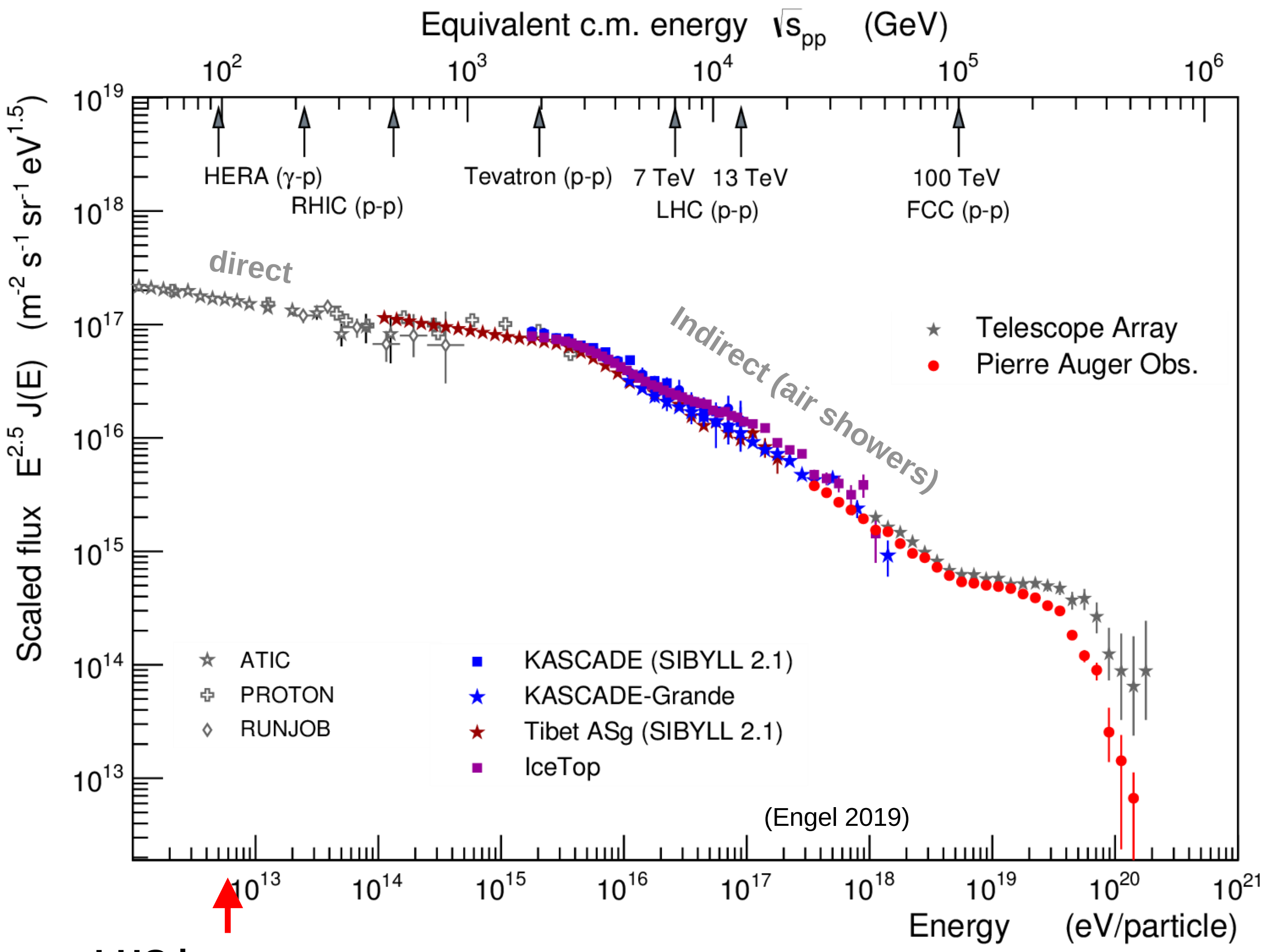
# Hadronic interactions at ultra-high energy

Felix Riehn, IGFAE (Santiago de Compostela)

Seminar at TU Dortmund - 06. 05. 2024

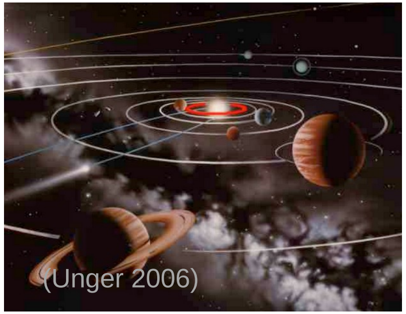
# Flux of charged cosmic rays




**LHC beam energy**

ASTROPHYSICS

Acceleration mechanism?




Charged cosmic rays linked to HE neutrinos & gamma rays?

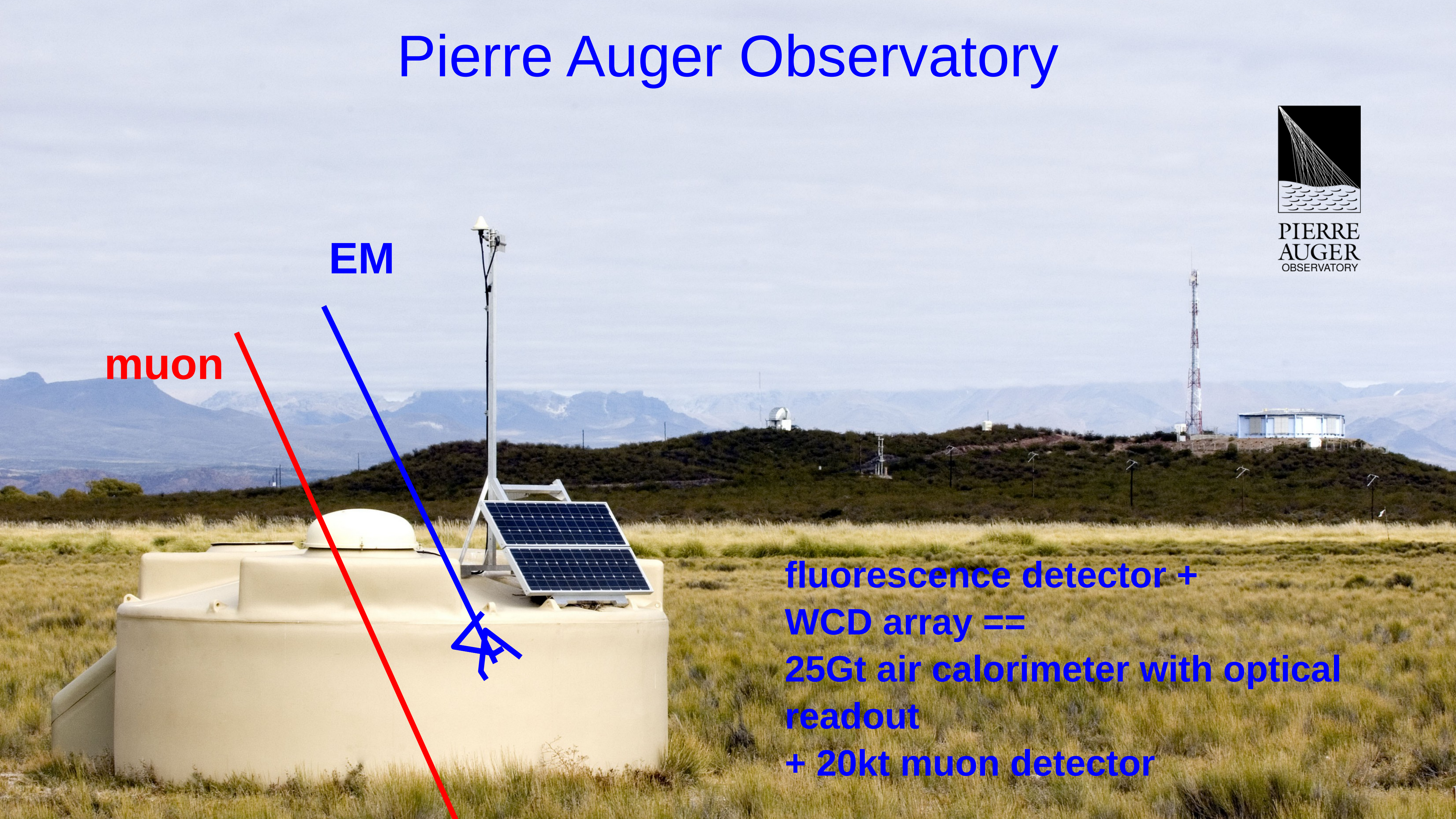
Gravitational waves?

But also: **UHE beam!**
**(from space!)**

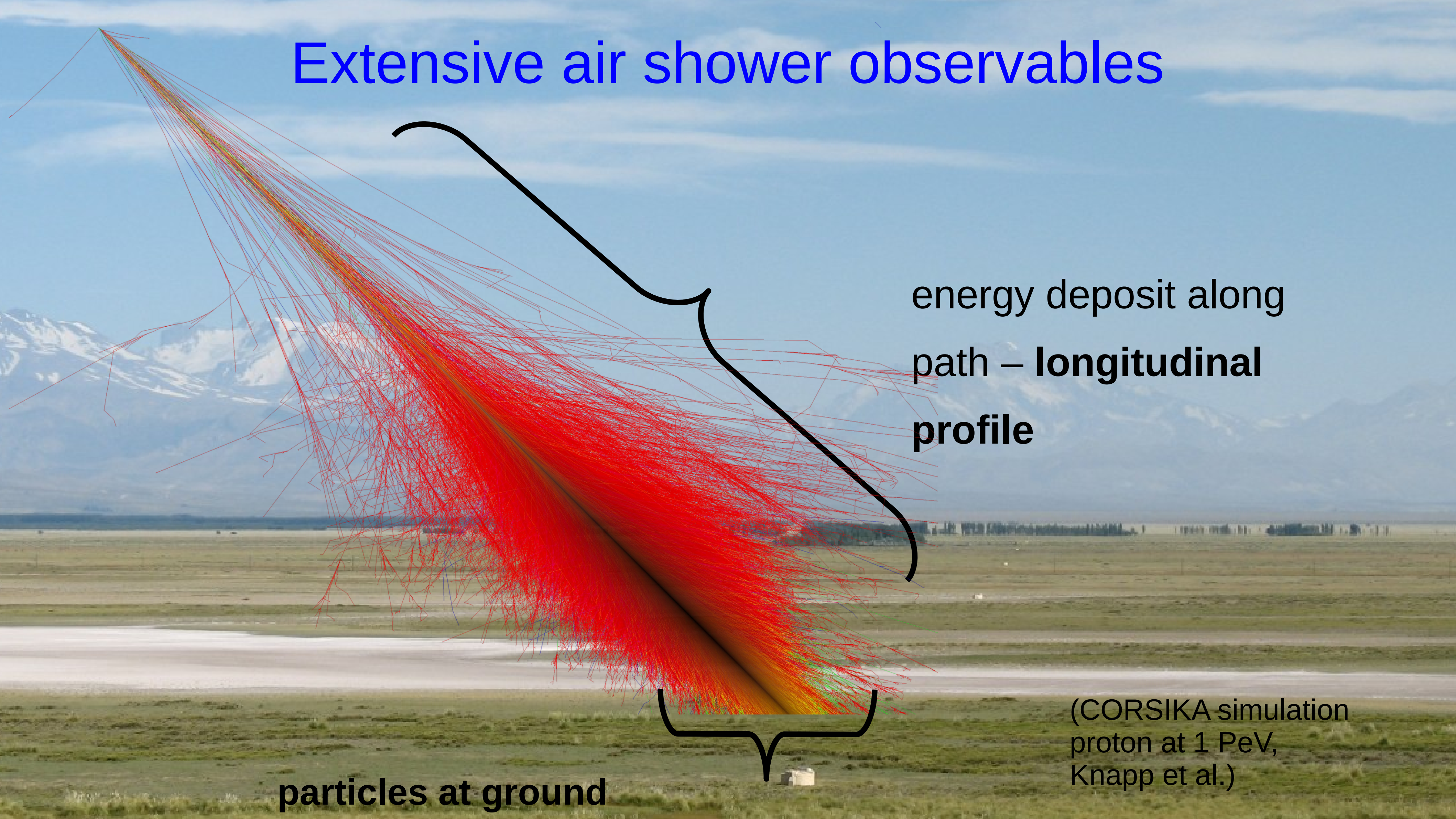
# Doing particle physics with UHECRs

Three problems:

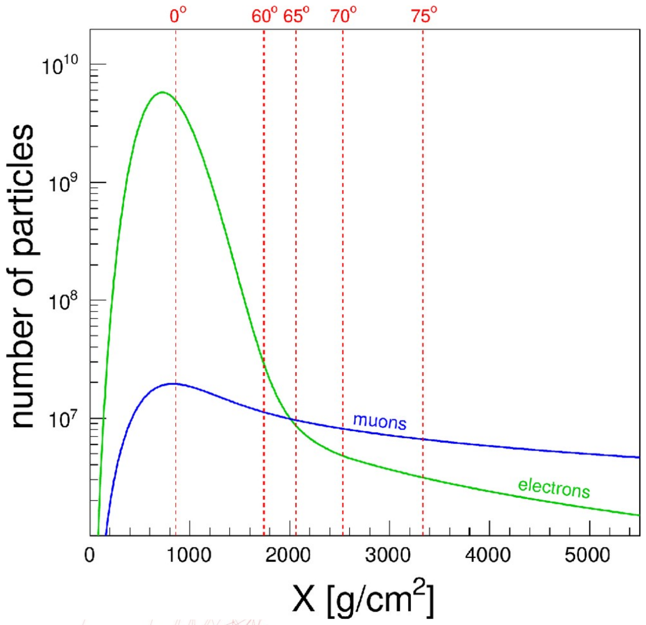
* indirect measurement (extensive air showers)
* unknown beam (mass composition of CRs)
* muon puzzle

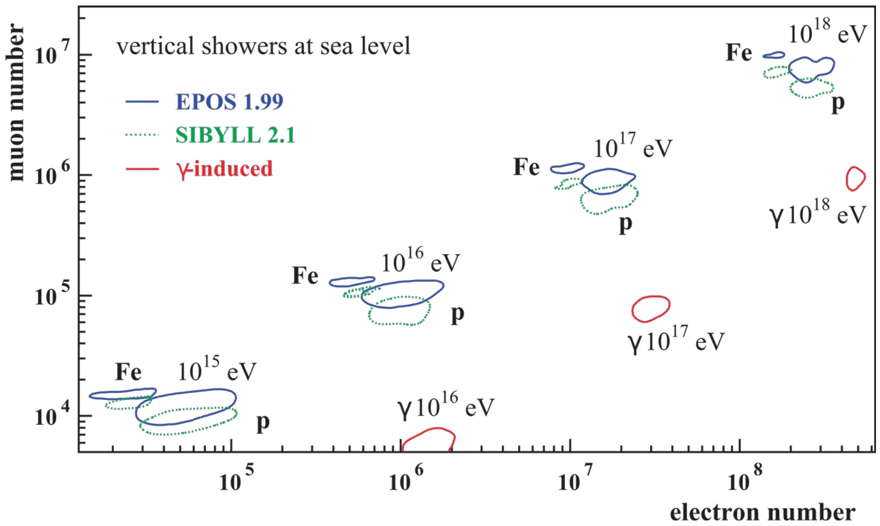

Pierre Auger Observatory
PIERRE
AUGER
OBSERVATORY
EM
muon
fluorescence detector +
WCD array ==
25Gt air calorimeter with optical
readout
+ 20kt muon detector

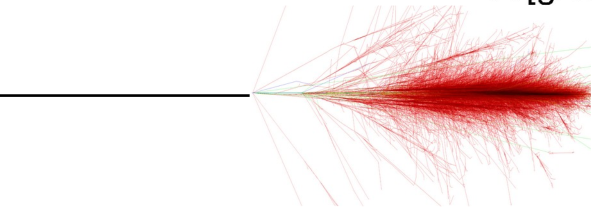
# Extensive air shower observables



# Extensive air shower observables



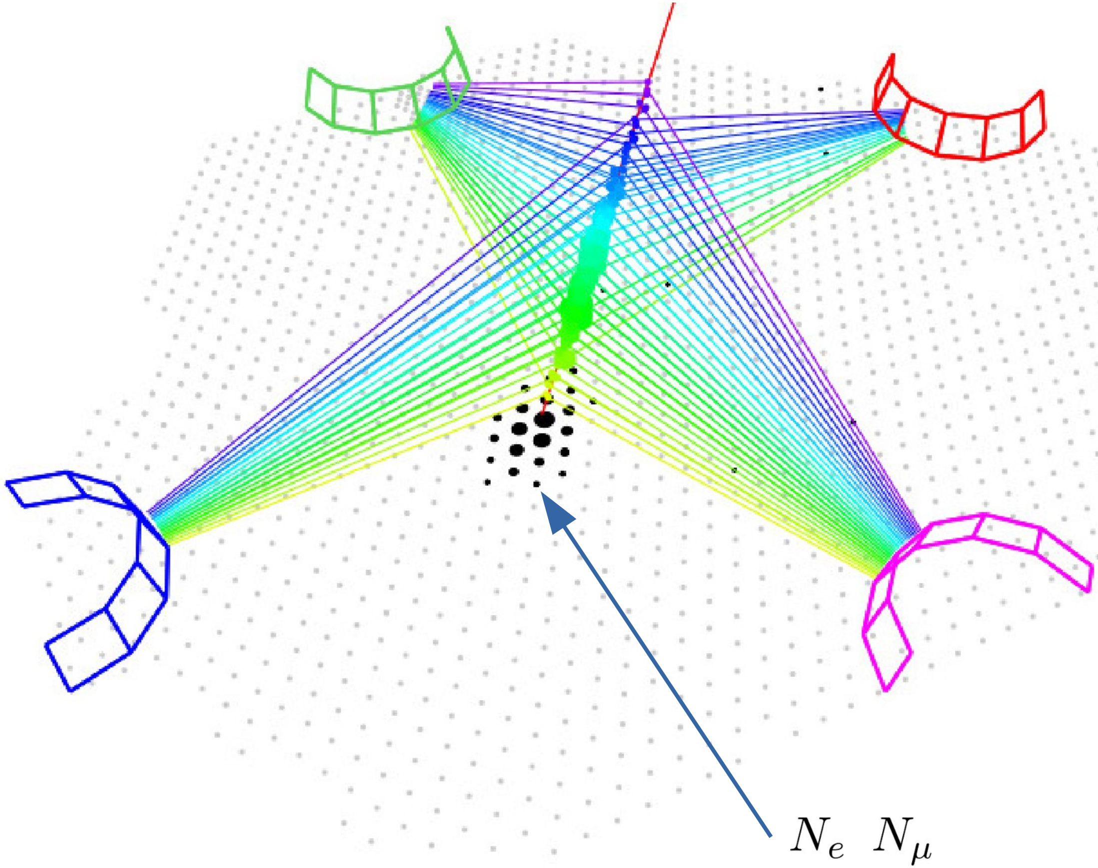



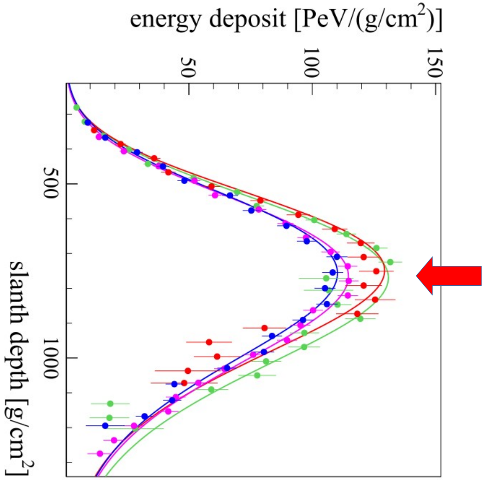



Interaction properties <==> CR mass

==> three measurements to do particle physics with CR!

