Quarkonium spectroscopy

with ATLAS experiment at LHC

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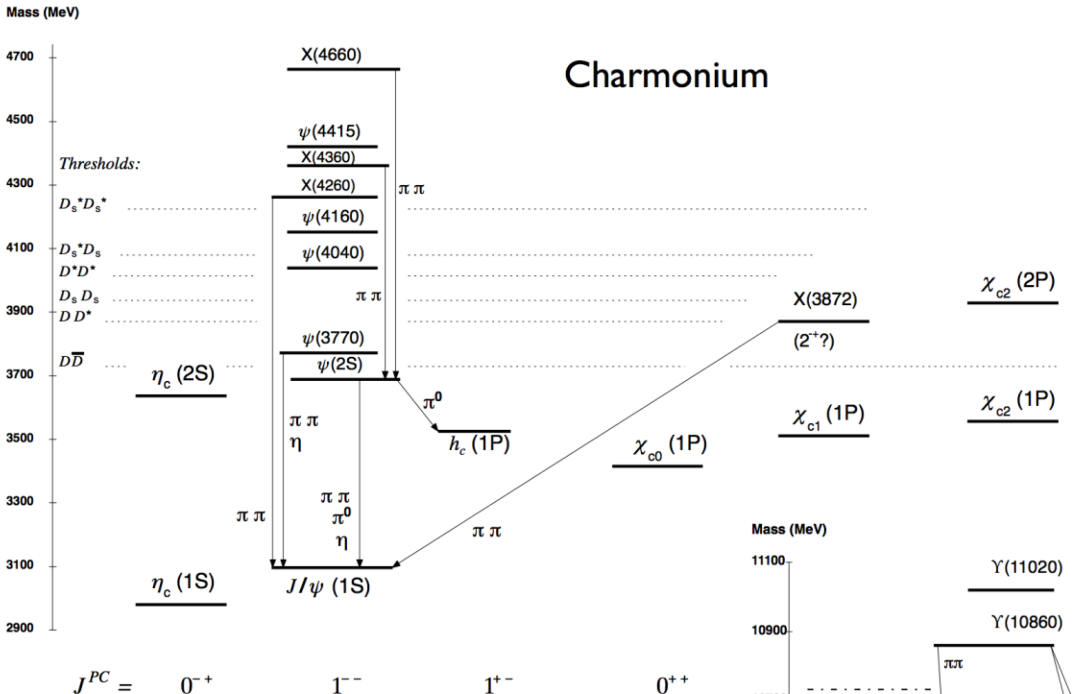
GGSWBS'18 Workshop, Tbilisi, 21 August 2018

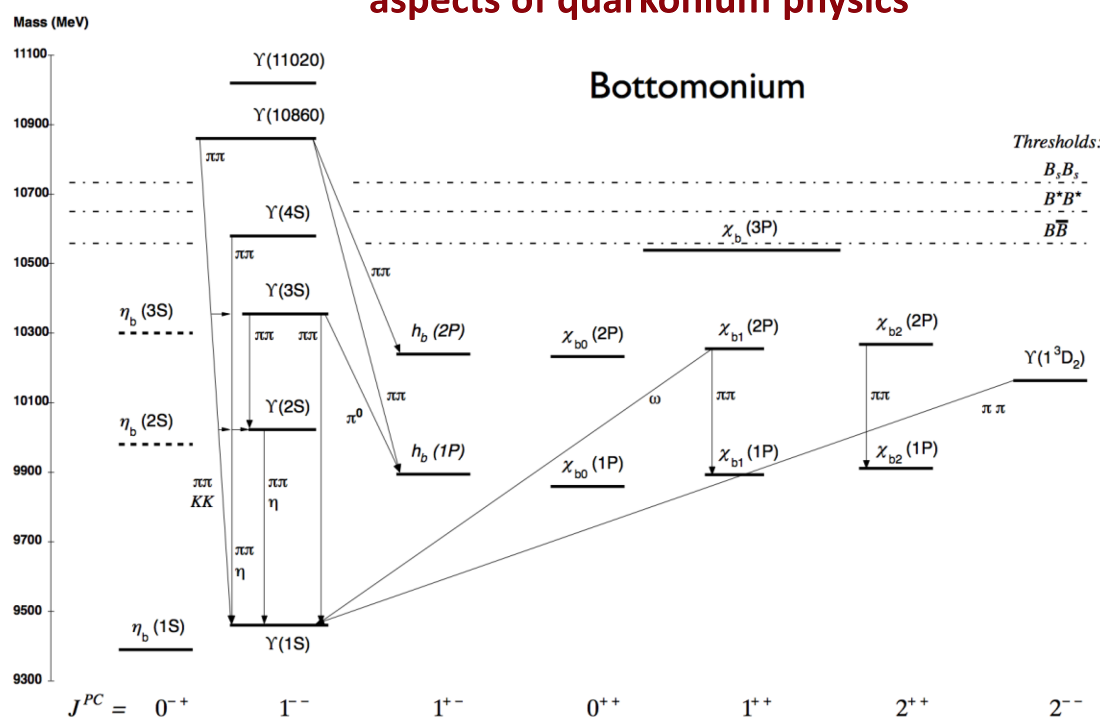
Talk outline



Heavy quarkonium states present a rich spectroscopy

Complex "ecosystem" – understanding quarkonium requires careful study of many transitions and decay channels

ATLAS has a long-standing and evolving programme of studies on various aspects of quarkonium physics



Several topics I cover today:

Recent results on quarkonium production:

- **$\psi(2S) \rightarrow J/\psi\, \pi^+\pi^-$**
- **$X_{c1,2} \rightarrow J/\psi\, \gamma$**

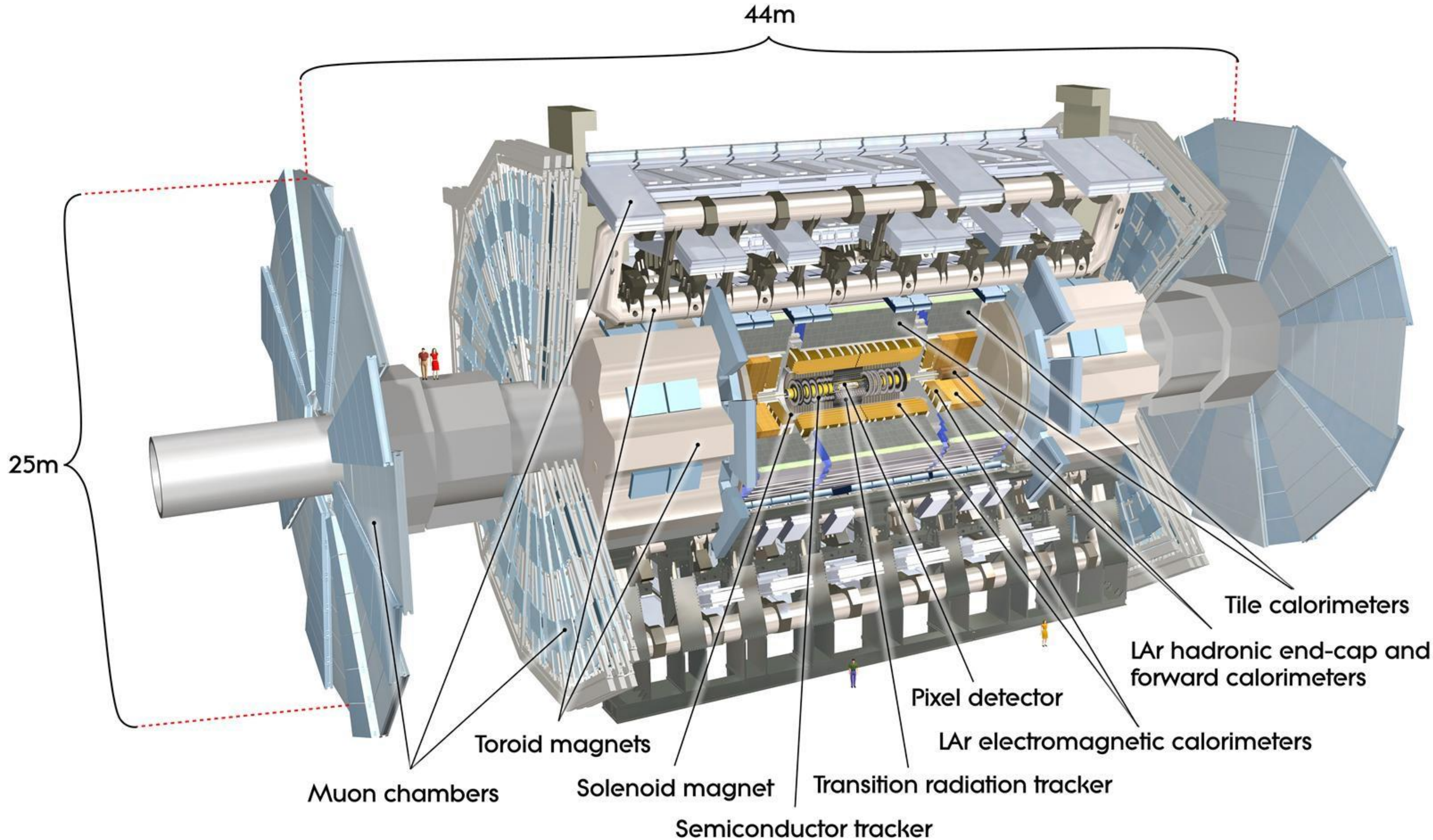
Recent results in spectroscopy proper

- **Discovery of $\chi_b(3P)$**
- **Search for X_b**

Asymmetric quarkonium B_c

X(3872) production

The ATLAS detector at LHC



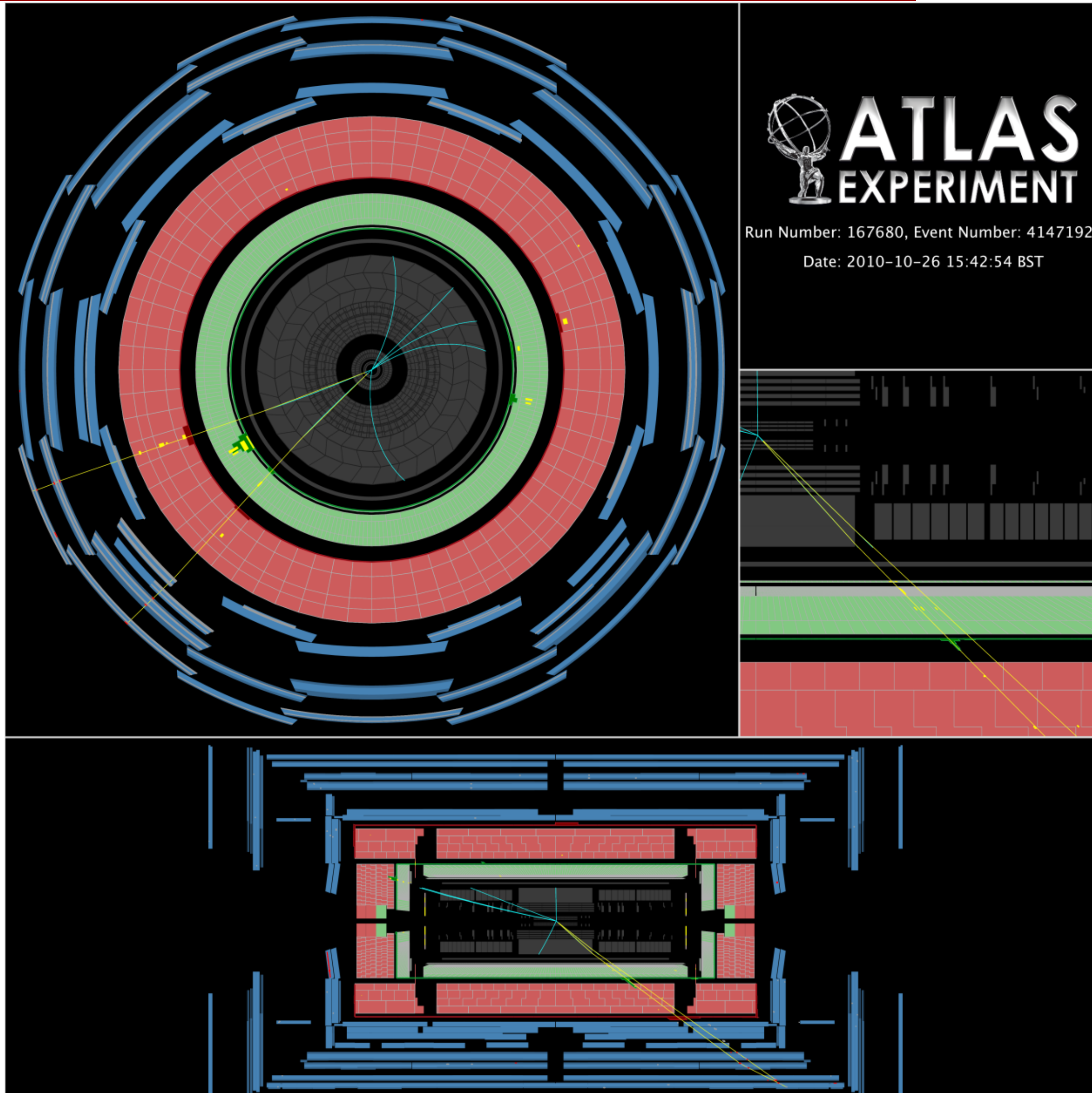
ATLAS event display: $\chi_c \rightarrow J/\psi(\mu^+\mu^-)\ \gamma$ candidate

Cross section views perpendicular and parallel to the beam line

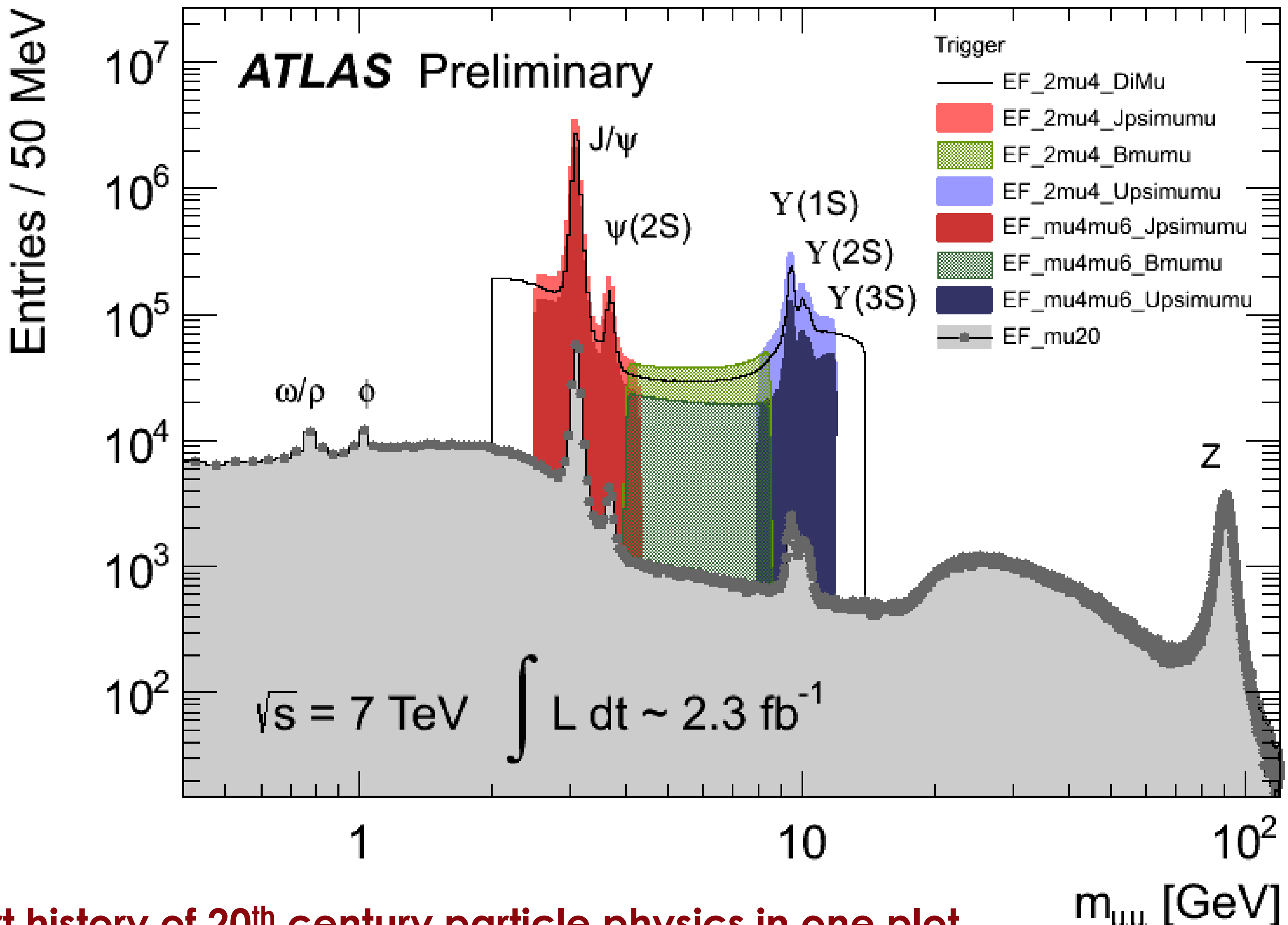
Two muon tracks spanning the Inner Detector and the Muon System

