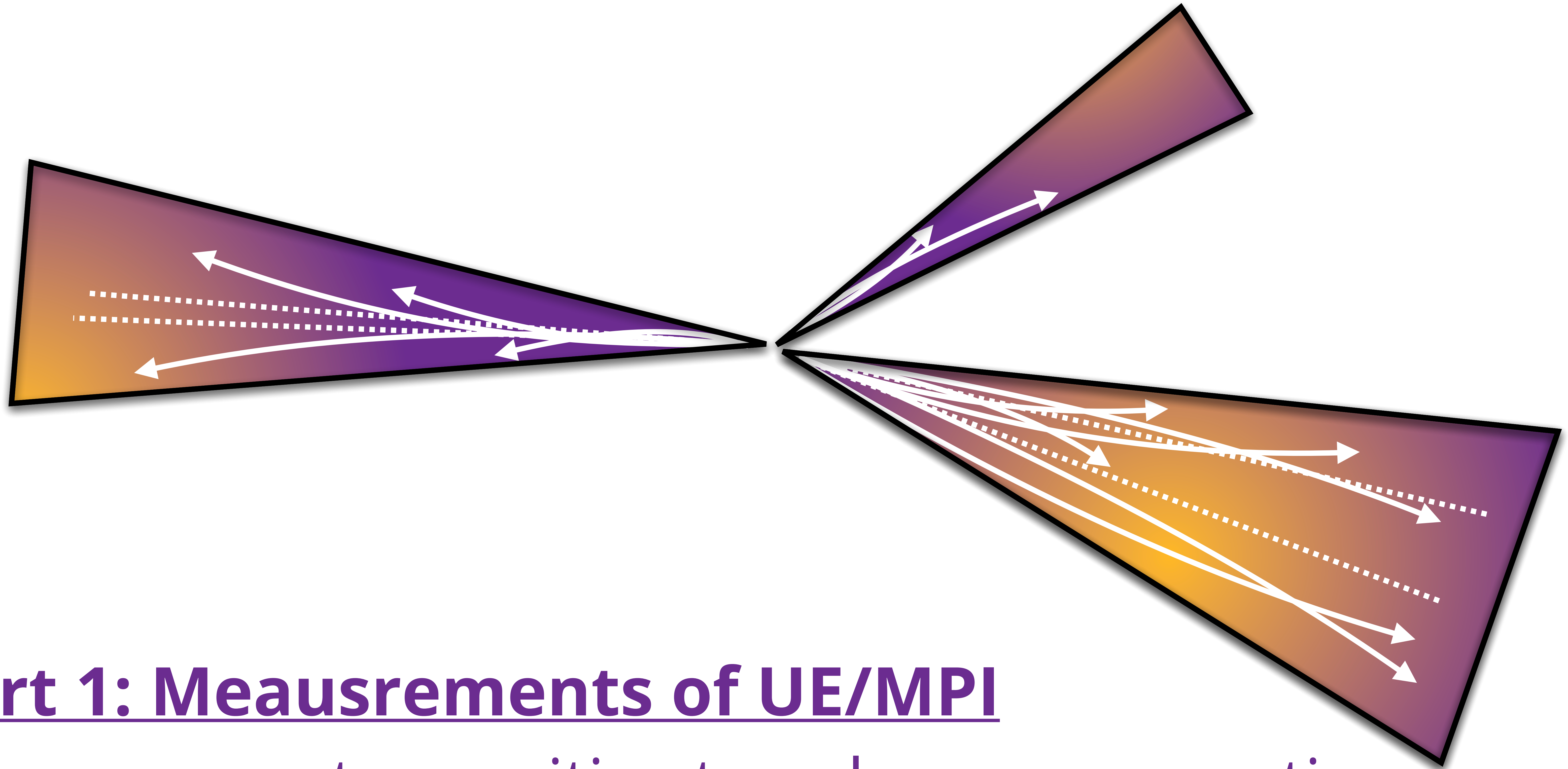
Studies of hadronisation and UE/MPI with ATLAS Run 2 data

14th International Workshop on Multiple Parton Interactions at the LHC (MPI@LHC 2023)
WG1: Minimum Bias, Underlying Event and Monte Carlo generators
University of Manchester, 20-24 November 2023

Matt LeBlanc (Manchester), for the ATLAS Collaboration
matt.leblanc@cern.ch, @TopPhysicist

Studies of hadronisation and UE/MPI with ATLAS Run 2 data



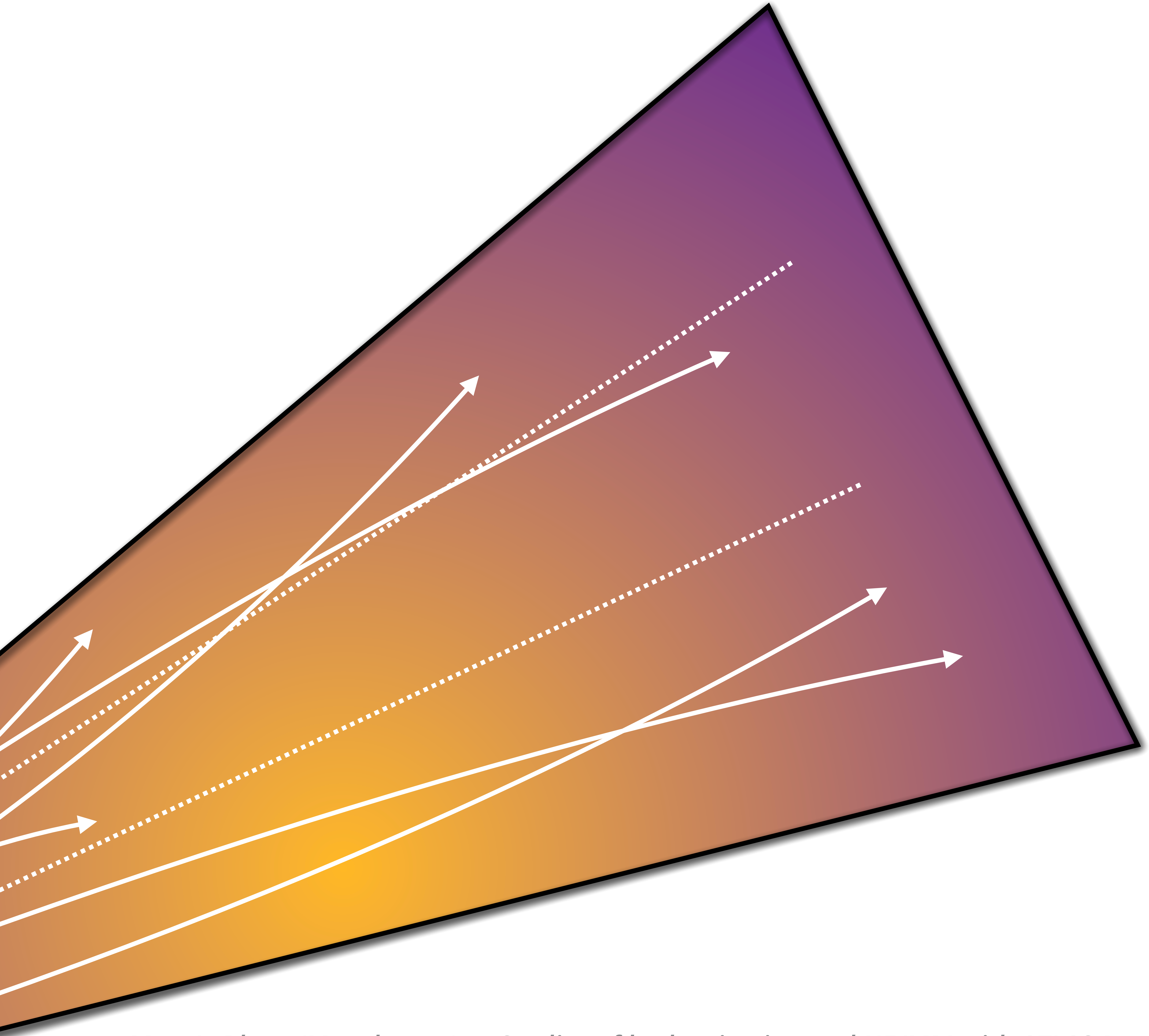
FROM FAR AWAY

Part 1: Meausrements of UE/MPI

Measurements sensitive to colour reconnection in ttbar events with ***ATLAS***

Eur. Phys. J. C 83, 518 (2023)

Studies of hadronisation and UE/MPI with ATLAS Run 2 data



From far away + Up Close

Part 2: Jet Substructure

ATLAS hadronisation & jet response

ATL-PHYS-PUB-2022-021

ATLAS Lund jet plane

PRL 124, 222002 (2020)

Part 1: Measurements of UE/MPI

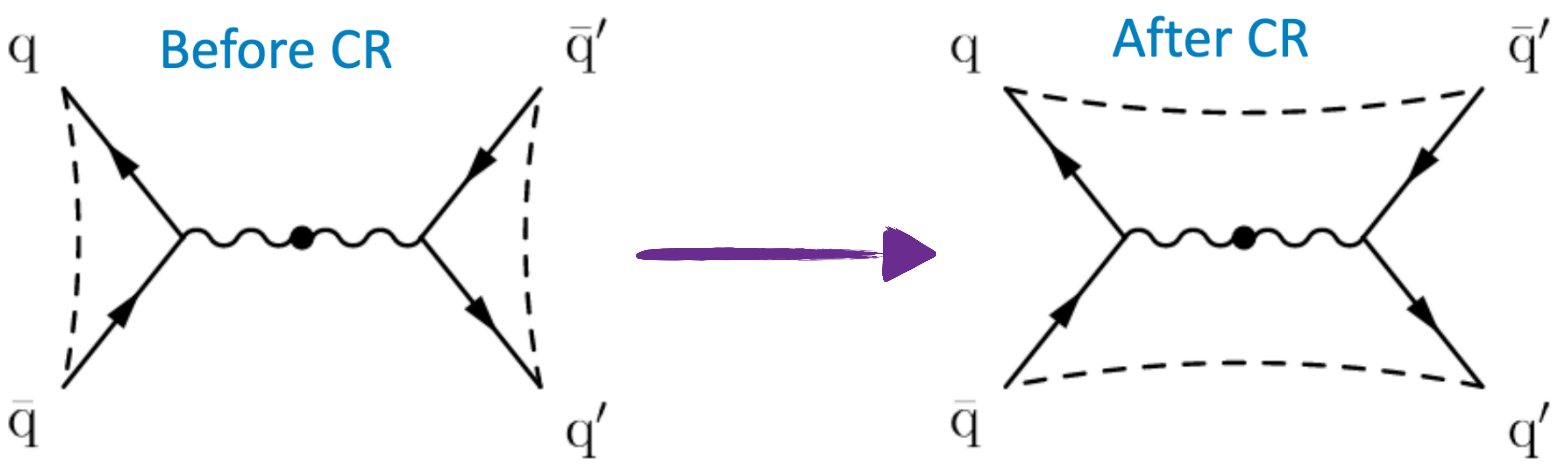
Measurements sensitive to colour reconnection
in ttbar events with ***ATLAS***

Eur. Phys. J. C 83, 518 (2023)

Overview

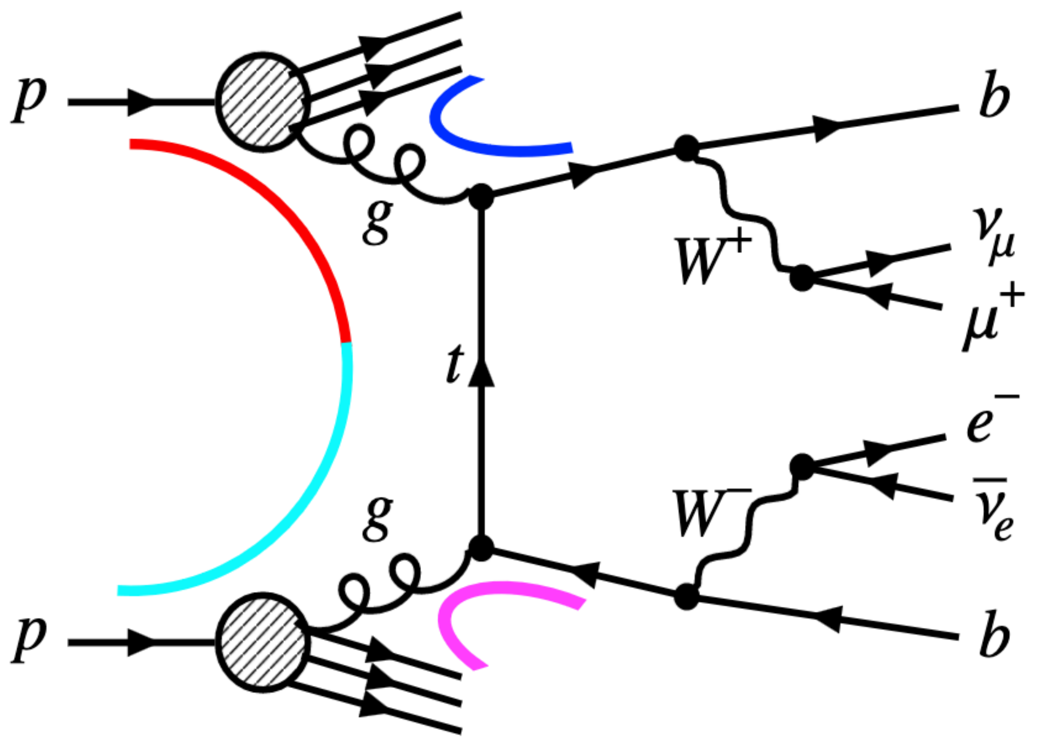
ATLAS, Eur. Phys. J. C 83, 518 (2023)
Adapted from S. Wahdan @ TOP 2022

- Colour-reconnection (CR) mechanism is poorly understood.
  - Can have CR between initial- and final-state,
- Several models are available, but none are based on first-principles physics.
  - In Pythia 8, more than 16 parametric models for different processes!
    - No common prescription for uncertainties → proliferating comparions leads to large systematics in *e.g.* $\boldsymbol{m_t}$ measurements.
- Improved understanding of CR in top events will improve precision m_t measurements.



	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single top modelling	0.01 ± 0.01
Background normalisation	0.03 ± 0.02
Jet energy scale	0.37 ± 0.02
b-jet energy scale	0.12 ± 0.02
Jet energy resolution	0.13 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.11 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.39 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.80 ± 0.06

