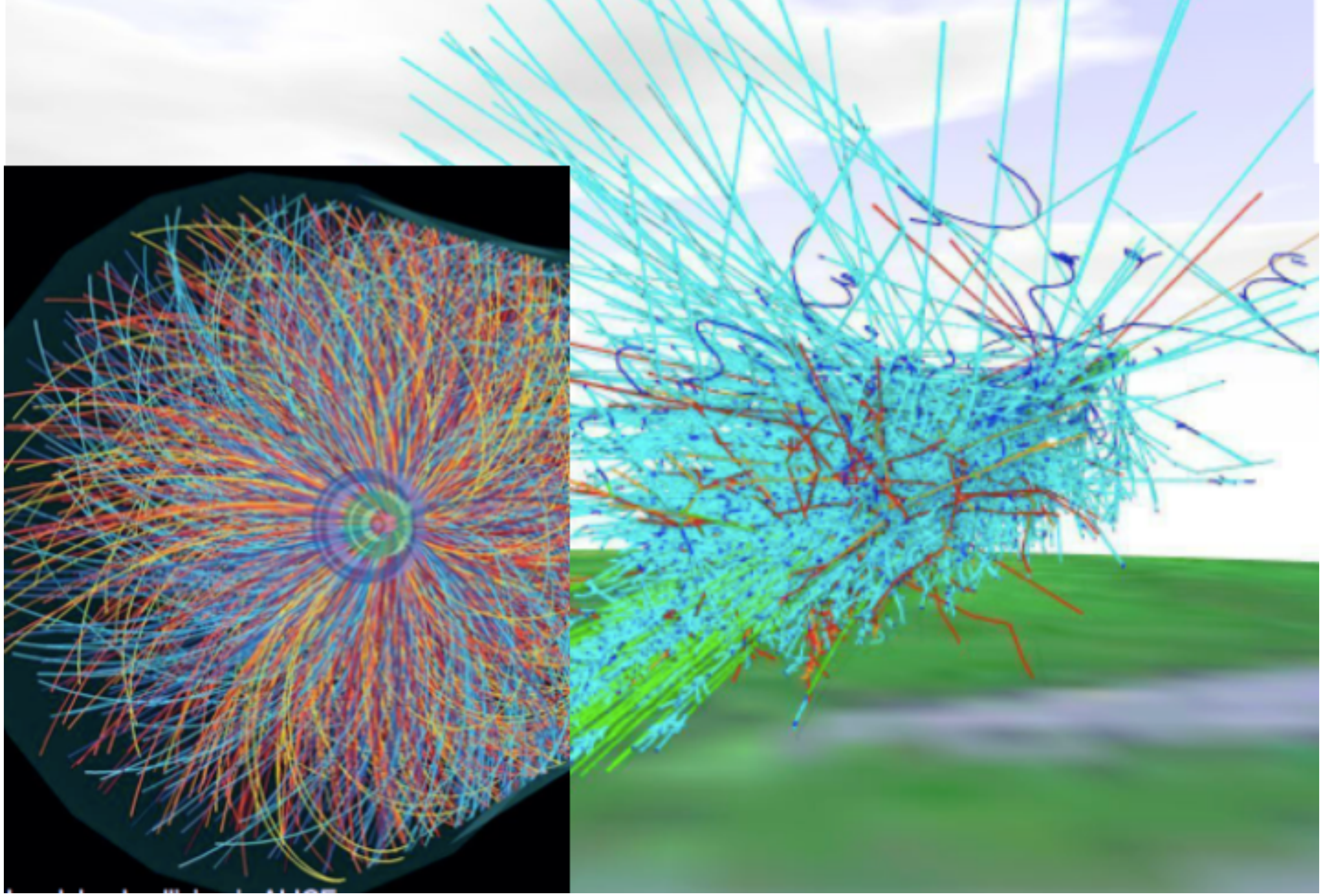


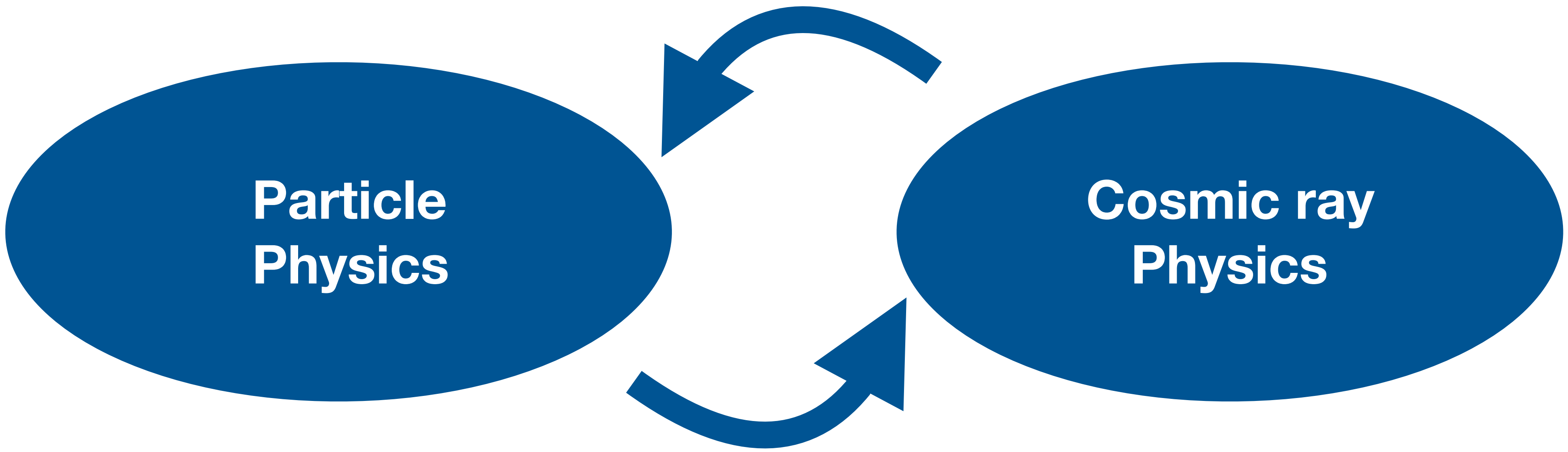
Particle physics with air showers at the highest energies

Antonella Castellina

Osservatorio Astrofisico di Torino, INAF & INFN

4th Uppsala Workshop PPNT19, 7-9 October 2019

Take home message



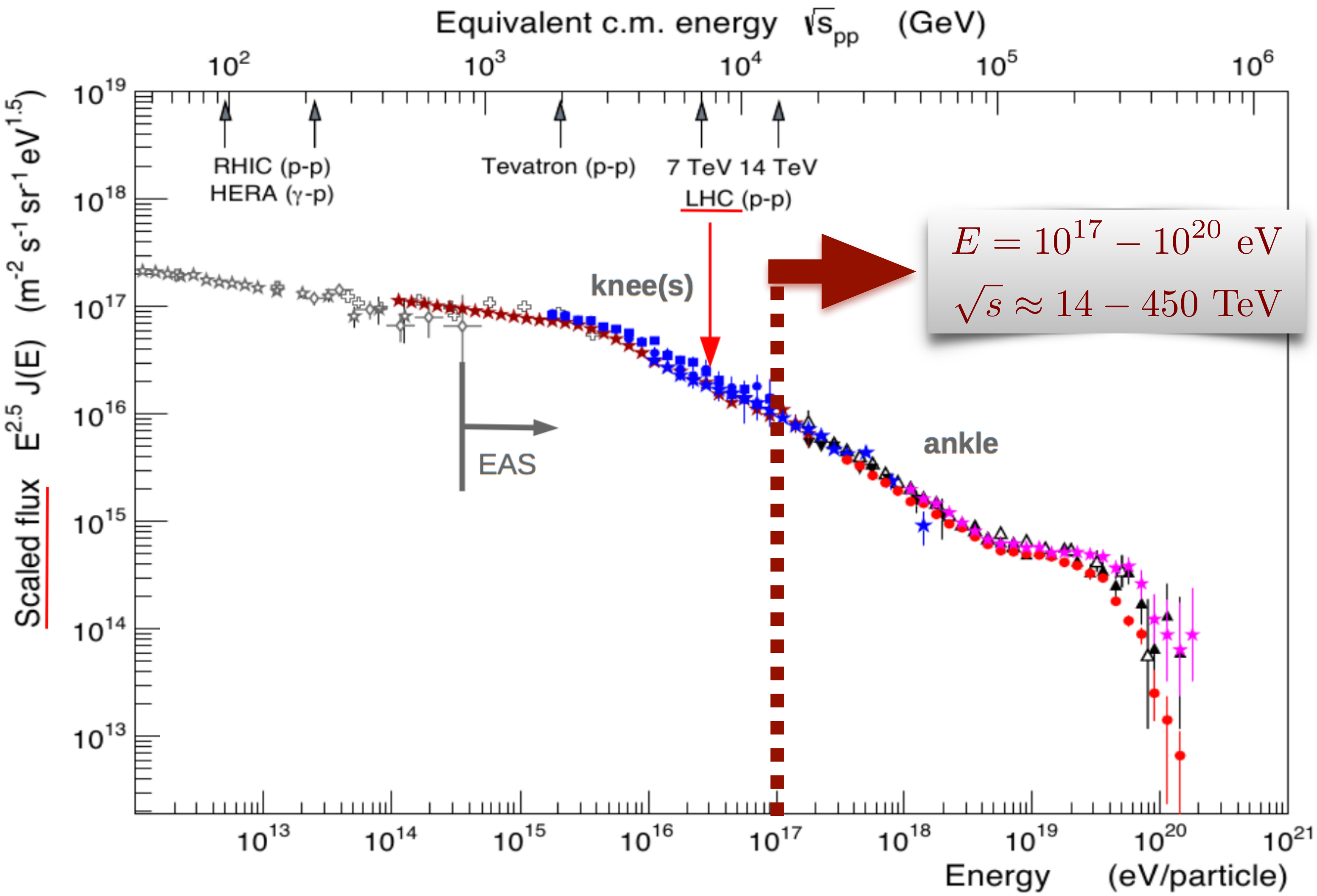
There is a strong correlation between CR physics and particle physics

➡ LHC tuning of hadronic interaction models employed in UHECR are needed to lower the systematic uncertainties on composition measurements

➡ contribution/constraints to the determination of hadronic interaction properties can be provided by Astroparticle Physics measurements in a very different energetic and kinematic phase space, for targets with <A>~14

➡ BSM searches at UHE can be performed exploiting Extensive Air Shower Arrays

CR flux and interaction energies

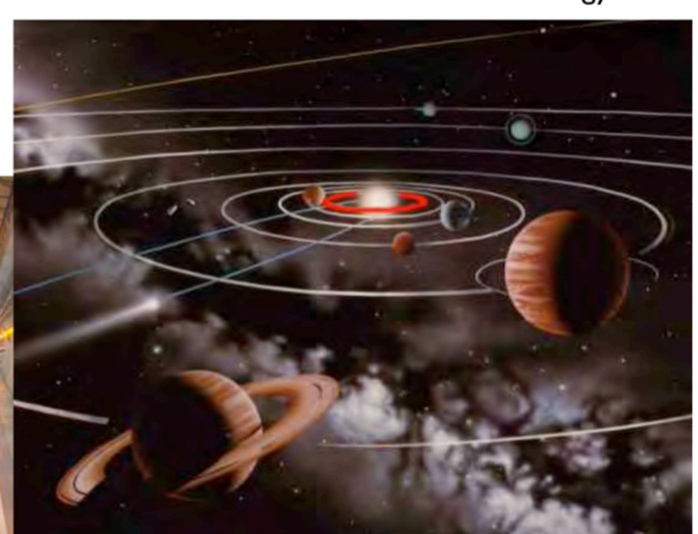


$E = 10^{17} - 10^{20}$ eV

$\sqrt{s} \approx 14 - 450$ TeV

to reach 10^{20} eV with current technology

Large Hadron Collider (LHC), 27 km circumference, superconducting magnets



(M. Unger, 2006)

ASTROPHYSICS

- ✓ where is the transition between a Galactic and an extra-Galactic origin of UHECRs?
- ✓ what is causing the suppression of the flux at the highest energies?
- ✓ can we perform UHECRs astronomy?

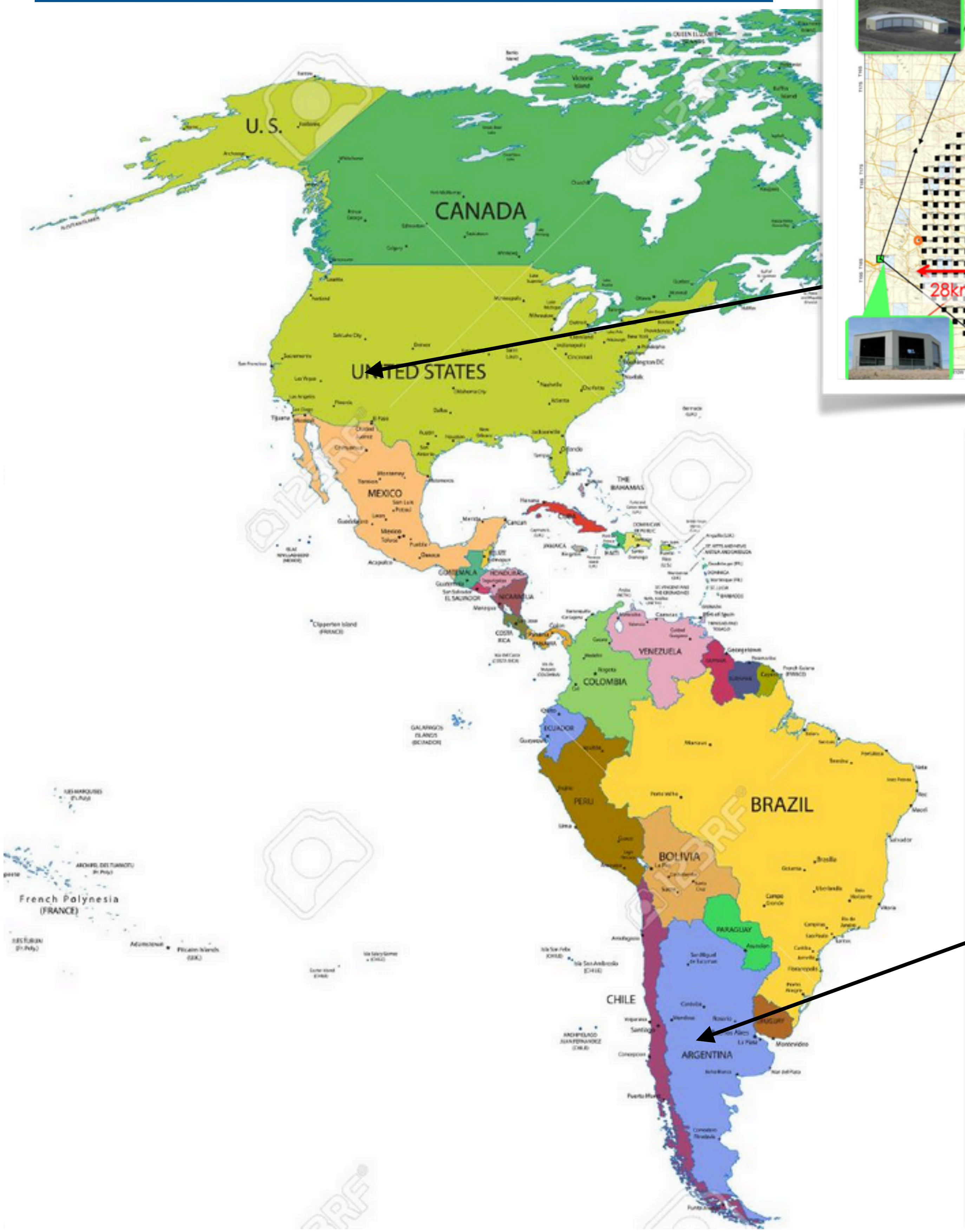
need for precise composition measurements

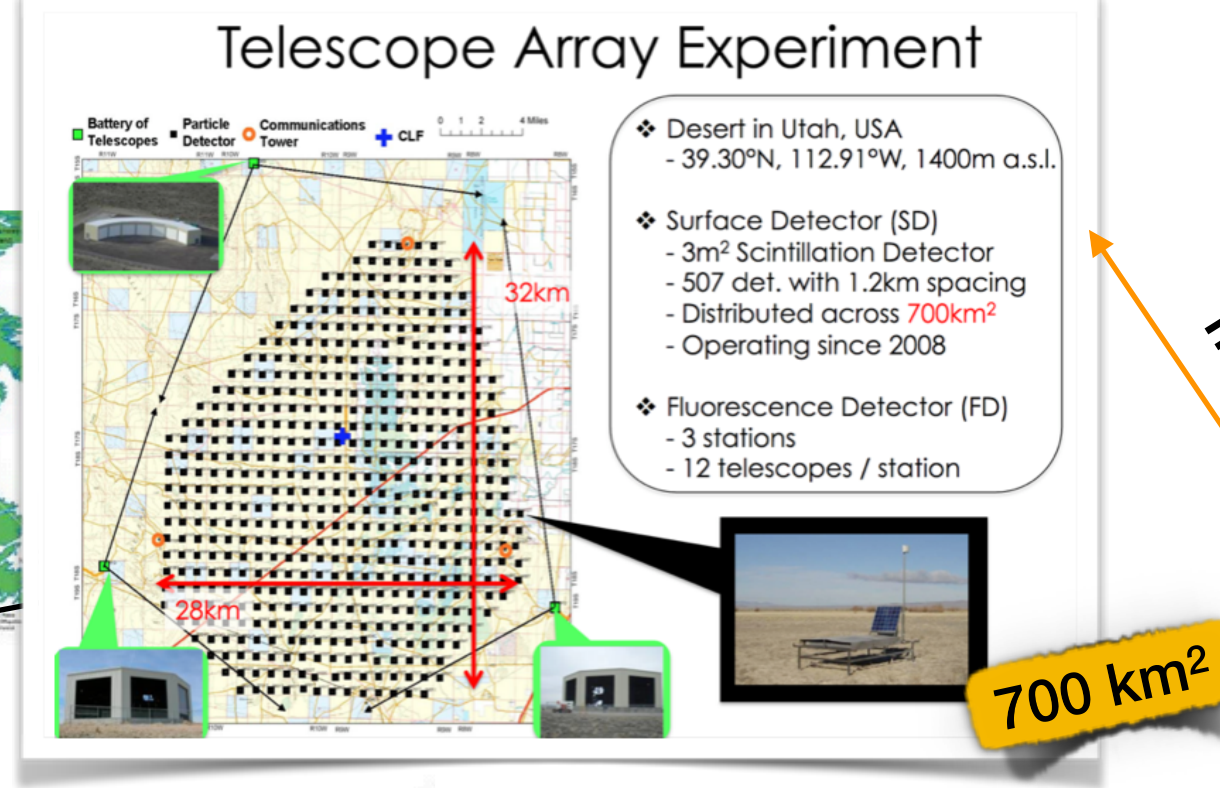
PARTICLE PHYSICS

- ✓ energy range >30 times larger that LHC
- ✓ very forward kinematic region
- ✓ p-nucleus or nucleus-nucleus interactions

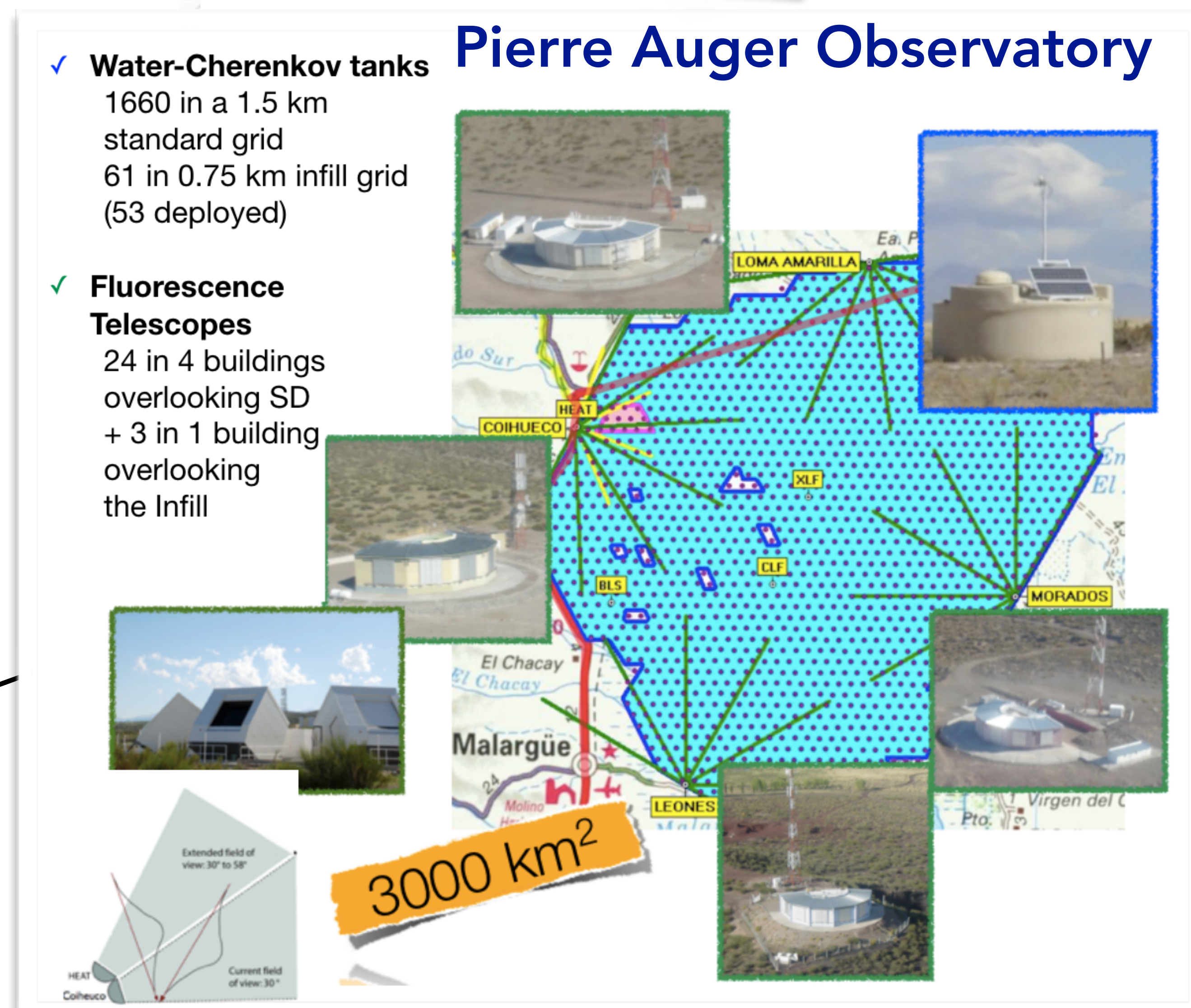
Tests of fundamental interactions and their models

UHECR detectors





not in scale !

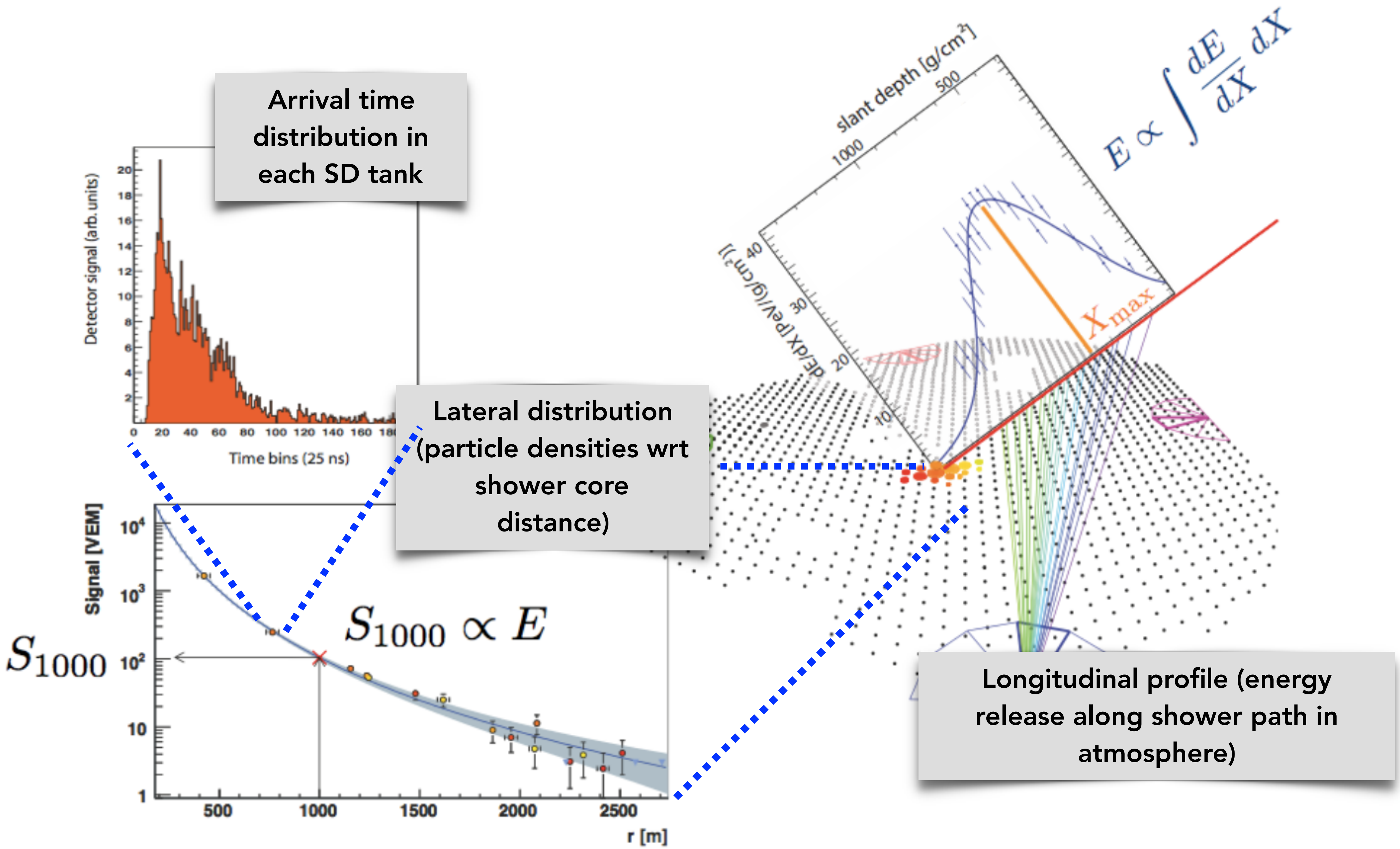


The shower observables

In a hybrid detector we can perform precision measurements of the shower observables

