Report on Tests and Measurements of Hadronic Interaction Properties with Air Showers

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Take-home message

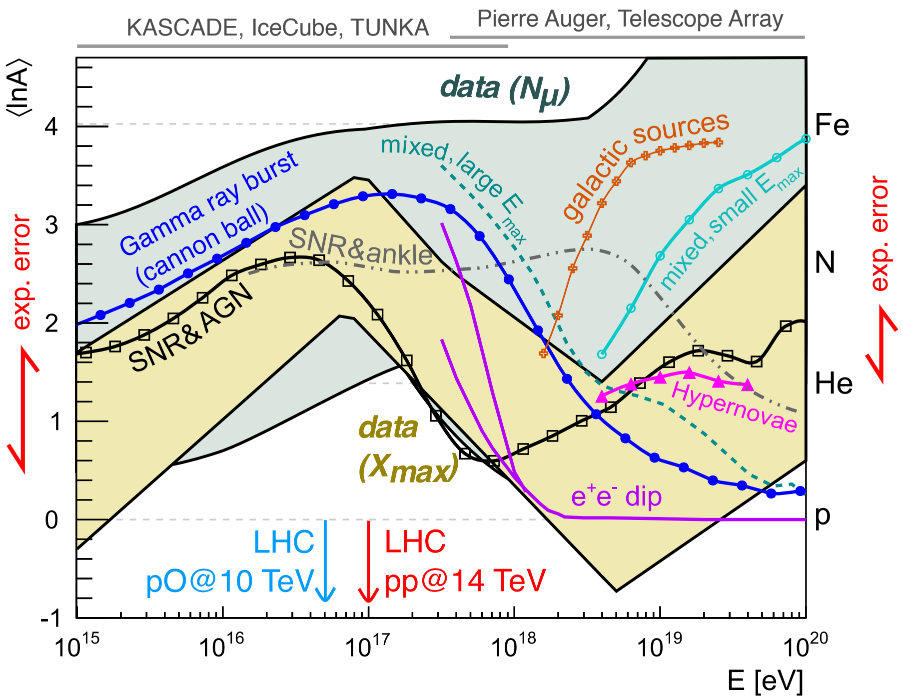
- Air shower observables sensitive to **cosmic ray mass** also sensitive to **hadronic interaction properties**, examples:
  - X_{max} high energy interactions p – Fe ~ 100 g cm-2
  - N_{μ} high and low energy Fe / p ~ 1.4

- Need to know cosmic-ray **energy** and **mass composition** precisely to test/measure hadronic interaction properties

- EM component: **mostly good data/MC agreement**

- Muon component
  - **data/MC mismatch** in lateral density, production depth, attenuation
  - **Muon density** measurements from **0.5 PeV to 10 EeV** converted into comparable z-factor for the first time
  - **Consistent picture (?)** seems to emerge after correcting energy-scales

Motivation



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

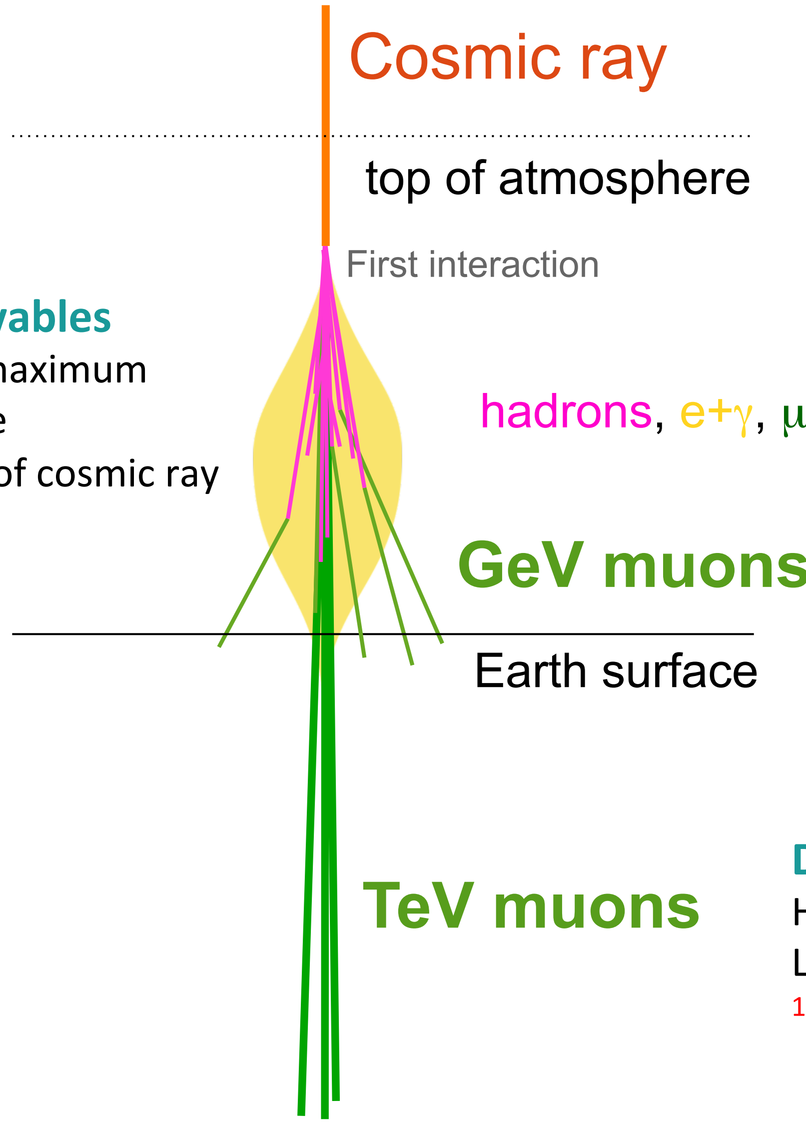
- Mass composition (<lnA>) carries imprint of cosmic-ray sources and propagation
- Uncertainties in hadronic interaction models dominate <lnA>, not experimental uncertainties
- **Muon Puzzle:** Muon measurements have much larger spread and are not consistent with X_{max}

Combined approach to get precise unambiguous <lnA> data

- Cosmic ray community probes air showers and quantifies inconsistencies
- Collider community provides **relevant reference measurements** for model tuning

Indirect search for physics beyond the standard model at 100 TeV scale

Probing air shower physics



Optical/radio observables

Depth X_{max} of shower maximum

Shape of shower profile

Direct Cherenkov light of cosmic ray

Ground observables

Lateral (muon) density profile

Muon fluctuations

11:30 talk by F. Riehn

Muon production depth

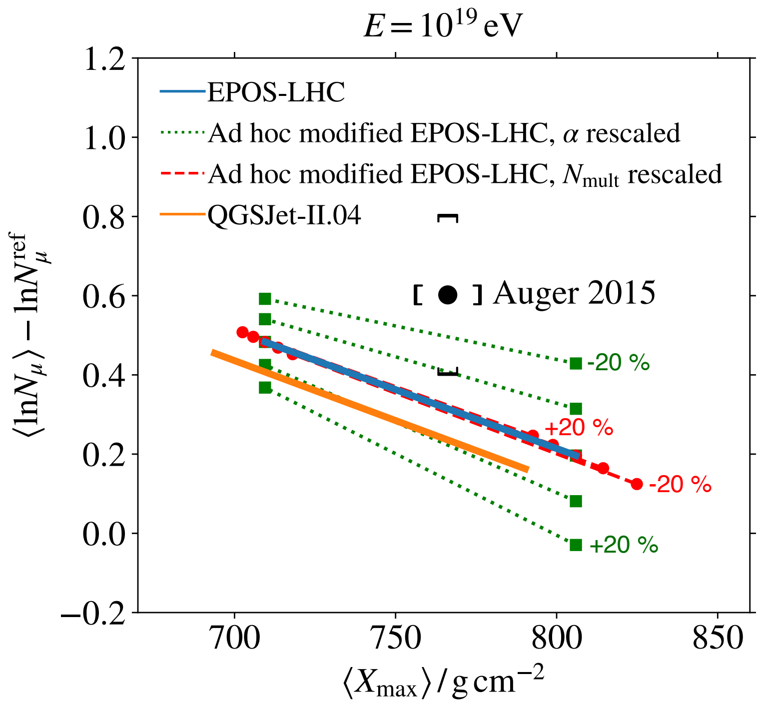
Deep underground observables

High-energy muon flux

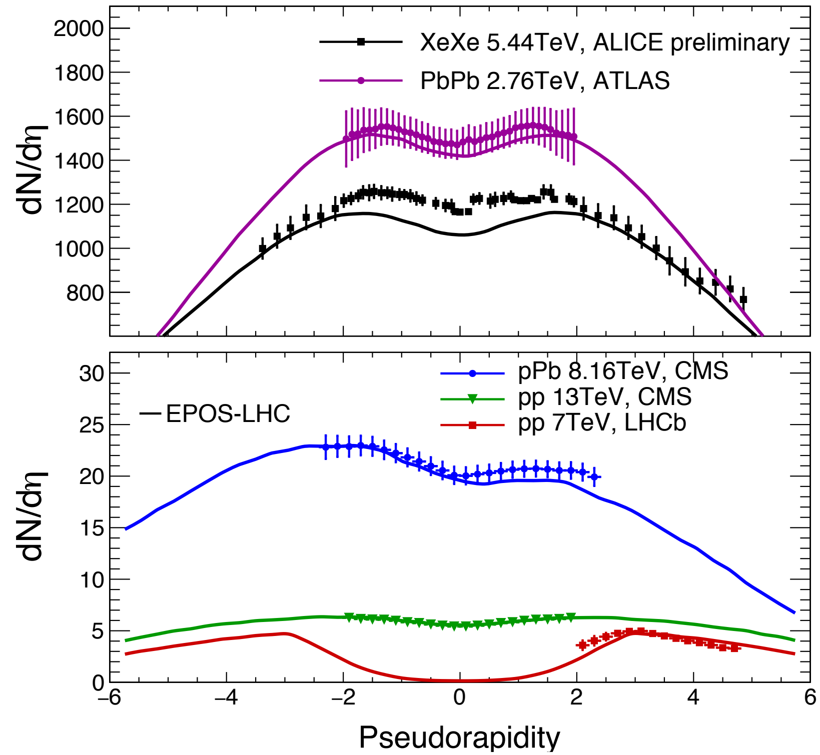
Lateral separation of TeV muons

14:40 talk by D. Soldin

Connection to LHC measurements



Based on Ulrich et al., PRD 83 (2011) 054026
and Auger: PRD 91 (2015) 032003



ALICE Xe-Xe arXiv:1807.09061; ATLAS Pb-Pb arXiv:1504.04337;
CMS p-Pb arXiv:1710.09355v2; CMS p-p arXiv:1507.05915v2;
LHCb p-p arXiv:1402.4430

- X_{max} sensitive to: **inelastic cross-section**, hadron multiplicity
- N_μ sensitive to: **energy fraction lost to π^0**, hadron multiplicity
- **Nuclear modification in forward-produced hadrons** expected, largely unexplored, proposal to measure **proton-oxygen collisions** during LHC-Run 3