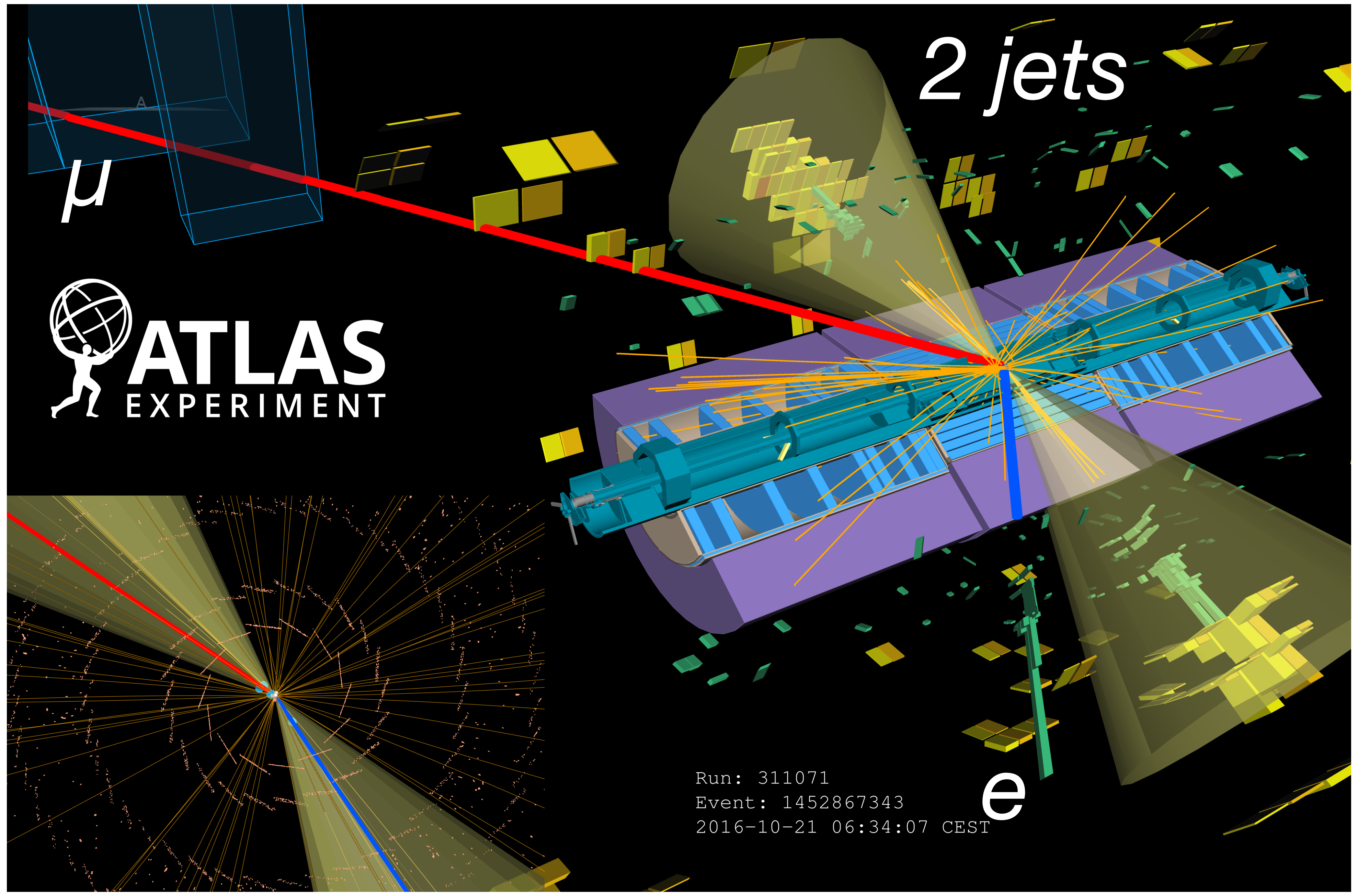
ATLAS-CONF-2022-058

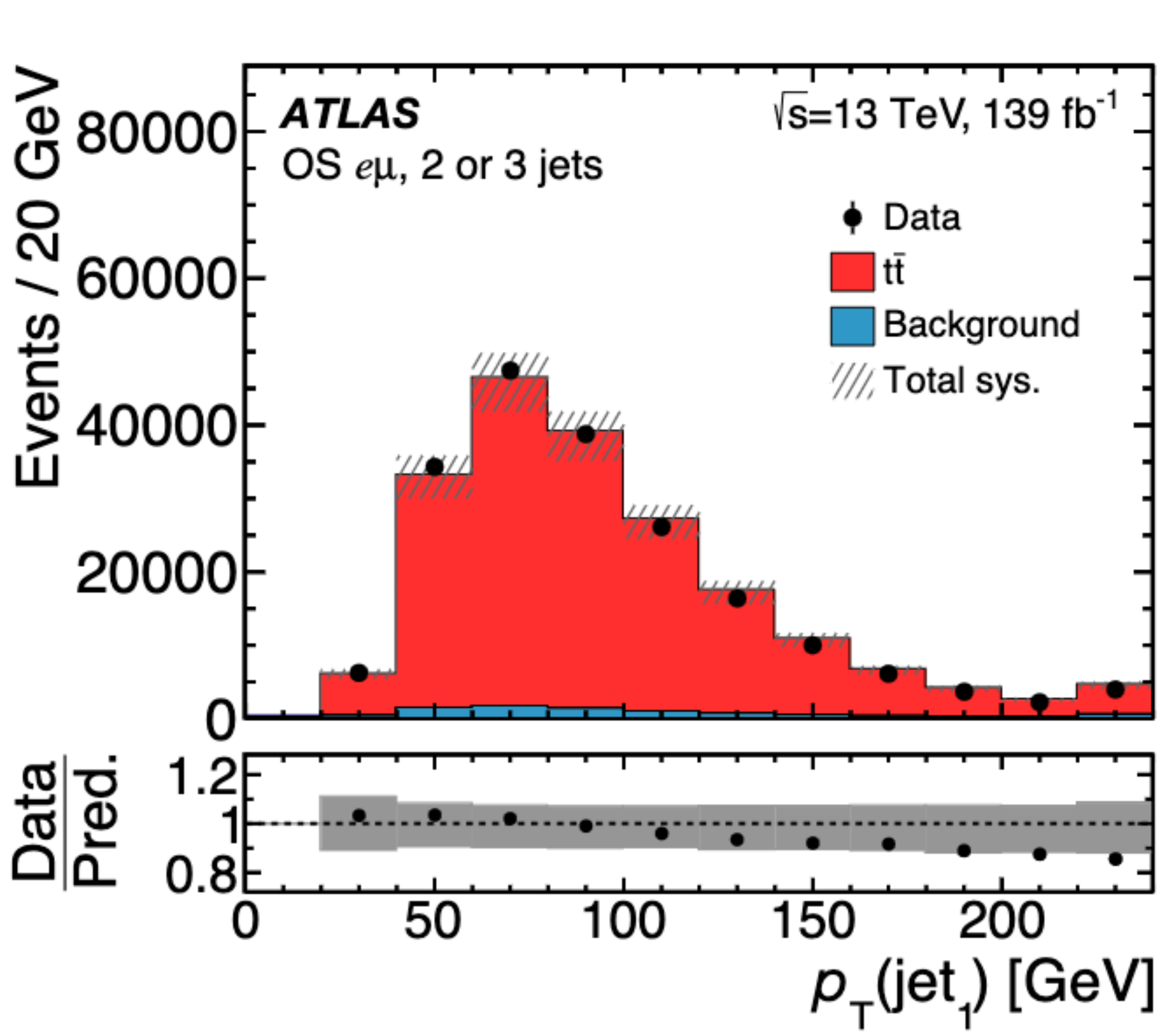


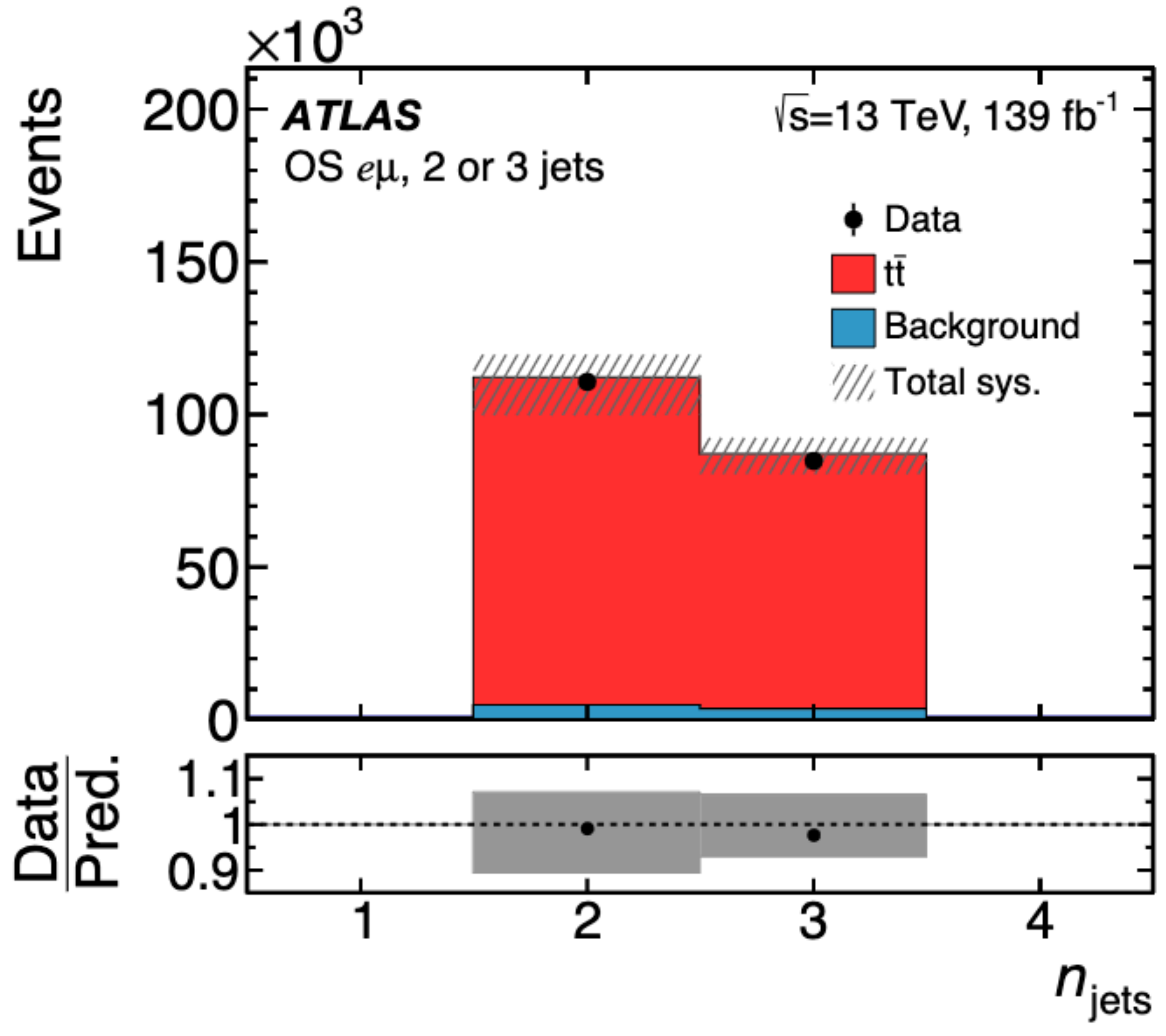
Overview

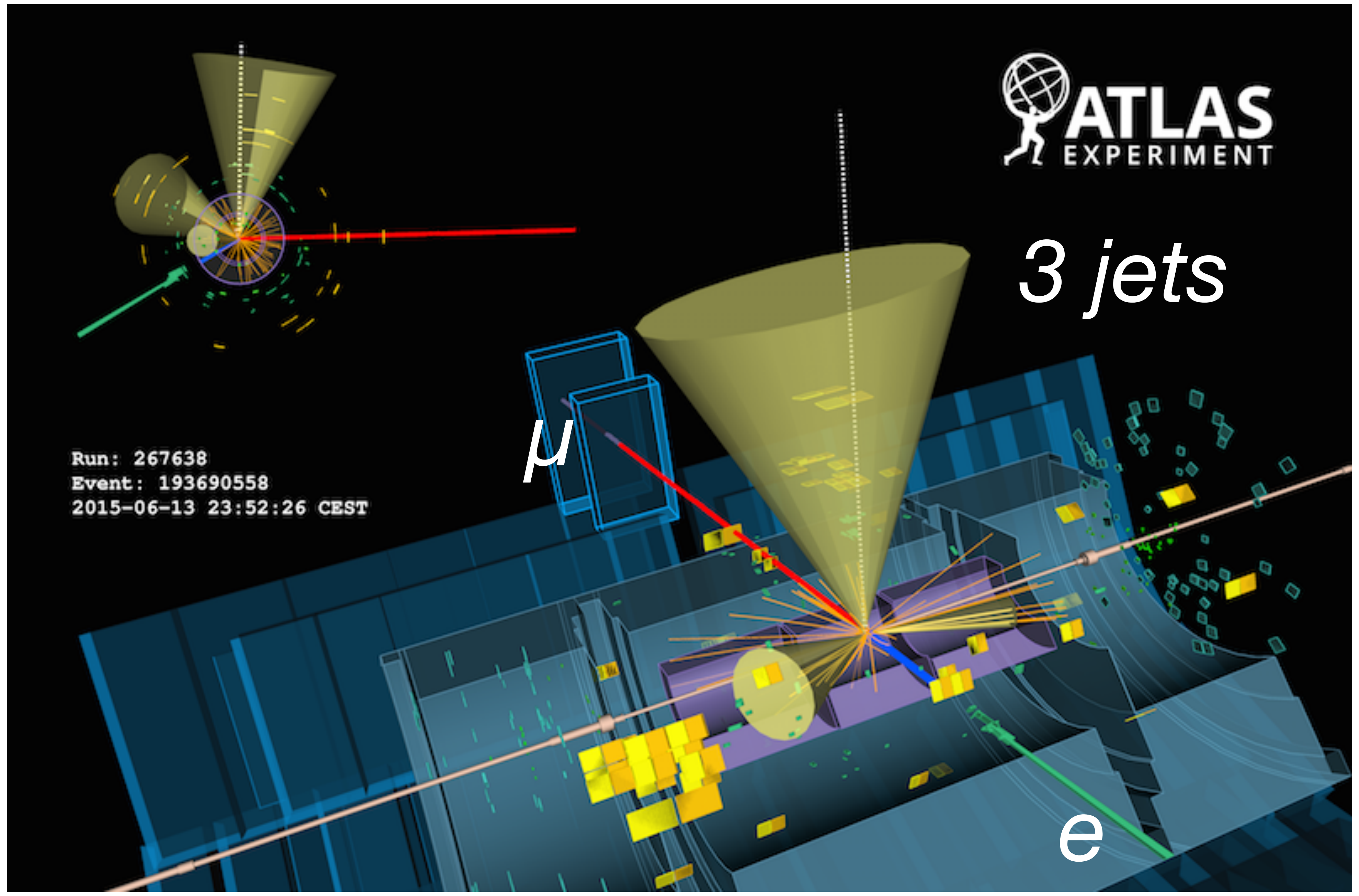
ATLAS, [Eur. Phys. J. C 83, 518 (2023)]

- Measurements of **charged particle multiplicity and charged particle H_T** (single- & double-differential).
  - Made using opposite-flavour dileptonic ttbar events (e,μ) with 2 or 3 jets (2 b-tags)
    - Signal purity ~96%





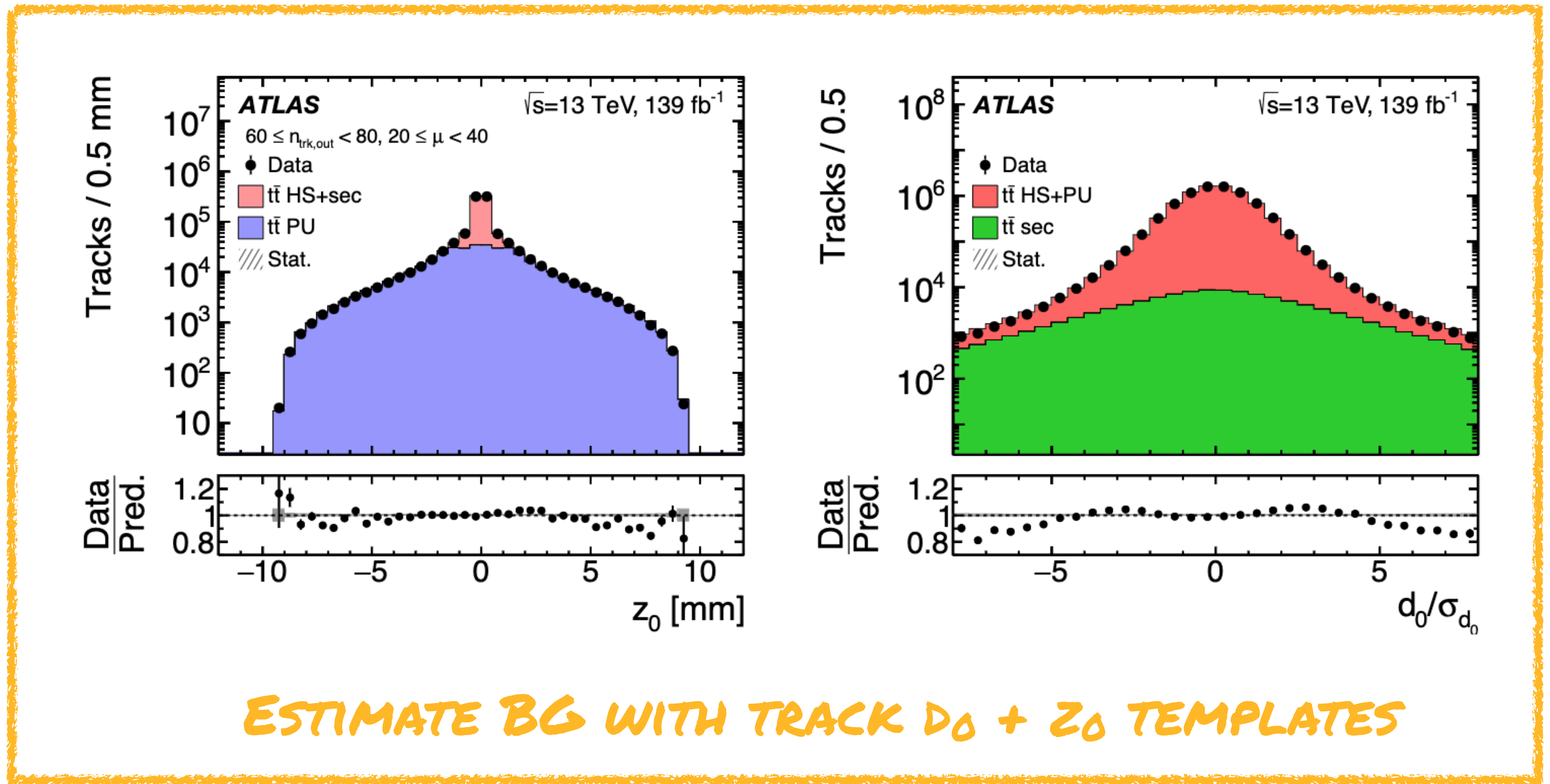


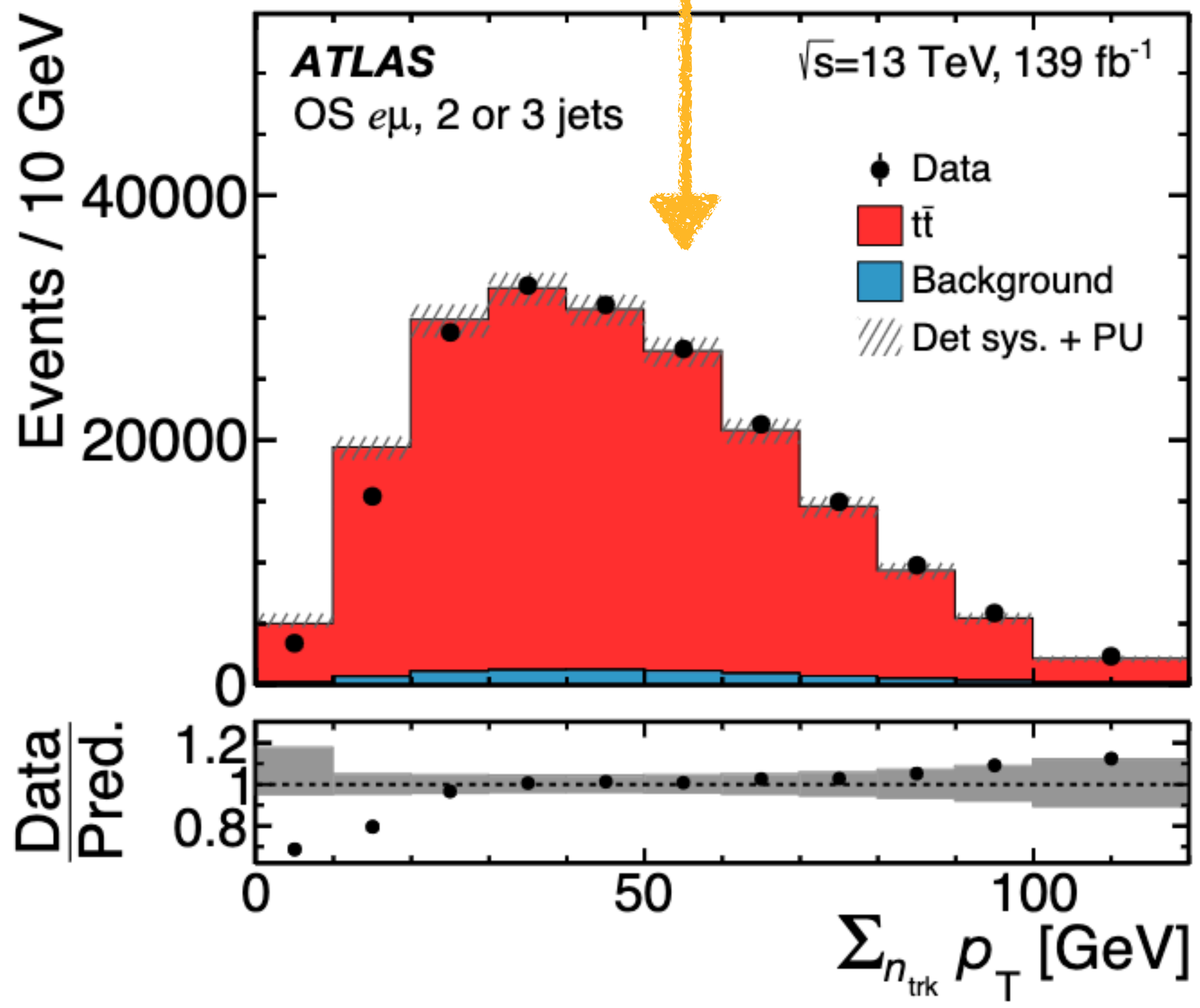


Overview

ATLAS, Eur. Phys. J. C 83, 518 (2023)

