X(3872) production and prospects from ATLAS

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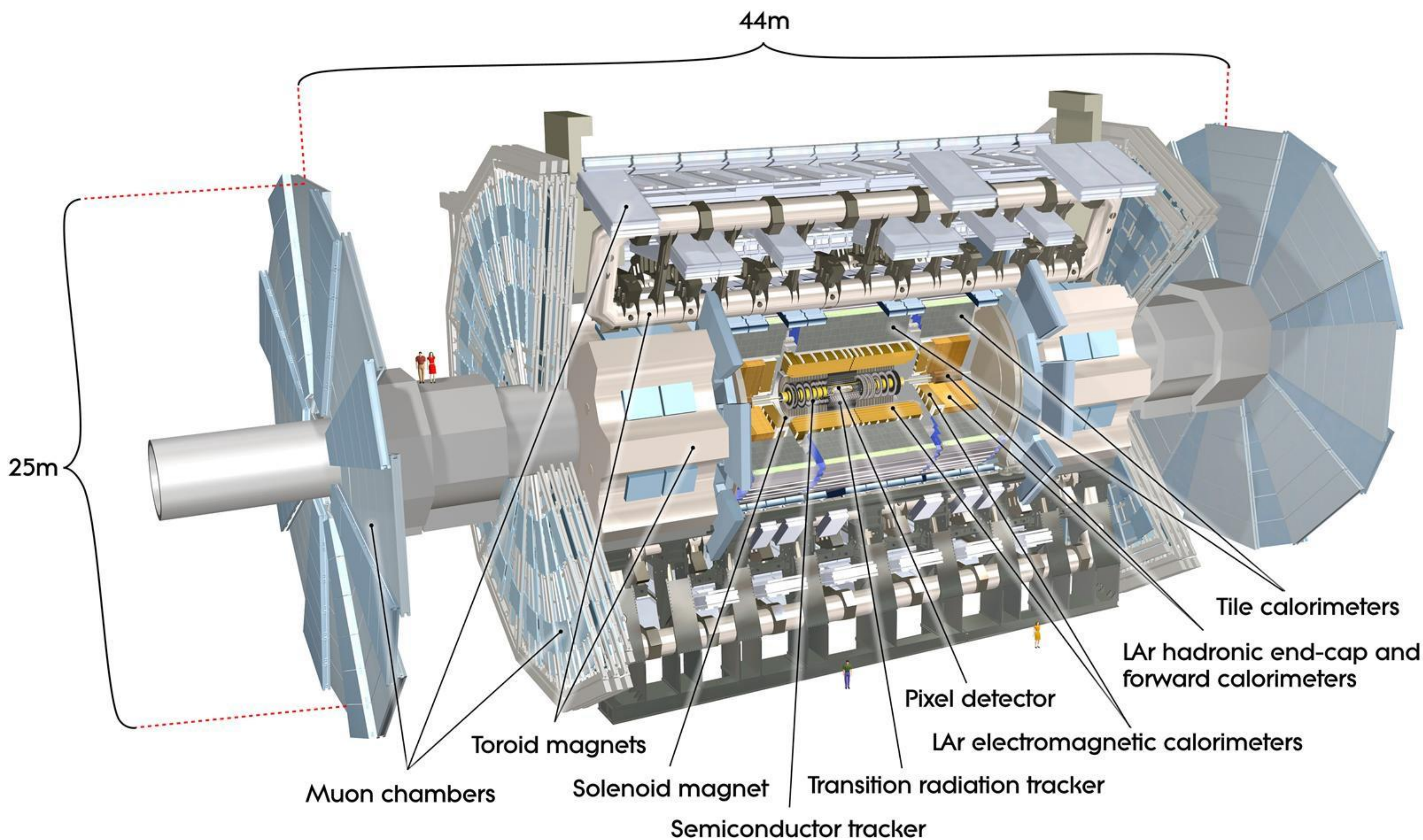
Exotic Hadron Spectroscopy
Edinburgh, 11 December 2017

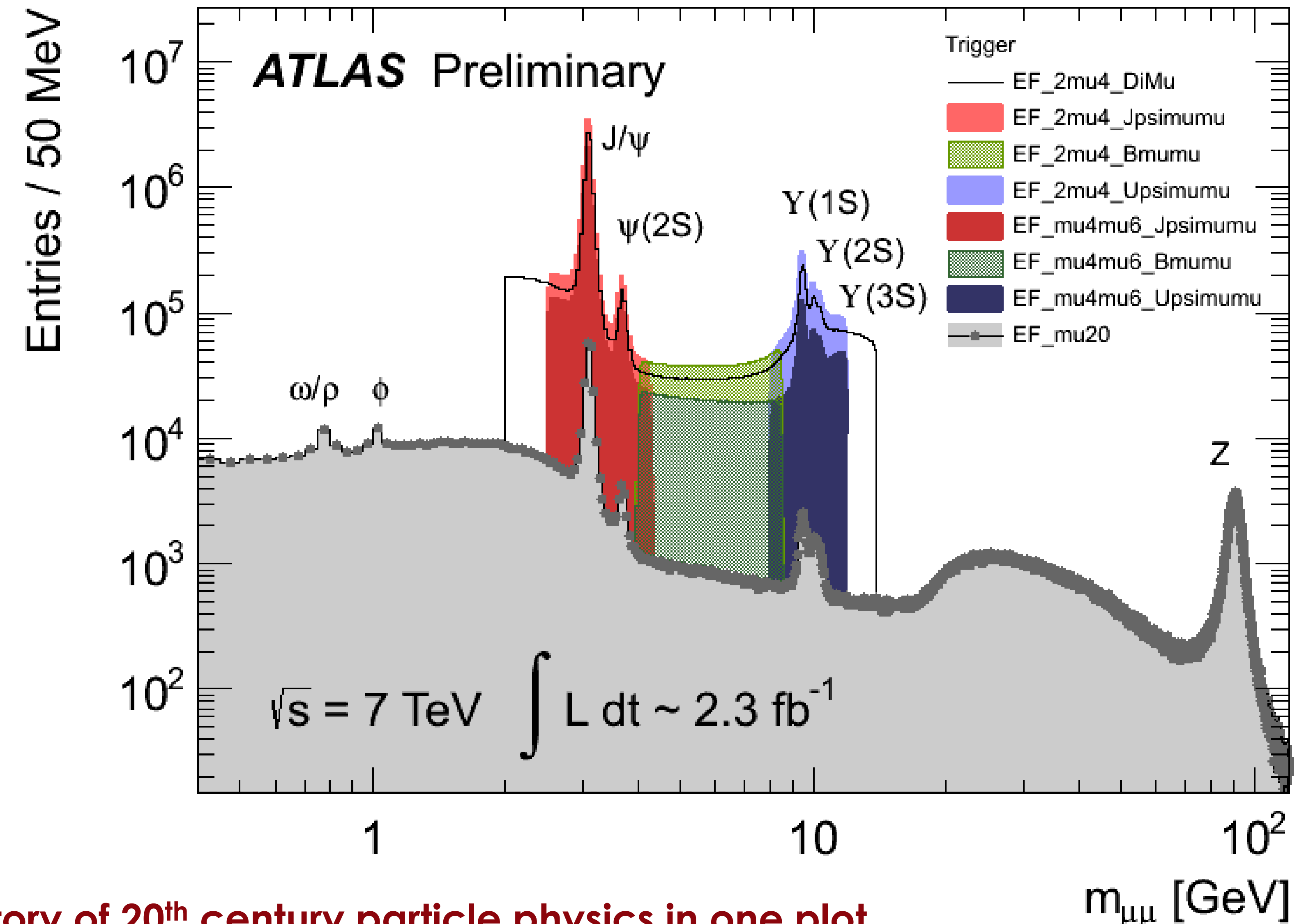
Outline

- ATLAS detector, (di-) muon triggers and LHC luminosity
- $\chi_{bJ}(3P)$ – an early contibution from ATLAS to heavy quarkonium spectroscopy
- Seacrches for X_b
- X(3872) production measurement, prompt and non-prompt
- Summary and perspectives

