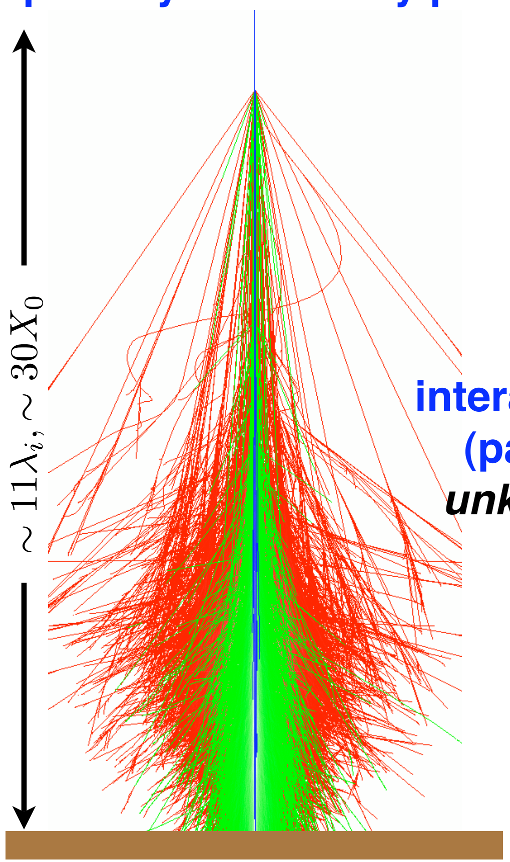
13th International Conference on Elastic & Diffractive Scattering
(13th "Blois Workshop")
CERN, 29th June - 3rd July 2009

Test of hadronic interaction models with air shower data

Jörg R. Hörandel, Radboud University Nijmegen http://particle.astro.kun.nl

Test of hadronic interaction models with air shower data



EDS '09
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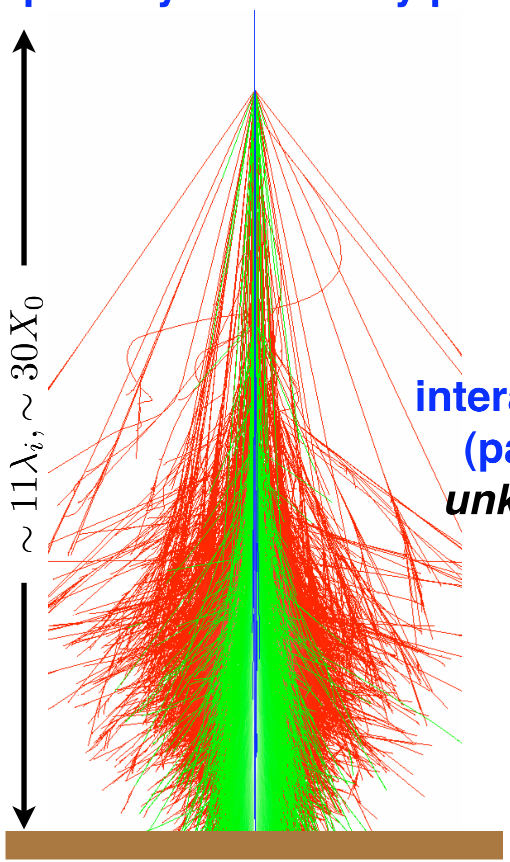
Test of hadronic interaction models with air shower data

primary cosmic-ray particle (type *unknown*)



air shower detector at ground level

Münchhausen problem

Jörg R. Hörandel, Radboud University Nijmegen http://particle.astro.kun.nl

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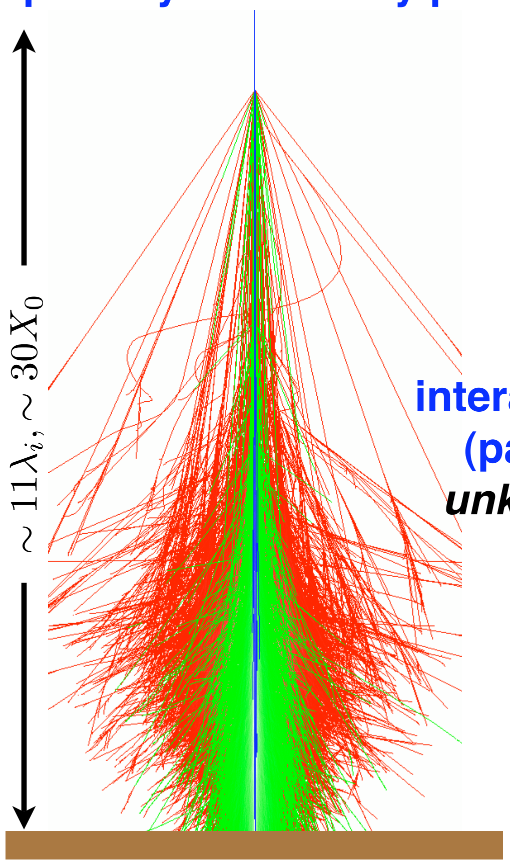
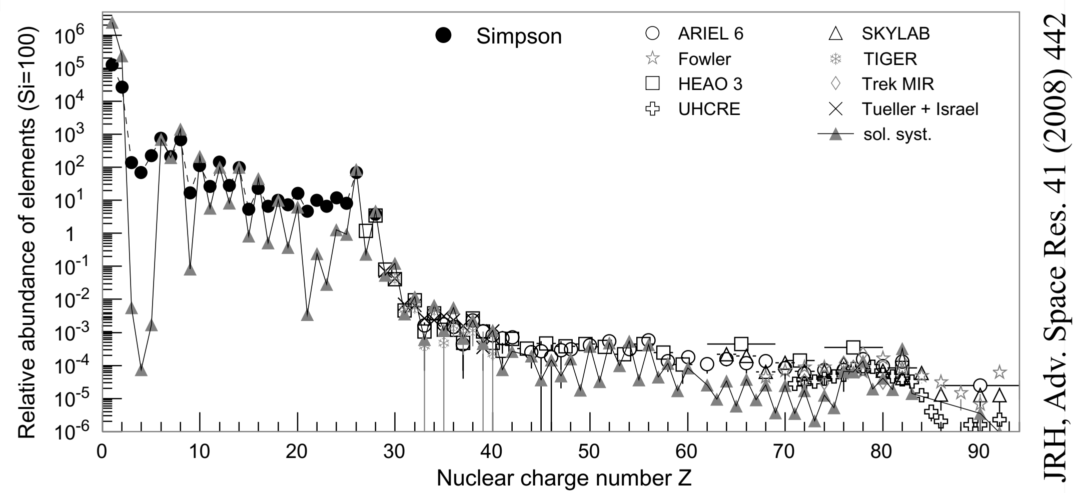


interactions (partly) *unknown*

abundance of elements in cosmic rays (~1 GeV/n)



air shower detector at ground level

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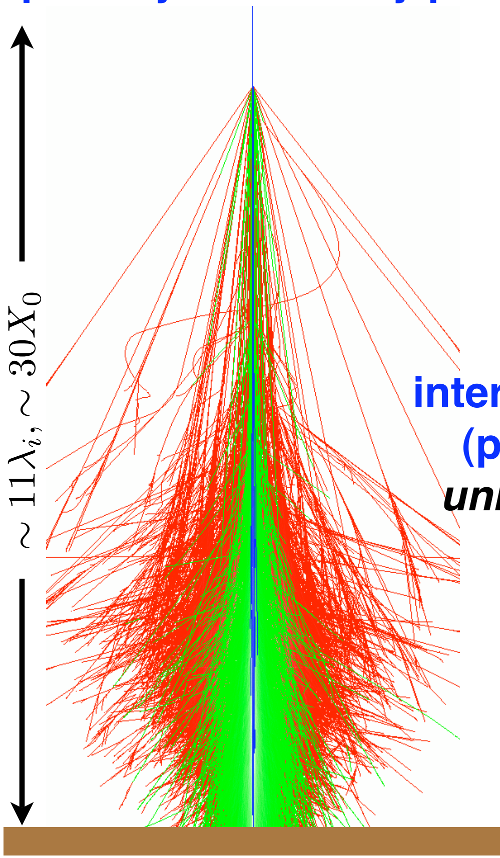

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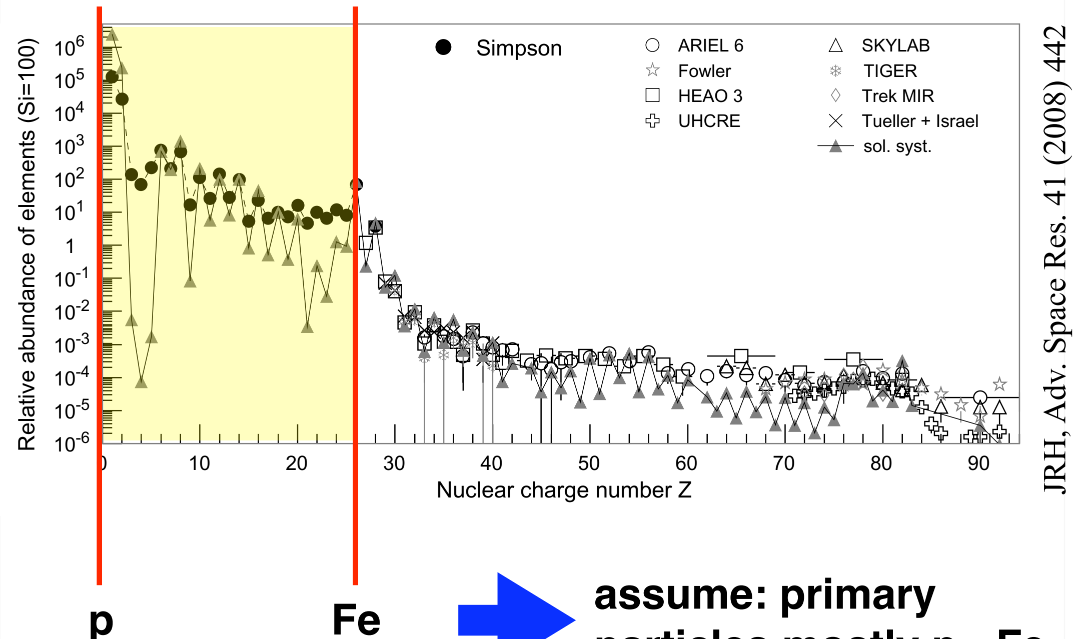


assume: primary particles mostly p - Fe

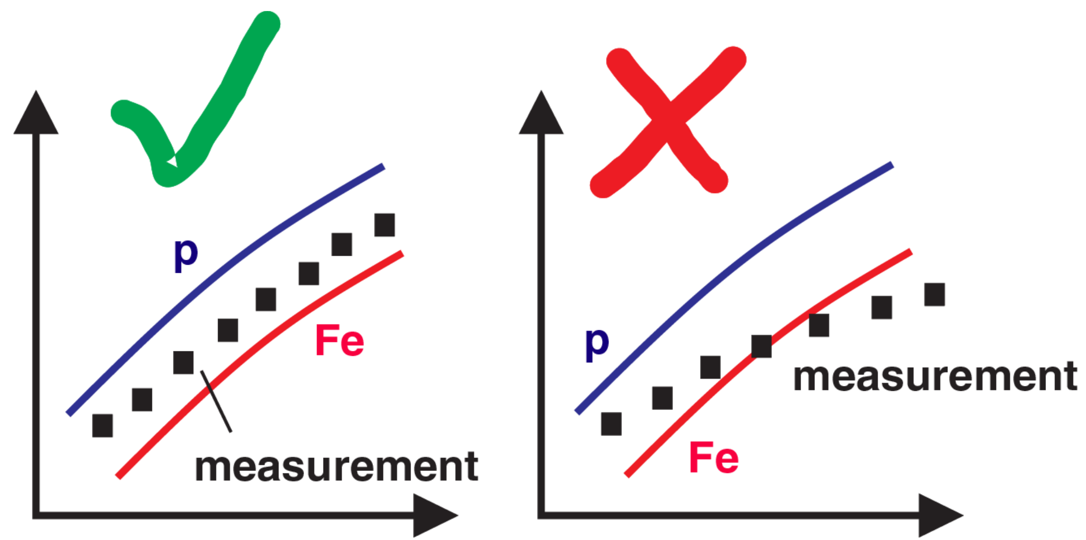
air shower detector at ground level

Test of hadronic interaction models with air shower data

Method:

- Measure correlation between air shower components (electromagnetic, muonic, hadronic)
- Compare to predictions of hadronic interaction models for extreme assumptions (p & Fe)

