Production of b and c hadrons with the ATLAS detector

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Atlas B-physics programme

- **Precise measurements**

--Rare decays of B-hadrons
--CPV
--Properties of entire family of B-mesons (B^+, B_d, B_s, B_c) and B-baryons (Υ, Λ_b)

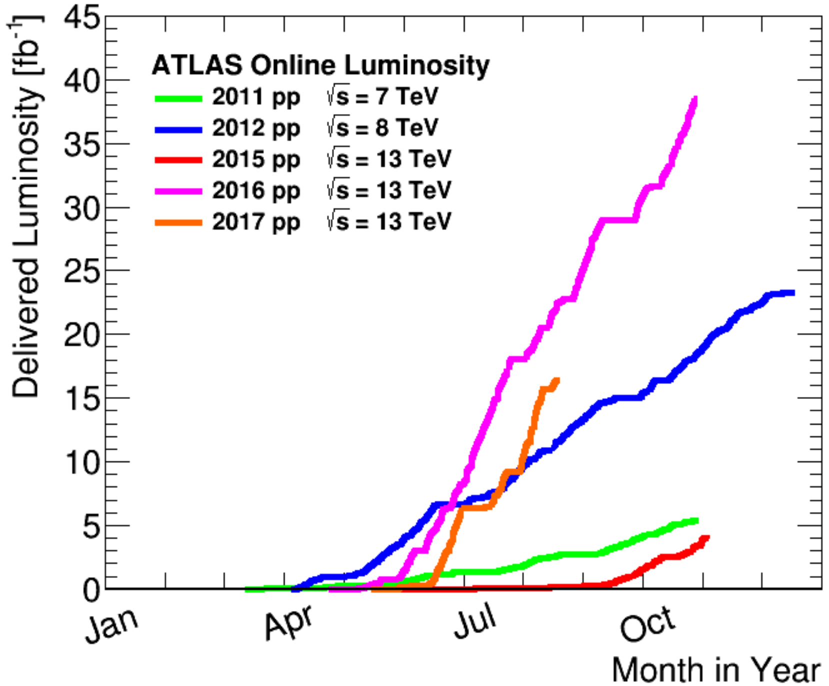
- **Spectroscopy**

--New states and decay modes

- **Quarkonia production**

--Inclusive quarkonia production($Onia \to \mu^+\mu^-$)
--Associated production(Onia+W/Z)

Quarkoina production



High luminosity and energy of the LHC allows a more detailed study.

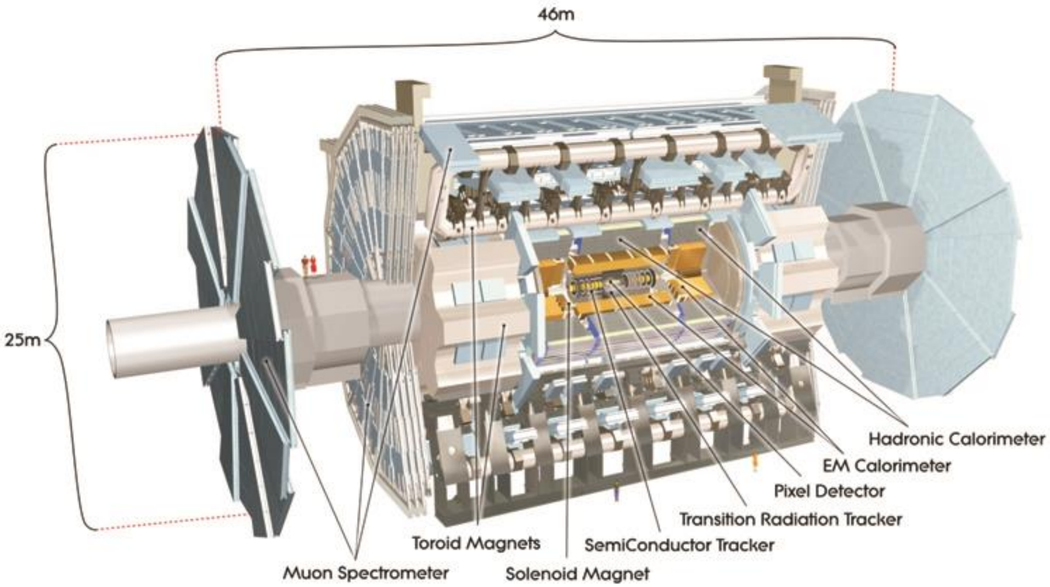
Heavy flavour production

1. A unique and important testing ground for QCD.
2. Play an important role in the determination of PDFs and form an important background for many searches

Recent results

--prompt J/ψ pair production
arXiv:1612.02950v2
--b-hadron pair production
arXiv:1705.03374v1

The ATLAS detector



Calorimeters (CALO)
-Pb/LAr accordion structure for EM
-e/γ trigger identification and measurement : $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$
-HAD: trigger and measurement of jets and E_T^{miss}, $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.3\%$
-Forward calorimeters(FCAL): covers up to |η|< 4.9

Inner detector (ID)
-|η|< 2.5
-Si pixels, Si strips, TRT
-Precise tracking and vertexing(in 2014, add Insertable B-layer)
-e/π separation
-Momentum resolution:
σ/p_T~$3.8 \times 10^{-4} p_T \oplus 1.5\%$

Muon Spectrometer (MS)
-Triggering|η|< 2.4
-Precision Tracking |η|< 2.7
-Magnetic filed produced by toroids
-Muon momentum resolution < 10% up to 1 TeV

b-hadron pair production

$$\boldsymbol{b-hadron \rightarrow J/\psi(\rightarrow \mu\mu) + X}$$

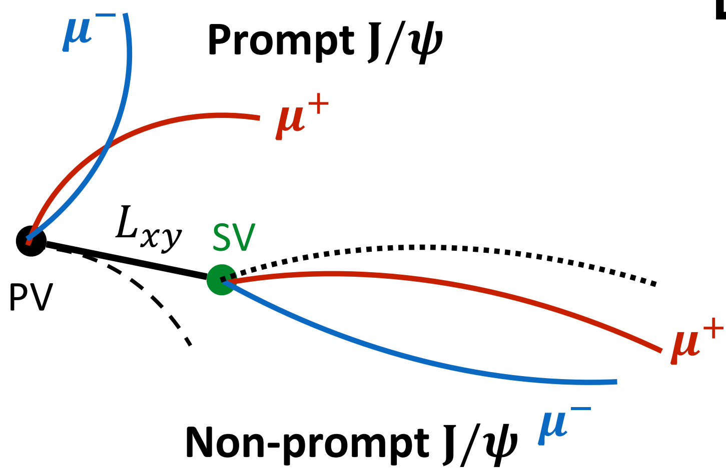
$$\boldsymbol{b-hadron \rightarrow \mu + X}$$

- An important input to improving theoretical predictions
- Important background of Higgs($\rightarrow b\bar{b}$)+V

11.4fb^{-1} of 8 TeV ATLAS data

arXiv:1705.03374v1(submitted to JHEP)

Signal extraction



- **Non-prompt J/ψ extraction**

Prompt

Produced from short-lived QCD decays (including feed-down from other charmonium states)

Non-prompt

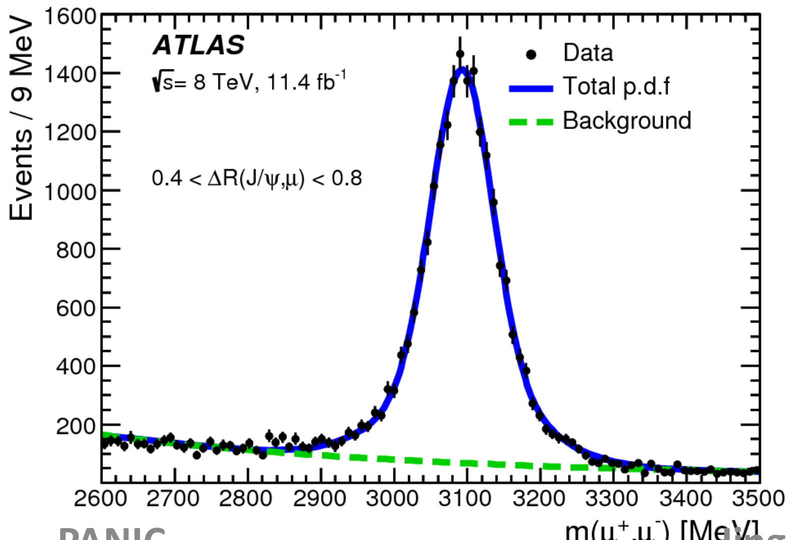
Produced in the decays of long lived b-hadrons - displaced decay vertex

