Air Shower Simulations

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3rd School on
Cosmic Rays and Astrophysics
Arequipa, Peru
2008

- Part 1: Astroparticle Physics, Air Showers and Simulations
- Part 2, 3: Hadronic & Nuclear Models, CORSIKA, Performance and Limitations
- Part 4: Selected Aspects of EAS Simulations, Simulation Techniques

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Shower development (qualitatively)

correlated!

crucial:

- inelastic cross-sections (s_{inel})
- hadronic particle production
  (inelasticity k_{inel} i.e. fraction of energy converted into secondaries)

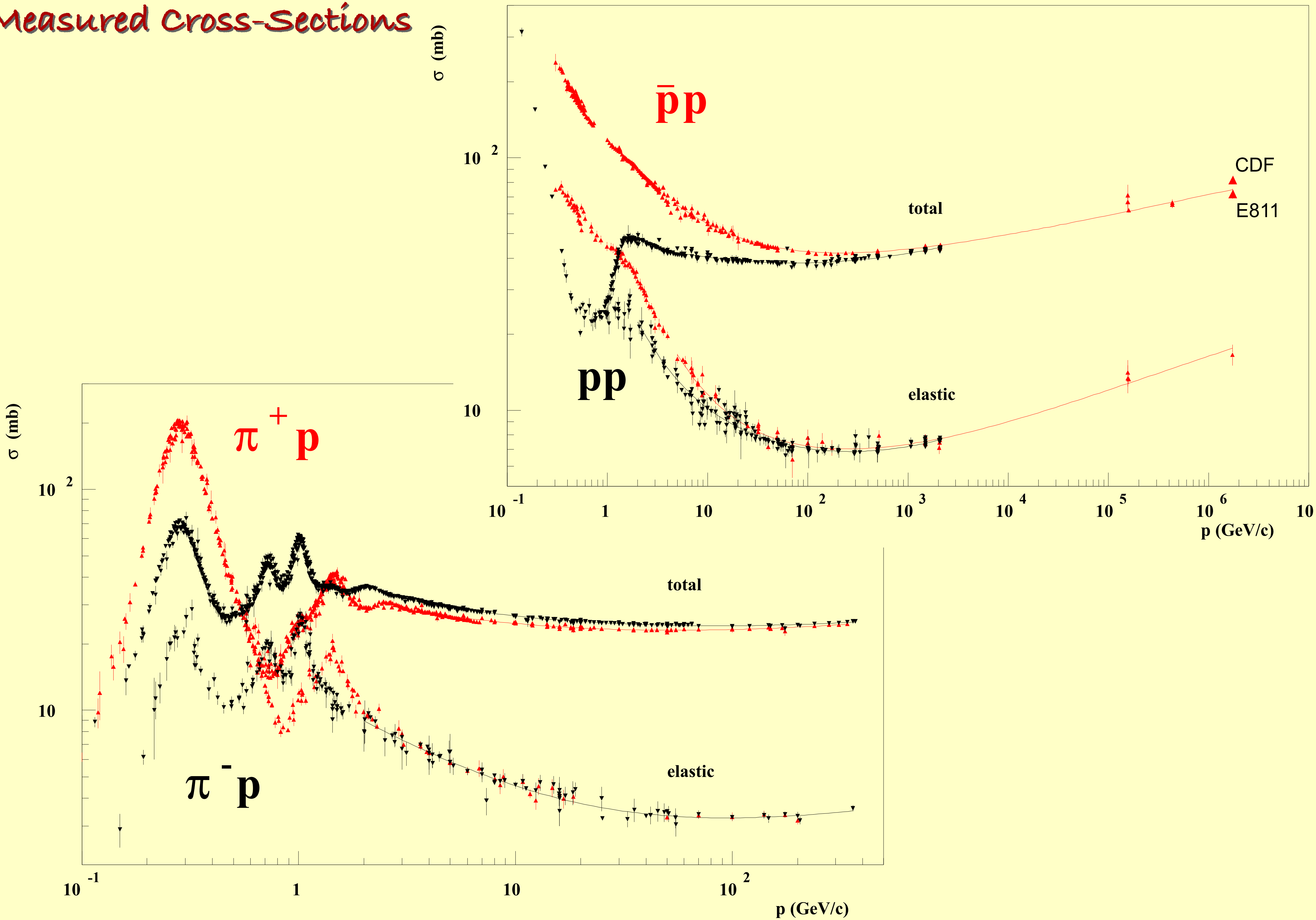
large cross-sections,
high inelasticity
} make short showers

small cross-sections,
low inelasticity
} make long showers

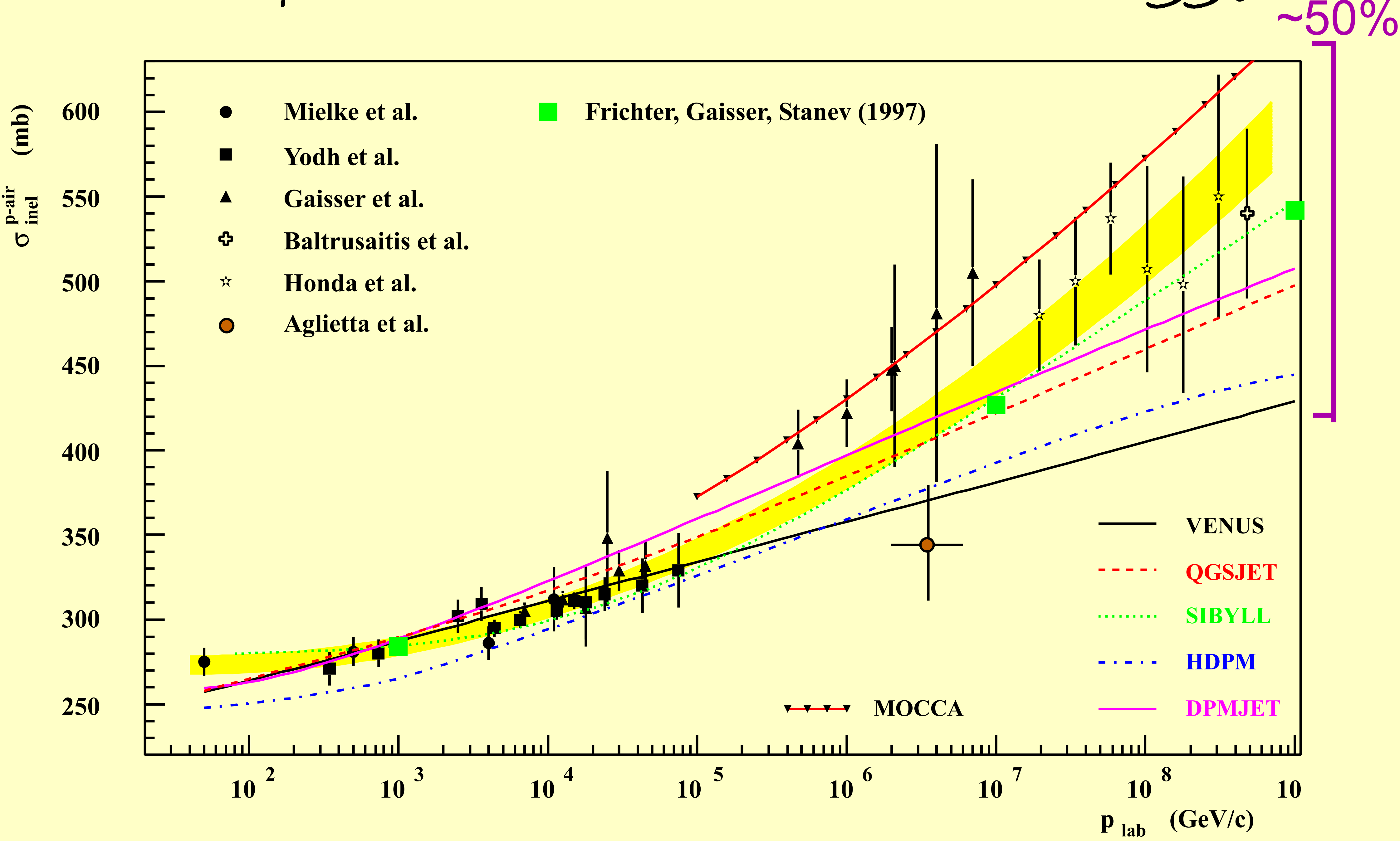
less crucial:

nuclear fragmentation, dE/dx, decays, tracking,
electromagnetic reactions, ...

Measured Cross-Sections



p-Air Inelastic Cross-Sections 1997



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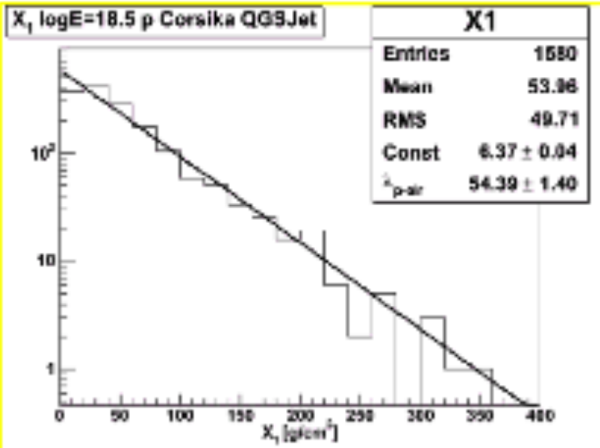
Measuring $\sigma_{p\text{-}air}$: De-convolution Method by HiRes

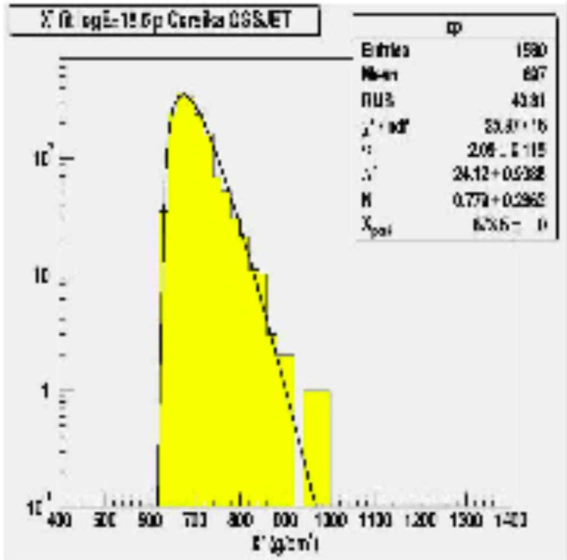
Pierre Sokolsky

Point of first interaction distribution. Exponential index reflects inelastic Cross-section



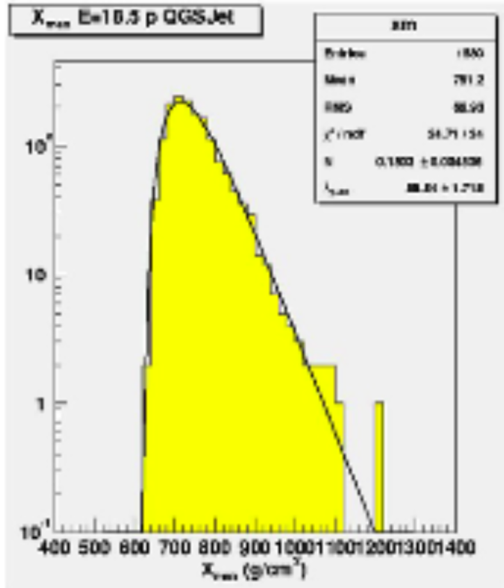
$\otimes$

Atmospheric part of air shower fluctuations



$=$

X_{max} distribution



$$f_{\text{int}} = e^{-\frac{x_1}{\lambda_{p-Air}}};$$

$$\lambda_{p-Air} = \frac{1}{\tilde{n}\,\sigma^{inel}_{p-air}};$$

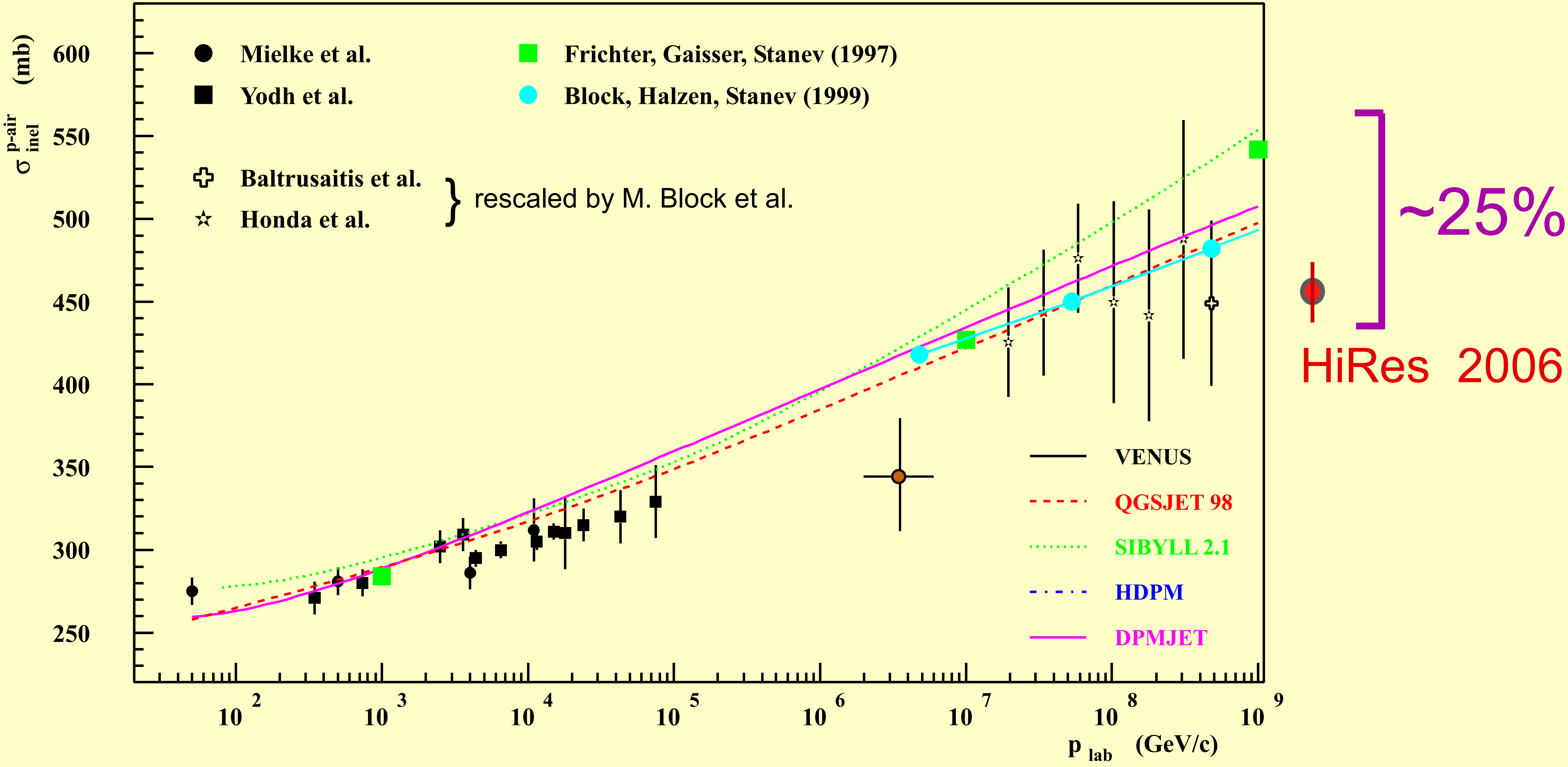
$$X' = X_{\max} - X_1$$

$$f_{fluct} = \left[\frac{x_{\max} - x_{peak} - x_1 + \Lambda'\alpha}{e}\right]^{\alpha} e^{-\frac{x_{\max} - x_1 - x_{peak}}{\Lambda'}}$$

$$f_{fluct}(x_{peak}(E), \Lambda'(E), \alpha(E)) \Rightarrow f_{fluct}(E)$$

$$P_m(x_m) = N \int_0^{x_m - x_{peak} + \Lambda'\alpha} e^{\frac{-x_1}{\lambda_{p-Air}}} \left[\frac{x_{\max} - x_{peak} - x_1 + \Lambda'\alpha}{e}\right]^{\alpha} e^{-\frac{x_{\max} - x_1 - x_{peak}}{\Lambda'}} dx_1;$$

p-Air Inelastic Cross-Sections 2001



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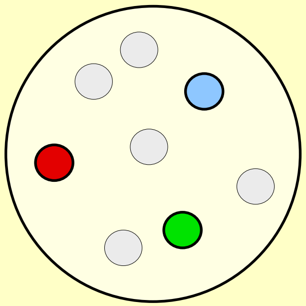
HERA measured structure functions at small x

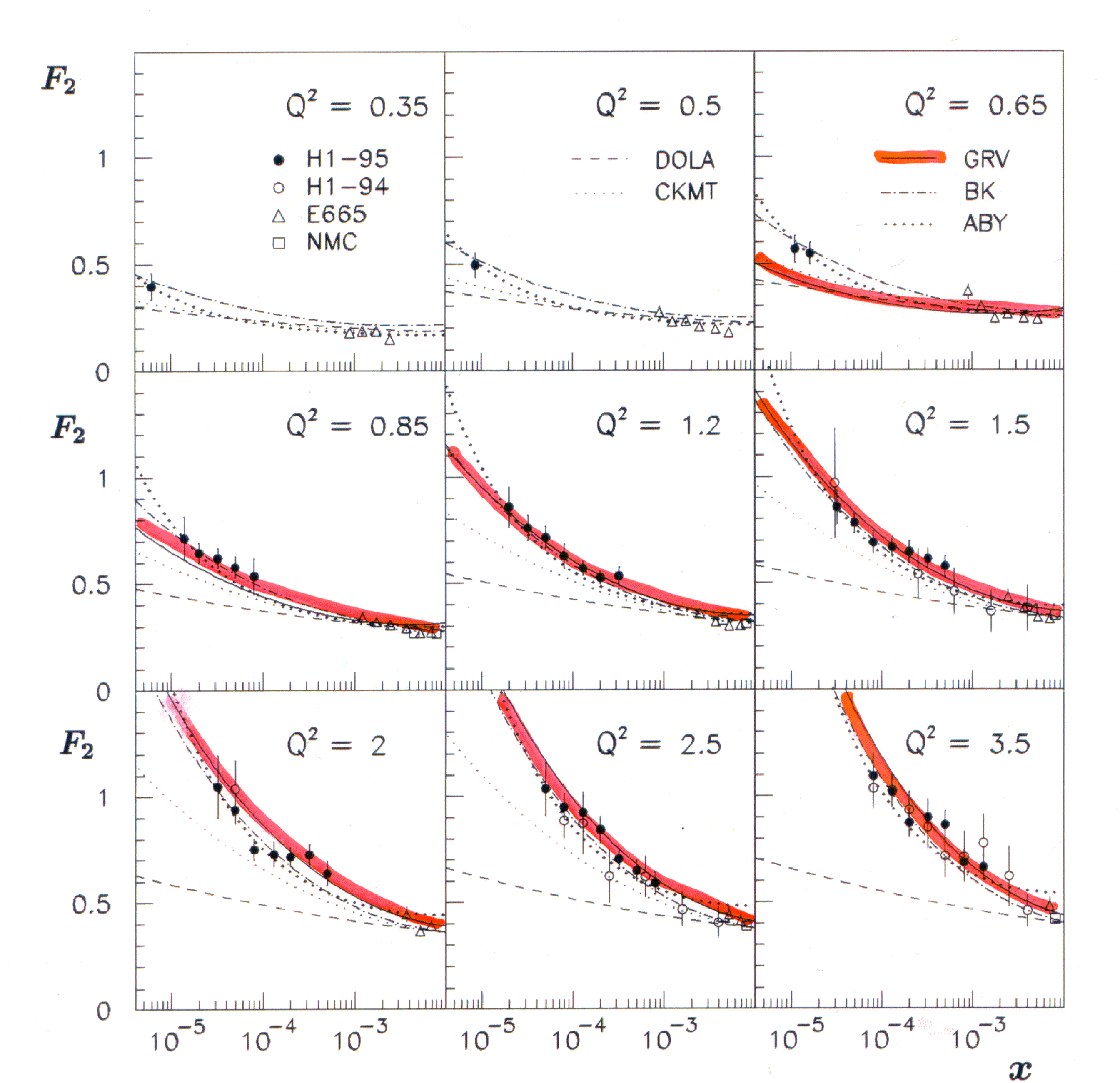


The more partons (quarks & gluons)
there are in a nucleon
at small x,

the more likely a collision is to
happen with a
high-energy projectile,

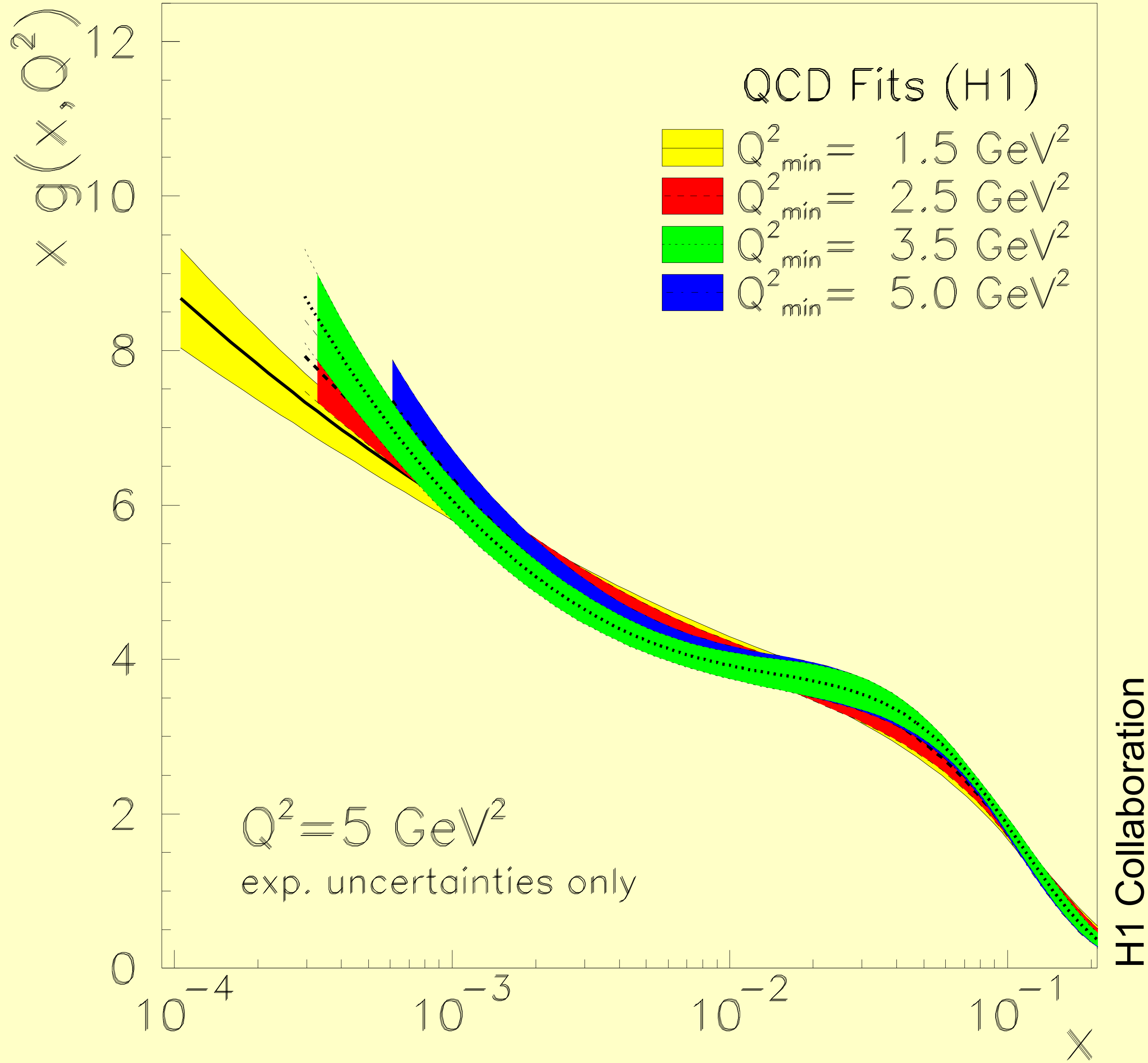
and the higher is the
interaction cross-section.

HERA data help with extrapolation of cross-sections to high energies.

