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CORSIKA 8

PIERRE AUGER OBSERVATORY

Implementation of Pythia 8/Angantyr in CORSIKA 8 and Its Tuning for Air Shower Physics

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BERGISCHE UNIVERSITÄT WUPPERTAL

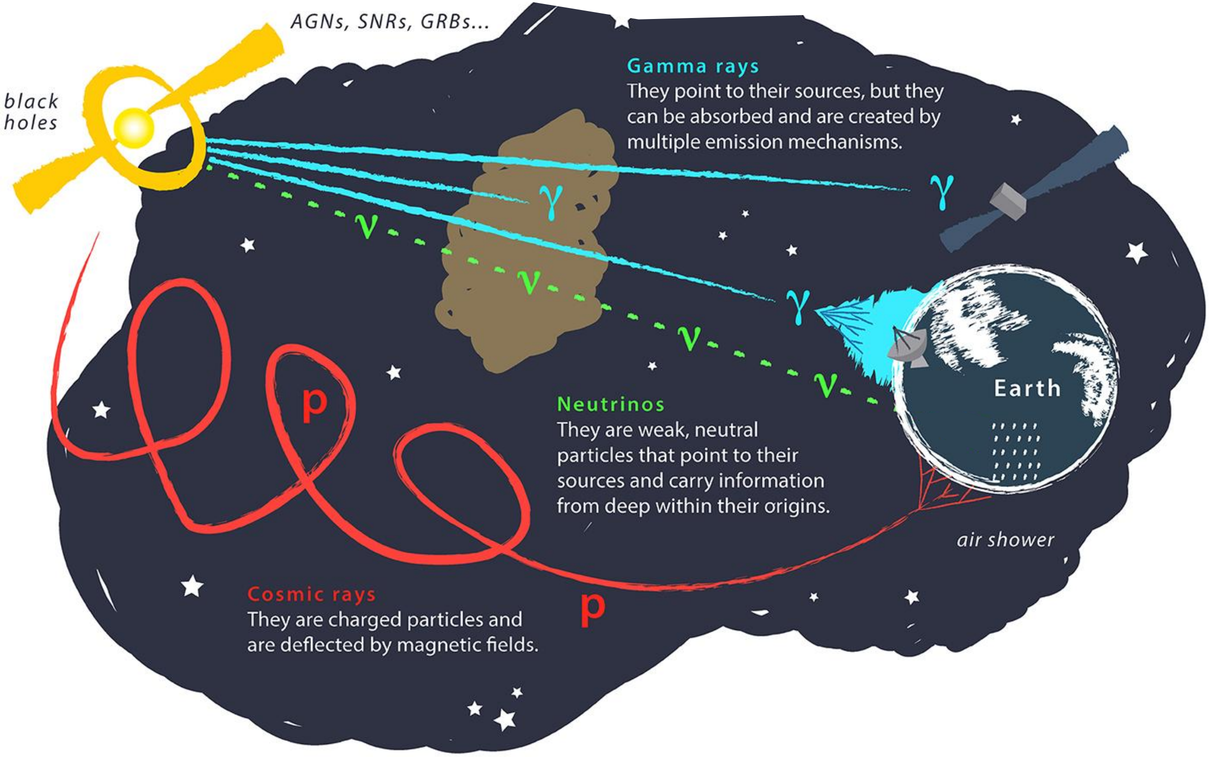
AGN: Active Galactic Nucleus
SNR: SuperNova Remnant
GRB: Gamma-Ray Bursts

Messengers of the Universe

violent astrophysical environments
- ↳ accelerate particles
- ↳ produce radiations

multimessenger picture { gamma rays, neutrinos, cosmic rays }

- ↳ each probe diff. physical processes
- ↳ provide complementary information about astrophysical sources



Juan Antonio Aguilar, Jamie Yang (IceCube/WIPAC)

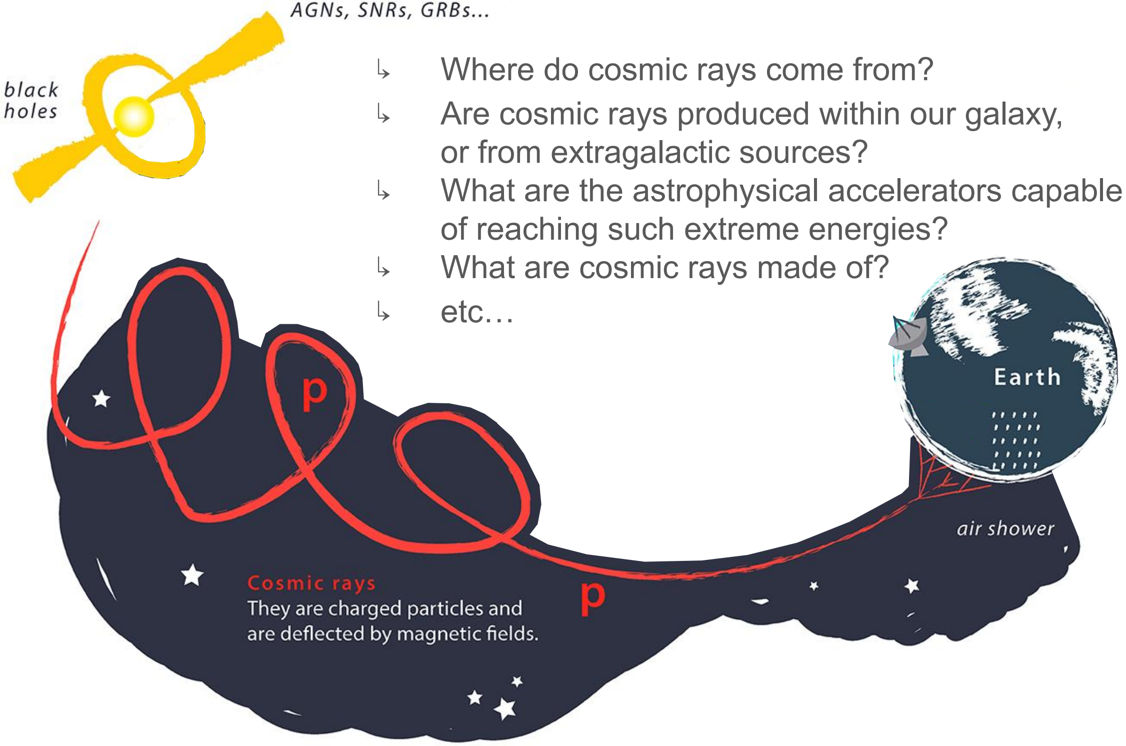
Messengers of the Universe

↳ cosmic rays

ultra high energy cosmic rays
$E_{UHECR} >> E_{man\text{-}made\ exp.}$

↳

unique opportunity to study particle interactions in extreme conditions
unlike at artificial colliders (LHC, RHIC,...)



- ↳ Where do cosmic rays come from?
- ↳ Are cosmic rays produced within our galaxy, or from extragalactic sources?
- ↳ What are the astrophysical accelerators capable of reaching such extreme energies?
- ↳ What are cosmic rays made of?
- ↳ etc…

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Cosmic rays

↳ all-particle energy spectrum

power-law behavior over many orders of magnitude
- ↳ E ~ O(10^9–10^{20}) eV

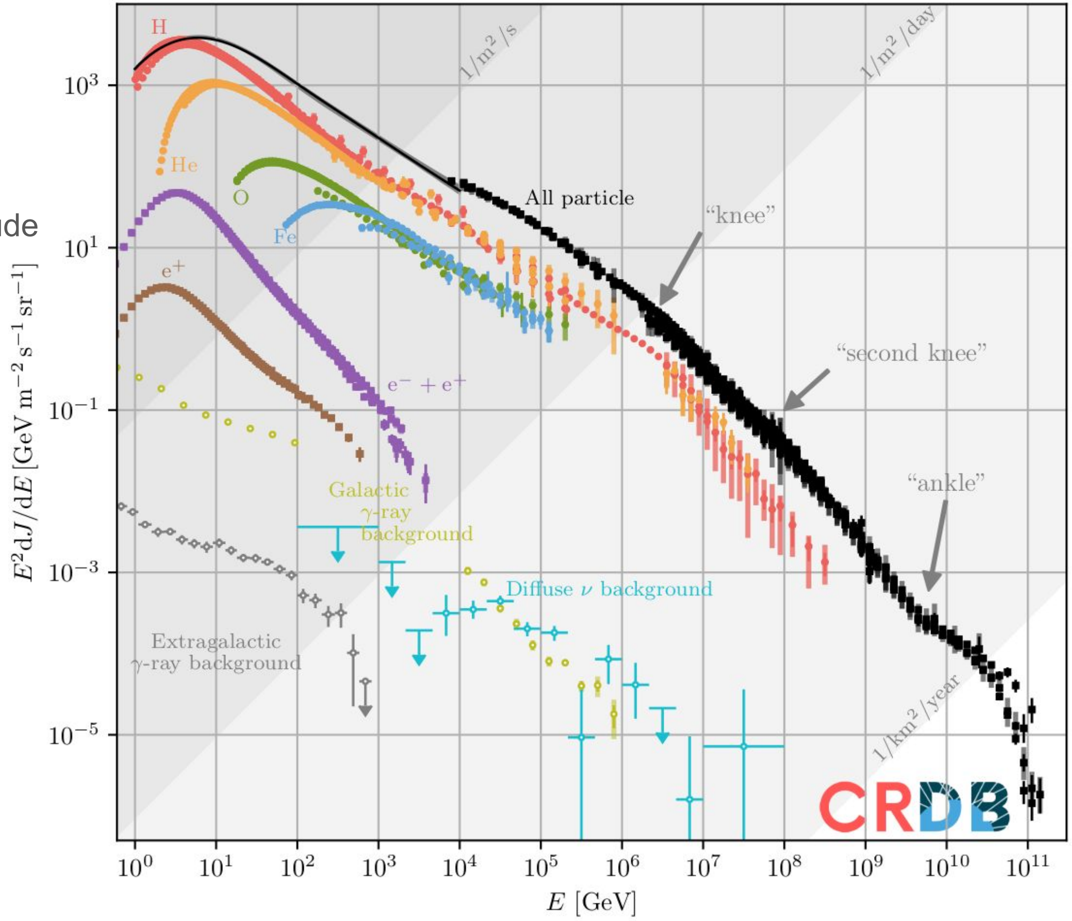
$$\frac{dJ}{dE} \propto E^{-\gamma}$$

direct measurements @ low E
- ↳ space-based, balloon-borne missions

indirect measurements @ high E
- ↳ ground-based experiments

spectral features
- ↳ knee, 2nd knee, ankle, suppression

different acceleration and propagation regimes
- ↳ galactic accelerators dominate @ low E
- ↳ extragalactic sources dominate @ high E



Eur. Phys. J. C 83 (2023) 971

Cosmic rays

↳ mass composition

direct measurements @ low E
provide precise mass composition

- ↳ ~ 90% protons
- ↳ ~ 9% helium nuclei
- ↳ ~ 1% heavier nuclei

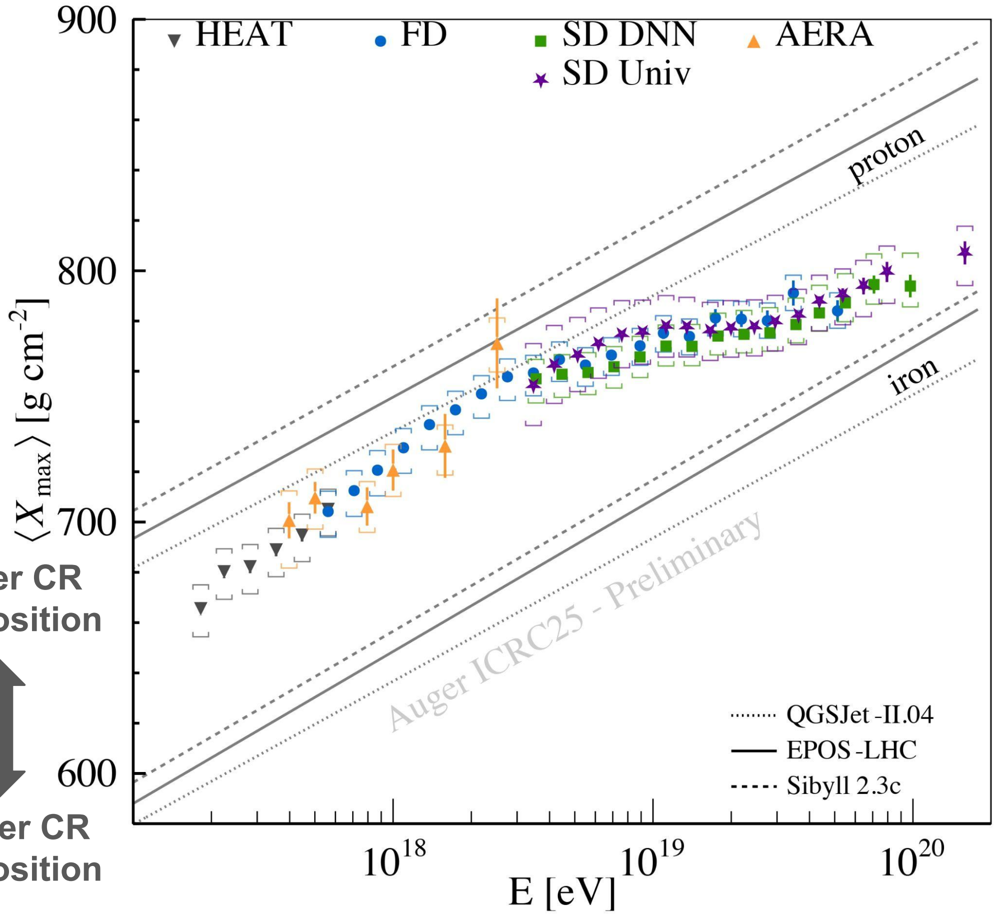
indirect measurements @ high E
infer mass comp. from **secondary signatures**

- ↳ compare exp. data vs. simulations
  - ↳ mass composition ∝ E
  - ↳ carry large simulation uncertainties

secondary signatures?

lighter CR composition

heavier CR composition



PoS ICRC2025 (2025) 331

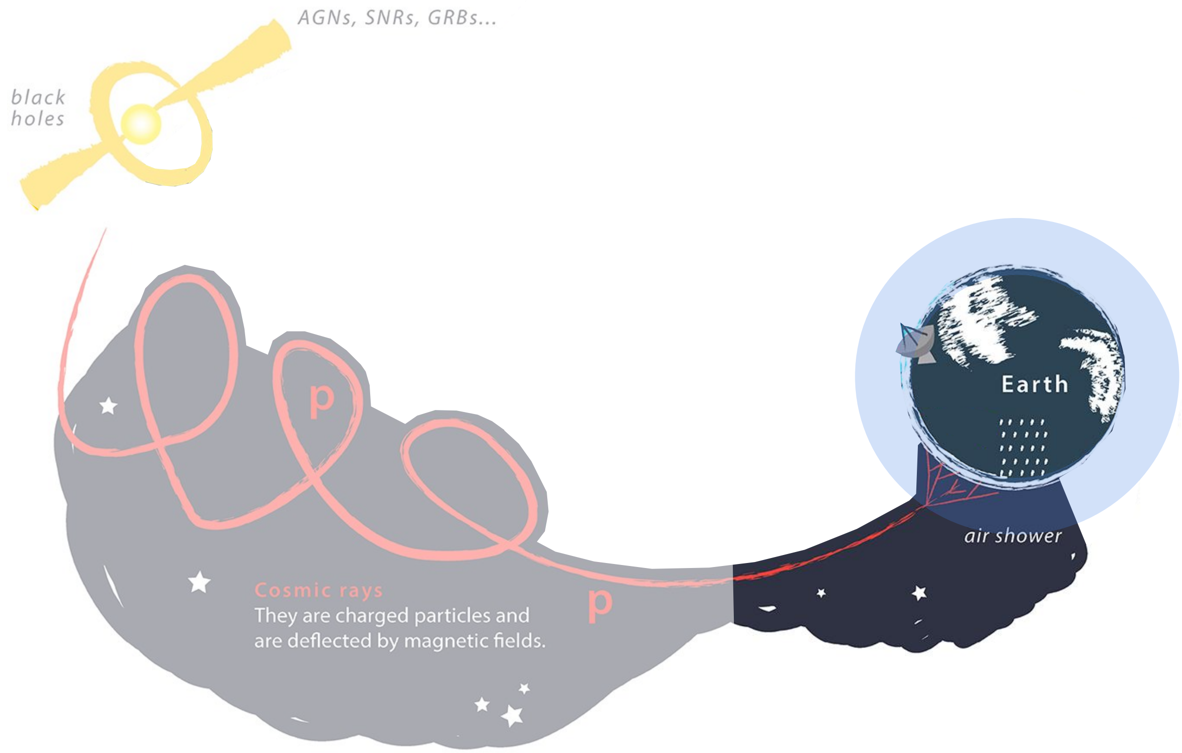
Cosmic rays

↳ secondary signatures

cosmic rays interact with
Earth's atmosphere

produce cascade
of secondary particles
= **air shower**

Earth's atmosphere: 78% N, 21% O, 1% Ar



Juan Antonio Aguilar, Jamie Yang (IceCube/WIPAC)

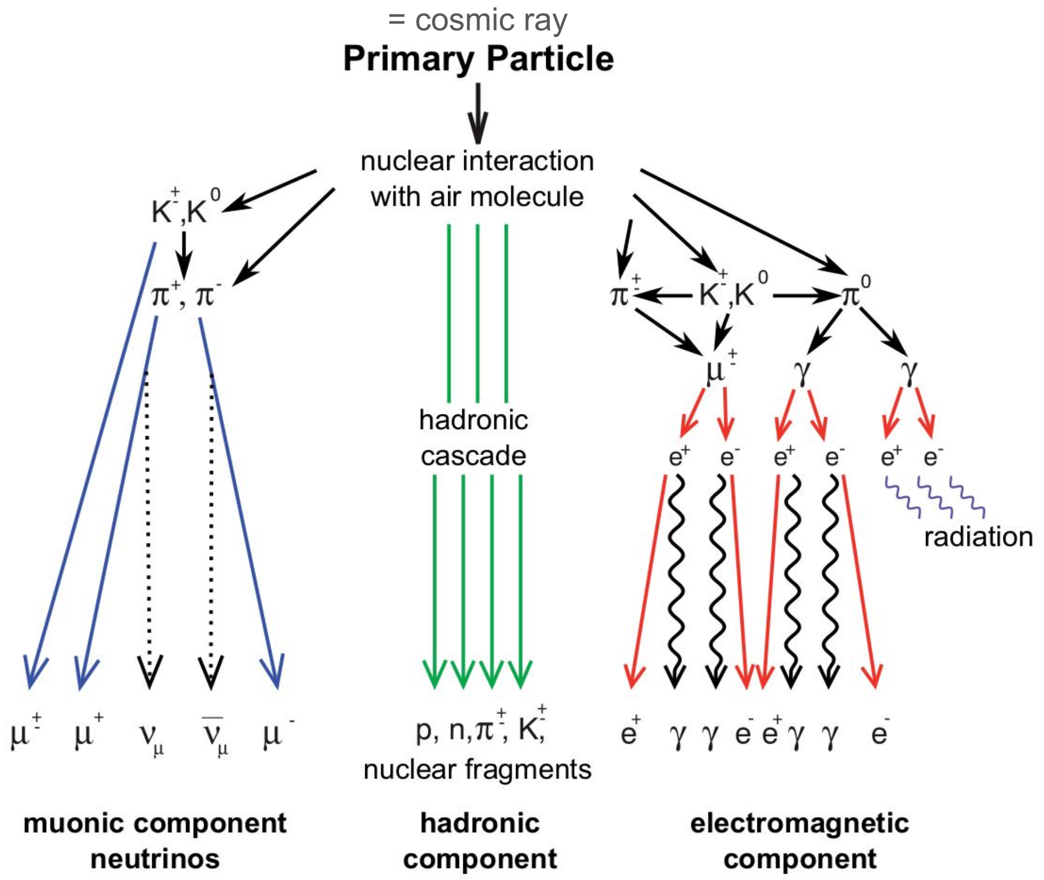
Cosmic rays

↳ air shower structure

air shower develop via part. interactions and decays

several shower components

- ↳ **hadronic** = shower backbone
  - ↳ mainly π,K, nucleons
  - ↳ transfer E to others components
- ↳ **electromagnetic**
  - ↳ from $\pi^0 \rightarrow \gamma$ decays
  - ↳ pair production/bremsstrahlung
  - ↳ carry large fraction shower E
- ↳ **muonic**
  - ↳ from π,K decays
  - ↳ μ weakly interact and lose little E } reach ground



arXiv:1504.06696 [astro-ph.IM]

Cosmic rays

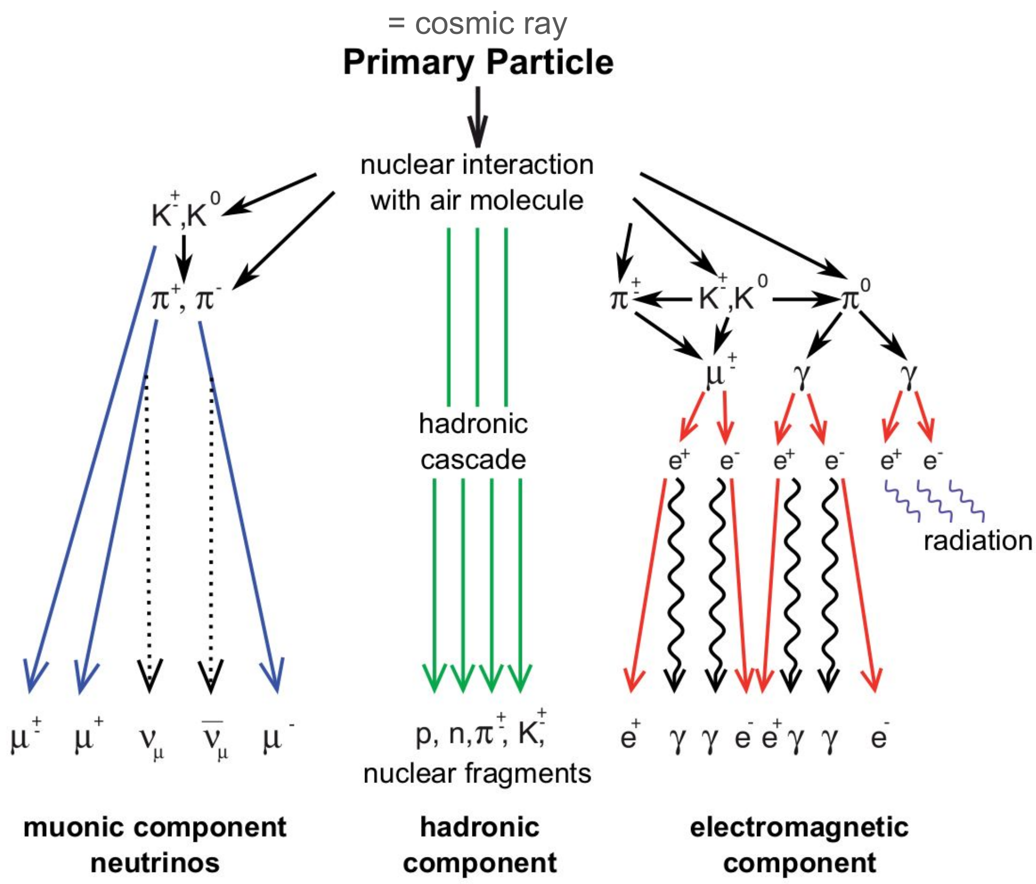
↳ air showers

study cosmic rays at highest energies

↳ need observatory capable of detection and accumulating sufficient statistics

indirect detection

PIERRE AUGER OBSERVATORY



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Pierre Auger Observatory

↳ overview

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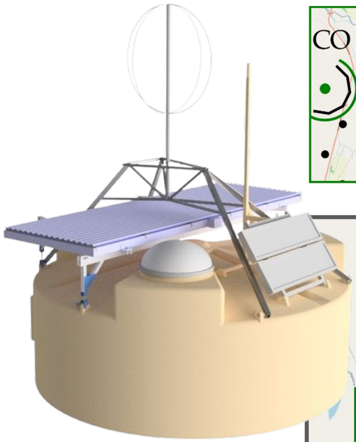
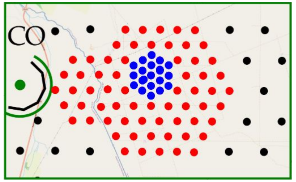
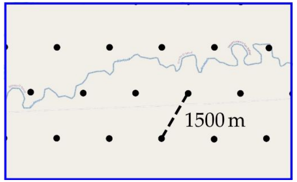
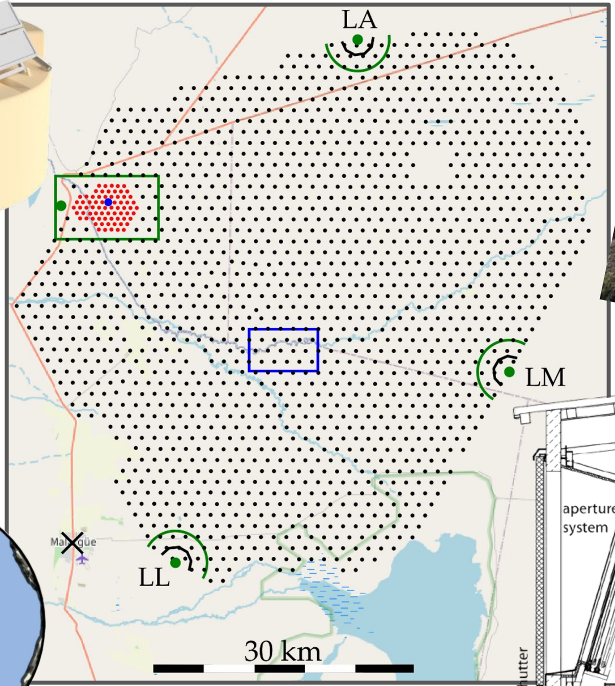
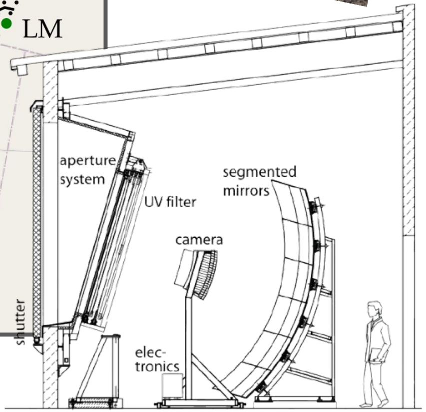










located in Malargüe, Argentina

~3000 km^2 instrumented area

- ↳ study UHE cosmic rays

hybrid detector design

- ↳ Surface Detector (SD)
  - ↳ ~1600 stations
    - ↳ water cherenkov detector
    - ↳ scintillator surface detector
    - ↳ radio antenna
- ↳ Fluorescence Detector (FD)
  - ↳ 4 sites around the SD array
  - ↳ 27 telescopes

