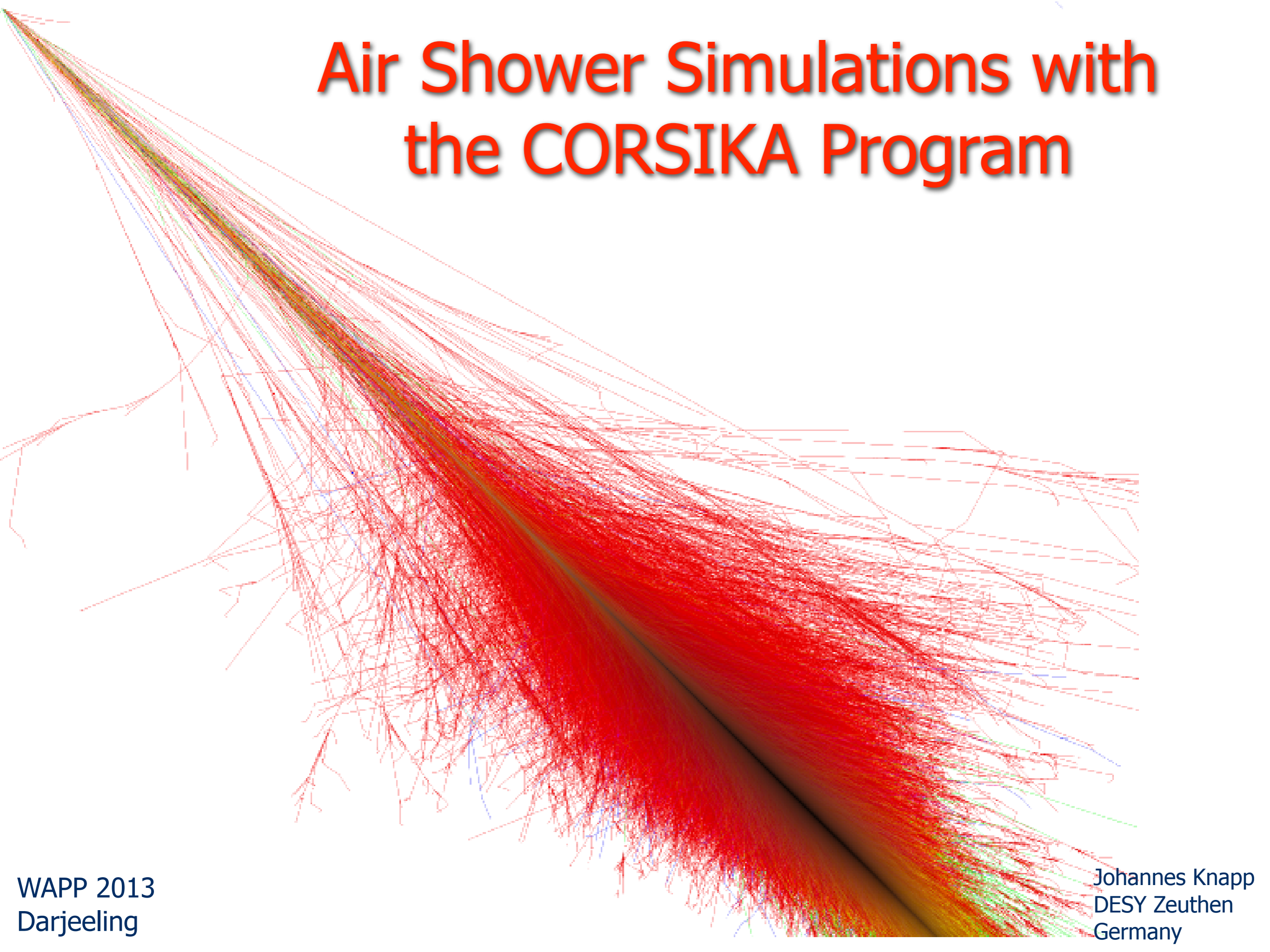
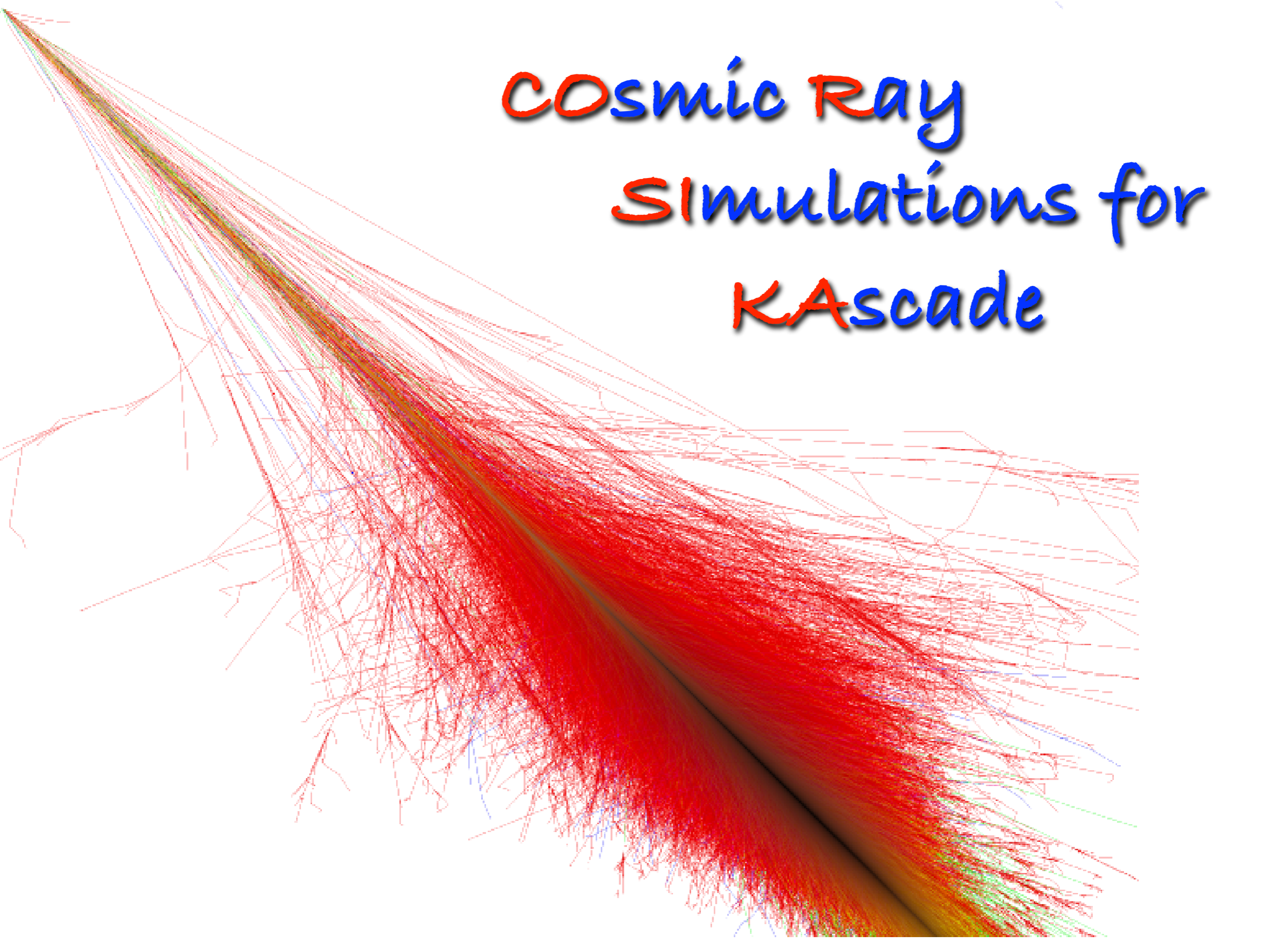


Air Shower Simulations with the CORSIKA Program

Air Shower Simulations with the CORSIKA Program



COSMIC RAY SIMULATIONS for KASCADE



COSMIC RAYS

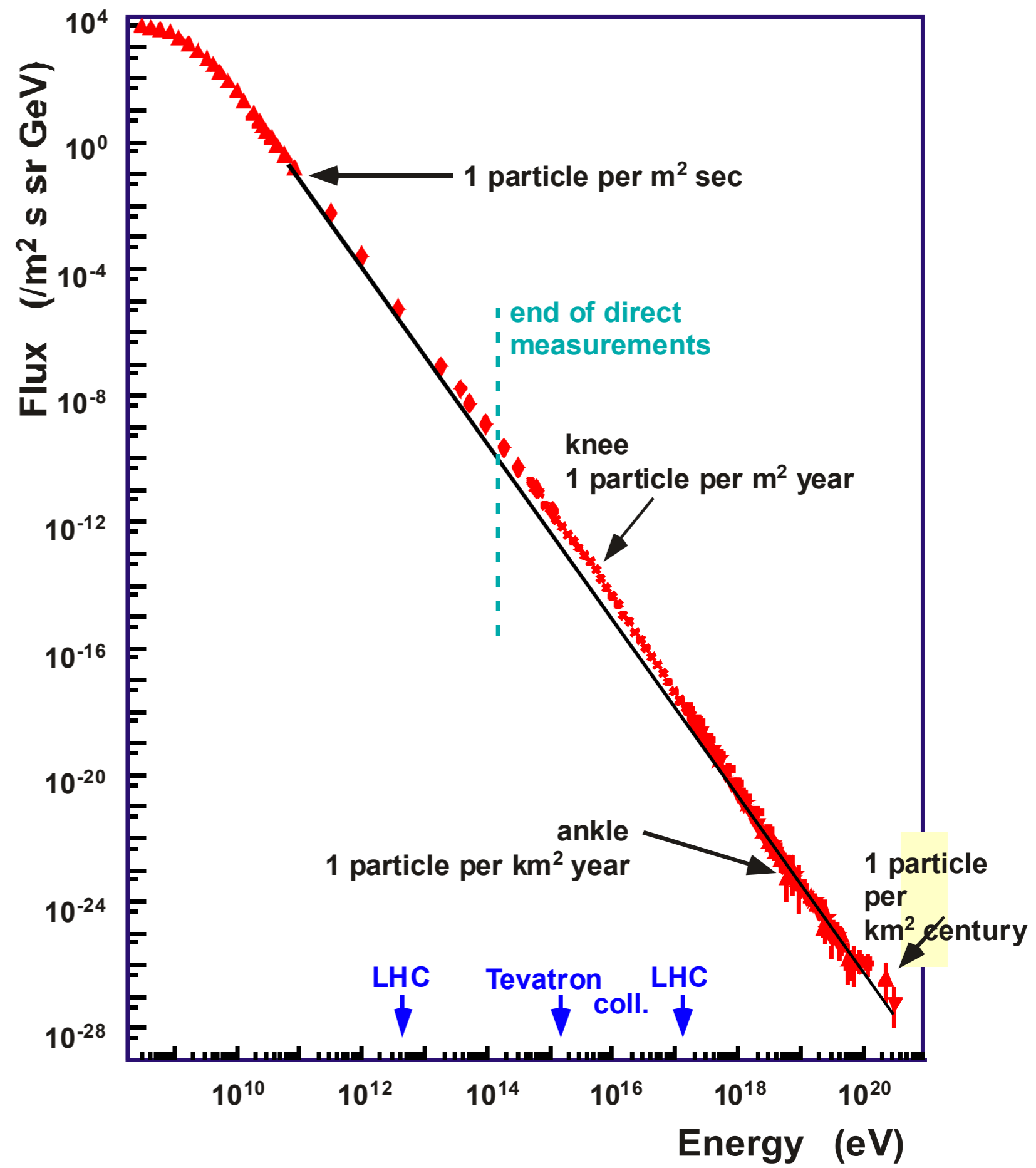
and

Air SHOWERS

COSMIC RAY FLUX:

steeply falling:

x 10 up in energy
1/500 down in flux



$$N_{\text{evts}} = \text{flux} \times \text{area} \times \text{time}$$

> 100
for <10% stat. error

~3 yrs
for a PhD

High-energy astro particles are very rare.

Therefore,

HUGE detection volumes (i.e. absorbers)
need to be instrumented

Natural detectors:

atmosphere,
water,
ice



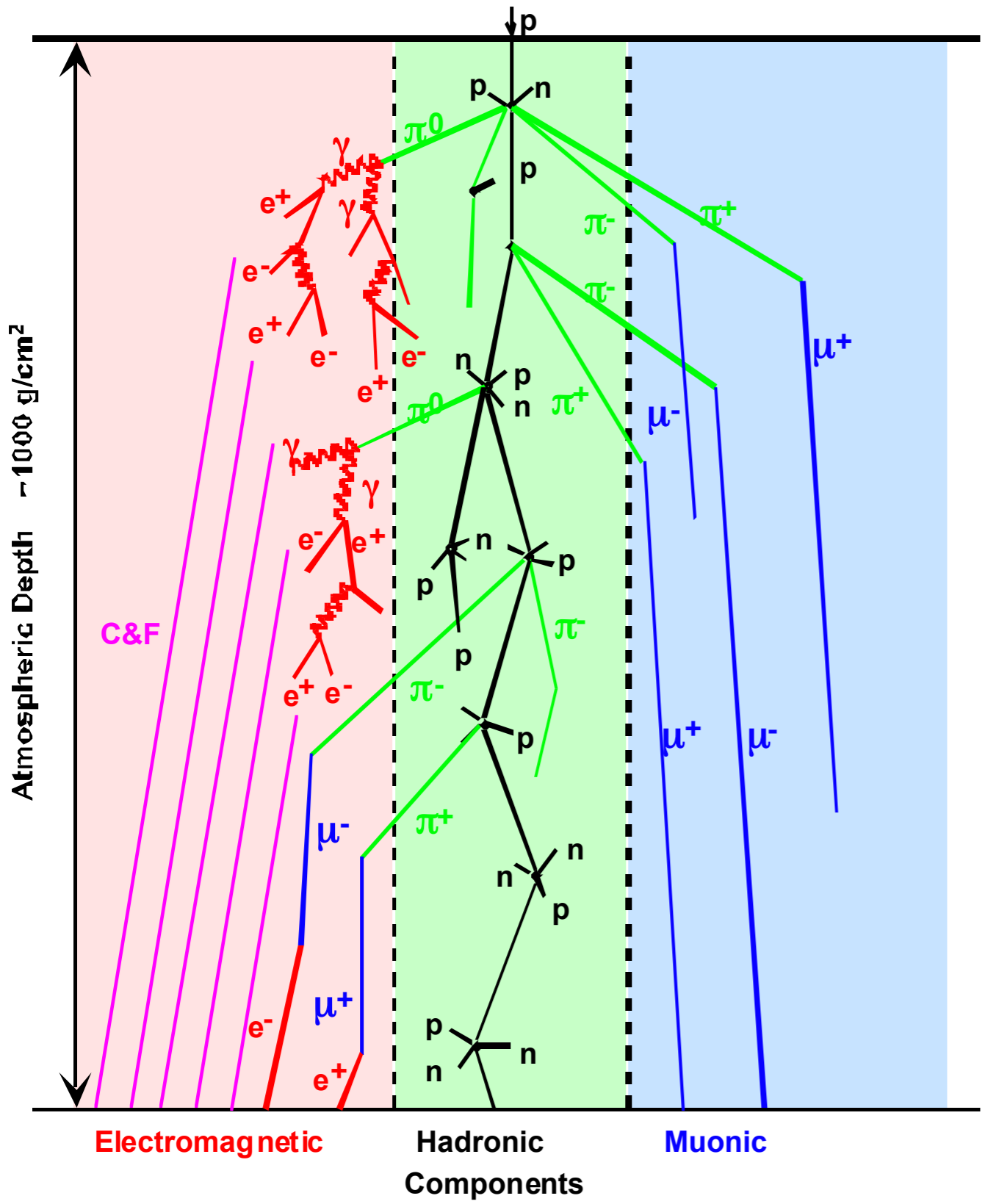
first target for
particles from space
i.e. "Air Showers"

down side:

no longer the primary CRs are measured,
but their secondary reaction products (EAS),
from which properties of primary have to be deduced.

Schematic Shower Development

energy, particle type, direction ???



p, n, π : near shower axis

μ, e, γ : more widely spread

e, γ : from π^0, μ decays ≈ 10 MeV

μ : from π^\pm, K , decays ≈ 1 GeV

$N_{e,\gamma} : N_\mu \approx 10 - 100$ varying with core distance, energy, mass, Θ, \dots

Details depend on:

hadronic and el.mag. particle production, cross-sections, decays, transport,

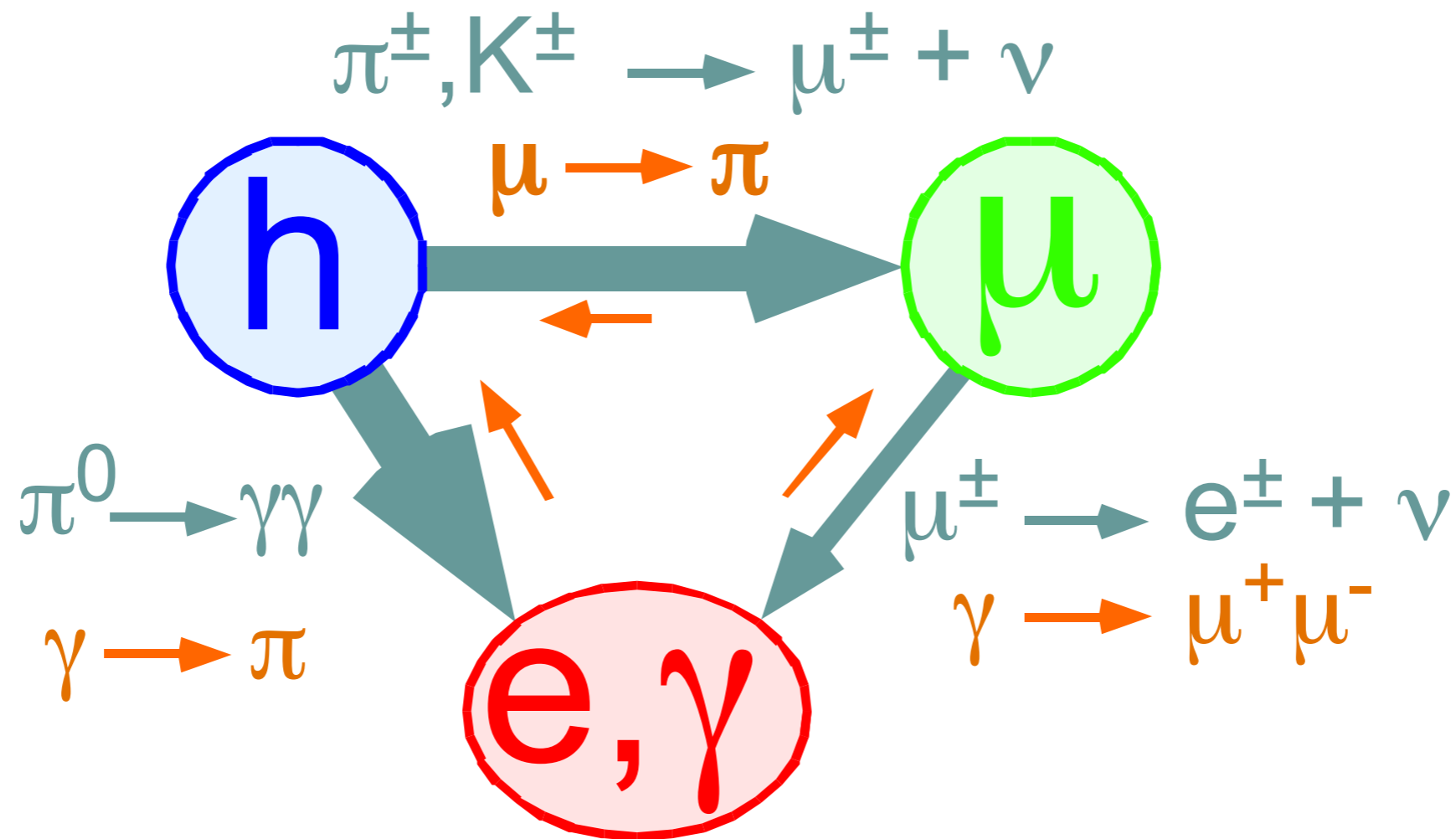
at energies from $\approx 10^6 \dots >10^{20}$ eV (far above man-made accelerators)

atmosphere, Earth magnetic field,

....

Complex interplay with many correlations

Energy Flow in EAS



Hadrons provide energy for **muonic** and **electromagnetic** components.
One way street for energy transfer into electromagnetic particles.
Details of energy transfer reactions do matter.

"Simulations"

and

"Models"

Oxford English Dictionary:

Simulation:

“**imitating the behaviour** of some situation or process by means of a suitably analogous situation or apparatus”

Model:

“A **simplified or idealised** description or conception of a particular system, situation, or process, that is put forward as a basis for theoretical or empirical understanding, or for calculations, predictions, etc.;

a **conceptual** or mental representation of something.”

Simulations

Large and complex problems can usually be dissected in smaller and simpler, but inter-dependent, sub-problems.

Simulation: numerical convolution of many individual, but inter-dependent, parts to a greater and more complex whole.
("do on the computer what nature does")

If the sub-processes are known in **ALL** details,

then the simulation produces the **CORRECT** result, with all **correlations, biases, selection effects** even with new features emerging from the complex interplay of the sub-processes.



Models

simplified, conceptual

If not all details are known (i.e. most common case),
or it is impractical to do a full simulation,

then "Models" of reality are used
(i.e. simplifications, assumptions, approximations, ...)

but "cutting corners" comes at a cost:

The more simplification - the easier to obtain a result, but

- the smaller the "confidence level"
- the more verification is needed

crucial : Is the model good enough (for the specific purpose) ?
When do simplifications start to affect the results ?

In Practice

- the precise and complete simulation of a complex problem may be *impossible* (or at least *very difficult*).
 - usually, "Simulation" and "Model" are mixed in various degrees find a good compromise:
 - The complexity of the problem* should be reflected in *the complexity of the simulations*.
 - interplay between sub-parts (*and emergence*) still qualitatively correct, even if some of the ingredients are not right.
- (... and, unfortunately, both names are often used synonymously.)

In air showers ...

many inter-dependent sub-processes (from 10^6 ... $>10^{20}$ eV)
to form

one large and complex process:

Extensive Air Showers

with:


dependencies of observables on

E, ϑ, r, \dots

correlations between them,

statistical fluctuations,

.....



cross-sections,
electromagnetic and hadronic
particle production,
low and high energy models,
particle decays,
atmosphere, tracking,
deflection in magnetic field,
energy losses, delta electrons,
Cherenkov & fluorescence light,
multiple scattering, absorption,

.....

Mostly very well known,
just the combination of all
makes it difficult.

Monte Carlo simulations of elementary processes
is the appropriate method to use.

Unknown at high energies :

- elemental composition
- energy spectrum
- details of nuclear and hadronic interactions

Construct a **model** based on reliable data and theories at lower energies.

Extrapolate it to UHECR region.

Find consistent description of all points (■) simultaneously.

Requires some iteration ...

Typical EAS analysis :

assume: flux, elemental composition,
hadronic & electromagnetic interaction model,
atmospheric parameters



most plausible :

p, He, ... Fe

extrapolated from
lower energies

simulate shower development,
detector response, measurement procedures, reconstruction

obtain fully inclusive simulated spectra, as they are measured

compare experimental data and simulations



i.e. perform a consistency check

in case of discrepancy :

difficult to identify origin

in case of agreement :

is parameter combin. unique ?

iterative process (many different experiments / variables / variable combinations)
to understand

cosmic ray physics and air shower development simultaneously.

CORSIKA

The beginnings 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 to Corsika:

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

105

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

H.J. GILS, D. HECK, J. OEHLISCHLÄGER, 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.Capdevielle¹, P.Gabriel, H.J.Gils, P.K.F.Grieder², 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

¹Laboratoire de Physique Théorique, Université de Bordeaux,
F-33170 Gradignan, France

²Physikalisches 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 $E_0 \geq 10^{15}$ eV can be determined by measuring electrons, muons and hadrons simultaneously with the KASCADE detector.

