# Air Shower Simulations

Johannes Knapp,
Physics & Astronomy
U of Leeds, UK

4th School on
Cosmic Rays and Astrophysics
Santo André, Brazil
2010

- Part 1: Astroparticle Physics, Air Showers and Simulations
- Part 2: Hadronic & Nuclear Models
- Part 3: CORSIKA Performance and Limitations

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# Archeology of CORSIKA

pre 1989

SH2C-60-K-OSL-E-SPEC (Grieder):

main structure,

isobar model for hadronic interactions

HDPM & NKG (Capdevielle):

high-energy hadronic interactions,

analytic treatment of el.mag.-subshowers

EGS4 (Nelson et al.):

electron gamma showers

CORSIKA Vers. 1.0 7 Feb 1990

# First official reference:

Computer Physics Communications 56 (1989) 105–113
North-Holland 

**A MULTI-TRANSPUTER SYSTEM FOR PARALLEL MONTE CARLO SIMULATIONS OF EXTENSIVE AIR SHOWERS**

H.J. GILS, D. HECK, J. OEHLSCHLÄGER, G. SCHATZ and T. THOUW

*Kernforschungszentrum Karlsruhe GmbH, Institut für Kernphysik, P.O. Box 3640, D-7500 Karlsruhe, Fed. Rep. Germany*

and

A. MERKEL

*Proteus GmbH, Haid-und-Neu-Strasse 7–9, D-7500 Karlsruhe, Fed. Rep. Germany*

Received 13 July 1989

extended version of EGS4. The program CORSIKA (COsmic Ray SImulations for KASCADE) simulates hadronic showers and has two options differing in their treatment of the electromagnetic subshowers and hence in their requirements of CPU time. It will be described elsewhere [12]. Examples of the computation time

[12] J.M. Capdevielle et al., KfK Report, to be published.

22th ICRC, Adelaide, Jan 1990

HE 7.3–3

# AIR SHOWER SIMULATIONS FOR KASCADE

J.N.Capdevielle[1], P.Gabriel, H.J.Gils, P.K.F.Grieder[2], D.Heck, N.Heide, J.Knapp, H.J.Mayer, J.Oehlschläger, H.Rebel, G.Schatz, and T.Thouw

Kernforschungszentrum und Universität Karlsruhe,
D-7500 Karlsruhe, Federal Republic of Germany
[1]Laboratoire de Physique Théorique, Université de Bordeaux,
F-33170 Gradignan, France
[2]Physikalisches Institut der Universität Bern,
CH-3012 Bern, Switzerland

## Abstract

A detailed simulation program for extensive air showers and first results are presented. The mass composition of cosmic rays with $E_0 \geqq 10^{15}$eV can be determined by measuring electrons, muons and hadrons simultaneously with the KASCADE detector.


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# Preface to KfK 4998 (1992)

Analyzing experimental data on Extensive Air Showers (EAS) or planning corresponding experiments requires a detailed theoretical modeling of the cascade which develops when a high energy primary particle enters the atmosphere. This can only be achieved by detailed Monte Carlo calculations taking into account all knowledge of high energy strong and electromagnetic interactions. Therefore, a number of computer programs has been written to simulate the development of EAS in the atmosphere and a considerable number of publications exists discussing the results of such calculations.

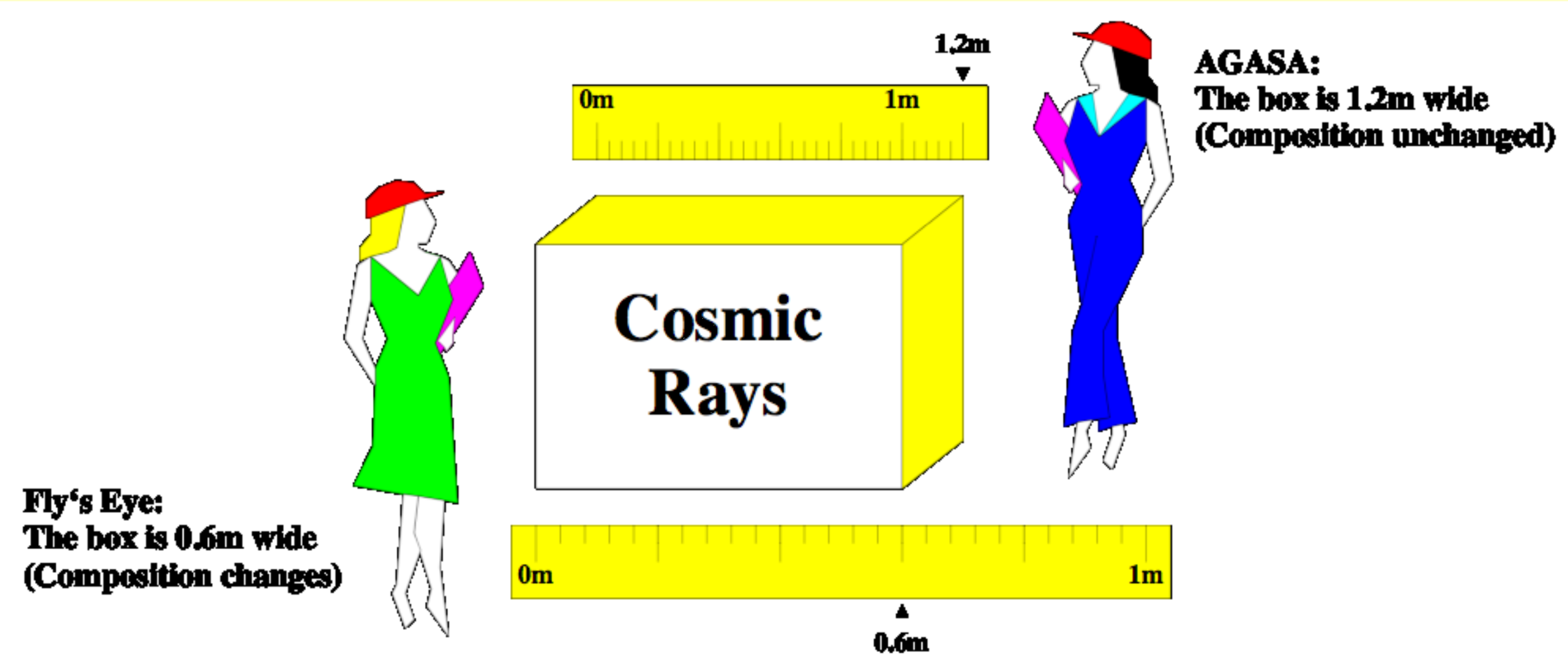
A common feature of all these publications is that it is difficult, if not impossible, to ascertain in detail which assumptions have been made in the programs for the interaction models, which approximations have been employed to reduce computer time, how experimental data have been converted into the unmeasured quantities required in the calculations (such as nucleus-nucleus cross sections, e.g.) etc.

This is the more embarrassing, since our knowledge of high energy interactions - though much better today than ten years ago - is still incomplete in important features. This makes results from different groups difficult to compare, to say the least. In addition, the relevant programs are of a considerable size which - as experience shows - makes programming errors almost unavoidable, in spite of all undoubted efforts of the authors.

We therefore feel that further progress in the field of EAS simulation will only be achieved, if the groups engaged in this work make their programs available to (and, hence, checkable by) other colleagues. This procedure has been adopted in high energy physics and has proved to be very successful.
It is in the spirit of these remarks that we describe in this report the physics underlying the CORSIKA program developed during the last years by a combined Bern-Bordeaux-Karlsruhe effort.

We also plan to publish a listing of the program as soon as some more checks of computational and programming details have been performed. We invite all colleagues interested in EAS simulation to propose improvements, point out errors or bring forward reservations concerning assumptions or approximations which we have made. We feel that this is a necessary next step to improve our understanding of EAS.

# ICRC Durban 1997: the Fly's Eye - AGASA




Use the same yardstick (i.e. Monte Carlo program)
to get consistent results in different experiments.

Use a well-calibrated, reliable yardstick
to get correct results.

# CORSIKA : the world-wide standard

(700 users, from 50 countries and 50 experiments)

KfK 4998 + FZKA 6019 > 870 citations !

by far the most cited work of its authors

( ... and more citations than all KASCADE papers together. ≈750)

# Performance

# Shower development (qualitatively)

correlated!

crucial:

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

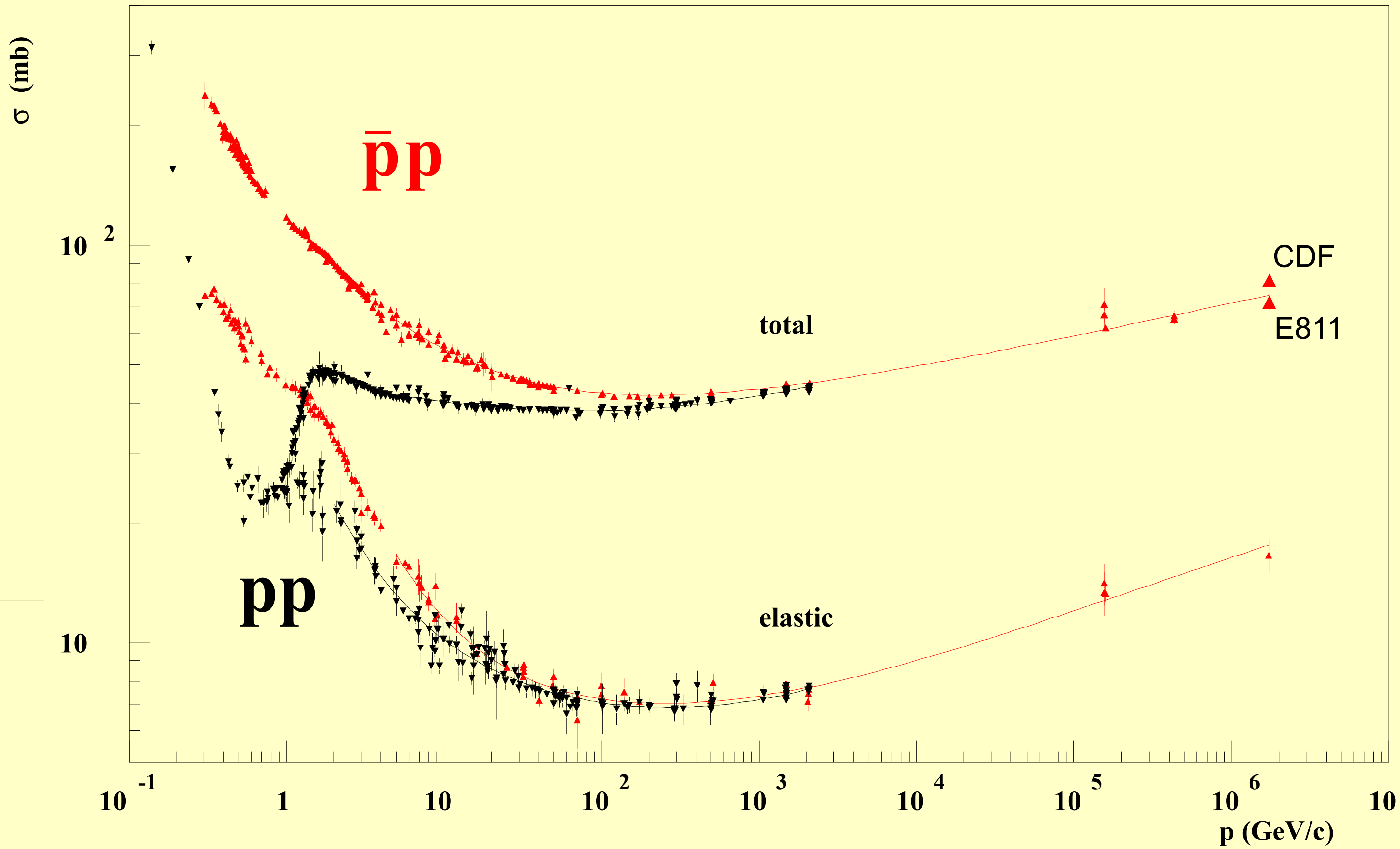
large cross-sections,
high inelasticity
} make short showers

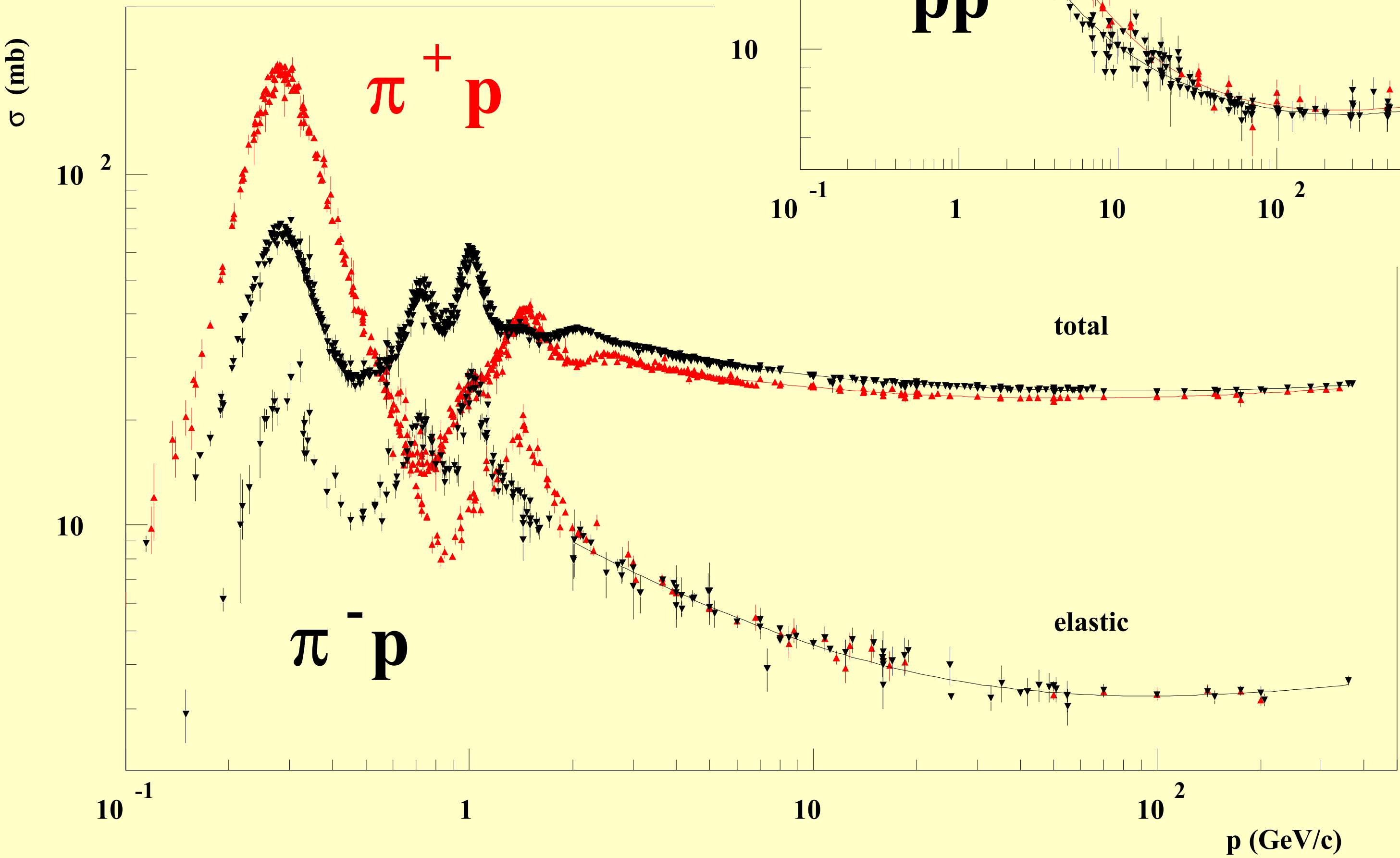
small cross-sections,
low inelasticity
} make long showers

less crucial:

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

# Measured Cross-Sections

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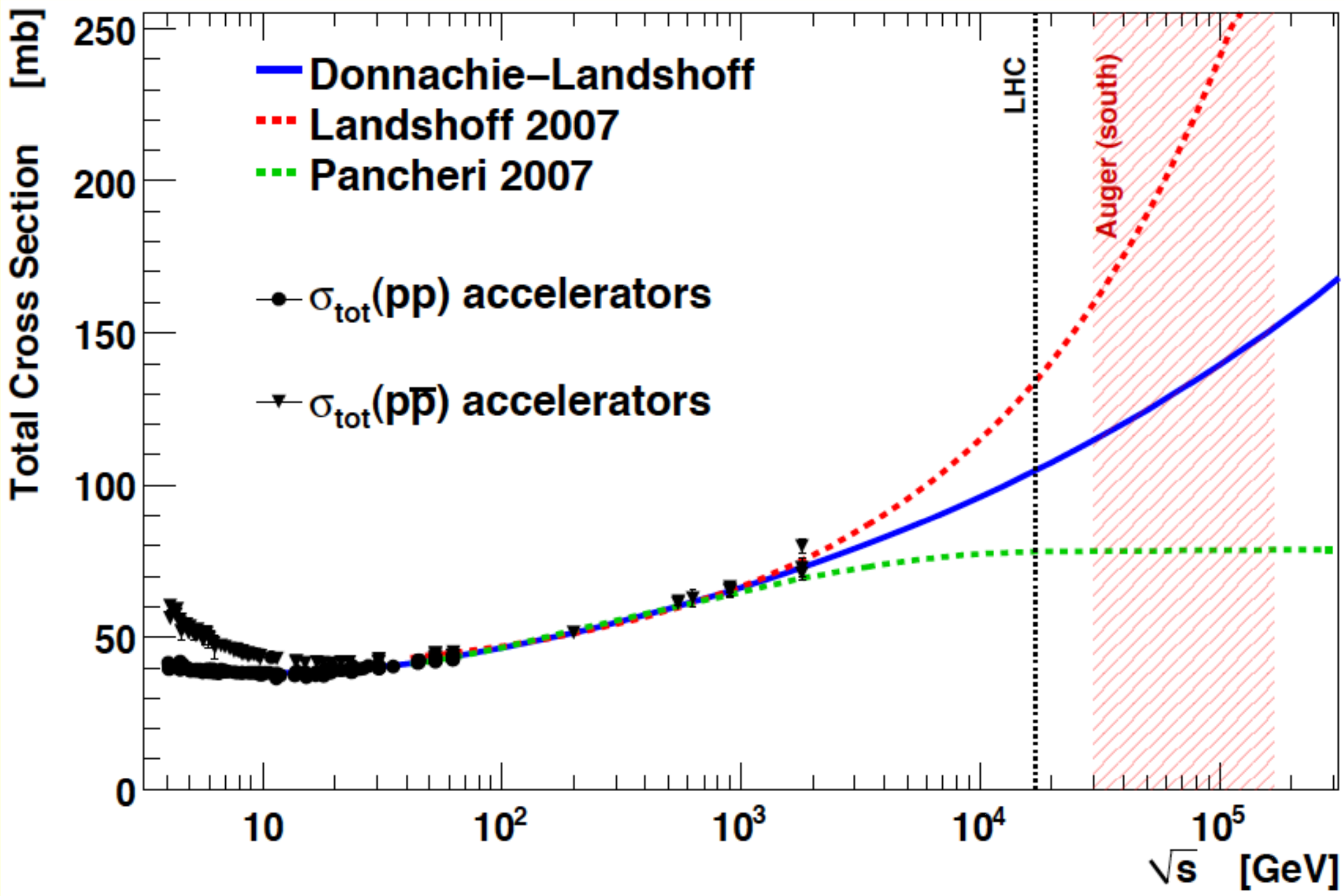
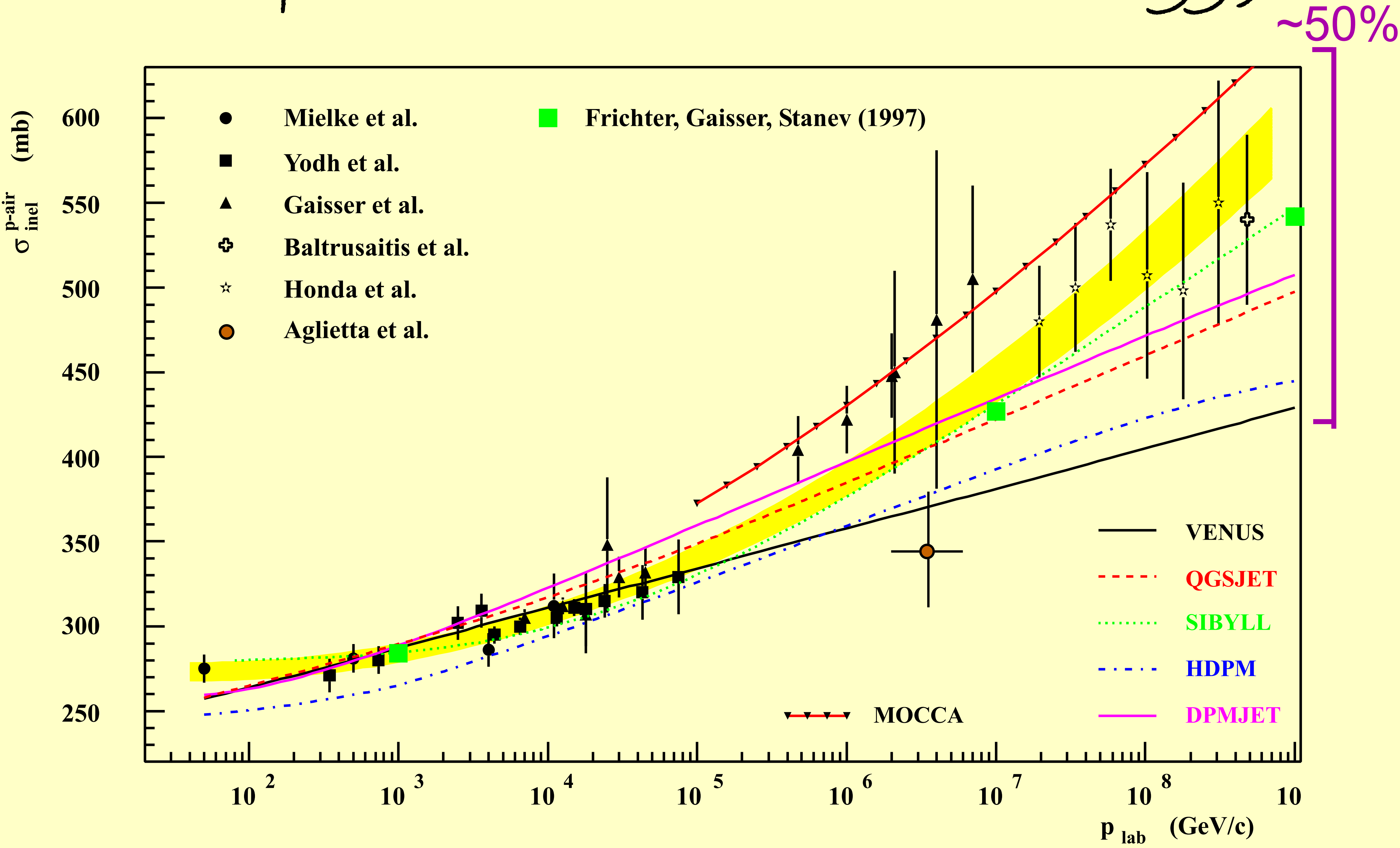
# Predicted p-p Cross-Sections



