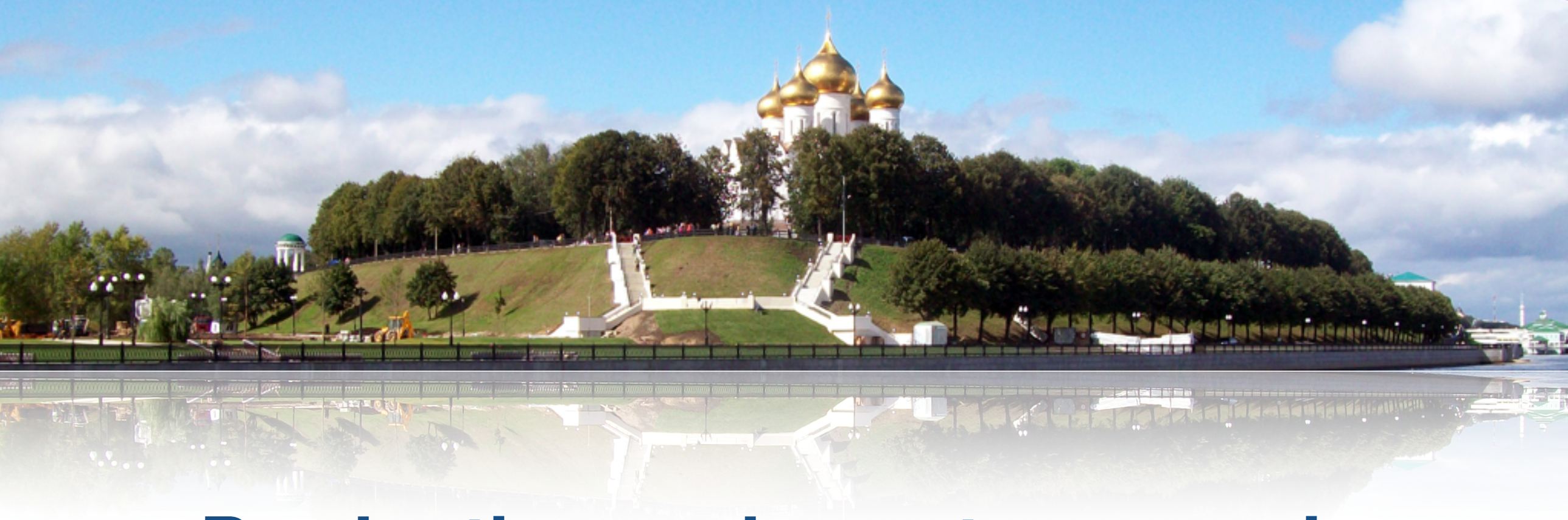


Production and spectroscopy in heavy flavour

Artem Maevskiy, SINP MSU
On behalf of the ATLAS collaboration

QFTHEP'2017
Yaroslavl, Russia
June 26 – July 3, 2017

Outline

- Measurement of *b*-hadron pair production at $\sqrt{s}$ = 8 TeV
- Measurement of the prompt J/ψ pair production at $\sqrt{s}$ = 8 TeV
- Production measurements of $\psi(2S)$ and $X(3872)$ at $\sqrt{s}$ = 8 TeV
- Non-prompt J/ψ production fraction at $\sqrt{s}$ = 13 TeV
- $B^{\pm}$ mass reconstruction at 13 TeV

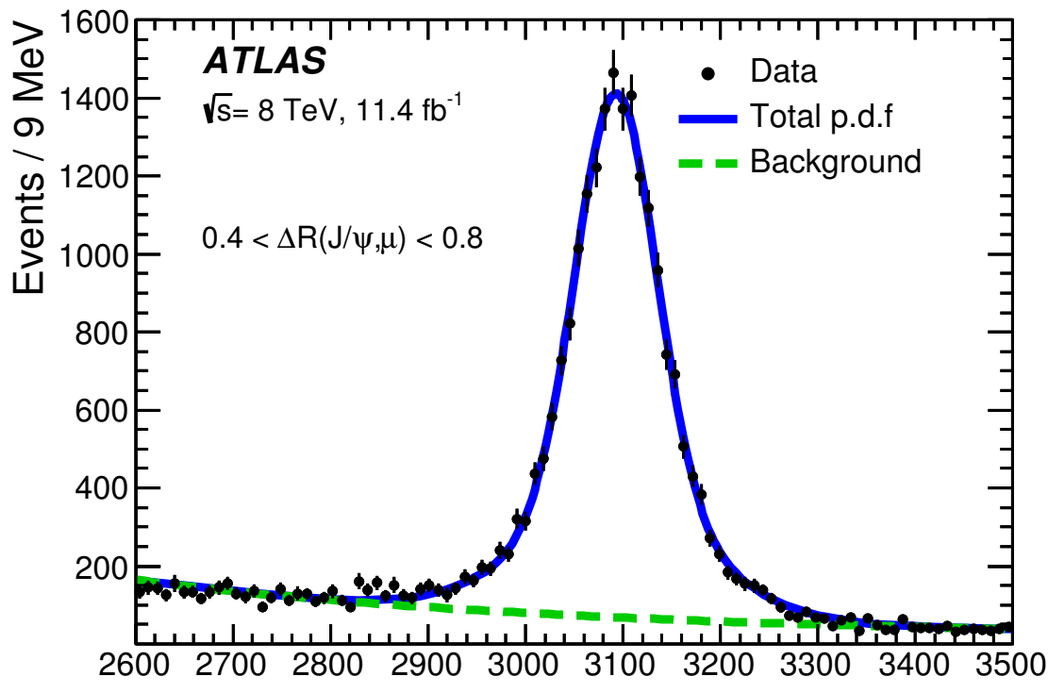
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

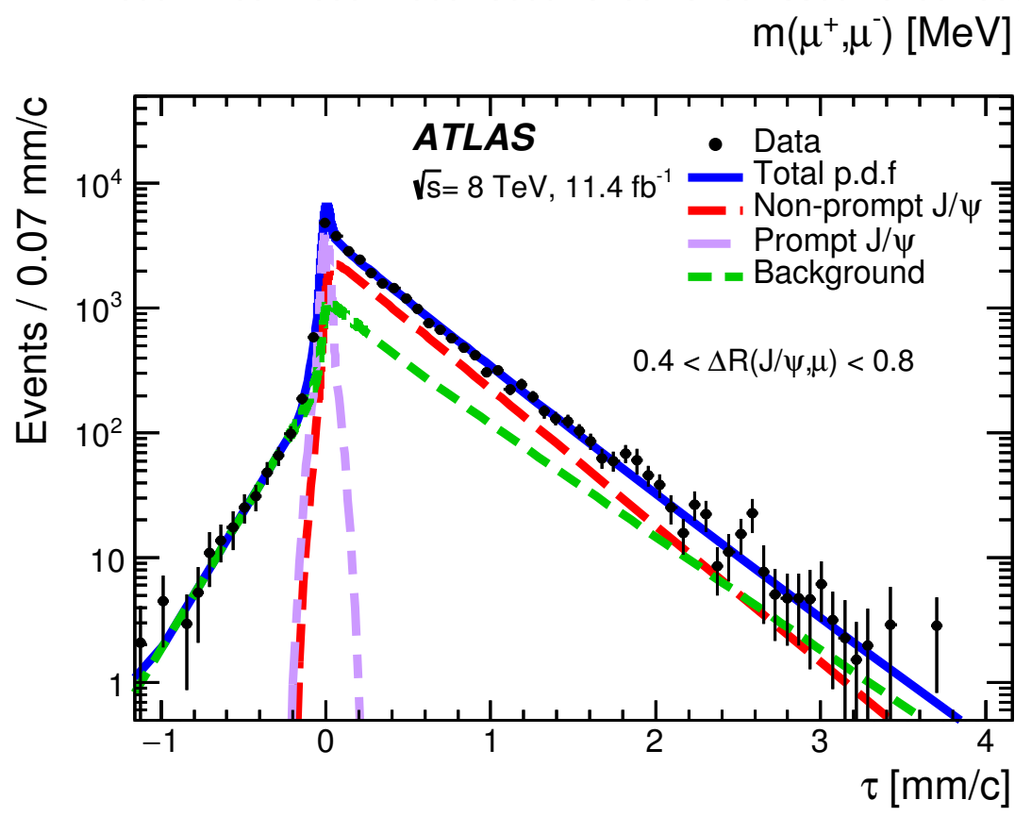
Measurement of b-hadron pair production

arXiv:1705.03374 (submitted to JHEP)

- Three muons in final state:
  - $b \rightarrow J/\psi\,(\mu\mu)$ + X and $b \rightarrow \mu$ + Y
- Trigger:
  - Two muons of opposite charge
  - Same production vertex
  - $p_T > 4$ GeV
  - $|\eta| < 2.4$
  - $2.5 < m_{\mu\mu} < 4.3$ GeV

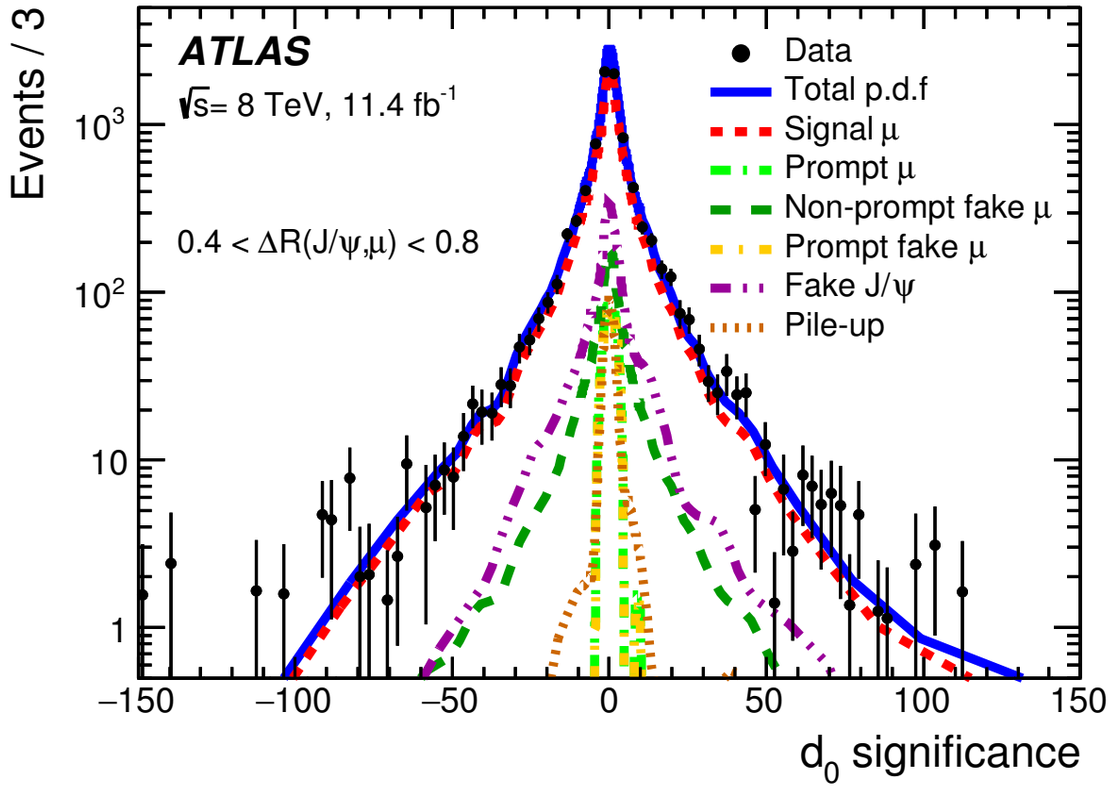
  $L^{int} = 11.4$ fb^{-1} ($\sqrt{s} = 8$ TeV)
- Fiducial volume:
  - $p_T(\mu) > 6$ GeV
  - $|\eta(\mu^{J/\psi})| < 2.3$
  - $|\eta(\mu^{single})| < 2.5$
- J/ψ yield extracted with a simultaneous mass-lifetime fit

