Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Cosmic Rays and Multiparticle Production at LHC

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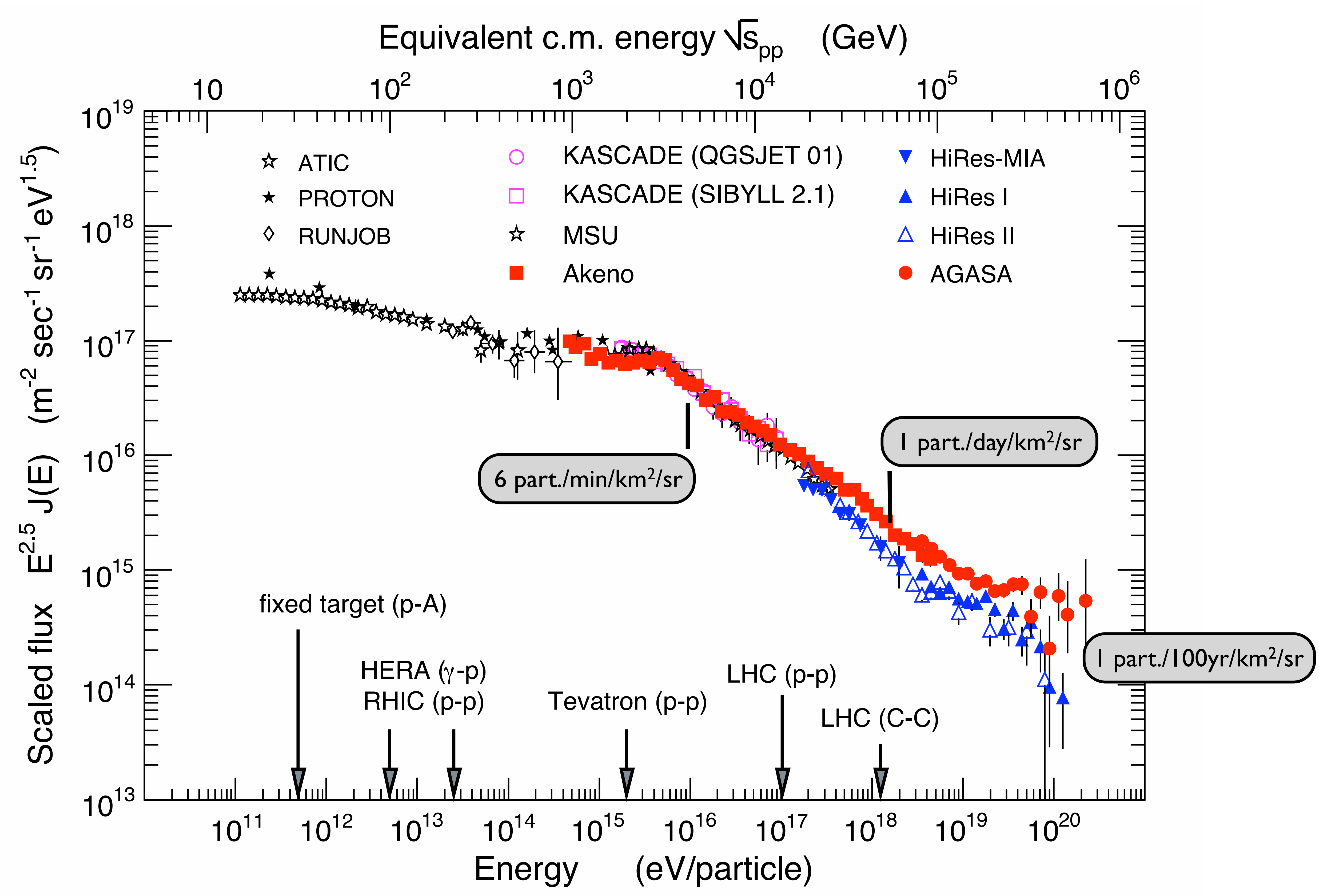
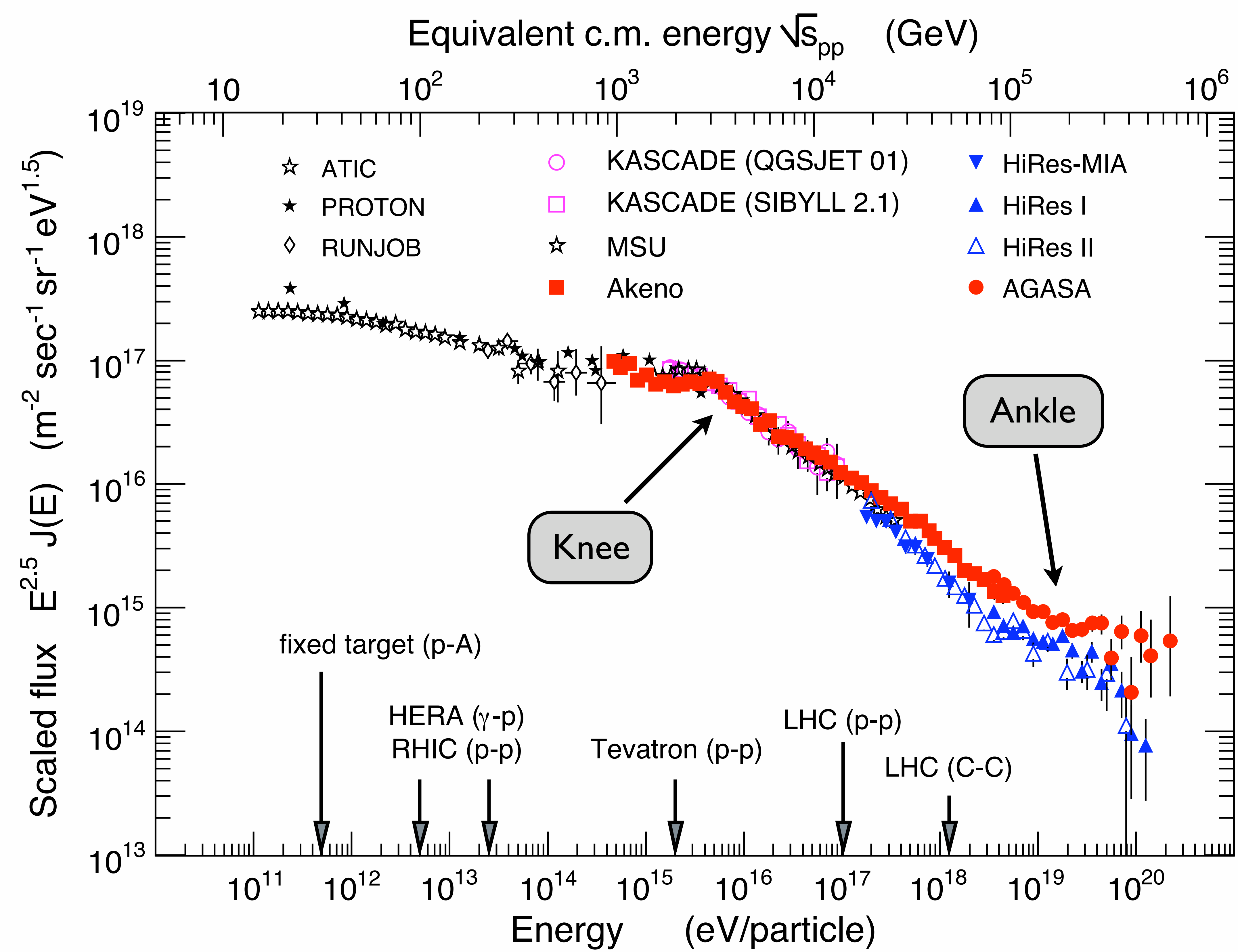
Outline

- Cosmic-ray physics
  - Flux & elemental composition
  - Measurement techniques and problems
- Simulation of air showers & multiparticle production
- What have we learned from HERA
- What do we hope to learn from LHC

Primary cosmic ray flux (1)

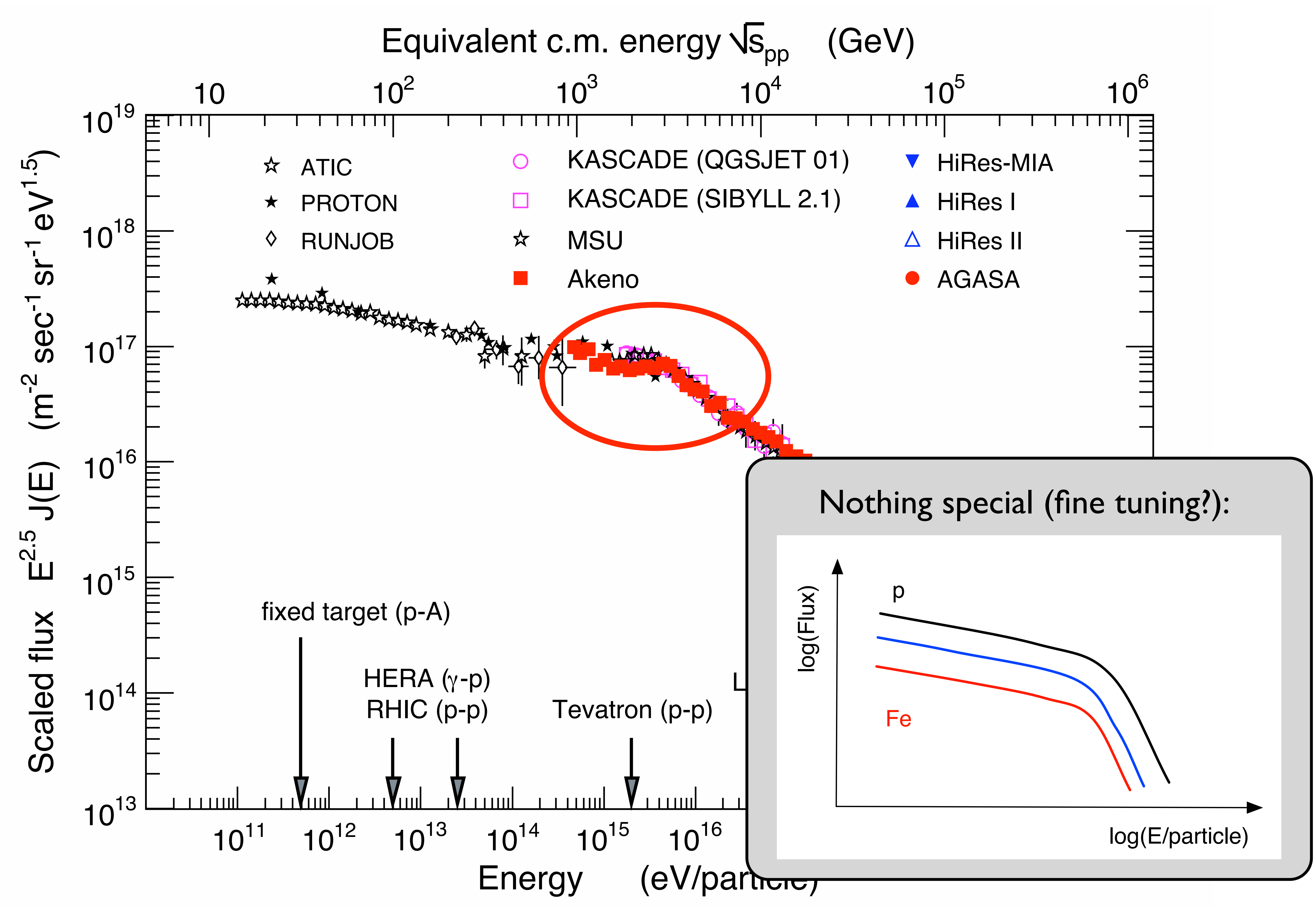


Primary cosmic ray flux (2)

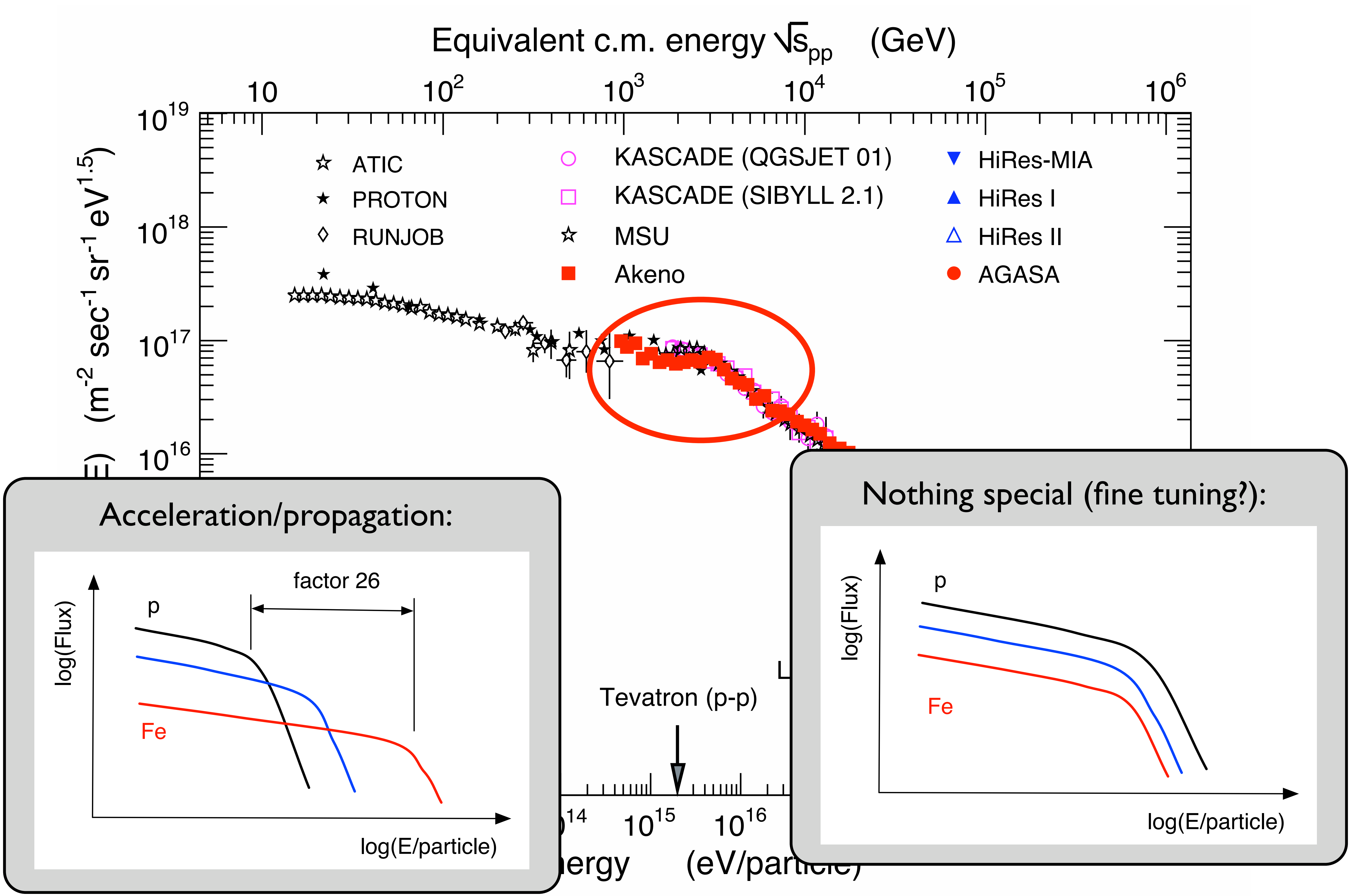


Greisen-Zatsepin-Kuzmin suppression?