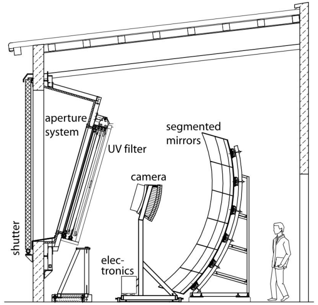
Steffen Hahn

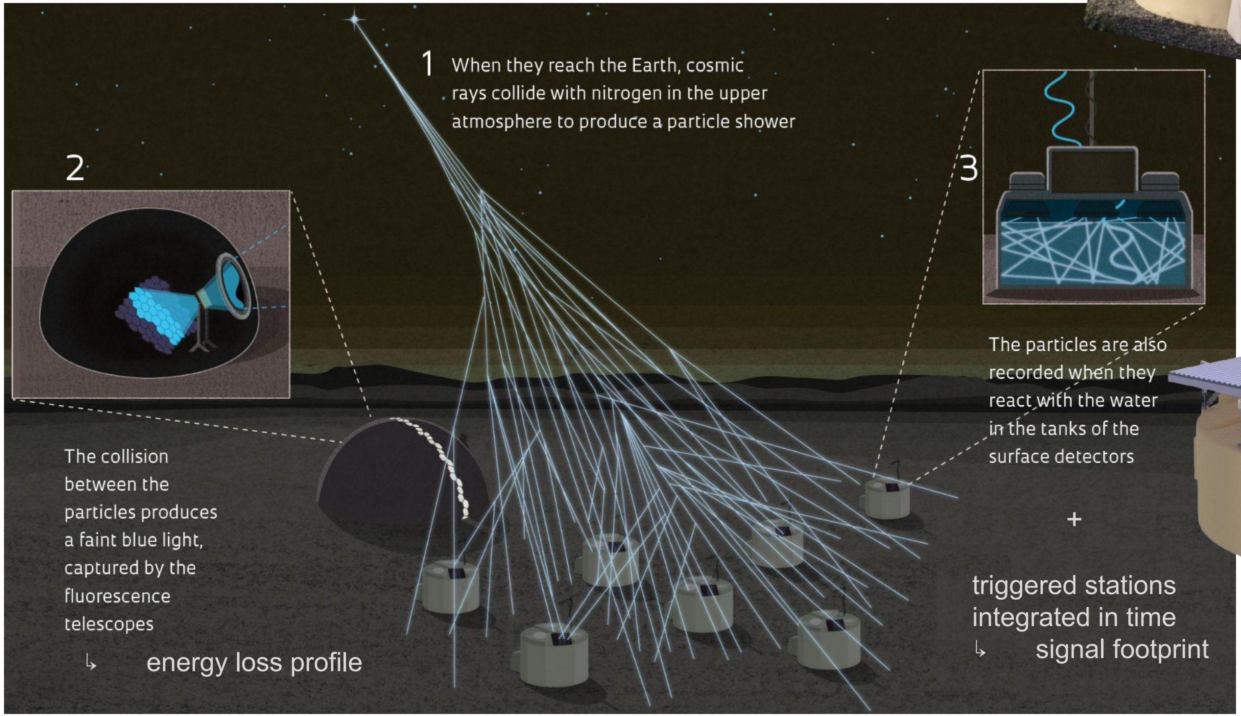
Nucl. Instrum. Meth. A 798 (2015) 172-213

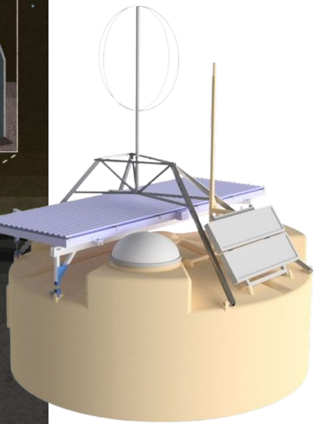
Indirect detection of air showers

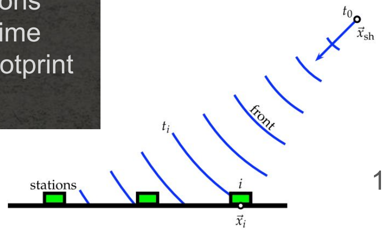
↳ at the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY









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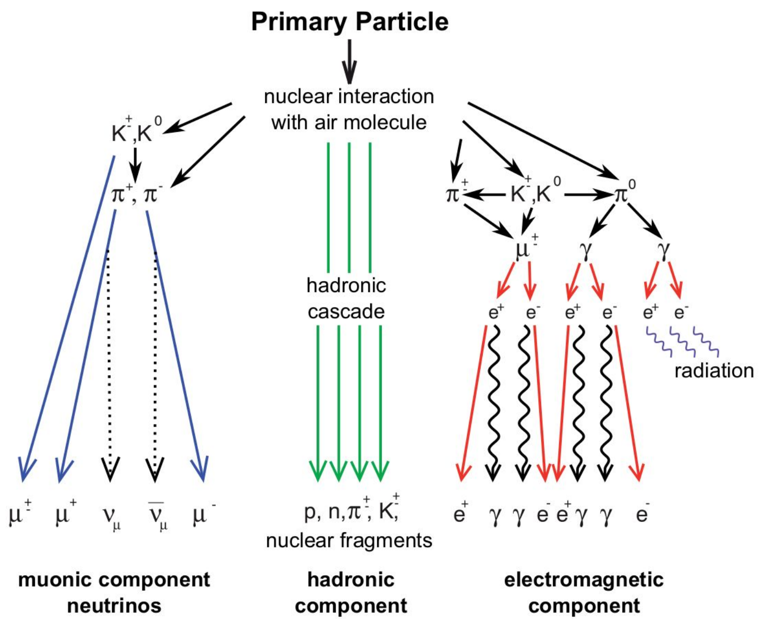
C. Fioravanti. Cosmic Rays, Still an Enigma. Nucl. Instrum. Meth. A 798 (2015) 172-213

Simulating air showers

↳ full simulation framework



simulating air showers = computationally complex

- ↳ detailed interaction physics
- ↳ track millions of secondary particles across atmosphere

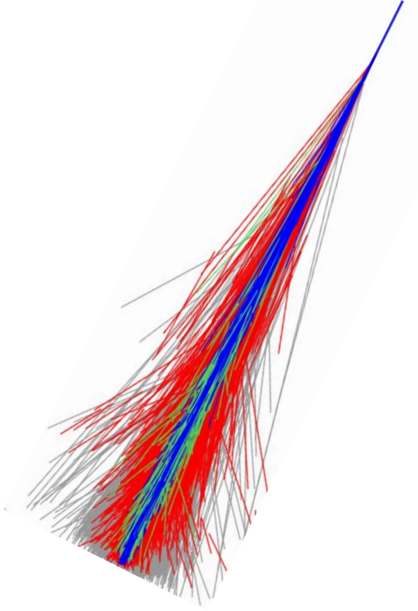
full simulation framework models the entire shower evolution

- ↳ from 1st interaction atop the atmosphere to particle distribution at the observation level

- ↳ **particle shower simulation codes**
  - ↳ provide full 3D simulations with detailed tracking of individual particle trajectories
- ↳ **hadronic interaction models**
  - ↳ predict outcomes of each collisions during shower development

Simulation framework

↳ particle shower simulation code



numerical code simulating full development of particle cascades in a medium

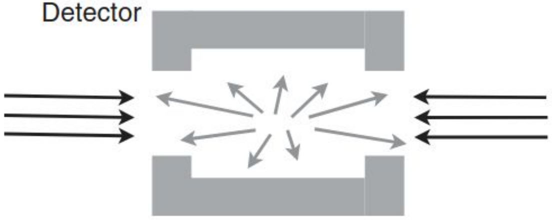
- ↳ tracks secondary particles individually in realistic 3D environments
  - ↳ position, time, energy, momentum evolution
- ↳ samples stochastic processes generating new particles
  - ↳ interactions, decays
- ↳ outputs measurable quantities
  - ↳ $N_p(X)$, dE/dX, dN/dr, dN/dE at observer level

CORSIKA 8 = new C++ particle shower simulation code

- ↳ successor of CORSIKA 7, with focus on modularity
- ↳ open-source community project
- ↳ hadronic interactions { high E = EPOS-LHC, QGSJet-II.04, Sibyll 2.3d; low E = FLUKA
- ↳ EM cascades handled by PROPOSAL

Simulation framework

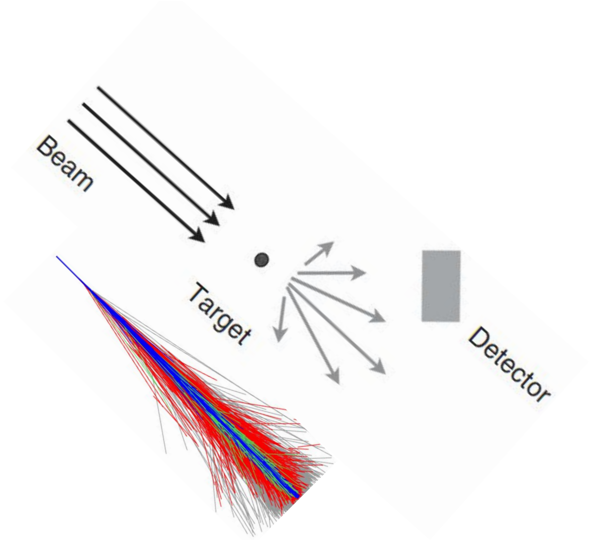
↳ hadronic interaction model (HIM)



HIM describe hadronic interactions

- ↳ combining { perturbative QCD (hard processes)
  + phenomenological models
  (soft interactions, diffraction, nuclear effects)
- ↳ linking QCD theory to experimental observables

- ↳ tuned to accelerator experimental data
- ↳ extrapolated to higher energies



different use case

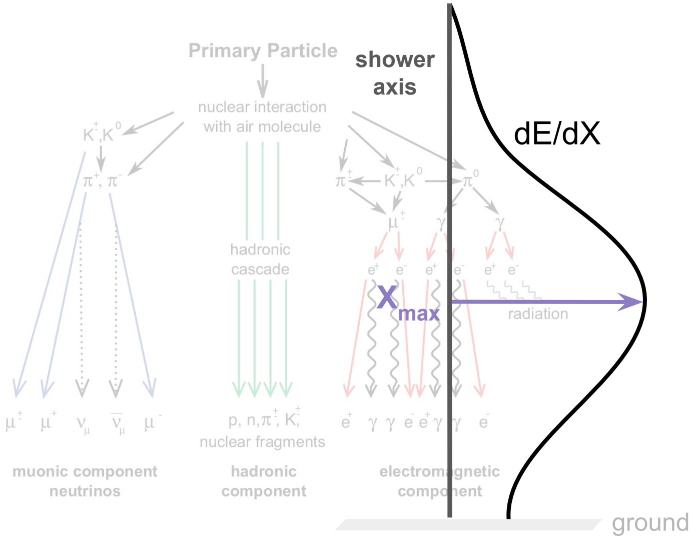
- ↳ particle physics = Herwig, **Pythia**, Sherpa
- ↳ air shower physics = EPOS-LHC, QGSJet, Sibyll

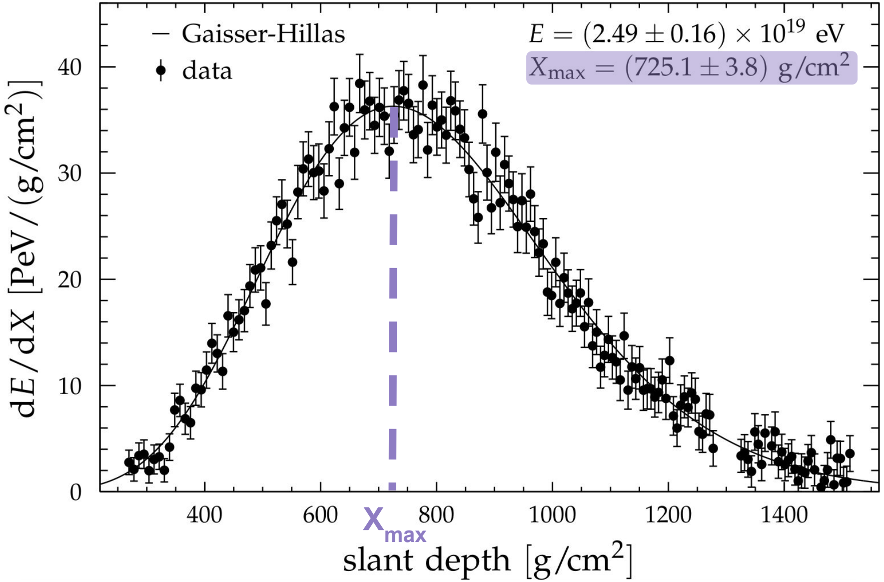
Indirect detection of air showers

↳ **relevant quantity: depth of the shower maximum X_{max}**

experimental measurement
@ Pierre Auger Observatory

energy deposited in the atmosphere ∝ air shower size





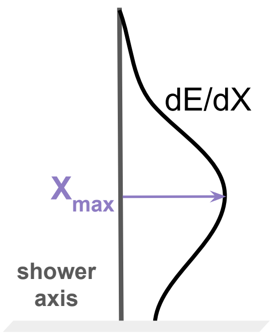
arXiv:1504.06696 [astro-ph.IM]   Phys.Rev.D 90 (2014) 12, 122005

Indirect detection of air showers

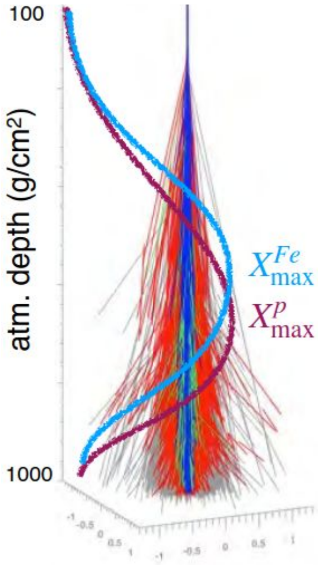
↳ **relevant quantity: depth of the shower maximum X_{max}**

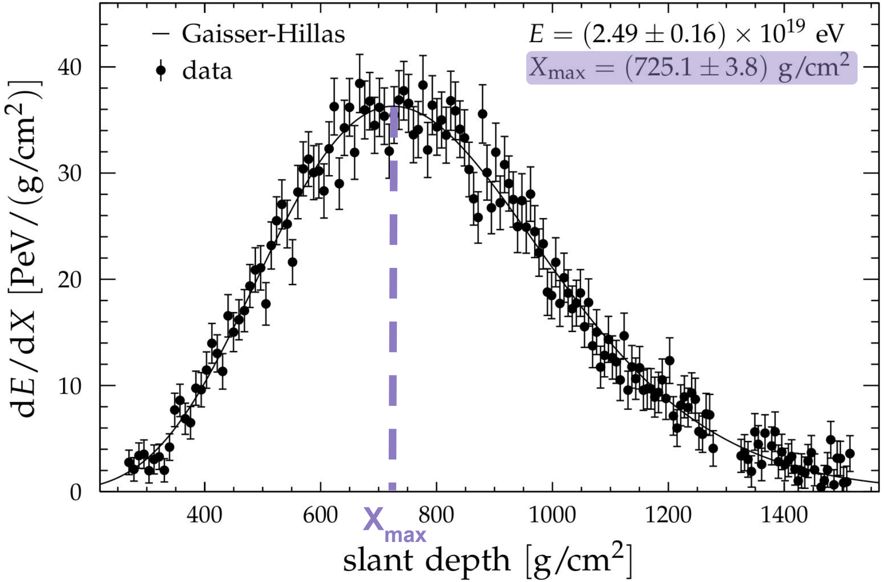
X_{max} ∝ mass of cosmic ray

experimental measurement @ Pierre Auger Observatory



dE/dX ∝ air shower size





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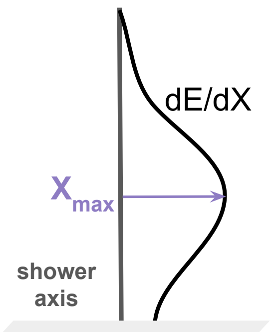

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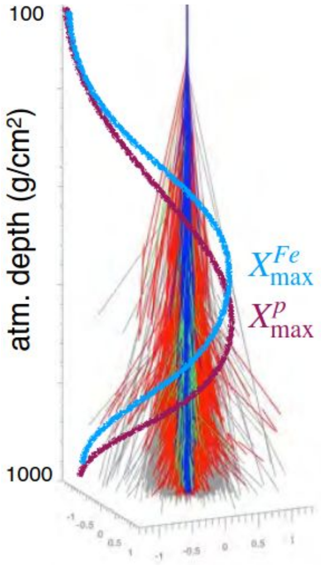
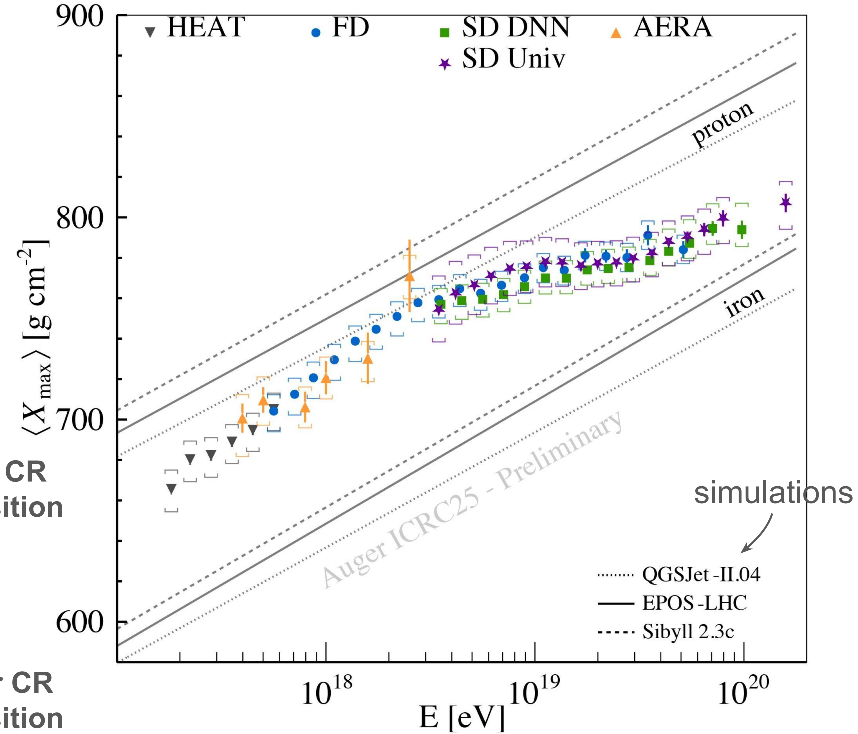


lighter CR composition

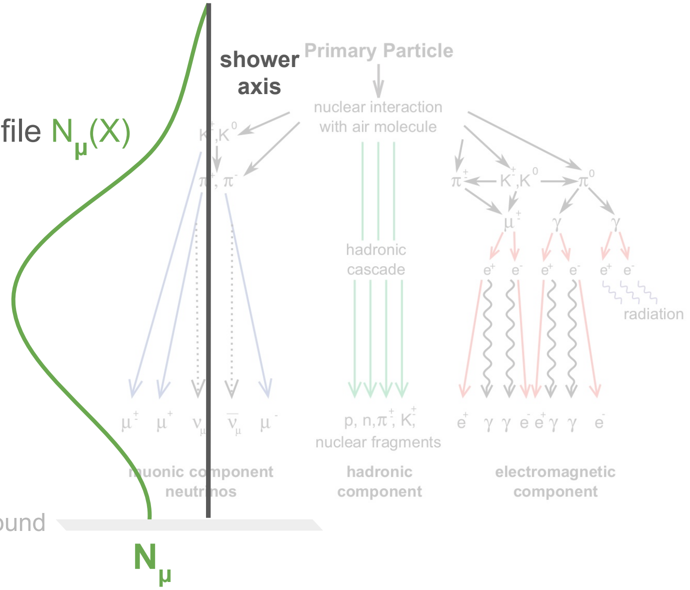
heavier CR composition

experimental measurement
@ Pierre Auger Observatory



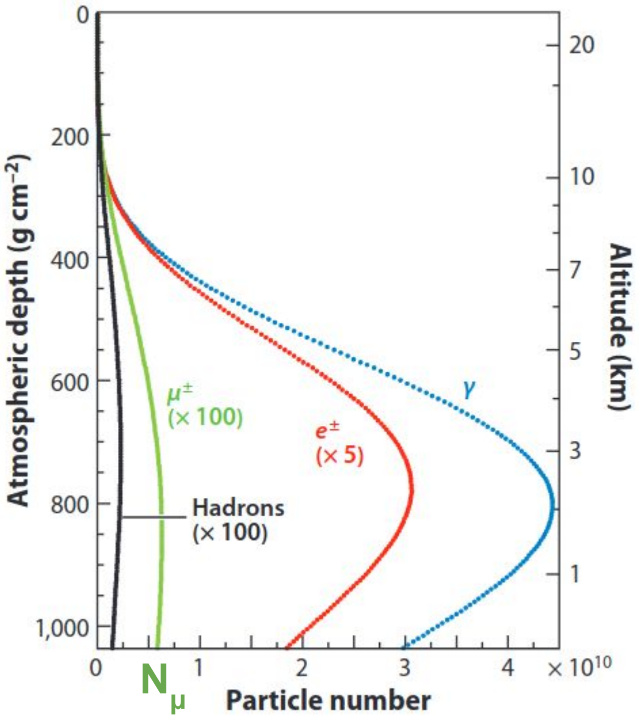
Indirect detection of air showers

↳ **relevant quantity: number of muons at ground N_μ**



number of muons reaching the ground

p@10^{19} eV air showers simulations using CORSIKA



arXiv:1504.06696 [astro-ph.IM] Annu. Rev. Nucl. Part. Sci. 61, 467-89 (2011)