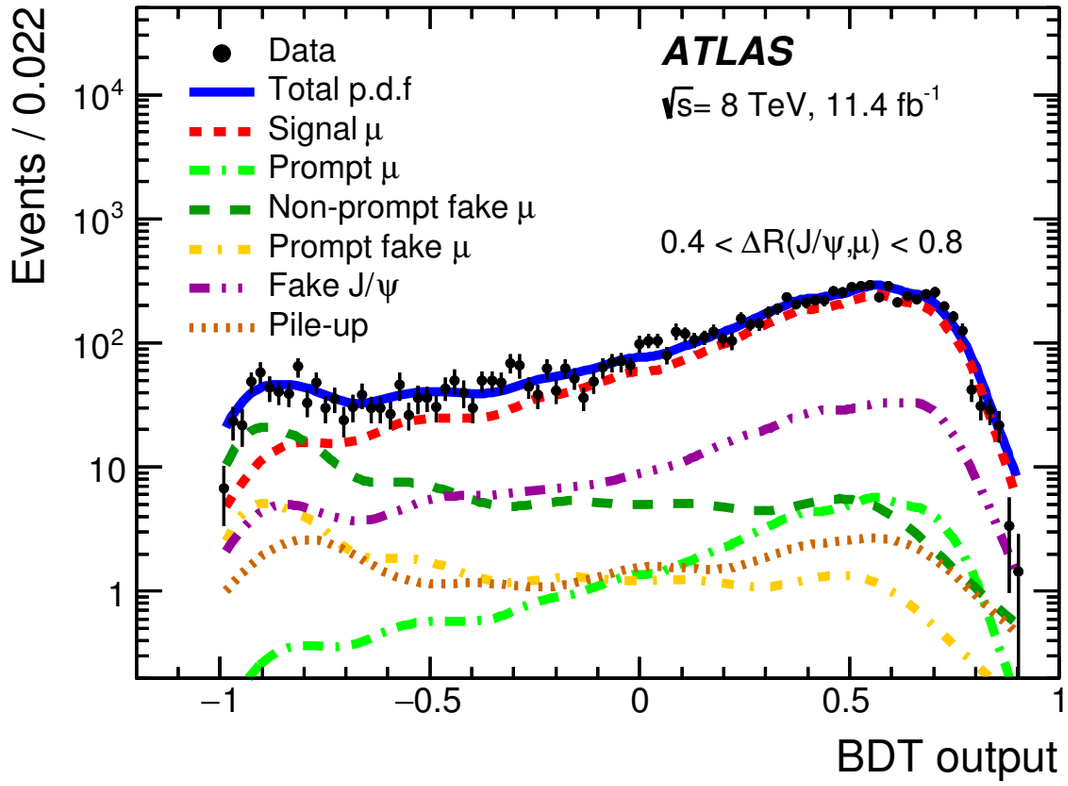




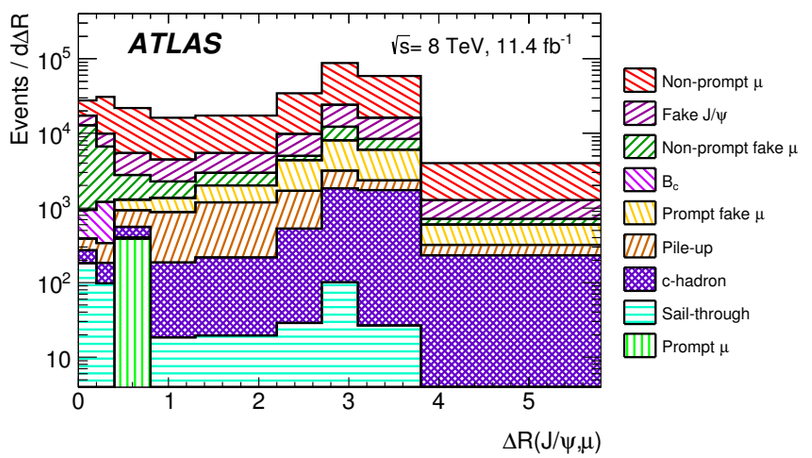
- Single μ signal extracted by fitting:
  - Transverse impact parameter significance $S(d_0) \equiv d_0 / \sigma(d_0)$
  - BDT output. BDT trained to discriminate signal and fake muons using
    - track deflection,
    - Inner Detector vs Muon Spectrometer momentum balance
    - absolute $|\eta|$

- for $\tau > 0.25$ mm/c ($\Rightarrow$ simpler single μ background)



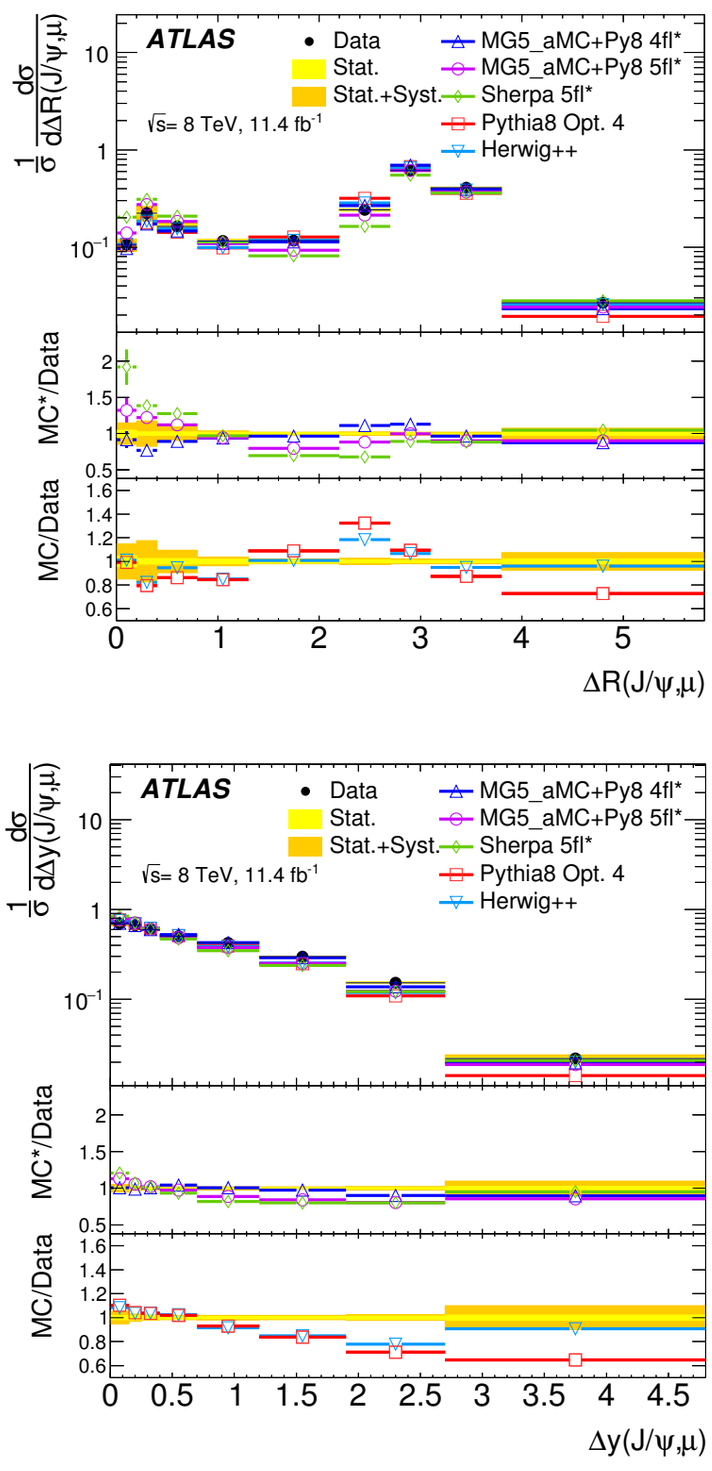


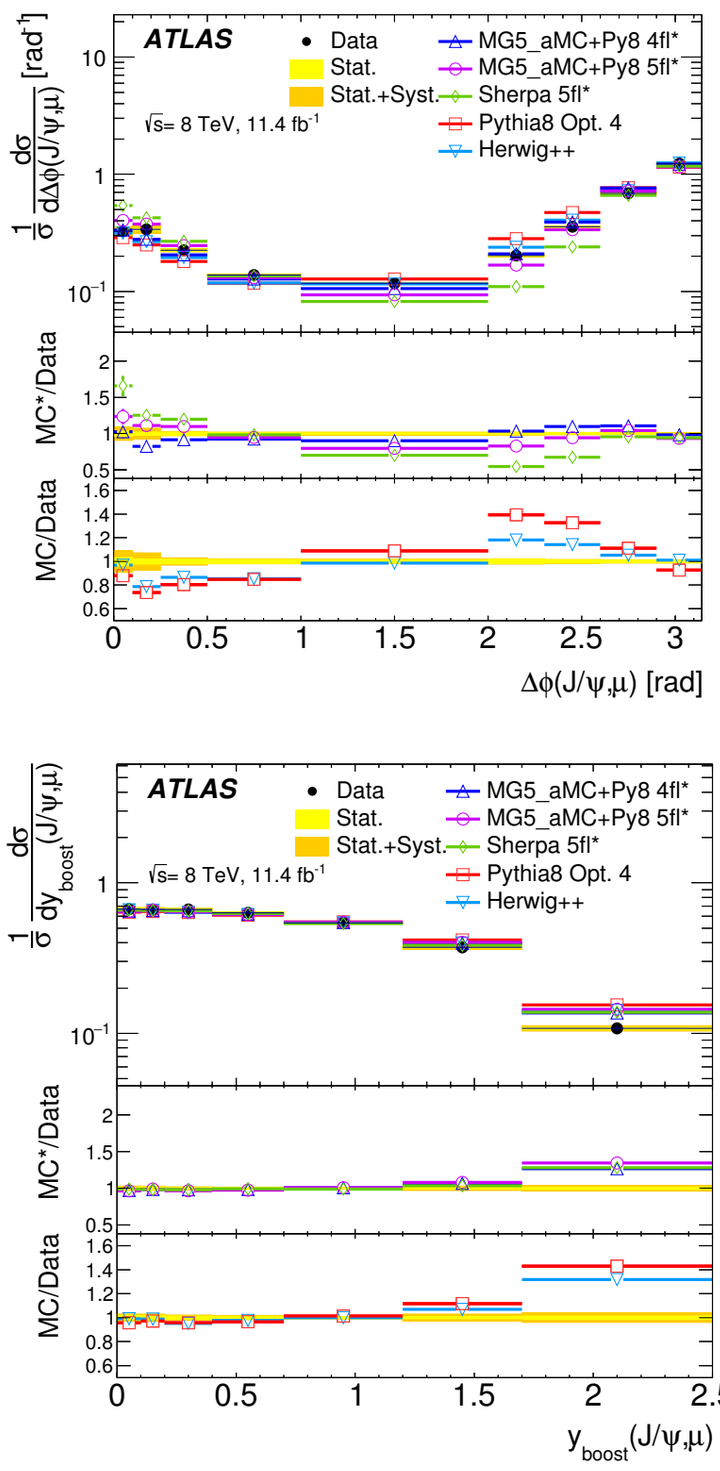
- Irreducible backgrounds estimated from MC and subtracted from the fit result:
  - $B_c \rightarrow J/\psi + \mu + X$
  - Semileptonic decays of *c*-hadrons
  - «Sail-through» fake muons (kaons and pions reaching muon spectrometer)

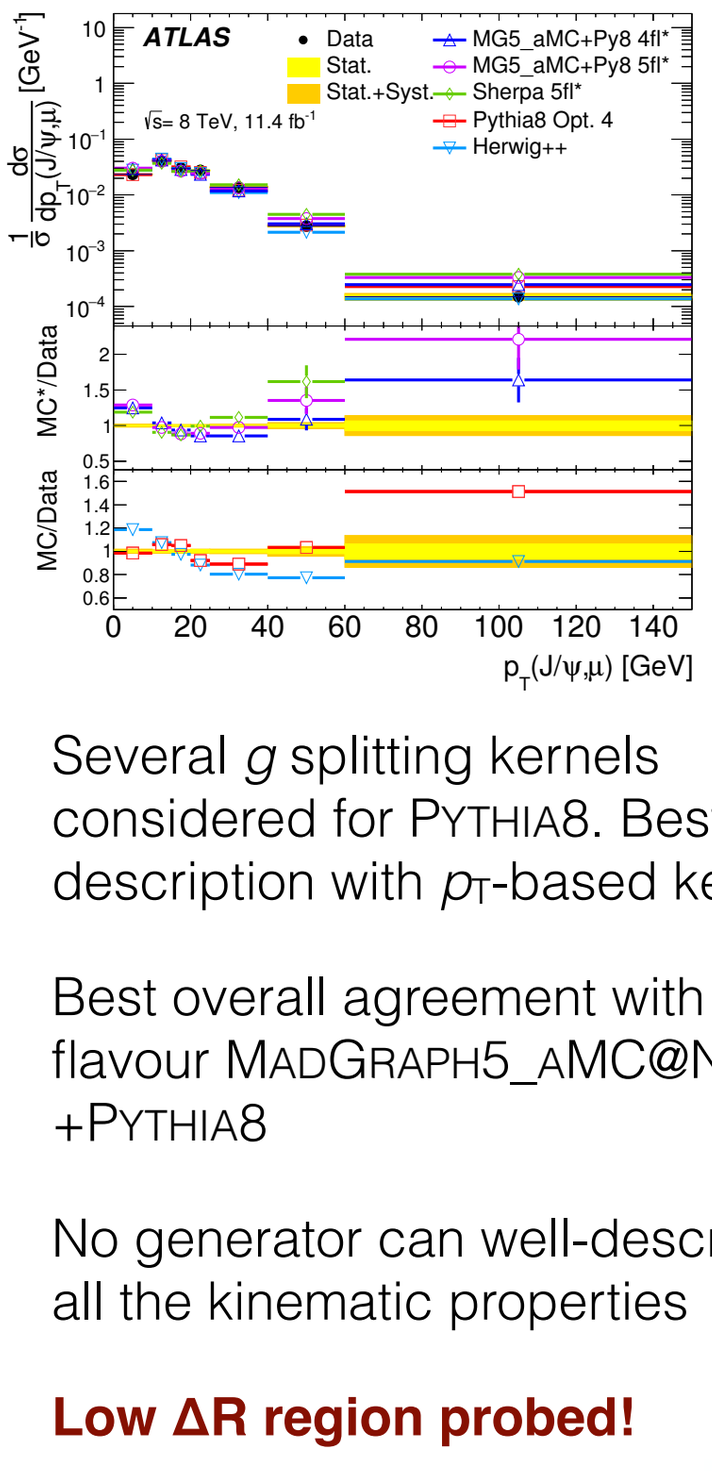


Results

Total cross section: $\sigma(B(\to J/\psi[\to \mu^+\mu^-] + X)B(\to \mu + X)) = 17.7 \pm 0.1(\text{stat}) \pm 2.0(\text{syst})$ nb.