KfK 4998
November 1992

The Karlsruhe Extensive Air Shower Simulation Code CORSIKA

J. N. Capdevielle, P. Gabriel, H. J. Gils, P. Grieder,
D. Heck, J. Knapp, H. J. Mayer, J. Oehlschläger,
H. Rebel, G. Schatz, T. Thouw
Institut für Kernphysik

Kernforschungszentrum Karlsruhe



Forschungszentrum Karlsruhe
Technik und Umwelt
Wissenschaftliche Berichte
FZKA 6019

CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers

D. Heck, J. Knapp, J. N. Capdevielle,
G. Schatz, T. Thouw
Institut für Kernphysik

Februar 1998

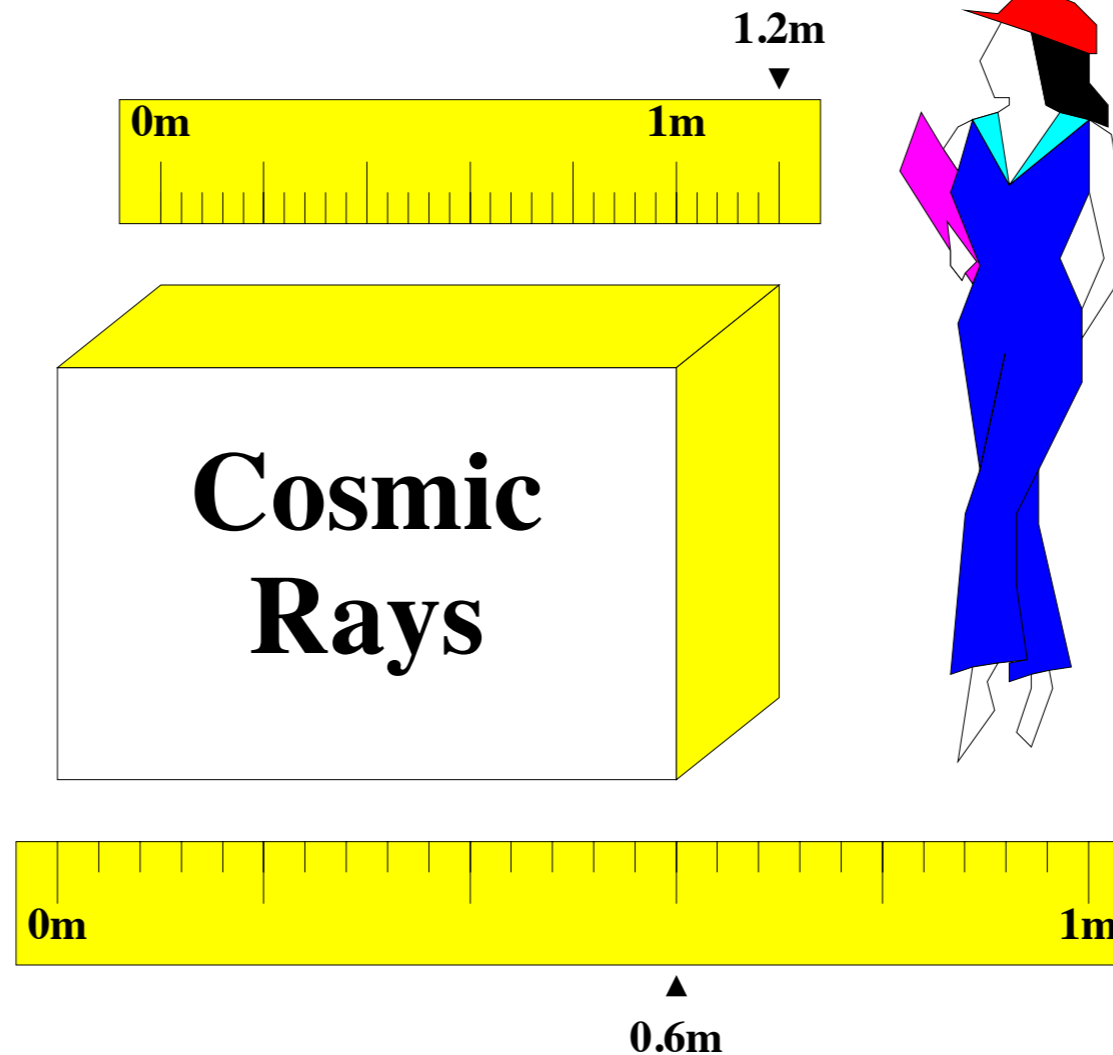
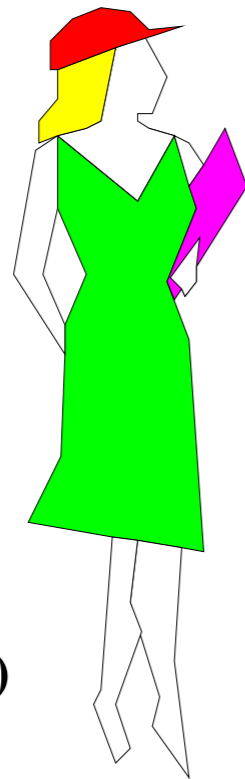
Preface to KfK 4998 (1992)

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.**

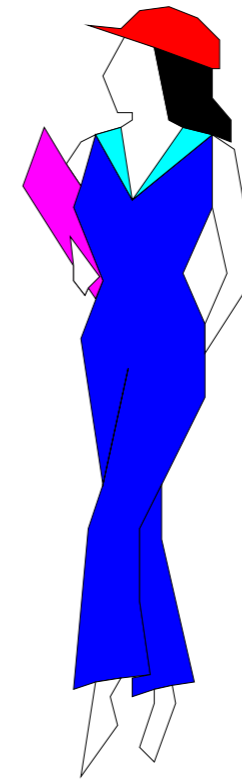
This is the more embarrassing, since our knowledge of high energy interactions - though much better today than ten years ago - is still incomplete in important features. This makes results from different groups difficult to compare, to say the least. In addition, the relevant programs are of a considerable 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

Fly's Eye:
The box is 0.6m wide
(Composition changes)

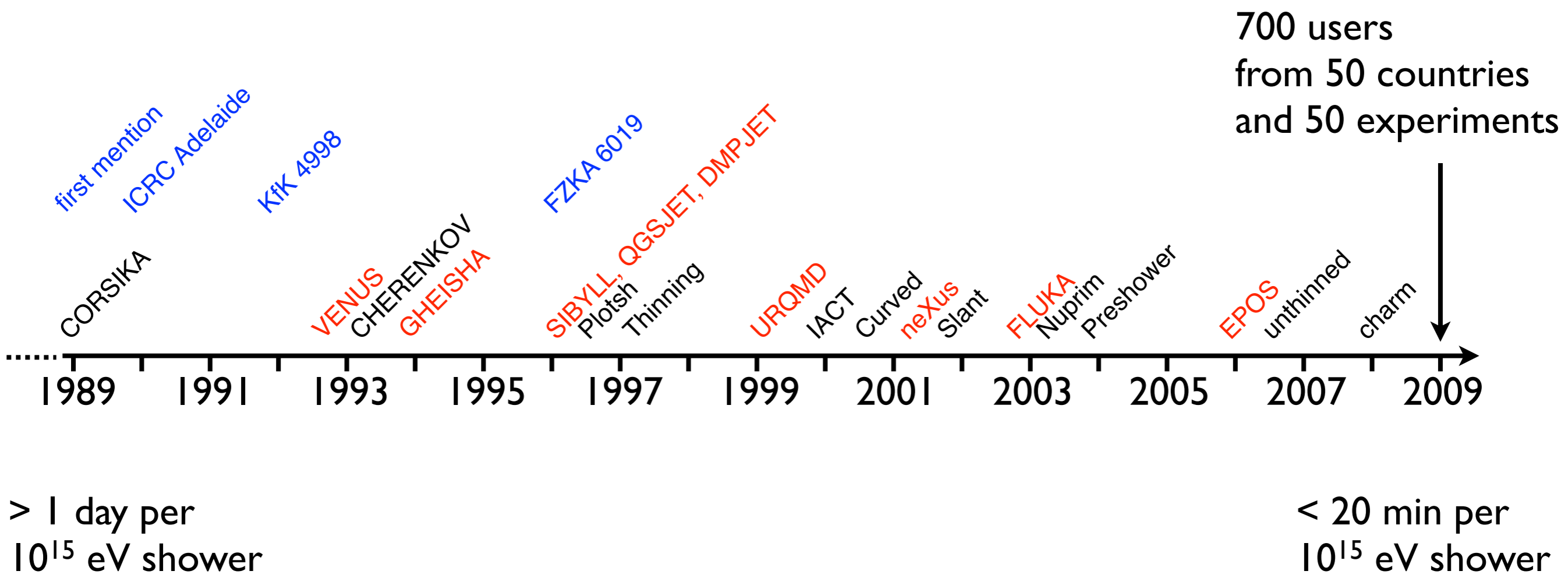


AGASA:
The box is 1.2m wide
(Composition unchanged)

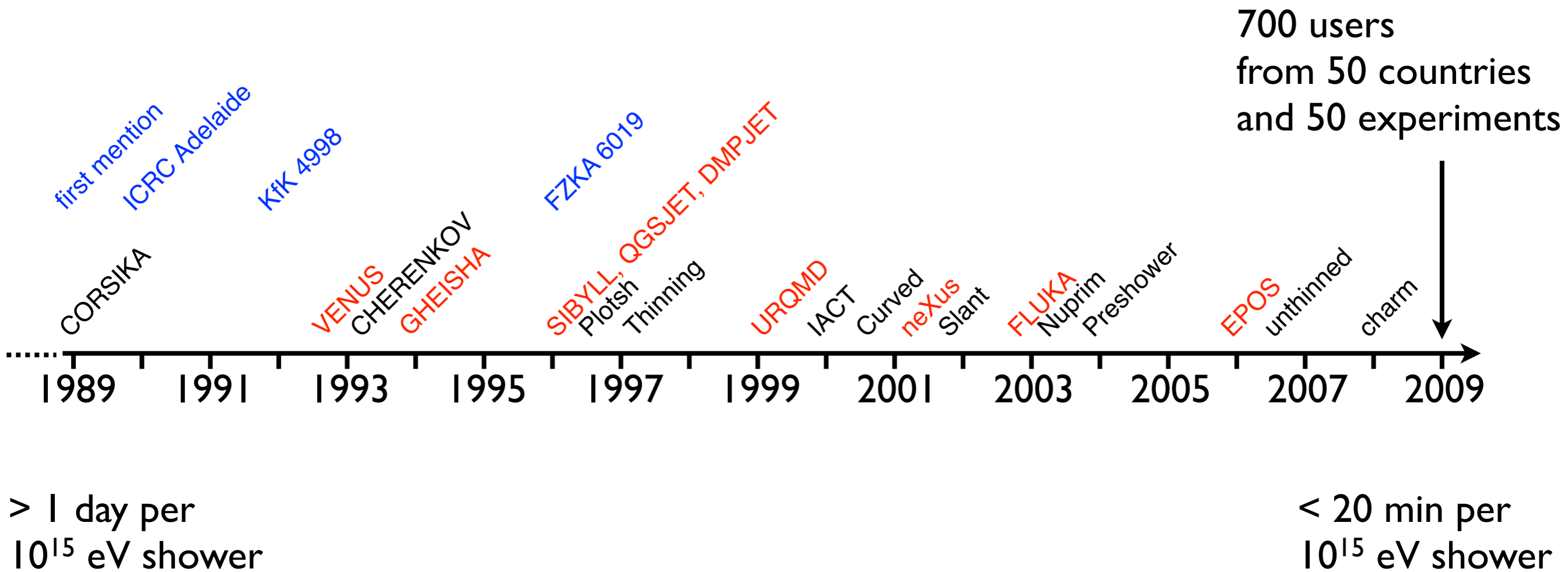


Use the **same yardstick** (i.e. Monte Carlo program)
to get **consistent results** in different experiments.
Use a **well-calibrated, reliable yardstick**
to get **correct results**.

The Timeline



The Timeline



KfK 4998 + FZKA 6019 > 1500 citations !

by far the most cited work of its authors

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

(≈ 750)

CORSIKA:

"as good as possible",
fully 4-dim.

tracking, decays, atmospheres, ...

el.mag.

EGS4 *

low-E.had.*

GHEISHA

FLUKA *

URQMD

high-E.had.**

QGJET **

DPMJET *

EPOS *

SIBYLL (*)

* recommended

* based on Gribov-Regge theory

* source of systematic uncertainty

Tuned at collider energies,
extrapolated to $> 10^{20}$ eV

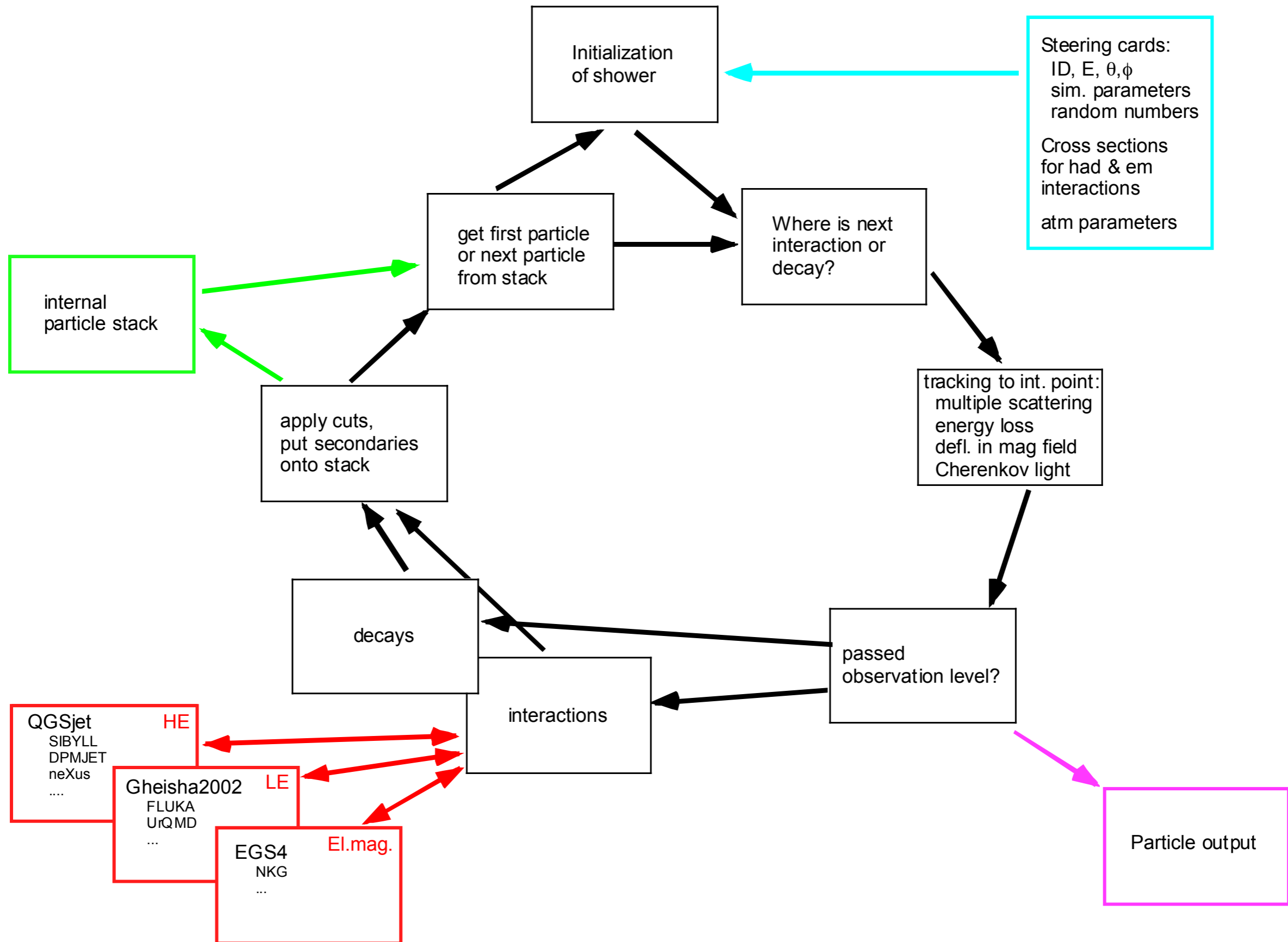
+ many extensions & simplifications

Sizes and runtimes vary
by factors 2 - 40.

Total: $\gg 10^5$ lines of code

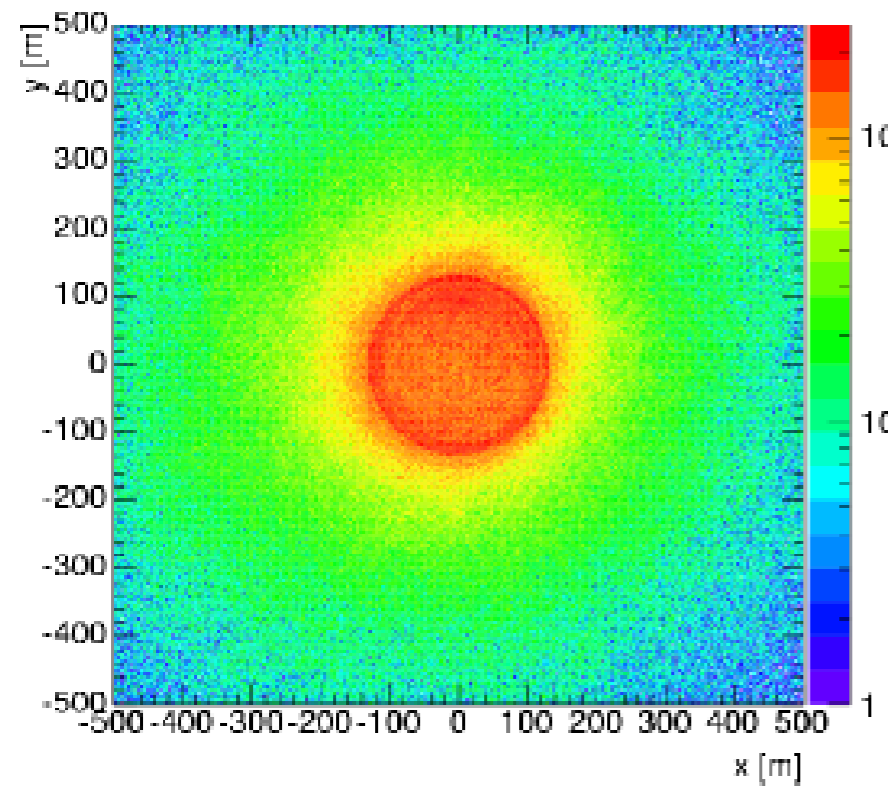
Many years of development.

CORSIKA flow diagram

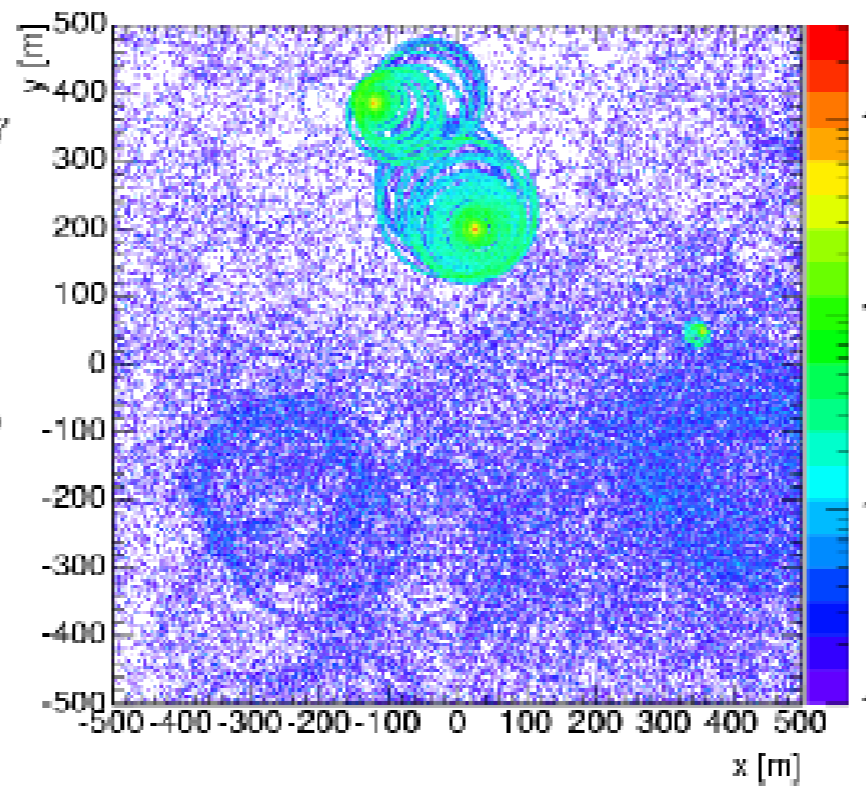


Examples of emerging features in detailed simulations:

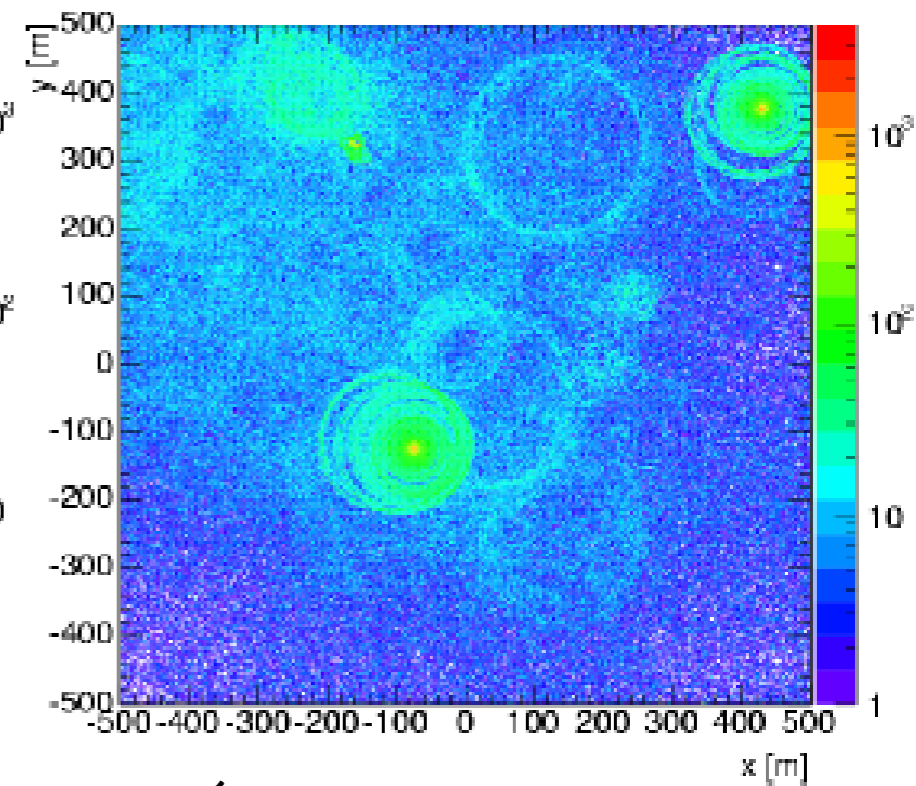
Cherenkov light:



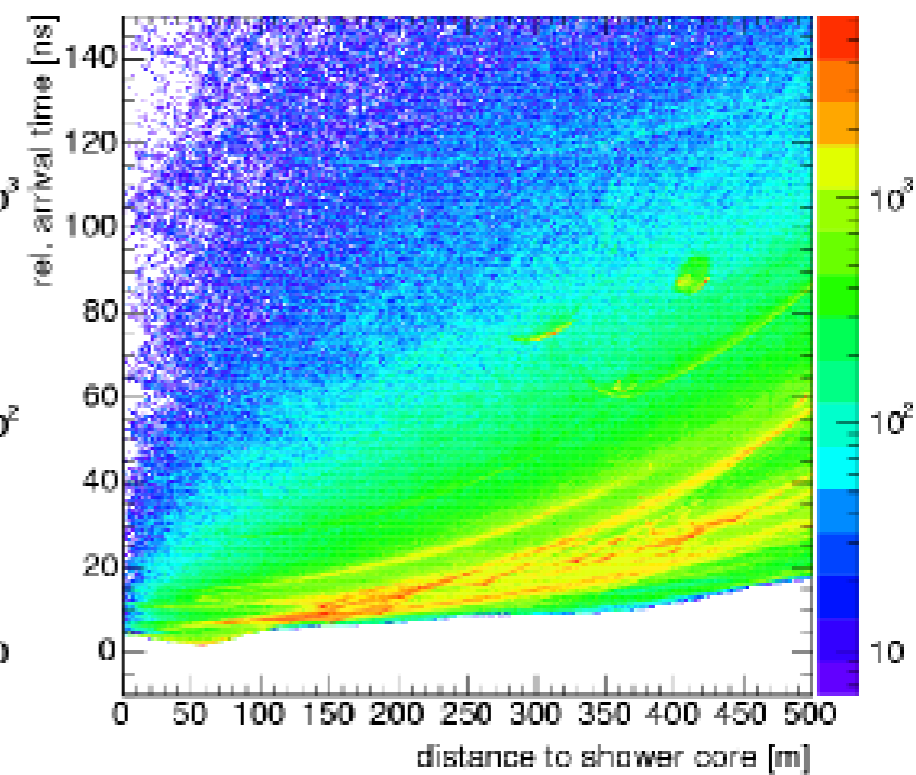
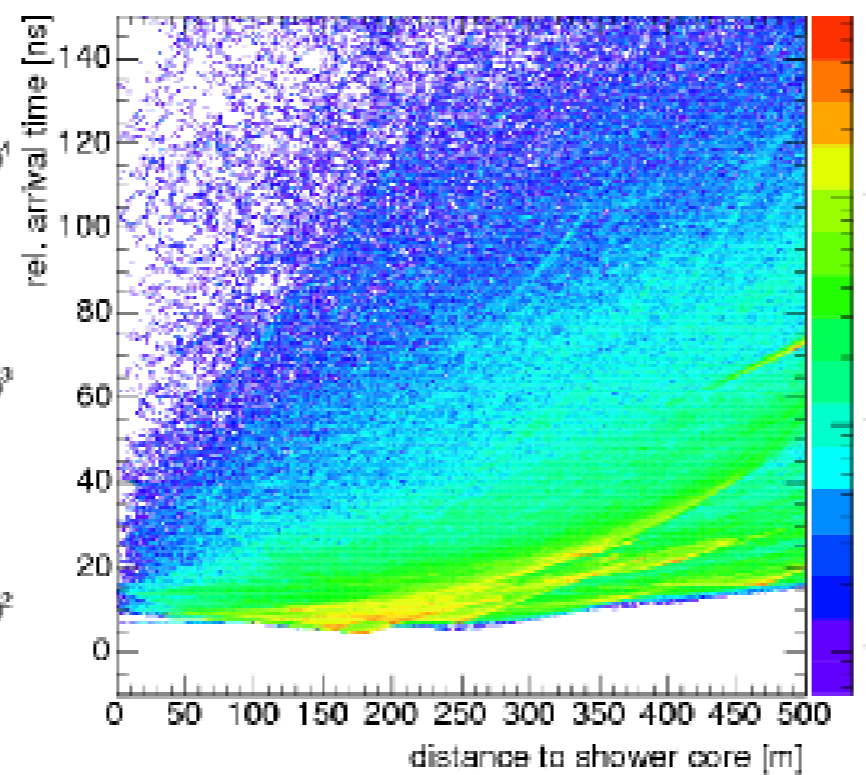
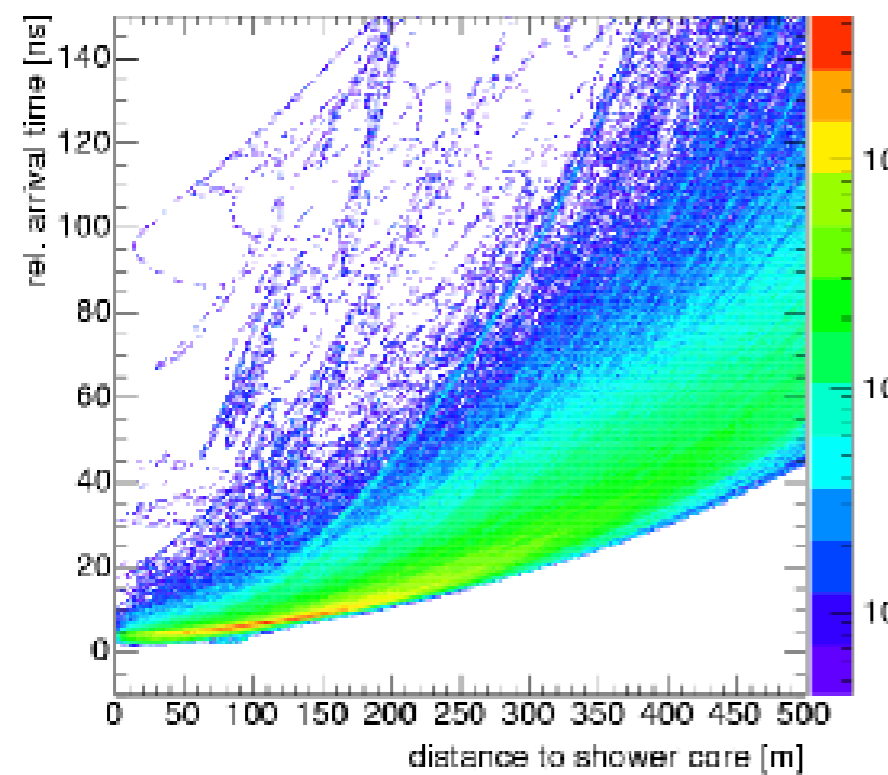
gamma 300 GeV



proton 90 GeV

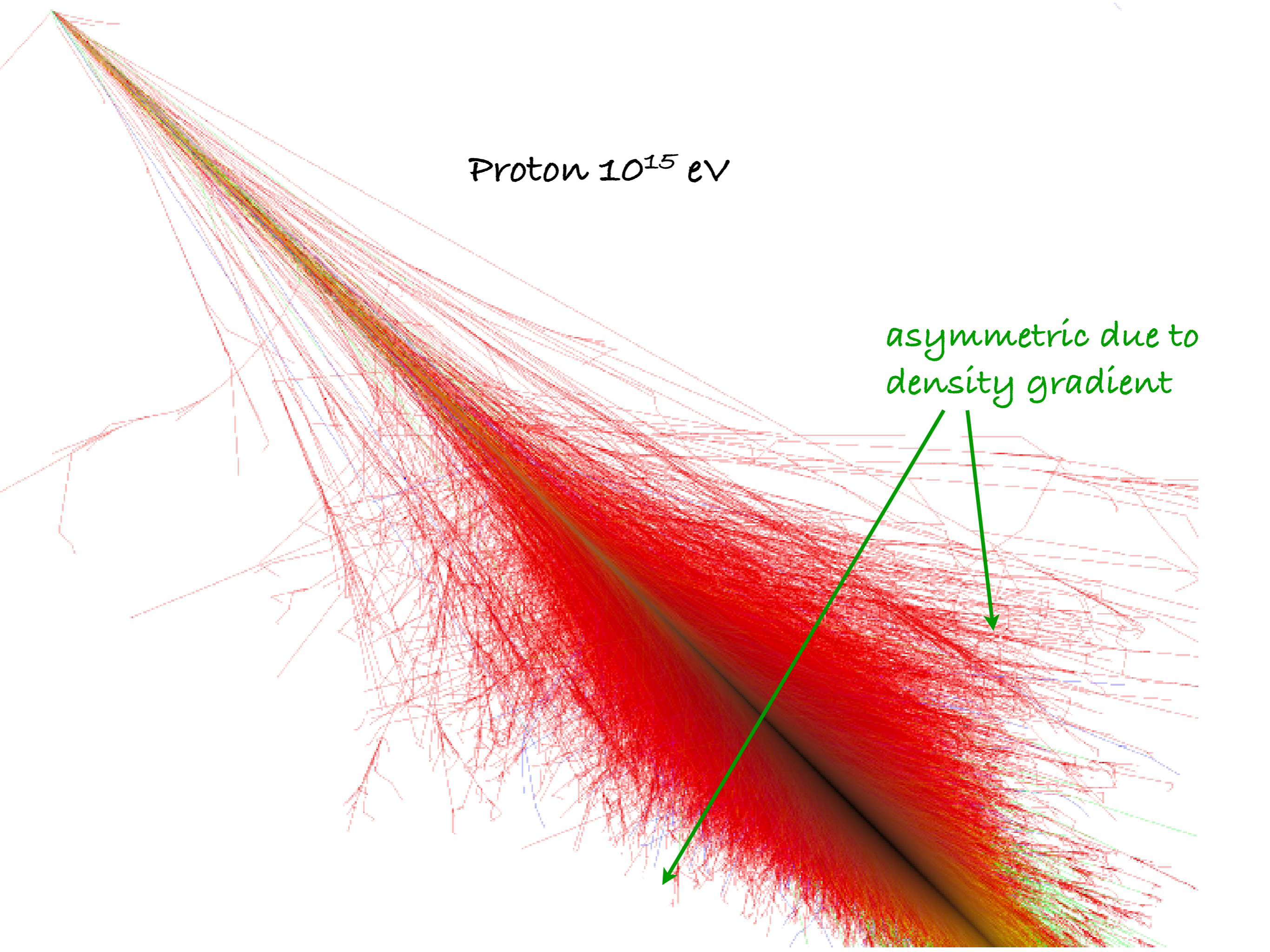


iron 50 GeV



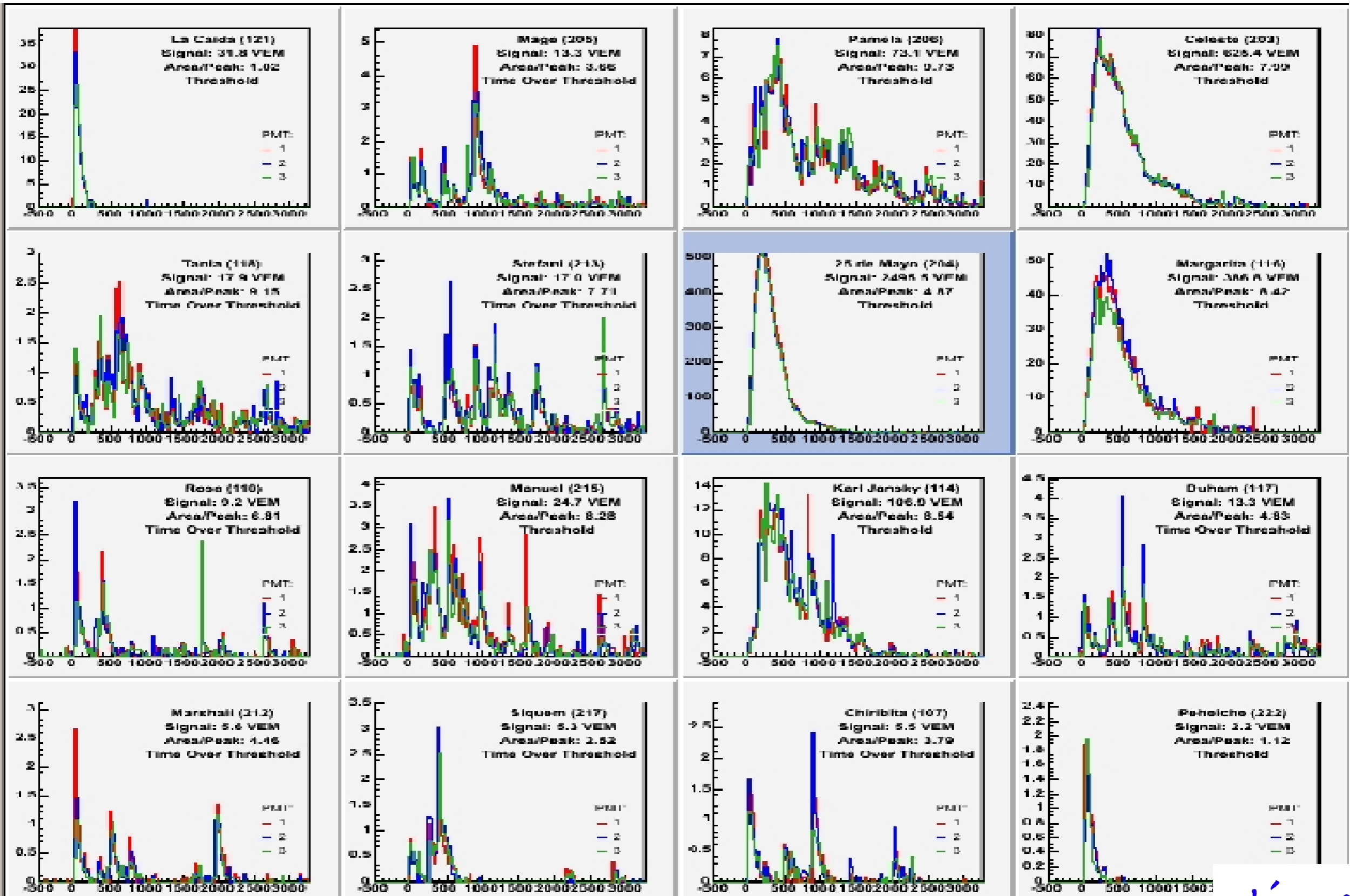
Proton 10^{15} eV

asymmetric due to
density gradient



Pulse Shapes in Water-Cherenkov Detectors

↑ signal



→ time

← 3µs →

High, smooth pulses close to shower core, low, spiky pulses far away.

Horizontal showers

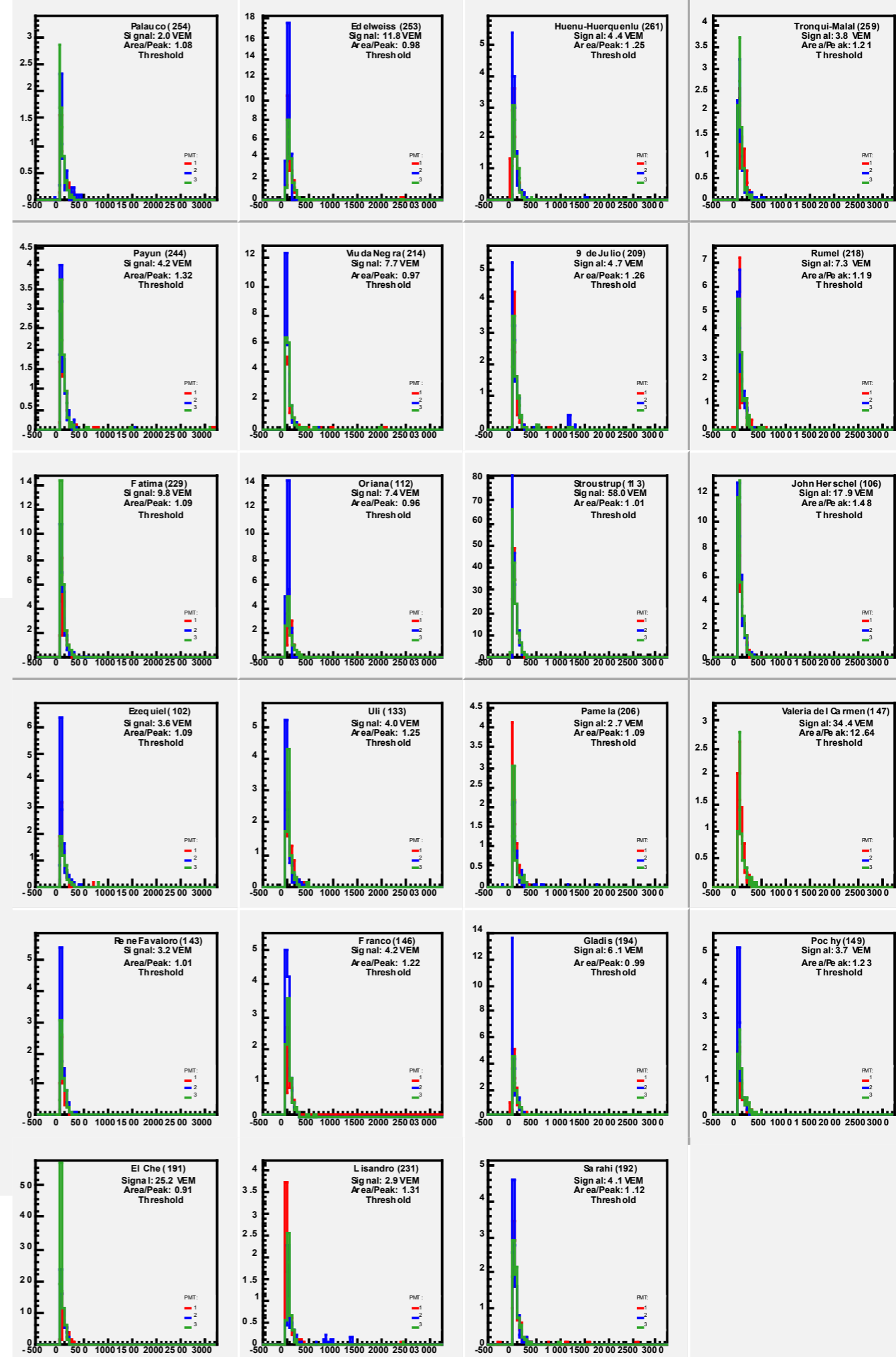
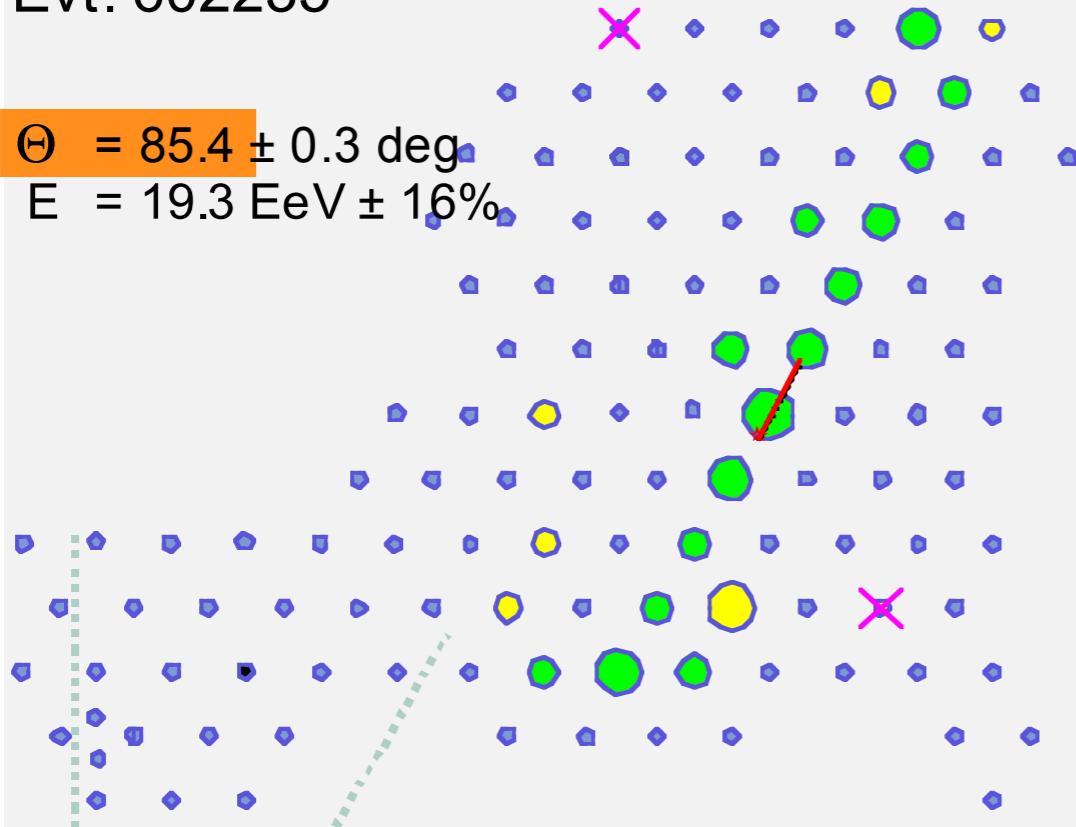
Only muons left in air shower.

Very narrow time traces.

Crucial for neutrino search with Auger.

Evt. 602235

$\Theta = 85.4 \pm 0.3 \text{ deg}$
 $E = 19.3 \text{ EeV} \pm 16\%$



Signal and Timing as function of θ , ϕ , mass, ...

- change in a complex way.
- are correlated
- changes are important for analysis

This behaviour and correlations *emerge automatically, qualitatively and quantitatively,* as consequence of convolution of basic transport & interaction processes particles in an air shower.

Many such effects in EAS physics.

Therefore:

detailed simulation (rather than simplified modelling) are so important.

Simulations vs Data:

... a few examples

Result:

fair agreement

from 10^{12} - 10^{20} eV

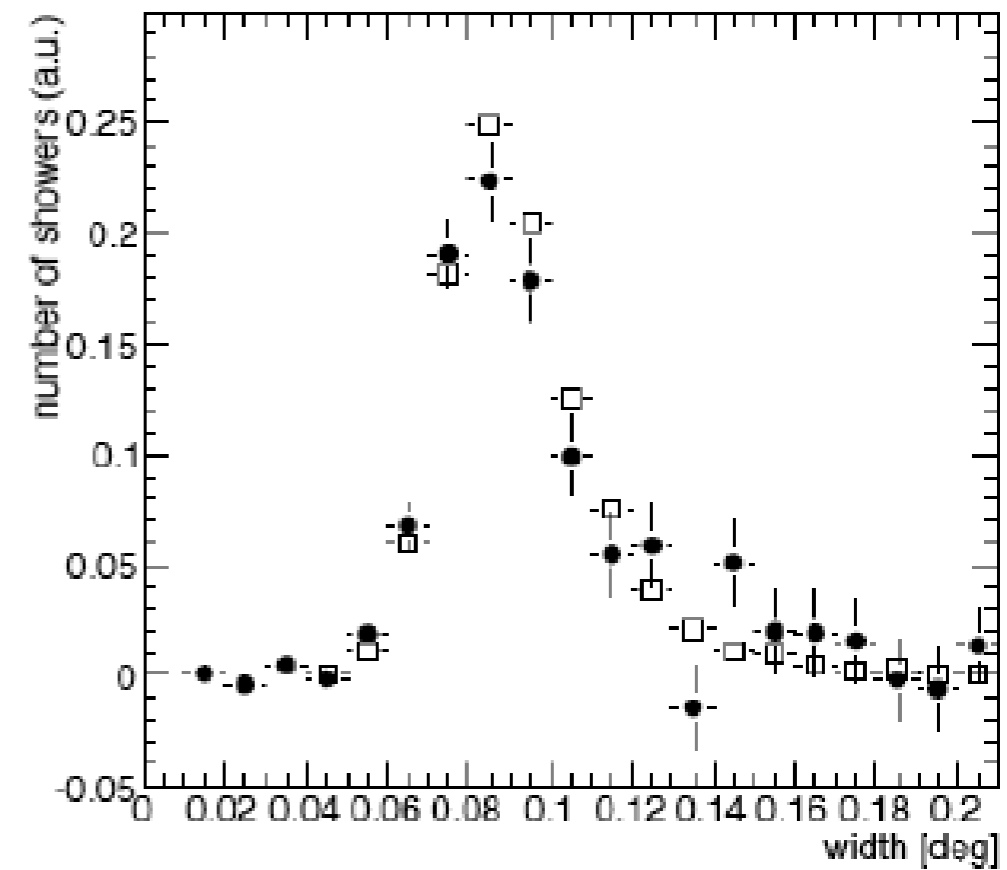
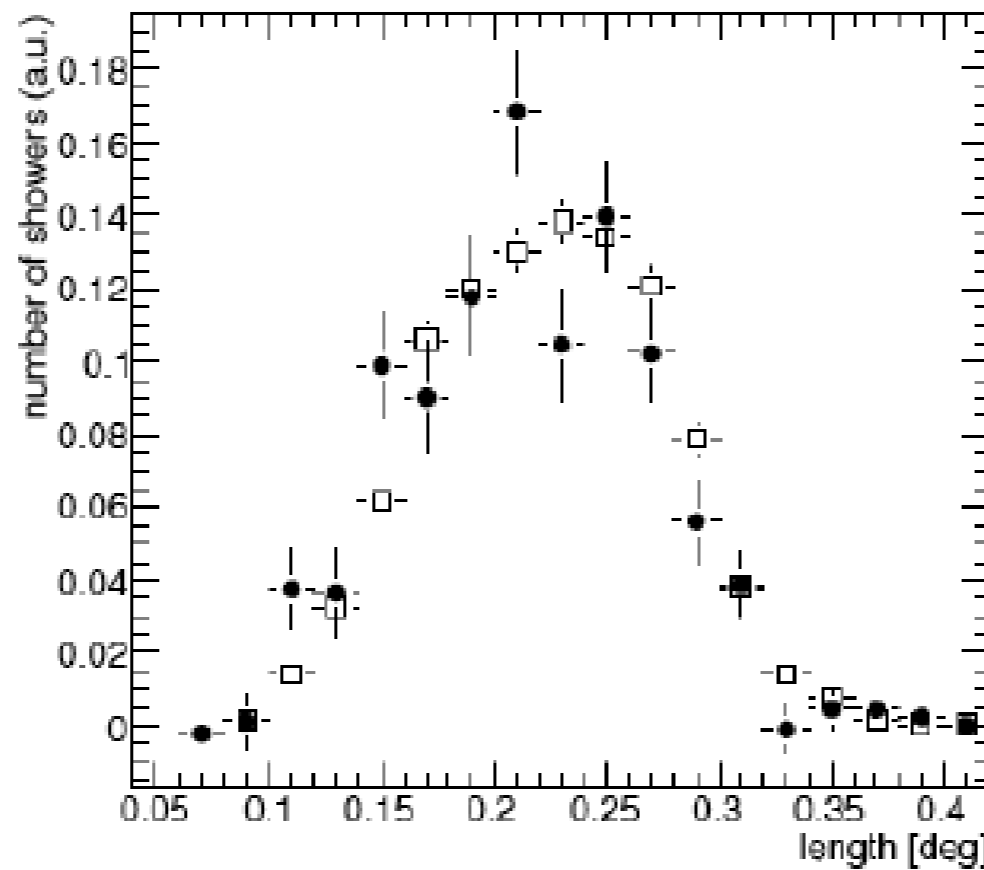
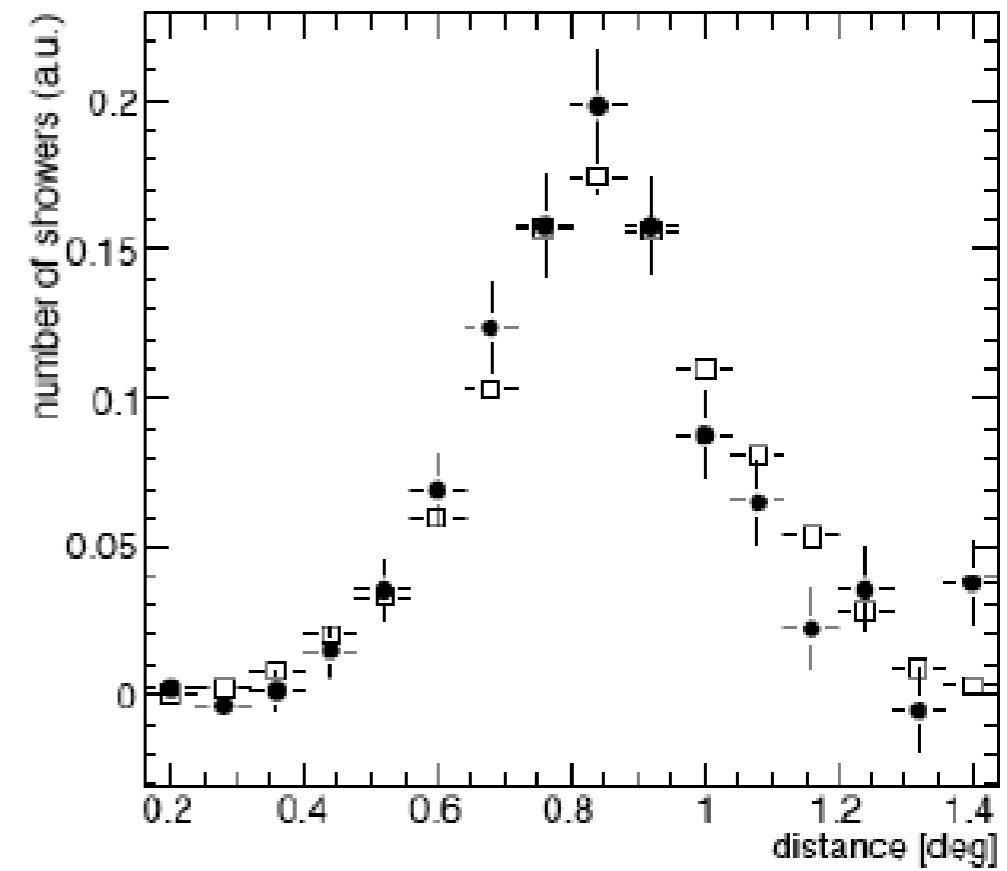
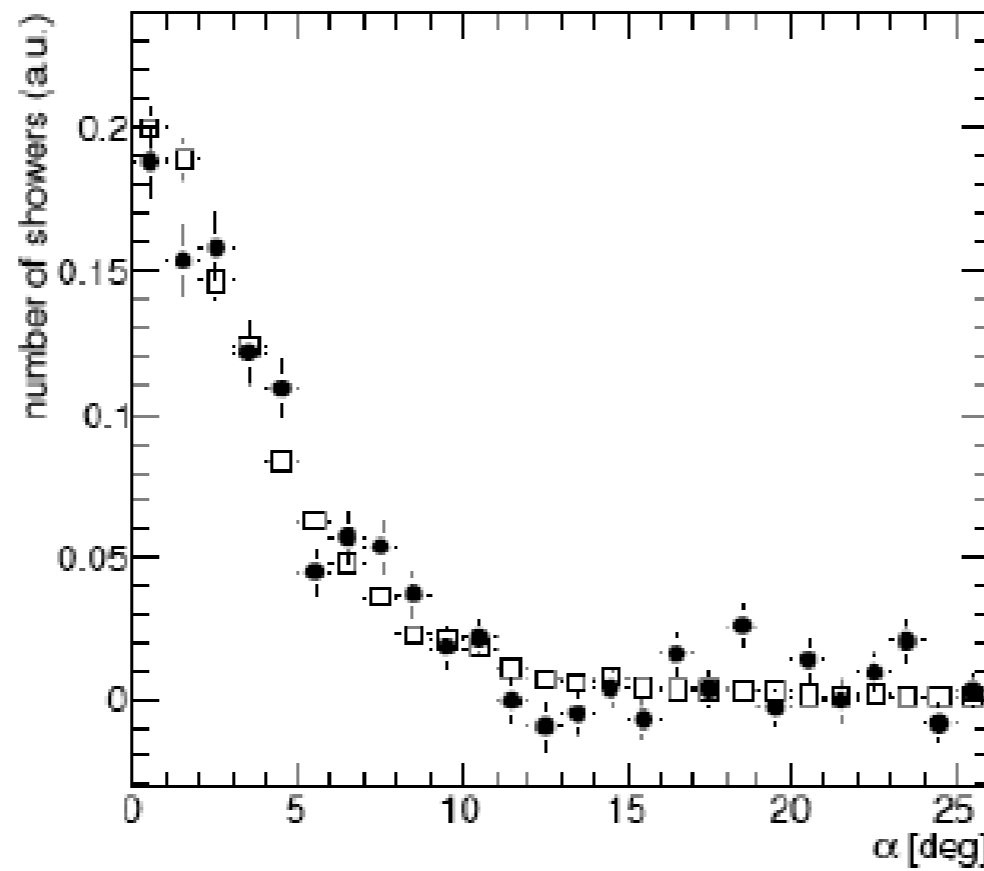
VERITAS