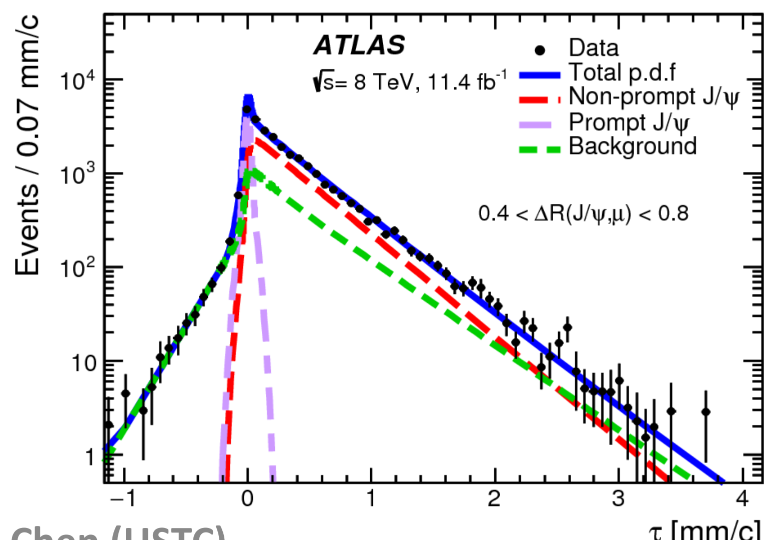
Pseudo-proper decay time

$$\tau(\mu\mu) = L_{xy} m(\mu\mu)/p_T(\mu\mu)$$

Simultaneous fit $m(\mu^+, \mu^-)$ and τ to extract non-prompt J/ψ

τ >0.25 mm/c, removing all of the prompt J/ψ candidates.





Signal extraction

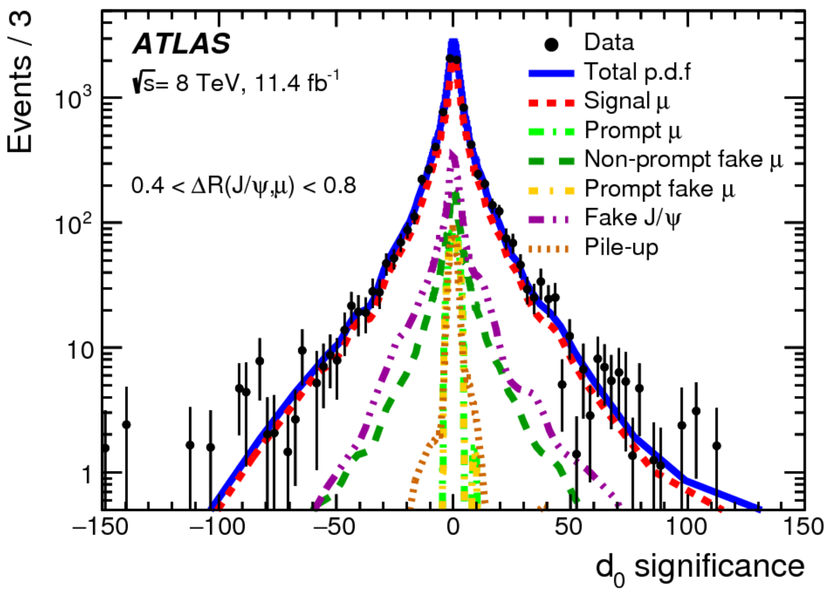
☐ 3rd muon extraction

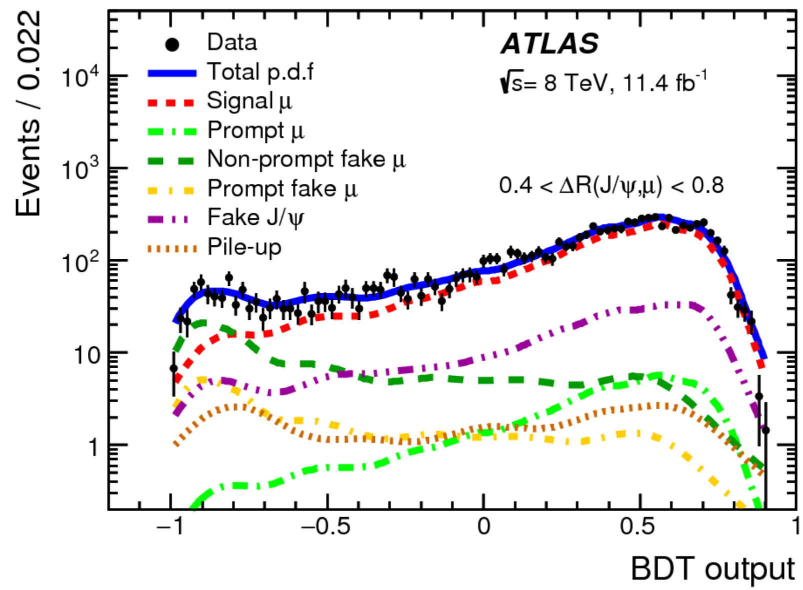
- Third-muon background : prompt muon, fake muon(decay-in-flight muon & hadronic shower leakage muons), fake J/ψ, pile-up