- Several *g* splitting kernels considered for PYTHIA8. Best description with p_T-based kernel
- Best overall agreement with 4-flavour MADGRAPH5_AMC@NLO +PYTHIA8
- No generator can well-describe all the kinematic properties
- **Low ΔR region probed!**

Prompt J/ψ pair production

«Prompt» = produced directly in the hard scatter including contributions of feed-down from higher charmonium states

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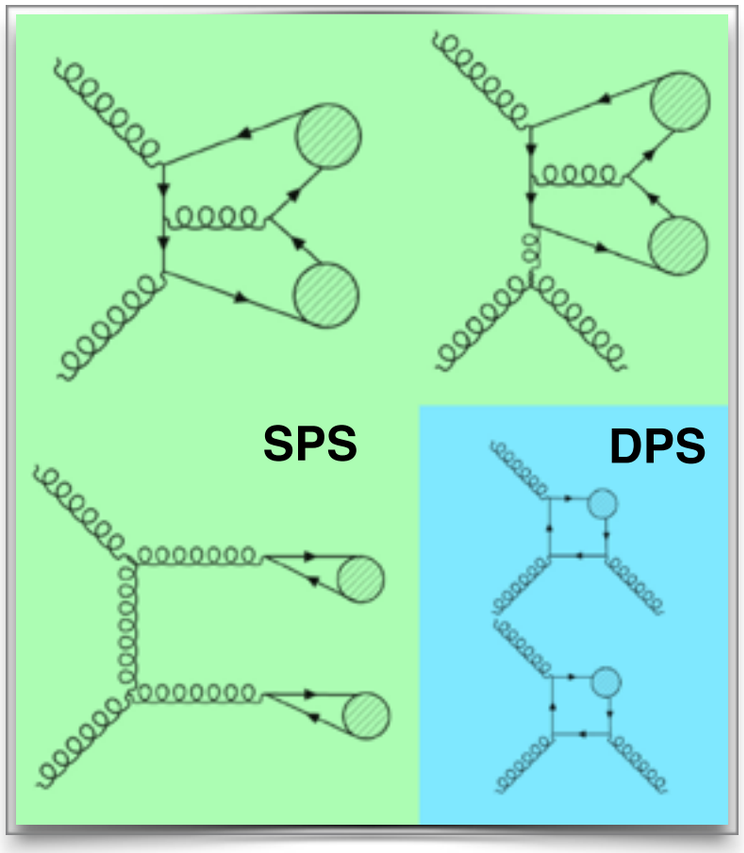


- J/ψ trigger
  - 2 *muons* with $p_T > 4$ GeV and $2.5 < m_{\mu\mu} < 4.3$ GeV
- $L^{int} = 11.4 \pm 0.3$ fb^{-1}
- Both J/ψ reconstructed in $\mu\mu$ channel
- Selection:
  - $|\eta^{\mu}| < 2.3$ and $p_T^{\mu} > 2.5$ GeV
  - $2.8 < m_{\mu\mu} < 3.4$ GeV
  - $|y^{J/\psi}| < 2.1$ and $p_T^{J/\psi} > 8.5$ GeV
  - track quality, muon quality, etc.
  - distance between decays along the beam axis < 1.2 mm
- Total of 1210 events
- Main backgrounds:
  - non-J/ψ events (continuum background)
  - non-prompt J/ψ
  - J/ψ from different primary vertices (pile-up background)
- Data-driven approach to extract DPS fraction

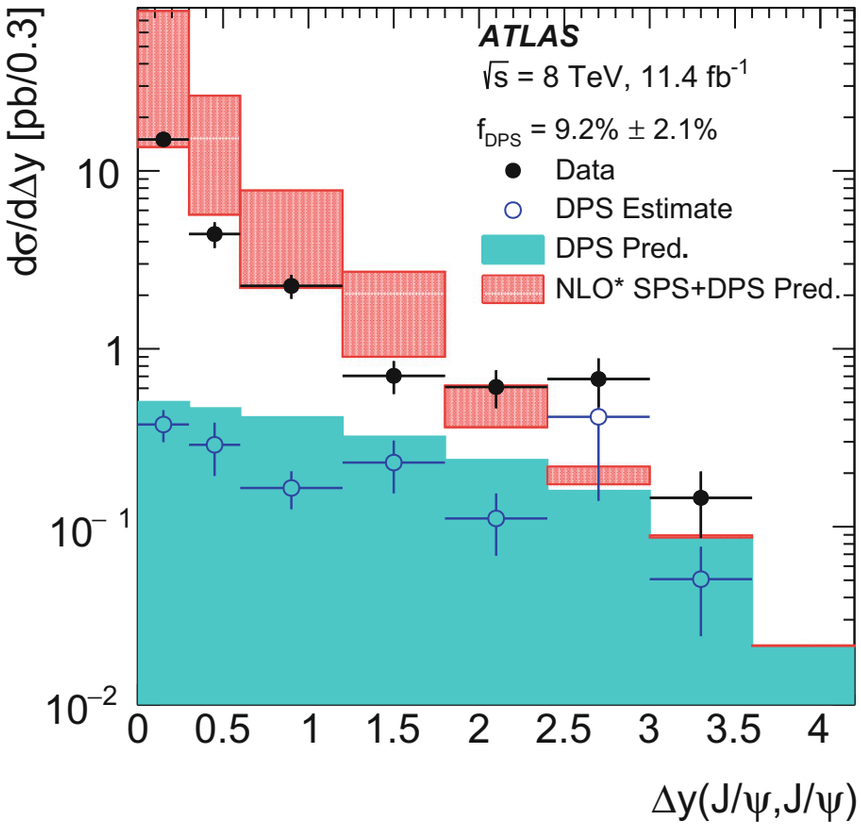
Separated with **$m(J/\psi_1)$ x $m(J/\psi_2)$ fit**

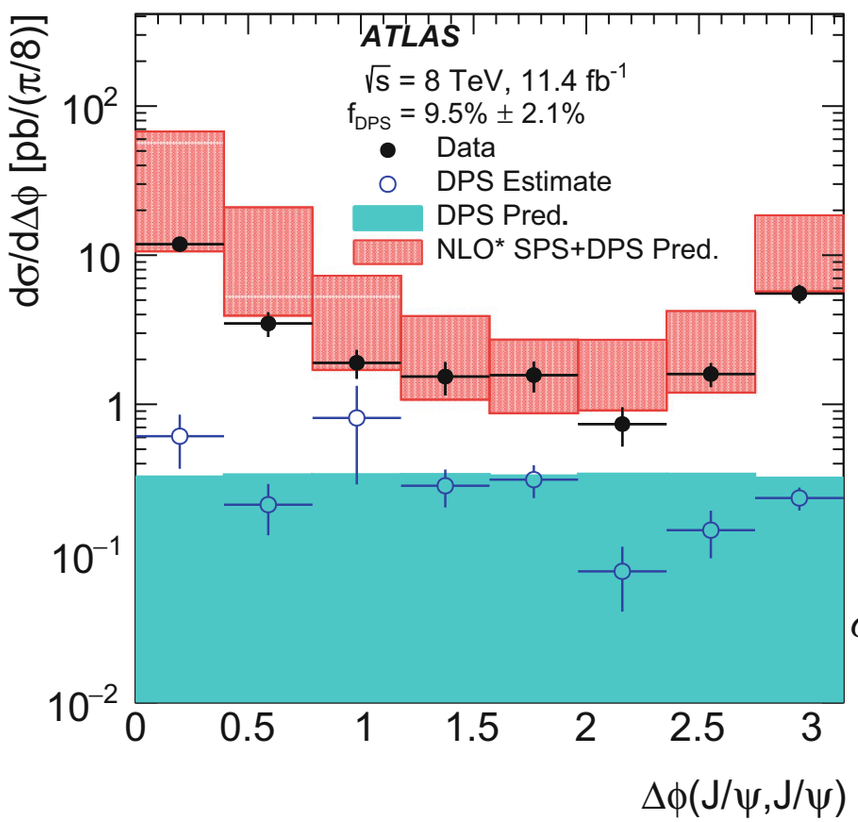
Separated with **$L_{xy}(J/\psi_1)$ x $L_{xy}(J/\psi_2)$ fit**