air shower simulation: CORSIKA
detector simulation: GEANT 3



KArlsruhe Shower Core and Array DEtector

Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components

T. Antoni et al, Nucl. Instr. & Meth. A 513 (2004) 490

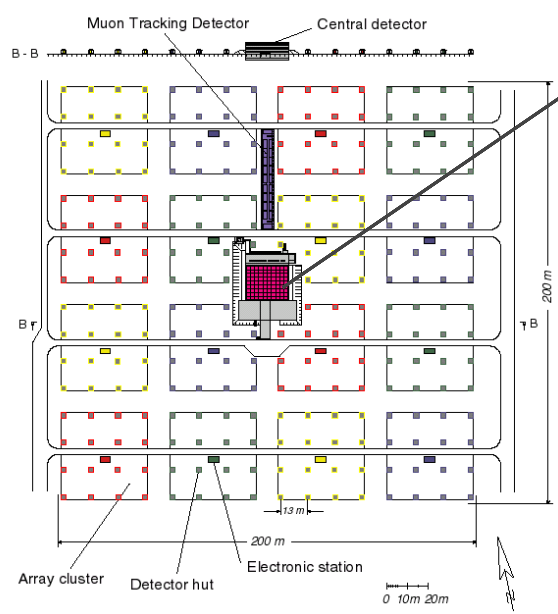
KASCADE

Hadron calorimeter

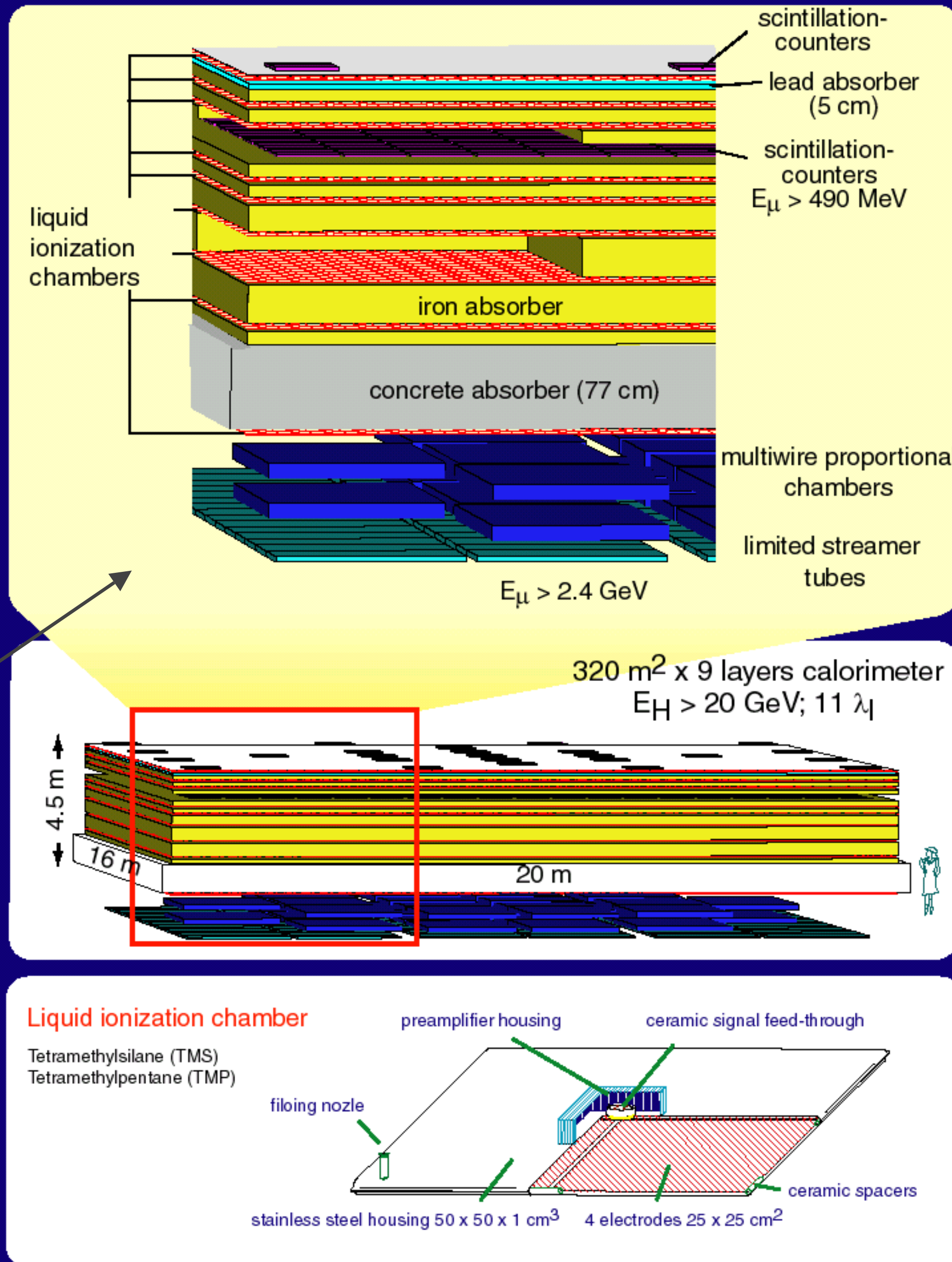
320 m² x 9 layers
liquid ionization chambers
44 000 electronic channels
$E_H > 20$ GeV

Field array 200 x 200 m²

e/γ detectors
μ detectors $E_\mu > 230$ MeV



T. Antoni et al, Nucl. Instr. & Meth. A 513 (2004) 490

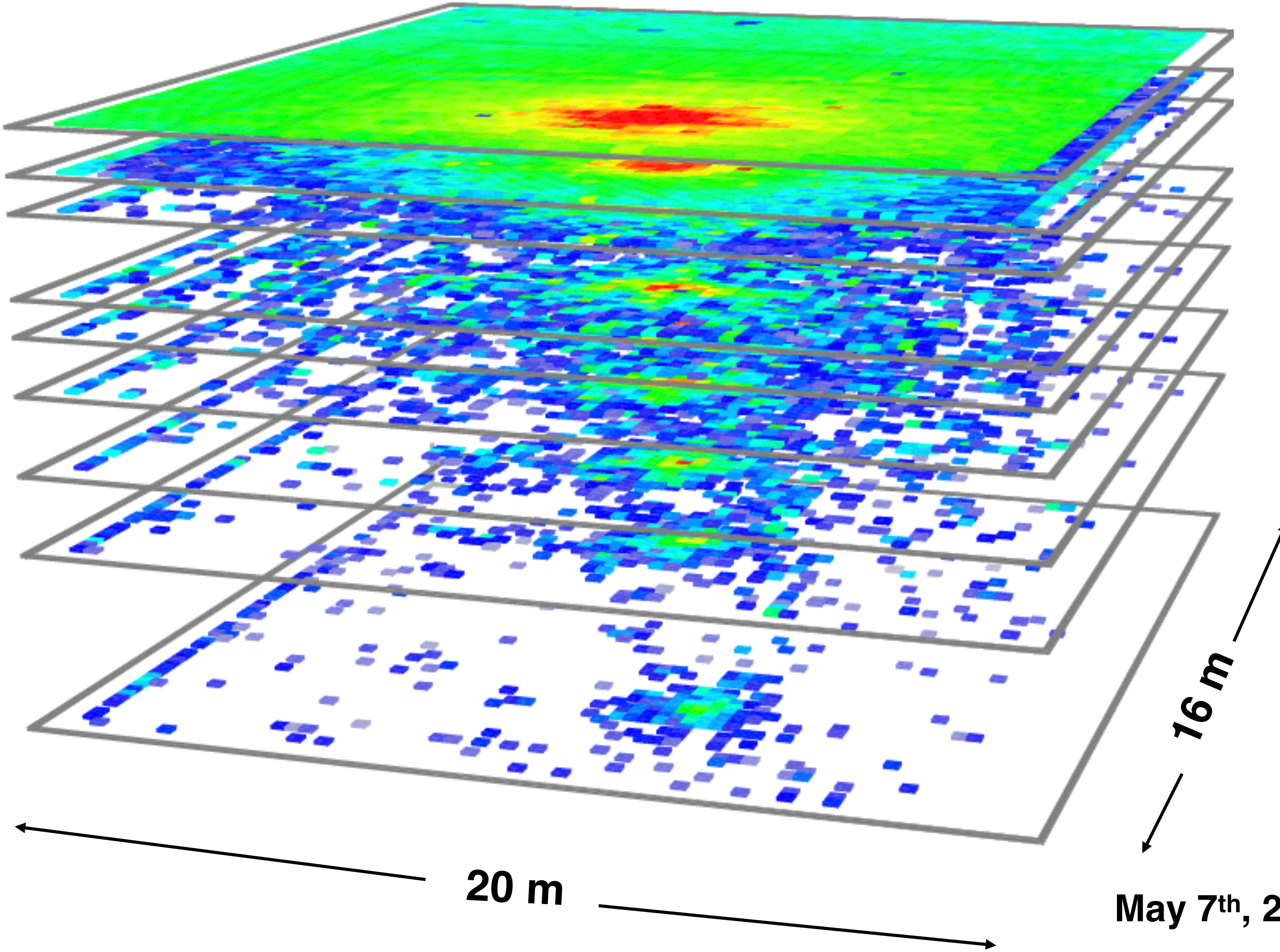


J. Engler et al., Nucl. Instr. & Meth. A 427 (1999) 528

Hadronic shower core

$E_0 \sim 6$ PeV

Number of reconstructed hadrons $N_h = 143$ $E_h > 50$ GeV



May 7th, 2002 9:45

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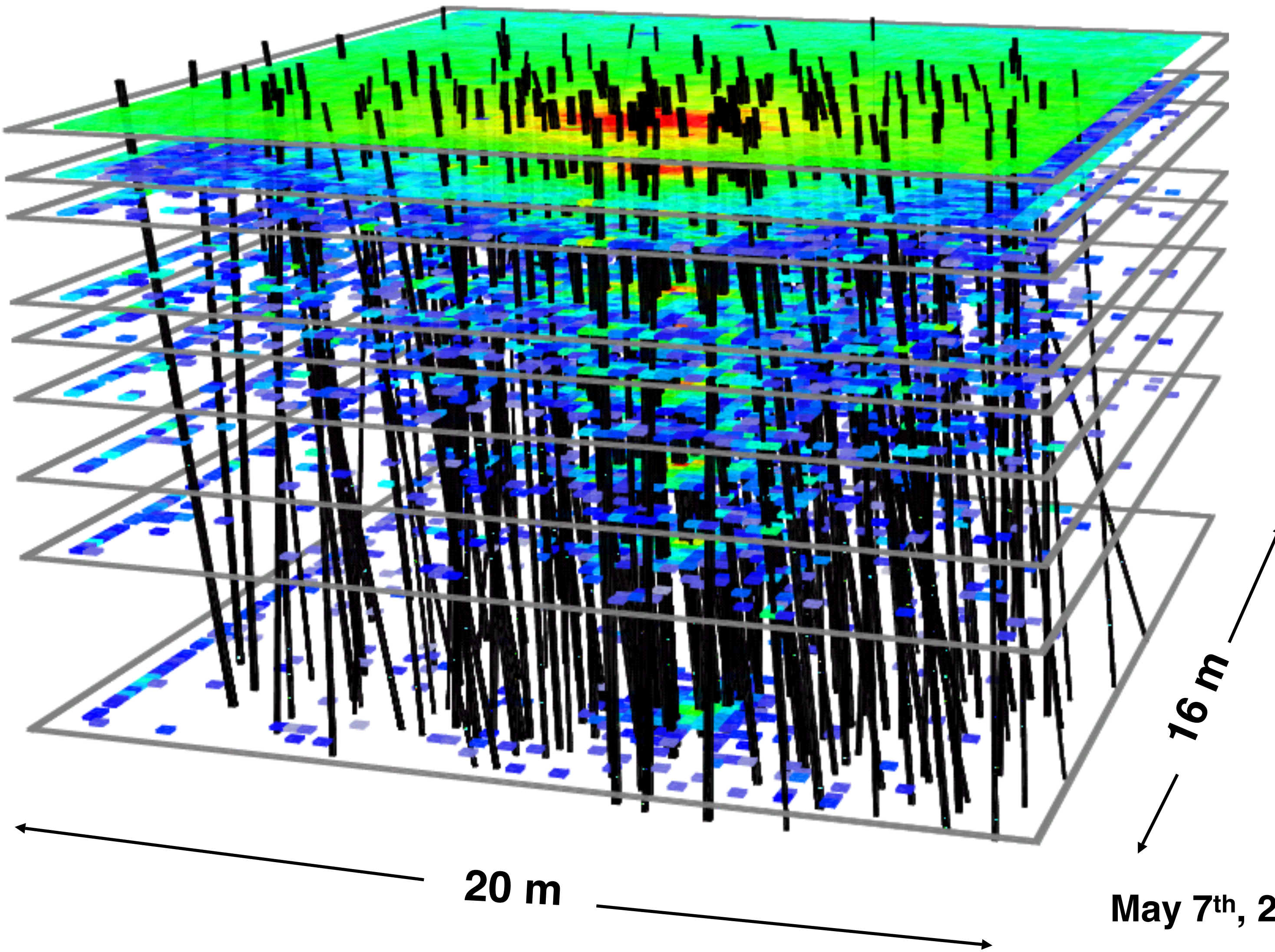
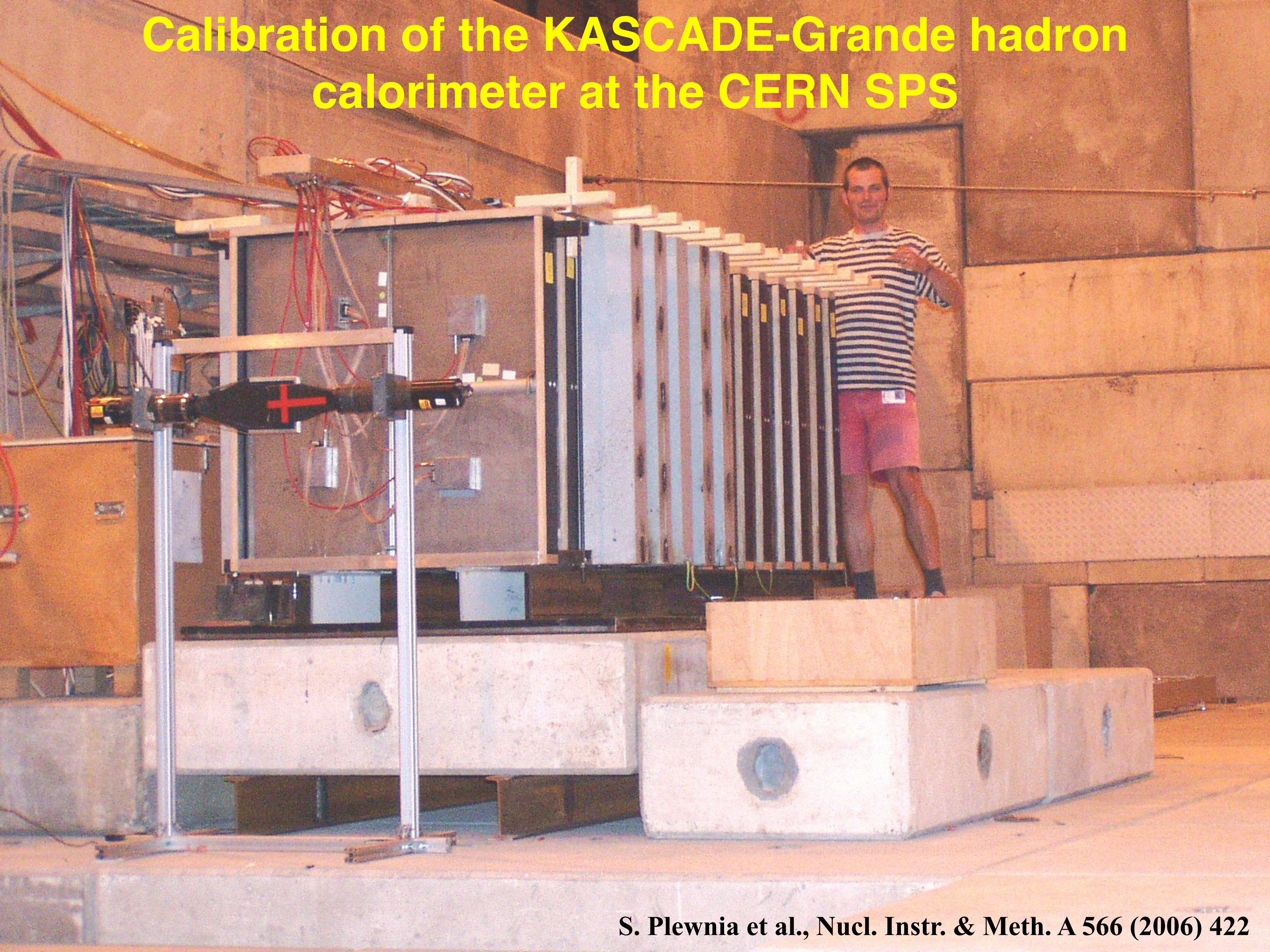