A photon tower in Eclectromagnetic Calorimeter

Invariant mass in the χ_c region



Muon and dimuon triggers in ATLAS



Short history of 20th century particle physics in one plot…

Trigger thresholds and yields

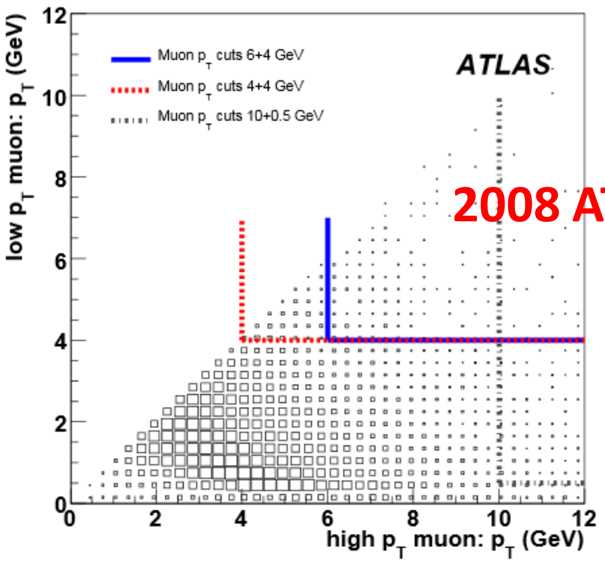
Most of the results presented here used data selection based on di-muon triggers

- typically mu4mu4, sometimes mu6mu4
- mu4mu4 un-prescaled at 7 TeV, mu6mu4 un-prescaled at 8 TeV
- little/no efficiency at low pt of the di-muon system
- unpleasant angular biases at high pt, where the two muons get close together

Single-muon triggers also used for data-driven determination of trigger efficiencies

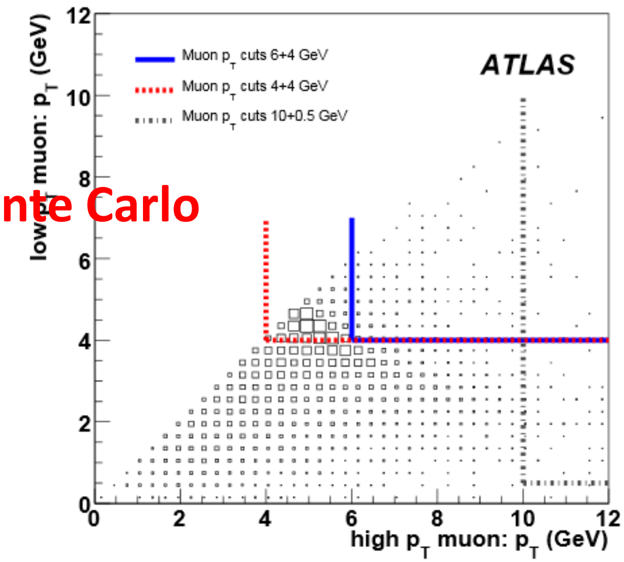
Inevitably need to increase thresholds with increasing luminosity

Other trigger chains in place, so far mostly used for performance studies



(a) J/ψ

2008 ATLAS Monte Carlo



(b) Υ

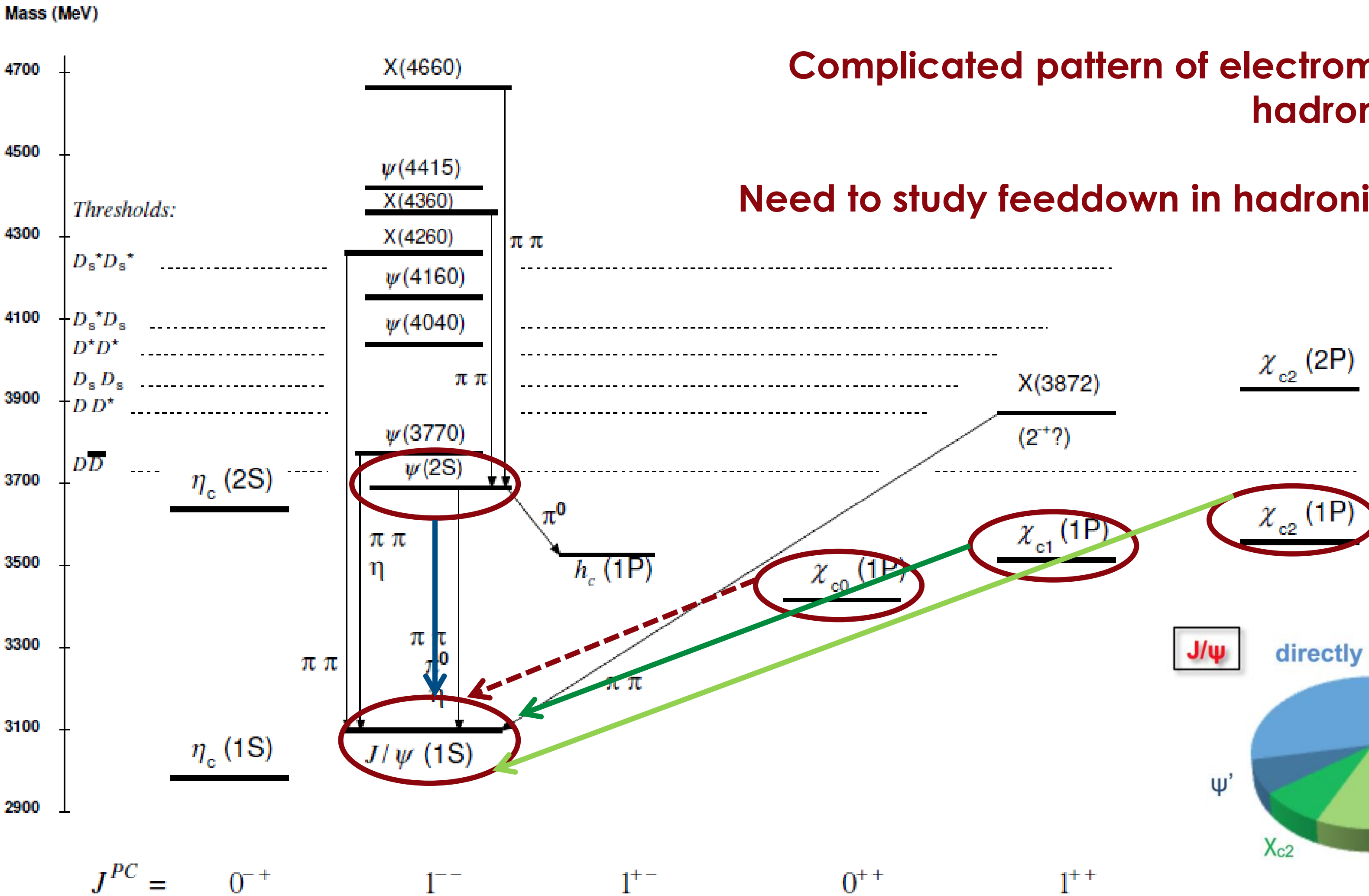
CERN-OPEN-2008-020

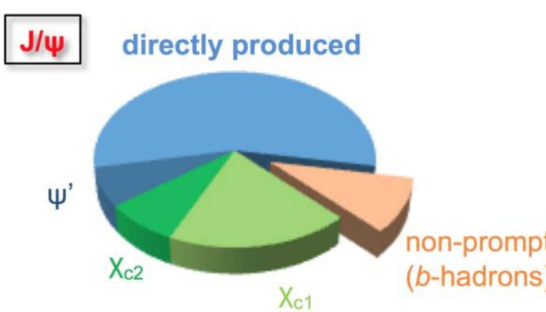
Charmonium spectroscopy and feeddown

Rich spectrum of states with a variety of quantum numbers

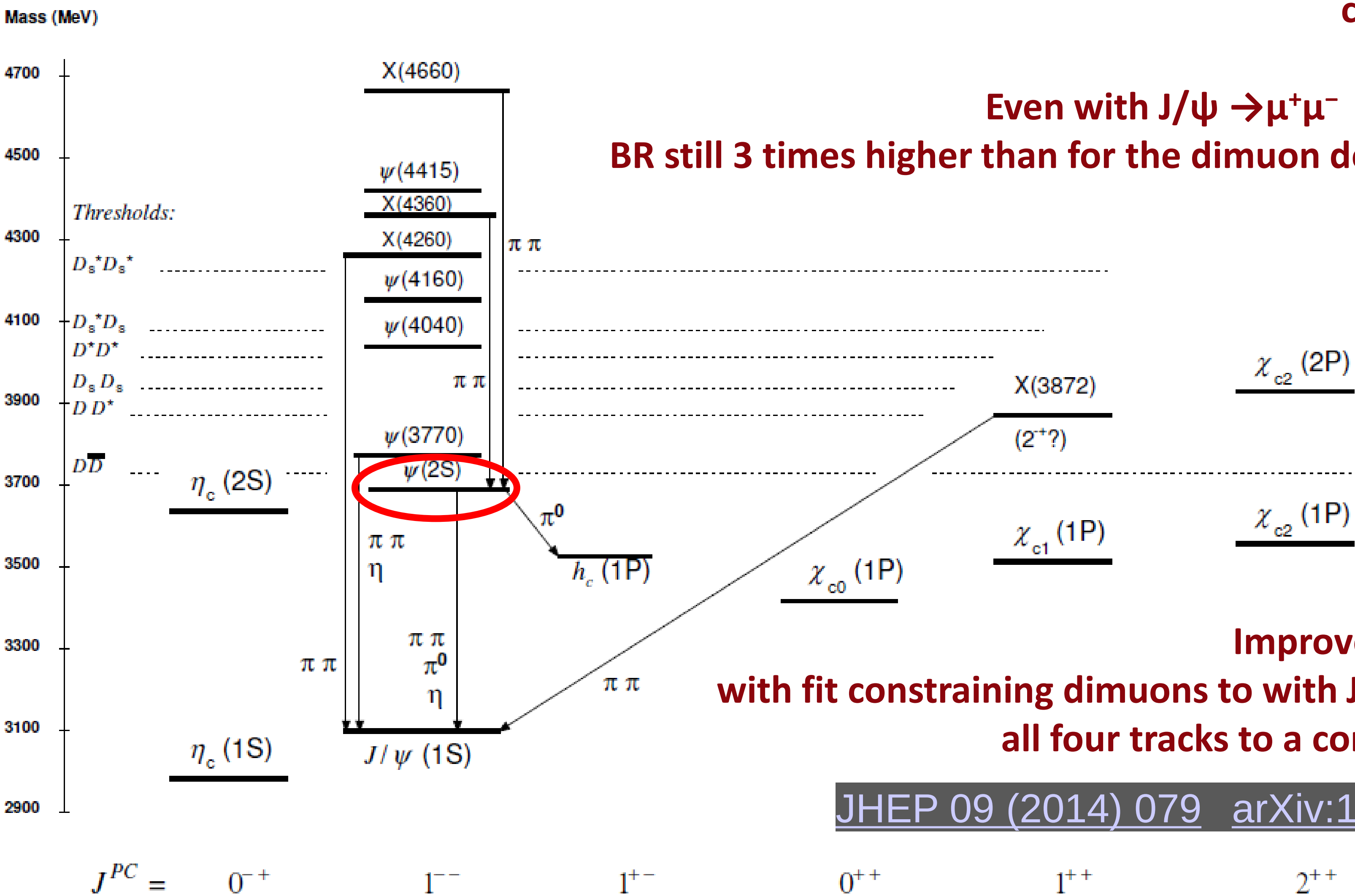
Complicated pattern of electromagnetic and hadronic transitions

Need to study feeddown in hadronic production





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



About a third of all ψ(2S) decays into J/ψ and a pair of charged pions

Even with $J/\psi \rightarrow \mu^+\mu^-$ requirement, BR still 3 times higher than for the dimuon decay of ψ(2S)

Improved resolution with fit constraining dimuons to with J/ψ mass and all four tracks to a common vertex

JHEP 09 (2014) 079 arXiv:1407.5532

$J/\psi(\to\mu^+\mu^-)\pi^+\pi^-$ candidates

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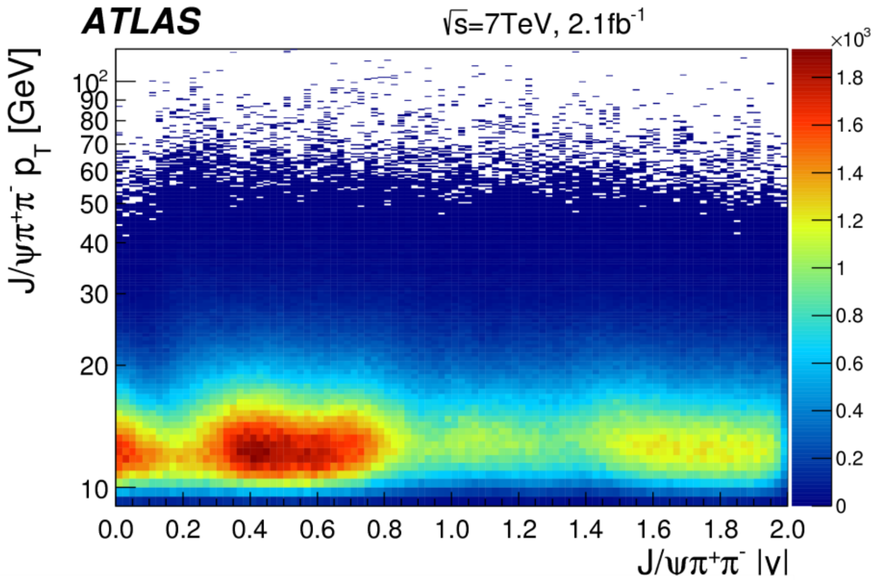
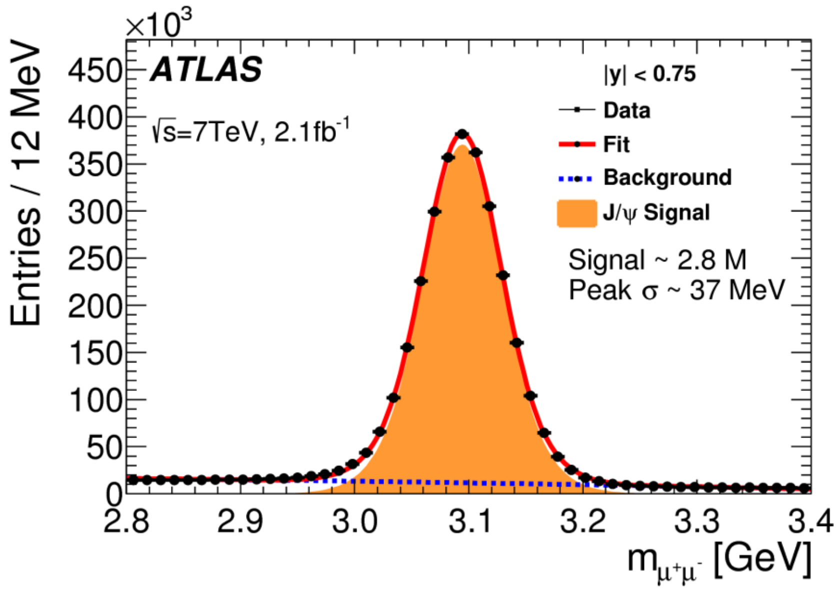
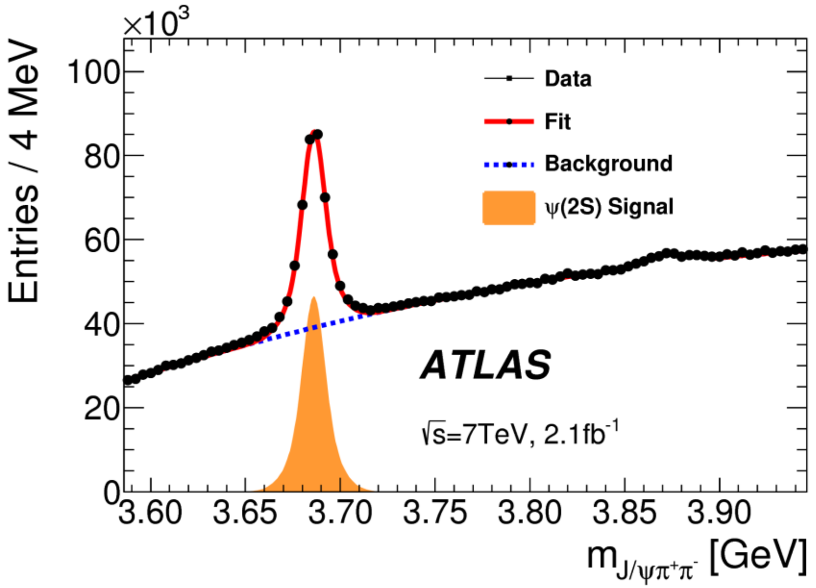
Scatter plot in p_T - rapidity space of $J/\psi(\to\mu^+\mu^-)\pi^+\pi^-$ candidates in the vicinity of $\psi(2S)$ mass

