UHECR air showers: challenging our understanding of particle physics?

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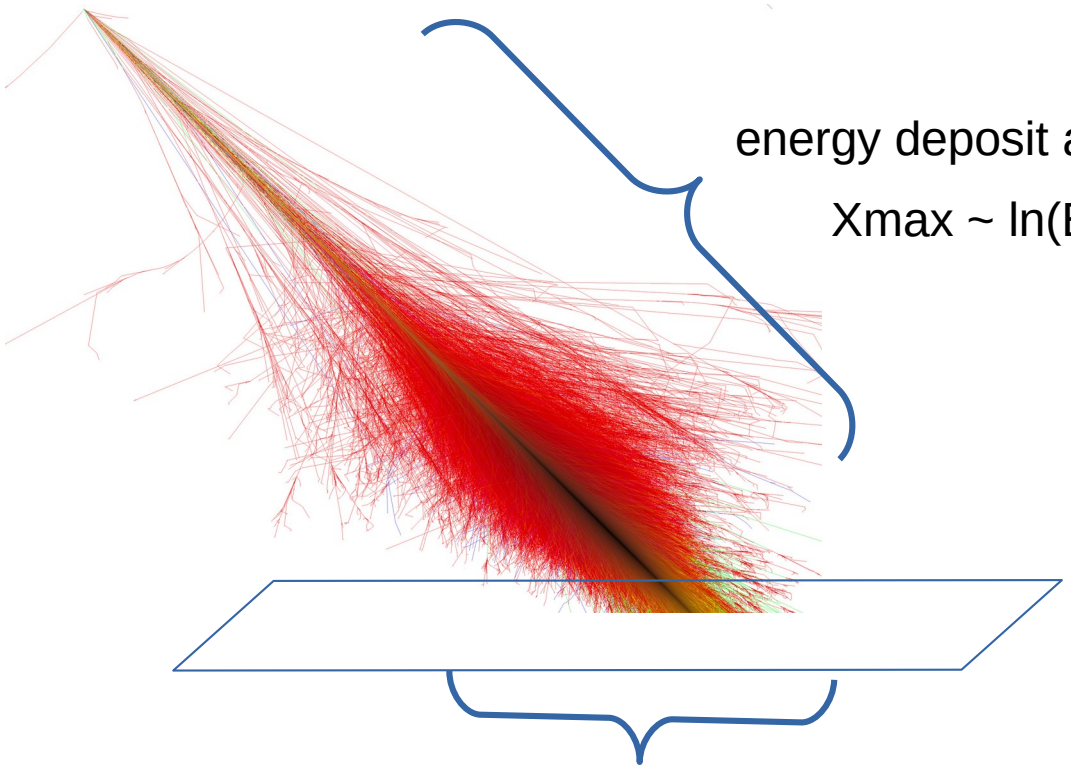
Rencontres du Vietnam: Theory meets experiment: particle astrophysics & cosmology

Quy Nhon, Vietnam

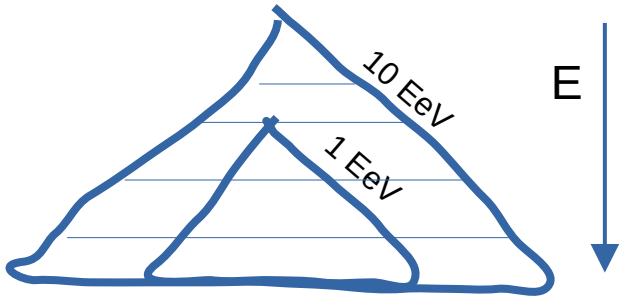
7.1.2023

Air shower observables



energy deposit along path

Xmax ~ ln(E)



Universal threshold:
critical energy of pions

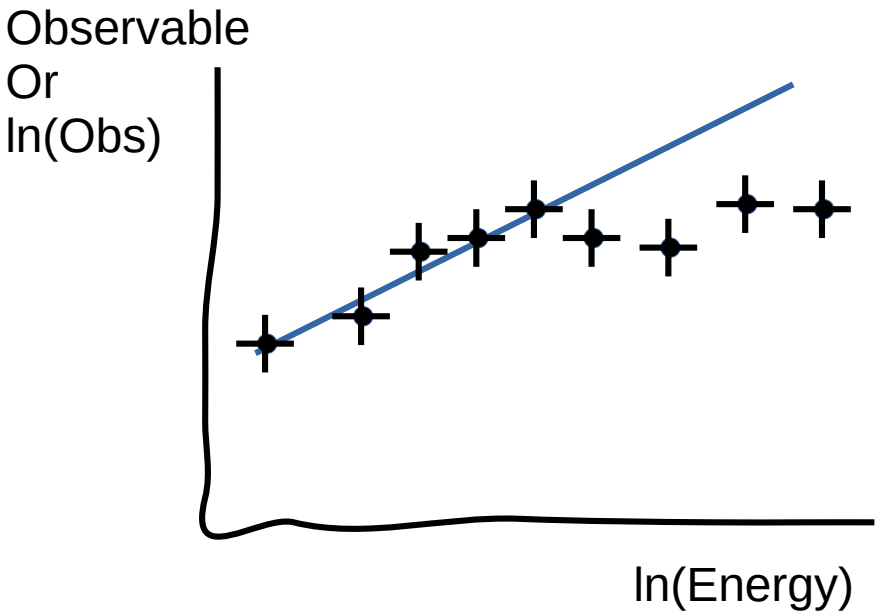
(CORSIKA simulation
proton at 10 EeV,
Knapp et al.)

