Air-shower measurements vs. hadronic interaction models: Investigations with KASCADE-Grande

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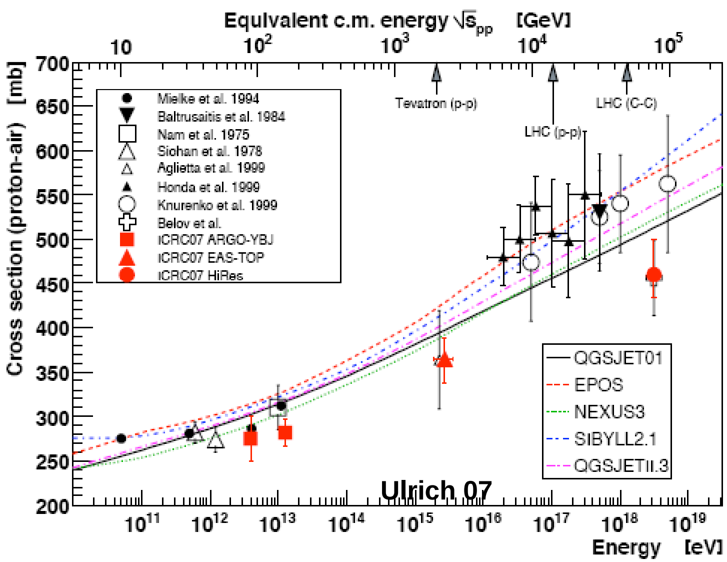
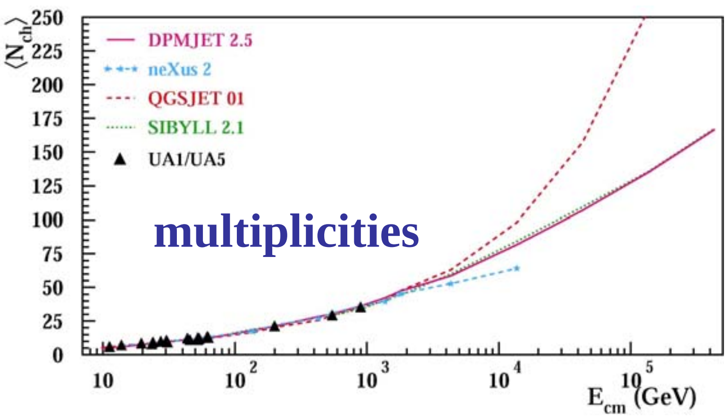
Hadronic Interactions: Problems

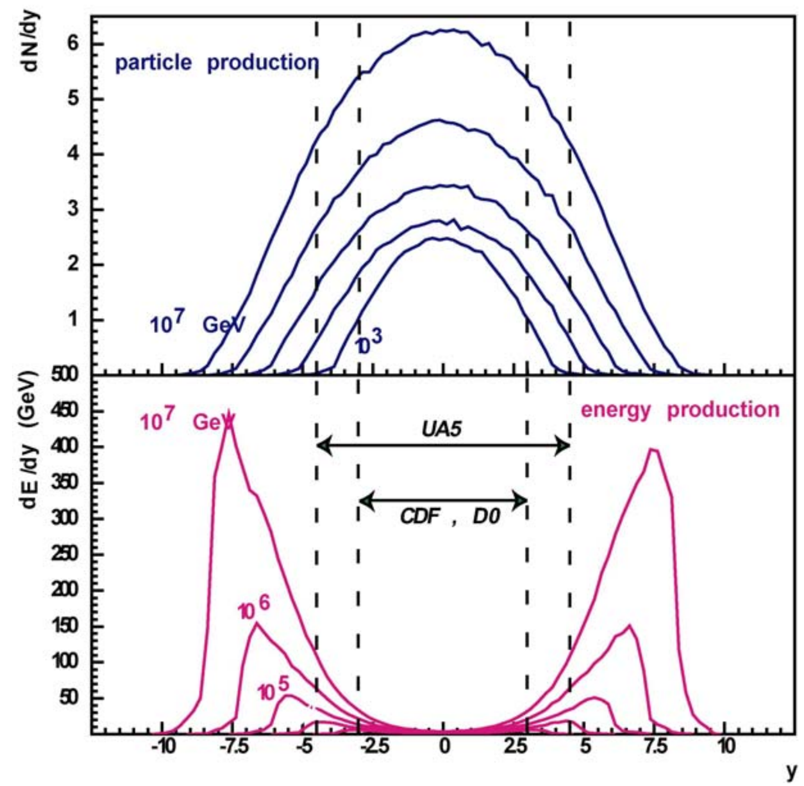
- **Extrapolation of cross-sections to ultra-high energies**
- **Secondary particle multiplicity in high-energy interactions**
- **Extrapolation of kinematics to the extreme forward region** (diffractive part of X-sections)

p-Air cross-section





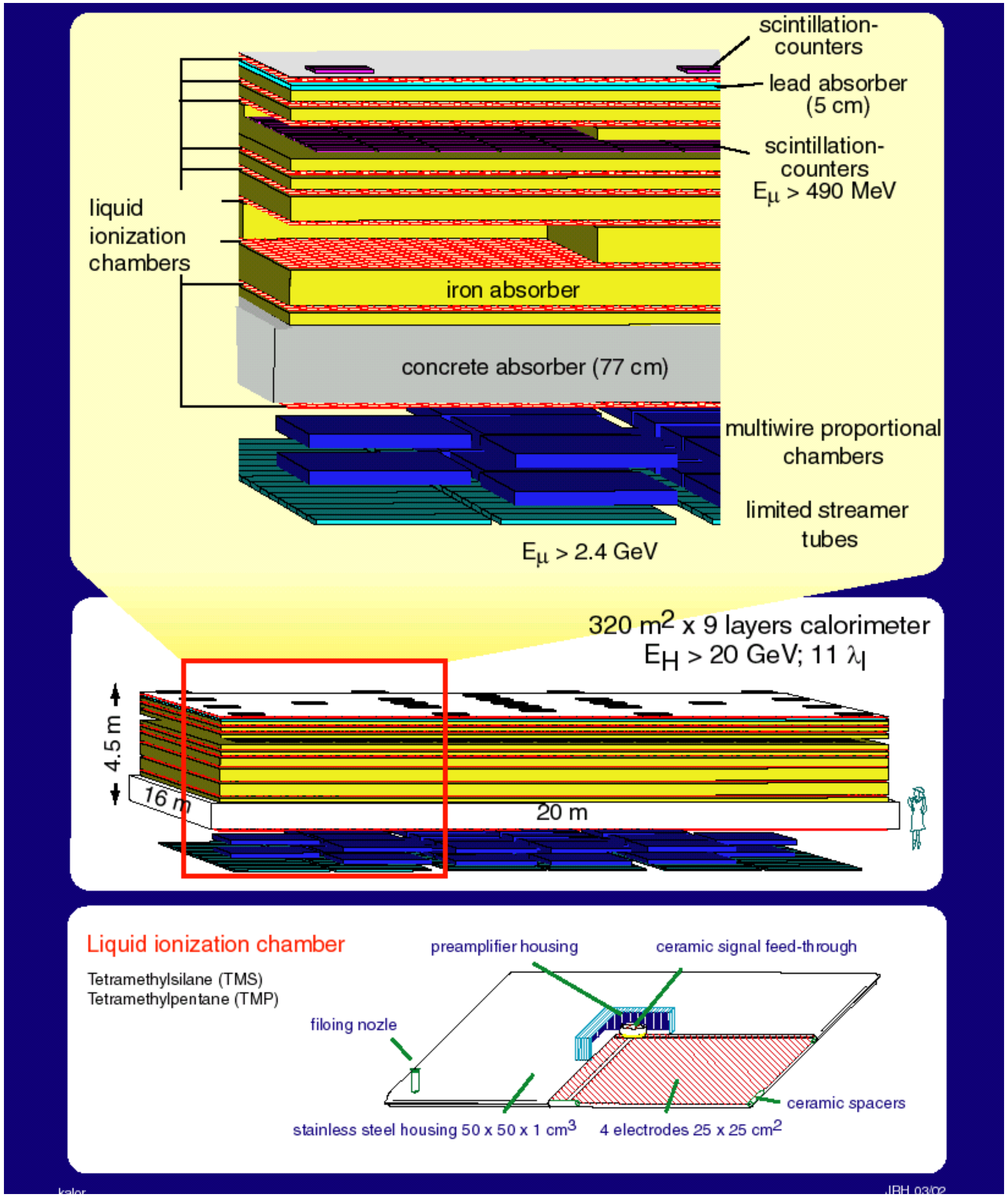
rapidity distribution



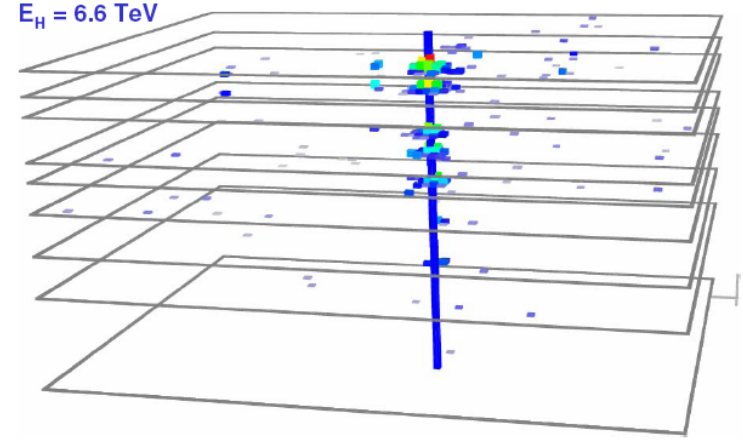
[CORSIKA (Heck et al) FZKA report 6019]

KASCADE: Hadron Measurements

hadrons in air shower cores



Unaccompanied hadron
E_H = 6.6 TeV



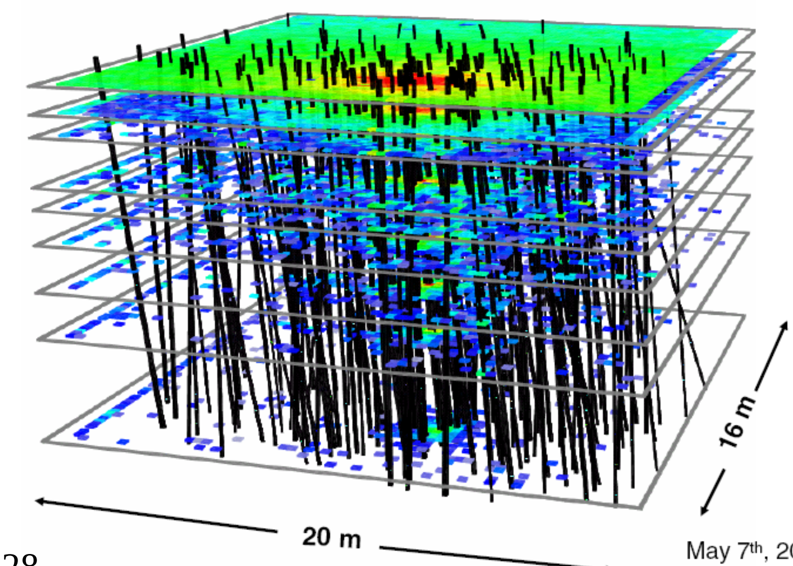
spatial resolution:
$\sigma_x \sim 10 - 12$ cm

angular resolution:
$\sigma_\Theta \sim 1^\circ - 3^\circ$

energy resolution:
$$\frac{\sigma(E)}{E}[\%] \sim \frac{250}{\sqrt{E/\mathrm{GeV}}}$$

$E_0 \sim 6$ PeV

Number of reconstructed hadrons $N_h = 143$



May 7th, 2002 9:45

J. Engler et al., Nucl. Instr. Meth. A 427 (1999) 528

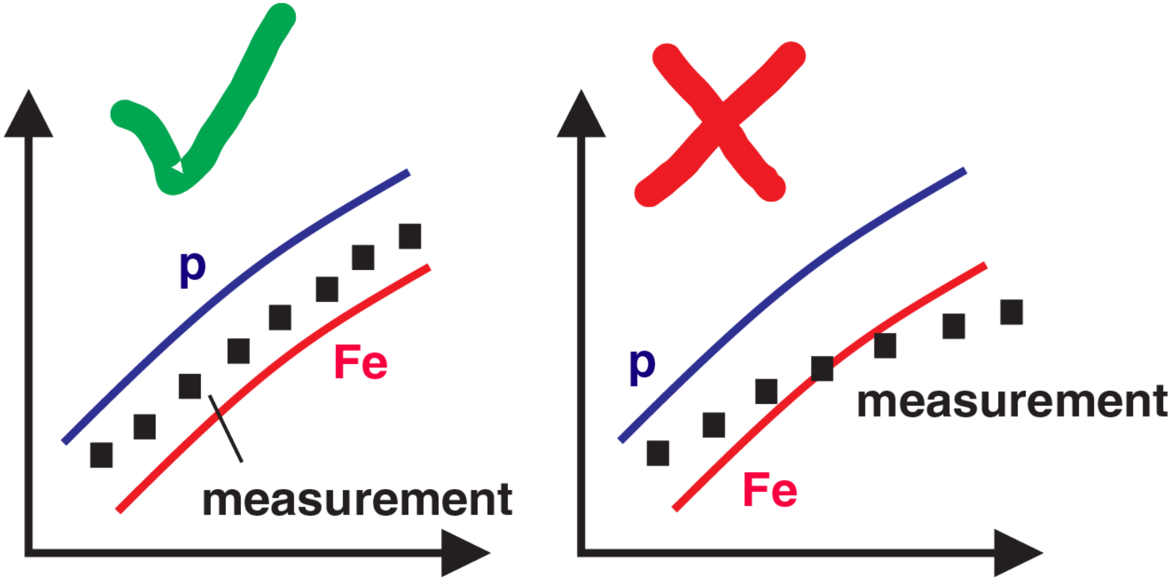
hadrons in air shower cores: test of hadronic interaction models

KASCADE observables per individual EAS:

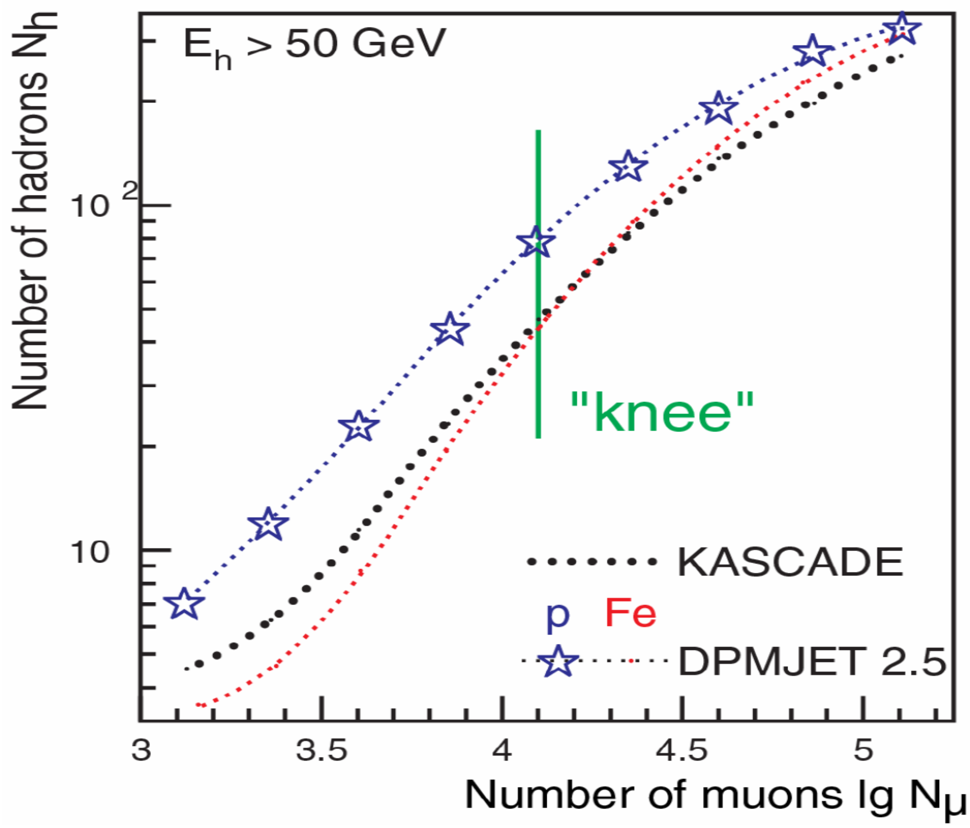
<u>from detector array:</u> **general shower parameters**

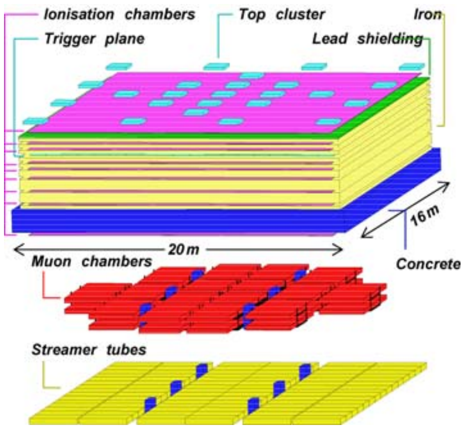
<u>from calorimeter:</u>

- **number of reconstructed hadrons** **(E_h>100GeV)** N_h
- **sum of the reconstructed hadronic energy** ΣE_h
- **energy of the leading hadron** E_h^{max}
- **parameters of the spatial hadron distributions** λ,....