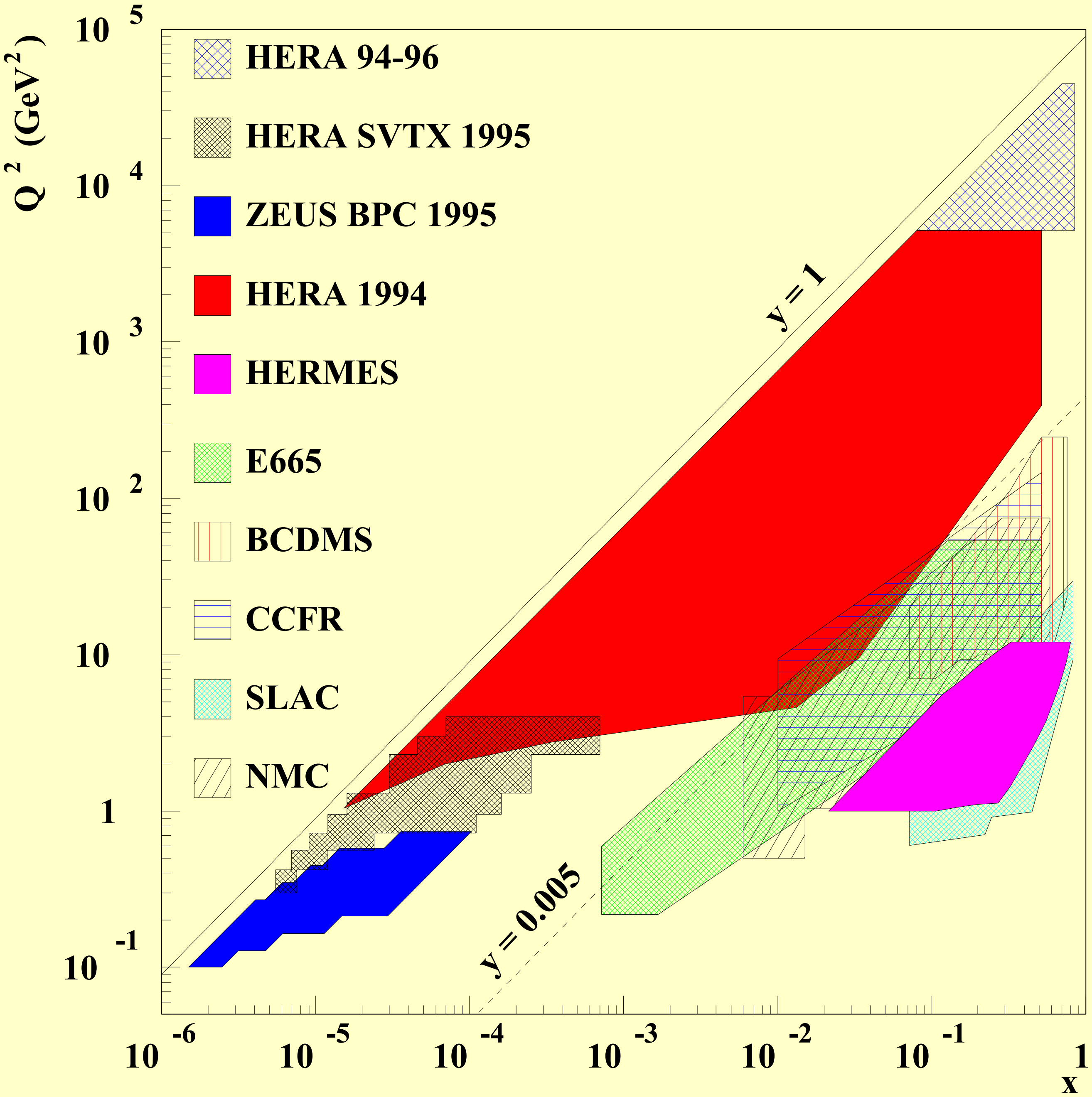


x = momentum fraction of a parton

Gluon density at low x



Coverage in x - Q² plane

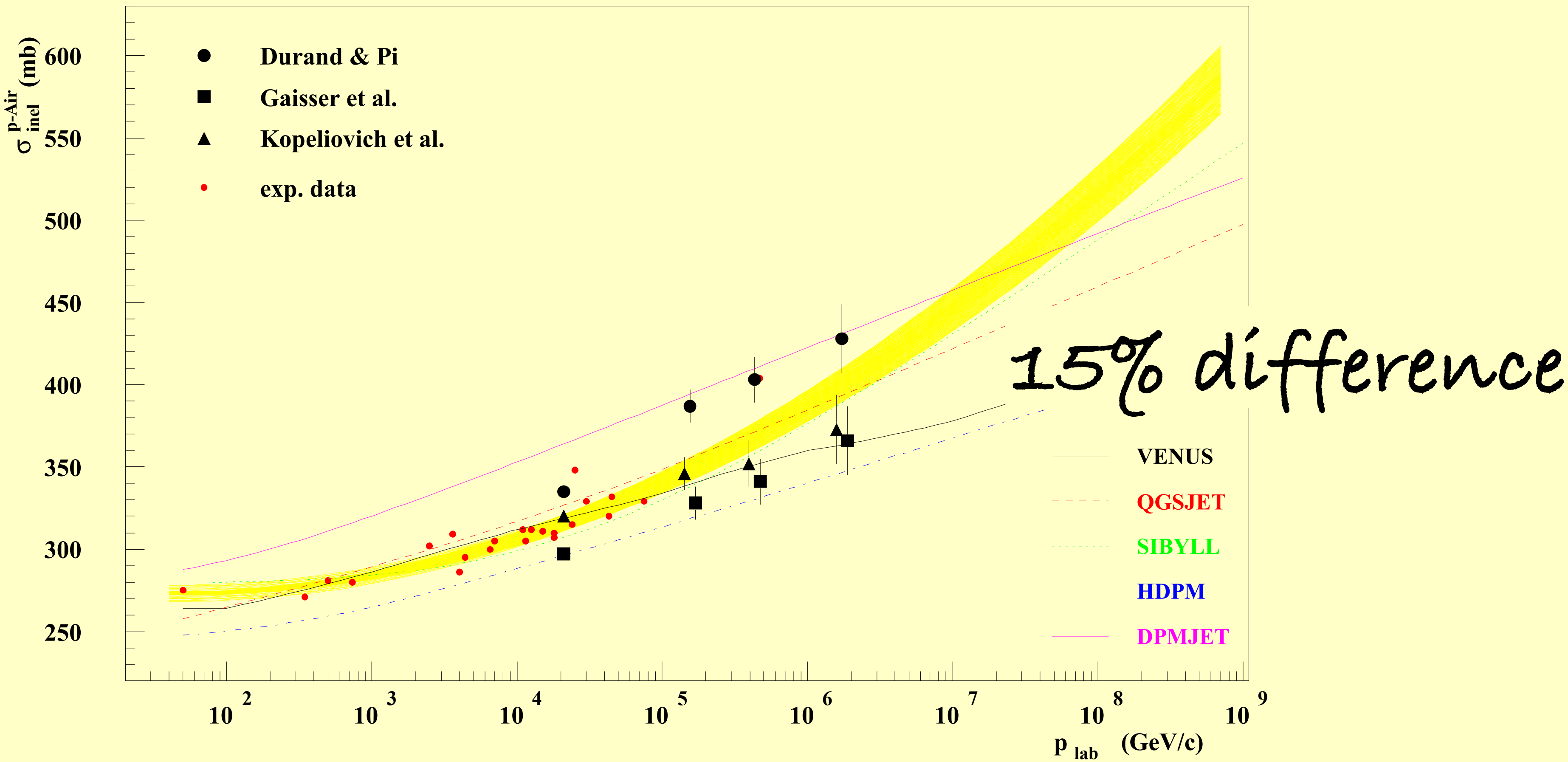


Cosmic Ray Regime:

$Q^2 \approx 0$

$x \approx 0$

Conversion from p-p to p-Air cross sections (Glauber Theory)

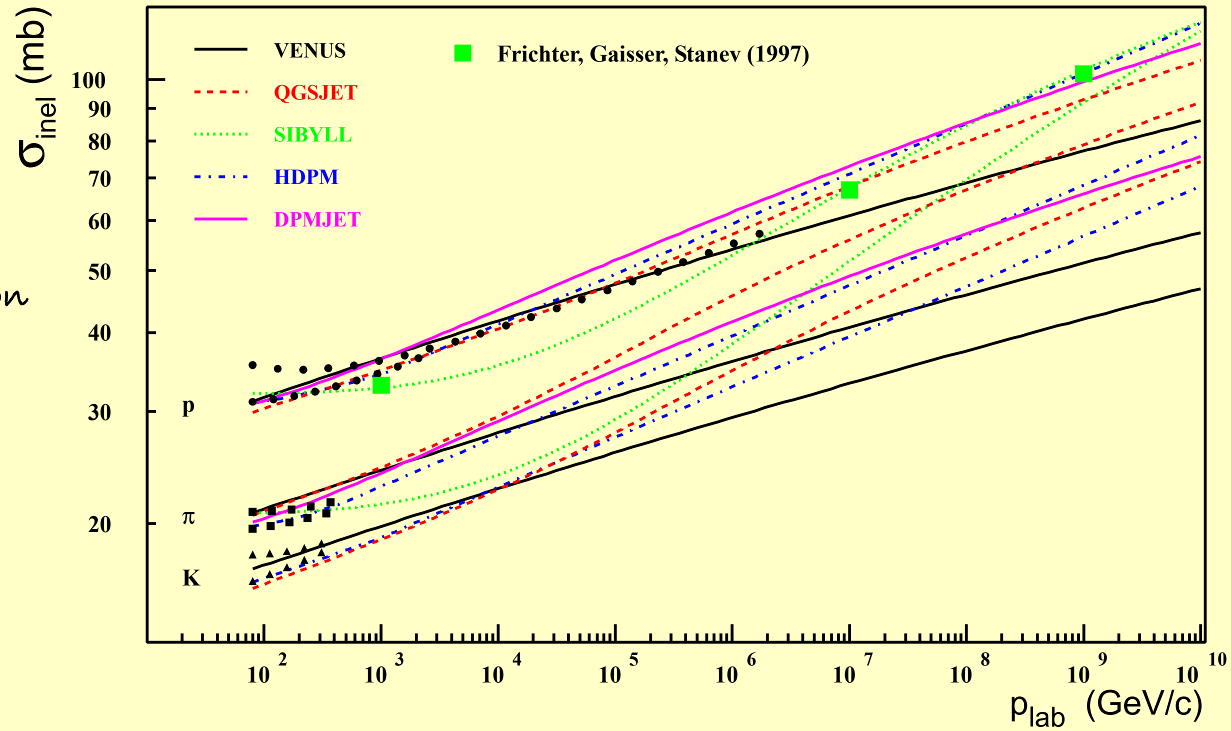


3 groups applied Glauber theory to deduce
the proton-Air inelastic cross-section from
the measured p-p cross-sections (SppS, Tevatron)

origin of difference? what exactly is the nucleon distribution of a nucleus?

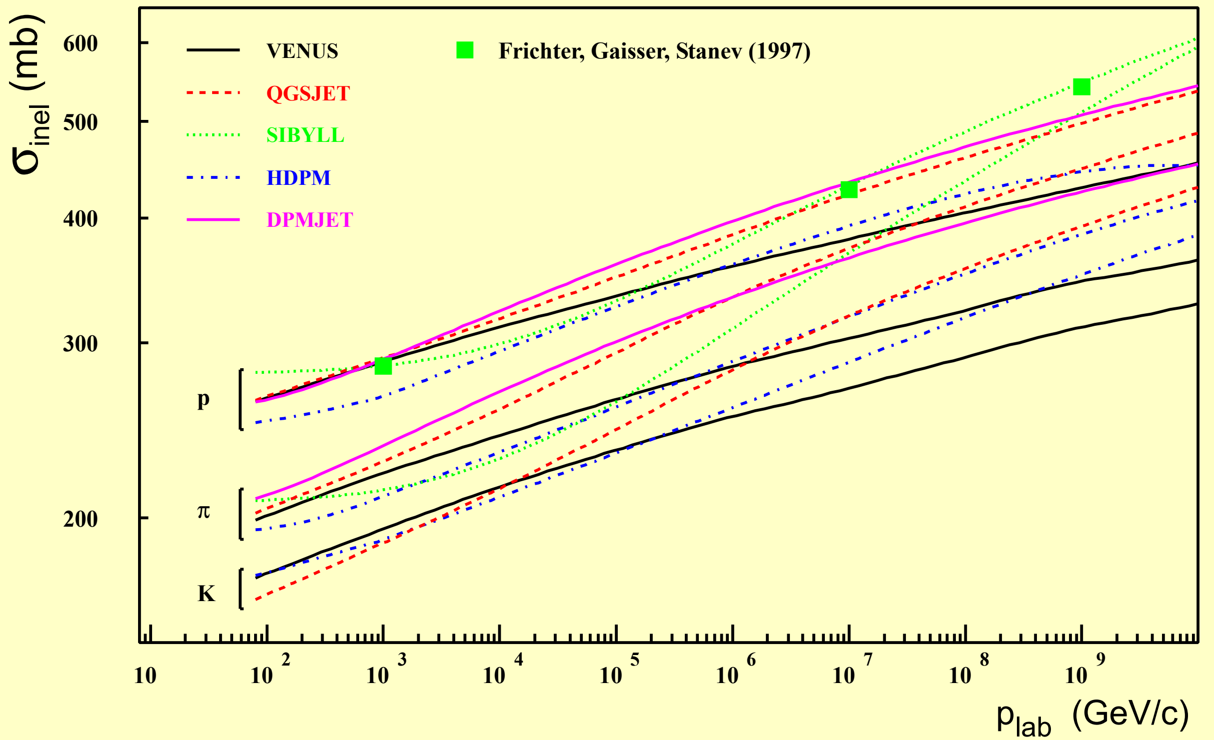
Cross-sections on Proton and Air

Hadron-Proton



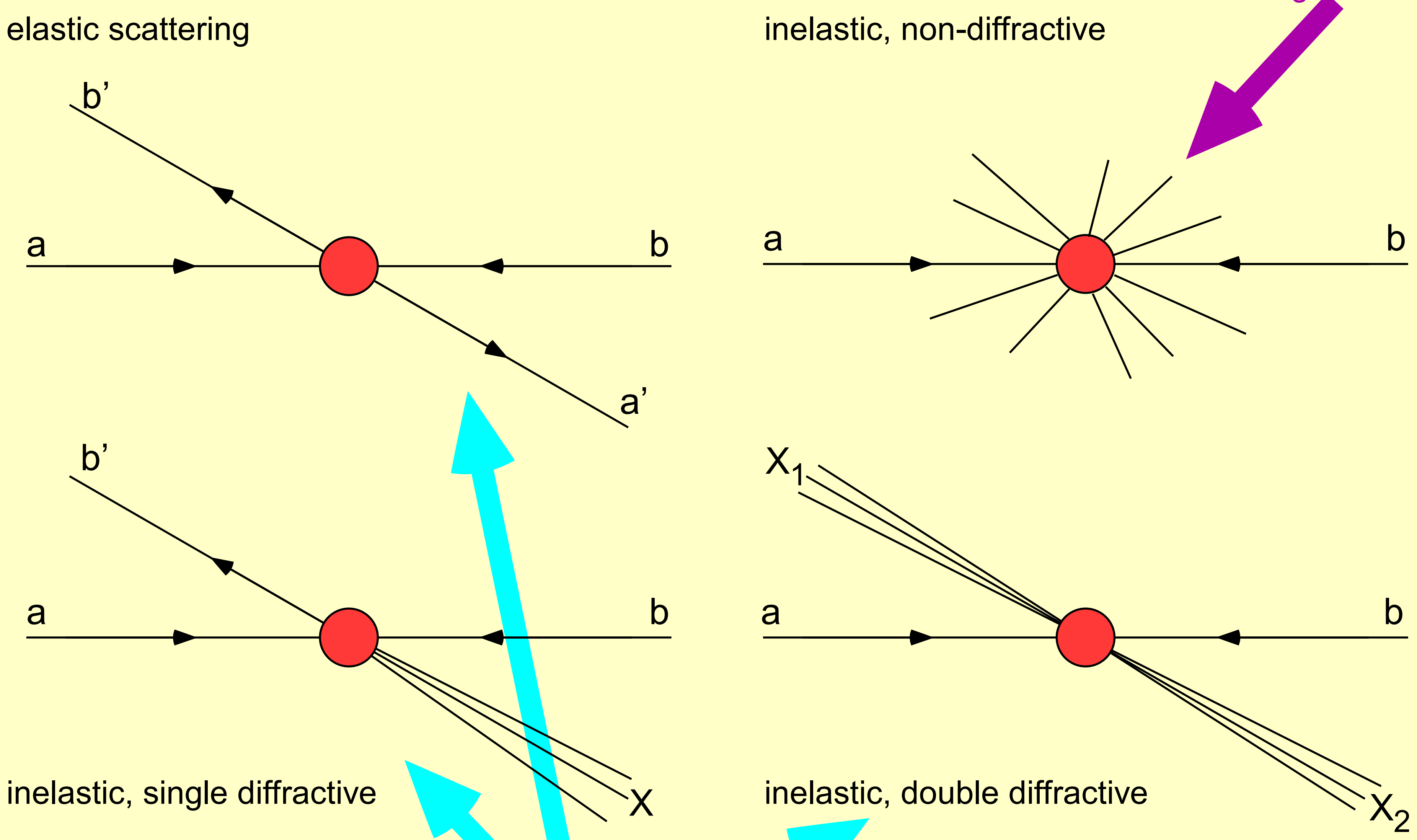
Where data exist
models agree,
where no data exist,
models diverge.

Hadron-Air



Soft Hadronic Interaction Types

particle production,
colour exchange,
high center-of-mass energy,
high inelasticity

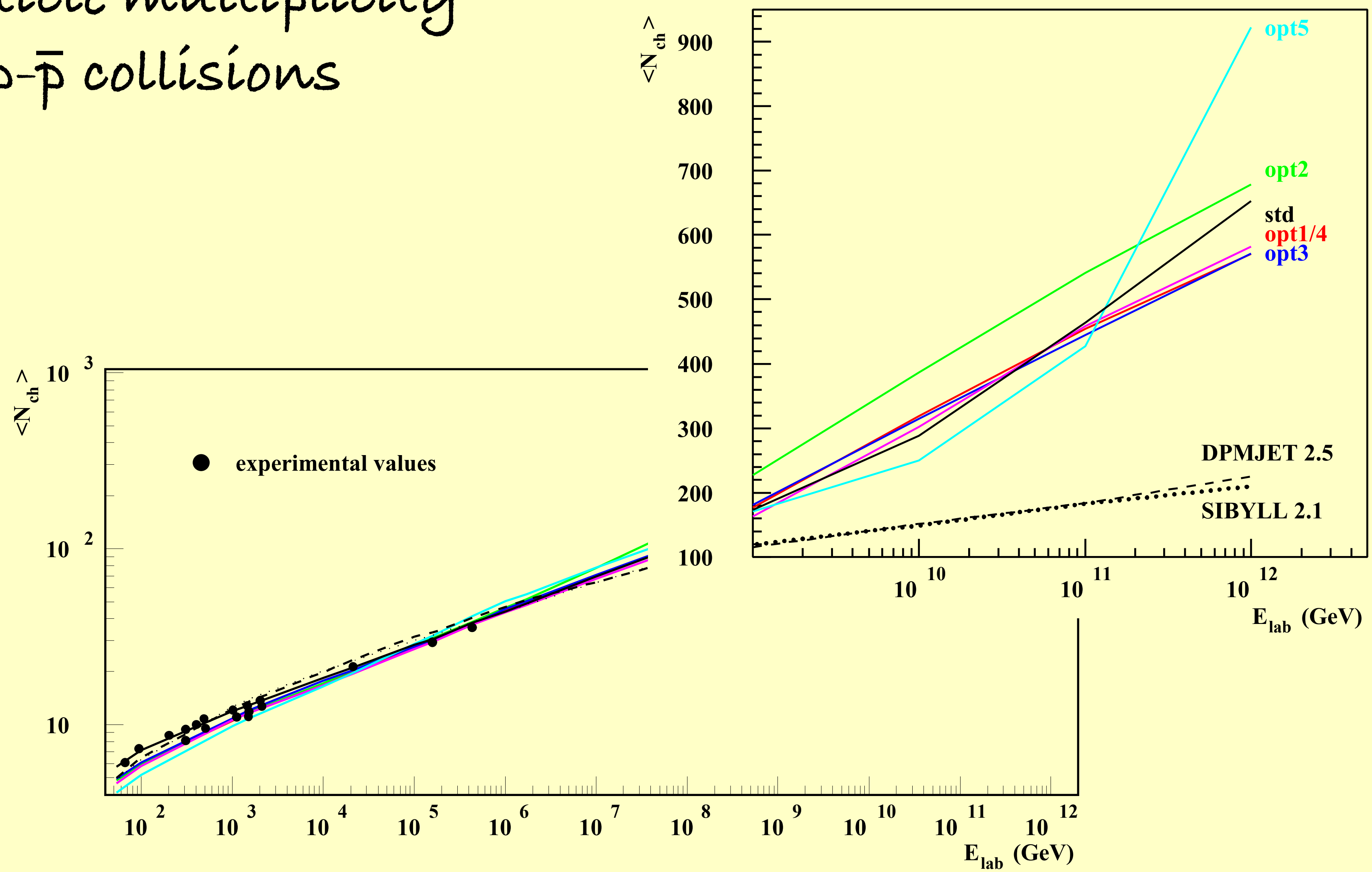


no colour exchange,
low center-of-mass energy,
low inelasticity

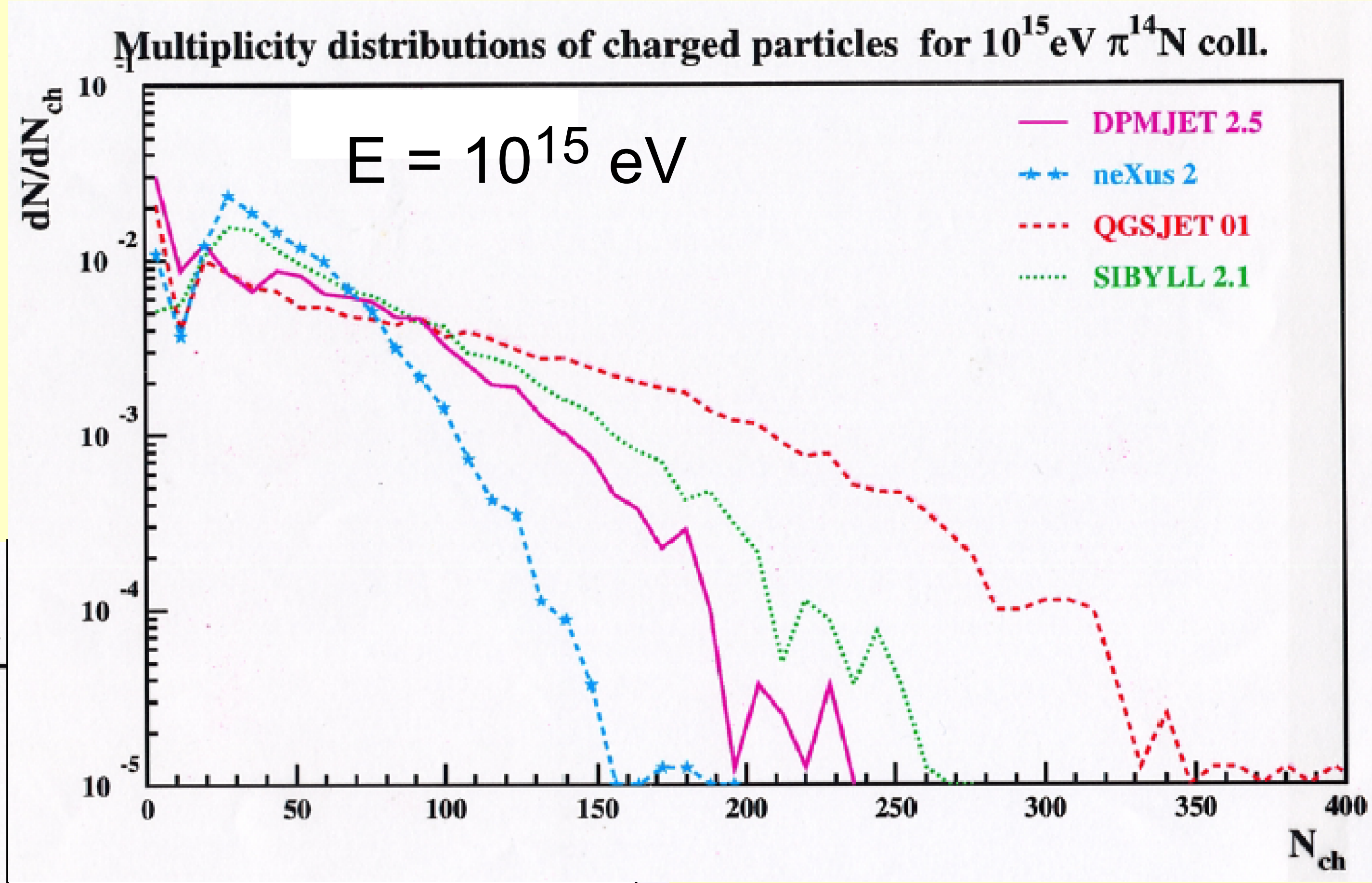
diffractive - non-diffractive ratio is very important

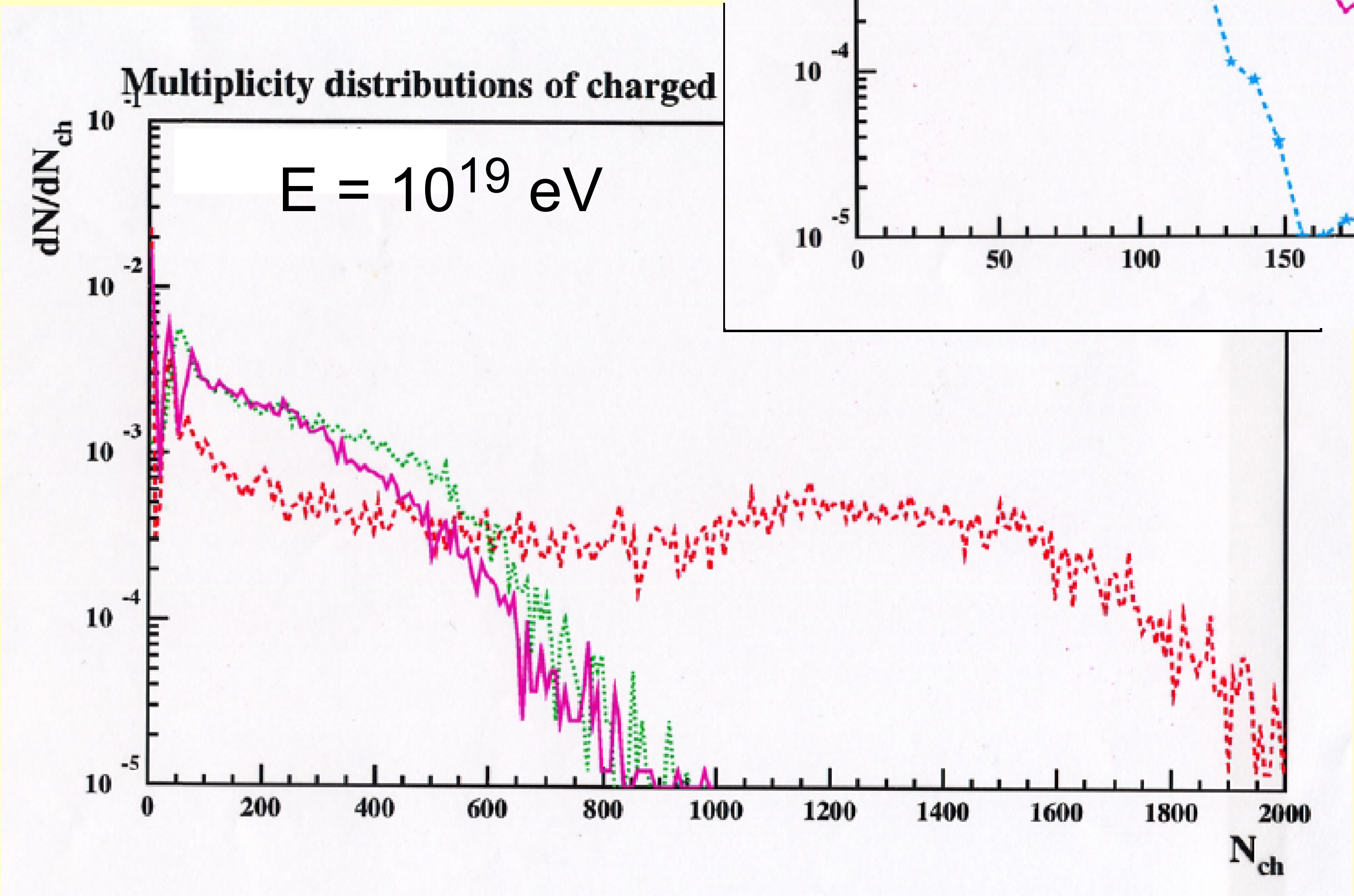
Results on particle production

particle multiplicity
in p-p̄ collisions



QGSJet produces much more secondaries than other models.