Subtracted using **d_z distribution**

L_{xy} — transverse decay length

d_z — distance between the two J/ψ decay vertices along the beam direction

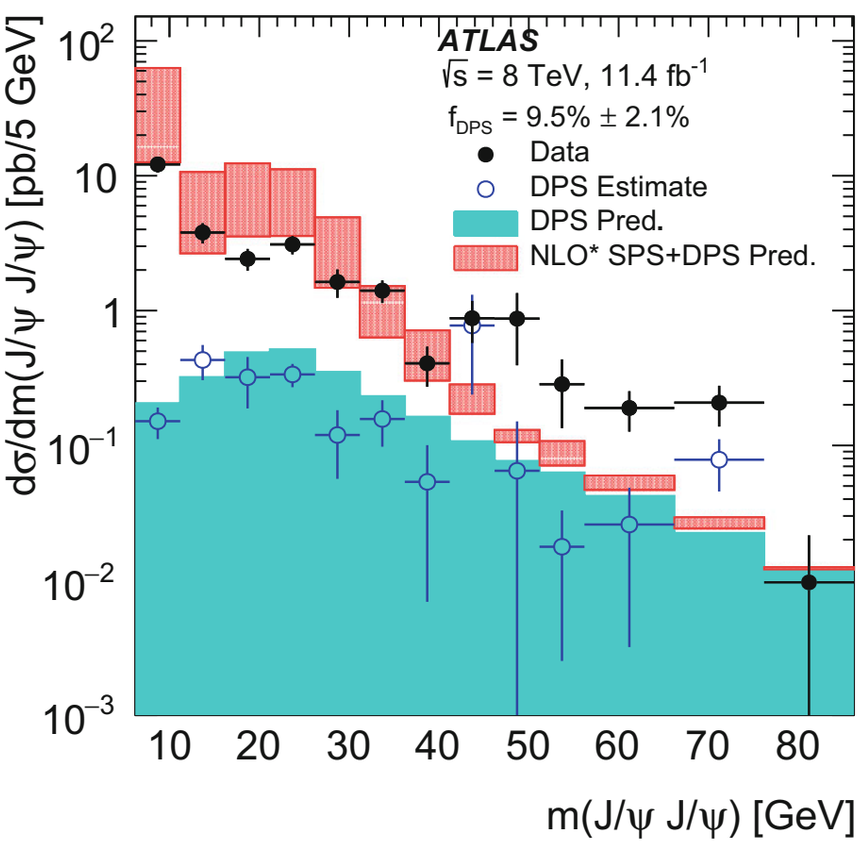


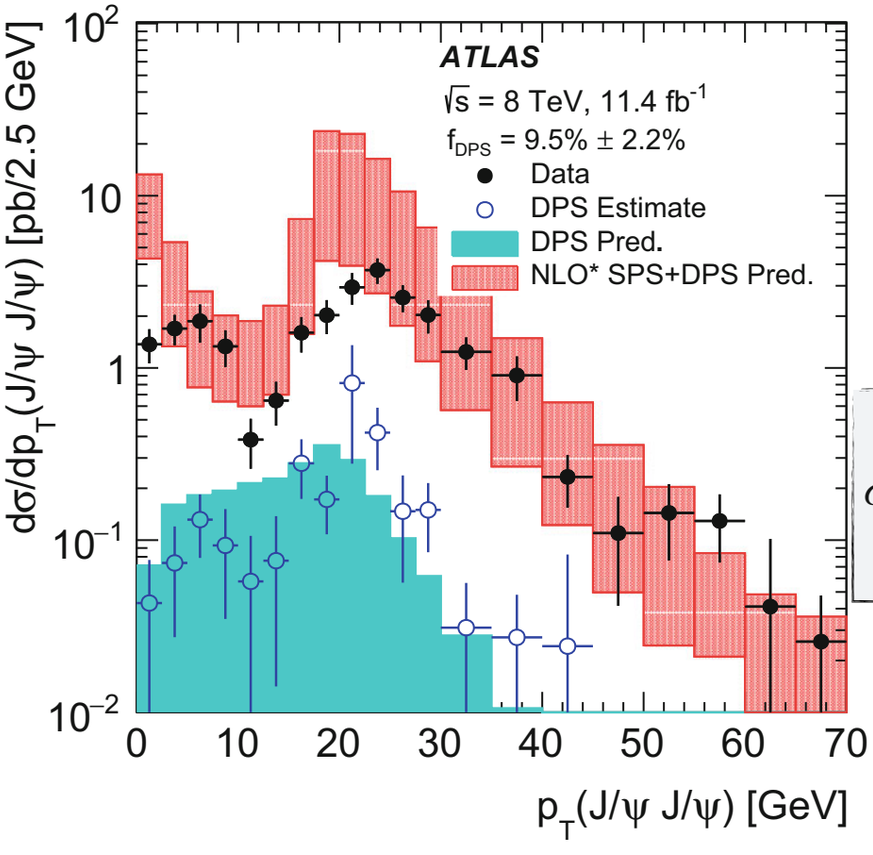


$$f_{\mathrm{DPS}} = (9.2 \pm 2.1\ (\mathrm{stat}) \pm 0.5(\mathrm{syst}))\%.$$

f_{DPS} — fraction of prompt-prompt di-J/ψ events that are due to double parton scattering (DPS)

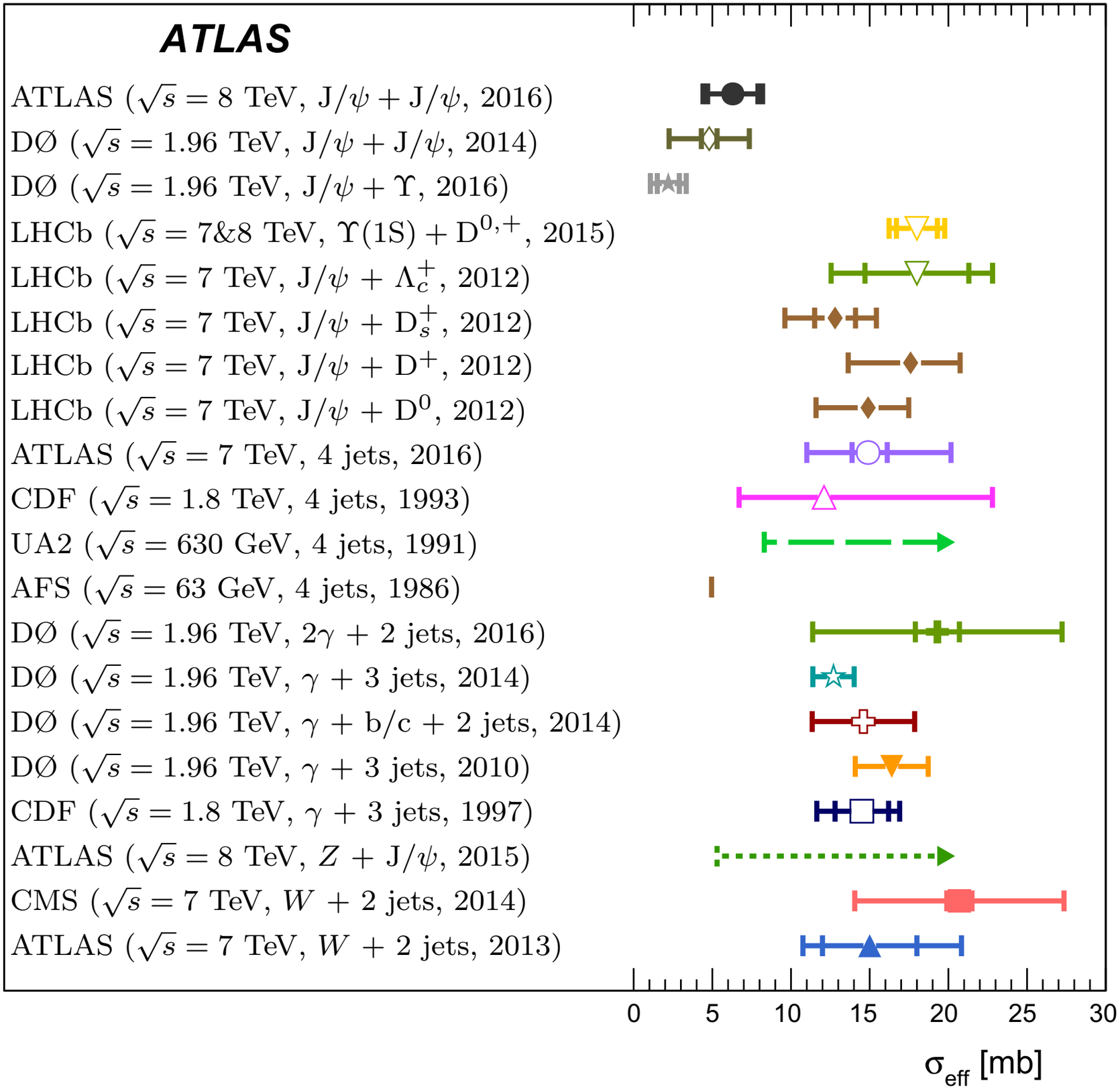
$$\sigma_{\mathrm{DPS}}^{J/\psi,J/\psi} = 14.8 \pm 3.5\ (\mathrm{stat}) \pm 1.5\ (\mathrm{syst}) \pm 0.2\ (\mathrm{BF}) \pm 0.3\ (\mathrm{lumi})\ \mathrm{pb}.$$





$$\sigma_{\mathrm{eff}} = 6.3 \pm 1.6\ (\mathrm{stat}) \pm 1.0\ (\mathrm{syst}) \pm 0.1\ (\mathrm{BF}) \pm 0.1\ (\mathrm{lumi})\ \mathrm{mb}.$$

$$\sigma_{\mathrm{eff}} = \frac{1}{2}\frac{\sigma_{J/\psi}^2}{\sigma_{\mathrm{DPS}}^{J/\psi,J/\psi}} = \frac{1}{2}\frac{\sigma_{J/\psi}^2}{f_{\mathrm{DPS}} \times \sigma_{J/\psi\,J/\psi}}$$



Some newer results not included in the plot:

CMS + Lansberg, Shao ($\sqrt{s}$ = 7 TeV, J/ψ + J/ψ, 2014, JHEP09(2014)094, 10.1016/j.physletb.2015.10.083)

8.2 ± 2.2 mb

CMS ($\sqrt{s}$ = 8 TeV, Y(1*S*) + Y(1*S*), 2016, JHEP05(2017)013)

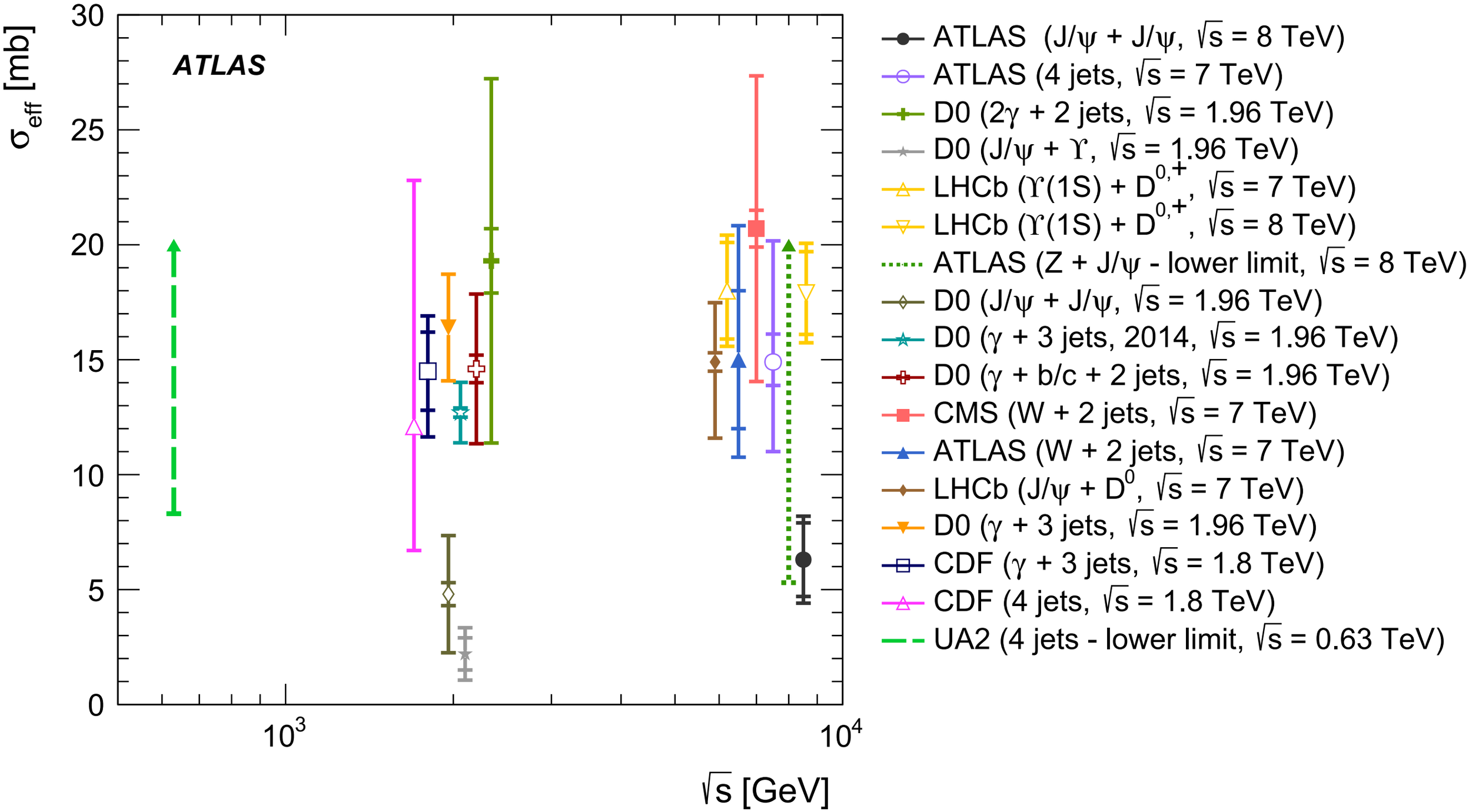
≈ 6.6 mb if f_{DPS} ≈ 10%

≈ 2.2 mb if f_{DPS} ≈ 30%

LHCb ($\sqrt{s}$ = 13 TeV, J/ψ + J/ψ, 2017, arXiv:1612.07451)

