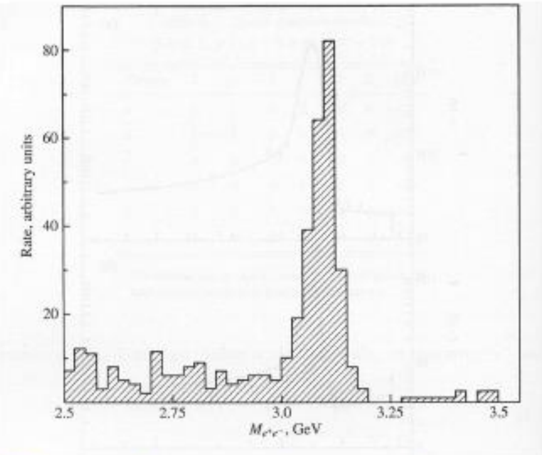
Quarkonium physics in ATLAS

(and LHC)

V Kartvelishvili

Lancaster University

The Beginning: J/ψ



$\Leftarrow$ **Discovery 1:** Ting's group

$$pN \to e^+e^-X$$

at $P_{\rm lab} = 30$ GeV/c

[Aubert et al., PRL, 6/11/1974]

Found a peak in e^+e^- inv.mass at 3.1 GeV, called it J.

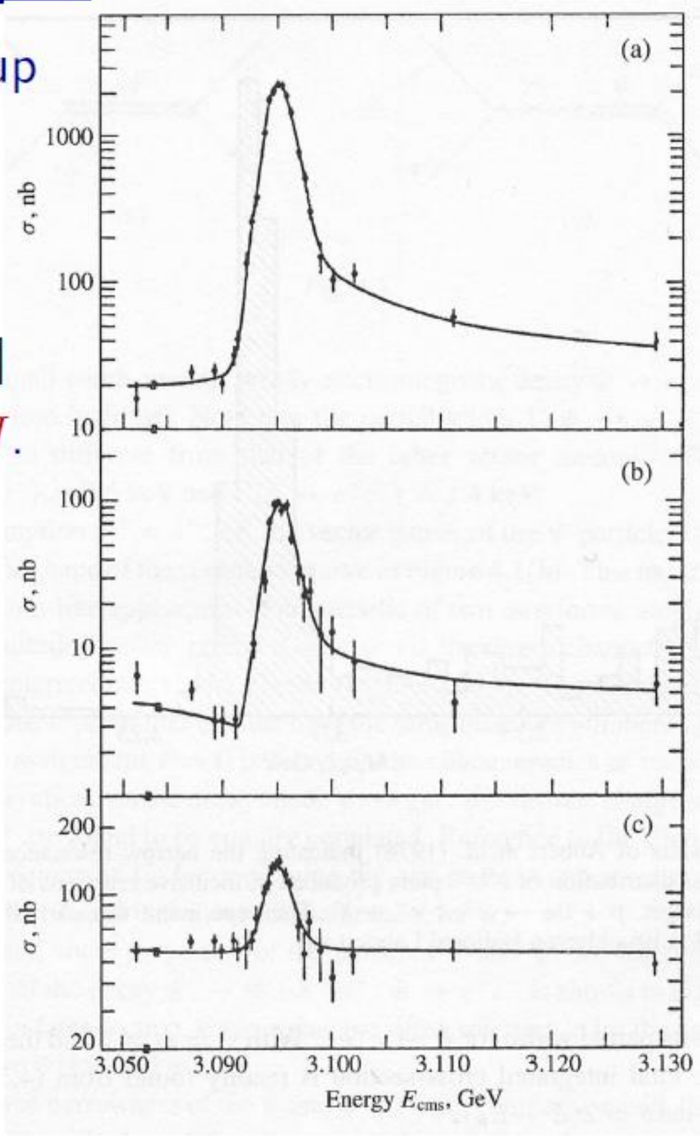
Discovery 2: Richter's group $\Rightarrow$

$$(a)\quad e^+e^- \to \text{hadrons}$$
$$(b)\quad e^+e^- \to \mu^+\mu^-$$
$$(c)\quad e^+e^- \to e^+e^-$$

[Augustin et al., PRL, 7/11/1974]

Found a peak in all these three cross-sections,

at the c.m.s. energy 3.1 GeV; called it ψ.



The quarkonium family now

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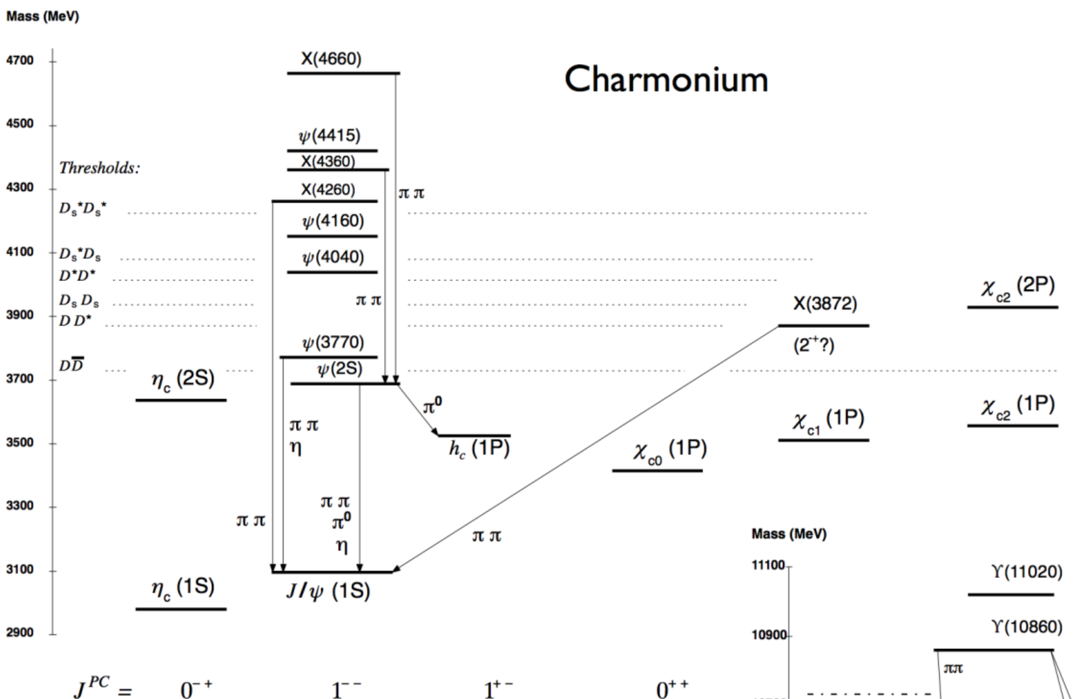
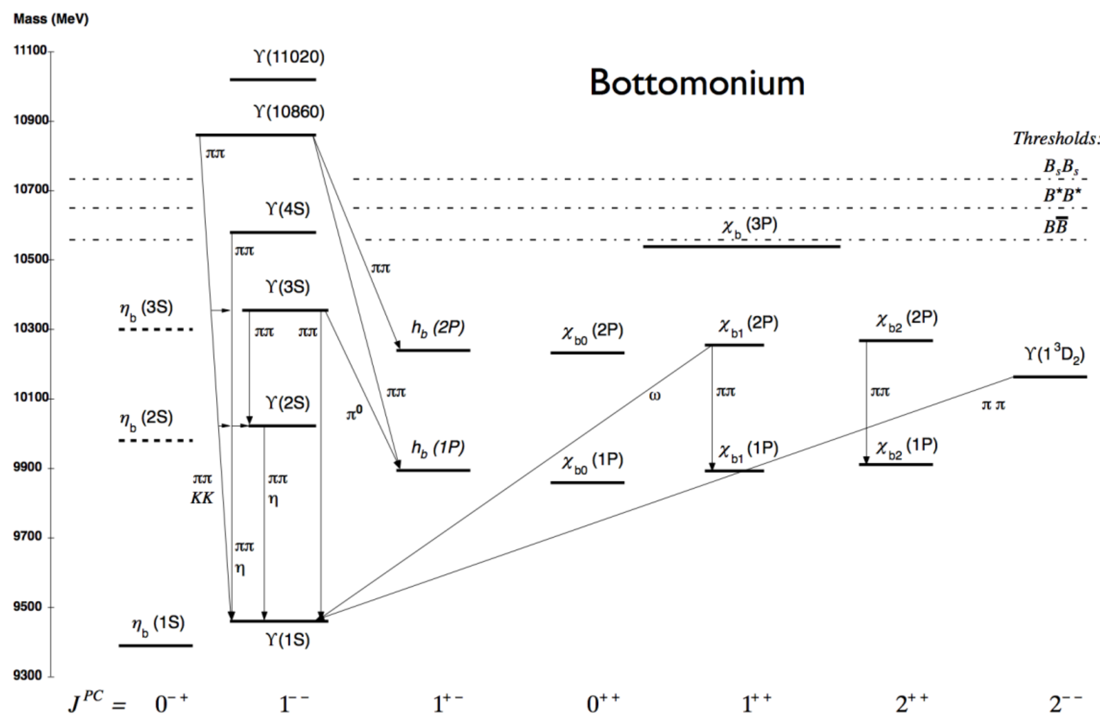


Quarkonium bound states produce a rich spectroscopy

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



Several topics I cover today:

- J/ψ production
- $X_{c1,2} \rightarrow J/\psi\, \gamma$
- Υ production
- Discovery of $\chi_b(3P)$
- Z+ J/ψ production
- X(3872), $\psi(2S) \rightarrow J/\psi\, \pi^+ \pi^-$

Theory of quarkonium production

Seemingly a ‘simple’ system: quark and anti-quark of same flavour in a bound state

Two dominant approaches:

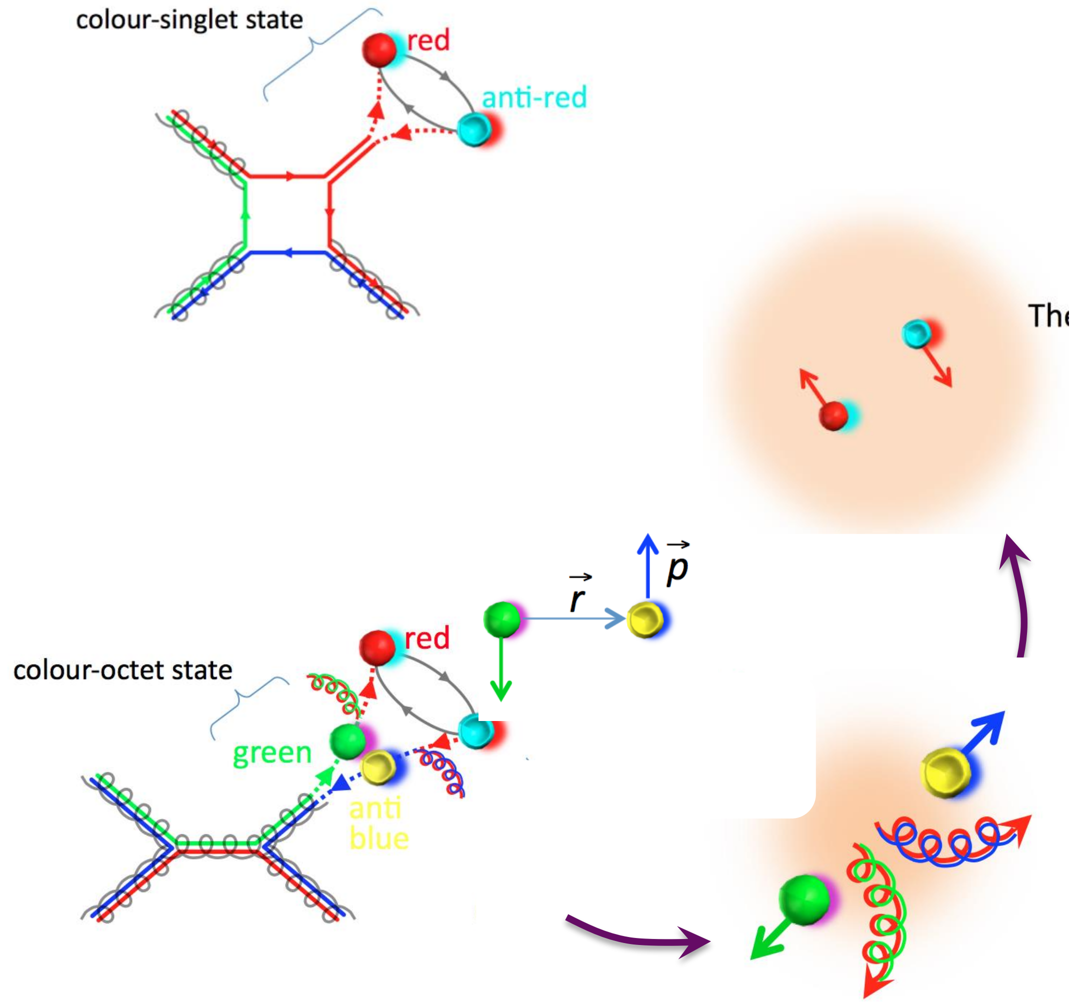
Colour Singlet Mechanism:

-- no free parameters
apart from usual QCD scales
-- C-even states enhanced

Non-Relativistic QCD (NRQCD)

‘Colour Octet’ calculations:

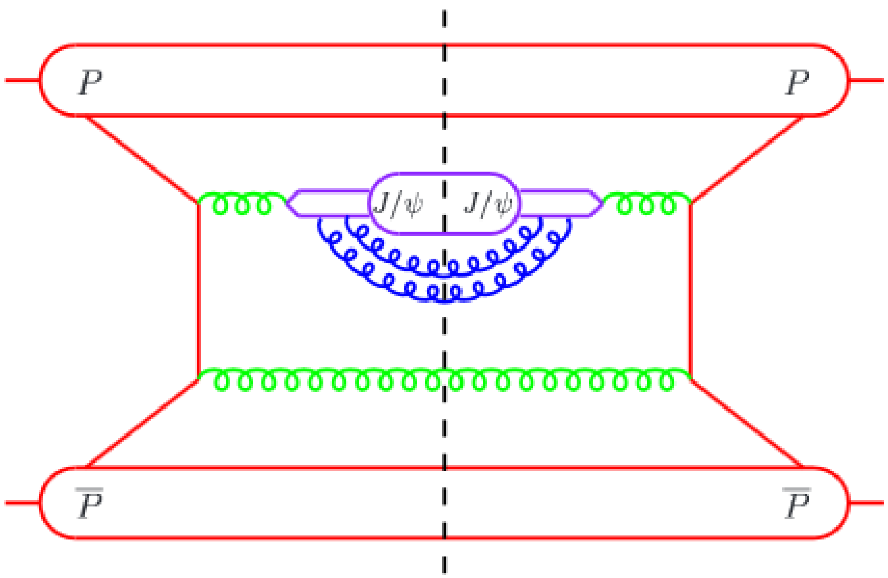
-- double-expansion in α_s and v
-- many free parameters (LDME)
-- extracted from data



A slide from G. Bodwin's talk:

- Conjecture (GTB, Braaten, Lepage): The inclusive cross section for producing quarkonium at large momentum transfer (p_T) can be written as hard-scattering cross section convolved with an NRQCD matrix element.

$$\sigma(H) = \sum_n \frac{F_n(\Lambda)}{m^{d_n-4}} \langle 0 | \mathcal{O}_n^H(\Lambda) | 0 \rangle .$$



- The "short-distance" coefficients $F_n(\Lambda)$ are essentially the process-dependent partonic cross sections to make a $Q\bar{Q}$ pair convolved with the parton distributions.
  - They have an expansion in powers of α_s.

Quarkonium production studies

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So why are we studying quarkonia at LHC?

Plenty of reasons, in no particular order:

- **Tests of QCD calculations at the perturbative/non-perturbative boundary**
- **New inputs – new constraints on theories**
- **Exceptionally useful for detector performance studies**
- **Standard candles for Heavy Ion physics, B-hadron production**
- **Backgrounds to many SM/BSM processes**
- **Test double-parton scattering effects, parton density functions**
- **Search for rare decays and probes of new physics**
- **Because it's interesting?**

Quarkonium spectroscopy and feeddown

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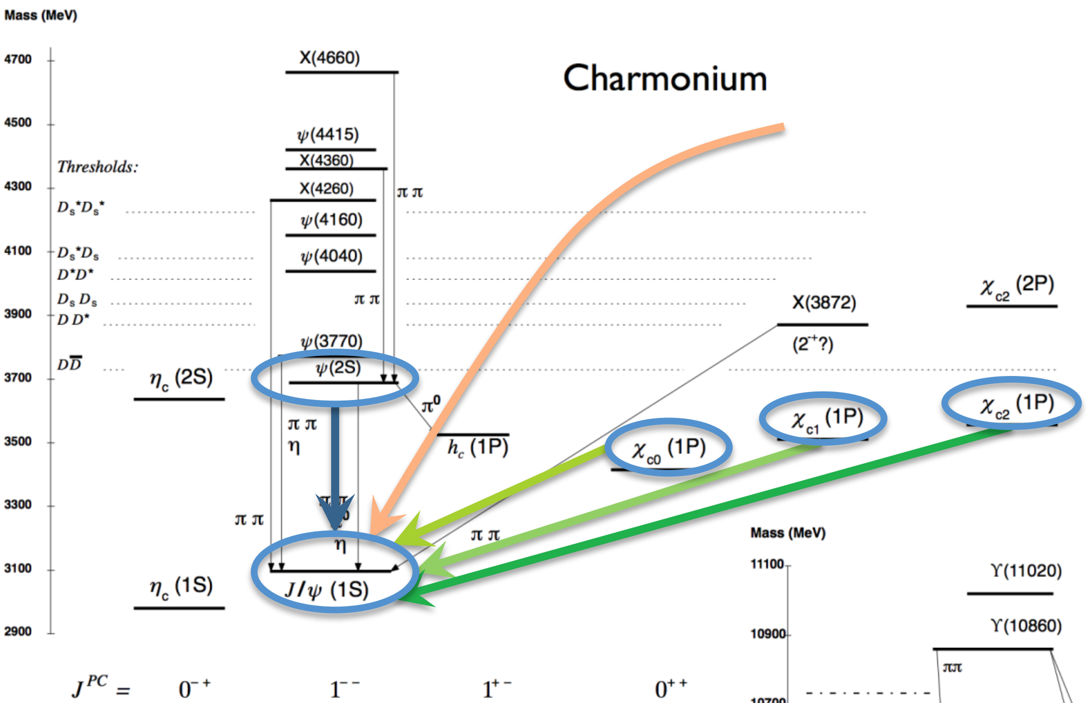
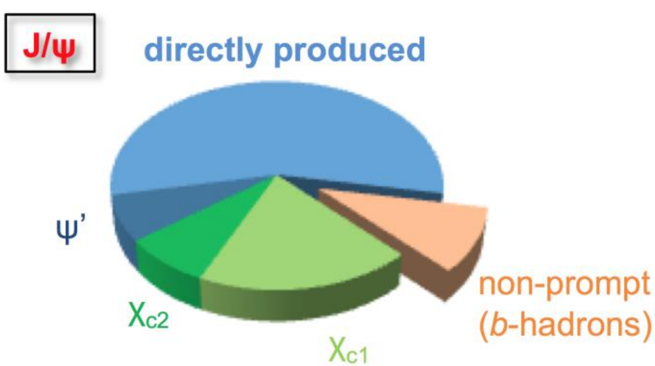
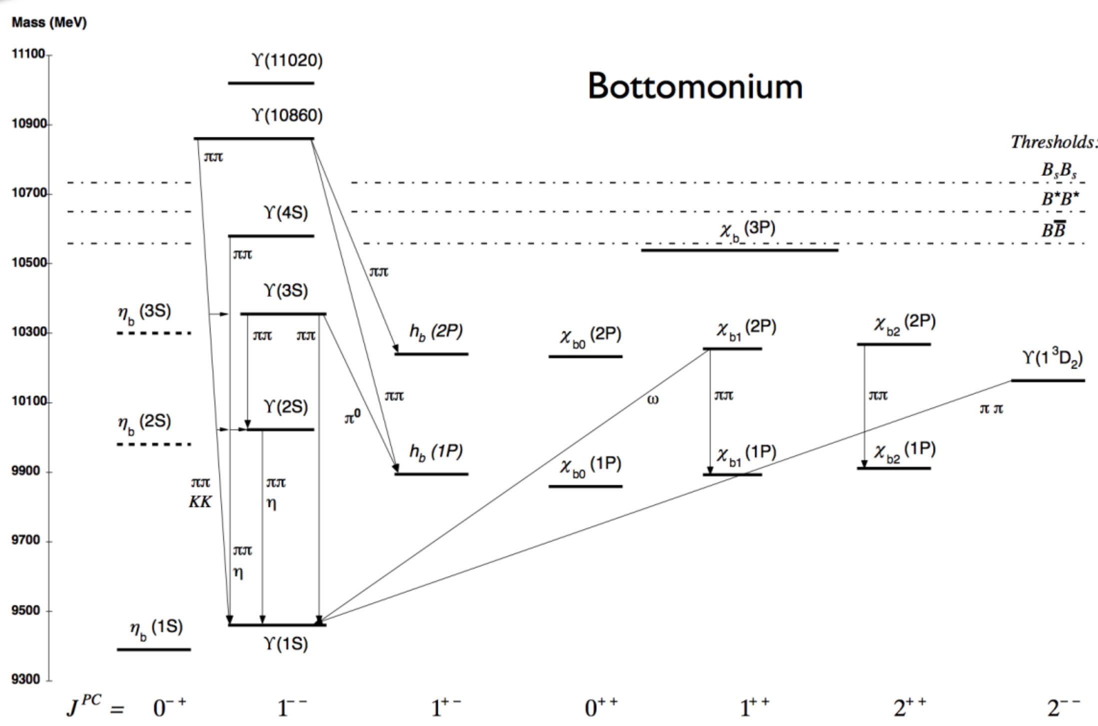


