Hadronic interactions from colliders to cosmic rays: Pythia 8/Angantyr for air shower simulations

RAPP 10 years

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PIERRE AUGER OBSERVATORY

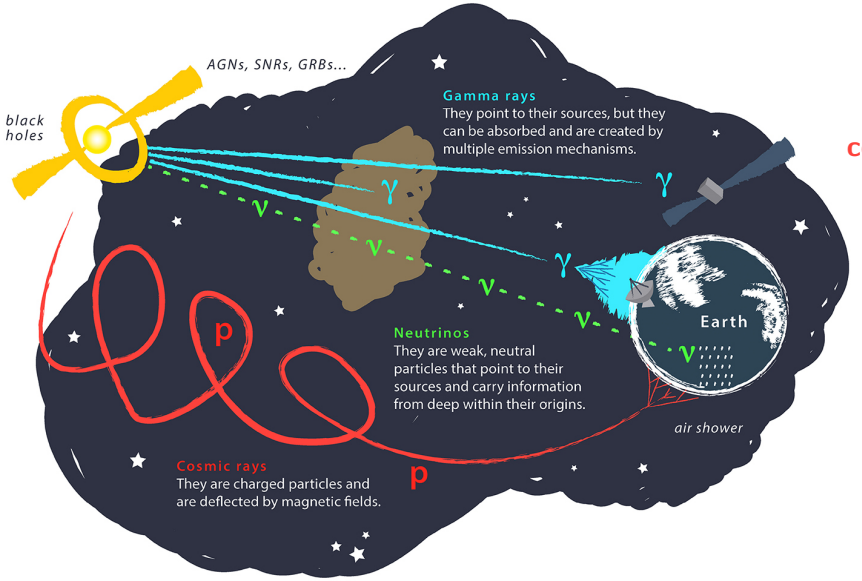
BERGISCHE UNIVERSITÄT WUPPERTAL

CORSIKA 8

SFB1491

DFG Deutsche Forschungsgemeinschaft German Research Foundation

Multimessengers for astronomy



cosmic rays (**CR**)

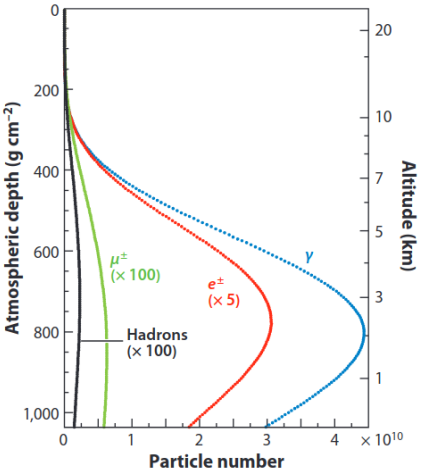
- ↳ origin
- ↳ E spectrum
- ↳ mass composition

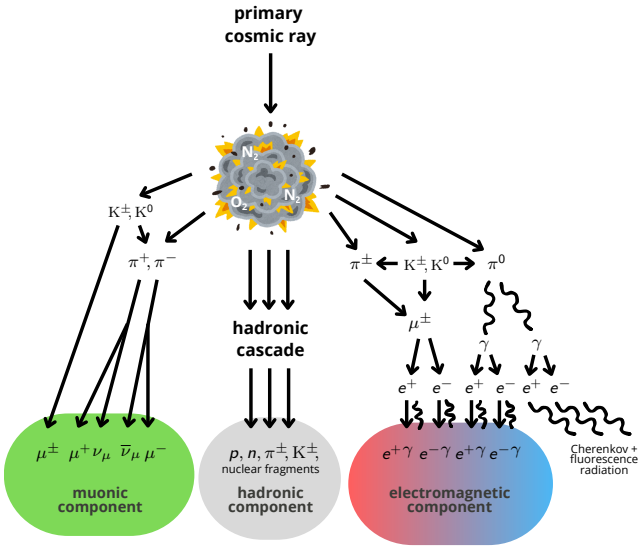
↓

CR detection via **air showers**

Juan Antonio Aguilar, Jamie Yang (IceCube/WIPAC)

