Measurements of heavy flavour production in *pp* collisions at ATLAS

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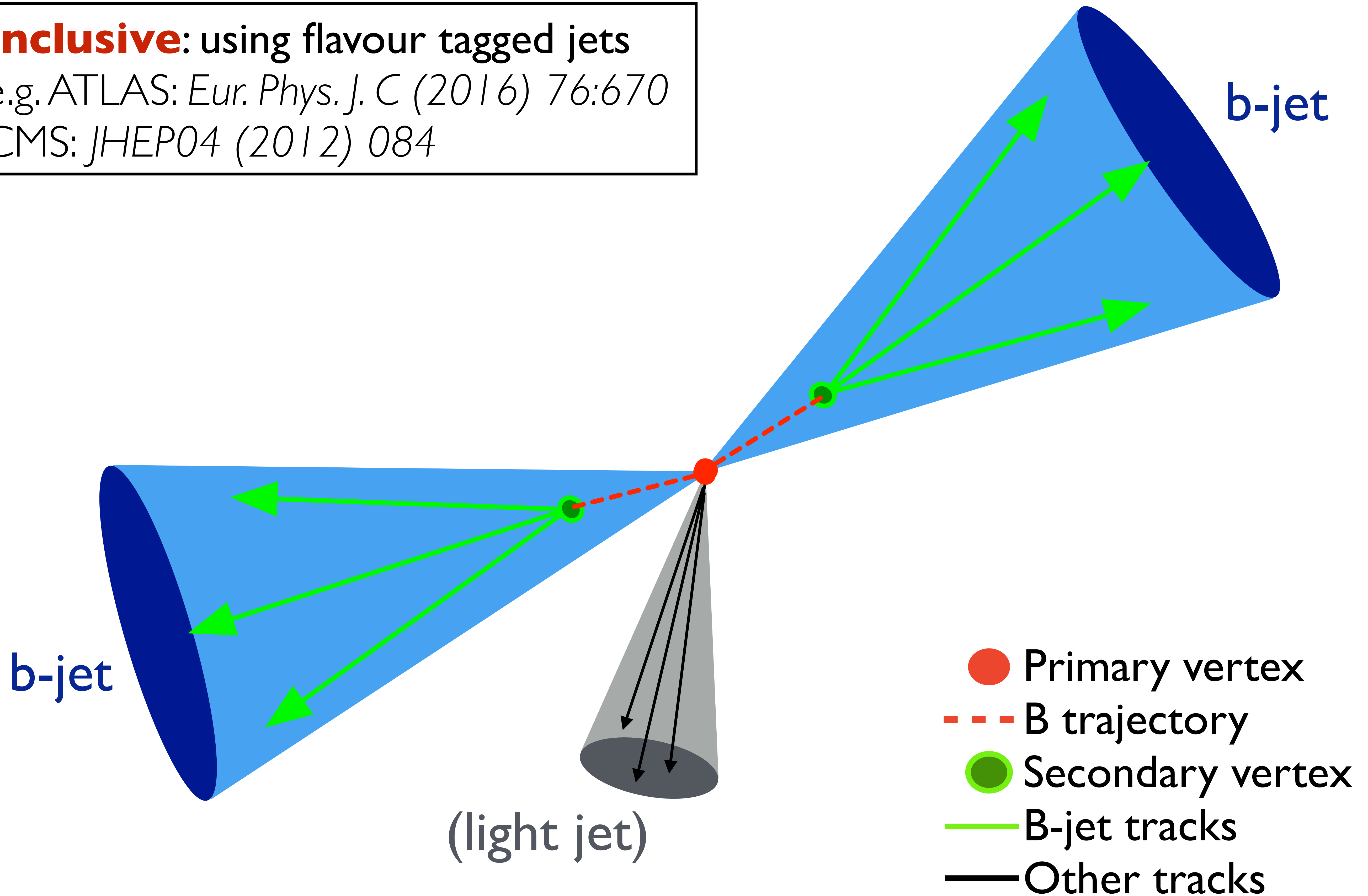
Why is heavy flavour production interesting?

- Production of c- and b-quarks is an excellent test of our understanding of QCD
  - NLO pQCD describes b-quark pair production fairly well, if the opening angle between the quarks is large…
  - … but if the opening angle is small, substantial differences between data and predictions are seen → not understood
- Heavy flavour production has an important role in the determination of PDFs
- Heavy flavour forms an important background for many searches
  - e.g. $b\bar{b}$+V is one of the main backgrounds in searches for Higgs decays to b-quark pairs in the VH production channel
    - Searches are most sensitive when the Higgs has high momentum, e.g. where b-quark pair opening angle is small → *just where the heavy flavour modelling is poorest*
- The importance of measuring heavy flavour production extends well beyond "pure QCD" studies

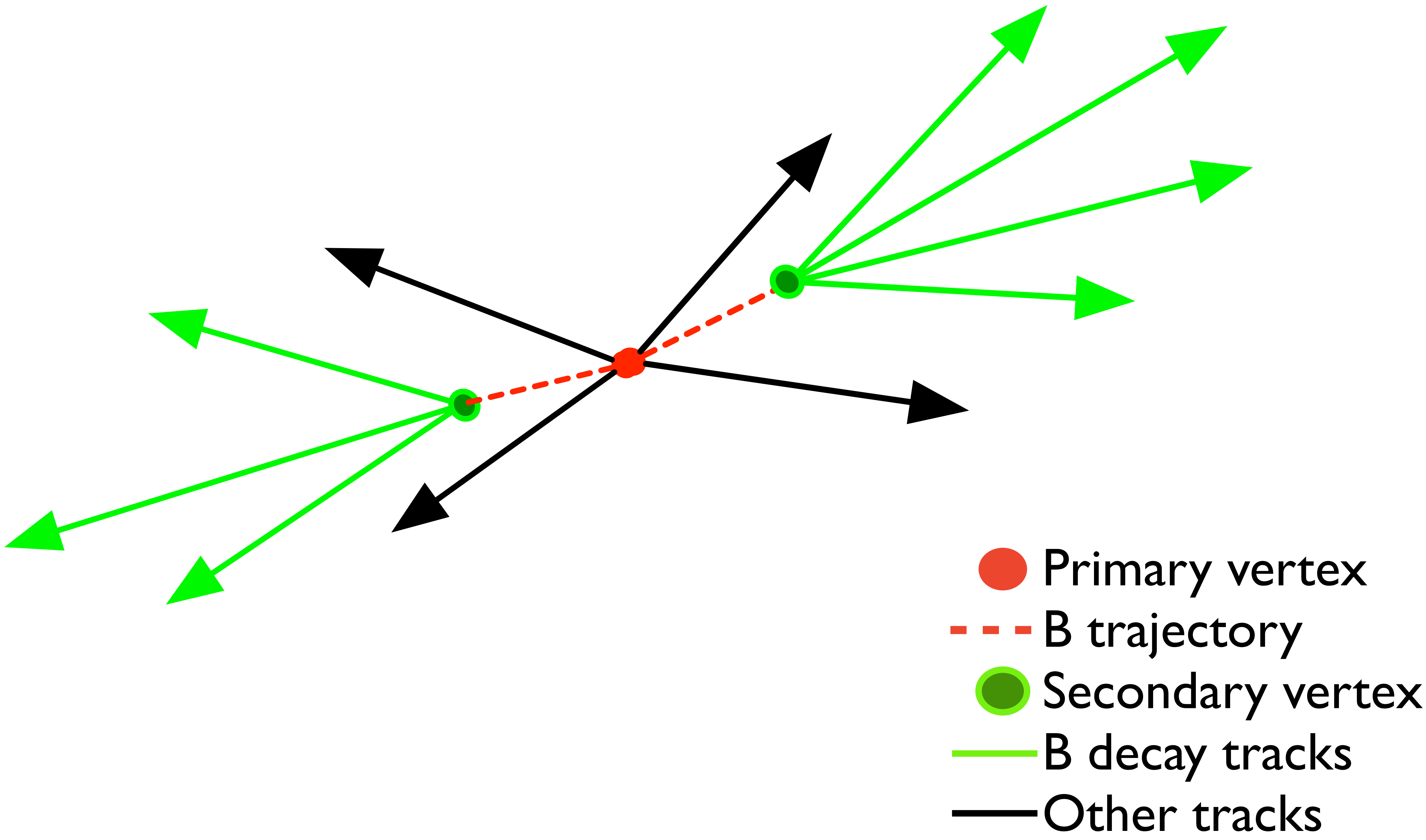
How to identify heavy flavour production

Inclusive: using flavour tagged jets
e.g. ATLAS: *Eur. Phys. J. C (2016) 76:670*
CMS: *JHEP04 (2012) 084*



How to identify heavy flavour production

Inclusive: using displaced vertices without jets
e.g. CMS: *JHEP03 (2011) 136*

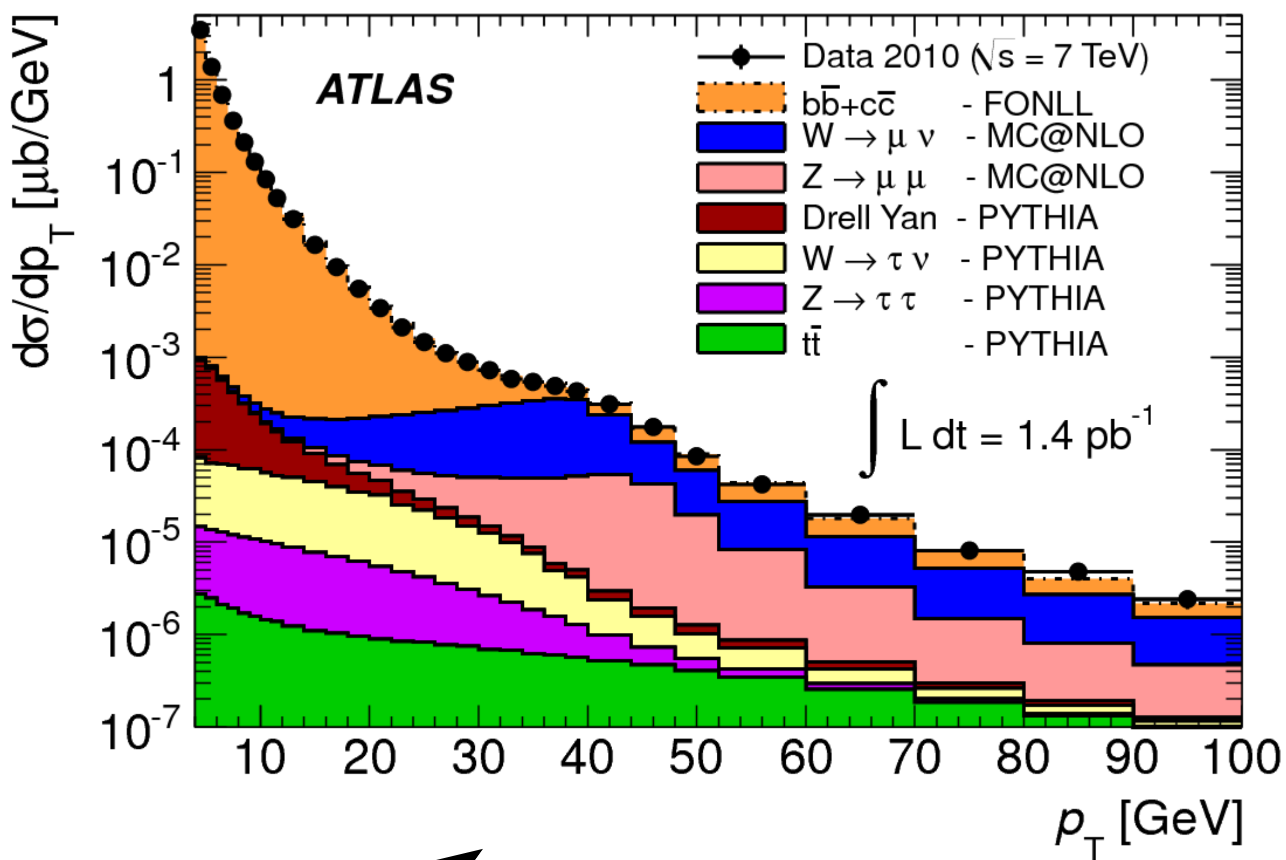


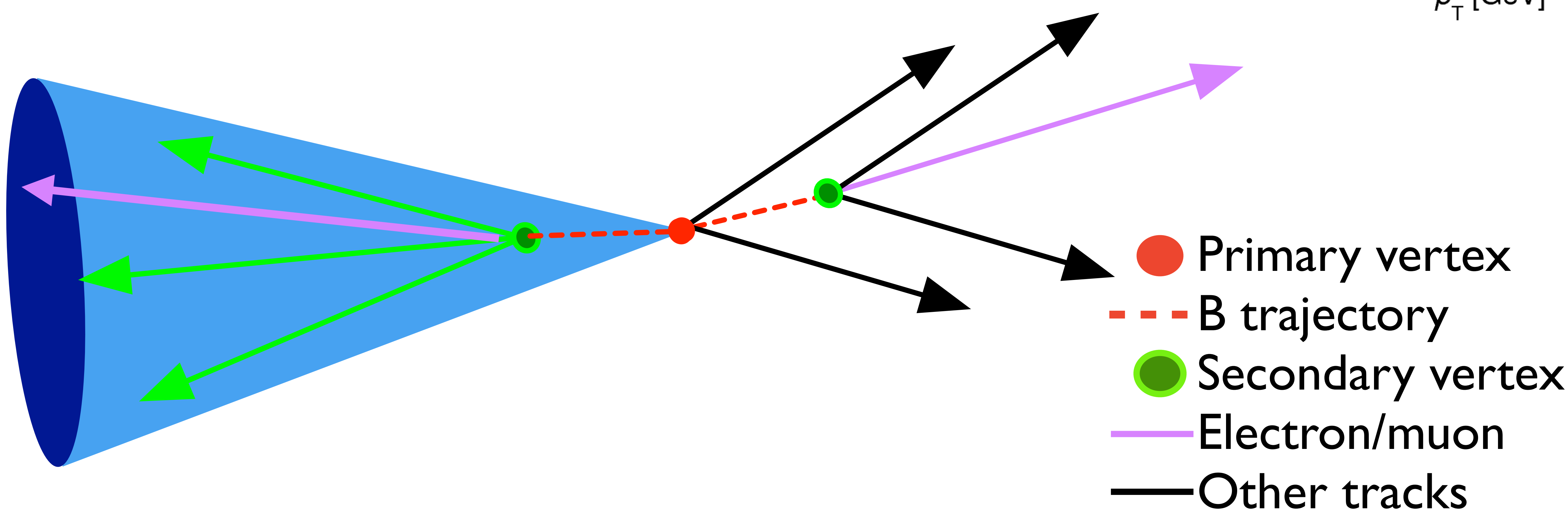
How to identify heavy flavour production