Telescope 1

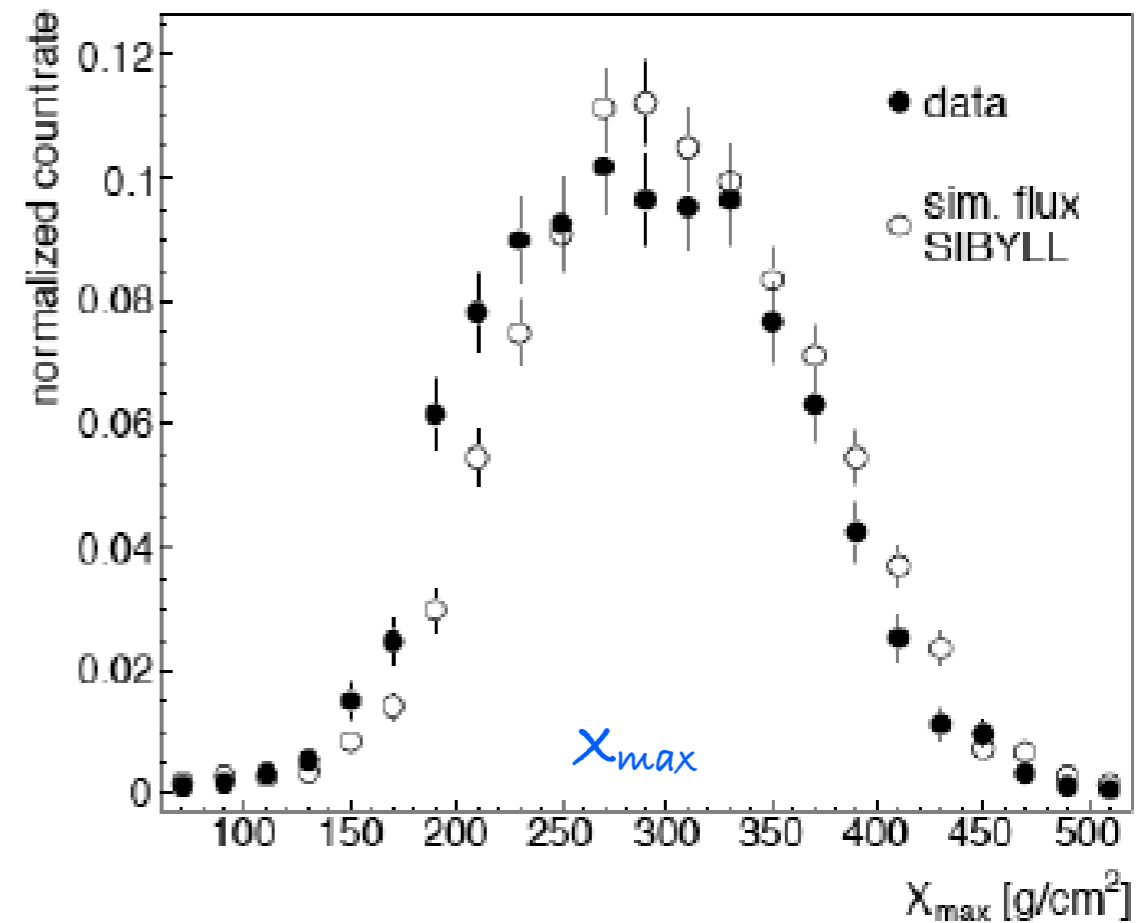
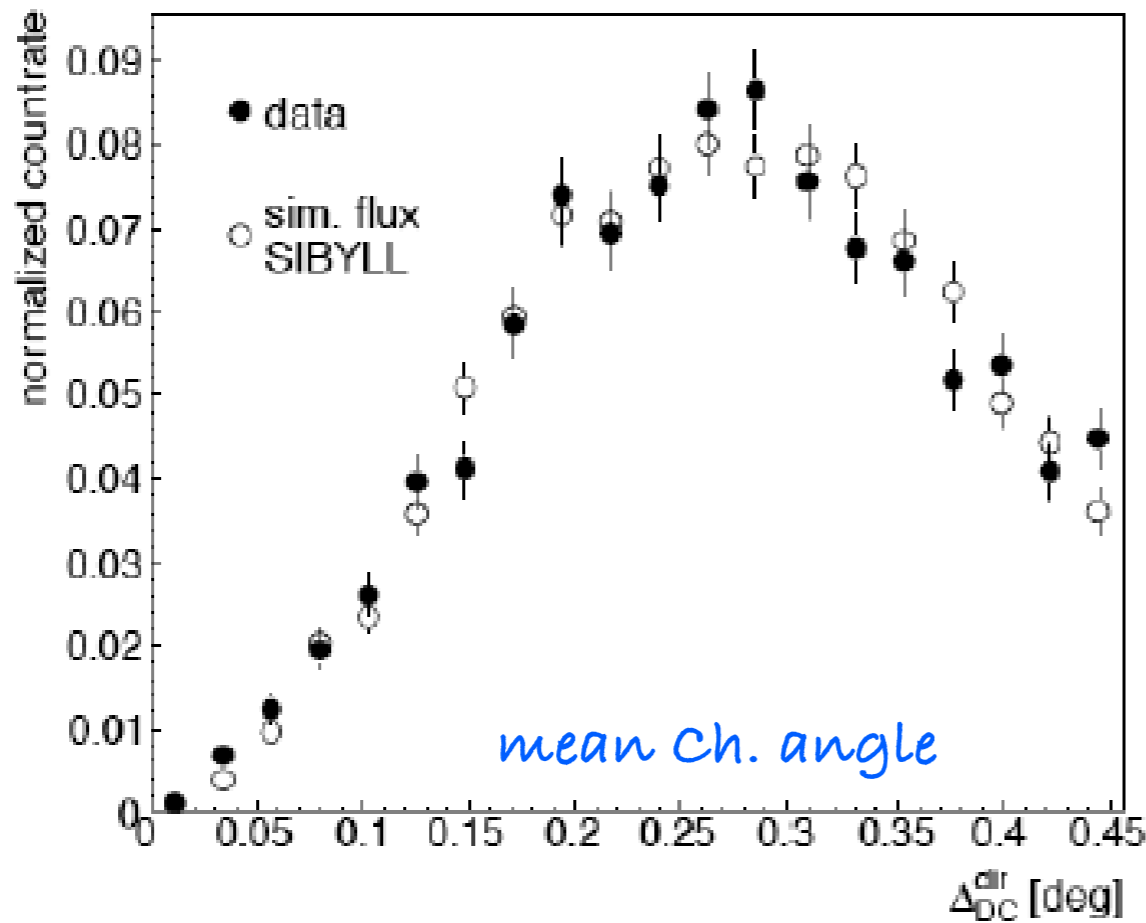
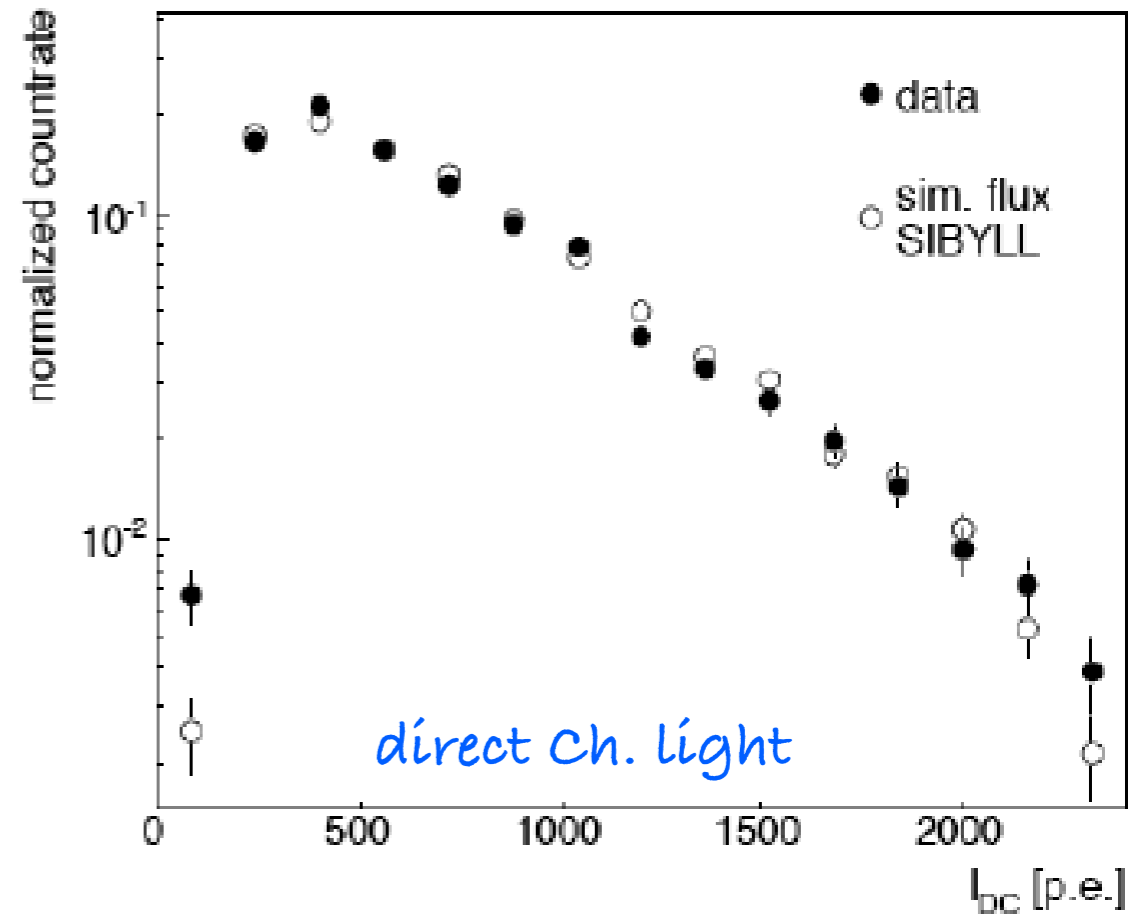
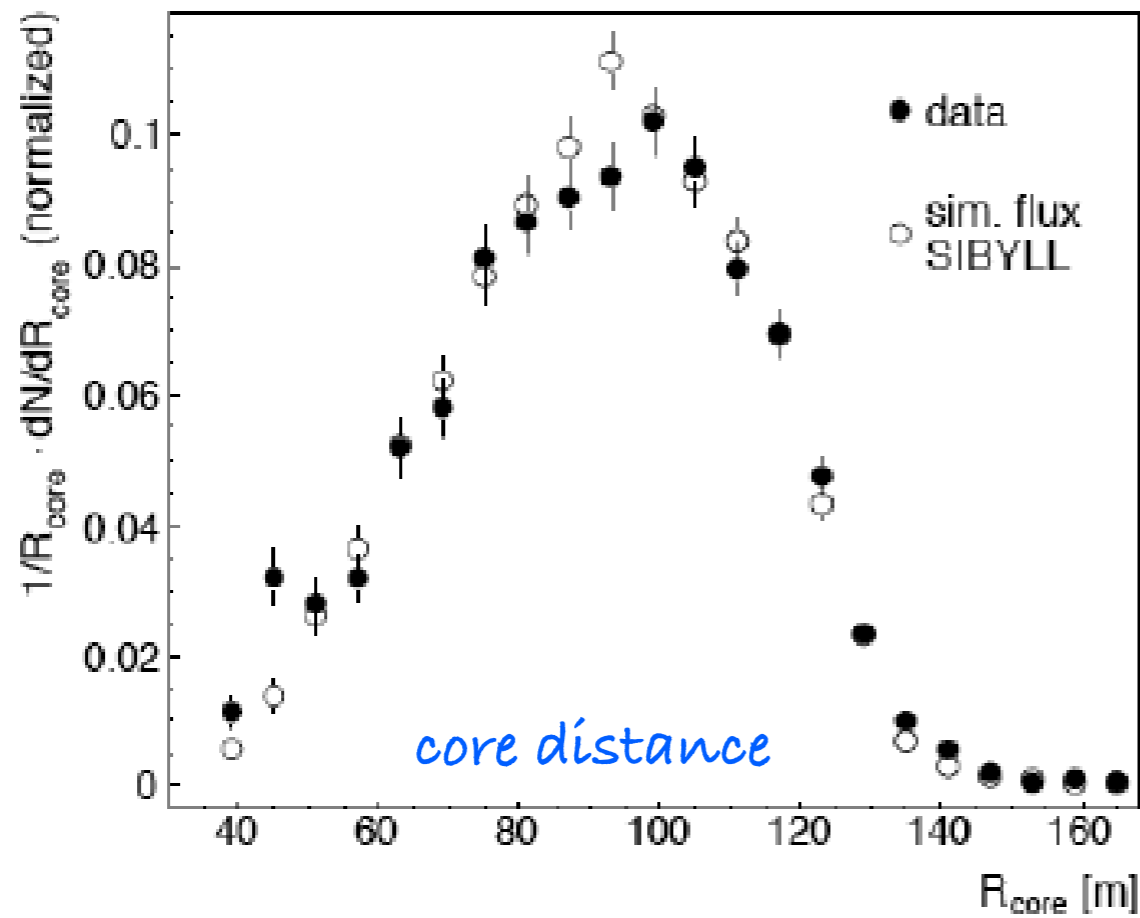
$E > 150 \text{ GeV}$