particles at (under)ground

Nmu ~ E

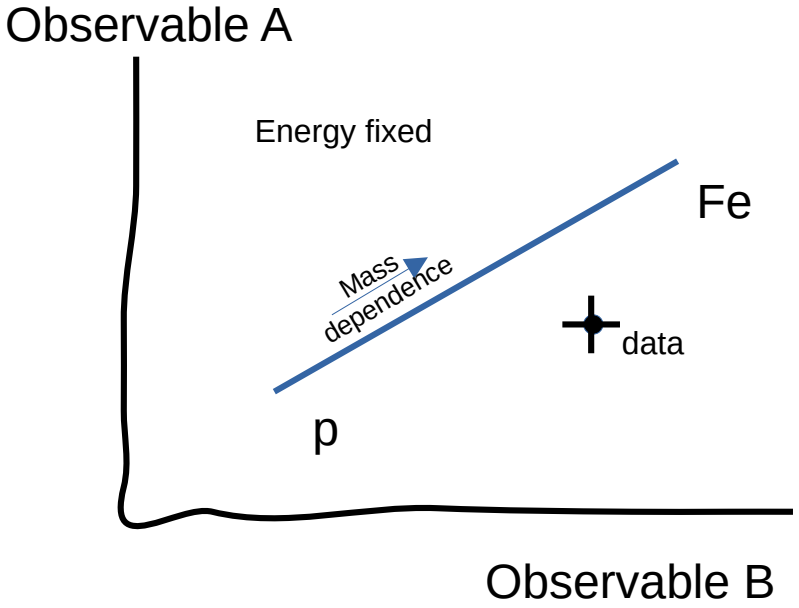
Signatures of new physics

Kinks in energy dependence



or

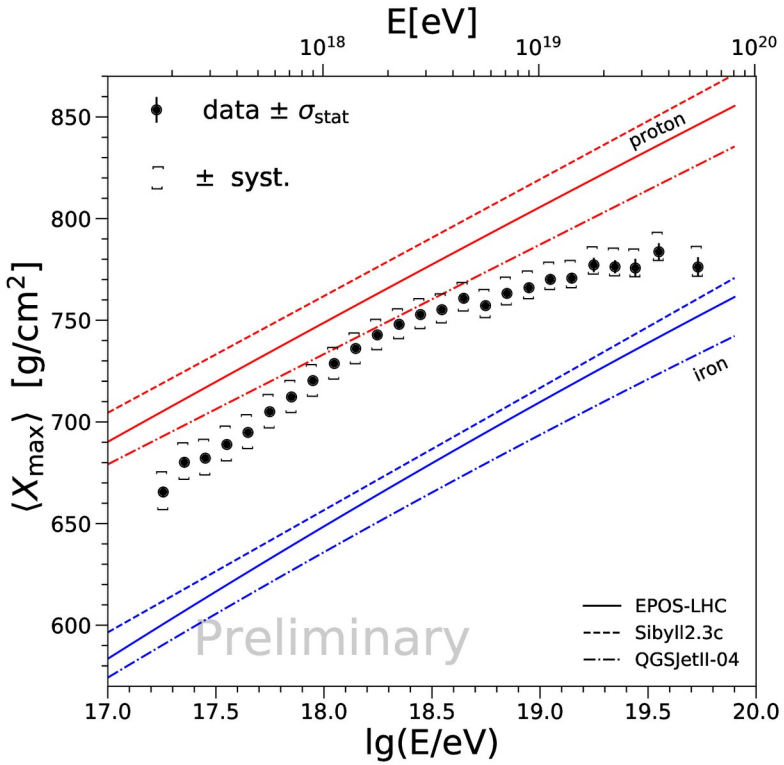
'Inconsistencies'

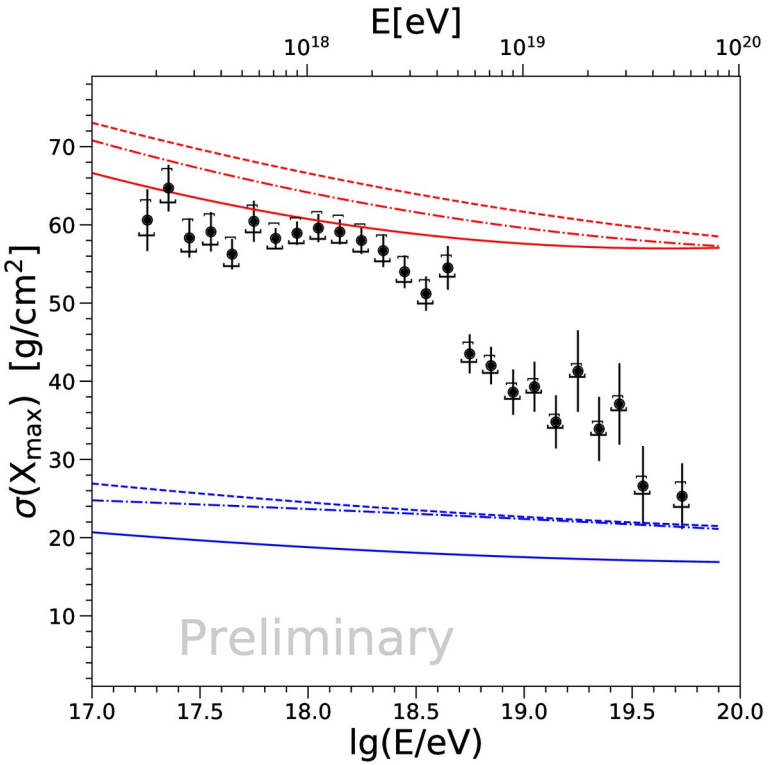


If Observable depends on mass:
Need to know mass composition

If both Obs A and Obs B
~ mass

Kink in evolution of shower maximum



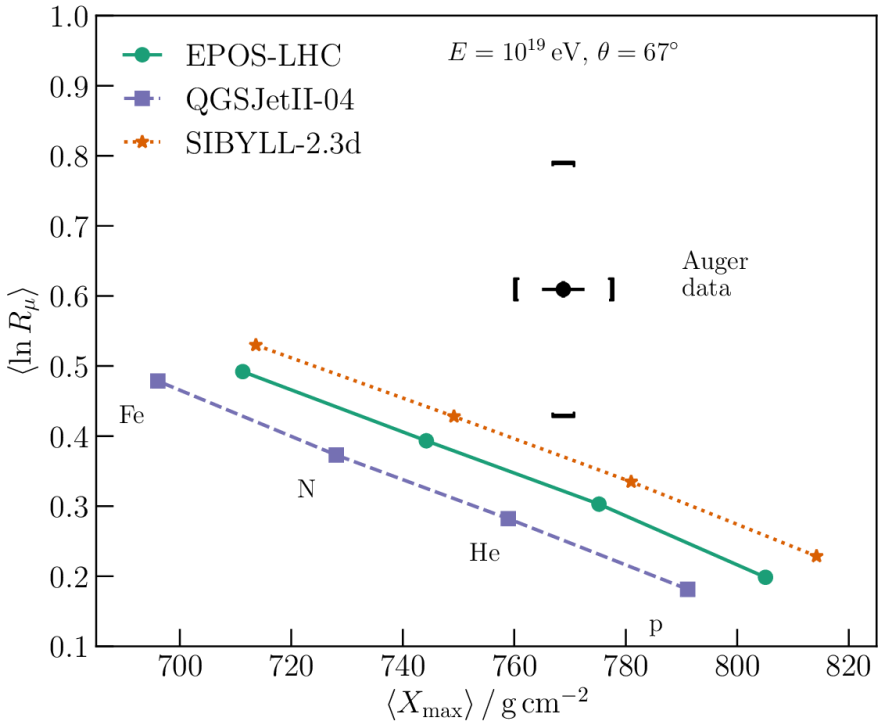


(Auger ICRC 2019)

