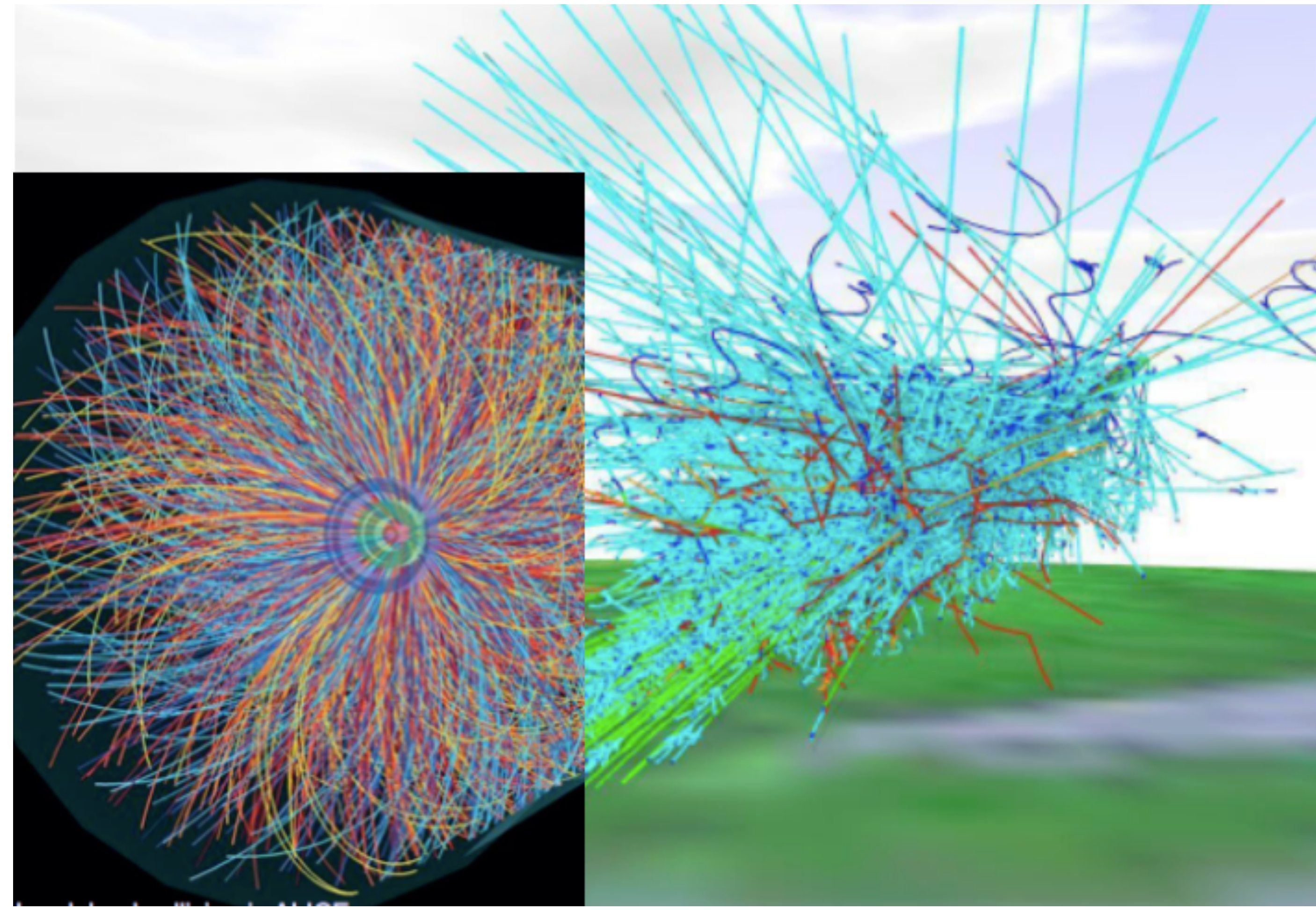
Extensive air showers and hadronic interactions at the highest energies



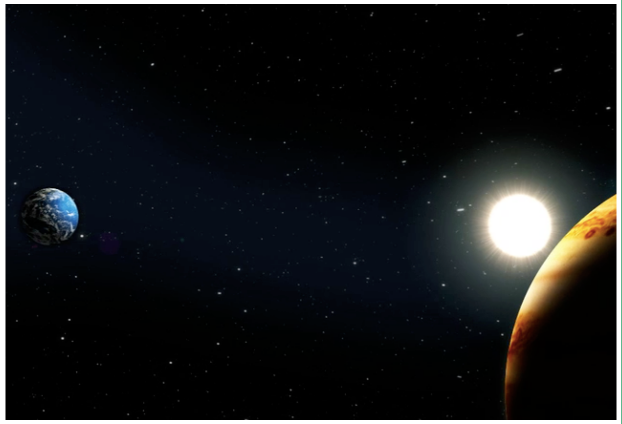
Antonella Castellina
INFN & INAF, Torino

Ultra High Energy Cosmic Rays - science case

What are the sources of the highest energy particles in the Universe?
How are they accelerated ?

cosmic ray sources
distribution
spectrum
composition

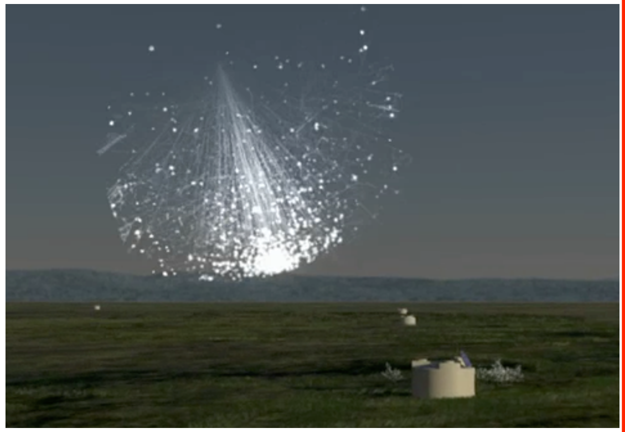
How do they propagate through the intergalactic space and its magnetic fields ?



propagation model

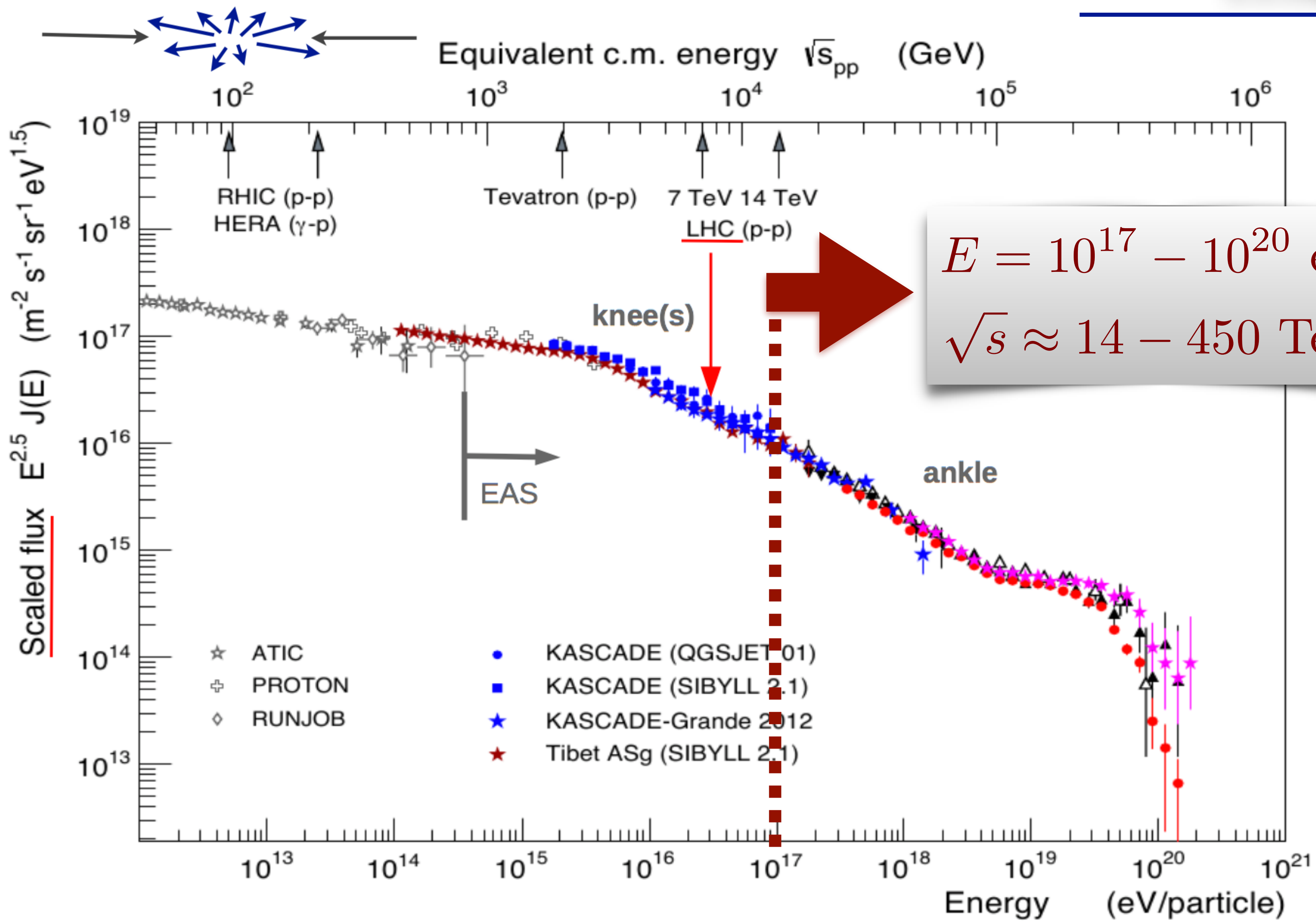
astrophysics	physics
magnetic fields	EM and hadronic
photon background	interactions
matter distribution	cross section

Despite an incredibly low rate, ~ 1 km^{-2} $century^{-1}$ above 10^{20} eV, can we study them from Earth?

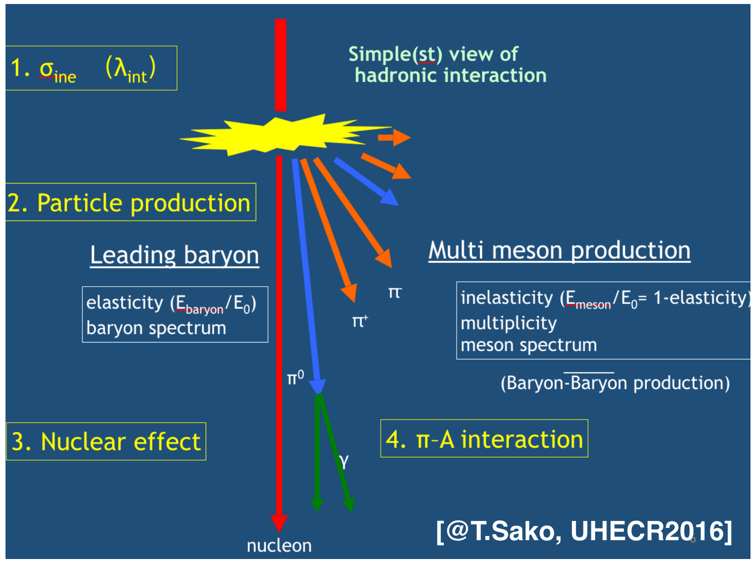


dedicated detectors
energy spectrum
composition
arrival directions

...but there is more !



$$E = 10^{17} - 10^{20}\ \mathrm{eV}$$
$$\sqrt{s} \approx 14 - 450\ \mathrm{TeV}$$



Laboratory energy

- Kinematic regions not reachable by accelerators
- Tests of fundamental interactions in extreme energy regimes
- Tests of hadronic interaction models

- \+ constrain or find hints of new phenomena (ultra-relativistic monopoles, violation of Lorentz invariance,...)

Extensive air showers

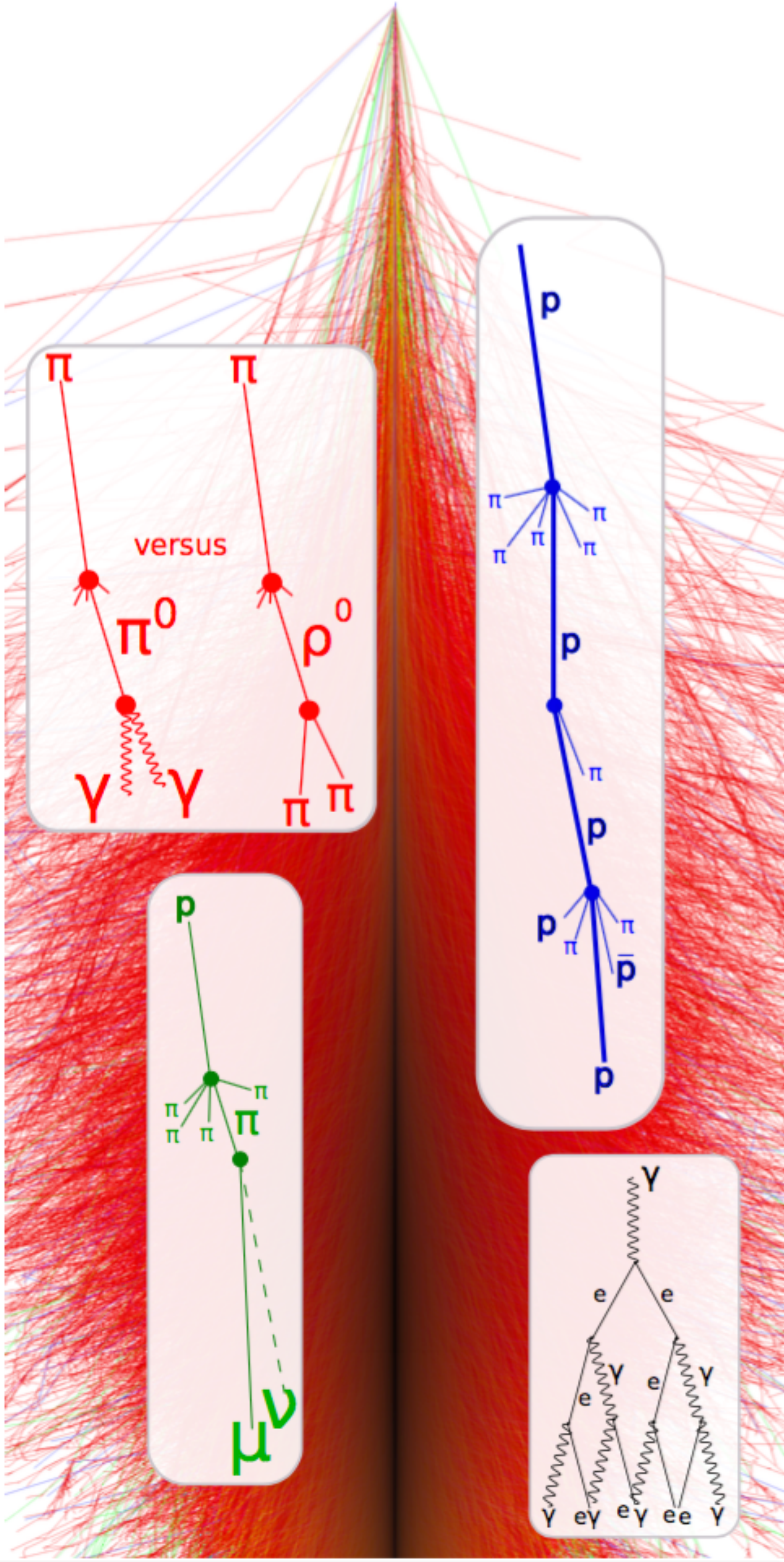
Primary particle interaction after crossing a column density X_0

$$p + Air \rightarrow hadrons$$
$$A + Air \rightarrow hadrons$$
$$\pi + Air \rightarrow hadrons$$

Components:

- hadronic : leading baryon, charged π, K, resonances, low energy nucleons, (anti)baryons
- electromagnetic : π^0—> γγ, γ from **η** nd **η**′ decay
- muonic: muons from pion decay

from 100% hadronic energy a the first interaction to ~90% EM and 10% muons at ground (for vertical showers)



Hadronic Showers

Proton showers

$$\langle X^p_{max}\rangle \approx \lambda_p + X_0 ln\left(\frac{E_0}{2N\epsilon^{em}_c}\right)$$

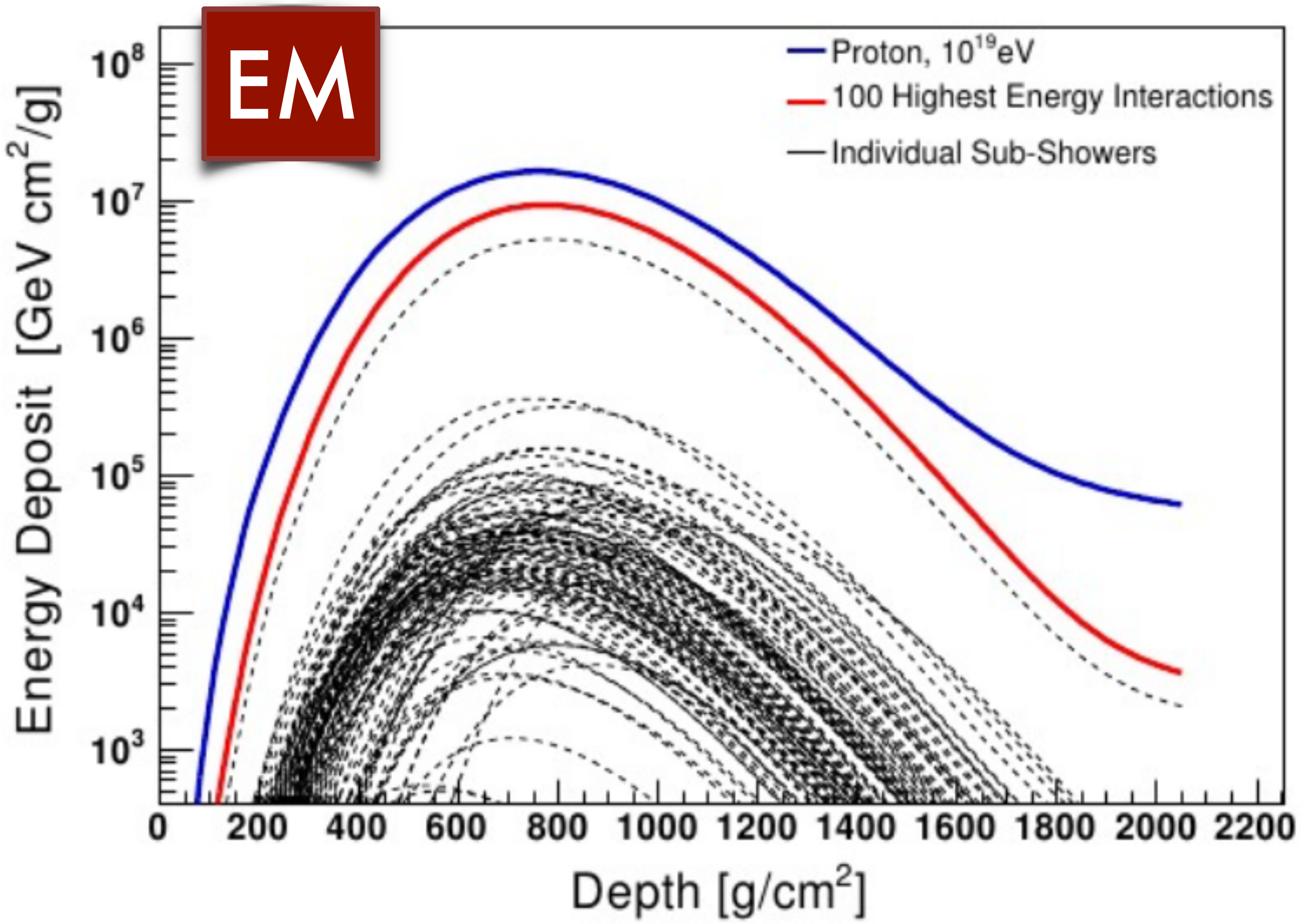
$$N_\mu \simeq \left(\frac{E_0}{E^\pi_c}\right)^\alpha \qquad \alpha = \frac{ln\ n_{ch}}{ln\ n_{tot}} \simeq 0.85$$

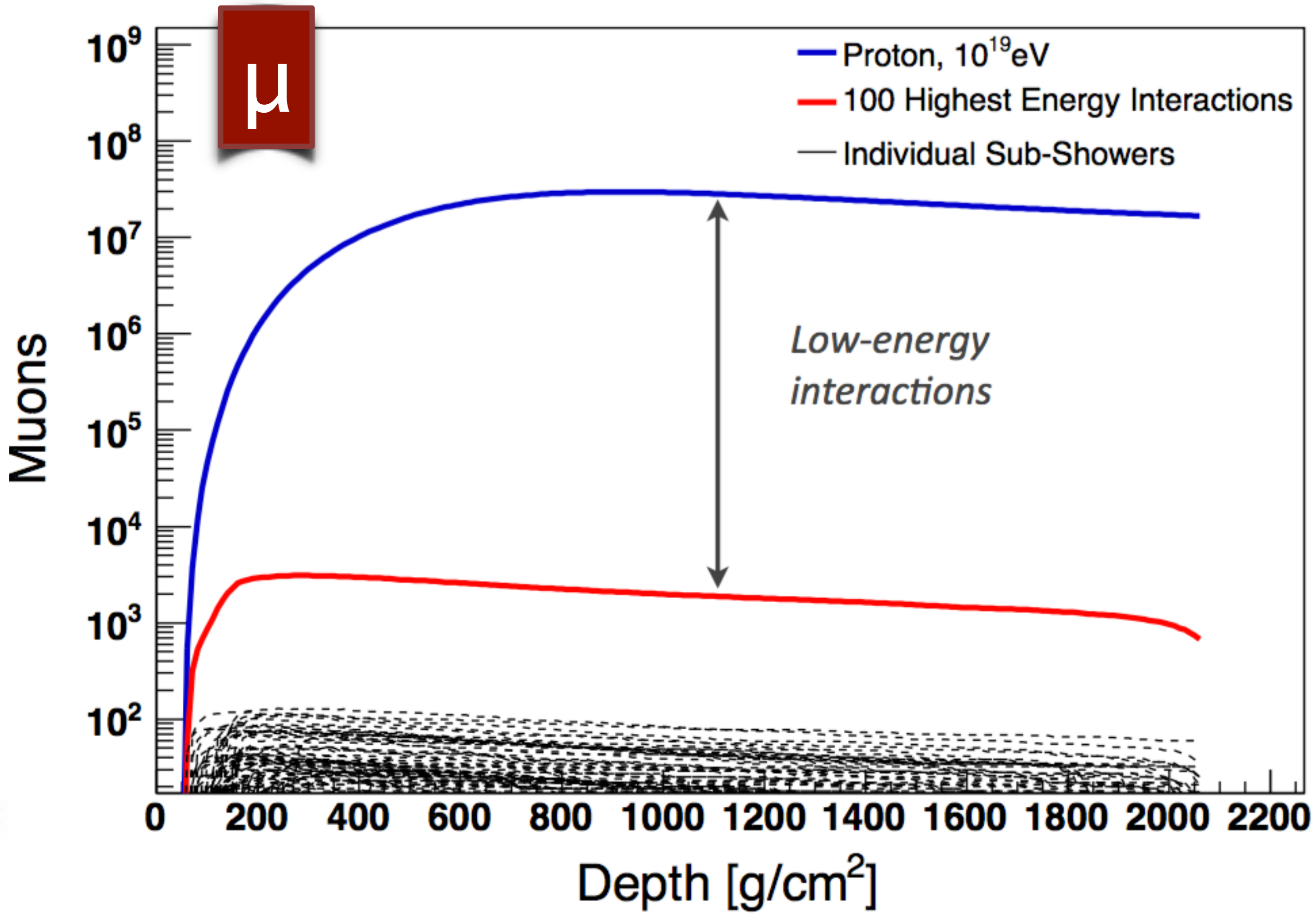
Nuclear shower - Superposition model

$$X^A_{max} = X^p_{max} - \lambda_I\ lnA$$

$$N^A_\mu = A^{1-\alpha} N^p_\mu$$

more muons
shallower X_{max}





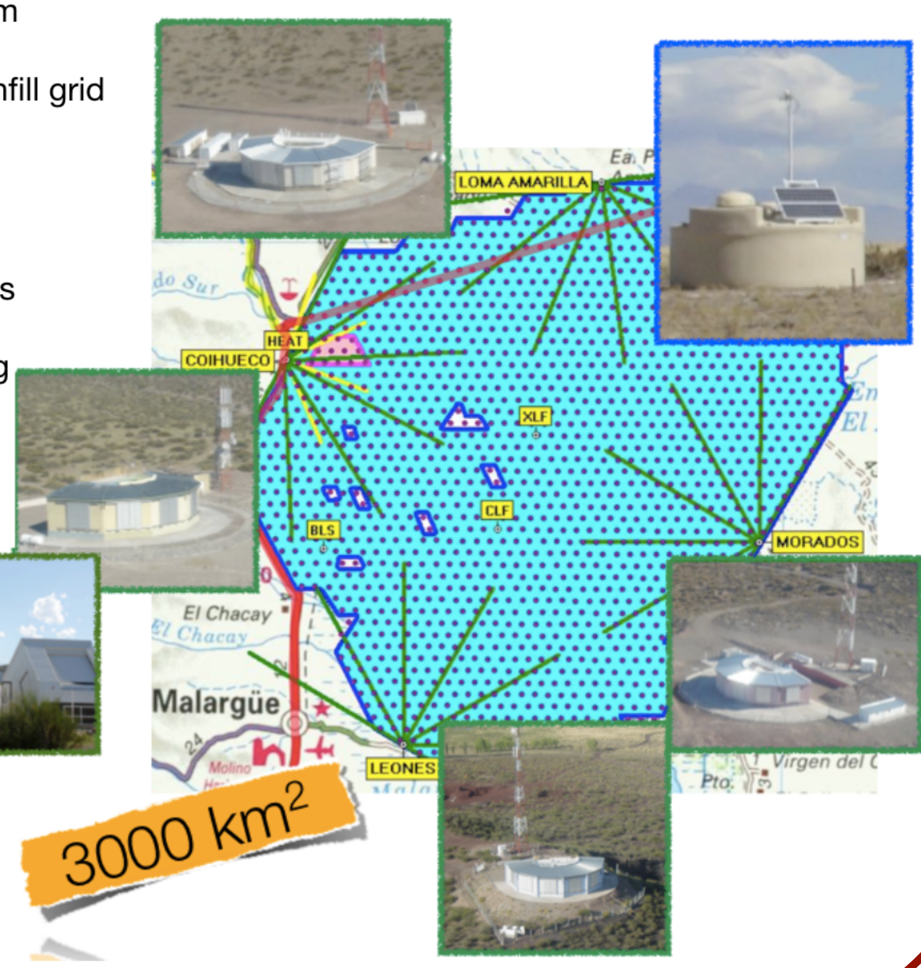
high energy interactions (HE γ from π^0 decay)

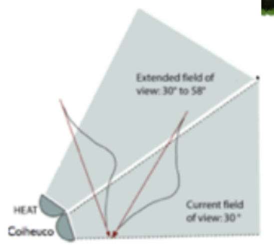
low energy interactions : [$E_{dec}(\pi^\pm)$ ~ 30-100 GeV]

UHECR detectors

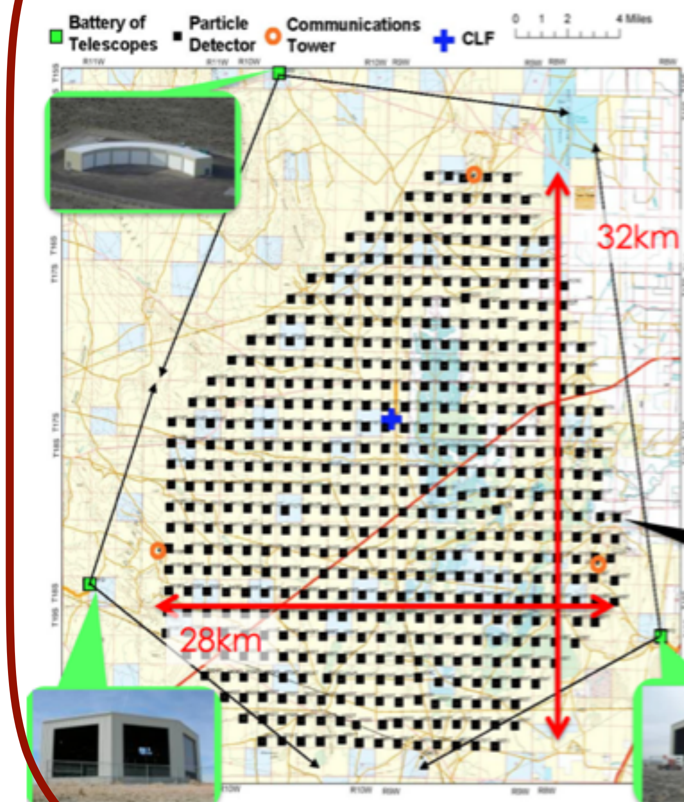
Pierre Auger Observatory

- ✓ **Water-Cherenkov tanks**
  1660 in a 1.5 km standard grid
  61 in 0.75 km infill grid (53 deployed)
- ✓ **Fluorescence Telescopes**
  24 in 4 buildings overlooking SD
  + 3 in 1 building overlooking the Infill





Telescope Array Experiment



- ❖ Desert in Utah, USA
  - 39.30°N, 112.91°W, 1400m a.s.l.
- ❖ Surface Detector (SD)
  - $3m^2$ Scintillation Detector
  - 507 det. with 1.2km spacing
  - Distributed across $700 km^2$
  - Operating since 2008
- ❖ Fluorescence Detector (FD)
  - 3 stations
  - 12 telescopes / station

Surface detector

- ✓ particle density and time distribution at ground
- ✓ muon production depth
- ✓ muons in vertical events (temporal distribution of signals)

Fluorescence detector

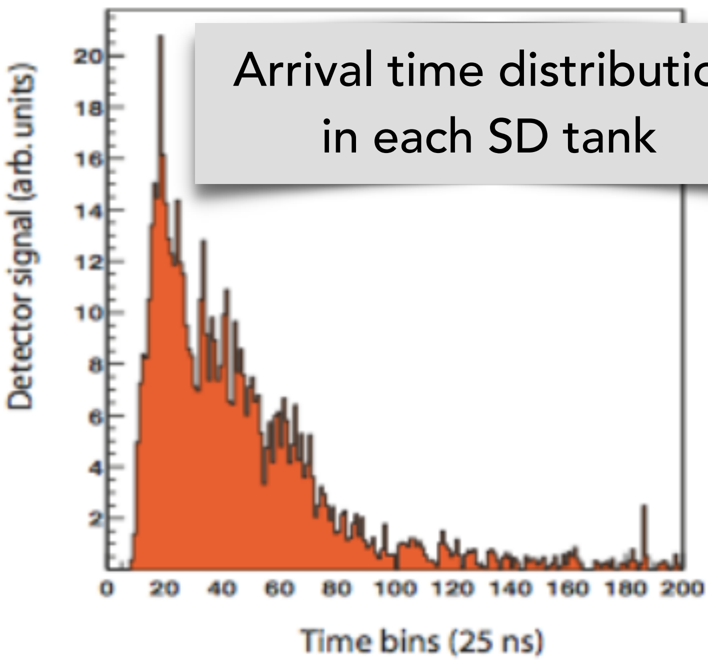
- ✓ longitudinal development of showers and mass fractions
- ✓ p-Air cross section