The ATLAS detector at LHC



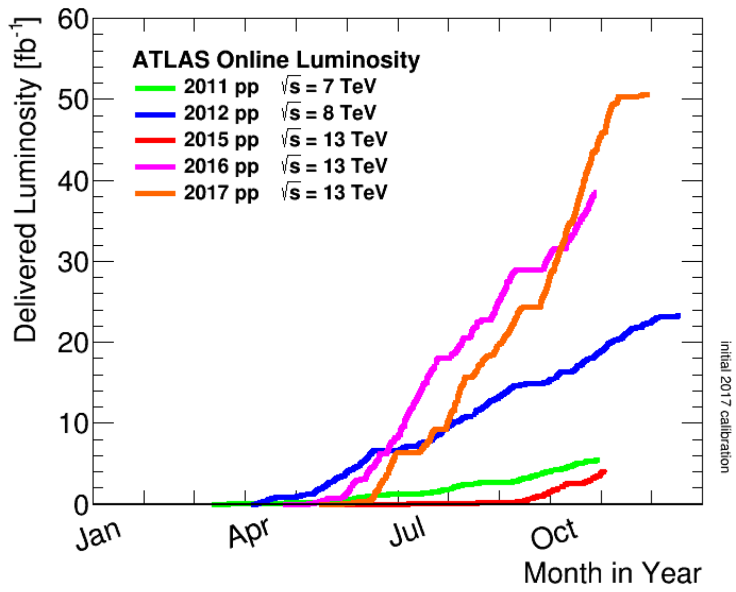
Muon and dimuon triggers in ATLAS

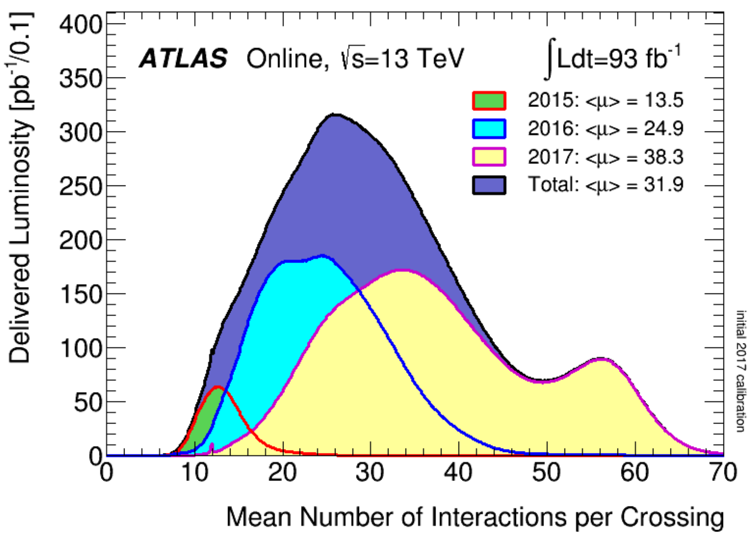


History of 20th century particle physics in one plot

LHC luminosity over the years

- ATLAS as a detector is optimised for "high pT" physics – Higgs and BSM searches
- In early years of LHC luminosity was not as high, could afford dimuon triggers with low thresholds
- Many quarkonium-related measurements made, including some rather unexpected "first observations
- In Run 2 our favourite low-pT dimuon triggers are heavily prescaled, and muon trigger thresholds creep higher and higher
- Need to be more and more creative and inventive to maintain interest in the area of heavy flavour physics





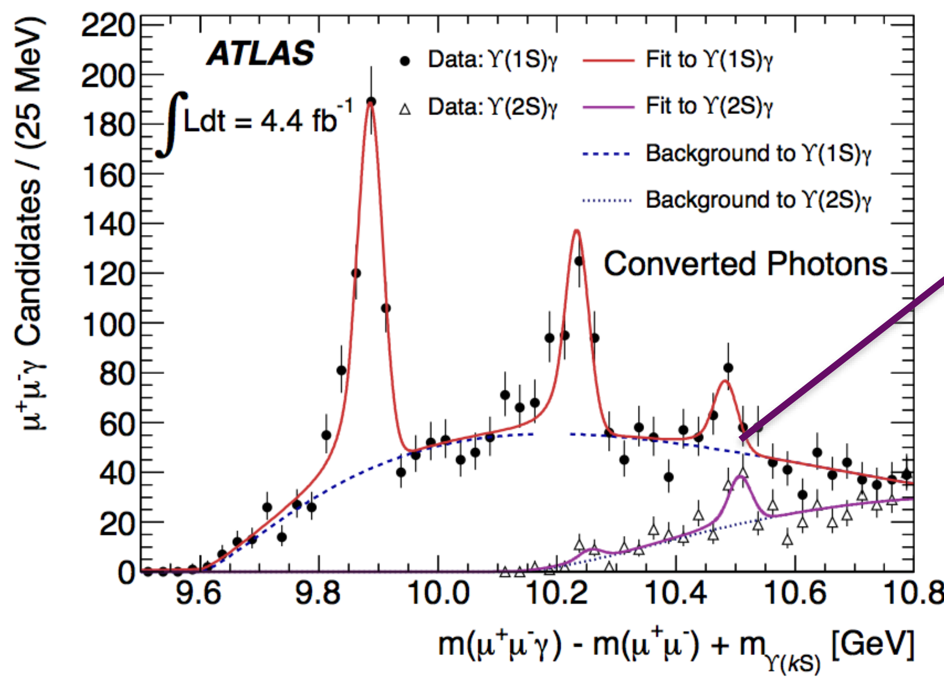
In fact, the first new state observed by any of the LHC experiments was not the Higgs, but rather the humble excited P-wave bottomonium, χ_{bJ}(3P)

