Hadronic interactions and the muon excess

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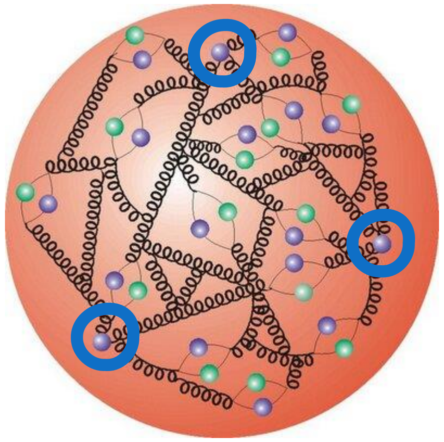
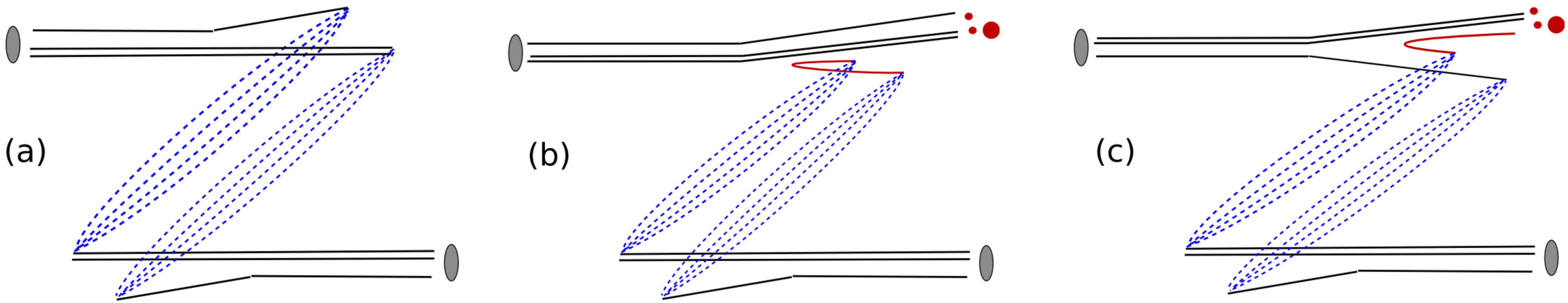
Hadronic interactions

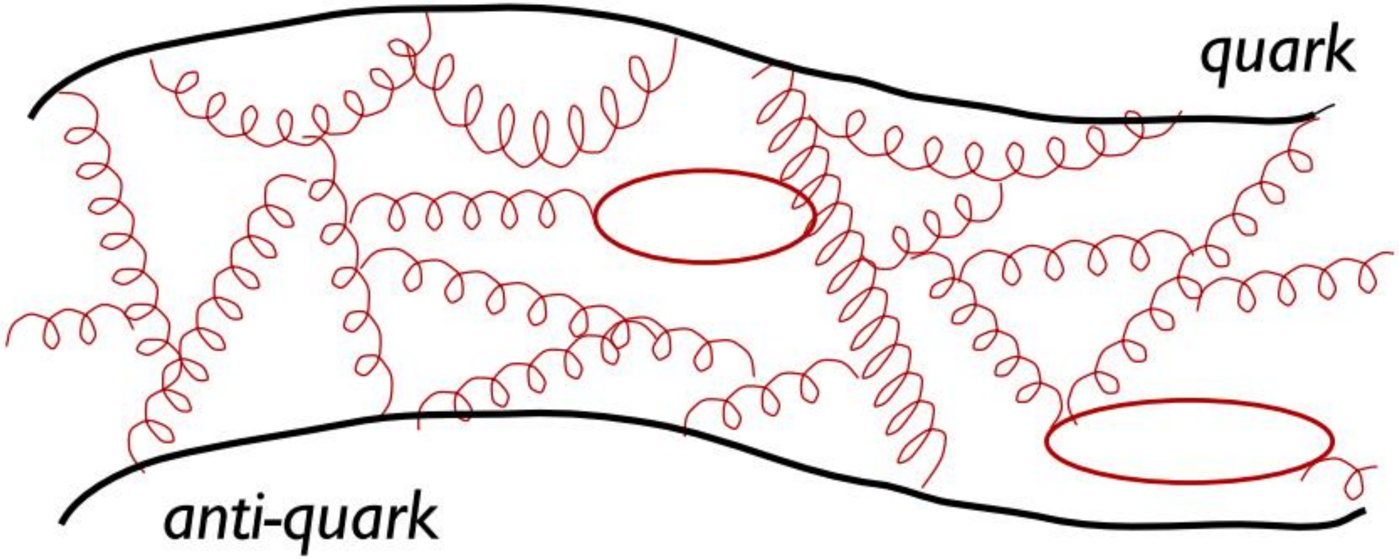


- **Challenges:**
  - Valence quarks (persistent, not localizable)
  - Confinement
  - Color field fluctuations (sea quark loops)
  - Perceivable sub-structure depends on type of probe
  - …and size of probe (scale)
  - …and energy (time scale)



F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300

Daily life of a meson

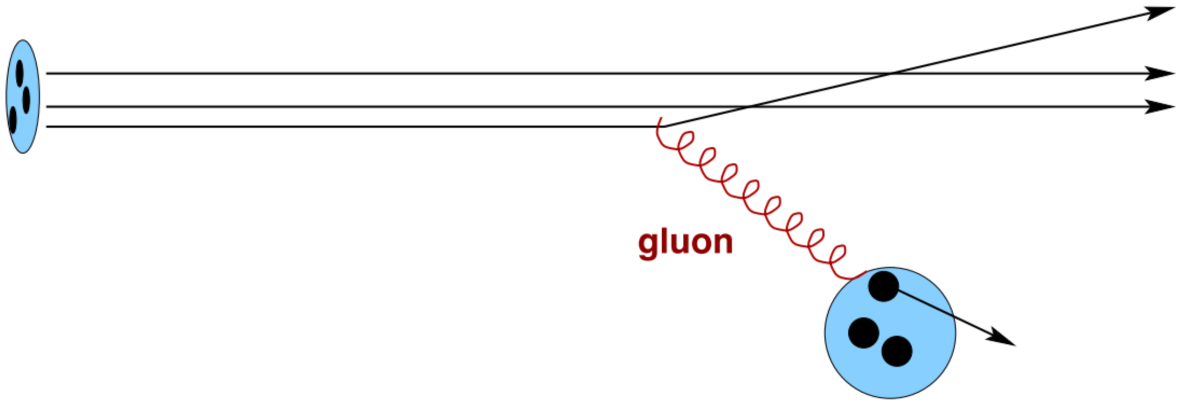


Partons (=quark or gluon) only asymptotically free

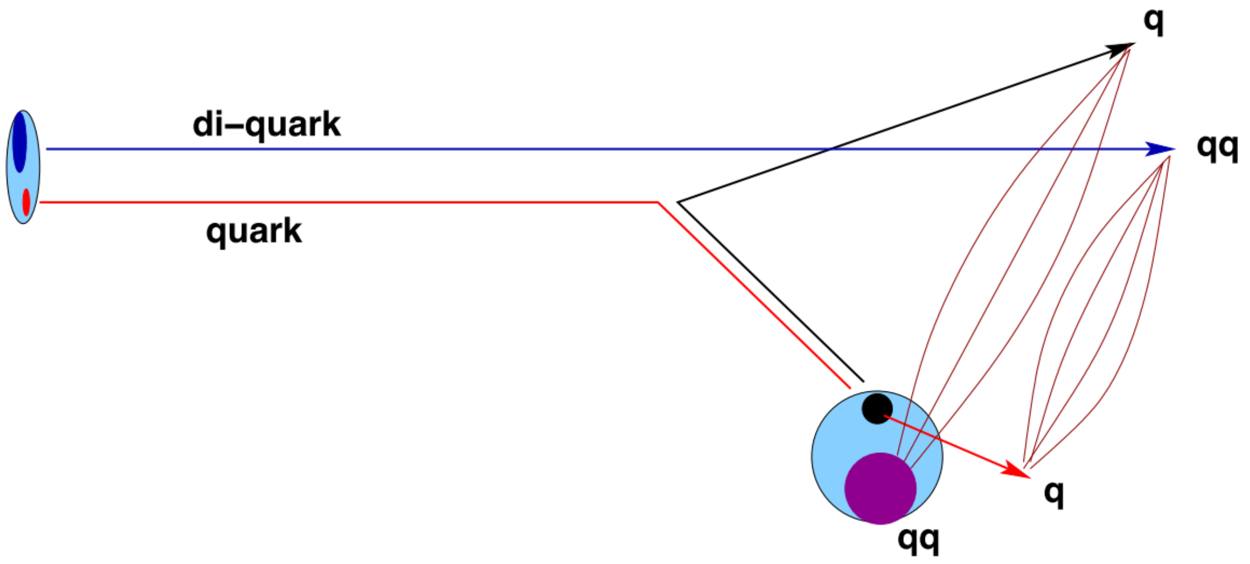
time

Color flow

Partonic view:



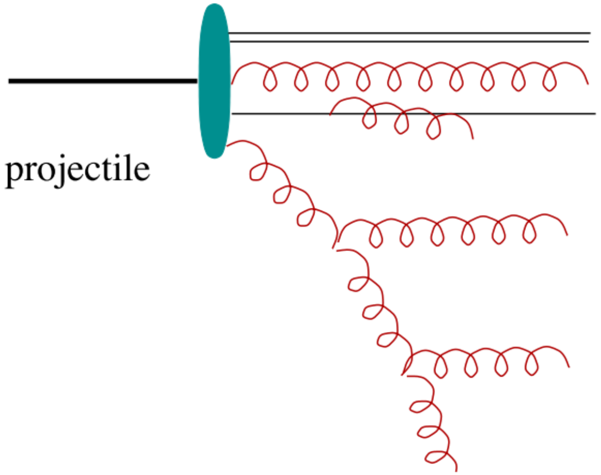
Color flow:



- Quark = color triplet (1 color)
- Gluon = color octet (2 colors)
- Colors neutralize each other forming color neutral states
- → concept of di-quark

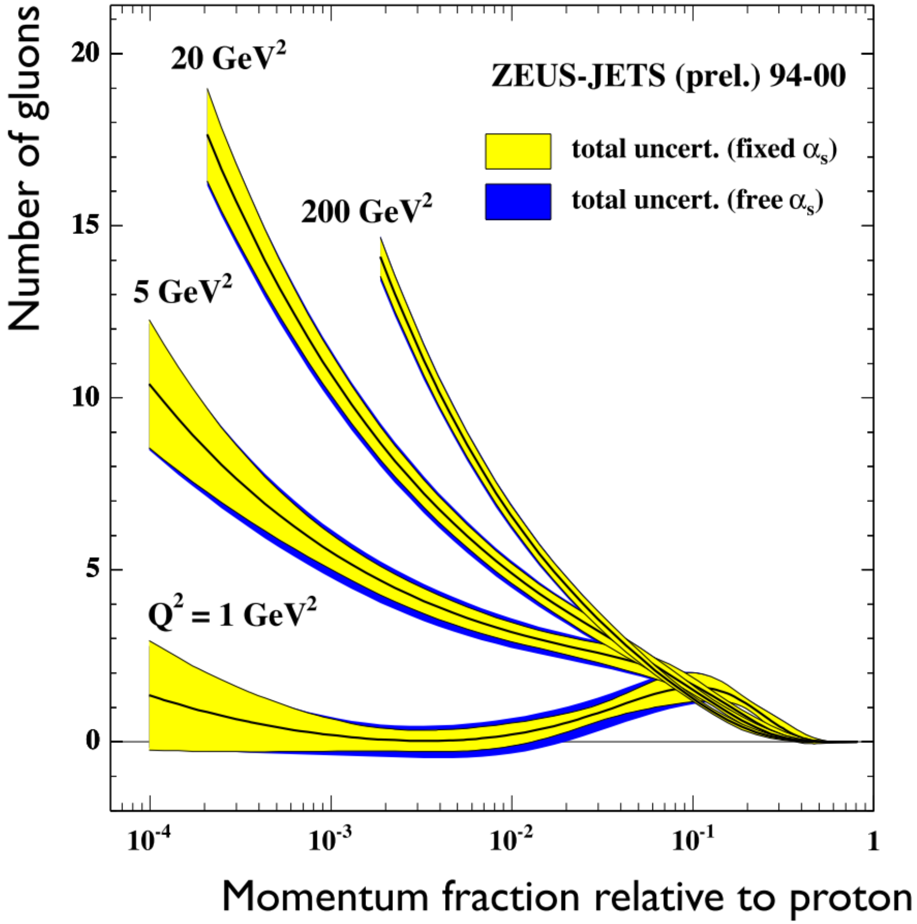
One-gluon exchange:
two color fields (strings)

Evolution of parton densities



Evolution of parton number
given by DGLAP equation
(and non-linear versions of it)

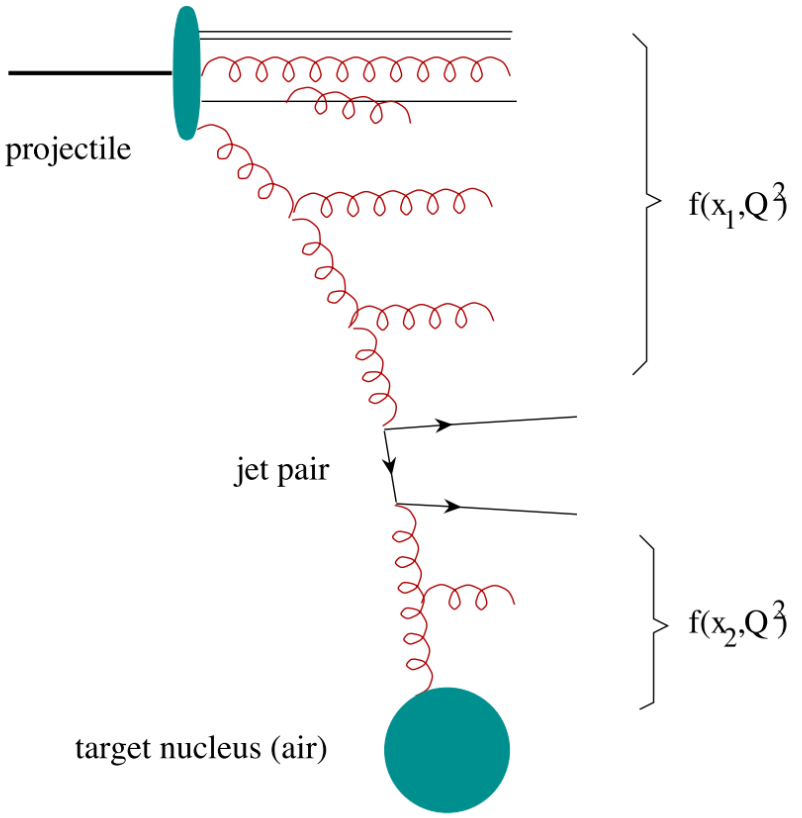
HERA data



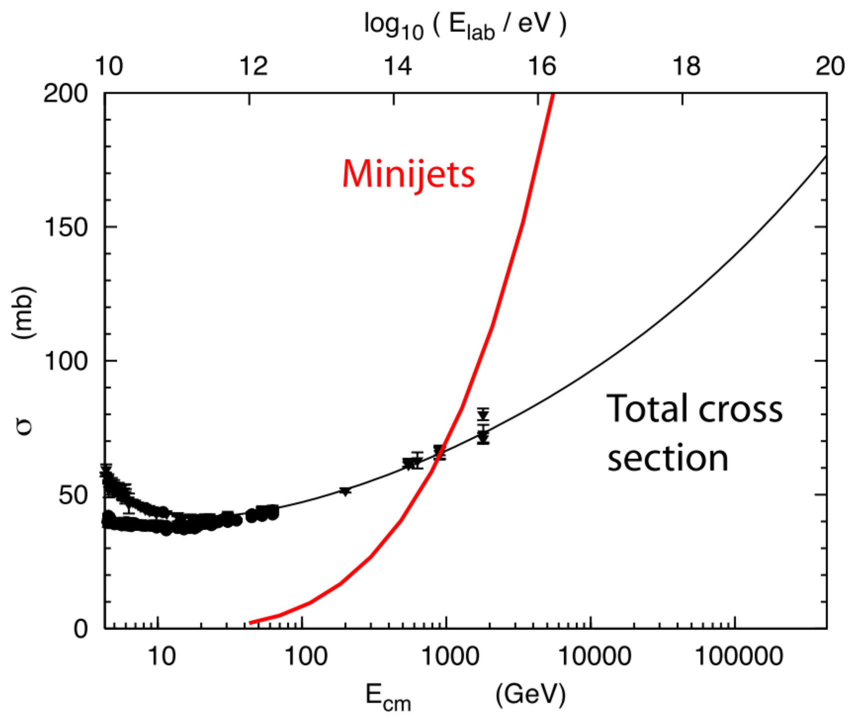
$$\frac{d f_i(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} \sum_j f_j(y,Q^2)\; P_{j\to i}\left(\frac{x}{y}\right)$$