Hybrid detector

- ✓ muons in inclined showers
- ✓ top-down analysis

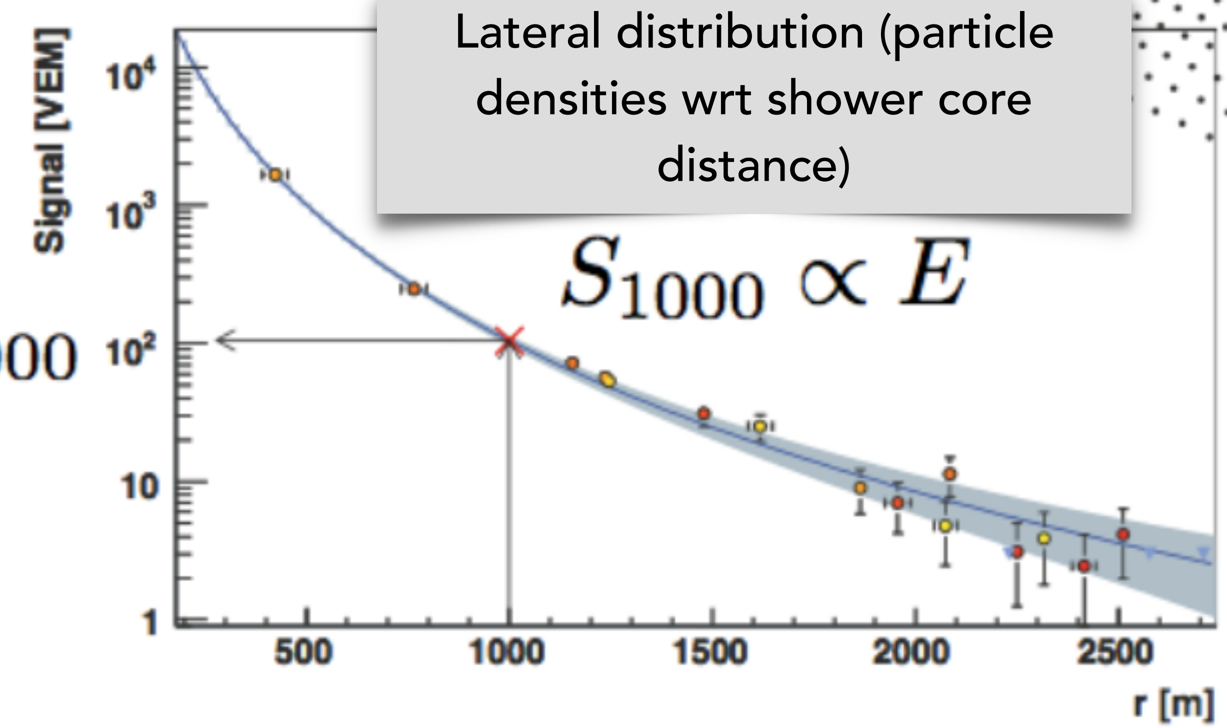
Shower Observables in a hybrid detector

Arrival time distribution in each SD tank



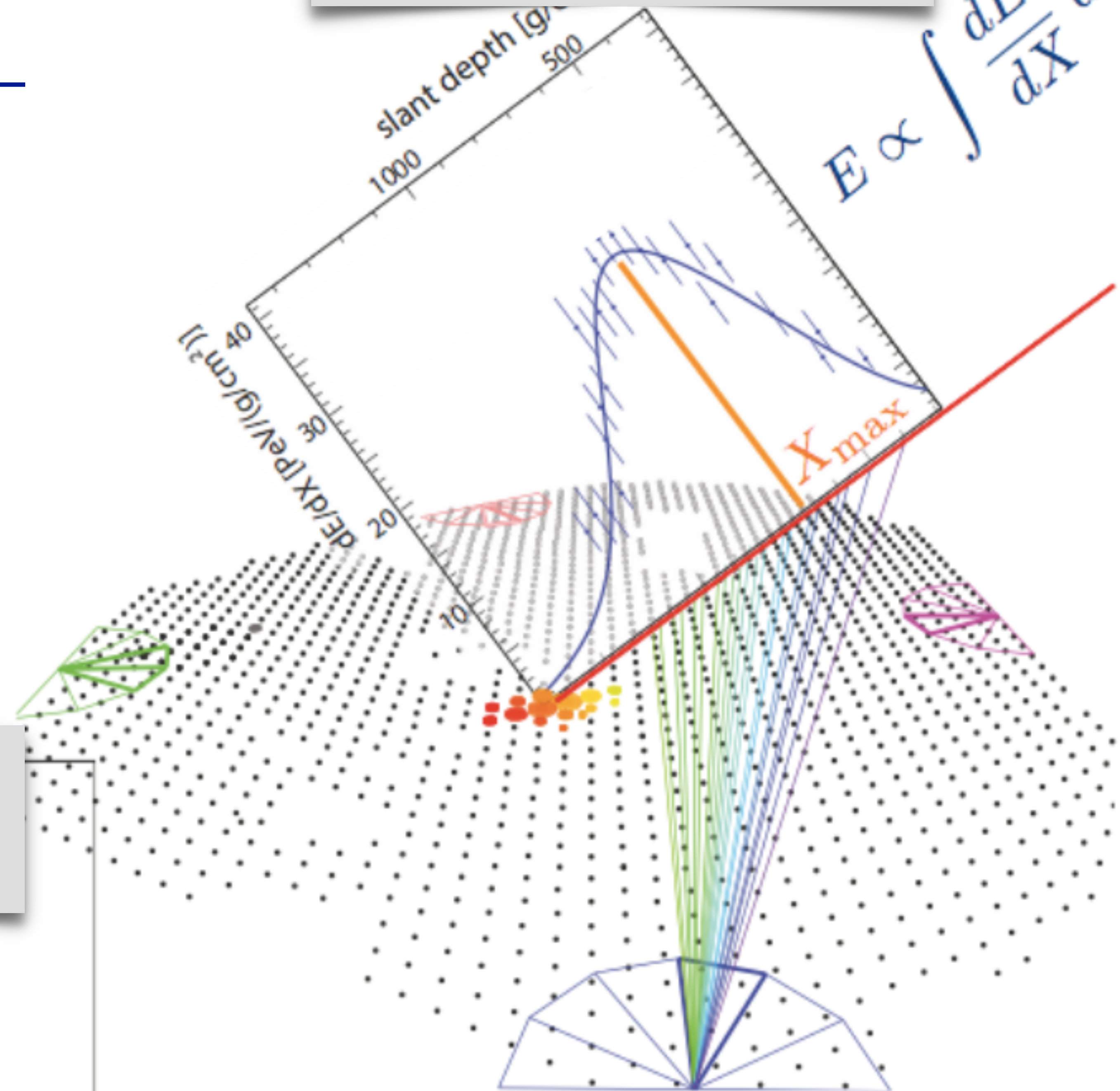
Lateral distribution (particle densities wrt shower core distance)

$$S_{1000} \propto E$$



Longitudinal profile (energy release along shower path in atmosphere)

$$E \propto \int \frac{dE}{dX}\,dX$$

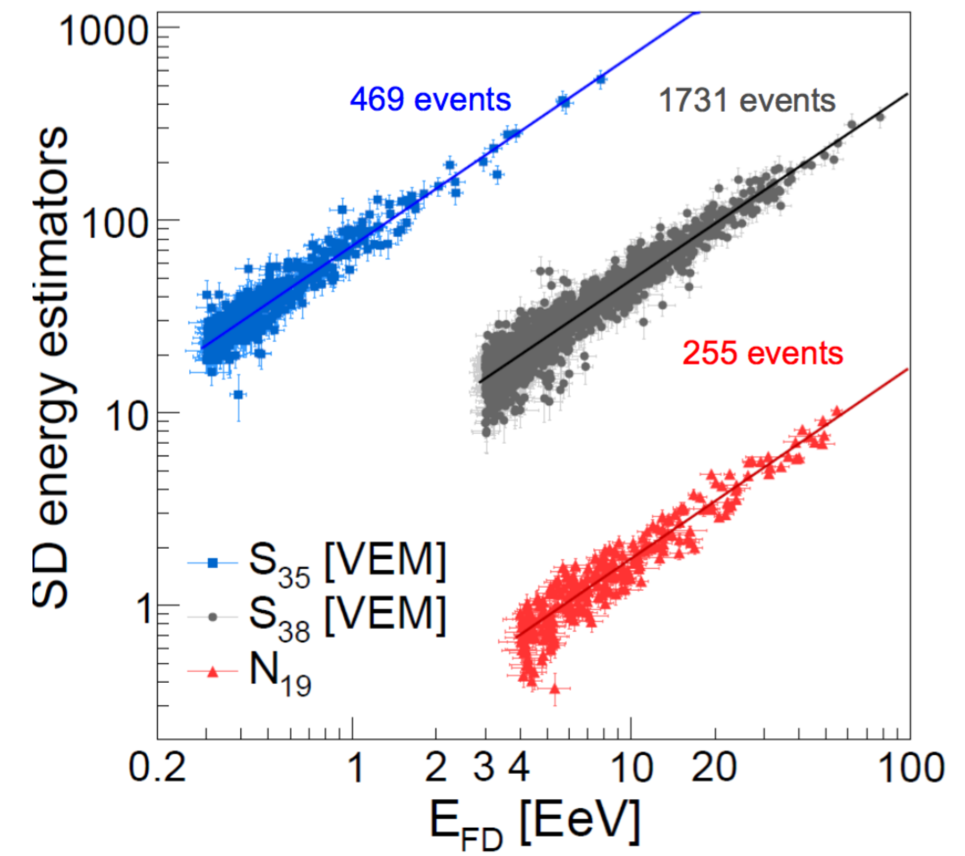


The measurement of energy

FD: calorimetric energy measurement
(13% duty cycle)

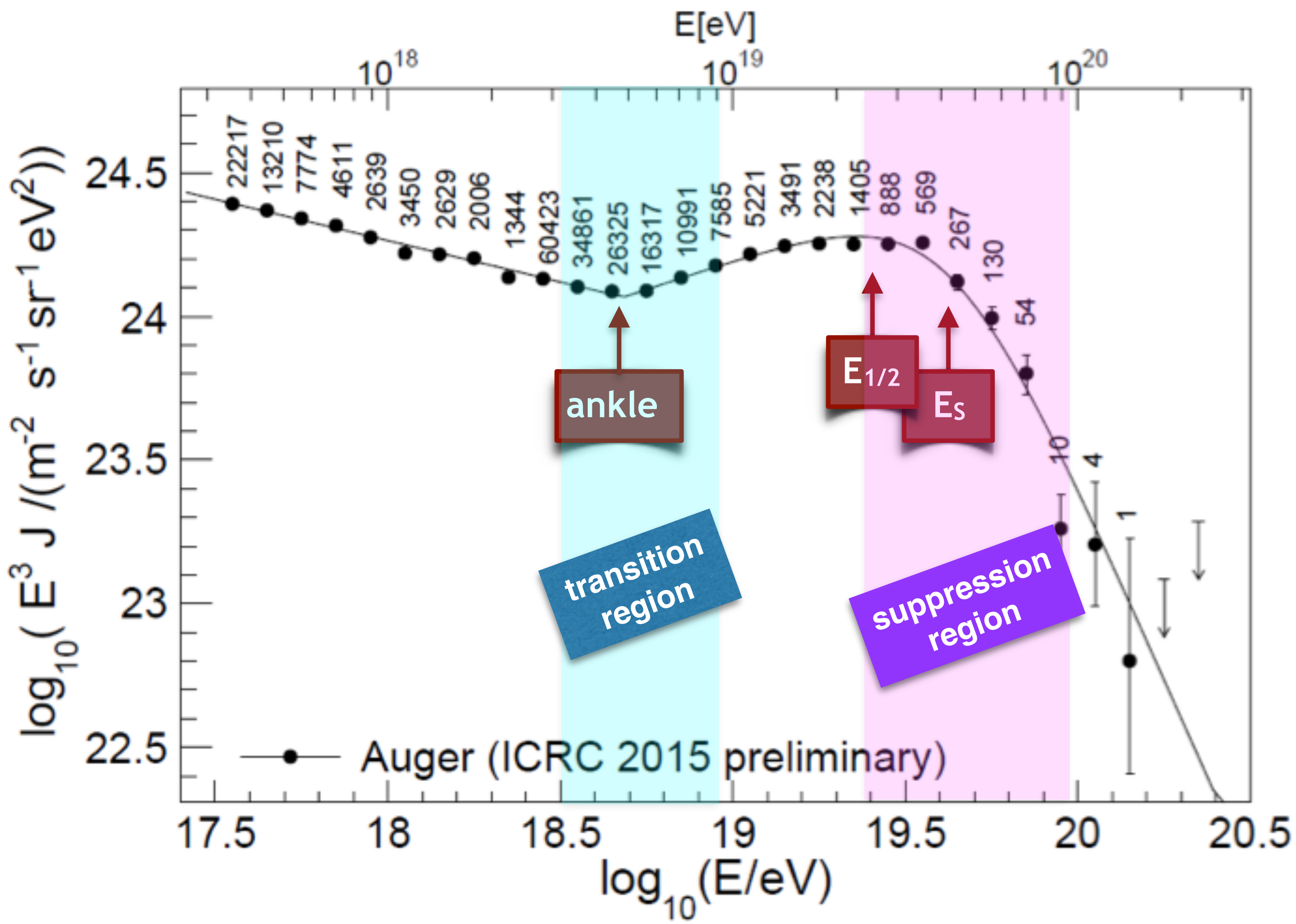
$$E_{Cal} = \int_0^\infty dX \frac{dE}{dX}$$
$$E_{Tot} = E_{Cal} + E_{Inv}$$

(evaluated from data, as $E_{Inv} \propto N_\mu$)



SD: shower size at ground as energy estimator

Hybrid events: absolute calibration of the full SD sample



Energy resolution:
15% for vertical events

Energy systematic uncertainty
FD energy scale 14%

Models

Air shower models needed to interpret the experimental results
CORSIKA, SENECA, COSMOS….

- include models of hadronic interactions (QGSJetII, EPOS, SIBYLL…), based on particle physics data (LHC, $\sqrt{s}$=7 TeV) and known theories
- must provide a consistent description of both astroparticle and hadronic particle physics
- ***the uncertainties in the models are currently the main source of systematics***

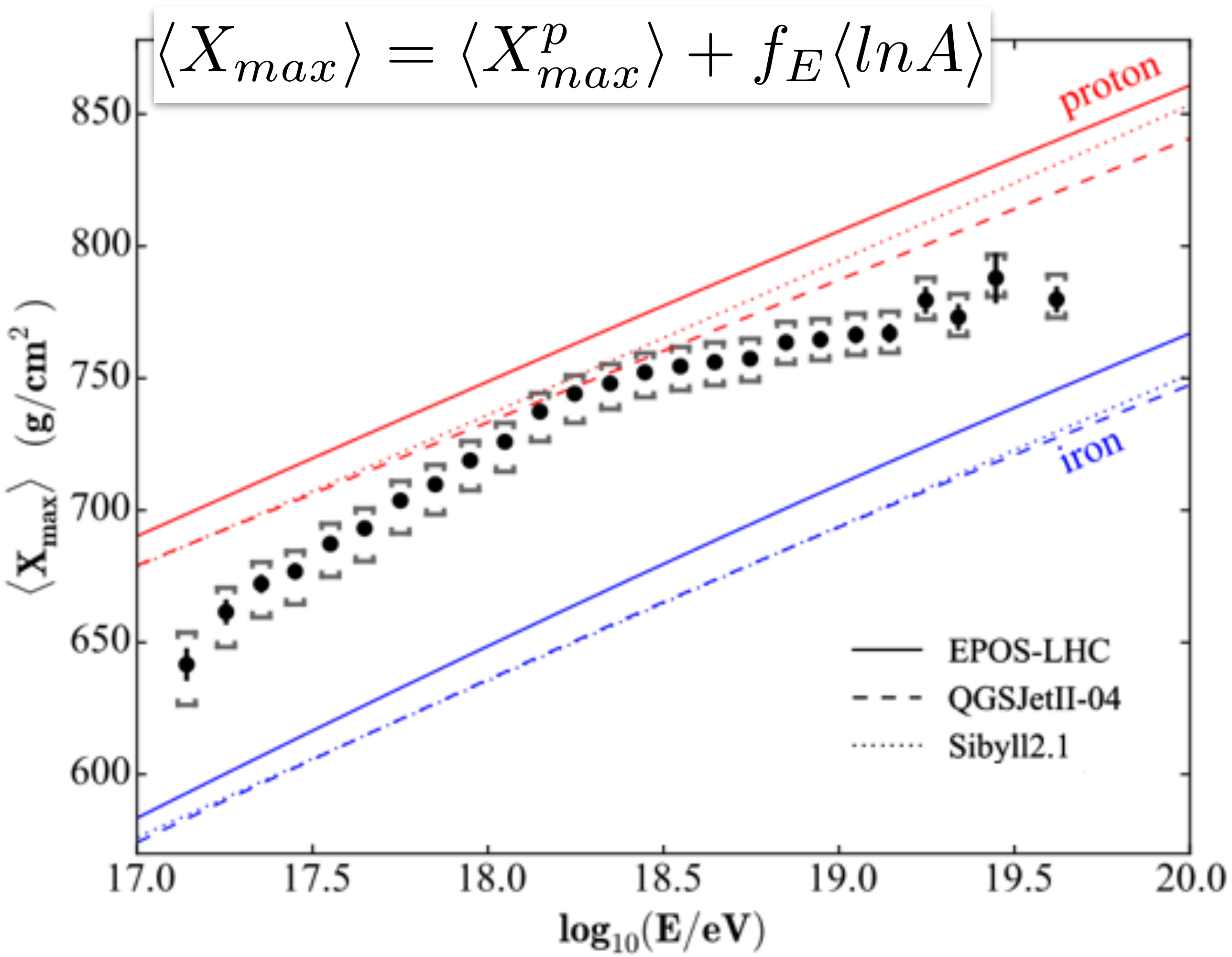
1. QGSJET-II-04 *[SO, 2011]*
   - QGS model *[Kaidalov & Ter-Martirosyan, 1982]* → QGSJET *[Kalmykov & SO, 1993, 1997]* → QGSJET-II *[SO, 2006]*
   - theoretically most advanced: e.g. microscopic treatment of nonlinear effects (Pomeron-Pomeron interaction diagrams)
   - ⇒ strong predictive power (minimal number of parameters)
2. EPOS-LHC *[Pierog, Karpenko, Katzy, Yatsenko & Werner, 2015]*
   - VENUS *[Werner, 1993]* → NEXUS *[Drescher, Hladik, SO, Pierog & Werner, 2001]* → EPOS *[Werner, Liu & Pierog, 2006]*
   - more phenomenological (e.g. parametrized saturation effects) but additional mechanisms (e.g. hydrodynamics for final states)
   - larger parameter freedom ⇒ better description of existing data
3. SIBYLL-2.3 *[Riehn, Engel, Fedynitch, Gaisser & Sranev, 2015]*
   - SIBYLL-1.7 *[Fletcher, Gaisser, Lipari & Stanev, 1994]* → SIBYLL-2.1 *[Ahn, Engel, Gaisser, Lipari & Stanev, 2009]*
   - relatively simple-minded ('minijet' approach)
   - has similarities to models used at LHC (e.g. PYTHIA)

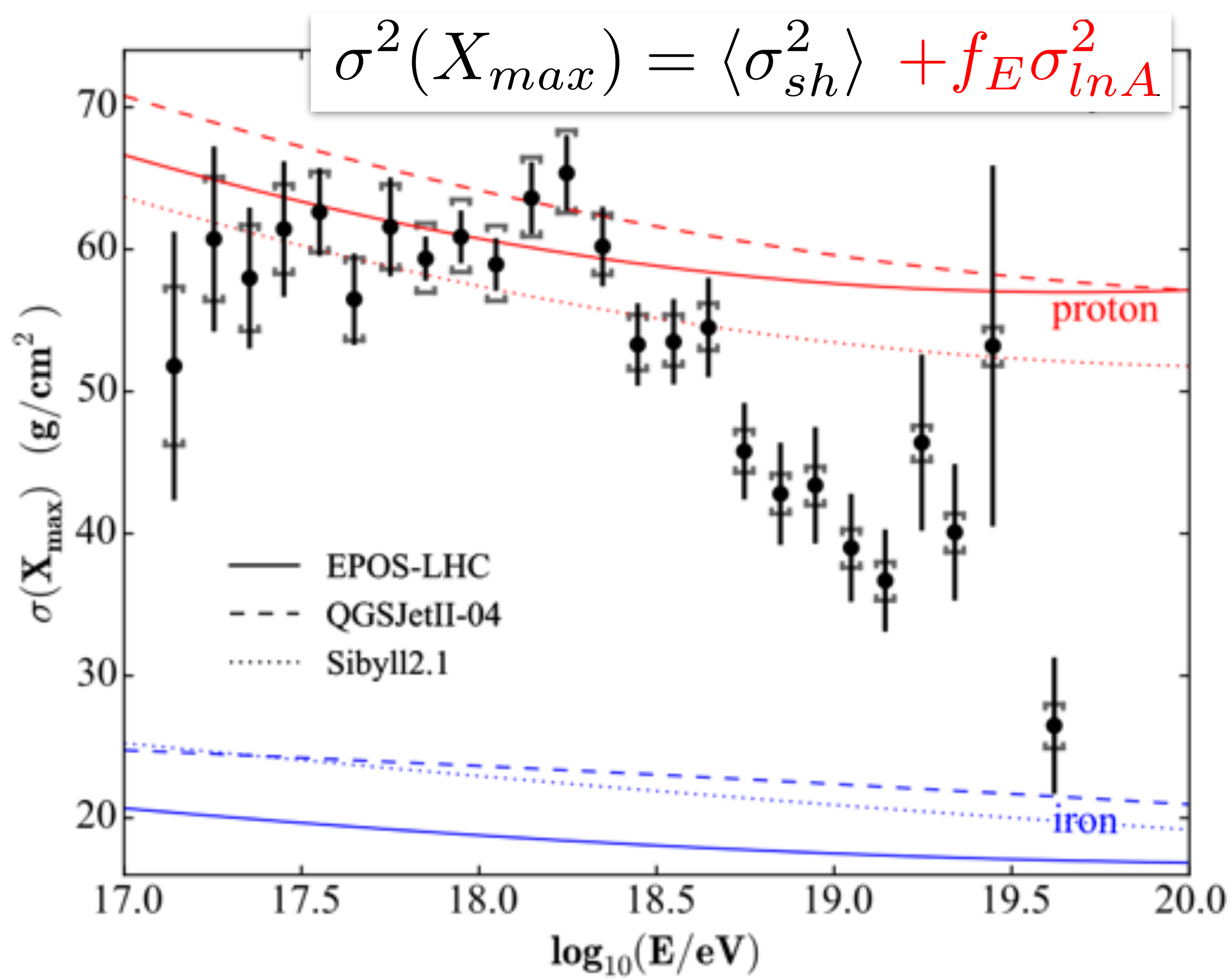
[@S.Ostapchenko, arXiv:1601.06567]

The measurement of X_{max}

$$D_{10} = \hat{D}_{10}\left(1 - \frac{d\langle \ln A\rangle}{d\ \ln(E/eV)}\right)$$

expected $\hat{D}_{10}$ = 54-64 g cm^{-2} decade^{-1}





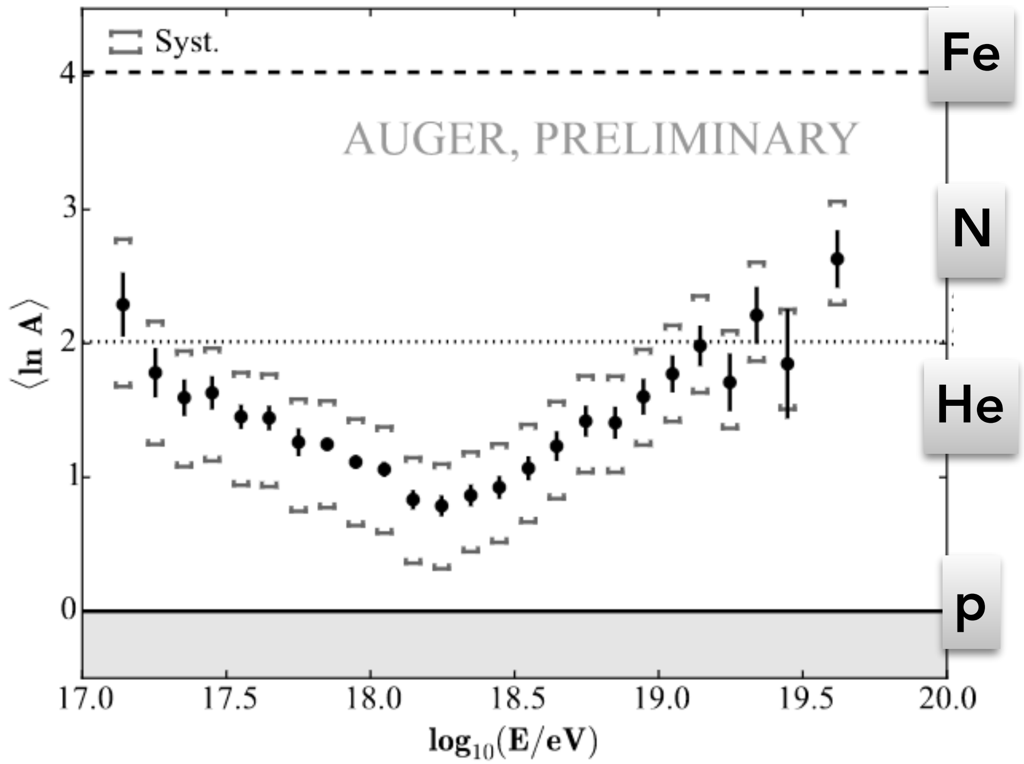
$$\frac{dX_{max}}{dlog_{10}E} = 86.5 \pm 5.0(stat)^{+3.8}_{-3.2}(sys)\ g\ cm^{-2}$$ E<$10^{18.3}$ eV

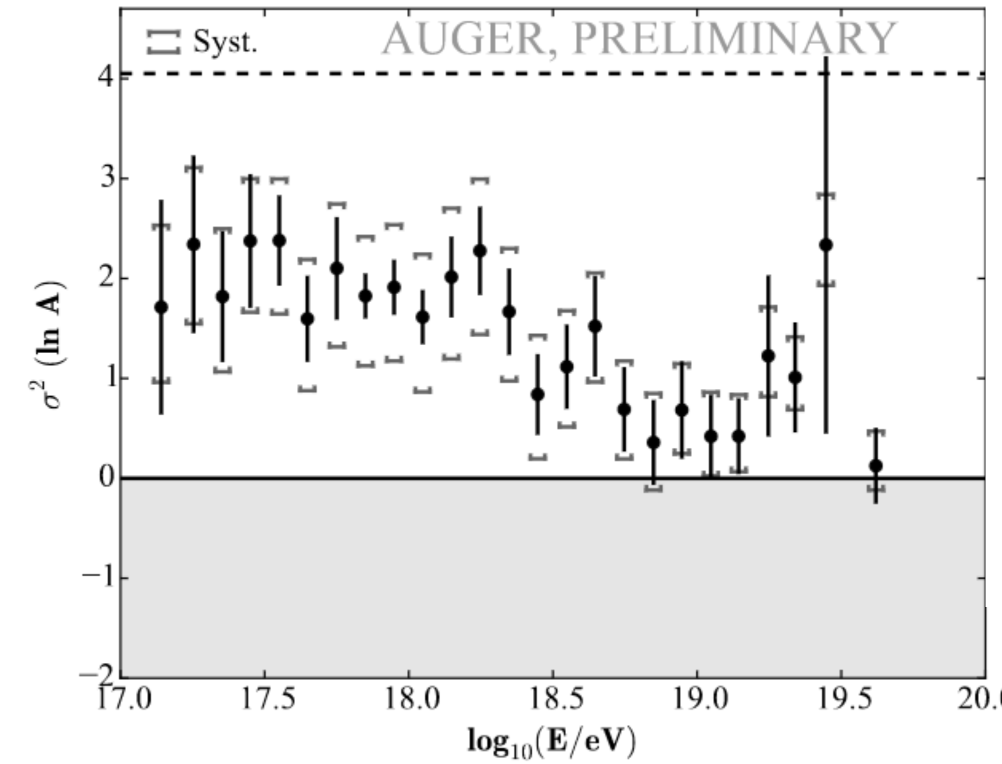
$$= 26.4 \pm 2.5(stat)^{+7.0}_{-1.9}(sys)\ g\ cm^{-2}$$ E>$10^{18.3}$ eV

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

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{\max}) - \sigma^2_{\text{sh}}(\langle \ln A \rangle)}{b\ \sigma^2_p + f^2_E}$$

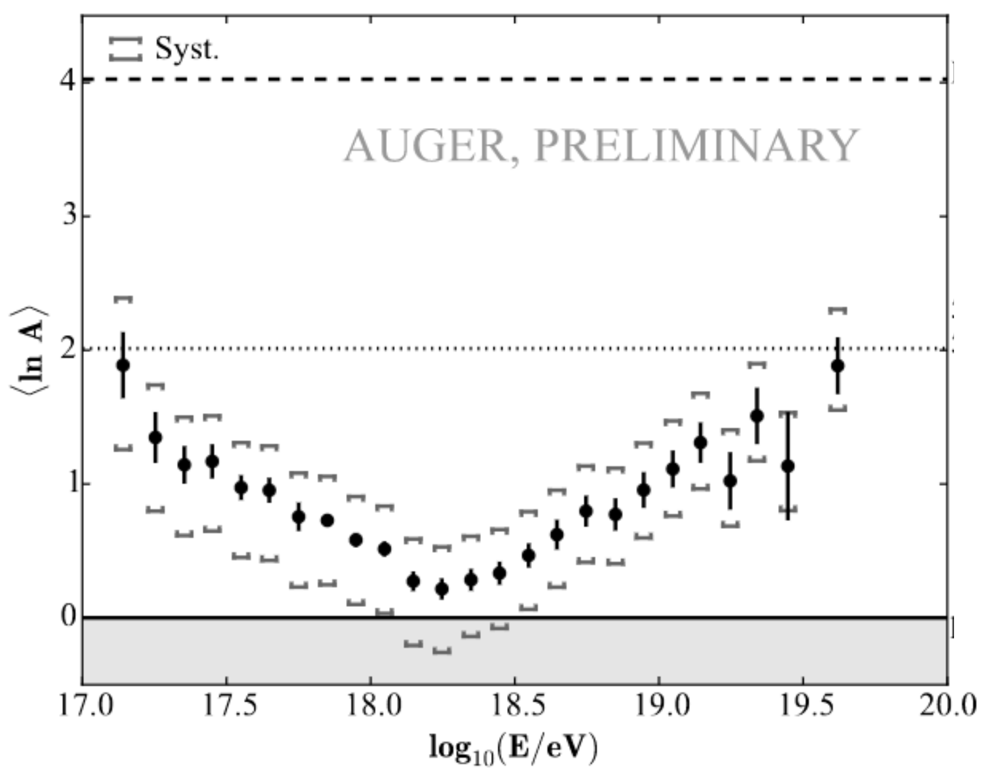
EPOS-LHC



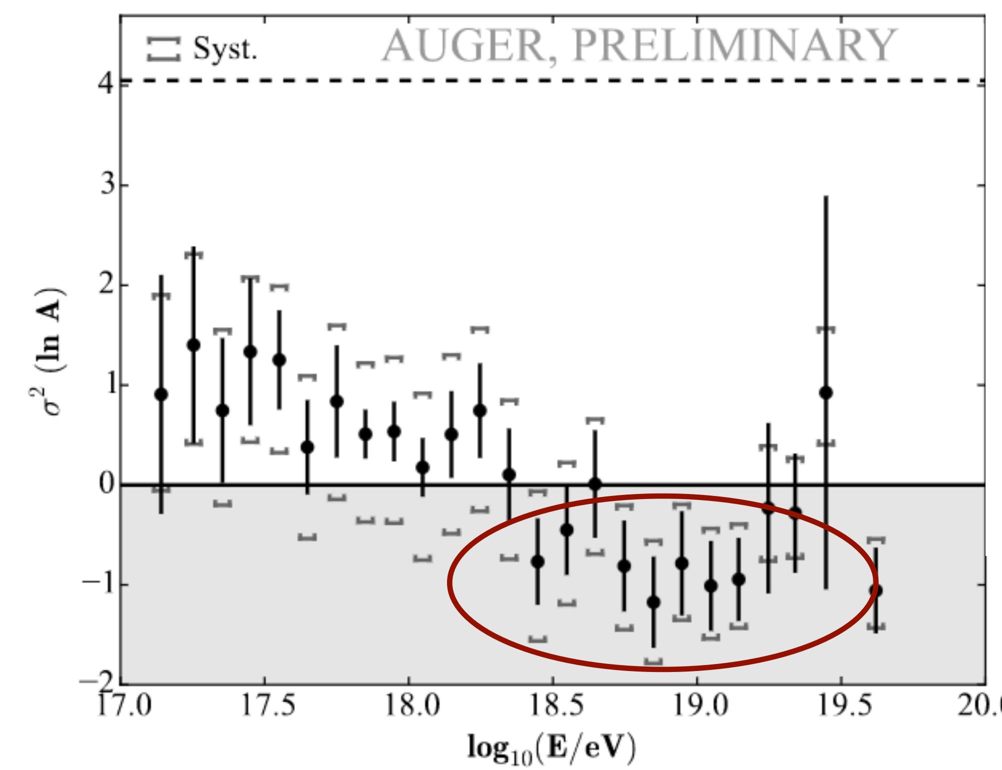


QGSJetII-04

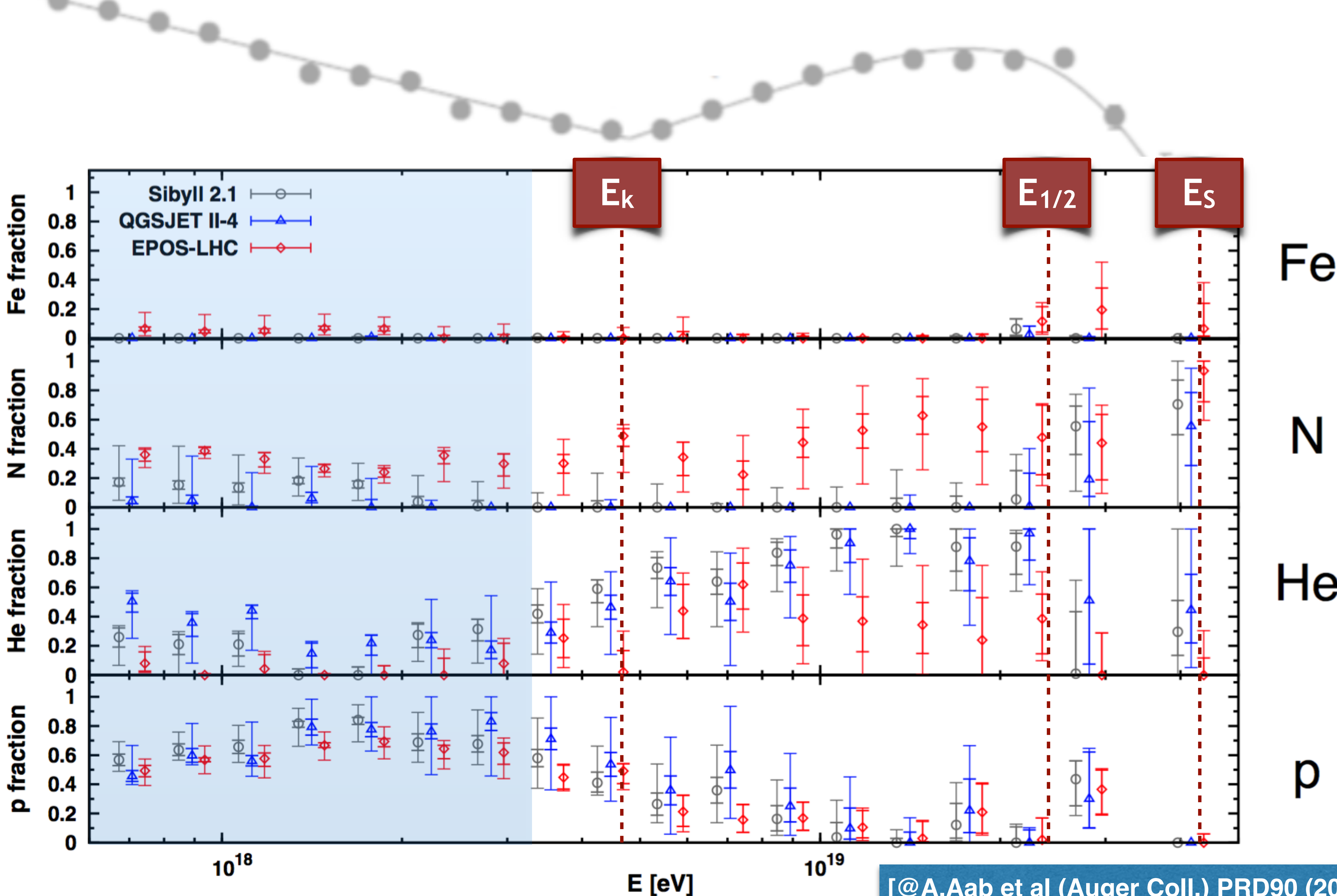
QGSJetII-04 (Mean of ln A)