Semi-inclusive: using leptons from semi-leptonic B-decays either with or without B-jets

e.g. ATLAS: *Phys. Lett. B707 (2012) 438, Nucl. Phys. B864 (2012) 341*

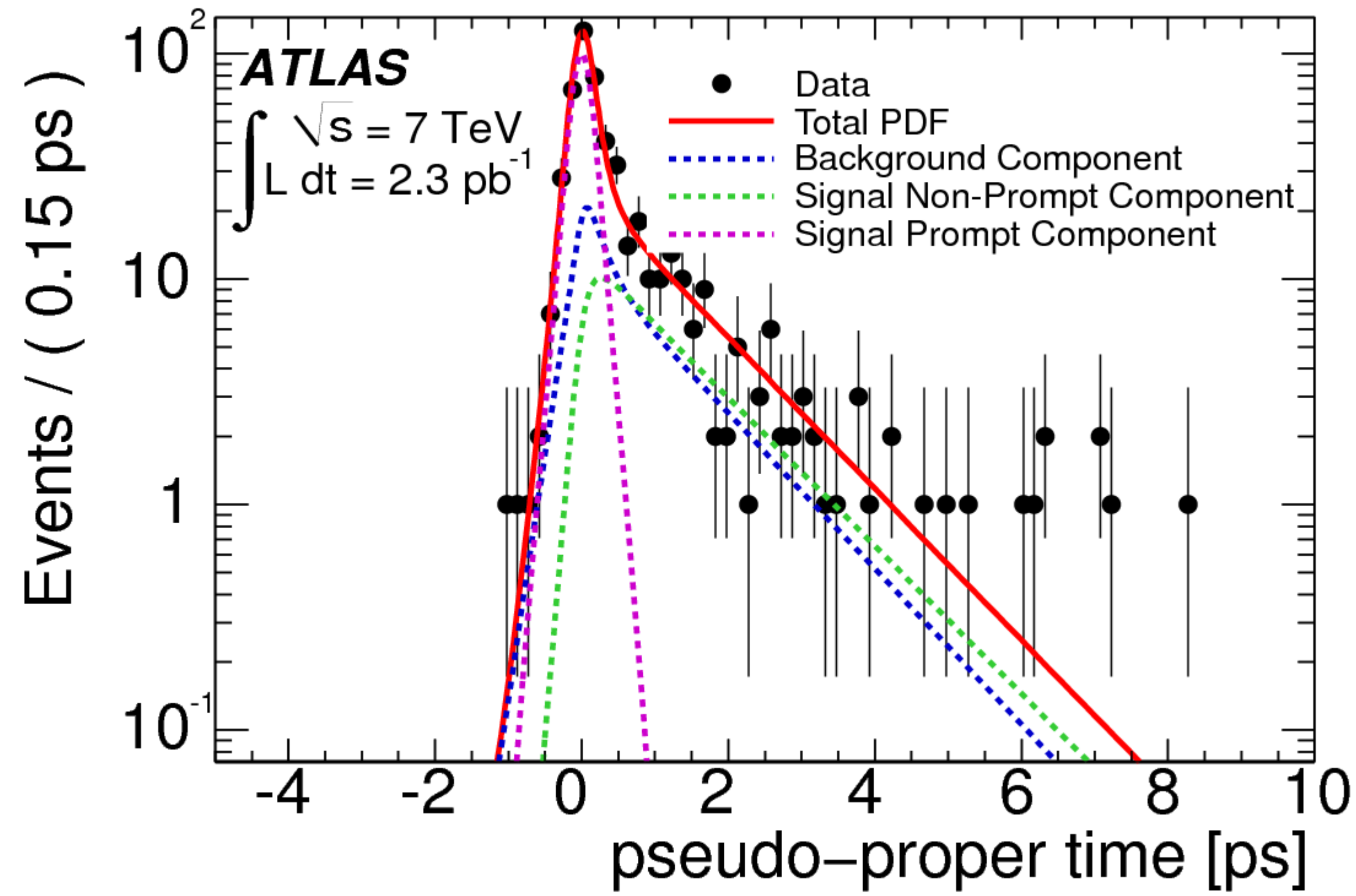
CMS: *JHEP06 (2012) 110*

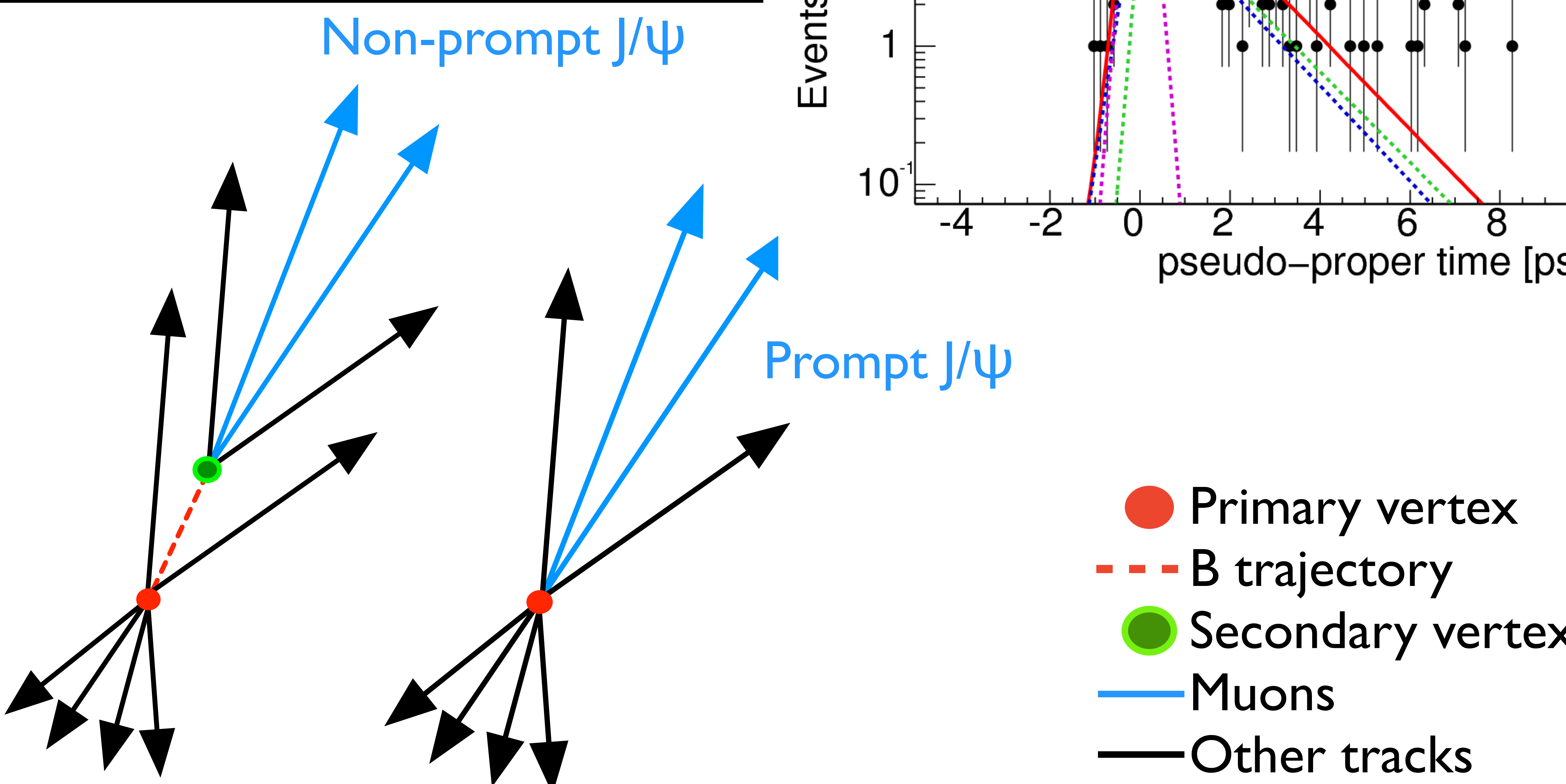




How to identify heavy flavour production

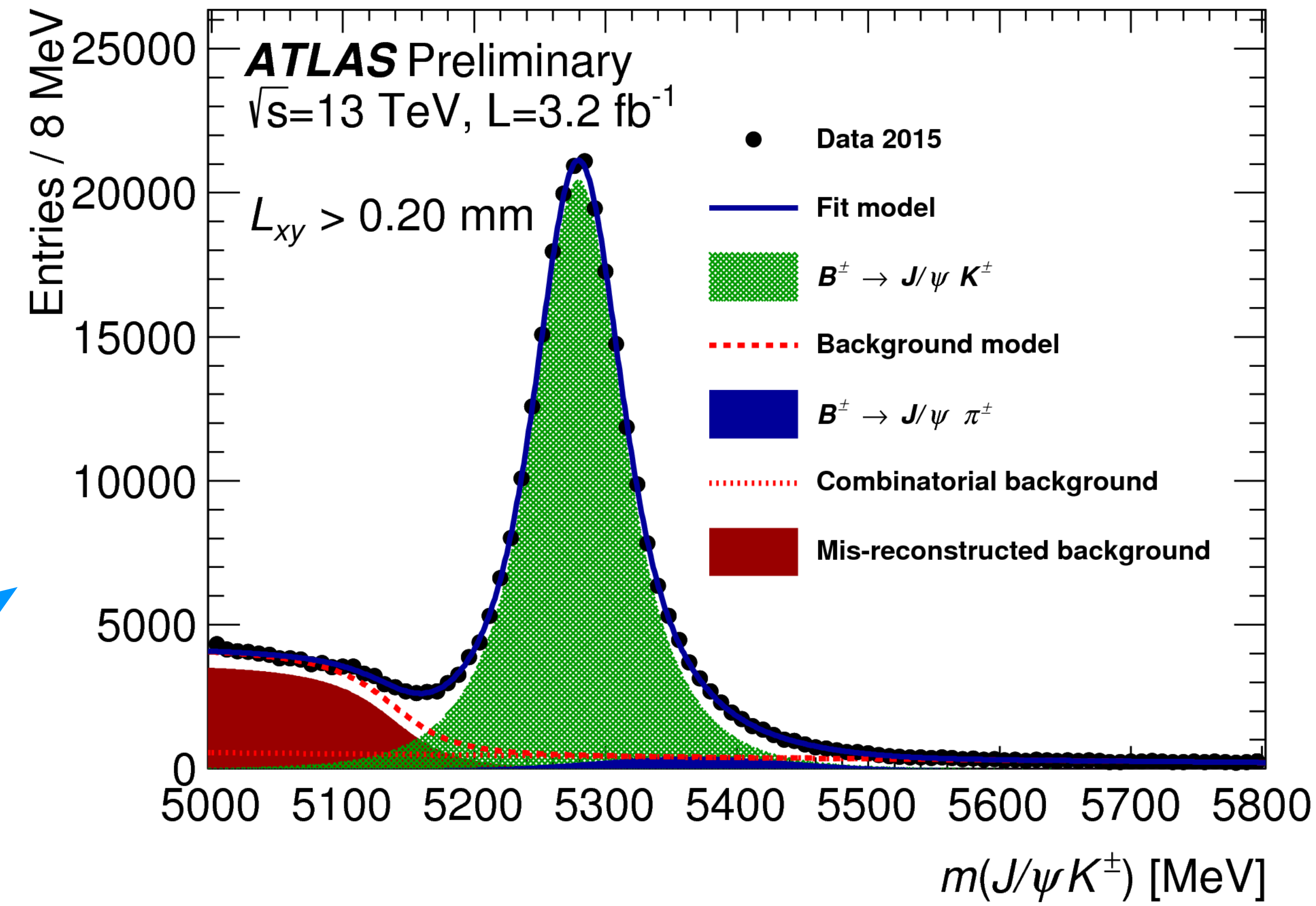
Semi-exclusive: using fraction of non-prompt J/ψ→μμ
e.g. ATLAS: *Eur. Phys. J. C 76(5), 1-47, (2016)*

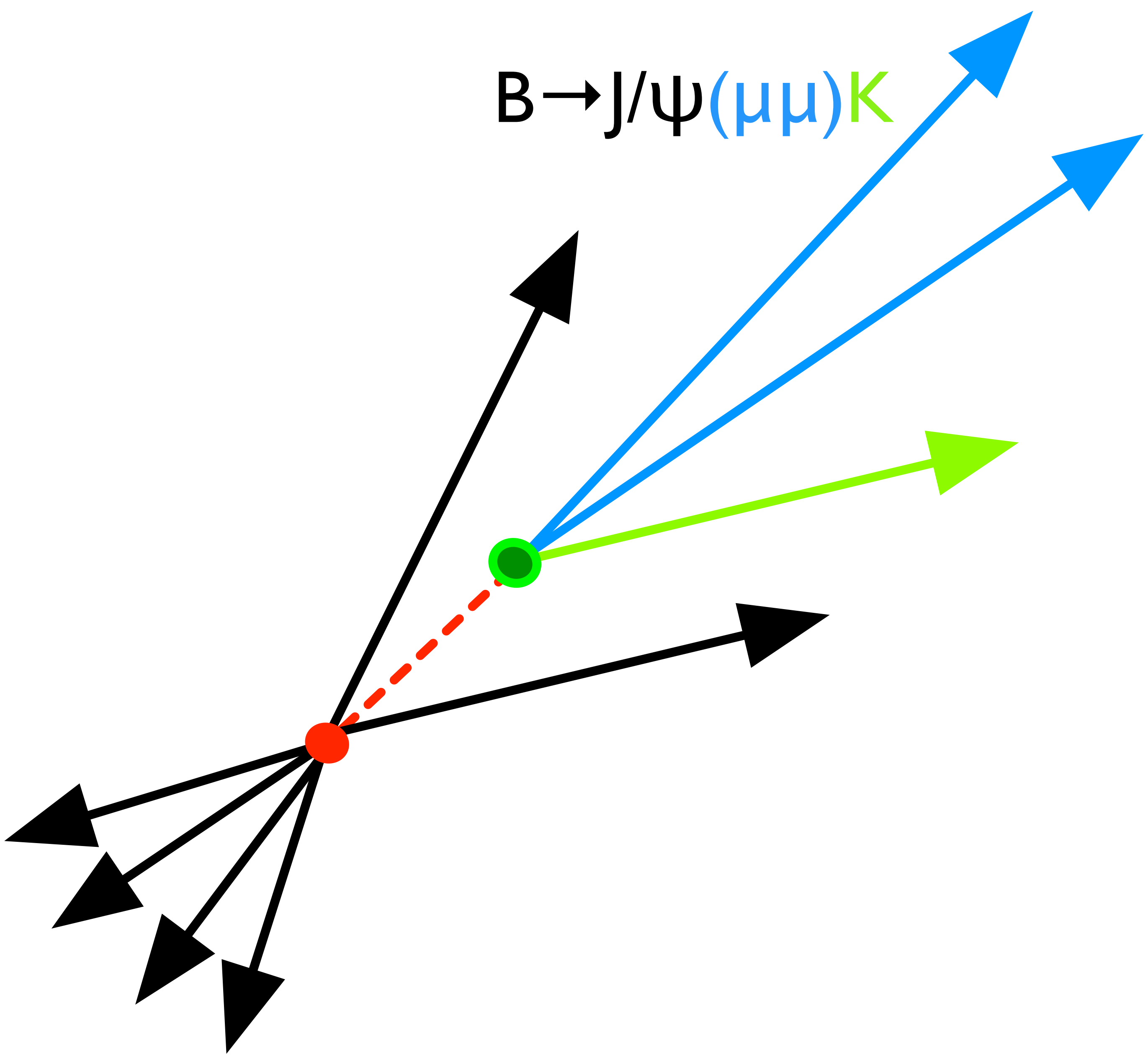




How to identify heavy flavour production

Exclusive: using fully reconstructed B-decays decaying to J/ψ(μμ)X
e.g. ATLAS: JHEP10 (2013) 042