- Simultaneous fit

-- Transverse impact parameter significance $S(d_0) \equiv d_0/\sigma(d_0)$

--BDT output



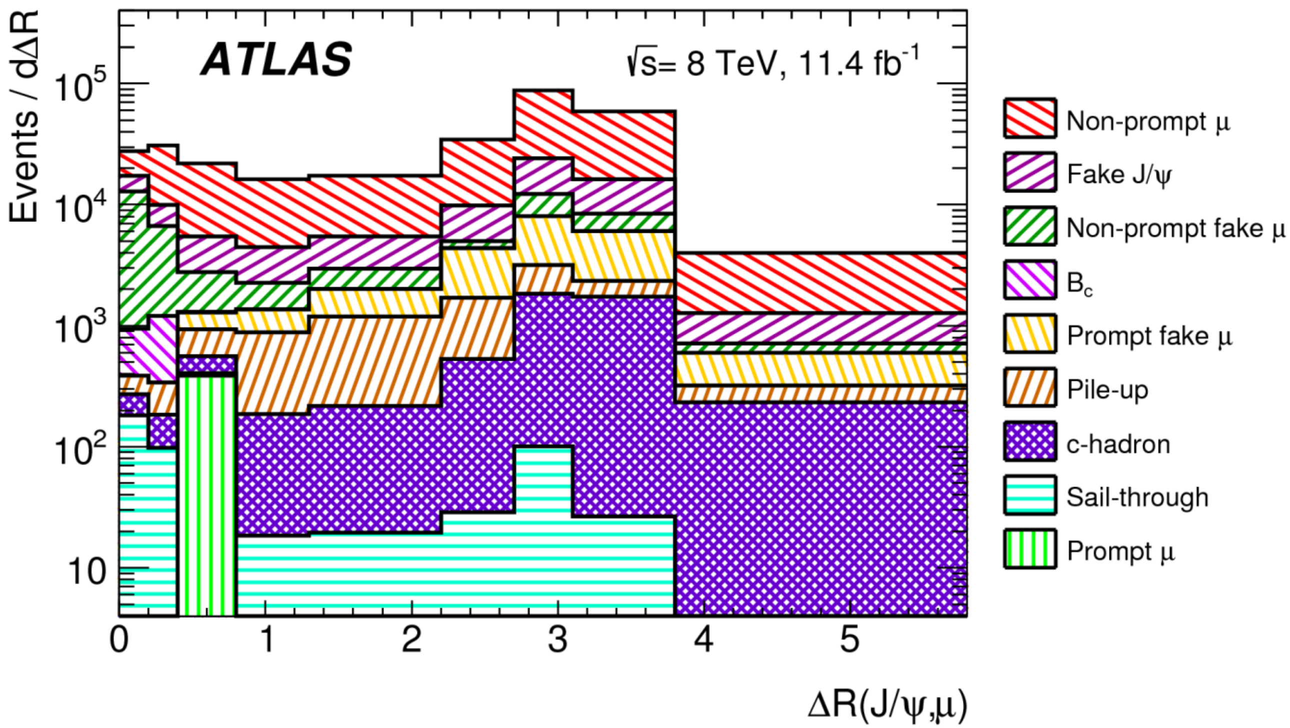


Signal extraction

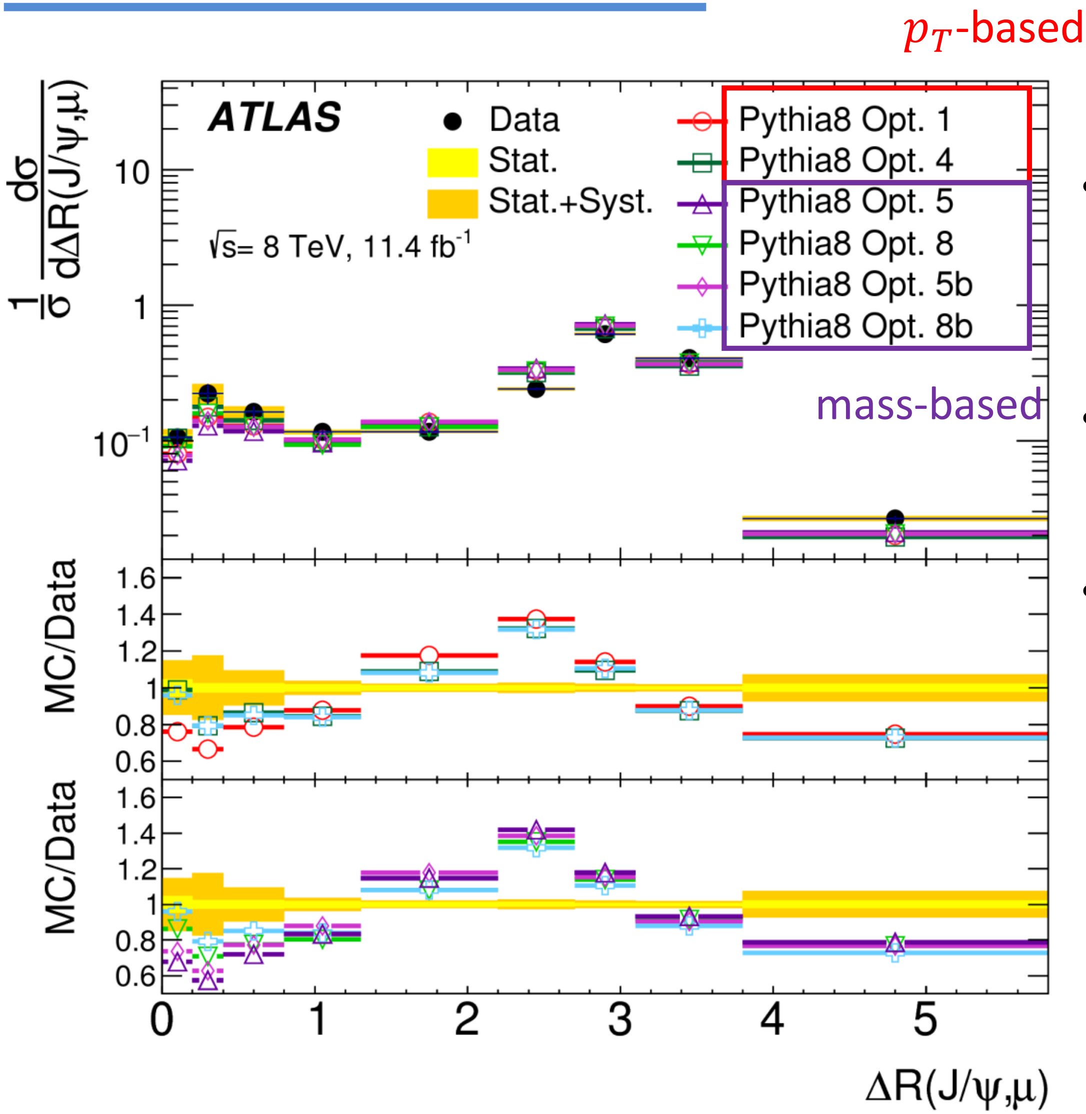
☐ **Irreducible backgrounds**

- $B_c \rightarrow J/\psi + \mu + X$, semileptonic decays of c-hadrons, sail-through
- Estimate from MC