model-dependent estimations in range

10.0 – 12.5 mb

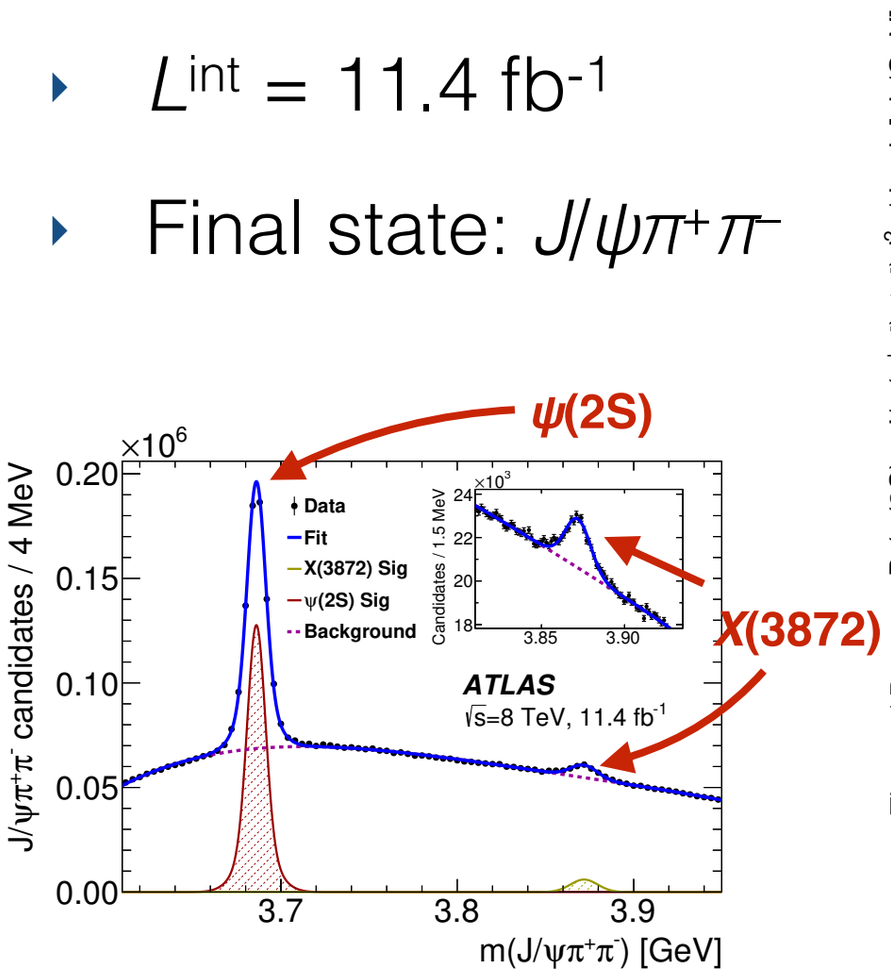

ATLAS
σ_{eff} [mb]
30
25
20
15
10
5
0
10^3
10^4
$\sqrt{s}$ [GeV]
ATLAS (J/ψ + J/ψ, $\sqrt{s}$ = 8 TeV)
ATLAS (4 jets, $\sqrt{s}$ = 7 TeV)
D0 (2γ + 2 jets, $\sqrt{s}$ = 1.96 TeV)
D0 (J/ψ + Υ, $\sqrt{s}$ = 1.96 TeV)
LHCb (Υ(1S) + $D^{0,+}$, $\sqrt{s}$ = 7 TeV)
LHCb (Υ(1S) + $D^{0,+}$, $\sqrt{s}$ = 8 TeV)
ATLAS (Z + J/ψ - lower limit, $\sqrt{s}$ = 8 TeV)
D0 (J/ψ + J/ψ, $\sqrt{s}$ = 1.96 TeV)
D0 (γ + 3 jets, 2014, $\sqrt{s}$ = 1.96 TeV)
D0 (γ + b/c + 2 jets, $\sqrt{s}$ = 1.96 TeV)
CMS (W + 2 jets, $\sqrt{s}$ = 7 TeV)
ATLAS (W + 2 jets, $\sqrt{s}$ = 7 TeV)
LHCb (J/ψ + D^0, $\sqrt{s}$ = 7 TeV)
D0 (γ + 3 jets, $\sqrt{s}$ = 1.96 TeV)
CDF (γ + 3 jets, $\sqrt{s}$ = 1.8 TeV)
CDF (4 jets, $\sqrt{s}$ = 1.8 TeV)
UA2 (4 jets - lower limit, $\sqrt{s}$ = 0.63 TeV)

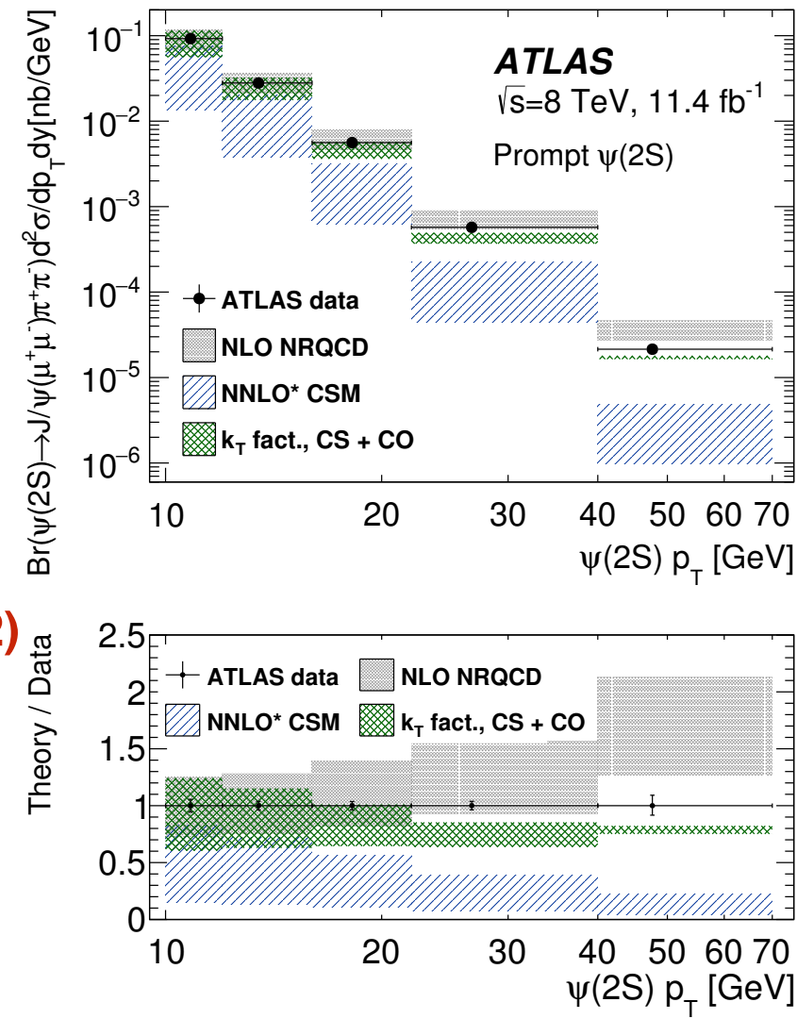
Production measurements of ψ(2S) and X(3872)

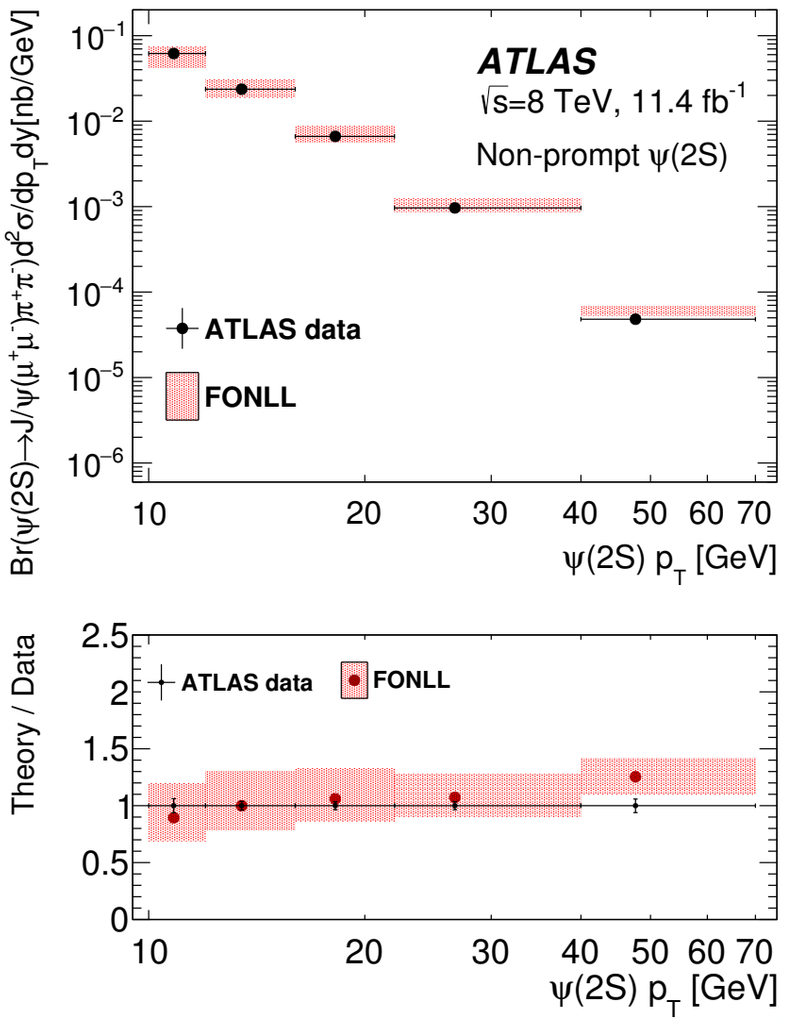
JHEP01(2017)117

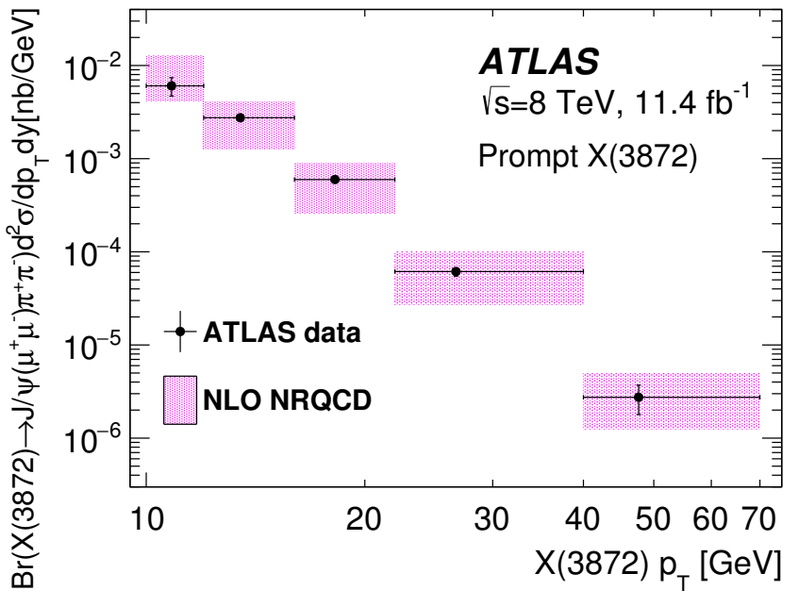
- Trigger on a pair of muons successfully fitted to a common vertex
- $\sqrt{s}$ = 8 TeV
- L^{int} = 11.4 fb^{-1}
- Final state: $J/\psi\pi^+\pi^-$

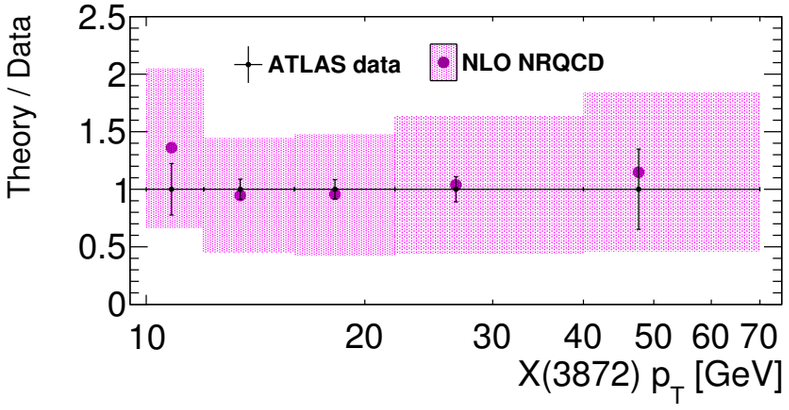
- Selection:
  - $|\eta^\mu| < 2.3$ and $p_T^\mu > 4$ GeV
  - $m_{\mu\mu}$ must fall into $m_{J/\psi}$ ±120 MeV
  - $|\eta^\pi| < 2.4$ and $p_T^\pi > 0.6$ GeV
  - $|y(J/\psi\pi^+\pi^-)| < 0.75$
  - $10 < p_T(J/\psi\pi^+\pi^-) < 70$ GeV
  - $\Delta R(J/\psi, \pi^\pm) < 0.5$
  - $m(J/\psi\pi^+\pi^-) - m(J/\psi) - m(\pi^+\pi^-) < 0.3$ GeV