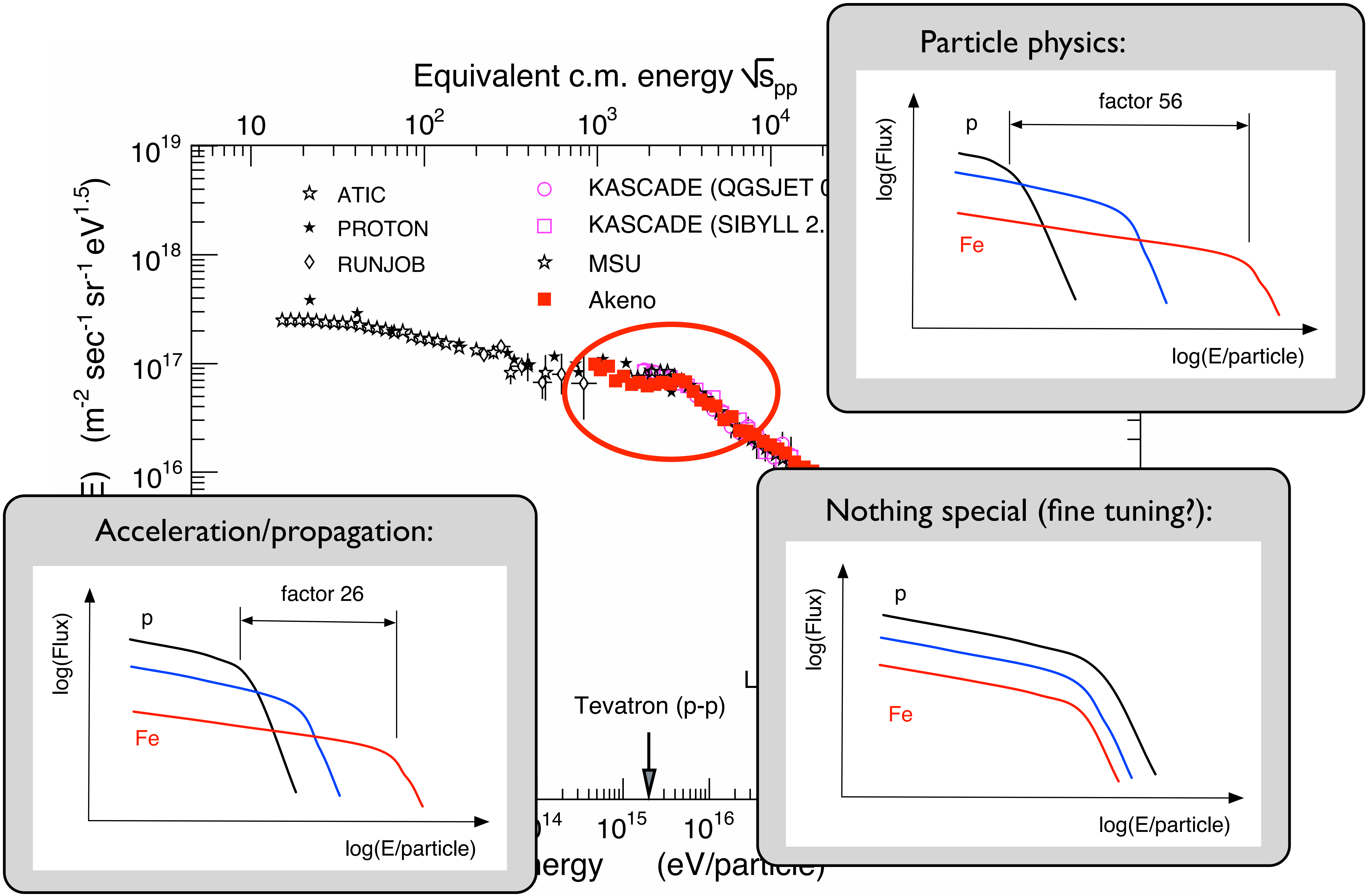
Knee: possible interpretations



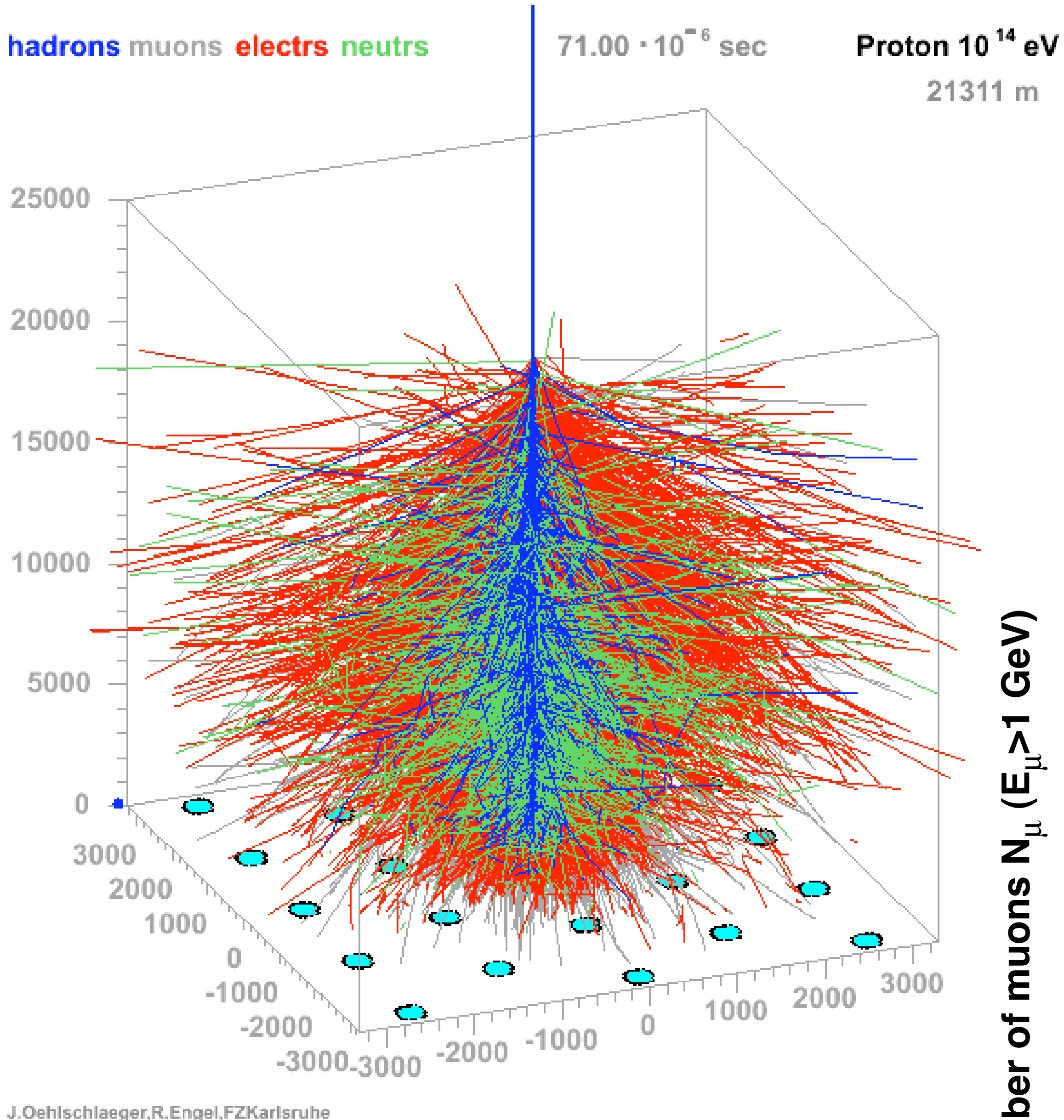
Knee: possible interpretations



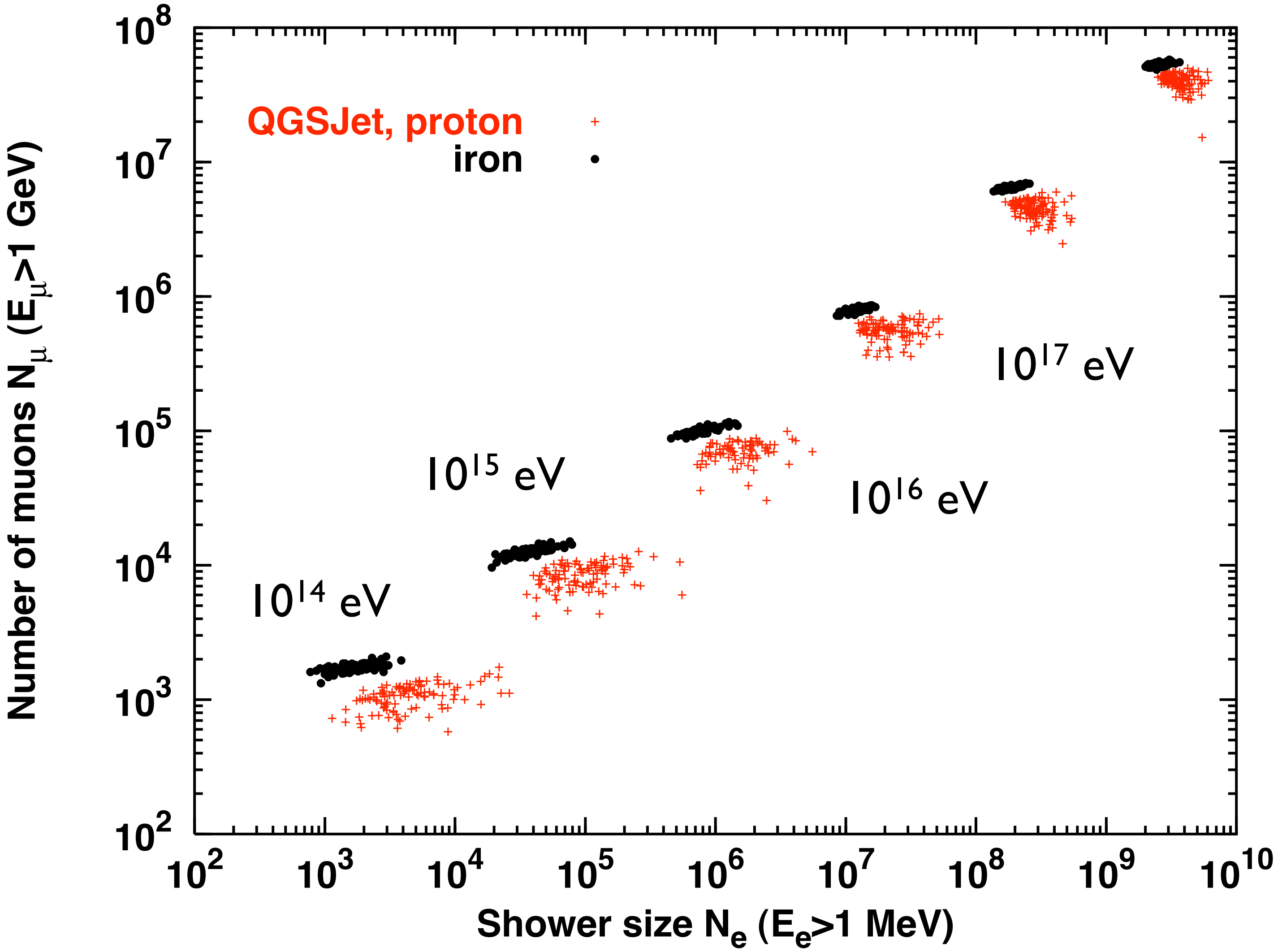
Knee: possible interpretations



Air shower ground arrays

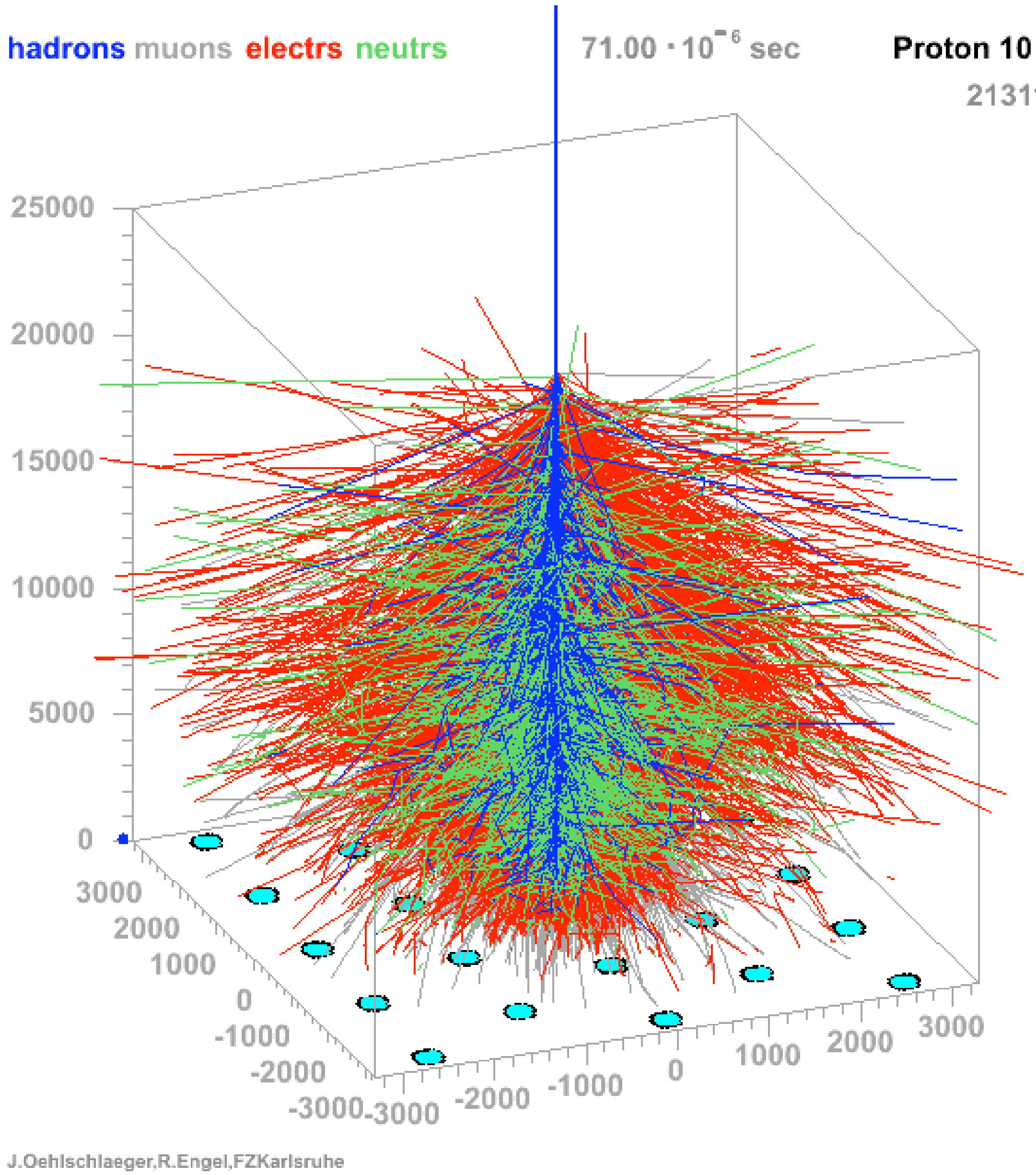


Combined energy-composition analysis



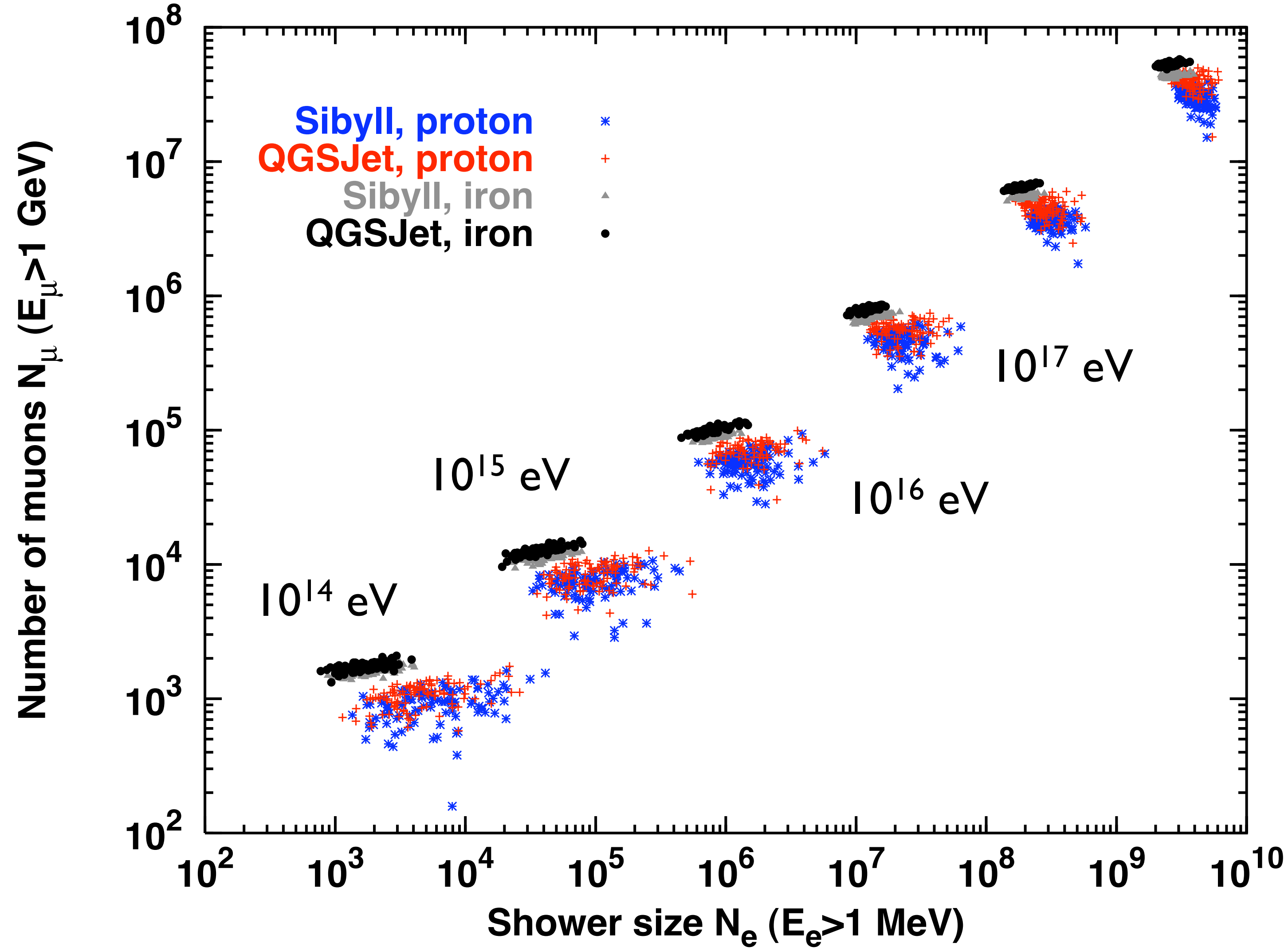
Example:
KASCADE-Grande (Karlsruhe)

Air shower ground arrays



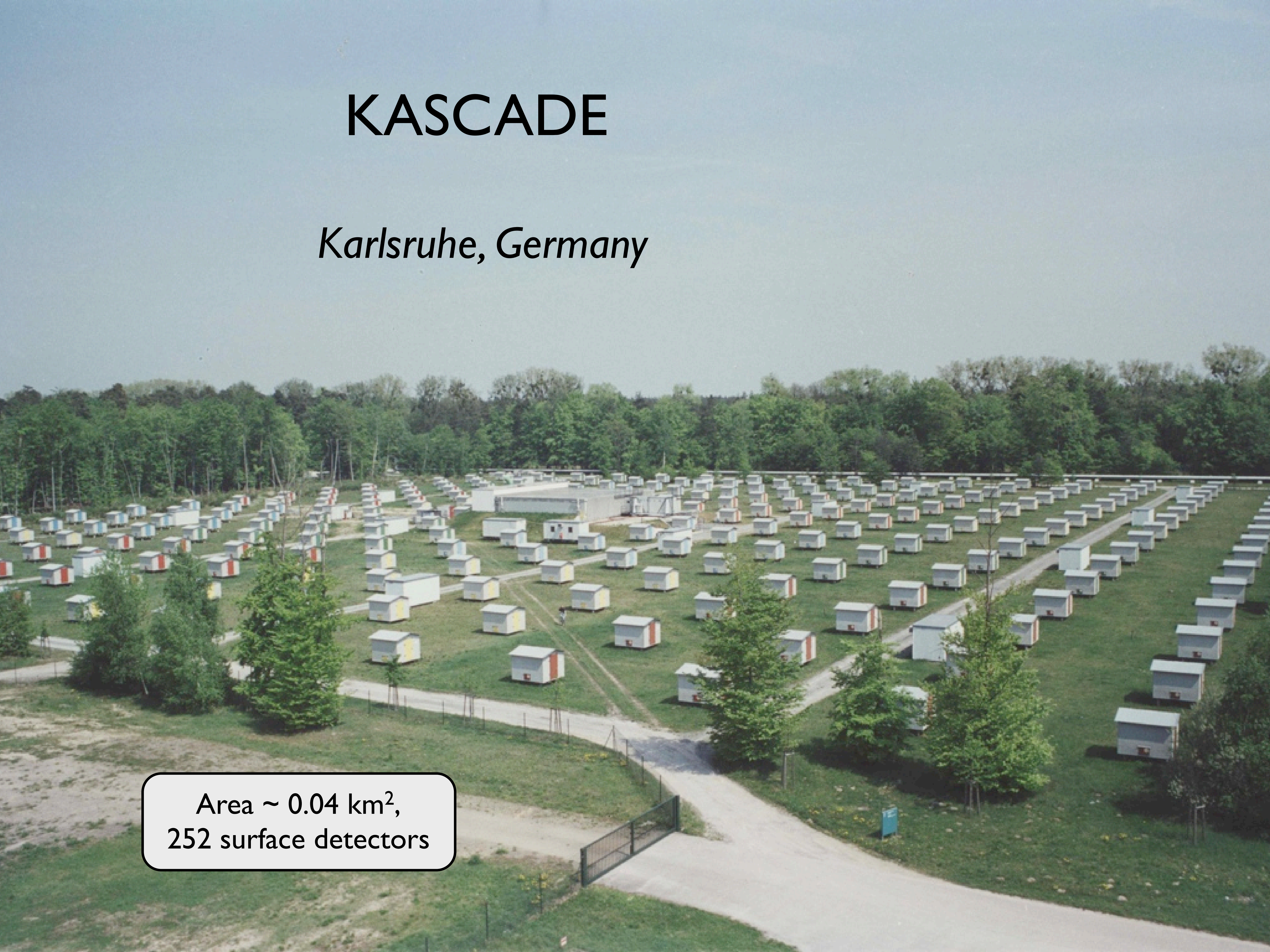
Example:
KASCADE-Grande (Karlsruhe)