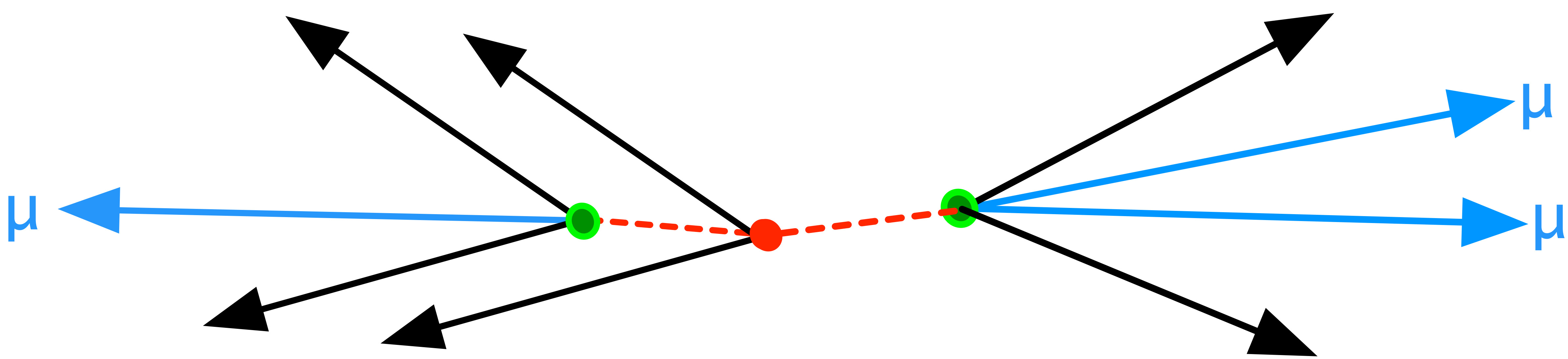




Primary vertex
b-quark trajectory
Secondary vertex
Muons
B-decay tracks
Other tracks

Heavy flavour pair production with J/ψ+μ

- Newly released measurement - submitted to JHEP (arXiv:1705.03374)
  - 8 TeV, 11.4fb^{-1}
  - Hybrid of semi-inclusive and semi-exclusive method: look for events with non-prompt $J/\psi \rightarrow \mu\mu$ on one side and a semi-muonic B-decay on the other
  - Exploits the huge J/ψ data sample collected by the 2012 ATLAS trigger menu
  - Total cross section measured in a fiducial volume defined by muon kinematics
  - Differential cross sections measured w.r.t. several variables and the shapes compared with relevant generator predictions



Event selection and fiducial volume definition

		μ1	μ2	μ3
Trigger	**p_T**	> 4 GeV	> 4 GeV	N/A
	$|\eta|$	< 2.4	< 2.4	N/A
	Charge	Oppositely charged		N/A
	Invariant mass	$2.5 < M_{\mu\mu} < 4.3$ GeV		N/A
Offline	**Trigger match?**	Yes	Yes	No
	p_T	> 6 GeV	> 6 GeV	> 6 GeV
	$|\eta|$	< 2.5	< 2.5	< 2.5
	Charge	Oppositely charged		N/A
	Invariant mass	$2.6 < M_{\mu\mu} < 3.5$ GeV		N/A
	μ pair $|\eta|$	< 2.3		N/A

For events with more than 1 J/ψ candidate, the pair with $M_{\mu\mu}$ closest to the table mass (3096.916 MeV) is designated as μ1 and μ2

For events with 4 or more muons, the non-J/ψ muon with the highest pT is taken as μ3

Differential cross section variables

$\Delta\phi(J/\psi,\mu)$	Azimuthal separation between the J/ψ and the third muon
$\Delta R(J/\psi,\mu)$	Separation between the J/ψ and the third muon in the azimuthal-rapidity plane*
$\Delta y(J/\psi,\mu)$	Rapidity difference between the J/ψ and the third muon
$p_T(J/\psi,\mu)$	Transverse momentum of the three muon system
$m(J/\psi,\mu)$	Mass of the three muon system
p_T/m, m/p_T	Ratio and inverse ratio of the three-body transverse momentum and mass
y_{boost}	Average rapidity of the J/ψ and the third muon

* split into low and high pT slices [low: $pT(J/\psi,\mu) < 20$ GeV]

Analysis procedure

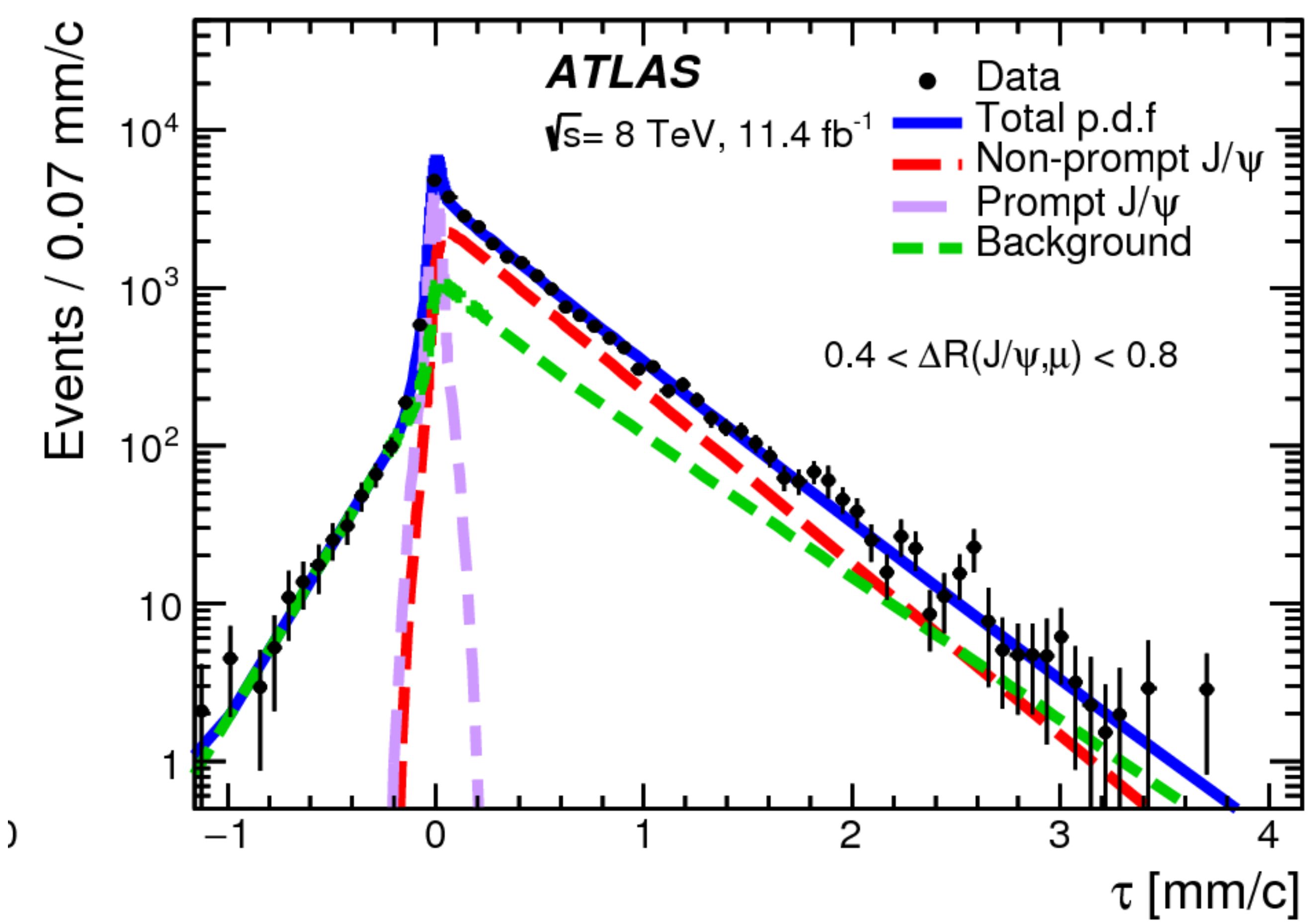
1. Select events: $J/\psi+\mu$
2. Bin the events according to the kinematic variable of interest
3. Correct for trigger and reconstruction efficiency (data driven)
4. Extract yield of non-prompt J/ψ
5. Extract yield of events also containing a μ from a B-decay*
6. Estimate contamination from irreducible backgrounds
7. Repeat for each bin in the range to get the differential cross section w.r.t. the variable of interest

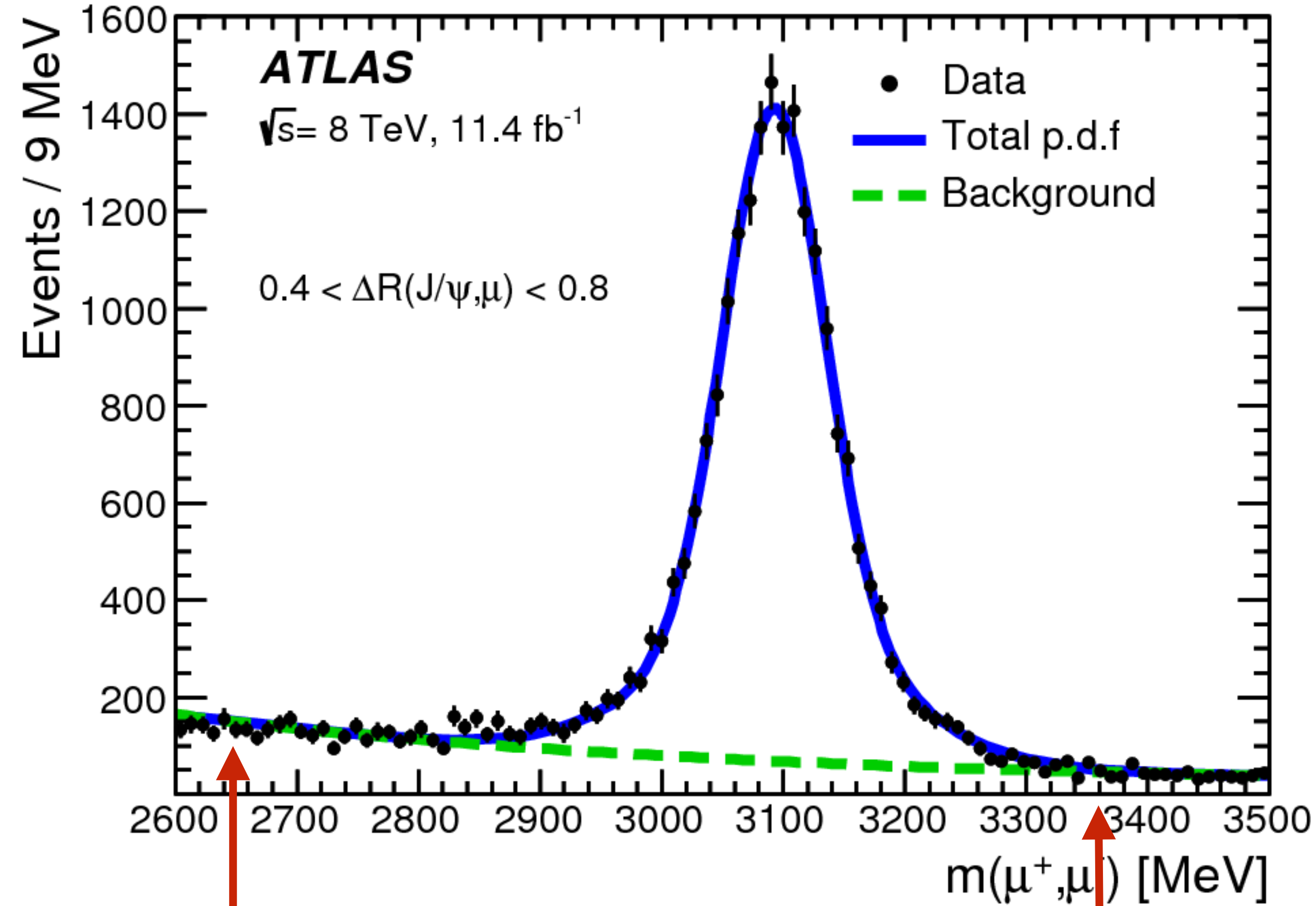
* prompt J/ψ are removed at this point by applying a lifetime cut $\tau > 0.25$ps. This must be corrected for later

Non-prompt J/ψ yield extraction

J/ψ lifetime distribution contains four components:
prompt and non-prompt real J/ψ, prompt and non-prompt continuum background