PRL 108 (2012) 152001

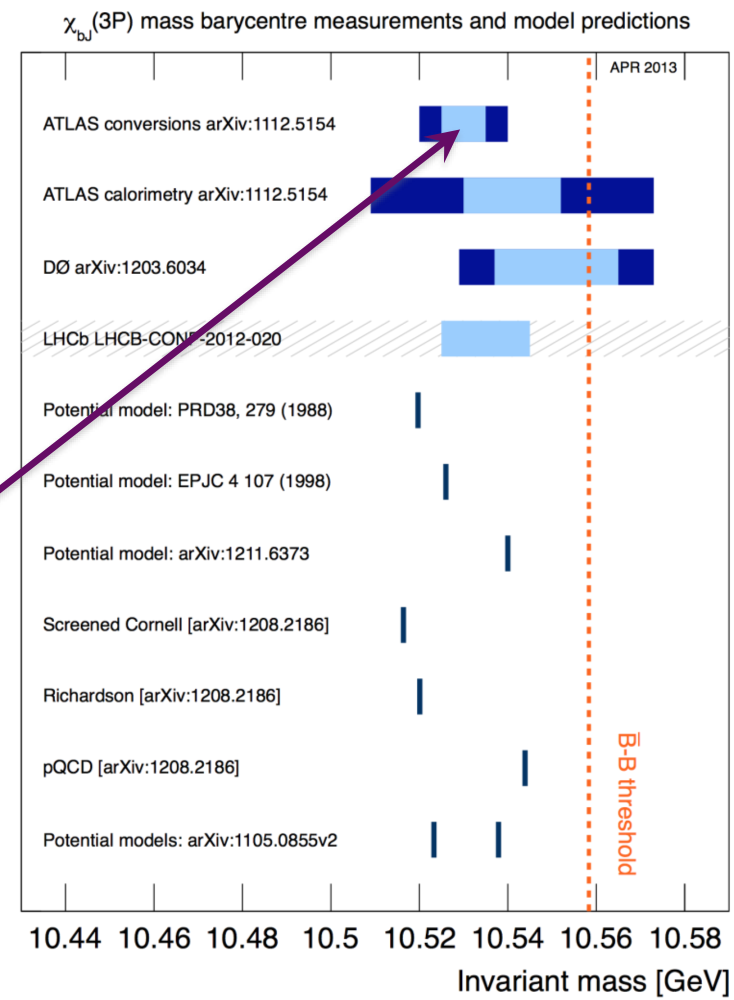
Observed by ATLAS in Υ(nS)+photon final state, using both converted and unconverted photons

Since then, confirmed by DØ and LHCb

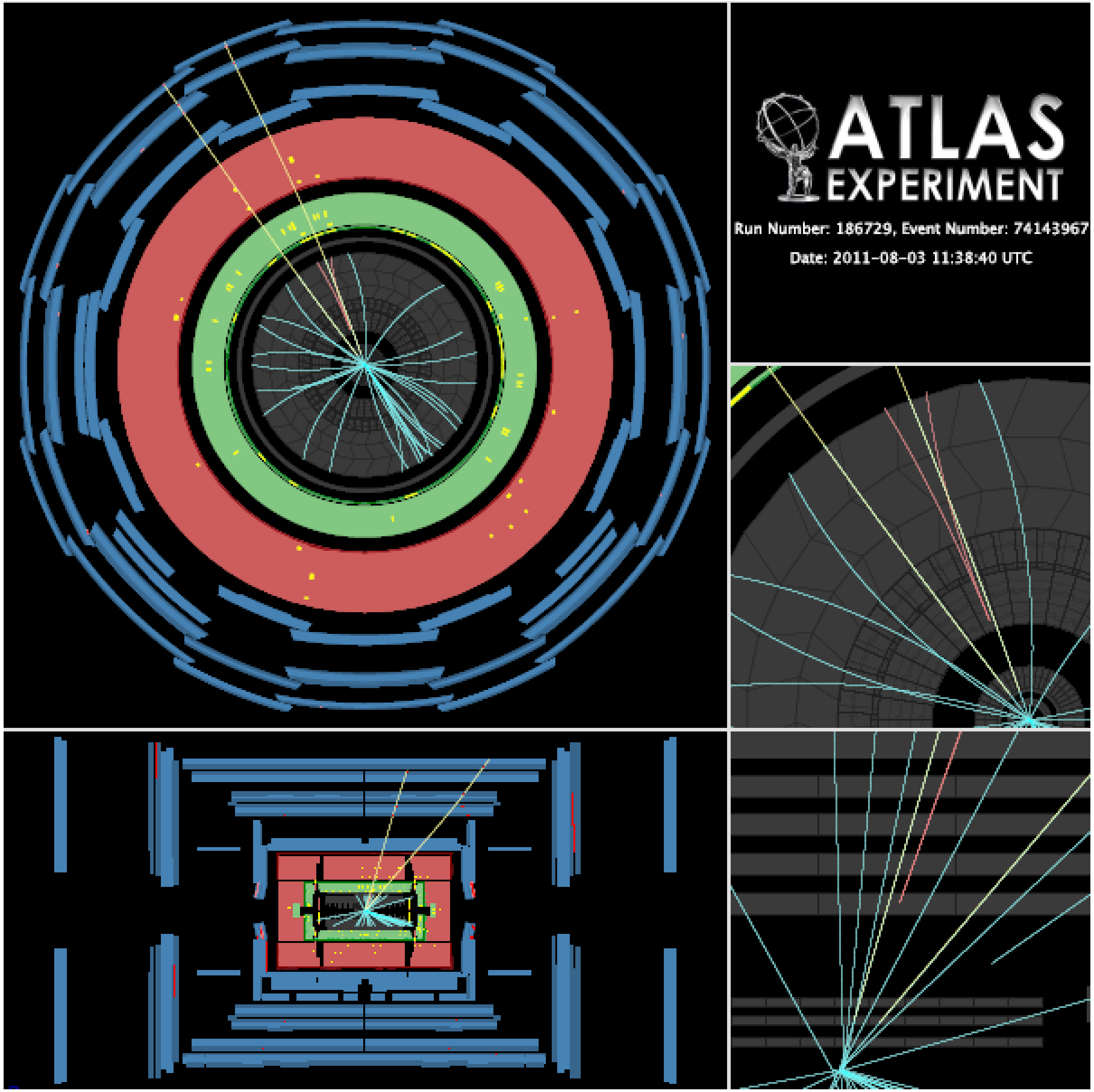
Relevant for this talk, as some exotic bottomonium state may be hiding in there…



light blue: statistical,
dark blue statistical+systematic



Event with $\chi_b(3P)$ candidate



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

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22 December 2011 Last updated at 10:59

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LHC reports discovery of its first new particle

By Jonathan Amos
Science correspondent, BBC News

The Large Hadron Collider (LHC) on the Franco-Swiss border has made its first clear observation of a new particle since opening in 2009.

It is called Chi_b (3P) and will help scientists understand better the forces that hold matter together.