JHEP 09 (2014) 079 arXiv:1407.5532



Resolution in $\mu^+\mu^-\pi^+\pi^-$ mass is greatly improved by a kinematic fit constraining $\mu^+\mu^-$ to J/ψ mass, and all four tracks to the same vertex





Prompt and Non-Prompt separation

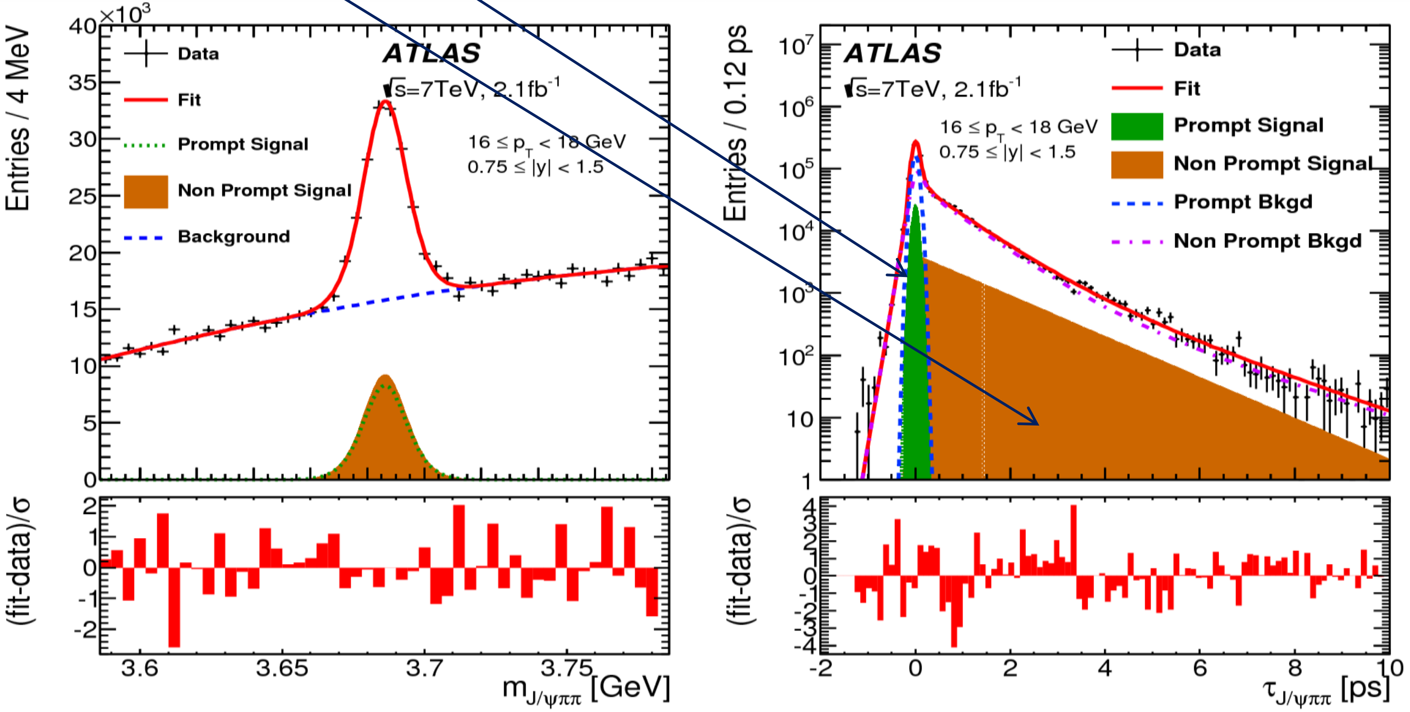
Use transverse decay length (lifetime) of the $\mu^+\mu^-\pi^+\pi^-$ vertex relative to the primary vertex to separate:

$$l_{J/\psi} = L_{xy} \cdot \frac{m_{J/\psi}}{p_T}$$

1. ***Prompt*** production -- from QCD (or short-lived) sources, with lifetimes consistent with resolution

JHEP 09 (2014) 079 arXiv:1407.5532

2. ***Non-prompt*** production -- from long-lived sources such as b-hadron decays



2D mass vs lifetime unbinned maximum-likelihood fit is done to extract ***Prompt*** and ***Non-prompt*** yields in each p_T – rapidity bin

Two projections shown for a sample bin

ψ(2S) → J/ψ(→μ⁺μ⁻)π⁺π⁻ production

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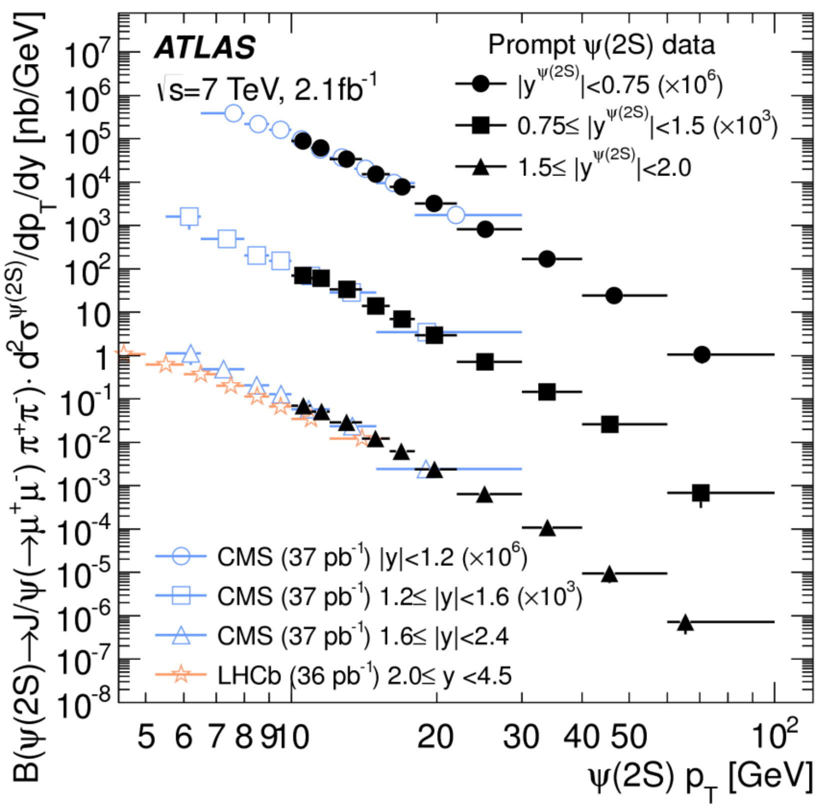
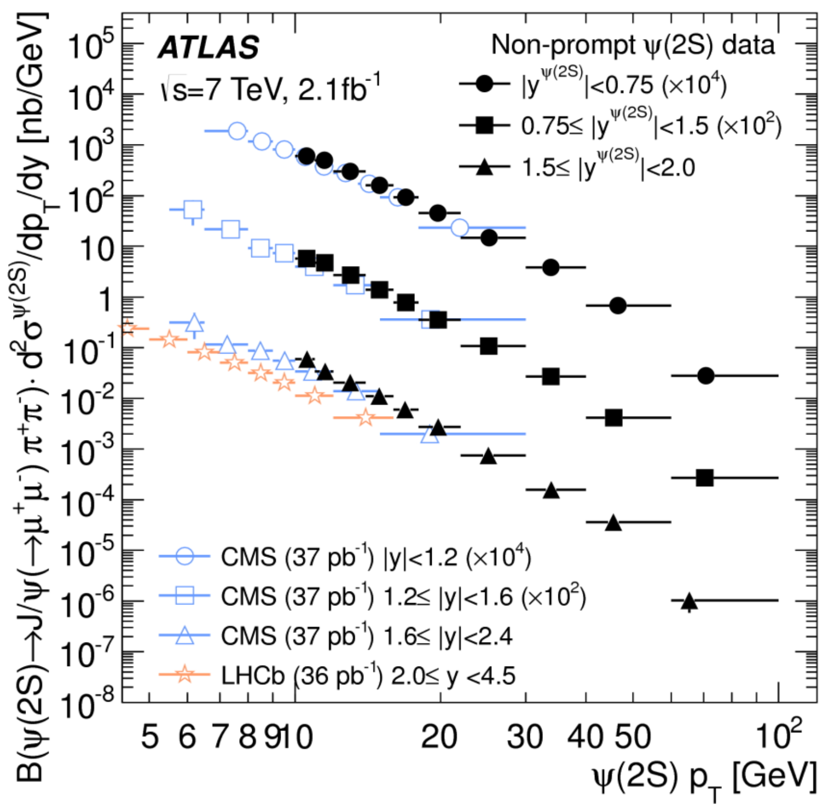
Measurement with 2.1 fb^{-1} of pp data at 7 TeV

Muon p_T > 4 GeV, pion candidate tracks p_T> 0.5 GeV

JHEP 09 (2014) 079 arXiv:1407.5532

- **Baseline channel for study of X(3872), extended p_T range probed to 100 GeV**
- **Good agreement with similar data from CMS and LHCb**



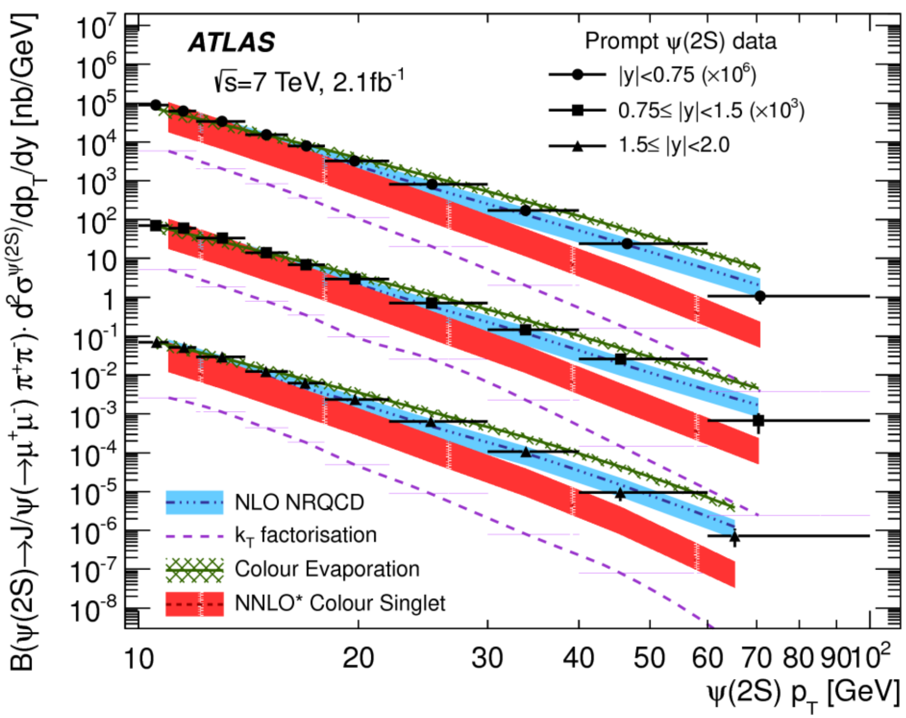


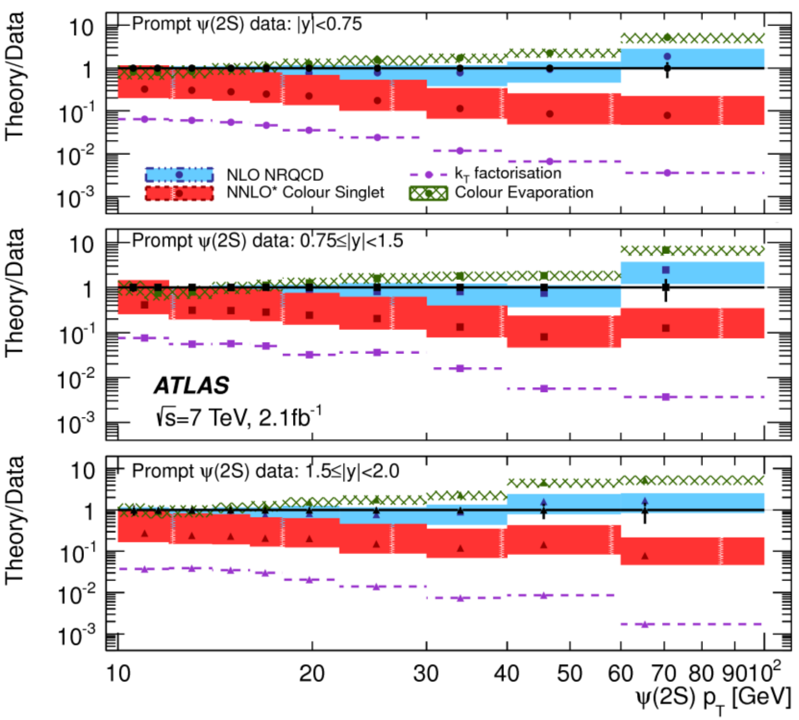
Prompt ψ(2S) → J/ψ π π production

JHEP 09 (2014) 079 arXiv:1407.5532

High precision wide reach prompt production cross-section in ψ(2S)→J/ψππ.

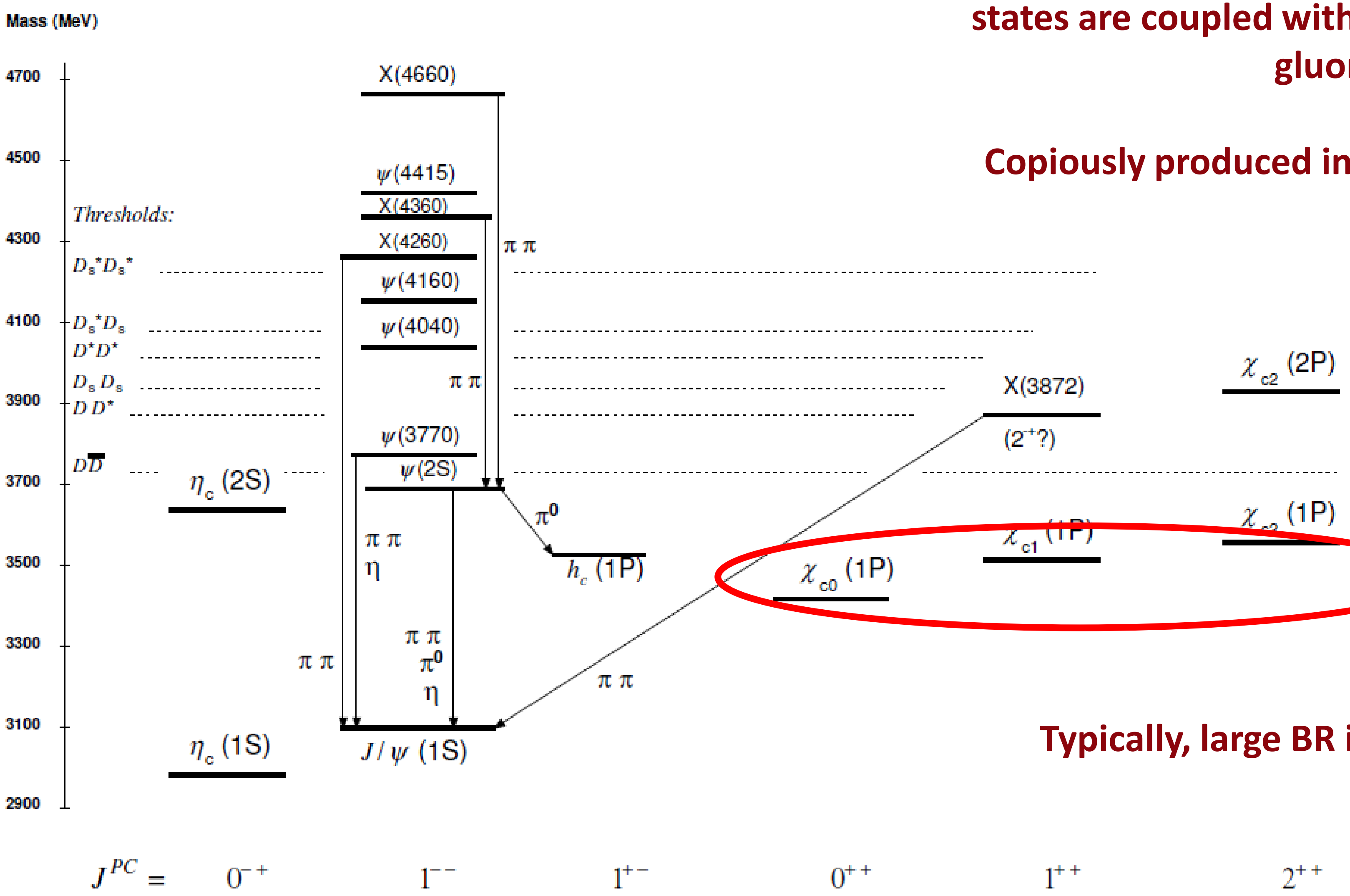
- **Agreement with NRQCD, possible slight overestimate at highest p_T**
- **k_T-factorisation model does not describe data well**
- **Colour Singlet NNLO* predictions undershoot at highest scales**





Production of P-wave charmonium states

[JHEP 07 (2014) 154](#) [arXiv:1404.7035](#)



C-even, P-wave charmonium states are coupled with the two-gluon channel

Copiously produced in hadronic collisions

Typically, large BR into J/ψ γ

$\chi_c \longrightarrow J/\psi(\rightarrow\mu\mu)\gamma$

P-wave charmonium production theoretically and experimentally tricky to handle

Important to understand this production channel to get a complete picture of quarkonium production.

