Modelling and observation of ultra-high energy cosmic rays

Jan Ebr

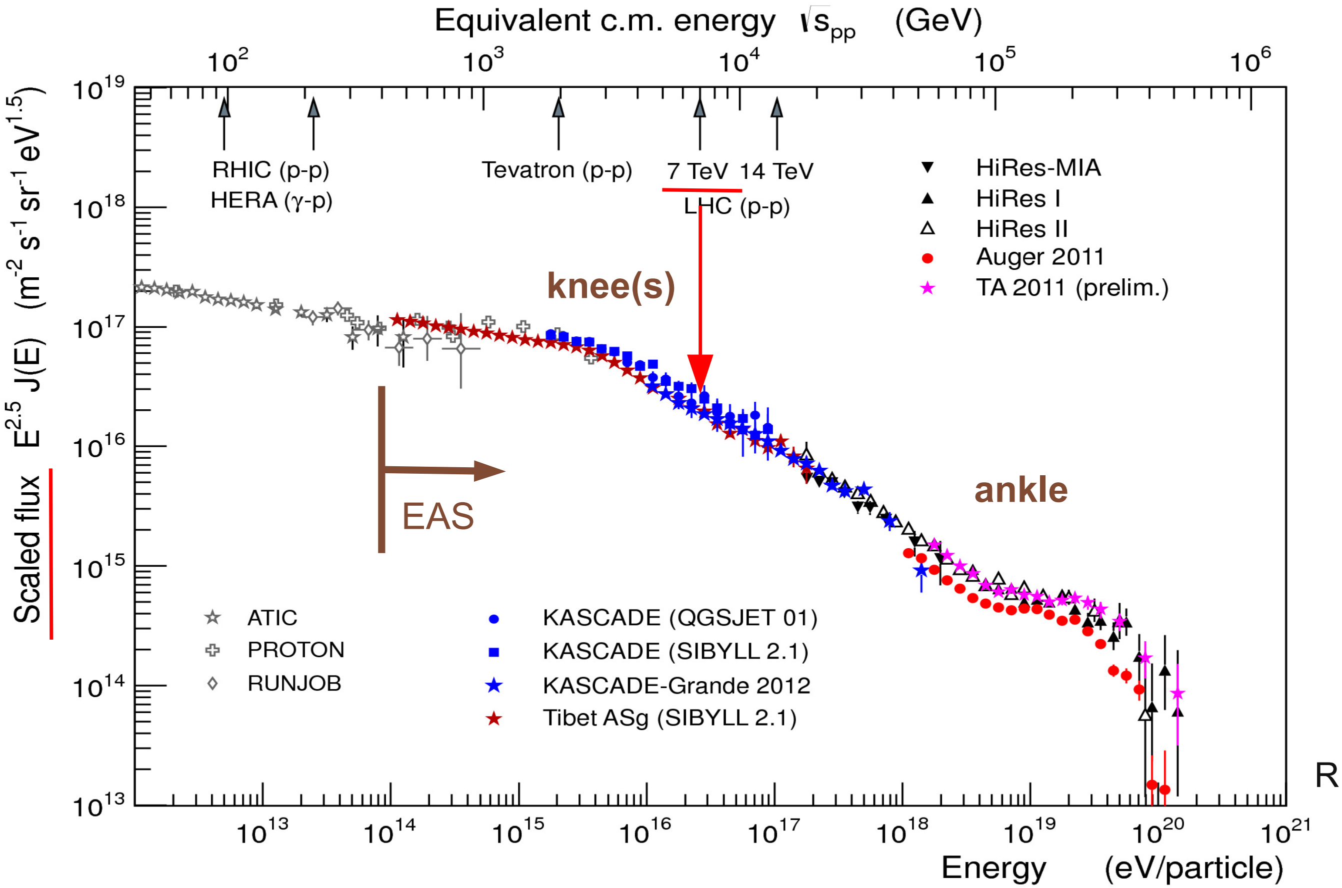
Overview

- (Ultra-high energy) cosmic rays
- Extensive air showers
- Pierre Auger Observatory (and other data)

- Theory: modified simulations to explain muon excess
    - soft-particle addition model
    - dark photons in electromagnetic cascades

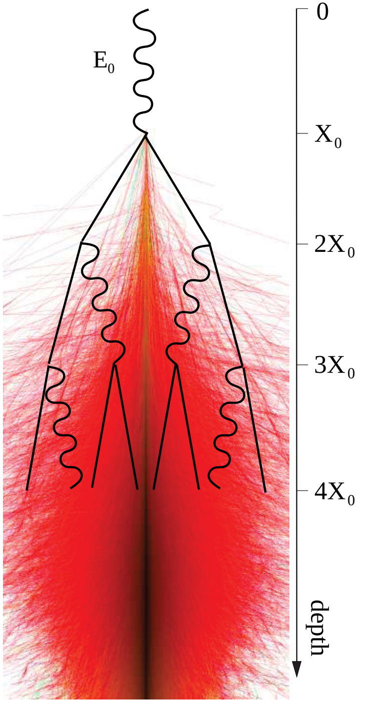
- Experiment: atmospheric monitoring using stellar photometry
    - FRAM telescope at Pierre Auger Observatory
    - Shoot-the-Shower program for anomalous profiles
    - precision aerosol measurements
    - future applications at the Cherenkov Telescope Array

Cosmic rays



R. Engel

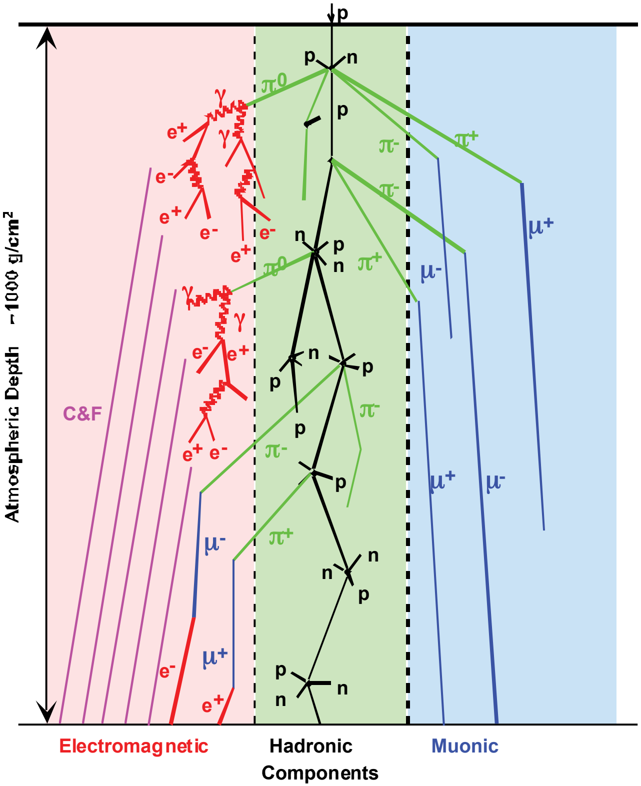
Extensive air showers (EAS)



M. Unger

- radiation length X_0
- 2^n particles after $n \cdot X_0$
- shower stops if $E_i < E^{\gamma}_{\rm crit}$

$$\rightarrow N_{\max} = E_0/E^{\gamma}_{\rm crit}, \quad X_{\max} = X_0 \ln(E_0/E^{\gamma}_{\rm crit})$$



J. Knapp

Muon number at ground:

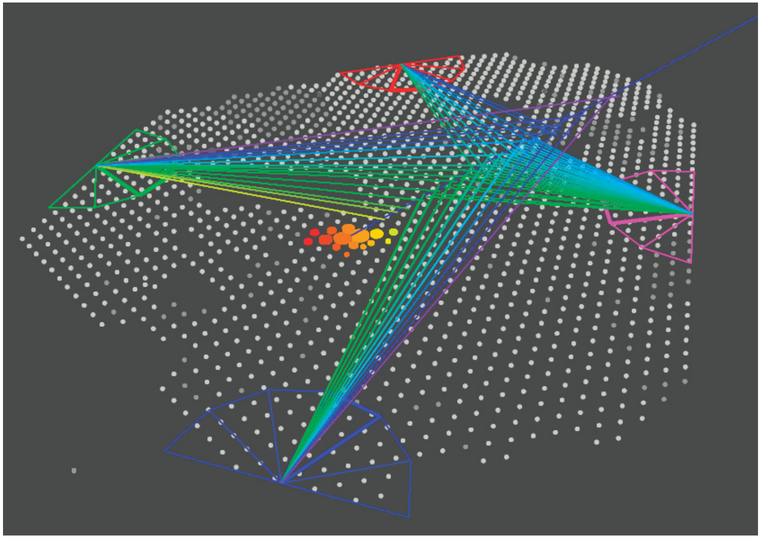
$$\langle N_\mu \rangle \sim (E_0/E^{\pi}_{\rm crit})^{\beta} A^{1-\beta}, \quad \beta = \ln(f_{\pm} N) / \ln(N)$$

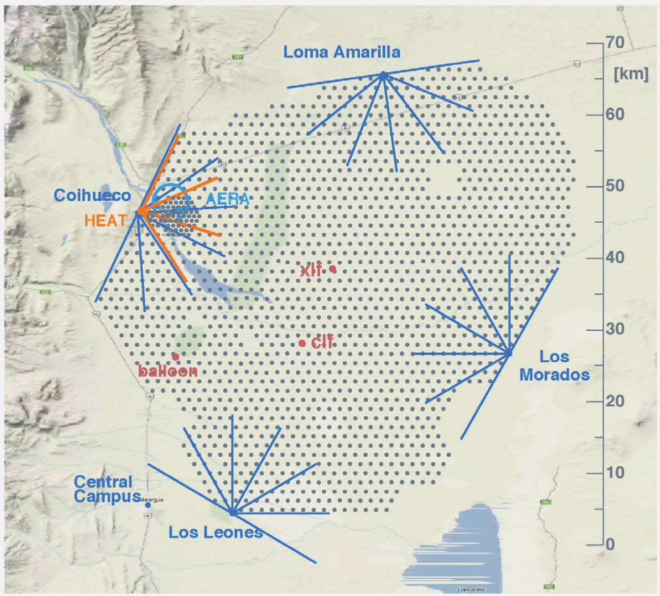
Shower maximum

$$X_{\max} \sim \lambda + X_0 \ln\left(\frac{E_0}{N\, E^{\gamma}_{\rm crit} A}\right)$$

The Pierre Auger Observatory

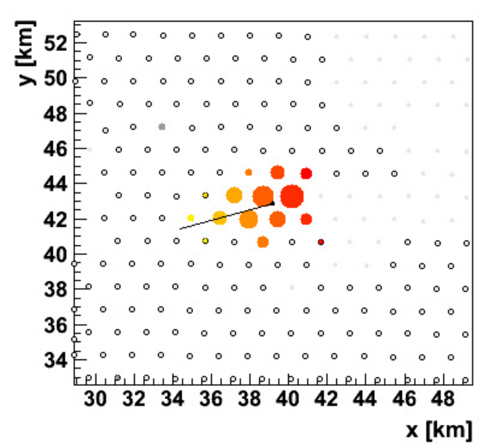
- Surface detector: 1600 water Cherenkov detectors accross 3000 km^2
  - particles arriving at ground level
  - 100 % duty cycle
  - well-known aperture
  - 1500 m spacing → E > $10^{18.5}$ eV
  - AMIGA: 750 m spacing → E > $10^{17.5}$ eV

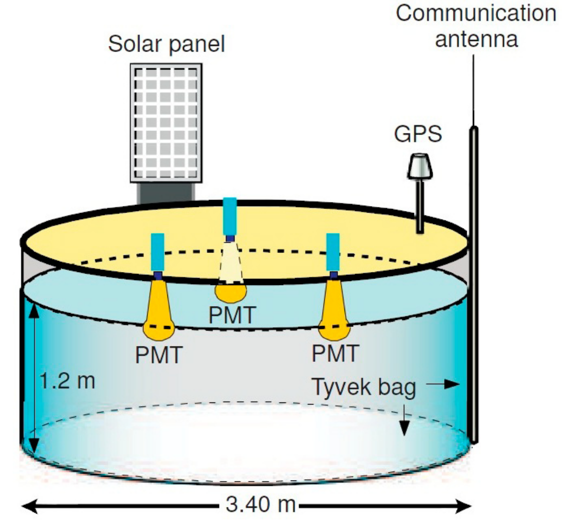


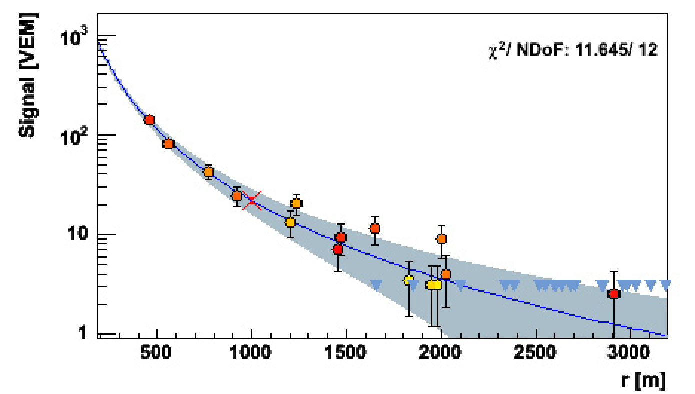


- Fluorescence detector: 24+3 telescopes of 28°×30° FOV
  - UV light from excited N_2
  - 13% duty cycle
  - good energy resolution
- Auxiliary devices
  - atmospheric monitoring
  - detector callibration

