

From the LHC to the Cosmos: ATLAS p+O minbias measurements

Lydia Beresford (DESY)

QCD@LHC 2026

28 September 2026

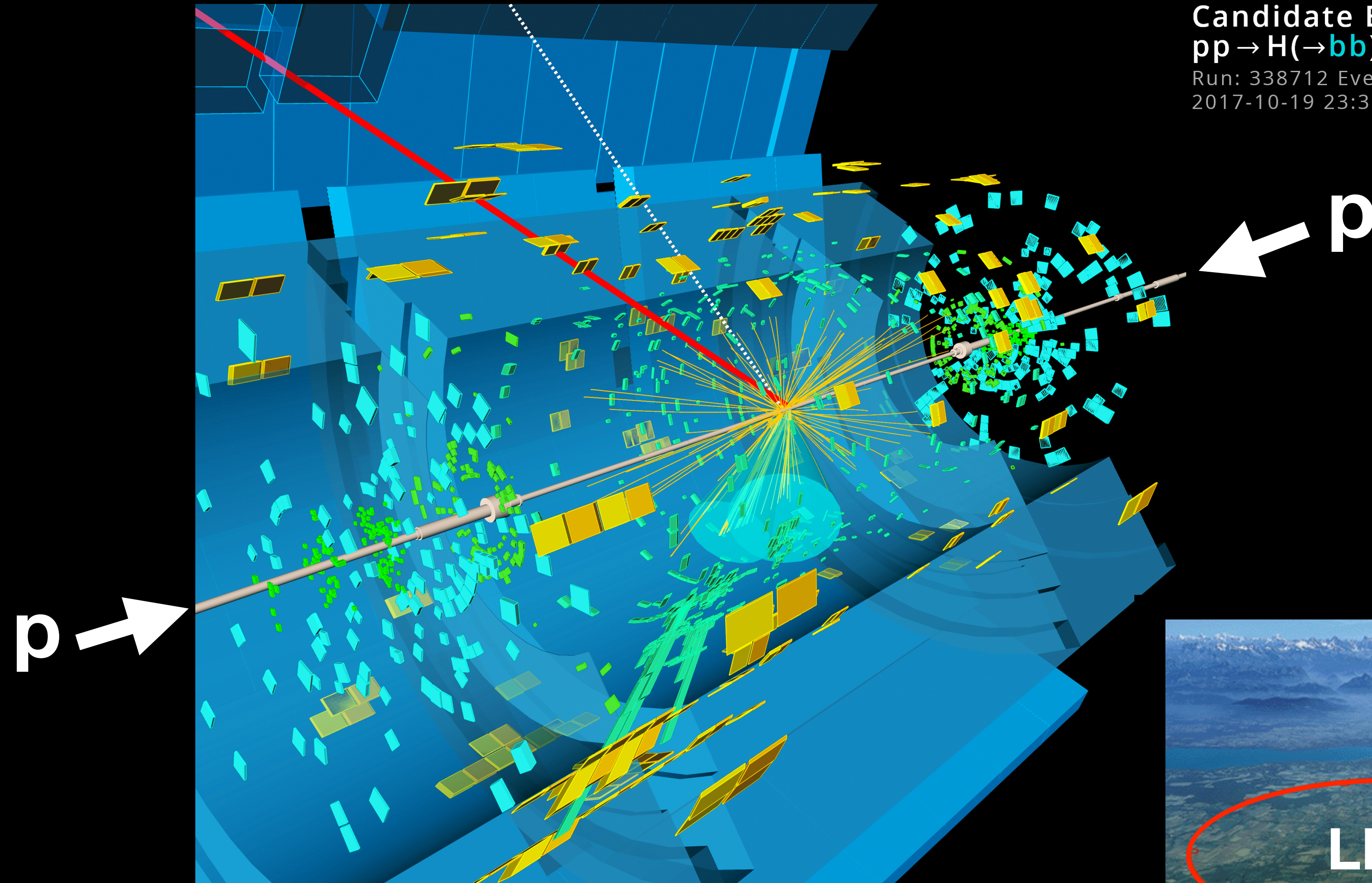


ATLAS
EXPERIMENT



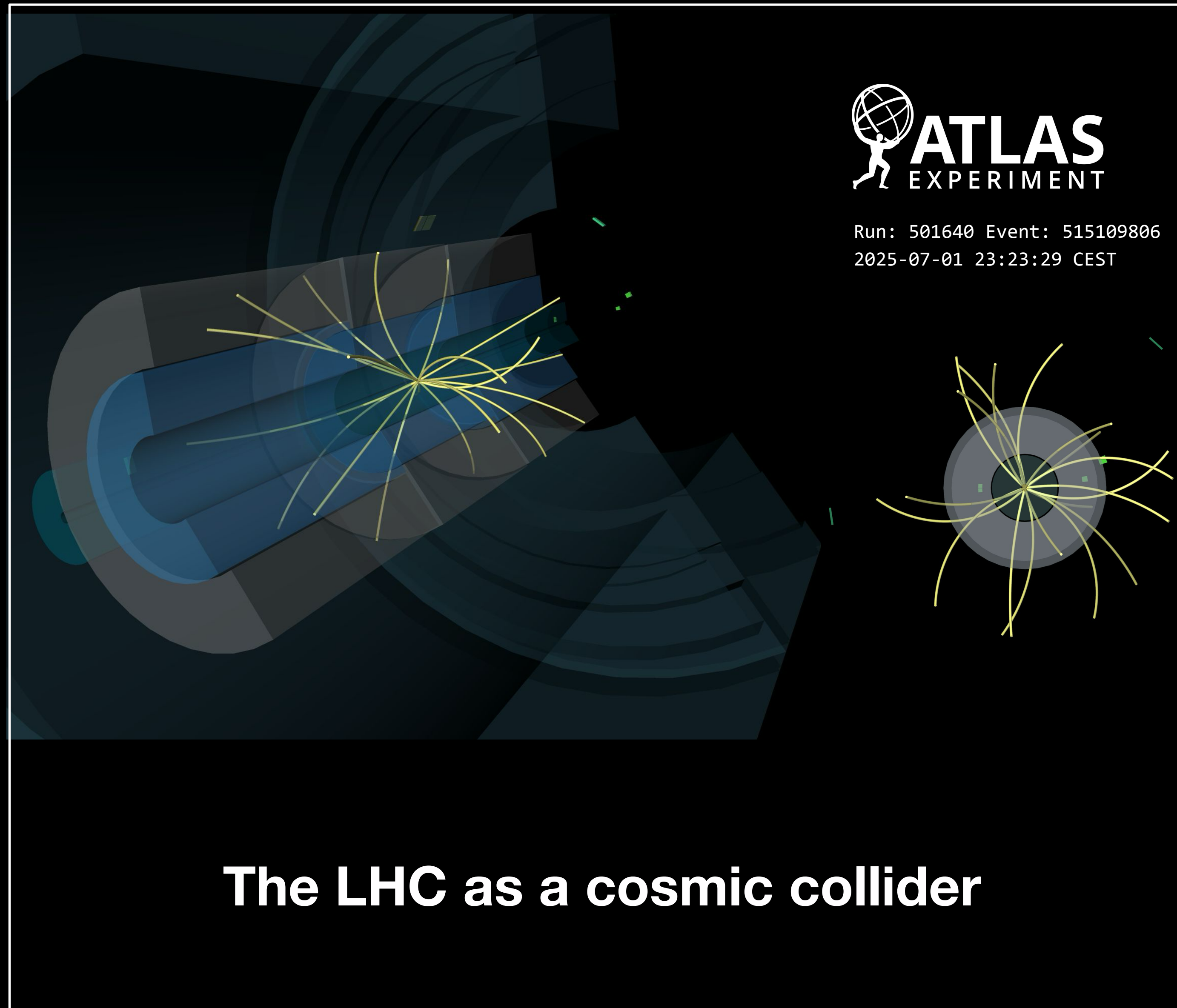
From the LHC to the cosmos

 **ATLAS**
EXPERIMENT
Candidate Event:
 $pp \rightarrow H(\rightarrow b\bar{b}) + W(\rightarrow \mu\nu)$
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST



World's highest energy **hadron** collider

Outline



Cosmic collisions

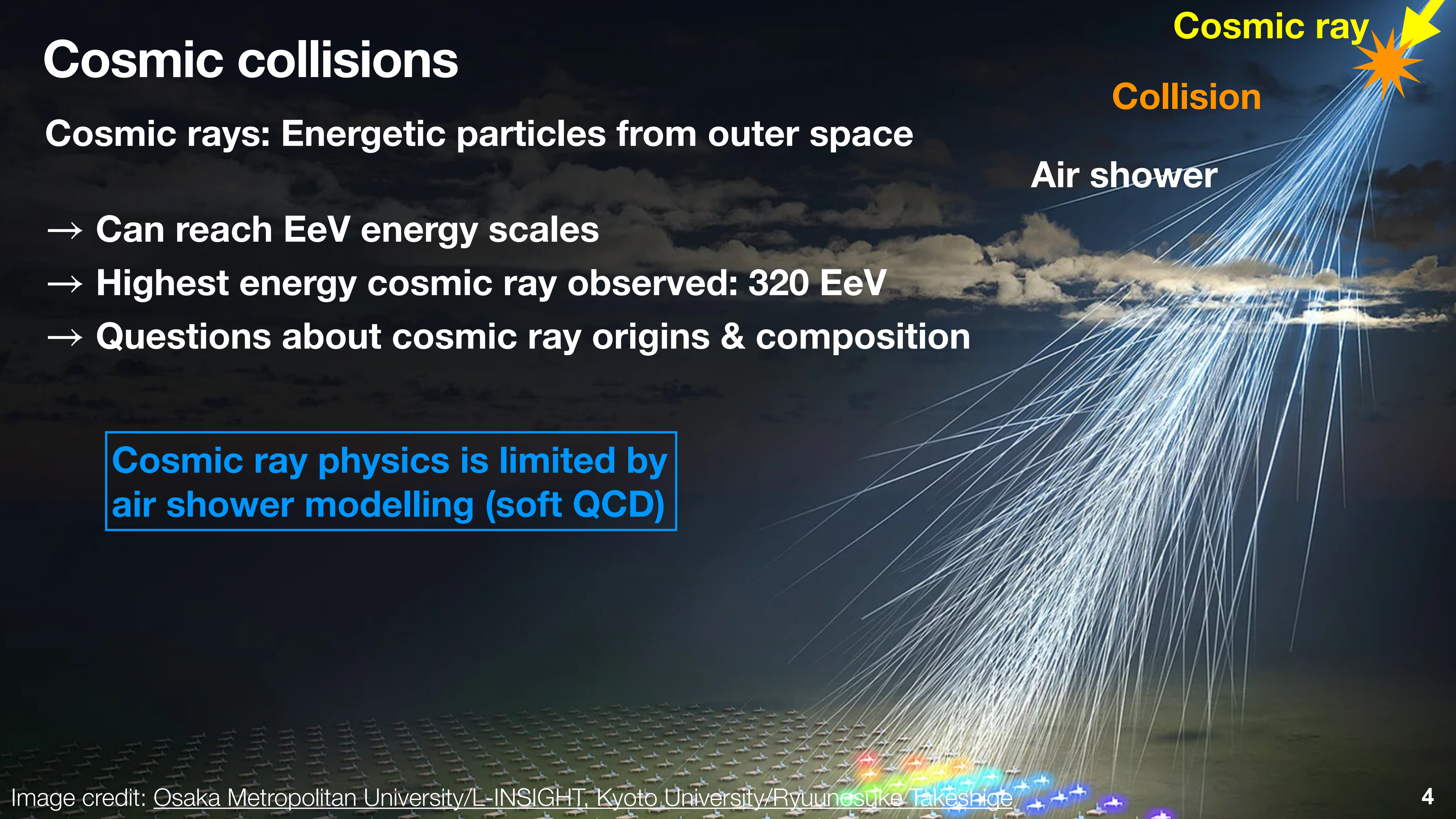
Cosmic rays: Energetic particles from outer space

- **Can reach EeV energy scales**
- **Highest energy cosmic ray observed: 320 EeV**
- **Questions about cosmic ray origins & composition**

**Cosmic ray physics is limited by
air shower modelling (soft QCD)**

Cosmic ray
Collision

Air shower



Soft QCD

Soft QCD in the sky!

Key area where knowledge of fundamental processes is limited

Theoretically:

- Beyond perturbative QCD regime
- Employ phenomenological models with tunable parameters

Measurements are vital

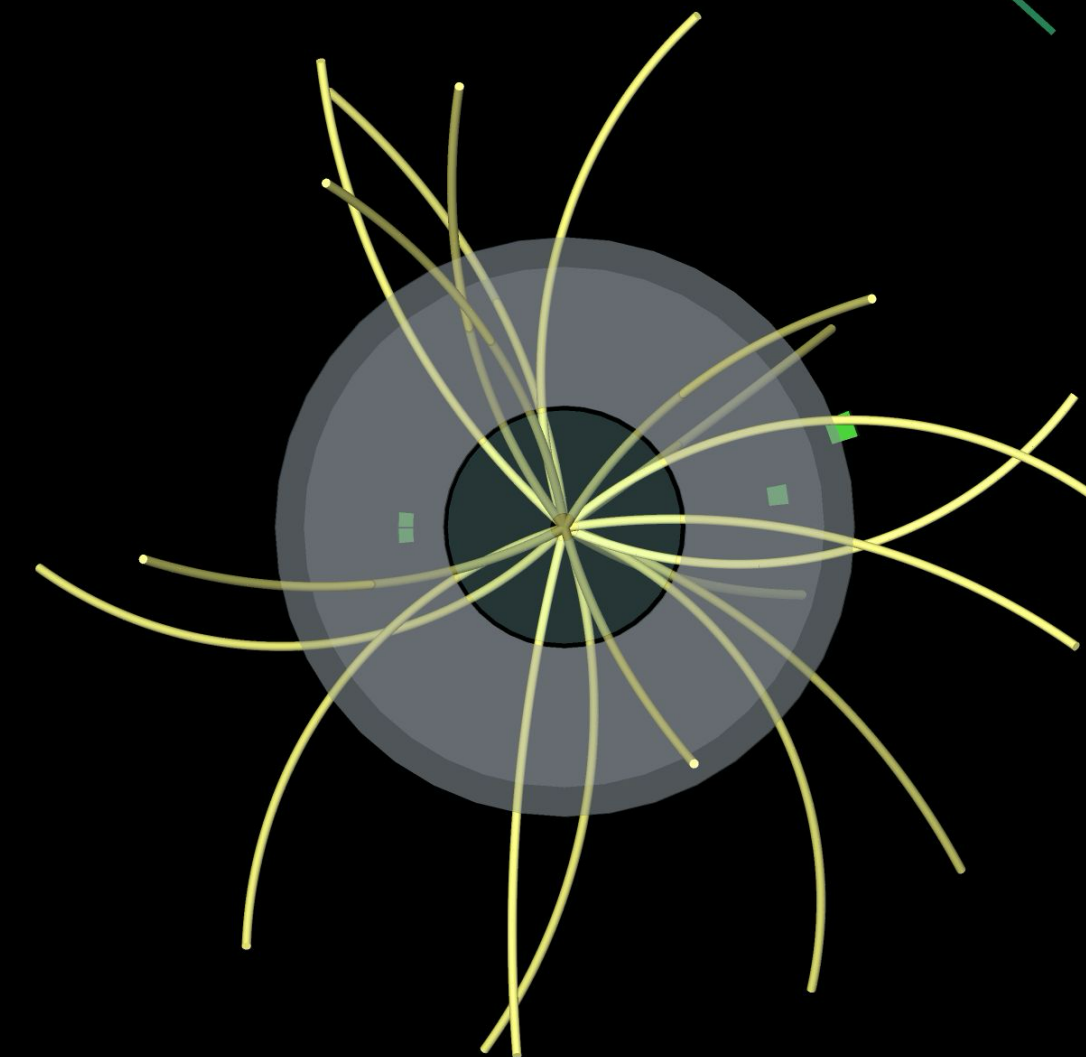
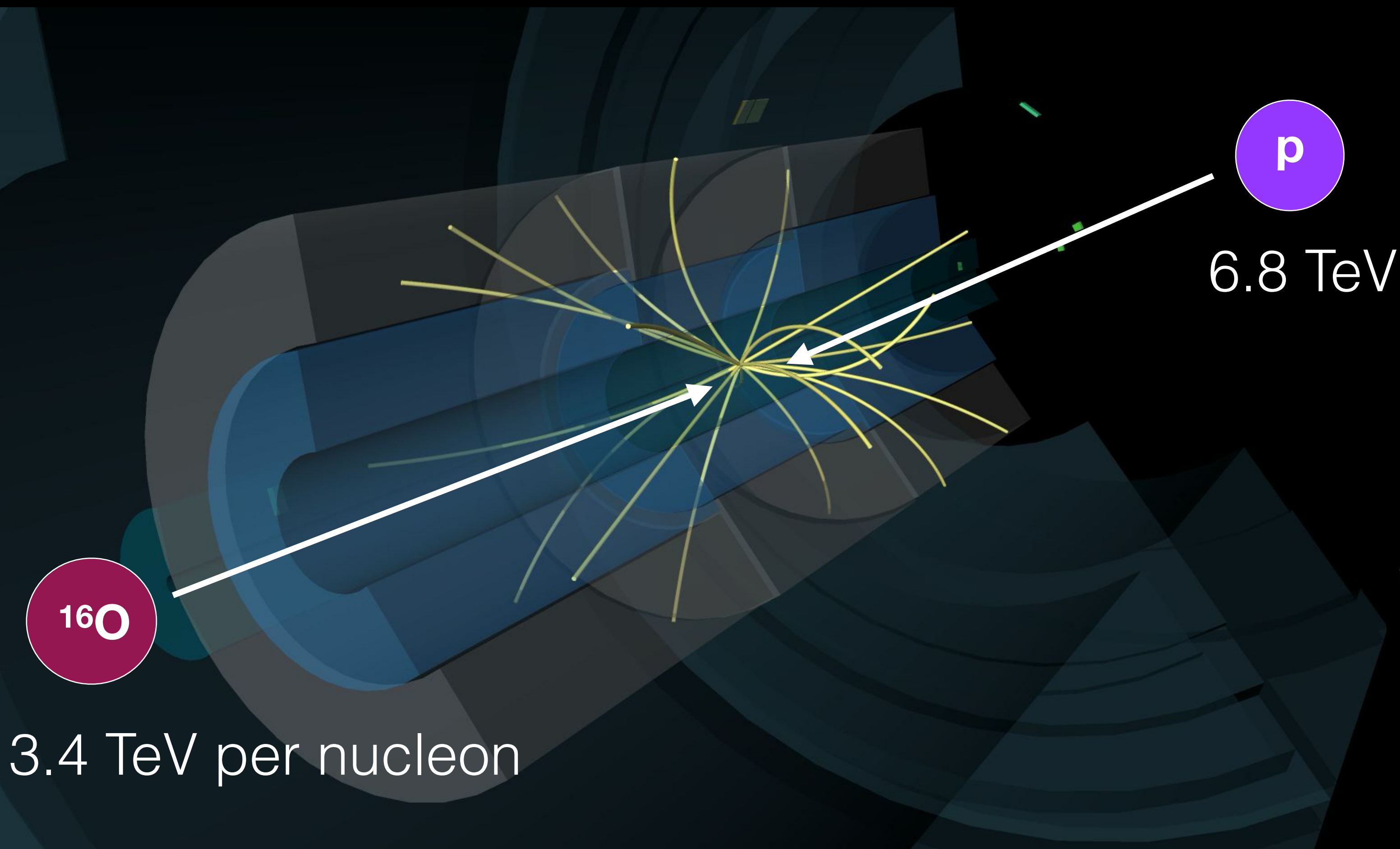
From the cosmos to the LHC

In July 2025 LHC became world's highest energy
proton-Oxygen collider $\sqrt{s_{NN}} = 9.62 \text{ TeV}$