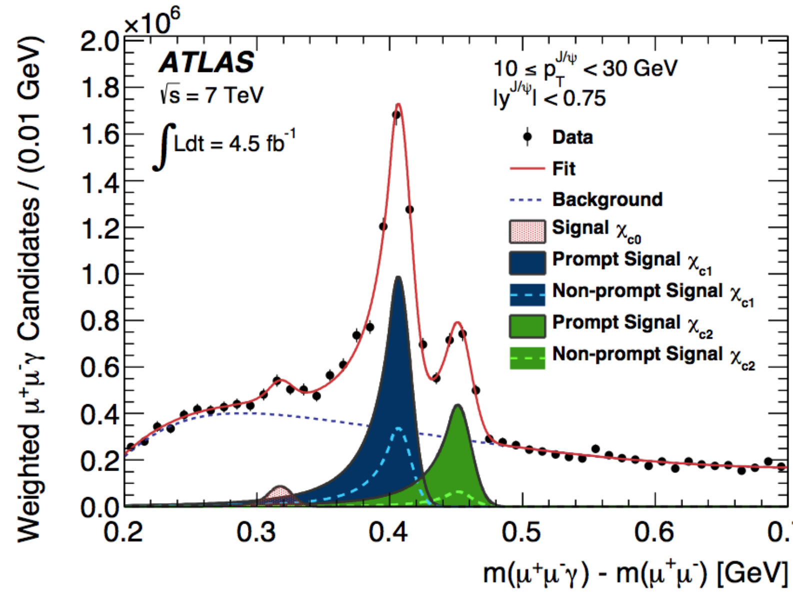
Experimentally challenging:

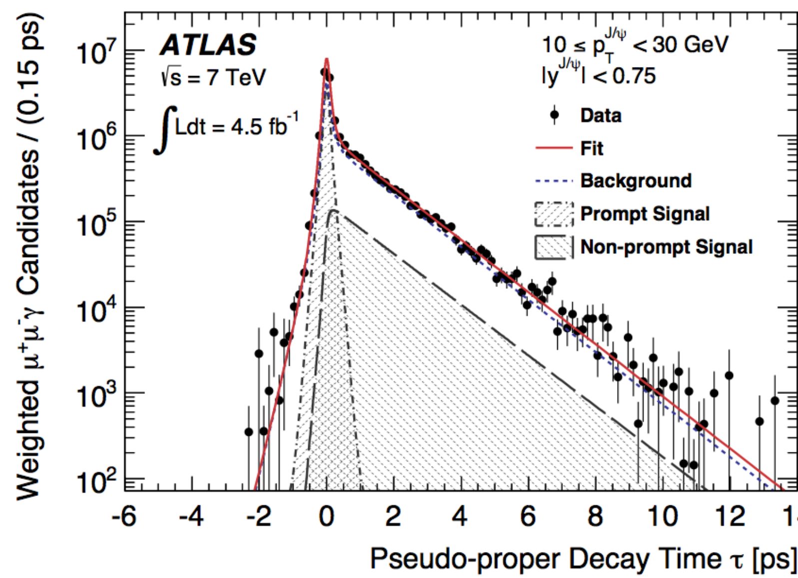
- low p_T muons
- precise reconstruction of soft (p_T>1 GeV) photon through conversions
  – low efficiencies

Perform unbinned maximum likelihood fit on acceptance- and efficiency-corrected mass and lifetime.

Extract prompt and non-prompt production of various χ_c states

JHEP 07 (2014) 154 arXiv:1404.7035





Prompt $\chi_c \rightarrow J/\psi\gamma$ and $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio

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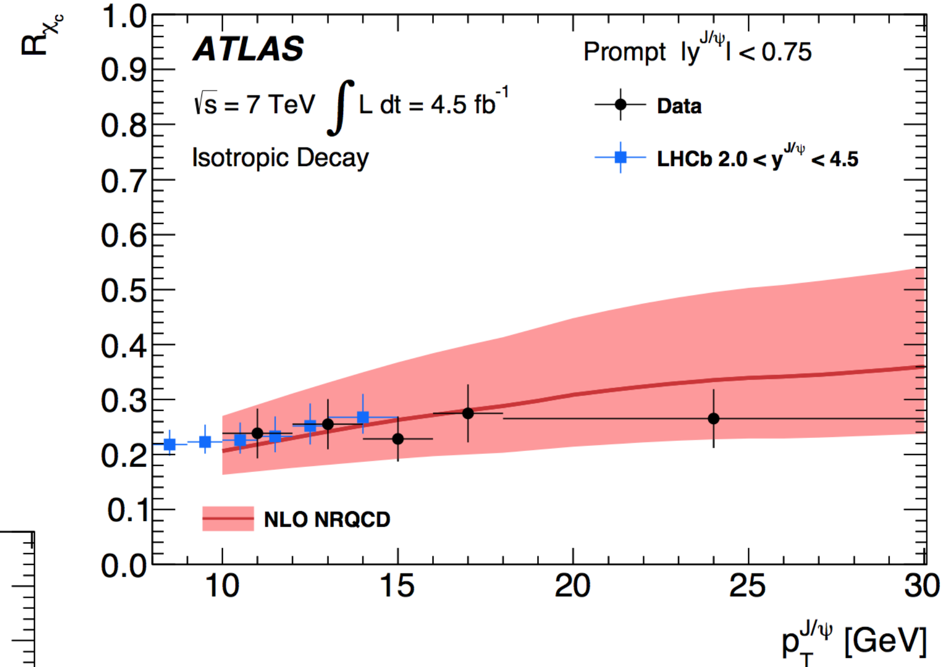
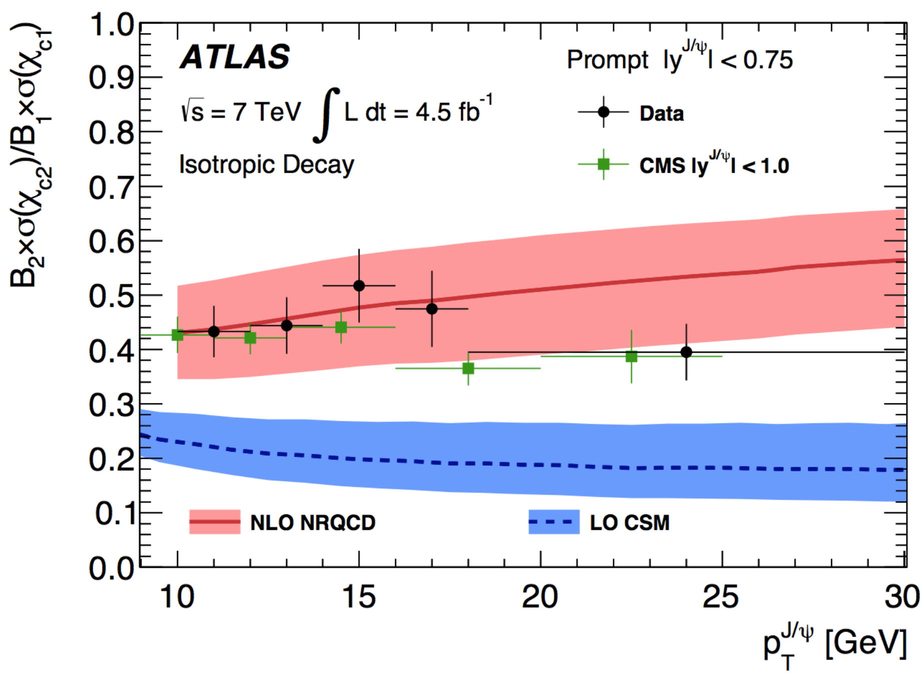
Fraction of prompt J/ψ produced in χ_c feed-down (right)→

Data show that between 20–30% of prompt J/ψ are produced in χ_c decays





Prompt χ_c cross-section ratio ← (left)

Data show more χ_{c1} than χ_{c2}

Possible sensitivity to presence of colour octet contributions in NRQCD ?

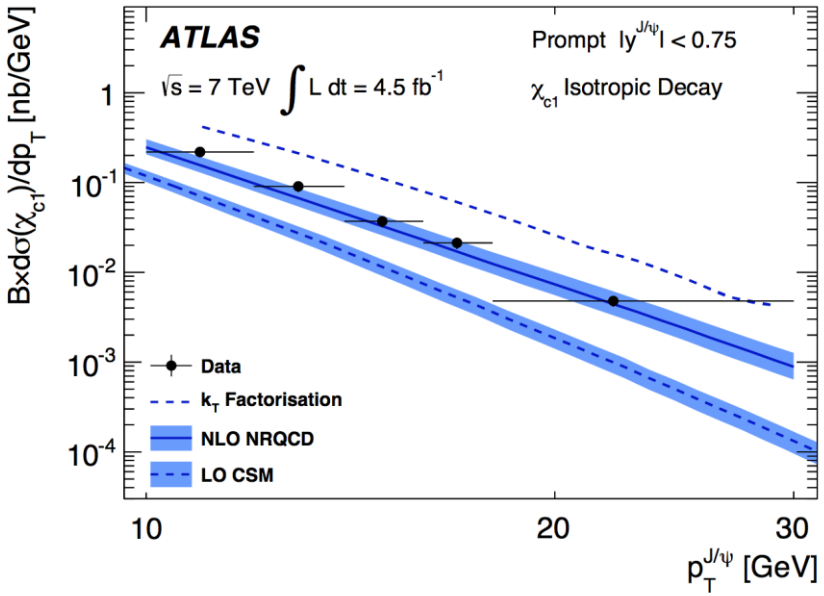
JHEP 07 (2014) 154 arXiv:1404.7035

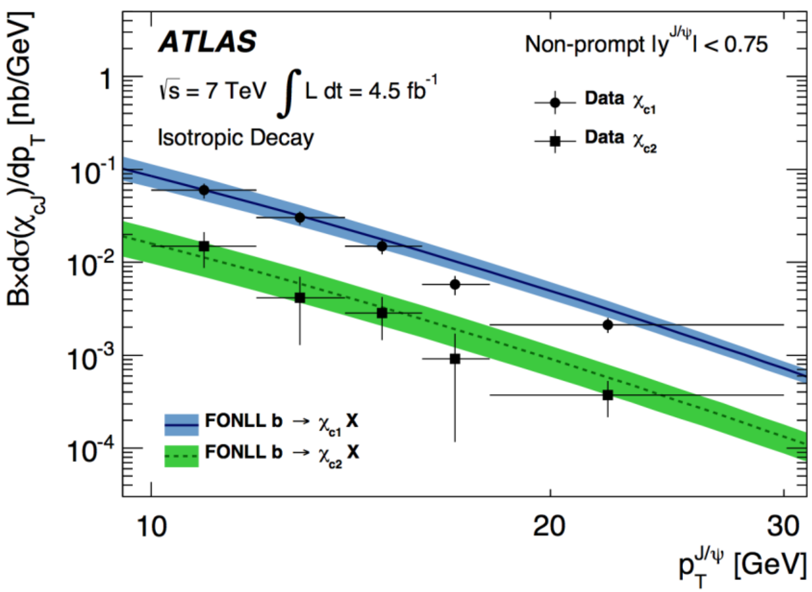
Absolute χ_c production rates

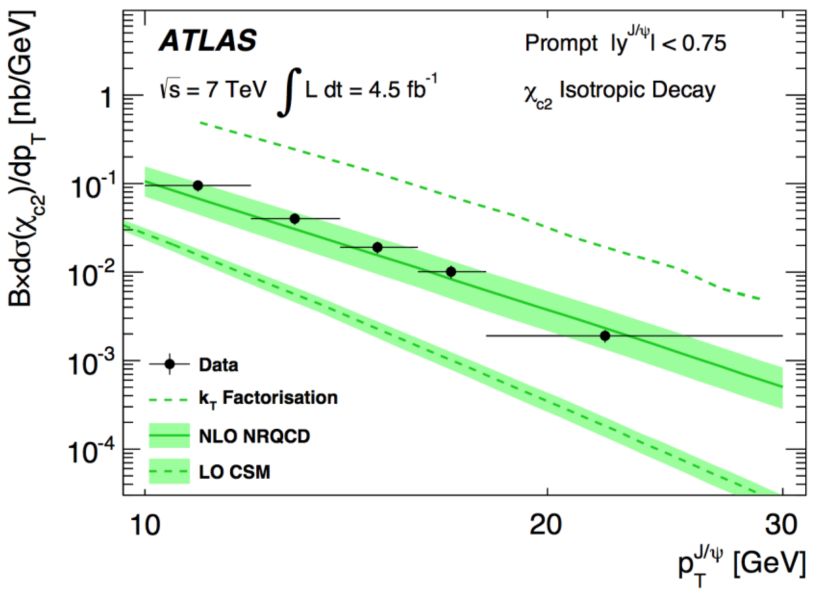
JHEP 07 (2014) 154   arXiv:1404.7035

First absolute prompt (right) and non-prompt (below) χ_{c1} and χ_{c2} differential cross sections, compared to predictions

NRQCD / FONLL able to describe the data, but some hints at high-p_T excess in the latter?







