Cosmic Ray Interactions near the GZK and below

Skopelos, 2005

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Overview

introduction

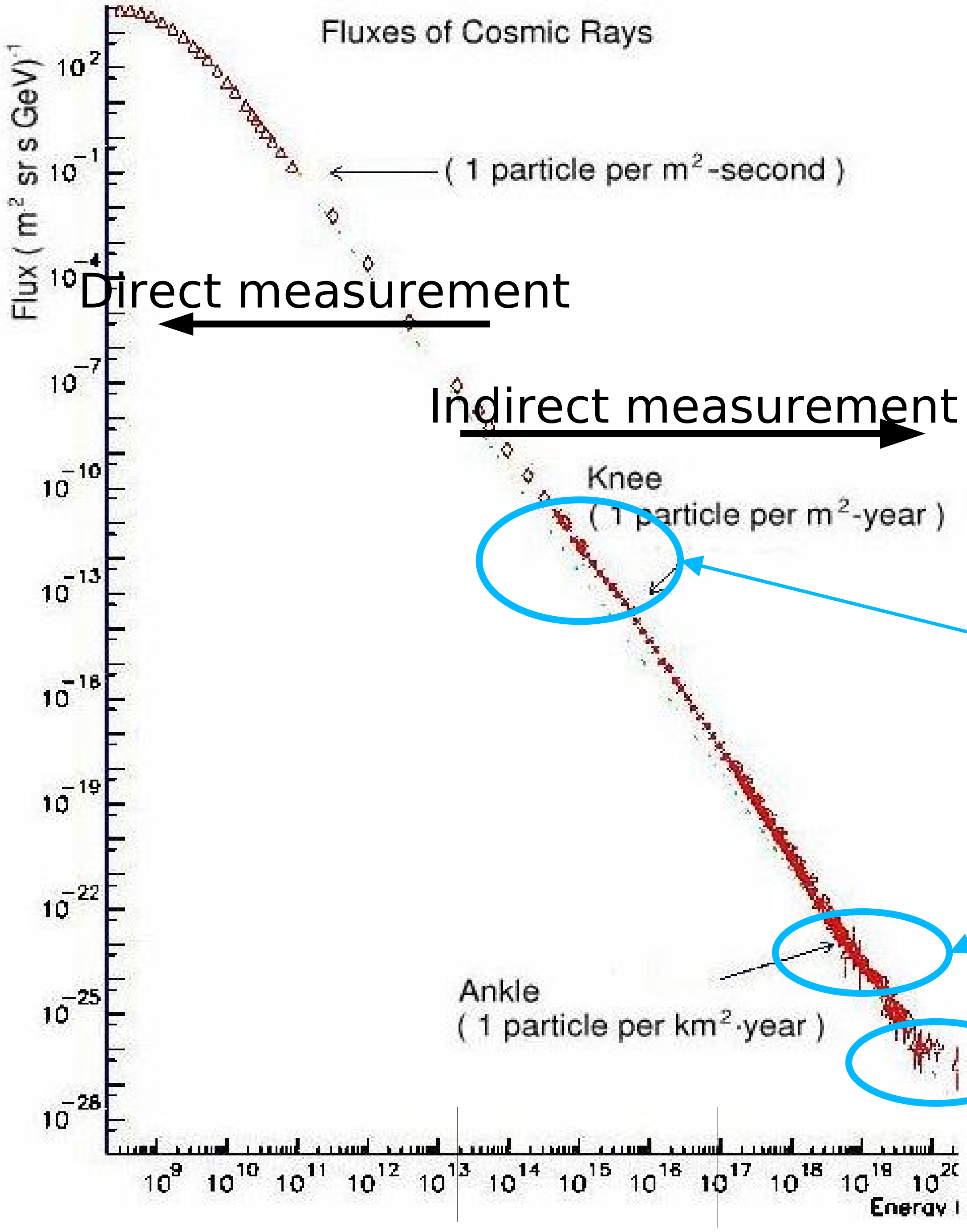
simulation of air-showers
- MC - hybrid

observables
- long-lat
- detector-simulations

input from hadronic models
- relevant physical input: sigma, dn/dxF,
- mult for muons, K - forward scattering

hadronic models and air shower data:
- muons bundles
- Kascade data
- Lateral distribution functions

The Cosmic Ray Spectrum



RHIC LHC

11 Energy-Decades
32 Decades in Flux

change in composition
light → heavy

Source
galactic → extragalactic??

should not be there

Status quo in ultra high energy cosmic rays

Hires and AGASA disagree on:

- normalization of cosmic ray flux
- trans-GZK events
- clustering of cosmic rays

Auger:

so far SD measurement calibrated with FD
no events above 1e20

Detection of UHECR

Direct detection not possible:

Flux very low:

E>1e20 eV

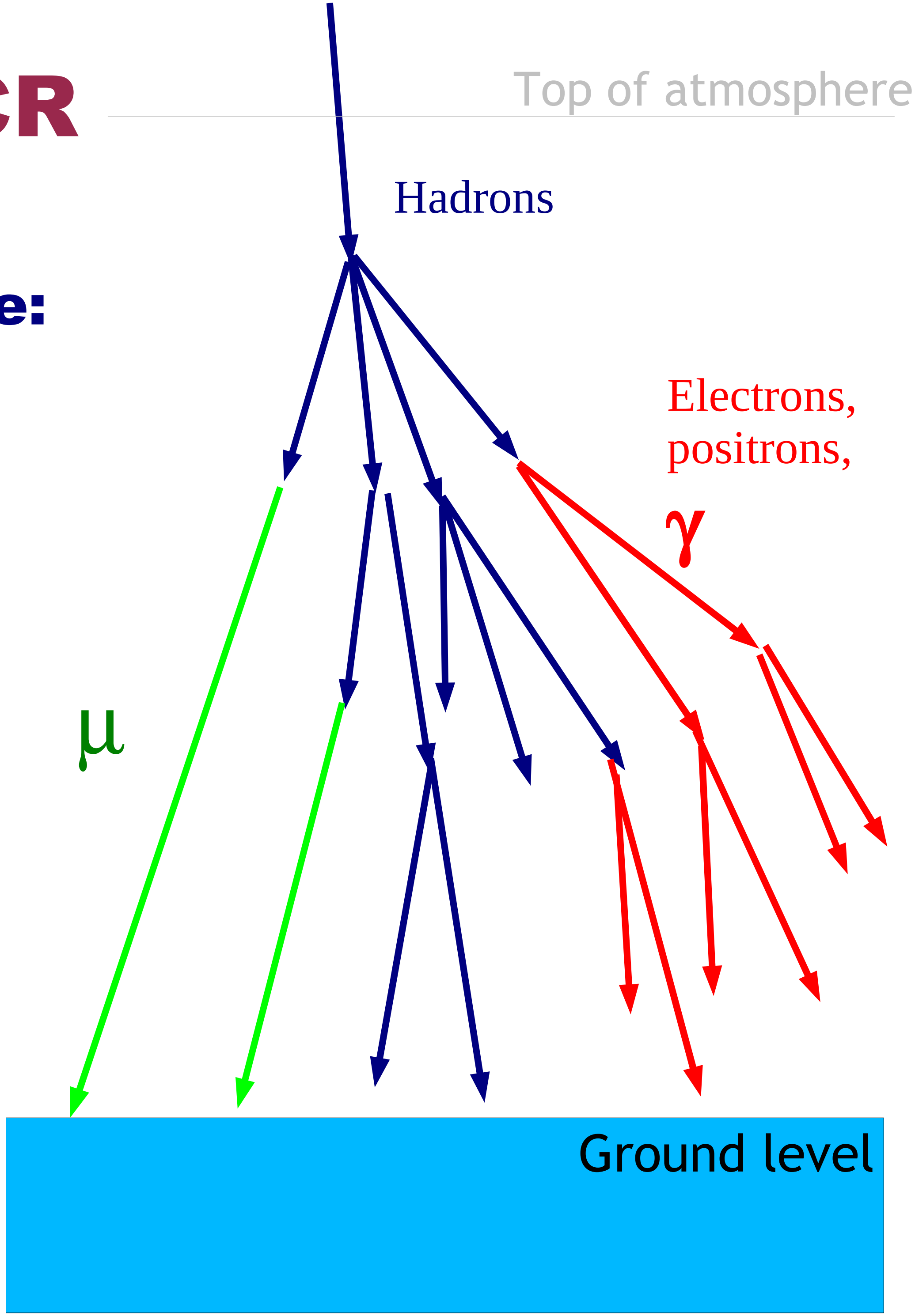
-> 1 particle/km^2/century

indirect detection via

AIR SHOWERS

induced by UHECRs

Reconstruct primary from shower properties:
- Energy,
- Arrival direction,
- Particle type



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Traditional Monte-Carlo method for air shower simulations

Choose some high energy
and low energy hadronic model

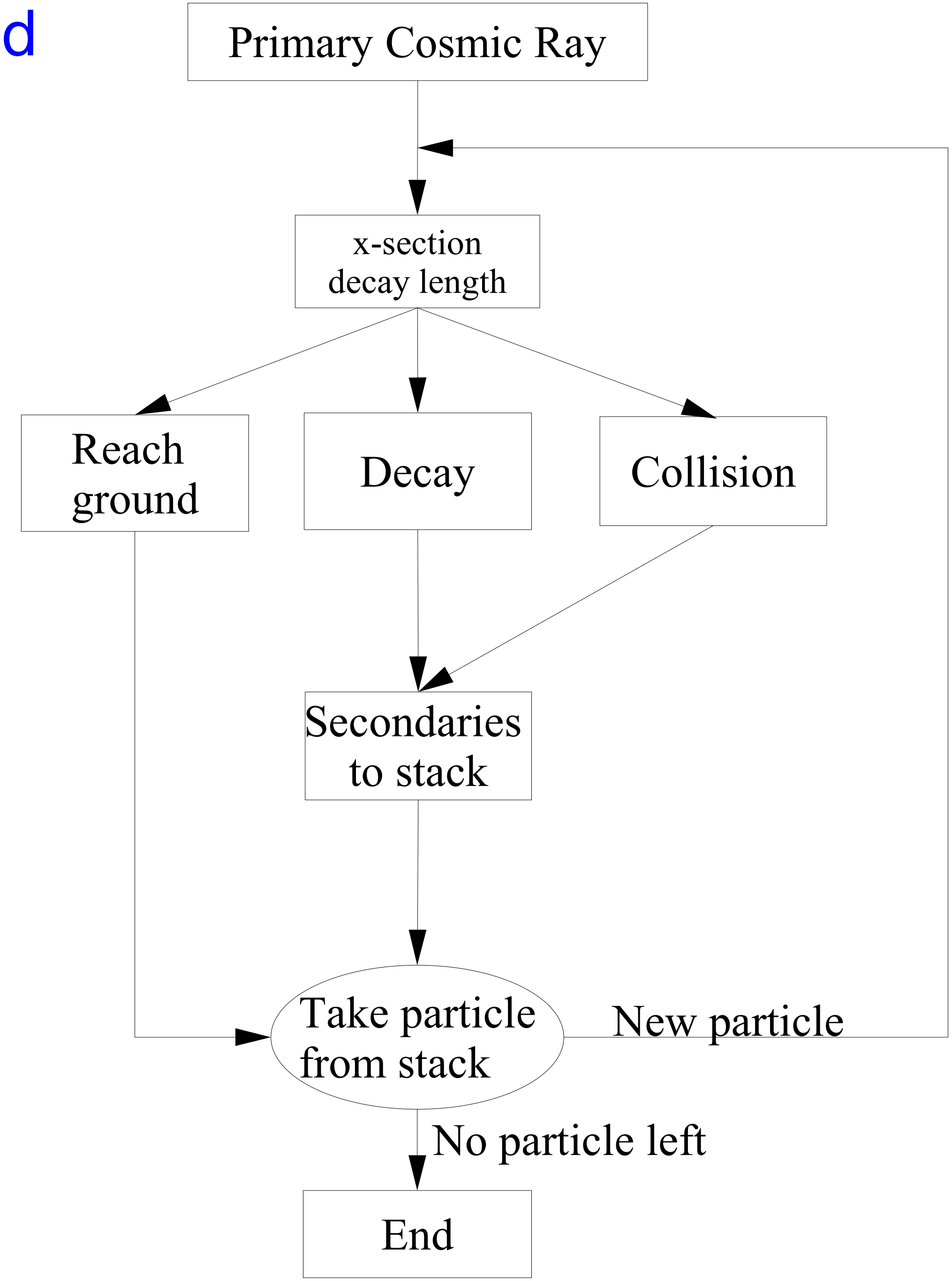
choose model for electromagnetic
interactions

Interaction length dependent
on thickness of material

decay length dependent on
geometrical path

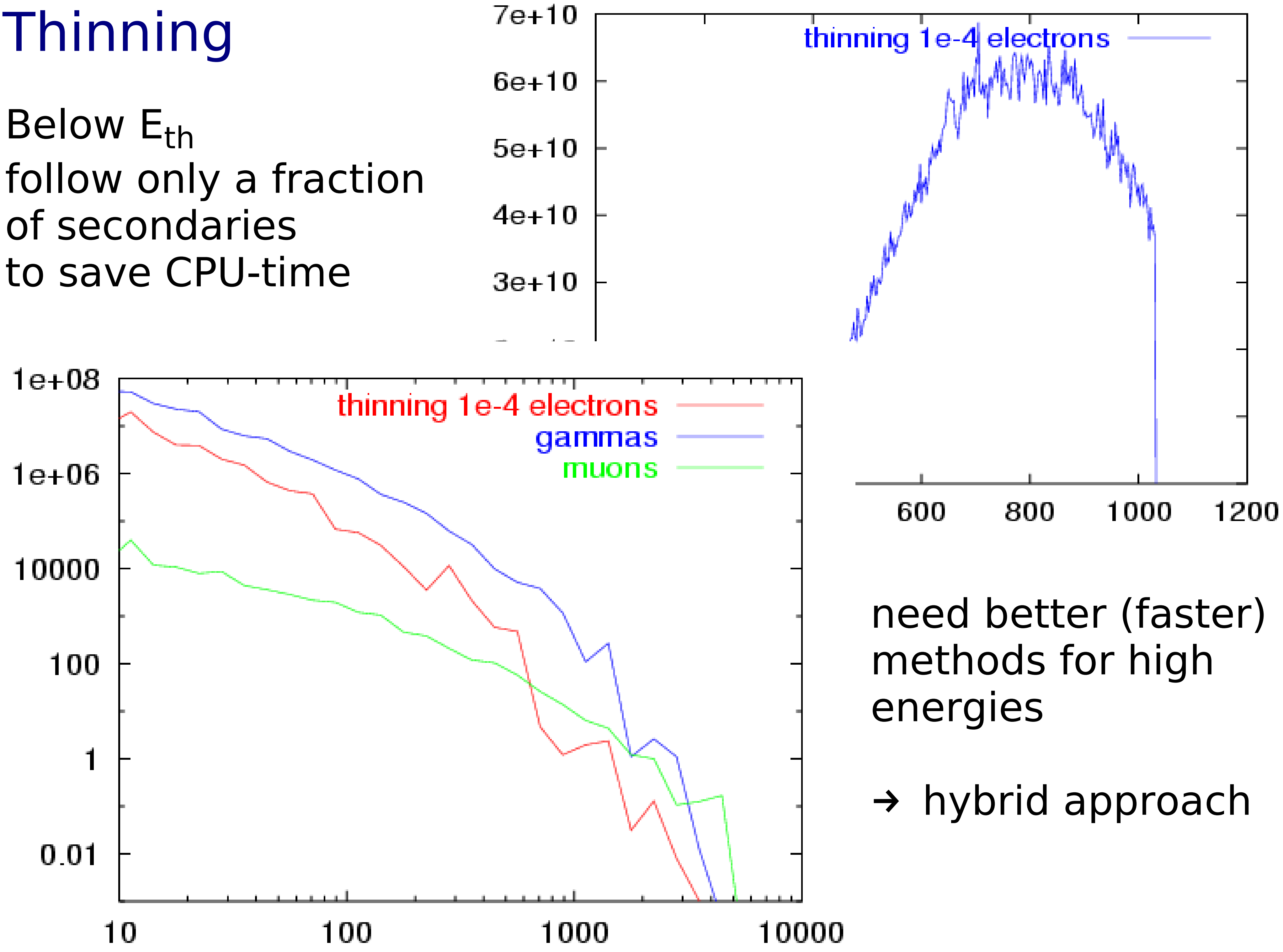
- MOCCA (Hillas),
- CORSIKA (Heck, Knapp et al),
- AIRES (Sciutto)