Air shower development



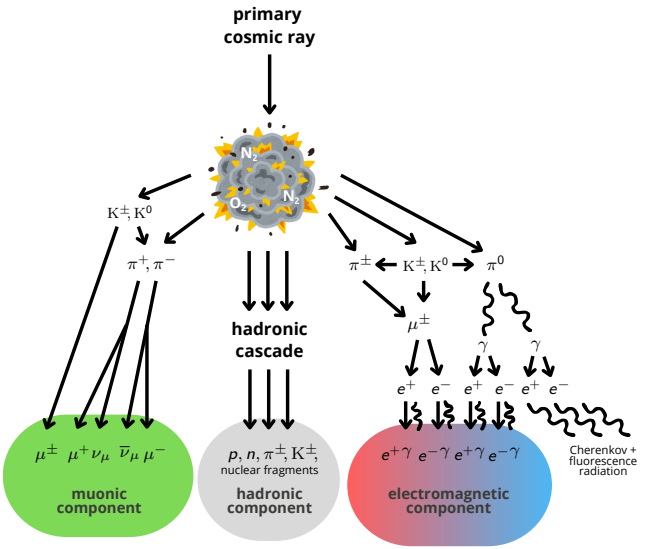


need to model individual **processes**
as they cannot be calculated

Annu. Rev. Nucl. Part. Sci. 61, 467-89 (2011)

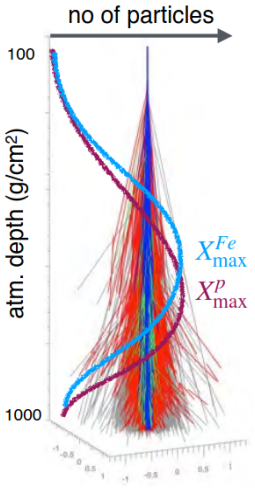
Air shower processes

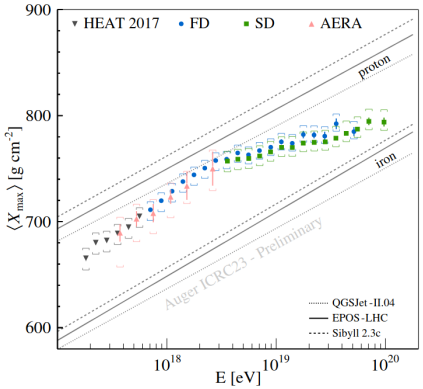
- **muonic**
  - $\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}/\overline{\nu}_{\mu}$
  - $K^{\pm} \to \mu^{\pm} + \nu_{\mu}/\overline{\nu}_{\mu}$
- **hadronic**
  - p-air/$\pi^{\pm}$-air/$K^{\pm}$-air
  - pp/$\pi^{\pm}$p/$K^{\pm}$
  - nuclear spallation
- **electromagnetic (EM)**
  - $\pi^0 \to \gamma\gamma$
  - $e^{\pm} \to e^{\pm} + \gamma$ (bremstrahlung)
  - $\gamma \to e^- e^+$ (pair production)
  - photonuclear int.

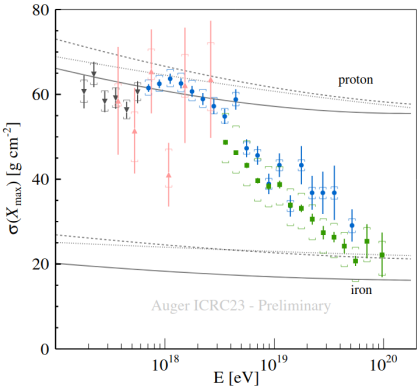


muonic and **hadronic** feeding the **EM** cascades,
EM cascade ends at $E_{\mathrm{crit}} \sim 80$ MeV for $e^{\pm}$ in air

CR mass composition



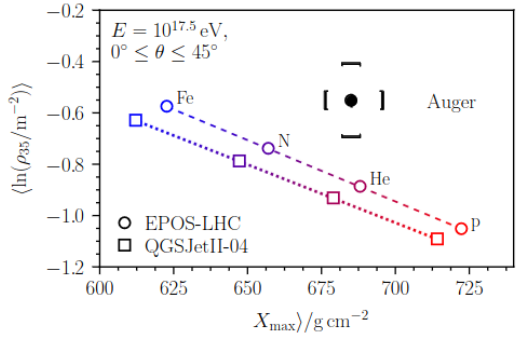


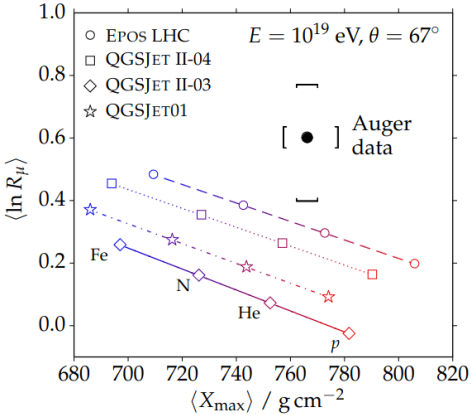


interpret mass of primary CRs by comparison with model predictions

PoS(ICRC2023)365

Muon Puzzle





- deficit of $\mu^{\pm}$ at ground for several air shower experiments (incl. Auger)
- large systematic uncertainties introduced in the analysis
  - ↳ interpretation of shower data