# Hybrid measurement at Pierre Auger Observatory





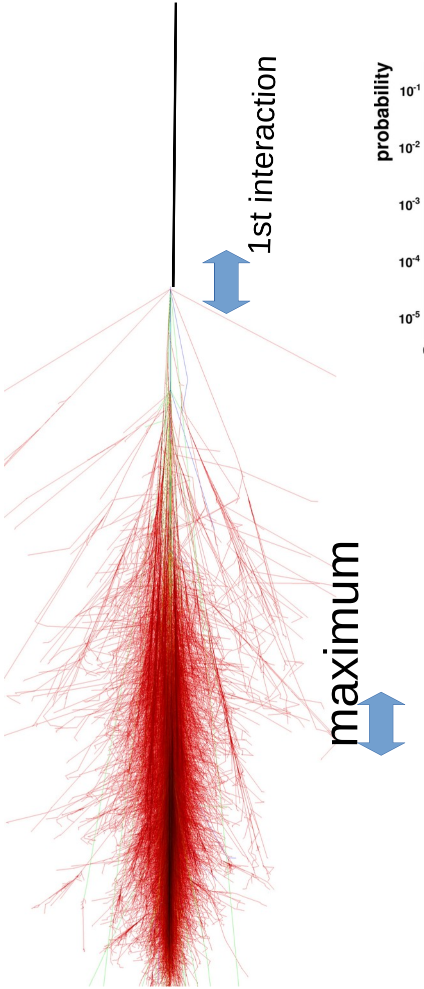

$N_e \quad N_\mu$

$E, X_{\max}$

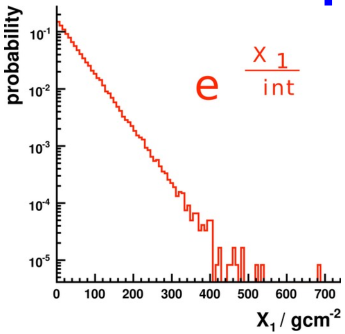
Related to primary?

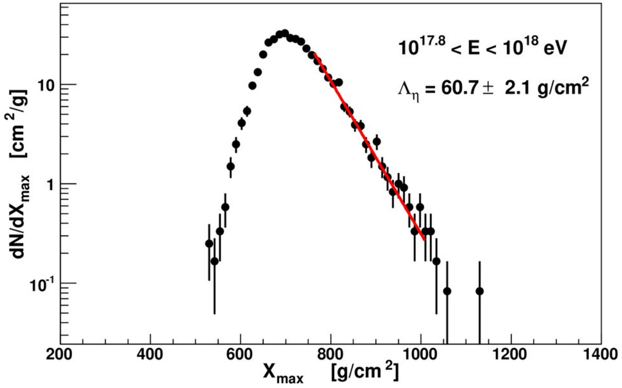
# Example of particle physics measurement: p-Air cross section

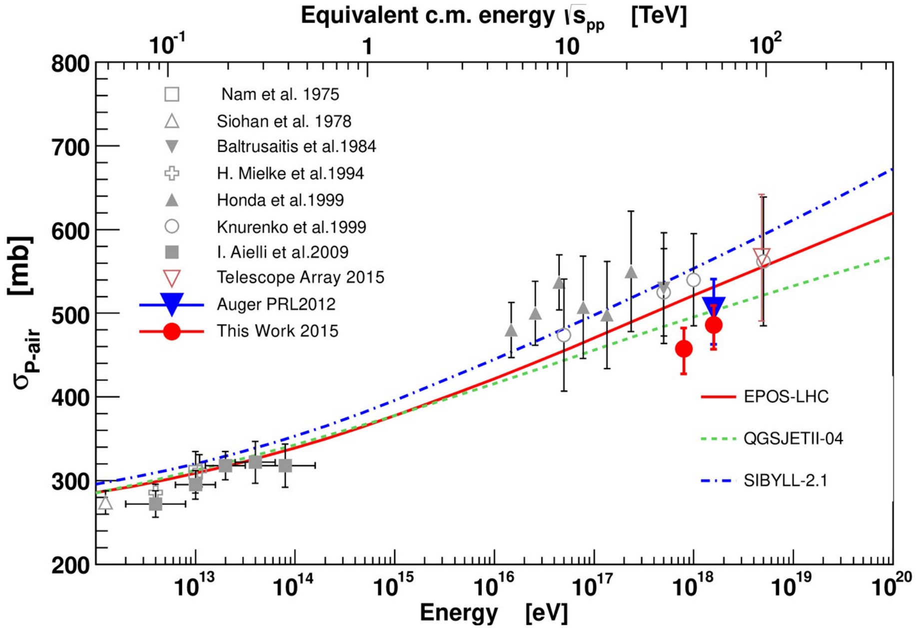
1st interaction



maximum



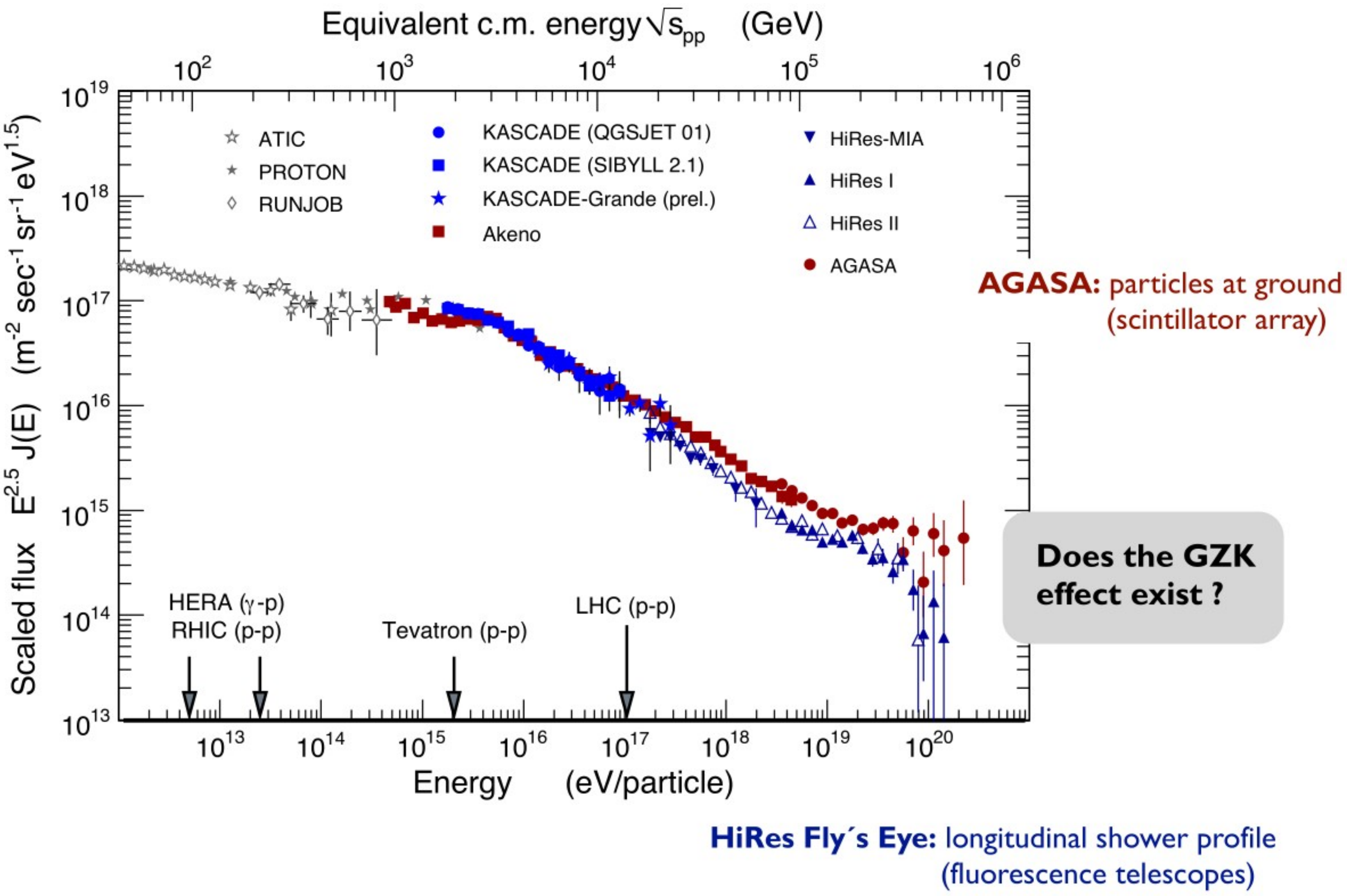




Deep showers

→ protons no need to measure mass

# New physics at Pierre Auger Observatory

(R. Engel Auger review 2023)

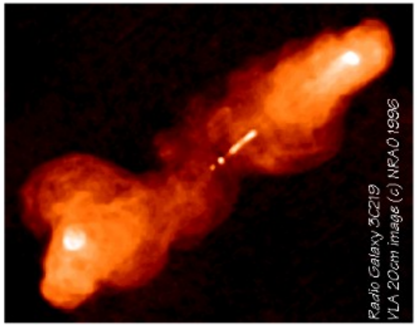



GZK effect:

→ flux limit due to interaction of CR protons with CMB photons

# Source and propagation model scenarios (2004)

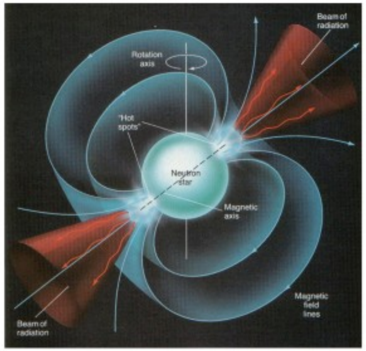
(R. Engel Auger review 2023)




**Active Galactic Nuclei (AGN):**
**Black Hole of ~$10^9$ solar masses**

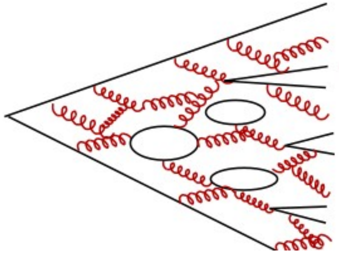
| | Process | Distribution | Injection flux |
|---|---|---|---|
| AGNs, GRBs, ... ( ☆ ) | Diffuse shock acceleration | Cosmological | p ... Fe |
| Young pulsars ( ☆☆ ) | EM acceleration | Galaxy & halo | mainly Fe |
| X particles ( ☆☆☆ ) | Decay & particle cascade | (a) Halo (SHDM)<br>(b) Cosmological | ν, γ-rays and p |
| Z-bursts ( ☆☆☆☆ ) | $Z^0$ decay & particle cascade | Cosmological & clusters | ν, γ-rays and p |

**Magnetars:**
**magnetic field up to ~$10^{15}$ G**




**X particles from:**
- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....

**Big Bang:**
**super-heavy particles,**
**topological defects:**
***$M_X$ ~ $10^{23}$ - $10^{24}$ eV***

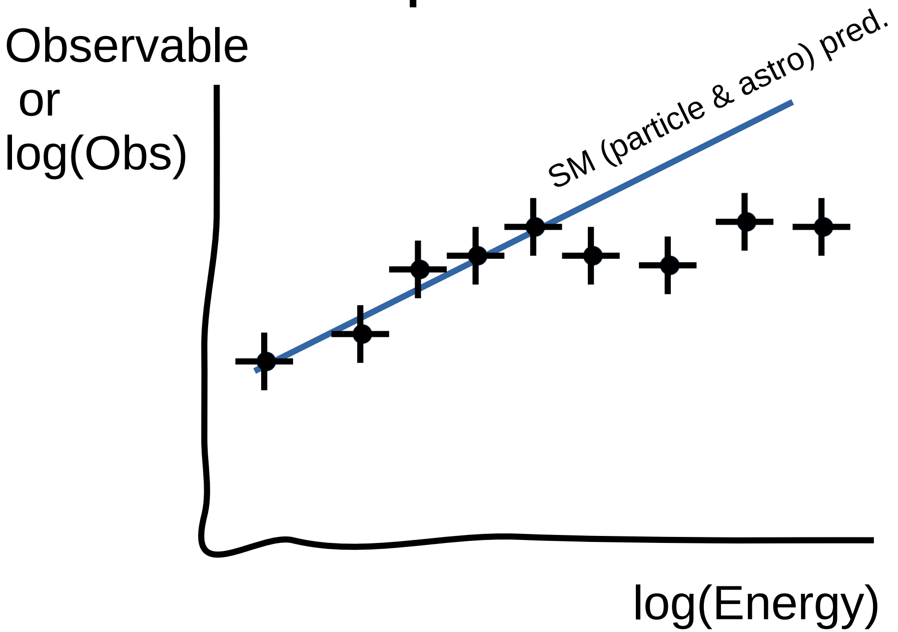


large fluxes of photons and neutrinos

**Every week 5-7 papers on UHECRs in the archive**

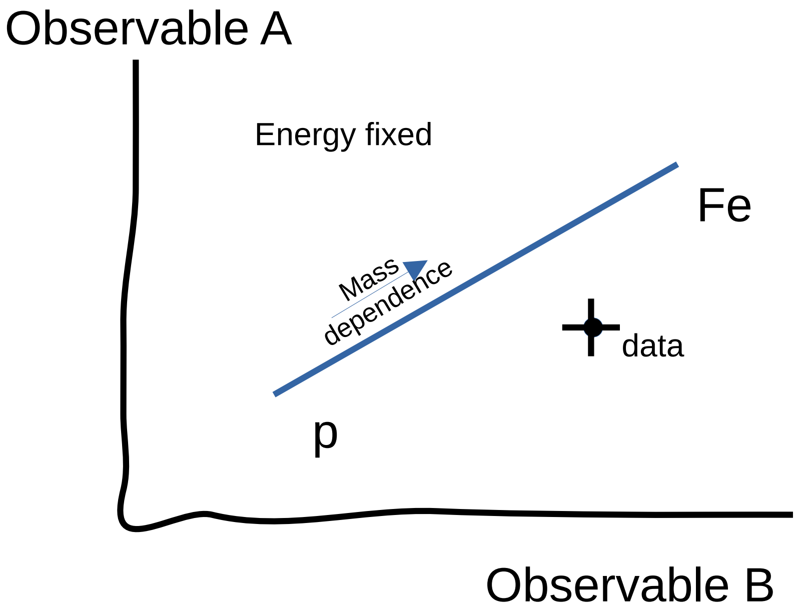
# Signatures of new physics

**Kinks in energy dependence**




**or**

**‘Inconsistencies’**



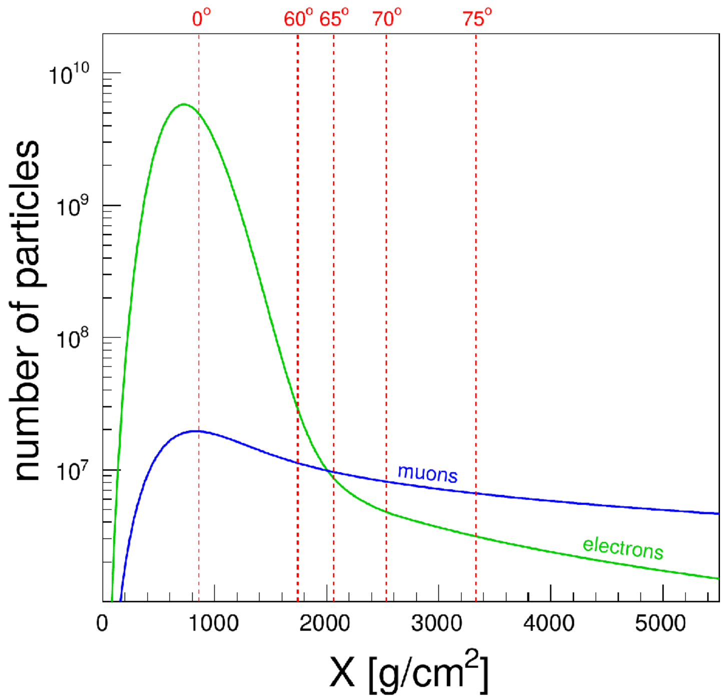

If Observable depends on mass:
Need to know mass composition

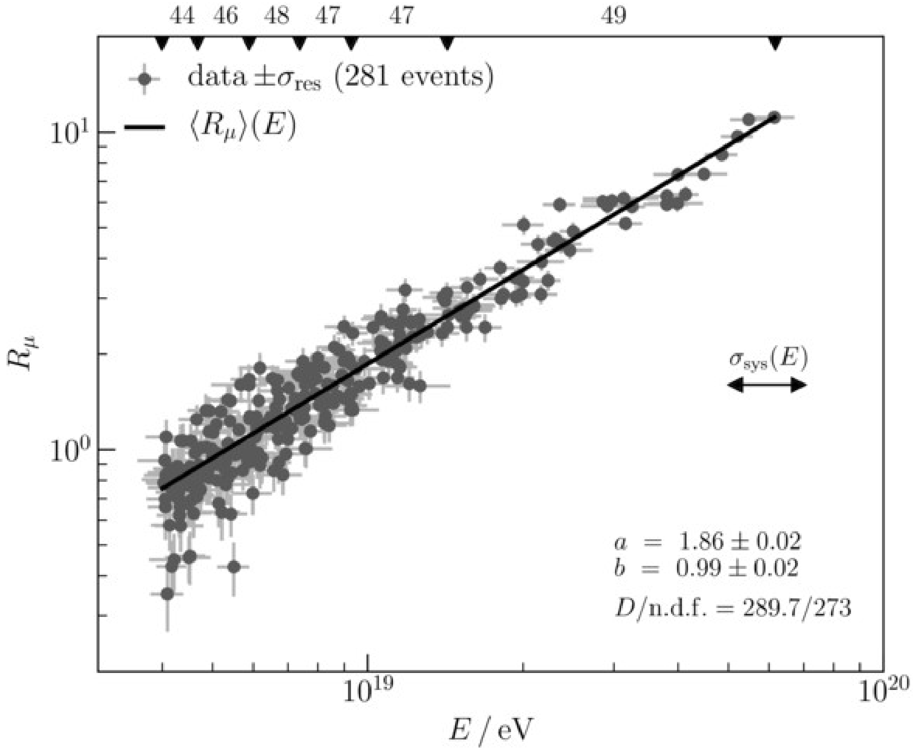
If both Obs A and Obs B
~ mass

# Measurement of muon content

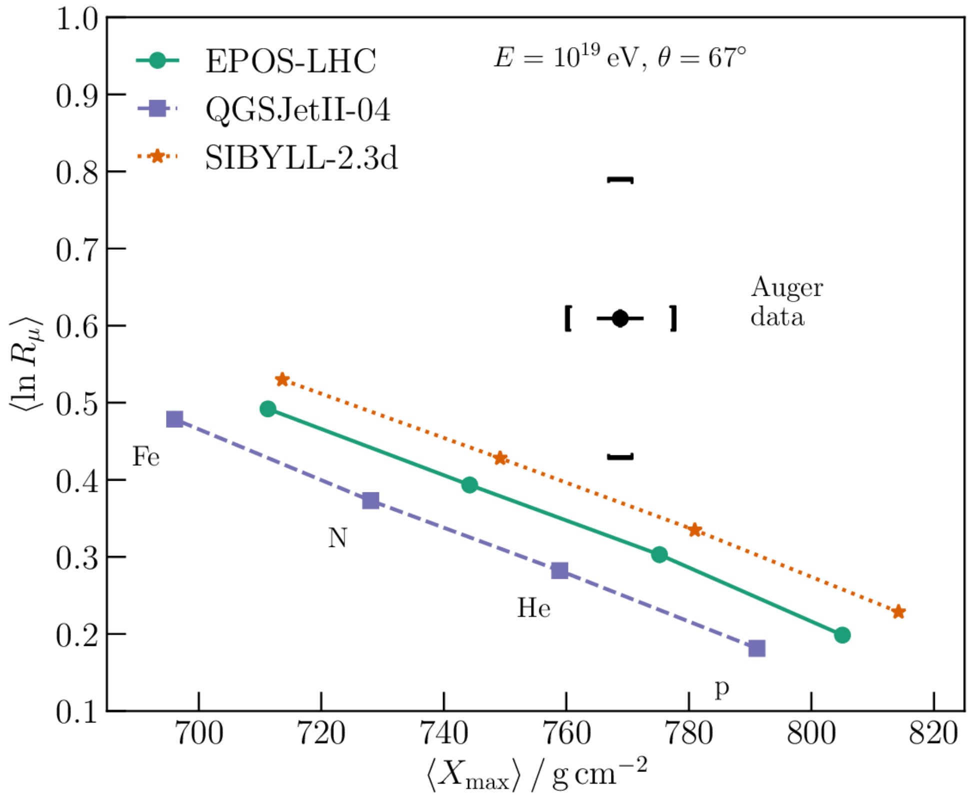
Hybrid (energy + Xmax)
+
inclined (surface signal → muons)