May 7th, 2002 9:45

Calibration of the KASCADE-Grande hadron calorimeter at the CERN SPS



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

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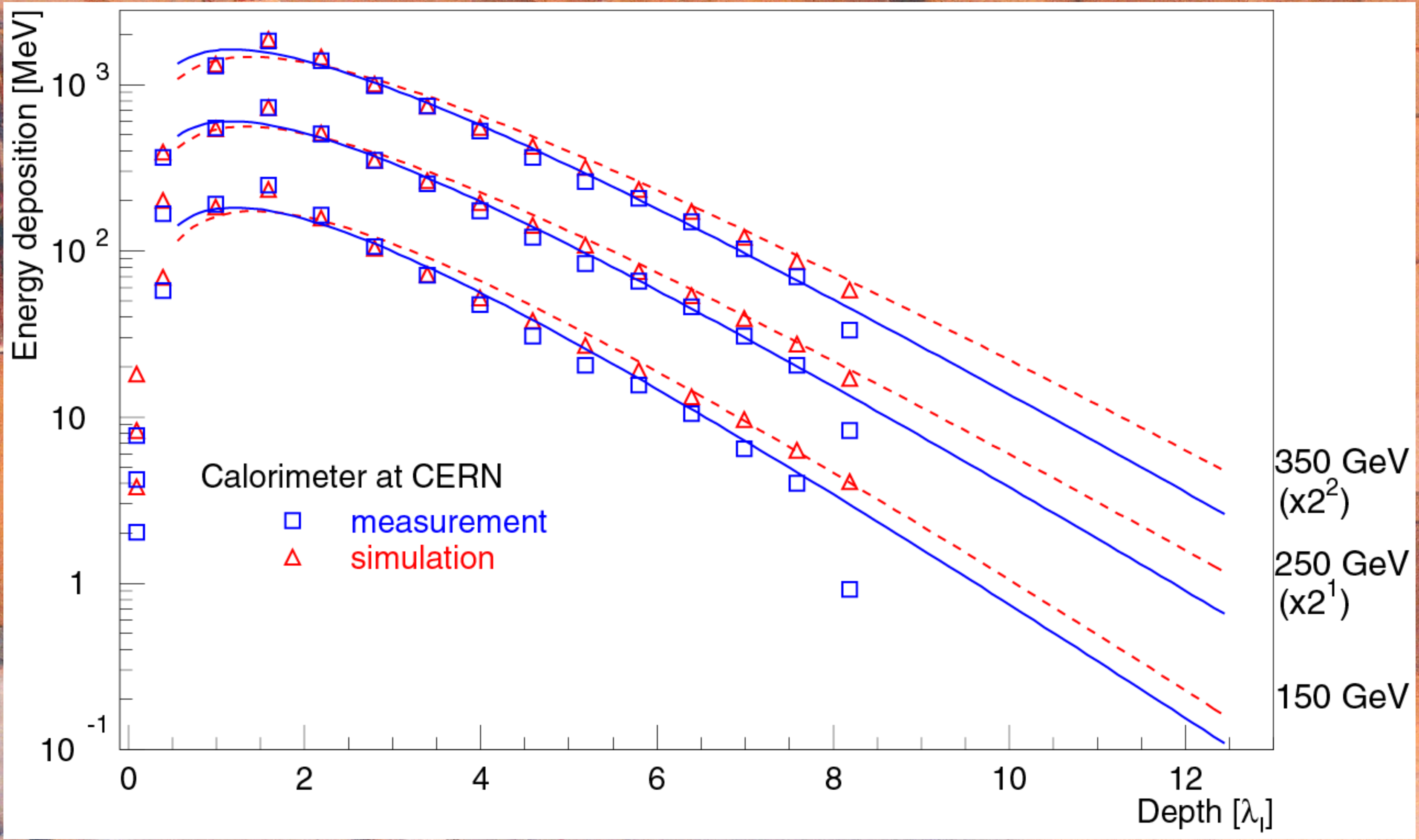

S. Plewnia et al., Nucl. Instr. & Meth. A 566 (2006) 422

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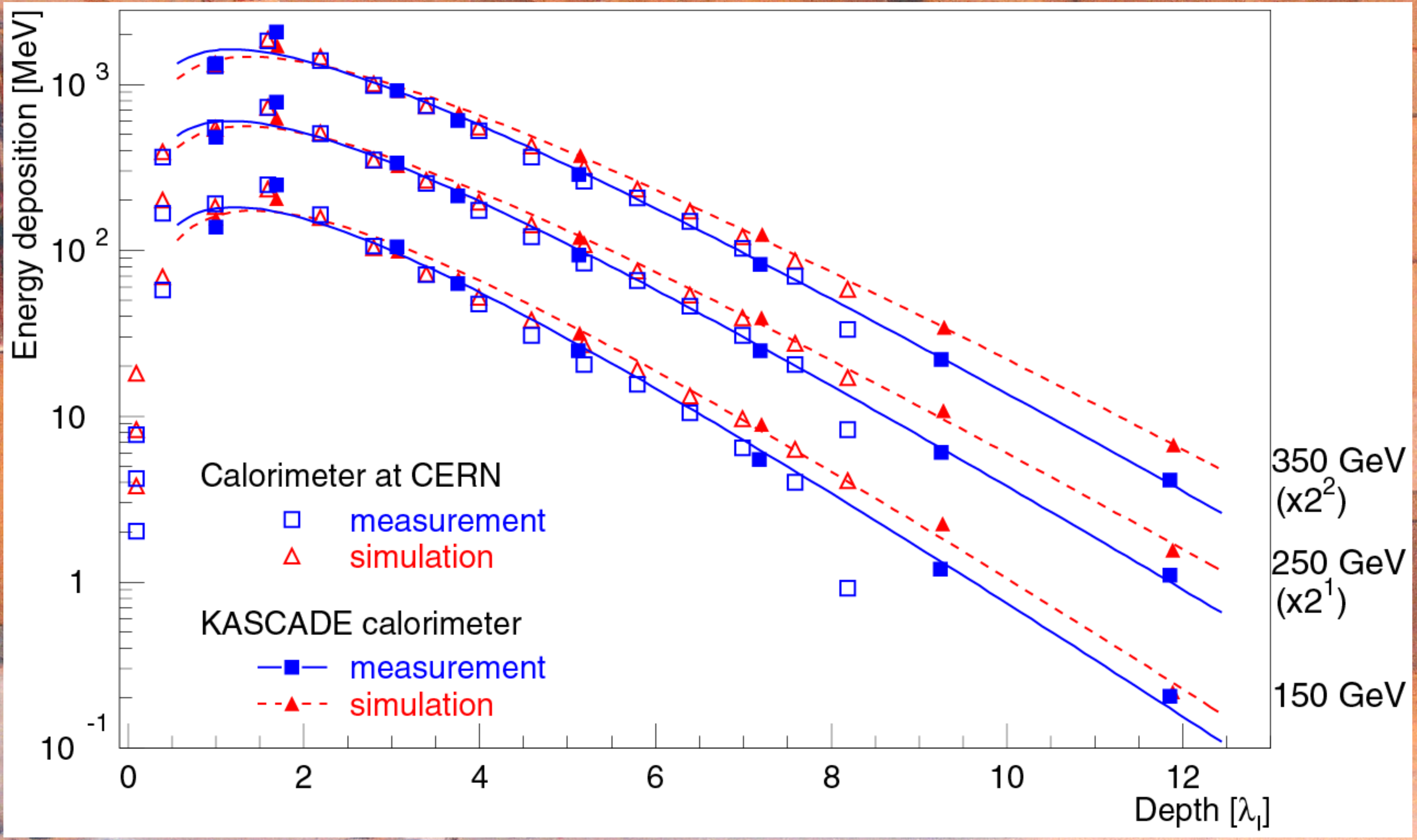
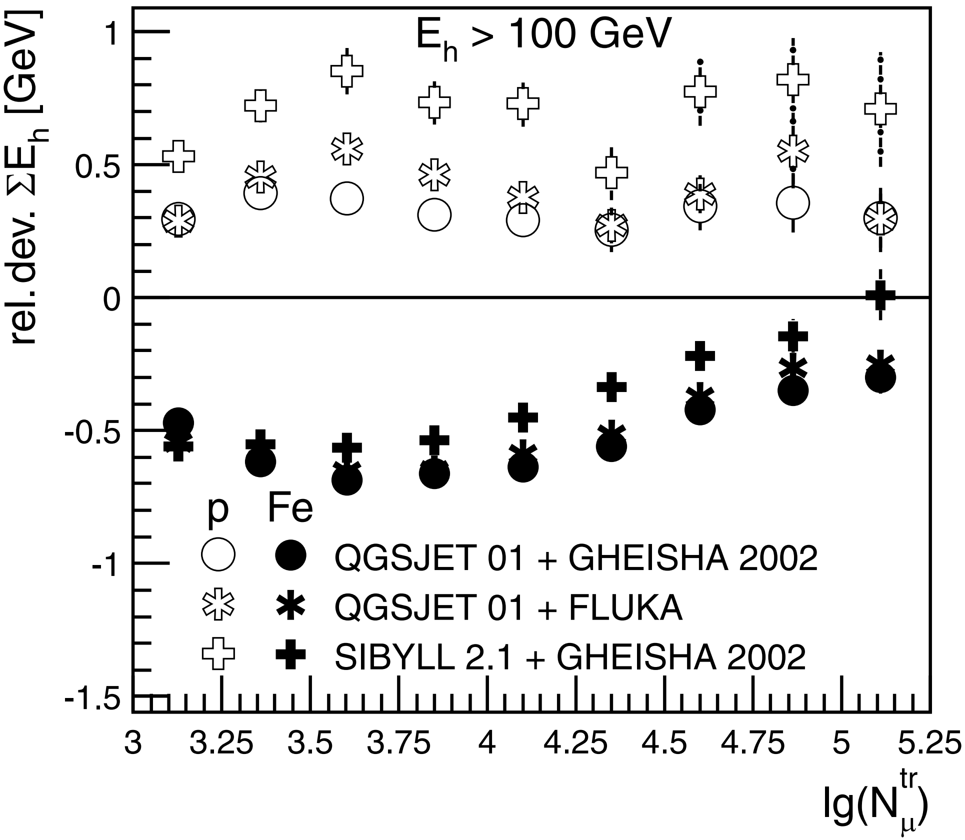


