The link between the highest-energy cosmic rays and particle physics at the LHC

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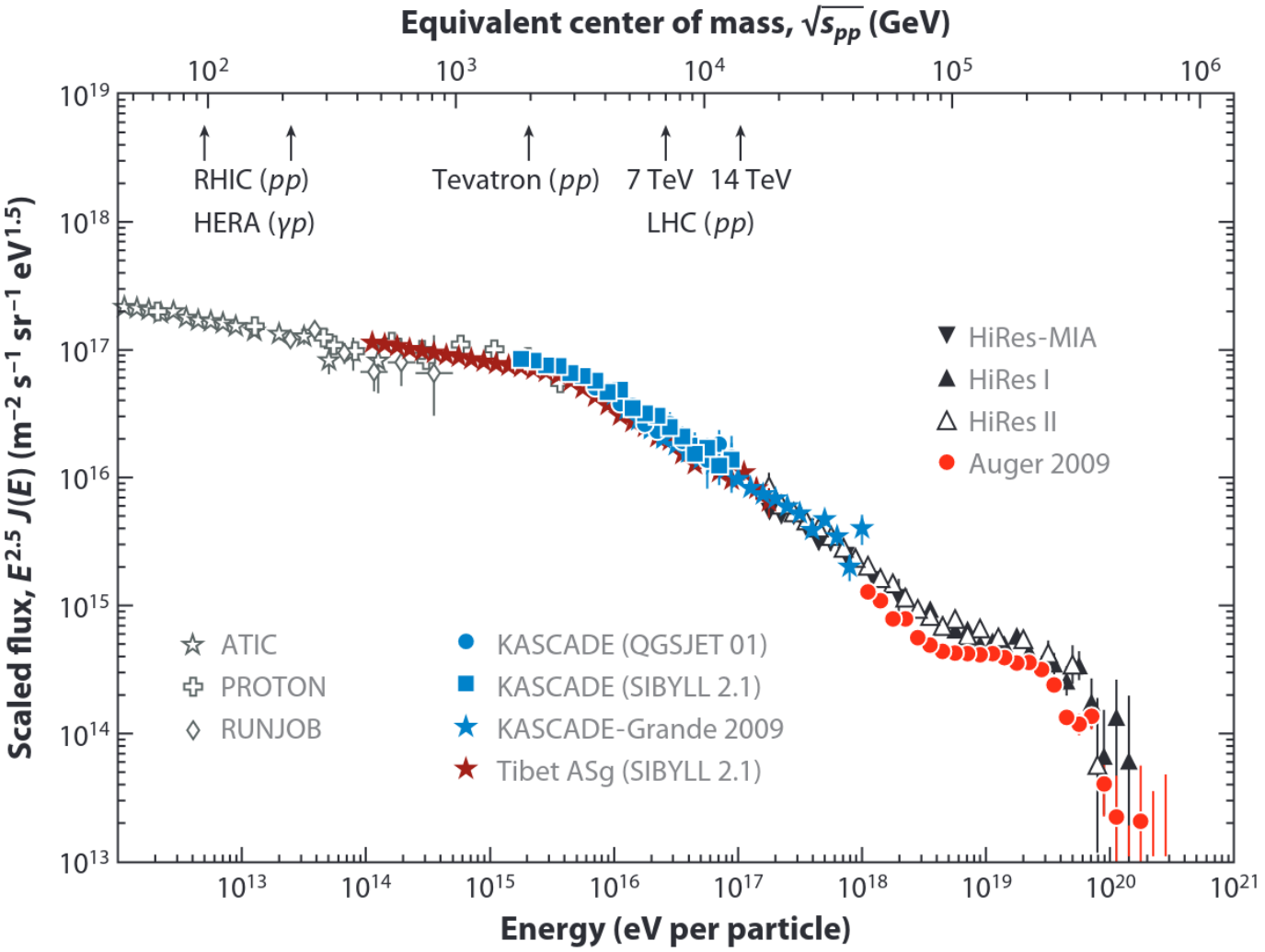
XI ICNFP 2022-09-05

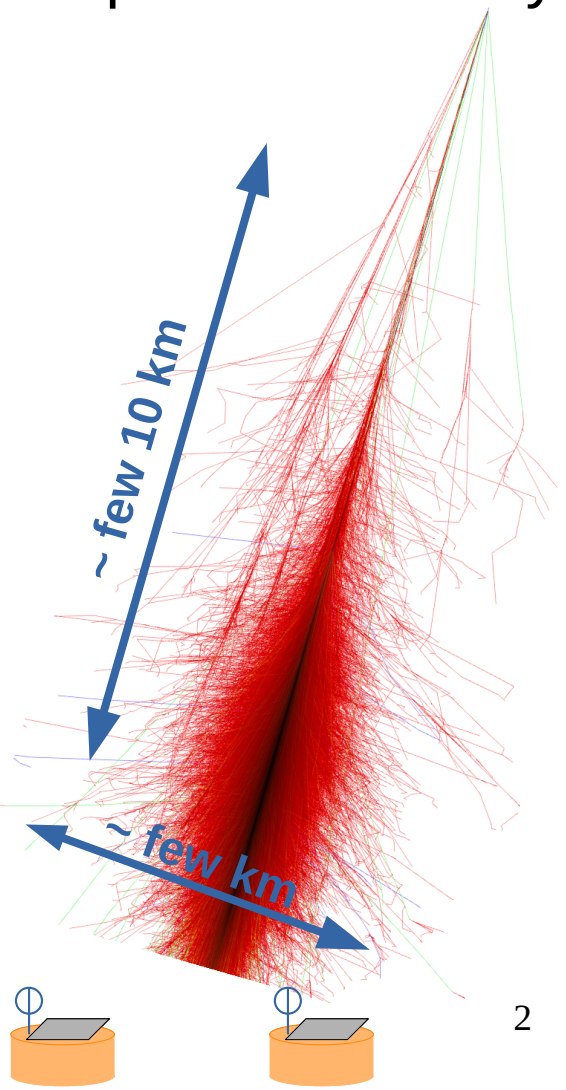
Karlsruher Institut für Technologie

CR energy spectrum



ultra-high energy CR

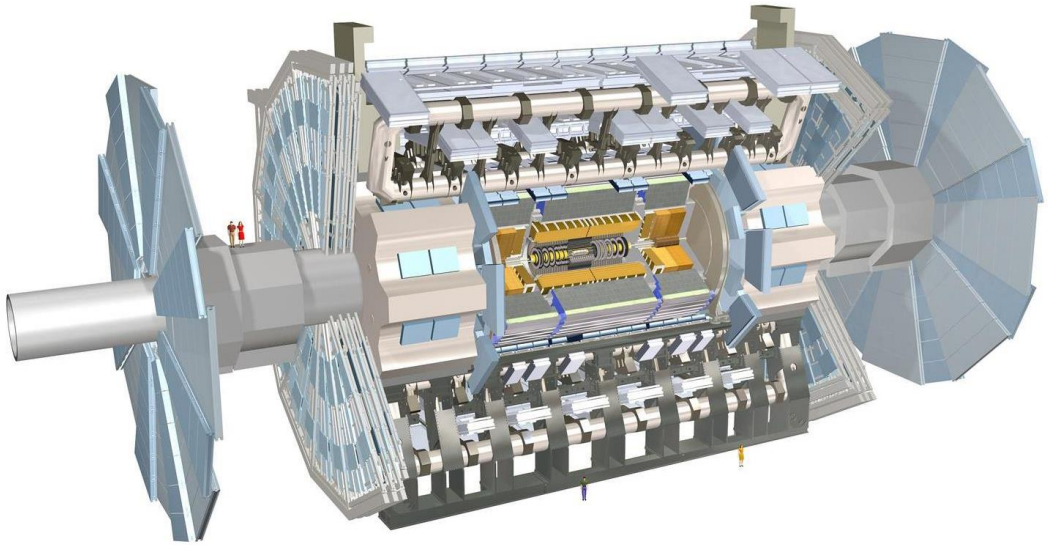
- up to √s ~ 500 TeV
- tiny flux:
  ≤ 1 particle / km² / yr