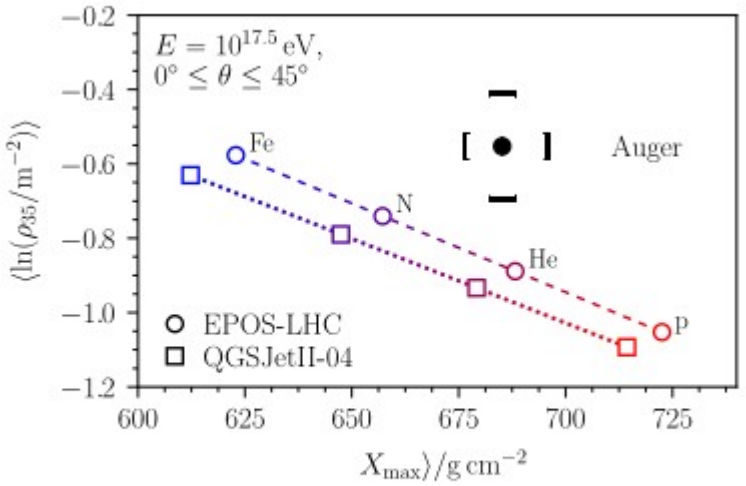
→ change of composition

We do observe such an inconsistency

Inclined showers



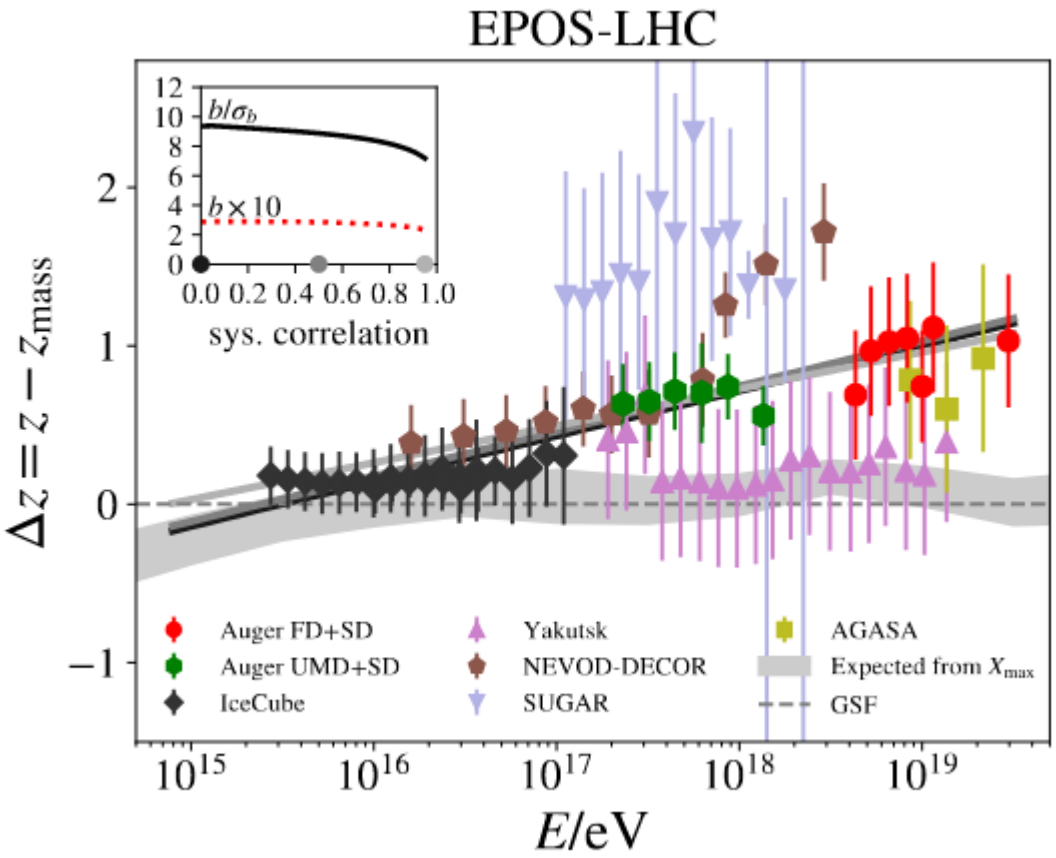
Underground muons



(Eur. Phys. J. C80 (2020) 751)

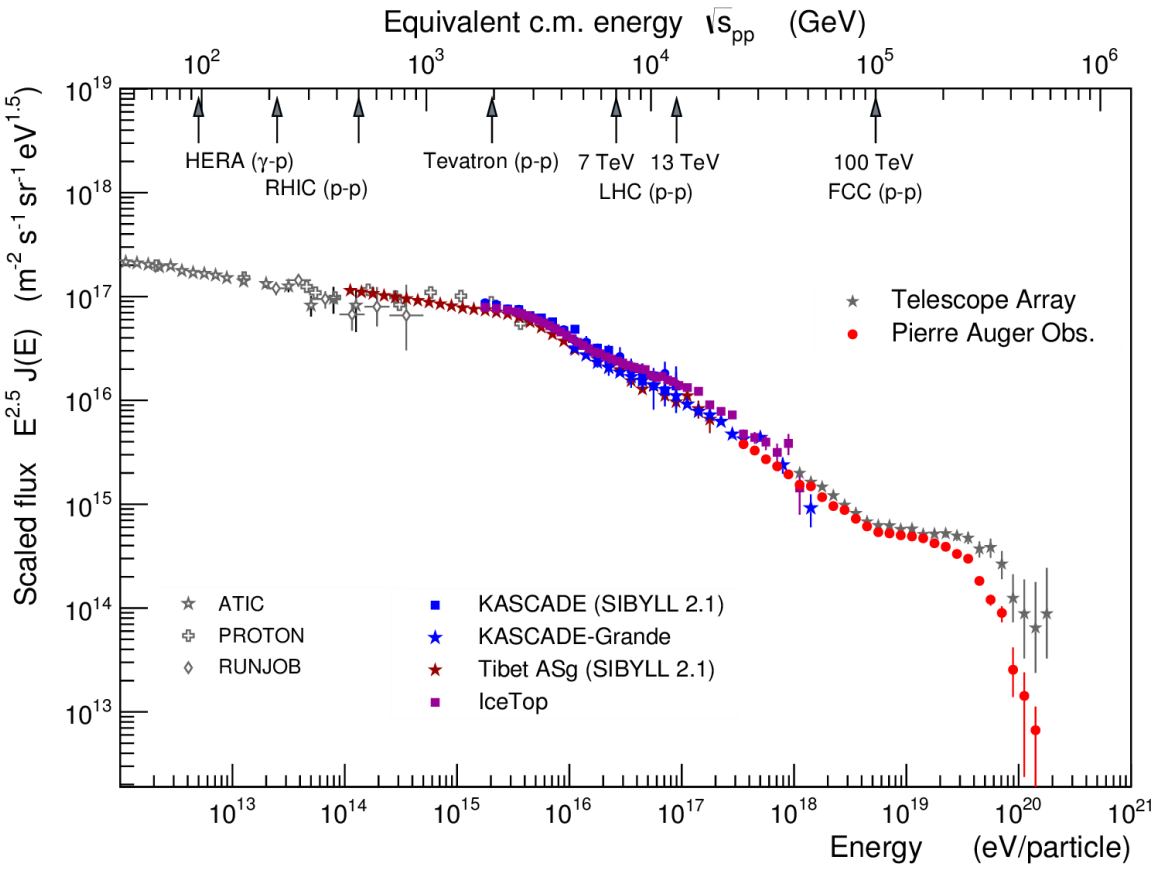
(PRD 91(2015) 032003, PRL 126 (2021) 152002)

Muon inconsistency omnipresent at UHE



(D. Soldin et al., ICRC 2021, arXiv:2108.08341)

Ultra-high energy cosmic rays



Energies well beyond LHC …

… and its a Nitrogen-Oxygen target …

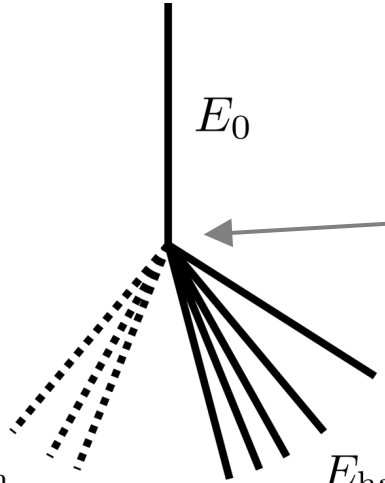
… and its mostly pions interacting

→ models extrapolate !!

What could possibly go wrong ..

Air shower development: two cascades

Assume: 1st interaction according to Standard Model



p-O or p-N interaction

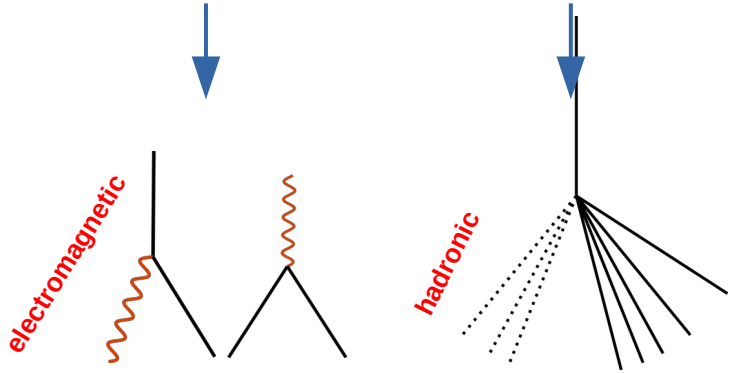
E_{em}
$\{\pi^0\ \gamma\ e^{\pm}\}$

E_{had}
$\{\pi^{\pm}\ \mathrm{K}^{\pm,0}\ \bar{N}\ N\}$

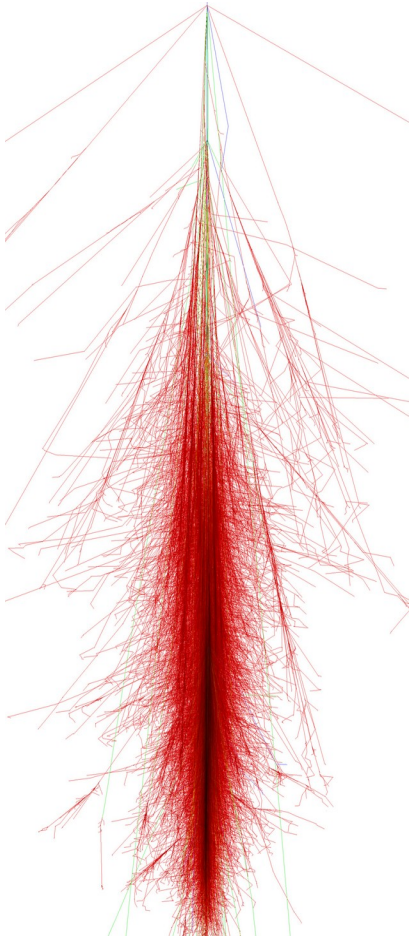
$c\tau_{\pi^0} = 25\,\mathrm{nm}\ \pi^0 \to \gamma\gamma$