S. Plewnia et al., Nucl. Instr. & Meth. A 566 (2006) 422

Low-energy interaction models

E < 200 GeV

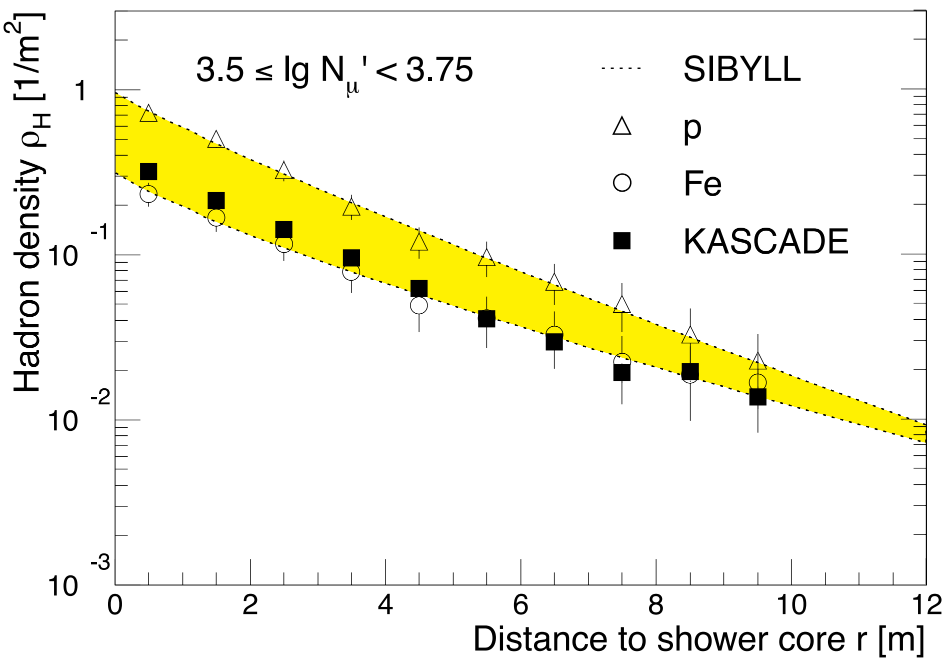


GHEISHA & FLUKA both OK

W.D. Apel et al., J. Phys. G: Nucl. Part. Phys. 34 (2007) 2581

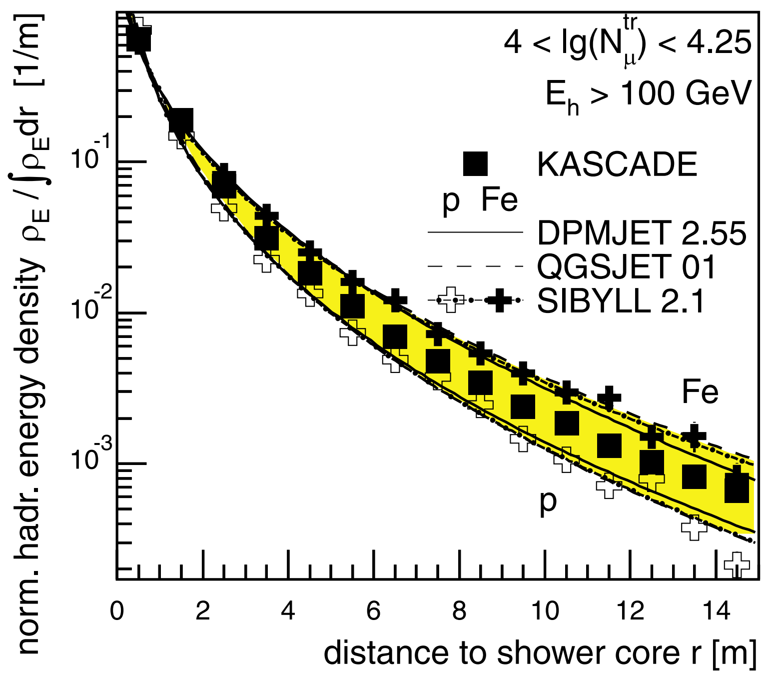
Hadronic interaction model SIBYLL

version 1.6



***not* compatible**

version 2.1



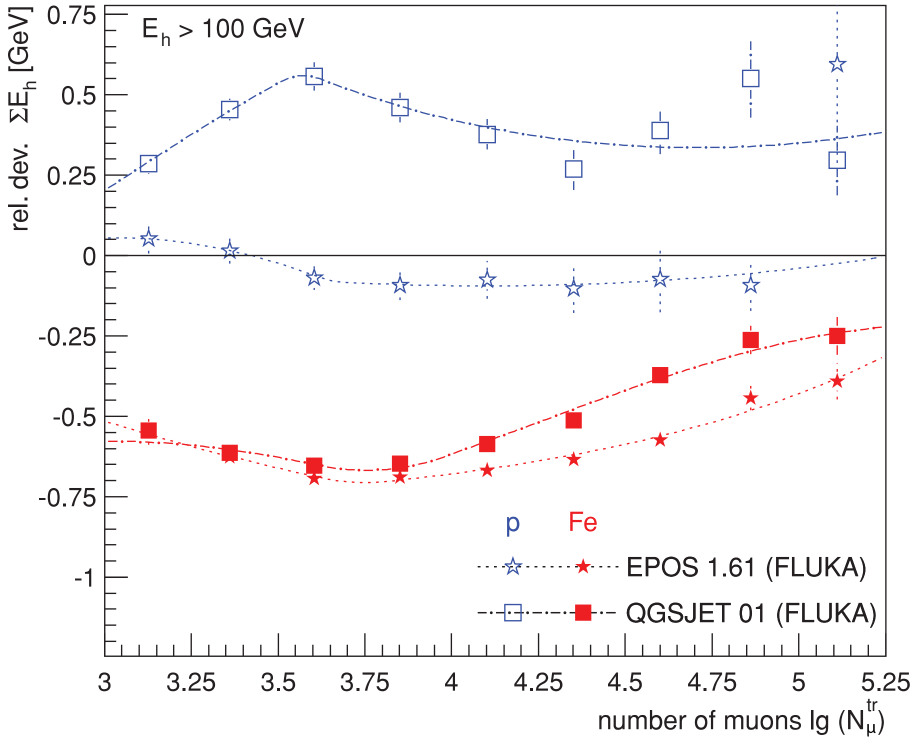
***compatible* with air shower data**

T. Antoni et al., J. Phys. G: Nucl. Part. Phys. 25 (1999) 2161

W.D. Apel et al., J. Phys. G: Nucl. Part. Phys. 34 (2007) 2581

KASCADE – Test of EPOS 1.6

$\Sigma E_h - N_\mu$



EPOS delivers not enough hadronic energy to the ground

W.D. Apel et al., J. Phys. G 36 (2009) 035201

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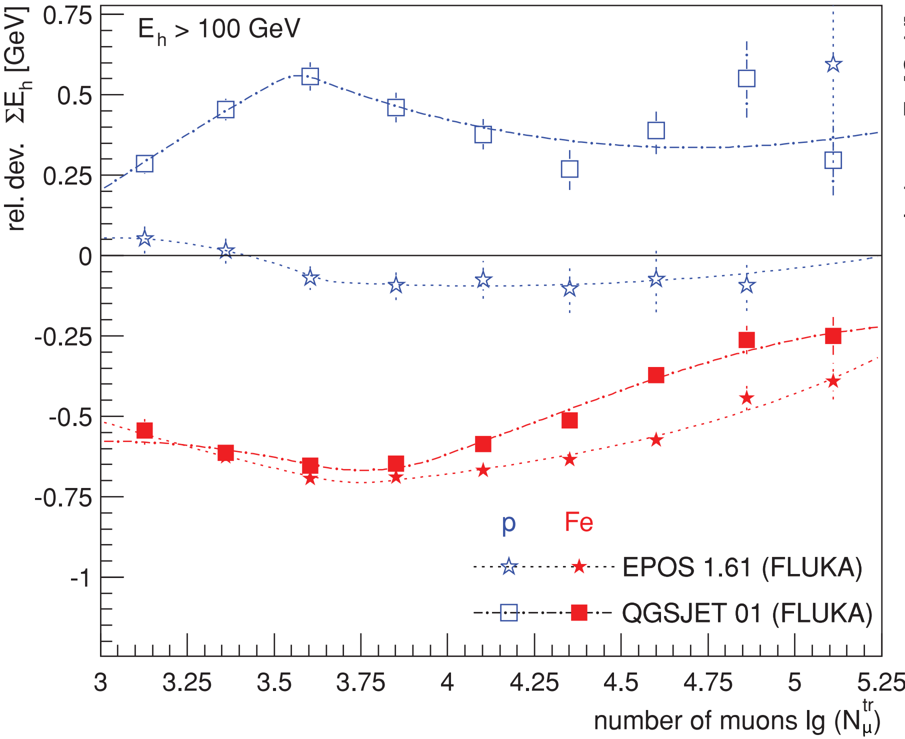

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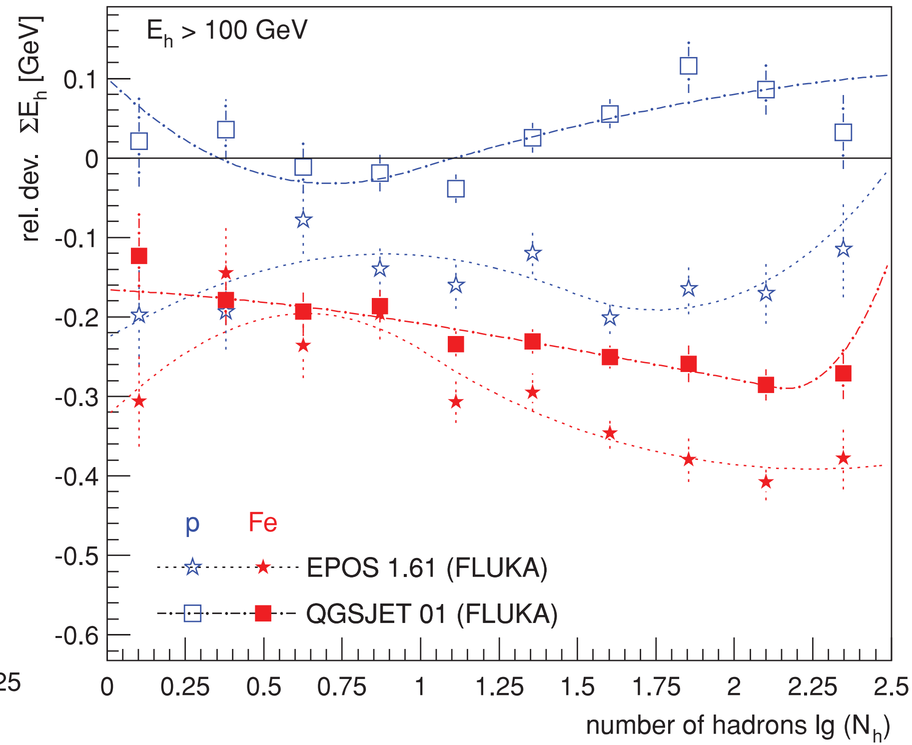

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→ energy per hadron too small

W.D. Apel et al., J. Phys. G 36 (2009) 035201

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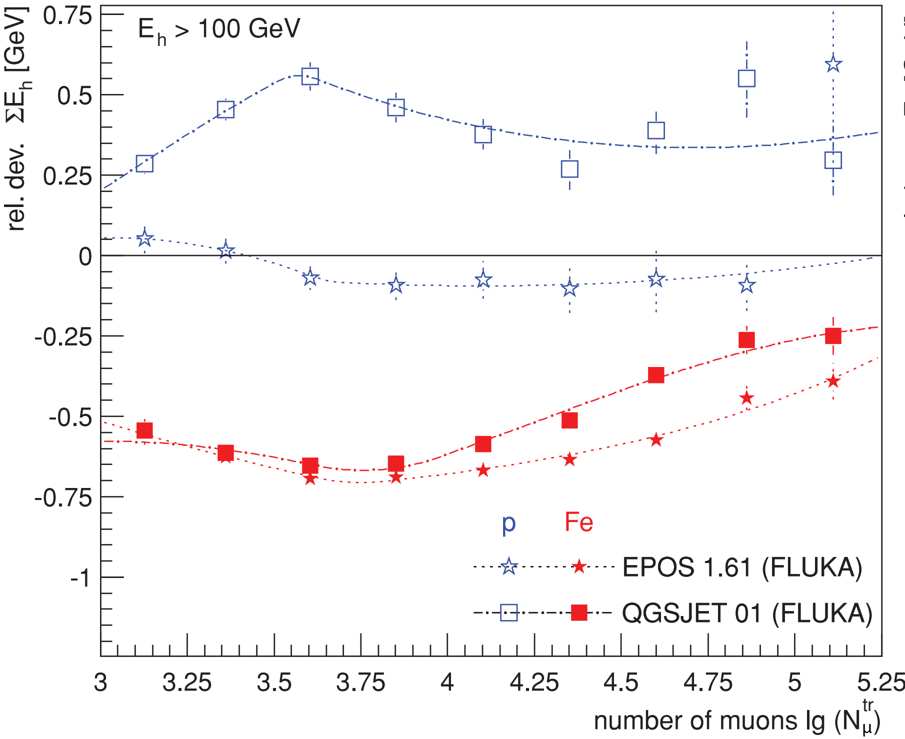

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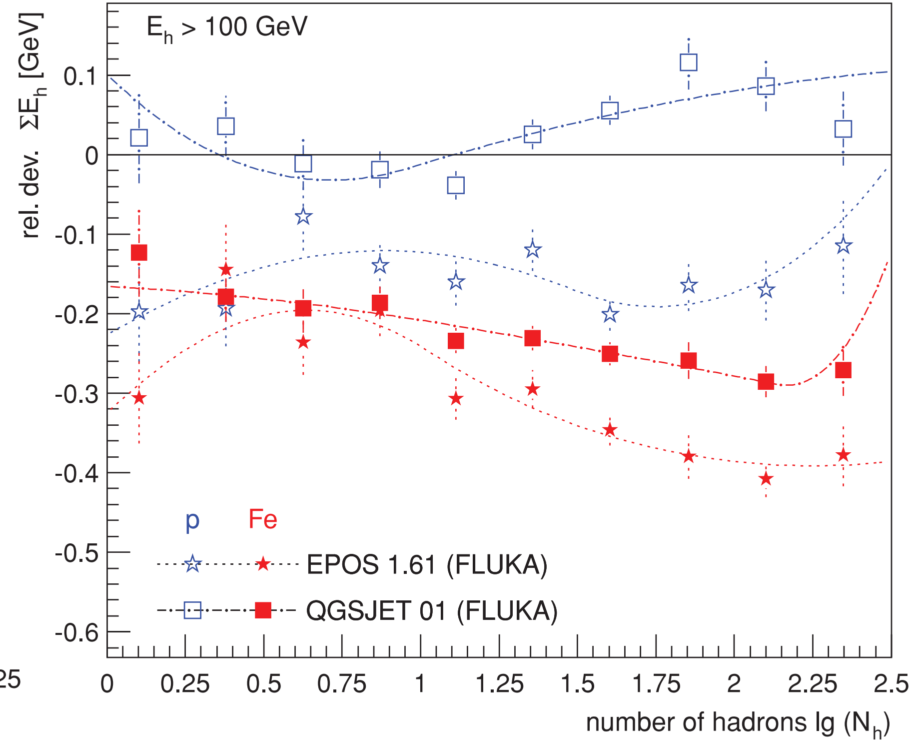


EPOS delivers not enough hadronic energy to the ground

→ energy per hadron too small

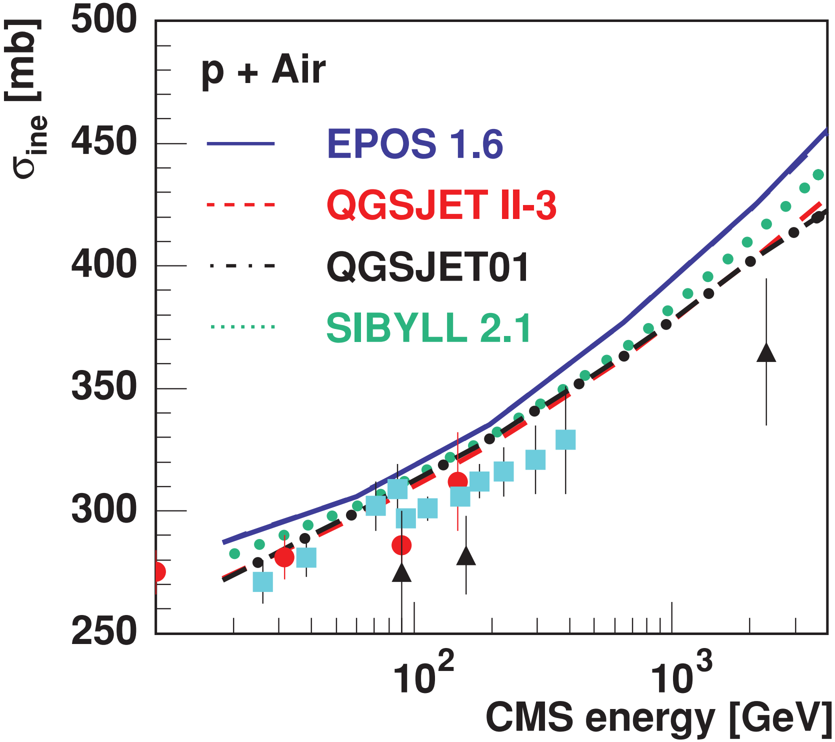
→ EPOS 1.6 is NOT CONSISTENT with KASCADE observations!