Indirect detection of air showers

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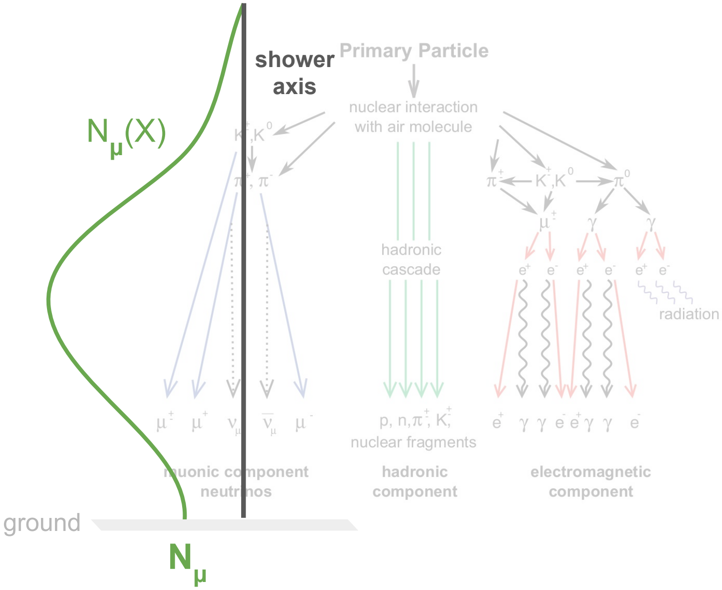


$N_\mu \propto$ mass of cosmic ray

μ at ground = early shower development in high altitude

heavier primary CR
↳ more nucleons
↳ more $\pi^\pm$, $K^\pm$

Decay channel	Branching ratio (%)
$\pi^+ \to \mu\nu_\mu$	99.987
$\pi^- \to \mu\bar{\nu}_\mu$	99.987
$K^+ \to \mu\nu_\mu$	63.56
$K^- \to \mu\bar{\nu}_\mu$	63.56
$K^0_L \to \pi^\pm\mu\nu_\mu$	27
$D^+ \to \mu\nu_\mu X$	16
$D^0 \to \mu\nu_\mu X$	7
$\Lambda_c^+ \to \mu\nu_\mu X$	4.5

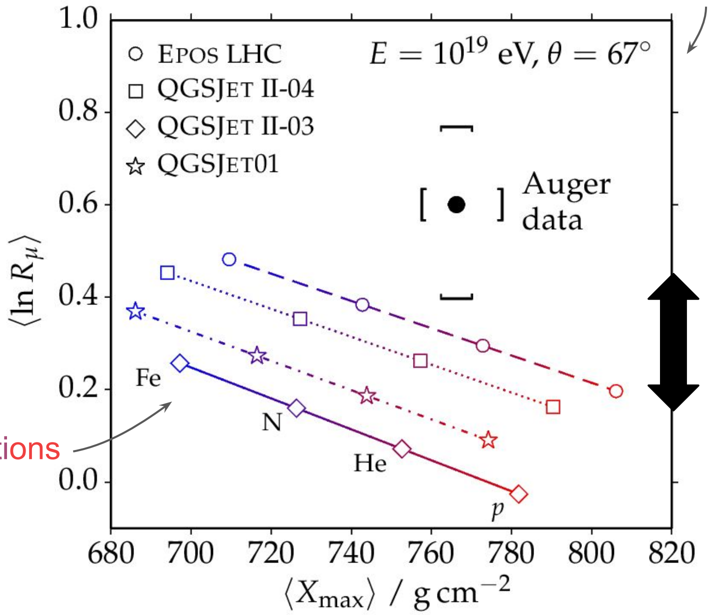
↳ more μ

arXiv:1504.06696 [astro-ph.IM]

Indirect detection of air showers

↳ **"Muon Puzzle"**

experimental measurement
@ Pierre Auger Observatory



μ content

simulations

"Muon Puzzle"

↳ discrepancies between simulations and experimental measurements

Phys. Rev. D 91, 032003 (2015)

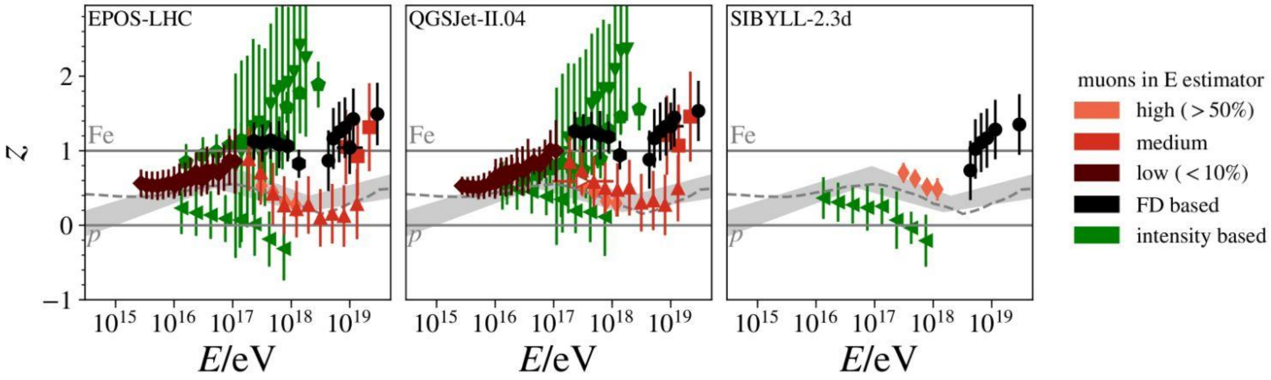
Indirect detection of air showers

↳ "Muon Puzzle" in other experimental apparatus

WHISP meta-analysis shows conflicting results between experiments
- ↳ combine data from many μ detectors
- ↳ account for different methods and thresholds
  - ↳ introduce normalized **z scale**

$$z = \frac{\ln\langle N_\mu\rangle - \ln\langle N_{\mu,\mathrm{p}}\rangle}{\ln\langle N_{\mu,\mathrm{Fe}}\rangle - \ln\langle N_{\mu,\mathrm{p}}\rangle}$$

- ↳ z = 1 iron primary
- ↳ z = 0 proton primary



measure the E_{shower} with little or no μ contribution
- ↳ show increasing μ deficit

z ↗ ∝ E

“Muon Puzzle”

↳ from model discrepancies to new modeling approaches

Pythia 8/Angantyr

↳ Pythia 8 (e^-e^+, pp/p$\bar{p}$)

↳ general purpose hadronic interaction model

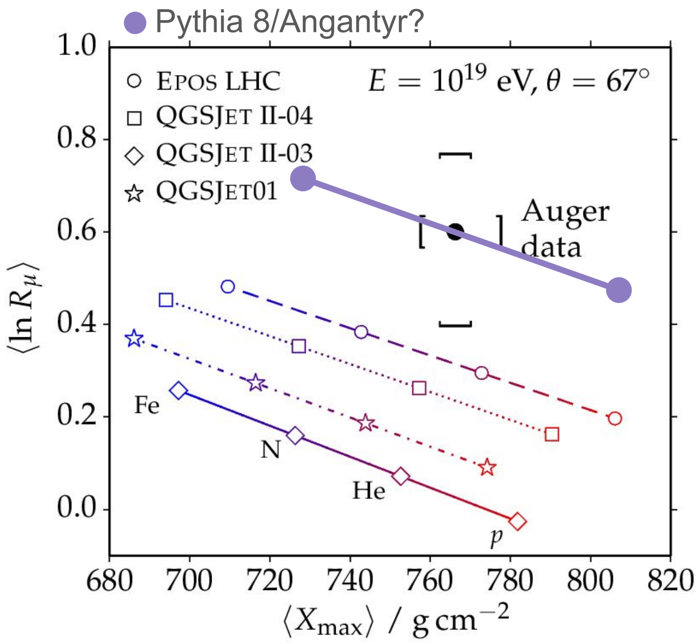
↳ Angantyr (hA, AA)

↳ extension of Pythia for heavy-ion collisions

↳ v8.312 update w/ variable energy and beam on event-by-event basis

bringing Pythia 8/Angantyr to air shower physics

1. implementation of Pythia 8/Angantyr in CORSIKA 8
2. tuning Pythia 8/Anganty for air shower physics



Phys. Rev. D 91, 032003 (2015)

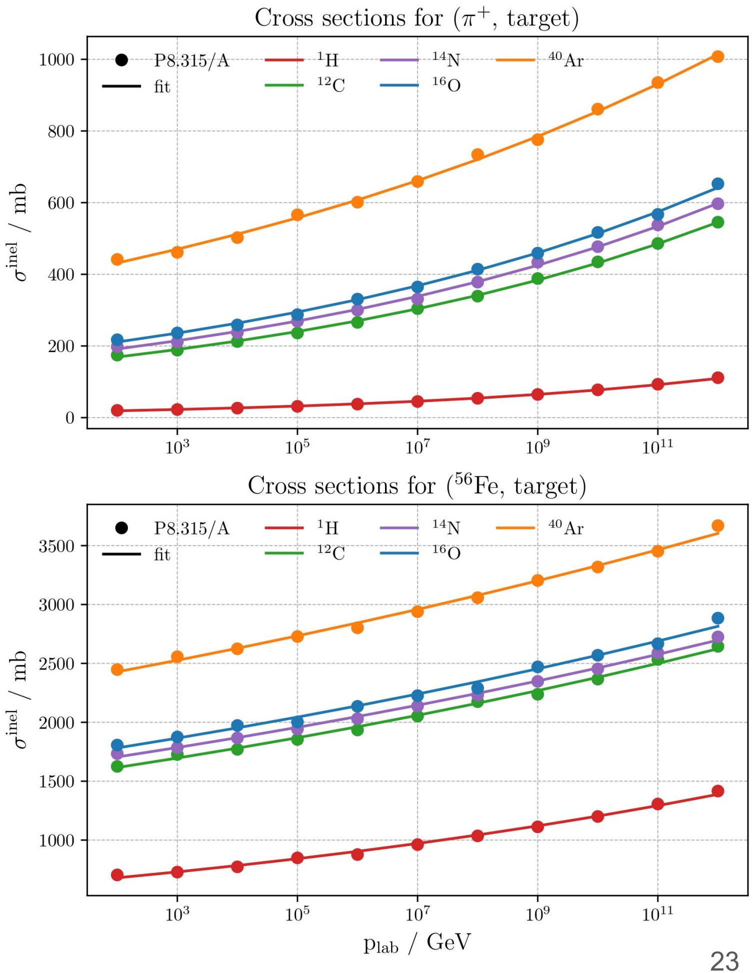
Implementation of Pythia 8/Angantyr in CORSIKA 8
and Its Tuning for Air Shower Physics

Pythia 8/Angantyr interface to CORSIKA 8

↳ technical changes

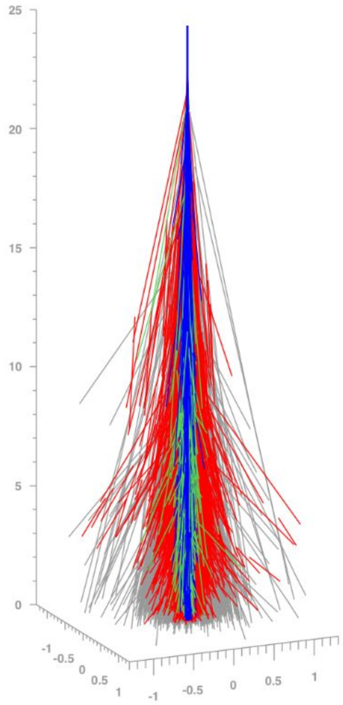
coordinated changes in { main C8 codebase; corsika-data submodule }

- ↳ integrated Pythia 8/Angantyr in the CORSIKA 8 build system
  - ↳ can be updated for new Pythia versions
- ↳ updated nuclear particle definitions in Pythia 8
  - ↳ stable isotopes up to ^{56}Fe
- ↳ set up reuse file for Angantyr initialization in corsika-data
- ↳ added tabulated Pythia 8/Angantyr cross sections in corsika-data
  - ↳ projectiles = hadrons and stable isotopes up to ^{56}Fe
  - ↳ targets = p, ^{12}C, ^{14}N, ^{16}O, ^{40}Ar
  - ↳ p_{lab} from 100 to 10^{12} GeV (discrete values of order of mag.)
- ↳ modified `pythia8` module in CORSIKA 8 for compatibility



Pythia 8/Angantyr interface to CORSIKA 8

↳ validating Pythia 8/Angantyr air showers



several shower geometries

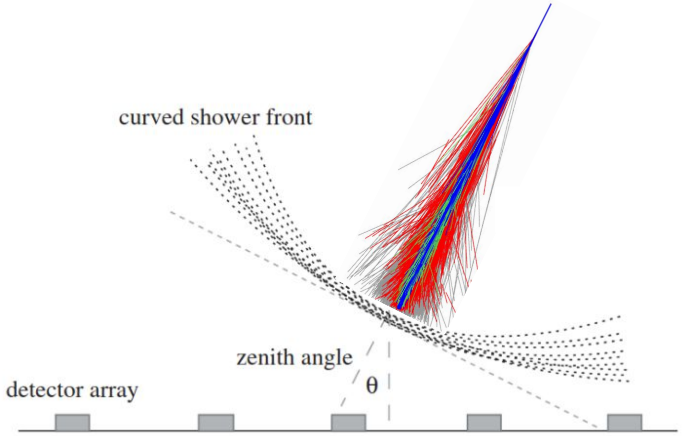
- ↳ vertical
- ↳ inclined
- ↳ horizontal

several shower primaries

- ↳ EM particle ($e^{\pm}$, γ)
- ↳ light nuclei (p, CNO)
- ↳ heavy nuclei (Fe)

several shower $E_{primary}$

several kinematic particle cuts



benchmarking C8+P8 full air showers

incl. different set of kinematic particle cuts

- ↳ vertical p@10^{17} eV
- ↳ inclined (θ = 60°) p@$10^{17.5}$ eV
- ↳ inclined (θ = 60°) p,Fe@10^{17}–10^{19} eV
- ↳ inclined (θ = 67°) p,Fe@10^{19} eV

} Auger cuts

1 MeV for $e^{\pm}$/γ
1 GeV for hadrons/μ

citation

Pythia 8/Angantyr interface to CORSIKA 8

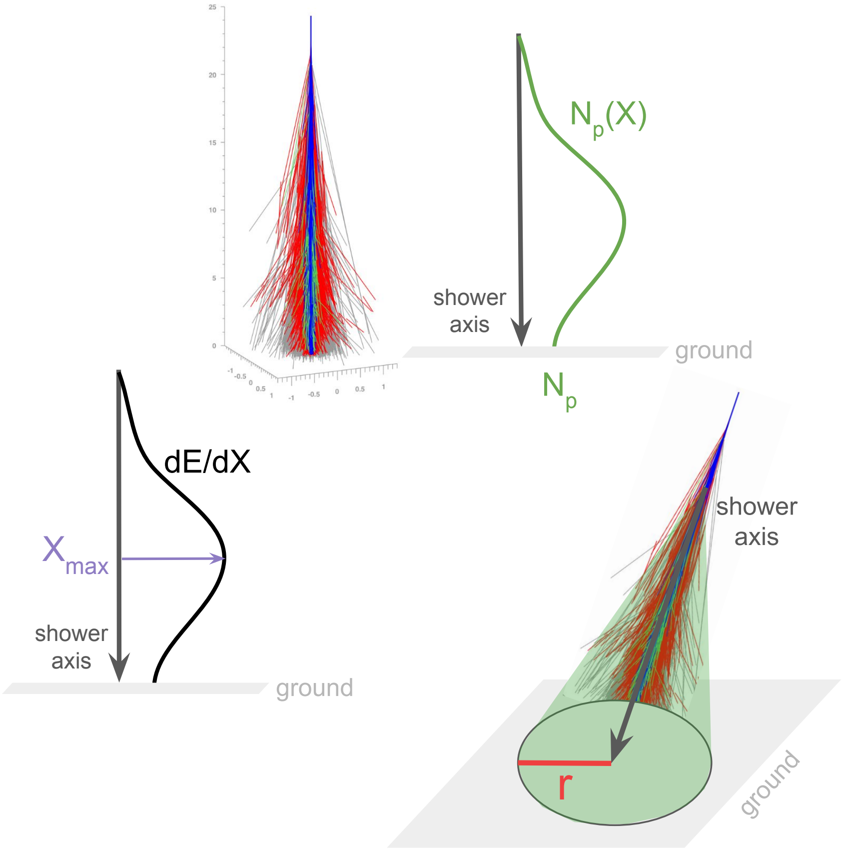
↳ validating Pythia 8/Angantyr air showers

longitudinal profile $N_p(X)$

longitudinal production profile $N_{p,\,prod}(X)$
- ↳ depth of the particle shower maximum $X_{p,max}$

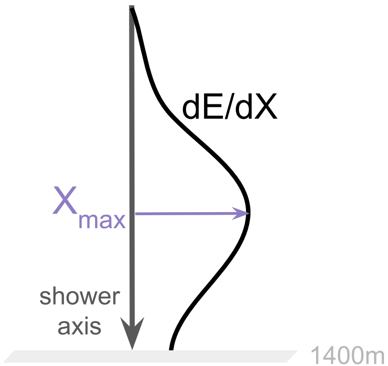
energy deposit profile dE/dX
- ↳ depth of the shower maximum X_{max}

particles at ground
- ↳ energy dN_p/dE
- ↳ lateral distribution dN_p/dr



Validating Pythia 8/Angantyr air showers

↳ depth of the shower maximum

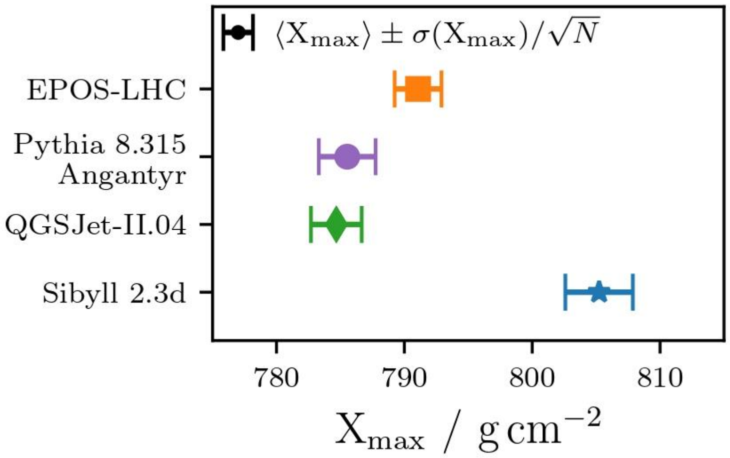


Pythia 8/Angantyr compatible with other HIMs

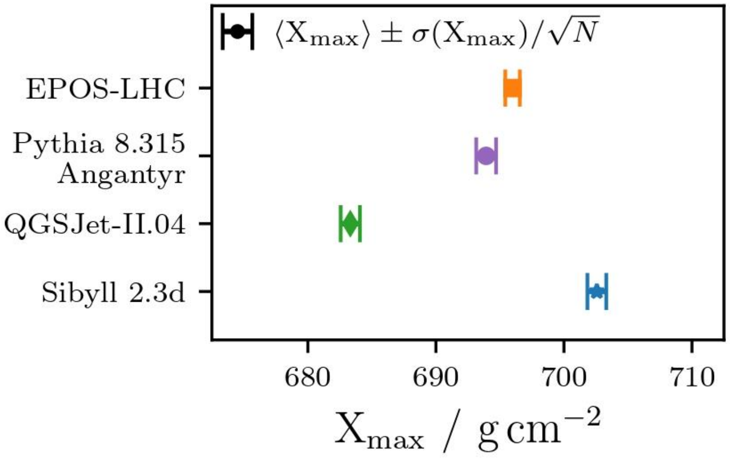
↳ deeper than QGSJet-II.04

↳ shallower than EPOS-LHC and Sibyll 2.3d

p@10^19 eV, θ=67°

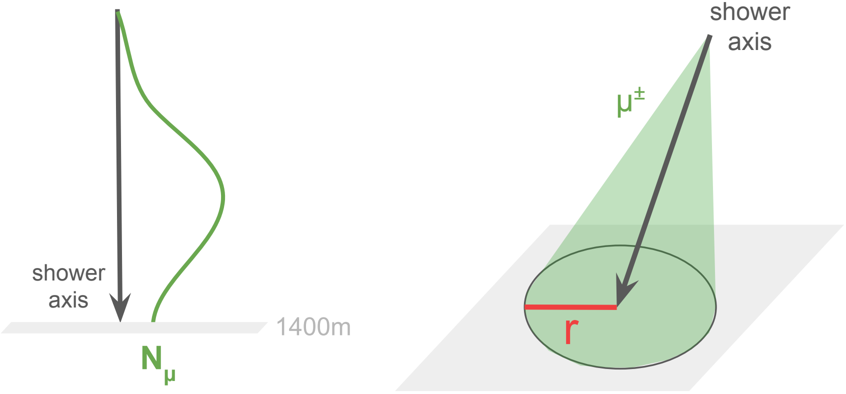


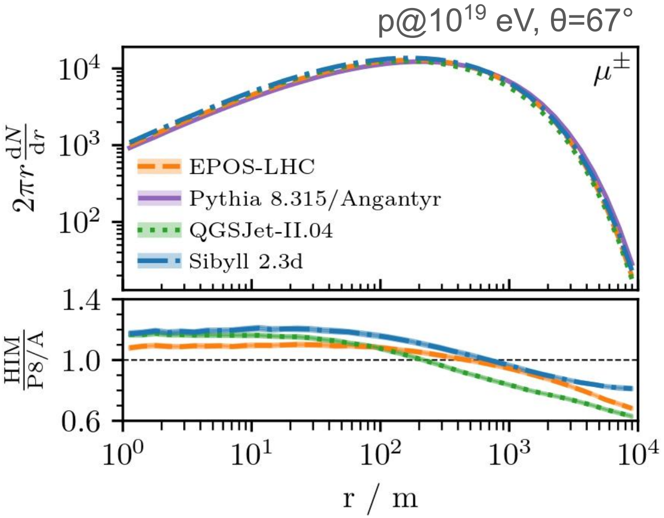
Fe@10^19 eV, θ=67°

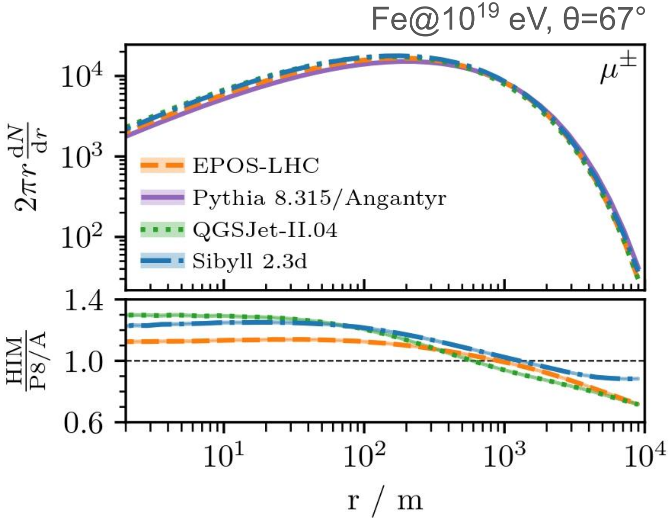


Validating Pythia 8/Angantyr air showers

↳ lateral distribution of muons at observer level





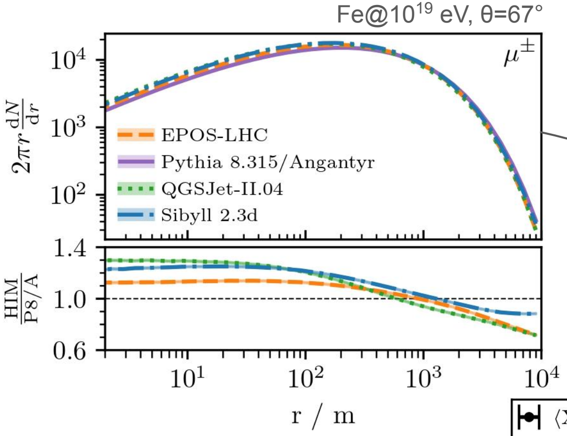


Pythia 8/Angantyr vs. other HIMs

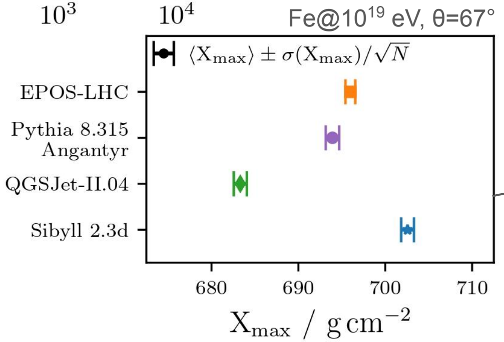
- ↳ less muon close to shower core
- ↳ more muons ~10km from shower core