Engel, Heck, Pierog, Annu. Rev. Nucl. Part. Sci. 61 (2011) 467

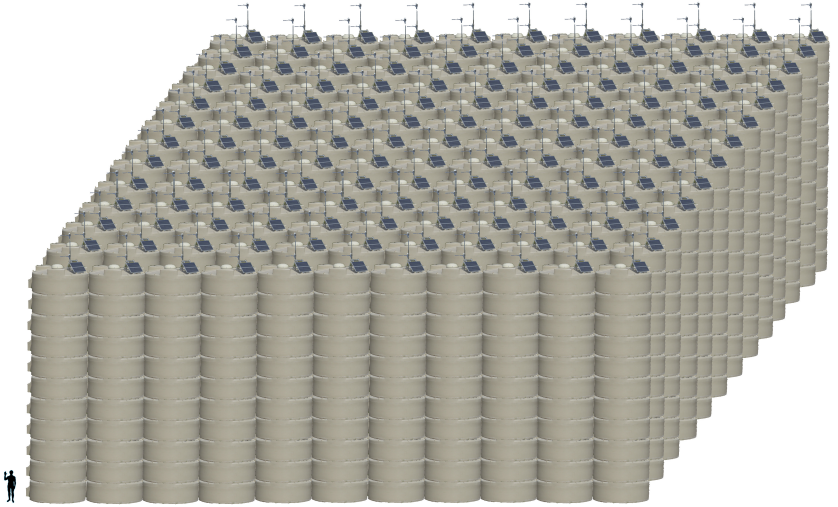
LHC/UHECR detectors

ATLAS



- 2 × 6.8 TeV beam
- √s = 13.6 TeV
- 7 kt detector

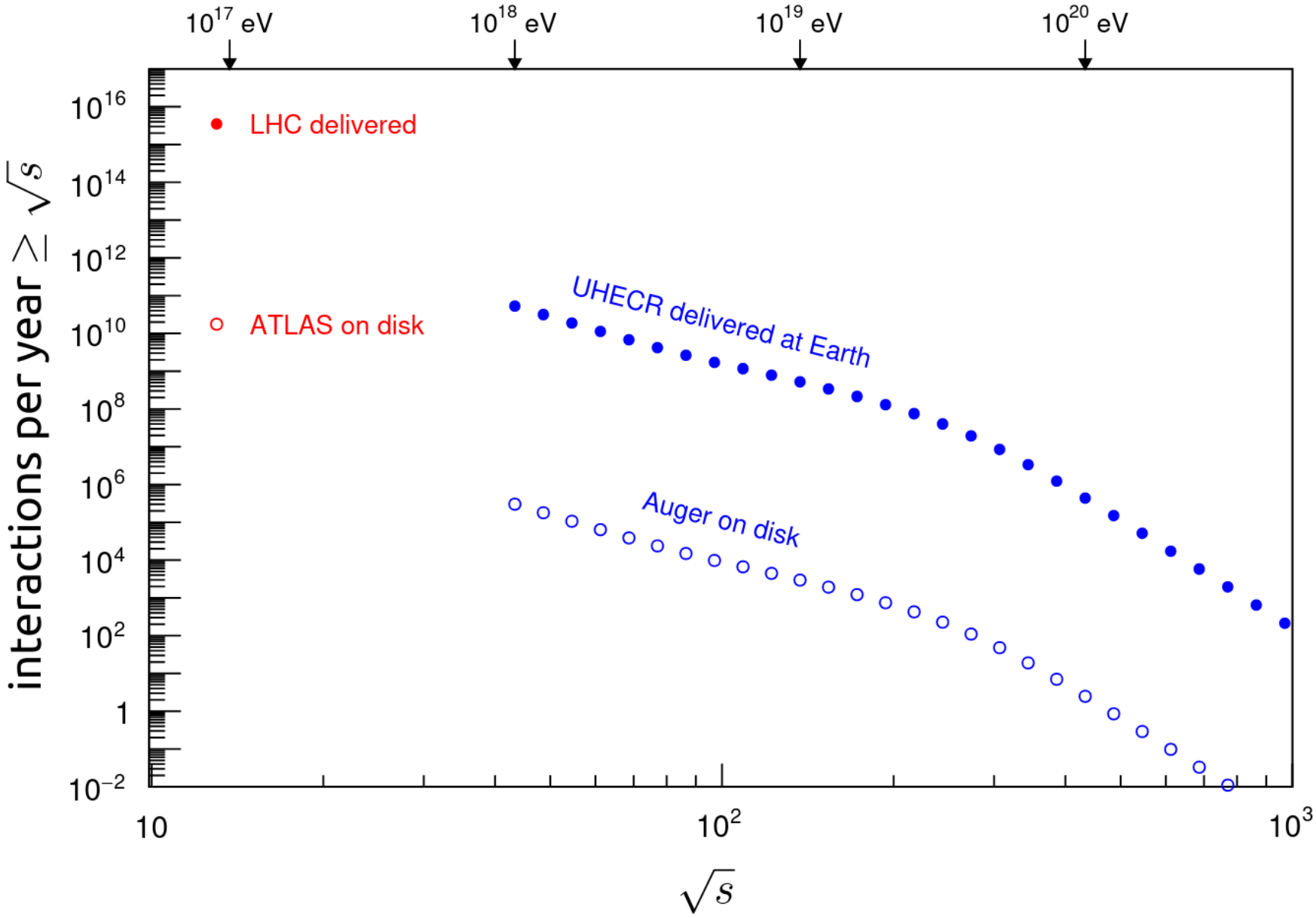
Auger



- ≤ 10^8 TeV beam, fixed-target
- √s ≤ 500 TeV
- 20 kt water-Cherenkov
- 25 Gt air calorimeter

from M. Unger

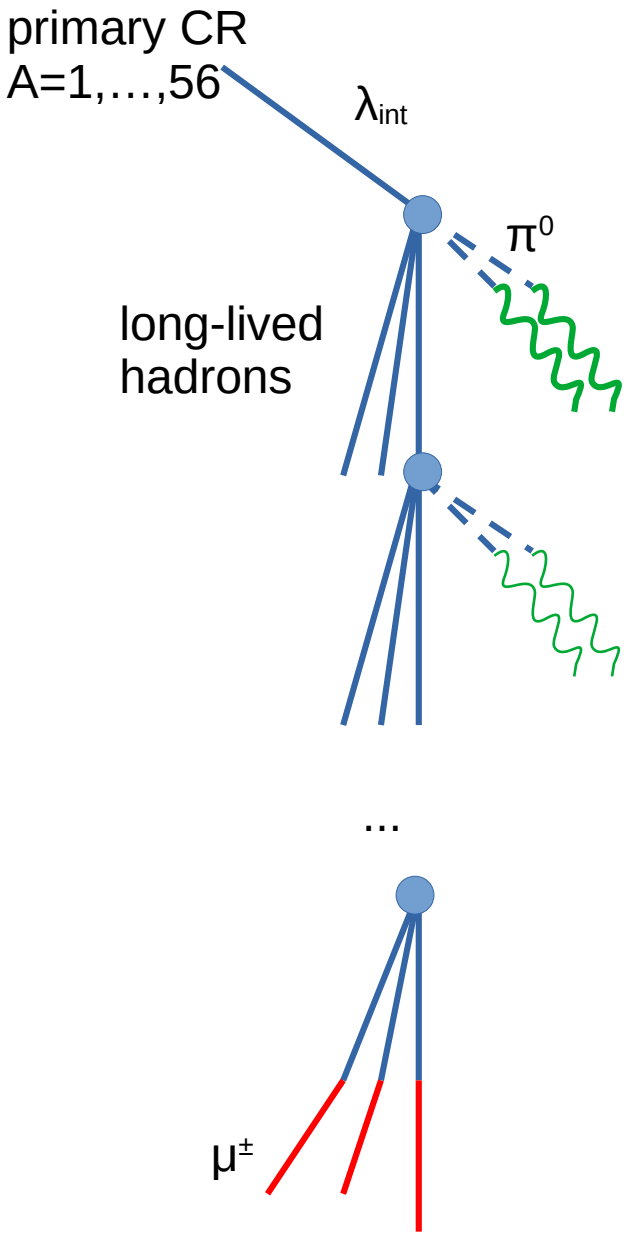
LHC/UHECR luminosity



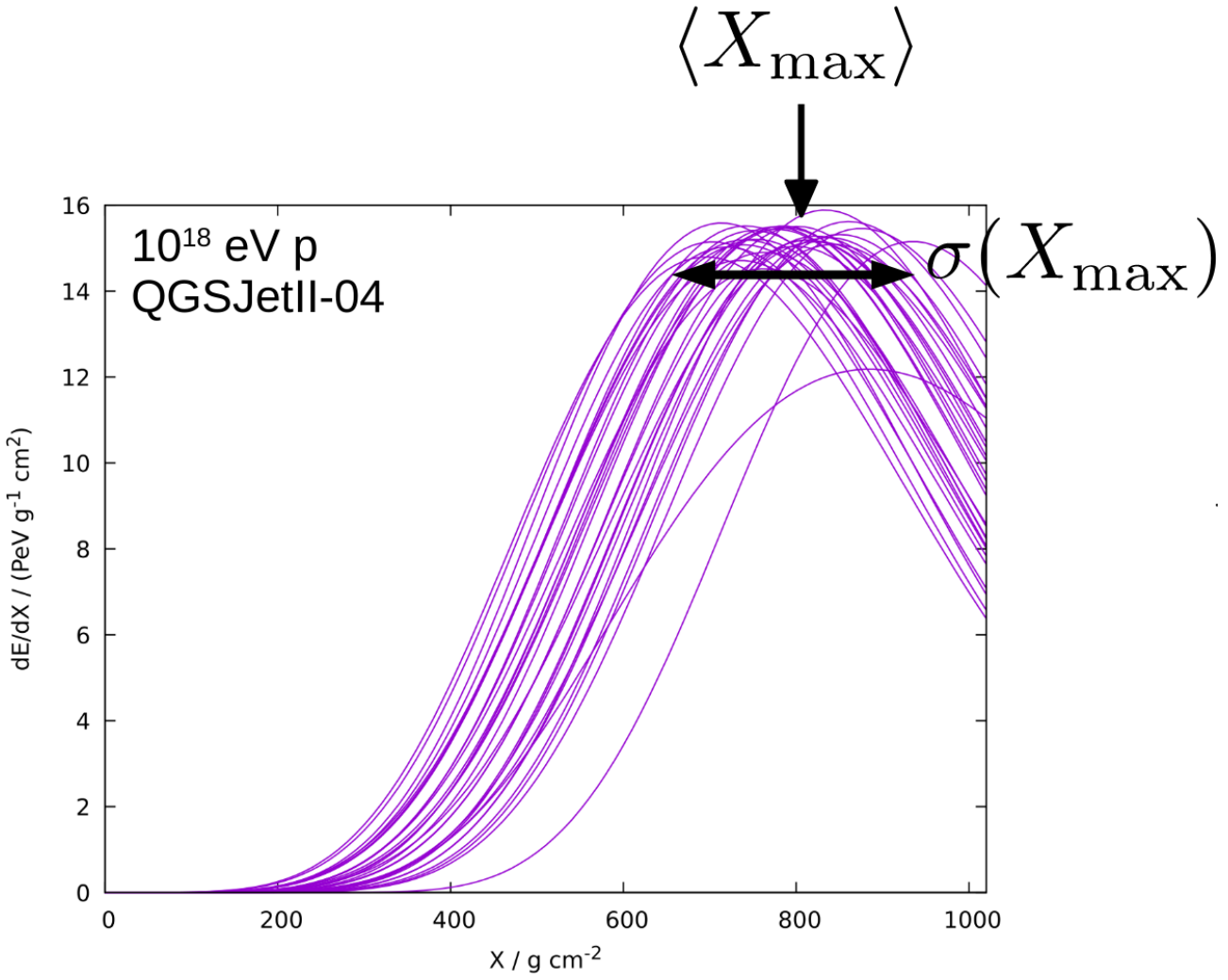
additional challenge: CR energy & species unknown a priori!