# p-Air Inelastic Cross-Sections 1997

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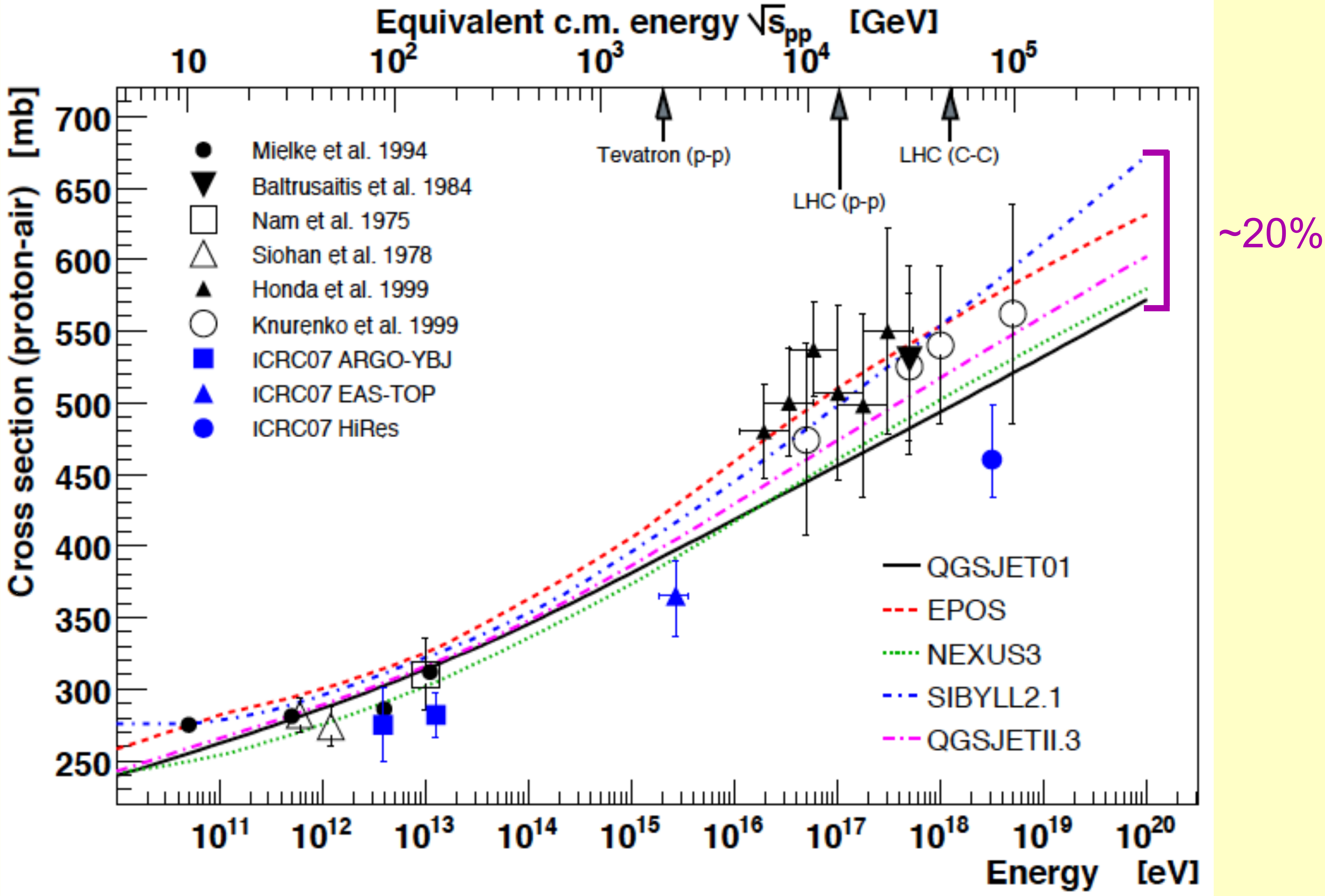
# p-Air Inelastic Cross-Sections 2008

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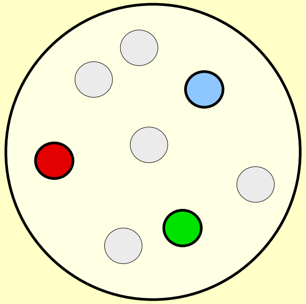
# HERA measured structure functions at small x

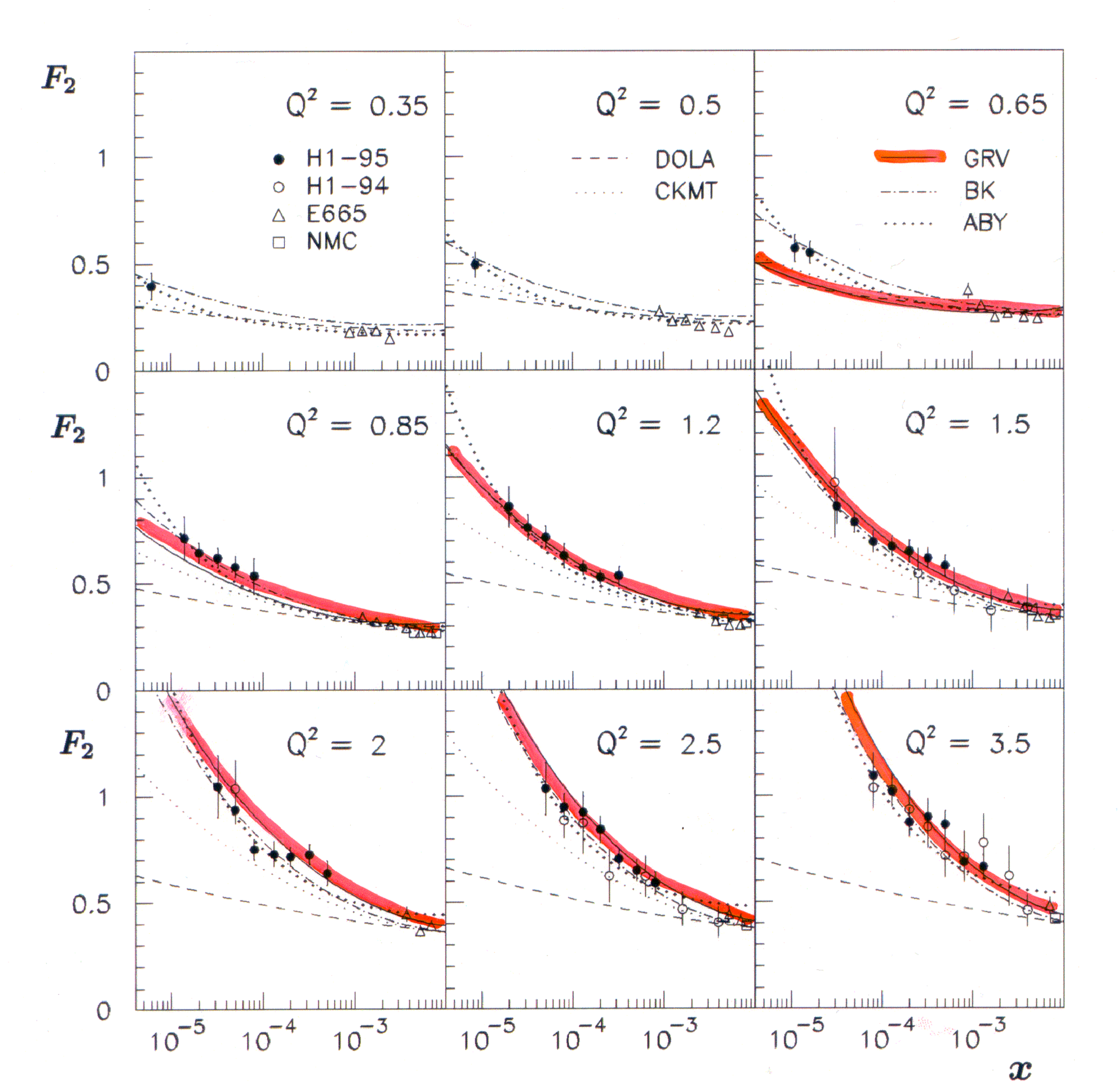


The more partons (quarks & gluons)
there are in a nucleon
at small x,

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

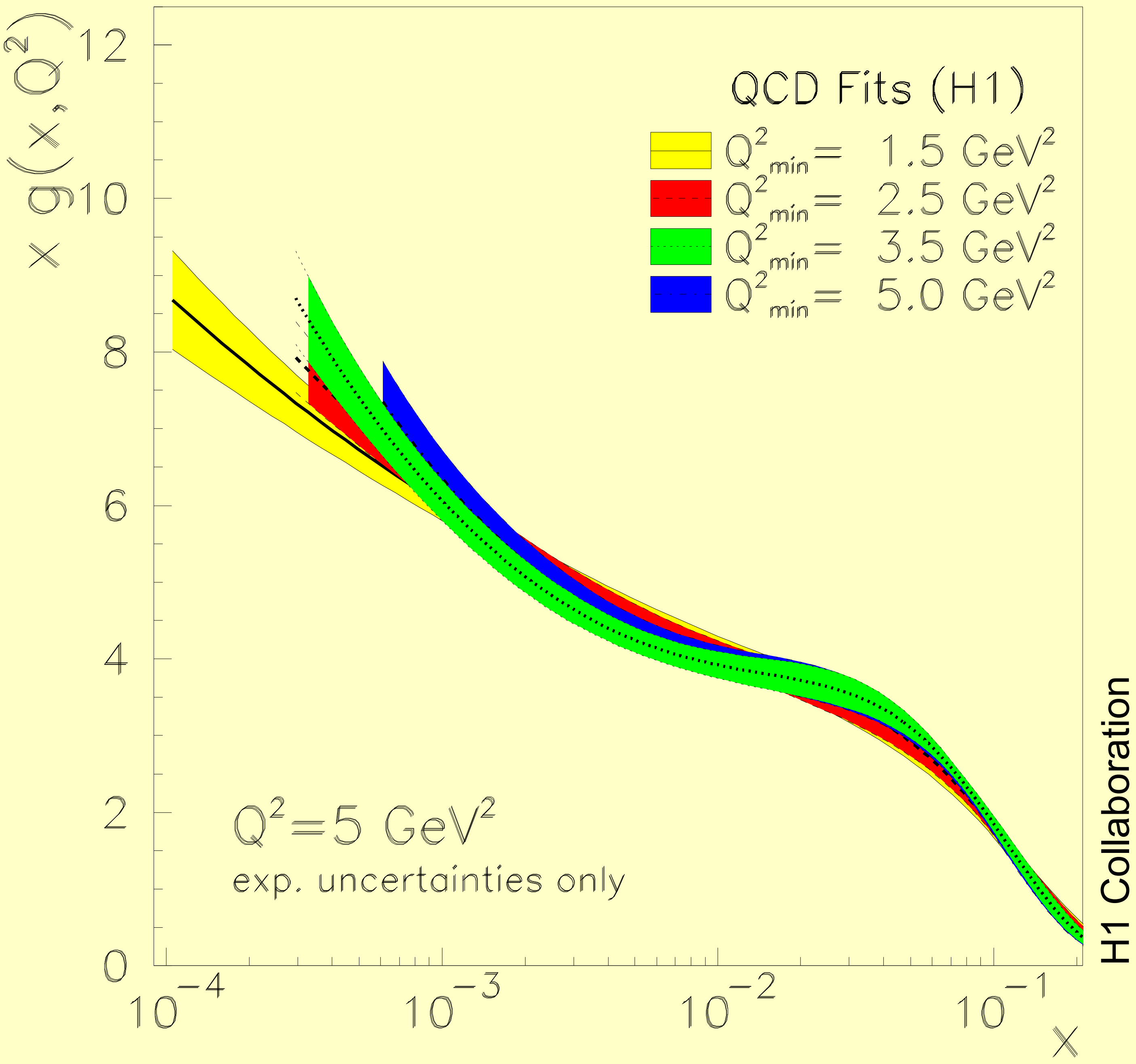
and the higher is the
interaction cross-section.

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

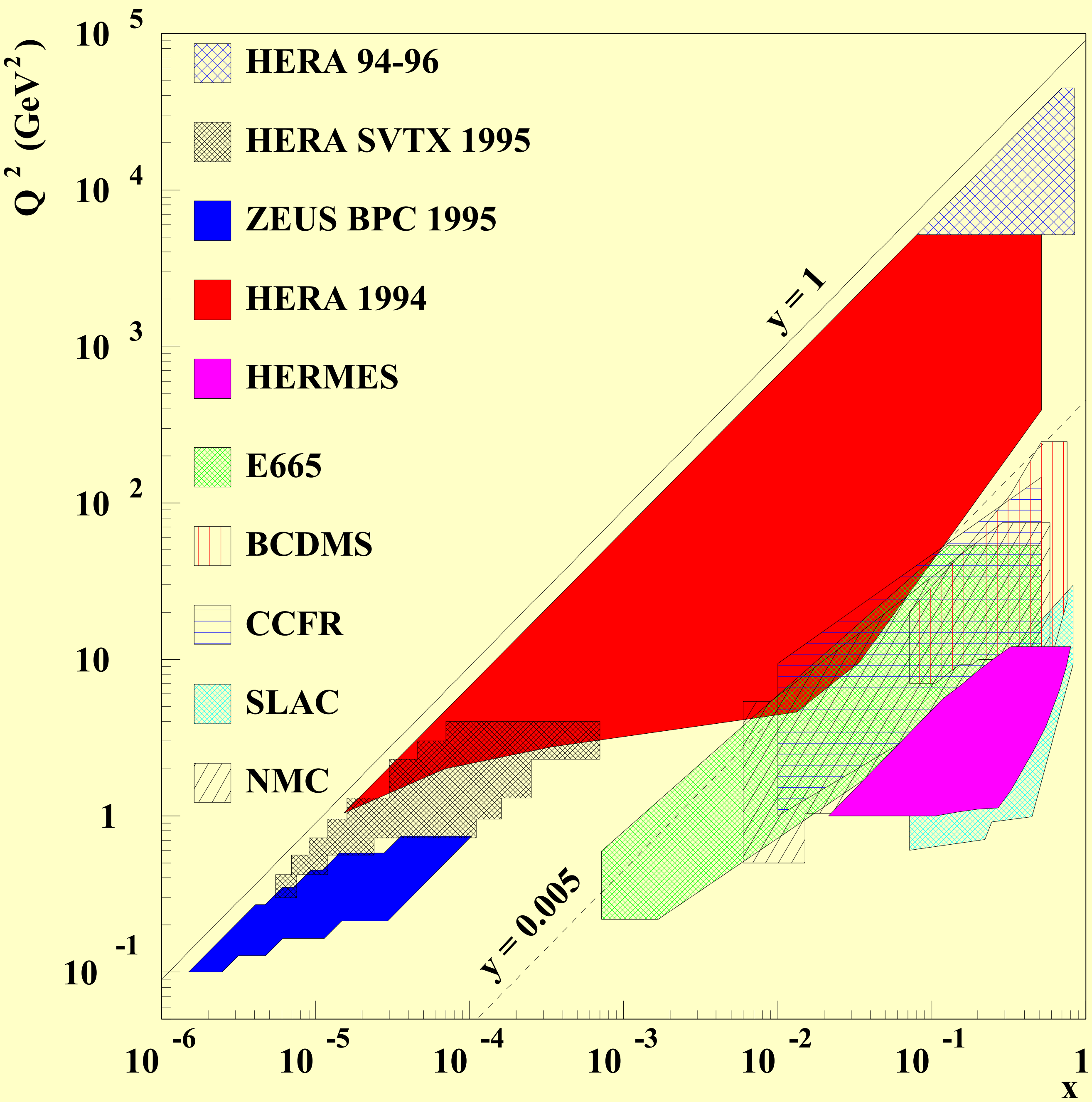



x = momentum fraction of a parton

# Gluon density at low x



# Coverage in x - $Q^2$ plane

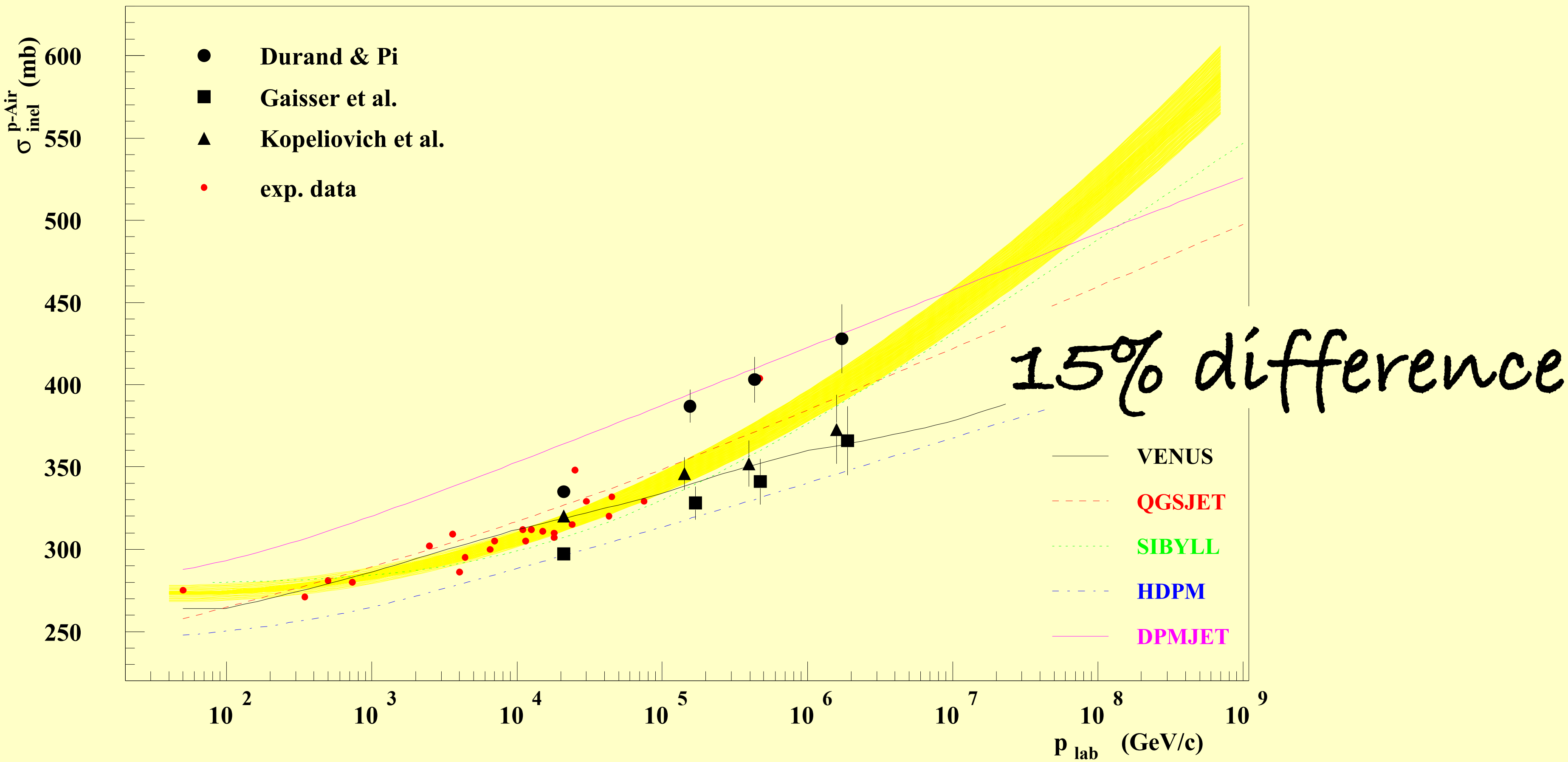



Cosmic Ray Regime:

$Q^2 \approx 0$

$x \approx 0$

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



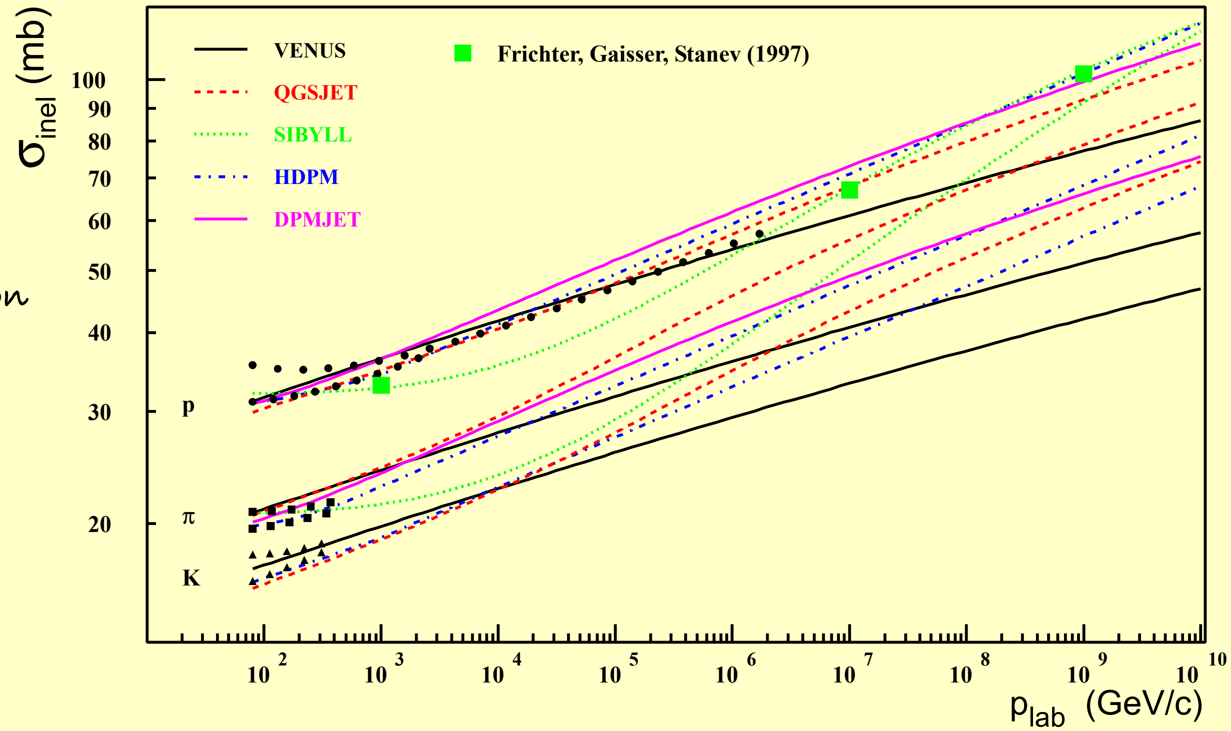

3 groups applied Glauber theory to deduce
the proton-Air inelastic cross-section from
the measured p-p cross-sections (SppS, Tevatron)