KASCADE data analyses: shower observable correlations





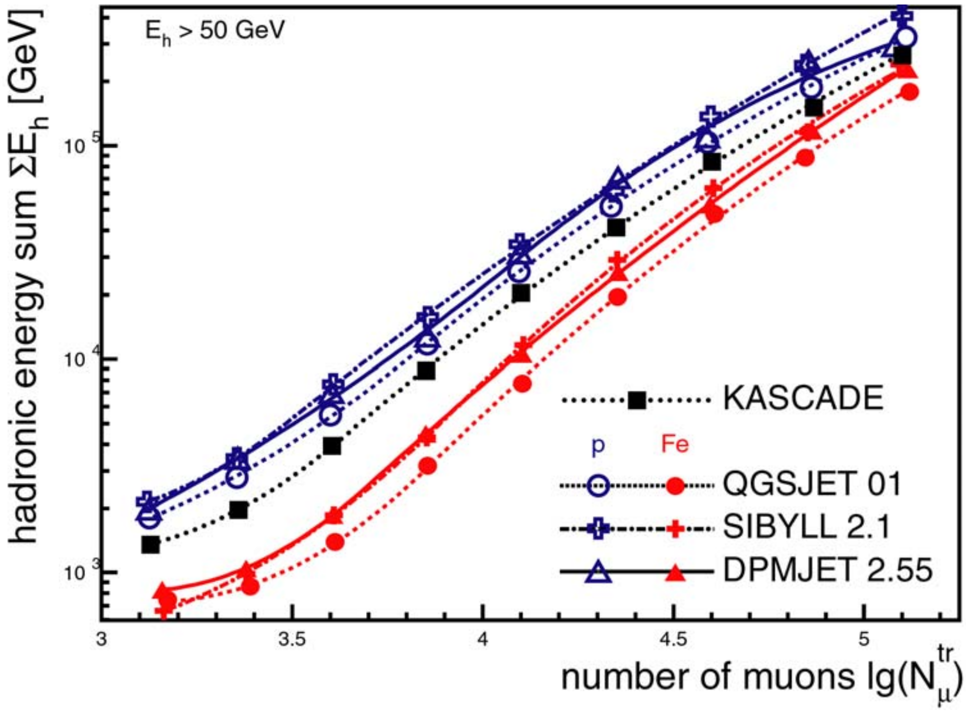
Example: hadrons vs. muons

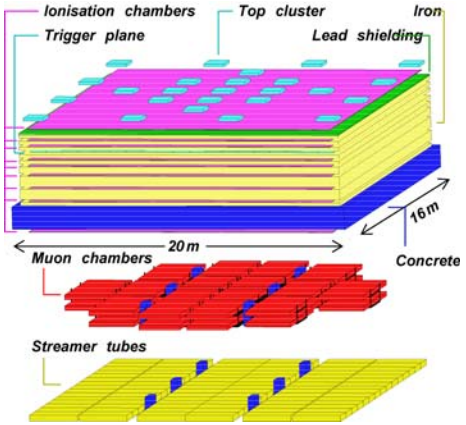
Investigated many correlation of observables of all three particle components

Electromagnetic Muonic Hadronic

By using full simulations (including detector response)

KASCADE data analyses: shower observable correlations



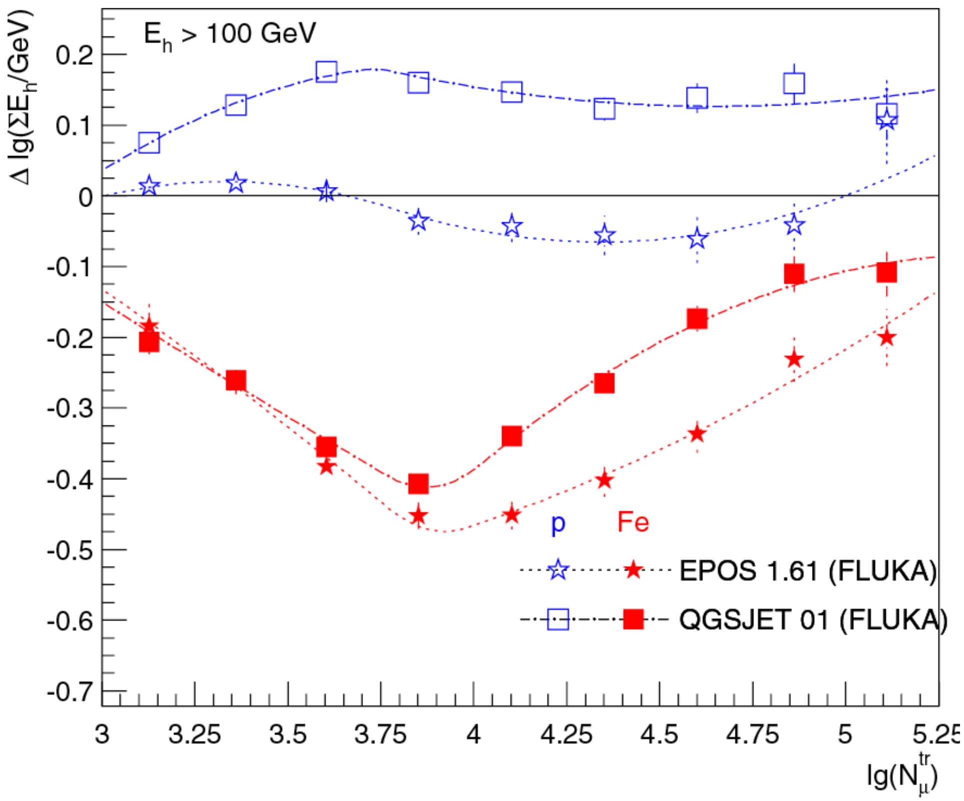


Example: hadrons vs. muons

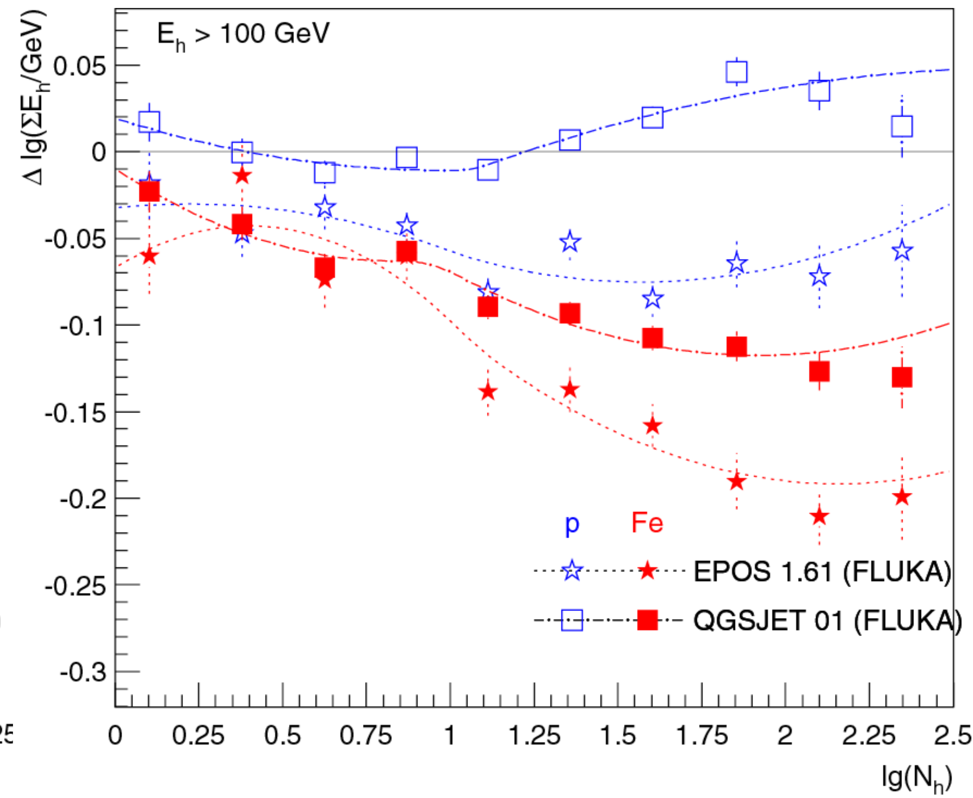
correlation of observables:
<u>no hadronic interaction model describes data consistently !</u>
➔ tests and tuning of hadronic interaction models !
➔ close co-operation with theoreticians
(CORSIKA including QGSJET, SIBYLL, FLUKA, GHEISHA,…..)

KASCADE – Test of EPOS 1.6 with hadrons

$\Sigma E_h - N_\mu$



$\Sigma E_h - N_h$

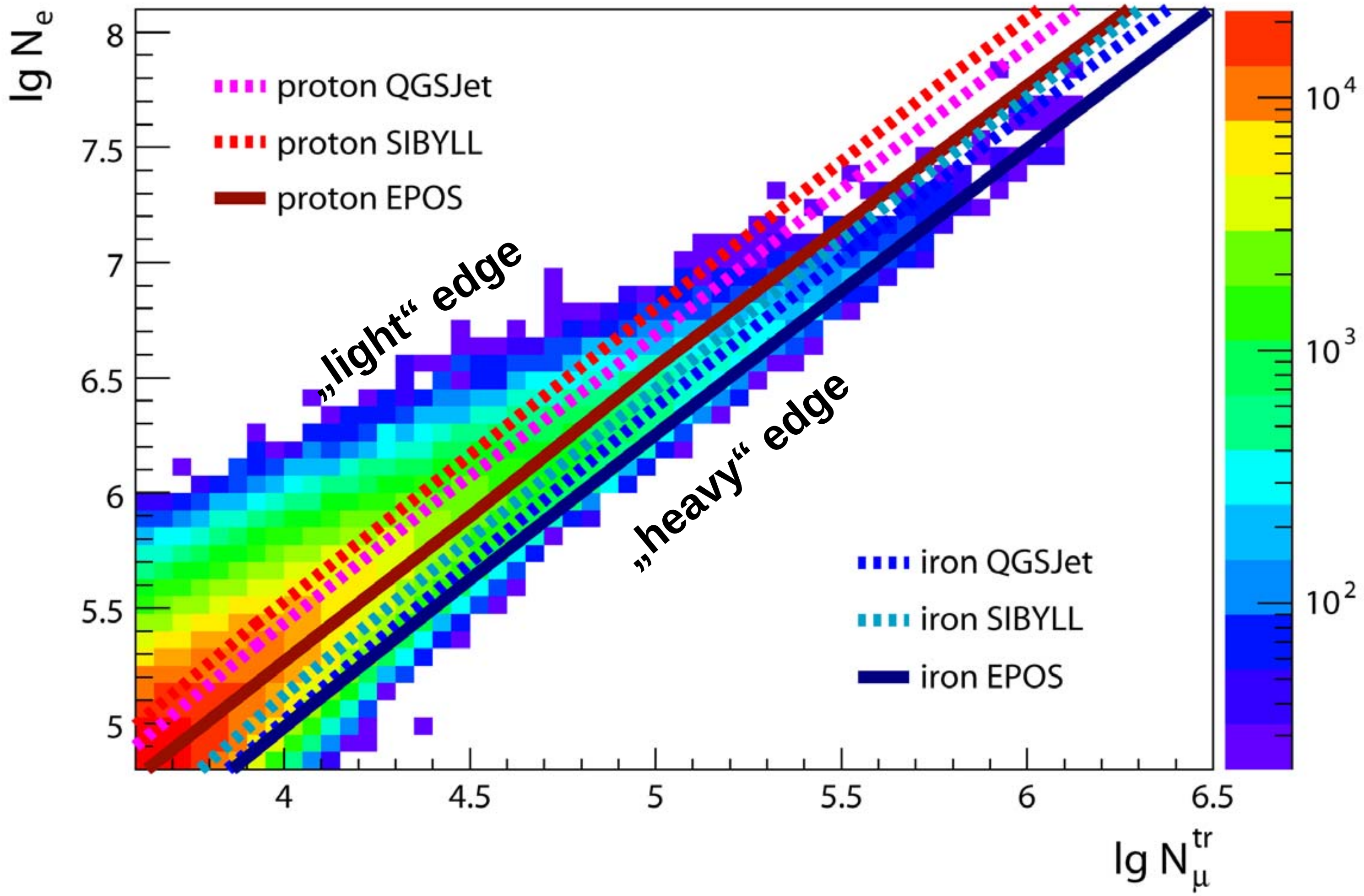


EPOS delivers not enough hadronic energy to the ground

→ energy per hadron too small

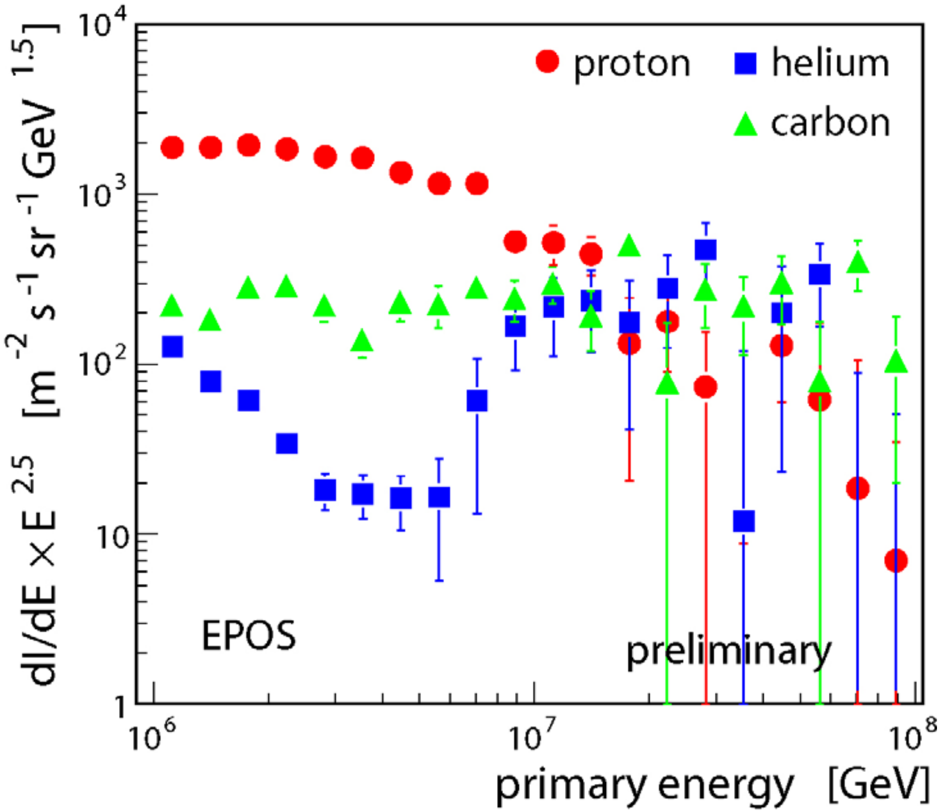
→ EPOS 1.6 is NOT CONSISTENT with KASCADE observations!

