalized product of the expected decay matrix element M squared and of the reconstruction efficiency (ε), $P(\Omega|J_X) = |M(\Omega|J_X)|^2 \, \varepsilon\,(\Omega)/I(J_X)$, where $I(J_X) = \int |M(\Omega|J_X)|^2 \varepsilon\,(\Omega)d\Omega$.

- In this analysis both S– and D–wave contributions are allowed.

- The background is subtracted using the sPlot technique.

- The 1^{++} hypothesis gives the highest likelihood value, as shown on the next slide.

X(3872) quantum numbers determination at LHCb (4)
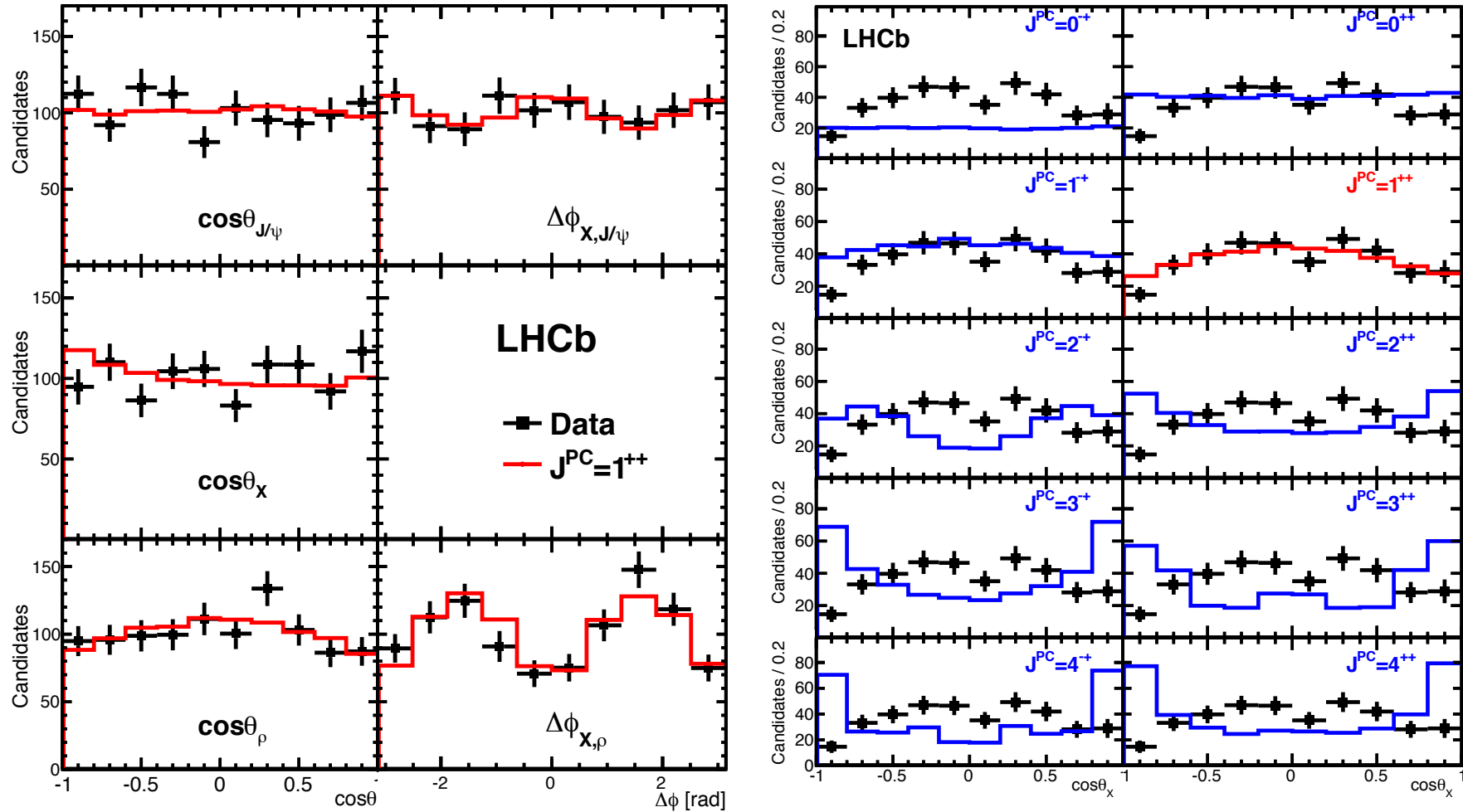
- Left: background-subtracted distributions of all angles for the data (points with error bars) and for the 1[++] fit projections (solid histograms).