(H. Dembinski, Auger 2015)



# Comparing muon content with Xmax

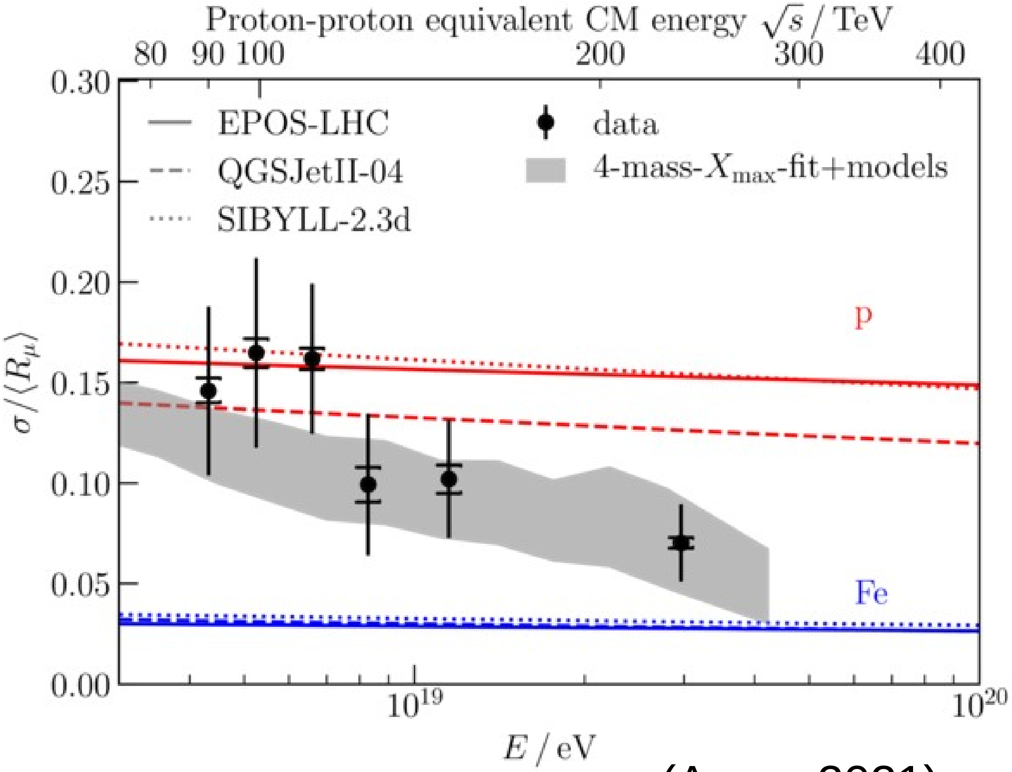



**Muon puzzle!**

Seen in many experiments !
see review by Dembinski et al.
(Astrophys. Space. Sci. 367, 27 (2022)))

# New physics?

Fluctuations are due to first interaction

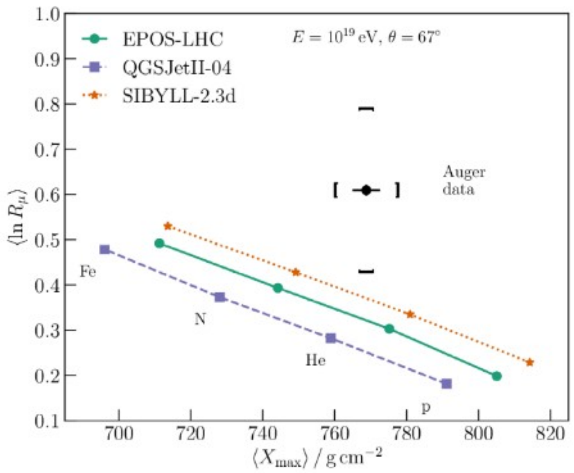



(Auger 2021)

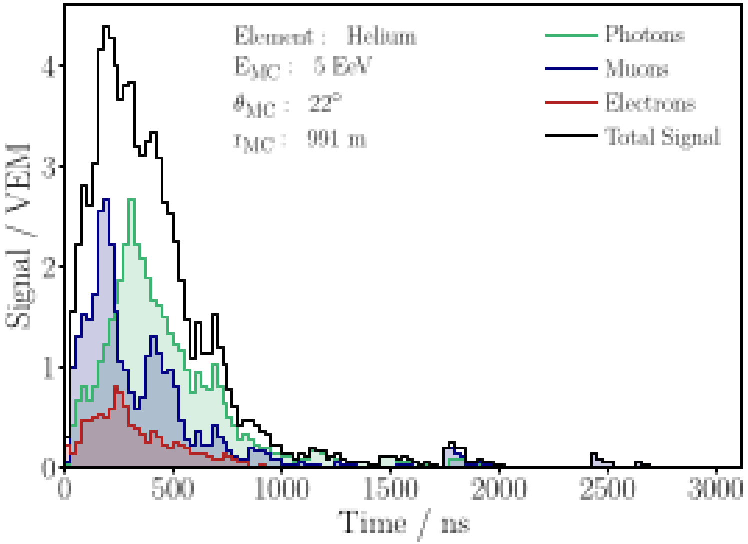
Fluctuations match expectation
→ no new physics needed/allowed

# Impact of the muon puzzle on UHECR

Cannot trust EAS simulations!
→ No ML, no detailed reconstruction



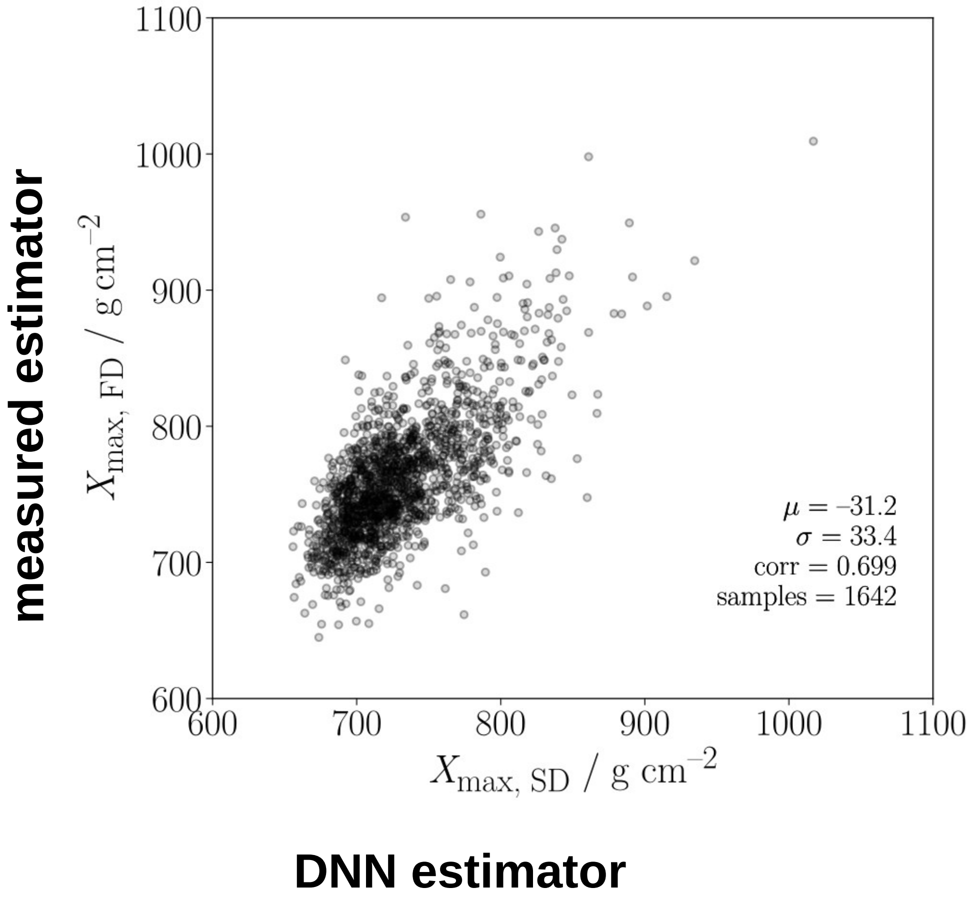

Simulated signal trace of one station




(Auger 2021)

→ No event-by-event PID with Auger Phase 1 (2004-2020) data !
Unless muon puzzle is fixed

# DNN for Xmax reconstruction




* Training DNN on simulations of surface detector signals to produce mass estimator Xmax

* Cross check with hybrid measurements results in **30g/cm2** bias (p – Fe ~ 100g/cm2 )

(Auger ICRC 2023, to be published)

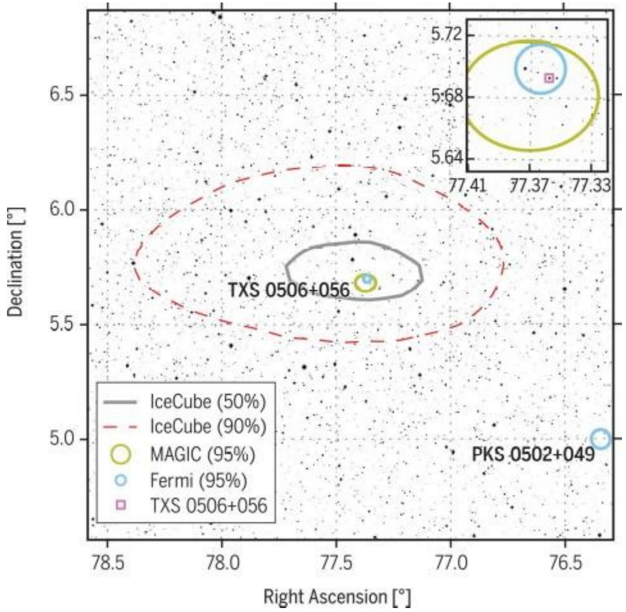
# Forget charged CRs, neutrinos !

*Interaction of UHECRs in source environment will produce HE neutrinos.*

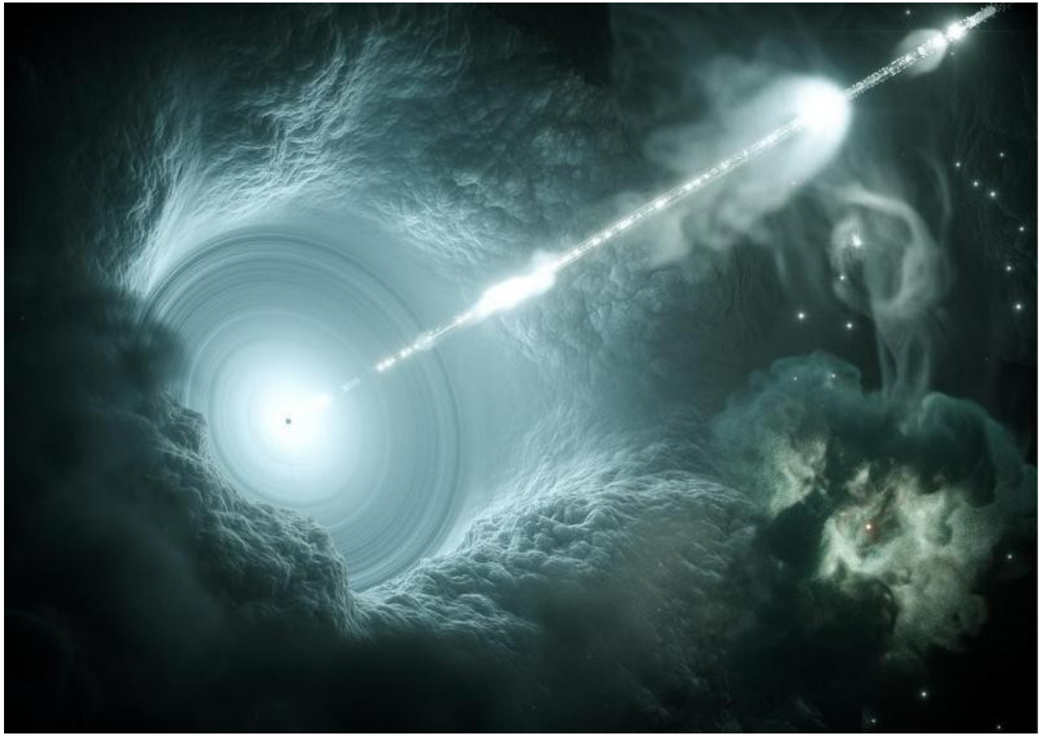
*HE neutrinos will reveal CR sources!*

# Yes, ..

## Multimessenger observation of blazar




(Science 361, eaat1378 (2018))

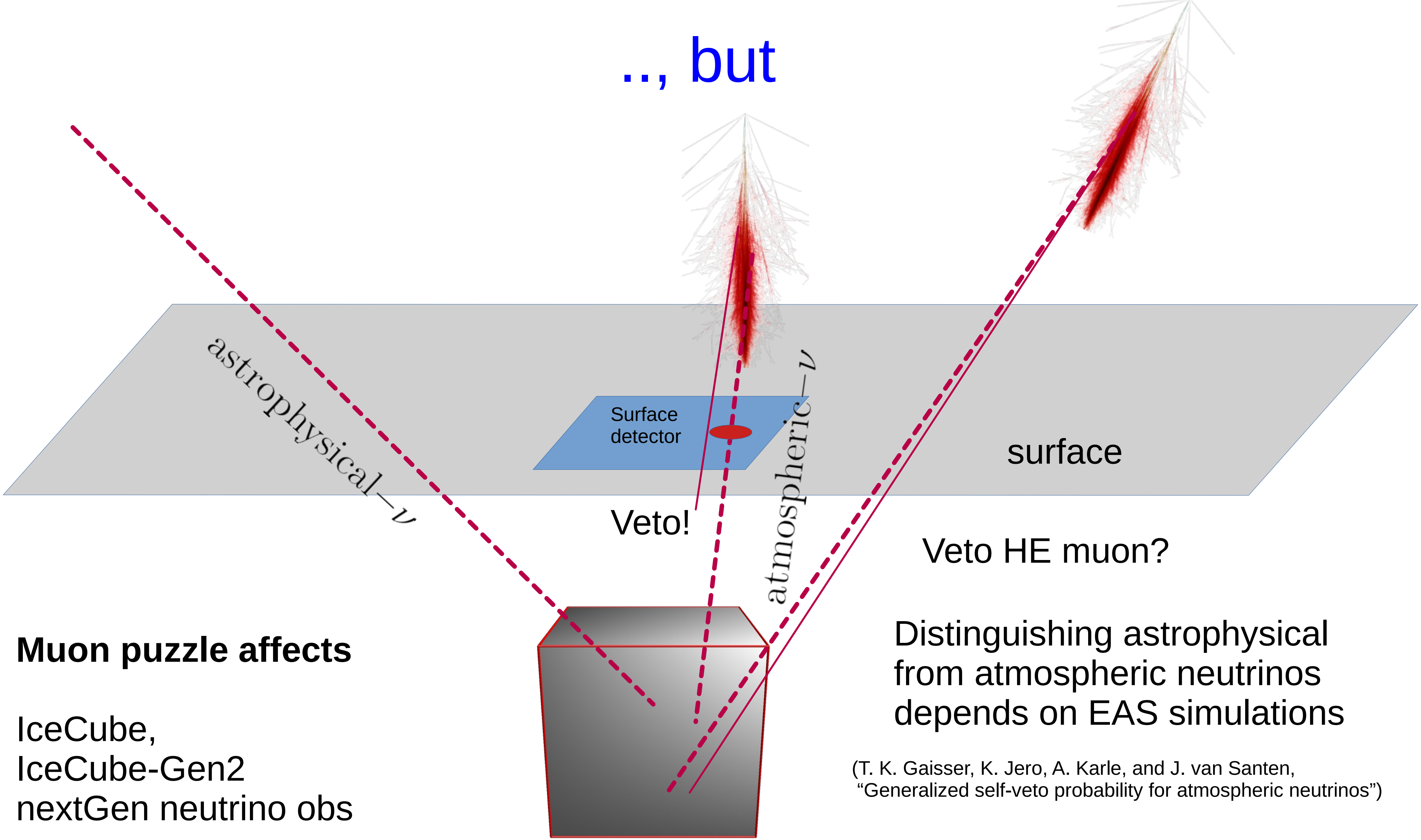


(DESY 2018)

But..

… The vast majority of neutrinos detected by IceCube arise from cosmic-ray interactions within Earth's atmosphere. Although atmospheric neutrinos are dominant at energies below 100 TeV, their spectrum falls steeply with energy, allowing astrophysical neutrinos to be more easily identified at higher energies. The muon-neutrino astrophysical spectrum, together with simulated data, was used to calculate the **probability that a neutrino at the observed track energy and zenith angle in IceCube is of astrophysical origin. This probability, the so-called signalness of the event (14), was reported to be 56.5% (17)**. Although IceCube can robustly identify astrophysical neutrinos at PeV energies, for individual neutrinos at several hundred TeV, an atmospheric origin cannot be excluded. ...

