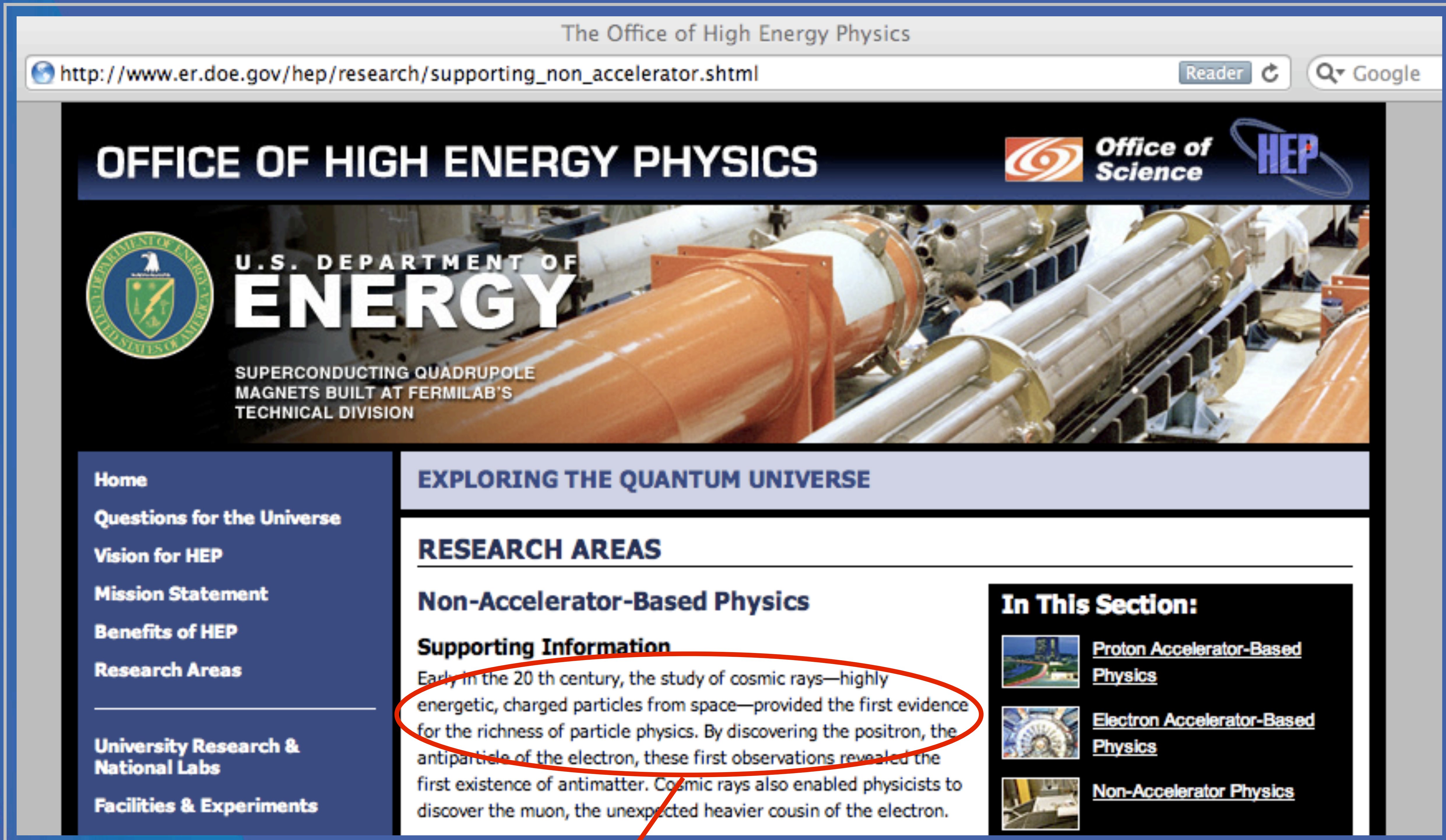
Pierre Auger Observatory

Eun-Joo Ahn

for the Auger group at Fermilab

EJA, Aaron Chou, Henry Glass, Carlos Hojvat, Peter Kasper,
Frederick Kuehn, Paul Lebrun, Paul Mantsch, Peter Mazur

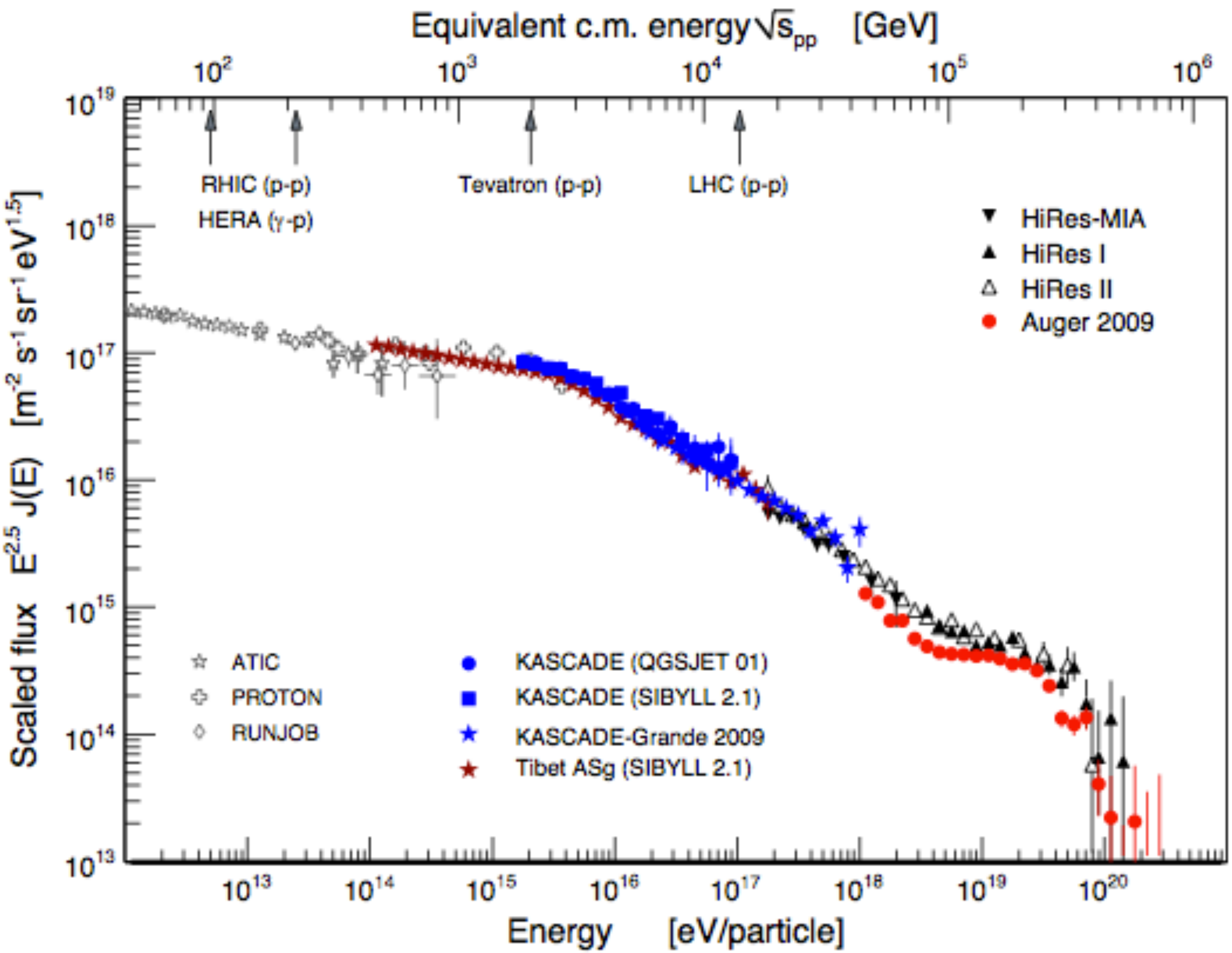
DOE non-accelerator review September 29th 2010



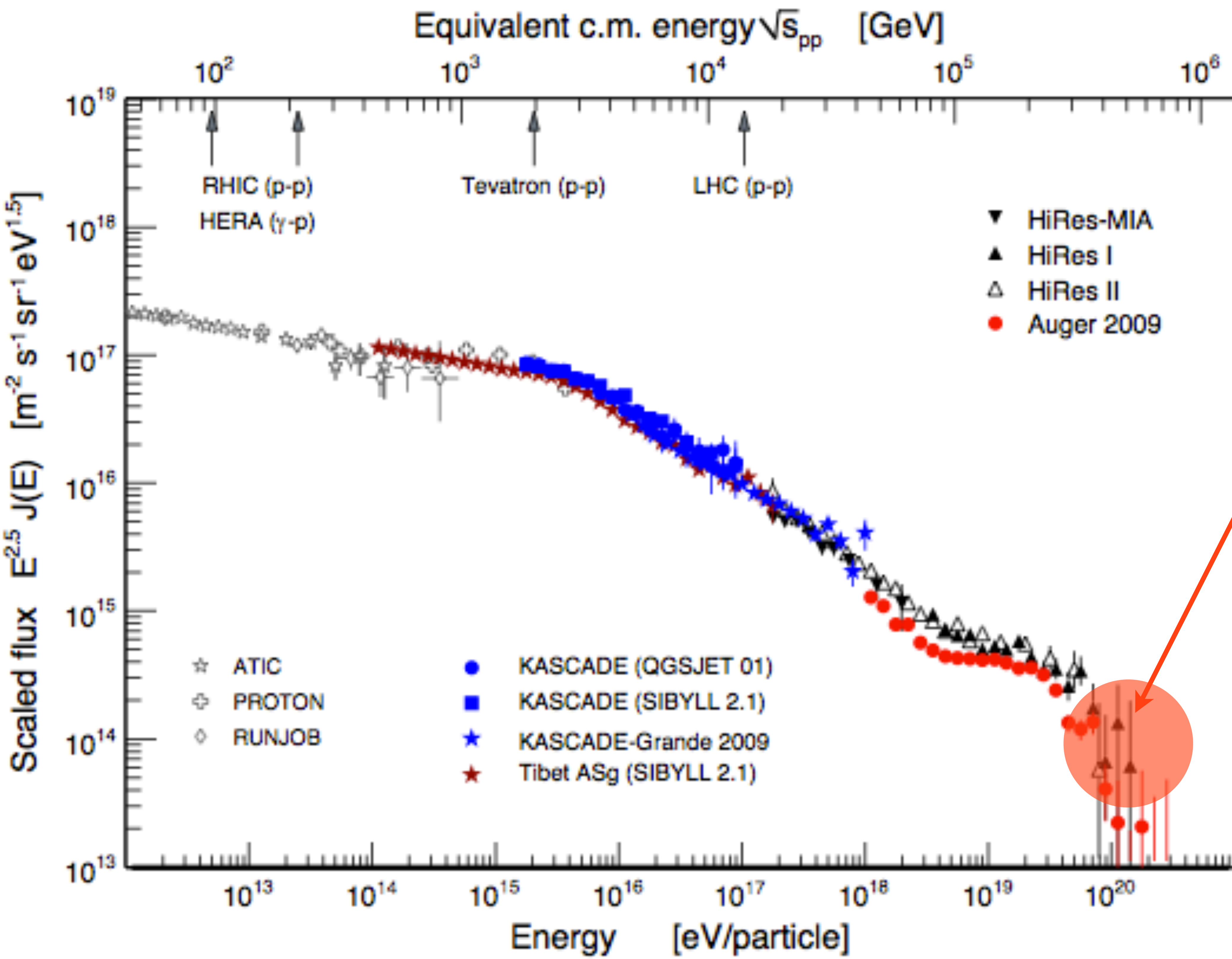
"... cosmic rays provided the first evidence for the richness of particle physics."

positron, muon, pion discovered from cosmic rays

Ultra high energy cosmic rays



Ultra high energy cosmic rays



$E_{lab} \approx 10^{20}$ eV

$E_{CM} \approx 400$ TeV

"high energy fixed target experiment"

Science goals of the Pierre Auger Observatory

To measure properties of UHECR with unprecedented statistics and precision

- **Where** are they coming from?
  - acceleration mechanism, source
  - Galactic -> extra-galactic transition

spectrum, anisotropy

- **What** are they?
  - composition
  - source

shower depth, neutrino limits,
photon limits, spectrum, anisotropy

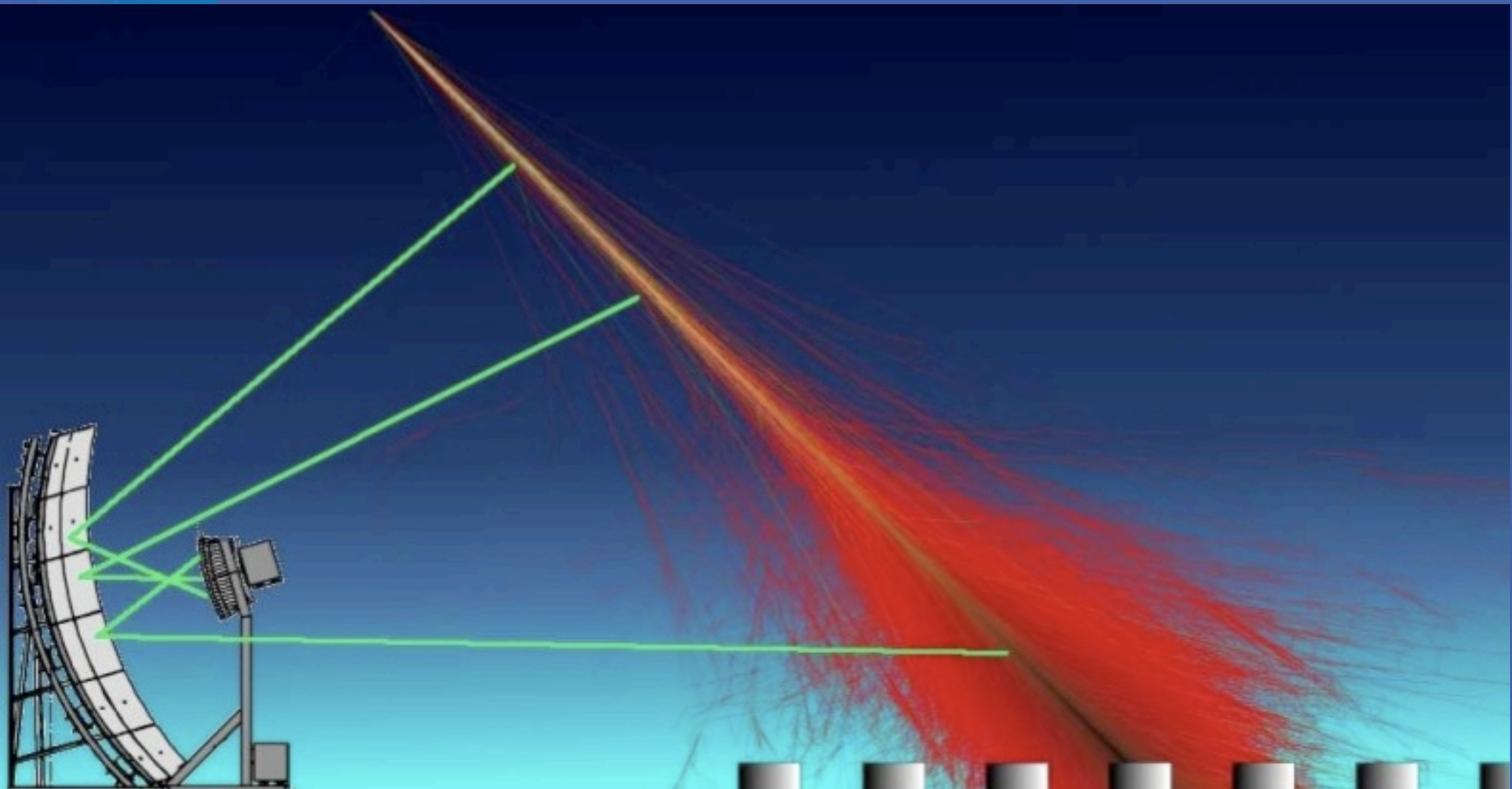
- **How do they interact?**
  - air shower development
  - high energy particle physics

shower depth

Fermilab

Observing ultra high energy cosmic rays

extensive air showers



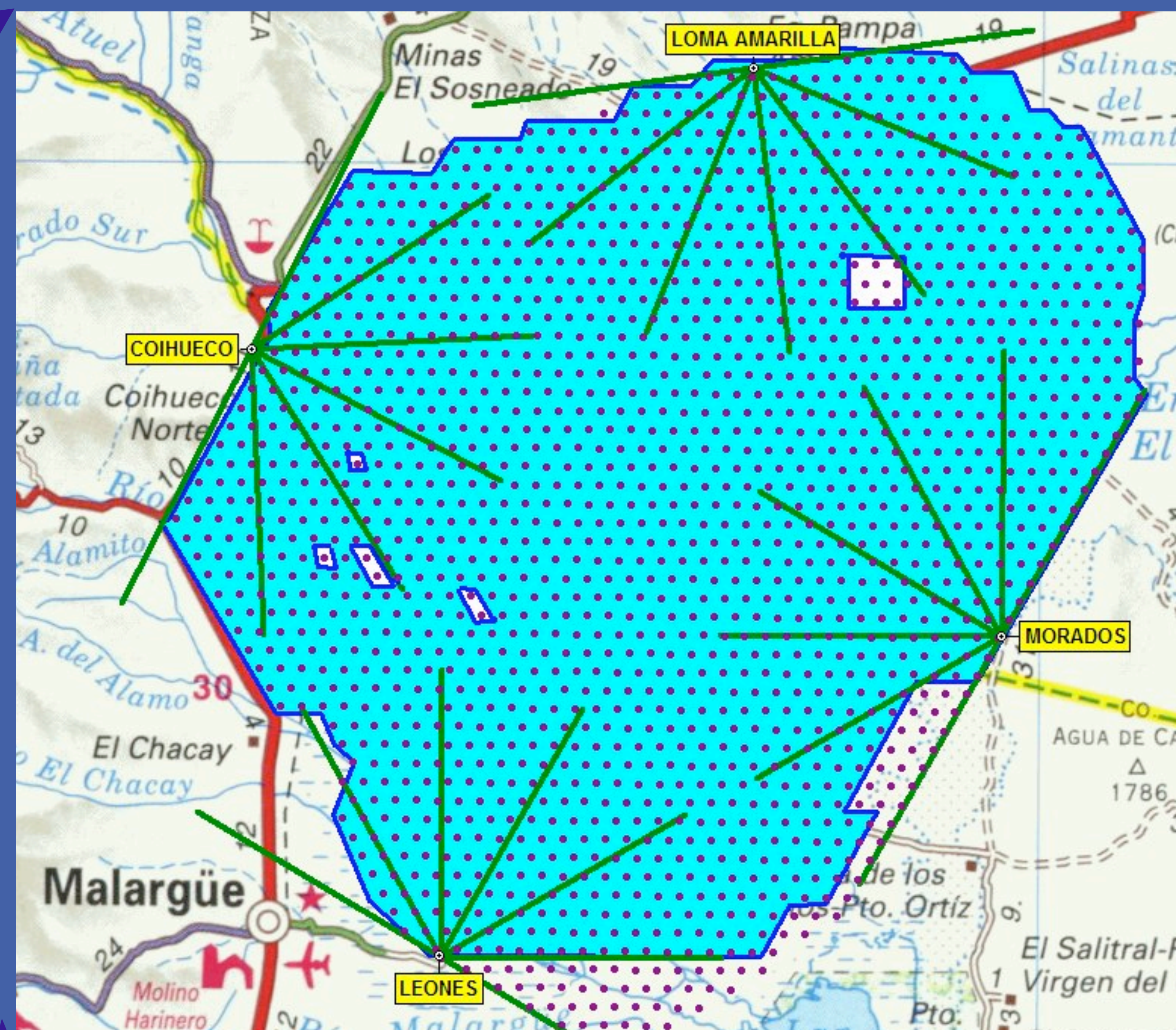
The Pierre Auger Observatory

http://www.auger.org

487 collaborators, 18 countries, 18 peer-reviewed journal papers, 130 PhD thesis

❖ Malargüe, Mendoza, Argentina ~ 3000 km^2, completed

- Hybrid: 24 air fluorescence telescopes (4 eyes) & 1600 water Cherenkov detectors
- Enhancements and R&Ds in progress