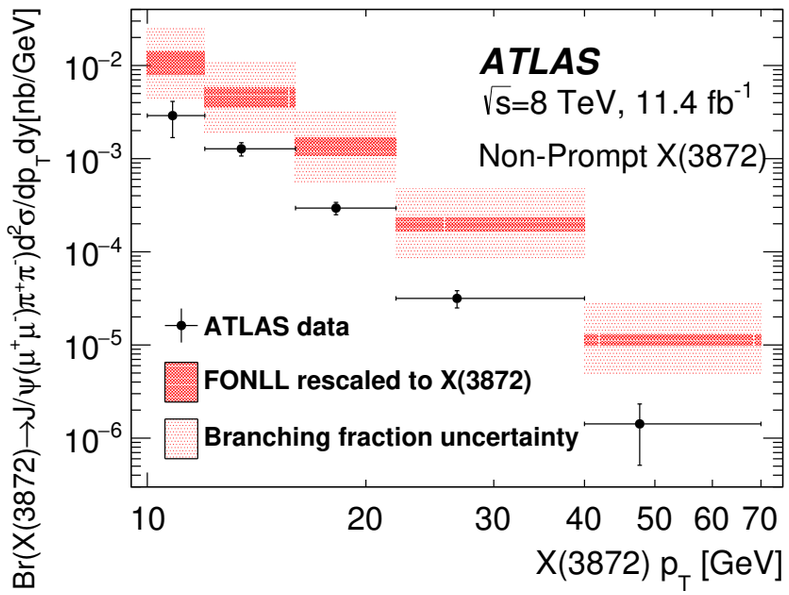


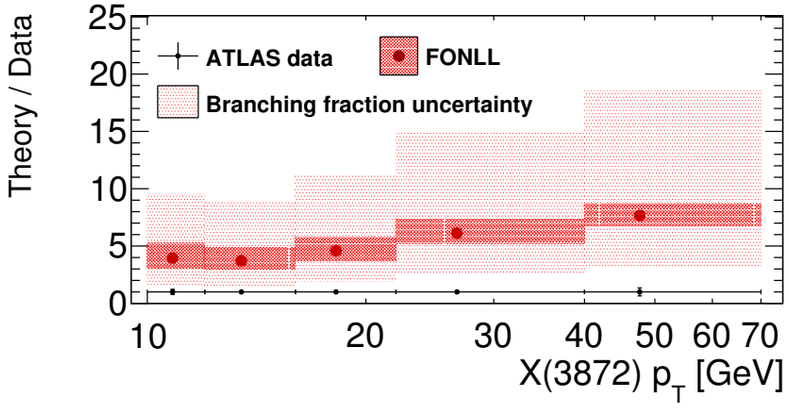


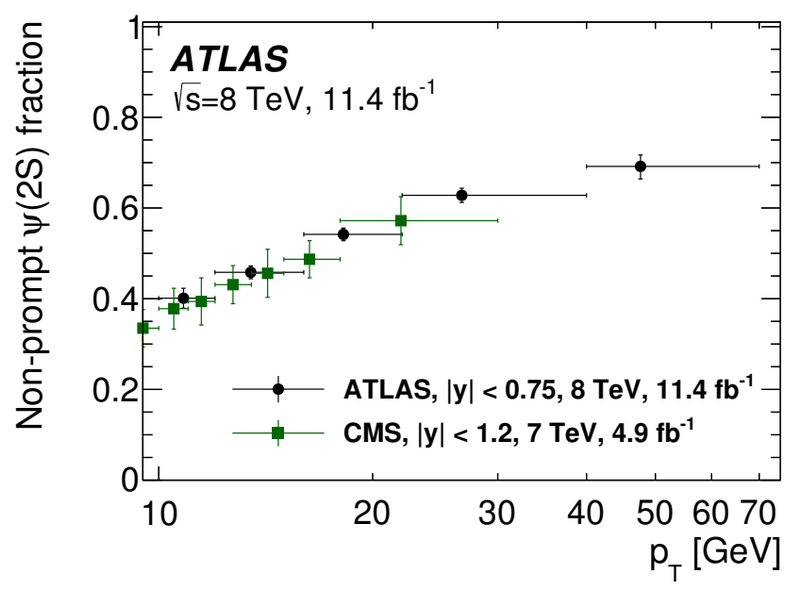


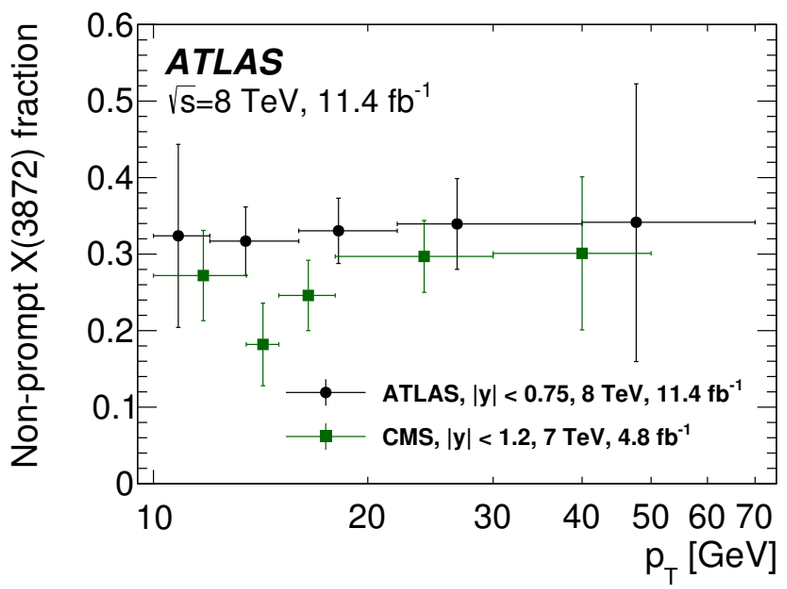












single lifetime model

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

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

double lifetime model

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

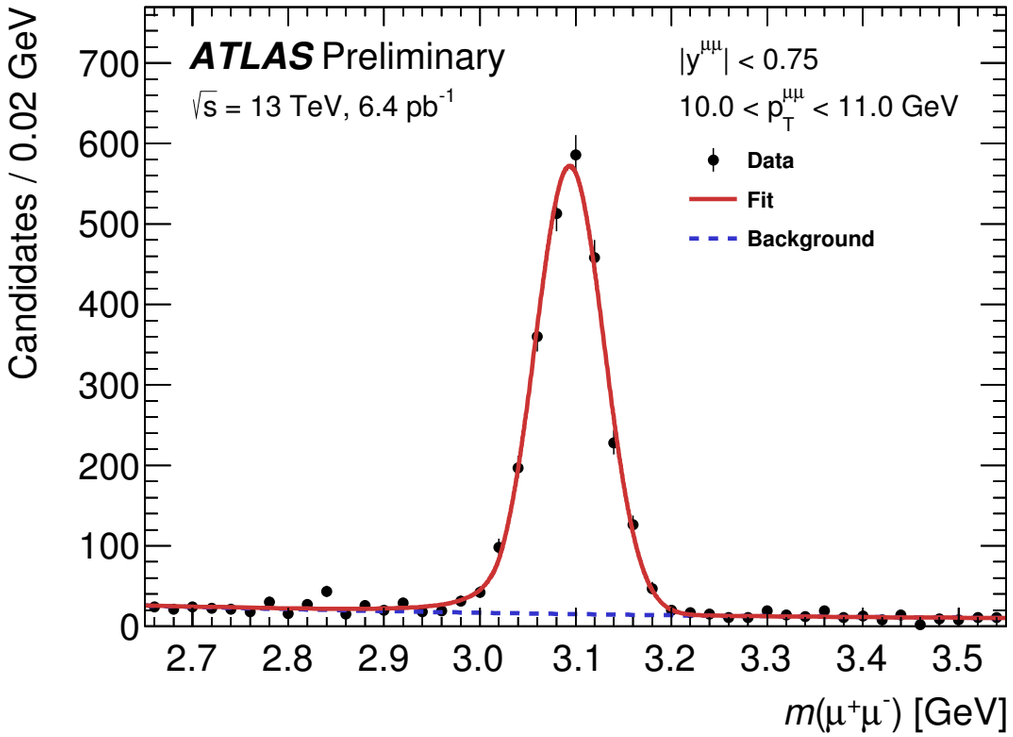
Non-prompt J/ψ production fraction at $\sqrt{s} = 13$ TeV

ATLAS-CONF-2015-030

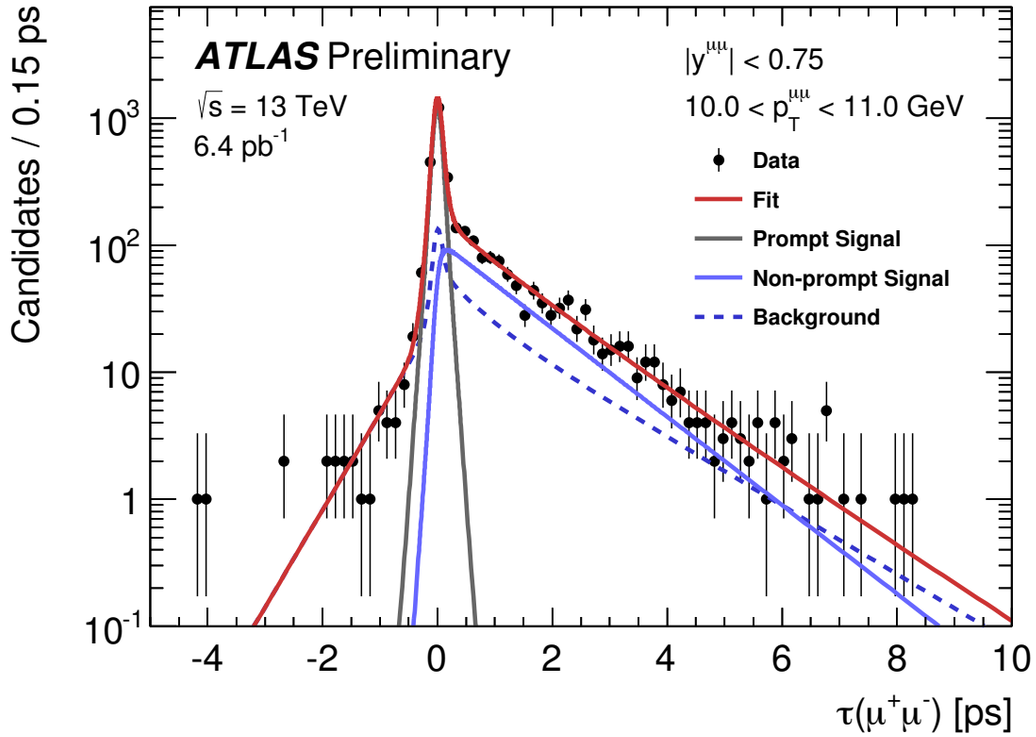
- μ pair fitted into a common vertex
- Two-dimensional fit
  - $m_{\mu\mu}$
  - Pseudo-proper decay time $\tau = L_{xy} \cdot \frac{m_{J/\psi}^{\mathrm{PDG}}}{p_{\mathrm{T}}}$
- Five components
  - 2 signal (prompt and non-prompt)
  - 3 background (prompt and non-prompt + fake muons)