- Right: Background-subtracted distribution of $\cos\theta_X$ for candidates with $|\cos\theta_\rho| > 0.6$ for the data (points with error bars) compared to the expected distributions for various X(3872) J^{PC} assignments (solid histograms).

X(3872) quantum numbers determination at LHCb (5)

- The analysis confirms that the eigenvalues of total angular momentum, parity and charge-conjugation of the X(3872) state are 1^{++}.

- These quantum numbers are consistent with those predicted by the molecular or tetraquark models and with the $\chi_{c1}(2^3P_1)$ charmonium state, possibly mixed with a molecule. Other charmonium states are excluded.

- No significant D–wave fraction is found, with an upper limit of 4% at 95% C.L.

- The S–wave dominance is expected in the charmonium or tetraquark models, in which the X(3872) state has a compact size. An extended size, as that predicted by the molecular model, implies more favorable conditions for the D–wave.

Conclusions

- LHC experiments have a rich program for studies of the X(3872) and other exotic hadron states.

- ATLAS has recently provided a comprehensive study of X(3872) and ψ(2S) production.

- LHCb has determined the quantum numbers of the X(3872) and separated the S– and D–wave modes; made the first production cross-section measurement in pp collisions, a precise mass measurement, an evidence of X(3872)$\rightarrow\psi$(2S)γ and a search for X(3872)$\rightarrow$p$\bar{\text{p}}$.

- CMS and ATLAS have performed searches for the X_b, the X(3872) bottomonium counterpart.

BACKUP

LHCb
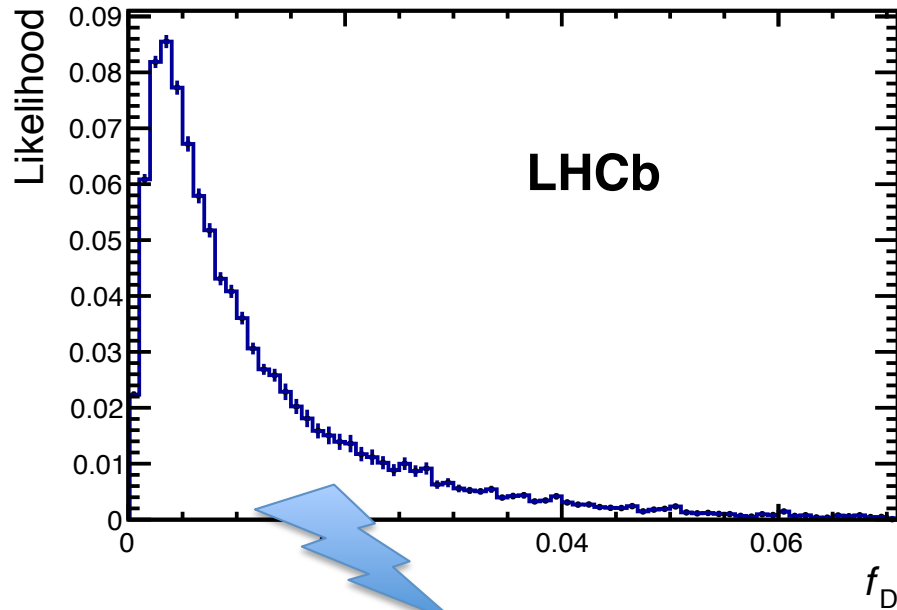
Likelihood-weighted distribution of the D–wave fraction. The distribution is normalized to unity.

Background-subtracted distribution of $\cos\theta_X$ for candidates with $|\cos\theta_\rho| > 0.6$ for the data (points with error bars) compared to the expected distributions for various $X(3872)$ J^{PC} assignments (solid histograms) with the B_{LS} amplitudes obtained by the fit to the data in the five-dimensional angular space. The fit displays are normalized to the observed number of the signal events in the full angular phase space.

LHCb 3 fb^{-1}

$t = -2\ln[\, L(J_X^{alt})/L(1^{++}) \,]$