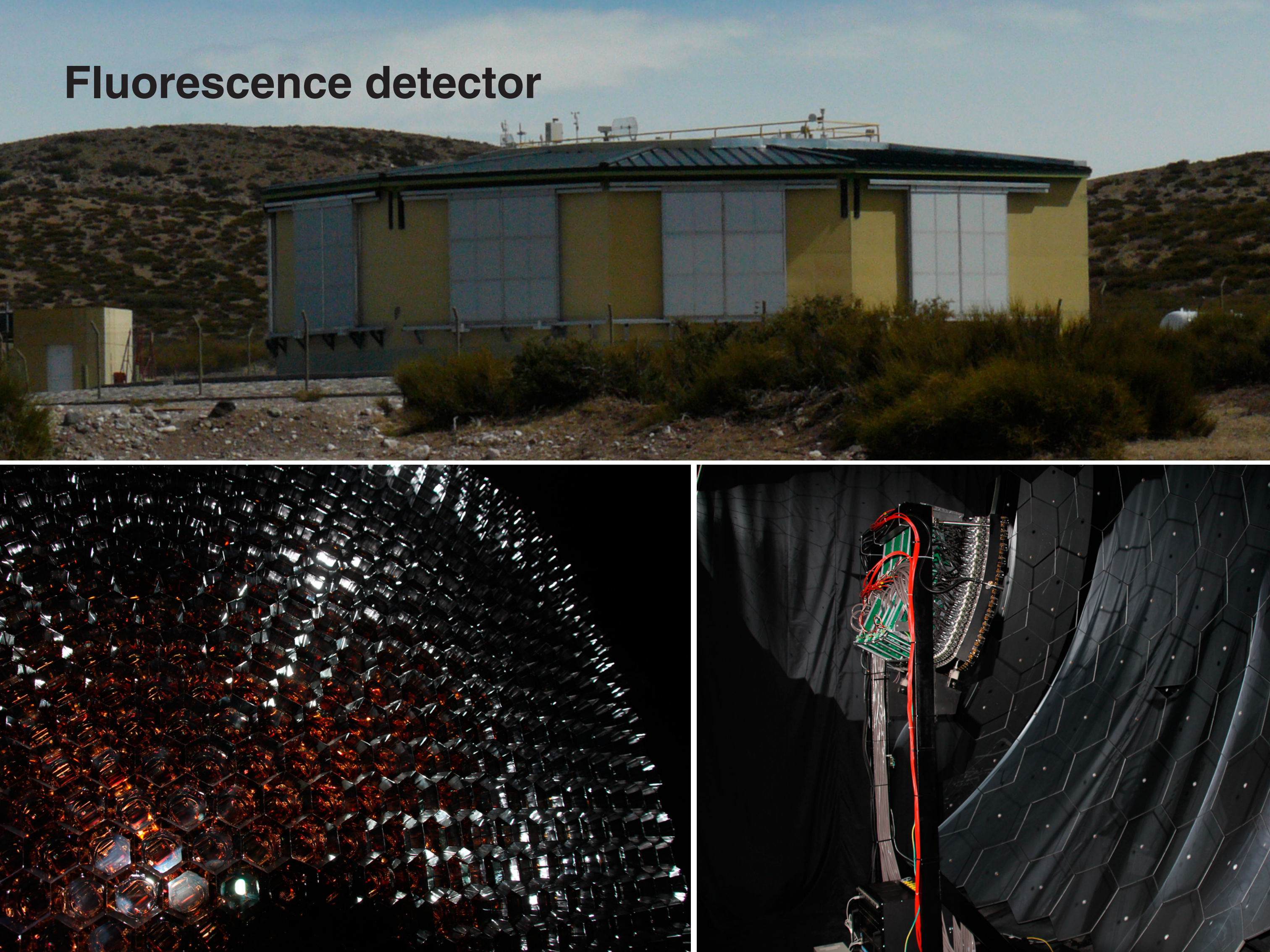
Surface detector





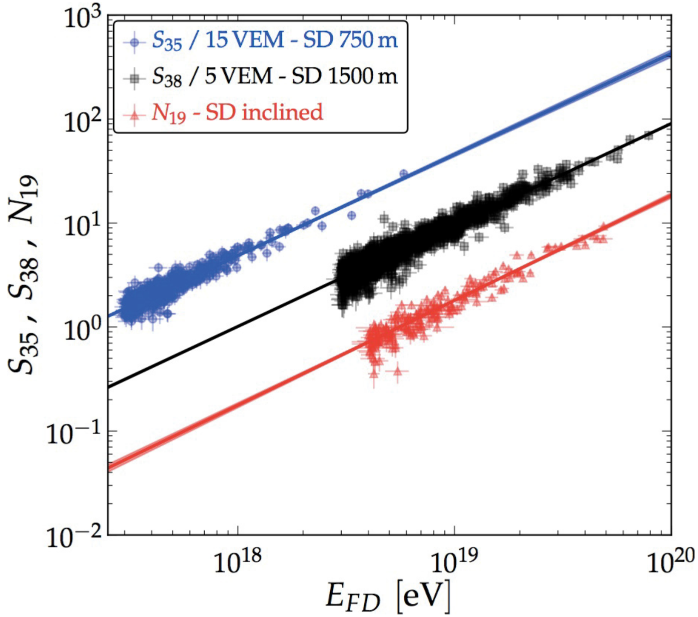


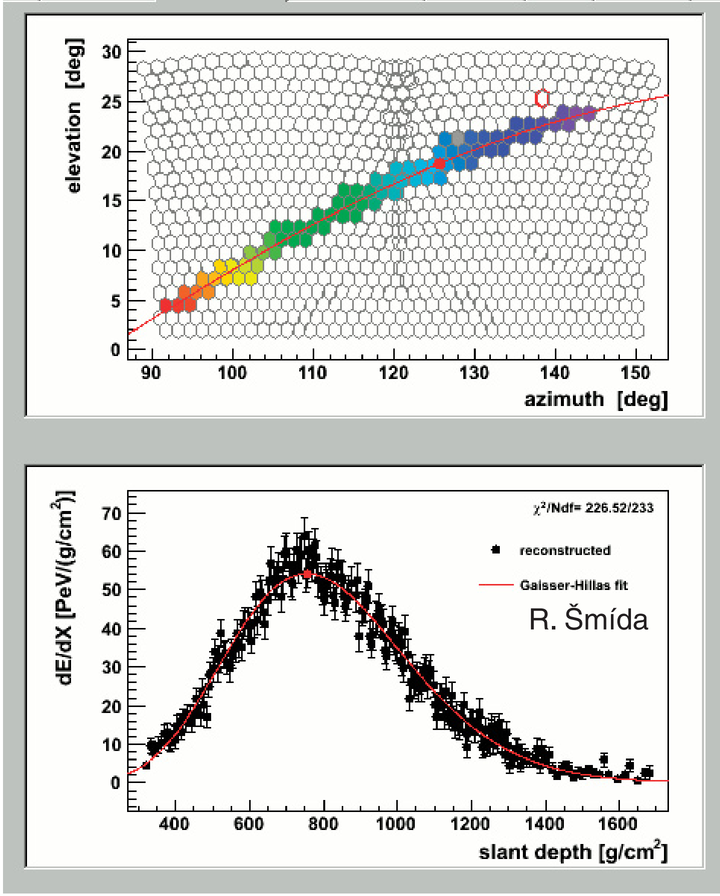
Fluorescence detector



Fluorescence detector

- Calibrimetric energy measurement (minus “invisible energy”)
- Calibrate energy estimators of SD
- Systematic uncertainty on the energy scale: 14%

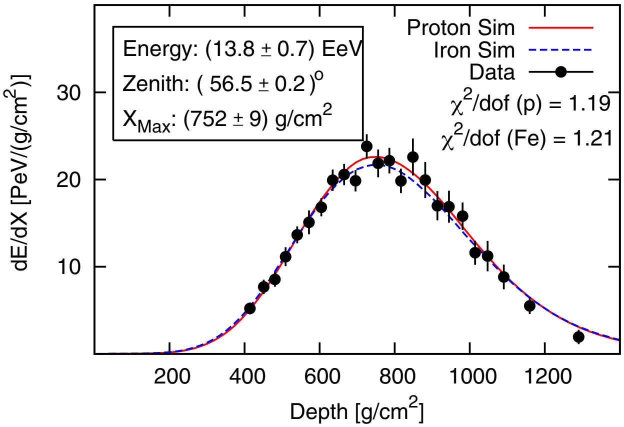


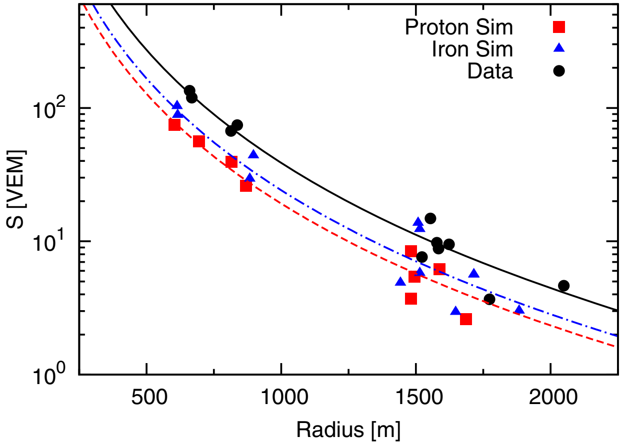


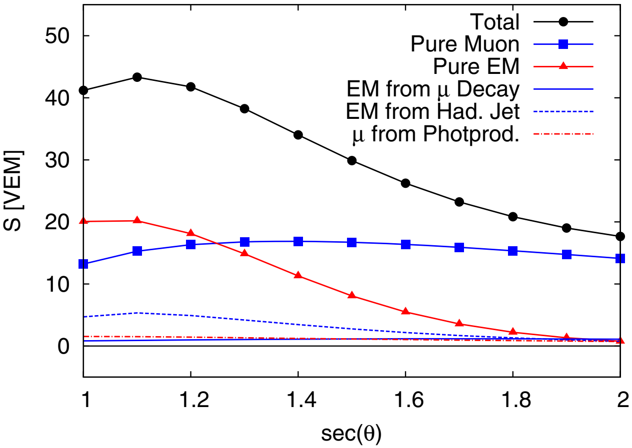
R. Šmída

- Energy resolution: 7–8 % (FD), 17–12 % (SD)

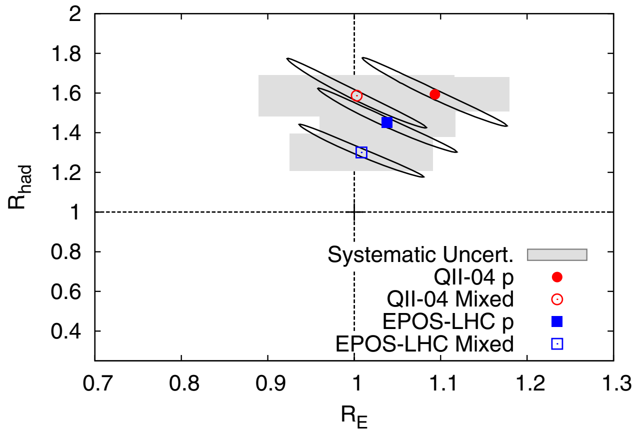
Auger muon excess







$$S_{\text{resc}}(R_E, R_{\text{had}})_{i,j} \equiv R_E S_{\text{EM},i,j} + R_{\text{had}} R_E^{\alpha} S_{\text{had},i,j}.$$



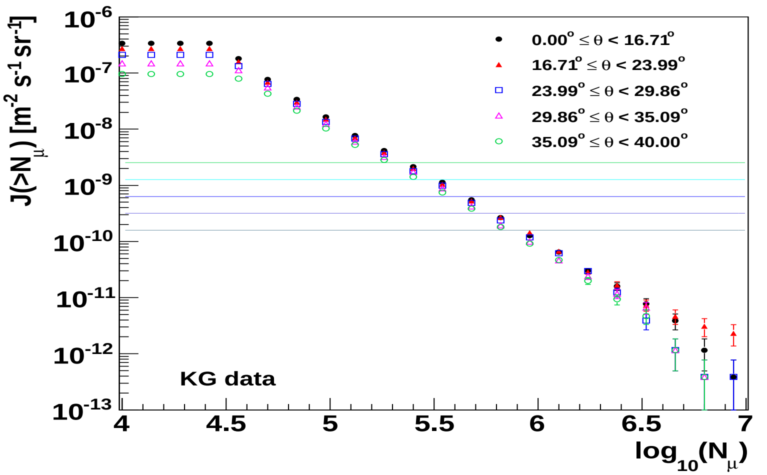
Pierre Auger Collaboration, PRL 117, 192001, 2016

KASCADE-Grande

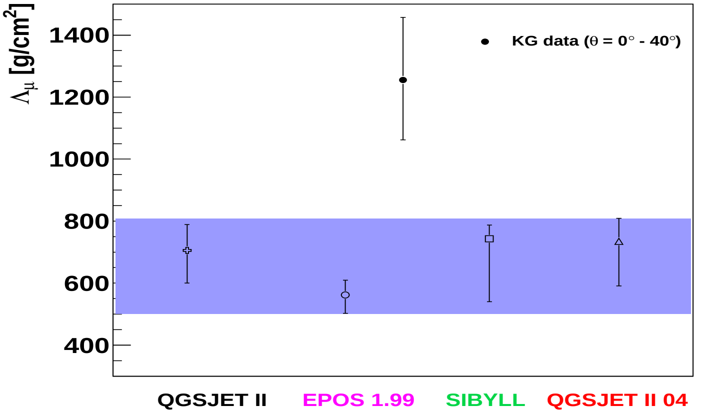
- Smaller, denser array: sensitive at lower energies (upto 10^{18} eV)
  - very high-quality muon measurements using the KASCADE array

- Muon attenuration length measurement: models predict wrong muon energy spectra

$$N_\mu = N_\mu^0 \exp[-X_0 \sec(\theta)/\Lambda_\mu]$$

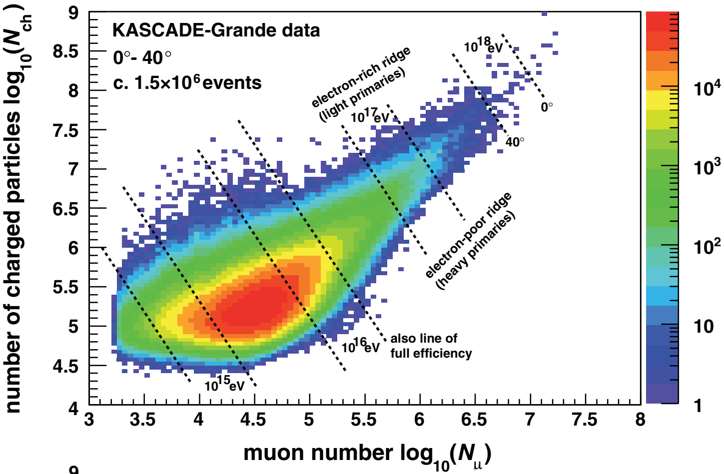


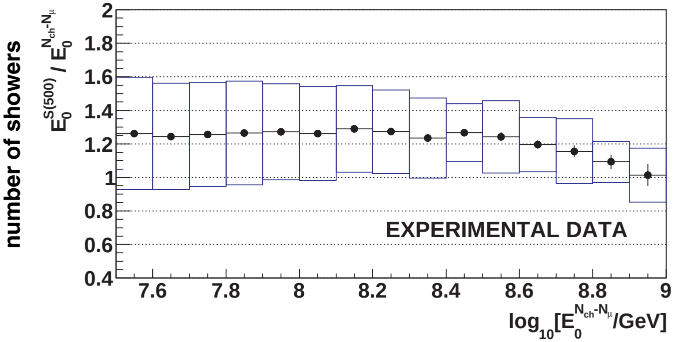
Arteaga-Velazquez for KASCADE-Grande, ICRC 2013