At 10^{10} GeV at Xmax ~$6\text{x}10^9$
particles ---> 1 year to simulate



Thinning

Below E_{th}
follow only a fraction
of secondaries
to save CPU-time



need better (faster) methods for high energies

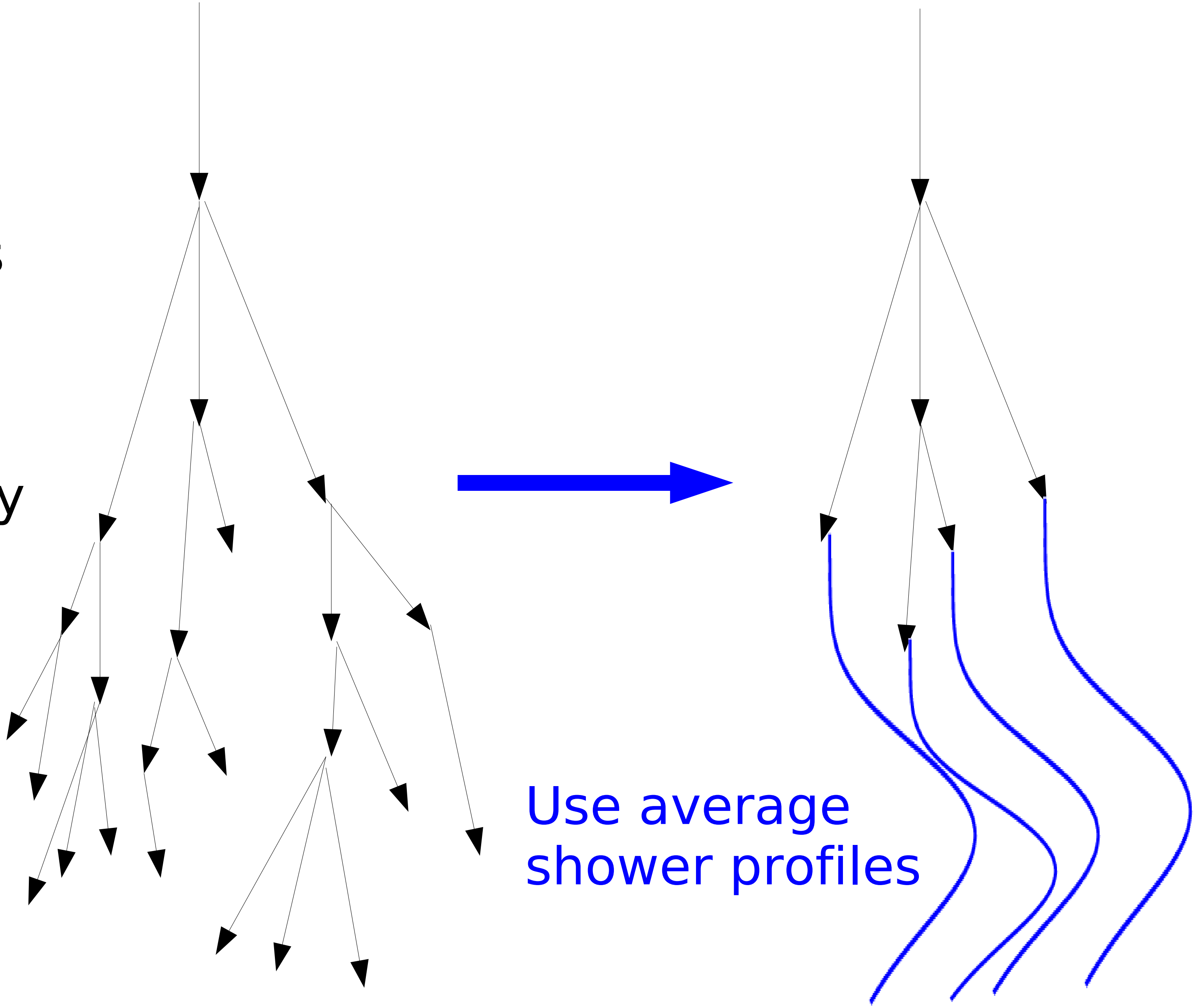
→ hybrid approach

1D Hybrid approach with Cascade Equations

neglect initial lateral spread

initial fluctuations by MC

compute shower profile numerically



Use average shower profiles

Cascade equations

$$\frac{\partial h_n(E,X)}{\partial X} = -h_n(E,X)\left(\frac{1}{\lambda_n(E)} + \frac{B_n}{E X}\right) + \sum_m \int_{E_{\min}}^{E_{\max}} h_m(E',X)\left(\frac{W_{mn}(E',E)}{\lambda_m(E')} + \frac{B_m D_{mn}(E',E)}{E' X}\right) \mathrm{d}E$$

h_n:number of hadrons n per dE

E: Energy   X: slant depth

B_n: decay constant

λ_n:interaction length

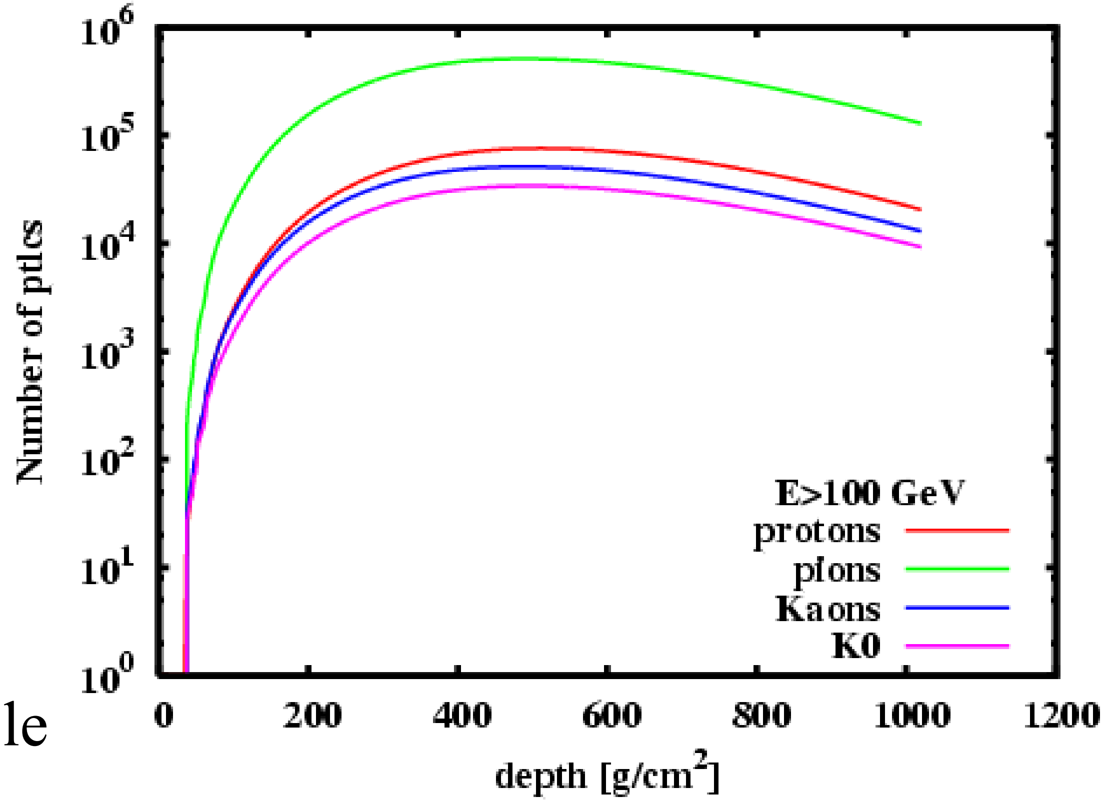
W_{mn}: collision function

D_{mn}: decay function

initial condition:

$h_n(E,X)=\delta(E-E_0)$ for a given particle

Solution:
$h_n(E,X)$



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The physics of hadronic interactions

$$\lambda_n = \frac{A\, m_u}{\sigma_{inel}}$$

Mean free path of particle n in the atmosphere

$$W_{mn}(E, E') = \frac{dN_{mn}}{dE'}$$

Spectrum of produced particles of type n from m+Air collision

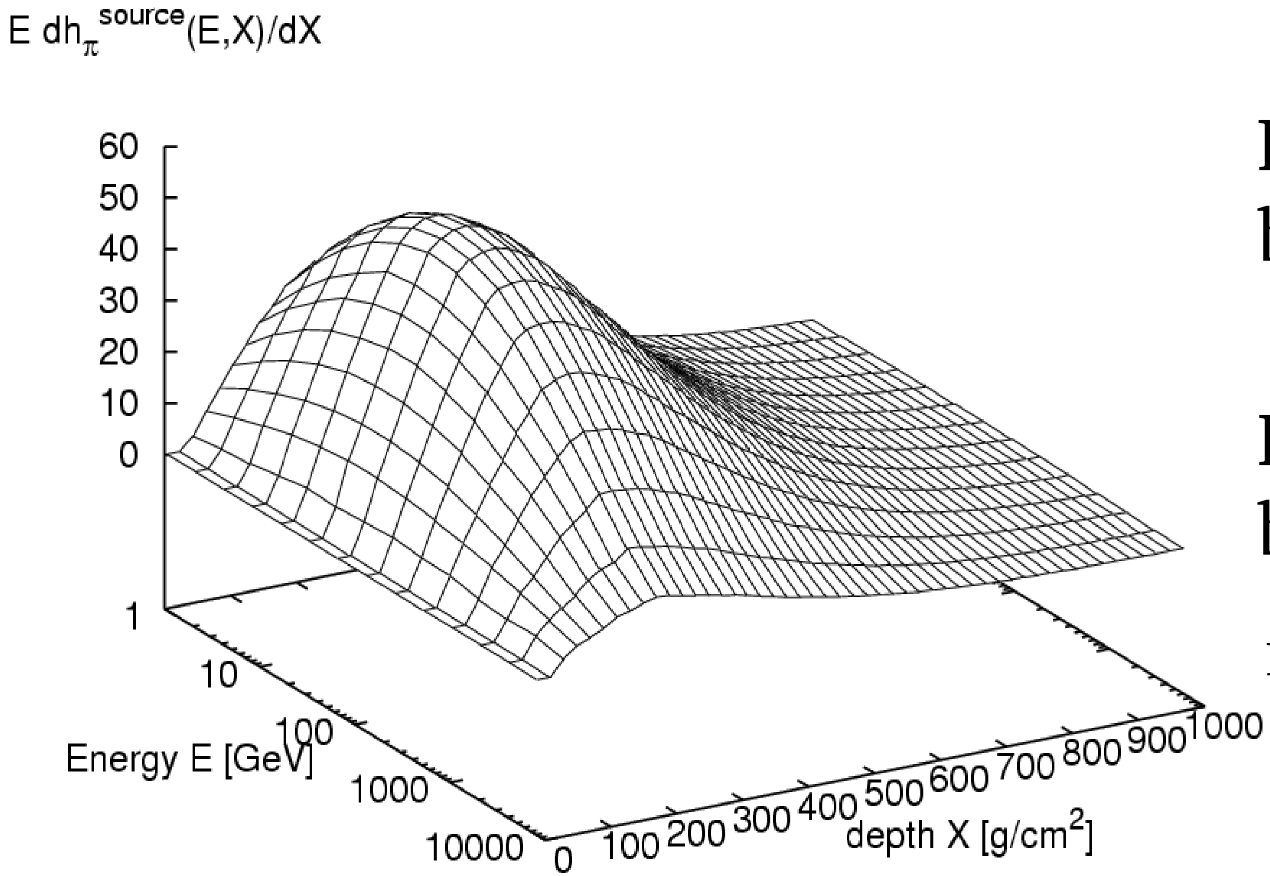
tabulated from MC

The Rest: Decays, electromagnetic interactions,
muon propagation,
under control (?)

Source function for low energy particles

$$\frac{\partial h_n^{source}(E,X)}{\partial X} =$$

$$\sum_m \int_{E_{min}}^{E_{max}} h_m(E',X) \left(\frac{W_{mn}(E',E)}{\lambda_m(E')} + \frac{B_m D_{mn}(E',E)}{E'X} \right) dE'$$



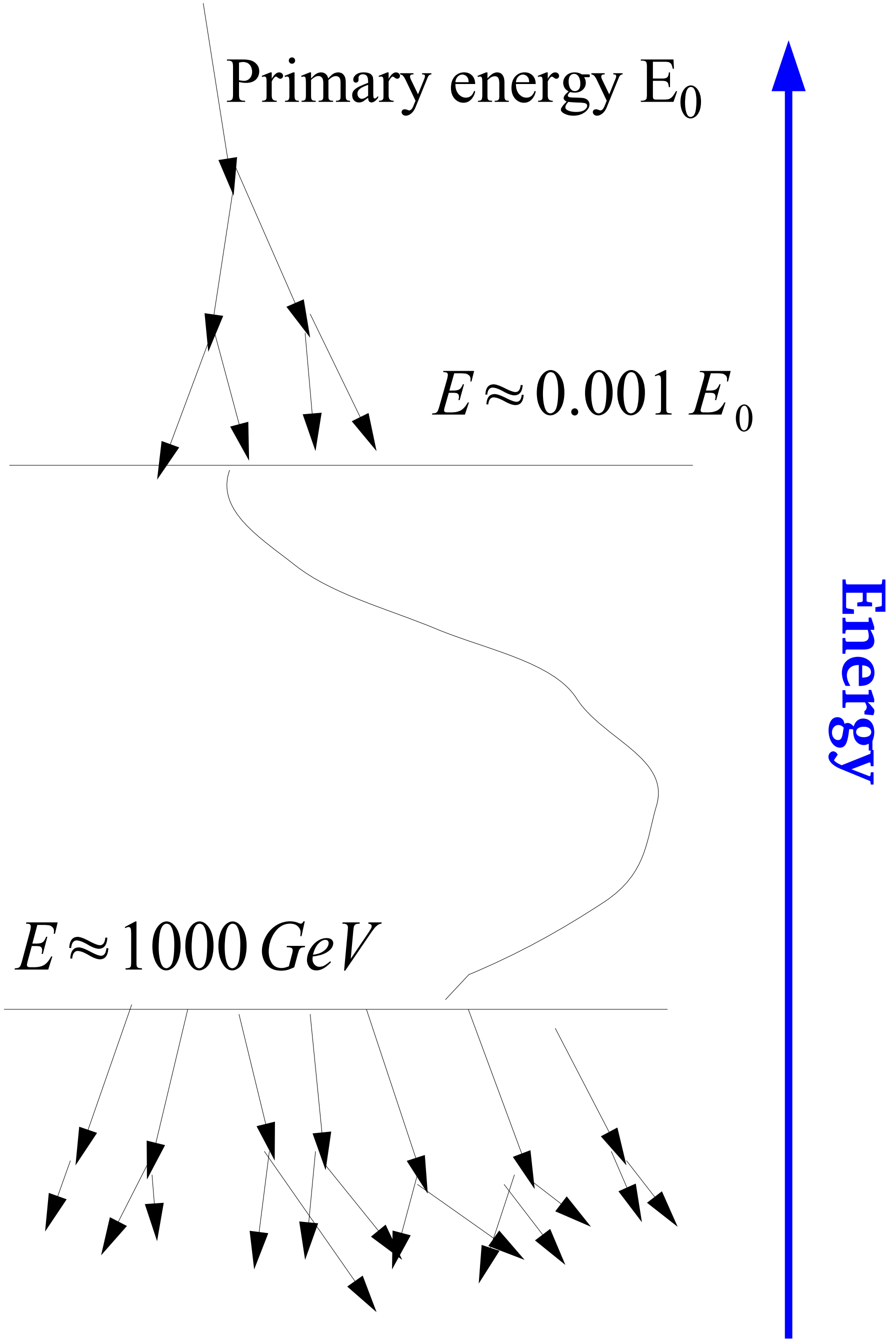
Production of hadrons below ~ 10^4 GeV

Electrons and photons below ~ 10 GeV

Place particles along shower axis

SENECA:
3D Hybrid Approach to Shower Simulation

HJD, G.Farrar
Phys.Rev.D67



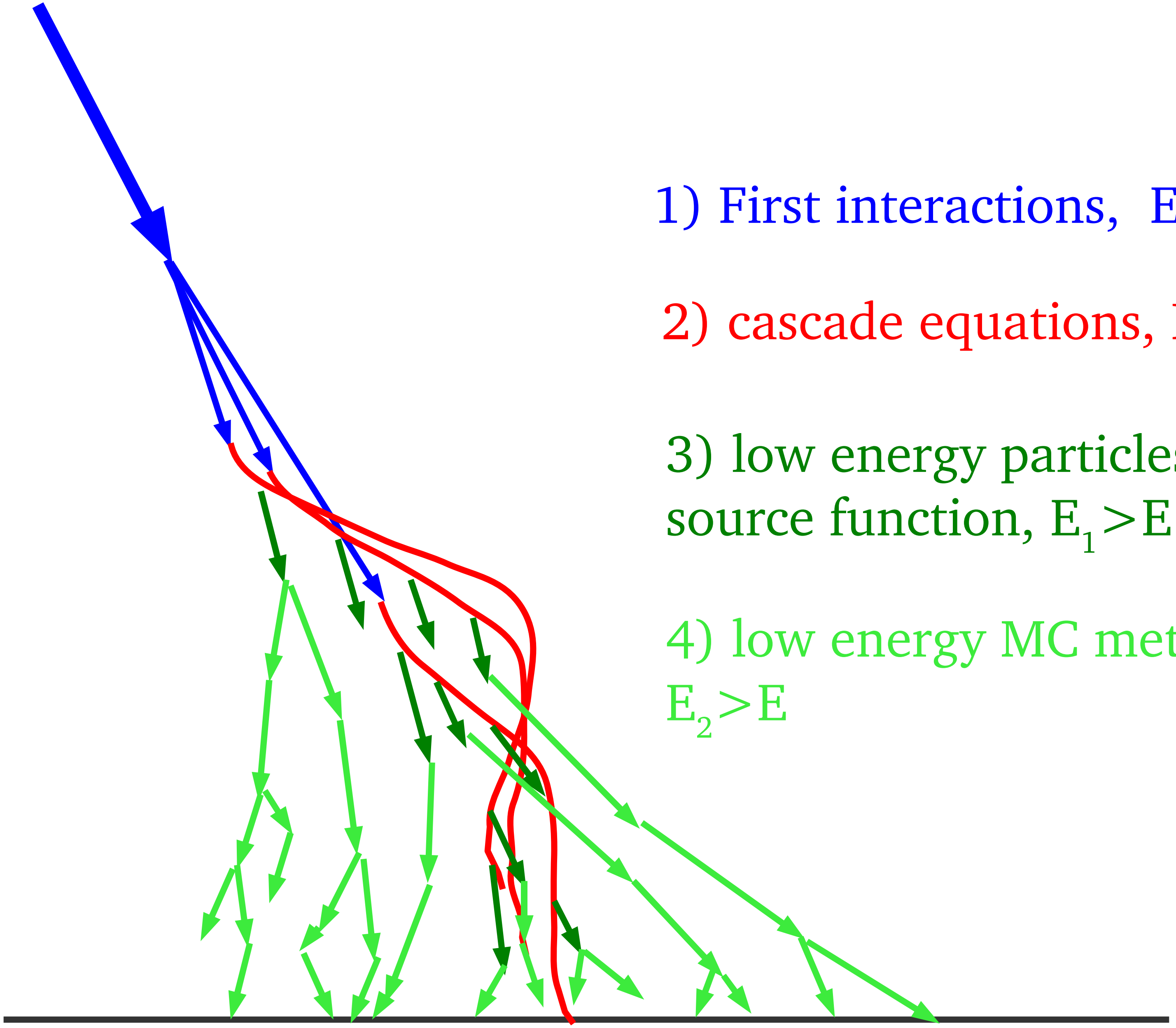
The initial part
of the shower
is calculated explicitly
to get natural fluctuations.