☐ **Extrapolation to the full range of τ and resolution corrections**

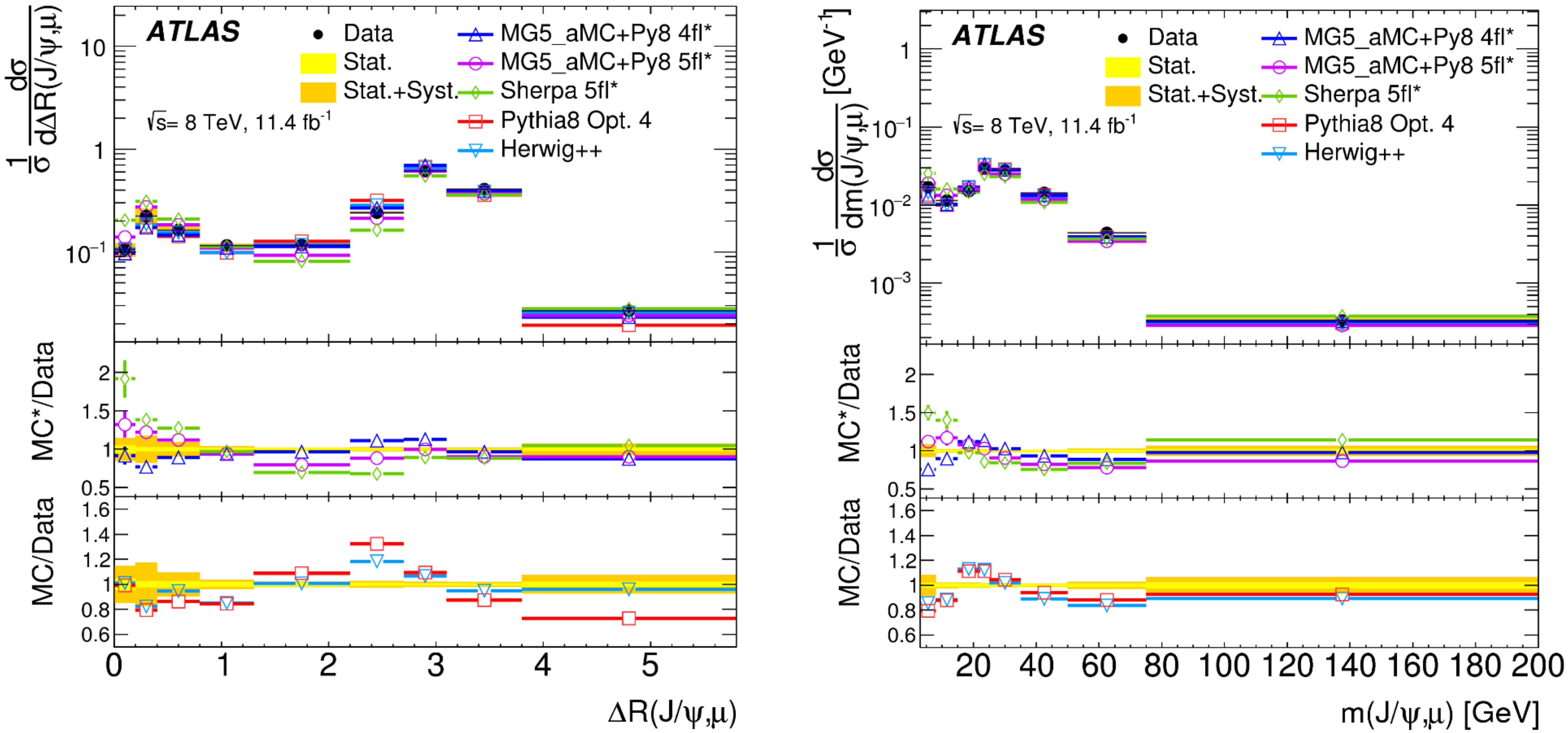


Results—Pythia8



- Pythia8 with several different options for the $g \to b\bar{b}$ splitting kernel.
- Pythia8 does not reproduce the shape of the angular distributions.
- The p_T-based scale splitting kernels (Opt. 1 and 4) generally give a better description of the low $\Delta R(J/\psi, \mu)$ region, with the kernel of Opt. 4 performing the best. This region is more suppressed in the mass-based scale kernels.

Results—Herwig, MadGraph, Sherpa

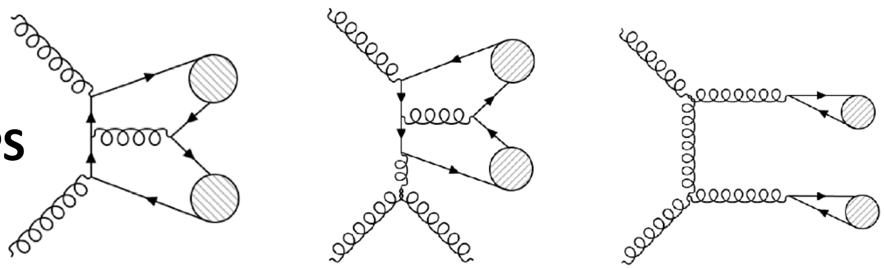


- $\Delta R(J/\psi,\mu)$ for $p_T > 20GeV$ and $p_T < 20GeV$, $\Delta\phi(J/\psi,\mu)$, $\Delta y(J/\psi,\mu)$, $y_{boost}(J/\psi,\mu)$, $p_T(J/\psi,\mu)$, $m^{\mu\mu\mu}/p_T^{\mu\mu\mu}$, $p_T^{\mu\mu\mu}/m^{\mu\mu\mu}$ are also compared.
- The 4-flavour prediction from Mad-Graph5_aMC@NLO+Pythia8 provides the best description of the data overall(in low $\mathrm{m}(J/\psi,\mu)$ region, 5 flavour provides a better description)

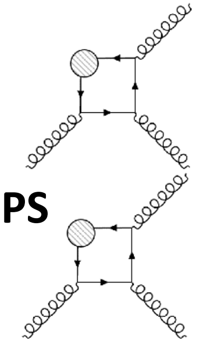
Prompt J/ψ pair production

$$J/\psi \rightarrow \mu\mu$$

SPS



DPS



- Sensitive to NLO and higher-order pQCD corrections
- Study and compare J/ψ production models
- DPS presents a unique insight into the structure of the proton(σ_{eff}) and allows a better comprehension of backgrounds to searches for new phenomena

$11.4 fb^{-1}$ of 8 TeV ATLAS data

arXiv:1612.02950v2(Eur. Phys. J. C77 (2017) 76)

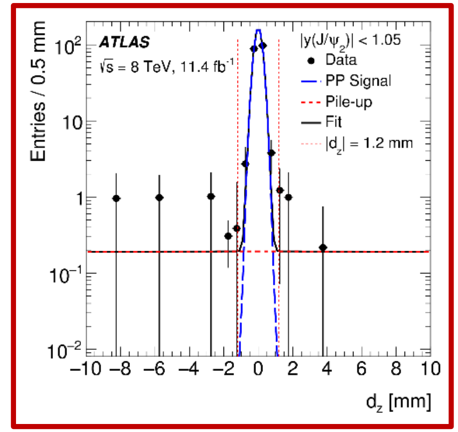
Signal extraction

- J/ψ reconstructed in $\mu\mu$ channel
- Correction for acceptance and efficiencies(trigger, reconstruction, and selection criteria) applied to data
- Backgrounds
- Steps:

--Non-J/ψ events $\Rightarrow$ 2D $m(J/\psi_1)$ and $m(J/\psi_2)$ fit

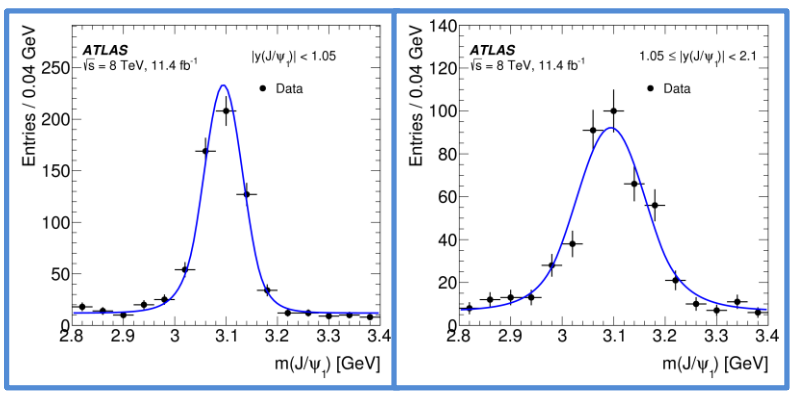
--Non-prompt J/ψ $\Rightarrow$ 2D $L_{xy}(J/\psi_1)$ and $L_{xy}(J/\psi_2)$ fit

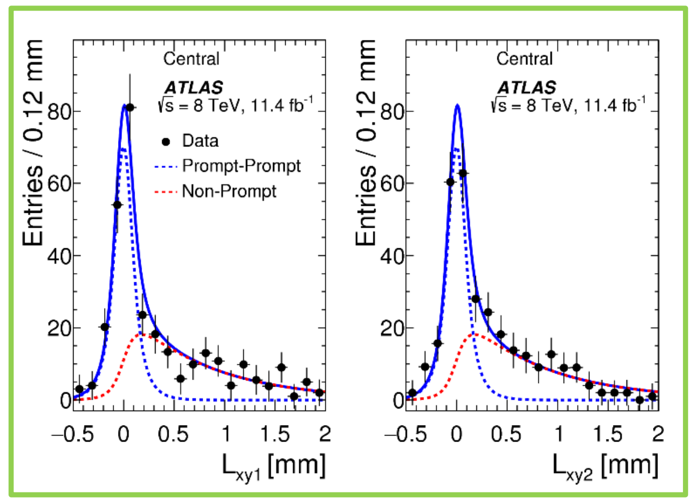
--Pile-up $\Rightarrow$ subtracted using d_z distribution



$|d_z| < 1.2mm$

The fits use the parameters derived from the inclusive J/ψ sample.