Equivalent fixed-target energy = 49 PeV



Run: 501640 Event: 515109806
2025-07-01 23:23:29 CEST

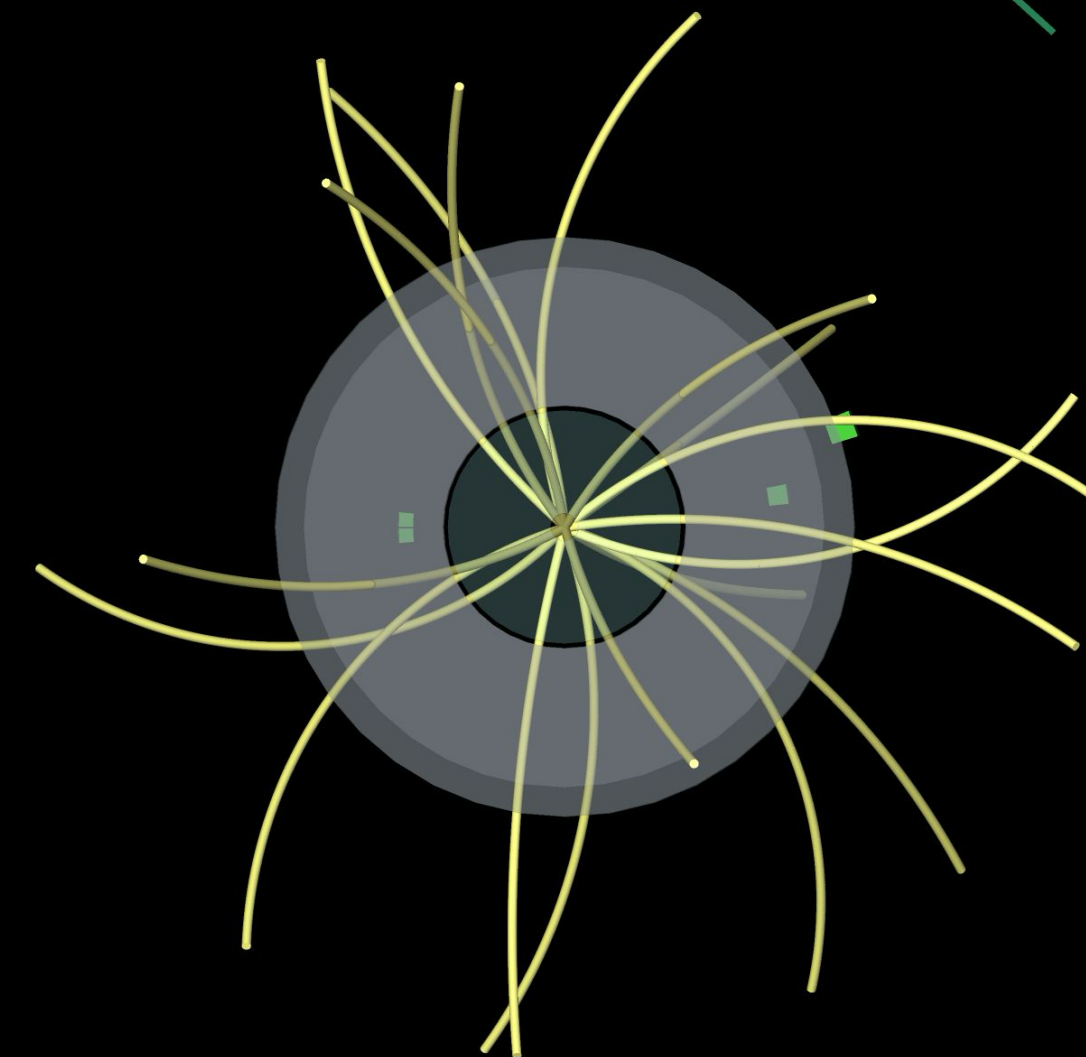
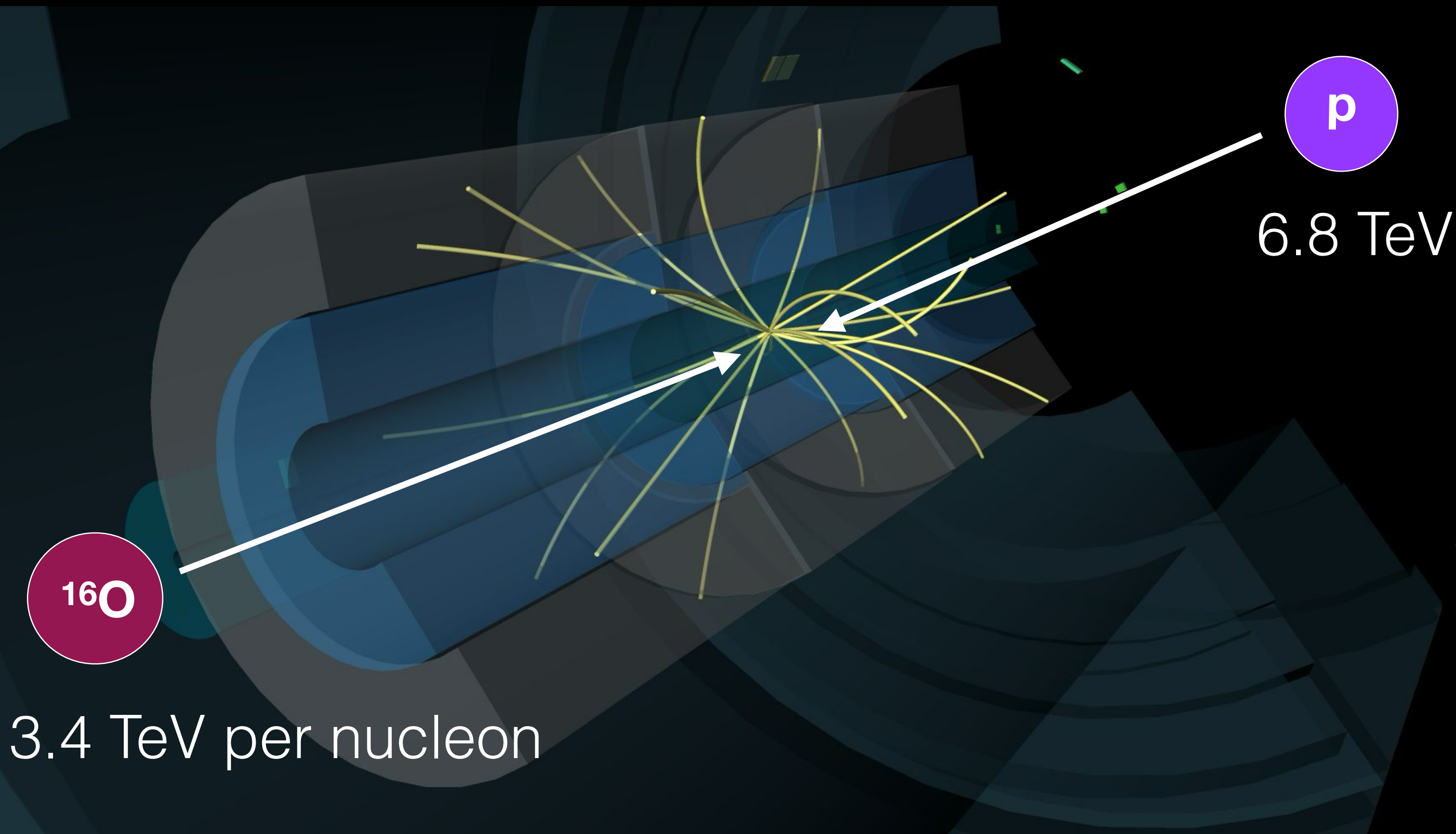


From the cosmos to the LHC

- Recreate physics of cosmic ray air showers in the lab
 - Models currently tuned to pp/p+Pb LHC data
 - Measure fundamental processes in p+O data
- Improve air shower modelling



Run: 501640 Event: 515109806
2025-07-01 23:23:29 CEST



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Measurement of Charged-Particle Production in $\sqrt{s_{\text{NN}}} = 9.62$ TeV Proton-Oxygen Collisions as a Probe of Cosmic-Ray Air Showers with the ATLAS Detector

[G. Aad](#) ¹⁰², [E. Aakvaag](#) ¹⁷, [B. Abbott](#) ¹²¹, [S. Abdelhameed](#) ^{83b}, [K. Abeling](#) ⁵⁴, [N.J. Abicht](#) ⁴⁸, [S.H. Abidi](#) ³⁰, [M. Aboelela](#) ⁴⁴, [A. Aboulhorma](#) ^{36e} *et al.* (ATLAS Collaboration)

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DOI: <https://doi.org/10.1103/f3nk-5lt9>

[ATLAS physics briefing](#)
[CERN news article](#)

From the cosmos to the LHC

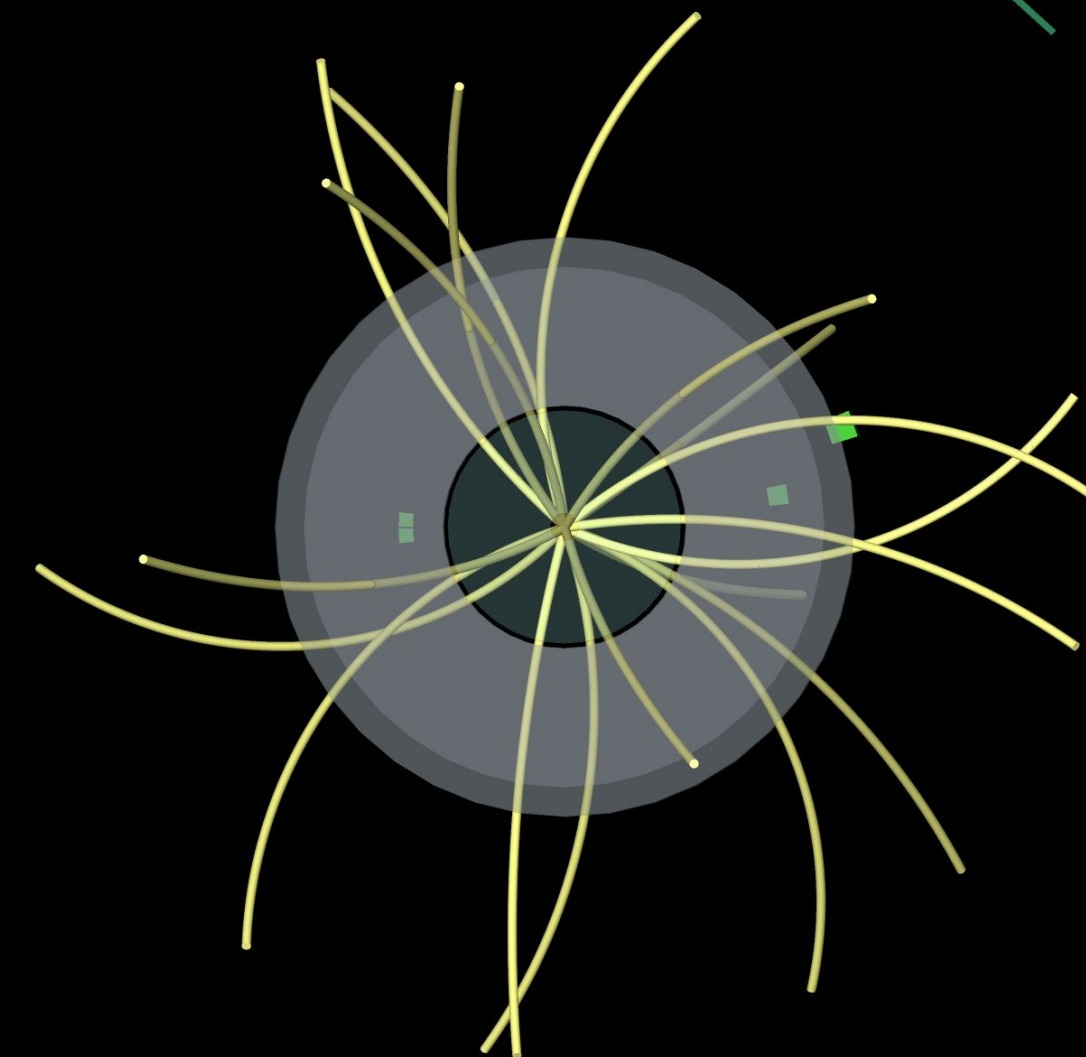
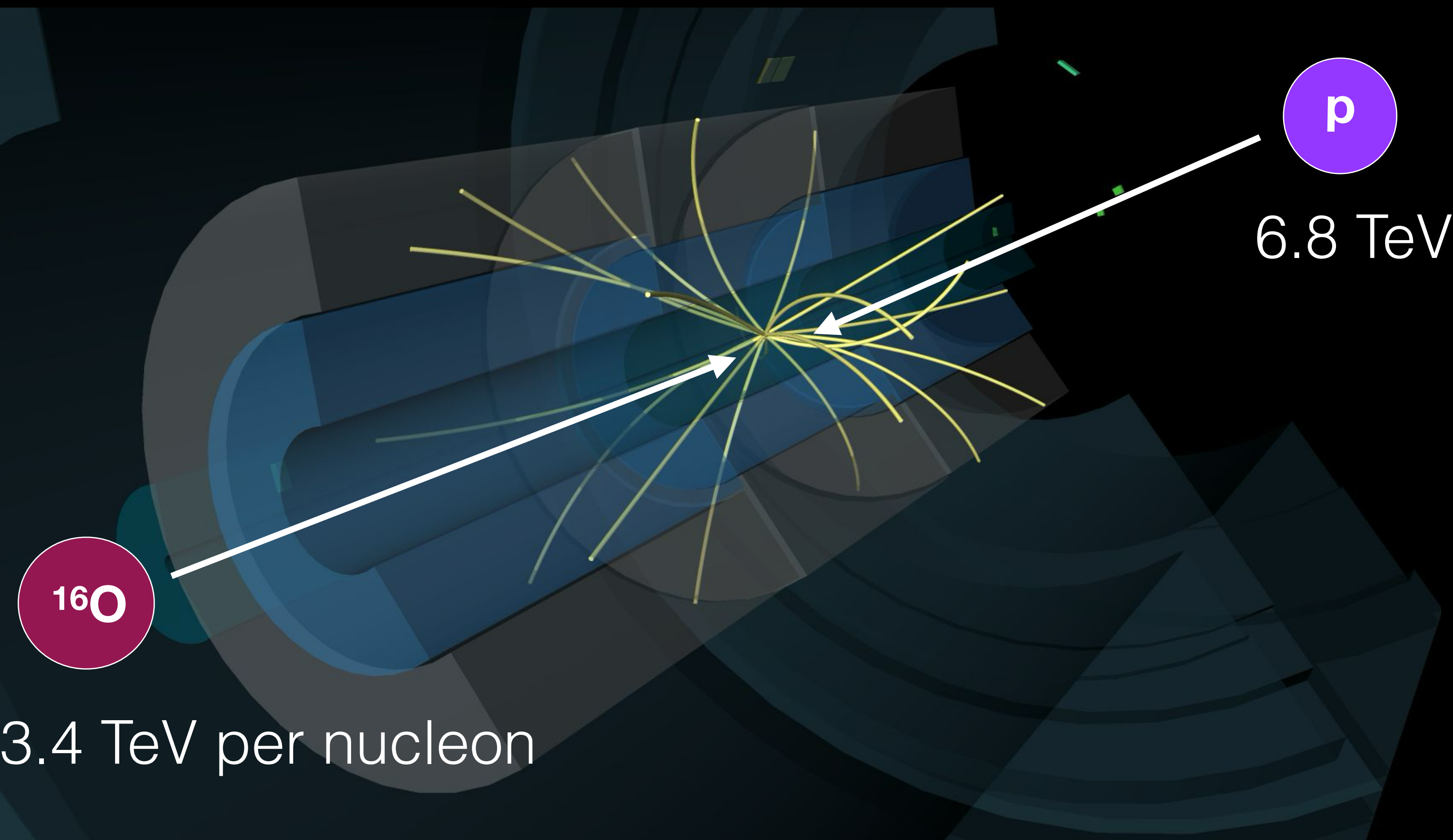
1st ATLAS p+O measurement: Measure prompt charged-particles

Inelastic cross-section & differential spectra

Uses $634 \pm 15 \mu\text{b}^{-1}$ p+O data with $\langle \mu \rangle \approx 0.025$



Run: 501640 Event: 515109806
2025-07-01 23:23:29 CEST

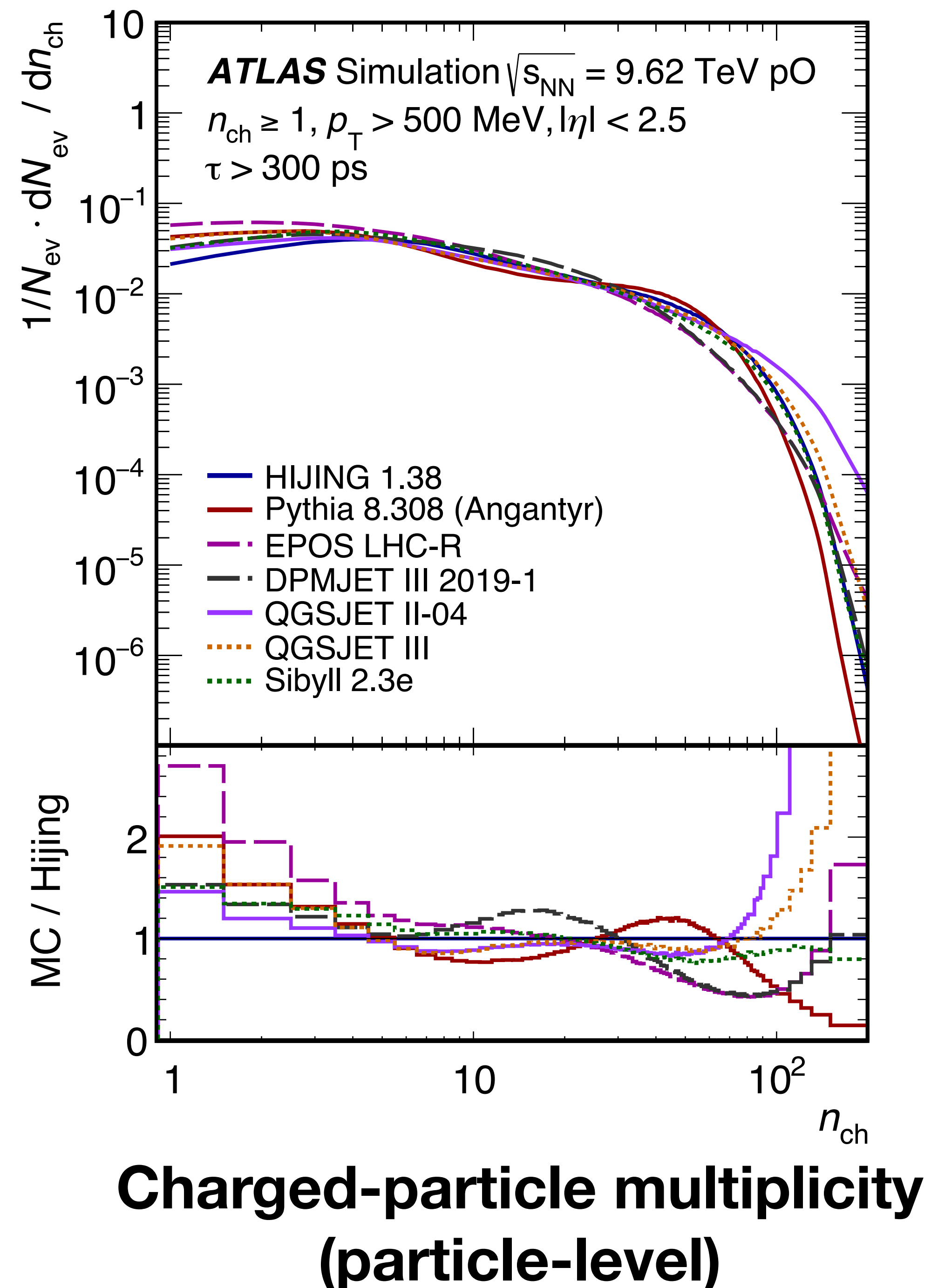


Motivation

Huge differences between models:
50–500% model spread

Which one is correct, if any?

Even 5%-level measurement
precision may improve p+O
knowledge by order of magnitude



Particle-level distributions

Hijing 1.38b

Pythia 8.308 (Angantyr)