Prediction of
perturbative QCD

(Perturbative) sub-structure of the proton



Proton-proton cross section

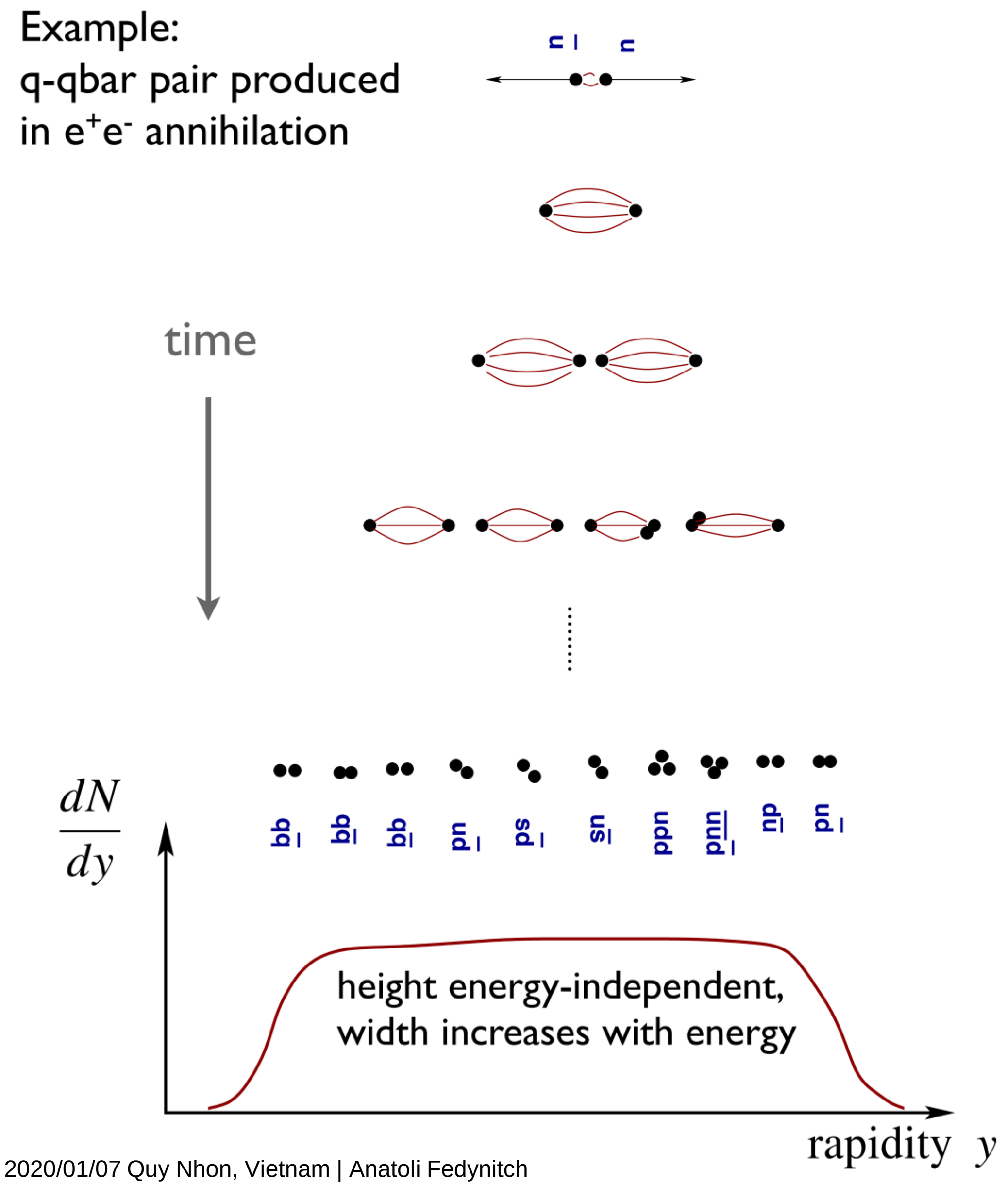


Minijet (~hard) cross section exceeding total interpreted as **multiple partonic interactions**

$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\rm cutoff}} dp_\perp^2\; f_i(x_1,Q^2)\; f_j(x_2,Q^2)\; \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

Momentum space & **collinear factorization**.
No transverse structure!

Formation of particles in string fragmentation (Lund-model)



Rapidity

$$y = \frac{1}{2} \ln \frac{E + p_{\parallel}}{E - P_{\parallel}}$$

Rapidity of massless particles

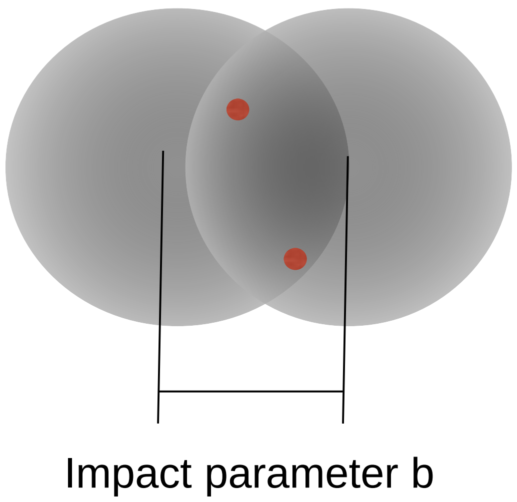
$$y = \frac{1}{2} \ln \frac{1 + \cos\theta}{1 - \cos\theta} = -\ln \tan \frac{\theta}{2}$$

Pseudorapidity

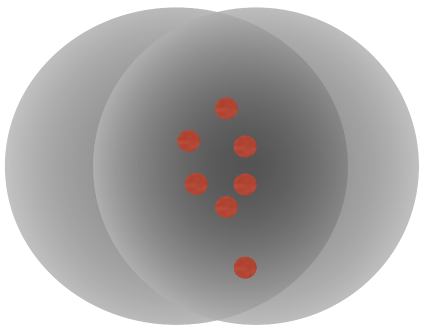
$$\eta = -\ln \tan \frac{\theta}{2}$$

High energies: Multiple partonic interactions

Low energy



High energy

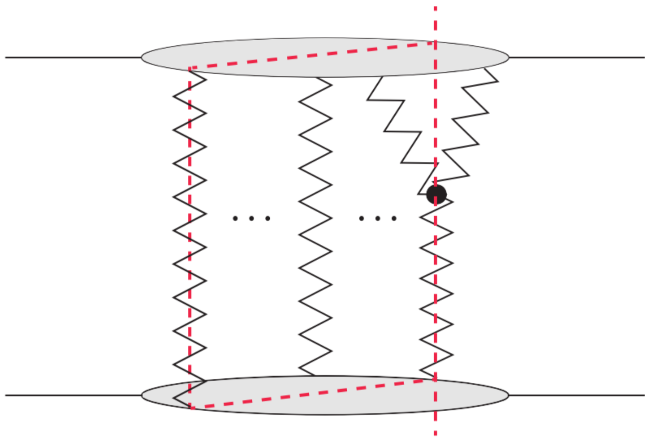


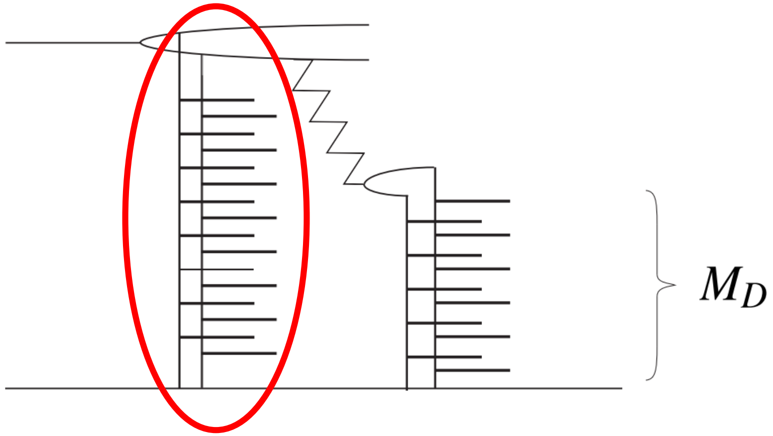
Simple MPI model:

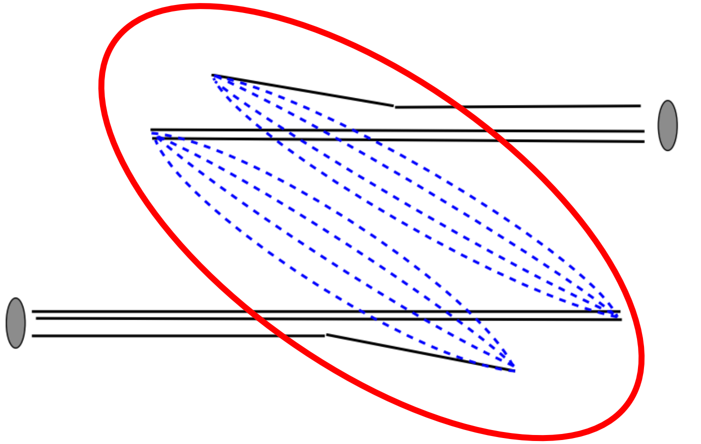
$$\sigma(n_{\mathrm{S}}, n_{\mathrm{H}}, \dots) = \int \mathrm{d}^2 \vec{B} \frac{(-2\chi_{\mathrm{S}})^{n_{\mathrm{S}}}}{n_{\mathrm{S}}!} \frac{(-2\chi_{\mathrm{H}})^{n_{\mathrm{H}}}}{n_{\mathrm{H}}!} \dots \; e^{-2\chi}$$

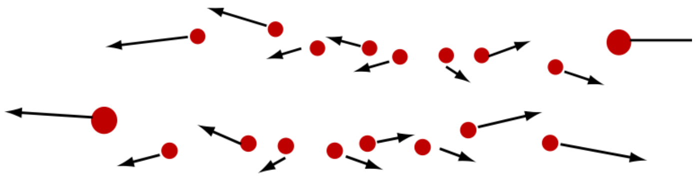
- multiple-cut structure from Eikonal expansion (“optics”)
- uncorrelated multiple interactions
- Collinear factorization not applicable due to missing transverse dependence

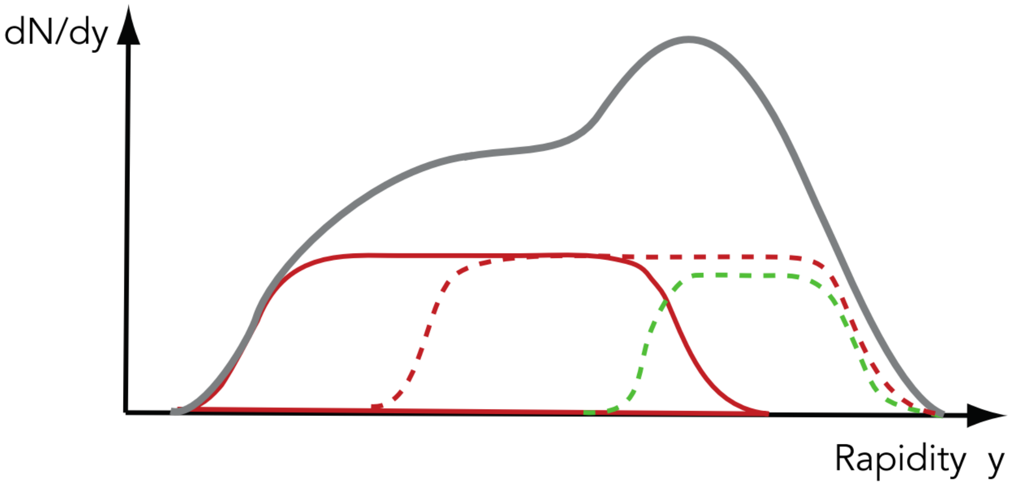
Graph cuts, strings and their signature in a detector