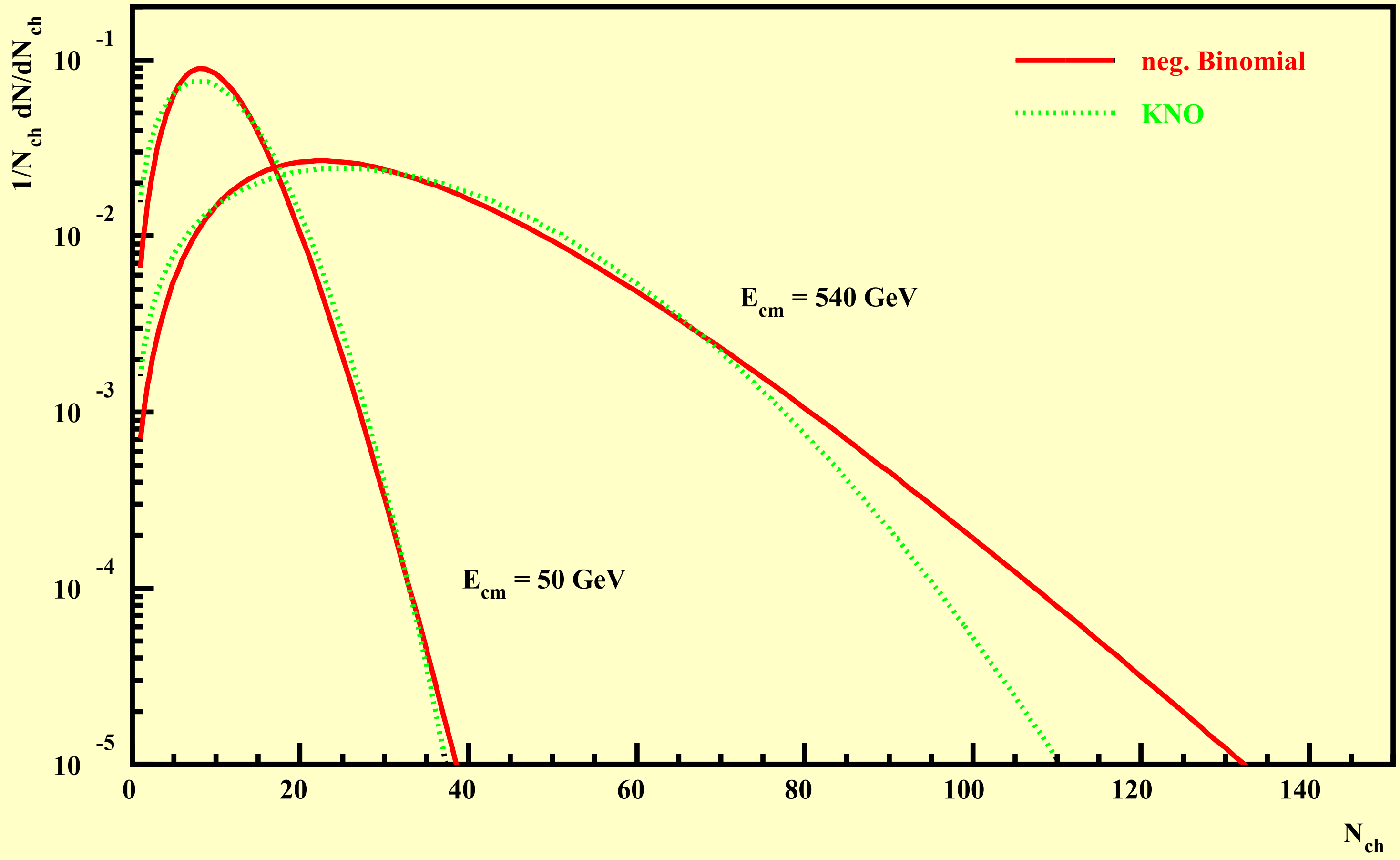
Huge difference, but does it matter ?

Multiplicity Distribution

at high energies: Negative Binomial Distribution

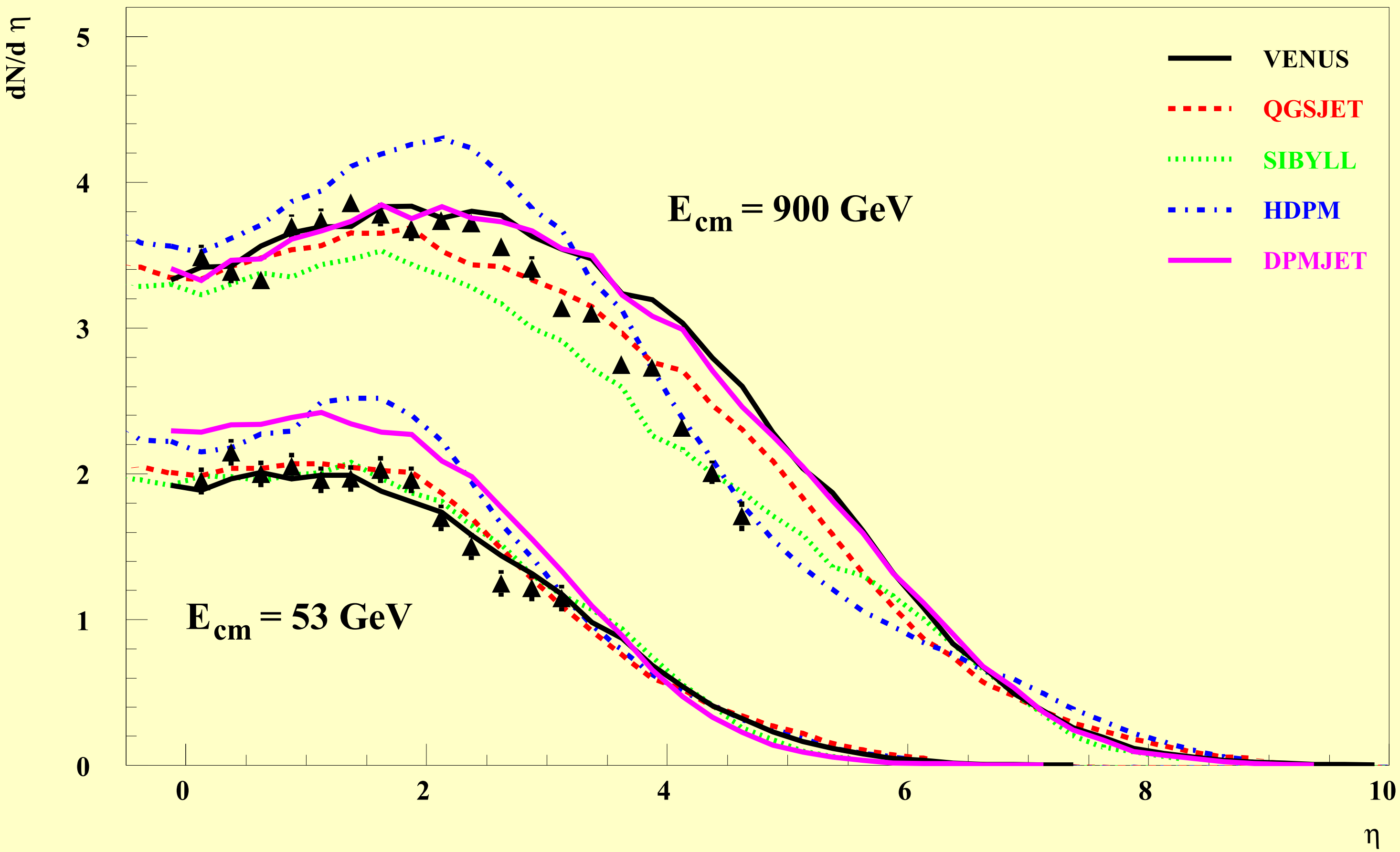
describes the wider range of values for n observed in collider data

$$P(n, \langle n\rangle, k) = \binom{n+k-1}{n} \left(\frac{\langle n\rangle/k}{1+\langle n\rangle/k}\right)^n \left(\frac{1}{1+\langle n\rangle/k}\right)^k$$



At ~10^{15} eV
negative binomial
distribution
is needed to describe
the experimental data.

UA5 results at the SPPS



Rapidity:

$$y = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$$

Pseudorapidity:

$$\eta = \frac{1}{2} \ln \frac{p+p_L}{p-p_L}$$

$$\eta = -\ln(\tan(\theta/2))$$

$\eta \sim y$
for high energies
(or zero mass)

(Pseudo)rapidity
is additive in Lorentz
transformation.

Pseudorapidity (η) distributions initially not very well described:

models can fit either dN/dη(η=0) or

the tail to large η-values,

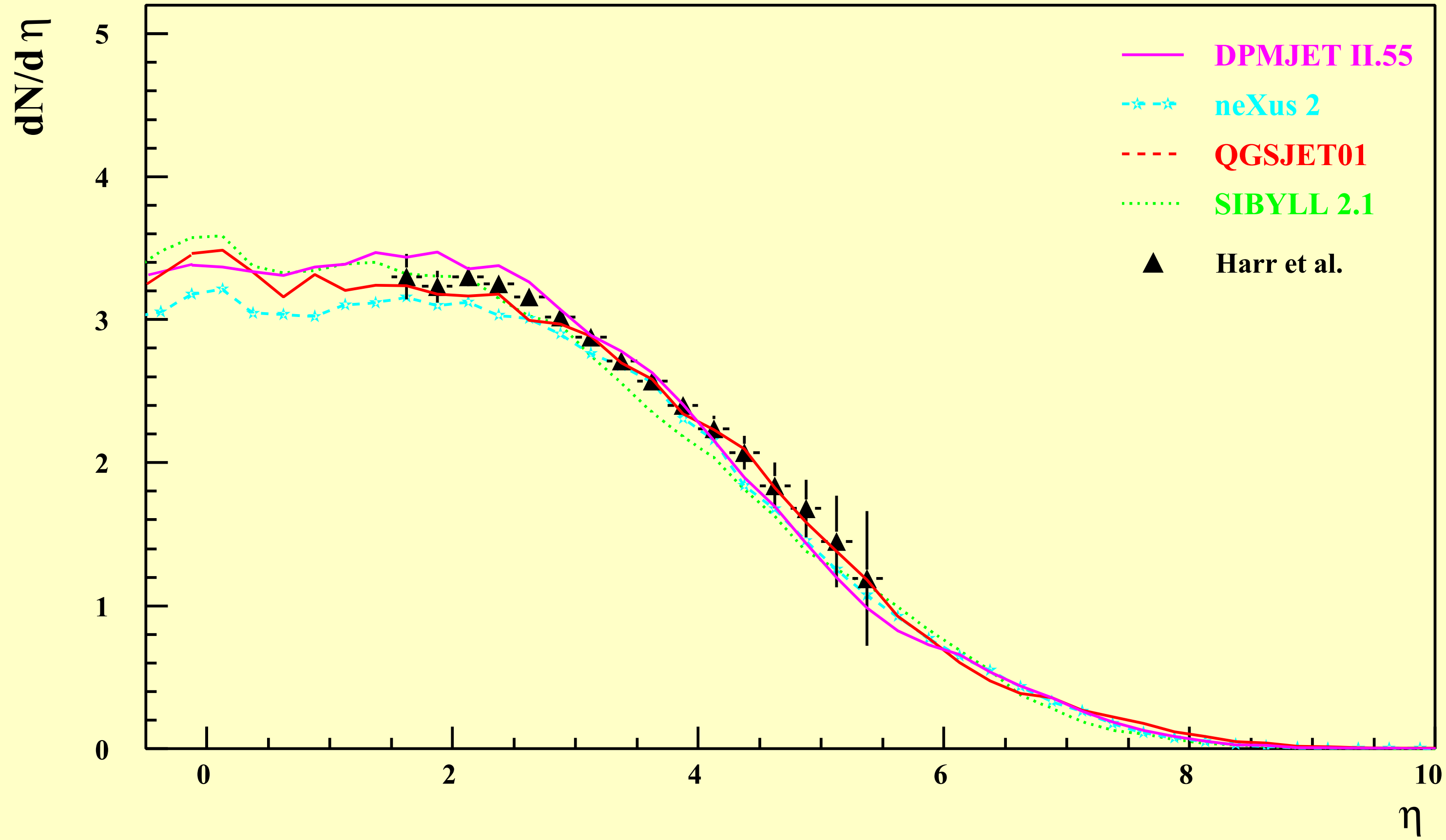
but not both.

are models wrong or badly tuned?

Another experiment at the same collider ....

E_{cm} = 630 GeV P238 (Harr et al.)

Simulations including experimental trigger

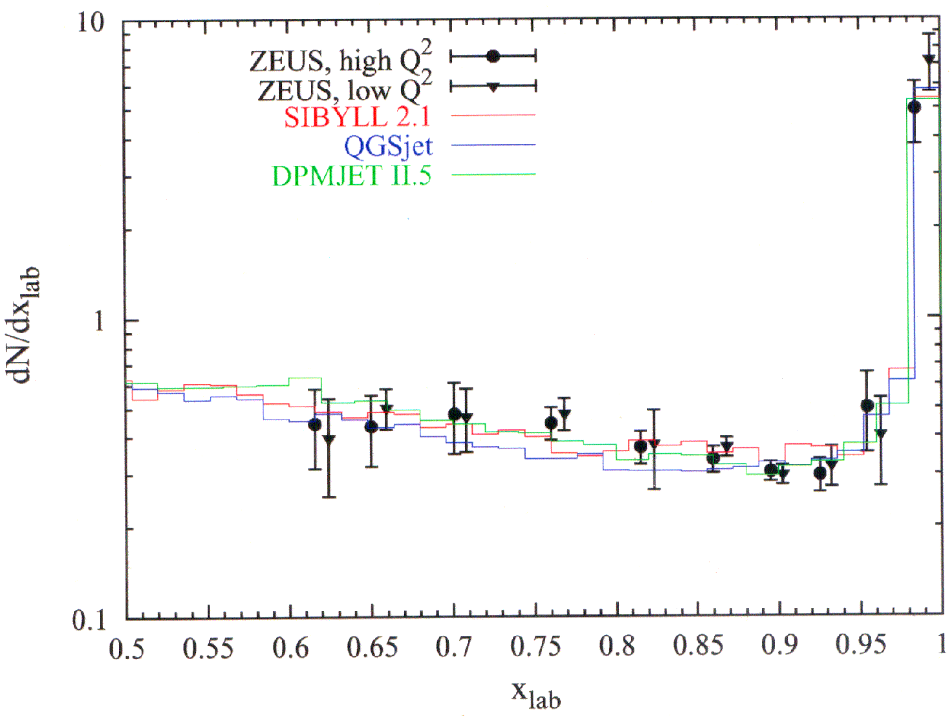


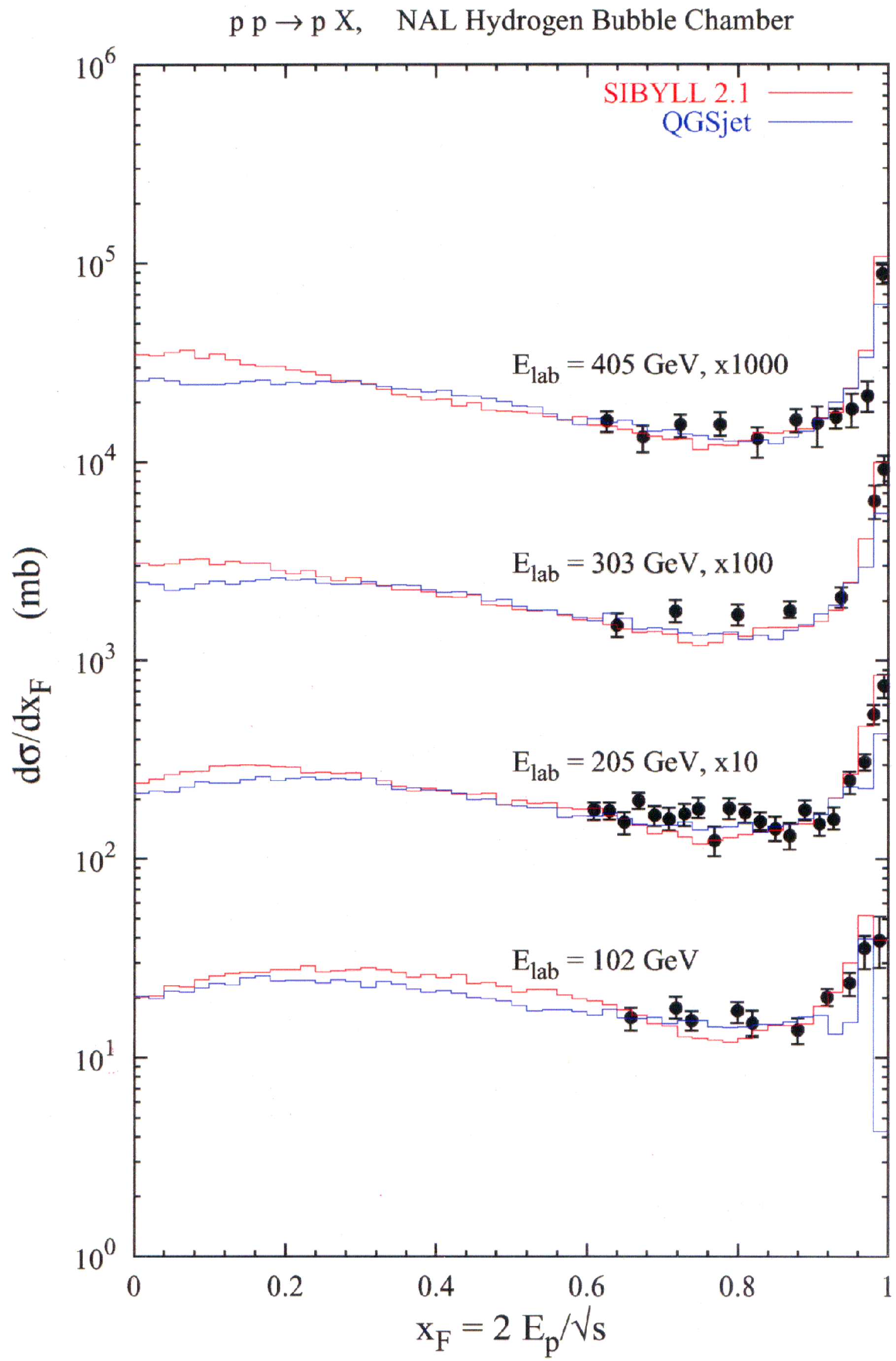
New experimental results in contradiction to older UA5 distributions, but very good agreement with simulations.

Experimental results are not always to be taken at face value.

Particle production in forward direction

... important since forward particles carry energy efficiently down the atmosphere