100% duty cycle for the Surface Detector

~15% duty cycle for the Fluorescence Detector



Energy calibration at Auger

$$E_{Cal} = \int_0^\infty dX \, \frac{dE}{dX}$$

$$E_{Tot} = E_{Cal} + E_{Inv}$$

ENERGY

calorimetric energy measurement with fluorescence telescopes

Invisible energy evaluated from dat, as $E_{inv} \propto N_\mu$

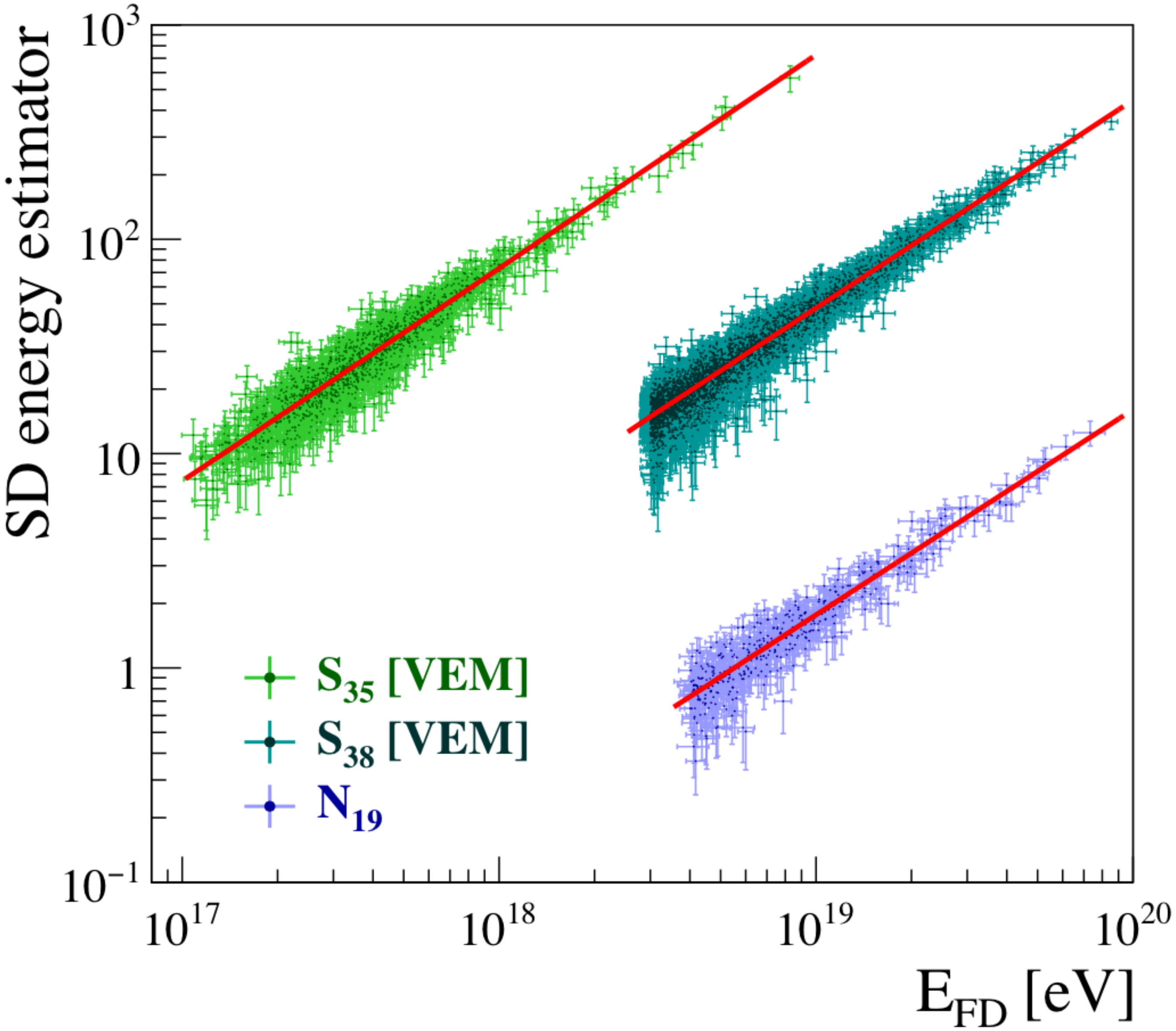
$\sigma(E_{FD})/E_{FD}$ ~ 8%
Systematic uncertainty 14%

CALIBRATION

provided by the correlation of SD energy estimator (S_{38}) with E_{FD}

$\sigma(E_{SD})/E_{SD}$ ~ 20% at 10^{18} eV
~ 7% above 2 10^{19} eV

data driven

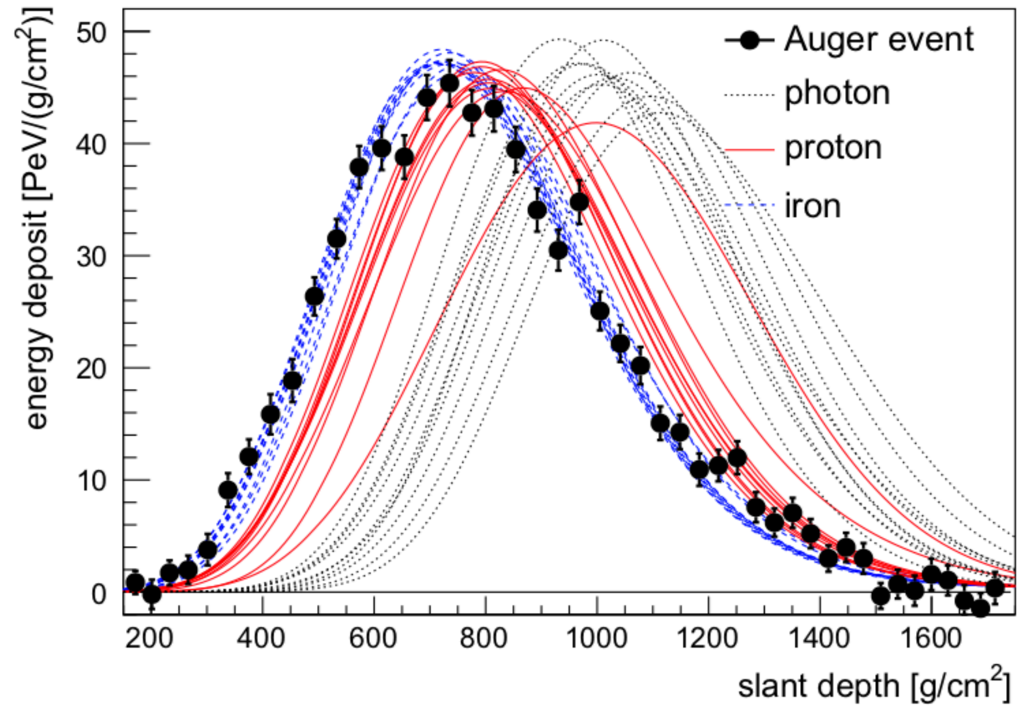


Composition-related observables

Distribution of X_{max}

$$\langle X_{max} \rangle = \langle X^p_{max} \rangle + f_E \langle lnA \rangle$$

$$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f_E \sigma^2_{lnA}$$



X_{max} resolution from 25 to 15 g cm^{-2} for increasing E

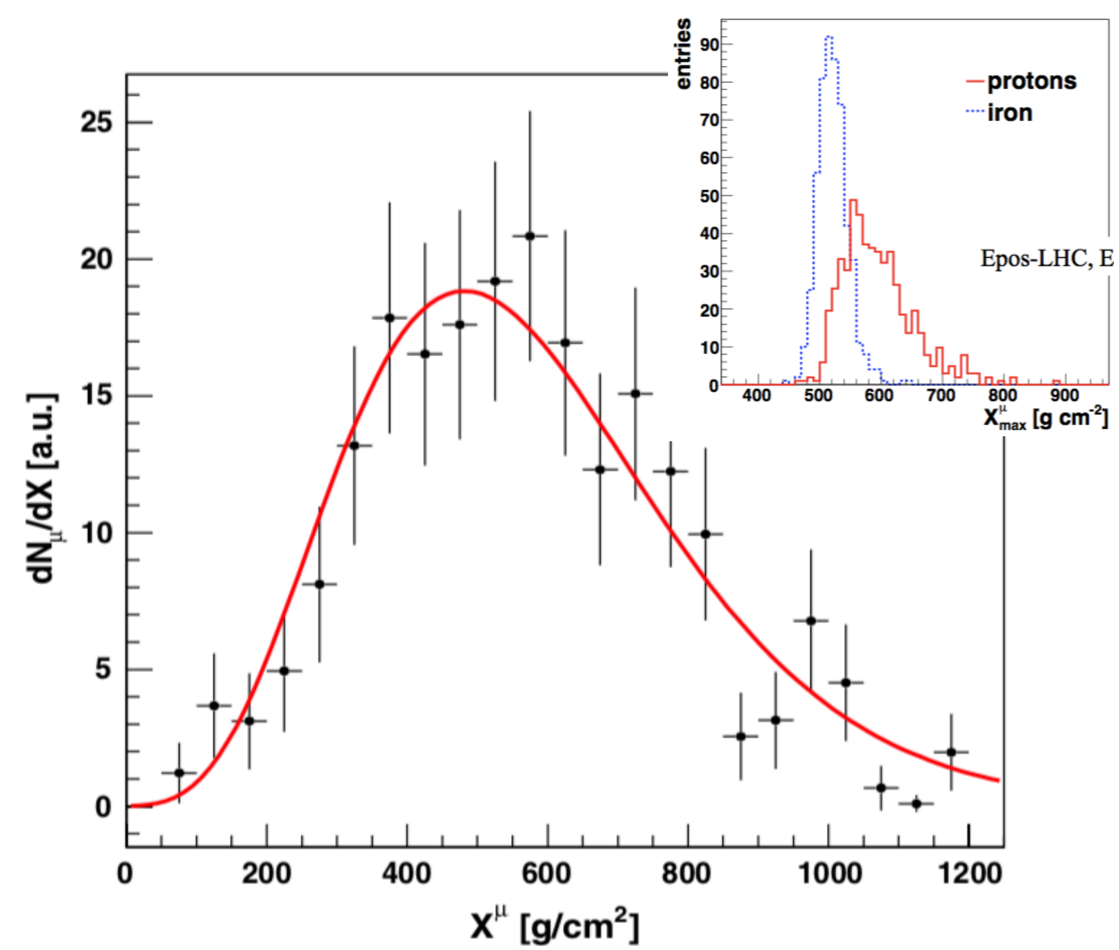
$\boldsymbol{\sigma}_{sys} \leq$ 10 g cm^{-2}

Separation between p and Fe showers ~ 100 g cm^{-2}

Muons: N_μ, muon production depth (X^μ_{max})

$$N^p_\mu \approx \left(\frac{E}{\varepsilon^\pi_d}\right)^\beta$$

$$N^A_\mu \approx A\left(\frac{E/A}{\varepsilon^\pi_d}\right)^\beta = N^p_{\mu,\max} A^{1-\beta}.$$

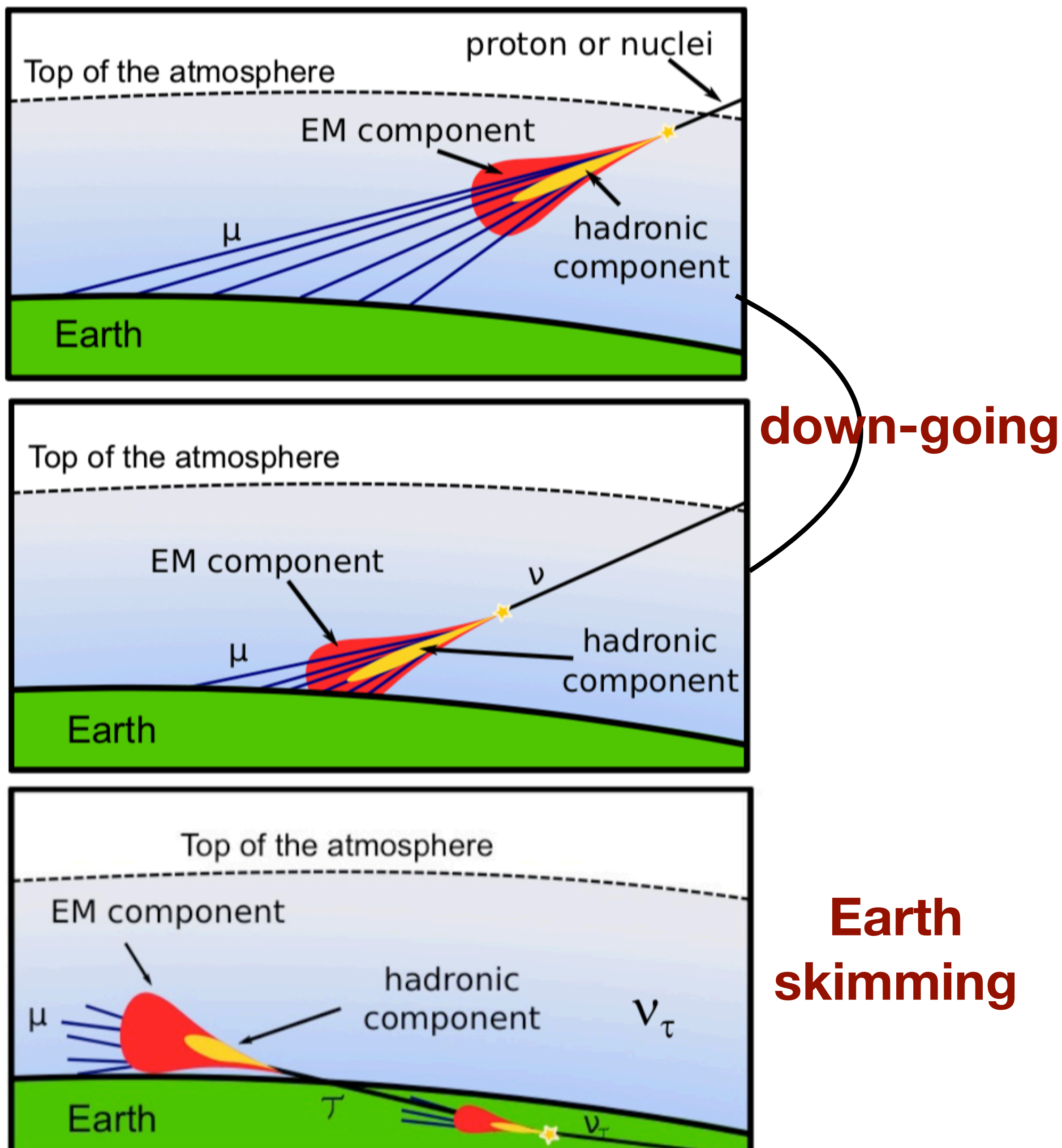


information about mass is model dependent

Neutral primaries

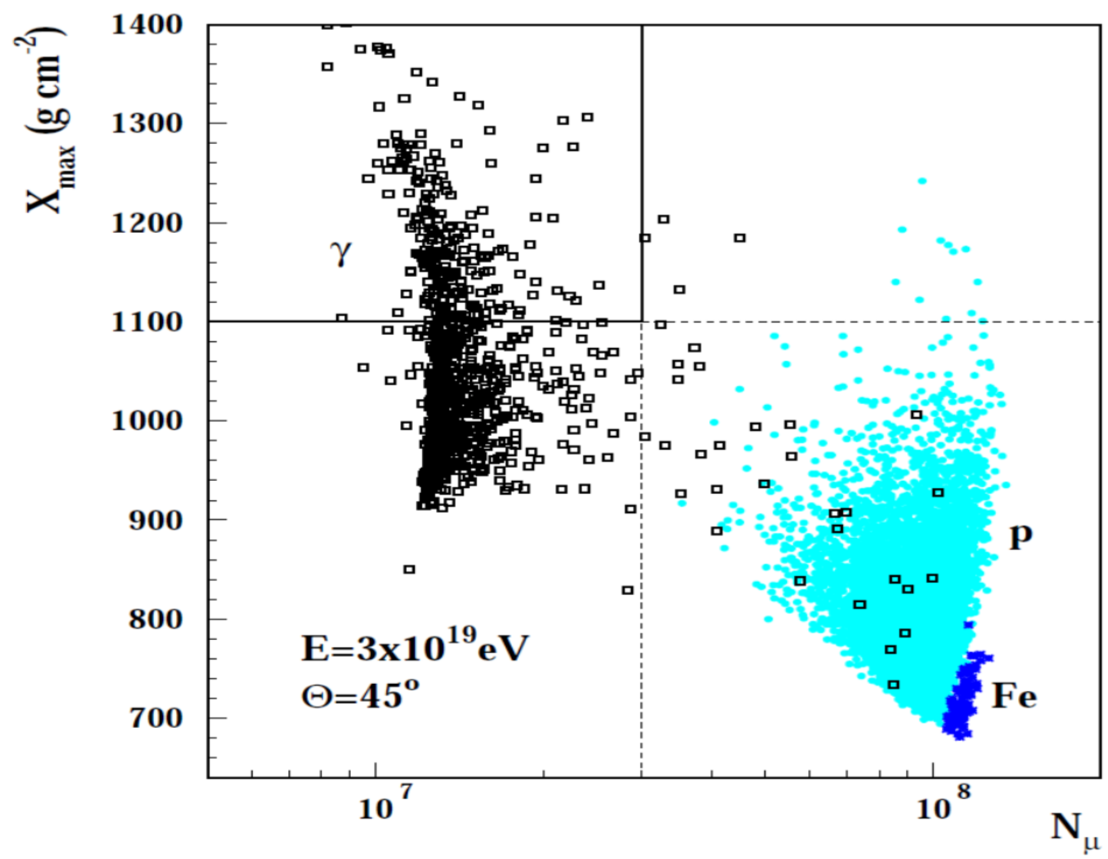
EAS from neutrino primaries

- ✓ horizontal events: very elongated
- ✓ look young: significant EM component, wide time distribution, strong curvature, steep LDF



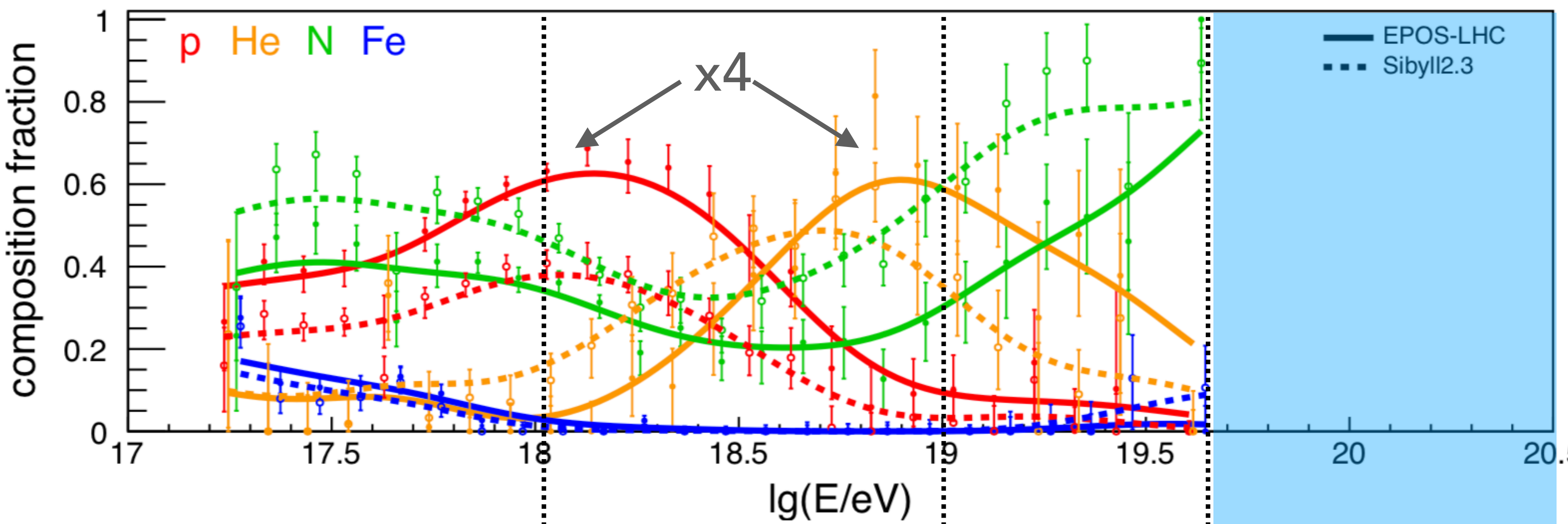
EAS from photon primaries

- ✓ develop deeper in atmosphere: larger X_{max}
- ✓ less muons
- ✓ look young: larger rise time, larger curvature
- ✓ steeper LDF
- ✓ less affected by uncertainties in the hadronic interaction models



Astrophysical interpretation

Mass fractions at Earth from fitting templates of 4 mass groups to the measured X_{max} distributions



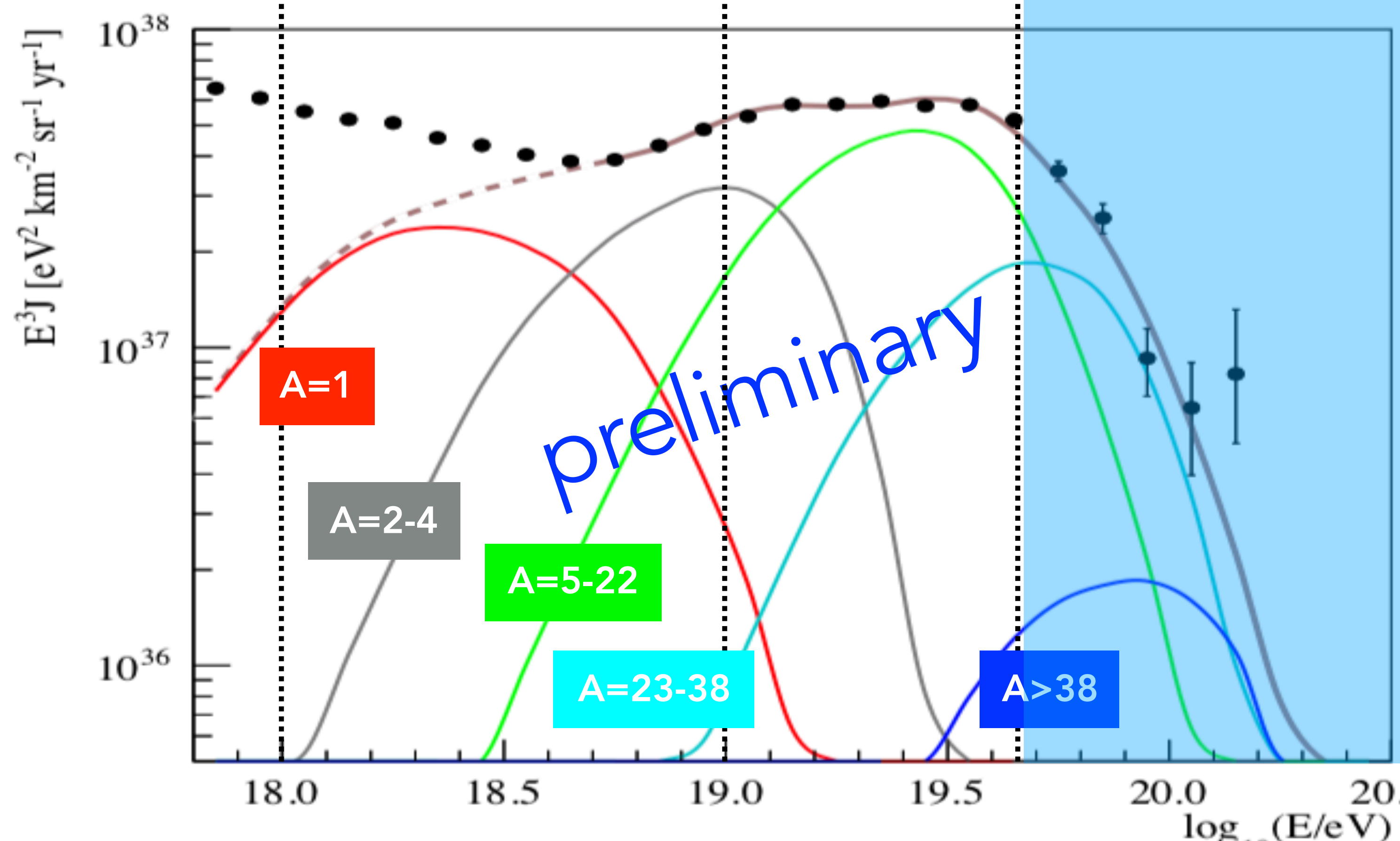
Peter's cycle ∝ E/Z

or

Spallation ∝ E/A ?

Combined fit of energy spectrum and X_{max} distribution

from a simplified astrophysical model of sources and injection



- UHECR spectrum at Earth
- Composition at Earth
- Neutrino fluxes
  - produced in the source
  - produced during propagation

[A.Castellina, PoS (ICRC2019) 004, Auger Highlight Talk]

Composition measurements

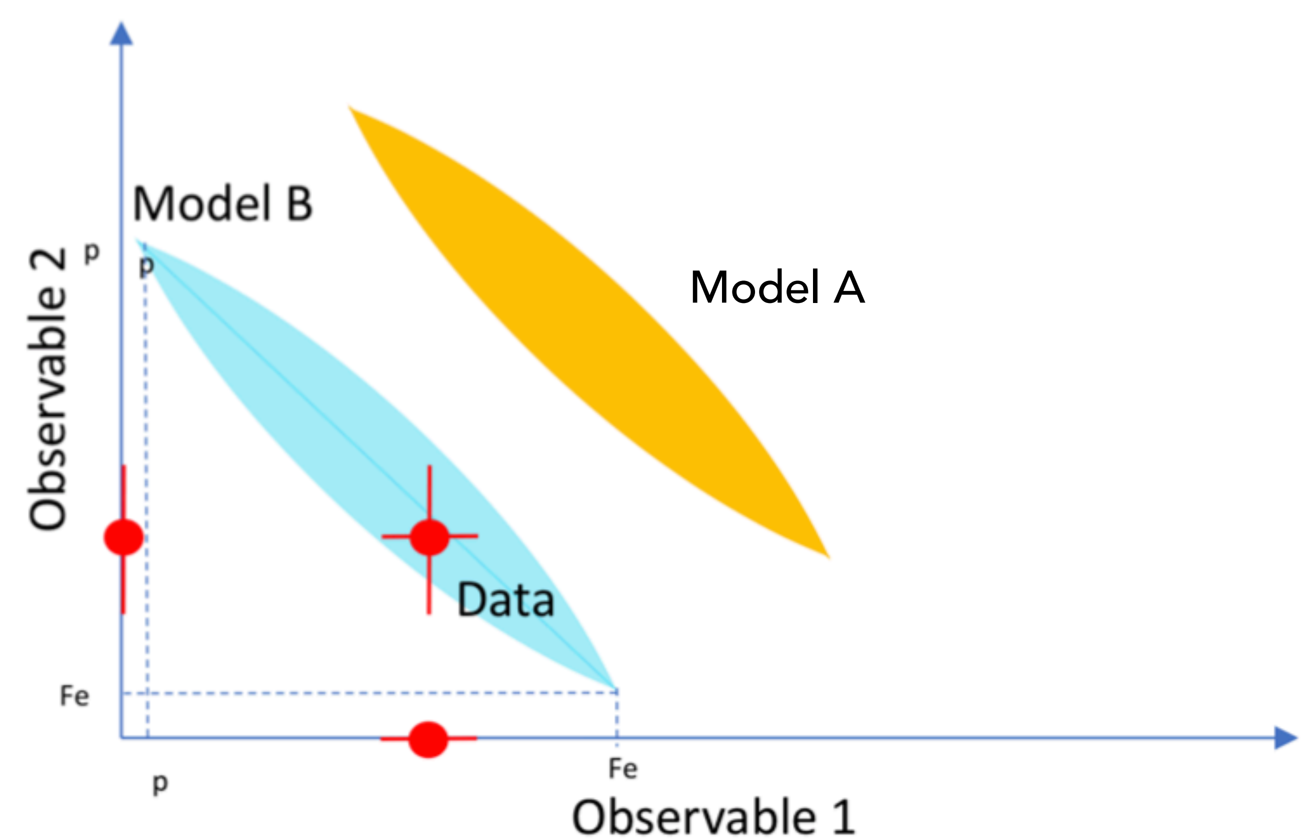
Air shower+hadronic interaction models are required to convert N_μ and X_{max} to A

→ large model uncertainty, maximum contribution to systematics

- these uncertainties arise from a lack of data on multiparticle production in the very forward phase space in hadron-nucleus interactions at UHE
- they increase for increasing energy (farther from the tested region)

General method

A. bad model: data outside model phase space
B. good model: model phase space encompasses data



Models

Air shower simulations

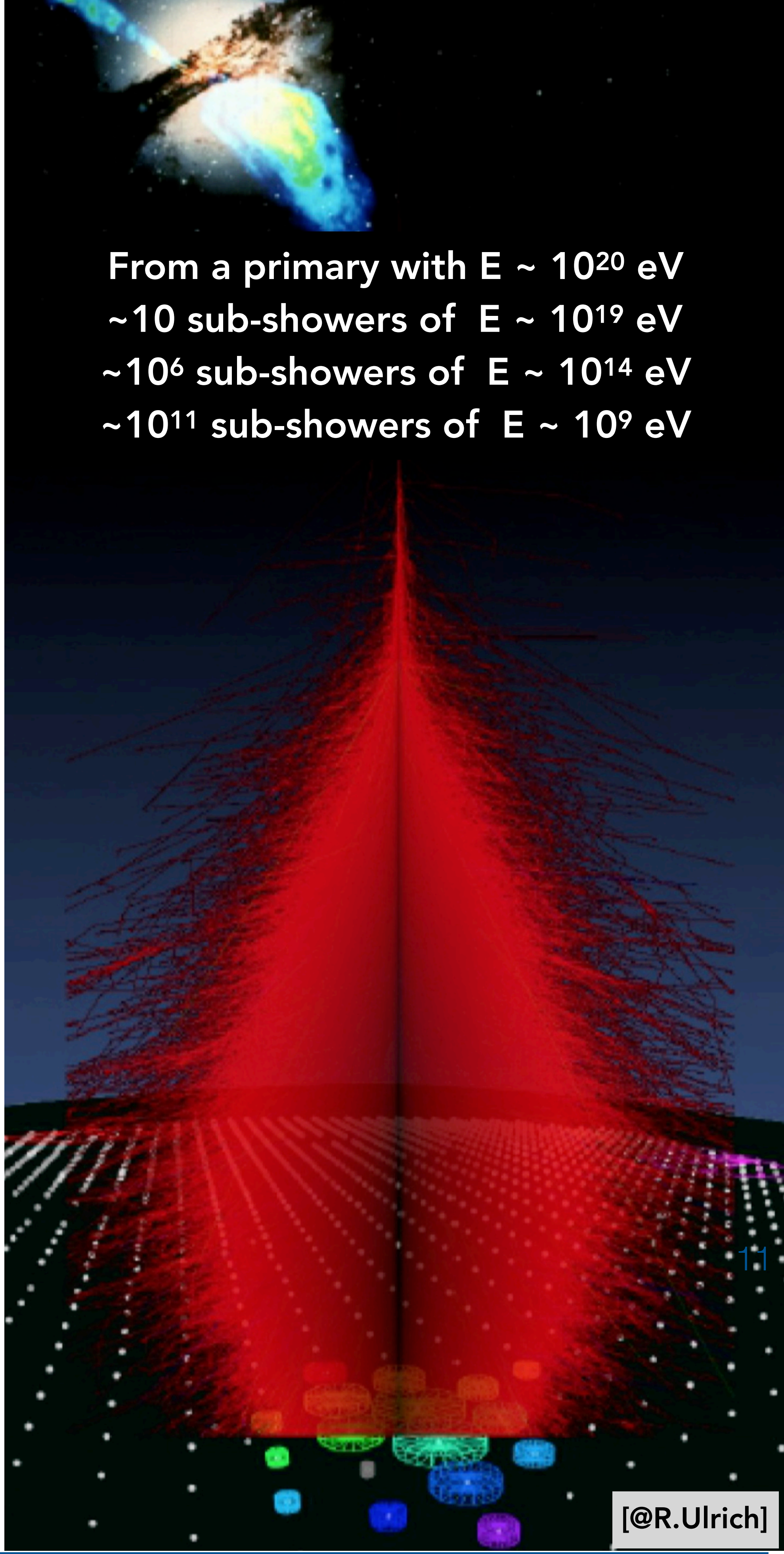
- ✓ start from a primary particle (E,A,ϑ,φ) interacting after crossing a column density X_0
- ✓ track the particles through the atmosphere
- ✓ include all particle interactions and decay modes
- ✓ include models of hadronic interactions