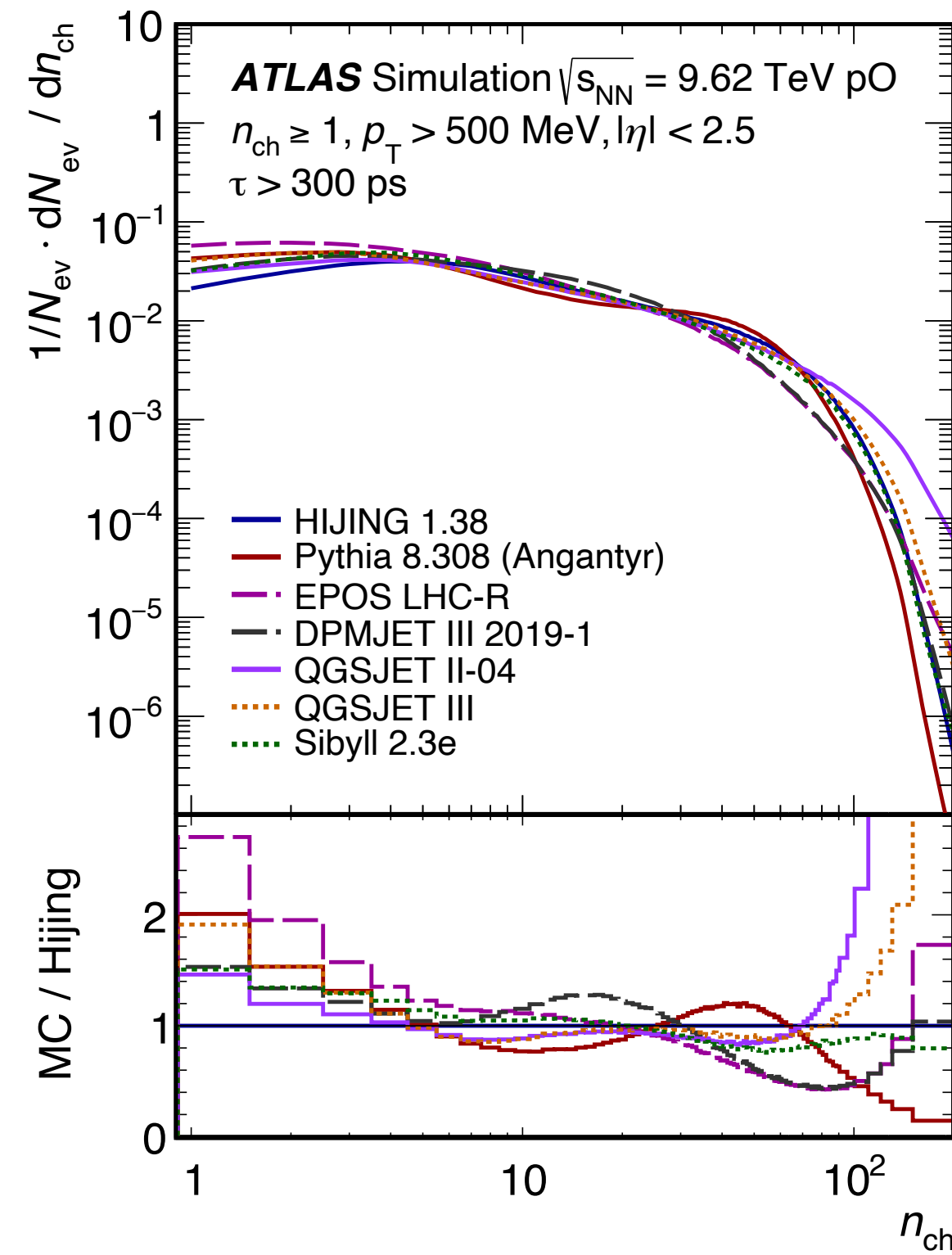
EPOS-LHCR

DPMJET III 2019-1

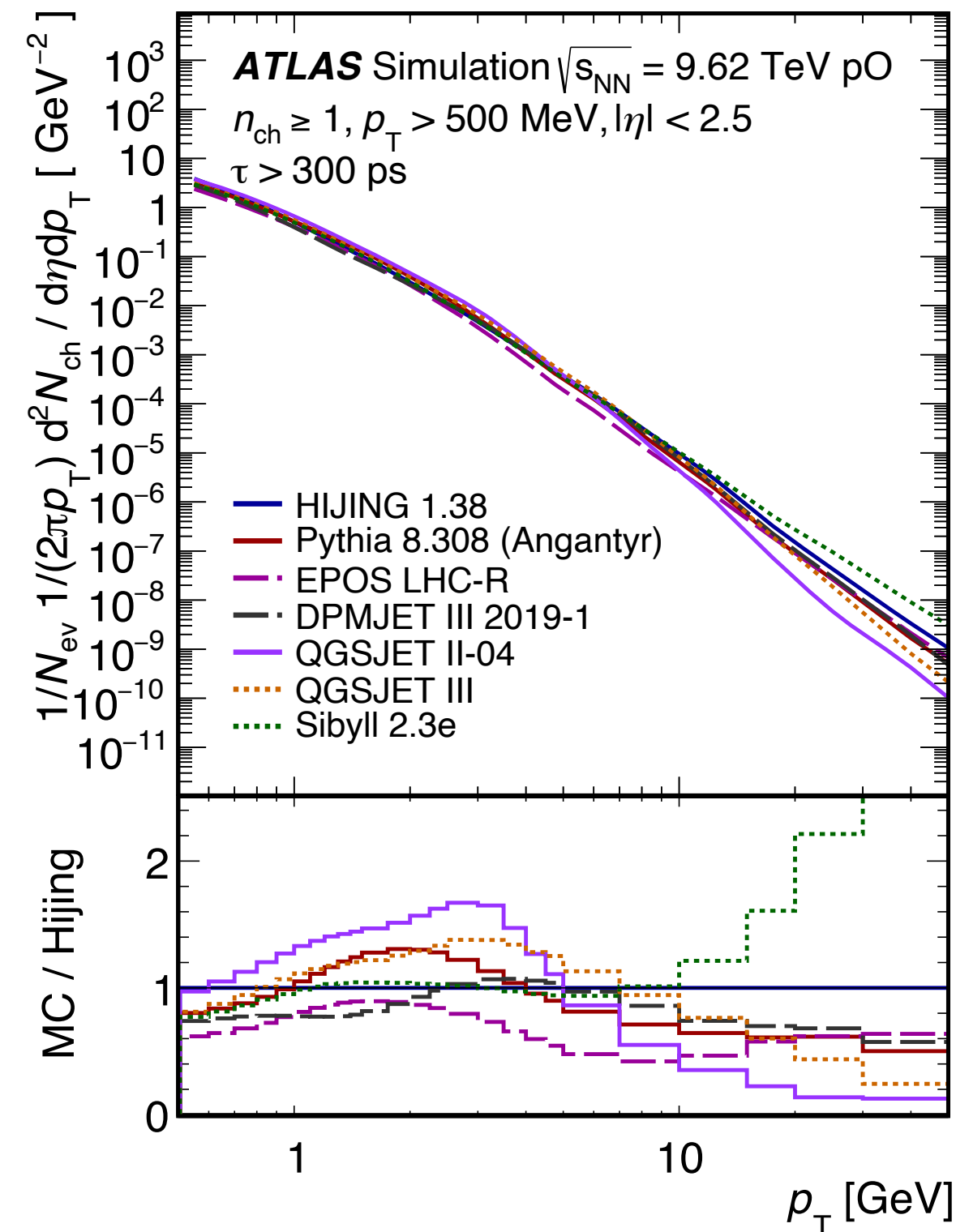
QGSJET II-04

QGSJET III

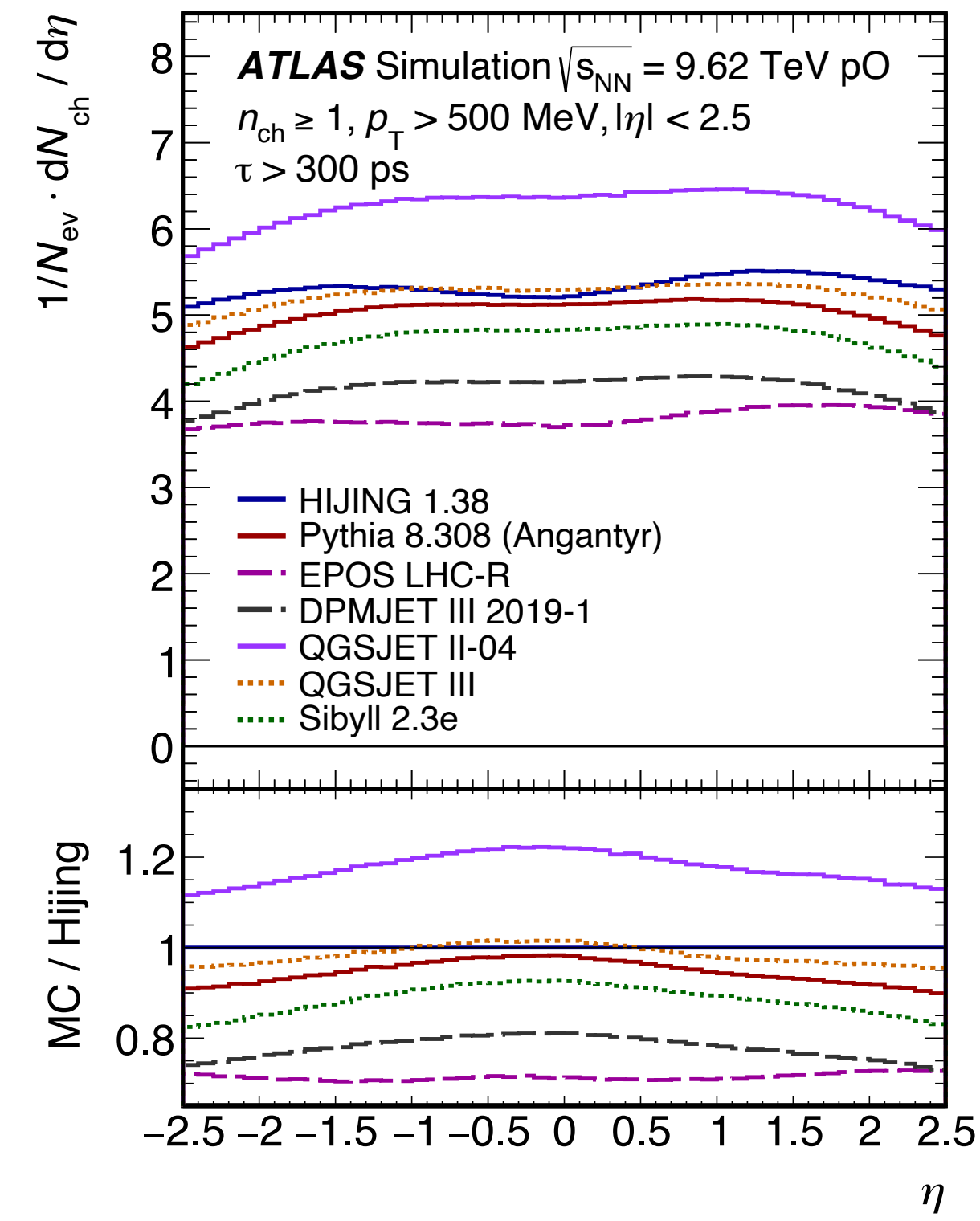
Sibyll 2.3e



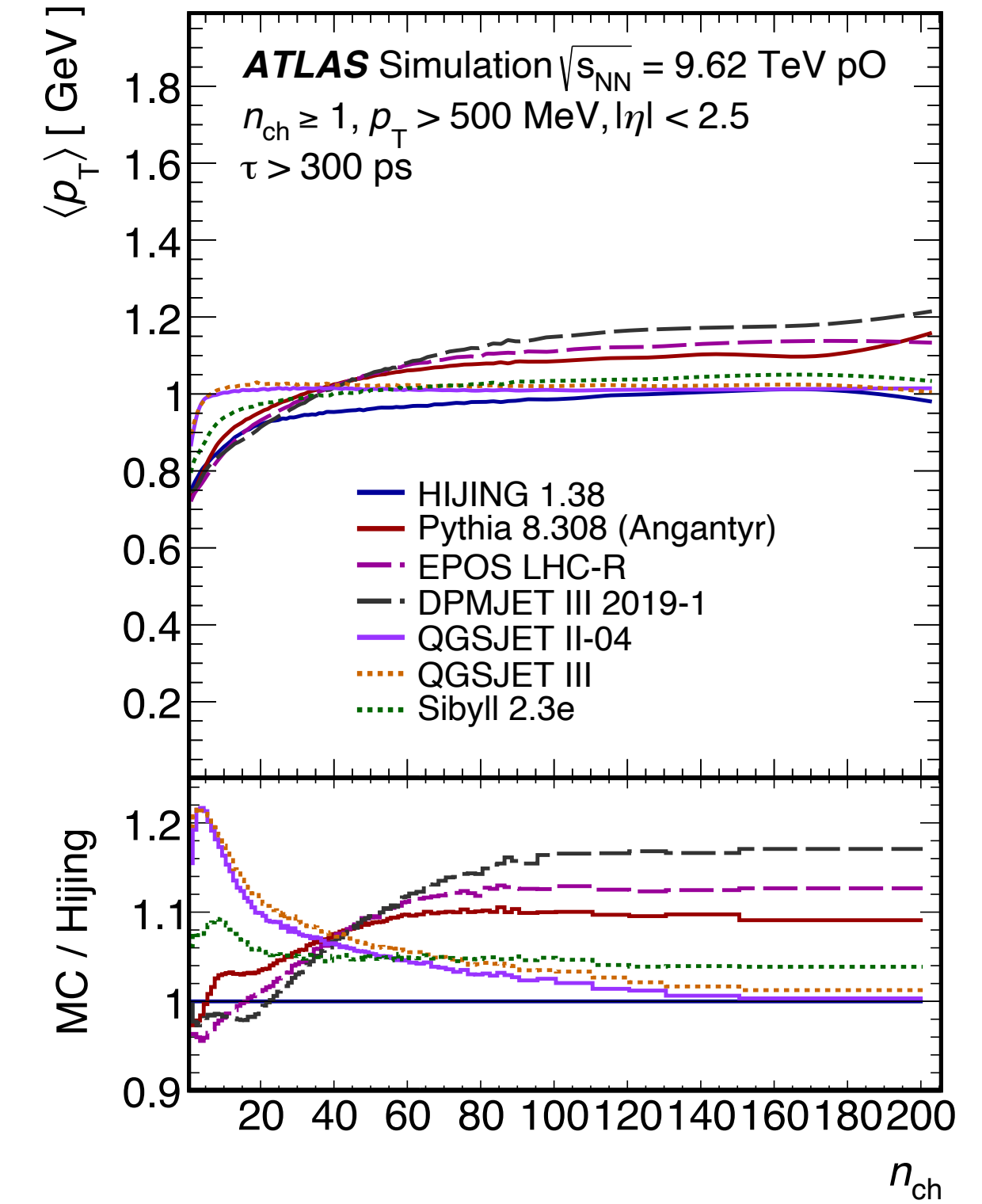
Multiplicity



Transverse momentum



Pseudorapidity

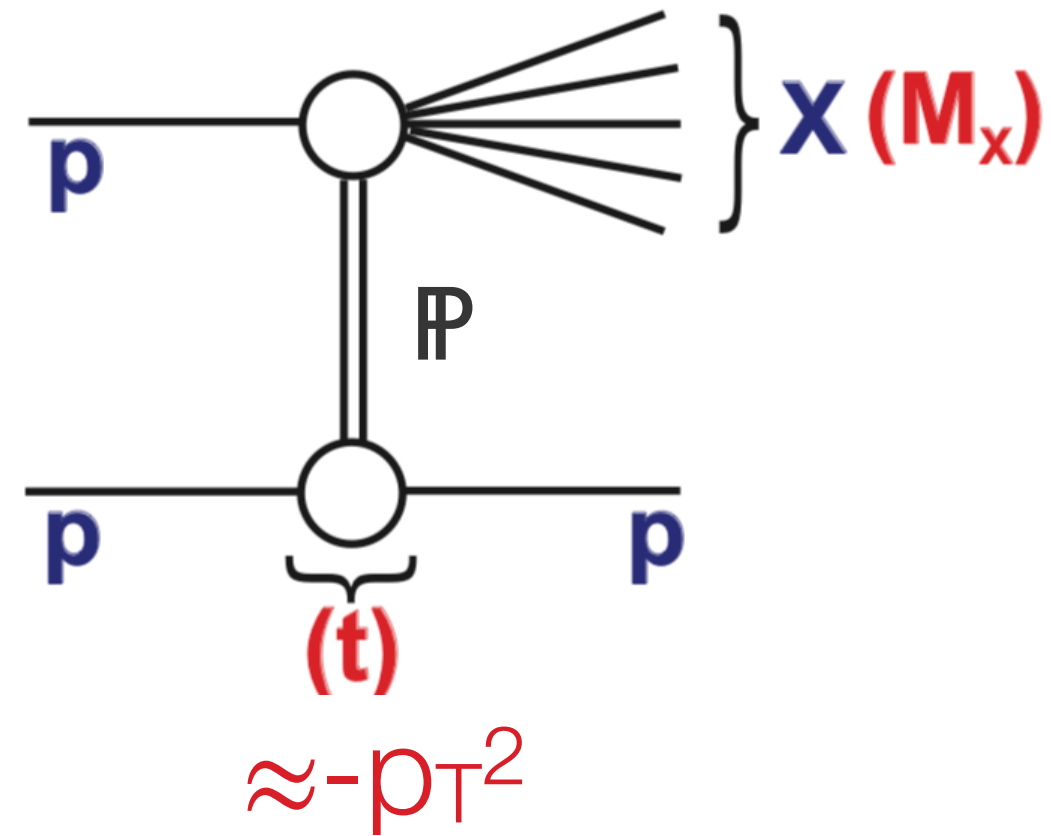


Mean p_T vs multiplicity

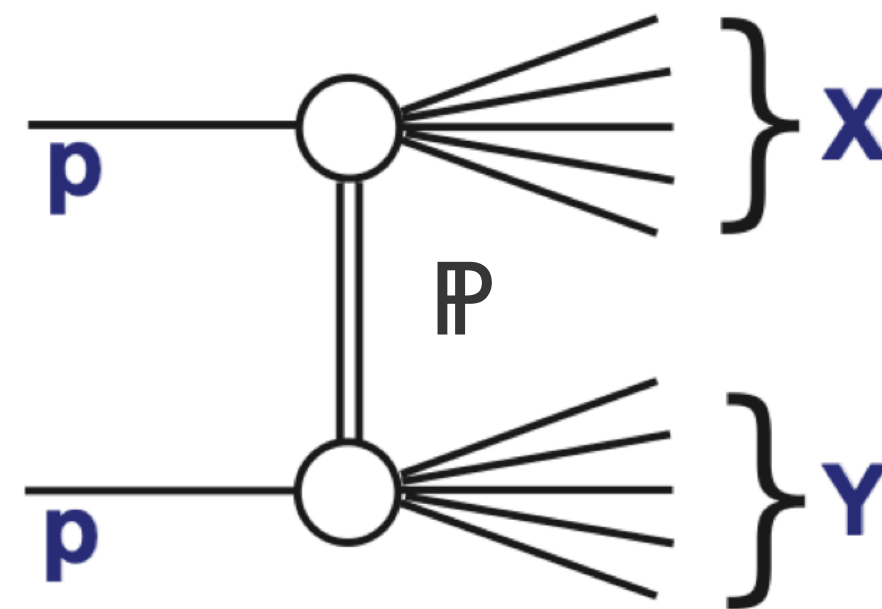
ATLAS minbias data =

$\mathbb{P}$ = Pomeron

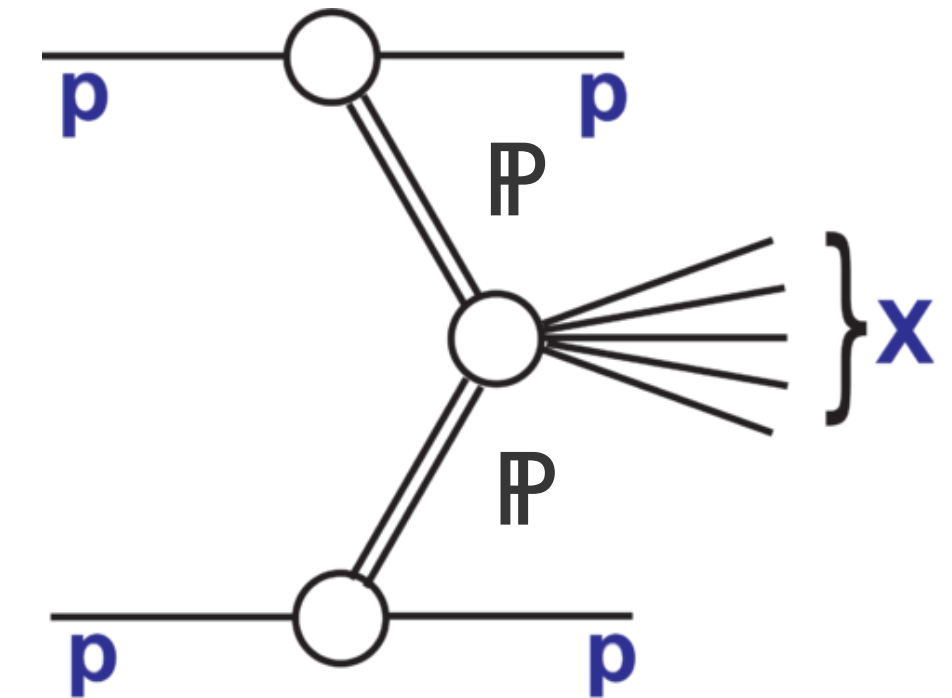
Single diffractive (SD)



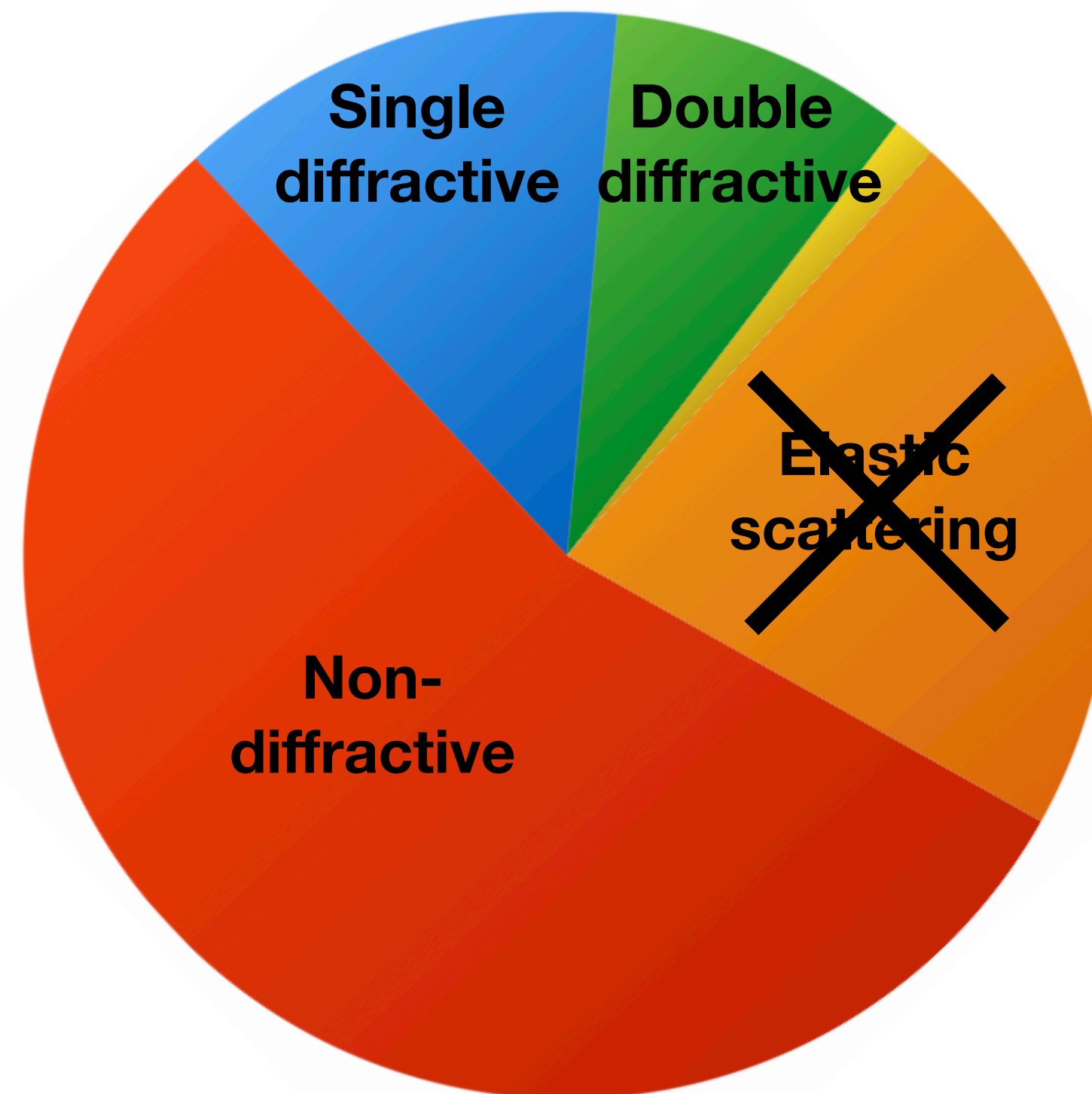
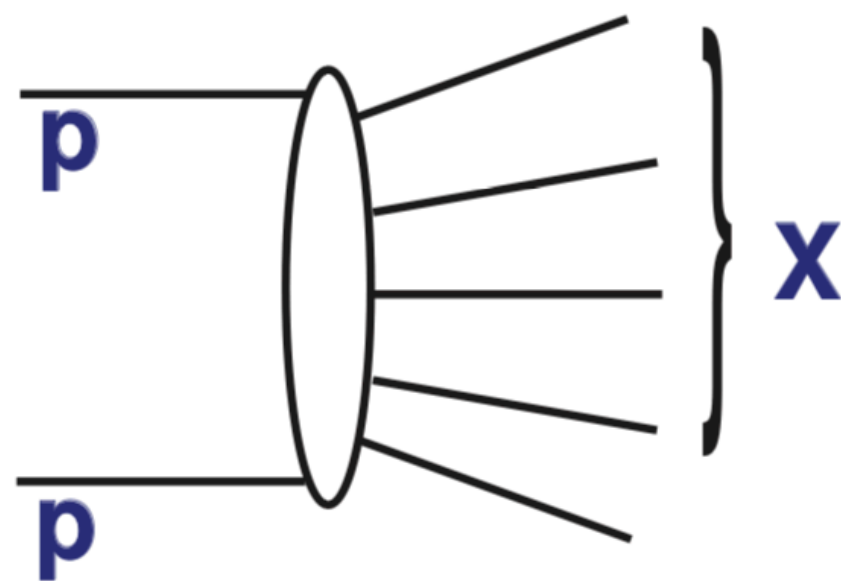
Double diffractive (DD)