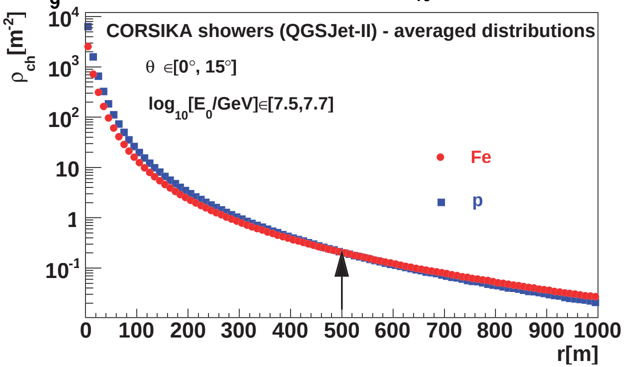


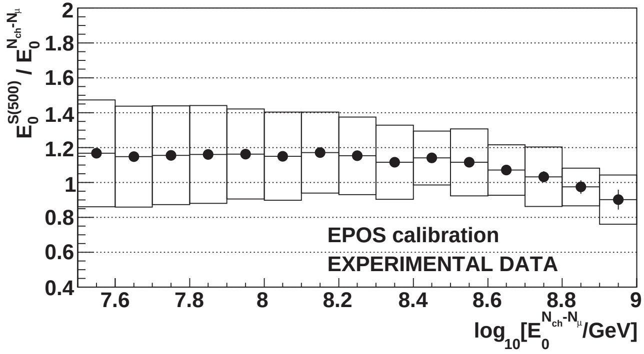
KASCADE-Grande

- Discrepancies between 2D-fitting method and "Auger-like" energy estimator



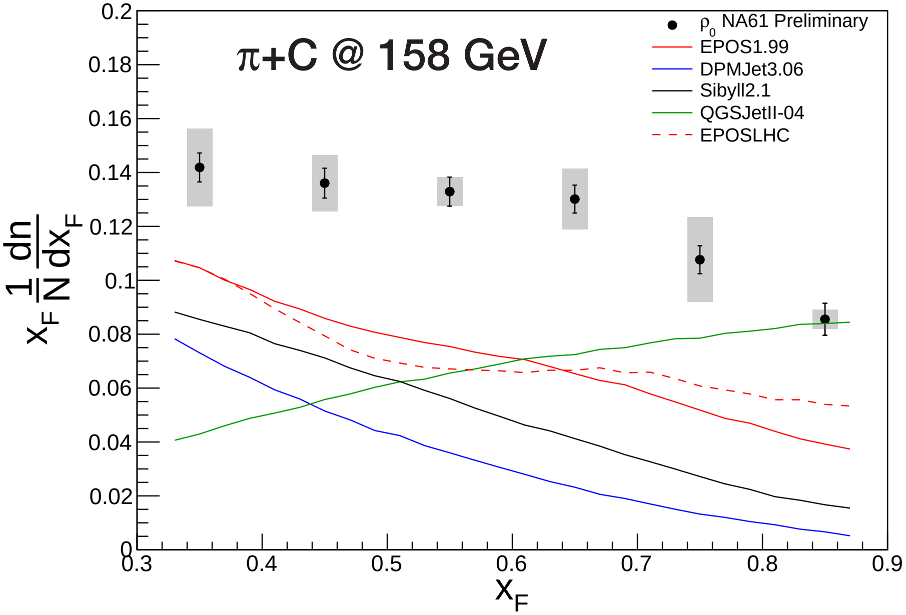


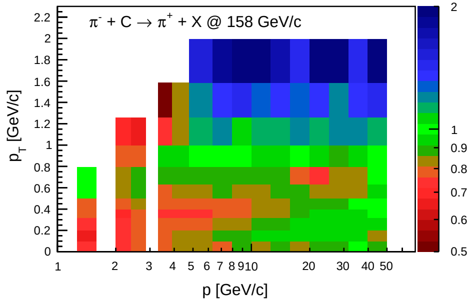




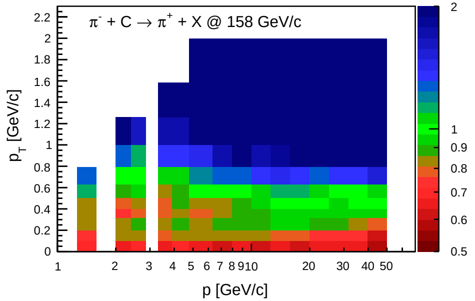
Toma for KASCADE-Grande, ICRC 2015

Detour: NA61

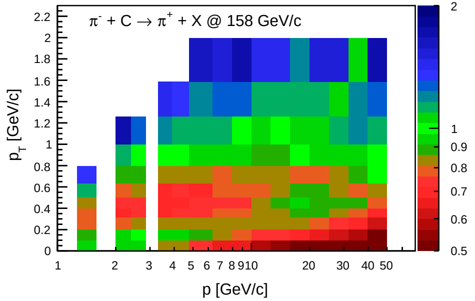




Sibyll-2.1



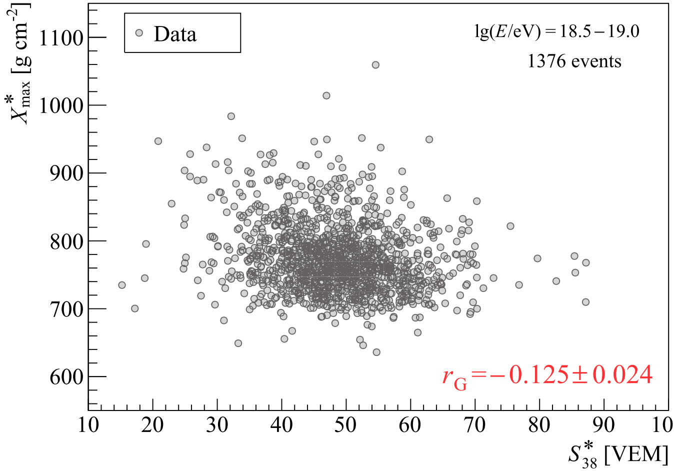
QGSJetII-04

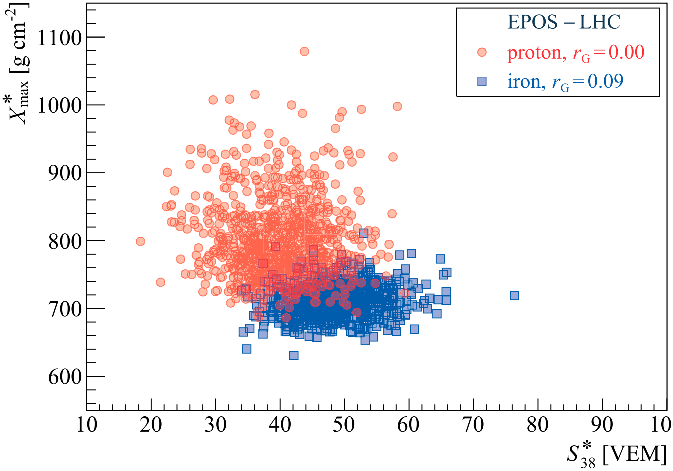


Hervé for NA61/SHINE Collaboration, ICRC 2015

What if? Proposed model changes

- Heavy flavours: probably insignificant
- Lorentz invariance violation: would have to be quite substantial
- Quark-gluon plasma: possible, maybe related to our model (see later)
- String percolation, Chiral symmetry restoration ...
  - changes in londitudinal evolution due to interactions, not composition
  - probably excluded by $X_{\mathrm{max}} - N_{\mathrm{mu}}$ correlation

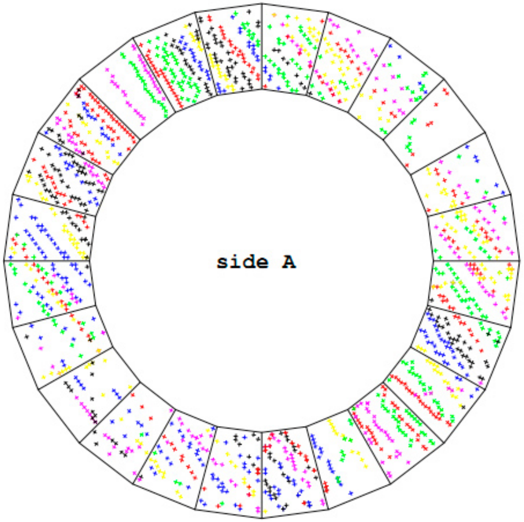


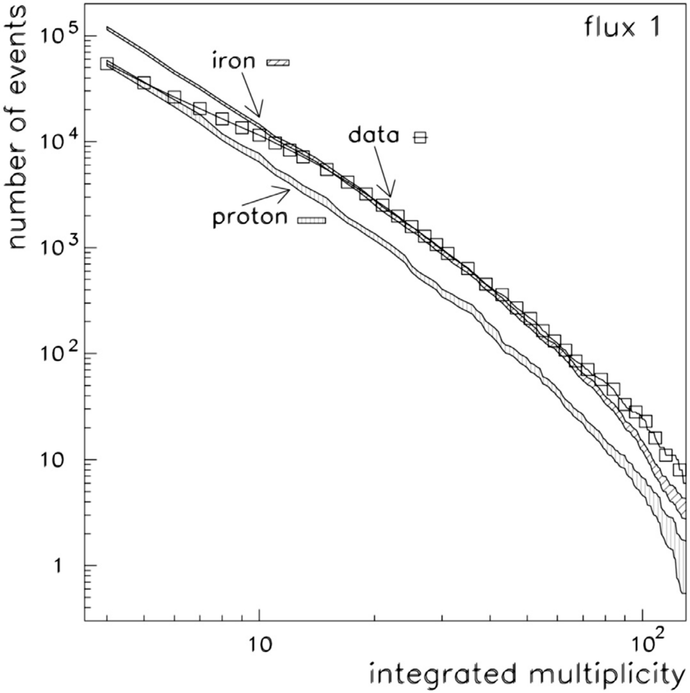


Pierre Auger Collaboration, Physics Letters B 762 (2016) 288–295

DELPHI as a cosmic ray detector

- rock overburden: vertical cutoff ~ 52 GeV
- cosmic measurement in concurence with normal run: effective uptime ~ 18 days





Bundles of parallel tracks in HCAL

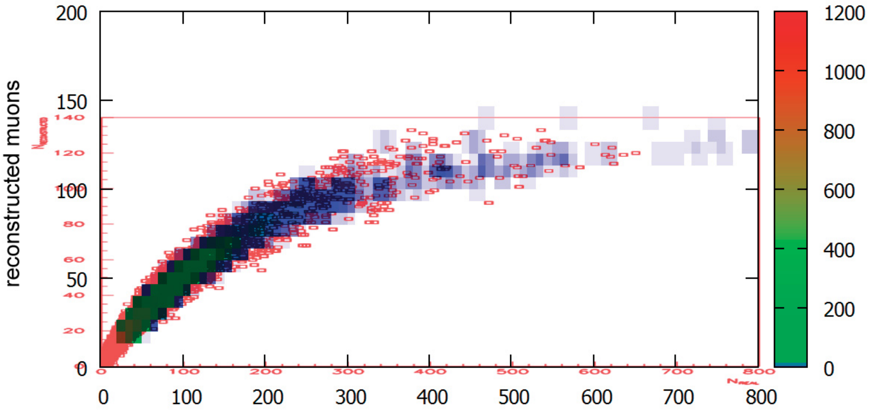
- not every muon reconstructed (shadowing, saturation, non-active areas)
- high-multiplicity events mainly from EAS between 10^{15}–$10^{17.5}$ eV

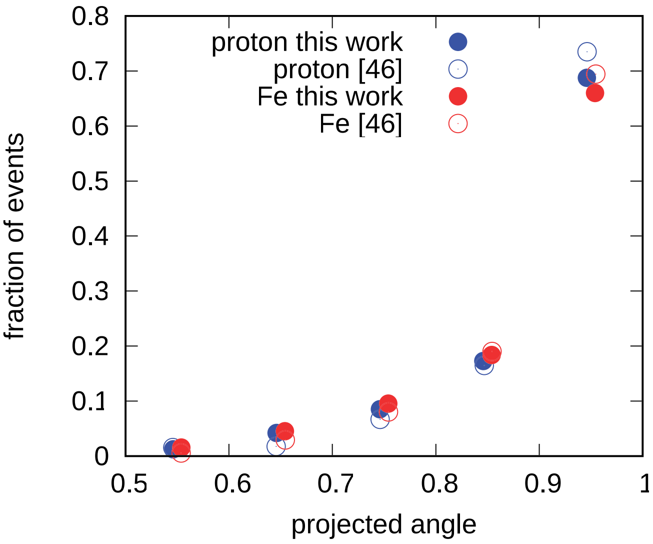
$DPH_{20} = 2.24 \pm 0.17$
$DPH_{80} = 1.45 \pm 0.23$

DELPHI Collaboration, Astropart.Phys.28:273-286,2007

DELPHI simulations

- whole relevant energy range (10^{14}–10^{18} eV), spectrum and chemical composition from KASCADE + Grande
- simple "toy DELPHI" to roughly reproduce the response of the system to EAS
- fit of efficiency and saturation