from M. Unger

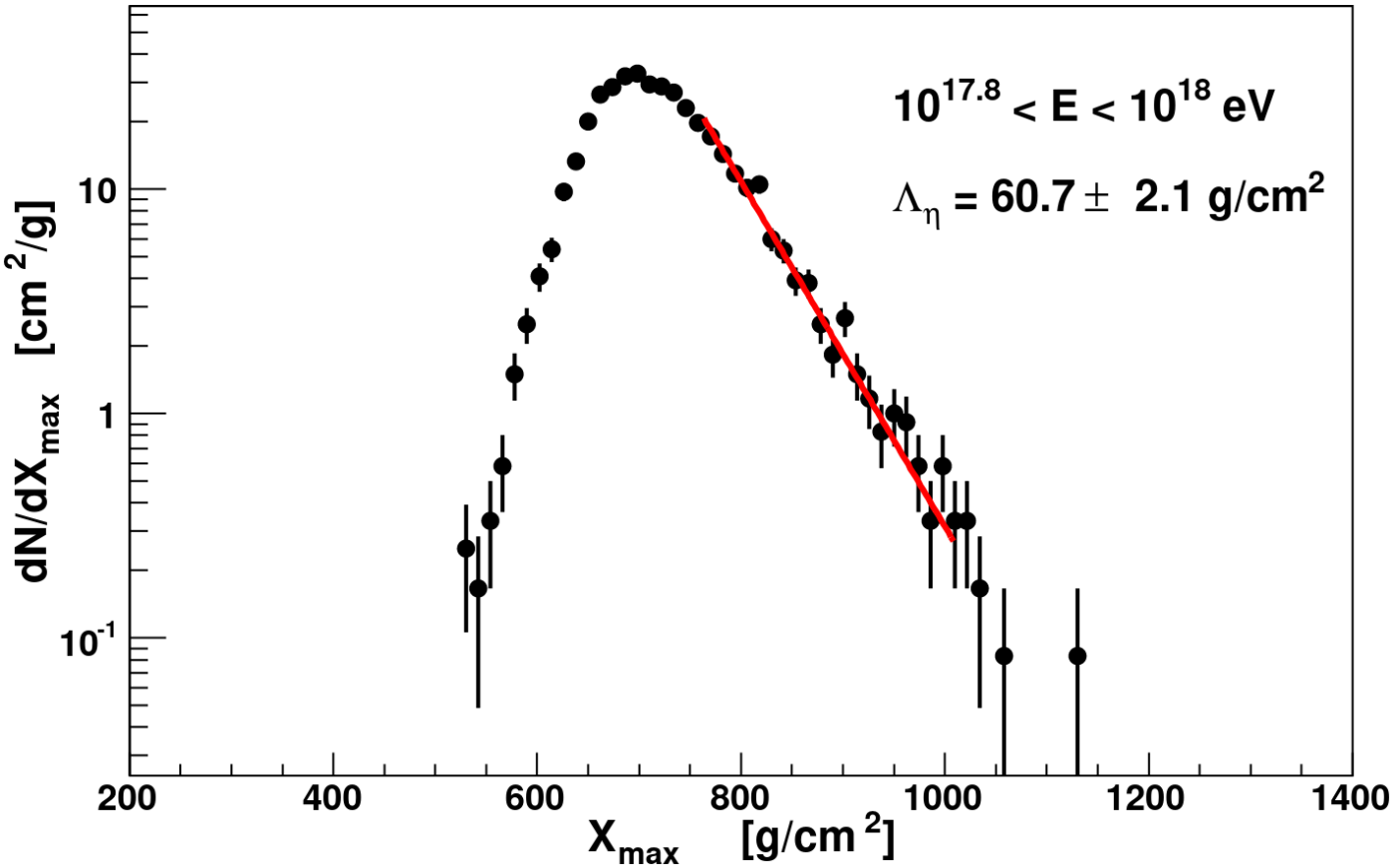
Air shower physics: EM component



- → EM shower, ~80-95 % of energy content
- sensitive to early (high-energy) interactions



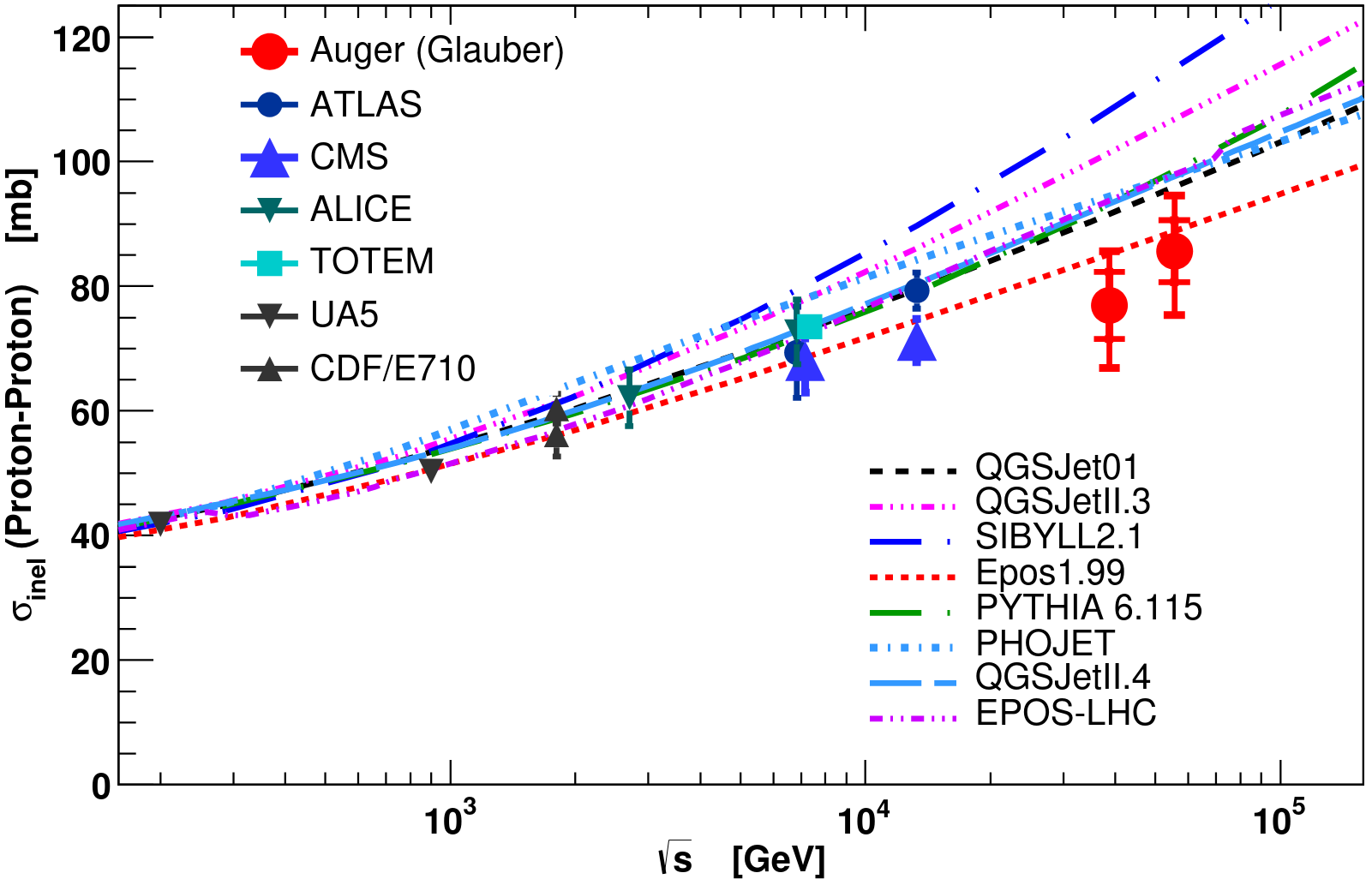
Inelastic p-Air & pp cross-section



1)cut to select deep showers (protons)
2)tail ~ exp(-X_{max} / Λ_η)
3)$\Lambda_\eta \leftrightarrow \sigma$(p-Air)
4)Glauber calculation to obtain σ(p-p)