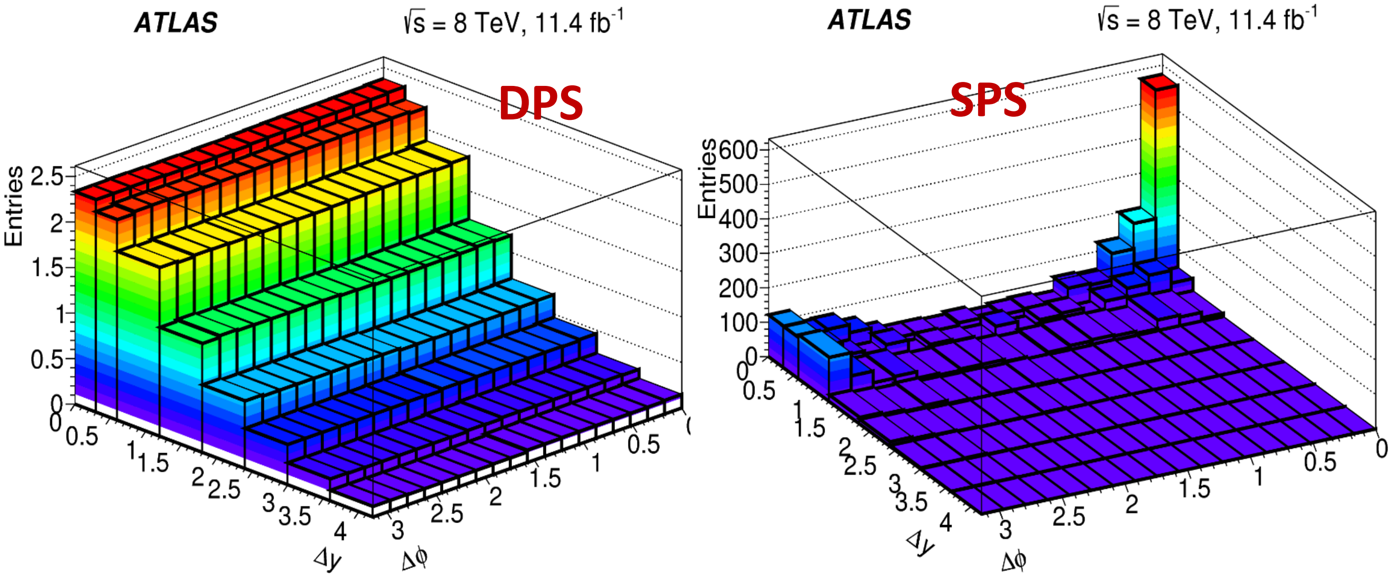


DPS extraction

Data-driven model-independent approach:

--DPS is simulated by combining re-sampled J/ψ mesons from two different random events in the di- J/ψ sample, normalized to DPS dominated region: $\Delta\phi \leq \pi/2, \Delta y \geq 1.8$

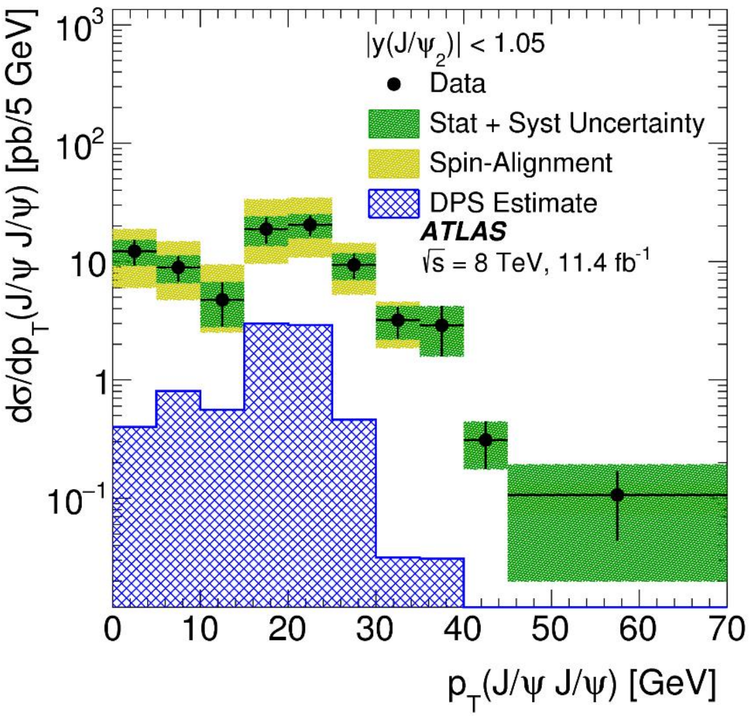
--SPS template is obtained by subtracting the DPS template

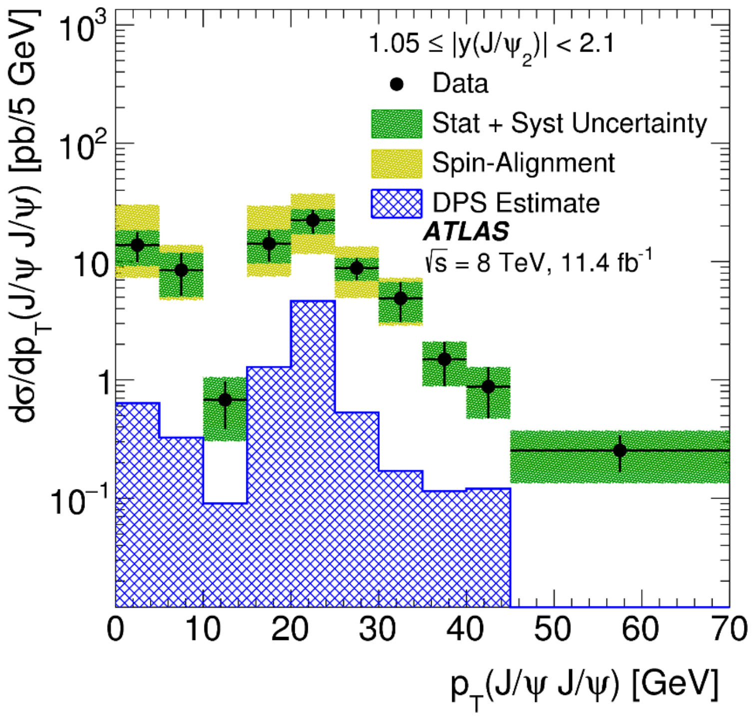


For SPS componts:

- Component near $\Delta\phi \approx \pi$: J/ψ are produced back to back in away topology
- Component near $\Delta\phi \approx 0$: J/ψ are produced in the same direction in towards topology

Cross-section measurement





- $p_T(J/\psi) > 8.5GeV, |y(J/\psi)| < 2.1$
- under the assumption of unpolarised J/ψ mesons

- Peak in low p_T: J/ψ's are in away topology
- Peak in high p_T: $J/\psi's$ are in towards topology and back-to-back with respect to an additional gluon