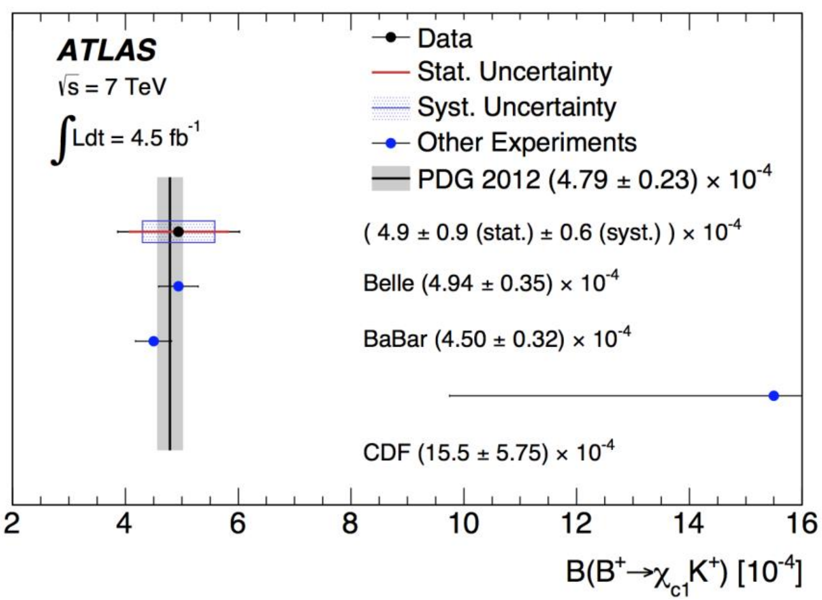
Measurement of Br($B^{\pm} \to \chi_{c1} K^{\pm}$)

Branching fraction measurement using same χ_c data sample and selections, can extract measurement of Br($B^{\pm} \to \chi_{c1} K^{\pm}$)

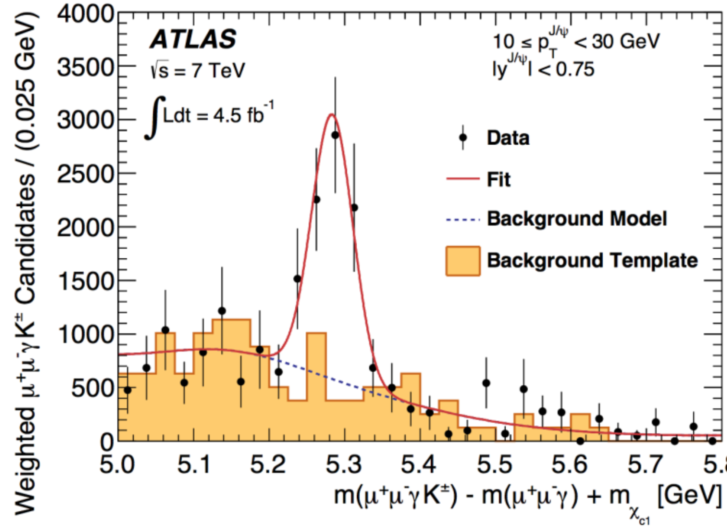
Use precisely-known $B^{\pm} \to J/\psi K^{\pm}$ decay as control.

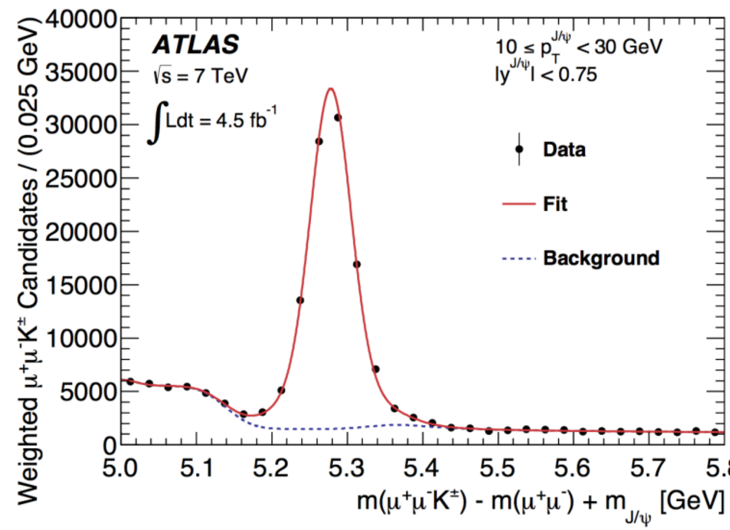
$$\mathcal{B}\left(B^{\pm} \to \chi_{c1} K^{\pm}\right) = \mathcal{A}_B \cdot \frac{N^B_{\chi_{c1}}}{N^B_{J/\psi}} \cdot \frac{\mathcal{B}\left(B^{\pm} \to J/\psi K^{\pm}\right)}{\mathcal{B}\left(\chi_{c1} \to J/\psi\, \gamma\right)}$$

ATLAS measurement not far from best B-factory results; prospects for improvements!



$B^{\pm} \to \chi_{c1} K^{\pm}$





$B^{\pm} \to J/\psi K^{\pm}$

Observation of the χ_b states

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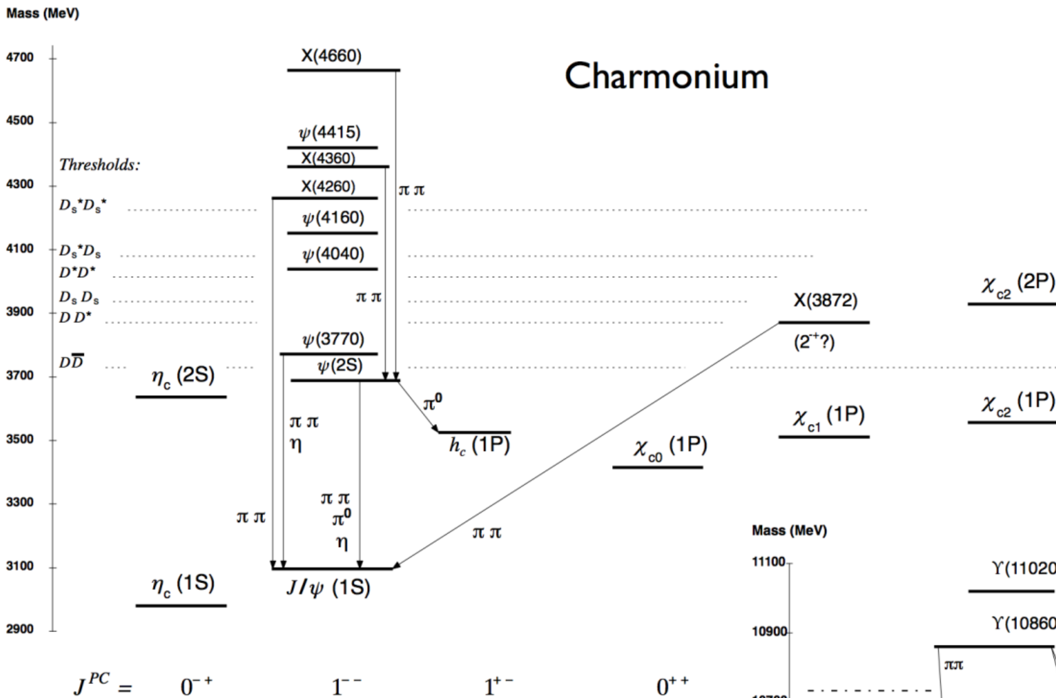
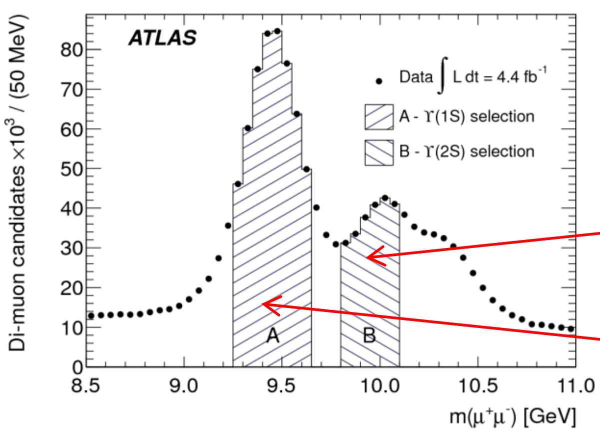
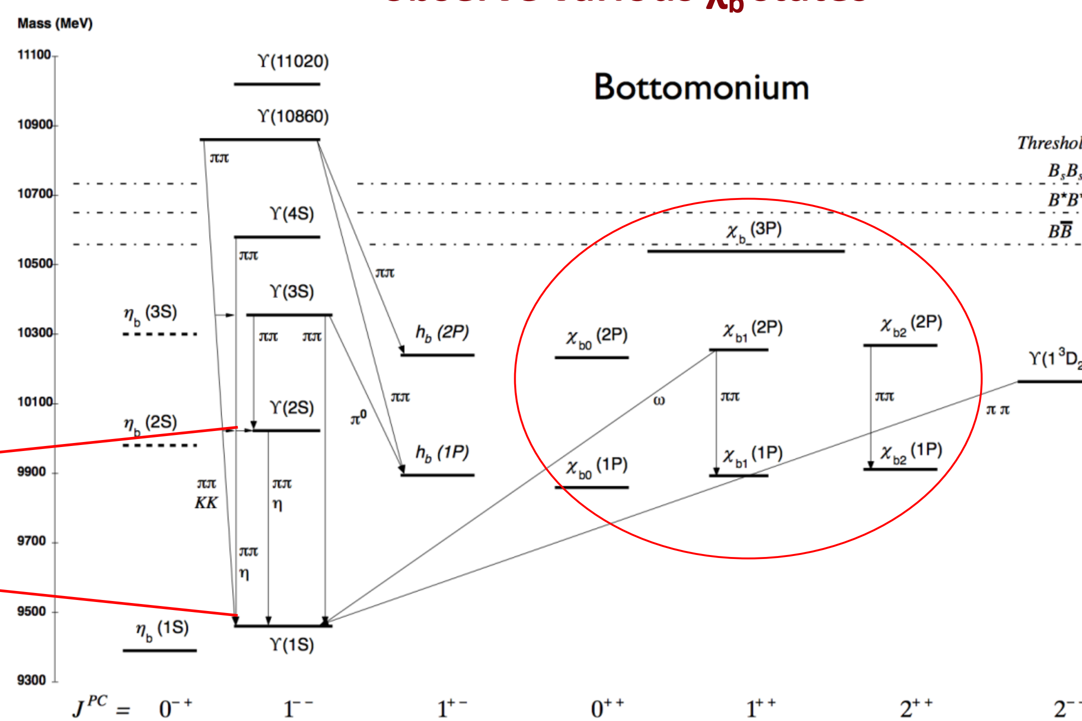


In a similar way to χ_{c1} and χ_{c2} states:

Combine dimuons from ϒ mass range with photons

search for peaks in the μμγ system to observe various χ_b states





First observation of the $\chi_{bJ}(3P)$ state

The three peaks correspond to decays $\chi_{bJ}(1P)$, $\chi_{bJ}(2P)$, $\chi_{bJ}(3P)$ into $\Upsilon(1S) + \gamma$

First observation of $\chi_{bJ}(3P)$

In fact, the first new state seen at the LHC

PRL 108 (2012) 152001 arXiv:1112.5154

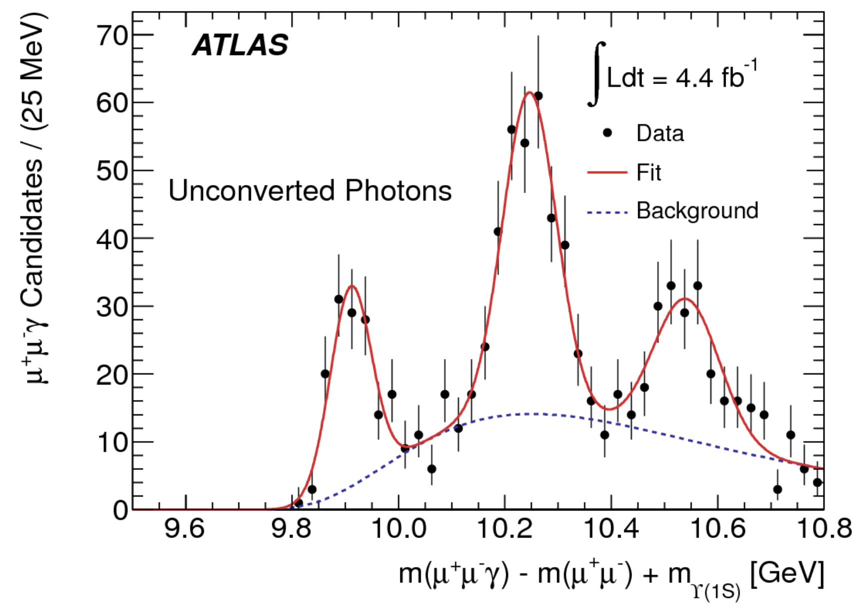
Significance of the new peak calculated through the difference of log-likelihoods with and without the peak in the fit:

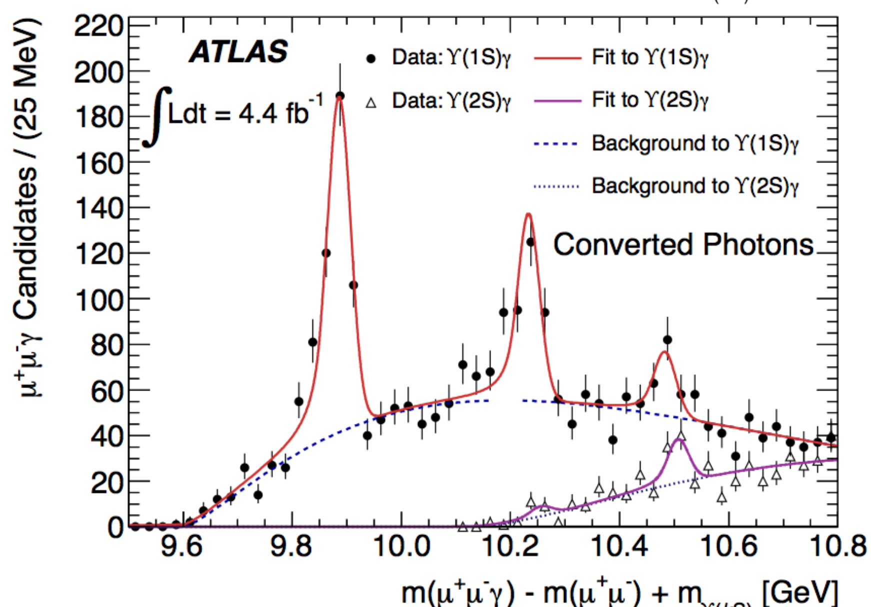
$D = \log (L_{with} / L_{without})$

With moderately large numbers involved, -2D is distributed as $\Delta\chi^2$

The "with" hypothesis won, with significance in excess of 6σ (separately for converted and unconverted photon cases)

Since then, confirmed by DØ and LHCb





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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Home > News > Science > LHCs first new particle

SCIENCE

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

By Mark Brown | 22 December 11

PRL 108 (2012) 152001 arXiv:1112.5154

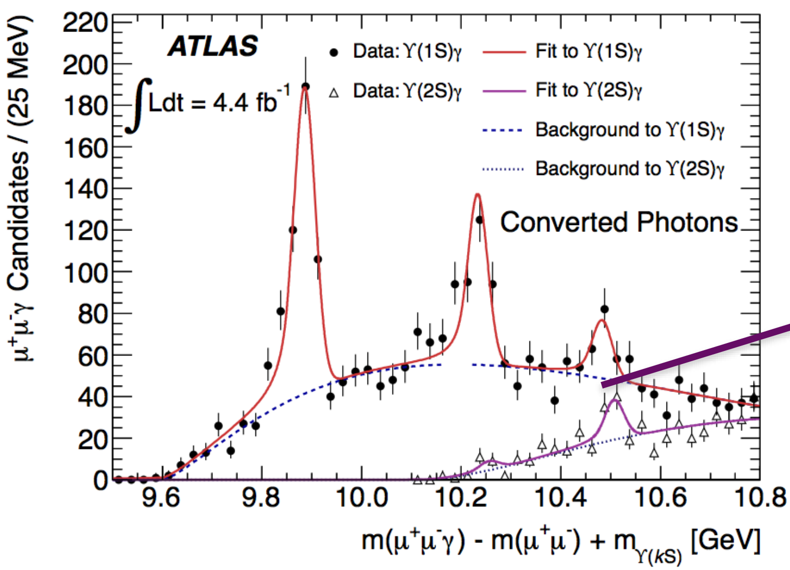
Mass barycentre of $\chi_{bJ}(3P)$ states

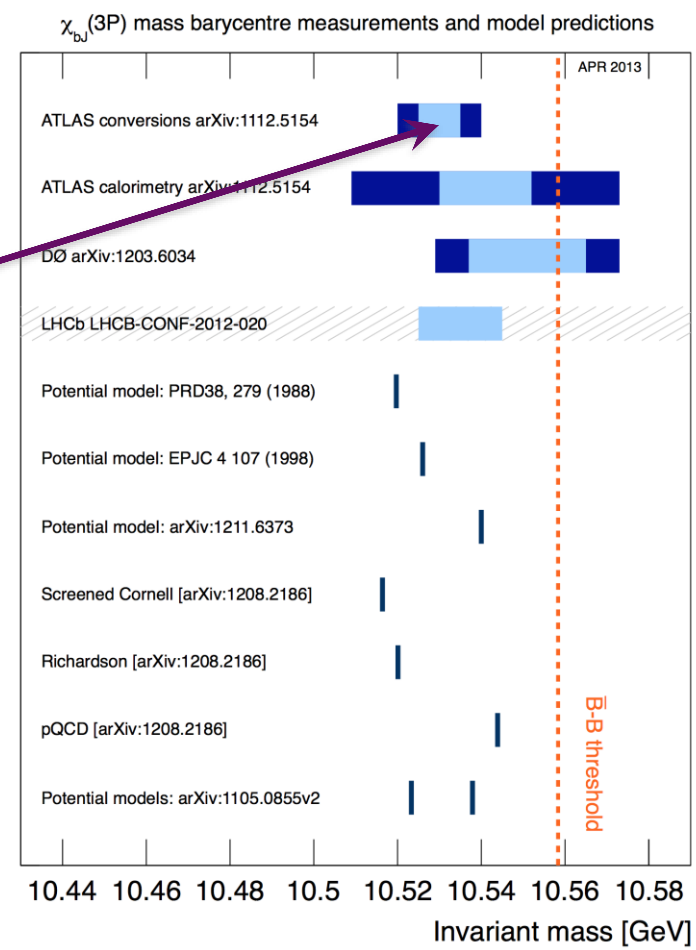
Lancaster University

PRL 108 (2012) 152001 arXiv:1112.5154

Measured by ATLAS to be 10.530 +/-0.005 (stat.) +/-0.009 (syst.) GeV

No quoted systematic for early LHCb observation, latest LHCb measurement results not included