- ✓ CORSIKA, SENECA, AIRES

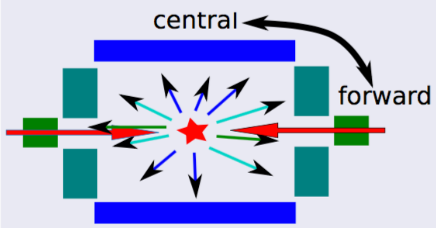
Hadronic interaction models

low energies [from parametrizations of data]
GHEISHA, FLUKA

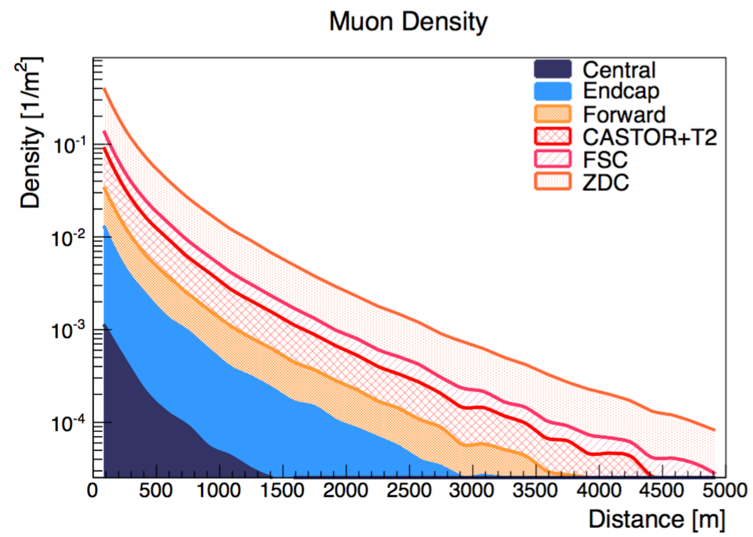
high energies [QCD-inspired]
QGSJetII-04 [S.Ostapchenko, PRD83 (2011) 014018]
EPOS-LHC [T.Pierog et al., PRC92 (2015) 034906]
Sibyll2.3c [F.Riehn et al., PoS(ICRC2017) 301]

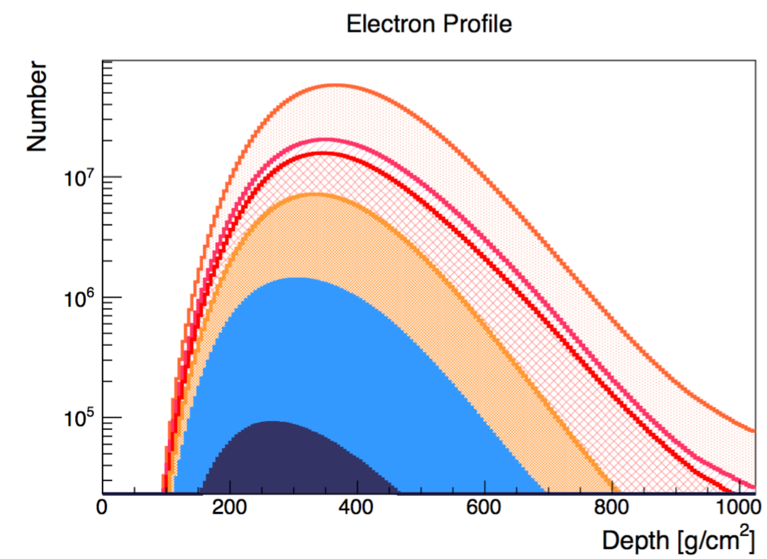


Sensitivity of EAS observables



- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

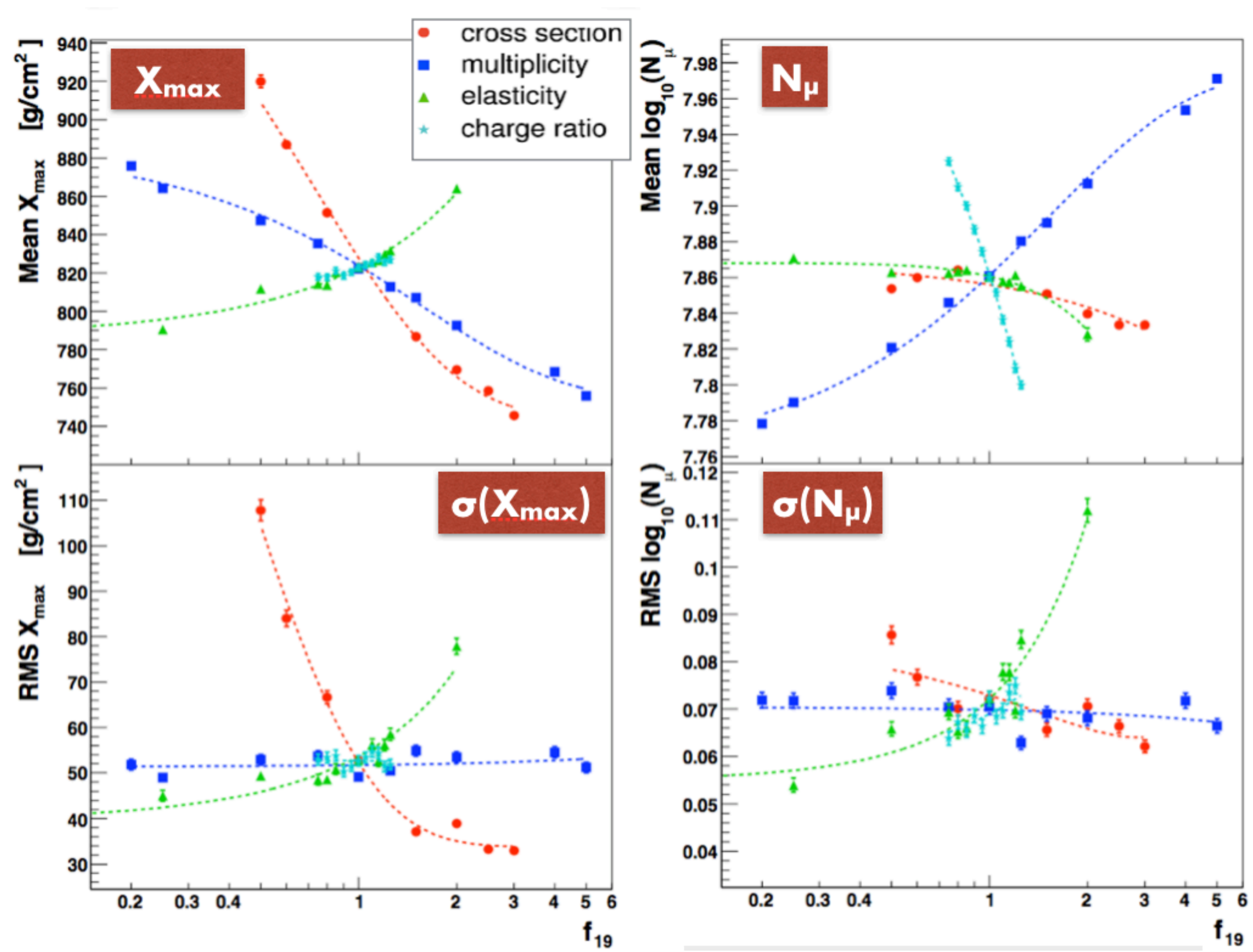




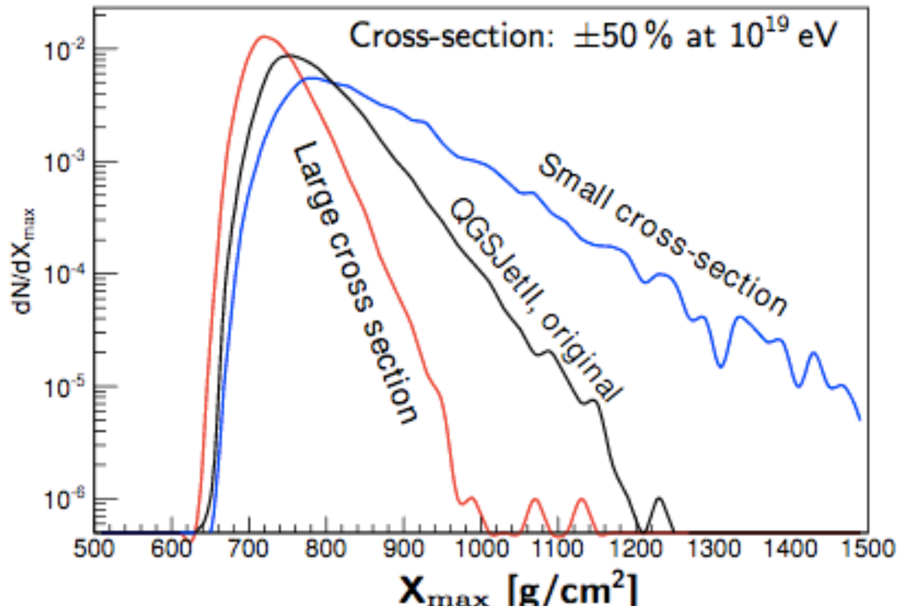
Individual hadronic interaction features can be artificially altered during EAS development :

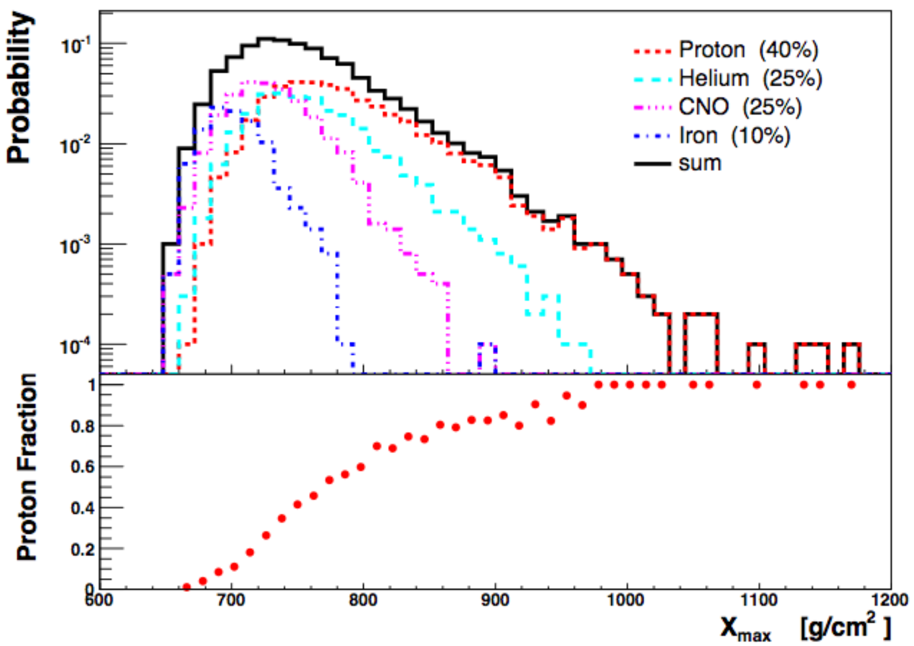
$$f(E,\, f_{19}) = 1 + (f_{19} - 1)\, F(E)$$

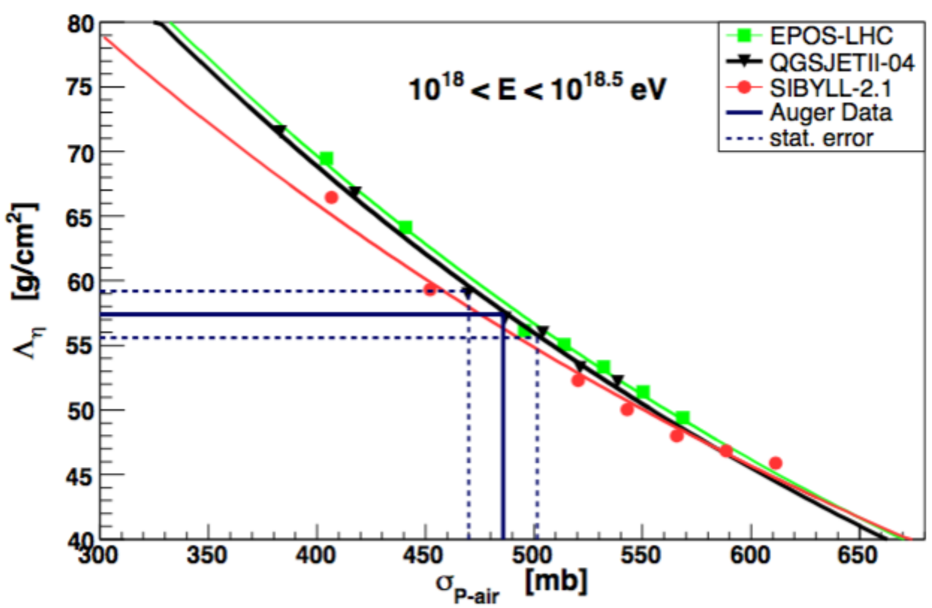
$$F(E) = \begin{cases} 0 & E \leq 1\,\mathrm{PeV} \\ \dfrac{\log_{10}(E/1\,\mathrm{PeV})}{\log_{10}(10\,\mathrm{EeV}/1\,\mathrm{PeV})} & E > 1\,\mathrm{PeV} \end{cases}$$



[@R.Ulrich et al., PRD83 (2011) 054026]







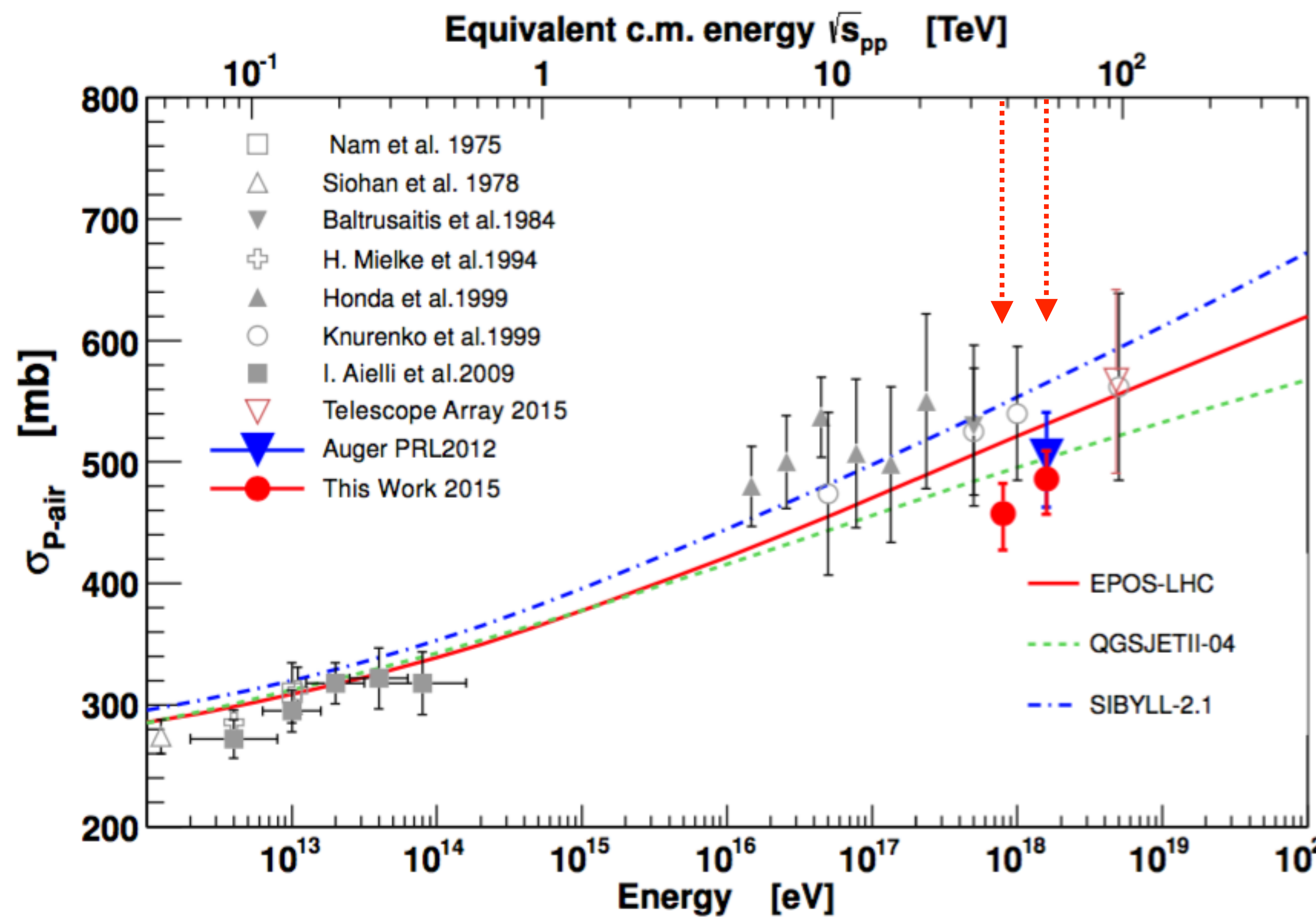
The p-Air cross section

The tail of the longitudinal distribution of X_{max} is sensitive to the p-Air cross section.

Select deeply penetrating EAS to enhance the proton fraction

$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}} \qquad \sigma_{p-Air} = \frac{<m_{Air}>}{\lambda_{int}}$$

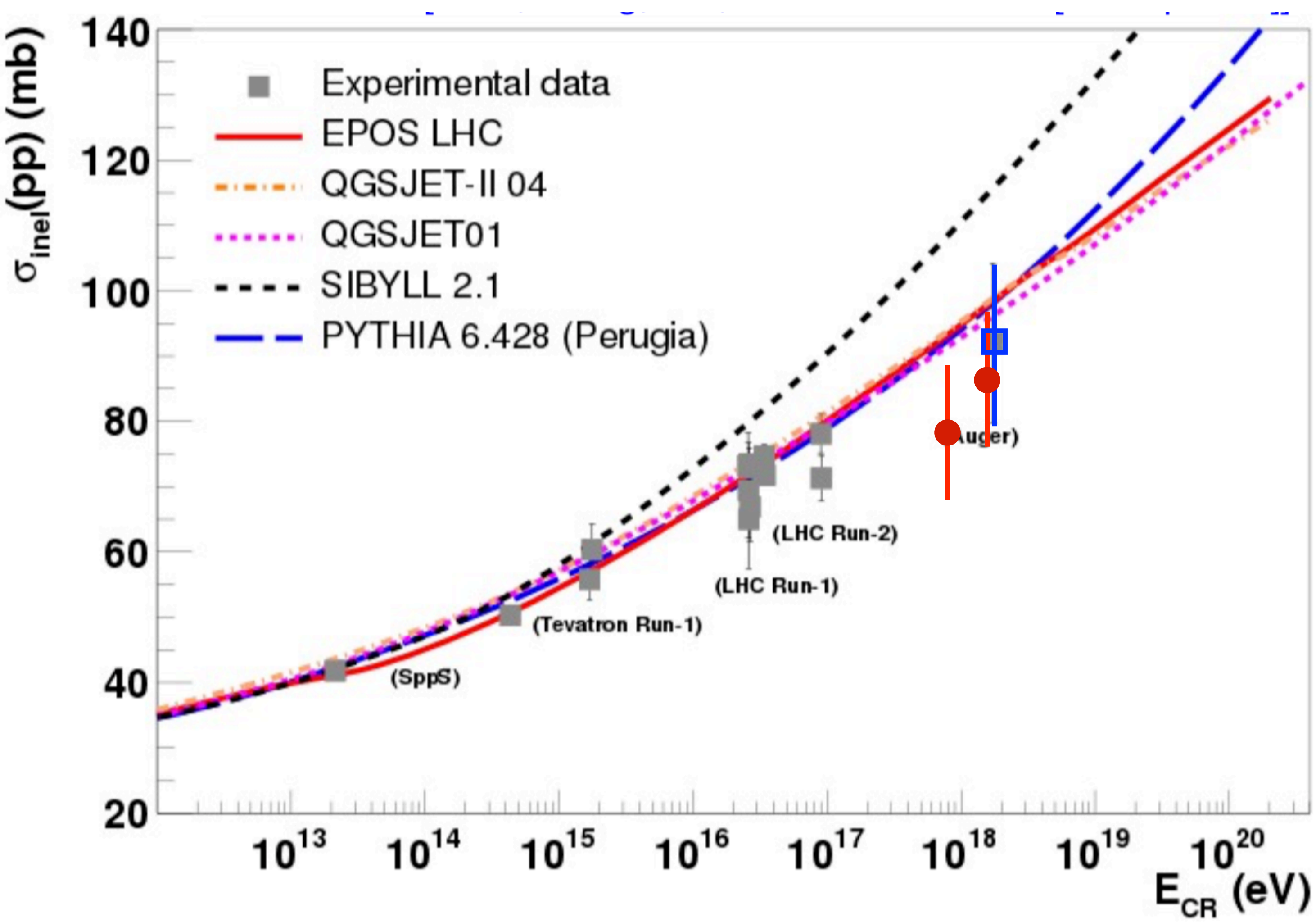
$$\frac{dN_{EAS}}{dX_{max}} \propto e^{-X_{max}/\Lambda_\eta} \qquad \lambda_{int} \leftrightarrow \Lambda_\eta$$

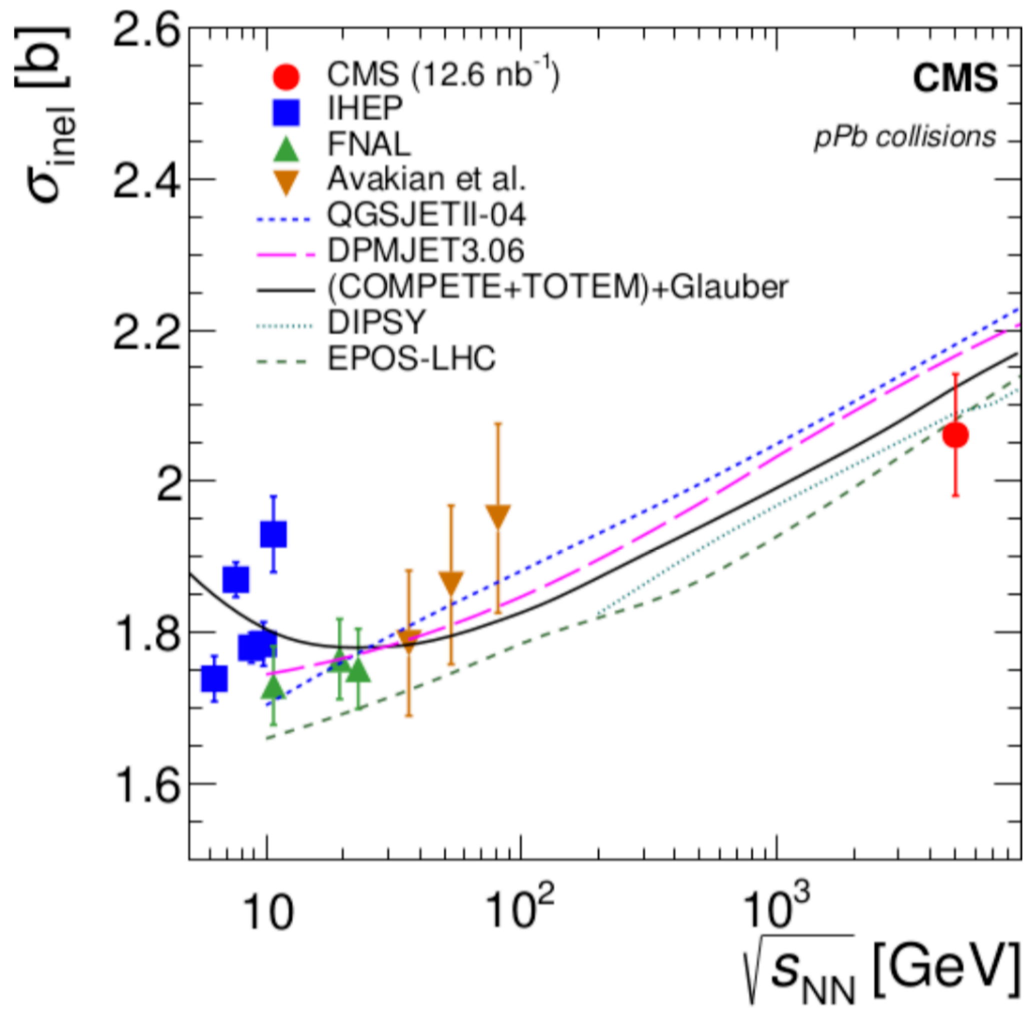


[@R.Ulrich, ICRC2015], R.Abbasi (ICRC2015)]

Inelastic p-p cross section

$\sigma_{tot,\ el,\ inel}$ = Key to constrain the UHECR penetration in the atmosphere
Glauber model validated by LHC heavy ion measurements (CMS p-Pb collisions)





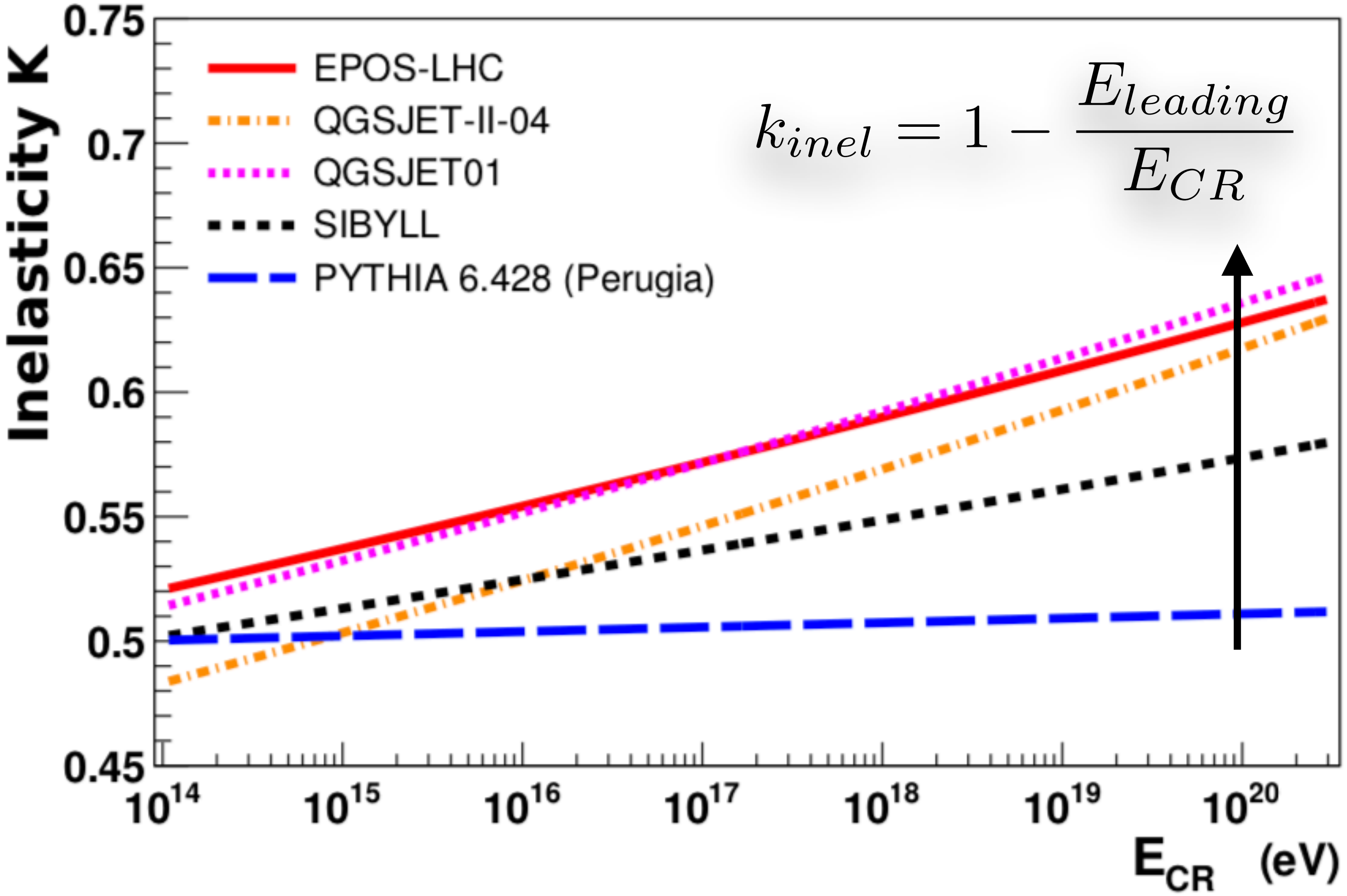
More precise data, more constraining to models

Note:

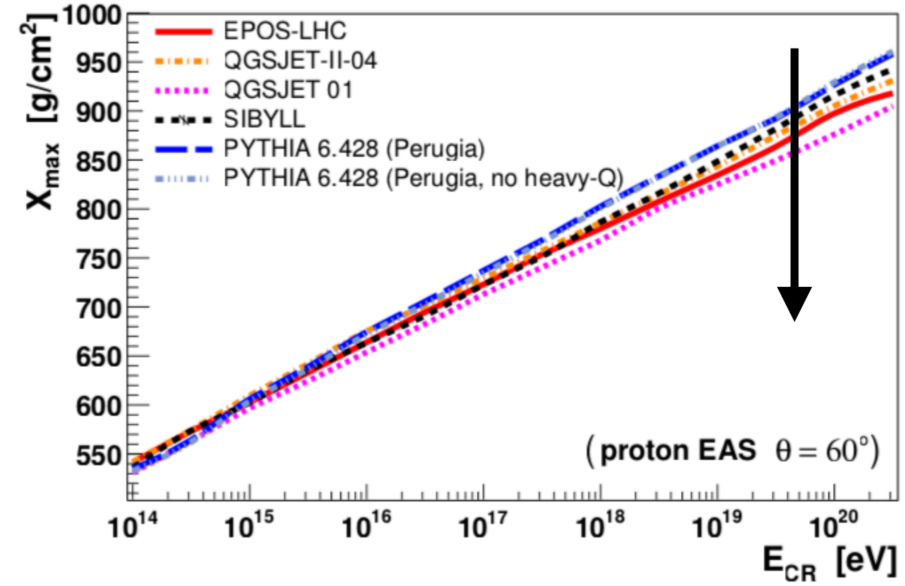
- the newest Sibyll2.3c predictions are ~ EPOS-LHC
- the extrapolation from Tevatron to LHC ~ that from LHC(14 TeV) to Auger !

