Spectroscopy, Production and Exotica in Heavy Flavour in ATLAS

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On behalf of the ATLAS Collaboration

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Outline

- ATLAS detector, (multi-,) muon triggers

Focus on recent results

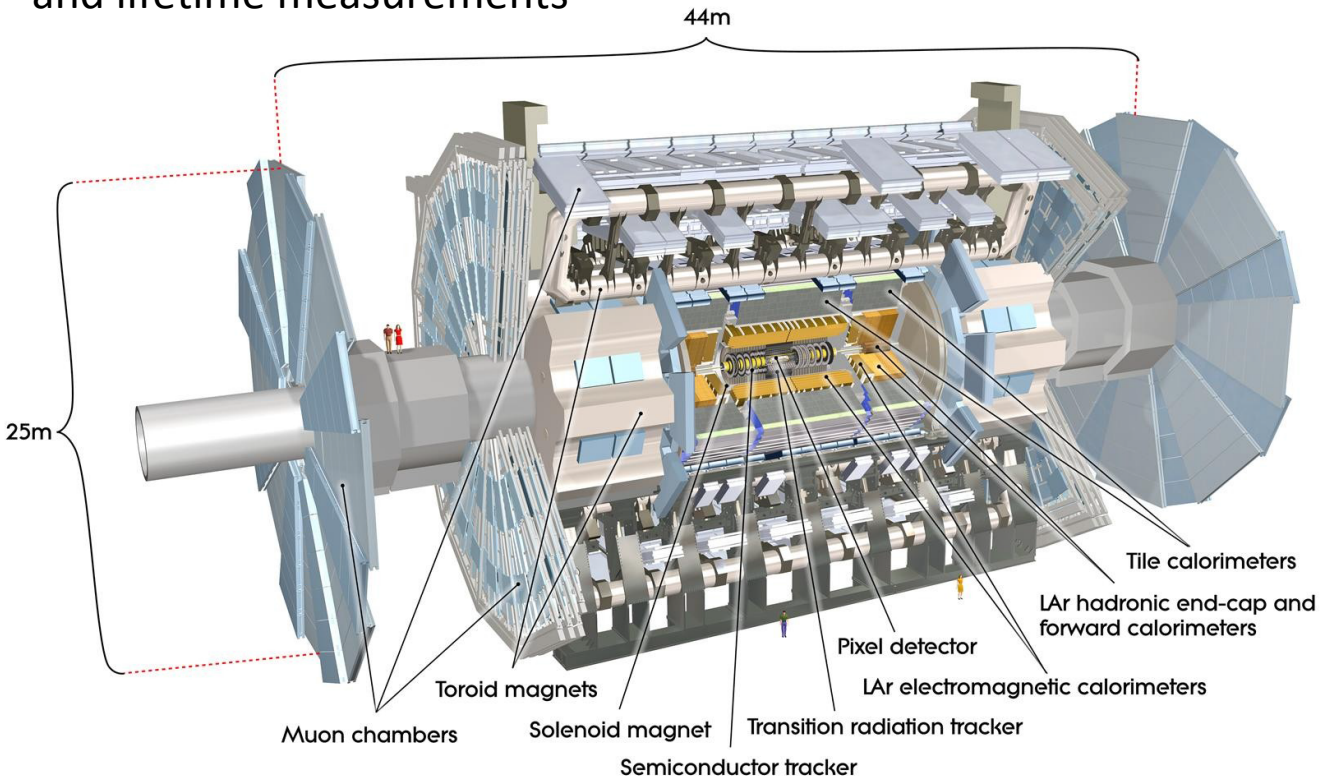
- bb correlation with J/ψ+μ JHEP 11 (2017) 62
- X(3872) production measurement, prompt and non-prompt JHEP 01 (2017) 117
- $B_s\pi$ states PRL 120 (2018) 202007

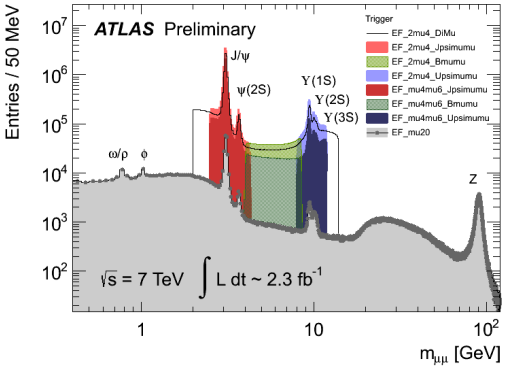
- Summary and perspectives

The ATLAS detector at LHC

Inner Detector
$|\eta|<2.5$, Solenoid B=2T
$\sigma/pT \sim 3.4\times10\text{-}4\ pT + 0.015$ for ($|\eta|<1.5$)
Used for Tracking and Vertexing:
Precise momentum
and lifetime measurements

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

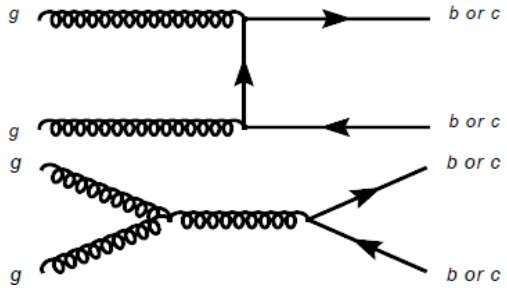




bb production at the LHC

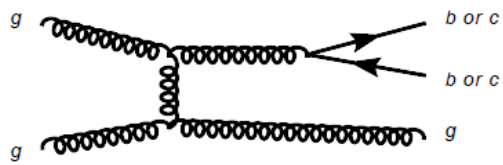
Needed for H→bb and new physics searches

Flavour creation



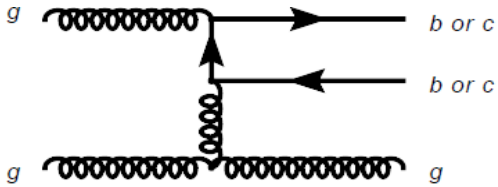
Large Δϕ, back-2-back pT balance

Gluon splitting



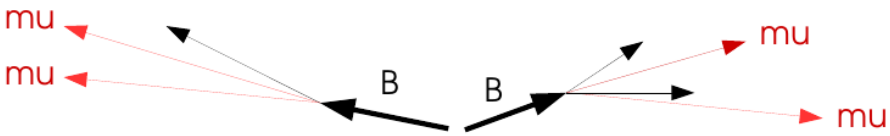
Small Δϕ, colinear

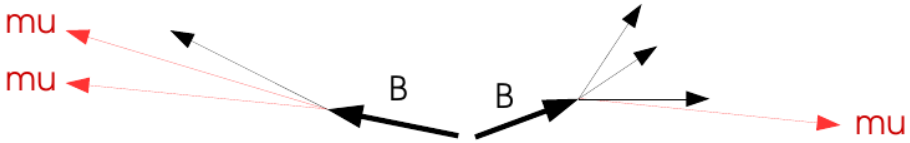
Flavour Excitation



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

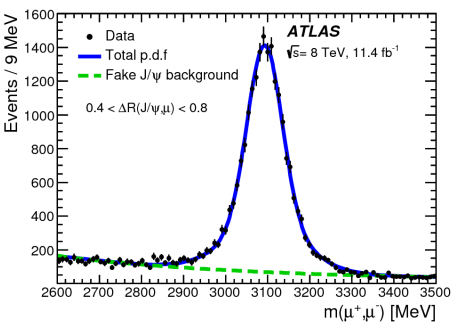
Additional muons

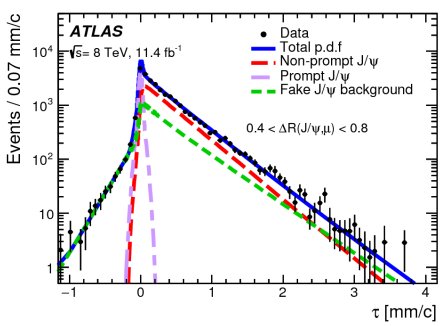
- $|\eta| < 2.5$
- 'Fakes' mainly J/ψ+K, control with BDT trained on Monte Carlo