$$\tau = L_{xy} \times m(J/\psi_{\mathrm{PDG}})/p_{\mathrm{T}}(\mu^{+}\mu^{-})$$



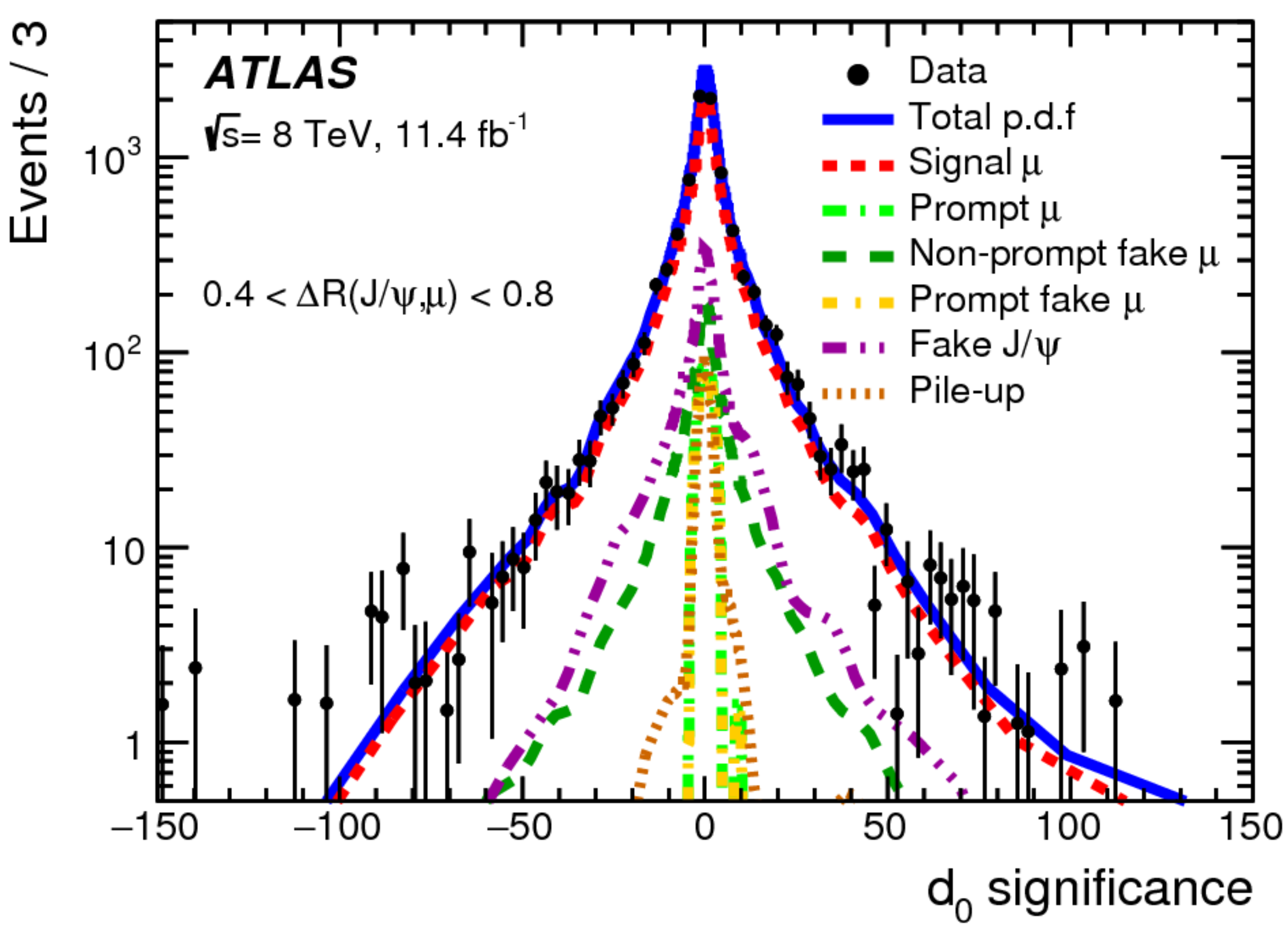


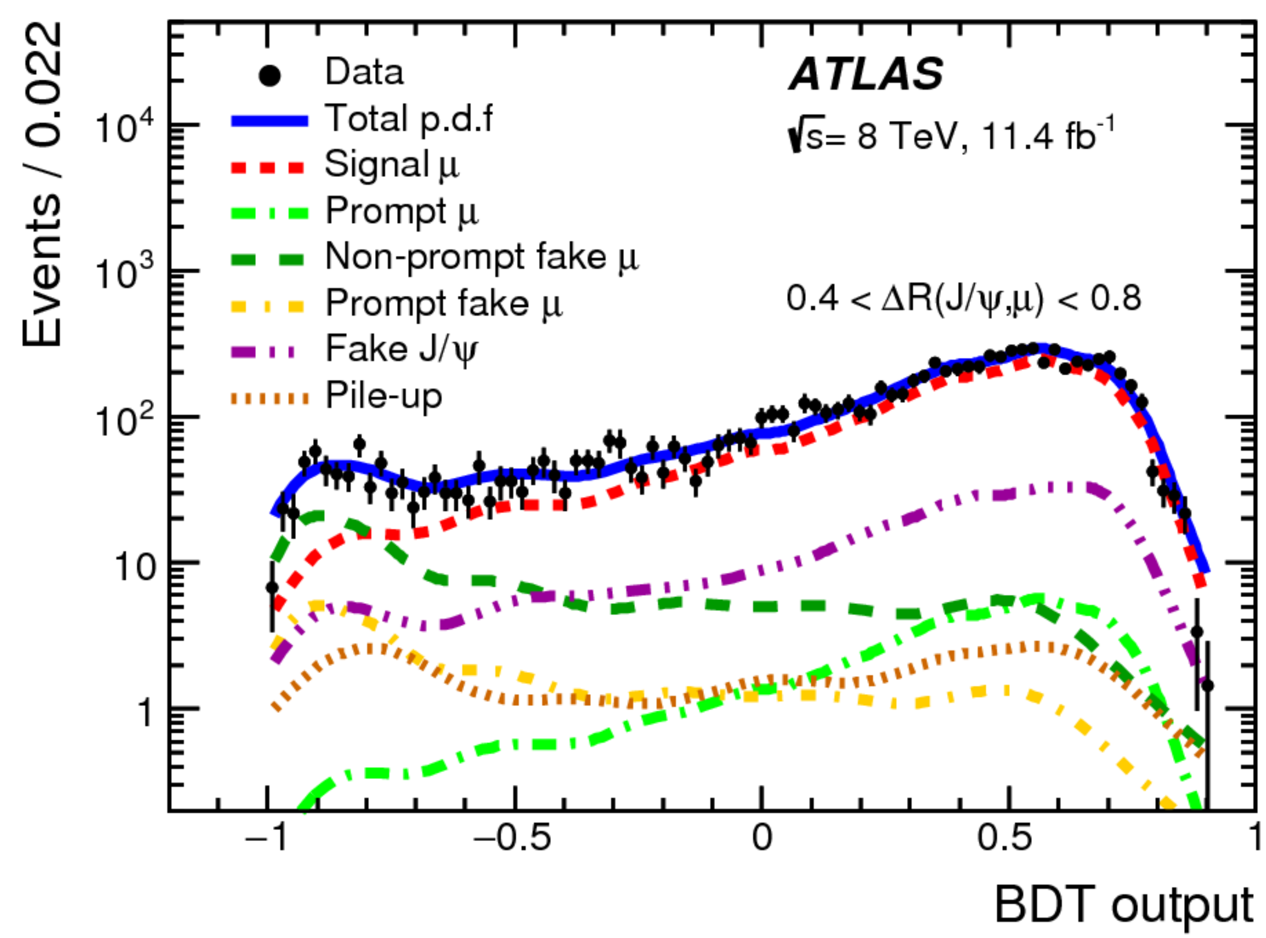
Pure background

Components are not separable in the lifetime distribution alone, but by *simultaneously fitting* with the mass distribution, the background components can be constrained by the mass sidebands

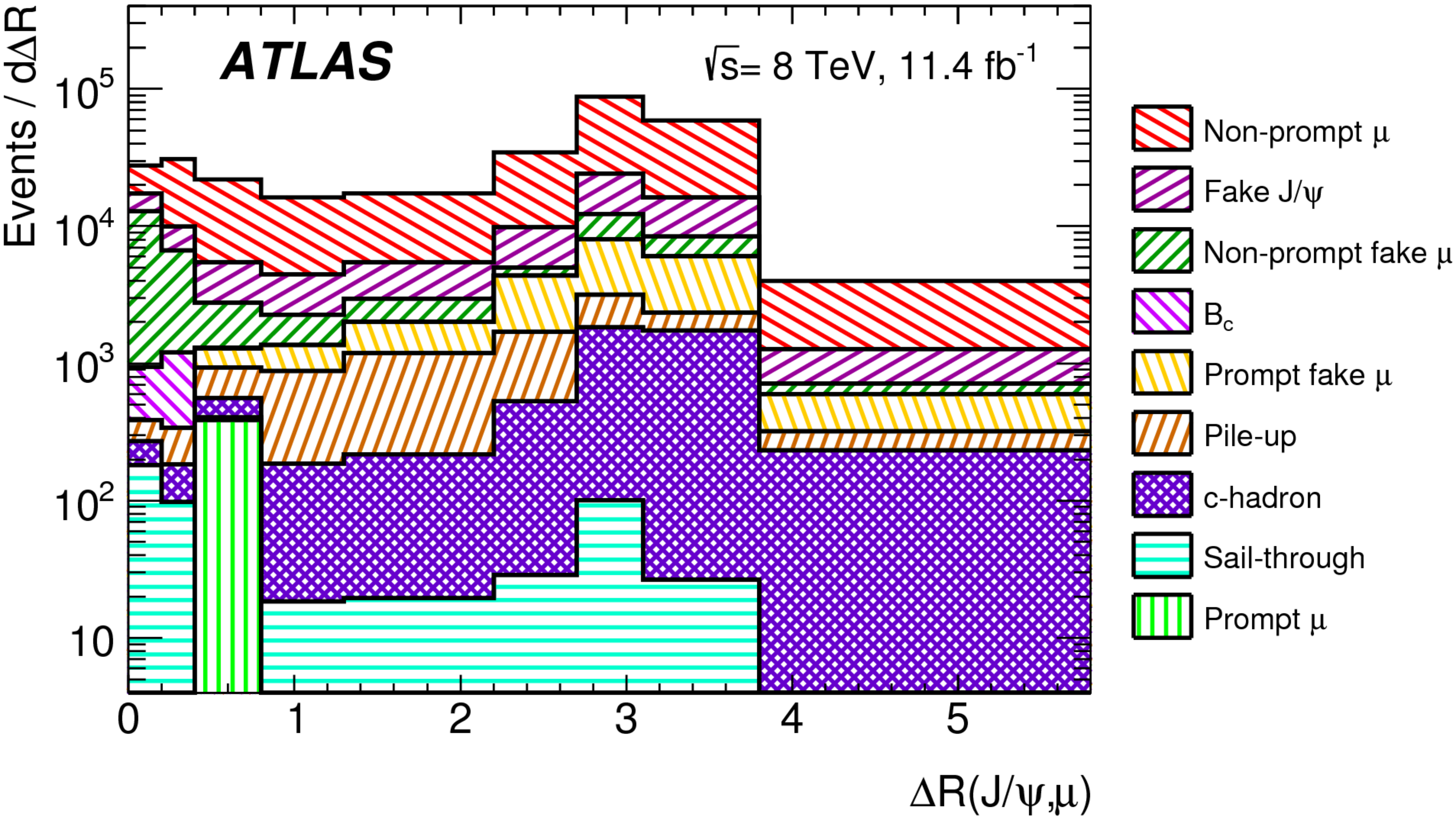
Yield of third muons from semi-leptonic B-decays

- Simultaneous fit of templates of two observables:
  - Transverse impact parameter significance of the 3rd muon ($S_{d0} = d_0/\sigma_{d0}$)
  - Output of a multivariate classifier trained to separate signal muons from instrumental backgrounds
- Fit components: signal μ, prompt μ, prompt and non-prompt fake μ (decays in flight and hadronic shower leakage), fake J/ψ, pile-up

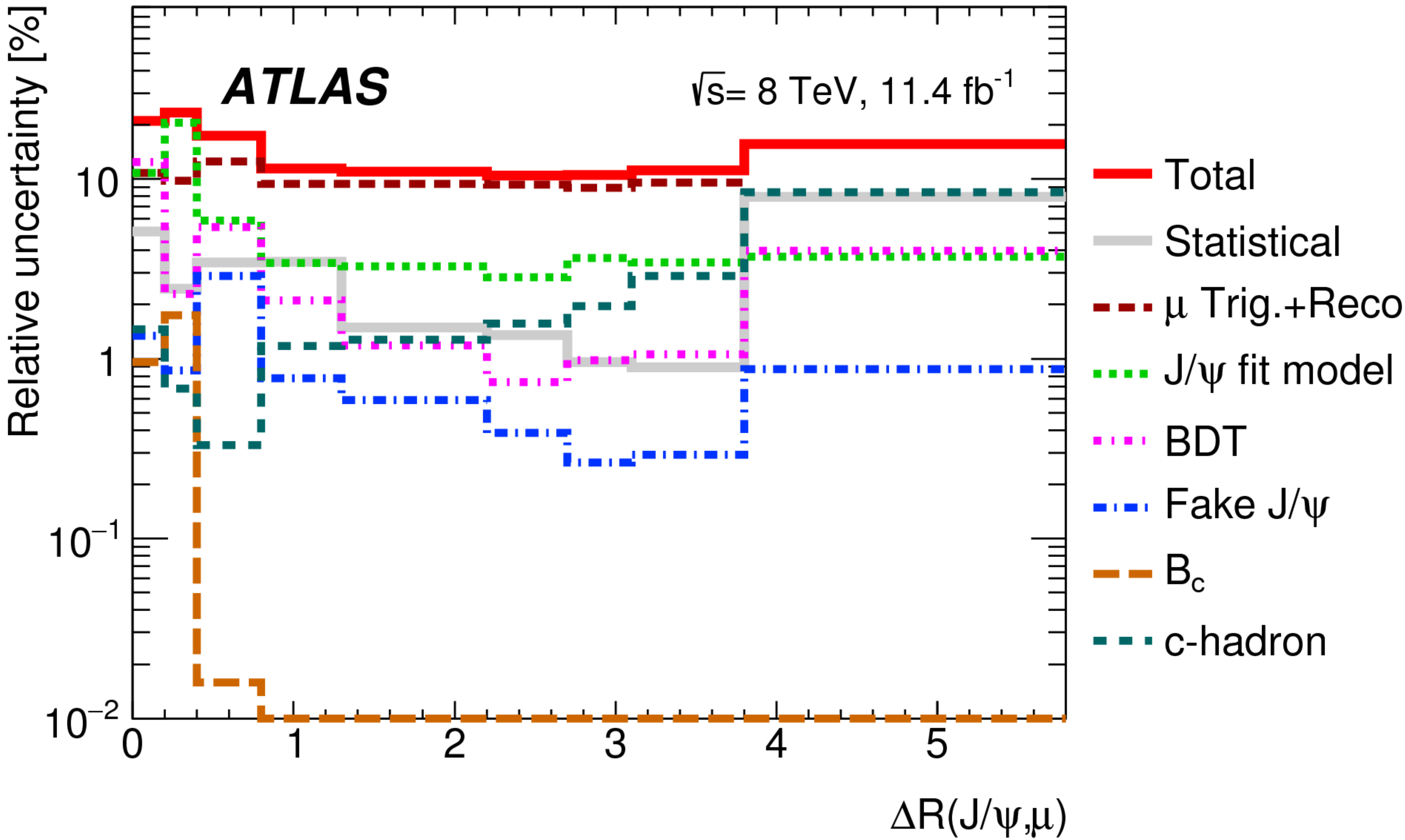




Background contributions



Systematics

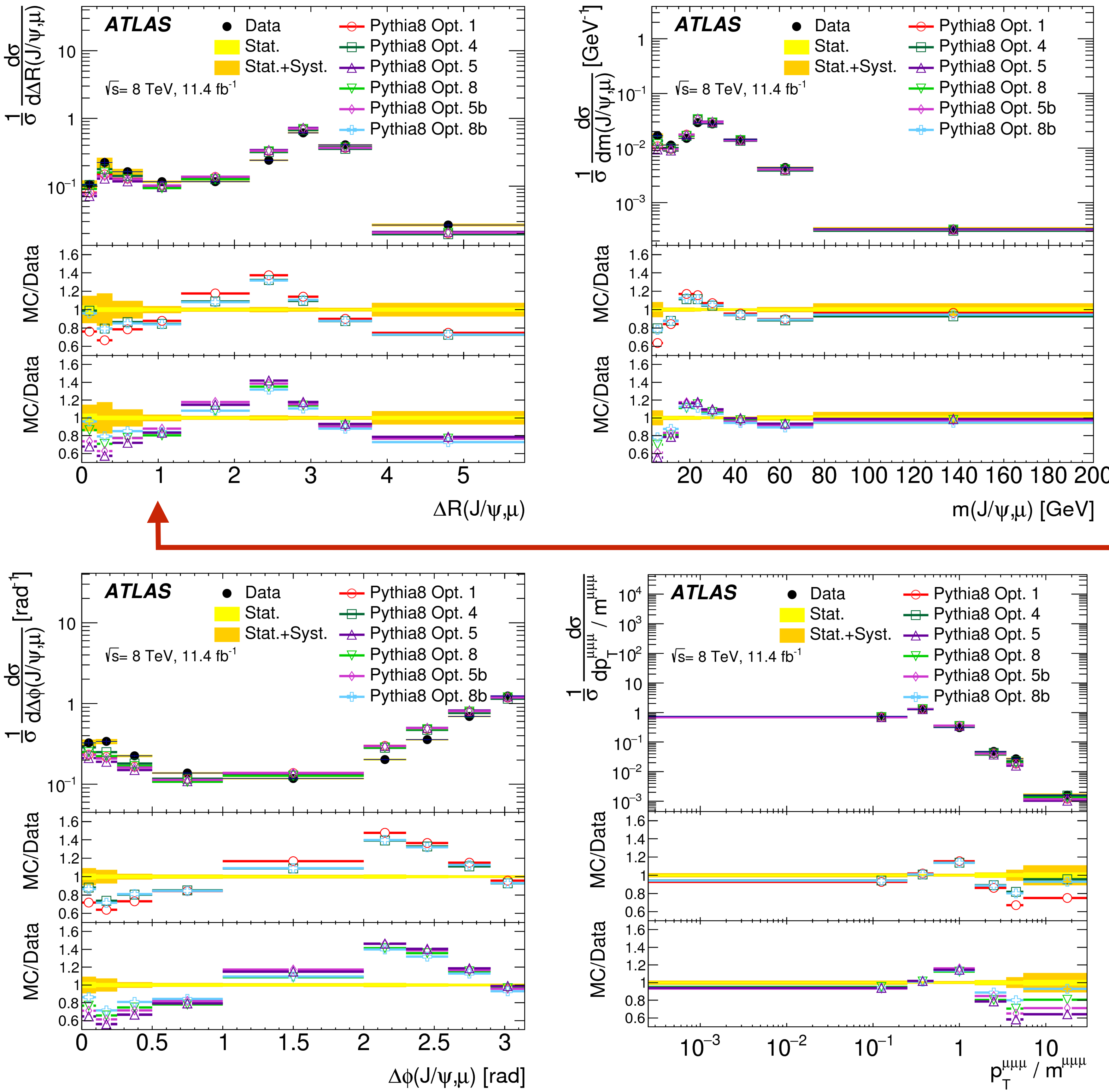


Additionally: luminosity (flat 1.9%), bin migration (~0.2%), pile-up double counting (~1%)