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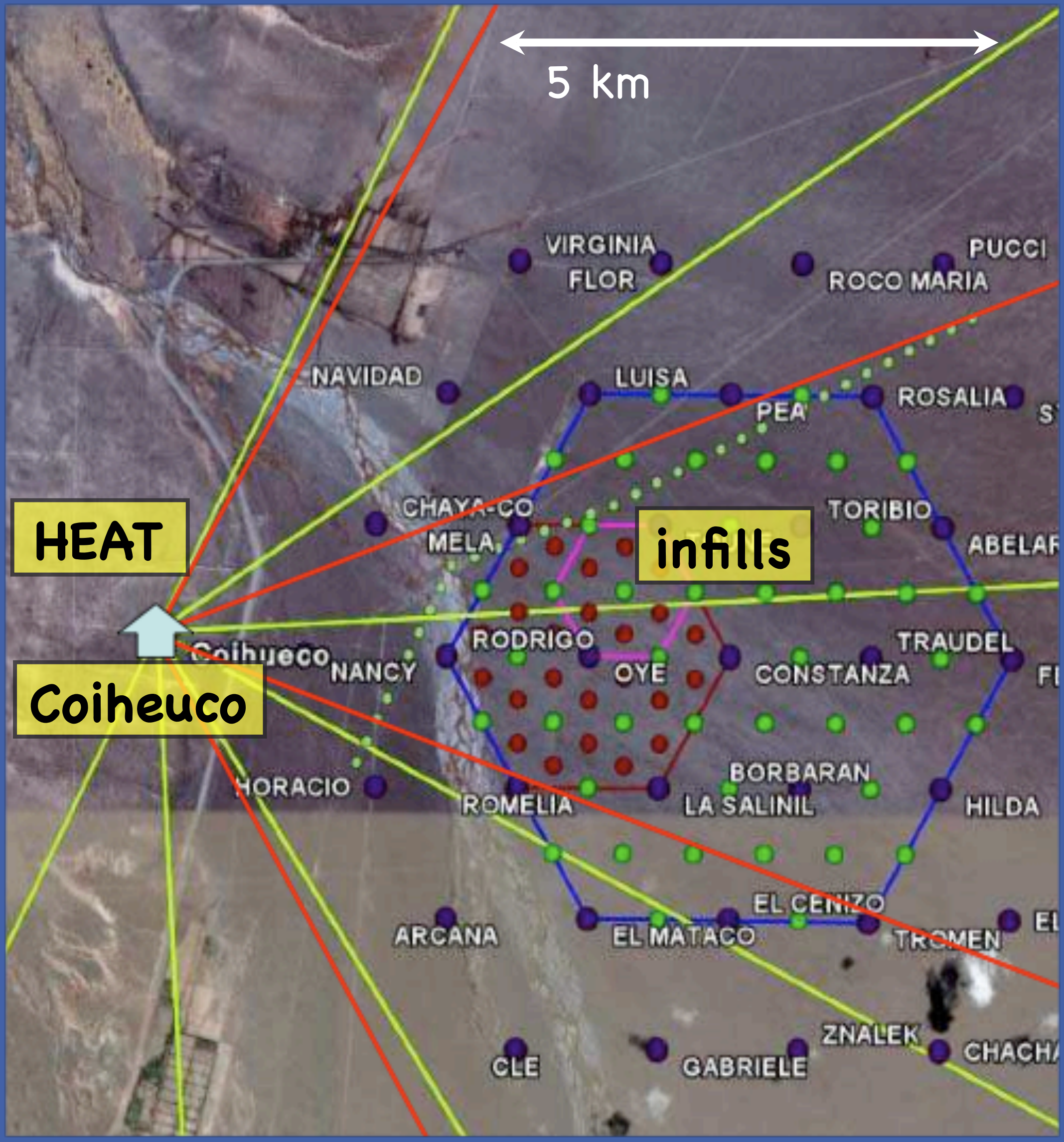
Enhancements

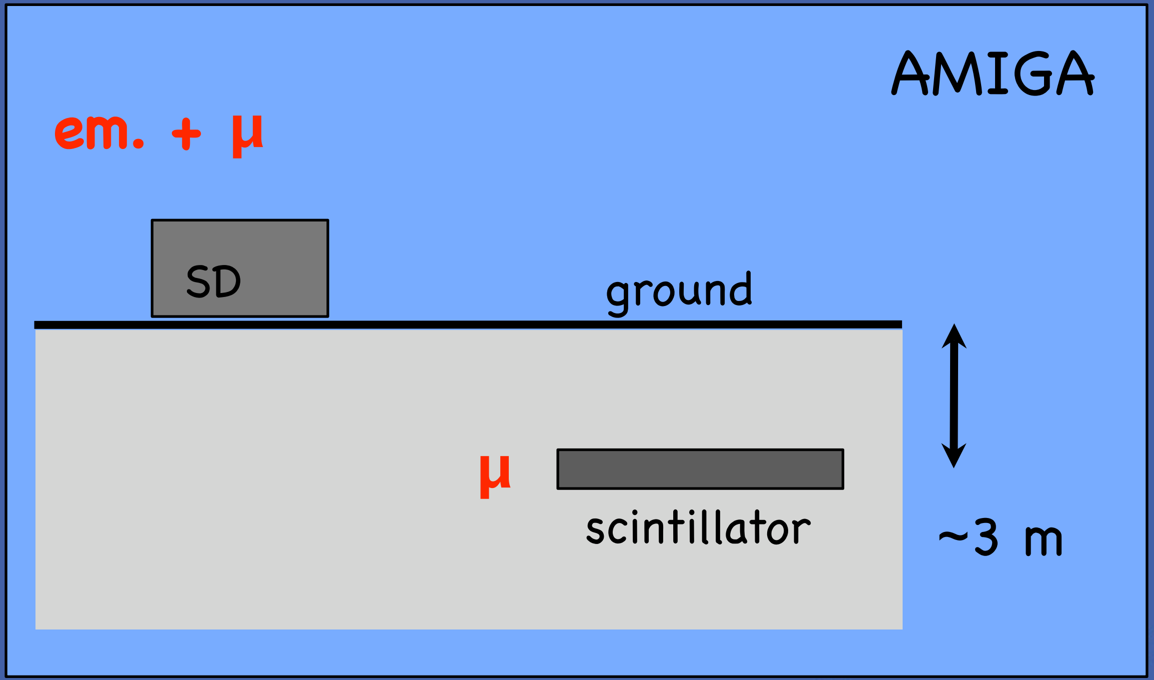
1. High Elevation Auger Telescope (HEAT)
   - 3 tilted telescopes: 30°-58°
2. Muons and Infill for the Ground Array (AMIGA)
   - underground scintillator for muon detection
   - SD spacing 750 m & 450 m

Objective:

- continuous energy measurement from ~10^{17} eV
- obtain better composition information



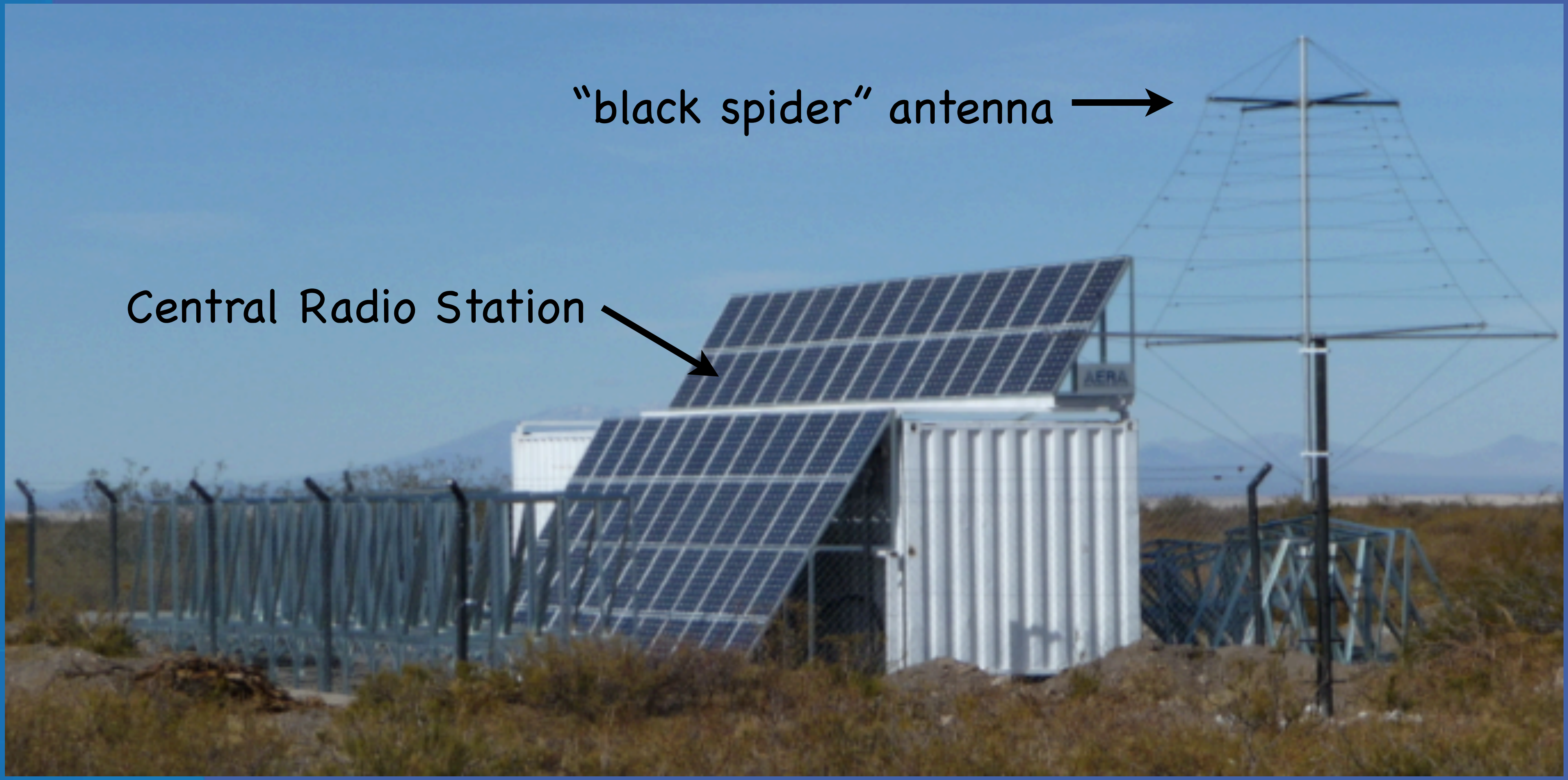
Infill + HEAT -> low energy hybrid trigger



R&D efforts

A. AERA (Auger Engineering Radio Array)

- Coherent radiation from shower cascade, 30-80 MHz
- Measure energy and composition
- Cost-effective, 100% duty-cycle
- Currently installing 24 stations over an area of 20 km^2



B. R&D Array (RDA)

- Auger enhancements and future detector R&D

C. Microwave detection

- Molecular bremsstrahlung by electrons in air shower with surrounding medium
- Isotropic emission in microwave length

1. Detection of shower profile: ~ 4 GHz

AMBER
Ohio State Univ.
two 2.4m dish
4 feeds

MIDAS
Univ. Chicago
one 4.5m dish
$20^o \times 10^o$ camera
55 feeds

2. Detection of shower footprints: 1-10 GHz

- Install microwave radiometers on existing SDs
- Commercial satellite TV microwave antenna or wideband horn antenna

Fermilab participation

- **Project Management headquarters for the Pierre Auger Observatory;**
- ES&H and quality assurance from Fermilab specialists (via Project Management office);
- Design and engineering support: surface detectors were developed at Fermilab;
  continuous support & maintenance, engineering expertise;
- AMIGA muon counter design and production;
- Detector studies: - surface detector stability and PMT linearity testing,
  - fluorescence detector systematic uncertainties;
- Physics analysis: - check for seasonal variation of data,
  - anisotropy in arrival direction: statistical tests and new methods,
  - composition and hadronic interactions at UHECR energies,
  - exotic particle search;
- Auger RDA: new surface detector design, communications algorithm;
- AIRFLY: absolute fluorescence yield measurement done at Fermilab Test Beam facility,
  in collaboration with Univ. Chicago.

Fermilab

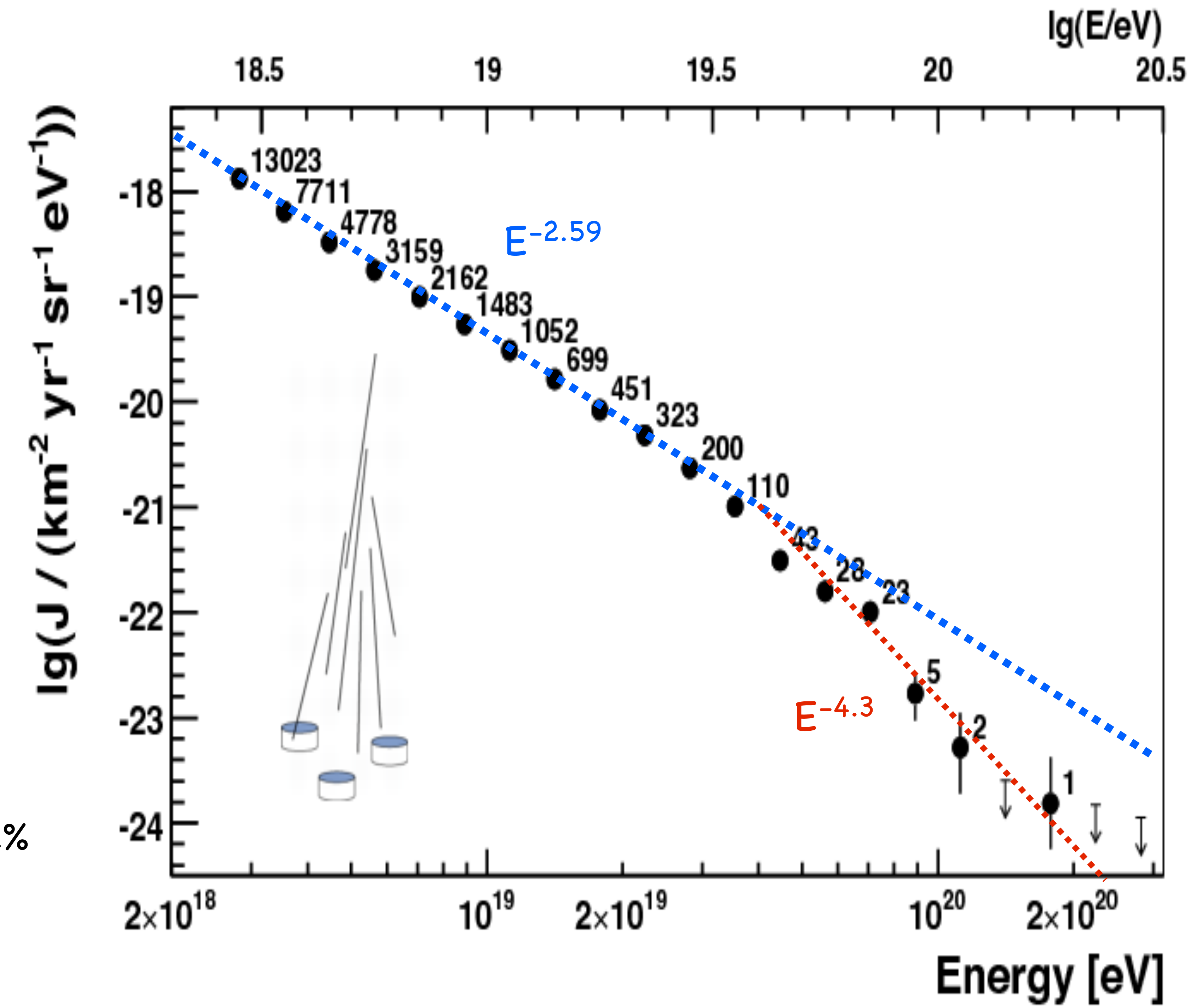
Fermilab participation

Fermilab scientists' roles:

- Eun-Joo Ahn: composition & hadronic interactions; fluorescence detector systematics
- Aaron Chou: exotic particle search
- Henry Glass: project management; cost, shipping; internal publications editor
- Carlos Hojvat: president of Fundacion Observatorio Pierre Auger Argentina; AIRFLY
- Peter Kasper: anisotropy; composition & hadronic interactions; RDA communications algorithm
- Fredrick Kuehn: anisotropy; AIRFLY; surface detector systematics
- Paul Lebrun: anisotropy; database mirror & maintenance; surface detector performance, stability, maintenance; surface detector PMT linearity testing
- Paul Mantsch: Project Manager: heads Project Management office; distributes resources for US institutions; manages & distributions Observatory resources; US country representative
- Peter Mazur: surface detector task leader and subtask leader; design, engineering, production, maintenance, operation. AMIGA muon counter design and production advisor and liason for extruded scintillator production

Science results from the Pierre Auger Observatory

I. UHECR spectrum

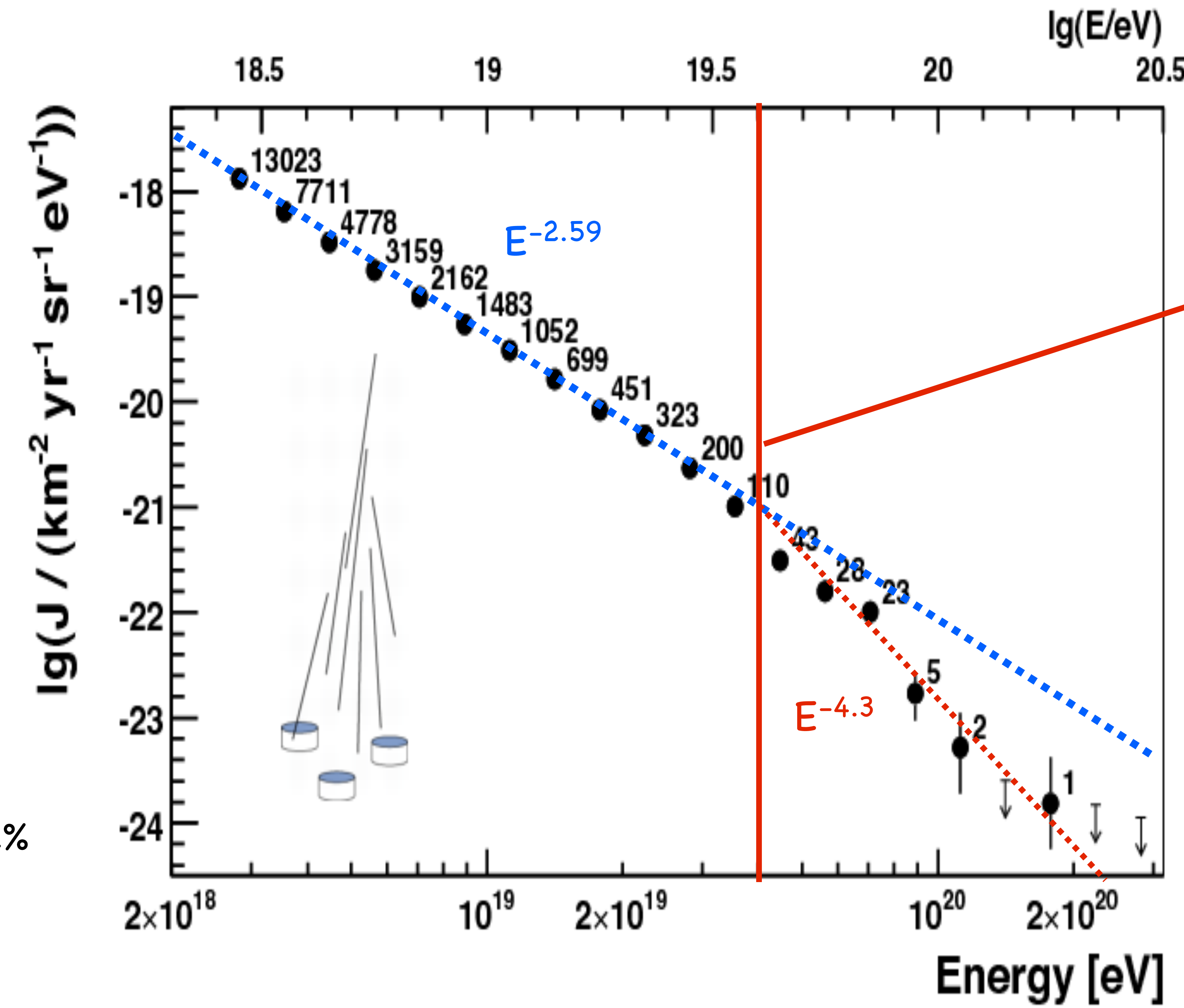


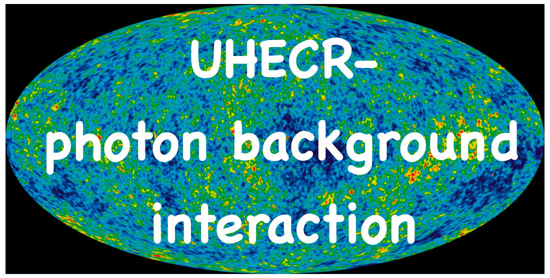
syst. energy uncertainty 22%

PRL **101**, 061101 (2008)
PLB **685**, 239 (2010)