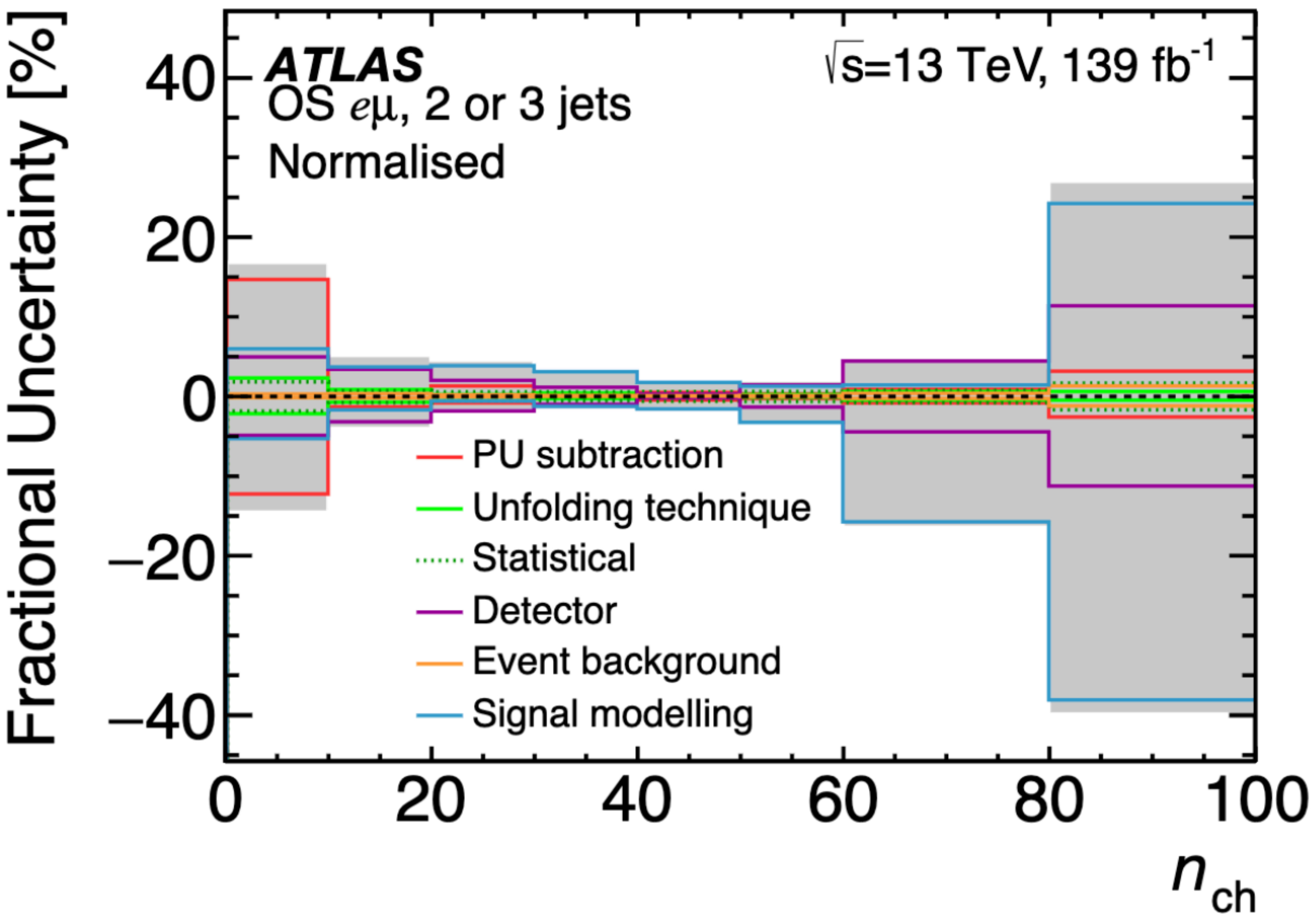
- Measurements of **charged particle multiplicity and charged particle H_T** (single- & double-differential).
  - Made using opposite-flavour dileptonic ttbar events (e,μ) with 2 or 3 jets (2 b-tags)
    - Signal purity ~96%
  - PV-associated 'tight' tracks are used for measurement.
    - Tracks associated with leptons or inside of jets (ΔR<0.4) are removed.
    - Remaining per-event background from pileup and secondary-vertex tracks estimated with MC templates (track d_0, z_0).

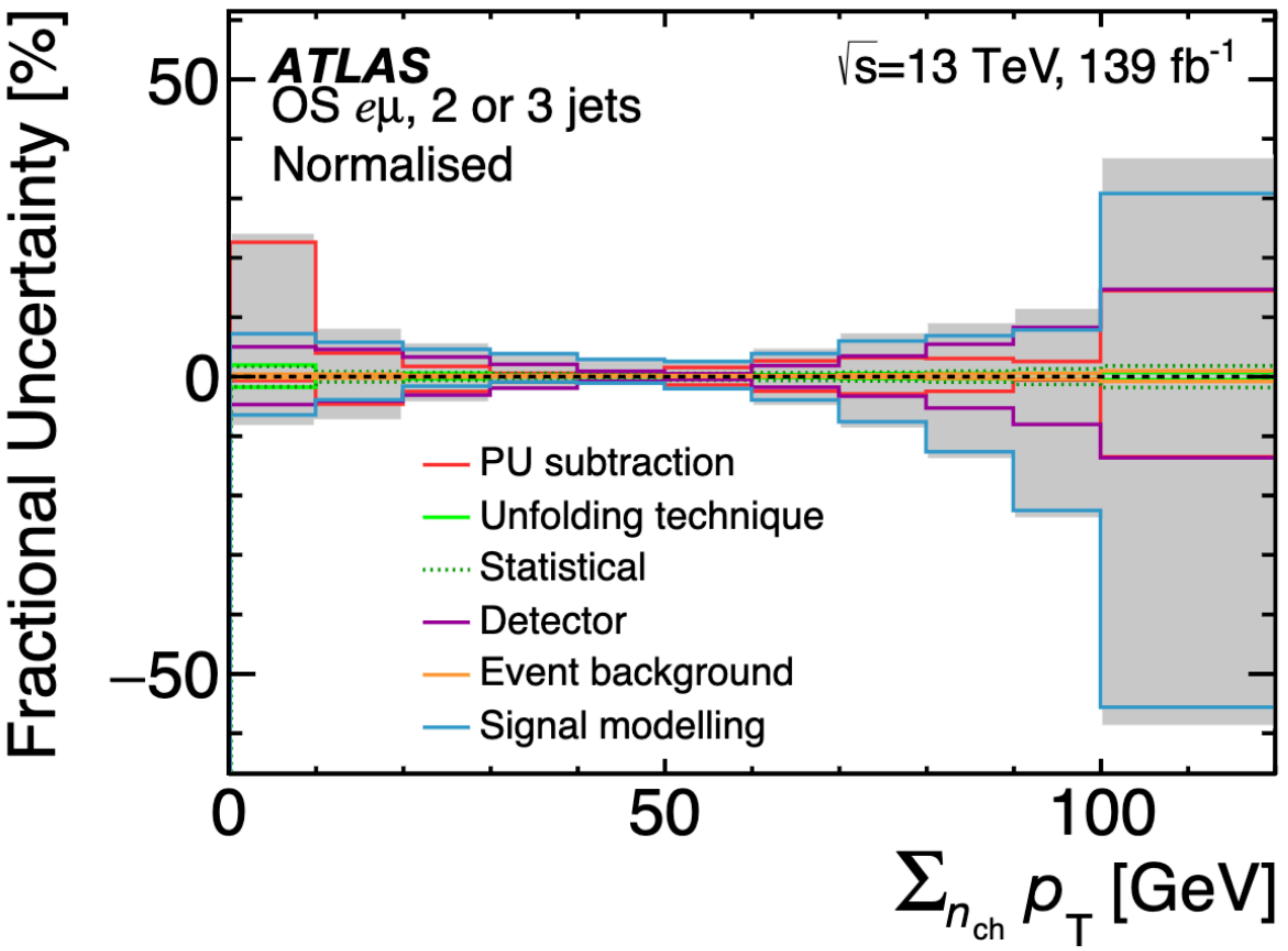




Systematic Uncertainties

ATLAS, Eur. Phys. J. C 83, 518 (2023)

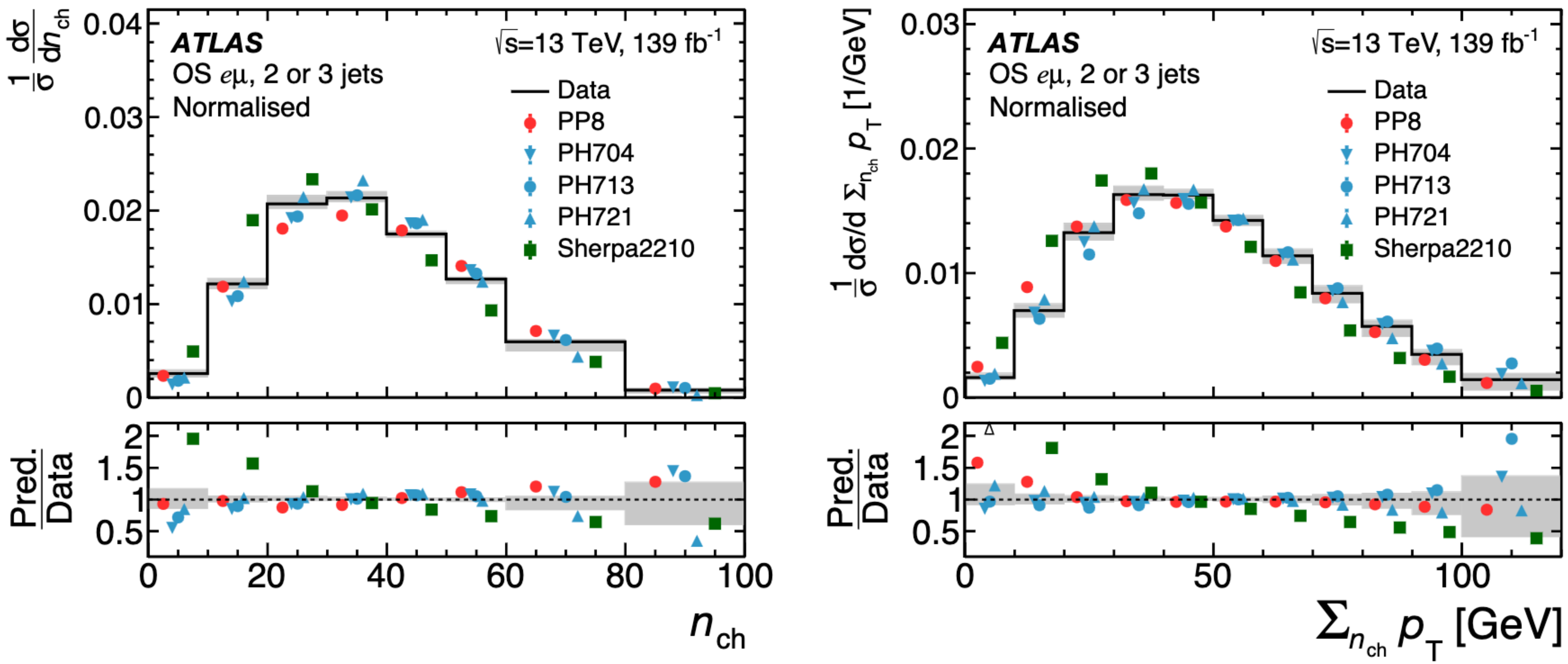




- Measured distributions are unfolded with Iterative Bayesian Unfolding (IBU)
- Dominant uncertianties related to **pileup-subtraction** (template fit) and **modelling (mostly PhPy8 *vs.* PhH7.1.3).**
  - Leading **experimental sources**: **track reconstruction efficiency** and **jet energy scale** (migrations in-/out-of acceptance).

Results: nominal MC setups

ATLAS, [Eur. Phys. J. C 83, 518 (2023)](#)

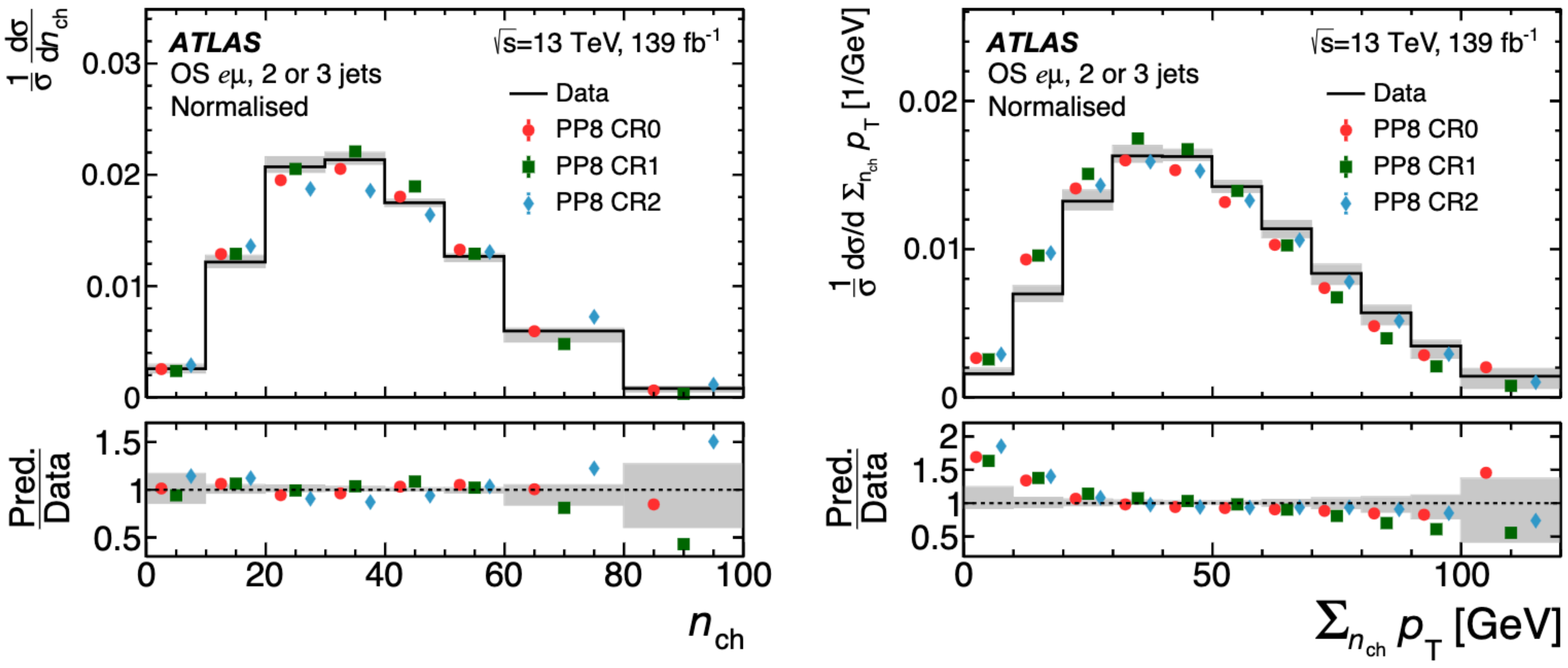


- **Powheg+Pythia8** desribe n_{ch} distribution best, while **Powheg+Herwig7** best describe summed Track p_T.
- **Sherpa 2.2.10** does not include CR, and so under-estimates both distributions.

Results: Pythia CR models

ATLAS, Eur. Phys. J. C 83, 518 (2023)

CR0: *MPI-based (default)*
CR1: *QCD-based junction model*
CR2: *Gluon-move (only gluons reconnect)*