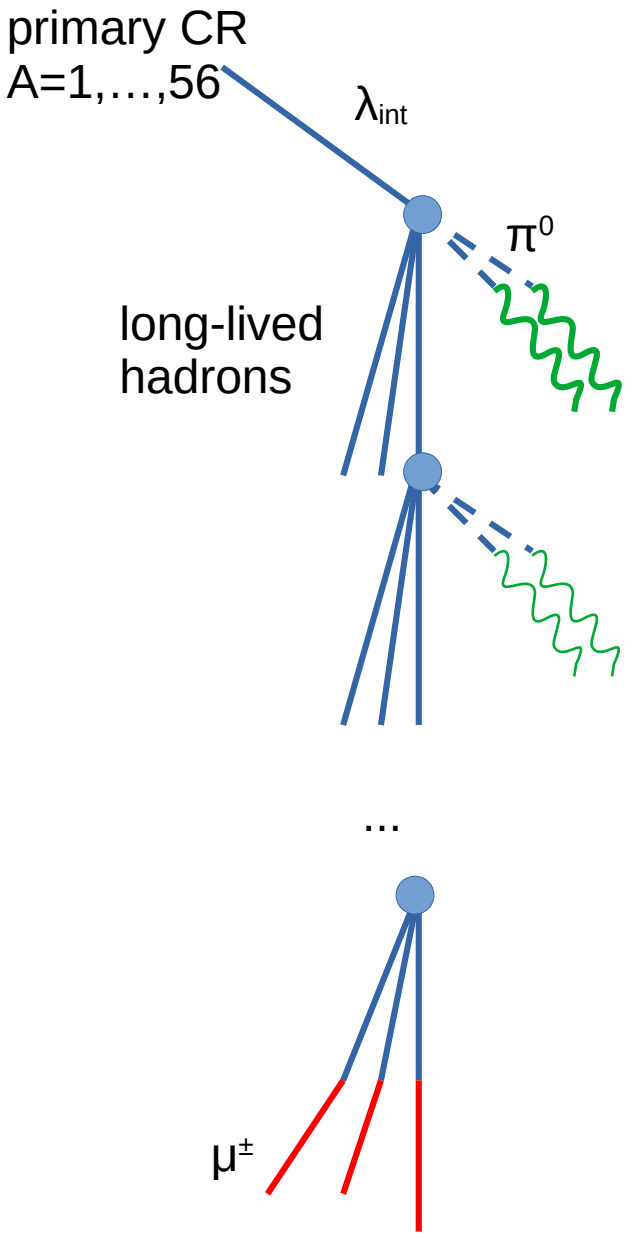
Pierre Auger Collaboration, PRL 109 (2012) 062002
R. Ulrich PoS ICRC2015 (2016) 401

Inelastic pp cross-section



cross-section measurement at $\sqrt{s}$ = 57 TeV

Air shower physics: muon component



toy model
assumptions:
- total (effective) hadron multiplicity *m*
- energy fraction of long-lived hadrons *α*

results:

$$N_\mu \sim A^{1-\beta} E_0^\beta$$

$$\beta = \frac{\ln(\alpha m)}{\ln(m)} \simeq 0.9$$

(see also Dariusz Góra's slides)

- note: small change δ*α* amplified by number of generations N_{gen} (5...10):

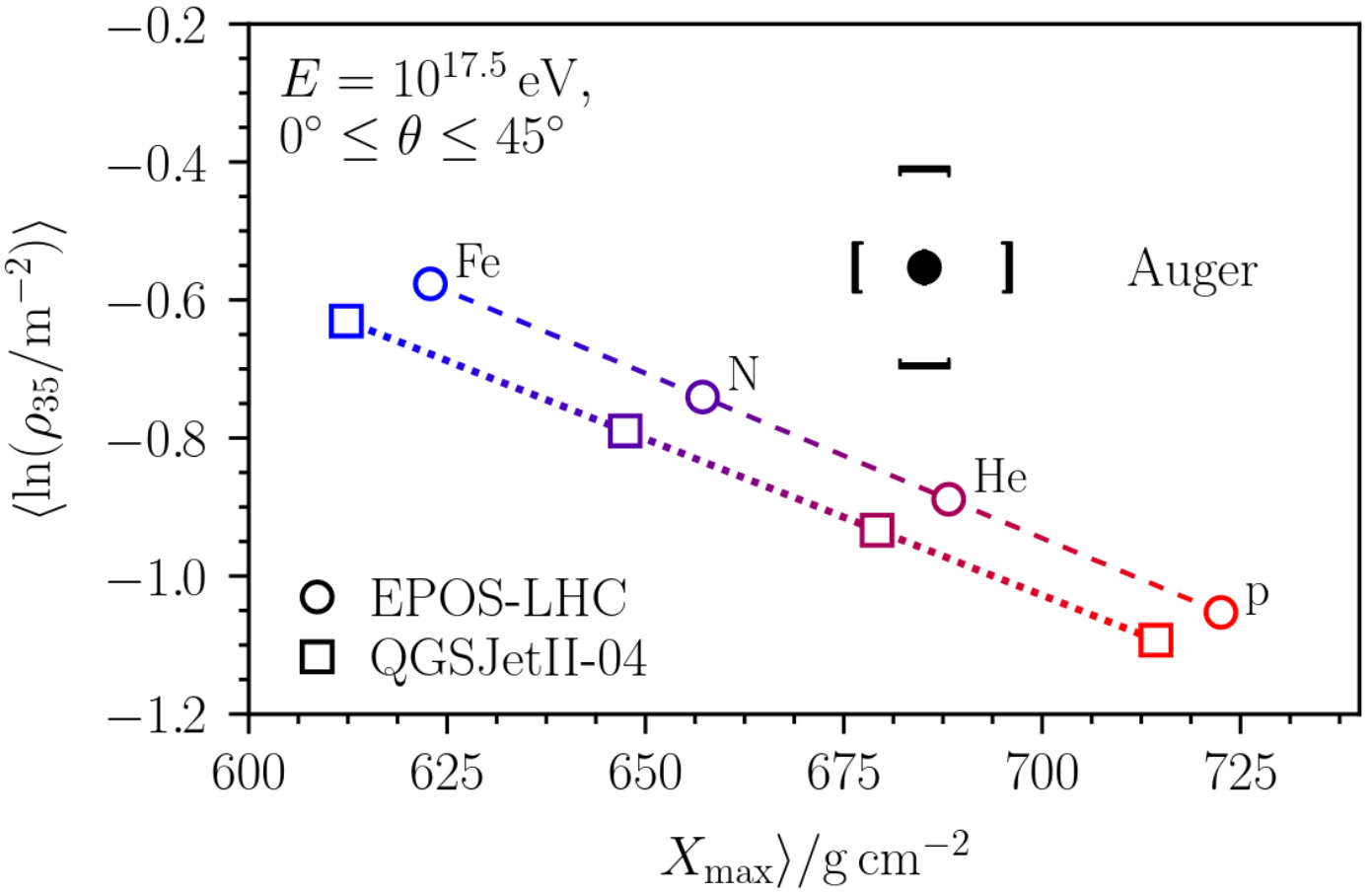
$$\frac{\delta N_\mu}{N_\mu} = N_{\mathrm{gen}} \frac{\delta\alpha}{\alpha}$$