- updated spectrum for the surface detector
- data taken: Jan 2004 - Dec 2008, 12 790 km^2 sr yr

Auger observes a suppression





suppression > 20 σ

4×10^{19} eV

syst. energy uncertainty 22%

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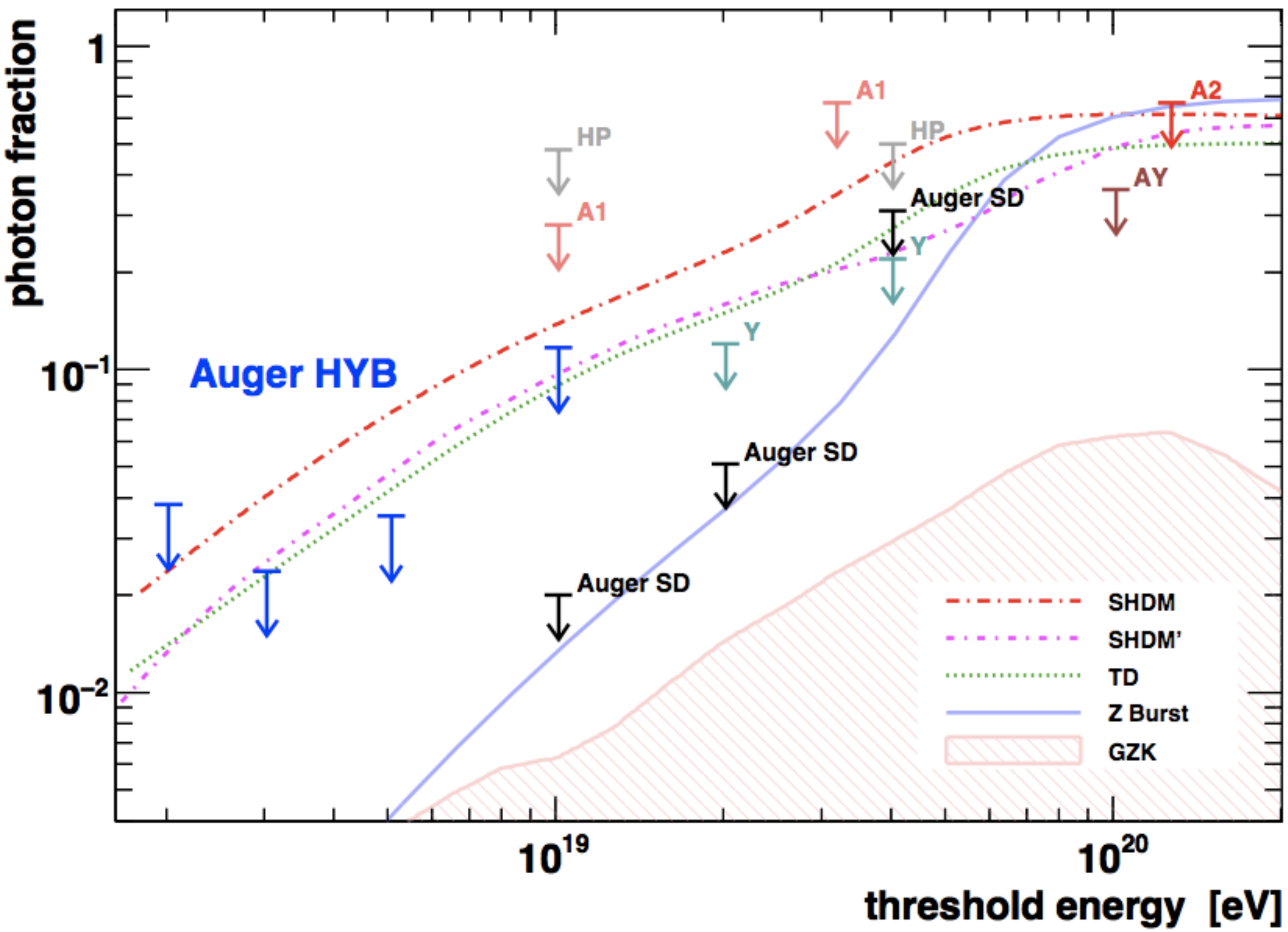
PLB **685**, 239 (2010)

- updated spectrum for the surface detector
- data taken: Jan 2004 - Dec 2008, 12 790 km^2 sr yr

II. Photon limits

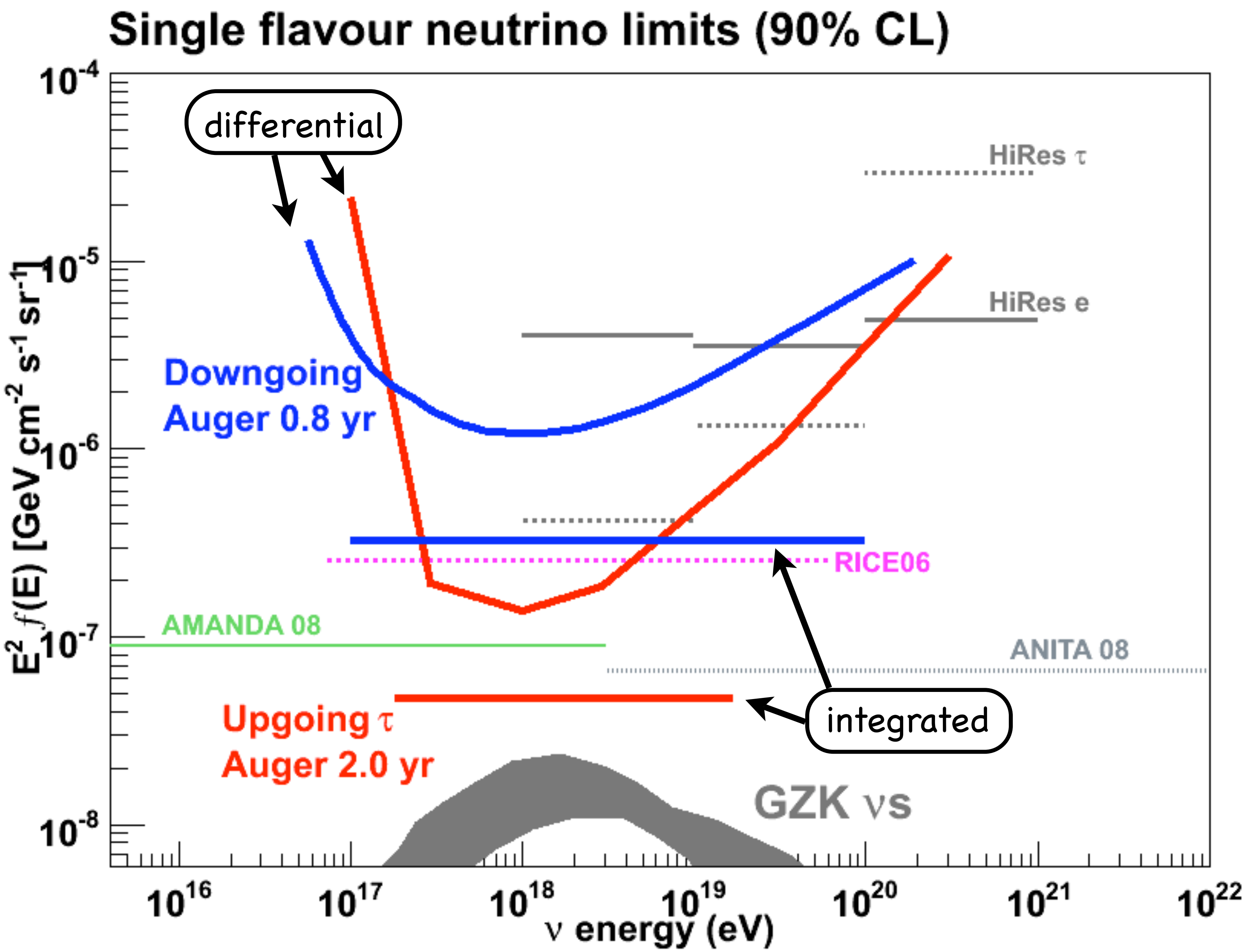
- Photons are candidates from astrophysical and exotic models:
  1. GZK photons : by-products of UHECR-photon background interaction
  2. "Top-down" scenarios (e.g. SHDM decay/annihilation produces photons)



Astropart Phys **31**, 399 (2009)

- 8 candidates, all consistent with fluctuations from protons/iron nuclei
- first low energy limits, rule out some top-down scenarios

III. Neutrino limits



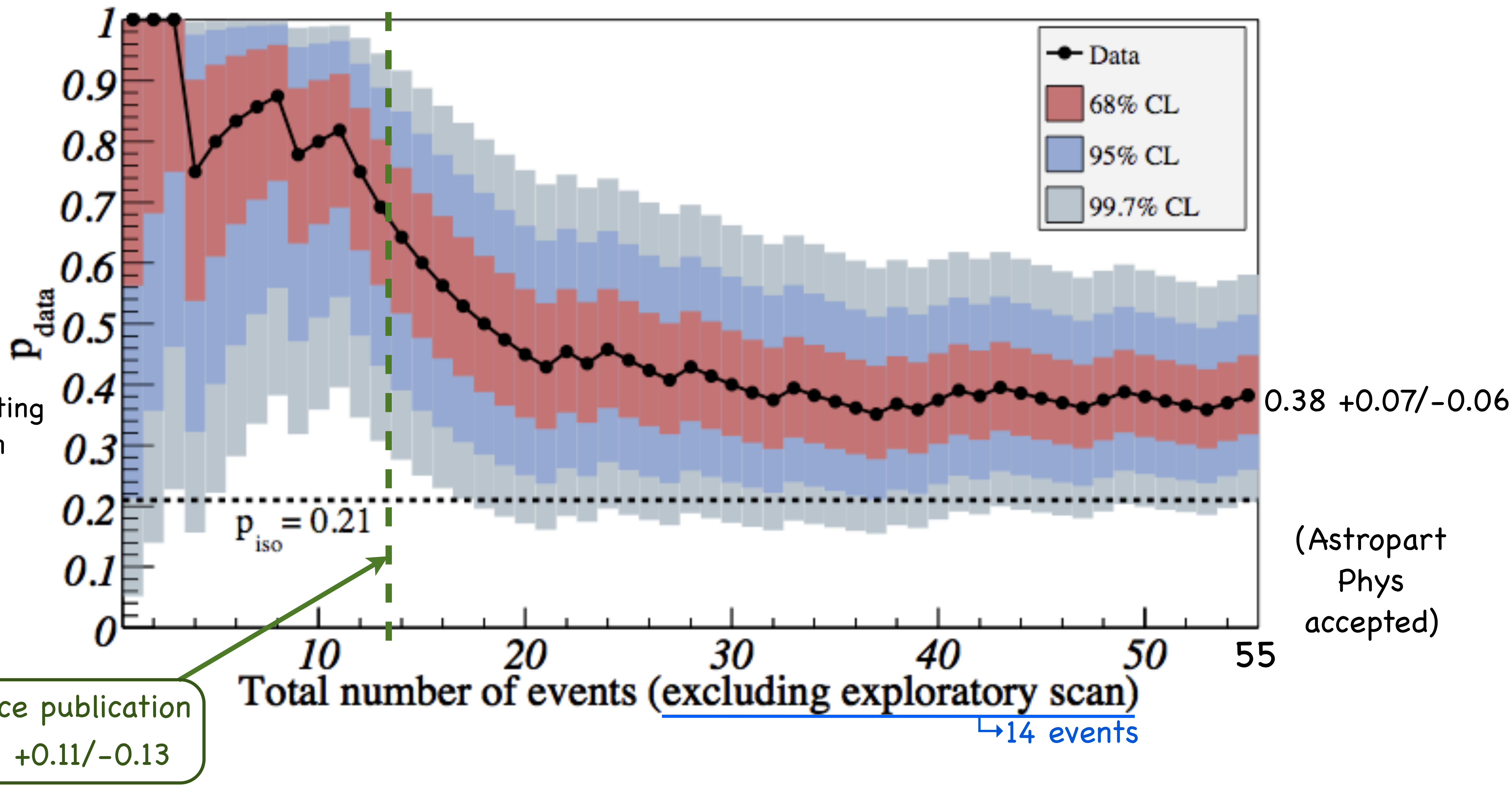
PRL **100**, 211101 (2008)

PRD **79**, 102001 (2009)

- Deeply penetrating horizontal (downgoing) - all flavours
- Earth-skimming (upgoing) - τ-neutrino
- No discovery, approaching cosmogenic/GZK neutrino limits
- Probe high energy neutrino properties

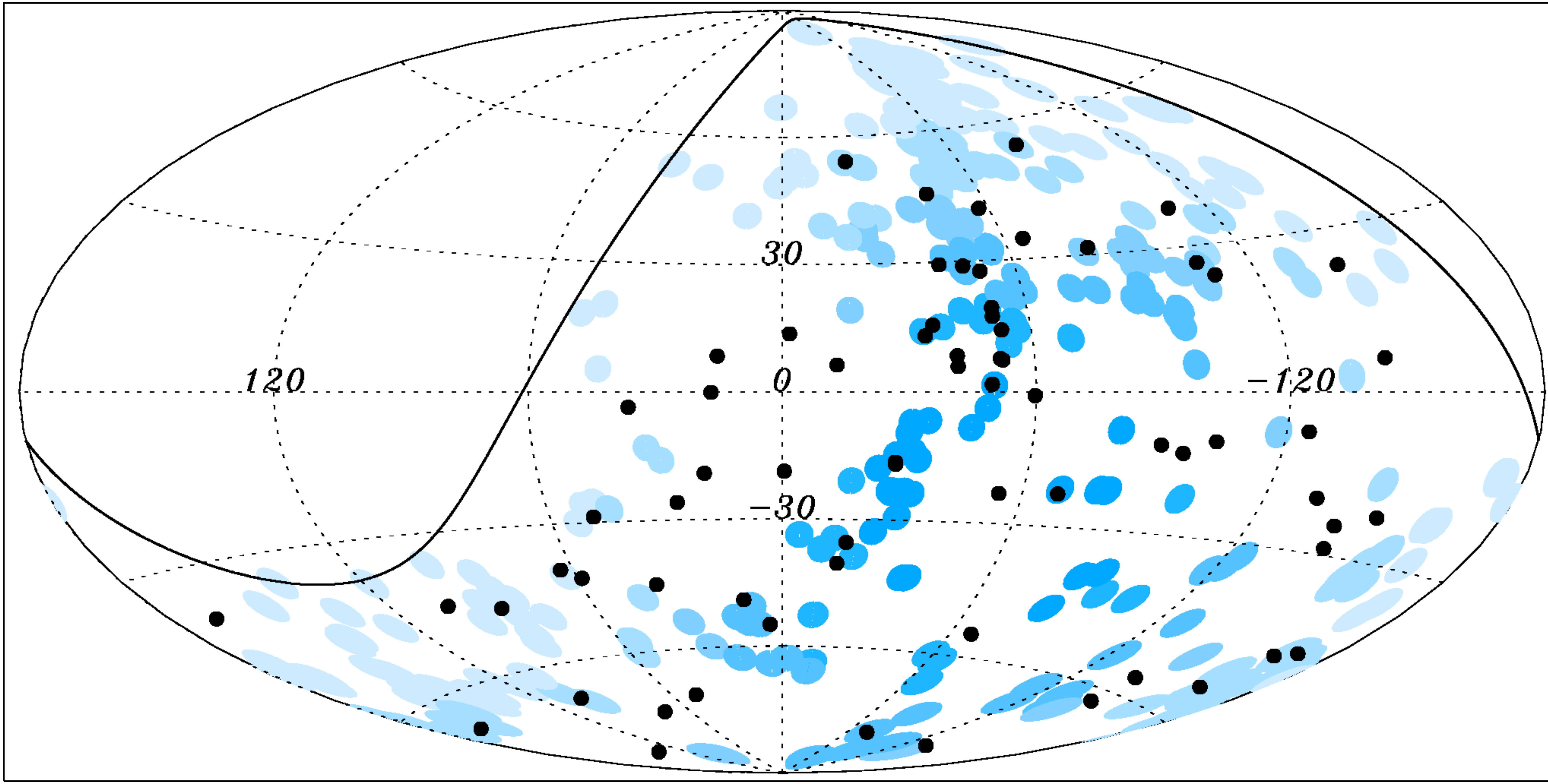
Fermilab

IV. Anisotropy



- 69 Events with energy > 5.5×10^{19} eV are anisotropic : 0.003 isotropic probability)
- Correlation with VCV catalogue: nearby AGN/matter

IV. Anisotropy



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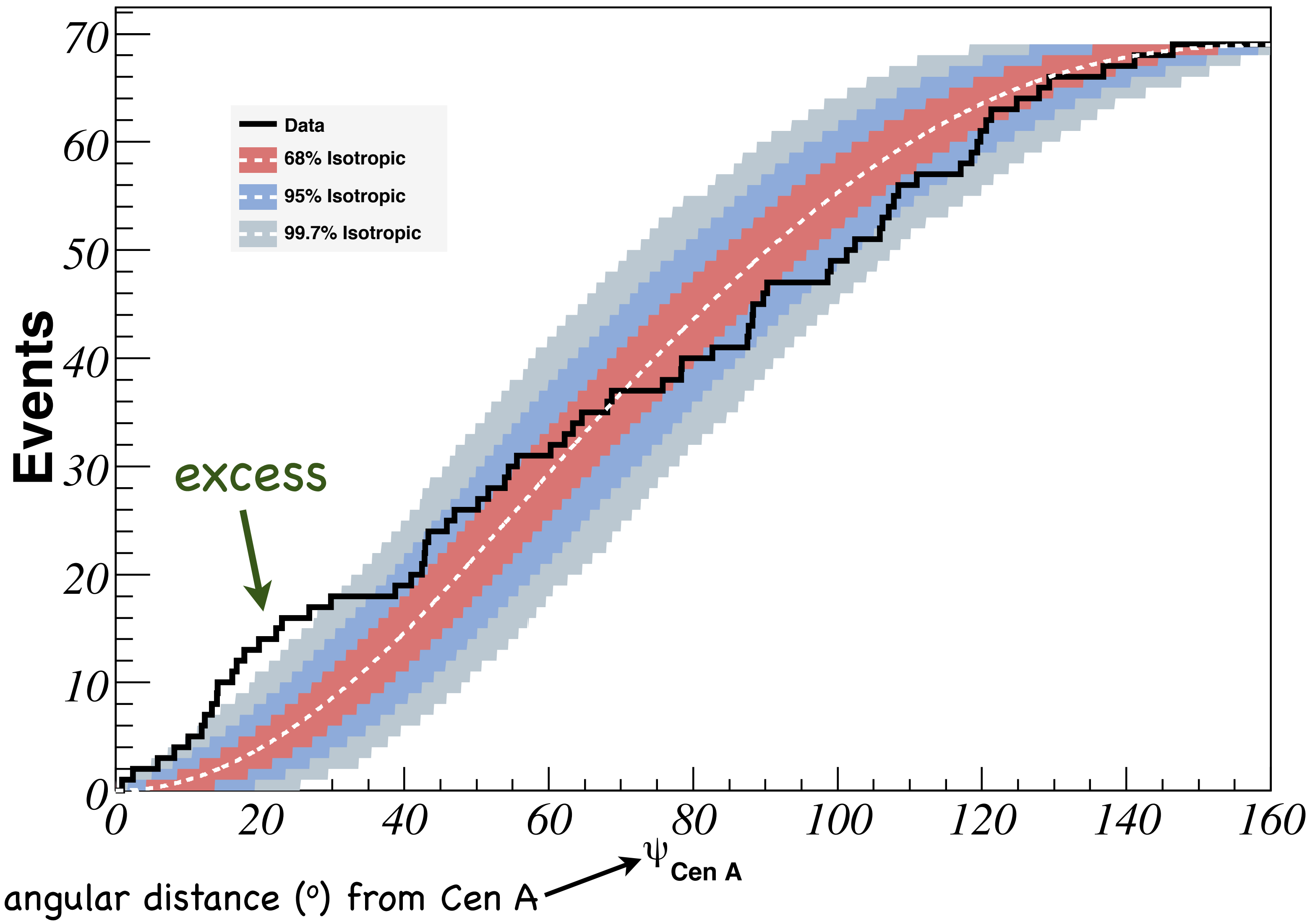