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

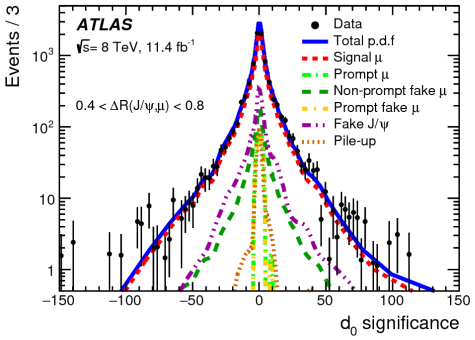
$$L_{xy} = \frac{\vec{L} \cdot \vec{p_T}(\mu\mu)}{p_T(\mu\mu)}$$

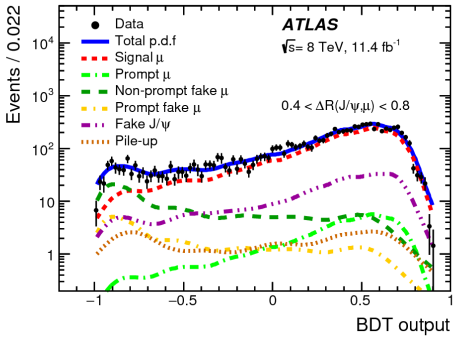
Use pseudo proper lifetime of J/ψ to separate prompt/non prompt J/ψ & background, in mass/ lifetime fit



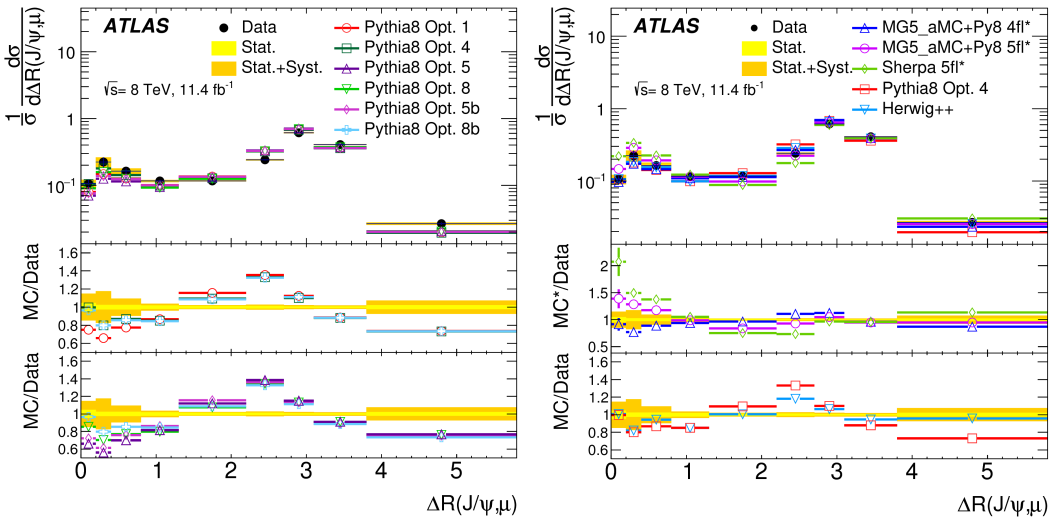


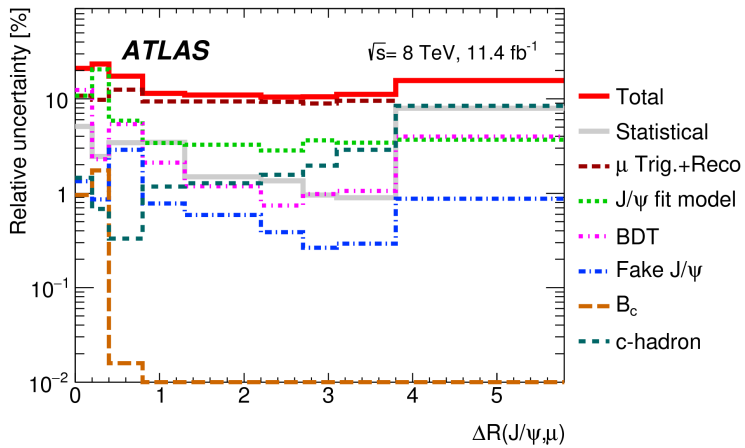
Use 3rd muon impact parameter and BDT to templates from MC to extract signal/prompt/ fake contributions





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

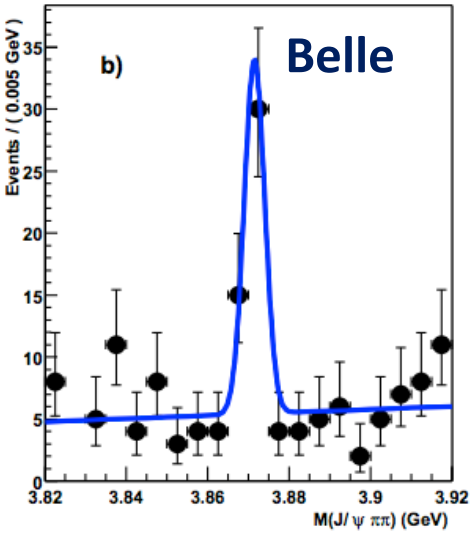
Subsequently confirmed by BaBar, CDF, D0 and now LHC experiments

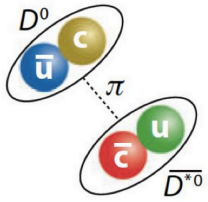
Current world average X(3872) mass very close to the $D^0 D^{0*}$ threshold

What is it? No clear picture yet!

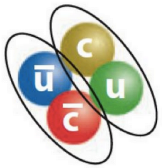
- *Loosely bound $D^0 - D^{0*}$ molecule?* Unlikely: NRQCD with this premise over-predicts production compared to CMS 2011 measurement
- *New excited charmonium state?* Unlikely: LHCb measured $J^{PC} = 1^{++}$, no such state expected around that mass
- *A mix of these two, $\chi_{c1}(2P)$ -($D^0 D^{0*}$), 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 $\psi(2S)$ 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 $\psi(2S)$ 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 [illegible] < 300, $p_T > 8$ GeV, $|y| < 2.3$

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

Pion

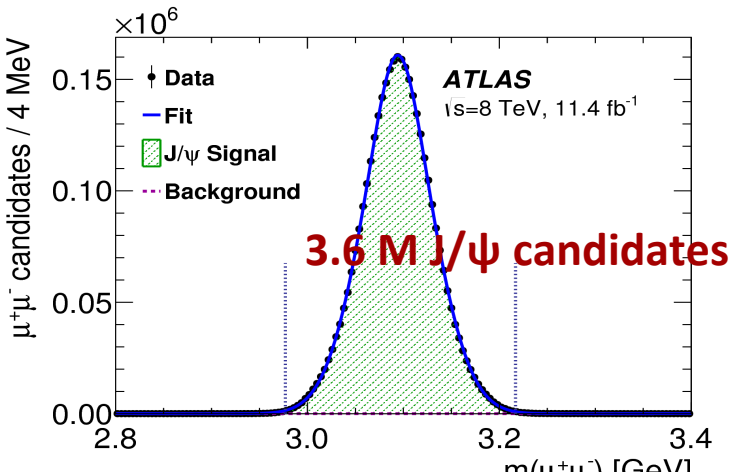
- Opposite sign, $p_T > 600$ MeV, $|\eta| < 2.4$

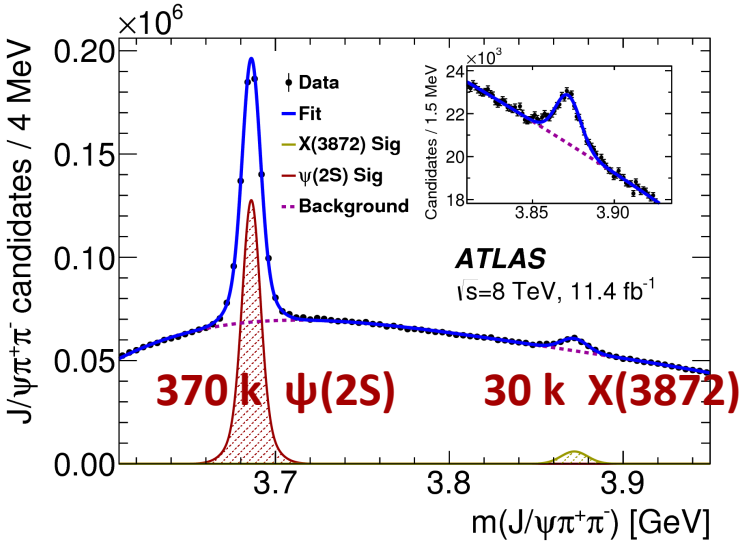
Constrained vertex fit on each $\mu^+\mu^-\pi^+\pi^-$ candidate:

- 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



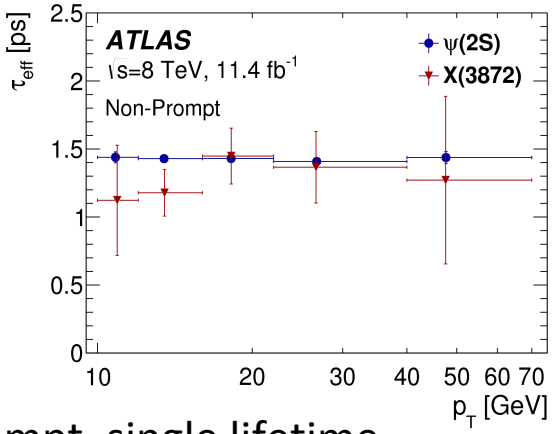


Single or Double lifetime hypothesis

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

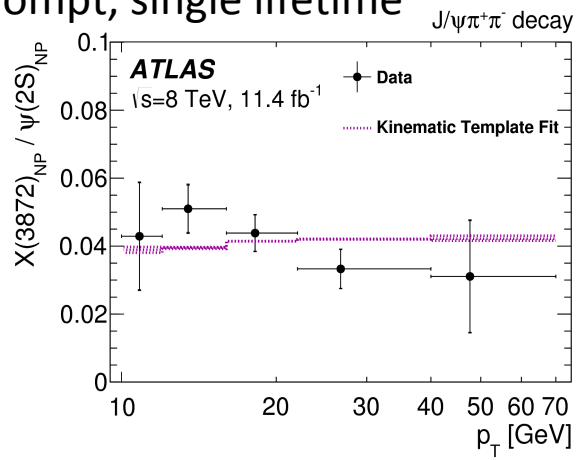
- same lifetimes for ψ(2S) and X(3872) in each p_T bin
- pT spectra of ψ(2S) and X(3872) linked through kinematics

➔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

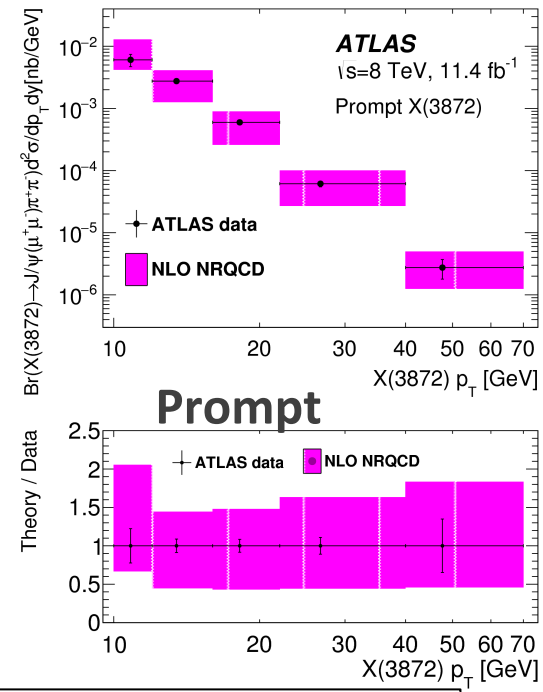
X(3872) cross sections

Prompt: **Described well by NLO NRQCD**

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

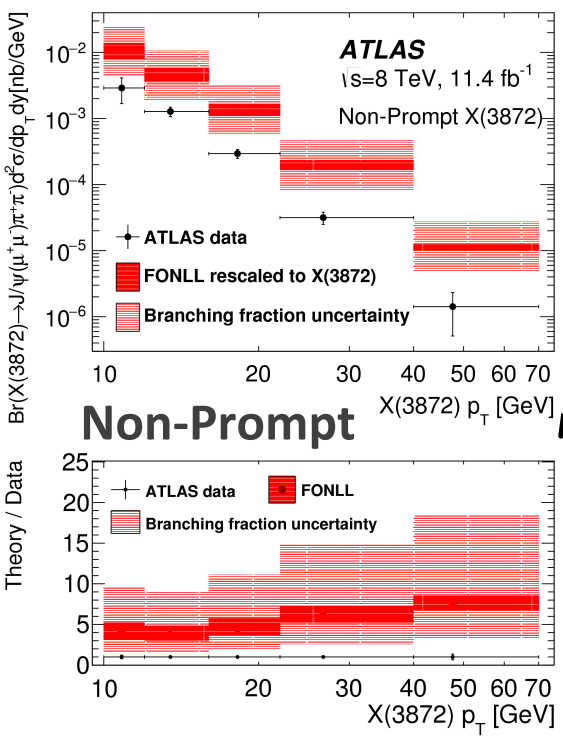
with $\chi_{c1}(2P)$ dominant (production parameters fitted to CMS data)

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]

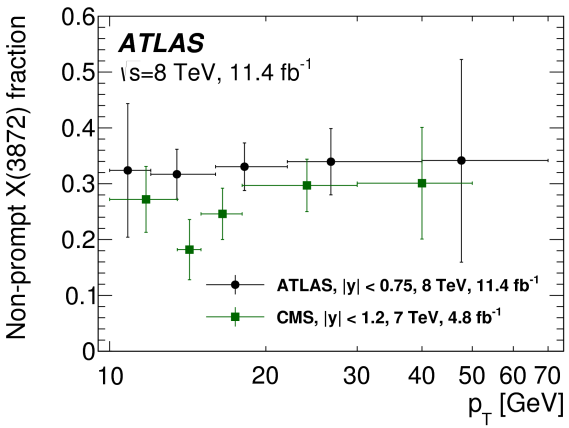
$$R_B = \frac{Br(B \to X(3872))Br(X(3872) \to J/\psi\pi^+\pi^-)}{Br(B \to \psi(2S))Br(\psi(2S) \to J/\psi\pi^+\pi^-)} = 18\pm8\ \%$$

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

Non-prompt fraction and ratio

Non-prompt fraction of X(3872):

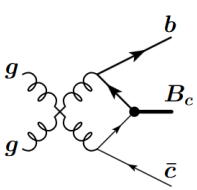
- no visible p_T dependence
- consistent with CMS result within errors
- Very unlike J/ψ's strong p_T dependence



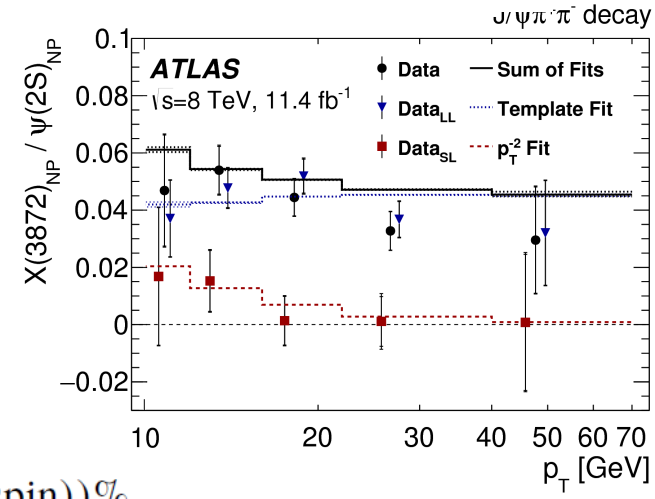
Ratio of non-prompt X(3872) : ψ(2S)