Air shower measurements

EM component

- Proton-air cross-section (next slide)
- Longitudinal shape
  - F. Diogo (Auger), ICRC 2015 arXiv:1509.03732v1
    - Average profiles parameterized by width L and asymmetry R
    - Agreement for EPOS-LHC, QGSJet-II.04, some tension for SIBYLL-2.1
- Moments of X_{max} distribution
  - J. Bellido (Auger), ICRC 2017 arXiv:1708.06592v2; Auger: JCAP 1302 (2013) 026
    - First two moments of X_{max} distribution converted to first two moments of lnA
    - EPOS-LHC, SIBYLL-2.3 ok; partially unphysical second moments for QGSJet-II.04
- Lateral density profile
  - S. de Ridder (IceCube) ICRC 2017 arXiv:1710.01194v1
    - <lnA> computed from <β> and in-ice energy loss (TeV muons)
    - Agreement for QGSJet-II.04, SIBYLL-2.3
    - Disagreement for SIBYLL-2.1, EPOS-LHC
- Attenuation with zenith angle
  - D. Ivanov (Telescope Array) TeVPA 2018
    - Agreement to 45 deg with QGSJet-II.03

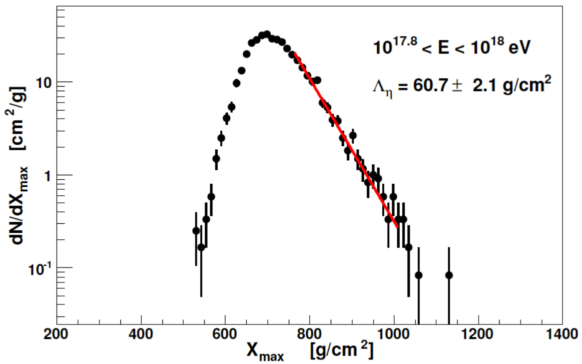
Proton-air cross-section

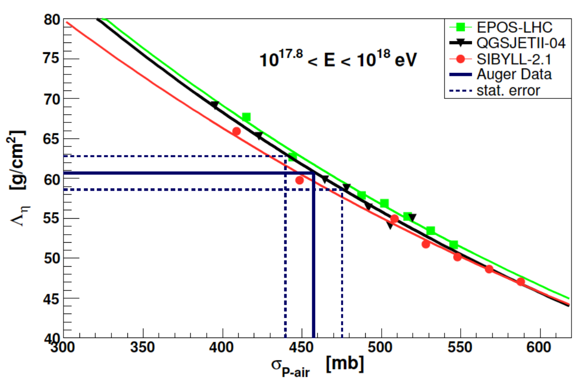
Prime example of measuring hadronic interaction property with air showers

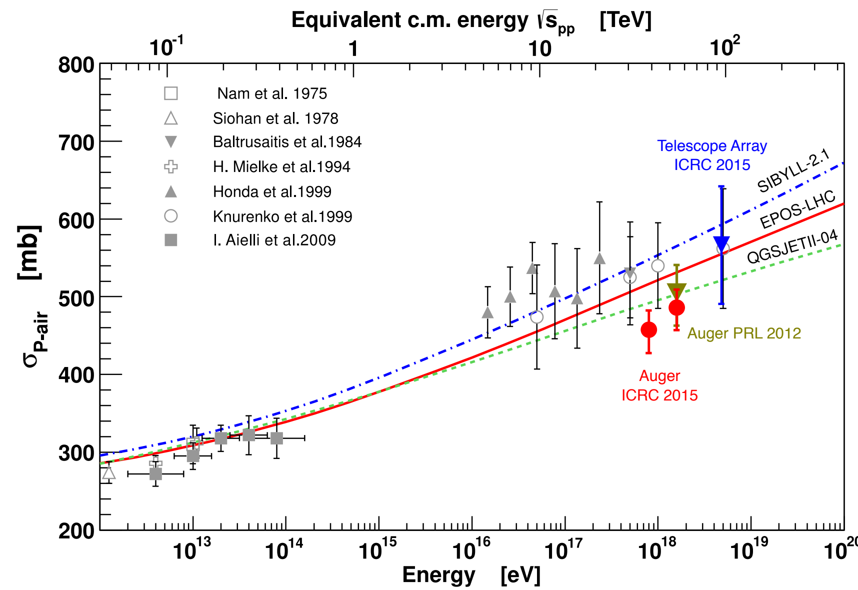
Based on tail of X_{max} distribution

$$\frac{dN}{dX_{\max}} \propto \exp\left(-X_{\max}/\Lambda_\eta\right)$$

- Decay constant Λ_η anti-proportional to $\sigma_{p\text{-}air}$
- Tail is proton-rich even in mixed composition







Auger: R. Ulrich et al. PoS(ICRC2015)401;
P. Abreu et al., PRL 109, 062002 (2012)
Telescope Array: R.U. Abbasi et al., PRD 92, 032007 (2015)

- Weak dependence on energy scale
- Weak dependence on mass-composition
- Good agreement between experiments
- Data starts to discriminate models

Muon component

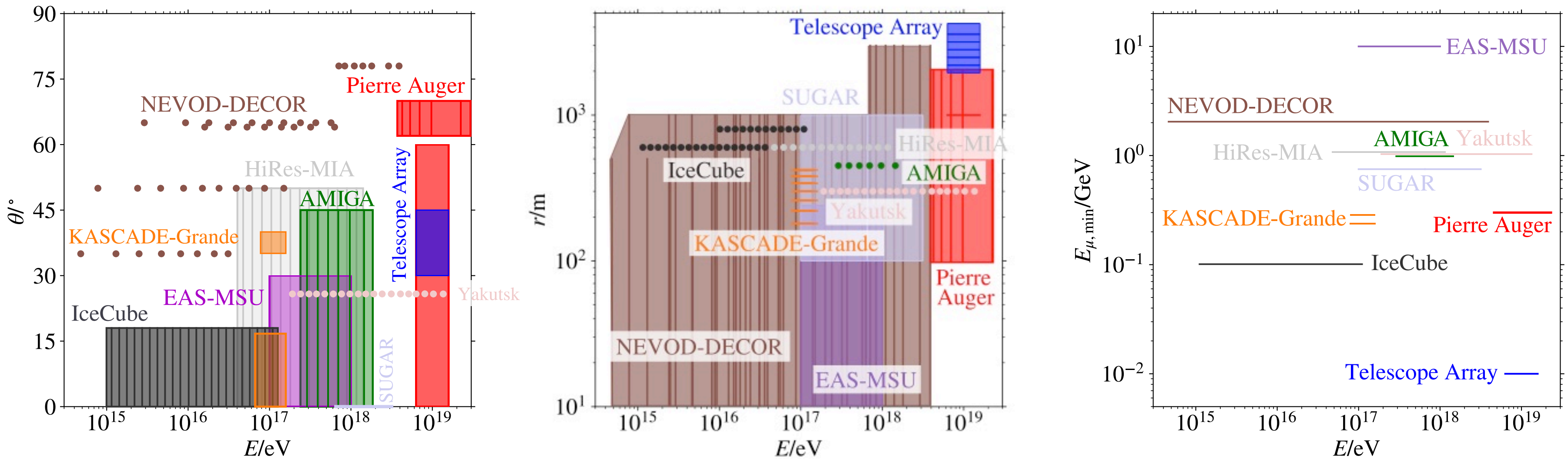
- Lateral density (rest of talk)
- Production depth/height
  - Auger: PRD 90 (2014) 012012, PRD 90 (2014) 039904, PRD 92 (2015) 019903; disagreement for QGSJet-II.04 and EPOS-LHC
  - KASCADE-Grande: Astropart. Phys. 34 (2011) 476; disagreement with QGSJet-II.02

Production depth preferred:
MPD follows longitudinal hadronic profile

- Attenuation with zenith angle
  - KASCADE-Grande: Astropart. Phys. 95 (2017) 25; disagreement with all current models
- High-energy muons: multiplicity
  - ALICE: JCAP 1601 (2016) 032; consistent with QGSJet-II.04
- TeV muons: flux
  - IceCube: Astropart. Phys. 78 (2016) 1; disagreement for SIBYLL-2.1, potentially fixed by adding charm
  - T. Fuchs (IceCube), ECRS 2016, arXiv:1701.04067; agreement for SIBYLL-2.1
- TeV muons: lateral-separation
  - D. Soldin (IceCube), ISVHECRI 2018; partial agreement for SIBYLL-2.1/2.3, disagreement for EPOS-LHC, QGSJet-II.04
- Rise-time
  - Auger: PRD 96 (2017) 122003; disagreement for QGSJet-II.04 and EPOS-LHC
  - Auger: PRD 93 (2016) 072006; disagreement for EPOS-LHC (500-2000 m), QGSJet-II.04 (500-1000 m), agreement for QSGJet-II.04 (1000-2000 m)

Muon measurements: overview

lines & boxes: result integrated over range

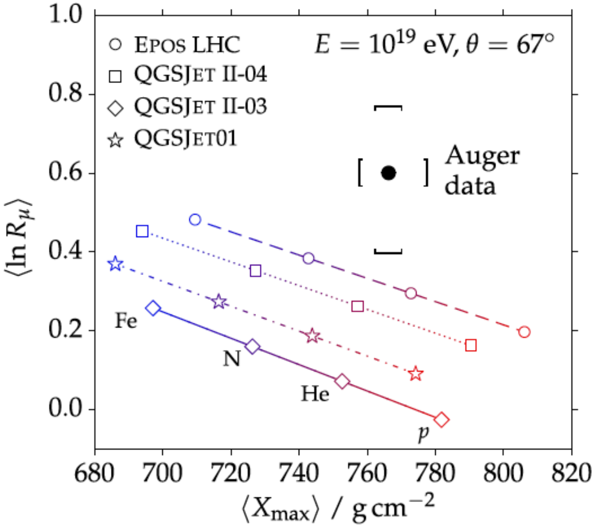


E = 0.5 PeV ... 20 EeV **θ** = 0 ... 78 deg **r** = 0 ... 4 km $\mathbf{E_{\mu,threshold}}$ = 0.01 ... 10 GeV

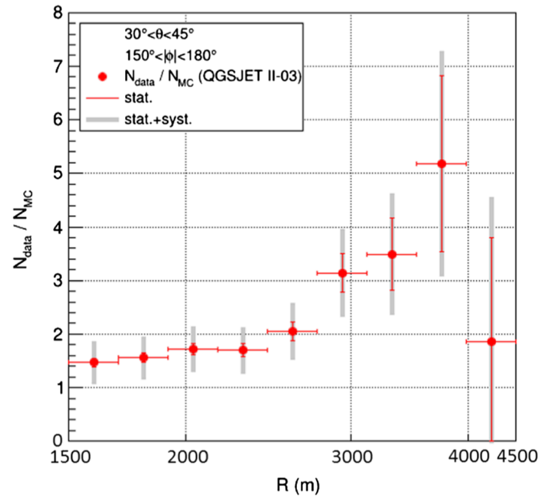
Pierre Auger	AMIGA preliminary: S. Müller poster ID 204; PRL 117 (2016) 192001; PRD 91 (2015) 032003
Telescope Array	PRD 98 (2018) 022002
IceCube	ISVHECRI 2018 preliminary
KASCADE-Grande	Astropart. Phys. 95 (2017) 25
NEVOD-DECOR	Phys. Atom. Nucl. 73 (2010) 1852, Astropart. Phys. 98 (2018) 13
SUGAR	PRD 98 (2018) 023014
EAS-MSU	Astropart. Phys. 92 (2017) 1
Yakutsk	Unpublished preliminary results
HiRes-MIA	PRL 84 (2000) 4276; not part of WG, only included for comparison