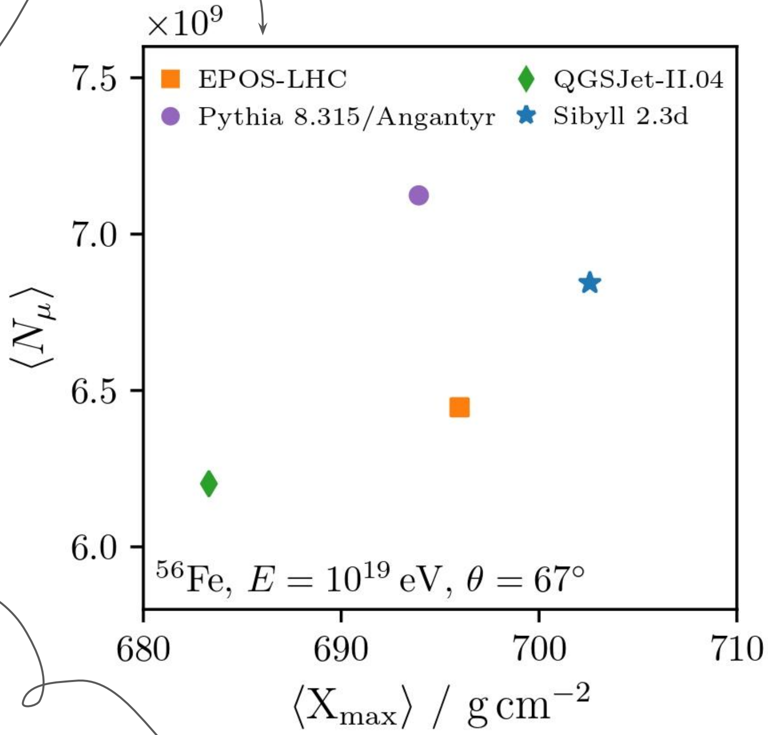
Validating Pythia 8/Angantyr air showers

↳ vs. Pierre Auger Observatory measurements



$$N_\mu = \int_0^{10^4} \frac{dN}{dr} dr$$





Validating Pythia 8/Angantyr air showers

↳ vs. Pierre Auger Observatory measurements

unified picture of N_μ and X_{max} with model predictions using Sibyll 2.3d as reference for common z scale

↳ translate Auger data from ⟨ln Rμ⟩ to z

$$z = \frac{\ln \langle N_\mu \rangle - \ln \langle N_{\mu,\mathrm{p}} \rangle}{\ln \langle N_{\mu,\mathrm{Fe}} \rangle - \ln \langle N_{\mu,\mathrm{p}} \rangle}$$

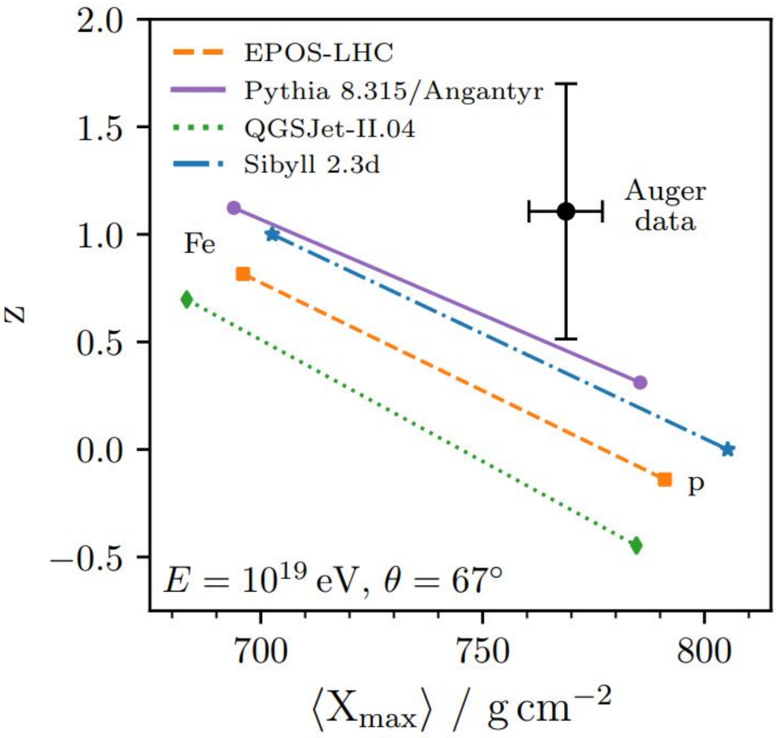
Sibyll 2.3d
Fe@10^{19} eV, θ=67°

Sibyll 2.3d
p@10^{19} eV, θ=67°

Pythia 8/Angantyr highest z scale value

↳ not compatible with Auger data

↳ yet closest to Auger data among HIMs



Implementation of Pythia 8/Angantyr in CORSIKA 8

↳ summary

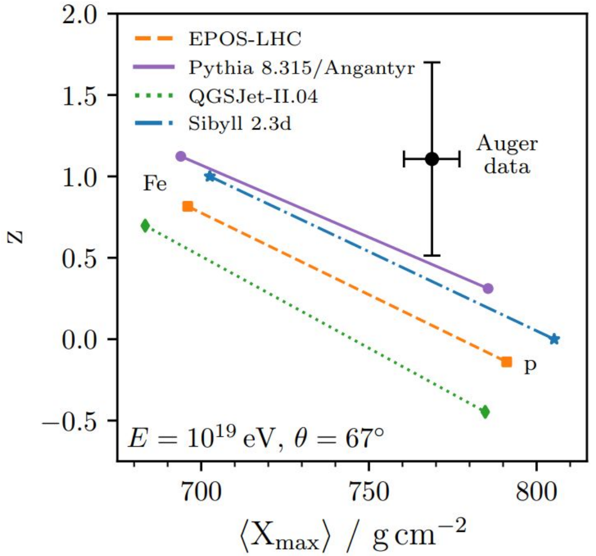
successful integration of Pythia 8/Angantyr into CORSIKA 8

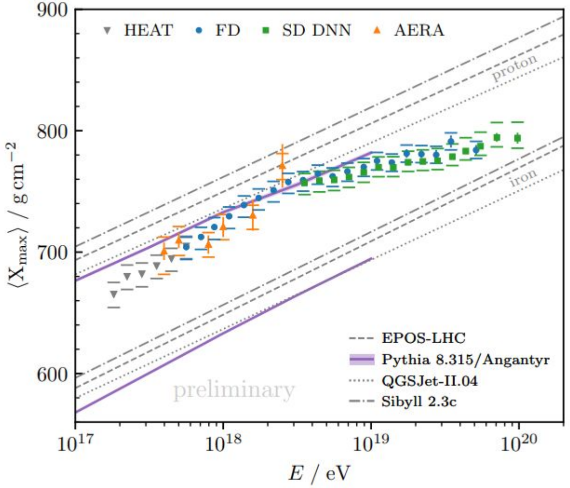
- ↳ consistent Angantyr initialization, interaction handling
- ↳ maintainable interface within the modular C8 ecosystem
- ↳ benchmarked at interaction level { cross sections / final states
- ↳ validated with full air-shower simulations

P8+C8 vs. Pierre Auger Observatory measurements

- ↳ highest N_μ predictions among models
- ↳ still underestimates Auger data
- ↳ X_{max} predictions indicate lighter composition

solid foundation for future tuning and systematic refinement of Pythia 8/Angantyr for air shower physics





Implementation of Pythia 8/Angantyr in CORSIKA 8 and Its Tuning for Air Shower Physics

Tuning for air shower physics

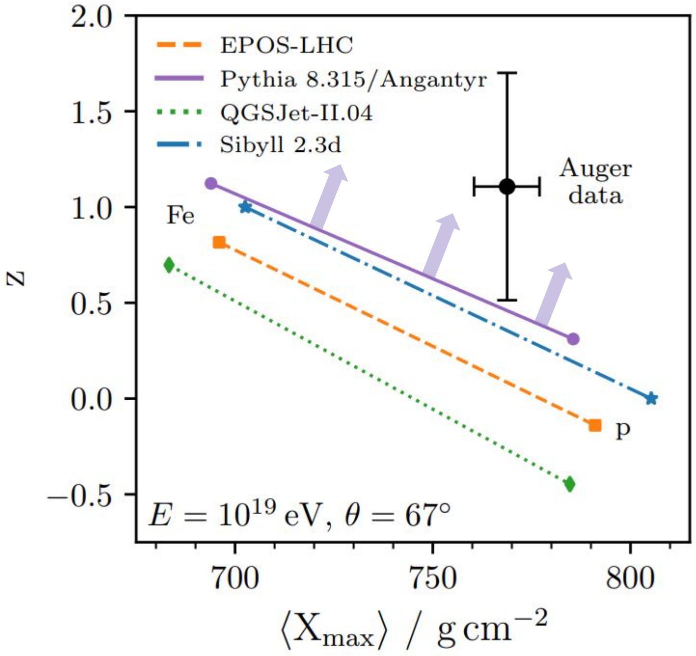
↳ motivation

HIMs use **phenomenological models** to describe particle collisions
- ↳ many parameters (O(10) to O(100)) not set from theory
- ↳ need to be tuned to experimental data

“tuning” = adjusting parameters

a “tune” = specific set of parameters + switches

many HIMs have limited, complex, or undocumented tuning interfaces
- ↳ attractive Pythia 8/Angantyr tuning interface
  - ↳ user-friendly and well-documented
  - ↳ existing published tunes (Monash 2013, ATLAS A14, …)



Tuning for air shower physics

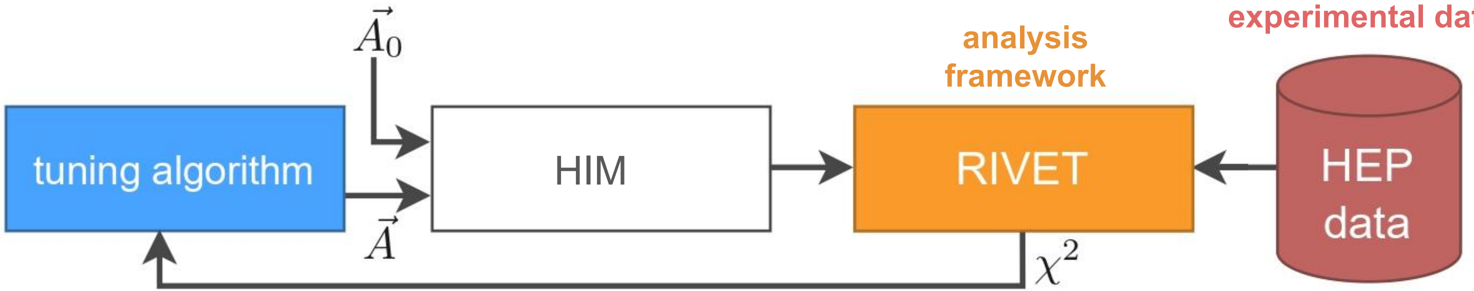
↳ automatic tuning

"manual" tuning requires significant expertise and time

↳ automatic tuning frames it as a multi-parameter optimization problem

experimental data

analysis framework

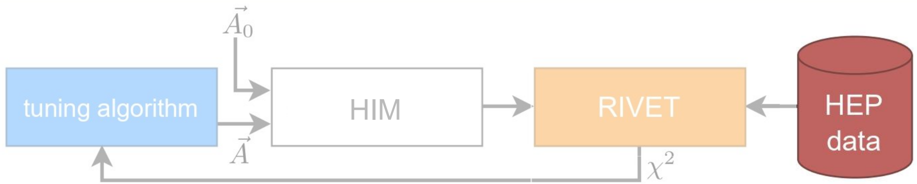


model ⇔ data agreement
quantified via χ^2

- ↳ improves reproducibility
- ↳ scales better with many parameters and observables
- ↳ requires machine-readable experimental data

Tuning for air shower physics

↳ High Energy Physics Database (HEPData)



open-access repository of experimental high energy measurements

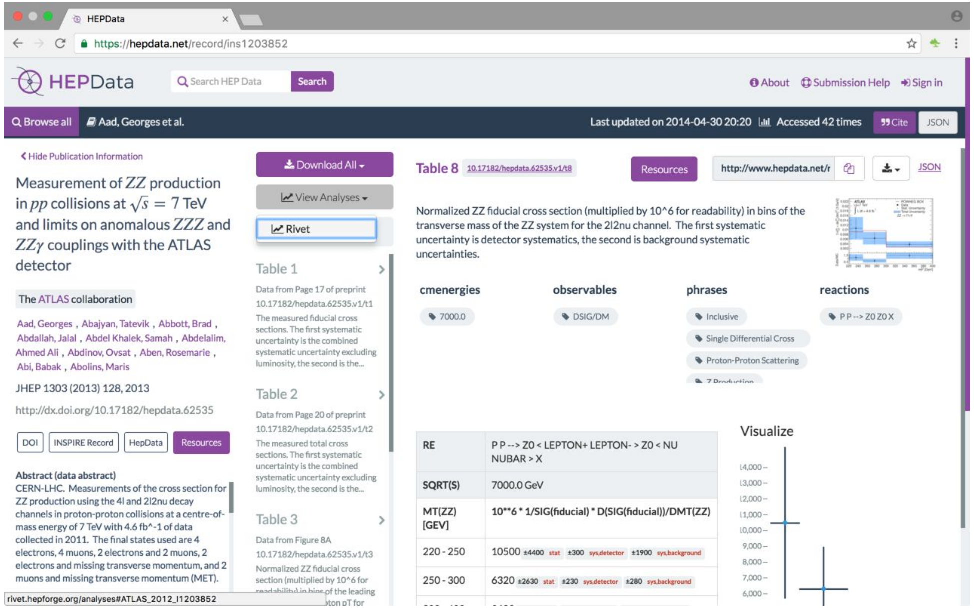
- ↳ different systems available { collider / fixed-target

stable and reliable reference for the community

- ↳ model validation and tuning without ambiguity

human- and machine-readable formats

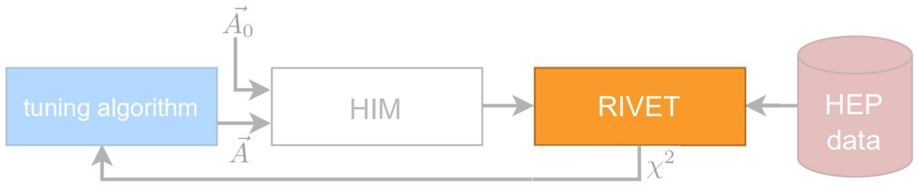
- ↳ YAML, CSV, ROOT, YODA/YODA2
- ↳ metadata
  - ↳ analysis selection
  - ↳ kinematic cuts
  - ↳ original publication
  - ↳ RIVET plugin associated



arXiv:1704.05473 [hep-ex]

Tuning for air shower physics

↳ RIVET



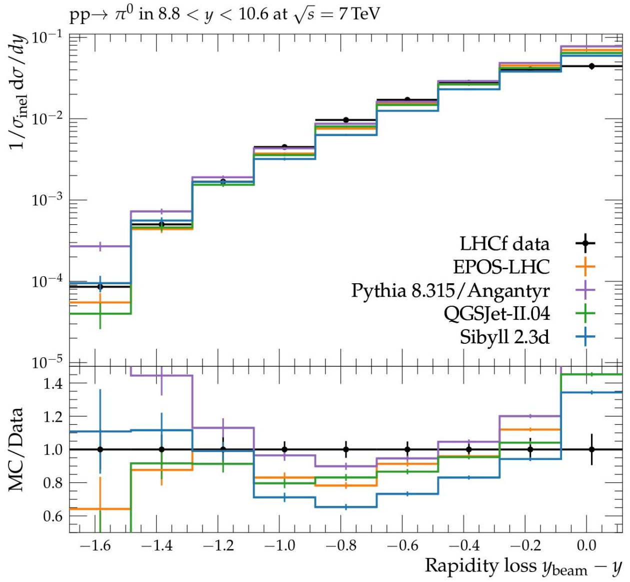
modular analysis framework

- ↳ C++ plugins
- ↳ python interface

RIVET is the most widespread way to **preserve the analysis code** from the LHC and other high-energy collider experiments

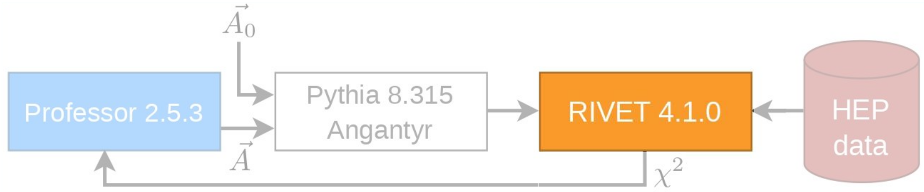
compares particle-level observables with **directly** experimental data

- ↳ bypassing detector simulation
- ↳ processes Monte Carlo events from HIMs
  - ↳ EPOS, Pythia, QGSJet, Sibyll, etc...
- ↳ outputs results as YODA histograms
- ↳ each publication = dedicated RIVET analysis plugin
  - ↳ RIVET supports custom analyses



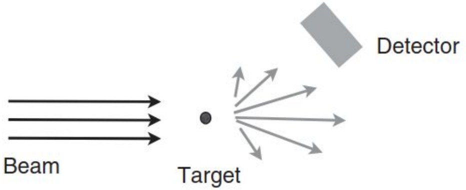
Tuning for air shower physics

↳ RIVETization efforts



fixed-target measurements @ Super Proton Synchrotron, CERN

↳ similar as late secondary interactions in air showers



RIVET plugin name	HEPData	RIVET	p_{beam} (GeV c^{-1})	projectile/target	observable
NA22_1990_I301243	✓	drafted	250	π^+p	$d\sigma/dx_F$, $d\sigma/dp_T^2$
NA22_1992_I322980	✓	drafted	250	π^+p, K^+p	$d\sigma/dx_F$, $d\sigma/dp_T^2$
NA61_2017_I1598505	✓	drafted	[20–158]	pp	$d^2n/dydp_T$
NA61_2017_I1600971		drafted	158, 350	π^-C	$x_F\, dn/dx_F$
NA61_2019_I1753094	✓	drafted	60, 120	pC	σ^{prod}, σ^{inel}
NA61_2022_I1868367		drafted	158	pp	$d^2n/dydp_T$, dn/dy
NA61_2023_I2155140		drafted	158, 350	π^-C	σ^{prod}, $d^2n/dpdp_T$

Tuning for air shower physics

↳ RIVETization efforts

fixed-target measurements @ Super Proton Synchrotron, CERN

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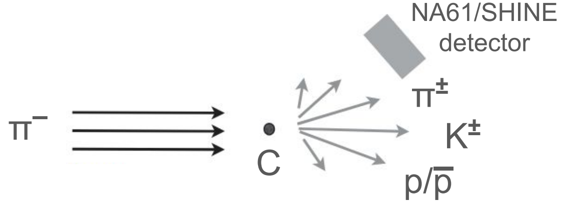

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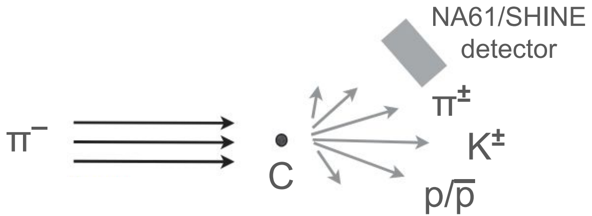
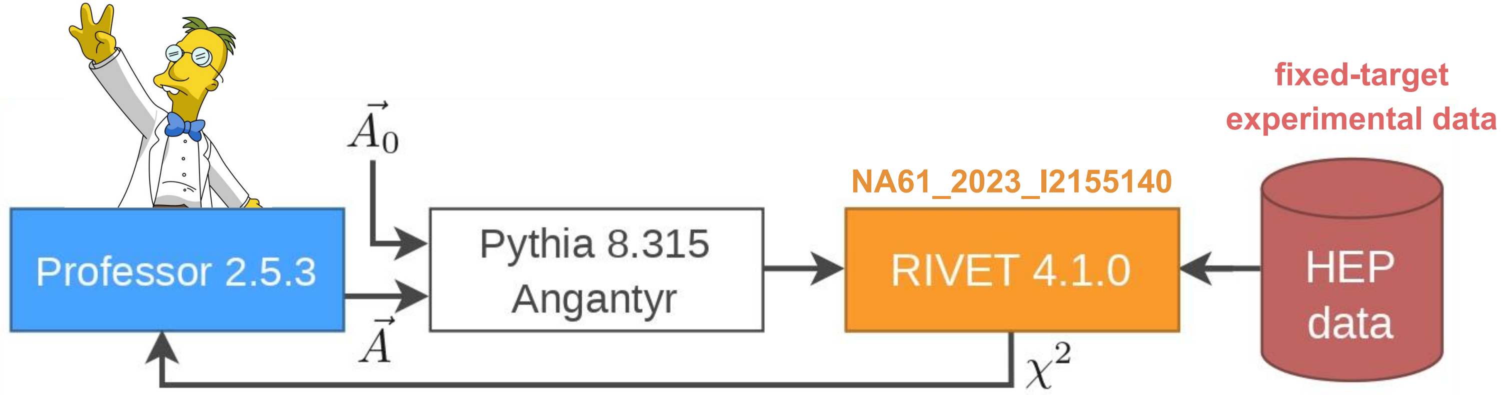
NA61_2023_I2155140		drafted	158, 350	π^-C	σ^{prod}, $d^2n/dpdp_T$

↳ focus of **Pythia 8/Angantyr “Wuppertal” tuning efforts**

Tuning for air shower physics

↳ **Pythia 8/Angantyr “Wuppertal” tuning efforts**





model ⇔ data agreement
quantified via χ^2

*surrogate built on HIM sampled events

Pythia 8/Angantyr "Wuppertal" tuning efforts

↳ Pythia parameters

Multiparton interactions	`MultipartonInteractions:pT0Ref`
	`MultipartonInteractions:ecmRef` → fixed!
	`MultipartonInteractions:ecmPow`

Lund string fragmentation	`StringZ:aLund` `StringZ:bLund`

Beam-remnant momentum distributions	`BeamRemnants:companionPower`
	`BeamRemnants:valencePowerMeson`
	`BeamRemnants:valencePowerUinP`
	`BeamRemnants:valencePowerDinP`

