Spectroscopy, Production and Exotica in Heavy Flavour in ATLAS

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On behalf of the ATLAS Collaboration

ICHEP 2018
Seoul, July 2018

Outline

- ATLAS detector, (multi-,) muon triggers

Focus on recent results

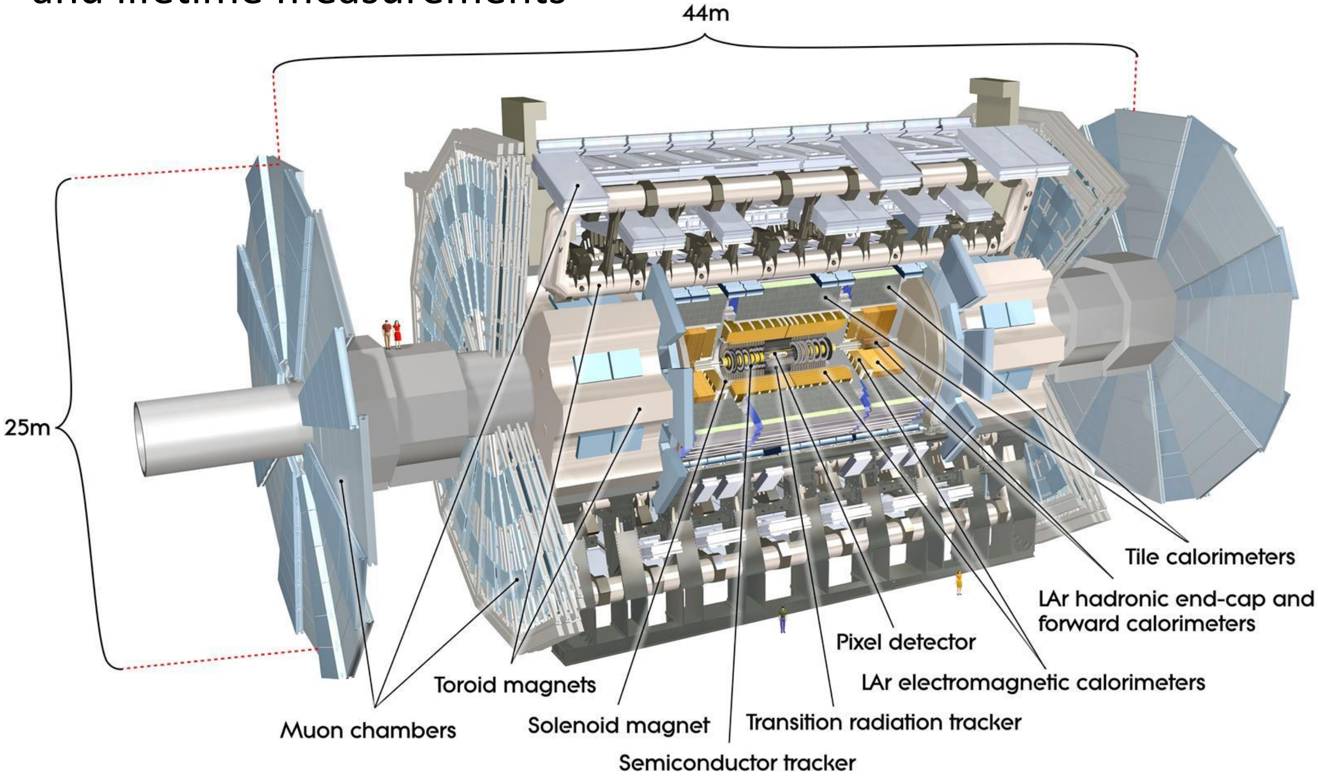
- bb correlation with J/ψ+μ JHEP 11 (2017) 62
- X(3872) production measurement, prompt and non-prompt JHEP 01 (2017) 117
- $B_s\pi$ states PRL 120 (2018) 202007

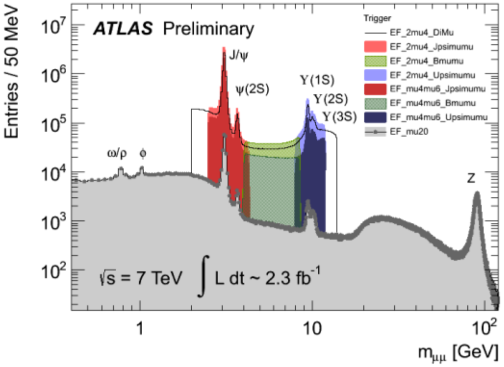
- Summary and perspectives

The ATLAS detector at LHC

Inner Detector
|η|<2.5, Solenoid B=2T
σ/pT ~ 3.4x10-4 pT + 0.015 for (|η|<1.5)
Used for Tracking and Vertexing:
Precise momentum
and lifetime measurements

Muon Spectrometer
|η|<2.7
Toroid B-Field, average ~0.5T
Muon Momentum resolution
σ/p< 10% up to ~ 1 TeV