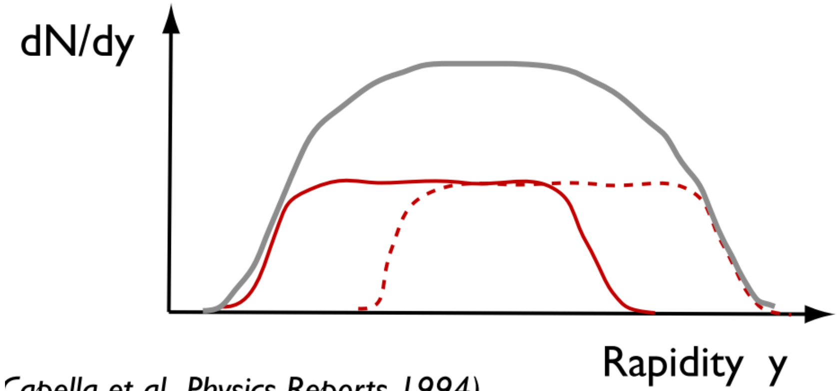






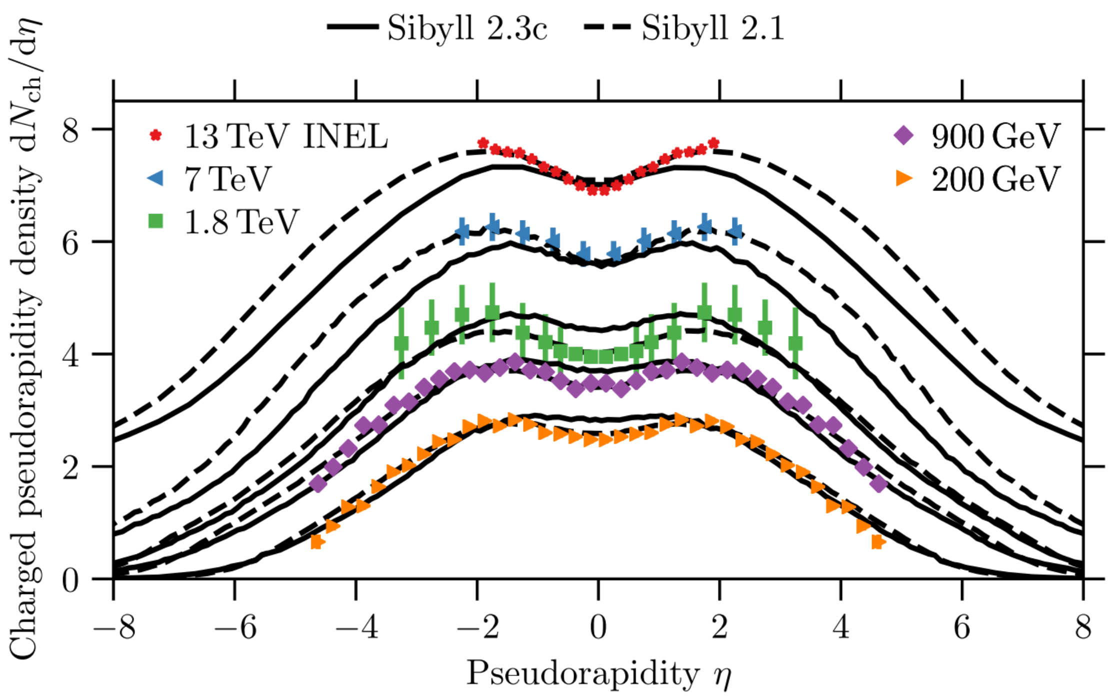


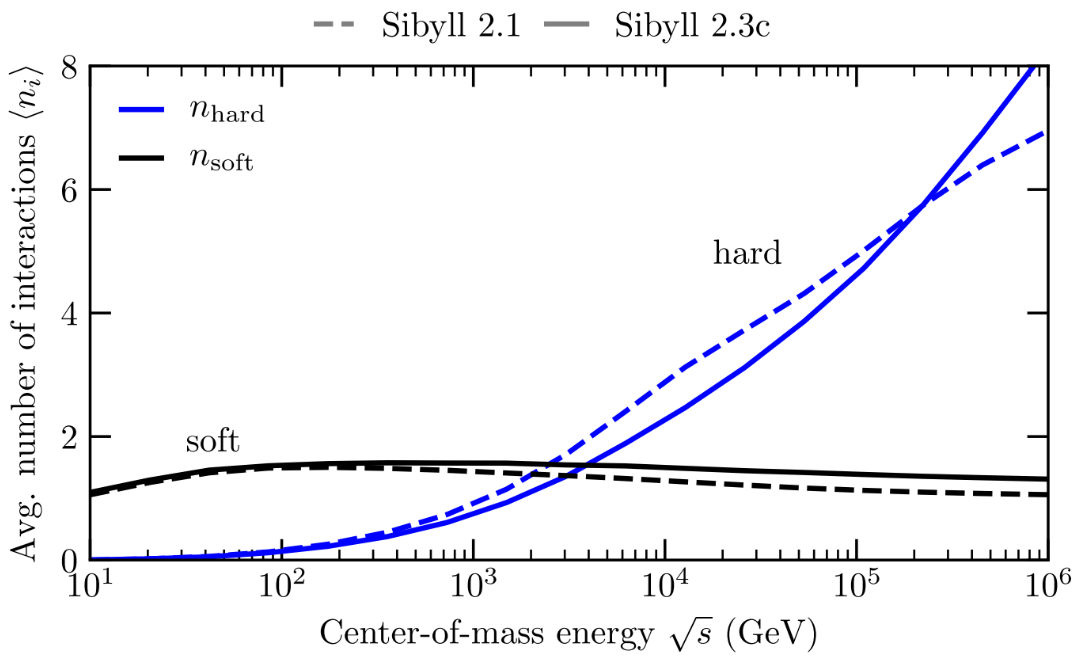




Capella et al., Physics Reports 1994)

View at collider



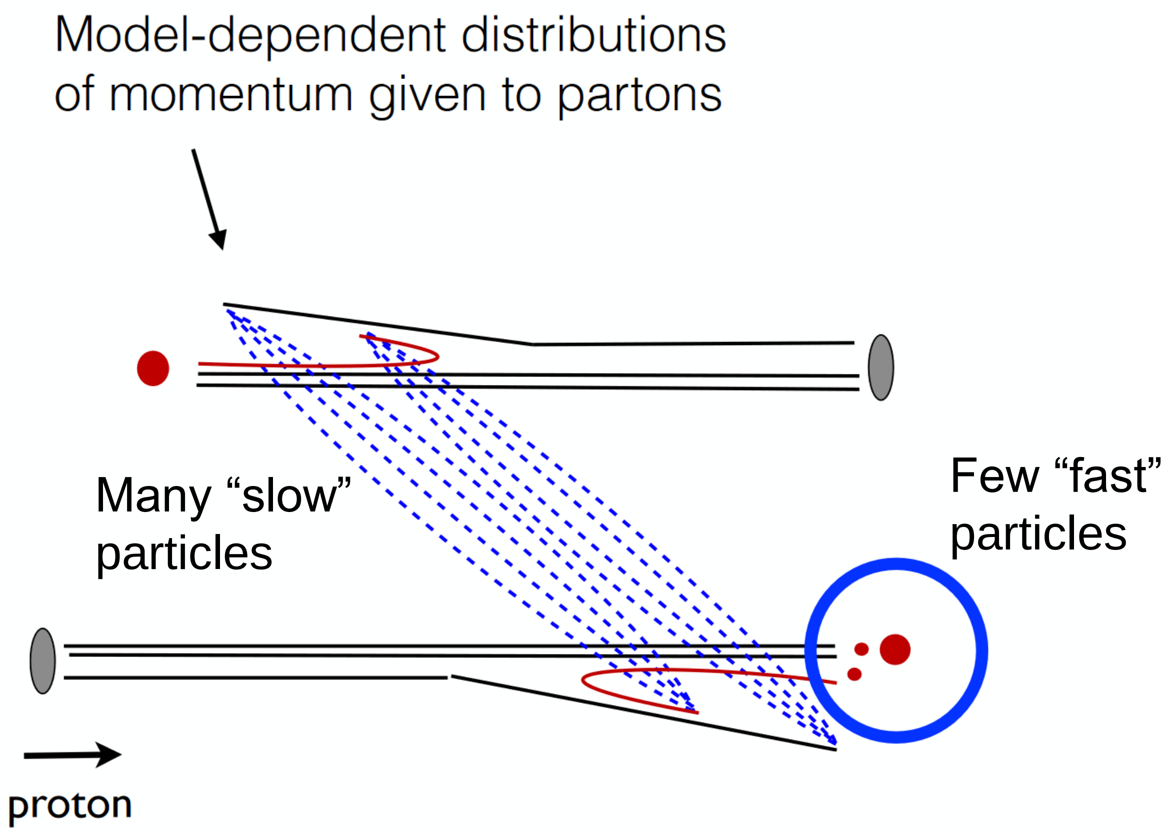


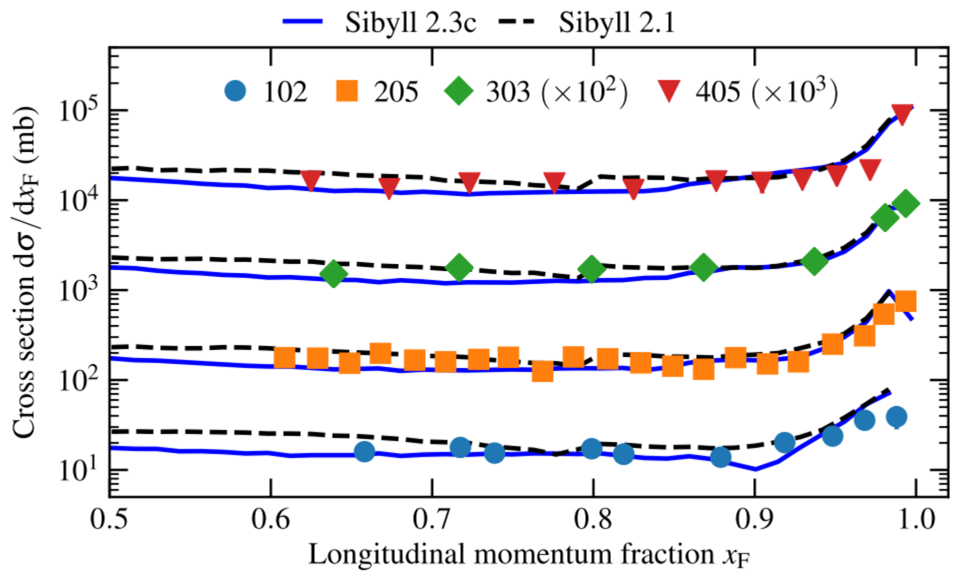
- Energy scaling:
  - Widening = growth of phase space = longer strings
  - Rise of the central plateau = MPI
- $n_{MPI} \sim n_{soft} + n_{hard} + n_{semihard} + \ldots$
- Also diffractive topologies

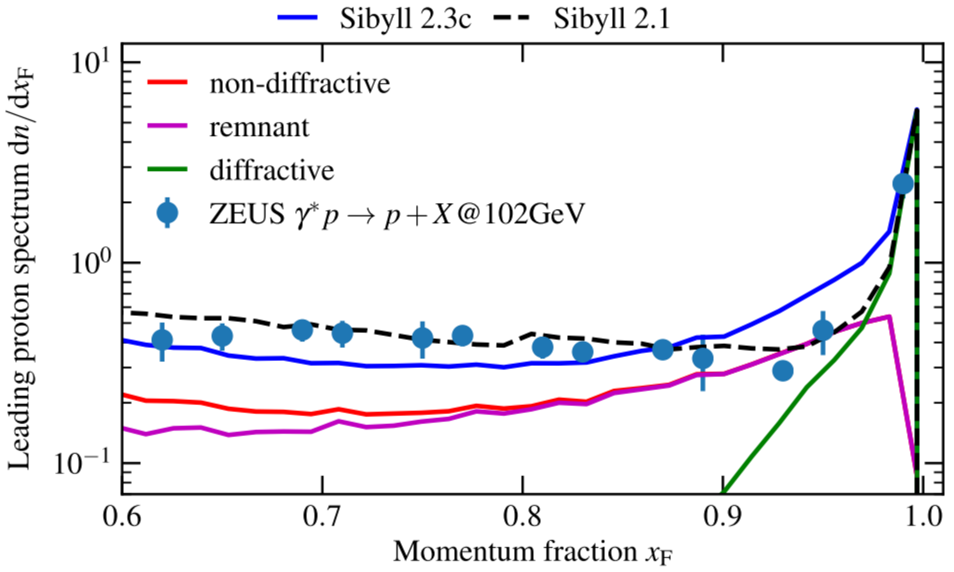
F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300

Leading particle effect

F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300



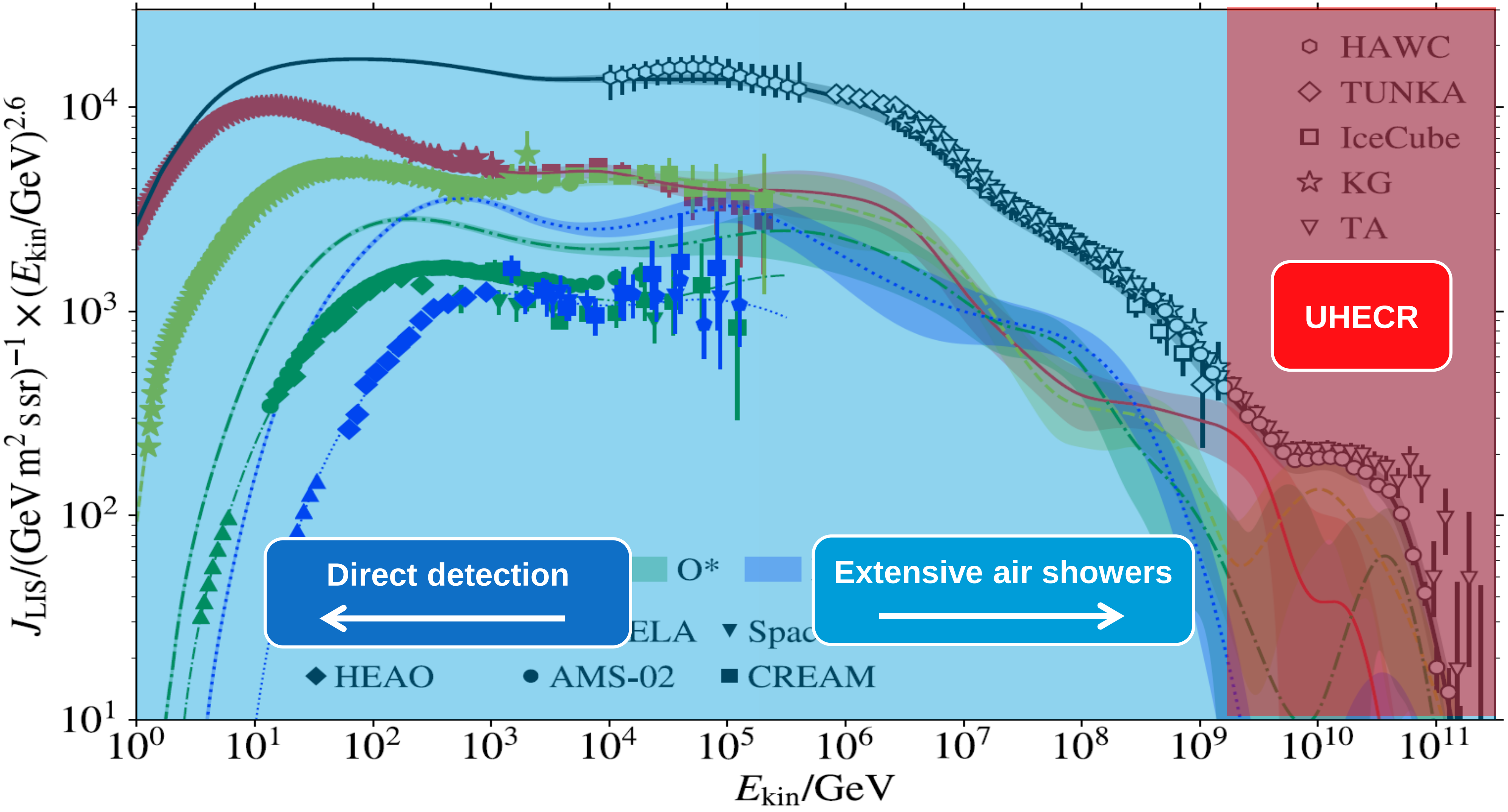




Crucial to describe energy transfer in particle cascades (air showers)