Combined energy-composition analysis



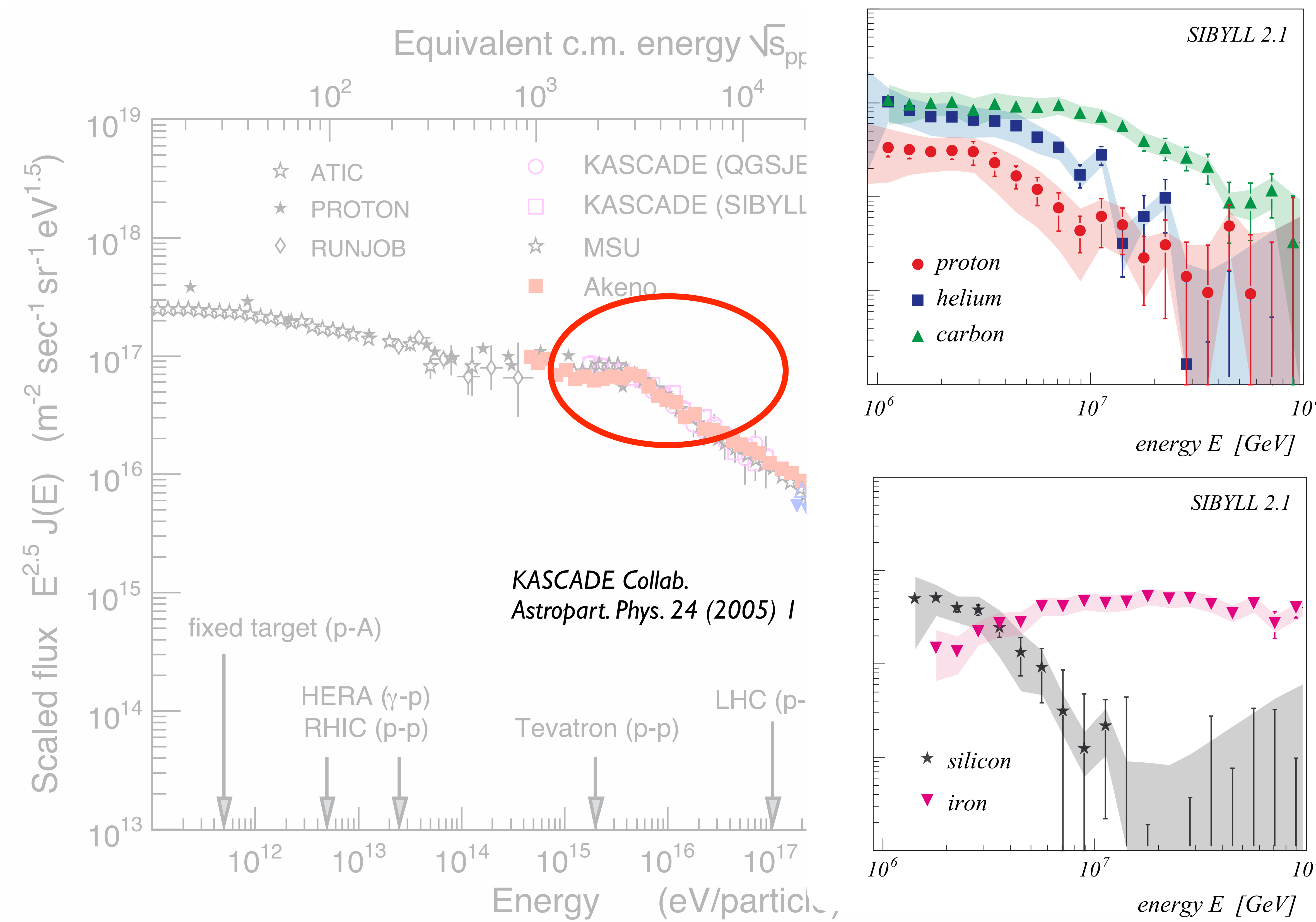
KASCADE

Karlsruhe, Germany

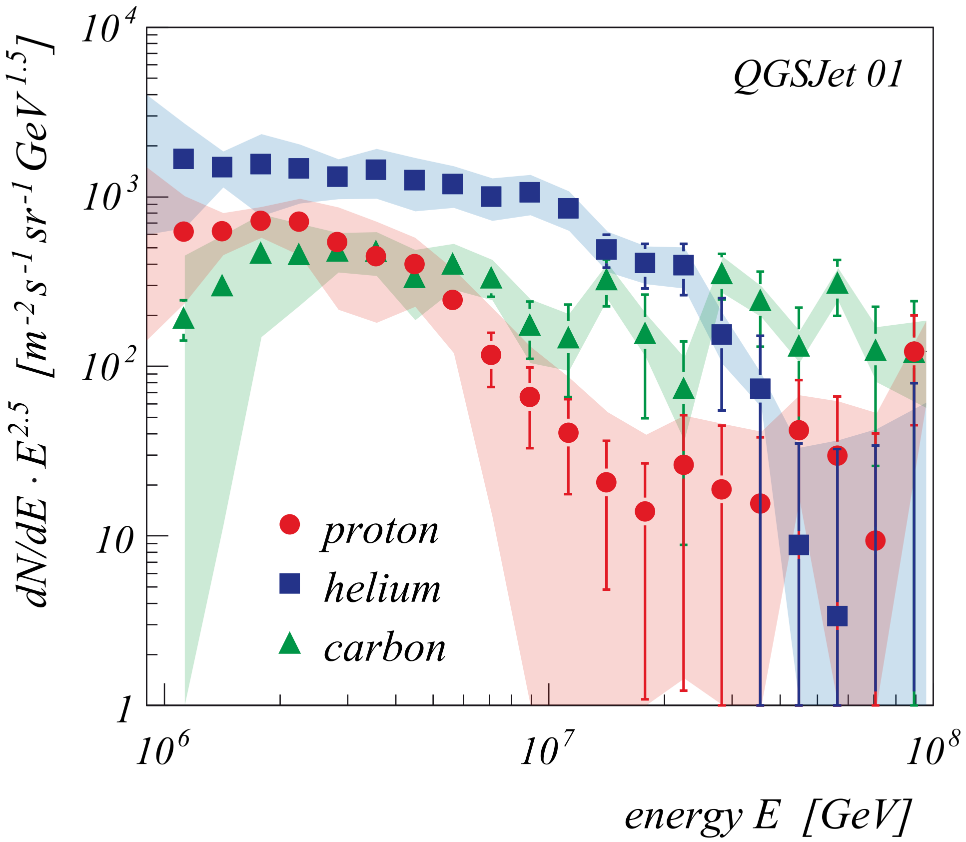


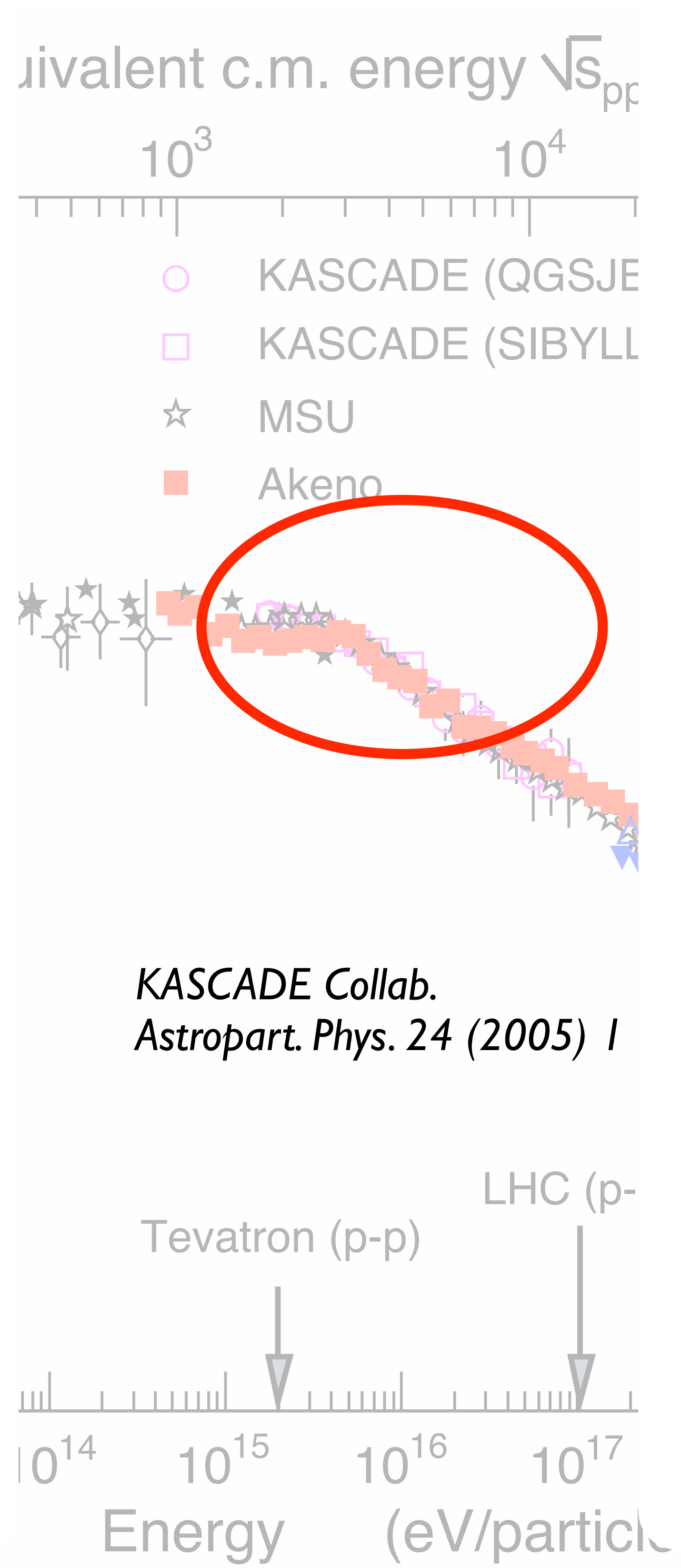
Area ~ 0.04 km^2,
252 surface detectors

Composition in Knee region (I)

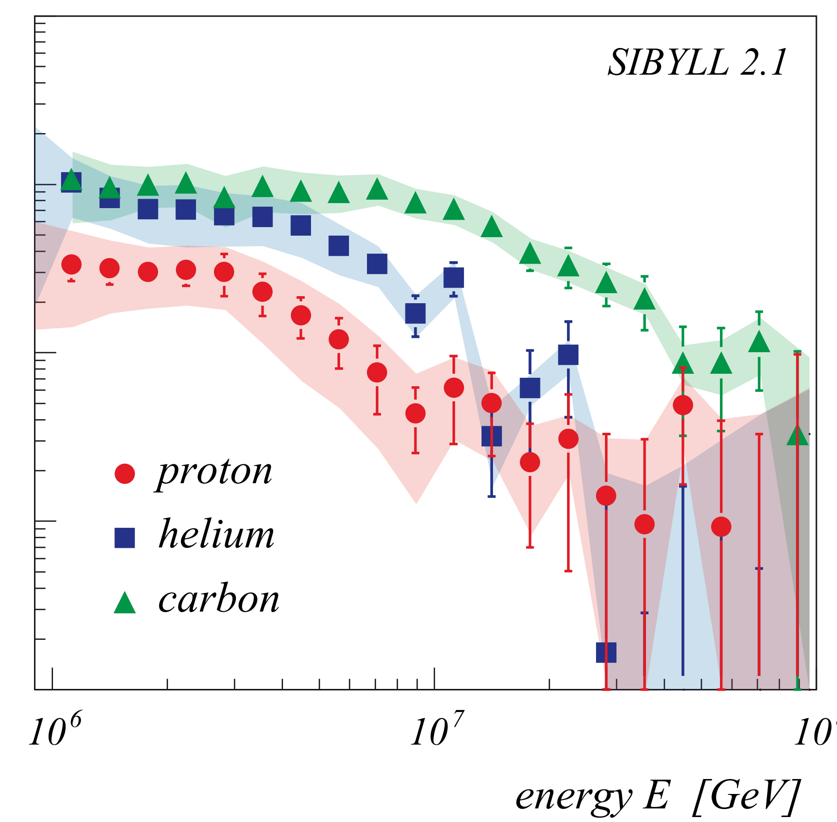


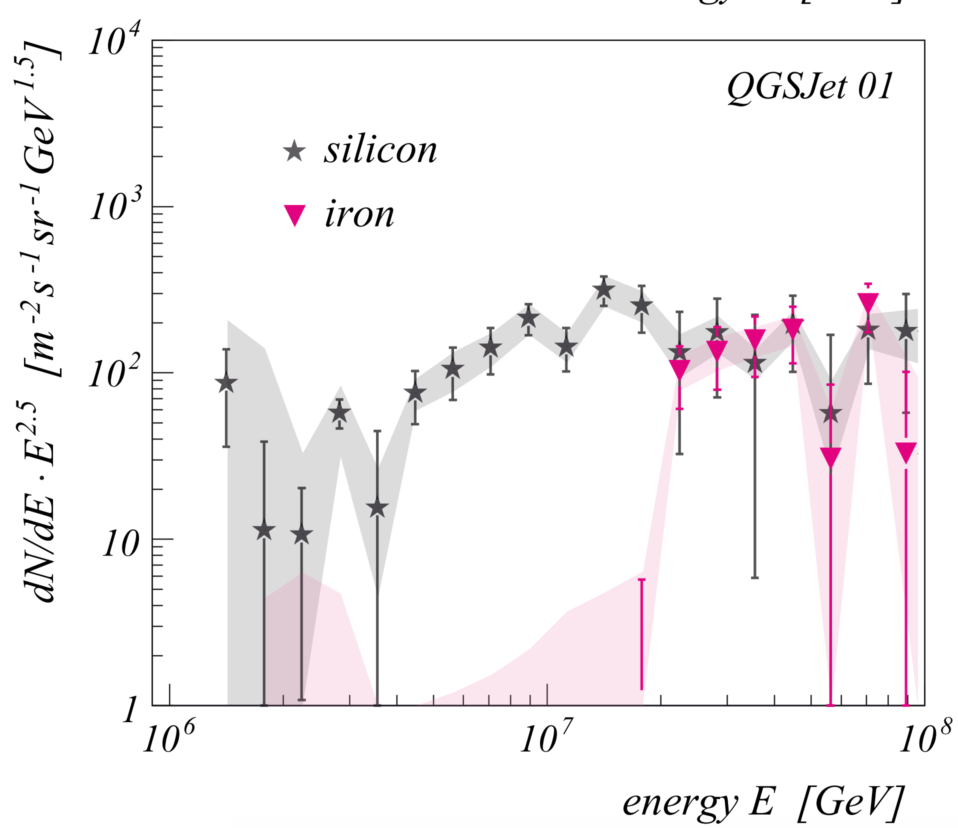
Composition in Knee region (I)

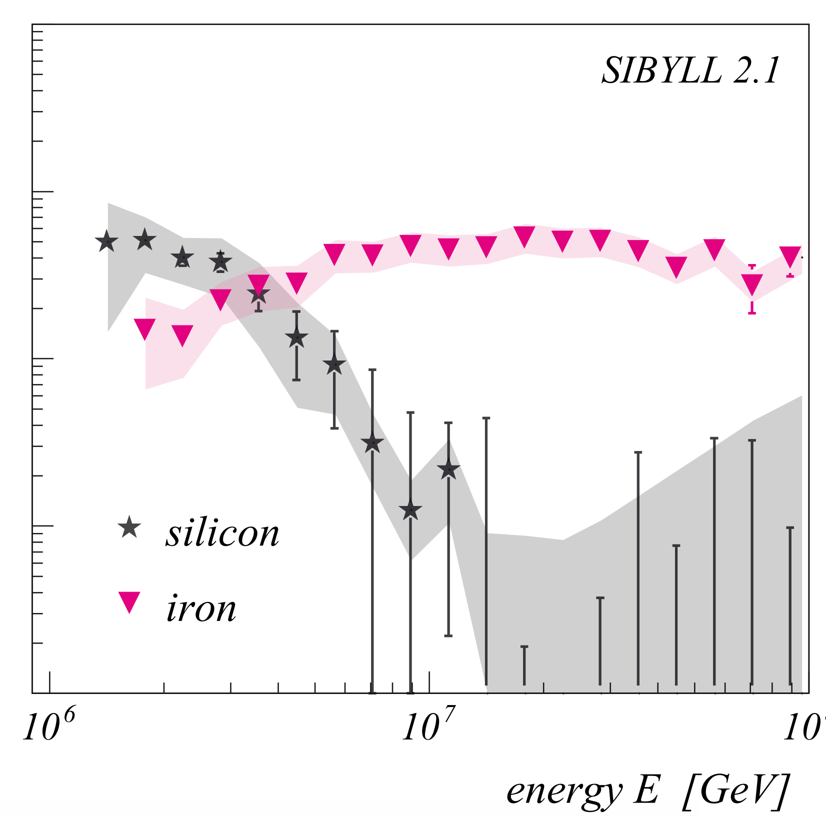




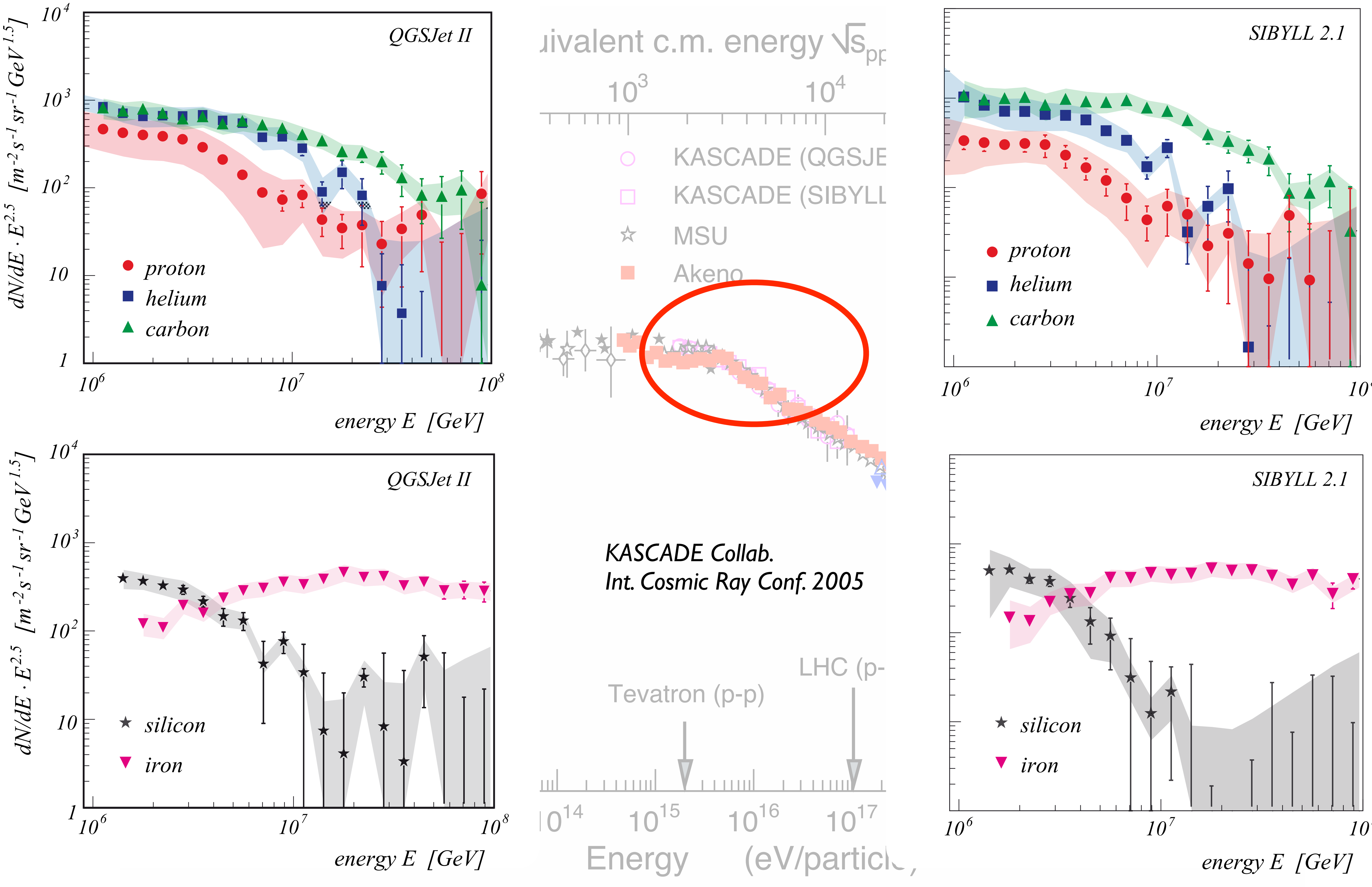
KASCADE Collab.
Astropart. Phys. 24 (2005) 1





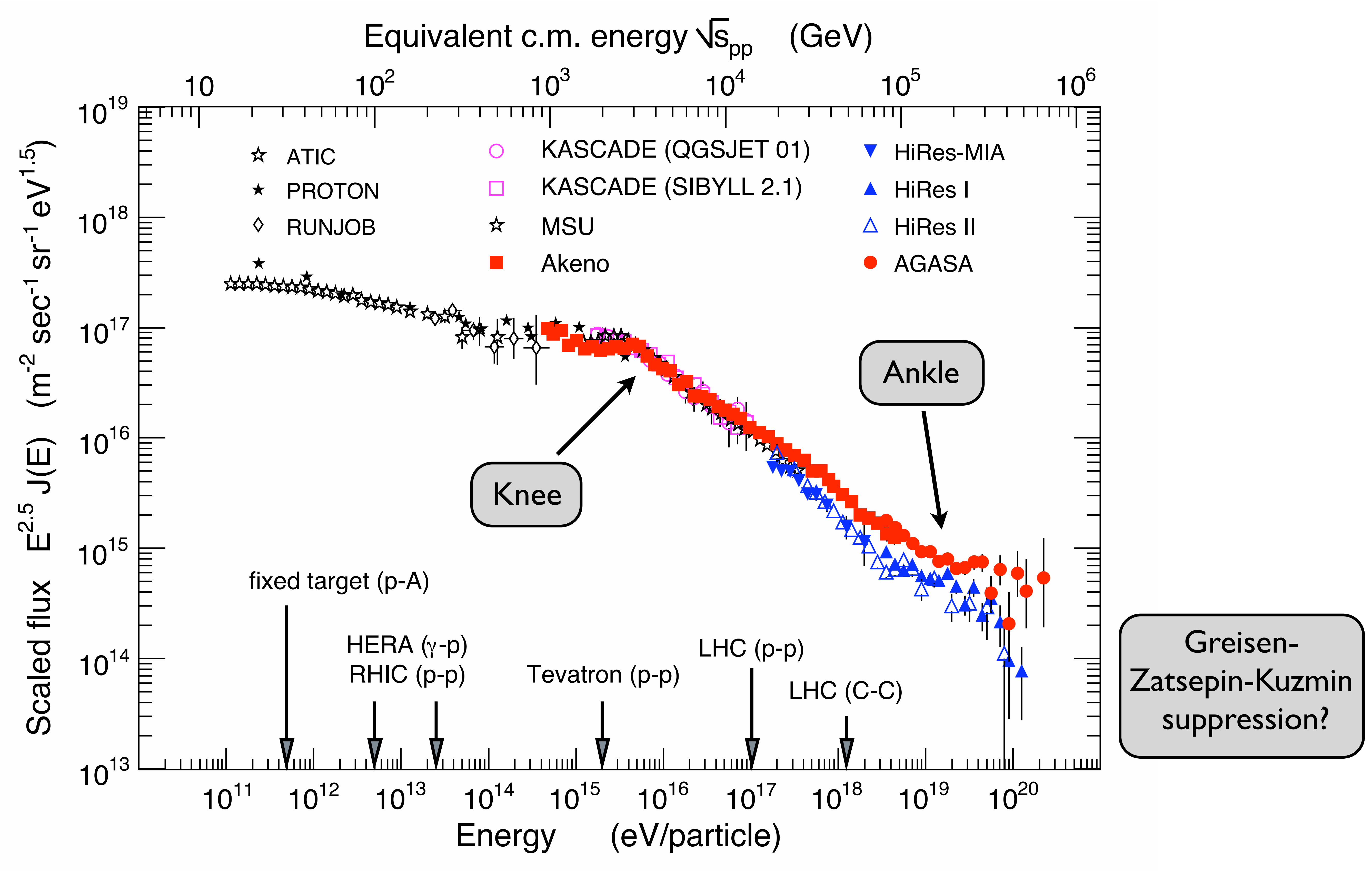


Composition in Knee region (2)