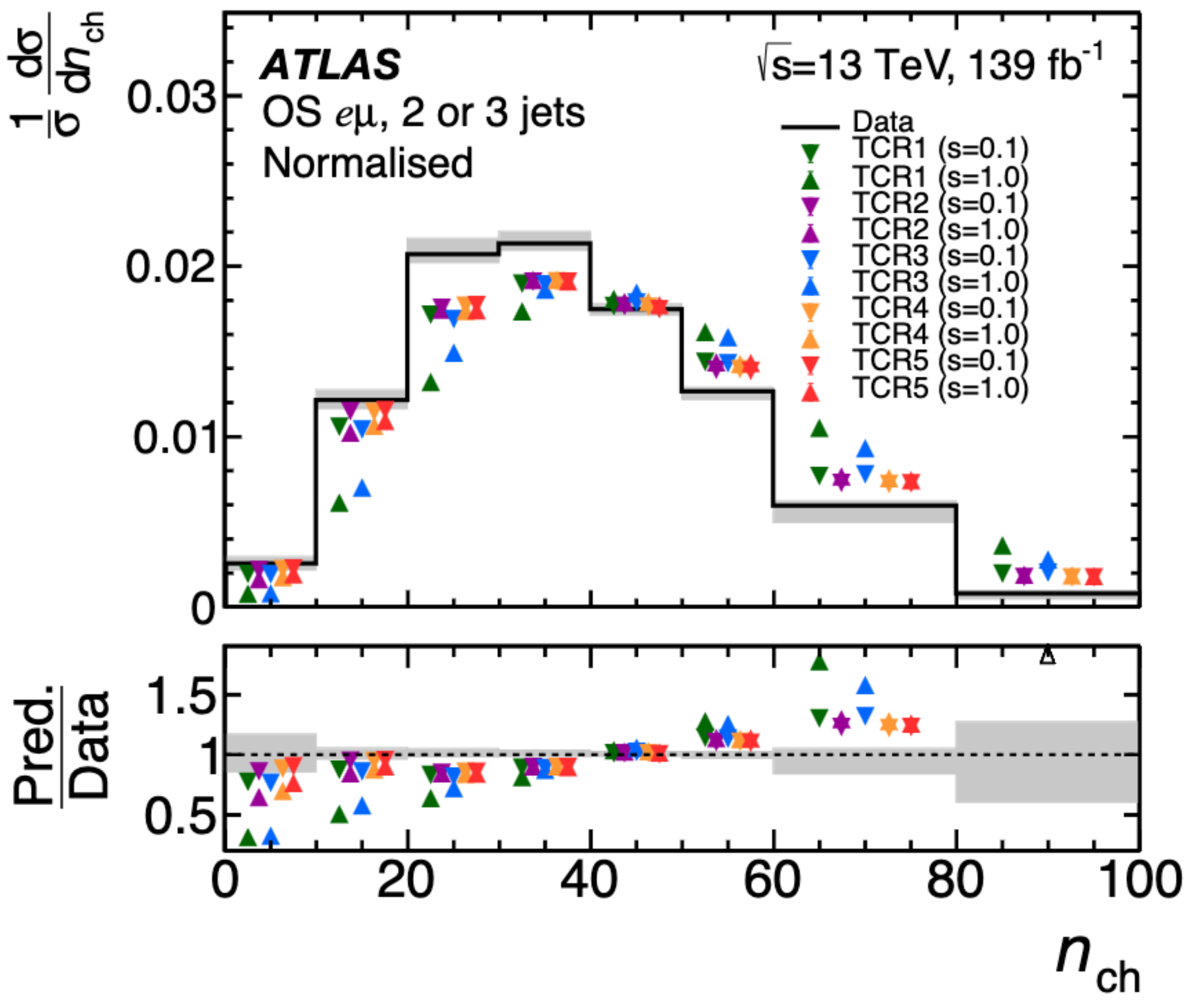


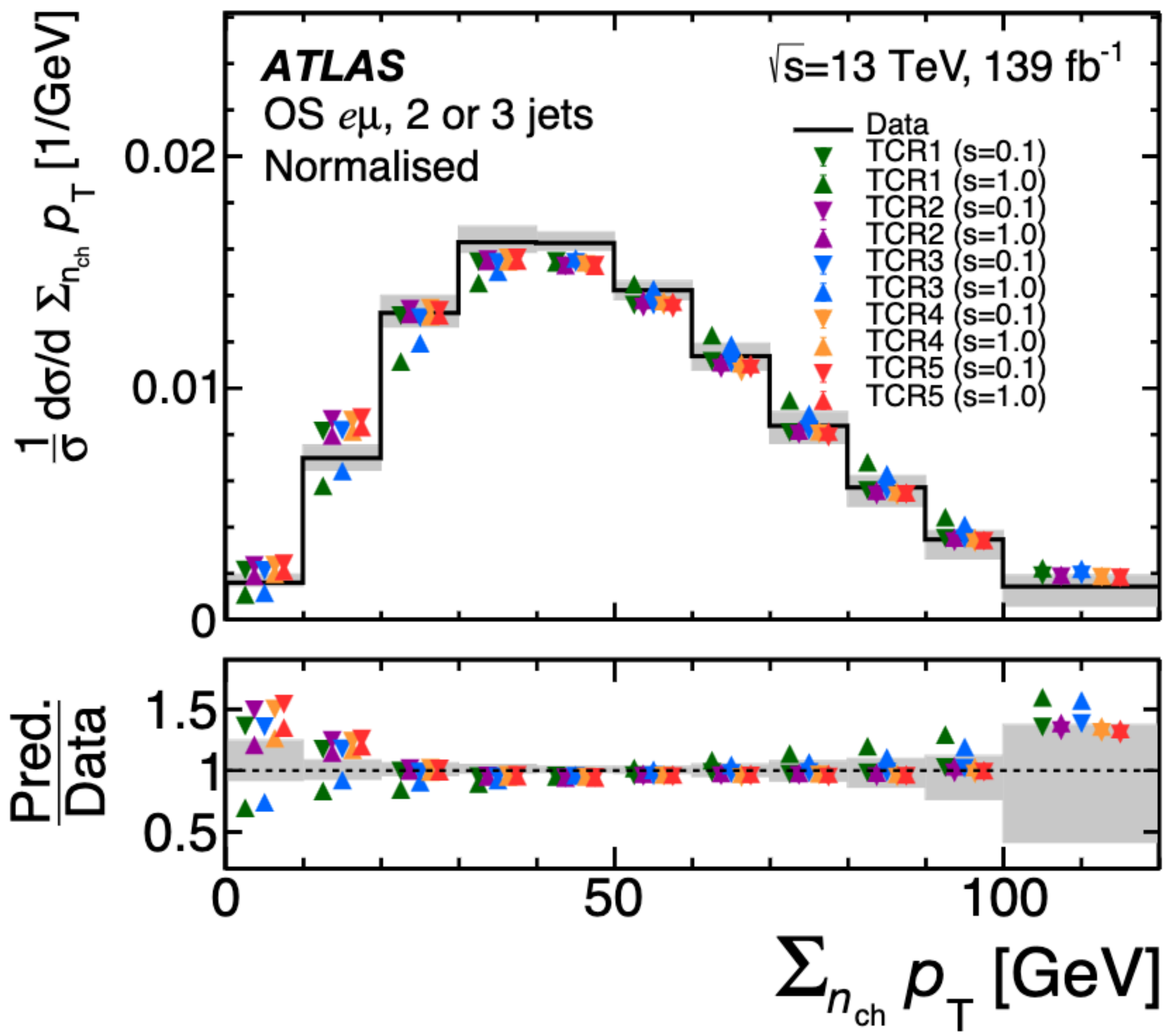
- Of the models in PP8, **nominal CR0 model (MPI-based)** describes n_{ch} best and **all models** exhibit a trend when compared to summed track p_T.

Results: Top-specific CR models

ATLAS, Eur. Phys. J. C 83, 518 (2023)

1. **Forced random (TCR1)**
   A gluon from $\{g_t\}$ is forced to exchange colours with a random gluon from the other set, $\{g_r\}$.
2. **Forced nearest (TCR2)**
   A gluon from $\{g_t\}$ is forced to exchange colours with the gluon from $\{g_r\}$ that minimises $m^2(g_t, g_r)$.
3. **Forced farthest (TCR3)**
   A gluon from $\{g_t\}$ is forced to exchange colours with the gluon from $\{g_r\}$ that maximises $m^2(g_t, g_r)$.
4. **Forced smallest $\Delta\lambda$ (TCR4)**
   A gluon from $\{g_t\}$ is forced to exchange colours with the gluon from $\{g_r\}$ for which the change in λ (available rapidity range of particle production) is smallest.
5. **Smallest $\Delta\lambda$ (TCR5)**
   This is the same as the previous model, except that gluons exchange colours only if $\Delta\lambda < 0$.

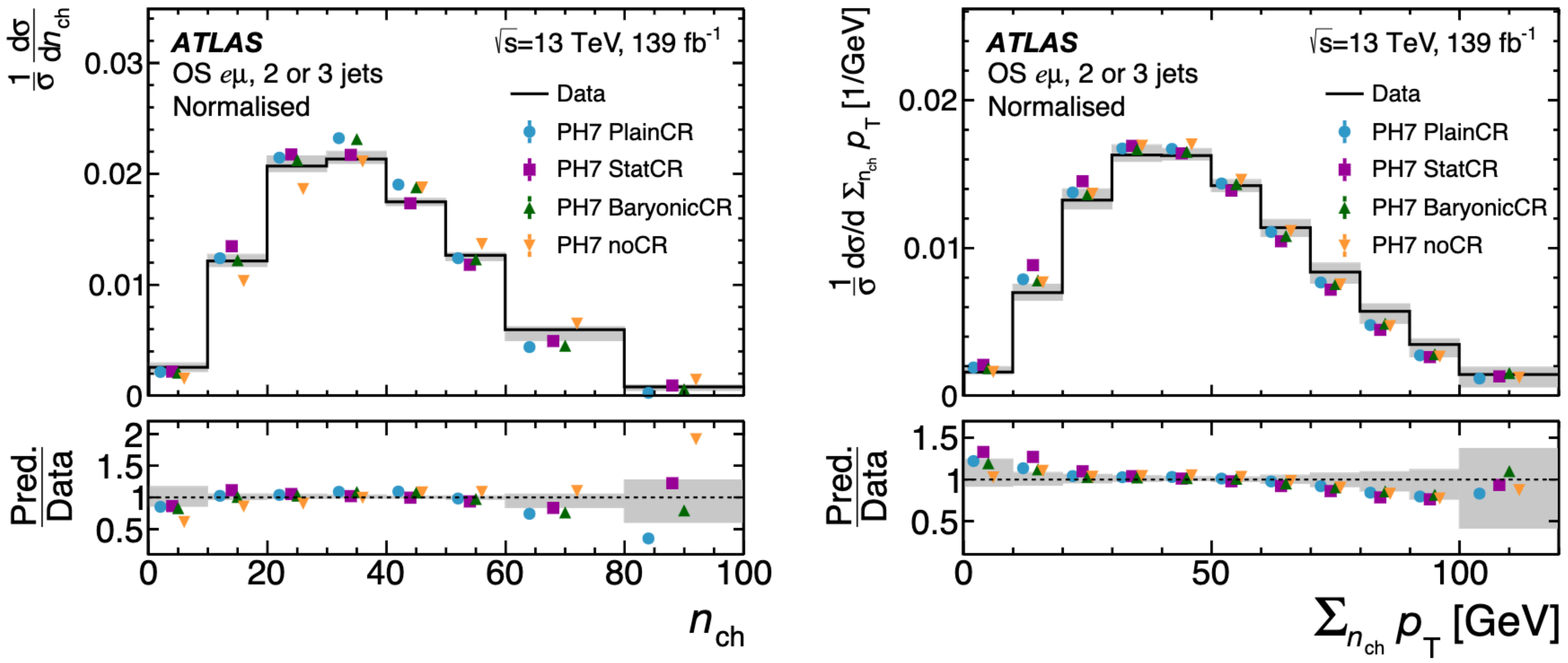




- **None of the top-specific colour reconnection models in Pythia 8 perform well:** changing how gluons exchange colours in top decays results in only small differences, except for TC1 & TC3, which disagree with the other models and the data strongly.

Results: Herwig CR models

ATLAS, Eur. Phys. J. C 83, 518 (2023)



- Of the models in PH7, the newly-introduced **Statistical CR model** performs best for n_{ch}, while for summed track p_{T} the **Baryonic CR model** performs best.
- **PH7 models perform best overall,** of all the comparisons made in this measurement!

Part 2: Jet Substructure

ATLAS hadronisation & jet response

ATL-PHYS-PUB-2022-021

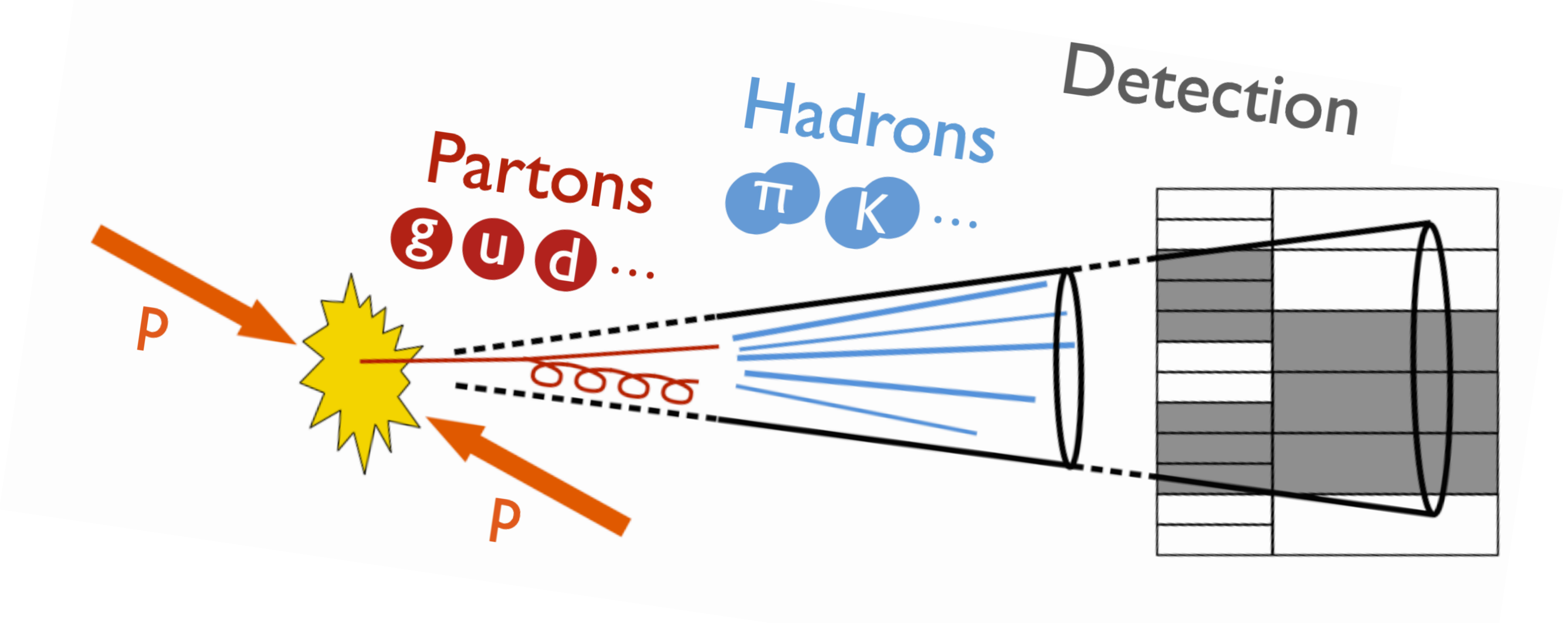
ATLAS Lund jet plane

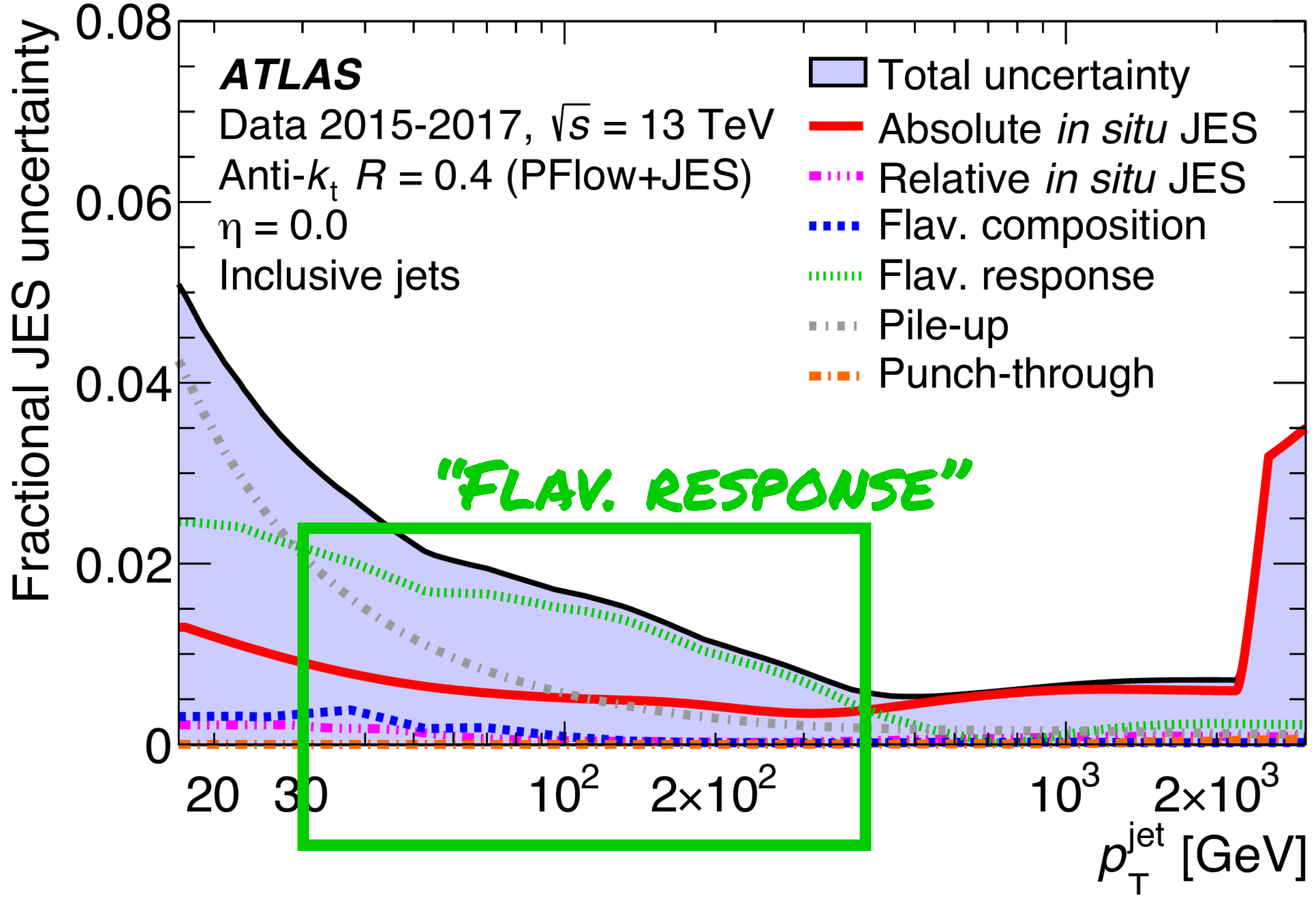
PRL 124, 222002 (2020)

The jet energy scale

ATLAS, Eur. Phys. J. C 81 (2021) 689

- Jets are complicated: composite objects w/ multiple scales, large areas.
  - Both **Theoretical & experimental** complexity
  - Although jets are typically hard objects, they are also sensitive to npQCD effects!
- The JES is a major source of systematic uncertainty in most physics analyses performed at the LHC.
  - Leading source of uncertainty depends on jet kinematics : **"Flavour Response"** dominates in region of interest for many studies in **Higgs & top** sectors!