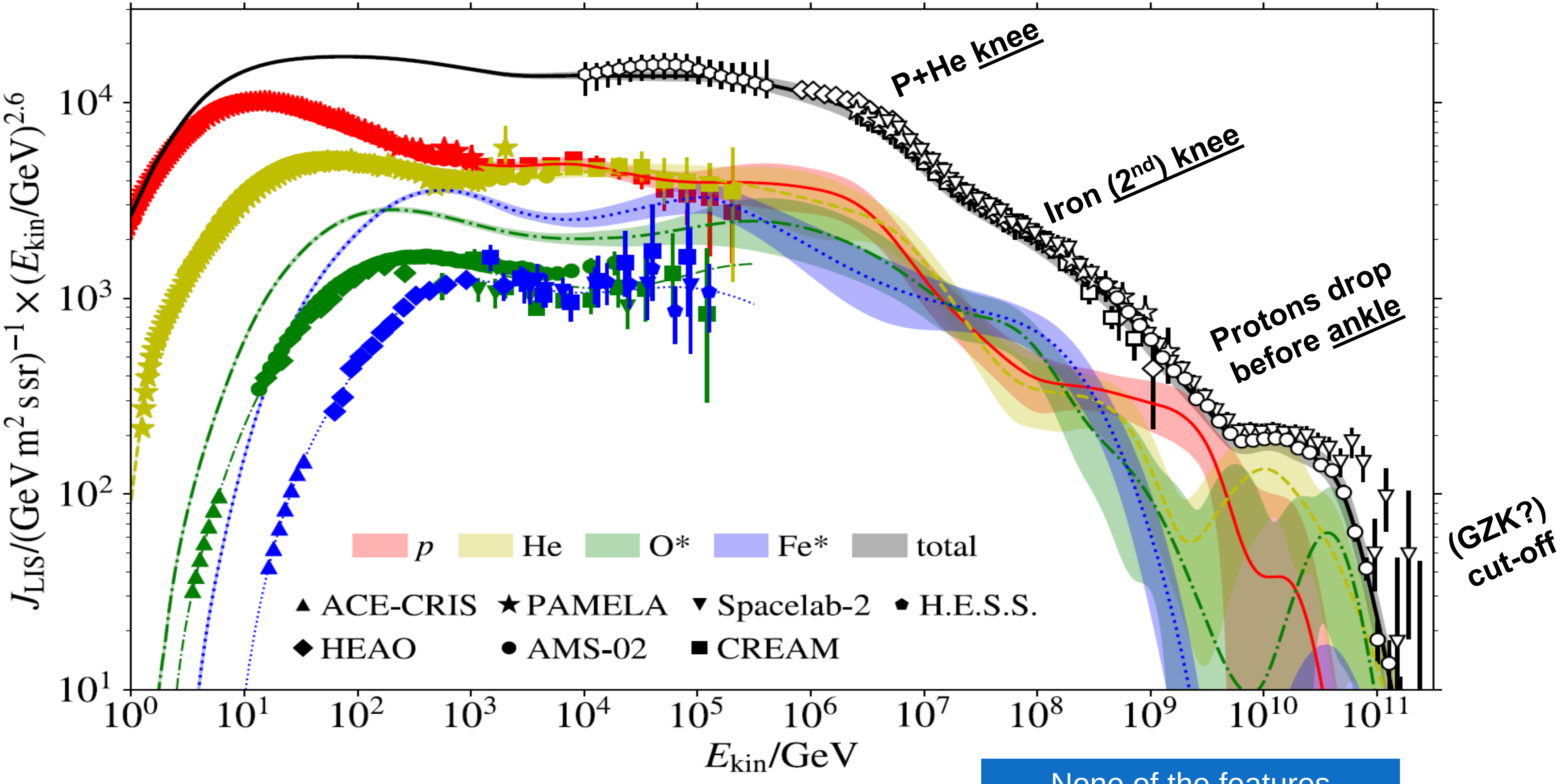
Cosmic Ray observations

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533



Cosmic Ray observations

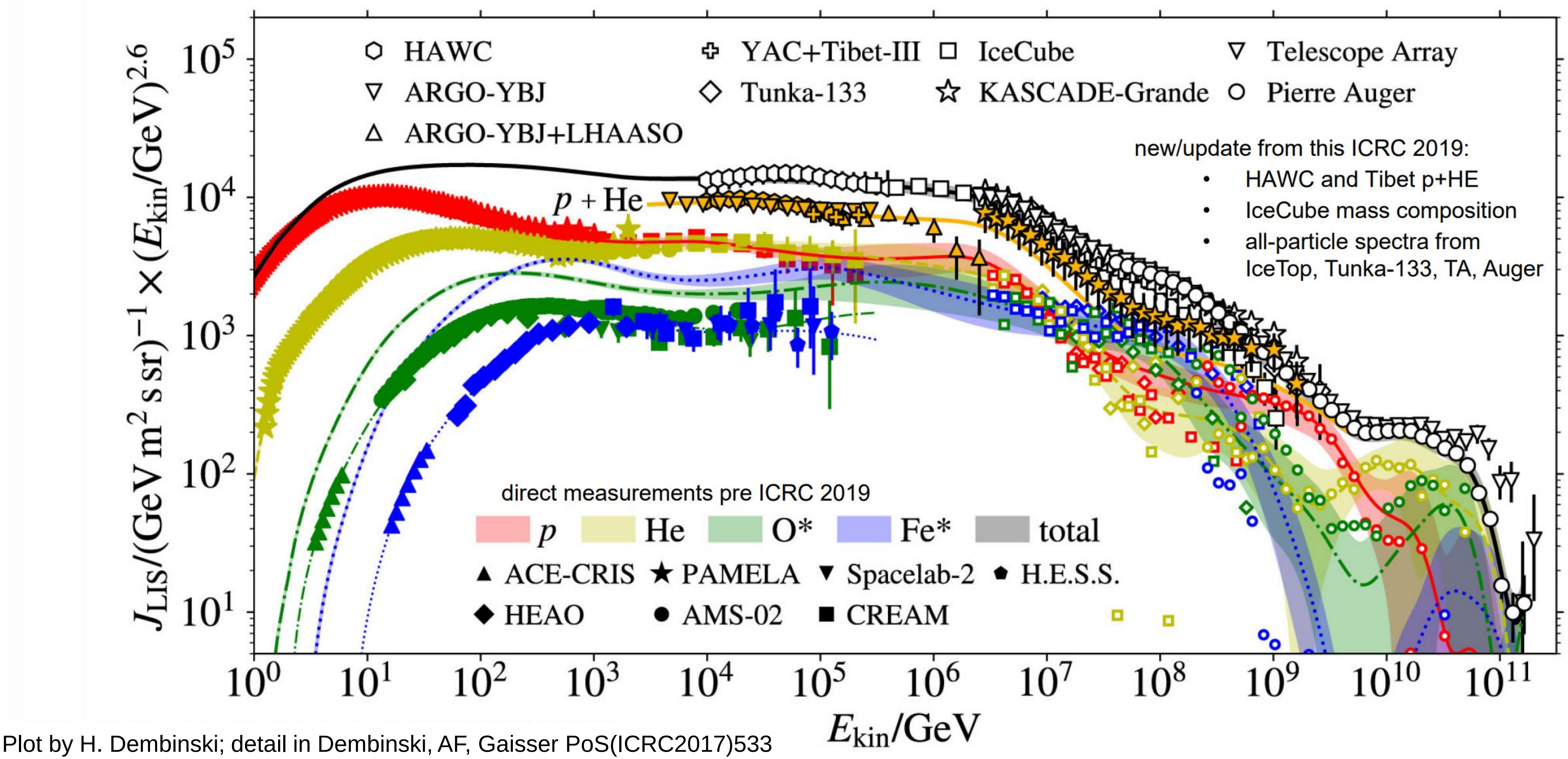
Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533 & in prep.



None of the features unambiguously explained!

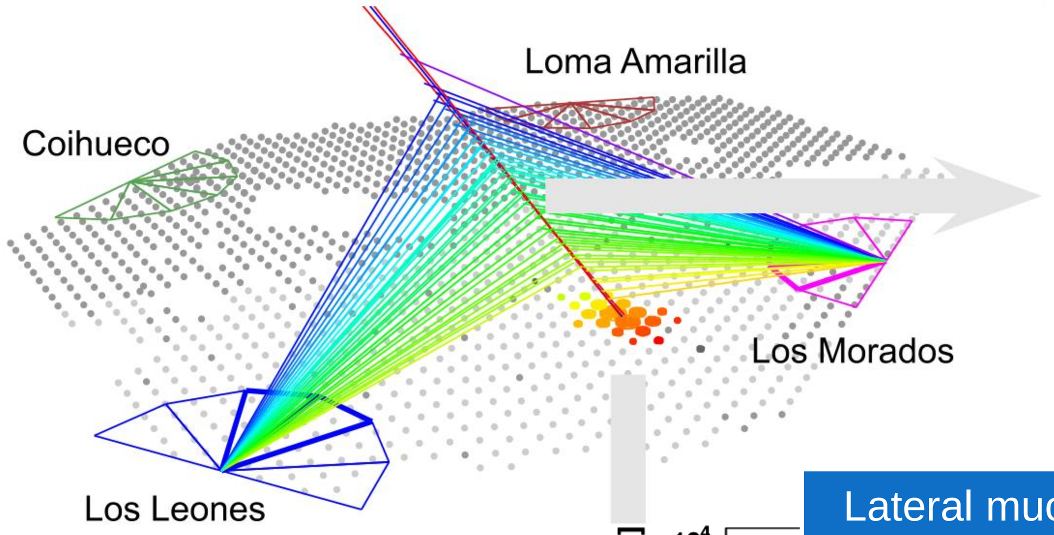
Latest version of GSF - Global Spline Fit

F. Schröder, ICRC 2019 rapporteur talk



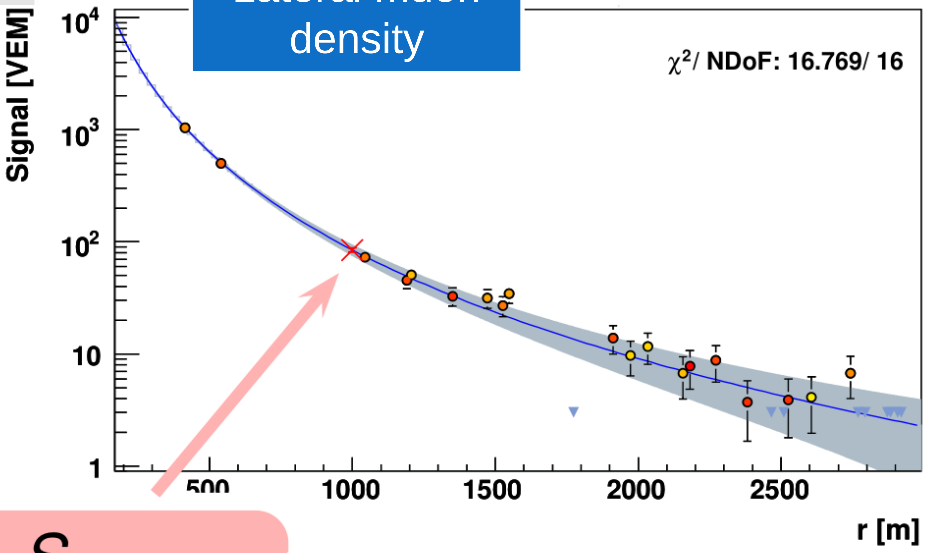
Plot by H. Dembinski; detail in Dembinski, AF, Gaisser PoS(ICRC2017)533

Hybrid air shower detection @ Pierre Auger



1. Xmax
2. Zenith, azimuth angle
3. Dist. of muons at ground
4. Dist. of electrons at ground

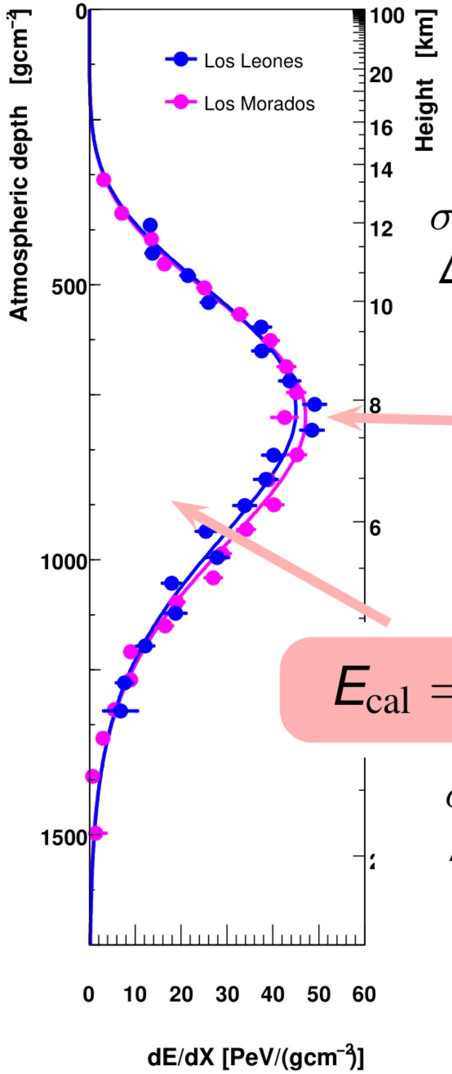
Lateral muon density



S_{1000}

$$E_{\mathrm{surface}} = f(S_{1000},\ \theta)$$

Calorimetric energy measurement



$$\sigma_{X_{\max}} \leq 20\,\mathrm{g/cm^2}$$
$$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$$

$X_{\max}$

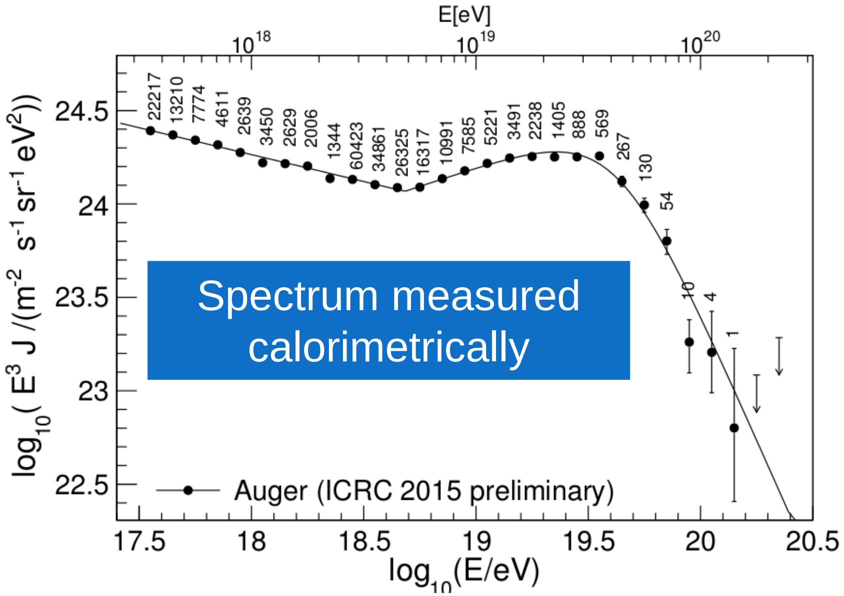
$$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$$