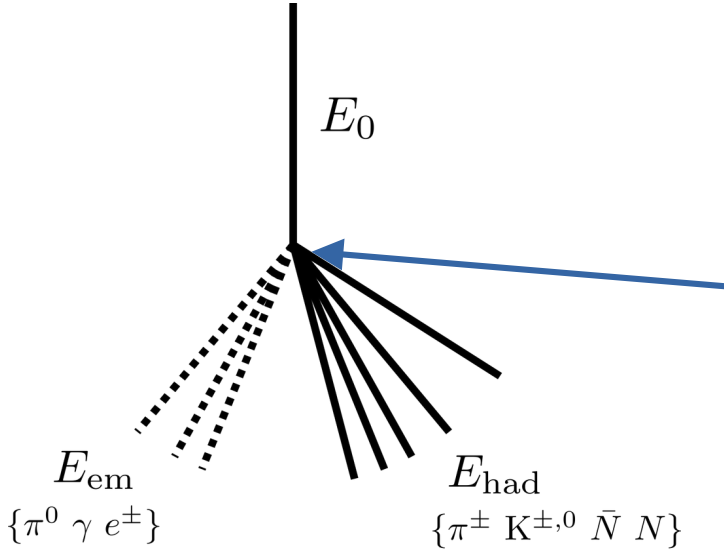
$c\tau_{\pi^{\pm}} = 7.8\,\mathrm{m}$

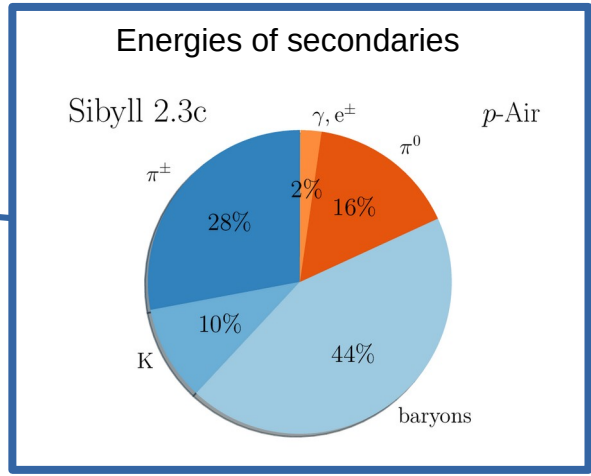
2nd interactions ..



Air shower development: energy flow







Only 80% energy remains in hadrons ..

EM cascade

hadronic cascade

Energy flow

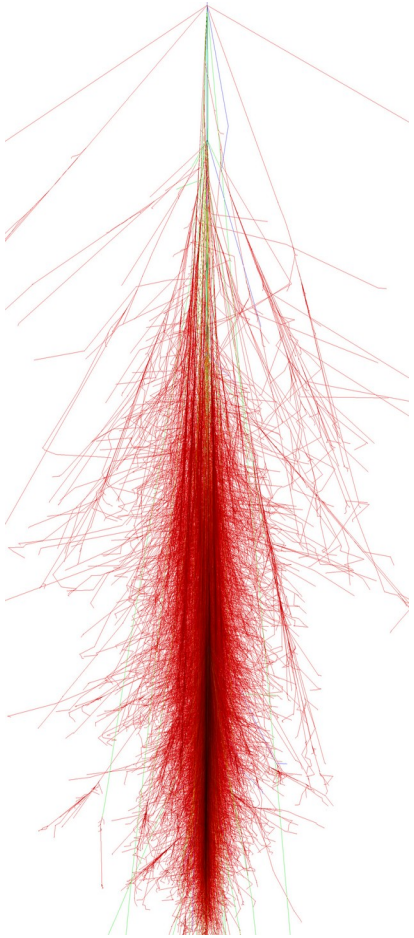
At the end: μ

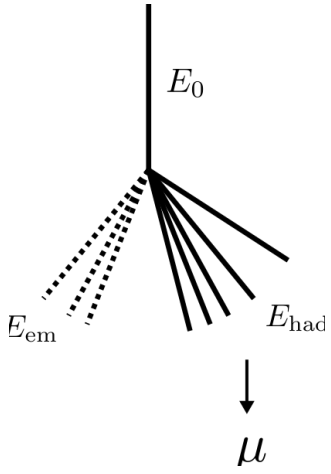
After n steps:

$$E_n^{\rm had} = 0.8^n\, E_0$$

$$E_n^{\rm EM} = (1 - 0.8^n)\, E_0$$

How to get more muons: two scenarios





1) New physics scenario

1st (UHE) interaction modified,
a process missing in interaction models

- exhibit Lorentz Invariance Violation?
- Chiral Symmetry Restoration
- severe enhancement of strangeness?
  (fireball, string-percolation)
- Higgsplosion
- ….

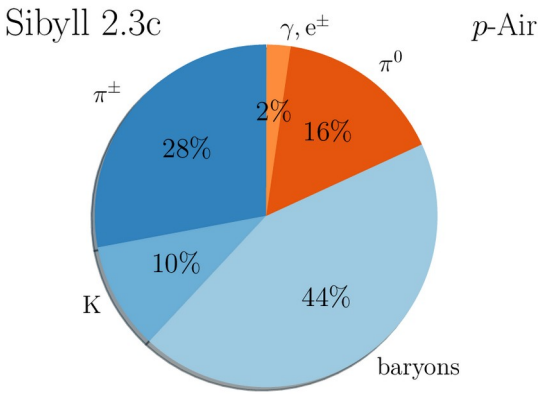
2) Standard physics scenario

all hadronic interactions modified by a small amount, interaction models essentially correct
- baryon production
- rho0 production
- enhanced production of hadron resonances (statistical hadronisation, QGP)

Distinguish: standard/exotic

Fluctuations!