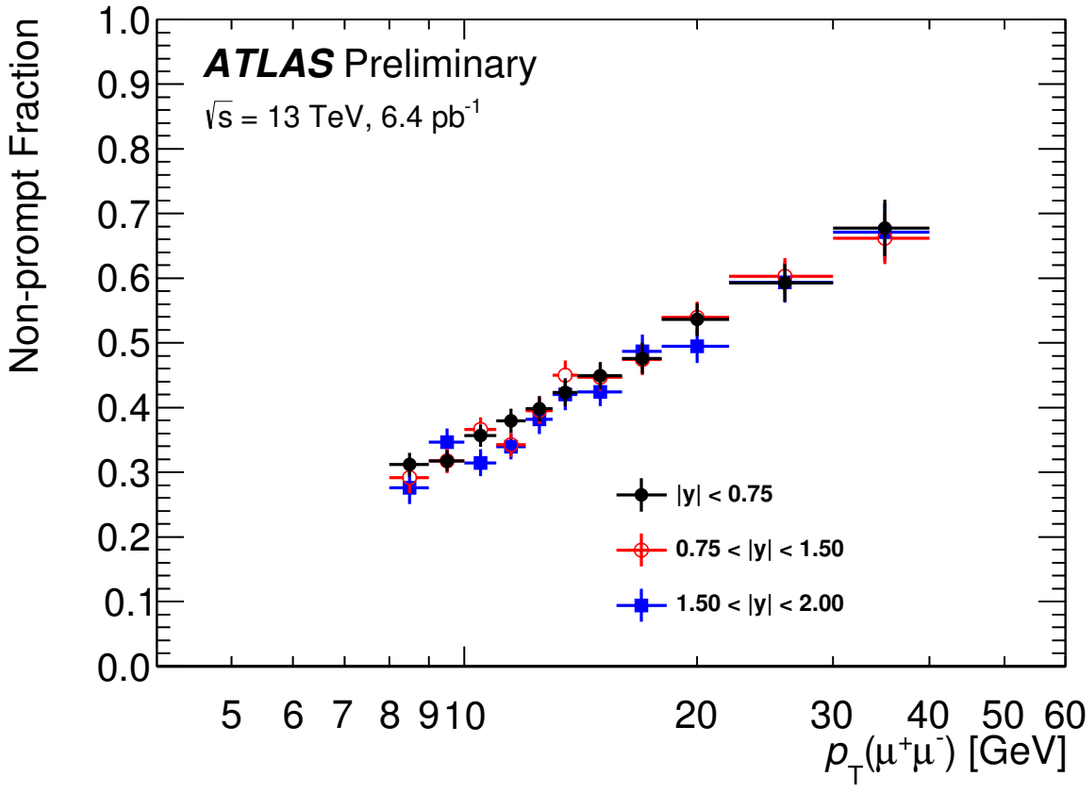
6.4 pb^{-1} of 13 TeV data

invariant mass

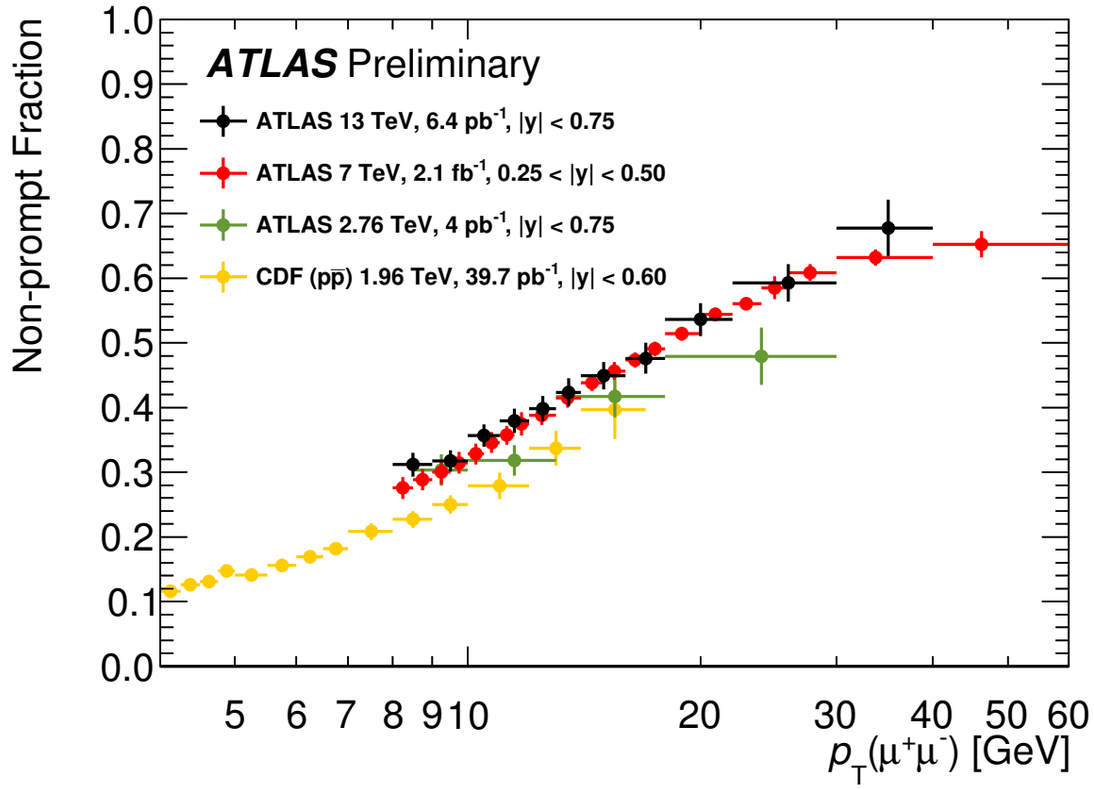


pseudo-proper decay time





fraction vs p_T at various $|y|$ intervals



fraction vs p_T at central $|y|$ region for ATLAS at various energies and CDF

- No apparent y-dependence
- Fraction increases with p_T
- No significant change between $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 13 TeV
- Noticeable difference with measurements at lower energies

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

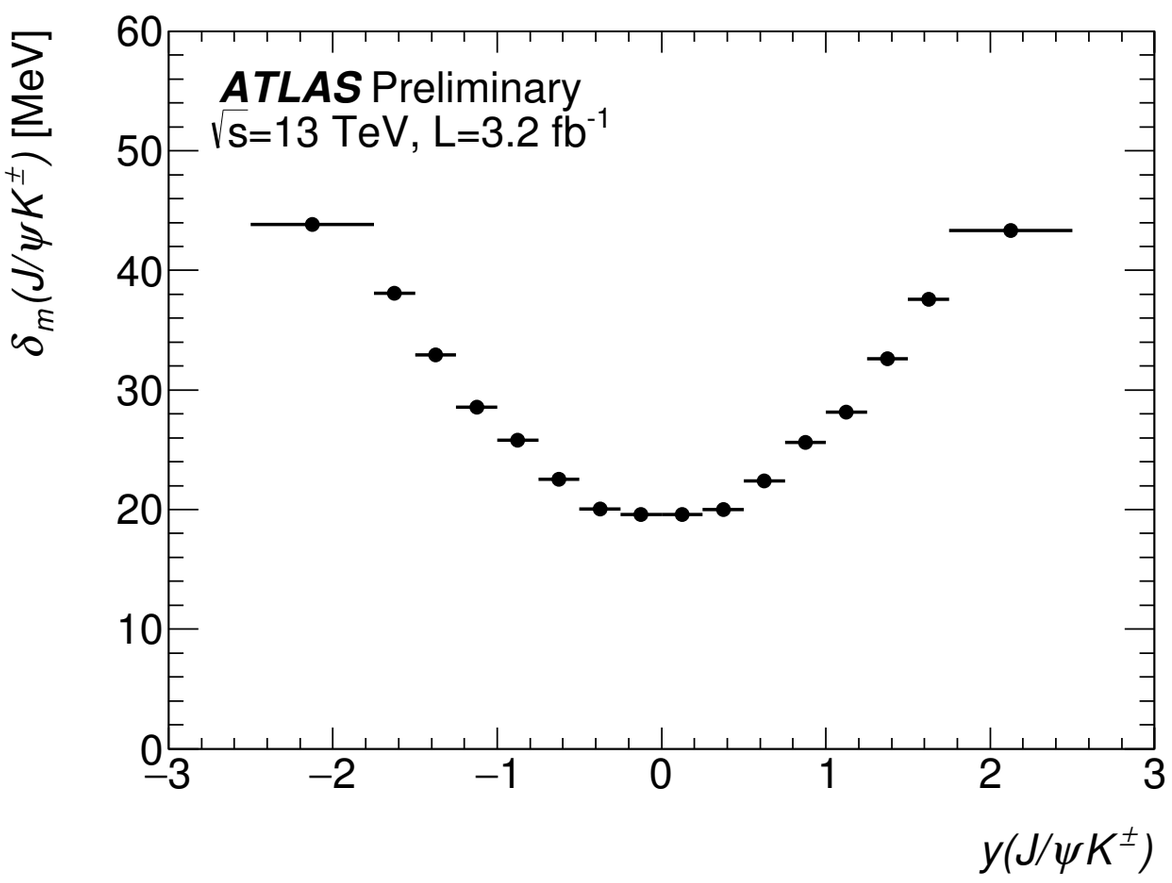
ATLAS-CONF-2015-064

- 3.2 fb^{-1} of 13 TeV data
- unbinned maximum likelihood fit with 4 components

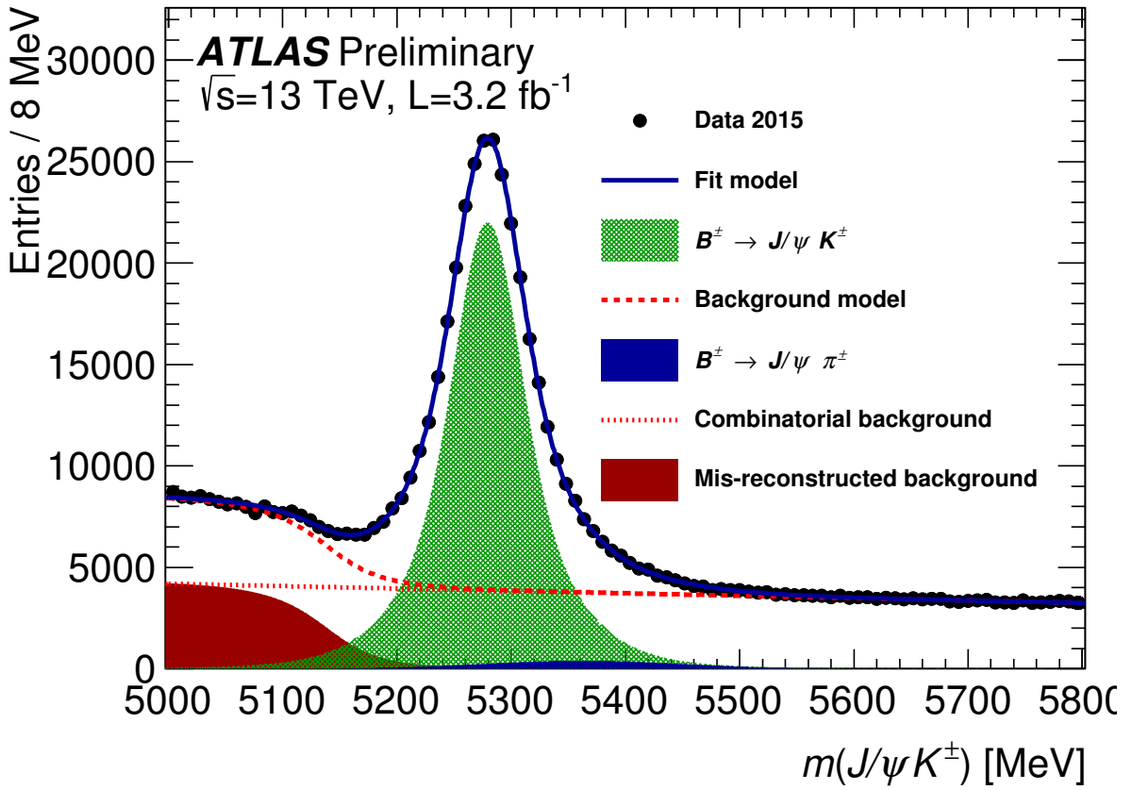
$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ \ln(f_s \cdot \mathcal{F}_s(m_i)) + f_s \cdot f_{Bx} \cdot \mathcal{F}_{B_x}(m_i) + f_s \cdot f_{B_\pi} \cdot \mathcal{F}_{B_\pi}(m_i) + (1 - f_s \cdot (1 + f_{B_x} + f_{B_\pi})) \mathcal{F}_{\text{bkg}}(m_i) \}$$

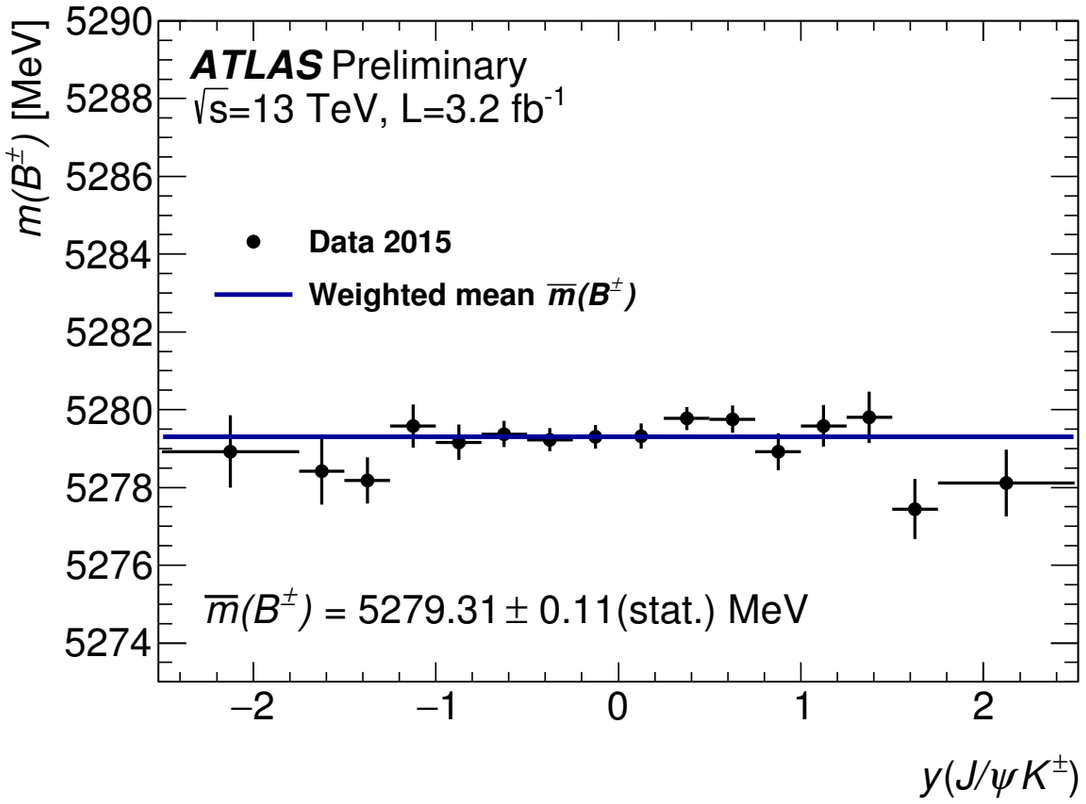
- Signal — double Gauss
- Combinatorial background — linear function
- Partially reconstructed decays $B \to J/\psi X$ — hyperbolic tangent
- Resonance background $B^{\pm} \to J/\psi \pi^{\pm}$ — Gauss (fixed shape)
- Parameters determined from MC:
  - final-state selection as signal
  - trigger prescale weights
  - kinematic weights (Bp_T and y dependent), derived from MC and data (sideband-subtraction)
- Relative fraction ($f_{B_\pi} = 3.7\%$), from acceptance (MC) and external branching ratio measurement (LHCb)