$$\sigma_E/E \sim 8\,\%$$
$$\Delta_{\mathrm{sys}} \approx 15\,\%$$

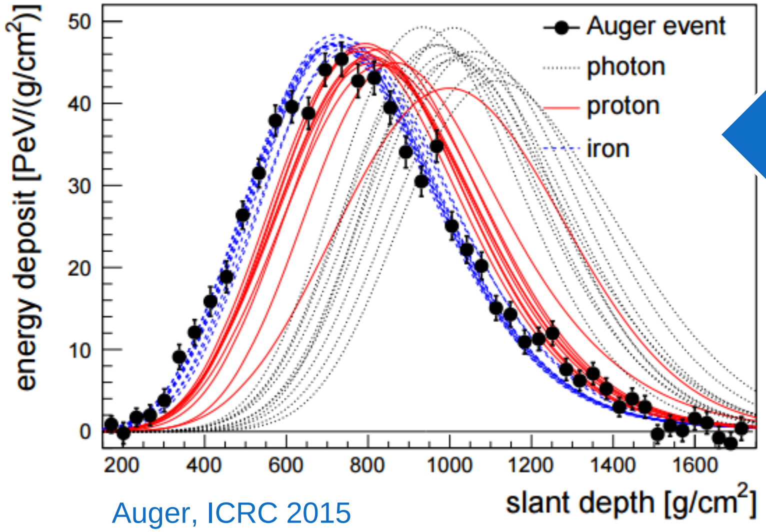
M. Unger, ICRC2017

Interpretation of UHECR mass composition

Data

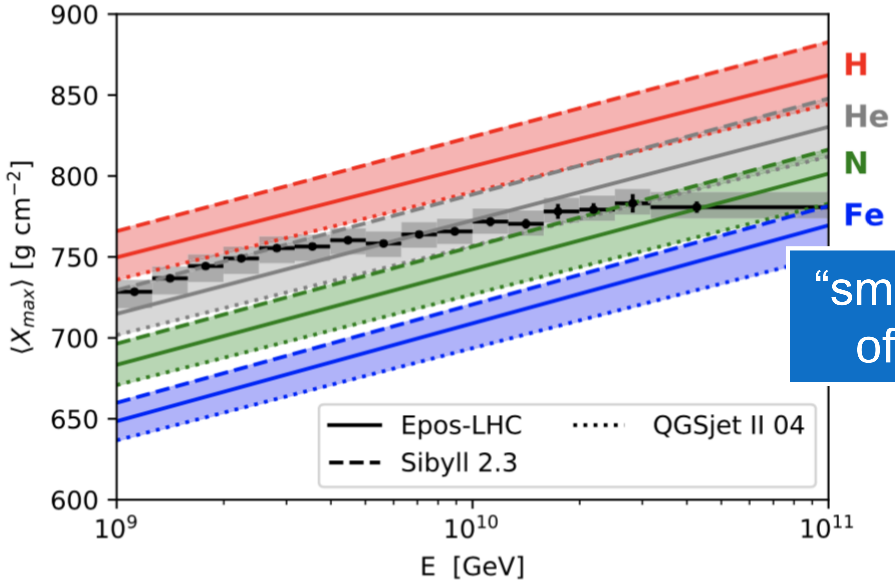


Spectrum measured calorimetrically



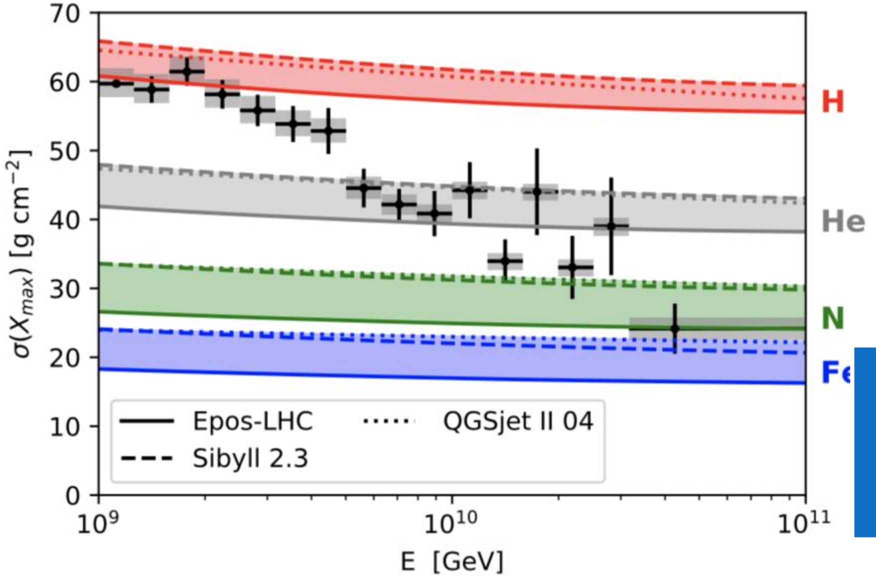
Auger, ICRC 2015

Model territory



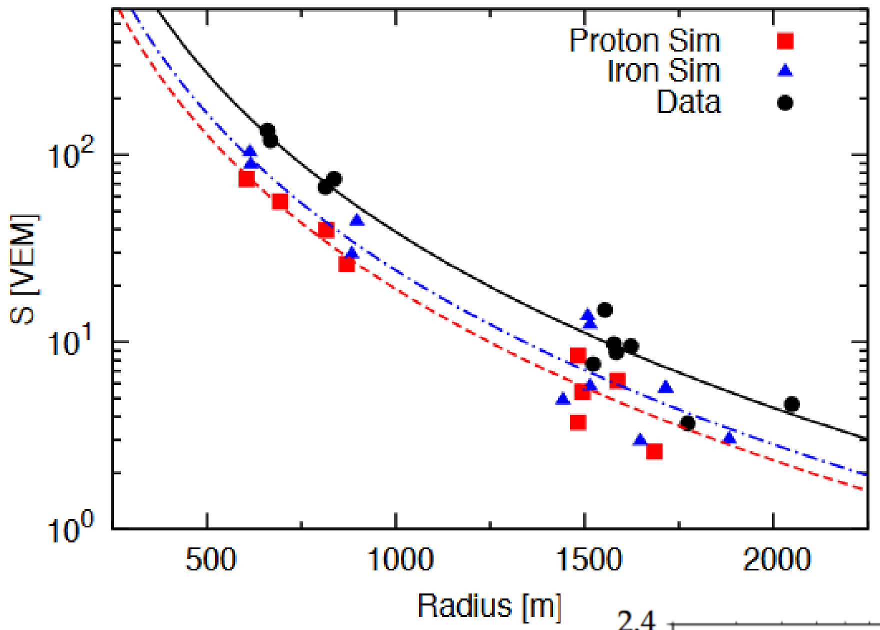
"smooth" increase of mean mass

UHECR are nuclei(?)



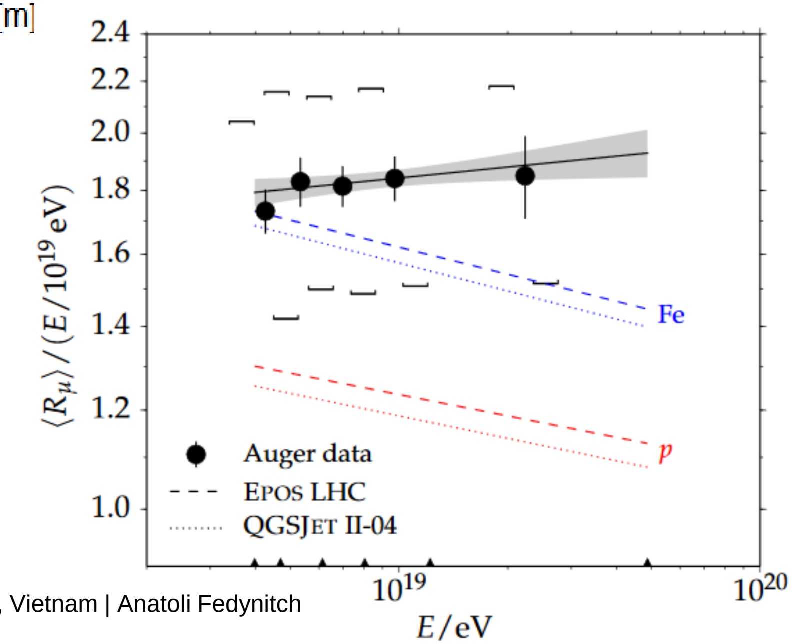
Decreasing fluctuations → mixture masses

Muon mystery

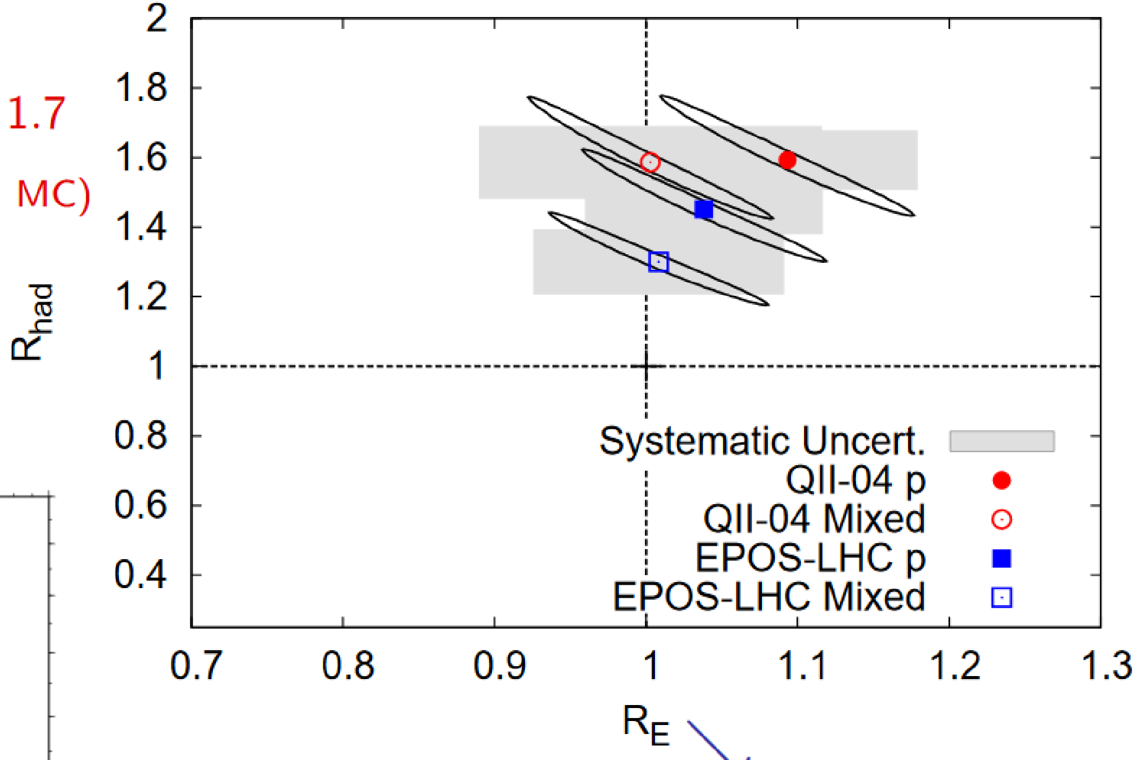


$1.2 < R_{had} < 1.7$

(muon deficit in MC)