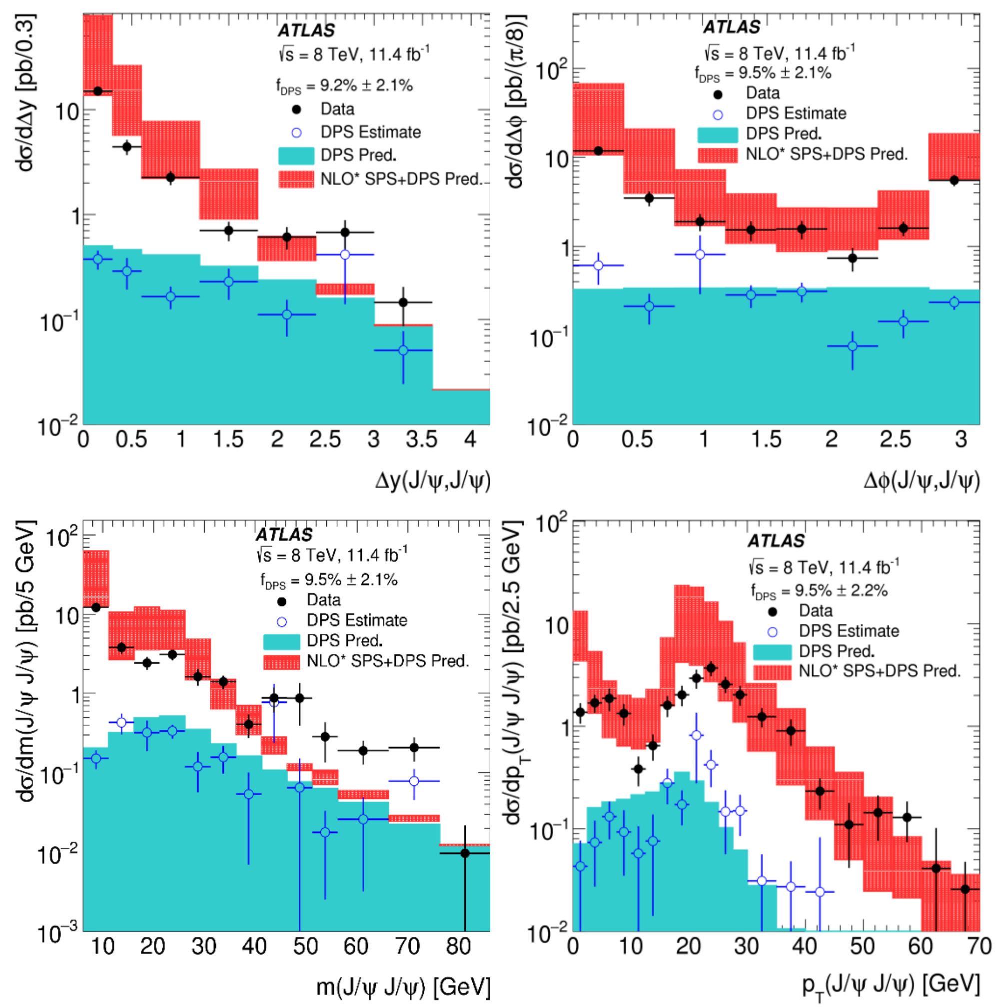
DPS measurement

- Calculated in muon fiducial volume(data set size limited, there are large fluctuations in the acceptance-corrected distributions)

- The data-driven DPS distribution approximately agrees with the DPS predictions

- There is disagreement at large Δy, large $m(J/\psi, J/\psi)$ and low p_T region(di-J/ψ production in an away topology)

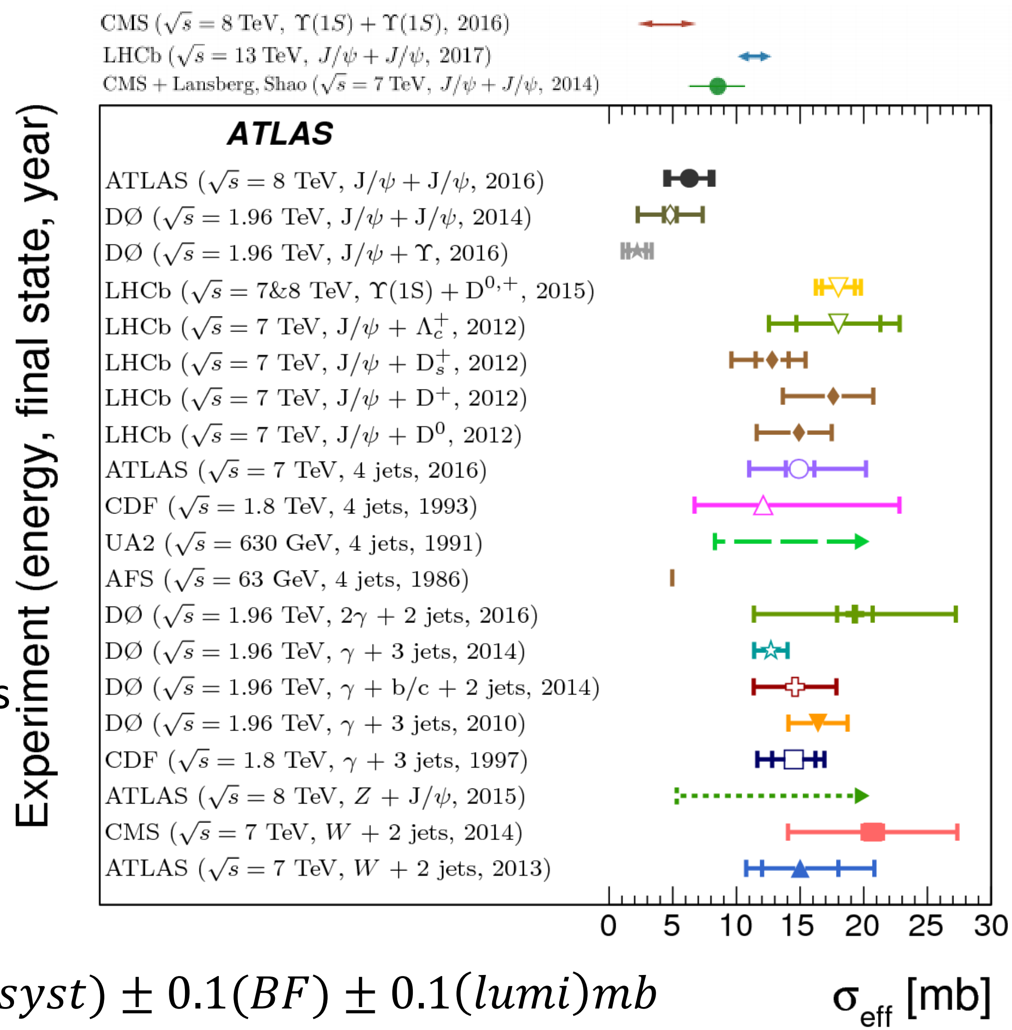
$$f_{\mathrm{DPS}} = (9.2 \pm 2.1\ (\mathrm{stat}) \pm 0.5\ (\mathrm{syst}))\%$$



Effective cross-section

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

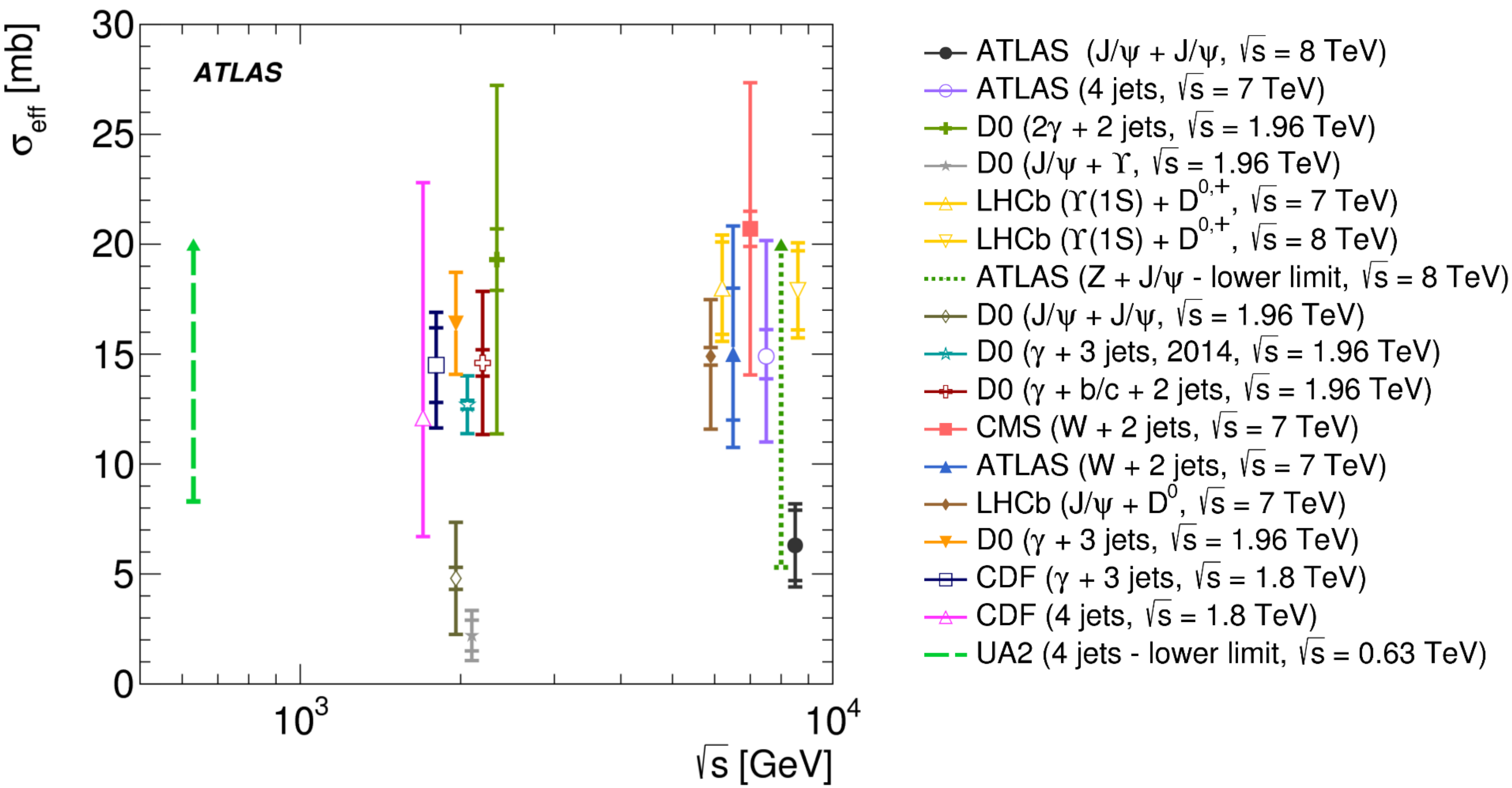
- J/ψ meson production is dominated by gluon–gluon interactions, the DPS cross-section is sensitive to the spatial distribution of gluons in the proton
- σ_{eff} 4~21mb from these experiments and measurements
- σ_{eff} measured in di-J/ψ final states generally lower than measured in other final states