- **muons sensitive to hadronic interactions from UHE to ~100 GeV**

J. Matthews, Astropart.Phys. 22 (2005) 387
J. Albrecht et al., Astrophys.Space Sci. 367 (2022) 3, 27

Muon measurements at Auger

see also Eva Santos' talk tomorrow afternoon

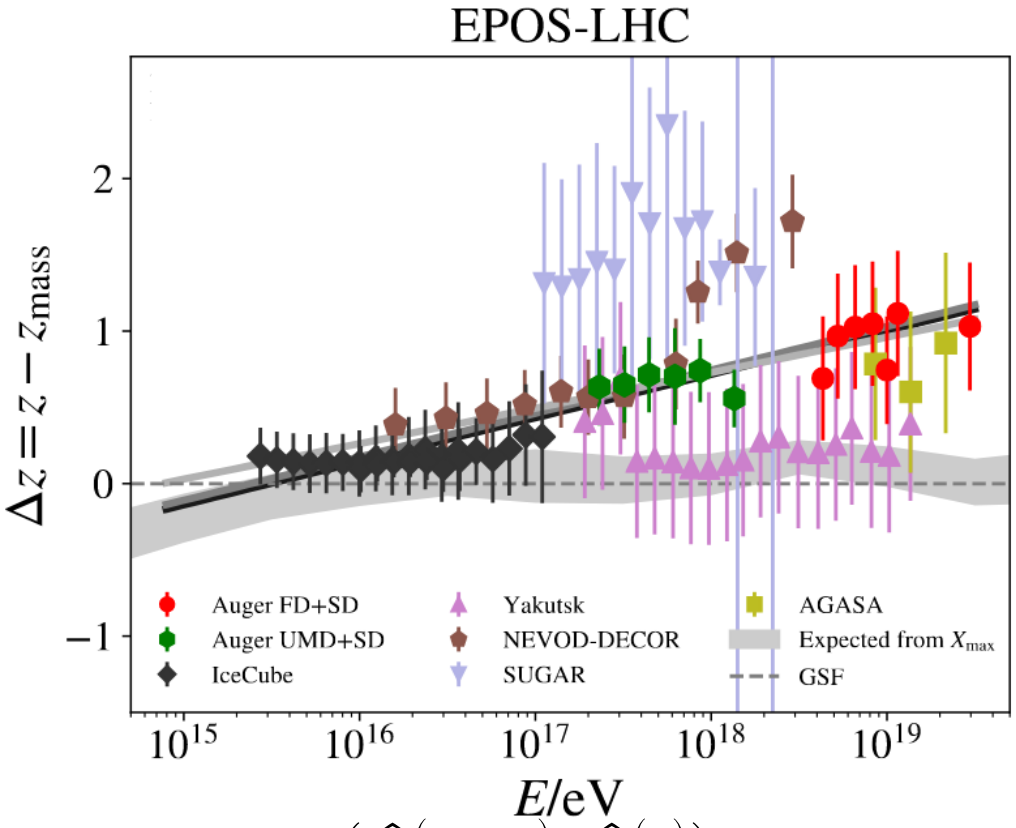


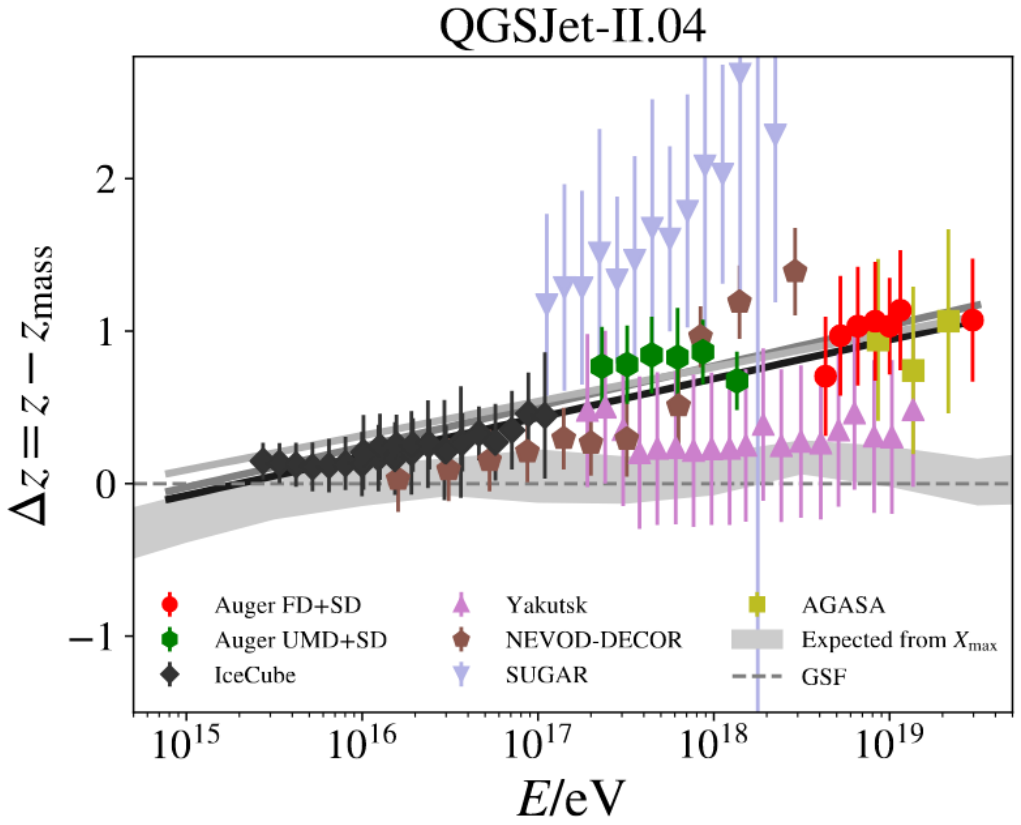
40 % deficit in models: "muon puzzle"
(X_{max} rather trustworthy)

Pierre Auger Collaboration, EPJC 80 (2020) 751

Meta-analysis

by **W**orking group on **H**adronic **I**nteractions and **S**hower **P**hysics





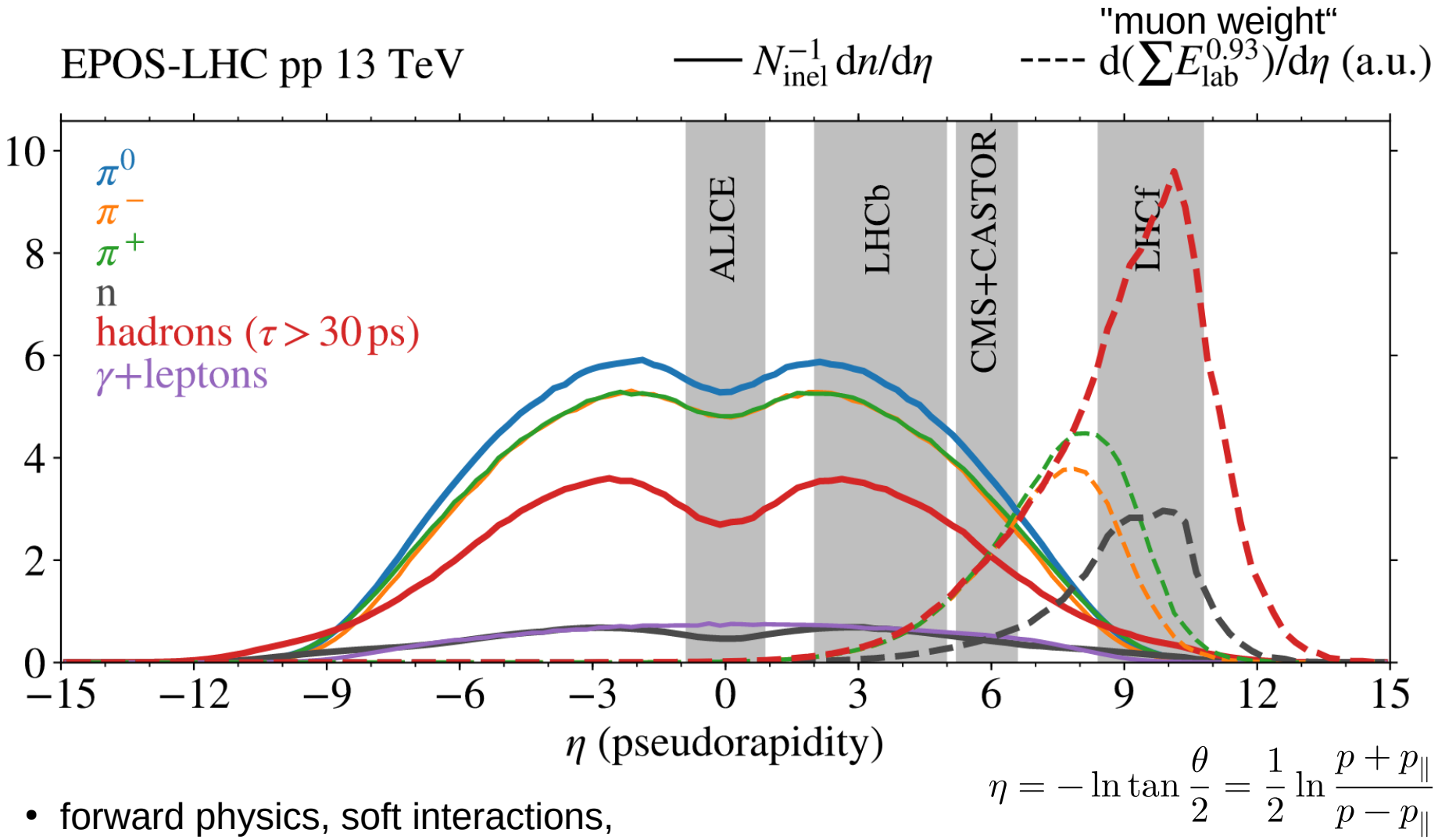
$$z = \frac{\log\left(\hat{N}_\mu^{(\mathrm{meas.})} / \hat{N}_\mu^{(\mathrm{p})}\right)}{\log\left(\hat{N}_\mu^{(\mathrm{Fe})} / \hat{N}_\mu^{(\mathrm{p})}\right)}$$

z_{mass} from flux model subtracted

- **linear fit with non-zero slope at >8 σ significance**
- **big issue in astroparticle physics**