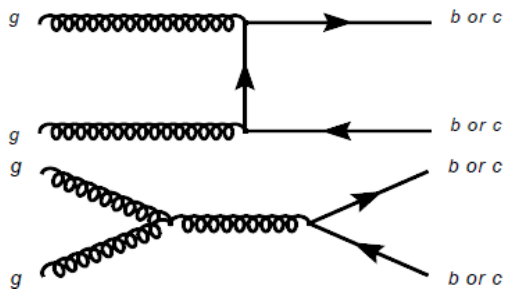


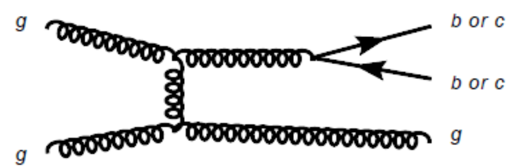


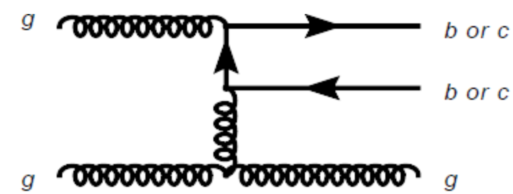
bb production at the LHC

Needed for H➔bb and new physics searches

Flavour creation	Gluon splitting	Flavour Excitation





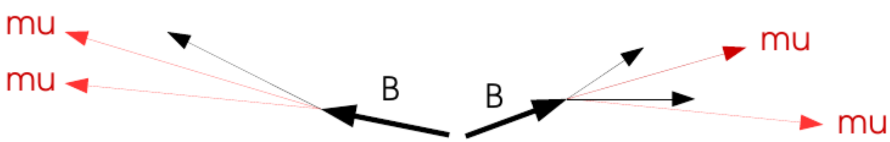


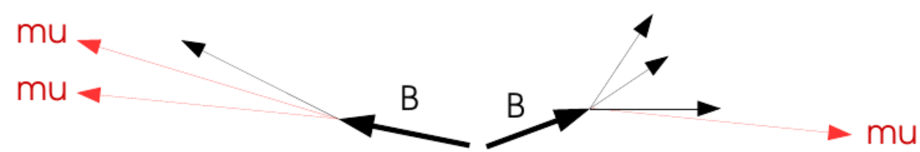
Large Δϕ, back-2-back pT balance

Small Δϕ, colinear

Large Δη, broad Δϕ

Need to tag both b's without losses when colinear





Unlike methods using b-jets, J/ψ+μ works for large and small separations

bb Event selection & analysis

J/ψ muons:

- $|\eta| < 2.3$
- $2.6 < m(\mu\mu) < 3.5$ GeV

1.9 M J/ψ candidates

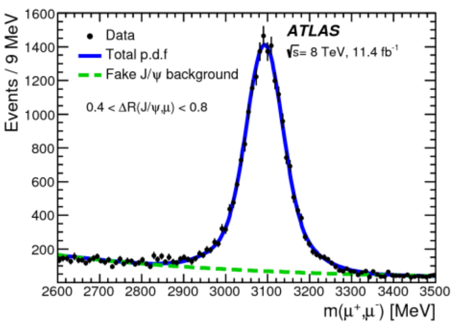
Additional muons

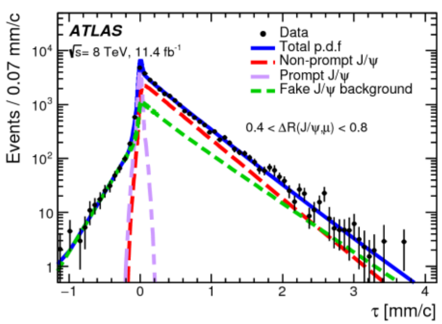
- $|\eta| < 2.5$
- 'Fakes' mainly J/ψ+K, control with BDT trained on Monte Carlo

$$\tau_{eff} = \frac{L_{xy}\, m(\mu\mu)}{c\, p_T(\mu\mu)}$$

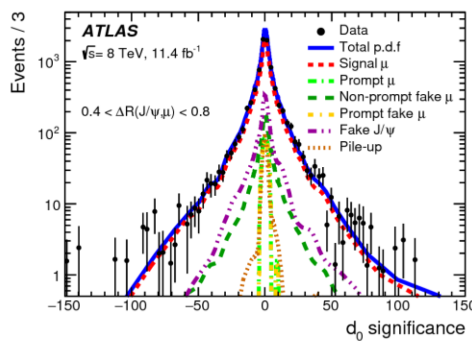
$$L_{xy} = \frac{\vec{L} \cdot \vec{p_T}(\mu\mu)}{p_T(\mu\mu)}$$

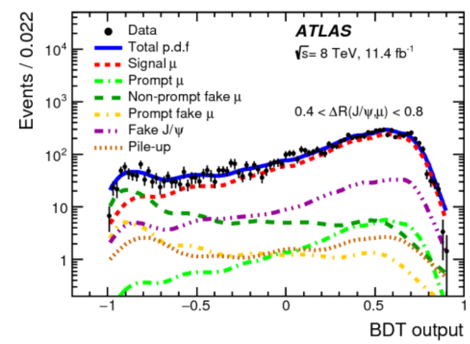
Use pseudo proper lifetime of J/ψ to separate prompt/non prompt J/ψ & background, in mass/lifetime fit



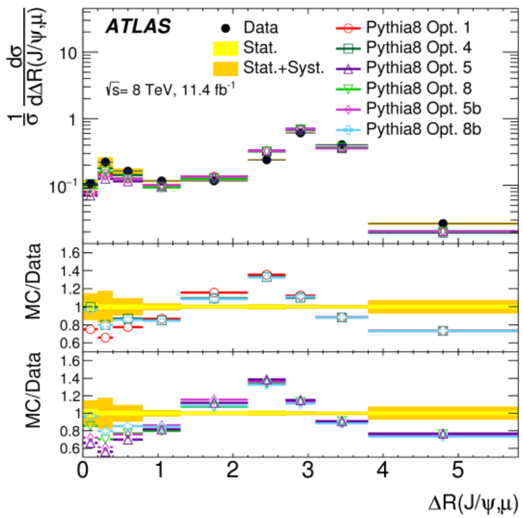


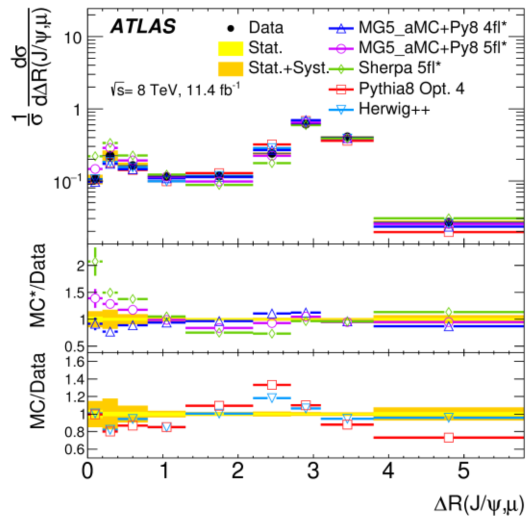
Use 3rd muon impact parameter and BDT to templates from MC to extract signal/prompt/fake contributions