Rich spectrum of states with a variety of quantum numbers

Complicated pattern of electromagnetic and hadronic transitions

Need to study feeddown in hadronic production





The ATLAS detector at LHC

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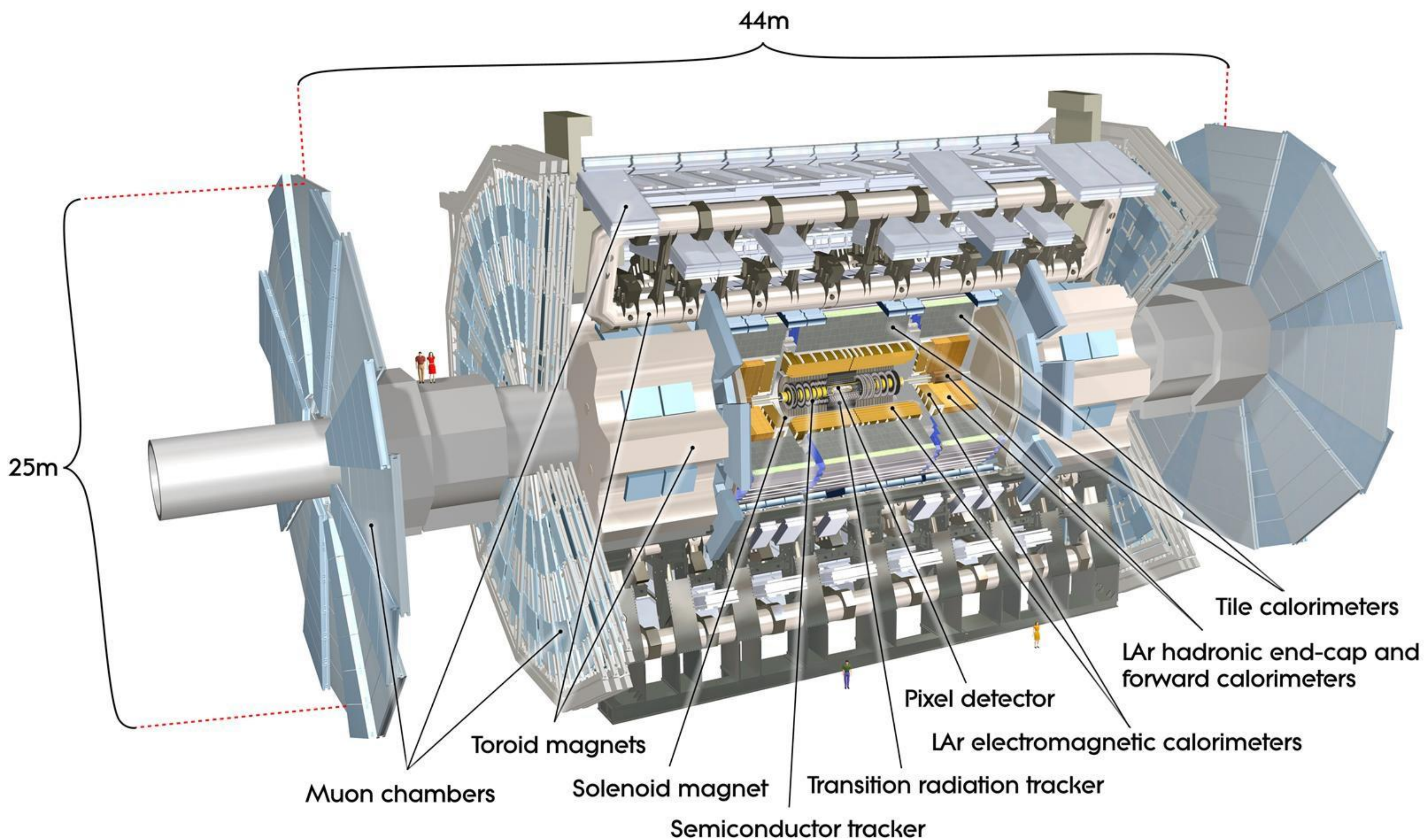


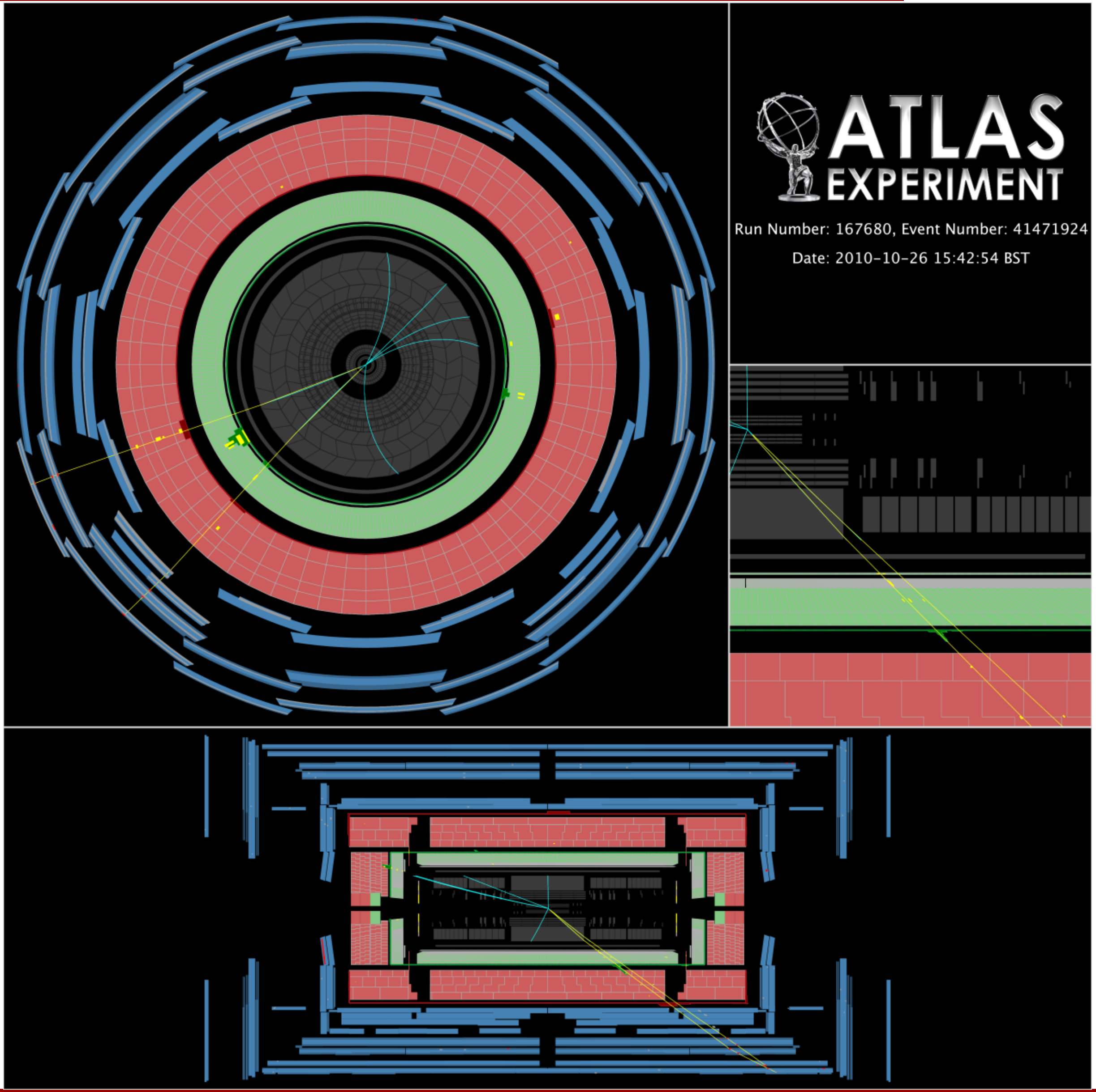
ATLAS event display: $\chi_c \rightarrow J/\psi(\mu^+\mu^-)\,\gamma$ candidate

Cross section views perpendicular and parallel to the beam line

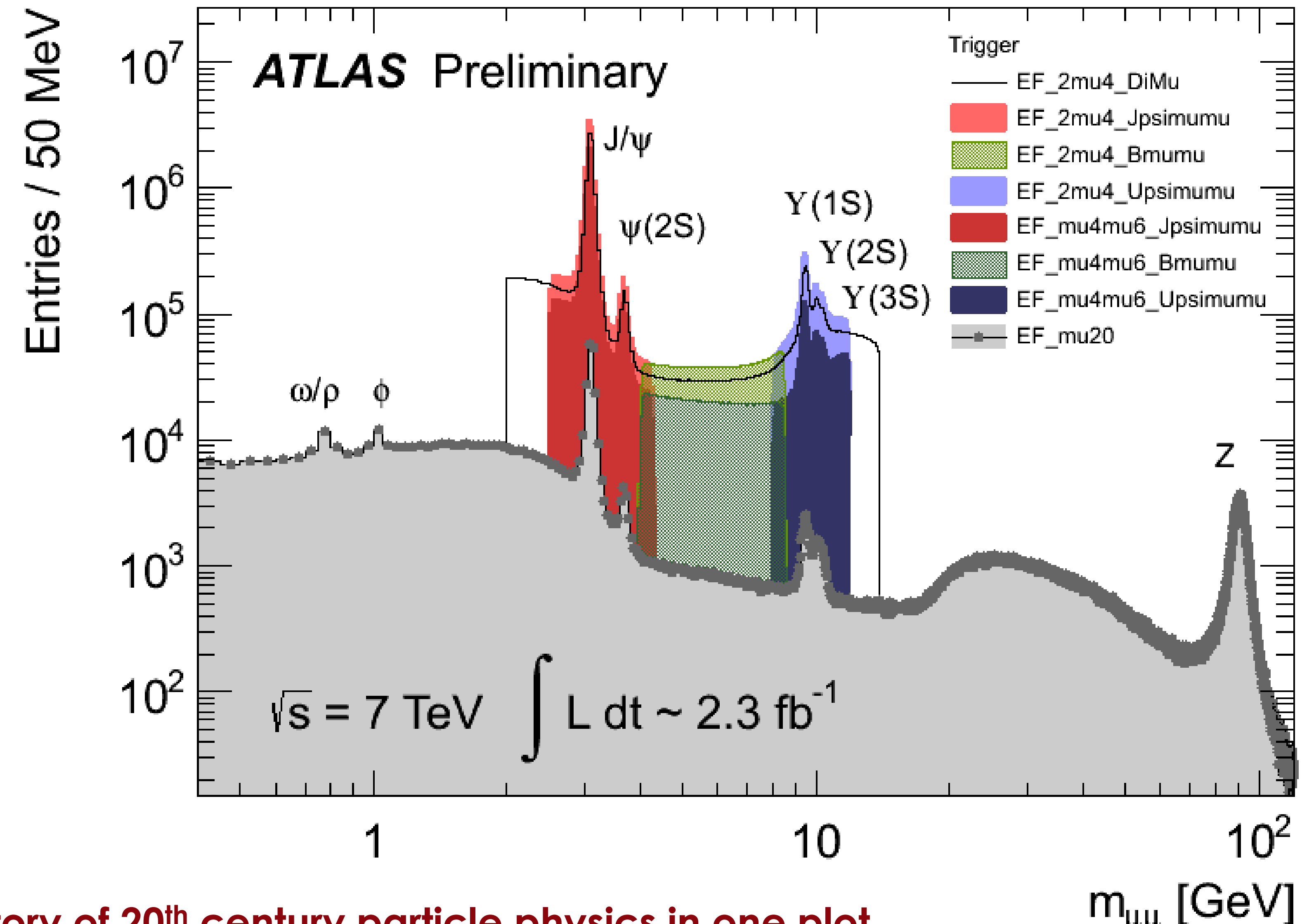
Two muon tracks spanning the Inner Detector and the Muon System

A photon tower in Eclectromagnetic Calorimeter

Invariant mass in the χ_c region



Muon and dimuon triggers in ATLAS



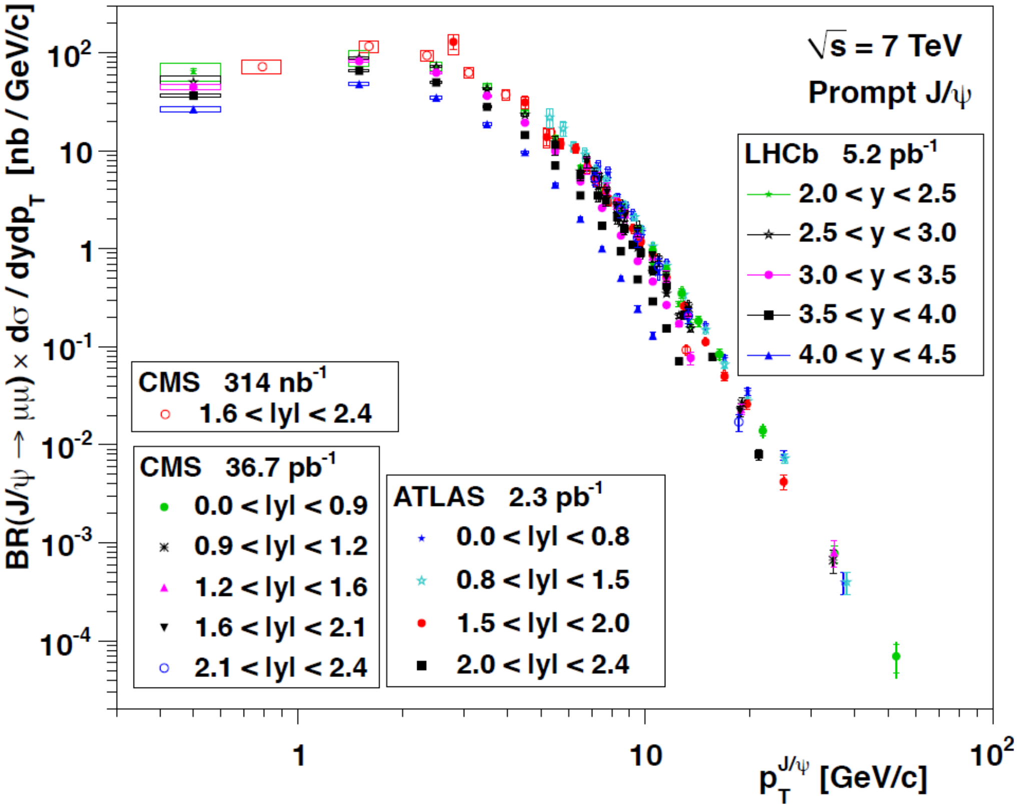
History of 20th century particle physics in one plot

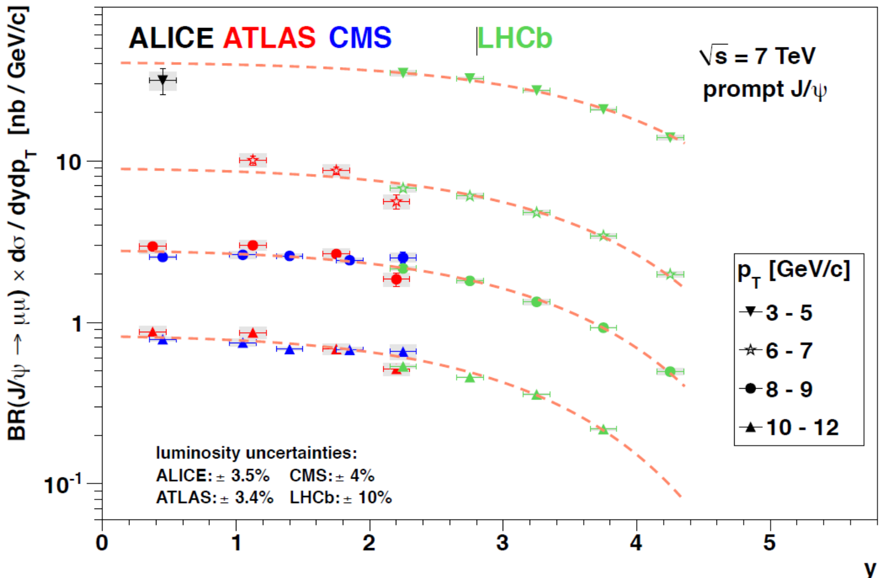
Prompt J/ψ production: LHC

Compilations by Hermine K. Woehri

(a few years old by now)