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

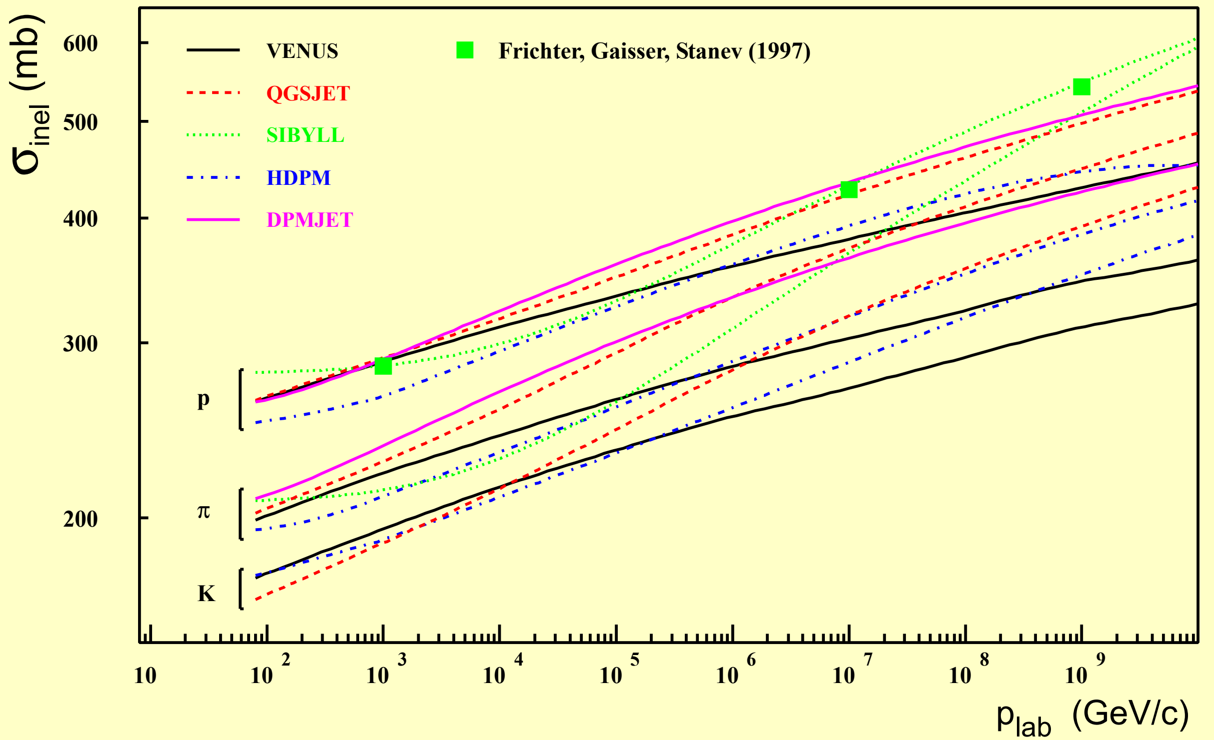
# Cross-sections on Proton and Air

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

Hadron-Proton




Hadron-Air

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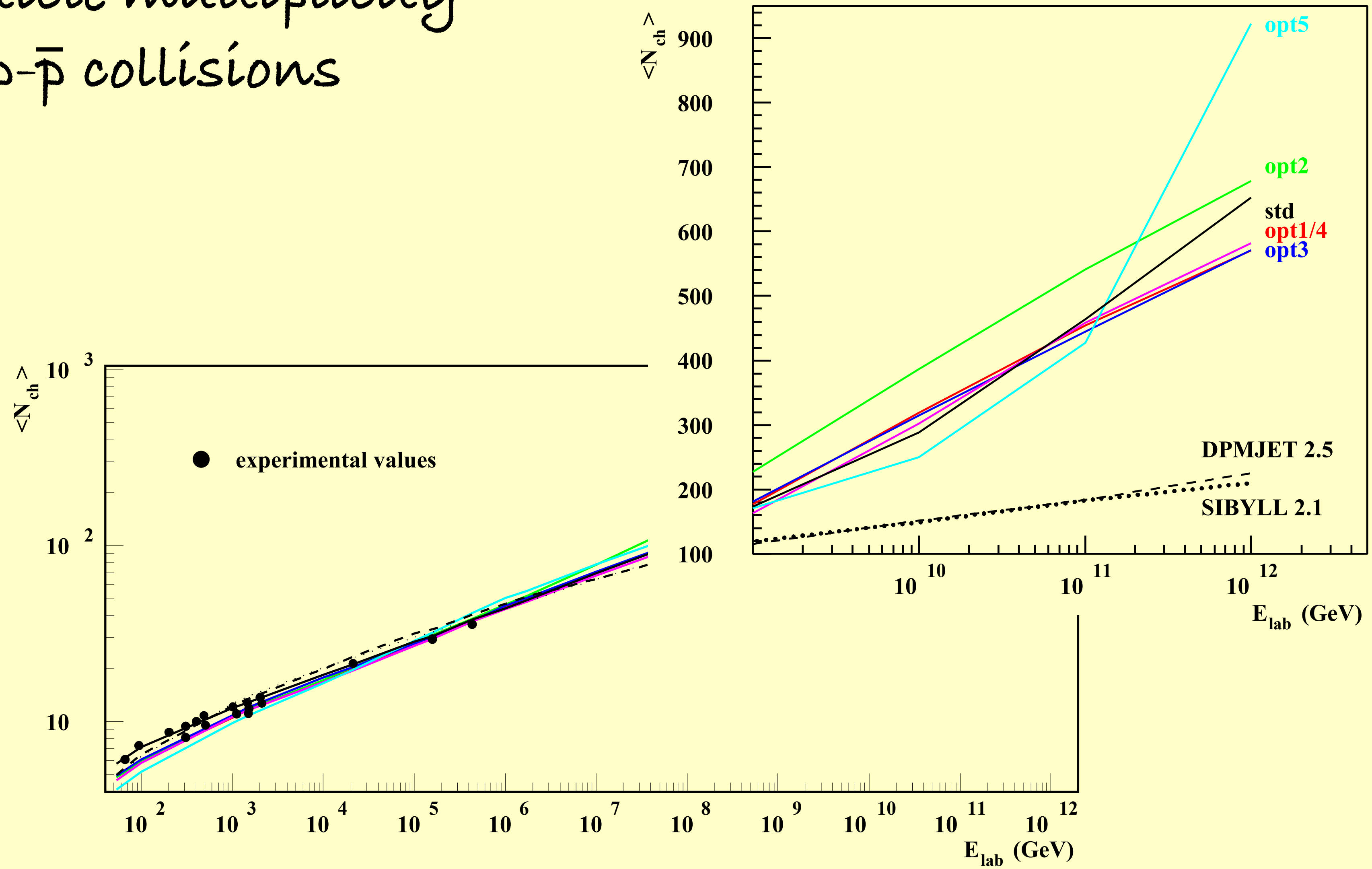
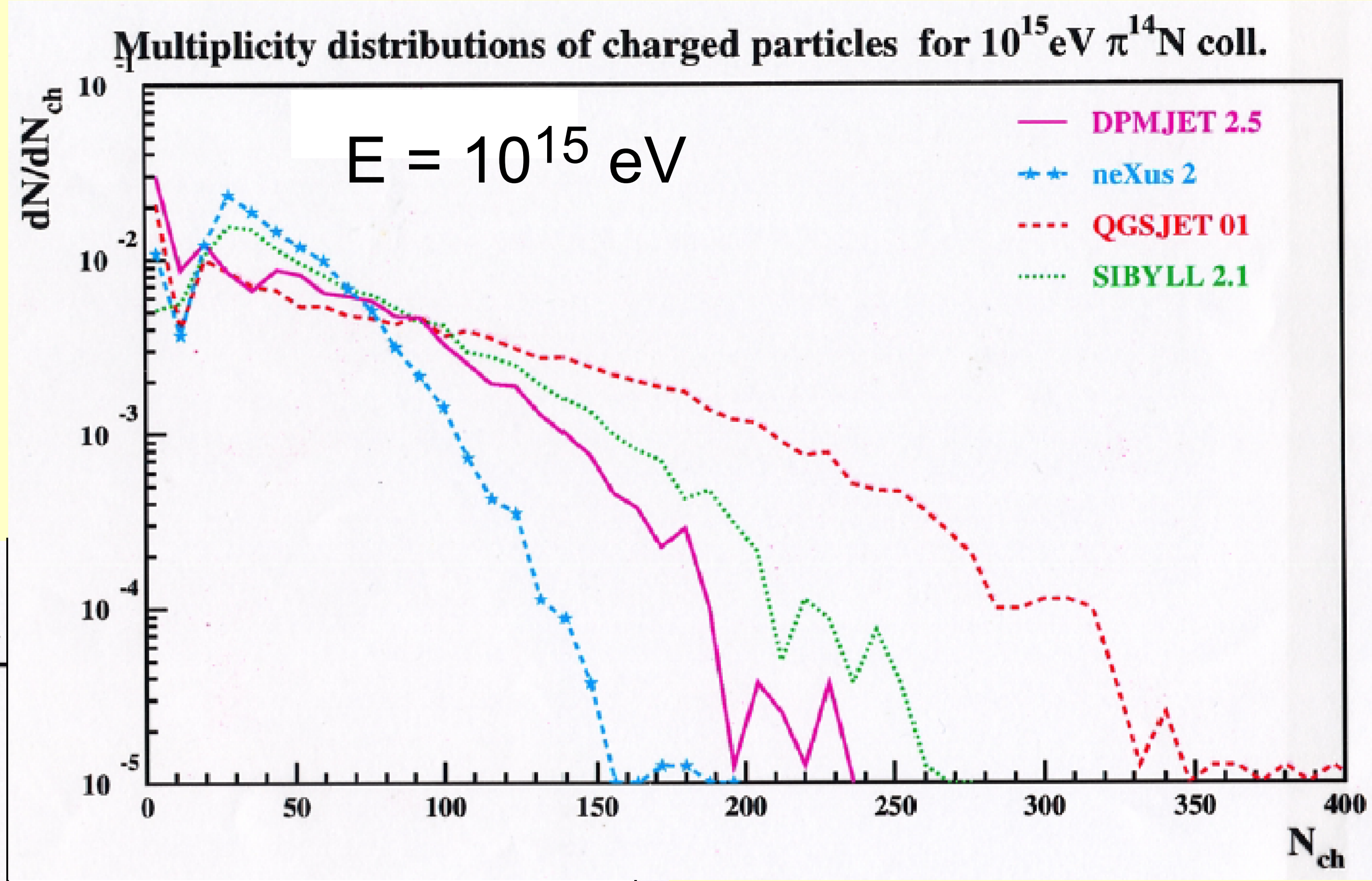
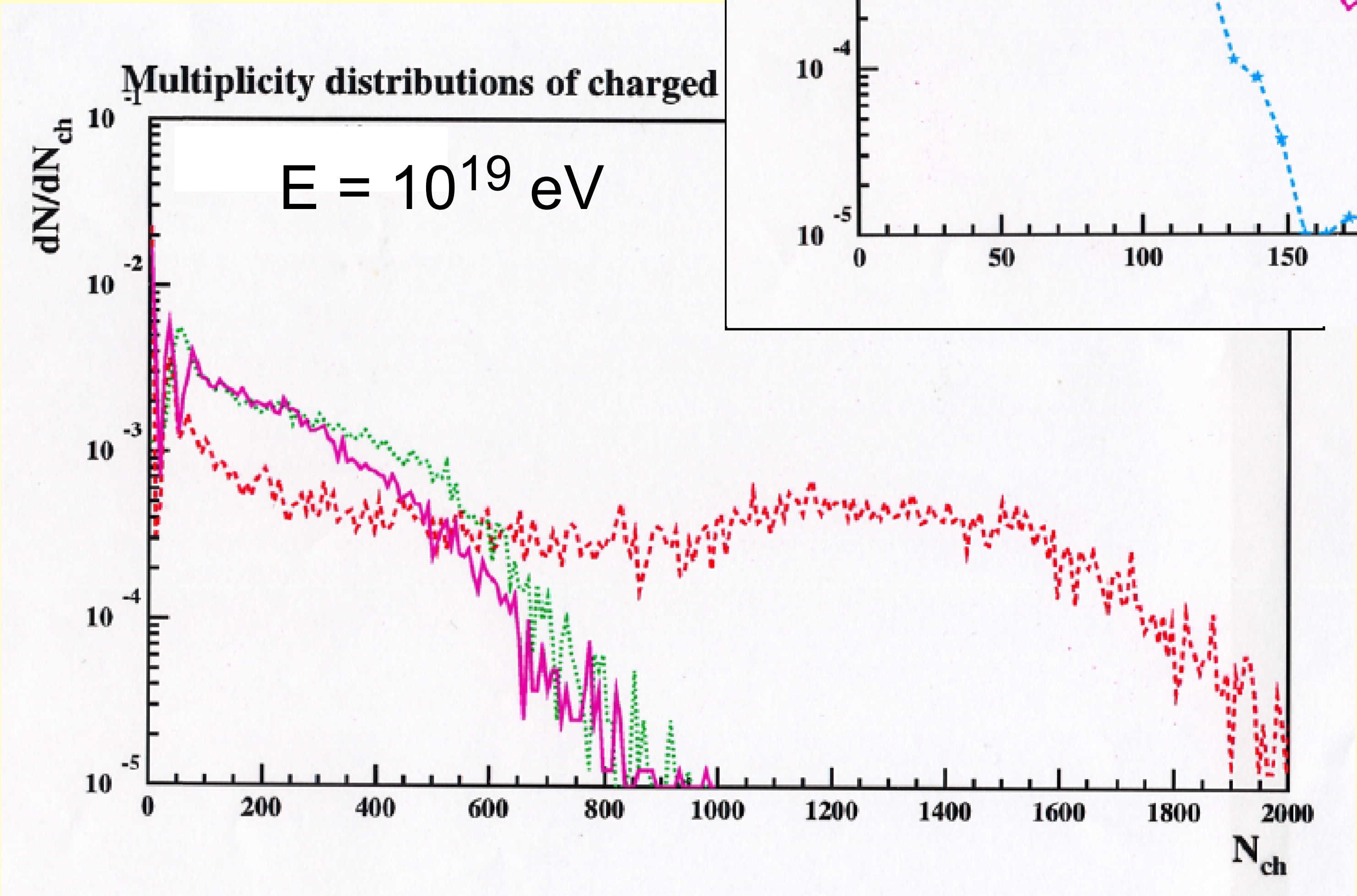
# Results on particle production

particle multiplicity
in p-$\bar{p}$ collisions



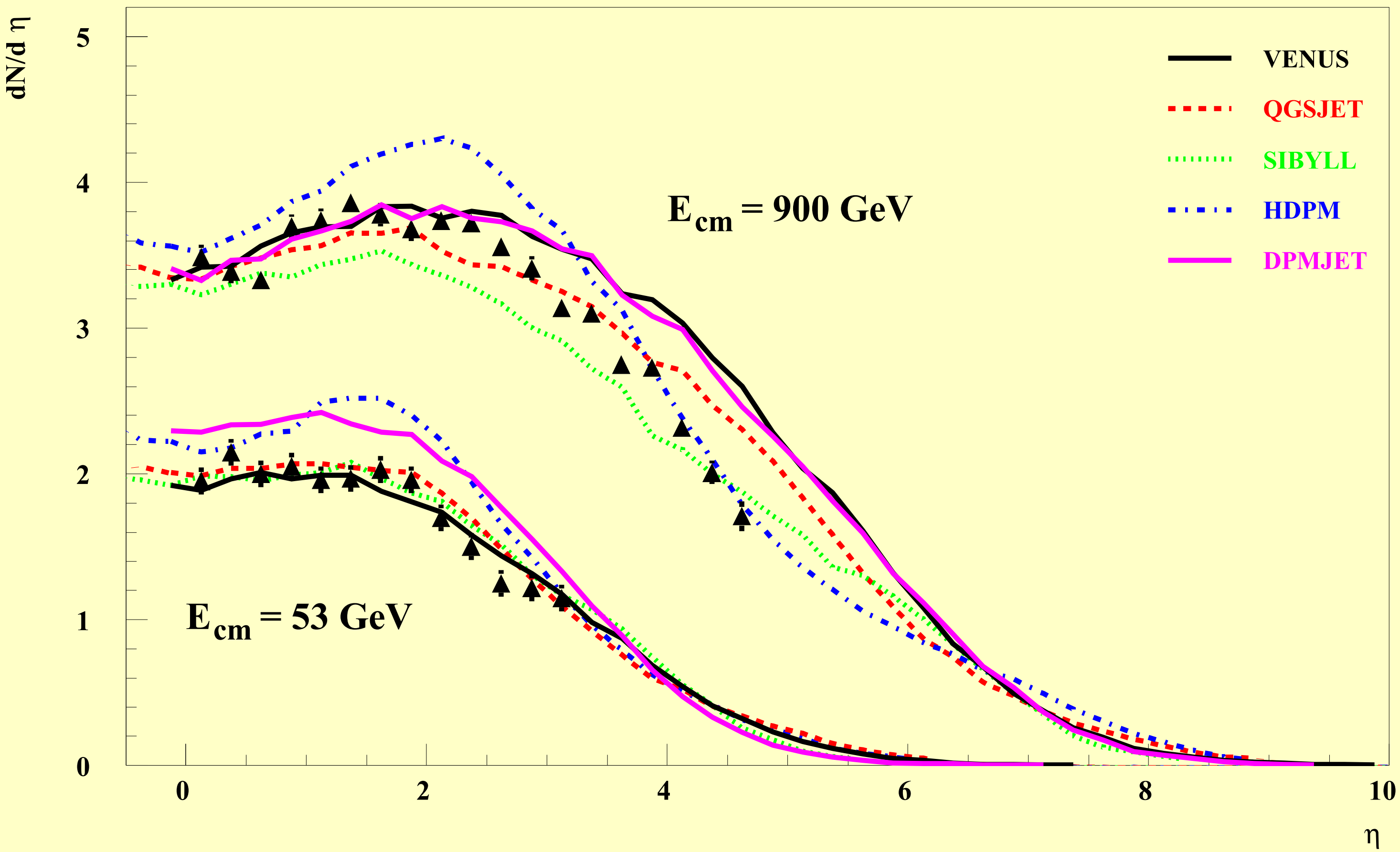
QGSJet produces
much more secondaries
than other models.




Huge difference,
but does it matter ?

# 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 ($\eta$) distributions initially not very well described:

models can fit either $dN/d\eta(\eta=0)$ or

the tail to large $\eta$-values,

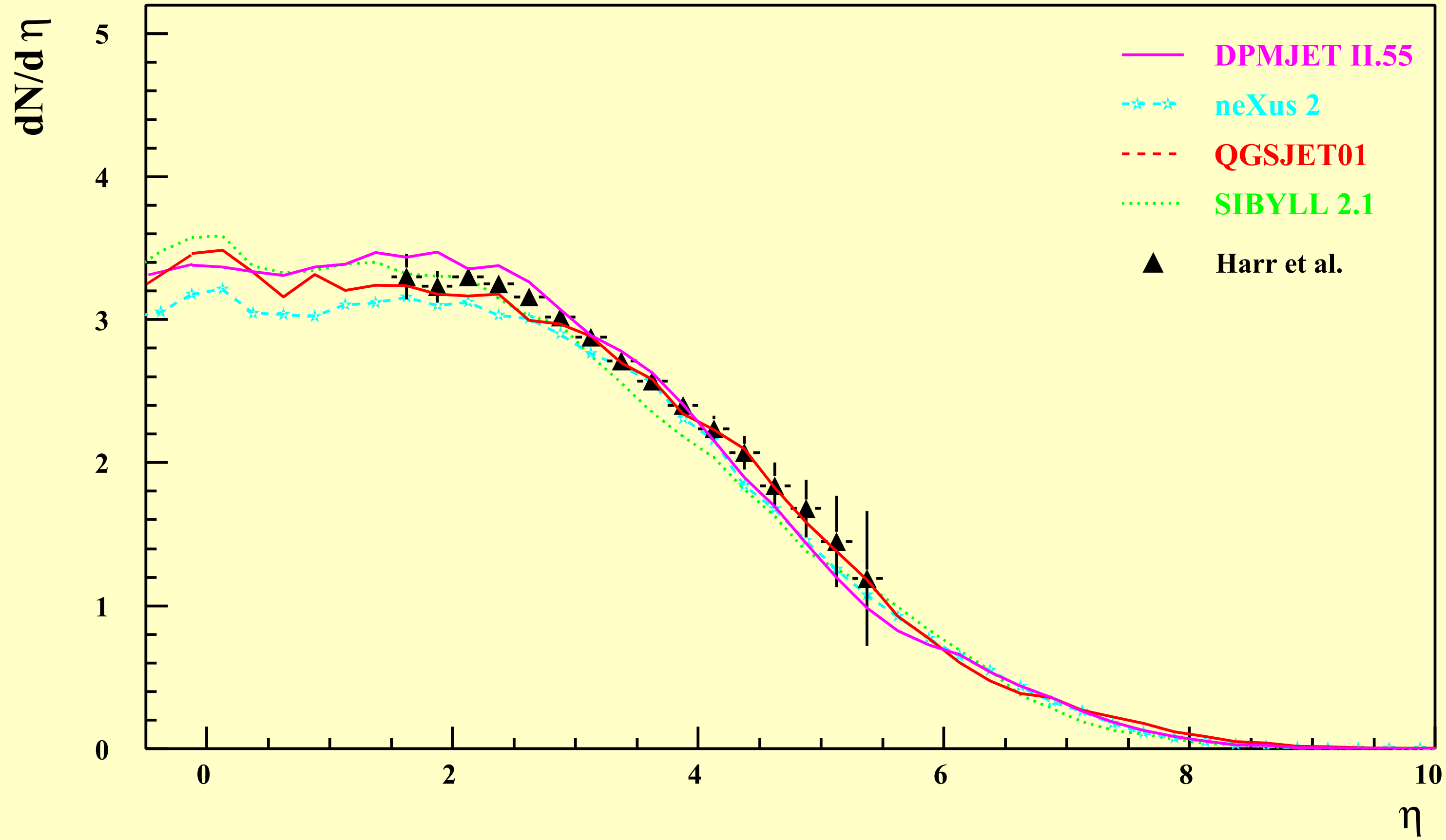
but not both.