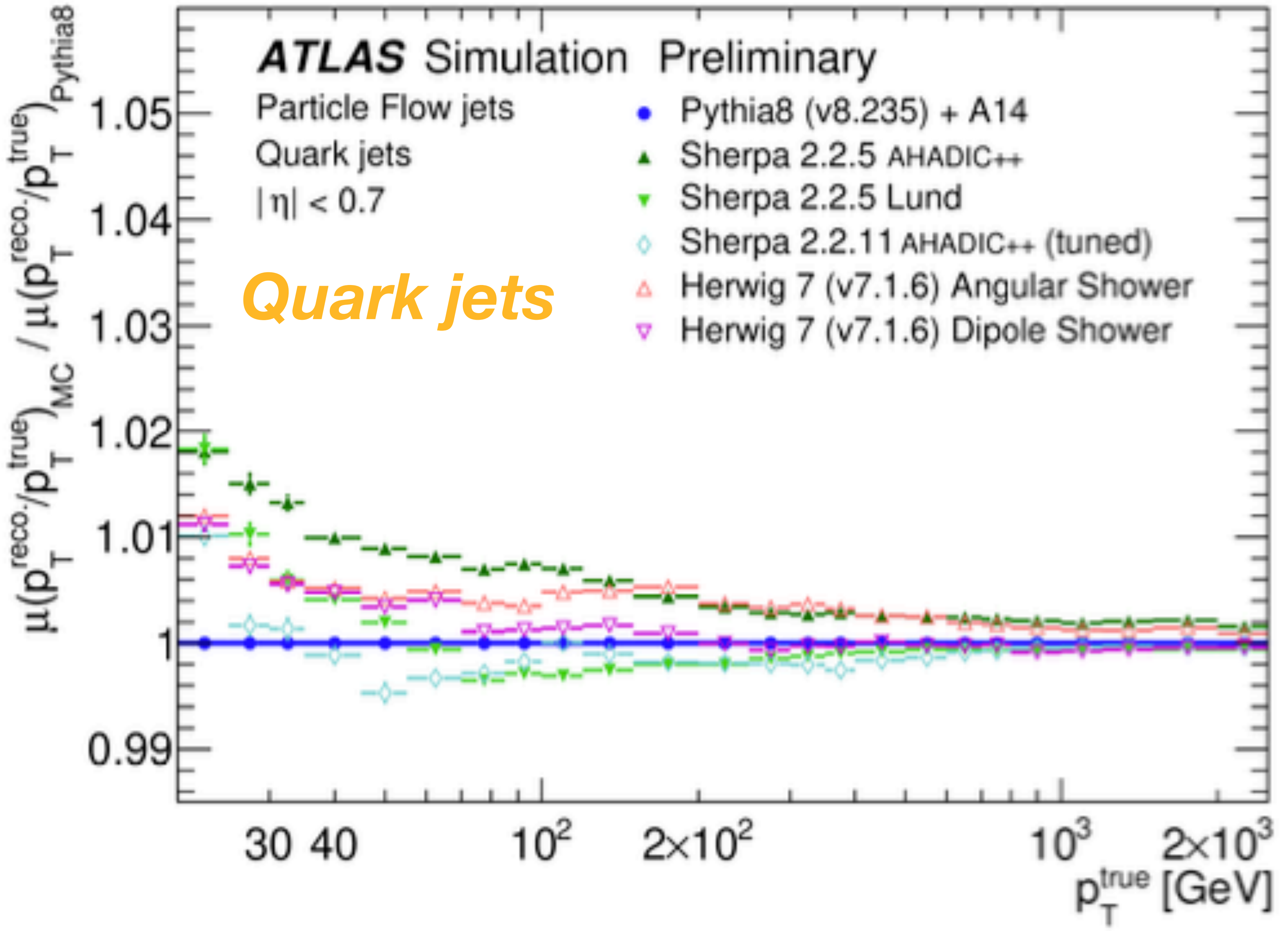


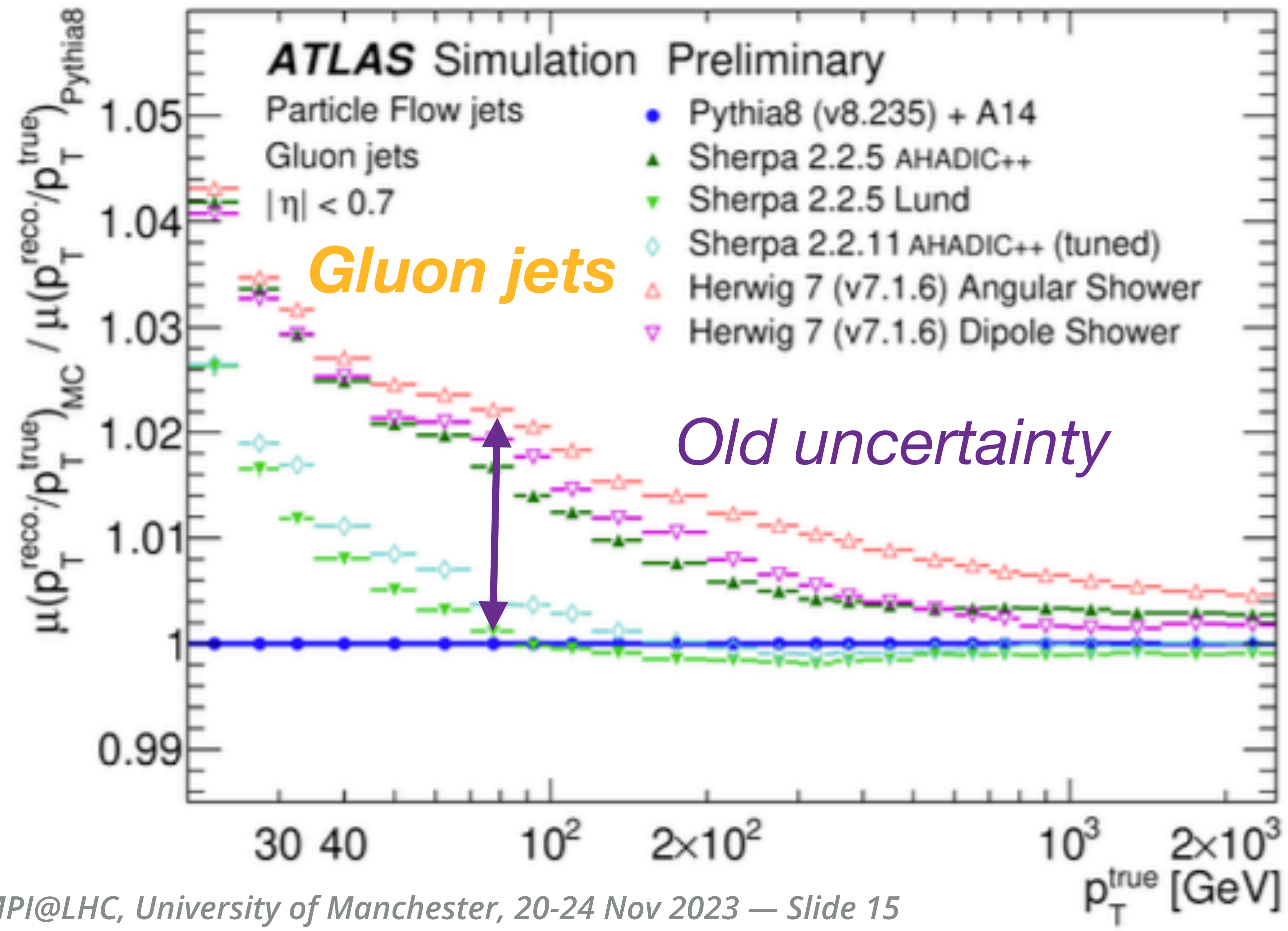
JES flavour response

ATLAS, ATL-PHYS-PUB-2022-021

- **Flavour Response** uncertainty originates from the differing detector response to quark- and gluon-initiated jets.
  - Gluon-initiated jets are wider and have more soft particles than quark-initiated jets of the same p_T (C_A/C_F).
    - Modelling of underlying particle spectrum in jets therefore matters a lot!
    - Previously, this unc. had been taken as the difference in the gluon-initiated jet response between **Pythia** and **Herwig**.

- ***What's really driving this difference?***

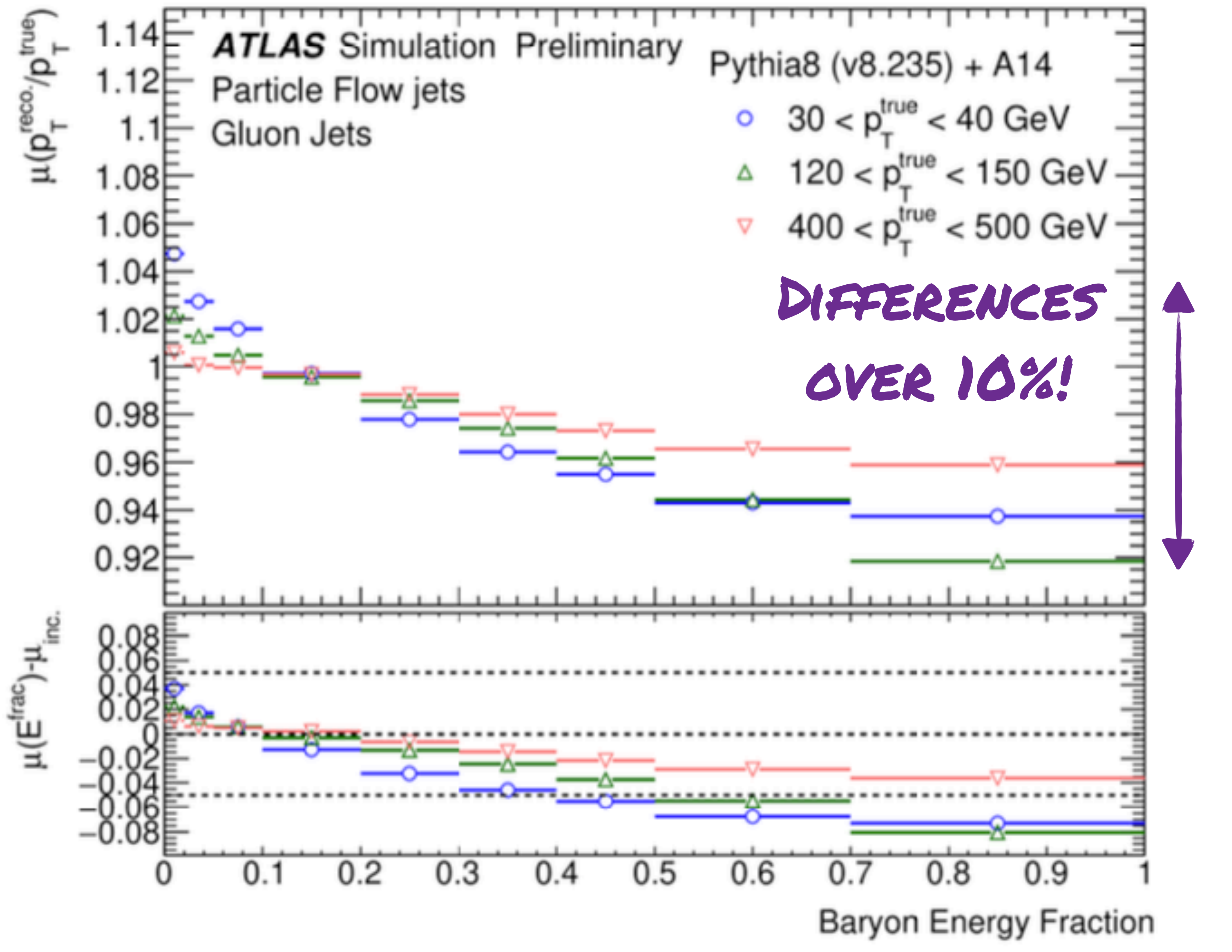


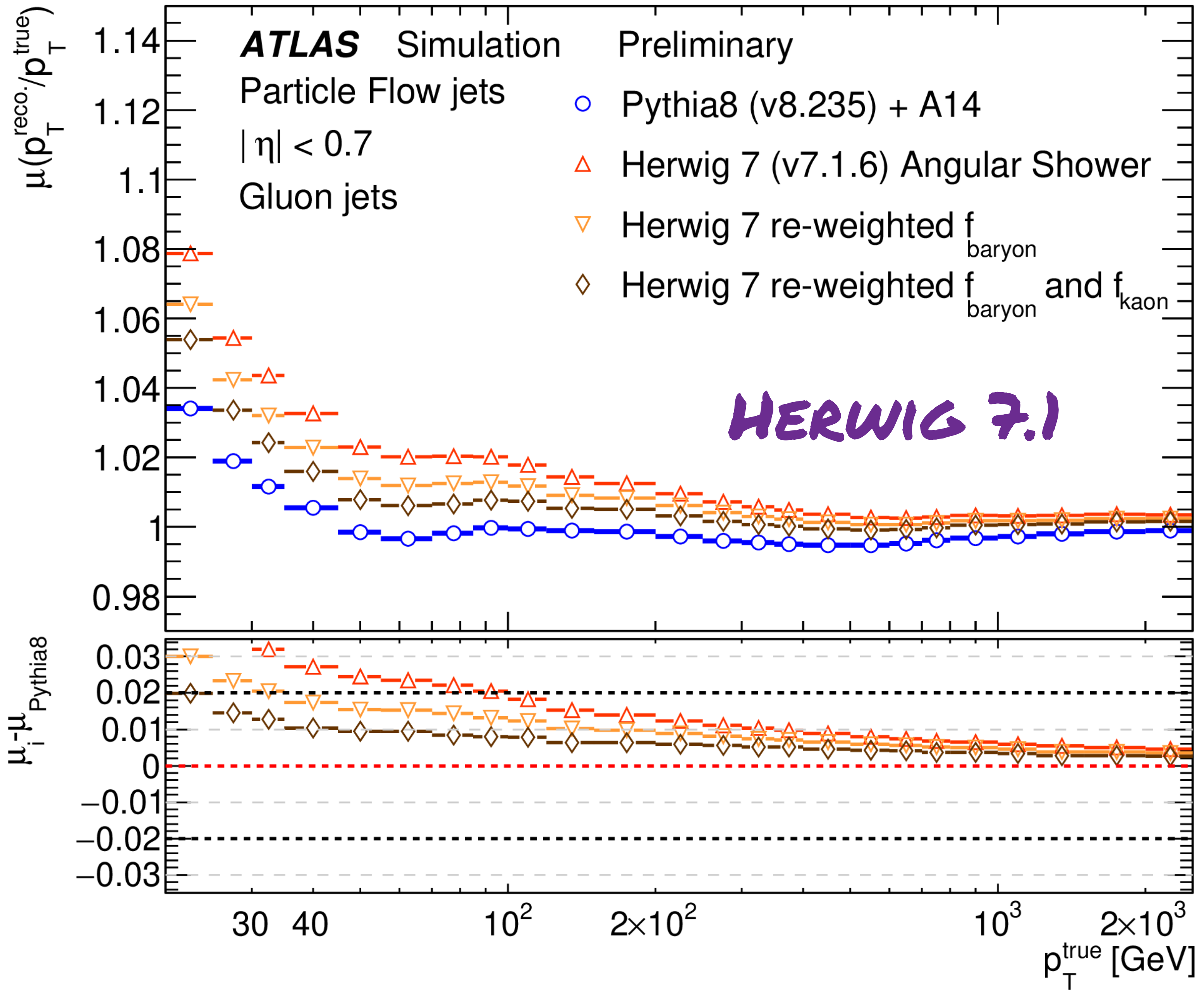


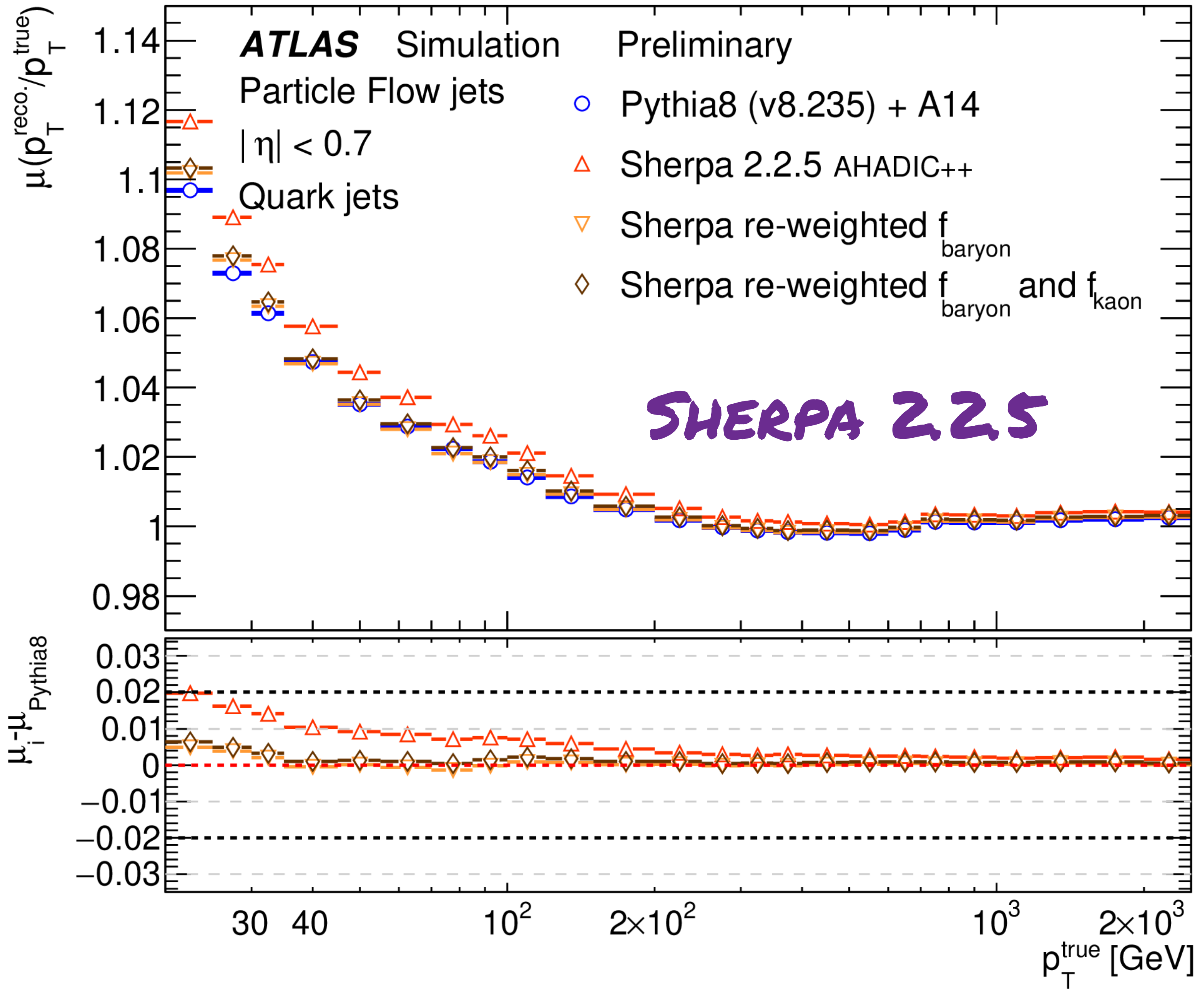
Reweighting baryon fractions

ATLAS, ATL-PHYS-PUB-2022-021

- JES is sensitive to the underlying jet **Baryon & Kaon fractions**.
  - **Variations over 10%** in Pythia as a function of Baryon fraction!
- Differences in baryon/kaon fraction partially drive the differences between generators
  - Seen by re-weighting
  - We need to use models that accurately represent available data…