gamma rays:
good agreement
of image param.
distributions

CR background:
absolute trigger
rate within 15%



G Maier,
29th ICRC Pune (2005)
astro-ph/0507445

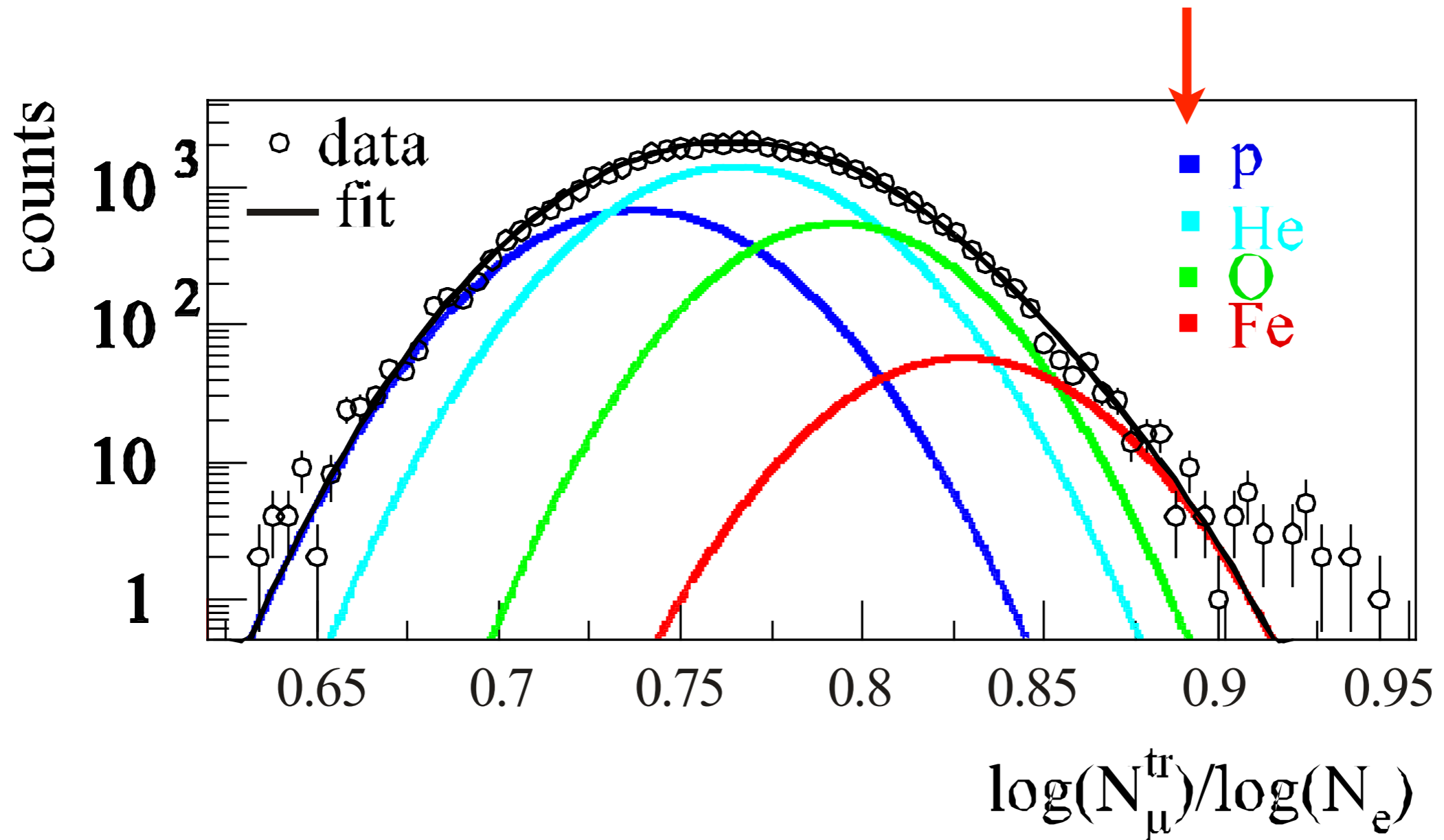


HESS 10-100 TeV mix of hadronic primaries

astro-ph/0701766

KASCADE: $10^{15} - 10^{16}$ eV
muon - electron ratio

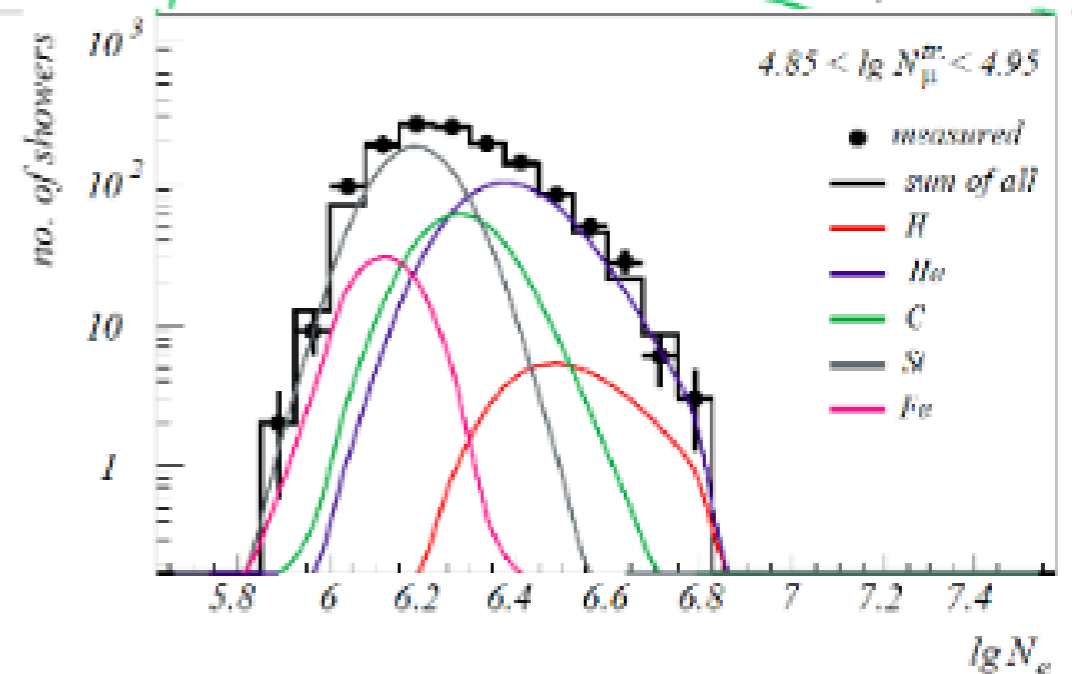
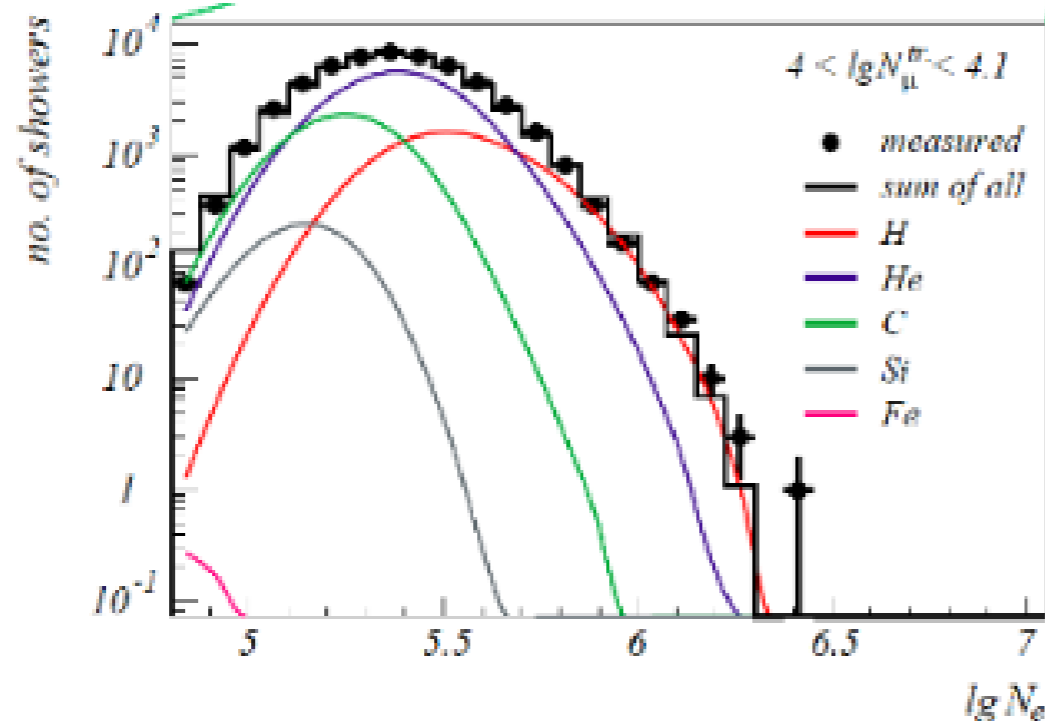
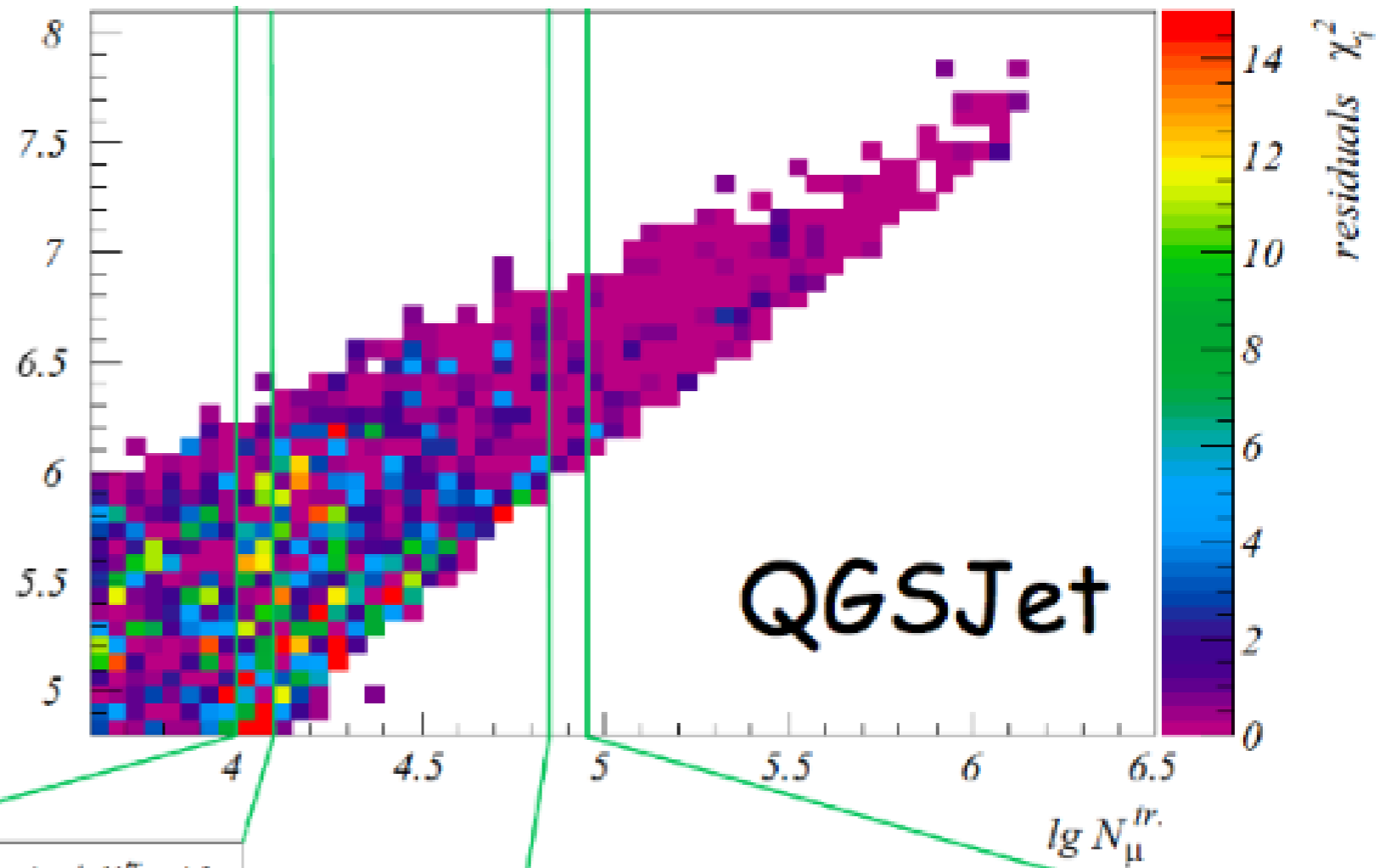
CORSIKA Simulations



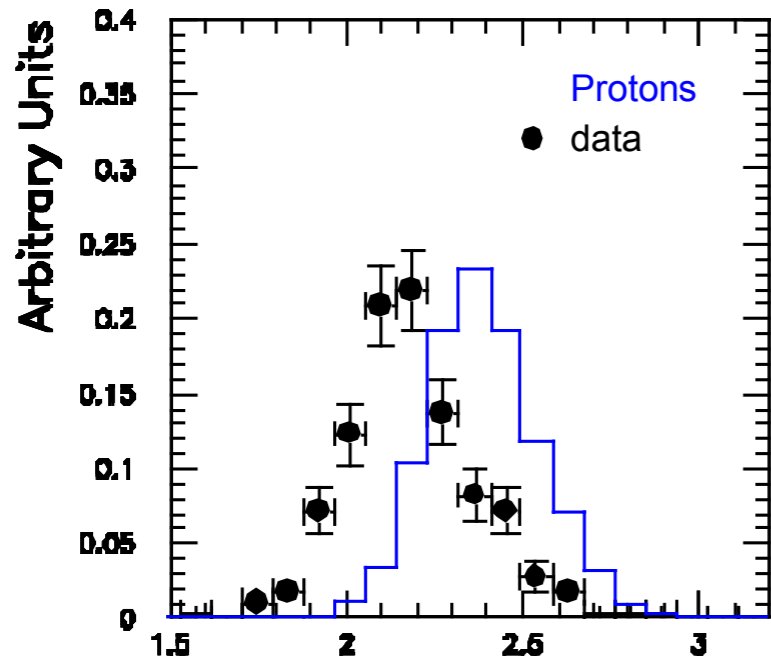
QGSJet - description of data

KASCADE

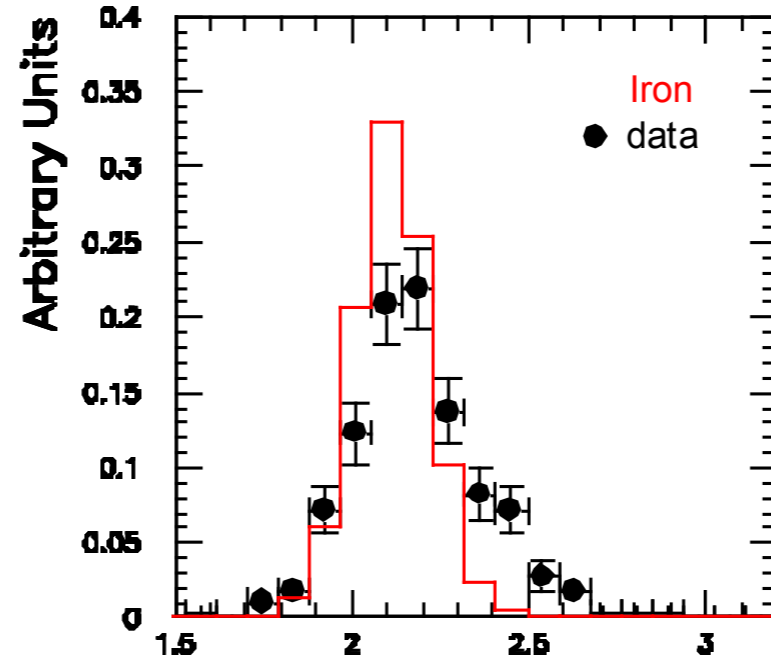
Fair agreement
of Monte Carlo
with exp. data.



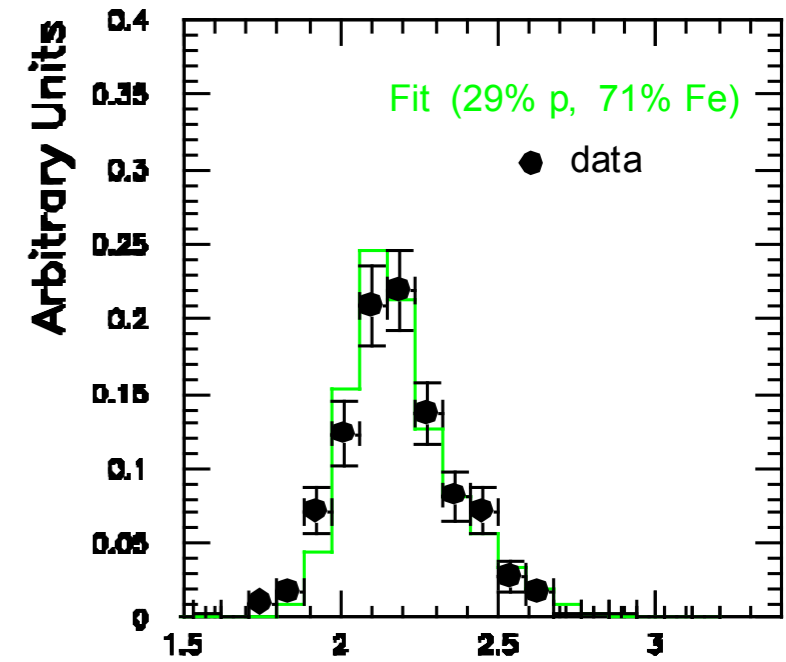
Haverah Park data 10^{17} - 10^{18} eV (re-analysed 2003)



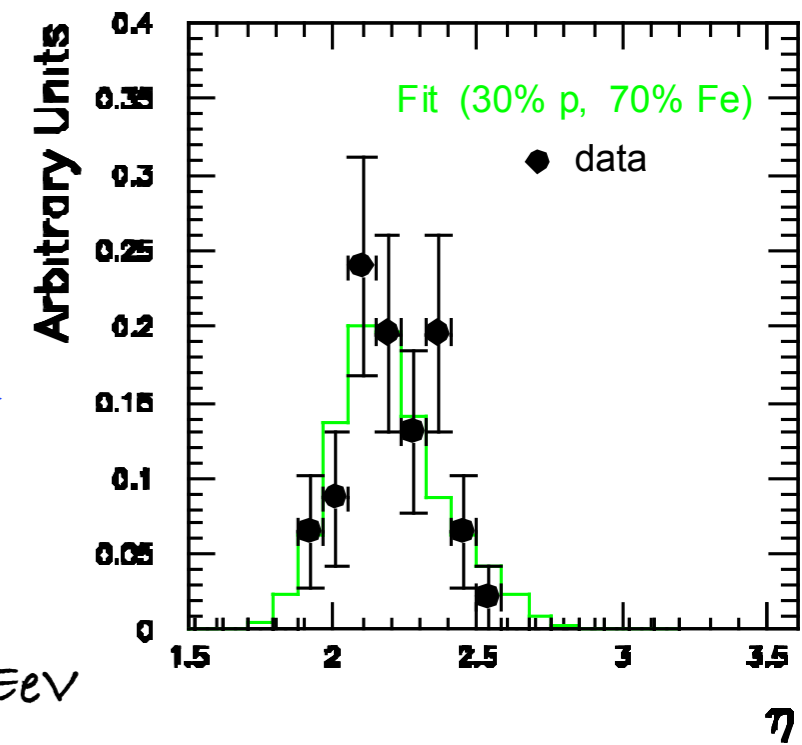
$0.2 \text{ EeV} < E < 0.6 \text{ EeV}$
292 events



$0.6 \text{ EeV} < E < 1 \text{ EeV}$
46 events

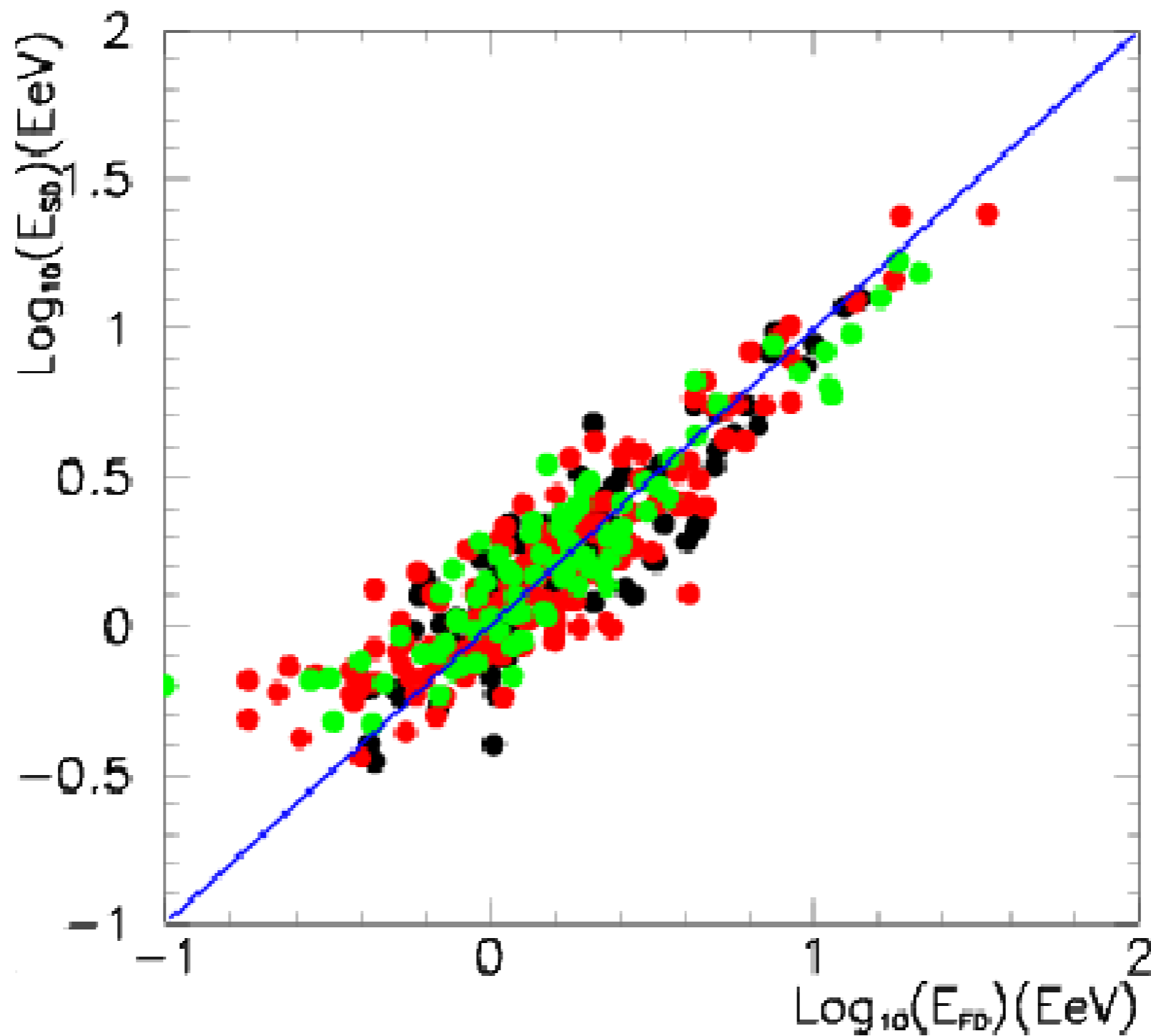


Models can describe data



FD VS SD energy

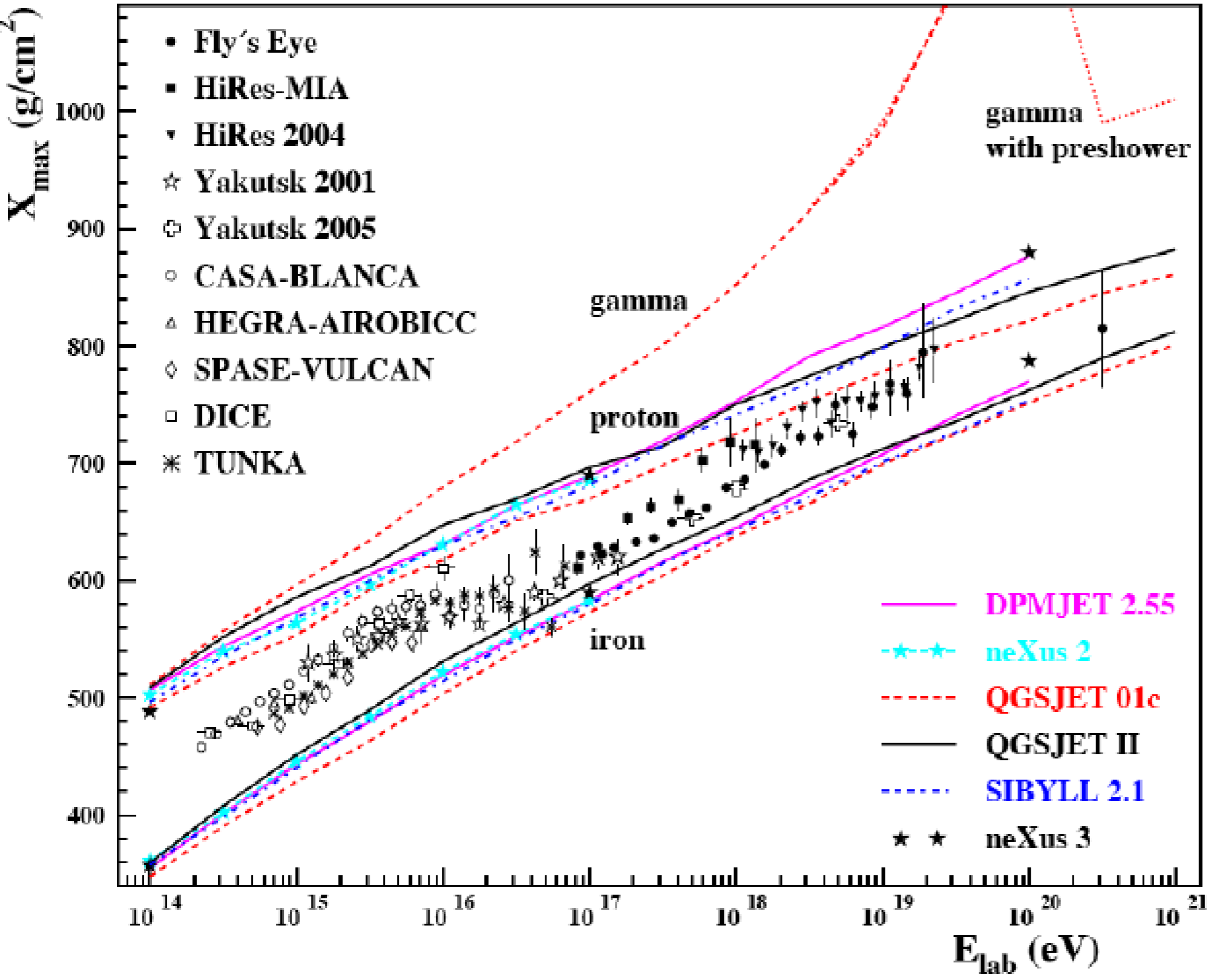
Auger ($E > 10^{18}$ eV)



- 0 - 25 deg
- 25 - 45 deg
- 45 - 60 deg

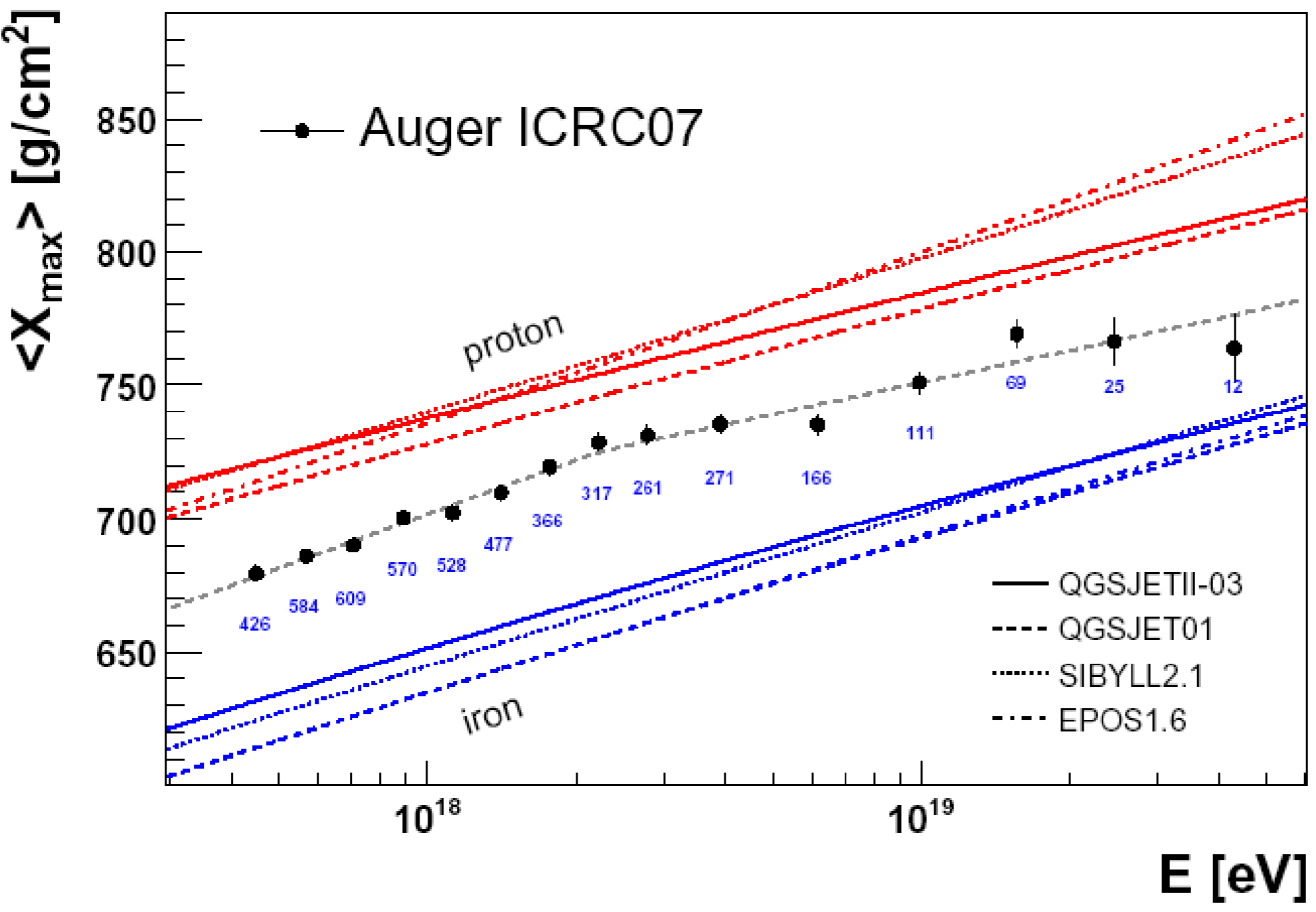
Clear correlation between SD and FD energy estimates,
i.e. shower models are **about right**. (better than 25%)

X_{max} as fct. of energy



MCS for mixed hadronic comp. are **consistent** with data. γ, ν showers look very different.

X_{max} as fct. of energy



MCS for mixed hadronic comp. are *consistent* with data. γ, ν showers look very different.

- Simulations with hadronic interaction models

- based on Gribov-Regge Theory
- tuned to accelerator data (mainly pp, pA, < TeV)
- extrapolated to all energies $10^6 \dots >10^{20}$ eV ...
 - all particles p, n, nuclei, π , K, Λ , ...
 - heavy mesons, baryons

produce showers that look very much like real events.

i.e. **CORSIKA** is not far off the truth.