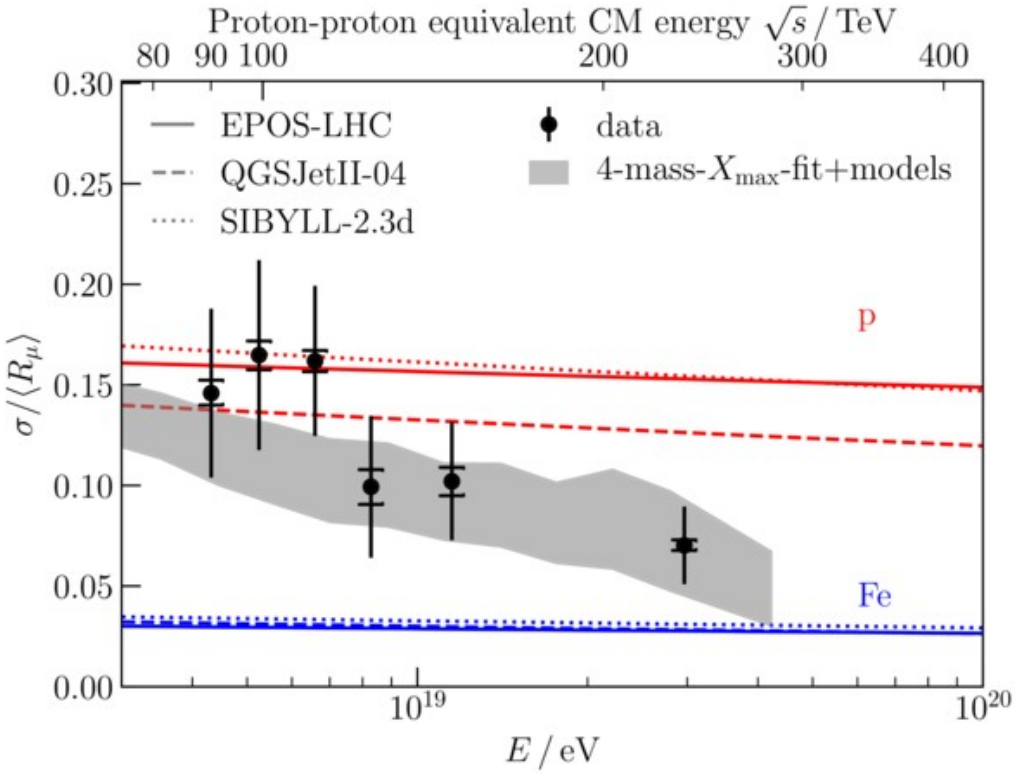
Energypartition



"fluctuations are dominated by the energy fluctuations in the 1st interaction"

(Cazon et al. PLB 784 (2018) 68)

Muon fluctuations

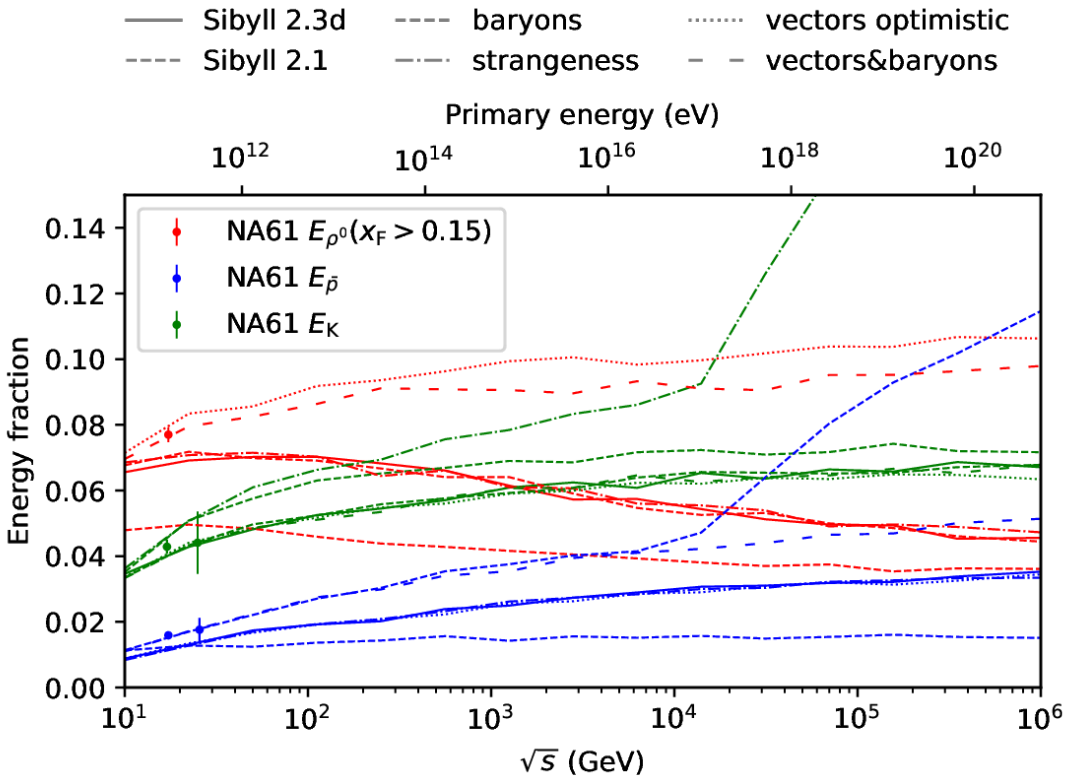


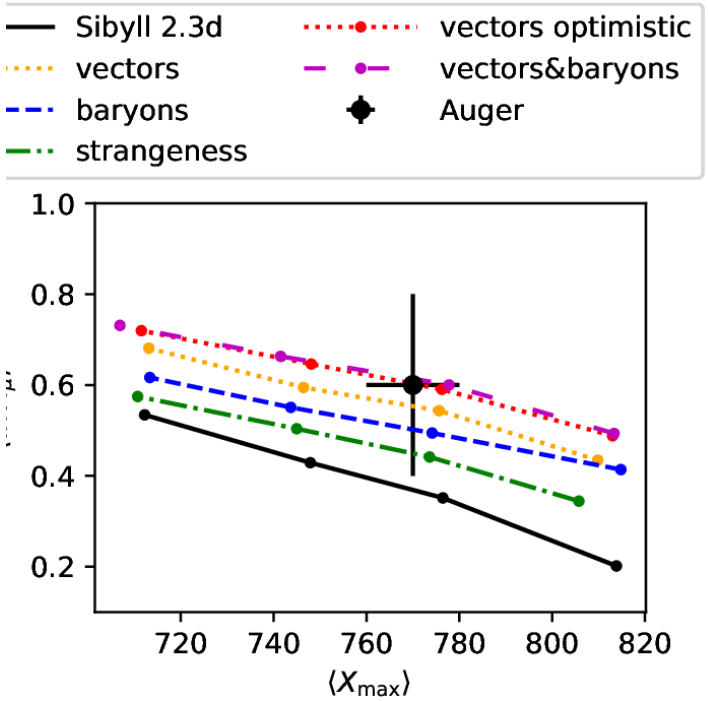
→ fluctuations consistent !

No (little) room for new physics in first interaction !
→ Scenario 1 constrained

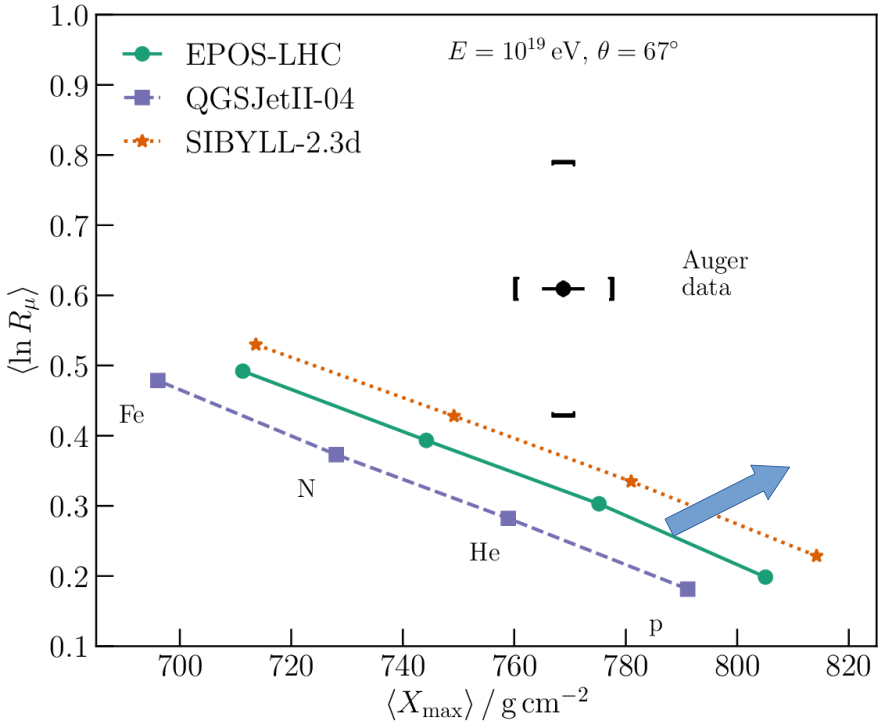
What about scenario 2 (standard physics)?