Muon measurements: examples

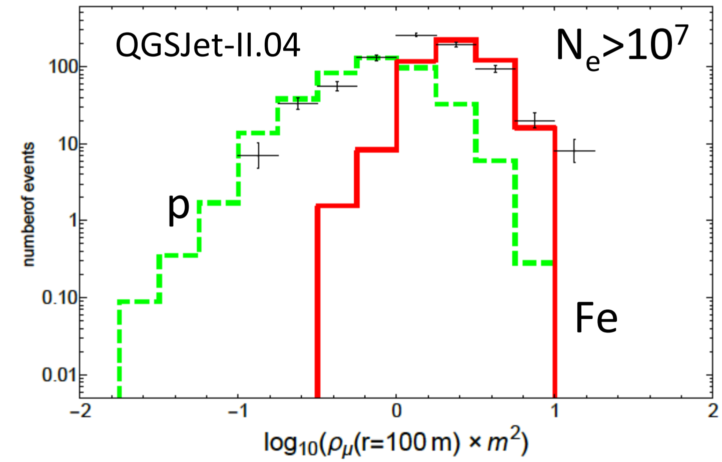
Pierre Auger



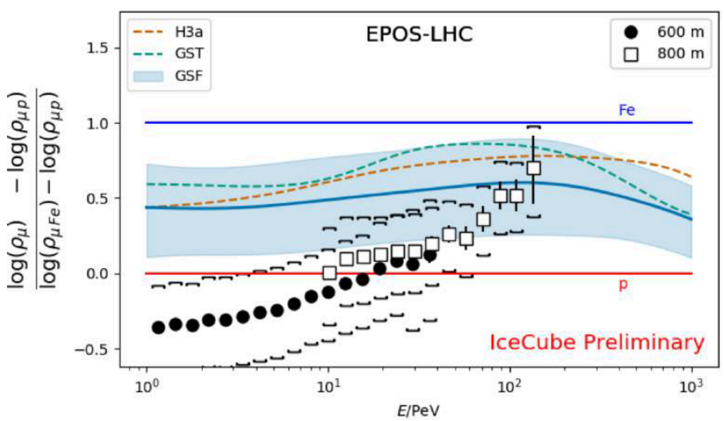
Telescope Array



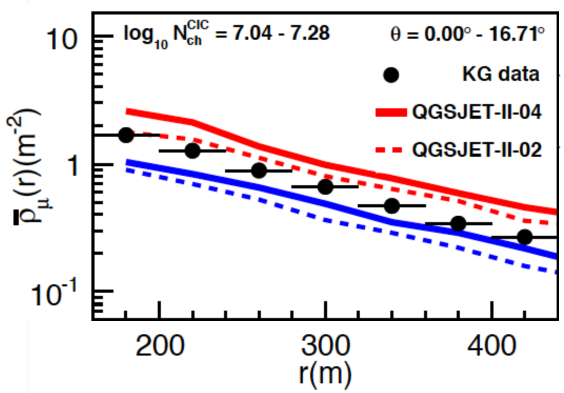
EAS-MSU



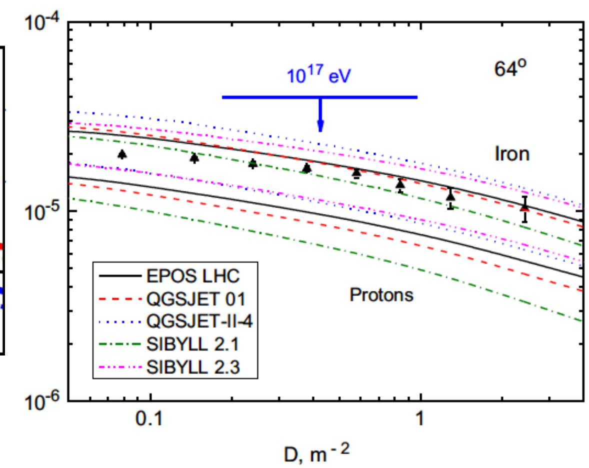
IceTop



KASCADE-Grande



NEVOD-DECOR

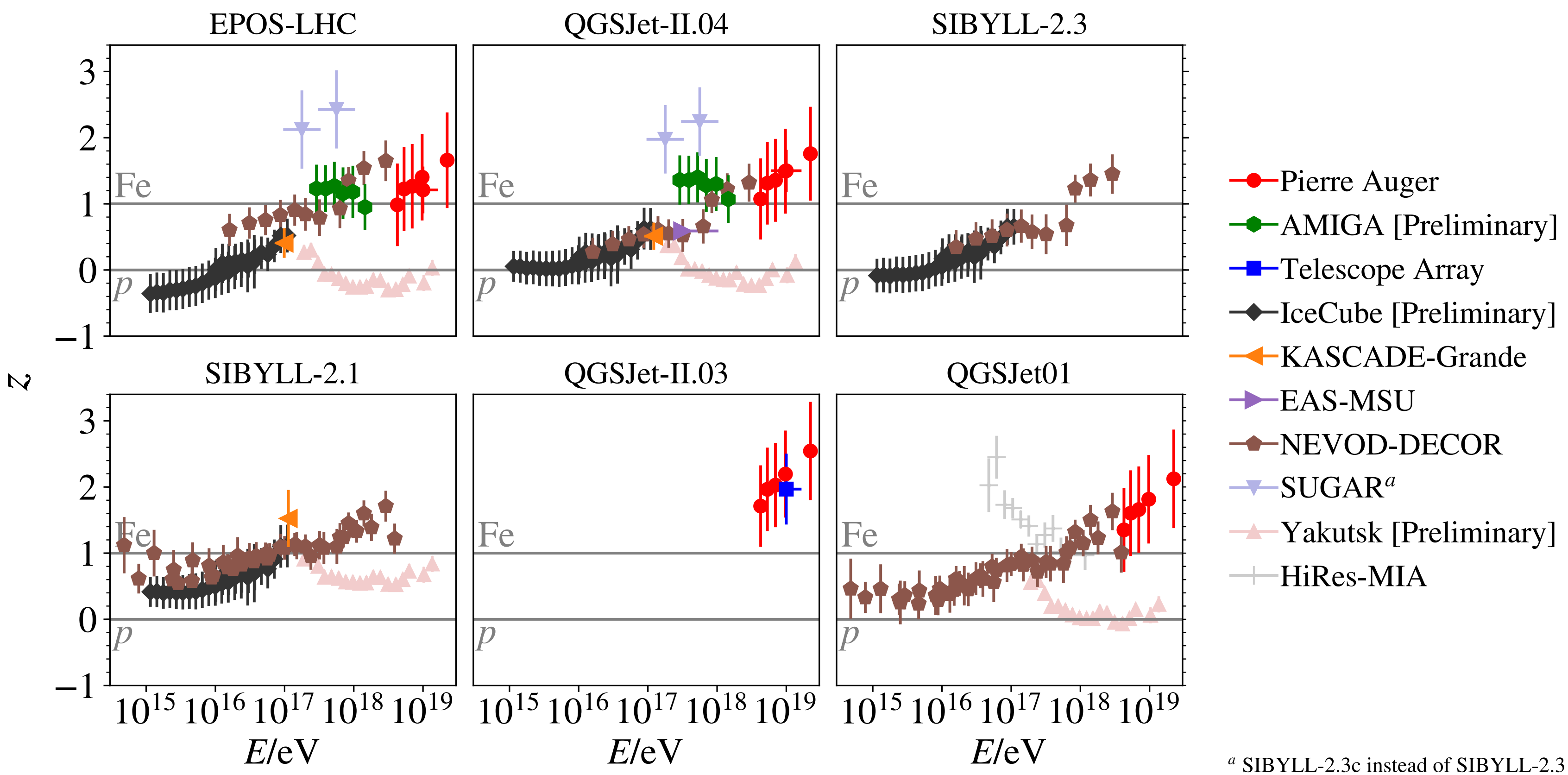


Combining muon measurements

Step 1: Convert all measurements to z-scale $z = \dfrac{\ln N_{\mu}^{\text{det}} - \ln N_{\mu,p}^{\text{det}}}{\ln N_{\mu,\text{Fe}}^{\text{det}} - \ln N_{\mu,p}^{\text{det}}}$

corrects simple biases;
z_p = 0 and z_{Fe} = 1

Potential divergence from differences in: **energy scale offsets**, shower age, lateral distances, muon energy thresholds



[a] SIBYLL-2.3c instead of SIBYLL-2.3

Energy rescaling 1

Muon density almost proportional to cosmic ray energy

- Excess/deficit over MC very dependent on potential energy scale offset
- Example: energy offset **-20 %** would cause -**18 %** muon deficit (MC relative to data)

Superposition model

$$N_\mu = A\left(\frac{E}{AE_0}\right)^\beta = A^{1-\beta}\left(\frac{E}{E_0}\right)^\beta$$

$$\frac{\tilde{N}_\mu}{N_\mu} = \left(\frac{\tilde{E}}{E}\right)^\beta$$

$$\langle \ln N_\mu \rangle = (1-\beta)\langle \ln A \rangle + \beta \ln(E/E_0)$$

independent of mass

$$\beta = 1 - \frac{\ln N_{\mu,\mathrm{Fe}} - \ln N_{\mu,p}}{\ln 56} \approx 0.9$$

data/MC muon ratio depends on absolute energy scale

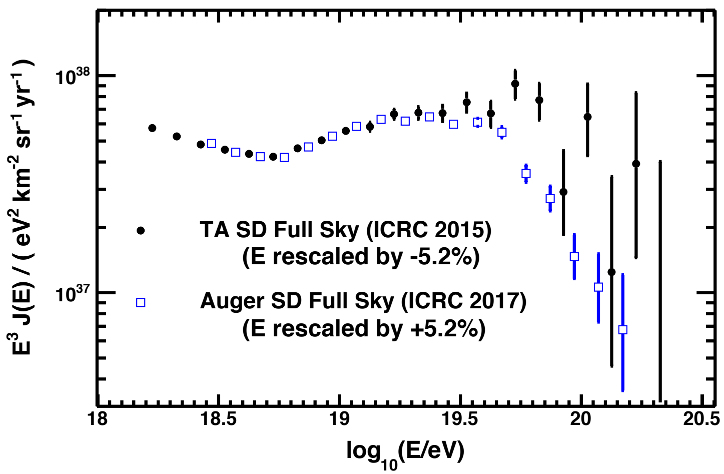
Energy rescaling 2

Cross-calibrate energy scales by matching all-particle fluxes

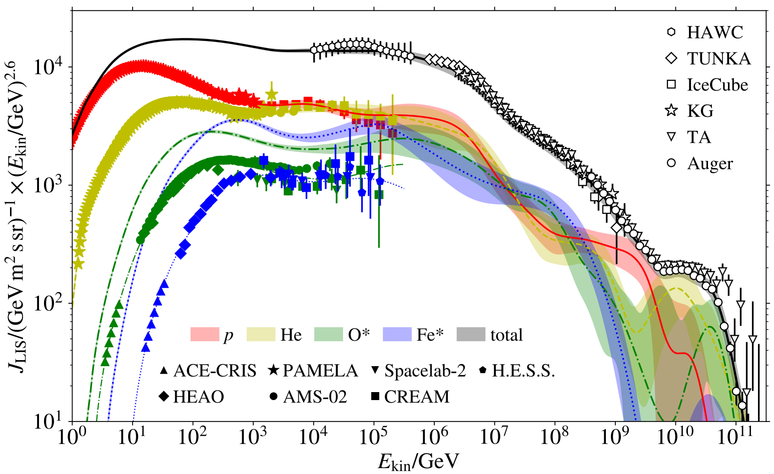
Spectrum WG: Auger **0.948** Telescope Array **1.052**

GSF (matched): SUGAR **0.948** KASCADE-Grande **0.95** IceTop **1.19** NEVOD-DECOR **1.08**