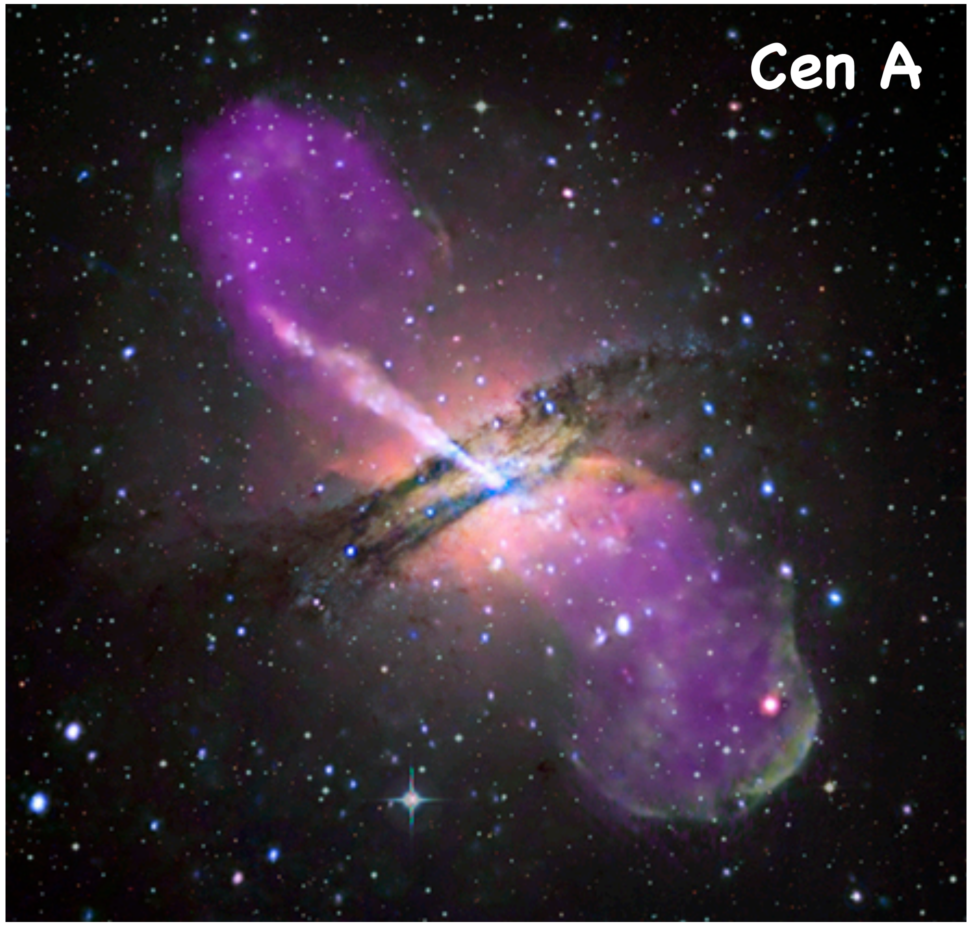

d ~ 3.8 Mpc

- Excess of events from region of Centaurus A
  - -> 13 events within 18° (isotropic distribution = 3.2 events)
- Cen A or structure behind?
- Composition study: proton with E travels same path as iron nuclei with 26xE
  - -> led by Fermilab Auger group

Spectrum, correlation suggests:

- Flux suppression observed at highest energy (> 4×10^{19} eV)
- Highest energy cosmic rays (> 5.5×10^{19} eV) have correlation with nearby AGNs

Source and propagation suggests:

- protons can escape accelerator without much energy loss; are stable
- heavier nuclei disintegrate in the source (& during propagation)

therefore: **UHECRs are protons, they come from astrophysical sources.**

Spectrum, correlation suggests:

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therefore: UHECRs are protons, they come from astrophysical sources. ?????????????????????

BUT

E.g. Physics Today May 2010

The highest-energy cosmic rays may be iron nuclei

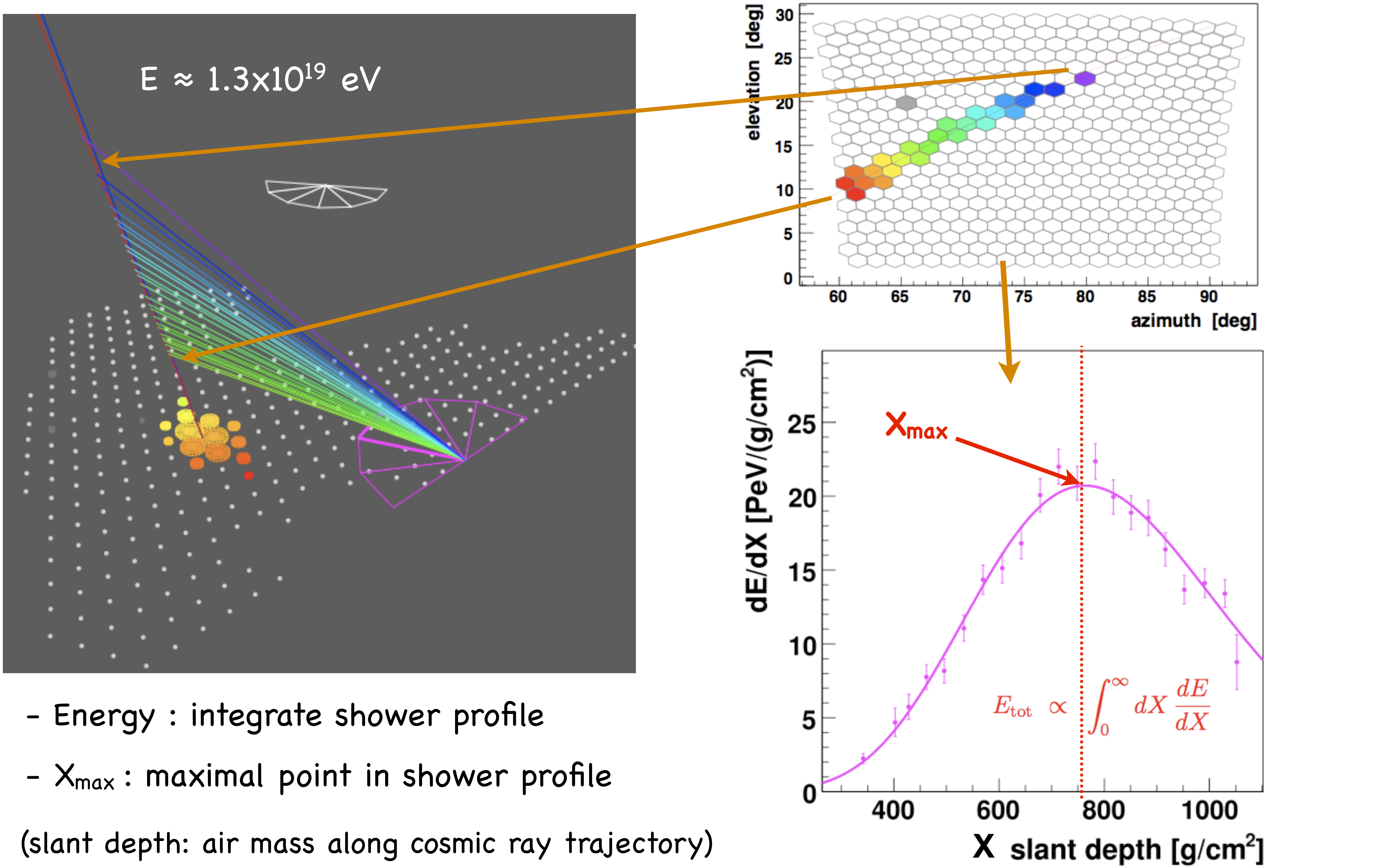
Or perhaps, at energies far beyond what terrestrial accelerators can produce, protons just look fat.

Protons or iron nuclei? Other elements? Exotic particles? New physics?

"... cosmic rays provided the first evidence for the richness of particle physics."

-> cosmic rays provide glimpse that something is not what it seems in particle physics

V. Composition

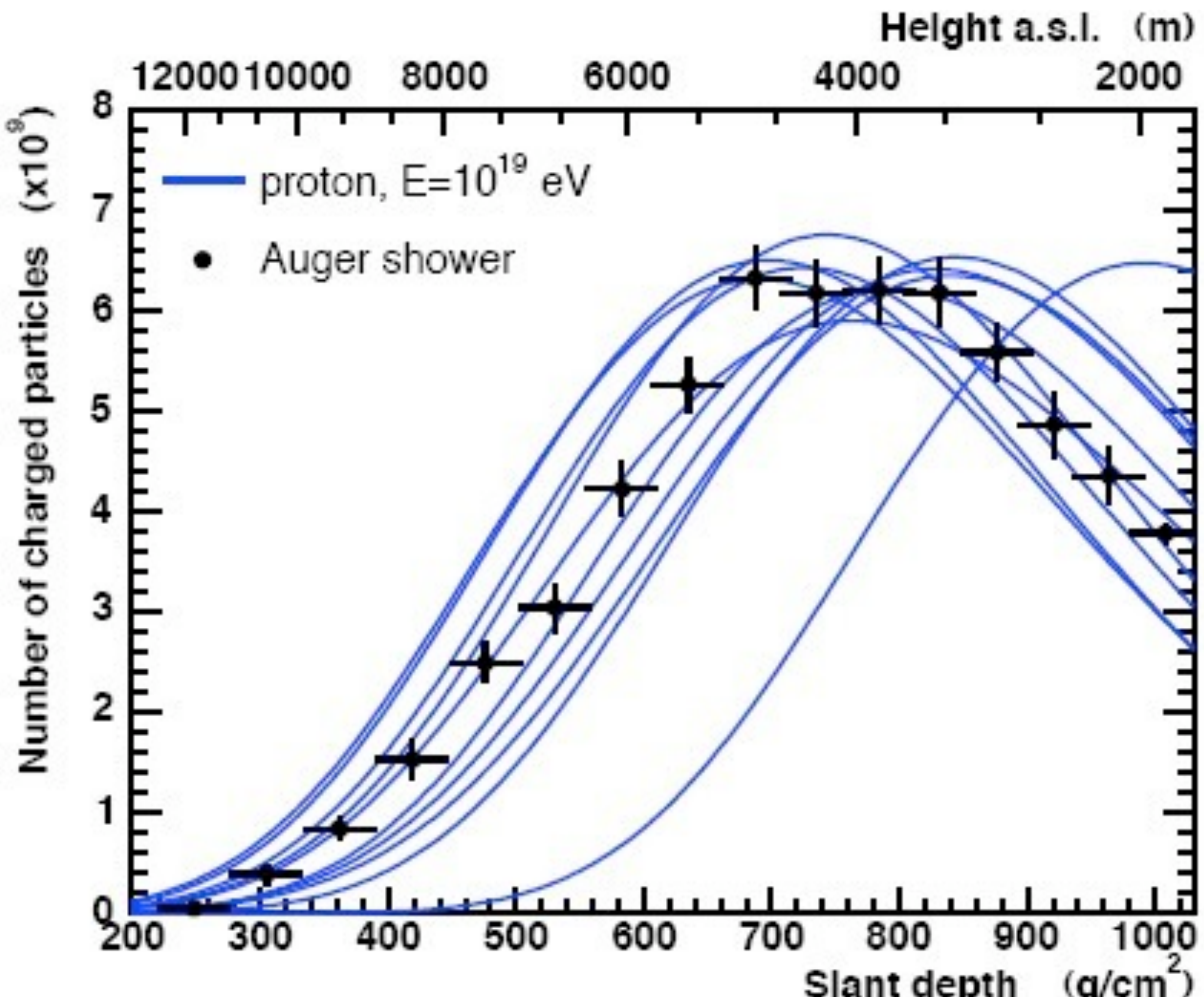


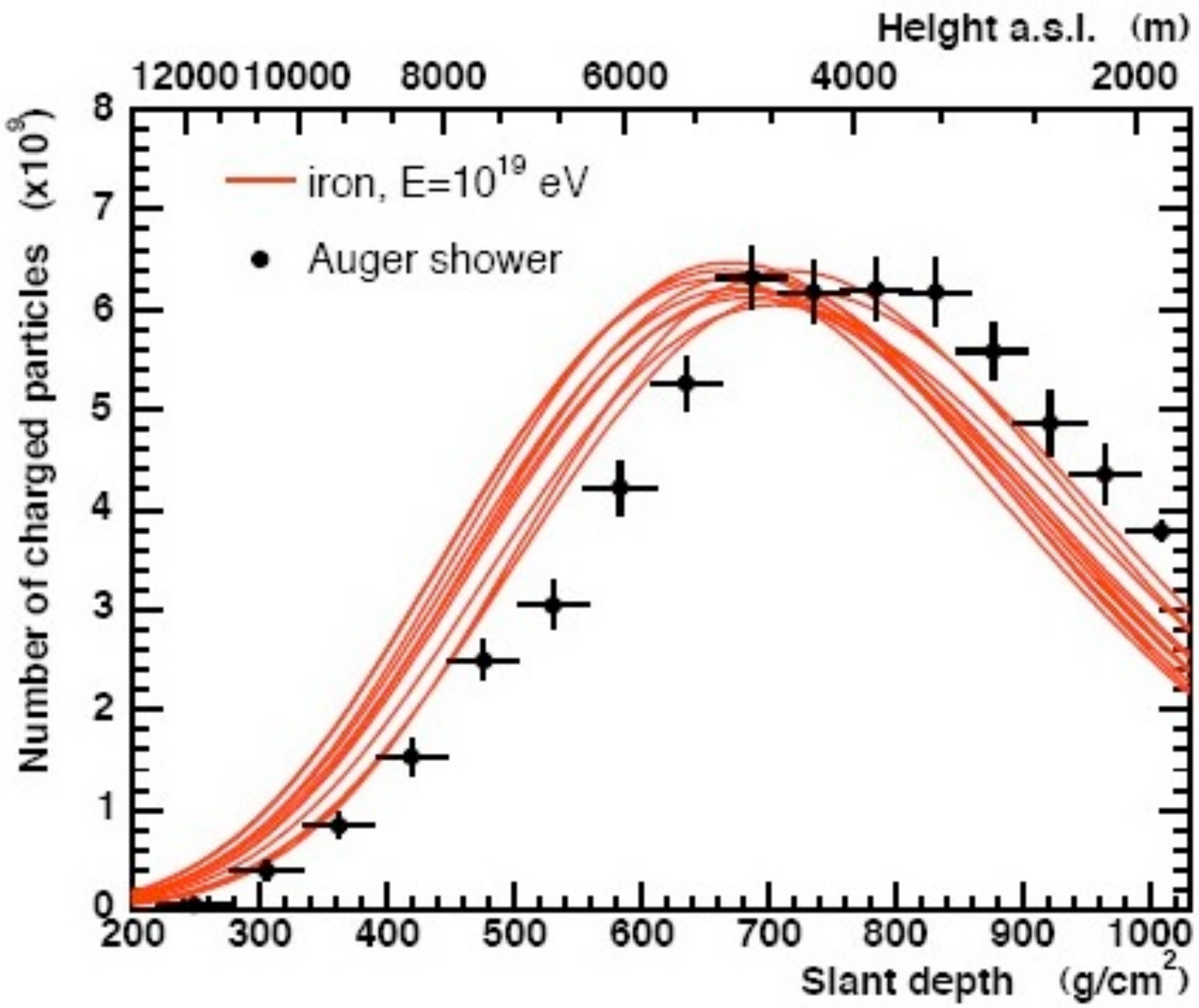
- Energy : integrate shower profile
- X_{max} : maximal point in shower profile

(slant depth: air mass along cosmic ray trajectory)

Behaviour of X_{max} tells about the composition:

- different particles develop different profiles;
- indirect inference from air showers: simulation required;
- hadronic interaction models: DPMJET, EPOS, QGSJET, Sibyll

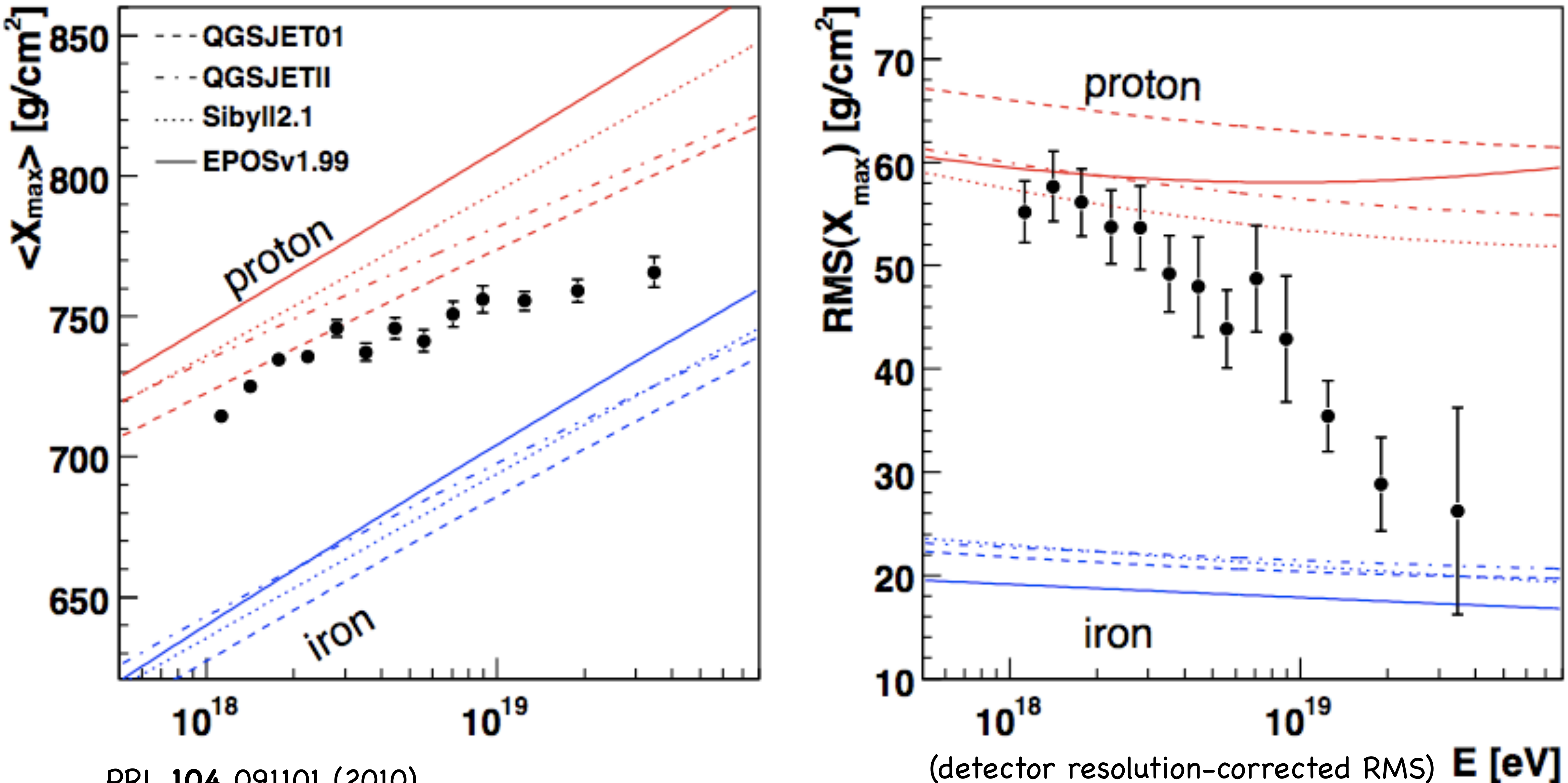




(Sibyll 2.1)

- protons develops deeper with larger fluctuations than iron nuclei

Data of X_{max} : mean and fluctuation (RMS)