QGSJetII-04 (Variance of ln A)



[@A.Porcelli et al (Auger Coll.) PoS (ICRC2015) 420]

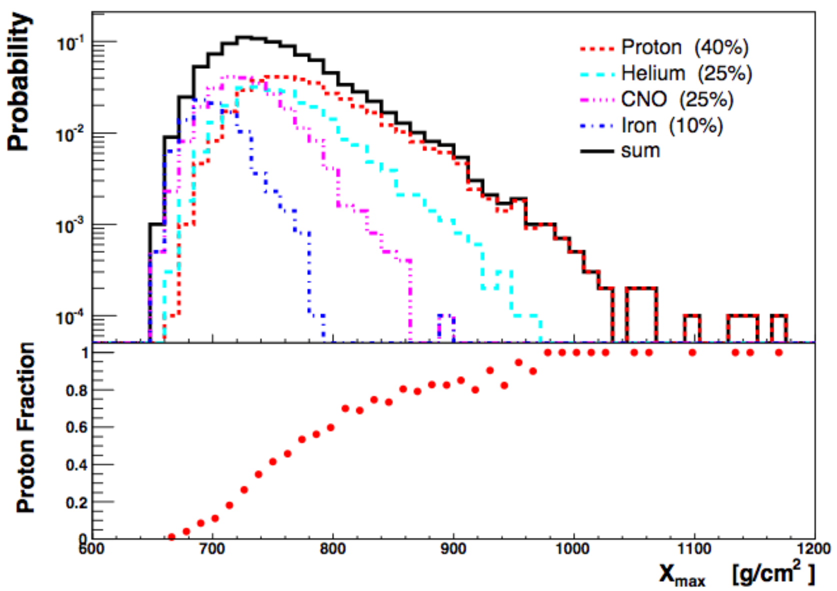


[@A.Aab et al (Auger Coll.) PRD90 (2014) 122006]

- **data better reproduced with a mixed composition**
- no significant contribution of Fe
- p fraction increases to >60% at the ankle, drops near 10^{19} eV, maybe rising again at higher energies —> but EG according to anisotropy limits !

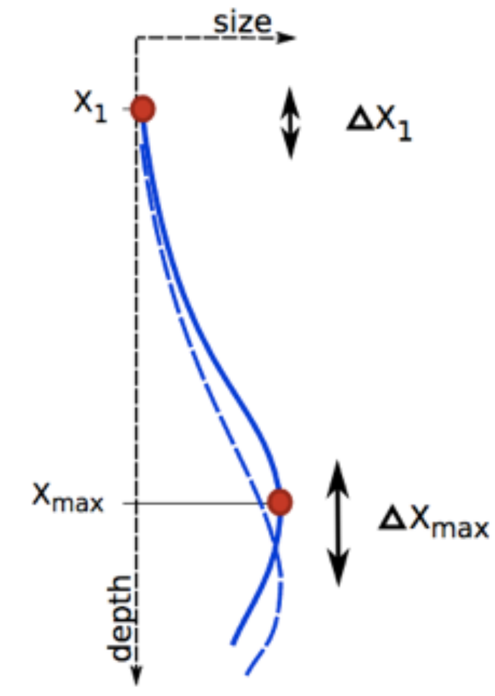
⇨ Selection of a "pure" sample of proton induced showers

The p-Air cross section



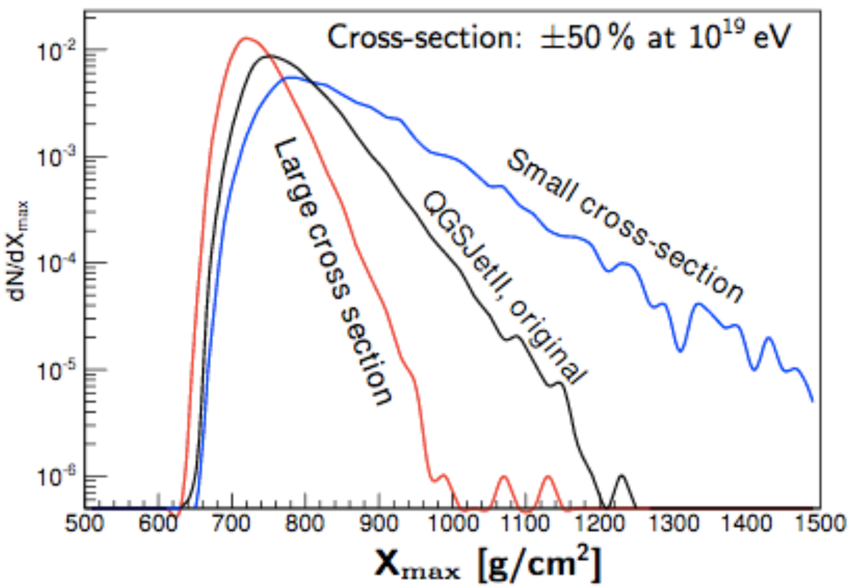
X_{max} = convolution between ΔX_1 and longitudinal shower development

The tail of the longitudinal distribution is sensitive to the p-Air cross section

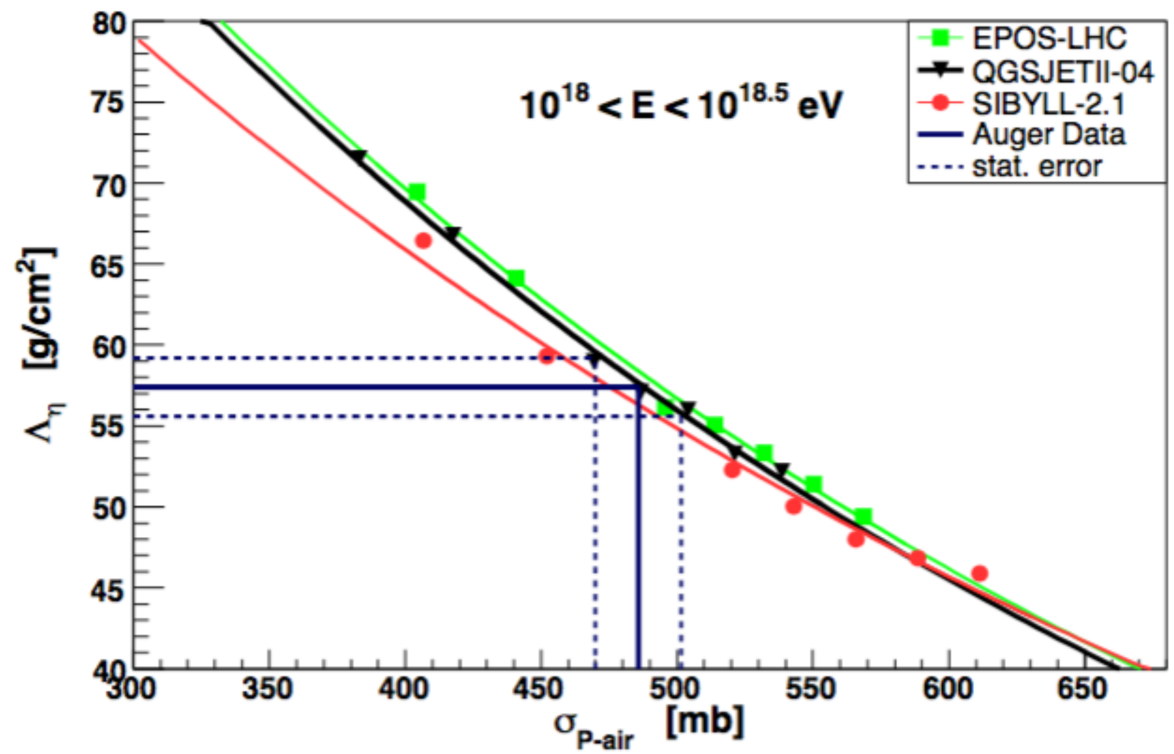


$$\frac{dp}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}} \qquad \sigma_{p-Air} = \frac{< m_{Air} >}{\lambda_{int}}$$

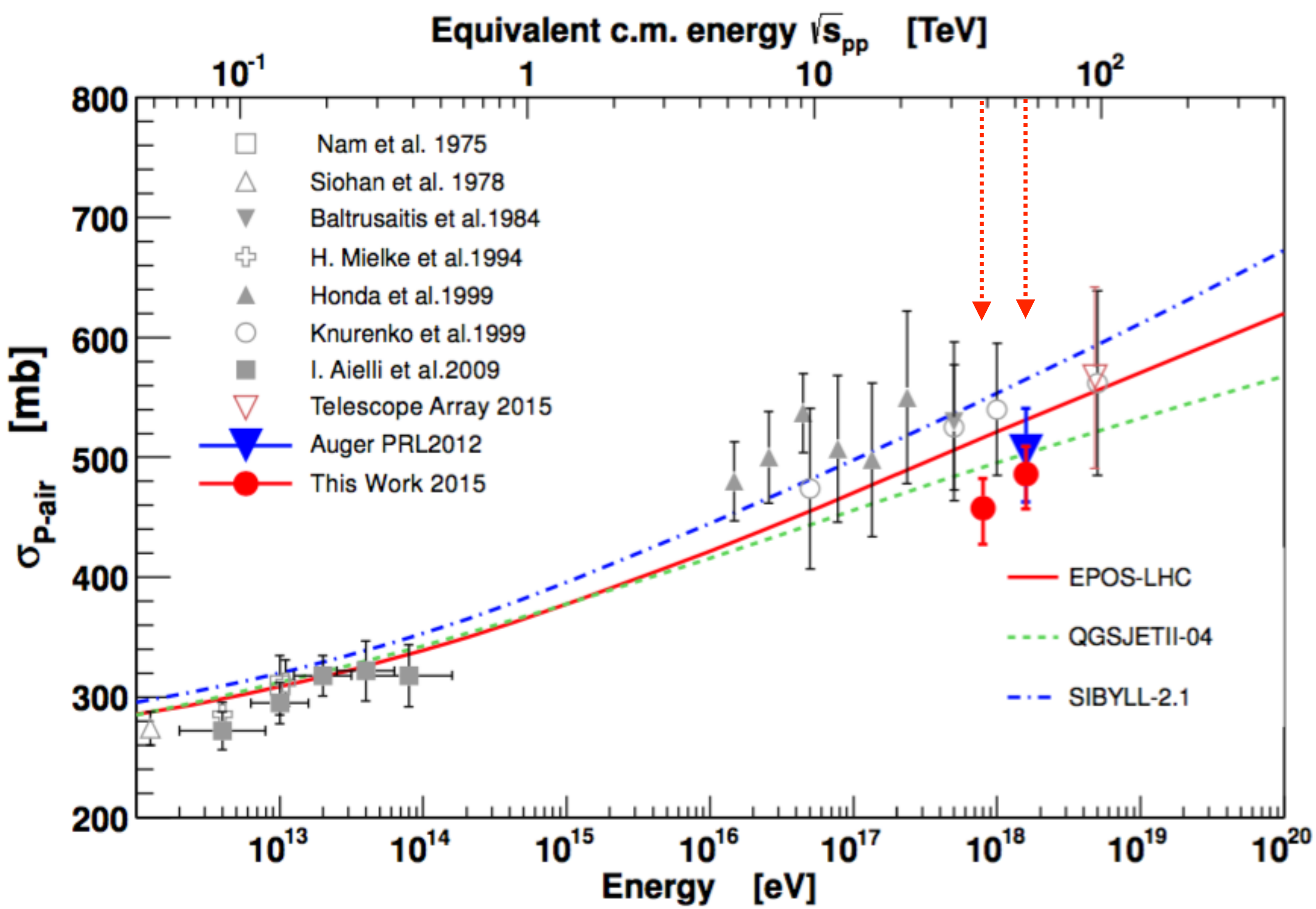
$$\frac{dN_{EAS}}{dX_{max}} \propto e^{-X_{max}/\Lambda_\eta} \qquad \lambda_{int} \leftrightarrow \Lambda_\eta$$



- measure Λ_η
- convert Λ_η to σ_{p-Air}



The p-Air cross section



Auger

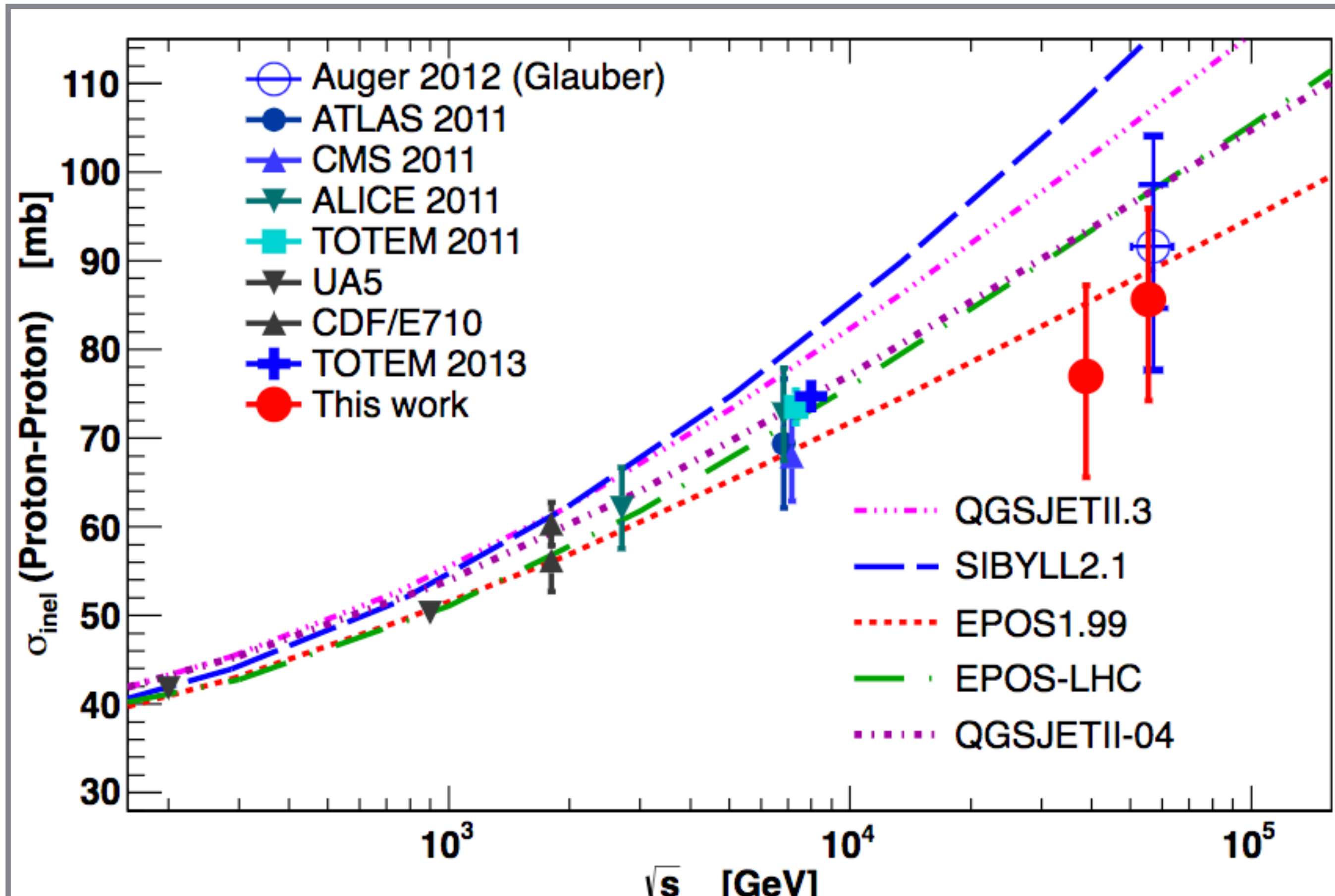
	$10^{17.8} - 10^{18}$ eV	$10^{18} - 10^{18.5}$ eV
Λ_η, systematic uncertainties (mb)	13.5	14.1
Hadronic interaction models (mb)	10	10
Energy scale uncertainty, $\Delta E/E = 14\%$ (mb)	2.1	1.3
Conversion of Λ_η to $\sigma_{\rm p-air}$ (mb)	7	7
Photons (mb)	+4.7	+4.2
Helium, 25% (mb)	-17.2	-15.8
Total systematic uncertainty on $\sigma_{\rm p-air}$ (mb)	+19/-25	+19/-25

Telescope Array

Systematic source	Systematics (mb)
Model Dependence	(±17)
20% Helium	− 18
Gamma	+ 23
Summary (20% Helium)	(−25,+29)

The p-p cross section

Glauber formalism extended to account for diffraction dissociation



$\sigma_{inel}(p-p)$

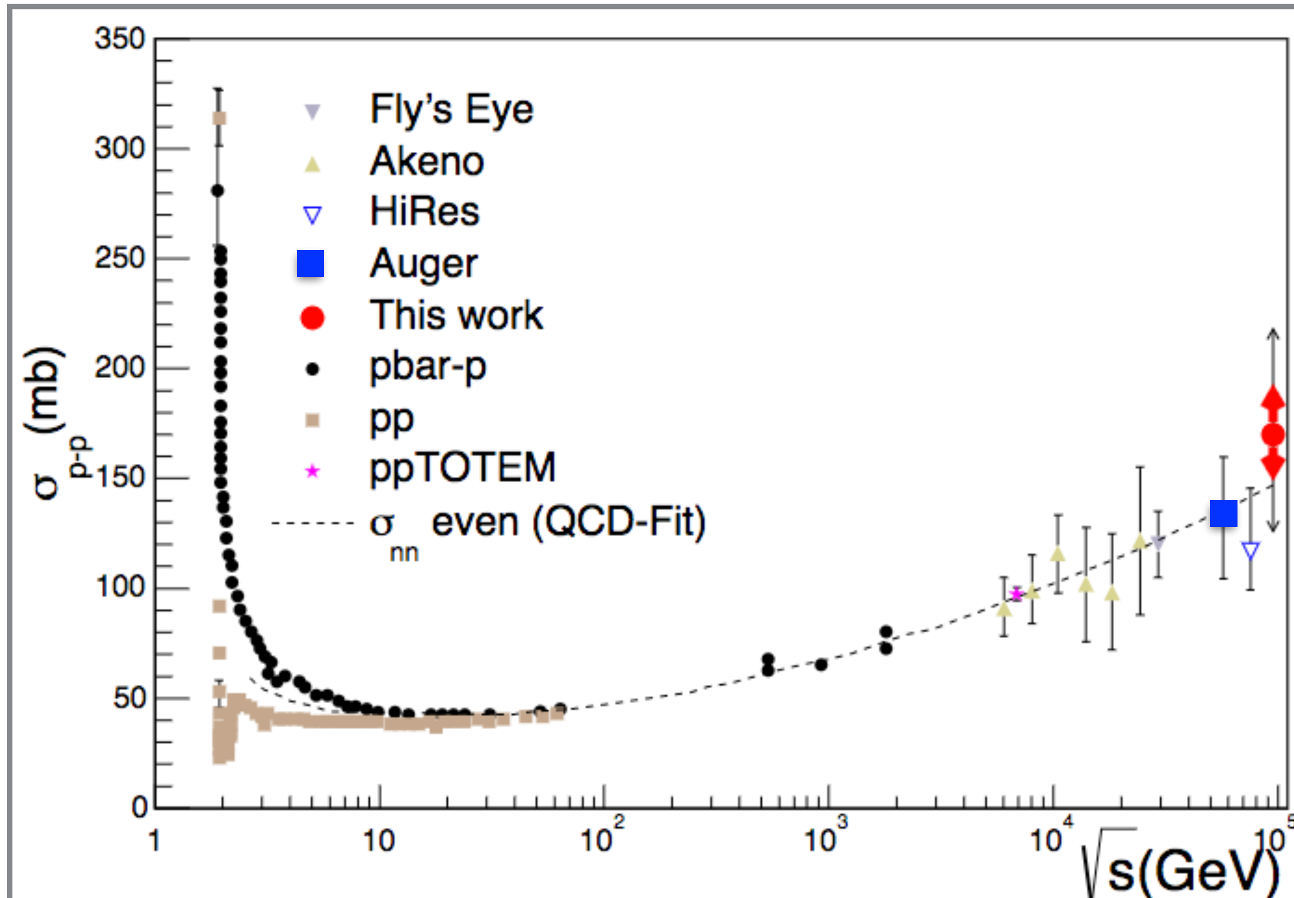
$$\sqrt{s} = 38.7 \pm 2.5\ TeV$$

$$76.95 \pm 5.4(stat)^{+5.2}_{-7.2}(sys) \pm 7.0(Glauber)mb$$

$$\sqrt{s} = 55.5 \pm 3.6\ TeV$$

$$85.62 \pm 5.0(stat)^{+5.5}_{-7.4}(sys) \pm 7.1(Glauber)mb$$

[@R.Ulrich (Auger Coll.) PoS (ICRC2015) 401]



$\sigma_{total}(p-p)$

$$\sqrt{s} = 57 \pm 0.3(stat) \pm 6.0(sys)TeV$$

$$133 \pm 13(stat)^{+17}_{-20}(sys) \pm 16(Glauber)mb$$

$$\sqrt{s} = 95^{+5}_{-8}\ TeV$$

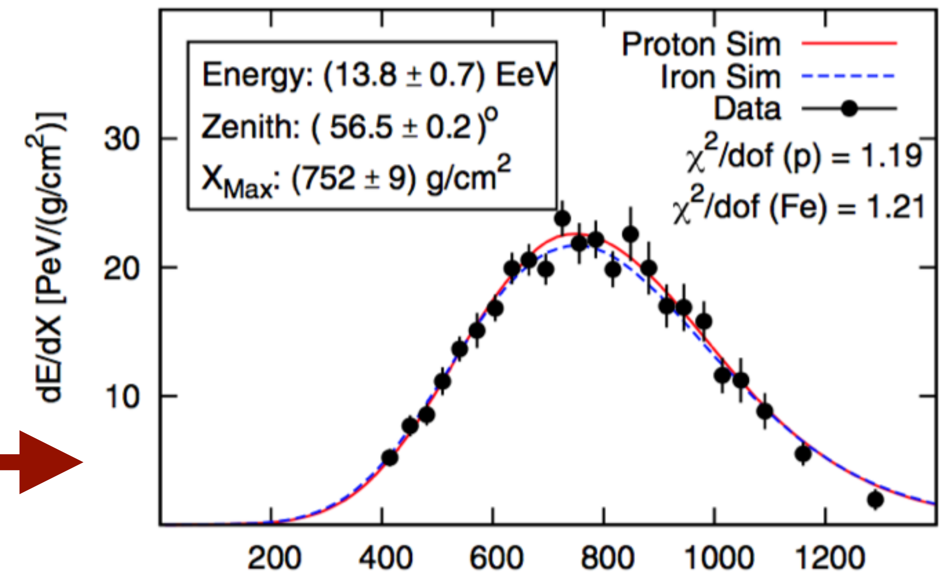
$$170^{+48}_{-44}(stat)^{+19}_{-17}(sys)mb$$

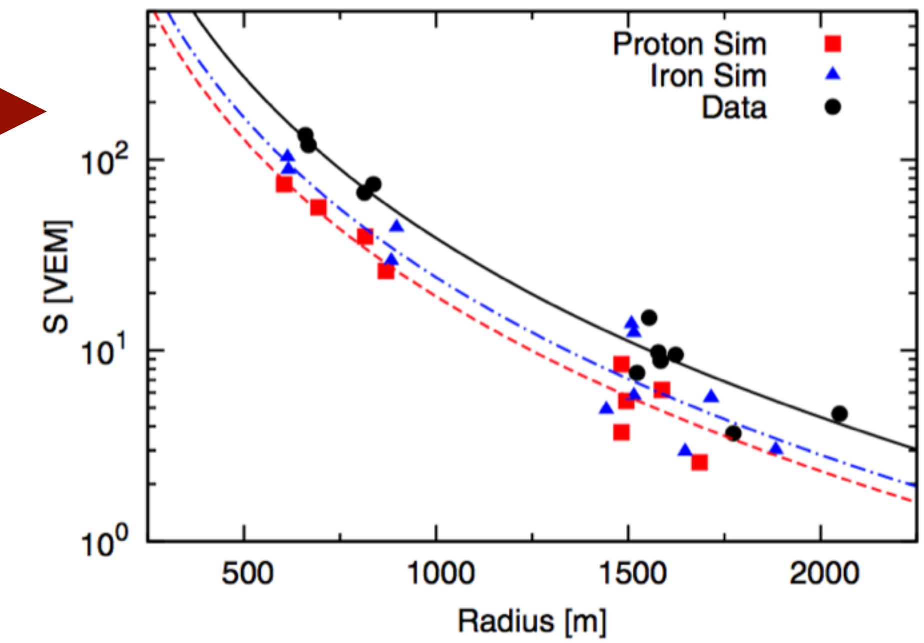
[@R.U.Abbasi (TA Coll.) PoS (ICRC2015) 402]

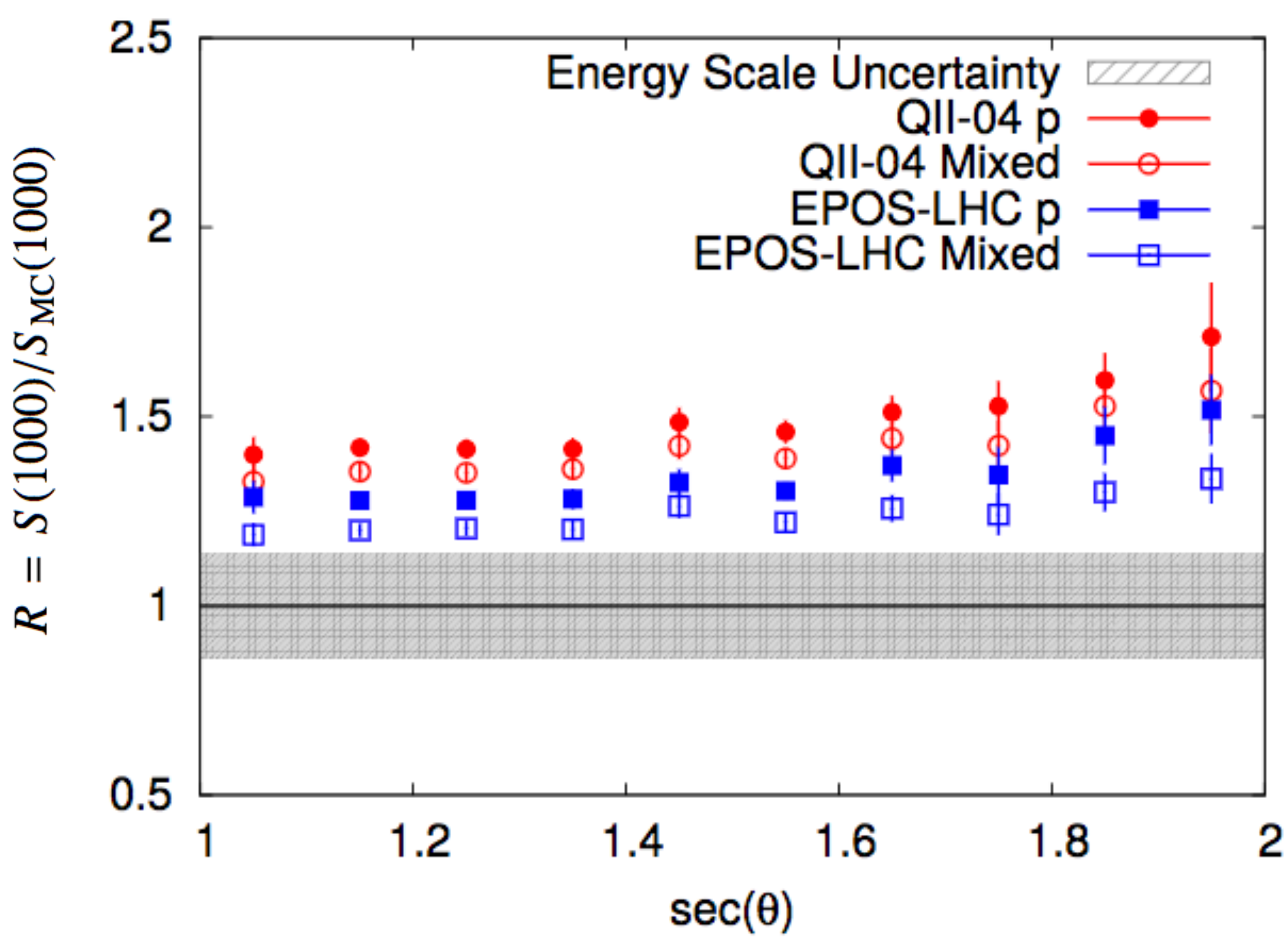
Top-down analysis

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)
- compare their simulated lateral distribution at ground with the measured one