D. Soldin, PoS(ICRC2021)349

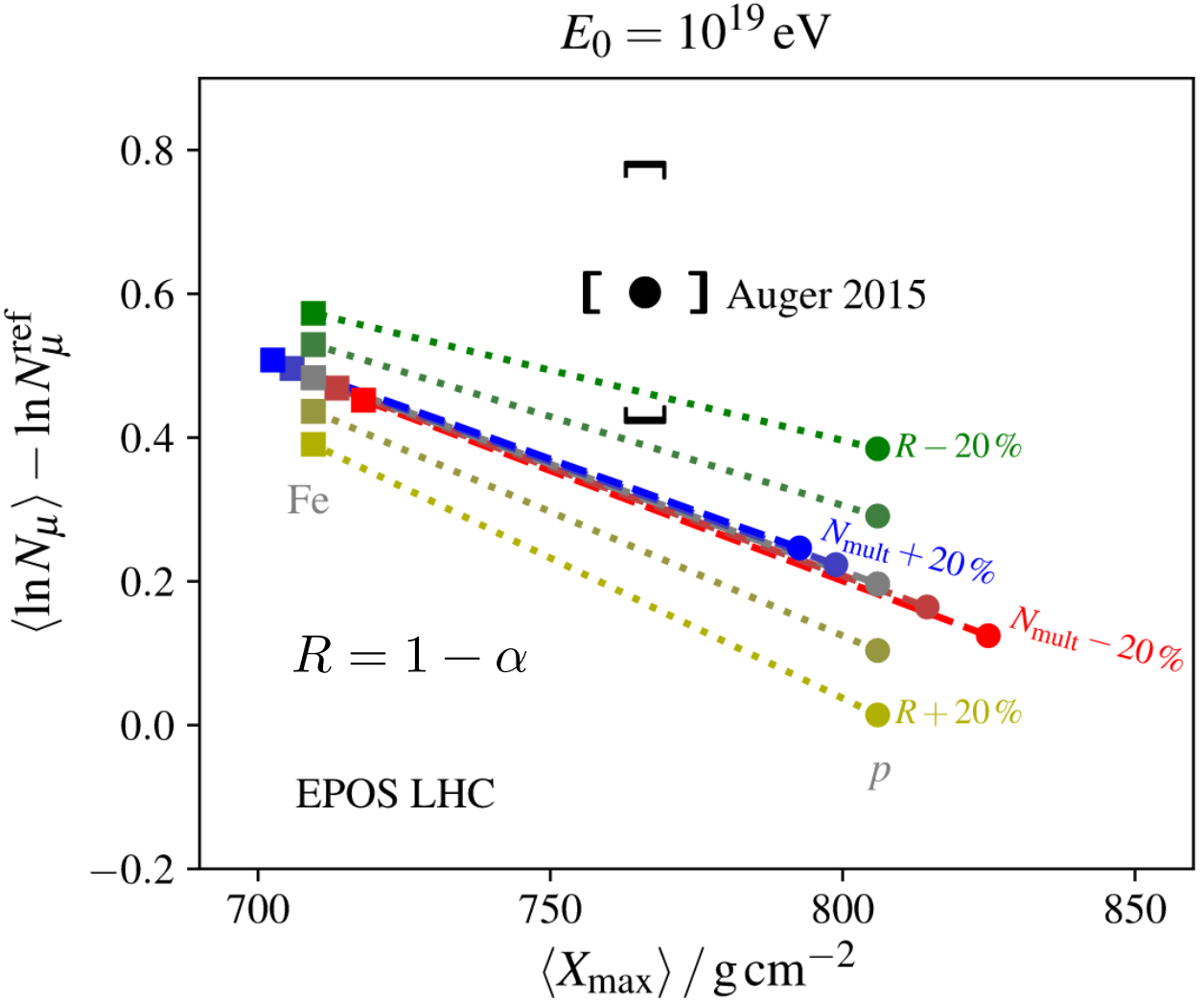
Relation to hadronic interactions



- forward physics, soft interactions, non-perturbative QCD
- hadronic interaction models rely on extrapolations
- dedicated LHC detectors provide valuable input

J. Albrecht et al., Astrophys.Space Sci. 367 (2022) 3, 27
MR, T. Pierog, R. Ulrich, 2108.03266

Impact of modified interactions

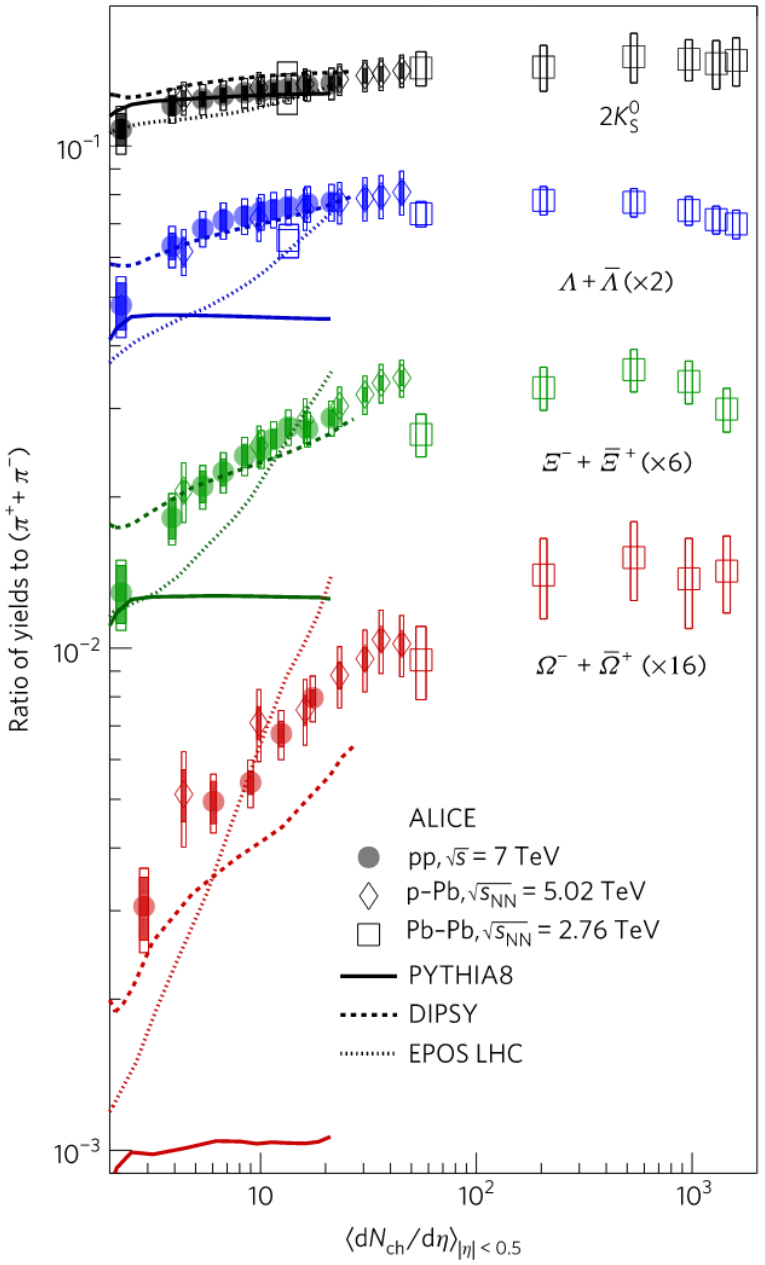


- ad hoc change of features
- gradually increase above threshold energy

- reduction of **π^0 energy fraction** very convenient to solve muon puzzle
- measure **hadron multiplicity** to improve X_{max} and N_μ predictions