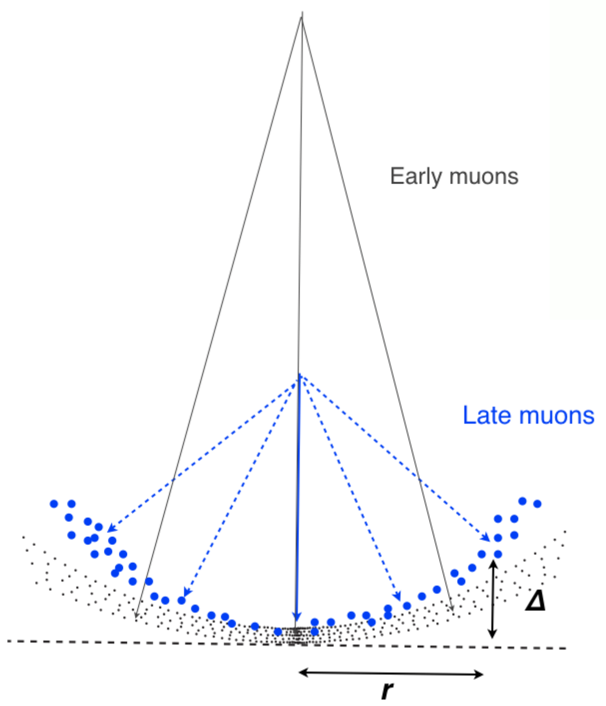
Auger, PRL 117, 2016

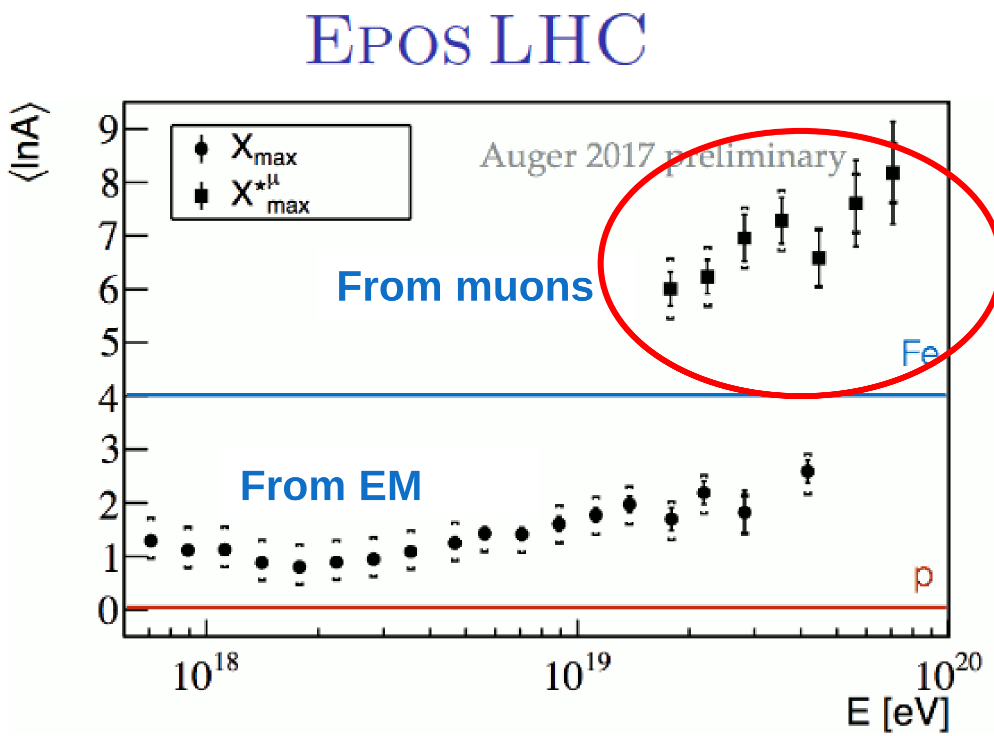


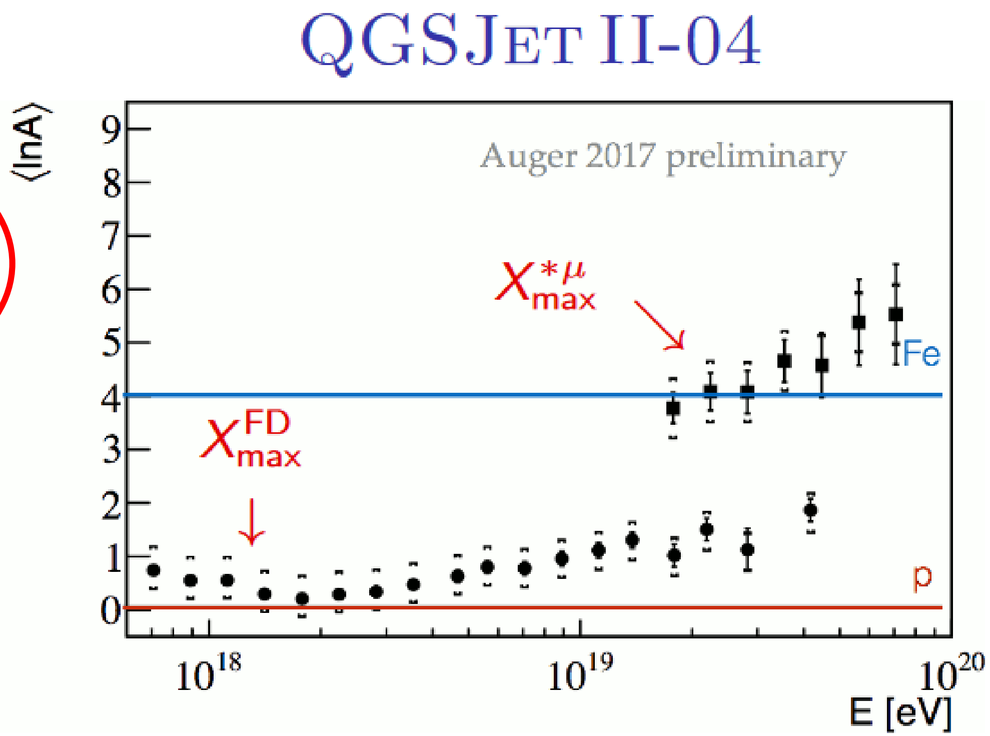
energy scale is OK

Production depth inconsistent with expectations

R. Prado, ISVHECRI 2018

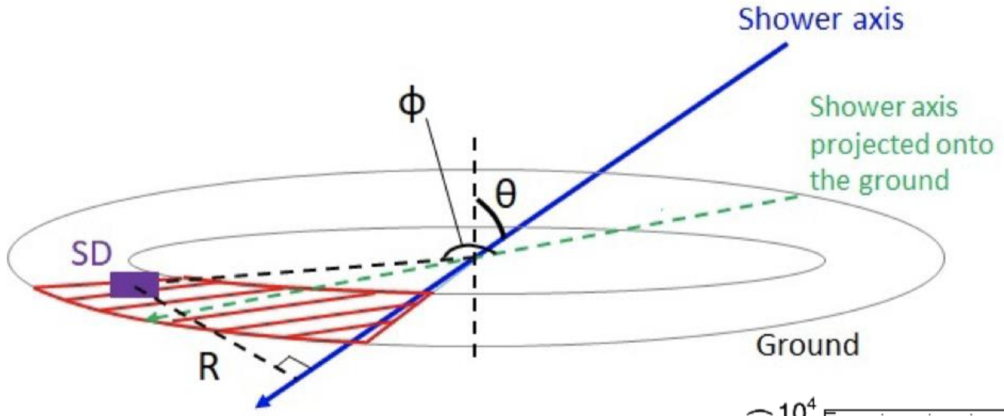


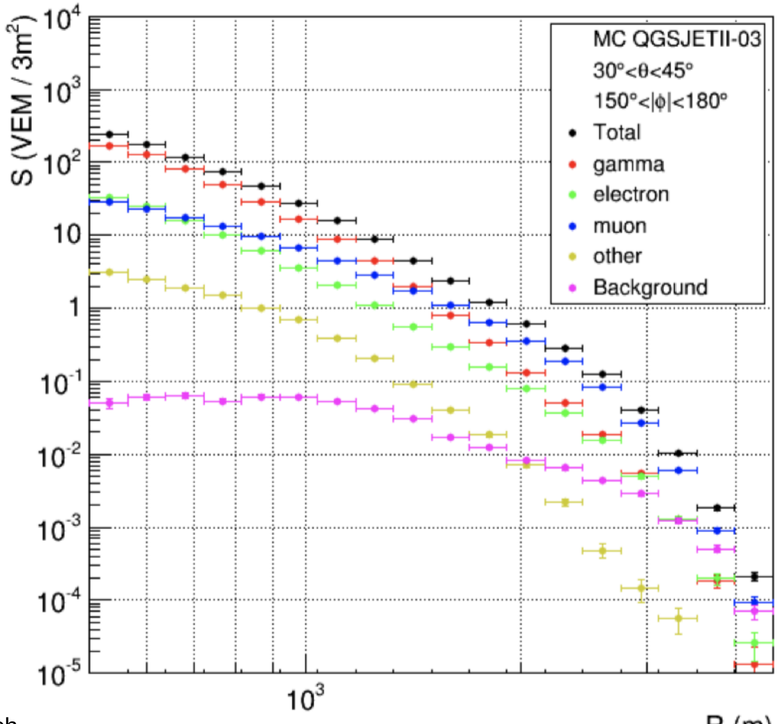


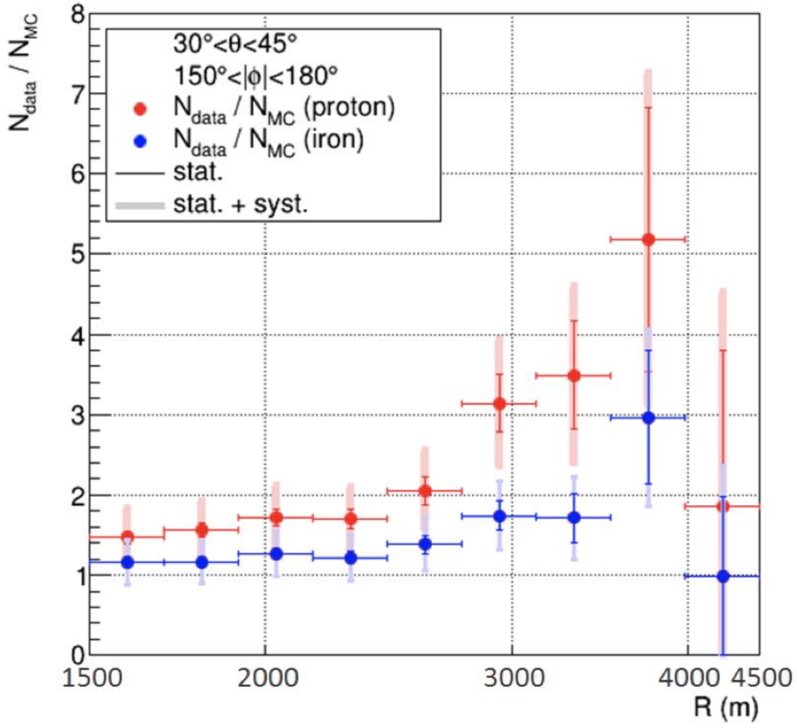


Observation by the Telescope Array

Takeishi (TA), UHECR 2018



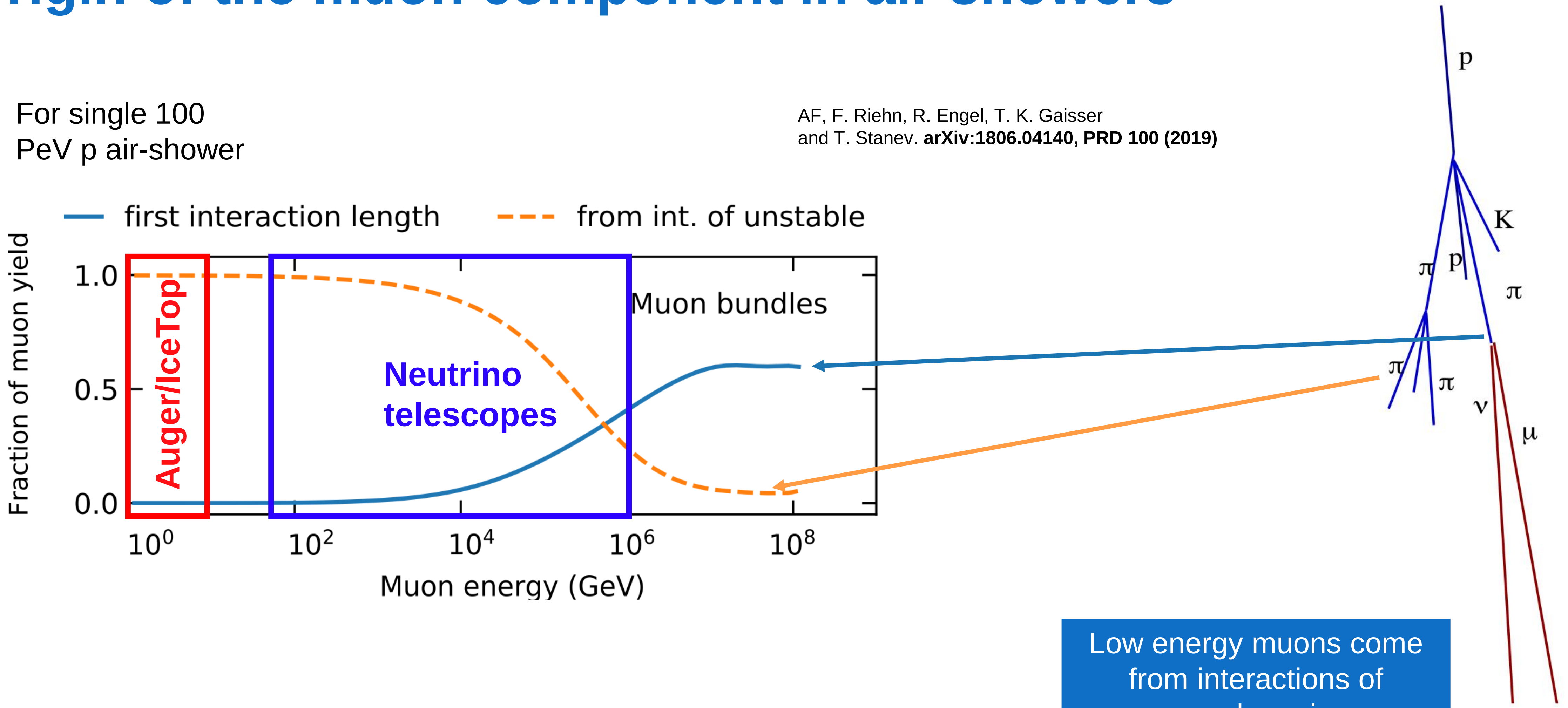




Origin of the muon component in air showers

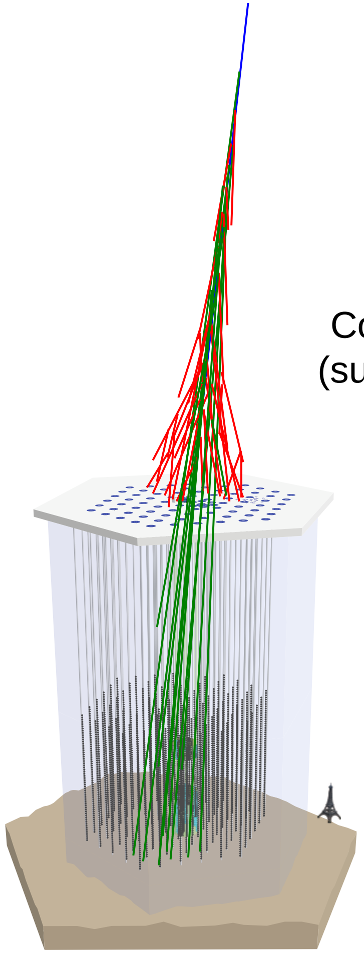
For single 100 PeV p air-shower

AF, F. Riehn, R. Engel, T. K. Gaisser and T. Stanev. **arXiv:1806.04140, PRD 100 (2019)**

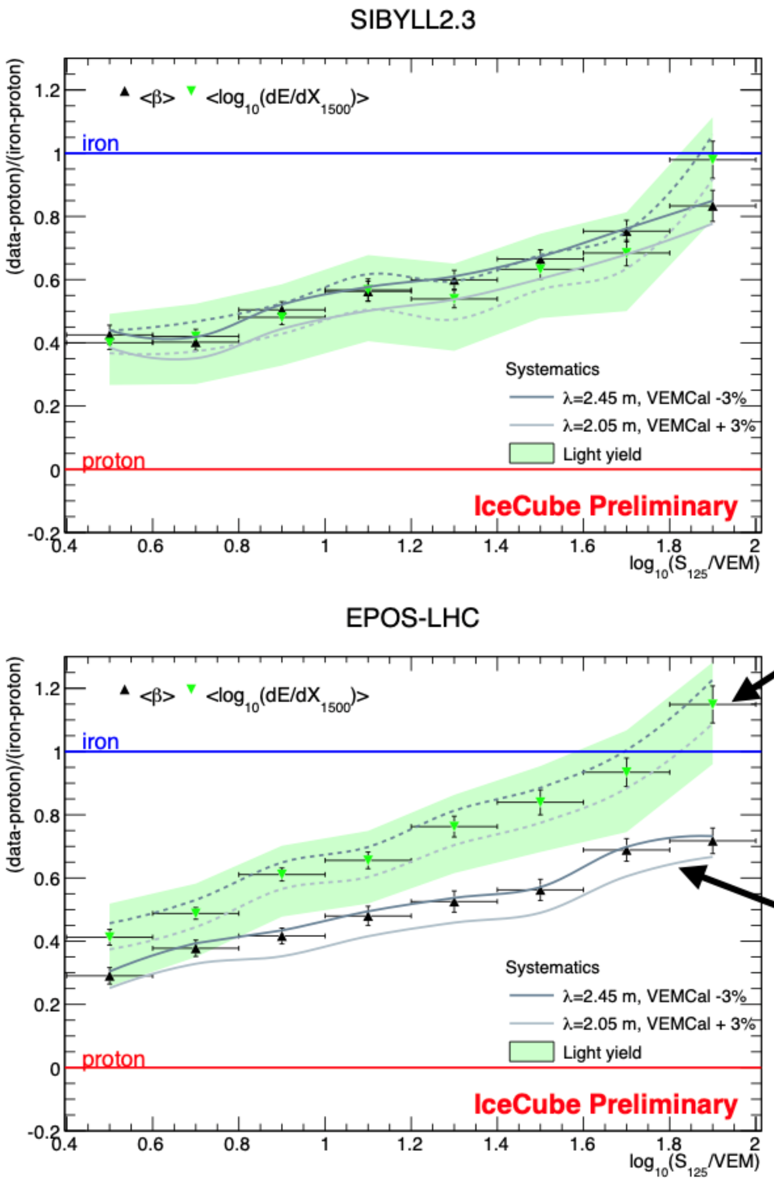


Low energy muons come from interactions of secondary pions

Hybrid detection by IceCube + IceTop



Correlation of low-energy (surface) muons and in-ice (>1 TeV)