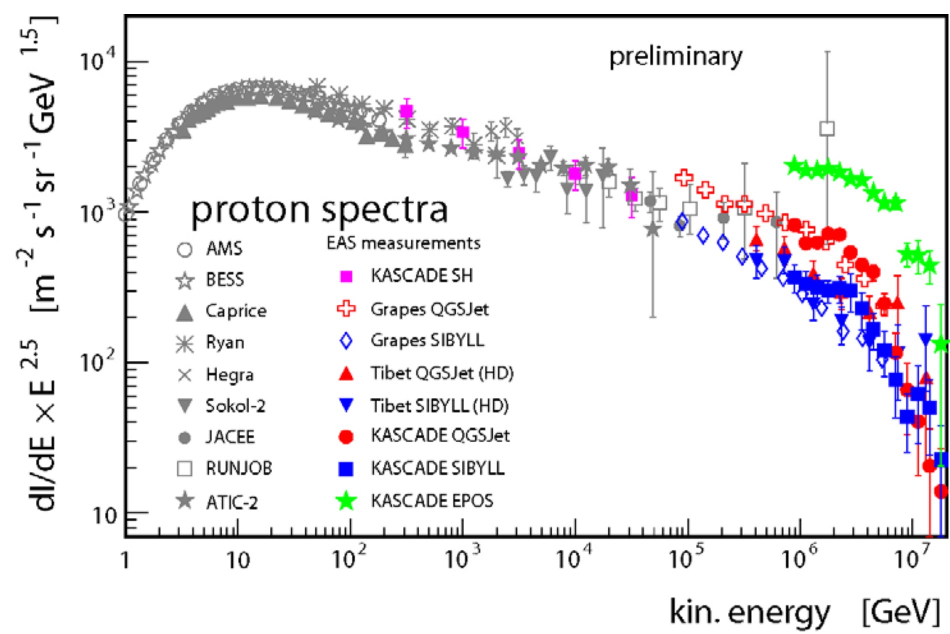
KASCADE : test of new hadronic interaction models EPOS 1.61



KASCADE: new hadronic interaction model: EPOS

- **unfolding based EPOS 1.61 and FLUKA (with CORSIKA 6.6)**





-) very proton dominant, but knee caused by light primaries
-) no iron needed
→EPOS predict too many muons or too less electrons (for KASCADE)

Shower observable correlations: Model tests

QGSJET 98
~~VENUS~~
~~SIBYLL 1.6~~

J. Phys. G: Nucl. Part. Phys. 25 (1999) 2161

DPMJET II.55
QGSJET 01
SIBYLL 2.1
~~NEXUS 2~~

~~DPMJET II.5~~

J. Phys. G: Nucl. Part. Phys. 34 (2007) 2581

~~EPOS 1.6~~
QGSJET II

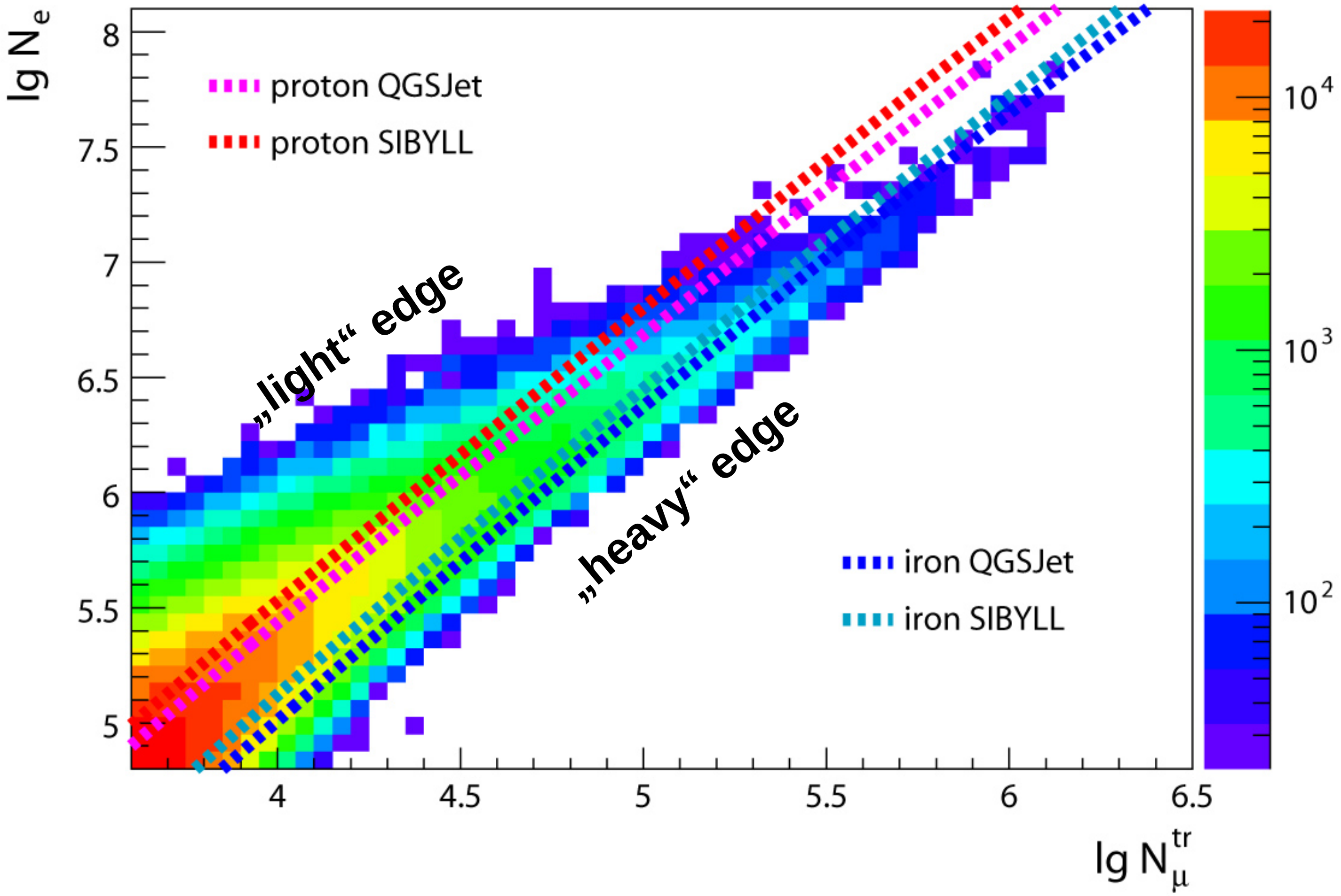
J. Phys. G: Nucl. Part. Phys. (2009) 035201

- •EPOS 1.6 is not compatible with KASCADE measurements
- •QGSJET-II has some deficiencies
- •QGSJET 01and SIBYLL 2.1still most compatible models

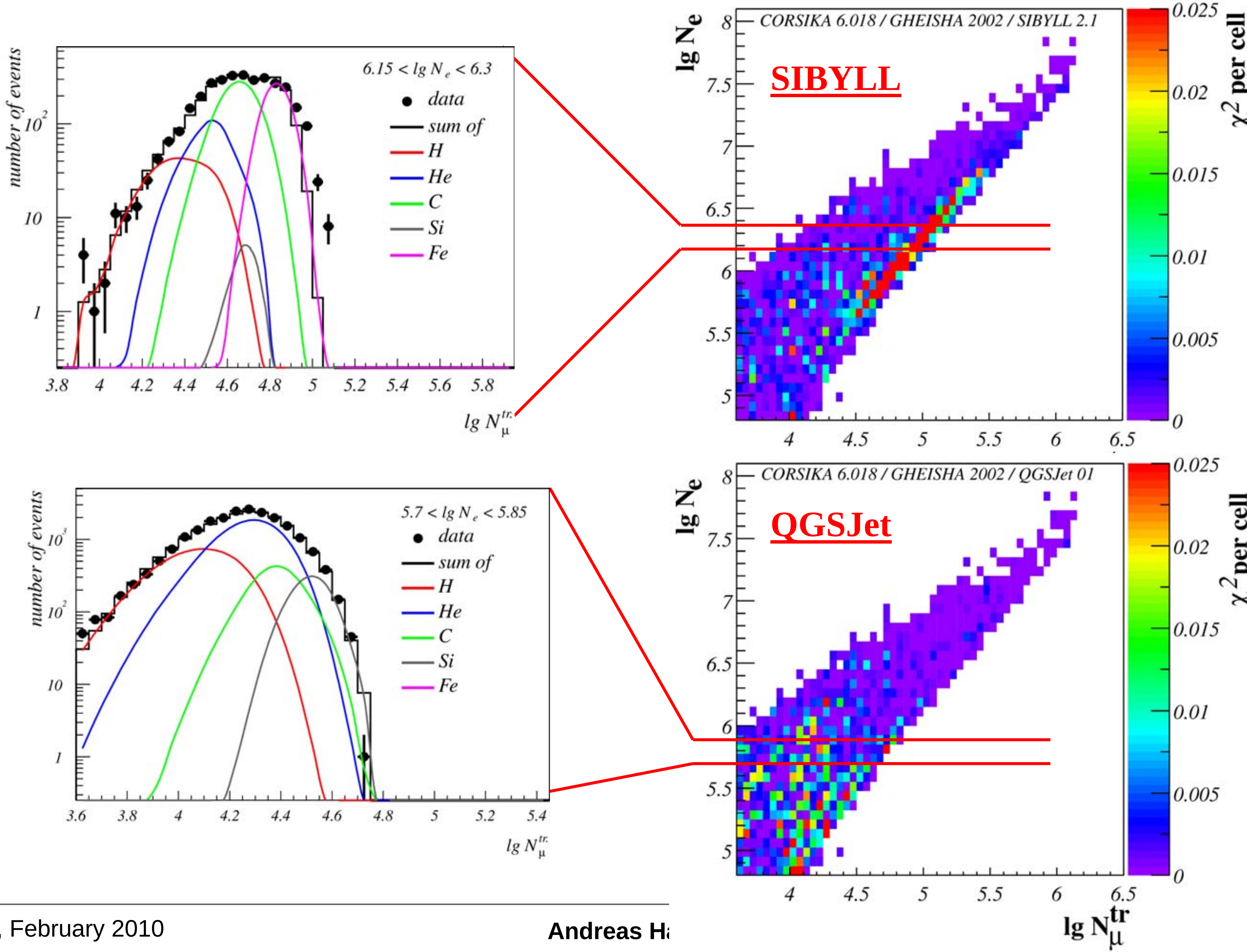
➔ New models are welcome for cross - tests with KASCADE data

Are the models self-consistent?

KASCADE : unfolding + hadron information



KASCADE: sensitivity to hadronic interaction models

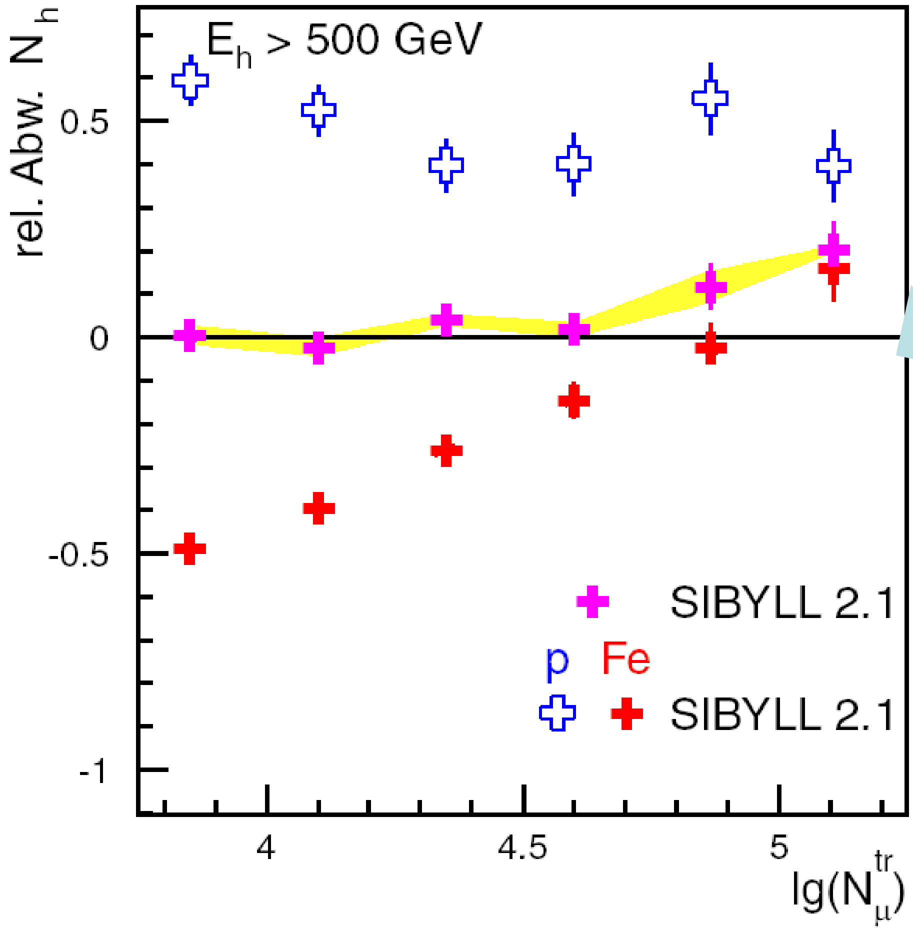


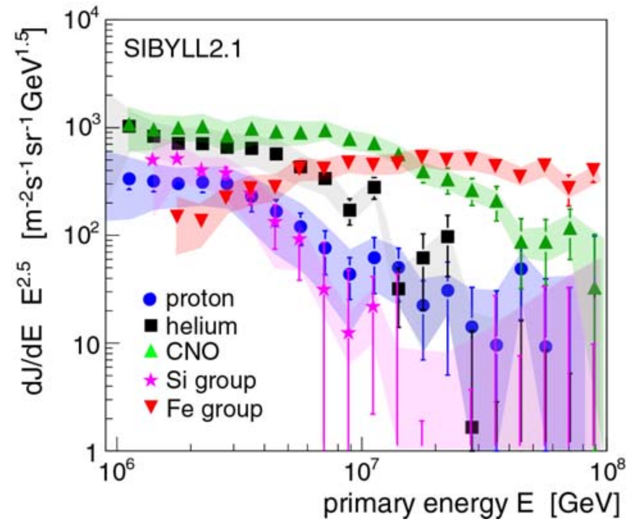
Shower observable correlations: Model tests with composition

SIBYLL 2.1

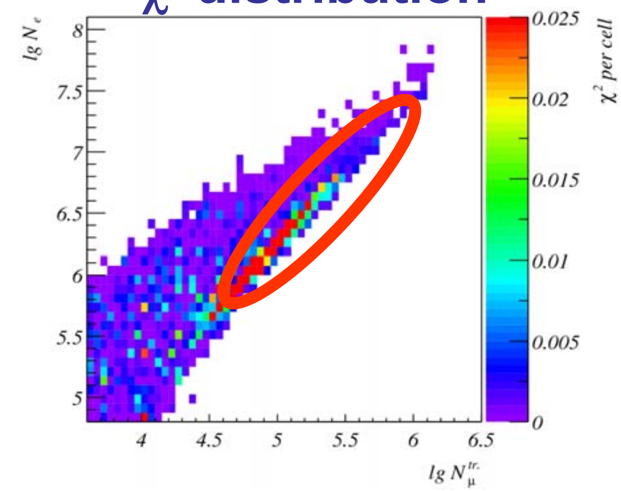
N_e-N_μ analysis

Number of hadrons vs. number of muons





χ^2 distribution

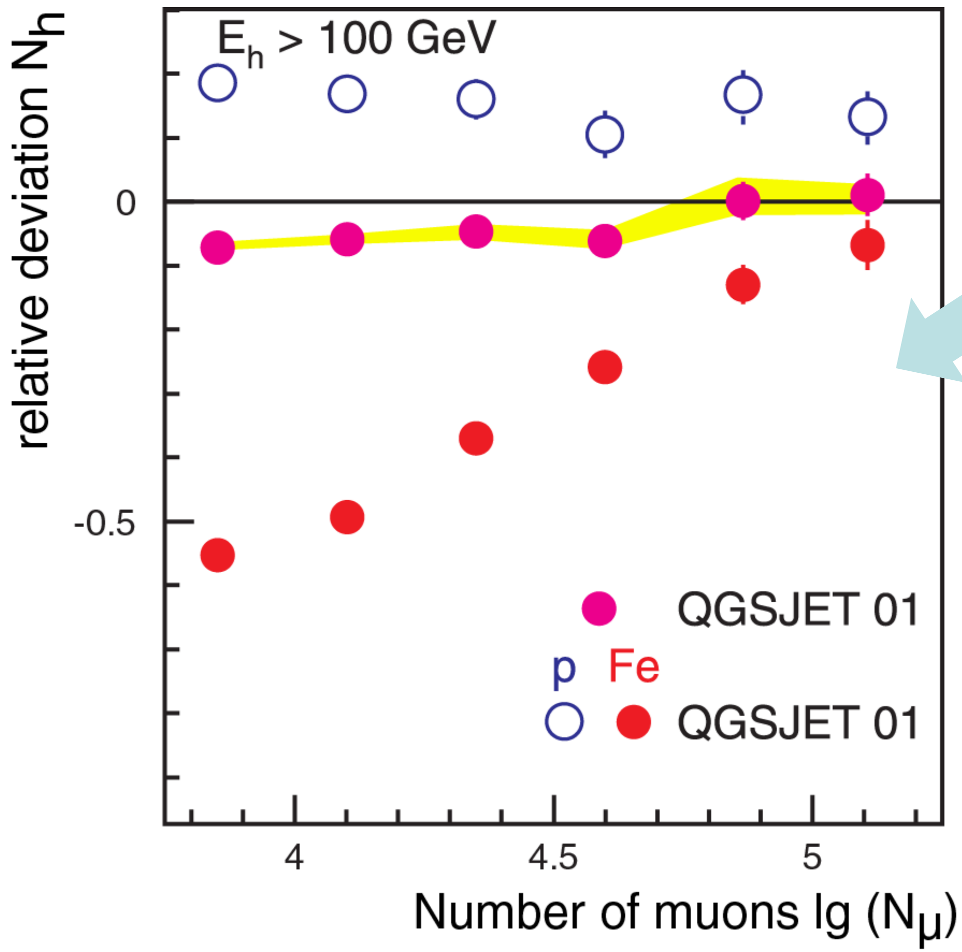


Inconsistencies at the level of 10% to 20%

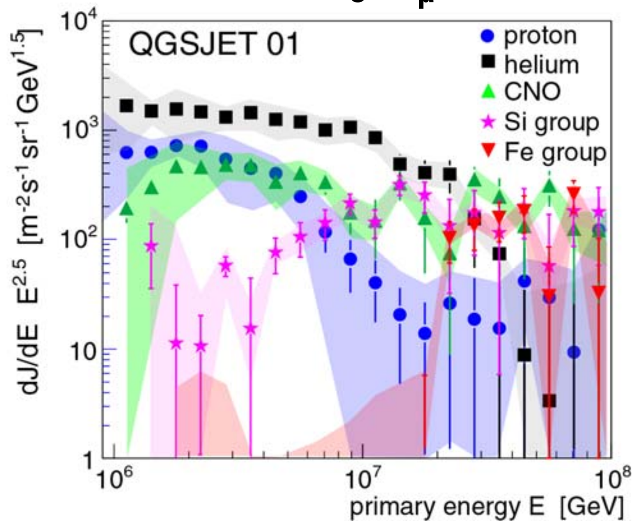
Shower observable correlations: Model tests with composition