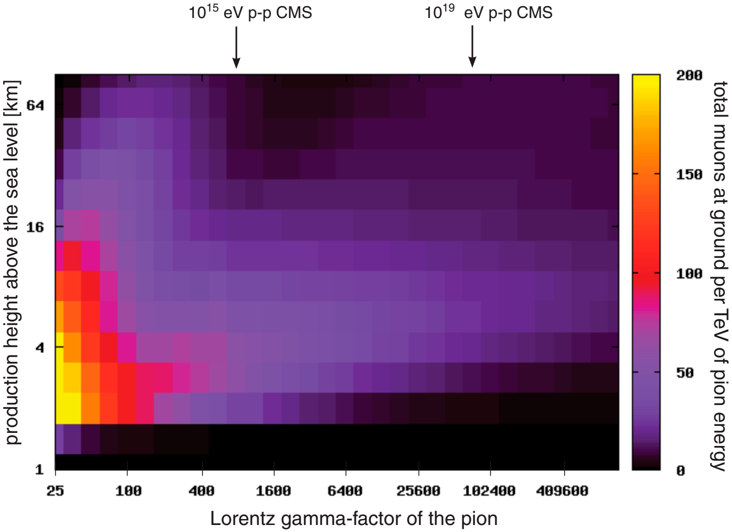


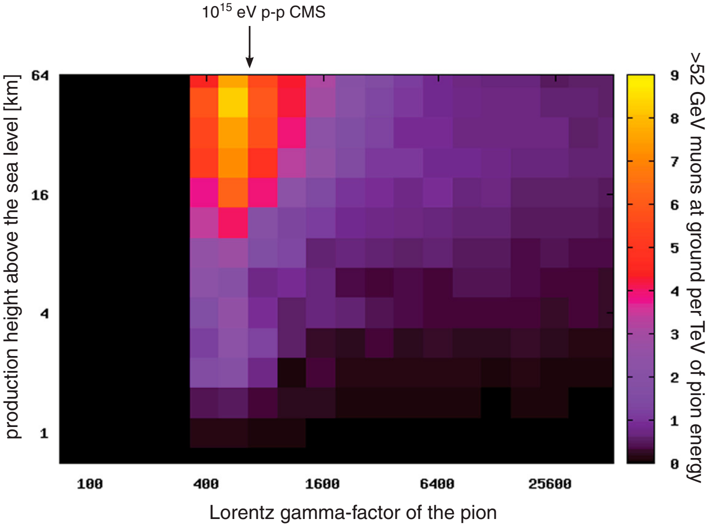


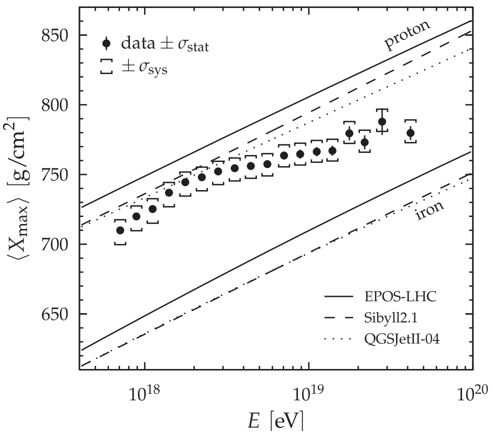
model	DPH_{20}	DPH_{80}	DPH_{20}	DPH_{80}
composition	p only	Fe only	mixed	mixed
QGSJET01	1.00	1.00	1.43	0.70
QGSJET-II-03	1.11	0.75	1.54	0.57
QGSJET-II-04	1.11	1.37	1.72	0.83
EPOS-LHC	0.85	0.86	1.27	0.59

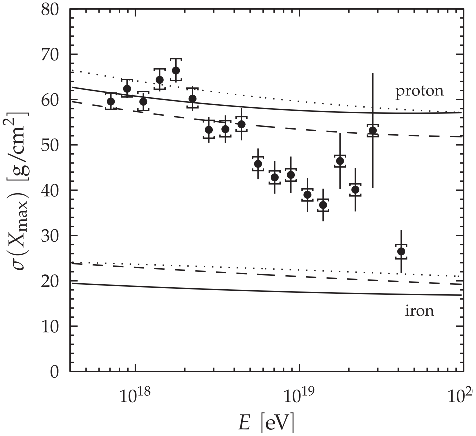
$$DPH_{20} = 2.24 \pm 0.17$$
$$DPH_{80} = 1.45 \pm 0.23$$

DELPHI-Auger connection?









- Auger depth of maximum constrains models
- Simulations at 3.2×10^{18} eV

Soft-particle addition model

particles: π, K, p, n
colour: $(\mathrm{NWT}+\mathrm{NWP})^{\eta}$
distribution $p\exp(-p/p_0)$

angle: within ~~1~~° 0.1° from axis in c.m.s.
shape: energy treshold (or special p_0)
filled vs. empty: p_0

	-1	-1/3	0	1/3	2/3	-1	-1/3	0	1/3	2/3
0.5 TeV	■	■	■	■	■	□	□	□	□	□
1 TeV	●	●	●	●	●	○	○	○	○	○
1.3 TeV	▲	▲	▲	▲	▲	△	△	△	△	△
1.6 TeV	▼	▼	▼	▼	▼	▽	▽	▽	▽	▽
2 TeV	◆	◆	◆	◆	◆	◇	◇	◇	◇	◇

p_0 = 200 MeV @ threshold
500 MeV @ 100 TeV

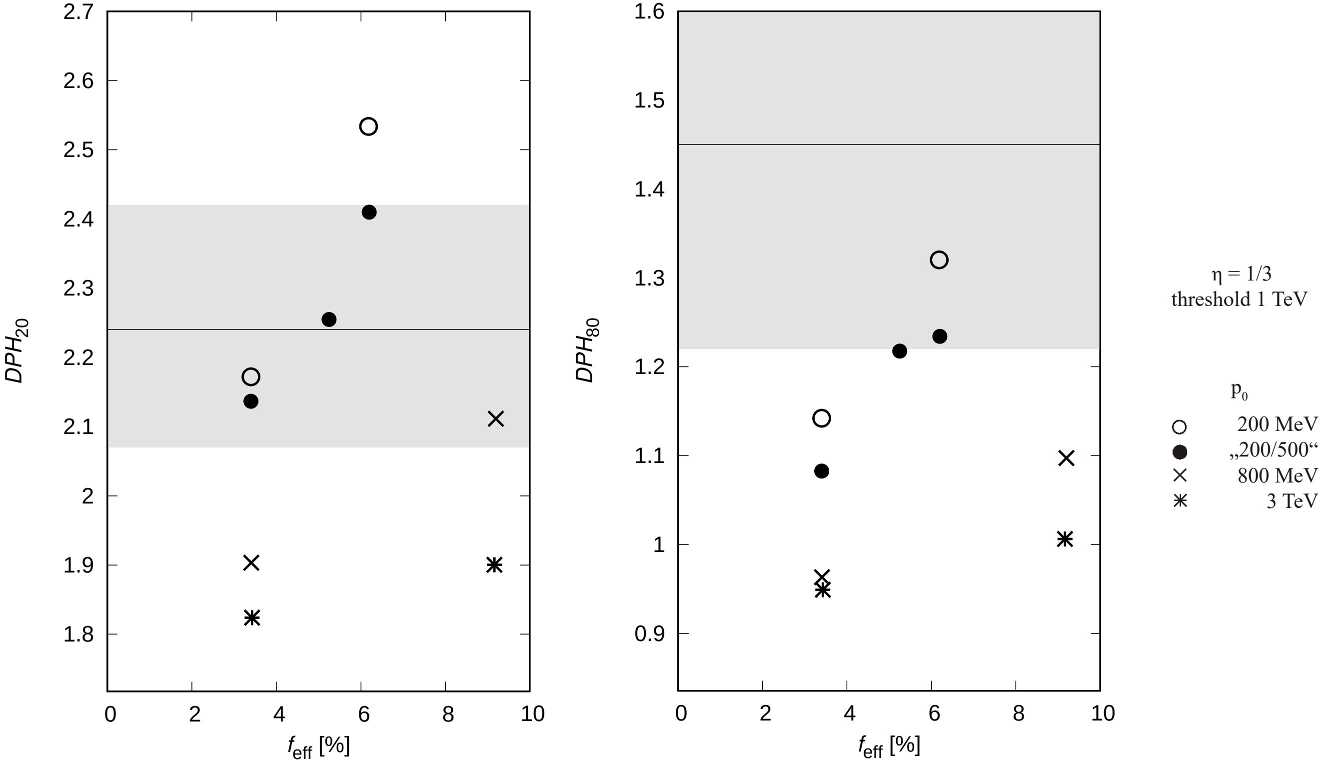
p_0 = 200 MeV

✕ p_0 = 800 MeV
✳ p_0 = 3 TeV

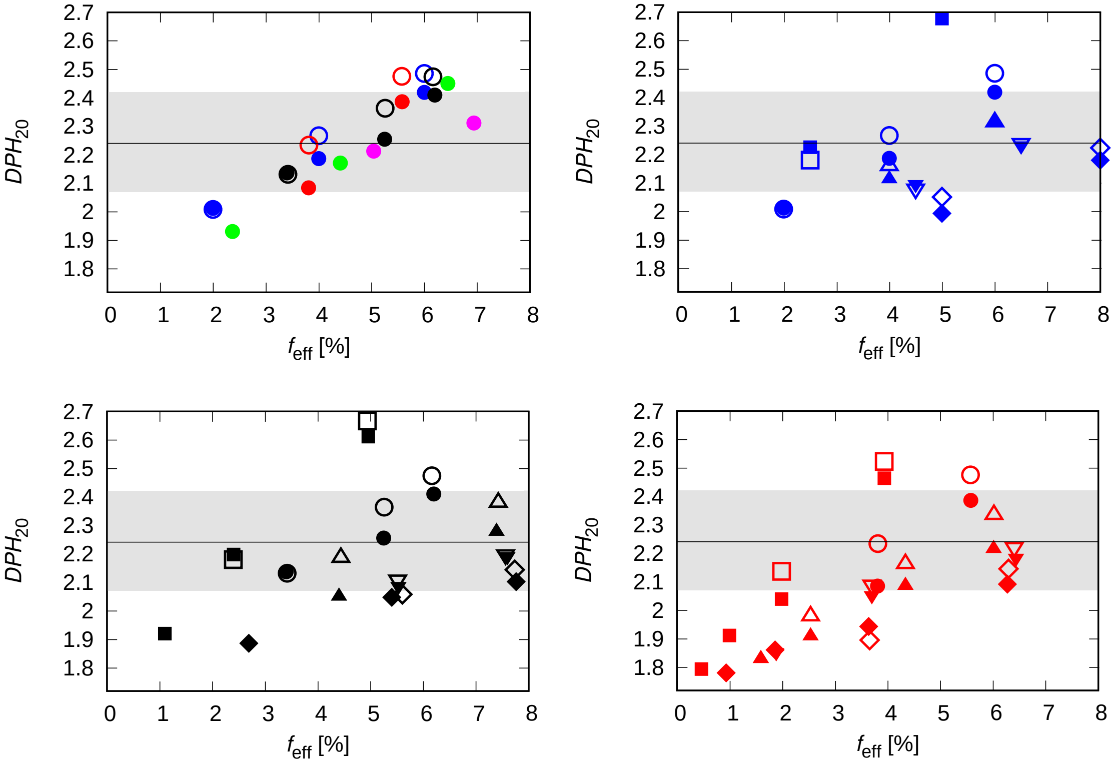
η = 1/3 and threshold 1 TeV

Ebr, Ridky, Necesal, Astropart.Phys.90:37-49,2017

SPAM: momentum distribution



SPAM: DELPHI data at multiplicities >20



color: η

blue = 0
black = 1/3
pink = 2/3
red = –1/3
green = –1

shape: threshold

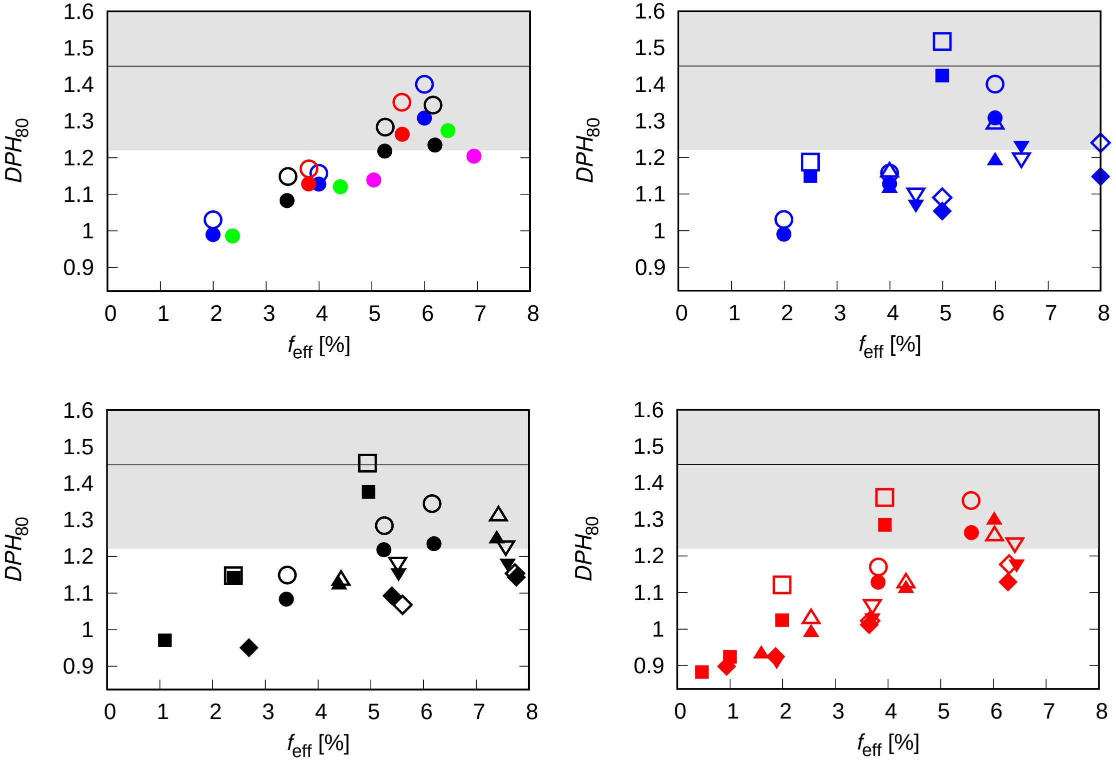
■ = 0.5 TeV
● = 1 TeV
▲ = 1.3 TeV
▼ = 1.6 TeV
◆ = 2 TeV