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

Effective cross-section

- In defining σ_{eff}, assumptions are made which lead to process and energy independence although there is no theoretical need for this independence.
- More measurements of σ_{eff} at different energies will be helpful to test this assumption.



Summary

☐ Production of b-hadron pairs

- Total fiducial cross section($p_T^{\mu} > 6GeV, \left|\eta_{\mu}^{J/\psi}\right| < 2.3, \left|\eta_{\mu}^{3^{rd}}\right| < 2.5$):

$$\sigma\big(B(\to J/\psi(\to \mu\mu) + X\,)B(\to \mu + X\,)\big) = 17.7 \pm 0.1(stat) \pm 2.0(syst)nb$$

- For Pythia8, the p_T-based splitting kernel gives the best agreement with data, performing comparably to Herwig++.
- For all generators, the best overall agreement with data comes from the 4-flavour MadGraph5_aMC@NLO+Pythia8 prediction.

☐ Production of prompt J/ψ pair

- The total cross-section over the full fiducial J/ψ rapidity:

$$\sigma(pp \to J/\psi\, J/\psi + X) = 160 \pm 12\ (\text{stat}) \pm 14\ (\text{syst}) \pm 2\ (\text{BF}) \pm 3\ (\text{lumi})\ \text{pb}$$

- The DPS cross-section, corrected for the muon acceptance in the full J/ψ rapidity:

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

- f_{DPS} taken from the Δy distribution:

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

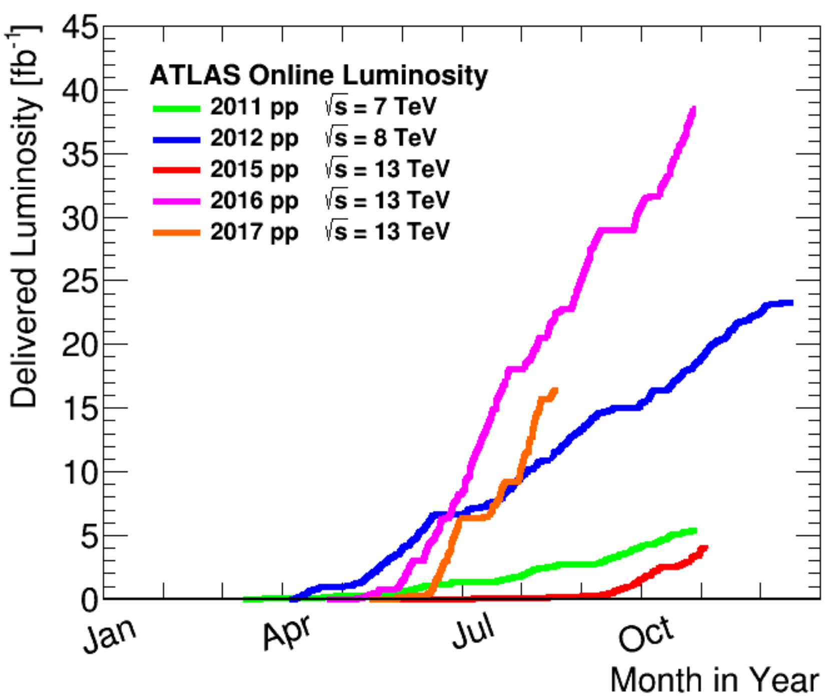
- The effective cross-section:

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

- NLO* describes the data well, possible explanations at large Δy and invariant mass might be needed.

backup

Recent results



High luminosity and energy of the LHC allows a more detailed study

- J/ψ + $W^{\pm}$ production
- J/ψ + Z production
- $\psi(2S) \to J/\psi\pi^{+}\pi^{-}$ production
- J/ψ and $\psi(2S)$production
- prompt J/ψ pair production
- χ_{c1}, χ_{c2}production
- b-hadron pair production
- $\chi_b \to \Upsilon(1S), \chi_b \to \Upsilon(2S)$ production
- Upsilon production

New results on the way

b-hadron pair production

$$\boldsymbol{b-hadron \rightarrow J/\psi(\rightarrow \mu\mu) + X}$$

$$\boldsymbol{b-hadron \rightarrow \mu + X}$$

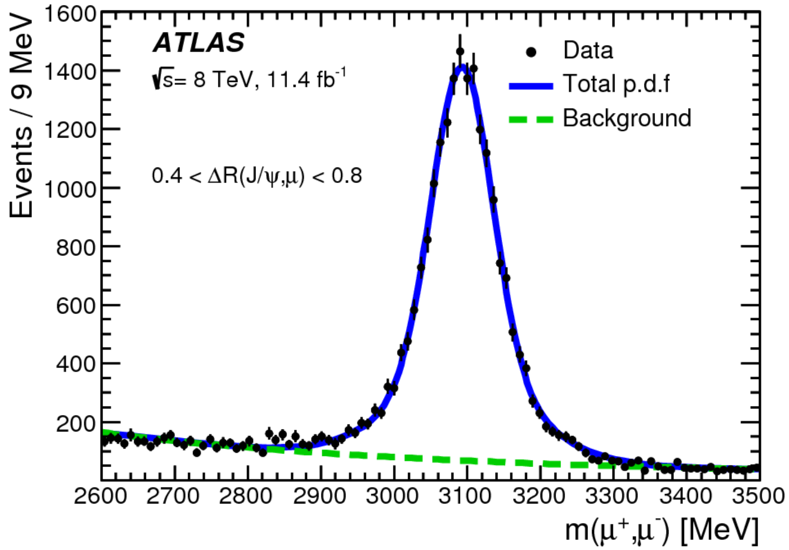
- An important input to improving theoretical predictions
- Important background of Higgs($\rightarrow b\bar{b}$)+V

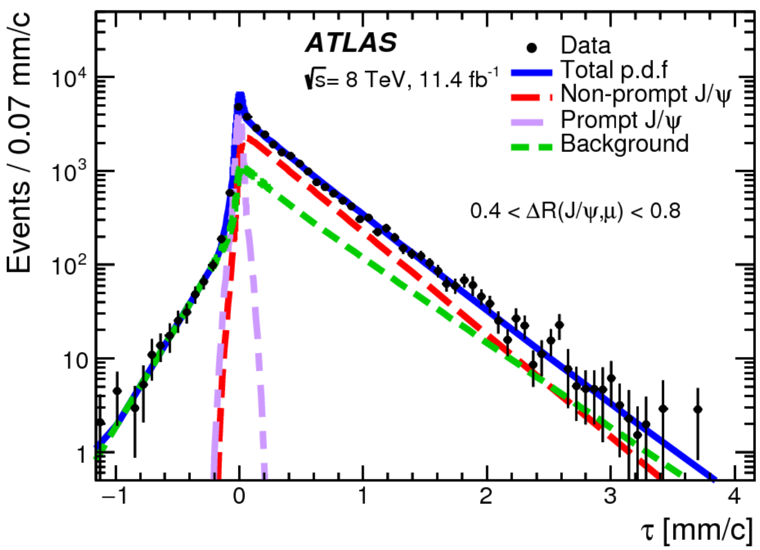
11.4fb^{-1} of 8 TeV ATLAS data

arXiv:1705.03374v1(submitted to JHEP)

Non-prompt J/ψ extraction

- Background: prompt J/ψ, fake J/ψ(J/ψ candidate comes from the dimuon continuum background)
- To increase the signal muon purity and improve the third-muon fit performance, the selected J/ψ in each event is first required to have τ>0.25 mm/c, removing all of the prompt J/ψ candidates.