QGSJET 01

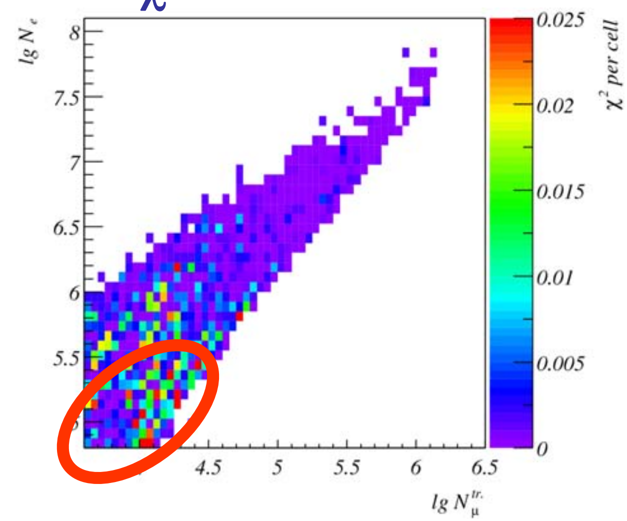
Number of hadrons vs. number of muons



N_e-N_μ analysis



χ^2 distribution

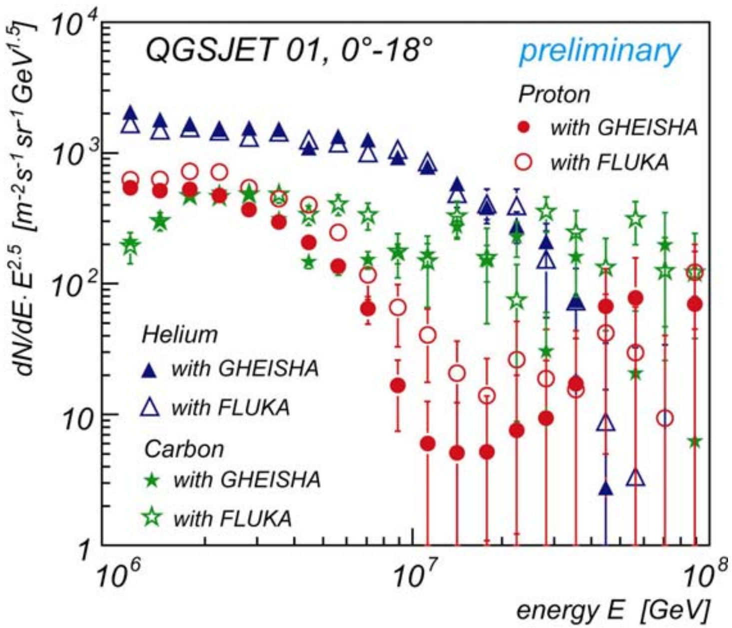


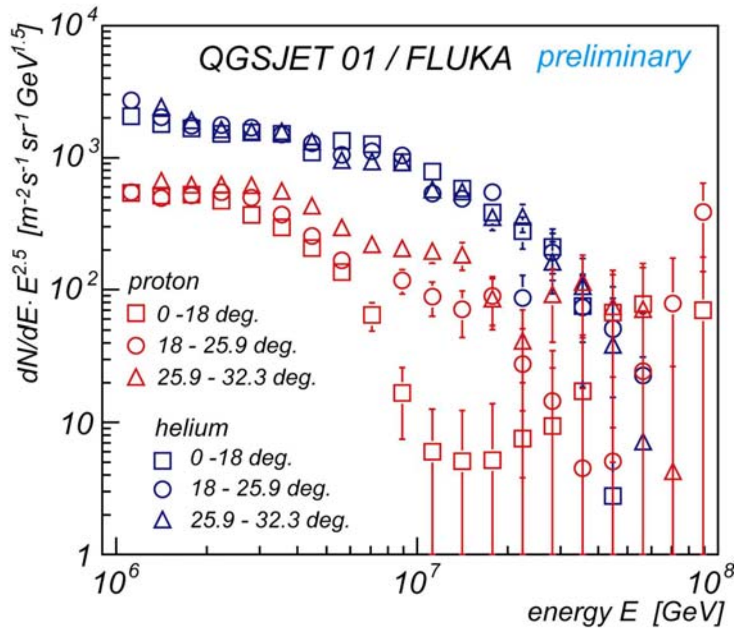
Low energy interaction models?

FLUKA

KASCADE results: confirmation

- same unfolding but based on two different low energy interaction models and different zenith angle ranges:
- GHEISHA 2002 and FLUKA (both with QGSJET01)
- 0-18°, 18-25.9°, 25.9-32.3° (all with QGSJET01/FLUKA)

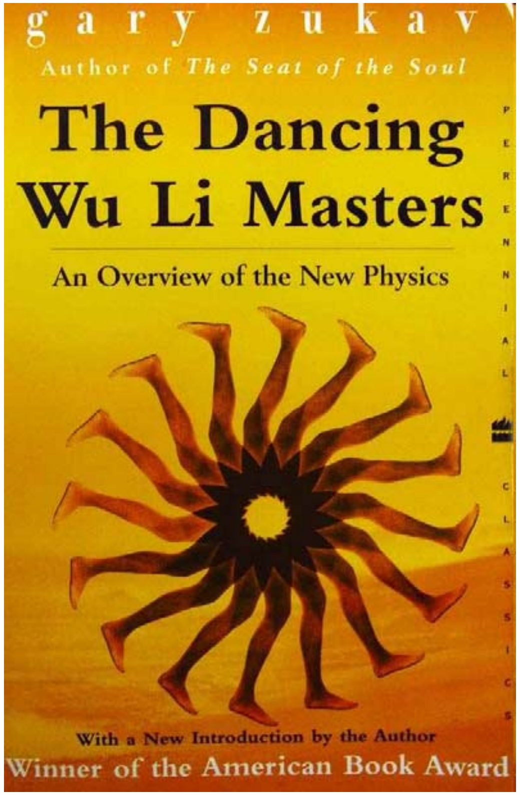




- Less dependence for unfolding based on different low energy hadronic interaction models
- Weak dependence on zenith angular binning (not significant)

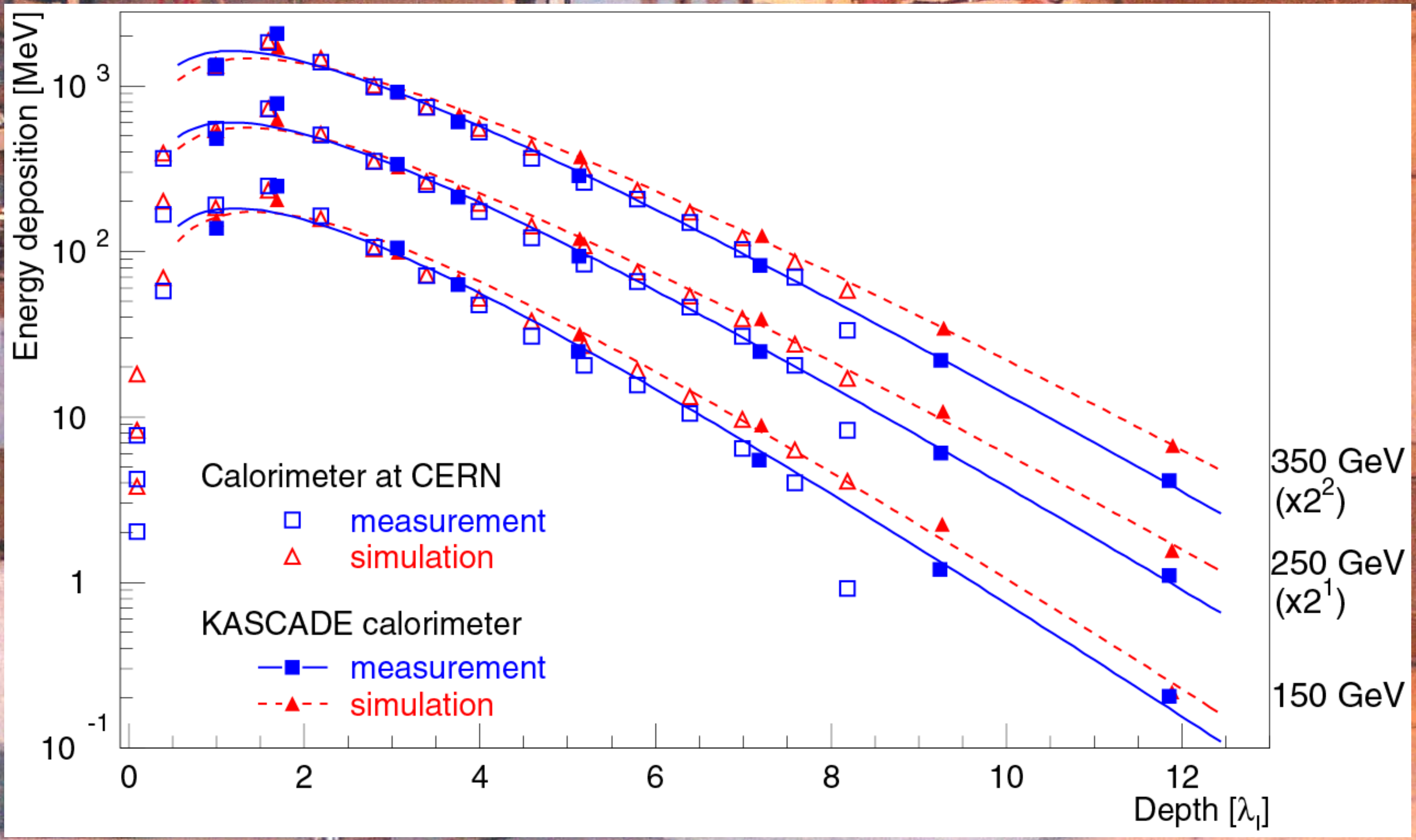
KASCADE collaboration, Astroparticle Physics (2009)

New physics?


gary zukav
Author of The Seat of the Soul
The Dancing Wu Li Masters
An Overview of the New Physics
With a New Introduction by the Author
Winner of the American Book Award
PERENNIAL CLASSICS

Calibration of the KASCADE hadron calorimeter at the CERN SPS

with hadrons up to 350 GeV



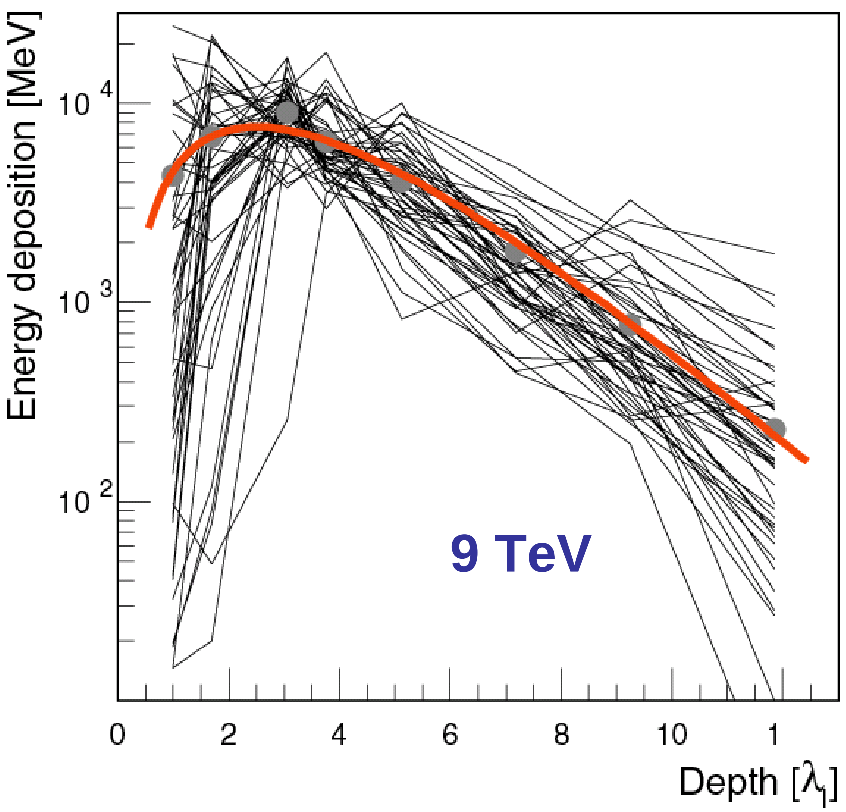
S. Plewnia et al., Nucl. Instr. & Meth. A 566 (2006) 422

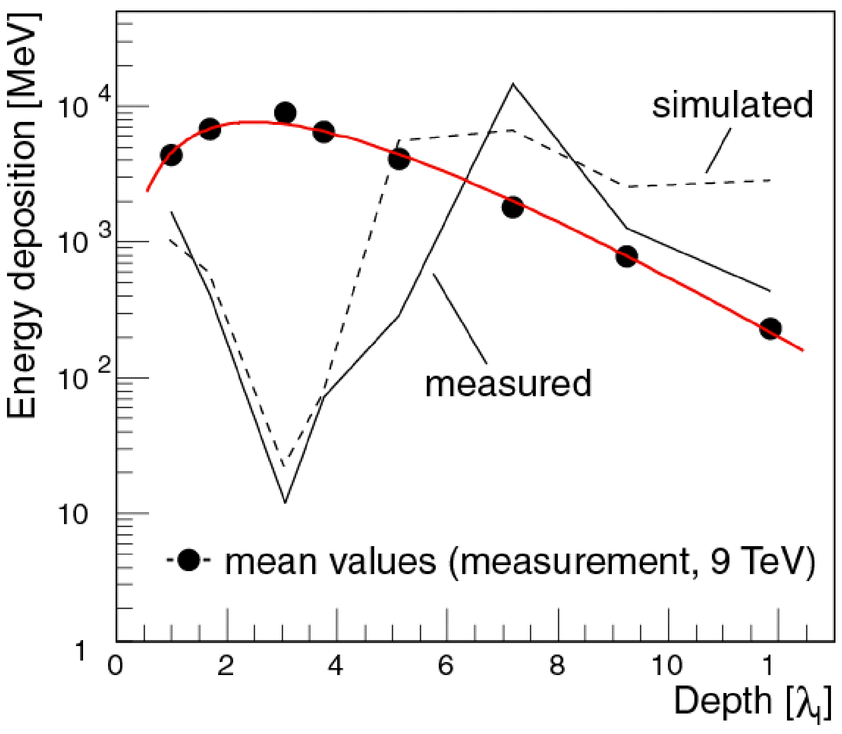
S. Plewnia et al., 29th ICRC, Pune 6 (2005) 17

Unusual events?