W.D. Apel et al., J. Phys. G 36 (2009) 035201

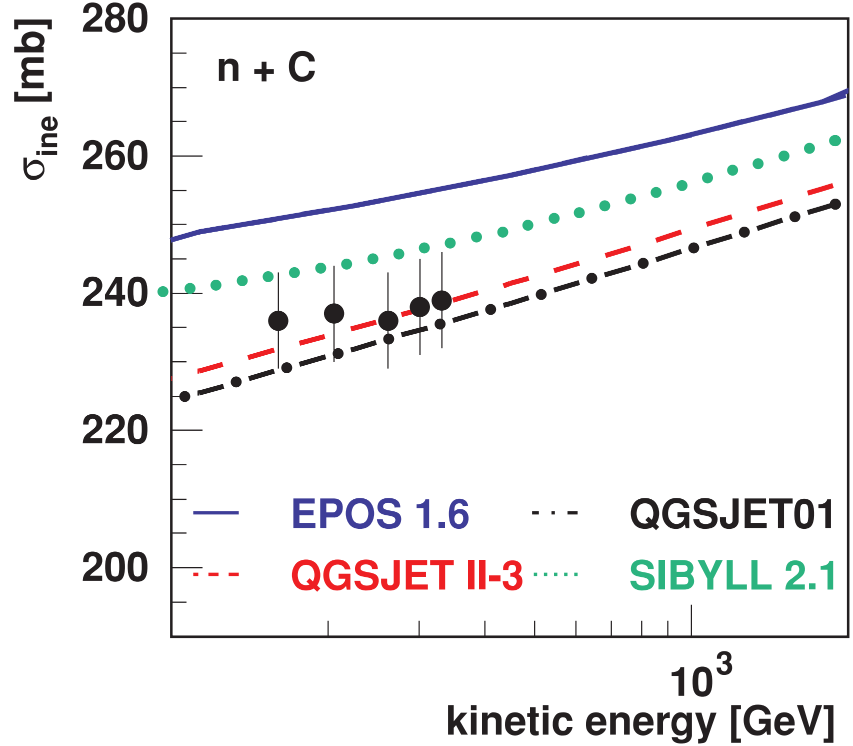
KASCADE – Test of EPOS 1.6

Inelastic cross sections

proton - air



neutron - carbon



cross sections in EPOS 1.6 too large

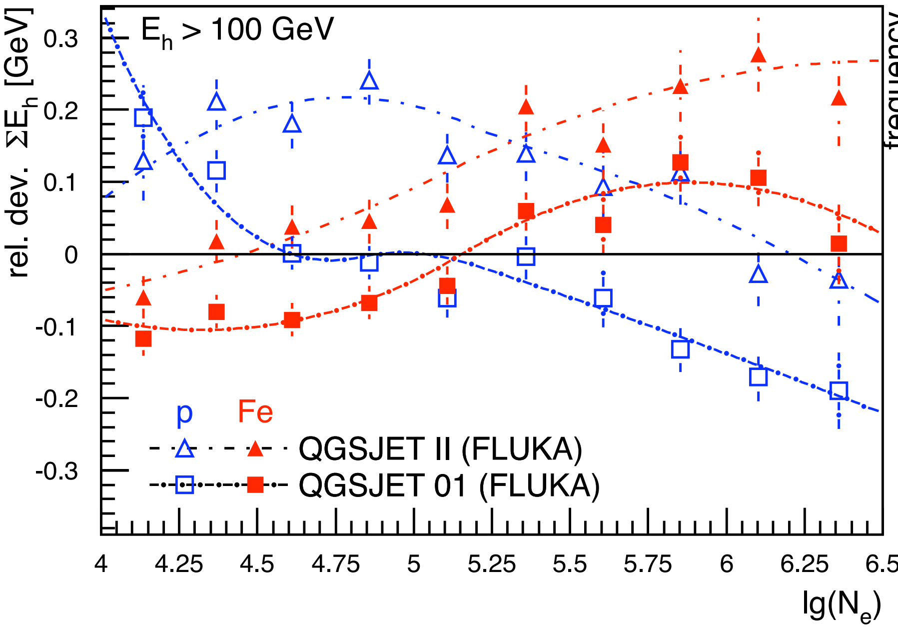
- ➡ new version EPOS 1.9 under investigation
- ➡ forthcoming studies

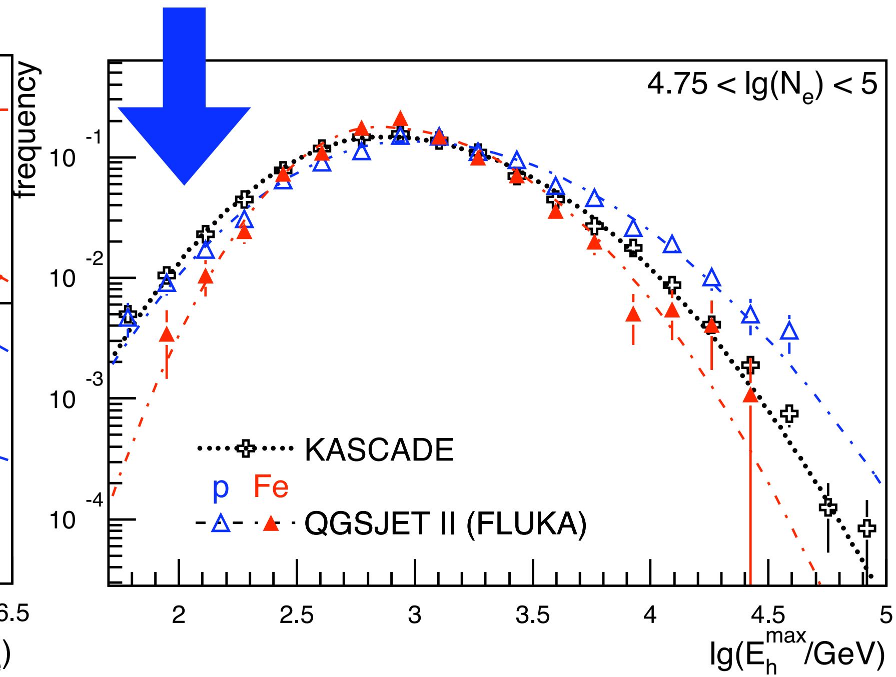
W.D. Apel et al., J. Phys. G 36 (2009) 035201

Hadronic interaction model QGSJET-II

hadr. energy sum vs. number of electrons

maximum hadron energy





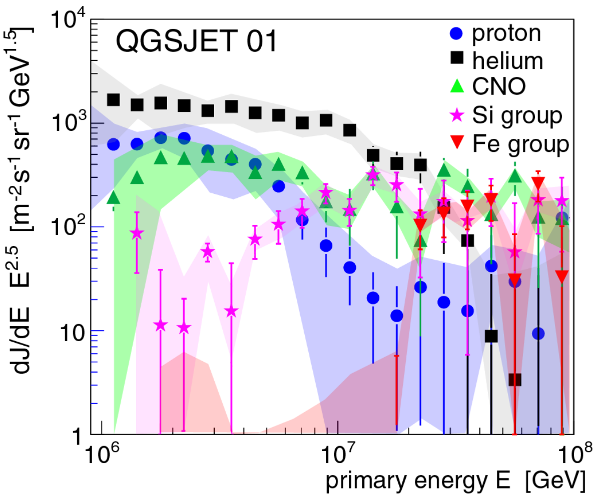
QGSJET-II exhibits some problems

JRH et al., ICRC 2009

Uncertainties quantitative

QGSJET 01

cosmic-ray composition from N_e-N_μ analysis

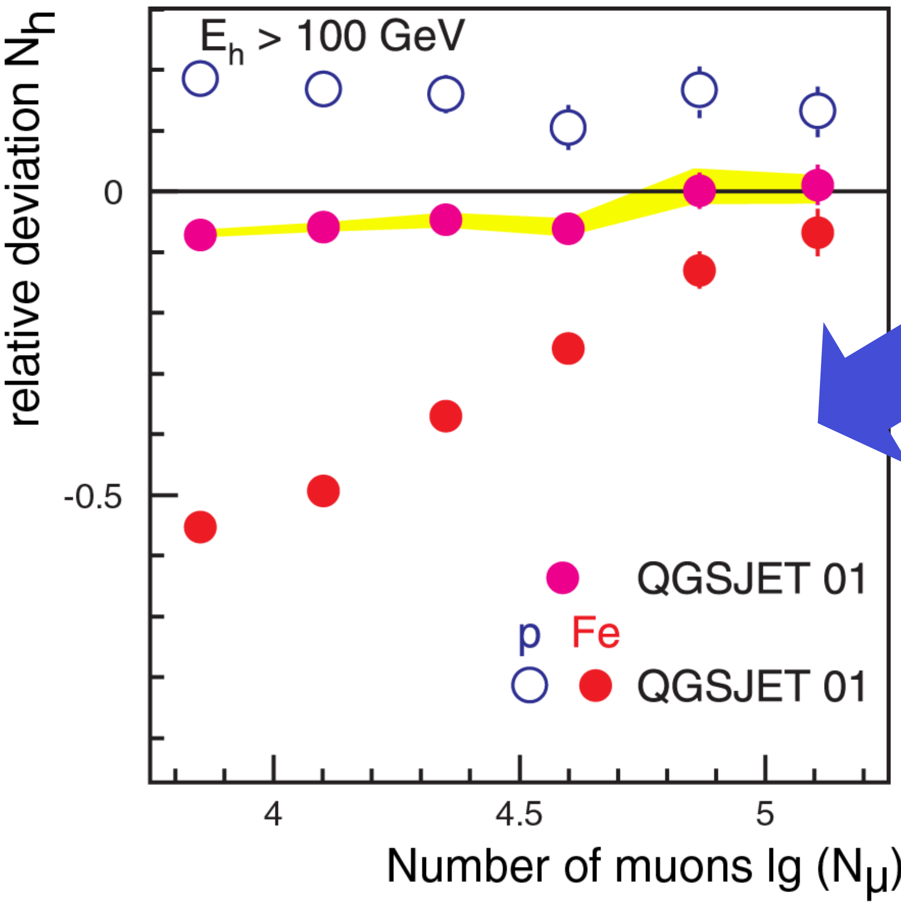


J. Milke et al., 29th Int. Cosmic Ray Conf. Pune 6 (2005)

Uncertainties quantitative

QGSJET 01

Number of hadrons vs. number of muons



cosmic-ray composition from

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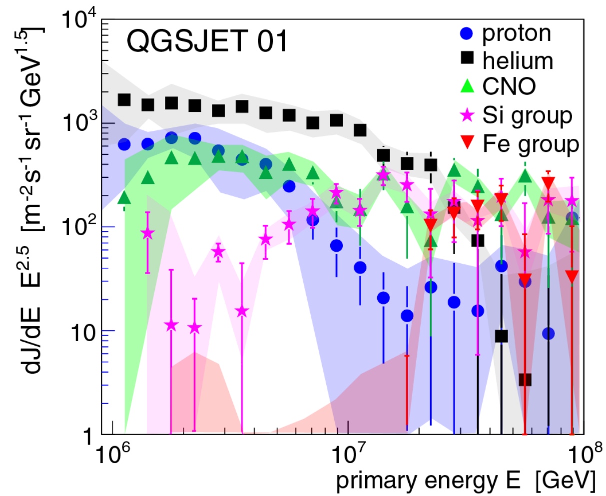


~10%-15% uncertainty

J. Milke et al., 29th Int. Cosmic Ray Conf. Pune 6 (2005)

Models tested in CORSIKA

QGSJET 98 VENUS SIBYLL 1.6		T. Antoni et al, J.. of Phys. G 25 (1999) 2161
DPMJET II.55 QGSJET 01 SIBYLL 2.1 NEXUS 2	DPMJET II.5	W.D. Apel et al., J. of Phys. G 34 (2007) 2581
EPOS 1.6		W.D. Apel et al., J. of Phys. G 36 (2009) 035201
QGSJET-II		J.R. Hörandel et al., ICRC 2009
EPOS 1.9		in progress

Models tested in CORSIKA

QGSJET 98
~~VENUS~~
~~SIBYLL 1.6~~ T. Antoni et al, J.. of Phys. G 25 (1999) 2161

DPMJET II.55 ~~DPMJET II.5~~
QGSJET 01
SIBYLL 2.1
~~NEXUS 2~~ W.D. Apel et al., J. of Phys. G 34 (2007) 2581

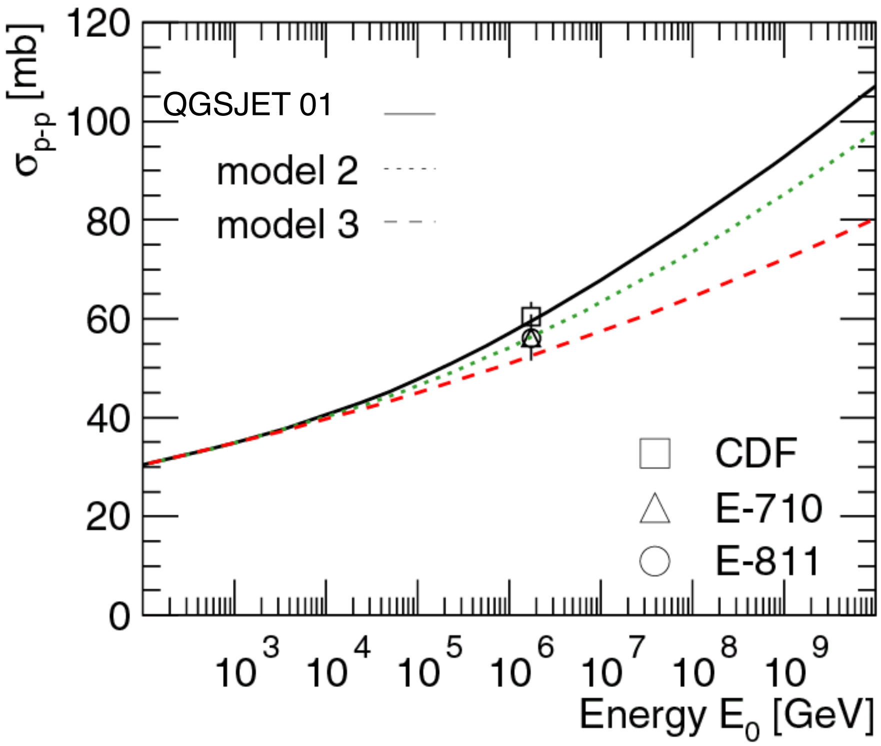
~~EPOS 1.6~~ W.D. Apel et al., J. of Phys. G 36 (2009) 035201