Once multiplicities grow
cascade equations solve
the transport analytically.
No thinning required !!

The low energy part again
can be done explicitly by
Monte Carlo to get the
lateral spread of the shower.

40x faster than pure MC

Visualization of procedure



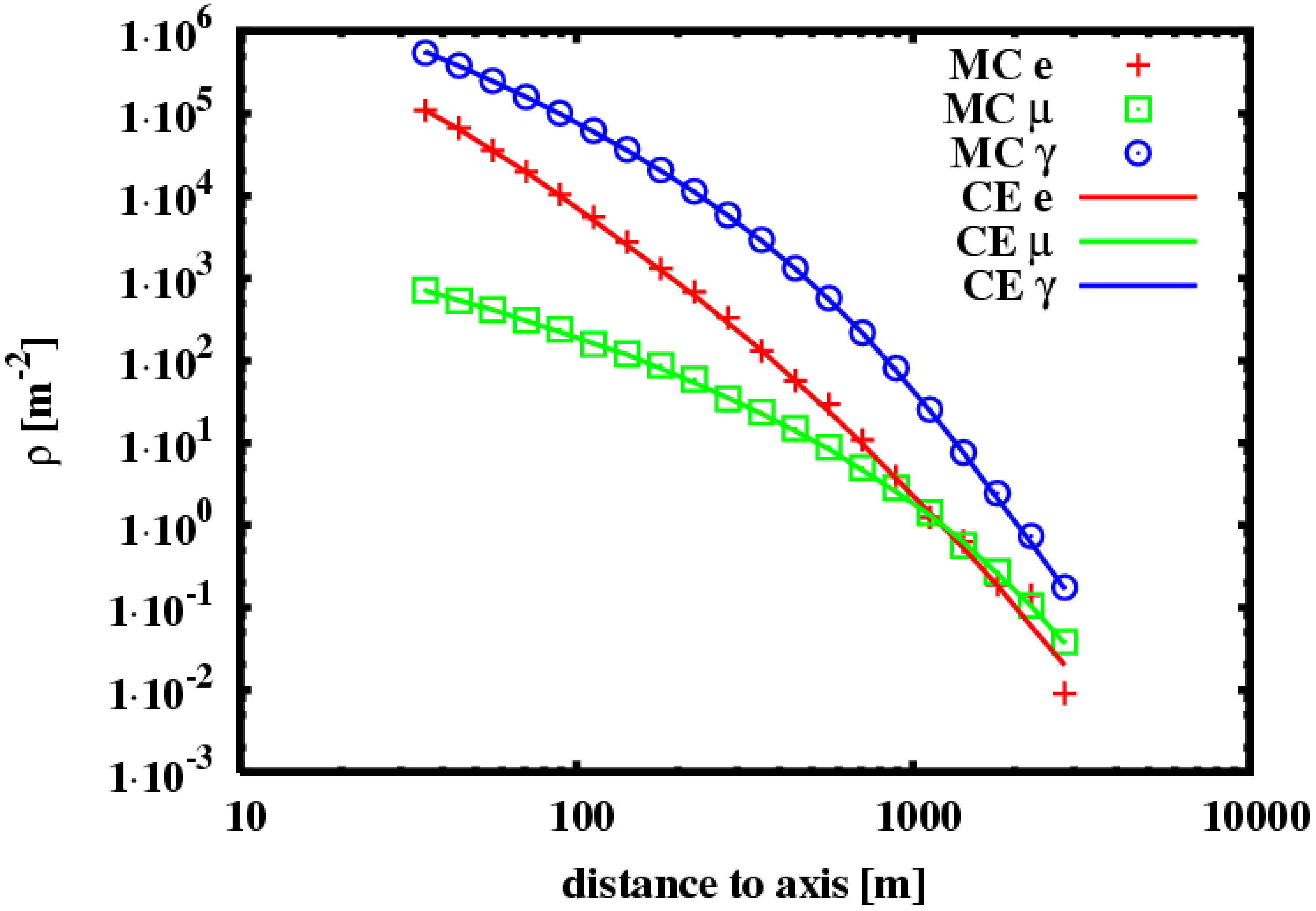
1) First interactions, $E>E_1$

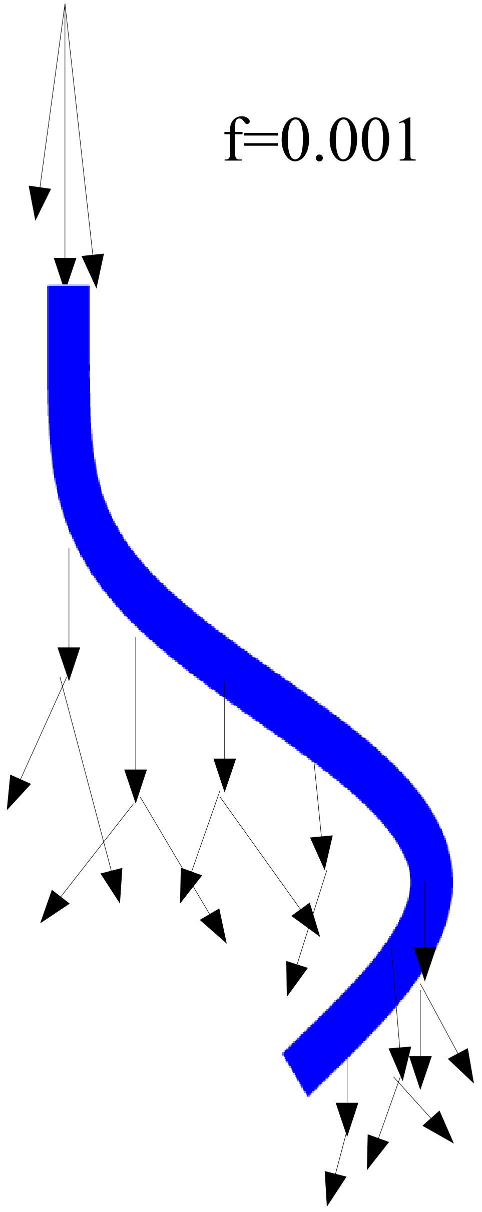
2) cascade equations, $E_1>E>E_2$

3) low energy particles from source function, $E_1>E>E_2$

4) low energy MC method, $E_2>E$

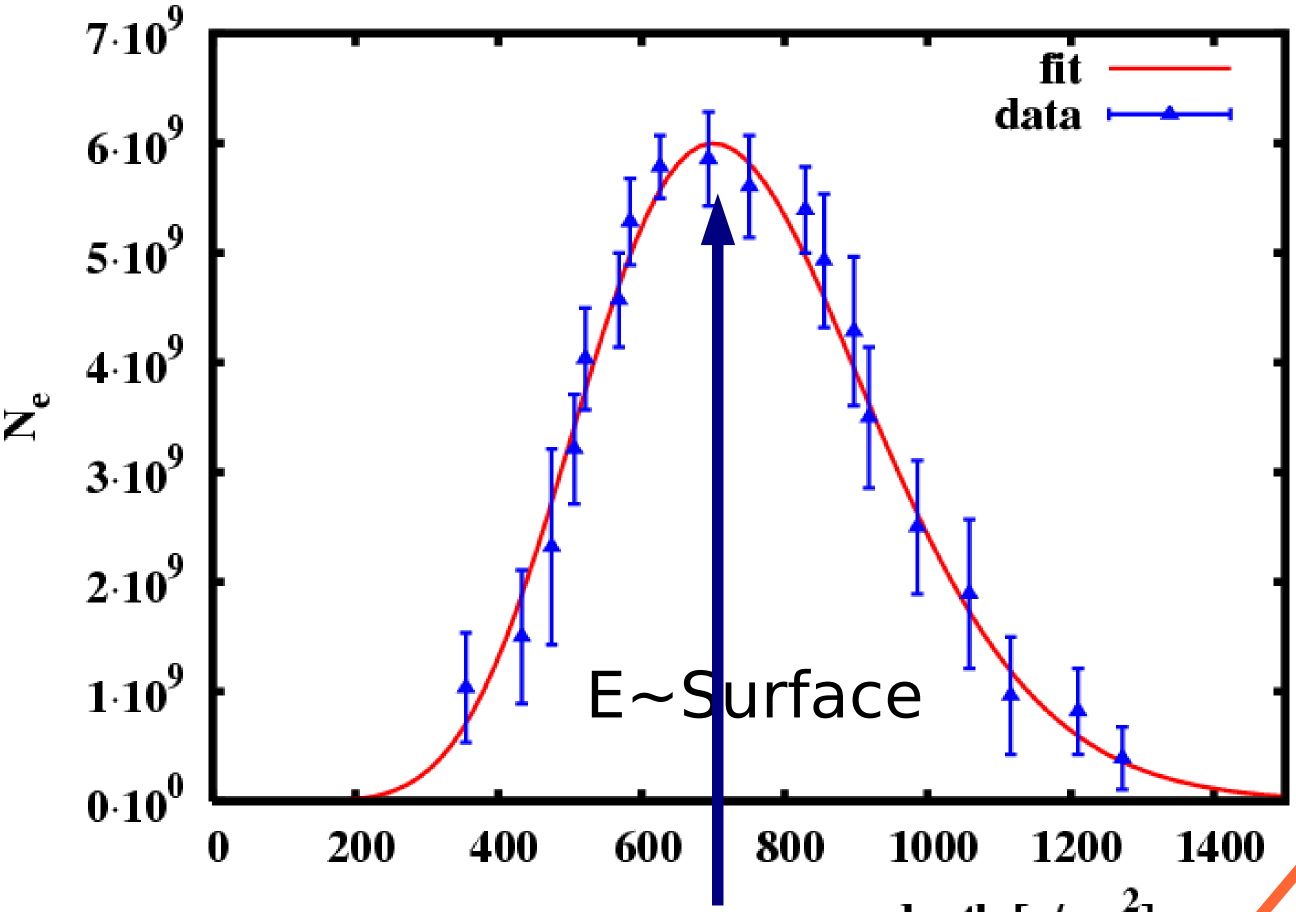
Lateral distributions with same high energy part





f=0.001

Longitudinal measurement with fluorescence light

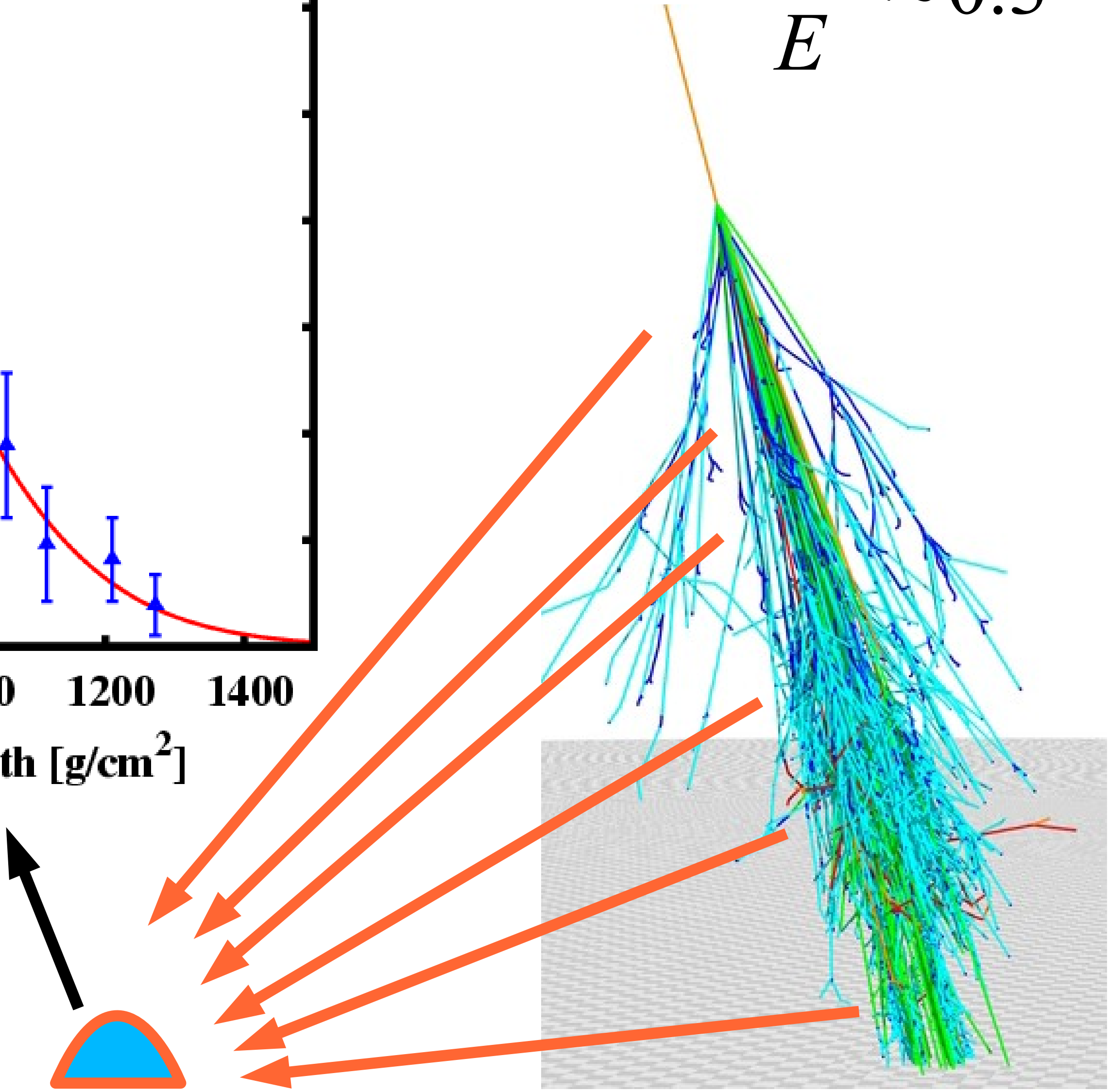


E~Surface

Xmax

$$\frac{\Delta E}{E} \approx 0.3$$

$$X = \int_{\infty}^{x} \rho(l)\, dl \ [\mathrm{g/cm^2}]$$



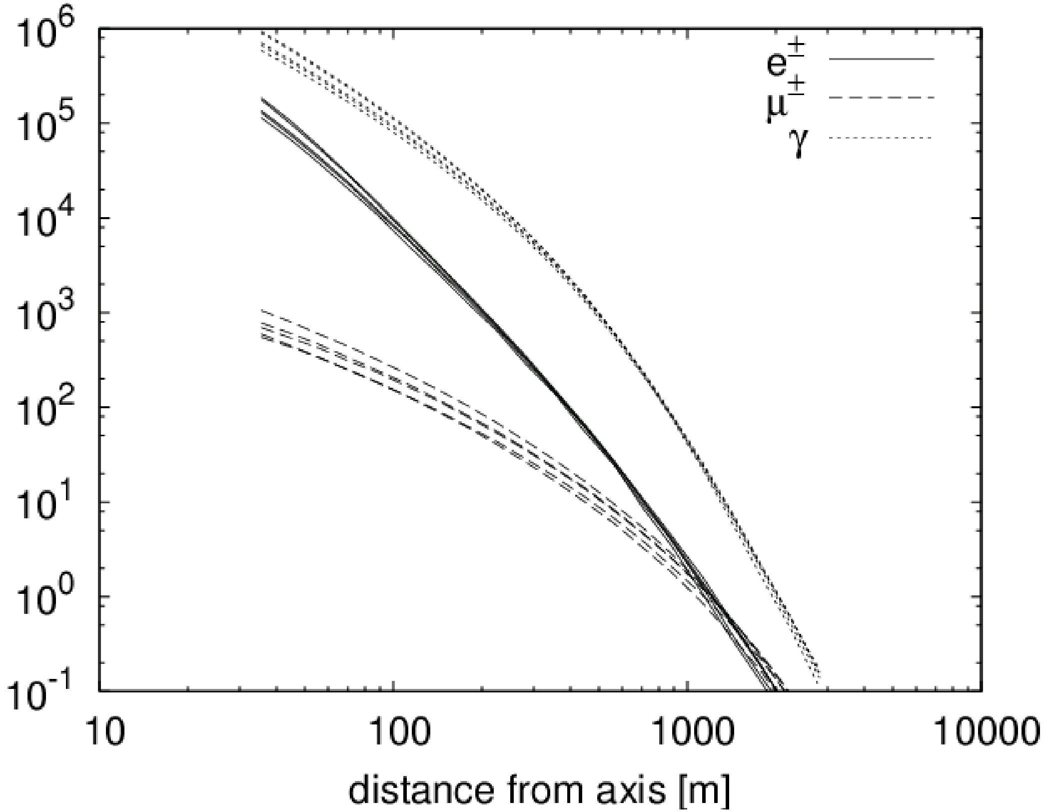
Fly's Eye detector

Lateral distribution functions

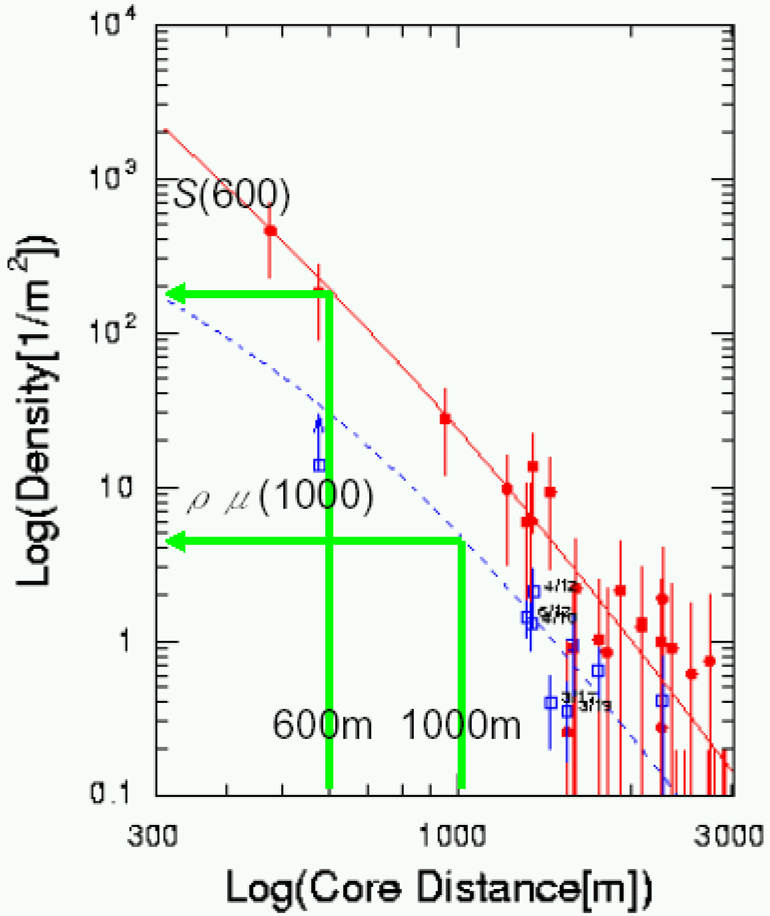
Fluctuations of the LDF of different showers cancel at some empirical distance from the shower axis
--> Energy estimator