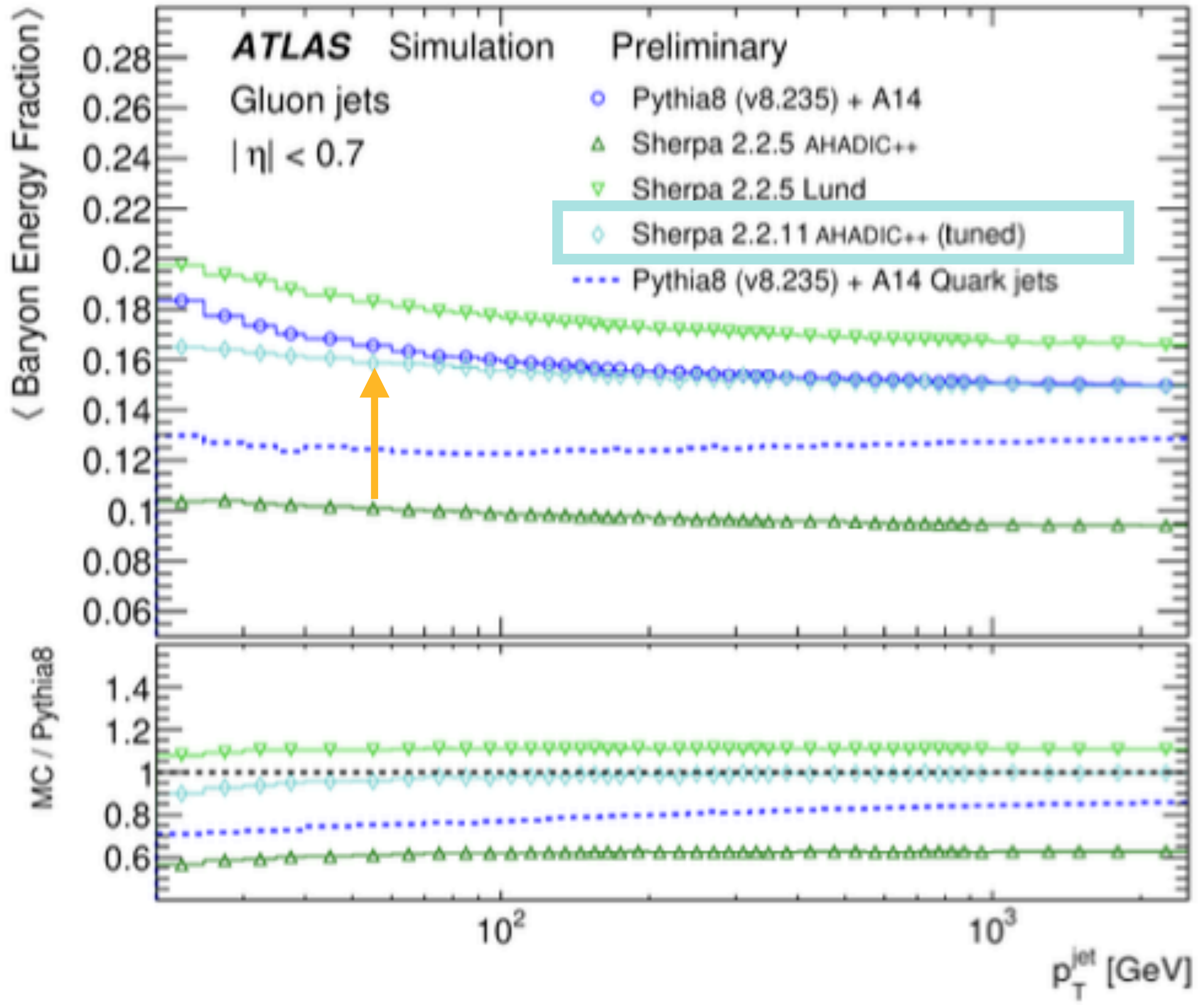


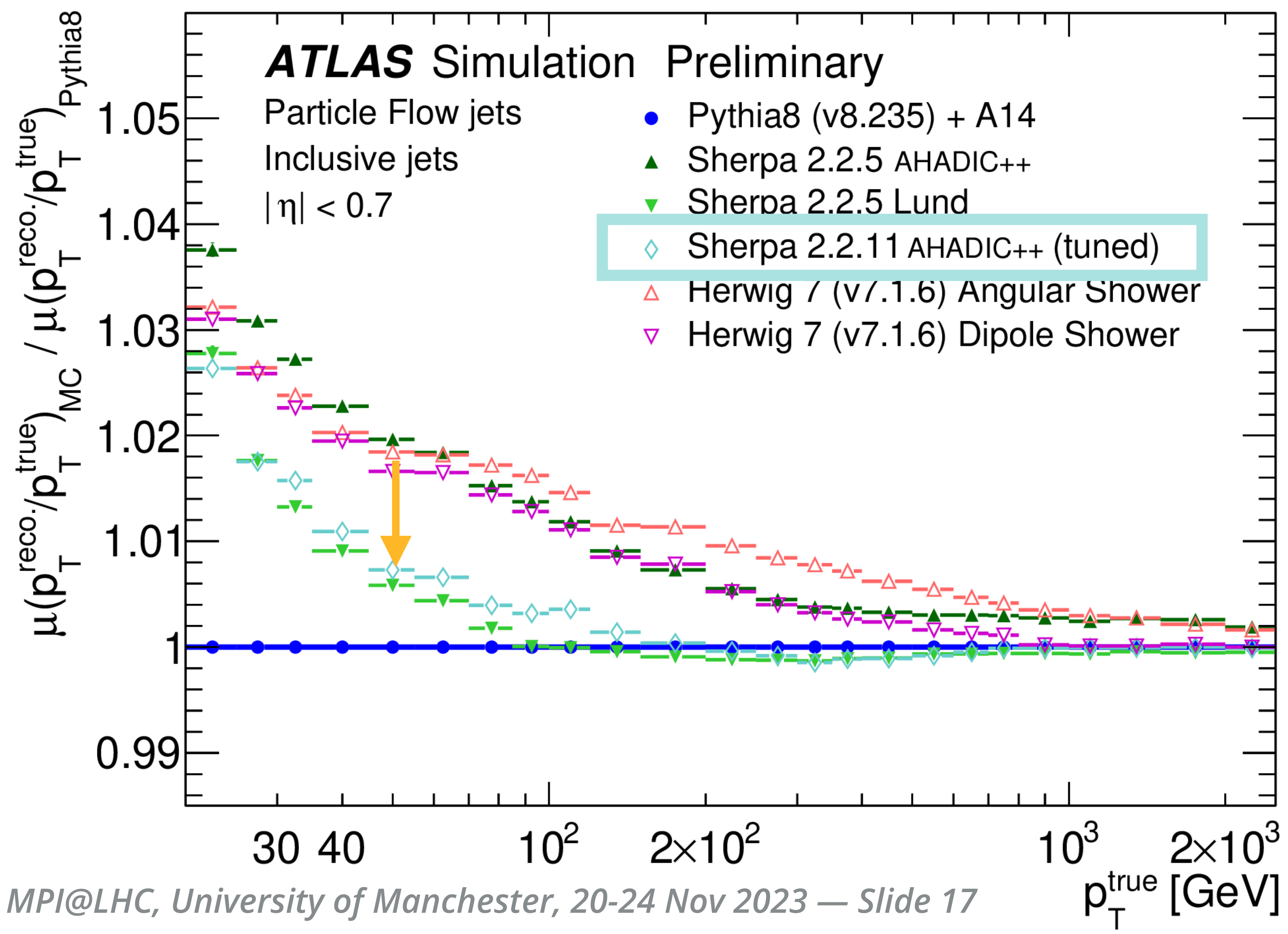


Impact of Sherpa 2.2.11 tune

ATLAS, [ATL-PHYS-PUB-2022-021]

- New Sherpa 2.2.11 tune, based on LEP data, results in Baryon fractions much closer to Pythia 8.1!

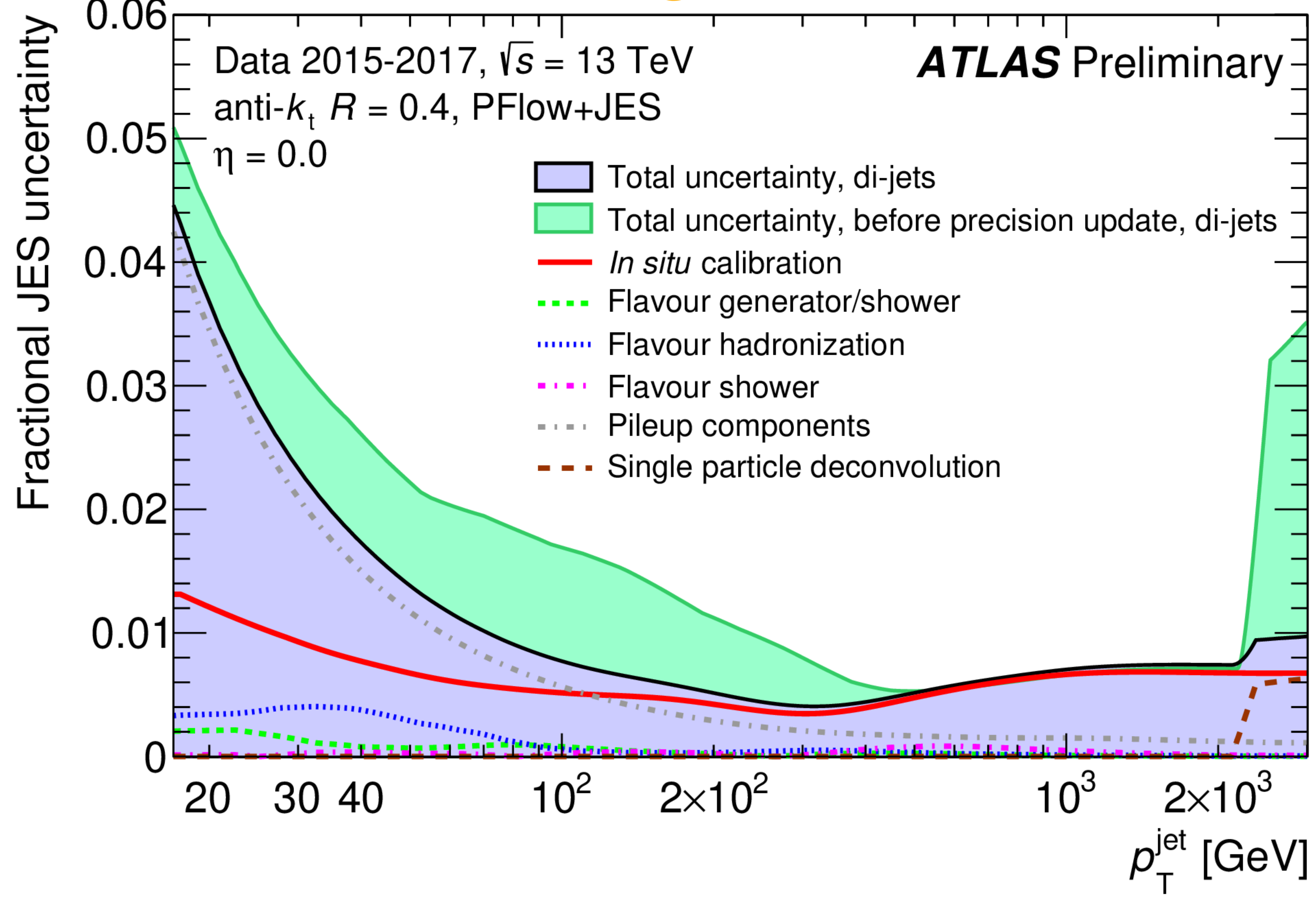




The *updated* jet energy scale uncertainties

ATLAS, JETM-2023-005; ATLAS & CMS, 1902.10229

Run 2 ‘legacy’ JES



- Updated uncertainties result in a percent-level JES in ATLAS above ~60 GeV in the central region!

- **Flavour response uncertainty updated** in ATLAS to use **three factorised comparisons,** rather than one catch-all:

Flavour generator/shower

Pythia8 [1] *vs*.
Sherpa v2.2.5 w/ Lund hadronisation (Pythia 6) [2][3]

Flavour hadronization

Sherpa v.2.2.11w/ AHADIC cluster hadronisation [2][4] (new tune [5]) *vs*.
Sherpa v2.2.5 w/ Lund hadronisation (Pythia 6)

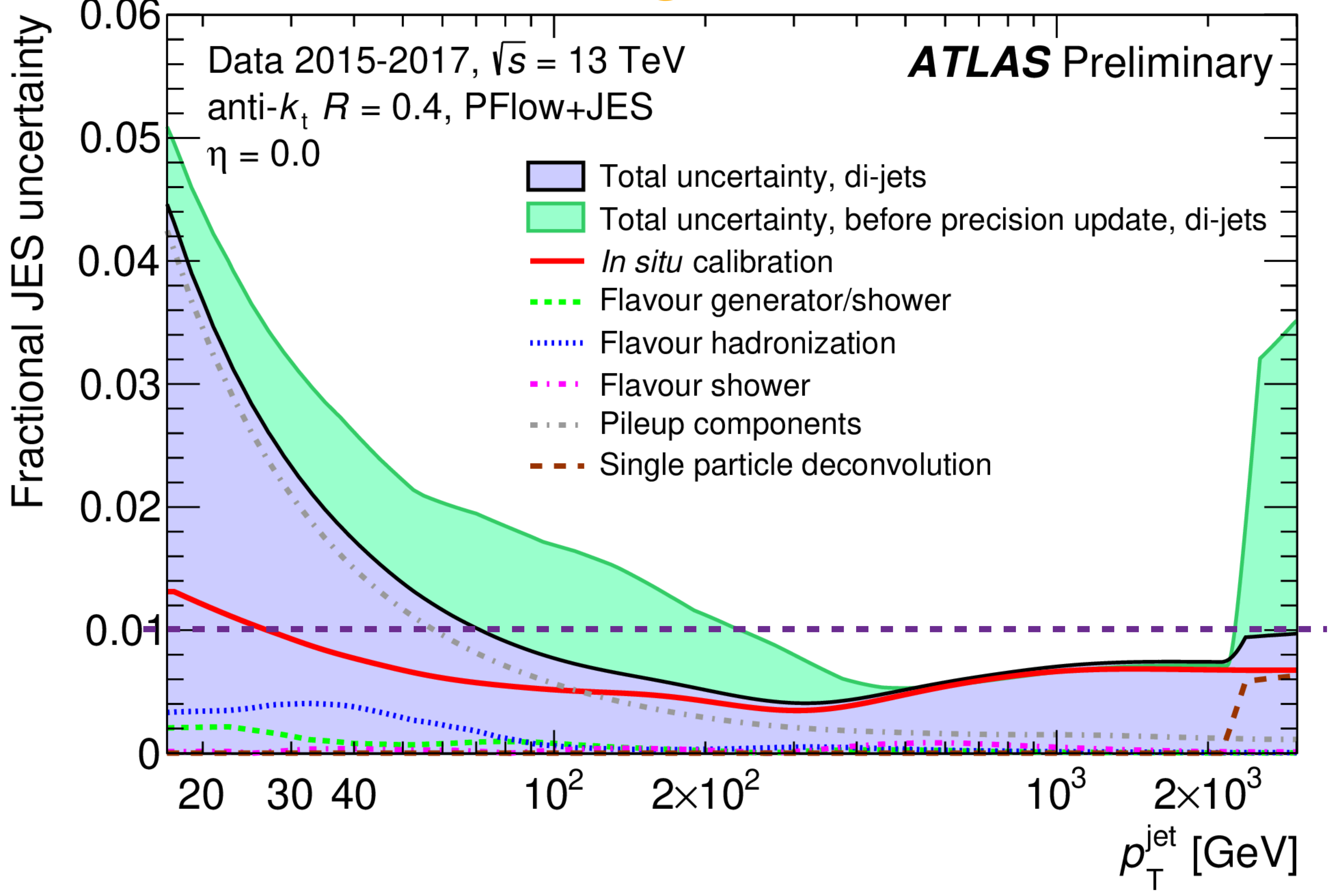
Flavour shower

Herwig7 angular parton shower [6][7] *vs*.
Herwig7 dipole parton shower [6][8] shower models

The *updated* jet energy scale uncertainties

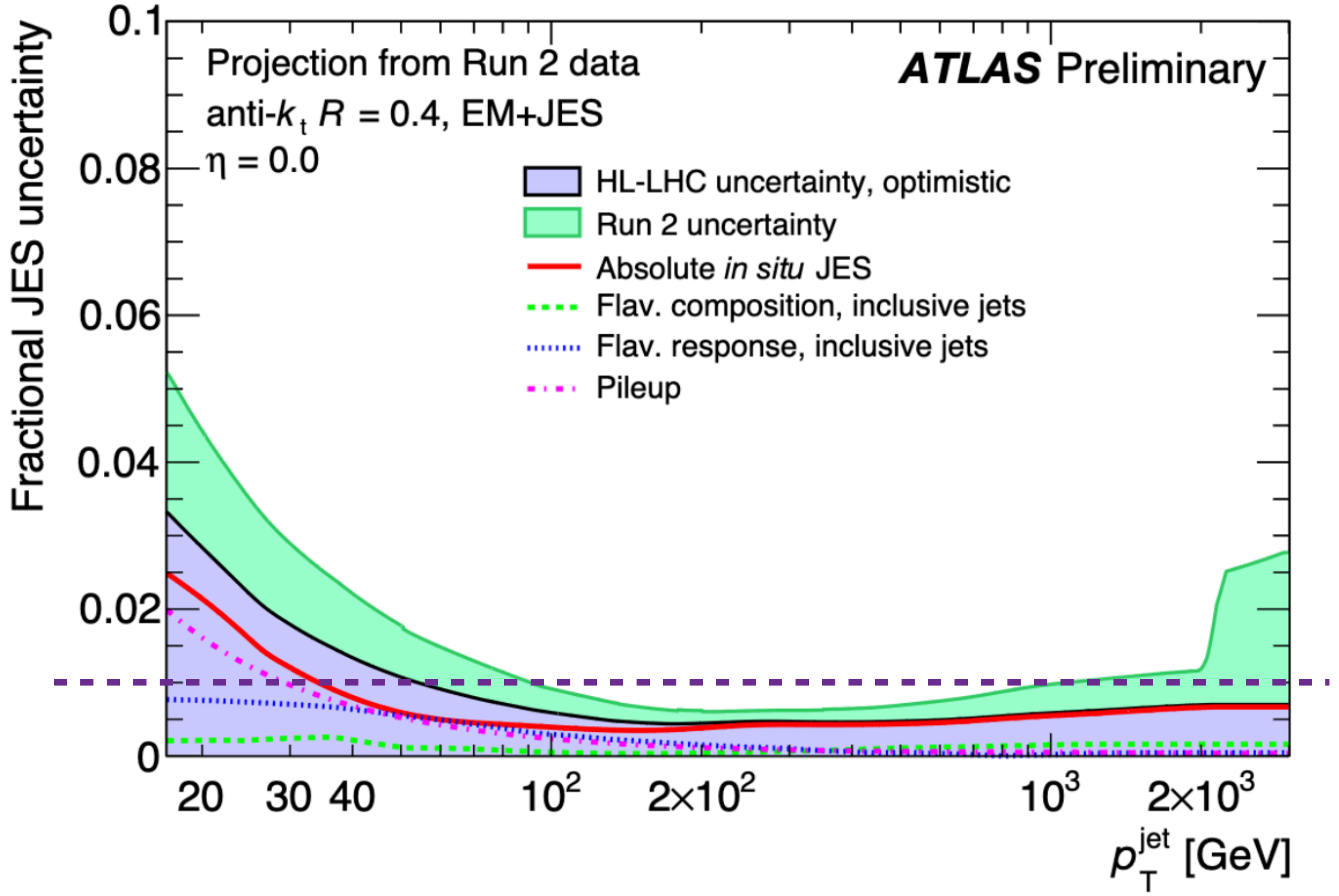
ATLAS, JETM-2023-005; ATLAS & CMS, 1902.10229

Run 2 'legacy' JES



- Updated uncertainties result in a percent-level JES in ATLAS above ~60 GeV in the central region!