(uncertainties < 30% for most observables)

- Everyone uses the **same code**.

THIS IS A REMARKABLE SUCCESS!

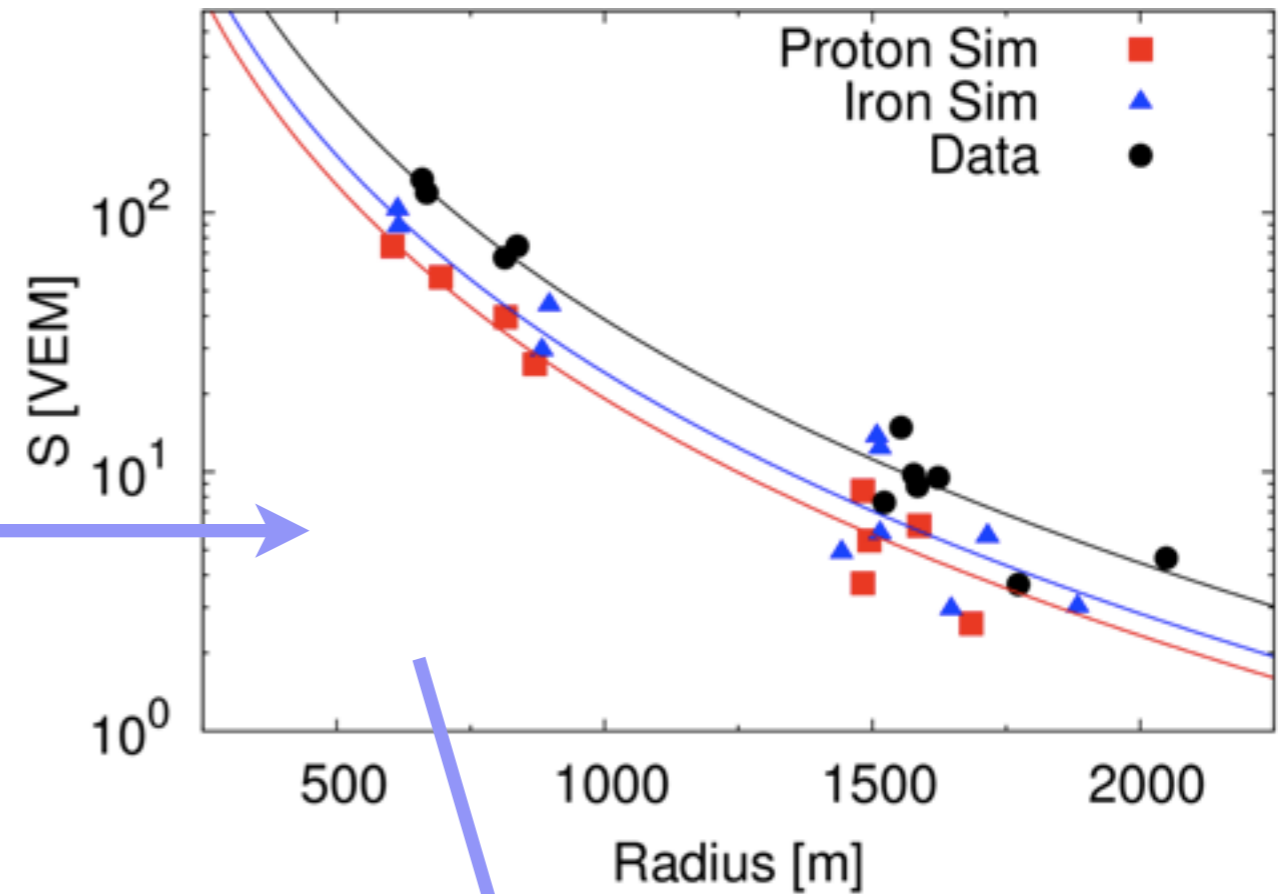
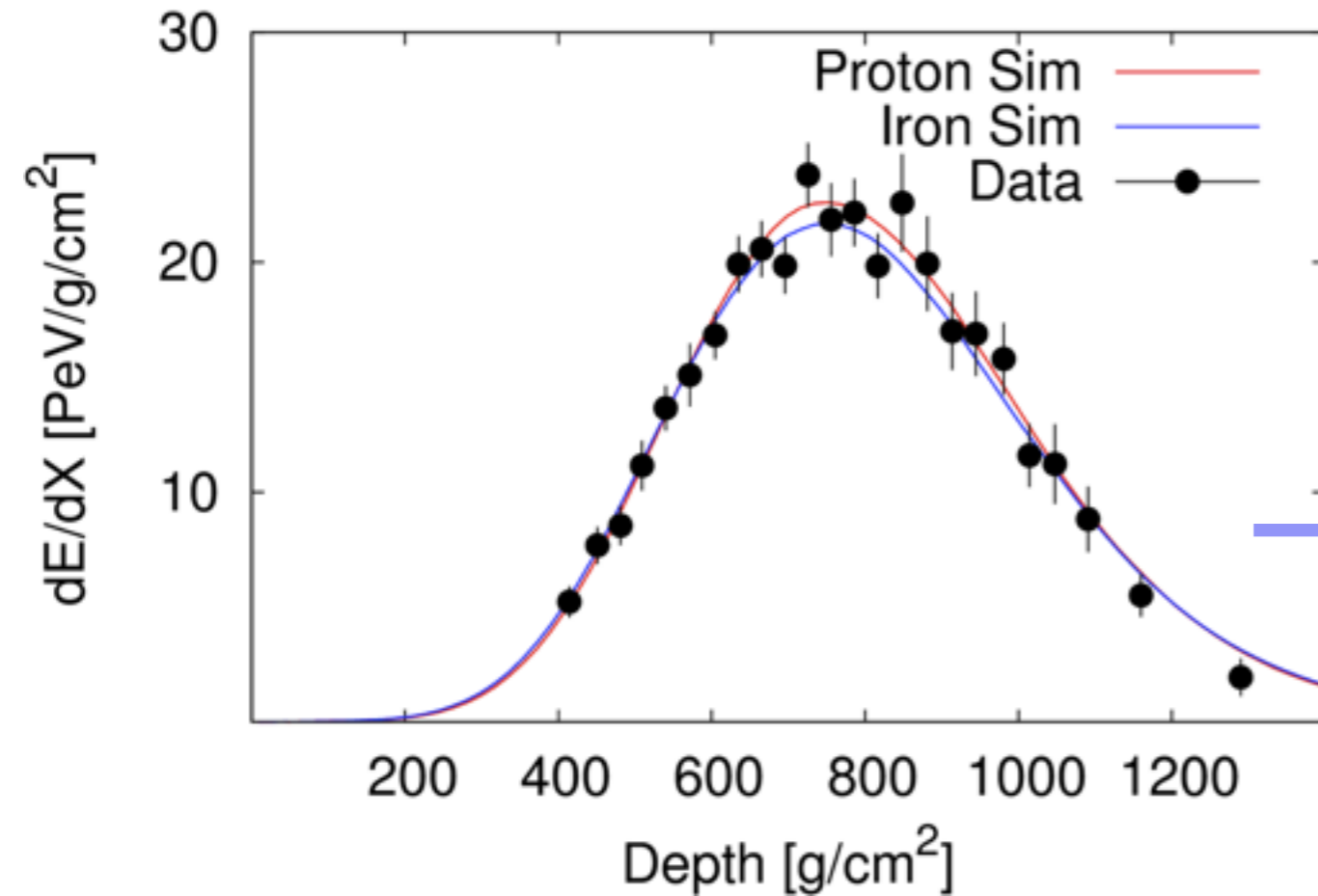
CORSIKA: is not perfect but gives reasonable agreement of simulations with air shower data from 10^{11} eV to 10^{20} eV:

HESS, VERITAS, MAGIC	γ ray astron.;	10^{11} - 10^{14} eV
KASCADE-Grande	CR showers;	10^{14} - 10^{17} eV
Haverah Park		10^{17} - 10^{18} eV
Auger		10^{18} - 10^{20} eV

reasonable agreement: $\sim 30\%$ level for $<10^{18}$ eV
larger for $>10^{18}$ eV

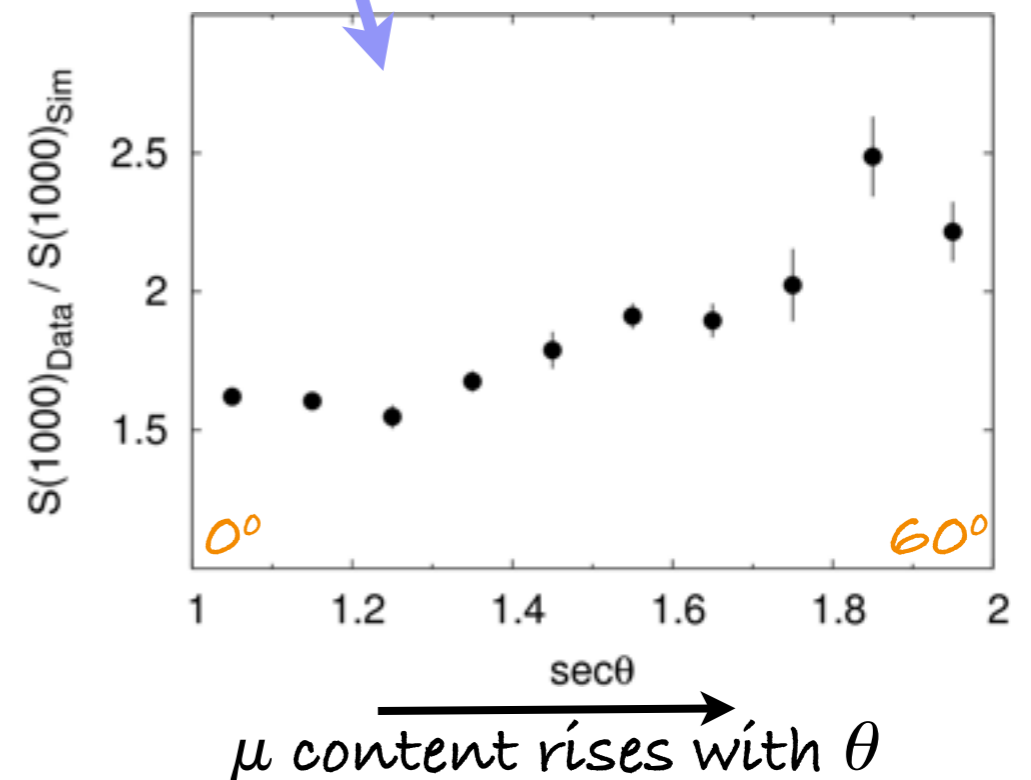
Are the EAS models right?

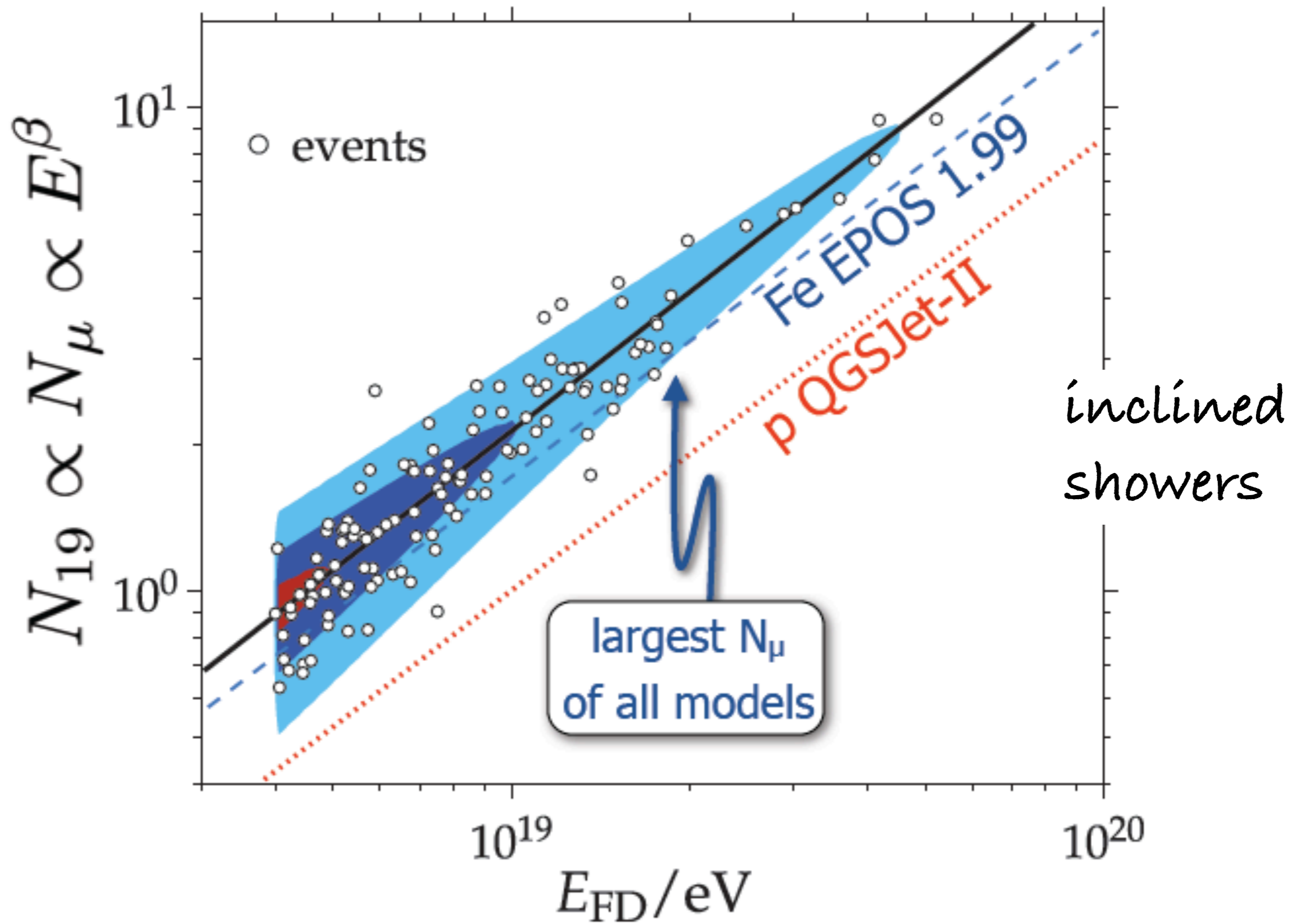
same simulated events have less signal in SD than the measured ones.



match the long. shower profile (as seen in FD) of a measured event with p and Fe simulations

models underestimate ground signal by **1.5 - 2x**

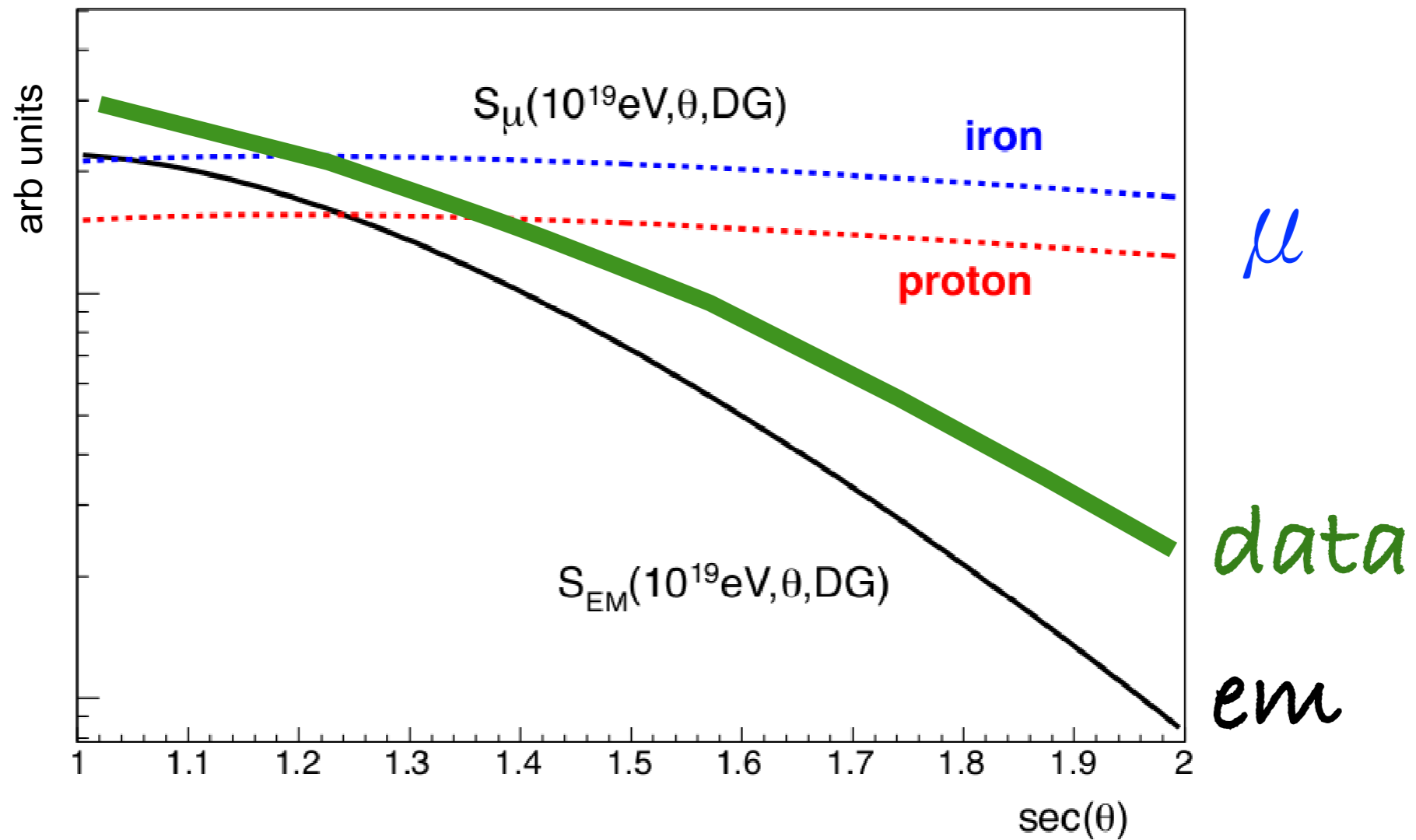




models underestimate N_{μ} by **25-100%**
 for Fe for p

universality:

em and muonic signal depend only on E and shower development (DG)



measure $S_{1000}(\theta)$, compare with simulations

Result: muon deficit ($\approx 53\%$) in simulations

i.e. 26% higher energy estimate than FD

Other methods:

jump method:

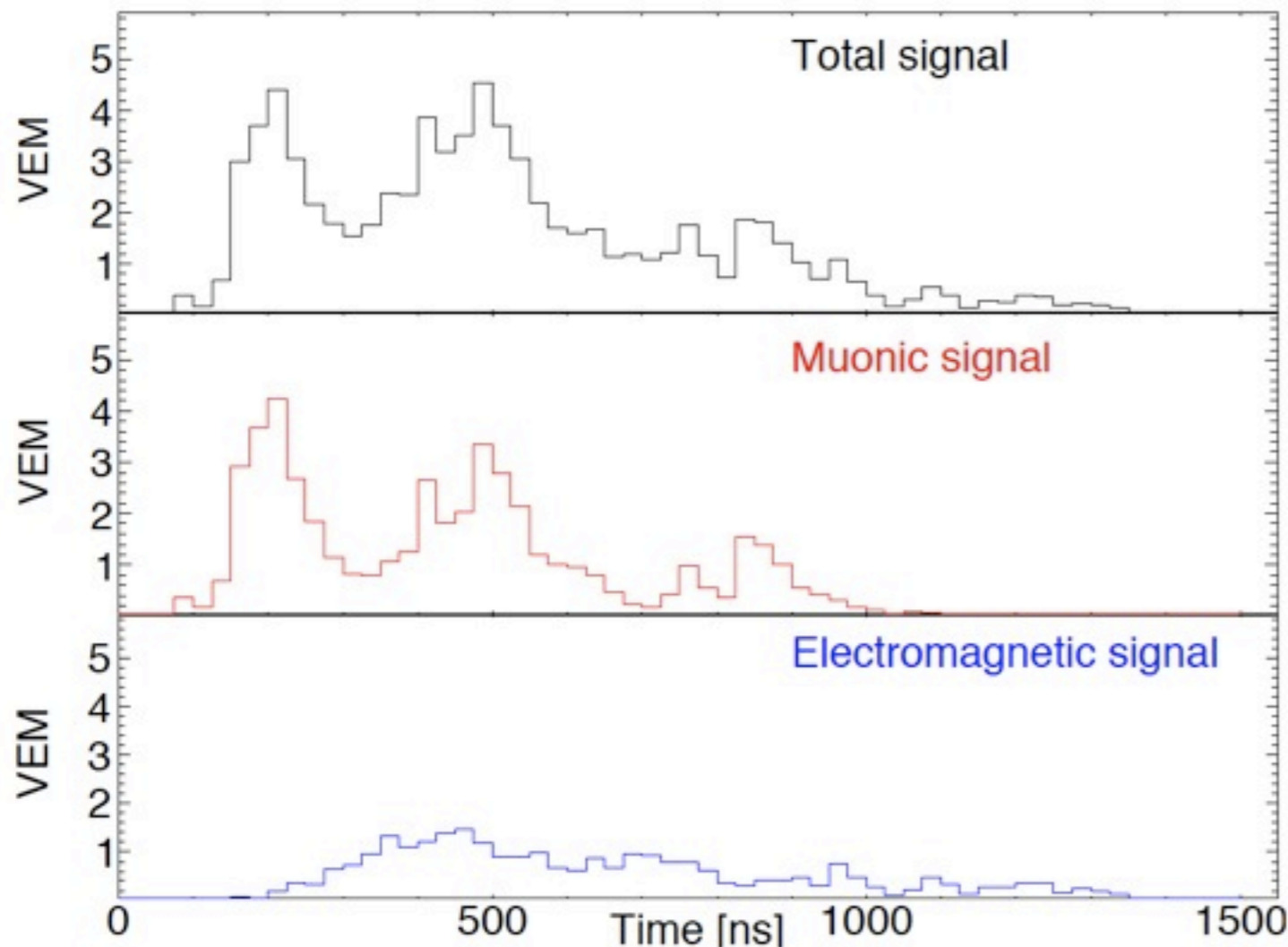
count muon peaks in time traces

smoothing method:

separate e, γ and μ signal

golden hybrid analysis:

compare SD with FD reconstruction



$$E_{e,\gamma} \approx \text{MeV}$$

$$E_{\mu} \approx \text{GeV}$$

$\approx 240 \text{ MeV}$ energy deposit

spiky

smooth

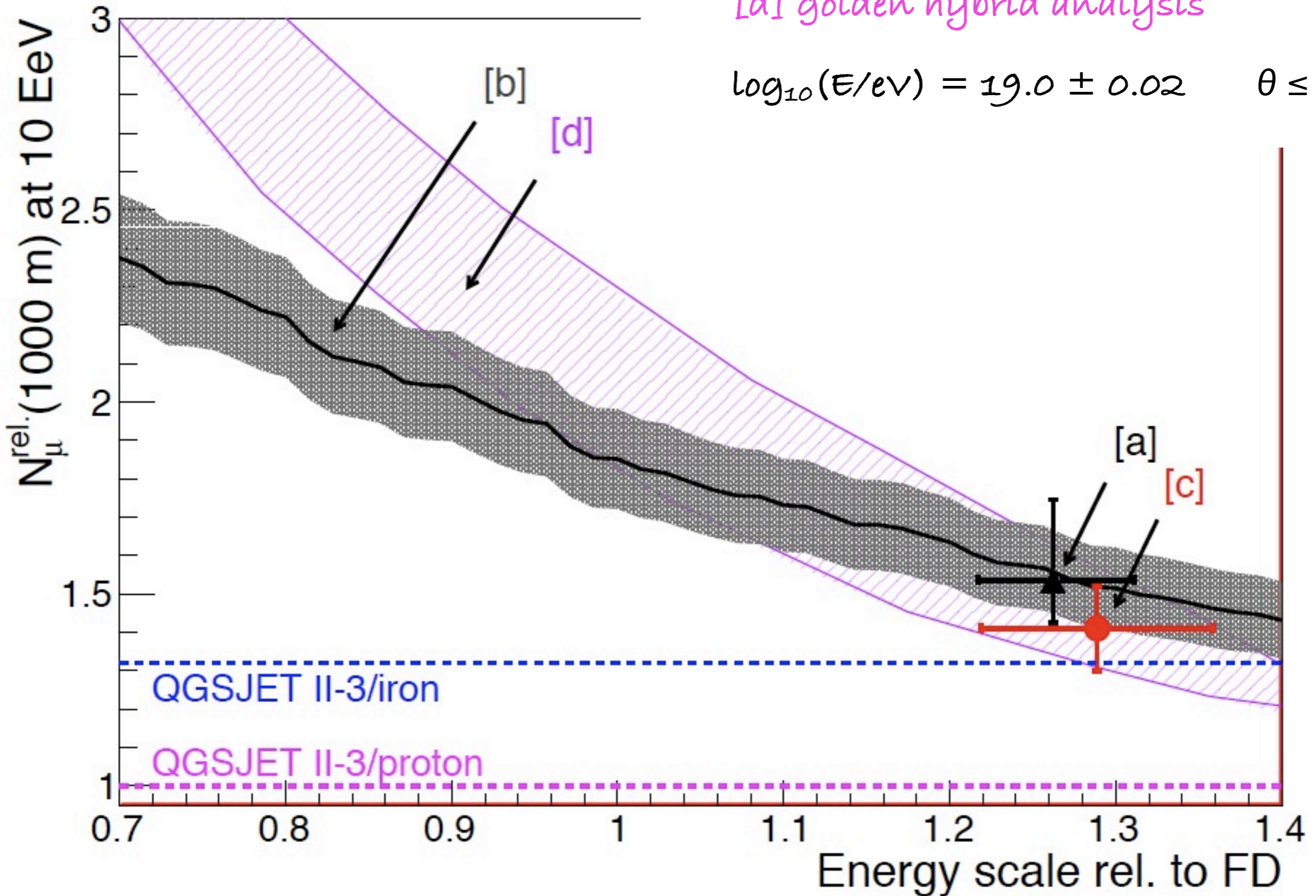
[a] universality method

[b] jump method

[c] smoothing method

[d] golden hybrid analysis

$$\log_{10}(E/\text{eV}) = 19.0 \pm 0.02 \quad \theta \leq 50^\circ.$$



[a] universality method

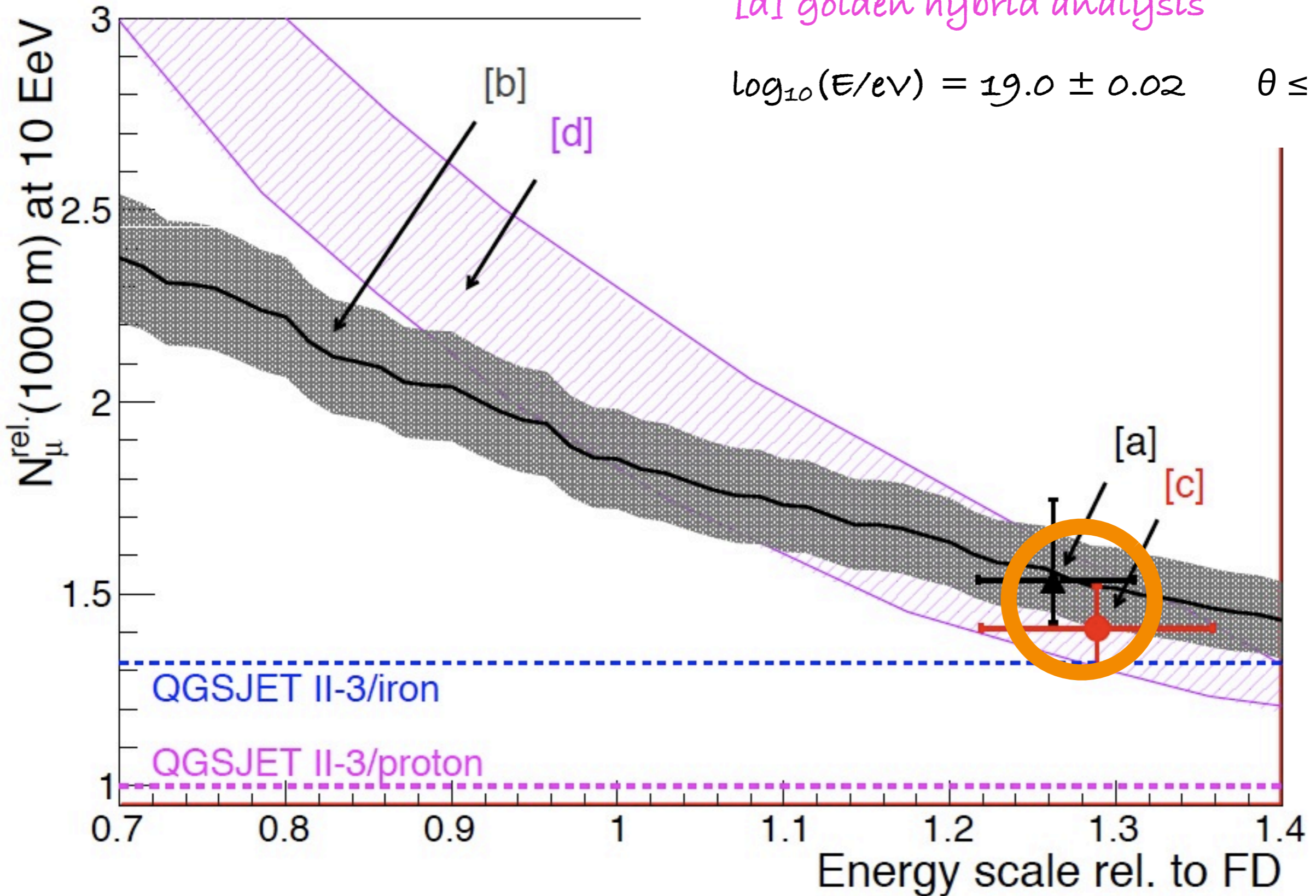
[b] jump method

[c] smoothing method

[d] golden hybrid analysis

$$\log_{10}(E/\text{eV}) = 19.0 \pm 0.02$$

$$\theta \leq 50^\circ$$



Consistent findings:

Air shower models require modifications:

MUONS need $\approx 1.3 - 2x$ more,
ground signal need $\approx 1.5 - 2x$ more

@ 10^{19} eV

for the **same** longitudinal profile.

hadronic model ?

fluorescence yield ?

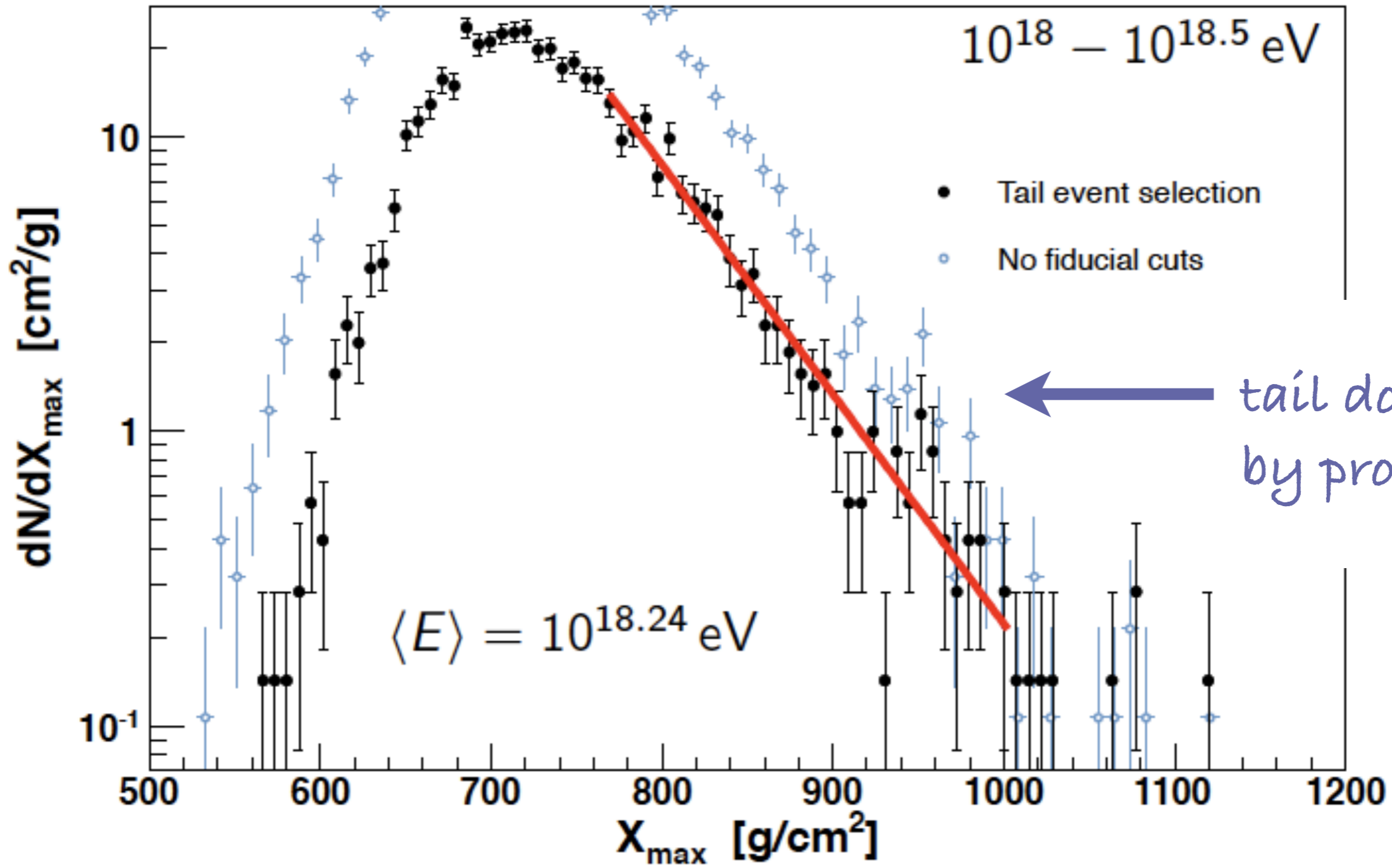
LHC results on cross-sections and particle production
(in very forward range) will provide helpful constraints.

EPOS: a new model, with enhanced baryon production
makes about 50% more muons, but has other problems...

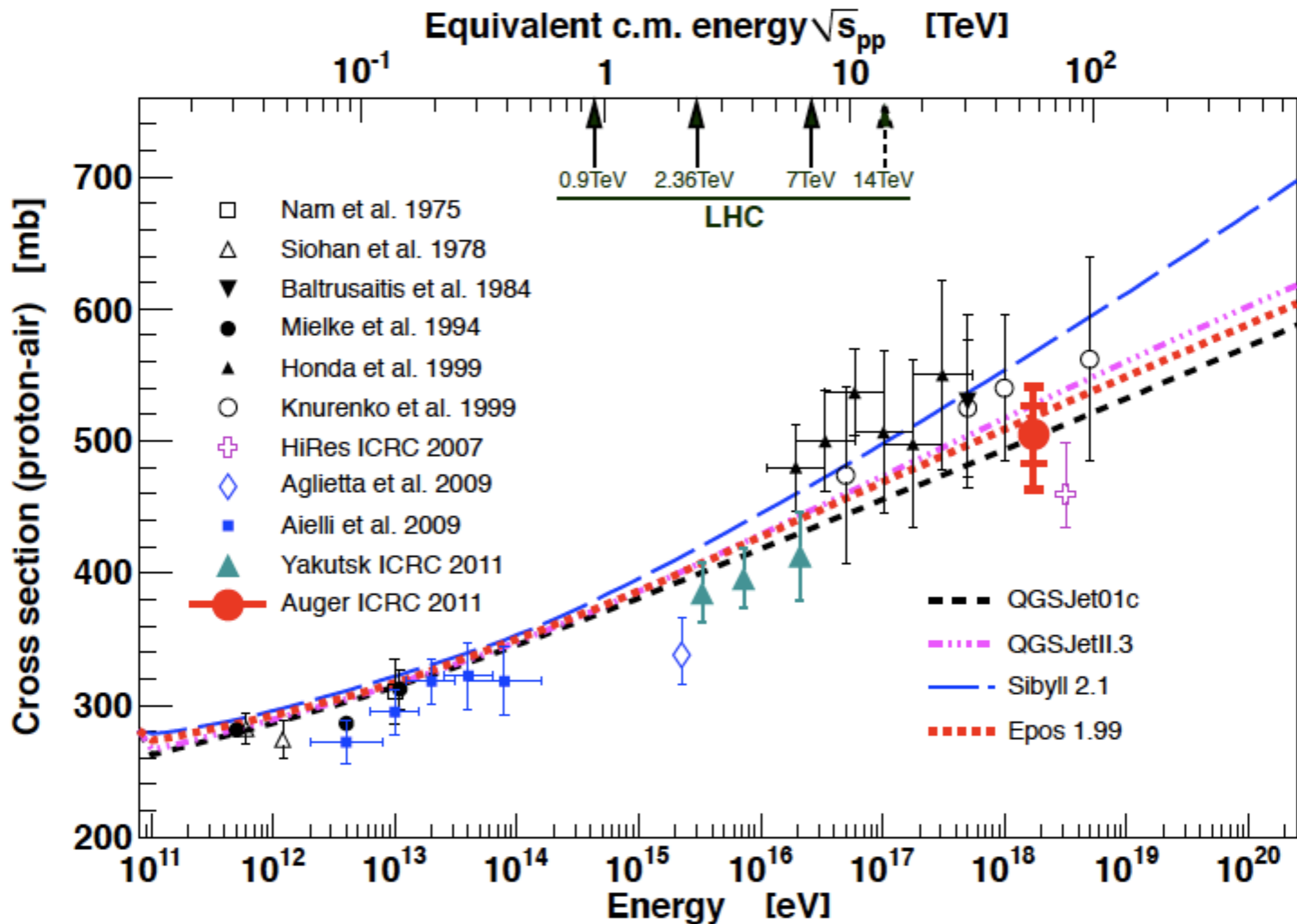
Proton-Air Cross-Section from Auger

... from tail of X_{\max} distribution

Fiducial Range

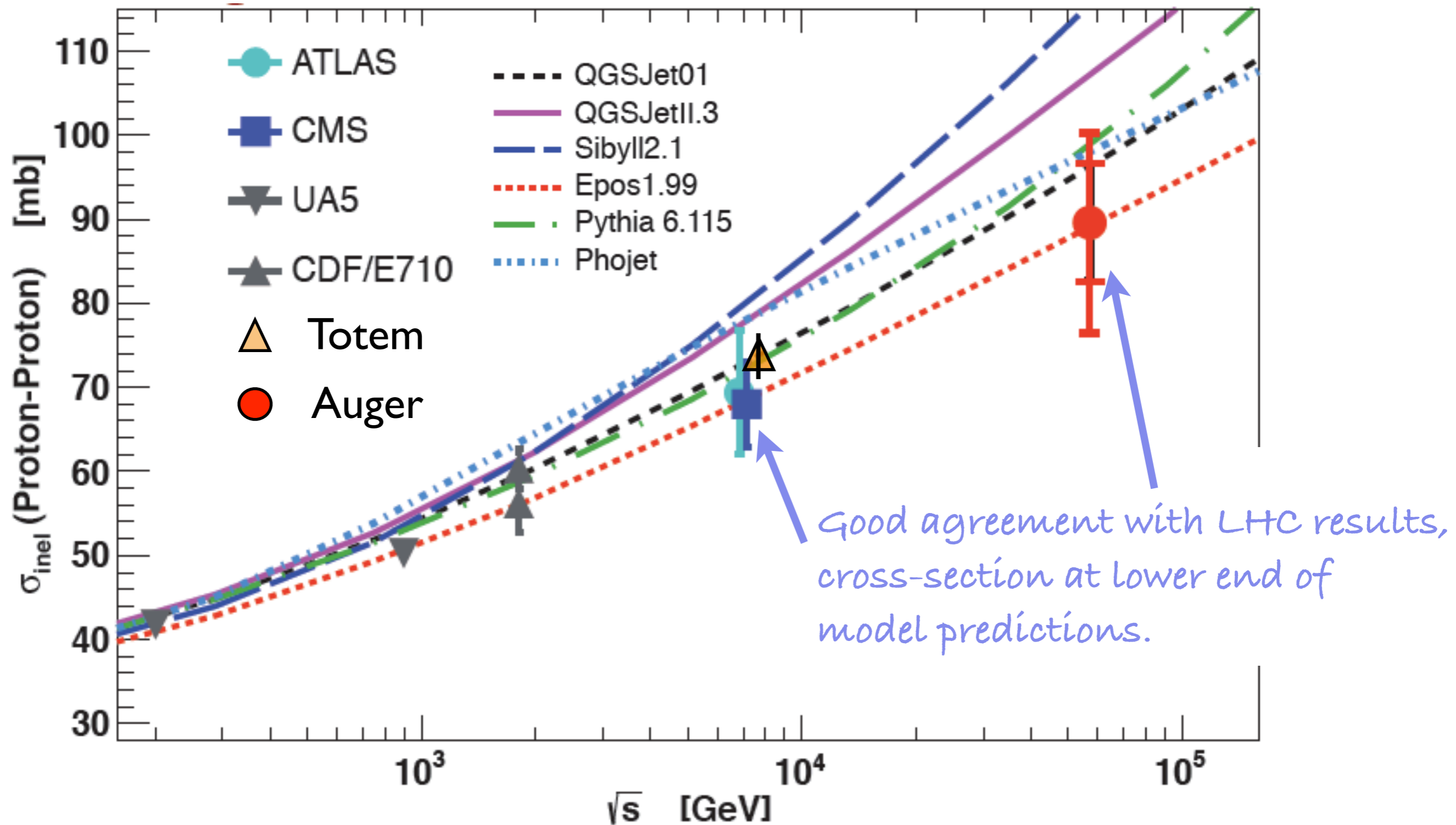


Proton-Air Cross-Section from Auger



$$\sigma(p\text{-air}) = 505 \pm 22 \pm 30 \text{ mb} \quad (@ 2 \text{ EeV})$$

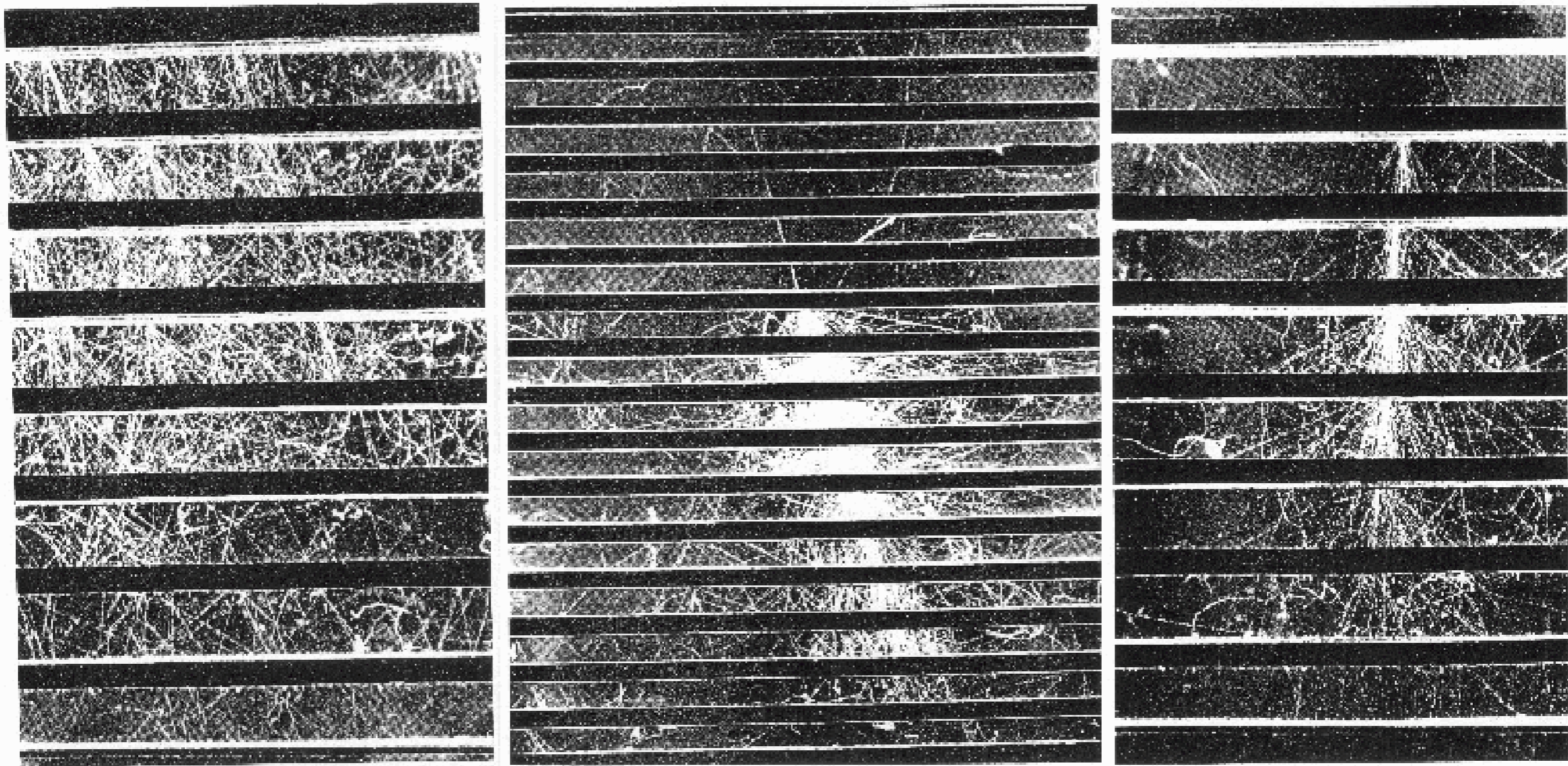
p-p cross-section (using Glauber model for conversion)



$$\sigma(p-p) = 90 \pm 7 \pm 10 \text{ mb} \quad (@ E_{\text{cm}} \approx 57 \text{ TeV})$$