Results and interpretation

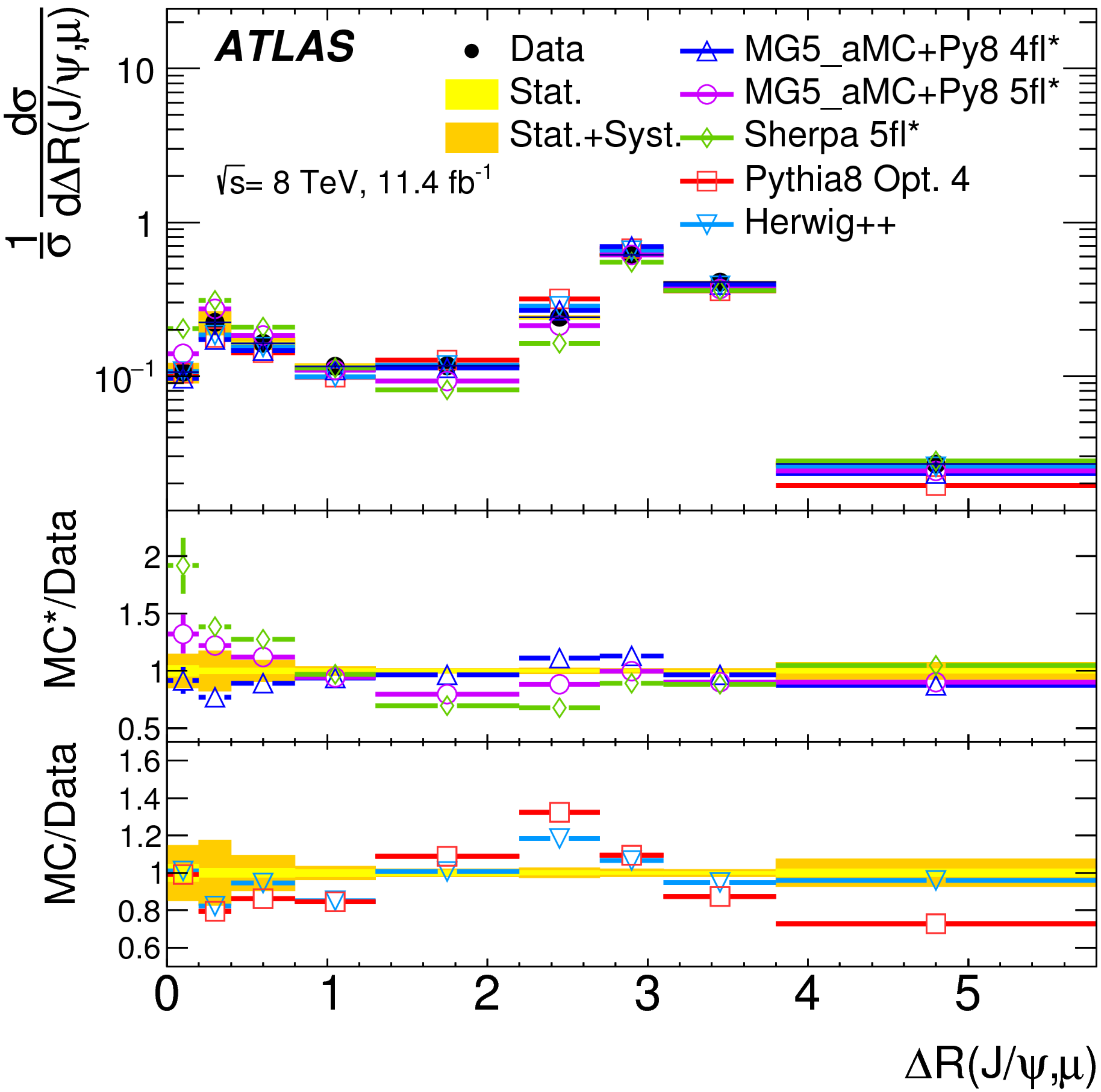
- Total fiducial cross section: σ [(B→J/ψ(μμ)X) · (B→μX)] = 17.7 ± 0.1 (stat.) ± 2.0 (syst) nb
- Comparisons of the differential cross sections with the following predictions are reported
    - Pythia8 with a variety of $g \rightarrow b\bar{b}$ splitting kernel settings → dominates the small angle B-hadron production
    - MadGraph5_aMC@NLOv2.2.2 at leading order in QCD, interfaced to Pythia8 parton shower model
        - Two samples - "4 flavour" and "5 flavour"
        - 4 flavour: b-quarks not included in the definition of a parton in the matrix element calculation, b-quark set to be massive
        - 5 flavour: b-quarks included in the definition of a parton in the matrix element calculation, b-quark set to be massless
        - To limit the computational load, samples were only produced up to the B-hadron pair - transfer functions used to correct to three-muon predictions
    - Sherpa2.1.1
    - EvtGen used for all B- and C- decays

Results: Pythia8



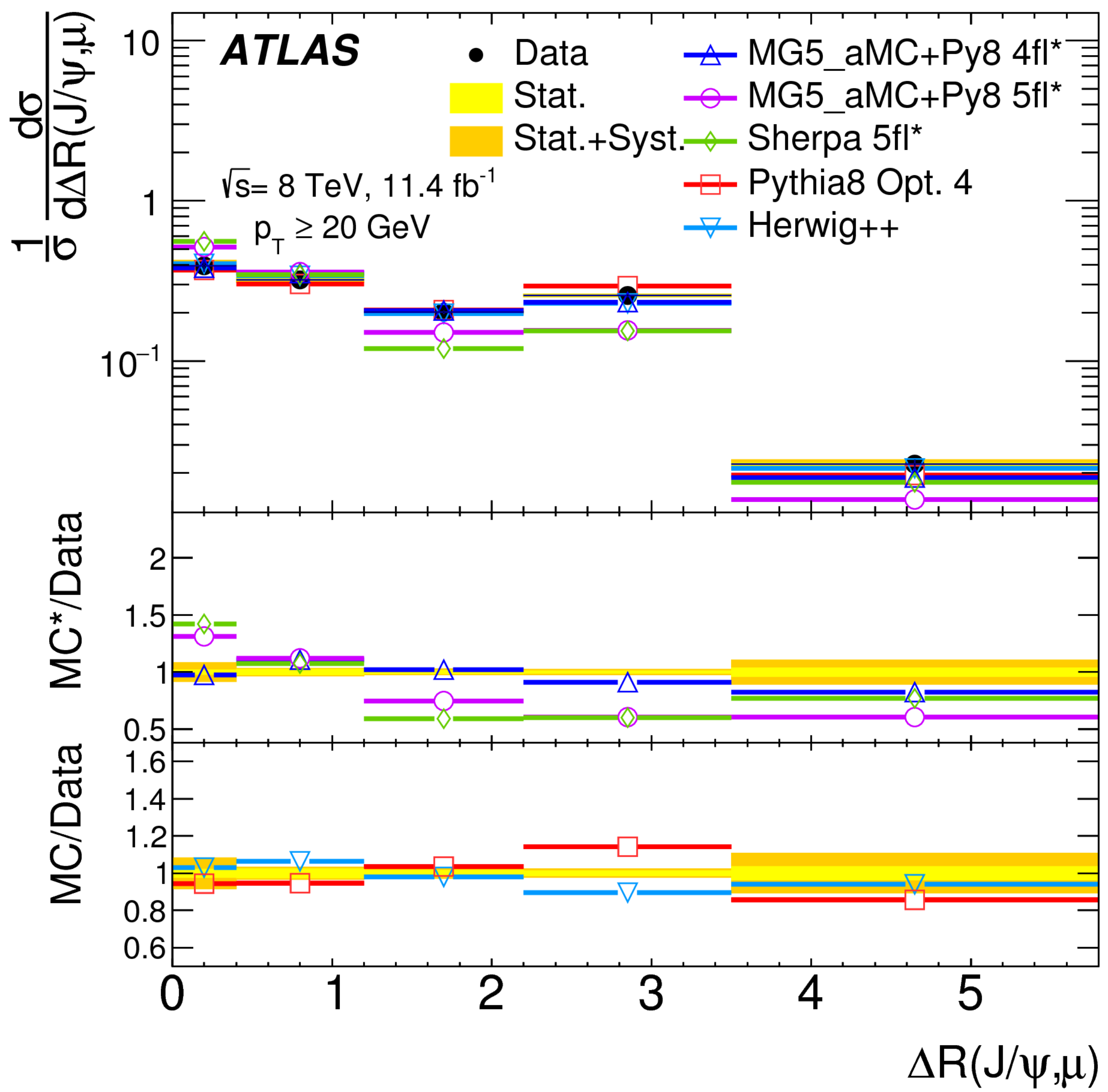
- Pythia8 doesn't reproduce the shapes of the angular distributions very well
  - pT-based splitting kernels give a better description at low ΔR (options 1,4)

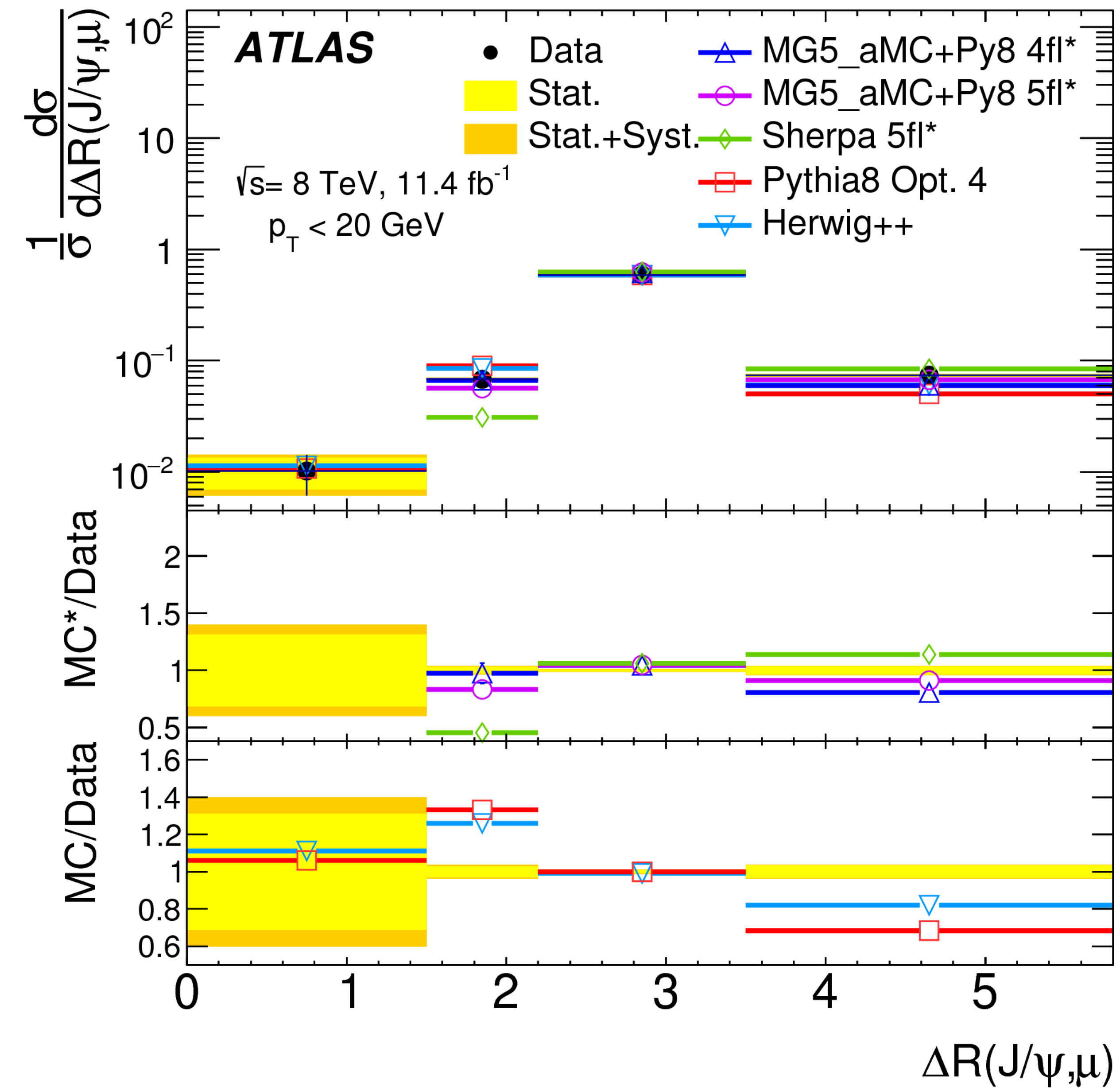
Results: Herwig, MadGraph, Sherpa - ΔR



- Herwig++ generally better than Pythia8
- MG5_aMC 4 flavour and 5 flavour sit on either side of the data, 4 flavour closer in shape to the data