(QGSJET-II) J.R. Hörandel et al., ICRC 2009

EPOS 1.9 in progress

Extrapolation of the uncertainties of accelerator data to air shower observables

p-p cross section



JRH, J. Phys. G 29 (2003) 2439

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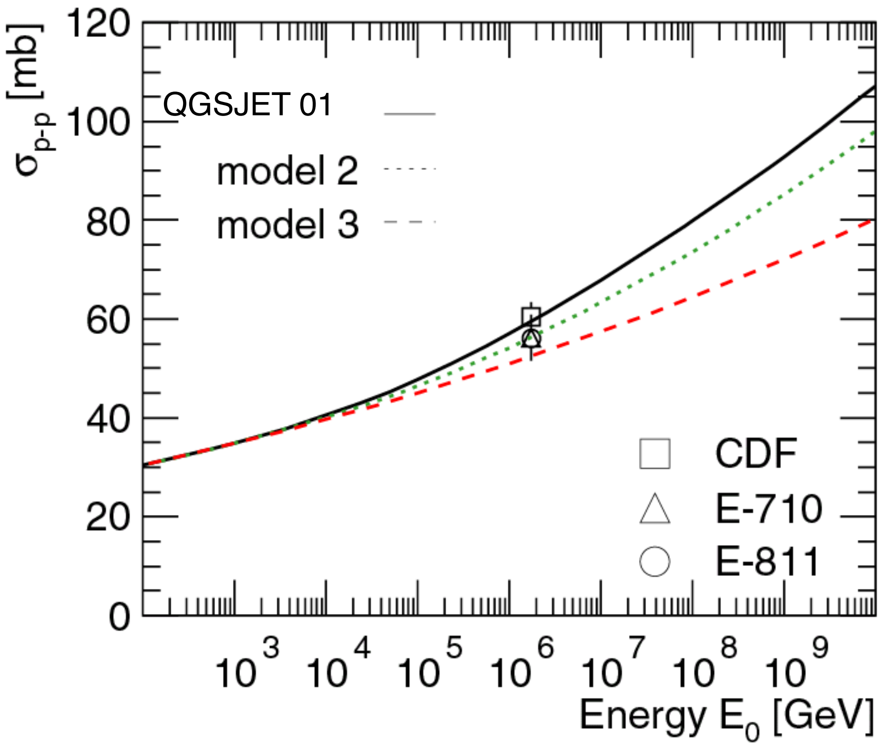
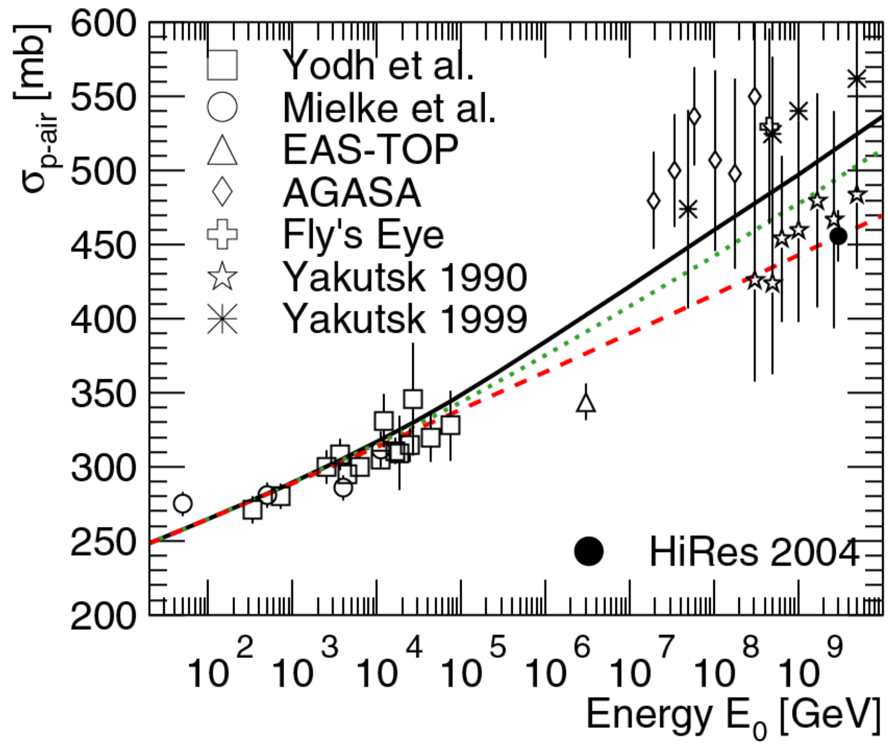


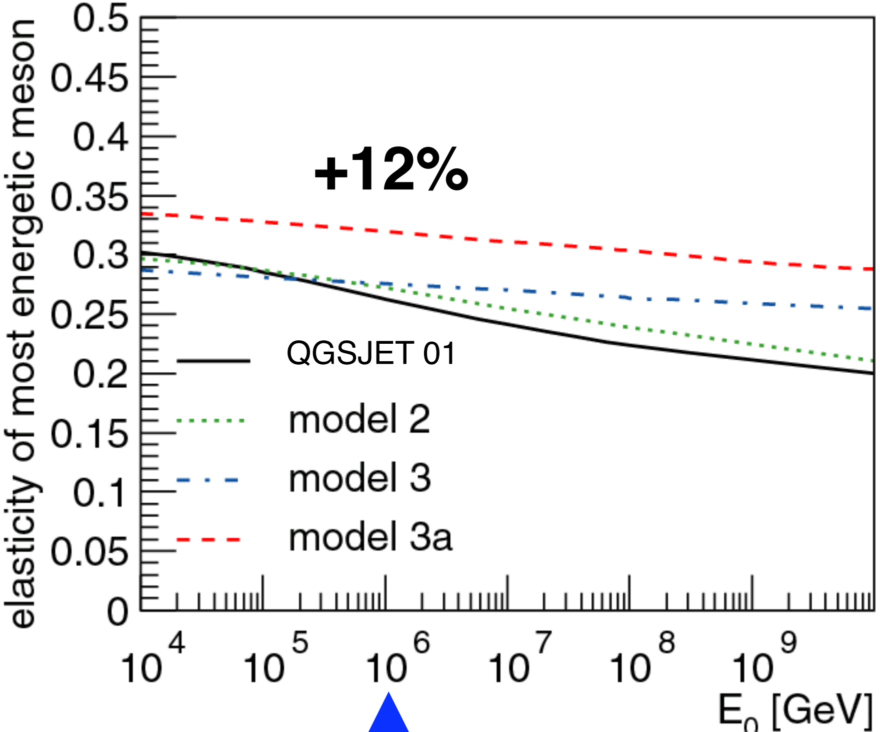
p-air cross section



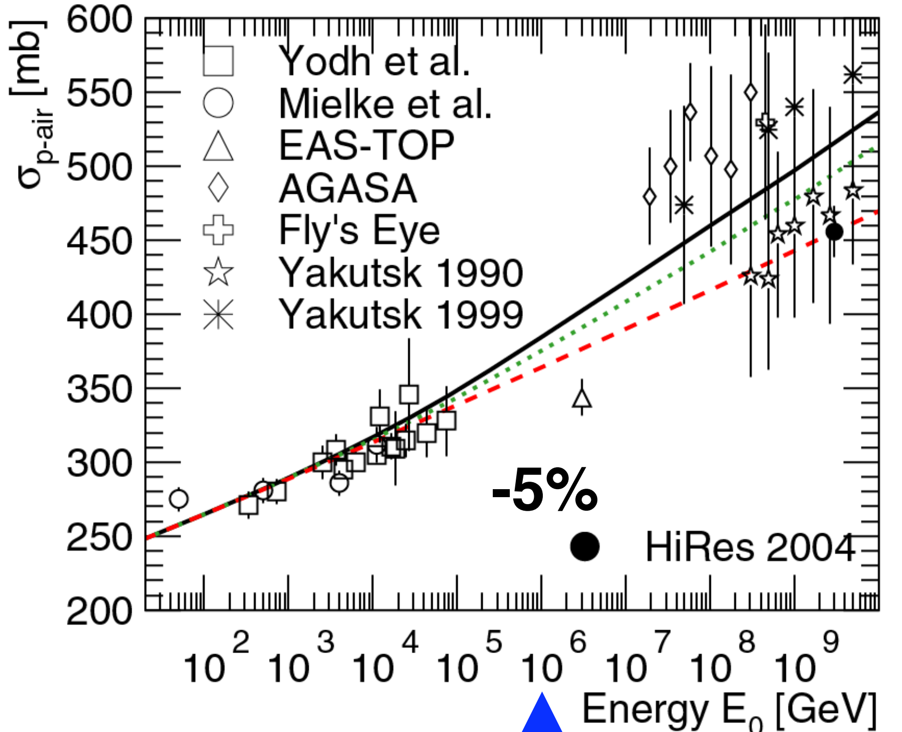
JRH, J. Phys. G 29 (2003) 2439

Extrapolation of the uncertainties of accelerator data to air shower observables

elasticity



p-air cross section



JRH, J. Phys. G 29 (2003) 2439

Average depth of the shower maximum

Heitler Model – X_{max}

JRH, Mod. Phys. Lett. A 22 (2007) 1533

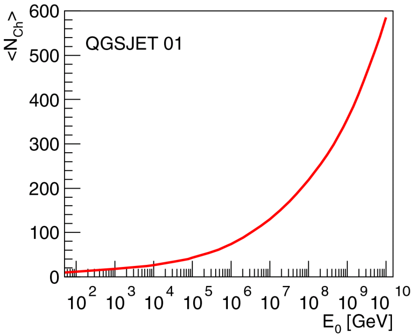
JRH, J. Phys. G 29 (2003) 2439

Average depth of the shower maximum

Heitler Model – X_{max}

multiplicity of charged particles produced in π-N interactions

$$N_{ch} = N_0 \left(\frac{E_0}{\text{PeV}} \right)^{\eta} \quad \eta=0.13$$



JRH, Mod. Phys. Lett. A 22 (2007) 1533

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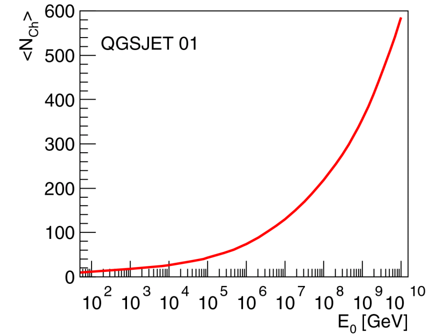
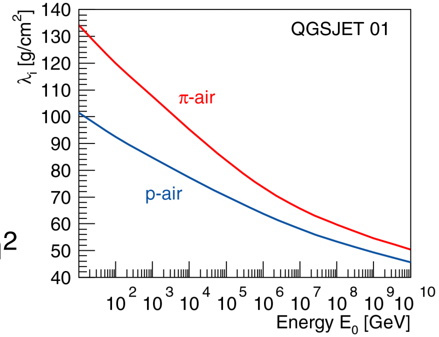


proton air interaction length

$$\lambda_i^{p-air} = \xi + \zeta \lg \frac{E_0}{\mathrm{PeV}}$$ ζ=-4.88 g/cm²



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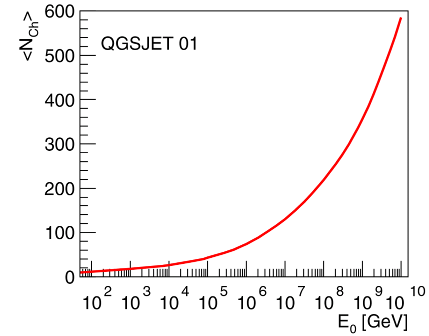

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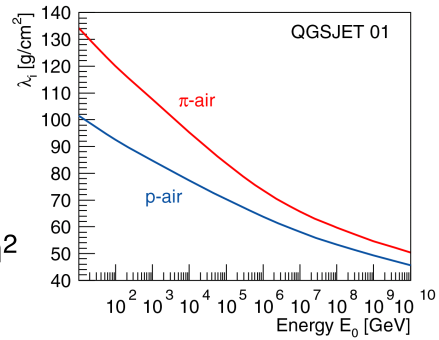


elongation rate

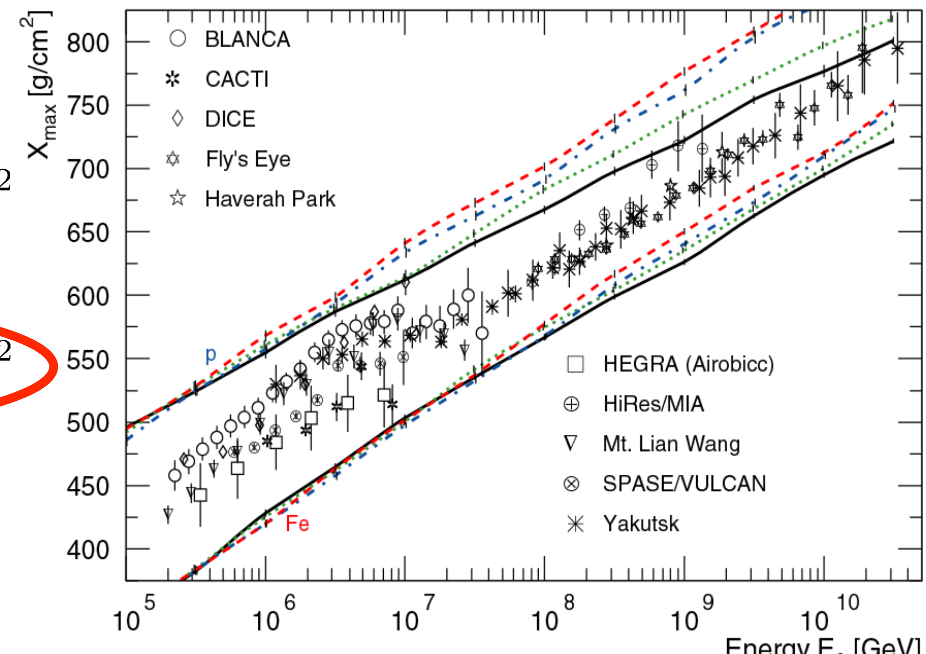
e/m shower $\Lambda^{\gamma} = X_0 \ln 10 \approx 84.4 \mathrm{g/cm}^2$

proton shower

$$\Lambda^p = X_0 \ln 10 - \eta X_0 \ln 10 + \zeta \ln 2 \approx 70 \mathrm{g/cm}^2$$