fill: p_0 @ 100 TeV

□ ○ △ ▽ ◇ empty = 200 MeV
■ ● ▲ ▼ ◆ filled = 500 MeV

p_0 @ threshold set to 200 MeV in both cases

SPAM: DELPHI data at multiplicities >80



color: η

blue = 0
black = 1/3
pink = 2/3
red = –1/3
green = –1

shape: threshold

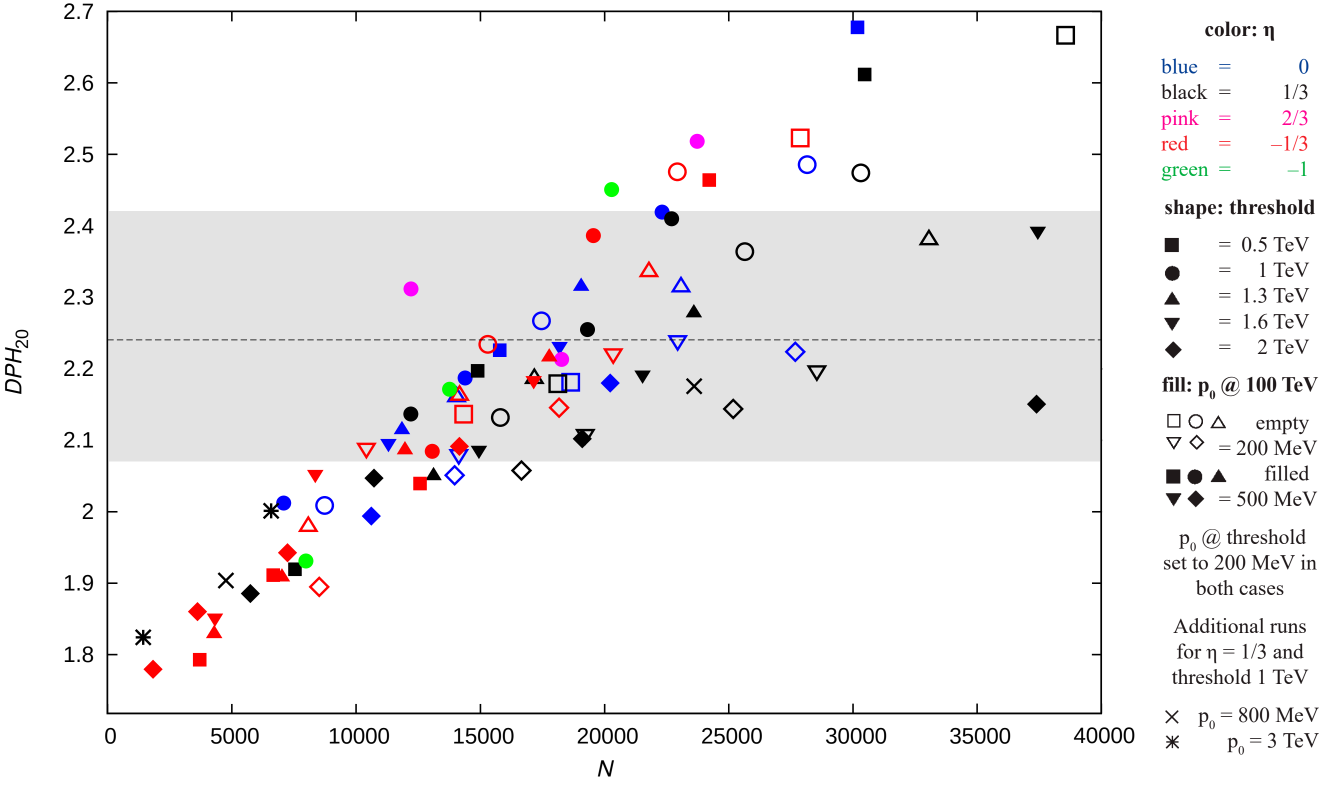
■ = 0.5 TeV
● = 1 TeV
▲ = 1.3 TeV
▼ = 1.6 TeV
◆ = 2 TeV

fill: p_0 @ 100 TeV

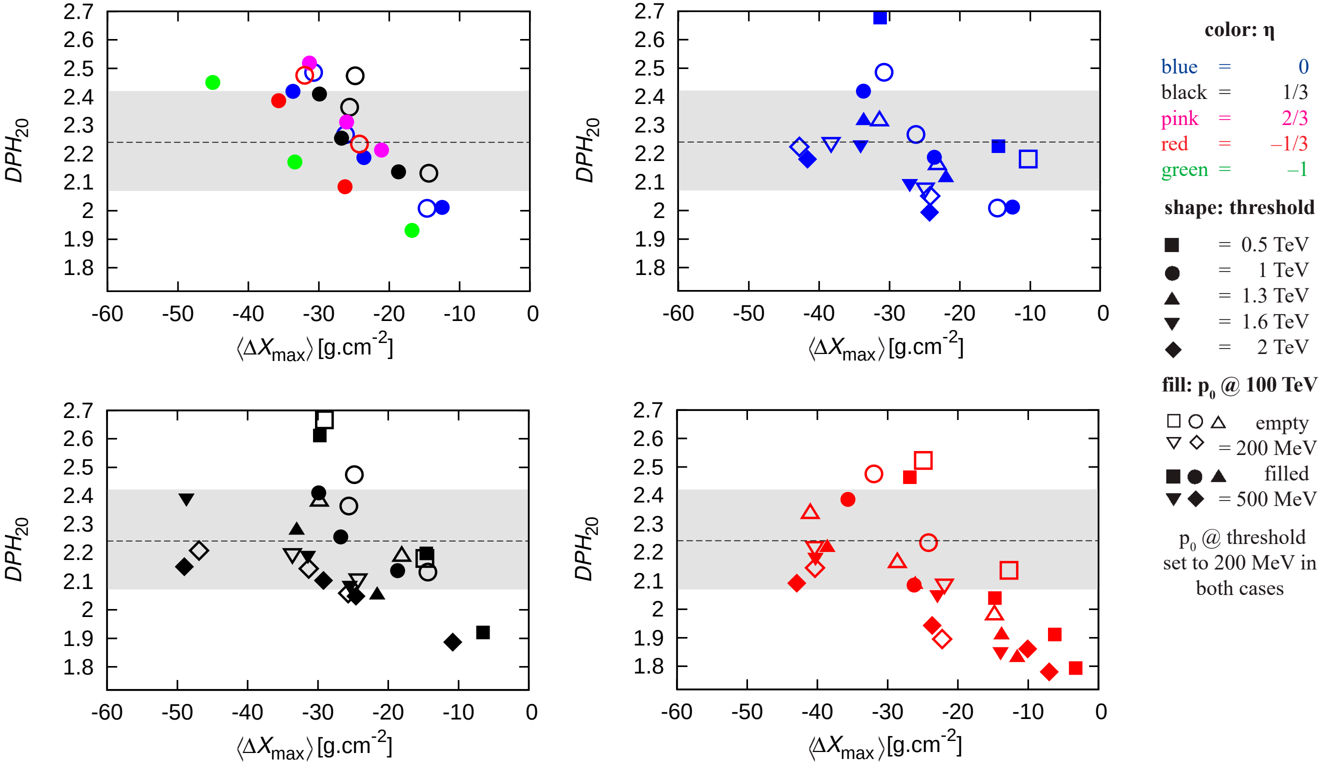
□ ○ △ empty
▽ ◇ = 200 MeV
■ ● ▲ filled
▼ ◆ = 500 MeV

p_0 @ threshold
set to 200 MeV in
both cases

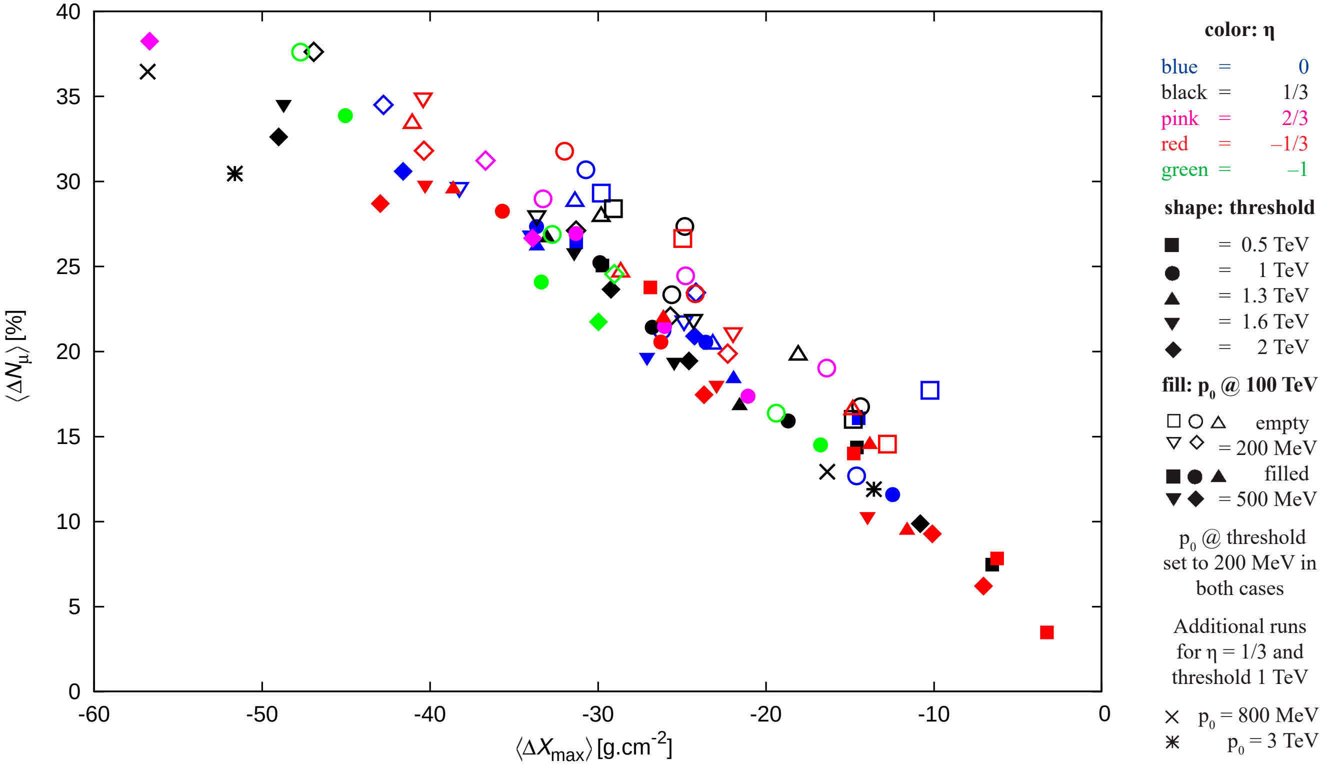
SPAM: total number of added particles



SPAM: DELPHI vs. Auger X_{max}



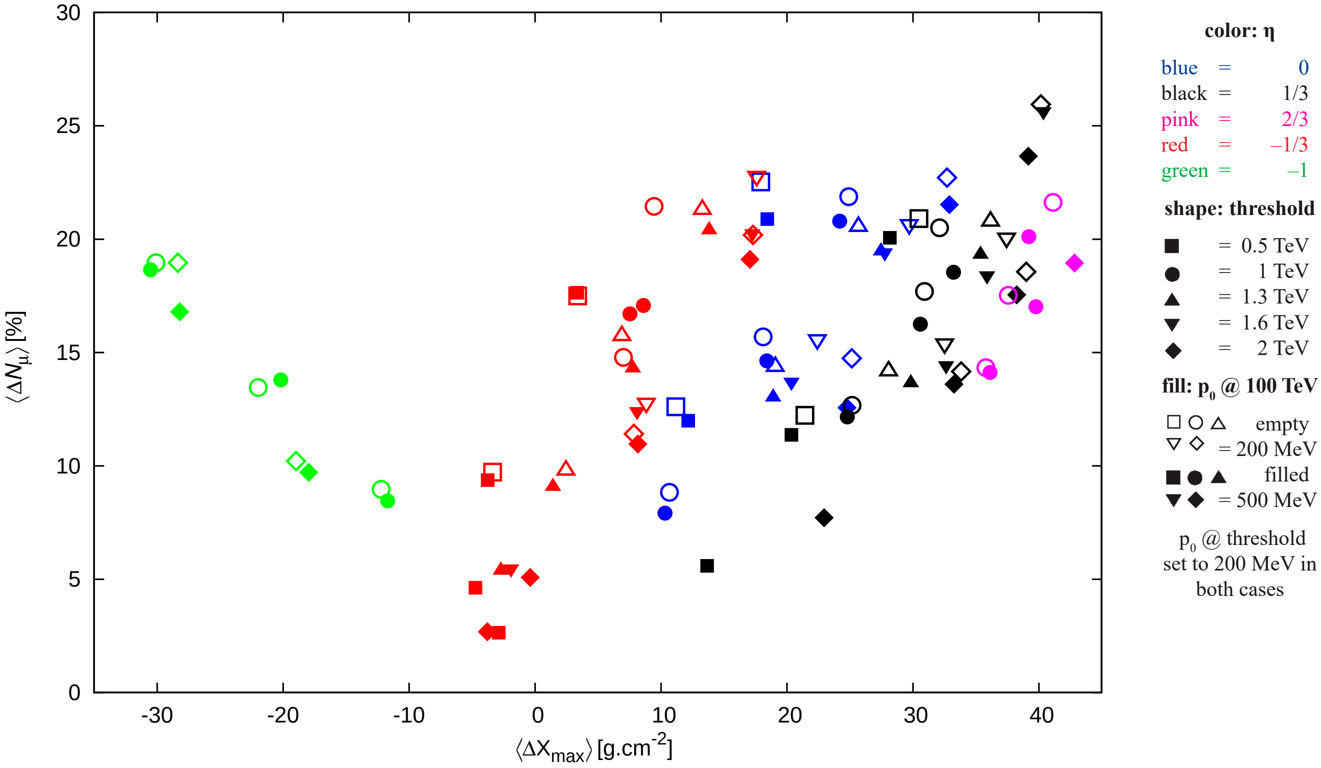
SPAM: Auger X_{max} vs. number of muons (protons)