# .., but




**Muon puzzle affects**

IceCube,
IceCube-Gen2
nextGen neutrino obs

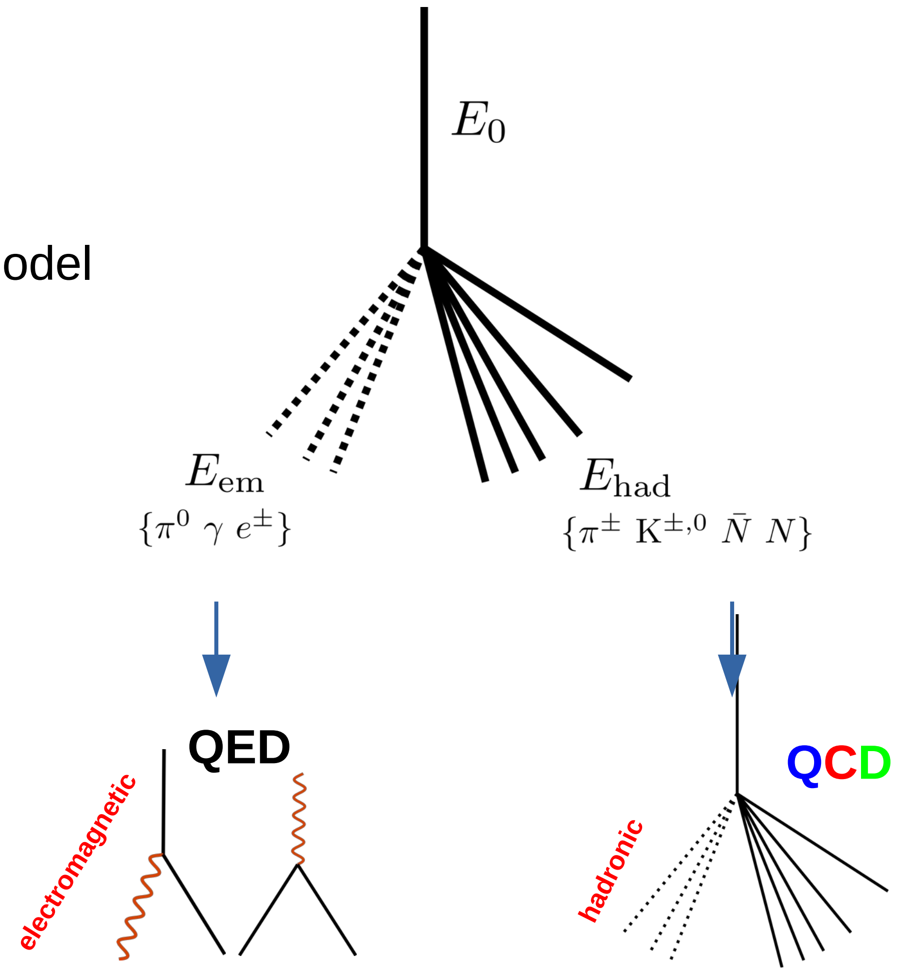
Distinguishing astrophysical from atmospheric neutrinos depends on EAS simulations

(T. K. Gaisser, K. Jero, A. Karle, and J. van Santen, "Generalized self-veto probability for atmospheric neutrinos")

# How to explain the muon puzzle

# Air shower development: two cascades

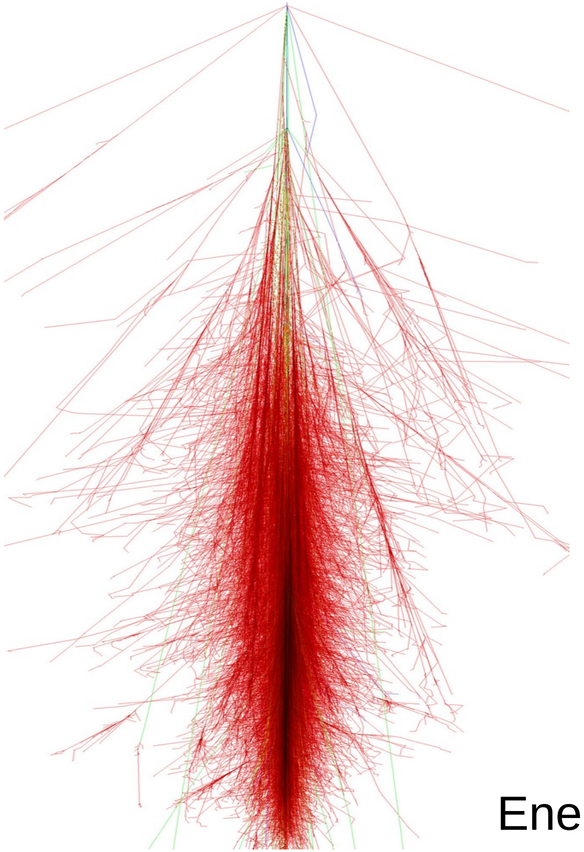
Assume: 1st interaction according to Standard Model

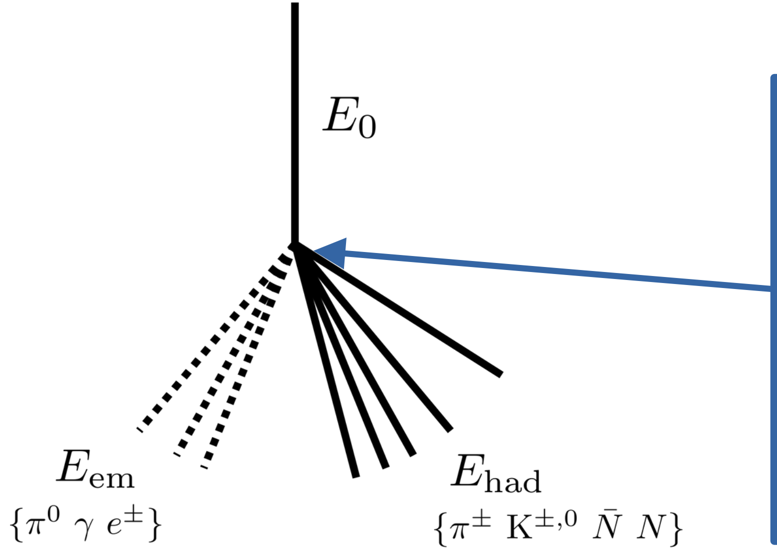


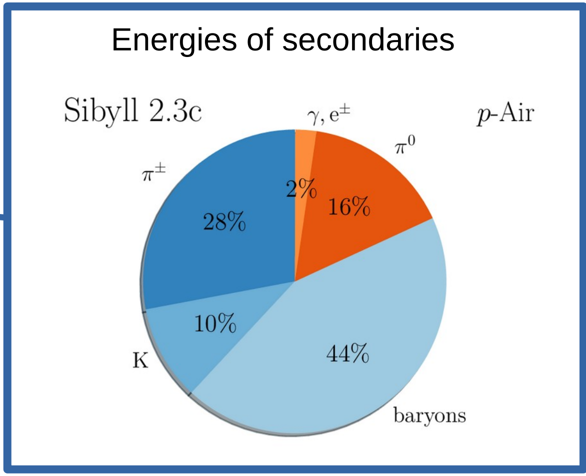

$$c\tau_{\pi^\pm} = 7.8\,\mathrm{m}$$
$$c\tau_{\pi^0} = 25\,\mathrm{nm}\ \pi^0 \to \gamma\gamma$$

2nd interactions ..

# Air shower development: energy flow






**EM cascade** **hadronic cascade**

Energy flow

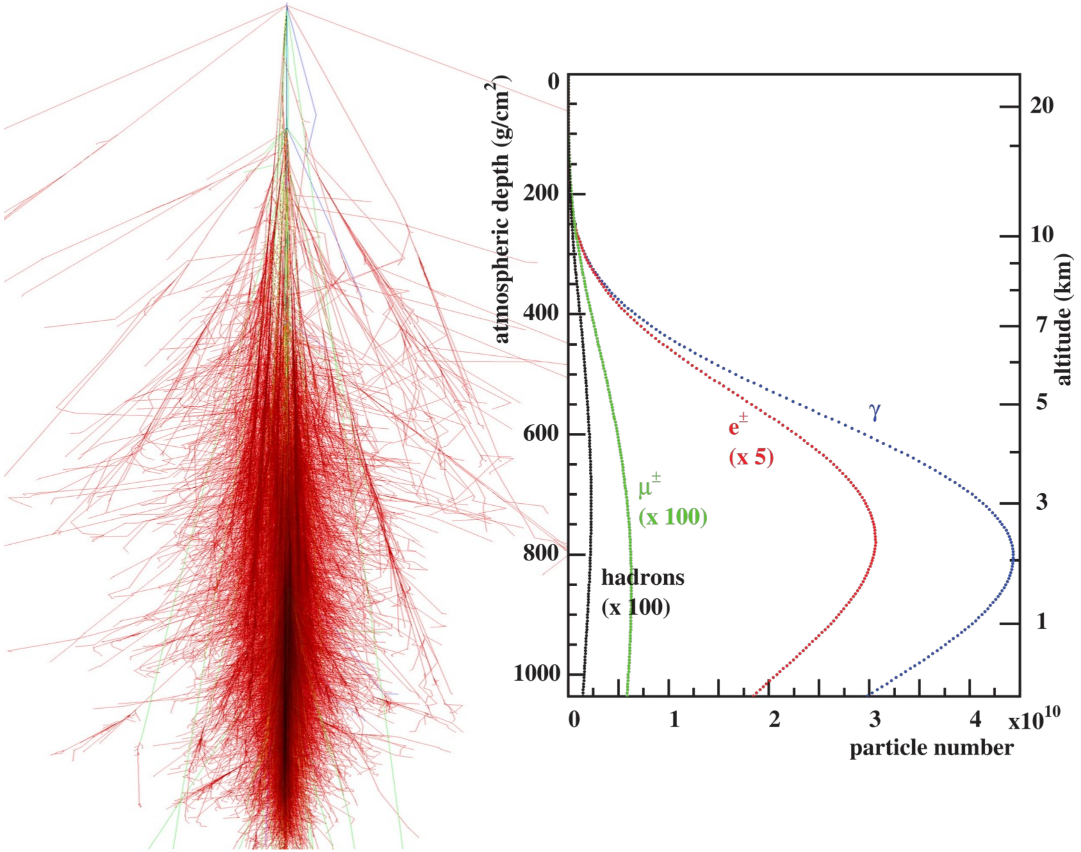
Only 80% energy remains in hadrons ..

After n steps:

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

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

# Air shower development: observables



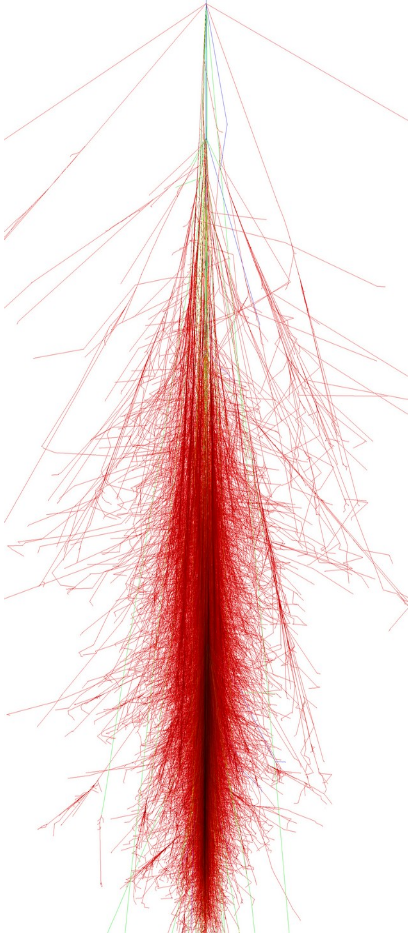

Shower profile & Xmax:
EM cascade,
first few hadronic interactions

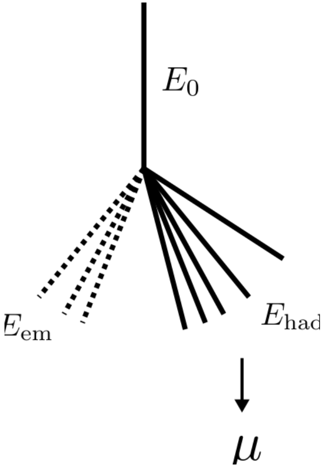
$$E_n^{\mathrm{EM}} = (1 - 0.8^n)\, E_0$$

muons: **Full** hadronic cascade
muons produced at end

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}$$

# How to get more muons: two scenarios






**1) New physics** scenario

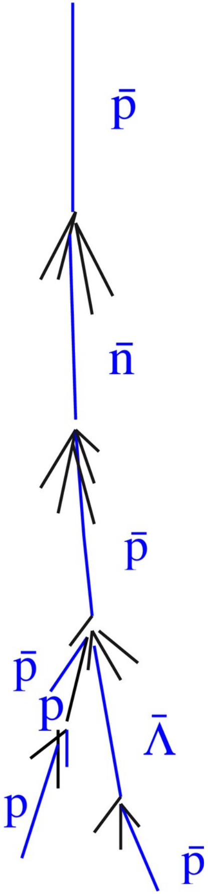
**1$^{st}$ (UHE) interaction** modified,
a process missing in interaction models

- 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 strangeness (QGP)

# More muons: baryon, rho0 and strange production




Baryon number conservation !

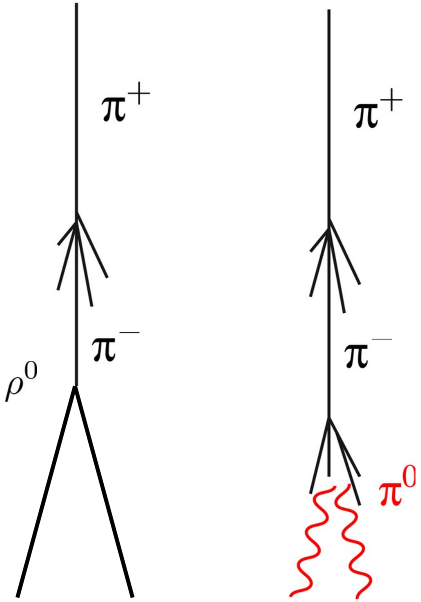
particle production until
Sub-relativistic !

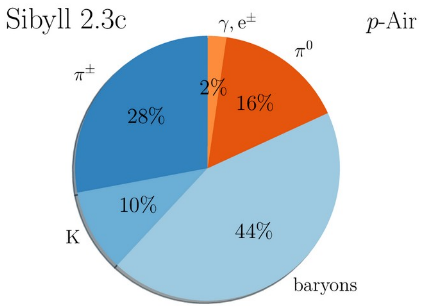
$$\pi^+ + p \;\rightarrow\; \text{leading} + X$$

$$\text{leading} : \pi(\text{spin} - 0) \text{ or } \rho(\text{spin} - 1)$$

$$\rho^0 \rightarrow \pi^\pm$$

$$\pi^0 \rightarrow 2\gamma$$



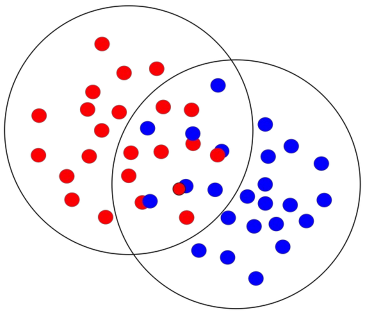



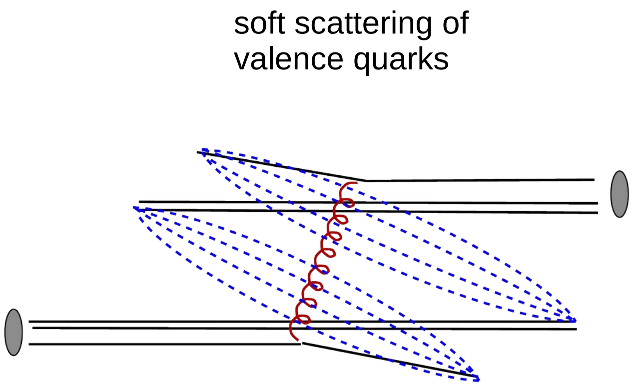

More Kaons → More Ehad

QCD conserves strangeness

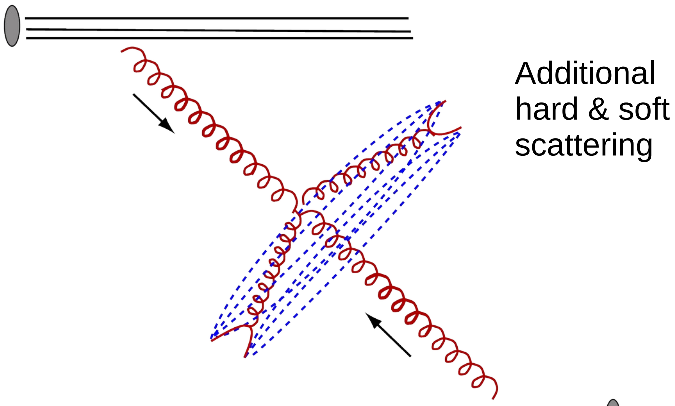
# Interlude: hadron interactions in SIBYLL

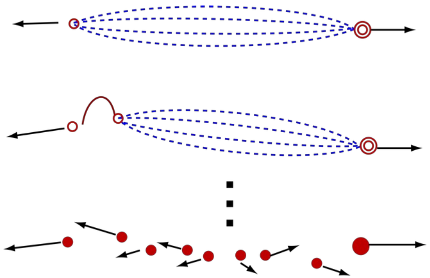
* parton picture
* LO QCD jets → minijets
* multiparticle interactions
* diffraction dissociation
* leading particles, associated production
* Lund string fragmentation