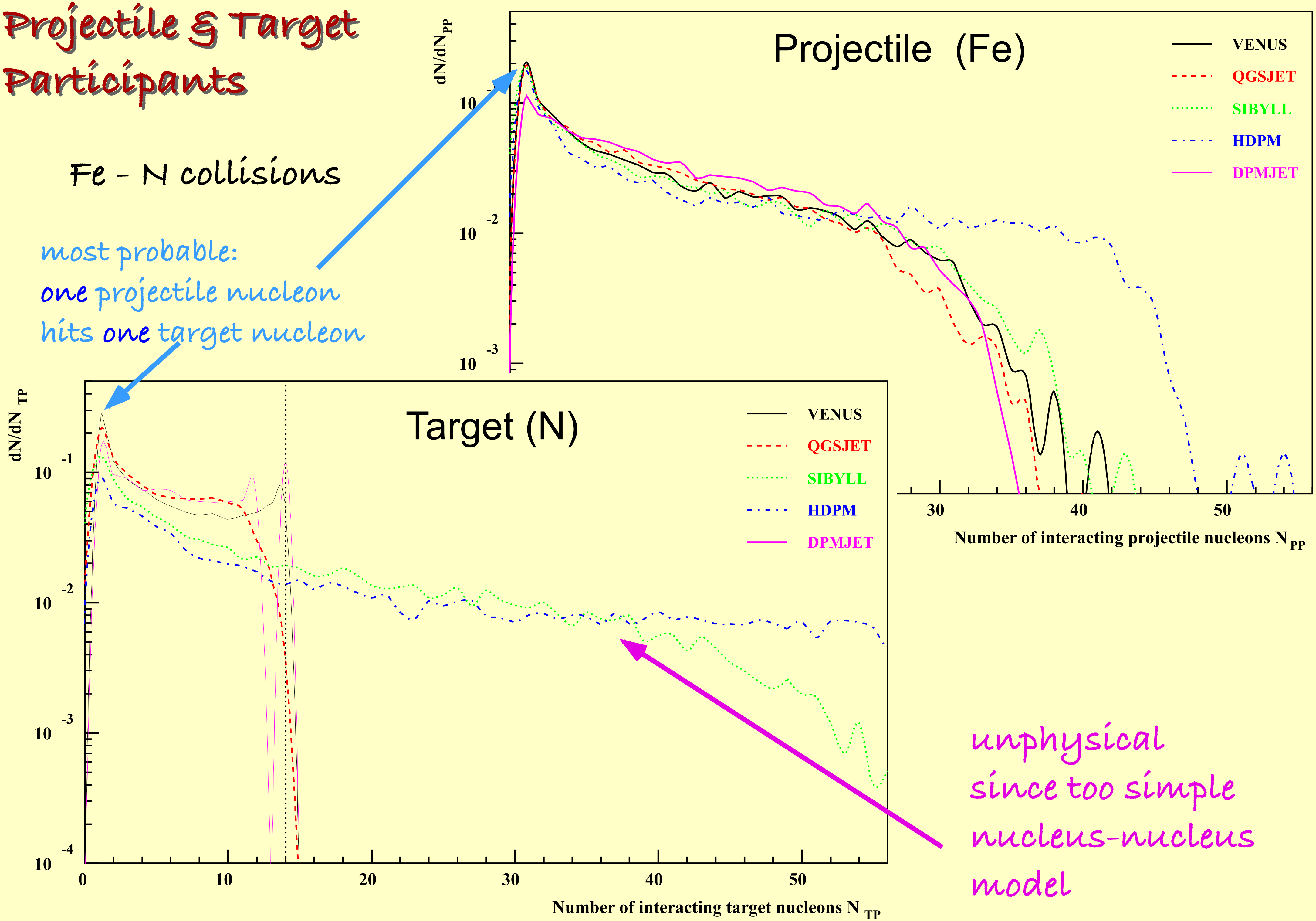




Projectile & Target Participants

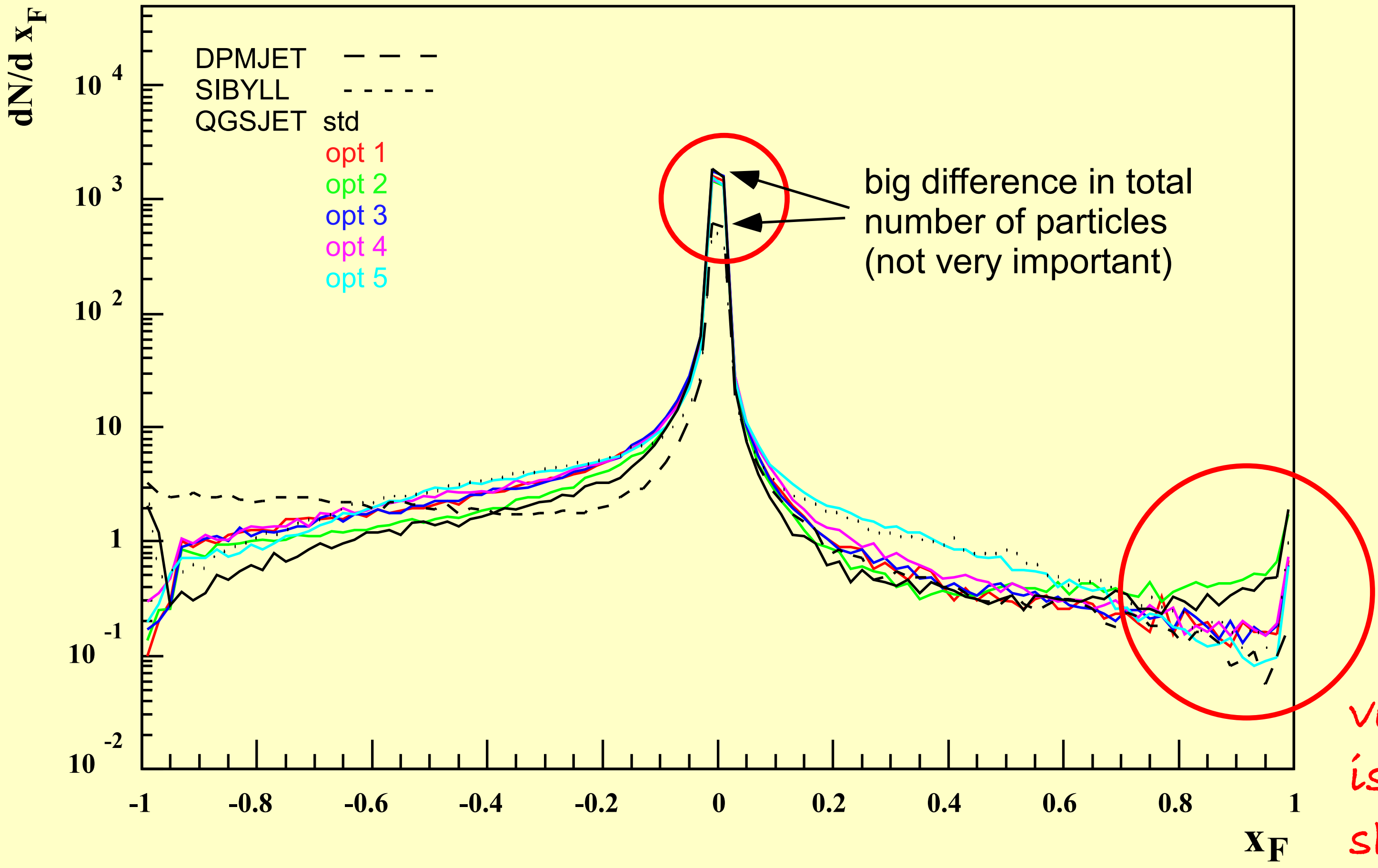
Fe - N collisions

most probable:
one projectile nucleon
hits one target nucleon



unphysical since too simple nucleus-nucleus model

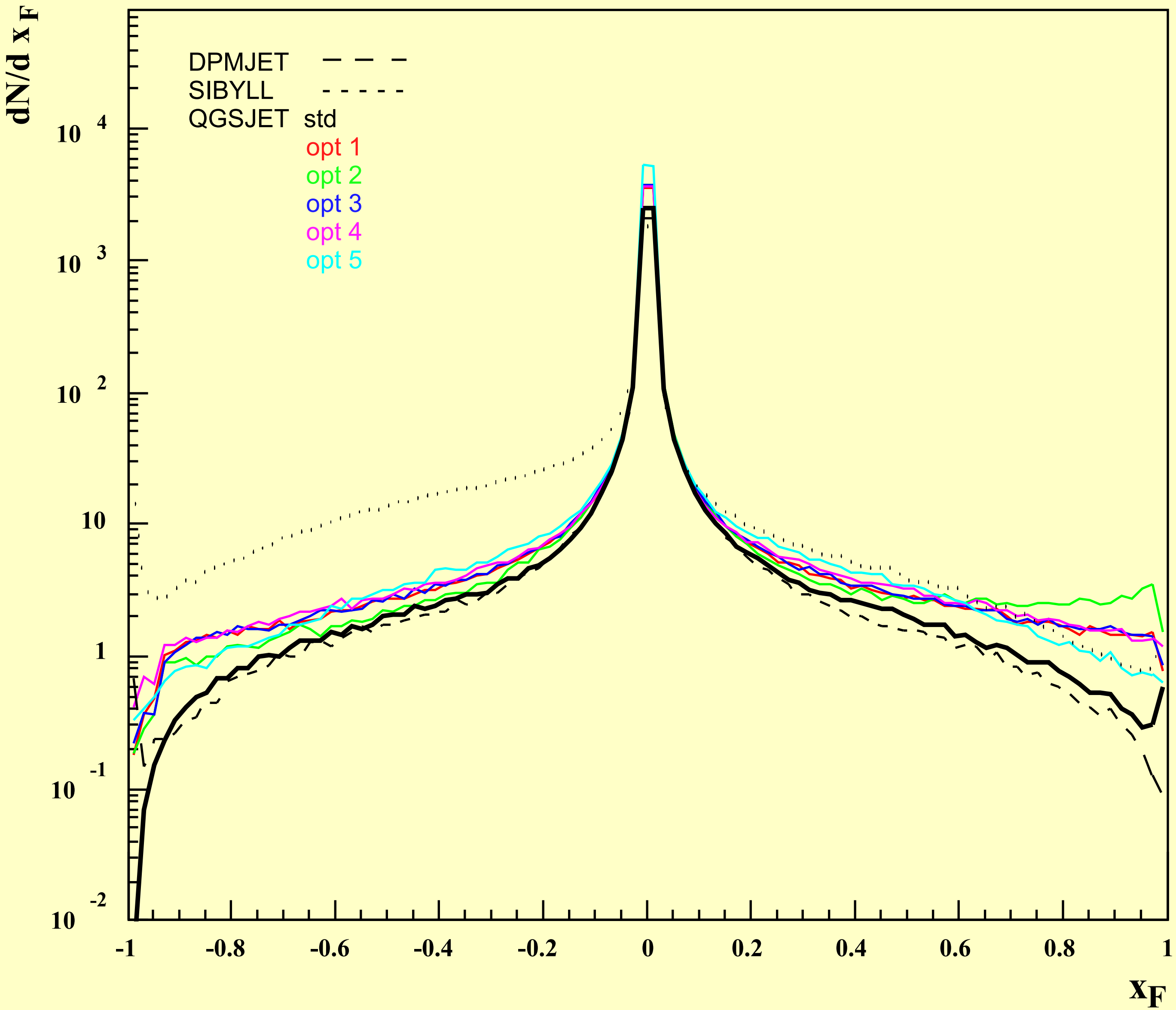
Feynman x distribution in p-N collisions

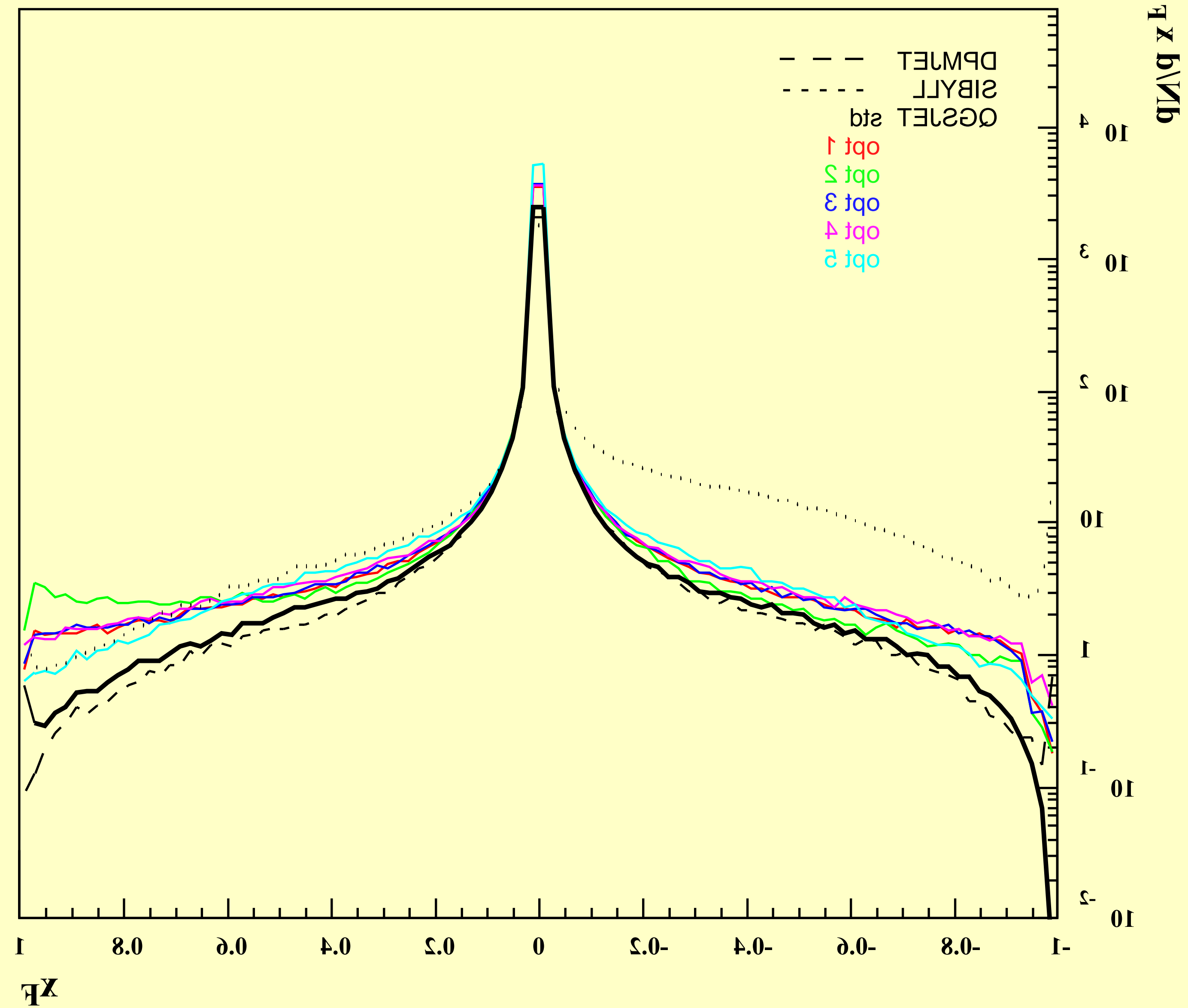


very forward region is important for shower development

Feynman x distribution in N-N collisions ...

... should be symmetric as well





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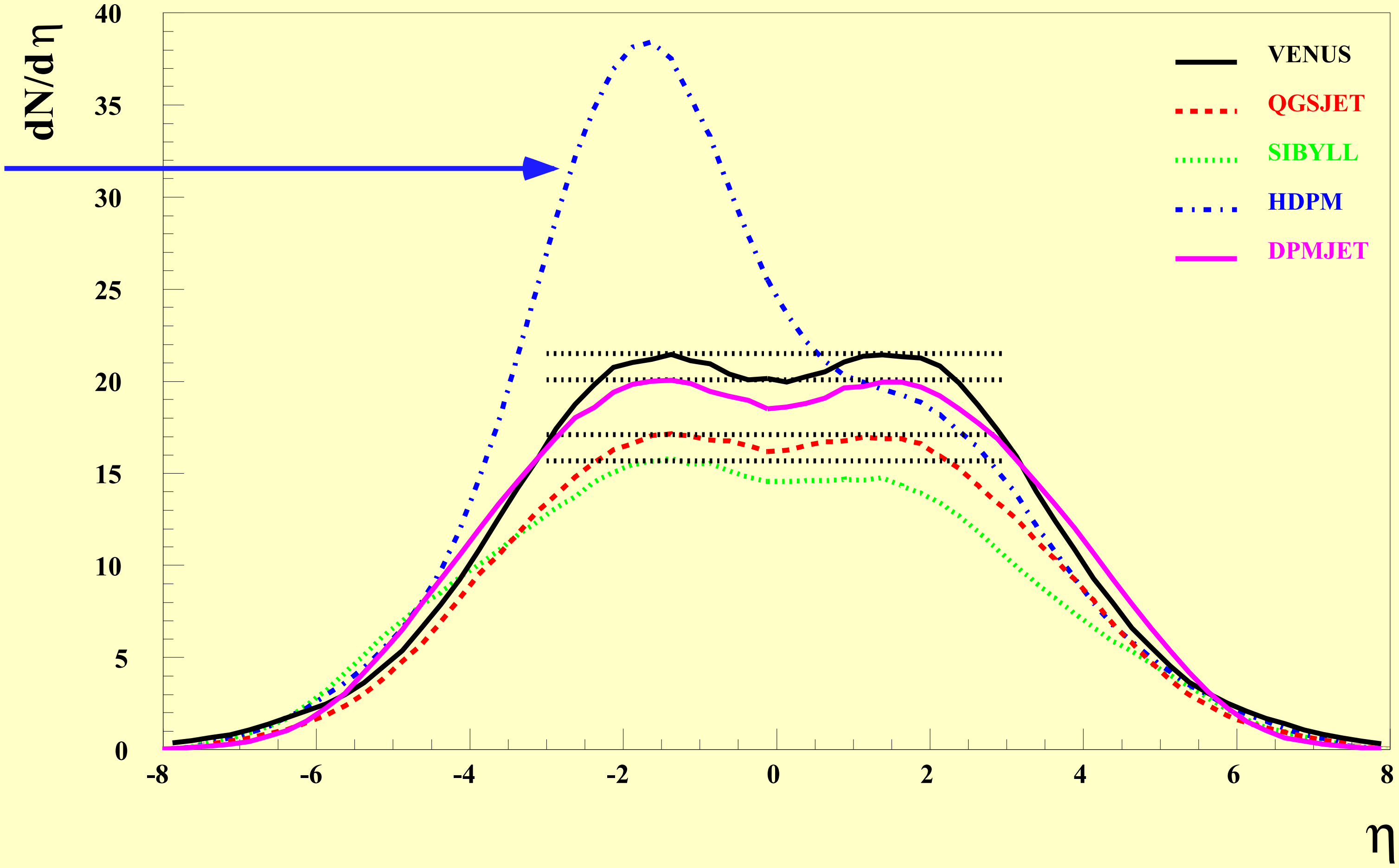
Nitrogen-Nitrogen Collisions

very bad !



... should be perfectly symmetric,
if nuclear interactions are treated well.

Longitudinal Shower Profiles

difference in X_{max},
but large fluctuations

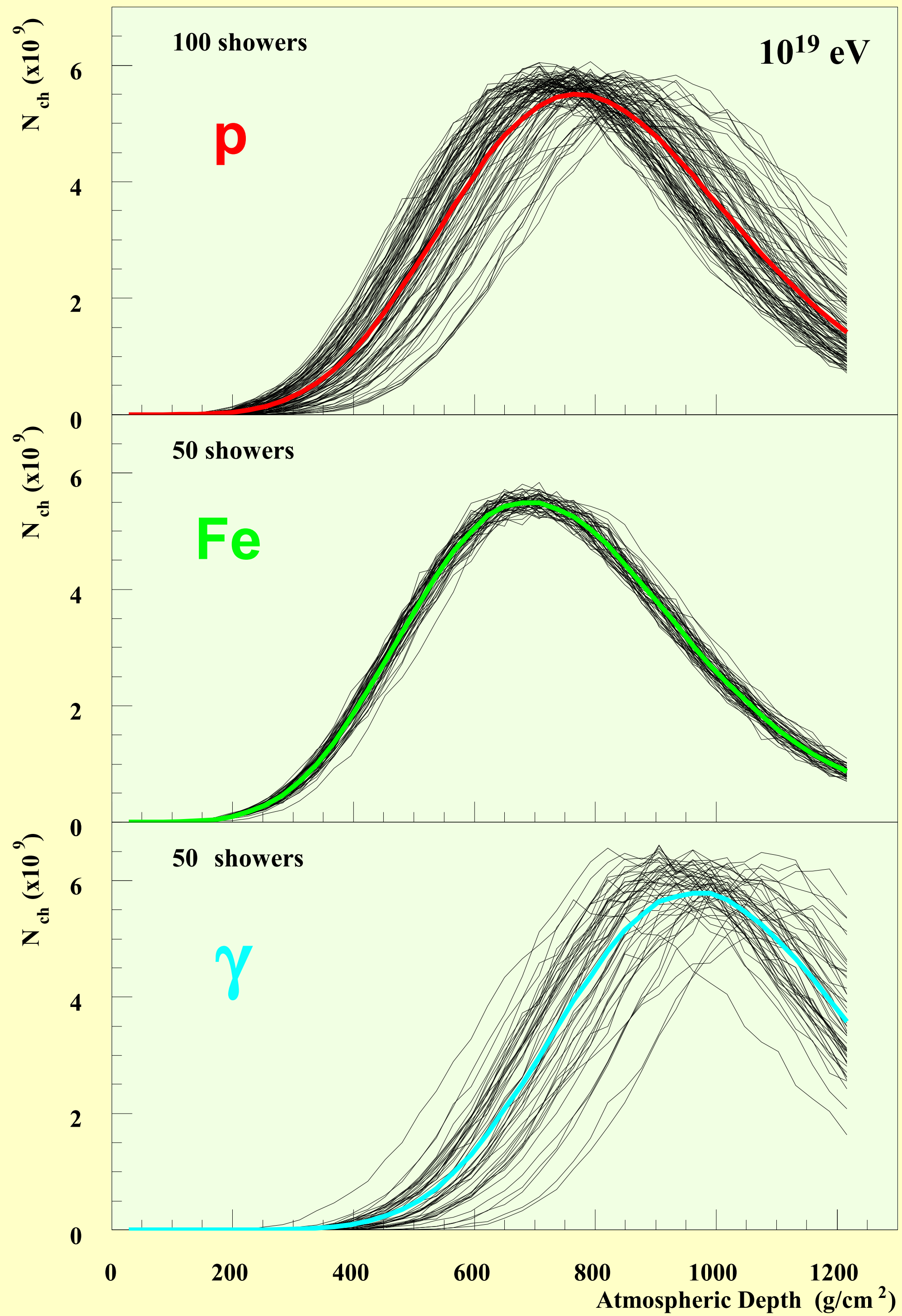
differences between
hadrons and photons are large

differences between
proton and iron (or nuclei)
are subtle

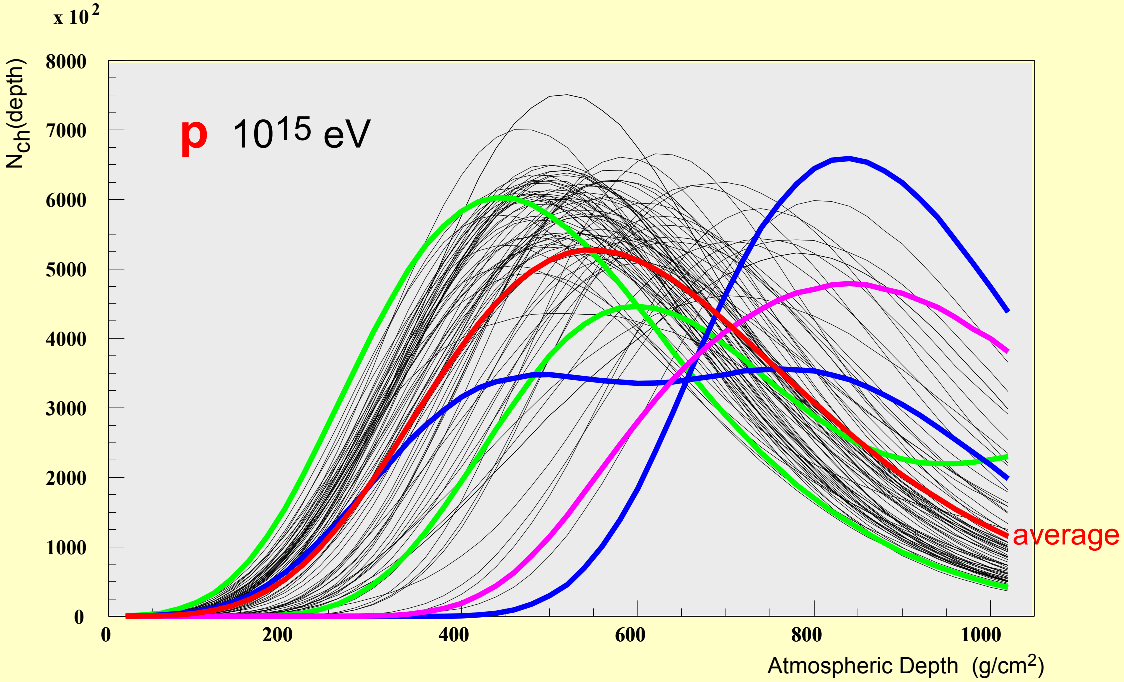
On average Fe have:

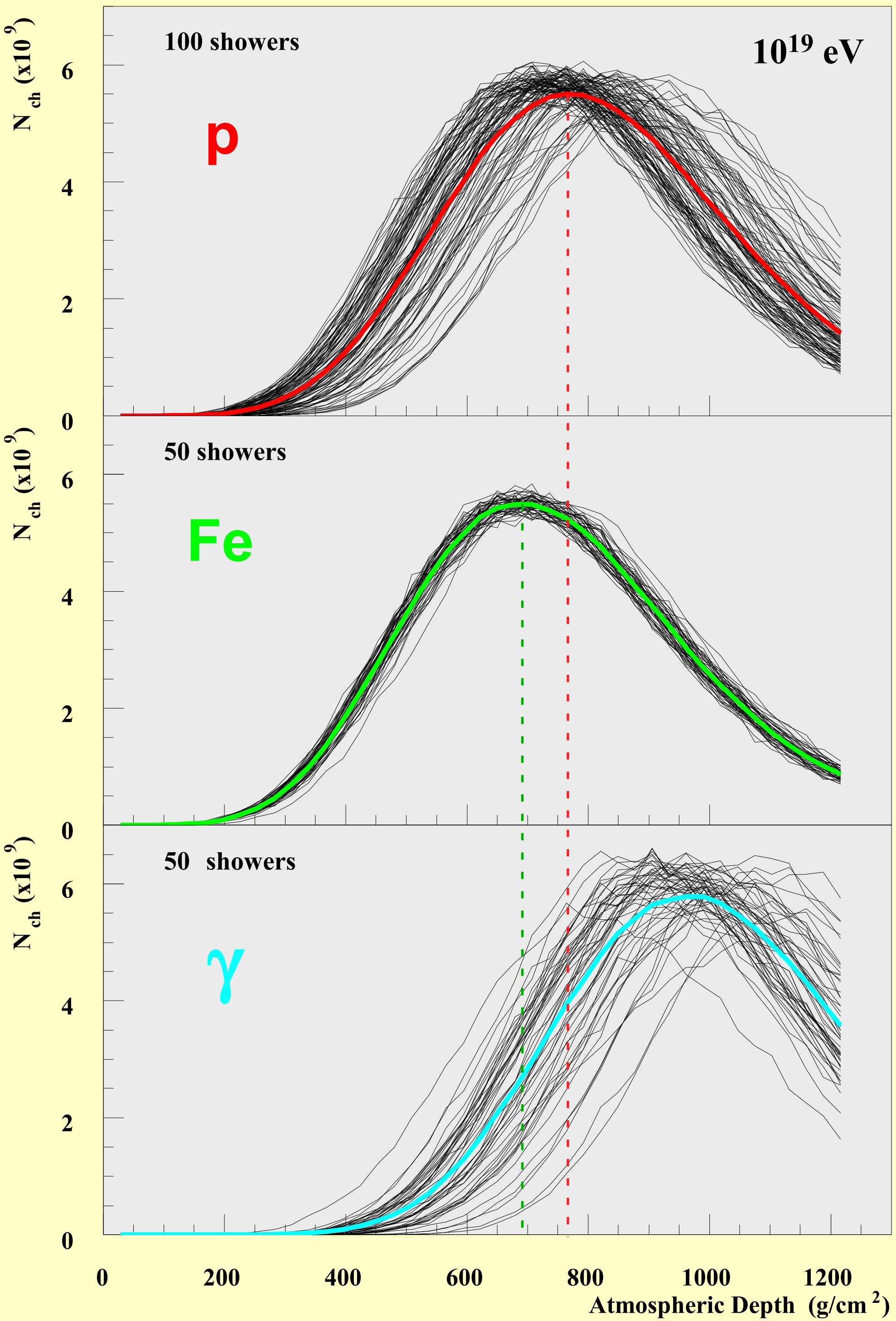
- higher 1st interaction, since σ_{int} larger,
- more secondaries, since $N_{sec} \sim \ln(E)$,
- more μ, less e,γ at ground,
- smaller fluctuations,
  since superposition of 56 subshowers
- faster signal rise, since μs faster

than p showers.



Longitudinal Shower Development





at lower energies:

large fluctuations

"strange" shower curves because of fluctuations in height and type of first few interactions.