Popcorn mechanism	`BeamRemnants:dampPopcorn`

Hardness of beam-remnant baryon fragmentation	`BeamRemnants:hardRemnantBaryon` → enabled
	`BeamRemnants:aRemnantBaryon`
	`BeamRemnants:bRemnantBaryon`

Pythia 8/Angantyr “Wuppertal” tuning efforts

↳ accessible phase space

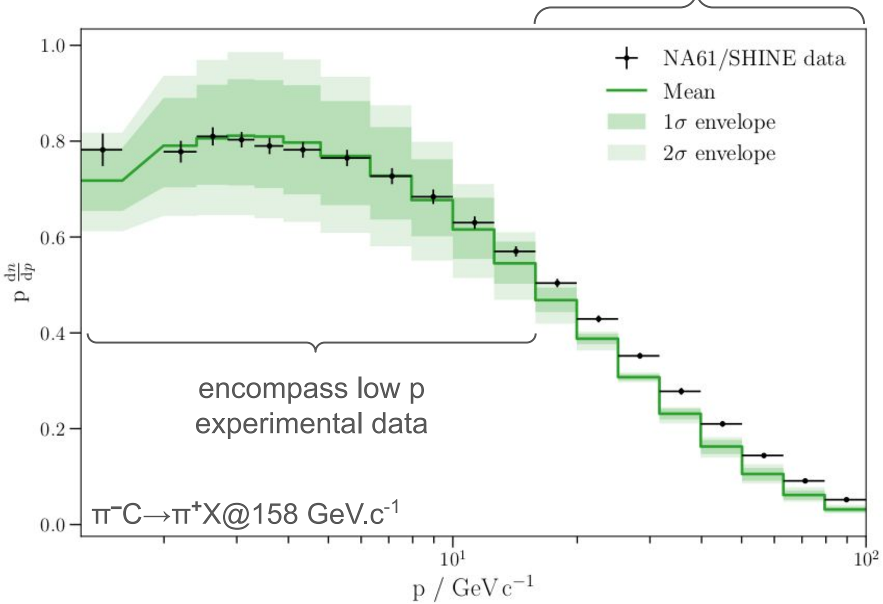
Pythia/Professor interface

```
Beams:idA = -211
Beams:idB = 1000060120
Beams:frameType = 2
Beams:eA = 158.
Beams:eB = 0.
SoftQCD:all = on
MultipartonInteractions:ecmRef = 21.5
BeamRemnants:hardRemnantBaryon = on

MultipartonInteractions:pT0Ref = {PT0REF}
MultipartonInteractions:ecmPow = {ECMPOW}
StringZ:aLund = {ALUND}
StringZ:bLund = {BLUND}
BeamRemnants:companionPower = {COMPANIONPOWER}
BeamRemnants:dampPopcorn = {DAMPPOPCORN}
BeamRemnants:valencePowerMeson = {VALENCEPOWERMESON}
BeamRemnants:valencePowerUinP = {VALENCEPOWERUINP}
BeamRemnants:valencePowerDinP = {VALENCEPOWERDINP}
BeamRemnants:aRemnantBaryon = {AREMNANTBARYON}
BeamRemnants:bRemnantBaryon = {BREMNANTBARYON}

Main:rivetAnalyses = {NA61_2023_I2155140}
```

```
PT0REF 0.5 1
ECMPOW 0 0.5
ALUND 0 2
BLUND 0.2 2
COMPANIONPOWER 0 4
DAMPPOPCORN 0 1
VALENCEPOWERMESON 0 1.6
VALENCEPOWERUINP 0 7
VALENCEPOWERDINP 0 4
AREMNANTBARYON 0 2
BREMNANTBARYON 0.5 5
```

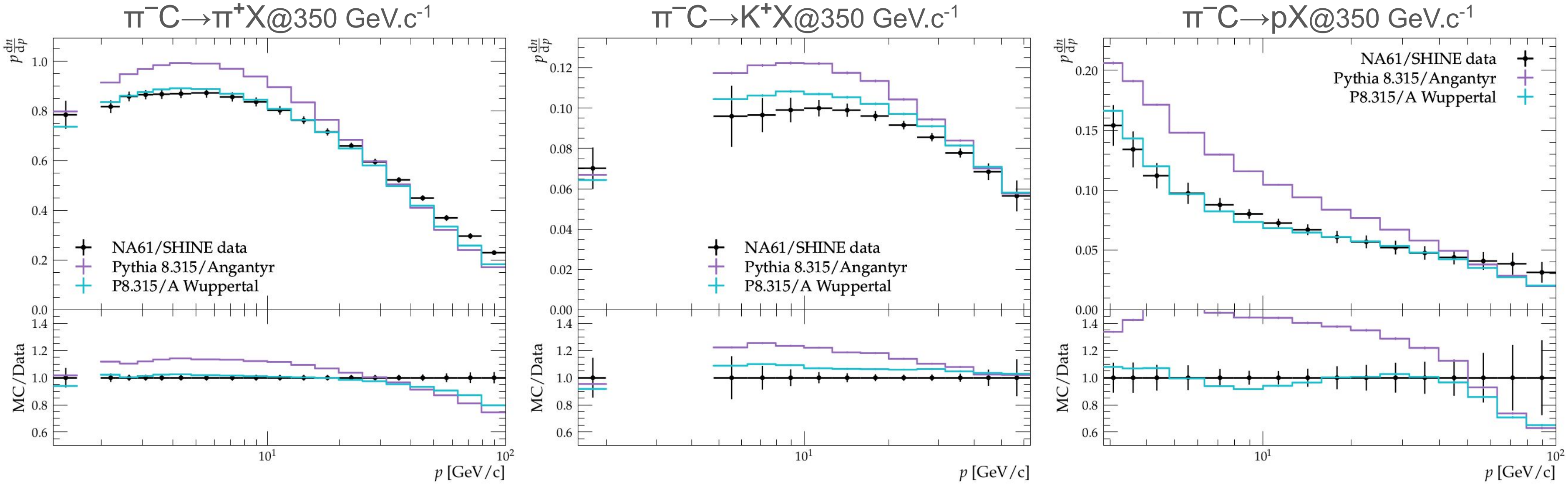
parameter phase space

high p tail outside sampled envelope



Pythia 8/Angantyr "Wuppertal" tuning efforts

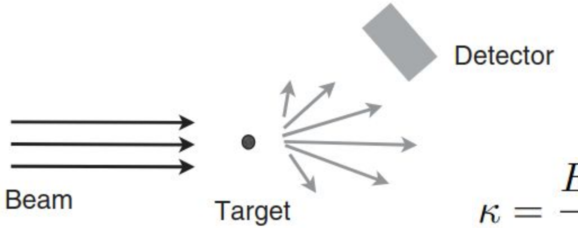
↳ resulting tune on NA61_2023_I2155140



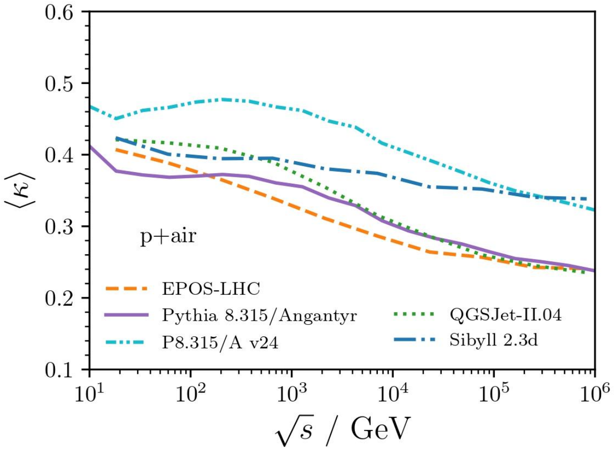
- ↳ for all outgoing secondaries studied ($\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$)
- ↳ at both p_{beam} = 158,350 GeV/c

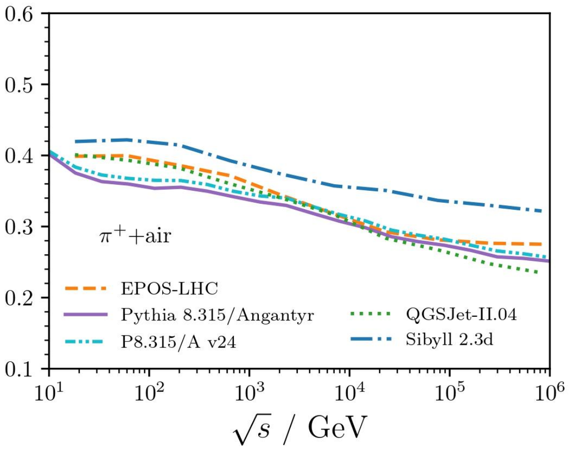
Pythia 8/Angantyr “Wuppertal” tuning efforts

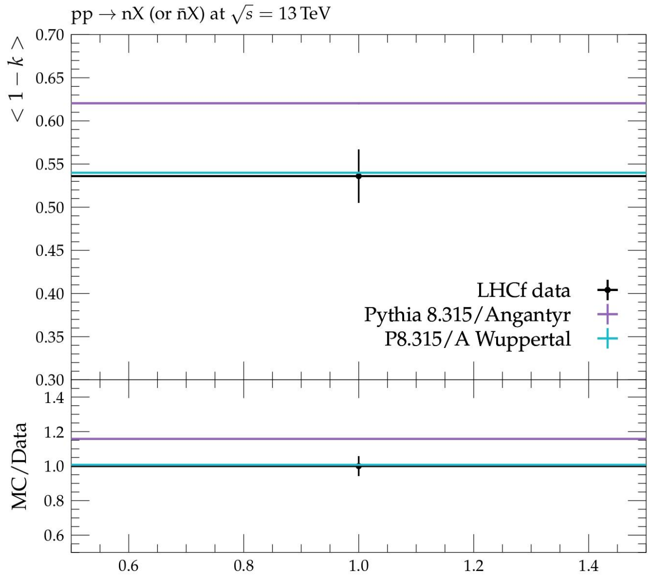
↳ **impact on elasticity**



$$\kappa = \frac{E_{\text{leading p/n}}}{E_{\text{beam}}}$$







↳ rise in p+air

↳ similar in π^++air

↳ agreement in pp with LHCf data

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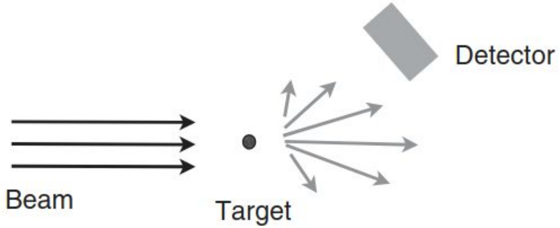
Pythia 8/Angantyr “Wuppertal” tuning efforts

↳ impact on accelerator measurements

fixed-target systems @ SPS

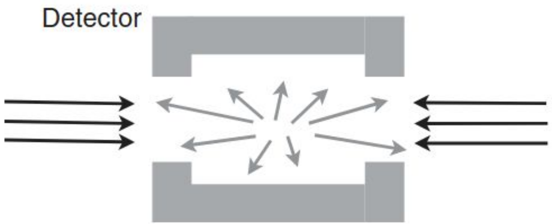
pp, pC, π^+p, K^+p, π^-C collisions @ p_{beam} = 120, 158, 250, 350 GeV
↳ NA22, NA61



collider systems @ LEP/SLAC, LHC

e^+e^- collisions @ $\sqrt{s}$ = 91.2 GeV
↳ ALEPH, DELPHI, L3, OPAL, SLD

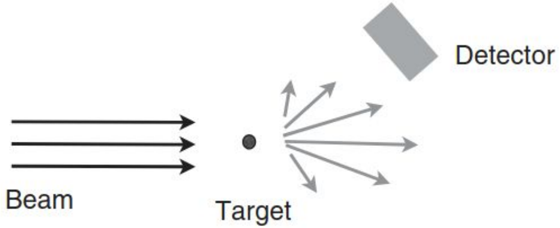
pp, pPb collisions @ $\sqrt{s}$,$\sqrt{s_{NN}}$ = 0.9, 2.36, 2.76, 7, 8, 13 TeV
↳ ATLAS, CMS/TOTEM, LHCf



Pythia 8/Angantyr “Wuppertal” tuning efforts

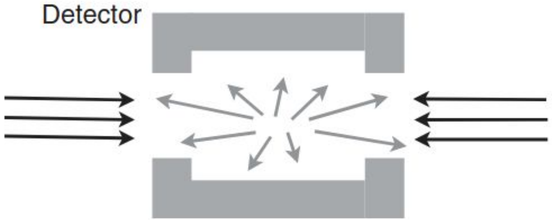
↳ impact on accelerator measurements

fixed-target systems @ SPS



- ↳ much improved agreement with NA61/SHINE data
- ↳ improved description of key fixed-target observables

collider systems @ LEP/SLAC, LHC

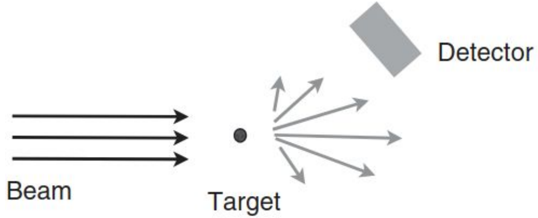


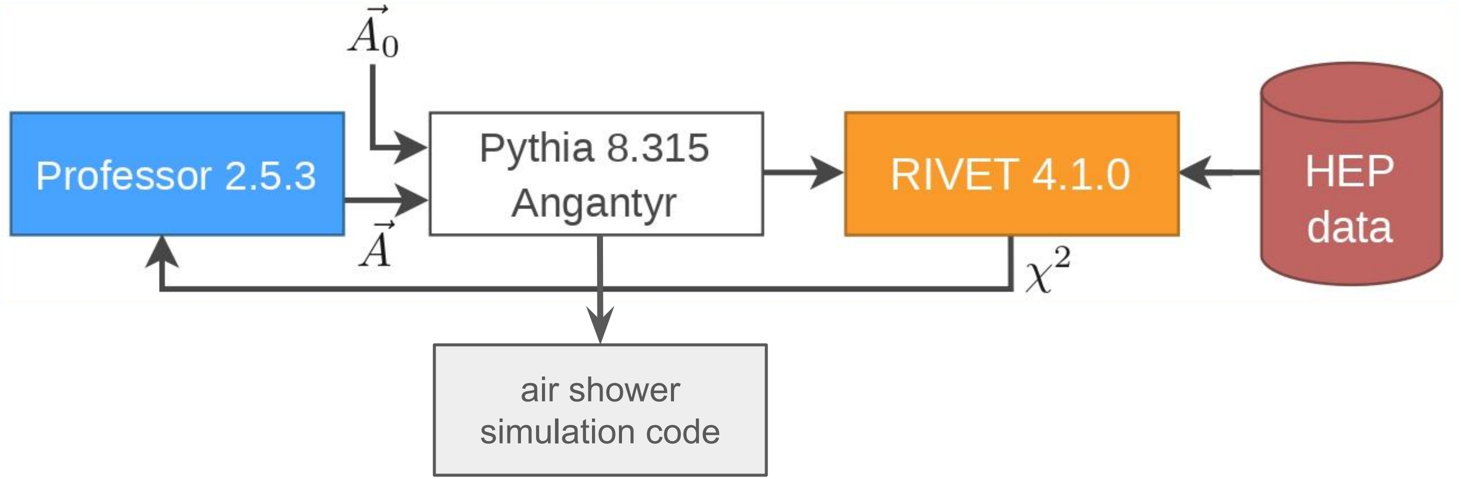
- ↳ consistent description of LEP/SLAC e^+e^- data
  - ↳ validation of fragmentation parameters
- ↳ mixed agreement with LHC data
  - ↳ improved agreement at high E, forward regions
  - ↳ reduced agreement at mid-rapidity, low-p_T regions

within the explored parameter space, **P8/A doesn’t simultaneously describe collider and fixed-target data without significant compromises**

Tuning for air shower physics

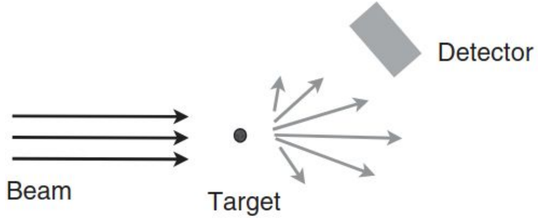
↳ **impact on air showers**

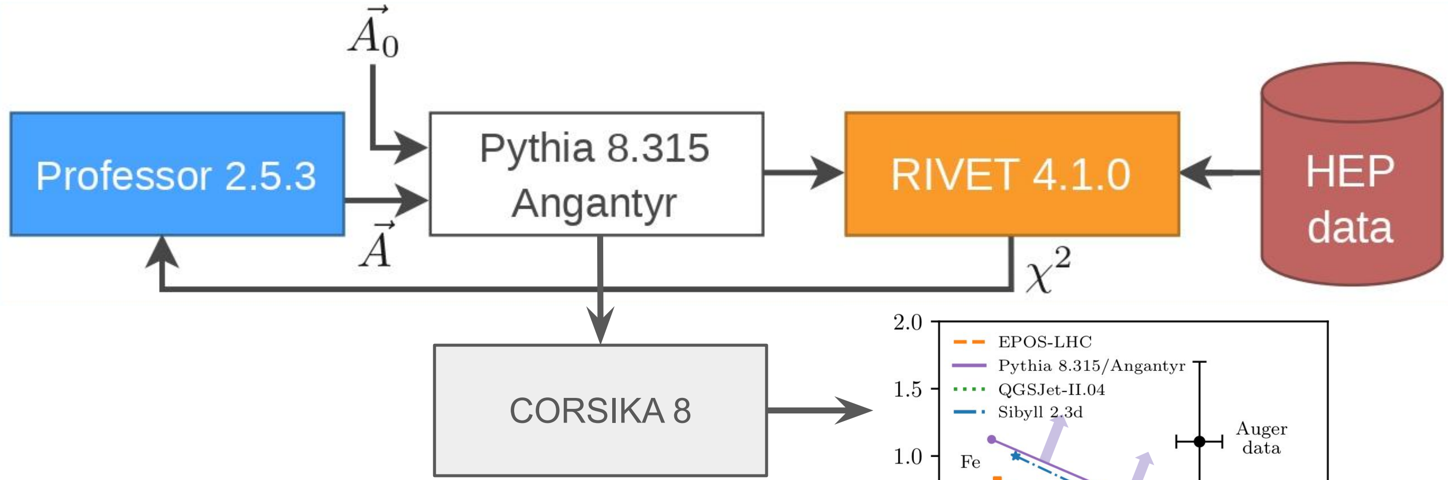


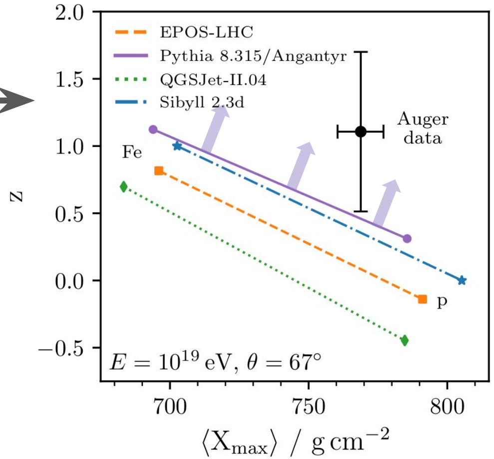


Tuning for air shower physics

↳ impact on air showers

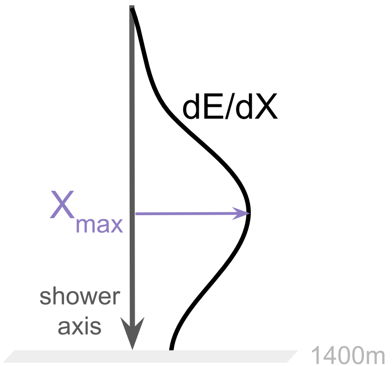


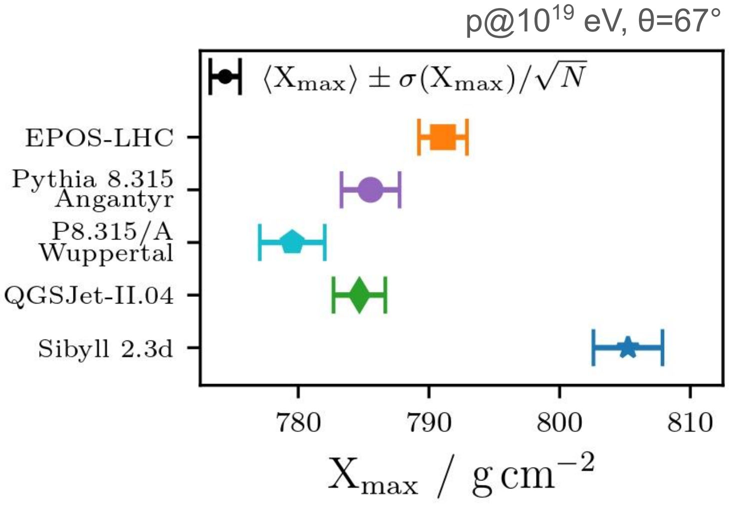


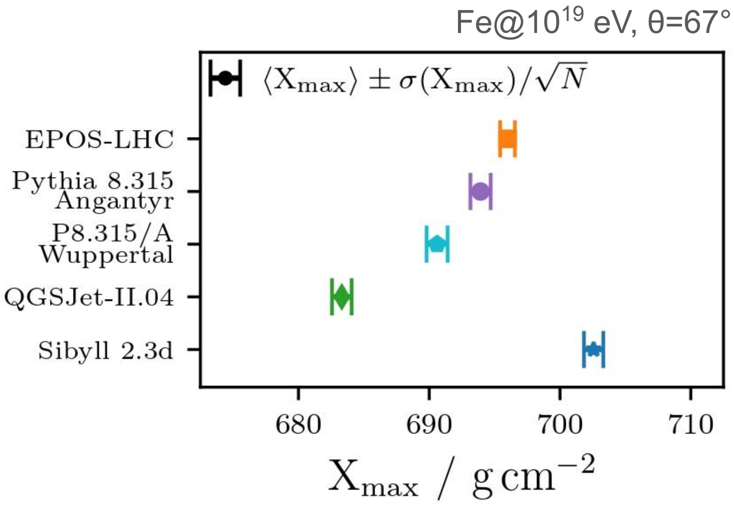


Pythia 8/Angantyr "Wuppertal" tuning efforts

↳ **depth of the shower maximum**





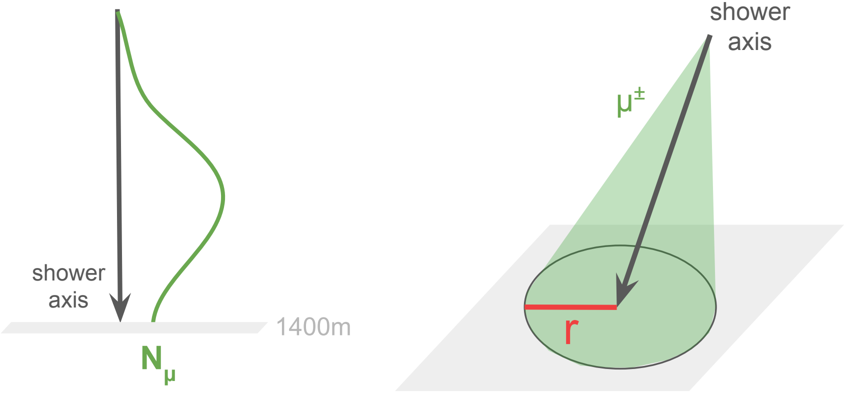


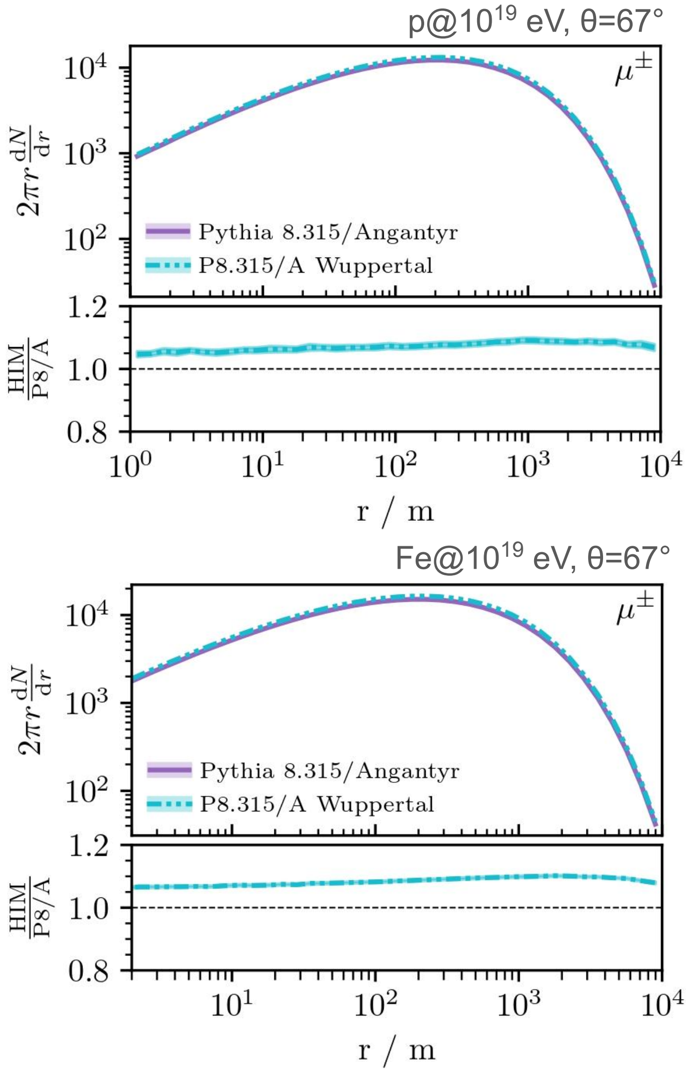
"Wuppertal" tune vs. default

↳ shift in X_{max} { $6\ g.cm^{-2}$ shallower for proton showers; $3\ g.cm^{-2}$ shallower for iron showers