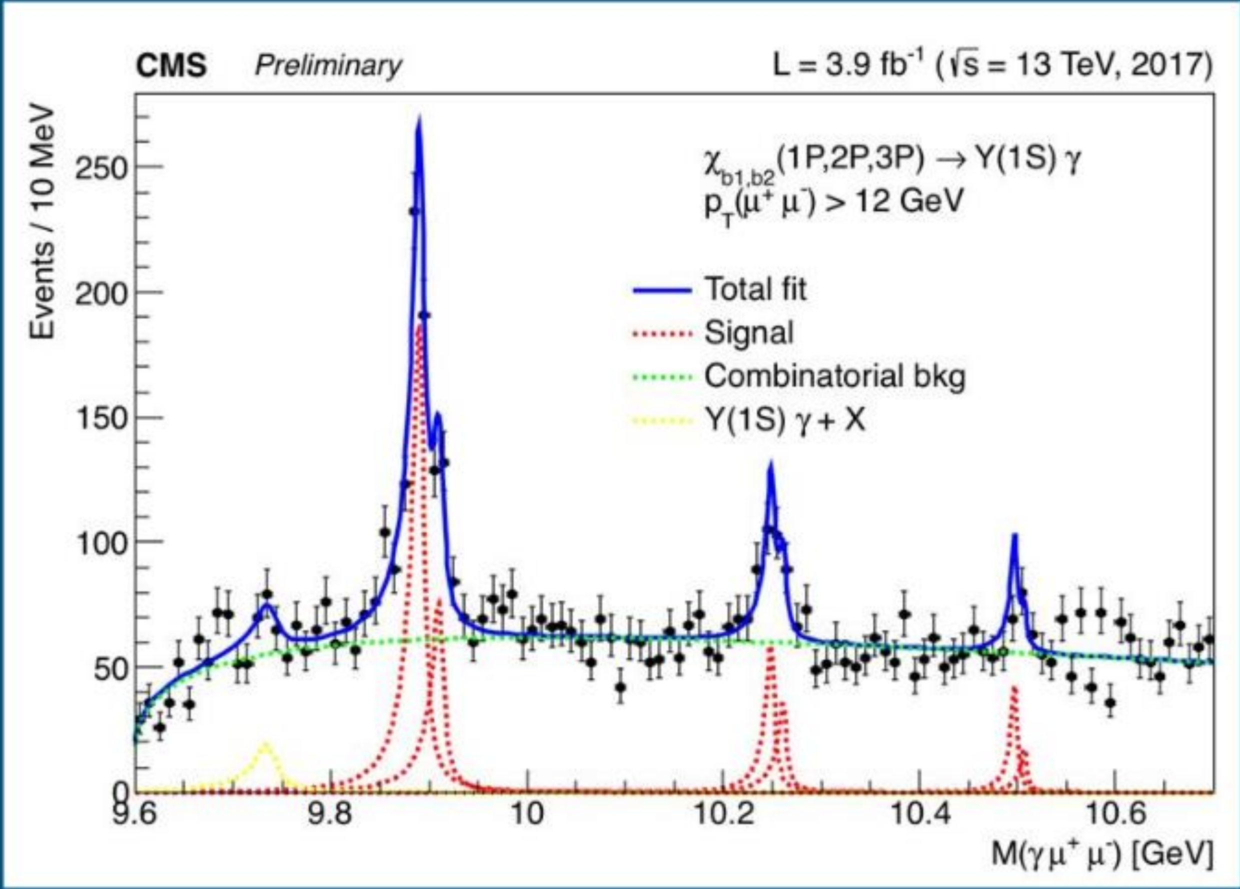
Possibly a mixture of $\chi_{bJ}(3P)$, X_b and a BBbar molecule?

M. Karliner, J. Rosner, PRD91 (2015) 014014; 1410.77293 [hep-ph]

Clearly, more studies needed…

Recently confirmed by CMS too…

$\chi_b \rightarrow \gamma\, \Upsilon (\rightarrow \mu^+\mu^-)$



Mass[χ_{b1}(1P)] = 9.890 ± 0.001 (stat.) GeV, Mass[χ_{b2}(1P)] = 9.910 ± 0.001 (stat.) GeV
Mass[χ_{b1}(2P)] = 10.248 ± 0.001 (stat.) GeV, Mass[χ_{b2}(2P)] = 10.260 ± 0.001 (stat.) GeV
Mass[χ_{b1}(3P)] = 10.497 ± 0.001 (stat.) GeV, Mass[χ_{b2}(3P)] = 10.507 ± 0.001 (stat.) GeV

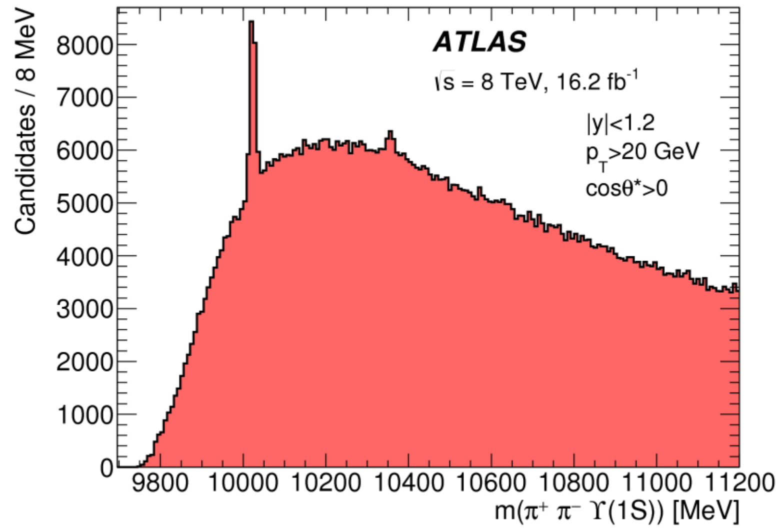
Search for X_b

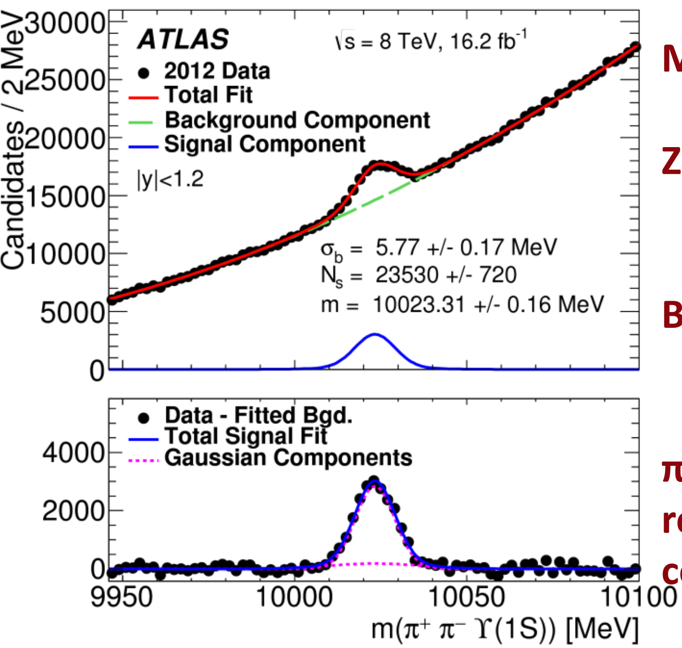
PLB740 (2015) 199-217 arXiv:1410.4409

ATLAS searched for an exotic bottomonium state X_b (analog of X(3872) in charmonium)

The $\pi^+\pi^-\Upsilon(1S)$ invariant mass distribution was analysed in the kinematic range most sensitive to an X_b signal: $|y| < 1.2$, $p_T > 20$ GeV, and $\cos\theta^* > 0$.

The only apparent peaks seen are at the masses of the $\Upsilon(2S)$ (10023 MeV) and $\Upsilon(3S)$ (10355 MeV).



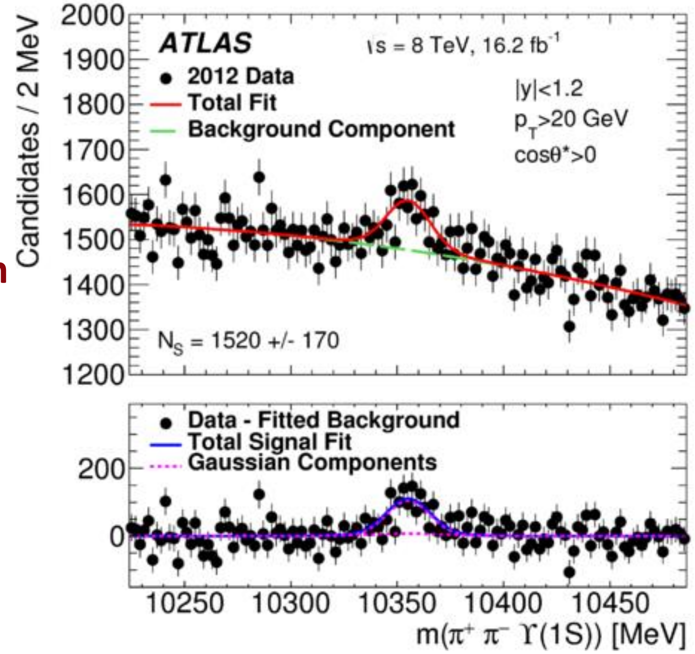


Mass resolution varies across the detector

Zoomed-in Υ(2S, 3S) peaks in the measured $\pi^+\pi^-\Upsilon(1S)$ mass in the barrel region

Background-subtracted data shown underneath

$\pi^+\pi^-\Upsilon(1S)$ invariant mass resolution (with $\Upsilon(1S)$ mass constraint) better than 6 MeV

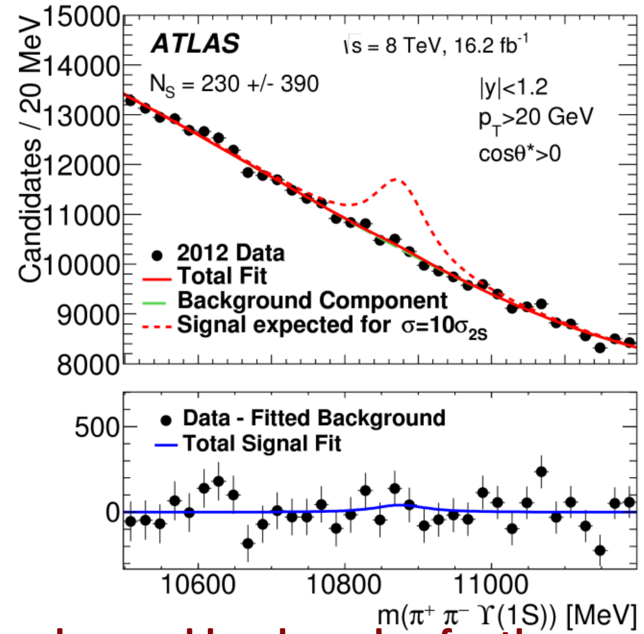


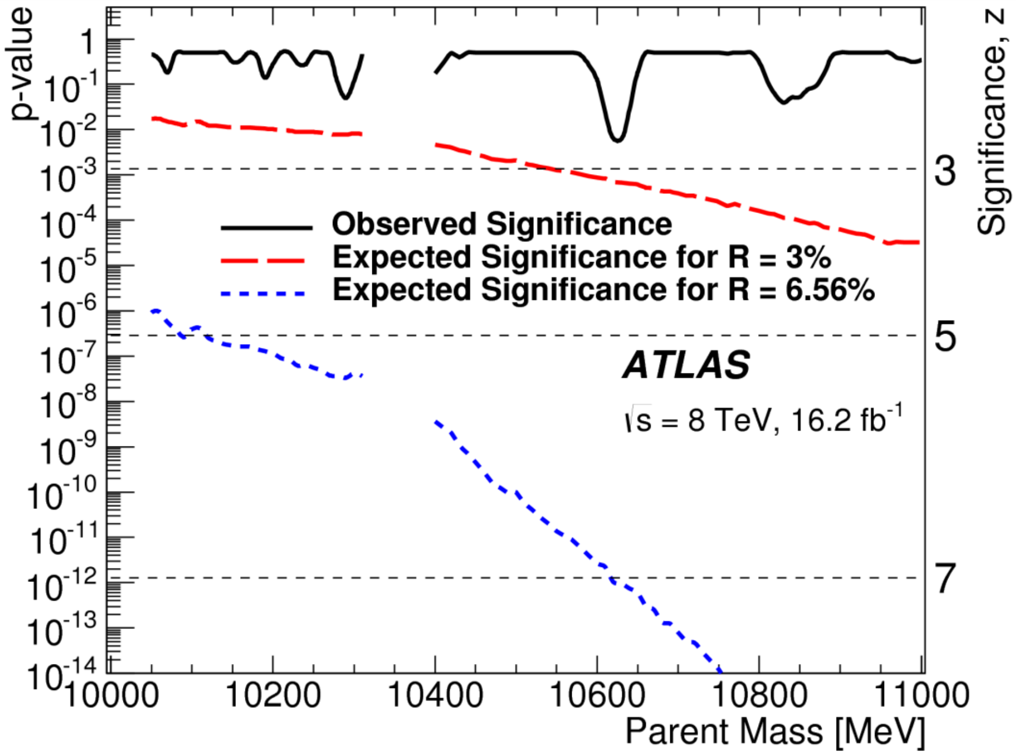
Search for more peaks

PLB740 (2015) 199-217   arXiv:1410.4409

Detailed fit results in one of interesting mass ranges →

Dashed line: a possible strong signal of the Υ(10860) with known BR into $\pi^+\pi^-\Upsilon(1S)$ cross section 10 x σ_{2S}





←

Left scale: observed local p-value for the background-only hypothesis

Right scale: significance of a peak in $\pi^+\pi^-\Upsilon(1S)$ (right scale)

vs mass of a hypothetical X_b parent state.