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Large Hadron Collider has first confirmed sighting of new particle (but it's not the Higgs)

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SCIENCE

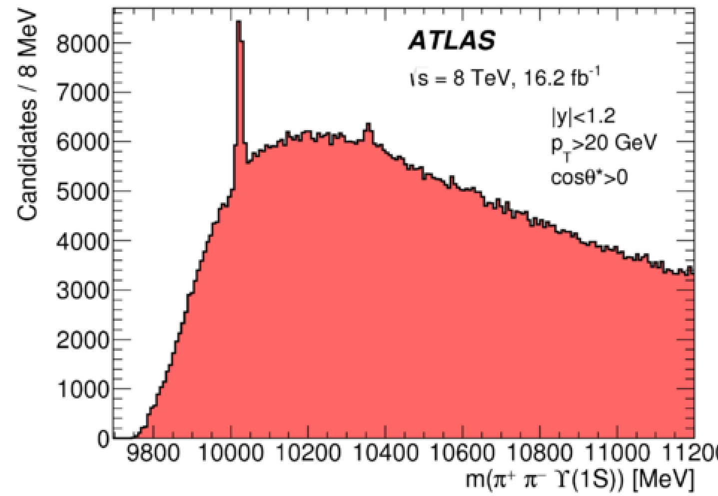
Large Hadron Collider discovers a new particle: the Chi-b(3P)

By Mark Brown | 22 December 11

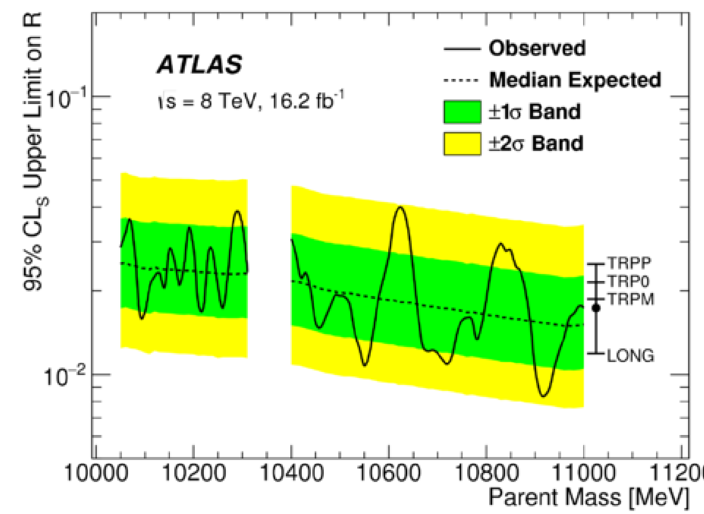
Phys.Rev.Lett. 108 (2012) 152001

Search for X_b in $\Upsilon\pi\pi$ decay mode

- **PLB 740 (2015) 199, arXiv:1410.4409**
- **Effective integrated luminosity 16.2 fb^{-1} at 8 TeV**
- **The $\pi^+\pi^-\Upsilon(1S)$ invariant mass distribution in the kinematic bin most sensitive to an X_b signal: $|y| < 1.2$, $p_T > 20$ GeV, and $\cos\theta^* > 0$.**



- **The only apparent peaks are at the masses of the $\Upsilon(2S)$ (10023 MeV) and $\Upsilon(3S)$ (10355 MeV).**
- **Observed 95% CL_S upper limits on the relative production rate $R = (\sigma B)/(\sigma B)_{2S}$ of a hypothetical X_b parent state decaying isotropically to $\pi^+\pi^-\Upsilon(1S)$**
- **The median expectation (dashed) and the corresponding ±1σ and ±2σ bands shown in green and yellow**



What is X(3872) ?

‘Exotic’ resonance first observed by Belle in 2003 in $J/\psi\pi^+\pi^-$ final state

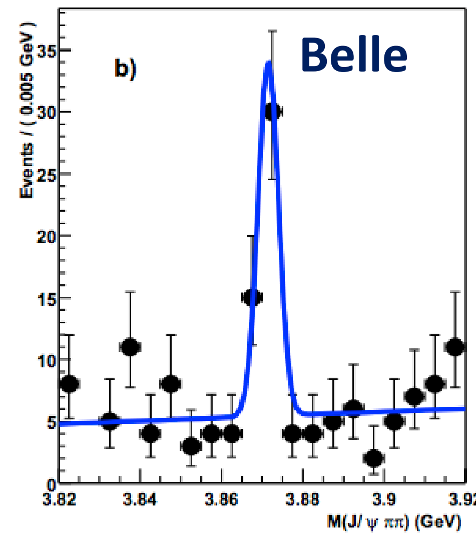
Soon after confirmed by BaBar, CDF, D0 and now LHC experiments

Current world average (3871.69 ± 0.17) MeV places X(3872) mass very close to the $D^0 D^{0*}$ threshold

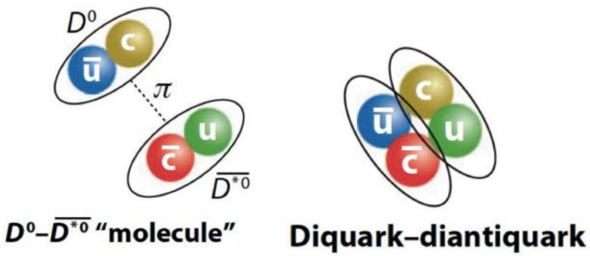
What is it? No clear picture yet!

- *Loosely bound $D^0 - D^{0*}$ molecule?* Unlikely: NRQCD with this premise over-predicts production compared to CMS 2011 measurement
- *New excited charmonium state?* Unlikely: LHCb measured $J^{PC} = 1^{++}$, no such state expected around that mass
- *A mix of these two, $\chi_{c1}(2P)$ -($D^0 D^{0*}$), with hadronic decays dominated by the $\chi_{c1}(2P)$ component?* Maybe, if the mixture is determined through fit to CMS results (arxiv:1304.6710)
- *Tetraquark (diquark – diantiquark)?* Possible, but hard to make any solid predictions

hep-ex/0309032



ATLAS has performed a measurement that may help answer some of these questions, and/or create new ones



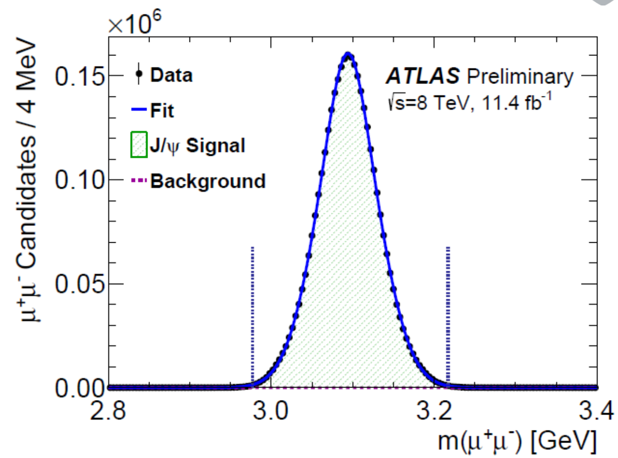
Measuring X(3872) and the well-studied ψ(2S) in the same analysis and in the same final state $J/\psi\pi^+\pi^-$ helps reduce systematics for various ratios and comparisons

Di-muon trigger with 4 GeV p_T threshold on each muon

Effective integrated luminosity 11.4 fb^{-1} at 8 TeV

Muon cuts:

- Opposite sign `combined' muons
- MCP cuts, $p_T > 4$ GeV, $|\eta| < 2.3$
- Good trigger object matching ($\Delta R < 0.01$)



J/ψ cuts:

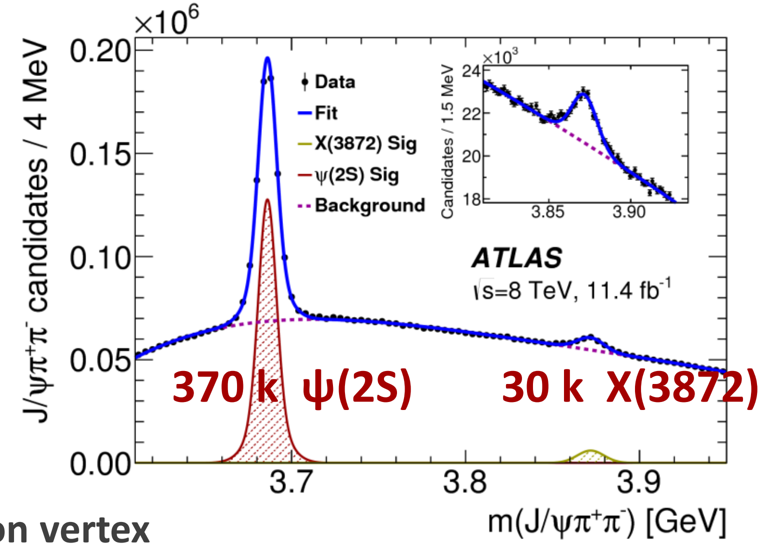
- $\chi^2_{dimu\_vtx} < 200$, $p_T > 8$ GeV & $|y| < 2.3$
- $|\, m(J/\psi) - m(J/\psi)_{PDG} \,| < 120$ MeV

Pion cuts

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

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

- $P(\chi^2_{J/\psi\pi\pi}) > 4\%$
- Opening angle $\Delta R(J/\psi, \pi^\pm) < 0.5$
- $Q = m(J/\psi\pi^+\pi^-) - m(J/\psi)_{PDG} - m(\pi^+\pi^-) < 300$ 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/ψ mass
- pion mass hypothesis used for the other two tracks

Outline of the Analysis

Analysis performed for |y| < 0.75 of the $J/\psi\pi^+\pi^-$ system, for optimal tracking resolution

p_T bin boundaries: [10, 12, 16, 22, 40, 70] GeV

Effective pseudo-proper lifetime $\tau = \frac{L_{xy}\, m}{p_T}$ with $L_{xy} = \frac{\vec{L} \cdot \vec{p}_T}{p_T}$

bin boundaries: [-0.3, 0.025, 0.3, 1.5, 15.0] ps

Each $J/\psi\pi^+\pi^-$ candidate weighted to correct for trigger/reco/acceptance losses

For each p_T and lifetime bin, binned 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, the yields in individual lifetime windows are subsequently fitted:
to determine lifetime dependence and hence
separate the signal into prompt and non-prompt components

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

Mass fits in lifetime windows

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

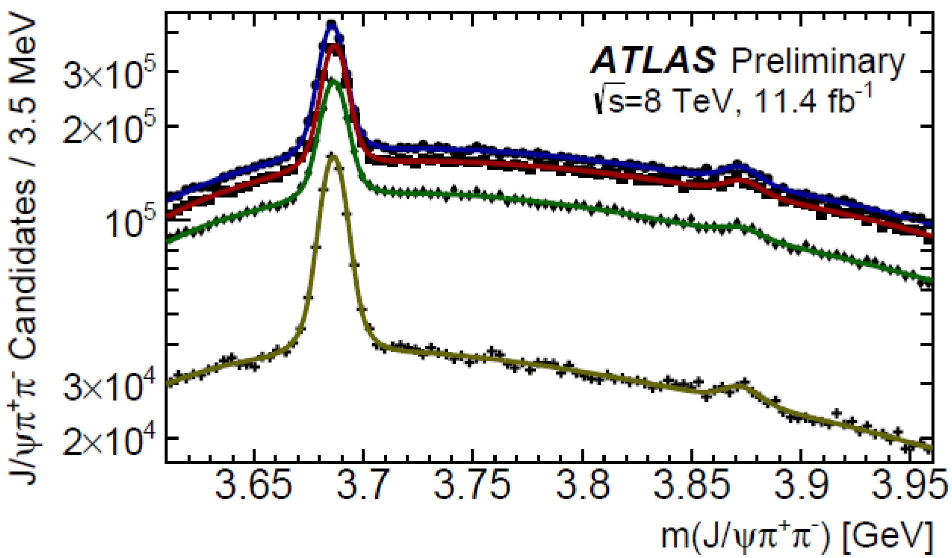
$$f(m) = f_{12}\left(Y^{\psi}G_1^{\psi}(m) + Y^{X}G_1^{X}(m)\right) + (1 - f_{12})\left(Y^{\psi}G_2^{\psi}(m) + Y^{X}G_2^{X}(m)\right)$$
$$+\mathrm{N_{bkg}}\,(m - m_0)^{p_2}\, e^{p_1(m-m_0)} P\,(m - m_0)$$

Fraction of narrow Gaussian f_{12} shared between $\psi(2S)$ and X(3872)

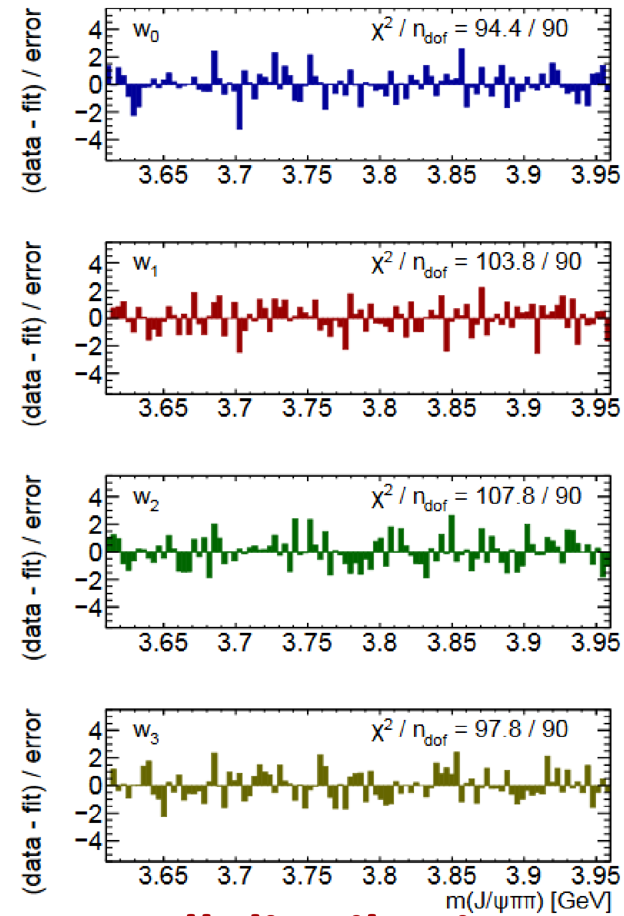
Resolution parameters linked by

$$\sigma_X = \kappa\sigma_\psi$$

Values of parameters f_{12} and κ determined from global fits
Verified with MC and varied during systematic studies