Spectrum WG



GSF



Spectrum WG: Auger and TA spectrum matched at ankle

GSF: **G**lobal **S**pline **F**it to cosmic-ray flux and composition data

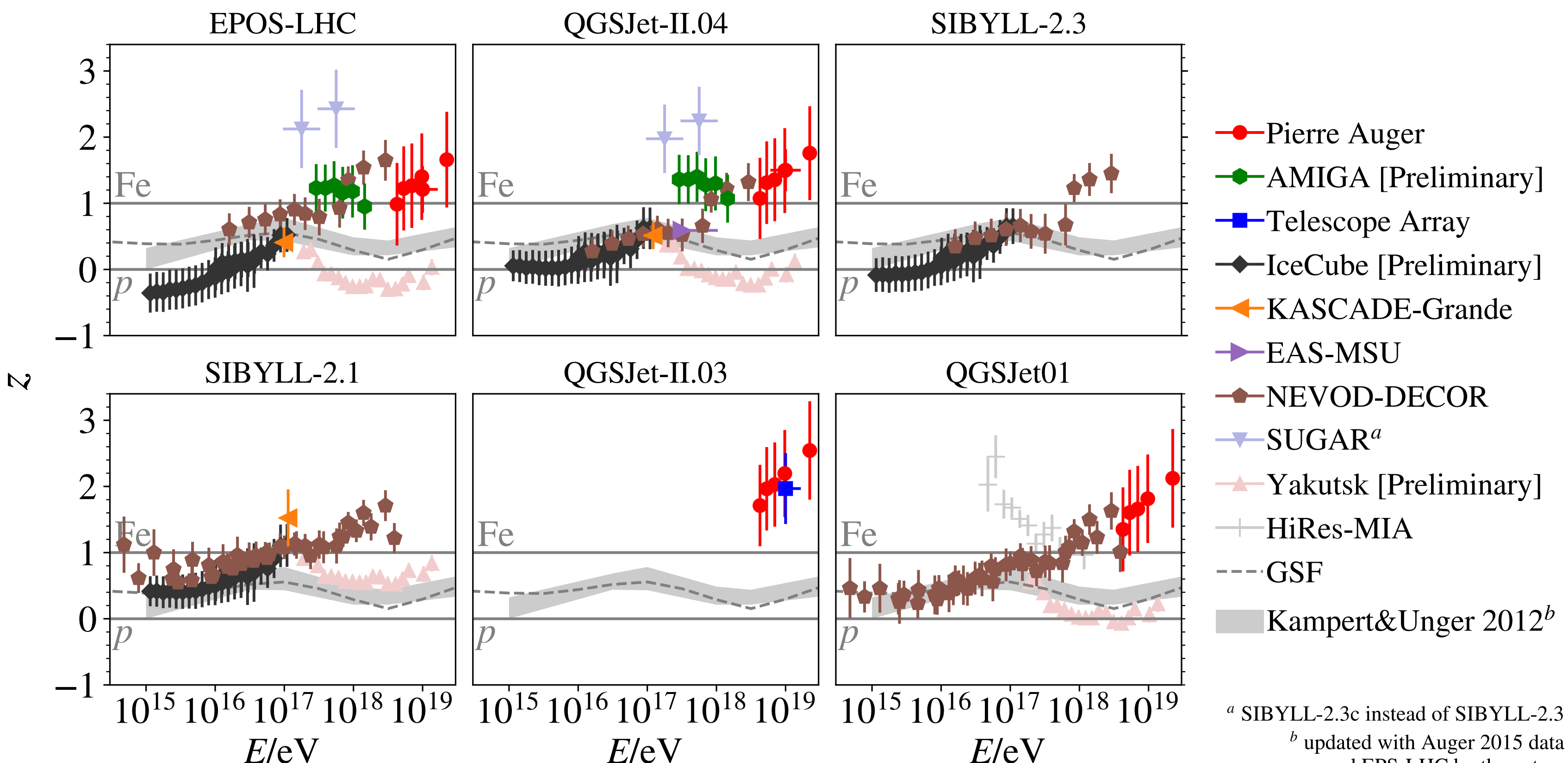
- Combines direct observations with indirect observations
- Energy-scale offsets fitted as nuisance parameters

This conference (Oct 8) and
HD, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn, T. Stanev, PoS(ICRC 2017)533

Combining muon measurements

Step 2: Apply energy scale corrections (before)

Still present: possible dependence on energy scale, shower age, lateral distance, energy threshold

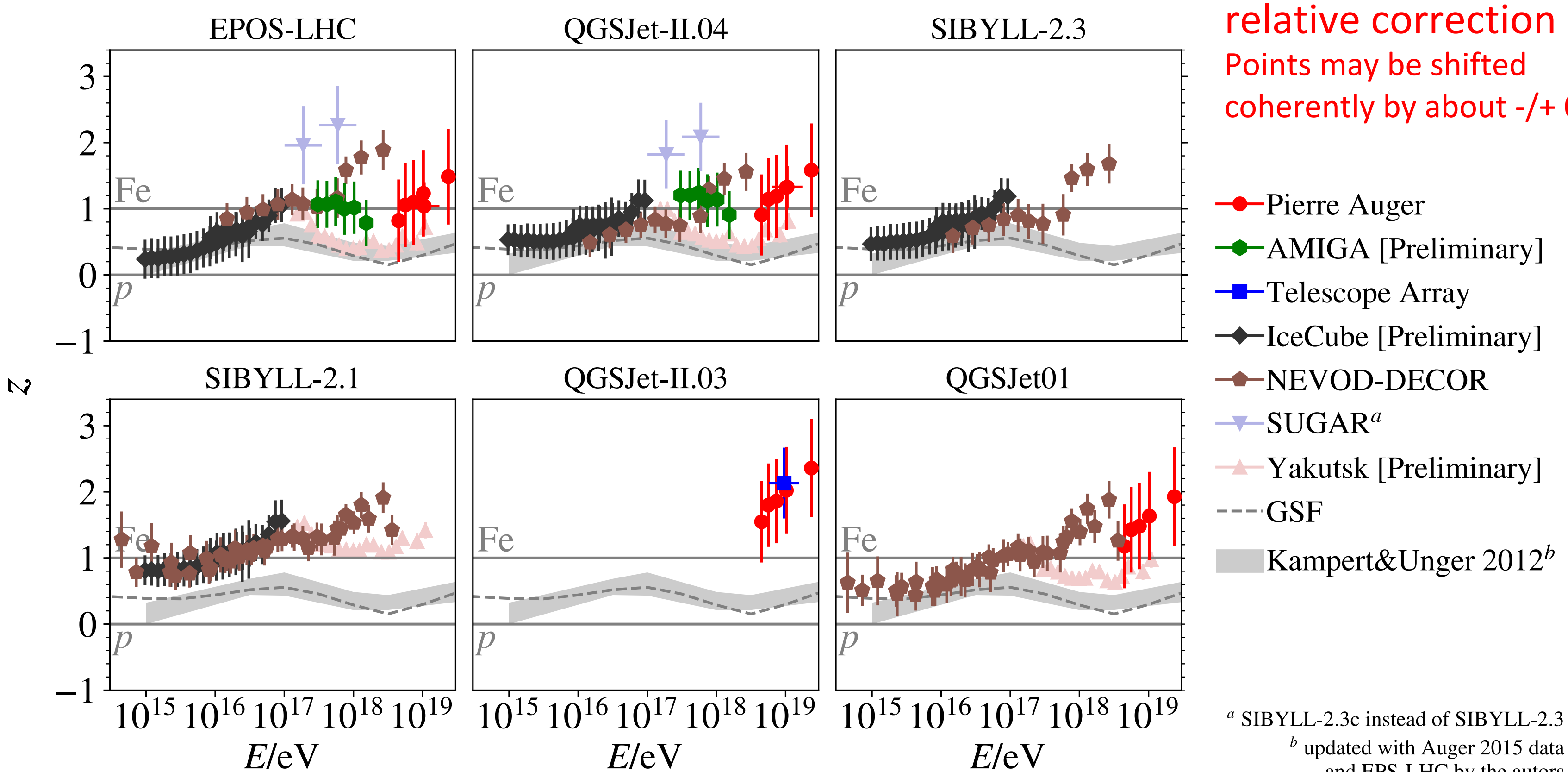


[a] SIBYLL-2.3c instead of SIBYLL-2.3
[b] updated with Auger 2015 data and EPS-LHC by the autors

Combining muon measurements

Step 2: Apply energy scale corrections (after, experiments with unknown scale not shown)

Still present: possible dependence on shower age, lateral distance, energy threshold