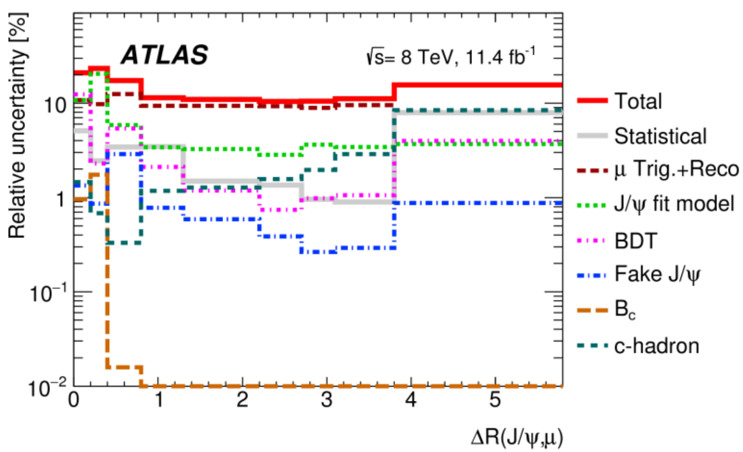




Comparisons with Models







Fiducial cross section is also measured
17.7 ± 0.1 (stat) ± 2.0 (syst) nb

Choose ΔR as an example – many more observables studied

- Pythia 8 poorly reproduces shape of the angular distributions
- The pT-based scale splitting kernels give better description at low ΔR – Opt 4 best overall
- Herwig++ is better than Pythia 8 for the ΔR
- 4- and 5-flavour MadGraph5 predictions sit either side of the data; 4-flavour is closer
- 5-flavour SHERPA & MadGraph similar
- Good understanding of systematics

What is X(3872)?

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

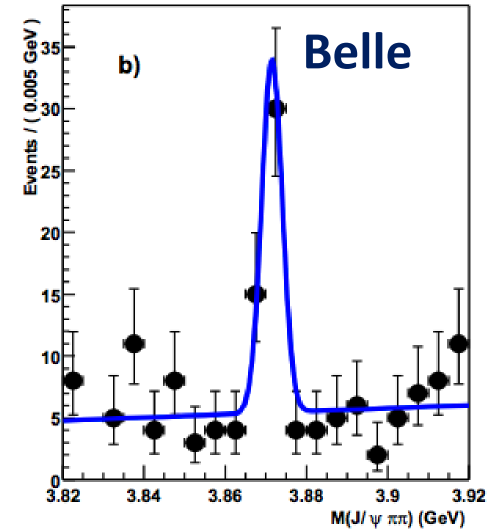
Subsequently confirmed by BaBar, CDF, D0 and now LHC experiments

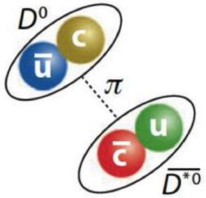
Current world average X(3872) mass very close to the $D^0 D^{0*}$ threshold

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 (PRD 96, 074014 (2017))
- *Tetraquark (diquark – diantiquark)?* Possible, but hard to make any solid predictions

hep-ex/0309032





D^0–$\overline{D}^{*0}$ "molecule"

Diquark–diantiquark

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

Outline of the X(3872) Analysis

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

Each $J/\psi\pi^+\pi^-$ candidate weighted to correct for trigger/reconstruction/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 narrow/wide Gaussian ratio common for the two states

Event selection

11.4 fb^{-1} at 8 TeV

Muon cuts:

- Opposite sign `combined' muons
- $p_T > 4$ GeV, $|\eta| < 2.3$

J/ψ cuts:

- χ^2 < 200, $p_T > 8$ GeV & $|y| < 2.3$

Use kinematic and vertex fits combined with mass and opening angle cuts to select signal and reject background

Pion cuts:

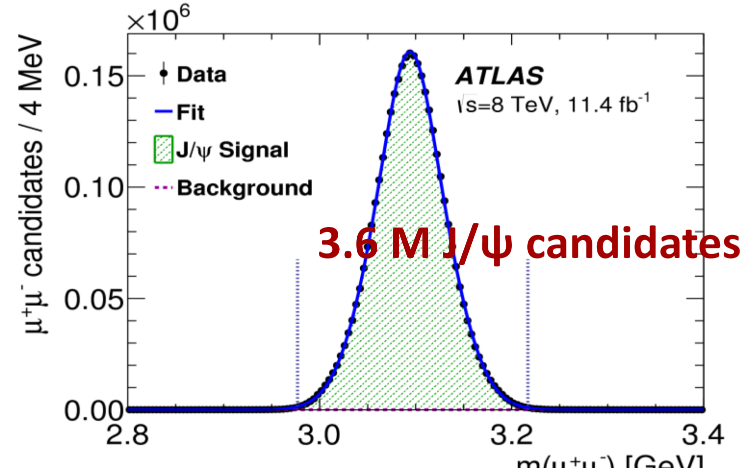
- Opposite sign, $p_T > 600$ MeV, $|\eta| < 2.4$