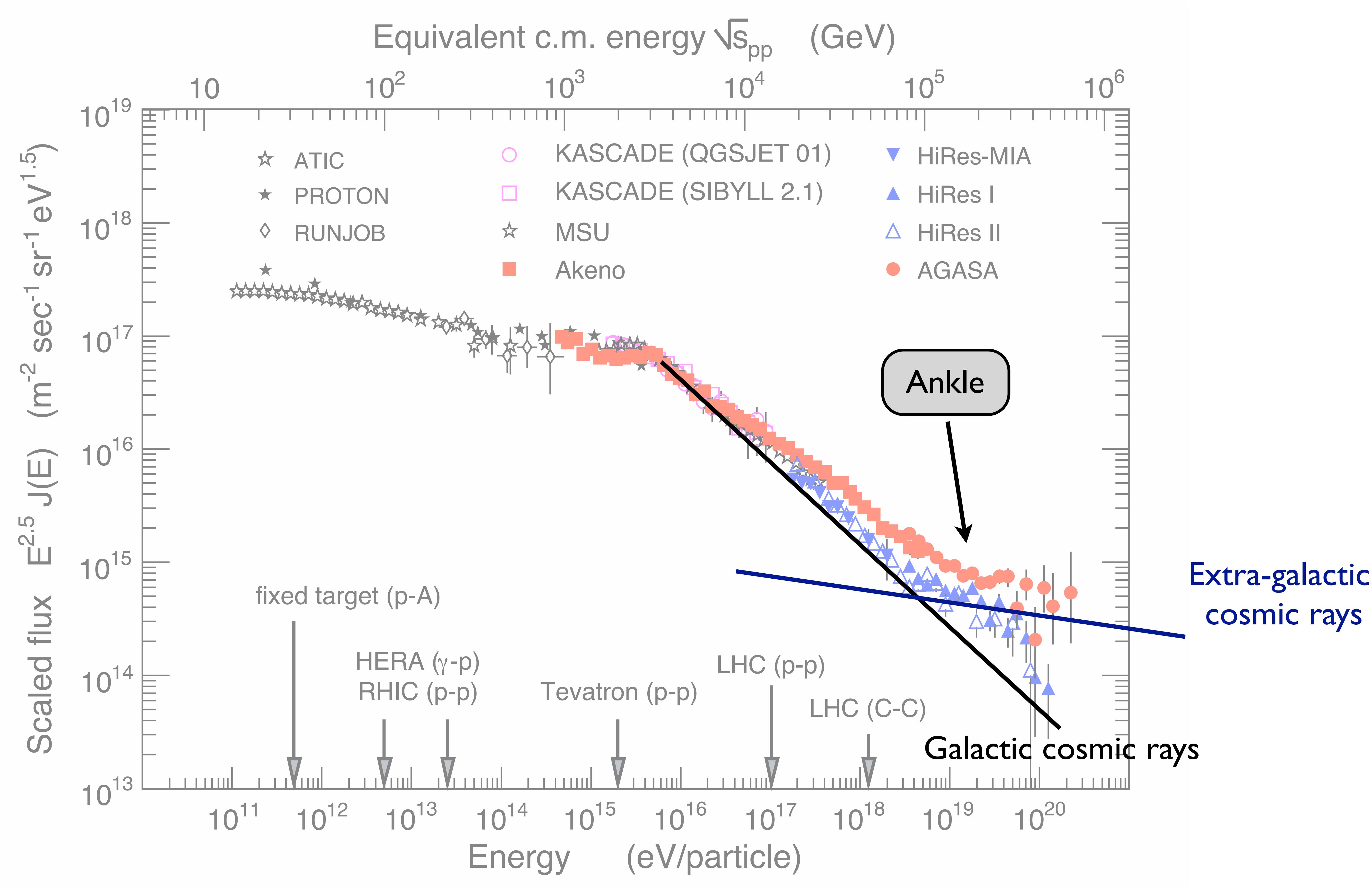


KASCADE Collab.
Int. Cosmic Ray Conf. 2005

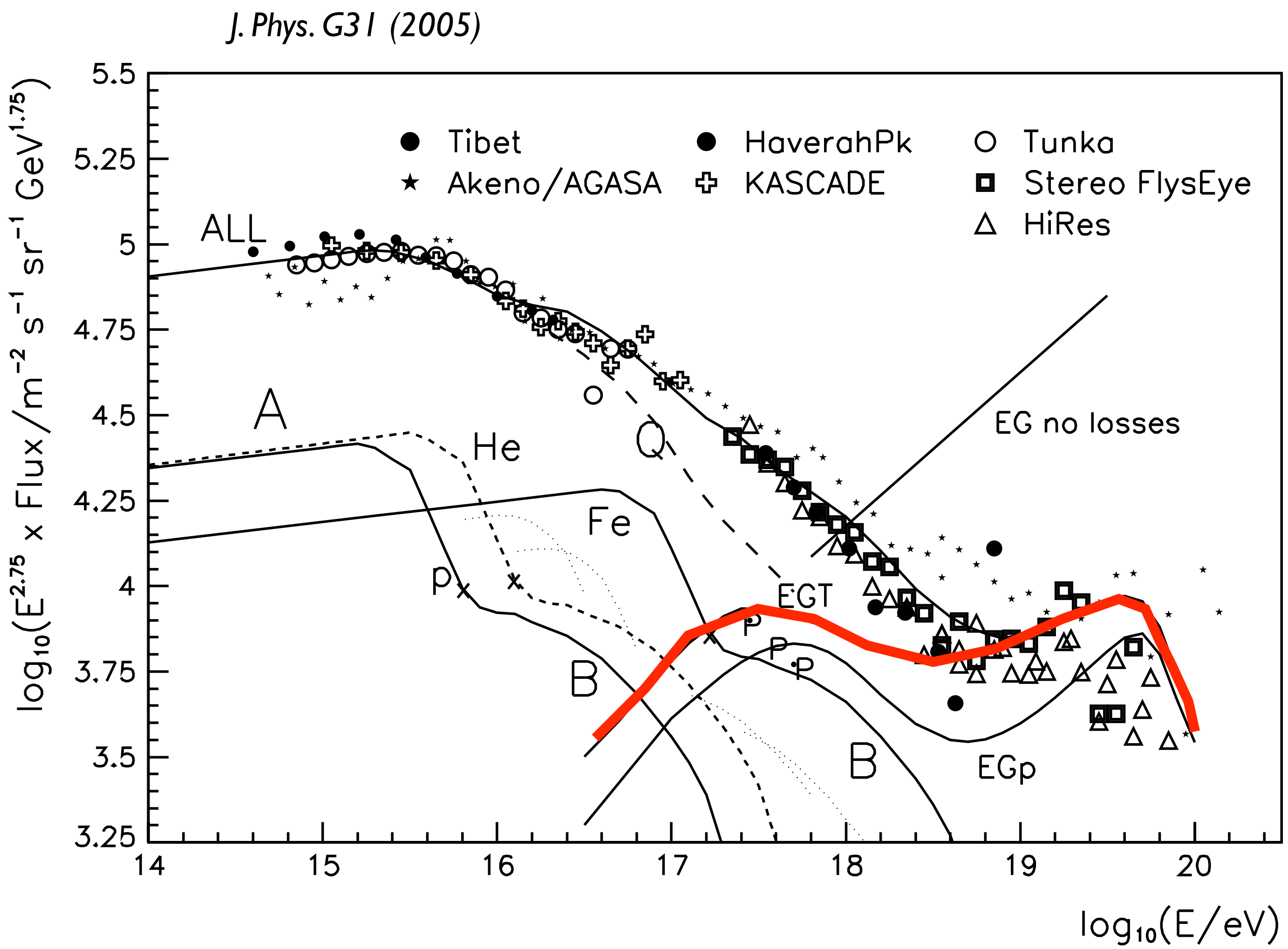
Primary cosmic ray flux



Primary cosmic ray flux: Ankle

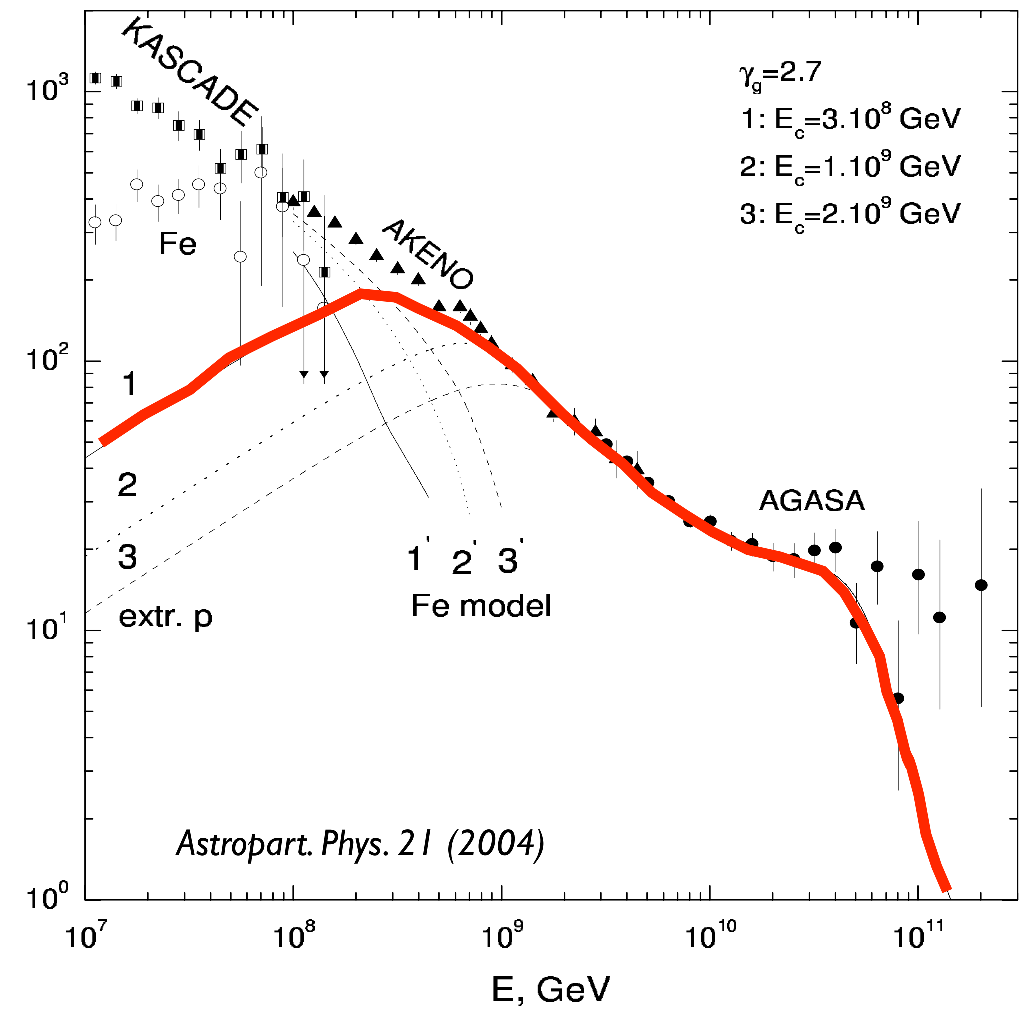


Ankle: possible interpretations



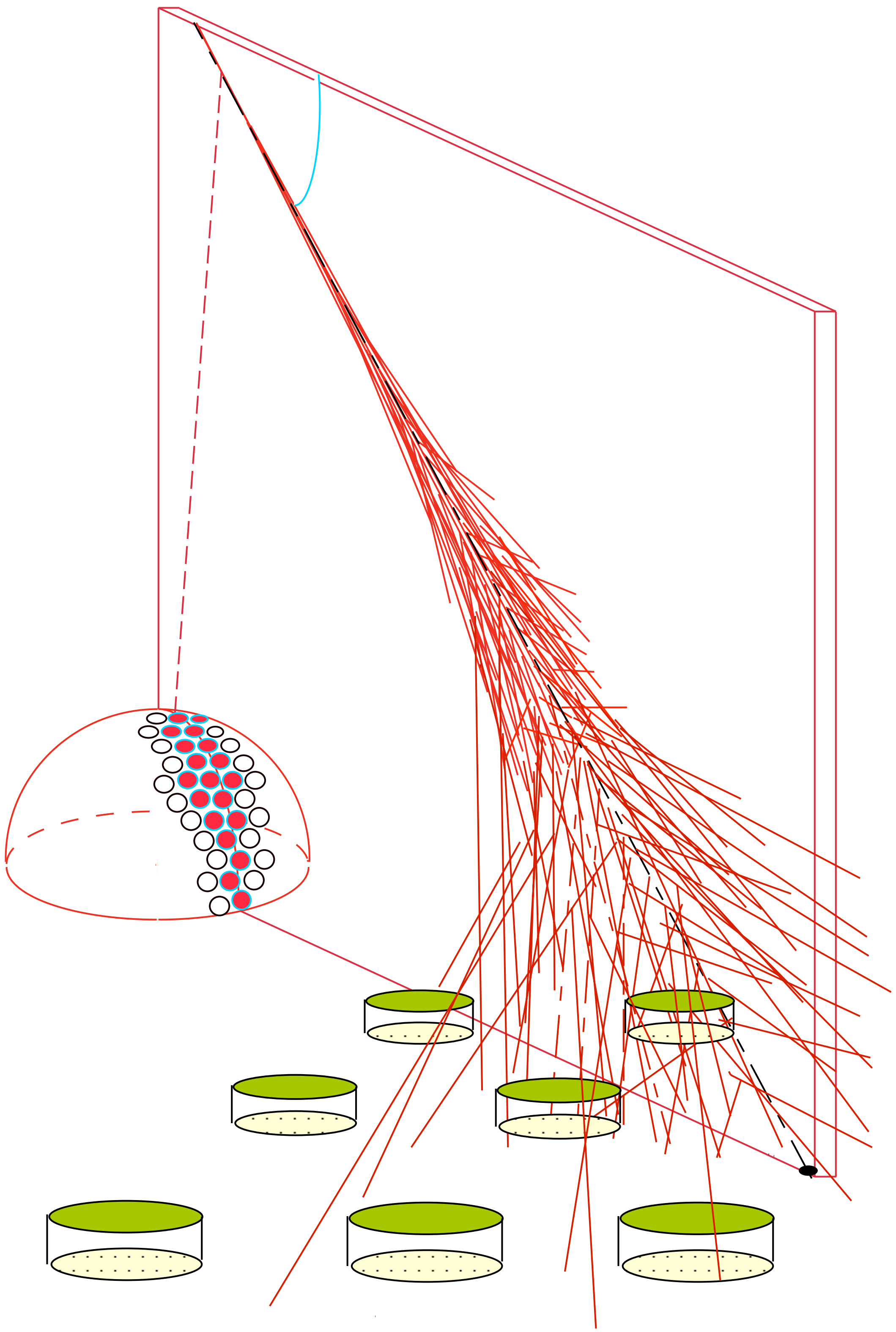
Hillas:
- Ankle is transition galactic to extragalactic cosmic rays
- Injection spectrum $dN/dE \sim E^{-2.3}$

Berezinsky et al.:
- Ankle is feature due to extragalactic proton propagation
- Injection spectrum $dN/dE \sim E^{-2.7}$

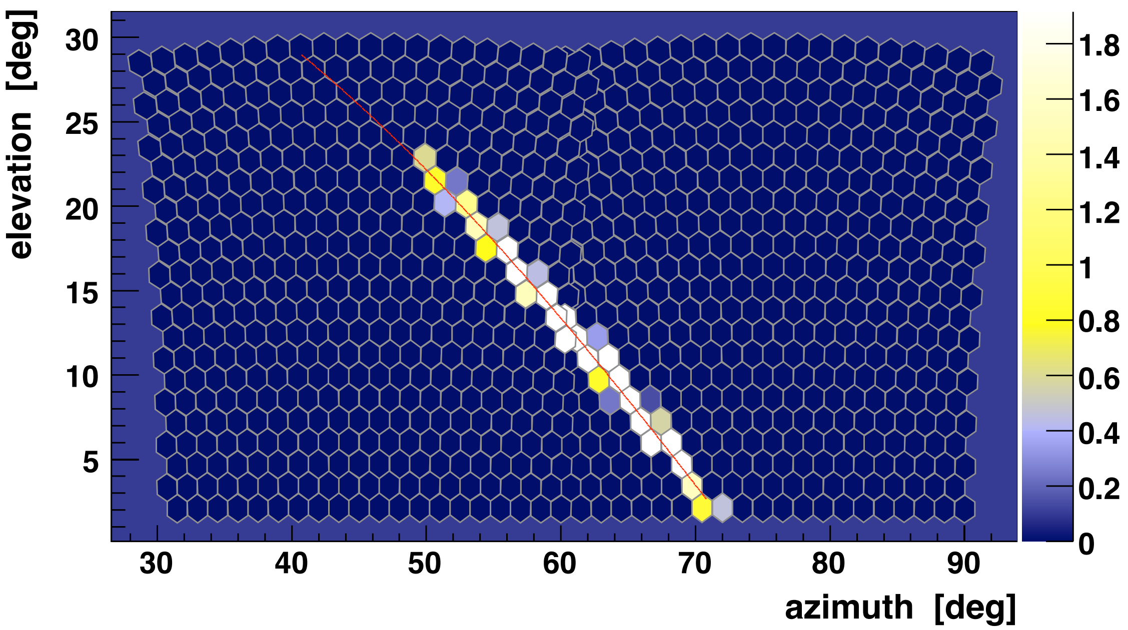


Elemental composition different

Fluorescence telescopes



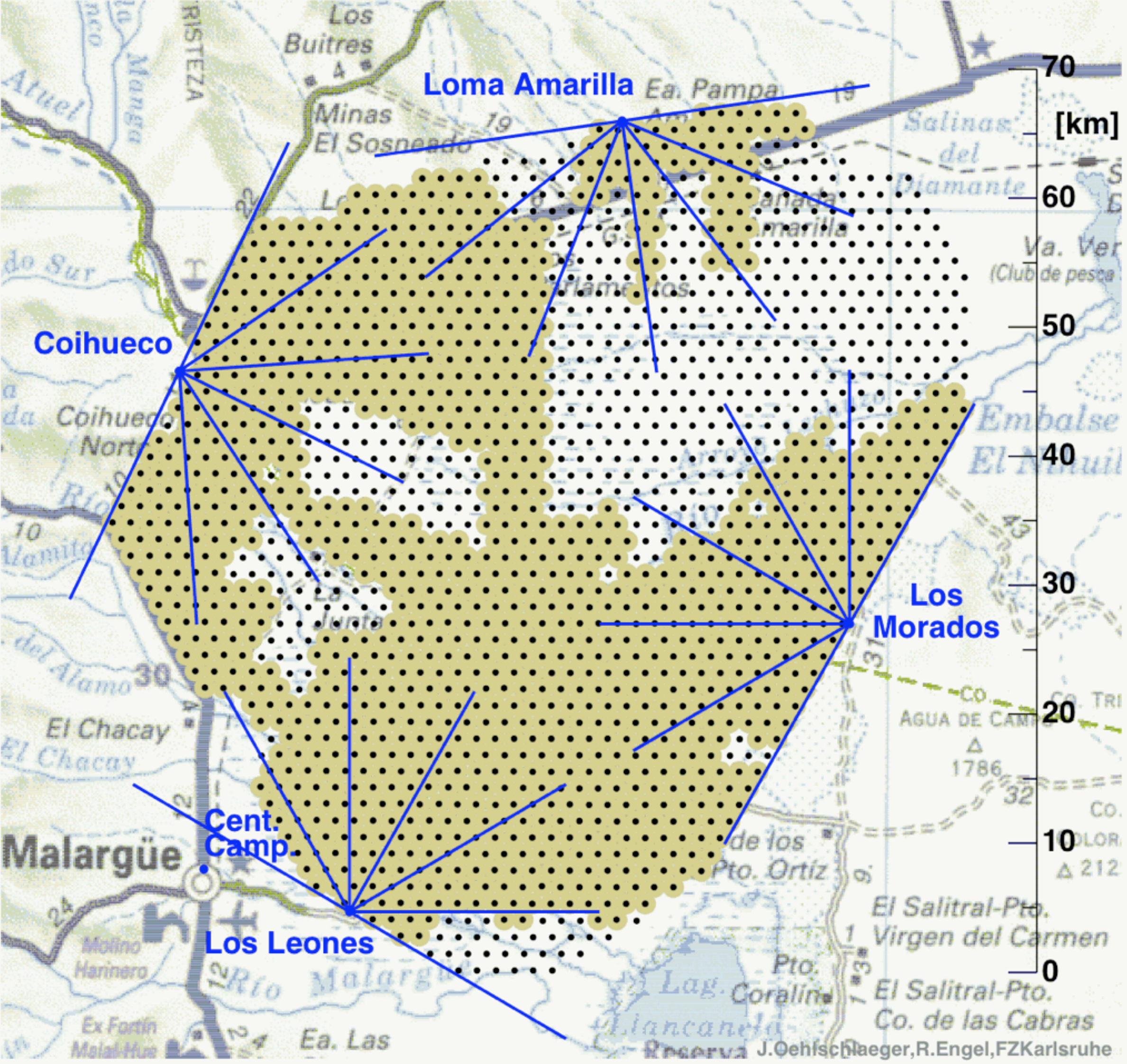
Example: Auger two-mirror event



Fluorescence light:

- Number of photons ~ ionization energy deposit
- Photons emitted isotropically
- Calorimetric energy measurement
- Shower profile measurement

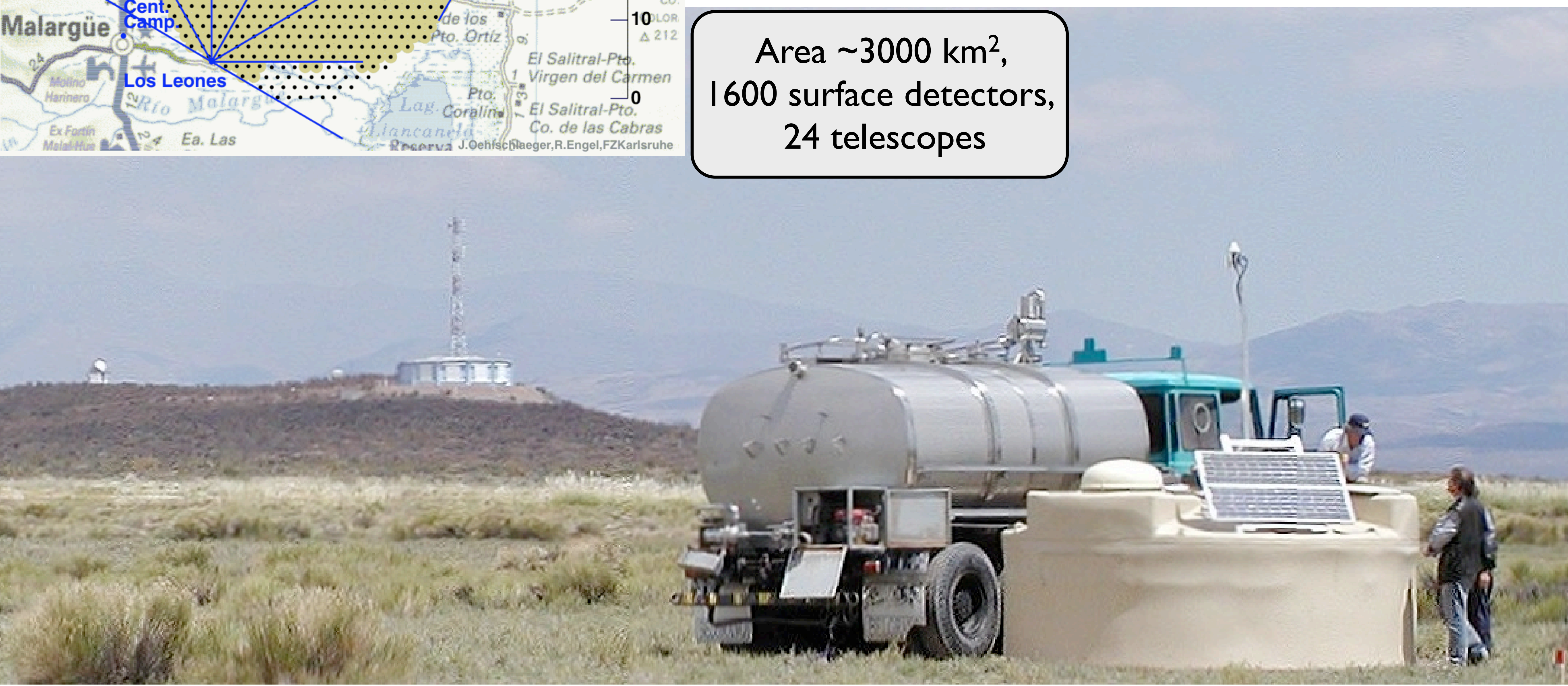
- Monitoring of atmospheric conditions
- Aperture depends on shower energy
- Good reconstruction of shower geometry needed



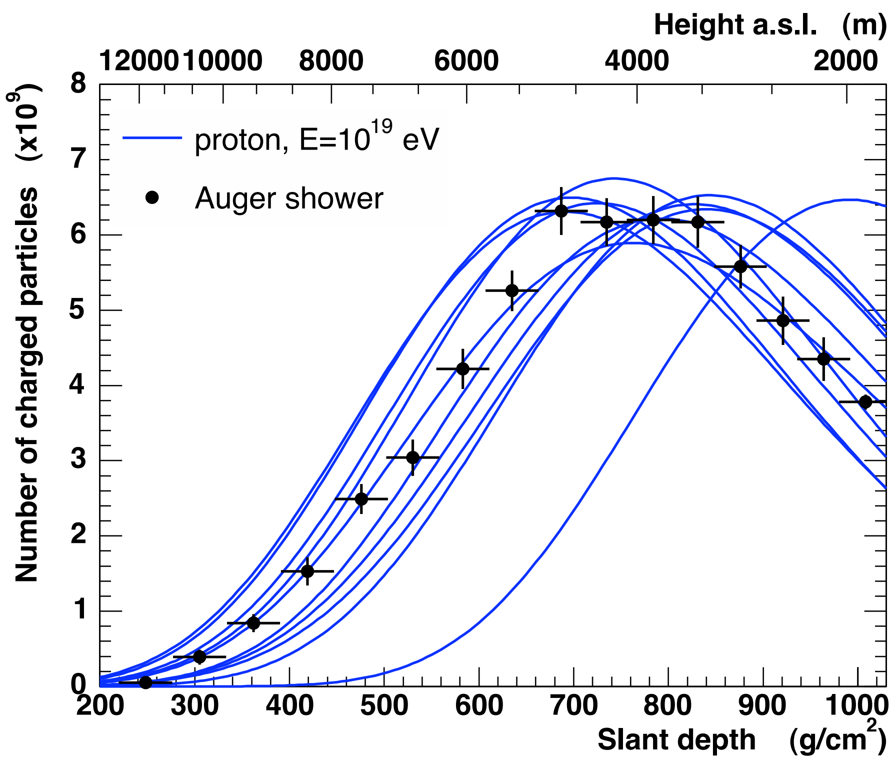
Southern Pierre Auger Observatory

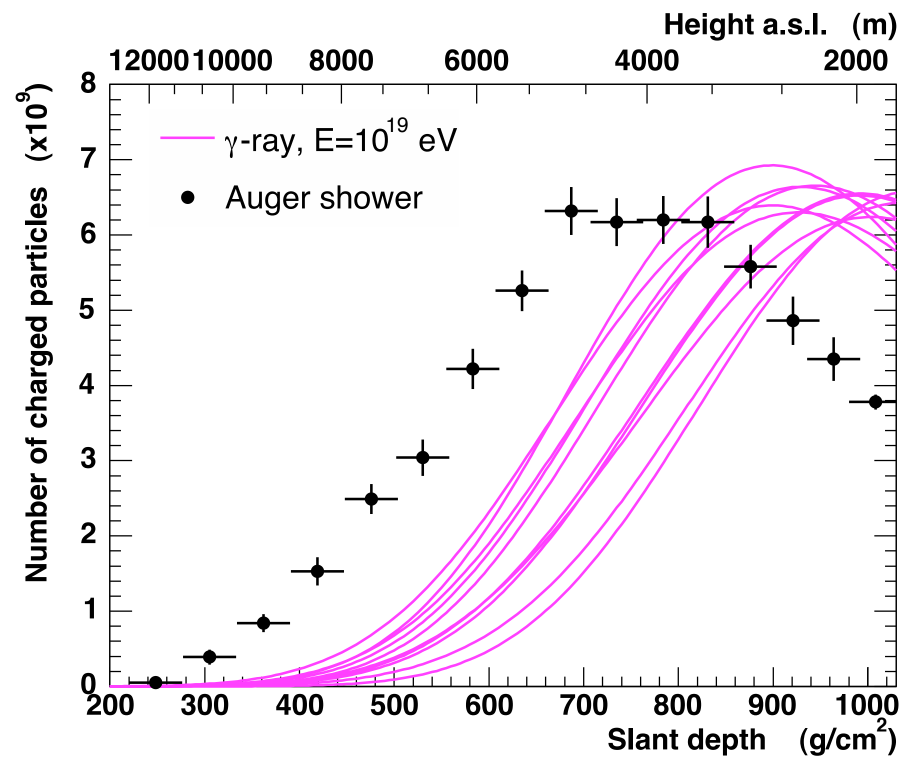
Malargue, Argentina

Area ~3000 km^2,
1600 surface detectors,
24 telescopes

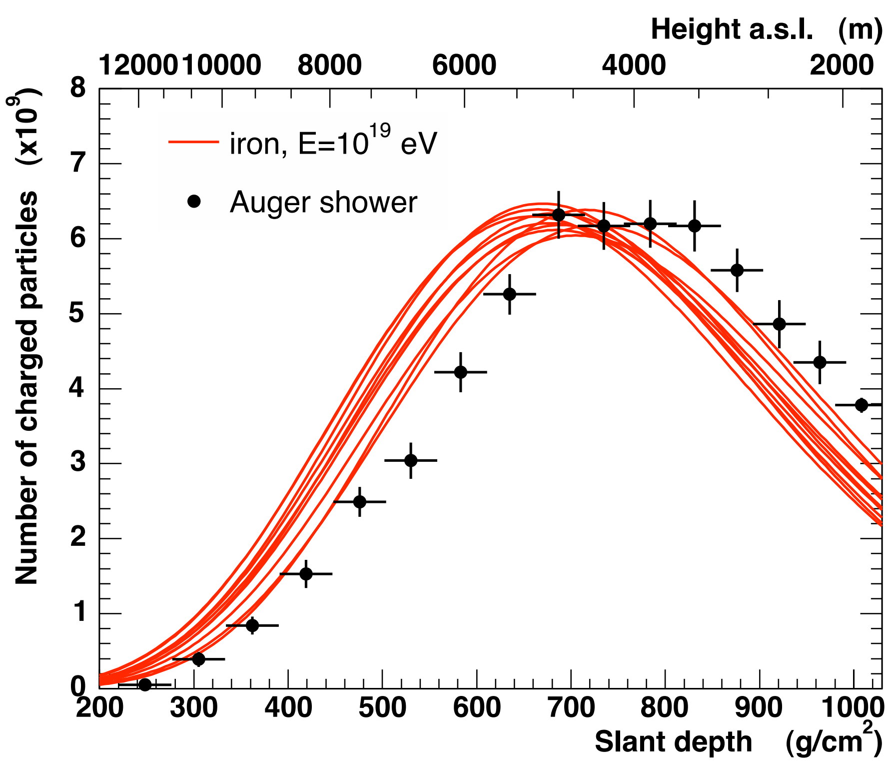


Composition analysis using shower profiles





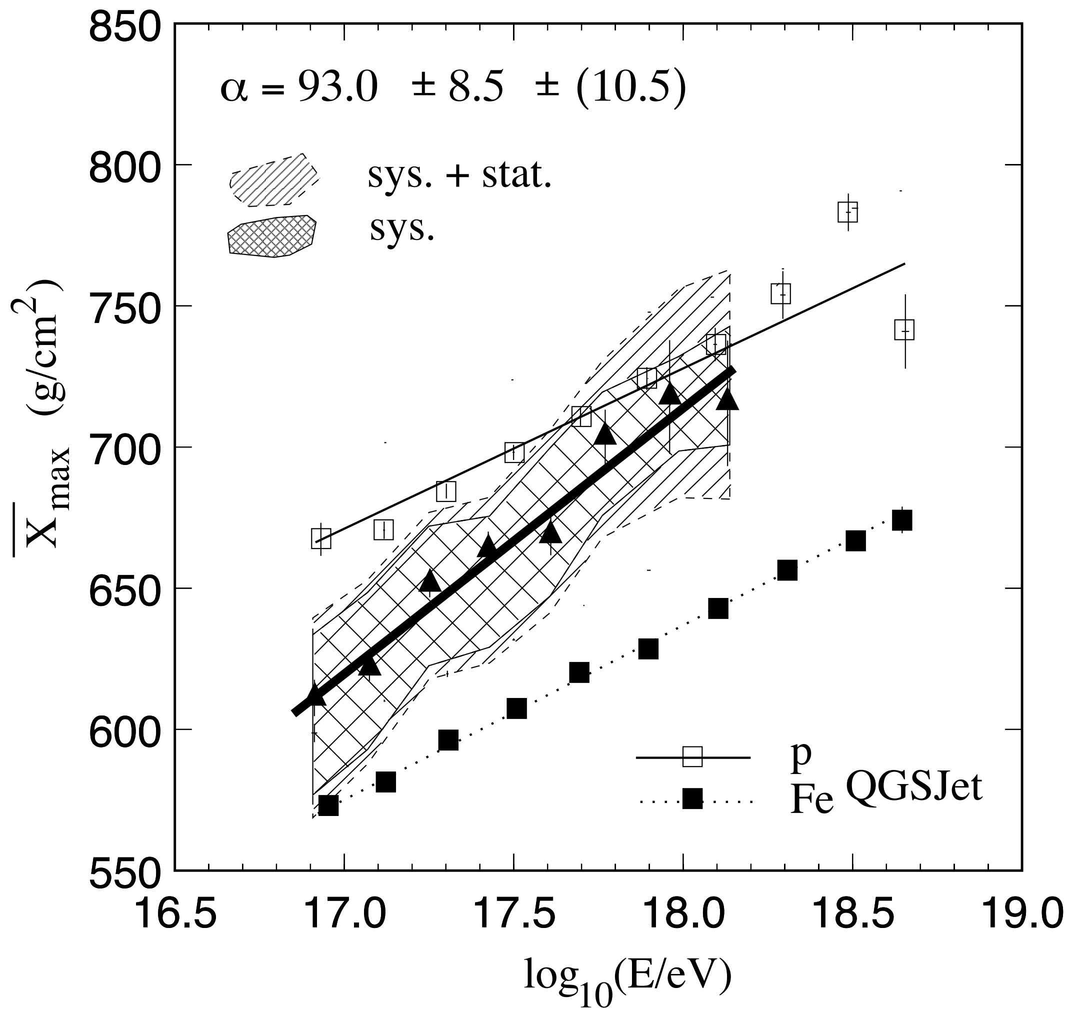
Example: event measured by Auger Collab. (ICRC 2003)

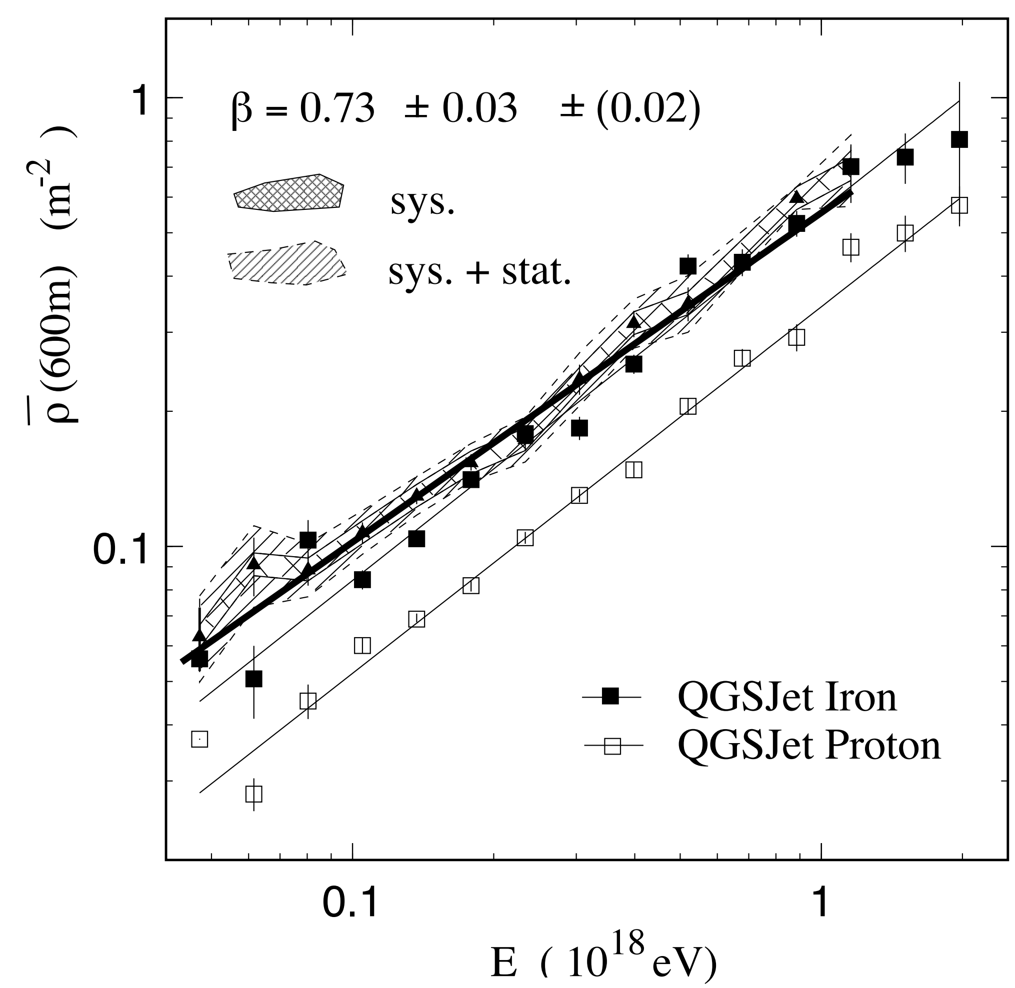


- Energy well determined
- Primary particle type: mean and fluctuations of shower depth of maximum