Dashed: expected values for various $R=(\sigma B)/(\sigma B)_{2S}$

Upper limits

[PLB740 (2015) 199-217](#) [arXiv:1410.4409](#)

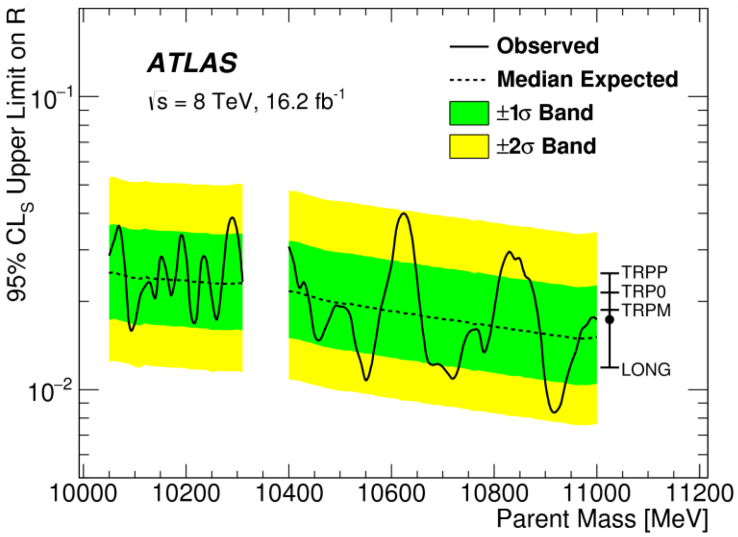
Solid line:

Observed 95% CL_S upper limits on the relative production rate $R = (\sigma B)/(\sigma B)_{2S}$ of an X_b state

Dashed line:

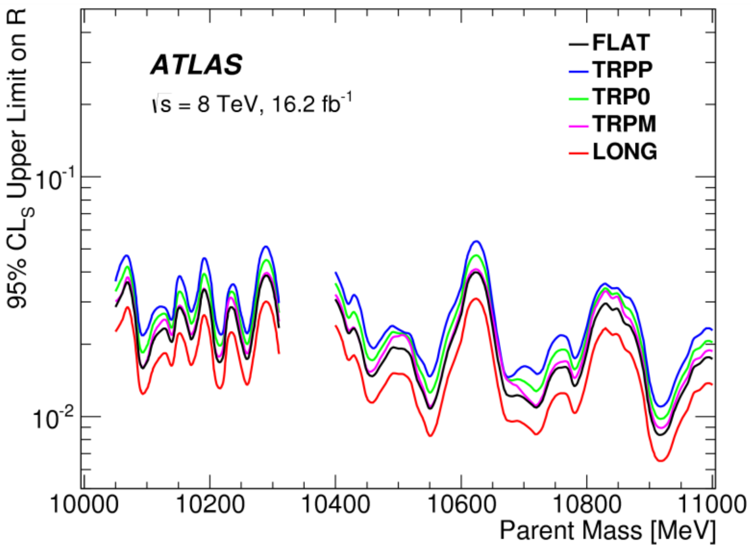
median expectation, with the corresponding $\pm1\sigma$ (green) and $\pm2\sigma$ (yellow) bands

Assuming isotropic decay into $\pi^+\pi^-\Upsilon(1S)$



In general, sensitivity depends on spin alignment of X_b

Limits are somewhat weaker for longitudinal polarisation, stronger for transverse



In short: no X_b candidate has been seen yet

Note: X_b may not exist at all

analogy with X(3872) may not be good (isospin):

F.-K. Guo, U.-G. Meißner, W. Wang, arXiv:1402.6236

B_c and $B_c(2S)$ observation

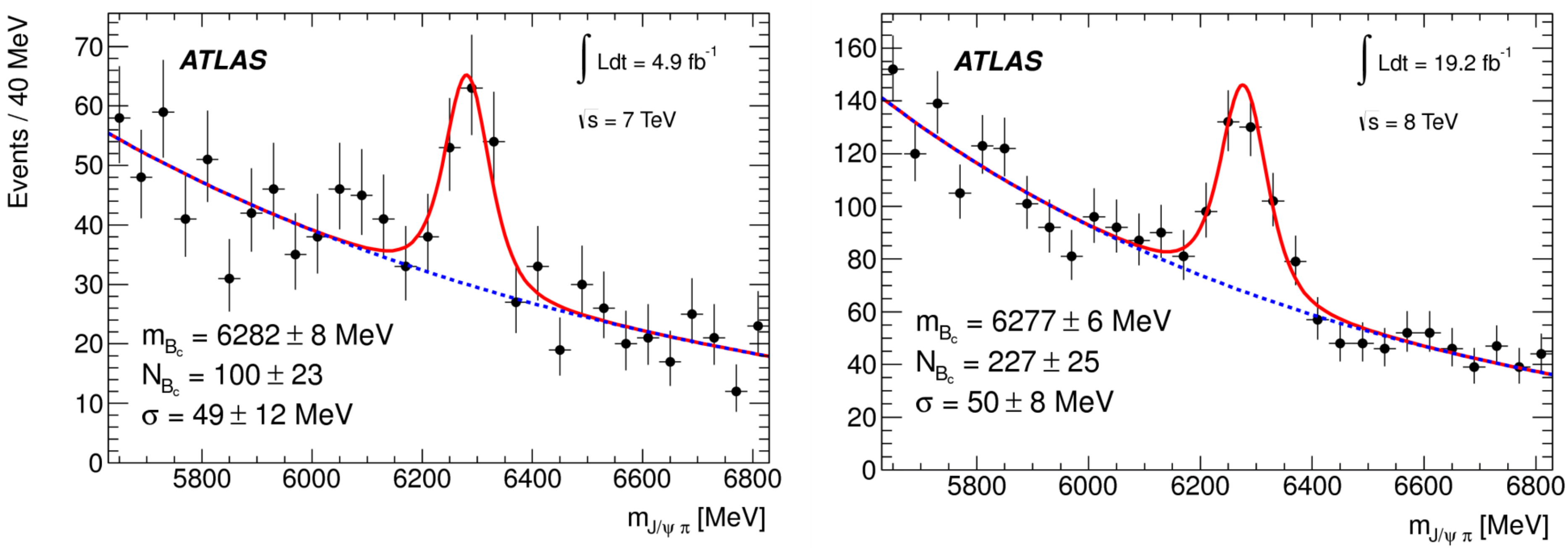
B_c system is arguably very interesting from the point of view of quarkonium spectroscopy

- well positioned in-between charmonium and bottomonium
- reliable predictions exist within various models

Ground state pseudoscalar B_c observed in ATLAS in $J/\psi\pi$ mode, both at 7 TeV and 8 TeV

- $J/\psi \rightarrow \mu\mu$ trigger, followed by "mu6mu4" selection
- Mass-constrained vertex fit with a pion track of $p_T > 4$ GeV and significant impact parameter wrt primary vertex

PRL 113 (2014) 212004 arXiv:1407.1032



B_c and $B_c(2S)$ observation

$B_c^{\pm}$ candidates combined with nearby tracks assuming pion masses

- p_T of $B_c^{\pm}$ candidates > 15 GeV (at 7 TeV) and > 18 GeV (at 8 TeV)

An excited state of the $B_c^{\pm}$ meson was observed in the decay mode into $B_c^{\pm}\pi^+\pi^-$, with $B_c^{\pm}\rightarrow J/\psi\pi^{\pm}$

- significances: 3.7 σ (7 TeV), 4.5 σ (8 TeV), 5.2 σ (combined)

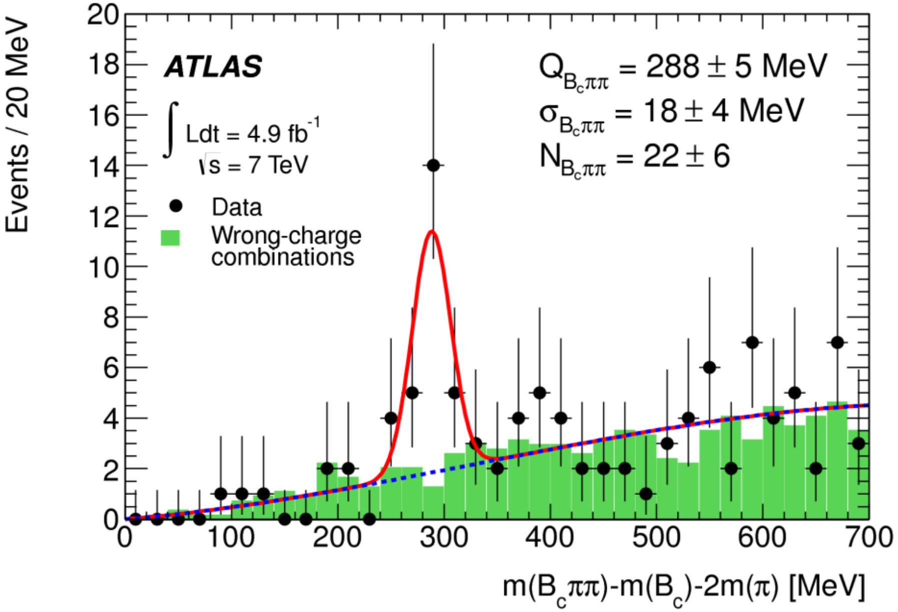
Appears as a peak in $Q = m(B_c^{\pm}\pi\pi) - m(B_c^{\pm}) - 2m(\pi^{\pm})$

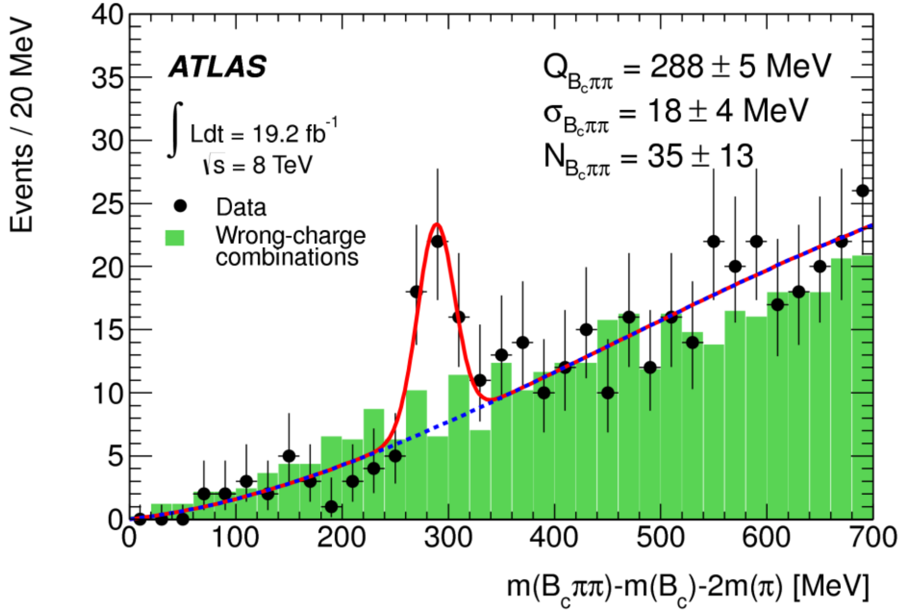
- observed mass 6842±4(stat)±5(syst) MeV

Stability of yields checked with $B^{\pm}\rightarrow J/\psi K^{\pm}$

Mass and decay mode consistent with expectations for $B_c^{\pm}(2S)$

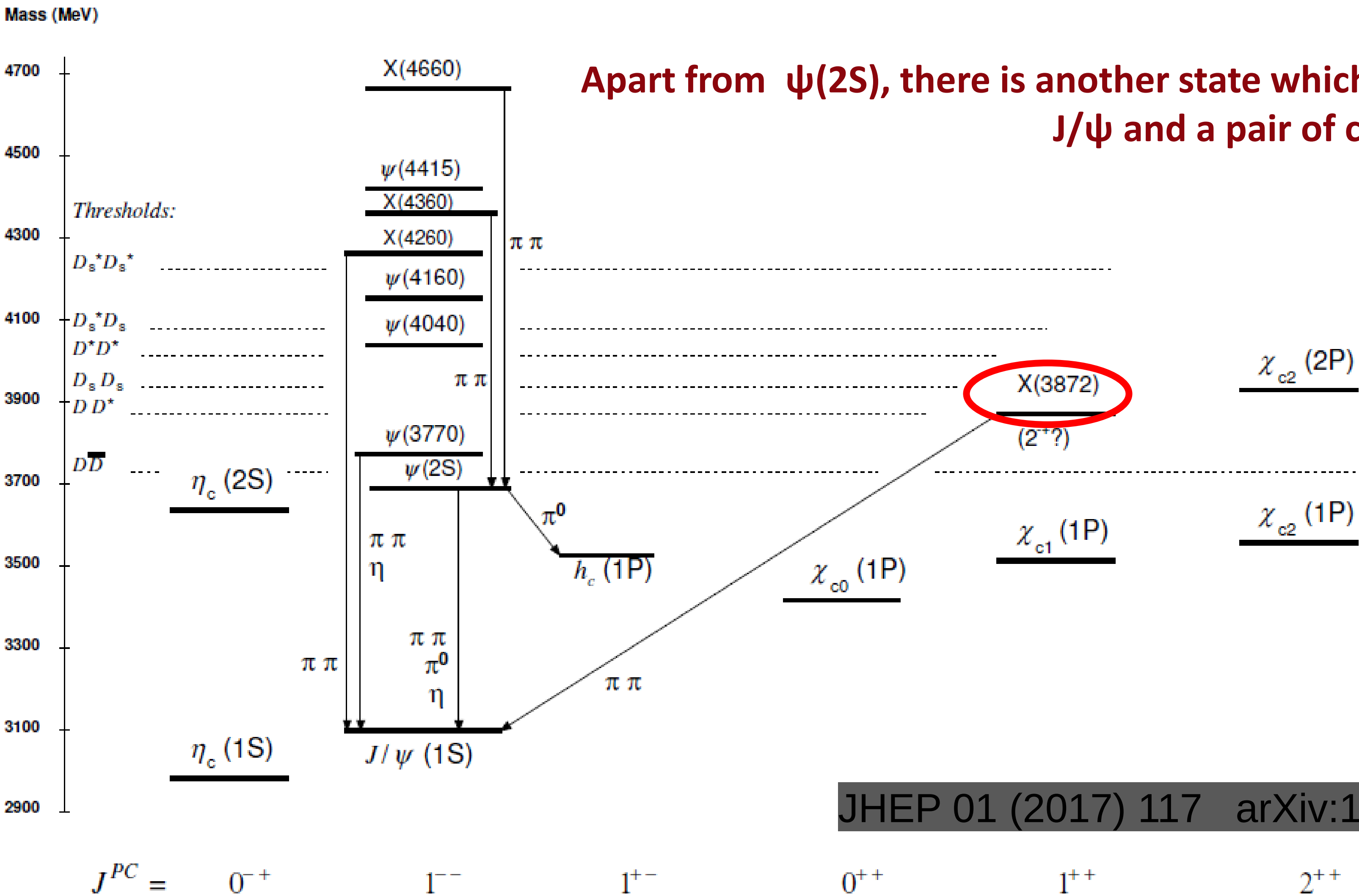
PRL 113 (2014) 212004
arXiv:1407.1032





Production of X(3872) → J/ψ π⁺π⁻

Apart from ψ(2S), there is another state which decays into J/ψ and a pair of charged pions



JHEP 01 (2017) 117 arXiv:1610.09303

What is X(3872) ?

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

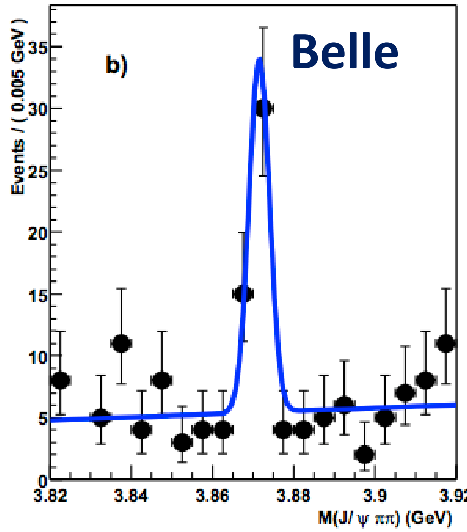
Soon after confirmed by BaBar, CDF, D0 and now LHC experiments

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

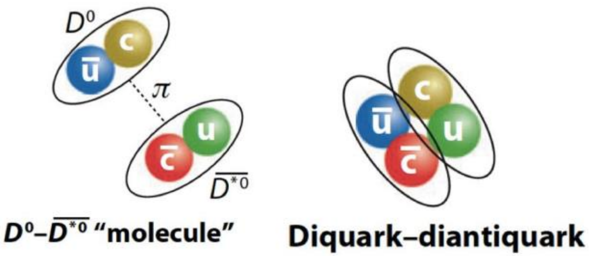
What is it? No clear picture yet!