Optimistic HL-LHC Projection



- Approaching 'optimistic' HL-LHC projections in Run 2 conditions: but Run 4 environment will be more difficult …
  - To see plans for improved pileup & *in situ* uncertainties, refer to ***ATLAS*** Eur. Phys. J. C (2023) 83:761

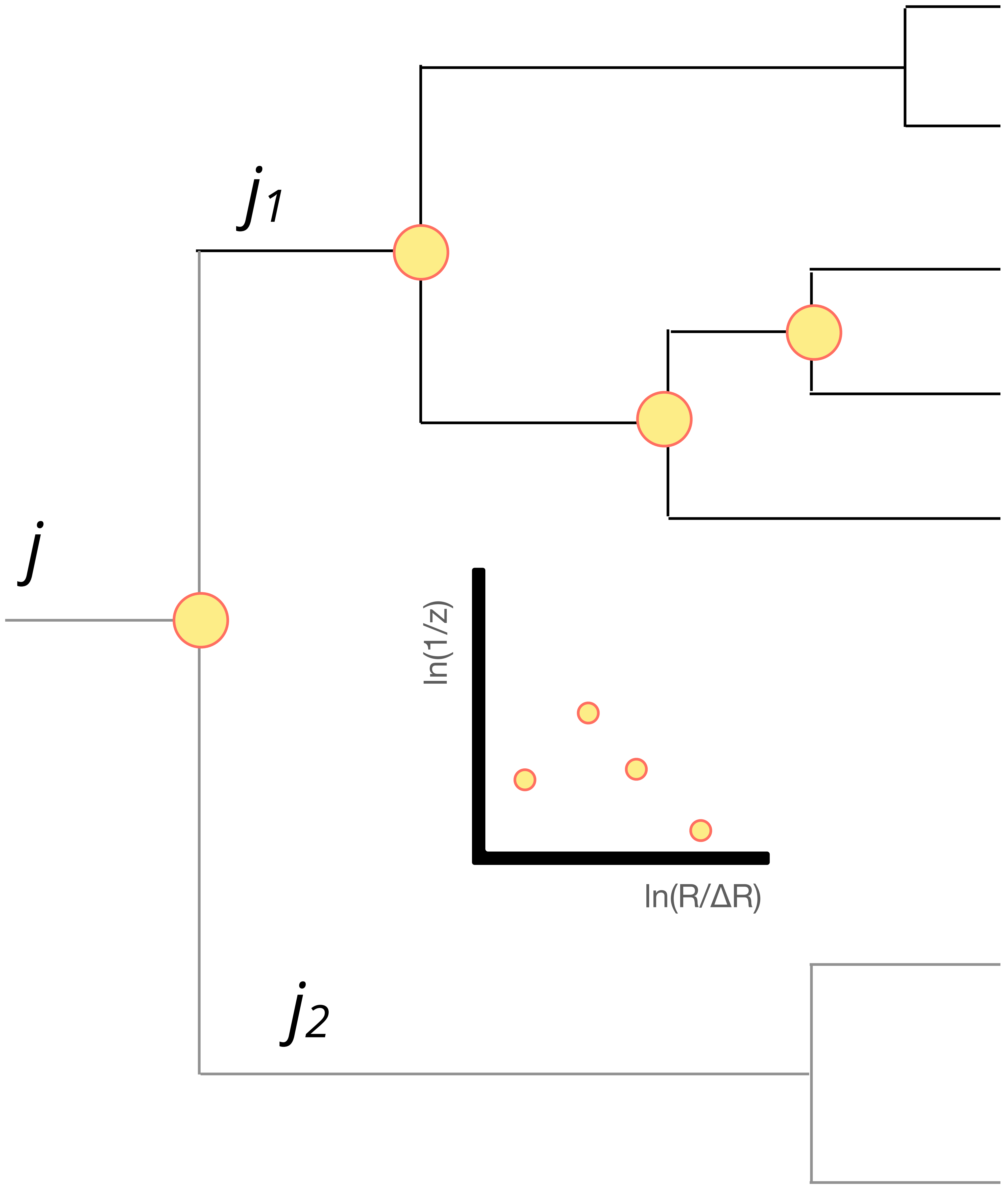
So — we're reducing the spread between PSMC predictions …

… but are they getting closer to data?

Lund jet plane

Dreyer, Salam & Soyez JHEP 12 (2018) 064

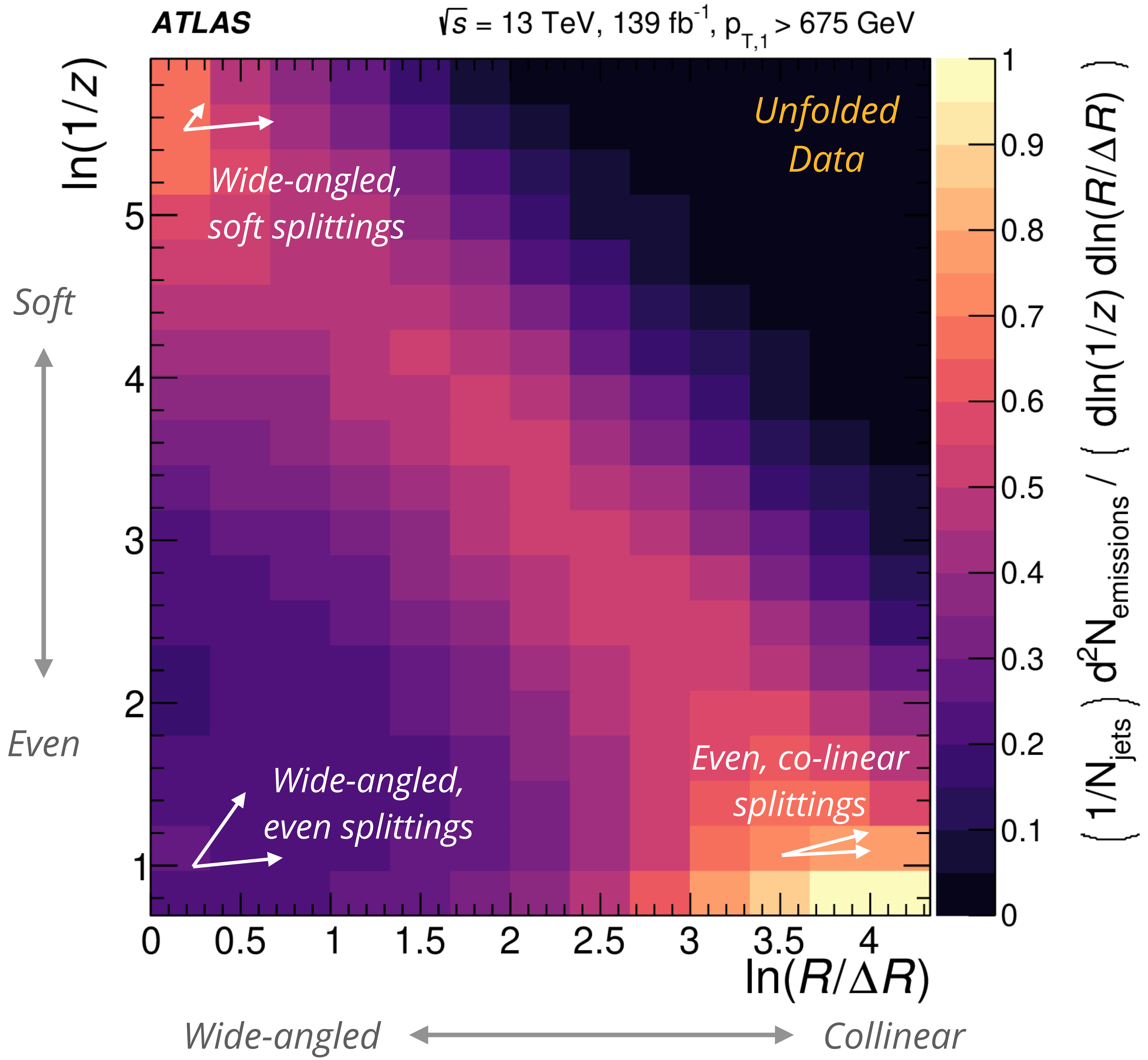
- **Lund Plane** : schema used by PSMC community for 34+ years (Andersson et al. Z.Phys.C 43 (1989) 625)
- Newly applied to JSS by **Dreyer *et al.***
  - **Key concept:** probe entire angle-ordered emission history of originating parton.
  - Parameterise emissions of **angle-ordered picture** in terms of their **relative energies (*z*)** and **angles (*ΔR*).**
- Powerful, physics-first representation of JSS:
  - ML/AI (1903.09644, 2012.08526),
    q/g tagging (2112.09140),
    PS development (1805.09327, 2205.02861),
    analytics (2007.06578),
    heavy-flavour (2106.05713, 2112.09650, 2202.05082)



Lund jet plane: data

ATLAS, PRL 124, 222002 (2020)

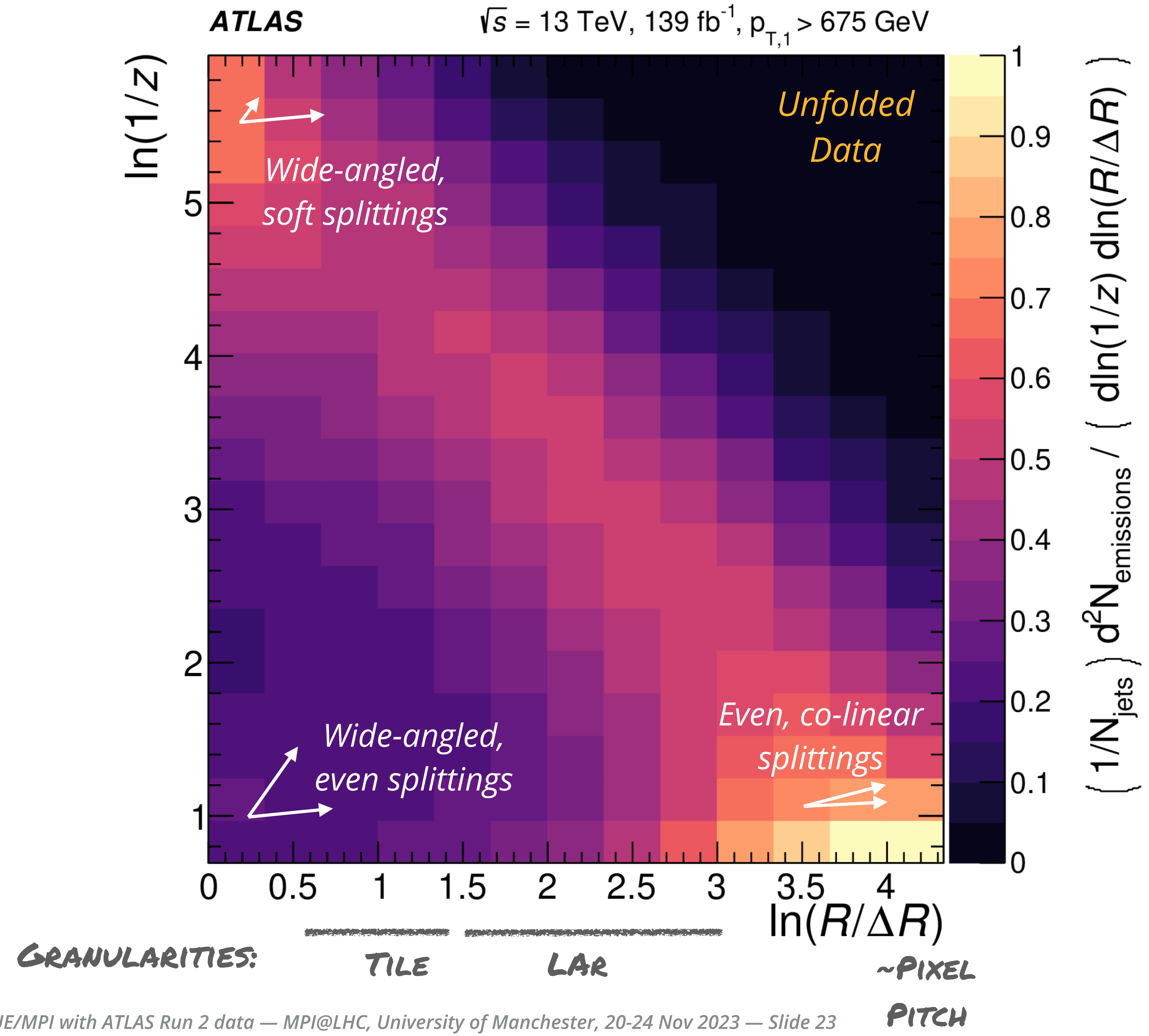
- Factorises different physics effects into different regions.
  - *Soft splittings vs. even splittings, wide-angled vs. collinear.*



Lund jet plane: data

ATLAS, PRL 124, 222002 (2020)

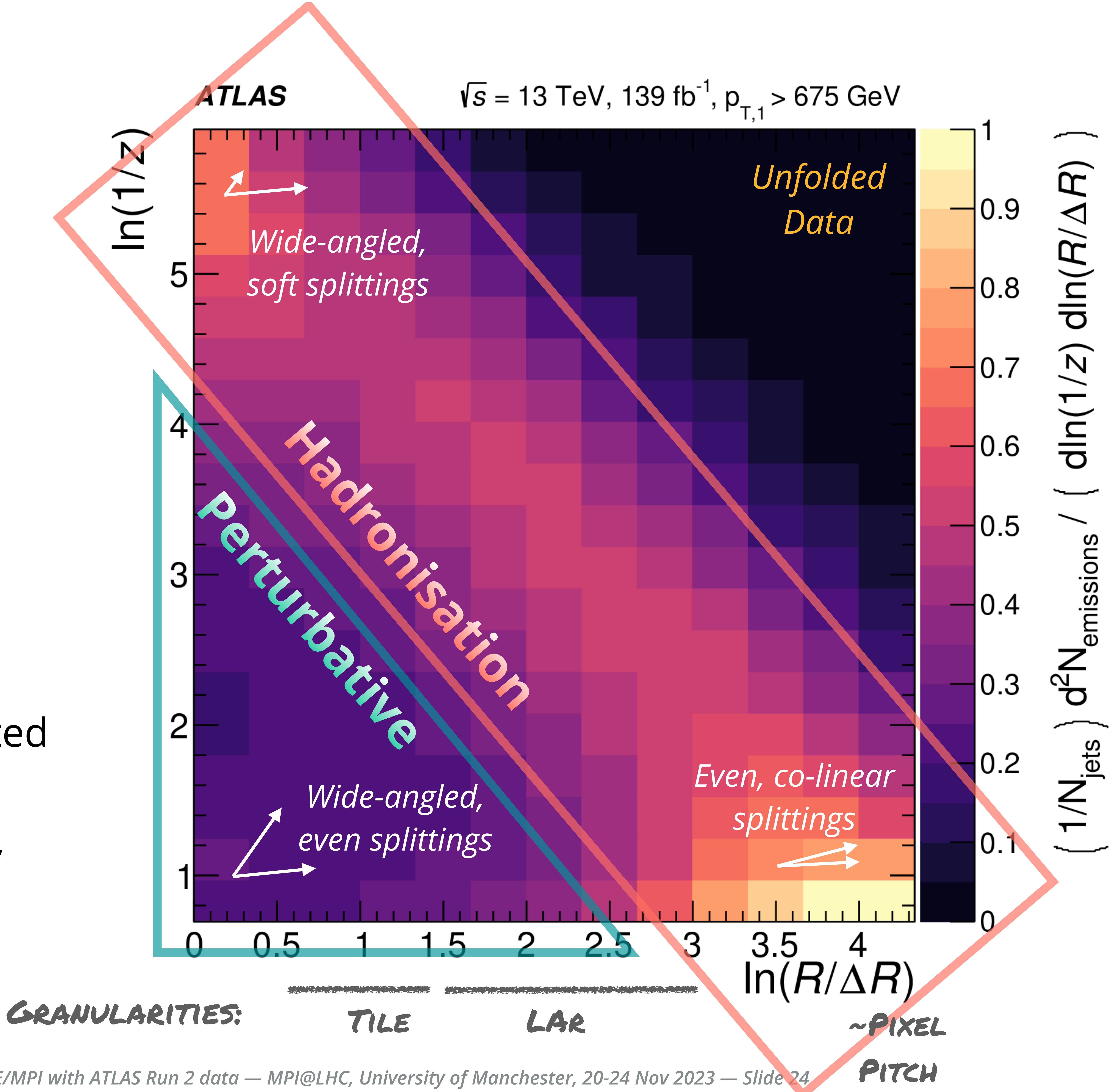
- Factorises different physics effects into different regions.
  - *Soft splittings vs. even splittings, wide-angled vs. collinear.*
- Calorimeter granularity is too coarse to resolve the most collinear splittings.
  - *Use tracks in jets → access smallest angular scales!*