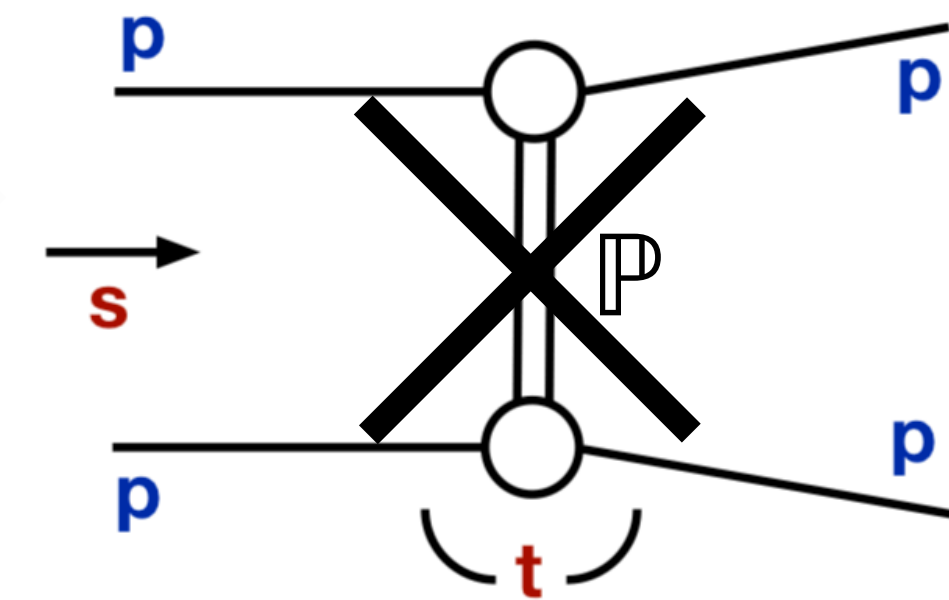
Central diffractive (CD)



Non-diffractive



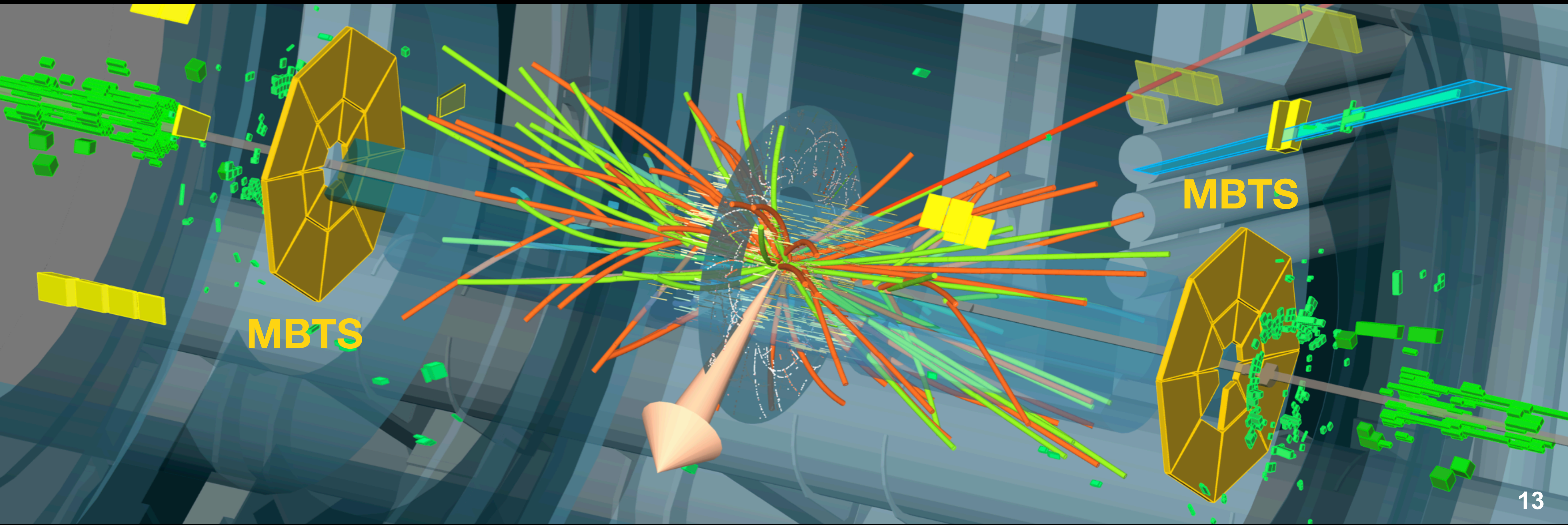
Elastic



A word on triggers

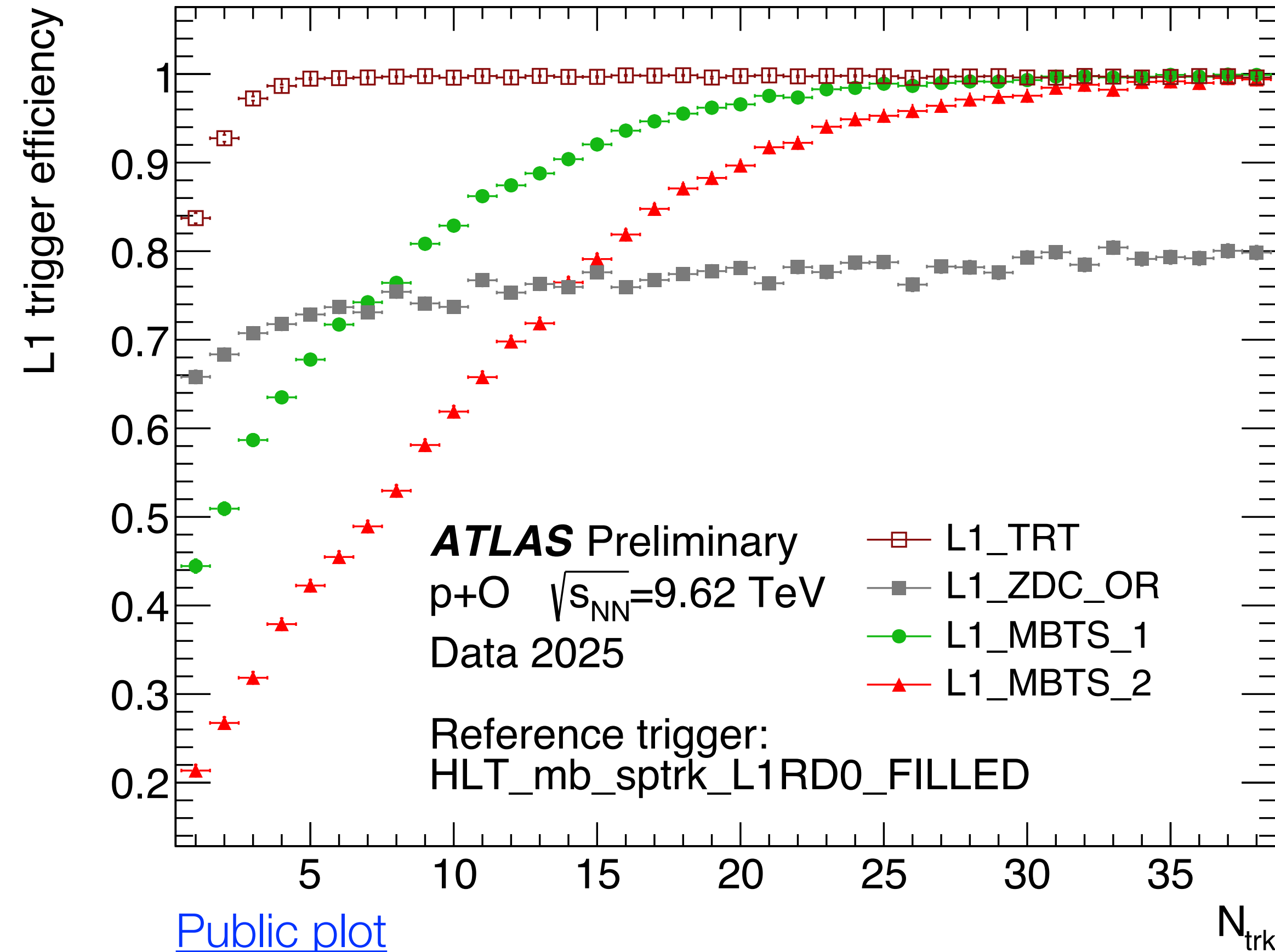
Traditionally we trigger using the Minimum Bias Trigger Scintillators (MBTS)

Hit in at least one MBTS module $2.08 \leq |\eta| < 3.75$ on A or C side (L1_MBTS_1 trigger)



A word on triggers

In p+O analysis we use **L1_TRT** trigger as its performance surpasses MBTS



**ATLAS has a
track trigger** 😊

L1_TRT: a signal in TRT detector consistent with presence of at least one charged particle in the TRT acceptance

L1_ZDC_OR: a signal above noise level in one or both arms of the ZDC

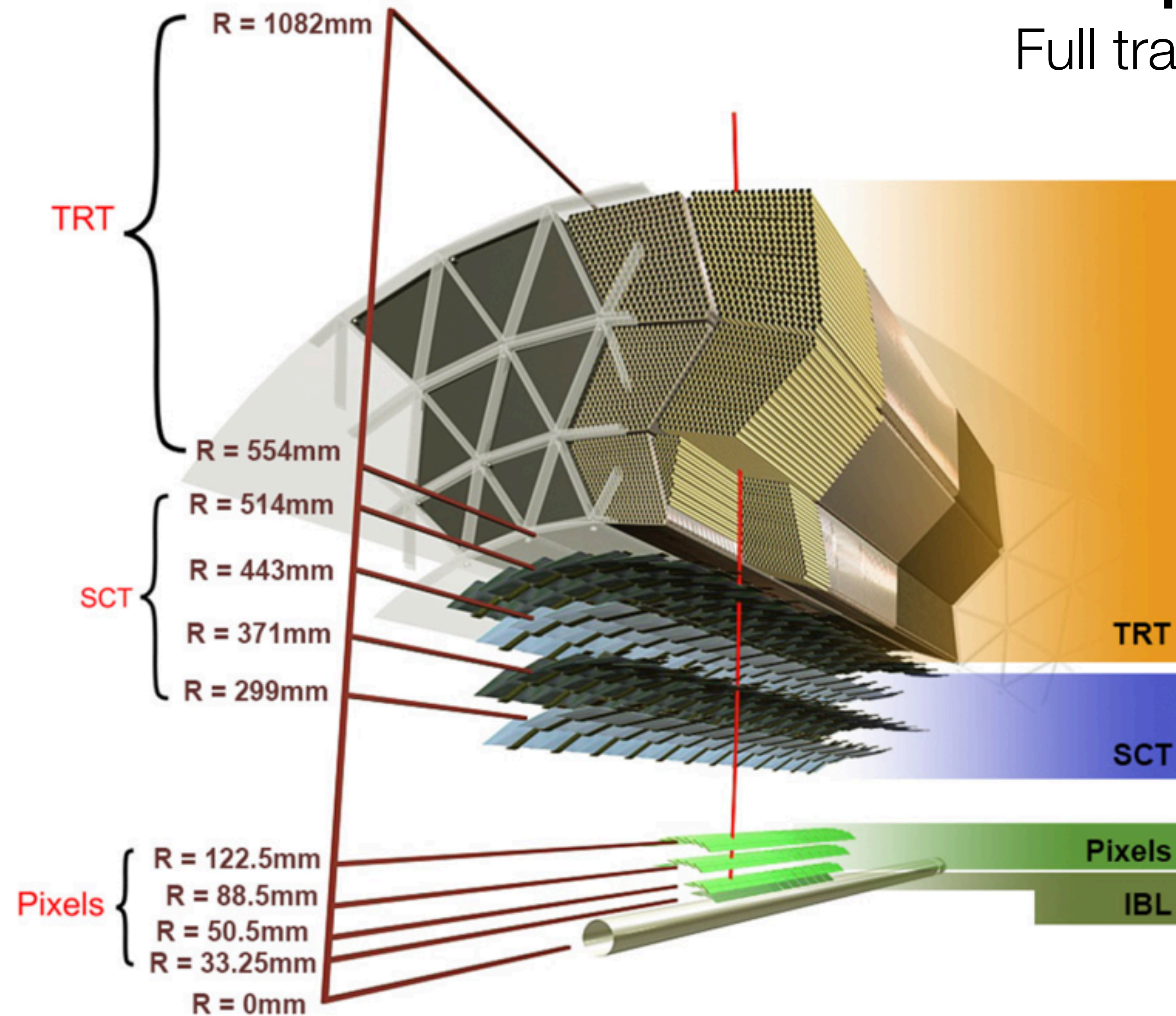
L1_MBTS_1 & L1_MBTS_2: a signal above noise level in at least one and at least two MBTS segments, respectively

ATLAS inner detector

Minbias track reconstruction

Track $p_T > 500 \text{ MeV}$, $|\eta| < 2.5$

Full track selection in backup



Event selection

Event requirement	Number of events
Initial	~300 million events
Data quality	Efficiency: 99.3%
Trigger	87.1%
At least one primary vertex	95.7%
Veto second vertex with ≥ 5 associated tracks	99.1%
At least one selected track	99.8%

Overall selection efficiency: 81.9%

~246 million events

Background estimation

Secondary particles e.g. from interactions of particles with detector material

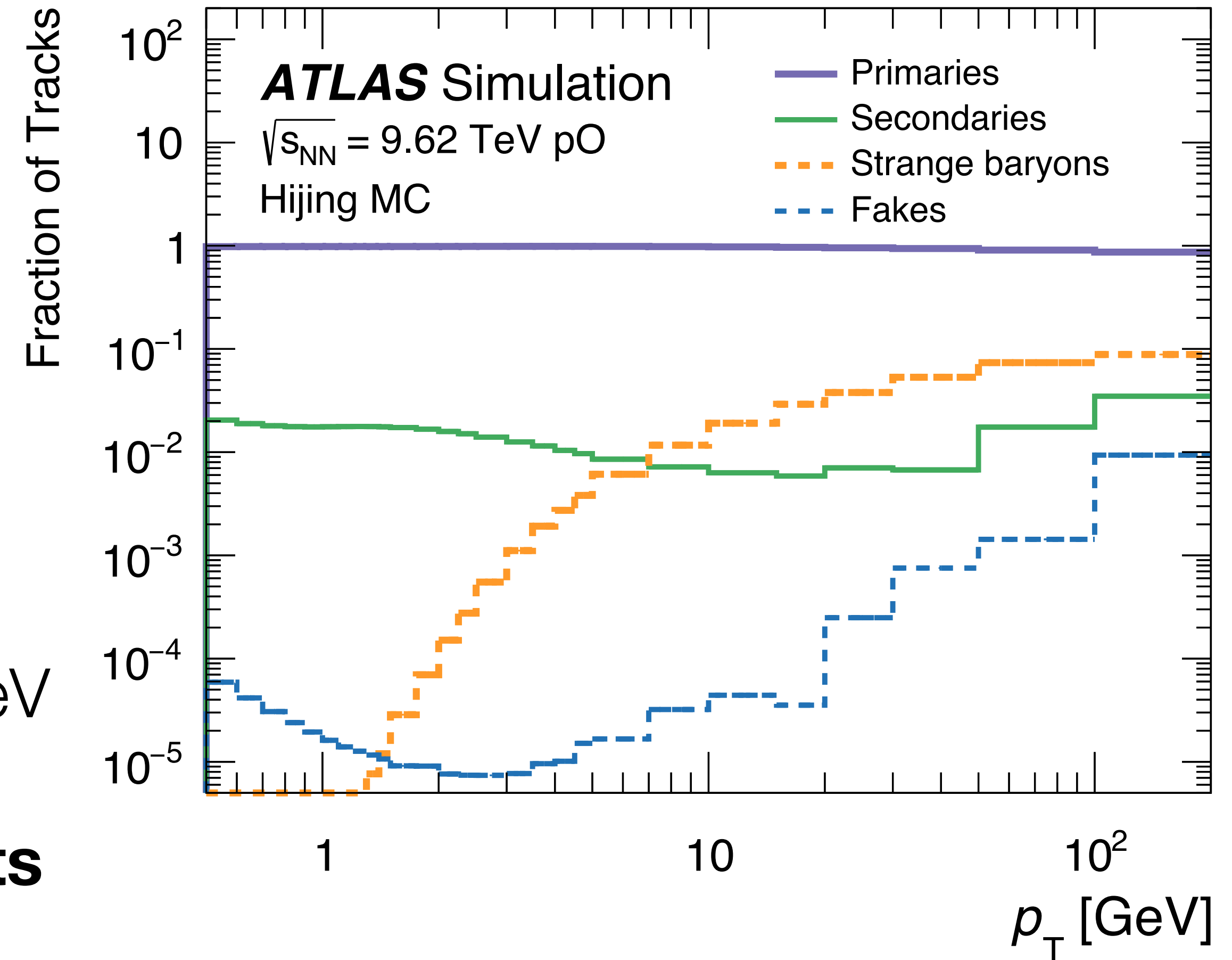
- MC + data-driven correction, $\sim 2.3\%$

Decay products from strange baryons

- Estimate using MC, dominates at $p_T \gtrsim 10$ GeV

Fake tracks reconstructed from random hits

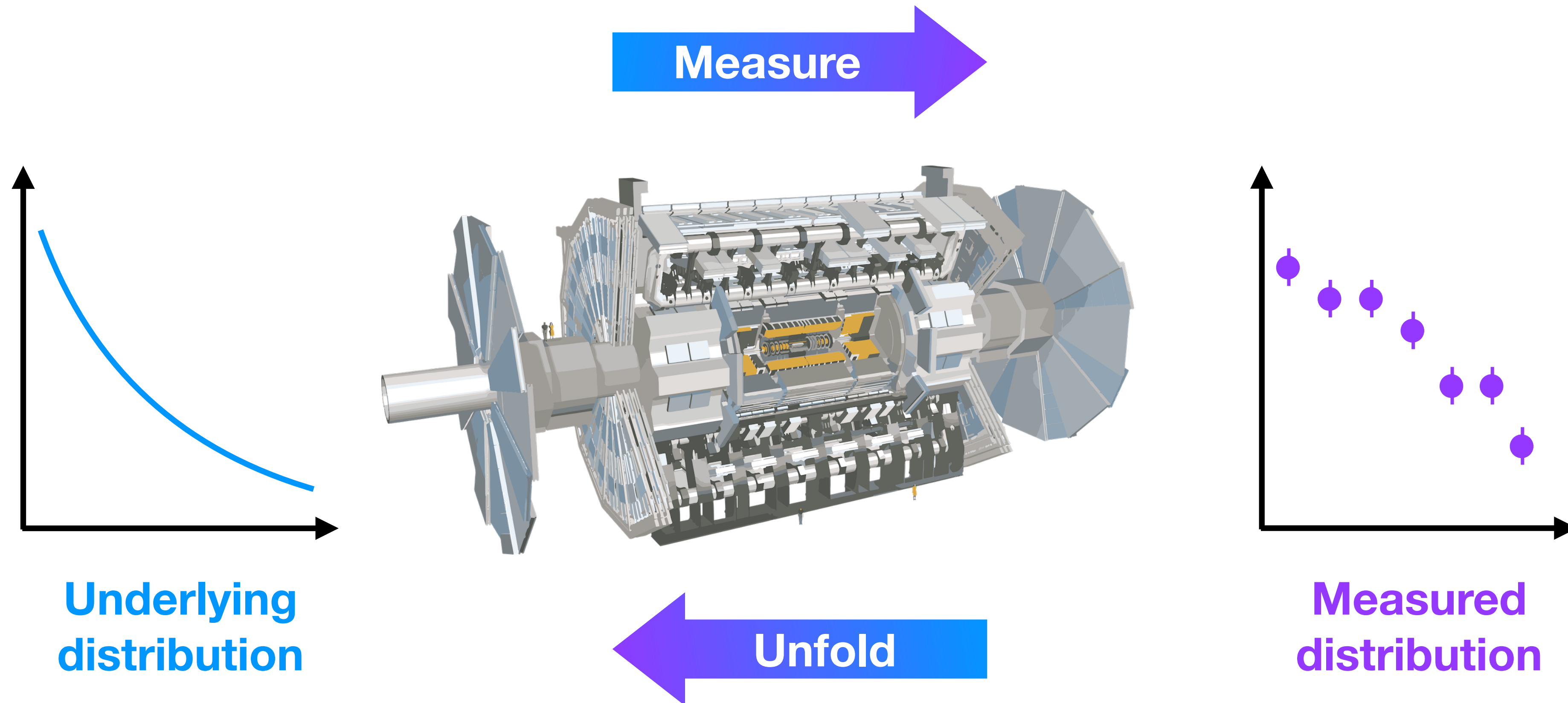
- Negligible



MC truth origin label
Hijing with full detector simulation

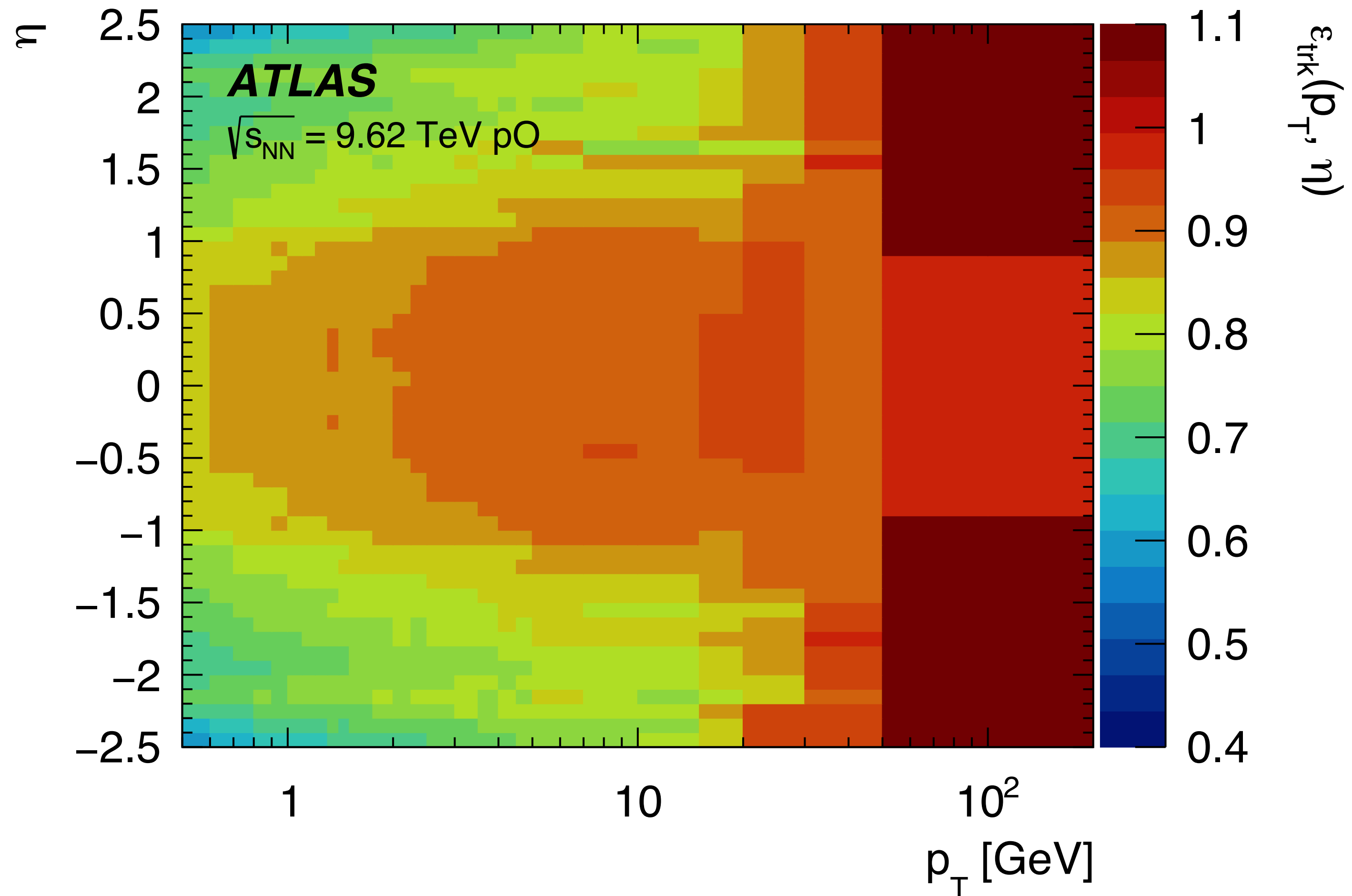
Unfolding

Correct for trigger & vertex inefficiencies then ‘unfold’ measured data



Iterative Bayesian unfolding applied to n_{ch} and p_{T} distributions, η corrected by track-weights