- *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

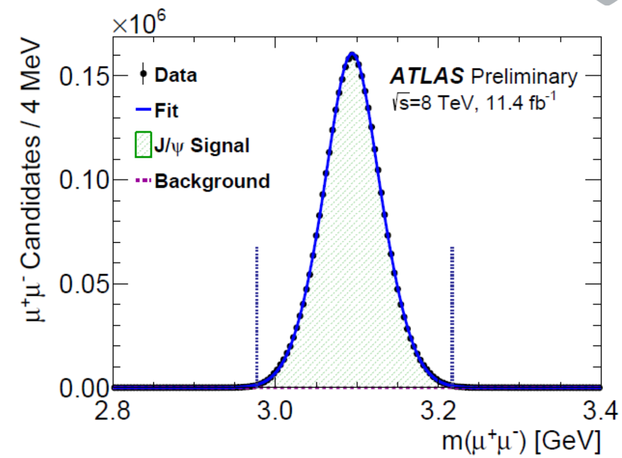
- Opposite sign, $p_T > 600$ MeV, $|\eta| < 2.4$

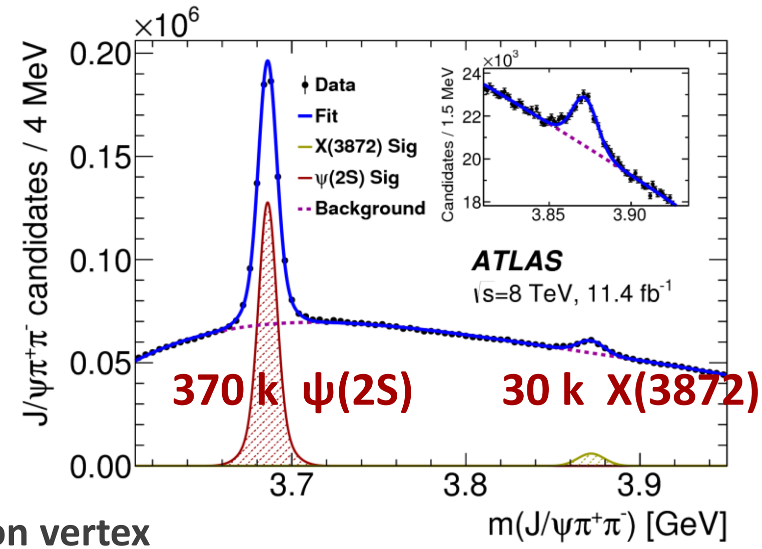
$J/\psi\pi^+\pi^-$ background suppression cuts

- $P(\chi^2_{J/\psi\pi\pi}) > 4\%$
- 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

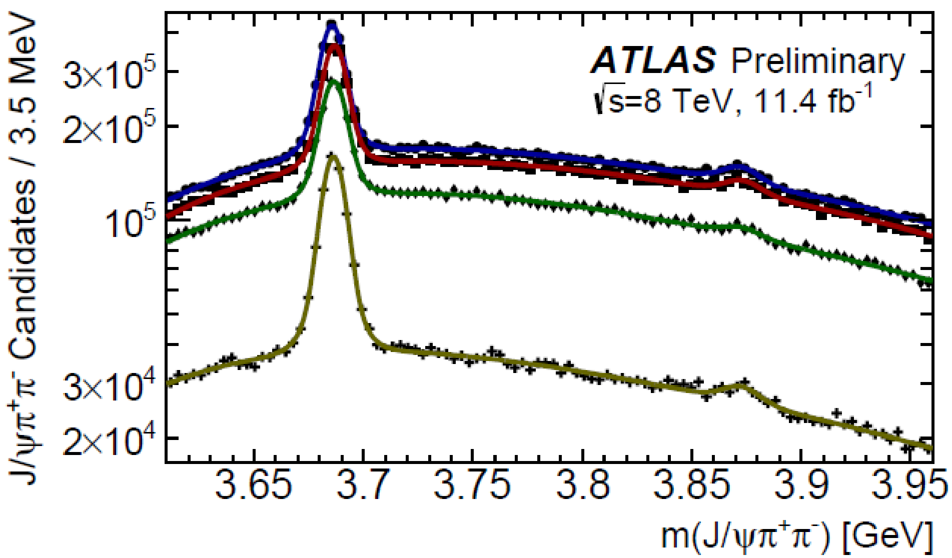
Mass fits: double-Gaussian signal peaks on a smooth background:

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

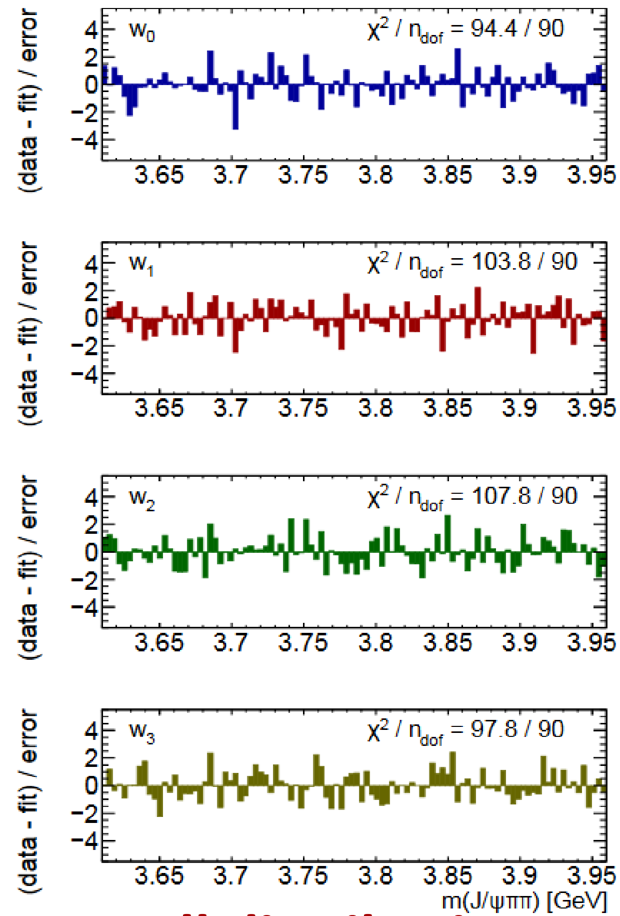
Fraction of narrow Gaussian f_{12} shared between ψ(2S) and X(3872)

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

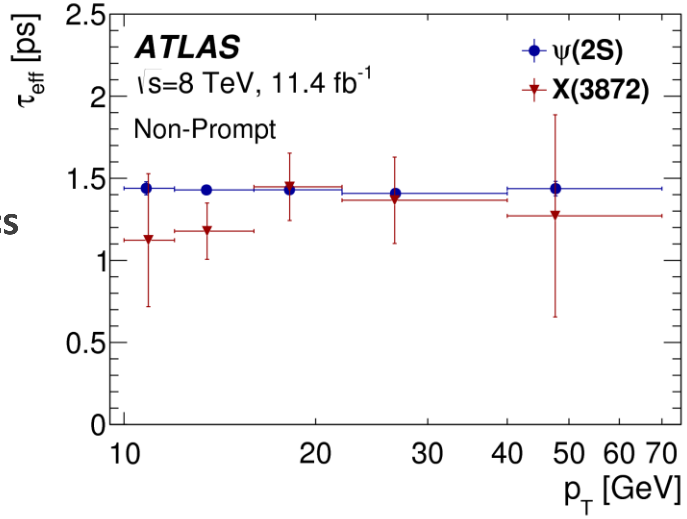


Pull distributions

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

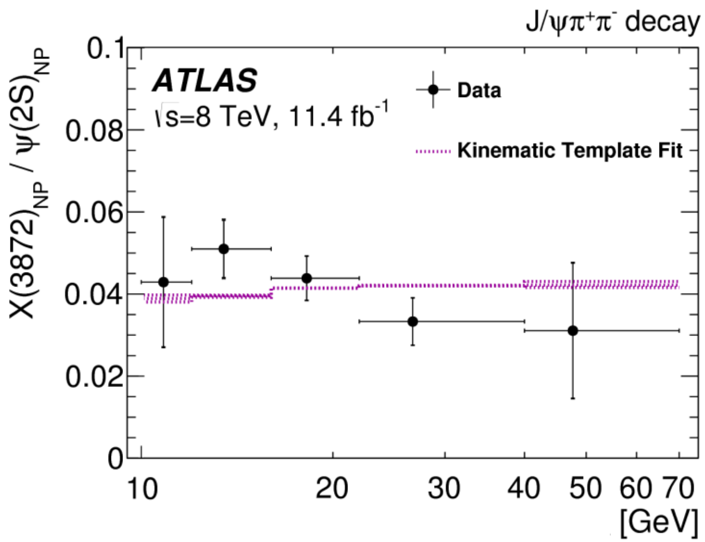


Effective lifetimes

- 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

Lancaster University

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 ± 0.004 ps
$\tau(B^0)$ = 1.525 ± 0.009 ps
$\tau(B_s^0)$ = 1.465 ± 0.031 ps
$\tau(\Lambda_b)$ = 1.451 ± 0.013 ps

τ_{LL} = 1.45 ± 0.05 ps

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

τ_{SL} = 0.40 ± 0.05 ps

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

X(3872) cross sections

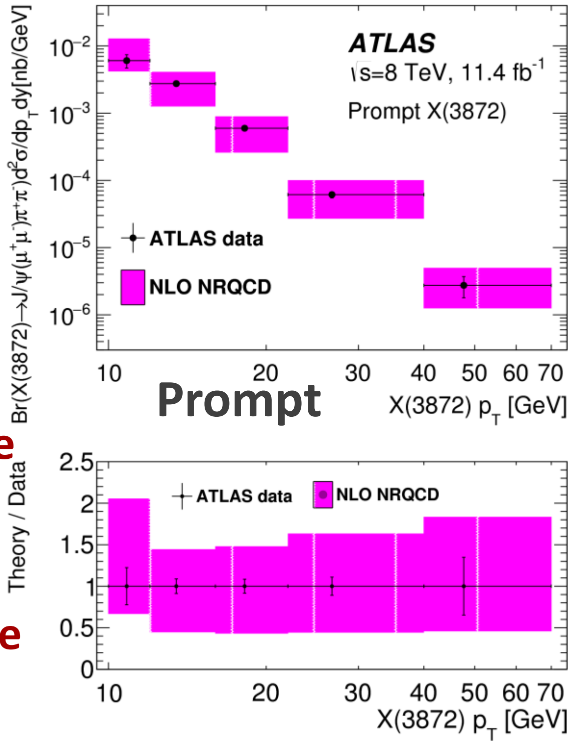
Prompt: **Described well by NLO NRQCD**

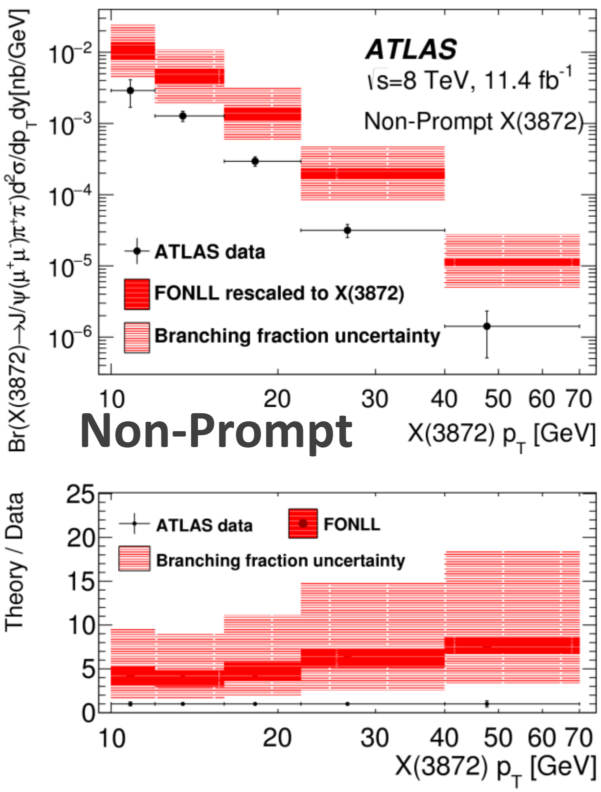
assumes X(3872) is a mix $\chi_{c1}(2P)$ - ($D^0 D^{0*}$)

$\chi_{c1}(2P)$ 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 ψ(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±8 %

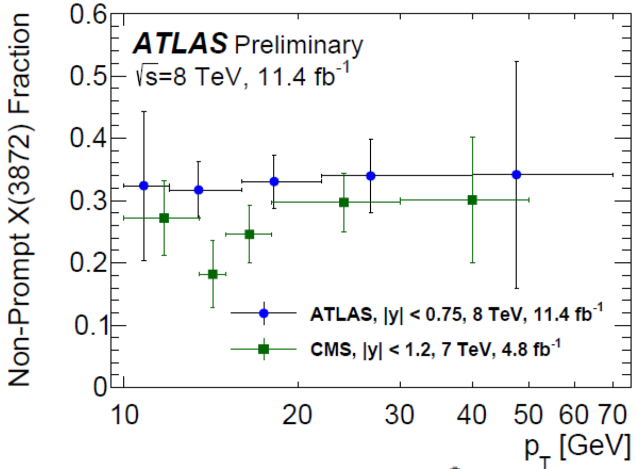
Clearly overshoots the data:

factor of 4 to 8, increasing with pT

Non-prompt fraction and ratio

Non-prompt fraction of X(3872):

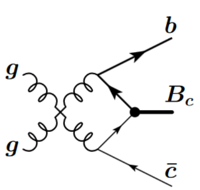
- no visible p_T dependence
- consistent with CMS result within errors



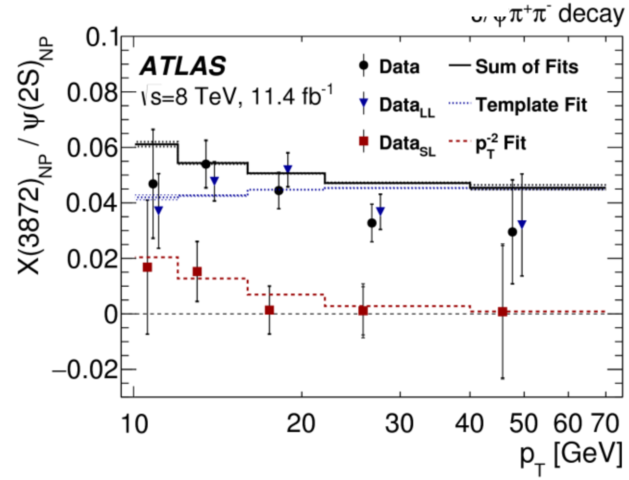
Ratio of non-prompt X(3872) : ψ(2S)

- 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?

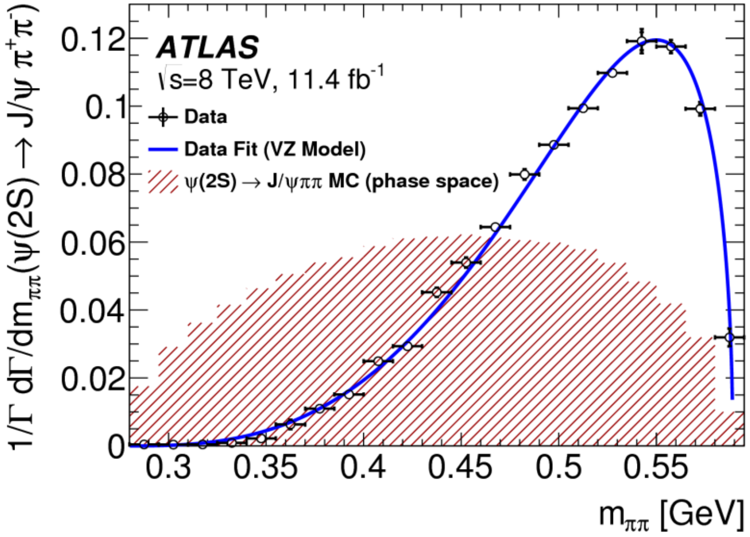
Di-pion mass distributions: results

In ψ(2S) to J/ψπ⁺π⁻ decays

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

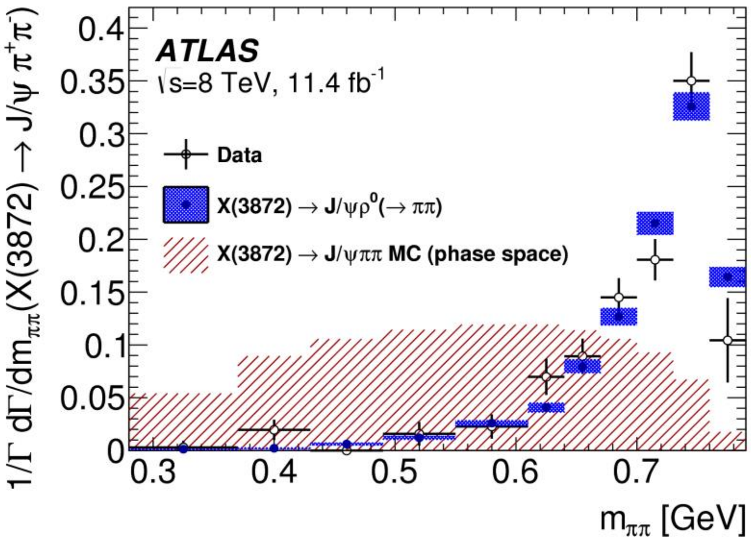
$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{\pi\pi}} \propto \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2 \times \mathrm{PS}$$

- found $\lambda = 4.16 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$
- 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?

The big puzzle is still there – what are the quarkonium states and how are they produced in hadronic collisions?

Vast amounts of data are now available from both the Tevatron and the LHC experiments

A number of new analyses are now in progress in ATLAS, some at an advanced stage

In general, very good synergy between the LHC experiments – complement each other in pT and rapidity, covering a huge range between them

More and more bits of the puzzle are becoming available

Maybe we are (slowly) getting (slightly) closer to the point of a big breakthrough in understanding?

THANK YOU!