Pythia 8/Angantyr "Wuppertal" tuning efforts

↳ lateral distribution of muons at observer level





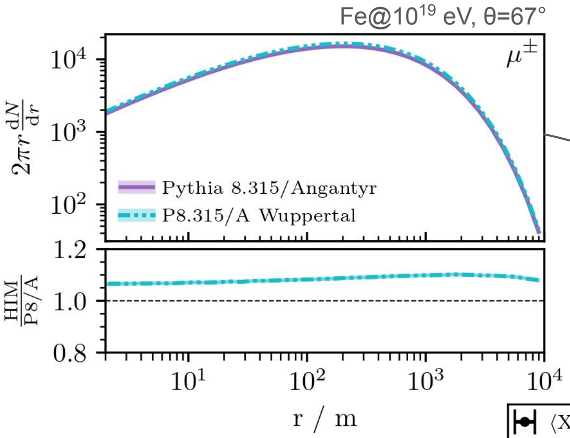
"Wuppertal" tune vs. default

↳ 5% more μ near shower core

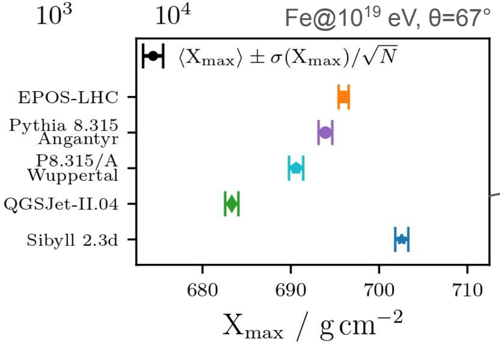
↳ rising up to 10% at larger lateral distances

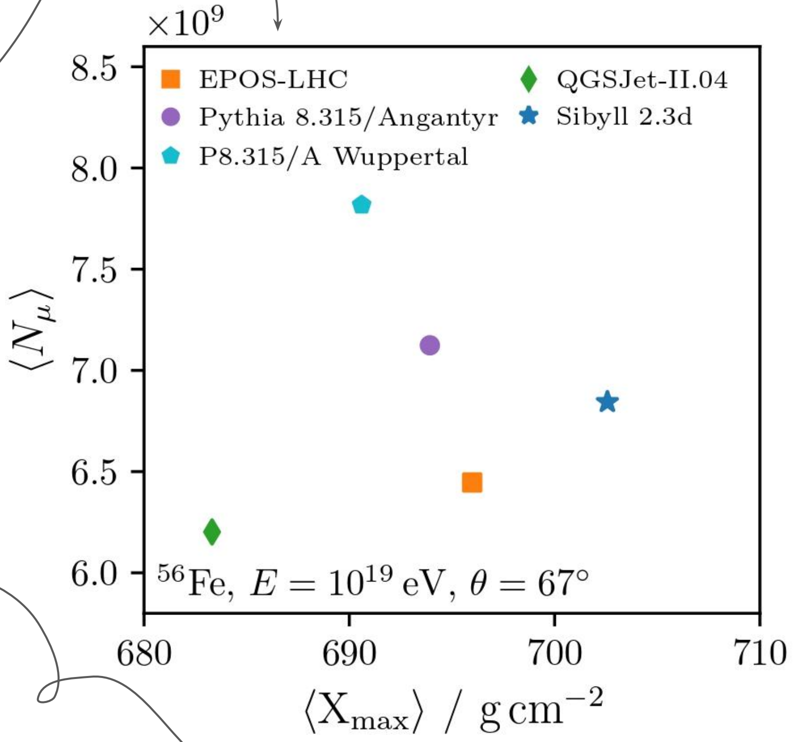
Pythia 8/Angantyr “Wuppertal” tuning efforts

↳ vs. Pierre Auger Observatory measurements



$$N_\mu = \int_0^{10^4} \frac{dN}{dr} dr$$





Pythia 8/Angantyr “Wuppertal” tuning efforts

↳ vs. Pierre Auger Observatory measurements

unified picture of N_μ and X_{max} with model predictions using Sibyll 2.3d as reference for common z scale

- ↳ translate Auger data from ⟨ln Rμ⟩ to z

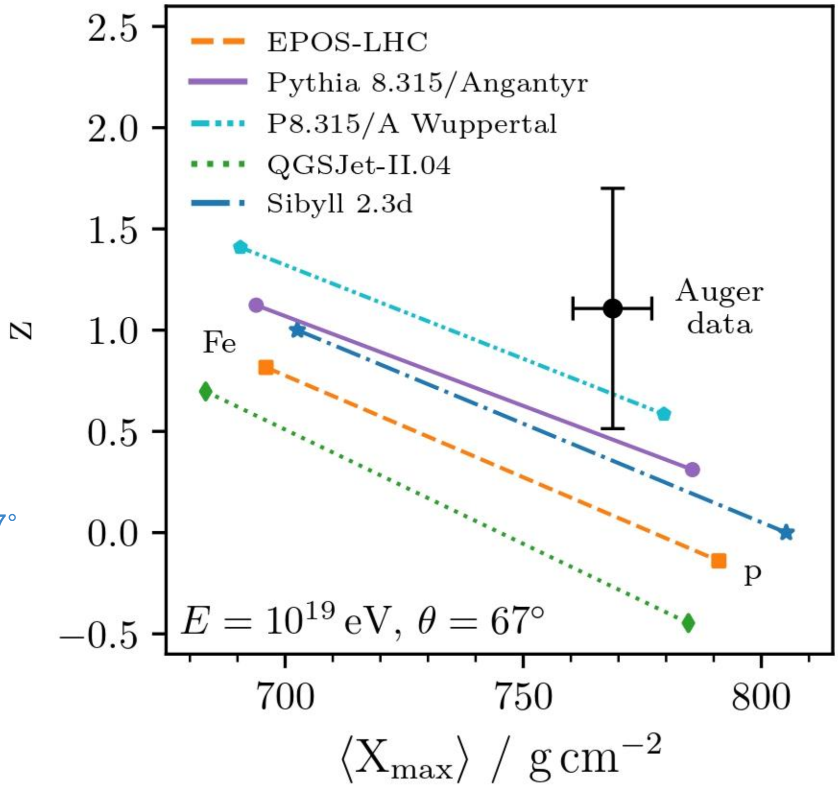
$$z = \frac{\ln \langle N_\mu \rangle - \ln \langle N_{\mu,\mathrm{p}} \rangle}{\ln \langle N_{\mu,\mathrm{Fe}} \rangle - \ln \langle N_{\mu,\mathrm{p}} \rangle}$$

Sibyll 2.3d
Fe@10^{19} eV, θ=67°

Sibyll 2.3d
p@10^{19} eV, θ=67°

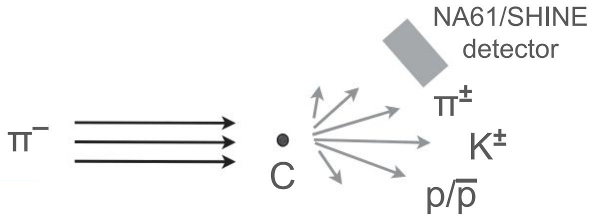
Pythia 8/Angantyr “Wuppertal” tune

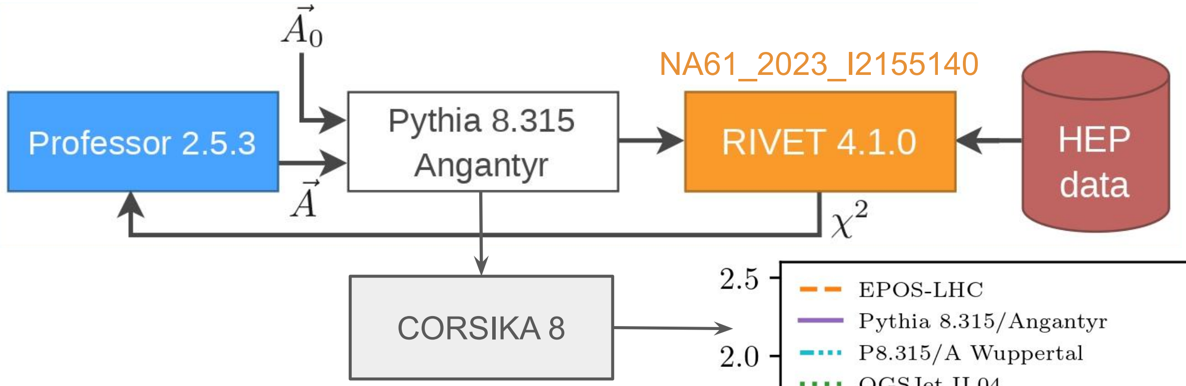
- ↳ compatible with Auger data
- ↳ highest z scale value among HIMs

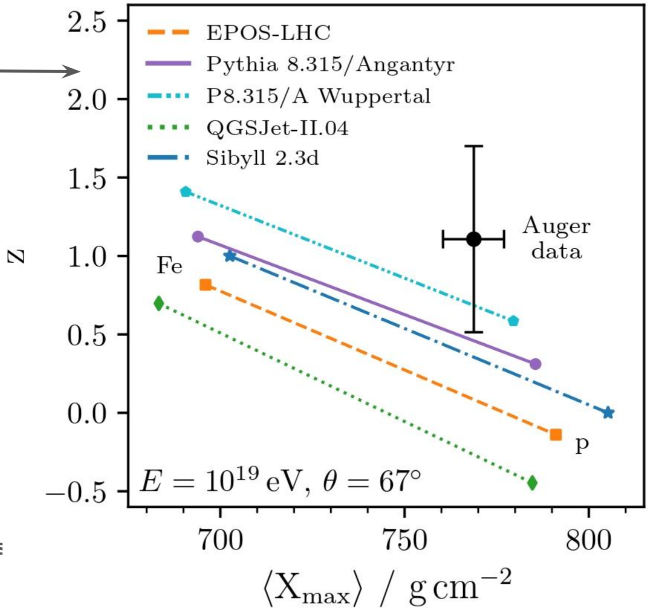


Tuning for air shower physics

↳ **summary**







Pythia 8/Angantyr "Wuppertal" tune

↳ compatible with Auger data

↳ unified description of LEP, SLAC, LHC, and fixed-target data remains challenging

↳ tuning efforts possibilities are endless (exp. data, parameters, new mechanisms, ...)


Thank you!

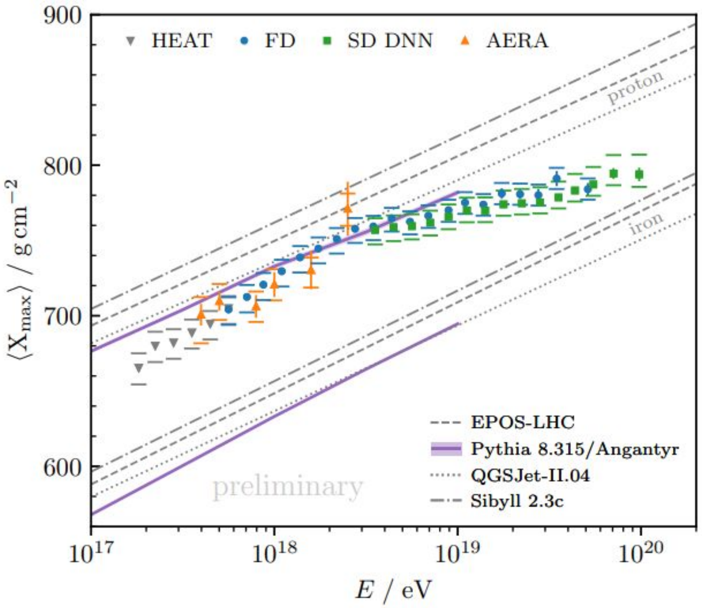
Back up

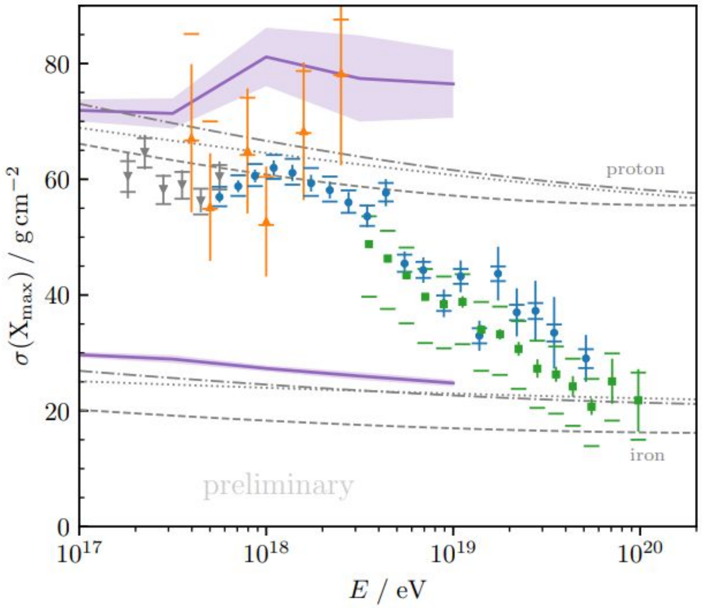
inclined ($\theta = 60°$) p,Fe@10^{17}–10^{19} eV

primary	10^{17}	$10^{17.5}$	10^{18}	$10^{18.5}$	10^{19}
proton	3000	3000	2000	999	1789
iron	3000	2000	2000	1000	1711

Pythia 8/Angantyr interface to CORSIKA 8

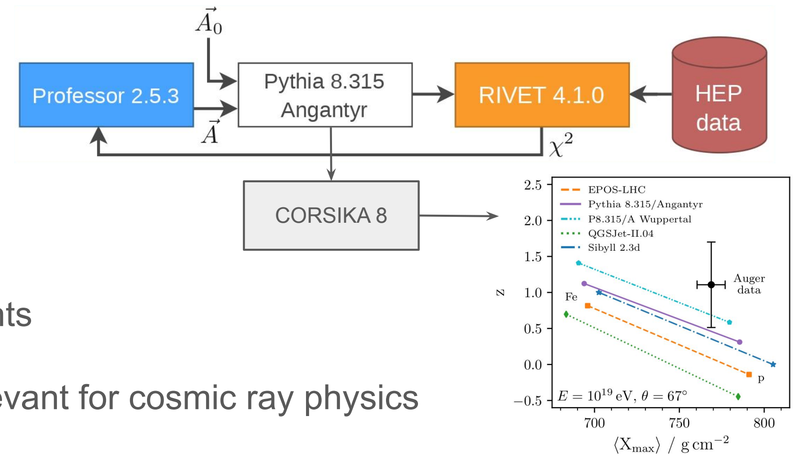
↳ vs. Pierre Auger Observatory measurements





Pythia 8/Angantyr+C8 yields shallower showers than other HIMs+C7

*accounting for known differences between C7 and C8 in terms of X_{max}



Tuning for air shower physics

↳ next steps

purse tuning efforts to balance collider and fixed-target constraints

complete HEPData and RIVET collection for measurements relevant for cosmic ray physics

↳ SMOG/SMOG2 @LHCb

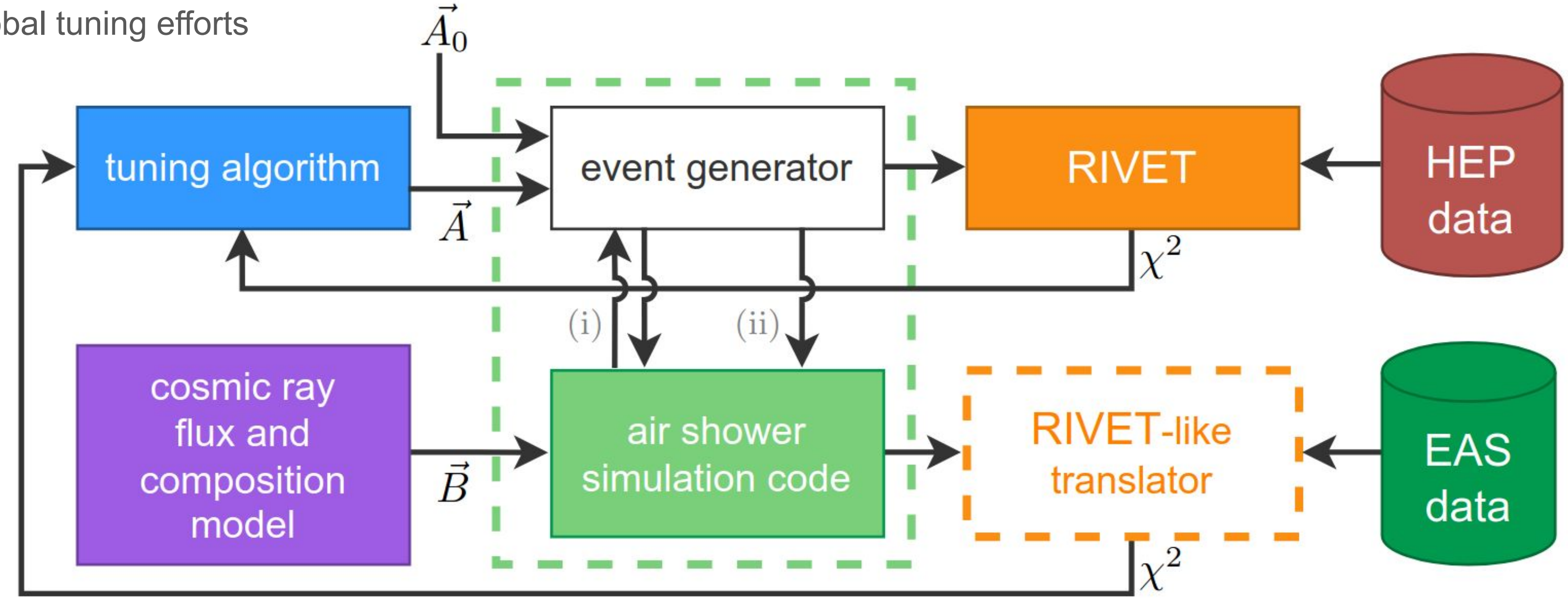
RIVET plugin name	HEPData	$\sqrt{s_{NN}}$ (GeV)	proj./target	observable
SMOG_2018_I1688924	✓	110.5	pHe	$d\sigma/dp\, dp_T$, $\langle x_F \rangle$
SMOG_2019_I1699199		86.6, 110.5	pHe, pAr	$d\sigma/dy^*\, dp_T$, $\langle x_F \rangle$
SMOG_2023_I2084295	✓	110.5	pHe	$R_{\overline{H}} = f(p, p_T)$
SMOG_2023_I2673124		68.5	pNe	$d\sigma/dy^*\, dp_T$, A_{prod}
SMOG_2023_I2678329		68.5	pNe	$d\sigma/dy^*\, dp_T$
SMOG_2023_I2682616		68.5	PbNe	σ ratio
SMOG_2024_I2788187		68.4	pNe	$P_{H,\overline{H}} = f(x_F, p_T, \eta)$
SMOG_2025_I2788187		68.5	pNe	$d^2\sigma/dp_T\, dy^*$

↳ pO and OO @LHC (Run 3 2025)