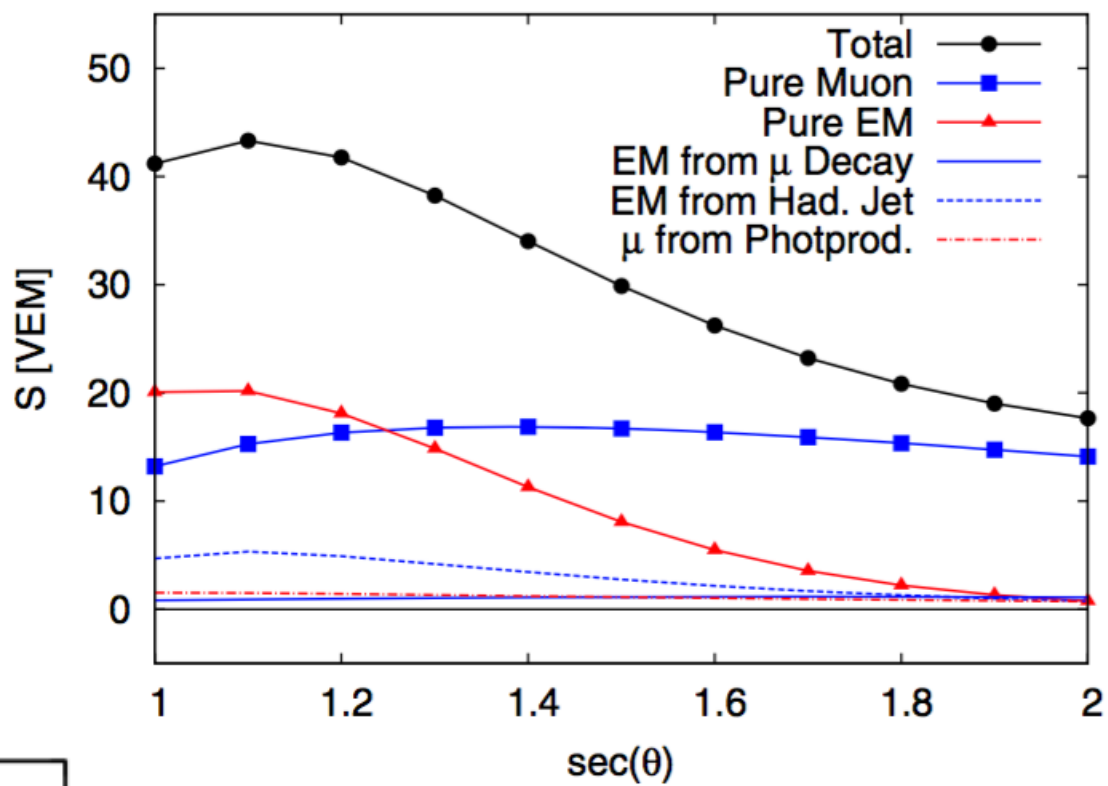


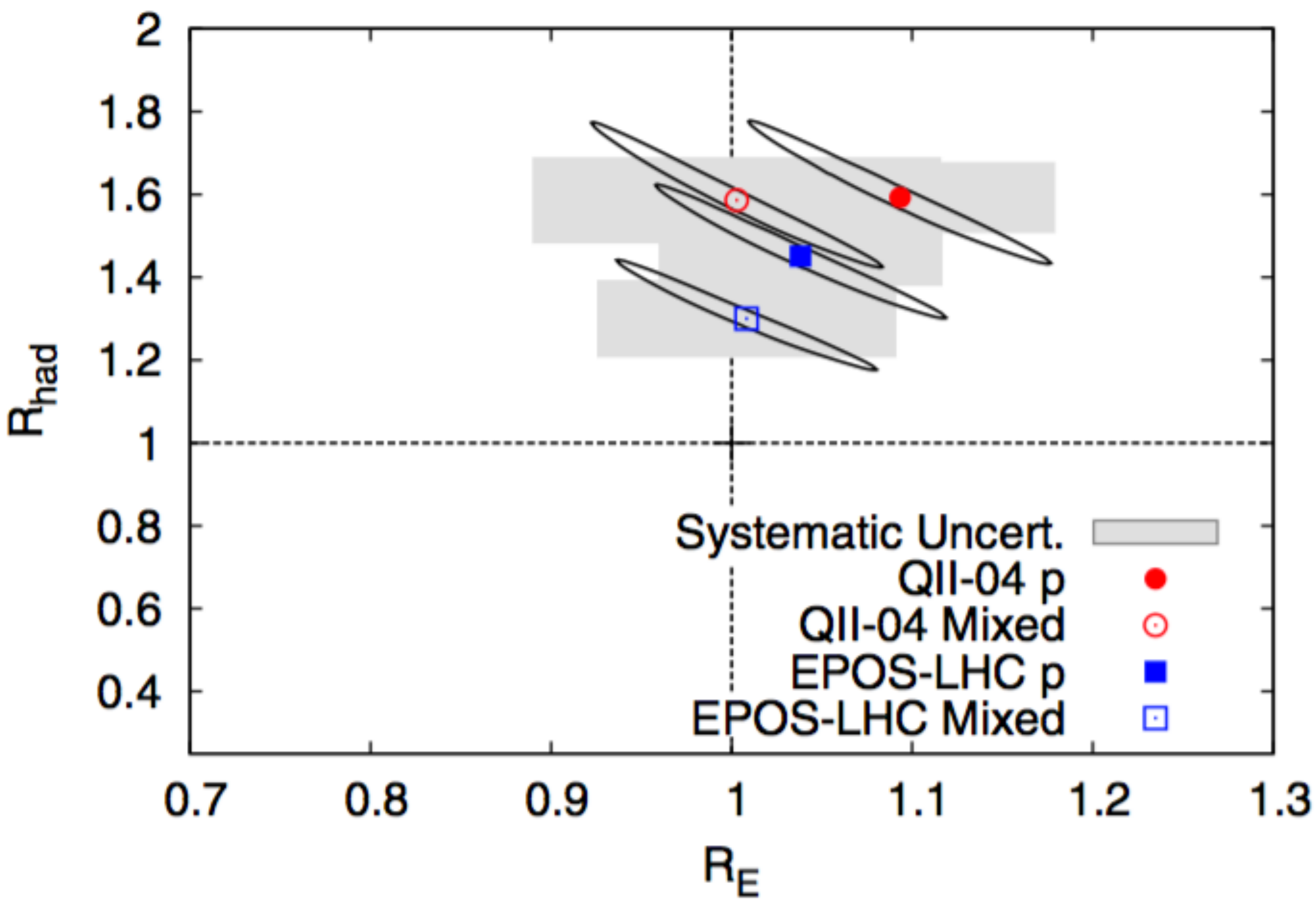


not enough muons in models (especially at large ϑ)

For given i-th shower and j-th composition evaluate energy and hadronic rescaling R_E and R_{had}

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

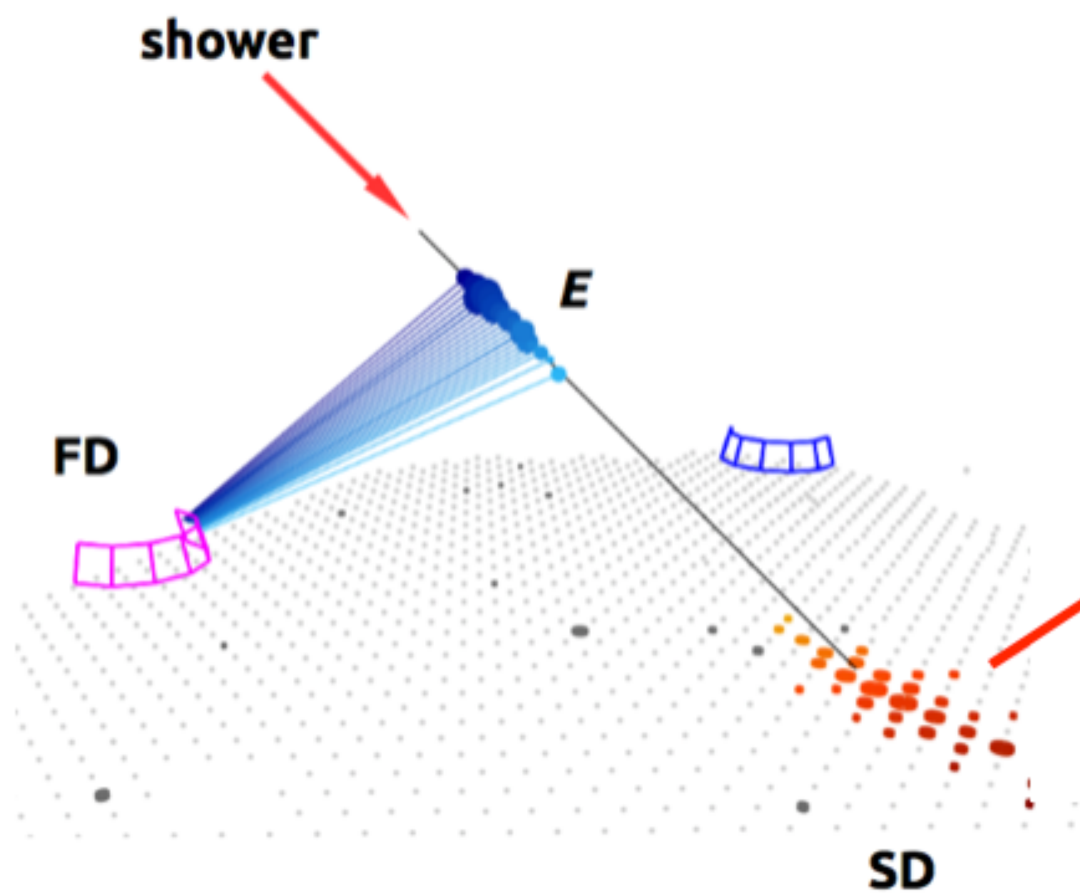


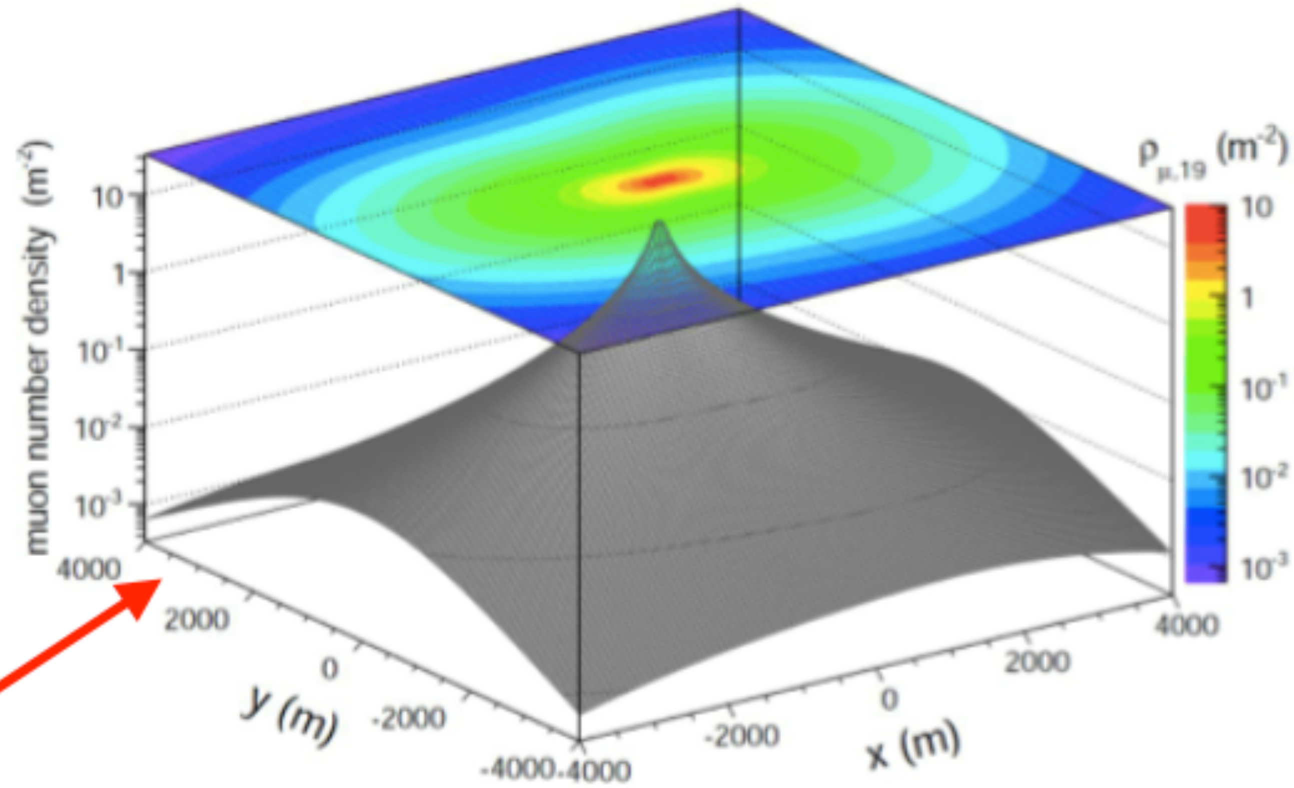


- no need for an energy rescaling
- observed muon signal 1.3-1.6 times larger than expected
- smallest discrepancy with prediction of EPOS-LHC for mixed composition (~2σ)

[@A.Aab et al (Auger Coll.) PRL117 (2016) 192001]

Inclined showers analysis

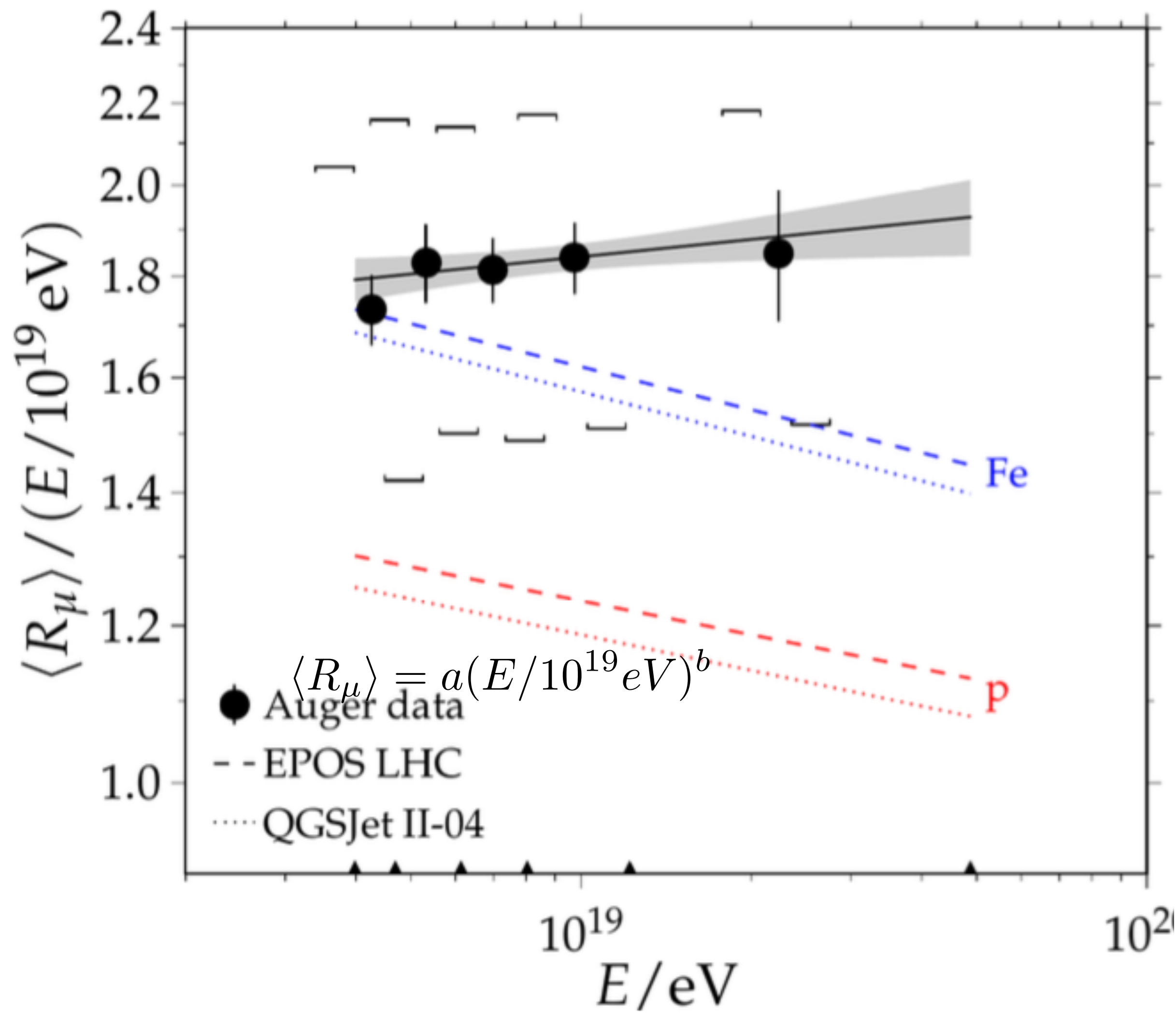


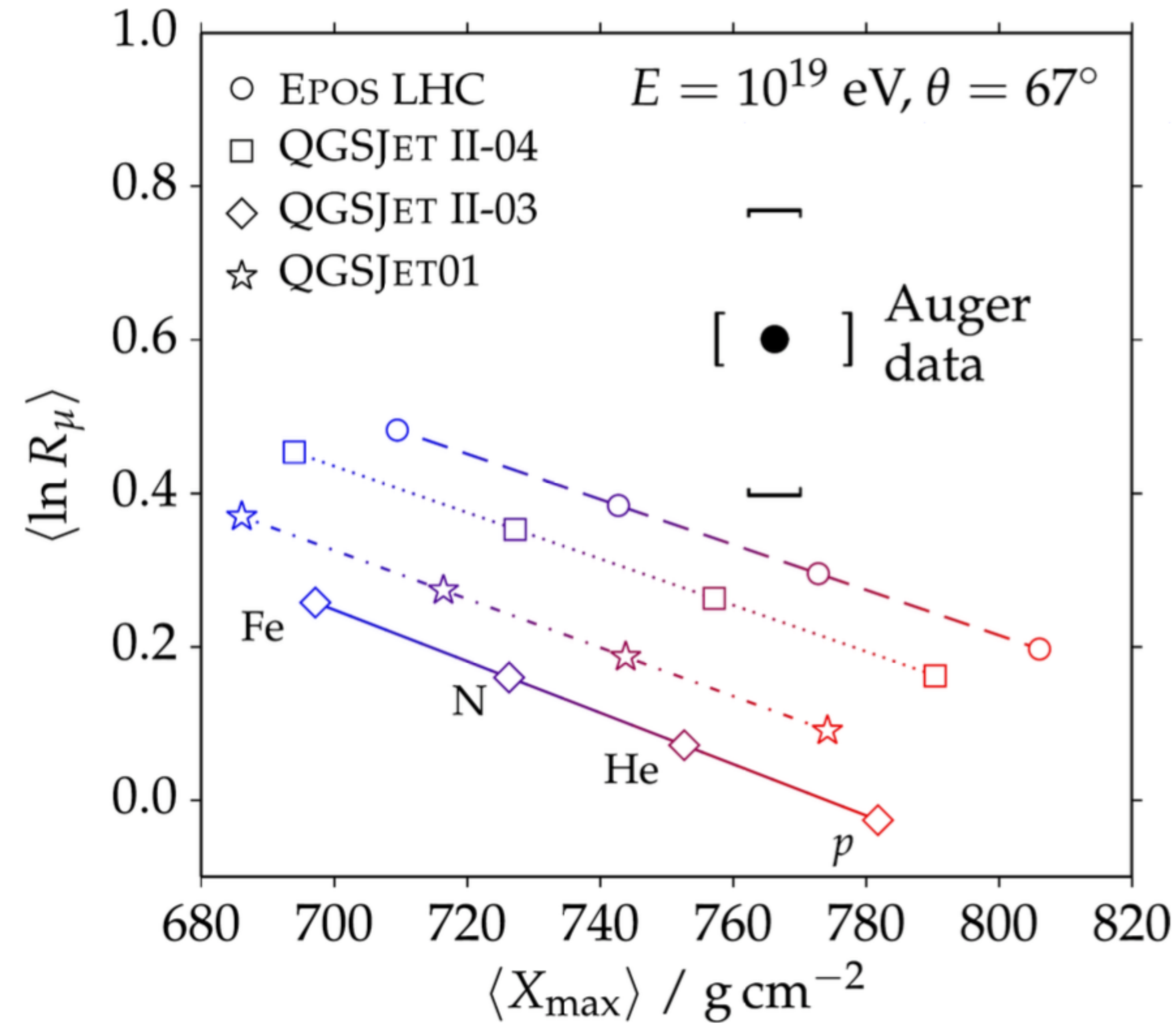


Example of $\rho_{\mu,19}$ for proton showers at θ=80°, ϕ=0° and core at (x,y) = (0,0)

- inclined muons (62^0-80^0)
- hybrid events
- reference map of muon density at ground

$$\rho_\mu^{rec} = R_\mu \ \rho_\mu^{map}(r, \theta, \phi)$$



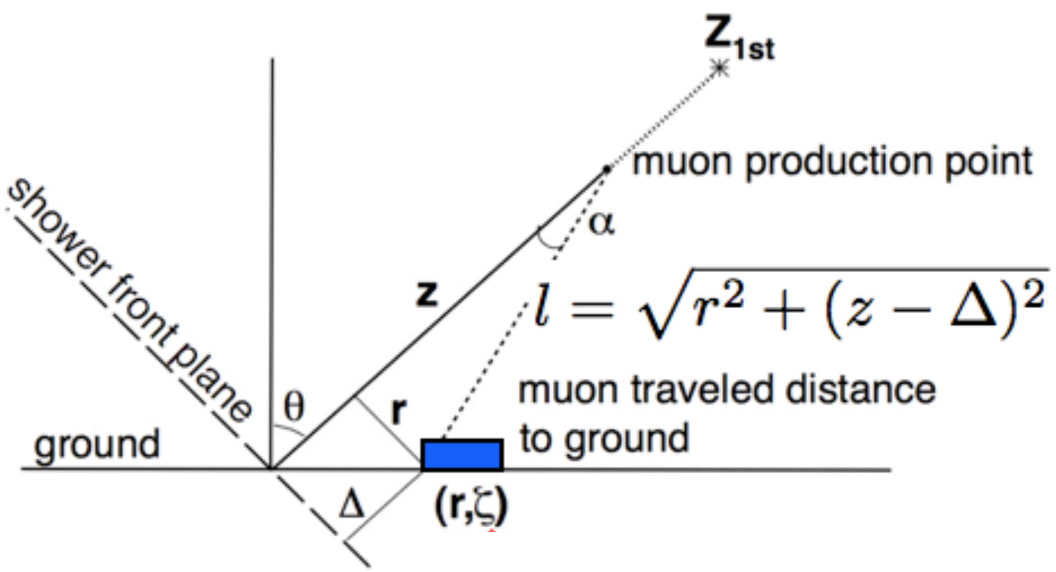


- difference in absolute value and slope
- no hadronic interaction model matches the measurements.

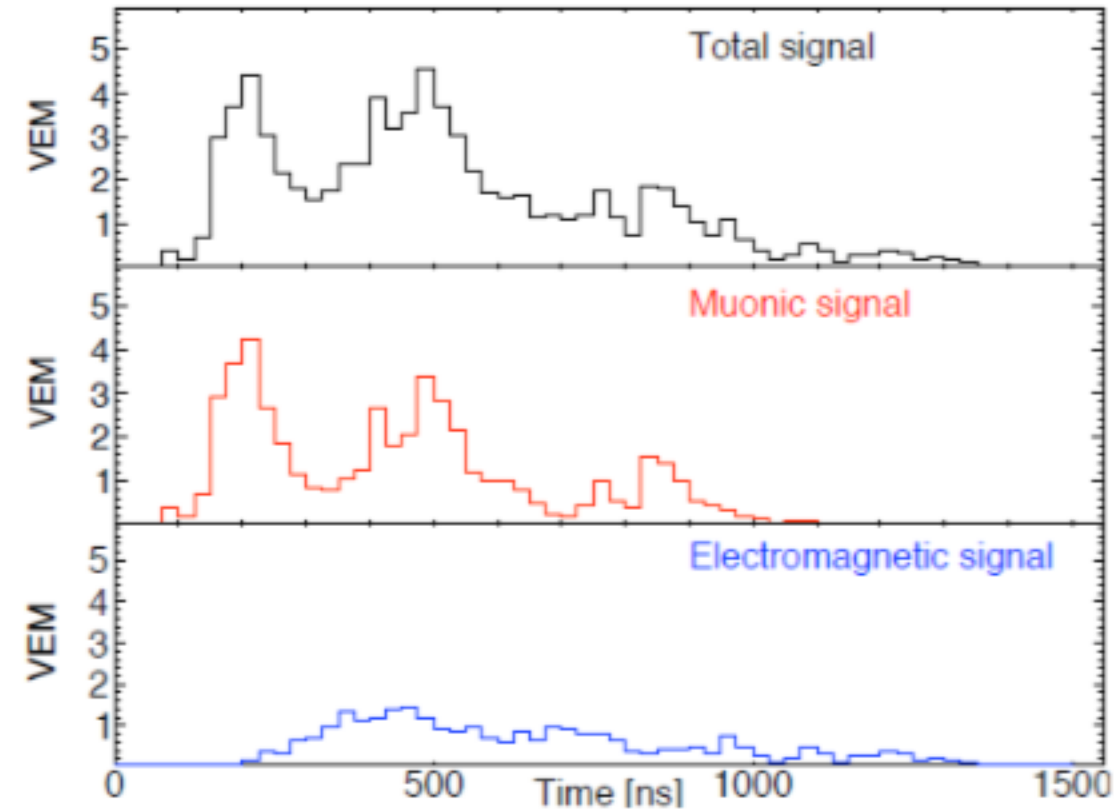
30% to 80%$^{+17}_{-20}$ (sys)% increase in $\langle N_\mu \rangle$ needed

[@A.Aab et al (Auger Coll.) PRD91 (2015) 032003+059901]

Muon production depth



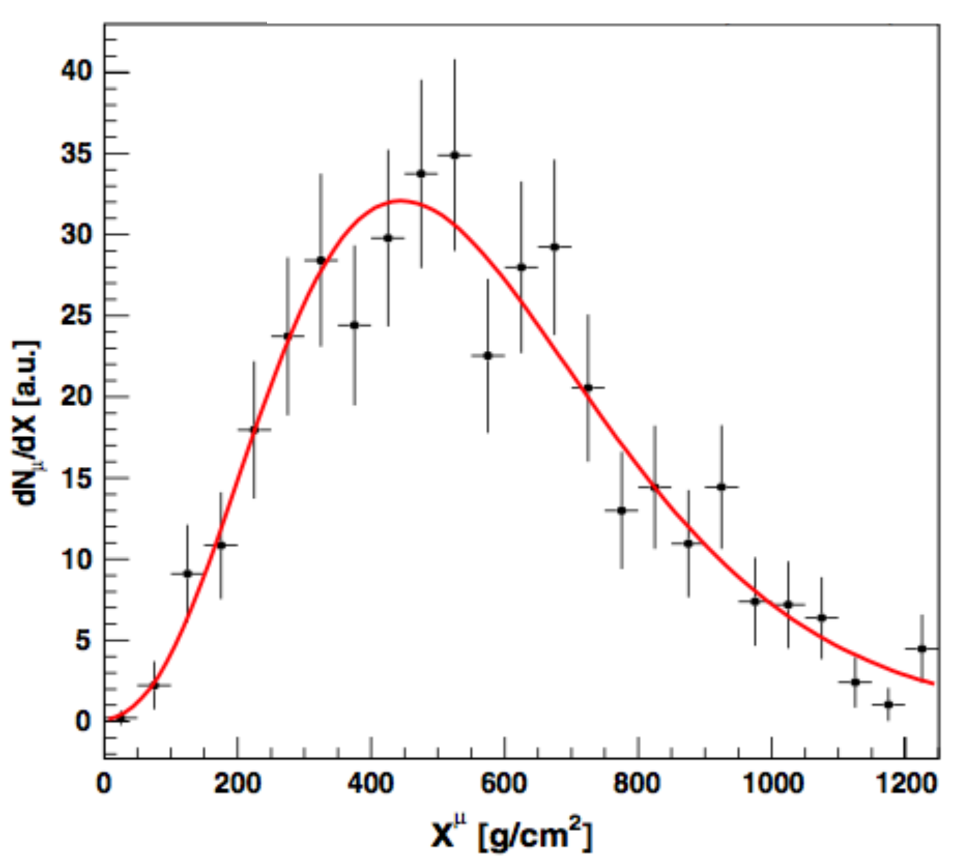
E>20 EeV, ϑ>55⁰, r>1700 m

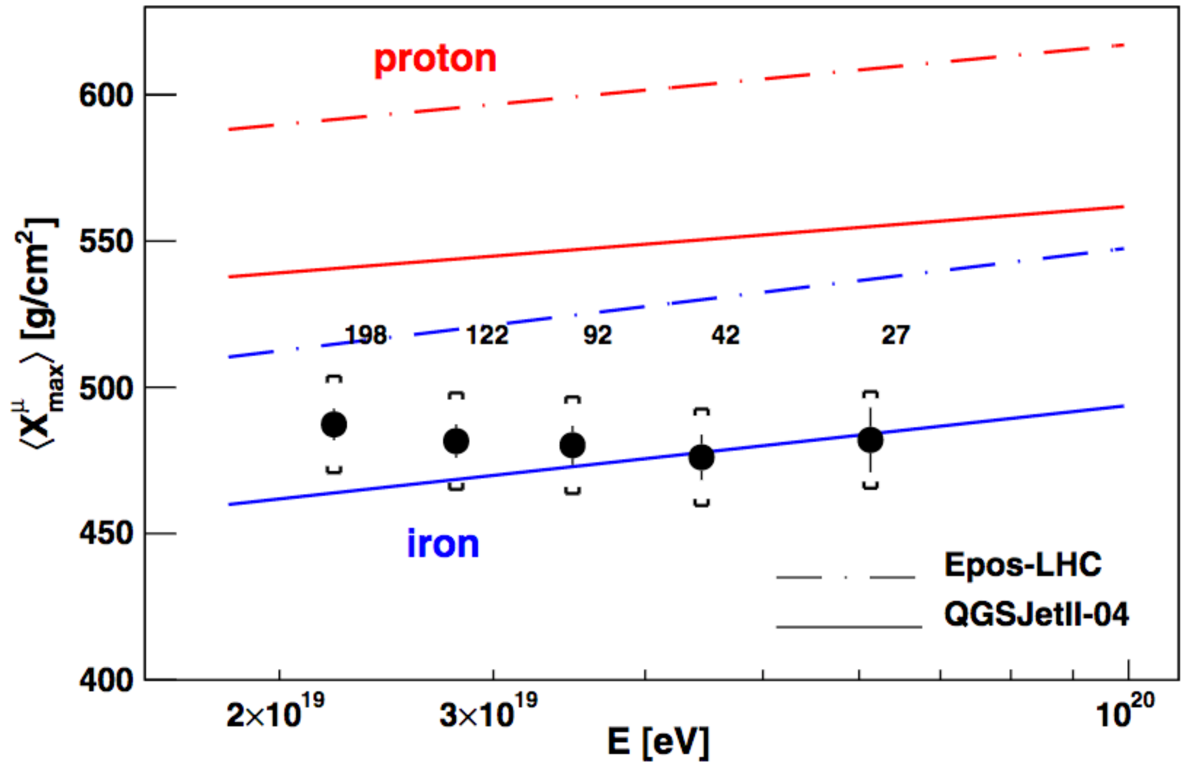


t [ns] → z [m] → X [g cm^{-2}]

$$z \simeq \frac{1}{2}\left(\frac{r^2}{c(t - \langle t_\epsilon \rangle)} - c(t - \langle t_\epsilon \rangle)\right) + \Delta - \langle z_\pi \rangle$$