**are models wrong or badly tuned?**

# Another experiment at the same collider ....

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

Simulations including experimental trigger

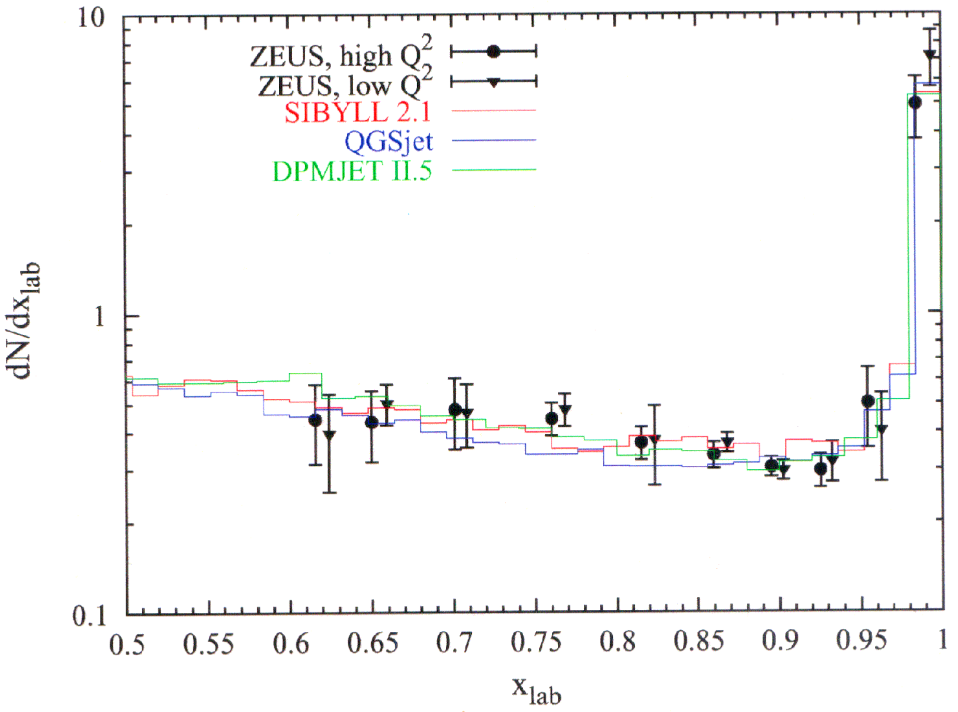


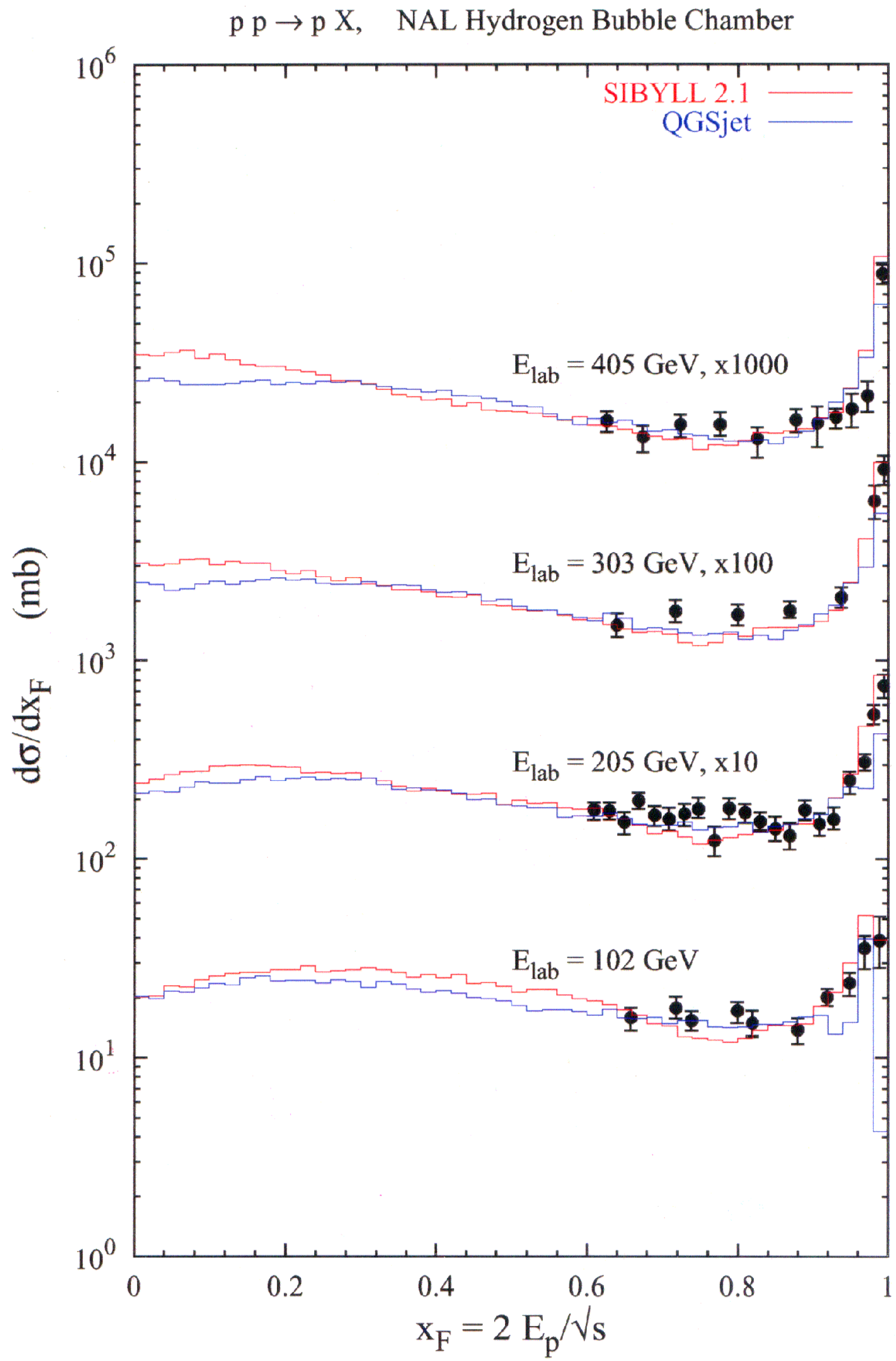

New experimental results in contradiction to older UA5 distributions, but very good agreement with simulations.

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

# Particle production in forward direction

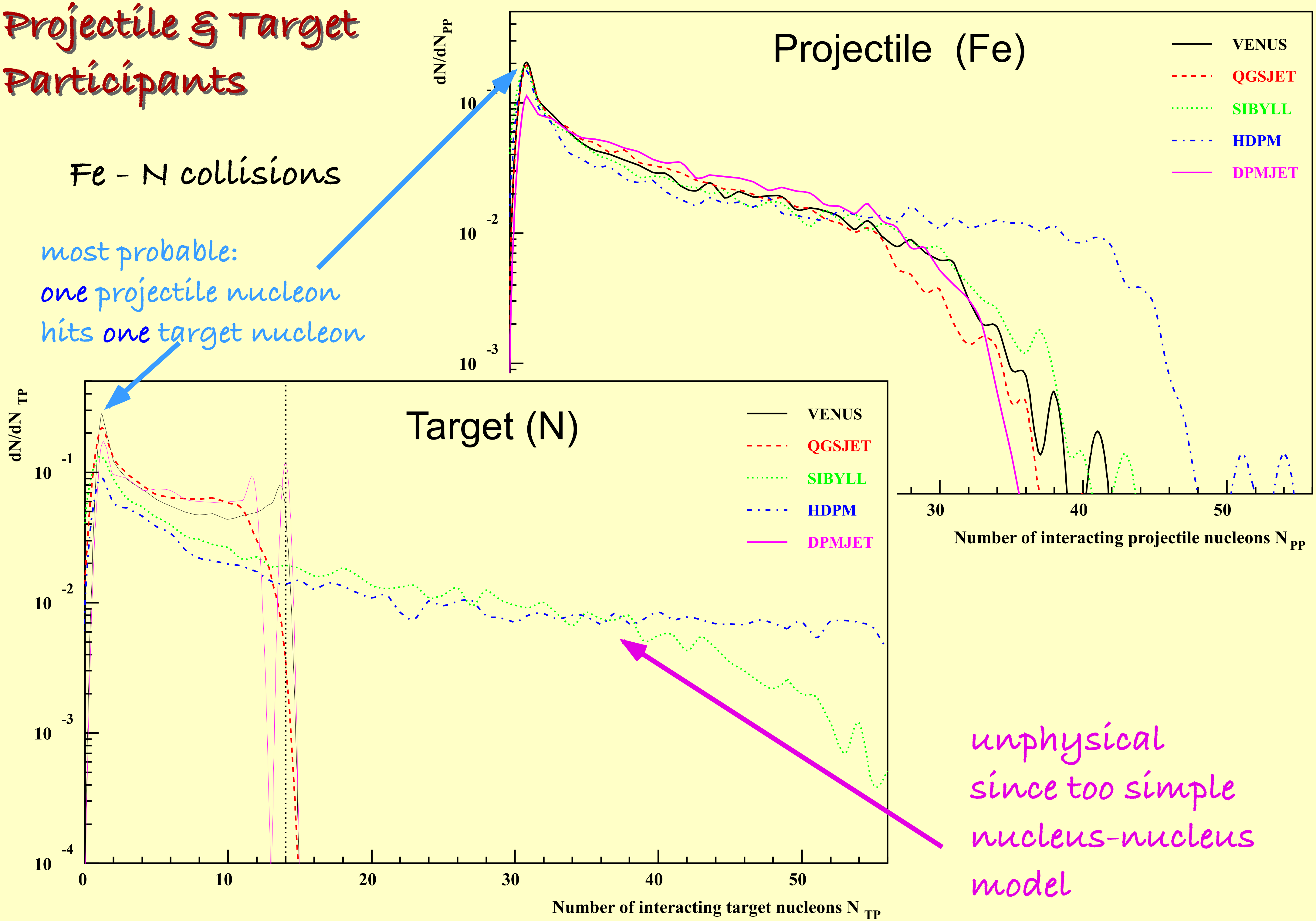
... important since forward particles carry energy efficiently down the atmosphere



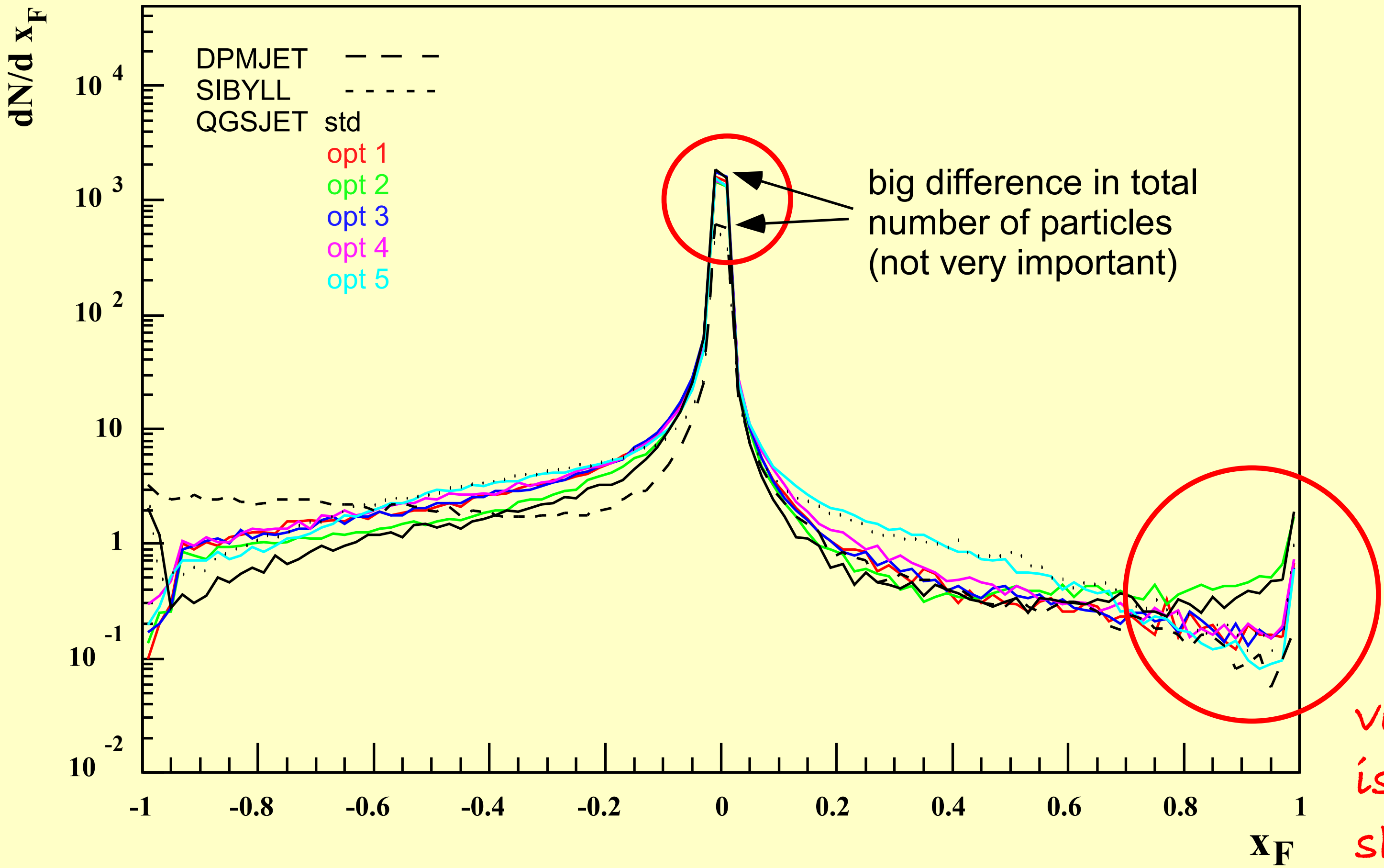



# Projectile & Target Participants

Fe - N collisions



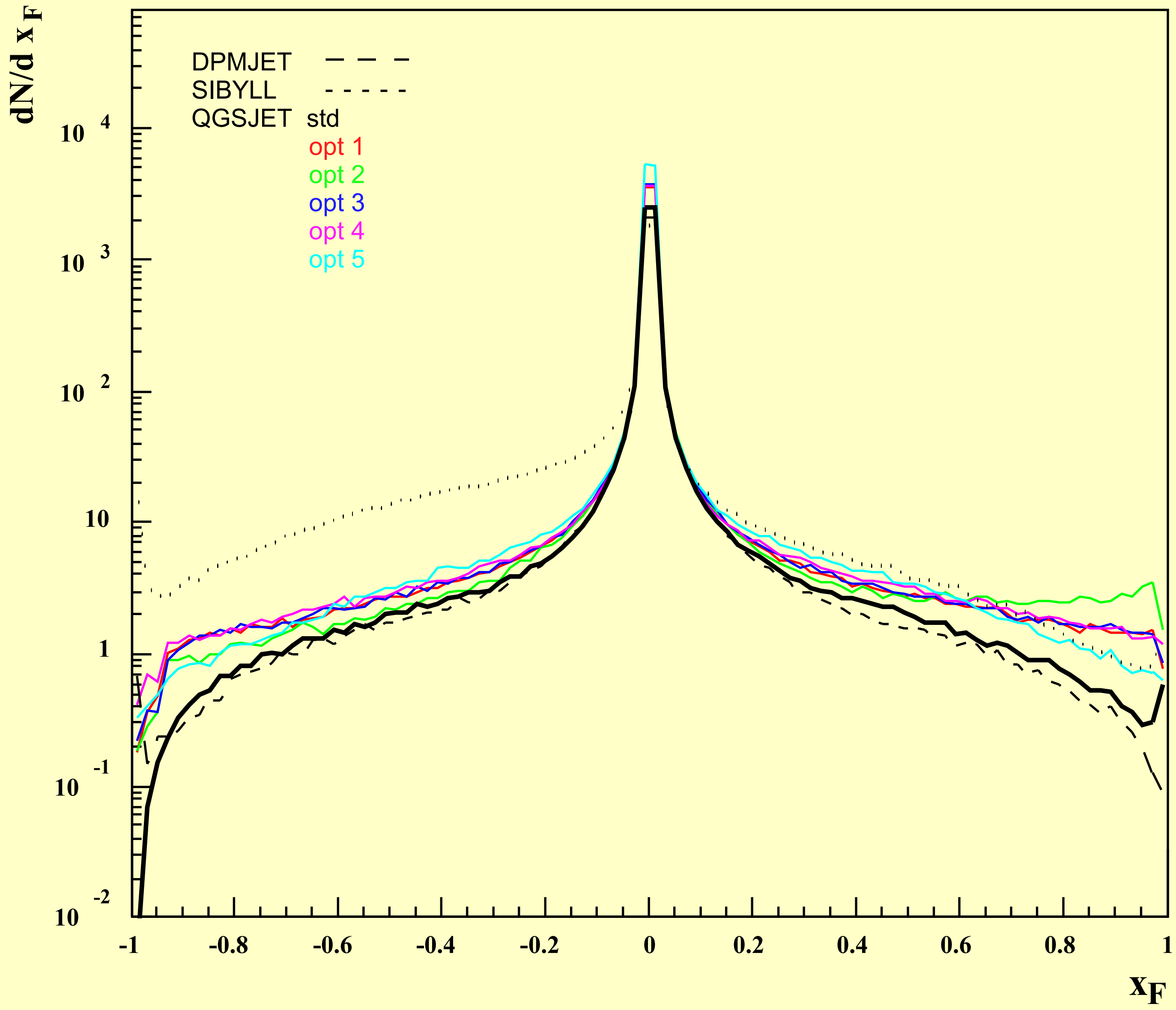
# Feynman x distribution in p-N collisions

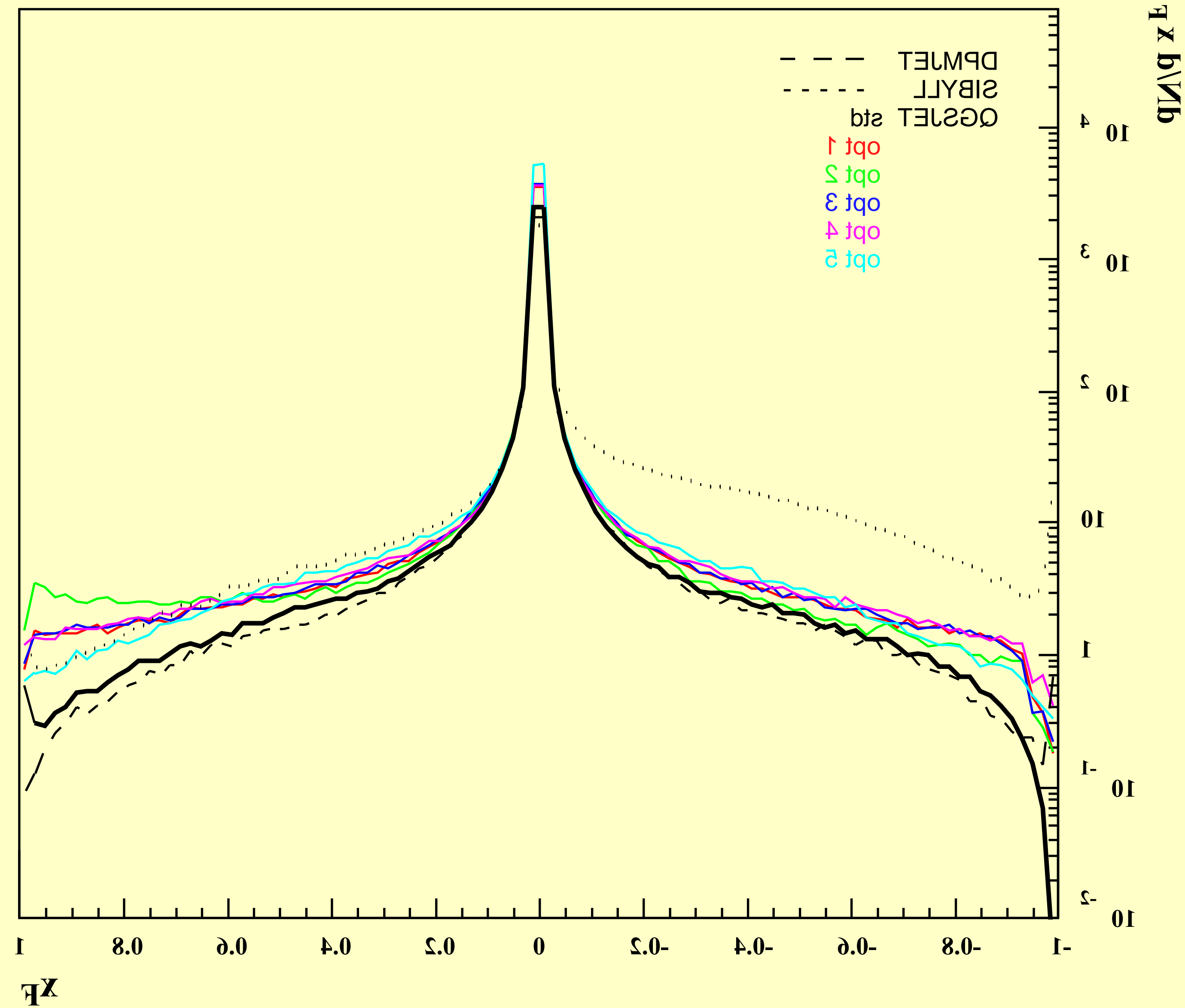



very forward region is important for shower development

# Feynman x distribution in N-N collisions ...

# ... should be symmetric as well



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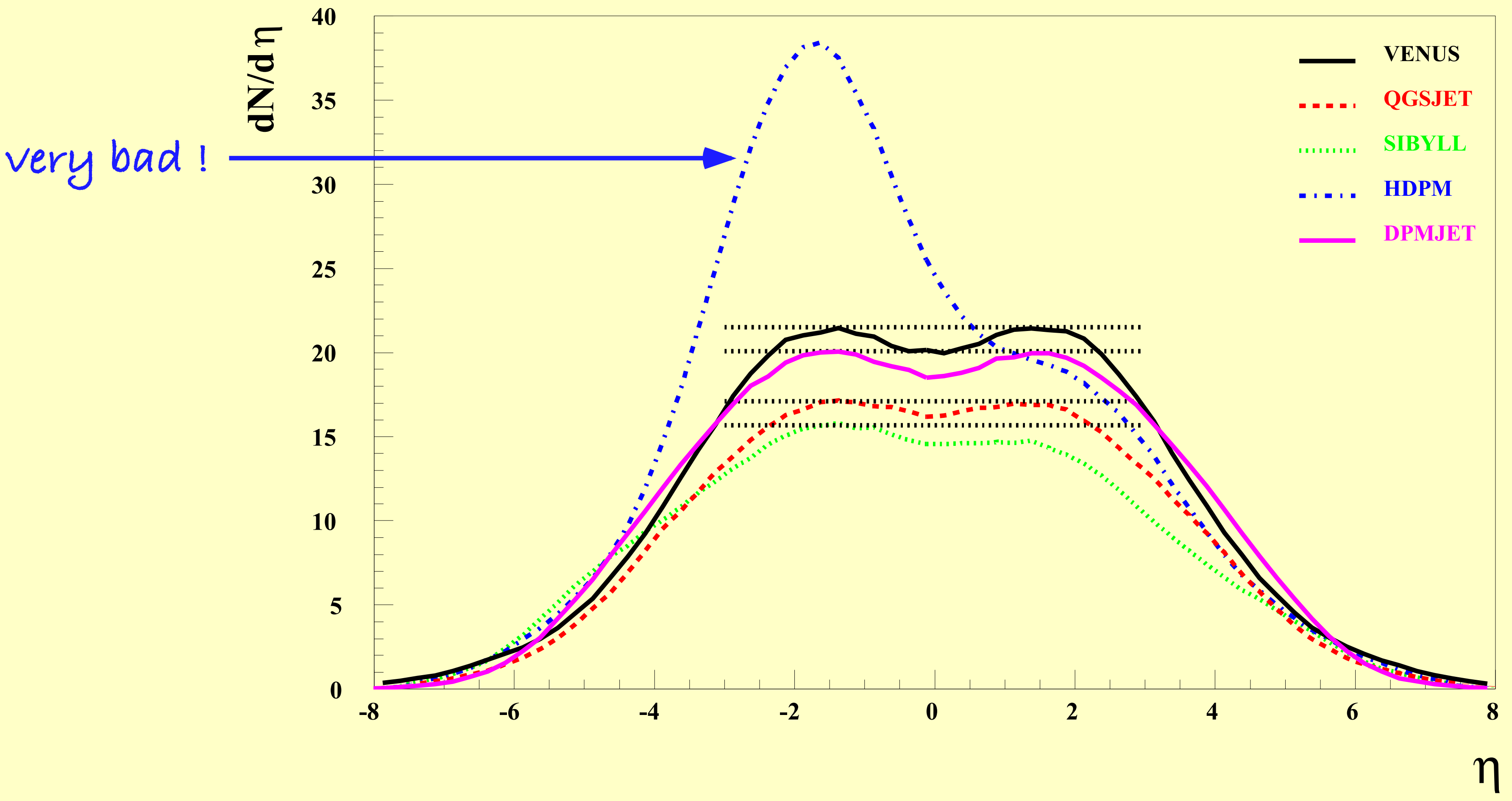
# Nitrogen-Nitrogen Collisions