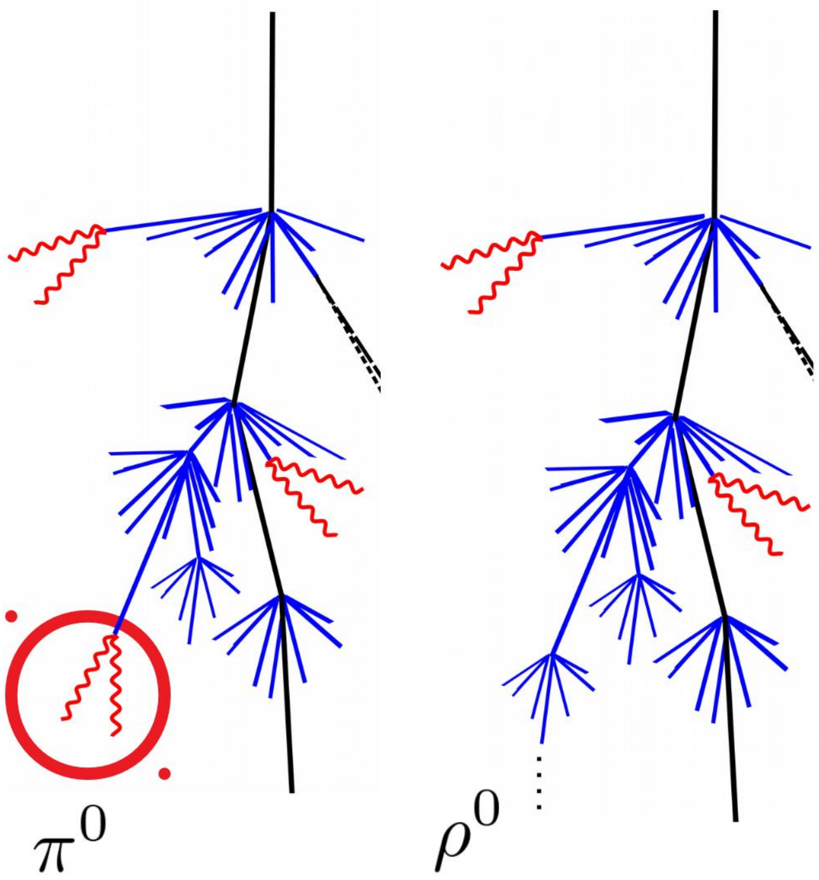


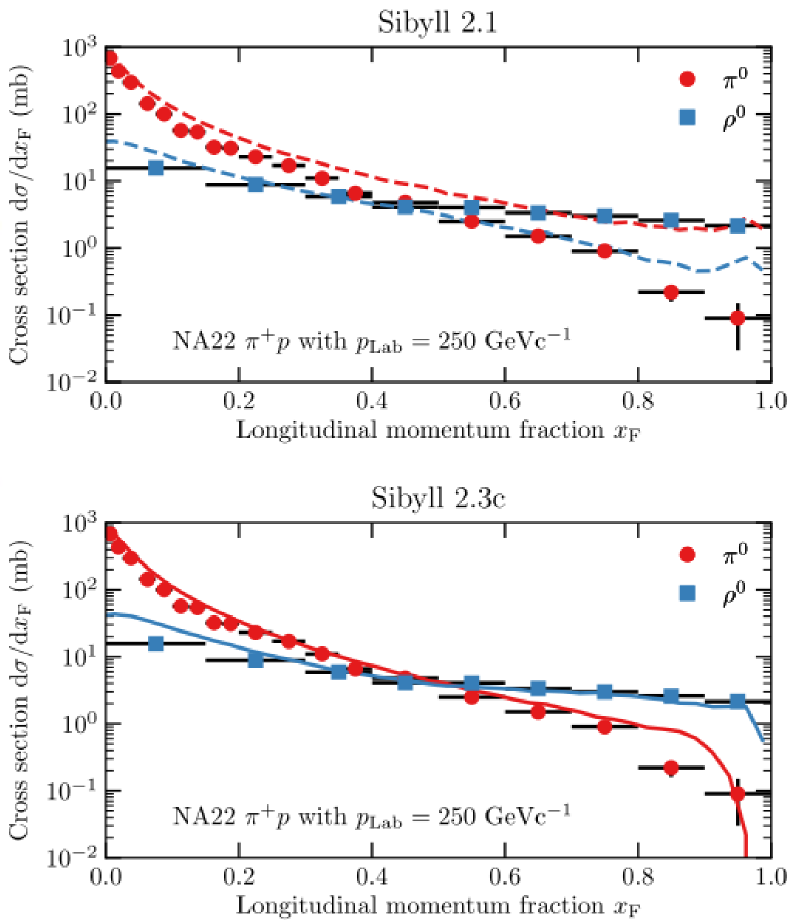
(de Ridder, Gaisser, IceCube, ICRC 2017)

In-ice muons (~300 GeV)

Surface muons (~1 GeV)

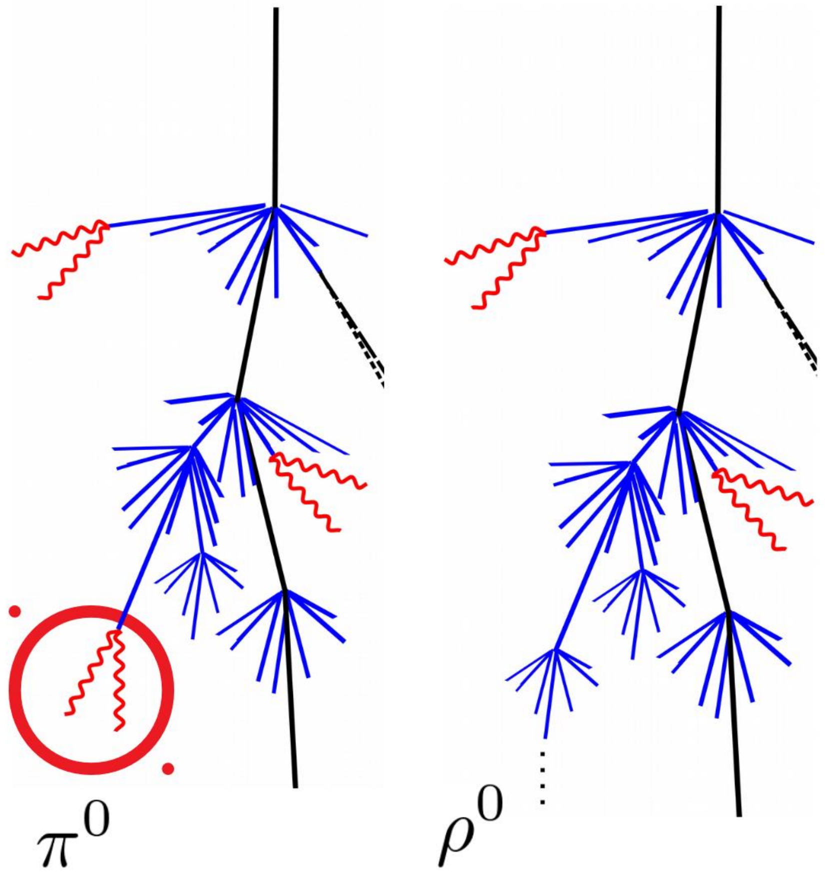
More hadrons through leading rho0 production

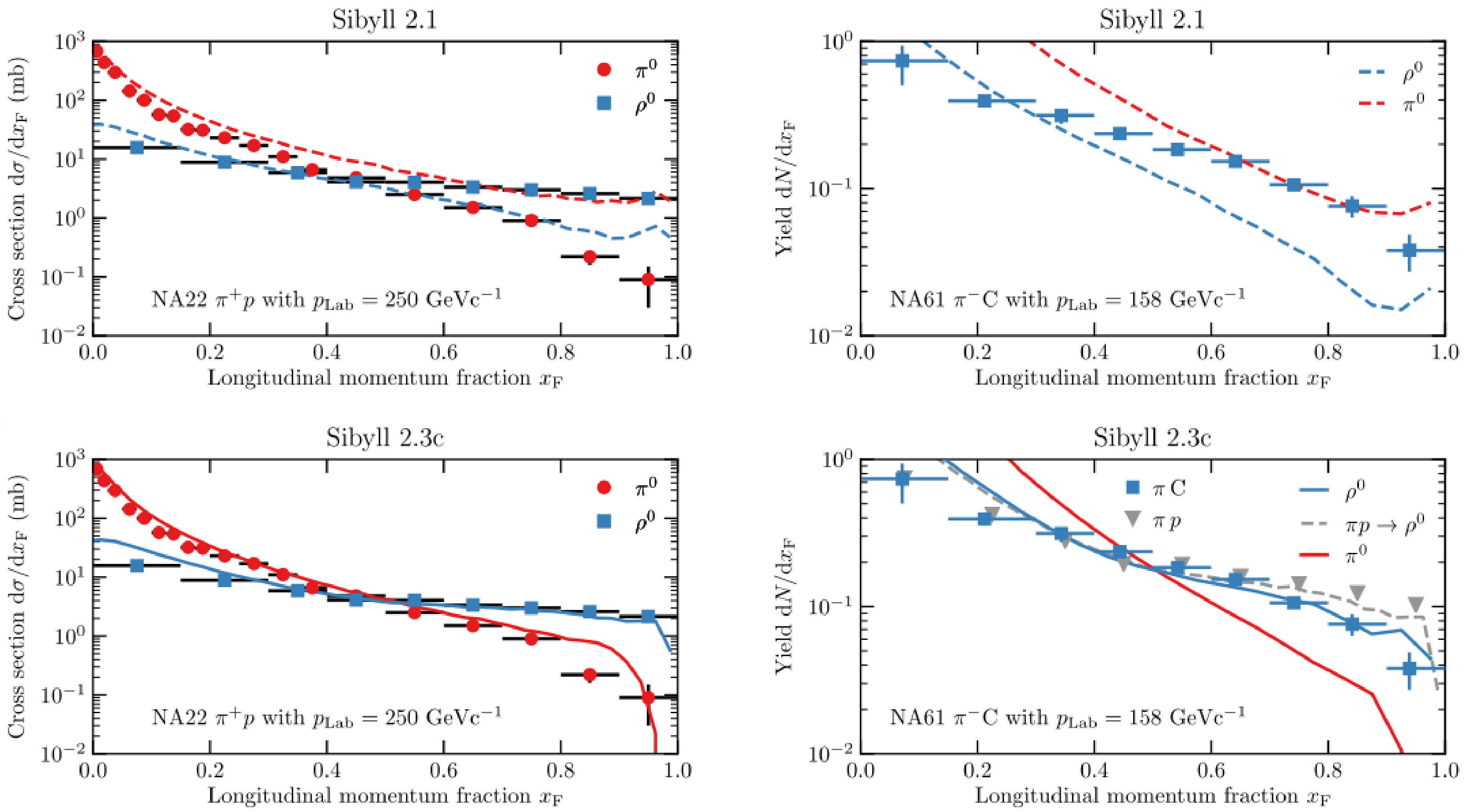




More hadrons through leading rho0 production

F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300

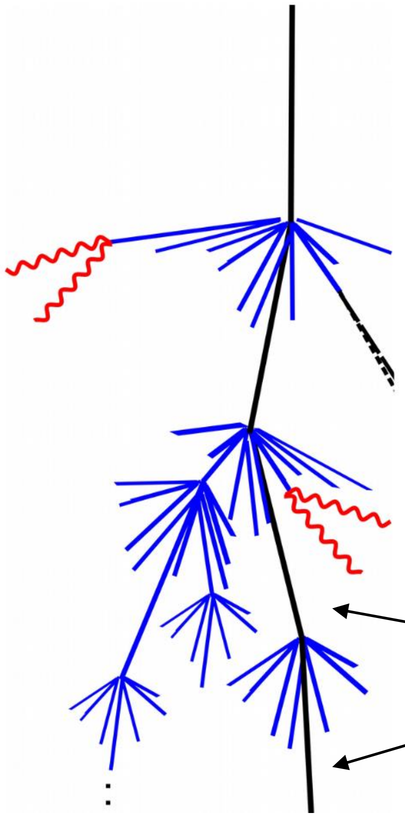




No fixed-target measurement of π^0 production off nulei

More low-energy muons through anti-baryons production

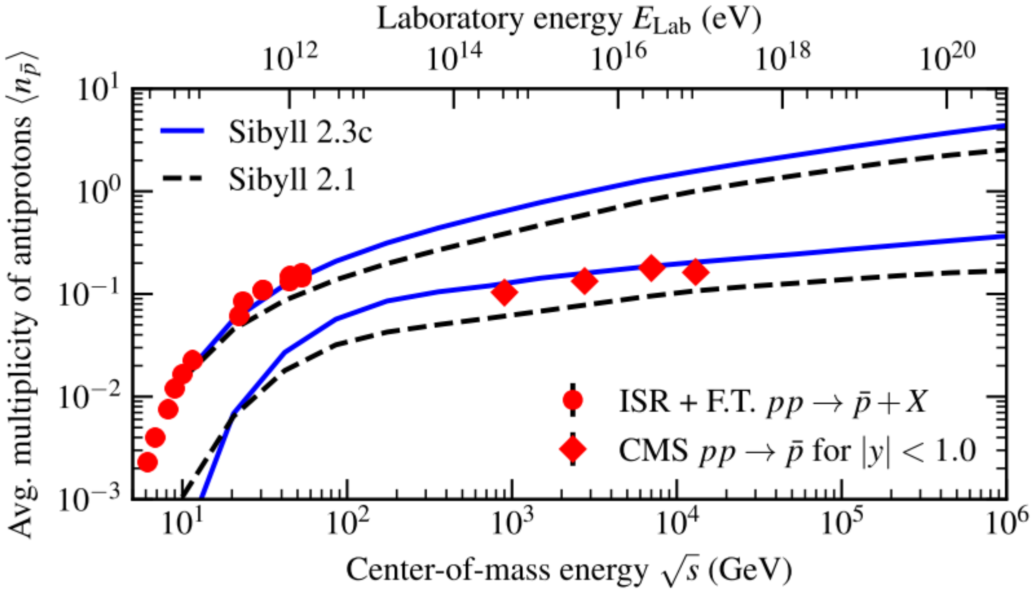
F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev
arXiv:1912.03300



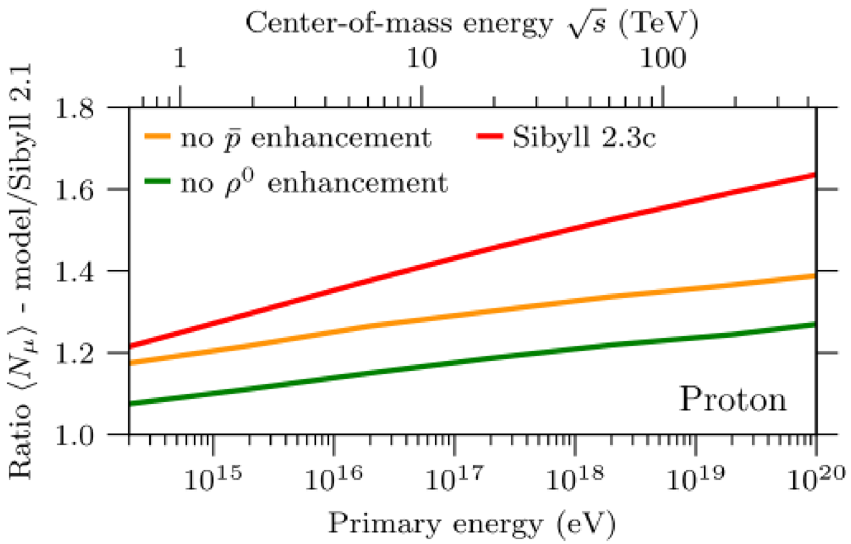
Antiproton or
antineutron

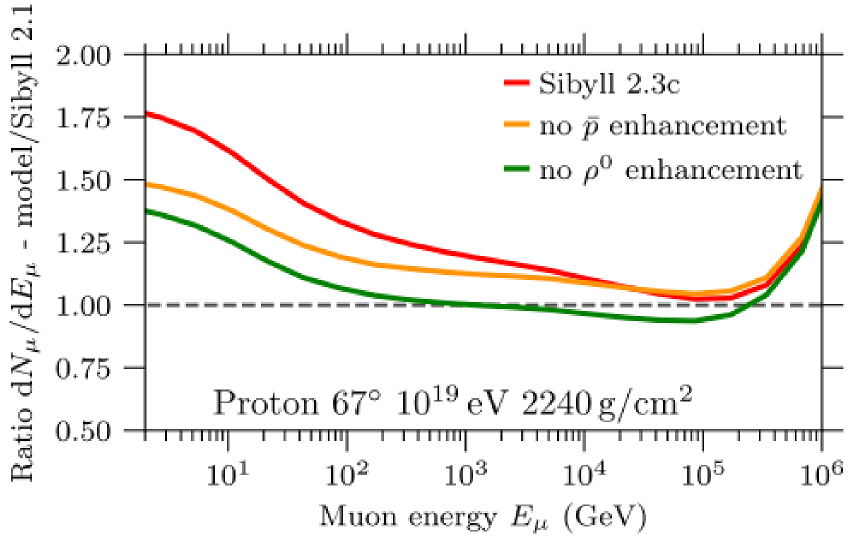
Baryon number conservation results in cascade regeneration:

- Each interaction yields at least one baryon
- These baryons re-interact, producing more pions
- Production was off in older models



Impact of corrections on expected muon number





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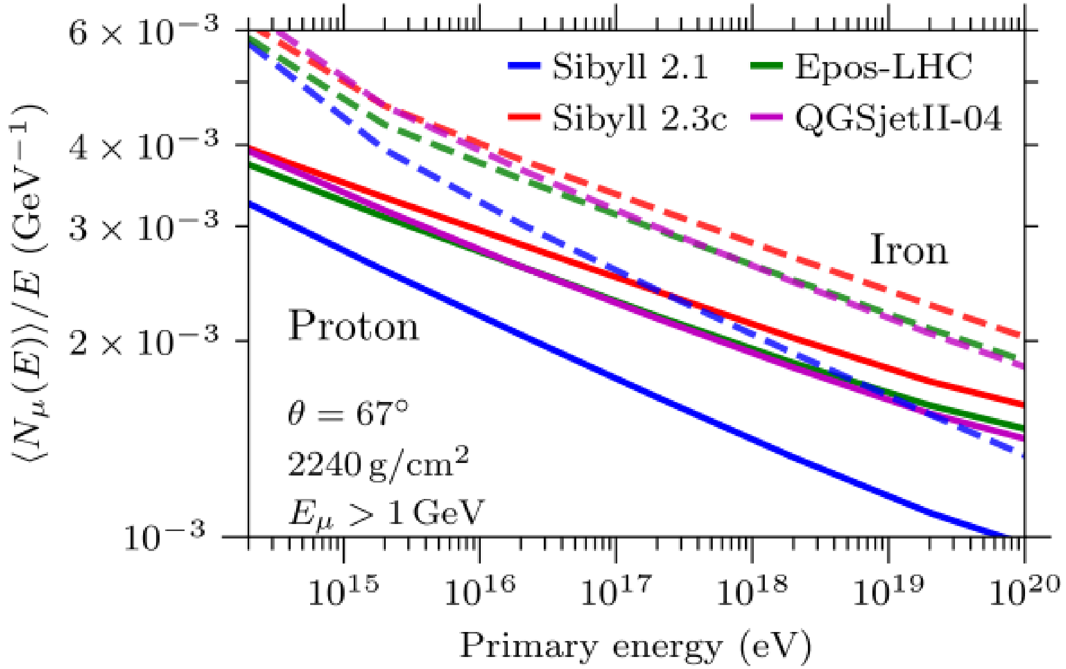
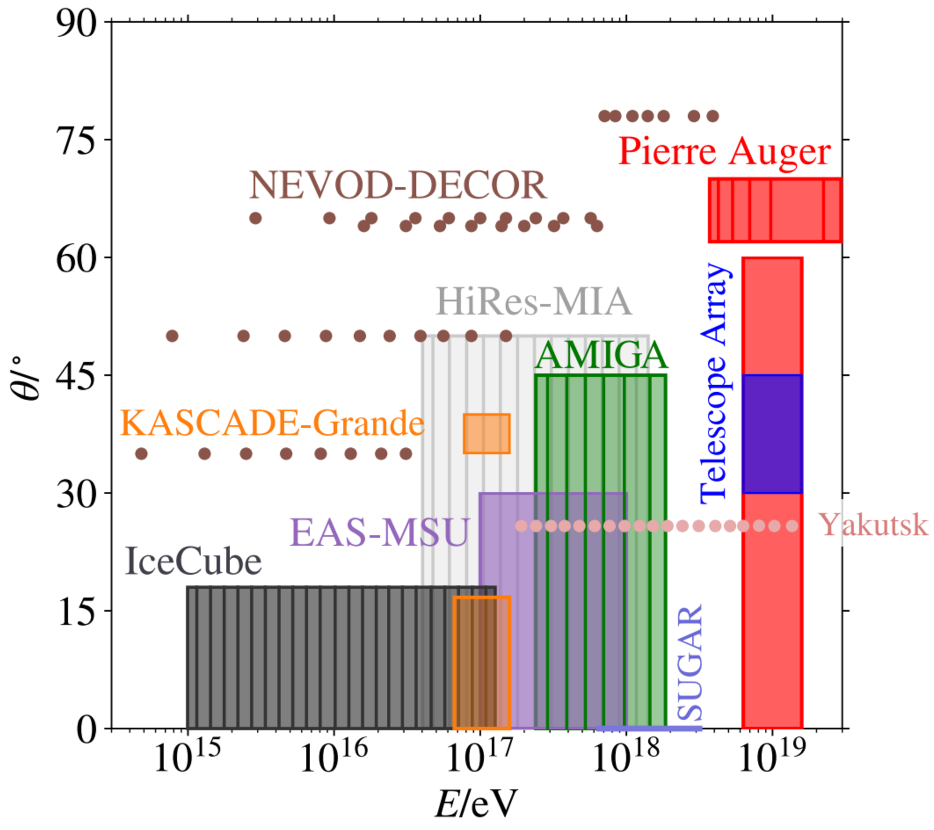
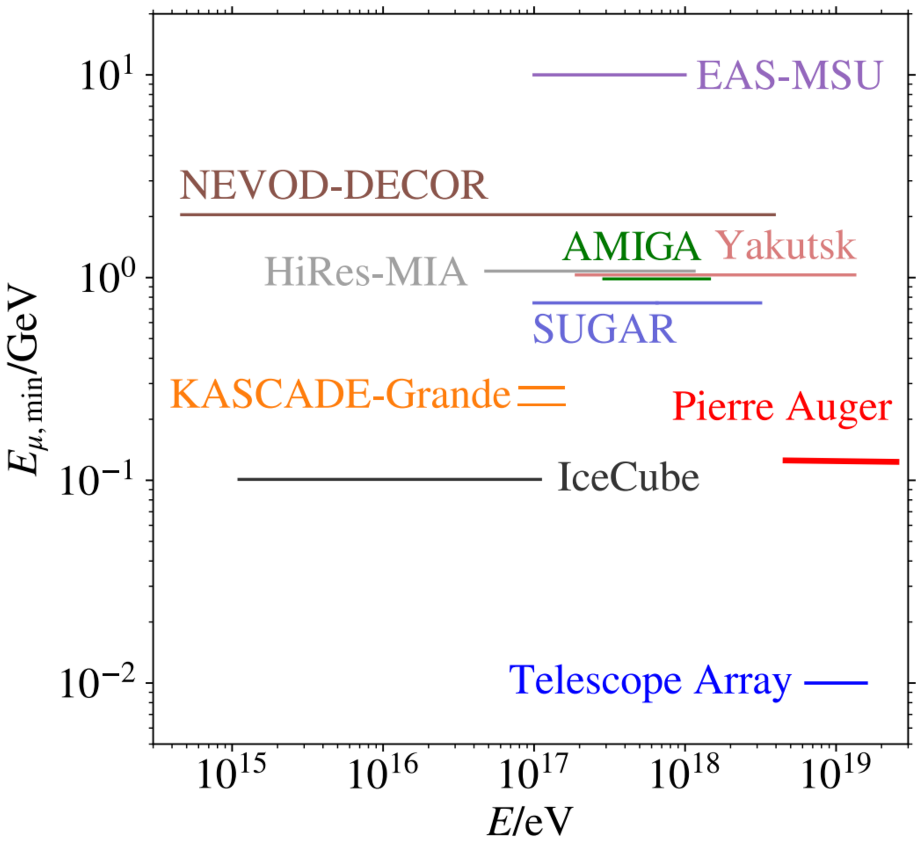


!75%! more muons in newer models at certain energies

Global characterization muon excess

L. Cazon (WHISP WG), ICRC 2019





Global characterization muon excess

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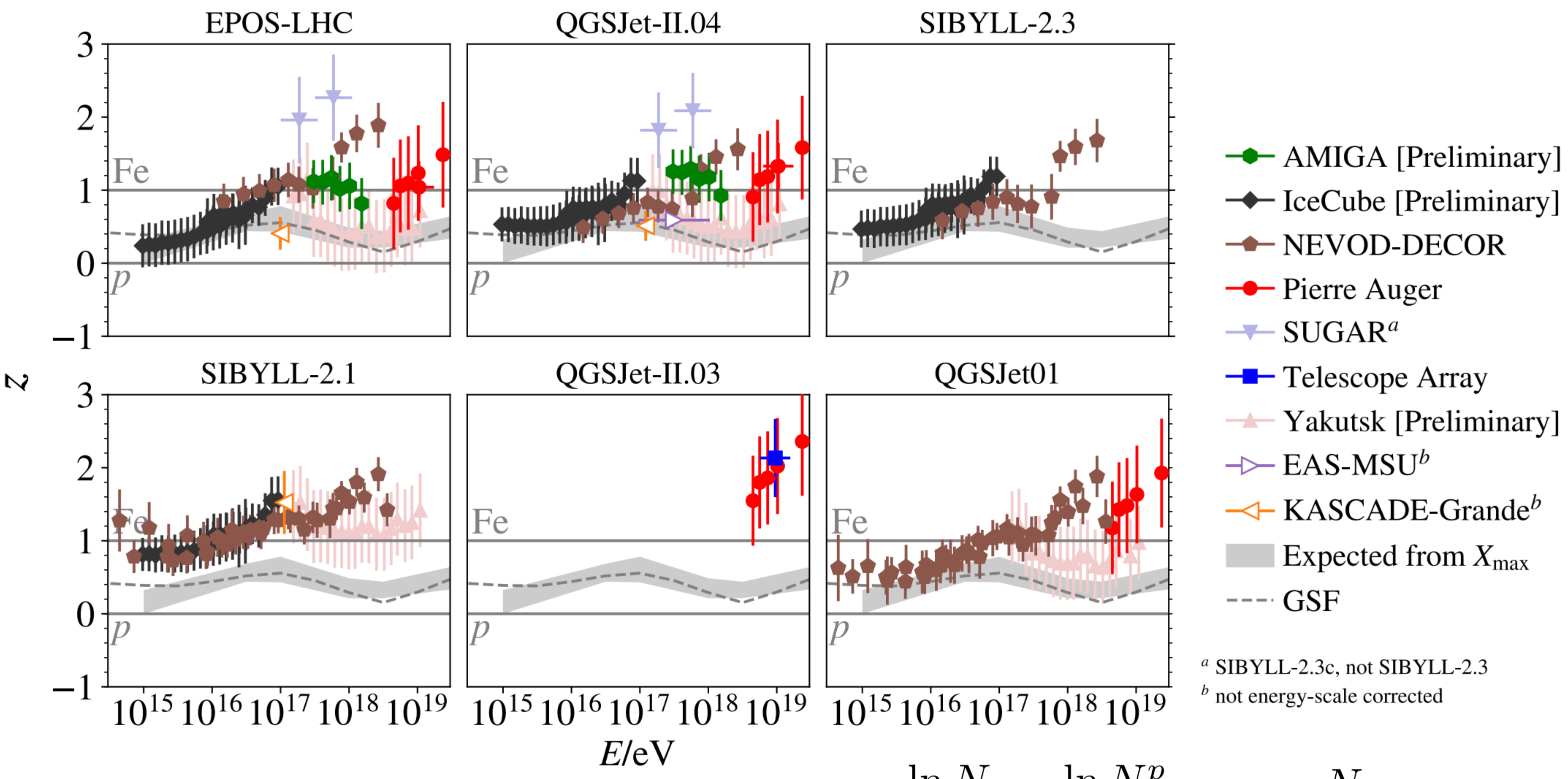
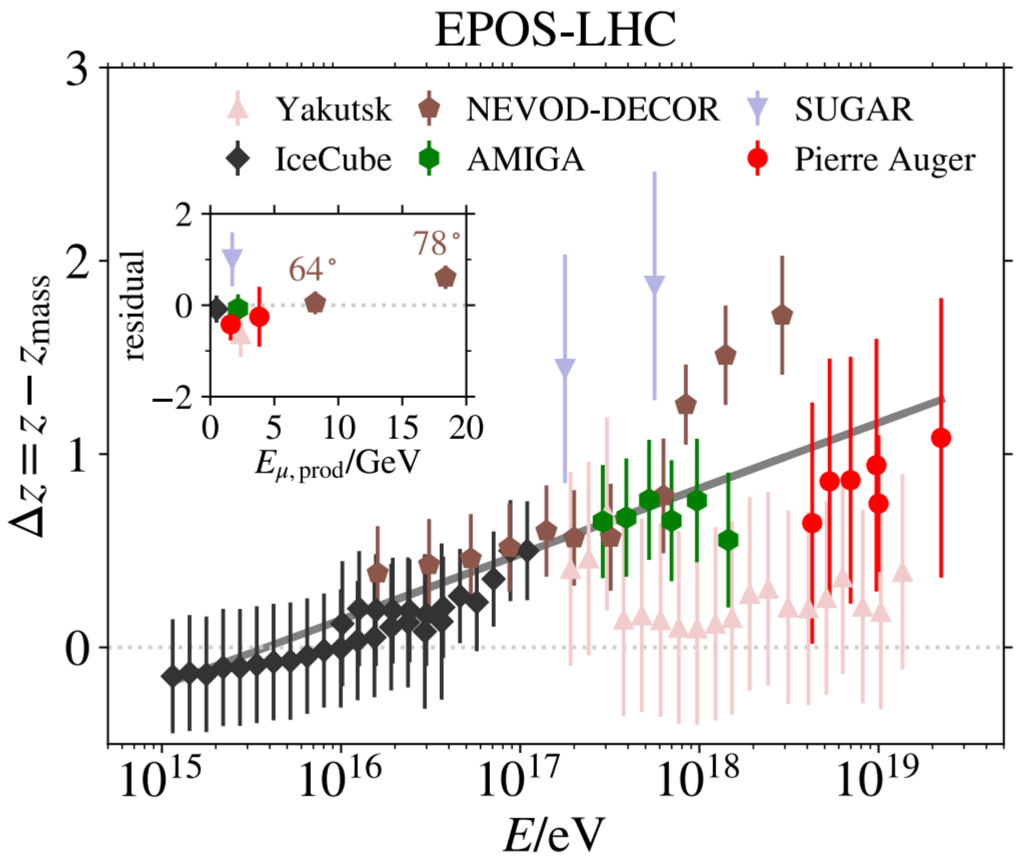


$$z = \frac{\ln N_\mu - \ln N_\mu^p}{\ln N_\mu^{Fe} - \ln N_\mu^p} \simeq 3 \ln \frac{N_\mu}{N_\mu^p}$$

Experimental bottom line

- **Consistent picture** after converting and cross-calibrating data
  - Post-LHC models describe muons better than pre-LHC models
- Smooth increase of $N_\mu^{data} / N_\mu^{MC}$ with energy (8 $\boldsymbol{\sigma}$ significance)



L. Cazon (WHISP WG), ICRC 2019

Conclusion

1. **Modeling hadronic interactions is difficult** and not compliant with current mainstream expectations (old school + not pure theory + FORTRAN 77 → few, rare papers)

2. Models still have many deficiencies and **available data is not fully exploited**

3. Evident problems in air shower interpretations hold back astrophysical progress

4. **New physics – yet unlikely:**
   - Each muon at ground is on average from 4^{th} - 6^{th} generation (number of preceding hadronic re-interactions
   - Getting things (multiplicity/phase space distribution) by 10% wrong means that the accumulated error is 1.1^6 = 77%
   - The problem is to identify what is off (proton/pion/nuclear effects), and how it behaves as a function of energy