Eur. Phys. J. C 80, 751 (2020)
Phys. Rev. D 91, 032003 (2015)

Hadronic interaction models (HIMs)

↳ models that predict the outcomes of hadrons colliding, including the types, energies, and directions of produced particles

HIMs in CR physics

- EPOS-LHC/R
- QGSJet-II.04/III.01
- Sibyll 2.3d/e

Pythia 8 (e^+e^-, $pp/\overline{p}p$)

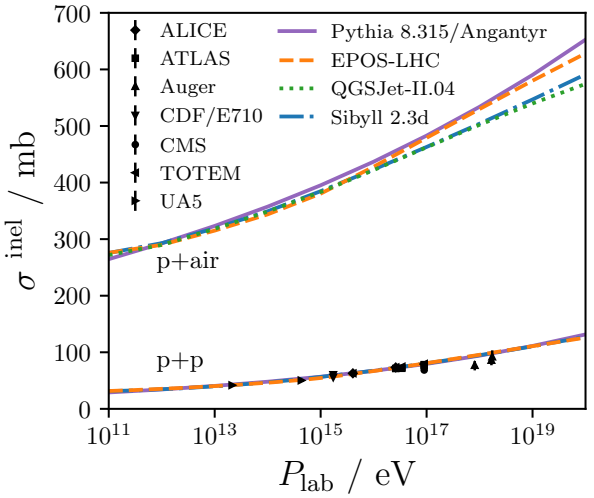
- general purpose hadronic interaction model

+

Angantyr (hA, AA)

- extension of Pythia for heavy-ion collisions
- inspired by old Fritiof model/wounded nucleons
- Glauber model with advanced fluctuation treatment
  - ↳ stack individual nucleon-nucleon sub-collisions
  - ↳ hadronize them together

Inelastic cross-section σ^{inel}



σ^{inel} is essential for 1st interaction in air shower development

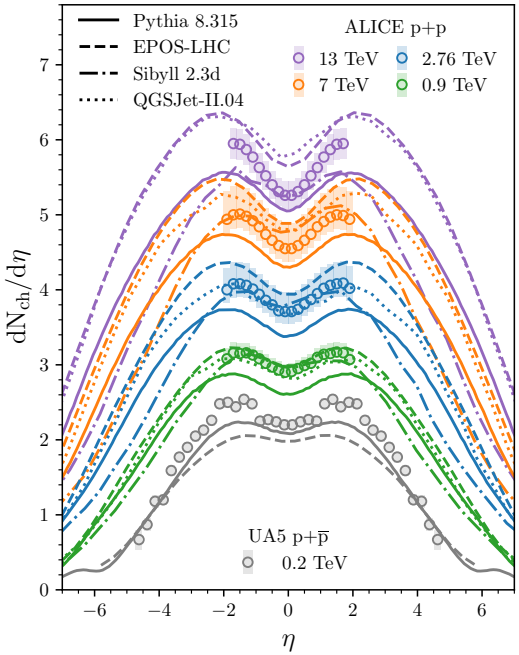
↓

- $\sigma^{\text{inel}}_{\text{p+air}}$(EPOS-LHC) $\sim$ $\sigma^{\text{inel}}_{\text{p+air}}$(P8/A)
  - ↳ comparable λ_{int} in air showers
- largest $\sigma^{\text{inel}}_{\text{p+air}}$ for P8/A at high P_{lab}
  - ↳ shallowest 1st interaction predicted in air showers among HIMs
- close agreement among models and experiments for $\sigma^{\text{inel}}_{\text{pp}}$