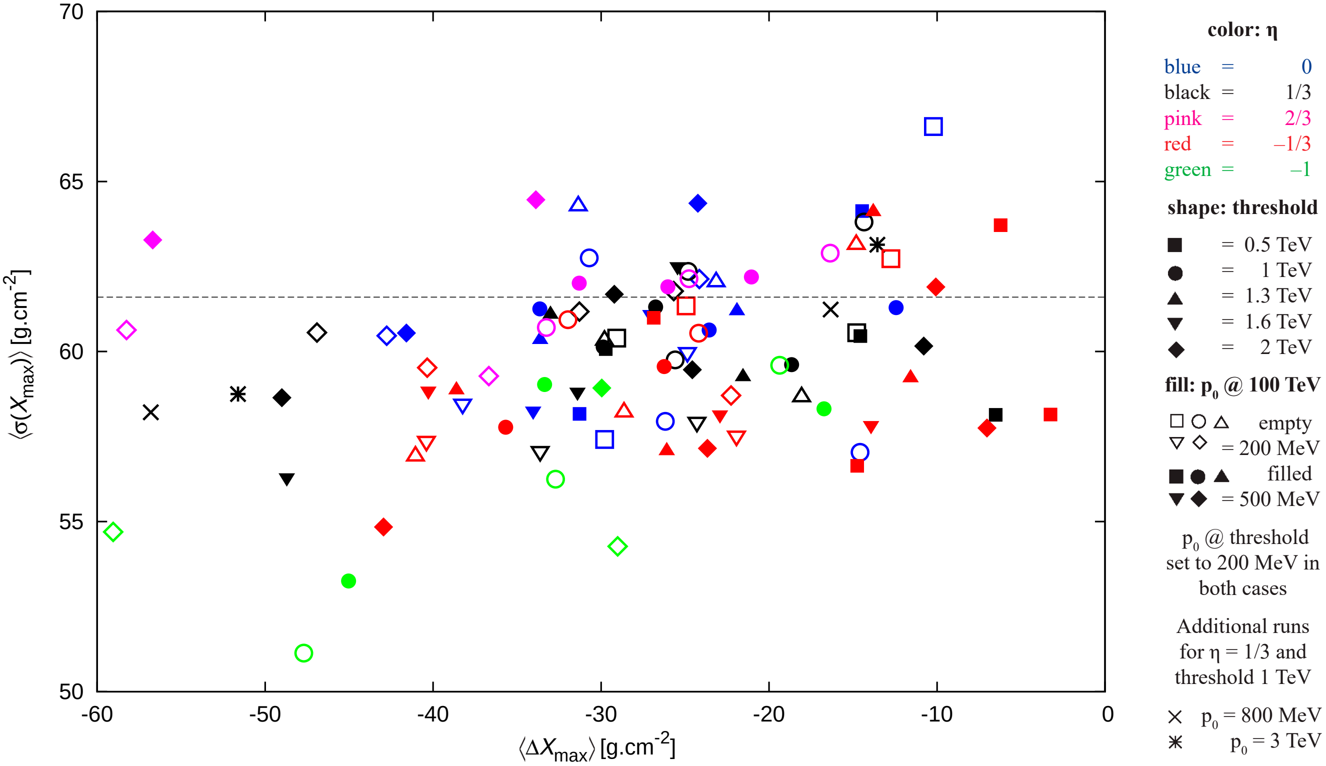
p_0 @ threshold set to 200 MeV in both cases

Additional runs for η = 1/3 and threshold 1 TeV

SPAM: Auger X_{max} vs. number of muons (irons)



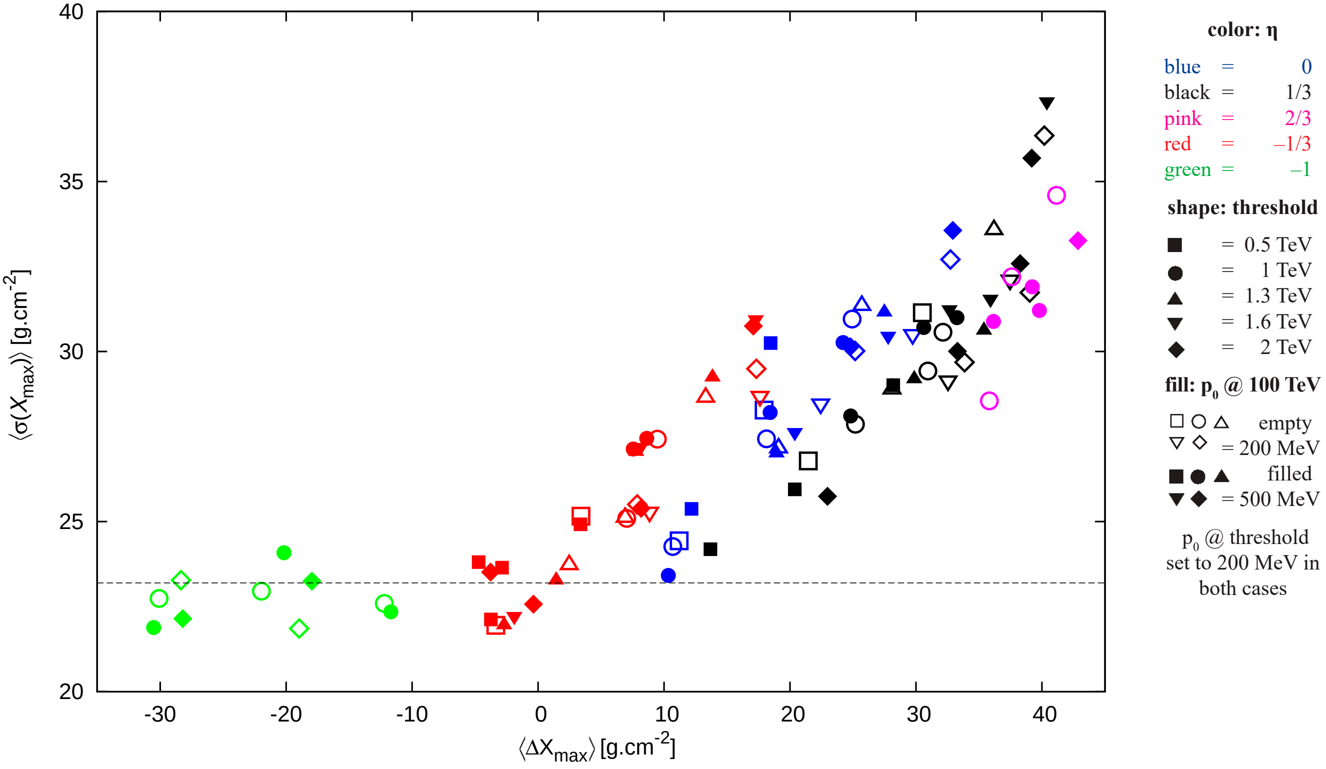
SPAM: Auger $X_{\max}$ vs. RMS (protons)



p_0 @ threshold set to 200 MeV in both cases

Additional runs for η = 1/3 and threshold 1 TeV

SPAM: Auger X_{max} vs. RMS (irons)



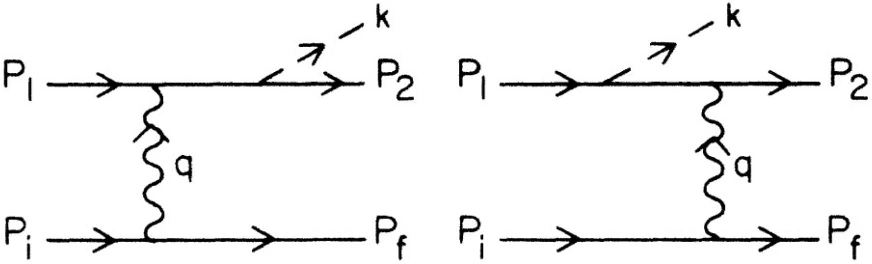
Dark photons in EAS

- *N. Arkani-Hamed et al., Phys.Rev. D79 (2009) 015014*
- Dark-matter models inspired by theory and some observations (ATIC, Pamela)
    - heavy DM particles: unobservable (low branching ratios)
    - light particles more attractive
- "Dark photons"
    - independent U(1) symmetry, interacts via klinetic mixing
        - "suppression factor"
    - decay to a pair, mostly leptons when light
    - produced in EM cascade via bremsstrahlung
        - a lot of opportunities in an EAS!
        - additionally suppressed by photon mass

- Calculation of Bremsstrahlung cross-section and simulation of production

Bremsstrahlung: a well-known process
(Tsai, 1974)

Analytical formula for the cross-section known:

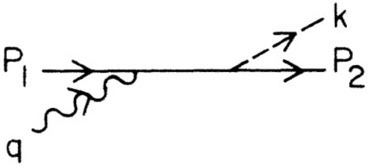


$$\frac{d\sigma}{dx} = \frac{4\alpha^3}{3E_1 m_e^2 x}\left[(x(3x-4)+4)\left(Z\ln\left(\frac{1194}{Z^{2/3}}\right)+Z^2\ln\left(\frac{184}{Z^{1/3}}\right)\right)-\frac{(x-1)\left(Z+Z^2\right)}{3}\right]$$

- minor corrections to individual scattering exist + the LPM effect (tames the divergence)

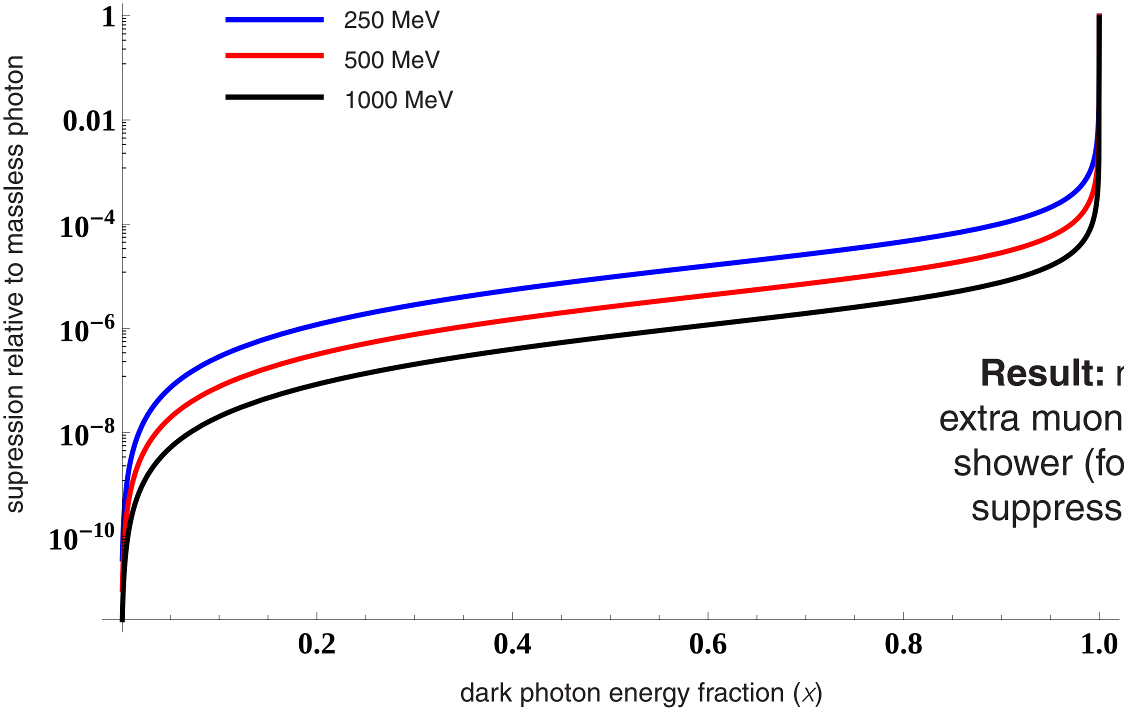
Surprisingly difficult in practice („a month of hard work“) → approximation (Weizsäcker-Williams)

$$\frac{d\sigma\left(2\to 3\right)}{d\left(P_1\cdot k\right)d\left(P_i\cdot k\right)} = \frac{d\sigma\left(2\to 2\right)}{d\left(P_1\cdot k\right)}_{t=t_{min}}\frac{\alpha}{\pi}\frac{\chi}{P_2\cdot P_i}$$



The result can be written in a compact form (neglecting electron mass where possible):

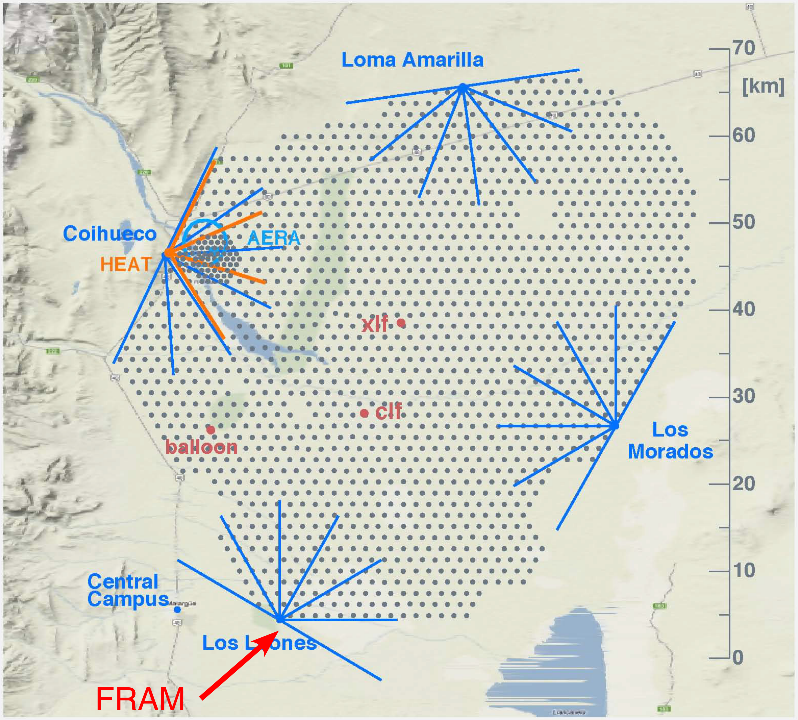
$$\frac{d\sigma}{dx} = \frac{4\alpha^3 x((x-2)x+2)}{E_1}\left[\frac{Z+Z^2-Z\ln\left(\frac{1194}{Z^{2/3}}\right)-Z^2\ln\left(\frac{184}{Z^{1/3}}\right)}{m_\gamma^2(x-1)-m_e^2x^2}+\frac{(Z+Z^2)\log\left(\frac{m_{e2}x^2}{m_\gamma^2(1-x)+m_e^2x^2}\right)}{m_\gamma^2(x-1)}\right]$$



Result: not a single extra muon for the whole shower (for reasonable suppression factors).