Baur et al., 1902.09265

How to suppress π^0

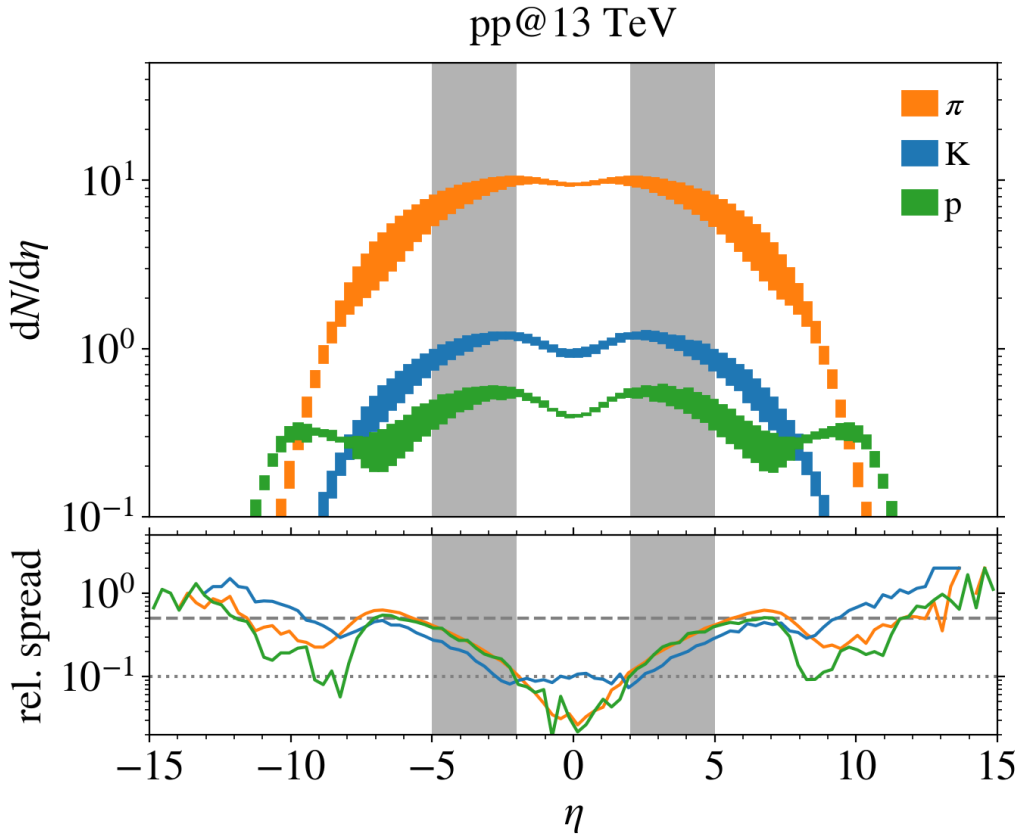


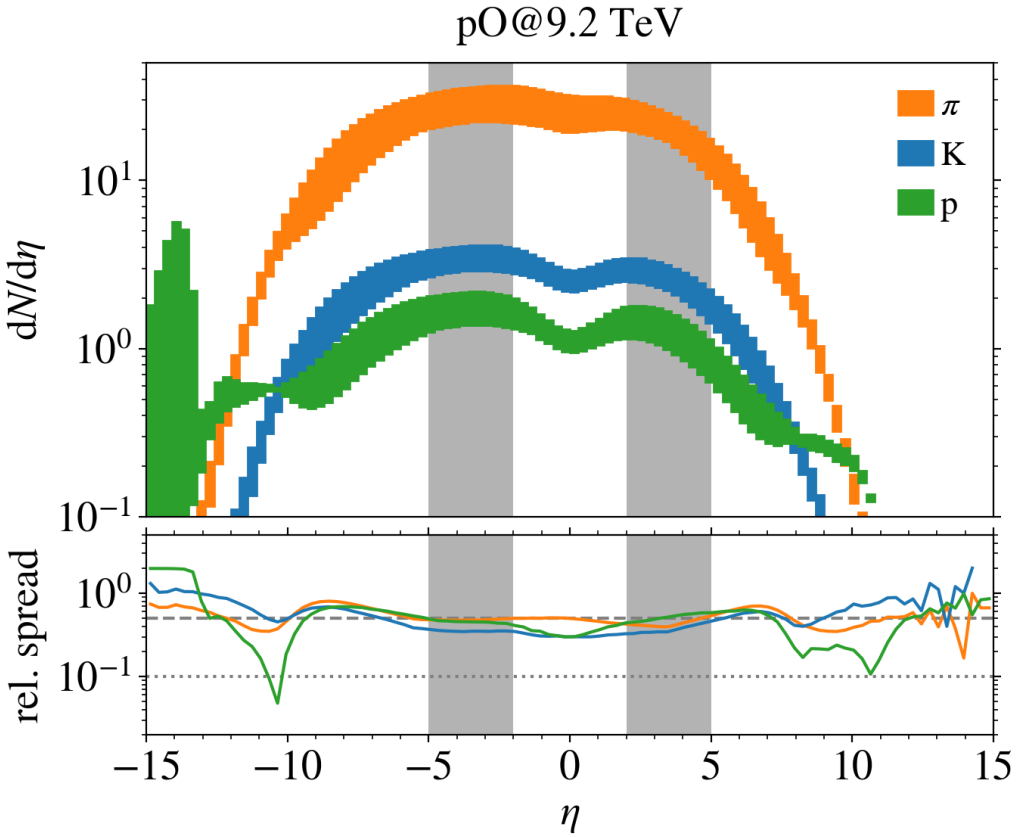
- $\pi^0/\pi^{\pm}$ ratio fixed, but π/hadron free
- reduction of π with collective effects, different hadronization
- strangeness enhancement observed at mid-rapidity in ALICE, independent of system size
- incorporation in interaction models
  - core-corona approach (EPOS)
  - string shoving, rope hadronization (PYTHIA)
  - strange fireball

ALICE, Nature Phys. 13 (2017) 535

Nuclear modification uncertainties

constrain first interaction!





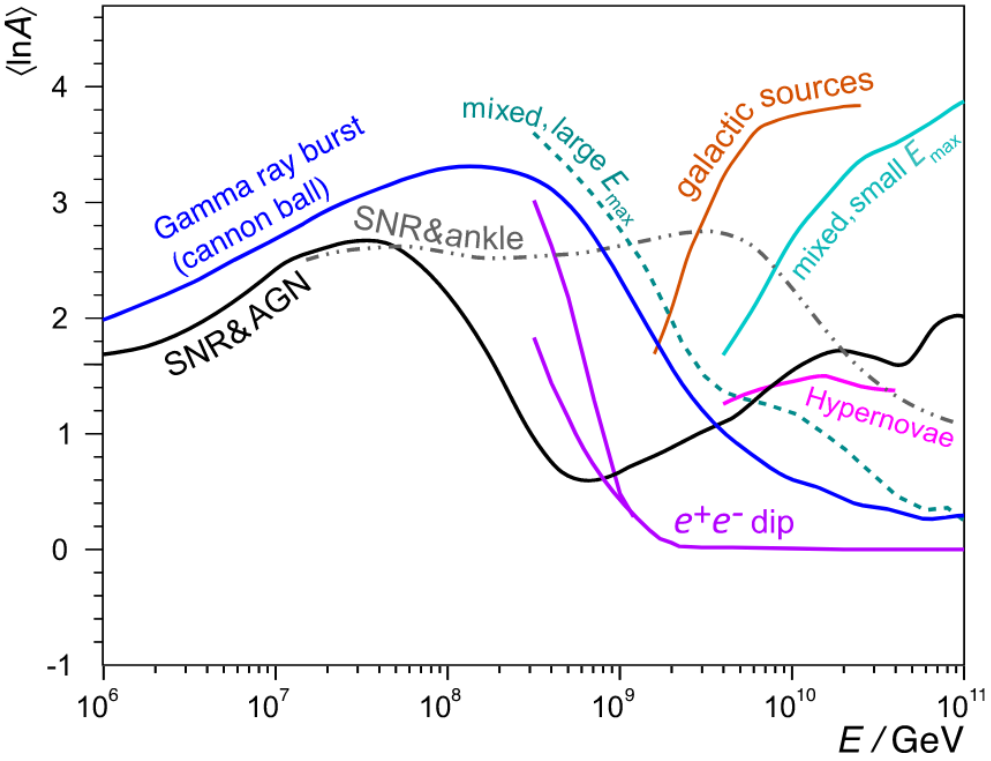
- spread between models (EPOS-LHC, QGSJet-II.04, SIBYLL-2.3)
- mostly tuned to pp data at |η| < 2
- variation in pp 10 %, in pO 50 %
- dedicated **pO run at LHC** planned, with LHCf still active

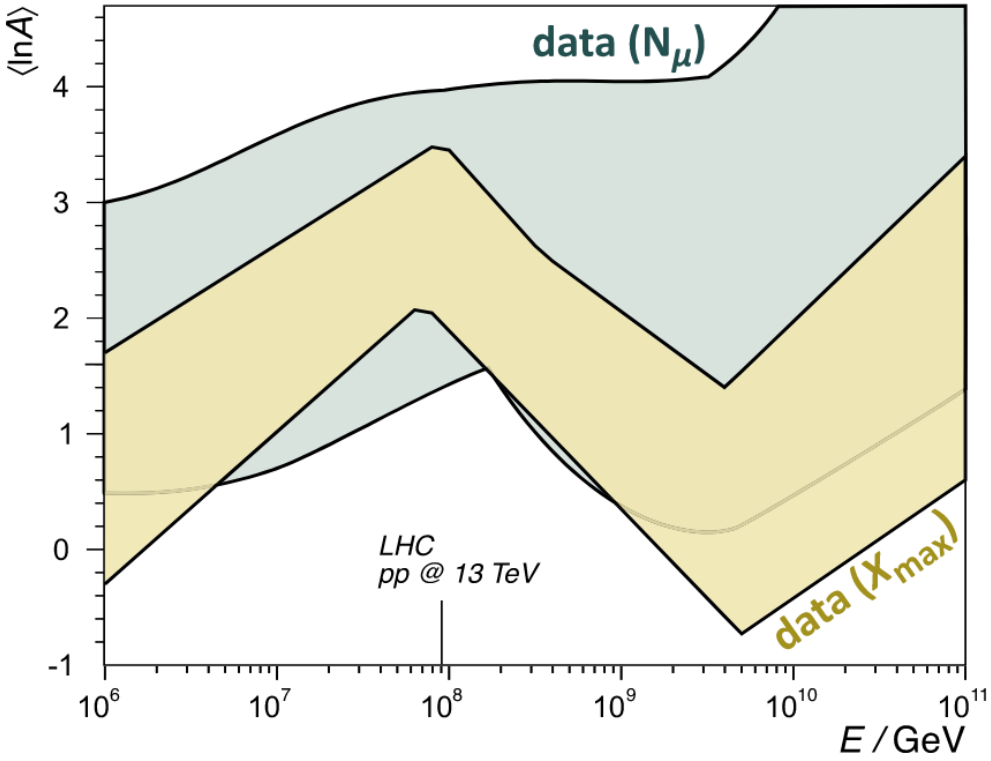
H. Dembinksi, R. Ulrich, T.Pierog, PoS(ICRC2019)235

Conclusions

- UHECR air showers probe phase-space difficult to access in accelerators
- solving *muon puzzle* imperative for astrophysics, provides new insight into hadronic interactions
- LHC provider of important input for model developers, dedicated measurements necessary
- **fruitful synergy between UHECR/ shower physics/LHC**