MPD $$X^\mu = \int_z^\infty \rho(z')dz'$$





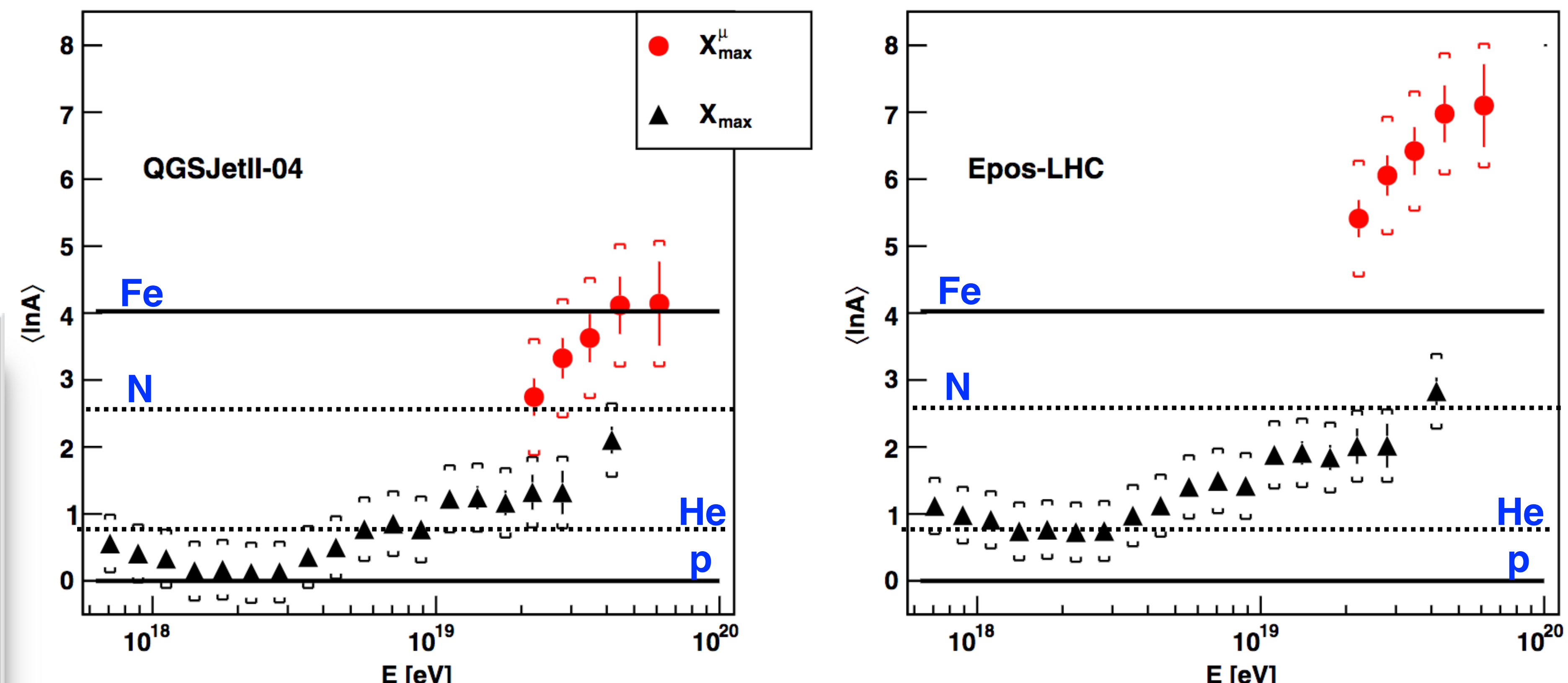
- if models are correct, there must be a transition from light to heavier masses - flatter than for pure composition
- no match with EPOS-LHC prediction
- analysis can be extended to lower E and ϑ by tagging the EM component (in progress)

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

with X=X_{max} or X^{μ}_{max}

EPOS-LHC fails to consistently reproduce both components

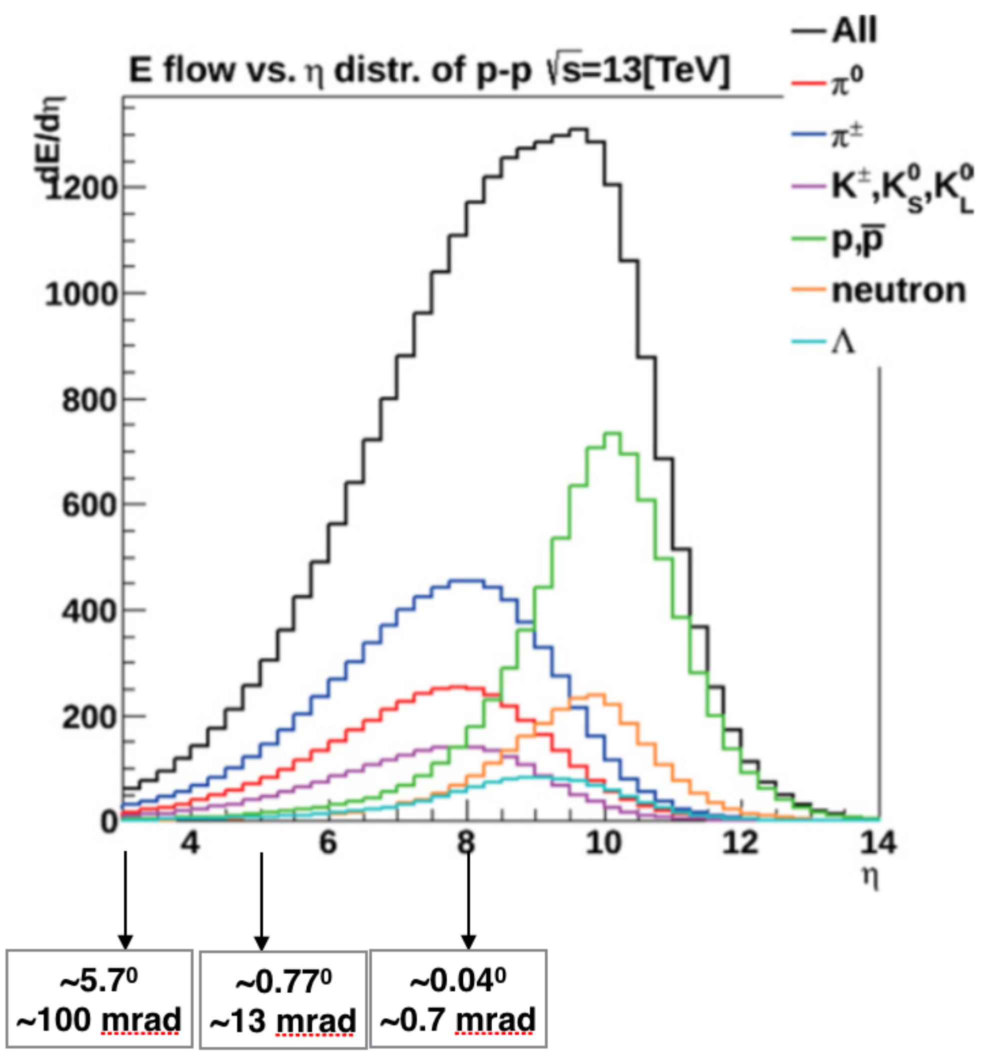
QGSJetII-04 better but at variance with X_{max} results

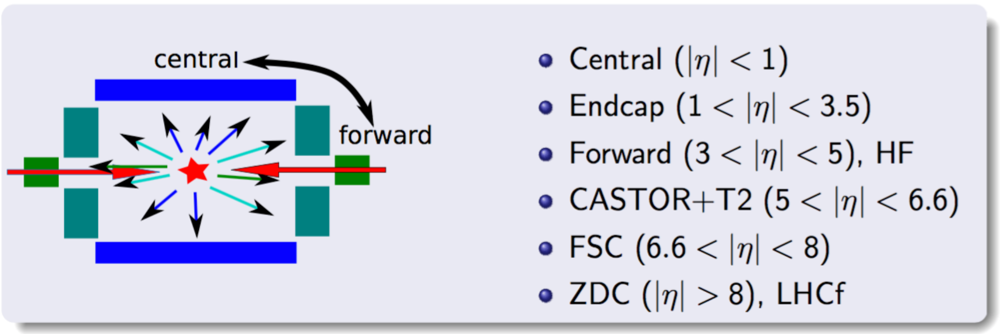


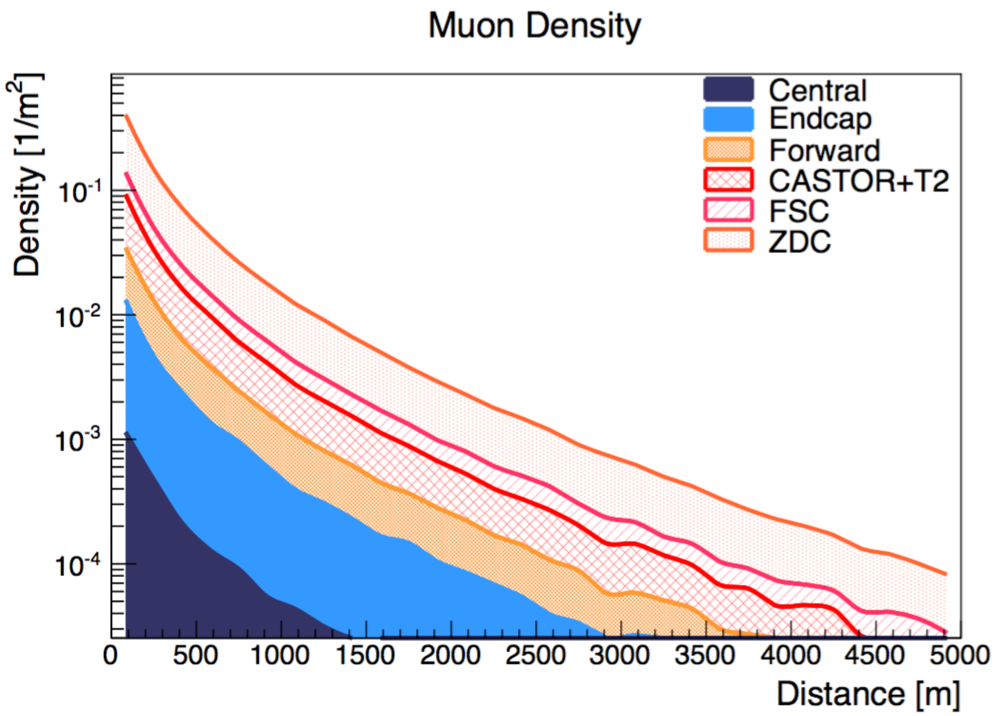
[@A.Aab et al (Auger Coll.) PRD90 (2014) 012012, PRD92 (2015) 019903]

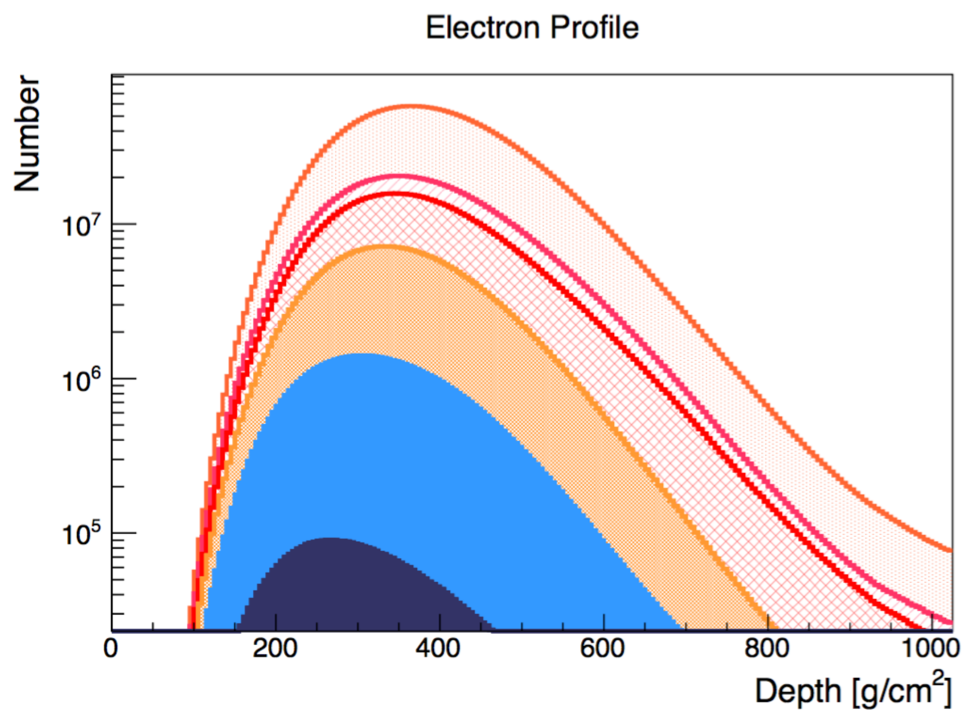
Hadronic interactions relevant for UHECRs

- σ_{prod} —> determines λ_{int} and the development of the EAS
- production spectra of forward secondaries
- inelasticity
- pion charge ratio
- baryon production
- ….









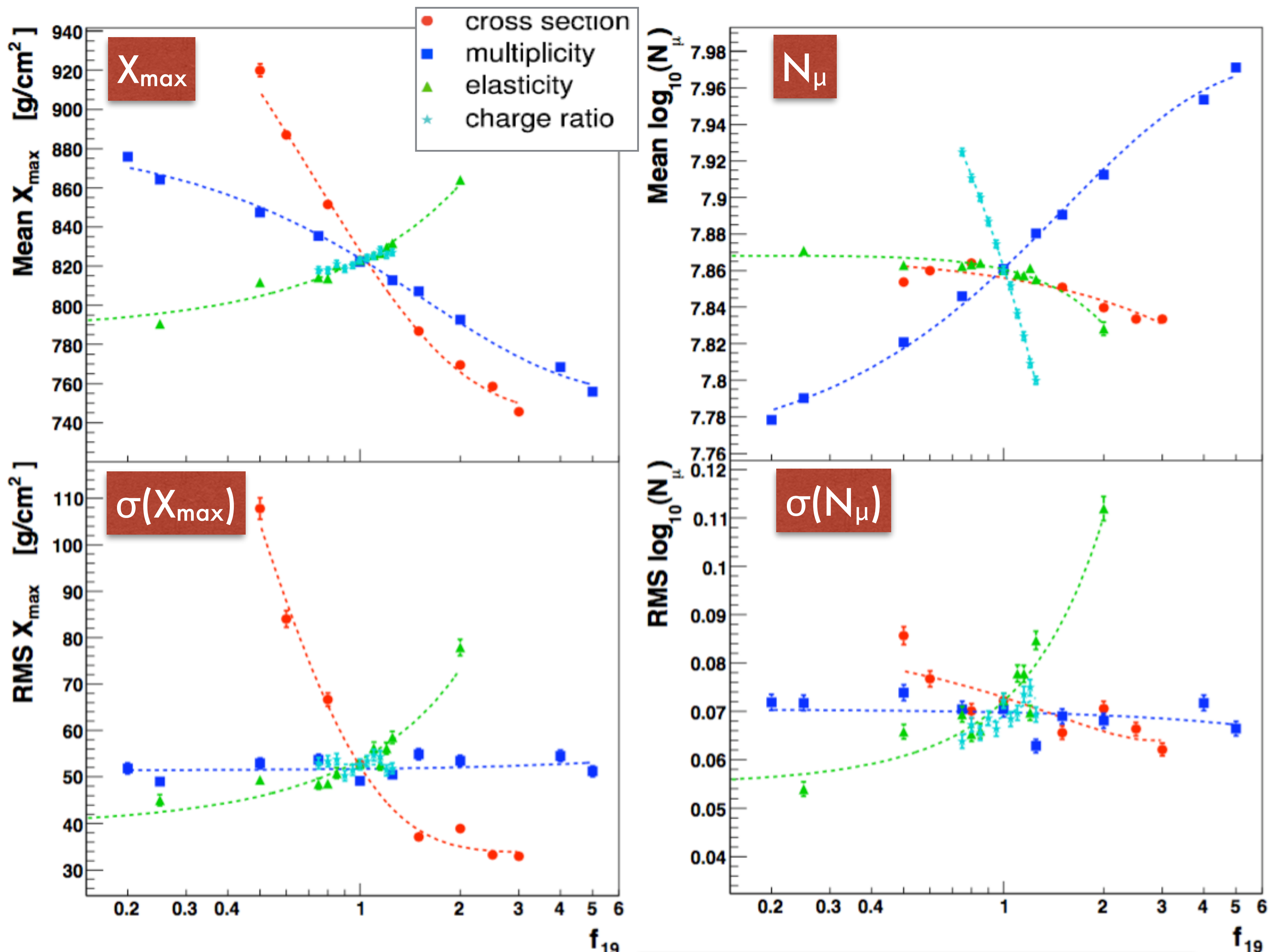
EPOS-LHC, QGSJetII-04
tuned to the LHC results at $\sqrt{s}$=7 TeV

Sensitivity of EAS observables

Individual hadronic interaction features can be altered during EAS development :

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

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

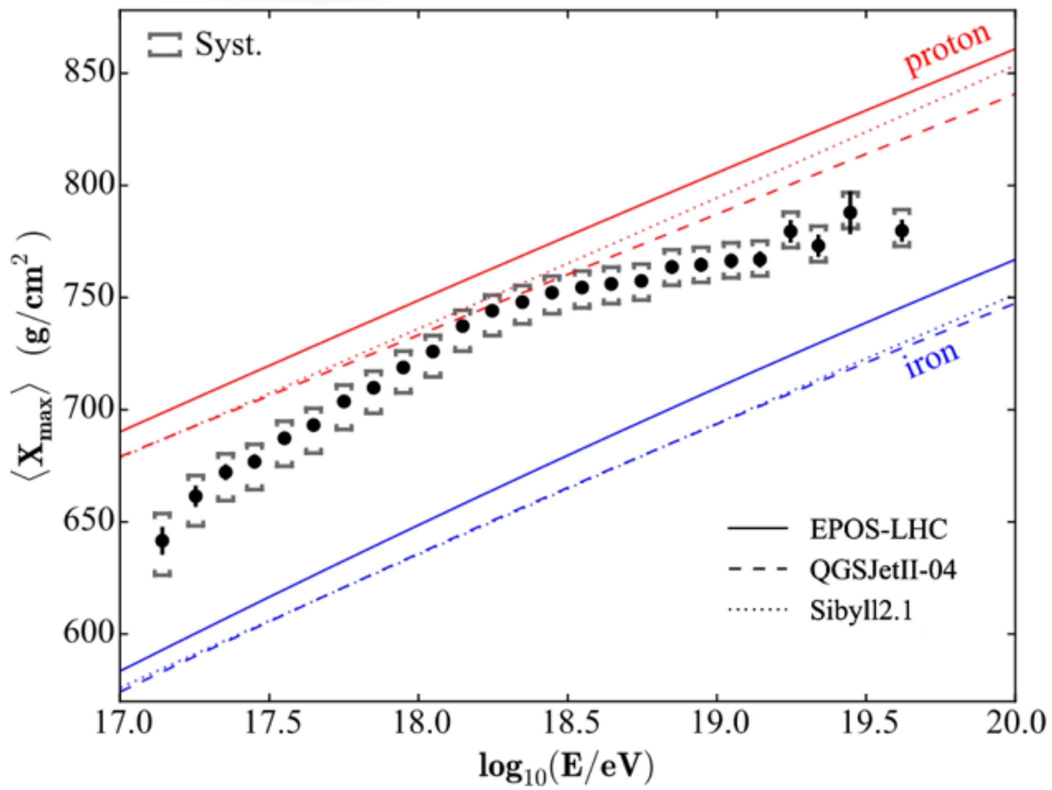


[@R.Ulrich et al., PRD83 (2011) 054026]

Example (proton showers) :

- 20% difference in cross section corresponds to ~30 g/cm^2 difference in <X_{max}>
- positive correlation of muon number with multiplicity. Only large change (> factor 2)in multiplicity can allow a 20% change in N (while a moderate change in modelling of low energy interactions would be enough)

Model uncertainties on X_{max}



1. **σ_{inel} for p-p, nucleus-nucleus collisions**

   greatly reduced by σ_{tot} and σ_{ela} measured at TOTEM and ATLAS

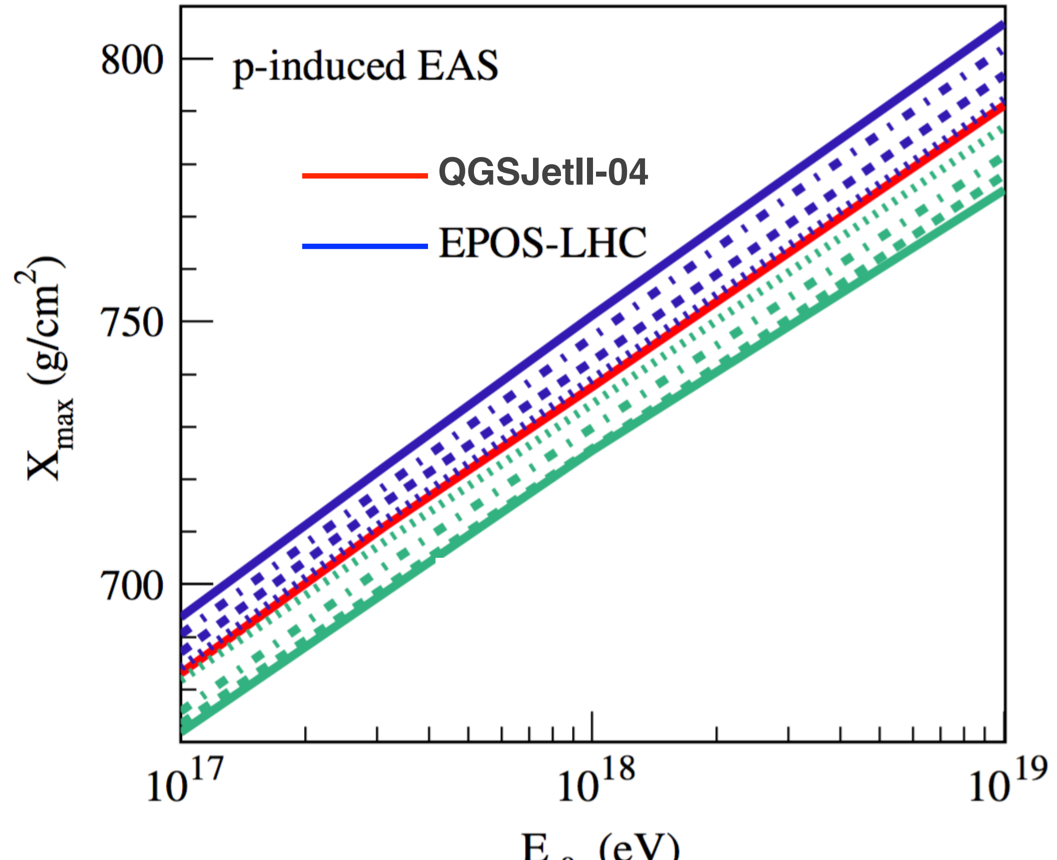
2. **rate of inelastic diffraction in p-p, p-nucleus interactions**

   → shape of very forward spectra of secondaries → longitudinal development of the EAS

for fixed (QGSJetII-04) model, it accounts for a ~10% uncertainty

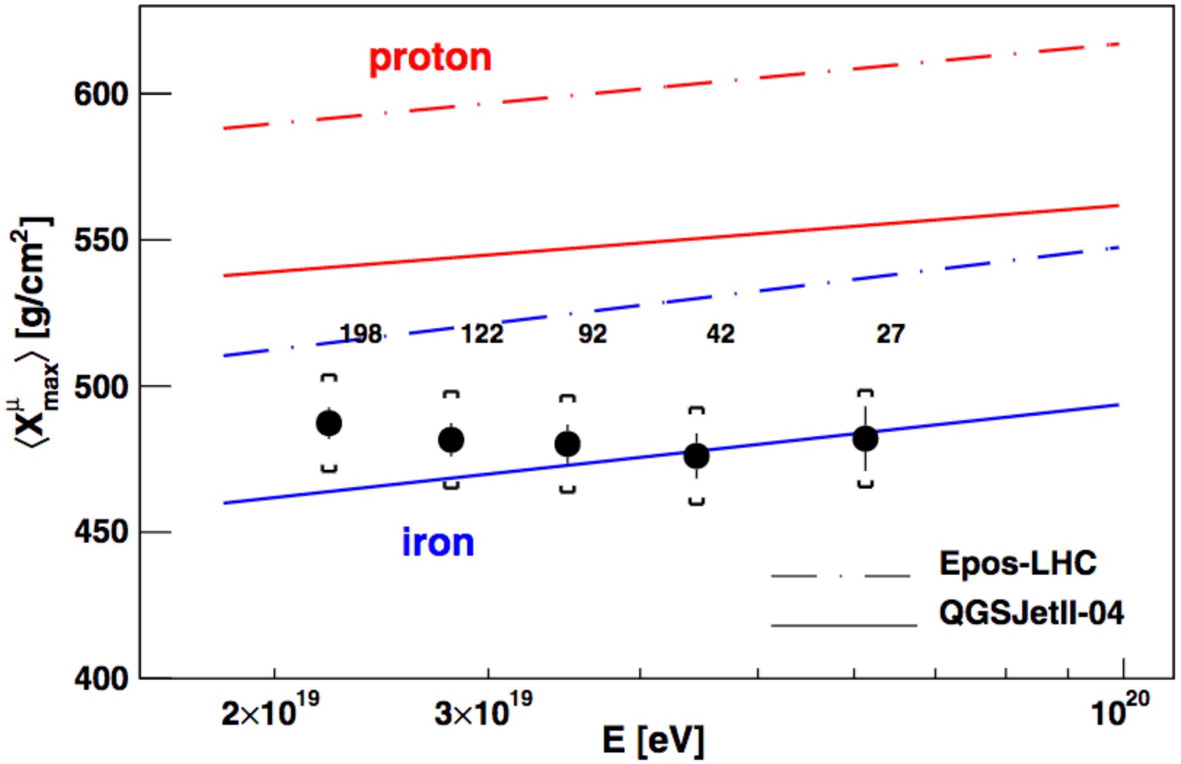
The remaining difference between EPOS-LHC and QGSJetII-04 (~15-20 g cm^{-2}) is equally shared by the model dependence on

- **position of first interaction and production of secondaries**
- **the hard or soft spectra of secondaries (harder in EPOS)**
- **the number of baryon-antibaryon pairs in π and K collisions**



[@S.Ostapchenko, M.Bleicher, PRD93 (2016) 051501]

Model uncertainties on X^{μ}_{max}



1 **σ_{inel} for p-p, nucleus-nucleus collisions**

but muons come mainly from LE interactions after many stages of the cascade

2 **forward spectral shape of secondary mesons**

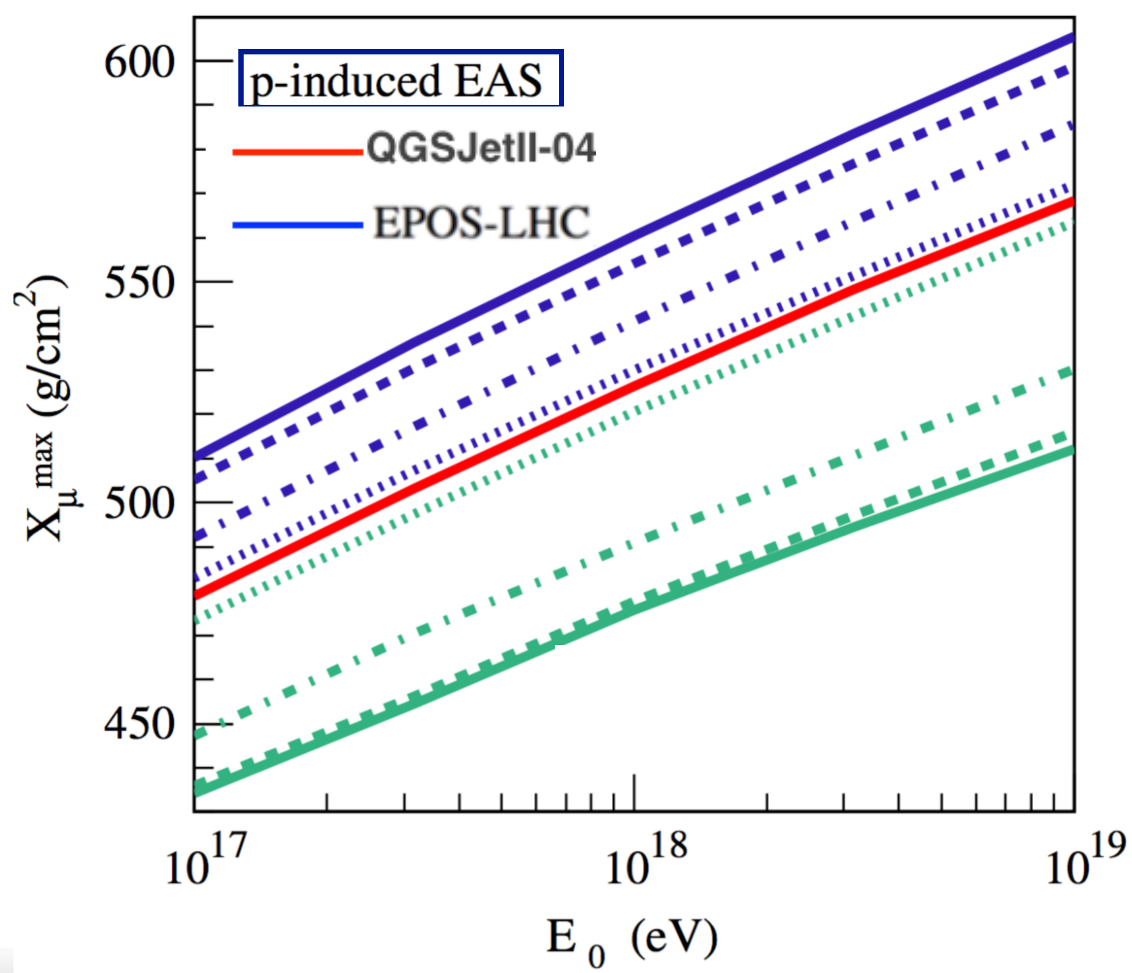
harder meson spectra or smaller $\sigma_{\pi\text{-}Air}$

3 **production of baryon-antibaryons in π-Air interactions**

more interactions even below hundreds of GeV

The large difference between EPOS-LHC and QGSJetII-04 (~70 g cm^{-2}) is due to the model dependence on

- **the number of baryon-antibaryon pairs in π and K collisions with air ~40%**
- **the hard or soft spectra of secondaries (harder in EPOS) ~35%**
- **the position of the primary interaction ~20%**

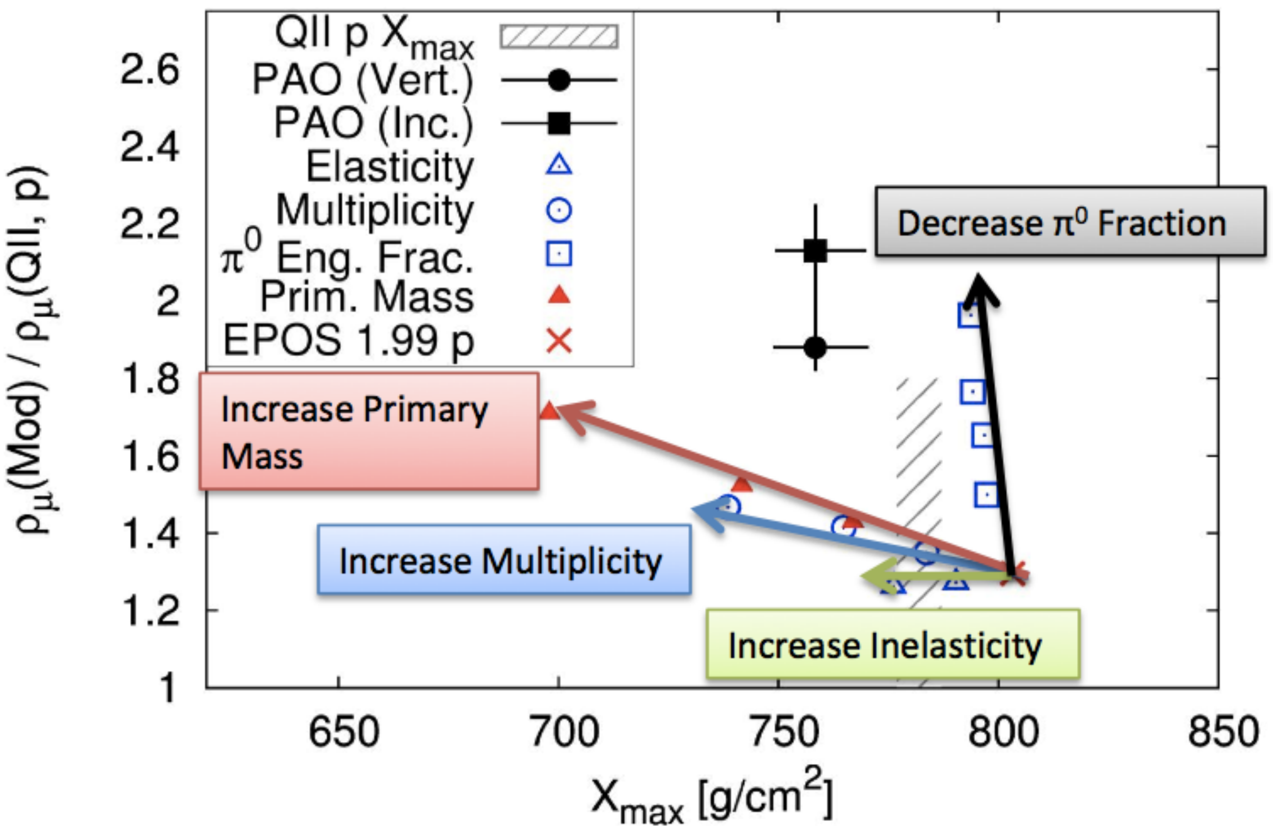


Increasing the muon production

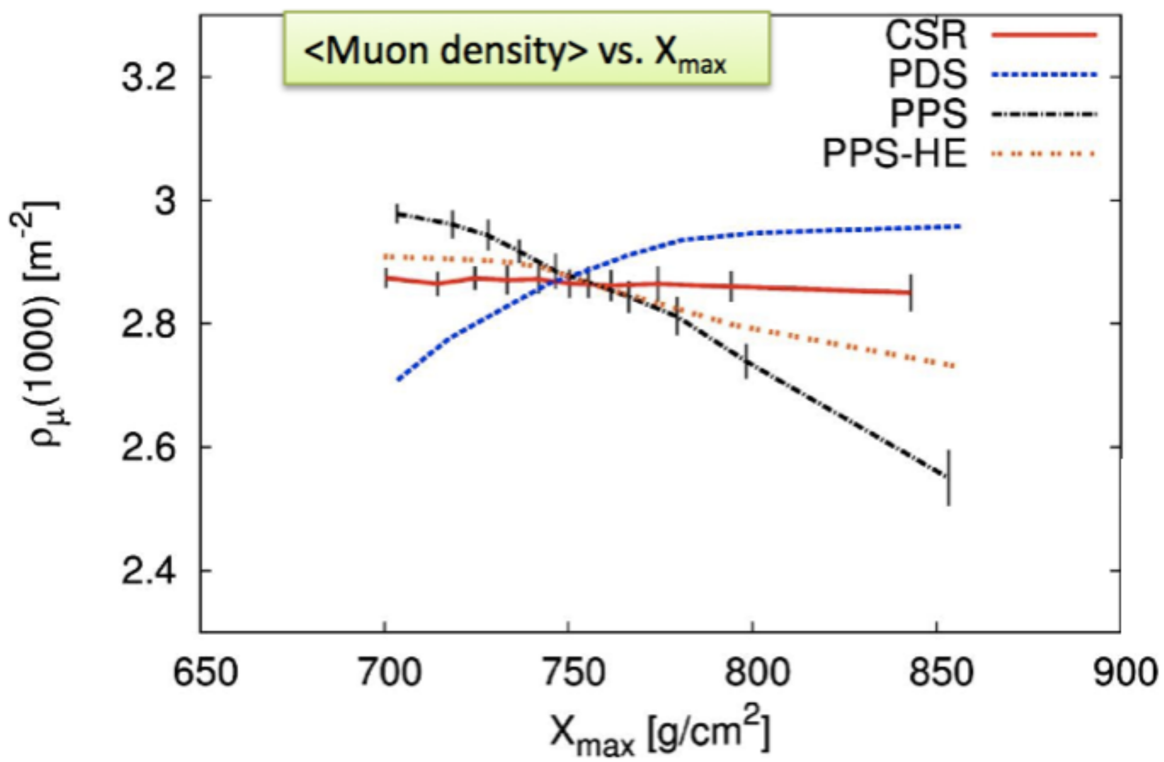
$$N_\mu = (N_{tot} - N_{EM})^n = \left(\frac{E_0}{E_{dec}}\right)^{1+lnR/lnN_{tot}}$$

$$E_{dec} = \frac{E_0}{(N_{tot})^n}$$

$$R = (N_{tot} - N_{EM})/N_{tot}$$



Modifications to models need to match the data on muons and maximum production depths for EM and μ components.