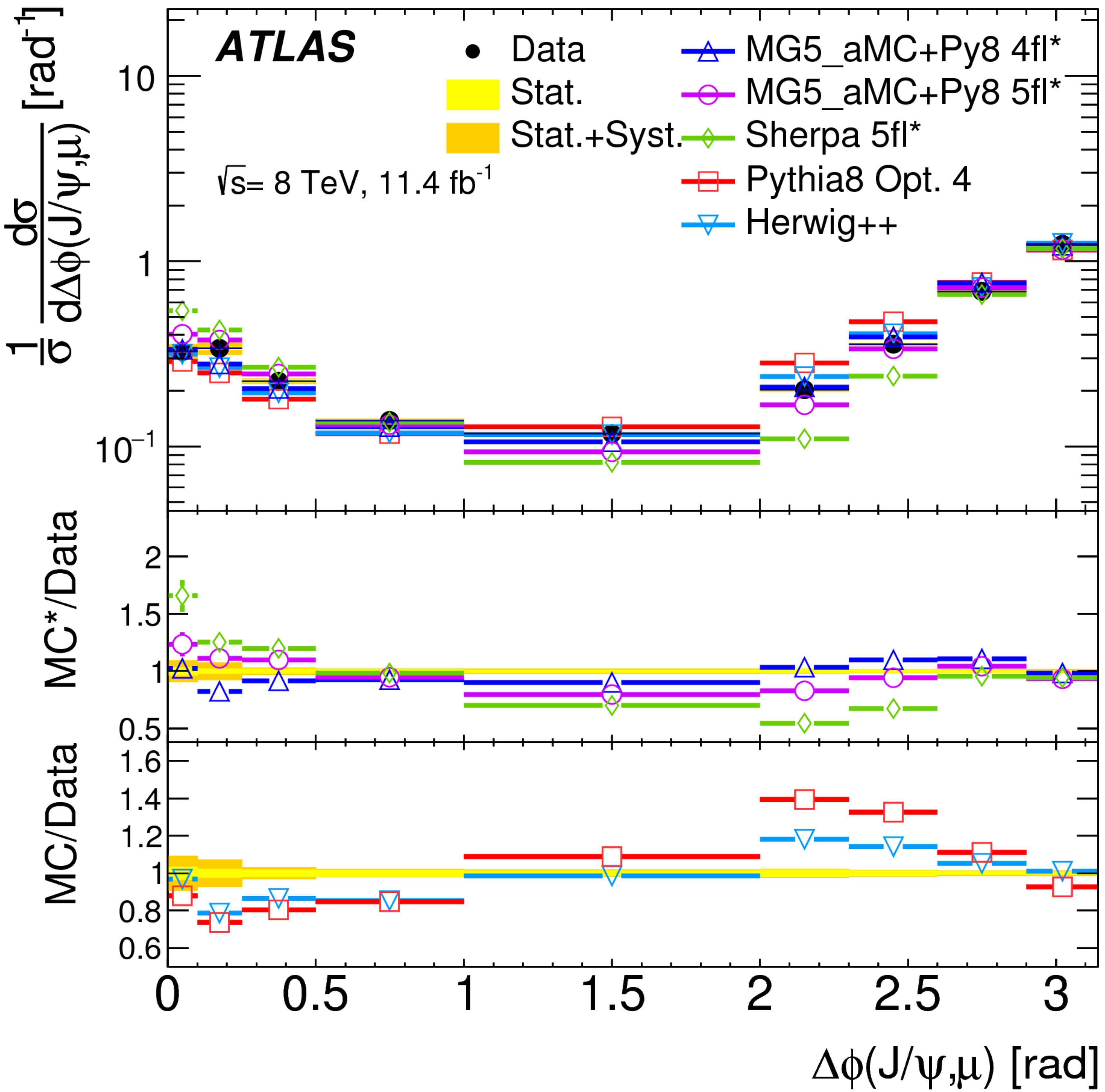
Results: Herwig, MadGraph, Sherpa - ΔR





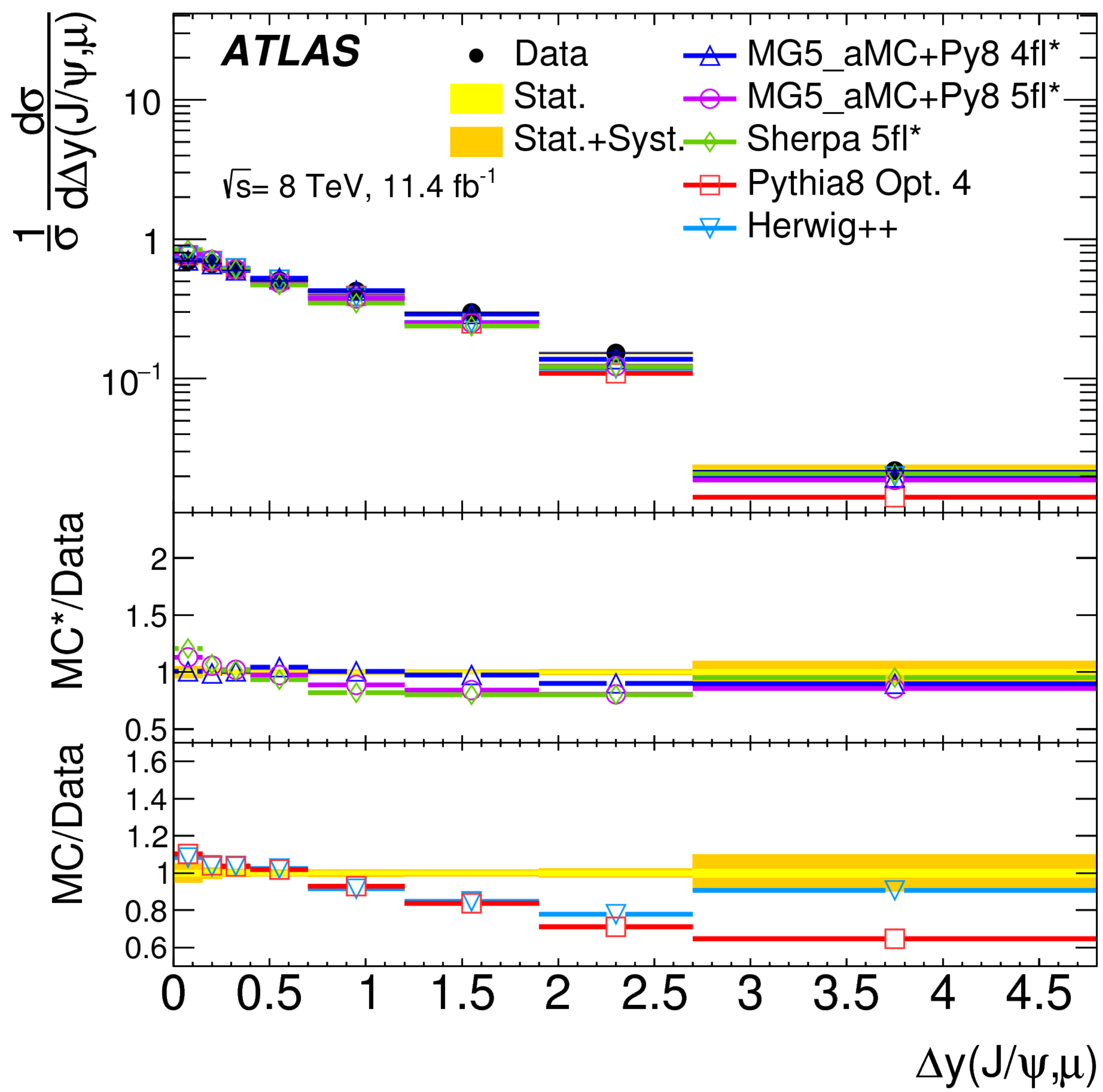
- Differences between 4 and 5 flavour emphasised at high p_T with 5-flavour moving further away from the data
- 5 flavour Sherpa similar in shape to 5 flavour MG5, but worse agreement

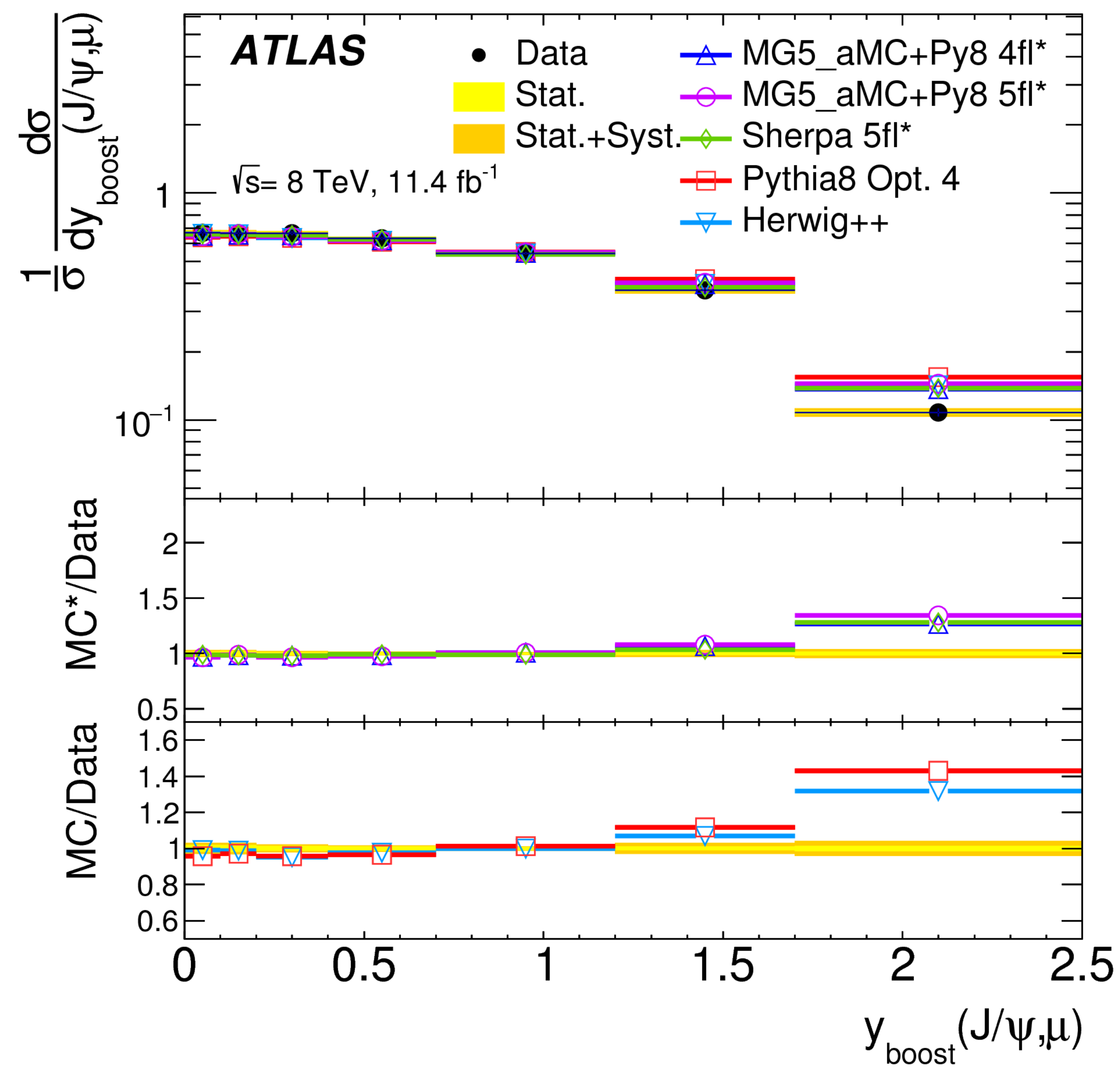
Results: Herwig, MadGraph, Sherpa - Δϕ



- Similar patterns seen in ΔR and $\Delta\phi$

Results: Herwig, MadGraph, Sherpa - Δy and y_{boost}

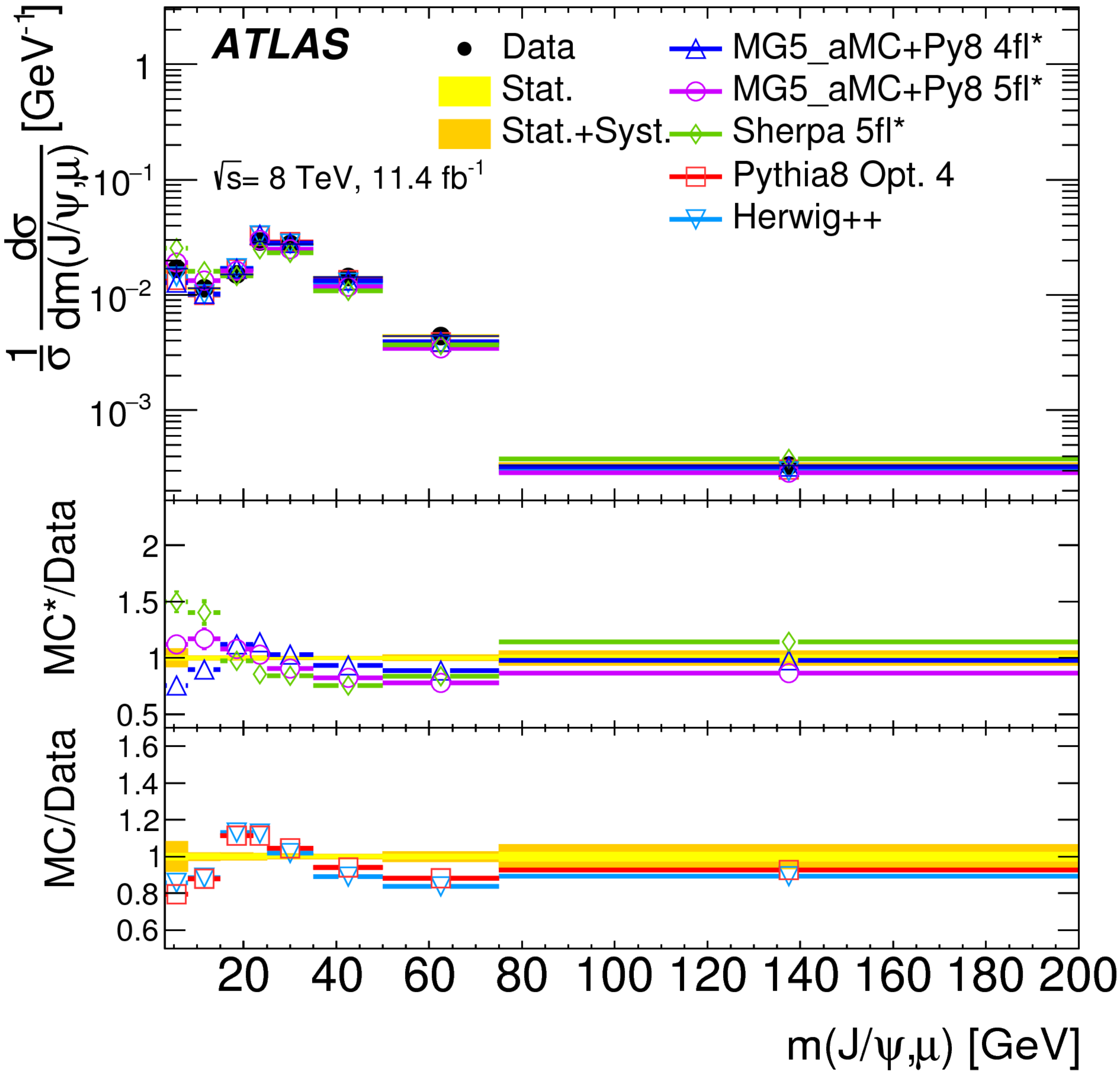




- For Δy MG5 and Sherpa both give a good description, whereas Herwig and Pythia perform poorly as Δy increases