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

# Longitudinal Shower Profiles

difference in $X_{max}$,
but large fluctuations

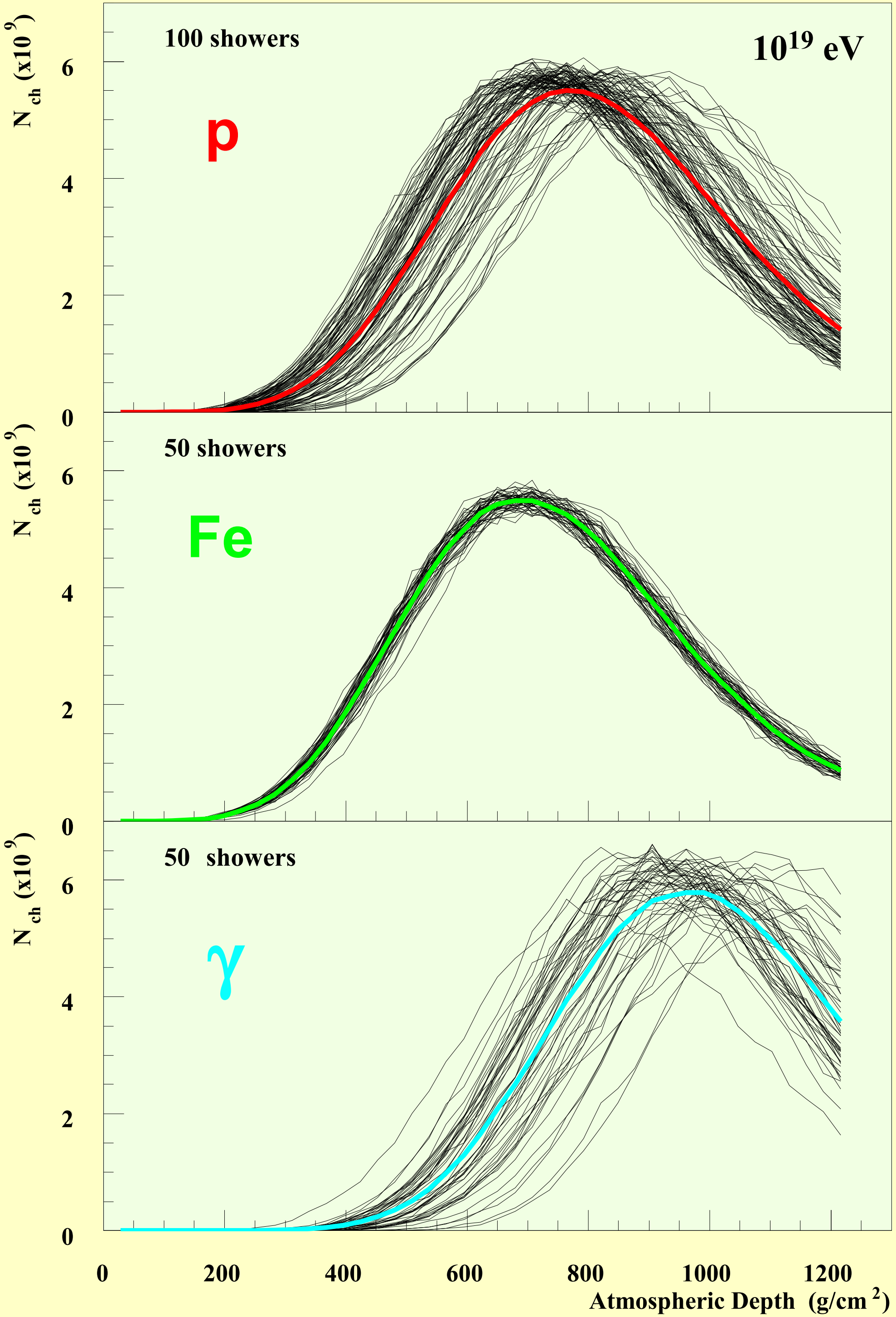
differences between
hadrons and photons are large

differences between
proton and iron (or nuclei)
are subtle

On average Fe have:

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

than p showers.

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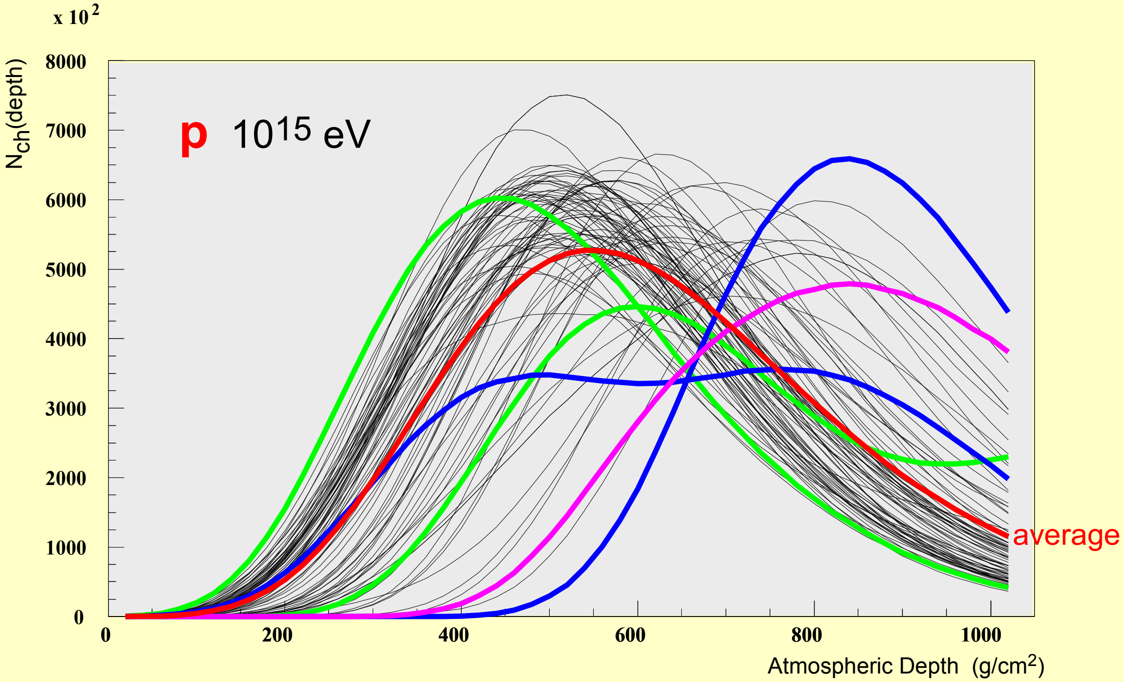
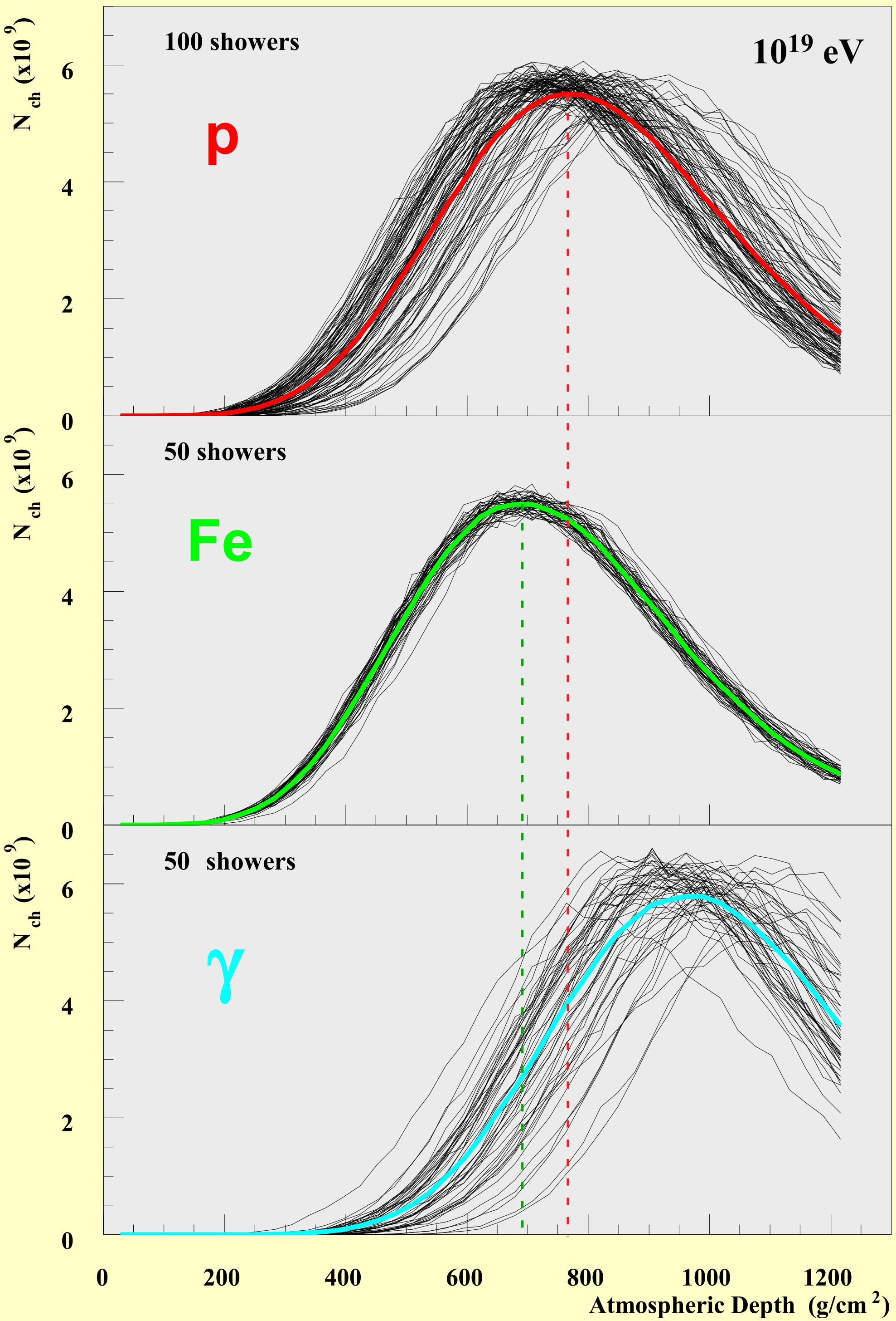
# Longitudinal Shower Development




at lower energies:

large fluctuations

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

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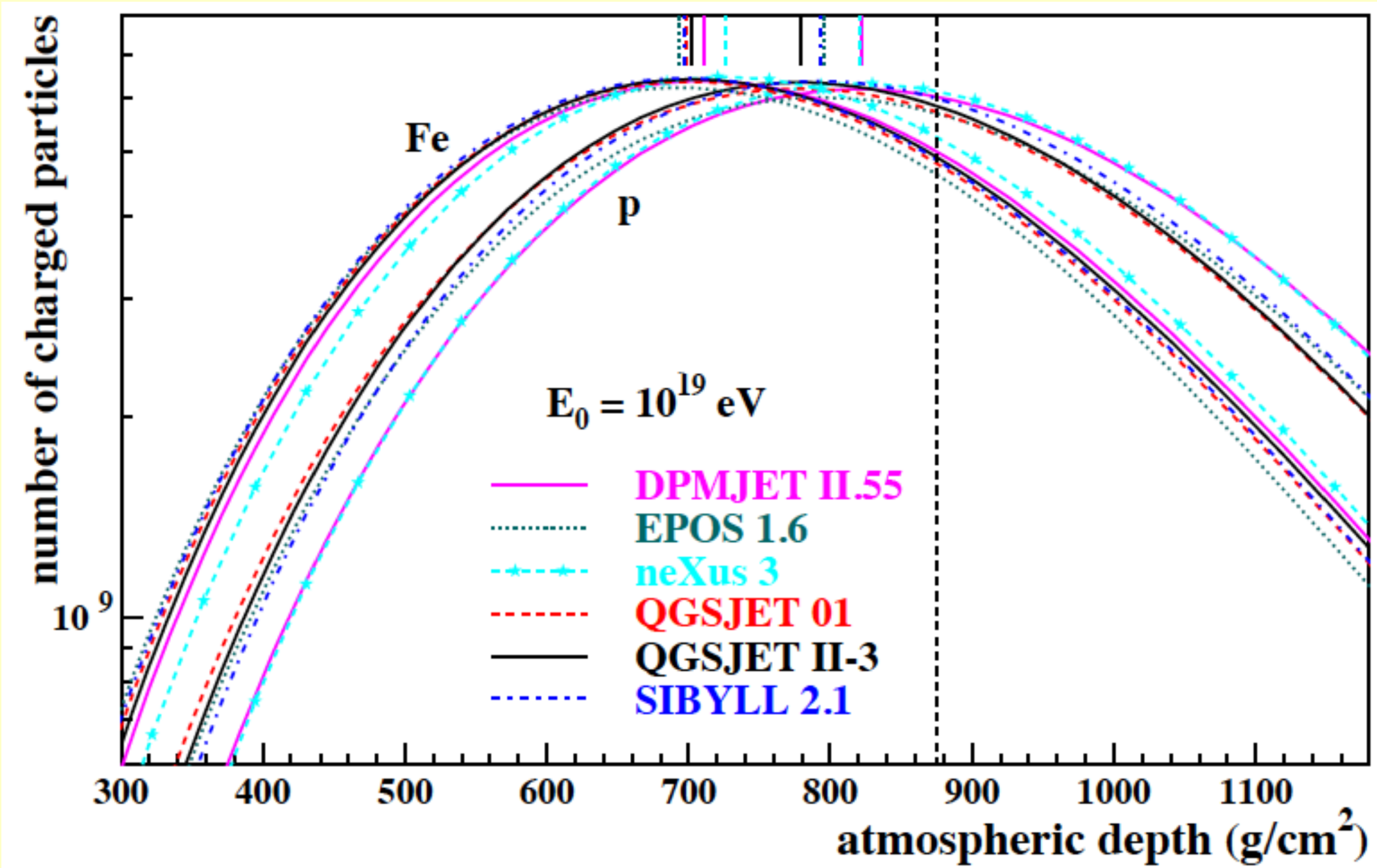
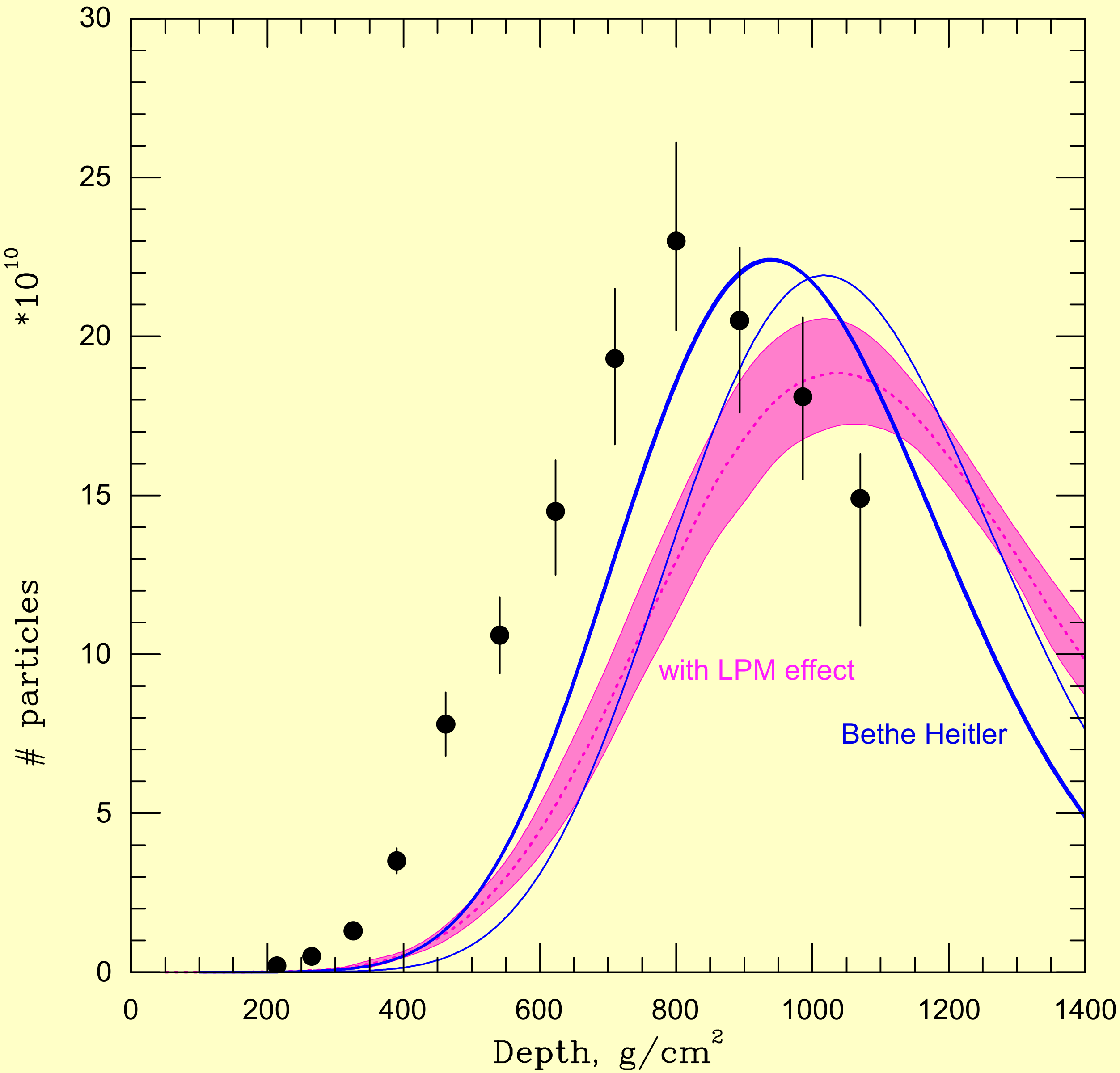
# Average Longitudinal Shower Development

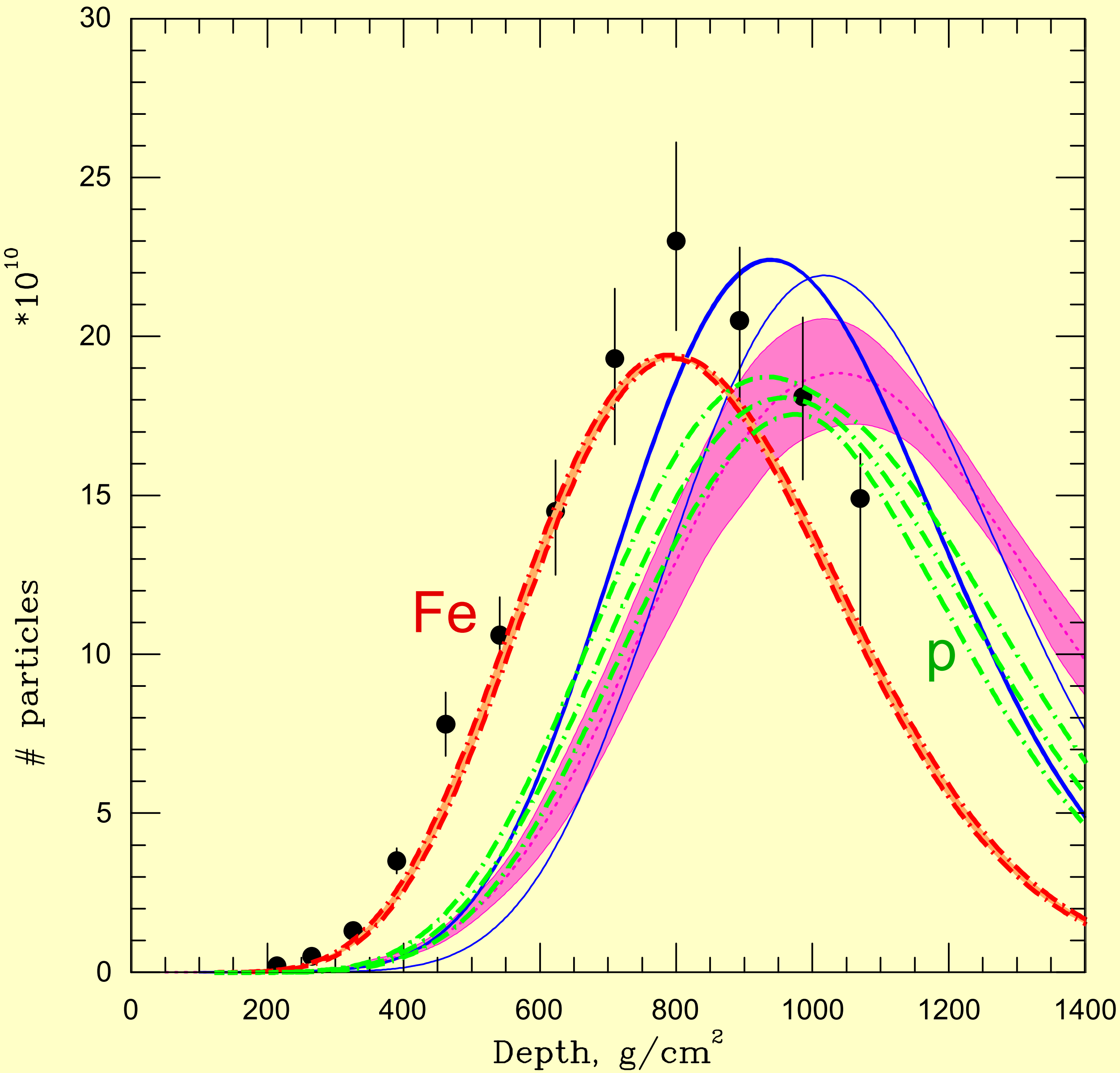
QGSJet well in line with other models.
High multiplicity
partly compensated by
lower cross-section and
partly irrelevant since mostly
low-energy particles produced.