Nice synergy between the LHC experiments





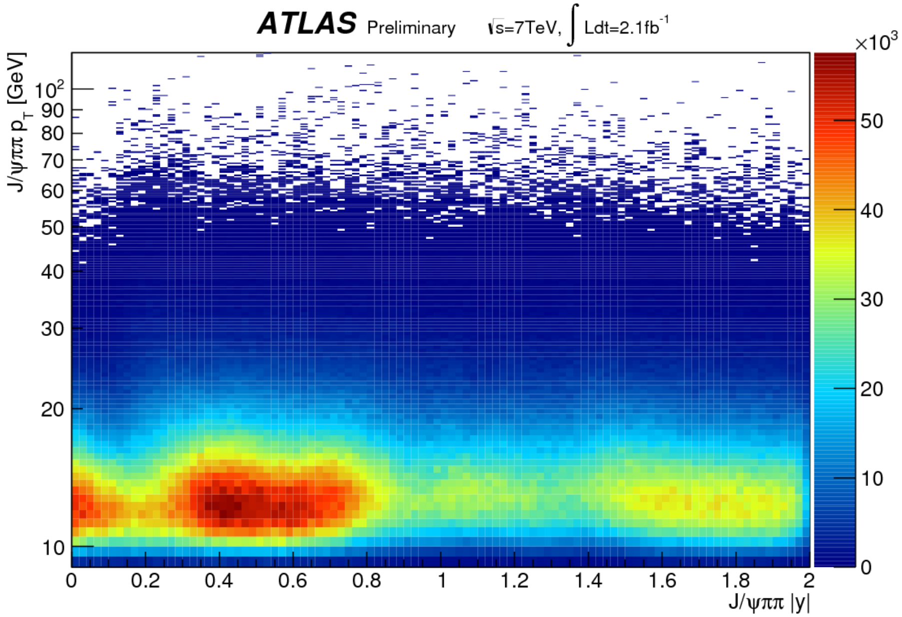
Between the experiments, a huge kinematic range is covered: $|y| < 4.5$, $0 < p_T < 100$ GeV

Over 6 orders of magnitude in p_T

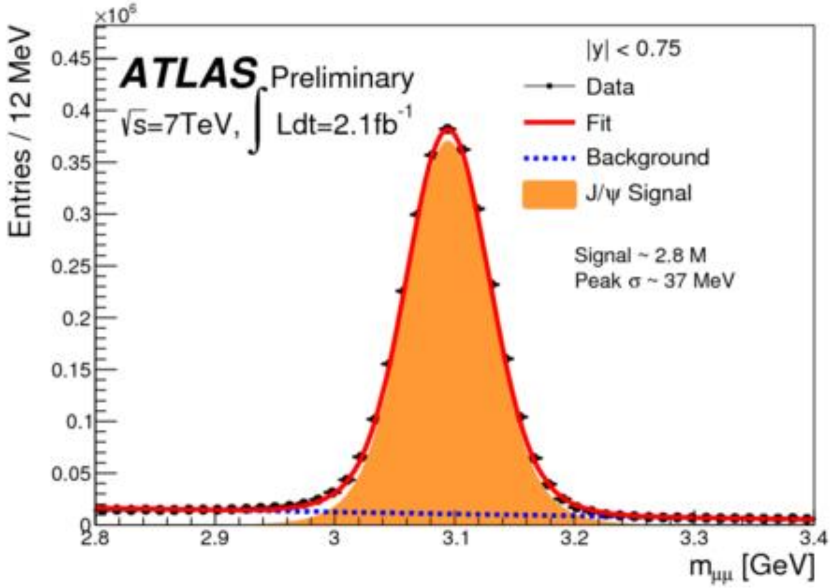
Given the diversity of experiments and conditions, consistency of measurements is really remarkable

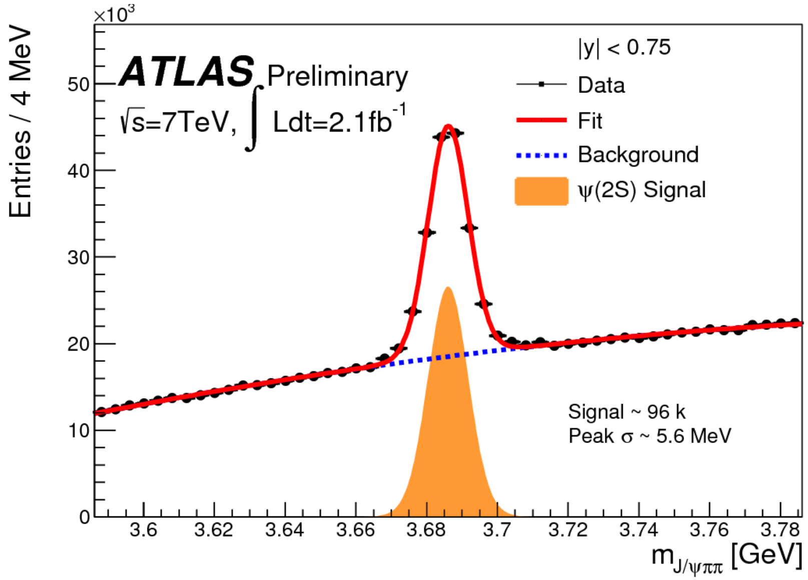
$J/\psi(\rightarrow\mu^+\mu^-)\pi^+\pi^-$ candidates

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



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 contributions

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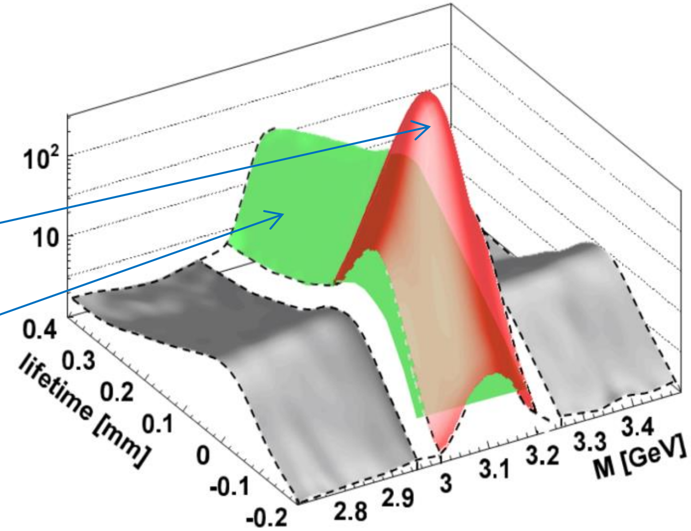
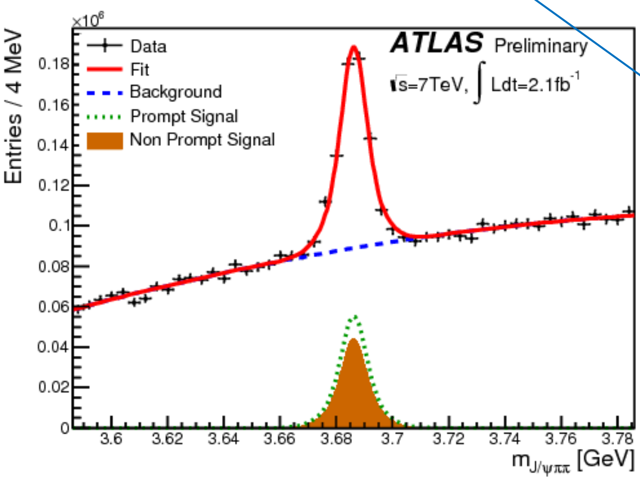


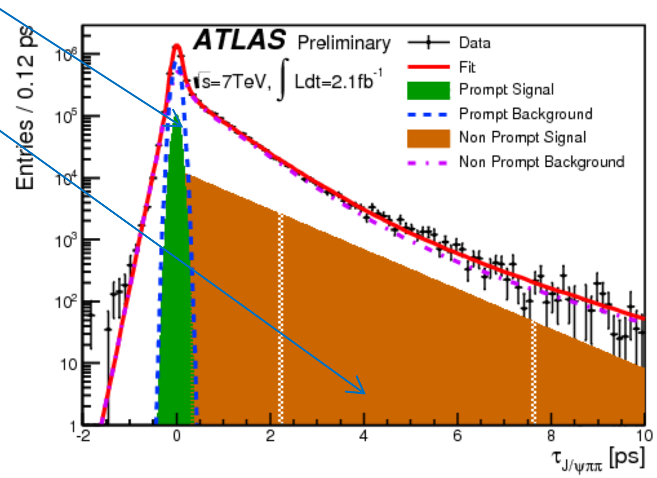
Use transverse distance (lifetime) $l_{J/\psi} = L_{xy} \cdot \frac{m_{J/\psi}}{p_T}$

of the J/ψ vertex relative to the primary vertex to separate:

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

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

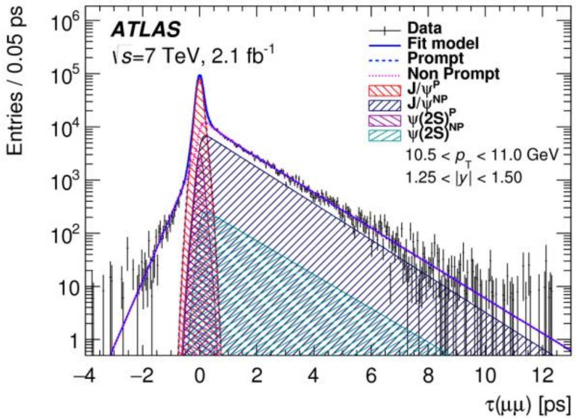


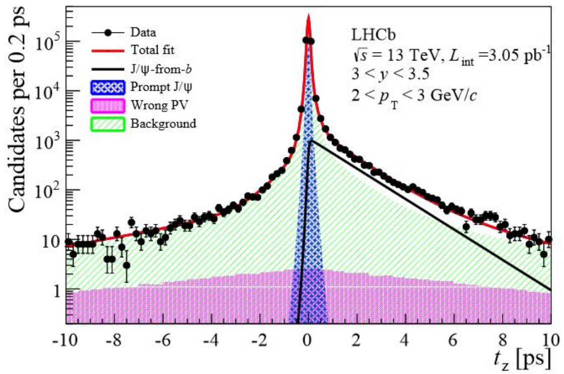


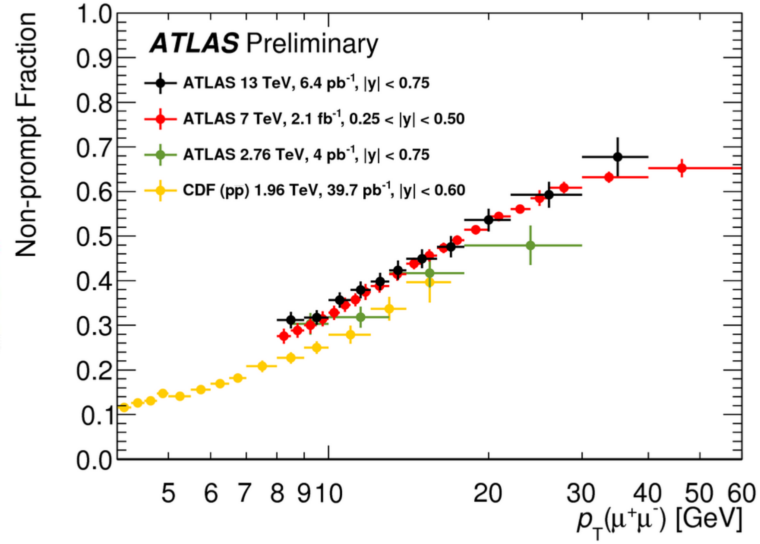
2D mass vs lifetime unbinned maximum-likelihood fit is done to extract ***Prompt*** and ***Non-prompt*** yields in each p_T – rapidity bin

Two projections shown for a sample bin

Non-prompt J/ψ fraction: LHC recent



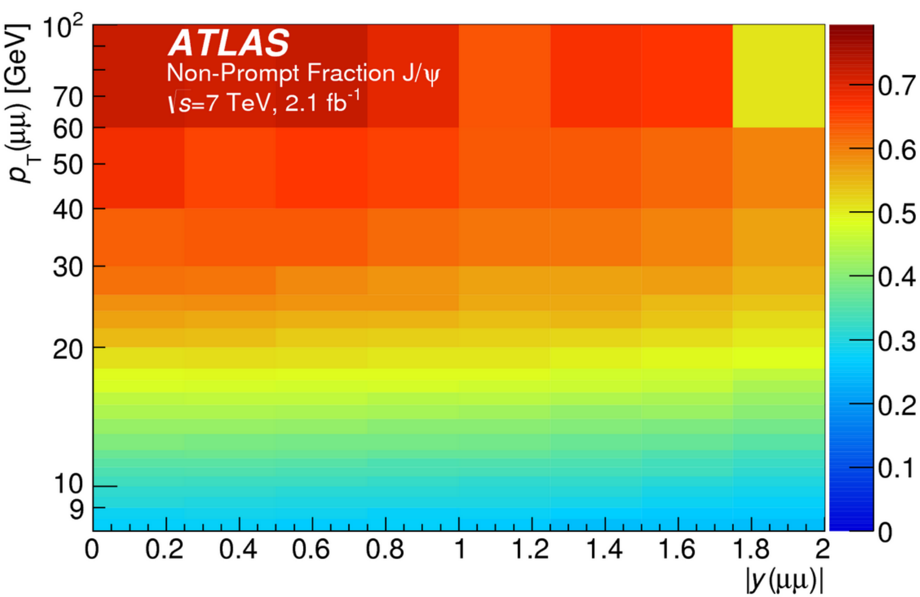


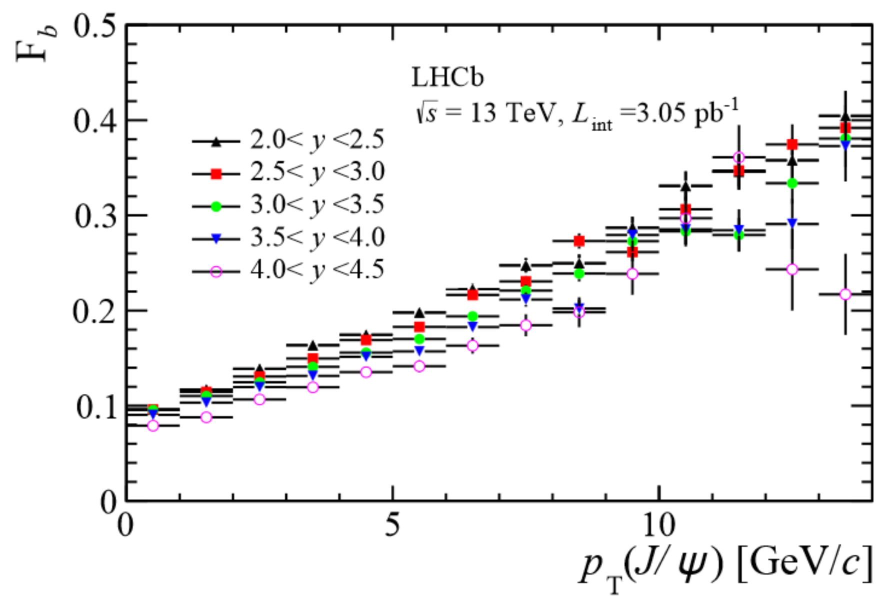


Strong pT dependence

No dramatic evolution with energy

Some dependence on rapidity forward





Prompt J/ψ production: LHC recent

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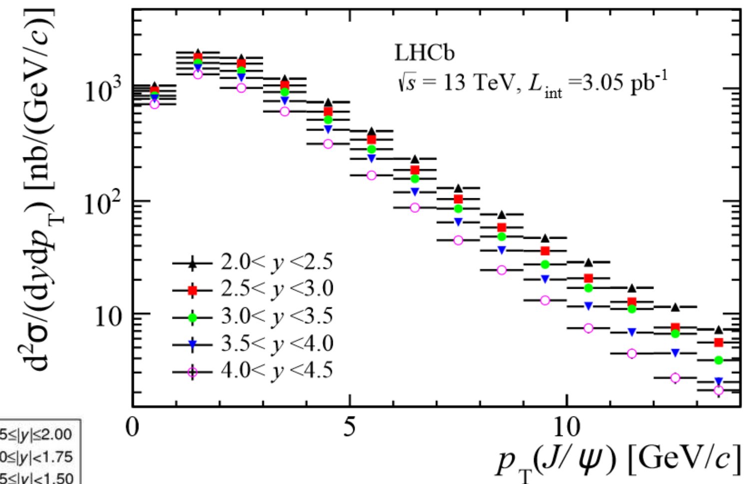
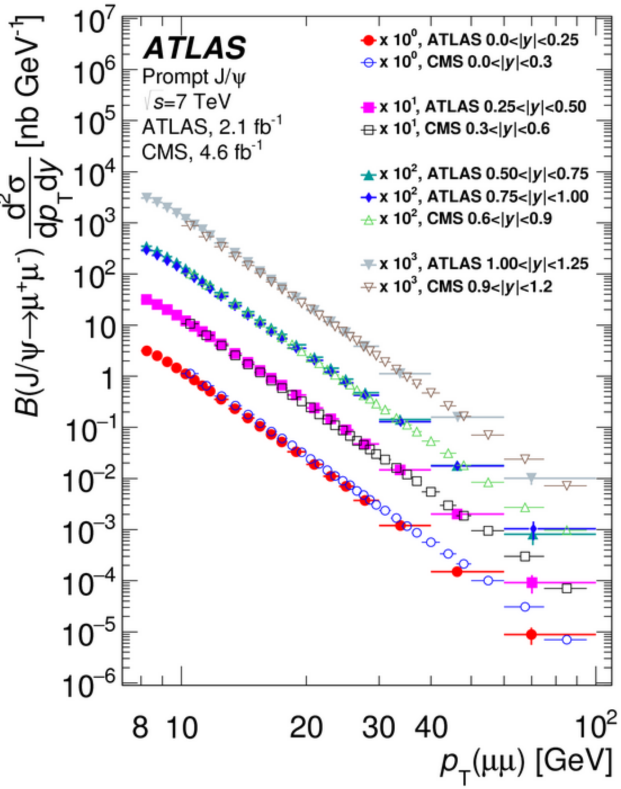
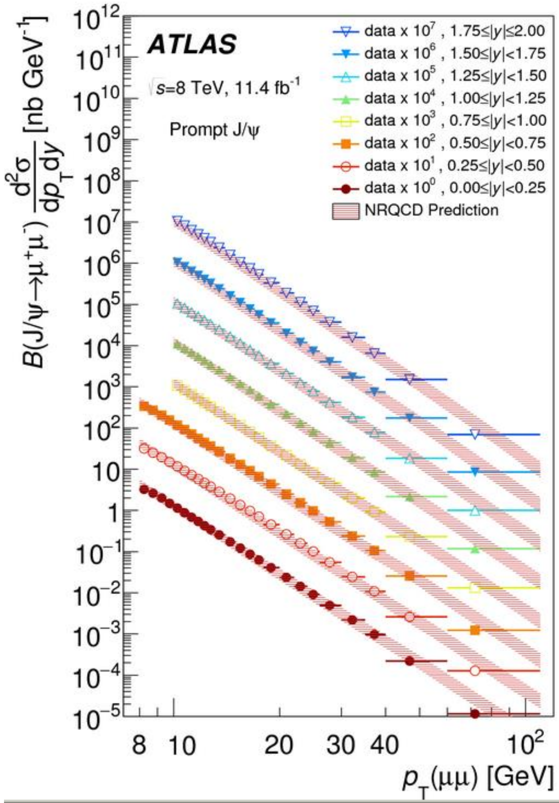
Detailed distributions in a number of bins in pT and rapidity