Charged particle pseudorapidity distribution

↳ constrained at mid-rapidity

- ALICE and UA5 measurements
- INEL trigger†



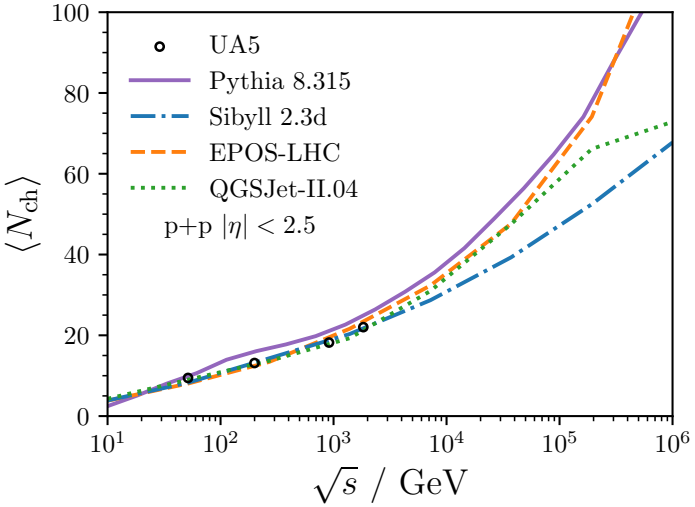
† ≥ 1 hit on either side

Average charged particle multiplicity

↳ constrained at lowest $\sqrt{s}$ by UA5 measurements

- NSD trigger[†]
- mid-rapidity

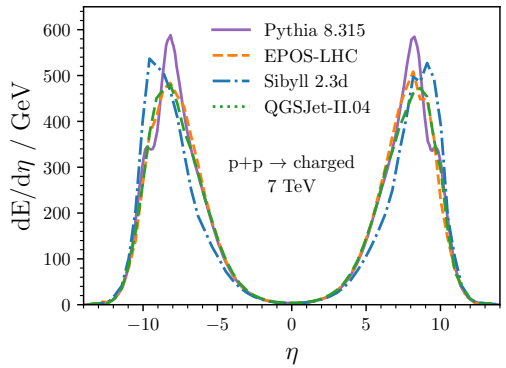
- HIMs diverge at high $\sqrt{s}$

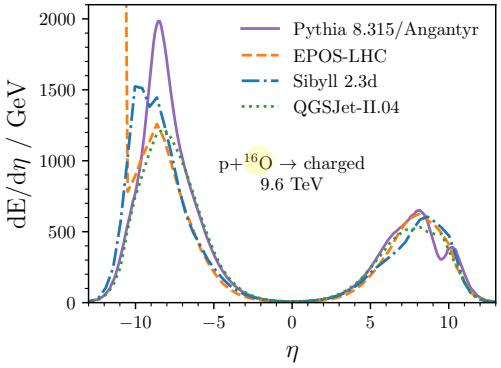


[†] ≥ 1 hit on both sides

Charged particle energy flow

↳ governs the calorimetric measurement of air showers





- reasonable agreement between models
- measurements (pO,OO)@LHC → provide new constraints on models
  ↳ towards a better understanding of air shower physics

From collider to cosmic rays

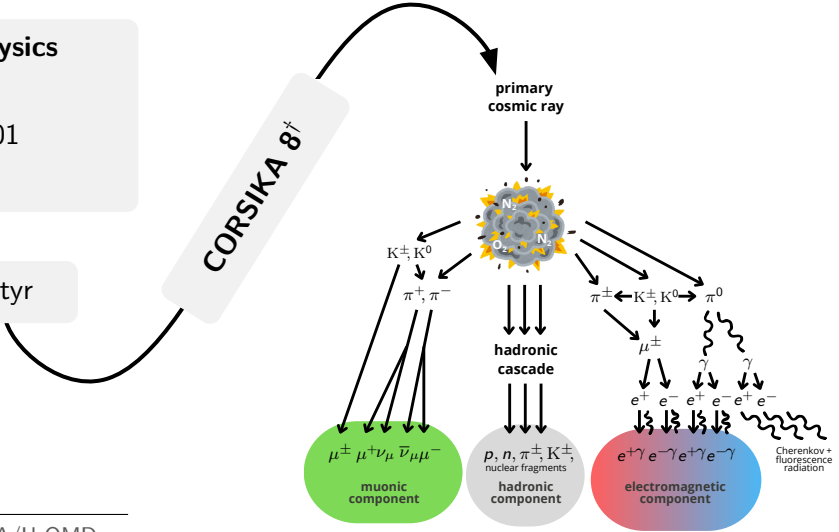
HIMs in CR physics

- EPOS-LHC/R
- QGSJet-II.04/III.01
- Sibyll 2.3d/e

+

Pythia 8/Angantyr

CORSIKA 8†



†incl. PROPOSAL, FLUKA/UrQMD

CORSIKA 8

The new C++ particle shower simulation code CORSIKA 8
is a successor of CORSIKA 7, with focus on modularity

- electromagnetic cascades handled by lepton propagator PROPOSAL
- several hadronic interaction models available
  - ↳ high energies: Sibyll 2.3d, EPOS-LHC, QGSJet-II.04/III.01, **Pythia 8/Angantyr**
  - ↳ low energies: FLUKA, UrQMD
- radio-emission calculation fully configurable by user, using two algorithms
  - ↳ CoREAS as in CORSIKA 7
  - ↳ ZHS as in ZHAires
- new features in C8: enhanced thinning, air shower genealogy, cross-media showers

code is considered **"physics-complete"** and container available since early this year

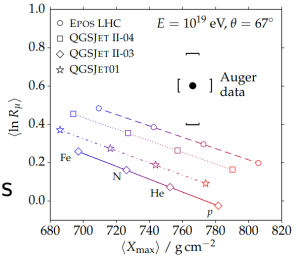
CORSIKA 8 + Pythia 8/Angantyr

- Pythia 8/Angantyr for hadronic interactions
  - tabulation of σ^{inel} for various (proj, target, $P_{\mathrm{lab}} \leftrightarrow \sqrt{s_{\mathrm{NN}}}$)
    - ↳ Pythia for pp, hp
    - ↳ Angantyr for pA, hA, AA
  - handling of projectile fragments
  - pre-initialization of Angantyr