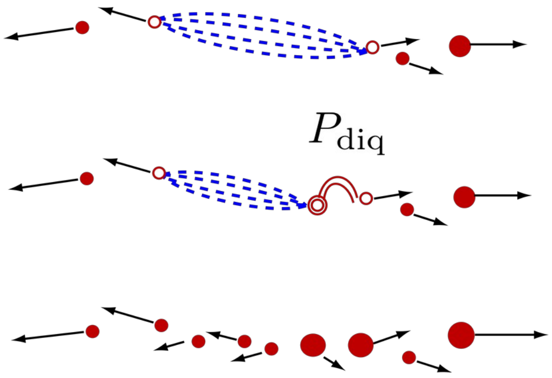

Model for:
Pions, Kaons, Protons and
Nuclei up to 1 PeV CoM

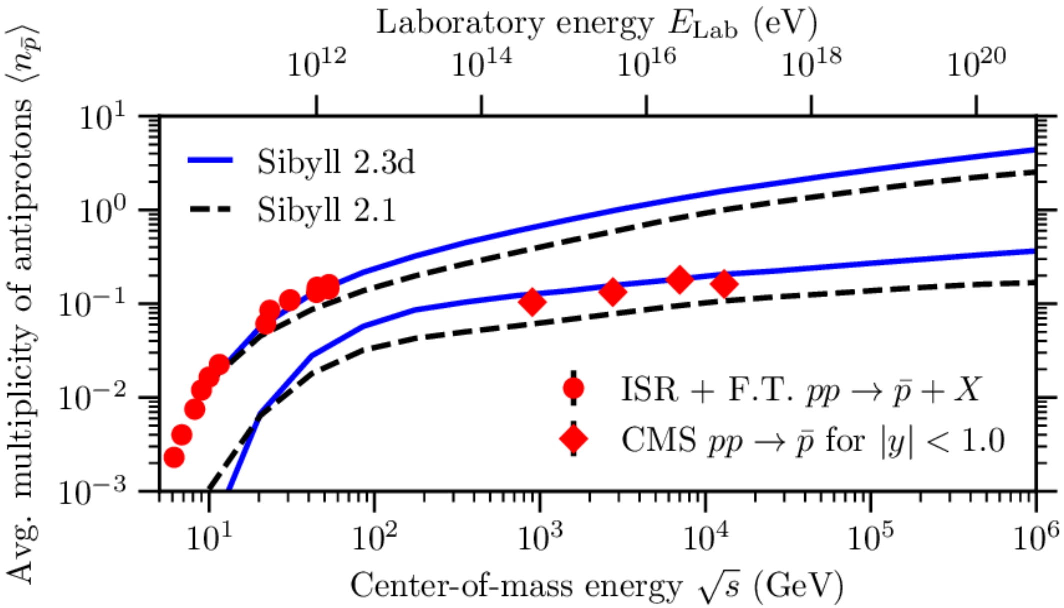


(PRD 80 (2009) 094003,
PRD 102 (2020) 6, 063002)

# Baryon production in SIBYLL



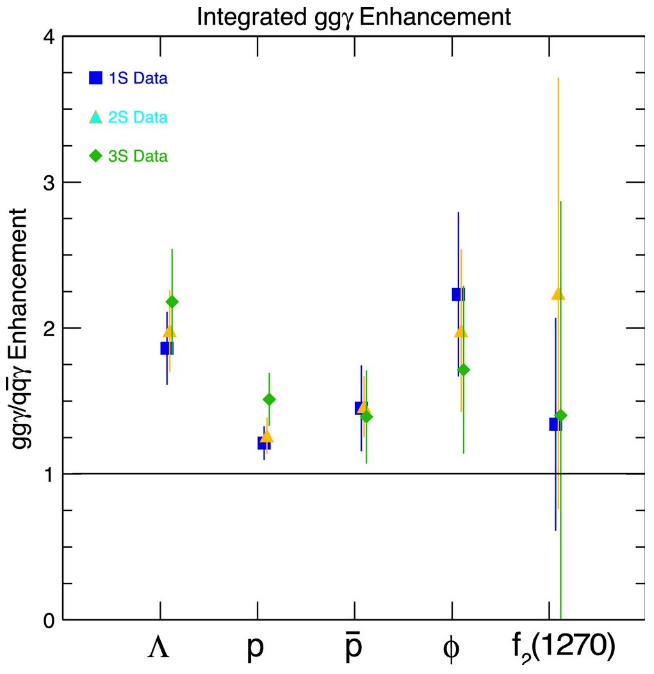




Sibyll 2.1 (from TeVatron times)

Fixed rate of baryon (diq) production

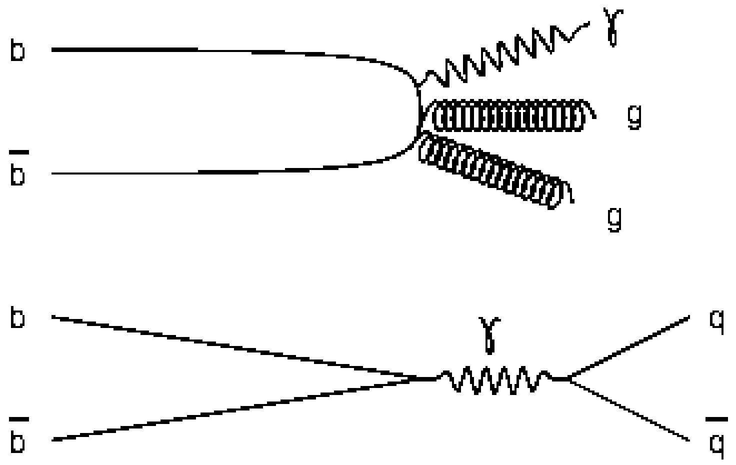
# Baryon production not universal ?

( CLEO collab. R.Briere et al, Phys.Rev.D**76**,2007 )



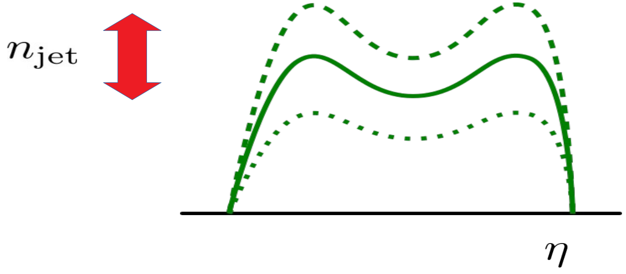

Pdiq depends on gluon density?

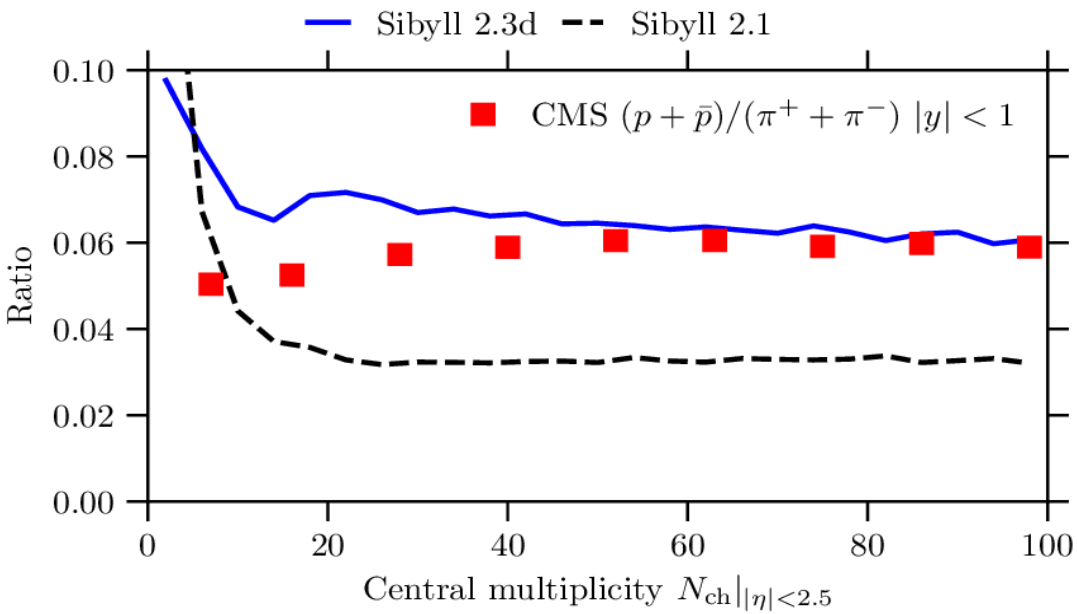
Decay of Υ(9460) resonance




Compare with off-resonance scattering

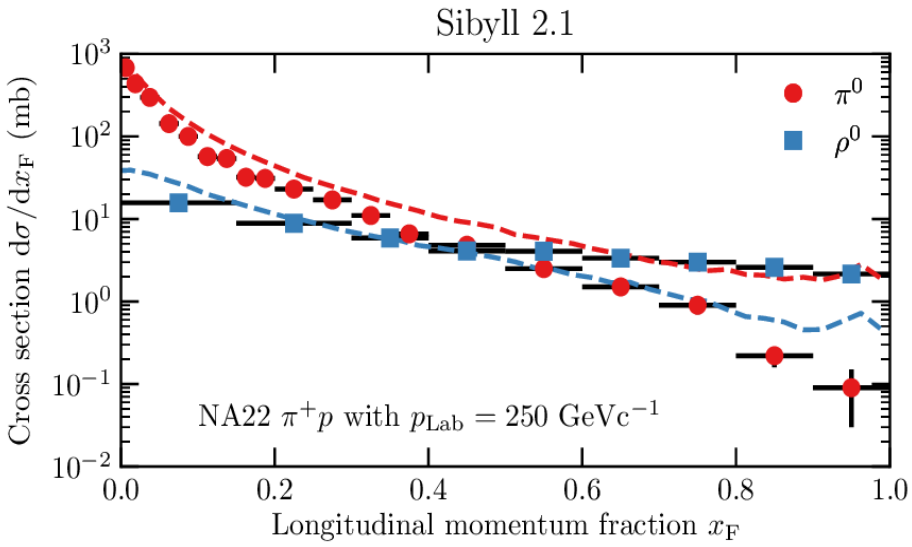
# Baryon production constant in rapidity

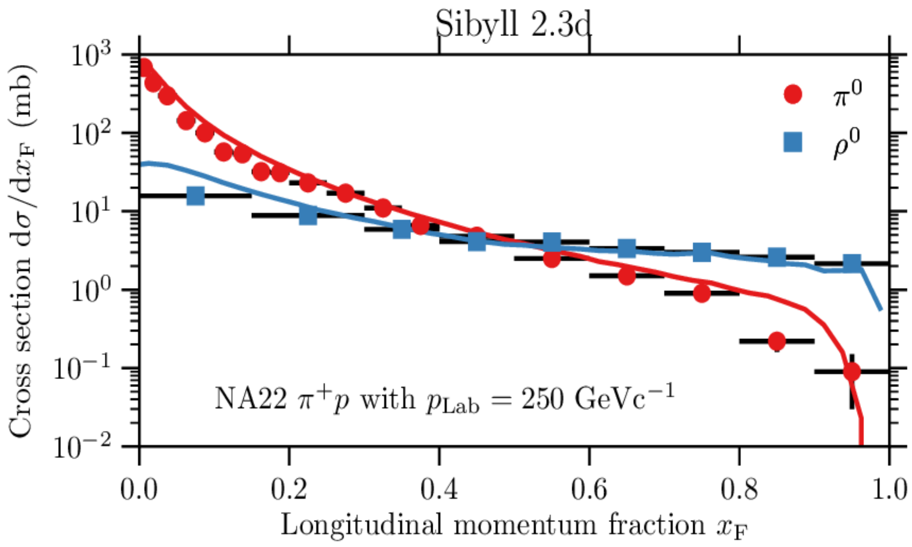


# Leading rho0

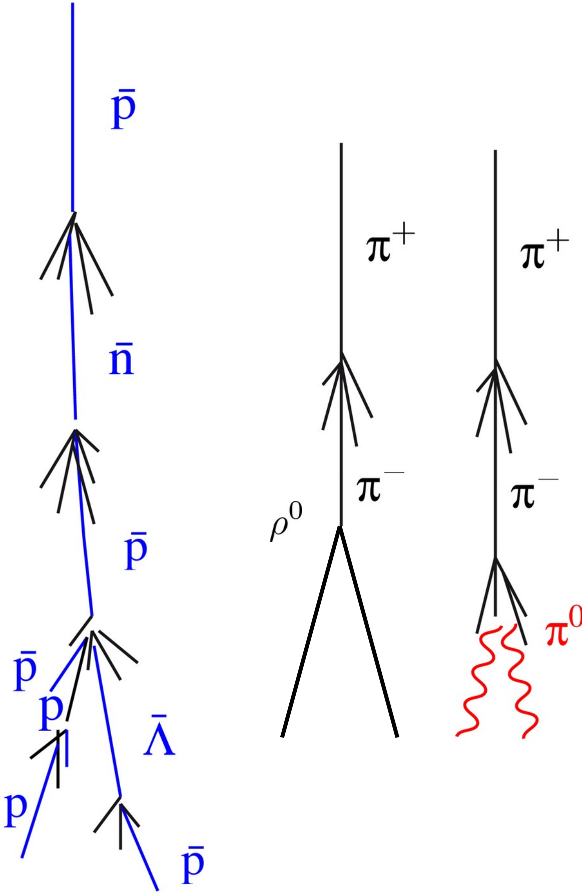
$$\pi^+ + p \rightarrow \text{leading} + X \qquad \text{leading} : \pi,\ \rho$$

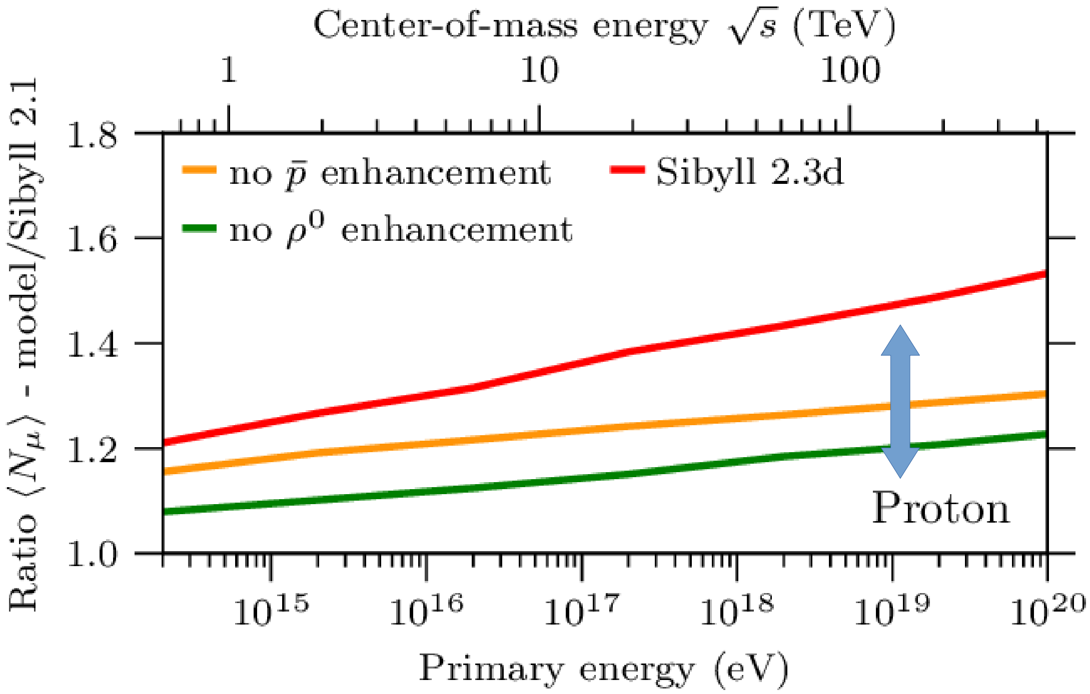



$$P_{\pi:\rho} = 1/3$$

# Effect on muons in EAS




~40% increase

# Muon discrepancy in Sibyll

30% enhancement in number of muons from 2.1 → 2.3d

Achieved through:

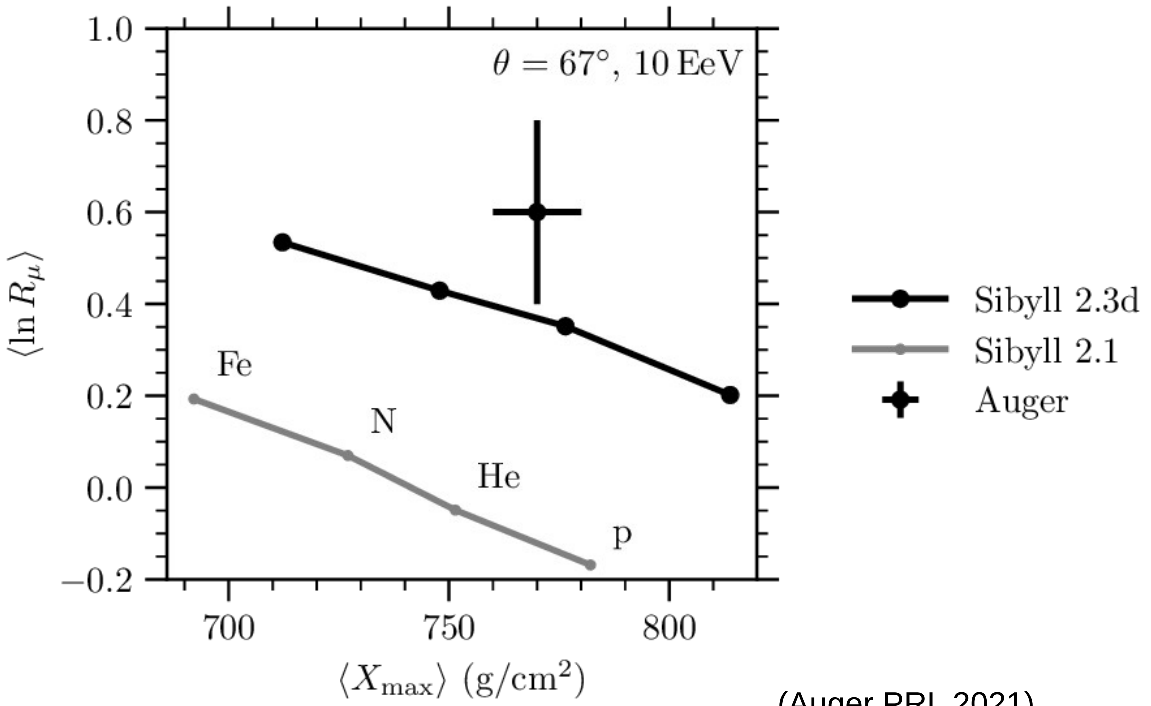
- baryon production
- Forward Rho meson production

Data driven (LHC,NA22/NA61) !

**NOT ENOUGH MUONS !**

Is there more room within standard physics ?

→ **Sibyll***




(Auger PRL 2021)

In addition, **ML** analyses require detailed simulations that are consistent with data

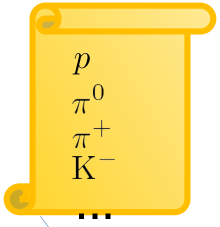
# Sibyll*

We want:

* test different scenarios
* simple adjustable parameters
* physically consistent events
(energy/momentum + Q,B,S conservation)

Therefore leave Sibyll unmodified, but alter final state.