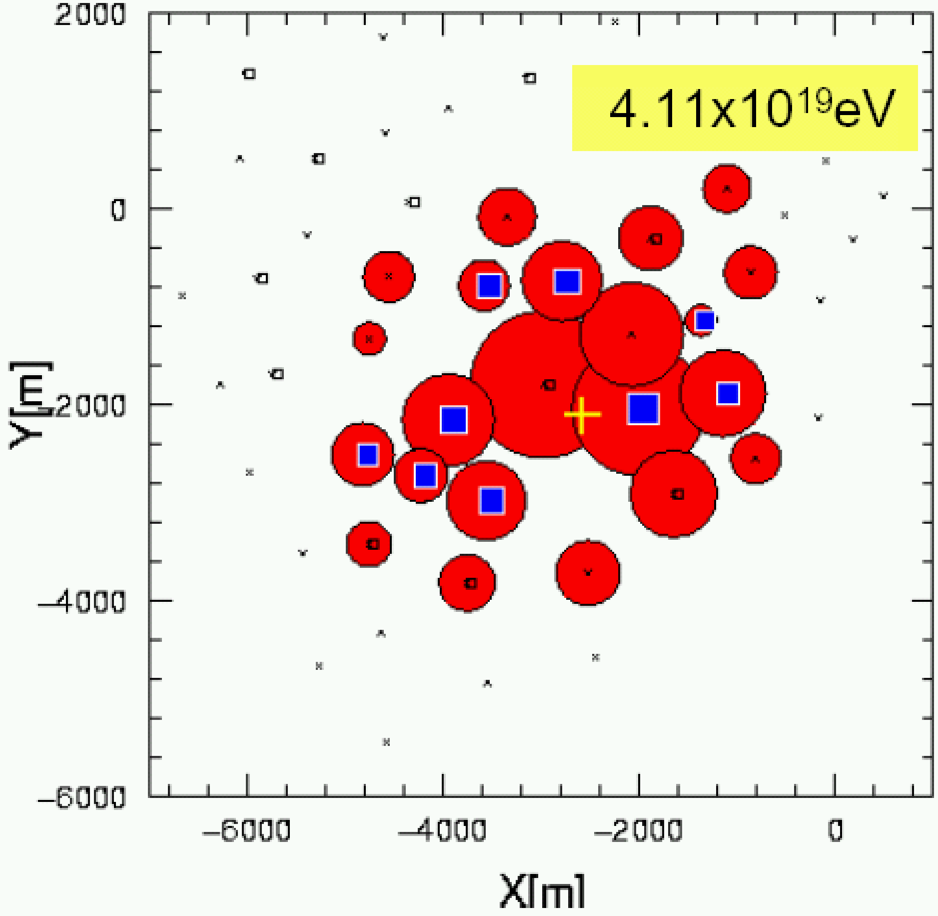
try to extract information about muons --> composition estimator

Common ground detectors:
- plastic scintillators
- water cherenkov



Event sample & observables





Energy estimator (charged particle density @600m): *S*(600)

From Kenji Shinozaki (AGASA)

Event generators commonly used in Air Shower Applications

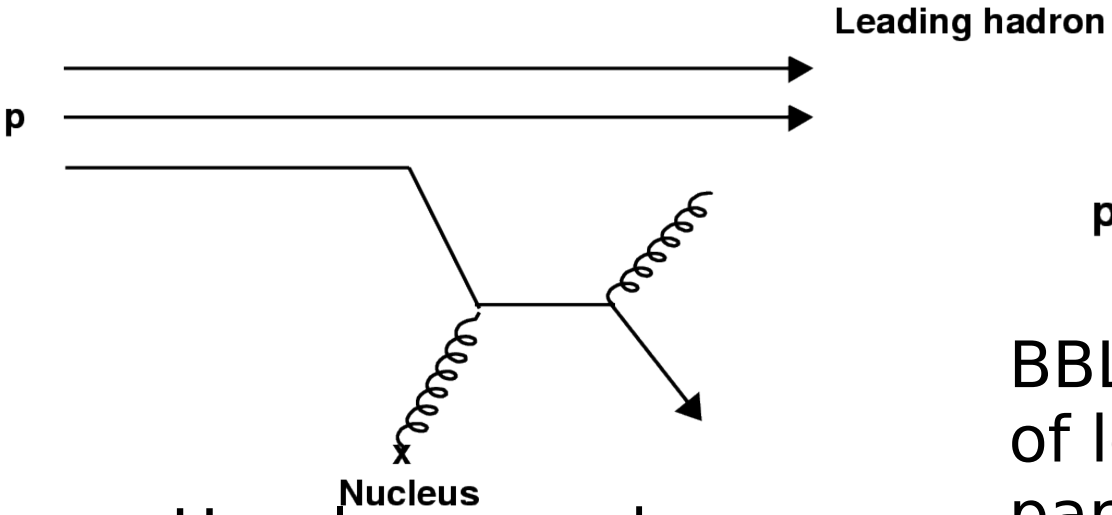
QGSjet01   (Ostapchenko, Kalmykov)
    multiple soft and semihard Pomeron exchange

QGSjet II   (Ostapchenko)
    enhanced Pomeron diagrams

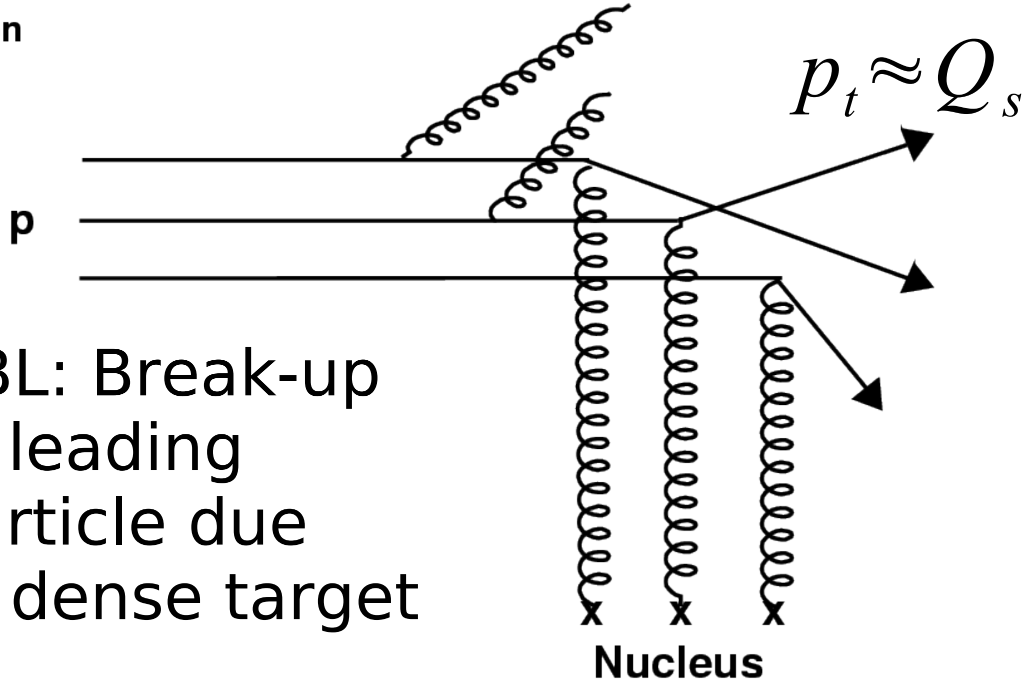
Sibyll 2.1   (Fletcher, Engel et al.)
    pQCD event generator with multiple soft int.
    energy dependent pt-cutoff

BBL 1.0   (HJD, Dumitru, Strikman)
    Implements parton saturation for forward scattering

BBL Monte Carlo



Usual approach
with leading particle



BBL: Break-up
of leading
particle due
to dense target

Valence quarks,
gluon distribution:

$$P_i(x) = f_i(Q_s^2(x), x)$$

$$<p_t> \approx Q_S(x)$$

valence quarks: GRV94 PDF (xf(x) dominant at high x)

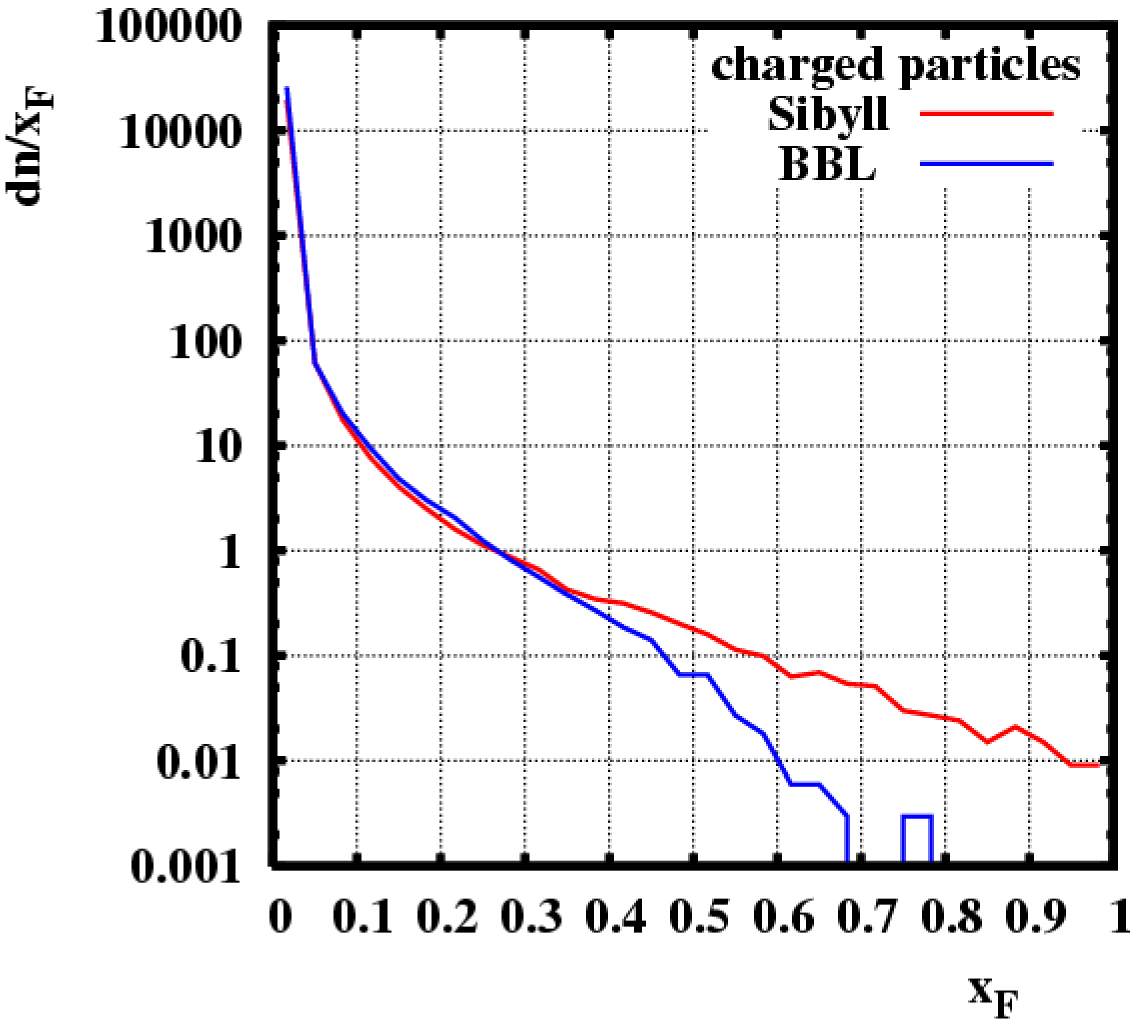
gluons: $$x\,g(x, q_t^2) \propto \frac{1}{\alpha_s} \min(q_t^2, Q_s^2(x))(1-x)^4$$

(Kharzeev, Levin, Nardi, NPA 2004)

Suppression of forward scatttering

Central p-N scattering

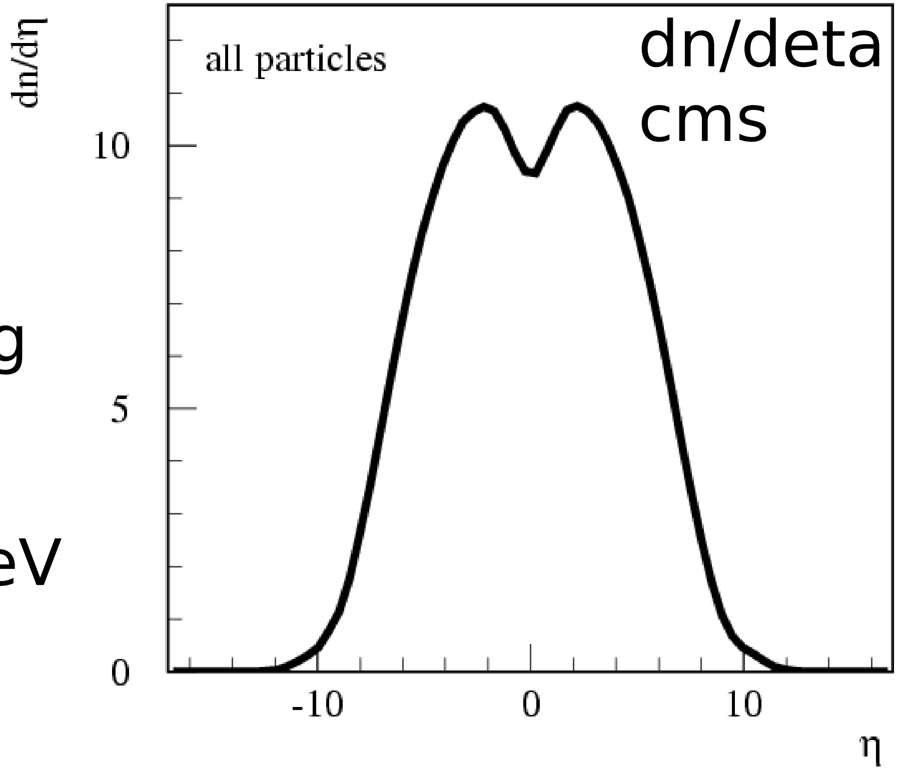
Forward scattering
suppressed
due to independent
 fragmentation
of leading quarks