Ebr, Necesal, Phys. Lett. B725 (2013) 185–189

FRAM telescope at the Pierre Auger Observatory



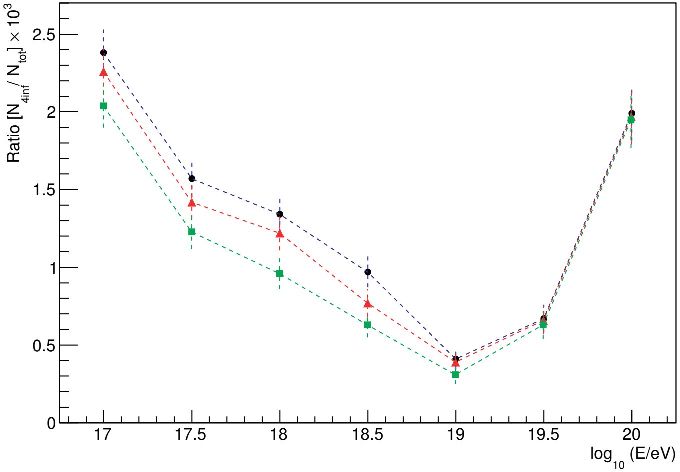
300/2.8 Nikkor with G4-16000
- 36×36 mm CCD, 7°×7° FoV

(30 cm SCT with G2-1600)

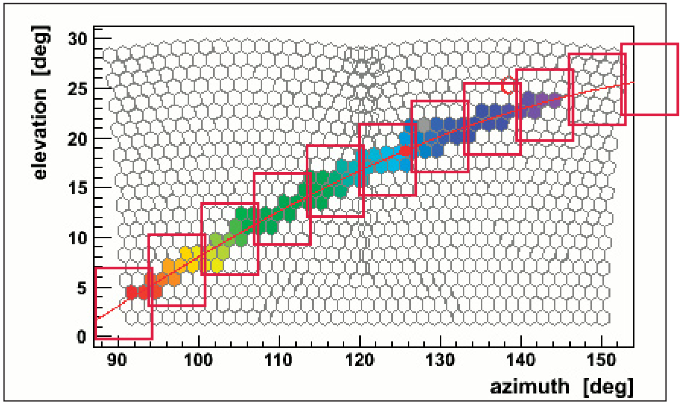

FRAM

Search for anomalous profiles

- Look for double-bump events to study hadronic interactions and composition
  - essentially assures presence of protons
  - allows independent cross-section measurement
- Eliminate false positives from clouds using rapid monitoring with FRAM
  - real-time reaction to anomalous shower candidates

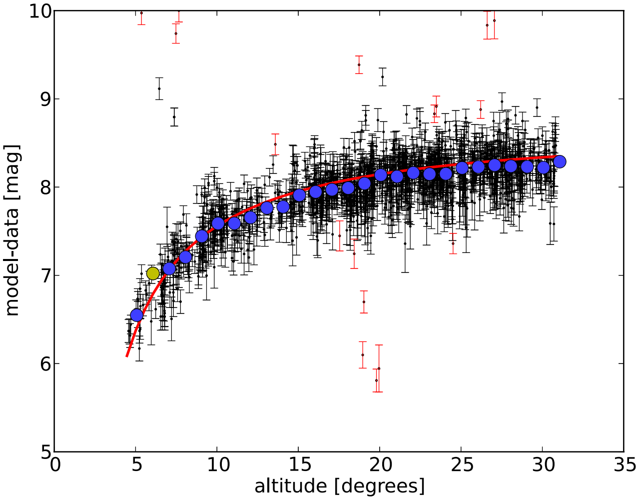


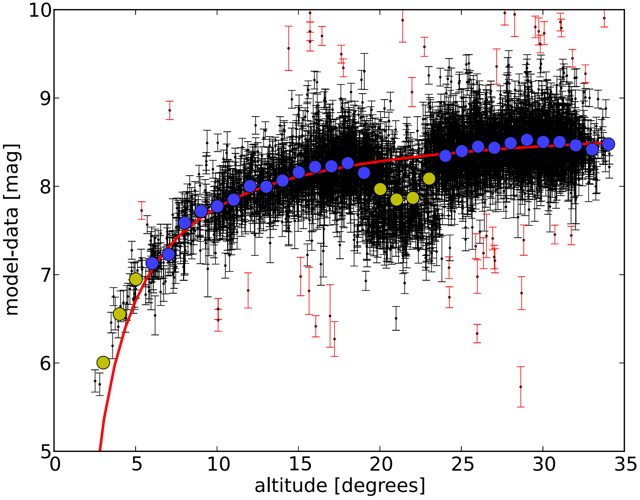
J. Blažek

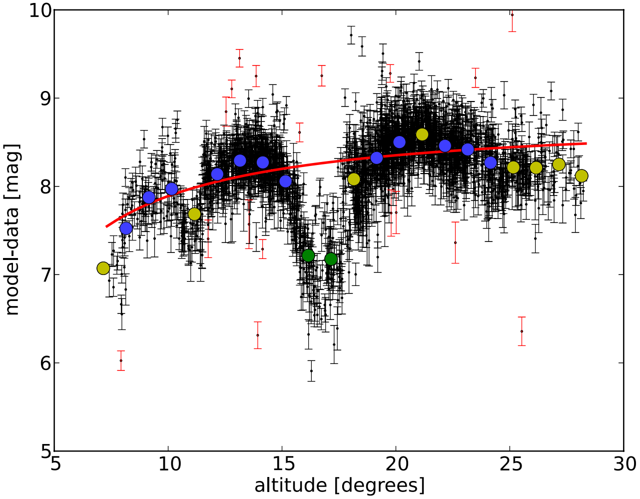


Shoot-the-shower program

- Semi-automatic analysis
    - database available to Auger
- Daily monitoring of operation
- More data needed for statistical analysis

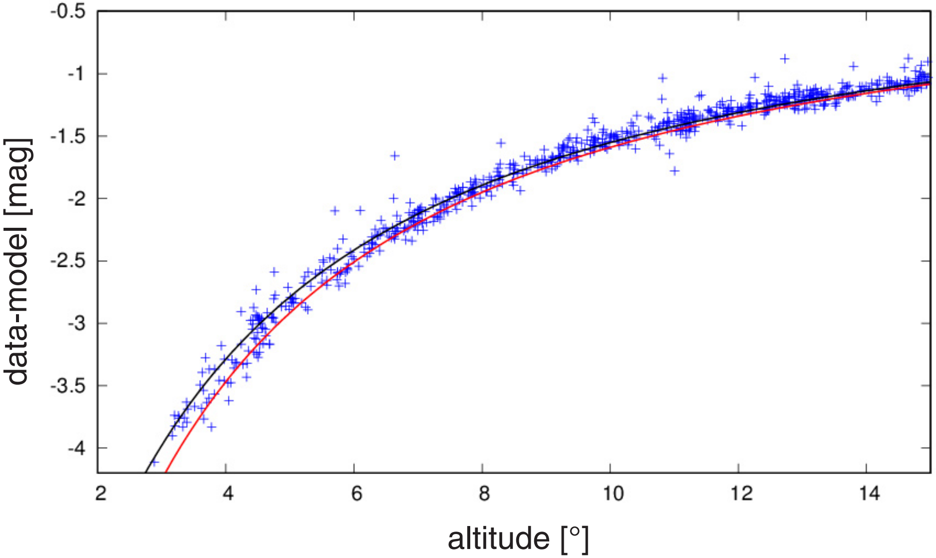






Aerosol measurements with FRAM

- Aerosols (VAOD – vertical aerosol optical depth) an important source of uncertainty in fluorescence measuremnts
  - both energy scale and composition affected
  - recently indications of discrepancies between different laser methods
  - FRAM: independent systematics, but only integral value
- Uses StS dataset + dedicated measurements



Model to fit of observed data

$$m_{\mathrm{inst}} = M m_{\mathrm{cat}} + Z_i + k_i A + c_1 (B-V)(c_2 (B-V) + 1) + R_1 r (R_2 r + 1) + k_c A (B-V)$$

- A: airmass $B-V$: color index ($m_{\mathrm{cat}} = B$) r: radial position on frame
- $M, c_1, c_2, R_1, R_2, k_c$ held constant; (Z,k)-pair for each scan

- M close to 1 for sufficient apertures (CCD chip very linear)

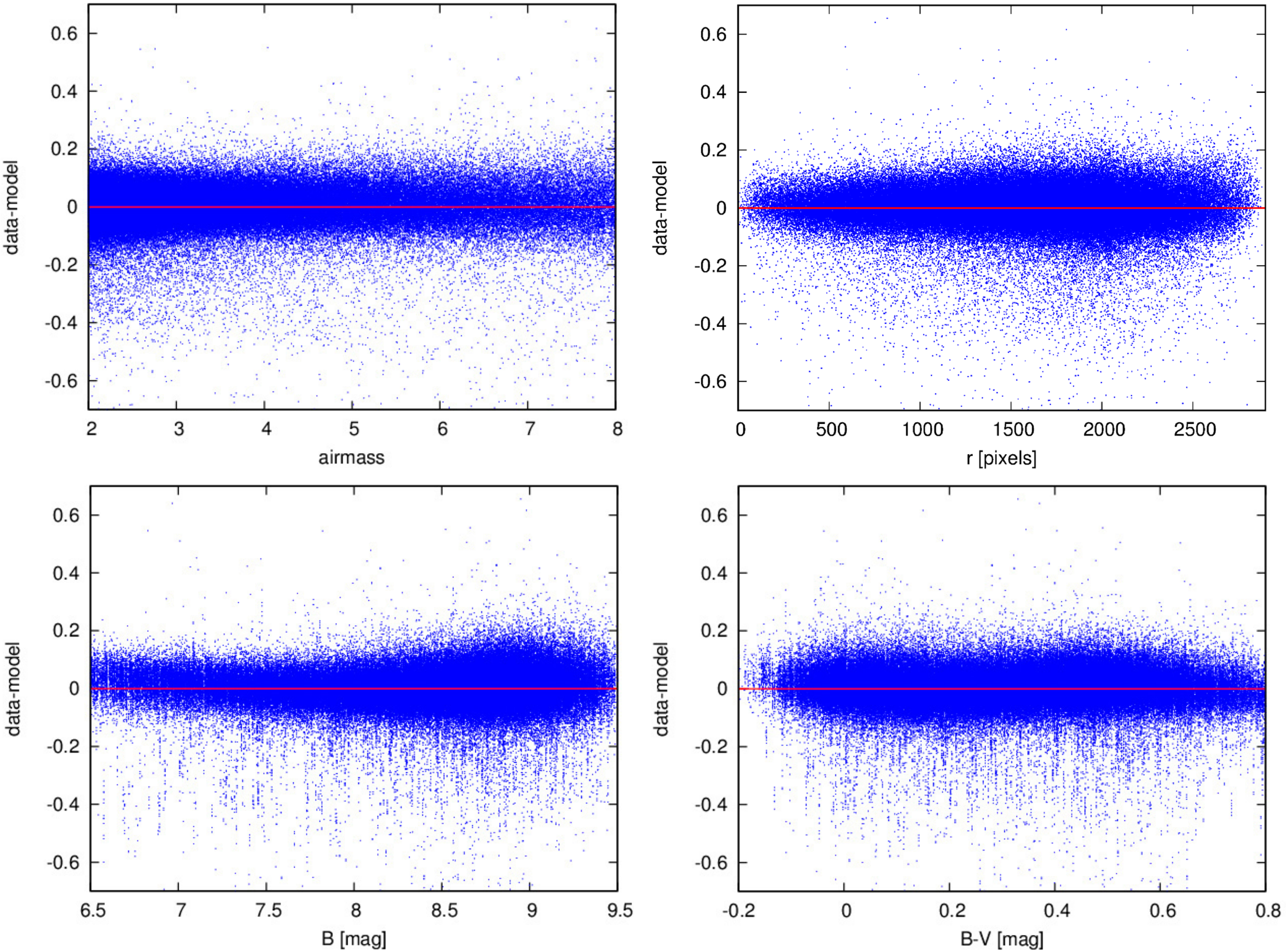
– cut on B > 6.5 to avoid saturated stars

– cut on B < 9.5 because of Tycho limitations

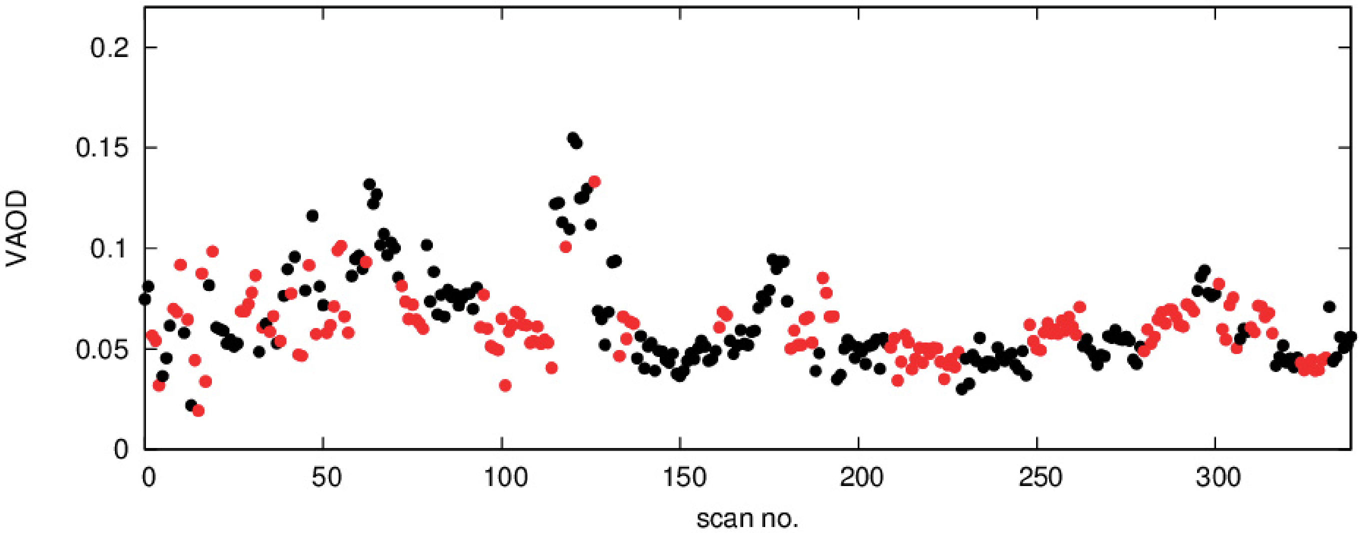
- k_c problematic (see later)