- CORSIKA 8 simulation workflow
  - set C8 shower settings
  - run single Pythia instance
    - ↳ perform (proj, target, $P_{\mathrm{lab}} \leftrightarrow \sqrt{s_{\mathrm{NN}}}$) hadronic collisions on event-by-event basis
    - ↳ interpolate from σ^{inel} tables
    - ↳ obtain secondary final state particles
  - handle EM particles via PROPOSAL
  - track internally in C8
  - store showers in particle stack + write C8 output files

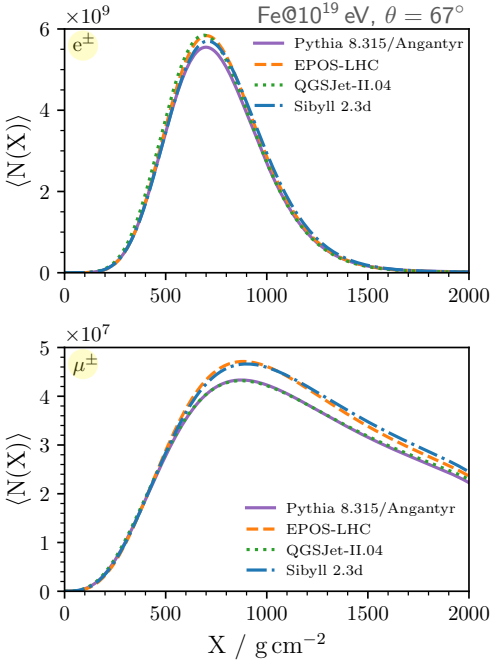
Validation efforts

↳ Pythia 8/Angantyr vs. others in C8



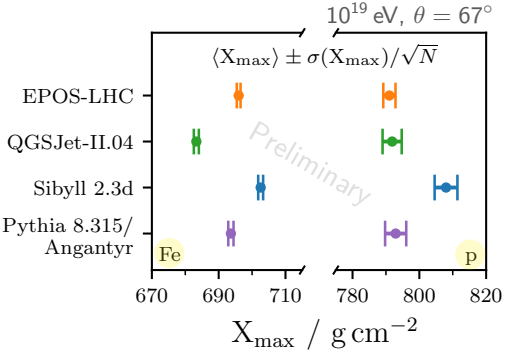
Full shower simulations

- p, ^{56}Fe primaries
- 10^{19} eV primary energy
- inclined ($\theta = 67°$)
- tracking energy thresholds
  - ↳ 1 MeV for γ and e$^{\pm}$
  - ↳ 1 GeV for hadrons and $\mu^{\pm}$
- thinning for γ and e$^{\pm}$ cascades

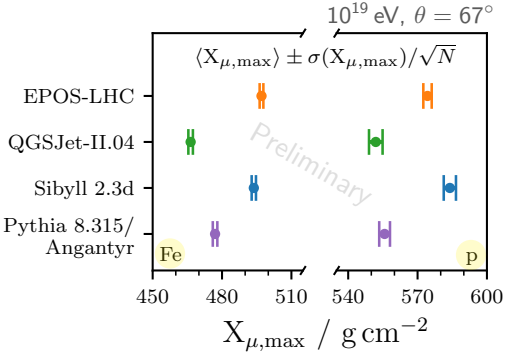


X_{max} and $X_{\mu,max}$

- X_{max} driven by EM cascade

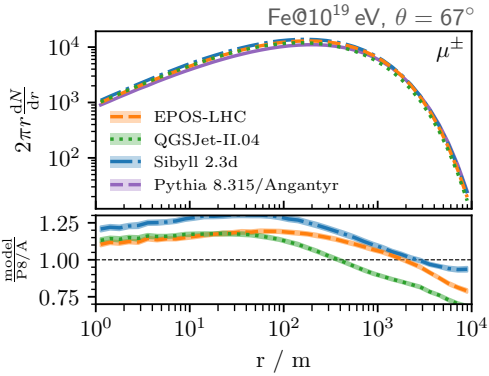


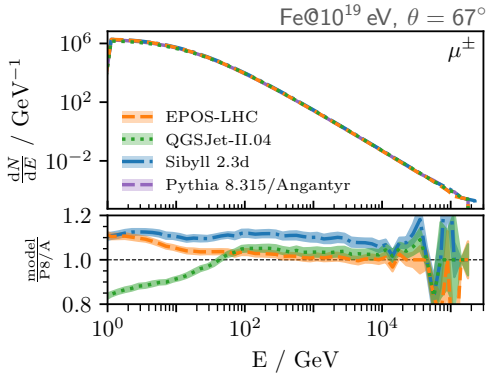
- $X_{\mu,max}$ driven by $\pi^{\pm}$+air interactions