- 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

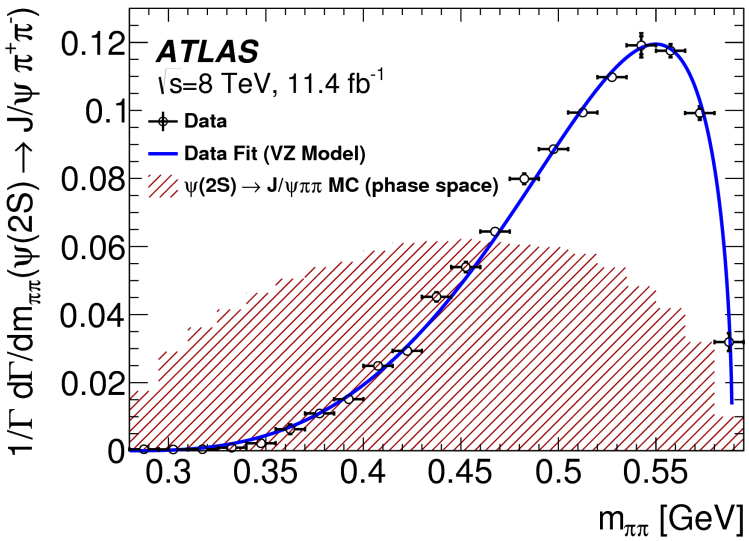
Di-pion mass distributions: results

In ψ(2S) to J/ψπ⁺π⁻ decays

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

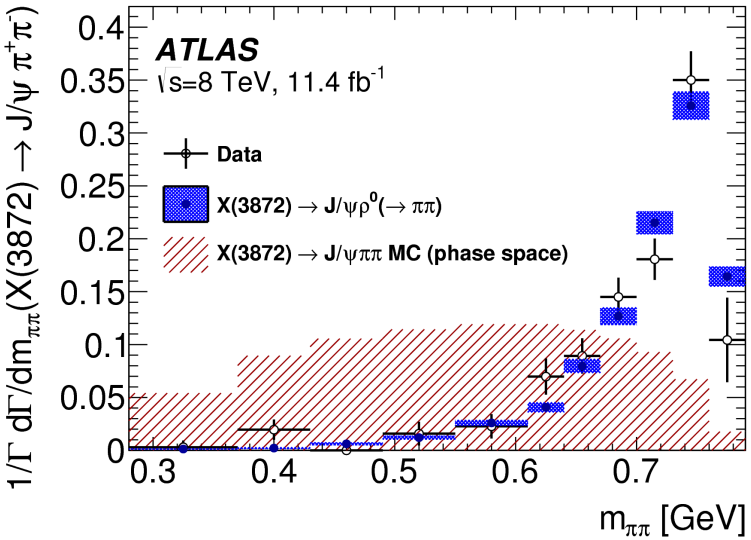
$$\frac{1}{\Gamma}\frac{d\Gamma}{dm_{\pi\pi}} \propto \left(m_{\pi\pi}^2 - \lambda m_\pi^2\right)^2 \times \mathrm{PS}$$

- 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

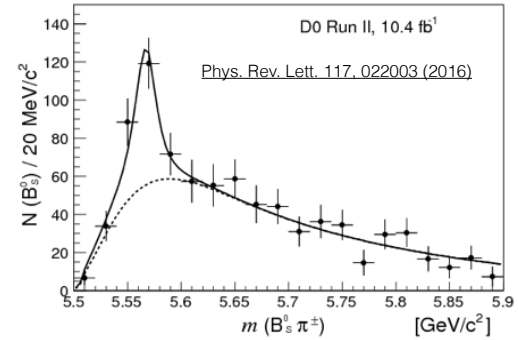
- dipion mass distribution has an even sharper peak at high masses
- in agreement with simulation where the di-pion system is produced via ρ^0 meson decay

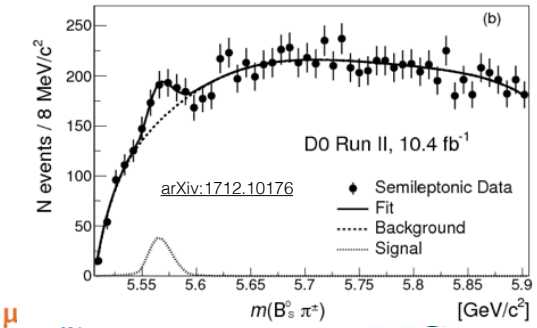


Structure in the $B_s^0\pi^\pm$ Spectrum?

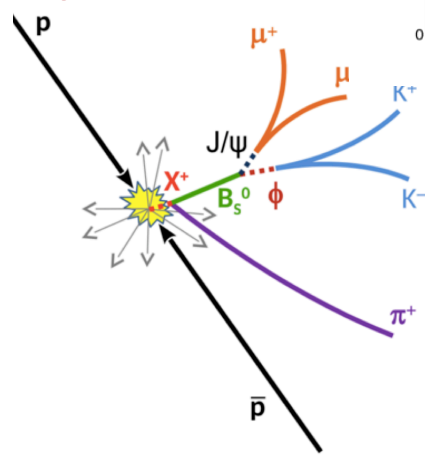
- **D-Zero published evidence for X(5568) in $B_s^0\pi^\pm$ spectrum**
  - $B_s^0 \rightarrow J/\psi\phi$, $B_s^0 \rightarrow \mu^\mp D_s^\pm(\phi\pi^\pm)X$
  - $m=5566.9^{+3.2}_{-3.1}(stat)^{+0.6}_{-1.2}(syst)$ MeV
- **Significance 6.7σ, bsud state?**

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**

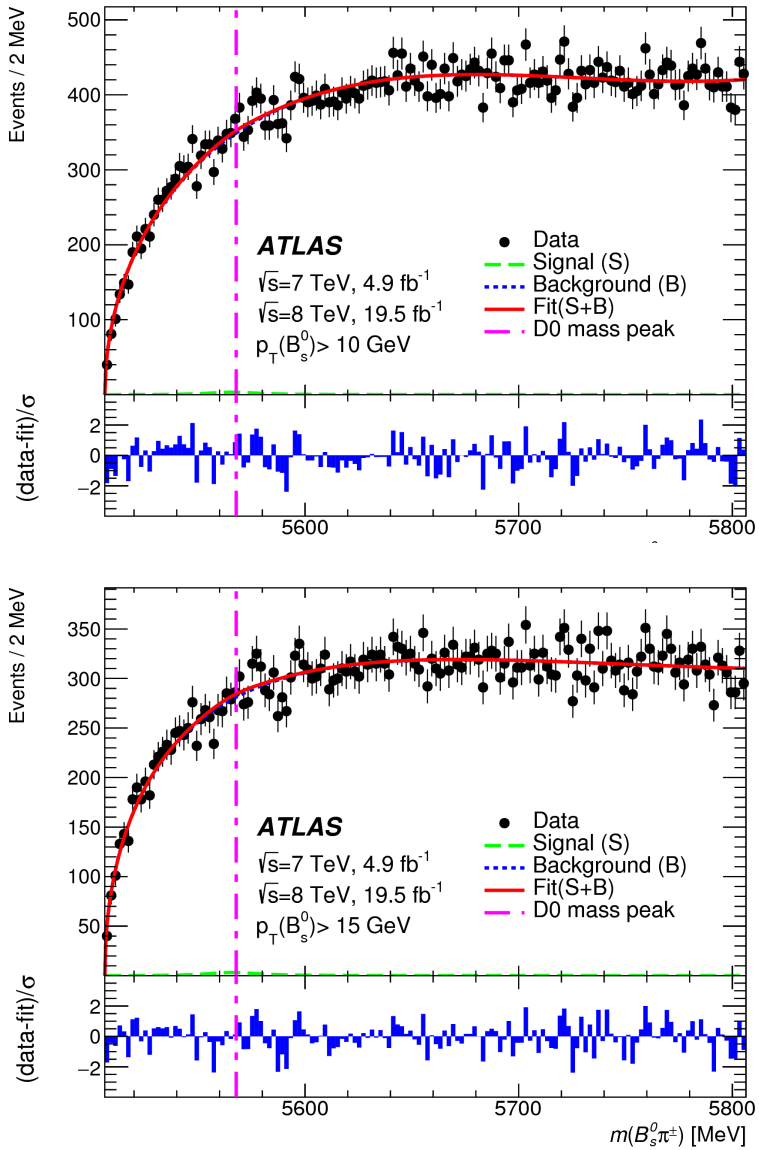
$M_{fit}(B_s^0)$=5366.6±0.1 MeV
$N(B_s^0)$=52750±280 (stat)