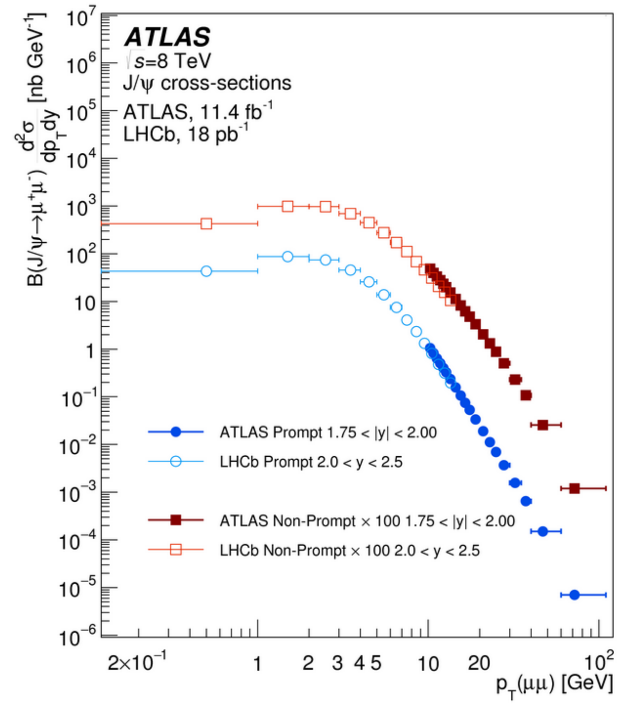
Low pT inaccessible for ATLAS, CMS at high energy / luminosity

Good consistency between ATLAS, CMS and LHCb where overlap

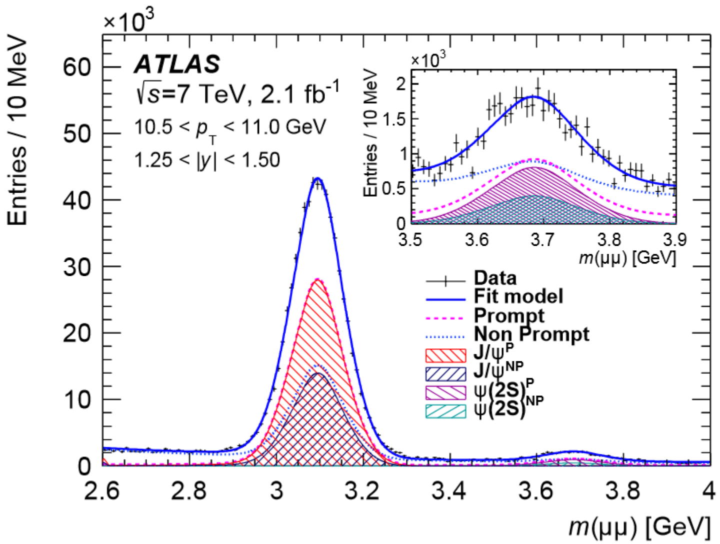








ψ(2S) production in dimuon decay mode



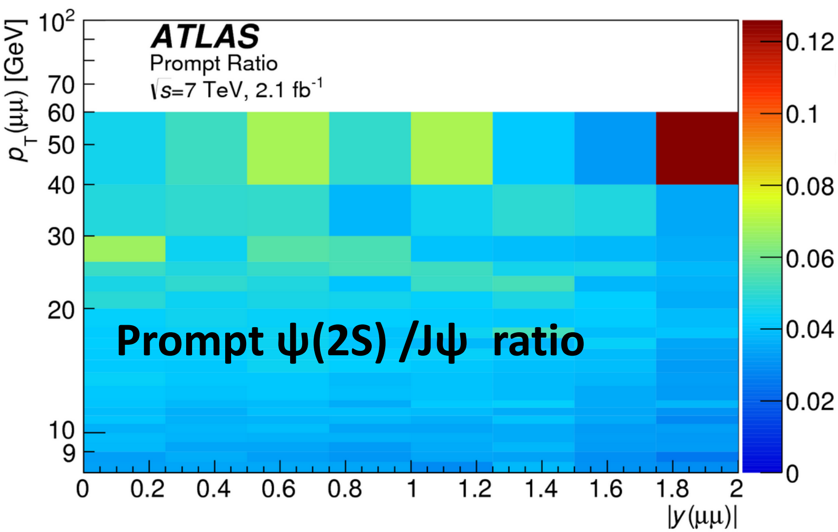
ψ(2S) more challenging: lower stats, higher background

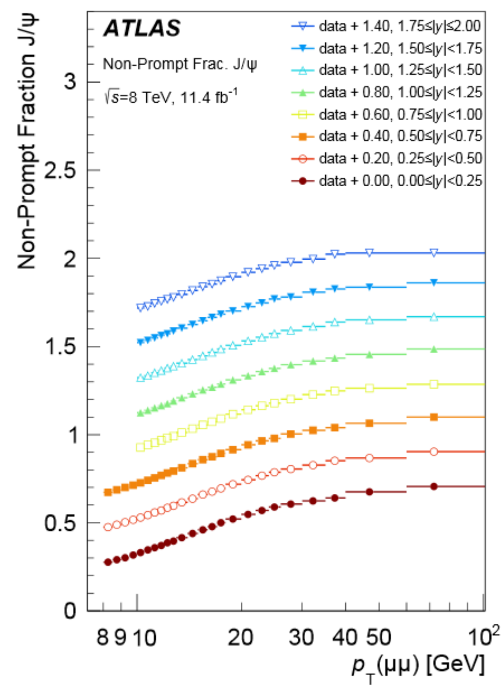
Production mechanism should be theoretically cleaner

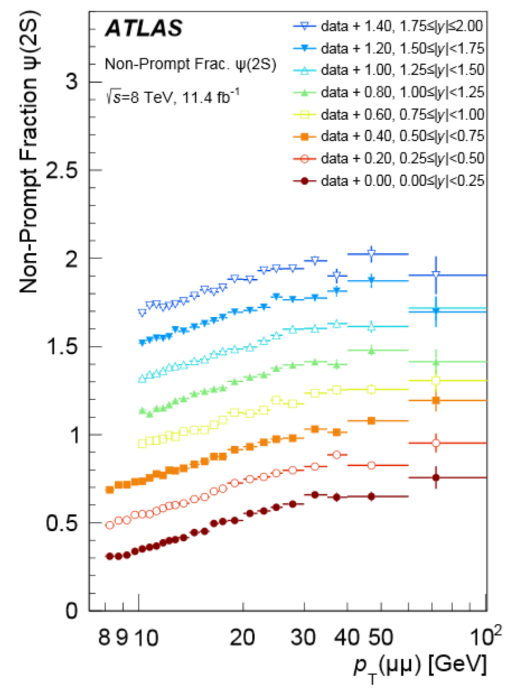
Curiously, non-prompt fraction very similar to J/ψ

Prompt ψ(2S) /Jψ ratio close to constant

Can these facts be understood within our current picture?





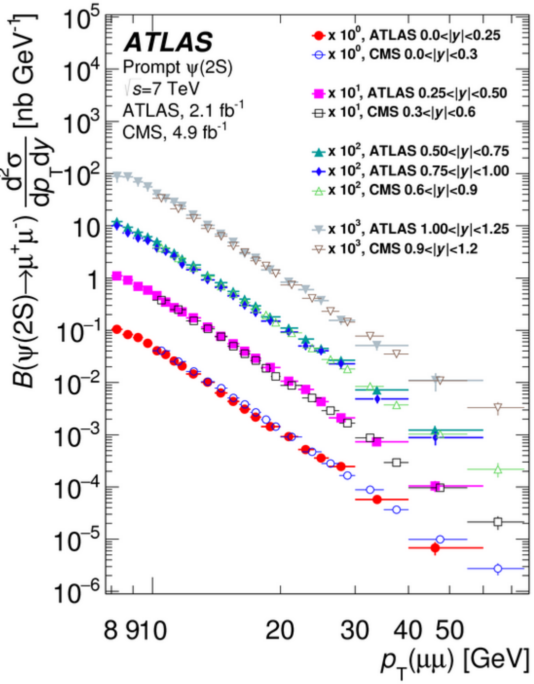


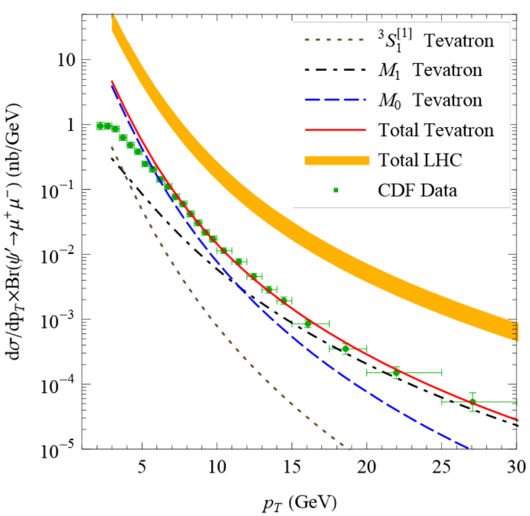
Prompt ψ(2S) production

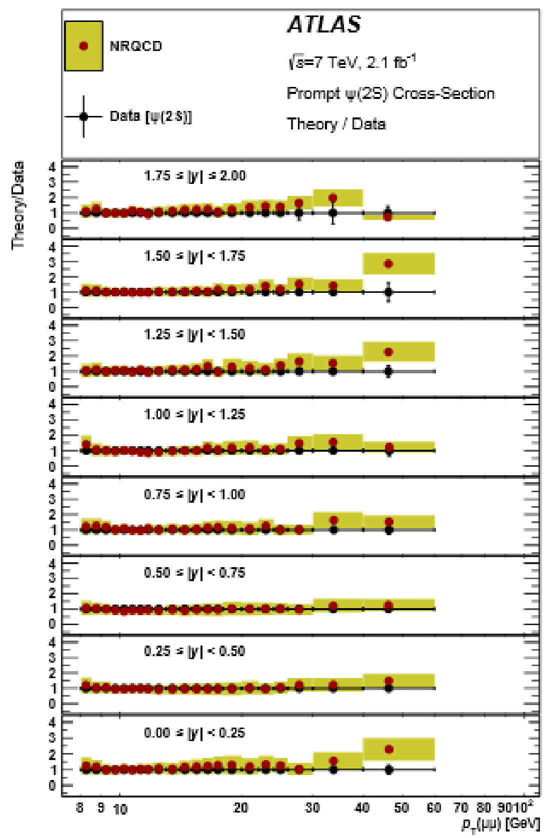
Again, ATLAS and CMS consistent

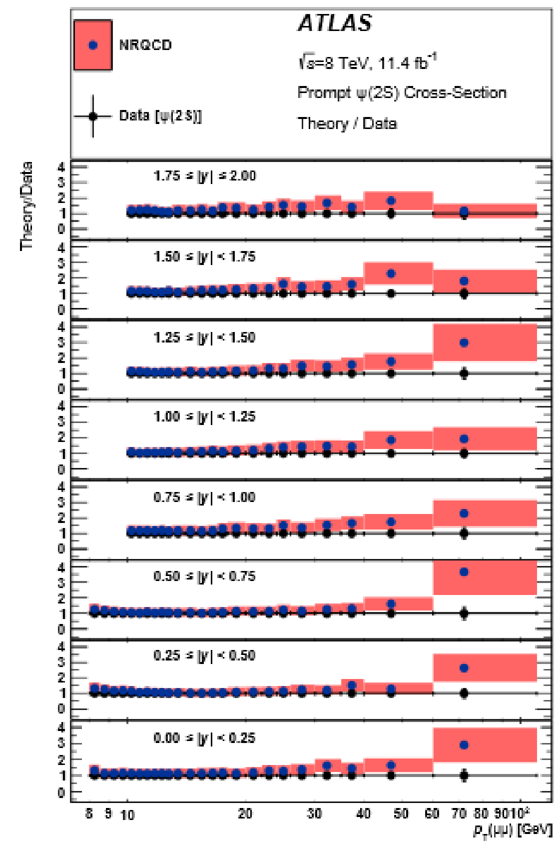
Could be used to extract some LDMEs (Ma,Wang,Chao,arXiv:1009.3655)

LDMEs from Tevatron fits in decent agreement with LHC data (maybe peeling slightly high at highest pT?)









Feeddown from C-even states

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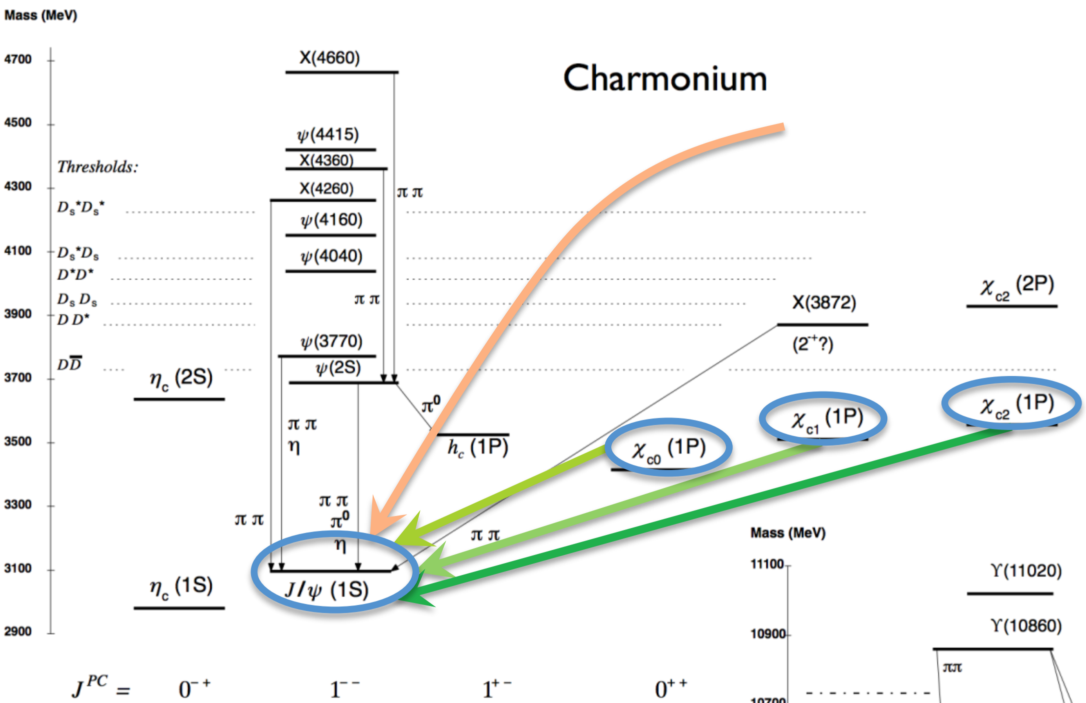
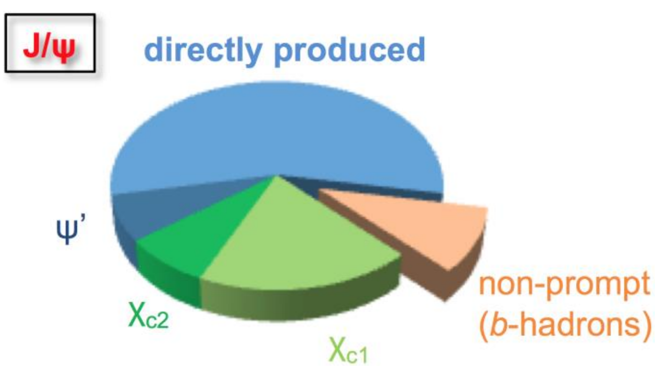
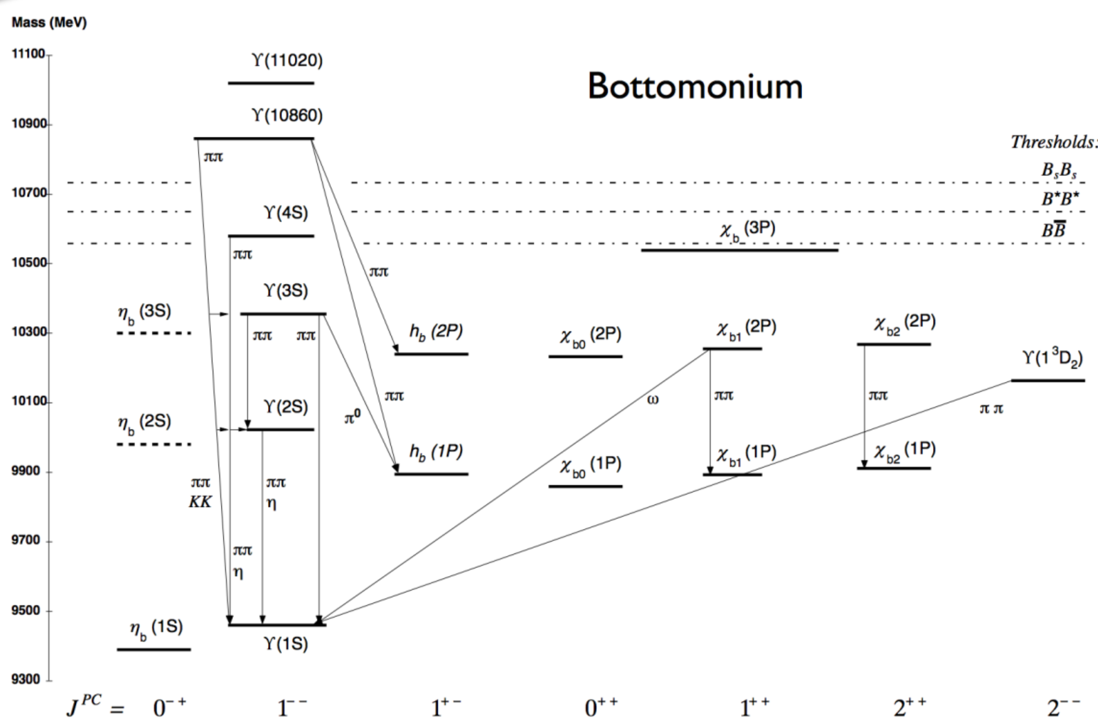


Rich spectrum of states with a variety of quantum numbers

Complicated pattern of electromagnetic and hadronic transitions

Need to study feeddown in hadronic production





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

P-wave charmonium production theoretically and experimentally tricky to handle

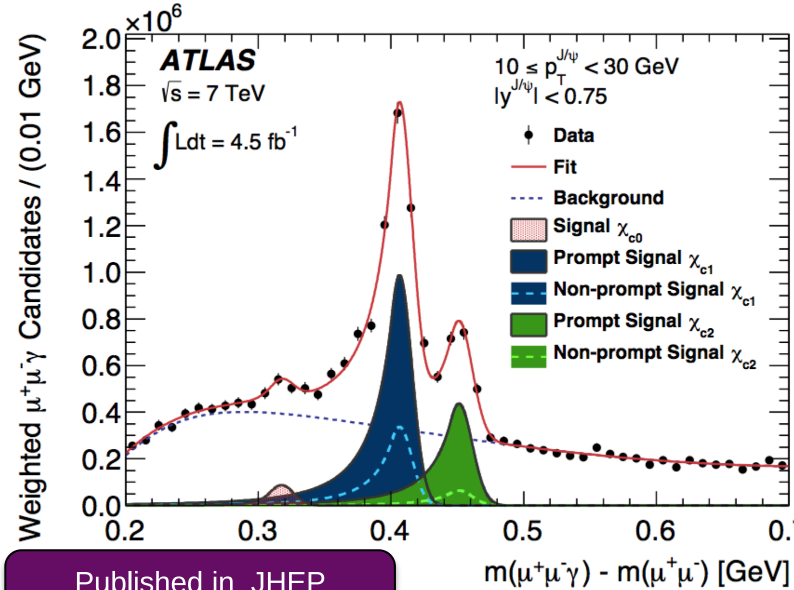
Important to understand this production channel to get a complete picture of quarkonium production.