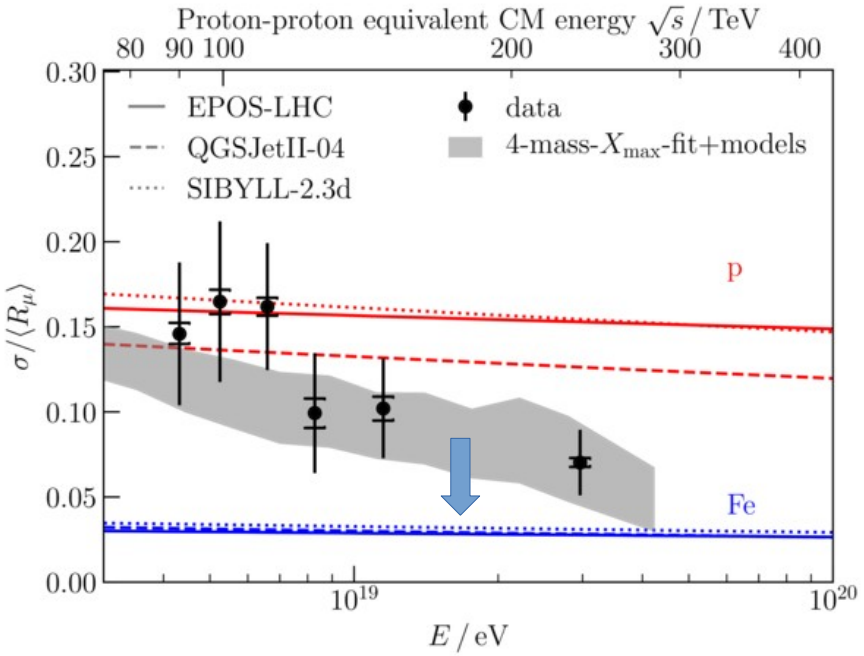
More muons


Sibyll 2.3d
Sibyll 2.1
baryons
strangeness
vectors optimistic
vectors&baryons
Primary energy (eV)
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
NA61 $E_{\rho^0}(x_F > 0.15)$
NA61 $E_{\bar{p}}$
NA61 E_K
Energy fraction
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10^1
10^2
10^3
10^4
10^5
10^6
$\sqrt{s}$ (GeV)


Sibyll 2.3d
vectors
baryons
strangeness
vectors optimistic
vectors&baryons
Auger
1.0
0.8
0.6
0.4
0.2
720
740
760
780
800
820
$\langle X_{max} \rangle$

What about Xmax ?

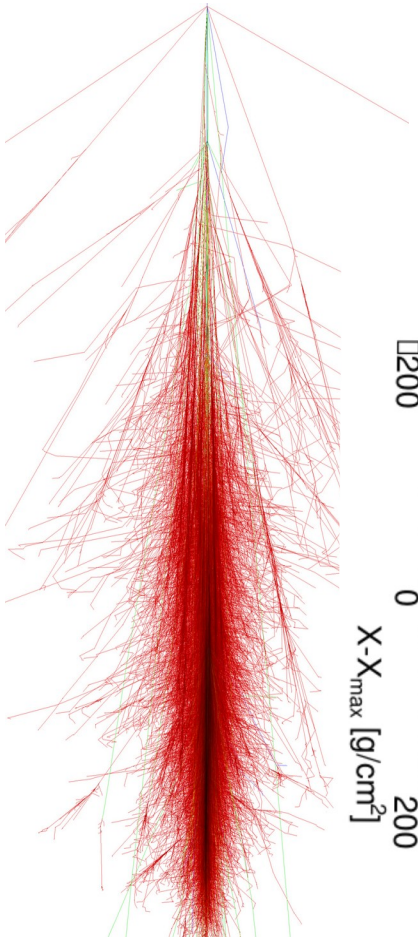


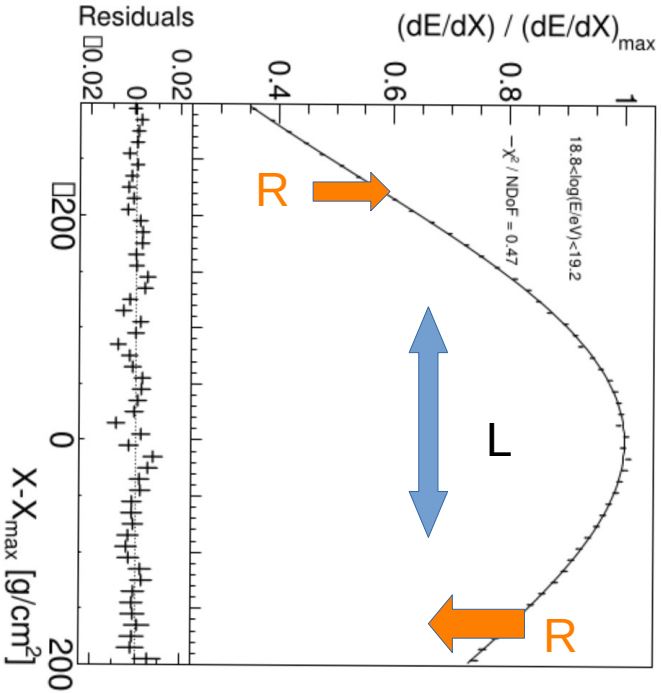


Ruled out exotic physics because of fluctuations

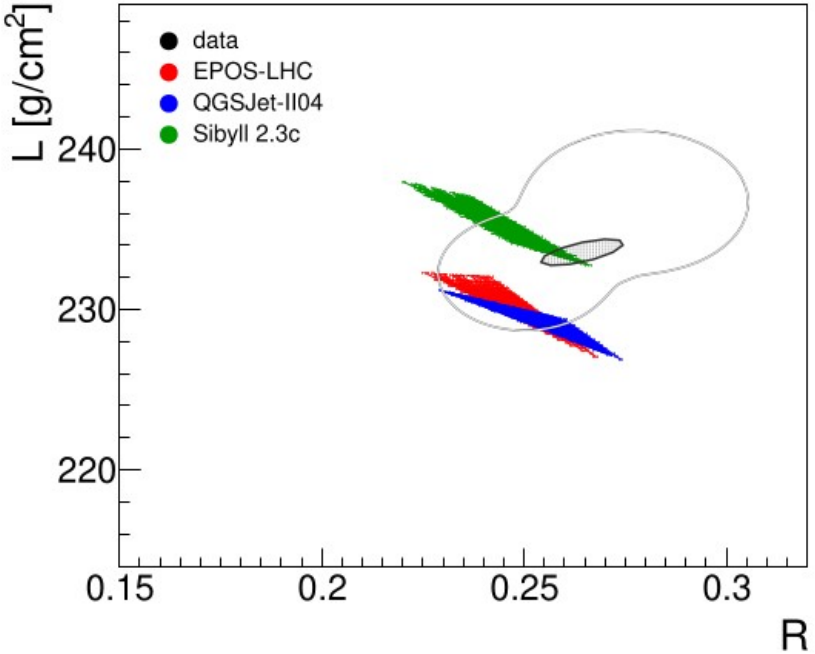
Could the Xmax prediction be wrong?