# The 3 x $10^{20}$ 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 ?



# Simulations vs Data:

... a few examples

# Result:

fair agreement from $10^{12}$ - $10^{20}$ eV

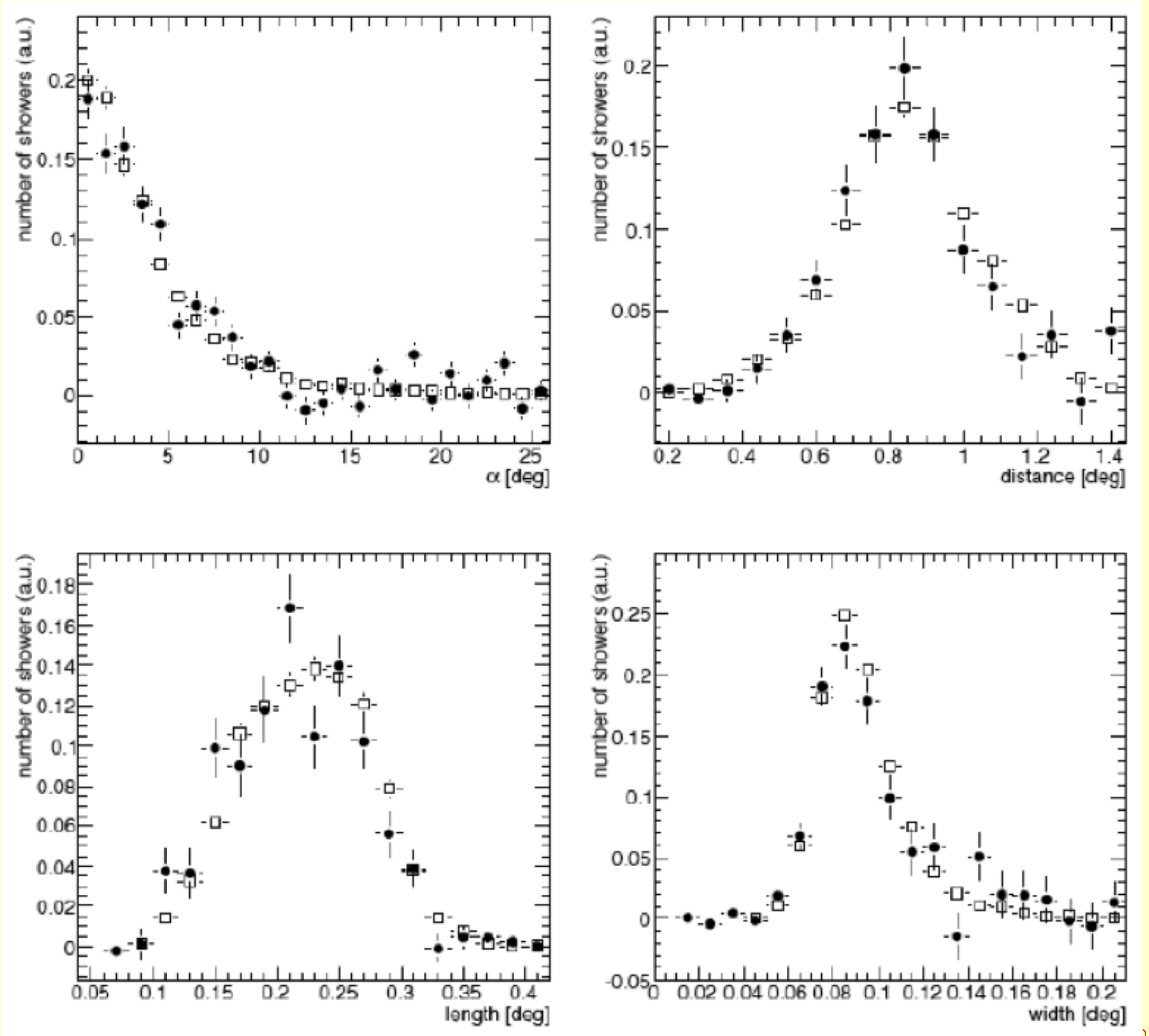
# VERITAS

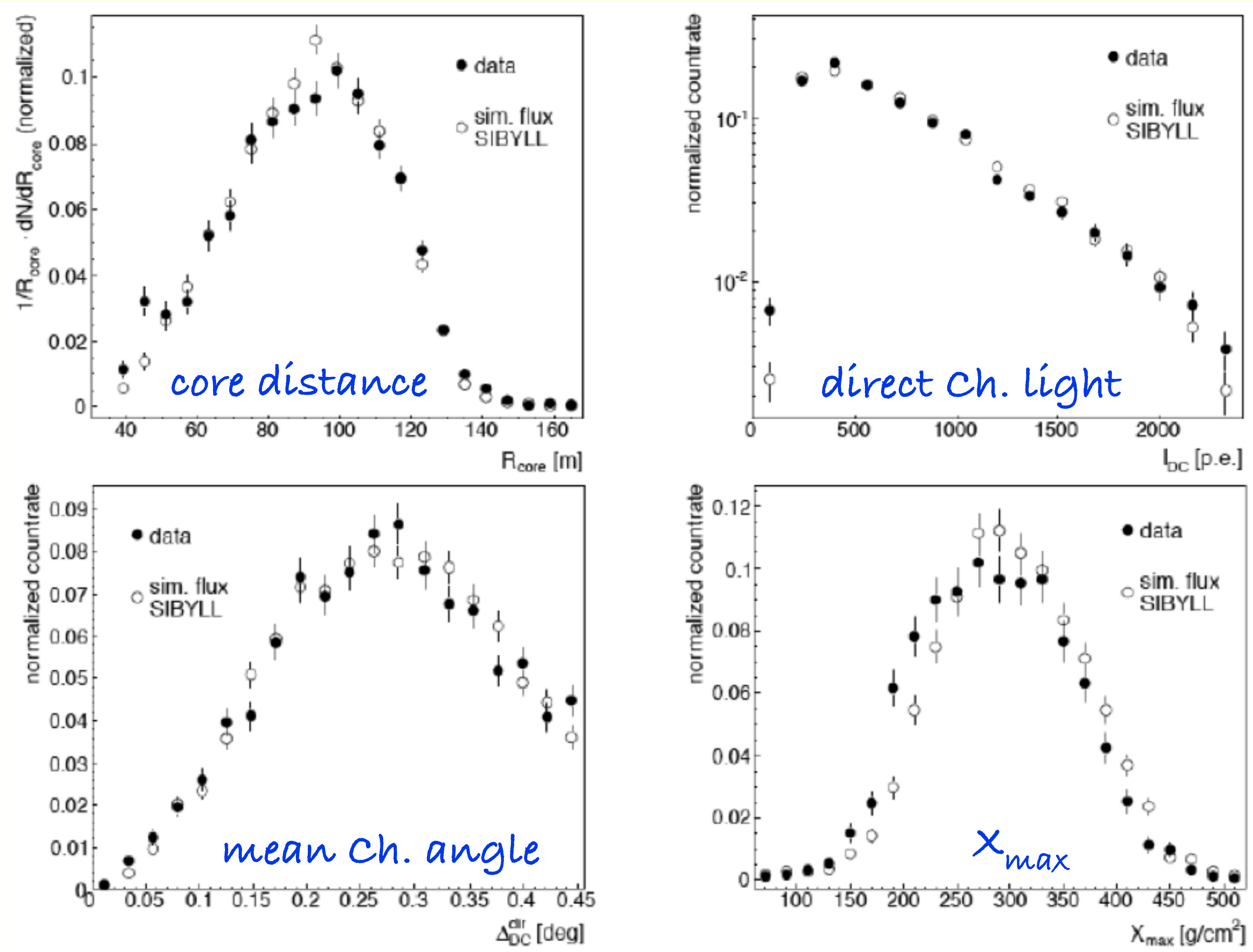
Telescope 1

E > 150 GeV

gamma rays:
good agreement of image param. distributions

CR background:
absolute trigger rate within 15%






# HESS: 10-100 TeV mix of hadronic primaries

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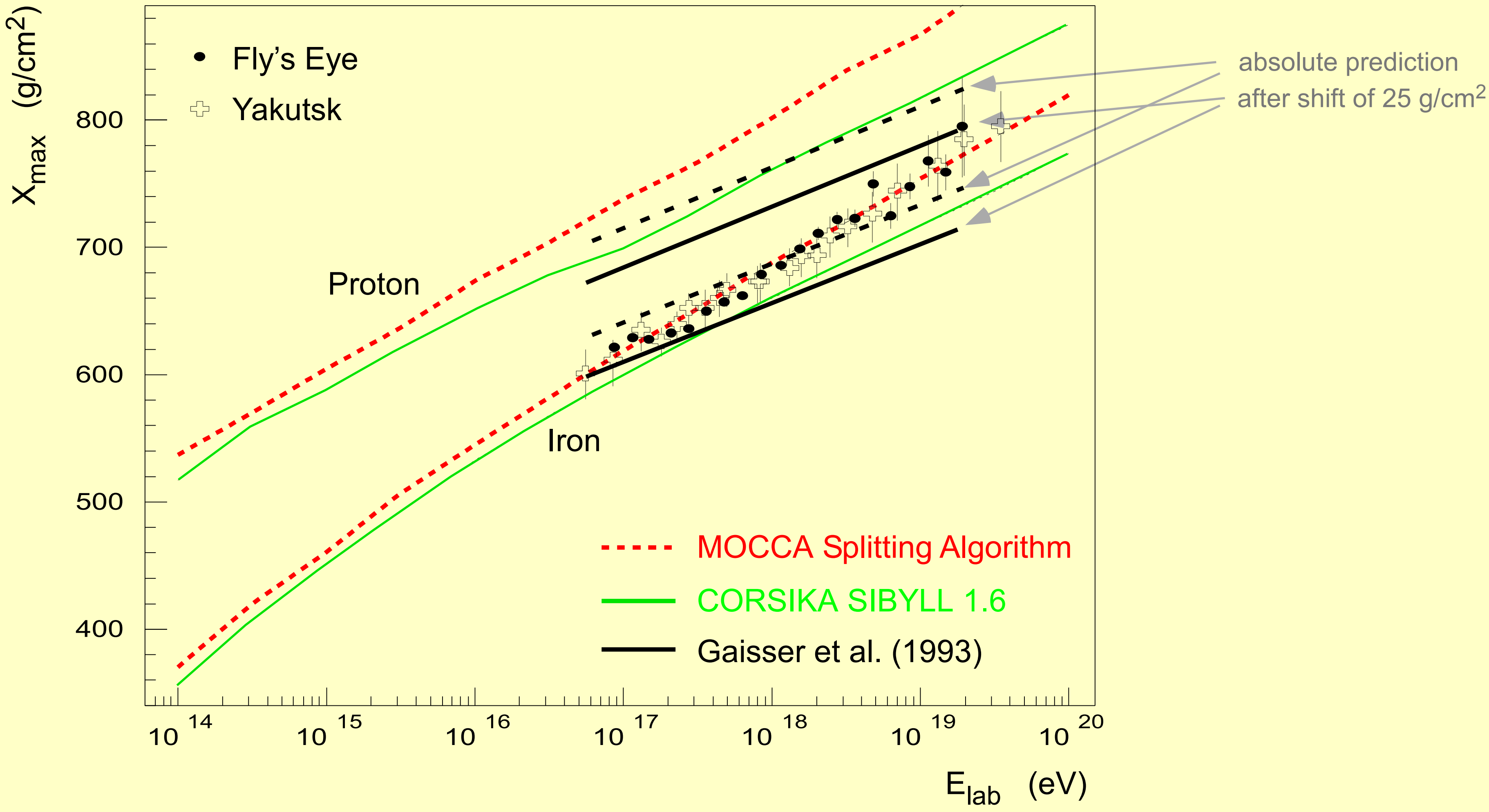
# Data versus Simulations

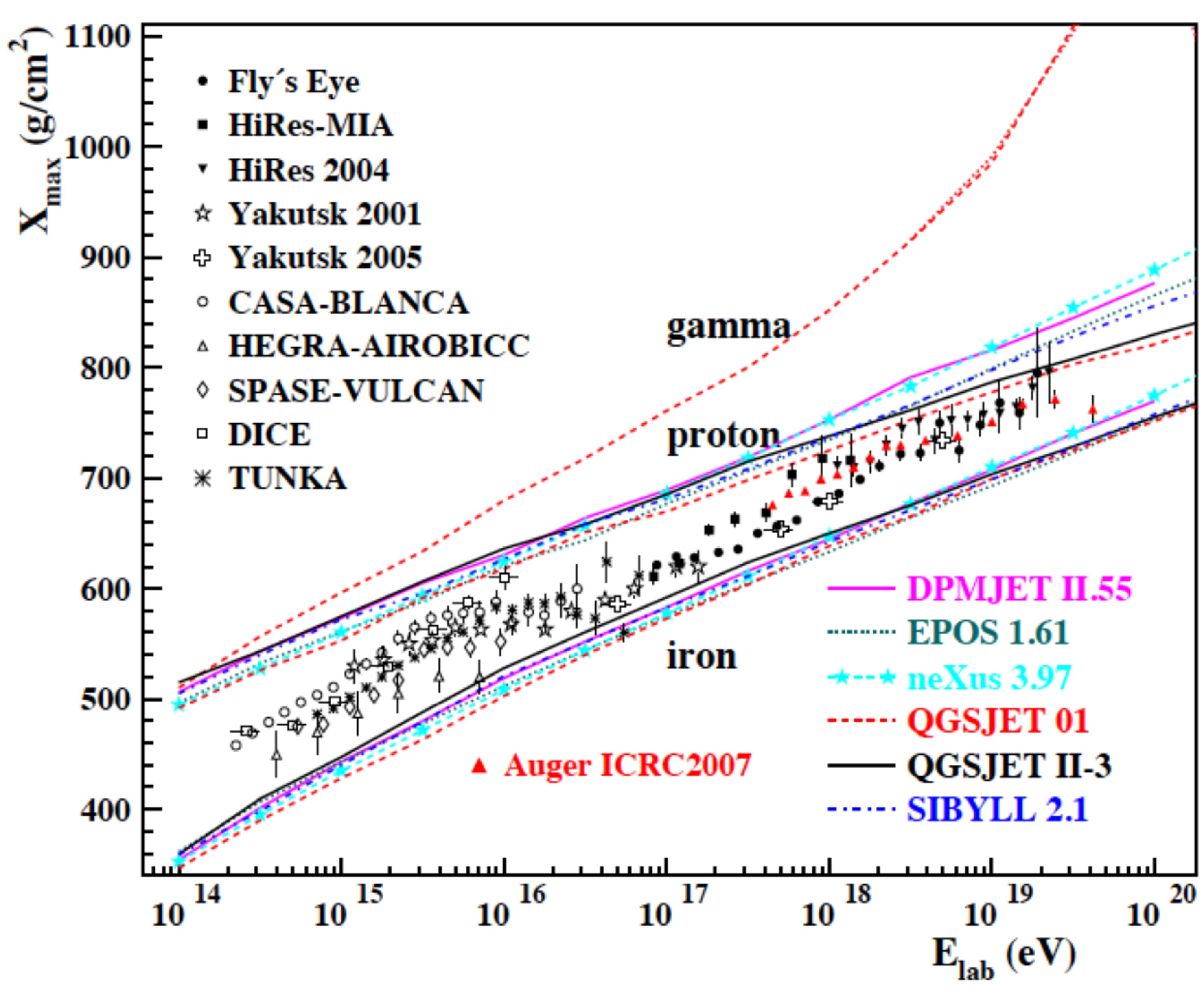
$X_{max}$ versus energy : comparison with model suggested composition change from Fe to p



# Data versus Simulations

$X_{max}$ versus energy

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

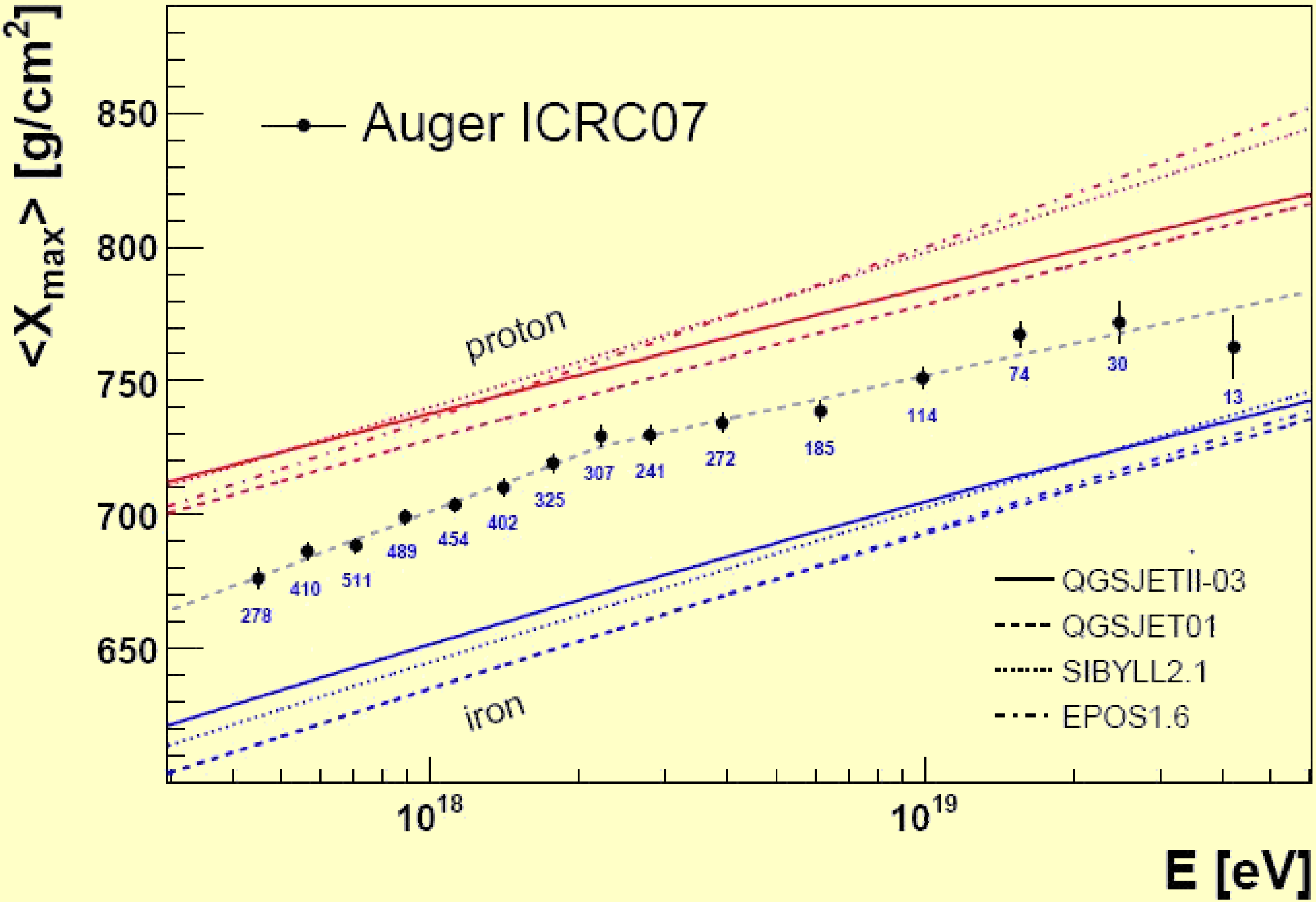



Model dependence of composition persists, though at much lower level.

# Data versus Simulations

MCs for mixed hadronic comp. are consistent with data.

γ, ν showers look very different.