[@D'Enterria et al., arXiv:1809.06406]

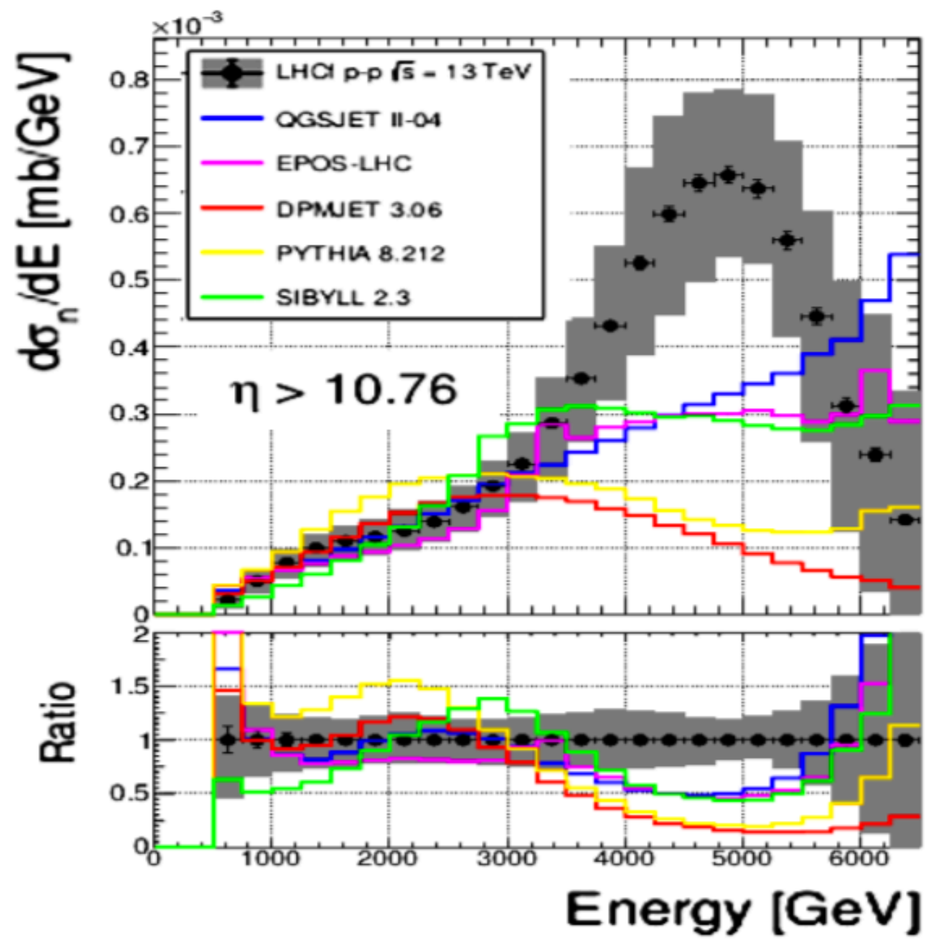
Inelasticity



$$k_{inel} = 1 - \frac{E_{leading}}{E_{CR}}$$

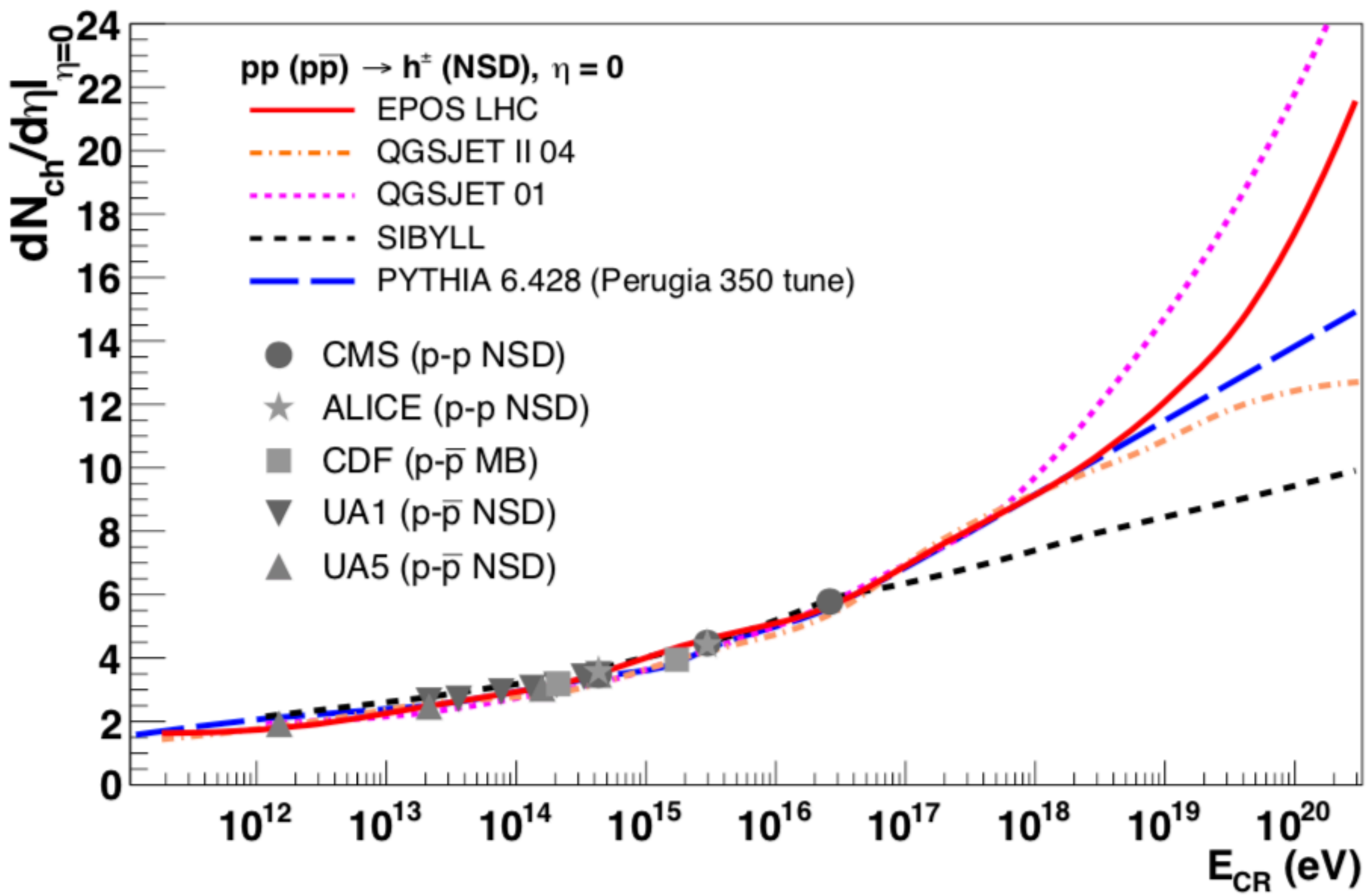


- a larger k_{inel} implies less energy available for forward particle production: the EAS develops faster, so X_{max} is shallower
- forward baryon production important for muon production: no models agree with LHCf measure of n in p-p(13 TeV)



[@D'Enteria, arXiv:1902.09505]

The central particle multiplicity

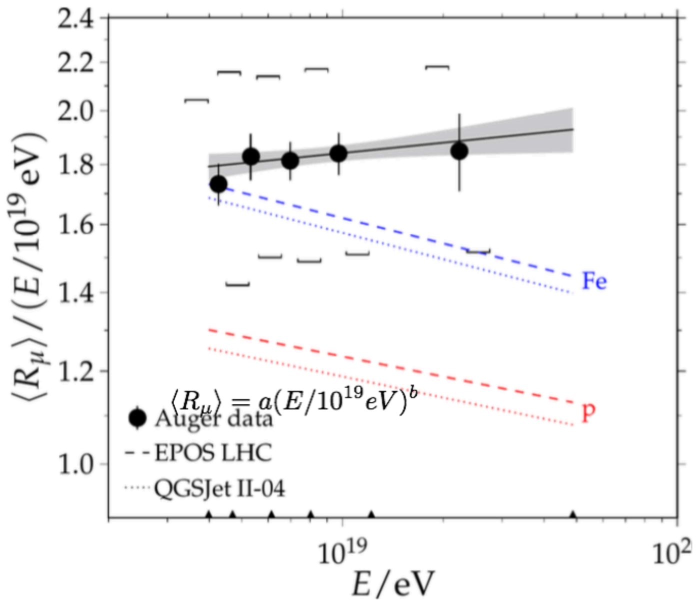


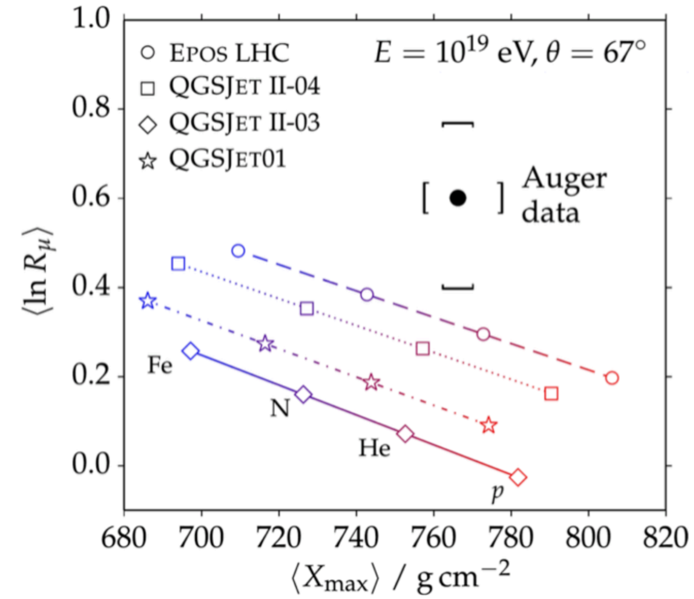
- while pre-LHC models gave differences up to a factor 2 at the predicted LHC particle multiplicities, post-LHC ones show a 30% difference at the GZK cutoff
- all models agree well up to $(dNch/d\eta)_{\eta=0}$~5.5 (E_{CR}~$10^{18.5}$ eV)
- note that the new version of Sibyll (2.3c) is now very similar to EPOS-LHC

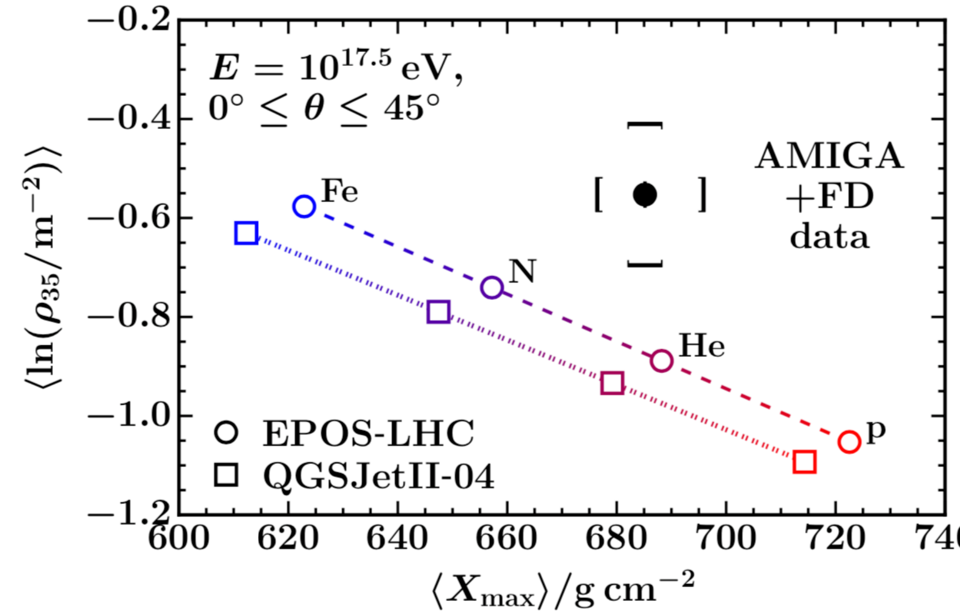
The muon problem

Measurements of the muonic component in inclined EAS

Muon number





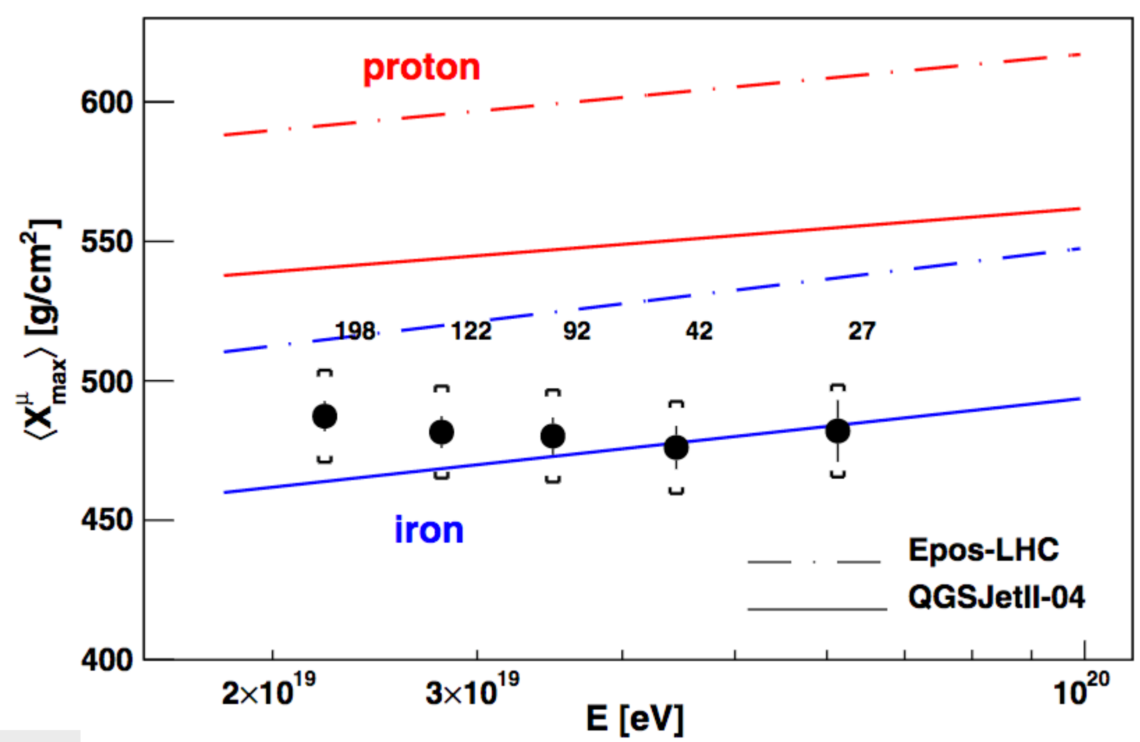


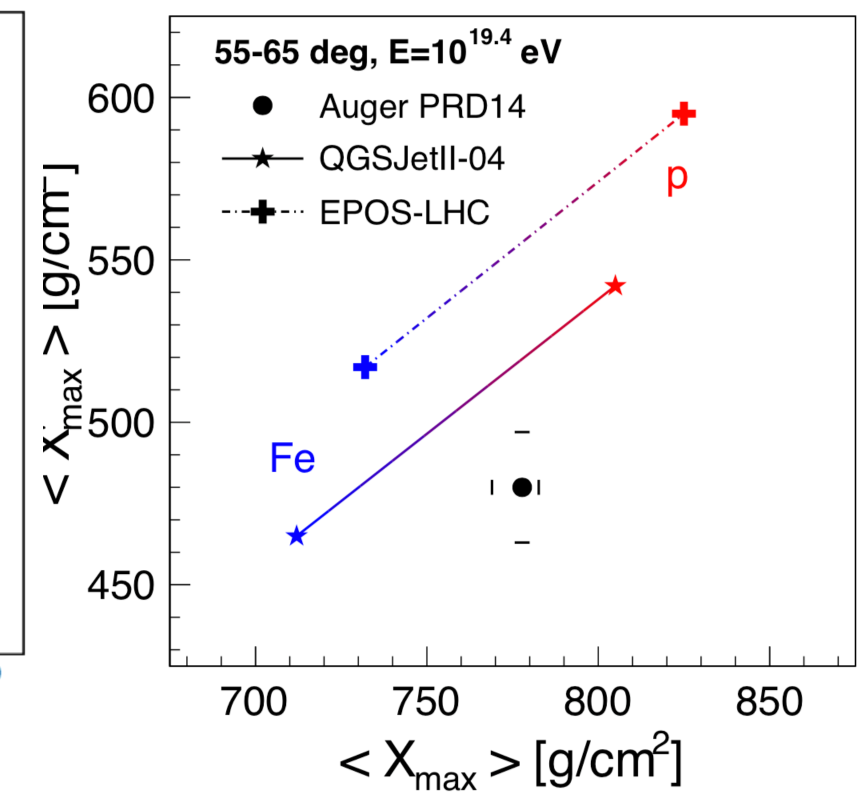
@10^{18} eV: 38% (53%)

@ 10^{19} eV: 30% to 80%$^{+17}_{-20}$ (sys)% increase in <N$_\mu$> needed

[@Auger Coll., PRLD91 (2015) 032003+059901]
[@F.Sanchez, PoS(ICRC2019) 411]

Muon production depth





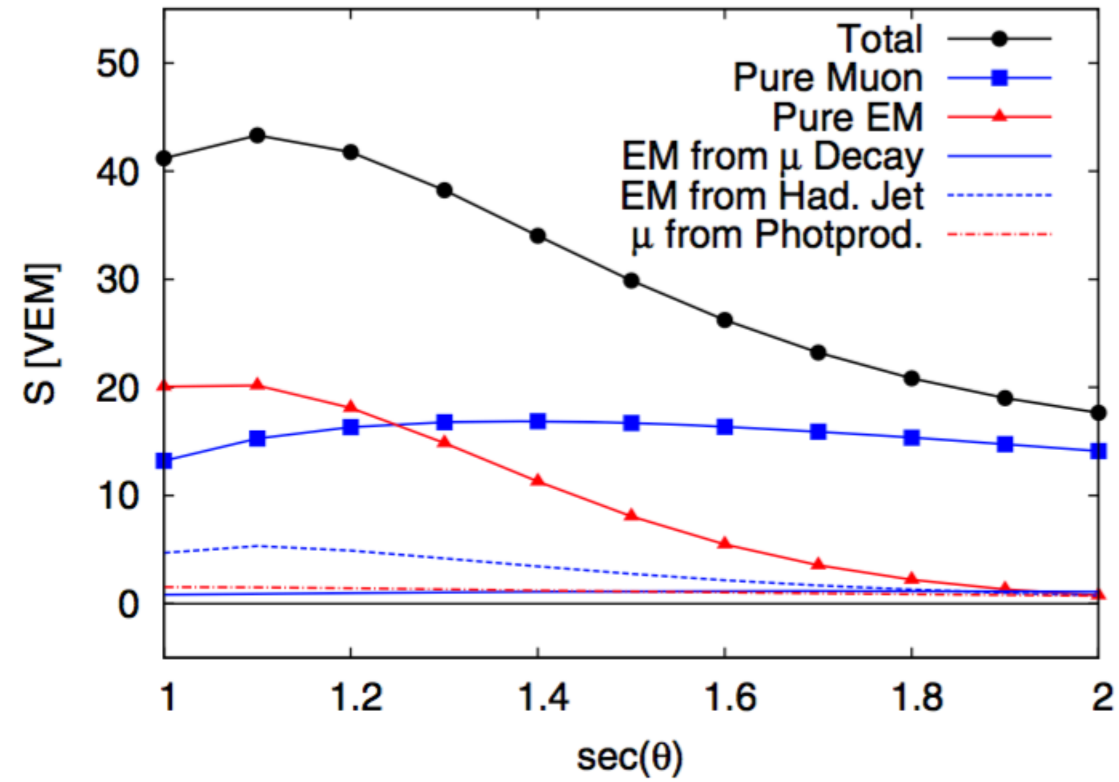
[@Auger Coll., PRLD90 (2014) 012012]

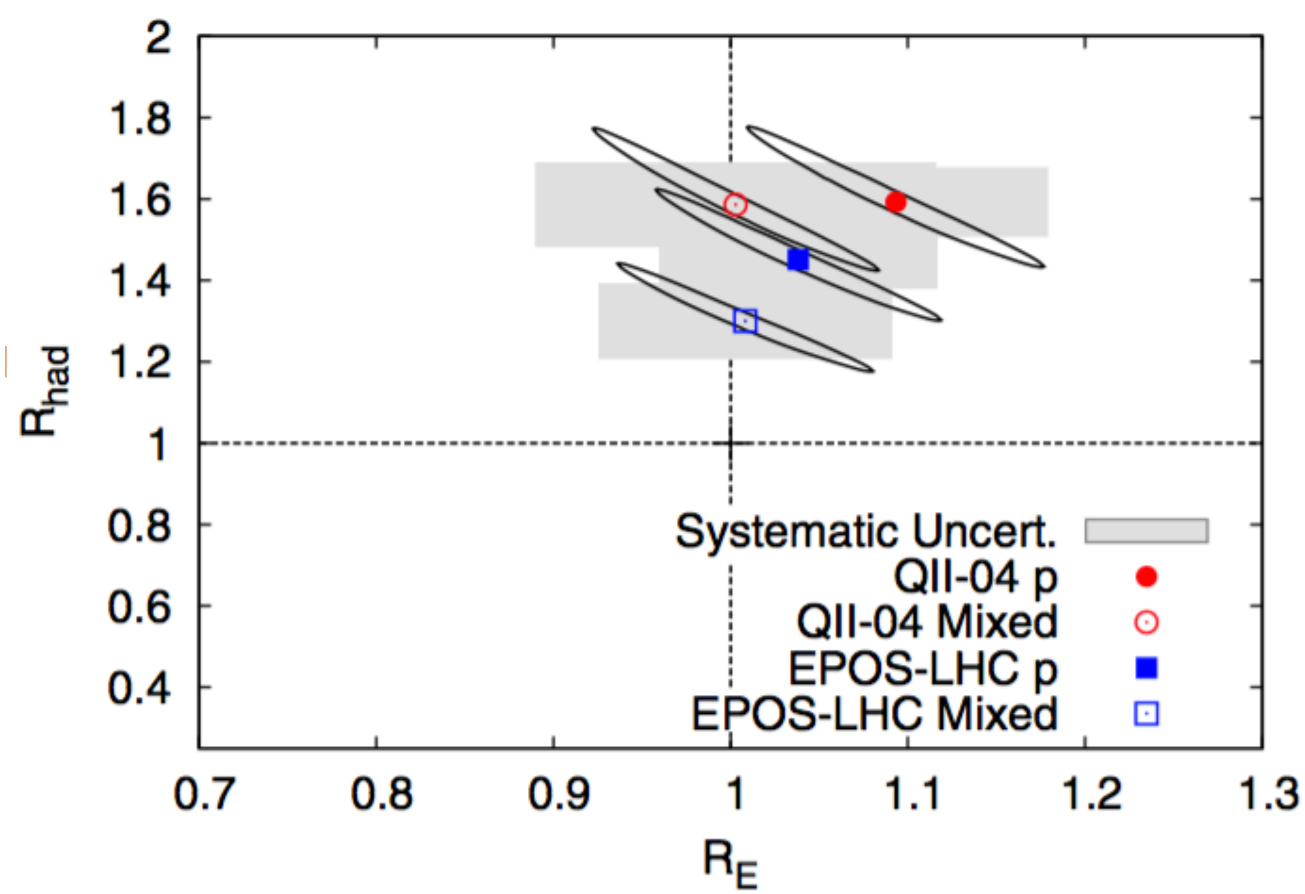
Hybrid events

E_0=6-16 EeV [E_{CM}=110-170 TeV]

match real events longitudinal distribution with a set of simulated p and Fe-induced showers (same E,ϑ as observed) and compare their simulated LDF at ground with the measured one

$$S_{res}(R_E, R_{had})_{i,j} = R_E S_{EM,i,j} + R_{had} R_E^{\alpha} S_{had,i,j}$$