Experimentally challenging:

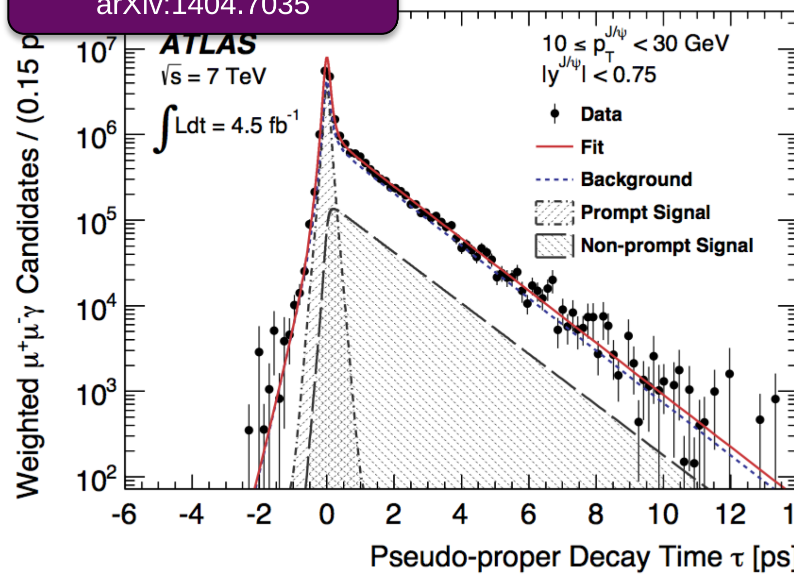
- low p_T muons
- precise reconstruction of soft (p_T>1 GeV) photon through conversions
  – low efficiencies

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

Extract prompt and non-prompt production of various χ_c states



Published in JHEP
arXiv:1404.7035



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

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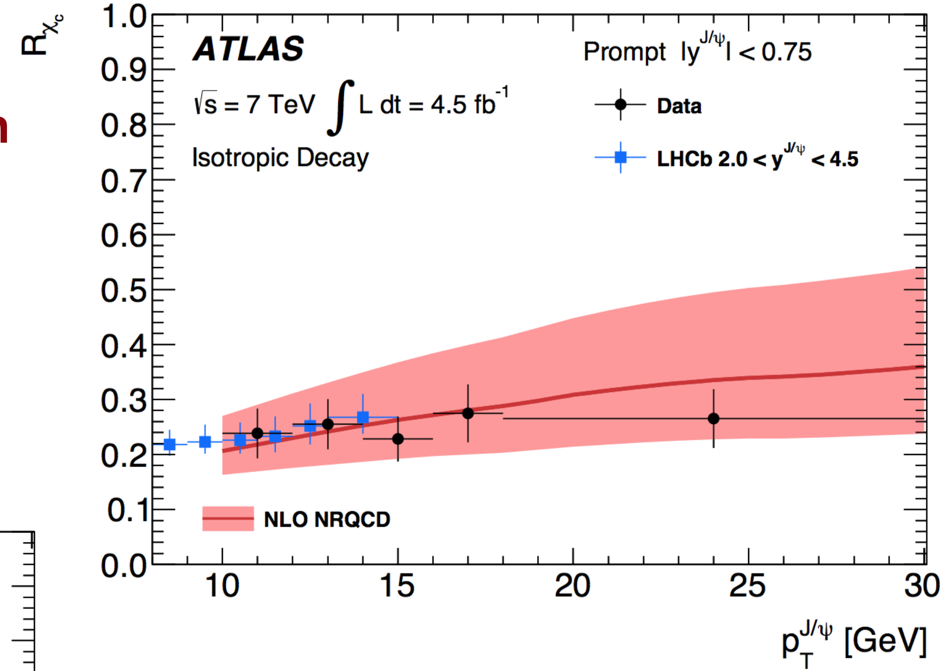
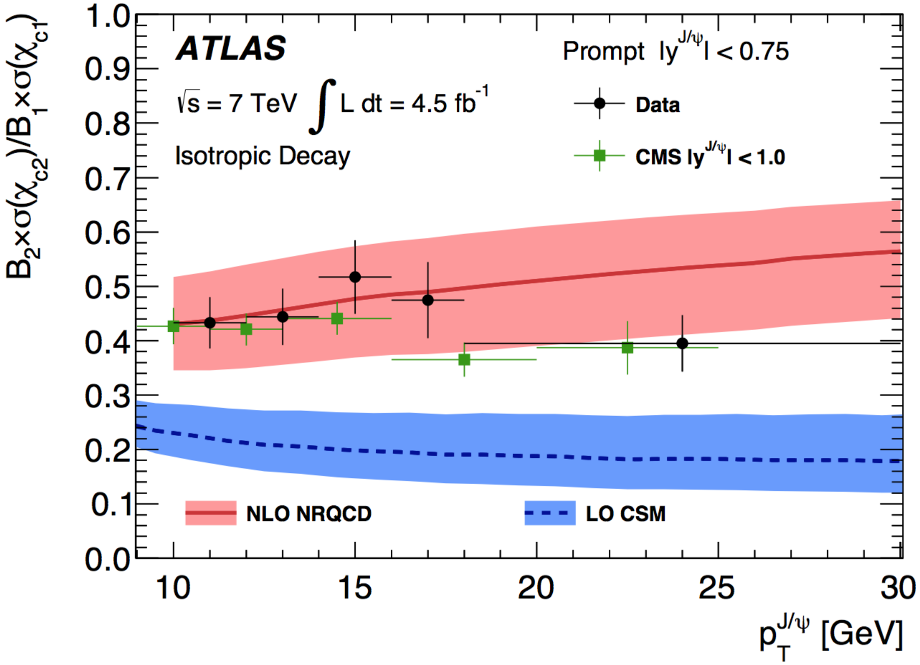
Fraction of prompt J/ψ produced in χ_c feed-down (right)→

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



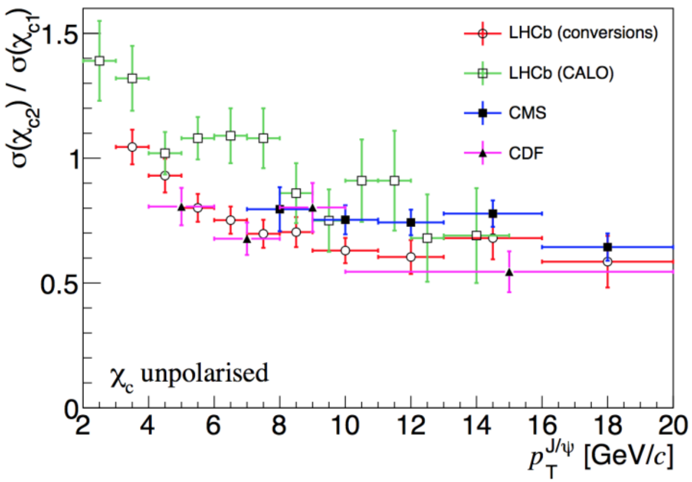


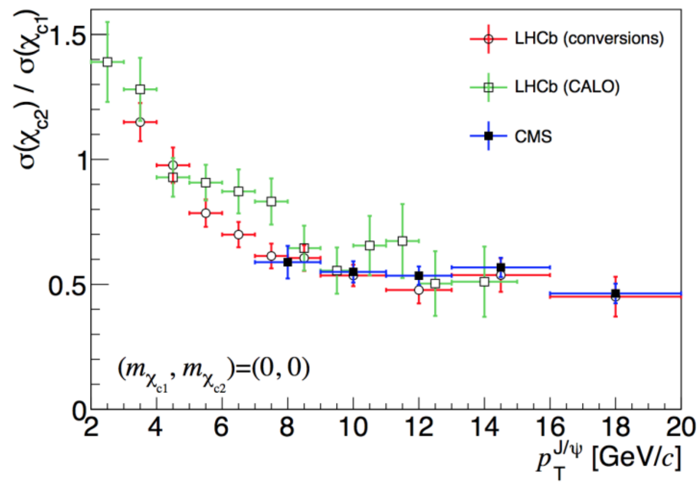
Prompt χ_c cross-section ratio ← (left)

Data show more χ_{c1} than χ_{c2}

Ratio sensitive to possible presence of colour octet contributions in NRQCD

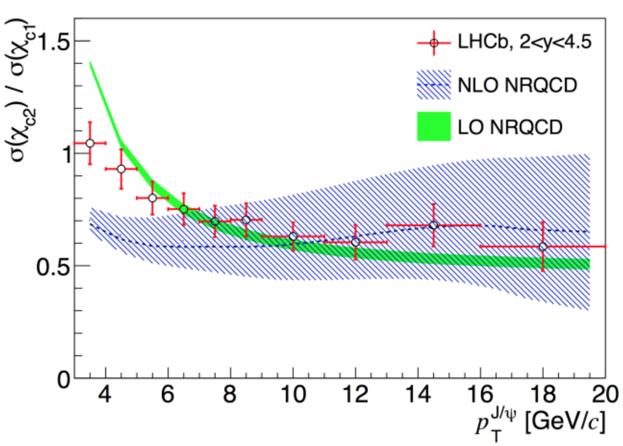
Comparison of relative χ_c rates

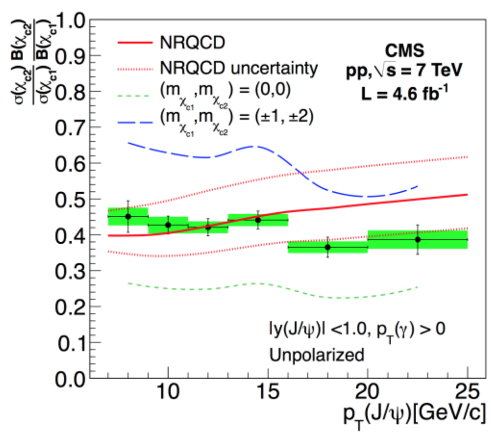


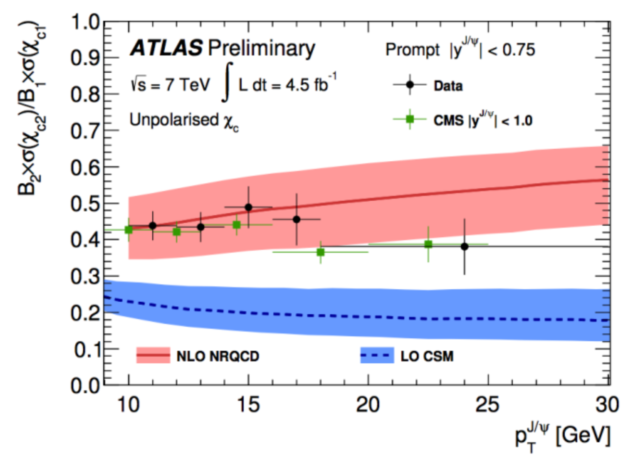


Data reasonably consistent with each other, NRQCD yields mixed results

Naively χ_{c2} should be enhanced at low p_T , as seen in LHCb data



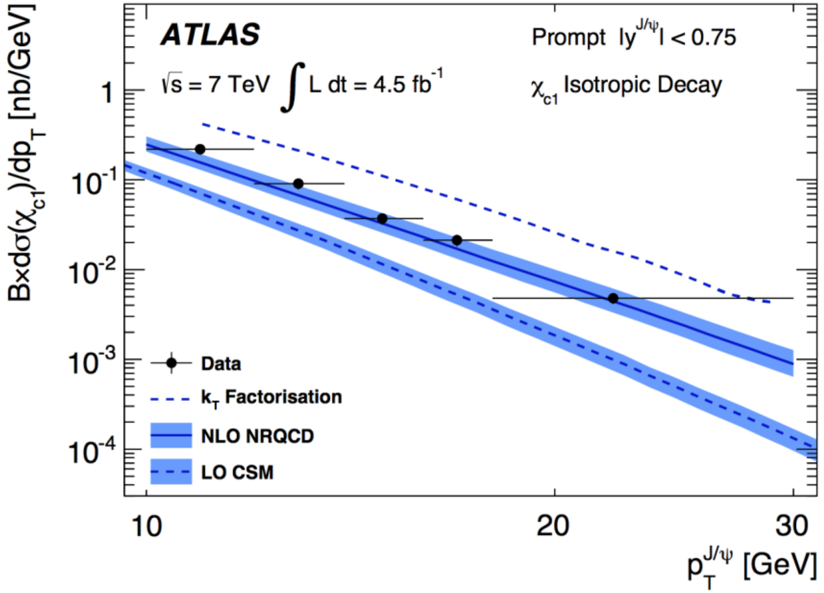


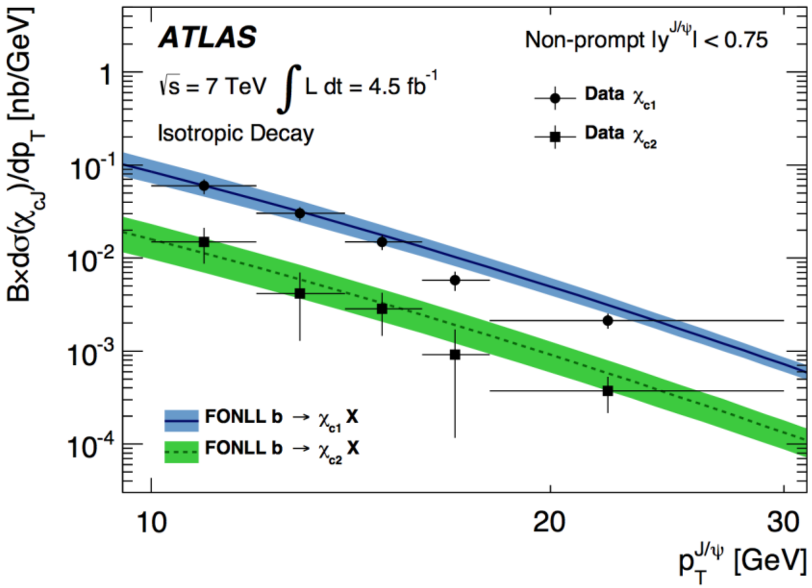


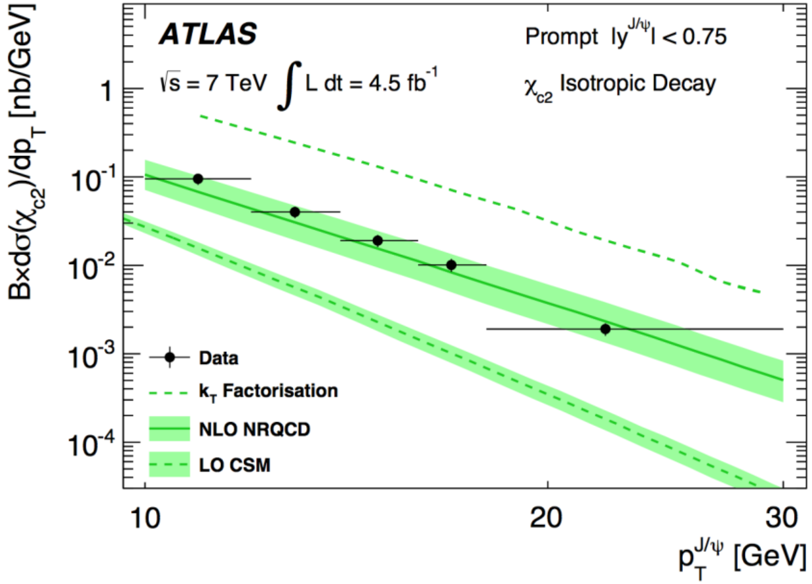
Absolute χ_c production rates

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?