PRL **104** 091101 (2010)

(detector resolution-corrected RMS)

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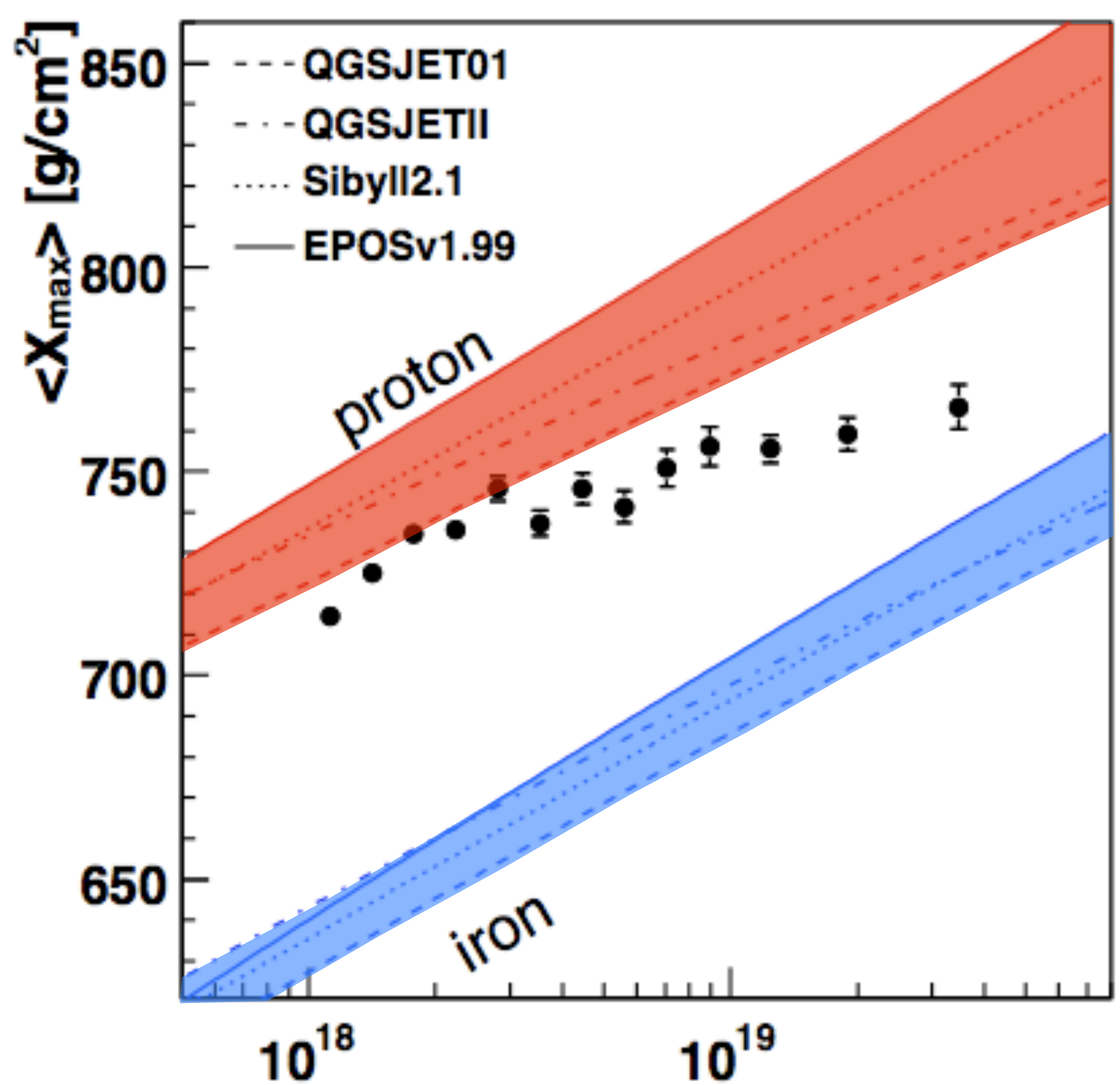
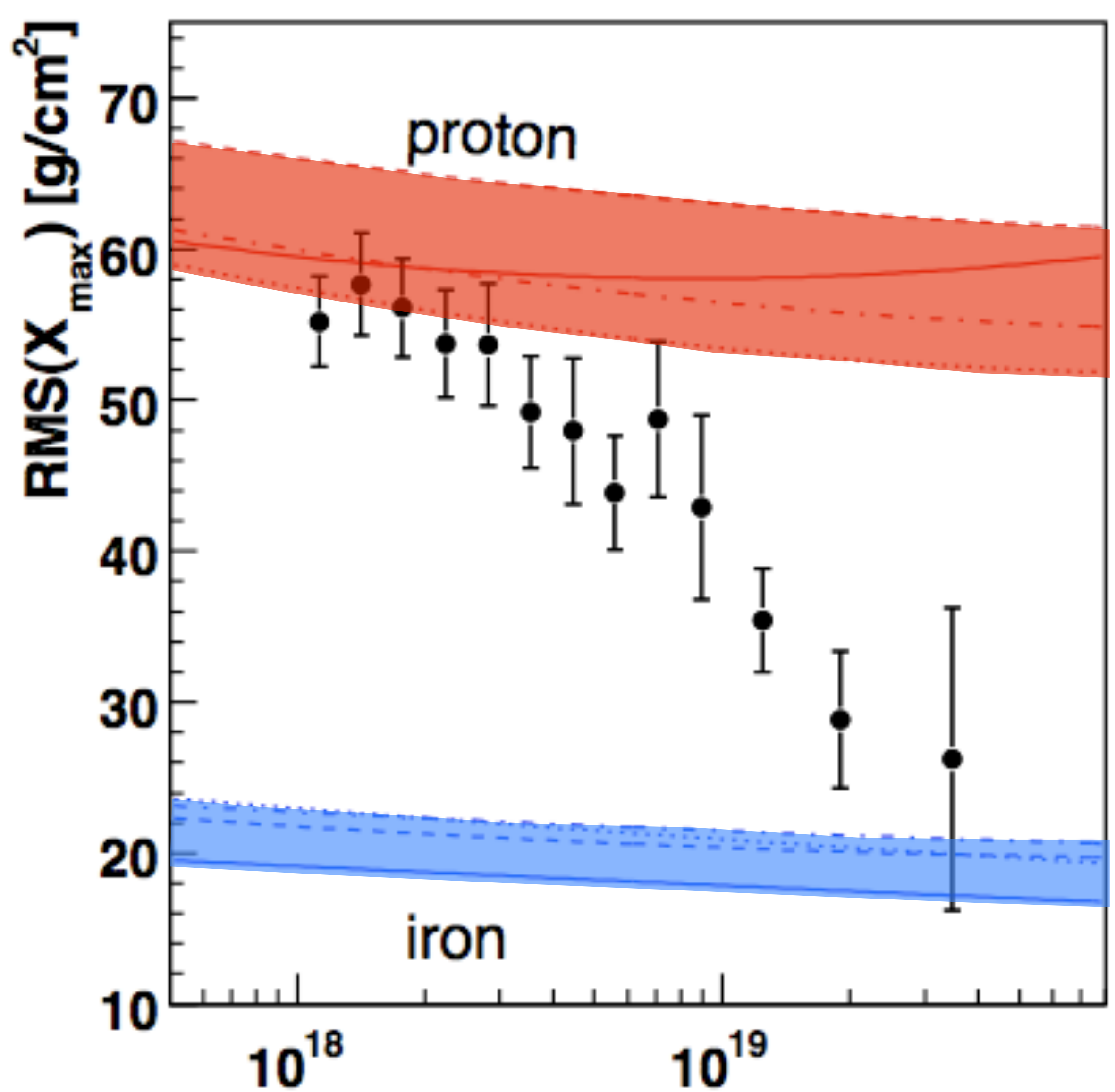
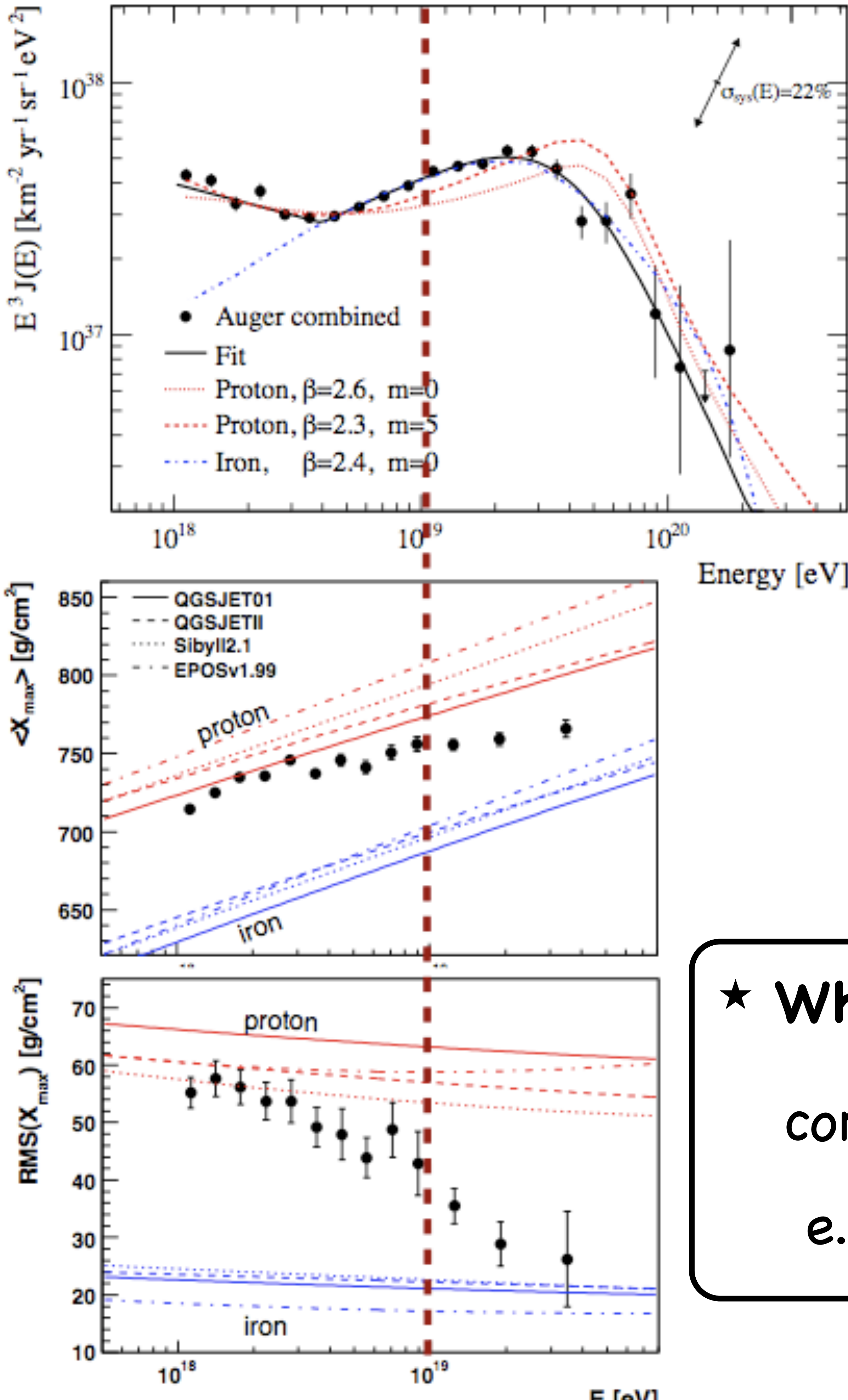


PRL **104** 091101 (2010)



(detector resolution-corrected RMS)

- Models give different predictions
- Data lies in between proton and iron nuclei predictions



Suppression observed E = 4×10^{19} eV

Correlation E > 5.5×10^{19} eV

➡ X_{max} highest bin E < 4×10^{19} eV

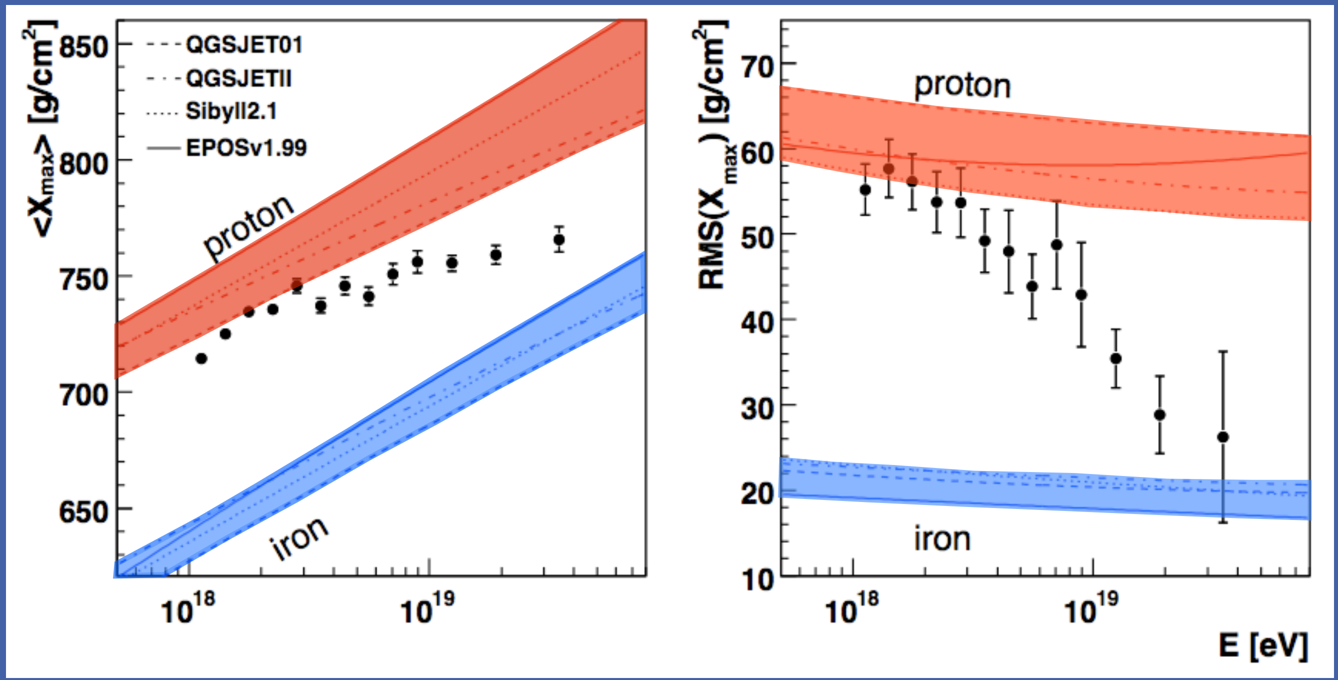
need more data!

★ **What** are they? **How do they interact**?

composition & particle characteristics,

e.g. cross sections at Auger energies

‣ Models give different prediction



❖ Hadronic interaction model required for data interpretation

- EPOS, QGSJET, Sibyll ...
  ➡ phenomenology-based: dual parton, minijets, pomerons, strings etc.

- "low energy" accelerator data
  ➡ cross section, particle distribution (p_T, pseudorapidity, multiplicity)

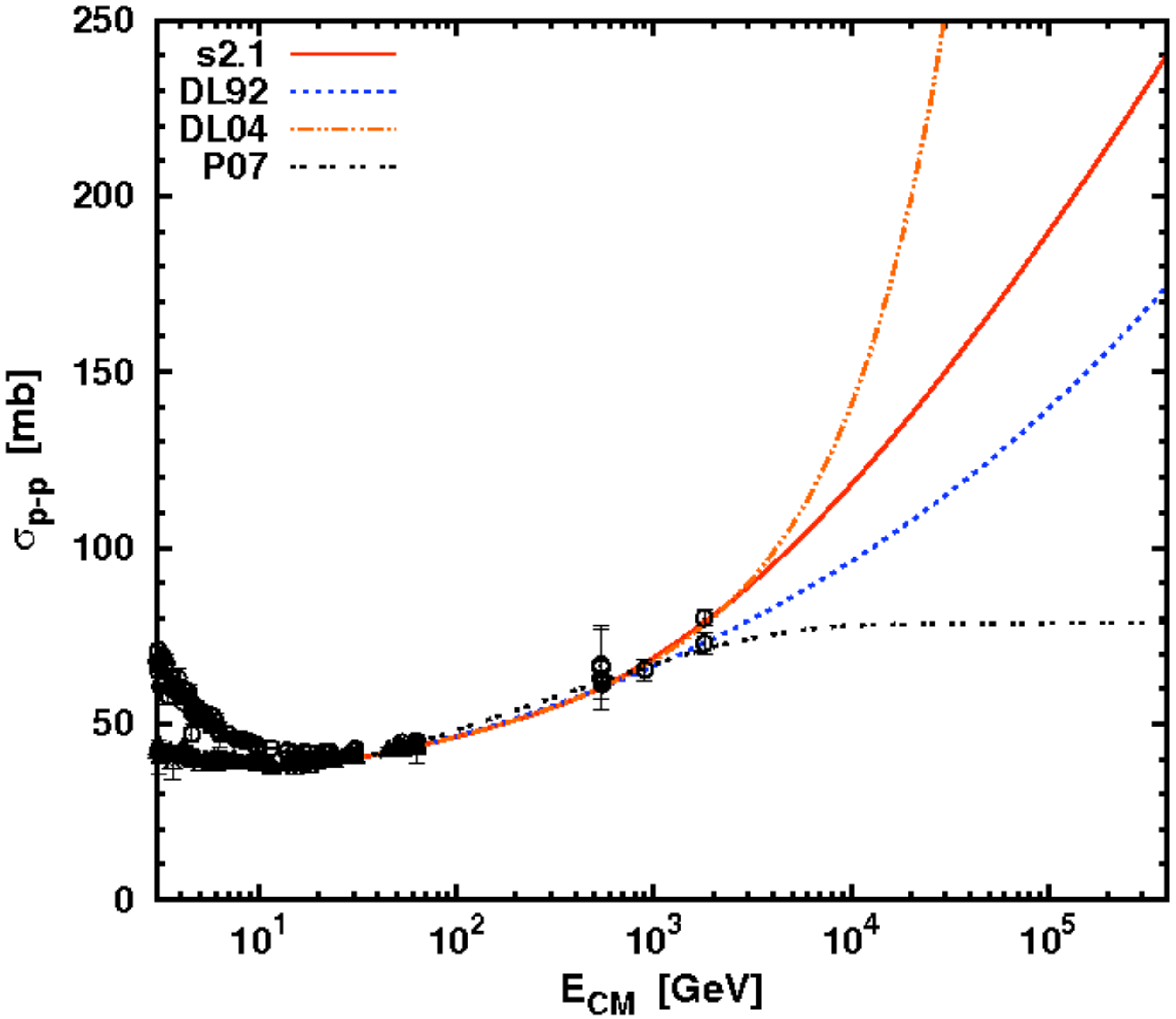
- extrapolate to higher energies

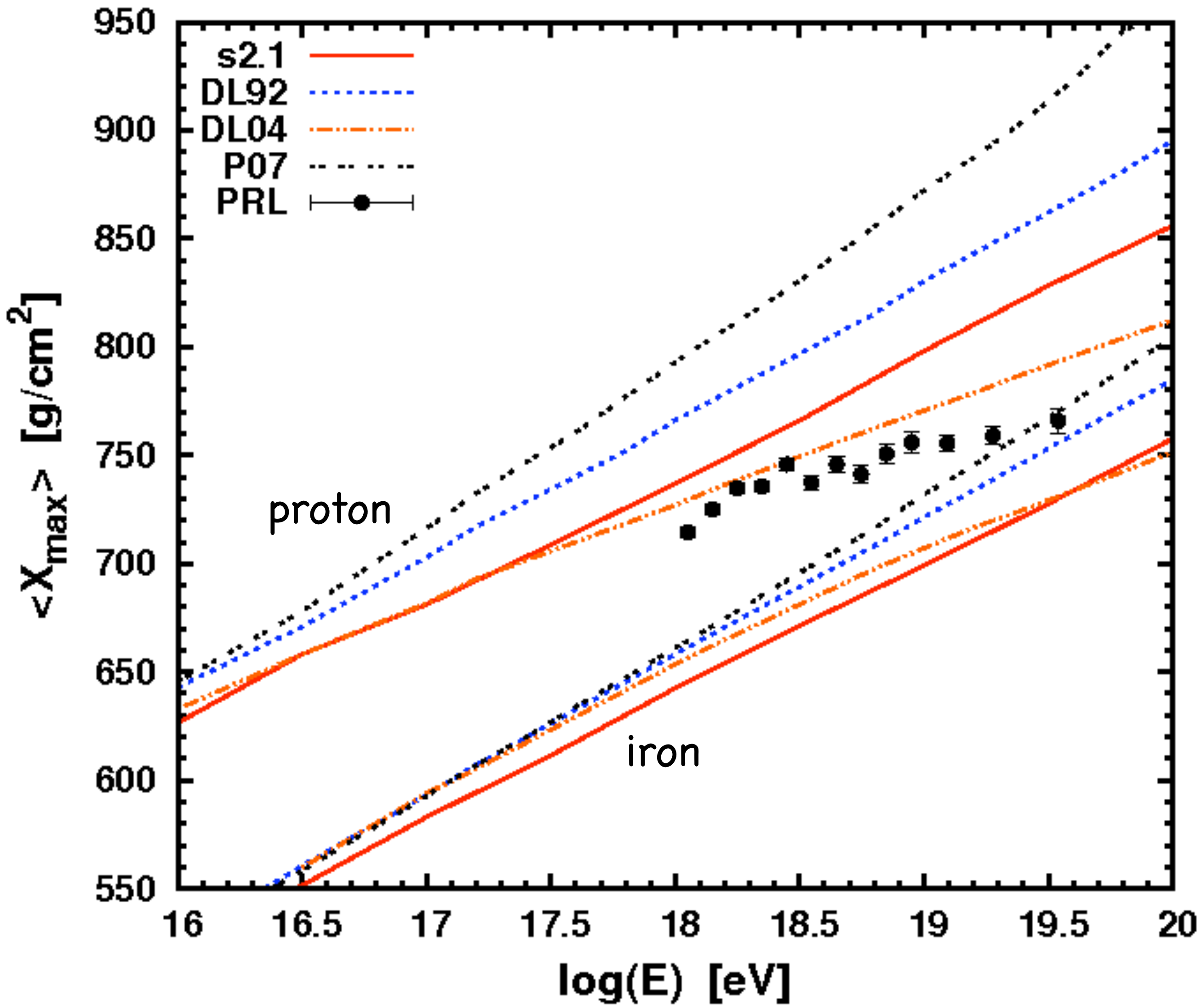
‣ Tevatron -> LHC : $E_{lab} \approx 10^{15}$ eV -> 10^{17} eV