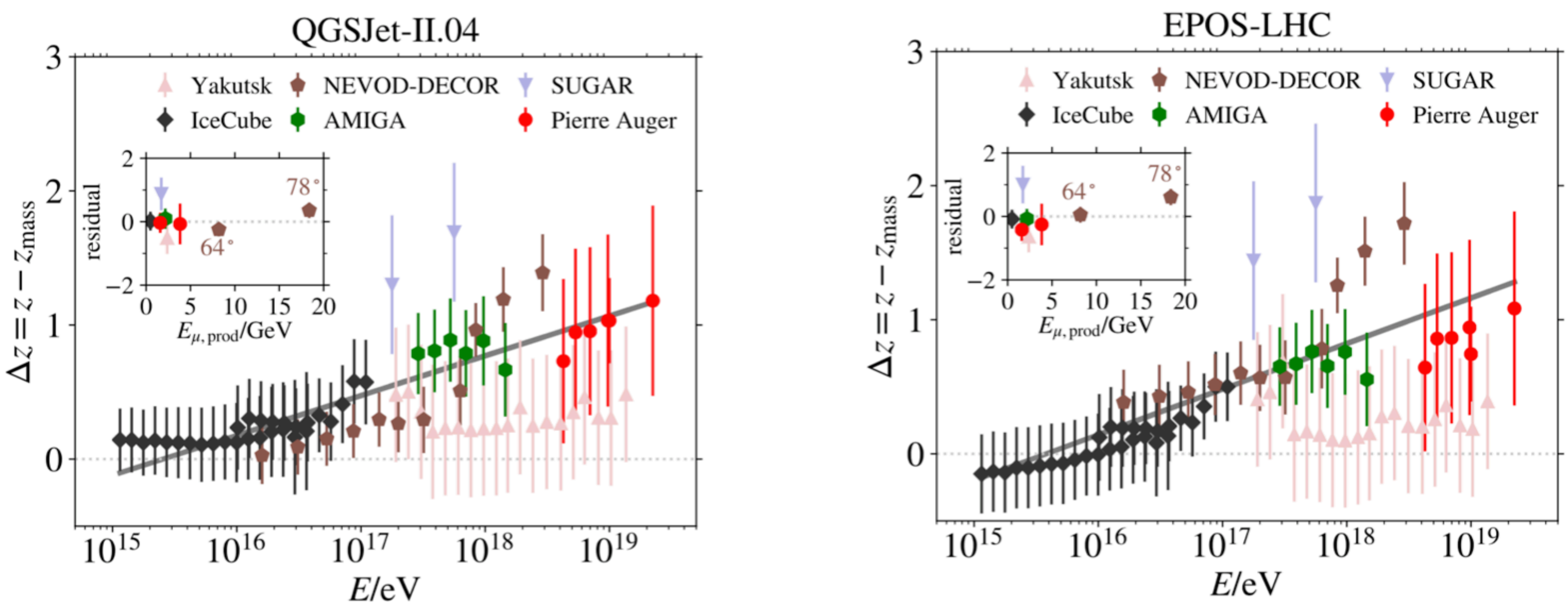
- no need for an energy rescaling
- observed muon signal 1.3-1.6 times larger than expected
- smallest discrepancy with prediction of EPOS-LHC for mixed composition (~2**σ**)

[@Auger Coll., PRL117 (2016) 192001]

Muons from EAS experiments

Clear muon deficit in simulations wrt observations

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



Slope significantly different from zero (>8σ) for E>10^{16} eV

The slope does not change if a different energy or mass scale is considered

[@L.Cazon, PoS(ICRC2019) 214]

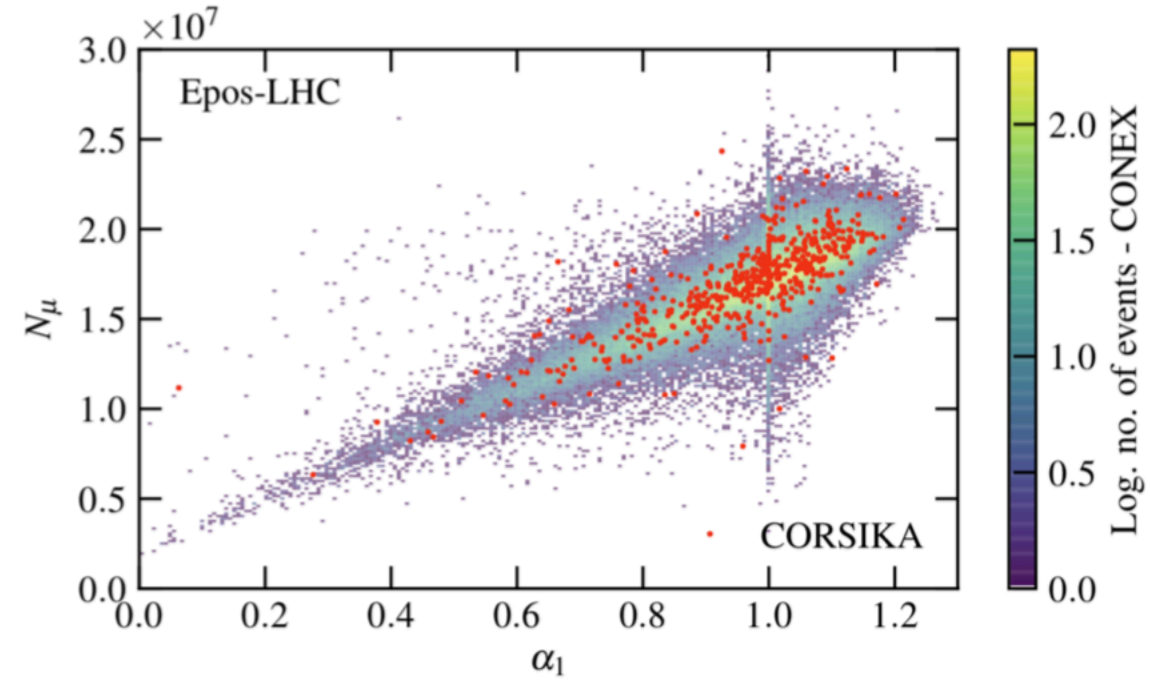
More information from muons in EAS

$$N_\mu = A^{1-\beta}\left(\frac{E_0}{E_{dec}}\right)^\beta$$

Strong correlation between E_{had}/E_0 and N_μ , independent on the hadronic interaction model

$$\alpha_1 = \sum_{i=1}^{m}\left(\frac{E_i^{\text{had}}}{E_0}\right)^\beta \qquad \beta = \frac{\log(m)}{\log(m_{tot})}$$

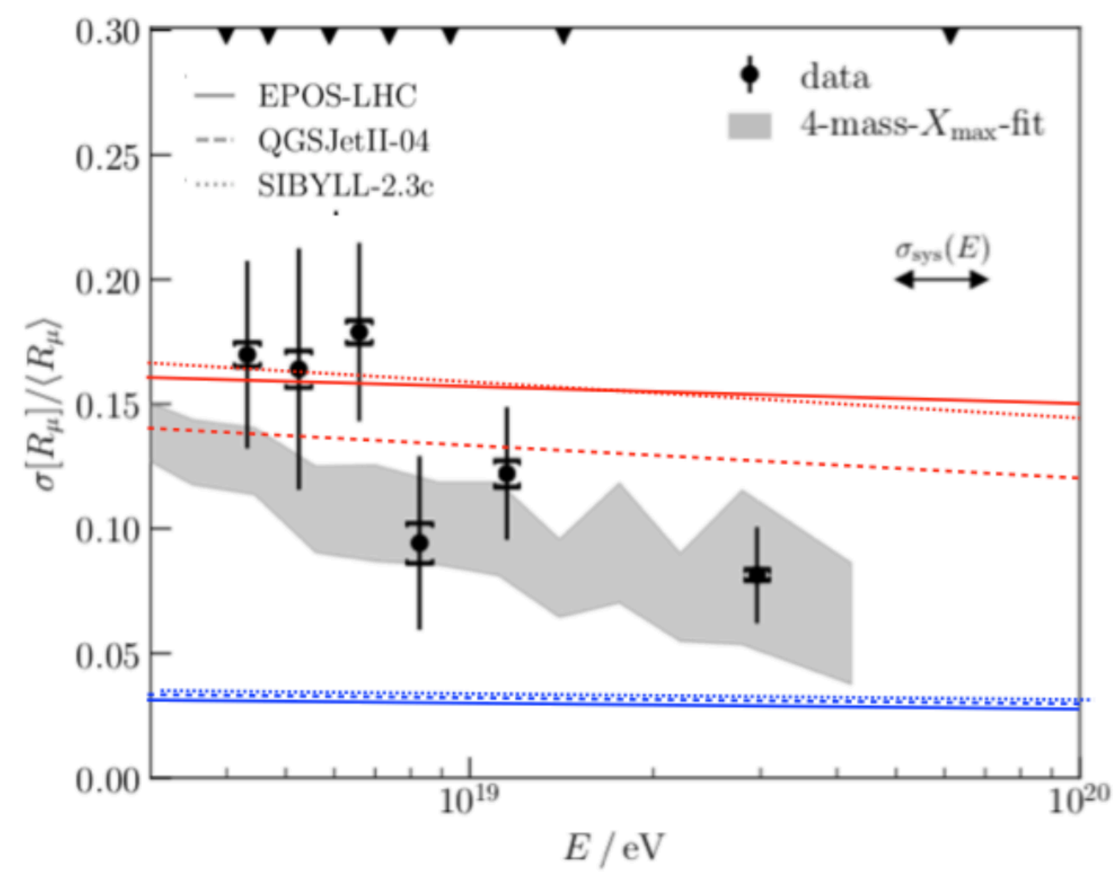
$$\left(\frac{\sigma(N_\mu)}{N_\mu}\right)^2 \simeq \left(\frac{\sigma(\alpha_1)}{\alpha_1}\right)^2 + \left(\frac{\sigma(\alpha_2)}{\alpha_2}\right)^2 + \ldots + \left(\frac{\sigma(\alpha_c)}{\alpha_c}\right)^2$$



Fluctuations in the muon number = probe of the first interation at UHE

First measurement of intrinsic fluctuations of muons in EAS

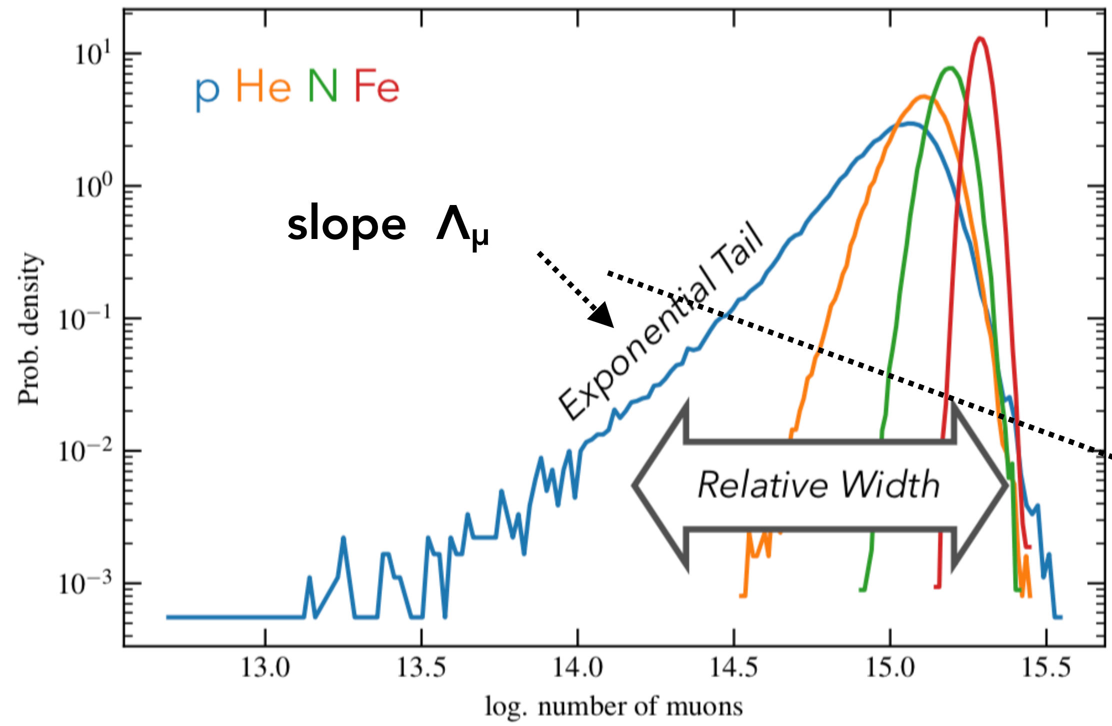
Post-LHC models describe well the fluctuations of energy partition in the first interaction up to UHE

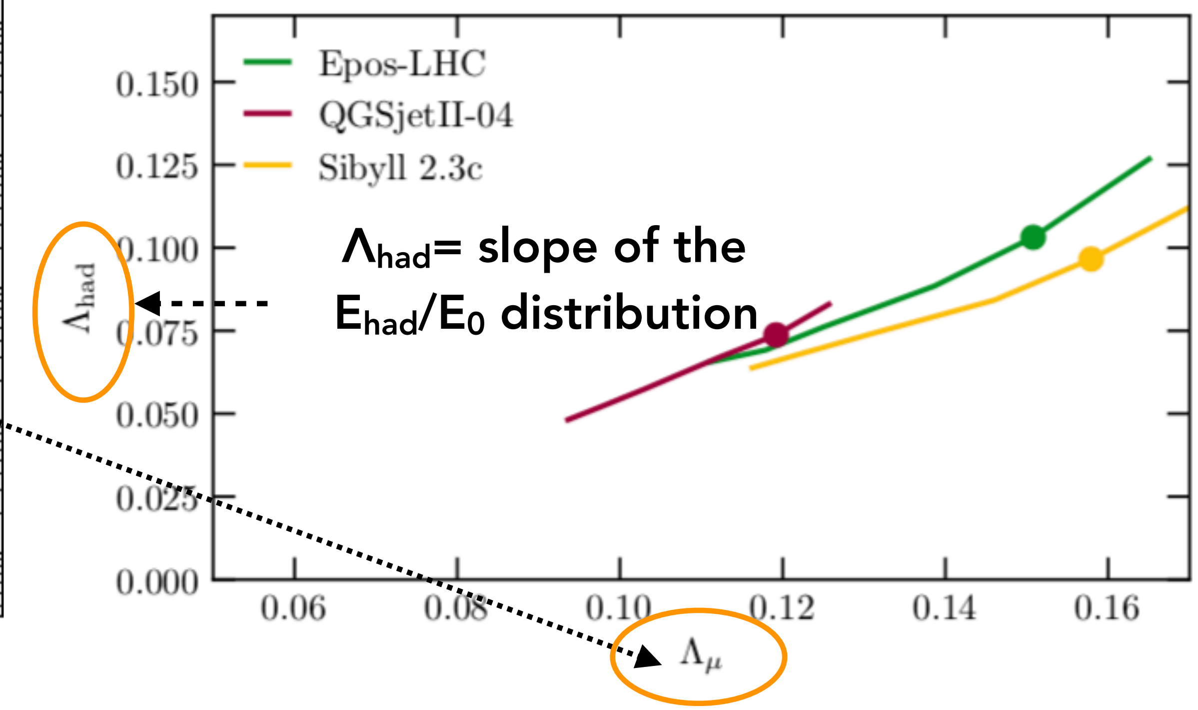


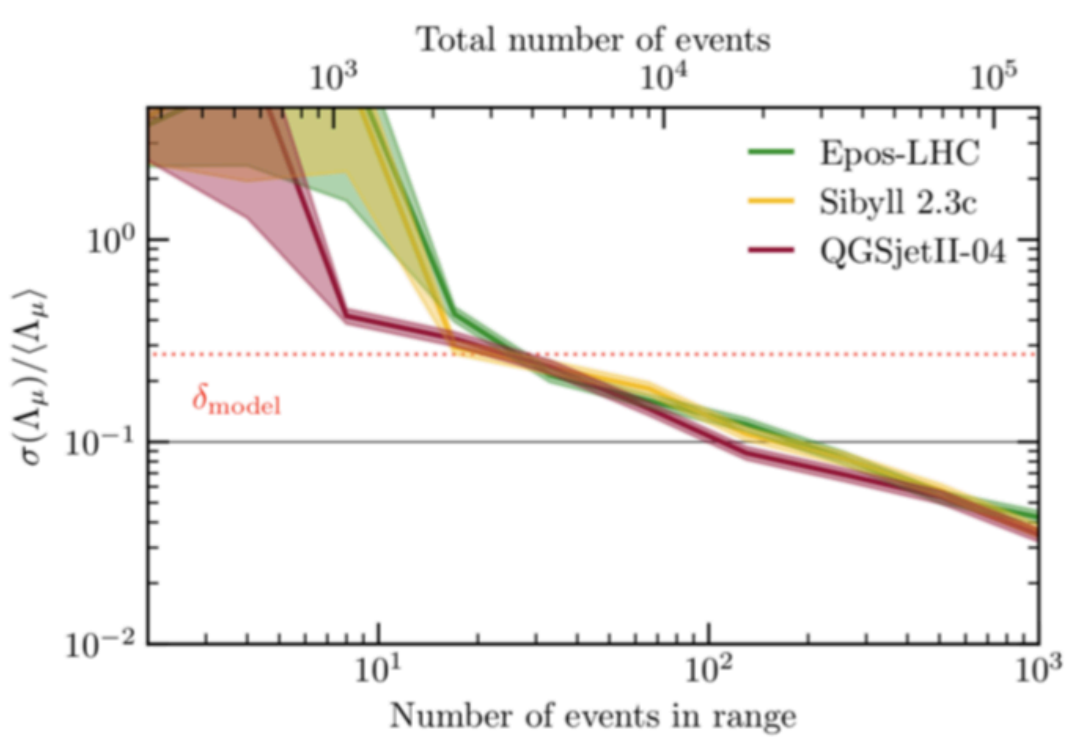
[@F.Riehn, PoS(ICRC2019) 404]

More information from muons in EAS

The measure of the proton exponential tail is related to the properties of multiparticle production of the first interaction







Precision depending only on number of events

Cross checks at the same $\sqrt{s}$=13 TeV (E_{CR}~10^{17} eV) possible :

- LHC : TOTEM, LHCf
- Auger: AMIGA infill

[@R.Conceiçao, PoS(ICRC2019) 226]

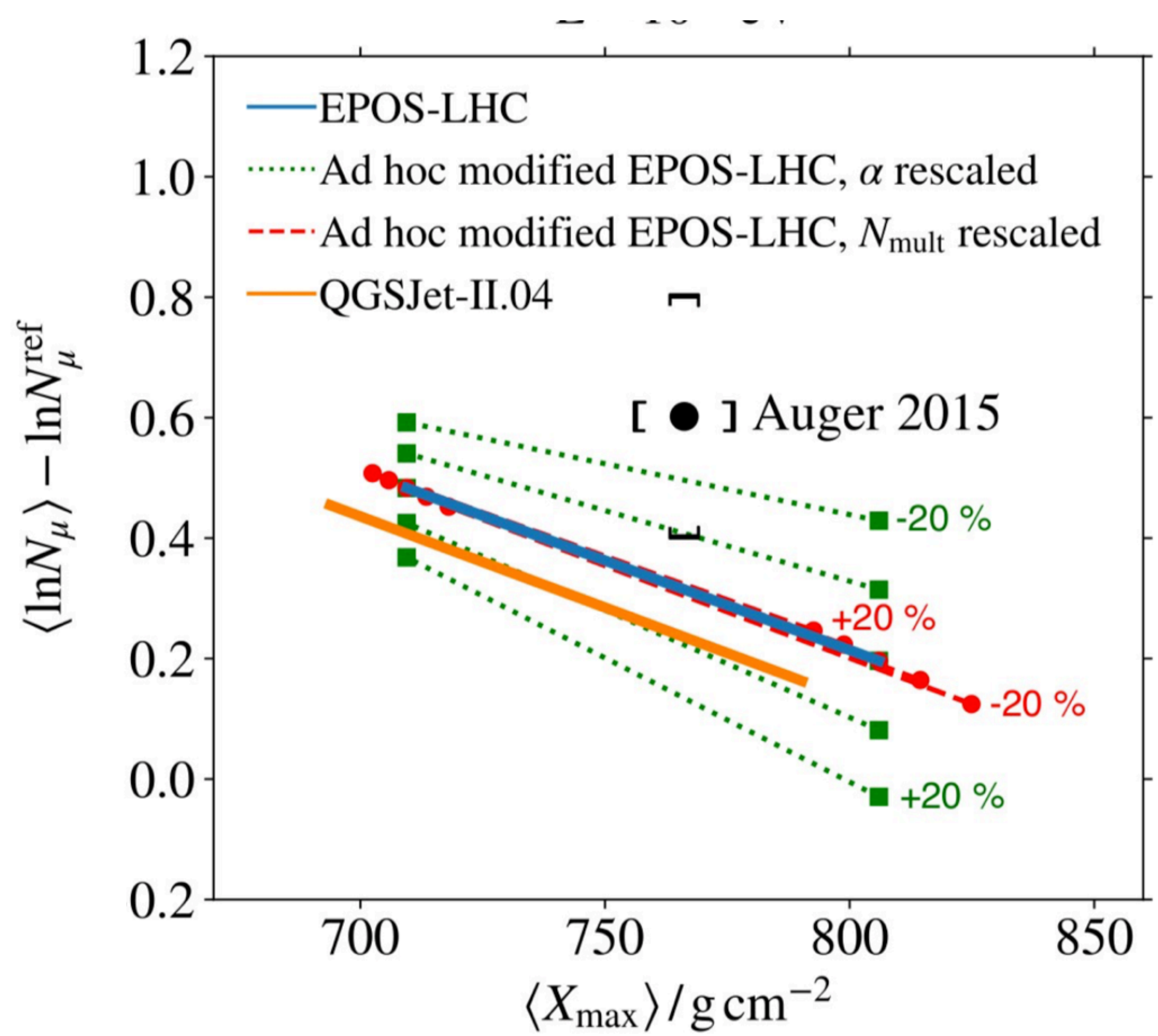
Solving the μ puzzle?

$$N_\mu = A^{1-\beta}\left(\frac{E_0}{E_{dec}}\right)^\beta$$

$$\beta = \frac{lnN_{had}}{ln(N_{had}+N_{em})} = 1 + \frac{1-\alpha}{ln(N_{had}+N_{em})}$$

- a change in multiplicity (N_{had}+N_{em}) affects both X_{max} and N_μ
- a change in **α** (fraction of energy going in π^0 in each interaction) modifies only N_μ [e.g. a small ~5% change in hadronic fraction in ~6 cascade steps produces a -30% in **α**]

- any change must be compatible with all moments (N_μ, X_{max}, X^μ_{max}, their fluctuations…)



More muons :

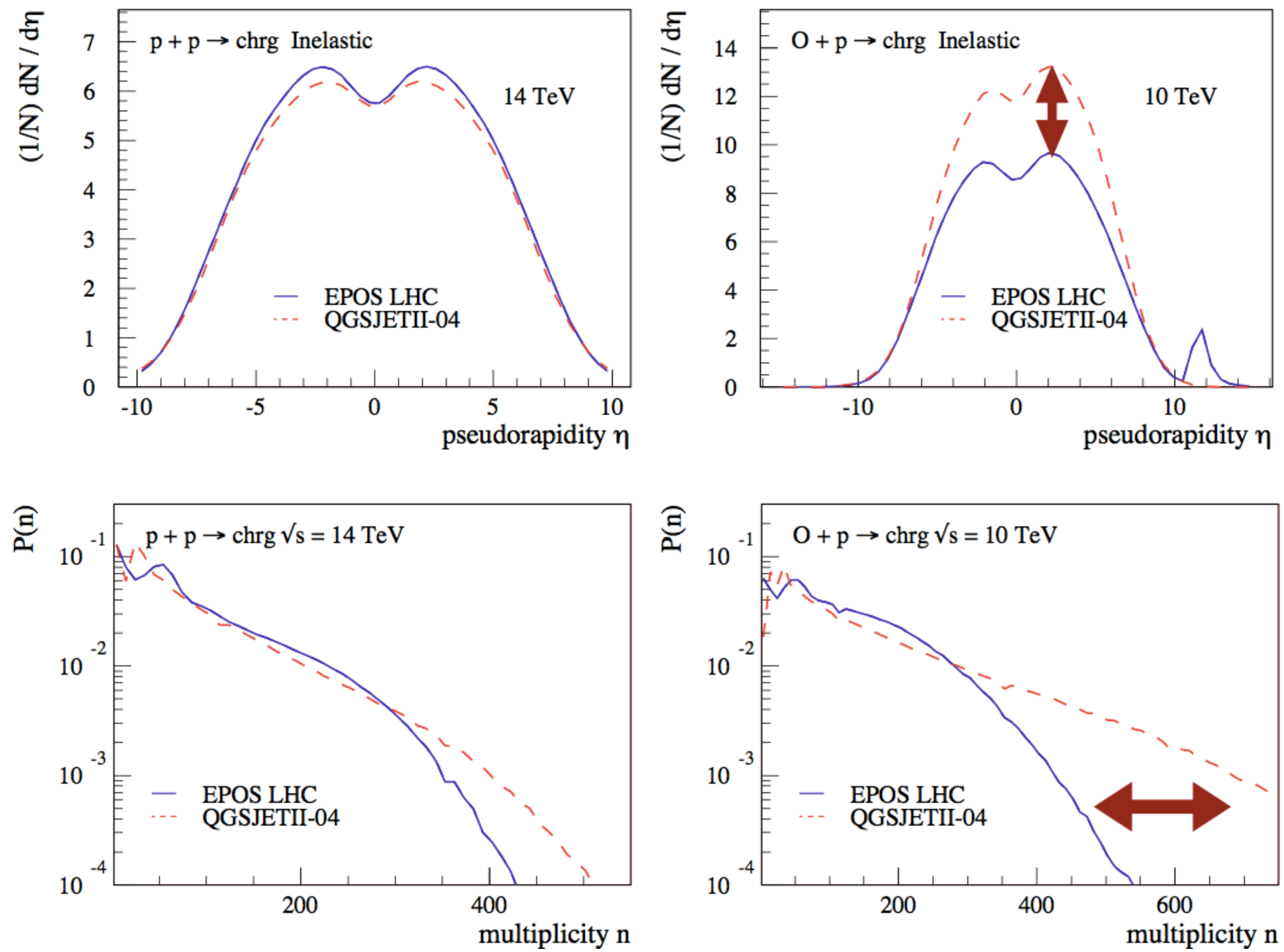
- ✓ **baryon-antibaryon production**
- ✓ **leading particle effect (π^0 replaced with ρ^0)**
- ✓ **QGP**
- ✓ **….**

[@H.Dembinski, PoS(ICRC2019) 235]

Future steps

Strong constraints from LHC measurements to extrapolations in energy

Main source of uncertainty from models is the difference between p-p and p-nucleus collisions



- p-light ion collisions: can provide calibration of nuclear effects in p-N interactions of EAS
- **O beam** as light ion have been chosen for a data acquisition in Run3 (2023)

Searches for Lorentz invariance violation

$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_i^{(n)} E_i^{2+n} = m_i^2 + \eta_i^{(n)} \frac{E_i^{2+n}}{M_{Pl}^n}$$

Effects suppressed for low energy and short travel distances : UHECRs !!!