Track reconstruction efficiencies

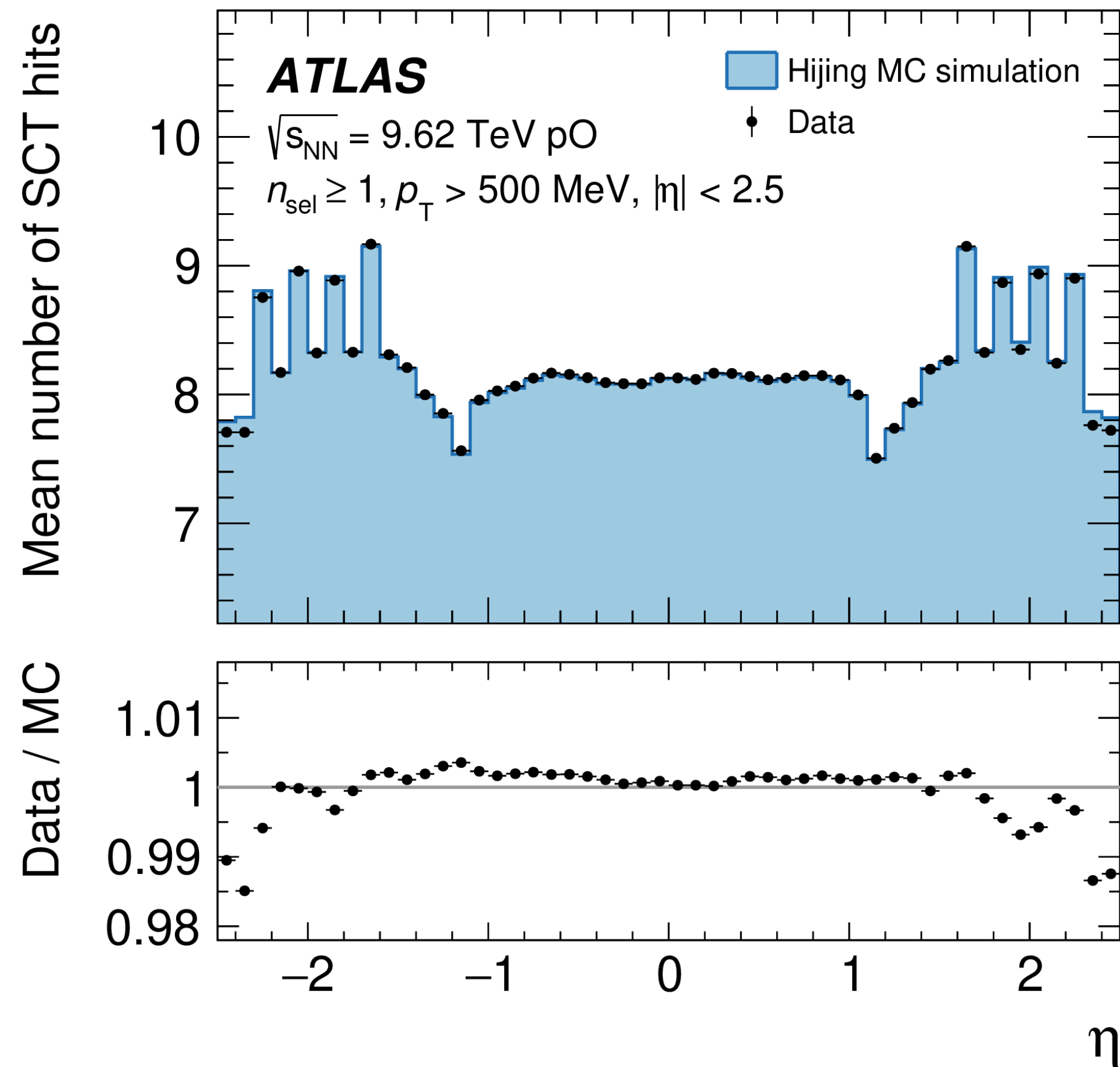


$$\epsilon_{\text{trk}} = \frac{N_{\text{reco}}^{\text{matched}}}{N_{\text{gen}}}$$

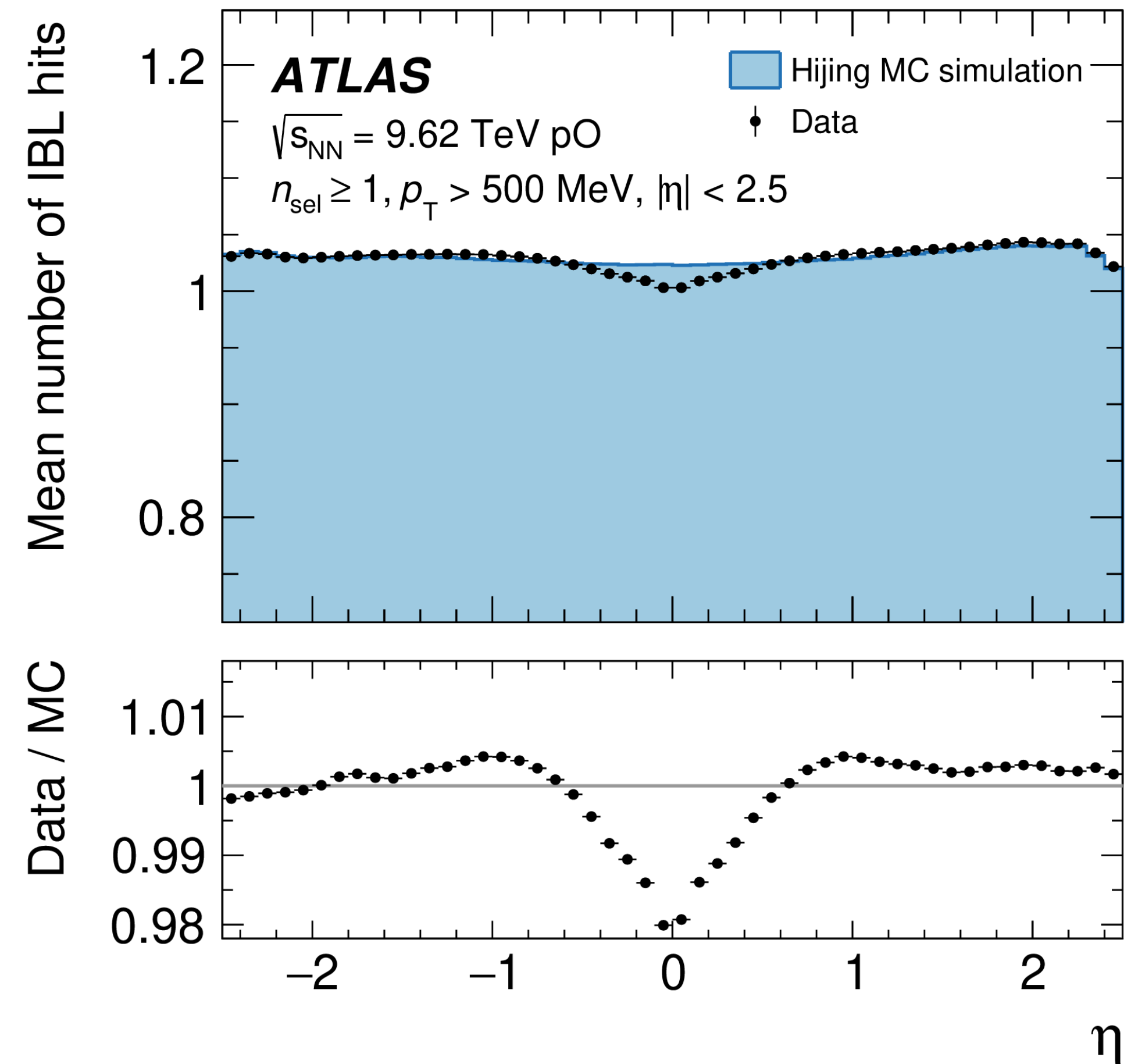
Accounts for out-of-kinematic-range migrations by allowing tracks to match with truth particles outside kinematic acceptance

Track modelling

Difficult to accurately model material between Pixel and SCT in $|\eta| > 1.5$ region (PP0)



Mis-modelling also seen in central region for inner tracking layers



Additional track efficiency corrections

Differences between simulated and observed track reconstruction efficiencies

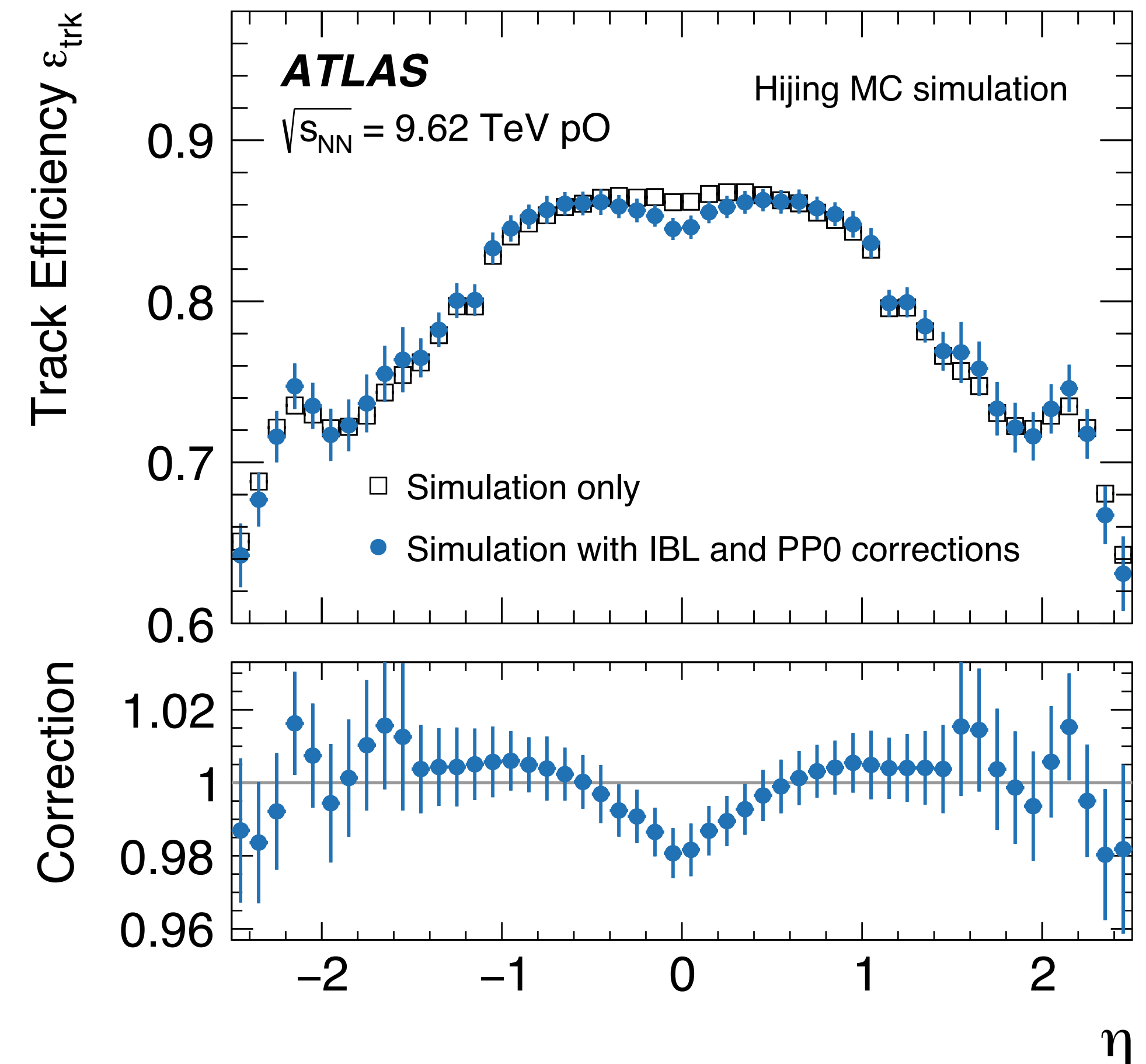
→ Apply corrections derived as a function of η

PP0 correction

- Accounts for mismodelled material between Pixel and SCT

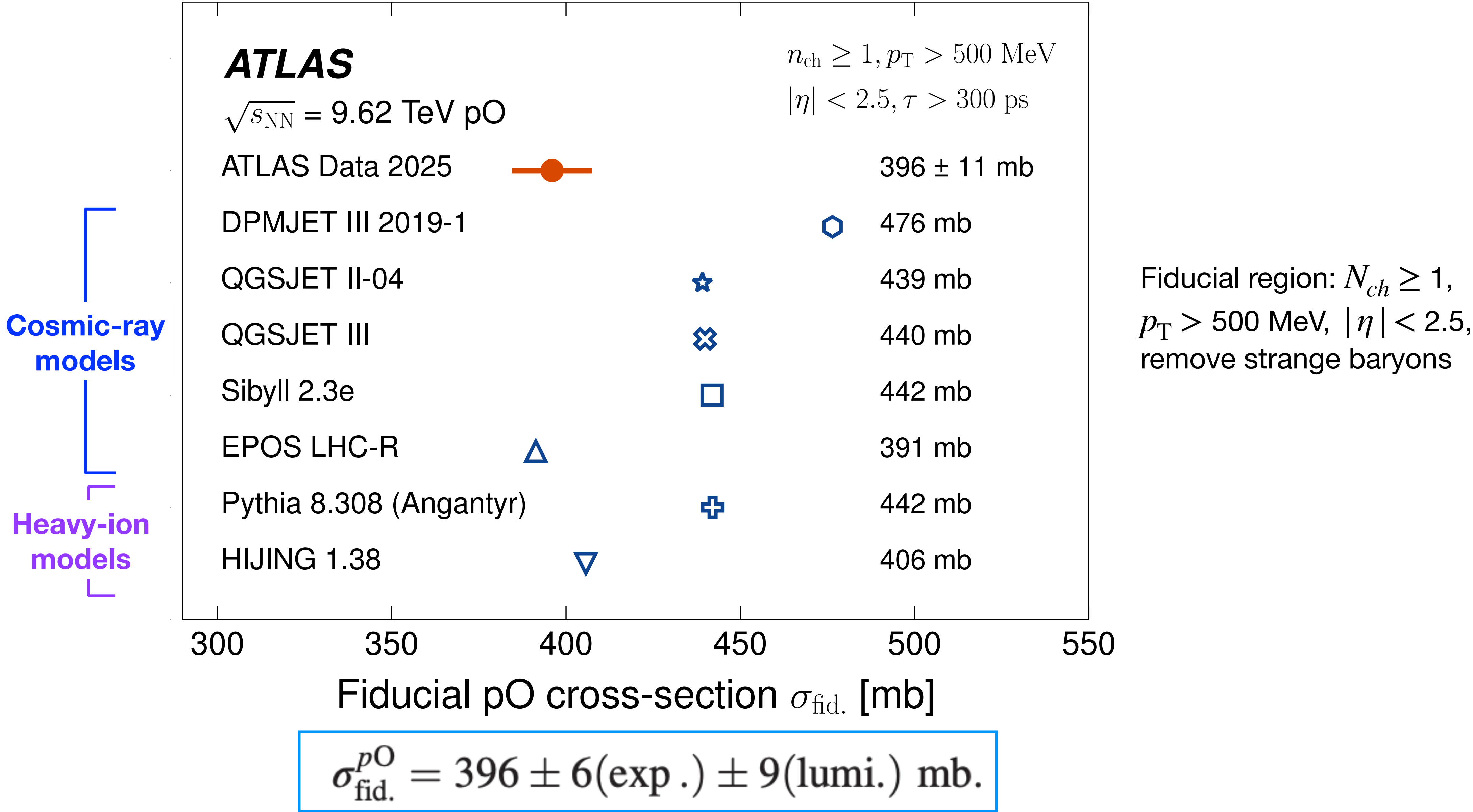
IBL hit correction

- Accounts for differences in IBL hit efficiency between data and simulation

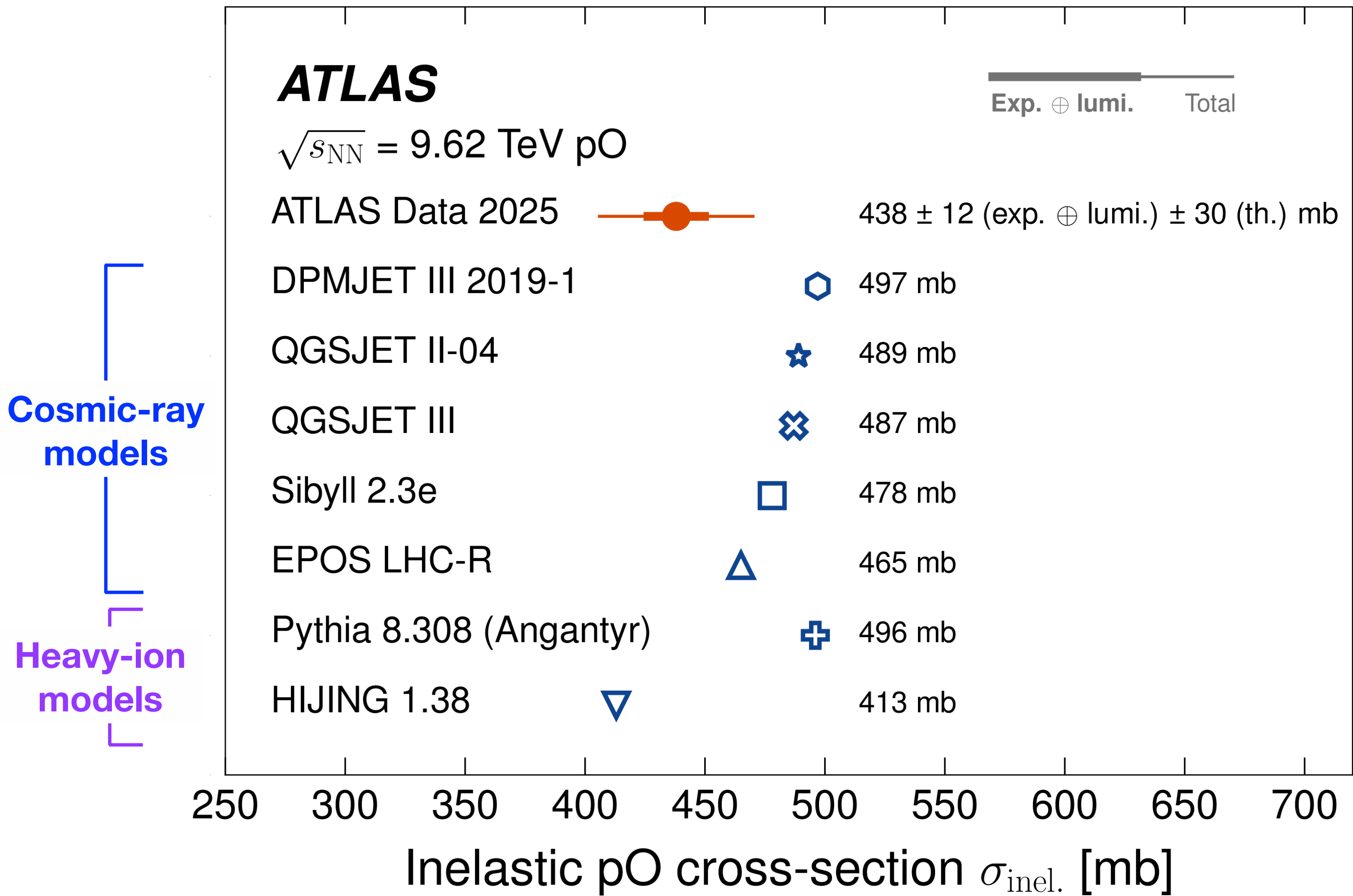


Track η distribution with & without
IBL and PP0 correction

First TeV-scale proton-Oxygen cross-sections



First TeV-scale proton-Oxygen cross-sections



Extrapolated to full phase-space inelastic cross-section:

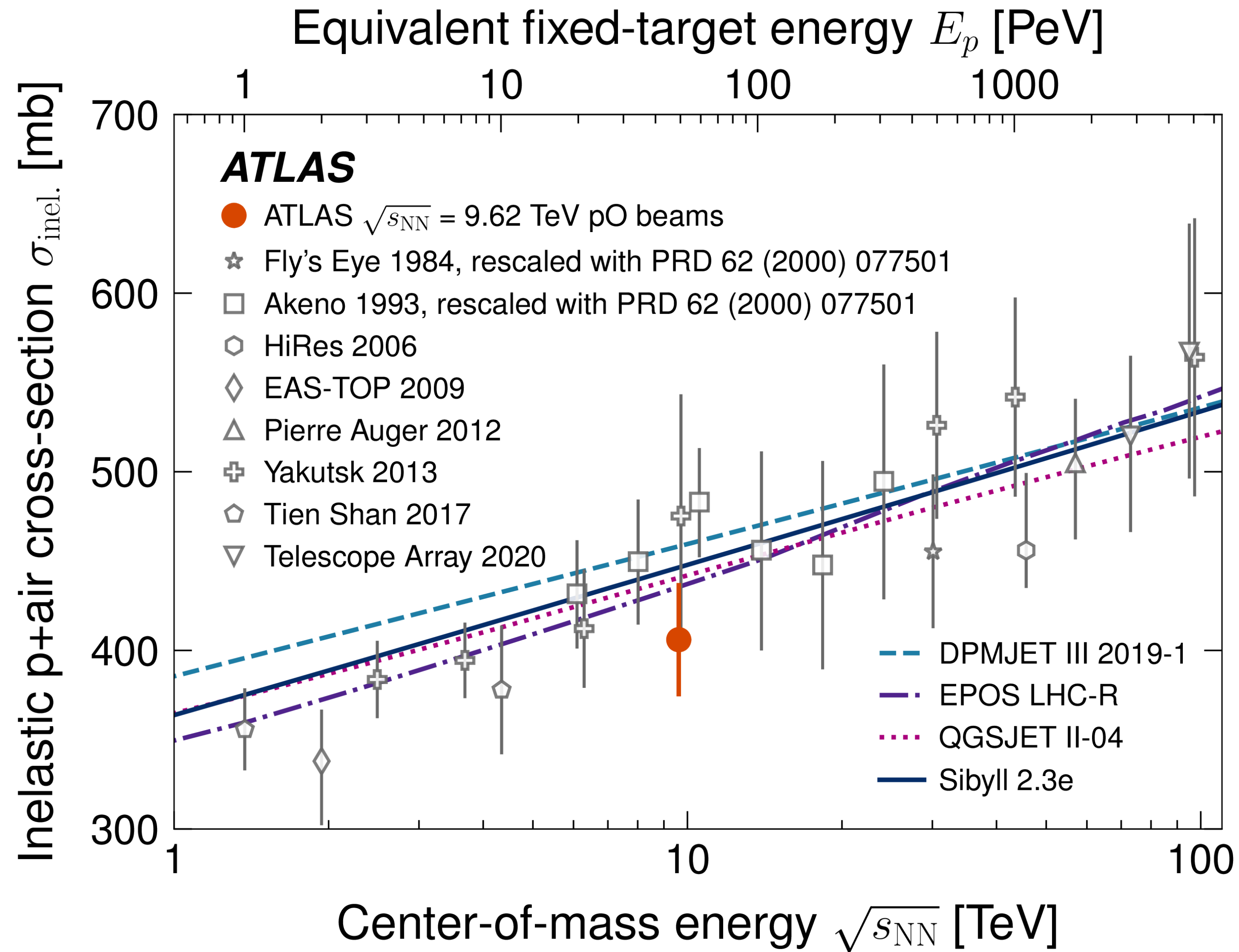
Divided by acceptance calculated using models (mean excluding Hijing as not tuned to previous LHC data & maximum difference from the mean as theory uncertainty)

$$\sigma_{\text{inel.}} = \sigma_{\text{fid.}} / A,$$

$$A = (90 \pm 6)\%$$

$$\sigma_{\text{inel.}}^{p\text{O}} = 438 \pm 6(\text{exp.}) \pm 10(\text{lumi.}) \pm 30(\text{th.}) \text{ mb.}$$

Cosmic comparisons



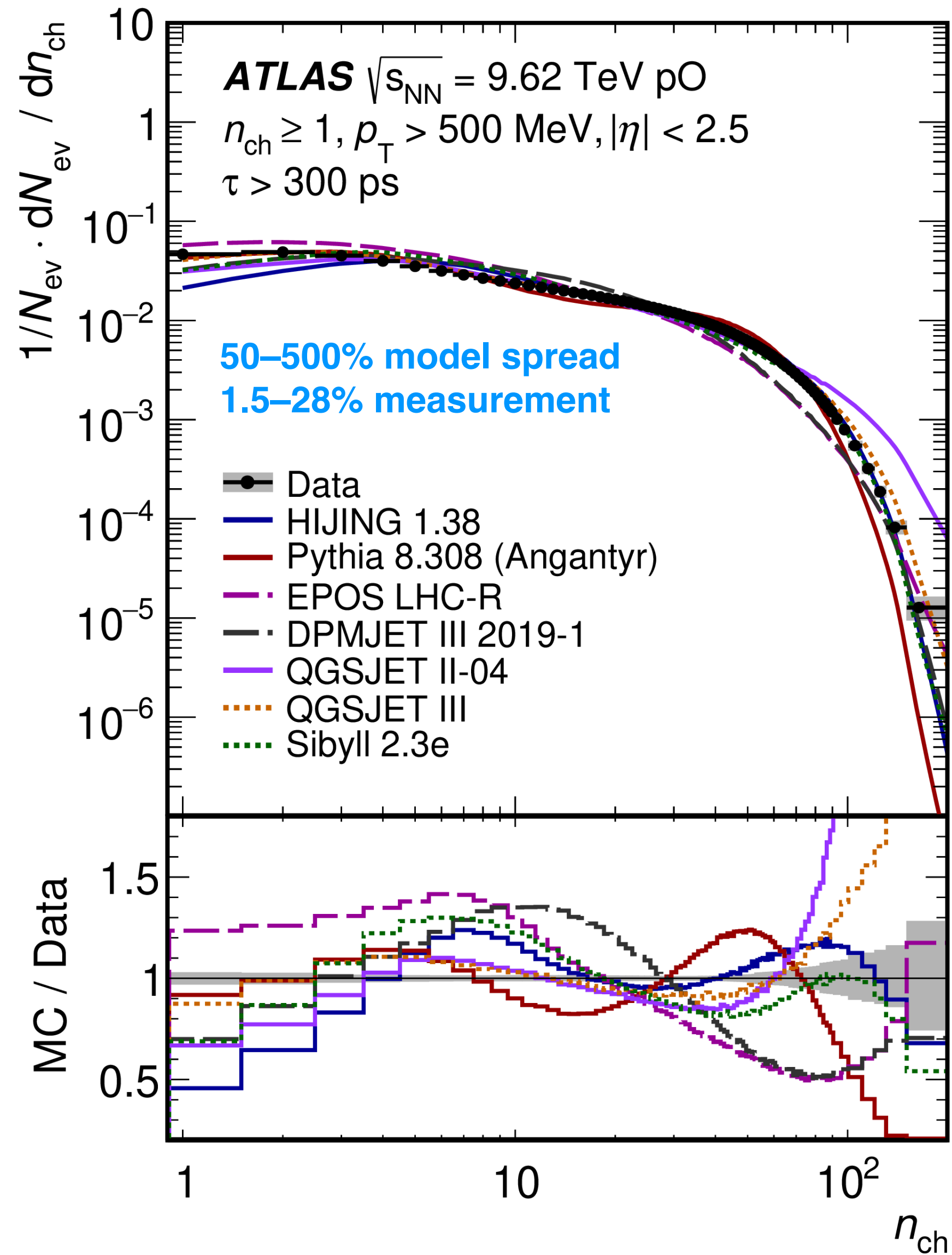
Assume air = 78% ^{14}N + 22% ^{16}O

$$\sigma_{\text{inel.}}^{p+\text{air}} = f_{\text{air}} \cdot \sigma_{\text{inel.}}^{p\text{O}}$$

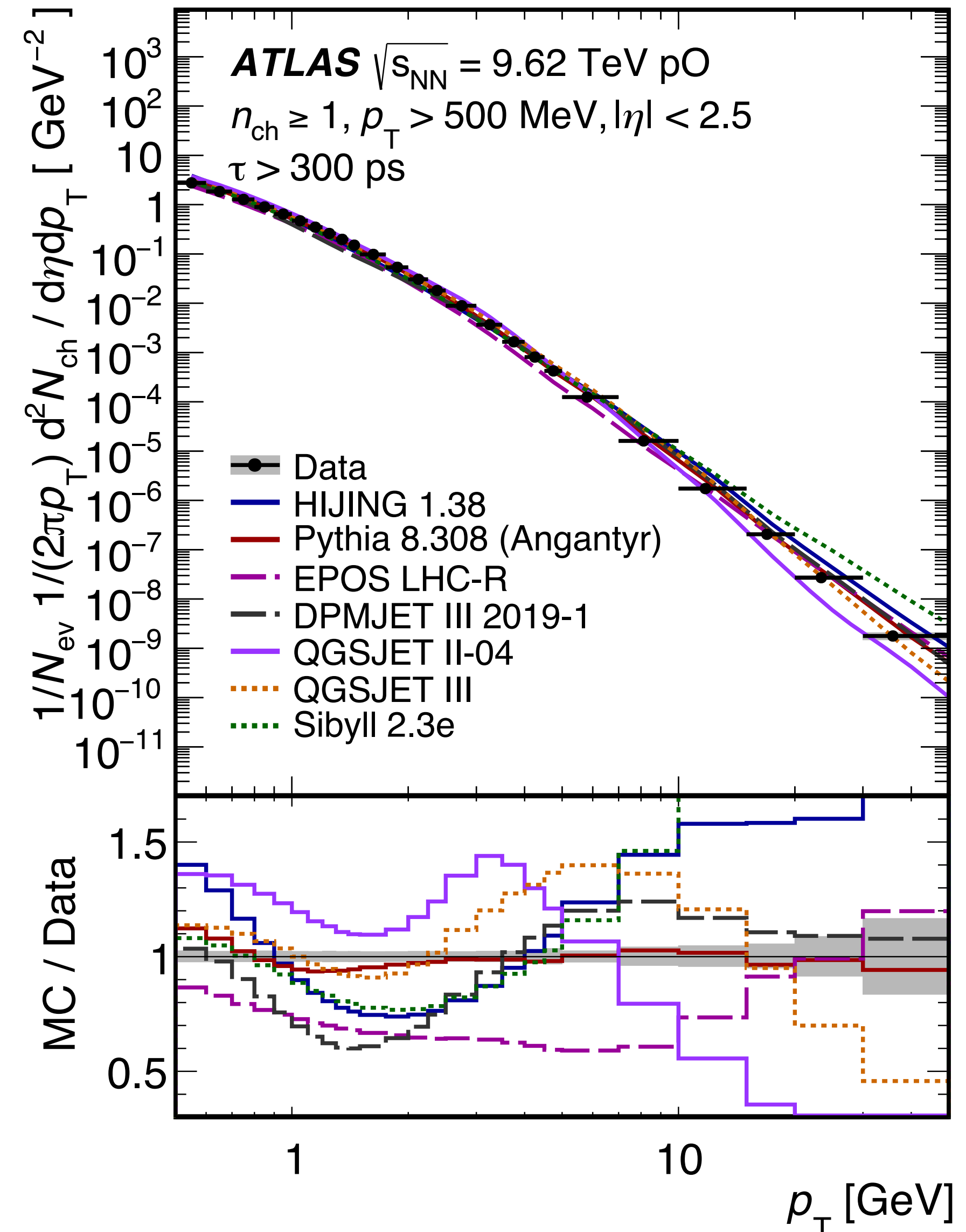
$$f_{\text{air}} = 0.78 \cdot (\sigma_{\text{MC}}^{p\text{N}} / \sigma_{\text{MC}}^{p\text{O}}) + 0.22$$

$$\sigma_{\text{inel.}}^{p+\text{air}} = 406 \pm 6(\text{exp.}) \pm 9(\text{lumi.}) \pm 28(\text{th.}) \text{ mb.}$$