- Pythia 8/Angantyr (P8/A)
  - ↳ highest σ^{inel}_{p+air} → expected shallowest 1st int. → X_{max} and $X_{\mu,max}$ both shift upward
  - ↳ shallower full and hadronic showers

Lateral distributions and energy spectra





- P8/A yields fewer $\mu^{\pm}$ closer to shower core than other HIMs
- P8/A predicts less $\mu^{\pm}$ in the 100 GeV to 10 TeV range
  - ↳ interesting tuning playground available for Pythia 8/Angantyr

Muon puzzle and Auger measurement

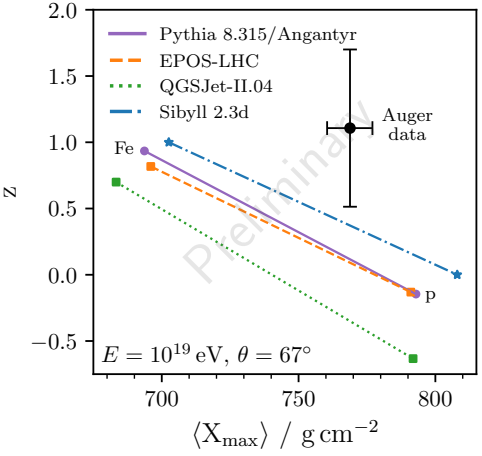
- z-scale approach

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

- Sibyll 2.3d used as reference
  - ↳ convert Auger measurements†
  - ↳ add HIMs from C8

Pythia 8/Angantyr is not compatible with Auger

↳ in its default configuration



†Phys.Rev.Lett. 126 (2021) 15, 152002

Muon puzzle and Auger measurement

Pythia 8/Angantyr is not compatible with Auger

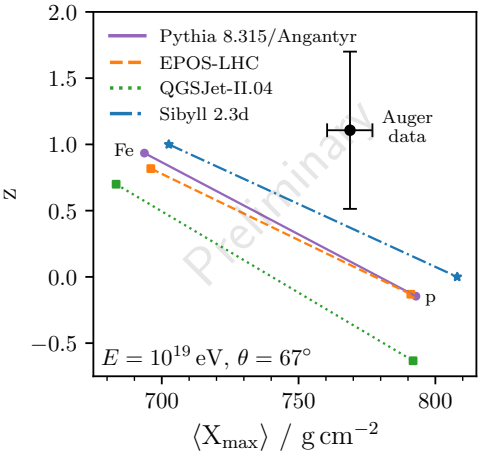
↳ in its default configuration

↓

platform for air shower physics tune

↳ fixed-target measurements† @Wuppertal

↳ (LEP, LHC, fixed-target) data* F4@SFB1491



†arXiv:2411.00111 [astro-ph.HE]

*PoS(ICRC2025)438

Workshop on the tuning of hadronic interaction models[†]

- took place in 22-25 January 2024 in Wuppertal
- discussed **classic** and **global tuning** of hadronic interaction models
  - ↳ "Road map for the tuning of hadronic interaction models with accelerator-based and astroparticle data" write-up
    - ↳ community effort
    - ↳ accepted for publication in Nature Reviews Physics[*]

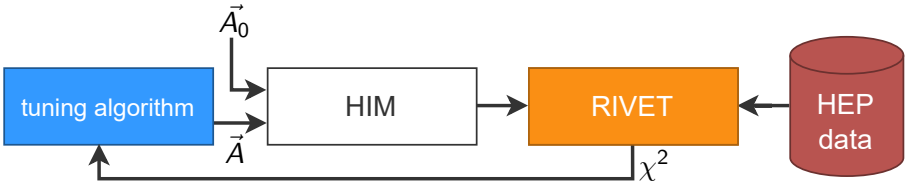
[†] indico.uni-wuppertal.de/event/284

[*] arXiv:2508.21796 [astro-ph.HE]

Classic tuning of HIMs

Pythia 8 can undergo an automatic tuning to accelerator dataset to better describe specific science cases

↳ Monash tune, ATLAS tunes, forward physics tune[†]



↓

ongoing efforts towards a fixed-target tune of Pythia 8/Angantyr[*]

[†] Phys. Rev. D 109, 016010 (2024)
[*] arXiv:2411.00111 [astro-ph.HE]

HEPdata

HEPData is and open-access repository used to **preserve and share experimental data**