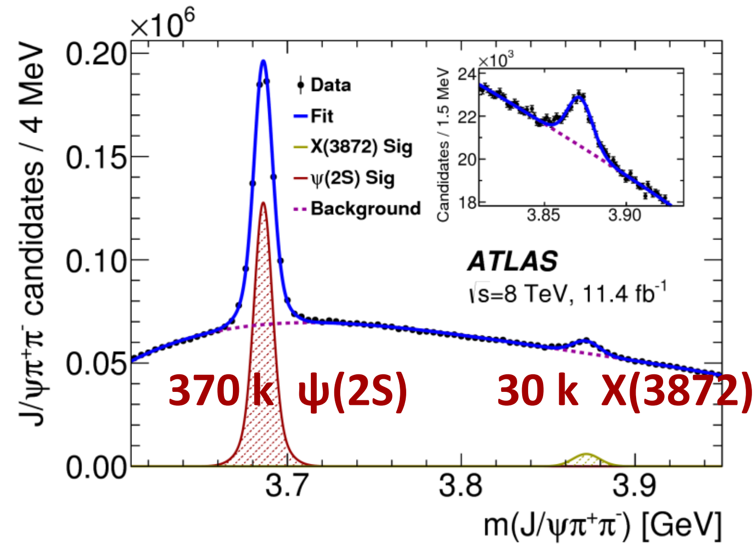
Constrained vertex fit on each $\mu^+\mu^-\pi^+\pi^-$ candidate:

- di-muon ($2.8 < m_{\mu\mu} < 3.4$) GeV fit to a single vertex
- di-muon mass constrained to the J/ψ mass
- pion mass hypothesis used for the other two tracks

$J/\psi\pi^+\pi^-$ 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



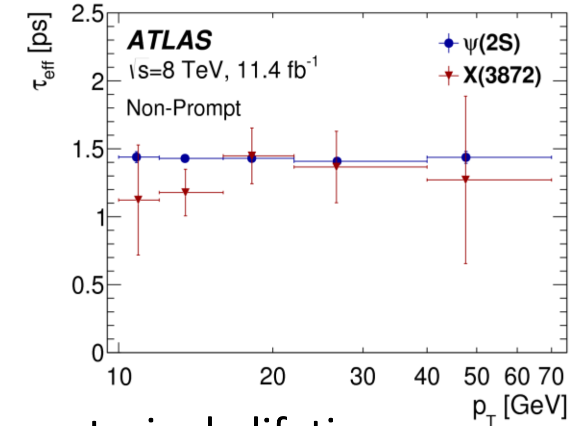


Single or Double lifetime hypothesis

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

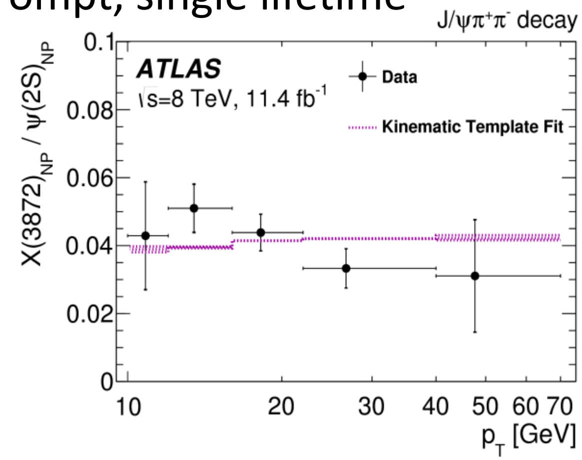
- **same lifetimes for ψ(2S) and X(3872) in each p_T bin**
- **pT spectra of ψ(2S) and X(3872) linked through kinematics**

➔Effective lifetimes for ψ(2S) consistent with single component independent of p_T ;



Non-prompt, single lifetime

X(3872) possibly slightly shorter in low p_T bins (from B_c?)



➔Double lifetime fit:

- **τ_{LL} = 1.45±0.05 ps determined from fits to ψ(2S), allowing for some SL contribution**
- **τ_{SL}=0.40±0.05ps obtained from simulation, varying B_c decay mode**

In either case, *X(3872):*ψ(2S) ratio vrs pT extracted

Fit to kinematic (p_T) templates **obtained from simulations of various b-hadron decays into ψ(2S) and X(3872)**

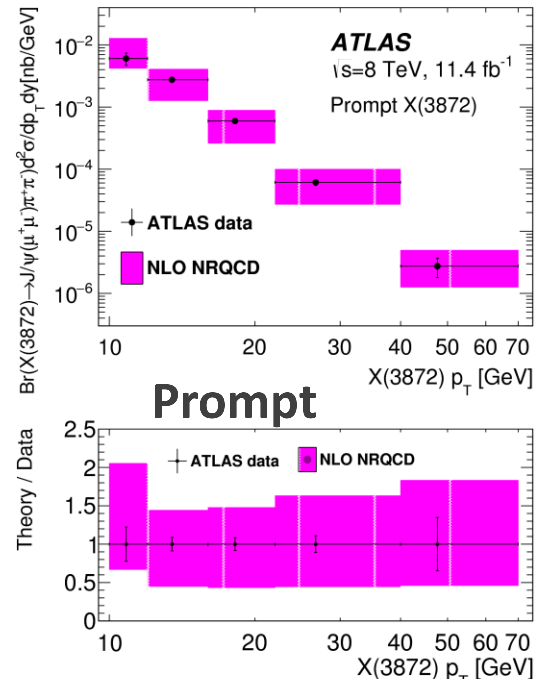
➔Extract overall non- prompt X(3872) : ψ(2S) ratio