EM shower profile





Shower profile parameters:

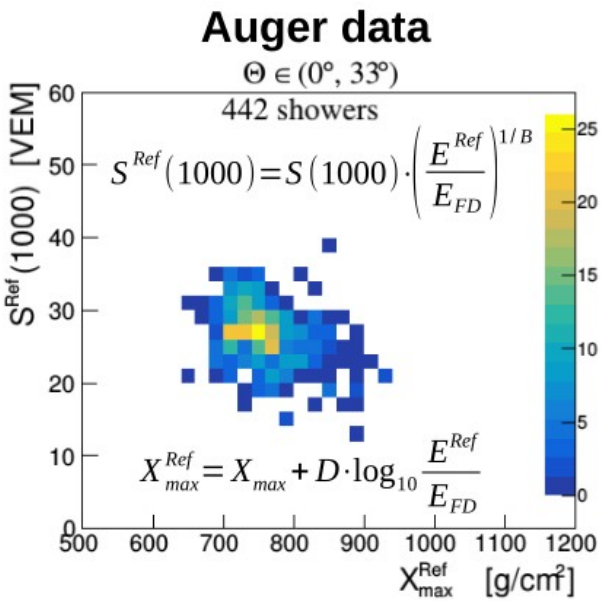


Auger, JCAP 03 (2019) 018

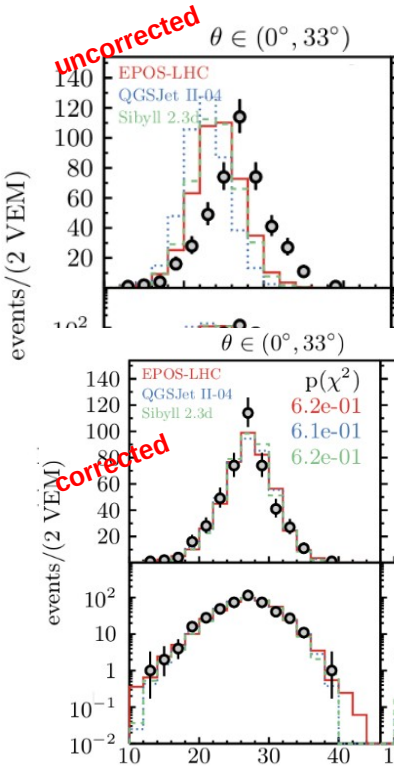
Shower profile is consistent
→ description of EM interactions adequate

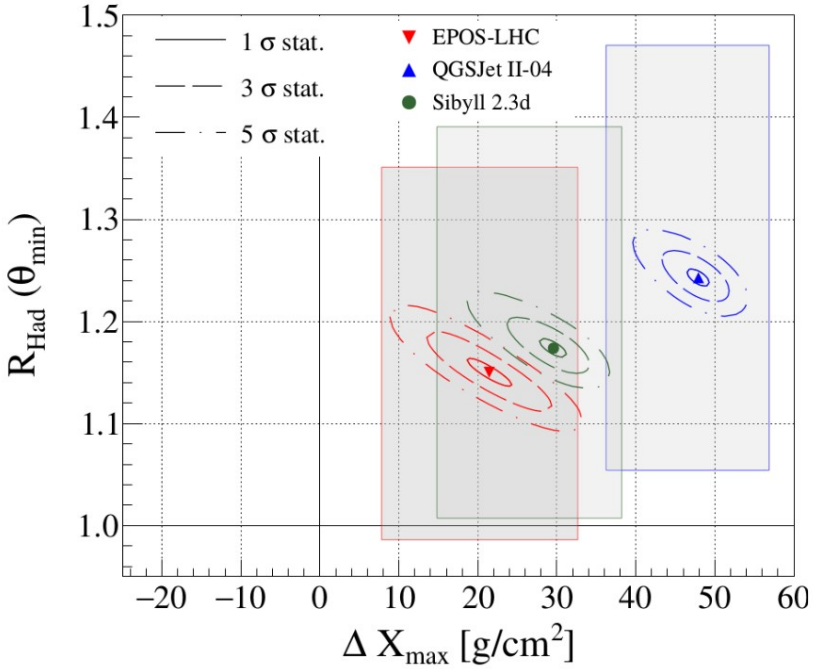
Could the predicted shower maximum be wrong?

Combined analysis: Xmax + Signal at ground
Including: Muon **and** Xmax correction



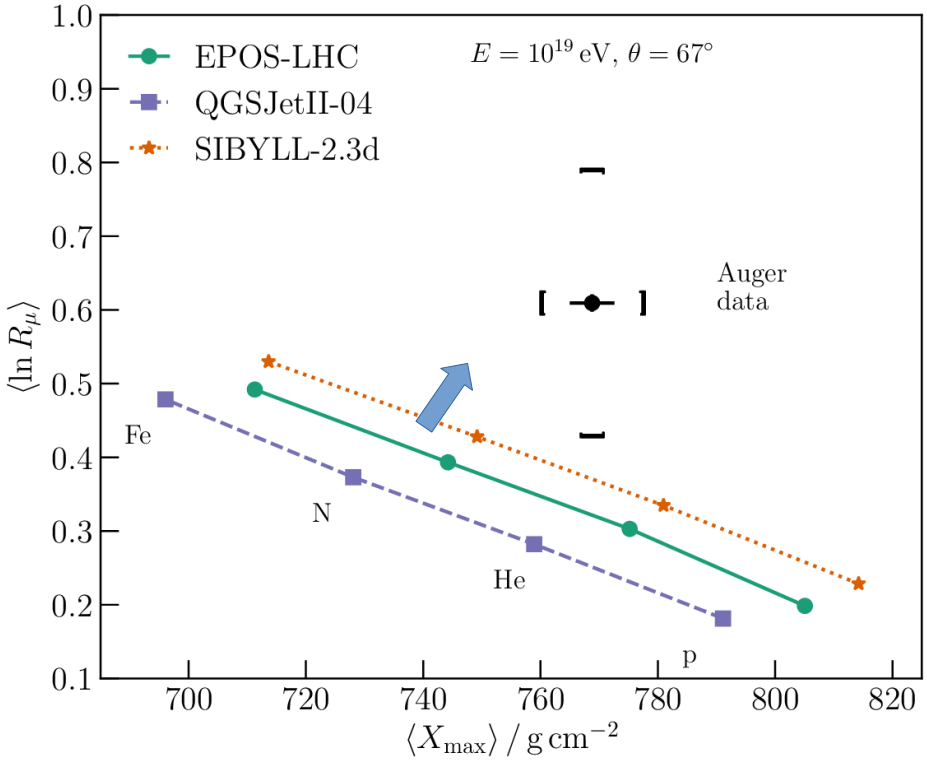
(Auger, J. Vicha ICRC2021)





Yes Indeed!
Best fit with Xmax shift !

New challenge (to you!)



Modify interactions such that:

* deeper Xmax
* NO (small) change in EM profile
  → play with cross section ?

and

* produce more muons

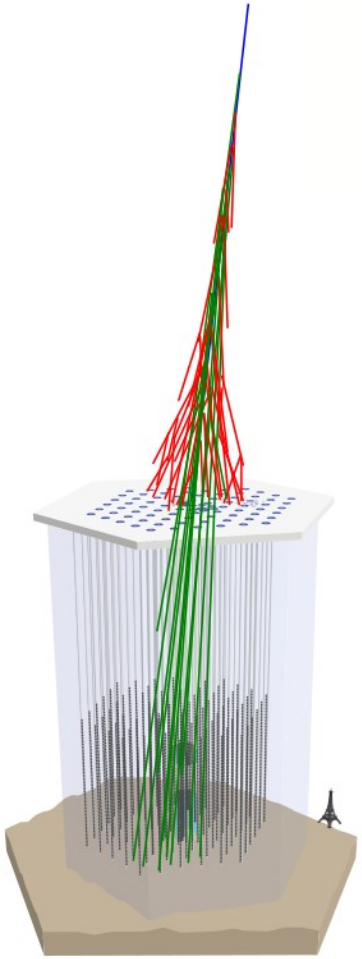
Summary

* observed air showers at UHE do not match SM prediction
    - more muons in measured showers
    - data also suggest showers are more penetrating
* possible explanations:
    - bad modeling of SM interactions (various scenarios)
    - new physics at UHE (strong constraints from fluctuations)