3 independent scenarios tested

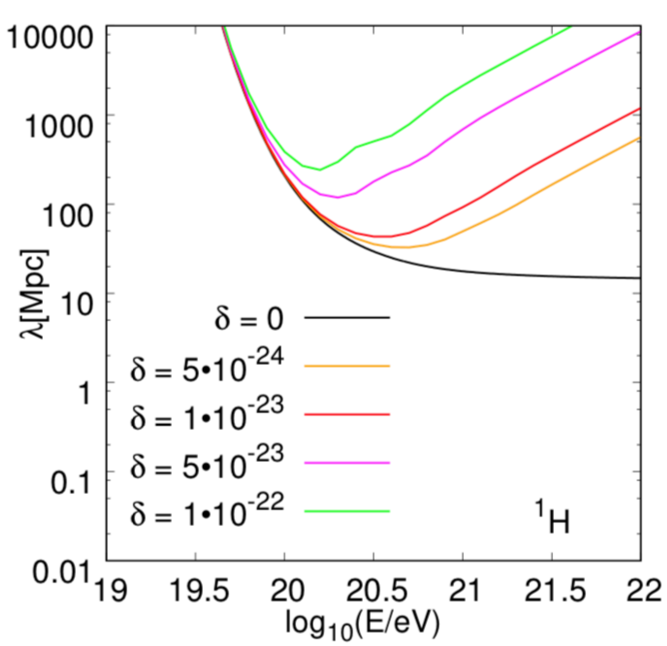
- Propagation of UHECRs
- Propagation of GZK photons
- Air shower physics

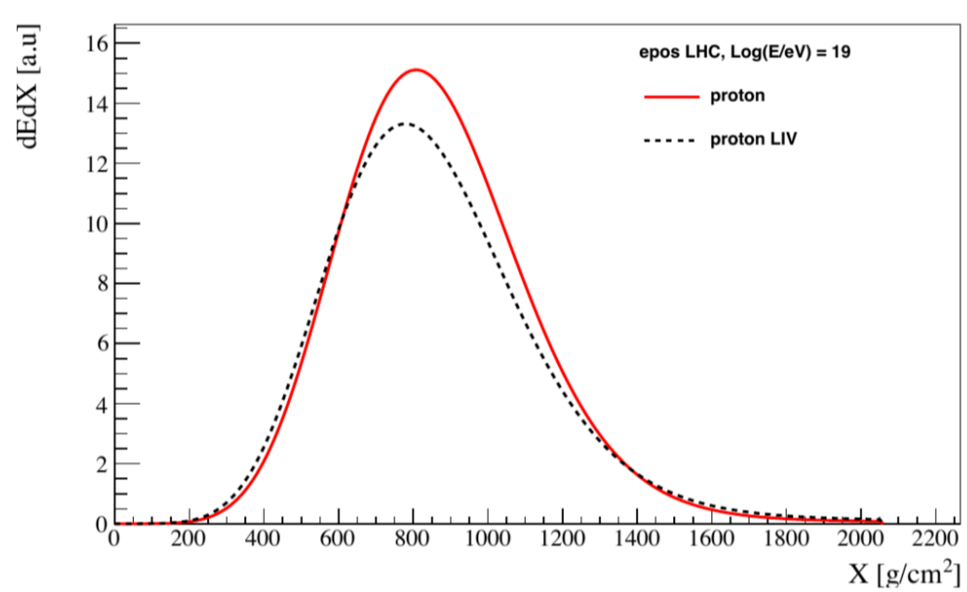
Auger data used

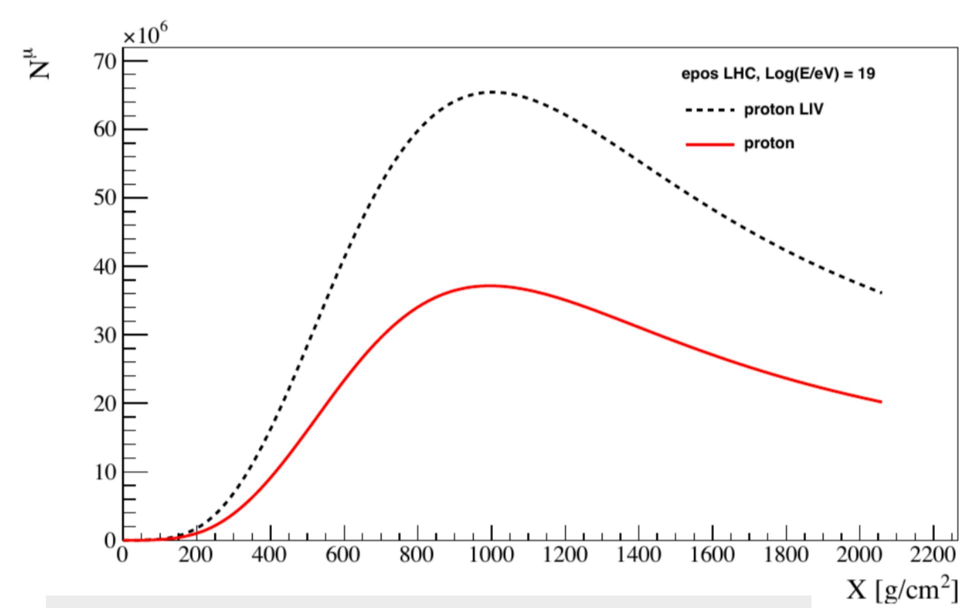
- Energy spectrum
- Xmax distributions

Combined fit starting from simple source model

- Upper limits on photon flux

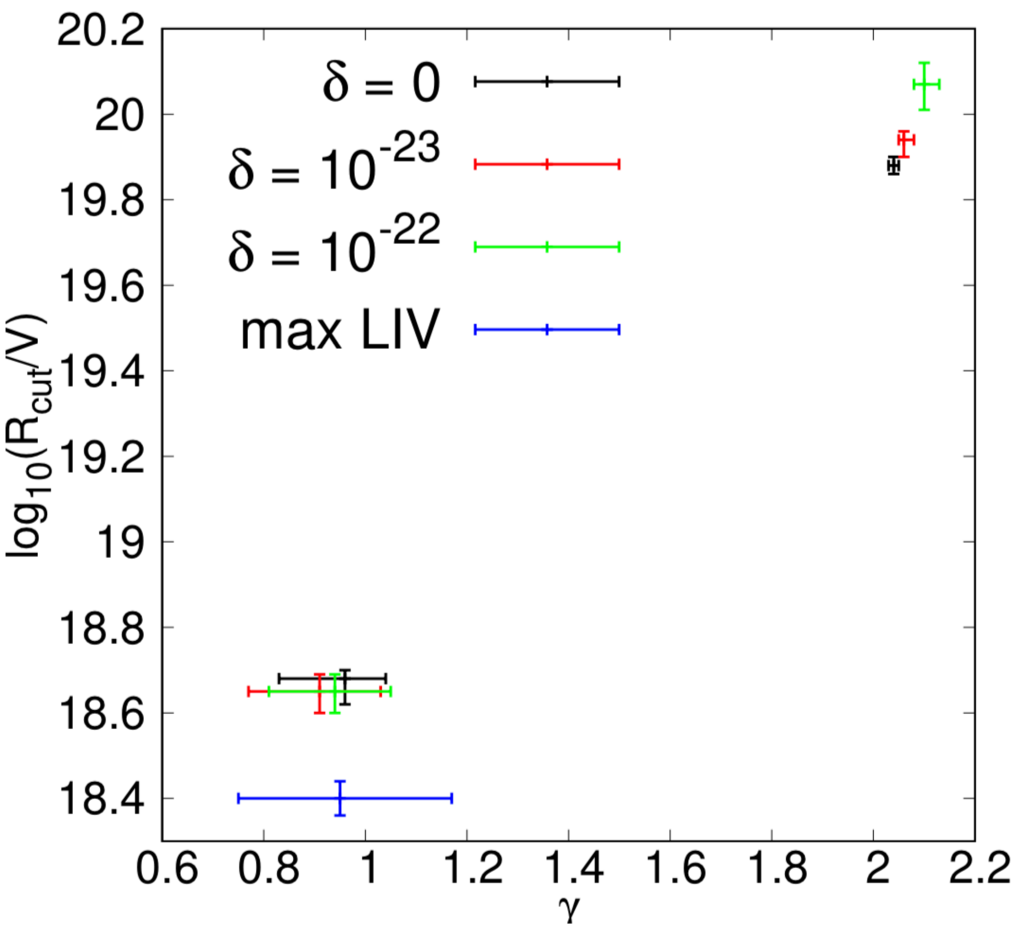






[@R.Guedes Lang, PoS(ICRC2019) 327]

LIV - hadron sector



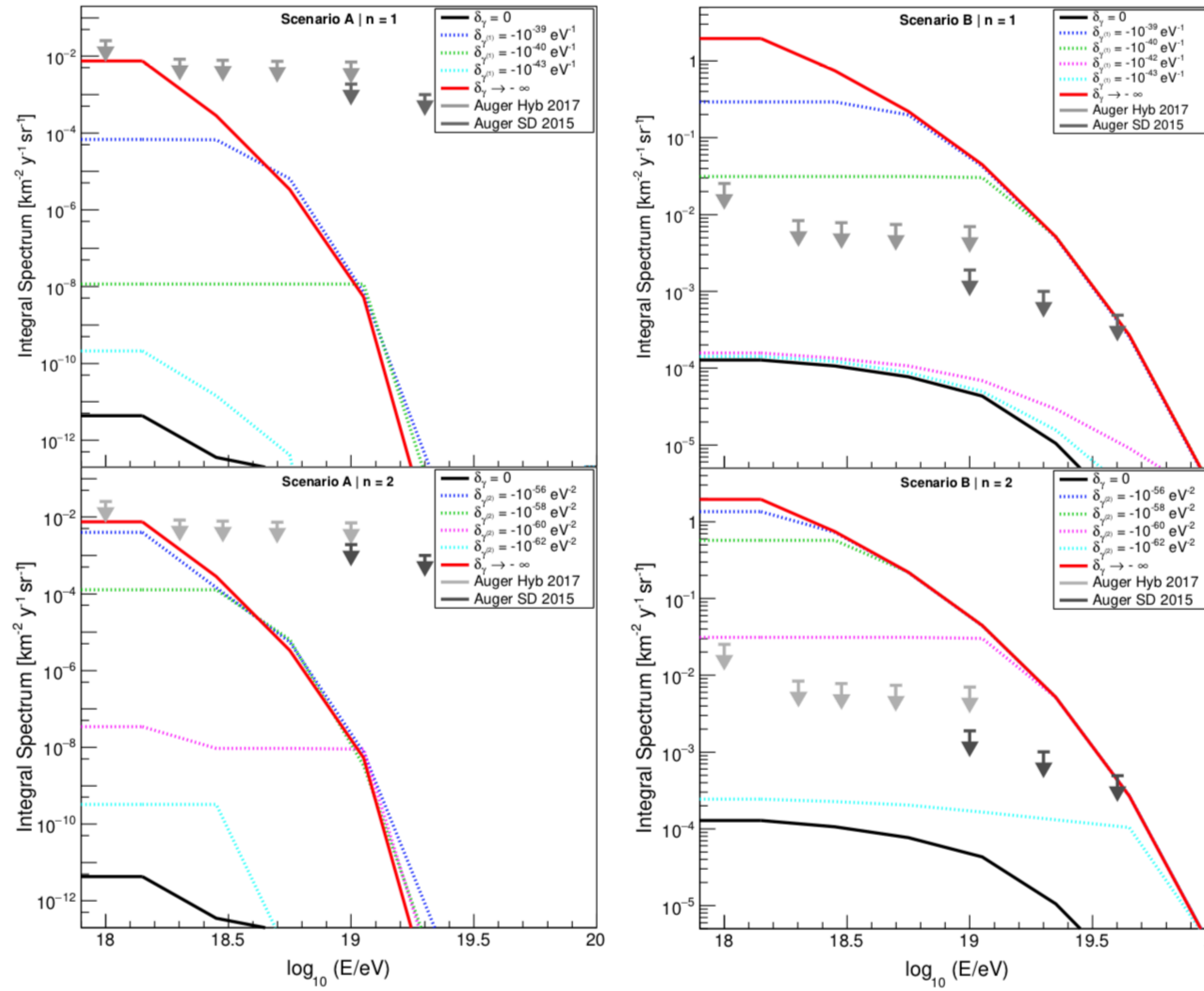
Combined fit

of spectrum+composition

Best fit: low maximum rigidity

LIV effects suppressed by energy

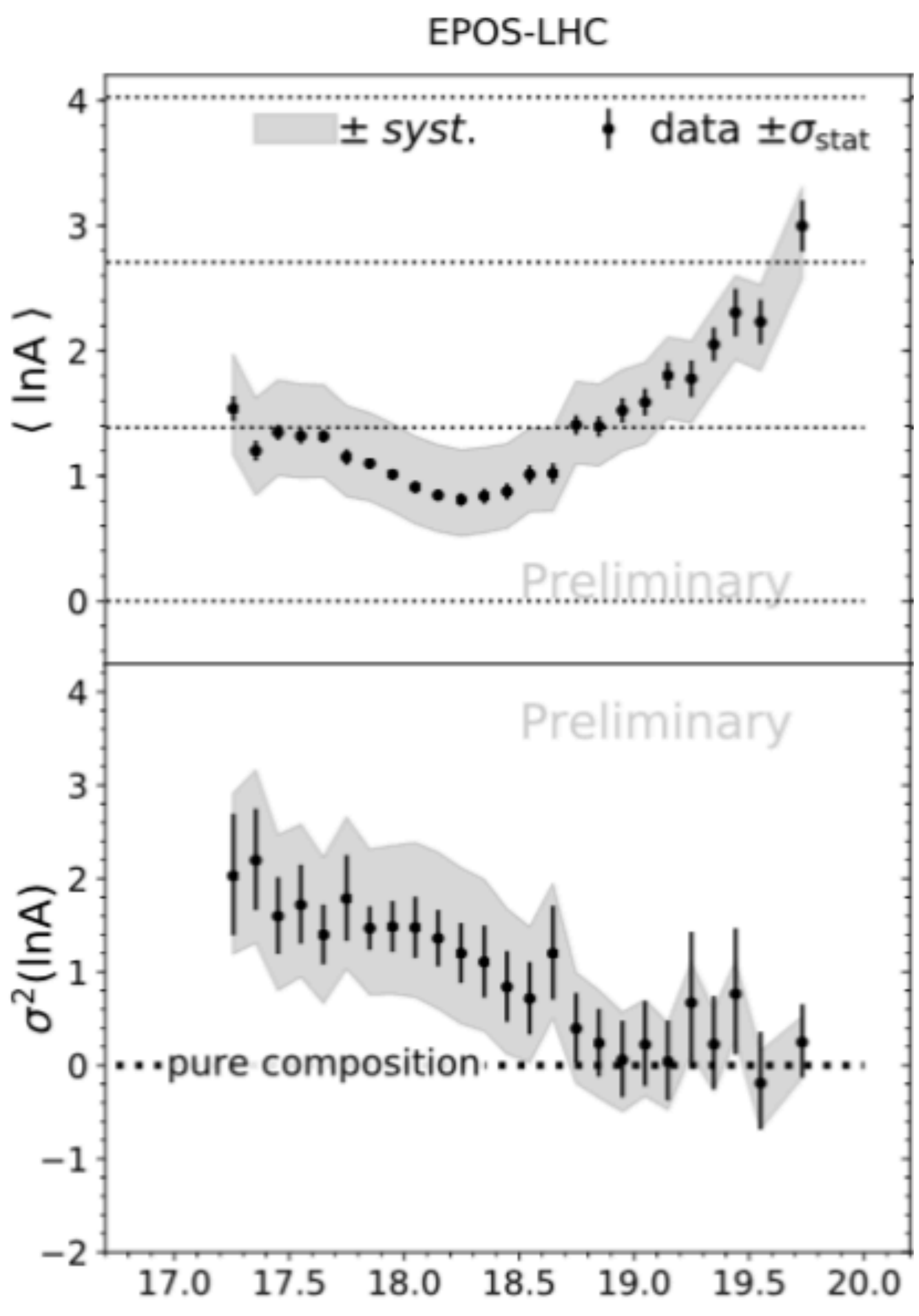
LIV - photon sector



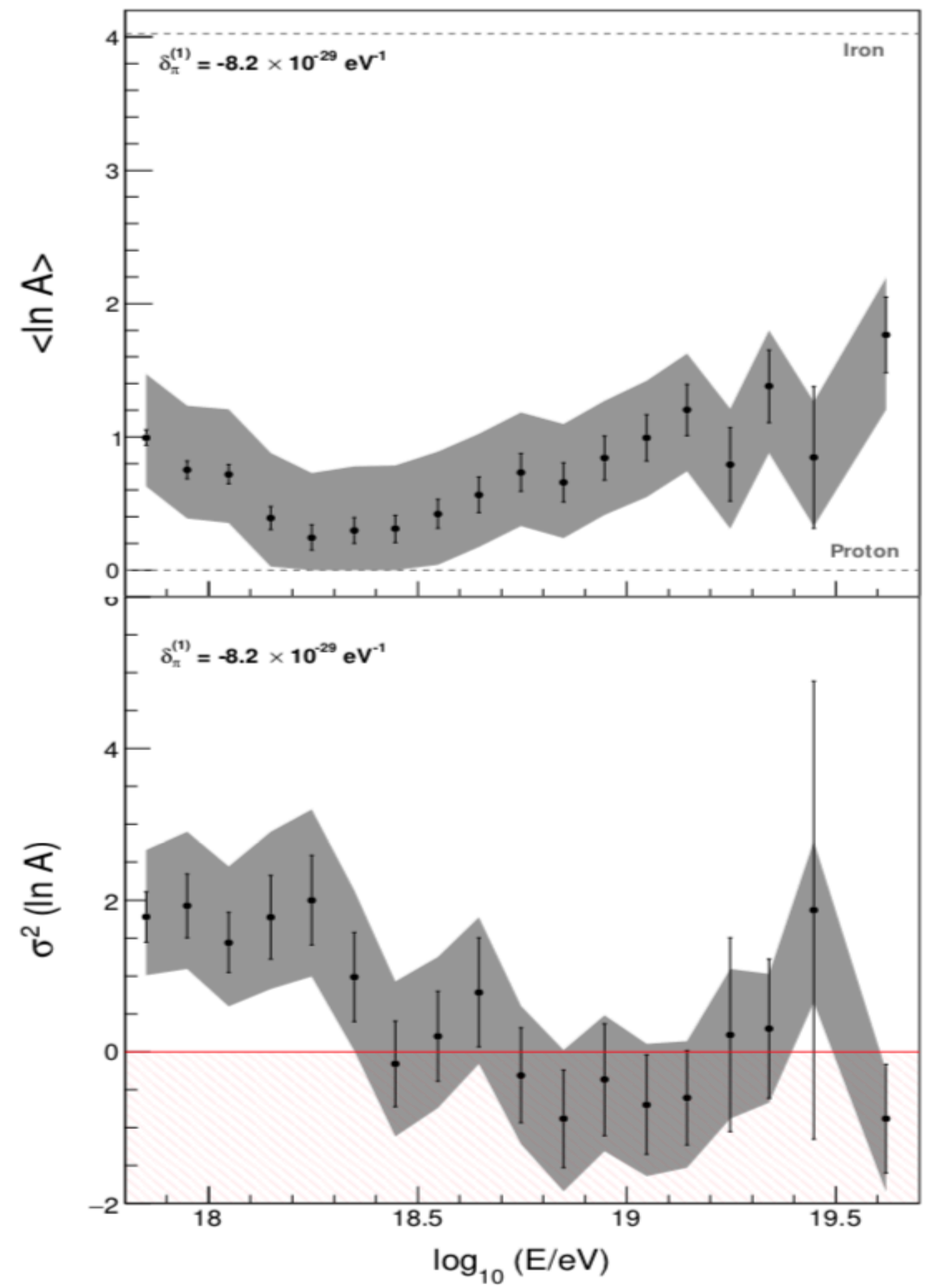
GZK photons propagated following the two scenarios (A=global and B=local minima)

- ➡ A: no limits on LIV can be imposed
- ➡ B: $\delta_\gamma^{(1)} \gtrsim -10^{-40}\,\mathrm{eV}^{-1}$ and $\delta_\gamma^{(2)} \gtrsim -10^{-60}\,\mathrm{eV}^{-2}$.

LIV - air showers



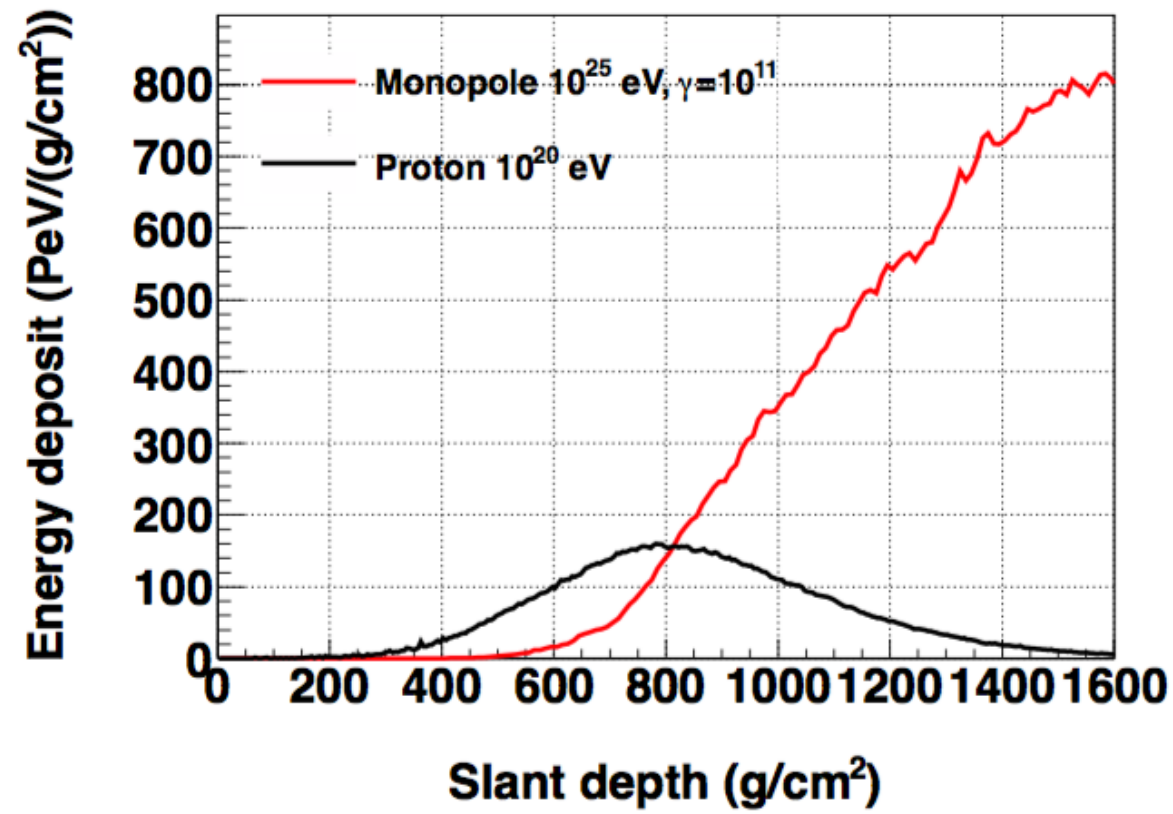
EPOS-LHC, LI

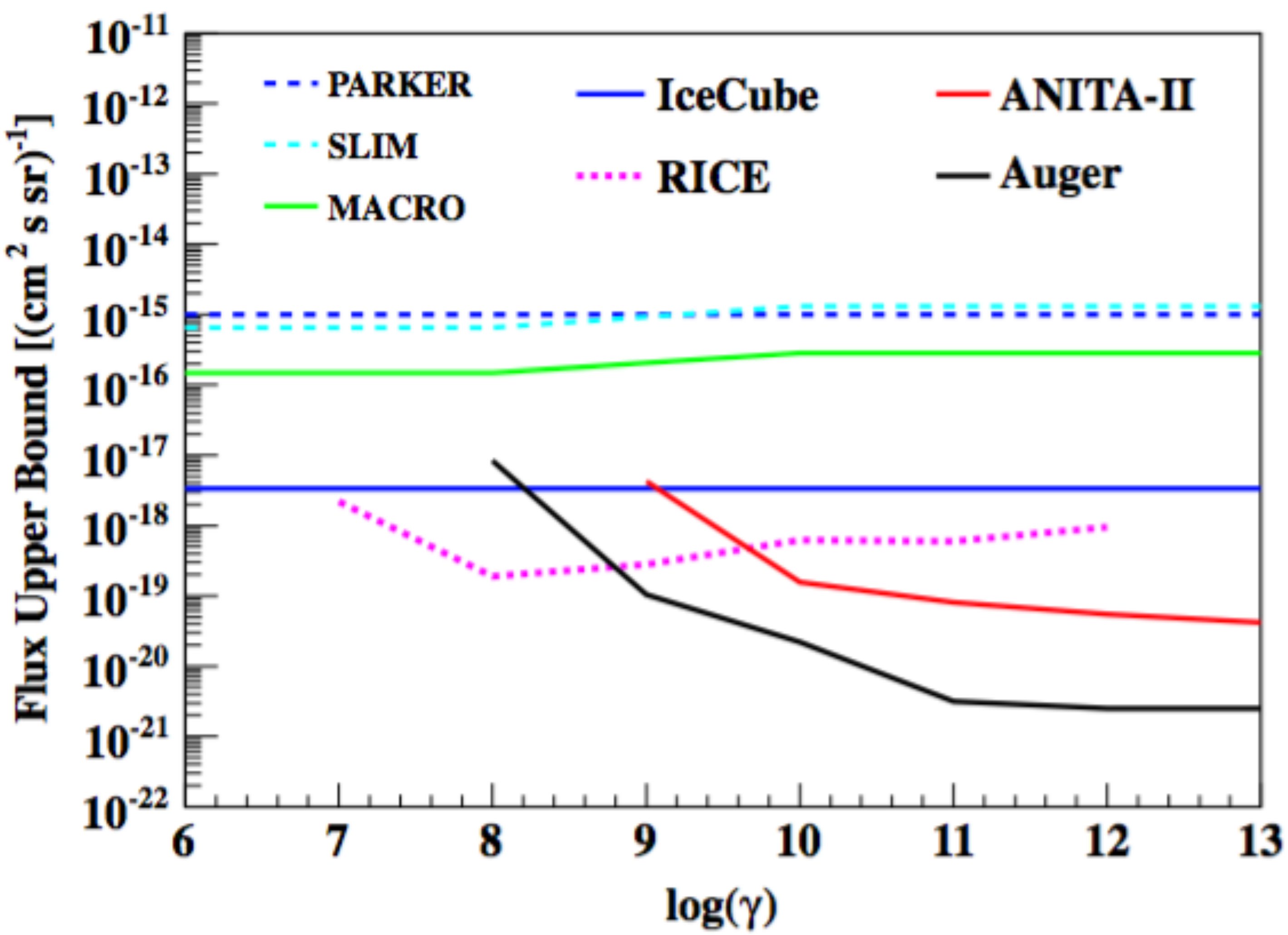


EPOS-LHC, LIV

Searches for magnetic monopoles

- intermediate mass ultra-relativistic monopoles with $M \sim 10^{11}$-10^{16} eV/c^2 (IMM), $E_{mon} \sim 10^{25}$ eV can be present today as relic of phase transitions in the early Universe
- search based on larger energy deposit and deeper development due to superposition of many showers produced by the IMM

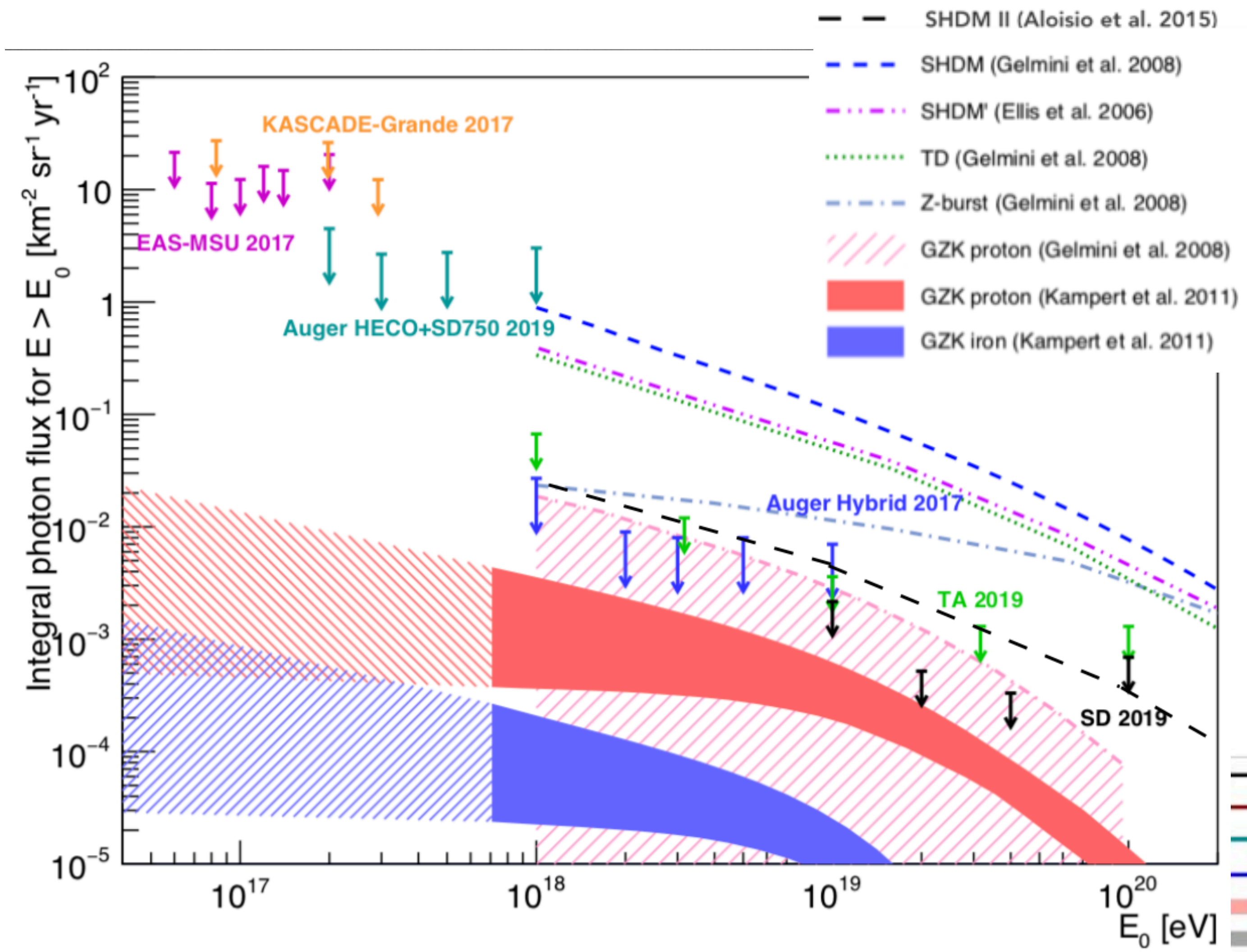




$\log_{10}(\gamma)$	$\mathcal{E}(\gamma)$ (km^2 sr yr)	$\Phi_{90\%\,C.L.}$ ((cm^2 sr s)$^{-1}$)
8	1.16	8.43×10^{-18}
9	9.52×10^{1}	1.03×10^{-19}
10	4.50×10^{2}	2.18×10^{-20}
11	3.15×10^{3}	3.12×10^{-21}
≥ 12	3.91×10^{3}	2.51×10^{-21}