Sibyll 2.3d



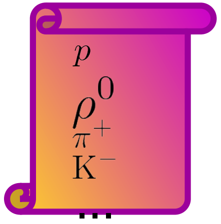

List of particle names & momenta

**Post-processing**

1) Replace *suitable* pairs/tripels of pions with desired hadrons at a **specific rate P**
*Example: for rho-meson replace (pi0,any) with (rho0,any)*

2) Recalculate momenta

**Sibyll***



# Energy- and phasespace dependent modifications

Start from Sibyll 2.3d and only change events **outside** of phasespace covered by accelerator experiments

$$P_i = P_{i,0} \cdot |x_\mathrm{F}|^{\epsilon_i} \cdot f(\sqrt{s}, E_\mathrm{thr})$$

Base rate

Longitudinal phasespace dependence

Epsilon → 1 max. change in forward phasespace

Epsilon → 0 no change

Energy dependence

* linear in log(s)
* zero at thresh.
* unity at 10**19eV

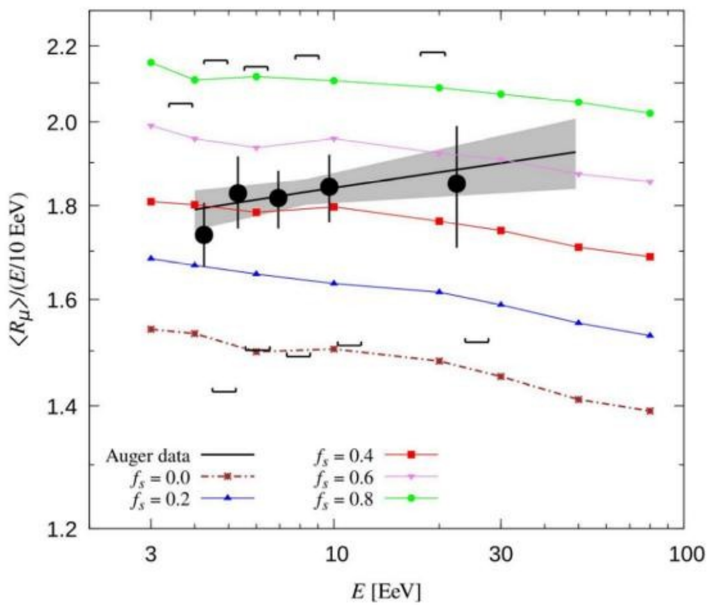
# Four variants

We test 4 scenarios:

- $S^\star(\bar{p})$ } Sibyll 2.3d
- $S^\star(\rho^0)$ } Sibyll 2.3d
- $S^\star(K^{\pm,0})$ — Kaon/strangeness enhancement
- $S^\star(\text{mix})$ — $\bar{p} + \rho^0$

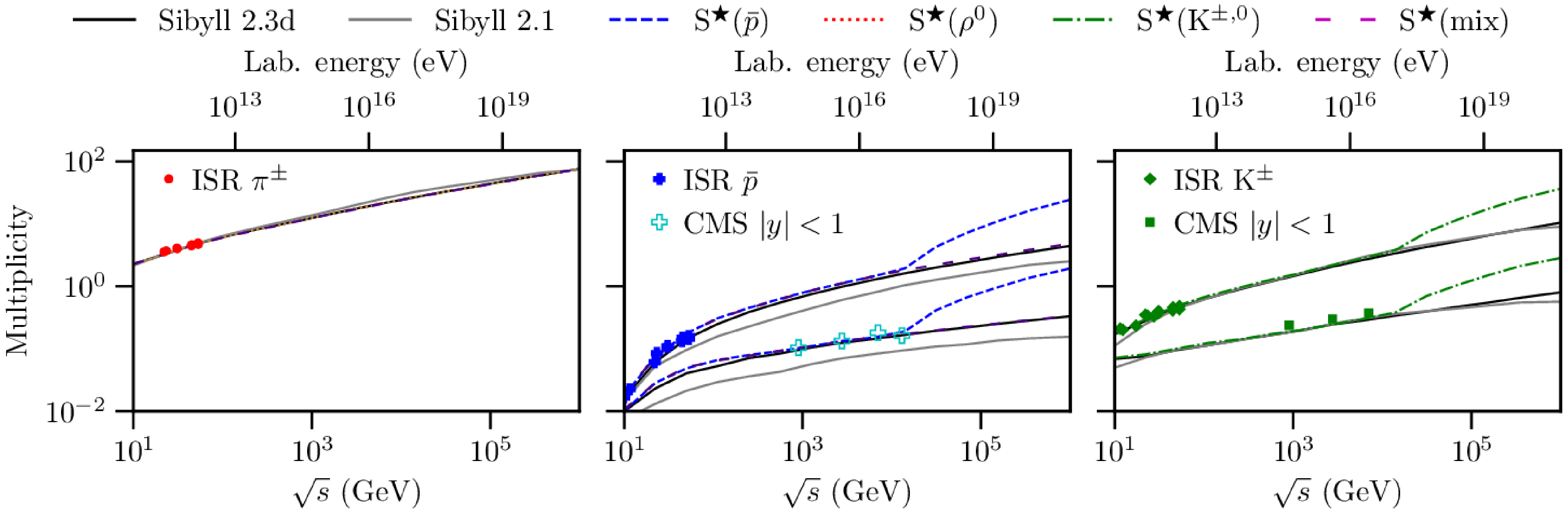
Enhancements fine-tuned

Kaon/strangeness enhancement




(Anchordoqui et al. 2017,
Manshanden 2022,
Sciutto et al. 2022,
Baur et al. 2023)

# Sibyll* variants in proton-proton

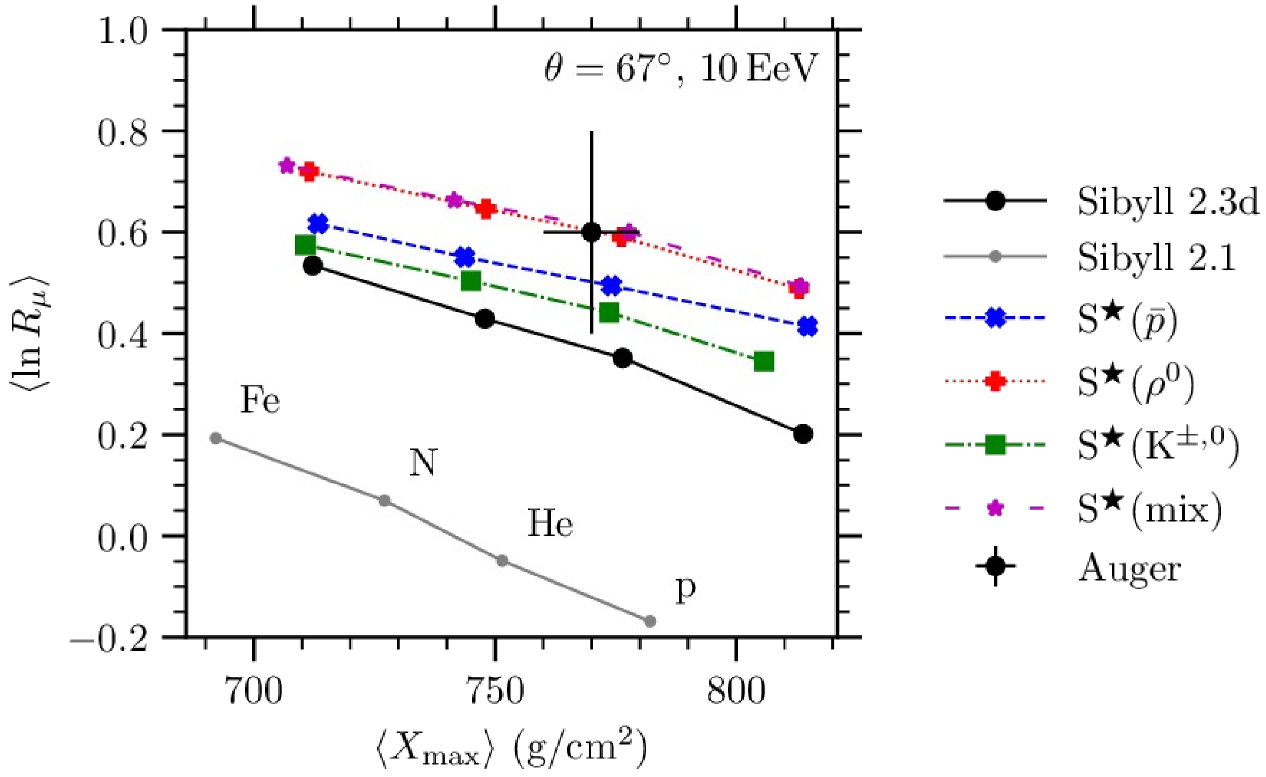


# Sibyll* vs Auger inclined

(Astropart.Phys. 160 (2024) 102964)

**YES!**

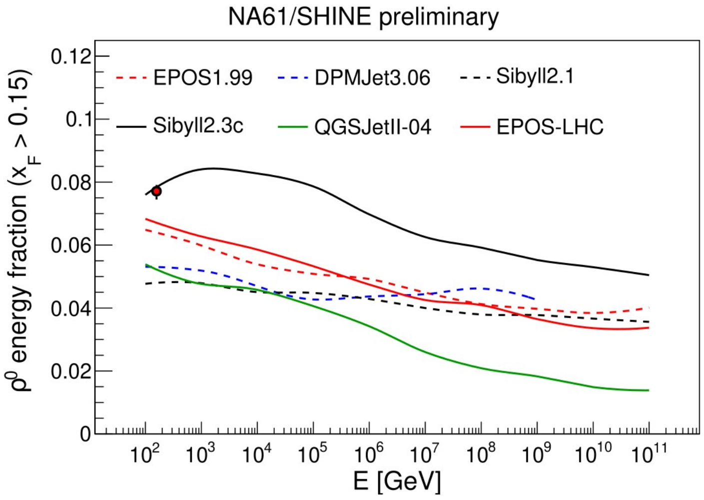
Finally sufficient muons

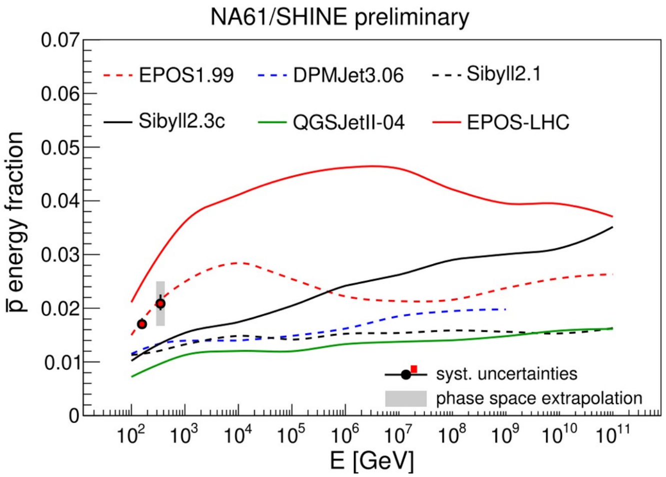



Preliminary studies suggest Sibyll* also works for machine learning

# More measurements needed

$\pi C$



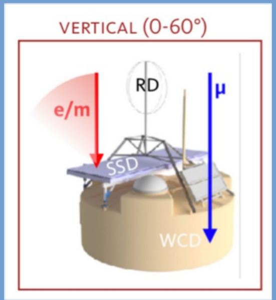

* baryon / rho0 production still uncertain !
solely based on NA49-pp and pC, NA22-pip and NA61-piC at ~20GeV

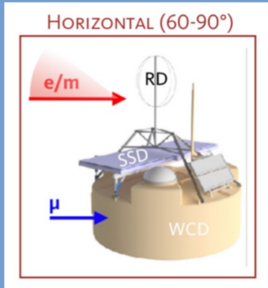
* LHCb – pO measurements at 110 GeV (SMOG)
and 9 TeV much desired to constrain baryon production.

* precision needed (in exp. data but **mostly** in model tuning)

# Dreaming of the future

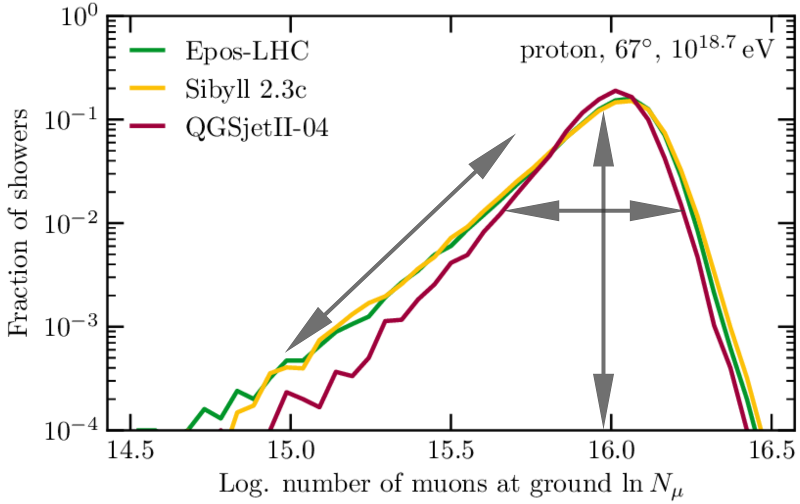
AugerPrime!

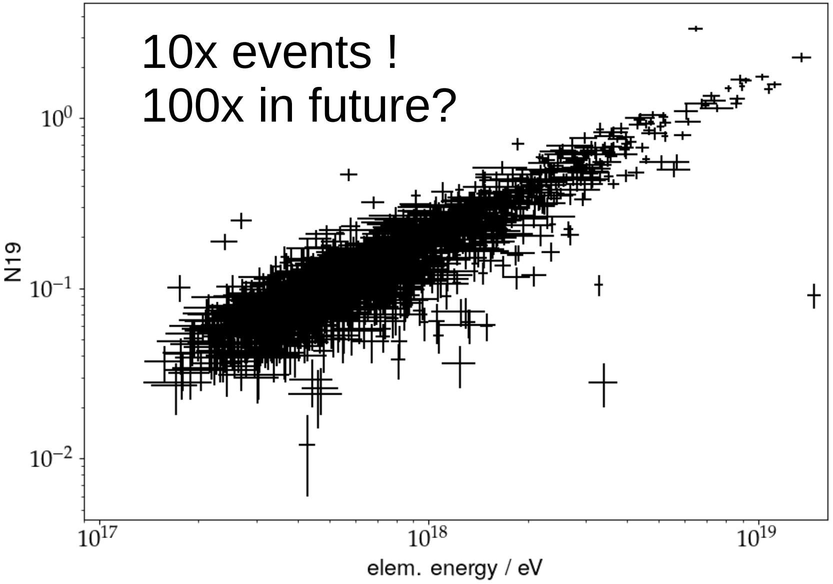



More observables!
More exposure! (Radio duty cycle → ~100%)
Better reconstructions (after muon puzzle)

Interaction physics is in the fluctuations !



# Summary

* air showers sensitive to hadronic interactions beyond LHC range

* muon puzzle

  - linked to details of hadronic interactions, unlikely new physics at UHE

  - introduces large/unknown systematic all terrestrial astroparticle experiments

* inclusive muon flux probes charm production in nuclear interactions

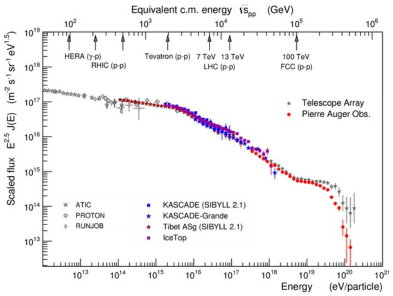
* LHCb best detector to help resolve muon puzzle through pO measurements

* AugerPrime will enhance sensitivity to UHE hadronic interactions

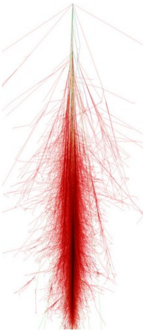
* after muon puzzle is resolved → probe 100TeV center-of-mass interactions

# Inclusive atmospheric flux

$$\Phi_\mu = \int$$




$$\times$$



$$\mathrm{d}E$$

Muons in single EAS: Nmu ~ E, mostly GeV-muons, at 10**19eV Nmu ~ O(100M)

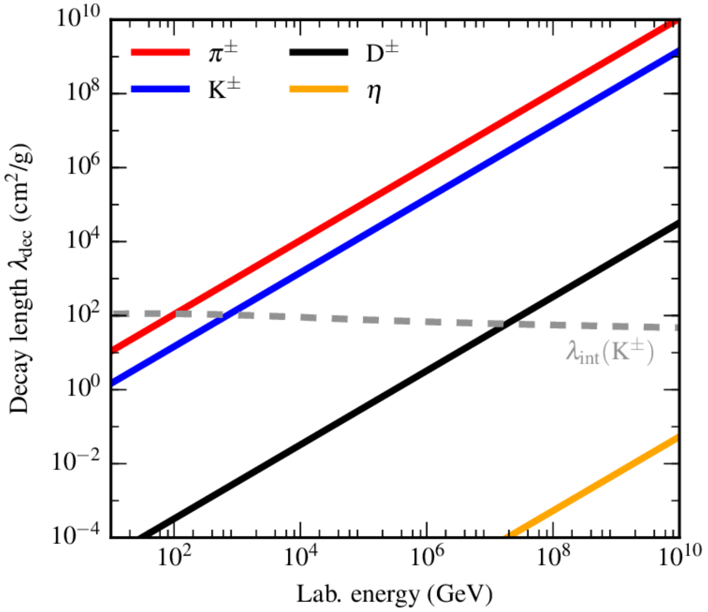
**But**

CR spectrum: ~E**-2.7..3

→ inclusive flux of muons (neutrinos) is dominated by first interaction!

→ flux of PeV muons (IceCube)→ ~10 PeV CR interactions == LHC energies

# PeV muons




..are decay product of…

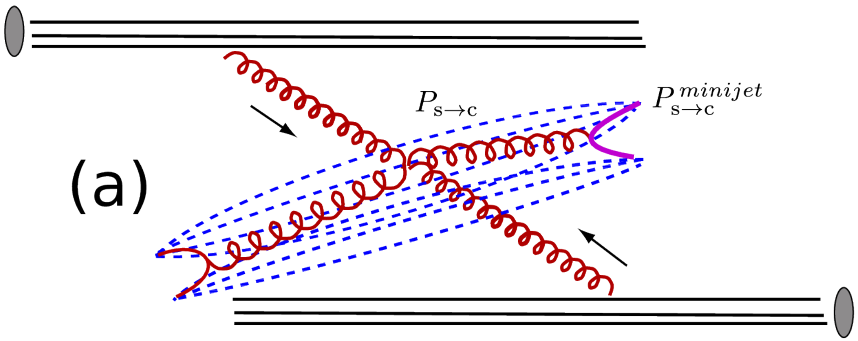
charmed hadrons !

PeV Kaons and Pions all interact !