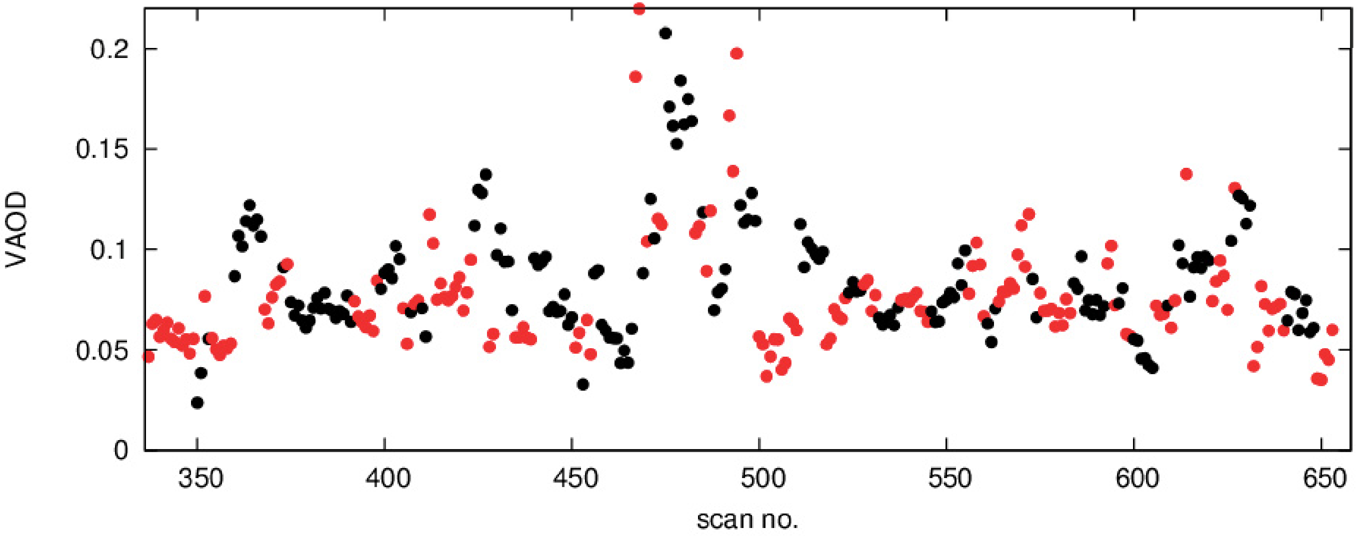
- Iteratively cut outliers (mostly errors in Tycho)

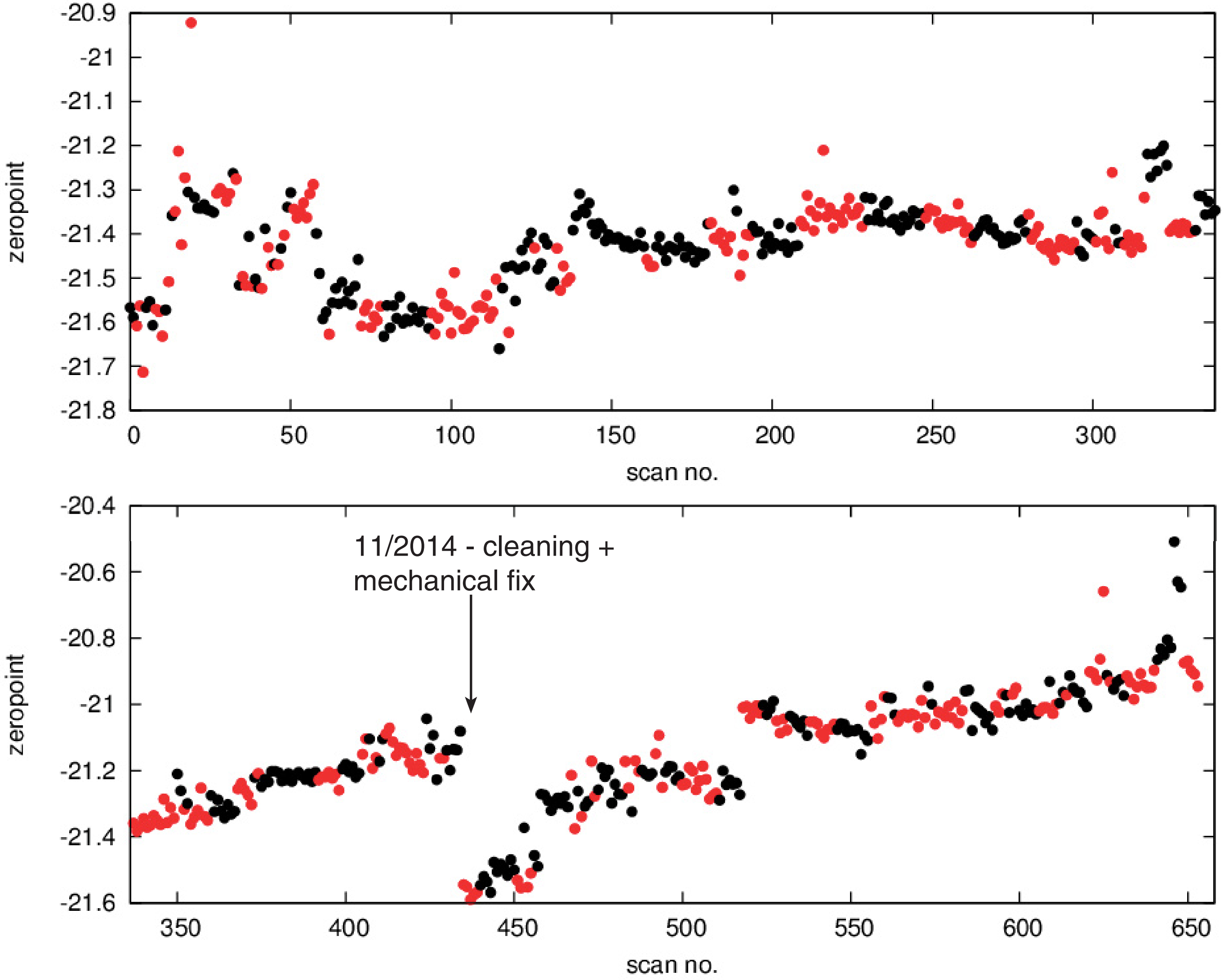
How well does the model describe the data?



RMS ~ 0.07 mag


VAOD
0.2
0.15
0.1
0.05
0
0
50
100
150
200
250
300
scan no.


VAOD
0.2
0.15
0.1
0.05
0
350
400
450
500
550
600
650
scan no.

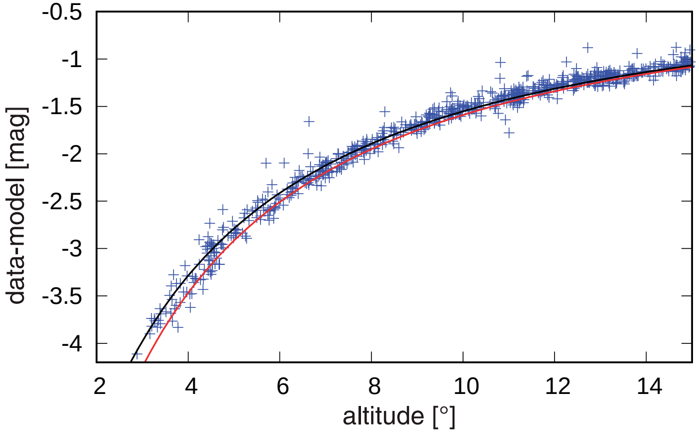


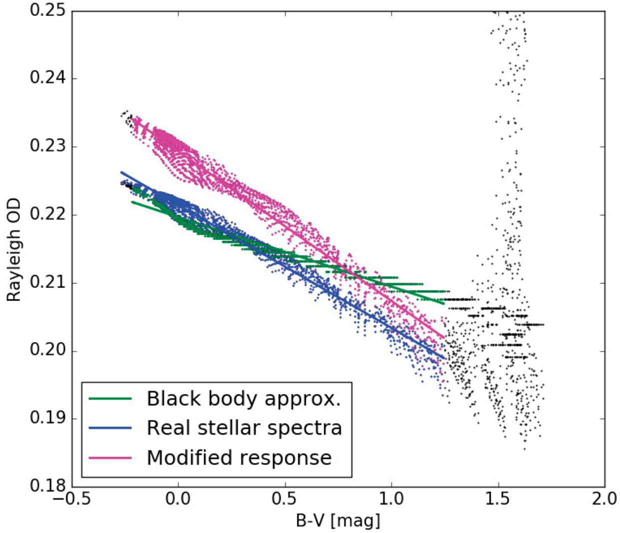
11/2014 - cleaning + mechanical fix

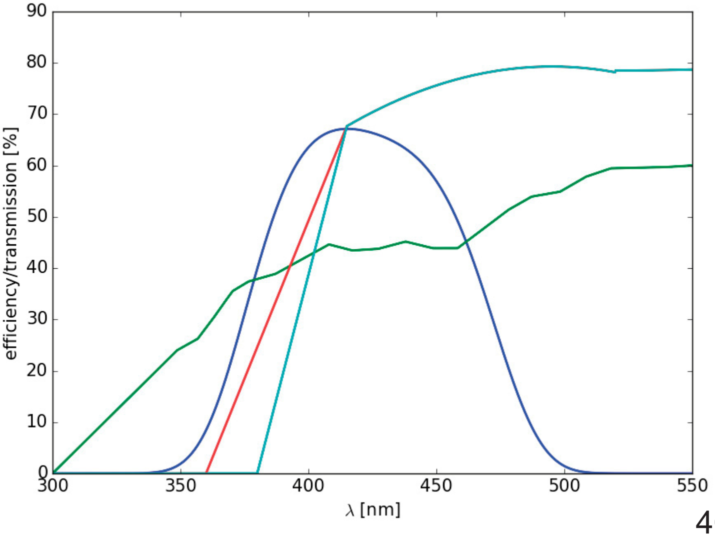
Improvements of aerosol measurement

- More realistic calculation of molecular contribution to extinction
  - stellar spectra
  - molecular absorbtion

$$\frac{J_{\text{ground}}}{J_{\text{space}}} = \int R(\lambda) \exp\left(-\tau(\lambda)A\right)\mathrm{d}\lambda$$



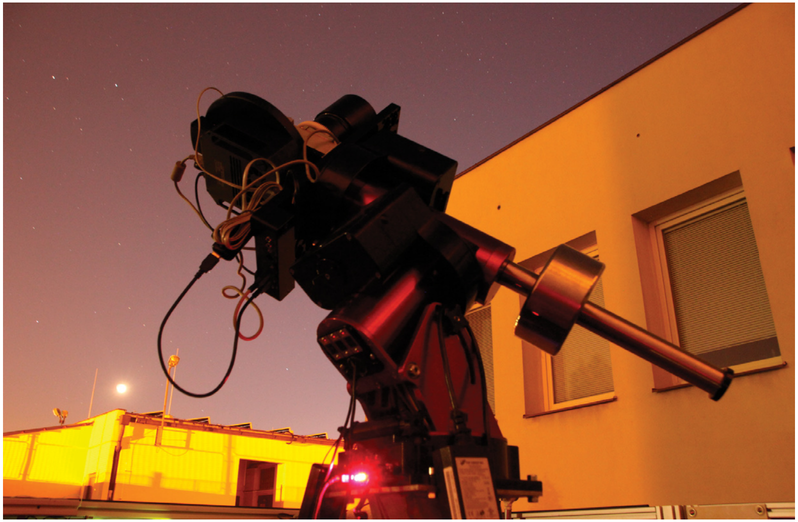


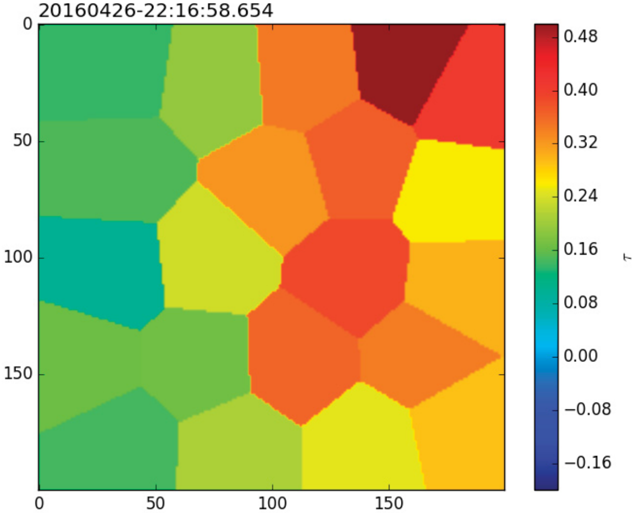


J. Juryšek

Further applications: Cherenkov Telescope Array

- Next generation in ground-based gamma-ray astronomy
- 2 sites, ~120 telescopes of 3 sizes (4–23 meters)
- Continuous, non-invasive aerosol measurement in limited FOV (4.5–10 deg.)
    - 3 CTA FRAMs in total , one already deployed in Chile





Summary

- A discrepancy between simulations and data exists regarding the muon content cosmc-ray initiated extensive air showers

- Adding soft-particles to hadronic interactions increases predcited muon numbers for both Auger and DELPHI

- Adding dark photons to EM cascades does not have any effect

- Anomalous shower profiles can be separated from cloud-induced background using rapid monitoring with FRAM

- FRAM can also provide integral VAOD measuerements indepently from laser-based devices

- Further applications of the FRAM method are found at the CTA observatory