First ATLAS p+O differential measurements

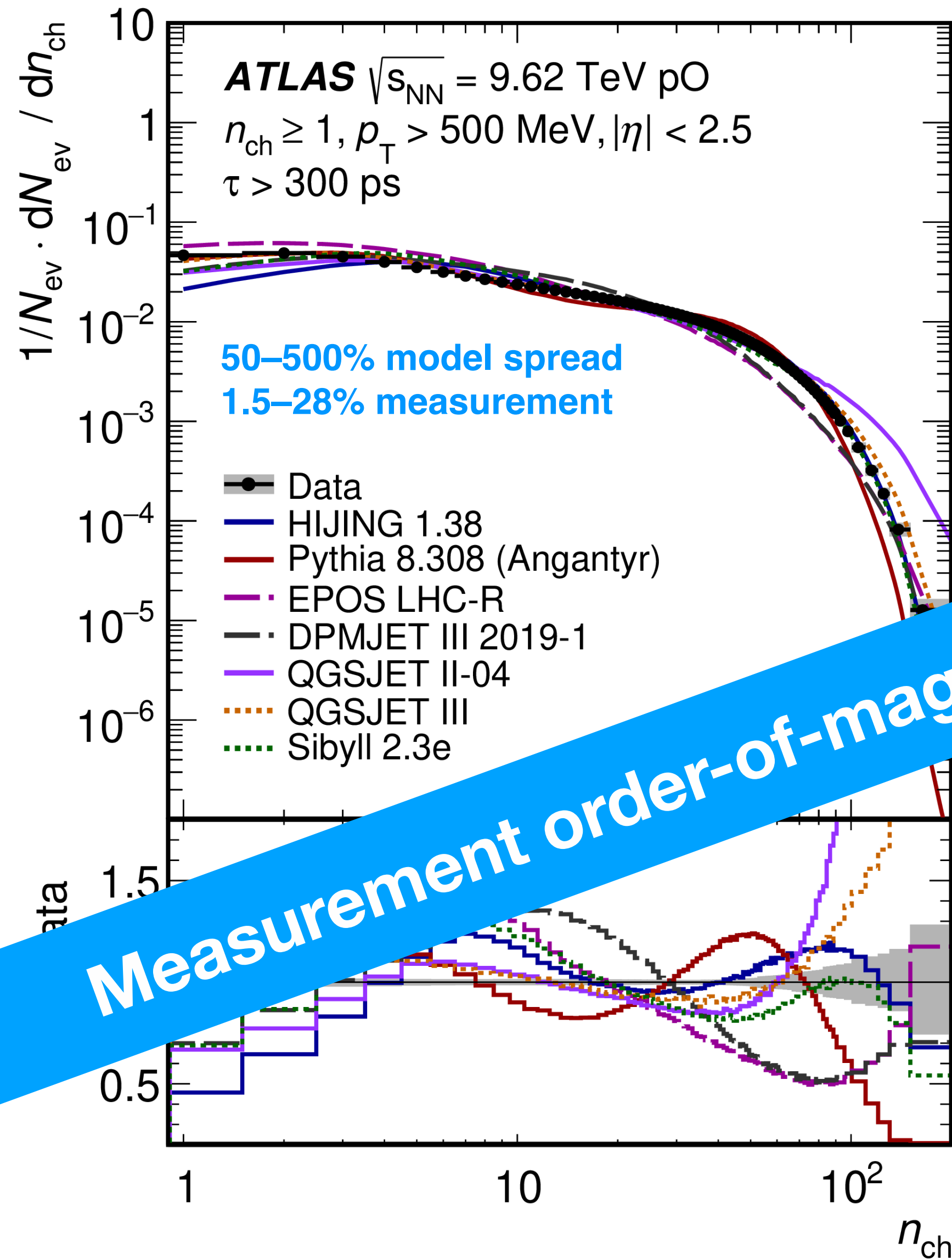


Multiplicity

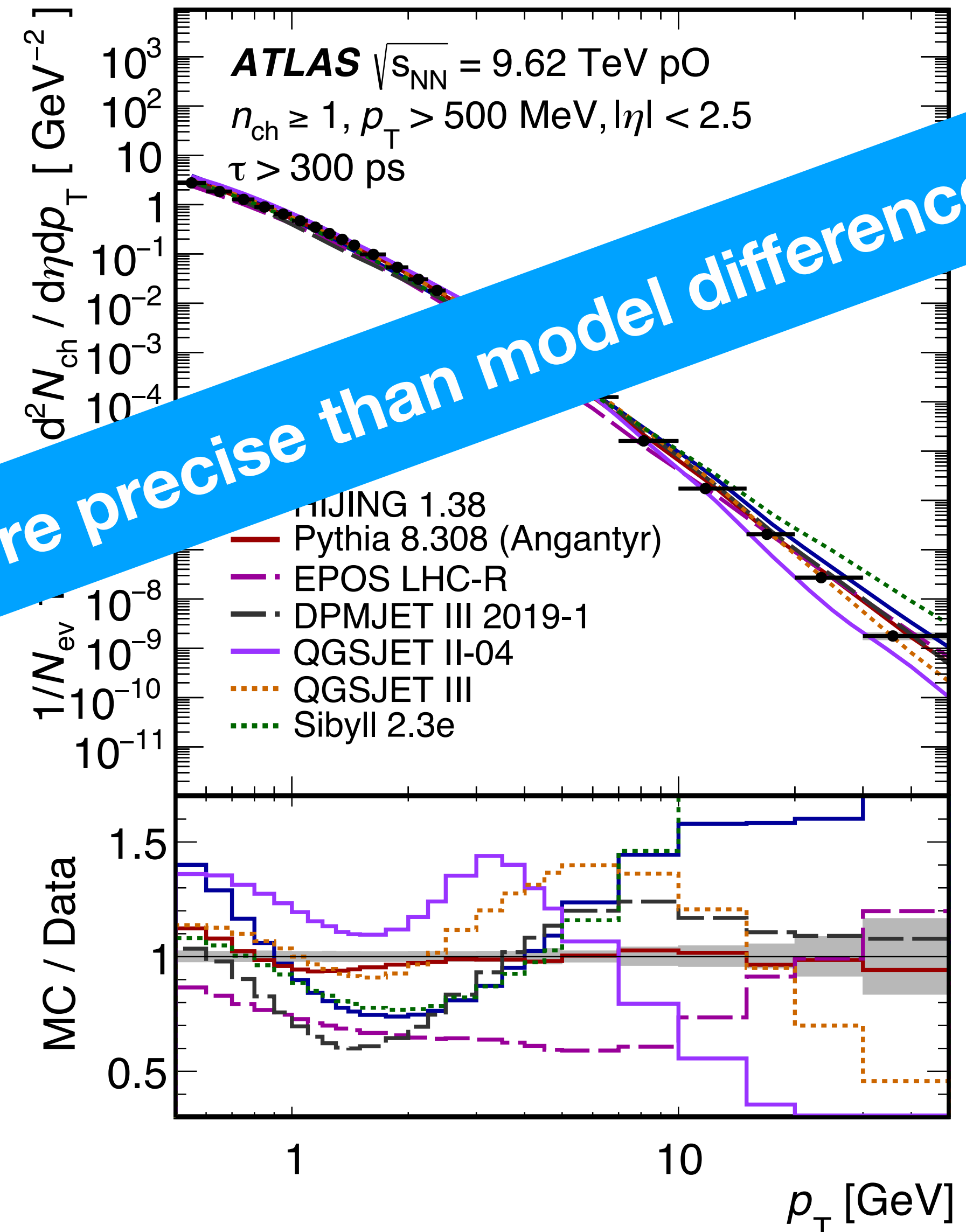


Transverse momentum

First ATLAS p+O differential measurements

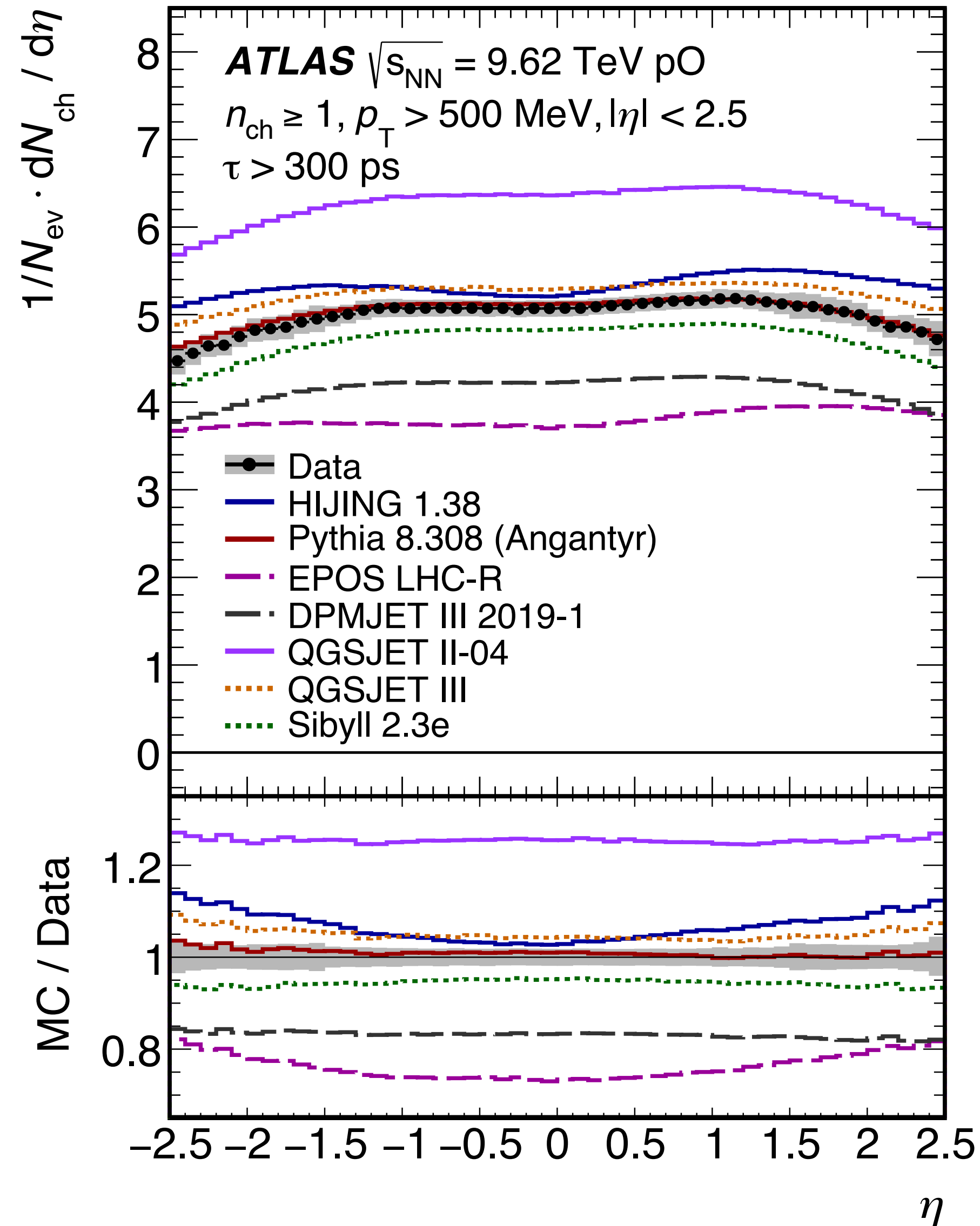


Multiplicity

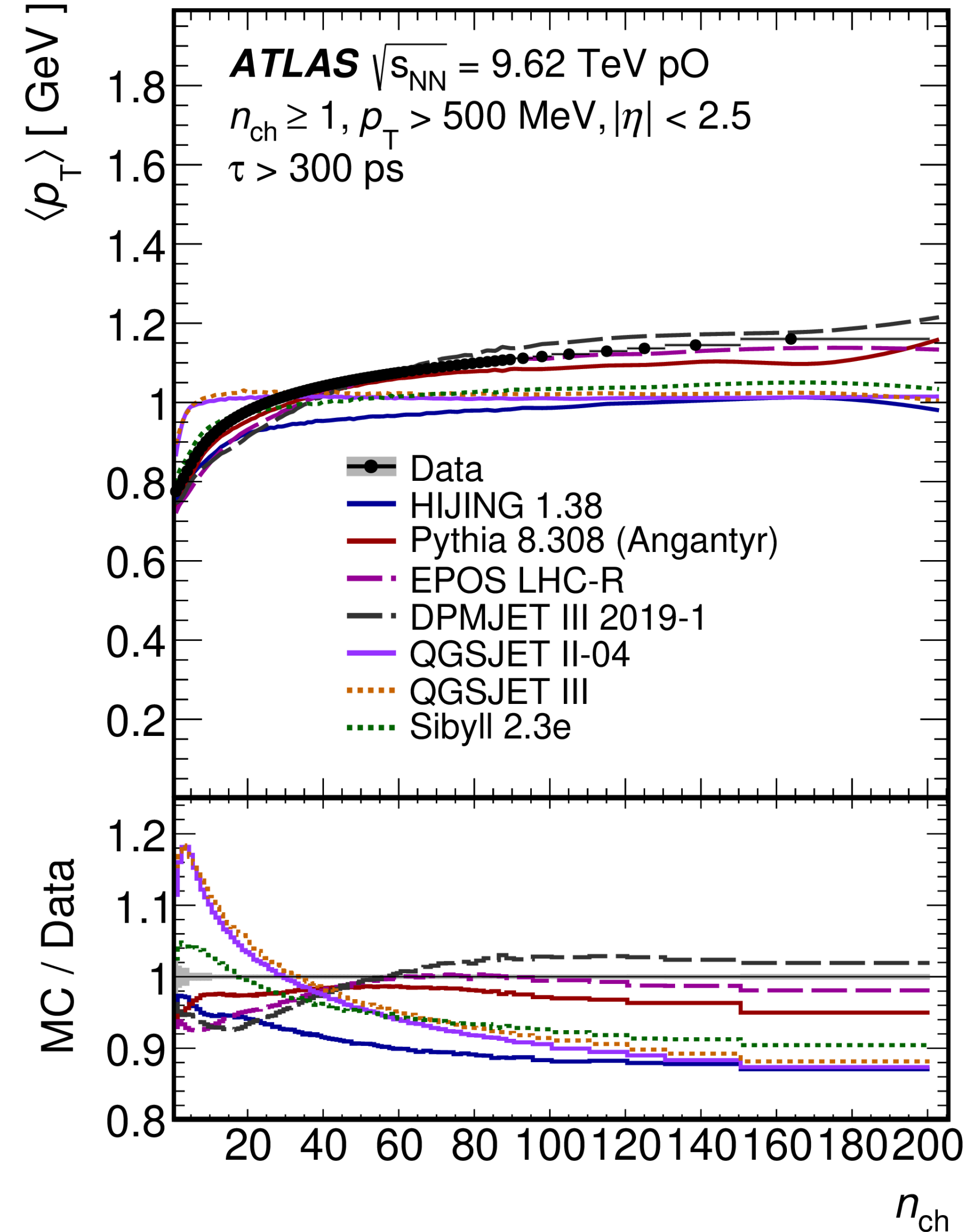


Transverse momentum

First ATLAS p+O differential measurements



η spectrum



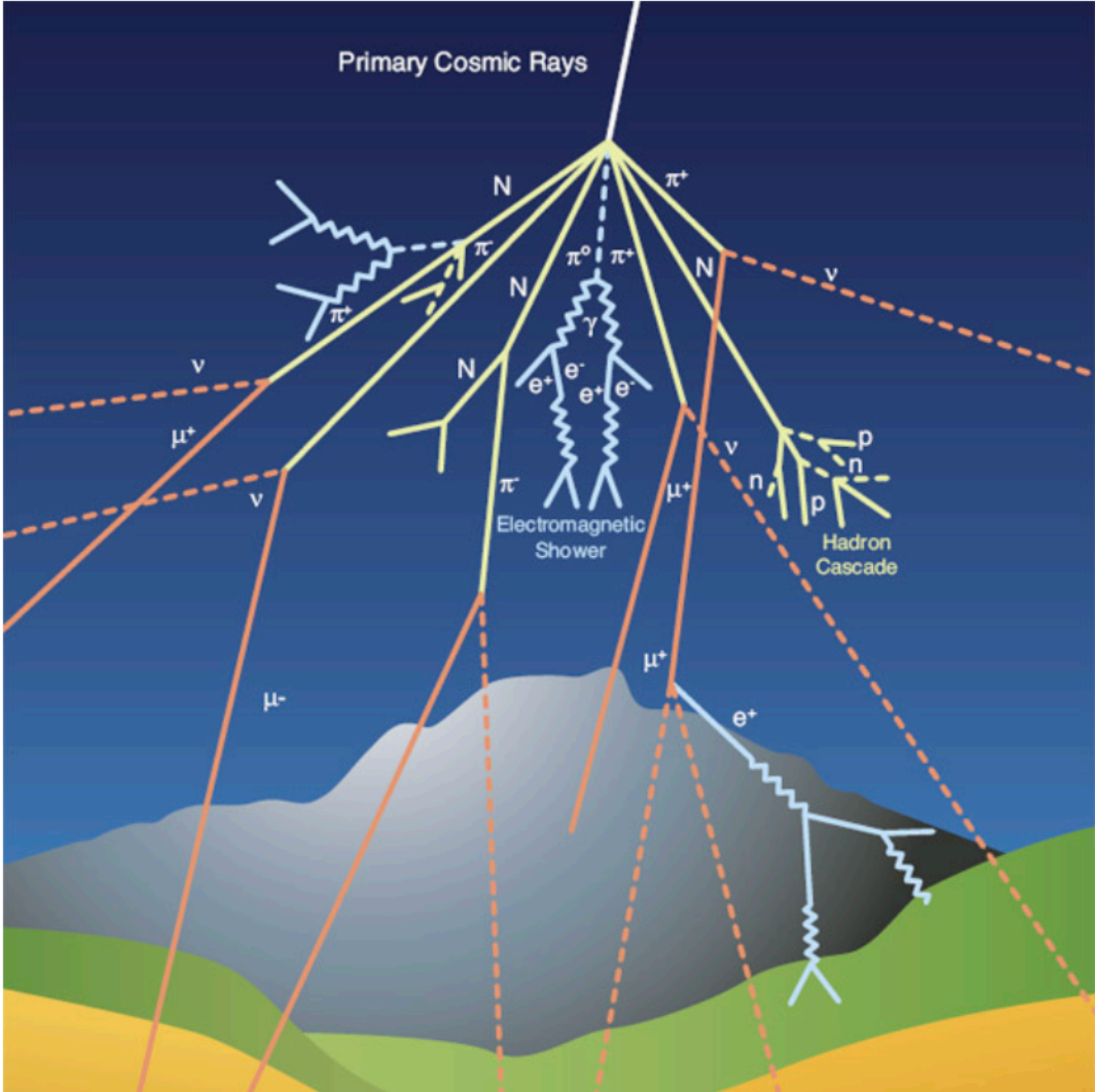
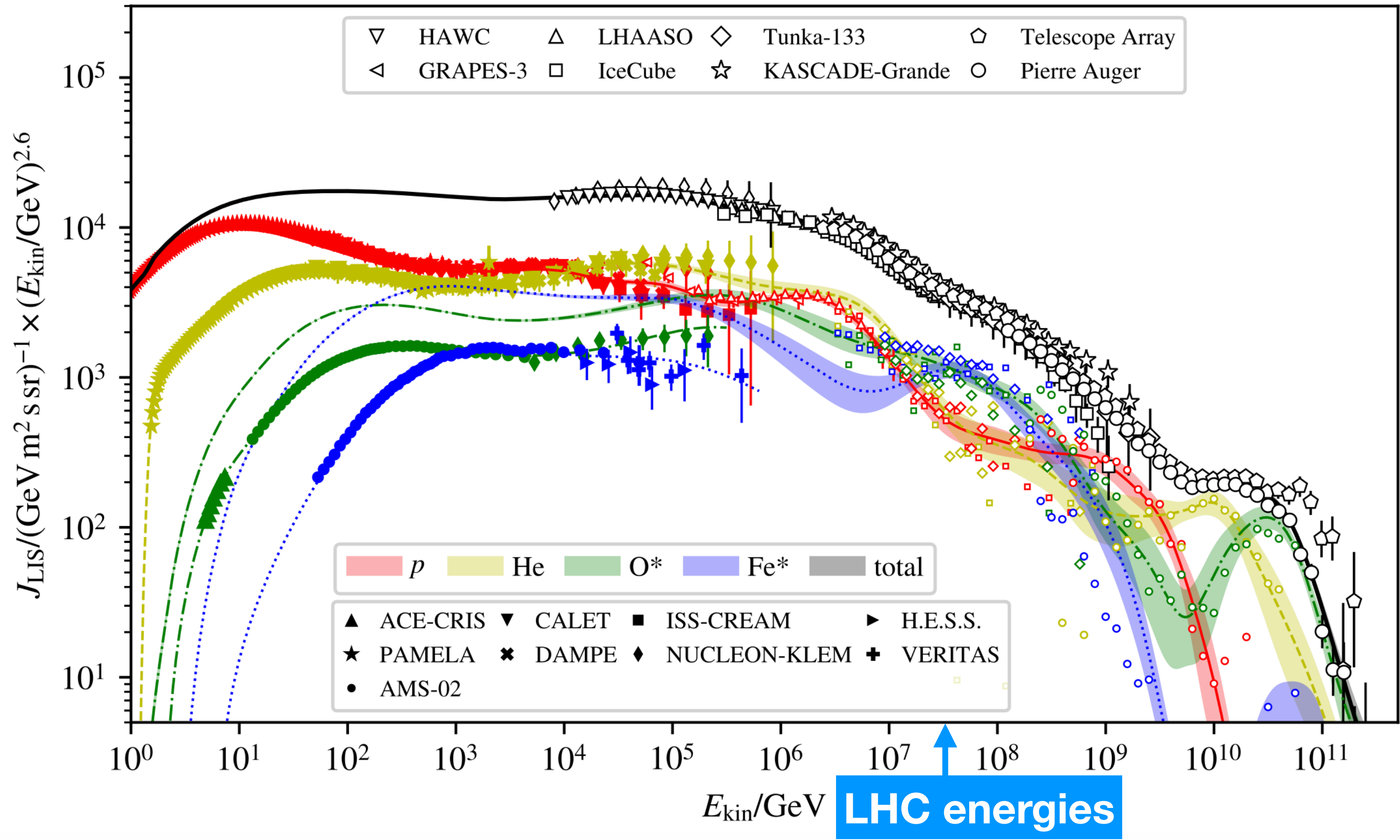
$\langle p_T \rangle$ vs n_{ch}

Summary

- In 2025 LHC became world's highest energy proton-Oxygen collider
- LHC p+O measurements → crucial inputs to improve modelling of cosmic ray air showers
- Presented 1st ATLAS p+O measurement
PRL 137 (2026) 121901

Backup

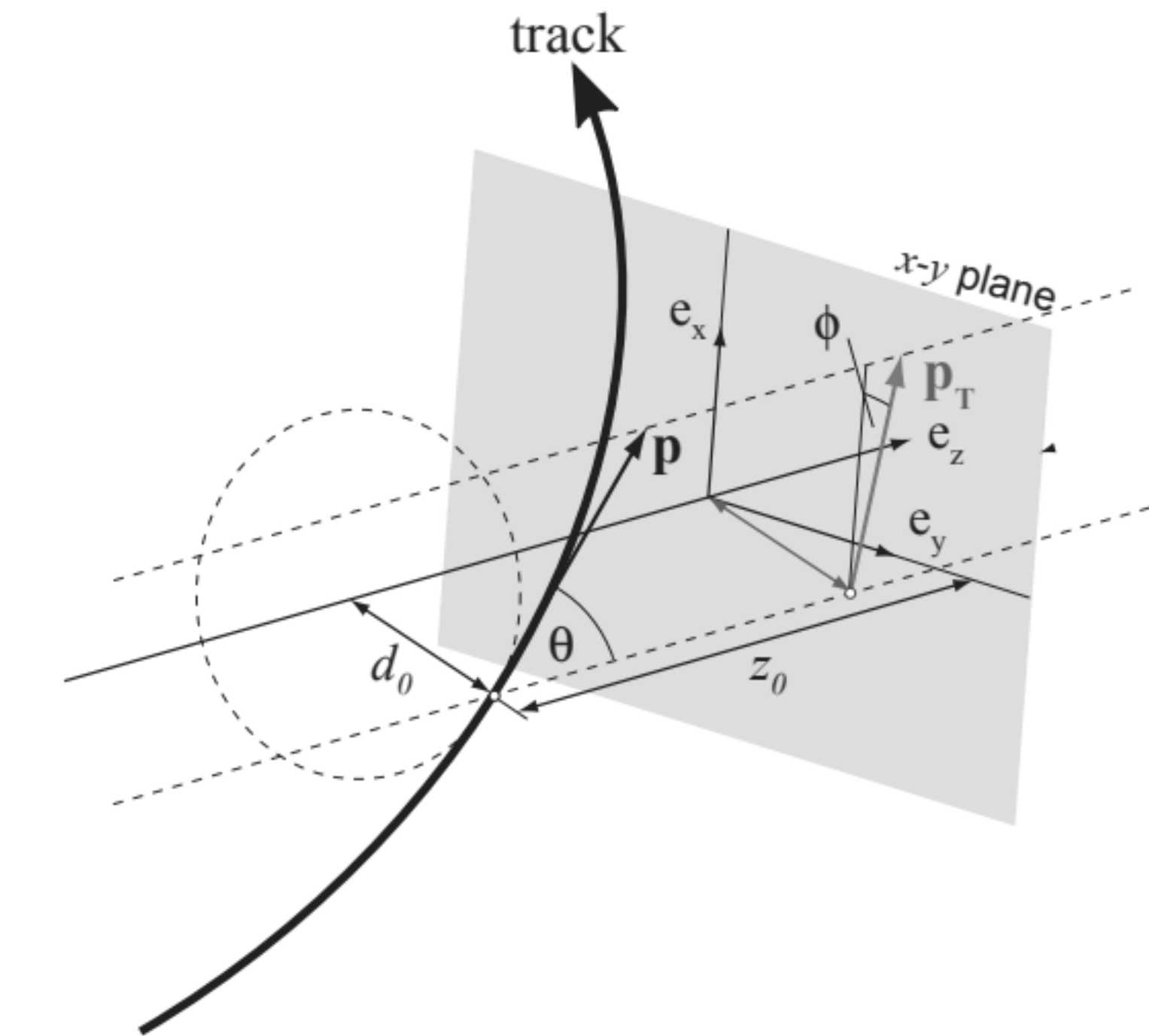
Cosmic-ray spectra



p+O event and track selections

Event requirement	Number of events
Initial	300,026,897
Data quality	297,851,889
Trigger	259,568,152
At least one primary vertex	248,463,797
Veto second vertex with ≥ 5 associated tracks	246,131,825
At least one selected track	245,739,812

Track requirement	Number of tracks
Initial	13,723,685,399
$p_T > 500$ MeV	6,365,824,120
$ \eta < 2.5$	6,258,204,726
$N_{\text{innermost}}^{\text{hits}} \geq 1$	5,763,416,052
$N_{\text{Pixel}}^{\text{hits}} \geq 1$	5,663,741,725
$N_{\text{SCT}}^{\text{hits}} \geq 6$	5,352,225,689
$ d_0^{\text{BL}} < 1.5$ mm	5,169,398,079
$ z_0^{\text{BL}} \sin \theta < 1.5$ mm	5,107,153,531
$P(\chi_{\text{trk-fit}}^2) > 0.01$ if $p_T > 10$ GeV	5,107,138,574



Global track parameters e.g.
wrt. perigee

$$\left(d_0, z_0, \phi, \theta, \frac{q}{p}\right)$$

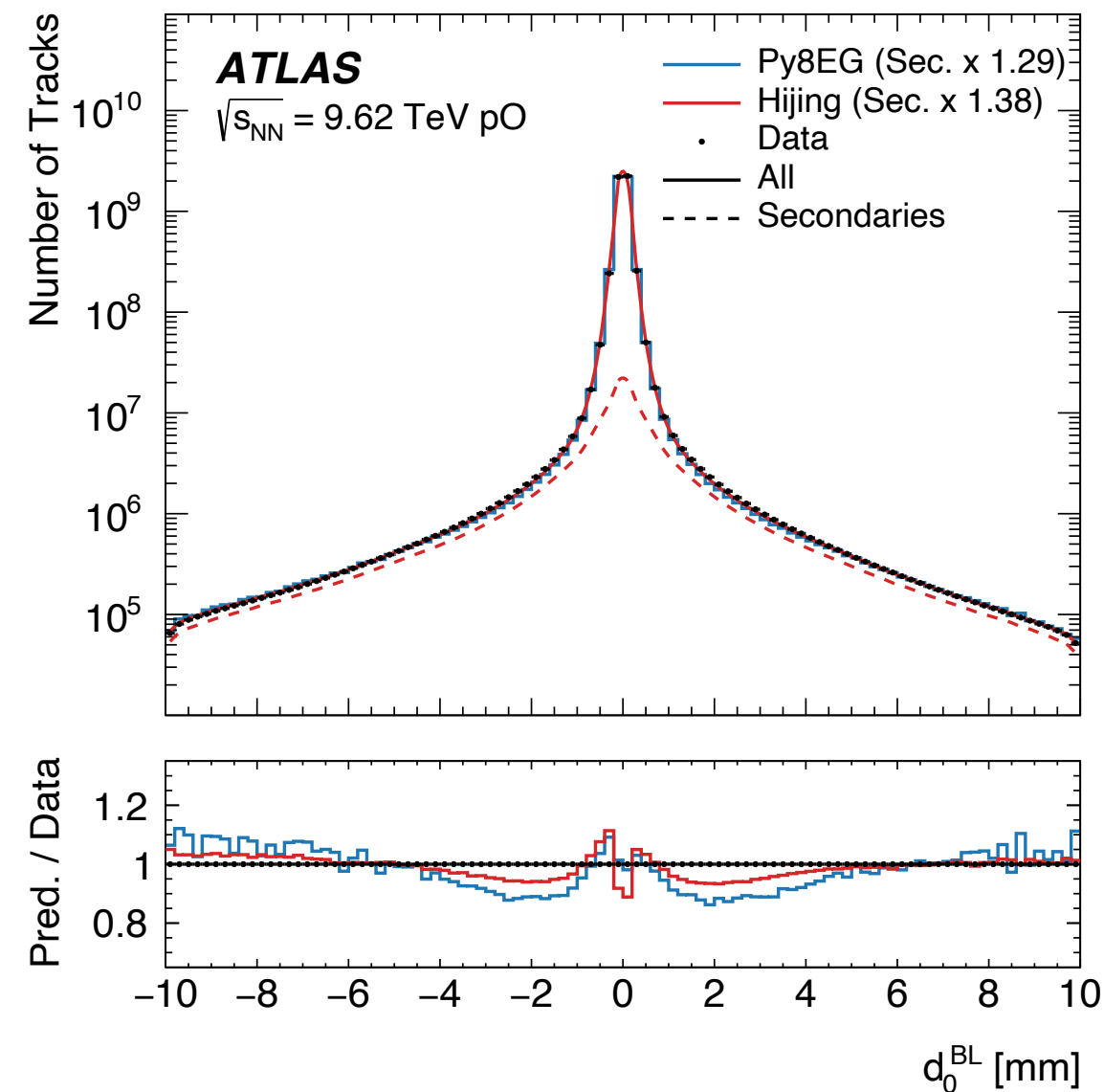
Variable definitions

The following charged-particle distributions are measured: multiplicity $(1/N_{\text{ev}})(dN_{\text{ev}}/dn_{\text{ch}})$, transverse momentum $(1/N_{\text{ev}})(1/2\pi p_{\text{T}})(d^2N_{\text{ch}}/d\eta dp_{\text{T}})$ [144], mean p_{T} ($\langle p_{\text{T}} \rangle$) versus n_{ch} , and pseudorapidity $(1/N_{\text{ev}})(dN_{\text{ch}}/d\eta)$. Here, n_{ch} is the charged-particle multiplicity in an event, N_{ev} is the total number of corrected events, and N_{ch} is the total number of charged particles in all events. Bayesian unfolding [145–147] is applied to correct the multiplicity of selected tracks, n_{sel} , to that of charged particles n_{ch} . Unfolding also corrects the p_{T} distribution of tracks to that of charged particles. For the dependence of $\langle p_{\text{T}} \rangle$ on n_{ch} , unfolding separately corrects $\sum p_{\text{T}i}^i$ (sum over all tracks and events) versus n_{sel} and the total number of tracks in all events versus n_{sel} , before taking the ratio. The η distribution is corrected using only weights as kinematic migrations in η are negligible.