p_T: 12-16 GeV

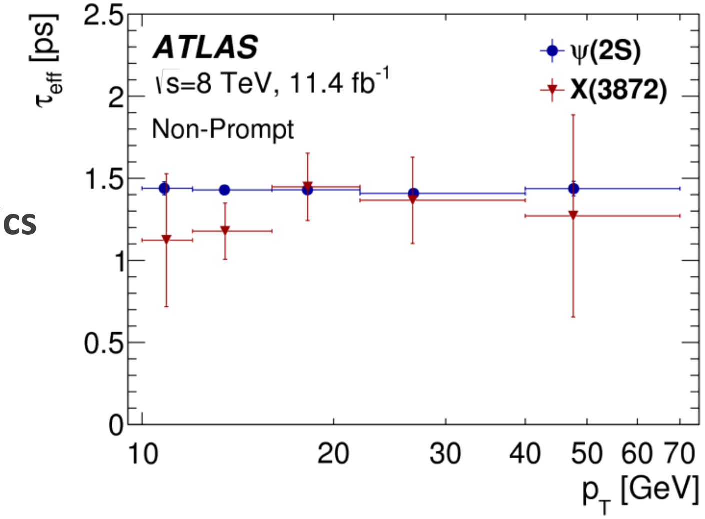


Pull distributions

Single lifetime fit - results

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

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

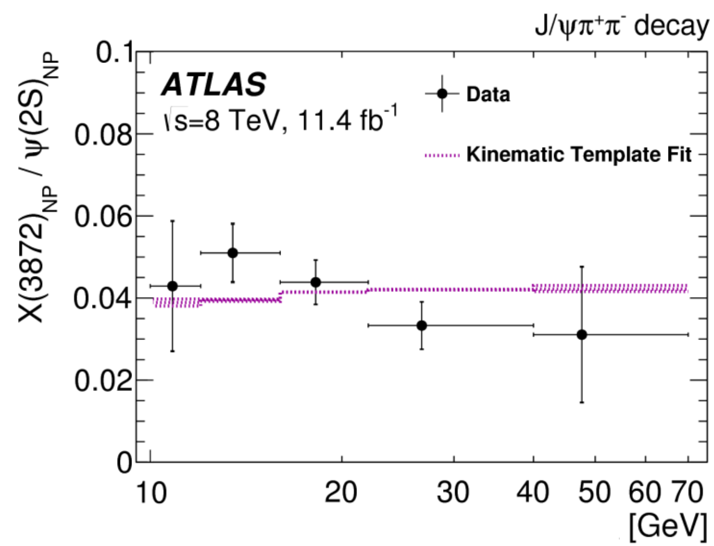


Effective lifetimes

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

Kinematic template obtained from simulations of various b-hadron decays into ψ(2S) and X(3872)

- takes into account mass difference and
- possible variation in mass of hadronic association



Non- prompt X(3872) : ψ(2S) ratio

- fit to kinematic template

$$R_B^{1L} = \frac{\mathcal{B}(B \to X(3872) + \text{any})\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B \to \psi(2S) + \text{any})\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (3.95 \pm 0.32(\text{stat}) \pm 0.08(\text{sys})) \times 10^{-2}$$

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 and long-lived
- two single-sided exponentials smeared with the same resolution function
- f_{SL} is a fraction of short-lived 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 short-lived contribution left free in the fit

Fixing the two lifetimes

- effective pseudo-proper lifetime depends on parent's lifetime and decay kinematics
- τ_{LL} determined from fits to ψ(2S), allowing for some SL contribution
- τ_{SL} obtained from simulation, varying B_c decay mode (low mass association gives shorter effective lifetime)
- both varied within shown limits during systematic studies

$\tau(B^{\pm}) = 1.638 \pm 0.004$ ps
$\tau(B^0) = 1.525 \pm 0.009$ ps
$\tau(B_s^0) = 1.465 \pm 0.031$ ps
$\tau(\Lambda_b) = 1.451 \pm 0.013$ ps

$\tau_{LL} = 1.45 \pm 0.05$ ps

$\tau(B_c)$ 0.507 +/-0.009 ps

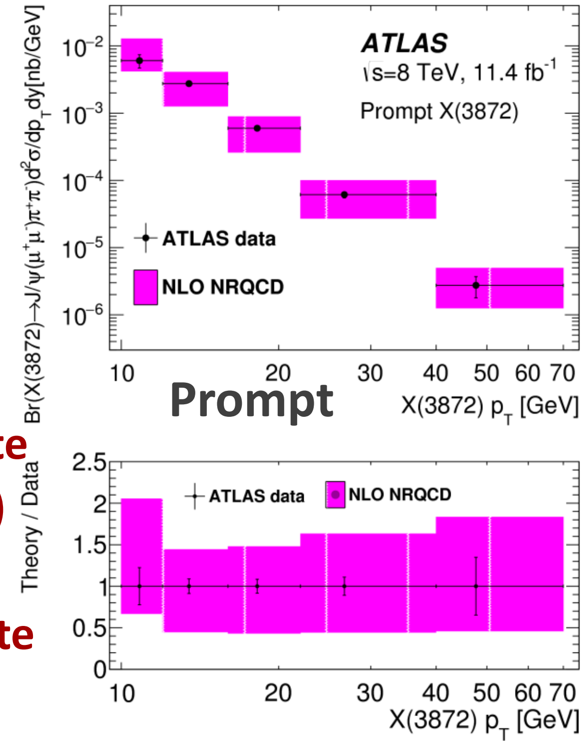
$\tau_{SL} = 0.40 \pm 0.05$ ps

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

X(3872) cross sections

Prompt: Described well by NLO NRQCD

- assumes X(3872) is a mix $\chi_{c1}(2P)$ - $(D^0 D^{0*})$
- $\chi_{c1}(2P)$ coupling assumed responsible for production
- parameters fitted to CMS data
- not surprising, CMS and ATLAS consistent



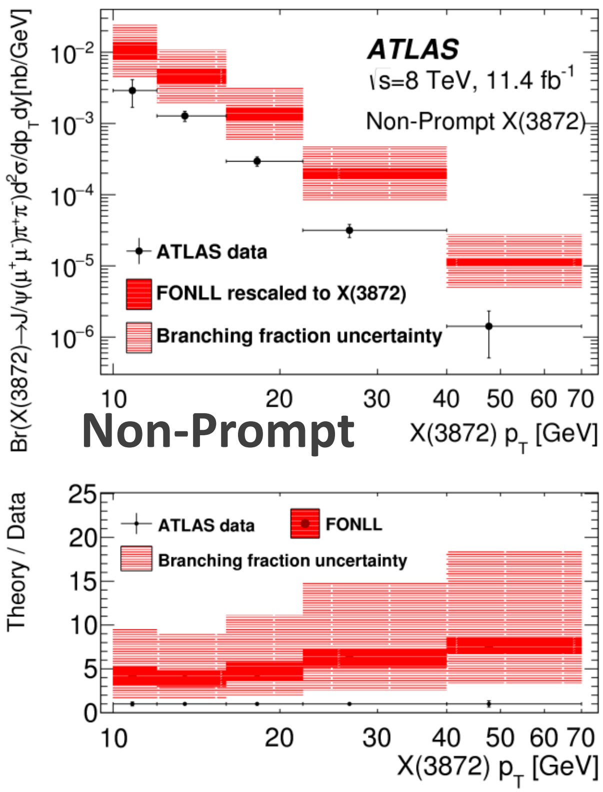
Non prompt:

use the same kinematic template to recalculate FONLL from $\psi(2S)$

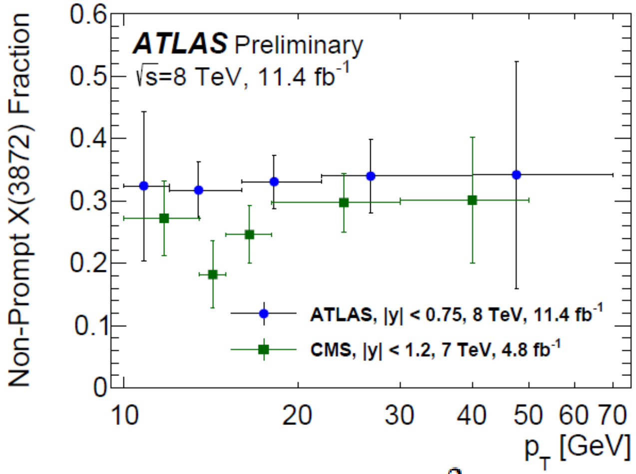
BR not measured – used estimate from Artoisenet, Braaten based on Tevatron data [hep-ph:0911.2016]

$$R_B = \frac{Br(B \to X(3872))Br(X(3872) \to J/\psi\pi^+\pi^-)}{Br(B \to \psi(2S))Br(\psi(2S) \to J/\psi\pi^+\pi^-)} = 18 \pm 8\ \%$$