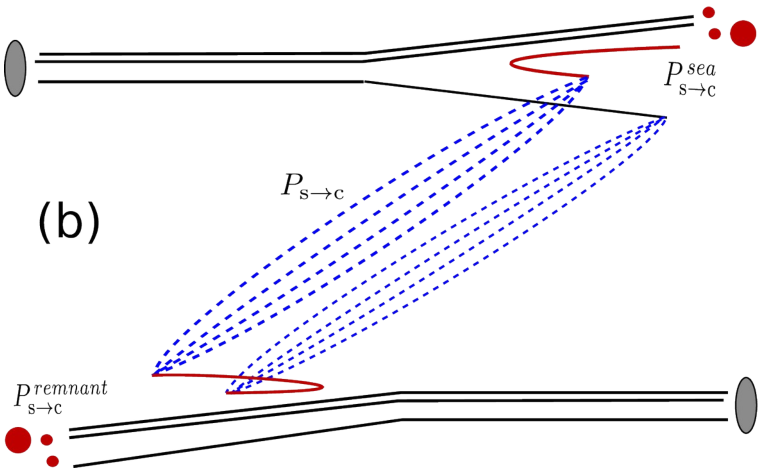
# Charm production in SIBYLL

Purely phenomenological!

$$m_c \approx 2\,\mathrm{GeV} \rightarrow \mathrm{pQCD} \rightarrow \mathrm{minijets}$$



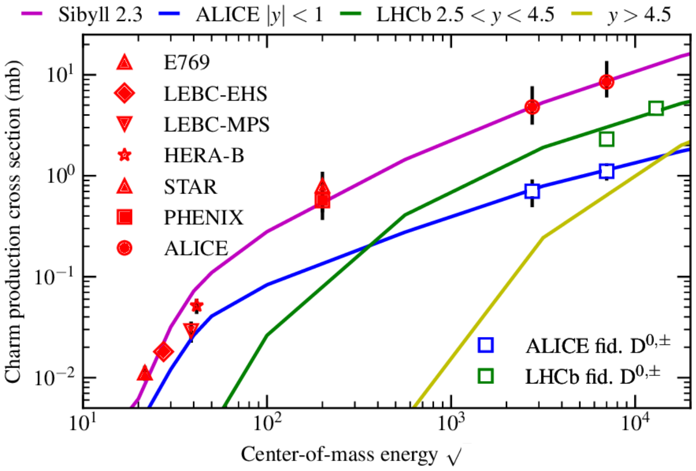

leading, soft charm
intrinsic

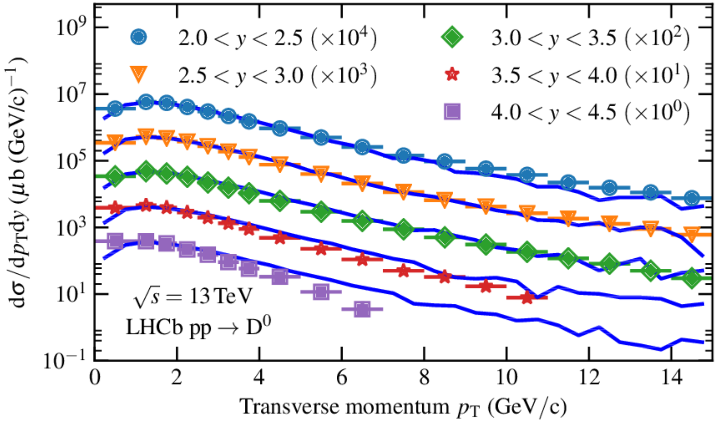



Mechanism:
Replace strange → charm

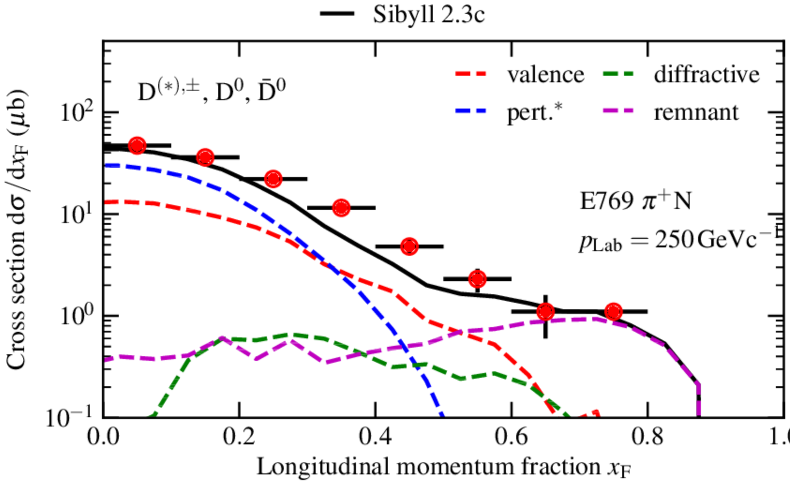
$$P_{s\to c}$$

# Charm tuning

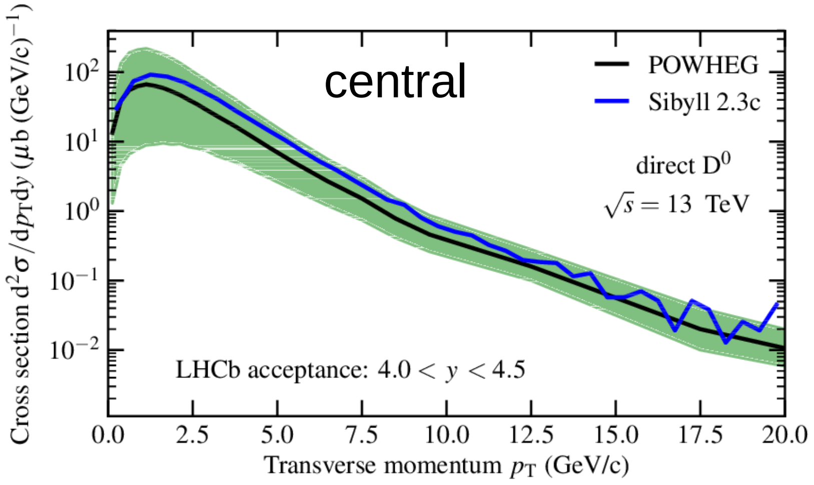


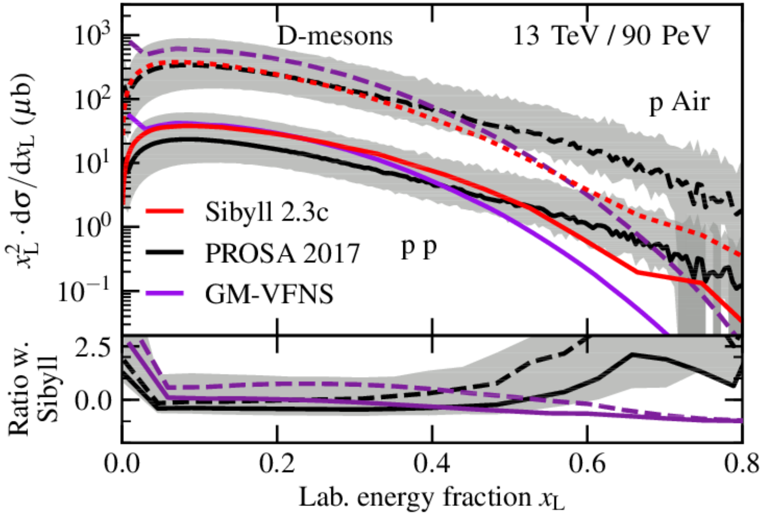

| parameter | value |
|---|---|
| perturbative | |
| $P^{\text{minijet}}_{s\to c}$ | 0.08 |
| non-perturbative | |
| $P^{\text{soft}}_{s\to c}$ | 0.004 |
| $P^{\text{sea}}_{s\to c}$ | 0.002 |
| $P^{\text{remnant}}_{s\to c}$ | 0.0 |
| $P^{\text{string}}_{s\to c}$ | 0.004 |



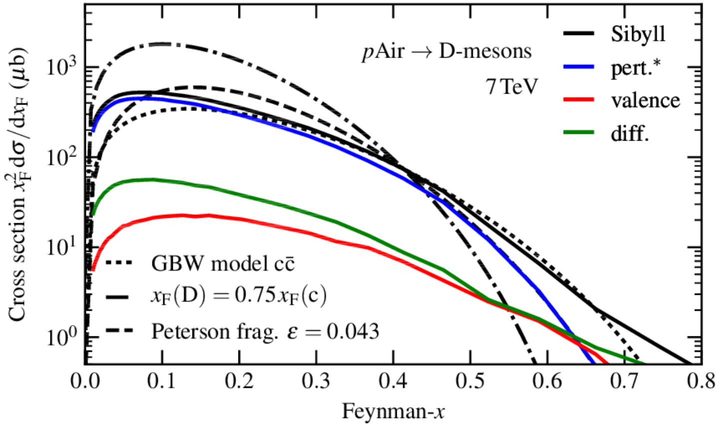
# SIBYLL vs. the rest



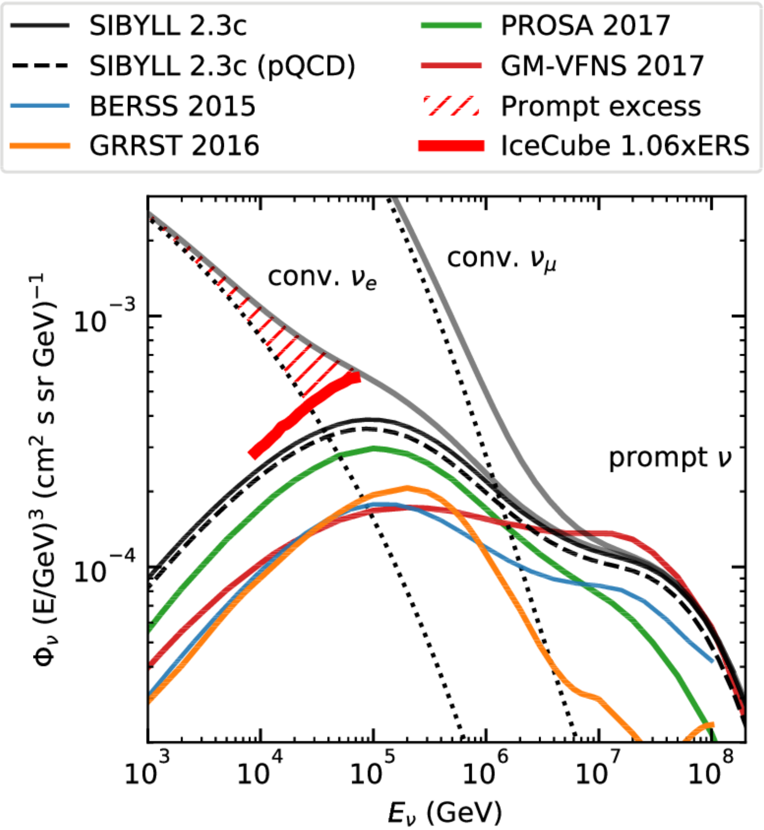

NLO QCD




(with M.V. Garzelli)



# Atmospheric lepton fluxes



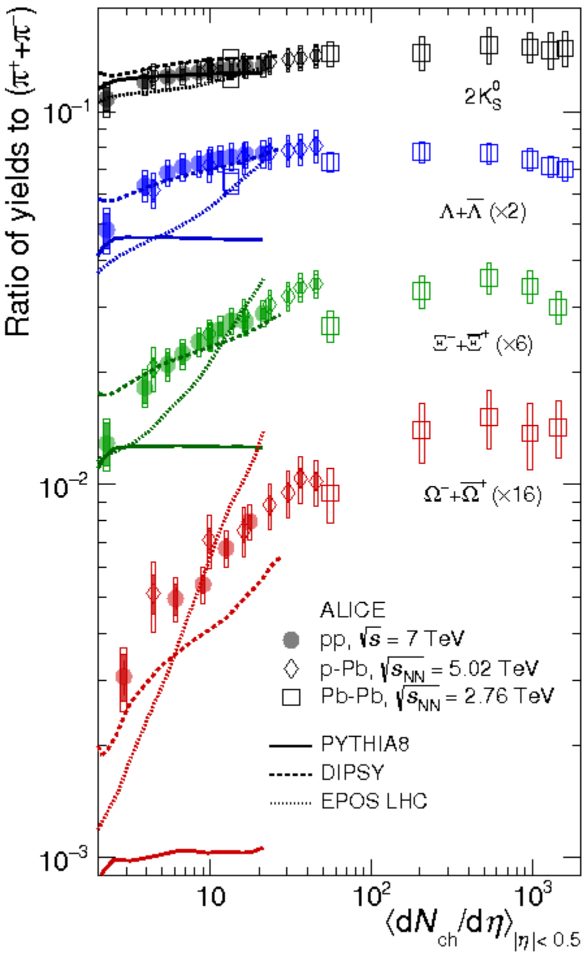

(MCEq, reference)

* Rich variety of model predictions

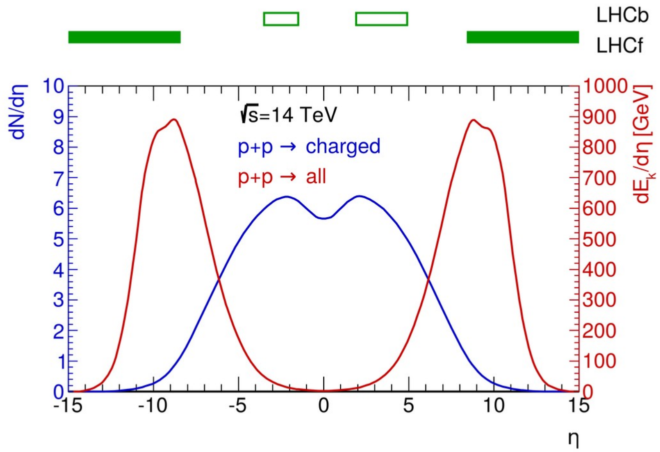
Again:

Input from LHCb crucial for transition
pp → pO
Charm prod == pQCD
Nuclear modification of PDFs ?
→ large effect at large xF

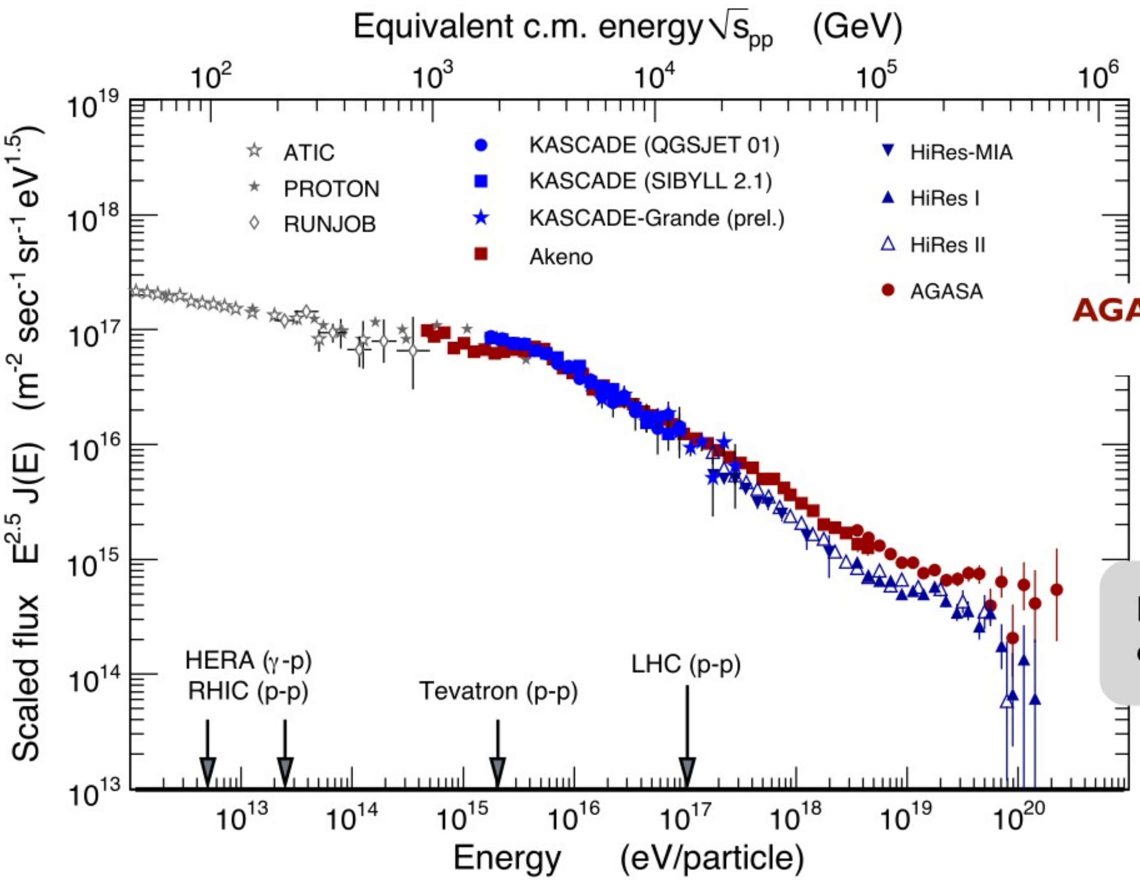
# More measurements: strangeness enhancement




* already in pp enhancement of strange production
* same behavior as pPb and PbPb
→ large parton density ?
* confirmation from LHCb at large(r) xF?
* confirmation in pO? At lower energy?



# UHECRs before the Pierre Auger Observatory




**AGASA:** particles at ground (scintillator array)

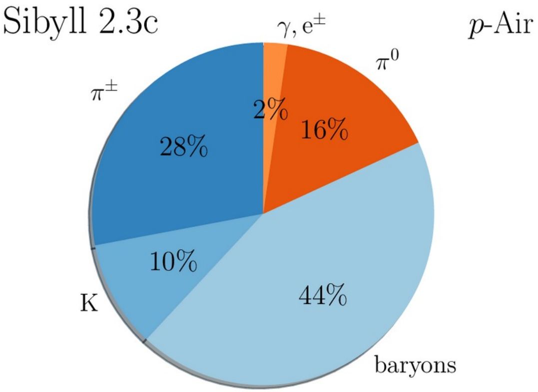
**Does the GZK effect exist ?**

**HiRes Fly´s Eye:** longitudinal shower profile (fluorescence telescopes)

# Distinguish: standard/exotic

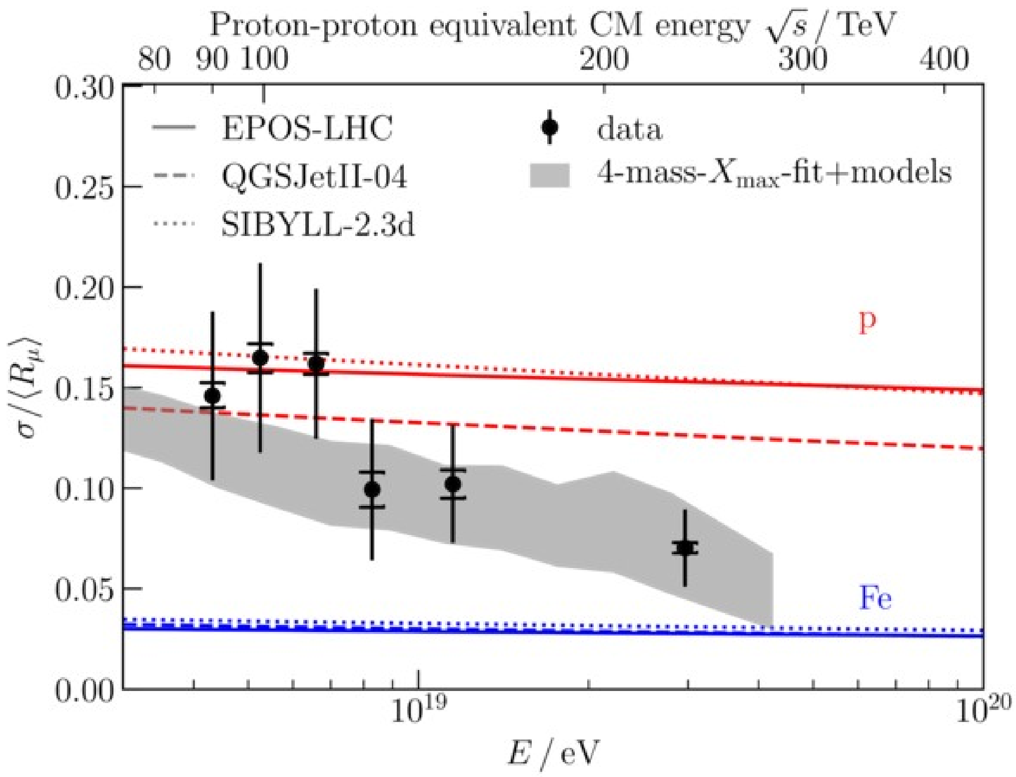
Fluctuations!