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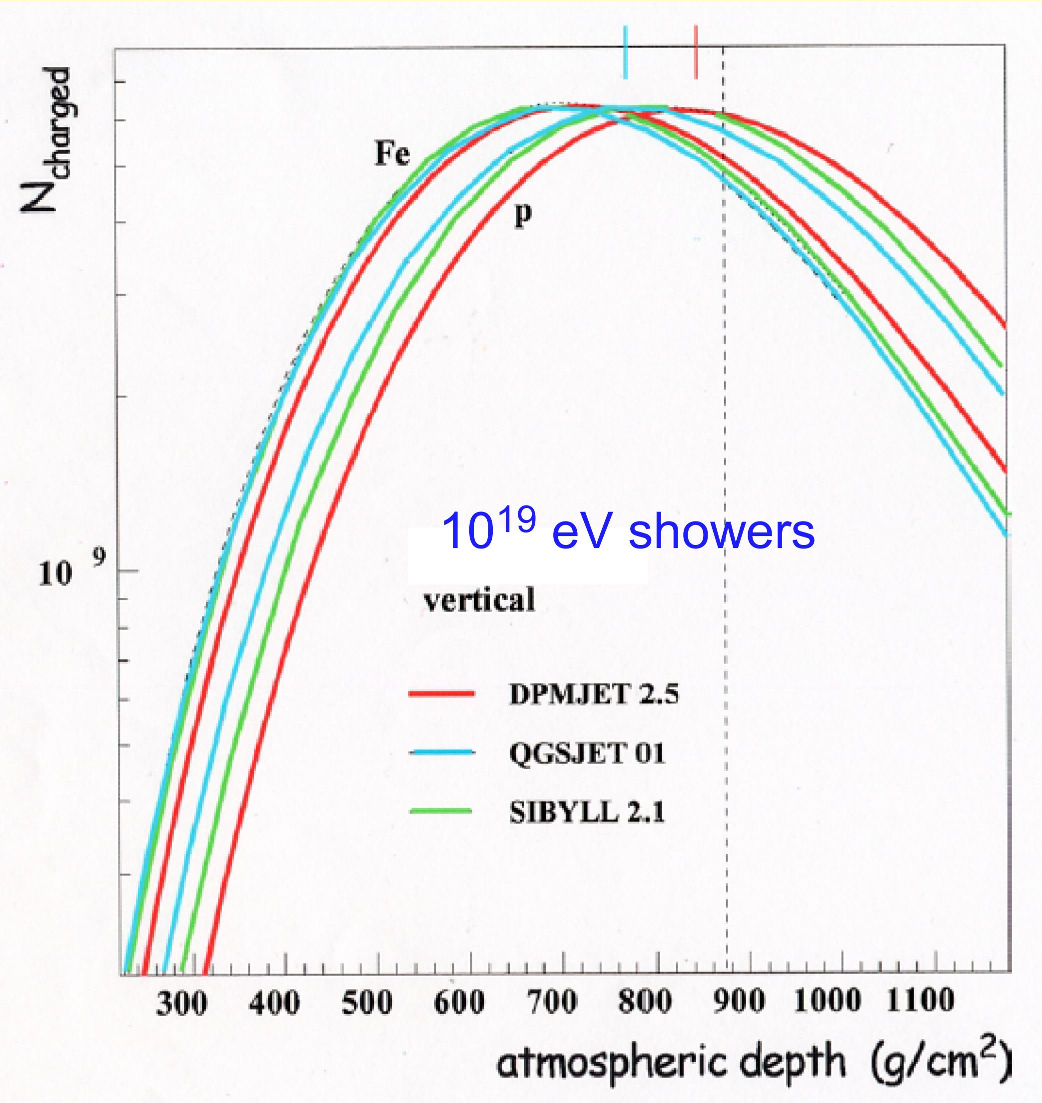
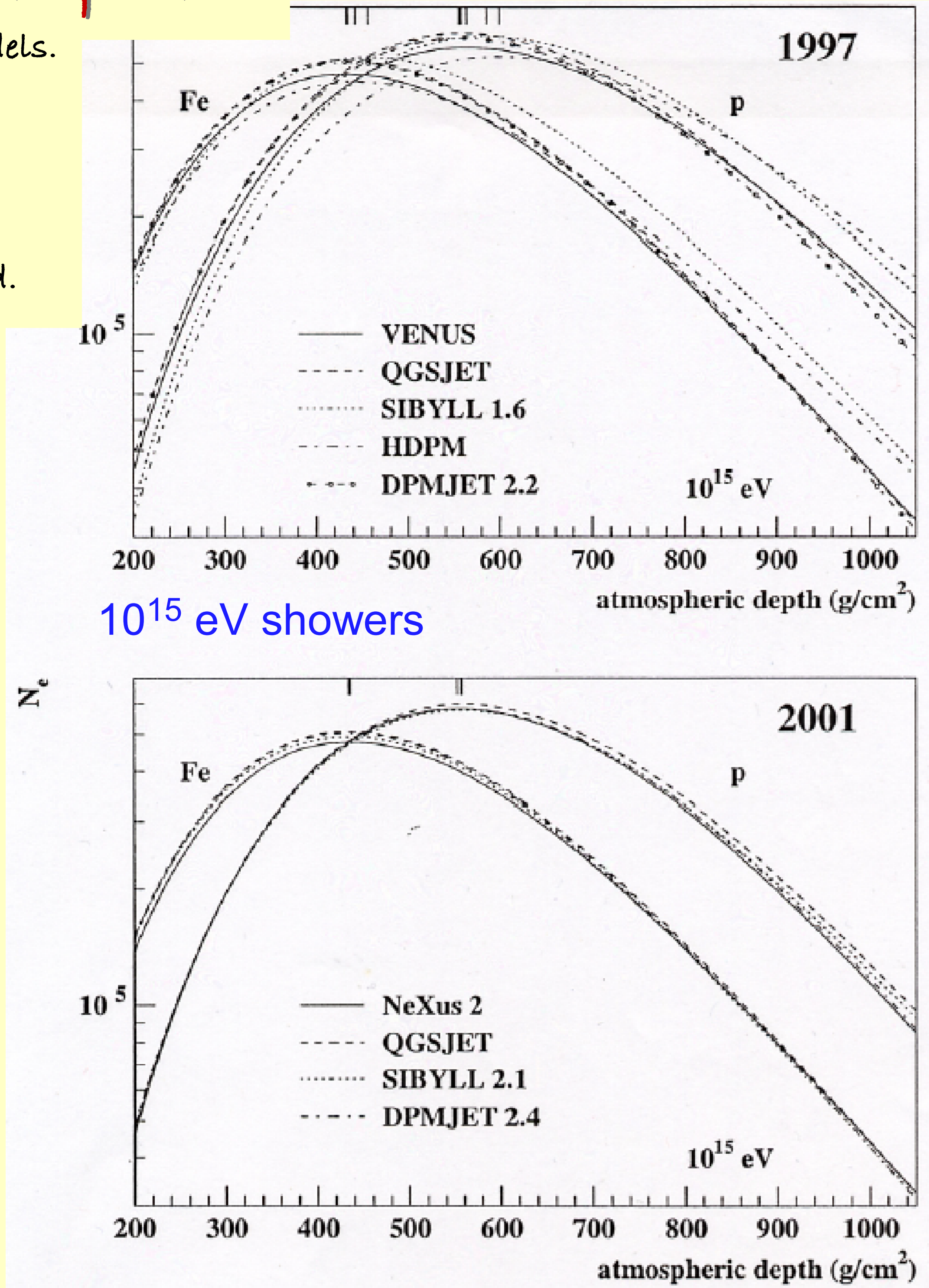
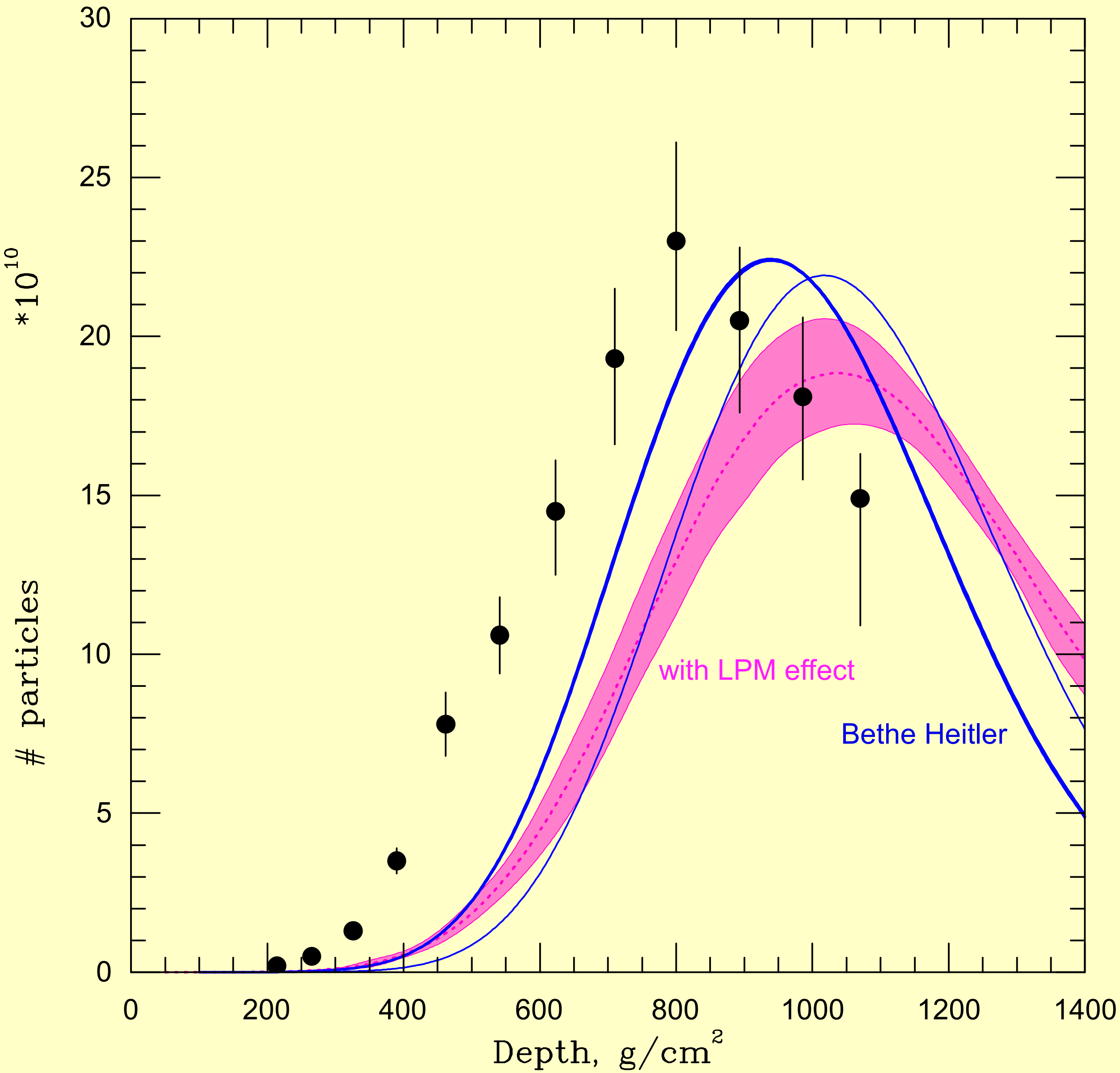
Average Longitudinal Shower Development

QGSJet well in line with other models.
High multiplicity
partly compensated by
lower cross-section and
partly irrelevant since mostly
low-energy particles produced.

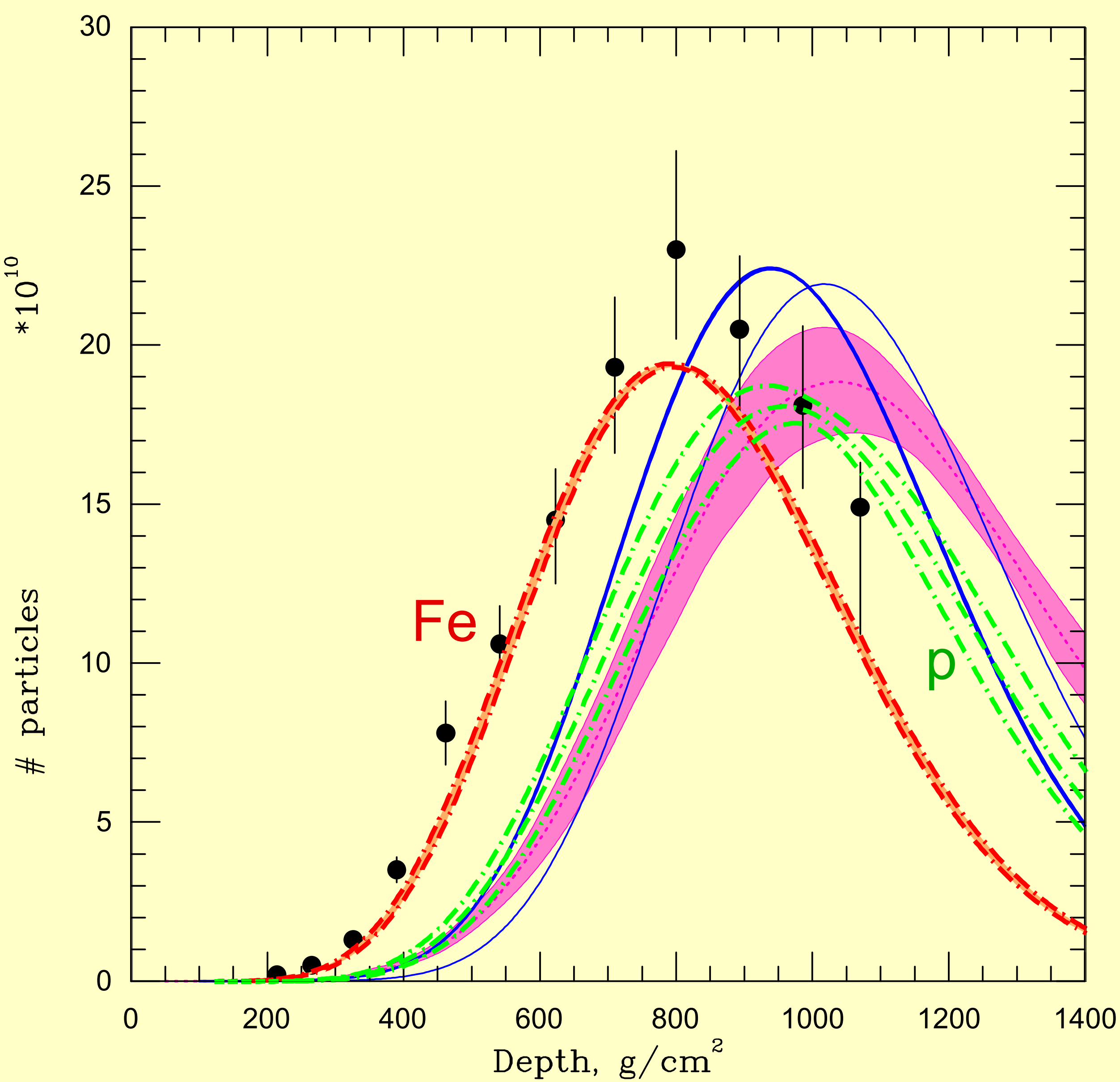




The 3×10^{20} eV Fly's Eye Event … is it a photon shower ?



The 3 x 10^{20} eV Fly's Eye Event ... is it a photon shower ?



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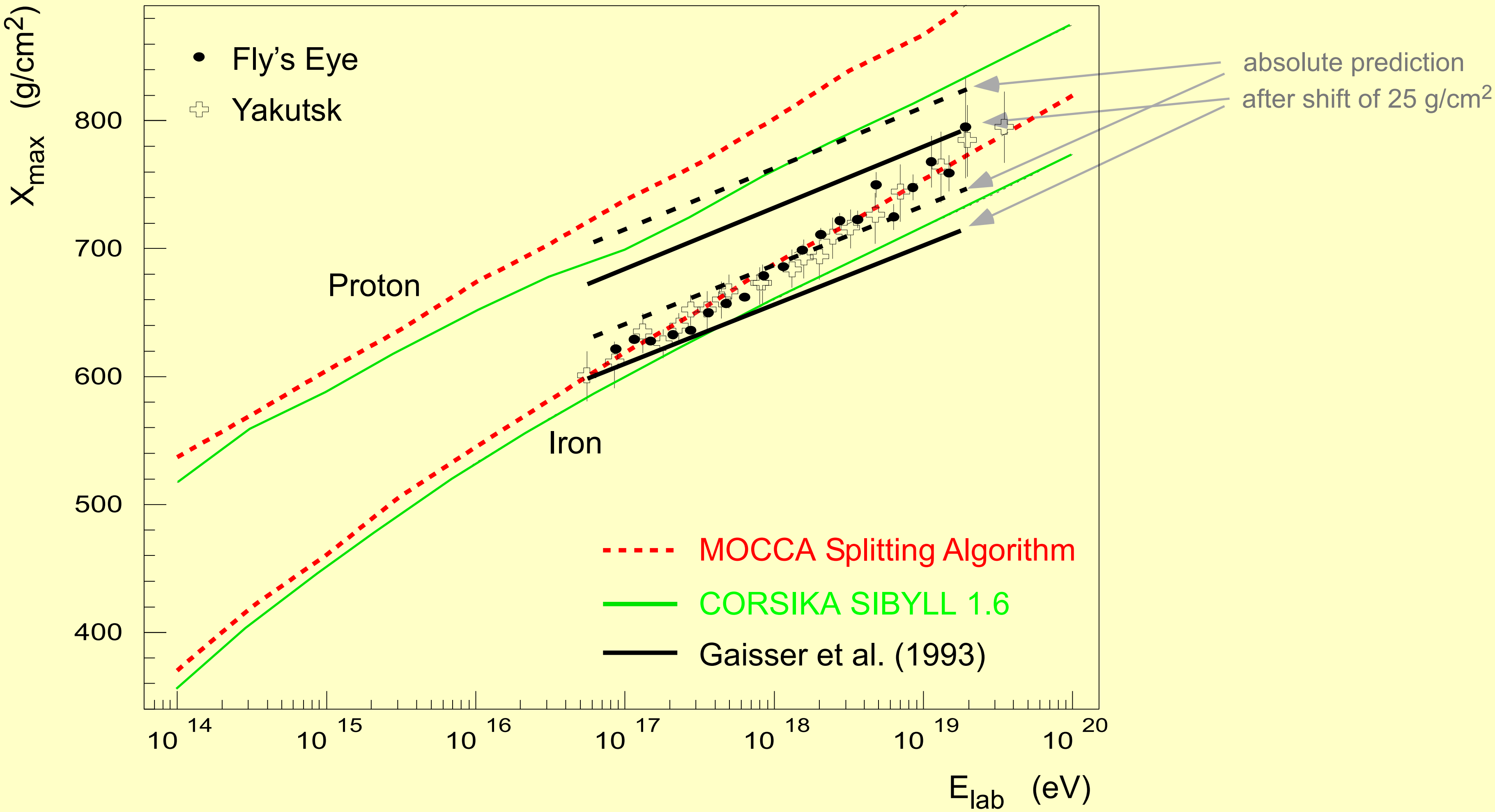
Data versus Simulations

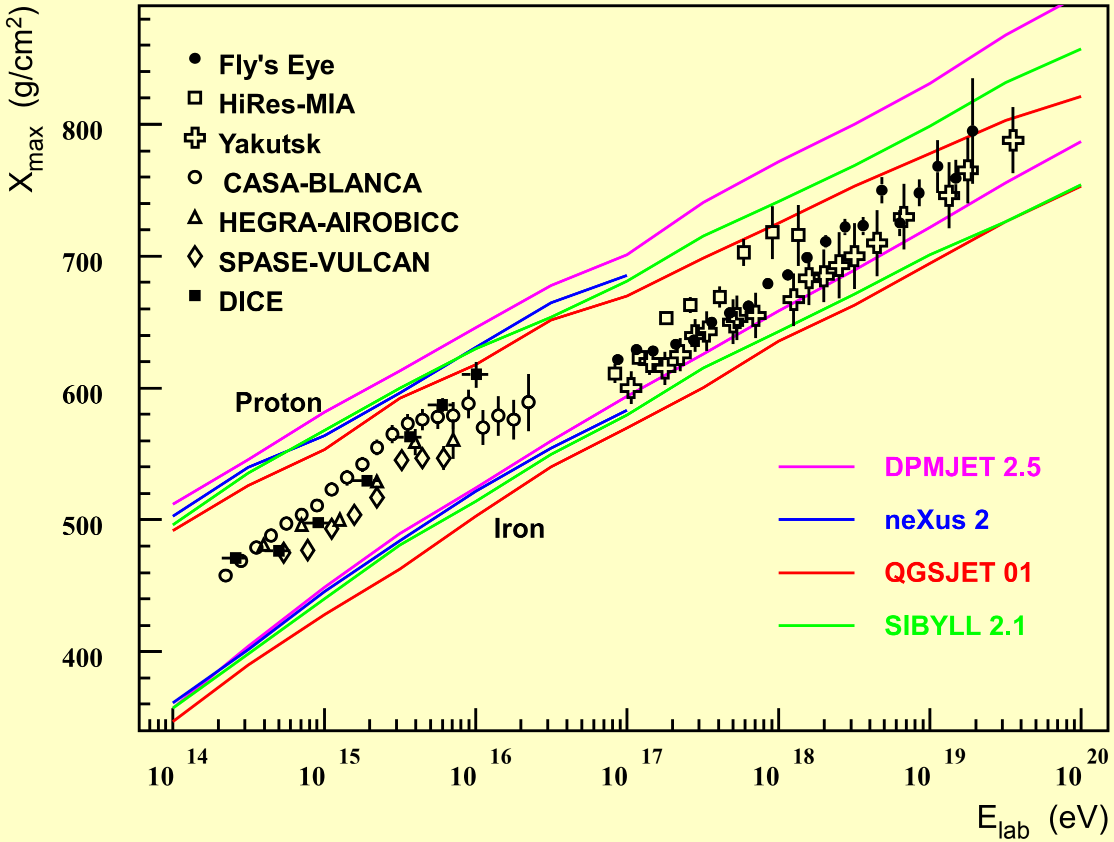
X_{max} versus energy : comparison with model suggested composition change from Fe to p



Data versus Simulations

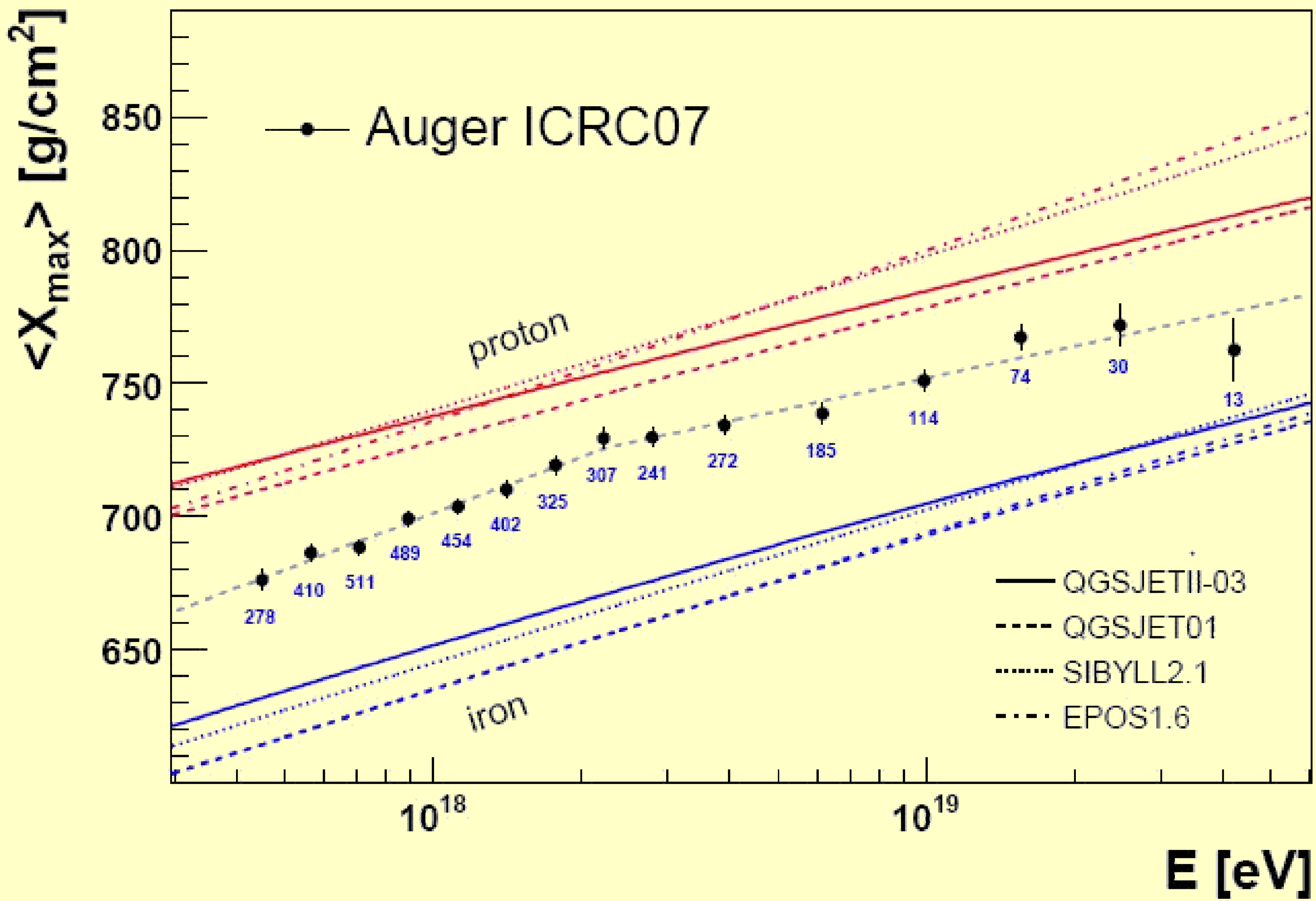
X_{max} versus energy

Now : in general good agreement (absolute prediction) over 6 orders of mag.



Model dependence of composition persists, though at much lower level.