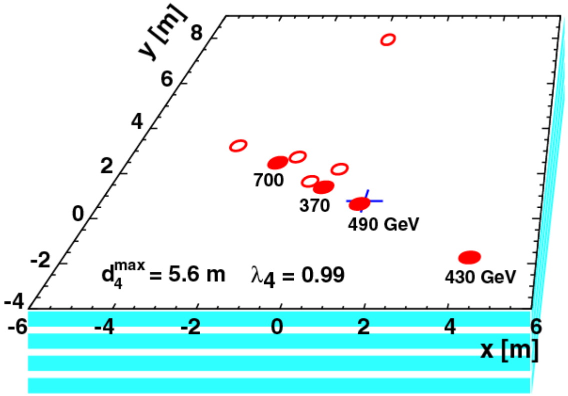
Hadrons measured in the calorimeter at an accelerator and in air showers

Fluctuations in shower development,
unusual events, long-flying component
🡐 In agreement with simulations

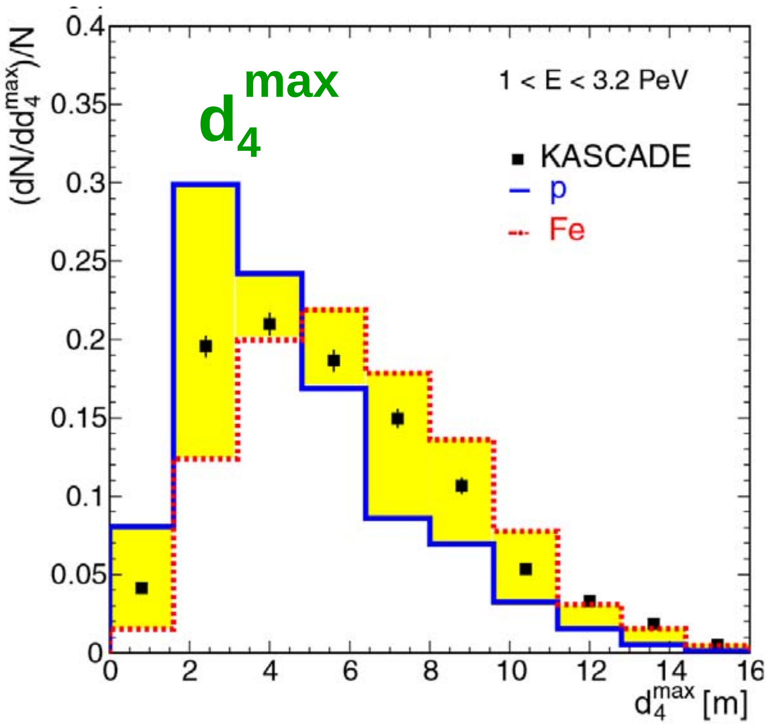


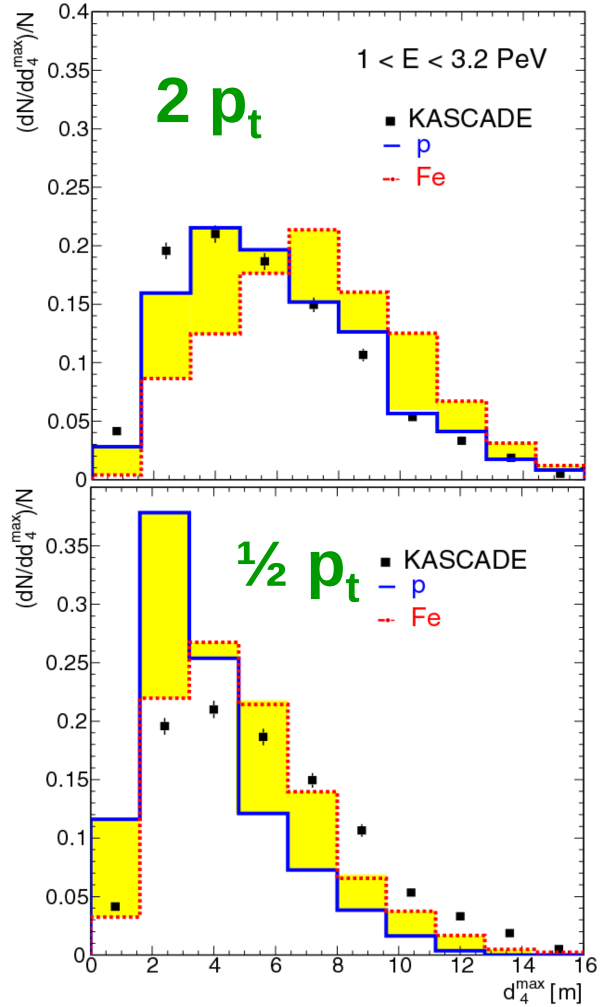


Spatial distribution: test of transverse momentum p_t in hadronic interaction



T. Antoni et al.,
Phys. Rev. D 71 (2005) 072002





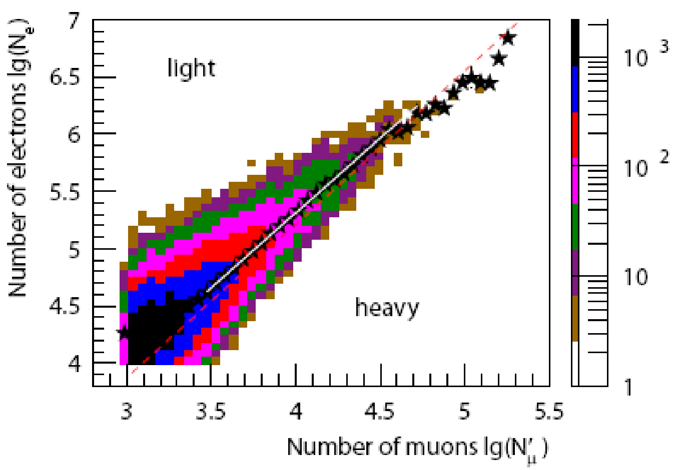
CORSIKA/QGSJET 01

Hadron Attenuation Length

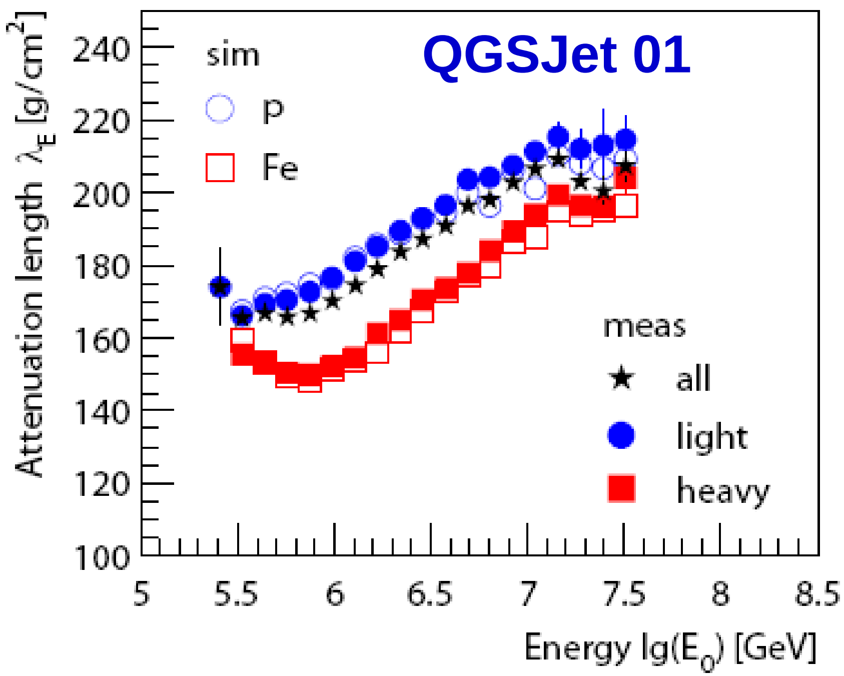
Method: measure hadronic energy sum at sea-level:

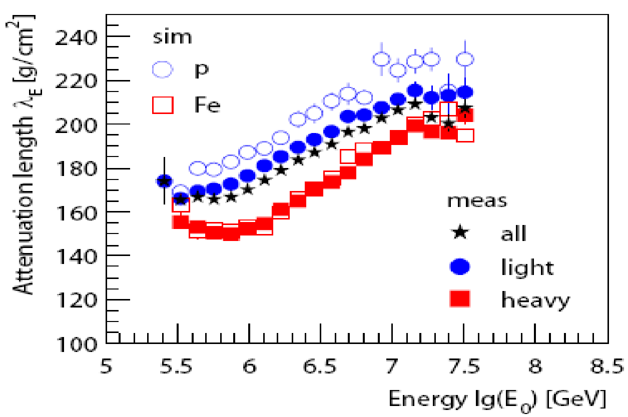
$$\Sigma E_H = E_0 \exp\left(-\frac{X_0}{\lambda_E}\right)$$

Divide data sample in light and heavy generated showers



Compare with simulations



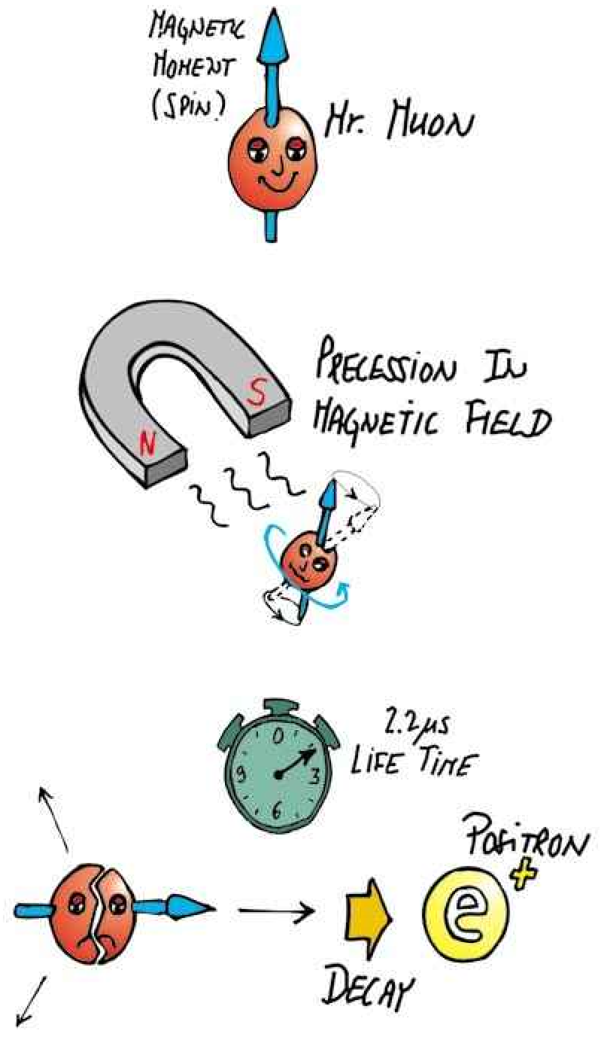


modified QGSJet 01: P-air cross-section: -5% Elasticity: +10%

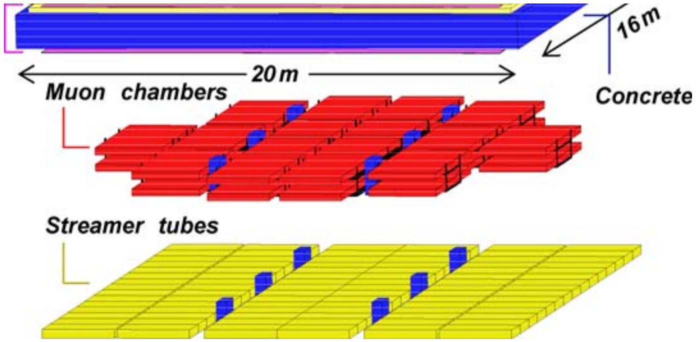
➔ Hint for model builders??

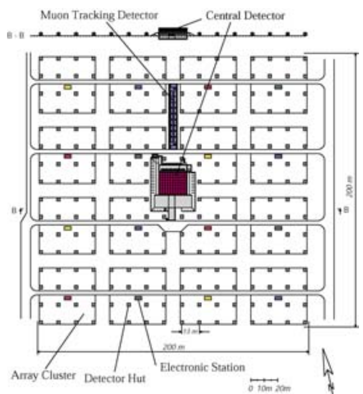
KASCADE coll, submitted to PRD

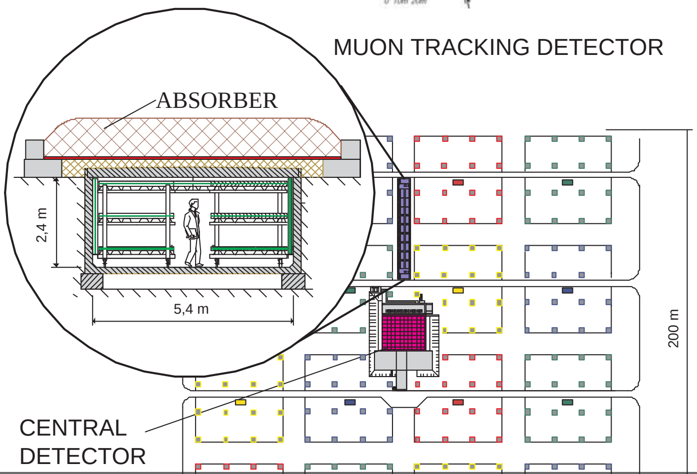
Muons as model tester!



HE Muon Measurements at KASCADE







- **Central Detector muon facility**

  E_μ^{thresh} = 2400 MeV

  ➔ **Muon Density measurements** $\rho_\mu^{2.4GeV}$
  ➔ **Lateral distributions**
  ➔ **Model tests (muon energy spectrum)**

  $$R_\rho^{2.4/0.23} = \rho_\mu^{2.4GeV} / \rho_\mu^{0.23GeV}$$

- **Muon Tracking Detector**

  E_μ^{thresh} = 800 MeV

  ➔ **Measurement of radial and tangential angles** ρ_μ, τ_μ
  ➔ **Muon production height**
  ➔ **Lateral distributions**
  ➔ **Model tests** (pseudorapidity)

  $$\eta_\mu = -\ln(\zeta/2) \quad \zeta = p_t/p_{||} = \mathrm{sqrt}(\rho^2 + \tau^2)$$

Muon Energy Spectrum

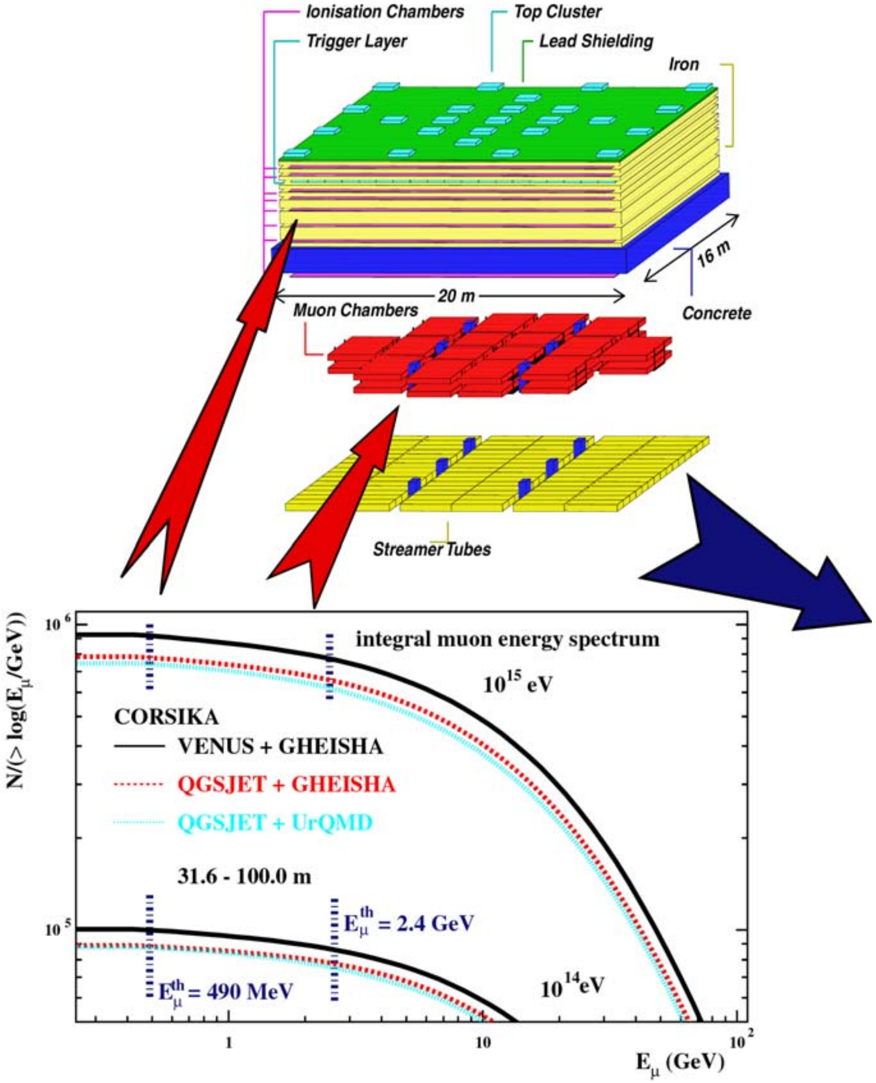
Muon density measurements

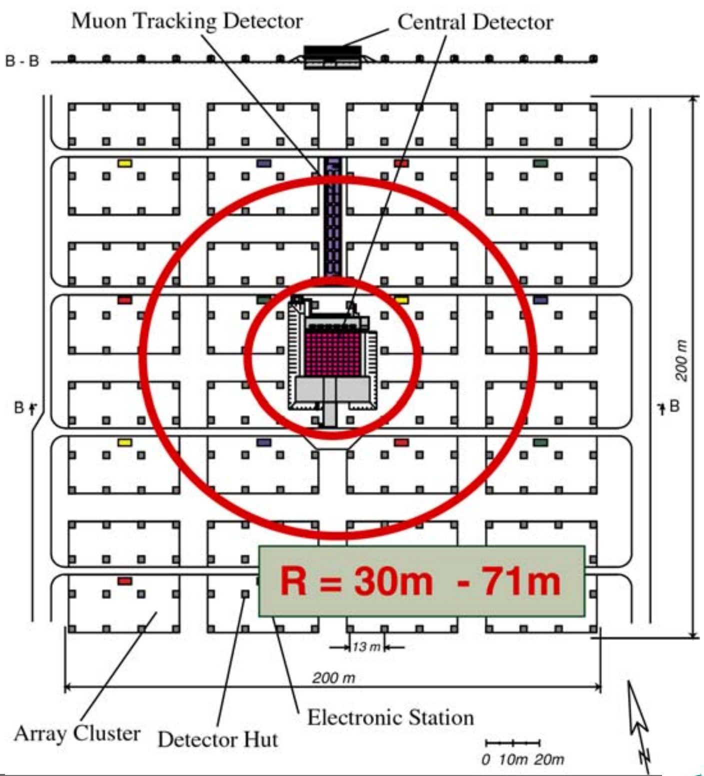
model sensitive parameter:

$$R_\rho = \frac{\rho_\mu^\star}{\rho_\mu^{tp}}$$

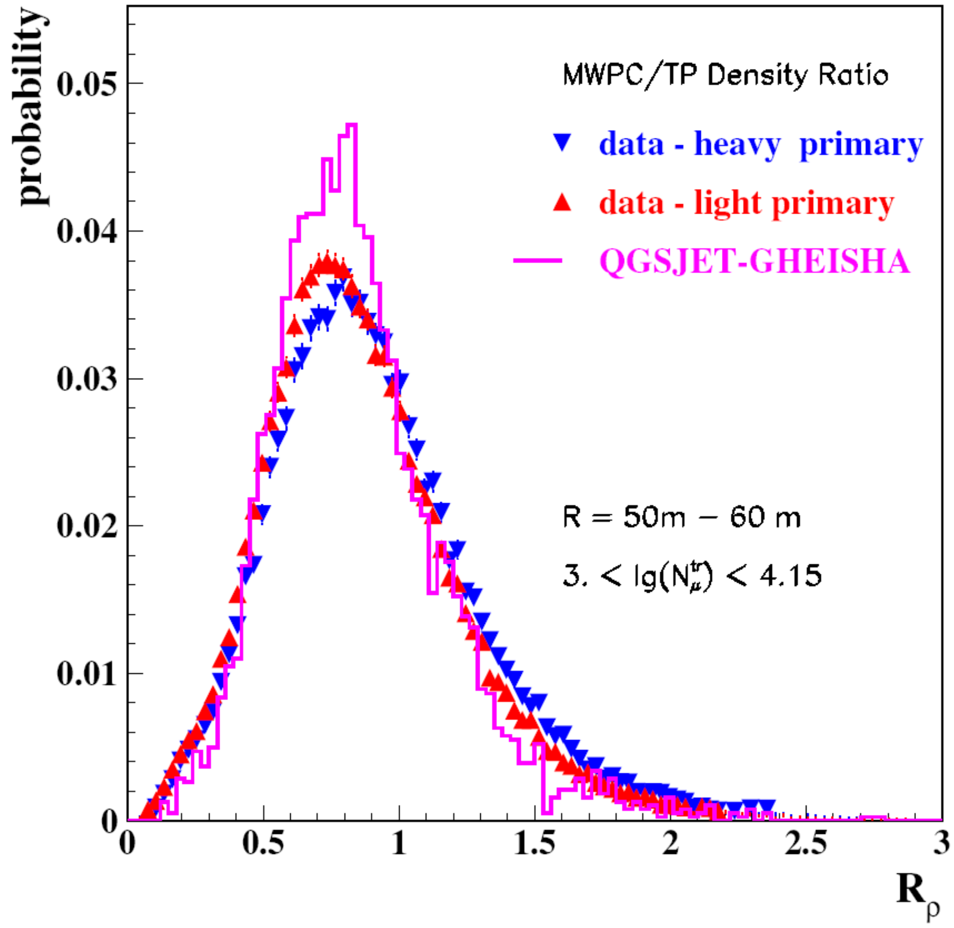
at MWPC $\rho_\mu^\star$ $(E_\mu^{th} = 2.4\ \text{GeV})$

at TP ρ_μ^{tp} $(E_\mu^{th} = 490\ \text{MeV})$





Muon Energy Spectrum

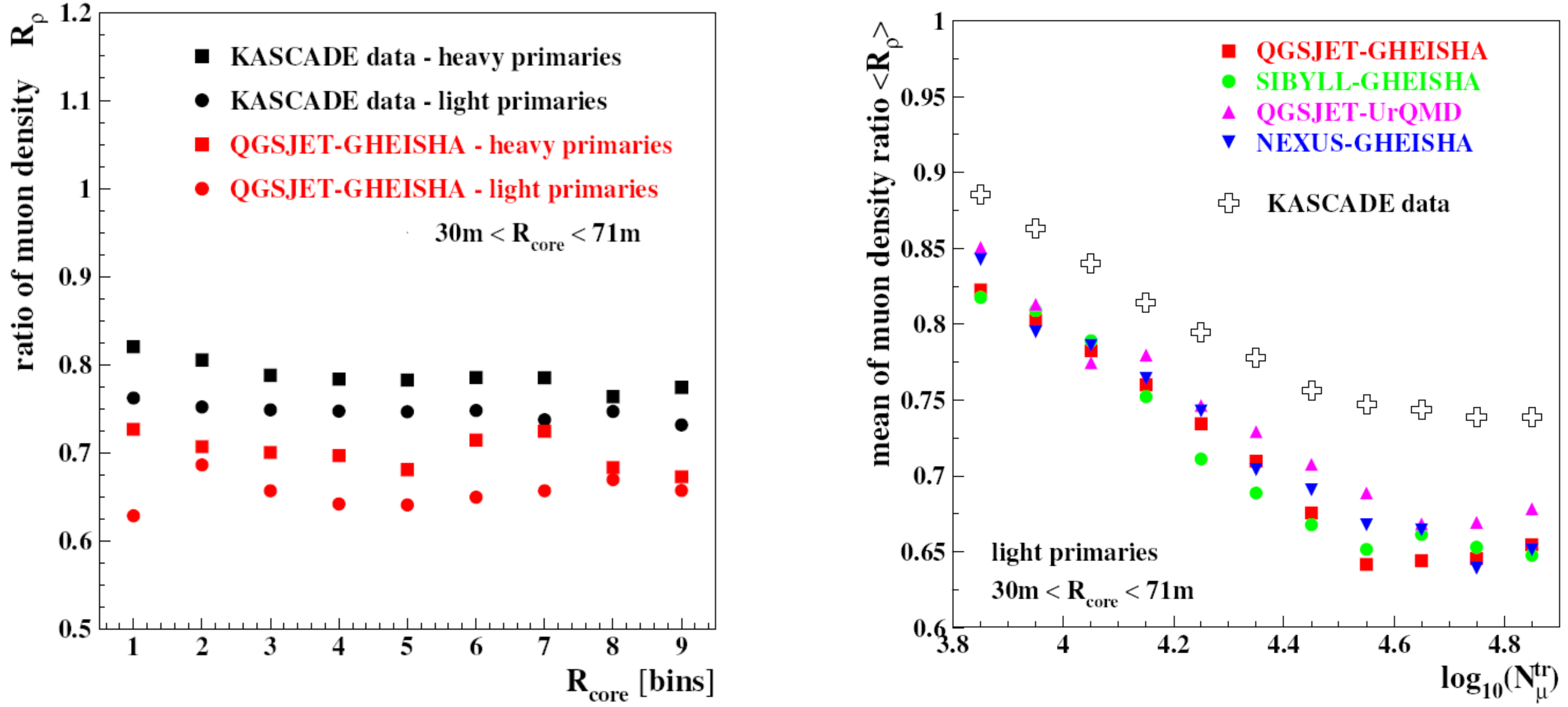


distribution of the muon density ratio for a certain range in distance and total EAS muon number.

investigated observables:
mean and rms of
R_ρ vs. primary energy
R_ρ vs. core distance

A.Haungs for KASCADE-Grande,
28th ICRC Tsukuba Japan (2003)

Muon Energy Spectrum



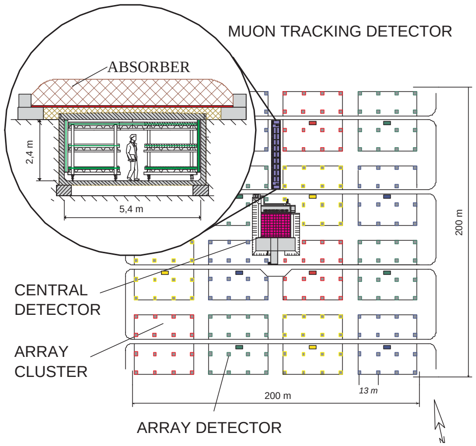
Results:

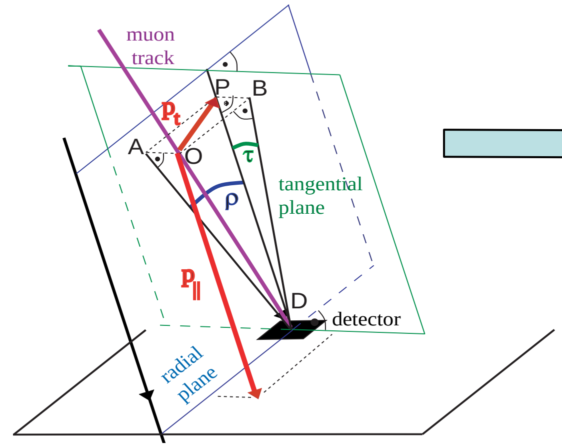
-) inconcistencies for all investigated model combinations

-) problem with the muon energy spectrum predicted by the models?

A.Haungs for KASCADE-Grande, 28th ICRC Tsukuba Japan (2003)

Muon pseudorapidity!

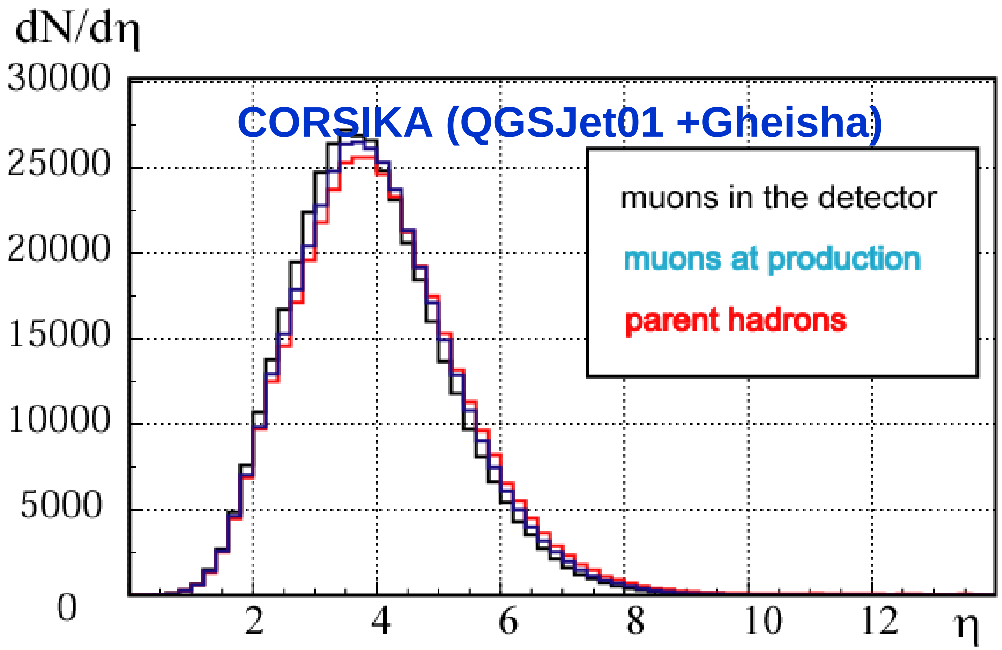




$$\zeta = \sqrt{\tau^2 + \rho^2} = \frac{p_t}{p_\parallel}$$

$$\eta = \ln \frac{2 \times p_\parallel}{p_t} = -\ln \frac{\zeta}{2}$$

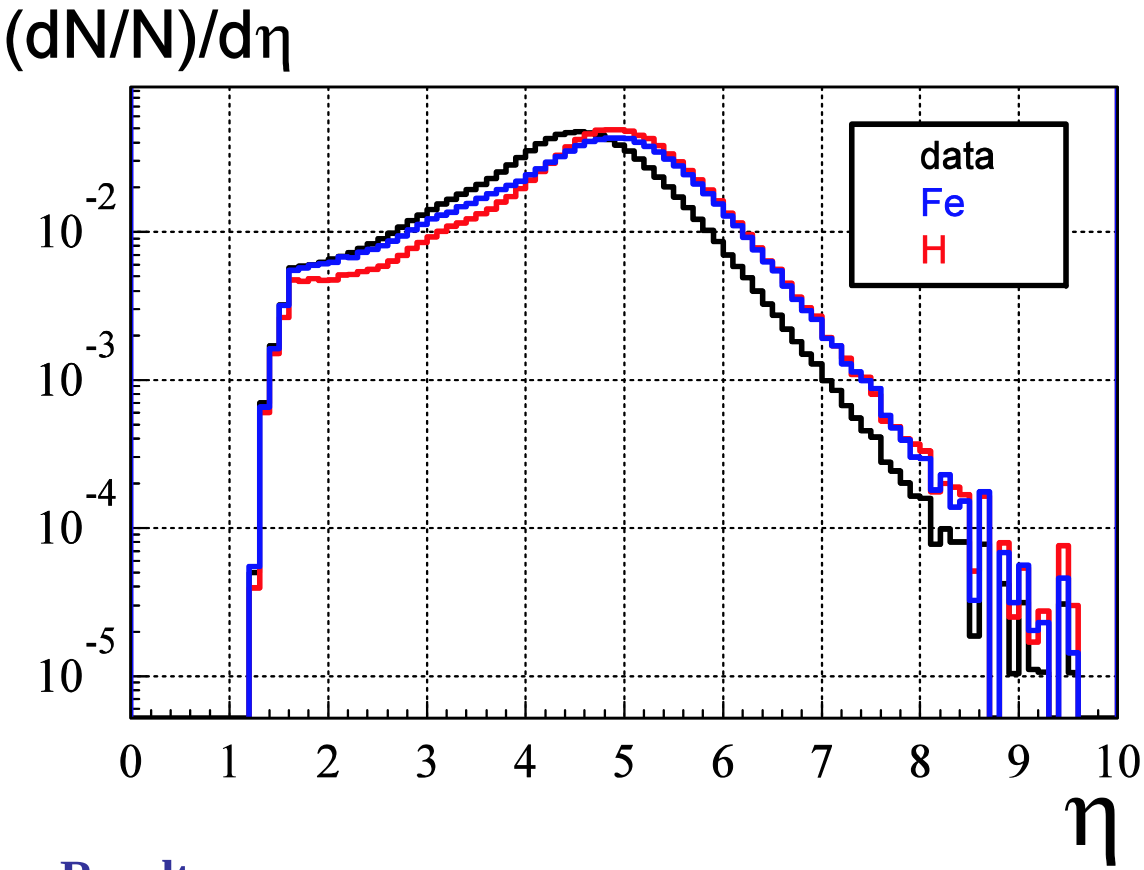
pseudorapidity



Pseudorapidity of muons is correlated with η of parent hadrons ➔ sensitivity to hadronic interaction models

J. Zabierowski for KASCADE-Grande, ISVHECRI 2008

Muon pseudorapidity!