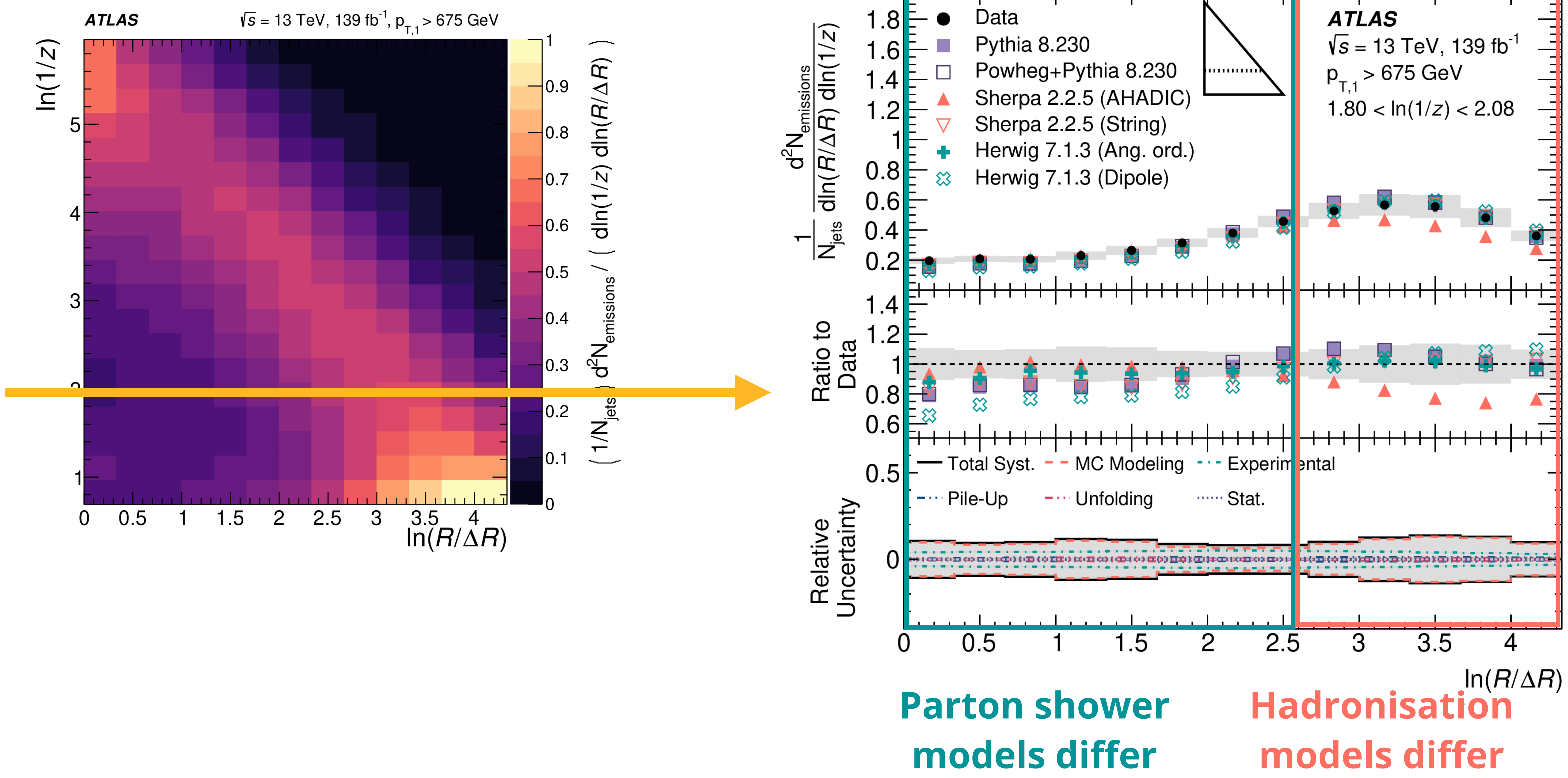


Lund jet plane: data

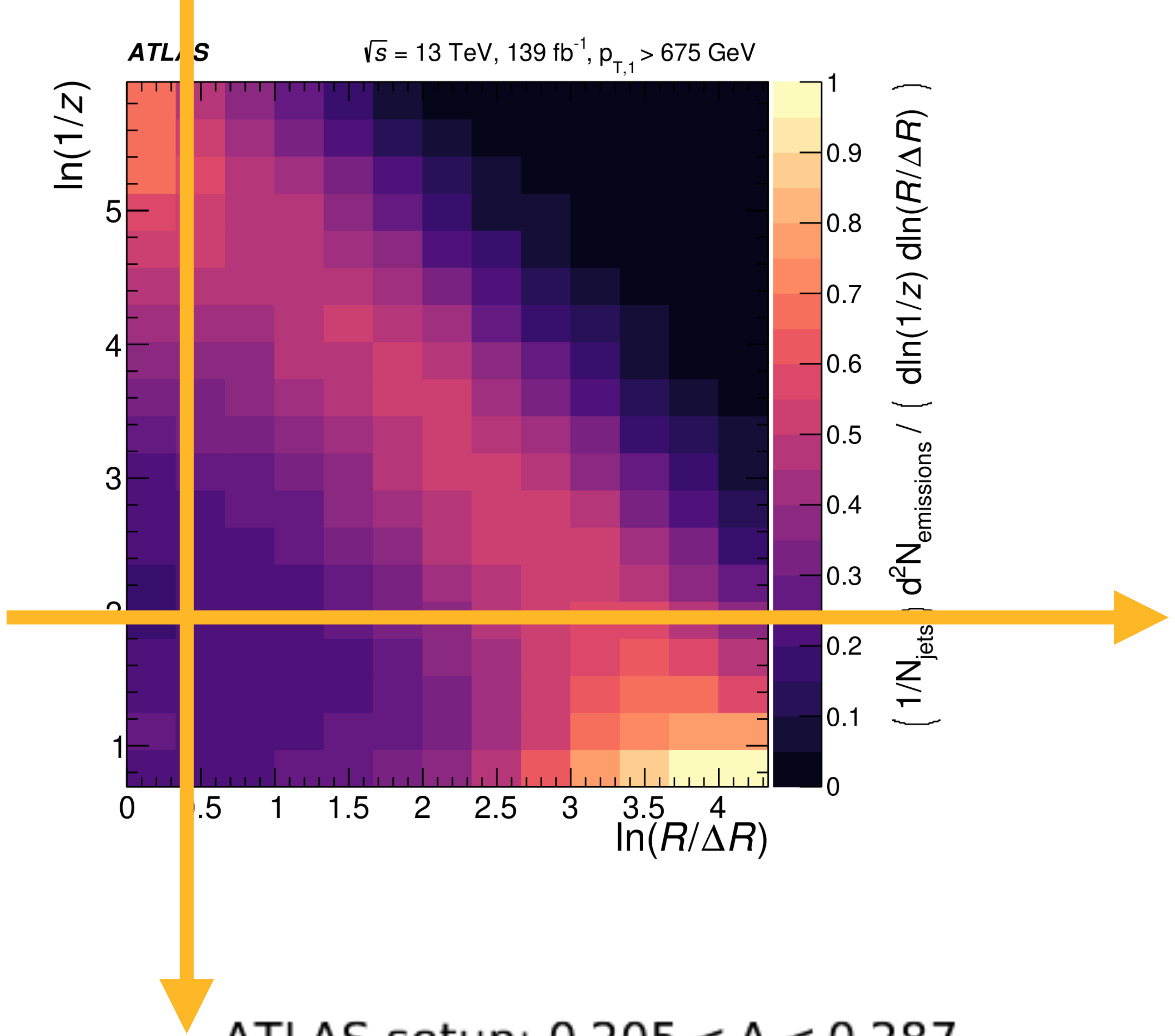
ATLAS, PRL 124, 222002 (2020)

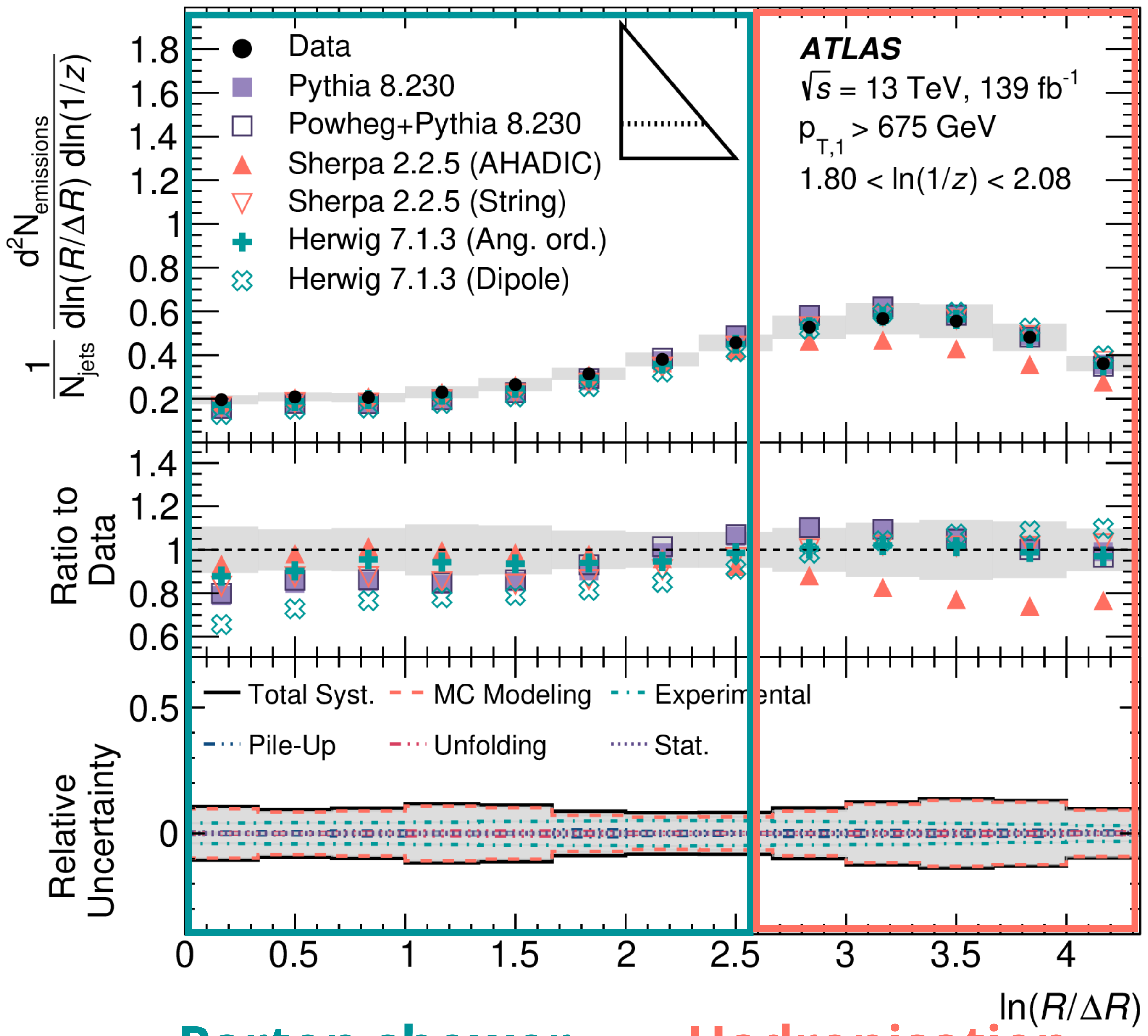
- Factorises different physics effects into different regions.
  - *Soft splittings vs. even splittings, wide-angled vs. collinear.*
- Calorimeter granularity is too coarse to resolve the most collinear splittings.
  - *Use tracks in jets → access smallest angular scales!*
- **Perturbative region,** uniformly populated (lower-left corner).
- **Non-Perturbative region,** enhanced by hadronisation (diagonal band).





- Easier to see factorised effects by slicing through LJP.
- Utility in data for improving MC models (*e.g.* hadronisation models → JES)
  - Can improve one aspect of simulation without disturbing another
  - Can mask non-perturbative aspects from classifiers

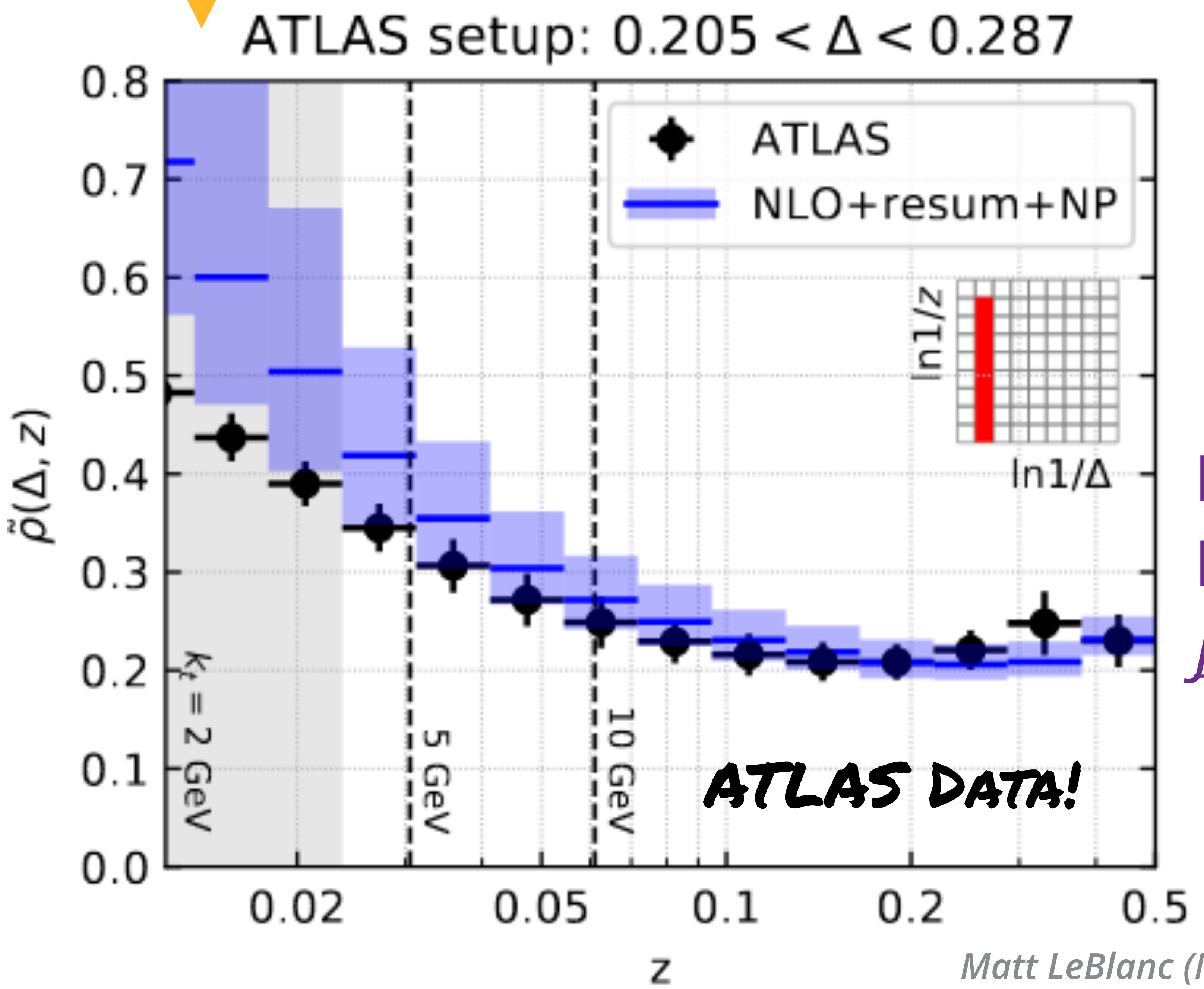




Parton shower models differ

Hadronisation models differ

- Easier to see factorised effects by slicing through LJP.
- Utility in data for improving MC models (*e.g.* hadronisation models → JES)
    - Can improve one aspect of simulation without disturbing another
    - Can mask non-perturbative aspects from classifiers



LJP @ NLL
Lifson, Salam, Soyez, *JHEP 10 (2020) 170*

- Calculation with NLL resummation compared to measured data
    - **Non-perturbative corrections small** despite charged-only measurement.
    - Predicton agrees well w/ data in perturbative region.

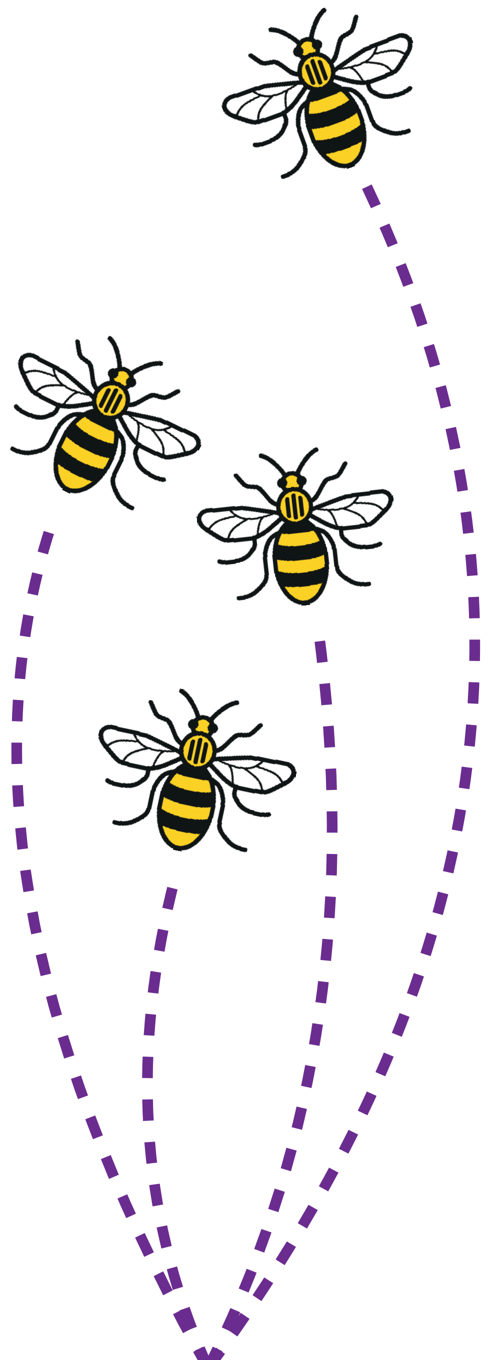
Many other JSS measurements at the LHC probe both hard & soft aspects of QCD!

Find them here:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCJetSubstructureMeasurements

Concluding remarks

- Multiple area of activity within ATLAS to improve understanding of non-perturbative QCD at the LHC. Some highlighted today:
  - New measurement of UE activity in ttbar events → **systematic comparisons of SOTA MC setups to LHC data.**
  - MC study of JES sensitivity to underlying particle spectra → better **understanding helped to substantially reduce JES uncertainty** related to PSMC modelling.
  - **Precision JSS measurements like the Lund jet plane are multi-faceted probes of QCD** → cleanly testing both perturbative- and non-perturbative aspects of jet formation.
- Hopeful that more **fruitful exchanges between experiment & theory** will result in more precise models and better understanding in the future!

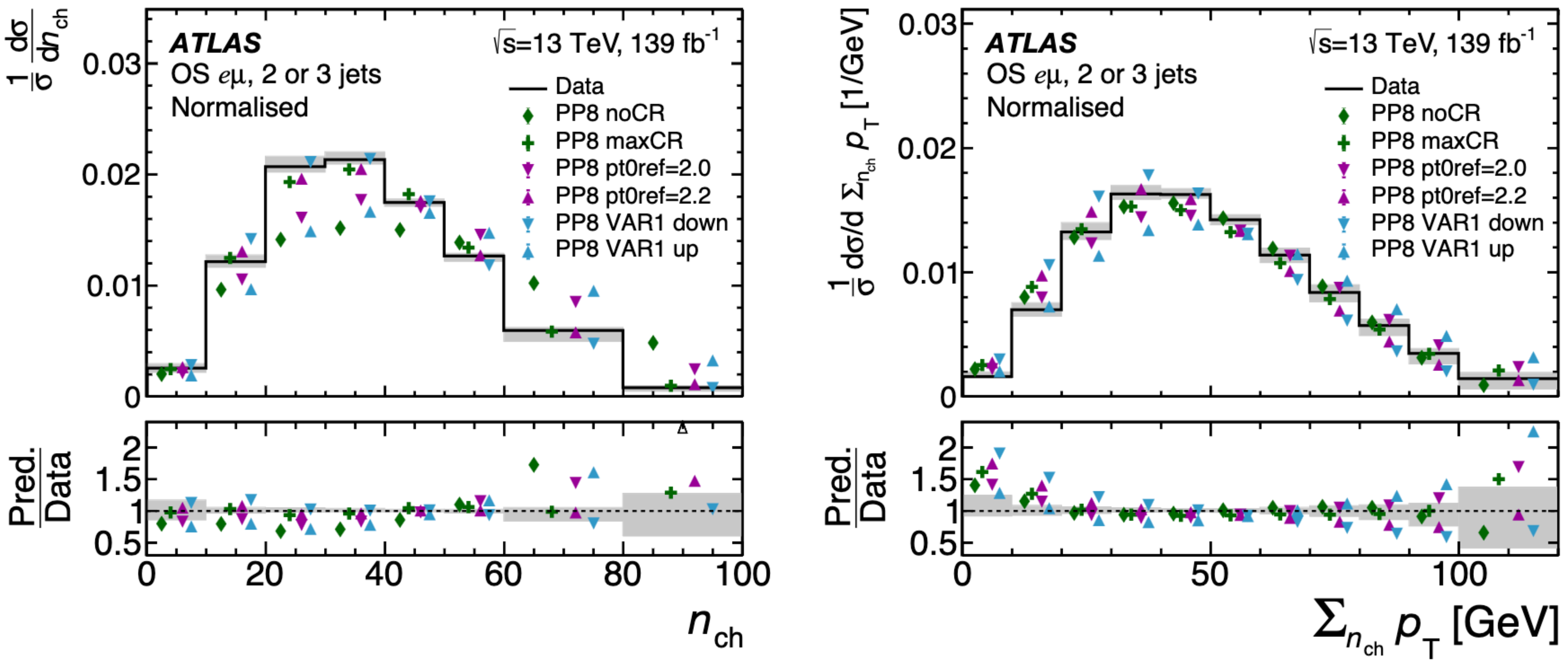


Questions?

Thanks for Listening!

Results: changing Pythia CR / UE parameters

ATLAS, Eur. Phys. J. C 83, 518 (2023)



Colour Reconnection Models

ATLAS, Eur. Phys. J. C 83, 518 (2023)

Observable	n_{ch}	$\sum_{n_{ch}} p_T$	Global(n_{ch},$\sum_{n_{ch}} p_T$)	$\sum_{n_{ch}} p_T$ in bins of n_{ch}
NDF	7	10	17	8
Generator set-up			χ^2	
POWHEG+PYTHIA 8.230	62	106	434	224
CR0	55	113	629	129
CR1	98	60	581	158
CR2	58	179	402	238
POWHEG+HERWIG 7.0.4	39	16	145	29
POWHEG+HERWIG 7.1.3	53	42	188	41
POWHEG+HERWIG 7.2.1	78	25	313	87
POWHEG+HERWIG Baryonic CR	75	20	241	29
POWHEG+HERWIG Stat CR	23	40	121	39
SHERPA 2.2.10	77	211	263	124