HiRes prototype & MIA measurement

HiRes Fly's Eye and MIA Collabs., Phys. Rev. Lett. 84 (2000) 4276



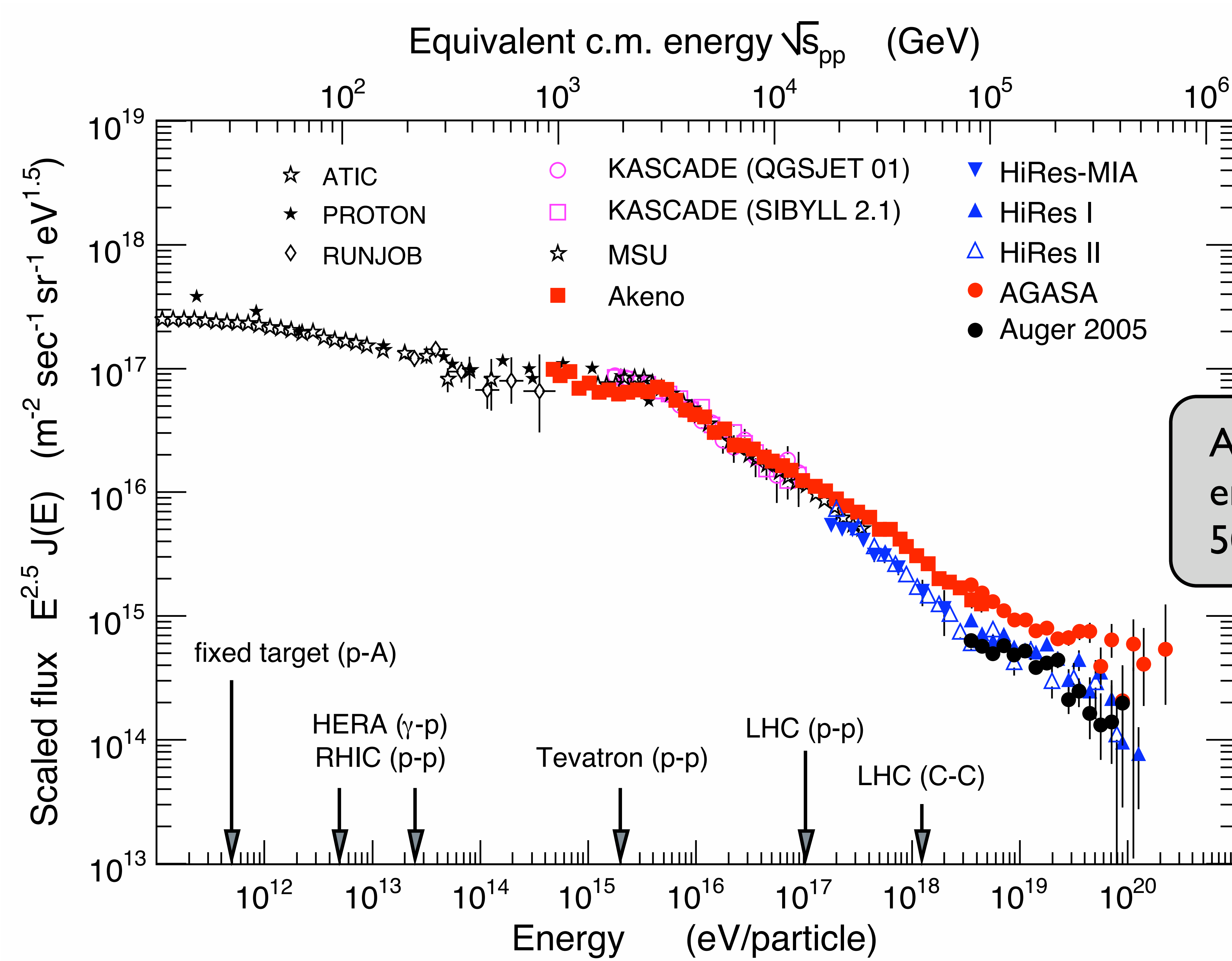


Depth of shower maximum: fast transition from heavy to light composition

↔

Muon density measurement at 600m from shower core:
very heavy primary particle expected

Cosmic ray flux: first Auger data



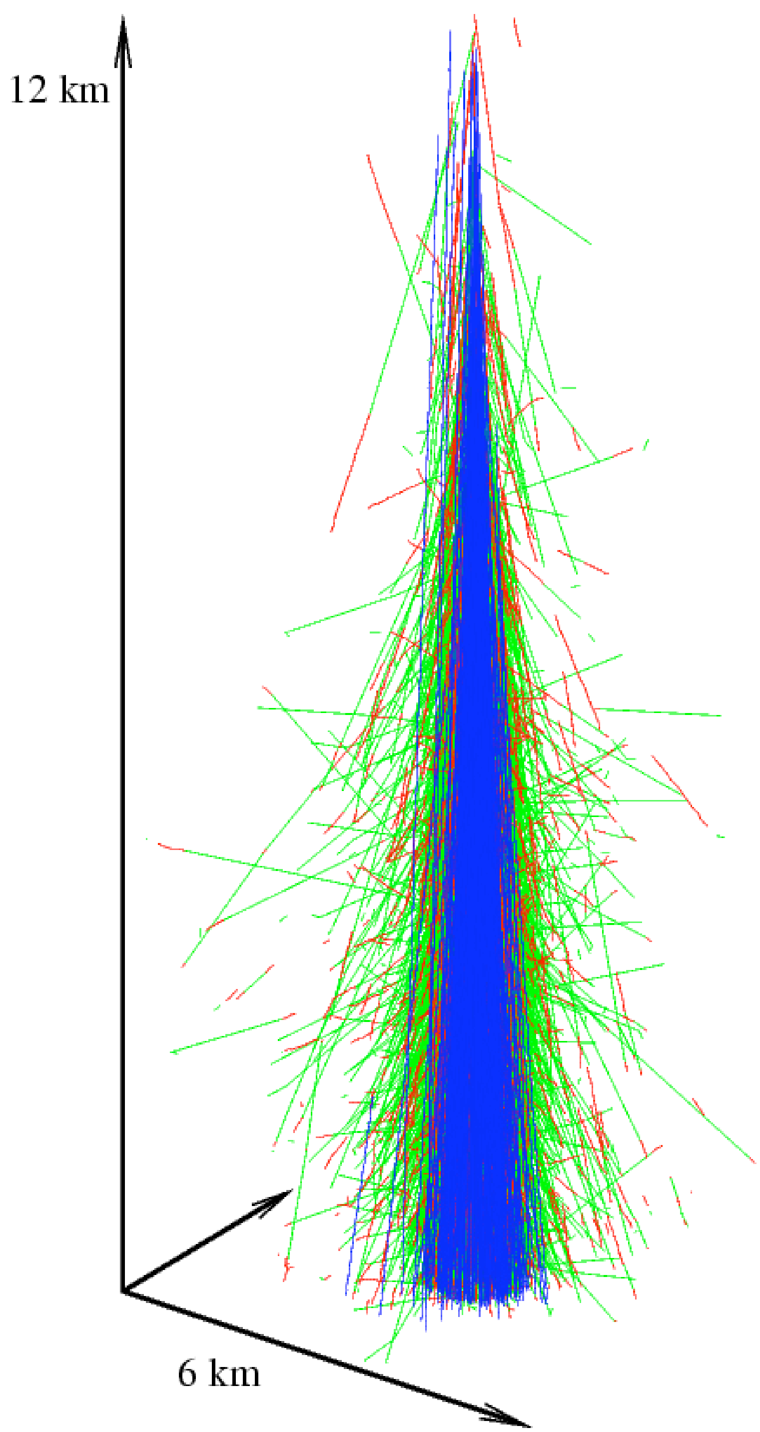
Auger Collab. astro-ph/0507150

Auger: still large sys. energy uncertainty (30% - 50%) and low statistics

Within sys. uncertainty of energy calibration

Simulation: particles at ground correspond to 25% higher shower energy than measured shower profile

Hadronic interaction models



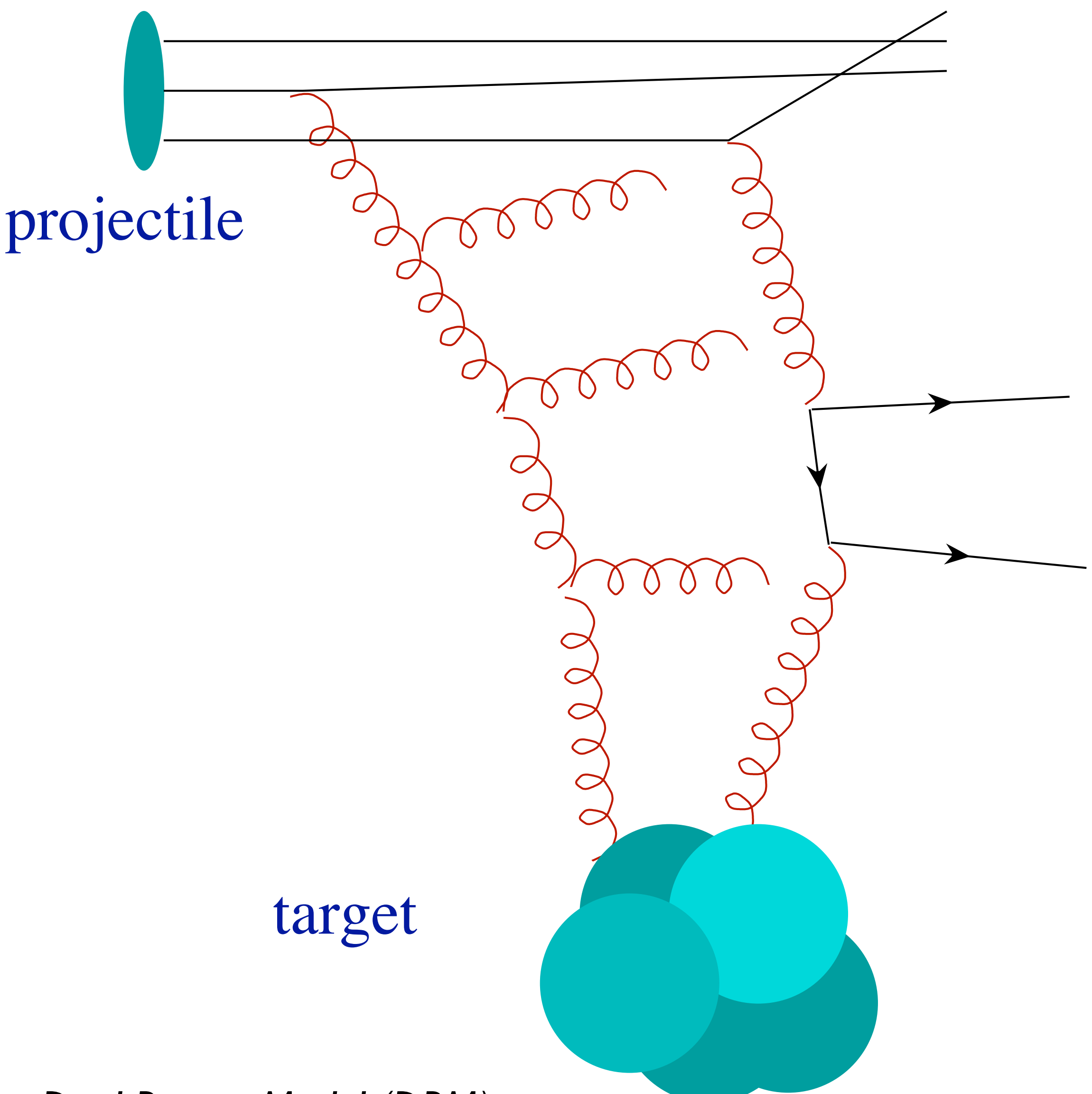
High-energy models:

- DPMJET II.5 and III
  (Ranft / Roesler, RE, Ranft)
- neXus 2 and 3
  (Drescher, Hladik, Ostapchenko, Pierog, Werner),
- EPOS *(Pierog, Werner)*
- QGSJET 01 and II
  (Kalmykov, Ostapchenko)
- SIBYLL 2.1
  (RE, Fletcher, Gaisser, Lipari, Stanev)

Low-/intermediate energy models:

- GHEISHA (GEANT3, Fesefeld)
- FLUKA (Ferrari, Ranft, Roesler, et al.)
- UrQMD (Bleicher, Stöcker, et al.)

Model assumptions



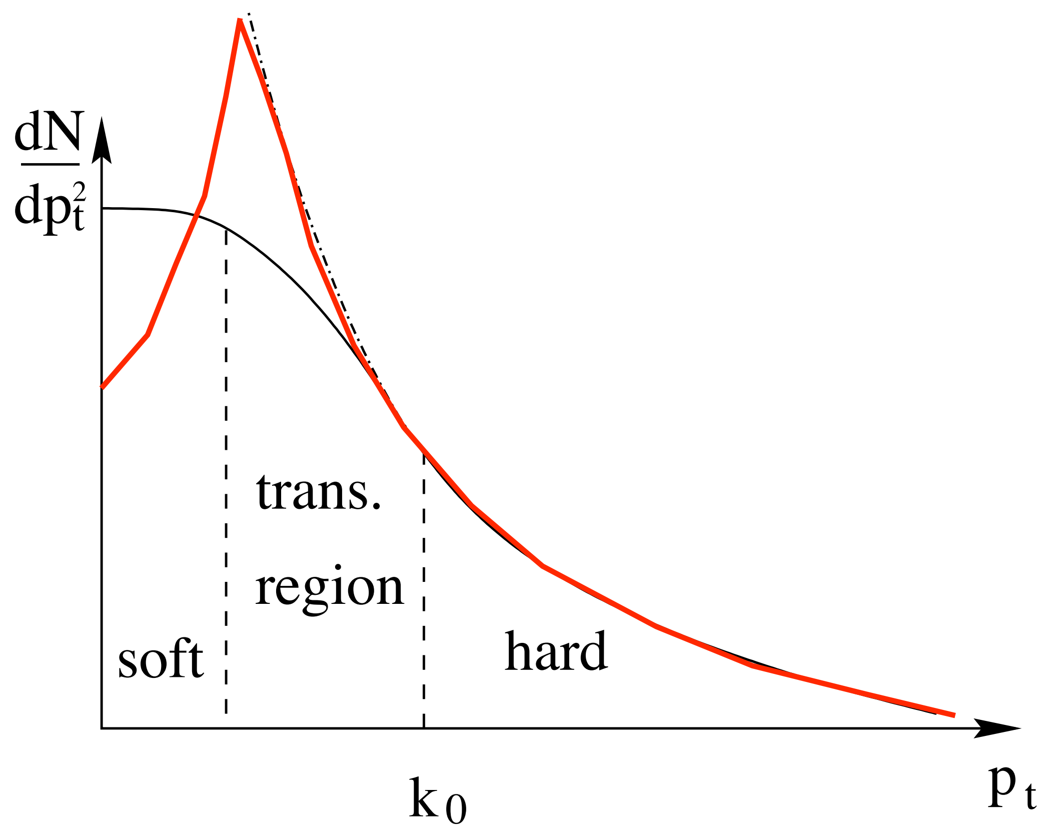
Dual Parton Model (DPM)
Quark-Gluon Strings Model (QGS)

- Gribov-Regge theory (pomeron)
- Minijets (cross section, multiplicity)
- Multiple interactions
- Unitarization of Born amplitudes
- Projectile / target remnants
- Glauber approximation for nuclei

- Many phenomenological model parameters

Examples:
- pQCD pt cutoff (energy-dependence)
- Factorization scale / k-factor
- Energy sharing for hadron remants
- Soft multiple interactions
- Diffraction dissociation