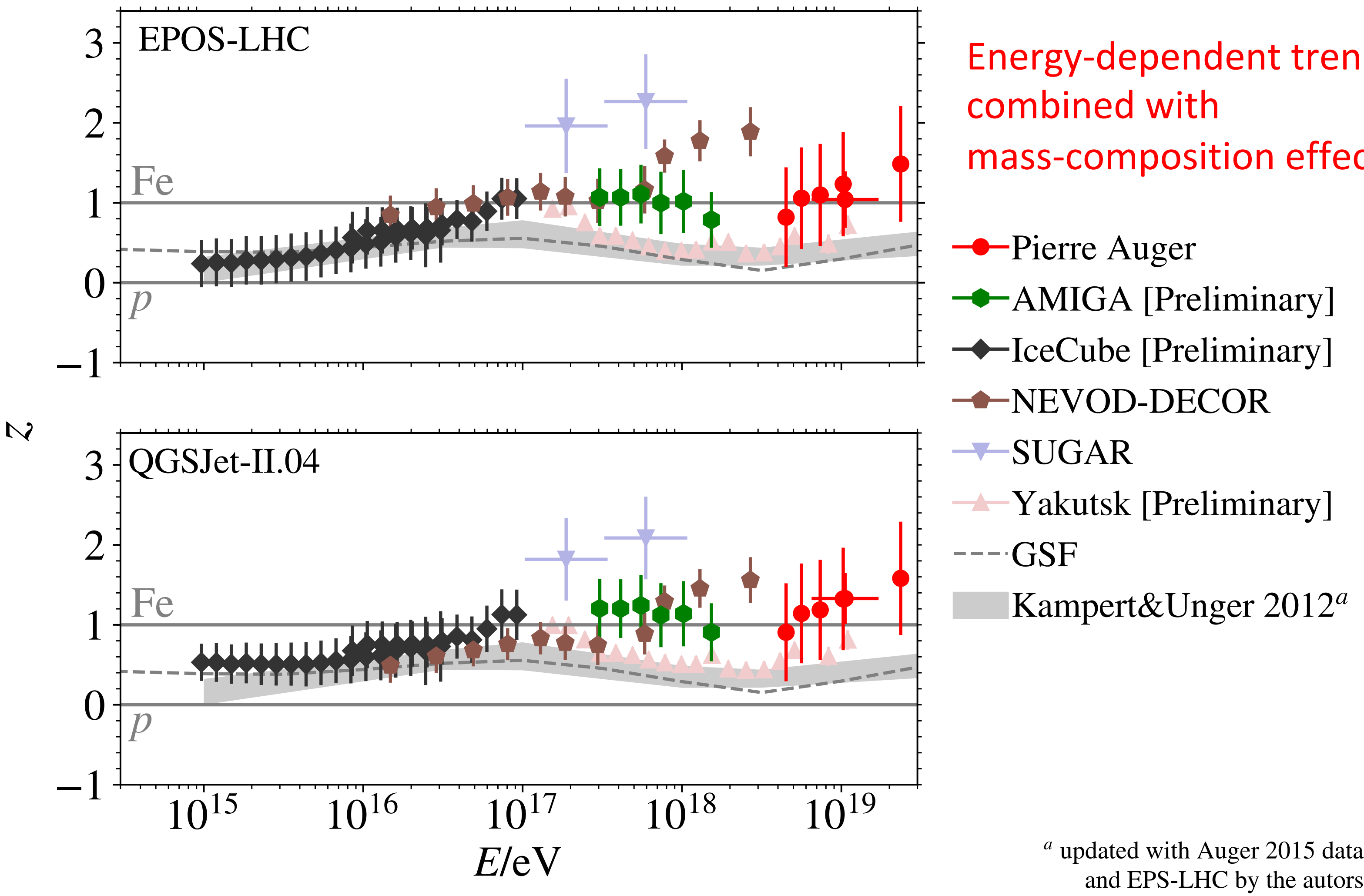


Absolute energy-scale still uncertain after relative correction

Points may be shifted coherently by about -/+ 0.25

Zoom on EPOS-LHC and QGSJet-II.04

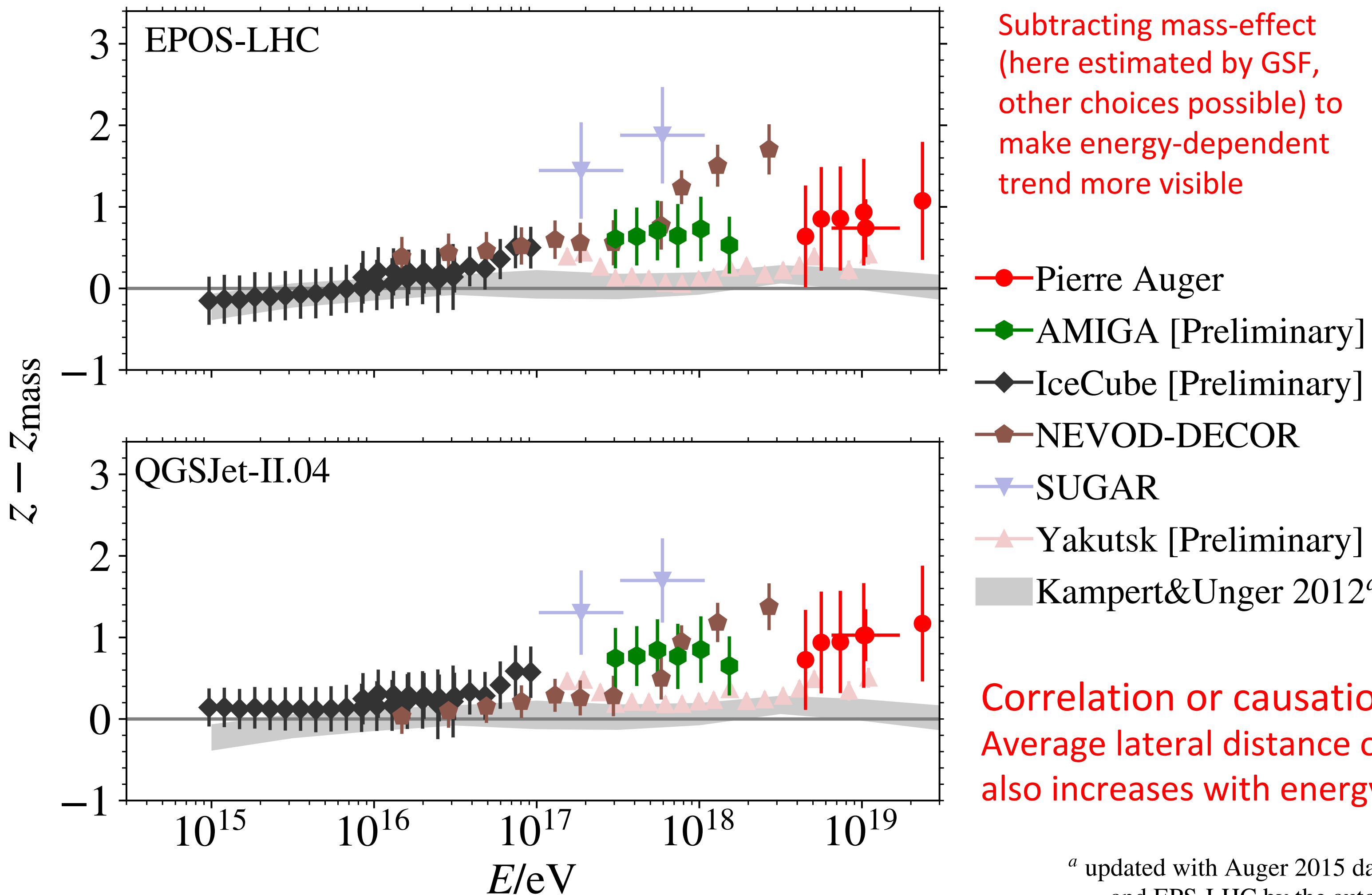
Still present: possible dependence on shower age, lateral distance, energy threshold



Energy-dependent trend combined with mass-composition effect

Energy-dependent discrepancy

Other effects also present: possible dependence on shower age, lateral distance, energy threshold



Subtracting mass-effect (here estimated by GSF, other choices possible) to make energy-dependent trend more visible

Correlation or causation?
Average lateral distance of data also increases with energy

[a] updated with Auger 2015 data and EPS-LHC by the autors

What we have learned

- Combining measurements is very powerful
  - Greatly extends phase-space coverage
  - Allows for cross-checks
  - Reasonable agreement in very diverse experiments

- Challenges and solutions
  - Muon measurements differ in many details
    - Convert to comparable quantity **z**

$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

  - Muon density depends on uncertain mass composition
    - **Subtract effect** using other variable (e.g. X_{max}) or model (e.g. GSF)
    - Alternative: Select protons (only deep showers) or iron (via direct Cherenkov light) out of mixed composition
  - Muon density offset almost proportional to energy scale offsets
    - **Cross-calibrate relatively** by matching fluxes of air shower experiments
    - **Cross-calibration globally** with model like GSF

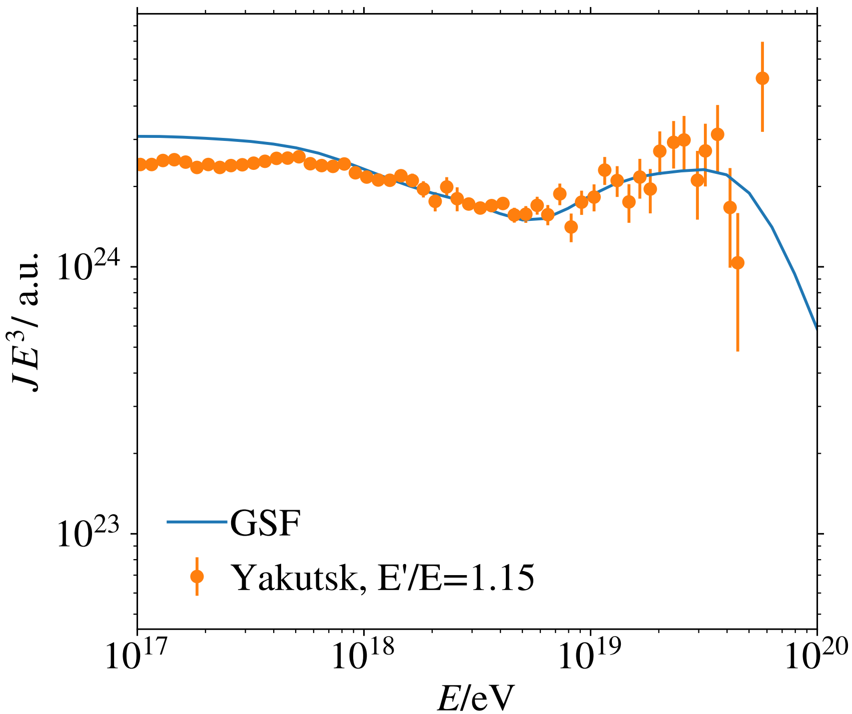
Summary & Outlook

- Summary
  - EM component: mostly good agreement between data and MC
  - Muon component: mostly disagreement between data and MC
    - Ok: TeV muon flux well described by SIBYLL-2.1
    - Not ok: Production depth, attenuation, lateral density profile
  - Muon lateral density profile
    - Consistent picture (?) after converting and cross-calibrating data
    - Smooth increase of data/MC ratio with energy? Checks needed, see outlook
    - Post-LHC models describe muons better than pre-LHC models
    - Data/MC ratio probably less than 1.5 at highest energies

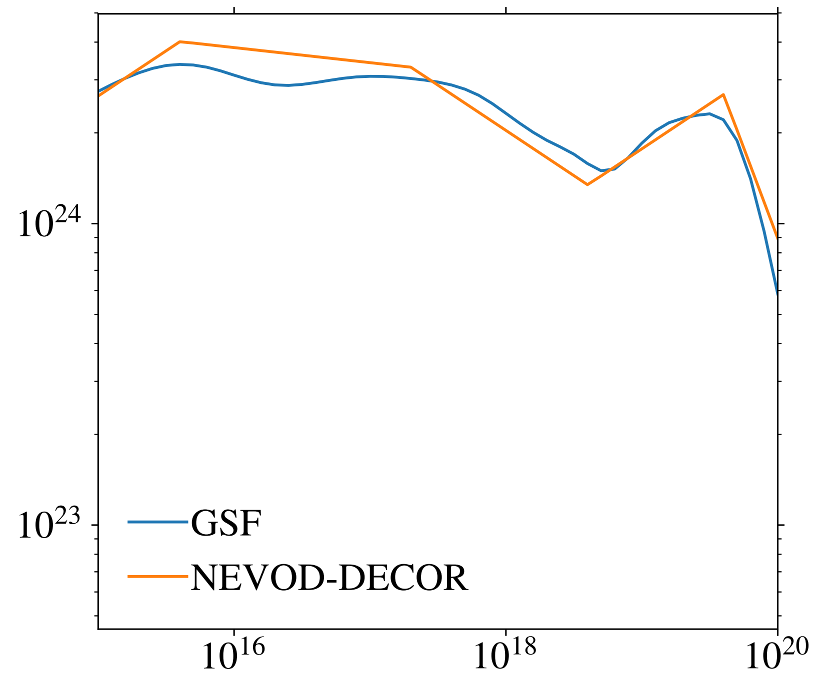
- Outlook
  - Finish muon density analysis
    - Study data/MC ratio further as function of...
      zenith angle, core-distance, muon energy threshold, age of shower
    - Try to resolve tensions between experiments
  - Develop recommendations for making comparable measurements

Backup

Energy scale offsets



Spectra differ, but not by simple energy scale offset



GSF: energy scale offsets

- **Energy-scale offsets** of experiments = major correlated systematic uncertainty
- Fit constrained **energy-scale adjustment factors** z_E as nuisance parameters