Data versus Simulations

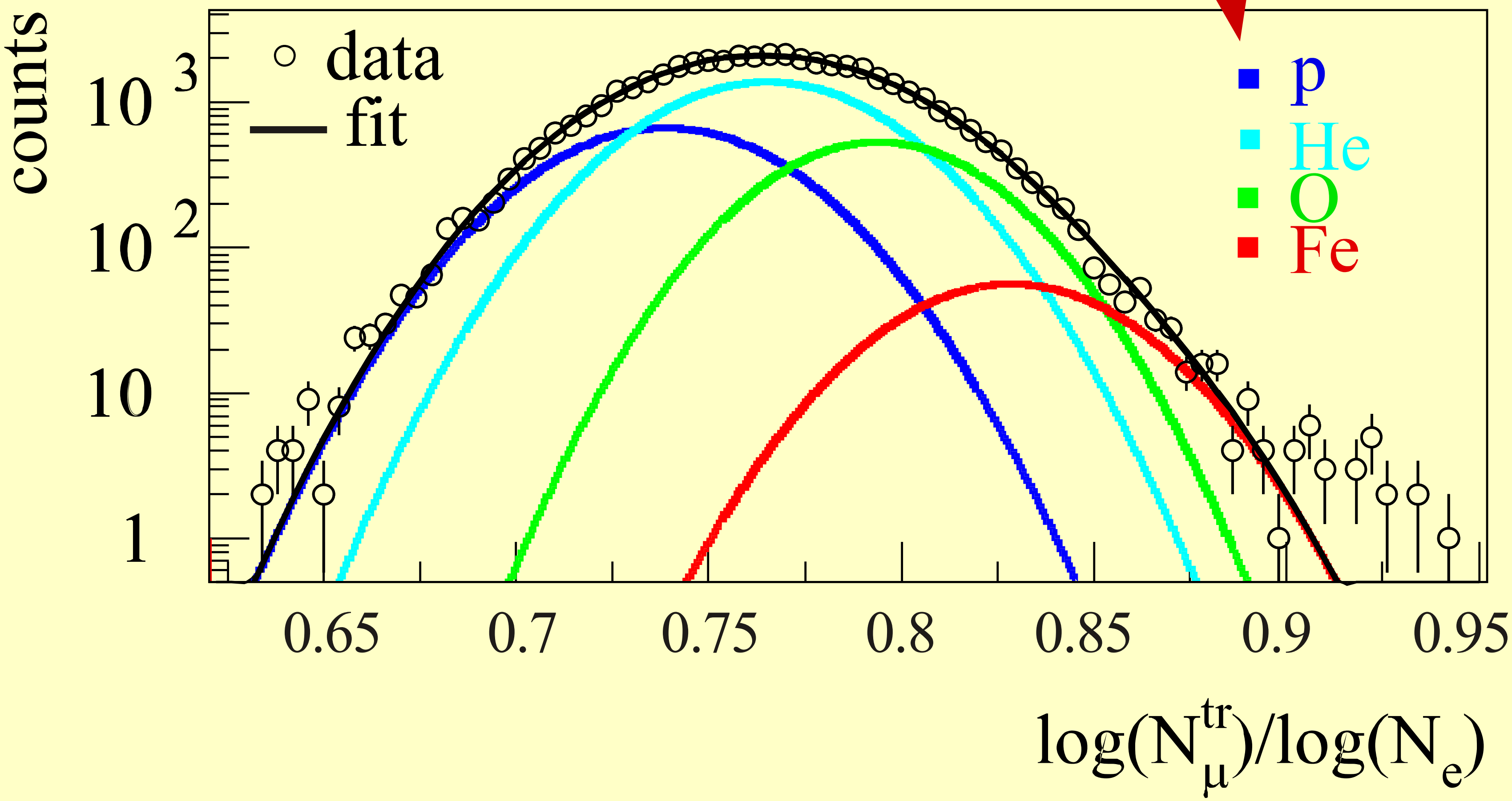


Data versus Simulations ... another example

KASCADE: 10^{15} - 10^{16} eV

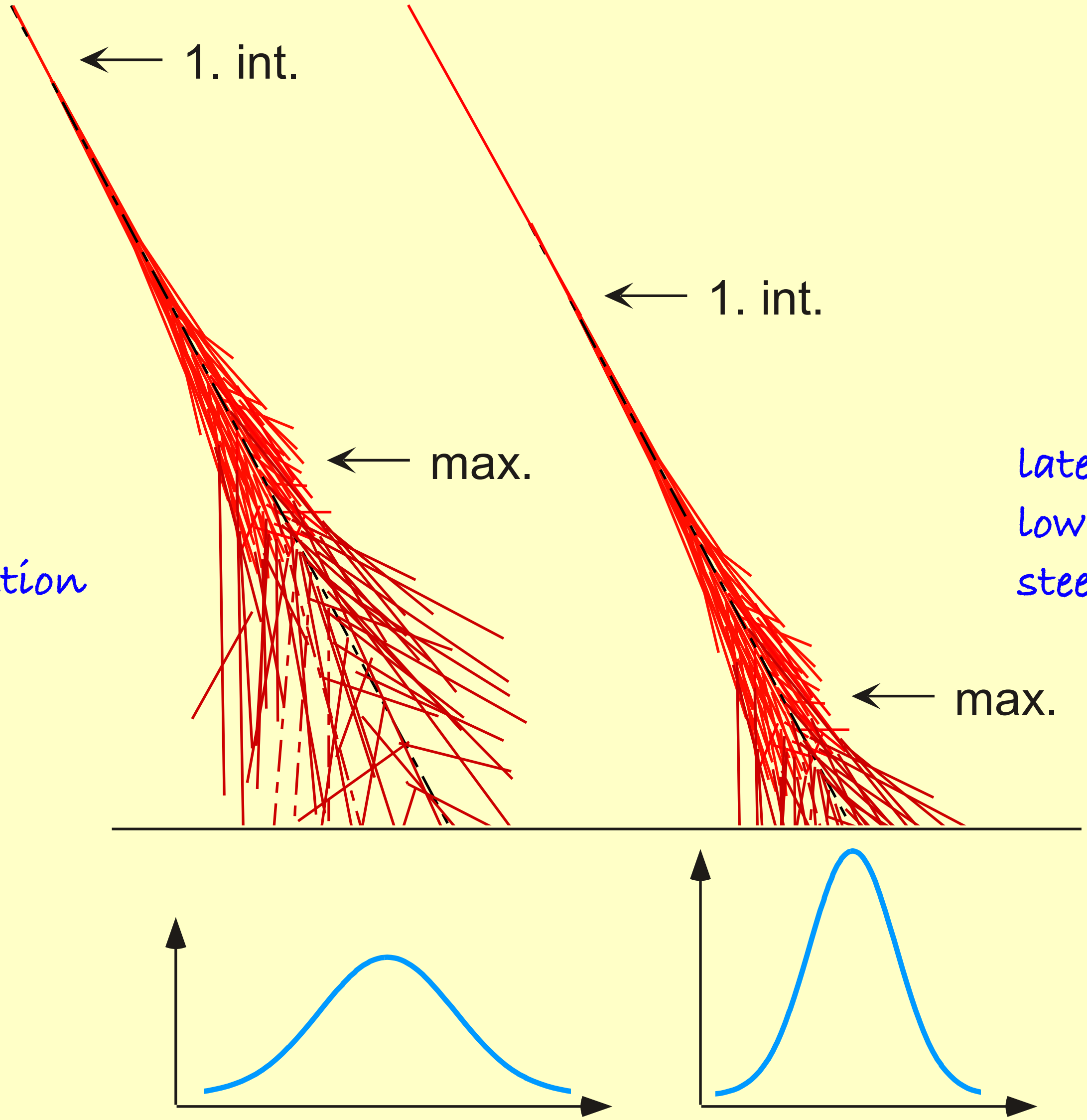
muon - electron ratio

CORSIKA Simulations



Lateral Distribution

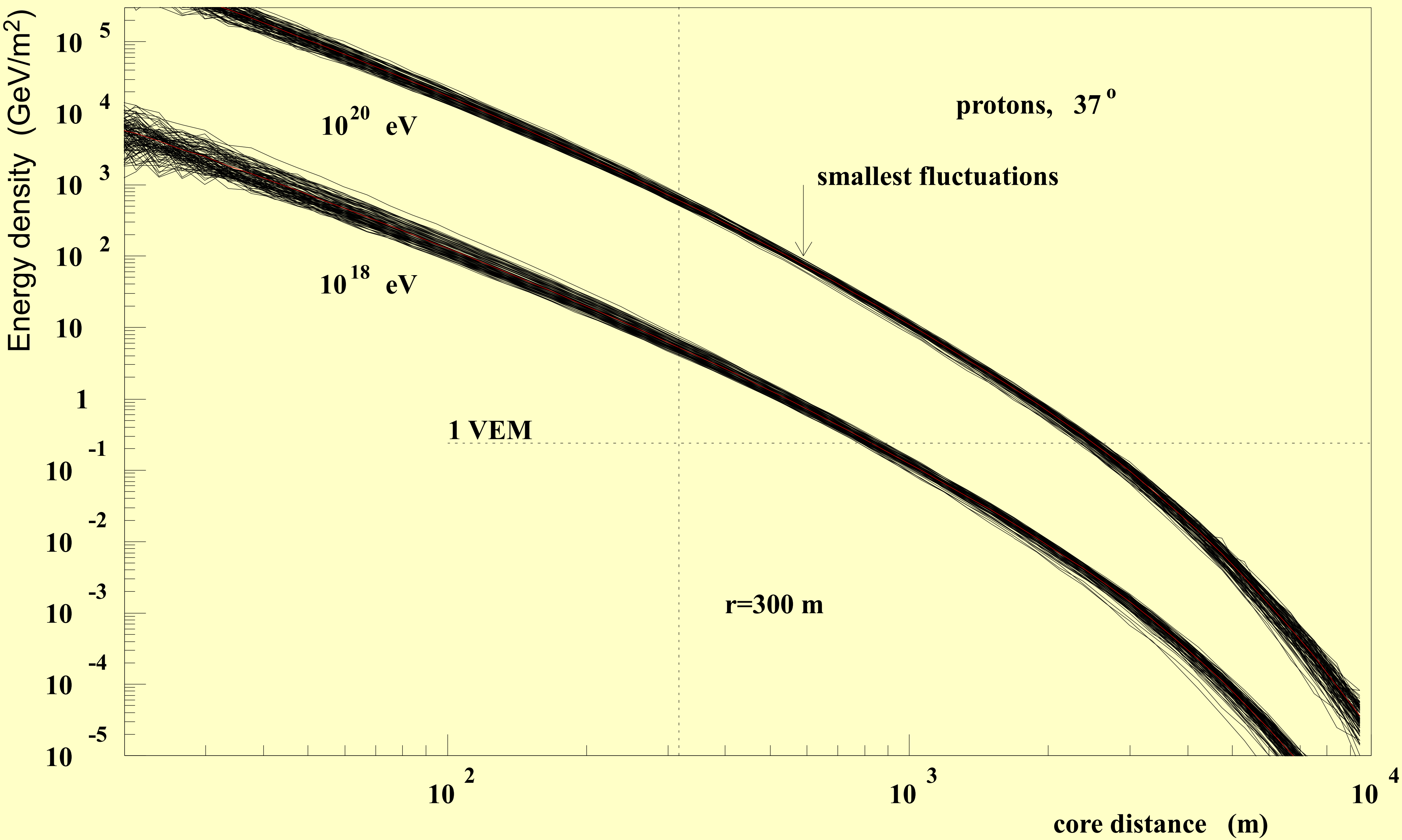
early start,
high maximum,
flat lateral distribution



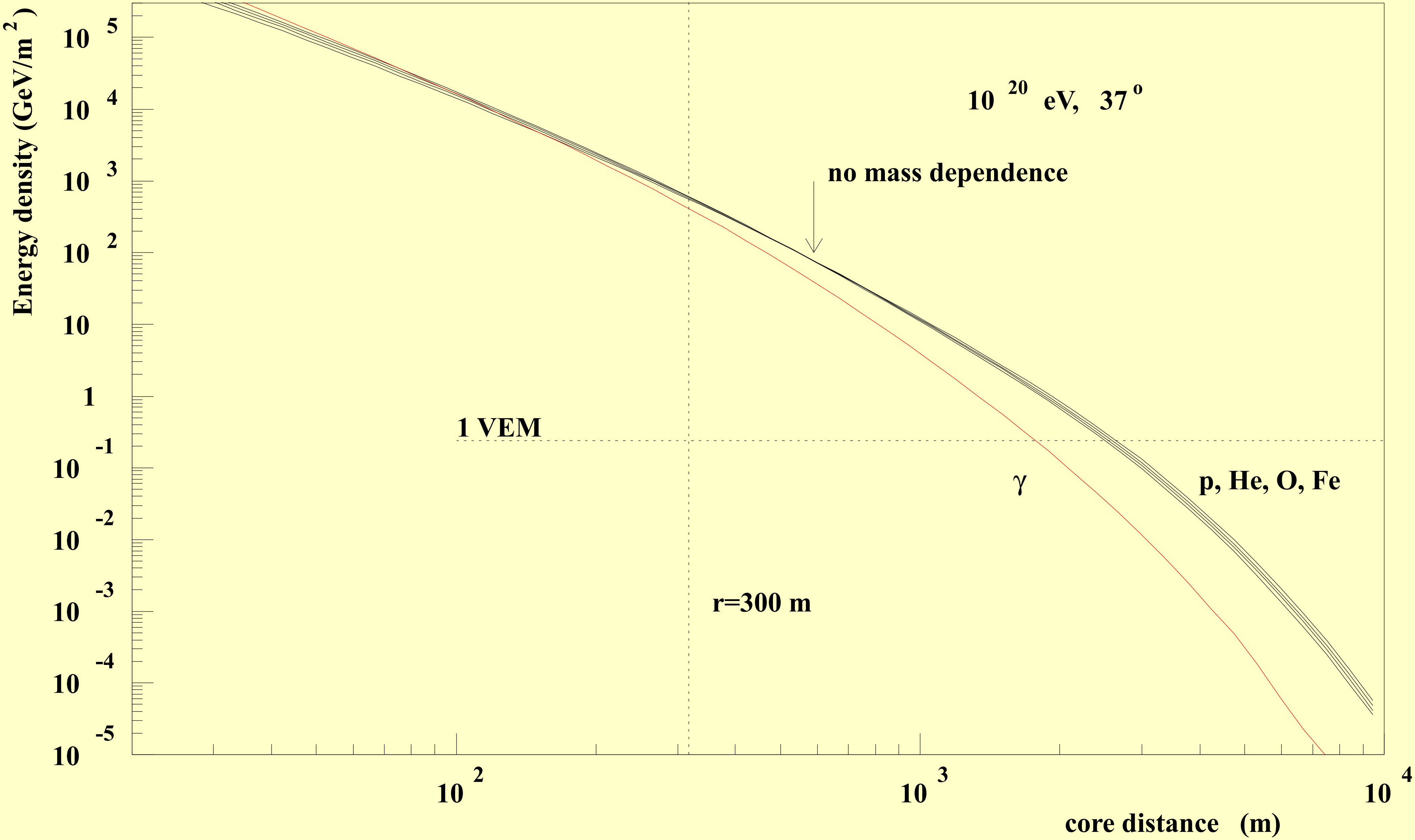
late start,
lower maximum,
steep lateral distribution

lateral distribution is sensitive to X_{max} (i.e. to particle type)

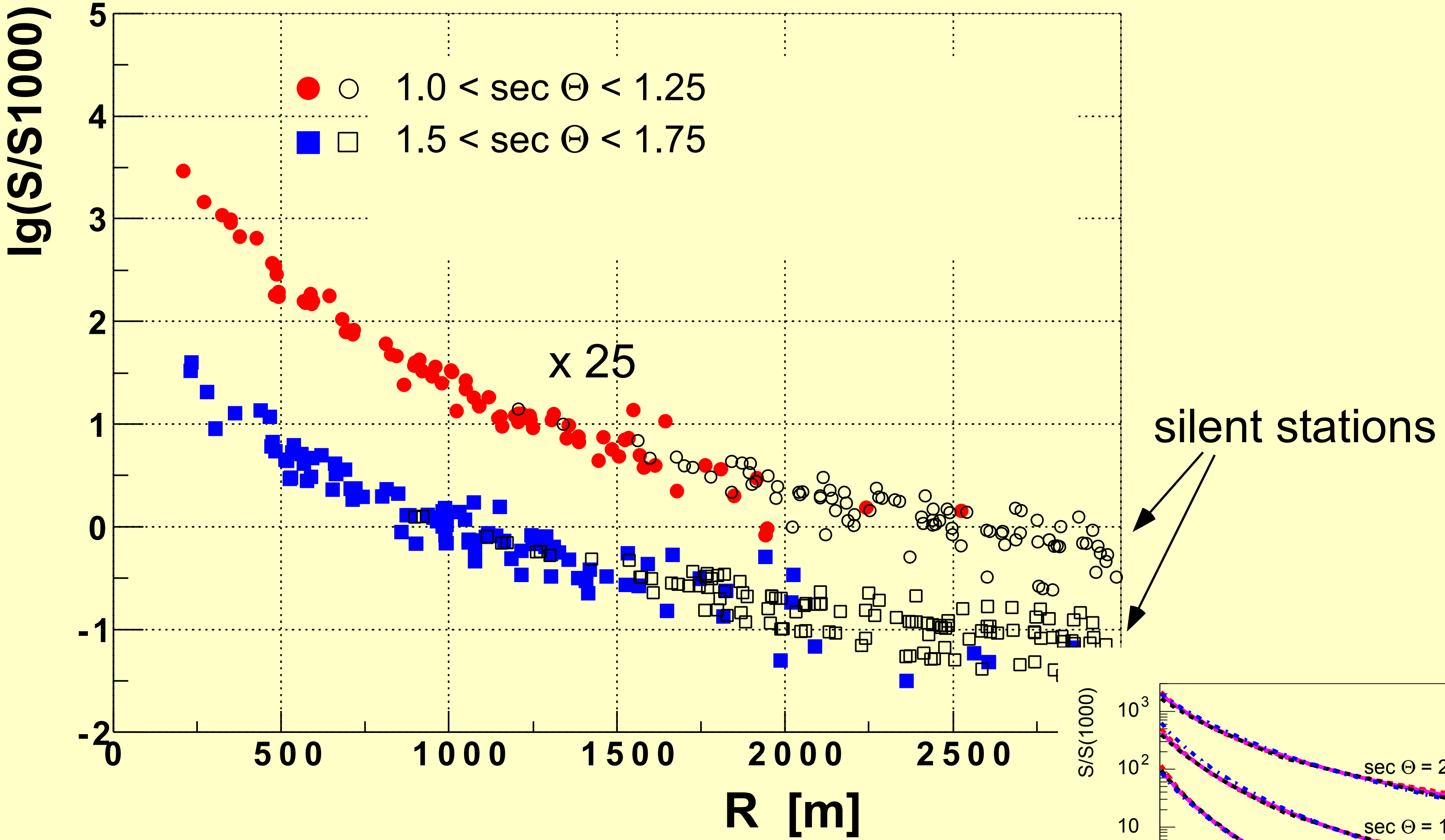
Lateral distribution of energy deposit: protons 37°

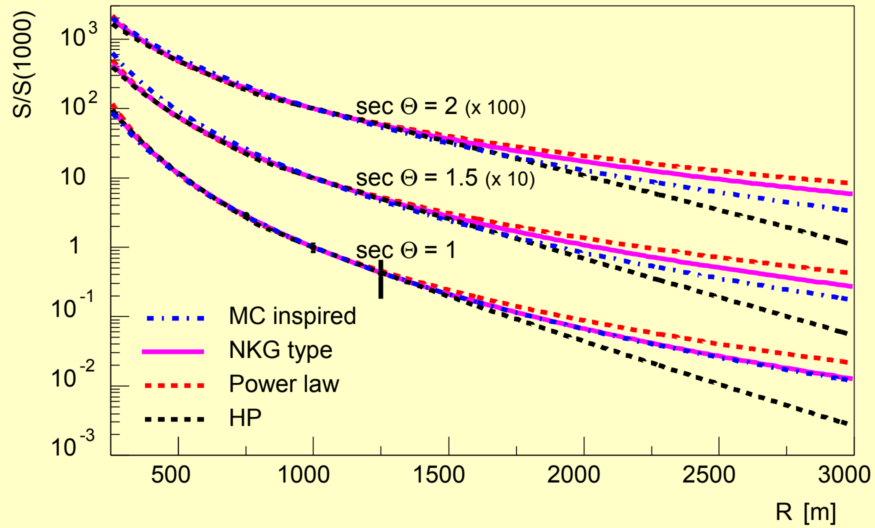


Lateral distribution of energy deposit: different masses



Lateral distribution (measured by Auger)





scale parameters

shape parameters

power law: $S(r) = S(1000)\ (r/1000)^{-\nu}$

NKG type: $S(r) = \text{const.}\ (r/r_s)^{-\beta-\delta}\ (1+r/r_s)^{-\beta}$ with $r_s = 700$ m, $\delta = 0.2$

MC inspired: $S(r) = 10^{A+Bx+Cx^2}$ with $x = \lg(r/1000\text{ m})$, B,C from MC

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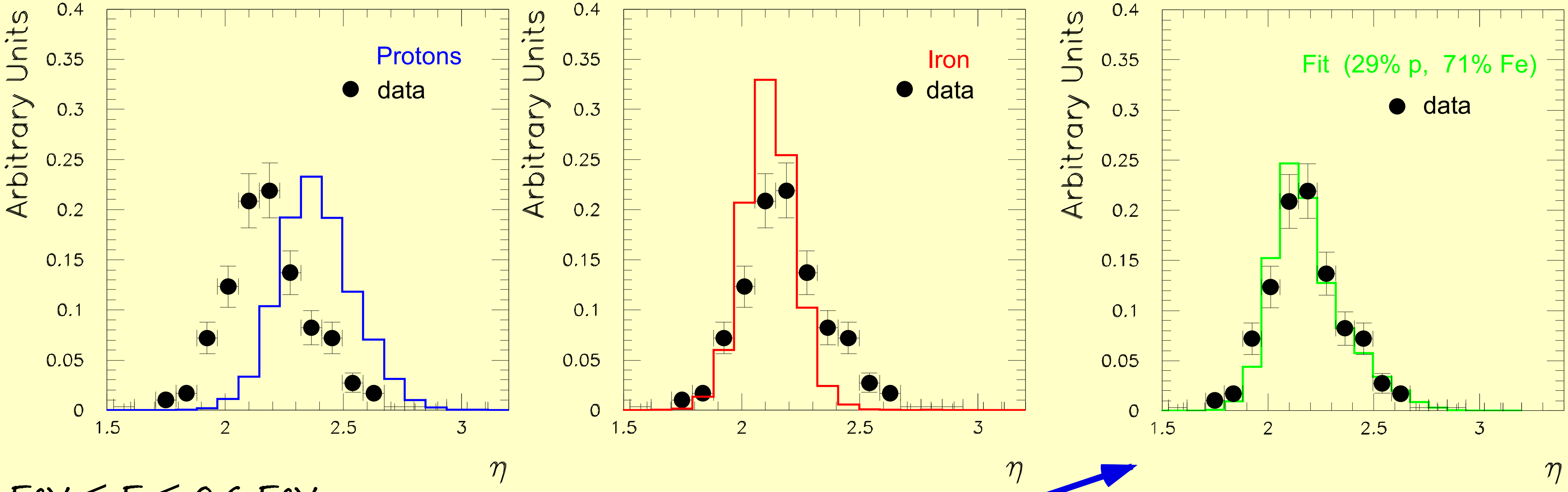
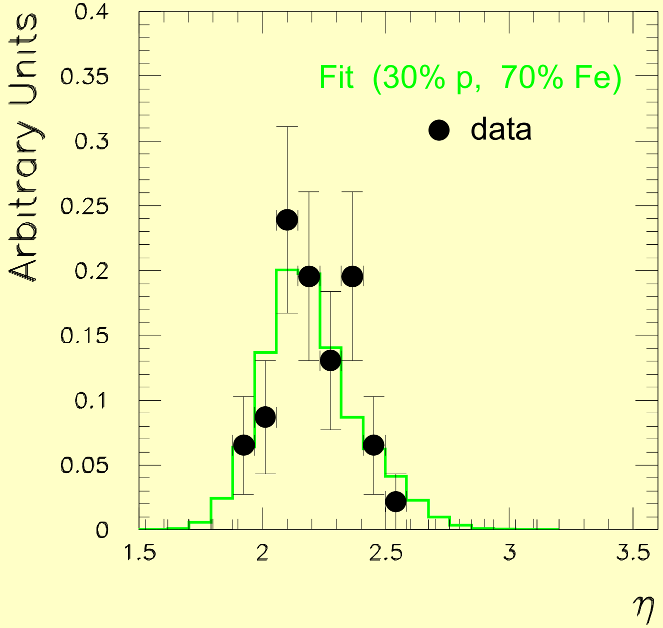
Haverah Park data (re-analysed 2003)