↳ large catalogue of analyses

↳ maintained by CERN

HEPData entries

- can be searched via many categories
- come with abstract and proper citation
- store data in tables via several formats
  ↳ YAML, YODA, ROOT, CSV

RIVET

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

↳ used for generator tuning

Each Rivet plugin consists of

- `.cc` file containing the analysis code
  - ↳ no-argument constructor
  - ↳ analysis event loop methods
    1. **init**: book histograms, initialize counters, etc.
    2. **analyze** events: select particles, apply cuts, construct observables, fill histograms etc.
    3. **finalize**: normalize/scale/divide histograms, tuples, etc.
  - ↳ minimal hook into the plugin system
- `.yoda` file containing the data points (from HEPData)
- `.info` file containing metadata
- `.plot` file setting plotting options

RIVETization efforts

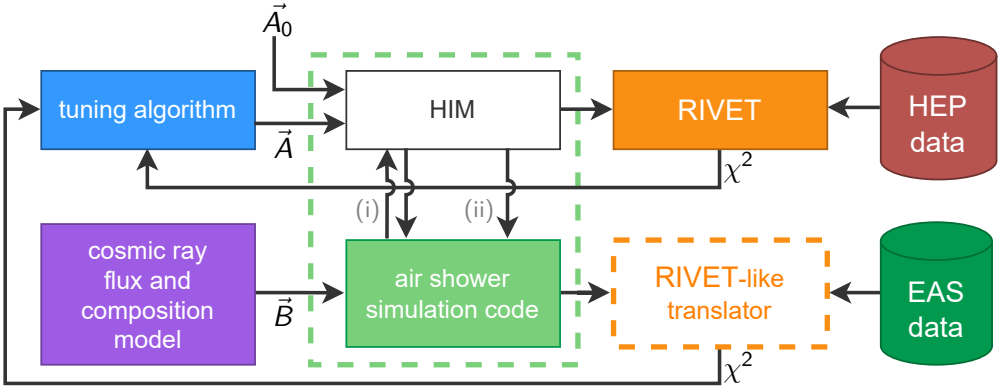
↳ writing RIVET plugins of fixed-target measurements

exp.	paper	HEPData	RIVET	collision system	p_{beam} (GeV/c)	observable	outgoing
E104	[1]	✓	✓	$\pi^{\pm}$p, $K^{\pm}$p, pp, $\overline{\text{p}}$p	[23 - 280]	σ_{tot}	
	[2]	✓	✓	$\pi^{\pm}$p, $K^{\pm}$p, pp, $\overline{\text{p}}$p	[200 - 370]	σ_{tot}	
	[3]			$\pi^{\pm}$C, $K^{\pm}$C, pC, $\overline{\text{p}}$C	[60 - 280]	σ_{prod}	
NA8	[4]	✓		π^-p, pp	[30 - 345]	$\mathrm{d}\sigma/\mathrm{d}t$	
NA22	[5]	✓	✓	π^+p, K^+p, pp	250	P_n	C
	[6]	✓		π^+p, K^+p, pp	250	$\mathrm{d}\sigma/\mathrm{d}t$	
	[7]	✓	✓	π^+p, K^+p, pp	250	$\mathrm{d}\sigma/\mathrm{d}x_F\,\mathrm{d}\eta\,\mathrm{d}p_T^2$	π^-, C^+
	[8]	✓		π^+p	250	$\mathrm{d}\sigma/\mathrm{d}x_F\,\mathrm{d}p_T^2$	$\rho^0, \rho^+, \omega, K^{*0}, \overline{K^{*0}}$
	[9]	✓	✓	π^+p, K^+p	250	σ, $\mathrm{d}\sigma/\mathrm{d}x_F\,\mathrm{d}p_T^2$	π^0, η
NA49	[10]	✓	✓	pp	158	$\mathrm{d}n/\mathrm{d}x_F\,y$, $\langle p_T\rangle$	π^+
	[11]		✓	pp	158	$\mathrm{d}n/\mathrm{d}x_F\,y$, $\langle p_T\rangle$	p
NA61/ SHINE	[12]	✓	✓	pp	[20 - 158]	$\mathrm{d}n/\mathrm{d}y$	$\pi^{\pm}$, $K^{\pm}$, p, $\overline{\text{p}}$
	[13]	∼	✓	π^-C	158	$\mathrm{d}n/\mathrm{d}x_F$	ρ^0, ω, K^{*0}
	[14]	✓	✓	pC	60, 120	$\sigma_{\text{prod}}, \sigma_{\text{inel}}$	
	[15]	✓	✓	pp	158	$\mathrm{d}^2n/\mathrm{d}y\mathrm{d}p_T$, $\mathrm{d}n/\mathrm{d}y$	K^0_s
	[16]	∼	✓	π^-C	158, 350	$p\,\mathrm{d}n/\mathrm{d}p_T^2$	$\pi^{\pm}$, $K^{\pm}$, p, $\overline{\text{p}}$