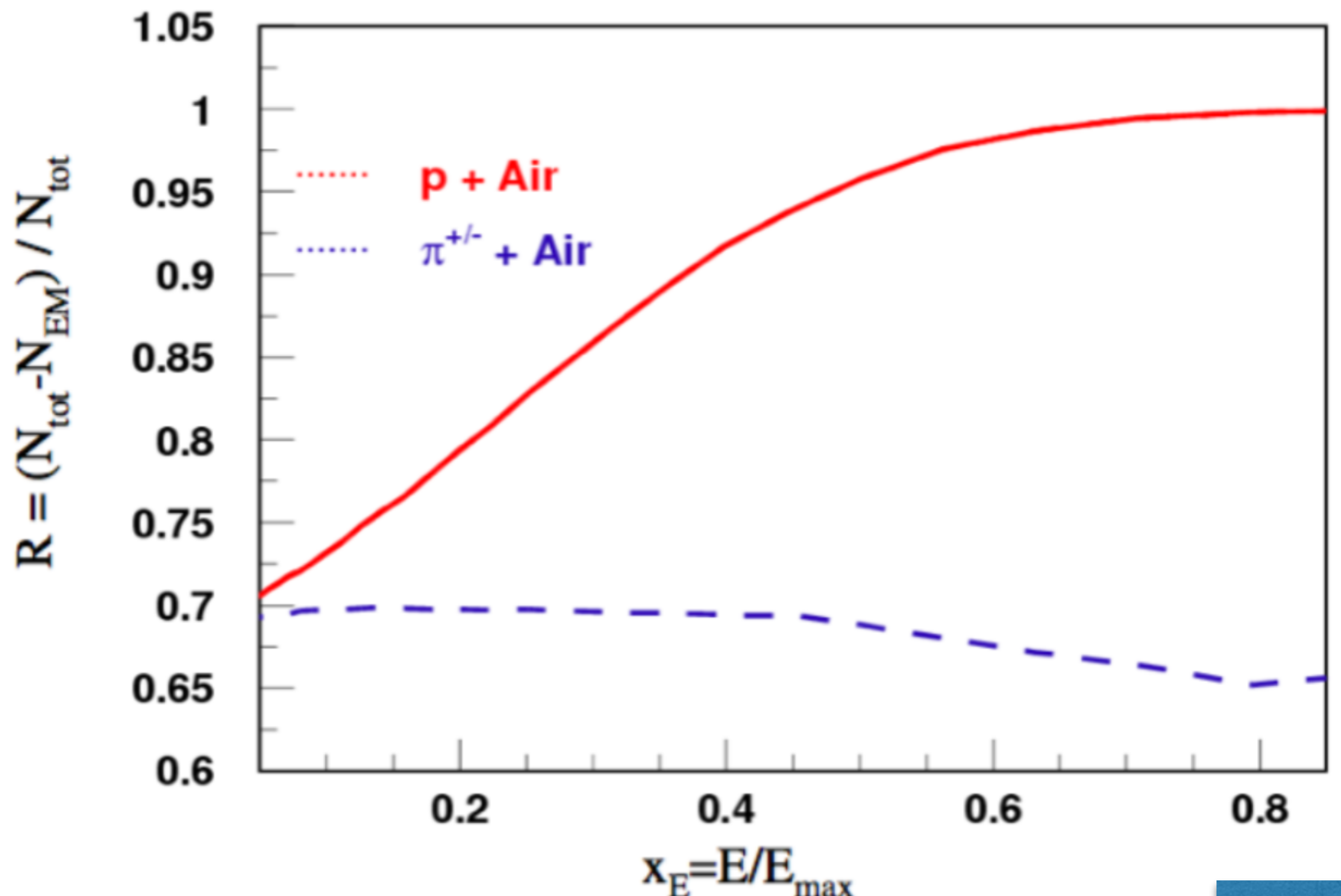


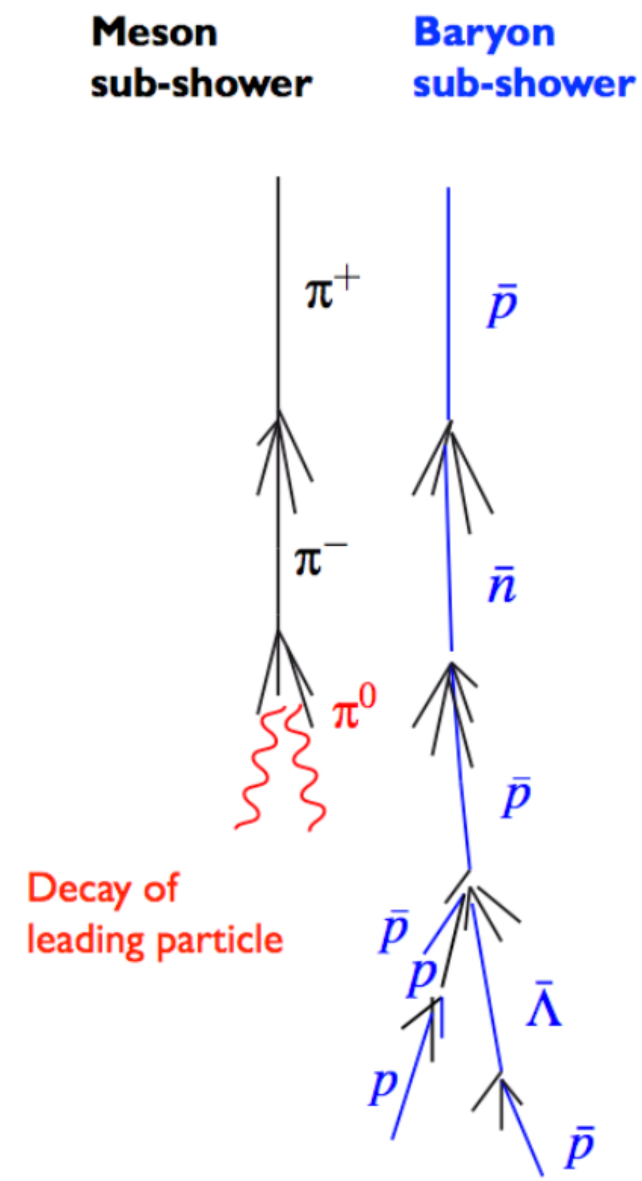
More muons :

- pion production suppression
- pion decay suppression
- leading particle effect : π^0 replaced with ρ^0
- baryon-antibaryon production
- ….others

(anti-)Baryon production

- increasing (anti)baryon production, more energy is left in the hadronic part (no leading π^0)
- increasing (anti)baryon production strongly enhance muon production
- almost not affecting X_{max}
- enhancement of mainly low-energy muons

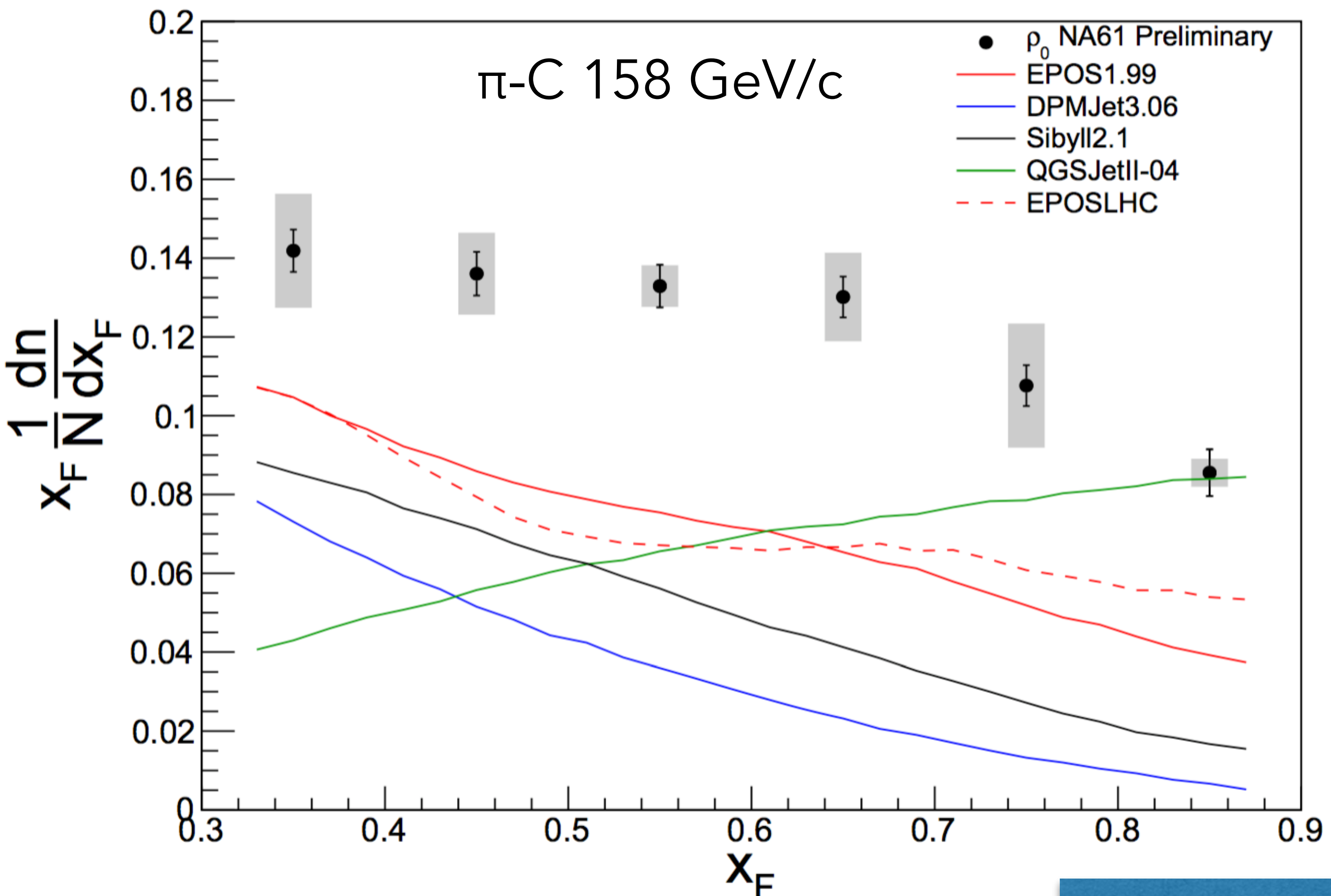


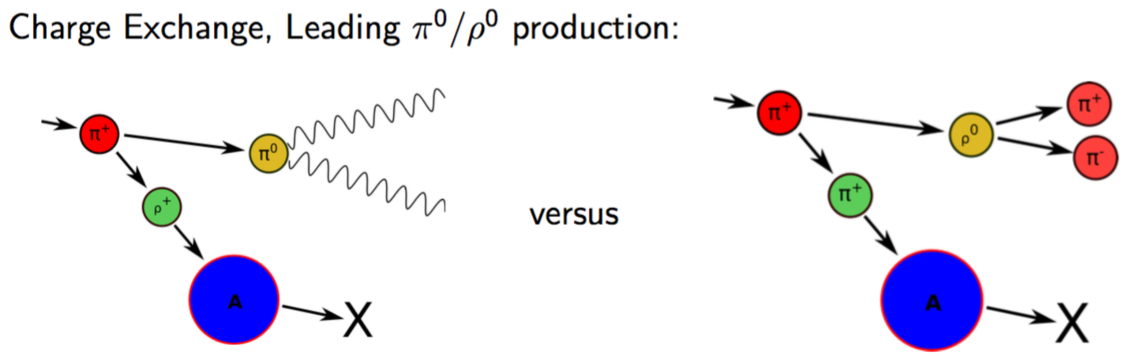


[@T.Pierog, K.Werner, PRL101 (2008) 171101]

Pion Leading particle effect

- change of leading particle in hadronic interactions: replace π^0 with ρ^0
- fixed target data indicate that the production of ρ^0 dominates that of π^0 for $x_F>0.5$
- Further tuning is required in models to reproduce the charged pion spectra and ρ^0 production in π−C interactions.





Change in relative weight of π^0 and ρ^0 multiplicities

Change in relative weight of EM and μ components in EAS

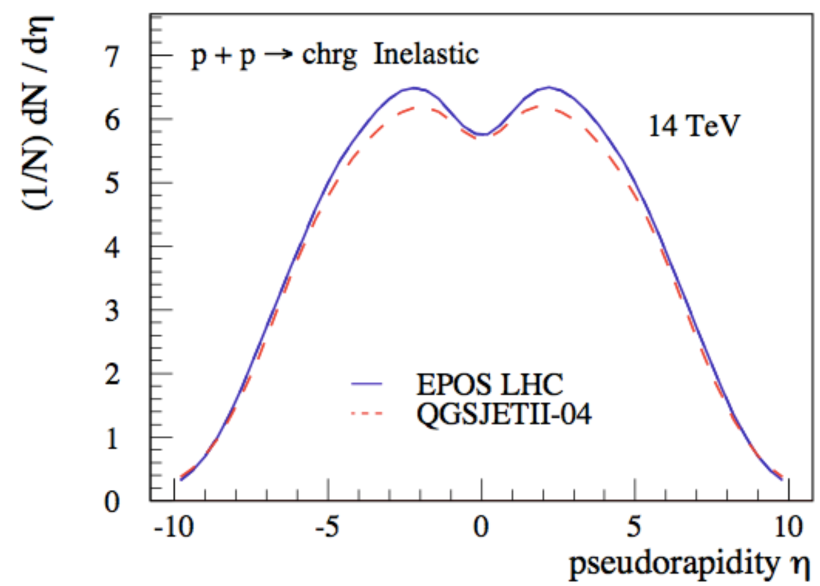
Increase of muons at all energies

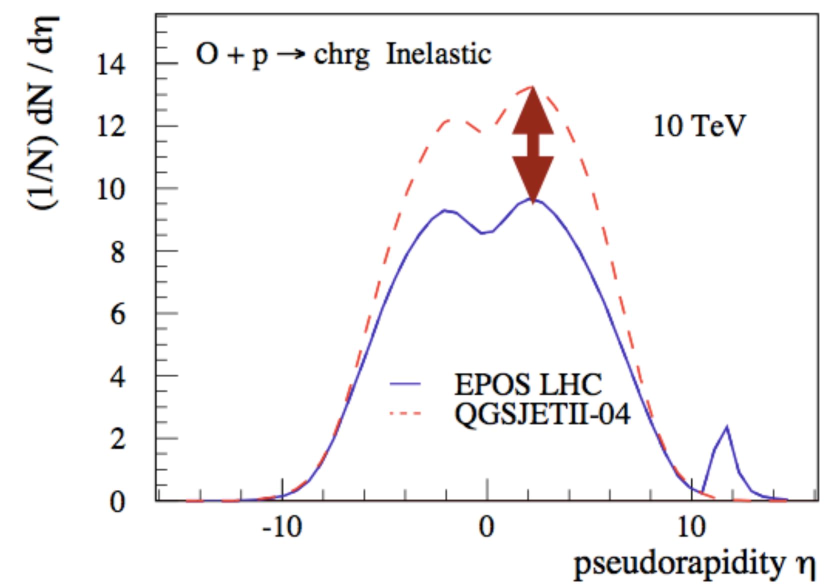
[@H-J. Drescher, PRD77 (2007) 056003]
[@M.Unger (NA61/SHINE COll.) Nucl.Phys.B(Proc.Suppl.)279 (2016)_118]

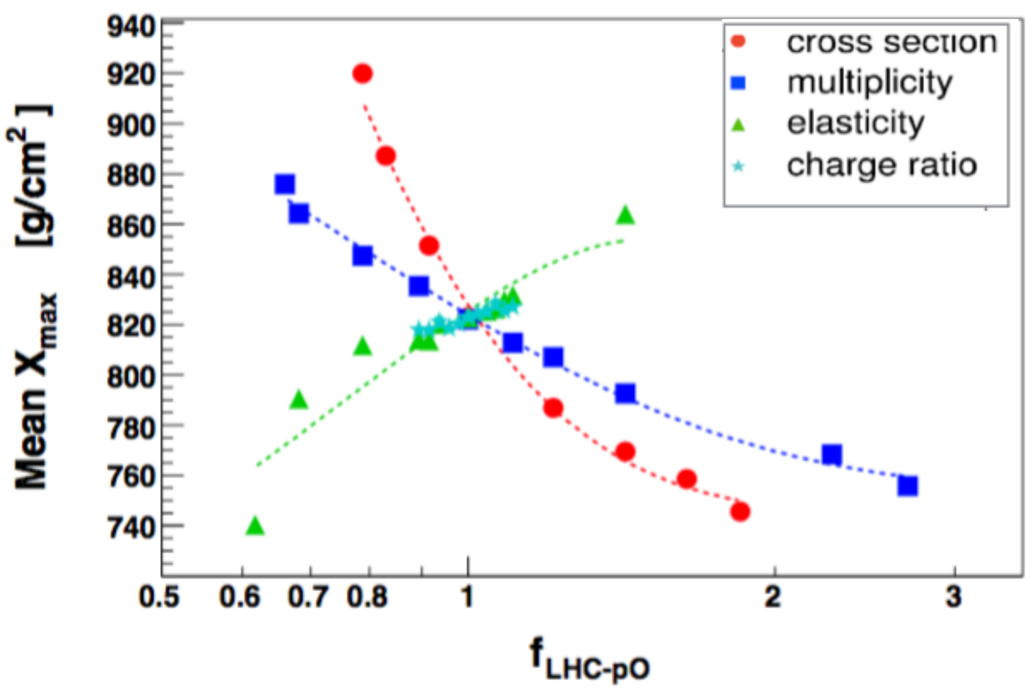
Future prospects -accelerators

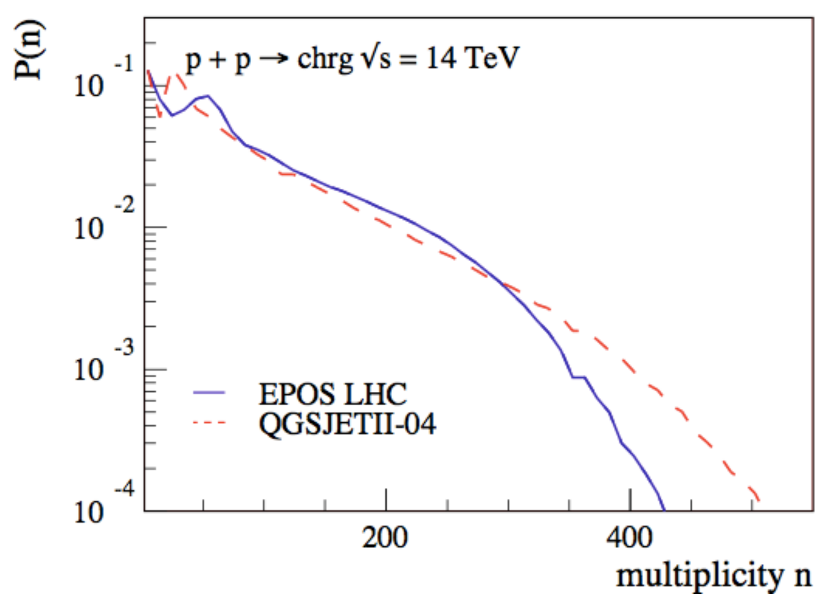
Strong constraints from LHC measurements to extrapolations in energy

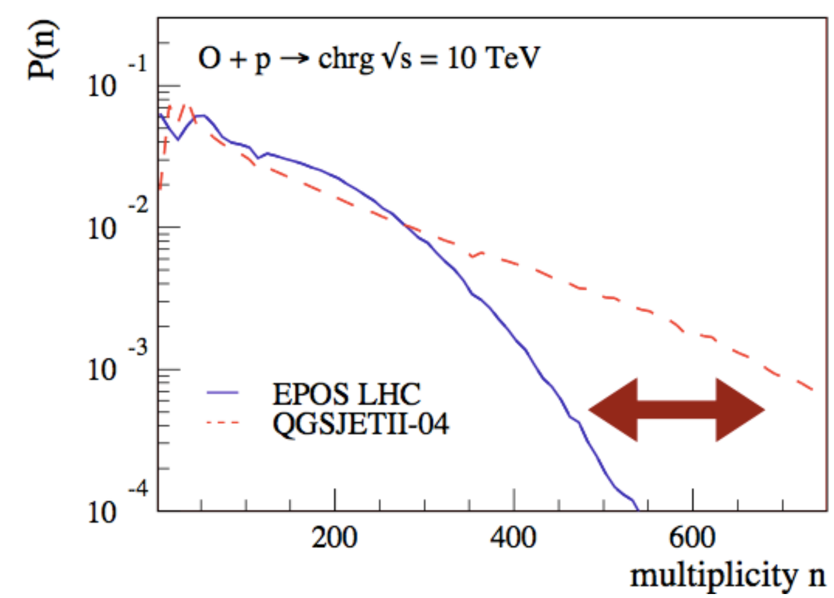
Main source of uncertainty from models is the difference between p-p and p-nucleus collisions











- **p-light ion collisions**: can provide calibration of nuclear effects in p-N interactions of EAS
- **O beam as light ion** can be chosen

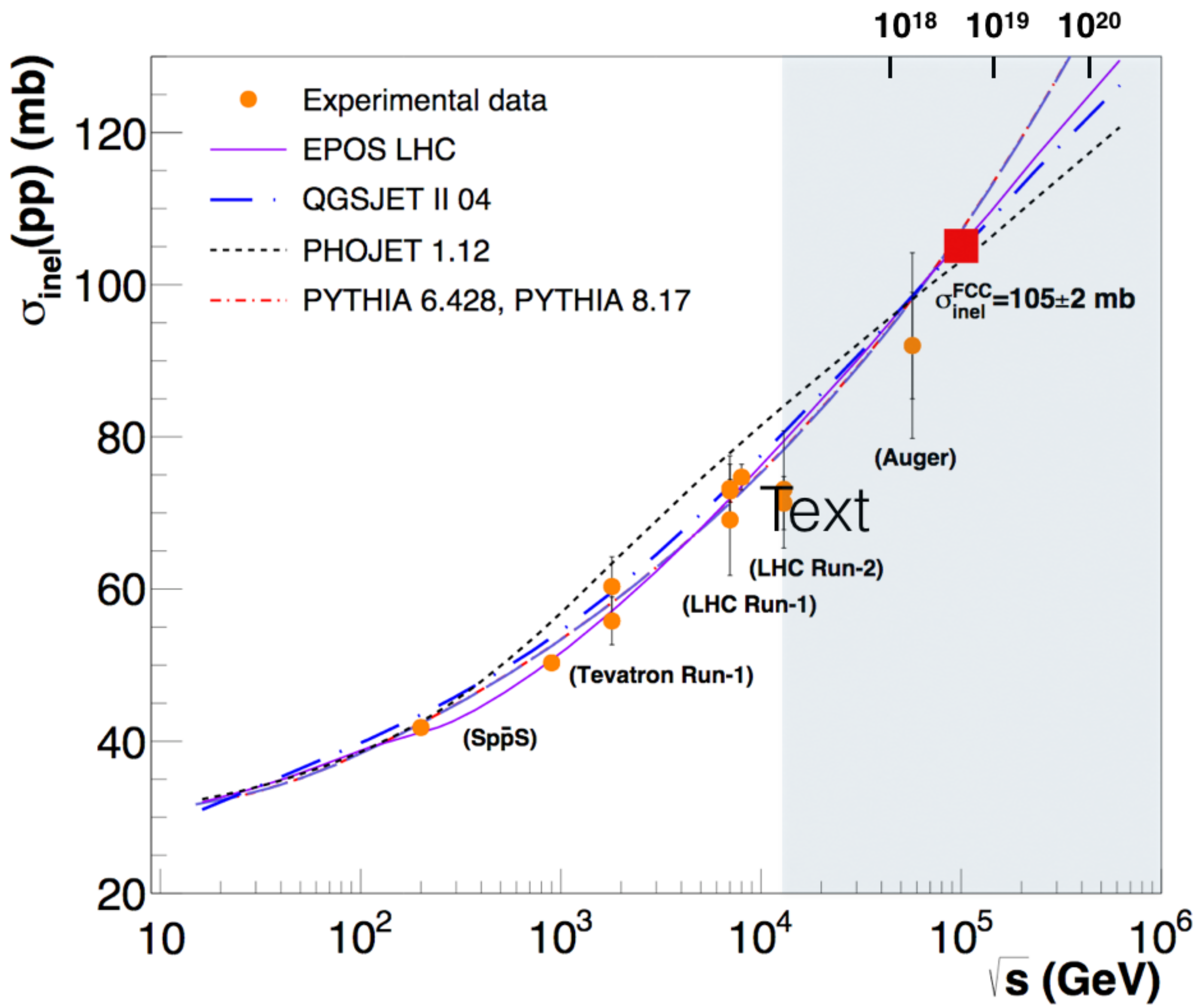
Future hadron colliders

FCC-hh (CERN), SppC (China)

Global properties of final states in hadronic interactions at $\sqrt{s}$=100 TeV (E_{CR}=5.3 10^{18} eV)

with MC used in colliders

with MC used in UHECR



E.g. at $\sqrt{s}$=100 TeV

$<\sigma_{inel}>$=105$\pm$2 mb (+43% wrt LHC-13 TeV)

[@D.D'Enterria, T.Pierog, J.High Energy Phys.08 (2016) 170]

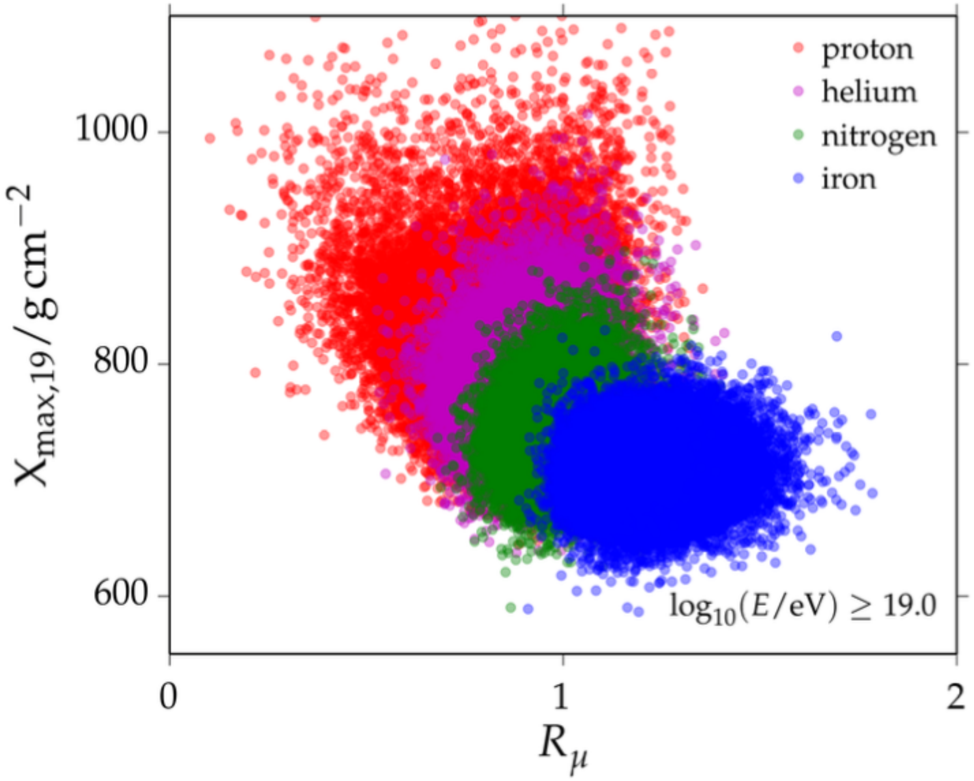
Future prospects - UHECRs

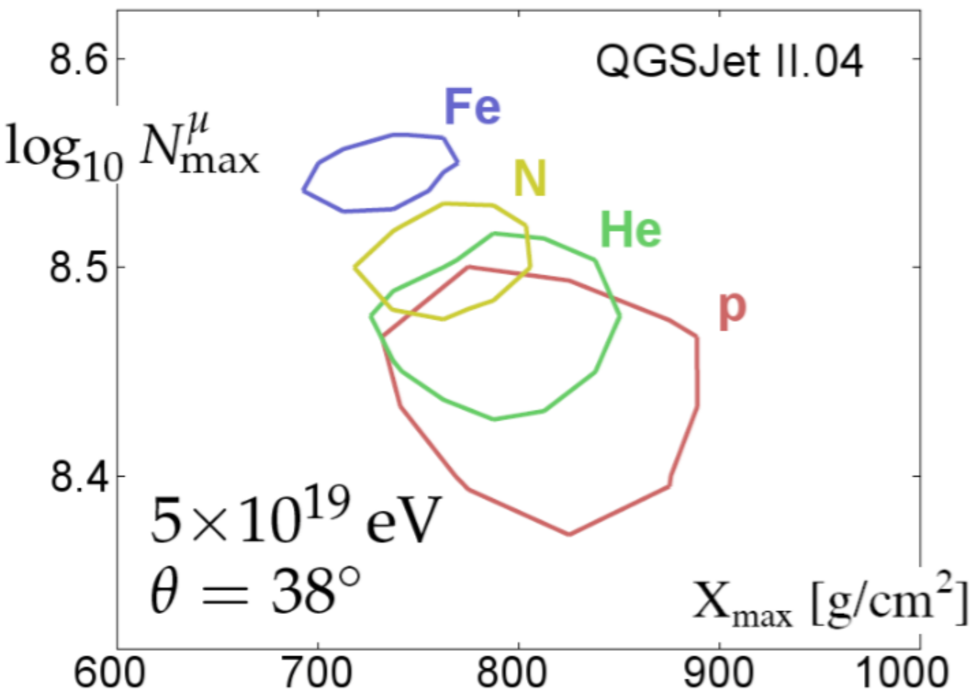
Models

- improve the description of pion interactions
- include in models all hints from MPD results
- try combined calculations including all data (Accelerators and UHECRs)