Upsilon system production

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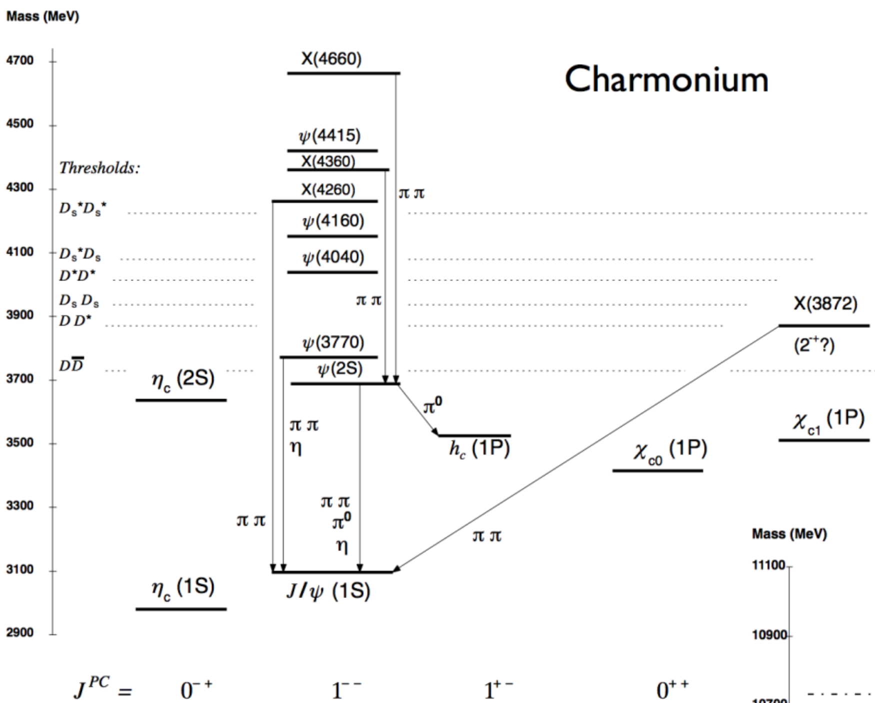


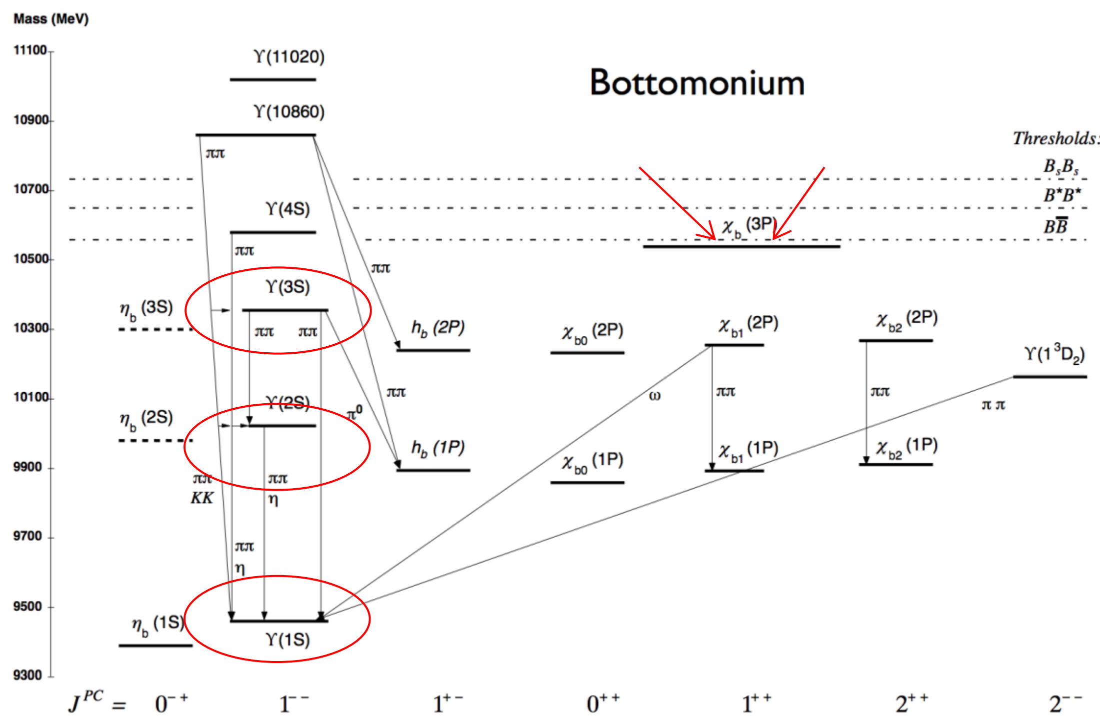
In b-anti-b system:
3 vector states below BB threshold
some more above threshold

Many more states in-between
with various quantum numbers

All LHC experiments studied production of vector states

...and some J++ states

ATLAS even discovered a new one!



Recent results from LHC on Upsilon

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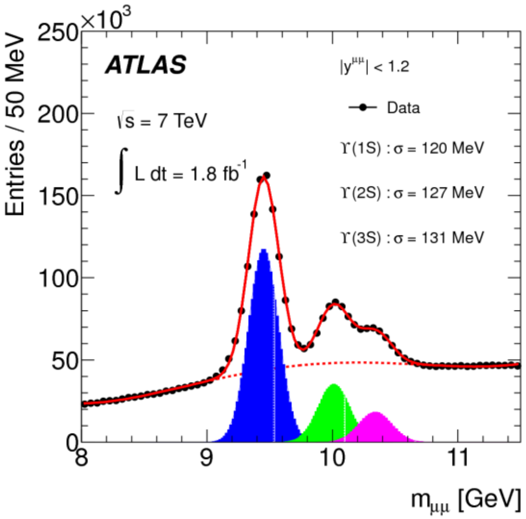
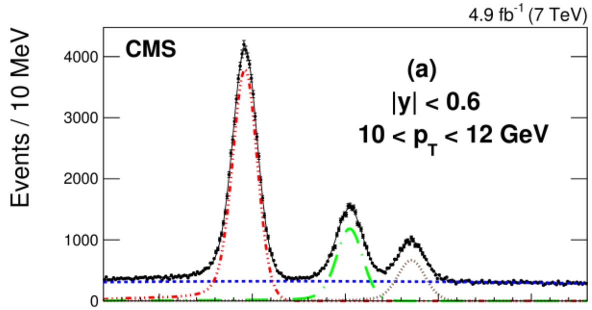
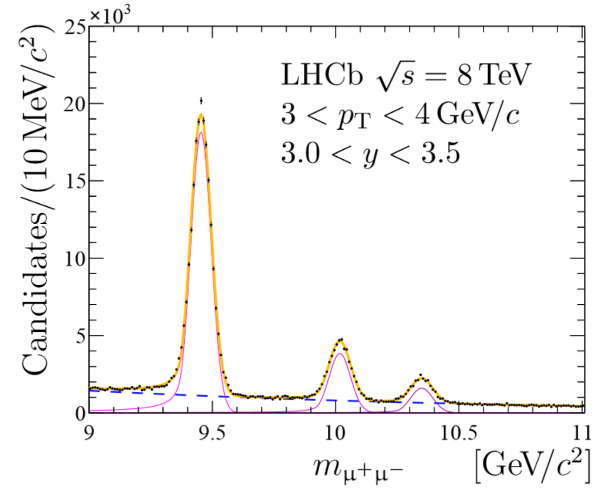
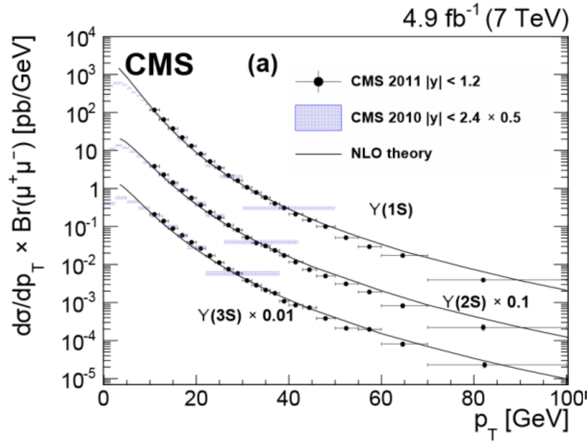


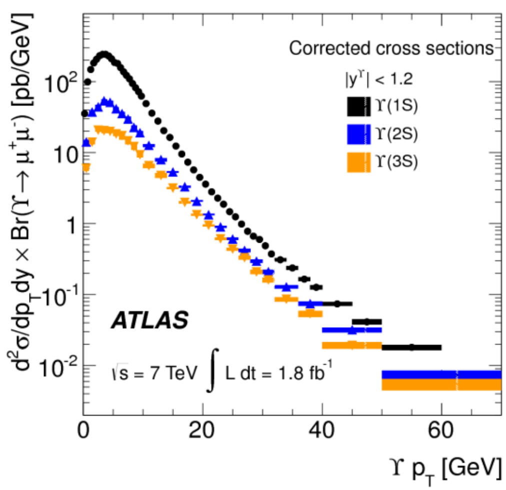


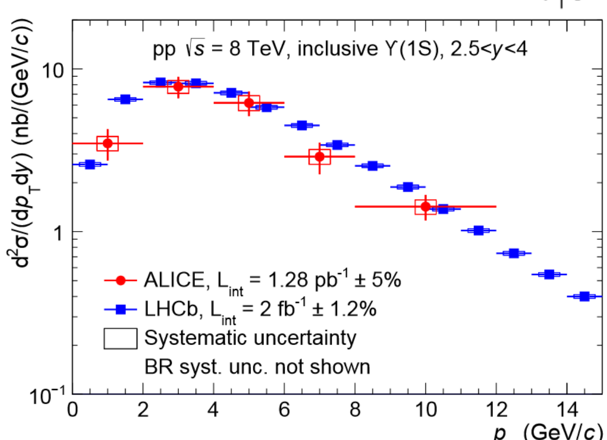
Good mass resolution allows for better separation between the Upsilon states

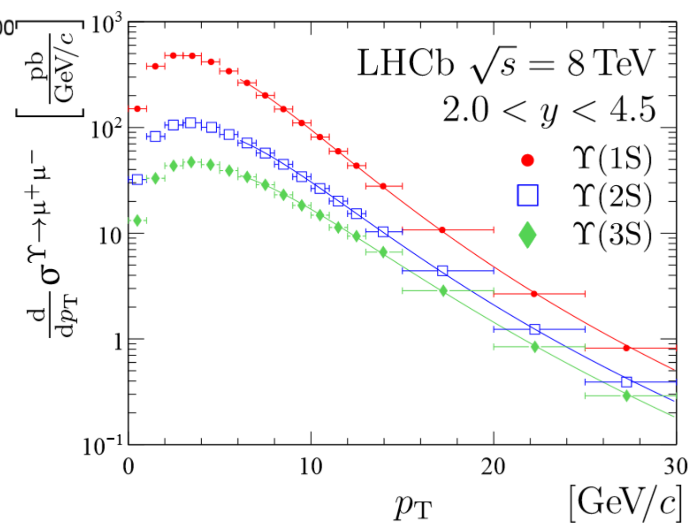




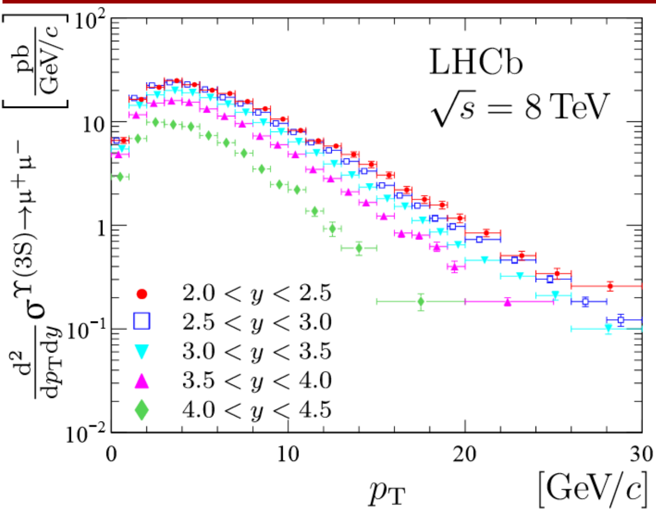
Very detailed data on production of all three ϒ states is available from all LHC collaborations





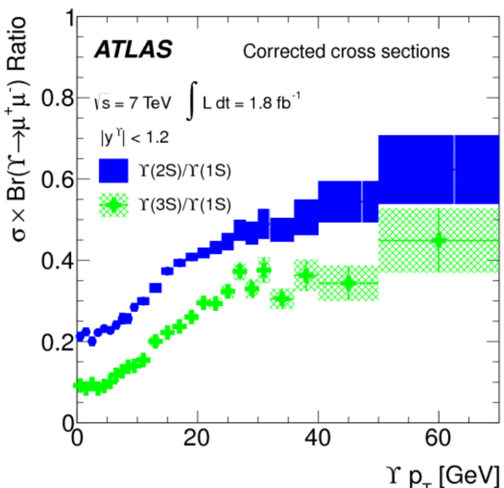


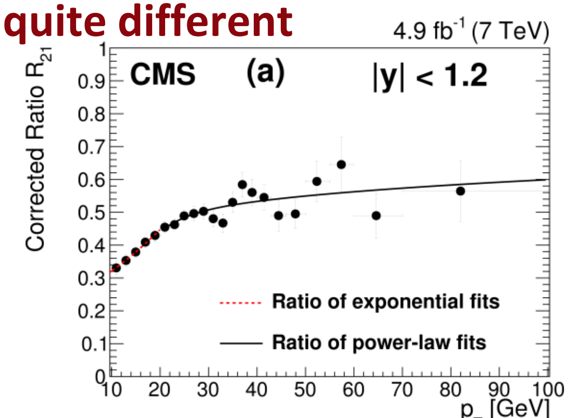
Ratios

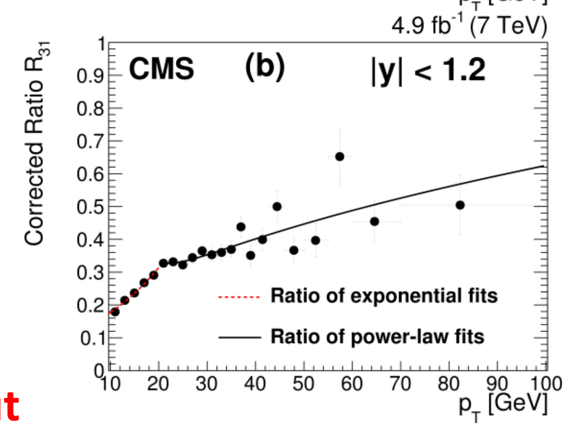


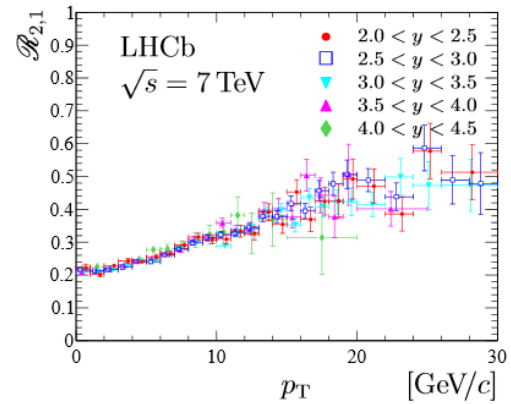
Ratios ϒ(3S)/ϒ(1S) and ϒ(2S)/ϒ(1S) show strong dependence on pT, hinting on a superposition of several mechanisms

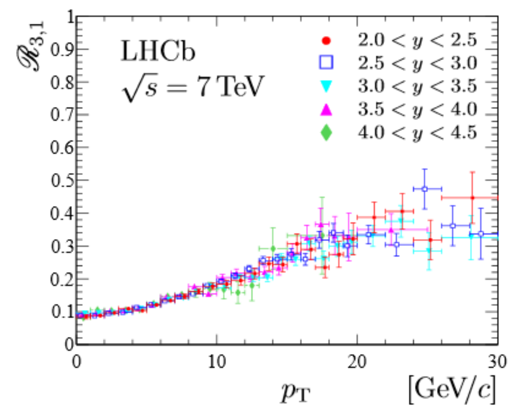
But no dependence on y, even at high y where pT spectra are quite different











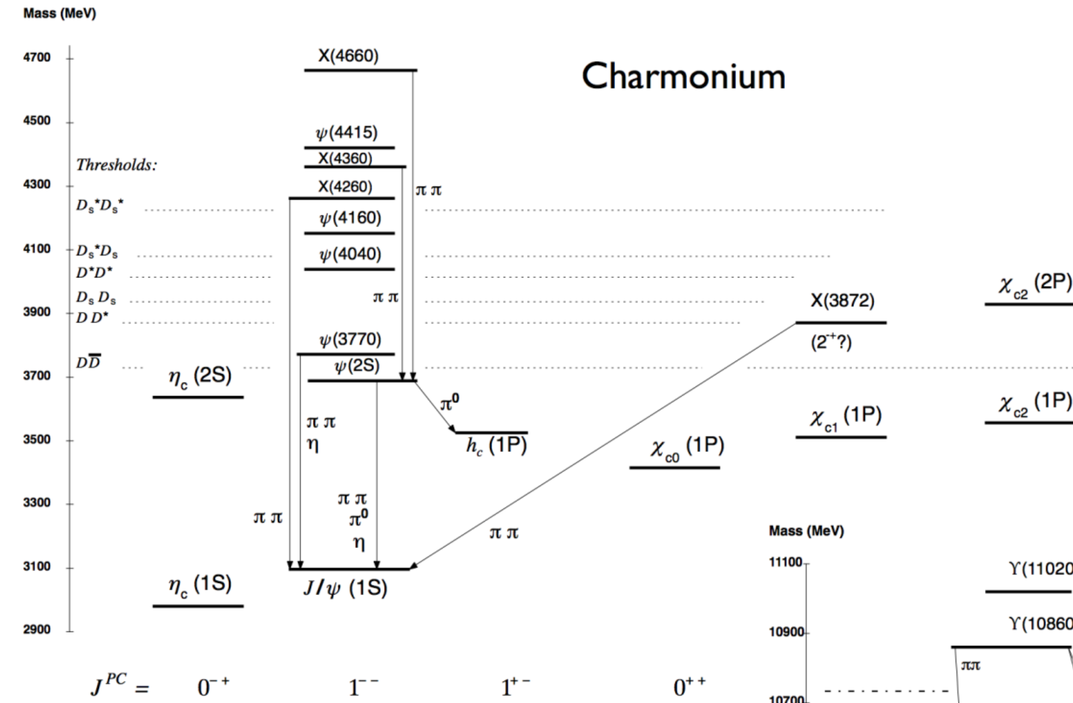
LHCb (EPJ C74 (2014) 3092):

feed-down from C-even states is about 50% for all three ϒ(nS) states

There is no "clean" state here like ψ(2s)

Can these experimental facts be reconciled within our current picture of production?