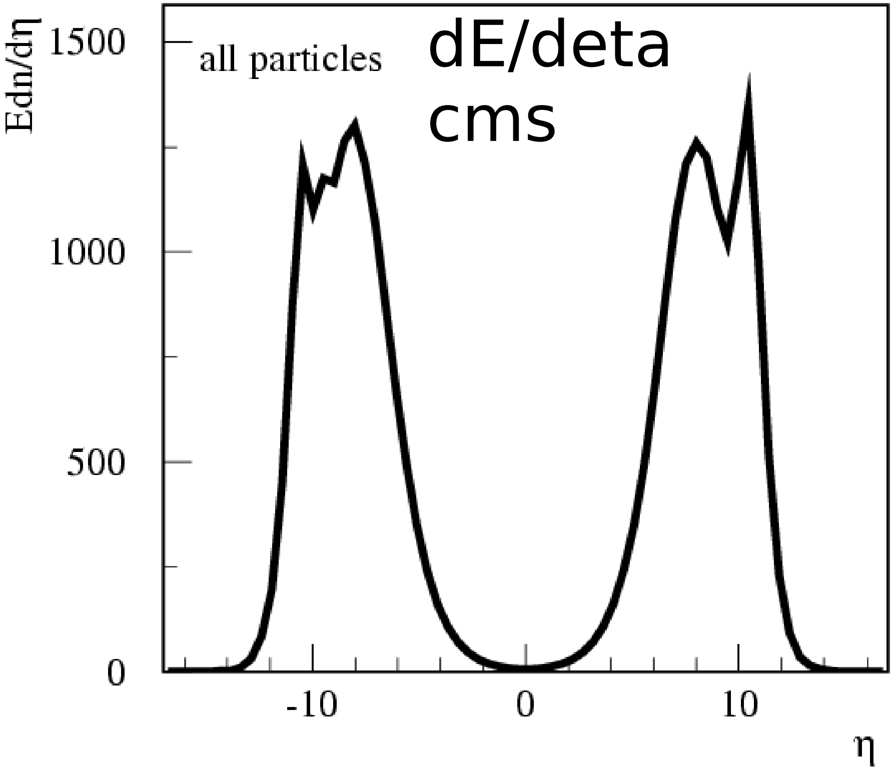
Forward scattering

for p-p
14000 GeV
cms

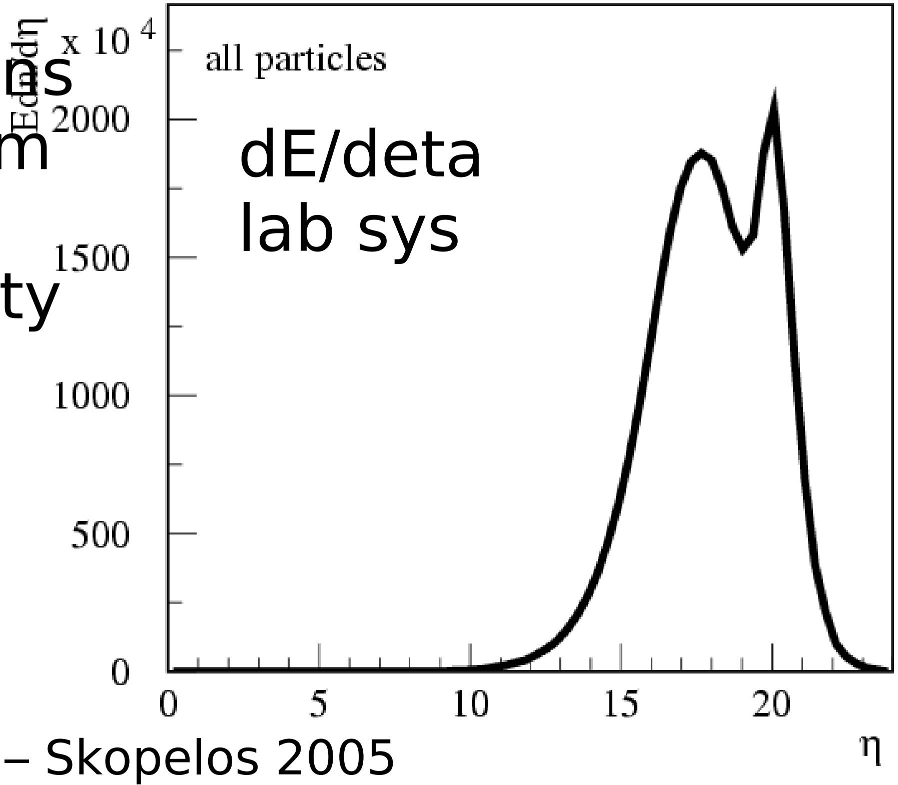
still, muons come from high multiplicity



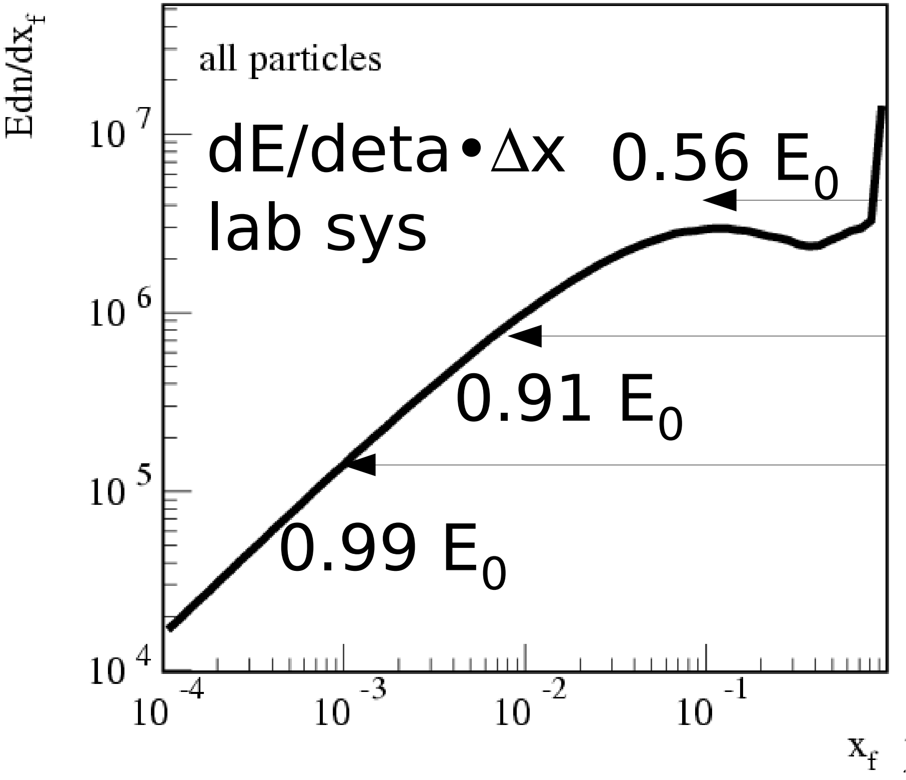
dn/deta
cms



dE/deta
cms



dE/deta
lab sys



dE/deta•Δx
lab sys

0.56 E_0

0.91 E_0

0.99 E_0

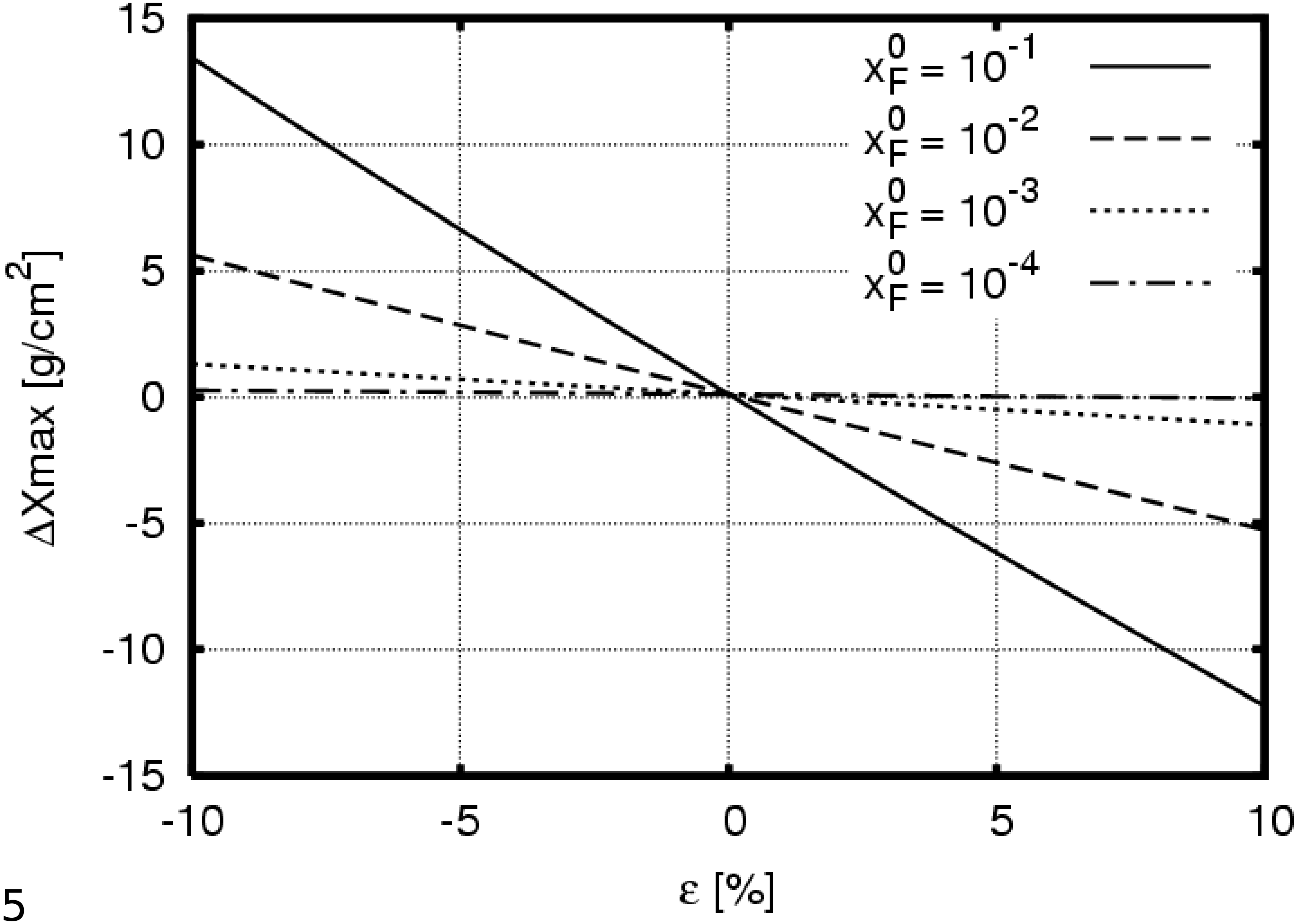
Sensitivity of Xmax to forward scattering