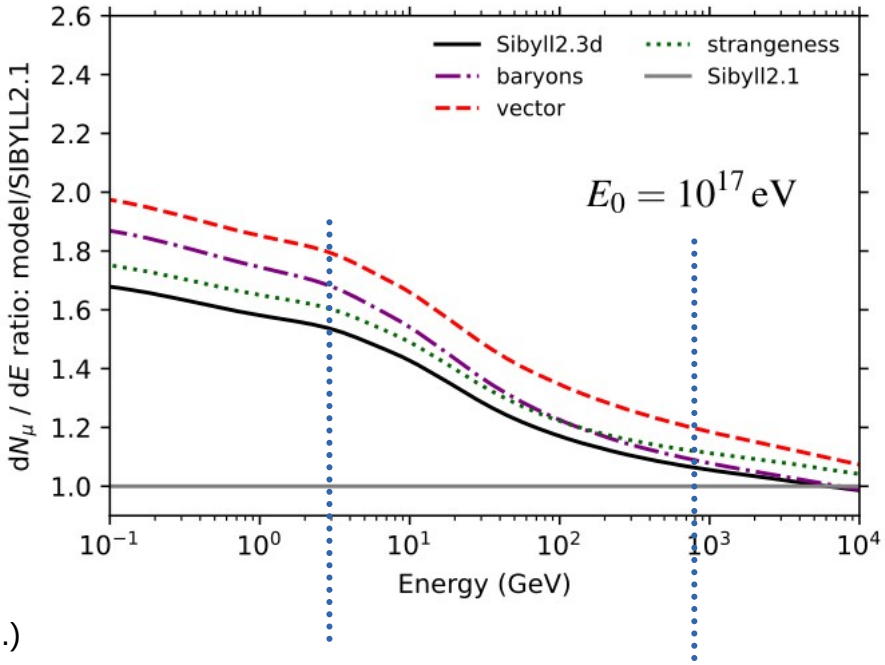
Way forward:

* more measurements

Future: more data for UHE interactions I

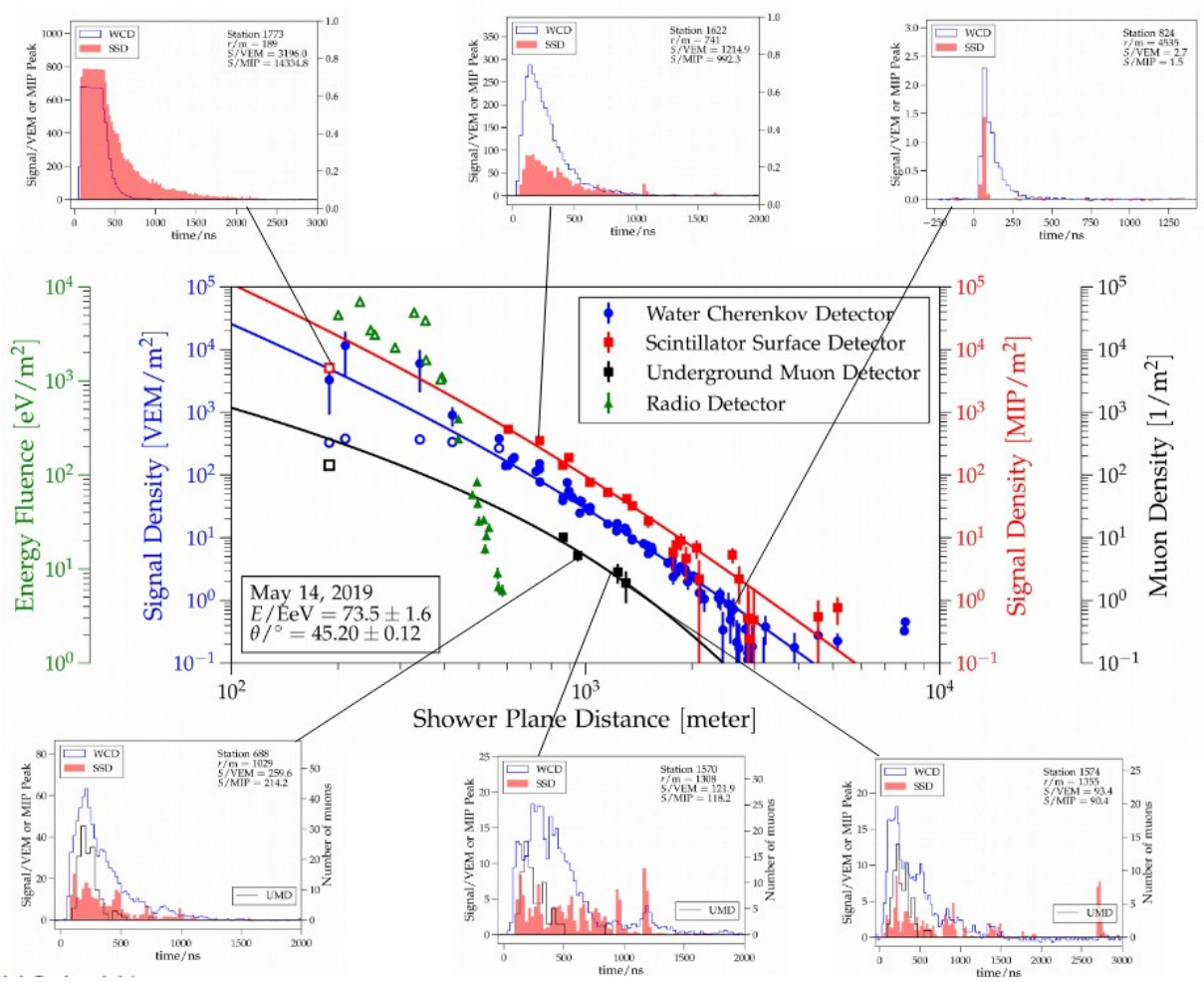


IceCube: surface muons (~GeV) and in-ice (~TeV) muons

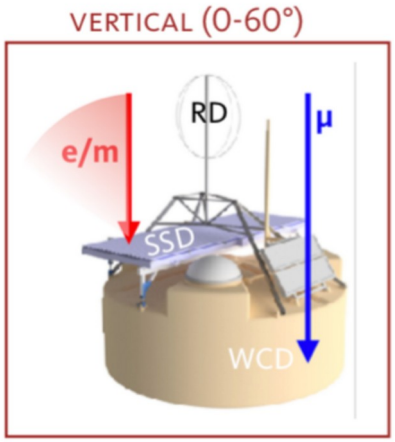


(D. Soldin et al.)

Future: more data AugerPrime



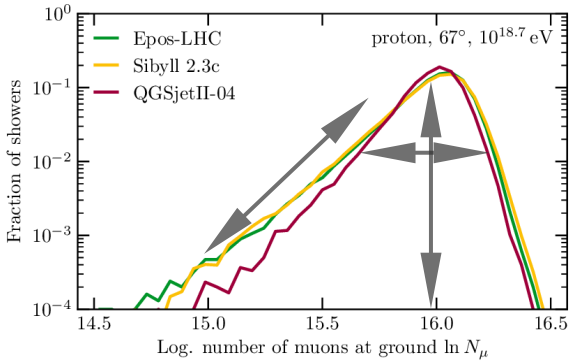
Multi hybrid measurement



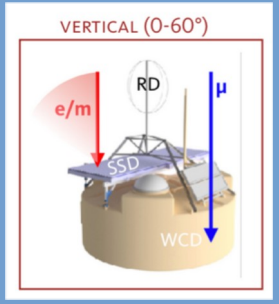
Future: more data for UHE interactions II

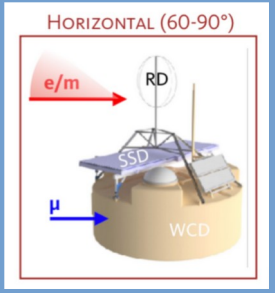
* Fluctuations! → muon distribution

tail ~ pion spectrum at large-xF



AugerPrime!





More observables!
More exposure! (Radio duty cycle → ~100%)