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

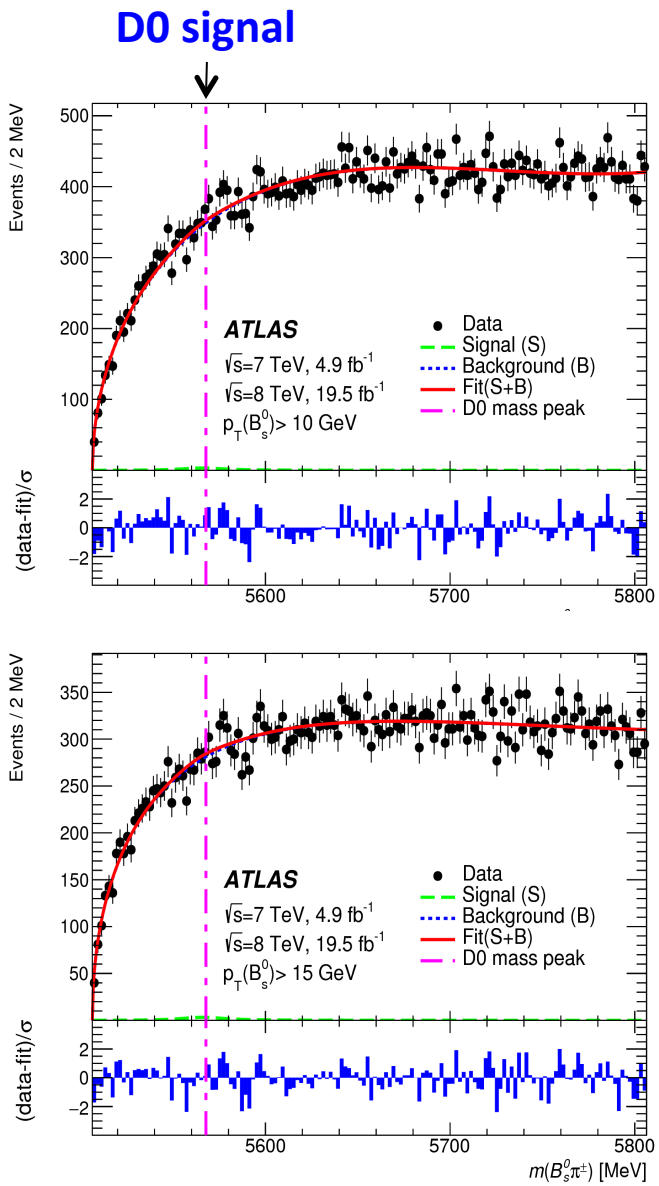
- **Combine B_s candidates with tracks from same primary vertex**
  - **Pion hypothesis, p_T>500MeV**
  - **Extended unbinned fit:**

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

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



Setting Limits



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

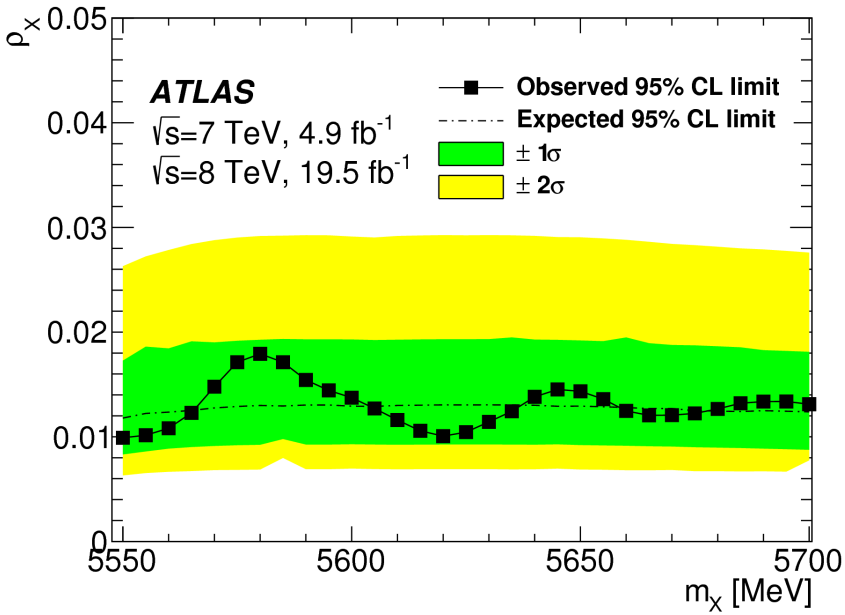
Extract 95% CL upper limit on production

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

<u>Event by event</u> resolutions and relative efficiencies needed

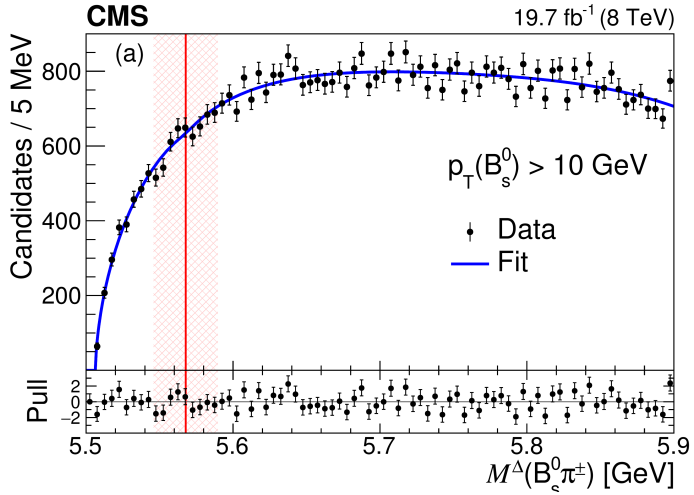
p_T(B) > 10 GeV:

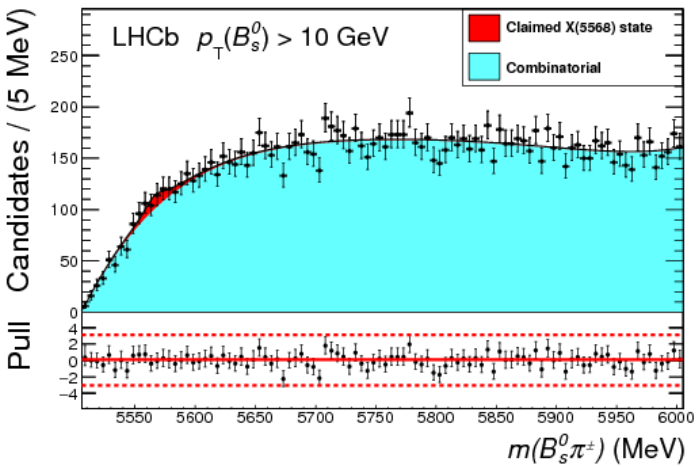
- **ρ_X < 0.015 @95% CL**

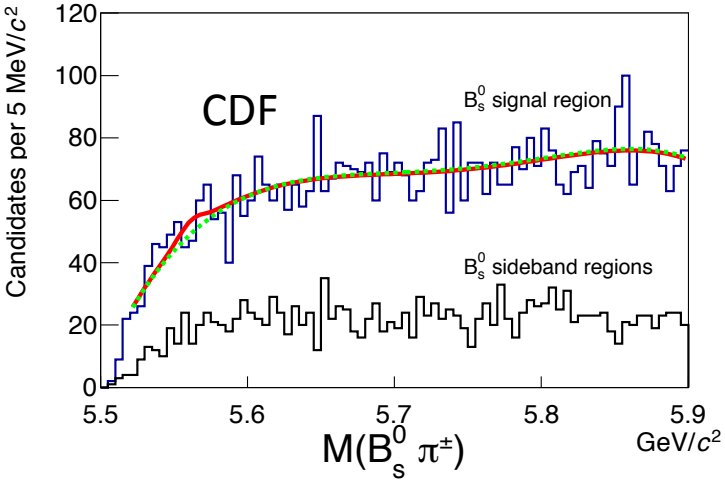
p_T(B) > 15 GeV:

- **ρ_X < 0.016 @95% CL**

Other recent searches eslewhere







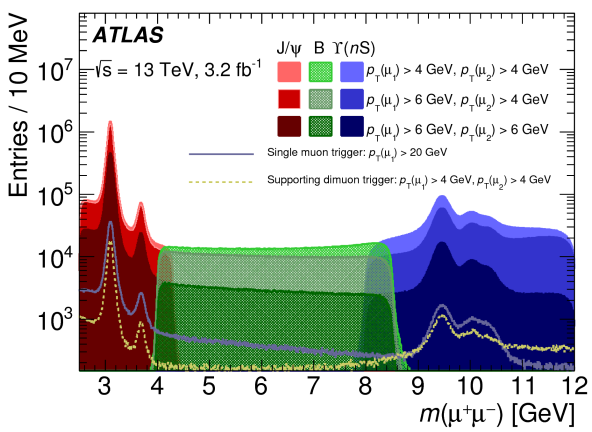
	ρ_X (p_T>10 GeV)
D-Zero	(8.6±1.9±1.4)%
ATLAS	<1.5%
CMS	<1.1%
LHCb	<2.4%
CDF	<6.7%

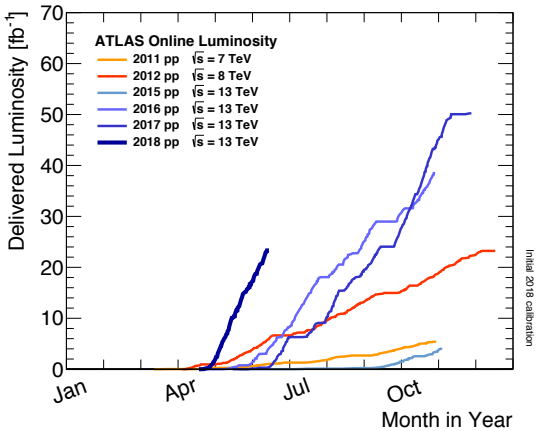
No significant X(5568) signal observed

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

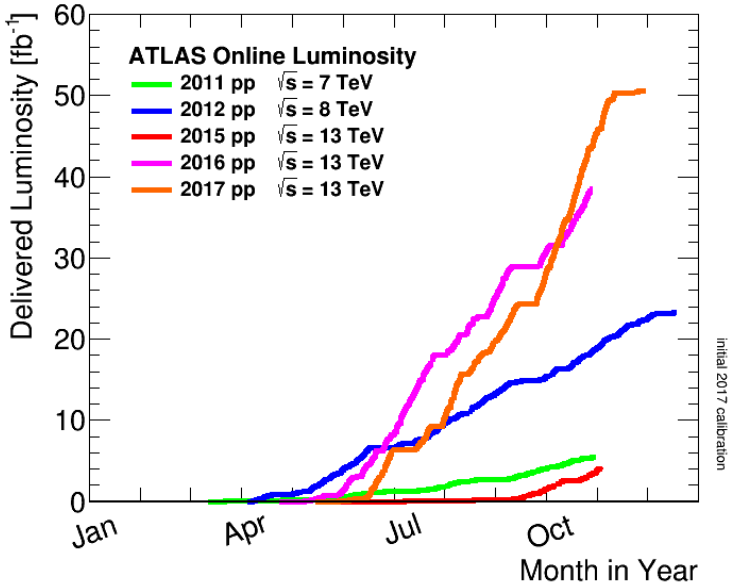
- A large amount of data collected at 13 TeV are still being studied, with new challenges, related to increasing trigger thresholds and increased high pileup