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

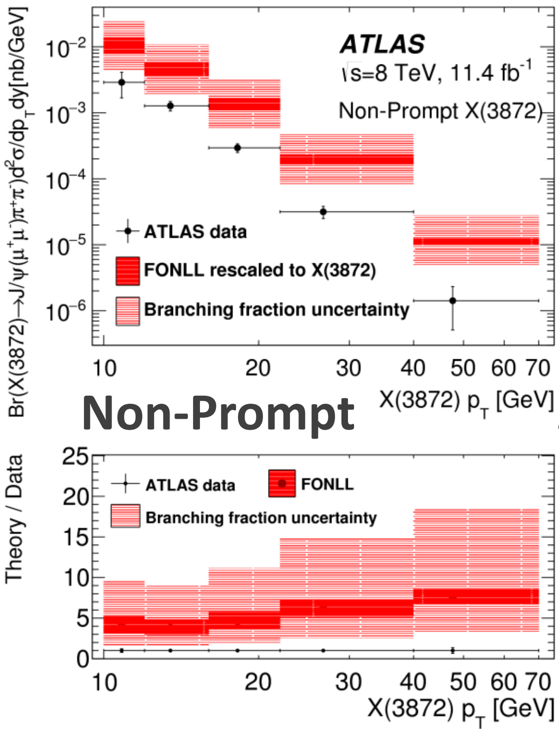
X(3872) cross sections

Prompt: **Described well by NLO NRQCD**

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



Non prompt:
use the fitted kinematic template to recalculate from FONLL ψ(2S) prediction

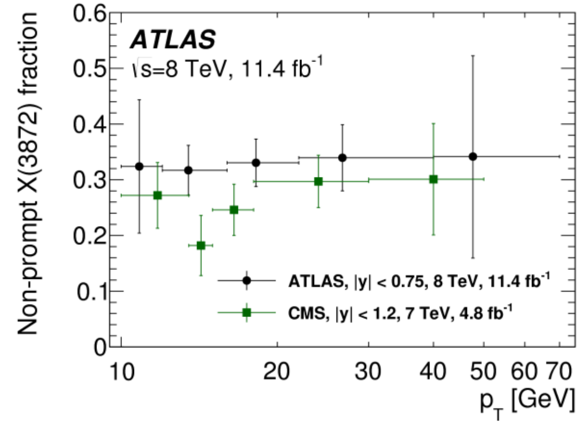


PBR not measured – estimate from Artoisenet, Braaten based on Tevatron data [hep-ph:0911.2016]

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

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

Non-prompt fraction and ratio



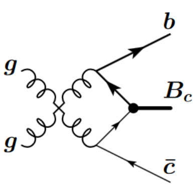
Non-prompt fraction of X(3872):

- no visible p_T dependence
- consistent with CMS result within errors
- Very unlike J/ψ's strong p_T dependence

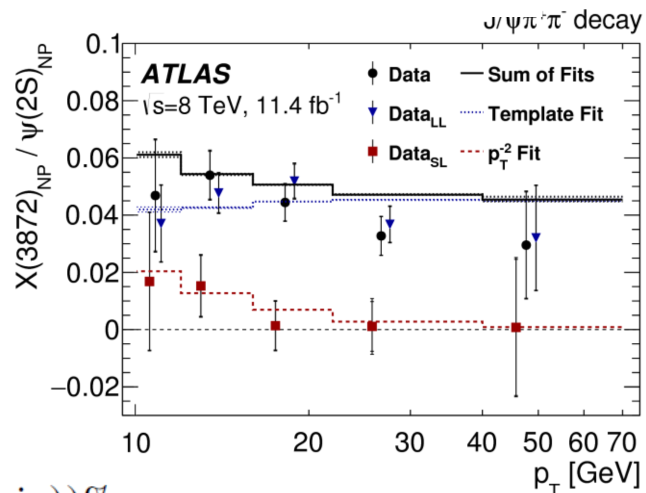
Ratio of non-prompt X(3872) : ψ(2S)

- 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: assuming non-fragmentation B_c dominate at low p_T [Berezhnoy, arXiv:1309.1979]
- fit with $a \cdot p_T^{-2}$ relative to fragmentation production
- 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 small fraction of b-hadrons at LHC => Indication X(3872) production enhanced in B_c decays