[@A.Aab et al (Auger Coll.) PRD94 (2016) 082002]

Photon fluxes

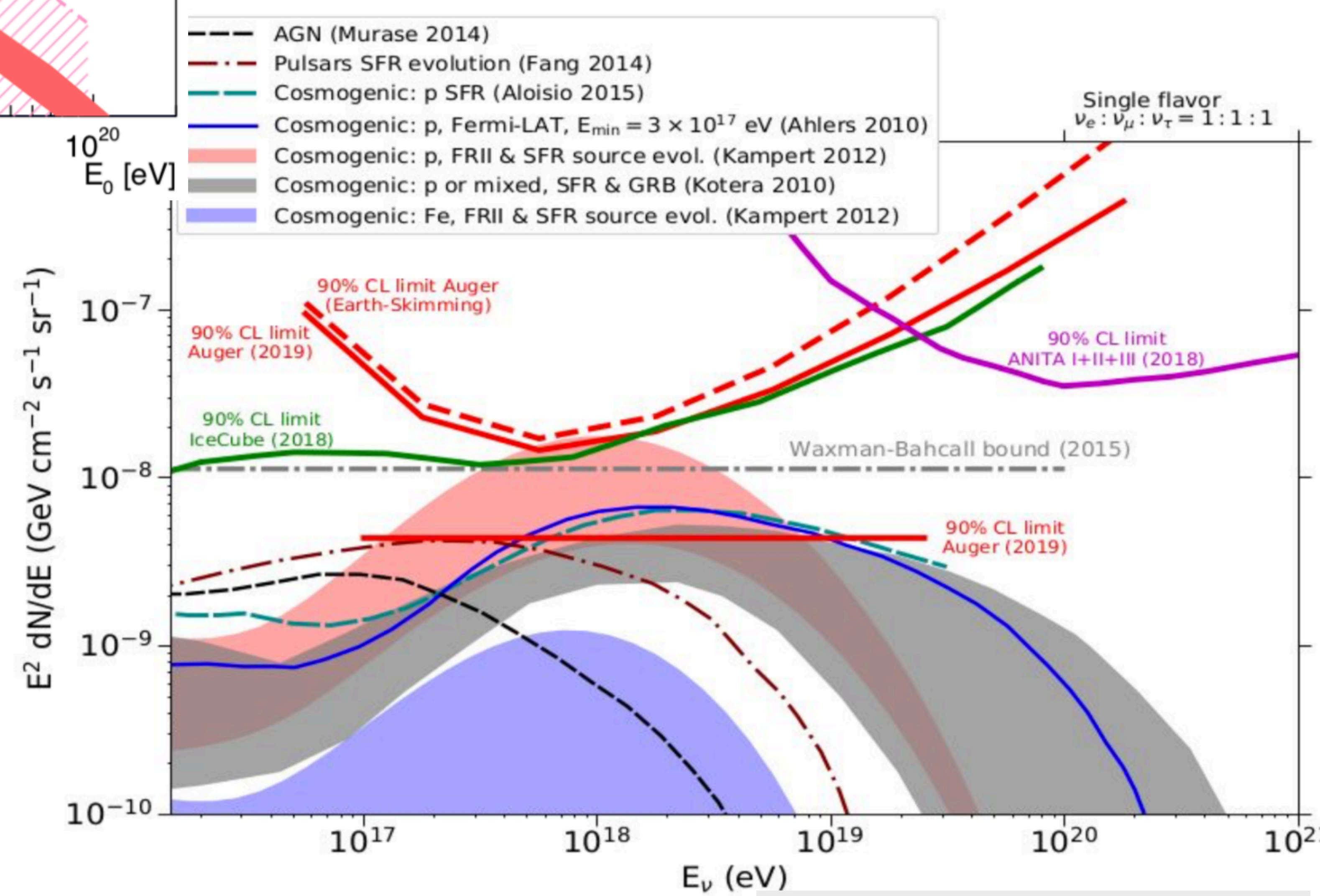


- Most sensitive EAS detector for E_γ>0.8 EeV
- Most optimistic models with proton primaries already excluded
- **Most top-down models excluded by experimental result**
- **Best U.L. $\tau_X > 10^{22}$ yr**

[@J.Rauenberg, PoS(ICRC2019) 398]

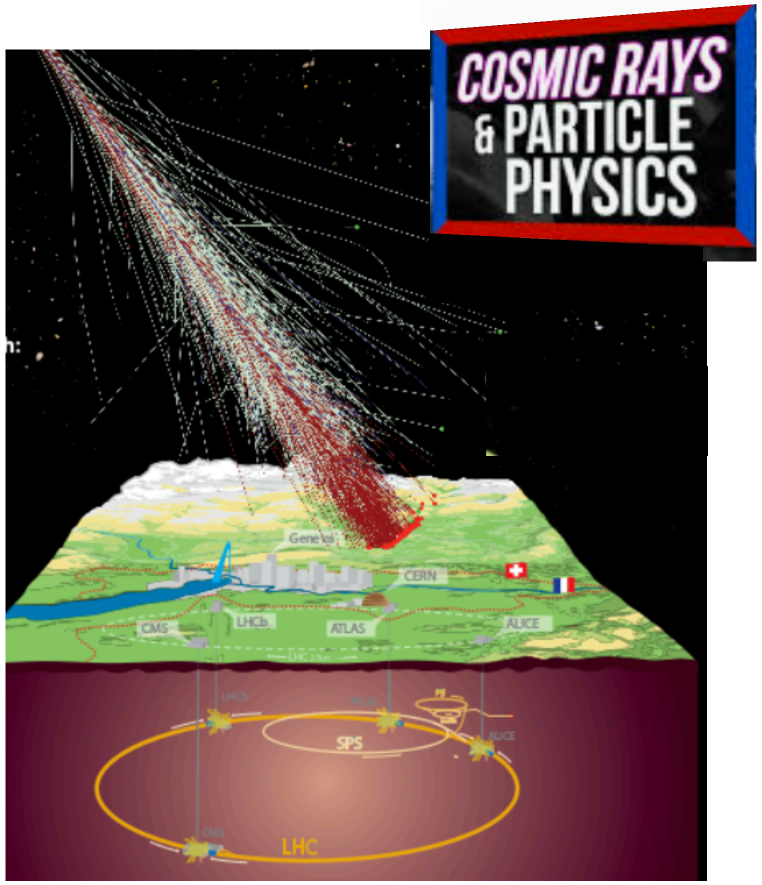
Neutrino fluxes

- Maximum sensitivity around EeV
  k (90% CL) < 4.4. 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}
- Exclusion of a significant region of sources parameter space (z_{max}, m)



[@F.Pedreira, PoS(ICRC2019) 979]

Conclusion



A wealth of information about hadronic interactions came from accelerator experiments, allowing fine-tuning of UHECR models used in simulations.
p-O run foreseen in 2023

More information obtained by CR measurements at UHE and in unexplored kinematic regions and interactions :

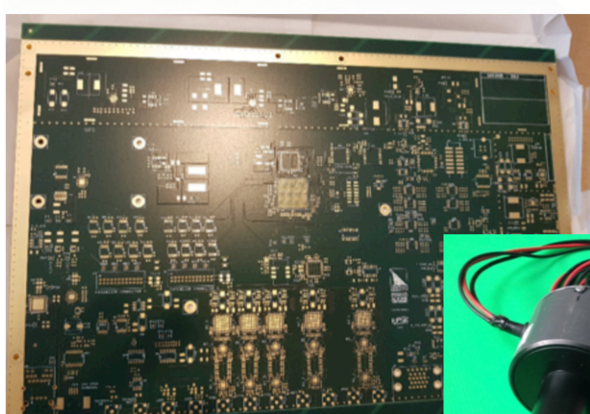
- p-p cross section
- muon puzzle
- muon fluctuations, slope of the muon distribution tail
- BSM searches (monopoles, LIV, top-down models)

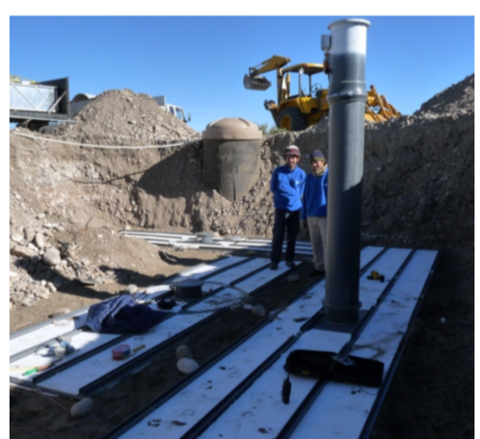
NEXT STEPS

Increase in statistics at UHE
Composition sensitivity at and above the suppression region (E>4 10^{19} eV)
More data on neutrinos and photons
More information on hadronic interactions

Backup

UHECR future: AugerPrime





a large exposure detector with composition sensitivity above ~4 10^{19} eV

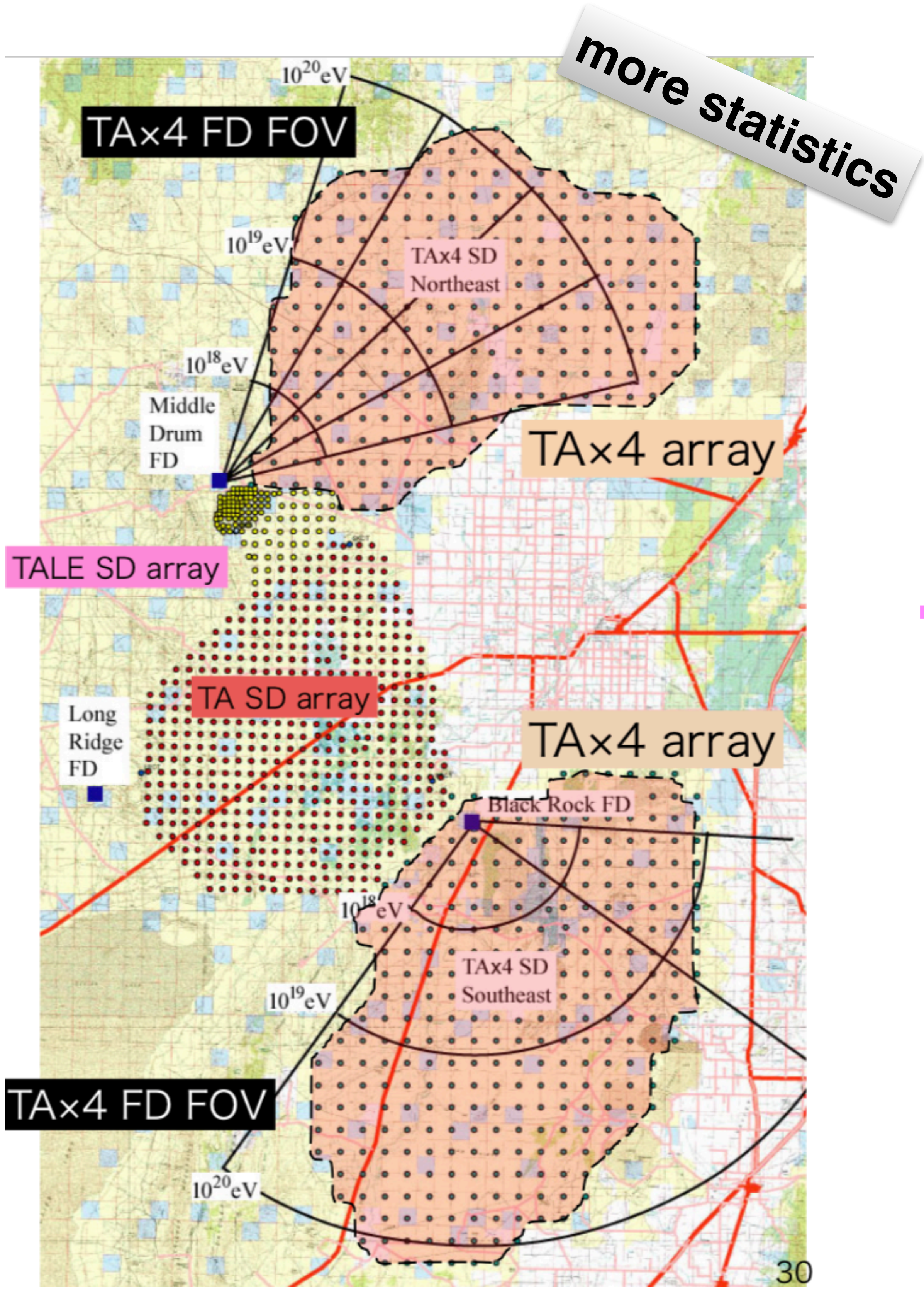
- ➡ 12 upgraded stations (Engineering Array) since 2016 with new electronics, higher sampling, large dynamic range
- ➡ the SSD preproduction array: 80 stations (since March 2019)
- ➡ 356 SSD stations already deployed
- ➡ Underground Muon detector
- ➡ the world-largest radio detector (3000 km^2)

more statistics, more observables

[A.Castellina+, EPJ Web Conf., 210 (2019) 06002]

UHECR future: TAx4

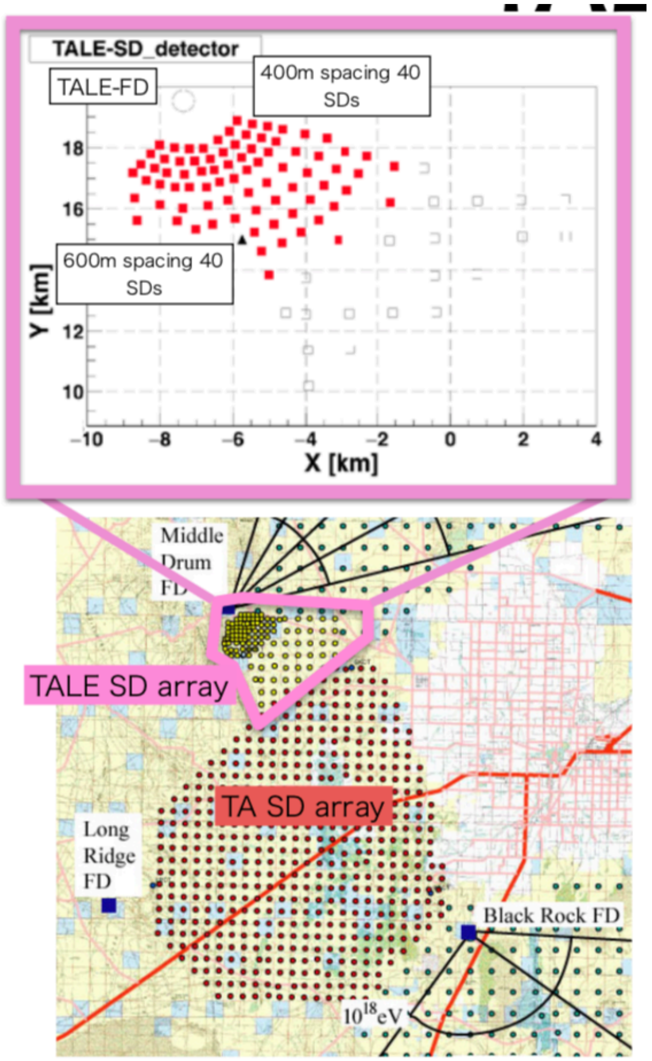
increase the coverage to ~3000 km² to
increase the statistics at UHE



➡ the SD array: increased by 500 stations with 2 km spacing

➡ the FD telescopes: increased by 4 FD in the Northern site, 8 in the Southern site

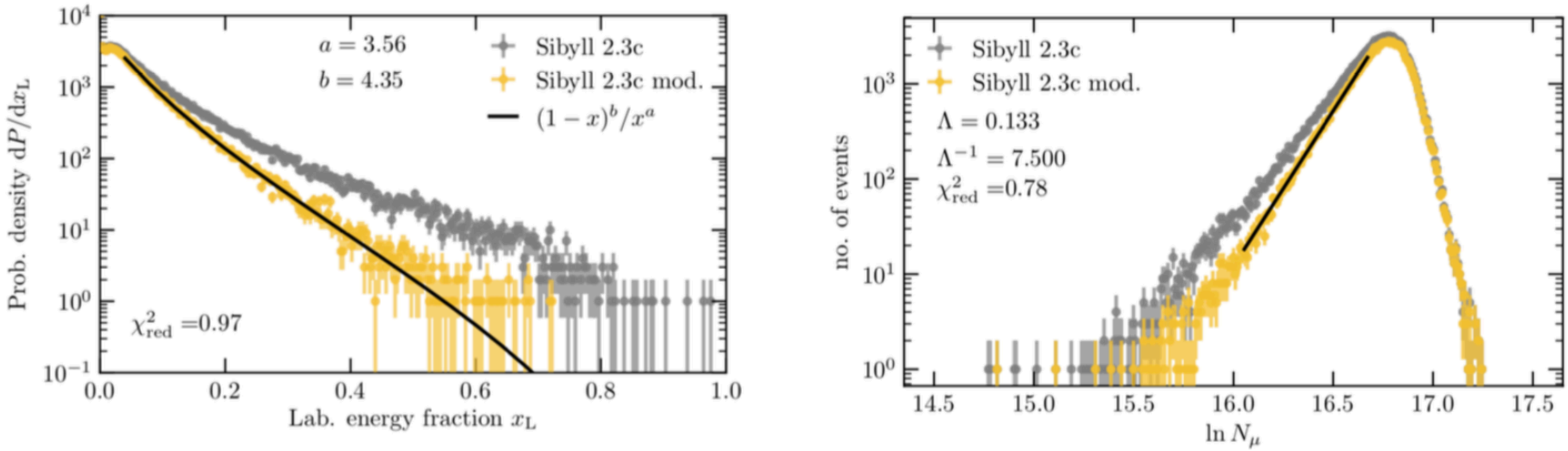
➡ TALE hybrid = low energy extension of TA hybrid sensitivity down to 10^{16} eV, with FDs observing higher elevation, Densely-arrayed SDs



[S.Ogio, Highlight Talk, PoS(ICRC2019) 013]

More information from muons in EAS

The slope Λ_{had} must be connected to the energy spectrum on neutral pions:
$E_{em} = 1 - E_{had}$ —> same fluctuations



MC simulations: changing the HE tail of the π^0 produces a change in the tail of the N_μ distribution

Λ_μ depends on the energy given to the leading pion

[@R.Conceiçao, PoS(ICRC2019) 226]

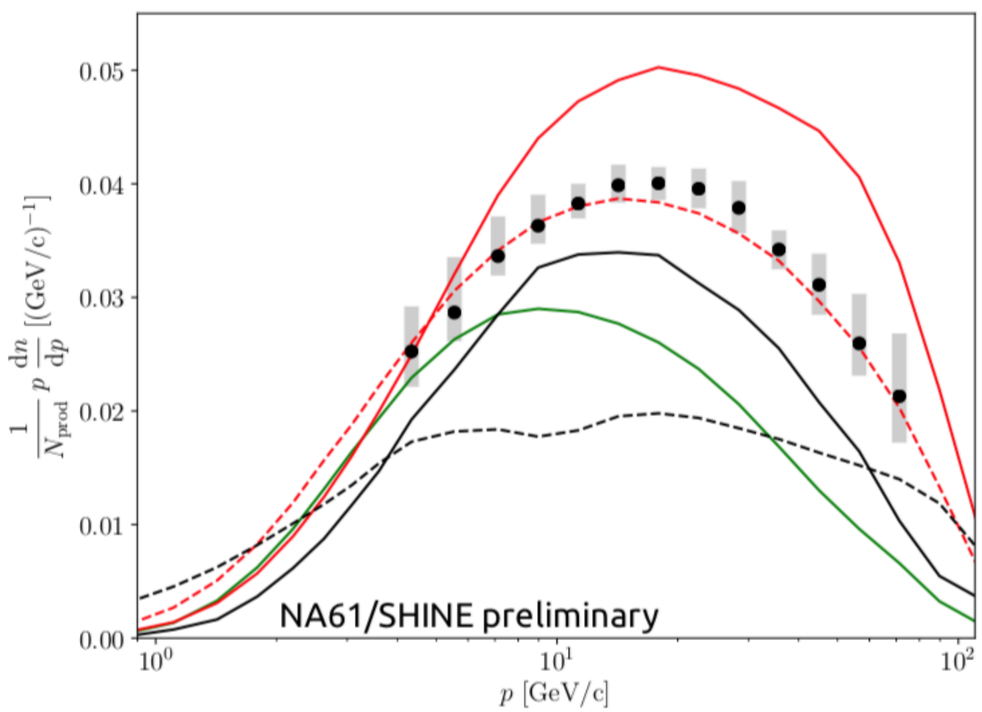
Solving the puzzle?

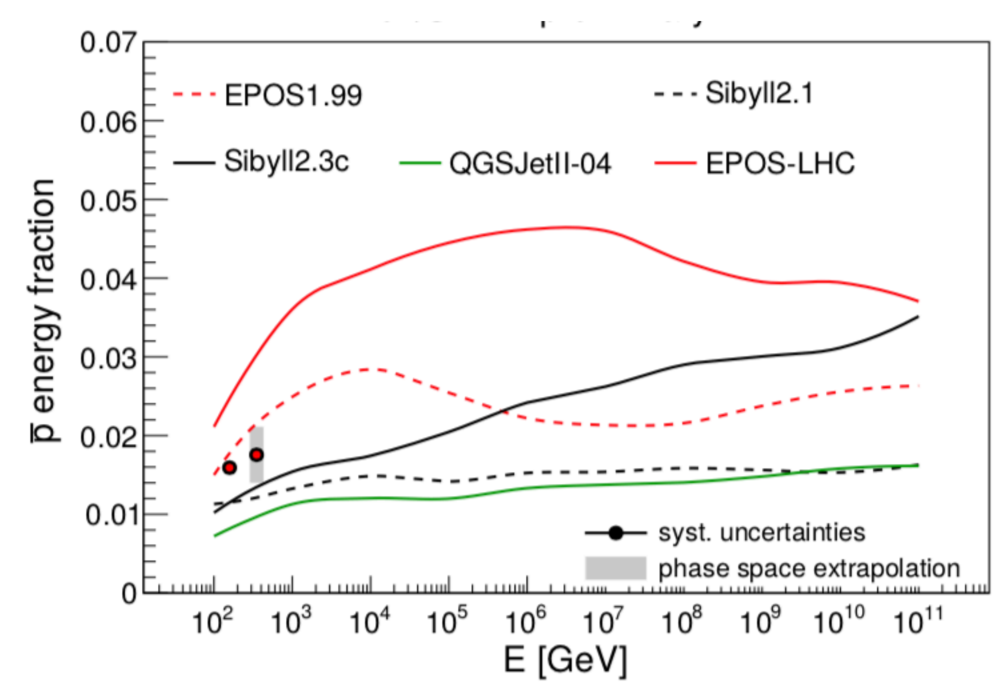
Hadronic interactions in EAS: π+Air

Energy fraction in each interaction $f \sim (2/3 + X)$ and $(1-f) = (1/3 - X)$ to π^0

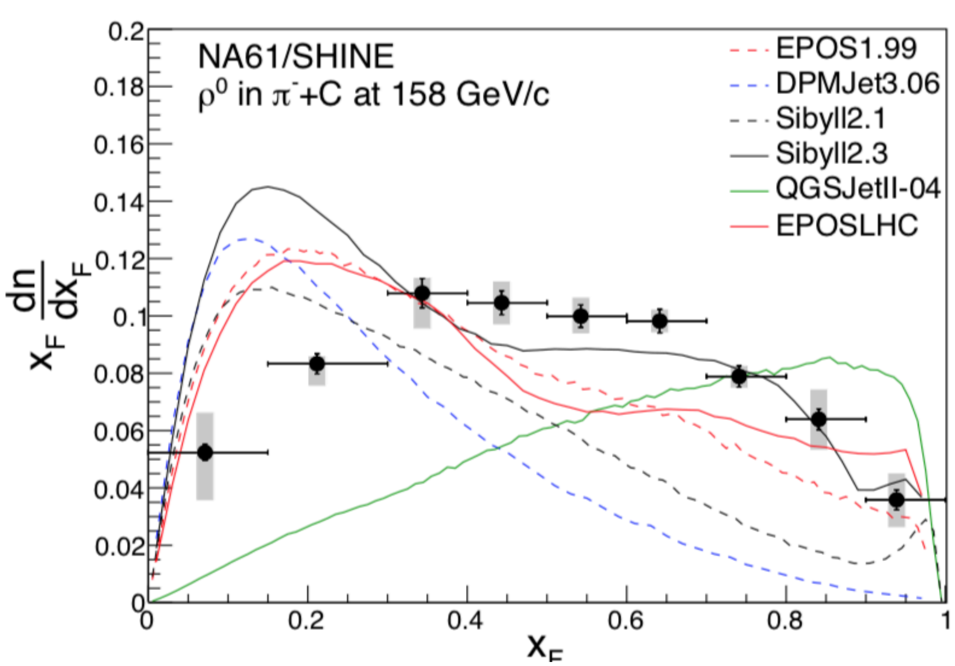
to $\pi^\pm$ to ρ^0, baryons and anti-baryons

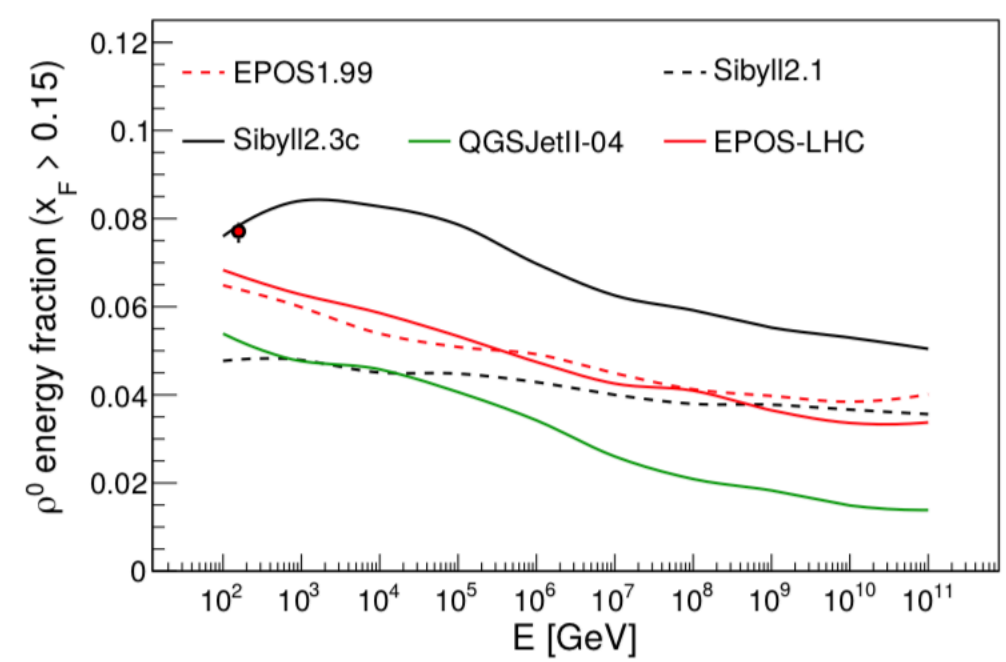
Increasing the baryon-antibaryon production





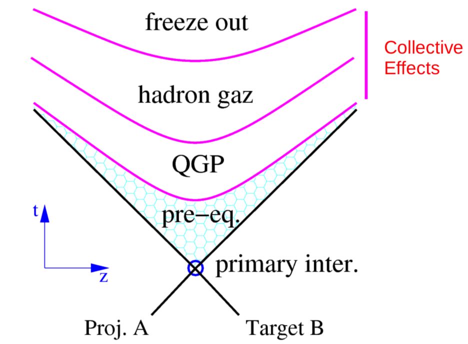
Leading particle effect: ρ^0 in place of π^0





