Measurements of $\psi(2S)$ and $X(3872) \rightarrow J/\psi \pi^+\pi^-$ 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:

- **$M(X(3872))$:** $3871.69 \pm 0.17$ 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
Event selection

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

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

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

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

Dedicated di-muon triggers for quarkonium
$Q \rightarrow \mu^+\mu^-$ 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 \(\Delta R(J/\psi, \pi^-) < 0.5\)
- \(Q = m(J/\psi \pi^+ \pi^-) - m(J/\psi)_{PDG} - m(\pi^+ \pi^-) < 300\) 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 \(J/\psi\) mass
- Pion mass hypothesis used for the other two tracks

370k \(\psi(2S)\); 30k \(X(3872)\)
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, $\tau$, 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 $\chi^2$ fit in the $J/\psi \pi^+ \pi^-$ invariant mass to determine $\psi(2S)$ 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 $\psi(2S)$ and $X(3872)$
Mass fits in four lifetime windows

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 $\sigma_\chi = \kappa \sigma_\psi$
- Values of fraction and $\kappa$ 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 fit probability distribution function:

\[ F^i(\tau) = (1 - f_{NP}^i) F_P^i(\tau) + f_{NP}^i F_{NP}^i(\tau) \]

Non-prompt fraction \( f_{NP}^i \):

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

Prompt signal \( F_P^i \):

- Described by a lifetime resolution function determined from the data

Non-prompt signal \( F_{NP}^i \):

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

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

Effective lifetimes:

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

Non-prompt \( X(3872) : \psi(2S) \) ratio

- Fit to kinematic template

\[
R_{1B}^{\psi(2S)} = \frac{Br(B \to X(3872))Br(X(3872) \to J/\psi \pi^+ \pi^-)}{Br(B \to \psi(2S))Br(\psi(2S) \to J/\psi \pi^+ \pi^-)} = (3.95 \pm 0.32(stat) \pm 0.08(sys)) \%
\]
Two-lifetime fits

Alternative lifetime model: two-lifetime fit

\[ F_{iNP}(\tau) = (1 - f_{iSL}) F_{LL}(\tau) + f_{iSL} F_{SL}(\tau) \]

- 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:

- \( \tau \) depends on parent’s lifetime and decay kinematics
- \( \tau_{LL} \) determined from fits to \( \psi(2S) \), allowing for some SL contribution
- \( \tau_{SL} \) obtained from simulation varying \( B_c \) decay mode
- Both varied within shown limits during systematic studies

\[ \tau(\Lambda_b) = 1.451 \pm 0.013 \text{ ps} \]
\[ \tau_{LL} = 1.45 \pm 0.05 \text{ ps} \]
\[ \tau(B_c) = 0.507 \pm 0.009 \text{ ps} \]
\[ \tau_{SL} = 0.40 \pm 0.05 \text{ ps} \]

Two-lifetime fit results quoted from now on, unless stated otherwise
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. $Pt$
Prompt: described well by NLO NRQCD

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

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

- 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)
- $R_B = 18 \pm 8\%$
\( \psi(2S) \): non-prompt fraction

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

\[ \text{Non-prompt X(3872) fraction} \]

Non-prompt \( X(3872) \): non-prompt fraction

- No visible \( p_T \) dependence
- Consistent with CMS result within errors
Non-prompt ratio

Ratio of non-prompt $X(3872):\psi(2S)$

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

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

$$\frac{\sigma(pp\rightarrow B_c) Br(B_c\rightarrow X(3872))}{\sigma(pp\rightarrow \text{non-prompt } X(3872))} = (25 \pm 13(stat) \pm 2(sys) \pm 5(spin))\%$$
Di-pion mass distributions: results

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

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

In X(3872) $\rightarrow J/\psi \pi^+ \pi^-$ decays:
- Di-pion mass distribution has an even sharper peak at high masses
- In agreement with simulation where the dipion system is produced via $\rho^0$ meson decay
- Also in agreement with previous observations
Differential cross sections are measured for the prompt and non-prompt production of the X(3872) and $\psi(2S)$ 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 $\psi(2S)$ branching fractions:
  \[ R_{2L}^{B_B} = (3.57 \pm 0.33(\text{stat}) \pm 0.11(\text{sys}))\% \]

- The fraction of short-lived non-prompt component in X(3872) production:
  \[ \frac{\sigma(pp \to B_c) Br(B_c \to X(3872))}{\sigma(pp \to \text{non-prompt} X(3872))} = (25 \pm 13(\text{stat}) \pm 2(\text{sys}) \pm 5(\text{spin}))\% \]
Measurements of $\psi(2S)$ and $X(3872) \rightarrow J/\psi \pi^+ \pi^-$
ATLAS Detector

General purpose detector

Dedicated di-muon triggers for quarkonium

\( Q \rightarrow \mu^+ \mu^- \) 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 \( J/\psi \) and 150 MeV at \( \Upsilon(nS) \)
### Systematics

#### Differential cross sections

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<th>Source of uncertainty</th>
<th>$\psi(2S)[%]$</th>
<th>$X(3872)[%]$</th>
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</thead>
<tbody>
<tr>
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<td>Min</td>
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#### Fractions

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<th>$f_\chi^X$</th>
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<td>1.3</td>
<td>1.5</td>
<td>2.4</td>
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</table>

- Typically, for $X(3872)$ errors are statistically dominated
- For $\psi(2S)$ 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: \[ w = (A \cdot \epsilon_{\text{trig}} \cdot \epsilon_{\pi\pi \text{reco}} \cdot \epsilon_{\mu\mu \text{reco}})^{-1} \]
- \( A \) Acceptance: probability that the daughter muons and pions fall within the fiducial region: \( p_T(\mu) > 4 \text{ GeV}, \eta(\mu) < 2.3, p_T(\pi) > 0.6 \text{ GeV}, \eta(\pi) < 2.4 \)
- The acceptance maps were calculated using high statistics generator-level simulations, with small detector-level corrections applied later
- \( \epsilon_{\mu\mu \text{reco}} \) Muon reconstruction efficiency: obtained using data-driven tag-and-probe method.
- \( \epsilon_{\pi\pi \text{reco}} \) 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 $\psi(2S)$ 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

$$f(m) = G_{12}(m) + N_{bkg}(\frac{m-p_0}{m_0-p_0})^p_1 e^{-p_2(m-p_0)-p_3(m-p_0)^2}$$

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