Energypartition




*"fluctuations are dominated by the 1$^{st}$ interaction"*

# Muon fluctuations




**4-mass-Xmax-fit:**

**Ansatz:** 4 different primaries

**Take:** Xmax measurements, Sibyll model

Example at 10**19eV:

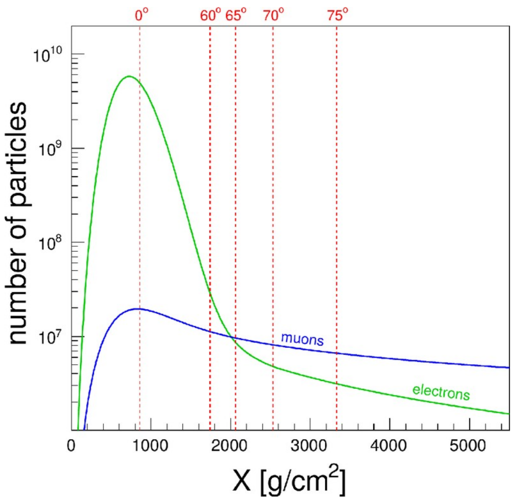
| | |
|---|---|
| 0% | iron |
| 60% | nitrogen |
| 37% | helium |
| 3% | proton |

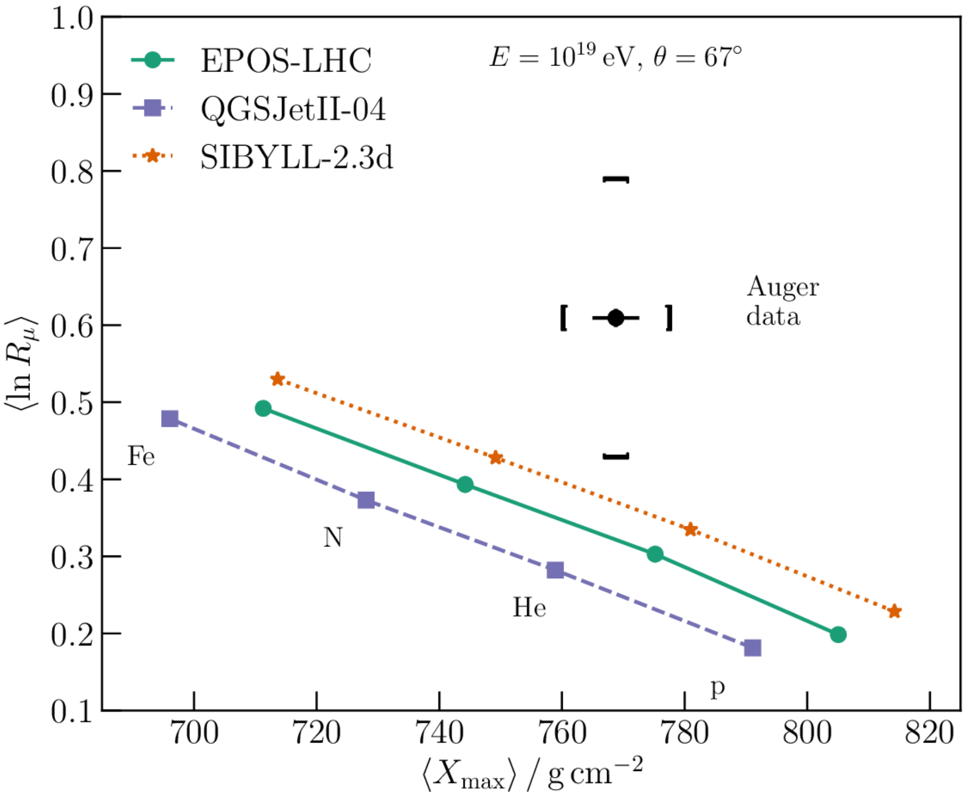
→ fluctuations consistent !

# Measurement of muon content

(H. Dembinski, Auger 2015)

Hybrid (energy + Xmax)
+
inclined (surface signal → muons)

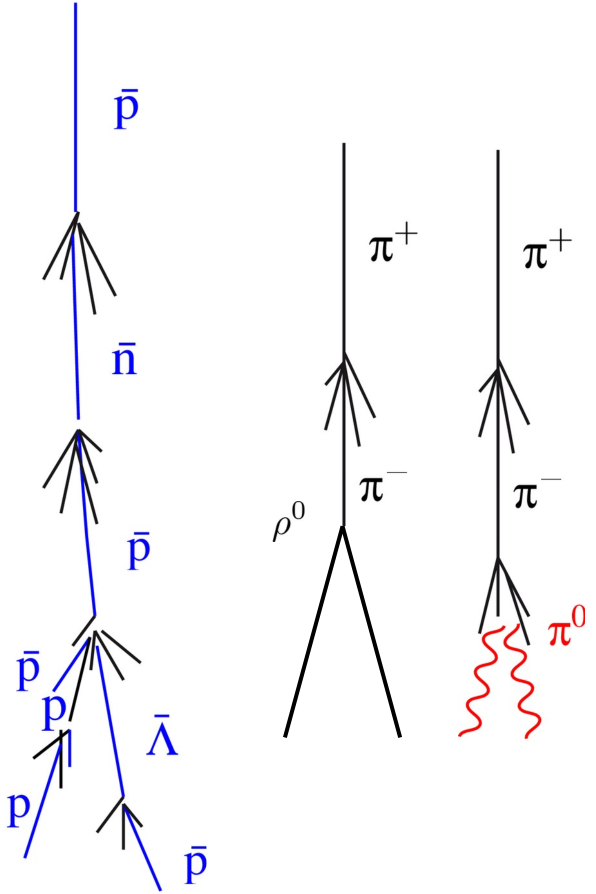


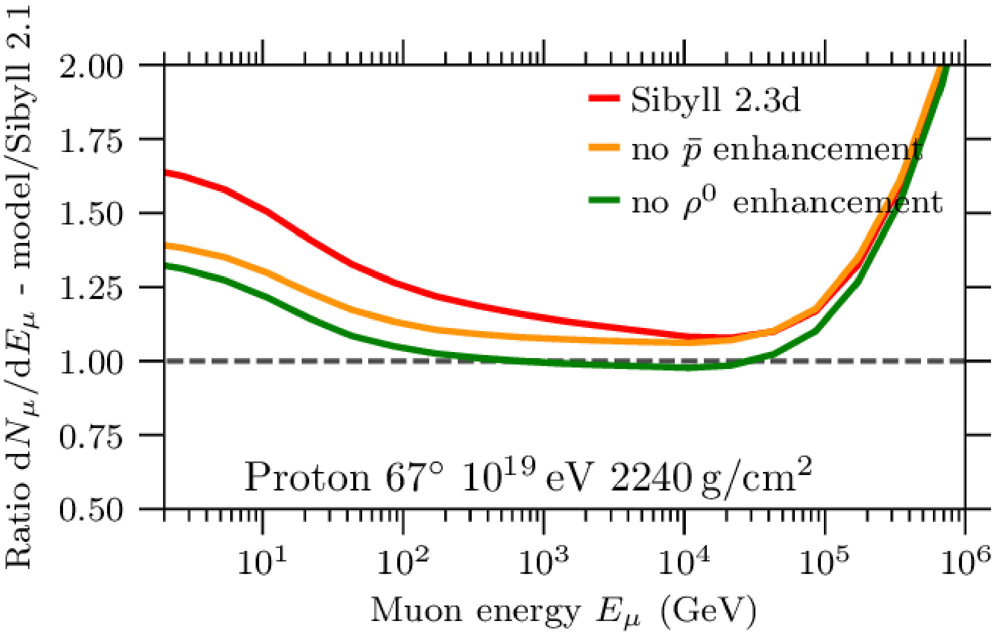




Seen in many experiments !
see review by Dembinski et al. (Astrophys. Space. Sci. 367, 27 (2022)))

**Muon puzzle!**

# Muon energy spectrum

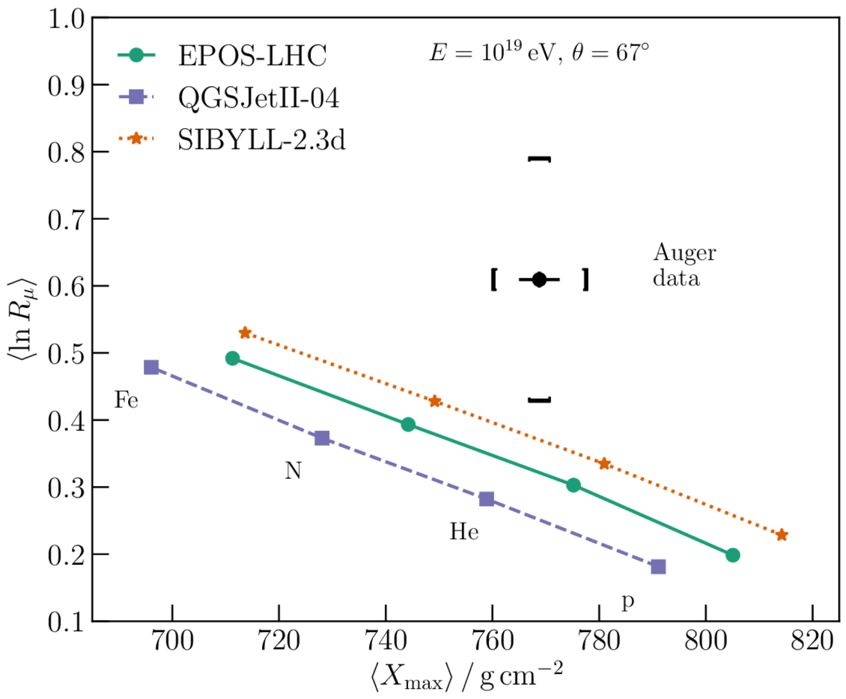


# Measurement of muon content

**2) Standard physics** scenario

- baryon production ✅
- rho0 production ✅
- enhanced strangeness (QGP) ?



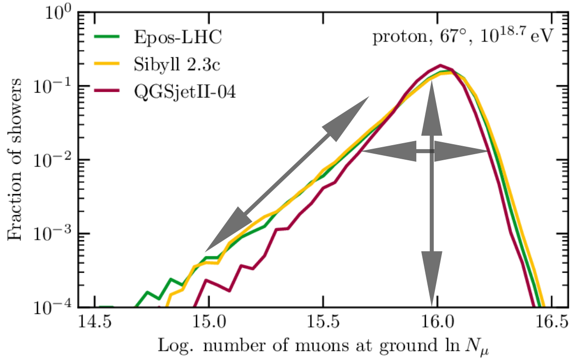

**Muon puzzle!**

*"Xmax- and muon-based observables of extensive air showers when compared with simulations give inconsistent interpretations for the cosmic ray mass"*

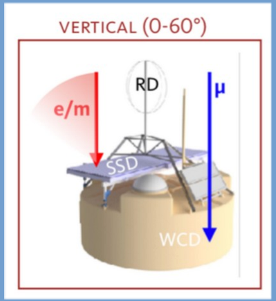
# More options for UHE interactions

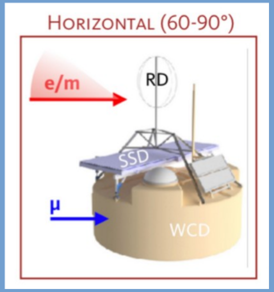
* Fluctuations! → muon distribution

tail ~ pion spectrum at large-xF




AugerPrime!




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

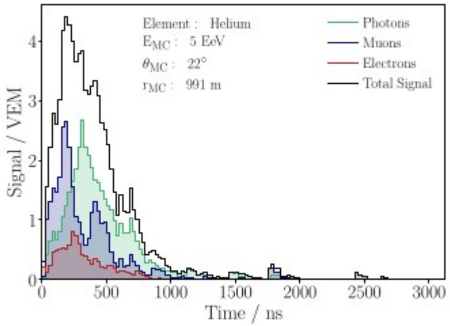
* high energy muons ! → IceCube

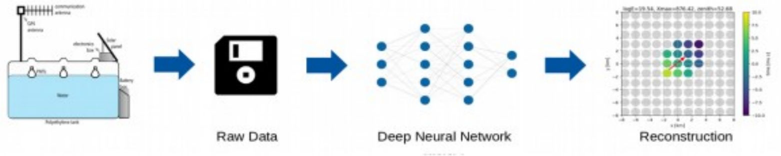
* inclusive muon and neutrino flux!

# Discrepancy is limiting factor in many applications

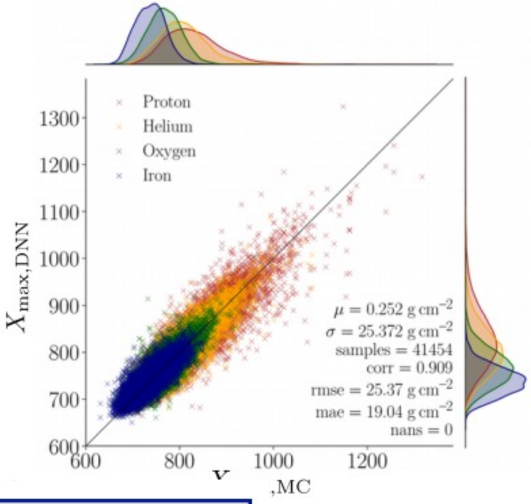
**One example:**

## Training of DNN with MC simulations

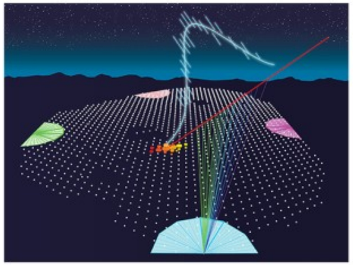


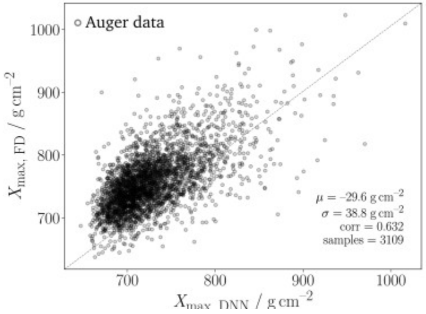




(Auger, JINST 16 (2021) 07, P07019)

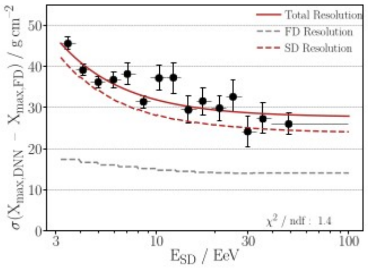


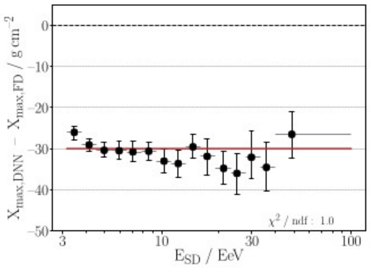

## Reconstructing Xmax: ultimate check with data



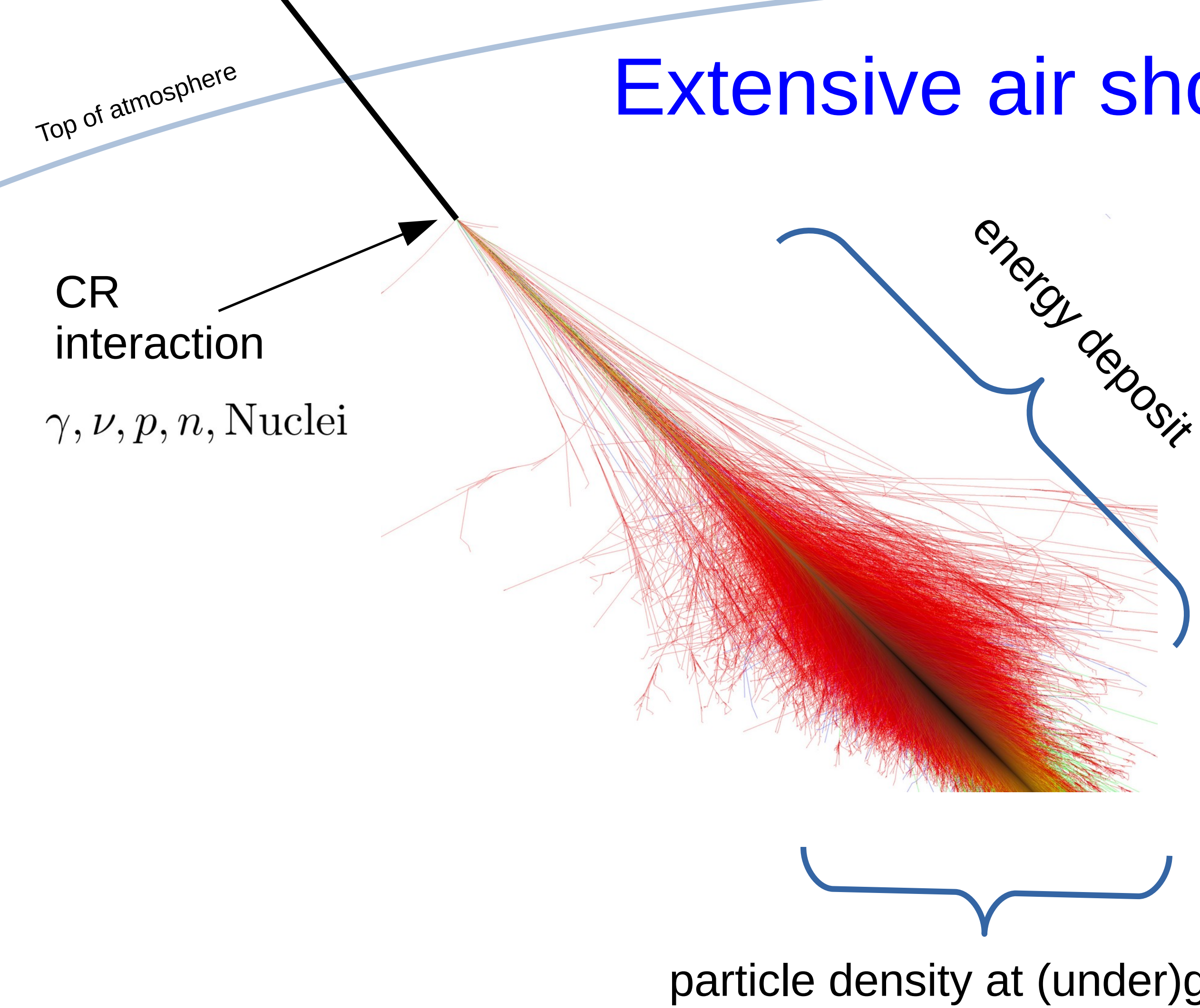



**Very good resolution, unexpected offset of ~30 g/cm²**



# Extensive air showers




Extensive air shower:

* $\gamma, e^{\pm}$
* $\mu^{\pm}$
* hadrons