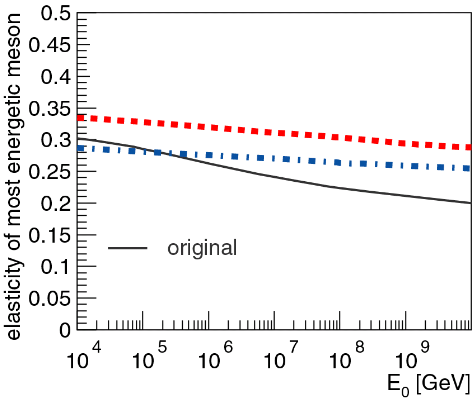
X_{max} for heavy nuclei

$$X_{max}^{A} = X_{max}^{p} - X_0 \ln A$$



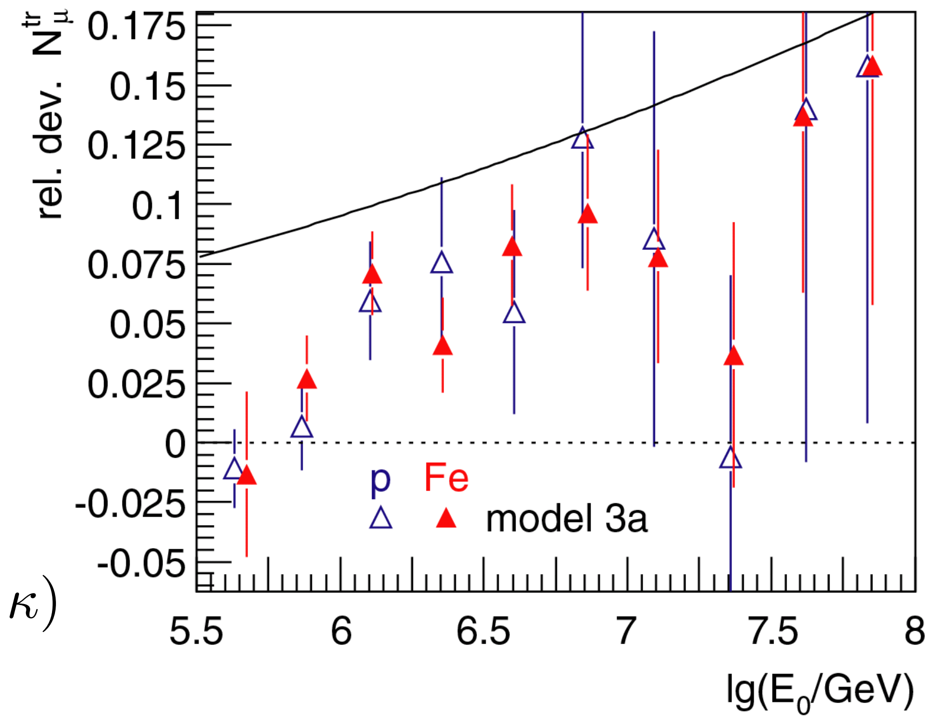
JRH, Mod. Phys. Lett. A 22 (2007) 1533

JRH, J. Phys. G 29 (2003) 2439



Elasticity ↗

δN_μ vs. E_0



Heitler model:

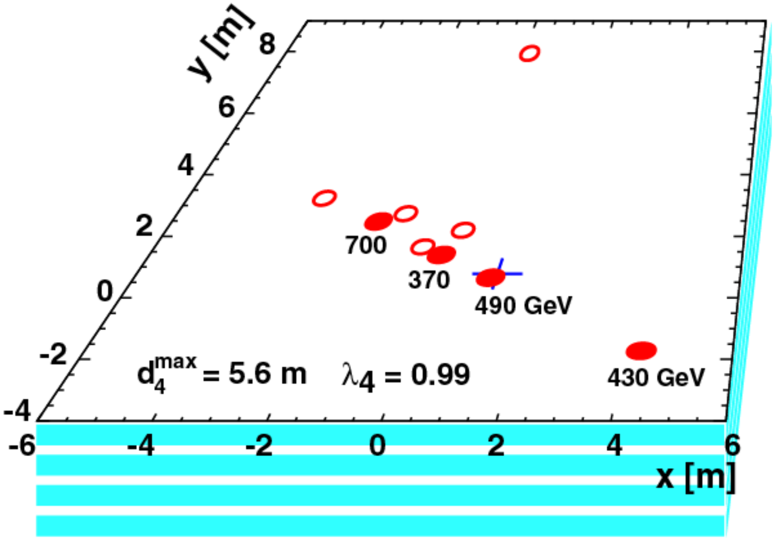
$$N_\mu = \left(\frac{E_0}{\xi_c^\pi}\right)^\beta \quad \xi_c^\pi \approx 20\ \mathrm{GeV}$$

$$\beta \approx 1 - 0.14(1-\kappa)$$

J. Matthews, Astropart. Phys. 22 (2005) 387

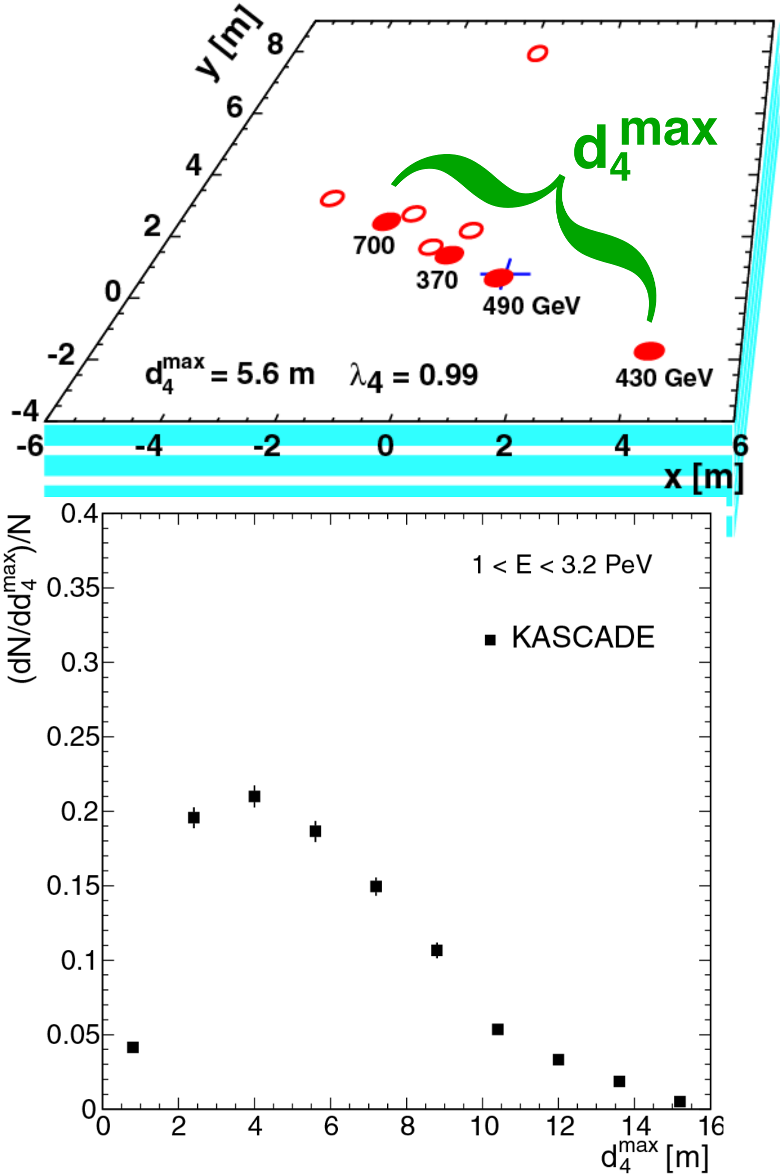
JRH et al., 29th Int. Cosmic Ray Conf. Pune 6 (2005) 121

Transverse momentum in hadronic interactions



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

Transverse momentum in hadronic interactions



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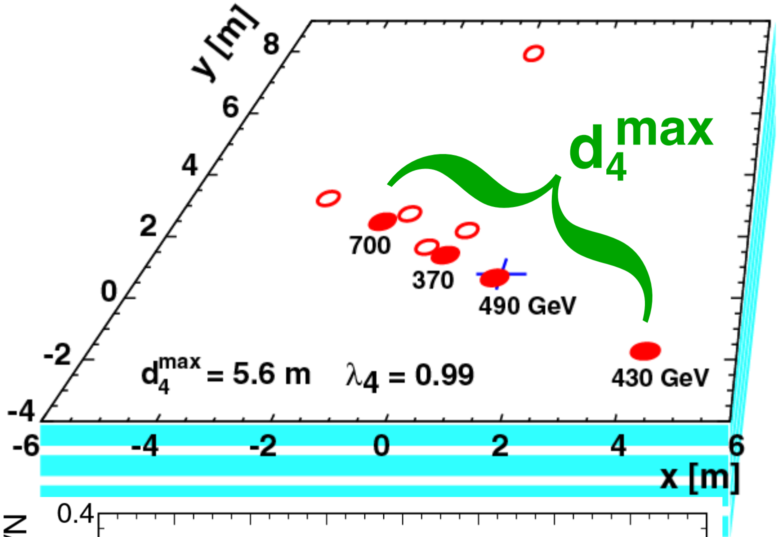
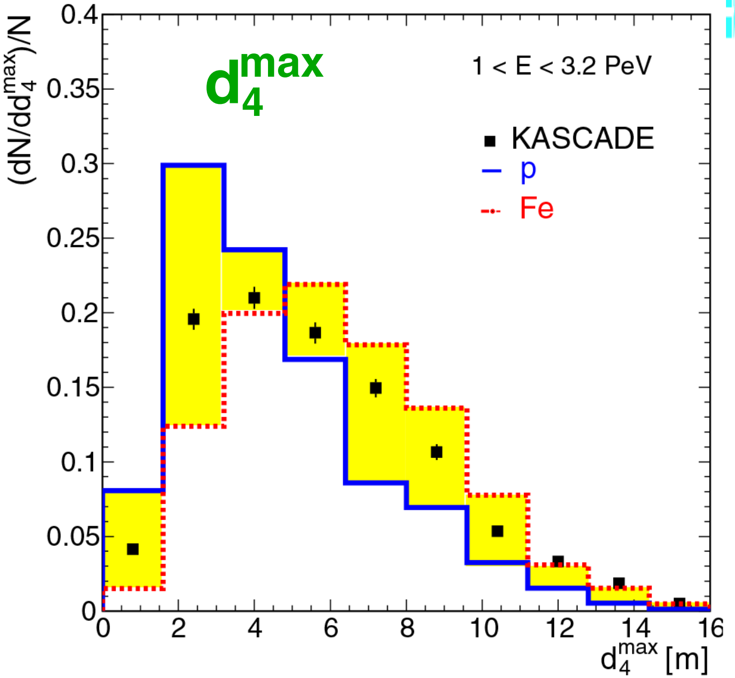
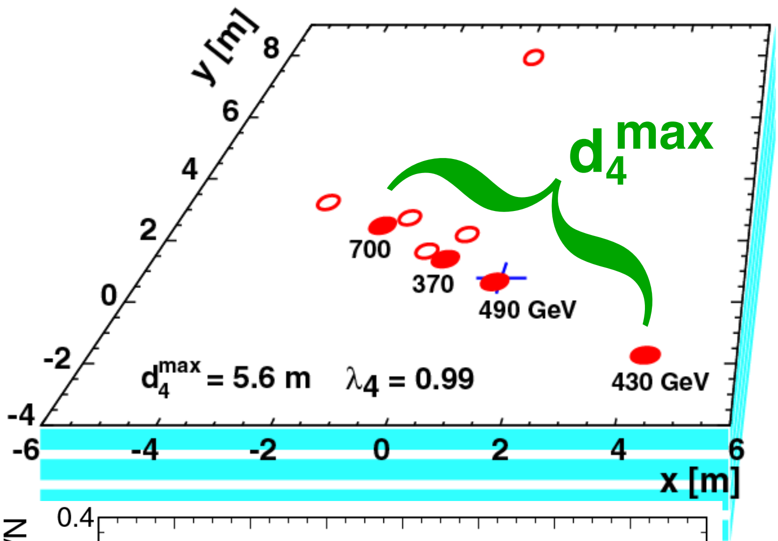