CORSIKA + QGSJet01 + FLUKA 2002 + full detector Monte Carlo simulations

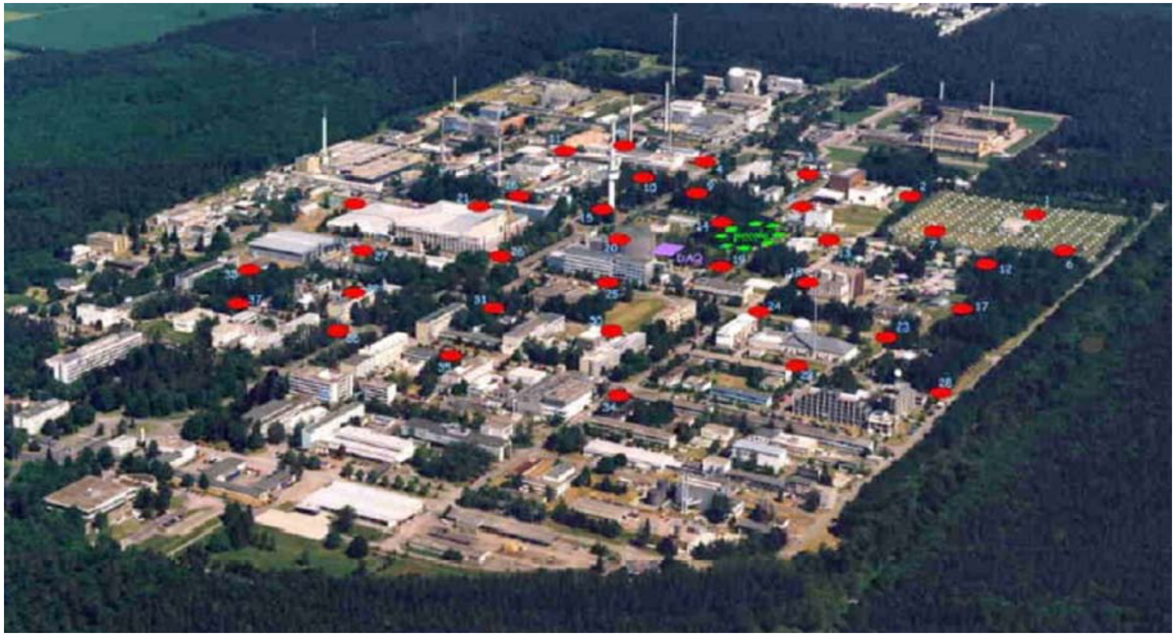
Results:

-) data shifted to the left? → model effect? systematics in measurements

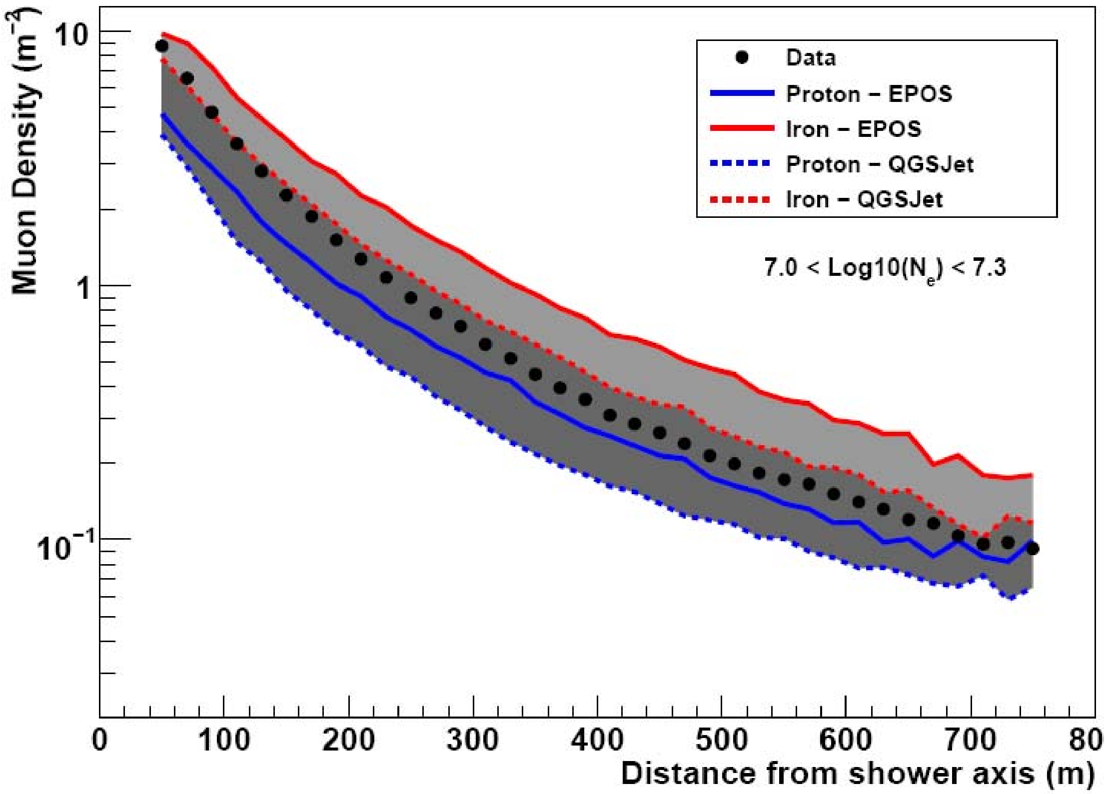
-) go a step further: muon momentum:

$$p = p_t \cdot \sqrt{1 + \frac{1}{\zeta^2}}$$

KASCADE-Grande



muon density investigations



- muon (local) density reconstruction possible for different distances

➔ composition sensitivity

➔ model tests

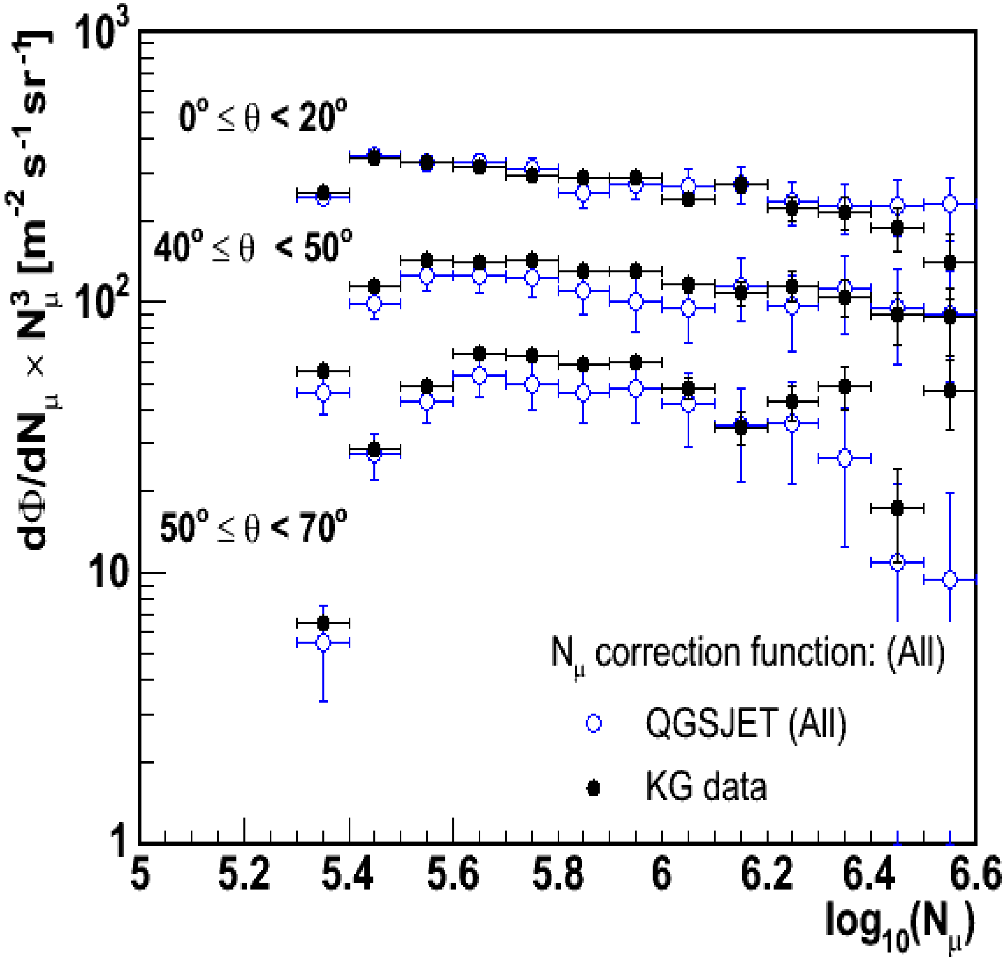
Vitor de Souza

Muon spectra

KG data vs MC

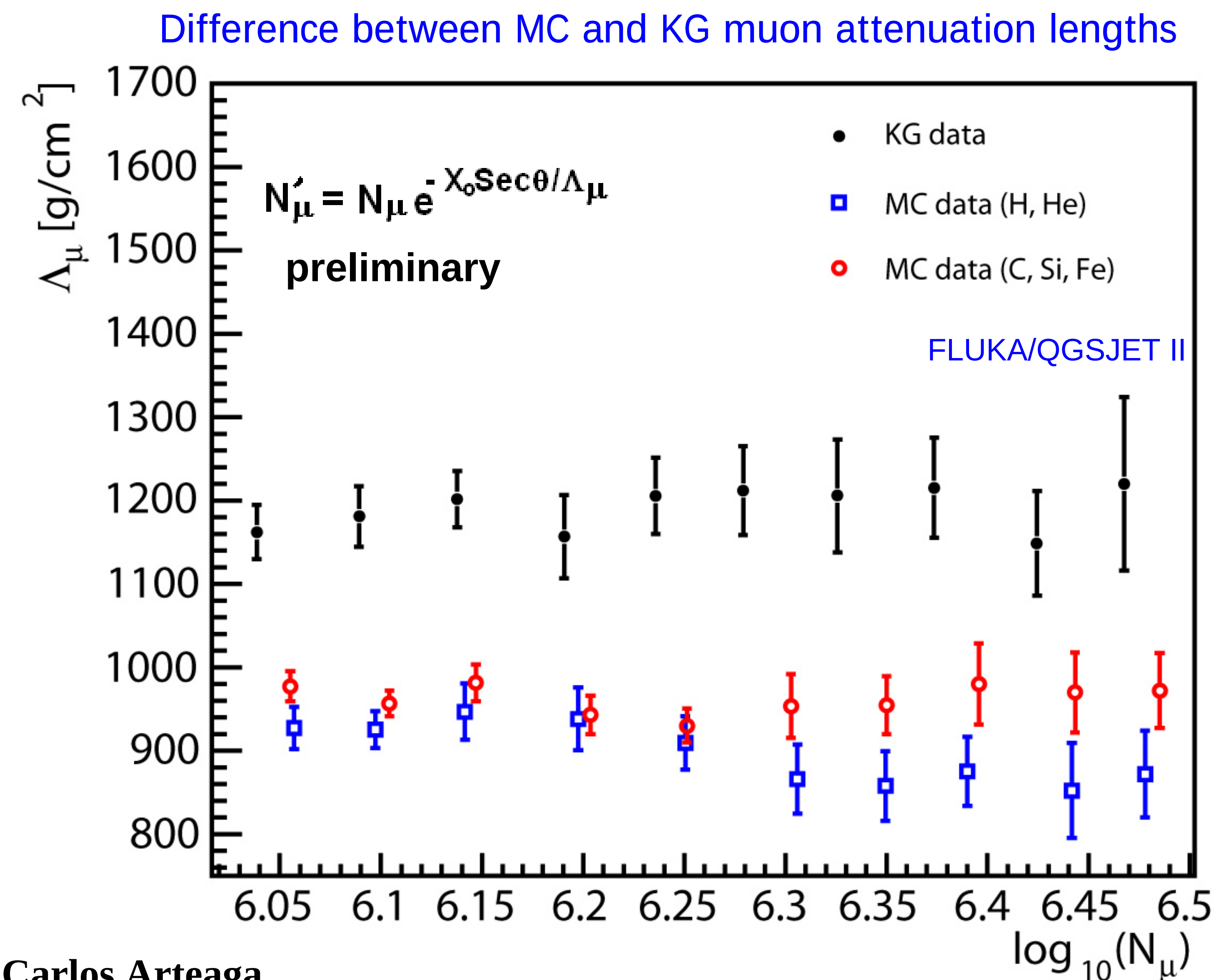
Discrepancy between MC (QGSJET II) and KG data increases with zenith angle.

Discrepancy also found when using EPOS



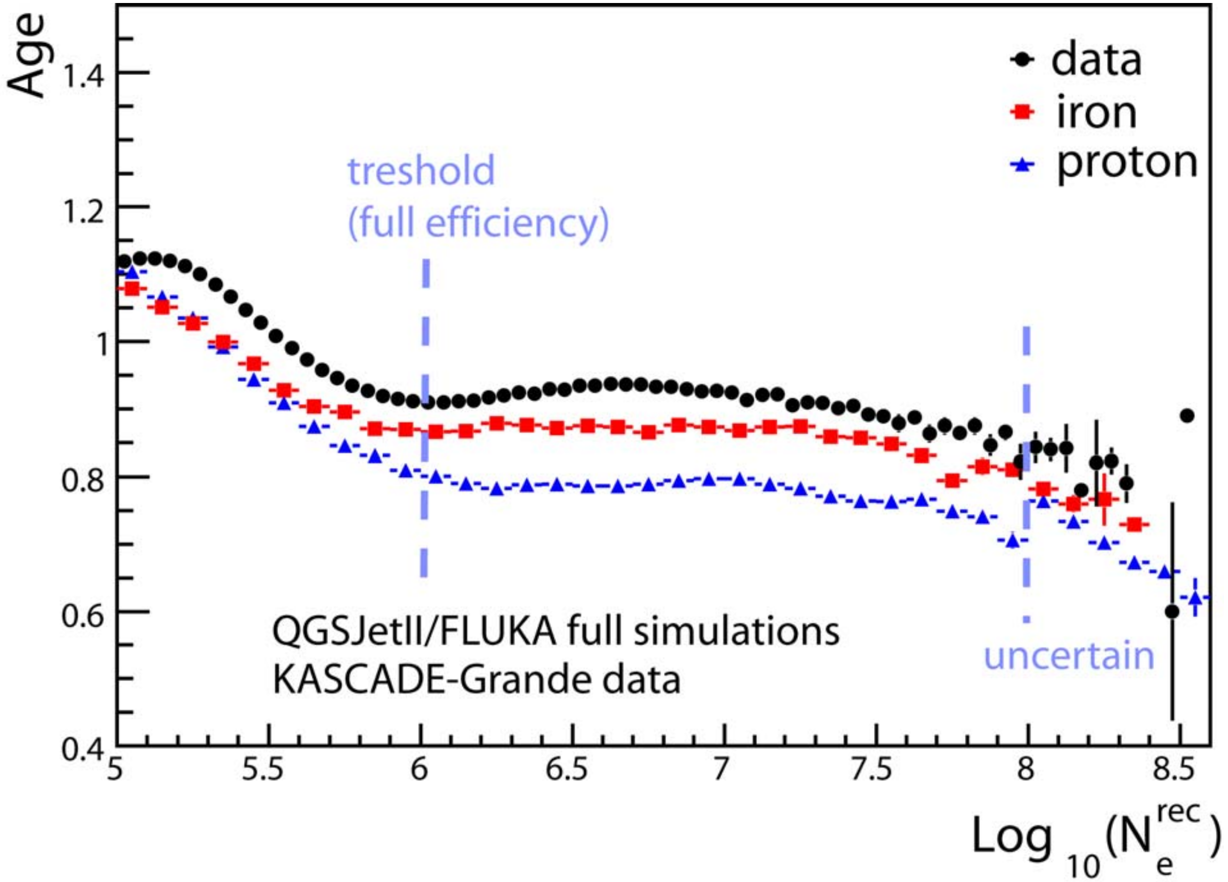
Juan Carlos Arteaga

Muon attenuation length



Juan Carlos Arteaga

electron number – age correlation
➔ composition sensitivity ?