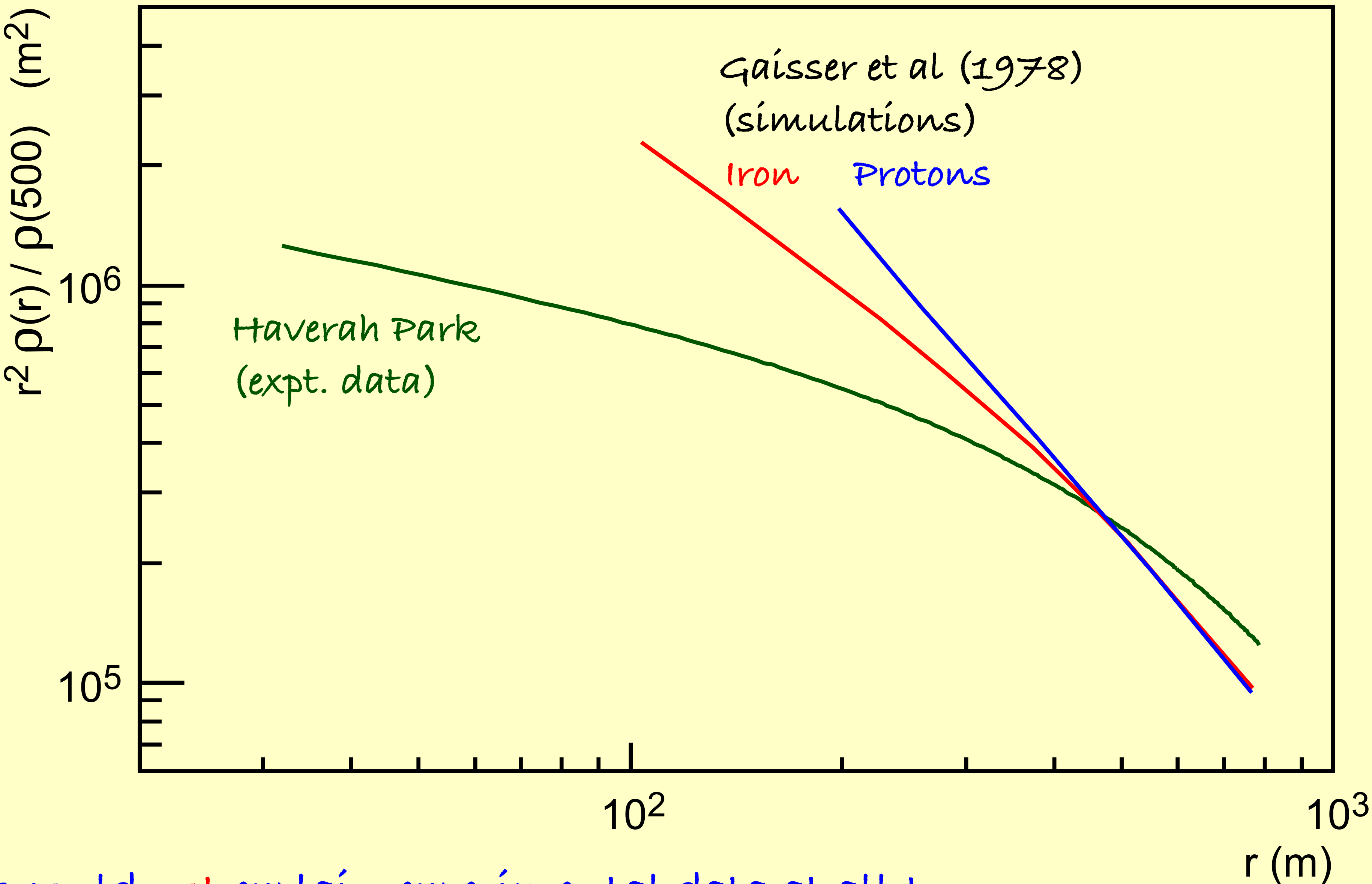
0.2 EeV < E < 0.6 EeV
292 events

Models can describe data



0.6 EeV < E < 1 EeV
46 events

State-of-the-art model 1978



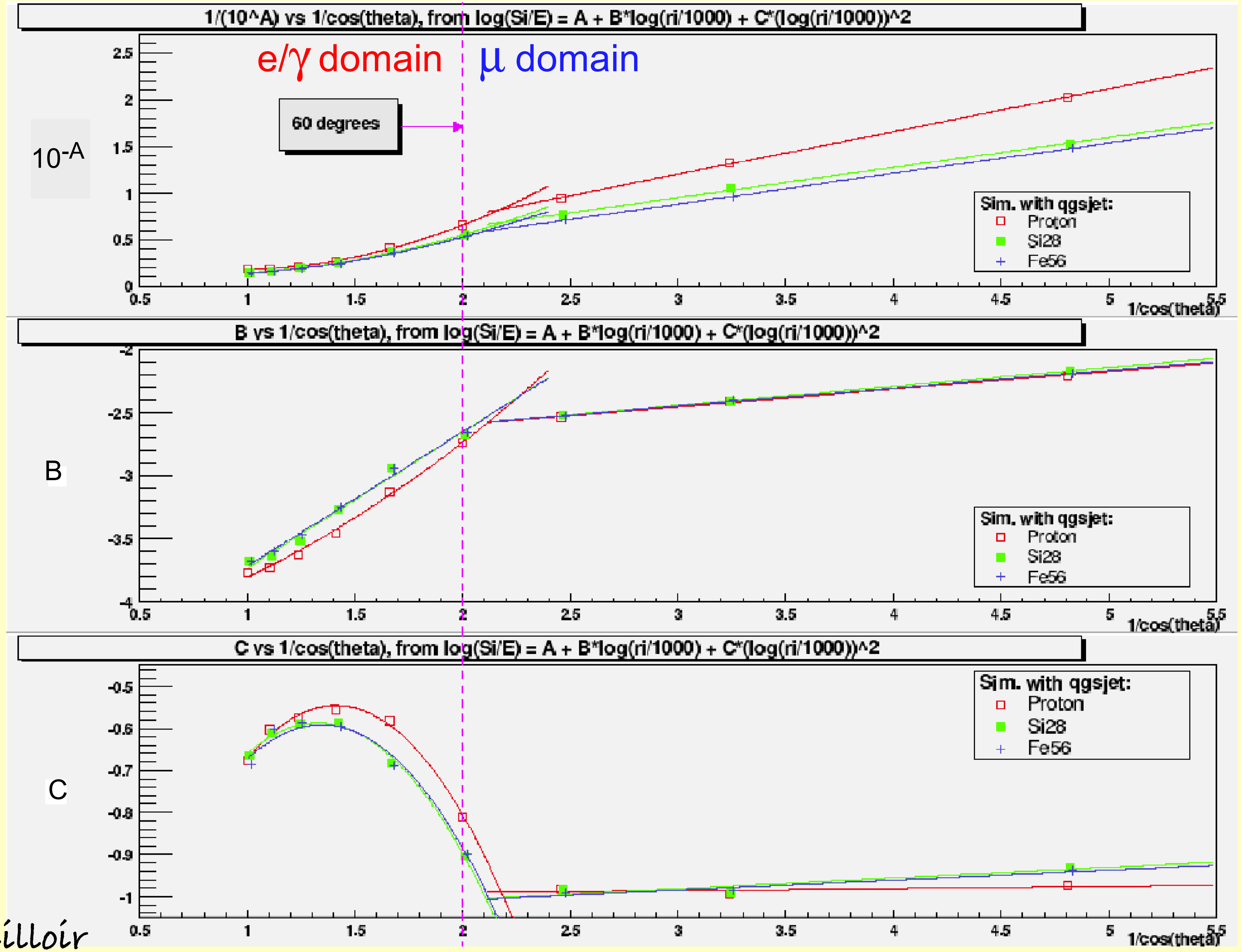
Models could not explain experimental data at all !

How to interpret the data? (mass >> Fe ???)

Inclined showers ($\Theta > 60^0$) are different

$$S(r) = E \cdot 10^{(A + Bx + Cx^2)} \qquad x = \lg(r/1000\ m)$$

$E = 1 \ldots 100$ EeV



P. Billoir

$< 60^0$:
el.mag. dominate

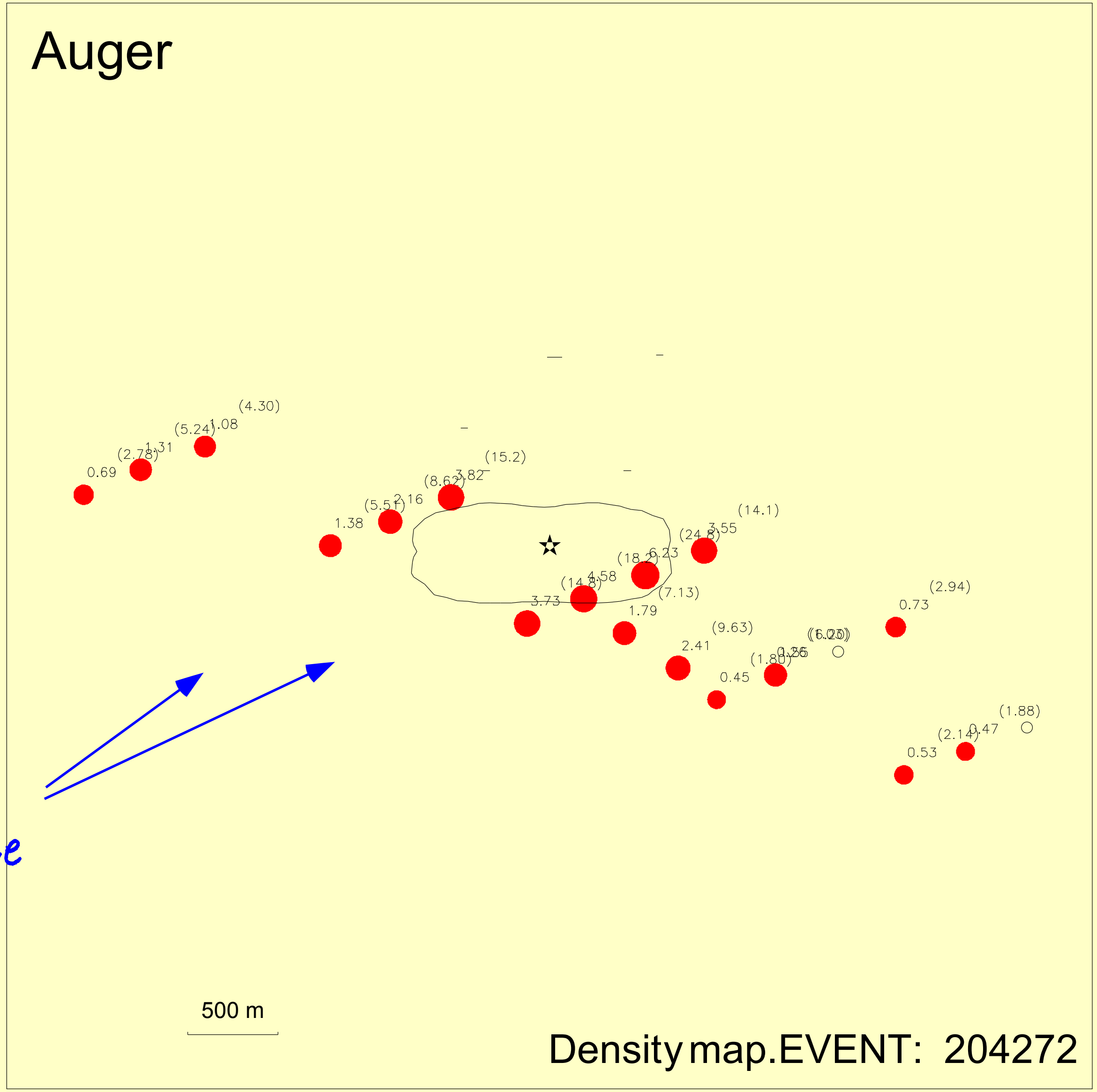
$> 60^0$:
muons dominate

Models tell us how to reconstruct air showers.

Near-Horizontal Events

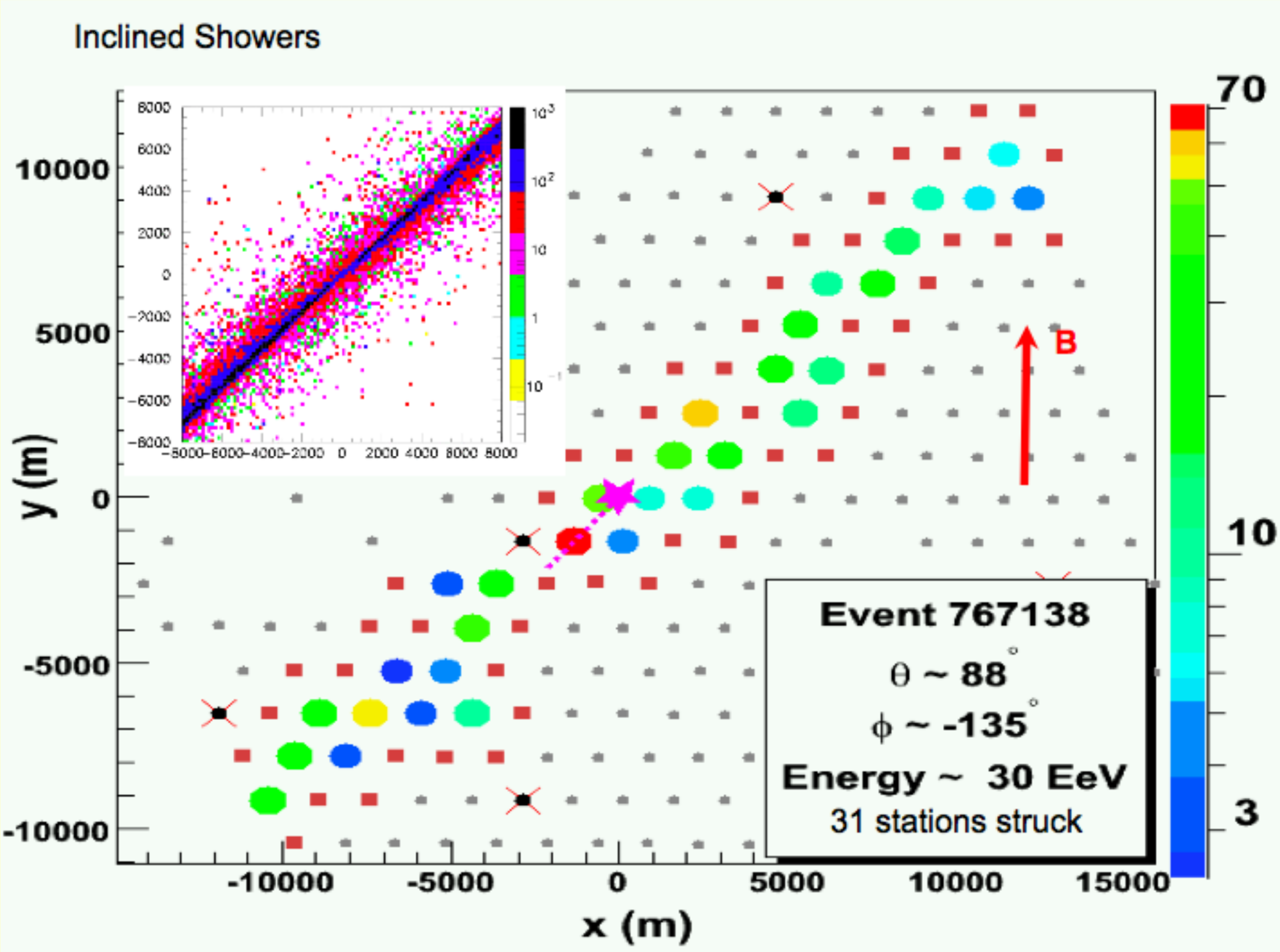
muonic component dominant
(very short pulses)

deflection in Earth magnetic field
(dependent on azimuth)



expected density contours
for specific angle of incidence

Pierre Auger Observatory



equipa 2008

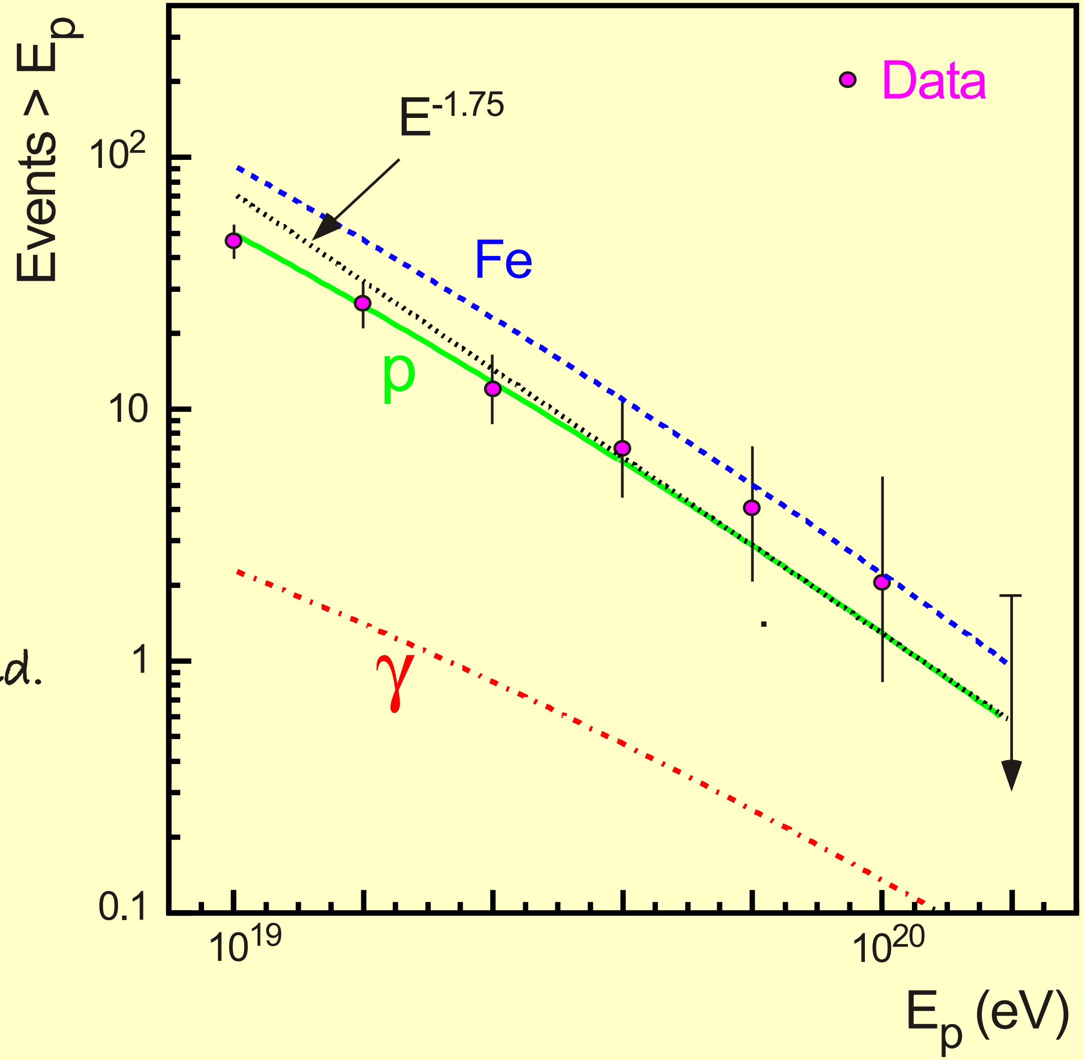
Primary γ's, e.g. from decays of topological defects ??

Haverah Park,
Ave et al., PRL 85 (2000) 2244

49 Events $> 10^{19}$ eV

$60^0 < \theta < 80^0$

thick atmosphere:
- only muons arrive at ground
- long path through atmosphere
  - with influence of mag. field.



γ/p< 40%

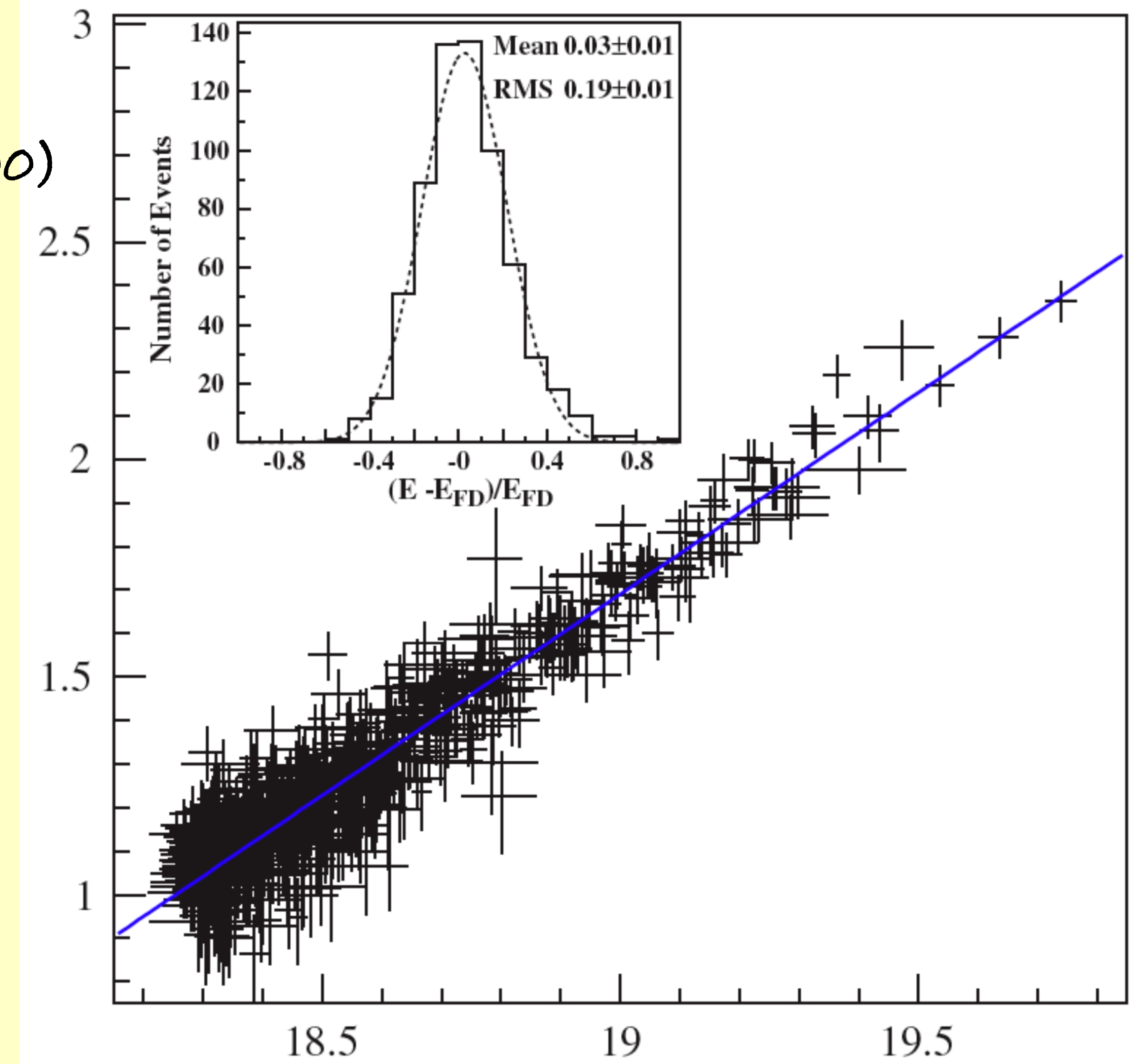
Fe/p< 54%

(95% confidence level)

This analysis could only be made since models do describe (roughly) the experimental data.