‣ Auger's enhancements : $E \approx 10^{17}$ eV

-> gap is decreasing

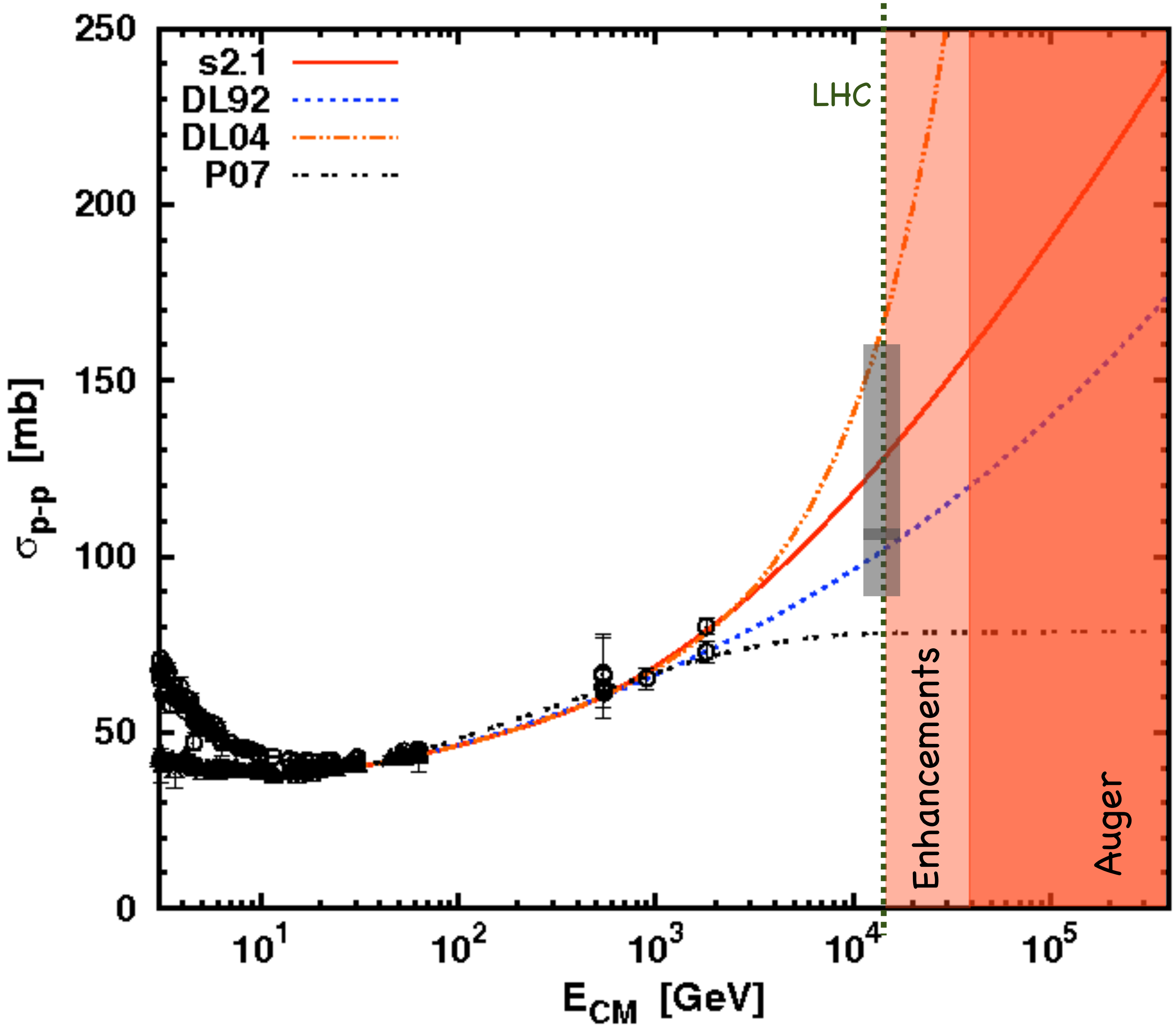
Testing cases of σ_{p-p} for effect on X_{max}





- range of X_{max} depends on the cross section model;
- composition can vary p <-> Fe depending on cross section;
- to understand composition, σ_{p-p} needs to be understood:
  - energy-consistent estimation possible at CR energy for the first time
  - other particle properties (inelasticity, multiplicity) can also be probed
  - effort is led by the Fermilab Auger group

Data and prediction of $\sigma_{p\text{-}p}$



LHC

125 ± 35 mb?
(P. Landshoff)

107.3 ± 1.2mb?
(M. Block)

UHECR

E.g. At 40 TeV
$\sigma_{p\text{-}air} \approx 800$ mb
if CRs are protons

- ★ LHC can tell us which theory is better at 7-14 TeV
- ★ Auger can tell us which theory is better, **up to a higher energy**

Plans for the future

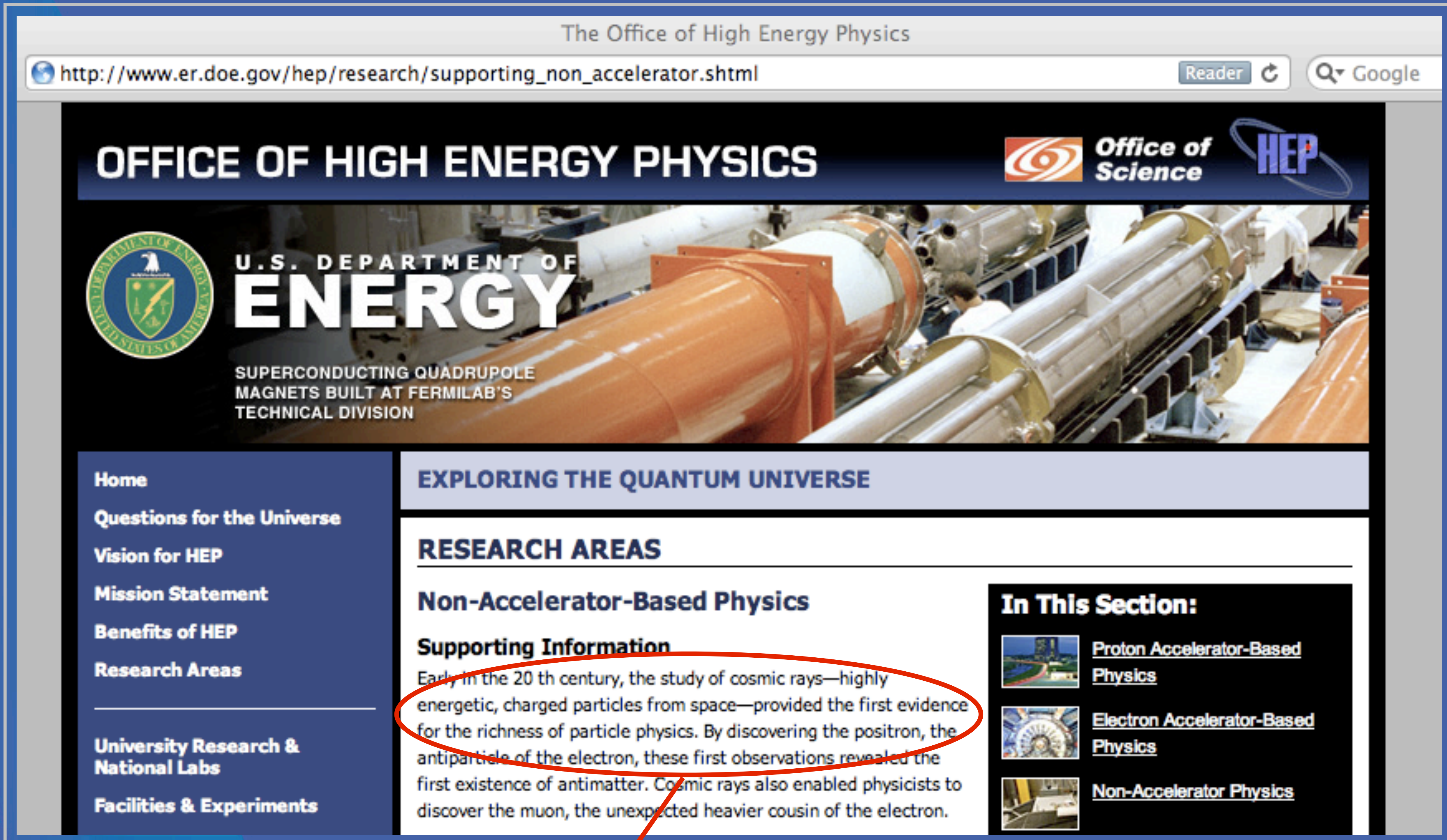
for the Pierre Auger Observatory

- Gather more data to understand highest energy cosmic rays origin and composition
- Understand composition and hadronic interactions
- Set better photon & neutrino limits at all energies
- Enhancements: low energy with HEAT and AMIGA
  - just commenced taking data
  - ➡ Better understanding of Galactic-to-extra-galactic transition
- Continue detector study with RDA, AERA & microwave R&D

Plans for the future

For the Fermilab Auger group:

- Anisotropy: - intrinsic anisotropy & correlation with catalogues and individual sources
  - Galactic source identification at lower energies
- Hadronic interactions: - complete study of proton-air cross section
  - effect of other particle properties (inelasticity, multiplicity)
  - composition
- Improve detector systematics: further develop study of PMT non-linearity
- Complete RDA work in design and algorithms (Colorado School of Mines, Colorado State Univ. at Ft Collins & Pueblo, Michigan Tech, Univ. New Mexico)
- Joint study with Univ. Chicago, Argonne Lab on microwave studies
- Maintain, operate, improve the surface detector array
- Operations management



"... cosmic rays provided the first evidence for the richness of particle physics."

cosmic rays can provide **new** evidence for the richness of particle physics

beyond current man-made accelerators

Summary

- Fermilab group active and lead in – physics analysis: anisotropy, composition,
  – detector studies: stability and systematics;
- Fermilab group plays leading role in Auger RDA design & management:
  – platform for R&D for future detectors;
- Fermilab group has led and leads the Auger design, operation, management;
- Fermilab hosts the project management office for the Pierre Auger Observatory.

❖ Auger has started making profound discoveries into understanding UHECRs;

❖ Need more statistics to understand what the highest energy cosmic rays are;

❖ Highest energy cosmic rays either not protons or hadronic interaction must change;

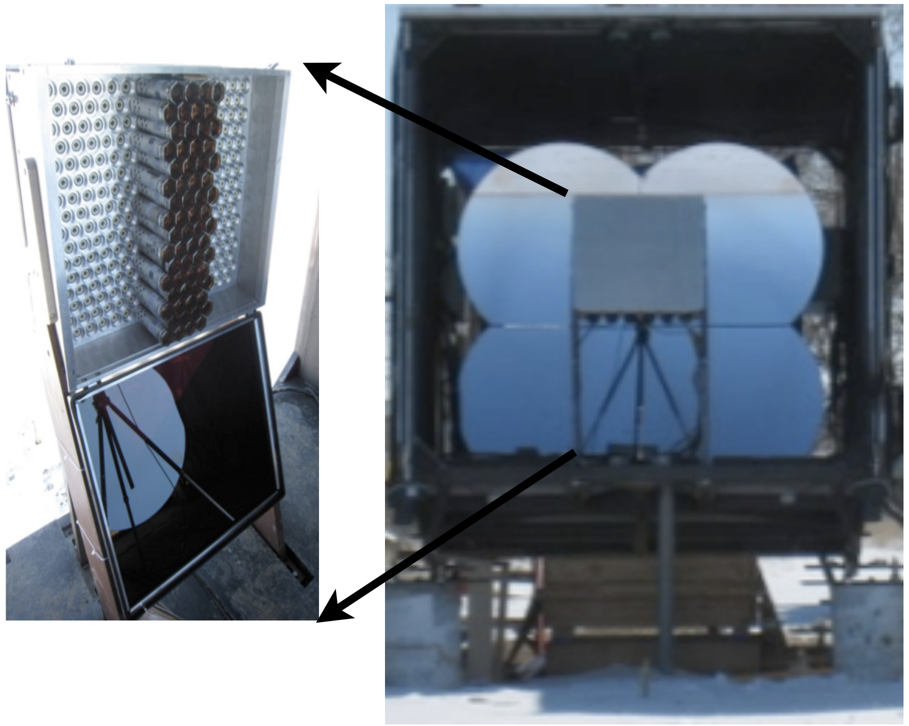
❖ Particle accelerator data are relevant to understand cosmic rays;

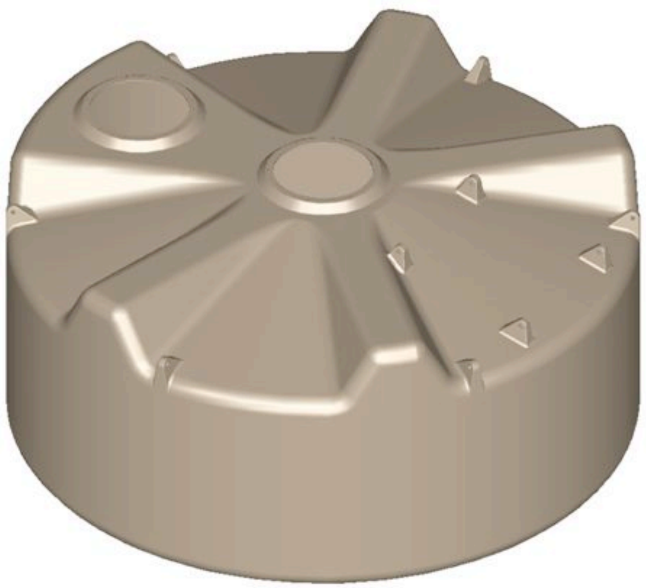
❖ Auger can probe particle physics beyond LHC.

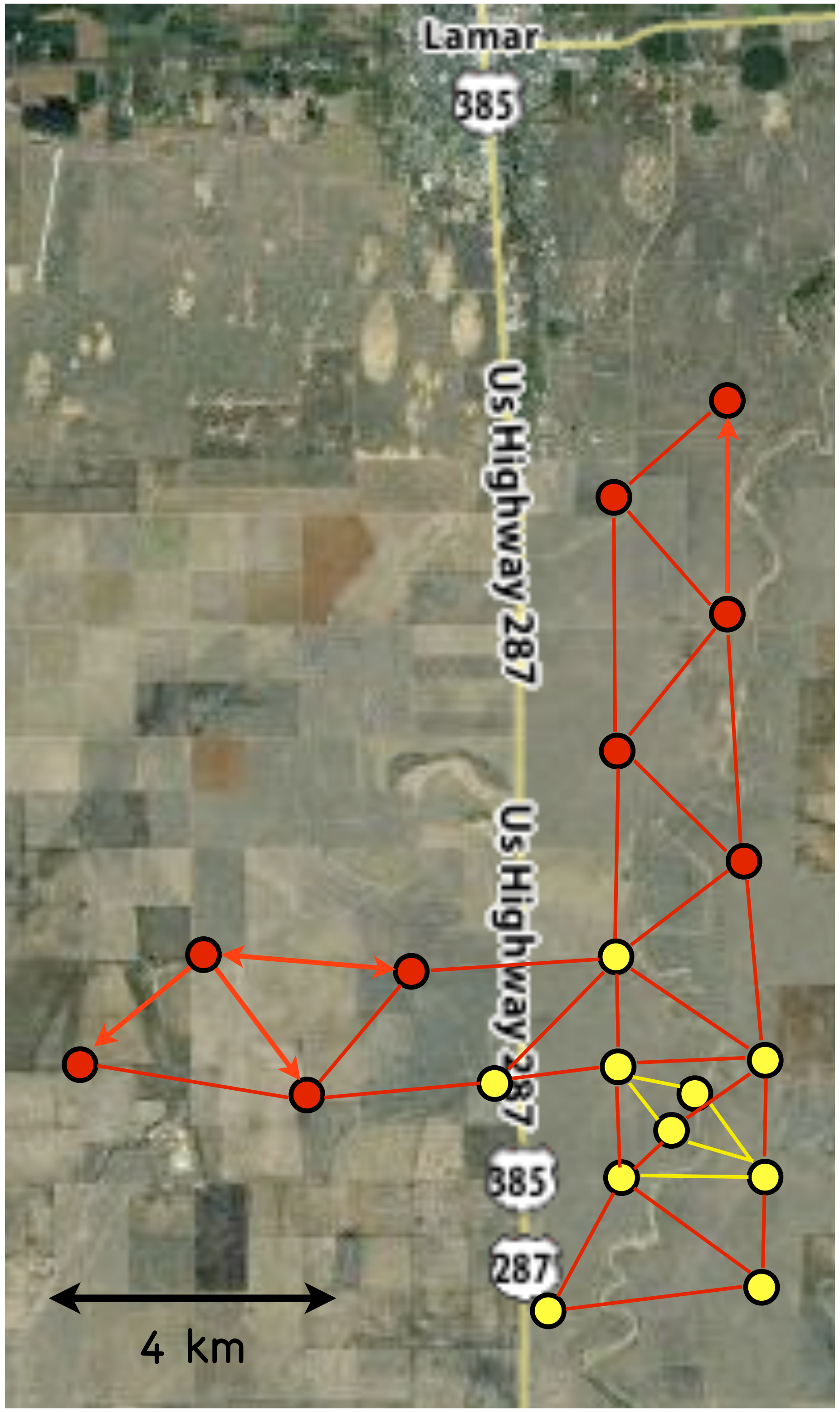
begin back ups

Auger R&D Array (RDA)