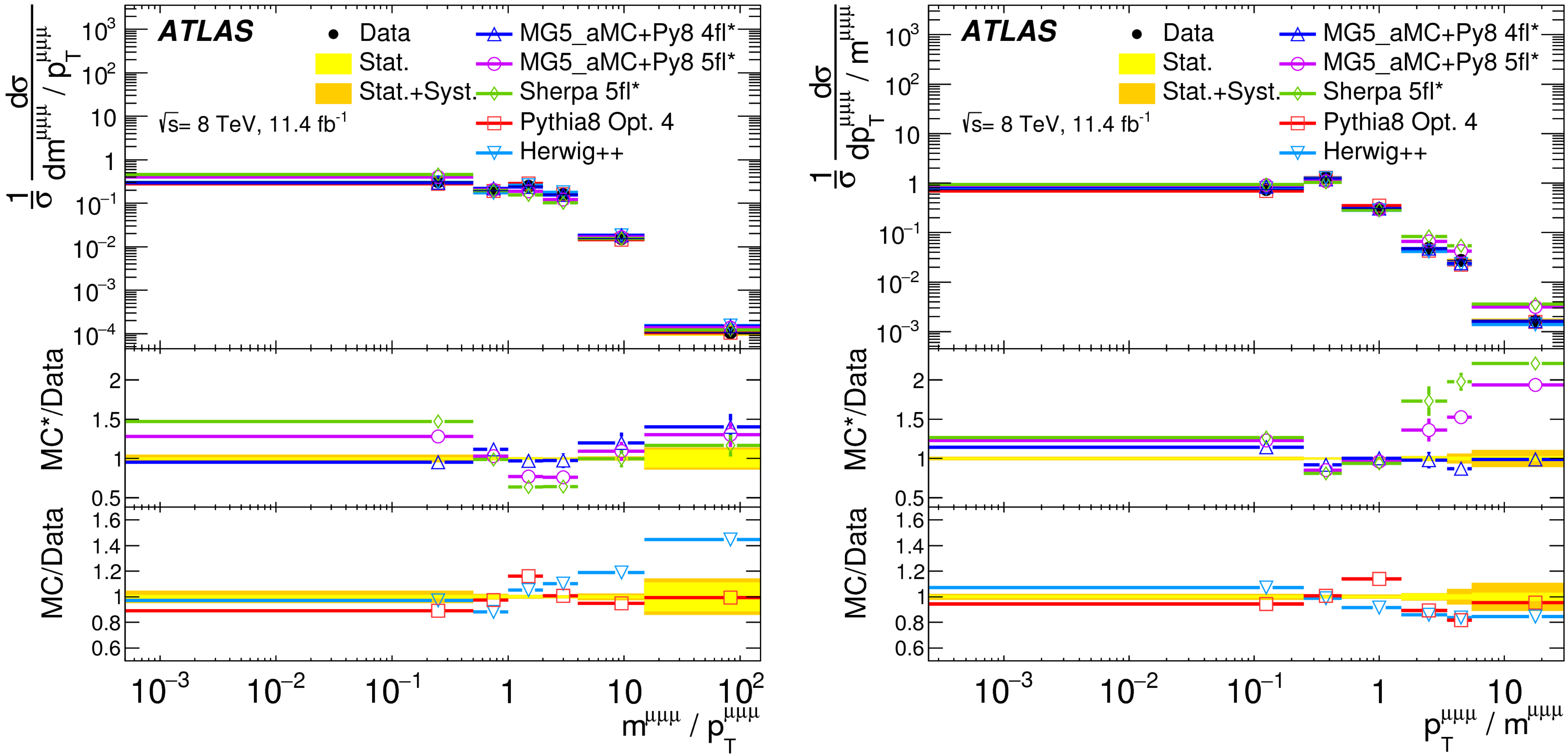
- For y_{boost} performance is broadly similar
  - Expected - this variable is more sensitive to PDFs than generator specifics

Results: Herwig, MadGraph, Sherpa - m(J/ψ,μ)



- Low m(J/ψ,μ) discriminates again between 4 and 5 flavour, but here the 5 flavour provides a better description

Results: Herwig, MadGraph, Sherpa - pT/m



- At high values of pT/m, 4-flavour predictions again outperform 5 flavour
- **Overall**: best description is from MG5_aMC+Py8 4 flavour

Conclusions

- Measurement of heavy flavour quark production is important for QCD phenomenology and studies of any process which have a large heavy flavour background
- ATLAS has released a new measurement of heavy flavour pair production, using $J/\psi \rightarrow \mu\mu$ on one side and semi-muonic B-decays on the other
- Predictions tested against results
  - Pythia8: pT-based splitting kernel gives the best results
  - Four flavour MadGraph5_aMC@NLO+Py8 gives the best overall performance
- Measurement guides future choices for heavy flavour modelling and should motivate further tunings

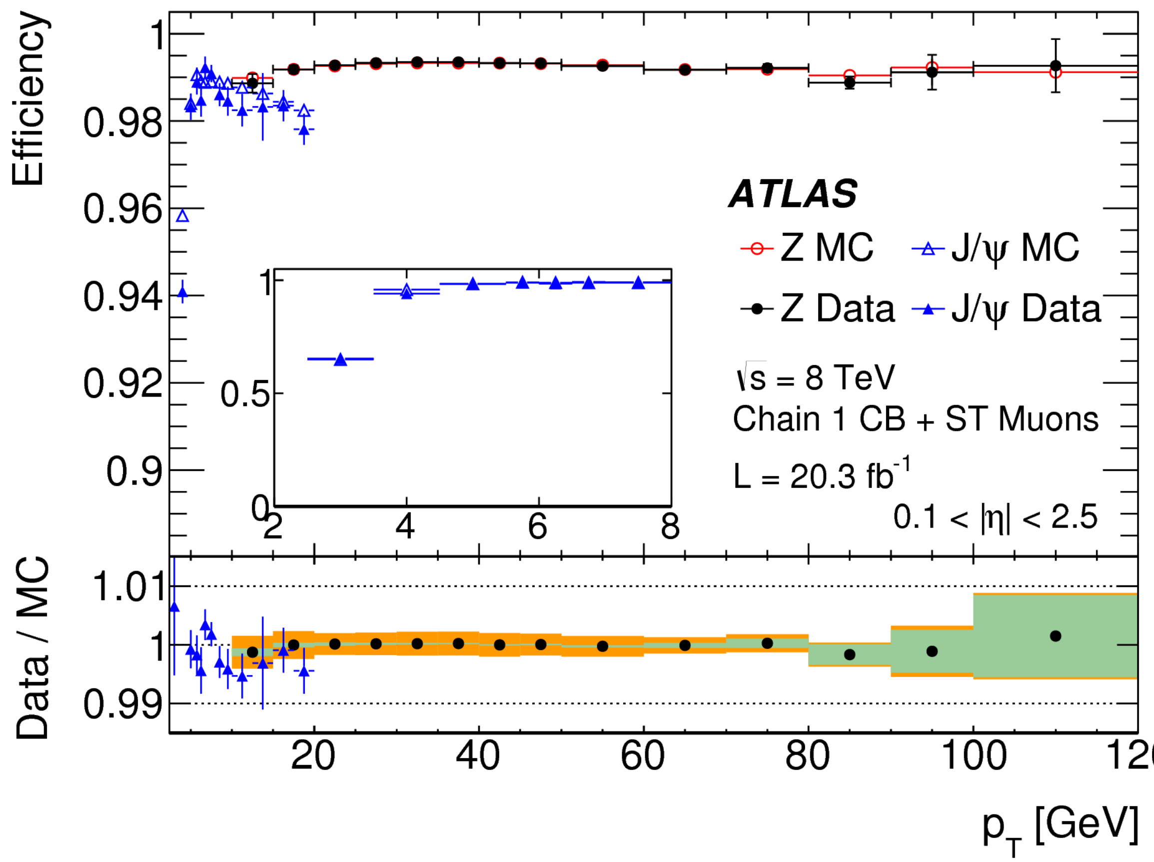
Supporting material

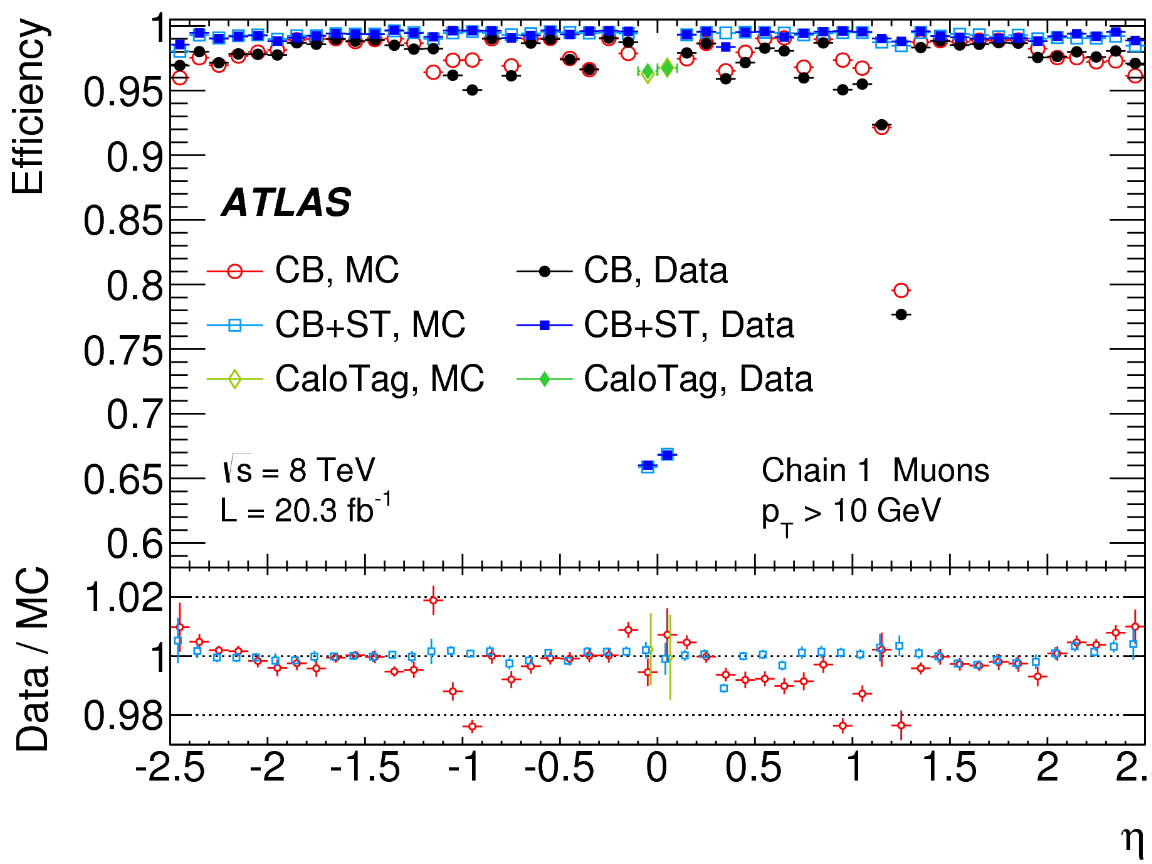
Trigger efficiency correction

- Single muon: from J/ψ tag and probe
  - Parameterised as function of p_T and $(q \times \eta)$
  - Simulation used to correct bias arising from T&P trigger (p_T>18GeV) and di-muon triggers used in the analysis
- Di-muon: done in two parts
  - vertex finding / opposite charge correction
  - correction for spatial overlap (drop in efficiency when $\Delta R < 0.2$)
- Correction to account for an inefficiency where the 3rd muon falls close to one of the other J/ψ legs

Offline reconstruction efficiency correction

- Applied per muon for each of the three muons in the event, parameterised as function of pT and (q x η)
  - Efficiency for a muon to be reconstructed as a track in the ID, parameterised as a function of p_T and η
  - Efficiency for a muon to be reconstructed as a muon, given that the ID track already exists: measured using J/ψ and Z tag-and-probe,



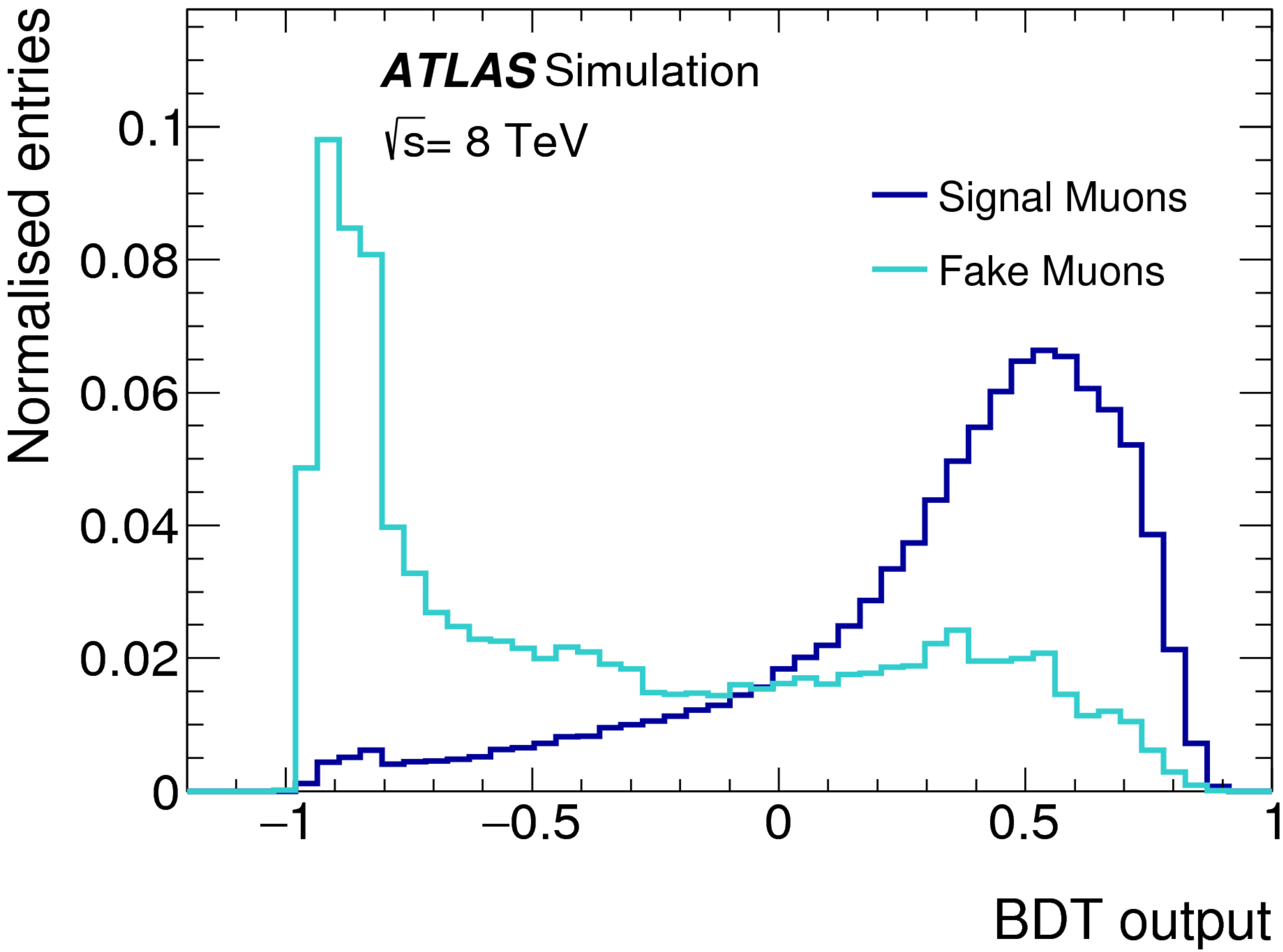


J/ψ 2D mass/lifetime fit functional forms

- Non-prompt J/ψ
  - Mass: combined Crystal Ball and Gaussian function
  - Lifetime: single-sided negative slope exponential
- Prompt J/ψ
  - Mass: as non-prompt
  - Lifetime: delta function at zero
- Prompt fake J/ψ background
  - Mass: constant
  - Lifetime: as prompt
- Single-sided fake J/ψ background
  - Mass: negative slope exponential function
  - Lifetime: single sided exponential decay function
- Double-sided fake J/ψ background
  - Mass: exponential decay function
  - Lifetime: double-sided exponential decay function
- Mass mean fixed to the same value for both CB and Gaussian; means of the decay time models fixed to zero
- CB n and α parameters fixed to values derived from an inclusive J/ψ fit, width floats
- All other values float in the fit