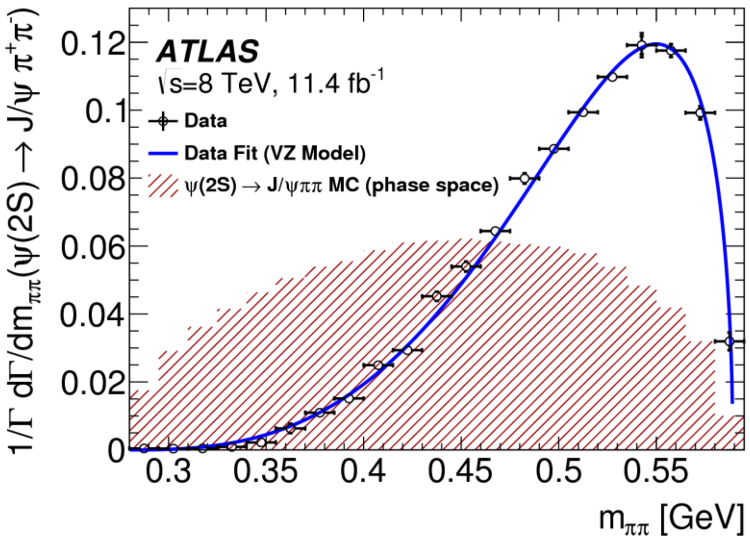
Di-pion mass distributions: results

In ψ(2S) to J/ψπ⁺π⁻ decays

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

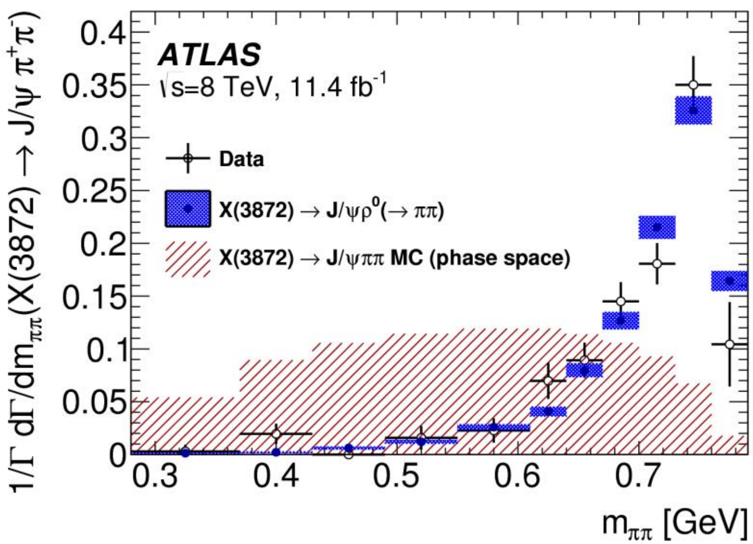
$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{\pi\pi}} \propto \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2 \times \mathrm{PS}$$

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



In X(3872) to J/ψπ⁺π⁻ decays

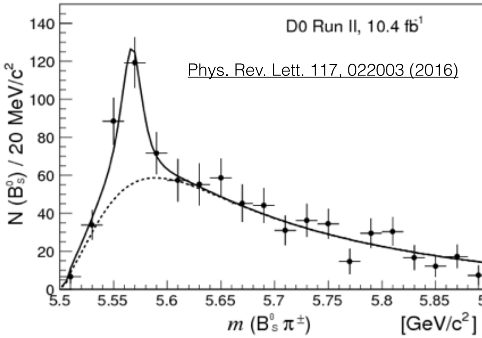
- dipion mass distribution has an even sharper peak at high masses
- in agreement with simulation where the di-pion system is produced via ρ^0 meson decay

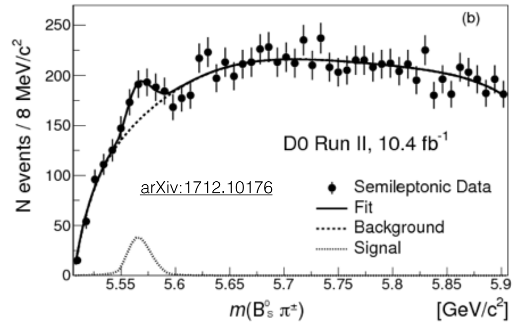


Structure in the $B_s^0\pi^\pm$ Spectrum?

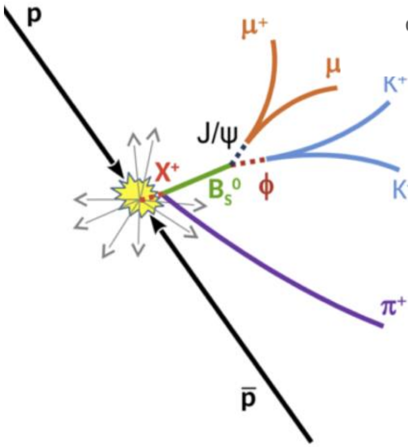
- D-Zero published evidence for X(5568) in $B_s^0\pi^\pm$ spectrum
  - $B_s^0 \rightarrow J/\psi\phi$, $B_s^0 \rightarrow \mu^\mp D_s^\pm (\phi\pi^\pm)X$
  - $m=5566.9^{+3.2}_{-3.1}(\text{stat})^{+0.6}_{-1.2}(\text{syst})$ MeV
- Significance 6.7σ, bsud state?

[PRL 117 (2016) 022003; PRD 97 (2018) 092004]





- ATLAS $B_s^0 \rightarrow J/\Psi(\mu\mu)\ \phi\ (KK)$
  [PRL 120 (2018) 202007]



- 4.9 fb^{-1} at 7 TeV
- 19.5 fb^{-1} at 8 TeV

$M_{fit}(B_s^0)=5366.6\pm0.1$ MeV
$N(B_s^0)=52750\pm280$ (stat)