1mm/c≈3.33564095 × 10^{-12} s

3rd muon extraction

- Third-muon background : prompt muon, fake muon(decay-in-flight muon & hadronic shower leakage muons), fake J/ψ, pile-up

--DIF : Muons are the result of the decay of a charged pion or kaon.

--Hadronic shower leakage muons : Charged hadrons leave tracks in the inner detector and charged particles from the shower in the hadronic calorimeter leave tracks in the muon spectrometer.

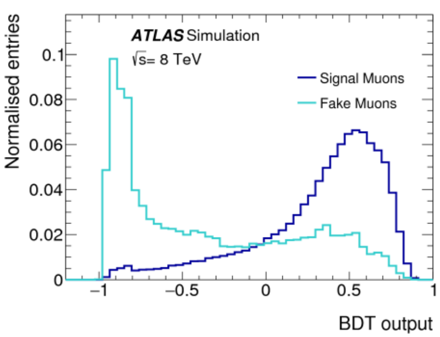
--Fake J/ψ: third muons in events where the J/ψ candidate is not a real J/ψ but from the continuum background.

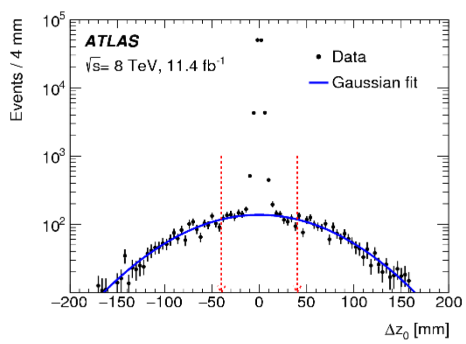
--Pile-up: events where the J/ψ and third muon are produced from different hard scatters in the same bunch crossing

- Simultaneous fit

-- Transverse impact parameter significance $S(d_0) \equiv d_0/\sigma(d_0)$

--BDT output





d_0 is the distance of closest approach of the track to the primary vertex point in the r-ϕ projection.

Δz_0 defined as the difference between the reconstructed z-position (at their respective points of closest approach to the beam axis) of the third-muon track and the J/ψ candidate muon which maximises the value of Δz_0.

Signal extraction

☐ Irreducible backgrounds

- $B_c \rightarrow J/\psi + \mu + X$, semileptonic decays of c-hadrons, sail-through

-- $B_c \rightarrow J/\psi + \mu + X$: Both the J/ψ and third muon originate in the decay of the same hadron(small contribution, taken from simulation).

-- Semileptonic decays of c-hadrons : production modes include separate $g \rightarrow b\bar{b}$ and $g \rightarrow c\bar{c}$ in the same hard scatter, or DPS producing $b\bar{b} + c\bar{c} + X$ in a single pp collision(c-hadrons have shorter lifetimes than b-hadrons, producing a narrower $S(d_0)$ distribution. Small contribution, taken from simulation).

--Sail-through : A charged pion or kaon traverses the detector to MS without interacting with the detector material or decaying(very similar to the signal third muons, taken from simulation).

- Estimate from MC

☐ Extrapolation to the full range of τ and Resolution corrections

- Once the signal yield has been determined, a correction must be applied to extrapolate the results obtained in the third muon fit (for τ >0.25 mm/c) to the full range of J/ψ pseudo-proper decay time.

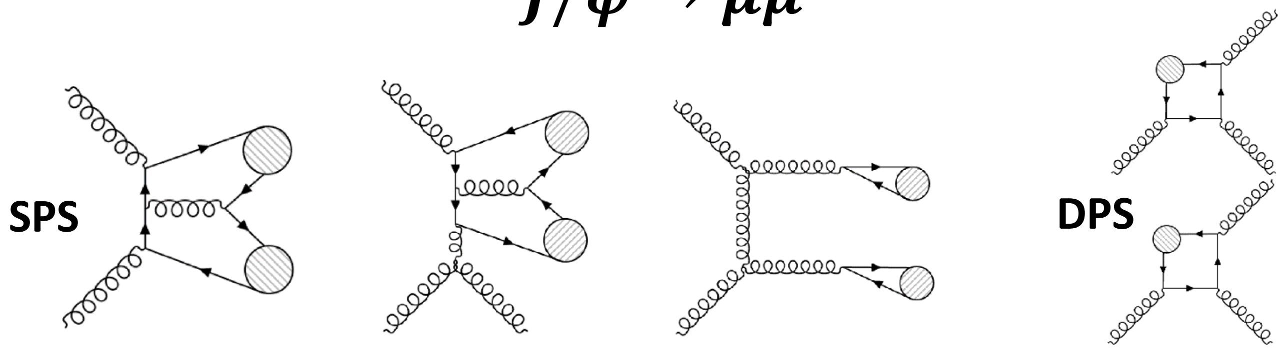
Pythia8 in different settings

Option label	Descriptions
Opt. 1	The same splitting kernel, $(1/2)(z^2+(1-z)^2)$, for massive as massless quarks, only with an extra β phase-space factor. This was the default setting in PYTHIA8.1, and currently must also be used with the MC@NLO [34] method.
Opt. 4	A splitting kernel $z^2+(1-z)^2+8r_q z(1-z)$, normalised so that the z-integrated rate is $(\beta/3)(1+r/2)$, and with an additional suppression factor $(1-m_{qq}{}^2/m^2_{\text{dipole}})^3$, which reduces the rate of high-mass $q\bar{q}$ pairs. This is the default setting in PYTHIA8.2.
Opt. 5	Same as Option 1, but reweighted to an $\alpha_s(km^2_{qq})$ rather than the normal $\alpha_s(p^2_T)$, with $k=1$.
Opt. 5b	Same as Option 5, but setting $k=0.25$.
Opt. 8	Same as Option 4, but reweighted to an $\alpha_s(km^2_{qq})$ rather than the normal $\alpha_s(p^2_T)$, with $k=1$.
Opt. 8b	Same as Option 8, but setting $k=0.25$.

Description of Pythia8 options. Options 2, 3, 6 and 7 are less well physically motivated and not considered here.

Prompt J/ψ pair production

$$J/\psi \rightarrow \mu\mu$$



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Main backgrounds

--Non- J/ψ events(semileptonic decays of b-hadrons, dimuon continuum events from Drell–Yan processes)
⇒ 2D $m(J/\psi_1)$ and $m(J/\psi_2)$ fit
To parameterise the mass distribution of J/ψ signal events, a large inclusive J/ψ sample selected from 8 TeV ATLAS data is used. It has the same selections with the di-J/ψ sample.

--Non-prompt J/ψ
⇒ 2D $L_{xy}(J/\psi_1)$ and $L_{xy}(J/\psi_2)$ fit

--Pile-up(the two J/ψ mesons originate from two independent pp collisions, have distributions similar to those from DPS)
⇒ subtracted using d_z distribution

J/ψ_1: leading J/ψ J/ψ_2: sub-leading J/ψ

Definition

NLO*: Leading-order DPS plus next-to-leading-order-colour singlet model SPS predictions without loops