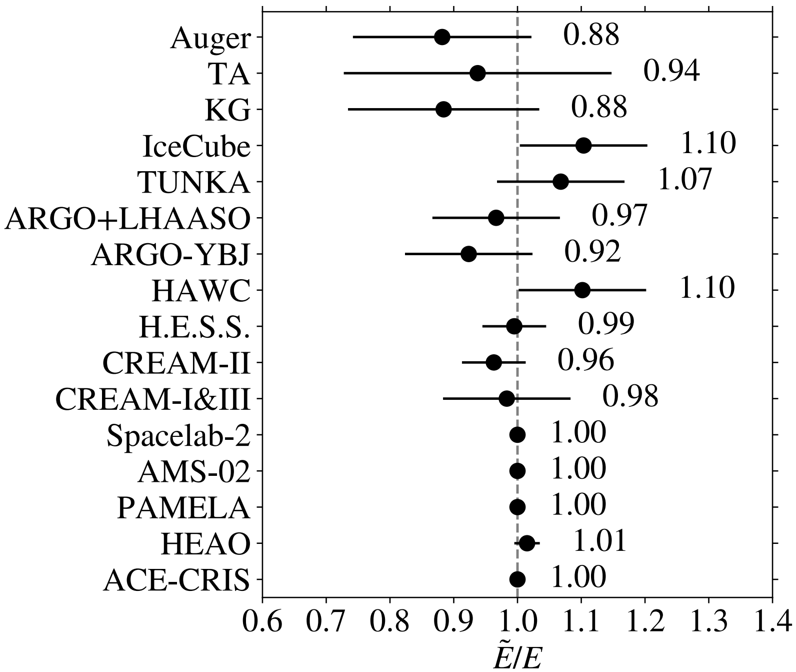
R. Barlow "Combining Experiments with Systematic Errors", arXiv:1701.03701

$$\tilde{J}(\tilde{E}) = J(E)\frac{\mathrm{d}E}{\mathrm{d}\tilde{E}} = J\left(\frac{\tilde{E}}{1+z_E}\right)\frac{1}{1+z_E}$$

Flux distortion caused by energy-scale offset z_E

$$S = \sum_i z_i^2 + \sum_j \left(\frac{z_{Ej}}{(\sigma[E]/E)_j}\right)^2$$

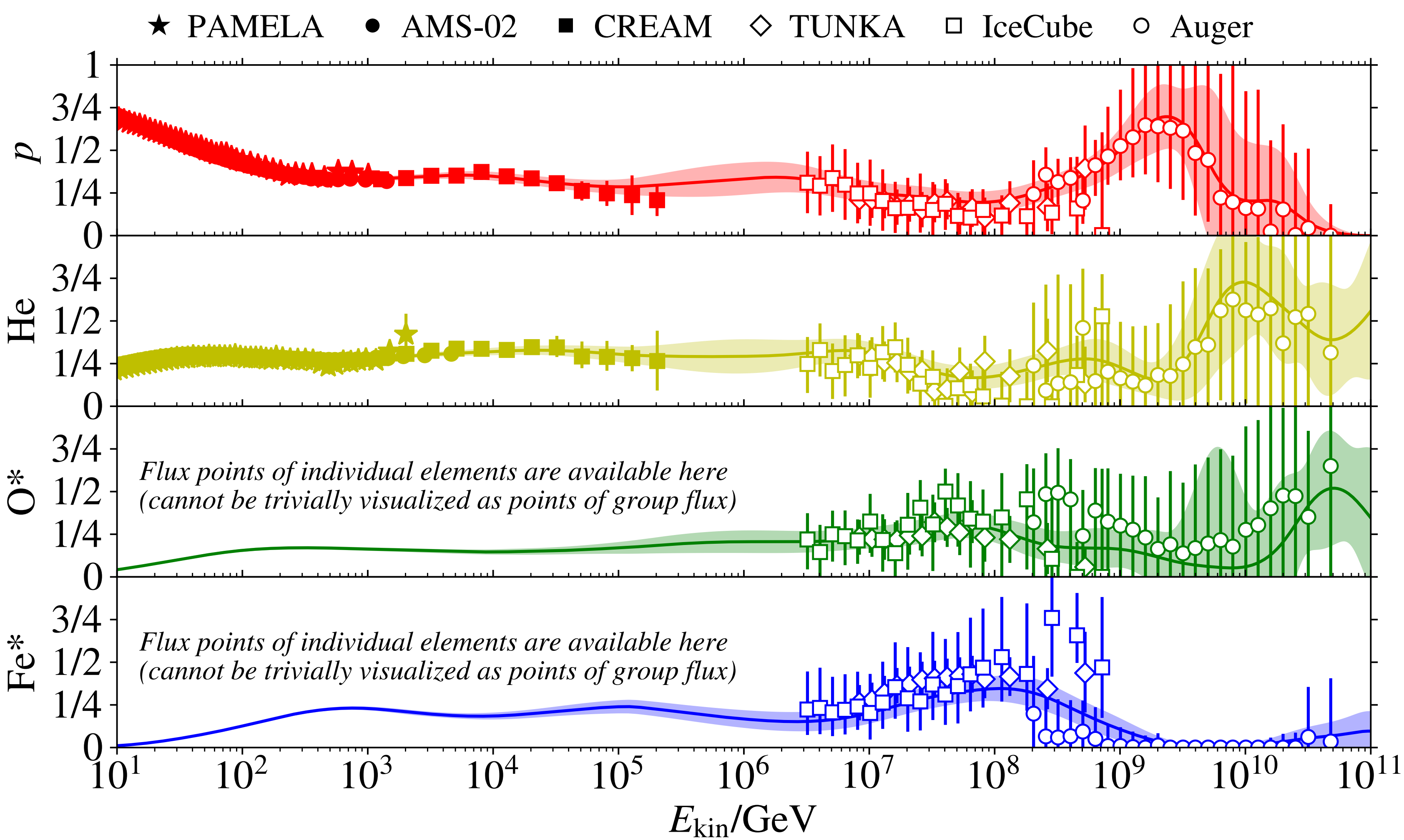
Flux residuals Energy-scale offset residuals



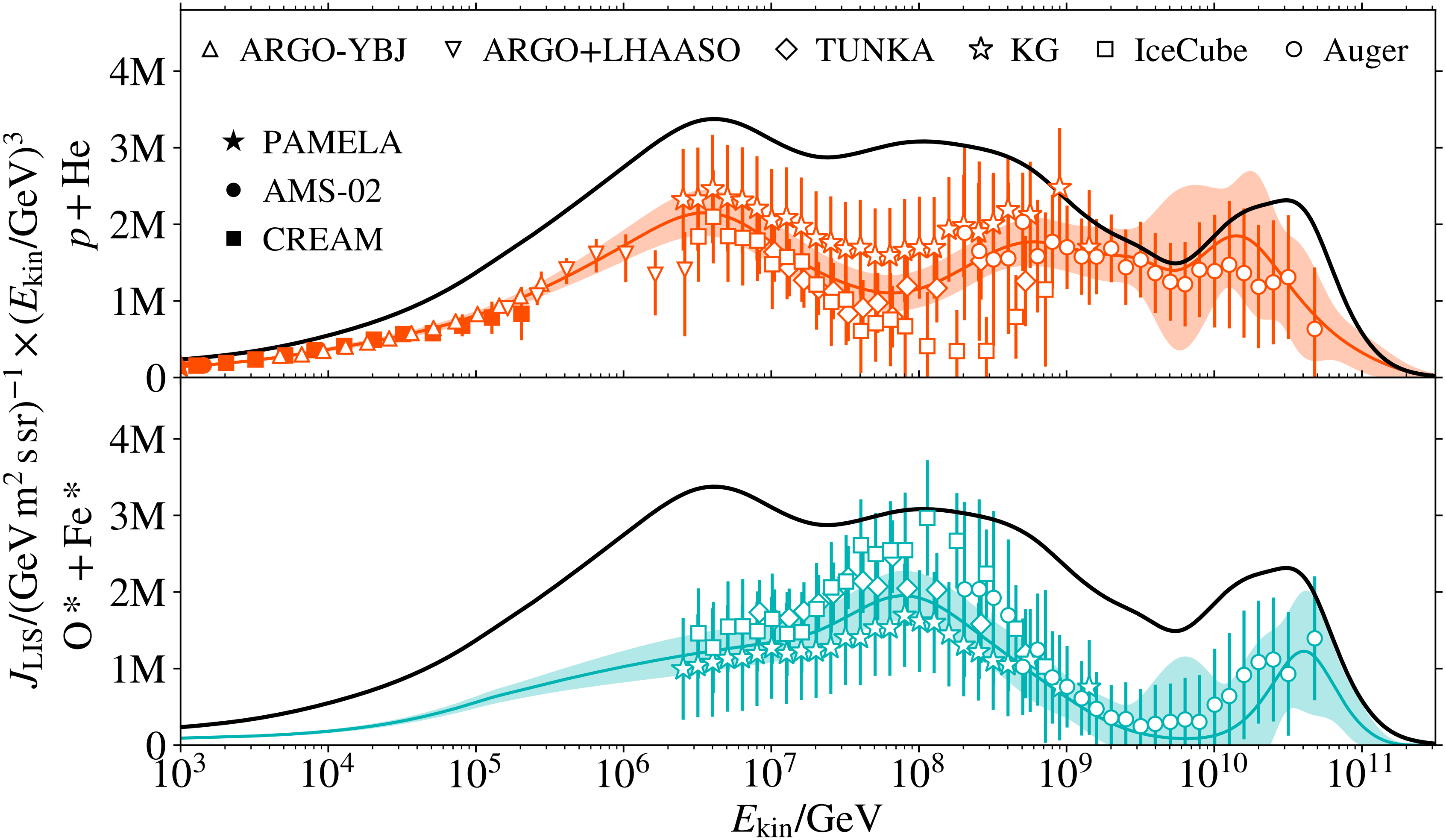
Fitted energy-scale offsets compatible with reported systematic uncertainties