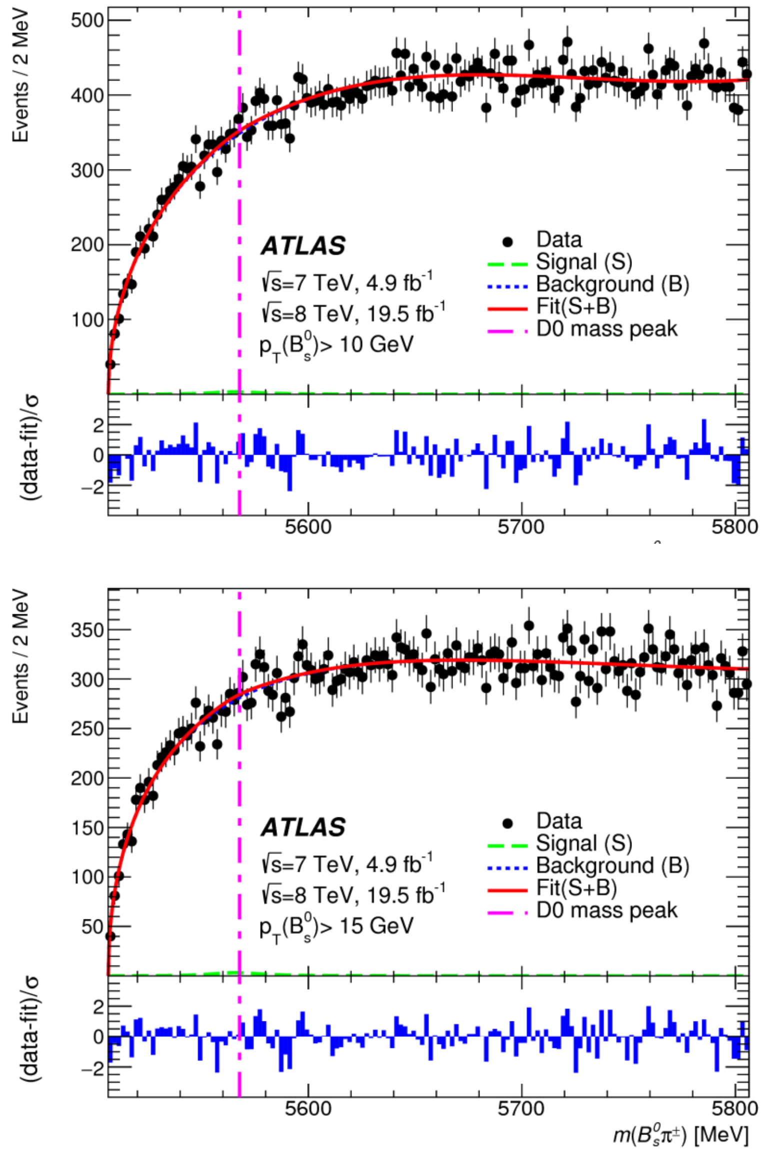
Study of $B_s^0\pi^\pm$ Candidates

- **Combine B_s candidates with tracks from same primary vertex**
  - **Pion hypothesis, p_T>500MeV**
  - **Extended unbinned fit:**

$m(B_s\pi)$ =

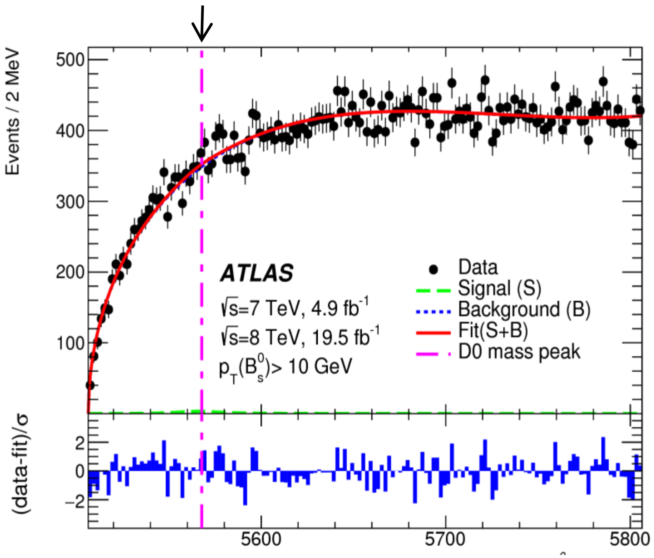
$m(J/\psi KK\pi) - m(J/\psi KK) + m_{fit}(B_s)$

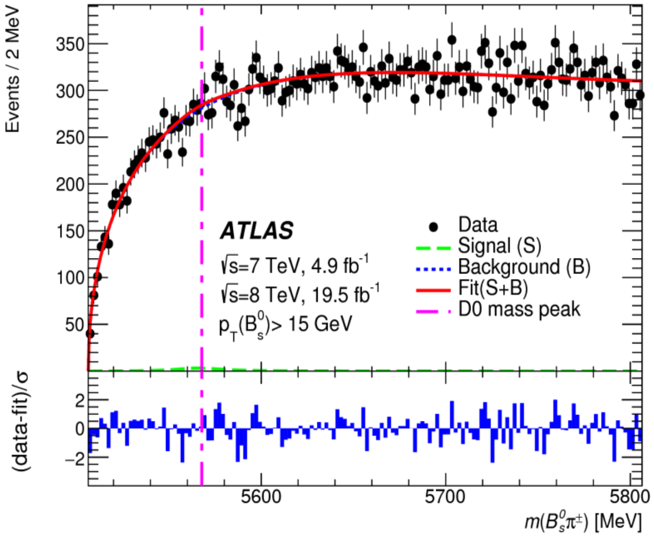
- **Consider**
  - **$p_T(B)$>10GeV**
  - **$p_T(B)$>15GeV**



Setting Limits

D0 signal





No significant X(5568) signal

Fitted X(5568) yields & Limits:

p_T(B) > 10 GeV:

- **N(X) = 60 ±140 (stat)**
- **N(X) < 382 @95% CL**

p_T(B) > 15 GeV:

- **N(X) = -30 ±150 (stat)**
- **N(X) < 356 (@95% CL)**

Relative Production Limits

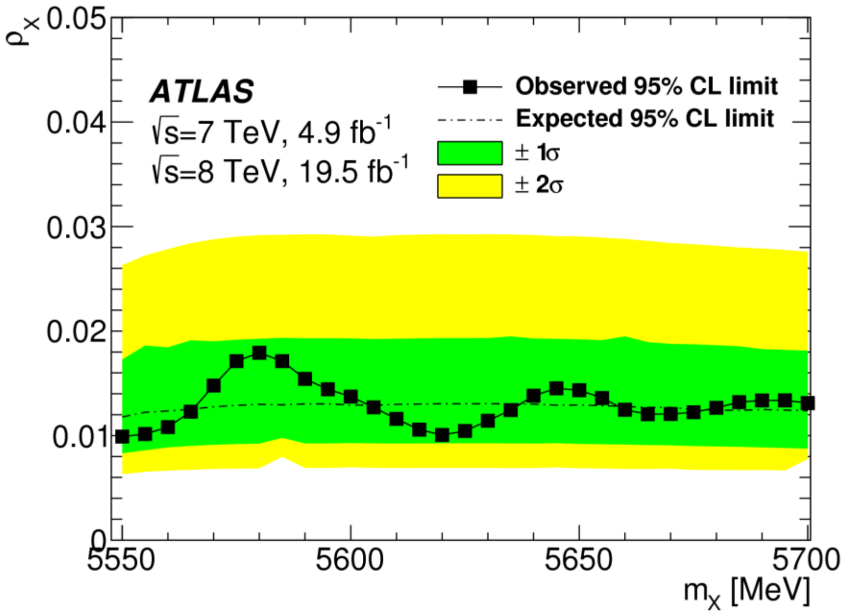
Extract 95% CL upper limit on production

Measure relative to B_s > given $p_T(Bs)$

Signal: Breit-Wigner from D0 observation

Scan range 5550 – 5700 MeV

$$\rho_X \equiv \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0 \pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})} = \frac{N(X)}{N(B_s^0)} \times \frac{1}{\epsilon^{\text{rel}}(X)}$$



Systematic uncertainties includes

Event by event resolutions and relative efficiencies needed

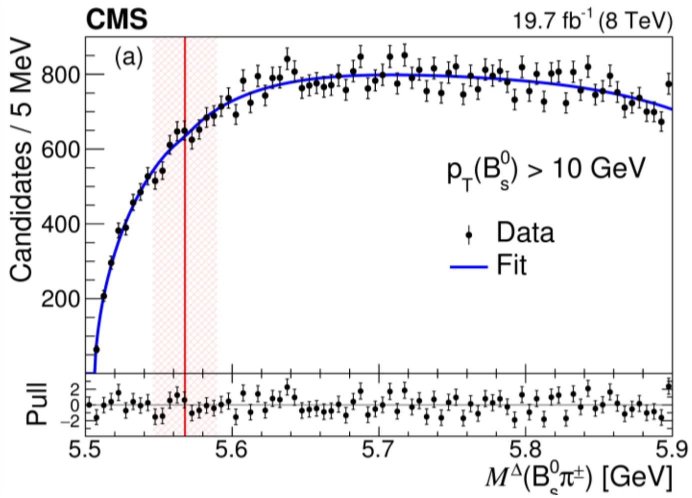
$p_T(B)$ > 10 GeV:

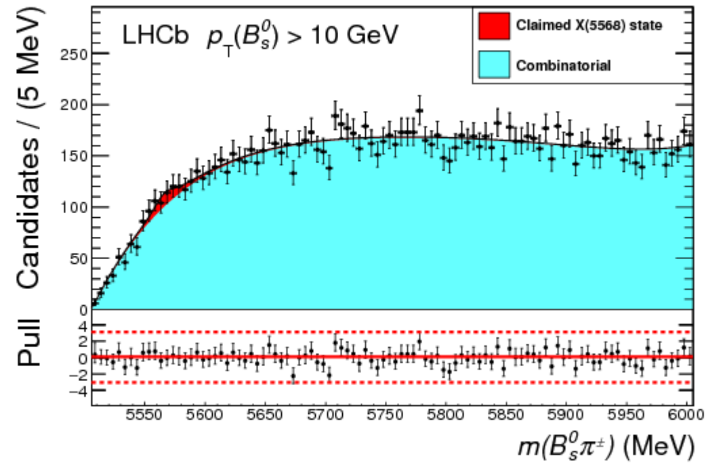
- **ρ_X < 0.015 @95% CL**

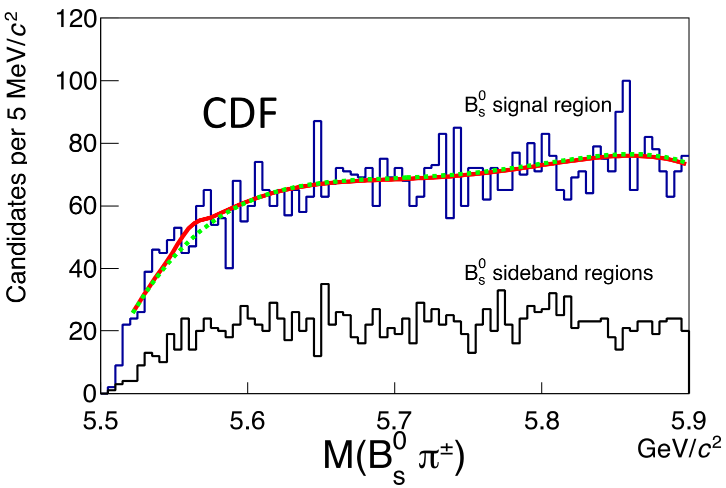
$p_T(B)$ > 15 GeV:

- **ρ_X < 0.016 @95% CL**

Other recent searches eslewhere







	ρ_X (p_T>10 GeV)
D-Zero	(8.6±1.9±1.4)%
ATLAS	<1.5%
CMS	<1.1%
LHCb	<2.4%
CDF	<6.7%

No significant X(5568) signal observed

Perspectives

- ATLAS is a "general purpose" experiment, and, due to the universality of the detector and ingenuity of analysers, a number of important contributions to heavy quark physics can be made
- Studies of bb production important for model building
- X(3872) production have been studied in some detail, with potentially interesting results
- No evidence for the X(5568) in the $B_s(J/\psi\phi)\pi$ channel, upper limit set

- A large amount of data collected at 13 TeV are still being studied, with new challenges related to increasing trigger thresholds and increased high pileup