Modify dn/dx_F by factor $(1+\varepsilon)$ for $x < x_F^0$

$(1-\varepsilon')$ for $x > x_F^0$ to conserve energy

Only possible with transport model since dn/dx_F is input

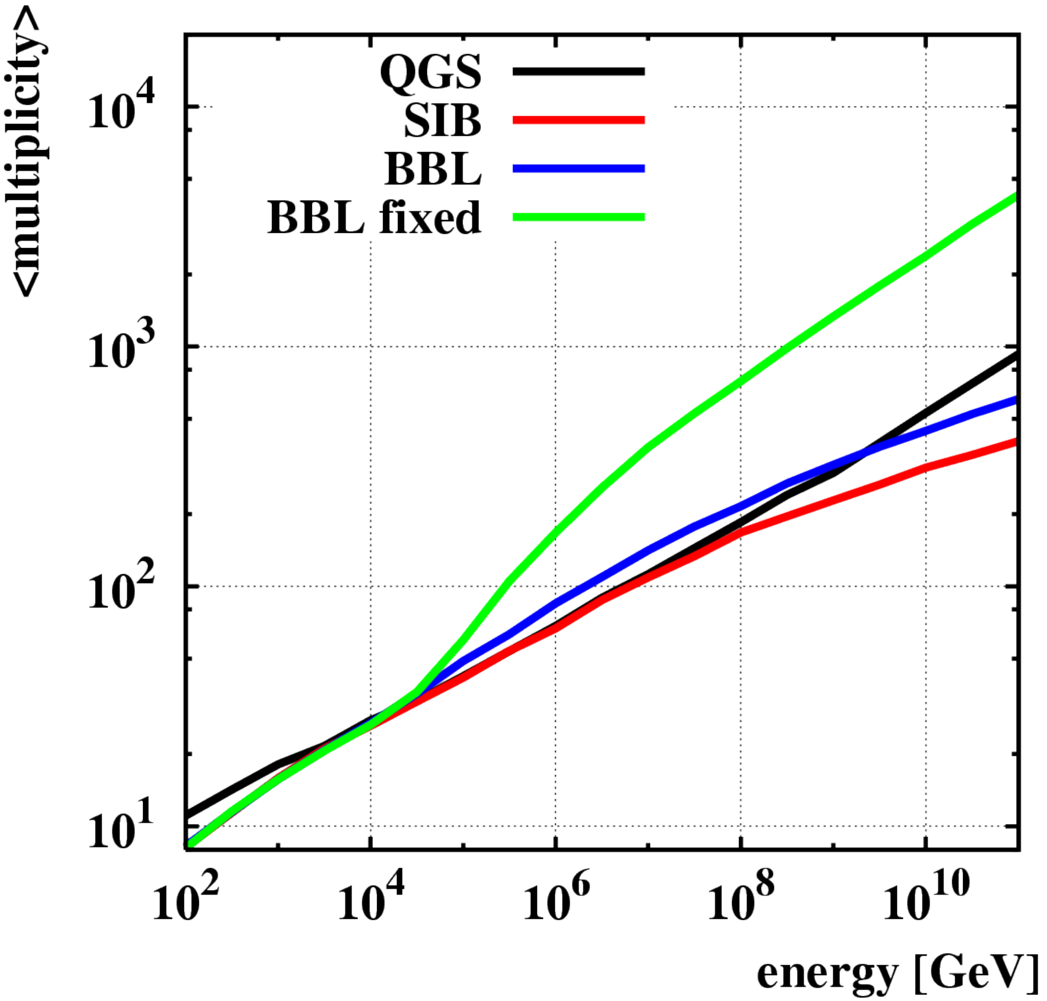
plot ΔX_{max} versus ε



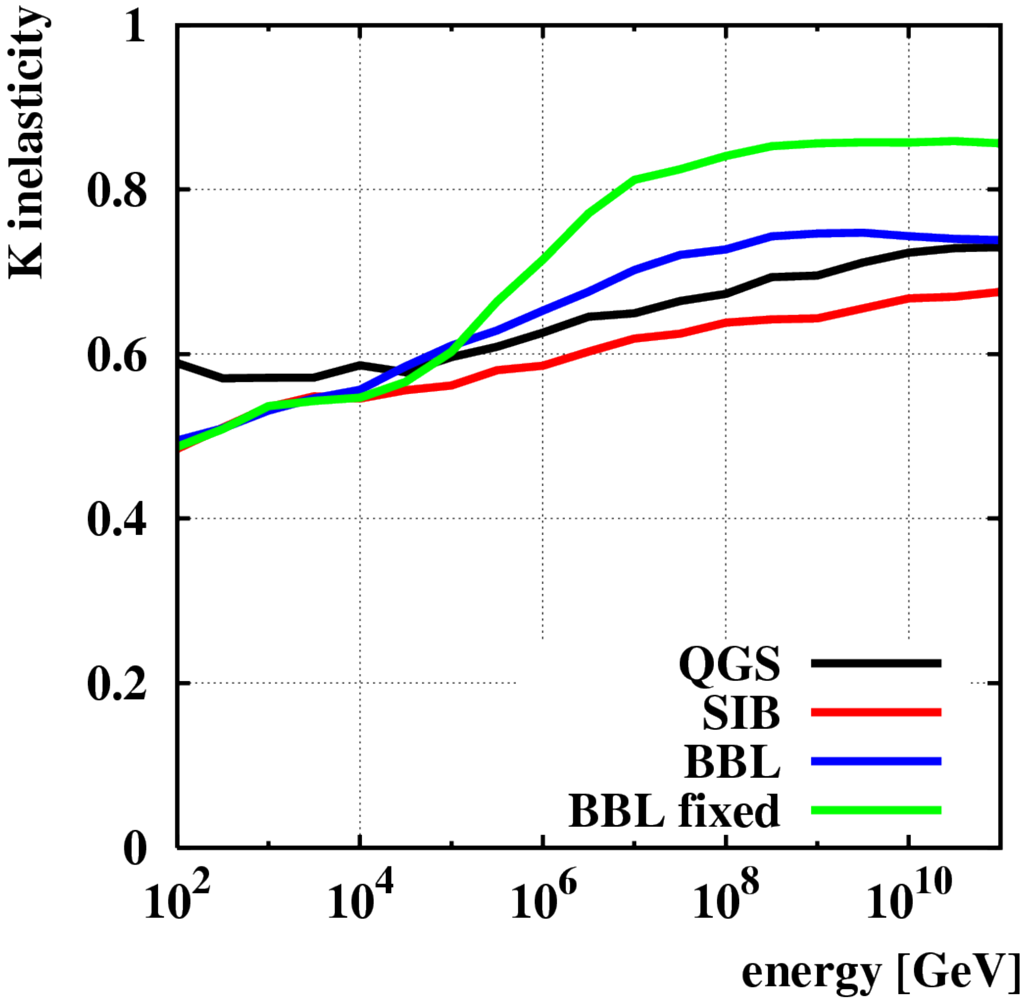
Event shape

Multiplicity

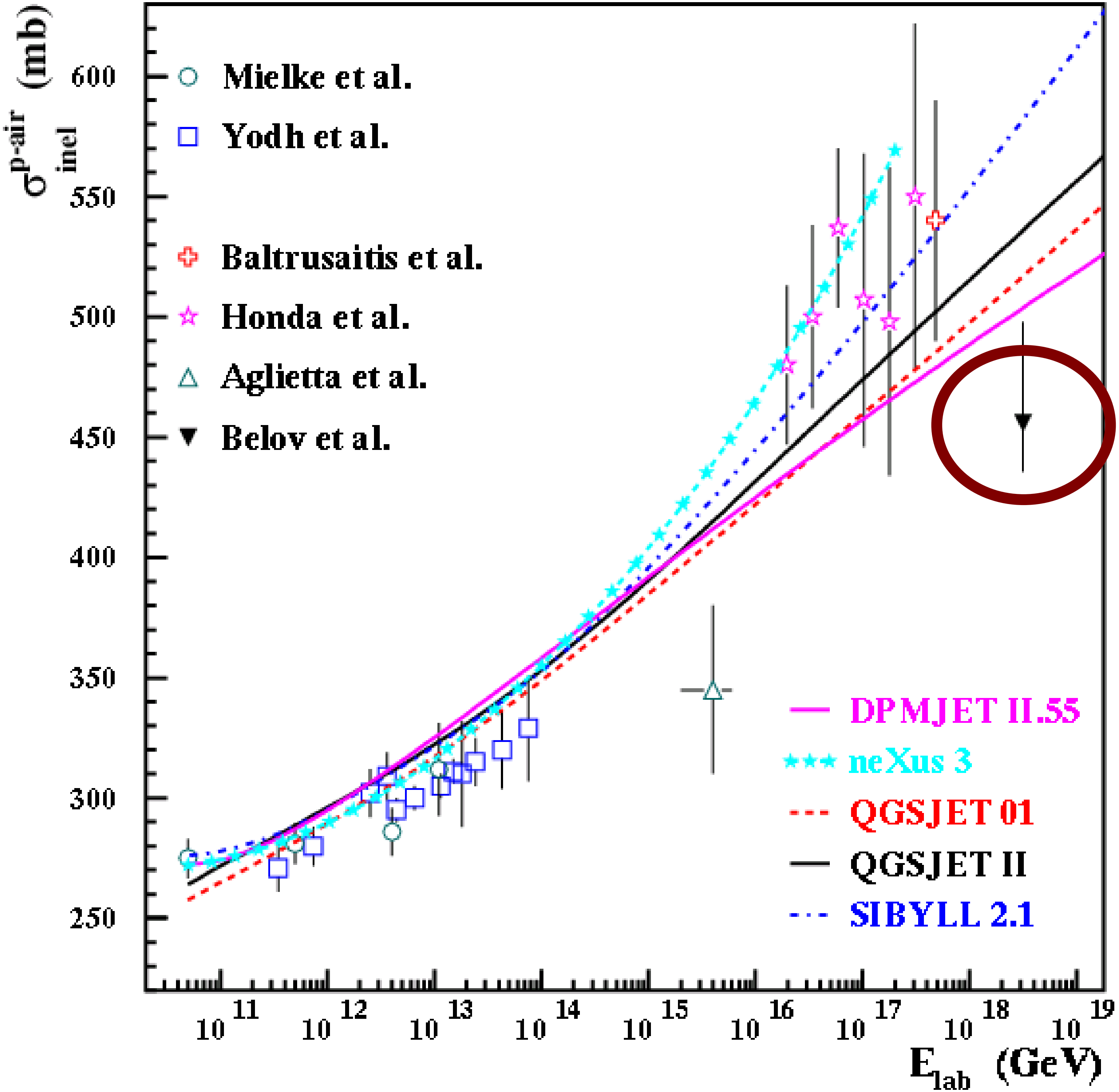
Inelasticity



K=1-<x_F of fastest particle>



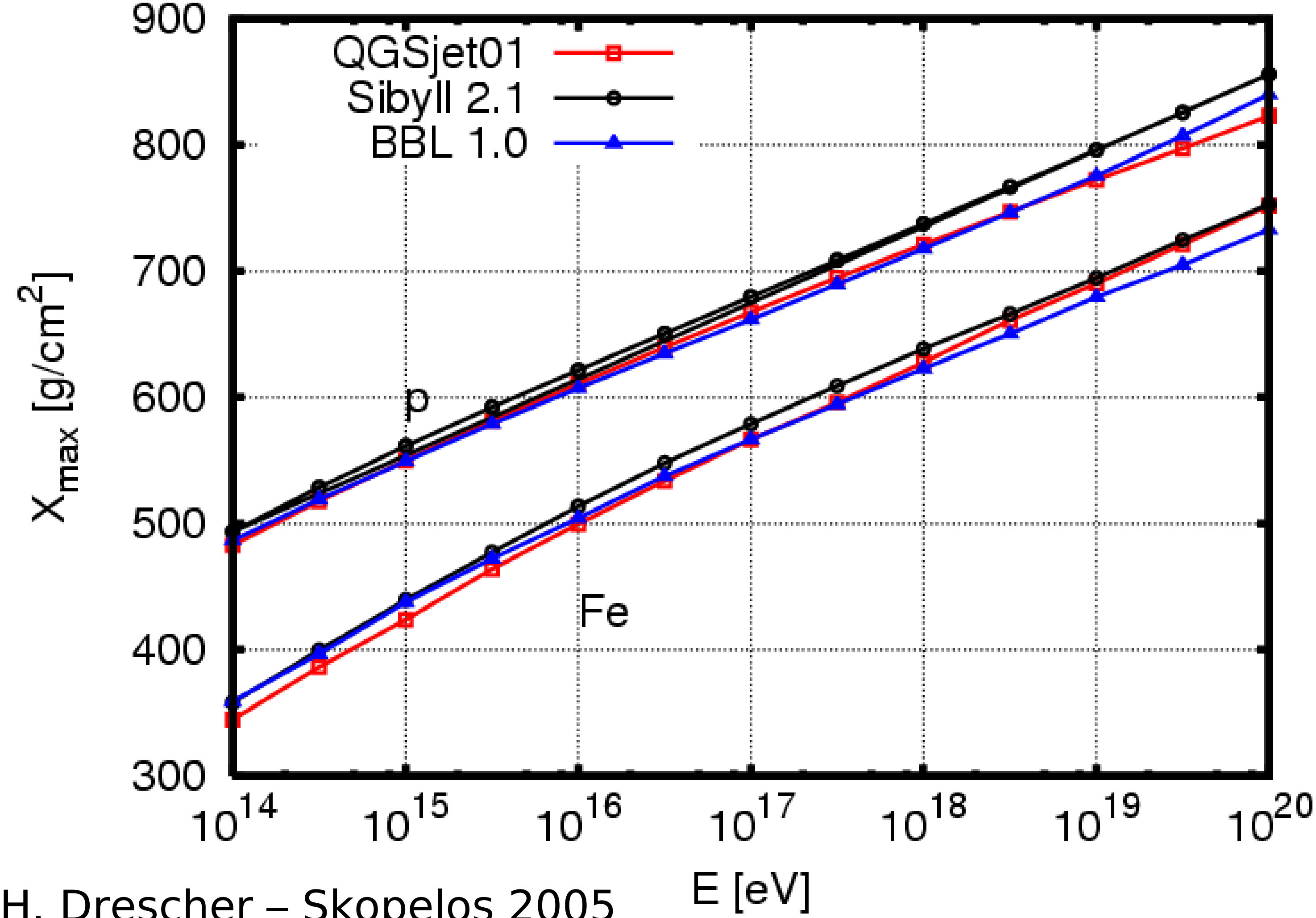
Inelastic p-Air cross section of commonly used models



Latest point from Hires (Belov) quite low

X_{max} for proton and Iron primaries

(Iron primary per superposition)



QGSjet and BBL very similar up to 10^{19} eV for proton primary

for Iron has BBL lowest X_{max} at highest energies

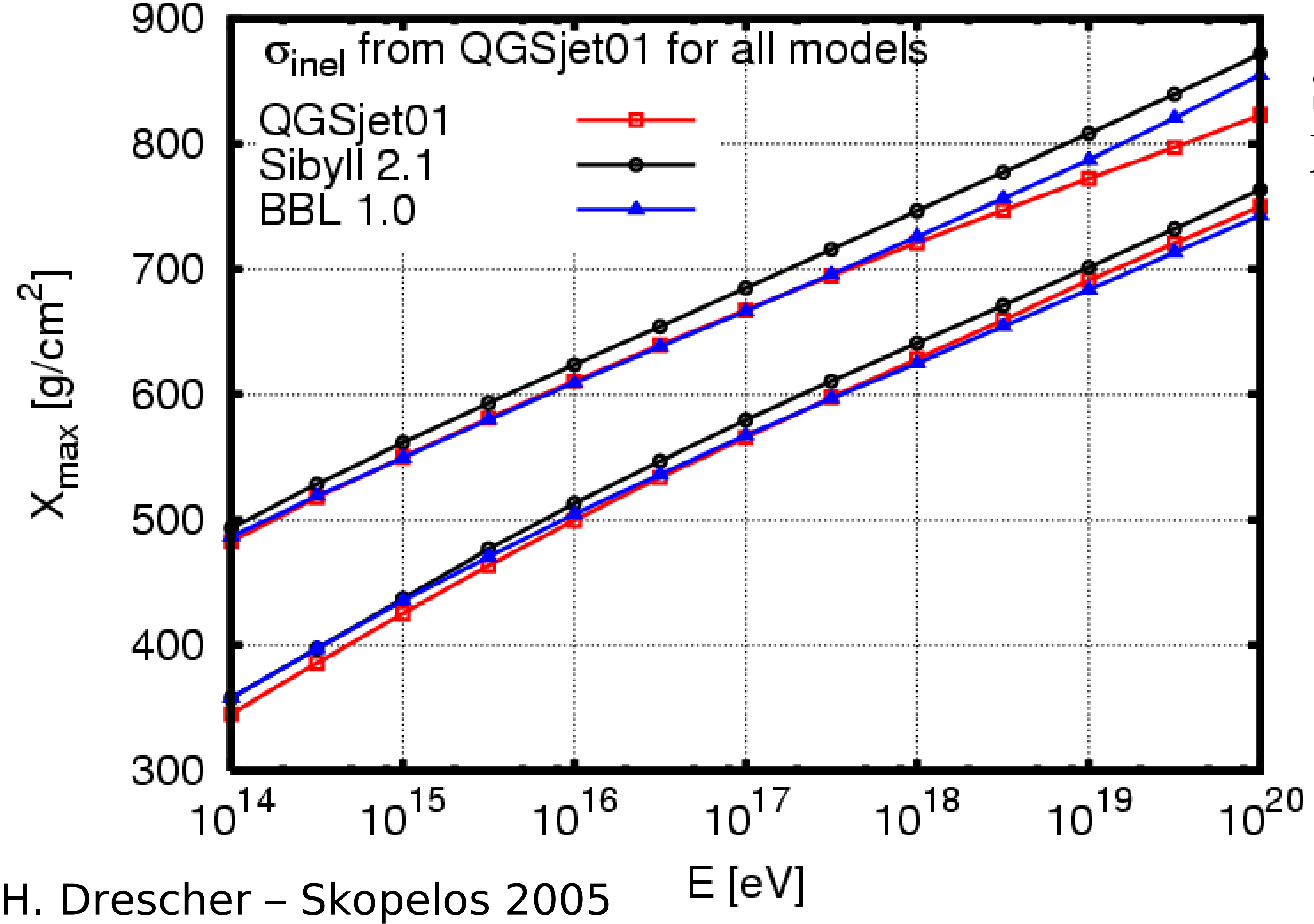
Xmax dominated by σ_{inel} and inelasticity K

How much of Xmax is due to forward scattering how much due to inelastic cross-section ???

Xmax computation for the same inelastic cross-section:

Can be done quickly with hybrid method:
fast computation of a mean shower

QGSjet σ_{inel} is lower than that of Sibyll



Shifts SIB and BBL Xmax by 10-15g/cm^2

Differences due to forward scattering are even higher: ca. 50 g/cm^2 at highest energies

Models differ more than they appear

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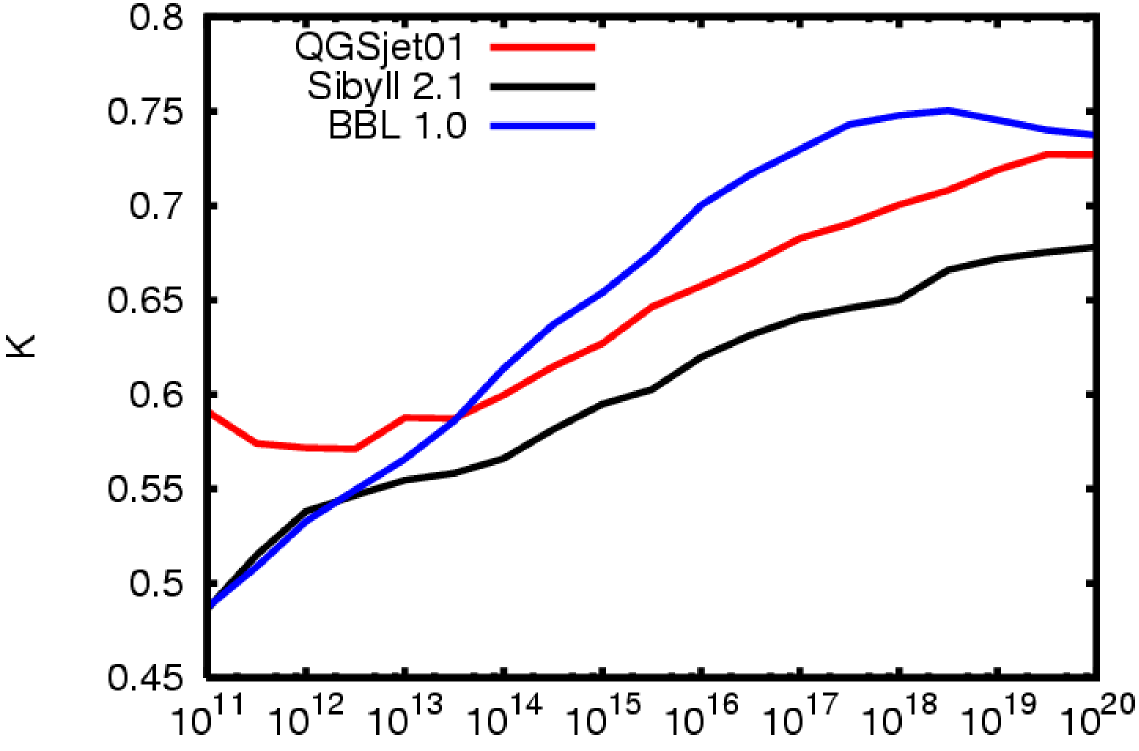
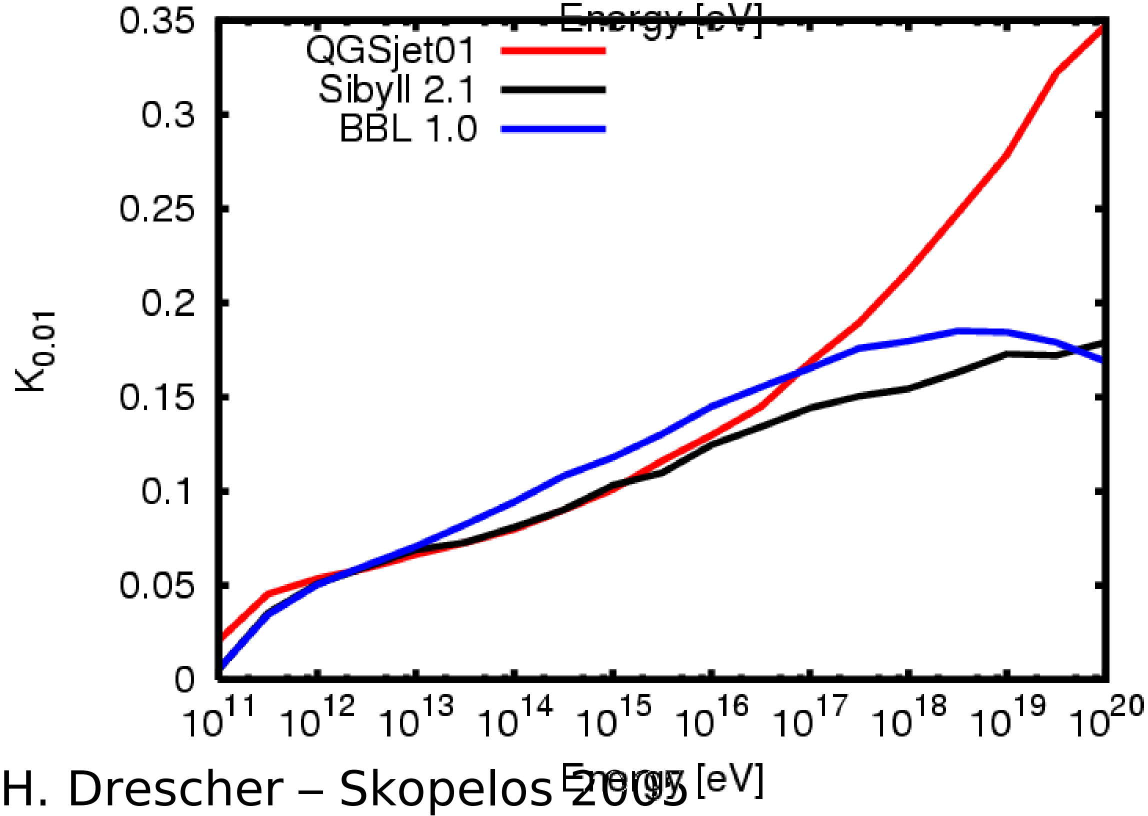
Inelasticity to quantify forward scattering



$$K = 1 - \langle x_F \rangle$$ of fastest particle

BBL has higher Xmax but higher K than QGSjet



$$K_{0.01} = 1 - \int_{0.01}^{1} x_F \frac{dn}{dx_F} dx_F$$

QGSjet has flatter x_F distribution

need more than K to describe forward scattering

Hadronic models and experimental cosmic ray air shower data

Muon bundles

Kascade results

Lateral Distributions (in Auger)