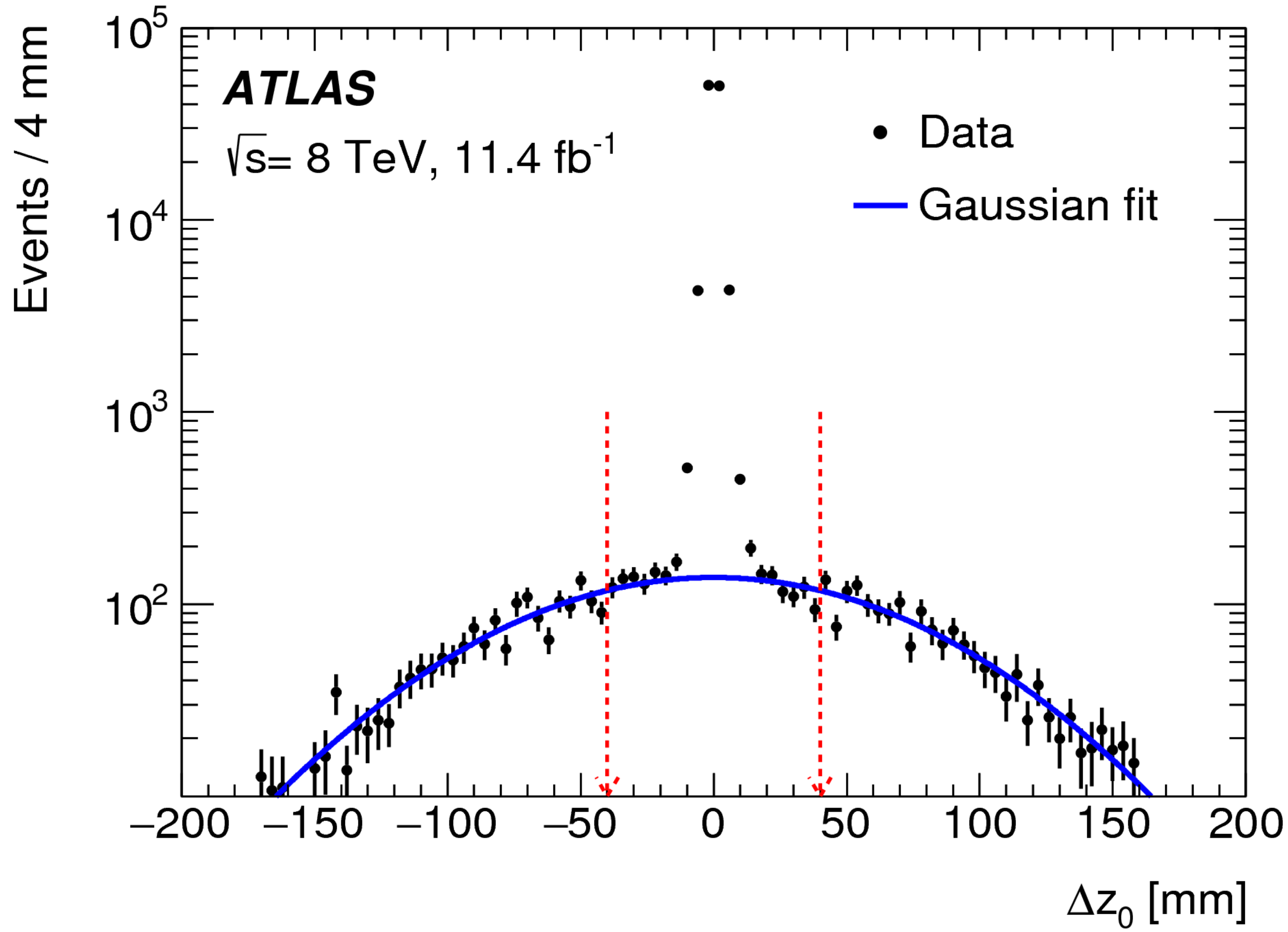
BDT

- Inputs constructed from kinematic variables that are sensitive to the production mechanism of the muons
  - Track deflection significance: max value of significance of difference in track curvature calculated downstream of a point somewhere along the inner detector track
    - DIF muons decaying in the ID typically have higher values than signal muons
  - Track deflection neighbour significance: largest value of significance of angular deflection between adjacent segments
    - DIF muons populate larger values
  - Momentum balance significance: significance of difference between ID momentum and MS momentum
    - Sensitive to kinks caused by DIF outside the ID. Such DIF muons will have a higher value
  - Absolute pseudorapidity: background muons more likely to have higher values
- Trained on signal/background muons identified as such by MC truth (Py8+sim)


ATLAS Simulation
$\sqrt{s}$= 8 TeV
Signal Muons
Fake Muons
Normalised entries
0
0.02
0.04
0.06
0.08
0.1
−1
−0.5
0
0.5
1
BDT output

Pile-up background

- J/ψ and μ from different pp collisions
- Use Δz_0, being the difference in reconstructed z-position of the 3rd muon and the muon used for the J/ψ which maximizes Δz_0



- Signal region defined by $\Delta z_0 < 40$mm
- Background under the signal peak estimated using Gaussian distribution extracted from full range

Summary of the 3rd muon 2D fit

- Signal μ: BDT and Sd0 fit templates taken from Py8 sample, using reconstructed muons matched to a truth muon which derives from a b-hadron.
  - Expected to populate the high values of the BDT output, signifying real muons, and have a wide Sd0 distribution indicating production away from the interaction point.
- Prompt μ: BDT and Sd0 templates taken from J/ψ muons in inclusive pp → J/ψ Pythia8 simulation, where J/ψ production is dominated by prompt production.
  - Muons are real and should thus occupy the high values in the BDT output distribution and will have a narrow Sd0 distribution as they are produced at the interaction point.
- Prompt and non-prompt fake μ: BDT and Sd0 fake muon templates are taken from the Py8 sample.
  - BDT shape has a large contribution at low values.
  - Sd0 template is derived separately for the prompt and non-prompt component as fake muons can have both prompt and non-prompt sources
- Fake J/ψ: BDT and Sd0 templates are derived from data and fixed in the fit.
- Pile-up: The BDT and Sd0 templates are derived from data and fixed in the fit.

Irreducible backgrounds

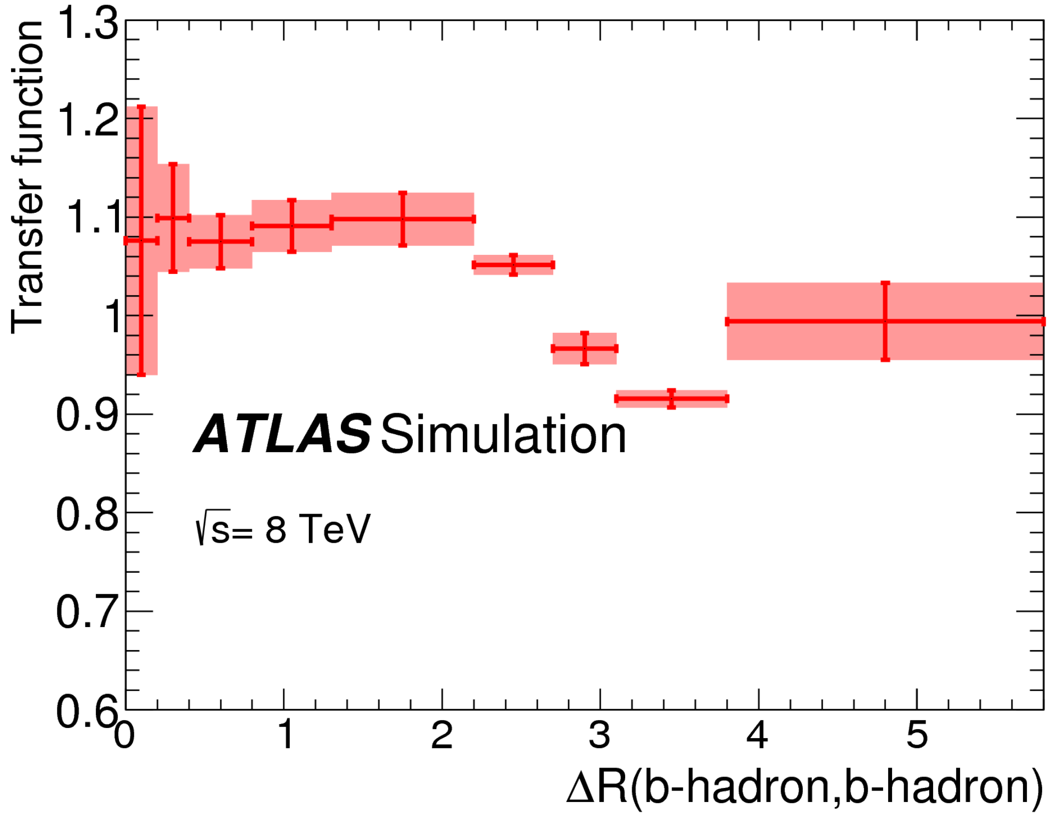
- Subtracted from post-fit signal yield, templates built from MC
  - $B_c \to J/\psi(\mu\mu)\mu X$, concentrated at low ΔR. Very small contribution
  - Open charm hadron decays (except those from B-decays): around 5% contamination
  - Punch-through - high momentum kaon or pion that manages to get through the calorimetry and into the muon system

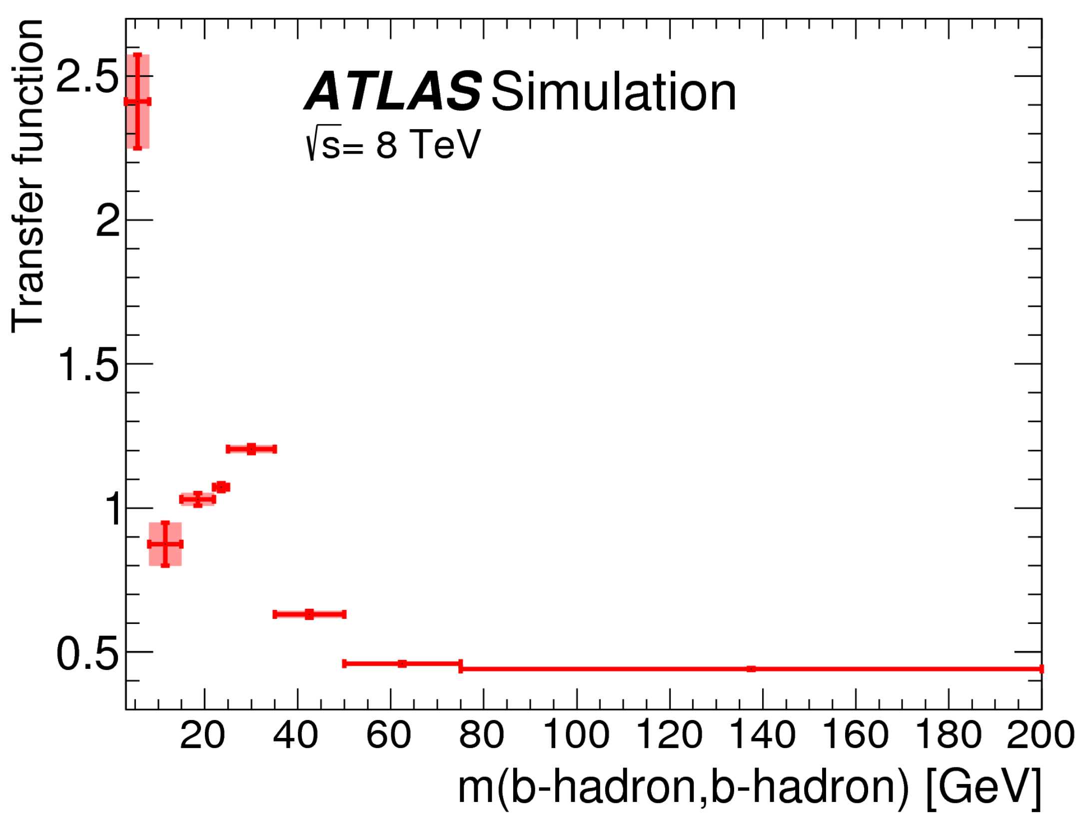
Pythia8 gluon splitting settings

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 [47] 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	As Option 1, but reweighted to an $\alpha_s(km^2_{qq})$ rather than the normal $\alpha_s(p^2_{\mathrm{T}})$, with $k = 1$.
Opt. 5b	As Option 5, but setting $k = 0.25$ (`TimeShower:scaleGluonToQuark = 0.25`).
Opt. 8	As Option 4, but reweighted to an $\alpha_s(km^2_{qq})$ rather than the normal $\alpha_s(p^2_{\mathrm{T}})$, with $k = 1$.
Opt. 8b	As Option 8, but setting $k = 0.25$ (`TimeShower:scaleGluonToQuark = 0.25`).

Transfer functions

- Cross sections for this analysis are computationally expensive due to the low production rate of b-hadrons and low branching for the 3-muon final state
- Develop transfer functions to translate to two b-hadron final states into the 3-muon final state
- Choose a two-B-hadron fiducial volume such that $\Delta R(B_1, B_2)$ matches closely $\Delta R(J/\psi, \mu)$
- Extract transfer fn by taking the ratio
- p_T and mass of the two-B-hadron samples needs correction due to the large fraction of momentum carried away by non-muons in the 3-muon decay
- Transfer functions derived for each generator set-up





Systematics

- Statistical uncertainty includes data and third muon templates taken from MC
- Trigger efficiency uncertainty includes single muon trigger efficiency, di-muon trigger efficiency, close-by muon correction, simulation based correction to trigger maps
- Reconstruction efficiency uncertainty combines muon and tracking
- Fit model uncertainty includes several variations in functional forms and fitting procedure
- BDT uncertainty includes uncertainties in simulation-derived templates and the data

Results: Herwig, MadGraph, Sherpa - $p_T(J/\psi,\mu)$