p+O Background estimation

Secondary particles e.g. from interactions of particles with detector material

- MC + data-driven correction $\sim 2.3\%$ dominant

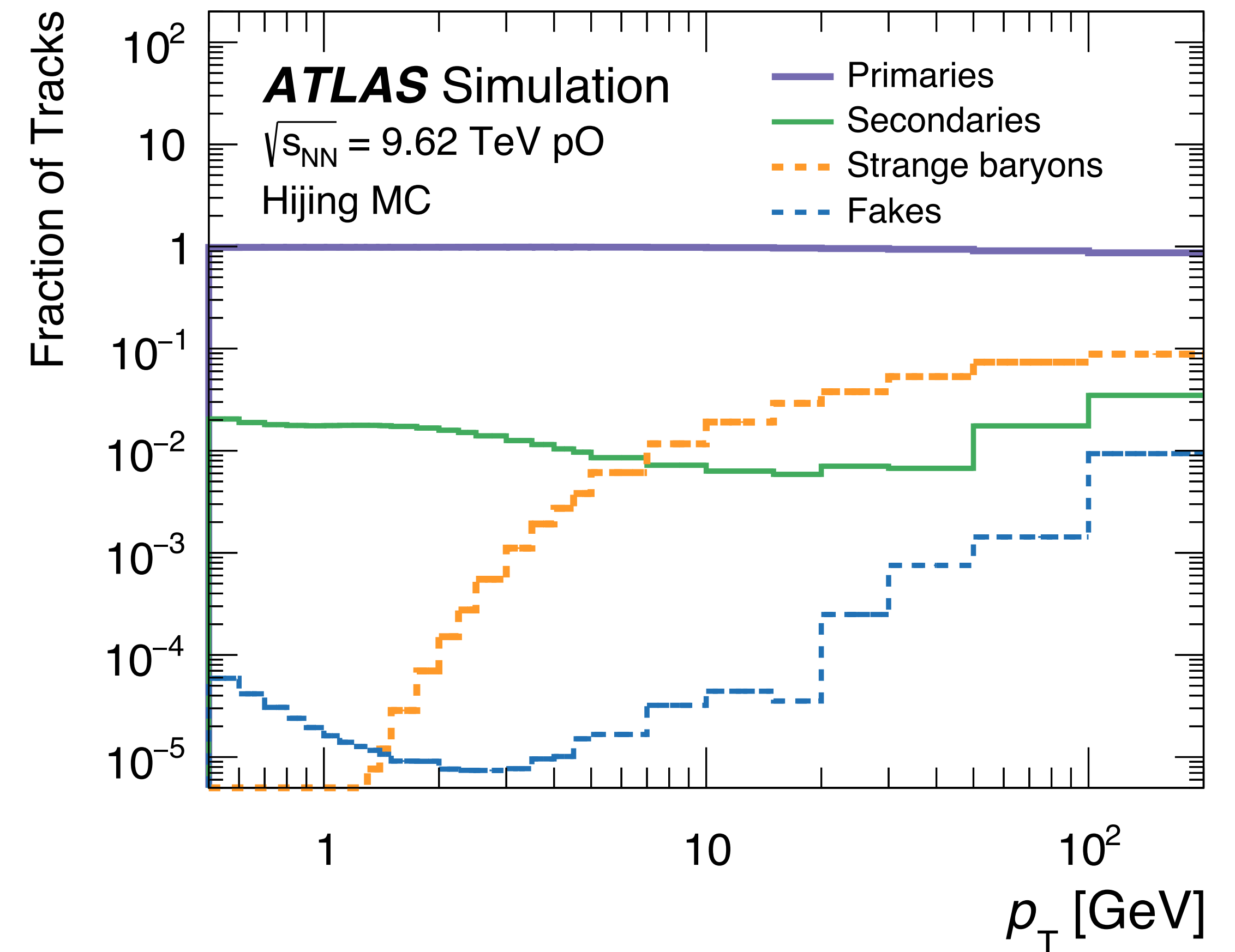


Decay products from strange baryons

- Estimate using MC, dominates at $p_T \gtrsim 10$ GeV

Fake tracks reconstructed from random hits

- Negligible

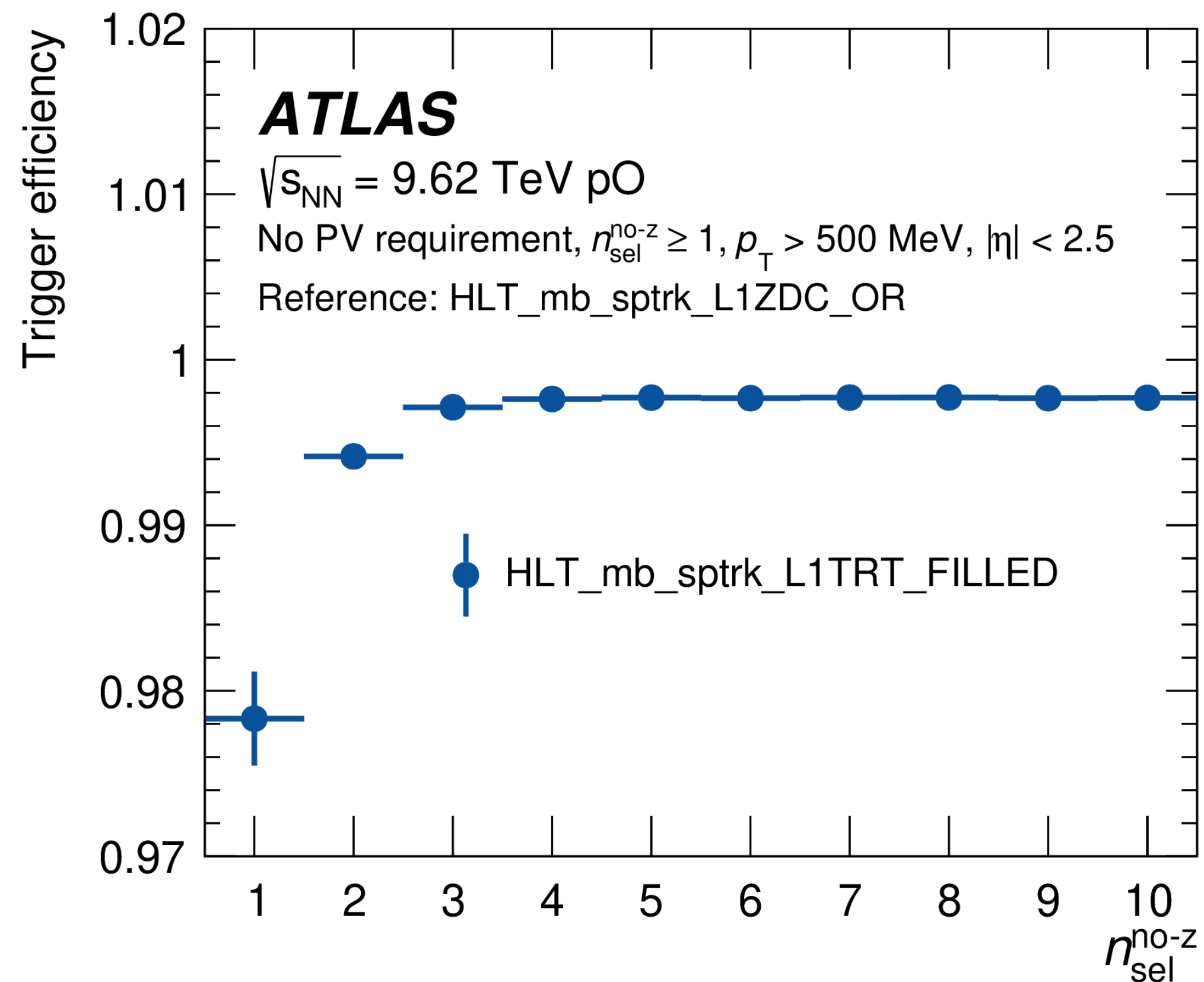


MC truth origin label

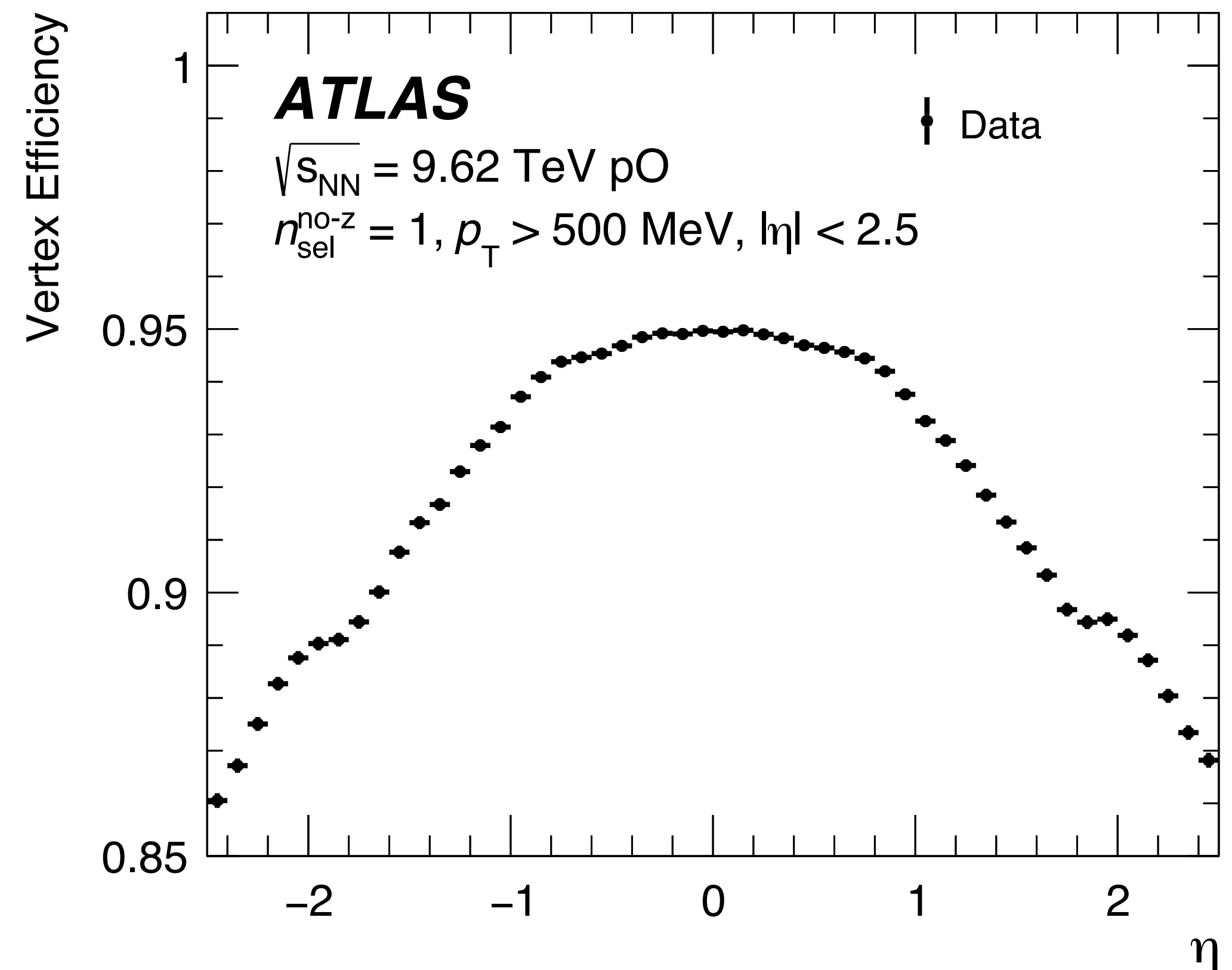
Hijing with full detector simulation

Trigger & vertex efficiency

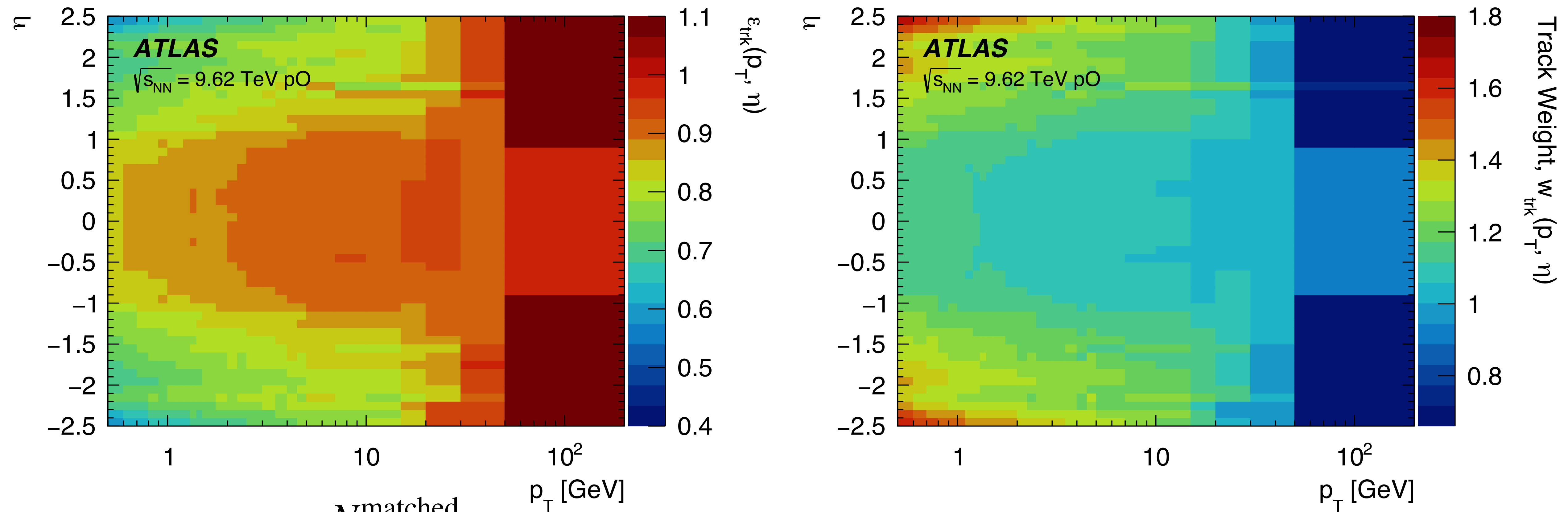
Integrated trigger efficiency: 99.6%
negligible p_T and η dependence



Integrated primary vertex
reconstruction efficiency: 99.5%
91.7% for 1 track, 100% after



p+O 2D track reconstruction efficiencies



$$\epsilon_{\text{trk}} = \frac{N_{\text{reco}}^{\text{matched}}}{N_{\text{gen}}}$$

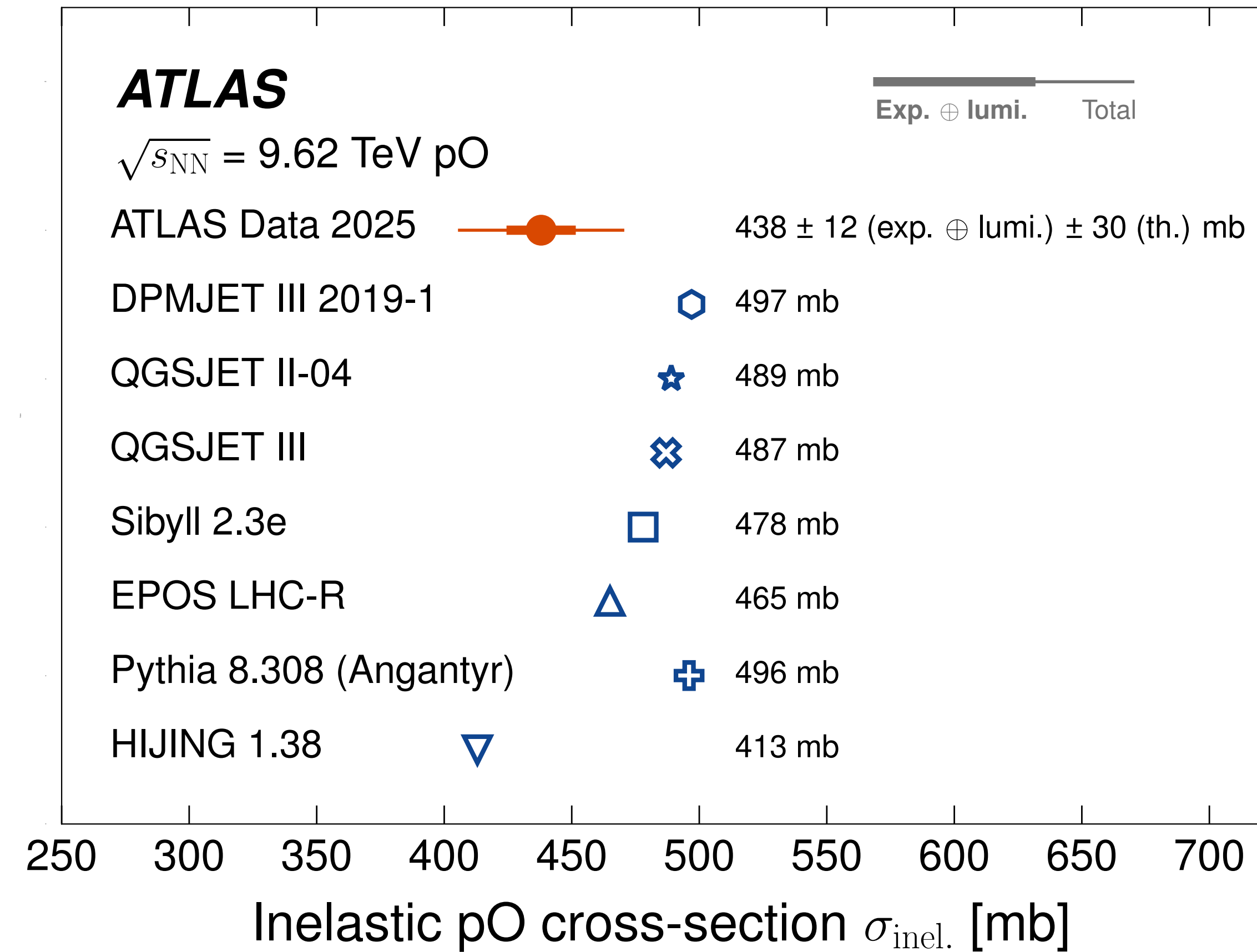
$$w_{\text{trk}}(p_T, \eta) = (1 - f_{\text{sec}} - f_{\text{sb}}) / \epsilon_{\text{trk}}$$

Accounts for out-of-kinematic-range migrations by allowing tracks to match with truth particles outside kinematic acceptance

p+O inelastic cross-section measurement

The cross section is extrapolated to the full inelastic phase space, $\sigma_{\text{inel}} = \sigma_{\text{fid}}/A$, using the mean fiducial acceptance A determined from DPMJET III 2019-1 (95.9%), EPOS LHC-R (84.2%), PYTHIA 8.308 (89.1%), QGSJET II-04 (89.9%), and Sibyll 2.3e (92.5%). This yields $A = (90 \pm 6)\%$, where the maximum difference from the mean is taken as the theory uncertainty. The measured cross section is

$$\sigma_{\text{inel}}^{pO} = 438 \pm 6(\text{exp.}) \pm 10(\text{lumi.}) \pm 30(\text{th.}) \text{ mb.} \quad (2)$$



p+O extrapolation to p+air cross-section

Hadronic modeling is the dominant uncertainty arising from the model-dependent extrapolation outside kinematic acceptance. This result is compatible with EPOS (465 mb) and HIJING (413 mb), while DPMJET III 2019-1 (497 mb), PYTHIA (496 mb), QGSJET II-04 (489 mb), QGSJET III (487 mb), and Sibyll (478 mb) overpredict data by up to 2 standard deviations.

The inelastic proton-air cross section is inferred from Eq. (2) using an MC-based scale factor, $\sigma_{\text{inel.}}^{p+\text{air}} = f_{\text{air}} \times \sigma_{\text{inel.}}^{p\text{O}}$, where $f_{\text{air}} = 0.78 \times (\sigma_{\text{MC}}^{p\text{N}} / \sigma_{\text{MC}}^{p\text{O}}) + 0.22$ assumes air comprises 78% nitrogen and 22% oxygen [152]. The ratio of the proton-nitrogen ($p\text{N}$) to $p\text{O}$ cross sections, $\sigma_{\text{MC}}^{p\text{N}} / \sigma_{\text{MC}}^{p\text{O}} = 0.90 \pm 0.02$, is taken as the mean of the values from DPMJET III 2019-1 (0.899), EPOS LHC-R (0.918), PYTHIA 8.308 (0.921), QGSJET II-04 (0.888), and Sibyll 2.3e (0.895). The 1.8% maximum difference from the mean is added in quadrature to the theory uncertainty. This yields $f_{\text{air}} = 0.93 \pm 0.02$ and a measured proton-air cross section of

$$\sigma_{\text{inel.}}^{p+\text{air}} = 406 \pm 6(\text{exp.}) \pm 9(\text{lumi.}) \pm 28(\text{th.}) \text{ mb.} \quad (3)$$

p+O systematic uncertainties

Source of uncertainty	Distribution	Range of values
Detector material	p_T	1% – 12%
	η	0.8% – 3.6%
	n_{ch}	0% – 18%
Track hits reconstruction	p_T	0.3% – 4%
	η	0.1% – 0.3%
	n_{ch}	0% – 4%
Nonprimaries background	p_T	0.3% – 3%
	η	0.5%
	n_{ch}	0% – 10%
Longitudinal vertex	p_T	0.3%
	η	0.2% – 1%
	n_{ch}	0% – 6%
Unfolding generator dependence	$\langle p_T \rangle$ vs. n_{ch}	0.25% – 2.5%
	p_T	1% – 23%
	η	0.5%
	n_{ch}	1% – 20%