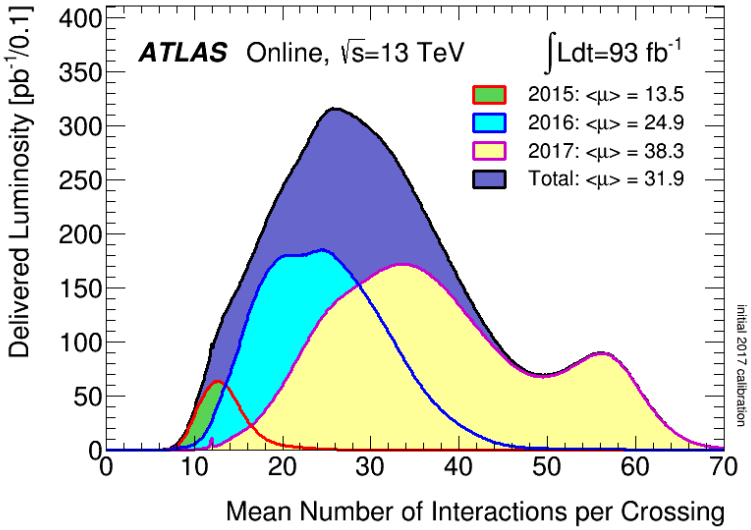




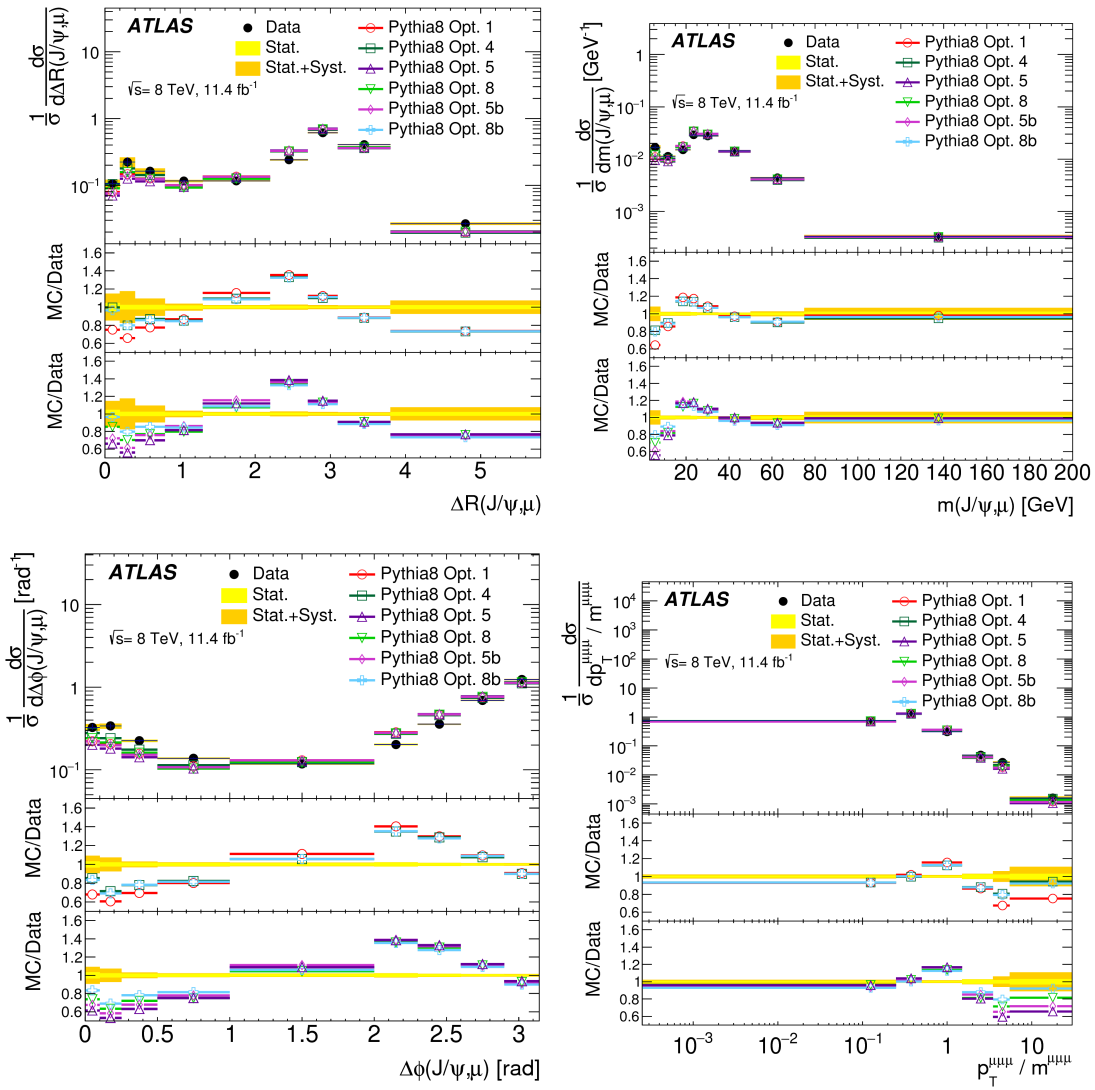
LHC luminosity over the years

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





Comparisons with Pythia

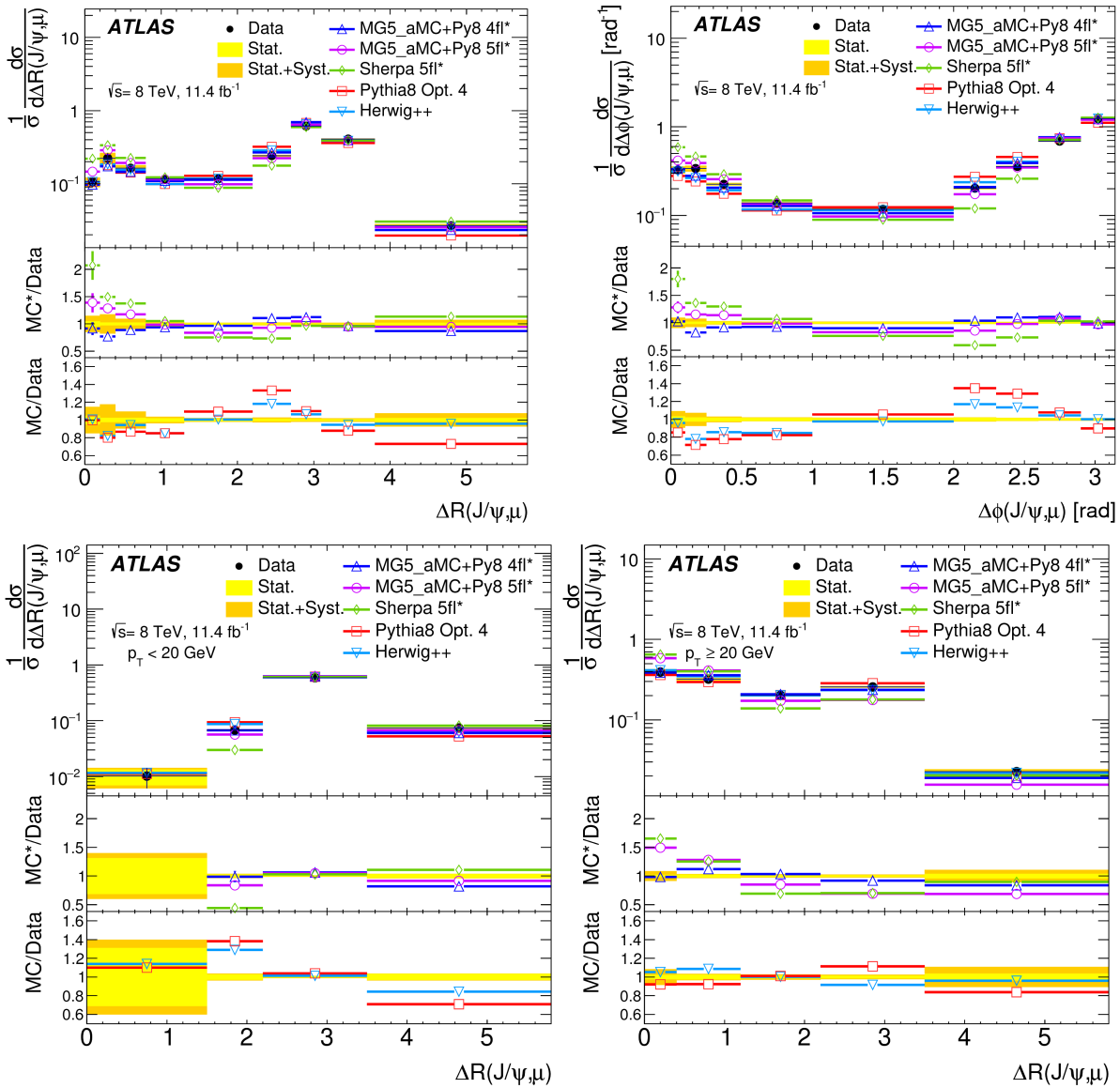


Pythia 8 does not reproduce well the shape of the angular distributions

The pT-based scale splitting kernels (Opt 1 and 4) give a better description at low ΔR

Overall the kernel of Opt 4 does best

Comparisons with Other Models



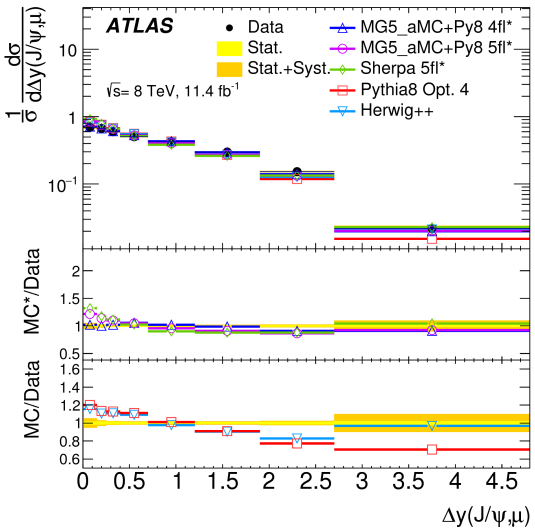
Herwig++ is better than Pythia 8 for the ΔR

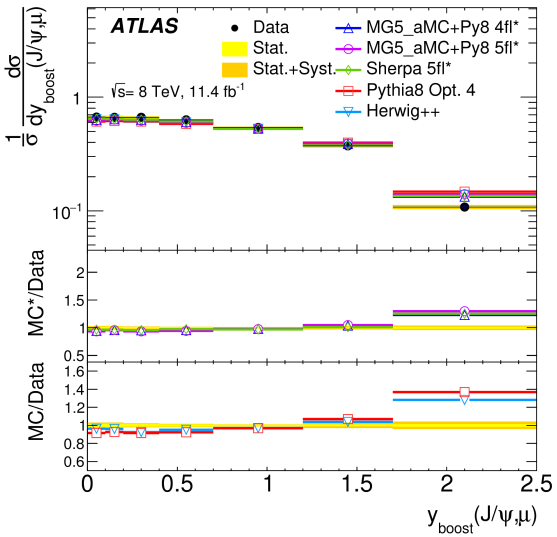
4- and 5-flavour MadGraph5 predictions sit either side of the data; the 4-flavour prediction is closer

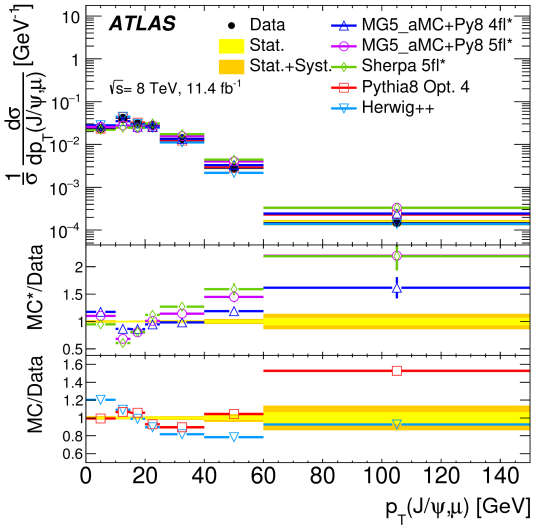
The 5-flavour Sherpa prediction is similar (but worse) than madGraph5

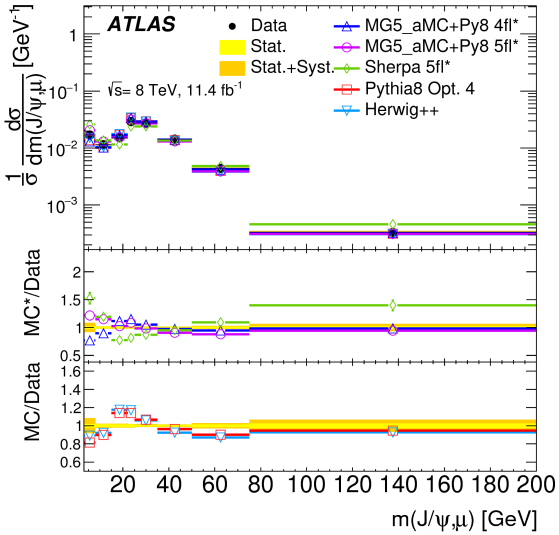
Difference between 4-flavour and 5-flavour predictions are larger in the high-pT ΔR distribution; the 4-flavour version is still closer to data