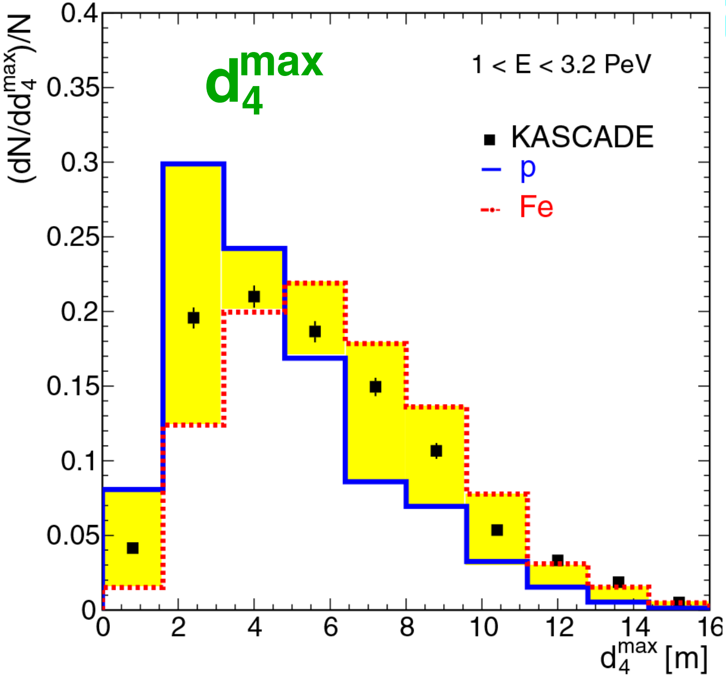


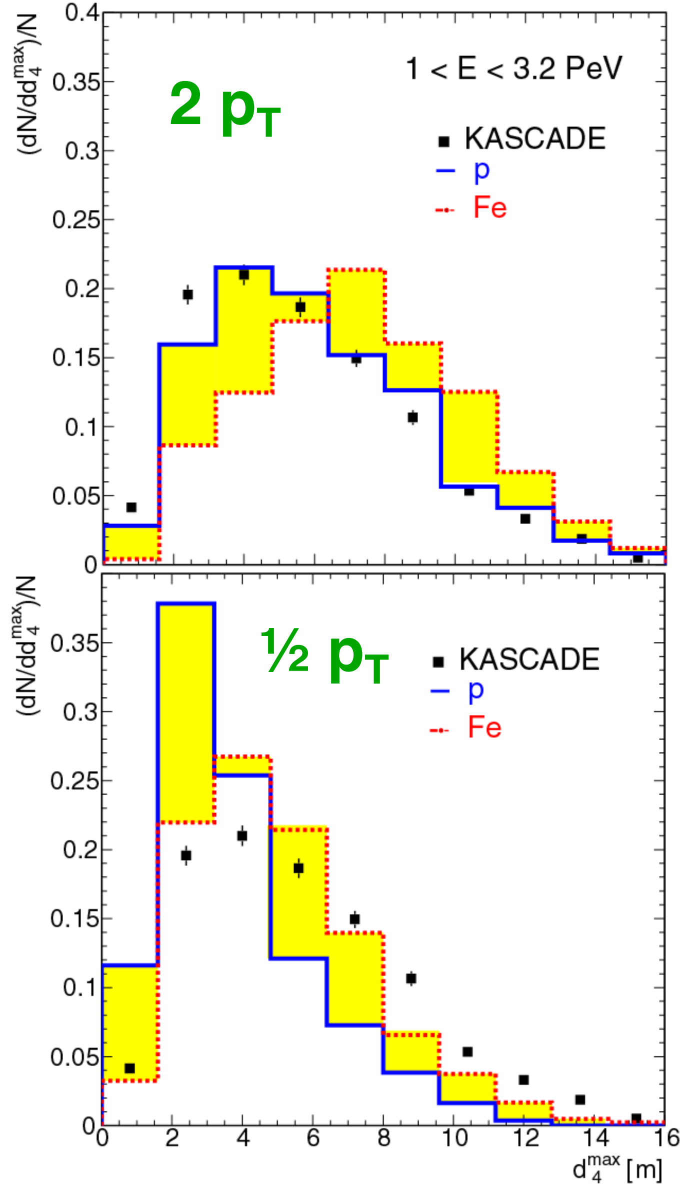
CORSIKA/QGSJET 01

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

Transverse momentum in hadronic interactions



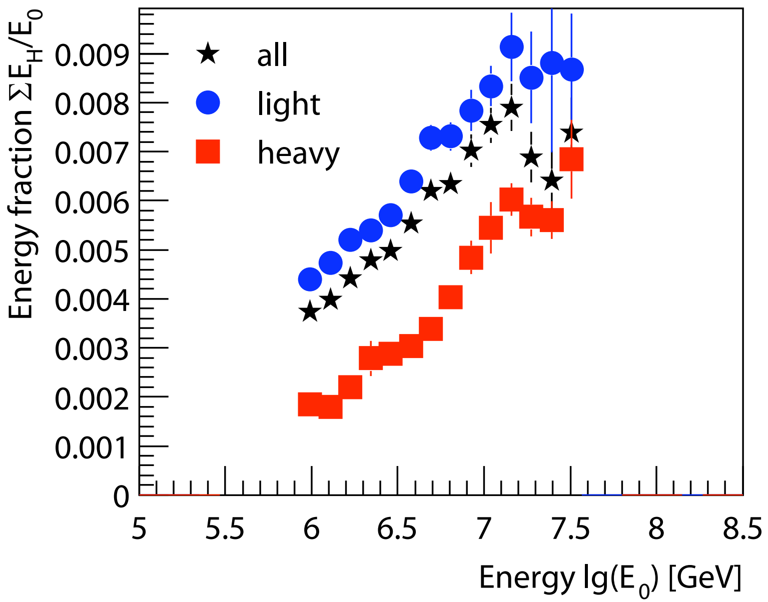




CORSIKA/QGSJET 01

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

Attenuation length of hadrons in air showers



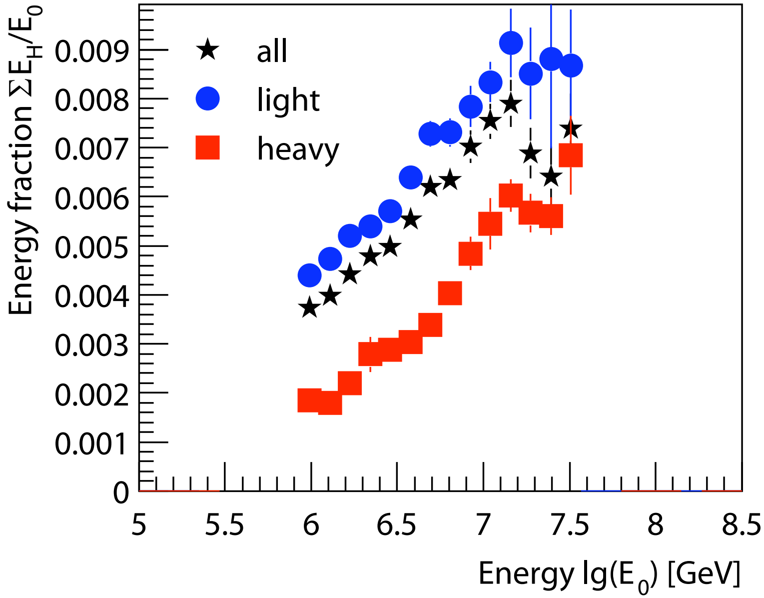
fraction of energy which reaches the ground in form of hadrons

$$R = \frac{\sum E_H}{E_0}$$

$$\lg E_0 \approx 0.19 \lg N_e + 0.79 \lg N'_\mu + 2.33.$$

W.D. Apel et al, submitted to PRD

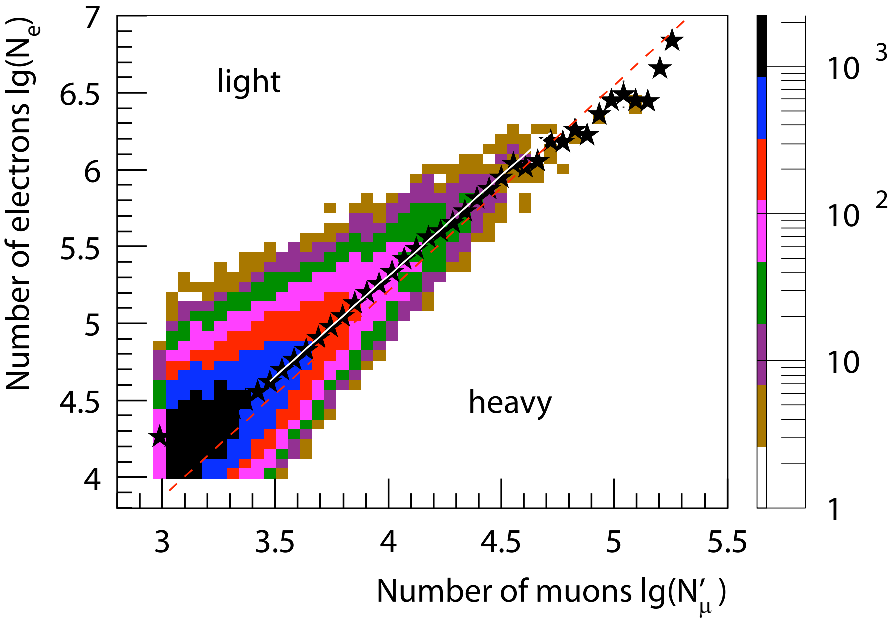
Attenuation length of hadrons in air showers



fraction of energy which reaches the ground in form of hadrons

$$R = \frac{\sum E_H}{E_0}$$

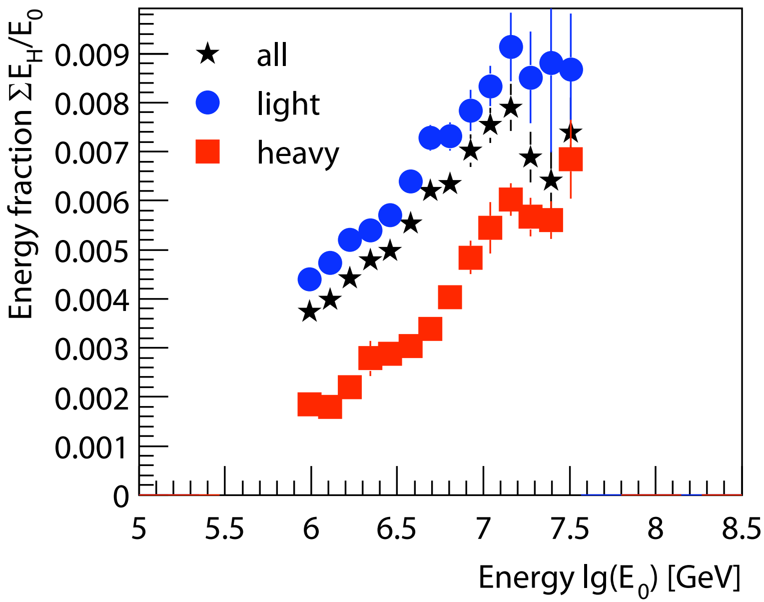
$$\lg E_0 \approx 0.19 \lg N_e + 0.79 \lg N'_\mu + 2.33.$$



use N_e and N_μ to select „light“ and „heavy“ component

W.D. Apel et al, submitted to PRD

Attenuation length of hadrons in air showers



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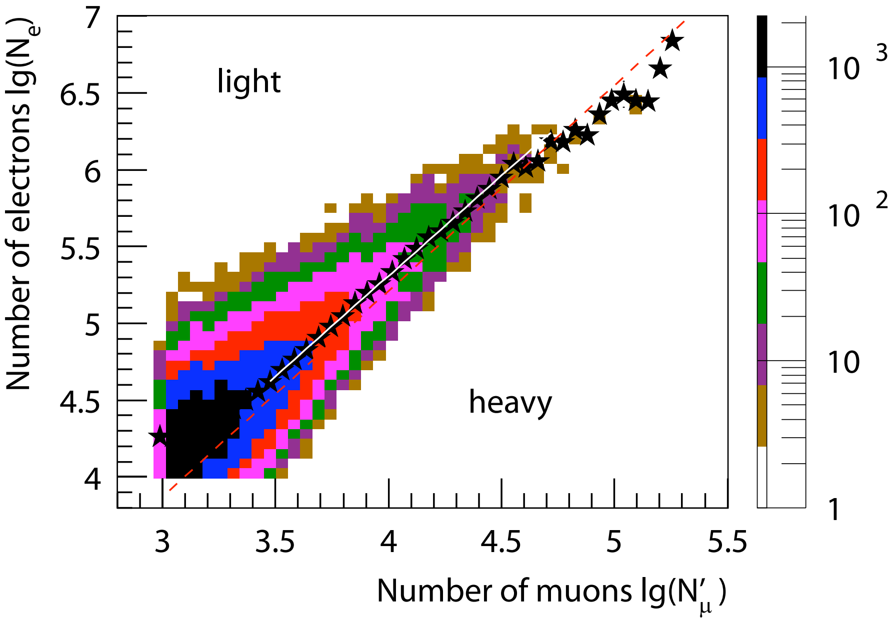


use N_e and N_μ to select „light" and „heavy" component

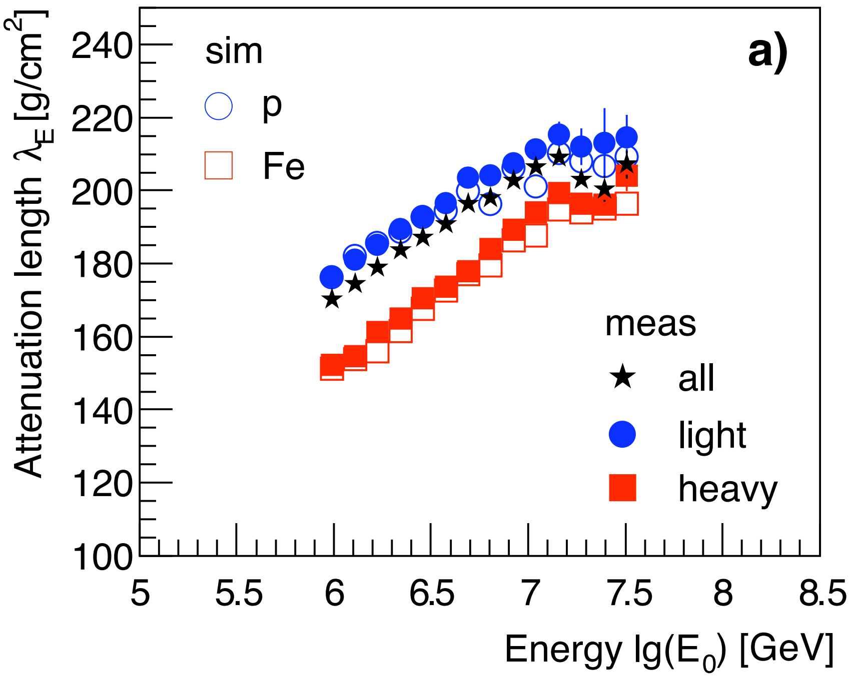
define attenuation length as

$$R = \exp - \left(\frac{X}{\lambda}\right)$$

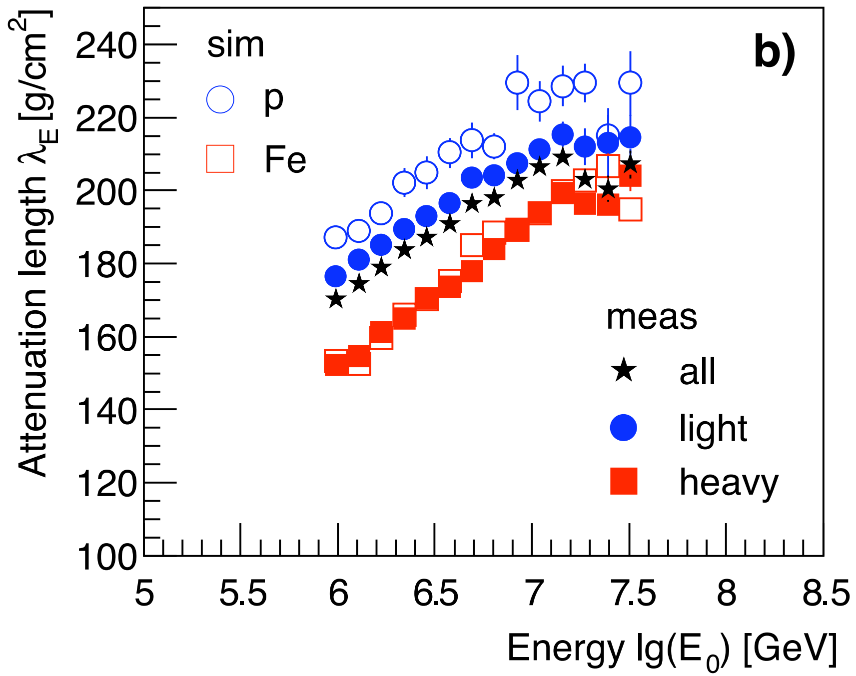
W.D. Apel et al, submitted to PRD

Attenuation length of hadrons in air showers

QGSJET 01



QGSJET 01 modified with lower inelastic cross sections



method very sensitive to inelastic cross sections

$$\sigma_{p-air} - 5\% \text{ at} 10^6 GeV$$

$$\epsilon + 12\%$$

W.D. Apel et al, submitted to PRD (2009)

Test of hadronic interaction models with air shower data

air shower data ...

- are used for quantitative tests of hadronic interaction models
- are used to improve interaction models
- provide information on hadronic interactions beyond accelerator range