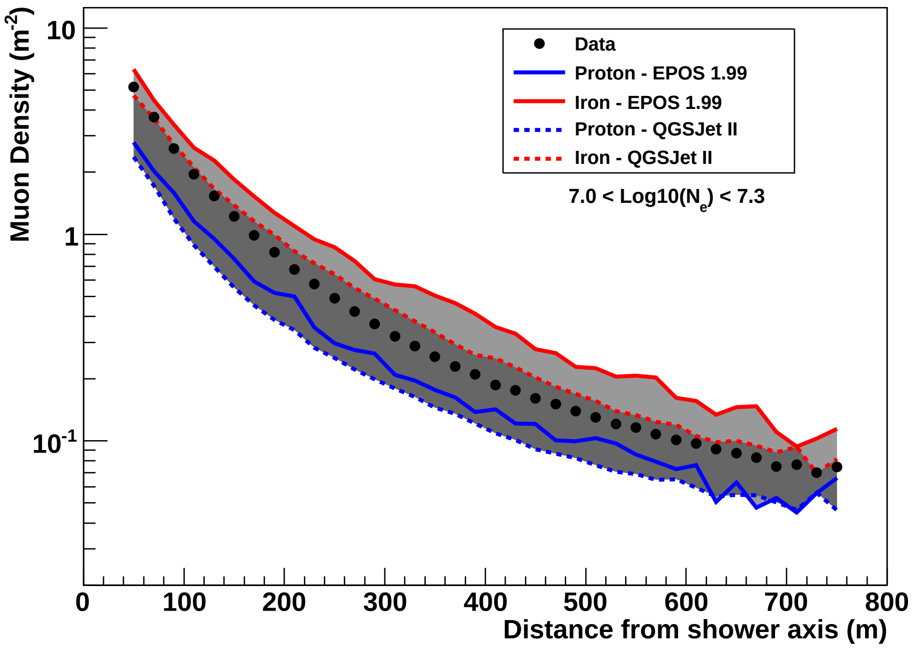
-Shape of distribution seems okay

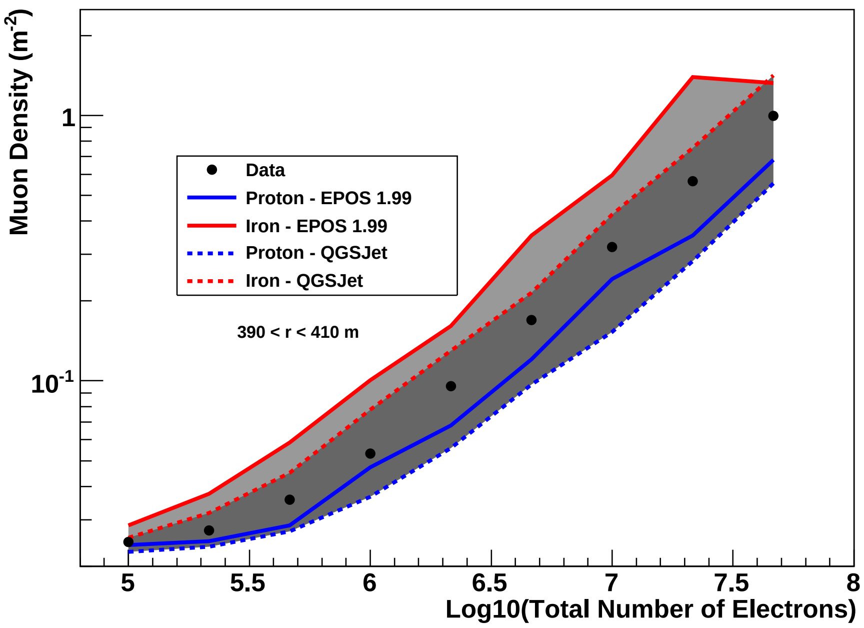
-Shift by ~0.05 in age (already seen in KASCADE)!!

Fabiana Cossavella

EPOS 1.99

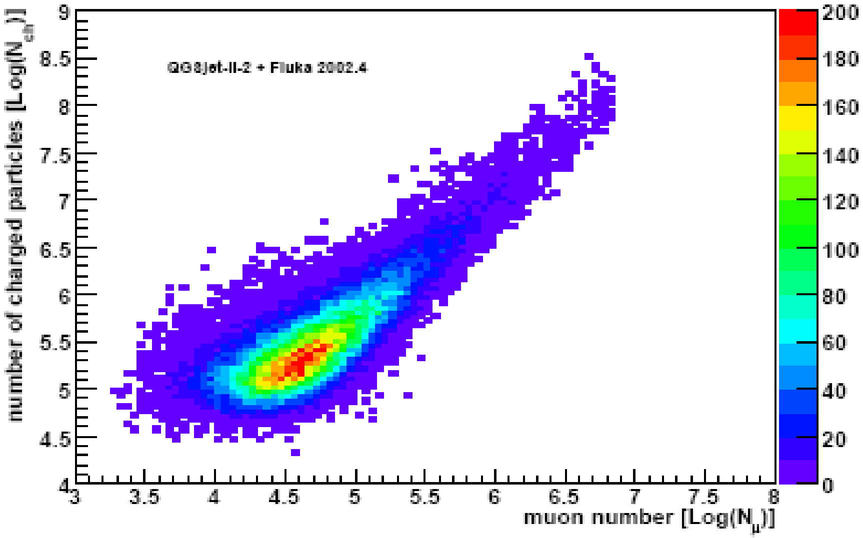
EPOS 1.99 – muon densities

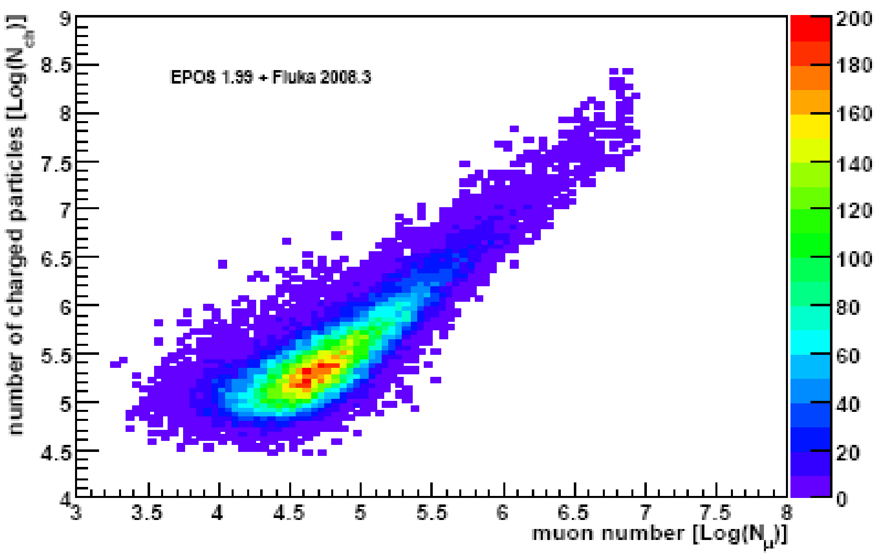


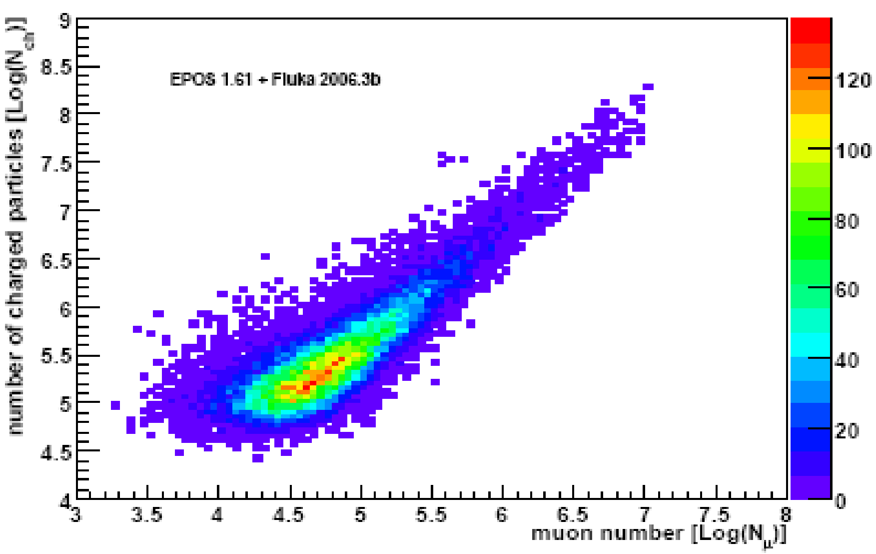


Vitor de Souza

N_{ch} – Nμ - Correlation

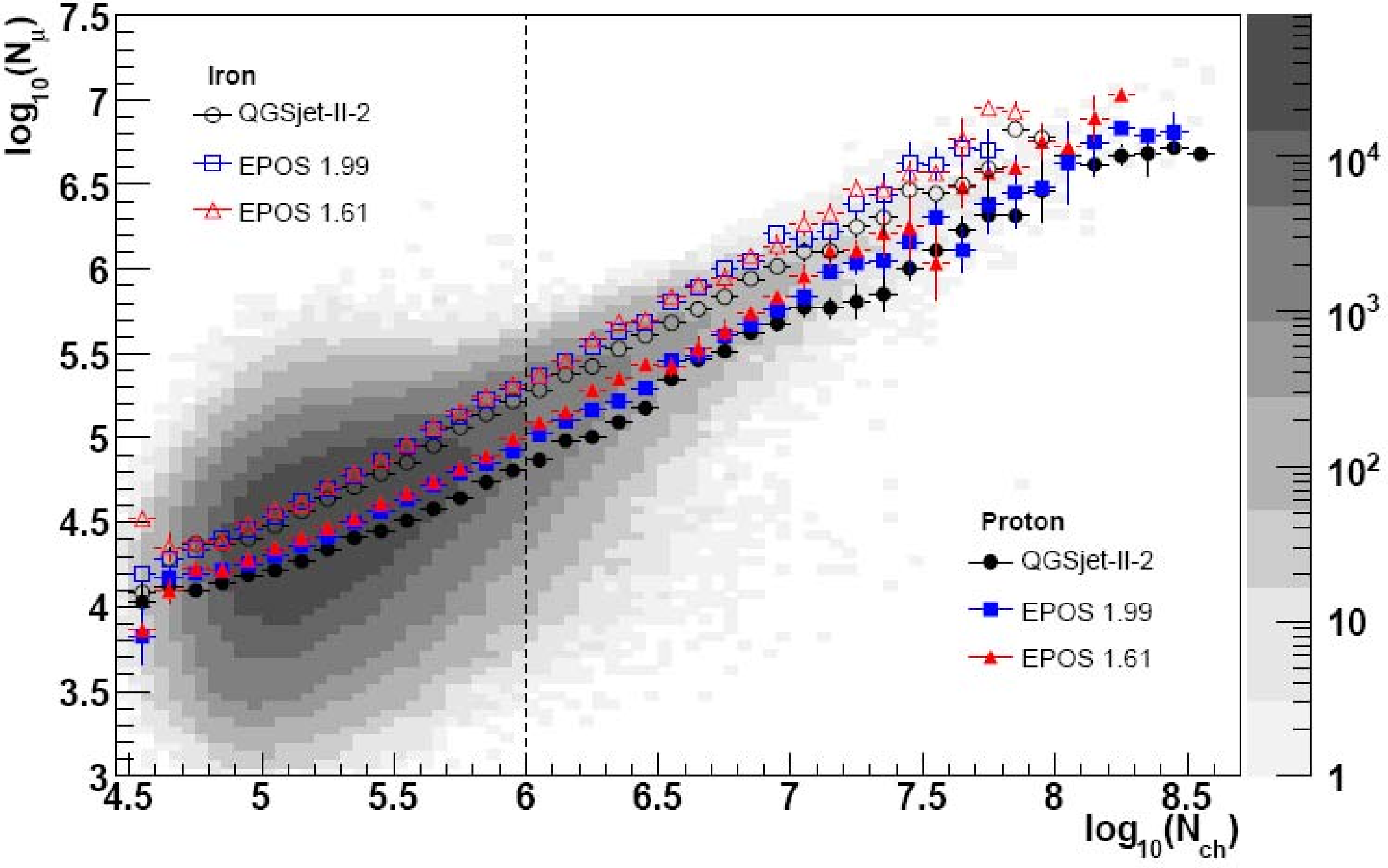






Donghwa Kang

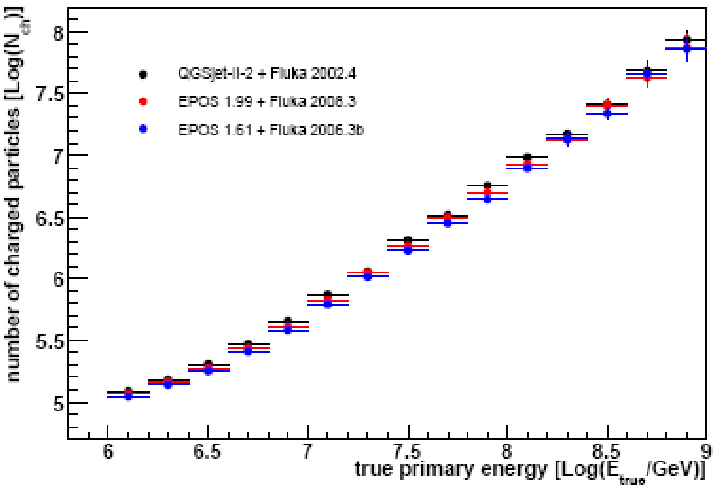
N_{ch} – Nμ - Correlation



- KASCADE-Grande 2 dim. Nch/Nm plot + proton and iron for QGSJet and EPOS
- Difference between the two EPOS in proton

Donghwa Kang

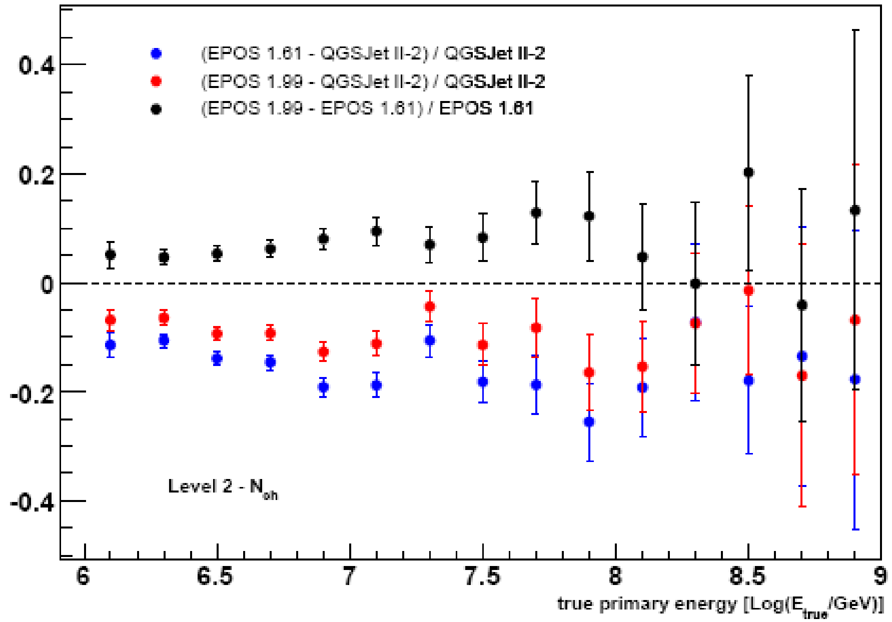
N_{ch} – Nμ - Correlation



Nch

- Deviation of EPOS relative to QGSJet

- EPOS has less Nch with respect to QGSJet (roughly 10%)



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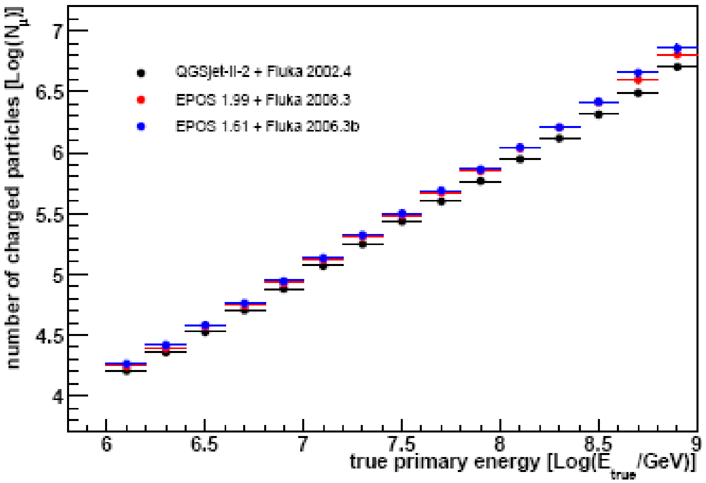
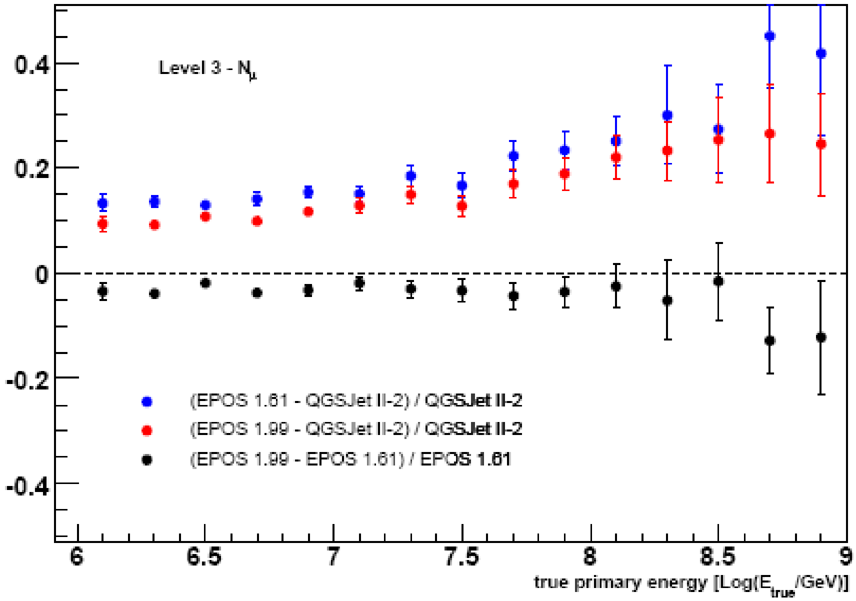
N_{ch} – Nμ - Correlation



Nμ



EPOS has more muons with respect to QGSJet

Donghwa Kang


THE END
T.H.DESIGN