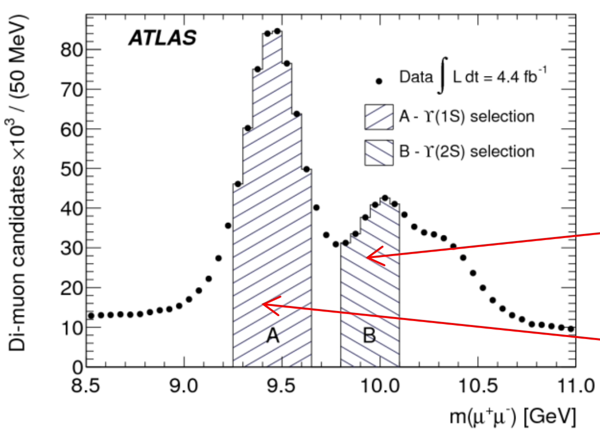
Observation of the χ_b states

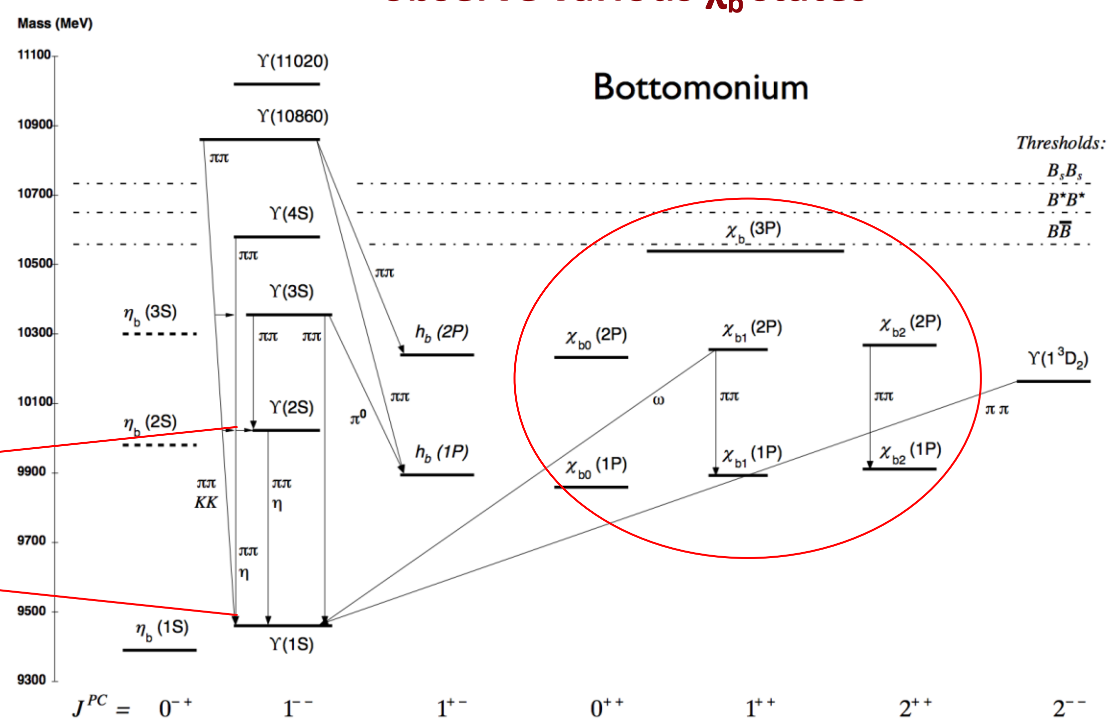


In a similar way to χ_{c1} and χ_{c2} states:

Combine dimuons from Υ range with photons

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





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

Significance of the new peak calculated through the difference of log-likelihoods with and without the peak in the fit: $D = \log(L_{with} / L_{without})$

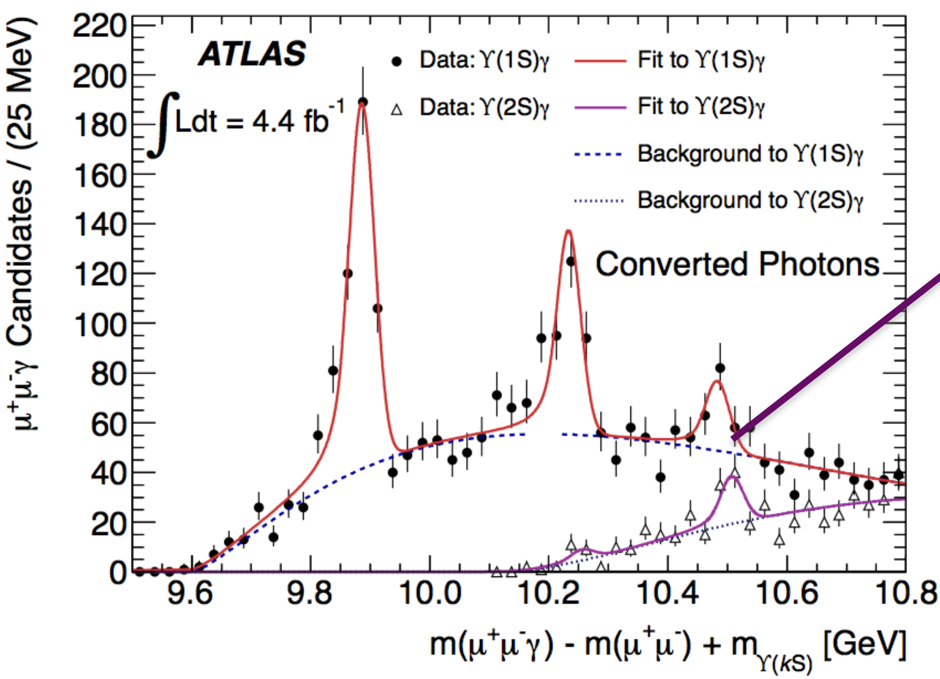
With moderately large numbers involved, -2D is distributed as $\Delta\chi^2$

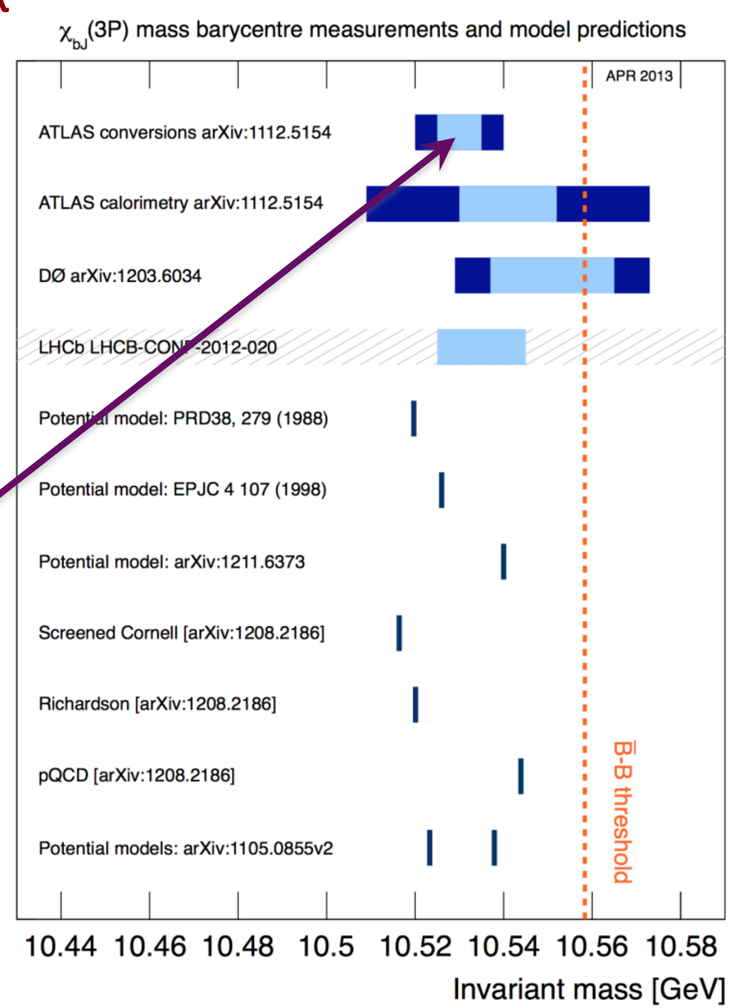
The "with" hypothesis won, with significance in excess of 6σ

Since then, confirmed by DØ and LHCb,

light blue: statistical,
dark blue statistical+systematic
[No quoted systematic for LHCb observation]

PRL 108 (2012) 152001





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

Phys.Rev.Lett. 108 (2012) 152001

“New observables” in quarkonium production

Clearly, despite 40+ years’ history, we still have no clear picture of quarkonium production in hadronic – and other -- collisions

New energy frontier and higher luminosities allow exploration of other reactions that may help understand better quarkonium production dynamics

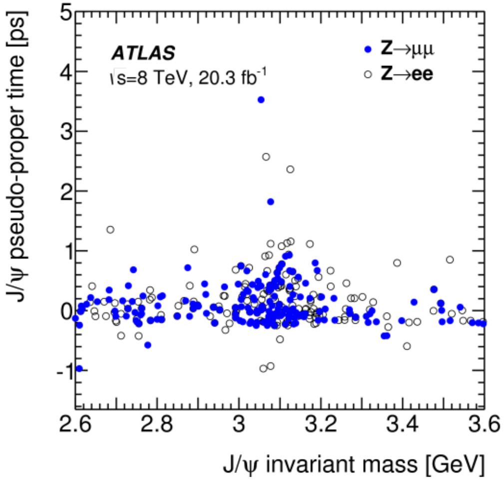
Simply speaking, more equations may help determine unknowns better, even if some new unknowns are introduced

Examples of these “new observables”: associated production of quarkonium with other objects, such as:

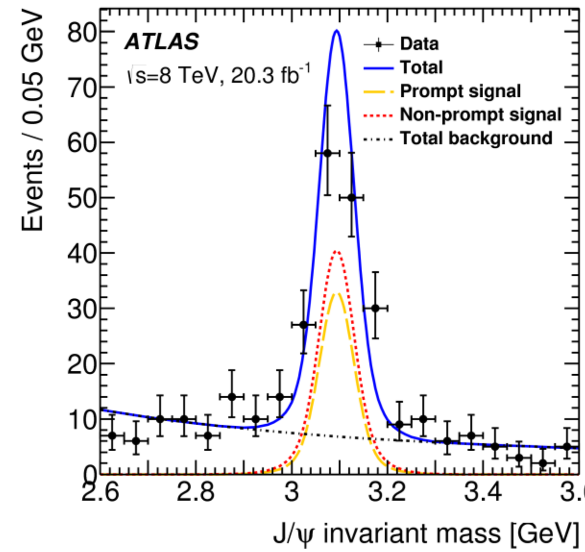
- other quarkonium (LHCb, CMS, now ATLAS)
- W and Z bosons (ATLAS)
- top quark pairs (new activity in ATLAS, TSU-Lancaster)
- other?

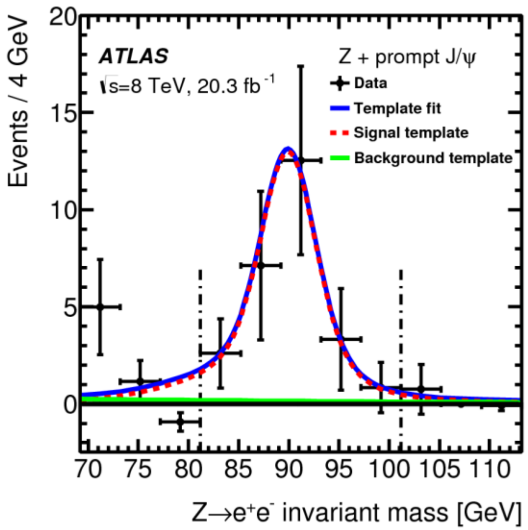
Associated production of J/ψ and Z boson

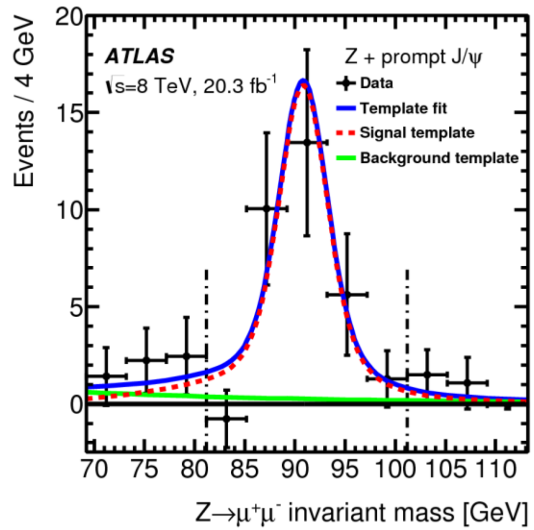
Identify events with a Z boson (decaying into electrons or muons) AND another pair of muons around the J/ψ mass range

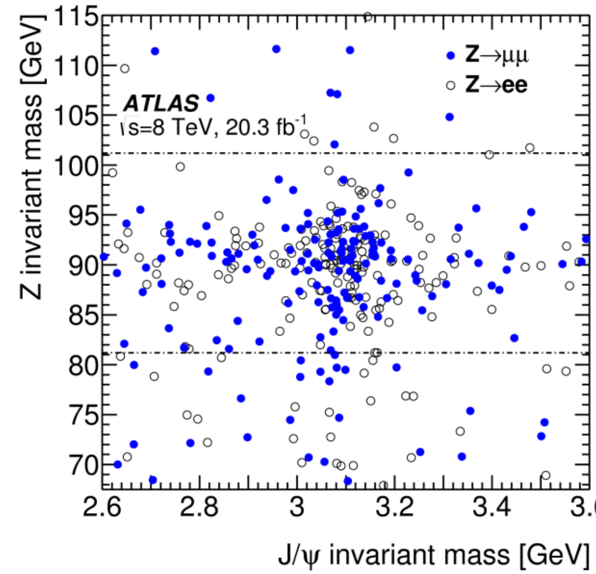


Some J/ψ are prompt, some are non-prompt

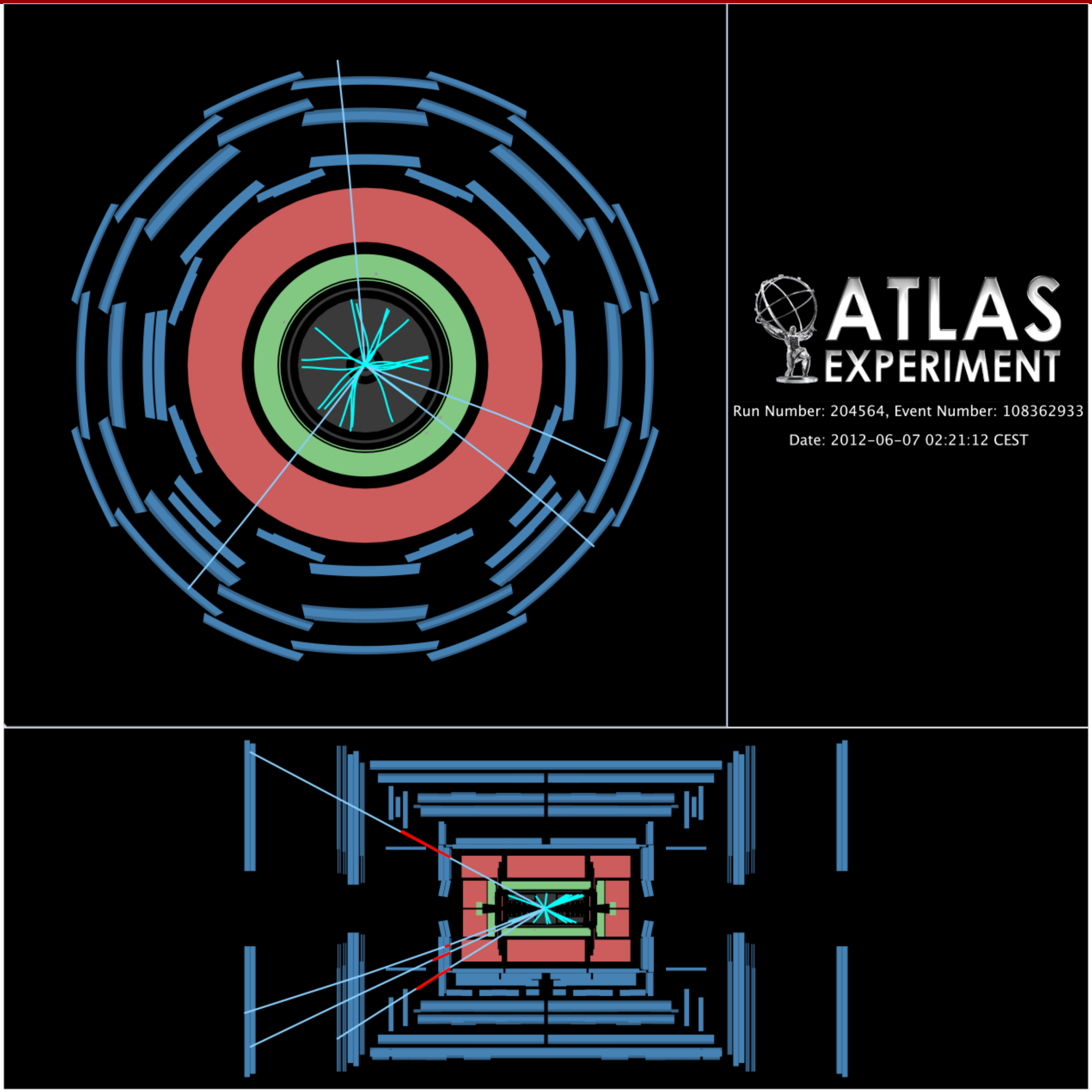




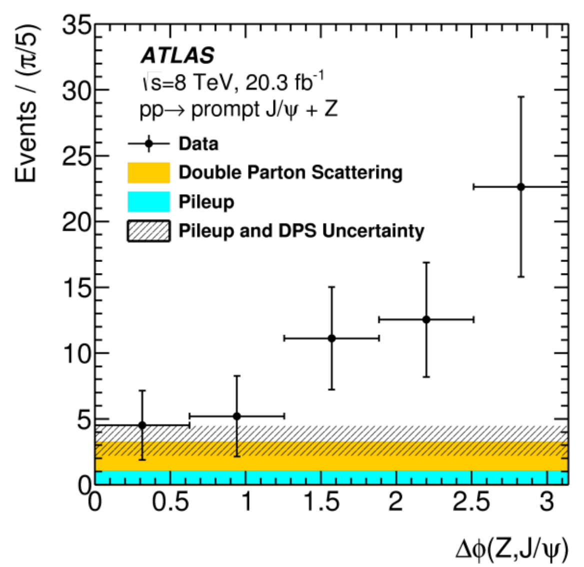




Z + J/ψ event candidate



Results



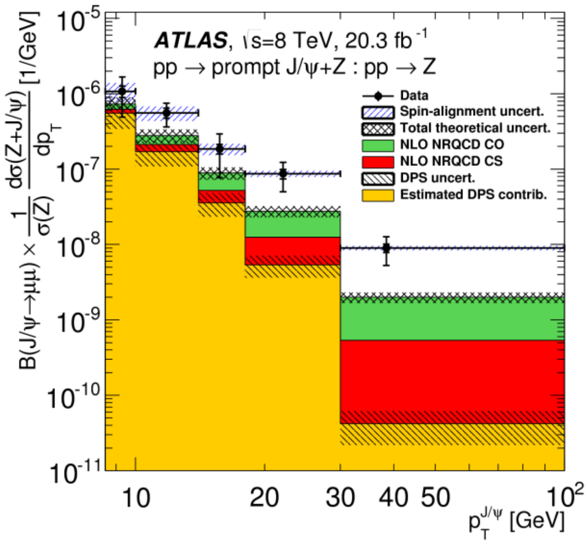
Z and J/ψ can be produced in:

separate hard collisions within the same pp event
(Double Parton Scattering --- DPS) -> isotropic in delta-phi
or in the same hard parton scattering
(Single Parton Scattering --- SPS) -> peaking at back-to-back

$p_T^{J/\psi}$ [GeV]	Inclusive prompt ratio [$\times 10^{-7}$/ GeV] value ± (stat) ±	(syst) ±	(spin)	Estimated DPS [$\times 10^{-7}$/ GeV] assuming $\sigma_{\rm eff} = 15$ mb
(8.5, 10)	10.8 ± 5.6	± 1.9	± 3.1	5.5 ± 2.1
(10, 14)	5.6 ± 1.9	± 0.8	± 1.2	1.7 ± 0.6
(14, 18)	1.9 ± 1.1	± 0.1	± 0.3	0.4 ± 0.1
(18, 30)	0.87 ± 0.37	± 0.12	± 0.09	0.05 ± 0.02
(30, 100)	0.090 ± 0.037	± 0.012	± 0.006	0.0004 ± 0.0002

$p_T^{J/\psi}$ [GeV]	Inclusive non-prompt ratio [$\times 10^{-7}$/ GeV] value ± (stat) ±	(syst) ±	(spin)	Estimated DPS [$\times 10^{-7}$/ GeV] assuming $\sigma_{\rm eff} = 15$ mb
(8.5, 10)	5.1 ± 4.2	± 0.9	± 0.3	2.07 ± 0.77
(10, 14)	9.2 ± 2.5	± 1.2	± 0.3	0.85 ± 0.30
(14, 18)	3.3 ± 1.2	± 0.4	± 0.1	0.26 ± 0.09
(18, 30)	3.04 ± 0.59	± 0.04	± 0.04	0.05 ± 0.02
(30, 100)	0.115 ± 0.039	± 0.002	± 0.001	0.0015 ± 0.0005

Theory predictions well below measurement, especially at high P_T



Measured cross section ratio (Z+ J/ψ) / Z differentially in P_T(J/ψ) separately for prompt and non-prompt J/ψ

Will hopefully stimulate further calculations

What is X(3872) ?