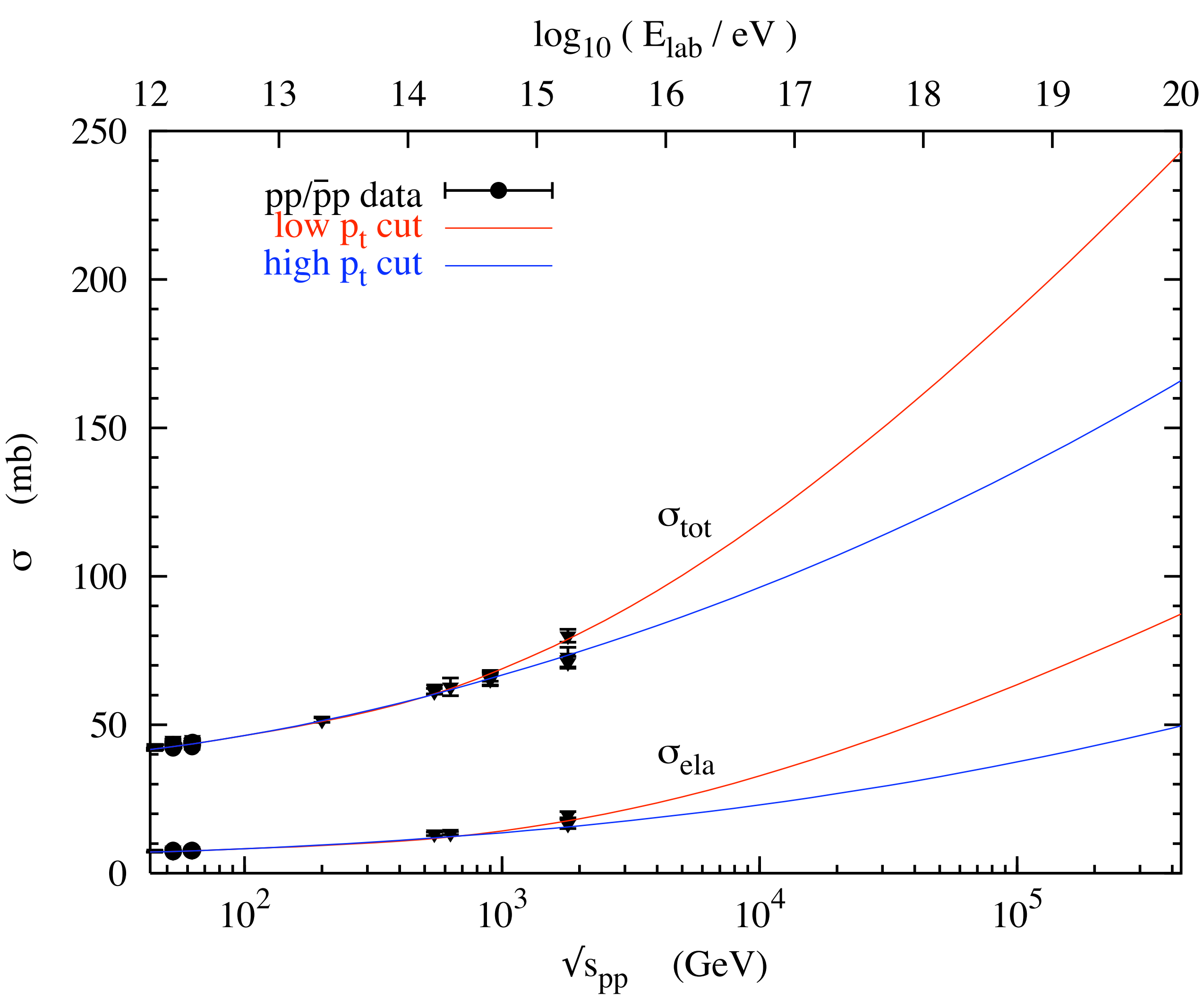
Conceptual problem: matching soft/hard



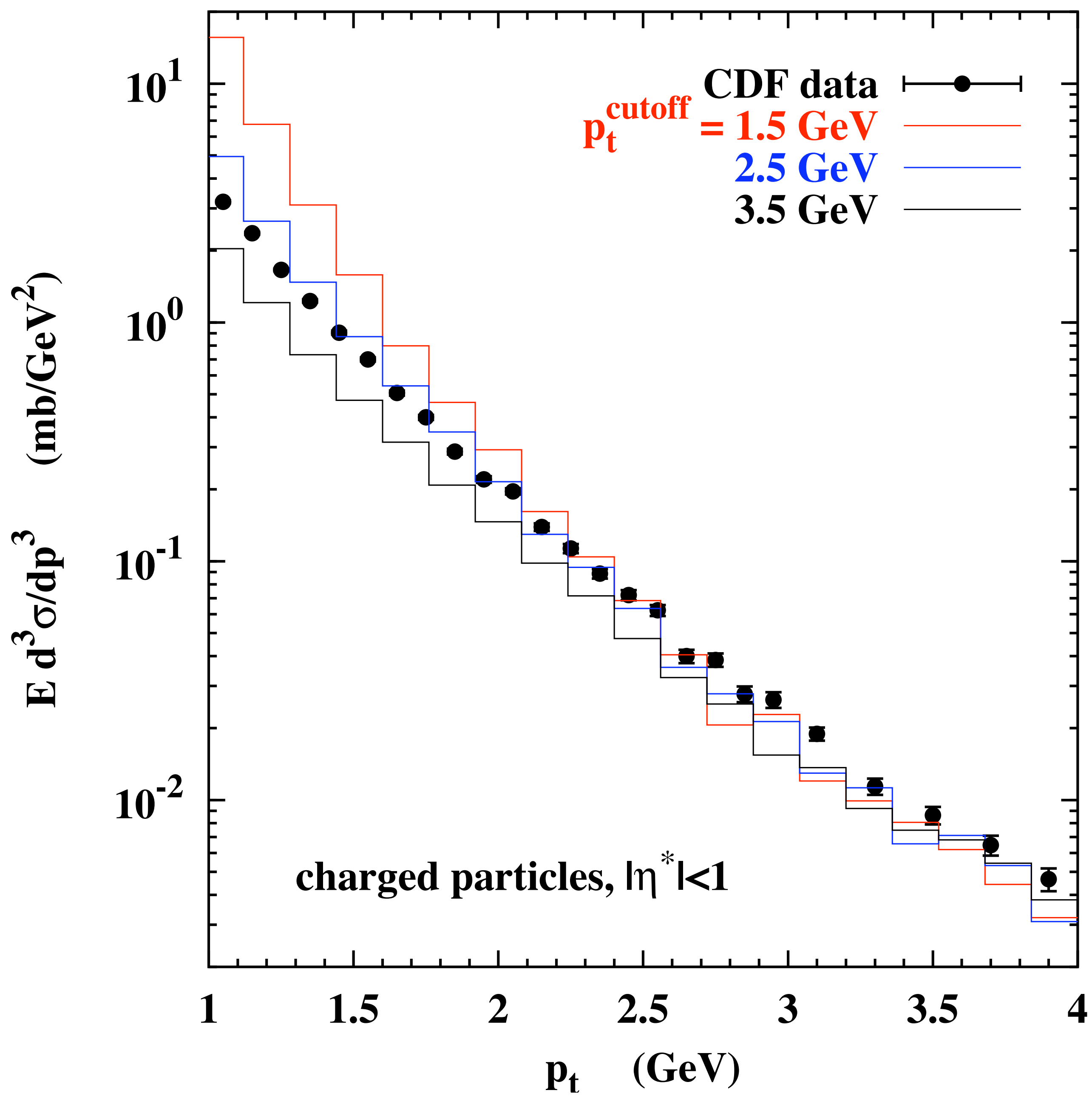
pt cutoff

$\sigma_{soft} \sim s^{0.1}$ $\sigma_{hard} \sim s^{0.3}$

Example: two cross section fits



HERA: parton densities & minijet model



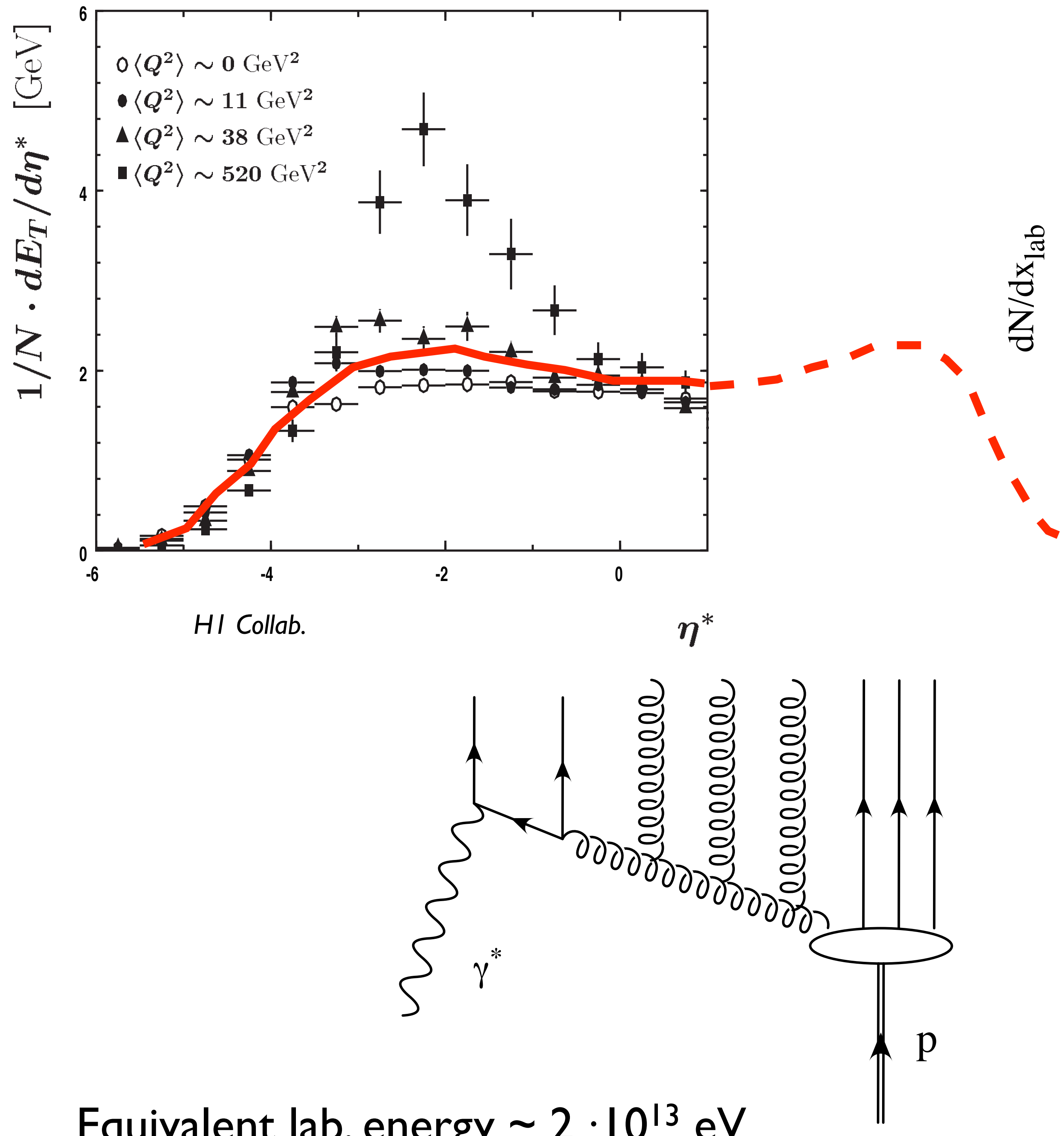
Minijet model unreliable:

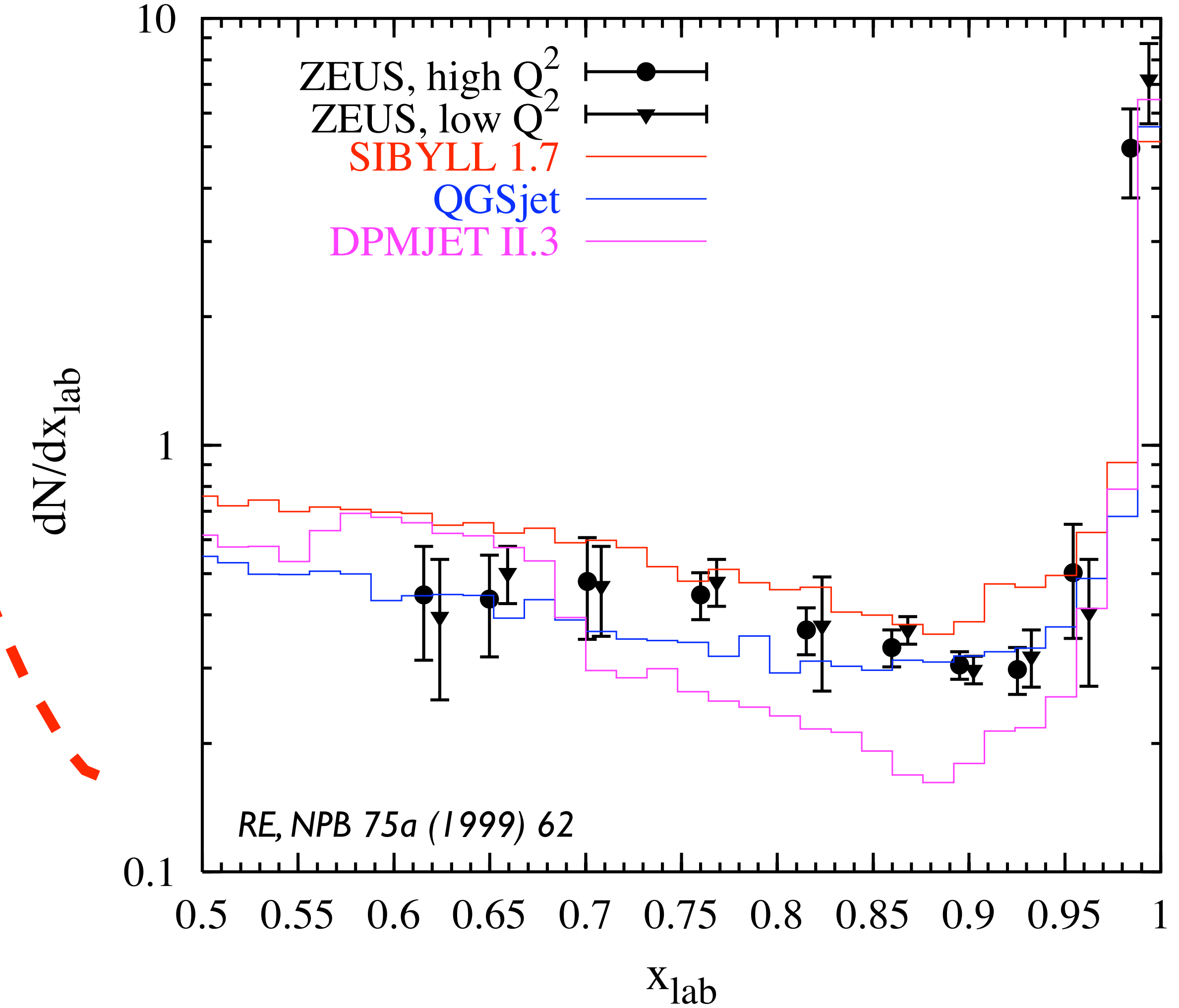
- Steeply rising parton densities
- PQCD seems to describe even semi-hard phenomena
- Saturation phenomena?

- PQCD cutoff cannot be energy-independent (simple model)
- Inclusive pt distribution
- Cross section extrapolation
- Multiplicity (mean & distribution)

- *DPMJET update (new PDFs, energy-dependent pt cutoff, string fusion)*
- *SIBYLL 1.7 → SIBYLL 2.1 (new PDFs, new diffraction, energy-dependent pt cutoff)*
- *QGSJET 01 → QGSJET II (new PDFs, re-summation of enhanced pomeron graphs)*

HERA: leading baryon production (1)



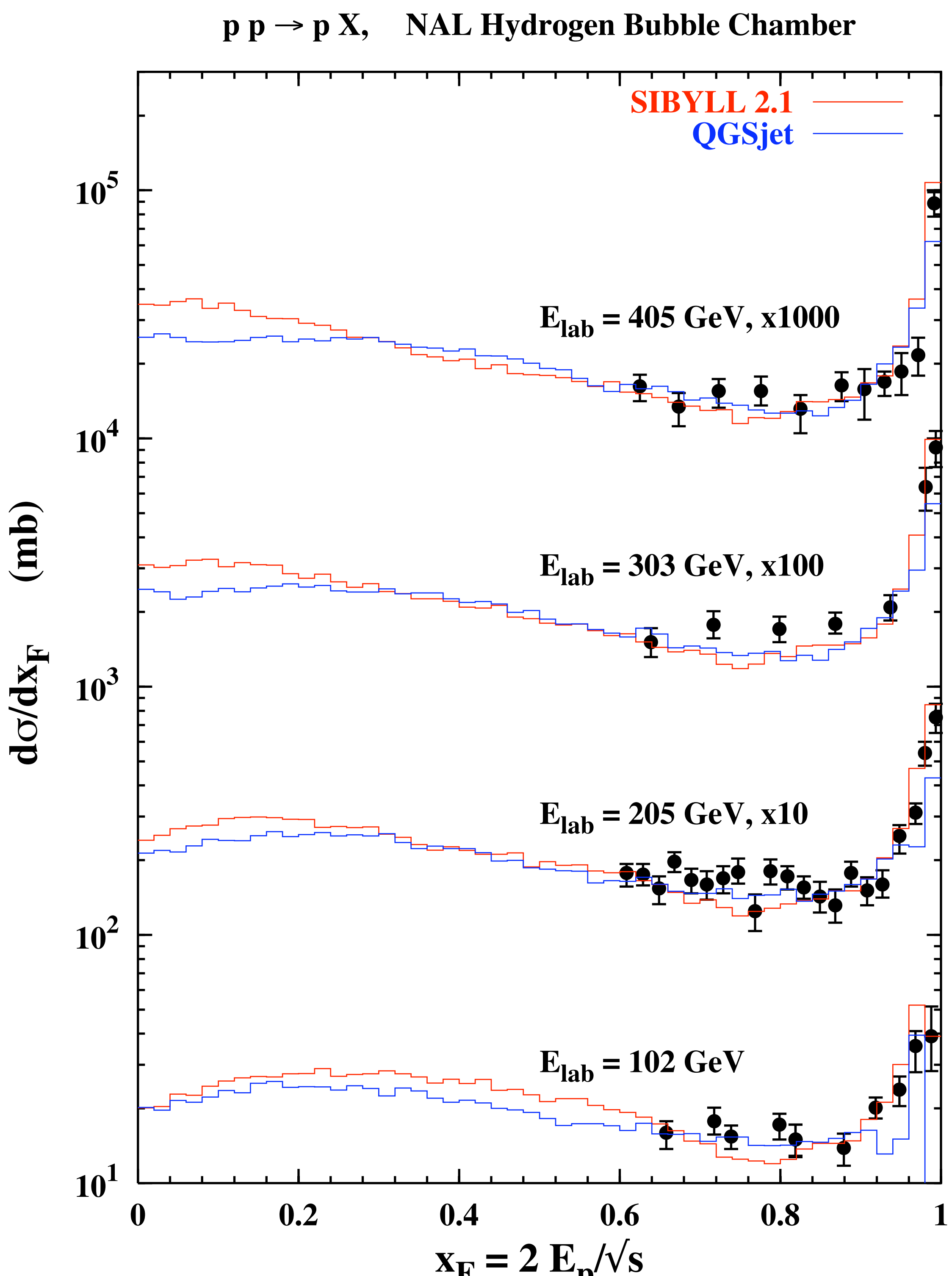


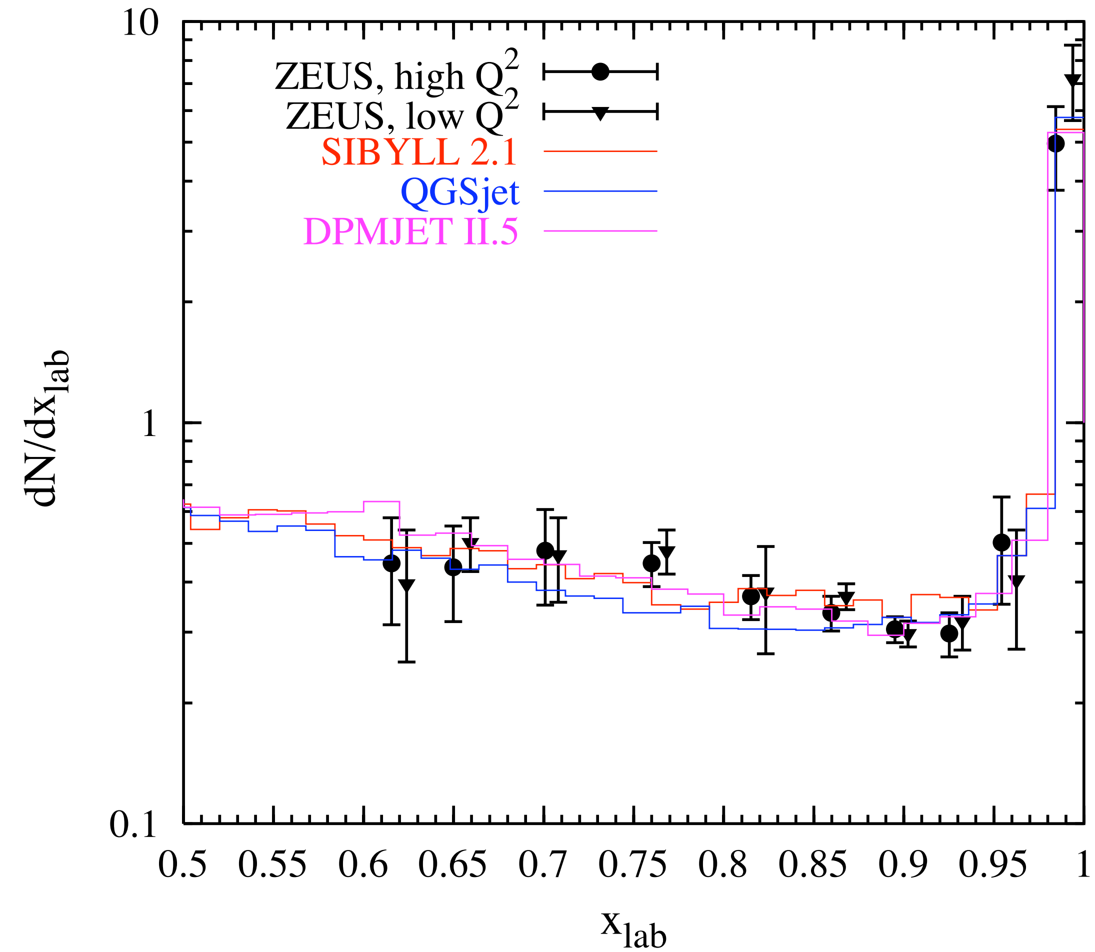
Measurement: γ*-p
Simulation: p-p

No model tuning

Equivalent lab. energy ~ 2 ·10¹³ eV

HERA: leading baryon production (2)