Tuning for air shower physics

↳ next steps

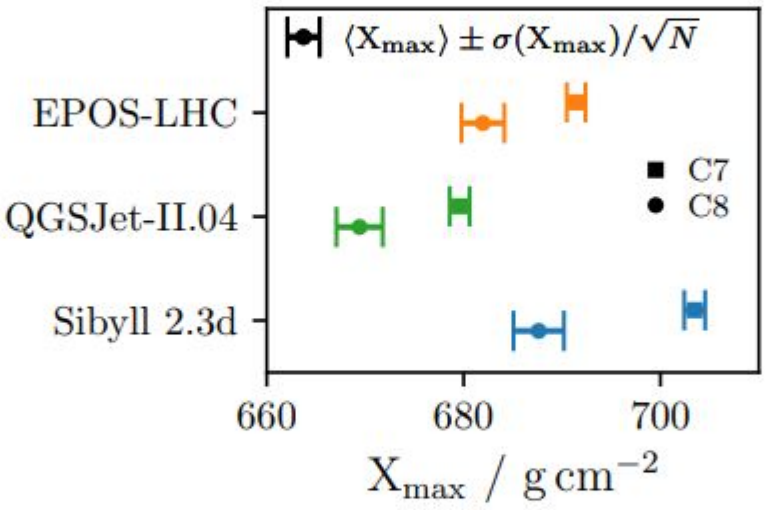
global tuning efforts



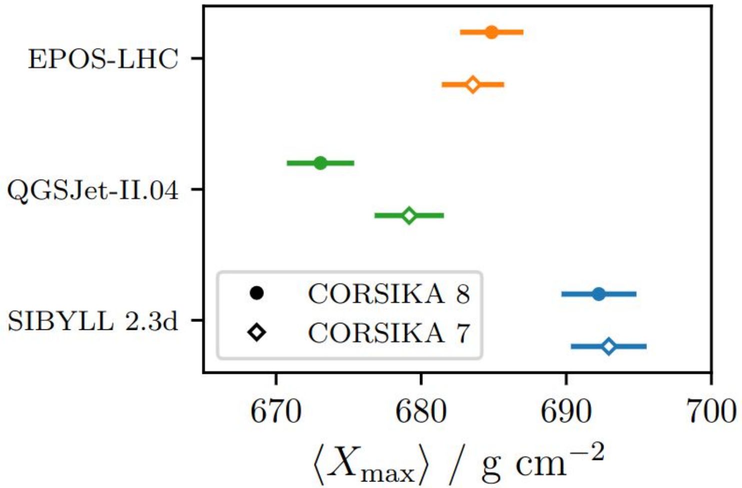
Simulation framework

↳ CORSIKA 7 vs. CORSIKA 8

p@10^{17} eV, θ=60°

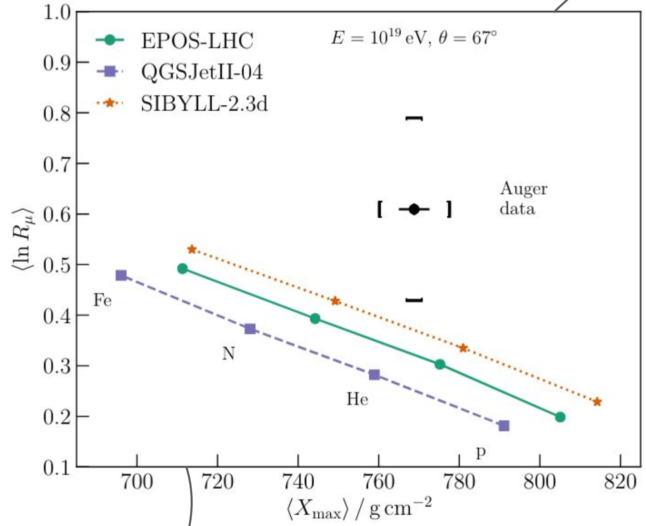


p@10^{17} eV, θ=0°

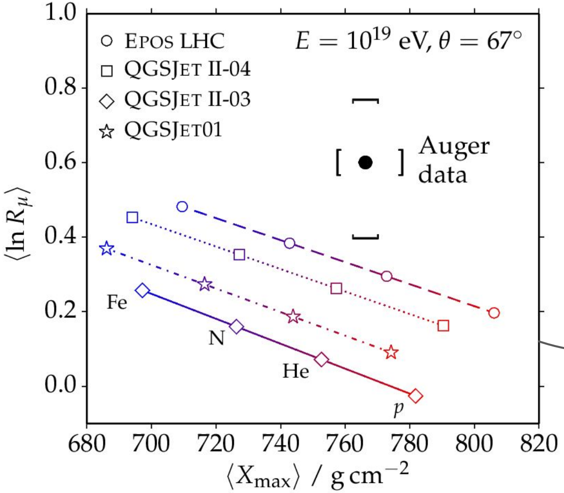


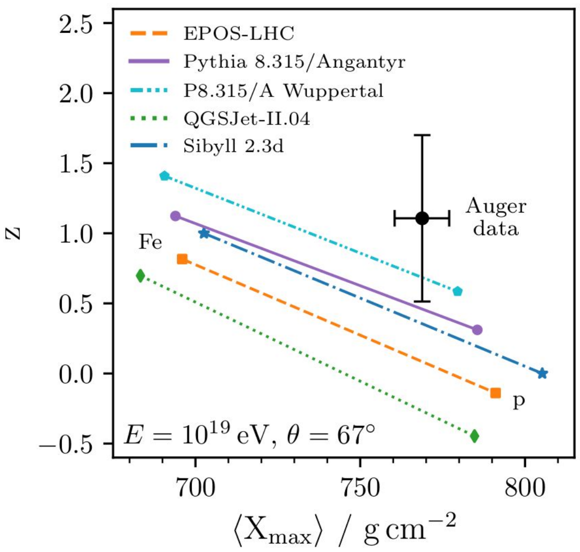
Tuning for air shower physics

↳ **z scale**



$$z = \frac{\ln \langle N_\mu \rangle - \ln \langle N_{\mu,\mathrm{p}} \rangle}{\ln \langle N_{\mu,\mathrm{Fe}} \rangle - \ln \langle N_{\mu,\mathrm{p}} \rangle}$$





Pythia 8/Angantyr parameters

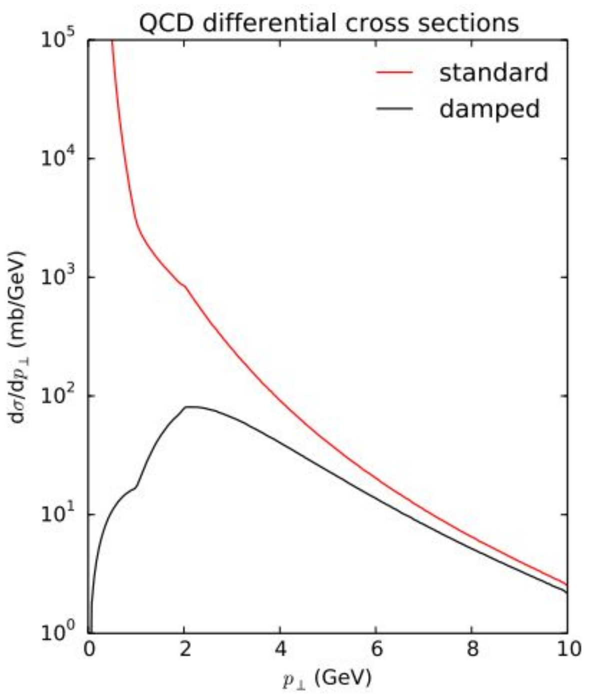
↳ multiparton interactions

reference value of the screening scale $p_{T,0}$. This is one of the central parameters in any Pythia tune, and its optimal value is strongly correlated with other model components

```
MultipartonInteractions:pT0Ref
MultipartonInteractions:ecmRef
MultipartonInteractions:ecmPow
```

reference center-of-mass energy used to define the scaling of $p_{T,0}$

power governing the energy evolution of the screening scale



$$p_{T,0} = (\texttt{pT0Ref}\ \mathrm{GeV}) \left(\frac{E_{CM}}{\texttt{ecmRef}\ \mathrm{GeV}} \right)^{\texttt{ecmPow}}$$

$$f_{\mathrm{damp}}(p_T) = \left(\frac{\alpha_S\left(p_{T,0}^2 + p_T^2\right)}{\alpha_S\left(p_T^2\right)} \frac{p_T^2}{p_{T,0}^2 + p_T^2} \right)^2$$

SciPost Phys. Codebases 8 (2022)

Pythia 8/Angantyr parameters

↳ Lund symmetric fragmentation function

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b\, m_T^2}{z}\right)$$

`StringZ:aLund`

regulates the hardness of the longitudinal momentum distribution in the z → 1 limit

`StringZ:bLund`

controls the suppression of high m_T at small z

Pythia 8/Angantyr parameters

↳ **beam-remnant momentum distributions**

$$g(x) \sim \frac{(1-x)^p}{x}$$

integer exponent p governing the assumed gluon momentum distribution used to model the x spectrum of companion sea quarks

```
BeamRemnants:companionPower
BeamRemnants:valencePowerMeson
BeamRemnants:valencePowerUinP
BeamRemnants:valencePowerDinP
```

power controlling the momentum distribution of valence quarks in mesons

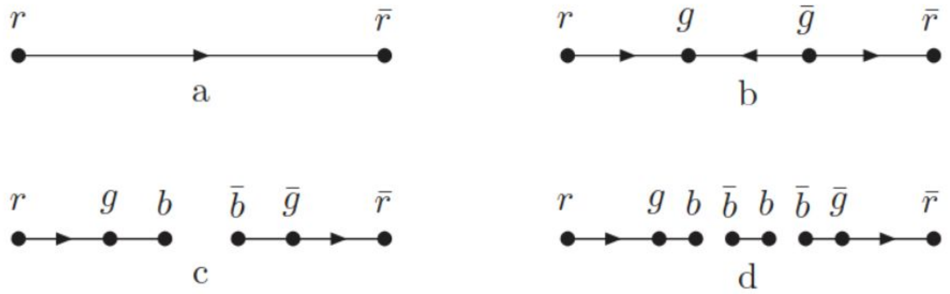
power controlling the momentum distribution of valence u quarks in the proton

power controlling the momentum distribution of valence d quarks in the proton

$$f(x) \sim \frac{(1-x)^{\text{power}}}{\sqrt{x}}$$

Pythia 8/Angantyr parameters

↳ **popcorn mechanism**



`BeamRemnants:dampPopcorn`

controls whether a beam-remnant diquark can hadronize via popcorn production

A value of 1 corresponds to ordinary hadronization, where the leading hadron approximately half of the time is a meson, while a value of 0 enforces leading baryon production. Intermediate values interpolate smoothly between these two extreme scenarios. This setting does not affect diquarks produced outside the beam remnant.

Pythia 8/Angantyr parameters

↳ **hardness of beam-remnant baryon fragmentation**

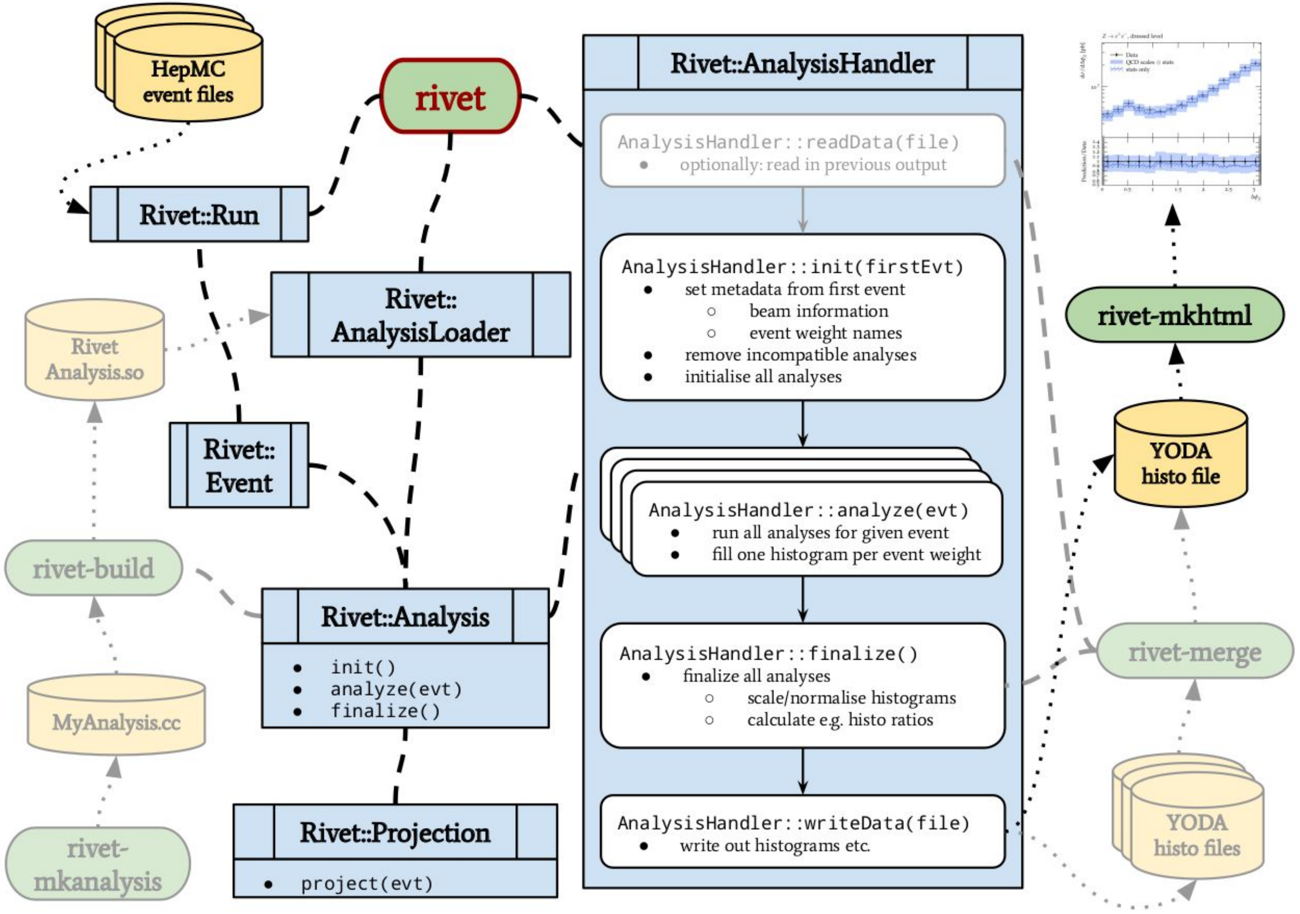
enables harder-than-normal fragmentation of beam-remnant baryons

```
BeamRemnants:hardRemnantBaryon
BeamRemnants:aRemnantBaryon
BeamRemnants:bRemnantBaryon
```

parameter a of the Lund symmetric fragmentation function used for hard remnant baryons

parameter b of the fragmentation function for hard remnant baryons.

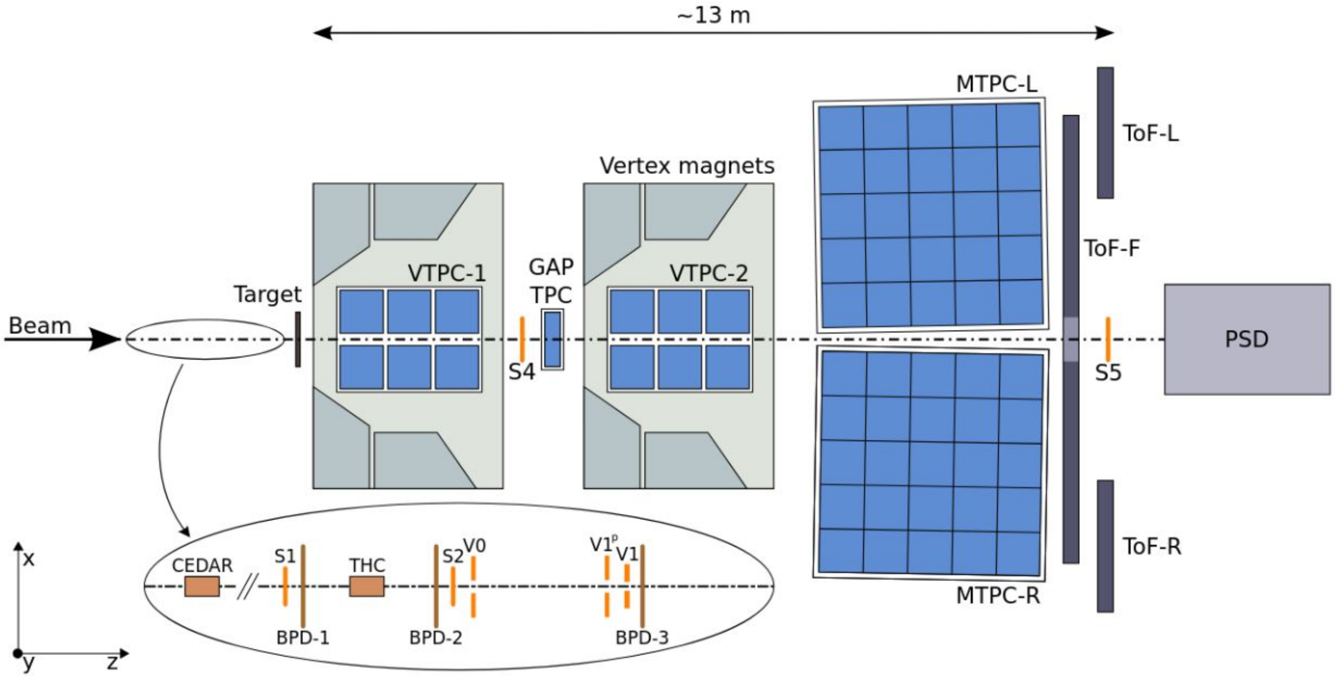
RIVET



SciPost Phys. 8 (2020)

NA61/SHINE

RIVET plugin name	ref.	VTPC	MTPC	GTPC	ToF-L/R	ToF-F	PSD
NA61_2017_I1598505	[78]	✓	✓	✓		✓	
NA61_2017_I1600971	[77]	✓	✓	✓		✓	
NA61_2019_I1753094	[79]	✓	✓	✓	✓		✓
NA61_2022_I1868367	[56]	✓	✓	✓	✓		
NA61_2023_I2155140	[68]	✓	✓	✓			



Eur. Phys. J. C 77.9 (2017)

Pythia 8/Angantyr “Wuppertal” tuning efforts

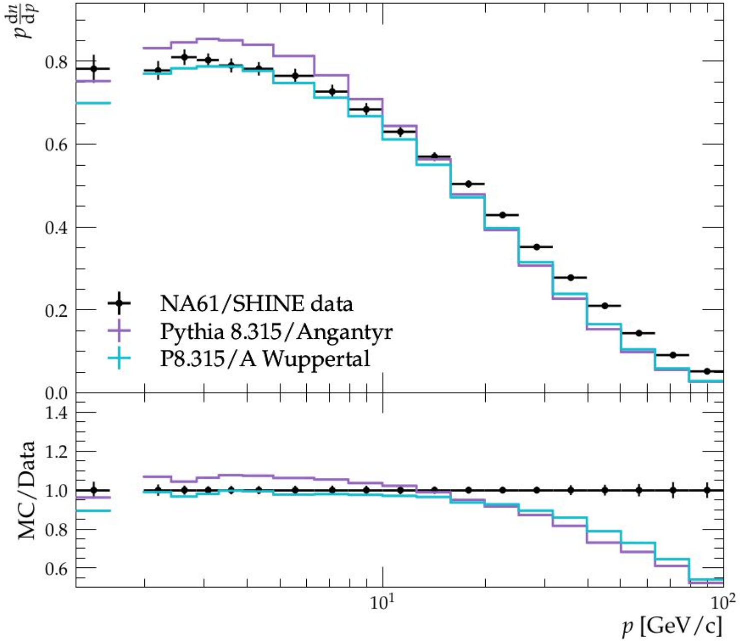
↳ resulting parameter values

type	parameter	default	“Wuppertal” tune
parm	MultipartonInteractions:pt0Ref	2.28	0.769878
parm	MultipartonInteractions:ecmRef	7000.	21.5
parm	MultipartonInteractions:ecmPow	0.215	0.223879
parm	StringZ:aLund	0.68	1.456674
parm	StringZ:bLund	0.98	1.458910
mode	BeamRemnants:companionPower	4	4
parm	BeamRemnants:valencePowerMeson	0.8	0.547789
parm	BeamRemnants:valencePowerUinP	3.5	0.010093
parm	BeamRemnants:valencePowerDinP	2.0	0.027153
parm	BeamRemnants:dampPopcorn	1.	0.380849
flag	BeamRemnants:hardRemnantBaryon	off	on
parm	BeamRemnants:aRemnantBaryon	0.	0.494058
parm	BeamRemnants:bRemnantBaryon	2.	3.346097

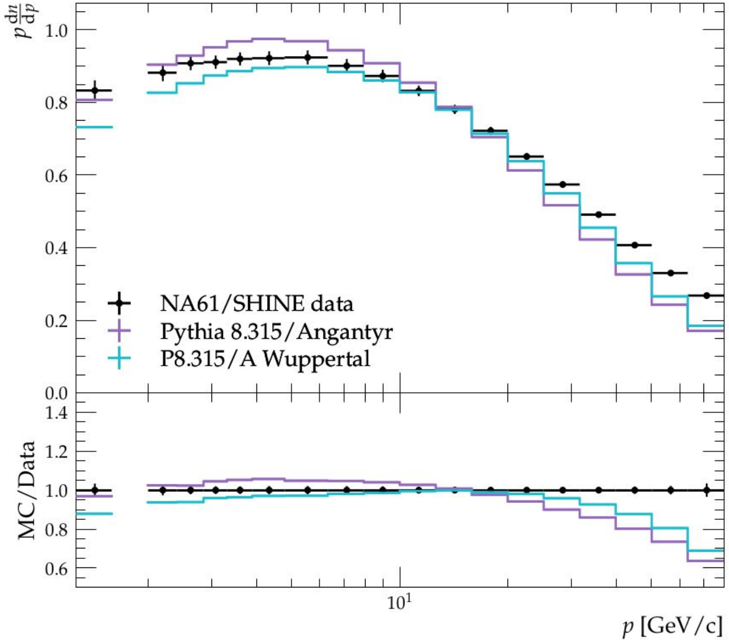
Pythia 8/Angantyr “Wuppertal” tuning efforts

↳ NA61_2023_I2155140

$\pi^- C \to \pi^+ X$@158 GeV.c^{-1}



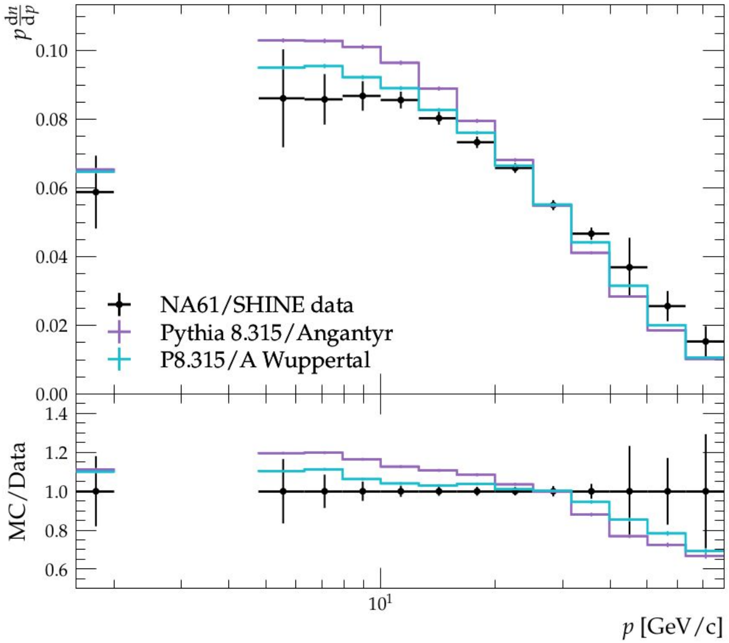
$\pi^- C \to \pi^- X$@158 GeV.c^{-1}



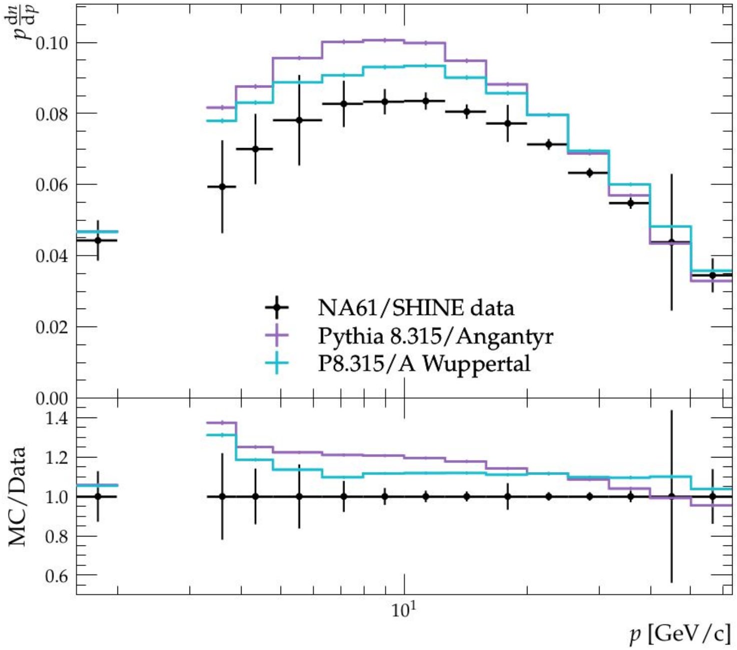
Pythia 8/Angantyr “Wuppertal” tuning efforts

↳ NA61_2023_I2155140

$\pi^- C \rightarrow K^+ X$@158 GeV.c^{-1}



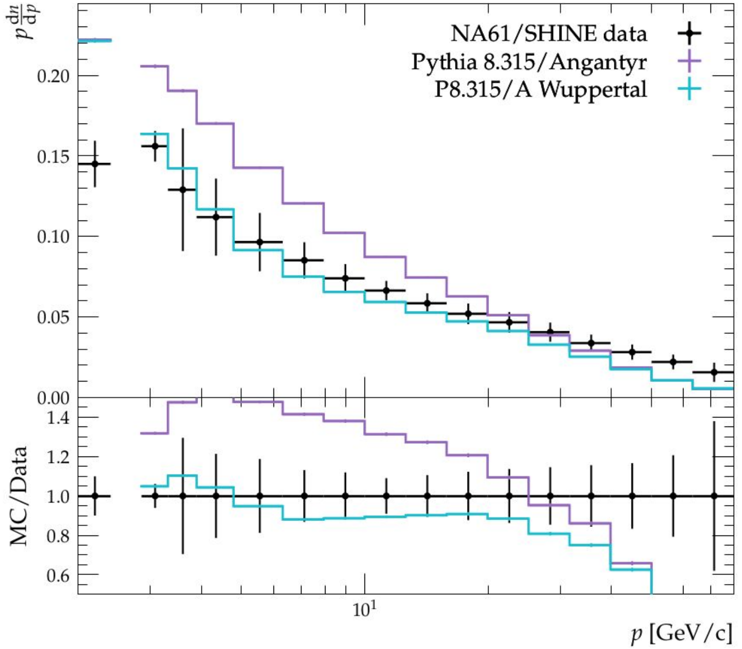
$\pi^- C \rightarrow K^- X$@158 GeV.c^{-1}