Clearly overshoots the data: factor of 4 to 8, increasing with pT



Non-prompt fraction and ratio



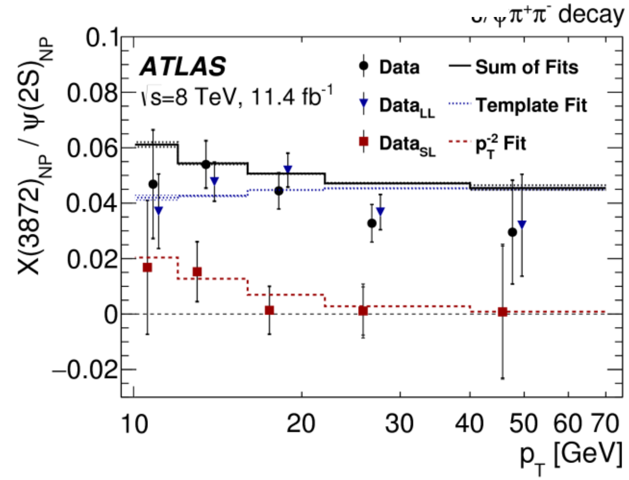
Non-prompt fraction of X(3872):

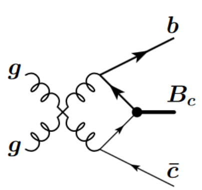
- no visible p_T dependence
- consistent with CMS result within errors

Ratio of non-prompt X(3872) : ψ(2S)

- long-lived part fitted to kinematic template

$$R_B^{2L} = \frac{\mathcal{B}(B \to X(3872) + \text{any})\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B \to \psi(2S) + \text{any})\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (3.57 \pm 0.33(\text{stat}) \pm 0.11(\text{sys})) \times 10^{-2}$$





- short-lived part: non-fragmentation contributions dominate at low p_T [Berezhnoy, arXiv:1309.1979]
- fit with $A \cdot p_T^{-2}$
- integrate the fits to determine the fraction of non-prompt X(3872) that is short-lived, for pT>10 GeV:

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

B_c production much smaller than other B => X(3872) production enhanced in B_c decays?

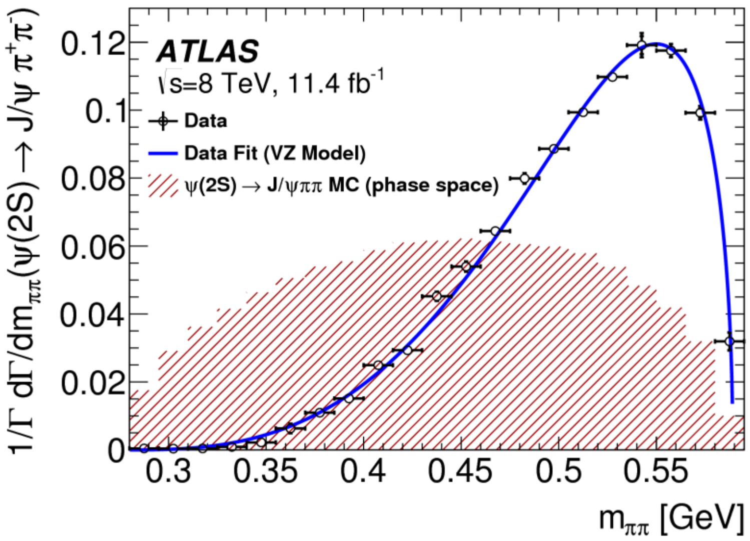
Di-pion mass distributions: results

In ψ(2S) to J/ψπ⁺π⁻ decays

- dipion mass distribution peaks at high masses
- fit to Voloshin-Zakharov function

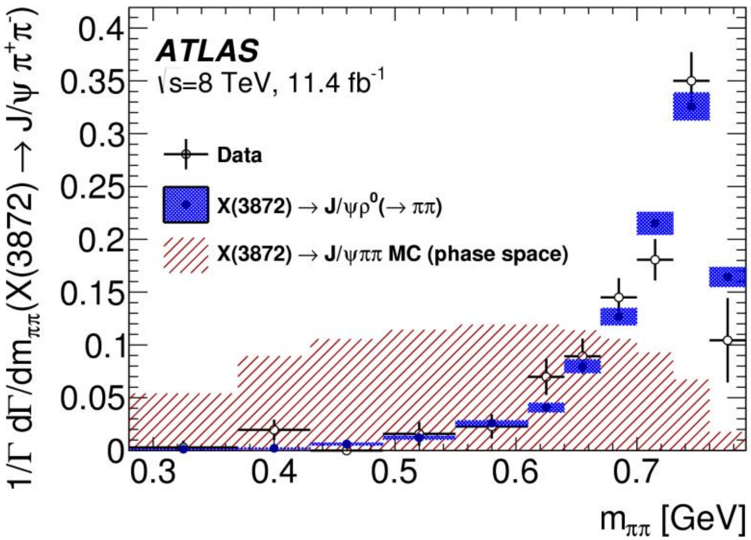
$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{\pi\pi}} \propto \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2 \times \mathrm{PS}$$

- found λ = 4.16 ± 0.06(stat) ± 0.03(syst)
- in agreement with previous measurements



In X(3872 to J/ψπ⁺π⁻ decays

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



Summary of X(3872) results

- **Differential cross sections are measured for prompt and non-prompt production of ψ(2S) and X(3872) states in the $J/\psi\pi^+\pi^-$ decay mode.**
- **Prompt production is described reasonably well by NRQCD with previously determined LDMEs.**
- **Two lifetime models for non-prompt production:**
- **single-lifetime model (with fitted effective lifetime)**
- **two-lifetime model (two fixed lifetimes, fitted fraction)**
- **Cross section results, non-prompt fractions largely indifferent to lifetime model**
- **Branching fraction ratios measured in the two models are slightly different:**

$$R_B^{1L} = \frac{\mathcal{B}(B \to X(3872) + \text{any})\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B \to \psi(2S) + \text{any})\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (3.95 \pm 0.32(\text{stat}) \pm 0.08(\text{sys})) \times 10^{-2}$$

$$R_B^{2L} = \frac{\mathcal{B}(B \to X(3872) + \text{any})\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B \to \psi(2S) + \text{any})\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (3.57 \pm 0.33(\text{stat}) \pm 0.11(\text{sys})) \times 10^{-2}$$