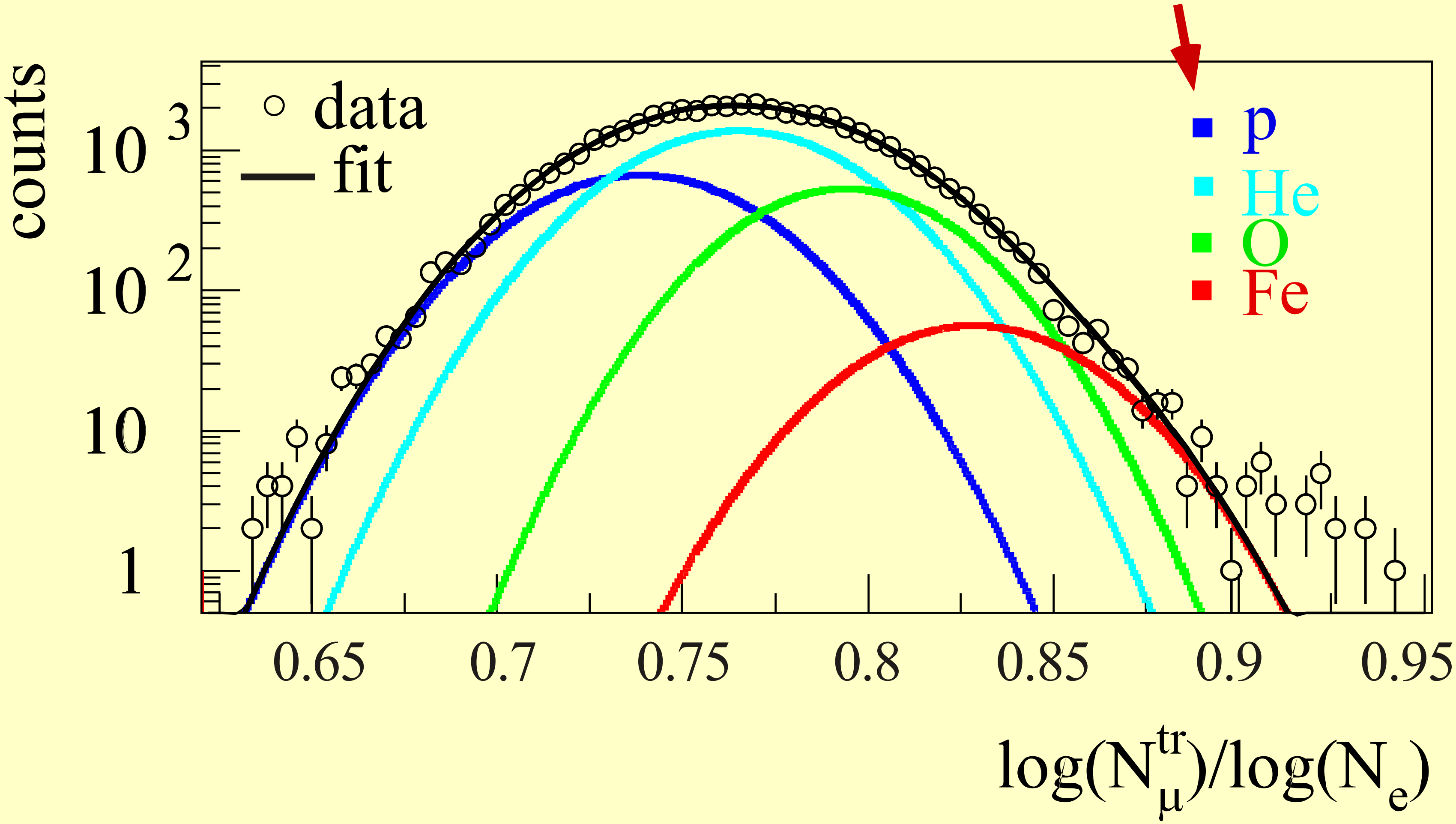


# Data versus Simulations ... another example

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

muon - electron ratio

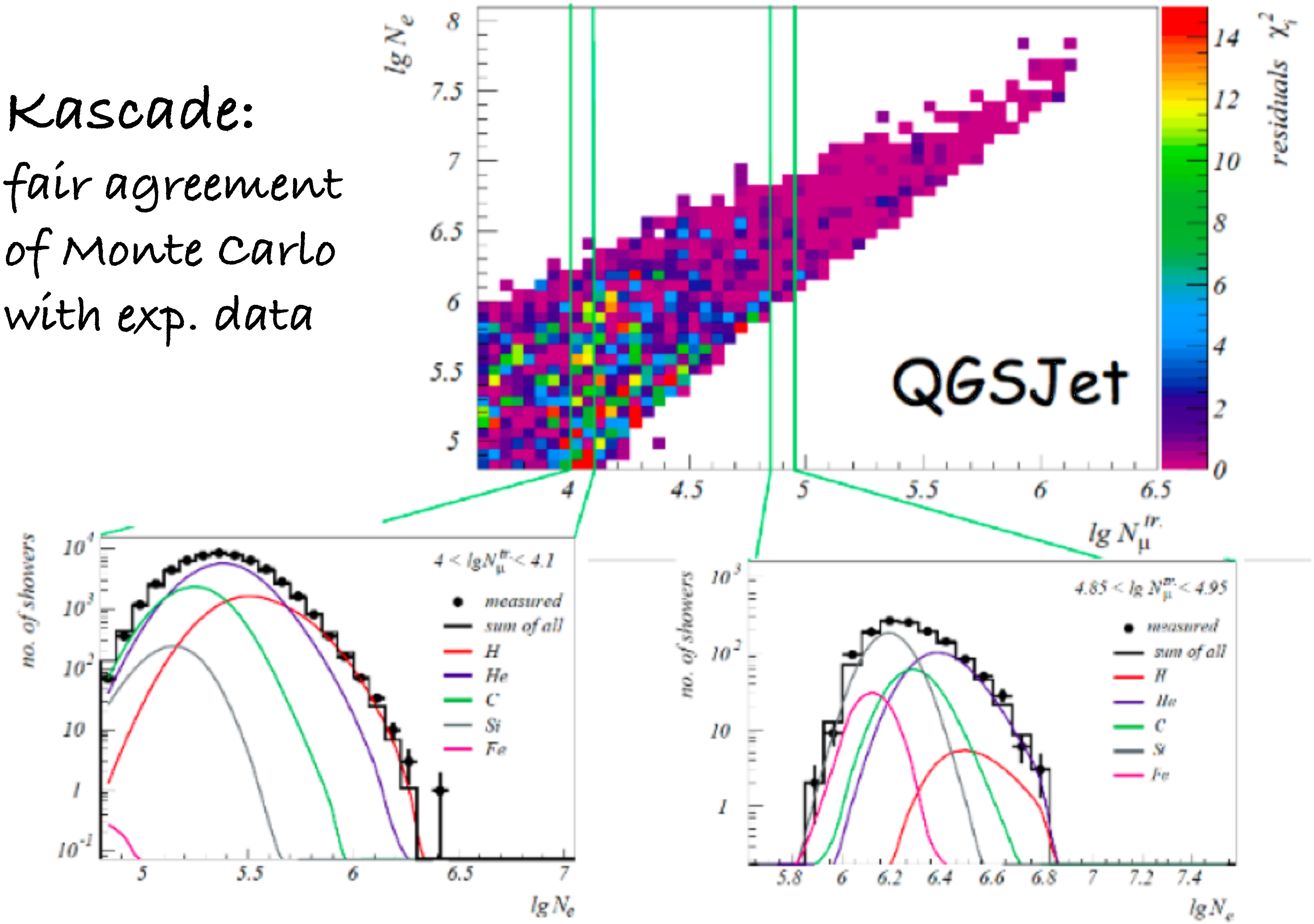
CORSIKA Simulations



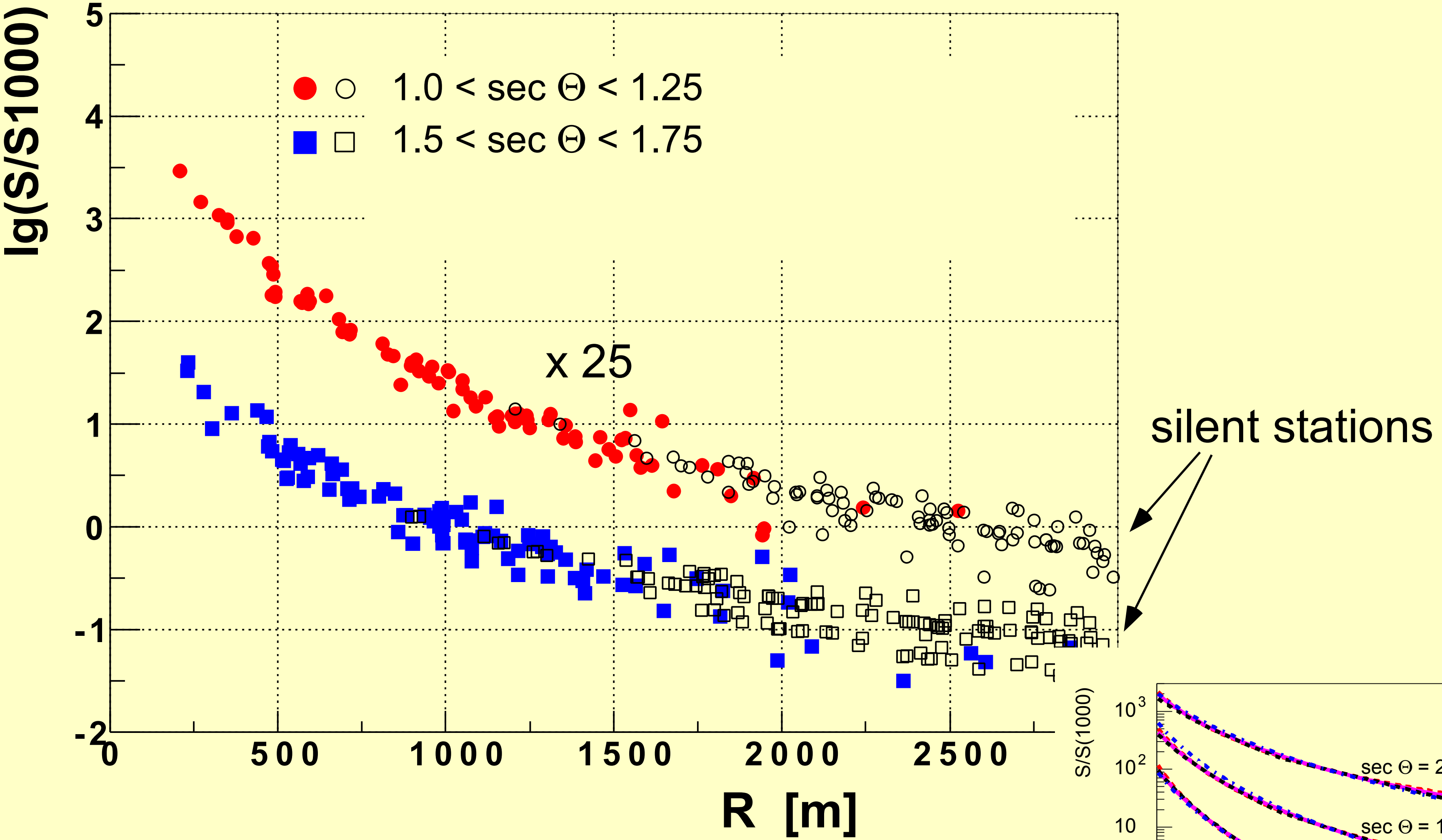
# QGSJet - description of data

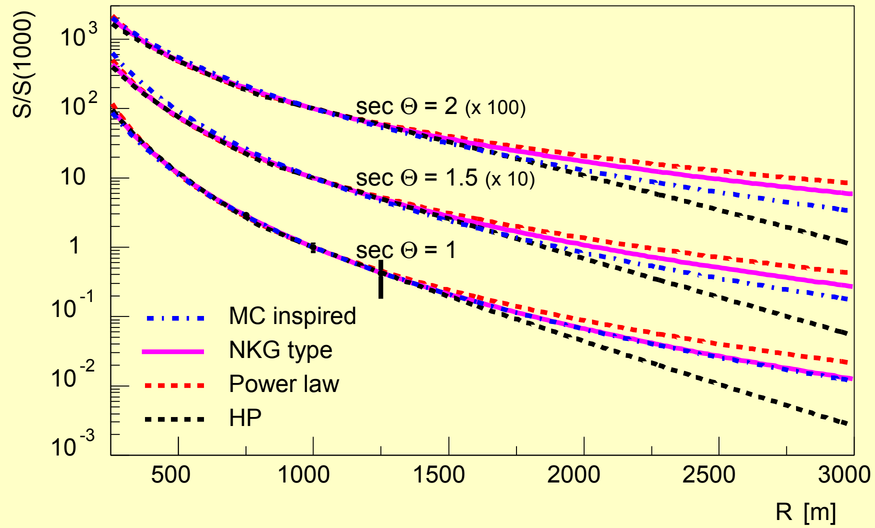
**Kascade:**

fair agreement of Monte Carlo with exp. data



# 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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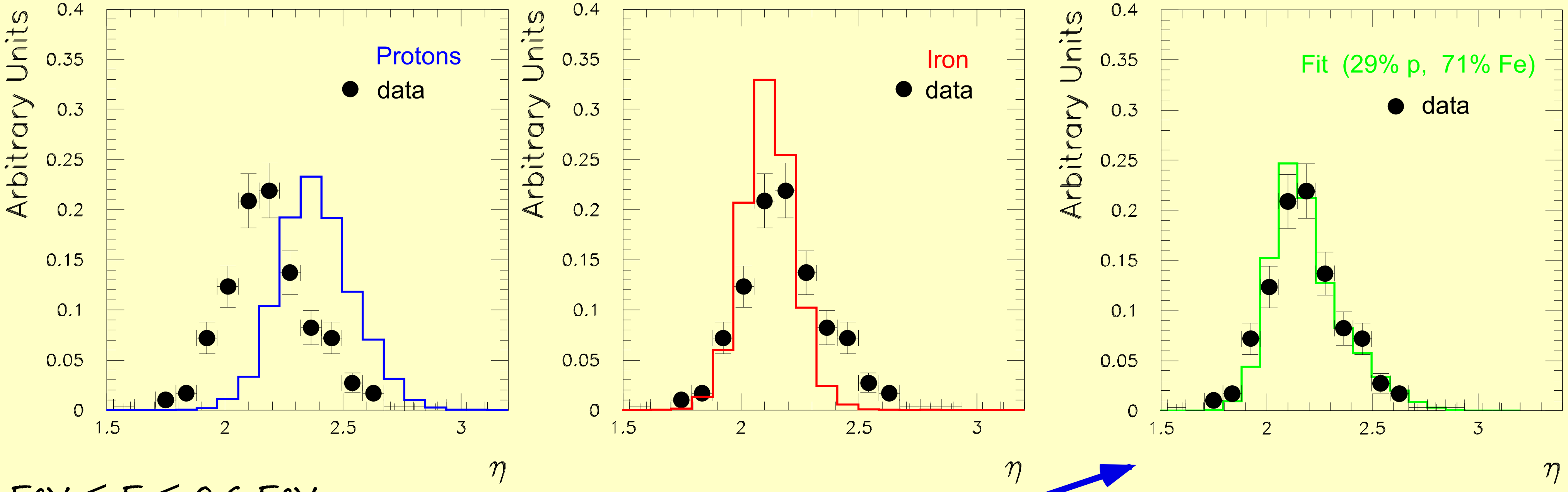
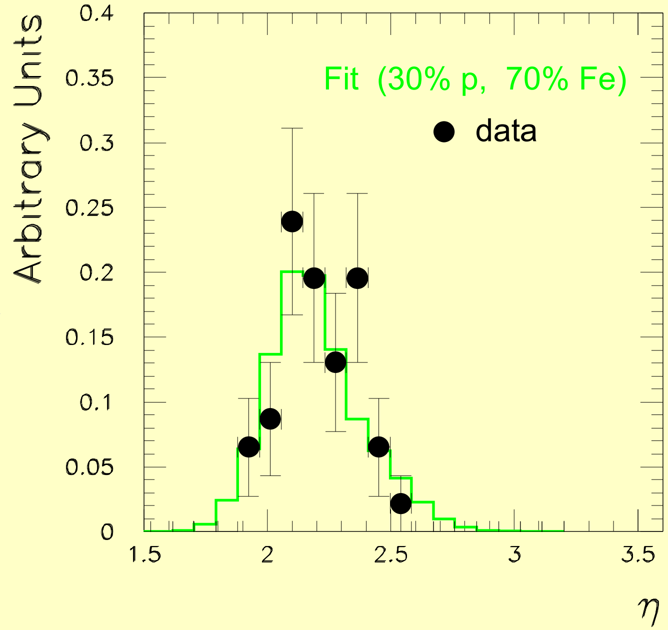
# Haverah Park data (re-analysed 2003)



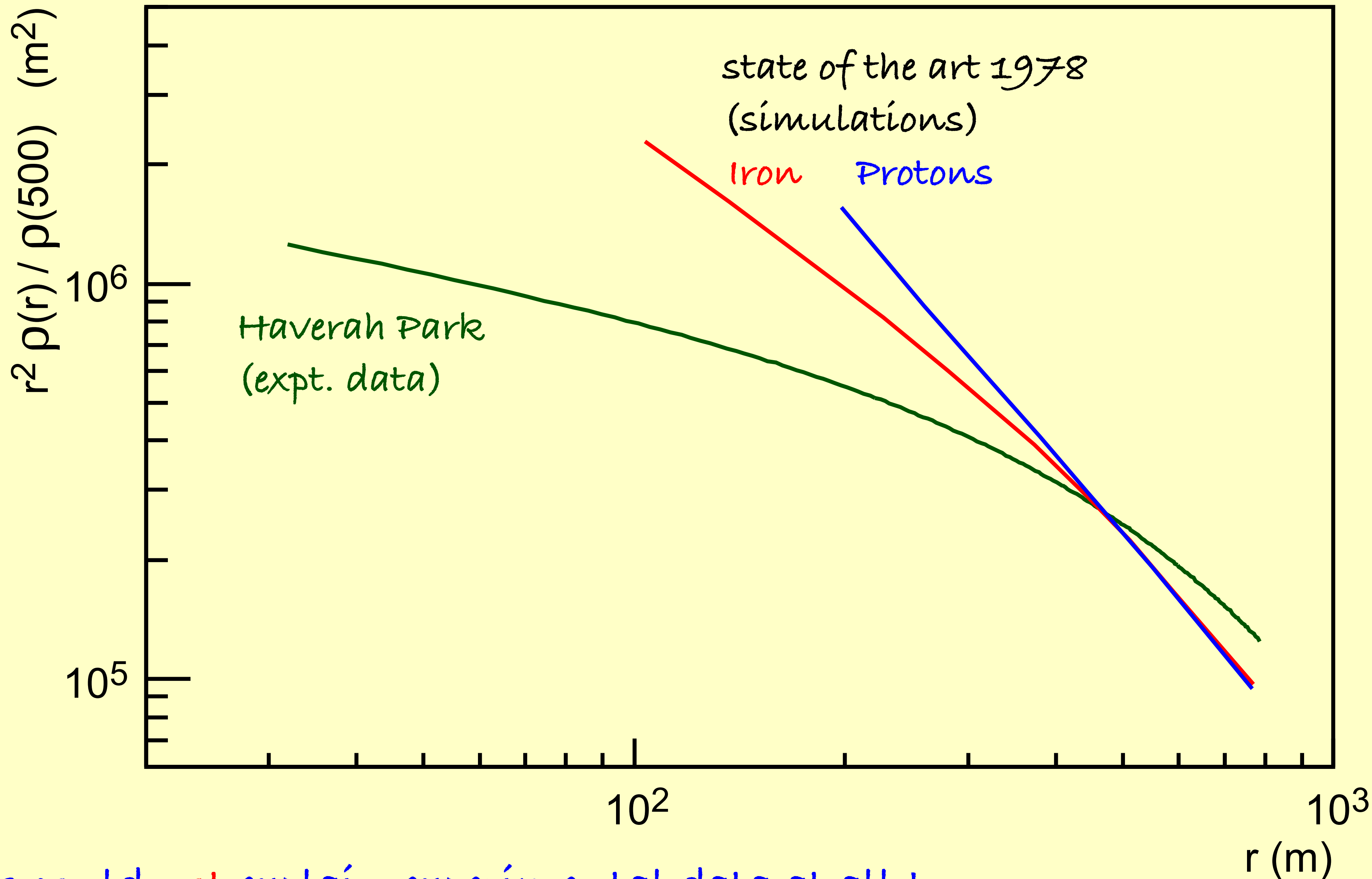

0.2 EeV < E < 0.6 EeV
292 events




**Models can describe data**

0.6 EeV < E < 1 EeV
46 events

# State-of-the-art model 1978



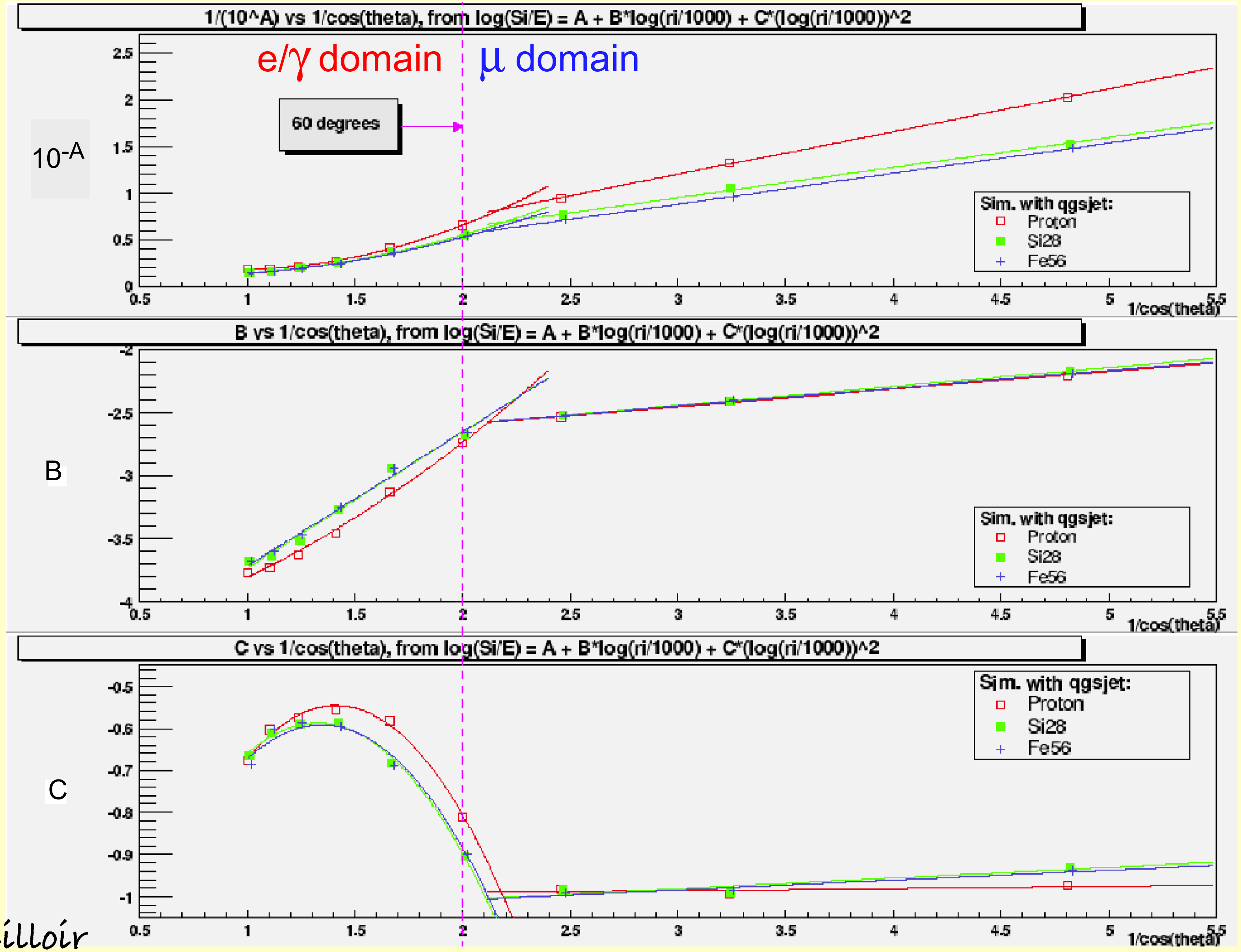

Models could not explain experimental data at all !

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.

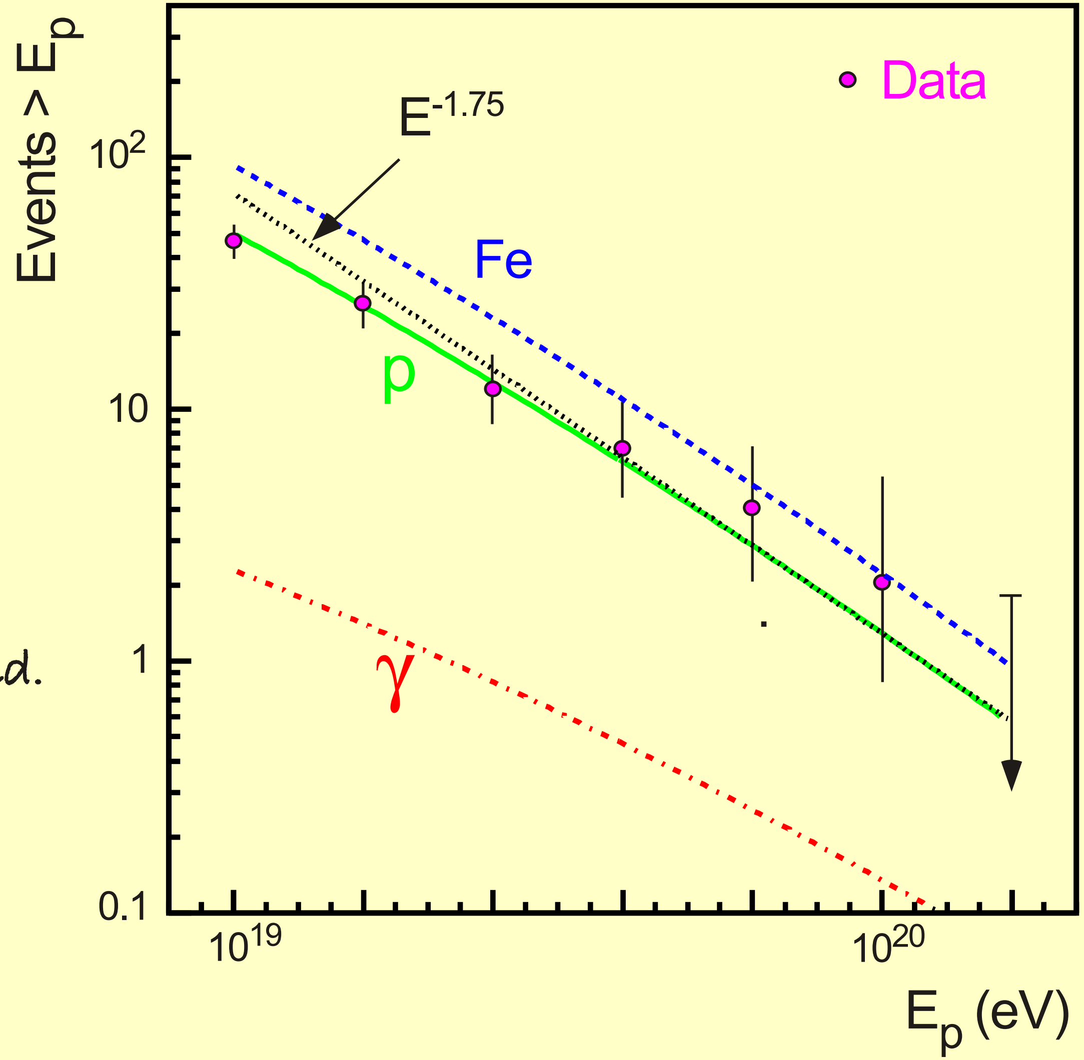
# Primary γ's, e.g. from decays of topological defects ??