Experiments upgrade : AugerPrime

- increased sensitivity to composition in the suppression region
- additional scintillators + increased FD duty cycle + upgraded electronics and dynamic range





Combining accelerator and UHECR data

[@C.Baus et al. PoS(ICRC2015) 418]

Multiple measurements (LHC and cosmic rays)

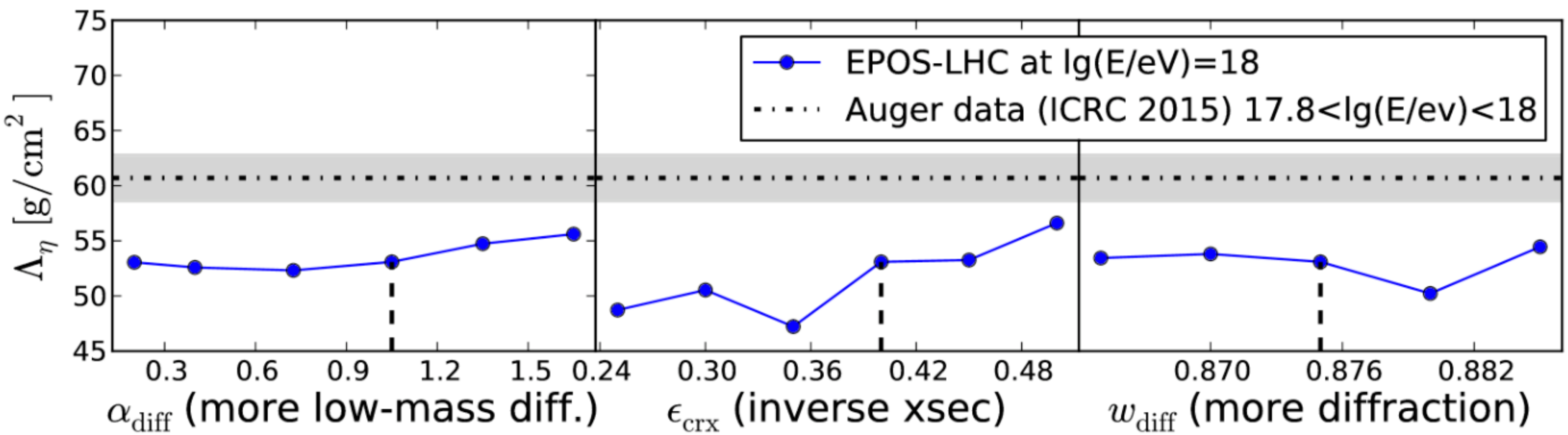
$\mathcal{L} = \mathcal{L}_{\text{astro}}\,\mathcal{L}_{\text{LHC}}$

Agreement Data-MC

Modify model parameters

sensitivity of parameters

First (promising) attempt with EPOS-LHC

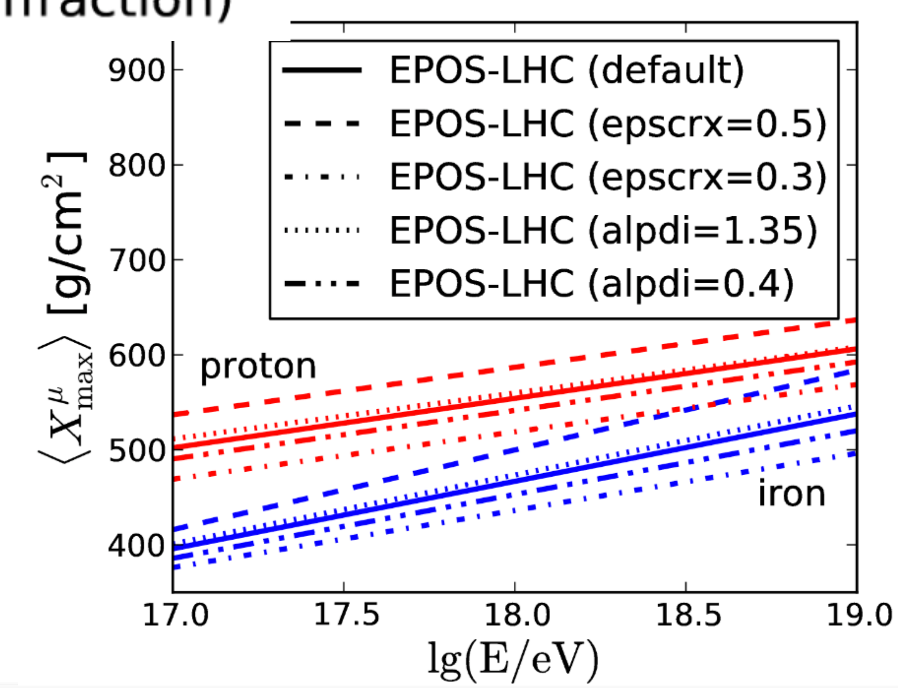


Tail of X_{max}

- *strongest dependence on saturation scale (slower rise of* **σ***)*
- need 3D shower simulations

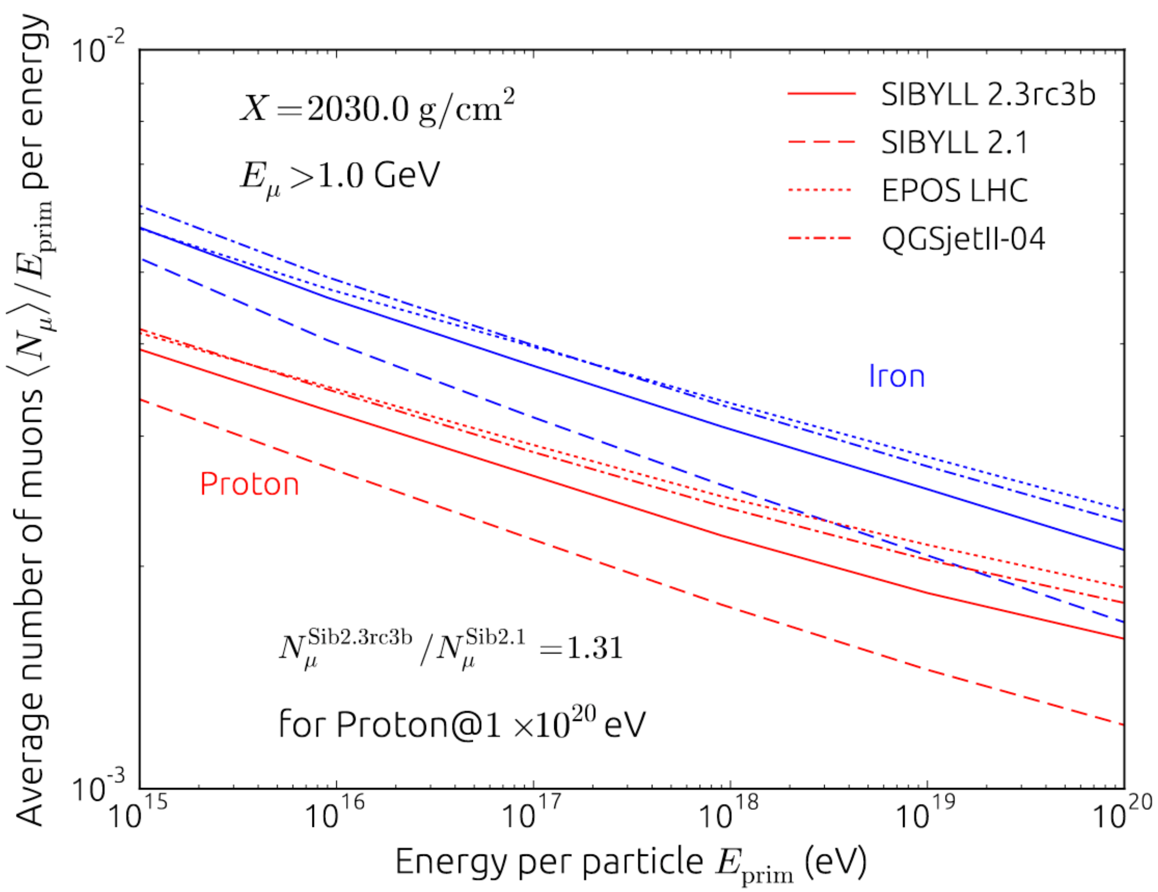
MPD

- *low possibility to use for mass composition*
- need 3D shower simulations

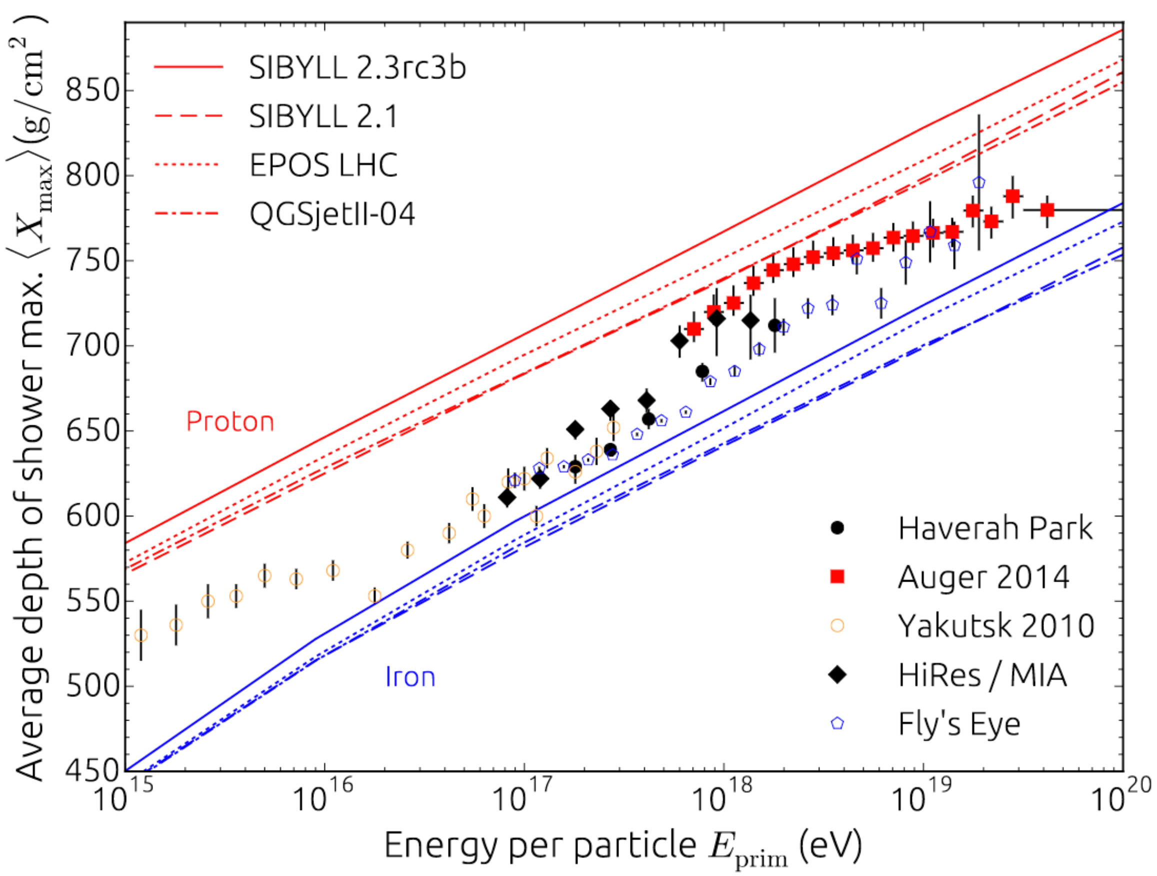


Example: Sibyll 2.3

- new fits to hadronic cross-sections
- diffractive dissociation
- *increased rate of baryon-antibaryon pair production*
- *leading particle effect* (ρ^0)
- production of charmed particles



increased muon number, closer to QGSJetII-04



deeper showers
existing data point to a "heavier" composition

Conclusion

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

More information is provided by CR measurements at ultra high energies and in unexplored kinematic regions and interactions

Same models can be used for accelerators and CR studies

Very strong interest of the UHECR community in the continuation and possibly in the extension of the programs about forward physics at LHC

larger energy
extended phase space
p-light nucleus observations

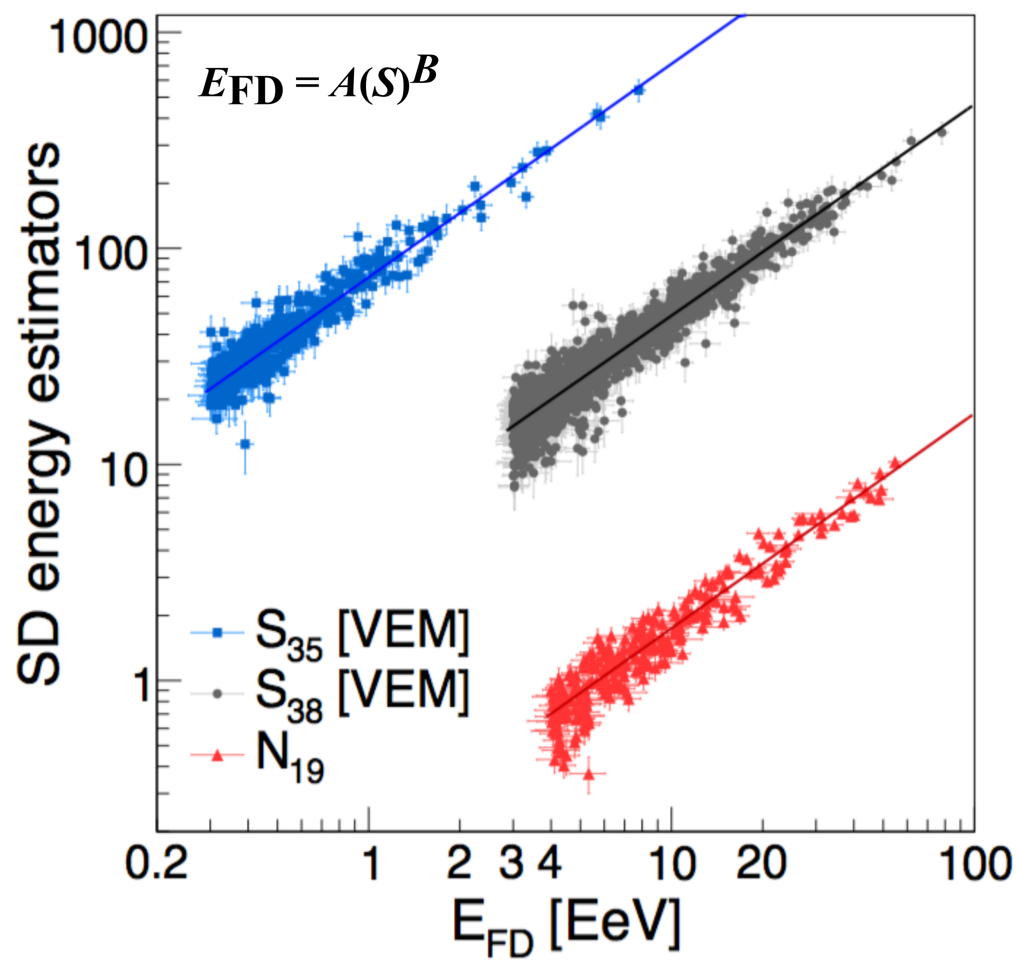
Further insights in hadronic interactions will come from both man-made accelerators and their future developments and from astrophysical objects studied in UHECR observatories and their upgrades

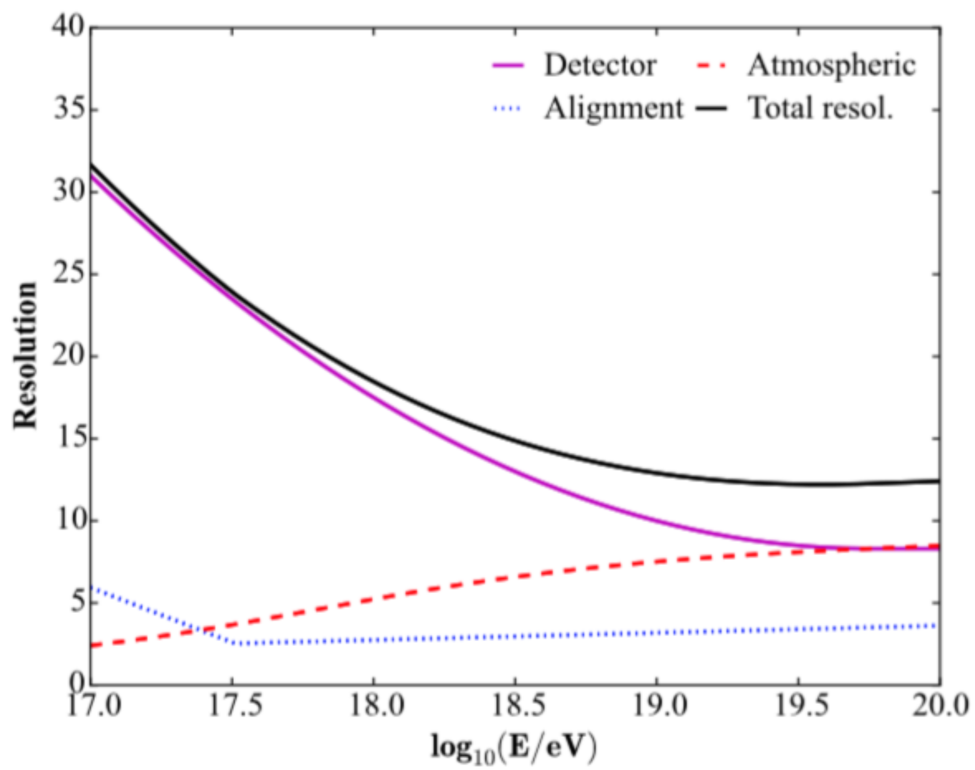
Let's keep and improve our communities interconnection !!!

Backup slides

SD	
SD annual exposure, θ < 60°	∼5500 km^2 sr yr
T3 rate	0.1 Hz
T5 events/yr, $E > 3$ EeV	∼14,500
T5 events/yr, $E > 10$ EeV	∼1500
Reconstruction accuracy (S_{1000})	22% (low E) to 12% (high E)
Angular resolution	1.6° (3 stations)
	0.9° (> 5 stations)
Energy resolution	16% (low E) to 12% (high E)
FD	
On-time	∼15%
Rate per building	0.012 Hz
Rate per HEAT	0.026 Hz
Hybrid	
Core resolution	50 m
Angular resolution	0.6°
Energy resolution (FD)	8%
X_{max} resolution	< 20 g/cm^2

Systematic uncertainty on energy scale	**14%**
Fluorescence yield	3.6%
Atmosphere	3.4-6.2%
FD calibration	9.9%
FD profile reconstruction	6.5-5.6%
Invisible energy	3.0-1.5%
Stability of energy scale	5%
…..	





[@A.Aab et al (Auger Coll.) NIM798 (2015) 172]

Measuring the primary mass

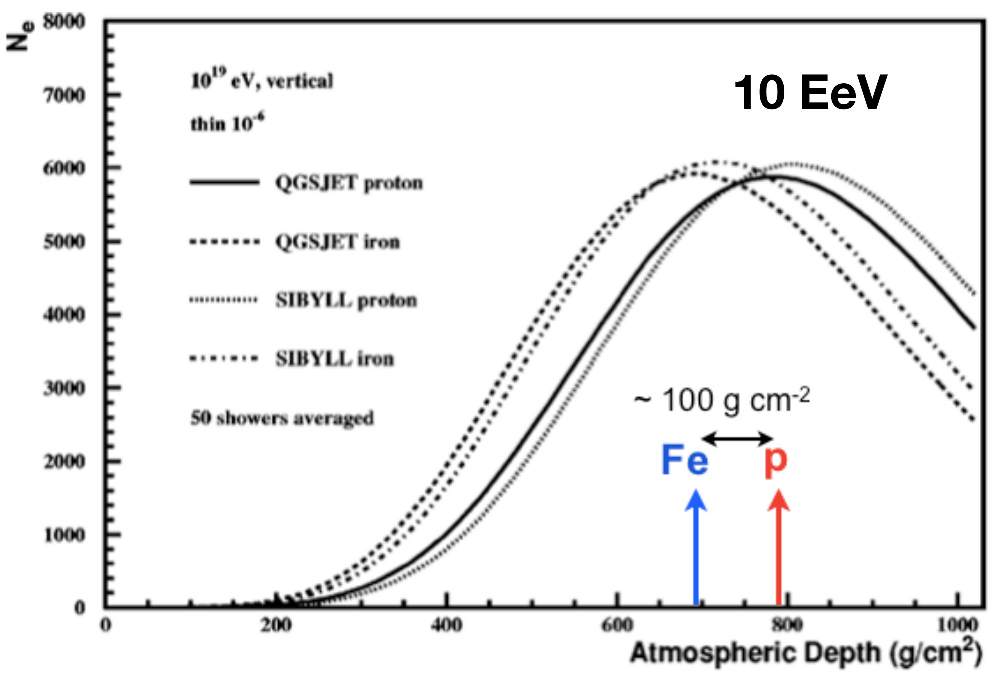
Depth of shower maximum and its fluctuations

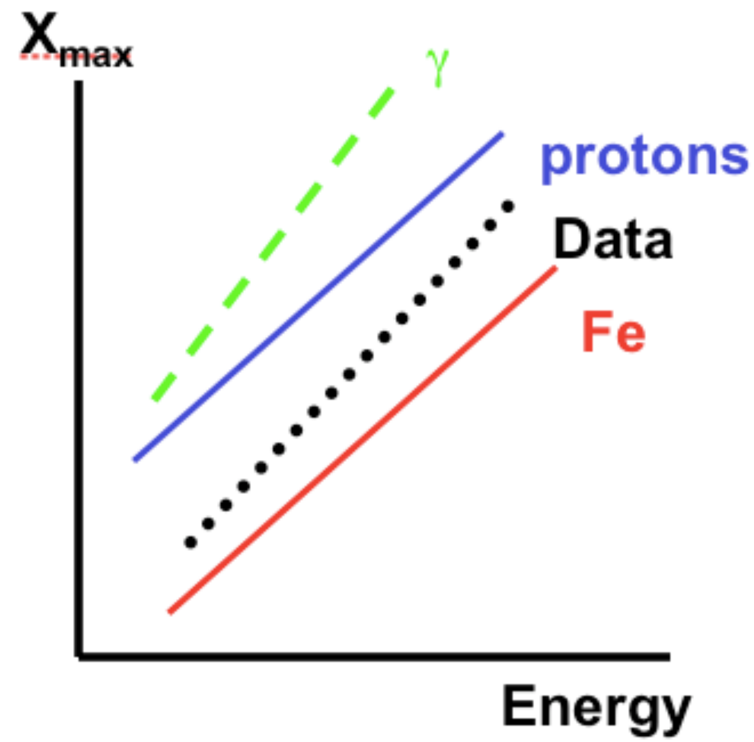
$$X_{max} = (1-B)X_0\left(ln\frac{E}{\epsilon} - \langle lnA\rangle\right)$$

at fixed energy, a nucleus shower develops faster than a proton shower

Fluorescence detectors

Elongation rate $$D_e = \frac{\delta X_{max}}{\delta lnE} = (1-B)X_0\left(1 - \frac{\delta\langle lnA\rangle}{\delta lnE}\right)$$





Muons

EAS produce more muons for increasing A

at shallower depth of maximum development

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

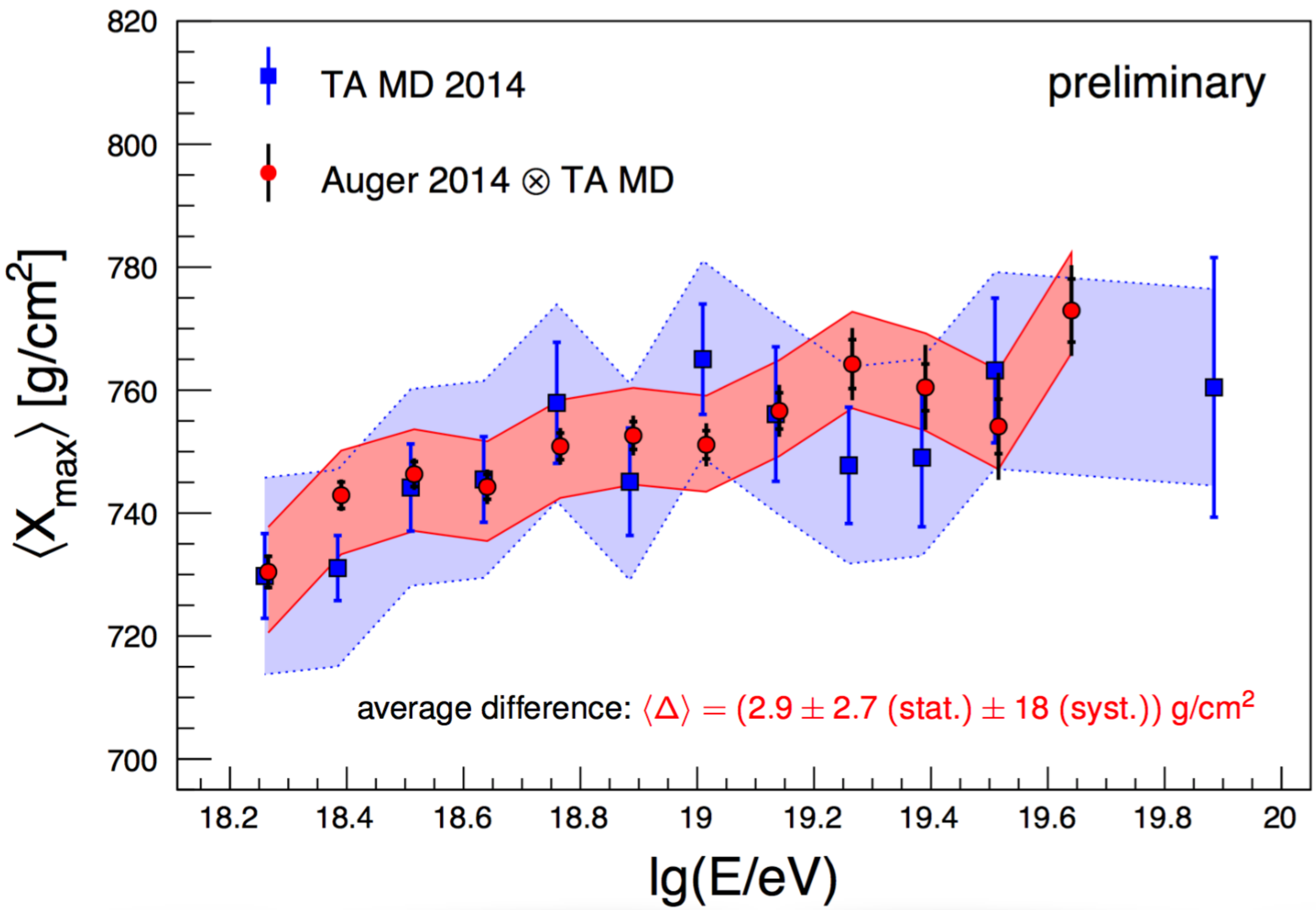
Surface detectors

rise time, curvature

muons and EM component in the shower have different path lengths and arrival times

Mass composition - Auger vs Telescope Array

[M.Unger, ICRC2015, arXiv:1511.02103]

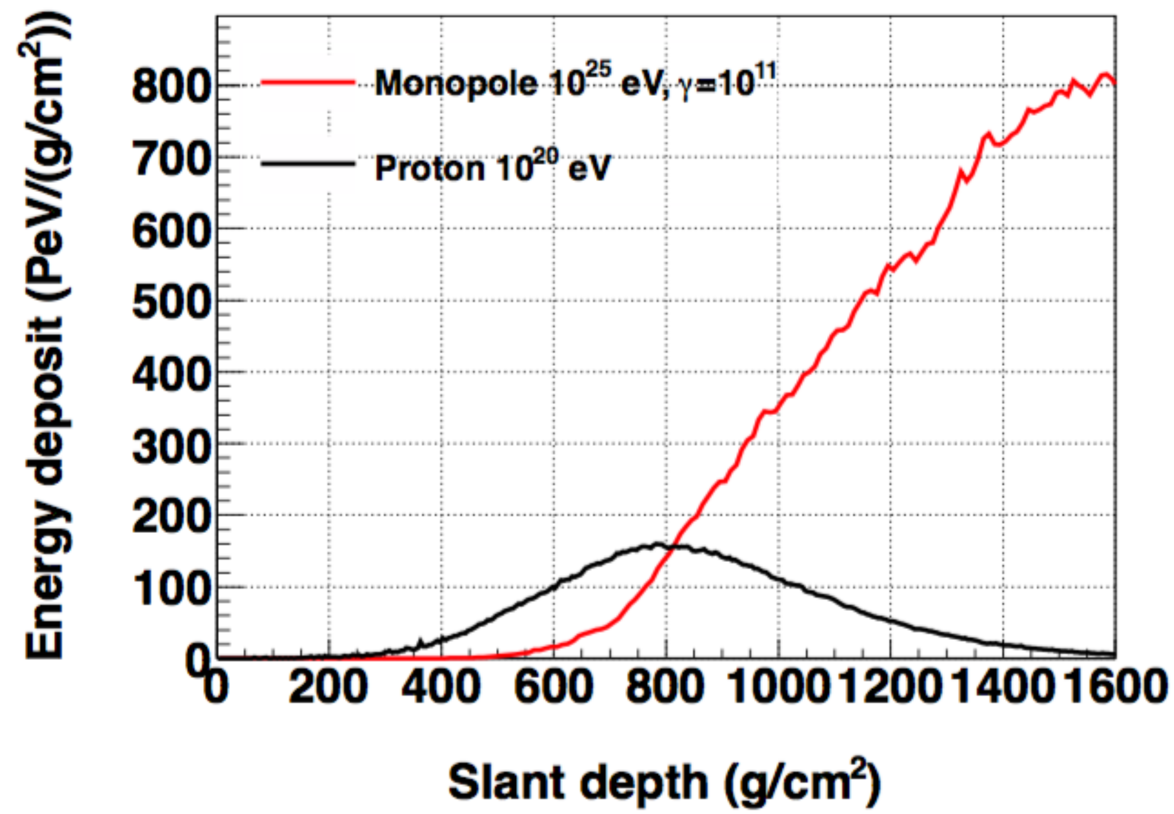


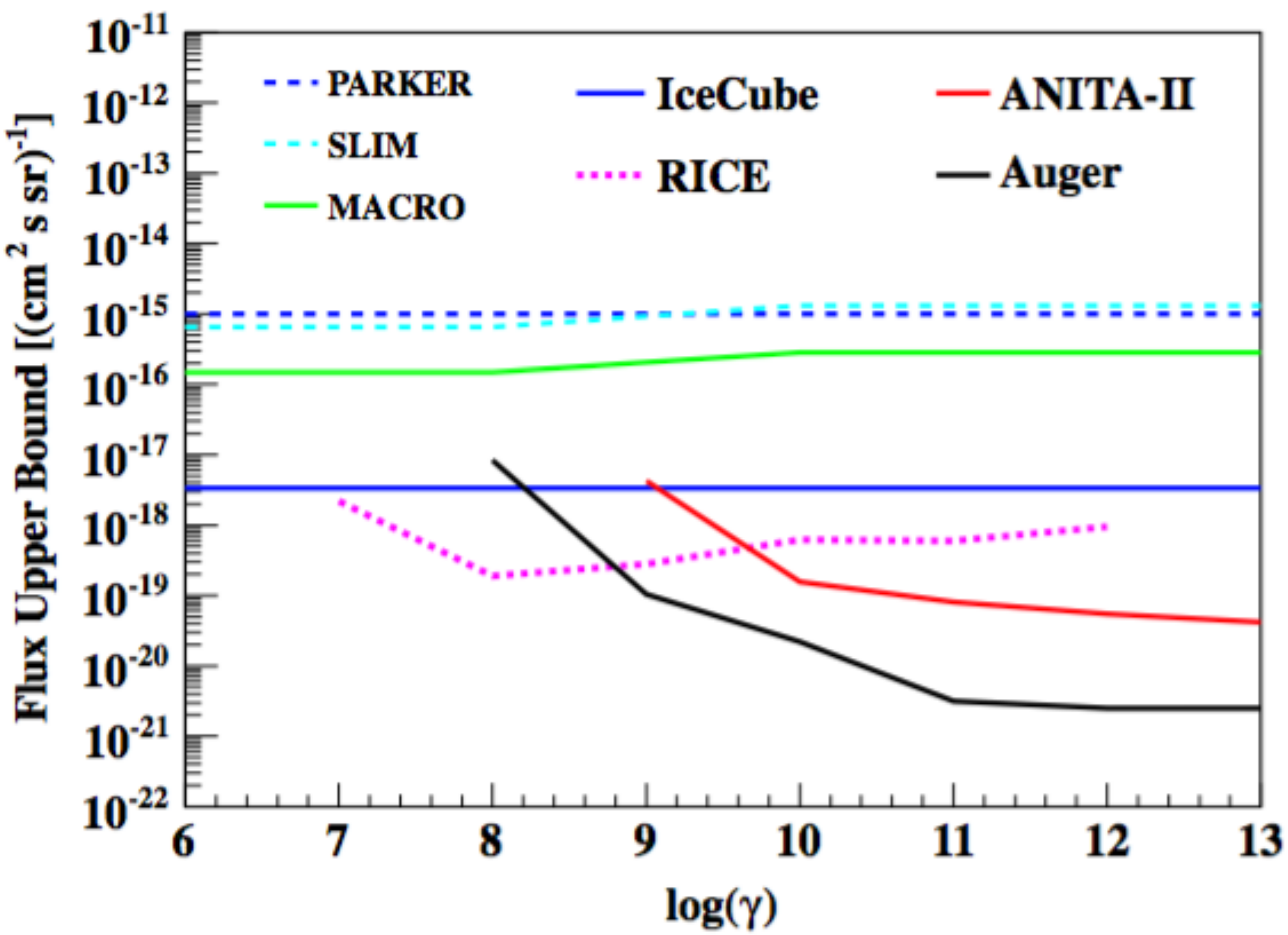
The two results are in good agreement within systematic uncertainties