Mass resolution

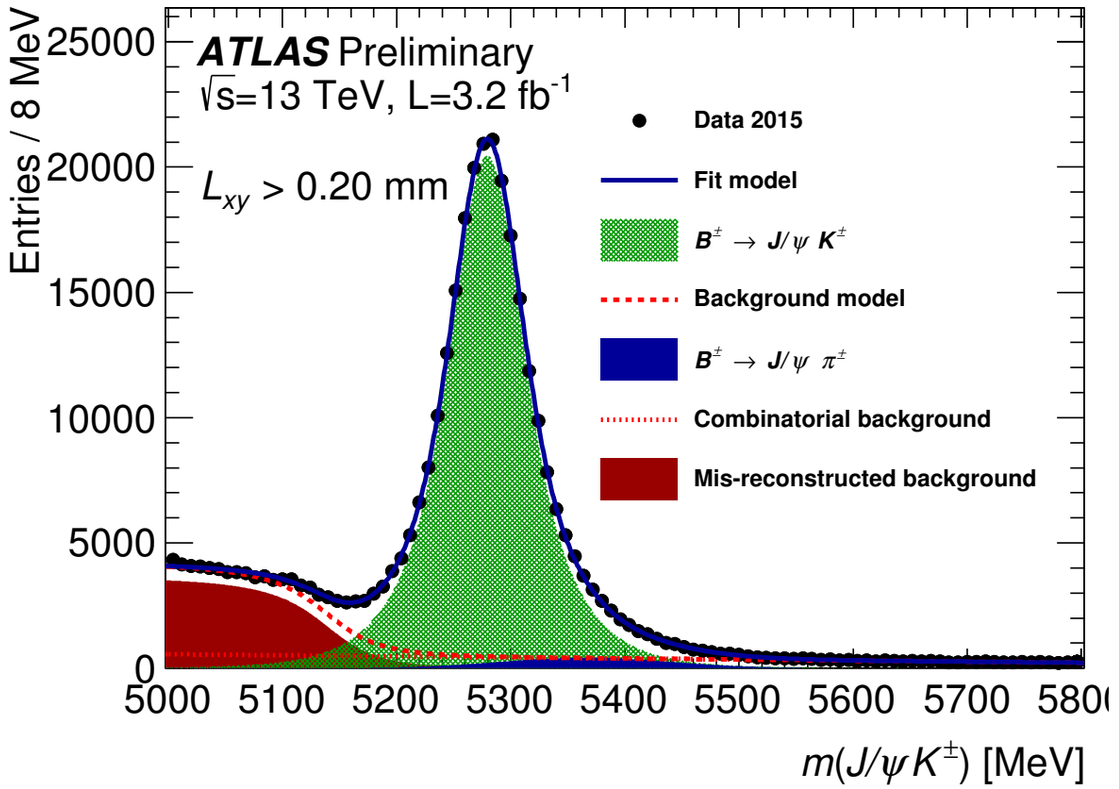


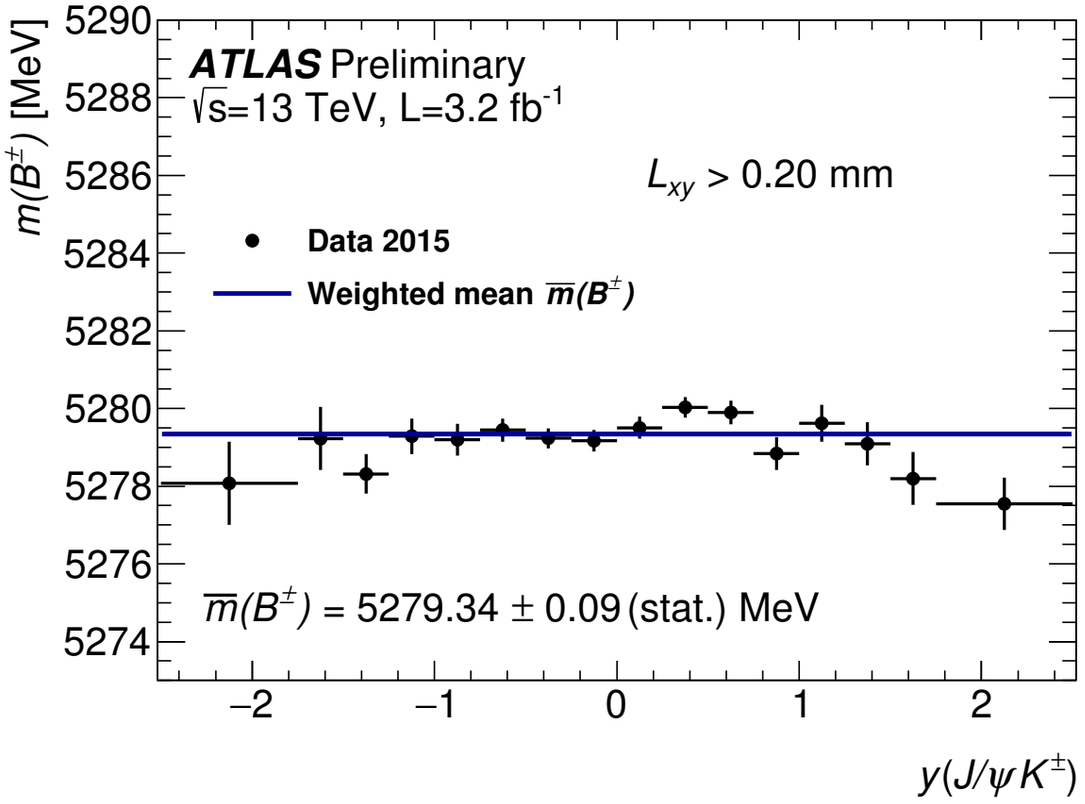
Default fit





Fit with $L_{xy} > 0.20$mm

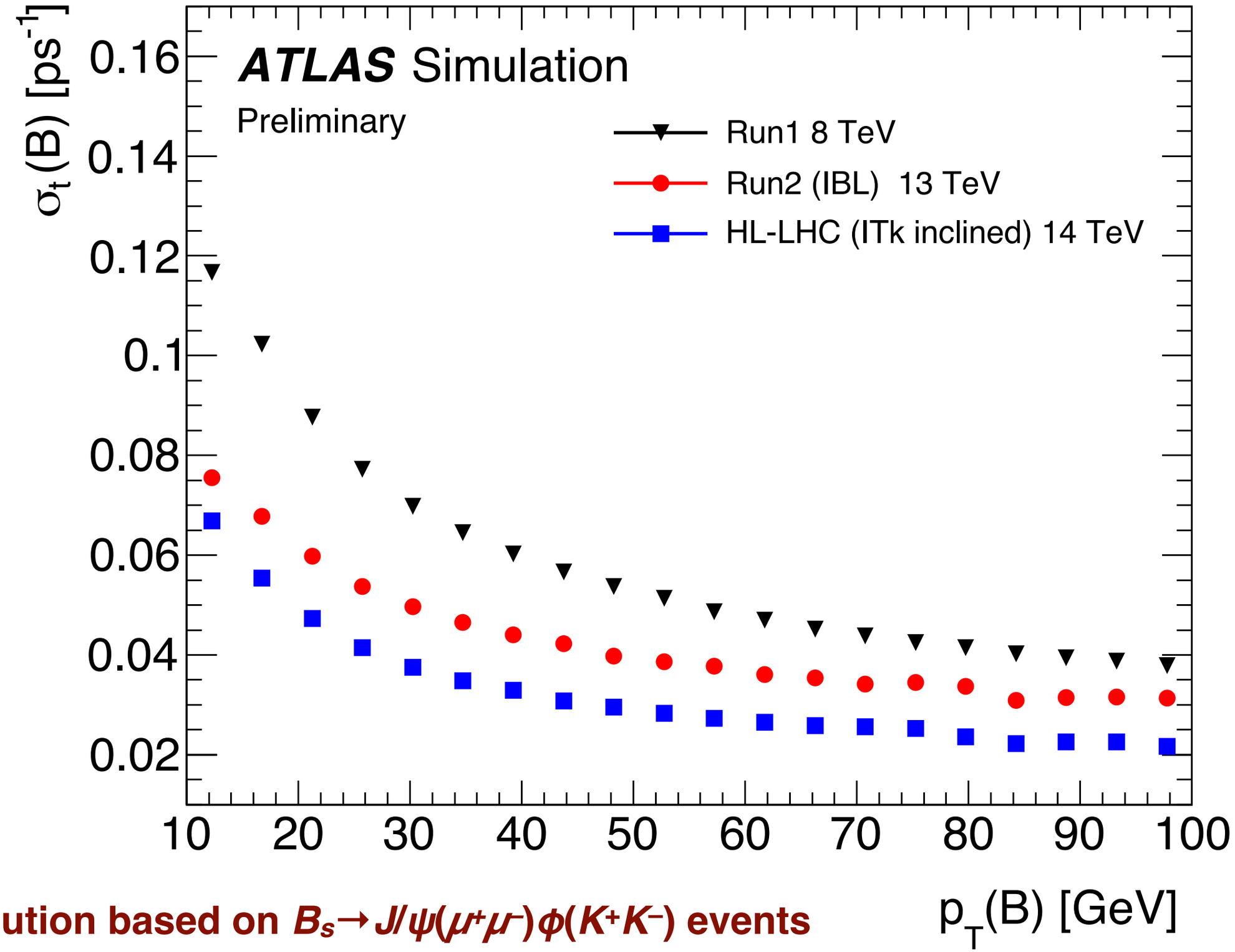




Fit	$B^{\pm}$ mass [MeV]	Fit error [MeV]
Default Fit	5279.31	0.11 (stat.)
$L_{xy} > 0.2$ mm	5279.34	0.09 (stat.)
World Average fit	5279.29	0.15
LHCb	5279.38	0.11 (stat.) ± 0.33 (syst.)

- Good stability of the mass fit over rapidity (deviations less than 0.1%)
  - ➡ Excellent ID momentum calibration
- ATLAS result is in agreement with PDG and LHCb
- Systematic uncertainty estimated to be 0.25 MeV. Not full:
  - Momentum scale and vertexing uncertainties not included

Lifetime resolution



Resolution based on $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ events

Summary

A number of heavy flavour ATLAS results presented:

- A measurement of *b*-hadron pair production
  - Predictions for **3-μ cross-section** compared to the data
  - Best overall agreement with **4-flavour MADGRAPH5_AMC@NLO+PYTHIA8**
- Prompt J/ψ pair production
  - A model with **LO DPS + NLO-colour singlet SPS** describes the data reasonably well
- ψ(2S) and X(3872) production
  - **ψ(2S) production** agrees well with **NLO NRQCD** and **FONLL** predictions for prompt and non-prompt production, respectively
  - **Prompt X(3872)** agrees well with **CMS** and **NLO NRQCD**
  - **FONLL** prediction overestimates the **non-prompt X(3872)** production
- Non-prompt J/ψ production fraction and $B^{\pm}$ mass reconstruction
  - One of the **first Run-2 results**
  - **Excellent detector performance**

Thank you

Backup slides

DPS extraction

- Purely data-driven approach
- Assumptions made:
  - In the DPS the two J/ψ are produced independently
  - DPS dominates and SPS is negligible in the region: $\Delta y \geq 1.8$; $\Delta\phi \leq \pi/2$
- Data templates obtained by combining J/ψ from two different random events
- Templates normalised to data in region $\Delta y \geq 1.8$; $\Delta\phi \leq \pi/2$
- Subtracted to obtain SPS templates
- SPS and DPS weight obtained as function of Δy and $\Delta\phi$