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

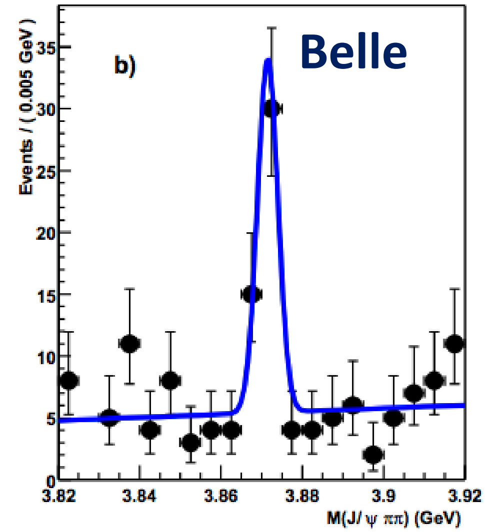
Soon after **confirmed by BaBar, CDF, D0** and now LHC experiments

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

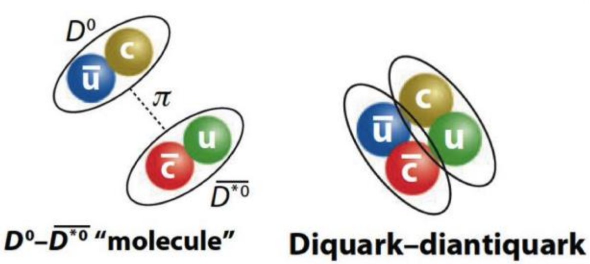
What is it? No clear picture yet!

- *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 presents a new 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

Event selection

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

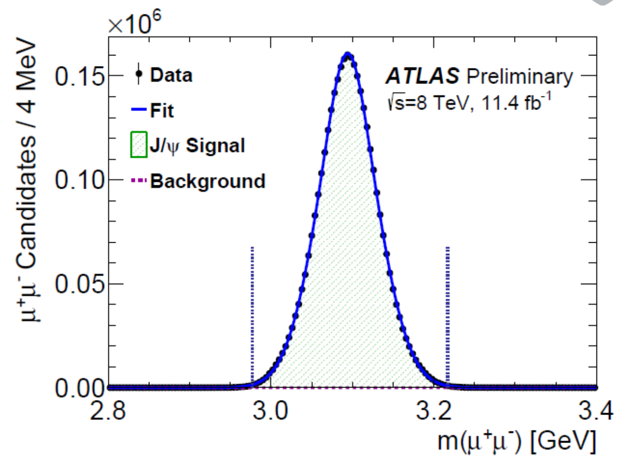
Effective integrated luminosity 11.4 fb^{-1} at 8 TeV

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

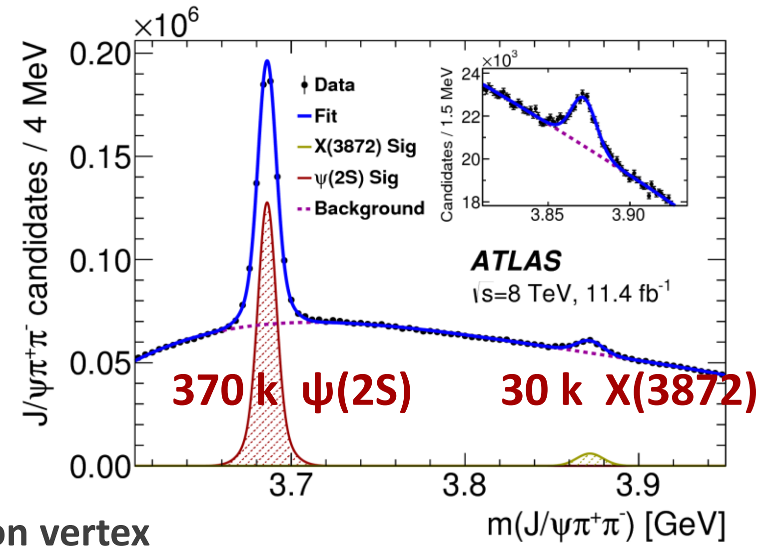


Pion cuts

- 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

X(3872) cross sections

Lancaster University

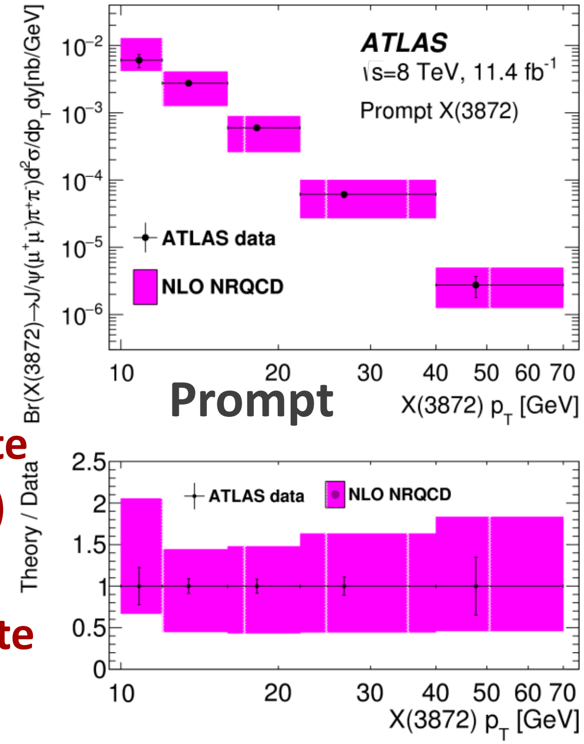
Prompt: **Described well by NLO NRQCD**

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



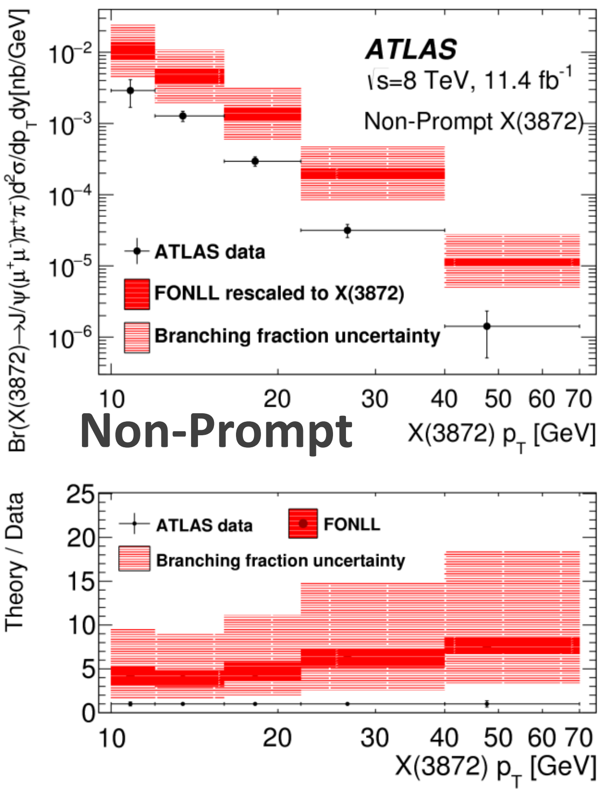
Non prompt:

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]

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

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



Non-prompt fraction and ratio

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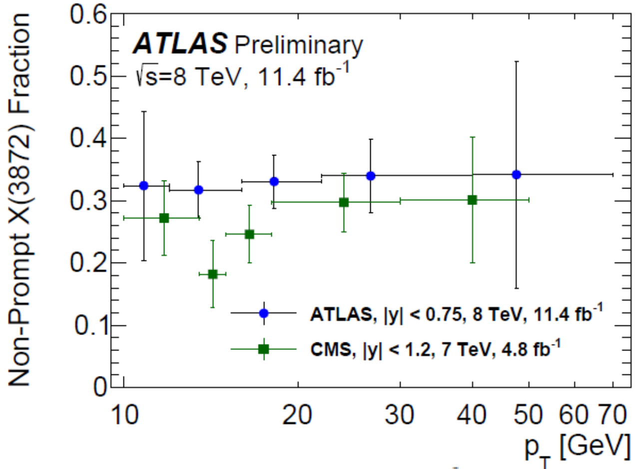


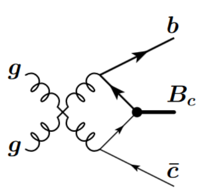
Non-prompt fraction of X(3872):

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

Ratio of non-prompt X(3872) : ψ(2S)

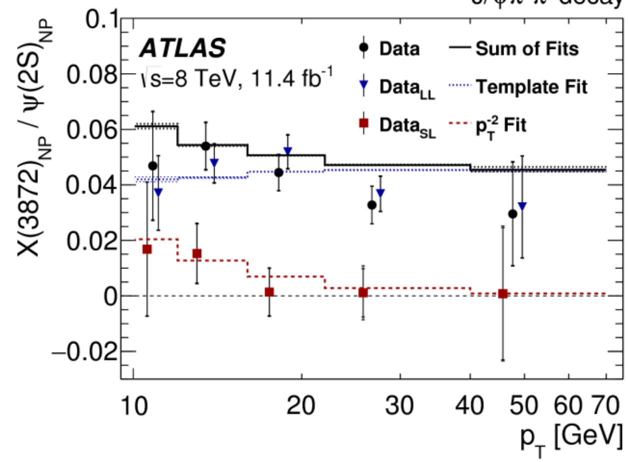
- long-lived part fitted to kinematic template

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



- 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?

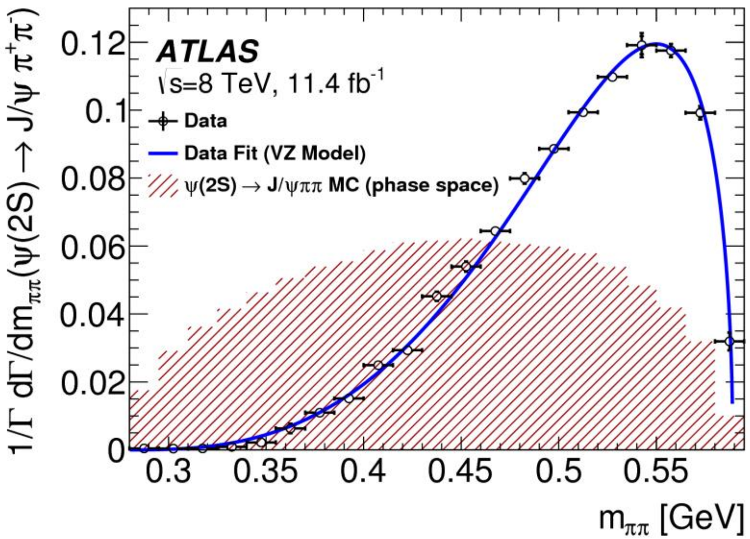
Di-pion mass distributions: results

In ψ(2S) to $J/\psi\pi^+\pi^-$ decays

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

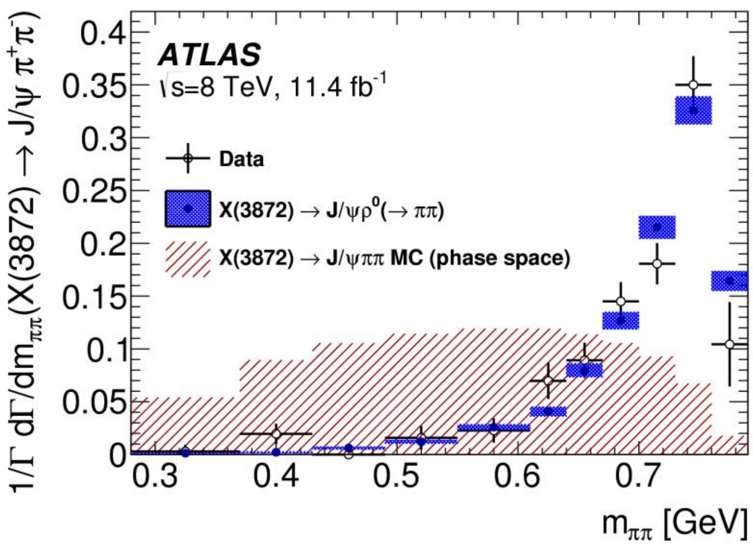
$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{\pi\pi}} \propto \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2 \times \mathrm{PS}$$

- found $\lambda = 4.16 \pm 0.06(\mathrm{stat}) \pm 0.03(\mathrm{syst})$
- in agreement with previous measurements



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

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

Instead of conclusions

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

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

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!

Backup slides

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 (next slide)

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

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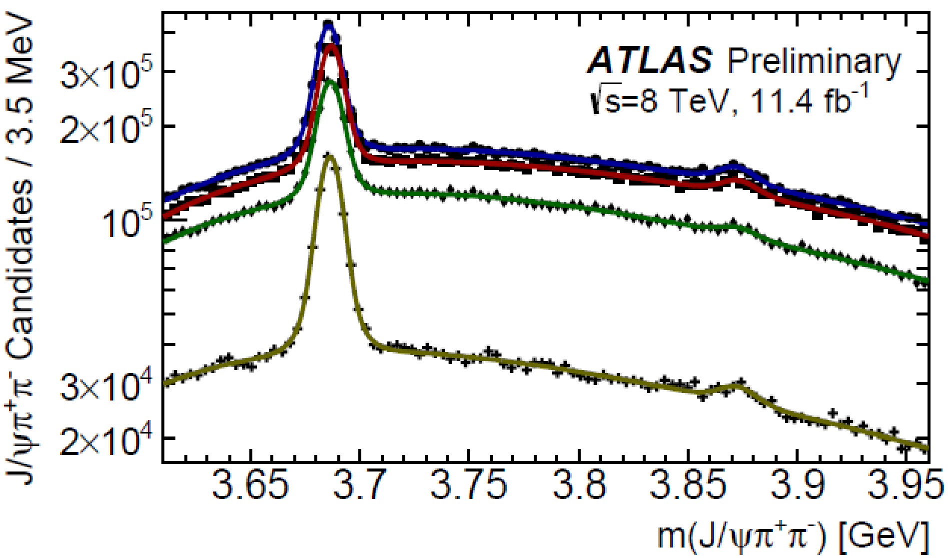
Mass fits: double-Gaussian signal peaks on a smooth background:

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

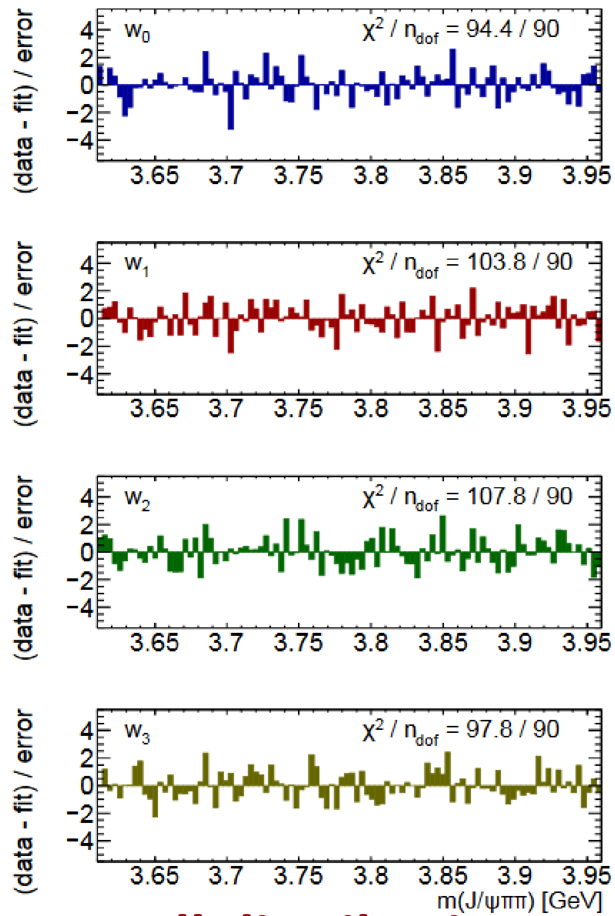
Fraction of narrow Gaussian f_{12} shared between ψ(2S) and X(3872)

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

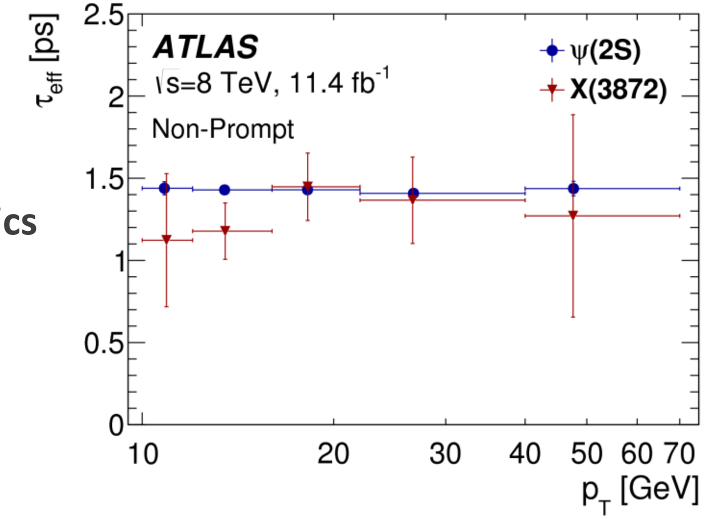


Pull distributions

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

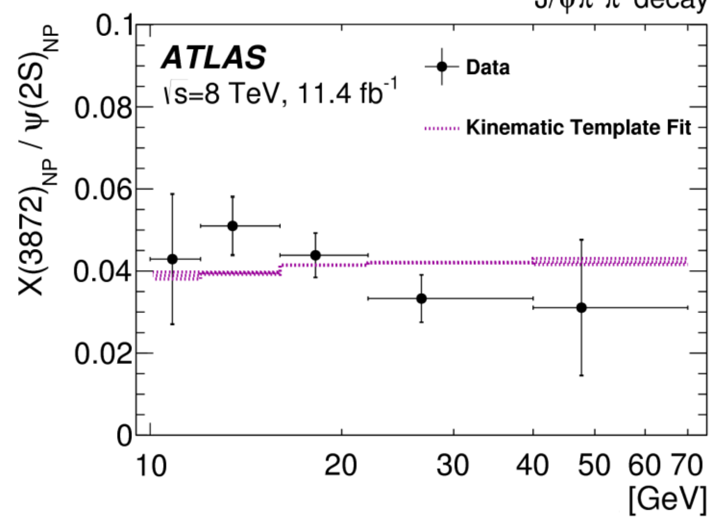


Effective lifetimes

- 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

$\tau(B^{\pm}) = 1.638 \pm 0.004$ 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

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

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