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%**

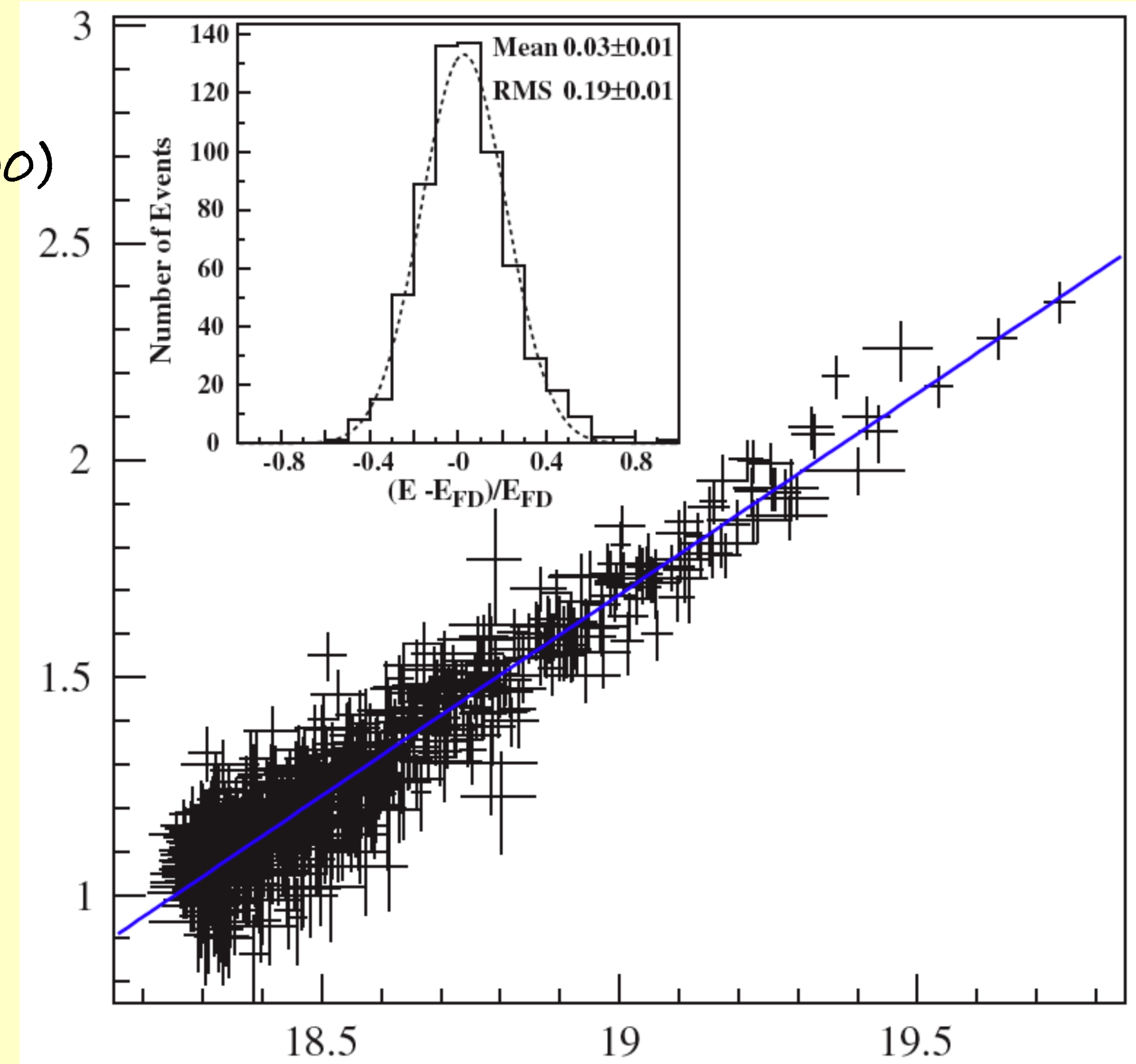
**Fe/p < 54%**

(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

# Muons in MACRO detector

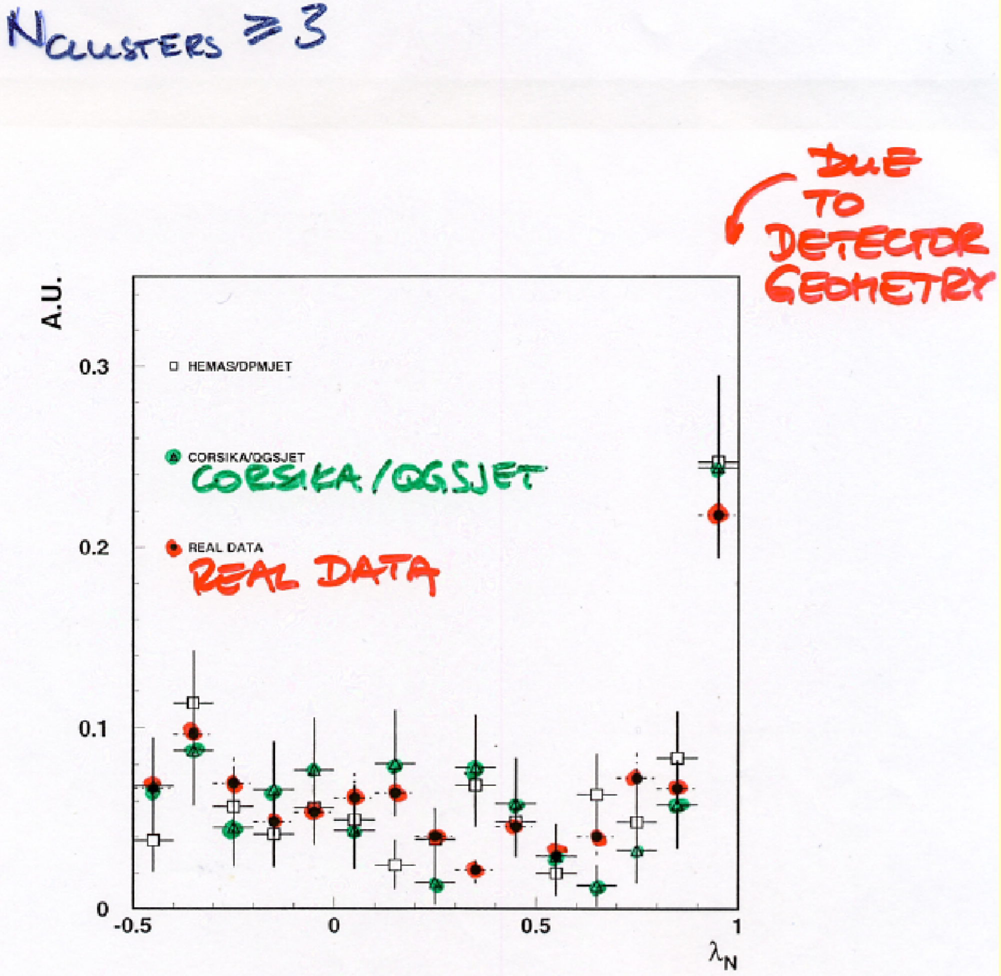



Figure 5.25: *Search for aligned clusters in the MACRO detector. We plot the normalized distributions of events as a function of the parameter $\lambda_N$ (see text), both for experimental (full circles) and simulated data (open markers).*

NOT ALIGNED

COMPLETELY ALIGNED

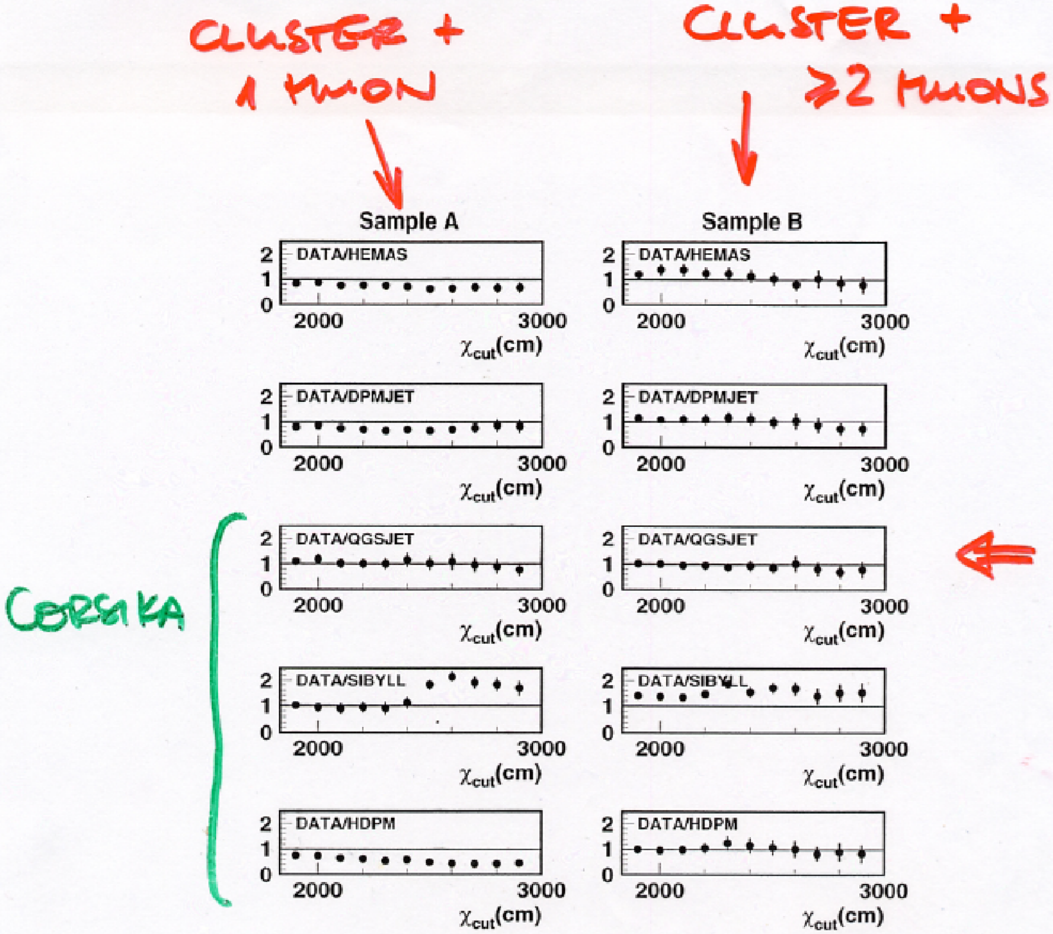



Figure 5.20: *2-cluster events ratio of experimental data over simulated data. The plots on the right refer to events reconstructed with a central cluster plus an isolated muon; on the right side: events reconstructed with a central cluster plus a cluster with at least two muons.*

CLUSTER + 1 MUON:

SENSITIVE TO EARLY INTERACTIONS

PhD thesis Marco Sioli, Bologna 1999

# Muon bundles in MACRO detector

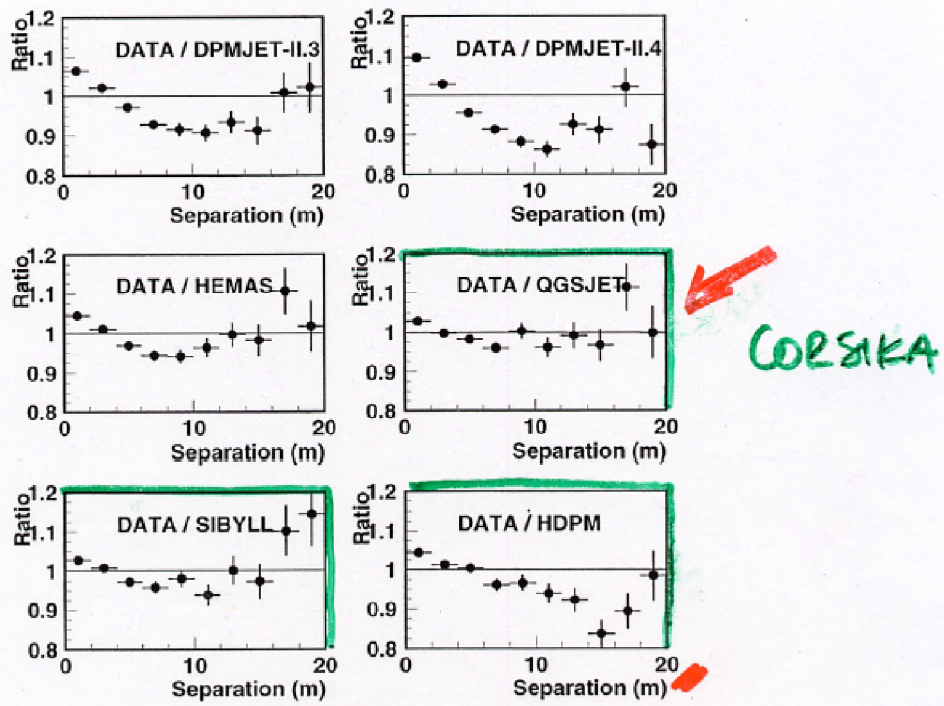



Figure 5.9: *Ratio between the experimental and simulated decoherence functions for the sample of* $N_{wire} \geq 8$. *The ratio was computed between distributions normalized to the same number of events.*

DISTRIBUTION OF DISTANCES BETWEEN TWO MUONS

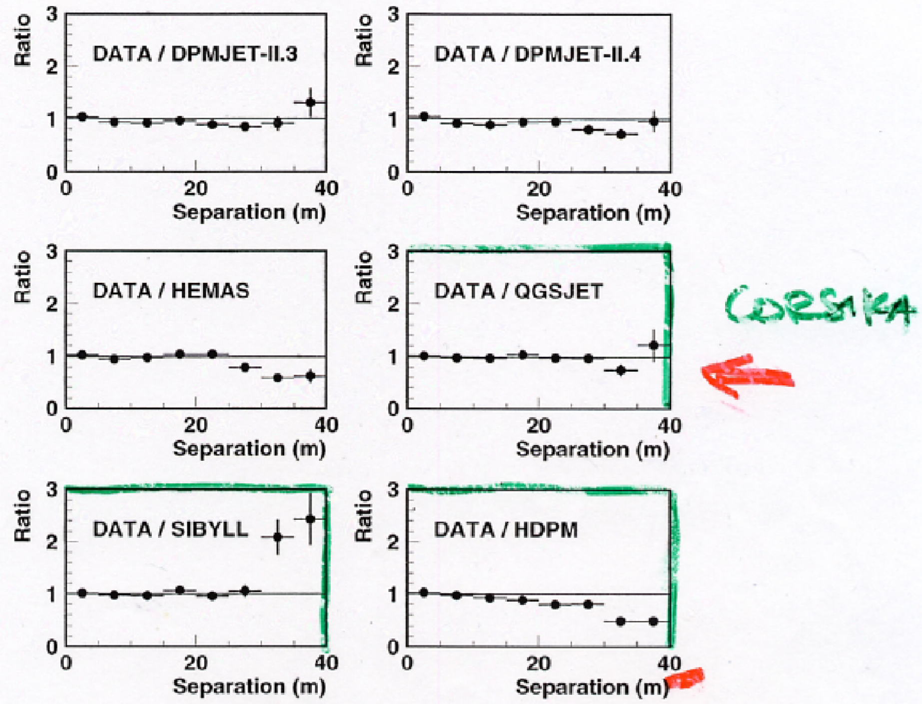



Figure 5.10: *Ratio between the experimental and simulated decoherence functions for the sample* $N_{wire} \geq 8$. *The ratio has been computed between distributions normalized to the same number of events.*

LARGER DISTANCES

**CORSIKA / QGSJet describes experimental data rather well.**

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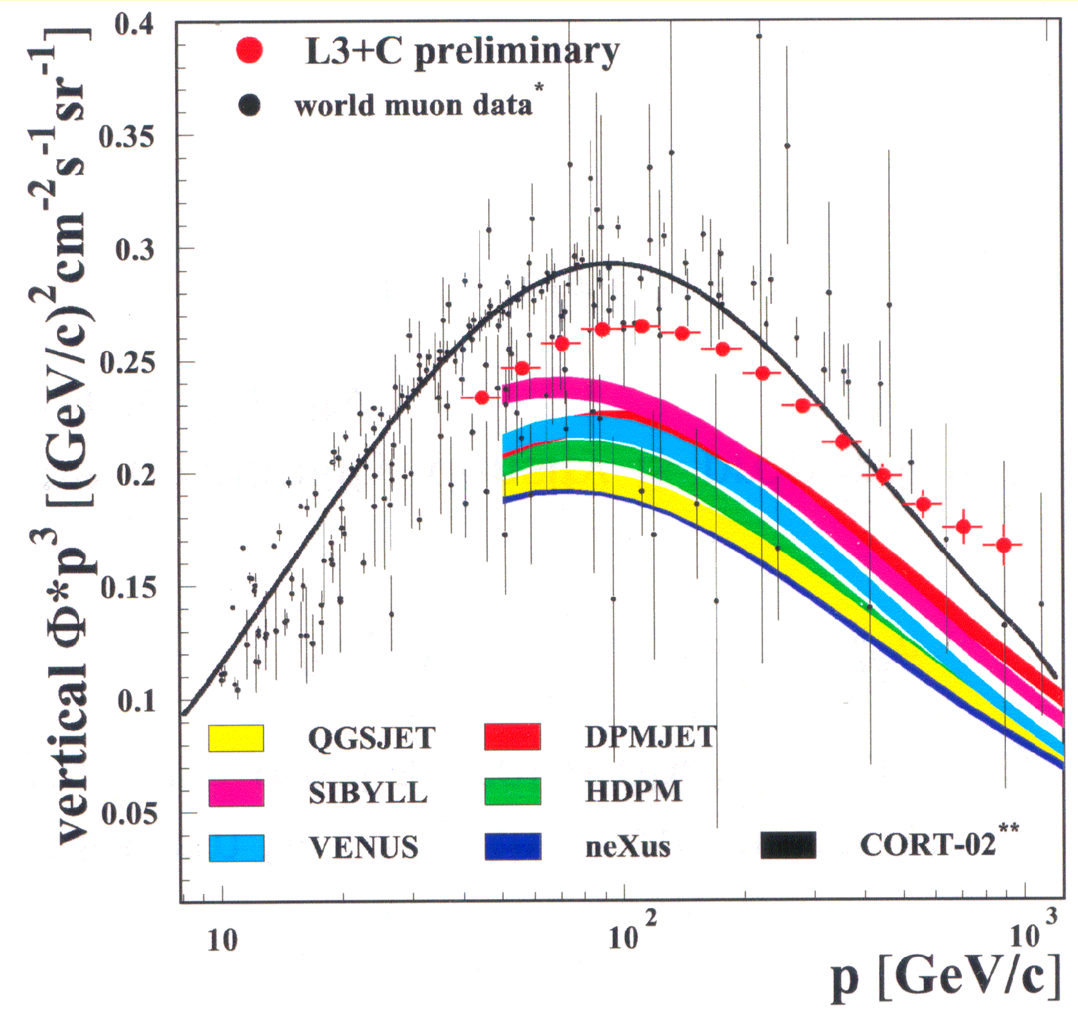
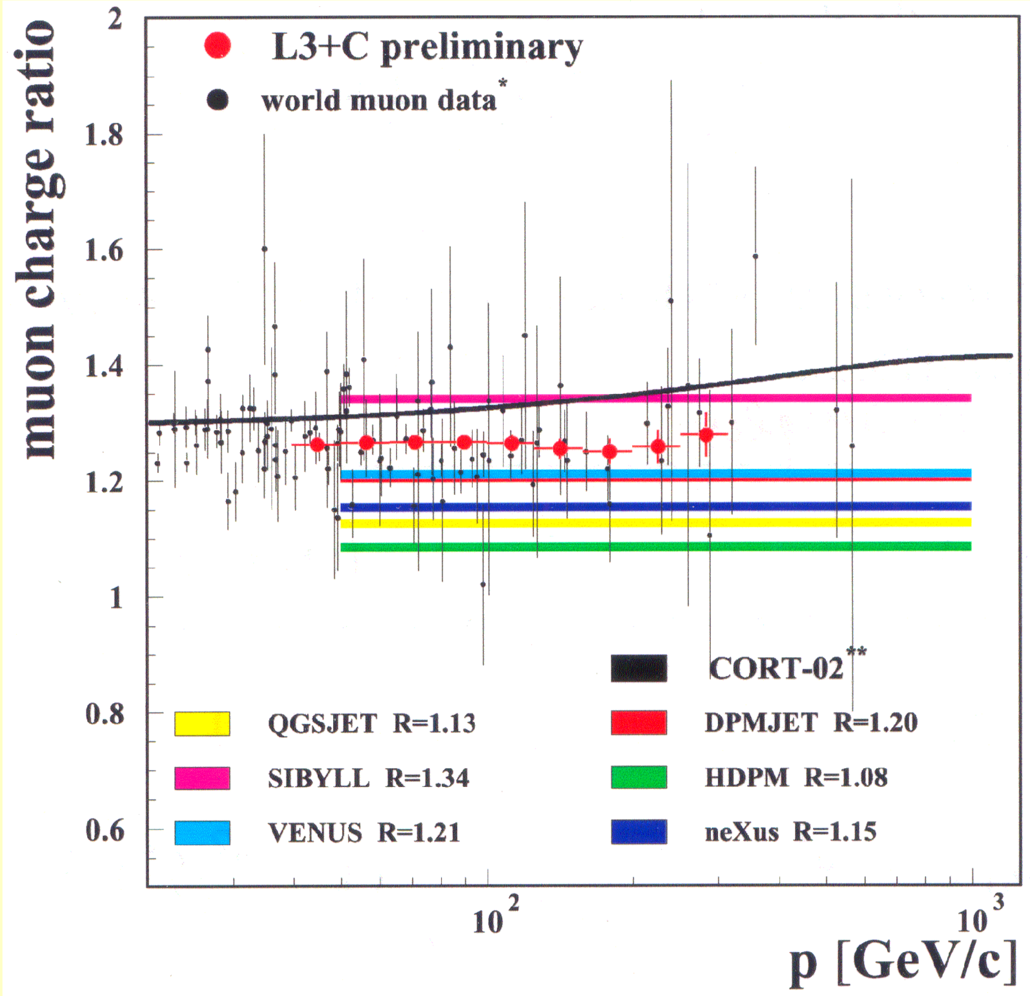
# L3+C Vertical Muon Spectrum & Charge Ratio ($\cos\theta > 0.98$)




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

# 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.