Other results





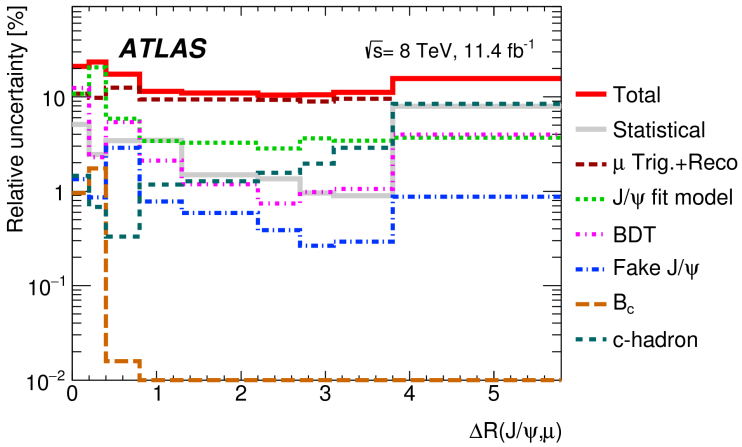




Similar picture for rapidities, pT, mass etc

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

Good understanding of systematics



Mass fits in lifetime windows

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

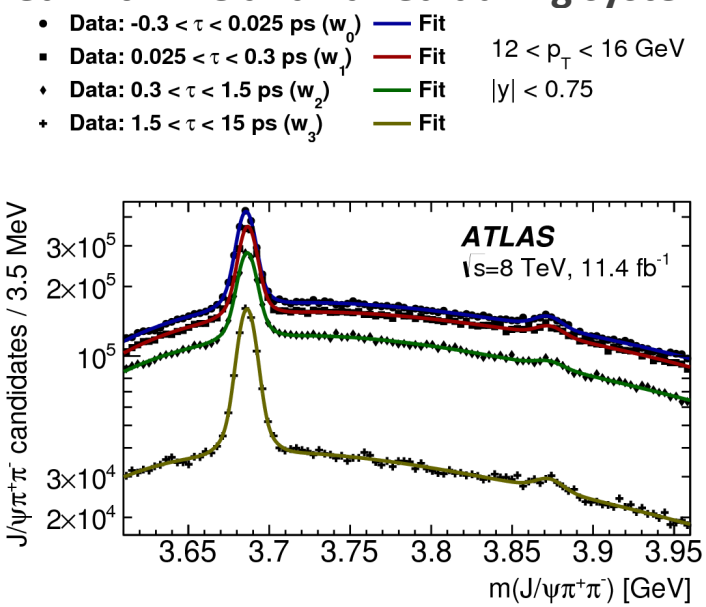
$$f(m) = f_{12}\left(Y^{\psi}G_1^{\psi}(m) + Y^{X}G_1^{X}(m)\right) + (1-f_{12})\left(Y^{\psi}G_2^{\psi}(m) + Y^{X}G_2^{X}(m)\right)$$
$$+\mathrm{N_{bkg}}\,(m-m_0)^{p_2}\,e^{p_1(m-m_0)}P\,(m-m_0)$$

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

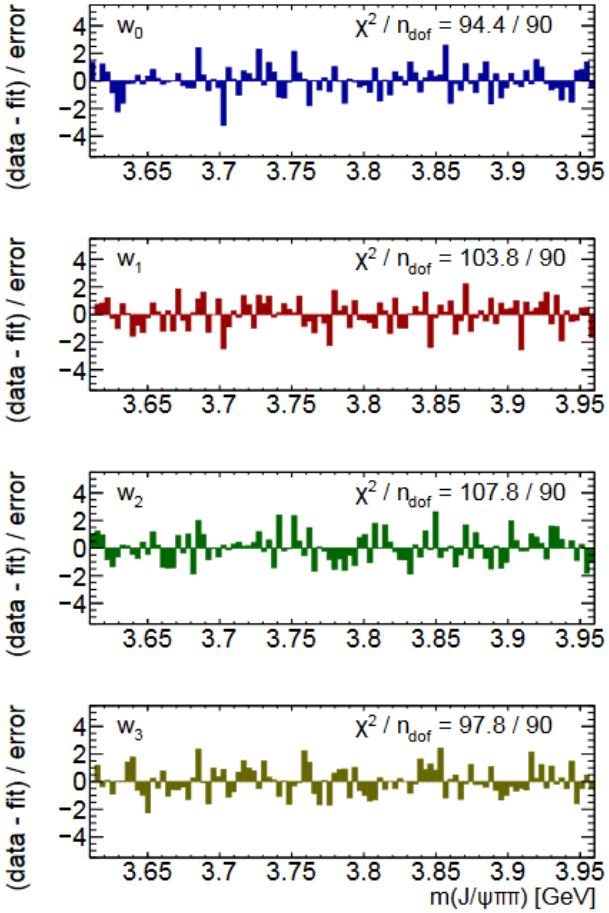
Resolution parameters linked by $\sigma_X = \kappa\sigma_\psi$

Values of parameters f_{12} and κ determined from global fits

Verified with MC and varied during systematic studies



p_T: 12-16 GeV

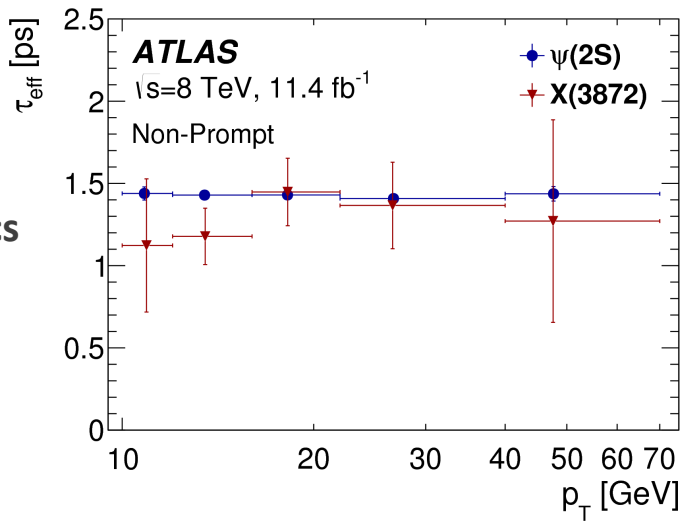


Pull distributions

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

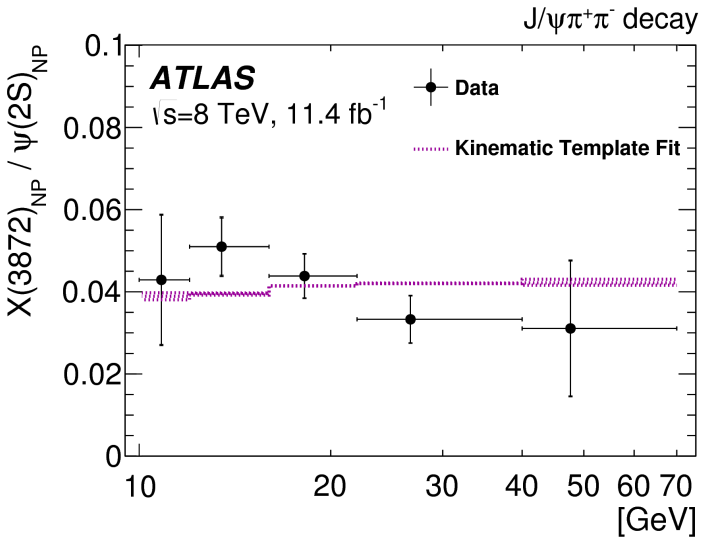


Effective lifetimes

- 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

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

Two-lifetime fits

Alternative lifetime model: **two-lifetime fit**

$$F^i_{NP}(\tau) = (1 - f^i_{SL})F_{LL}(\tau) + f^i_{SL}F_{SL}(\tau)$$

- non-prompt component presented as a sum of short-lived and long-lived
- two single-sided exponentials smeared with the same resolution function
- f_{SL} is a fraction of short-lived within non-prompt – supposedly from B_c decays
- statistical power of data does not allow determination of two free lifetimes
- the two lifetimes fixed, the fraction of short-lived contribution left free in the fit

Fixing the two lifetimes

- effective pseudo-proper lifetime depends on parent's lifetime and decay kinematics
- τ_{LL} determined from fits to $\psi(2S)$, 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 limits shown during systematic studies

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

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

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

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

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

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

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