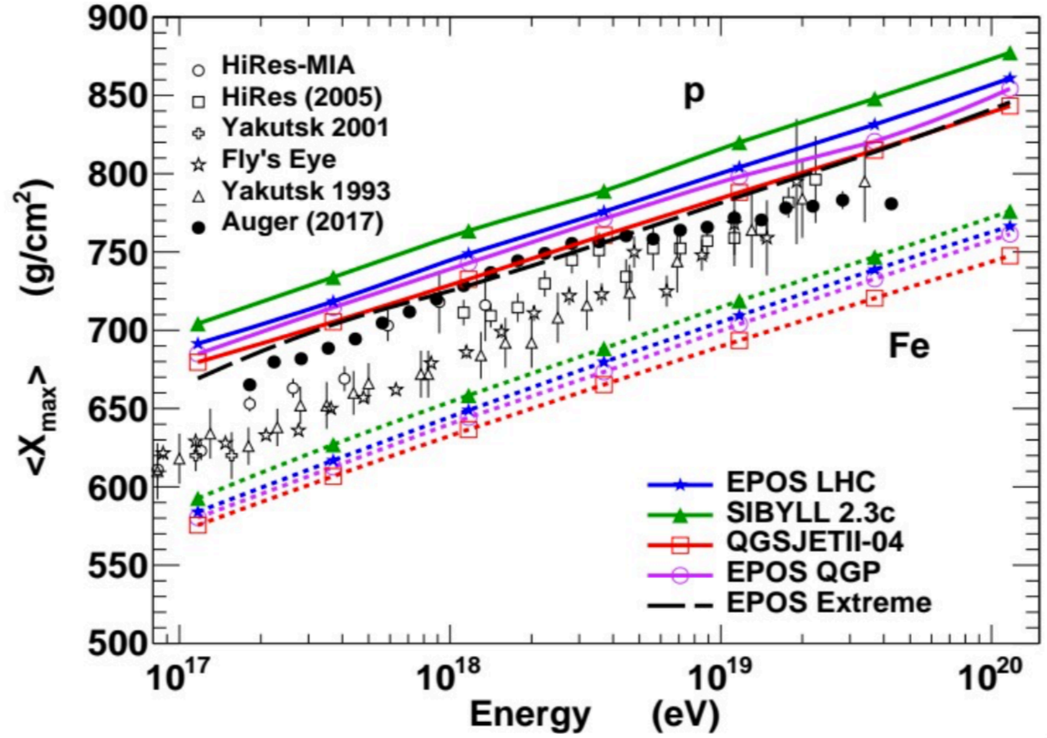
[M.Unger, PoS(ICRC2019) 446]

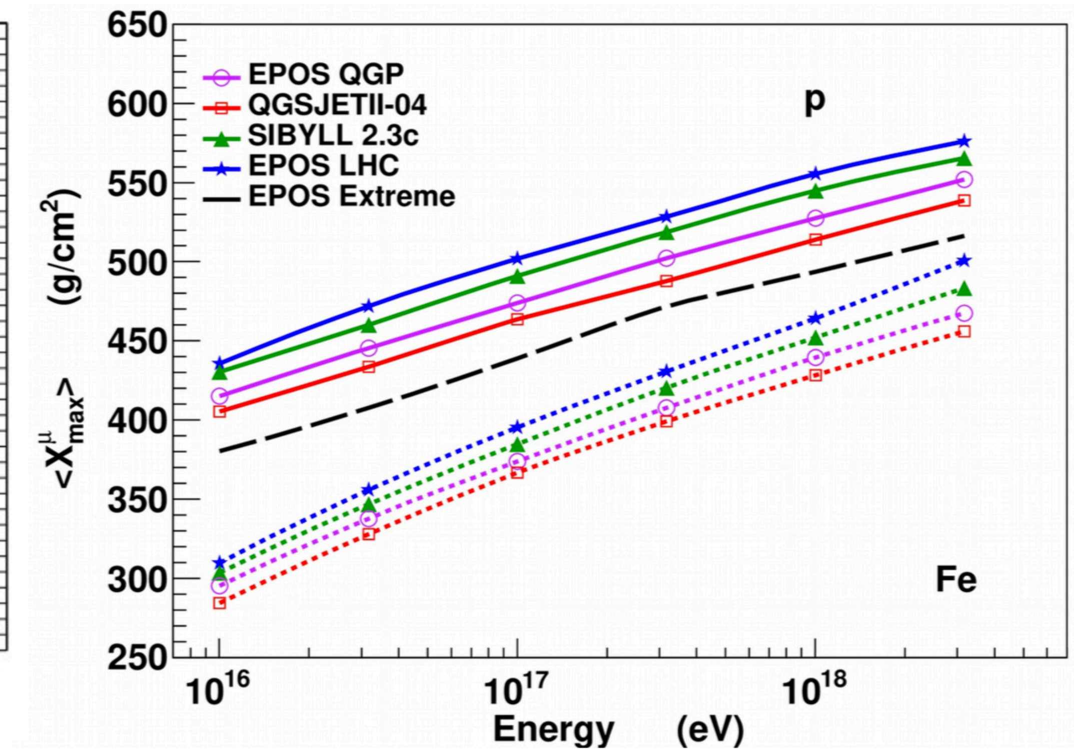
Solving the puzzle?



Collective hadronization: QGP

Production of higher mass particles not suppressed=more massive hadrons





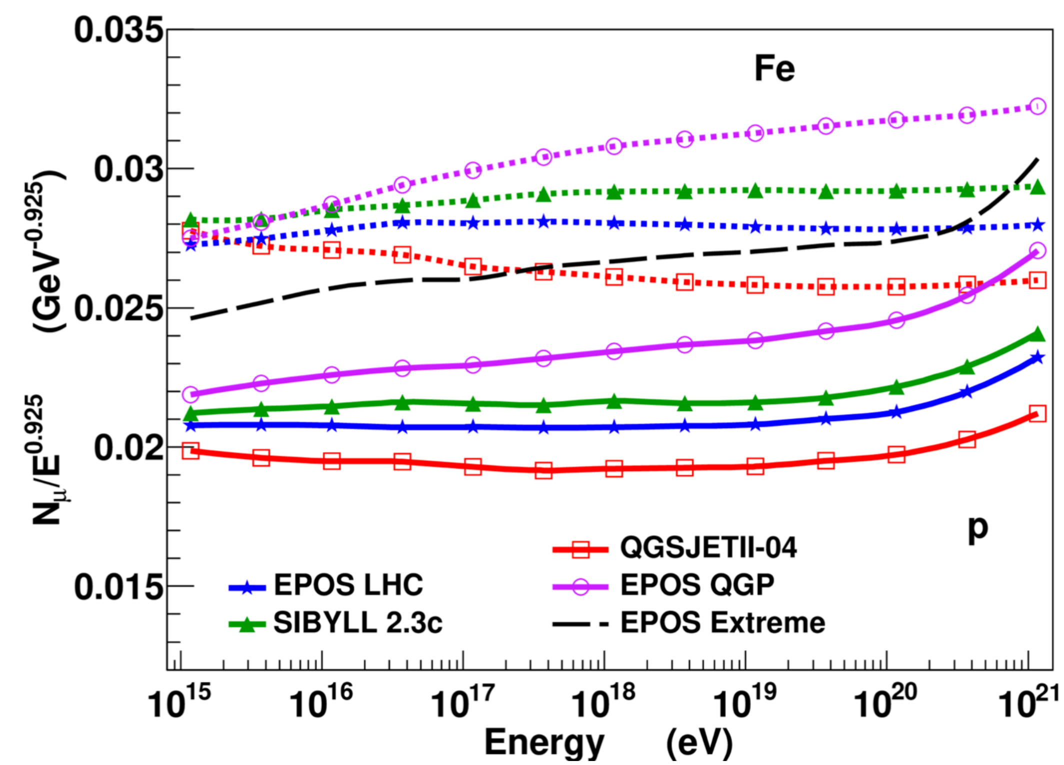
EPOS-QGP

Xmax almost not affected (reduced by few g/cm² only)

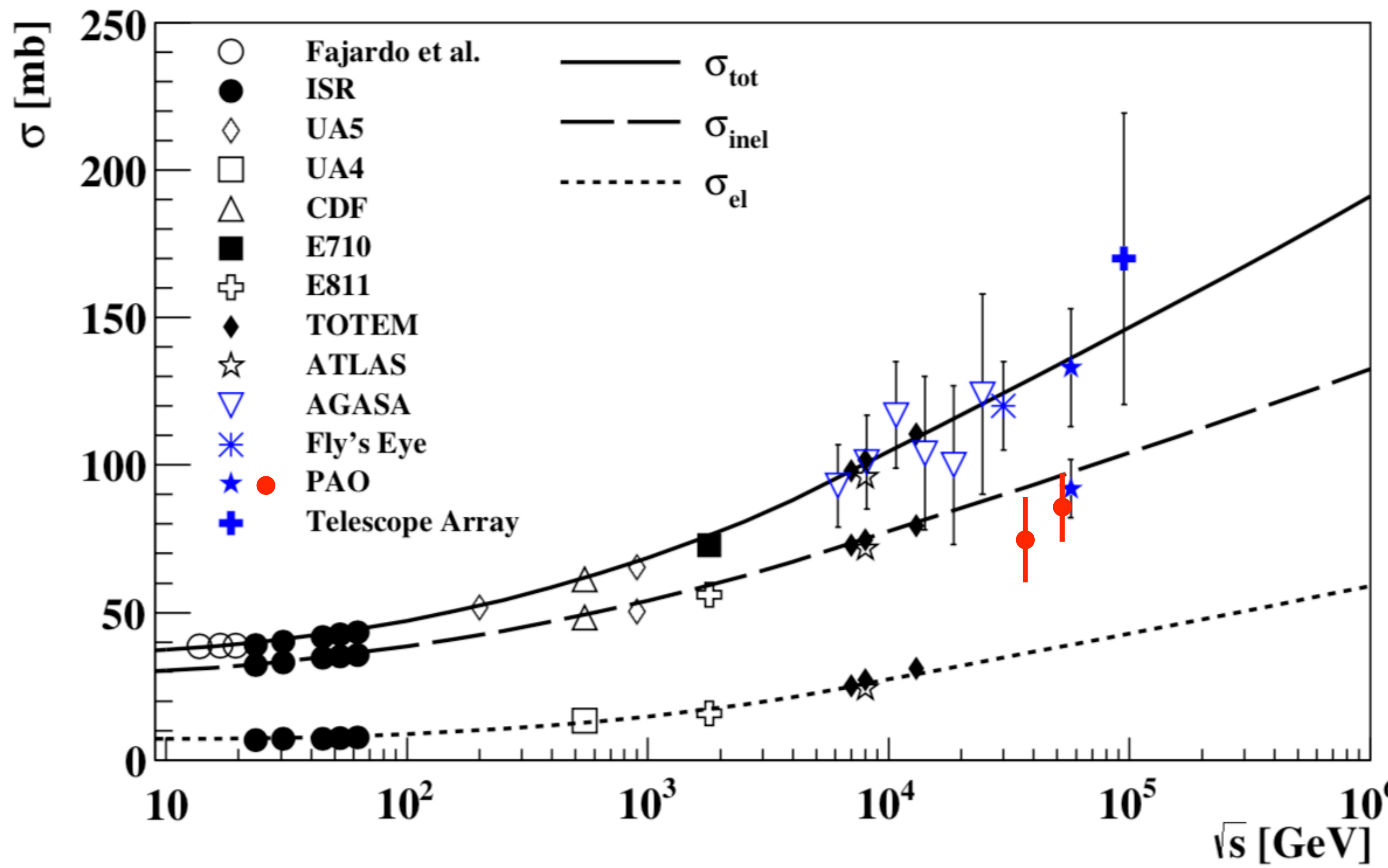
X^{μ}_{max} shallower wrt to EPOS-LHC

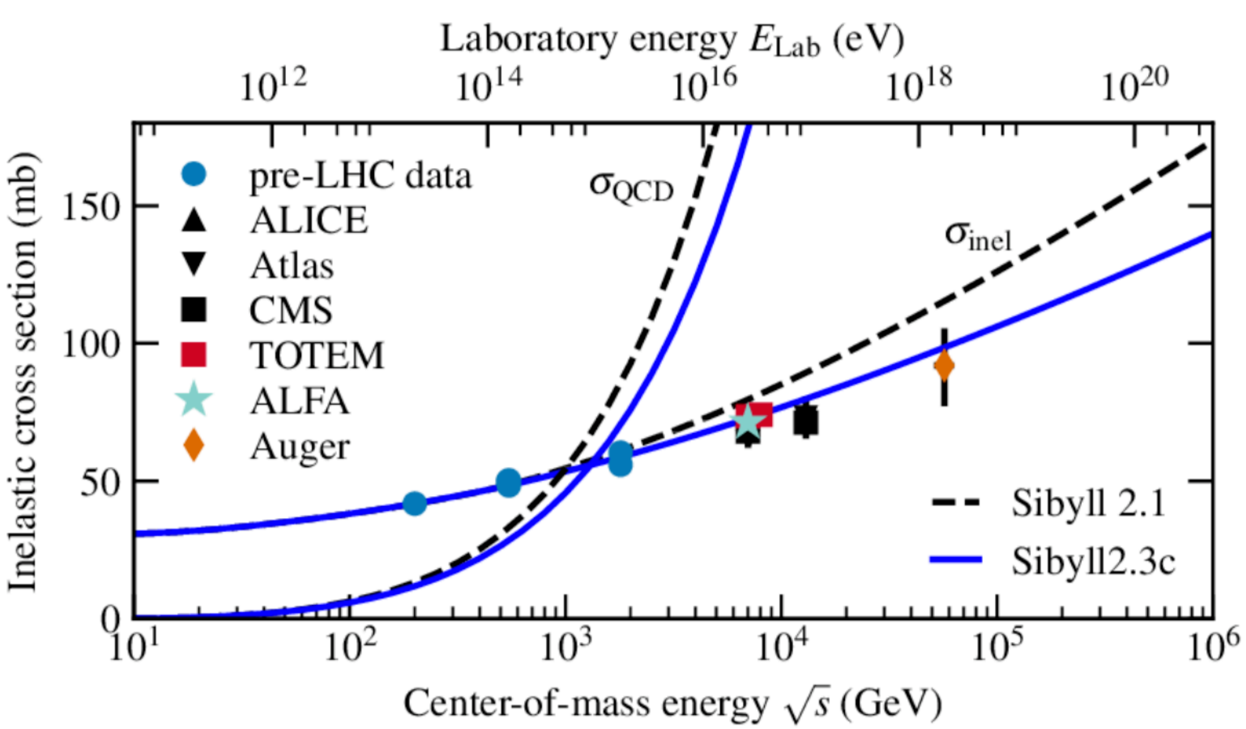
Slope of muon production larger wrt other models

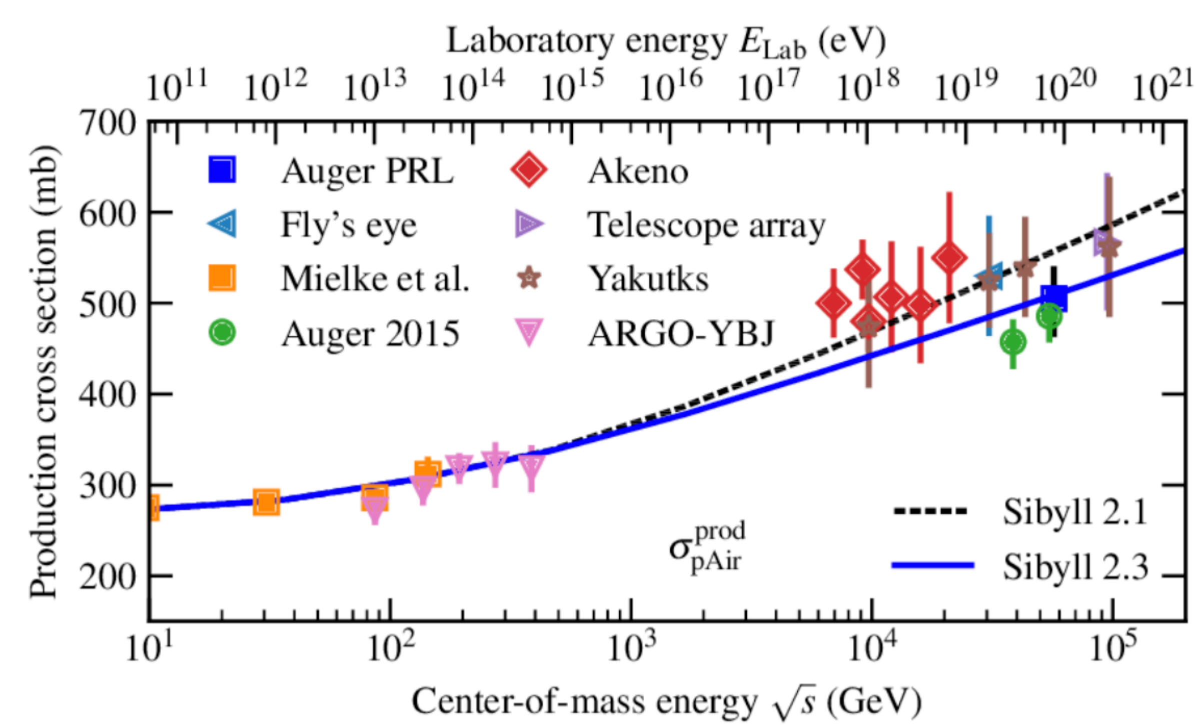
Not enough to reproduce data



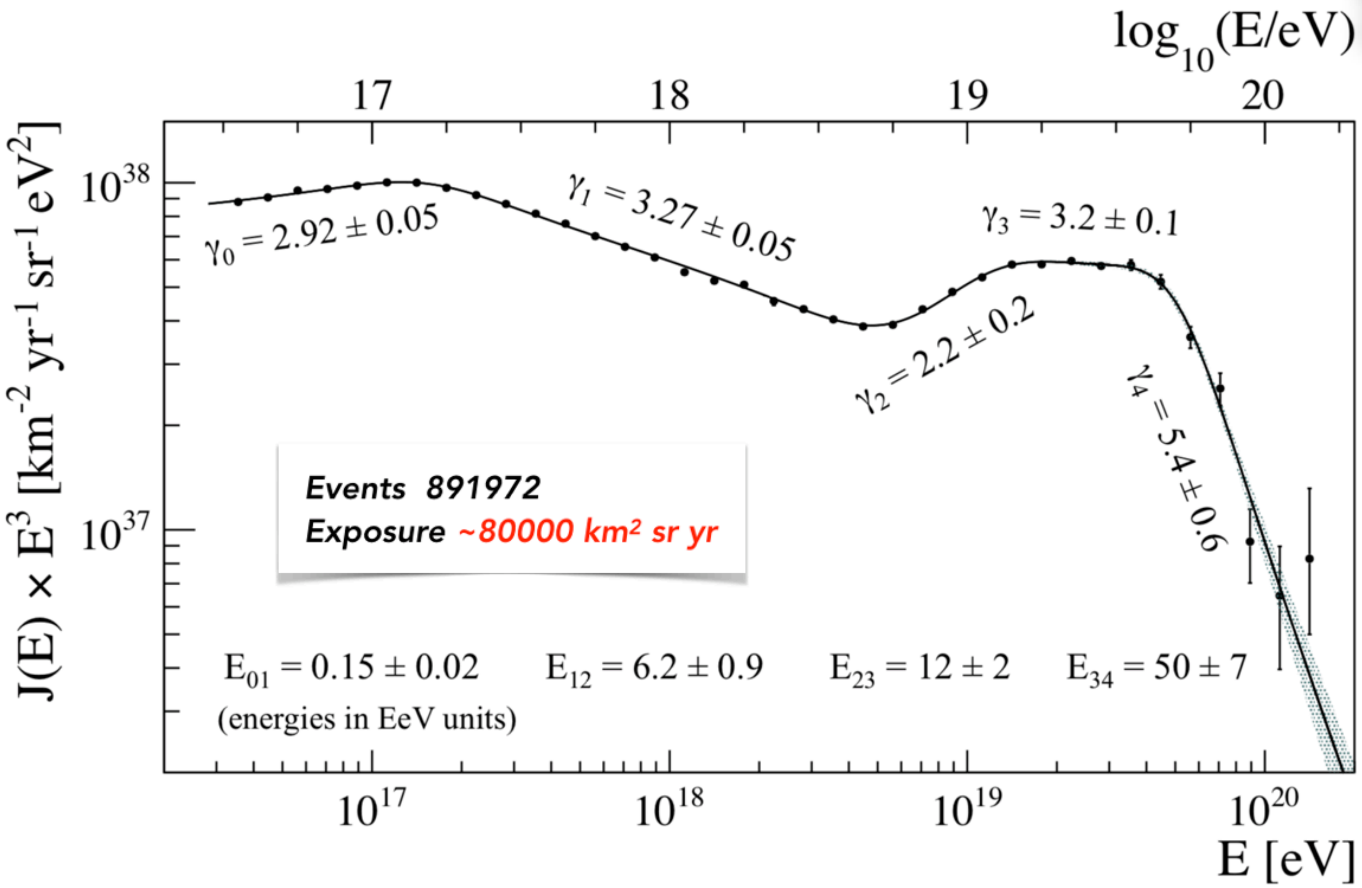
The p-p cross section







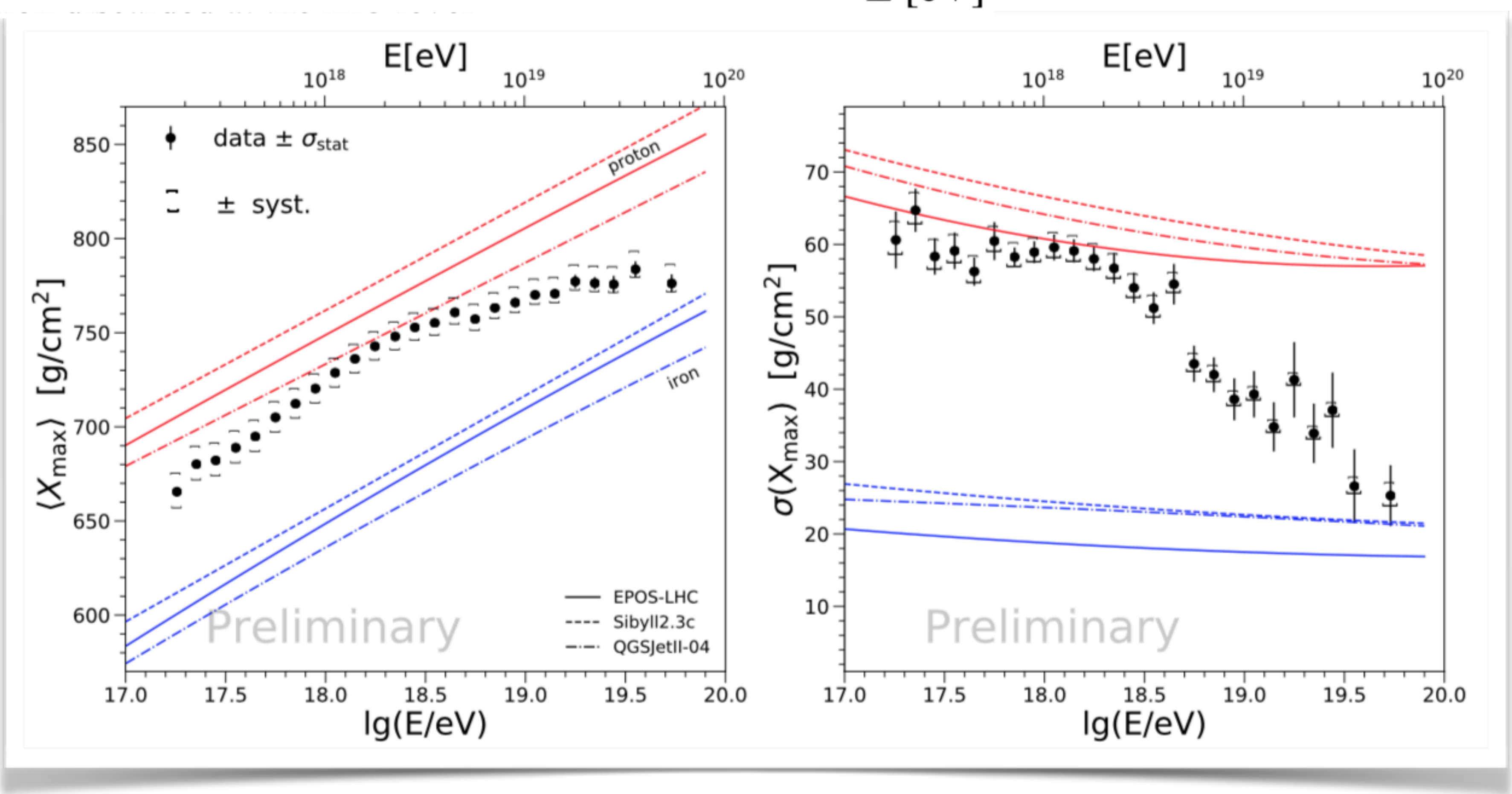
Some results from Auger



$\sigma(E_{FD})/E_{FD}$ ~ 8%

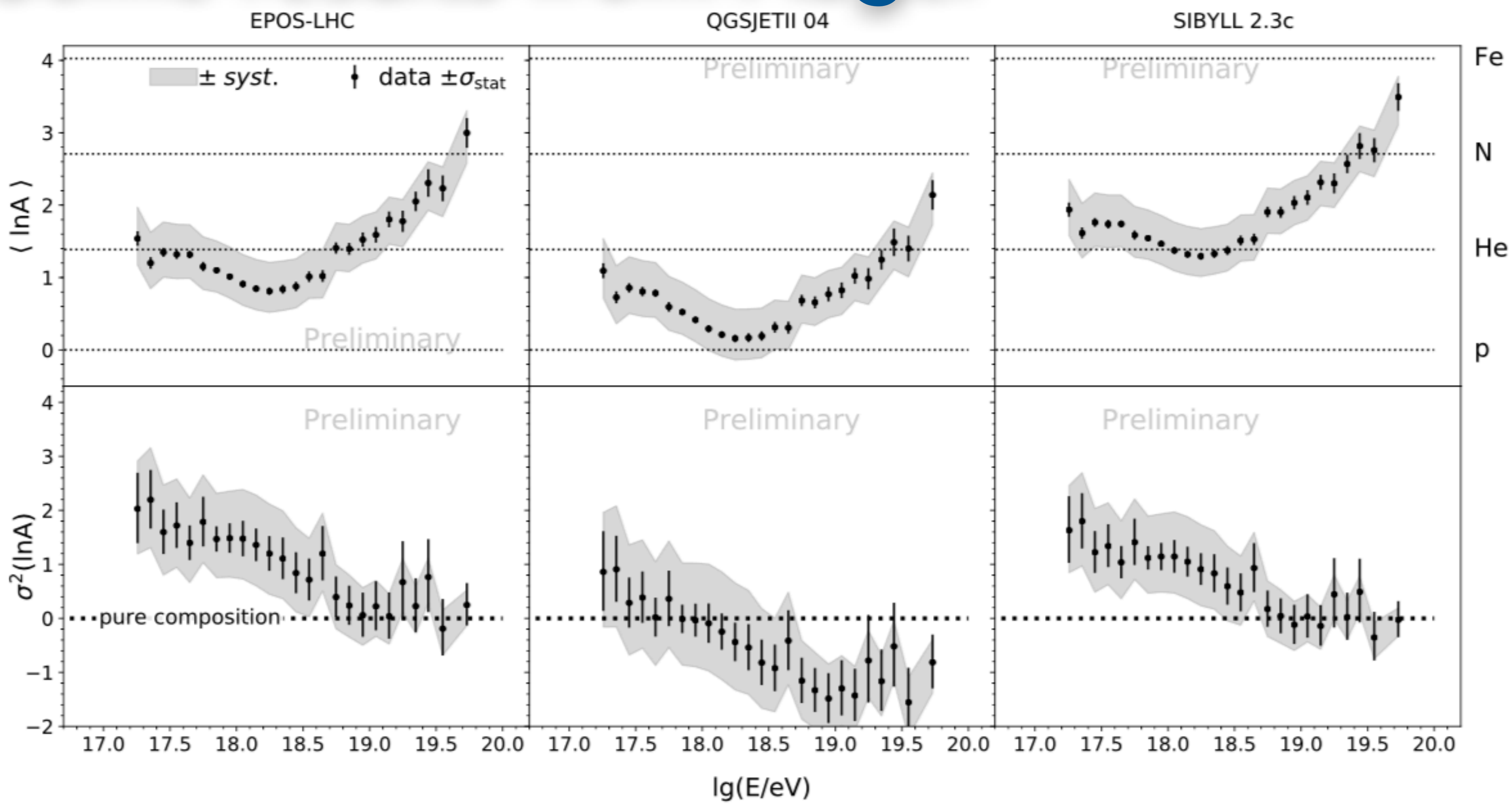
$\sigma(E)/E$ ~ 12% to 8% for increasing E

Systematic uncertainty on energy scale 14%



[A.Castellina, PoS (ICRC2019) 004, Auger Highlight Talk]

Some results from Auger



$$\langle lnA \rangle = ln\ 56\ \frac{\langle X \rangle - X_p}{X_{Fe} - X_p}$$

with X=X_{max} or X^{μ}_{max}