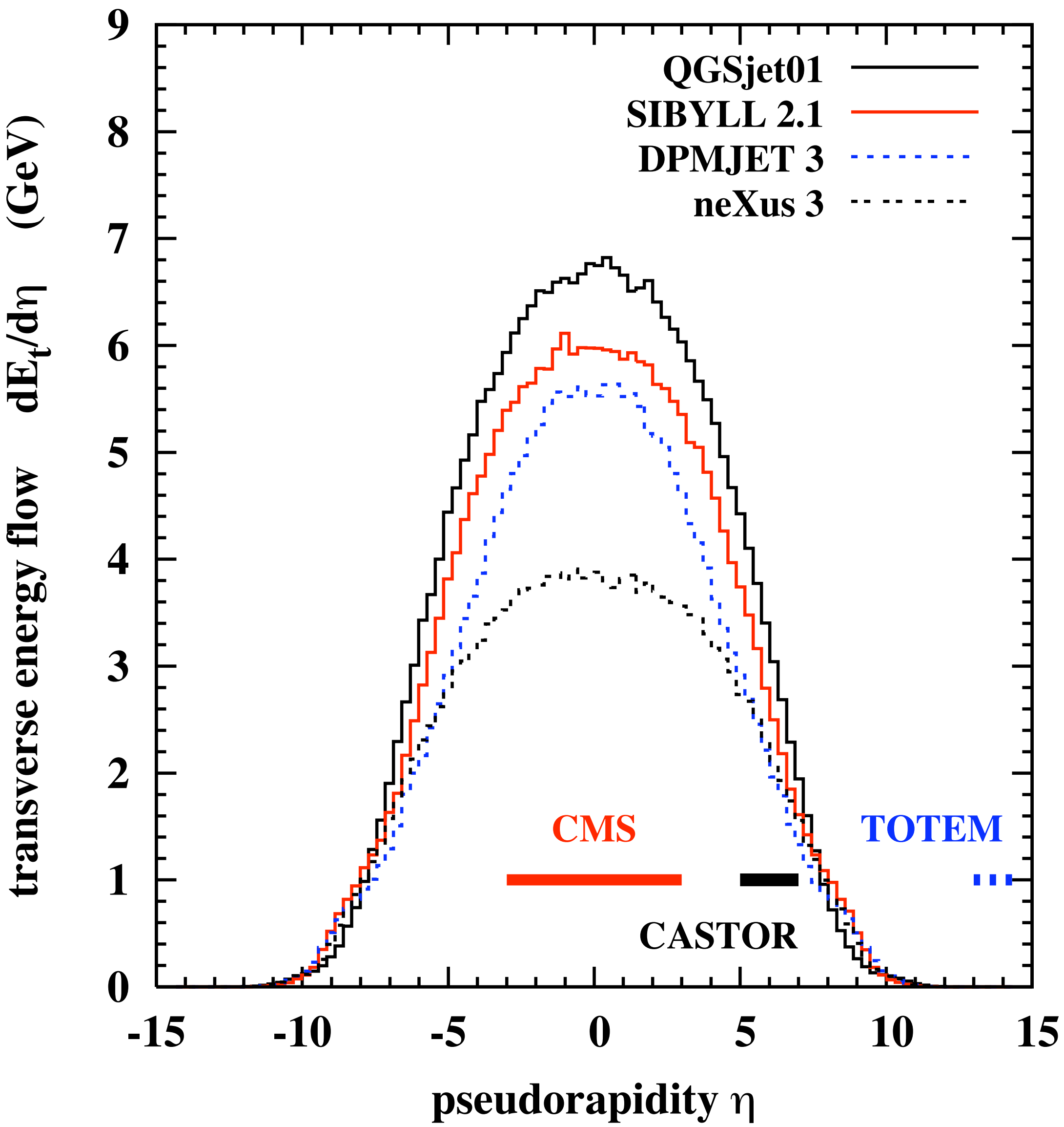


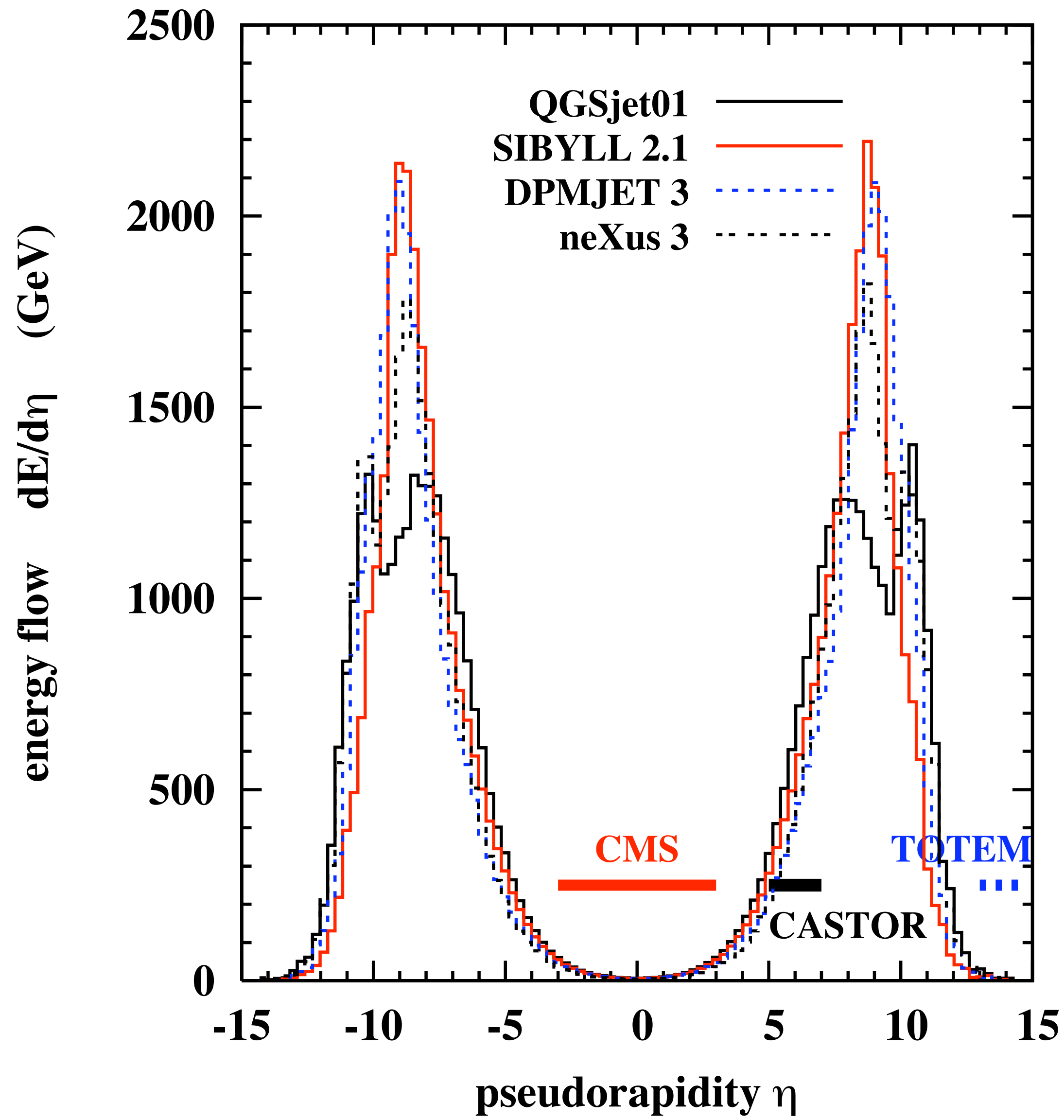
After tuning

Detailed comparison with proton and neutron data in preparation (T. Sloan et al.)

LHC: minimum bias measurements (1)

Simulations: p-p at 14 TeV CMS



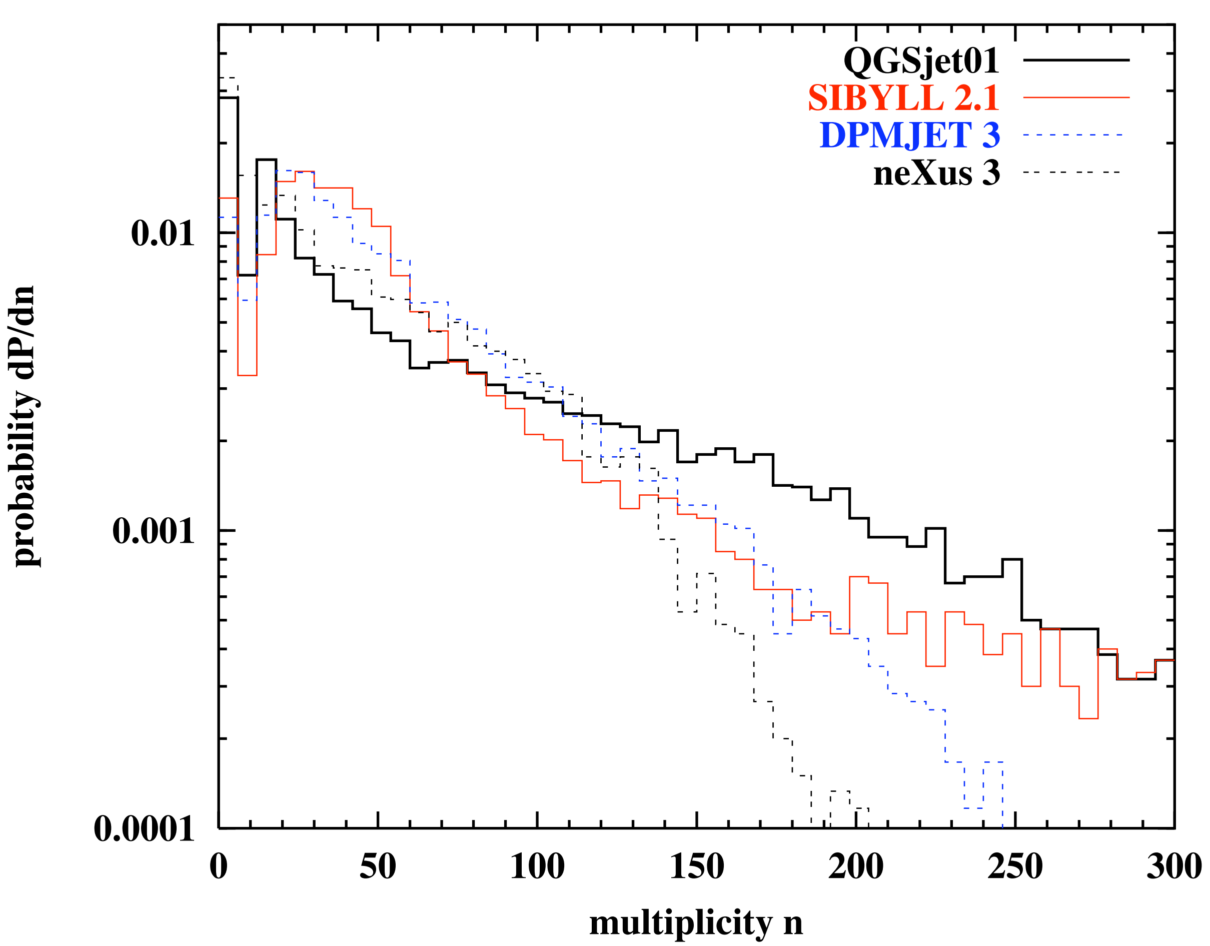


Limited predictive power of models, no direct correlation between central/forward particle production:

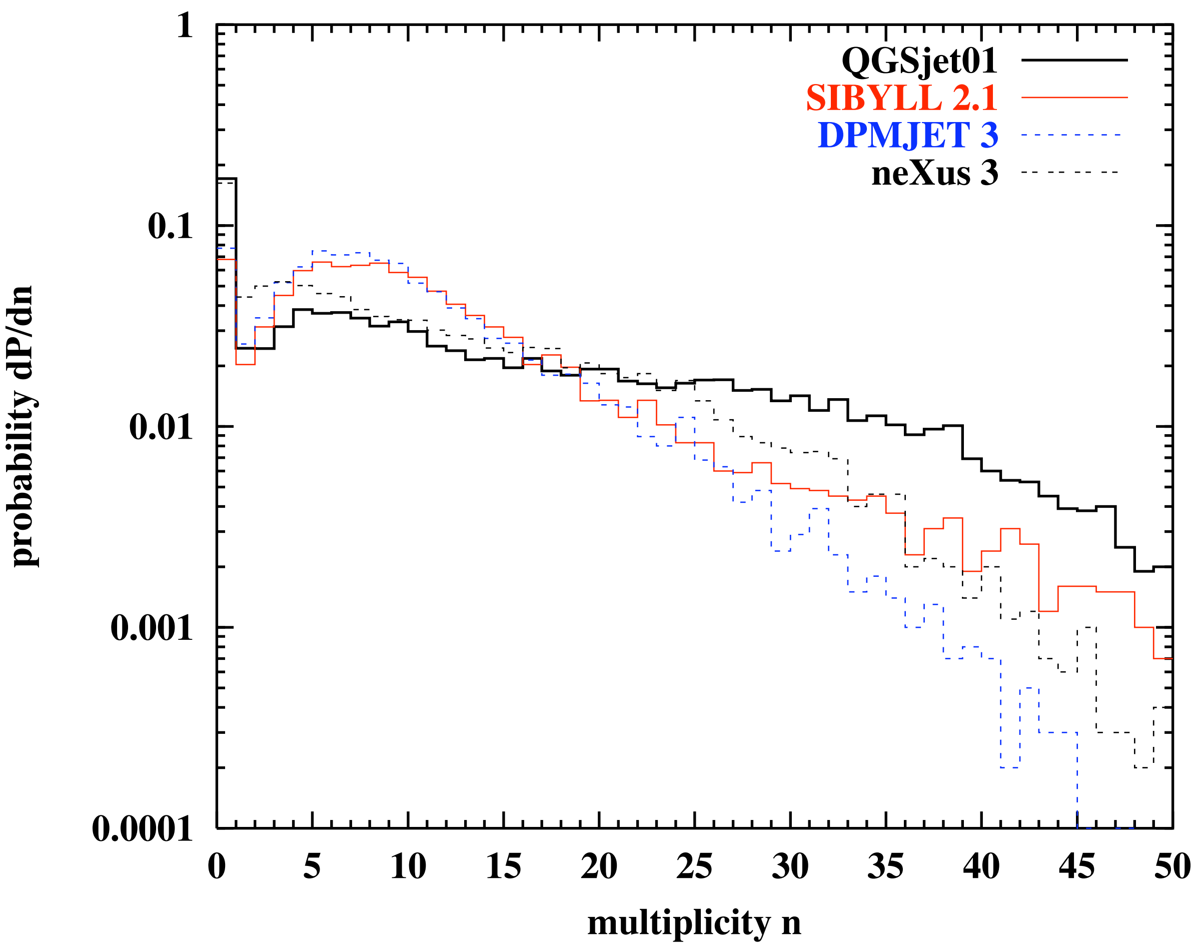
forward measurements needed

LHC: minimum bias measurements (2)

Multiplicity distributions (p-p at 14 TeV CMS)



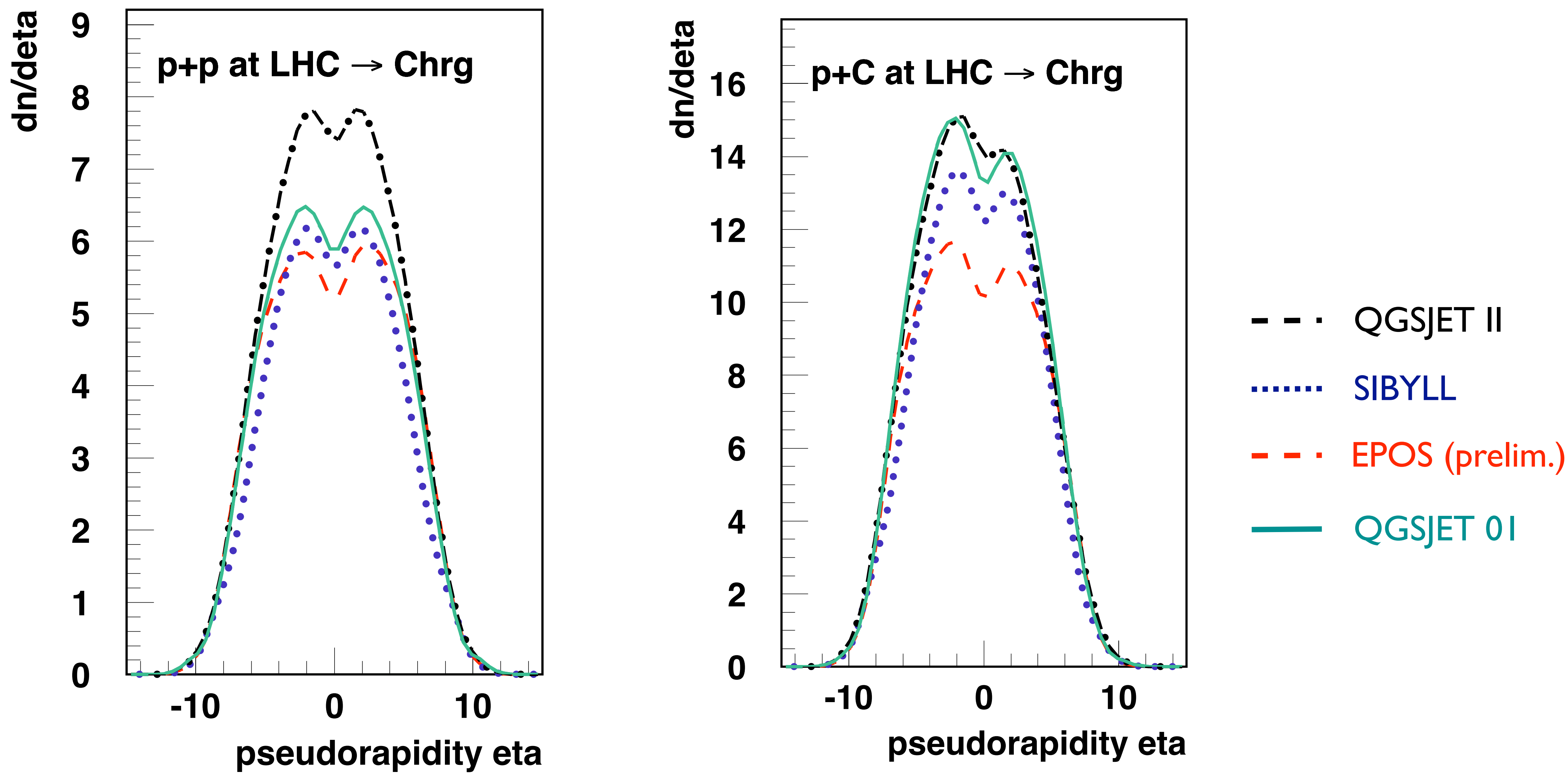
Central detector (-3 < η < 3)



Forward detector (5 < η < 7)

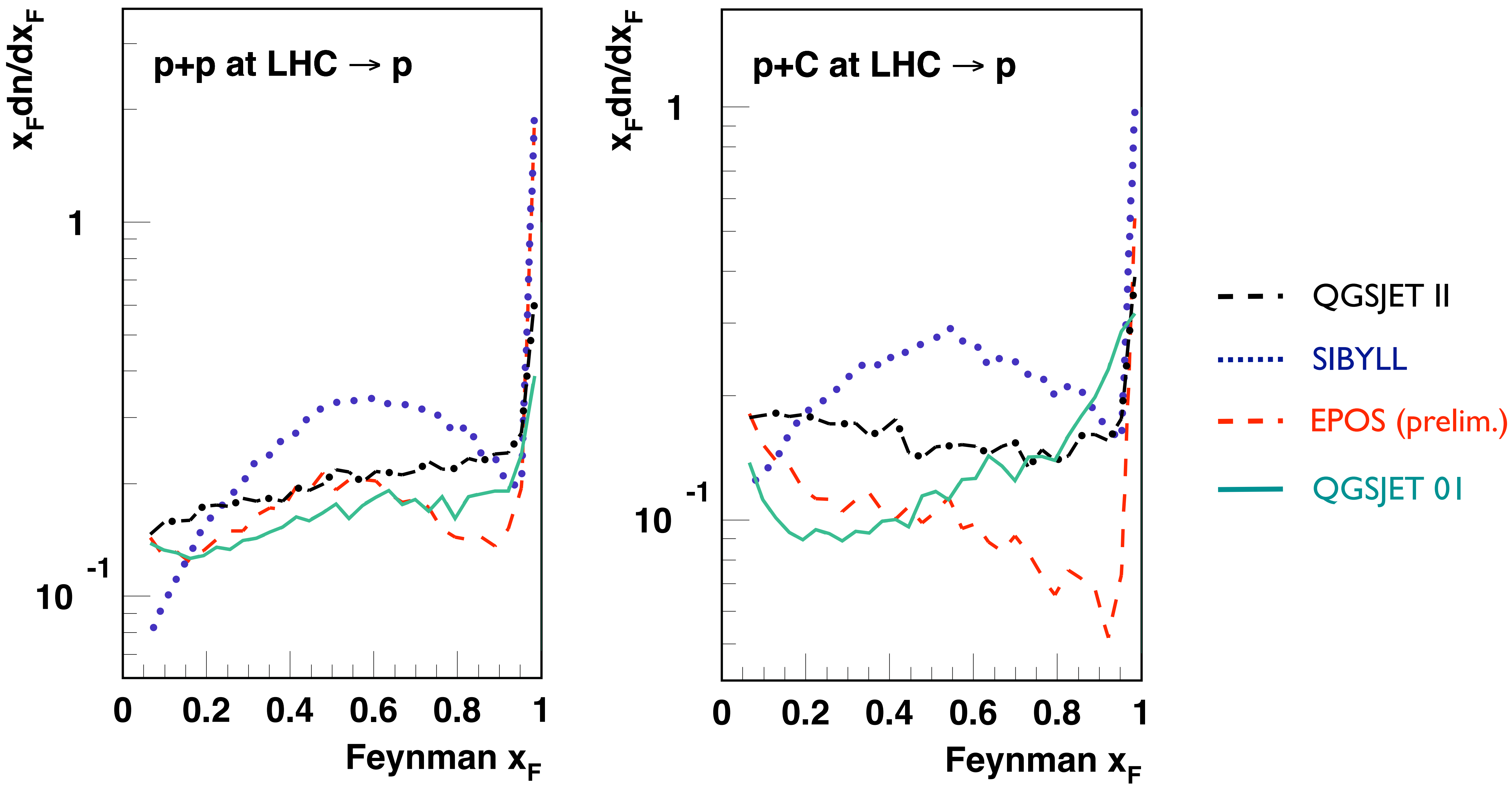
Even simple distributions are very interesting

LHC: light ion option (1)



Models don‘t show a simple one-to-one correspondence of central particle production in p-p and p-C collisions

LHC: light ion option (2)



Models don't show a simple one-to-one correspondence of forward particle production in p-p and p-C collisions

Summary & conclusions

- Cosmic ray physics depends on particle physics measurements
- Precision of elemental composition analyses limited by modeling of hadronic interactions
- Indications of serious shortcomings in simulations (or new particle physics?)
- HERA has answered many questions in a way that make predictions more difficult (impossible?)
- Minimum bias and cross section measurements at LHC will reduce spread of extrapolations significantly
- Central and forward detectors are needed to exploit physics potential
- Data taking during the initial low luminosity runs of LHC will be of outstanding importance