- **Both are smaller than 18 ± 8 % estimated from Tevatron data, made under implicit same-parent-mix assumption.**

- **Two-lifetime model allows for a significant fraction of non-prompt X(3872) to be produced in decays of B_c, which have shorter lifetime and expected to have steeper p_T dependence.**
- **In this model the fraction of non-prompt X(3872) produced from B_c decays is measured to be**

(for pT>10 GeV)
$$\frac{\sigma(pp \to B_c + \text{any})\mathcal{B}(B_c \to X(3872) + \text{any})}{\sigma(pp \to \text{non-prompt } X(3872) + \text{any})} = (25 \pm 13(\text{stat}) \pm 2(\text{sys}) \pm 5(\text{spin}))\%$$

Perspectives

- ATLAS is a "general purpose" experiment, not optimised for spectroscopic studies
- Nevertheless, due to the universality of the detector and ingenuity of analysers, a number of important contributions to heavy quark physics have been made
- No clear signs of X_b production have been found yet, but X(3872) production have been studied in some detail, with potentially interesting results
- A large amount of data collected at 13 TeV still has to be studied, but new challenges are related to increasing trigger thresholds and very high pileup
- Will keep trying to contribute to this area, provided enthusiastic manpower can be found

THANK YOU!

Backup: Table of results for ψ(2S) and X(3872)

	p_{T} range [GeV]				
	10–12	12–16	16–22	22–40	40–70
	Cross sections times branching fractions [pb / GeV]				
$\psi(2S)_{\mathrm{P}}$	$92.4 \pm 1.9 \pm 4.8$	$27.97 \pm 0.27 \pm 1.02$	$5.61 \pm 0.06 \pm 0.19$	$0.57 \pm 0.01 \pm 0.02$	$0.021 \pm 0.001 \pm 0.001$
$\psi(2S)_{\mathrm{NP}}$	$61.9 \pm 1.9 \pm 3.4$	$23.66 \pm 0.27 \pm 0.85$	$6.63 \pm 0.06 \pm 0.22$	$0.97 \pm 0.01 \pm 0.03$	$0.048 \pm 0.001 \pm 0.003$
$\psi(2S)_{\mathrm{NP}}^{\mathrm{LL}}$	$60.8 \pm 1.6 \pm 4.0$	$23.09 \pm 0.27 \pm 1.46$	$6.53 \pm 0.06 \pm 0.41$	$0.93 \pm 0.01 \pm 0.06$	$0.047 \pm 0.002 \pm 0.003$
$\psi(2S)_{\mathrm{NP}}^{\mathrm{SL}}$	$1.1 \pm 2.4 \pm 3.9$	$0.56 \pm 0.37 \pm 1.14$	$0.11 \pm 0.08 \pm 0.29$	$0.04 \pm 0.01 \pm 0.04$	$0.001 \pm 0.002 \pm 0.002$
$X(3872)_{\mathrm{P}}$	$6.05 \pm 1.30 \pm 0.38$	$2.75 \pm 0.20 \pm 0.13$	$0.60 \pm 0.04 \pm 0.02$	$0.06 \pm 0.01 \pm 0.00$	$0.003 \pm 0.001 \pm 0.000$
$X(3872)_{\mathrm{NP}}$	$2.90 \pm 1.20 \pm 0.21$	$1.28 \pm 0.20 \pm 0.07$	$0.29 \pm 0.04 \pm 0.01$	$0.03 \pm 0.01 \pm 0.00$	$0.001 \pm 0.001 \pm 0.000$
$X(3872)_{\mathrm{NP}}^{\mathrm{LL}}$	$1.87 \pm 0.82 \pm 0.14$	$0.92 \pm 0.16 \pm 0.06$	$0.29 \pm 0.04 \pm 0.02$	$0.03 \pm 0.01 \pm 0.00$	$0.001 \pm 0.001 \pm 0.000$
$X(3872)_{\mathrm{NP}}^{\mathrm{SL}}$	$1.02 \pm 1.49 \pm 0.20$	$0.35 \pm 0.25 \pm 0.06$	$0.01 \pm 0.06 \pm 0.02$	$0.00 \pm 0.01 \pm 0.00$	$0.000 \pm 0.001 \pm 0.000$
	Fractions				
$F_{\mathrm{NP}}^{\psi(2S)}$	$0.40 \pm 0.01 \pm 0.02$	$0.46 \pm 0.00 \pm 0.01$	$0.54 \pm 0.00 \pm 0.01$	$0.63 \pm 0.00 \pm 0.01$	$0.69 \pm 0.01 \pm 0.02$
$F_{\mathrm{SL}}^{\psi(2S)}$	$0.02 \pm 0.04 \pm 0.06$	$0.02 \pm 0.02 \pm 0.05$	$0.02 \pm 0.01 \pm 0.04$	$0.04 \pm 0.01 \pm 0.04$	$0.03 \pm 0.03 \pm 0.05$
$F_{\mathrm{NP}}^{X(3872)}$	$0.32 \pm 0.12 \pm 0.02$	$0.32 \pm 0.04 \pm 0.01$	$0.33 \pm 0.04 \pm 0.01$	$0.34 \pm 0.06 \pm 0.01$	$0.34 \pm 0.18 \pm 0.03$
$F_{\mathrm{SL}}^{X(3872)}$	$0.35 \pm 0.39 \pm 0.05$	$0.28 \pm 0.16 \pm 0.04$	$0.03 \pm 0.19 \pm 0.05$	$0.03 \pm 0.26 \pm 0.05$	$0.03 \pm 0.63 \pm 0.13$
	Ratios				
$X(3872)_{\mathrm{P}}/\psi(2S)_{\mathrm{P}}$	$0.065 \pm 0.014 \pm 0.004$	$0.098 \pm 0.007 \pm 0.004$	$0.106 \pm 0.008 \pm 0.004$	$0.107 \pm 0.011 \pm 0.004$	$0.128 \pm 0.044 \pm 0.012$
$X(3872)_{\mathrm{NP}}/\psi(2S)_{\mathrm{NP}}$	$0.047 \pm 0.019 \pm 0.004$	$0.054 \pm 0.008 \pm 0.003$	$0.044 \pm 0.006 \pm 0.002$	$0.033 \pm 0.007 \pm 0.001$	$0.030 \pm 0.019 \pm 0.003$
$X(3872)_{\mathrm{NP}}^{\mathrm{LL}}/\psi(2S)_{\mathrm{NP}}^{\mathrm{LL}}$	$0.031 \pm 0.014 \pm 0.002$	$0.040 \pm 0.007 \pm 0.003$	$0.044 \pm 0.006 \pm 0.003$	$0.033 \pm 0.006 \pm 0.002$	$0.030 \pm 0.019 \pm 0.003$
$X(3872)_{\mathrm{NP}}^{\mathrm{SL}}/\psi(2S)_{\mathrm{NP}}^{\mathrm{LL}}$	$0.016 \pm 0.024 \pm 0.003$	$0.015 \pm 0.011 \pm 0.003$	$0.001 \pm 0.008 \pm 0.002$	$0.001 \pm 0.009 \pm 0.004$	$0.001 \pm 0.024 \pm 0.005$