TA cannot distinguish between pure proton or mixed composition with the current level of uncertainty

Ultra-relativistic 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





Best limit for $\gamma \geq 10^9$

$\log_{10}(\gamma)$	$\mathcal{E}(\gamma)$ (km^2 sr yr)	$\Phi_{90\%\,\mathrm{C.L.}}$ ((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]

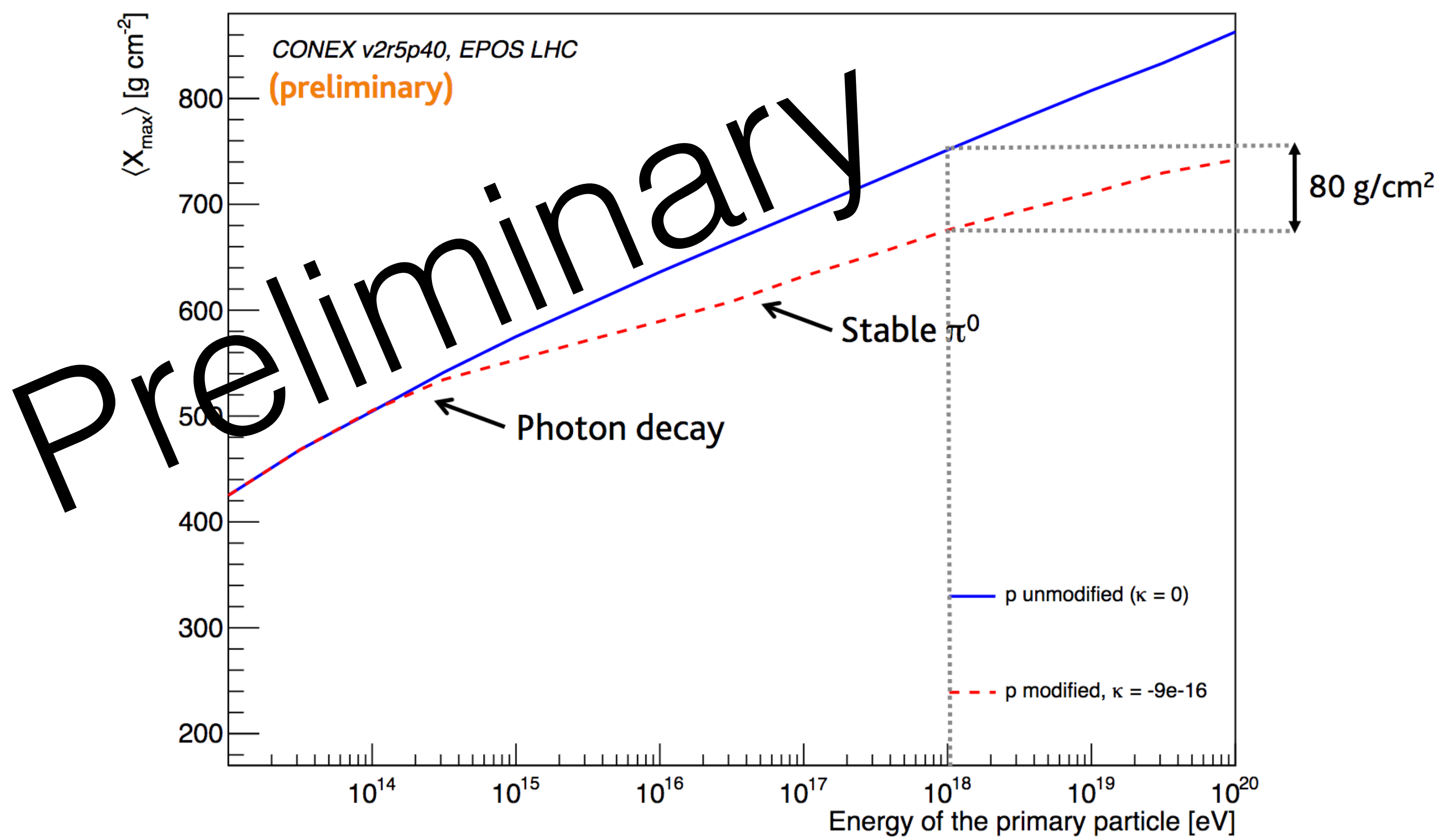
Lorentz invariance violation

- UHE hadronic primaries contain at least a pair of very high energy photons
- LIV can modify the photon dispersion relations leading to a different shower development

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \overline{\psi}\left[\gamma^{\mu}(i\partial_{\mu} - eA_{\mu}) - m\right]\psi - \frac{1}{4}(k_F)_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

k here included for isotropic, nonbirefringent LIV

- First two terms in the Lagrangian correspond to **conventional QED**
- **Last term** introduces a dimension-four operator that breaks Lorentz symmetry while preserving CPT and gauge invariance [Chadha & Nielsen 1983] [Kostelecký & Mewes 2002]



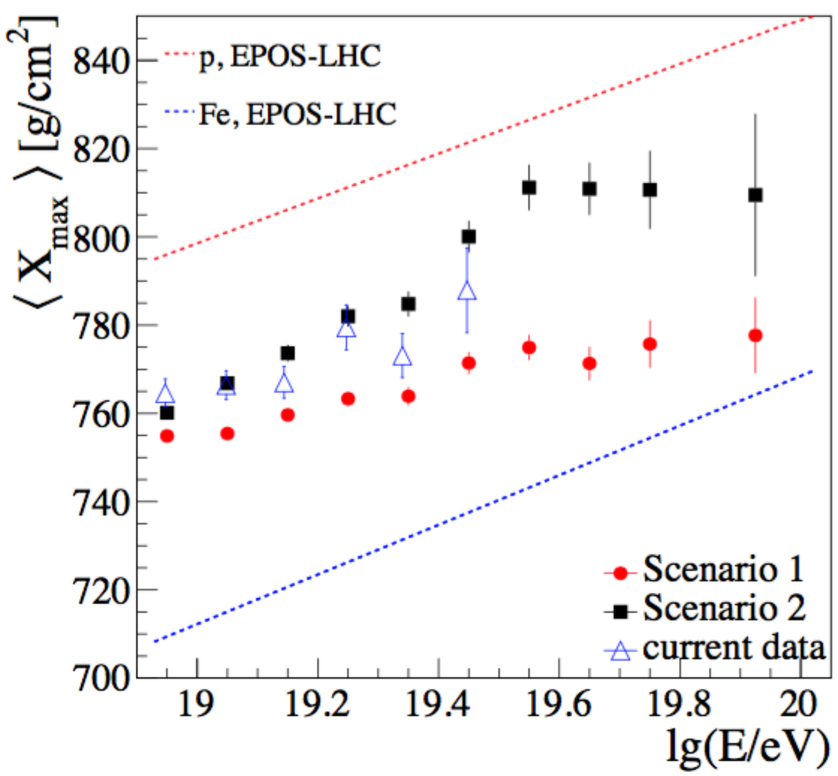
- Change in $<X_{max}>$ above 1 EeV **well above** our X_{max} resolution

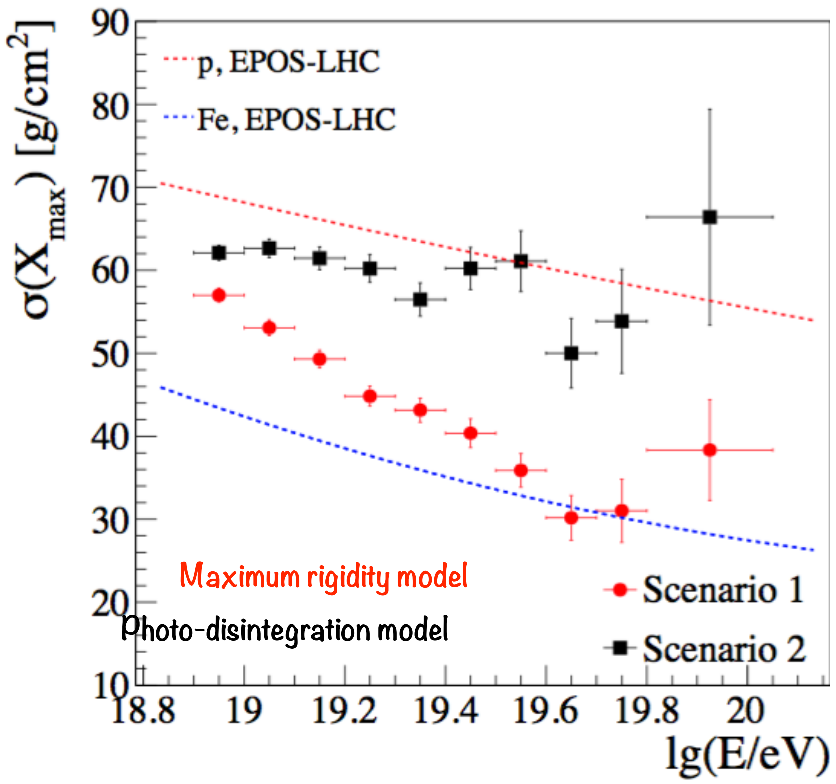
[@F.Klinkhamer and M.Risse., PRD77 (2007) 016002]

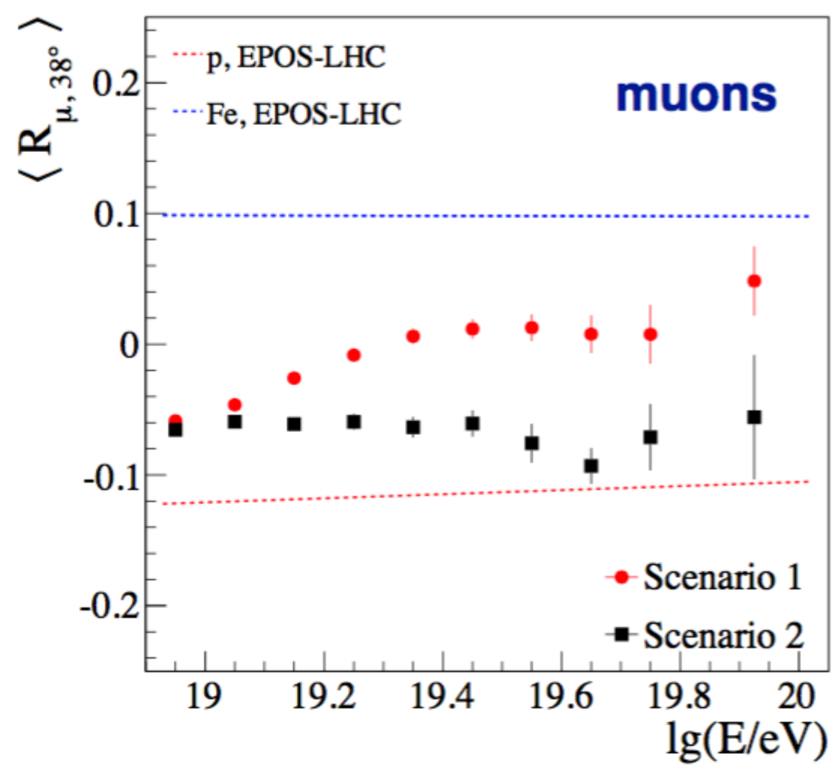
AugerPrime

- **increased sensitivity to composition in the suppression region**
- additional scintillators
- increased FD duty cycle (from 15% to 50%)
- upgraded electronics and dynamic range

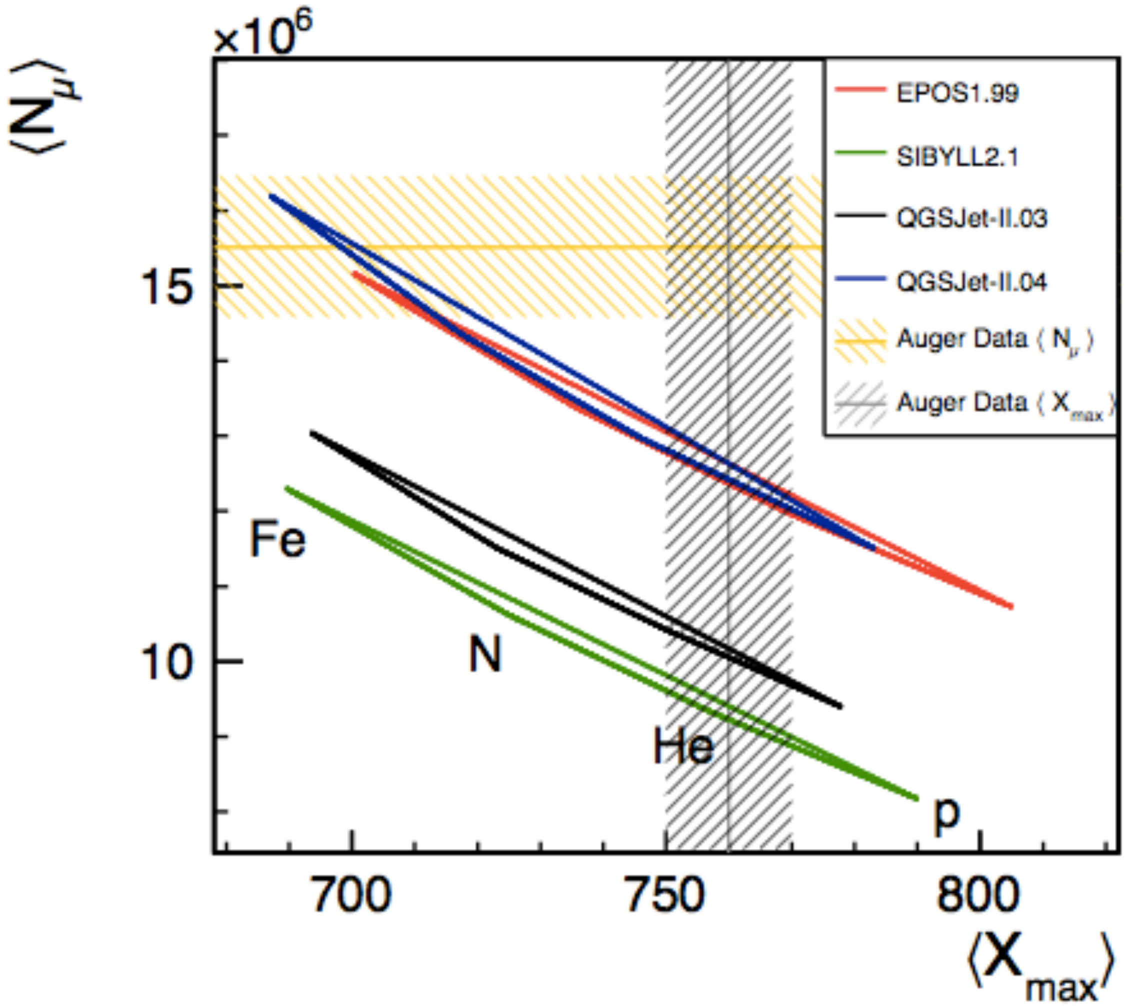
$\log_{10}(E/\mathrm{eV})$	$\mathrm{d}N/\mathrm{d}t\vert_{\mathrm{infill}}$ $[\mathrm{yr}^{-1}]$	$\mathrm{d}N/\mathrm{d}t\vert_{\mathrm{SD}}$ $[\mathrm{yr}^{-1}]$	$N\vert_{\mathrm{infill}}$ [2018-2024]	$N\vert_{\mathrm{SD}}$ [2018-2024]
17.5	11500	-	80700	-
18.0	900	-	6400	-
18.5	80	12000	530	83200
19.0	8	1500	50	10200
19.5	$\sim$1	100	7	700
19.8	-	9	-	60
20.0	-	$\sim$1	-	$\sim$9



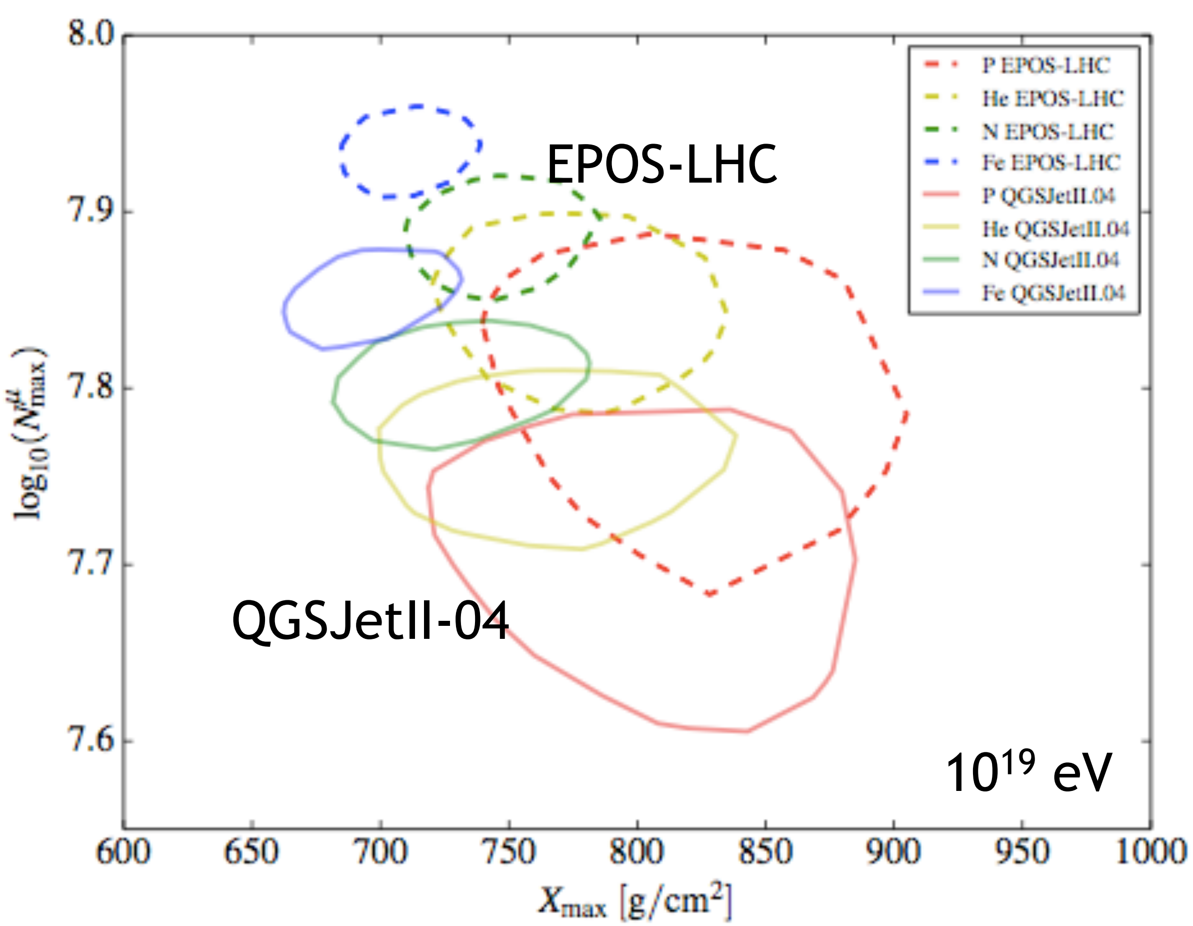


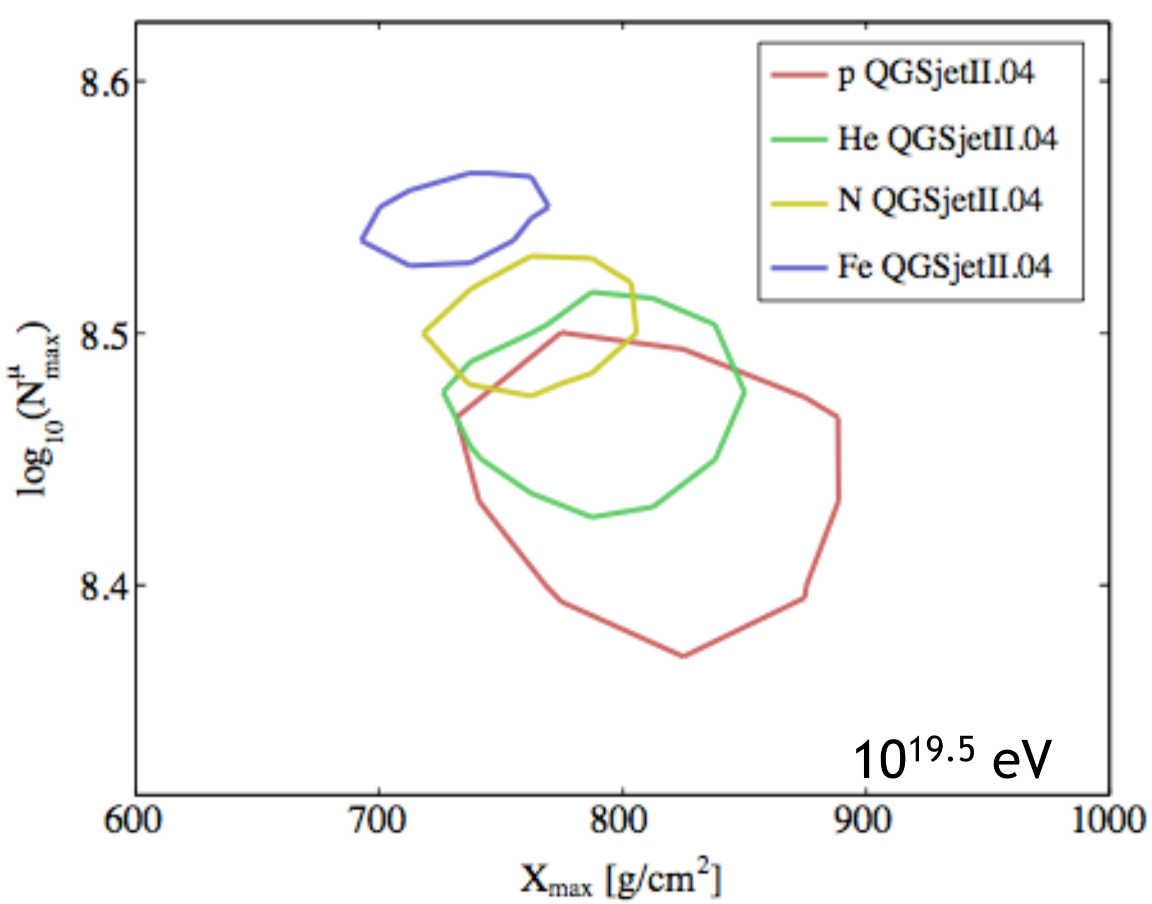


N_μ - Xmax correlation



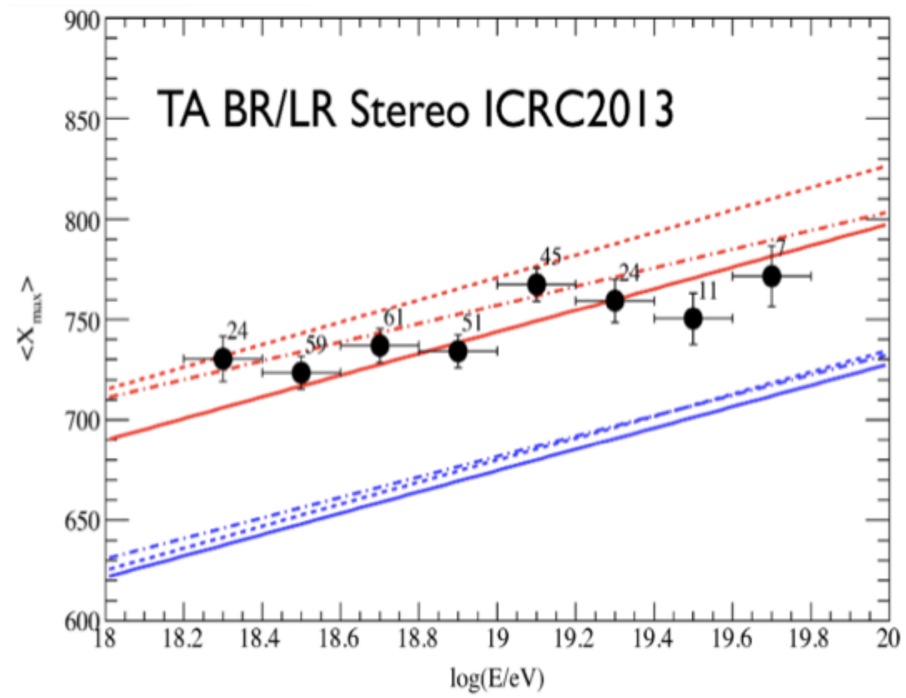
- ✓ differencies in $\log_{10}N^{\mu}_{max}$ and X_{max} are of the order of $\Delta \log_{10}N^{\mu}_{max} \sim 0.1$ and $\Delta X_{max} \sim 15$ g cm^{-2}
- ✓ need detector resolutions of the order of shower fluctuations to infer the primary mass on event-by-event basis

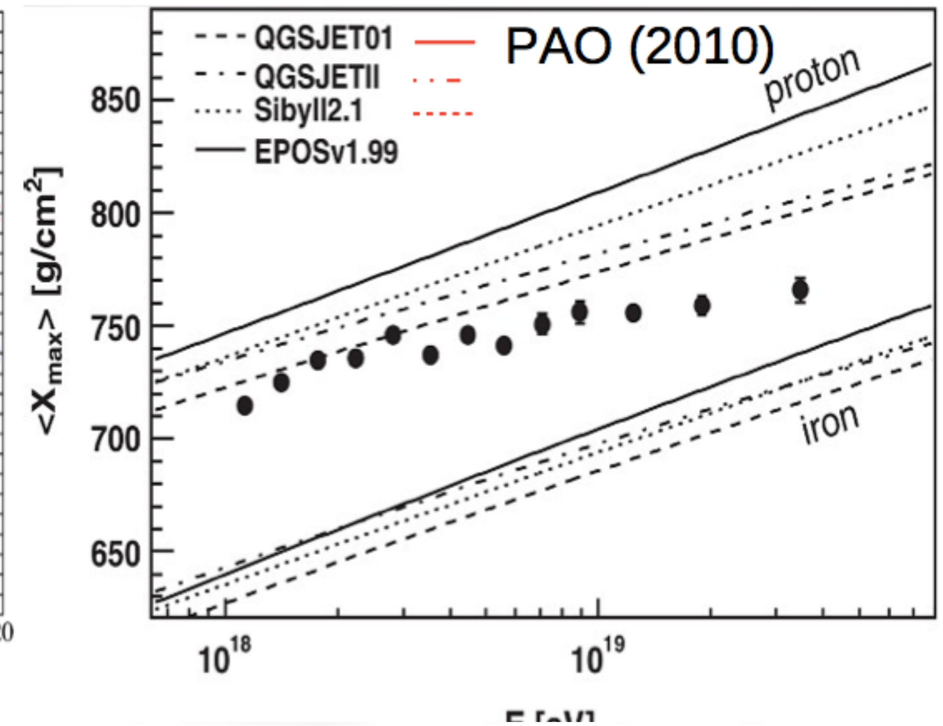




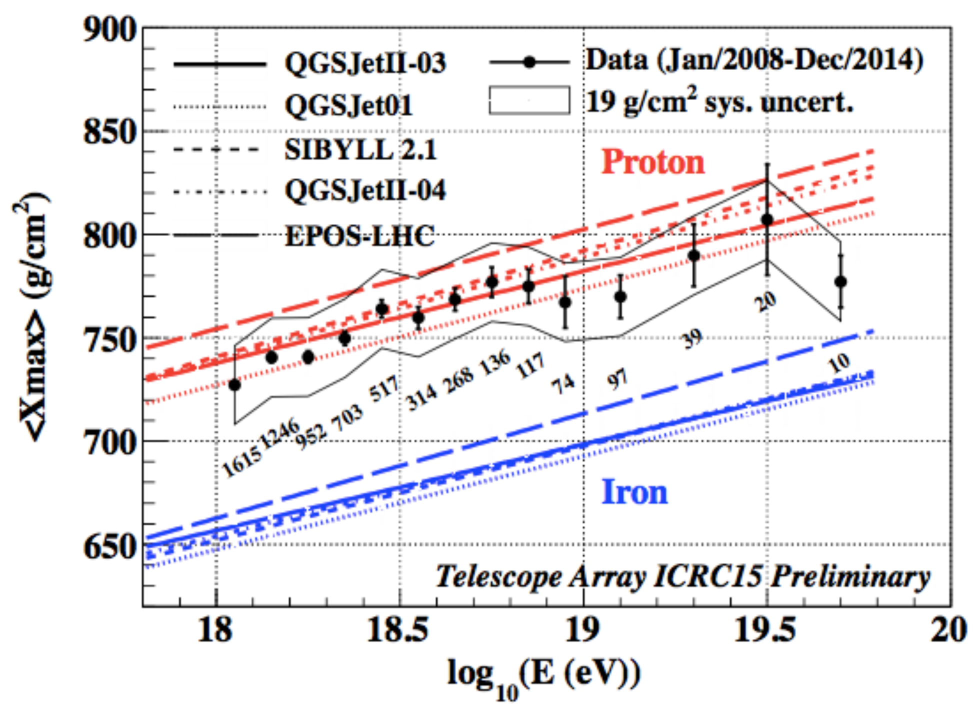
The EM profile

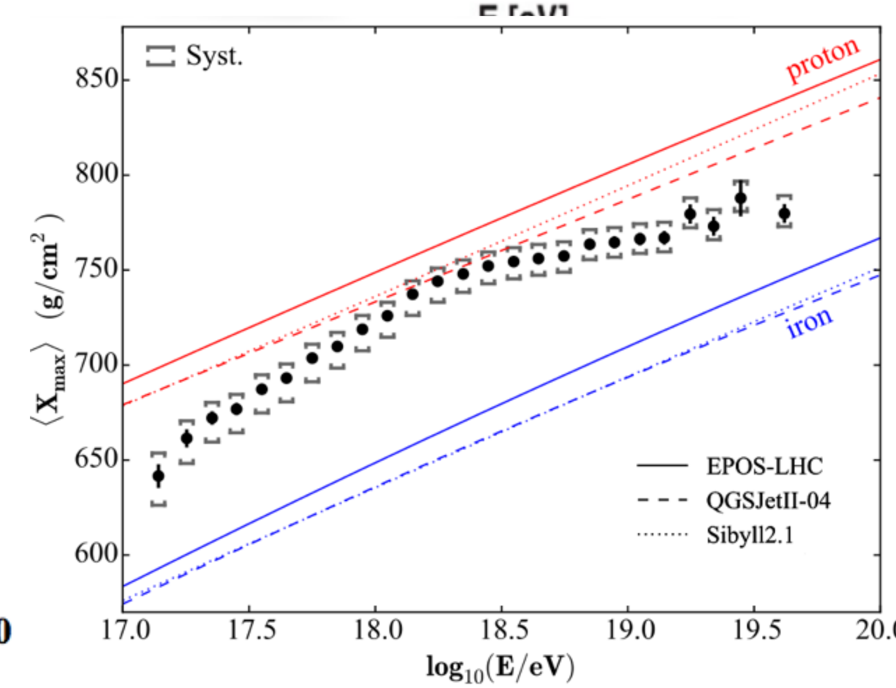
before LHC





after LHC





- ✓ changes in slopes: smaller for EPOS and larger for QGSJetII
- ✓ only ~20% uncertainty between the two models - before it was ~50% - to be compared to a difference in p-Fe X_{max} of ~100 g cm^{-2}