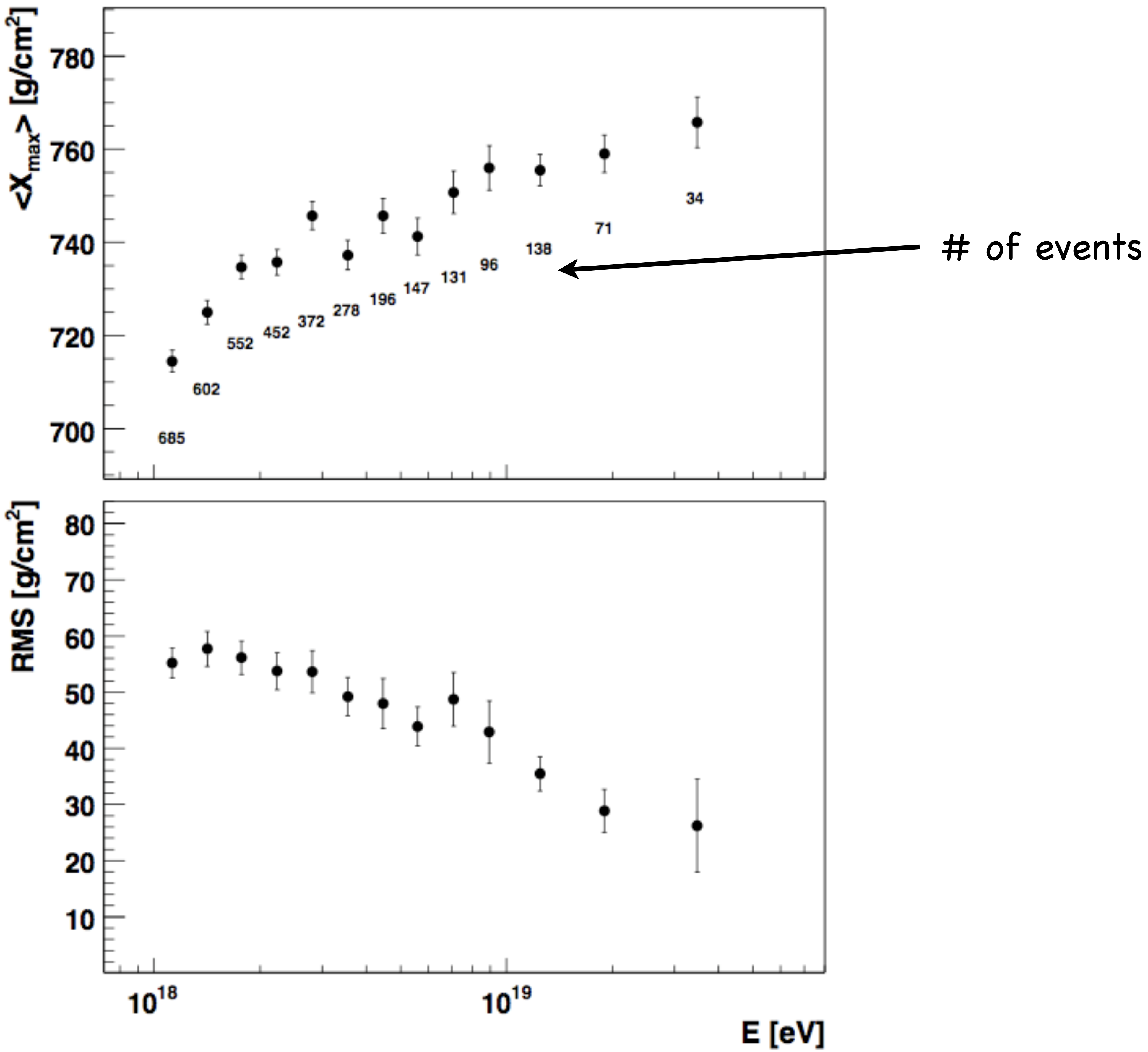
- Testbed for Auger enhancements
- Future detector R&D
- Lamar, CO
- 10 tanks + 10 nodes
  - atmospheric monitoring
  - new communication scheme
  - new surface detector tank design & SD electronics



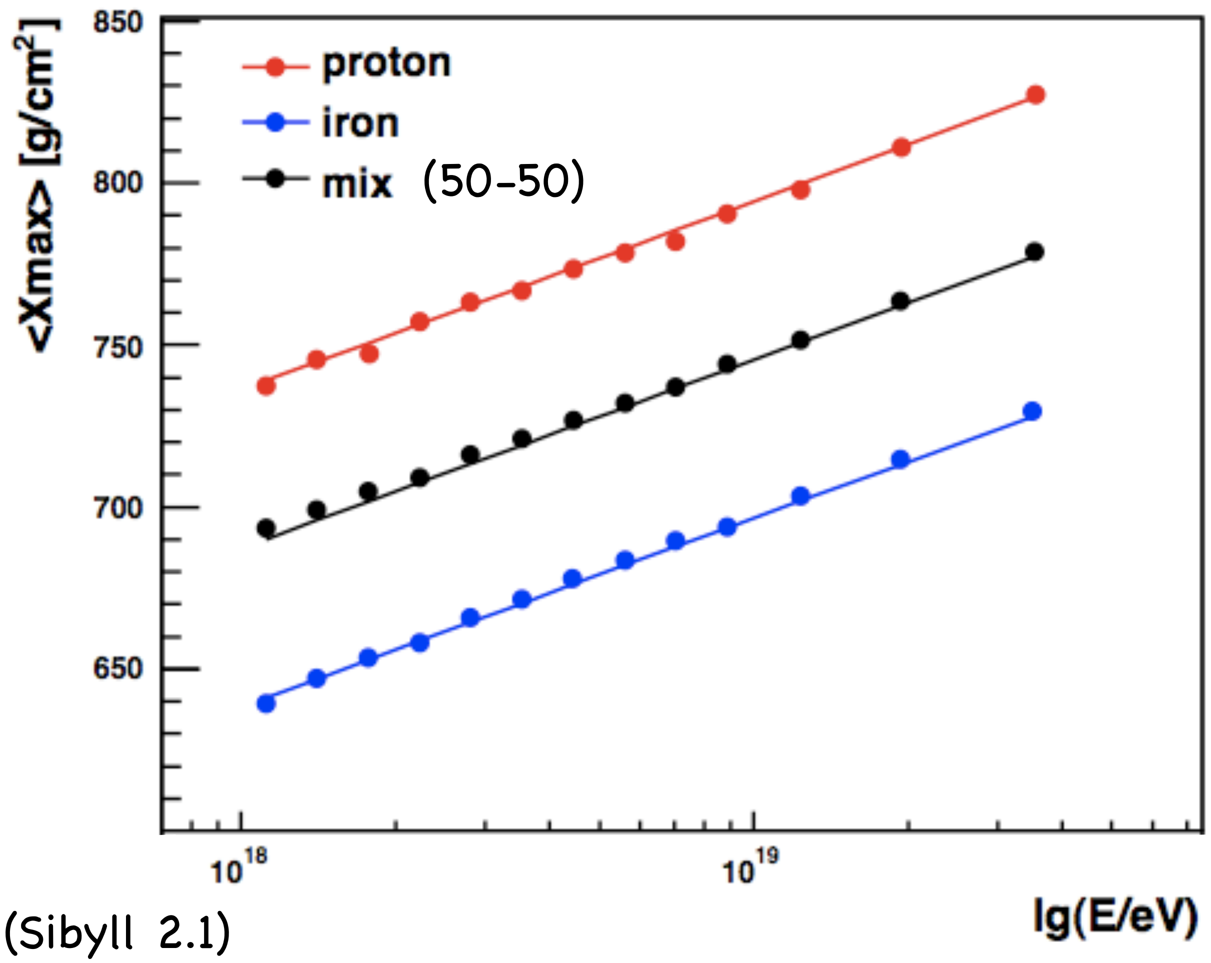




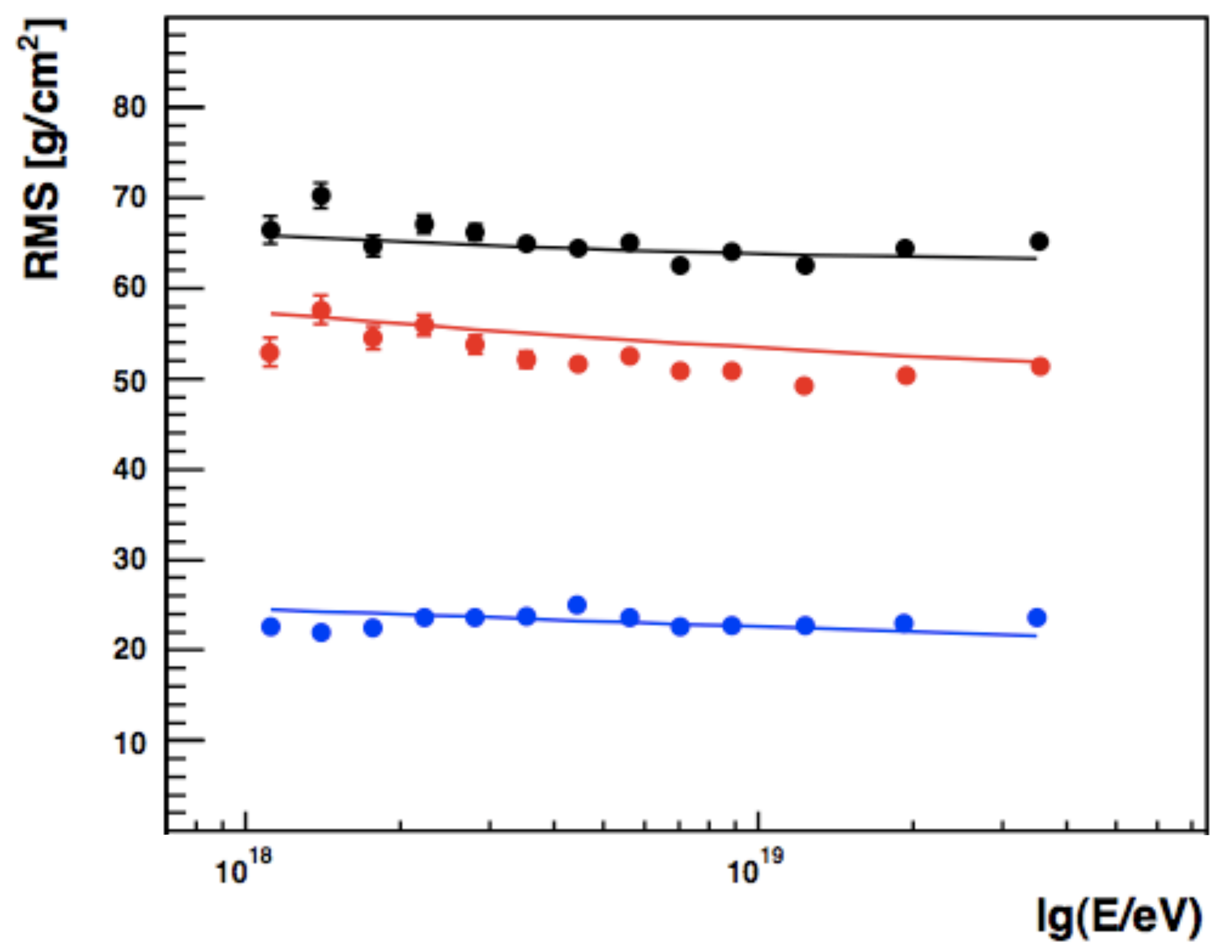
Data of X_{max} : mean and fluctuation (RMS)



Behaviour of X_{max}: mixing proton and iron nuclei

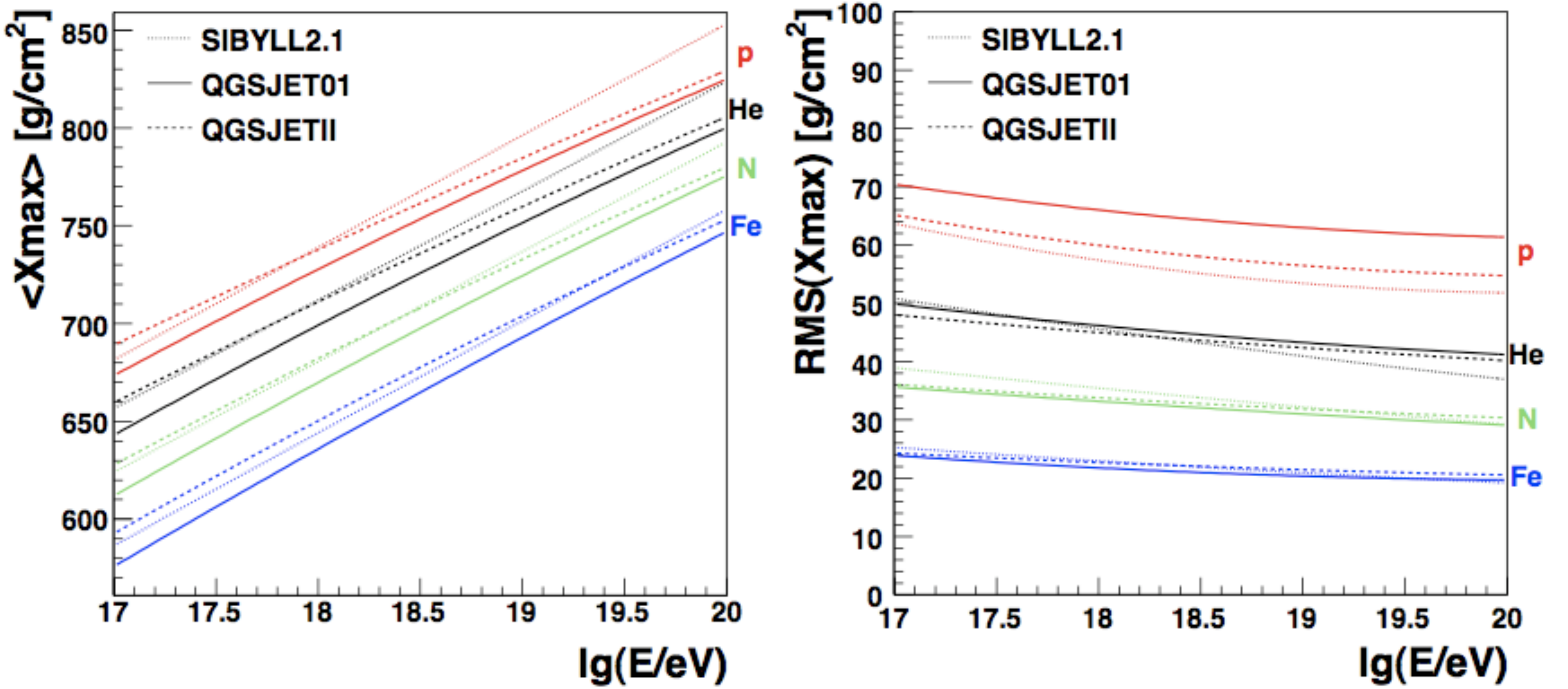


(Sibyll 2.1)



- Mix of proton and iron nuclei shows linear behaviour for $\langle X_{max} \rangle$
- RMS increases as the iron nuclei fraction increases before decreasing
- 50-50 mix has higher RMS than proton
- RMS of 40% proton & 60% iron nuclei ≈ RMS of pure proton

Behaviour of X_{max}: assuming various compositions



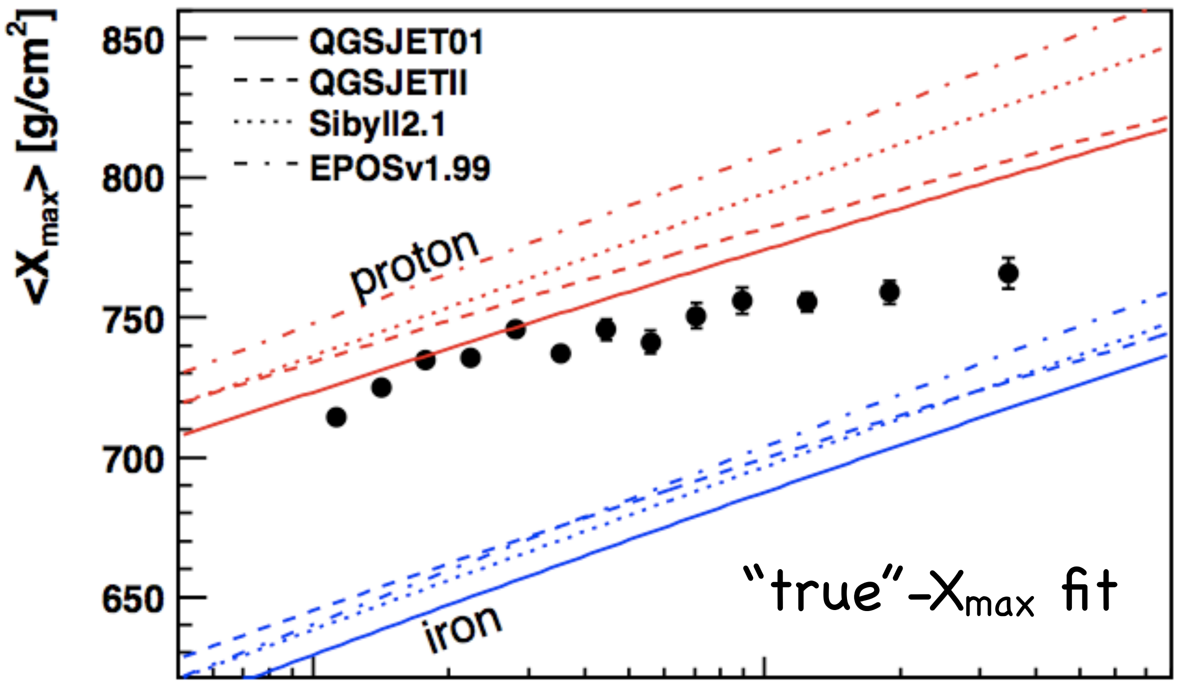
p : most stable

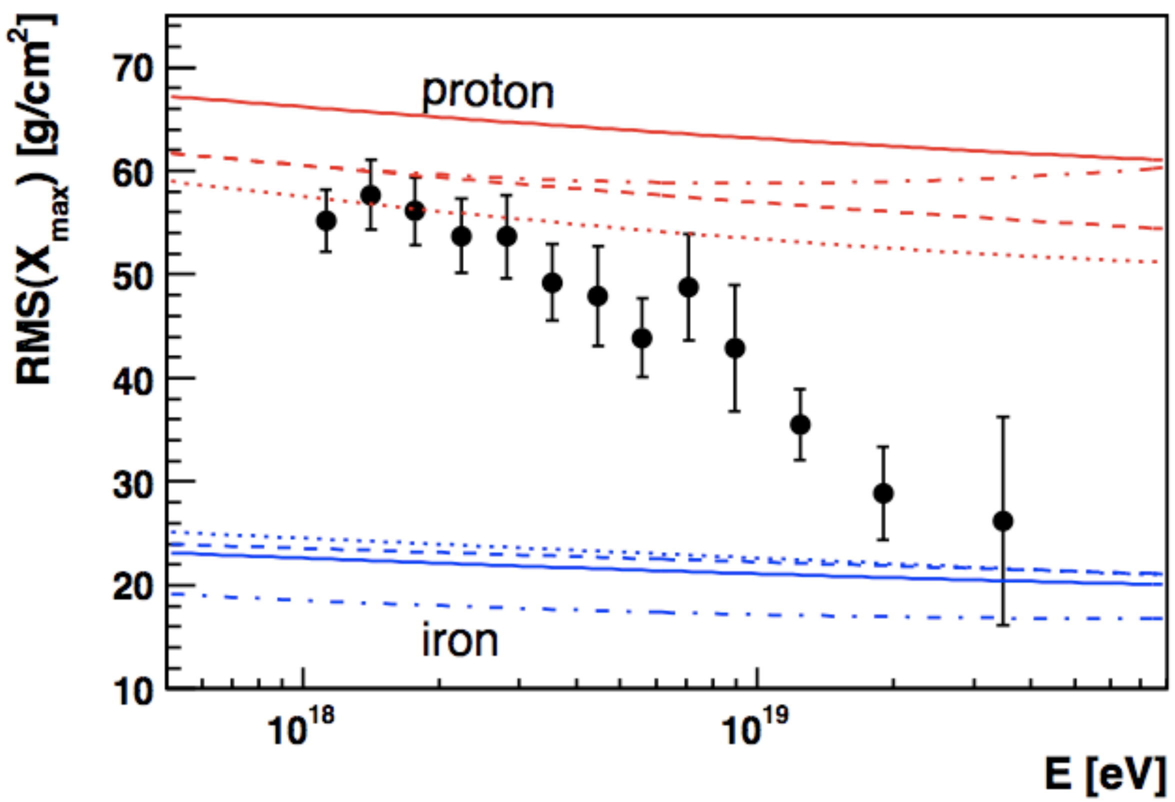
He : disintegrate during propagation

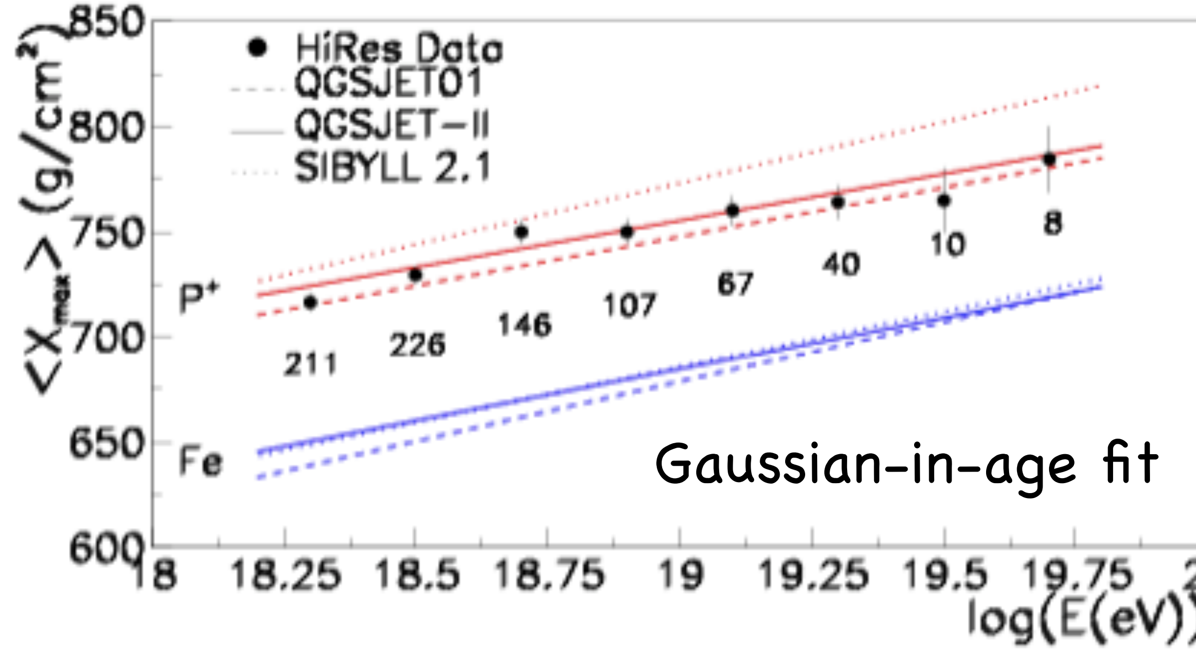
N (CNO) : disintegrate during propagation