GSF energy scale anchored by **direct measurements**

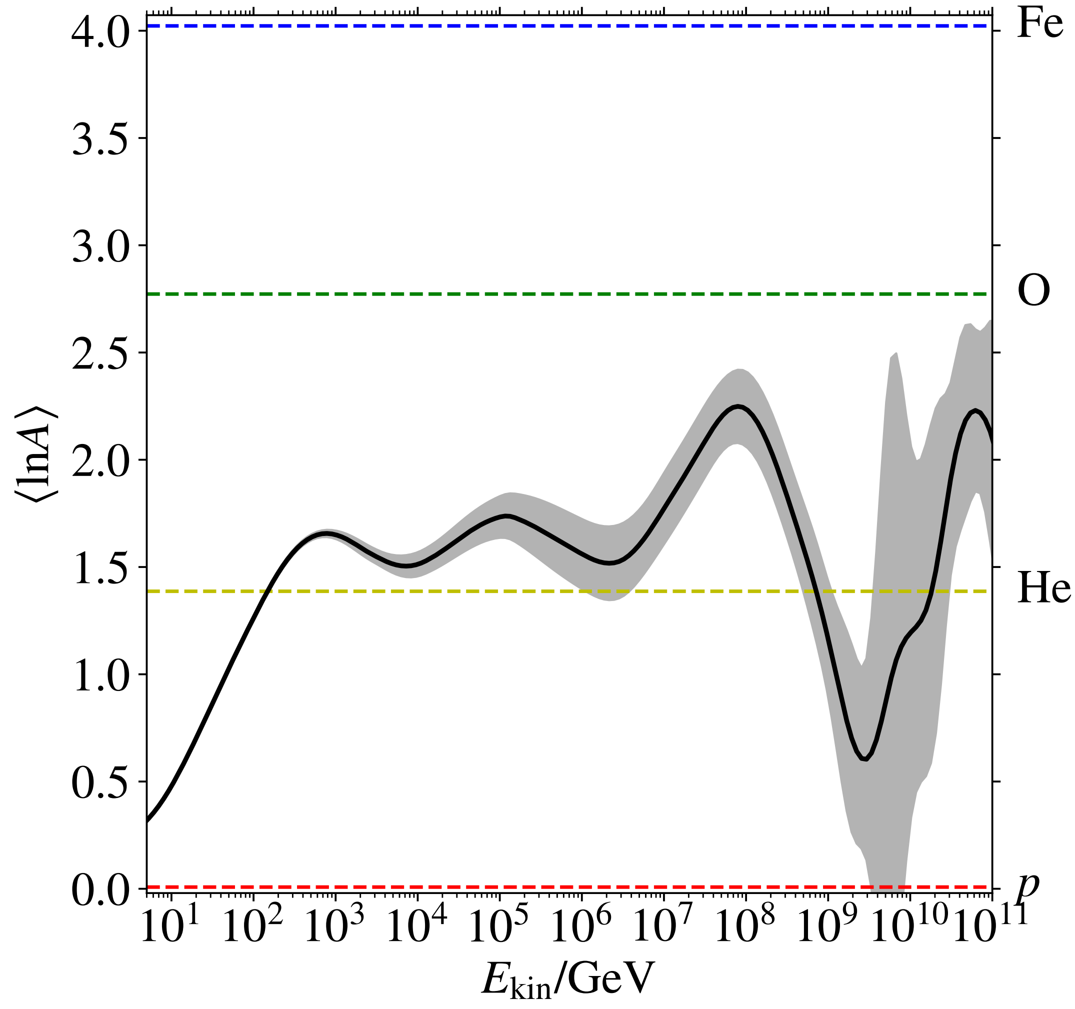
GSF: composition details 1



GSF: composition details 2



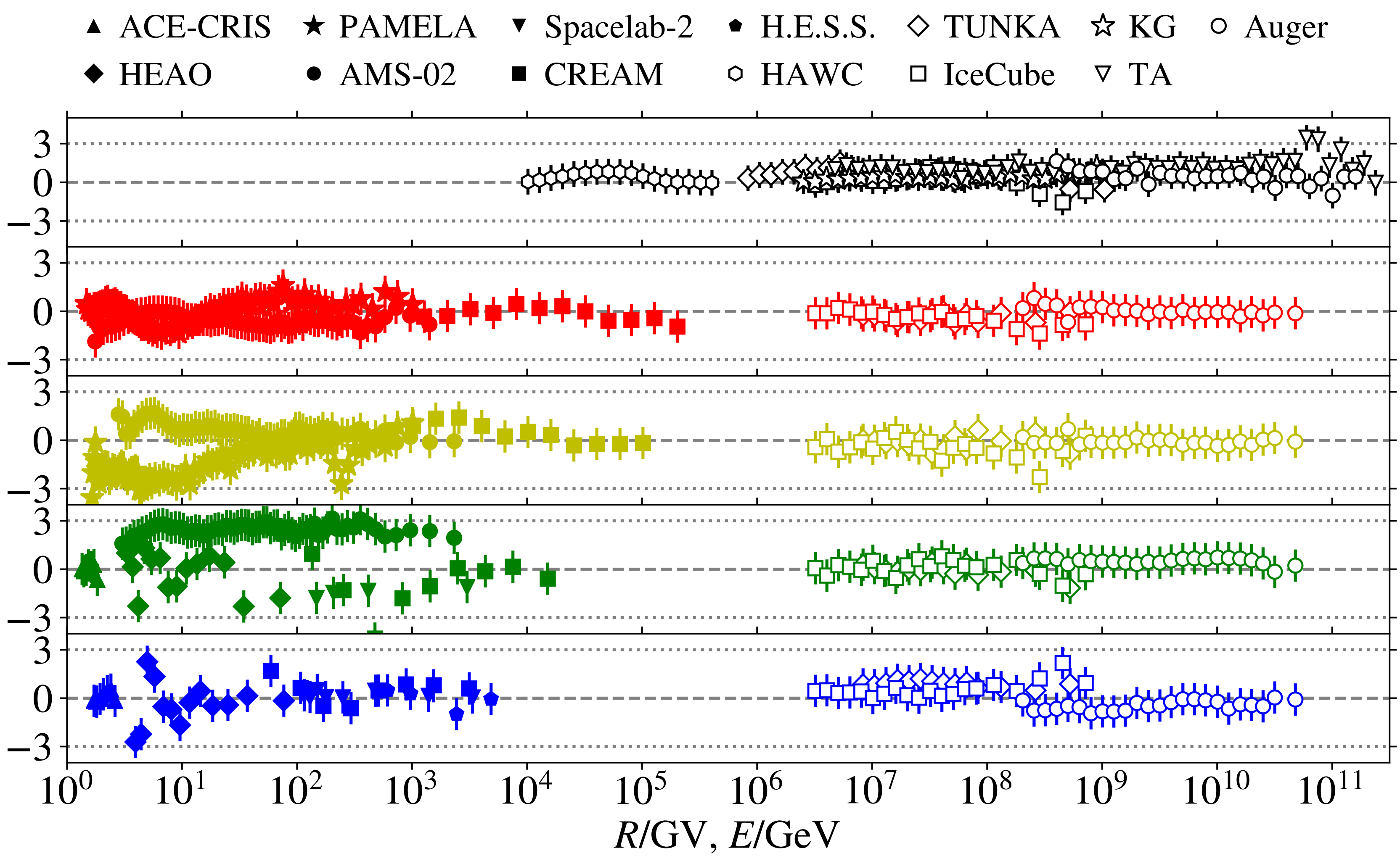
GSF: <lnA>



⟨lnA⟩
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Fe
O
He
p
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
E_{kin}/GeV