essential: results for muons

Muon Bundles from CosmoLEP

LEP experiments measure cosmic ray air-showers undergound

only high energy muons reach the detector

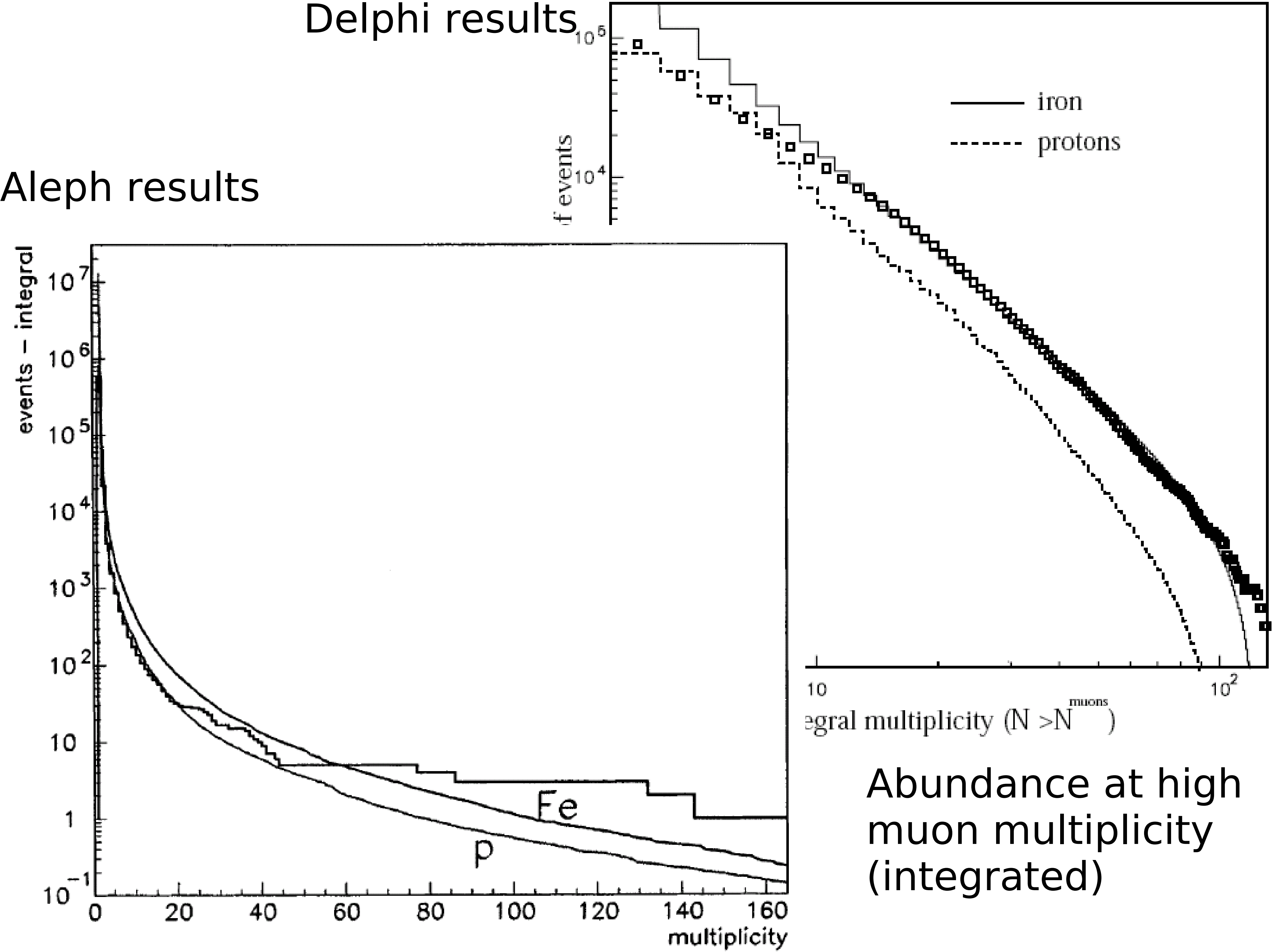
L3:	-30 m	15 GeV cut-off
DELPHI:	-100 m	50 GeV
ALEPH:	-125 m	70 GeV cut-off

Measure multiplicity of muons in detectors

strategy: forward folding
- with flux of cosmic ray spectrum from other experiments
- simulate detector response for extreme assumptions
- pure proton and pure Iron

Delphi results

Aleph results

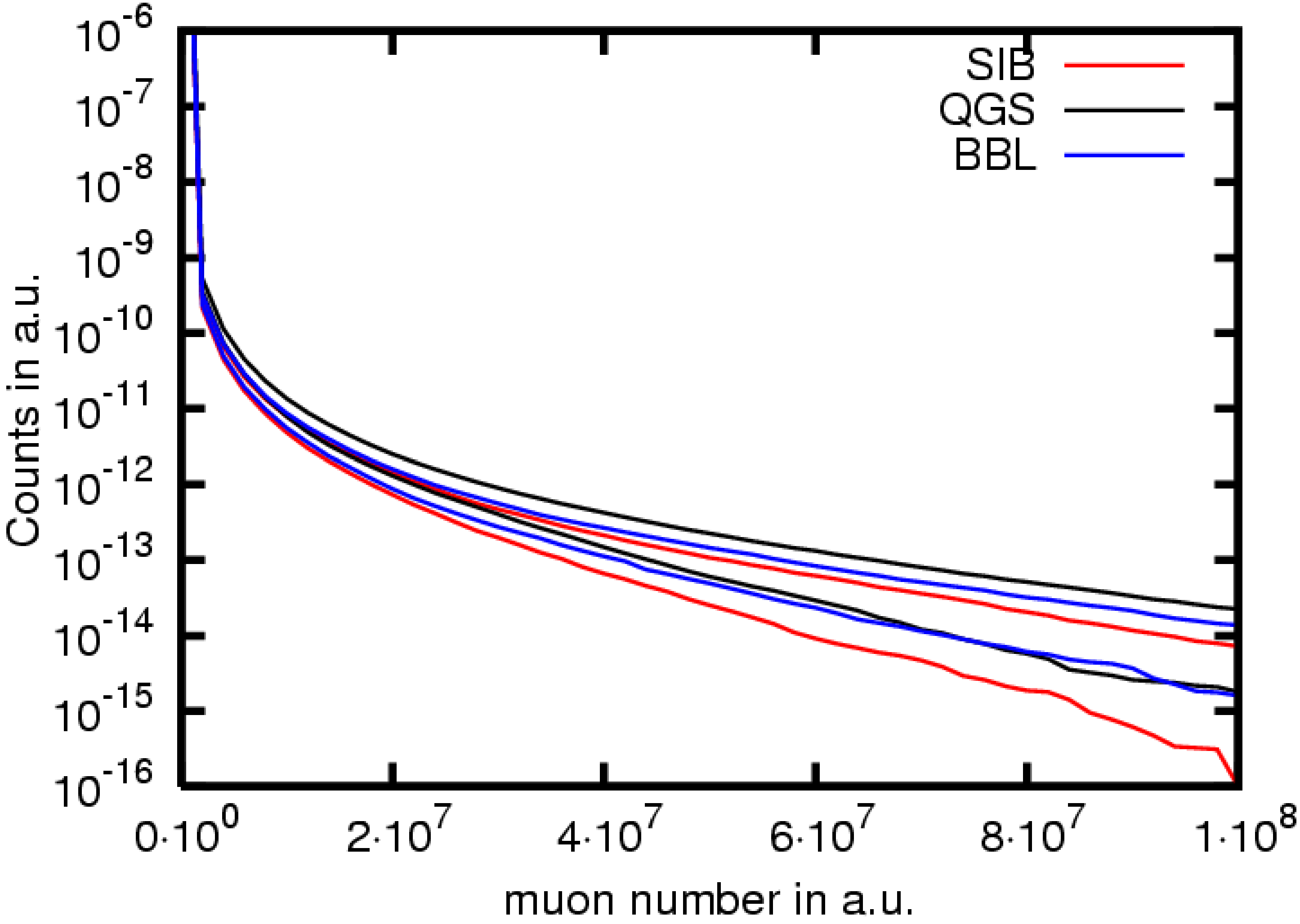


Abundance at high muon multiplicity (integrated)

Simulation results for the three models

(only vertical showers were simulated, E_{muon}>50 GeV)

Assumed
cosmic ray flux:
$F \sim E^{-3}$



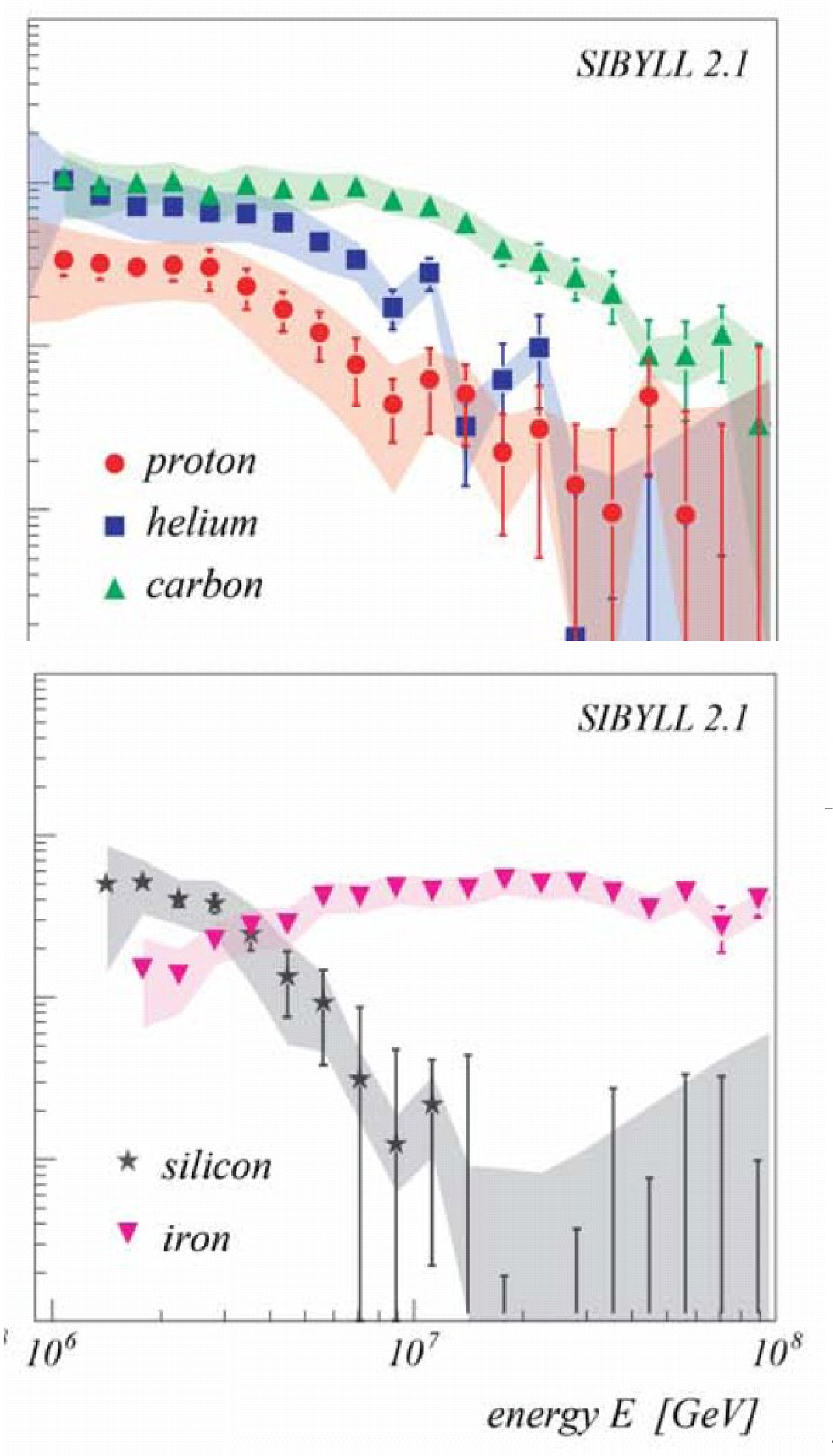
Upper line for Iron
lower line for proton

Kascade

get composition around the knee (10^{15}-10^{16} eV) by measuring electrons and muons with a ground array (Karlsruhe)

To deconvolve composition, they fit model results for different primaries to experimental data

here: goodness of fit on N_{el} – N_{muon} plane



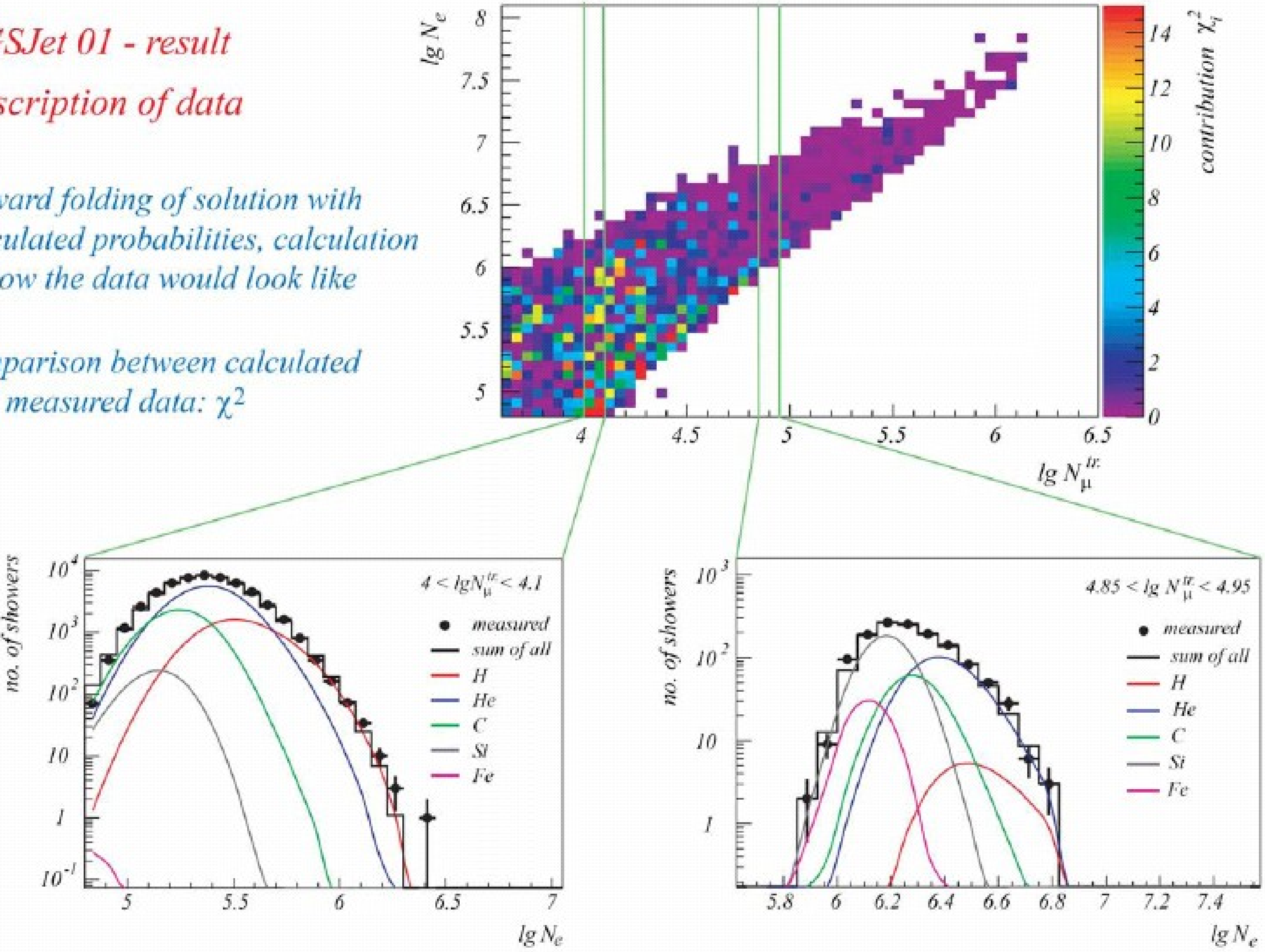
From Holger Ulrich (Kascade)

QGSJet 01 - result

Description of data

forward folding of solution with calculated probabilities, calculation of how the data would look like

comparison between calculated and measured data: χ^2



QGSJET01: electron poor

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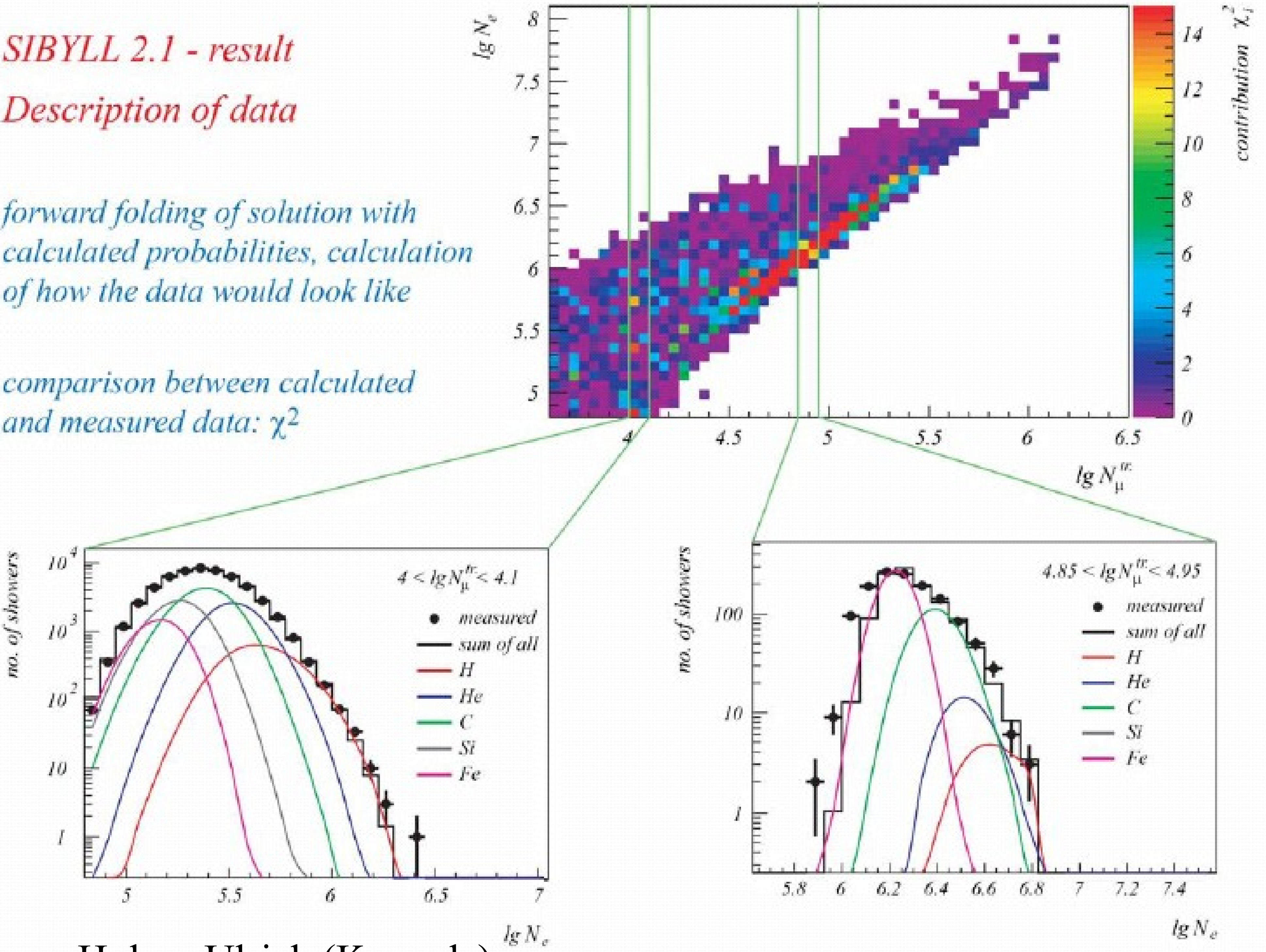
From Holger Ulrich (Kascade)