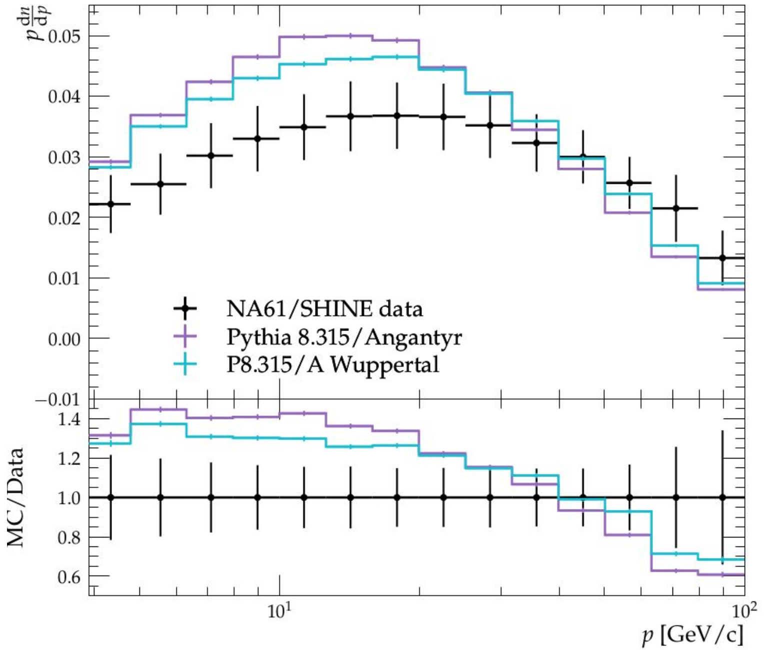
Pythia 8/Angantyr “Wuppertal” tuning efforts

↳ NA61_2023_I2155140

$\pi^{-}C \rightarrow pX$@158 GeV.c^{-1}



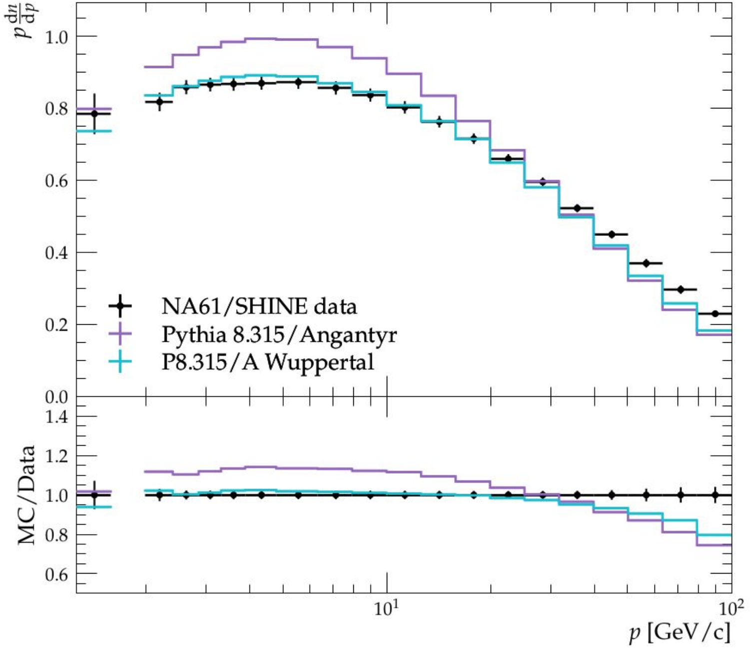
$\pi^{-}C \rightarrow \bar{p}X$@158 GeV.c^{-1}



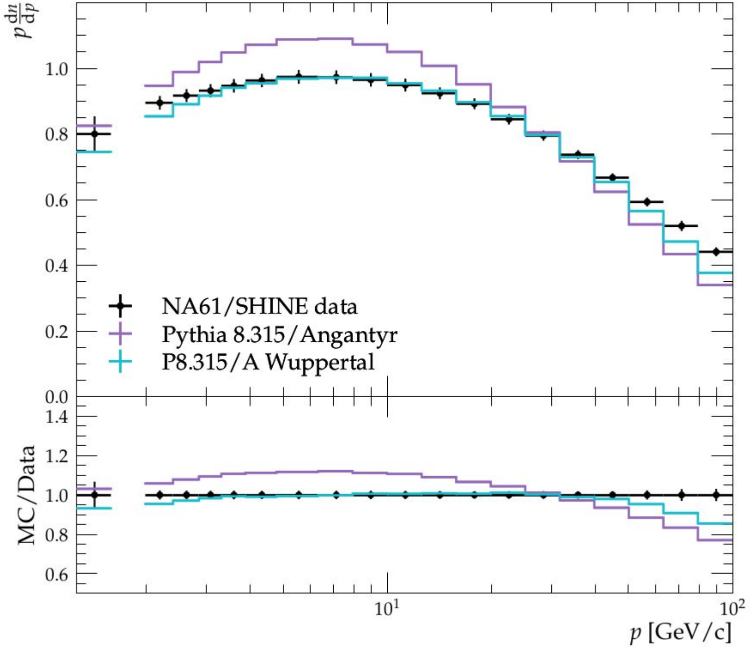
Pythia 8/Angantyr “Wuppertal” tuning efforts

↳ NA61_2023_I2155140

$\pi^- C \to \pi^+ X$@350 GeV.c^{-1}



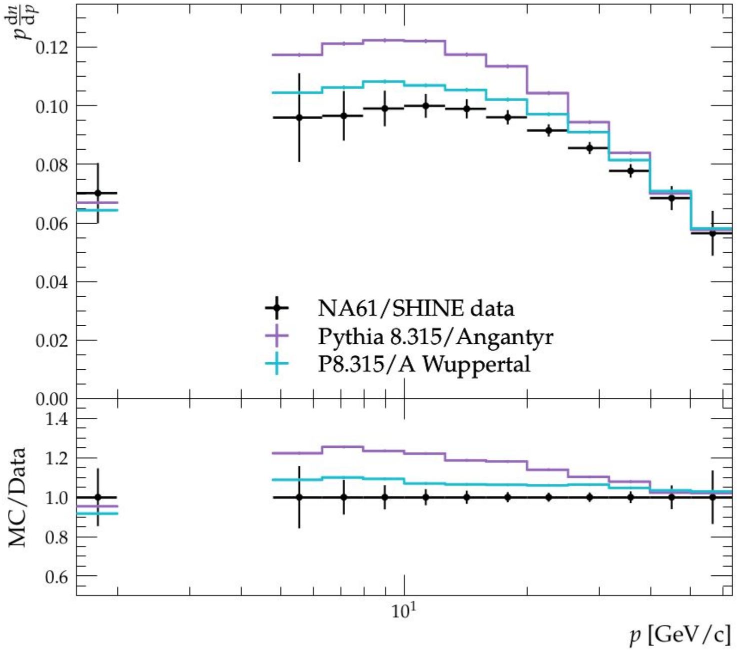
$\pi^- C \to \pi^- X$@350 GeV.c^{-1}



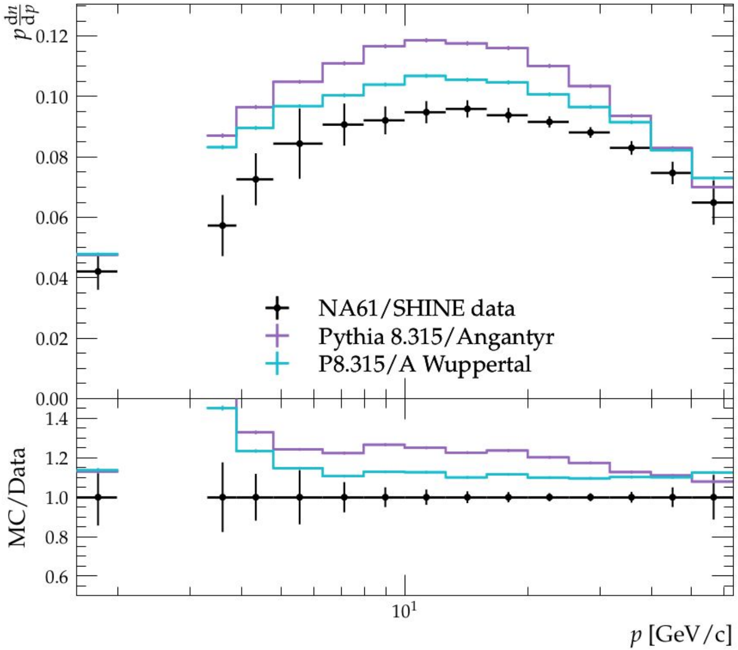
Pythia 8/Angantyr "Wuppertal" tuning efforts

↳ NA61_2023_I2155140

$\pi^- C \rightarrow K^+ X$@350 GeV.c^{-1}



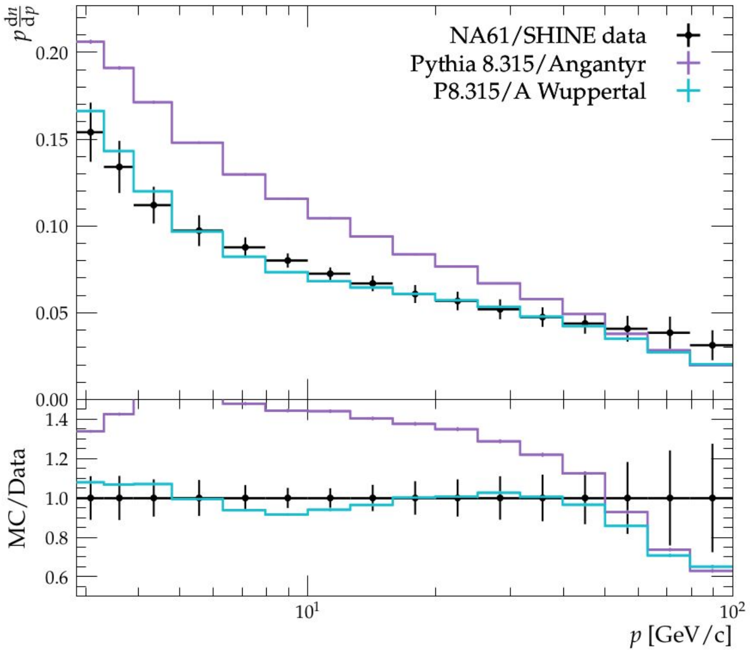
$\pi^- C \rightarrow K^- X$@350 GeV.c^{-1}



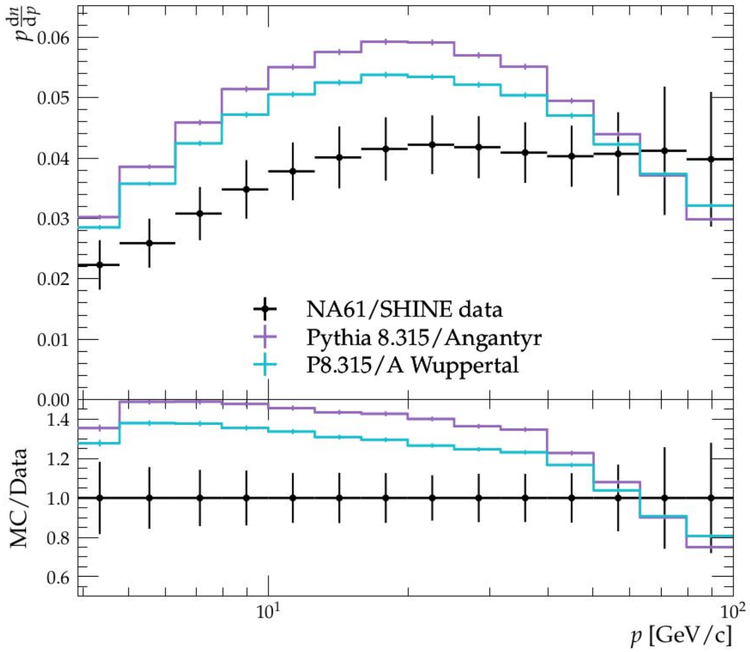
Pythia 8/Angantyr "Wuppertal" tuning efforts

↳ NA61_2023_I2155140

$\pi^-C \rightarrow pX$@350 GeV.c^{-1}



$\pi^-C \rightarrow \bar{p}X$@350 GeV.c^{-1}



Pythia 8/Angantyr “Wuppertal” tuning efforts

↳ LEP RIVET cross-check

RIVET plugin name	HEPData	RIVET	$\sqrt{s}$ (GeV)	proj./target	observable
ALEPH_1996_I428072	✓	✓	91.2	e^+e^-	$d\sigma/dx_p\, x_E\, \zeta_p$, dN/dN_{ch} + event shapes
DELPHI_1998_I473409	✓	✓	91.2	e^+e^-	dN/dp
DELPHI_2011_I890503	✓	✓	91.2	e^+e^-	dN/dx_b, $\langle x_b \rangle$
L3_1992_I334954	✓	✓	91.2	e^+e^-	$P(N_{ch})$ + event shapes
L3_2004_I652683	✓	✓	91.2	e^+e^-	$d\sigma/d\zeta_p$, $P(N_{ch})$ + event shapes
OPAL_1998_I472637	✓	✓	91.2	e^+e^-	$d\sigma/dx_p\, \zeta_p$, N_{ch}
SLD_1999_I469925	✓	✓	91.2	e^+e^-	dN/dx_p, $\langle n \rangle$

Pythia 8/Angantyr “Wuppertal” tuning efforts

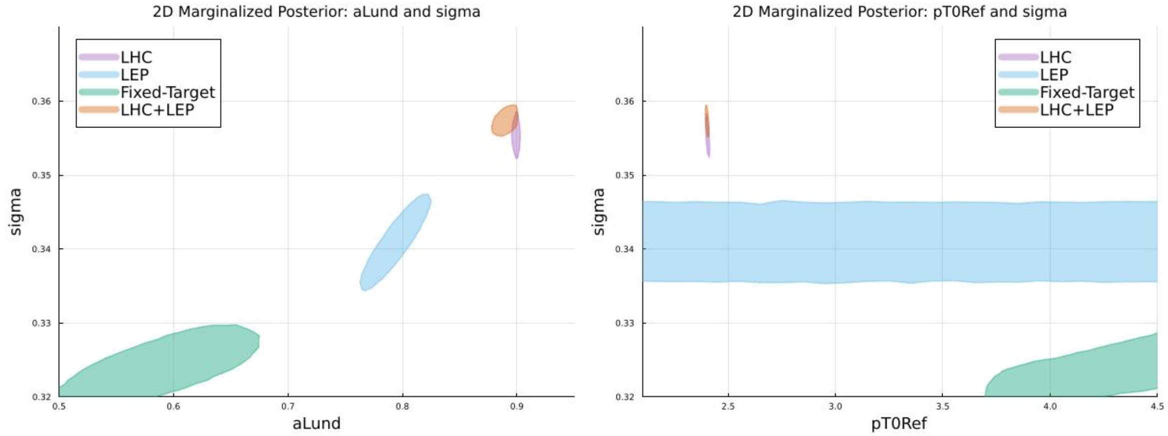
↳ LEP RIVET cross-check

RIVET plugin name	HEPData	RIVET	$\sqrt{s}, \sqrt{s_{NN}}$ (TeV)	proj./target	observable
ATLAS_2010_I882098	✓	✓	0.9, 2.36, 7	pp	$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$, $\mathrm{d}\sigma/\mathrm{d}\eta\,\mathrm{d}p_{\mathrm{T}}$, $\mathrm{d}\sigma/\mathrm{d}N_{\mathrm{ch}}$, $\langle p_{\mathrm{T}} \rangle$
ATLAS_2015_I1360290	✓	✓	2.76	PbPb	$\mathrm{d}^2N_{\mathrm{ch}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta$, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\lvert\eta\rvert$
ATLAS_2015_I1386475	✓	✓	5.02	pPb	$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$
CMS_2010_I855299	✓	✓	7	pp	$\mathrm{d}^2N_{\mathrm{ch}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta$, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$
CMS_2011_I879315	✓	✓	0.9, 2.36, 7	pp	P_n, $\langle p_{\mathrm{T}} \rangle$
CMS_2015_I1384119	✓	✓	13	pp	$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$
CMSTOTEM_2014_I1294140	✓	✓	8	pp	$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$
LHCF_2016_I1385877	✓	✓	7, 2.76	pp	$\langle p_{\mathrm{T}} \rangle$, $\mathrm{d}\sigma/\mathrm{d}y$, $\mathrm{d}^3\sigma/\mathrm{d}p^3$
LHCF_2018_I1518782	✓	✓	13	pp	$\mathrm{d}\sigma/\mathrm{d}E$
LHCF_2020_I1783943	✓	✓	13	pp	$\mathrm{d}\sigma/\mathrm{d}E\,\mathrm{d}\eta$, $\mathrm{d}E/\mathrm{d}\eta$, $\langle 1-k \rangle$
LHCF_2023_I2658888	✓	✓	13	pp	$\mathrm{d}\sigma/\mathrm{d}x_{\mathrm{F}}$
TOTEM_2012_I1115294	✓	✓	7	pp	$\mathrm{d}N/\mathrm{d}\eta$

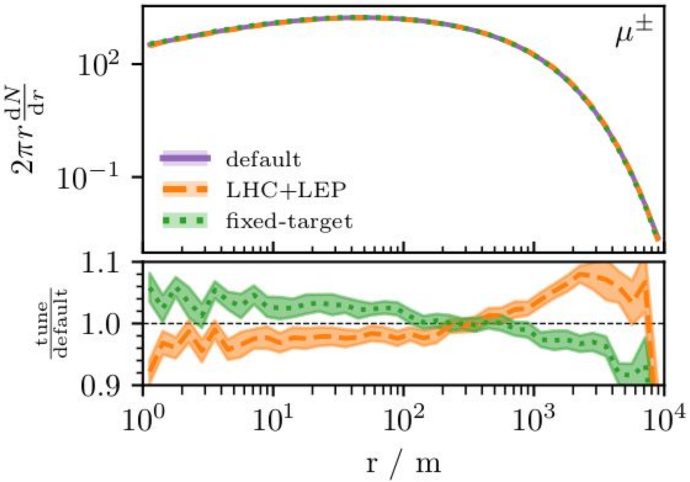
Tuning for cosmic ray physics

↳ Pythia 8/Angantyr tuning efforts

```
MultipartonInteractions:pt0Ref
MultipartonInteractions:ecmRef
StringZ:aLund
StringPT:sigma
```



	RIVET plugin name	RIVET histogram	observable
fixed-target	EHS_1988_I265504	d06-x01-y01	$d\sigma/dp_T^2$
LEP	ALEPH_1996_I428072	d17-x01-y01	$d\sigma/d\zeta_p$
		d59-x01-y01	$P(N_{ch})$
	L3_2004_I652683	d65-x01-y01	$d\sigma/d\zeta_p$
LHC	ATLAS_2010_I882098	d10-x01-y01	$d\sigma/d\eta\, dp_T$
		d17-x01-y01	$d\sigma/dN_{ch}$



Impact on air showers

Ad-hoc modifications of **collider observables** applied to final-state particles

↳ cross section

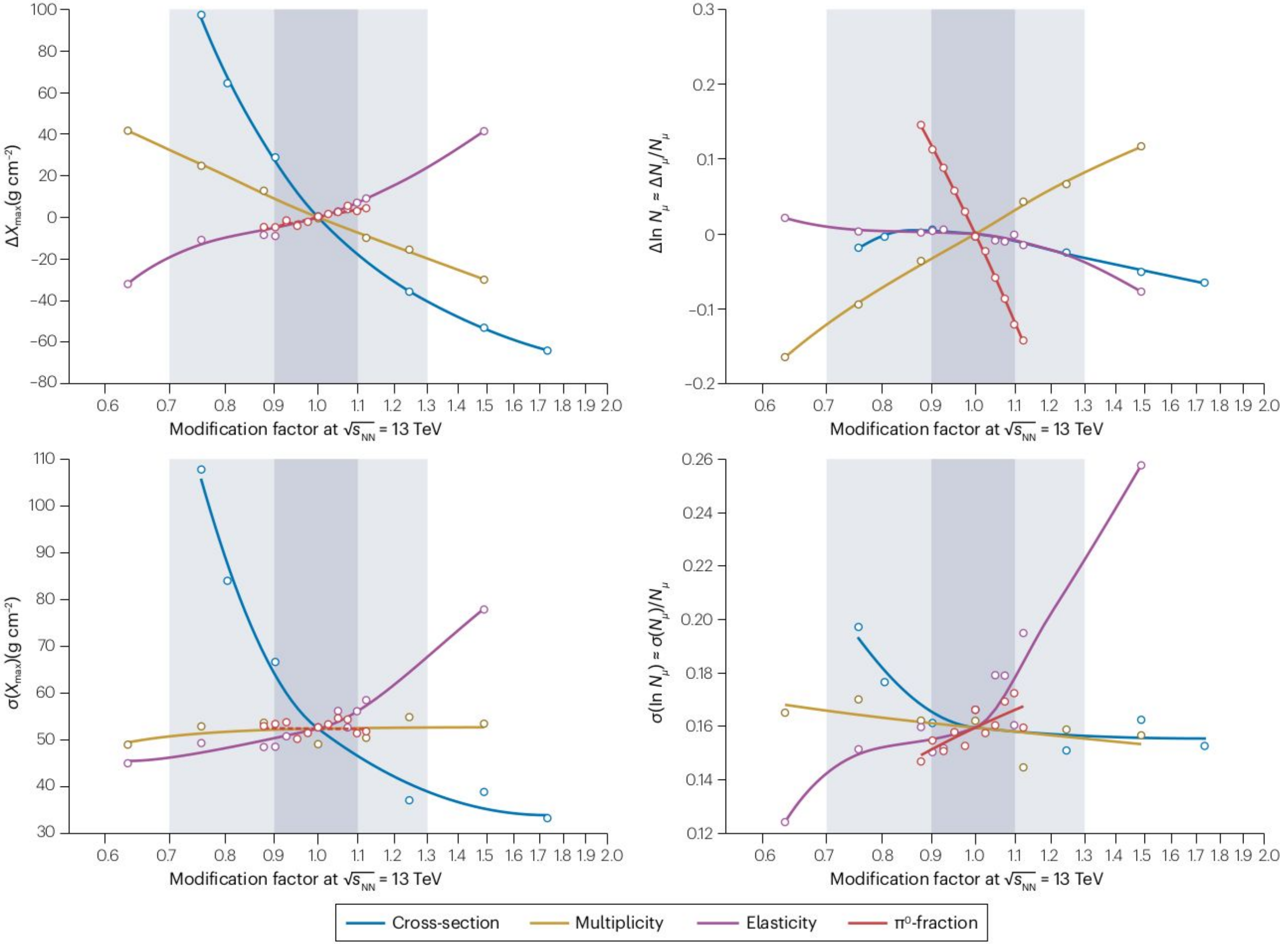
↳ multiplicity

↳ elasticity

↳ π^0 fraction

Shower fluctuations

↳ $\sigma(X_{max})$, $\sigma(N_\mu)$ in narrow E interval



Effects of changing basic observables of hadronic interactions to different extensive air shower observables for $10^{19.5}$ eV proton showers simulated with CONEX using SIBYLL 2.1 as the baseline model

Nature Rev.Phys. 8 (2026) 98-114