Fe : heaviest abundant element, survive long-distance propagation

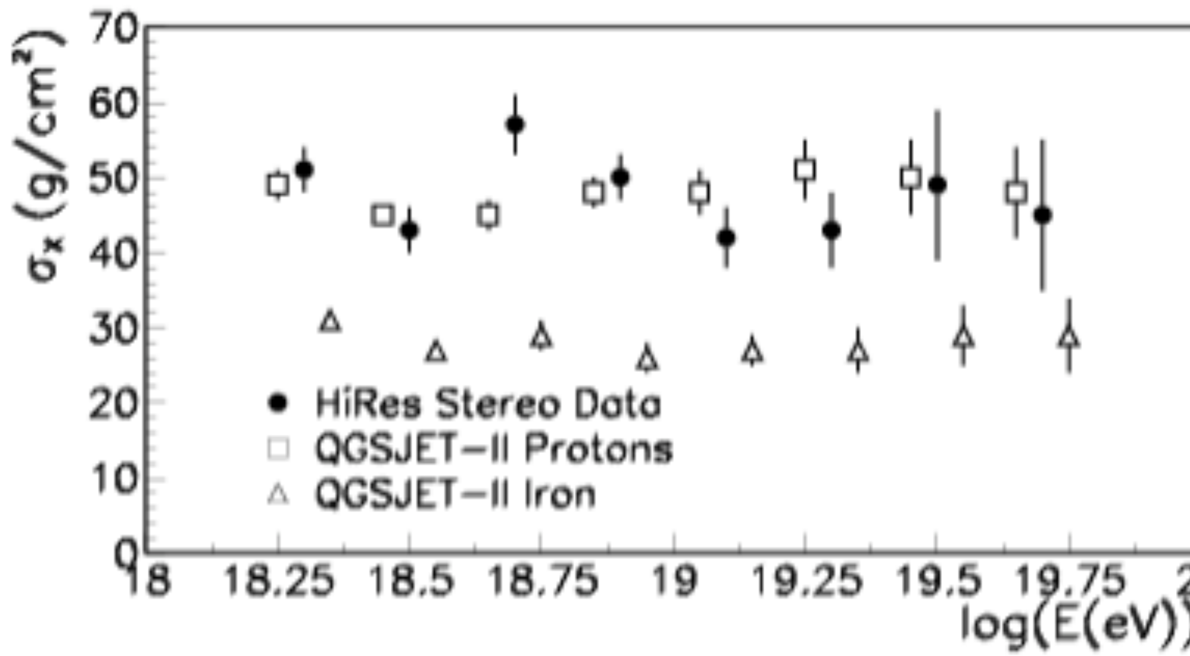
Comparing X_{max} of Auger and HiRes







Gaussian fit to distribution truncated at 2xRMS



N(Auger) = 3754

PRL **104** 091101 (2010)

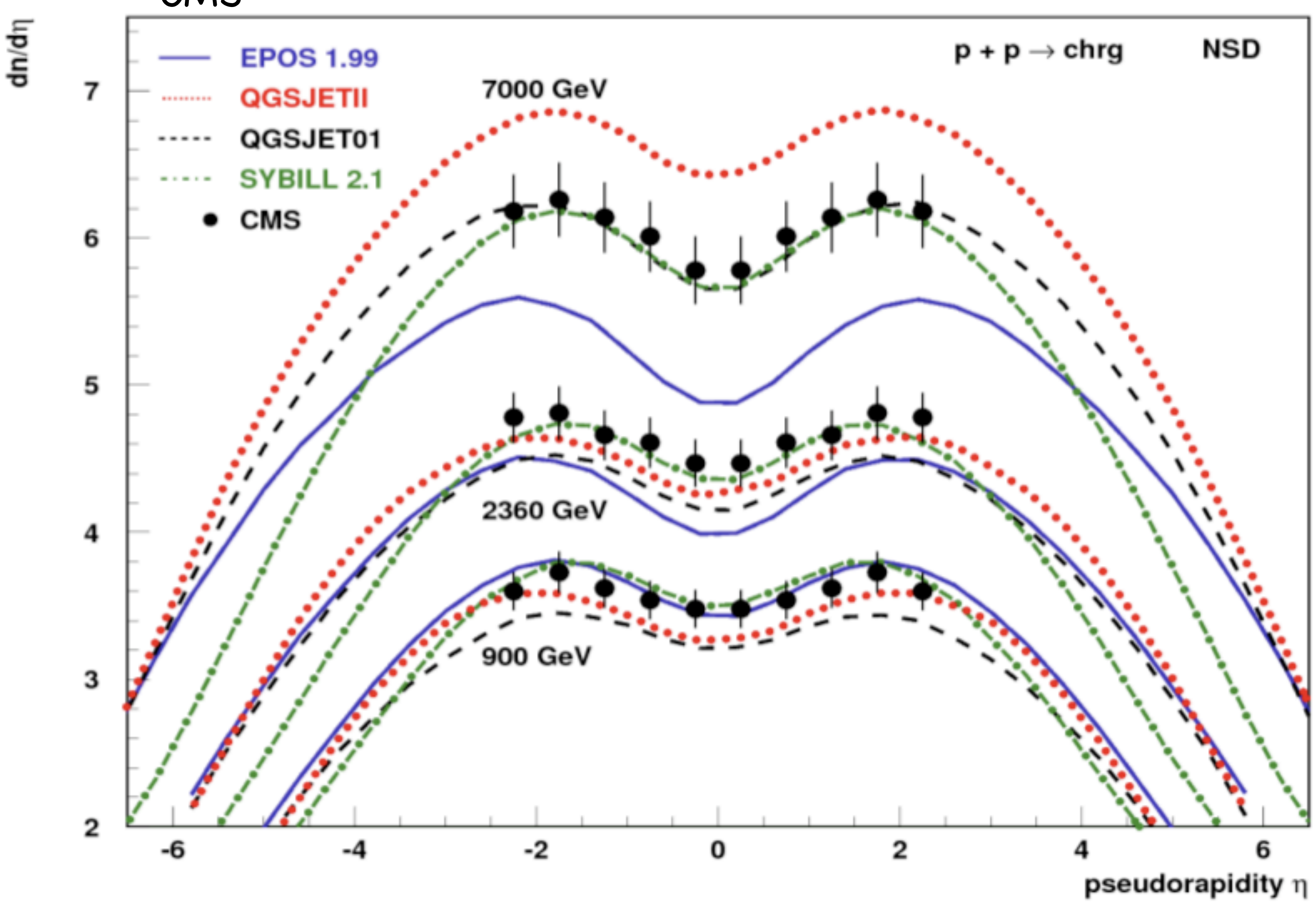
N(HiRes) = 815

PRL **104** 161101 (2010)

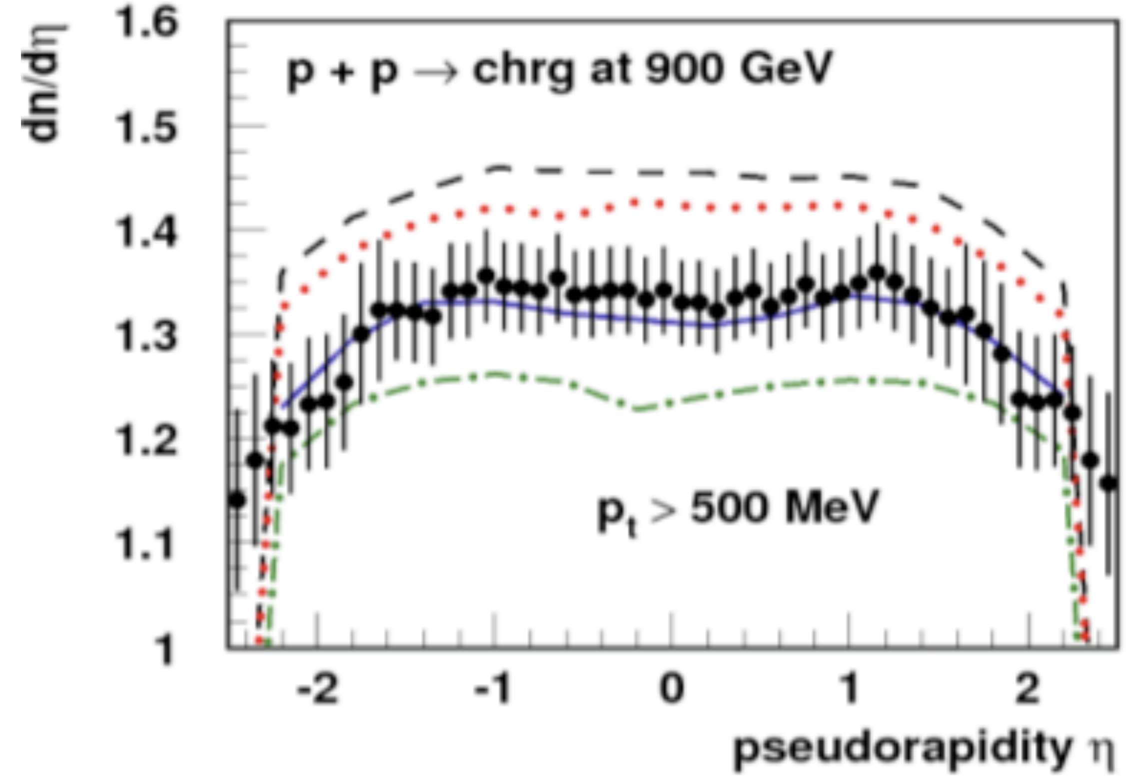
Cosmic ray hadronic interaction models at LHC

1. Pseudorapidity distribution

CMS



ATLAS

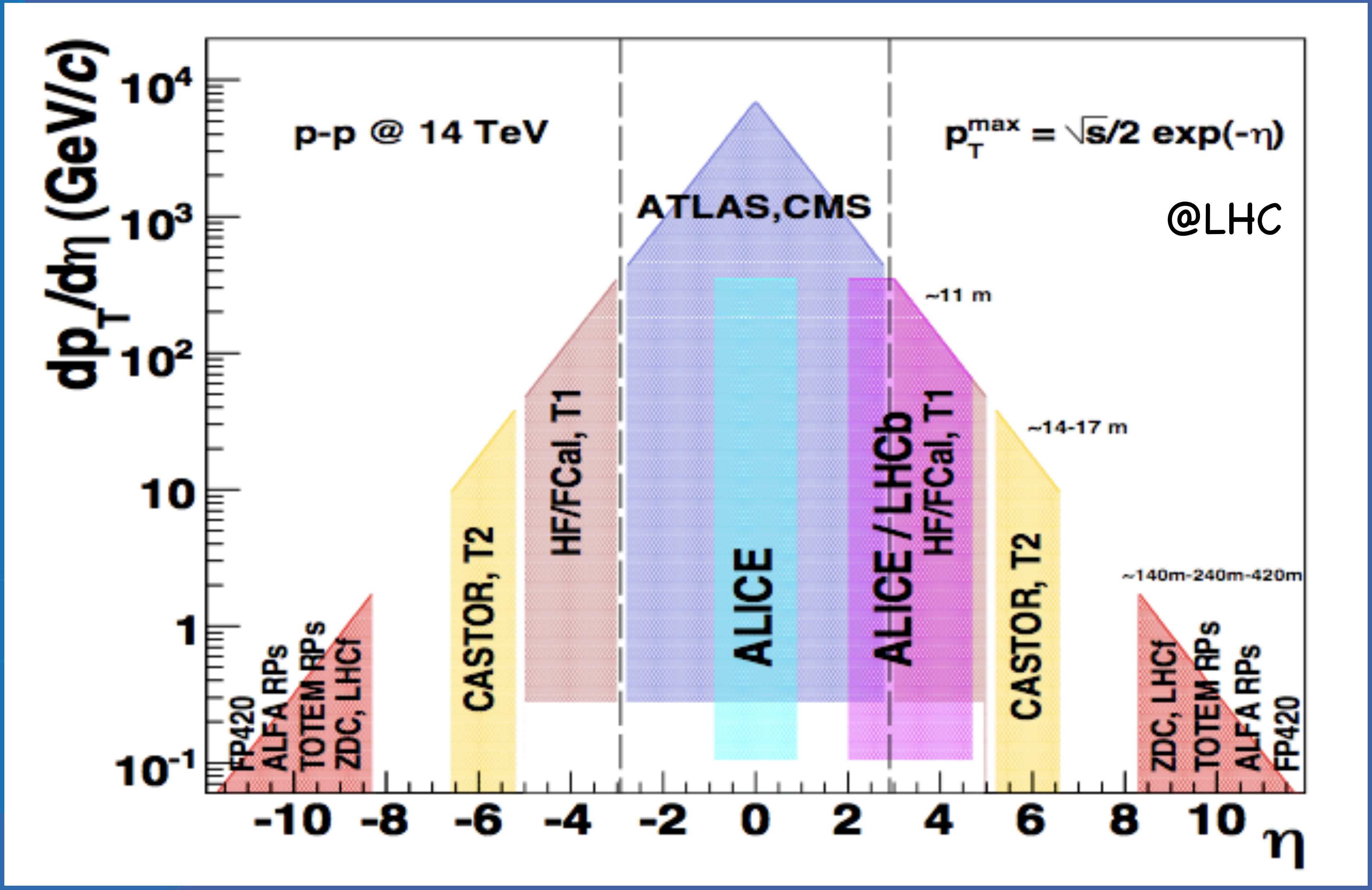


- multiplicites are NOT underestimated (in central region)

- very good at 900 GeV (EPOS) ; good overall average (Sibyll & QGSJET01)

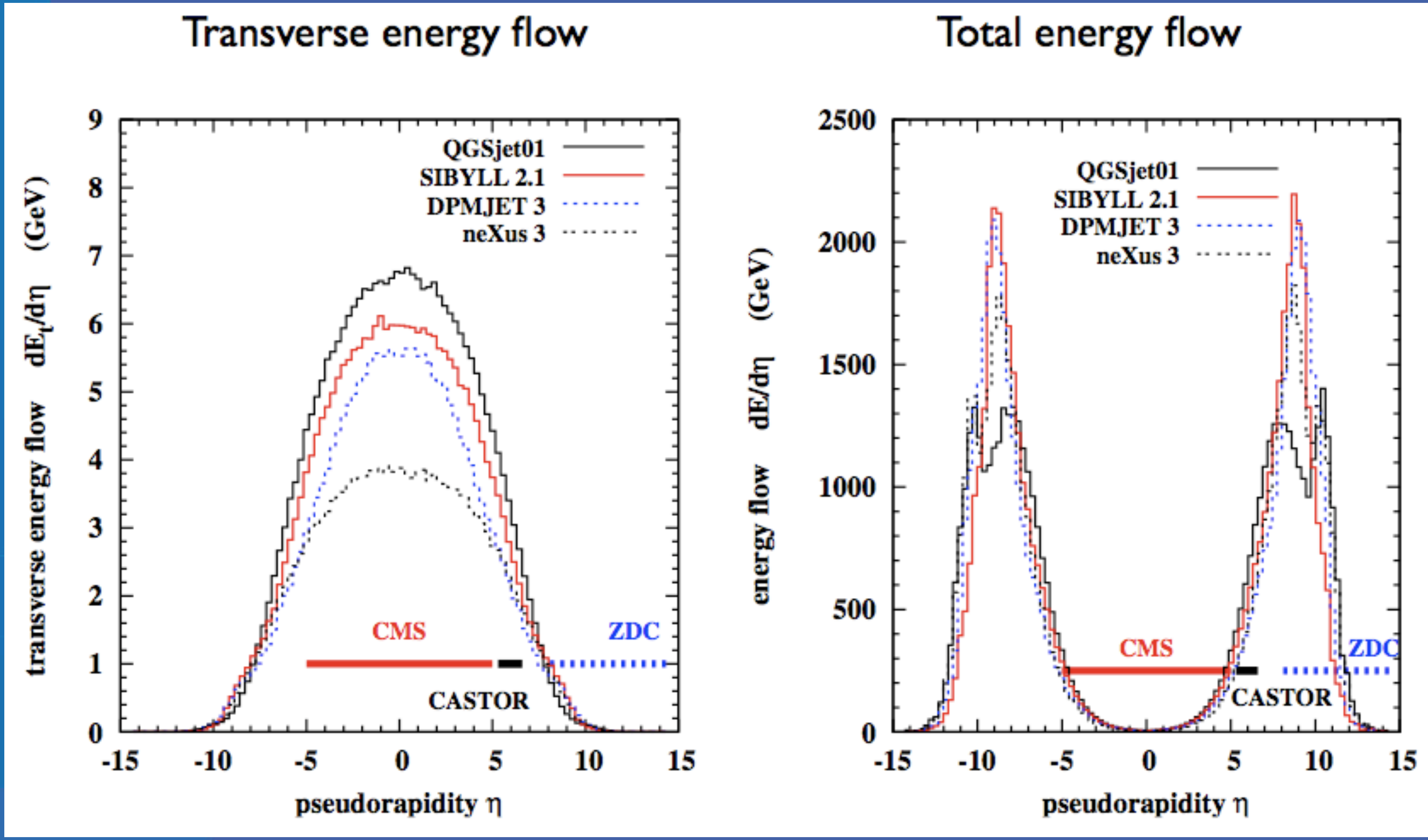
Data from accelerator -> used in cosmic ray hadronic interaction models

- Fixed target experiments - larger phase space, lower energy (E_{lab} < 800 GeV)
  - nuclei targets
- Colliders - smaller phase space, higher energy ($E_{lab} < 10^{15}$ eV -> 10^{17} eV)
  - p-p or heavy ion collision (N/O/Ar - N/O/Ar collision?)



Data from accelerator -> used in cosmic ray hadronic interaction models

- Fixed target experiments - larger phase space, lower energy (E_{lab} < 800 GeV)
  - nuclei targets
- Colliders - smaller phase space, higher energy ($E_{lab} < 10^{15}$ eV -> 10^{17} eV)
  - p-p or heavy ion collision (N/O/Ar - N/O/Ar collision?)



end back ups