SIBYLL 2.1 - result

Description of data

forward folding of solution with calculated probabilities, calculation of how the data would look like

comparison between calculated and measured data: χ^2

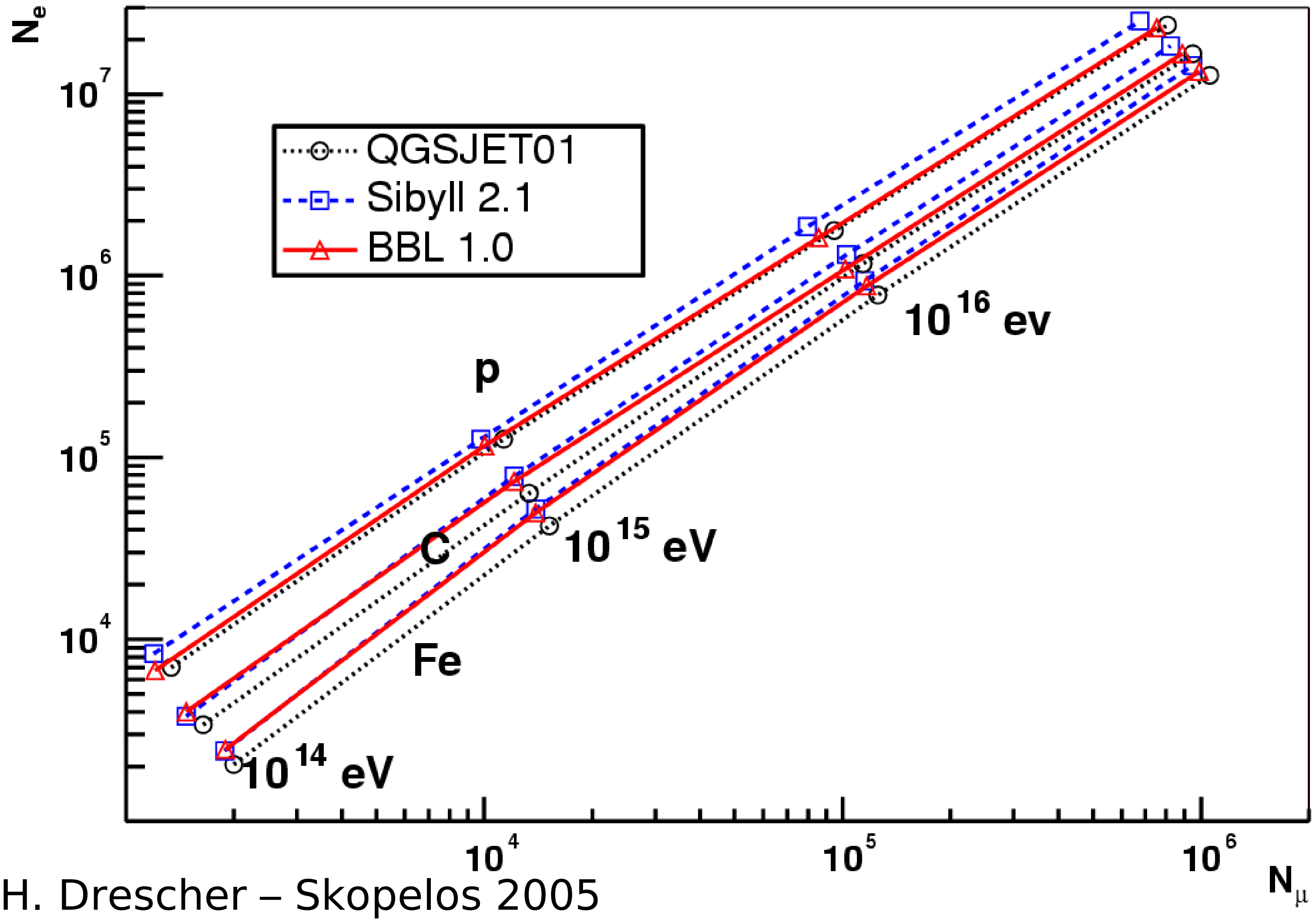


From Holger Ulrich (Kascade)

Too electron rich/muon poor

Electron and Muon numbers

BBL reproduces Sibyll at low energies (by construction)
and is similar to QGSjet at higher energies.
--> same as a function of primary mass A.

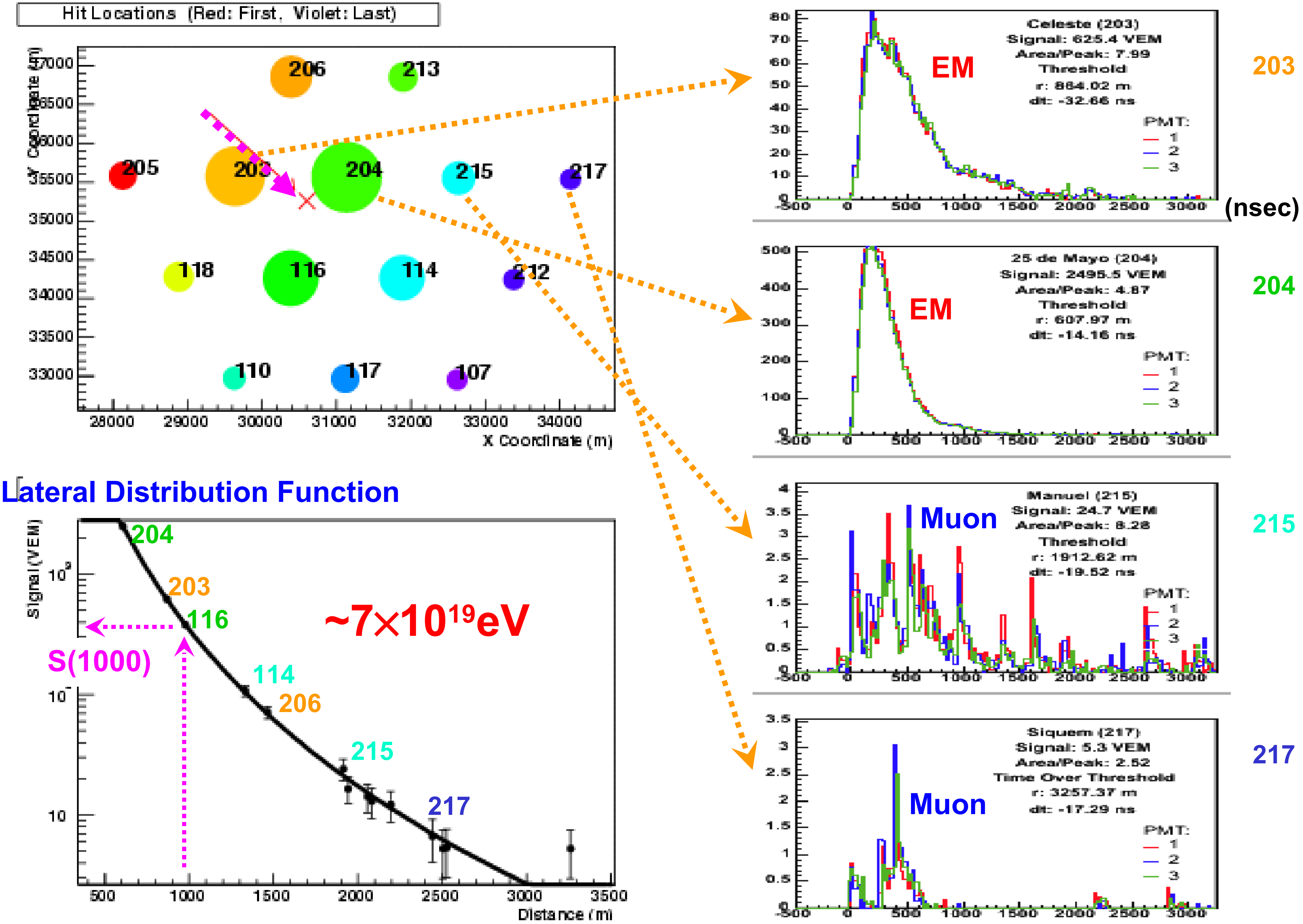


Maybe helps to resolve known problems of models
at KASCADE ;-)

but: full implementation of N-N scattering necessary

A Typical Auger Event (Zenith~35°)

From
Katsushi Arisaka



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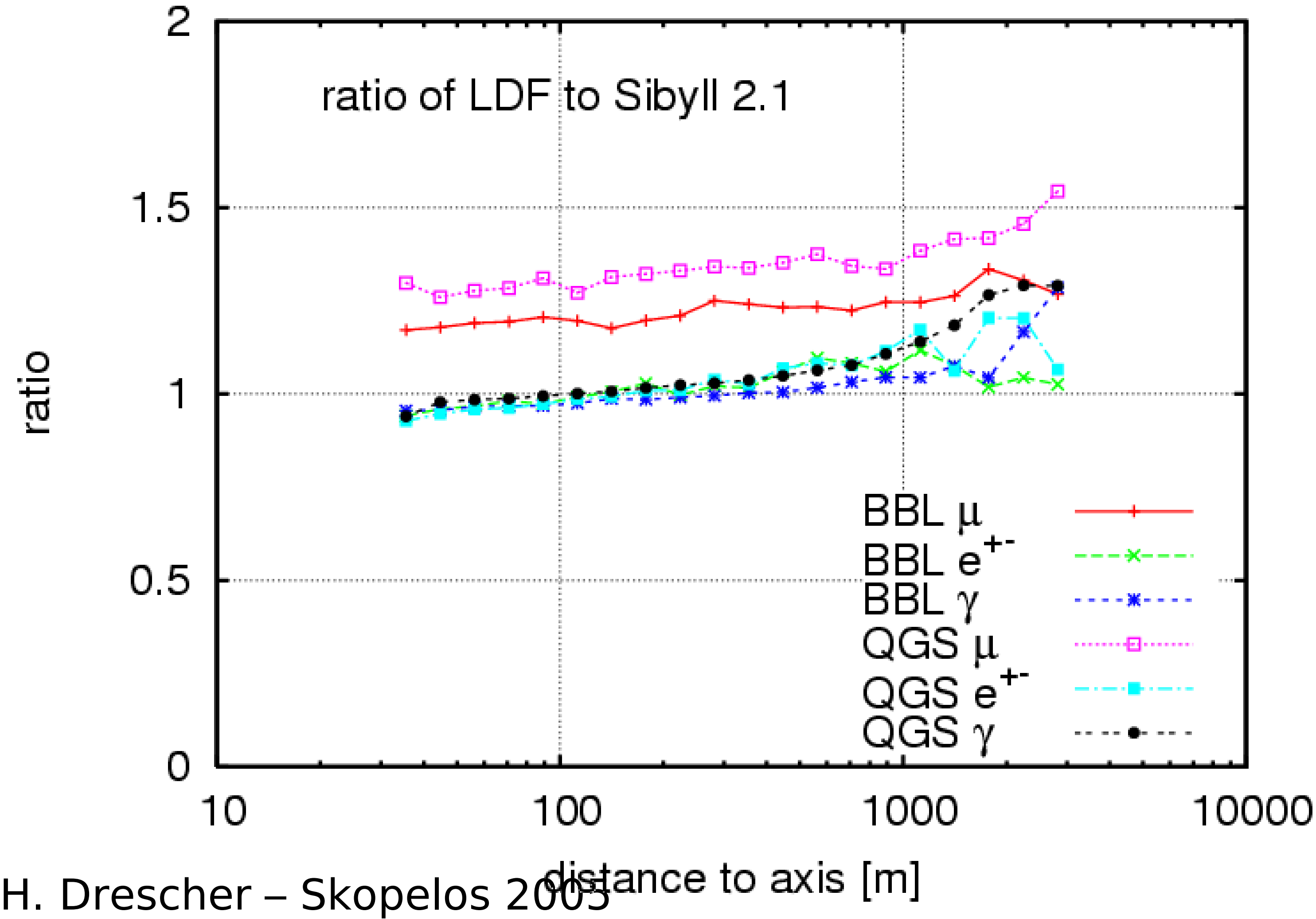
Lateral Distribution Functions

Forward suppression in BBL leads to enhanced particle production at small x --> more muons

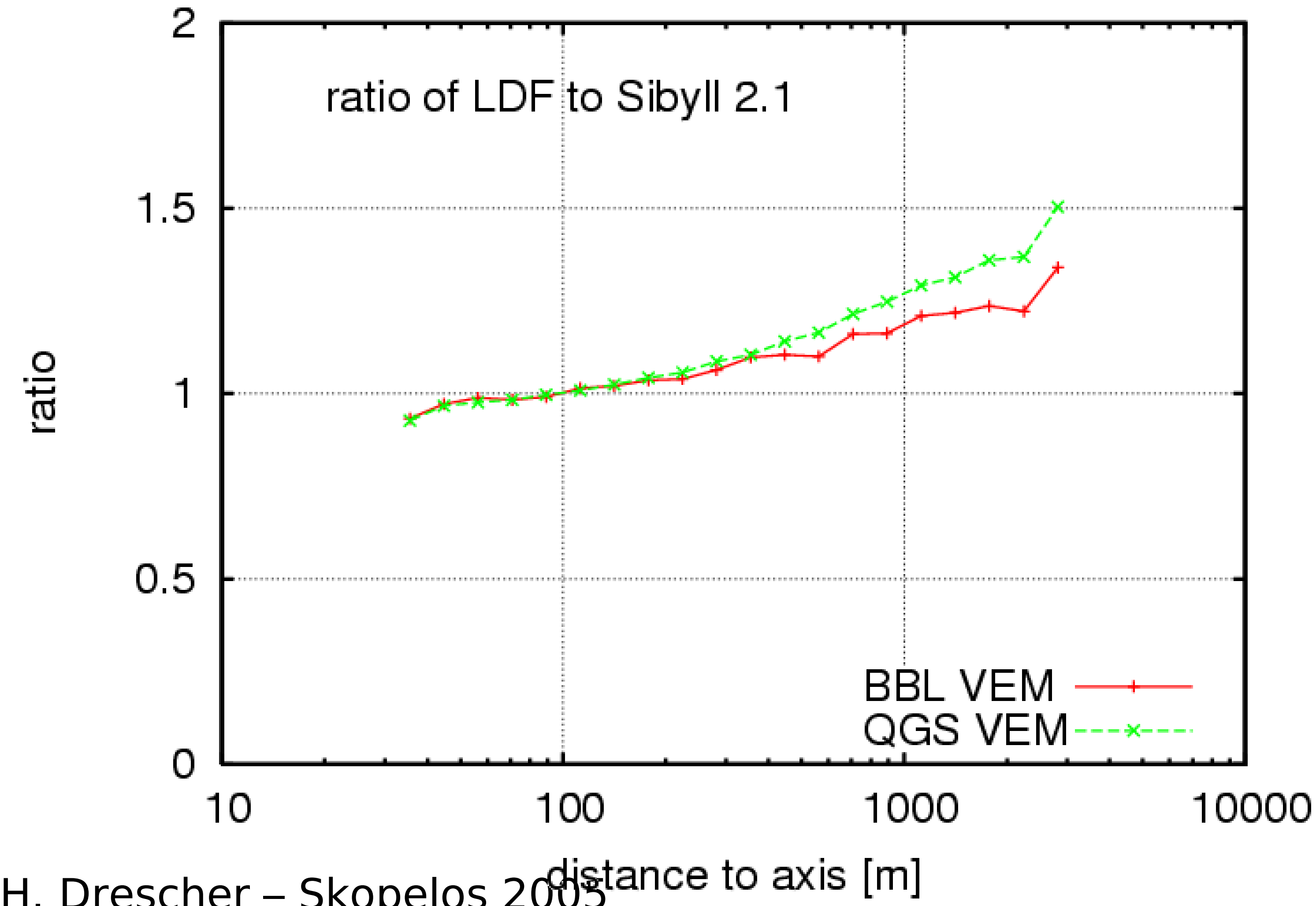


Slope for em particles quite insensitive to high energy hadronic part

Vertical proton 10^{19}eV showers, Auger-altitude

LDF in VEM units

flatter LDF since γ dominate at low r, μ at large r



~ 25% difference at 1000m

Energy calibration of Auger with MC is still 25 higher than fluorescence!

Summary

- fast air shower simulations with hybrid apporach
- Forward scattering suppression with BDL
- Air Shower data and hadronic interaction models

try to use hadronic models in air shower simulations
- for the interpretation of data
- to learn about interactions

(if possible both)