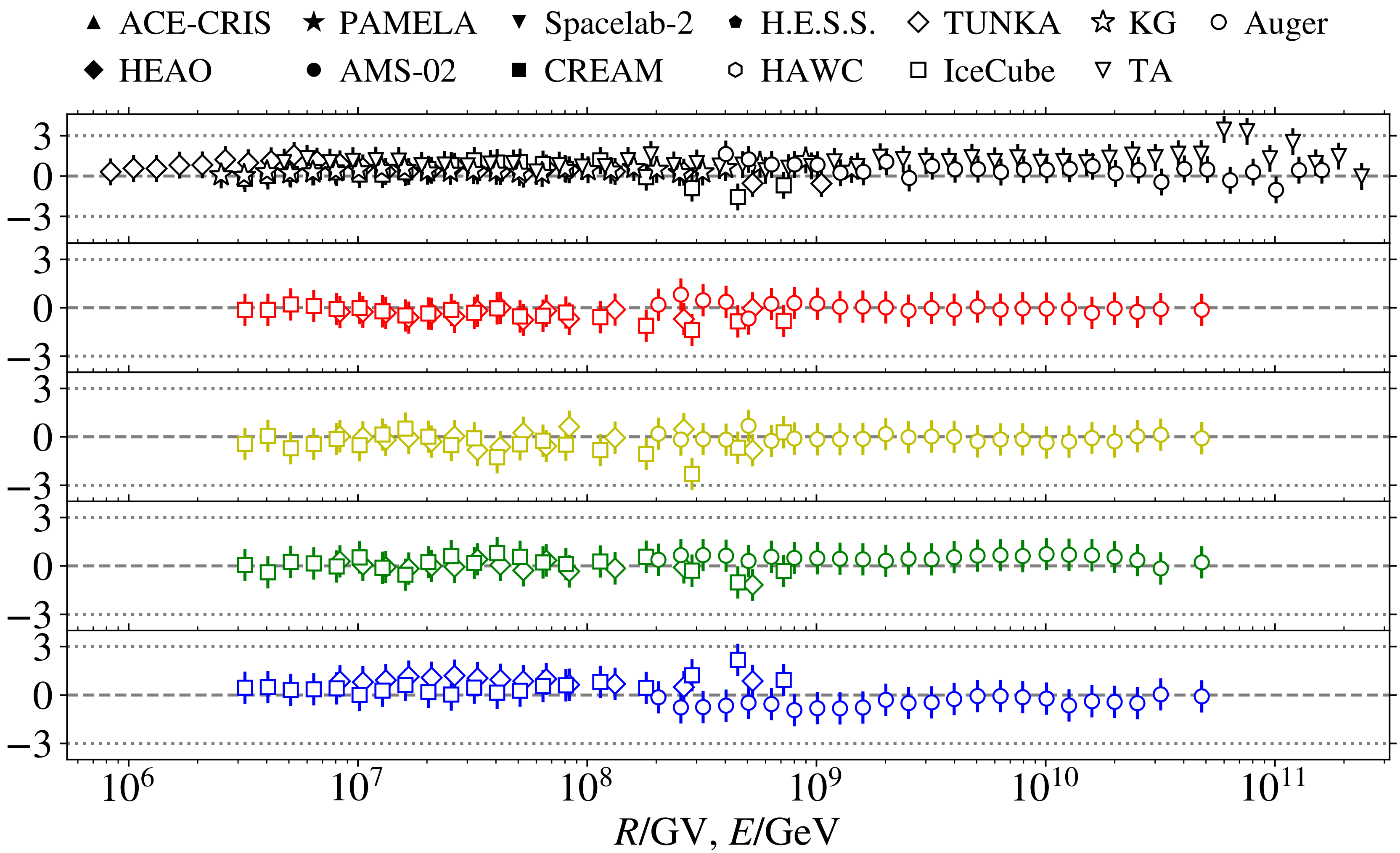
GSF: residuals

$\chi^2/n_{dof} = 1358.3/895 = 1.5$



GSF: residuals zoom

χ^2/n_{dof} = 1358.3/895 = 1.5



Fitting data with correlated errors

10 points, two groups
with systematic offset
and correlated errors

Fit line y = a + b x

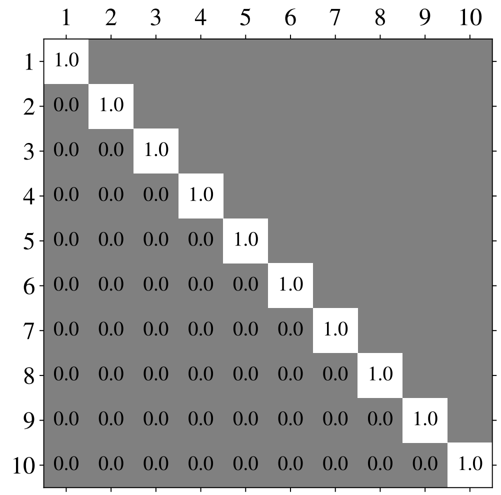
Truth: a = 1, b = 2

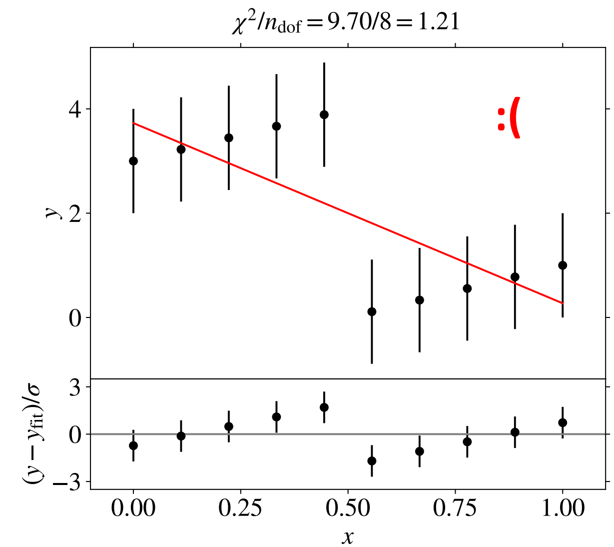
Generalized least-squares, minimize

$$Q = (\vec{y} - \vec{y}_{\rm fit})^T C^{-1} (\vec{y} - \vec{y}_{\rm fit})$$

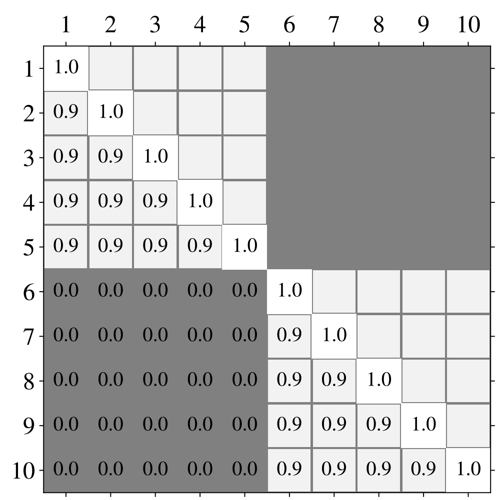
C ... covariance matrix of data

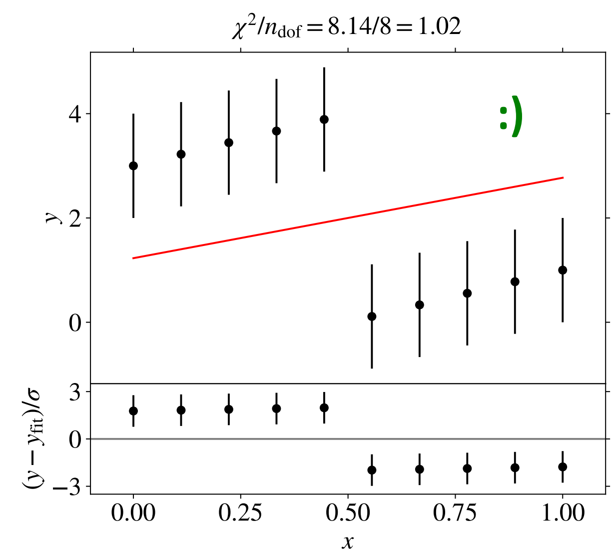
correlation
ignored





correlation
correctly
handled





Flux model

Flux of leading element L

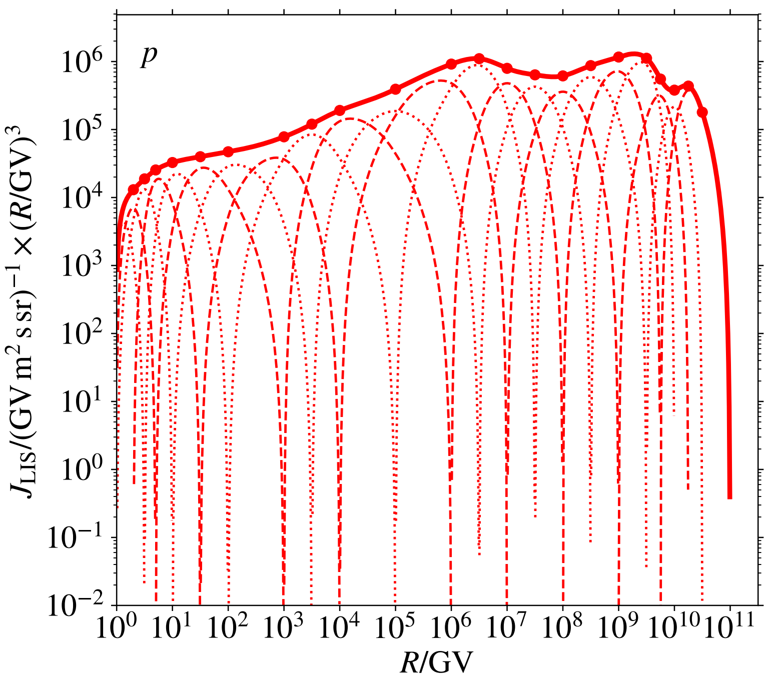
$$J_L(R) = [R/\mathrm{GV}]^{-3} \sum_k a_{Lk}\, b_k(\ln[R/\mathrm{GV}])$$

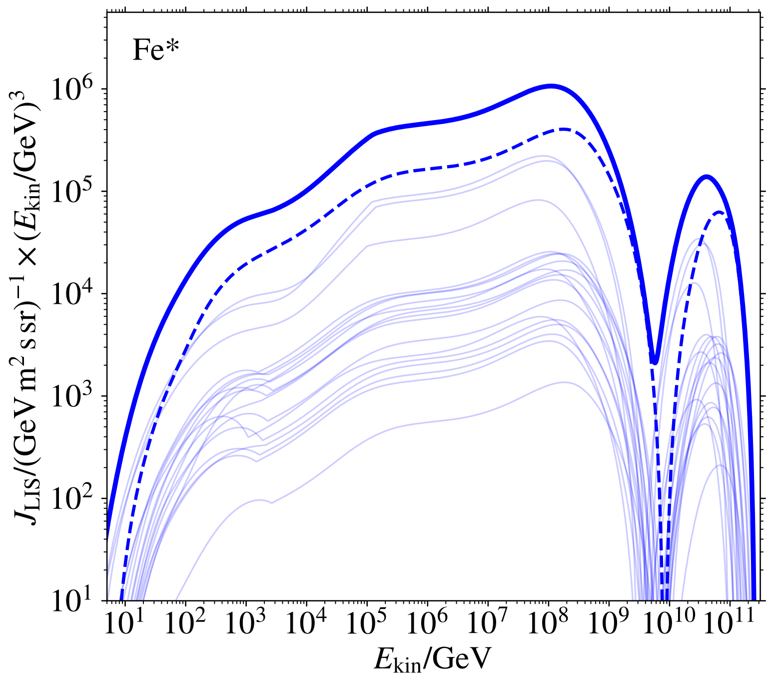
amplitudes (a_{Lk}), B-splines (b_k)

Total flux

$$J(E) = \sum_L \sum_j w_{Lj}\, J_L(R_j(E)) \left(\frac{\mathrm{d}R}{\mathrm{d}E}\right)_j$$

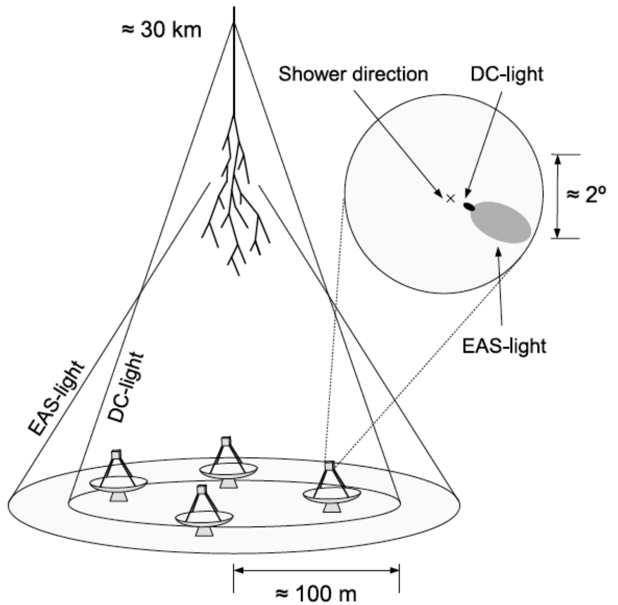
flux ratios (w_{Lj})

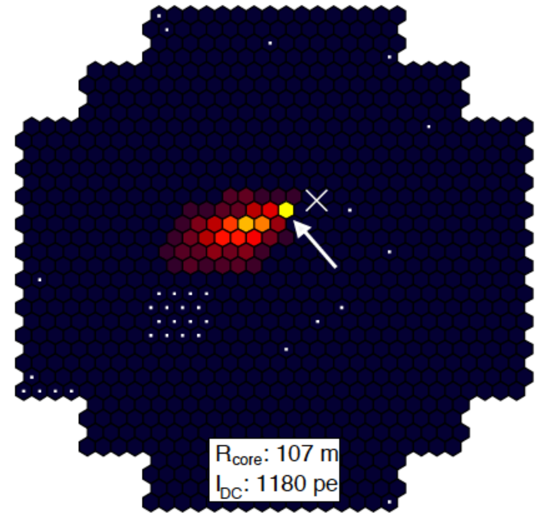




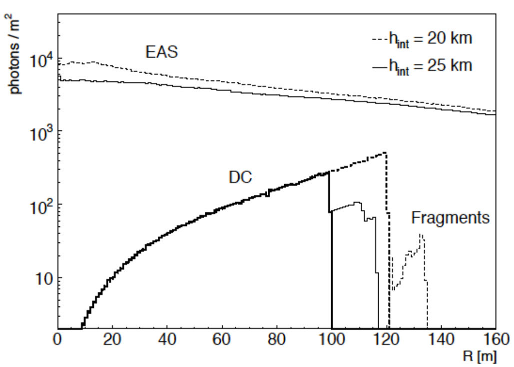
Direct Cherenkov light

H.E.S.S.: Phys.Rev. D75 (2007) 042004





H.E.S.S. event with bright pixel from DC light

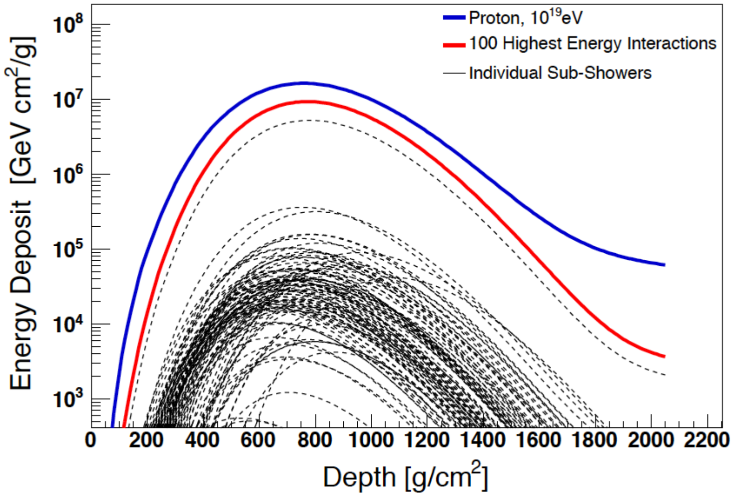


DC light in Pierre Auger Observatory/Telescope Array?

Simulated direct Cherenkov light from 50 TeV iron nucleus

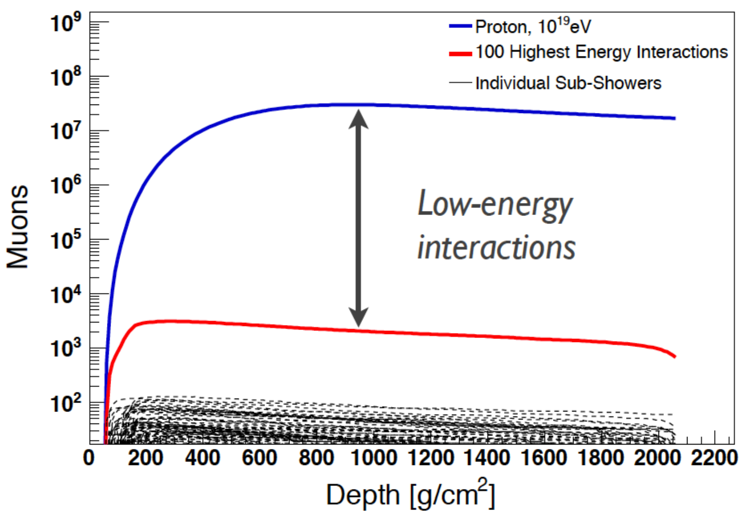
High resolution array could observe first interaction and nuclear break-up

Probing air shower physics



X_{max} is sensitive to high energy interactions

- High-energy sub-showers dominate X_{max}



N_μ is sensitive to high and low energy interactions

- N_μ depends on **energy not lost to EM component** and **energy dispersion** among secondary particles