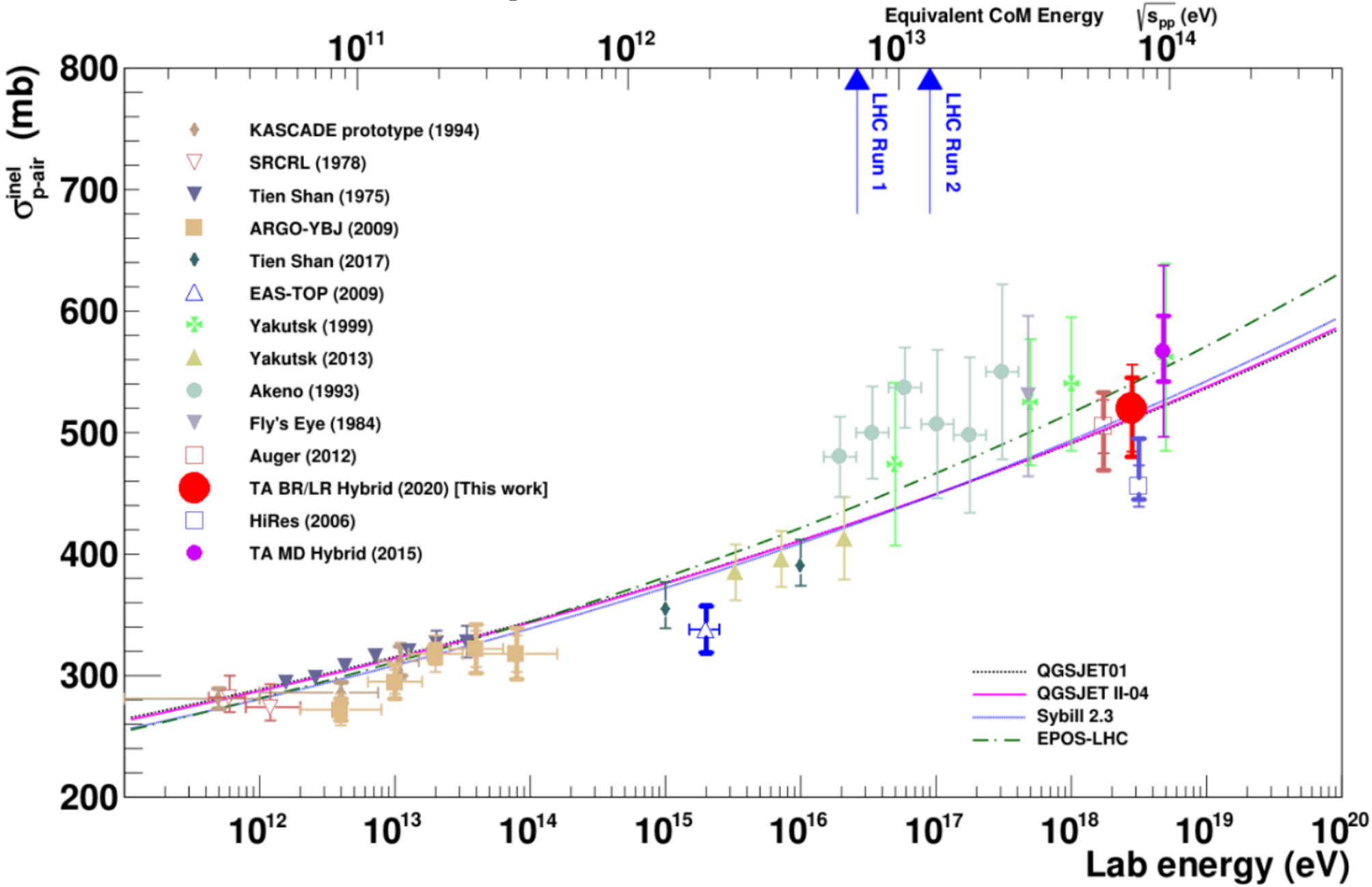
Backup slides





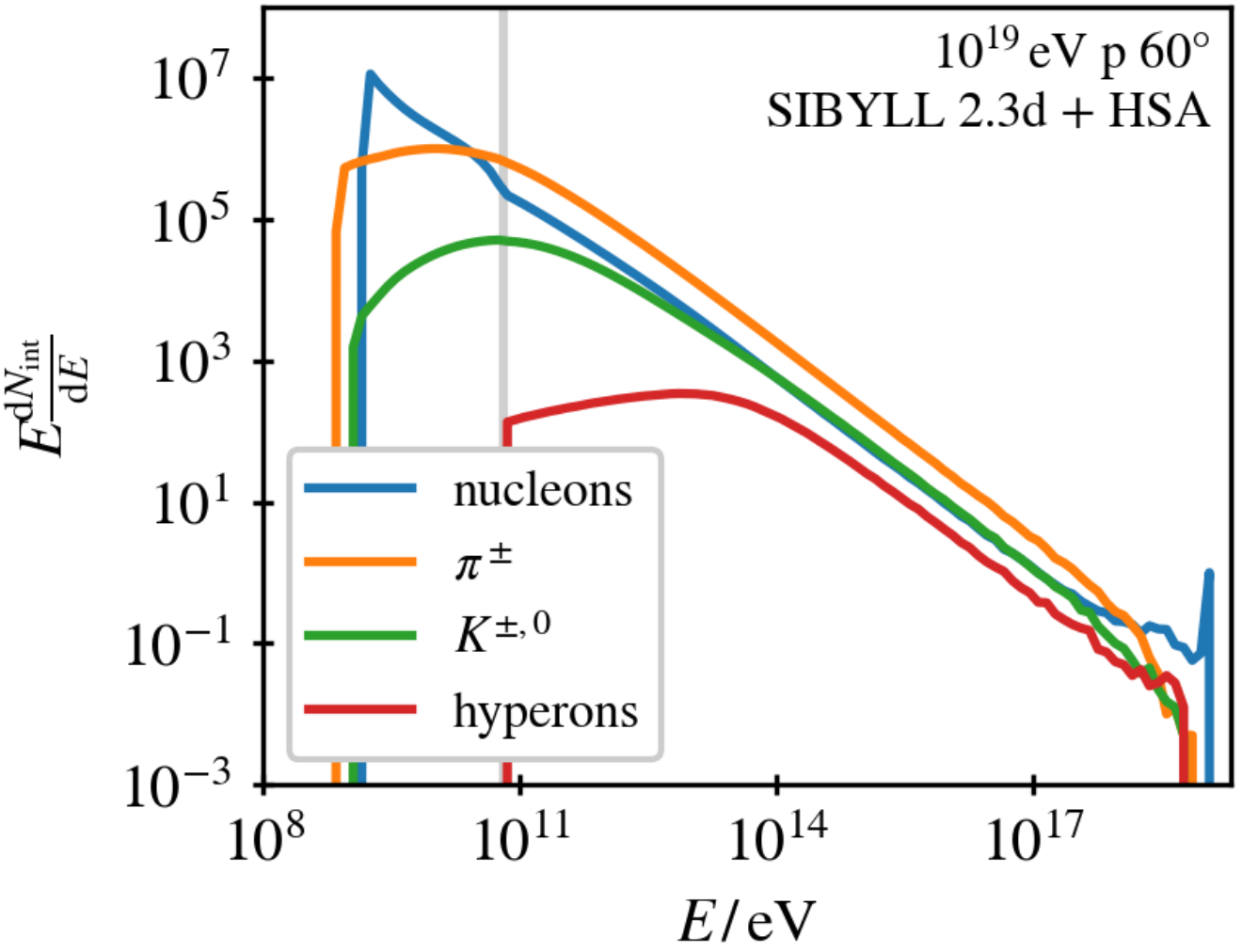
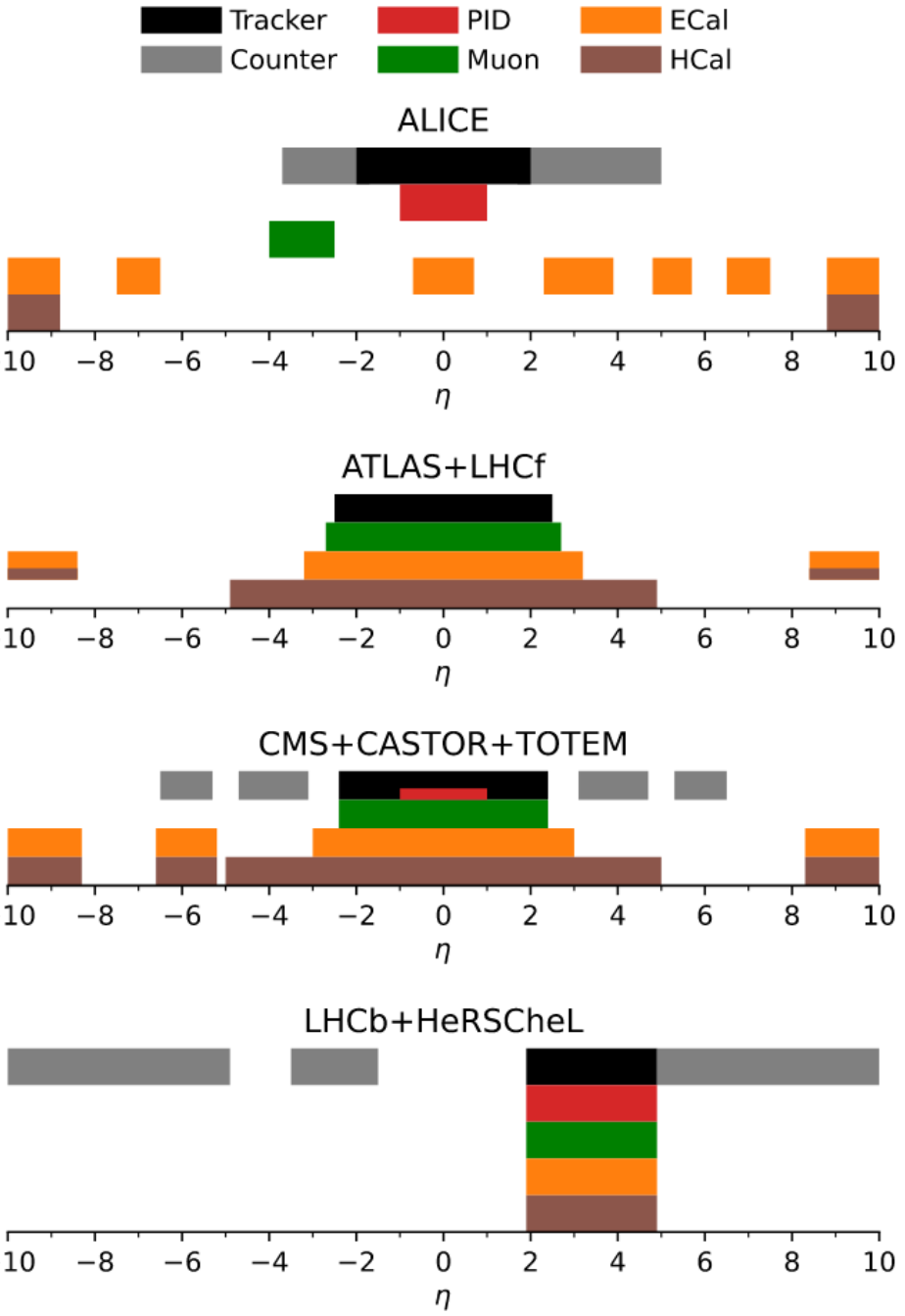
K.-H. Kampert, M.Unger,Astropart. Phys. 35 (2012) 660

Inelastic p-Air cross-section



Telescope Array Collaboration, PRD 102 (2020) 062004

"interaction spectrum"



LHC detector acceptances