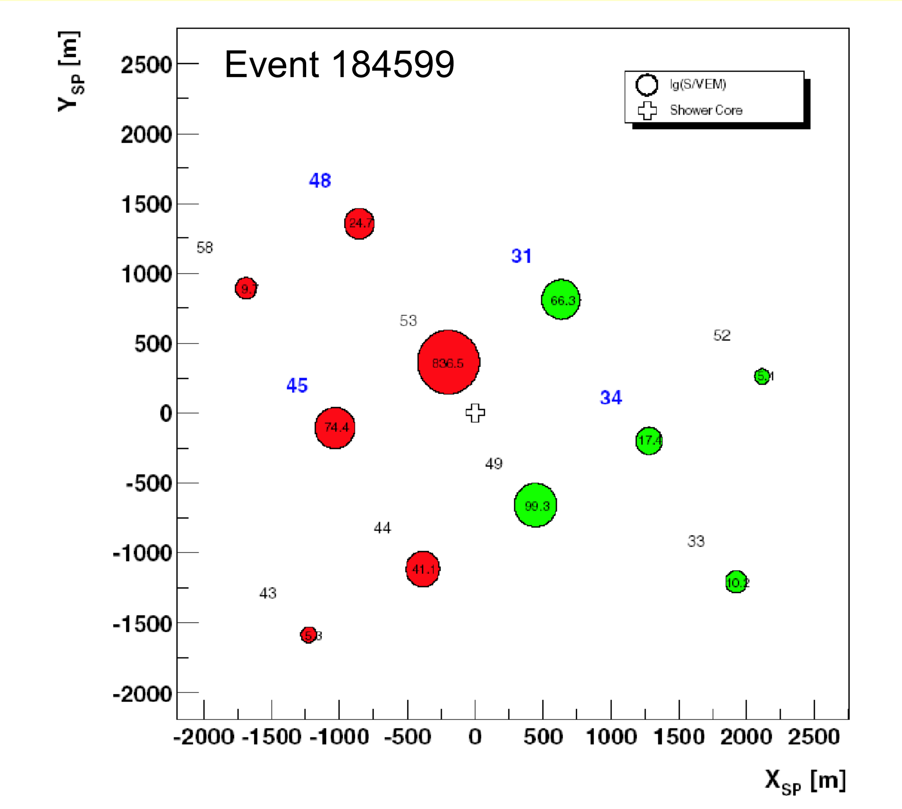
Auger Data

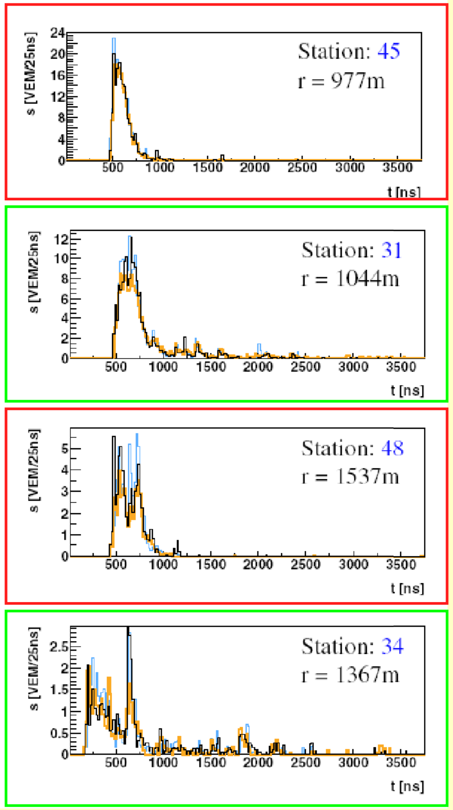
log$_{10}$ (S1000) from SD

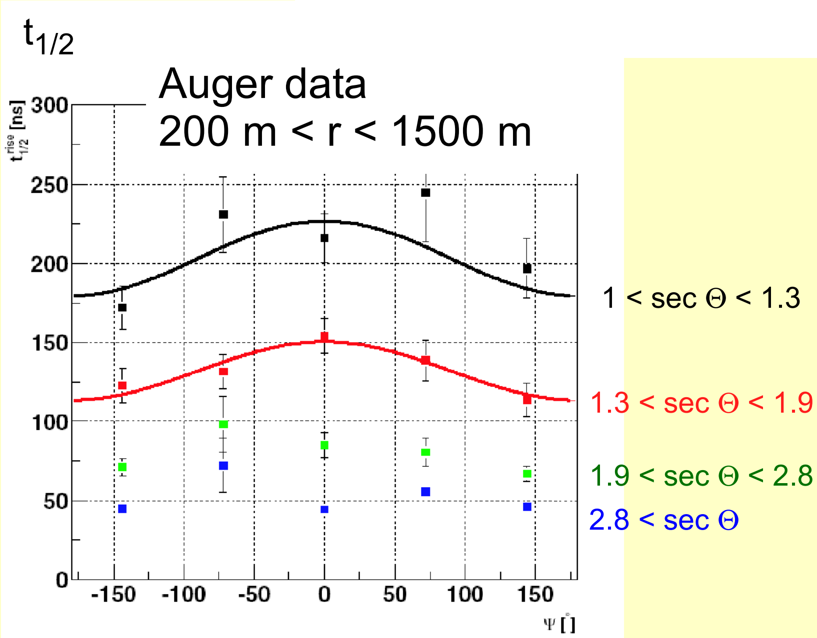


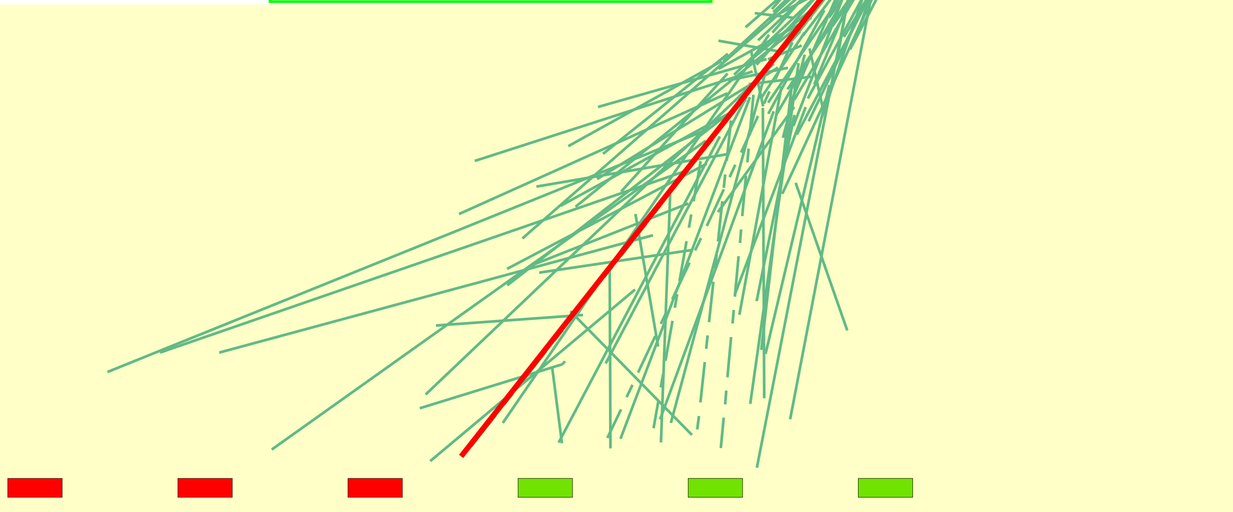
log$_{10}$ (E/EeV) from FD

Azimuthal Asymmetry in Signal and Rise Time









Johannes Knapp, Arequipa 2008

Muons in MACRO detector

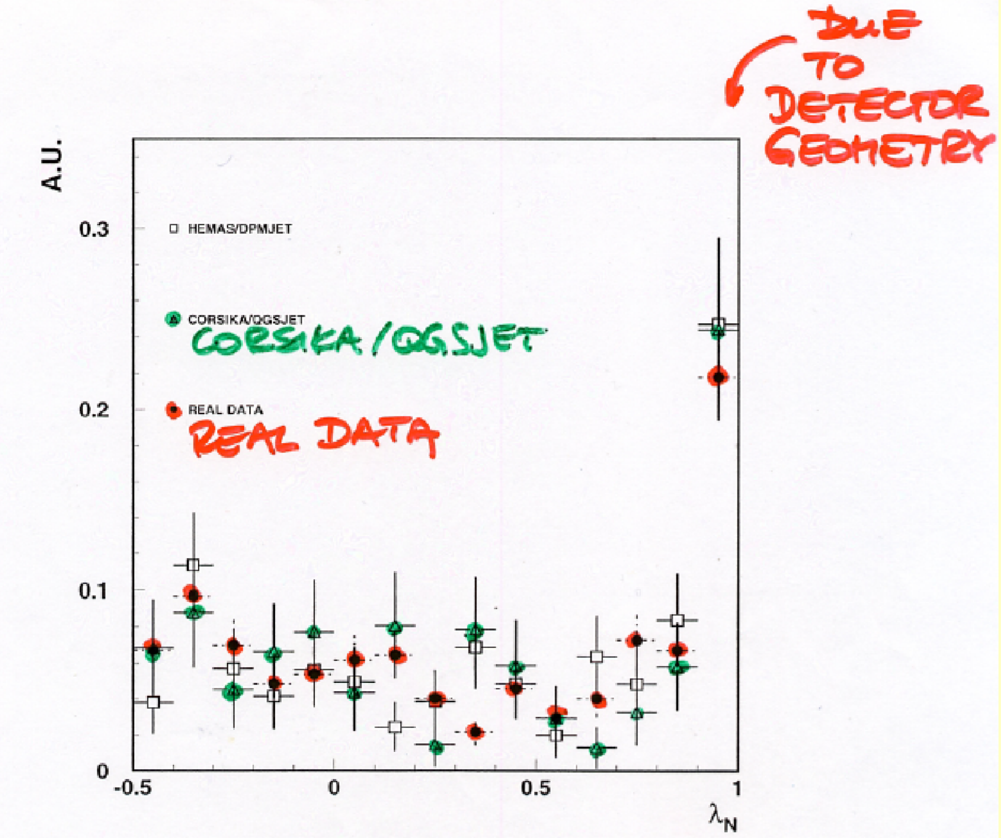


Figure 5.25: *Search for aligned clusters in the MACRO detector. We plot the normalized distributions of events as a function of the parameter λ_N (see text), both for experimental (full circles) and simulated data (open markers).*

NOT ALIGNED

COMPLETELY ALIGNED

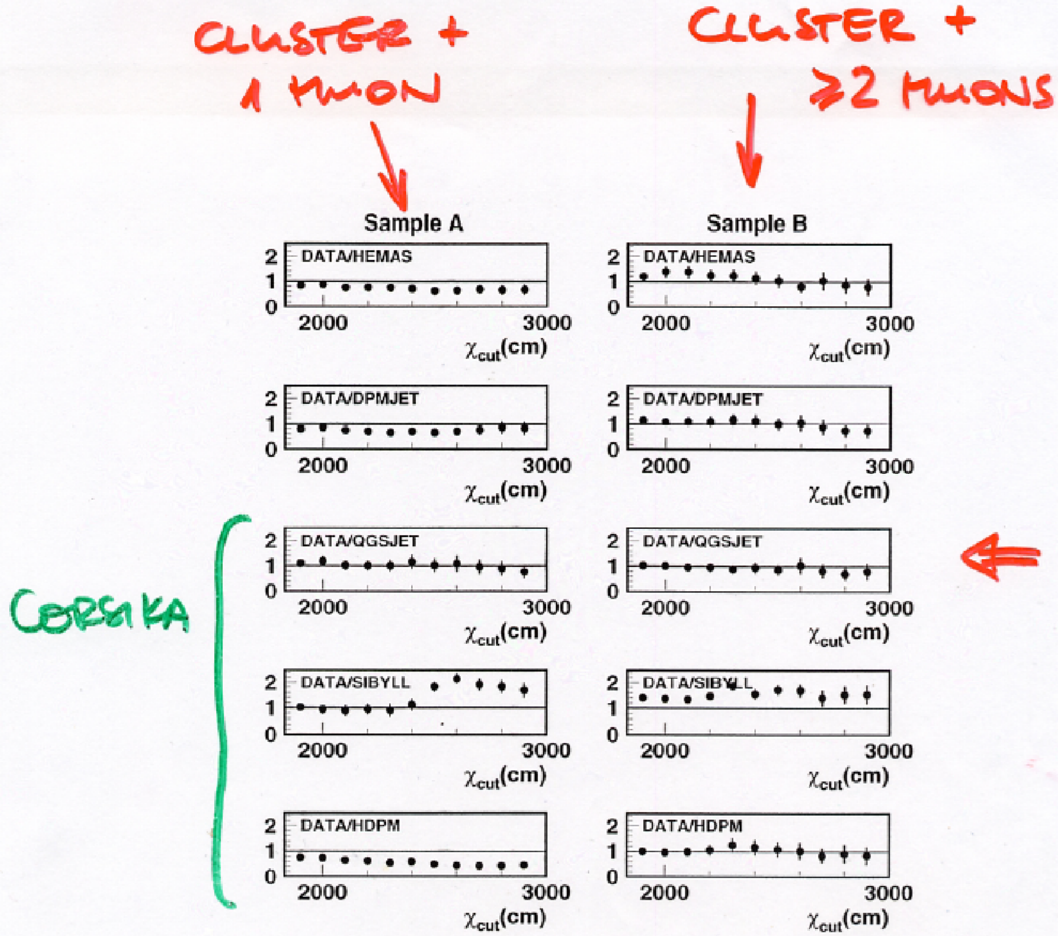


Figure 5.20: *2-cluster events ratio of experimental data over simulated data. The plots on the right refer to events reconstructed with a central cluster plus an isolated muon; on the right side: events reconstructed with a central cluster plus a cluster with at least two muons.*

CLUSTER + 1 MUON:

SENSITIVE TO EARLY INTERACTIONS

PhD thesis Marco Sioli, Bologna 1999

Muon bundles in MACRO detector

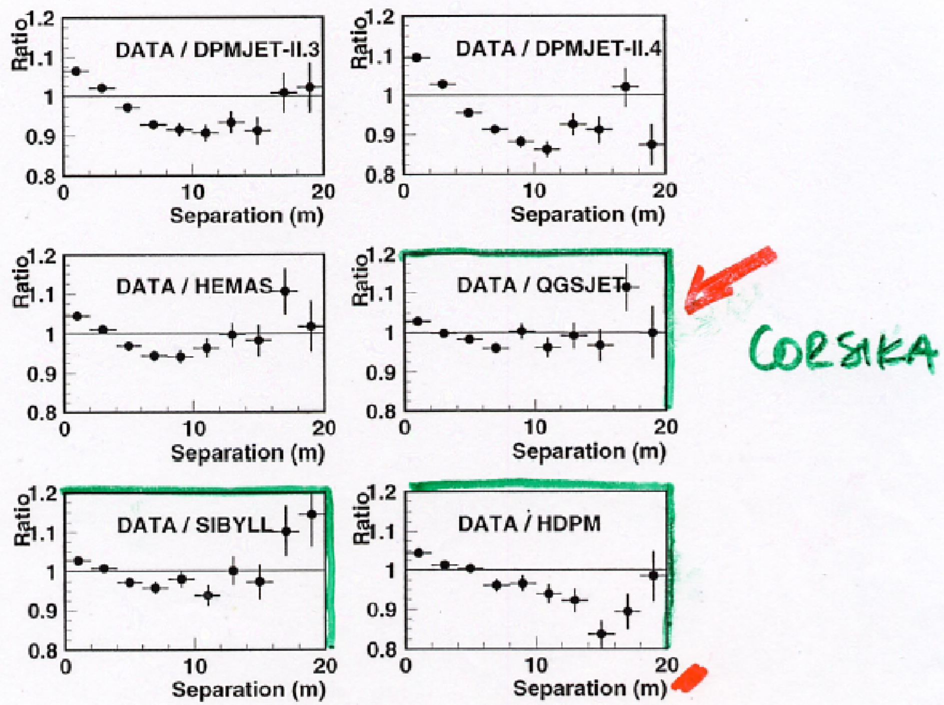


Figure 5.9: *Ratio between the experimental and simulated decoherence functions for the sample of $N_{wire} \geq 8$. The ratio was computed between distributions normalized to the same number of events.*

DISTRIBUTION OF DISTANCES BETWEEN TWO MUONS

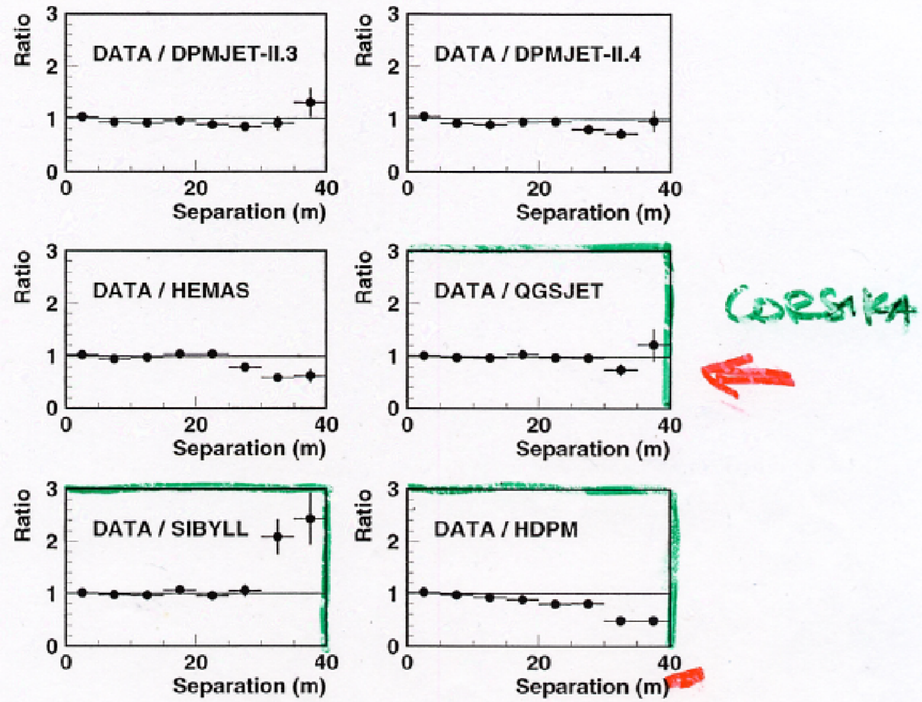


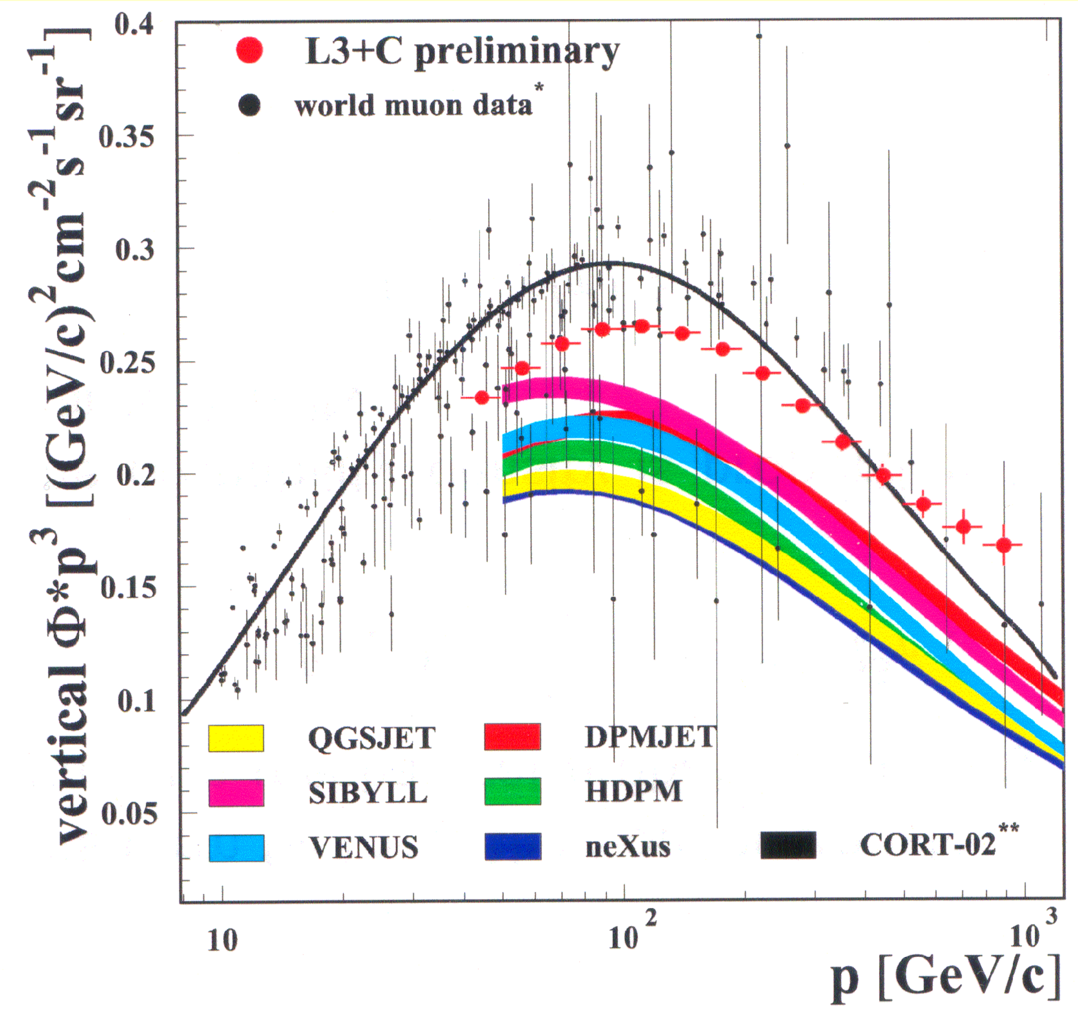
Figure 5.10: *Ratio between the experimental and simulated decoherence functions for the sample $N_{wire} \geq 8$. The ratio has been computed between distributions normalized to the same number of events.*

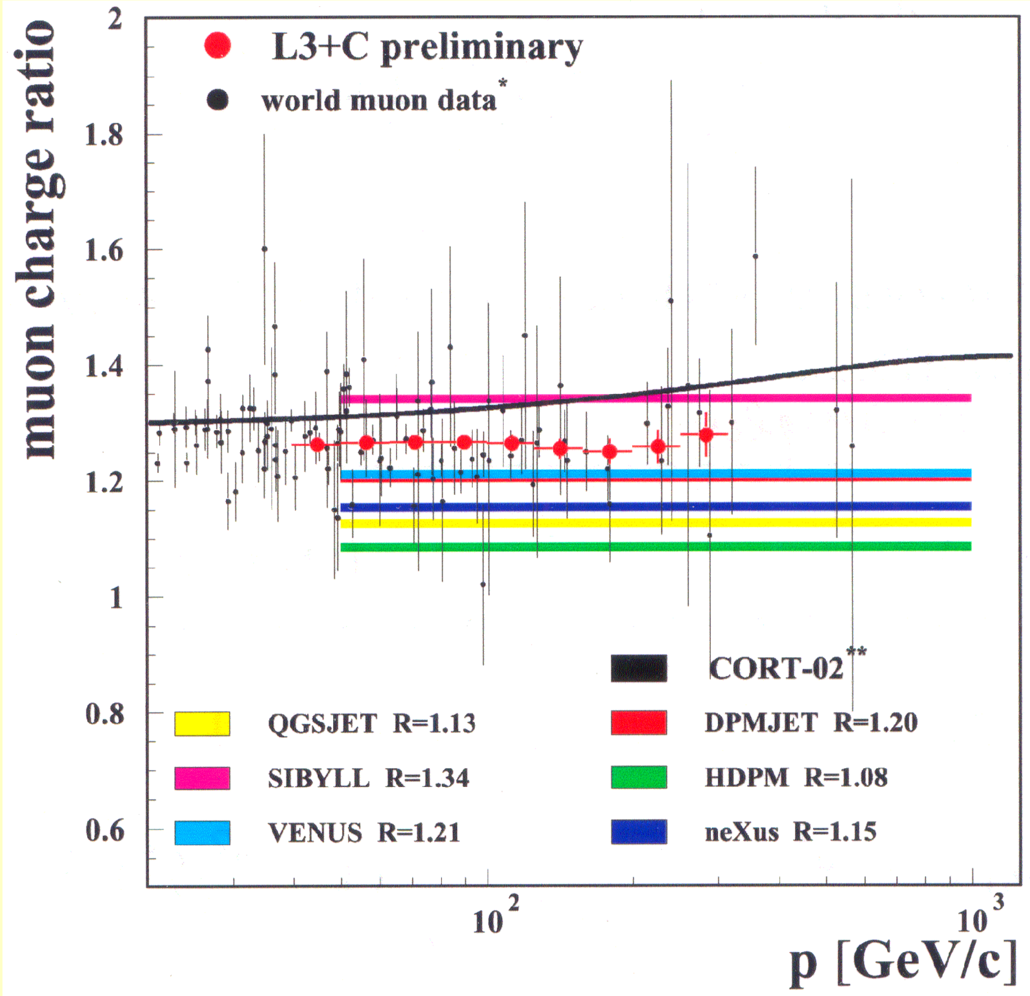
LARGER DISTANCES

CORSIKA / QGSJet describes experimental data rather well.

PhD thesis Marco Sioli, Bologna 1999

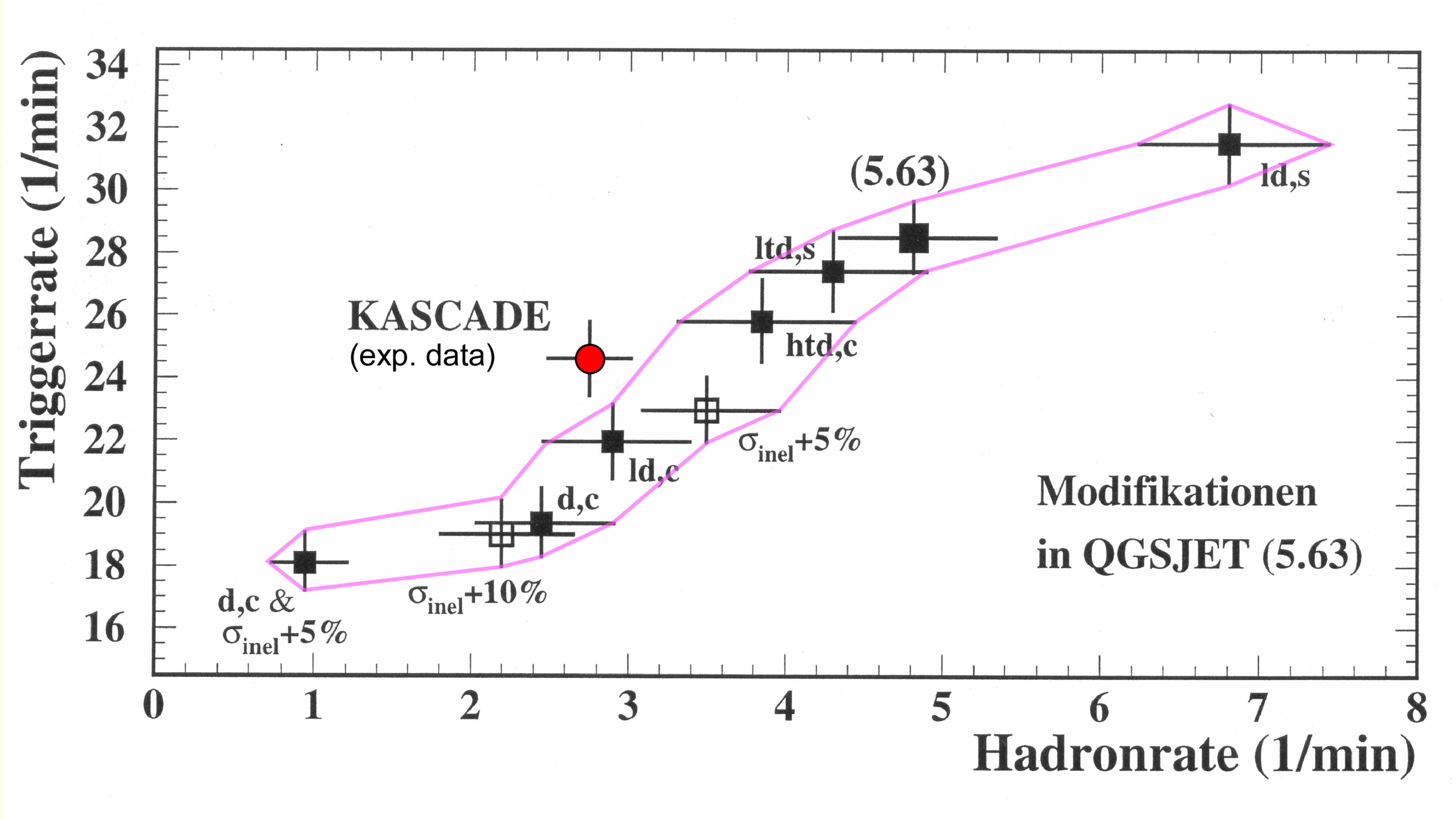
L3+C Vertical Muon Spectrum & Charge Ratio (cosθ > 0.98)





statistical errors only
* hep-ph/0102042
** hep-ph/0201310

KASCADE hadron and trigger rates



ltd: low-mass target diffraction switched off
htd: high-mass target diffraction switched off
c: constant inelastic cross-section
s: reduced inelastic cross-section

Summary & Outlook

- Great improvements in EAS simulations in past few years.
  Soft hadronic and nuclear interactions modeled on basis of
  Gribov- Regge & Glauber Theory.
  New models allow a safer extrapolation to highest energies.

- Assumption of a mixed CR composition (p, He, ... Fe)
  and extrapolation of models from 100 GeV range (e.g. QGSJET)
  yields amazingly good agreement with CR data from $\sim 10^{12}$ .... 10^{19} eV.

- Many new accelerator experiments will provide new experimental input to
  cross-sections, diffraction and hadronic particle production under small angles.

- New astroparticle experiments will provide new constraints at higher energies
  and data with improved quality (e.g. KASCADE-Grande, Auger, ICE Cube ......
  AMS, direct C, ...)

Only HEP and Astroparticle physicists together can solve the problem of
origin of the high energy cosmic rays (the highest-energy particles in the universe)
and its hadronic interaction with the atmosphere.