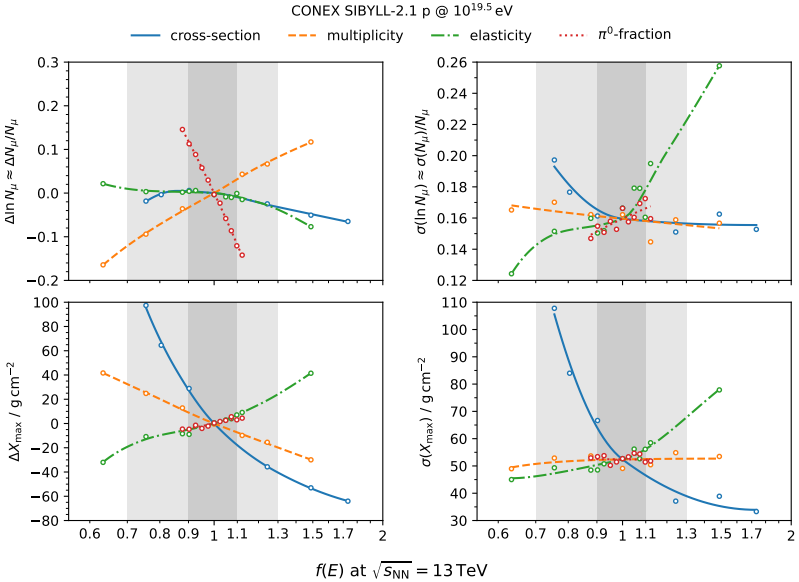
$\sigma_{\text{prod}} = \sigma_{\text{tot}} - \sigma_{\text{coherent nucleus}} - \sigma_{\text{quasi-elastic}}$

Global tuning of HIMs

↳ with accelerator-based and **astroparticle** data



Air shower observables sensitive to interaction features

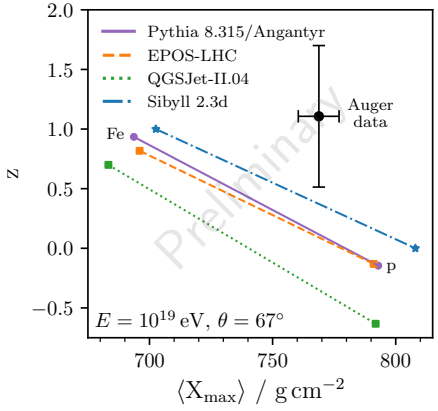


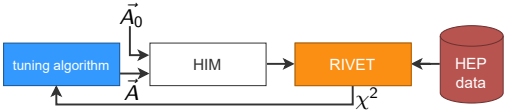
Astrophys.Space Sci. 367 (2022) 3, 27

Conclusion

successful implementation of
Pythia 8/Angantyr in CORSIKA 8

- validated efforts[‡]
  - ↳ p and Fe primaries
  - ↳ vertical and inclined geometries
- comparable to other models and experimental measurements
- classic tuning efforts for CR physics
  - ↳ fixed-target measurements[†] @Wuppertal
  - ↳ (LEP, LHC, fixed-target) data[*] F4@SFB1491

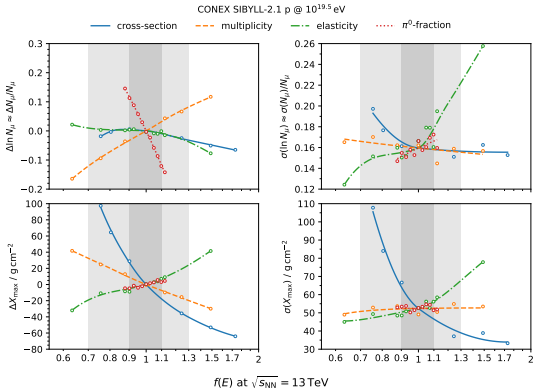


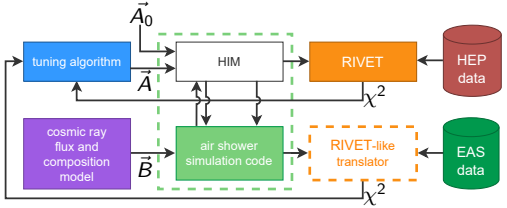


[‡] PoS(ICRC2025)267
[†] arXiv:2411.00111 [astro-ph.HE]
[*] PoS(ICRC2025)438

Outlook

- upcoming global tuning efforts
  - ↳ discussed at workshop
  - ↳ detailed in workshop write-up†
- to be continued in phase 2 @SFB1491
- another workshop planned in Dortmund (2026/2027)





† arXiv:2508.21796 [astro-ph.HE]