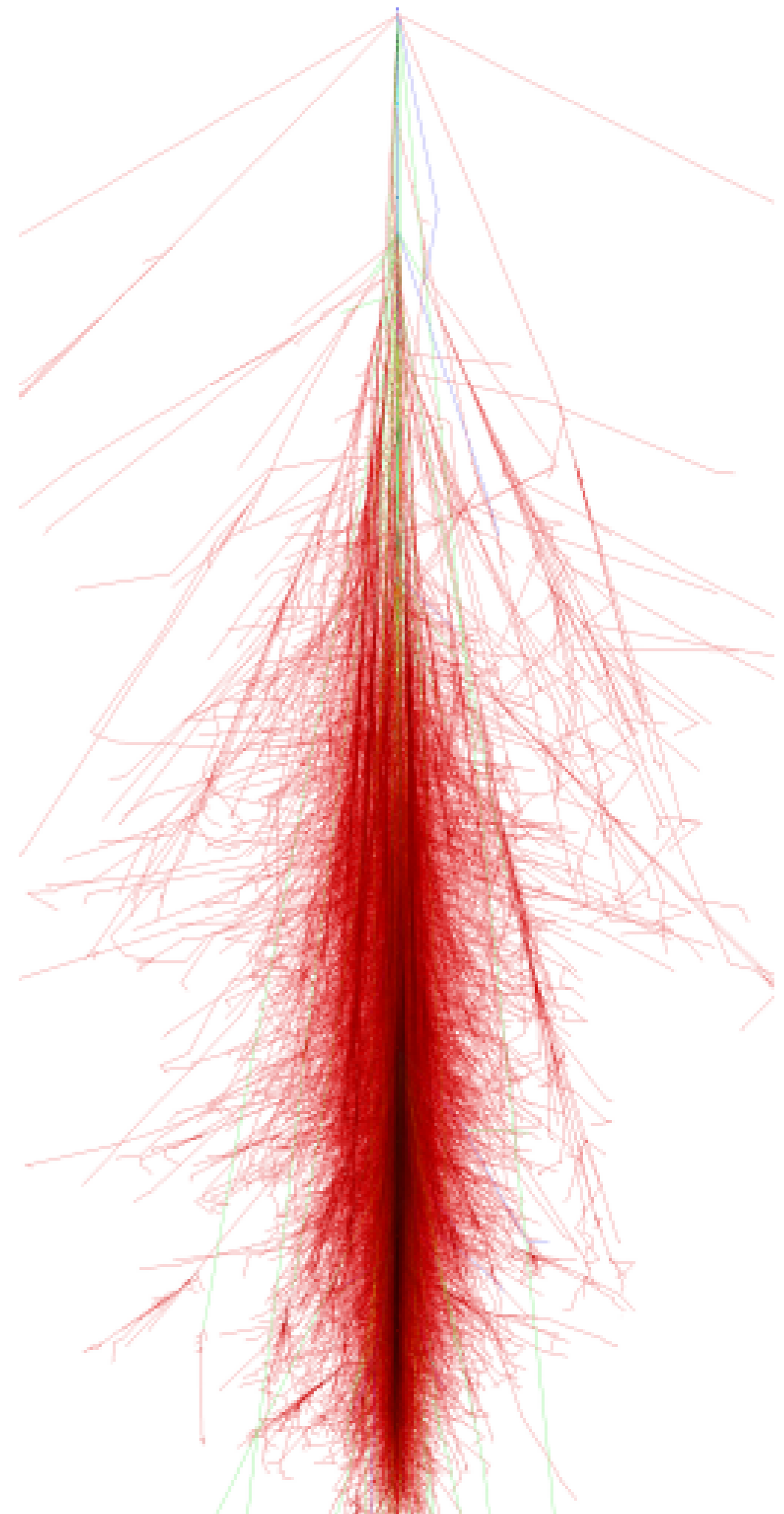
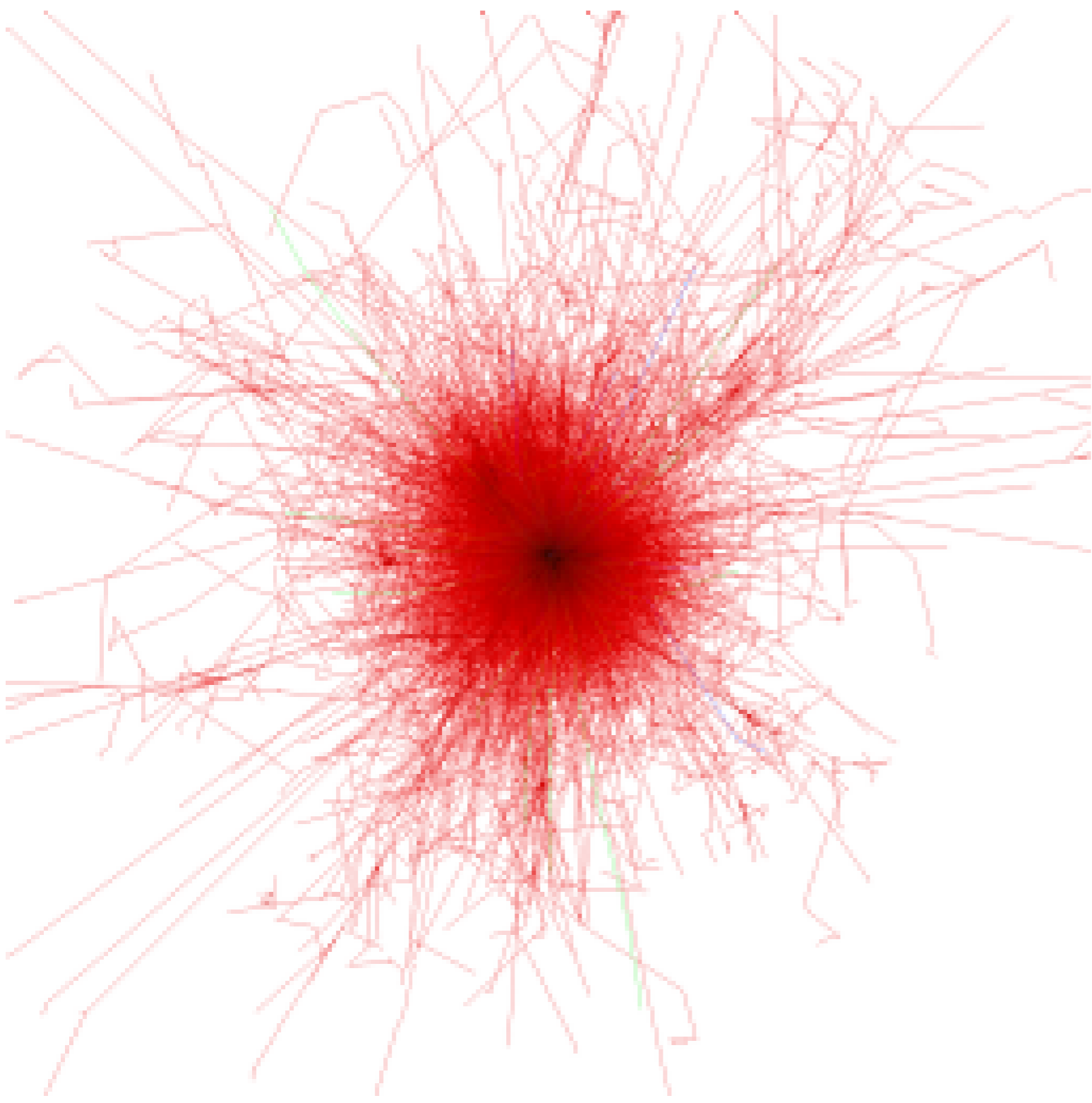
Educational
Images

Visualise and understand what is going on ...

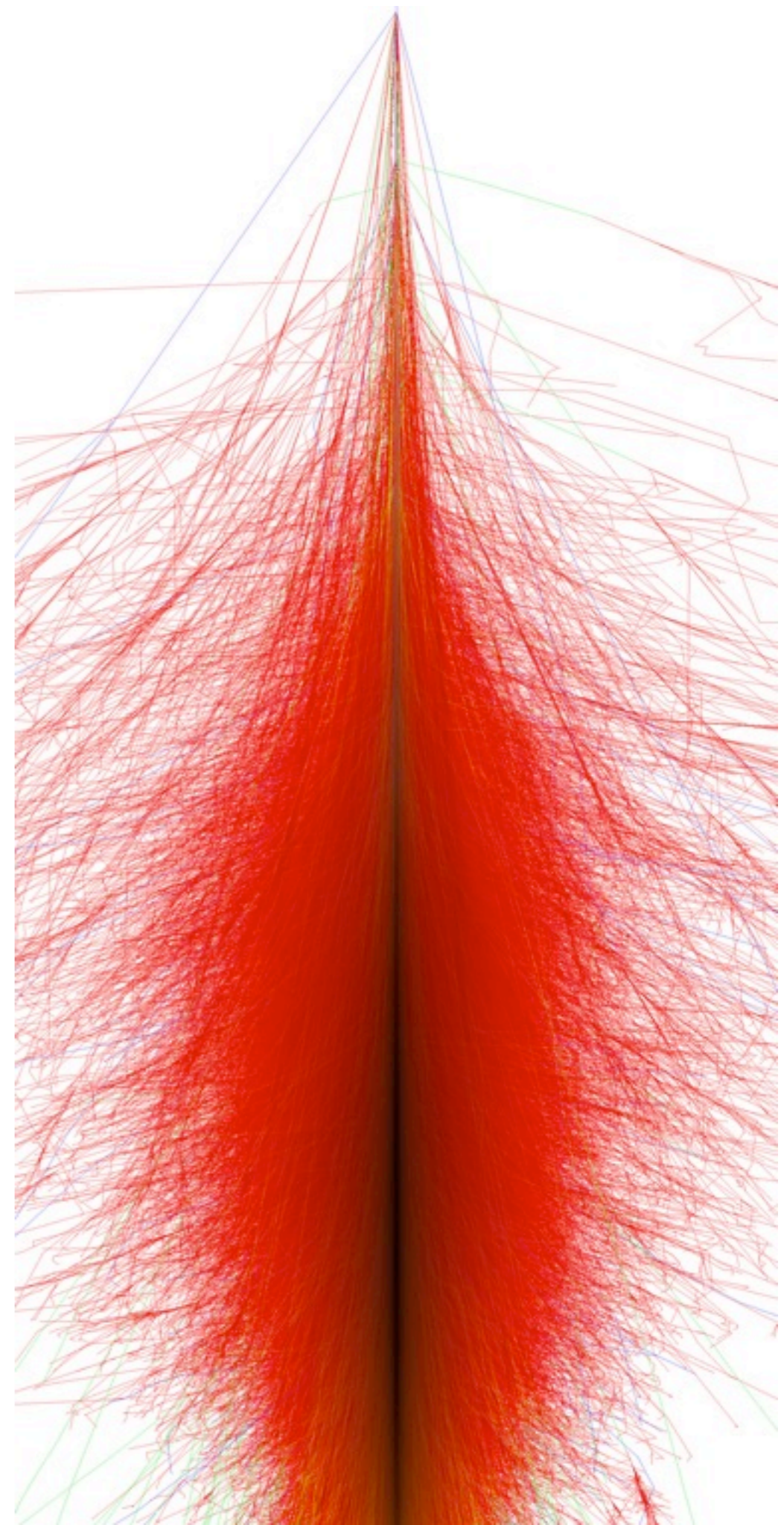
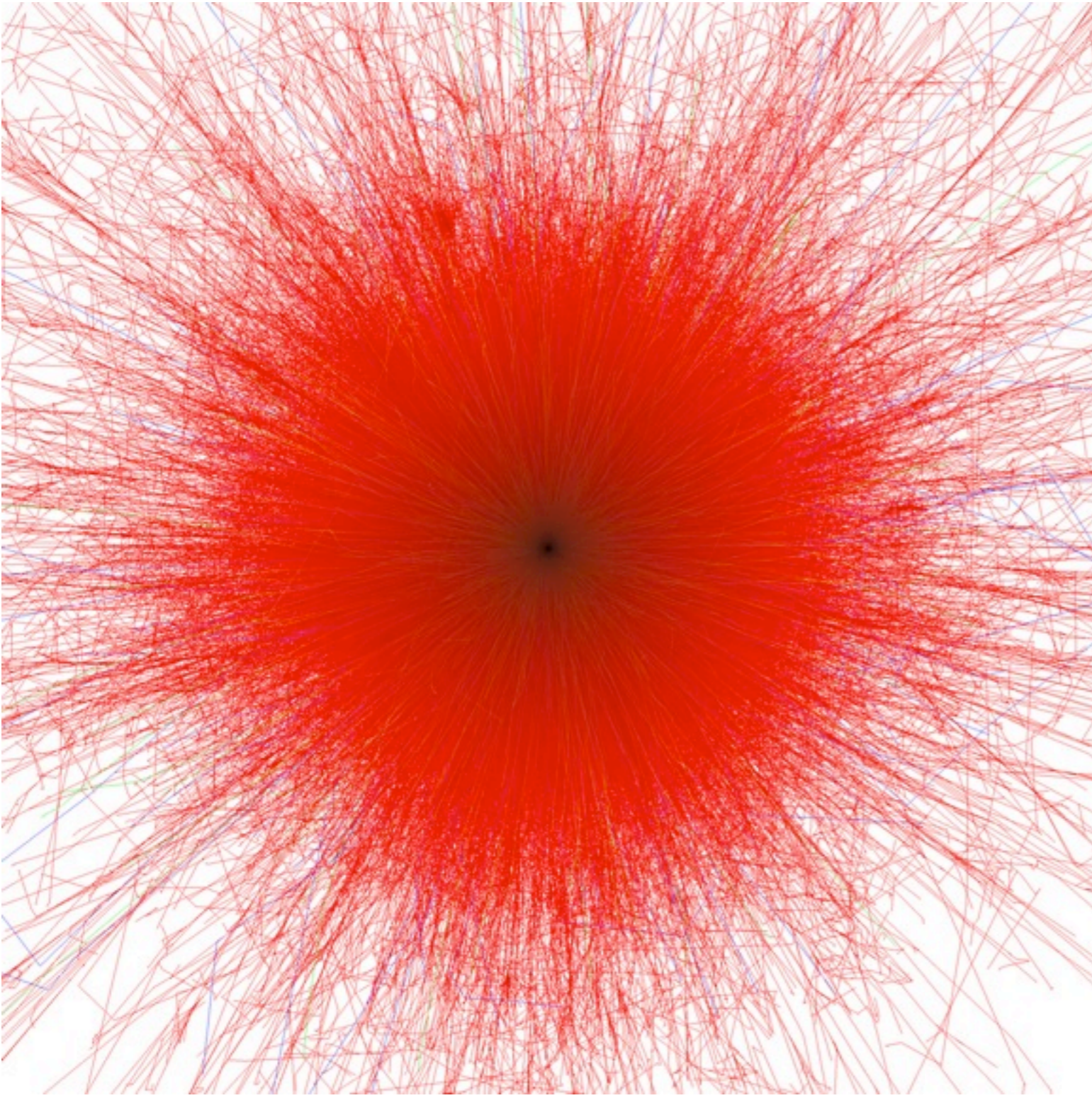


... as with early bubble and cloud chamber photos.

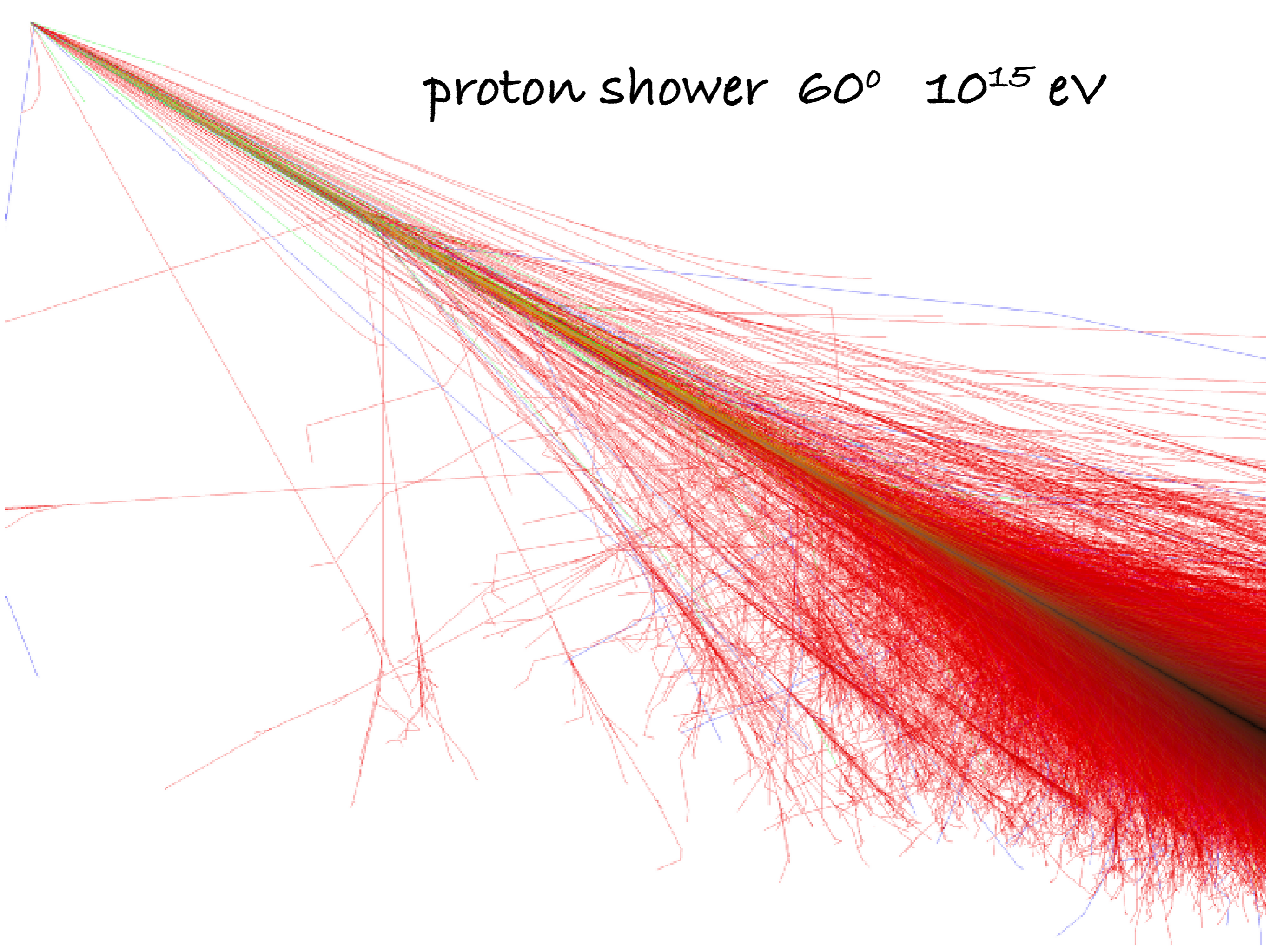
proton shower 10^{12} eV



proton shower 10^{14} eV



proton shower 60° 10^{15} eV

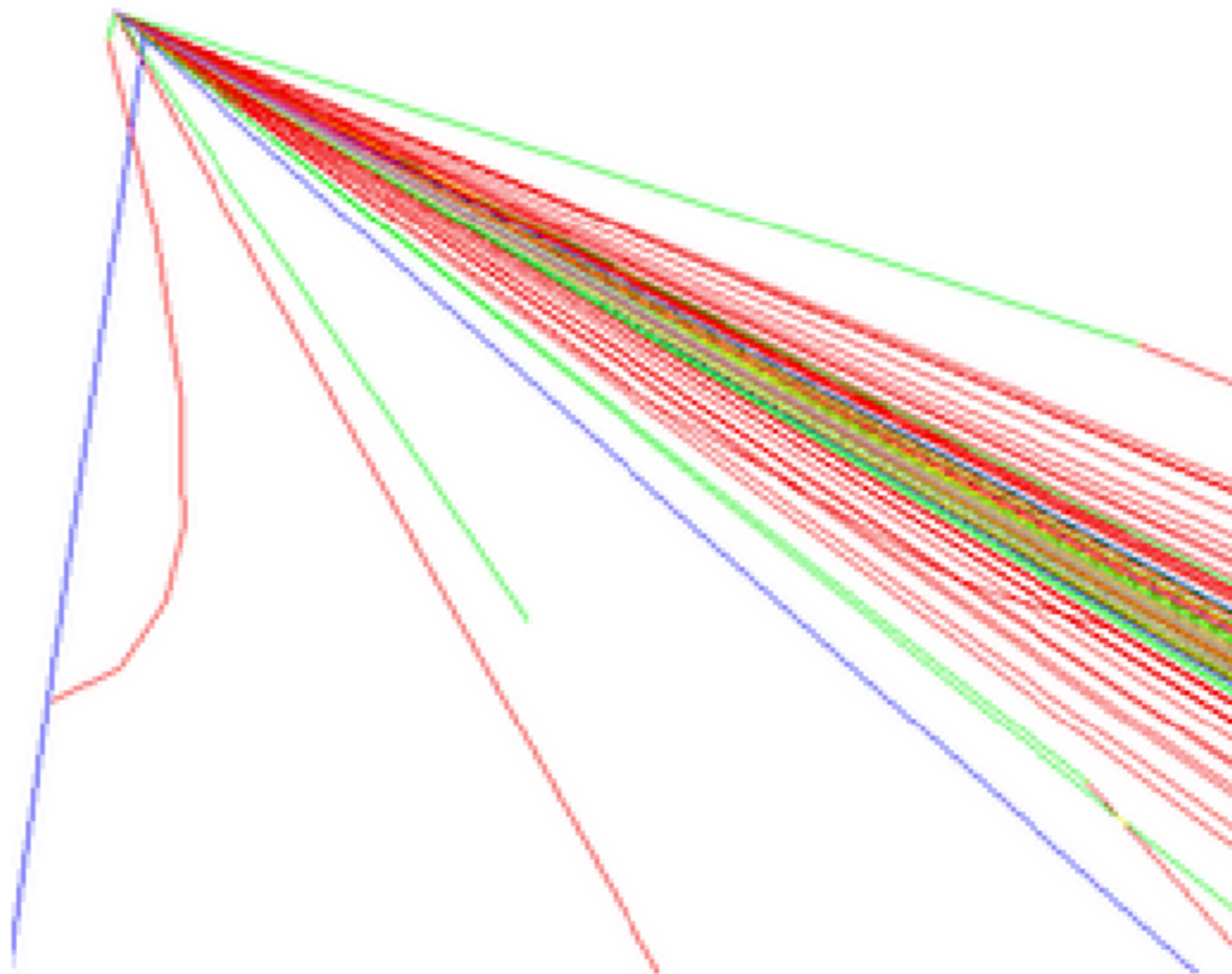


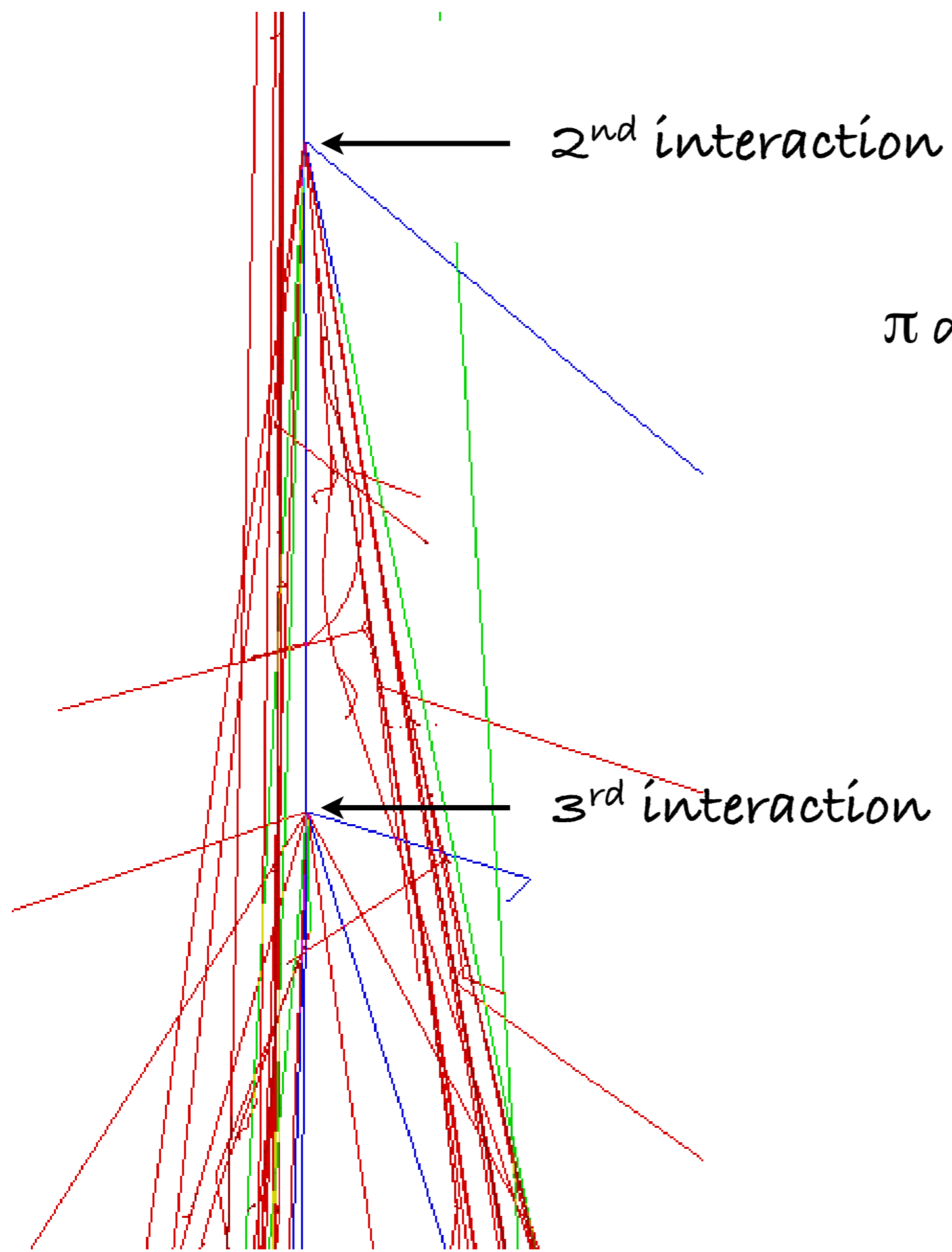
proton 10^{15} eV
1st interaction

electrons/photons

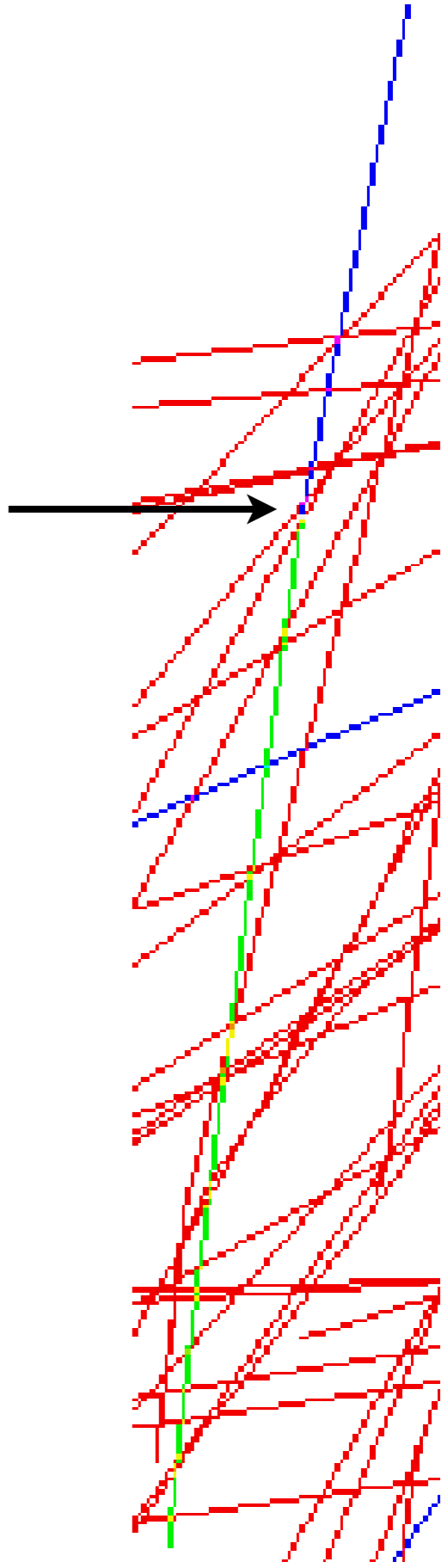
muons

hadrons

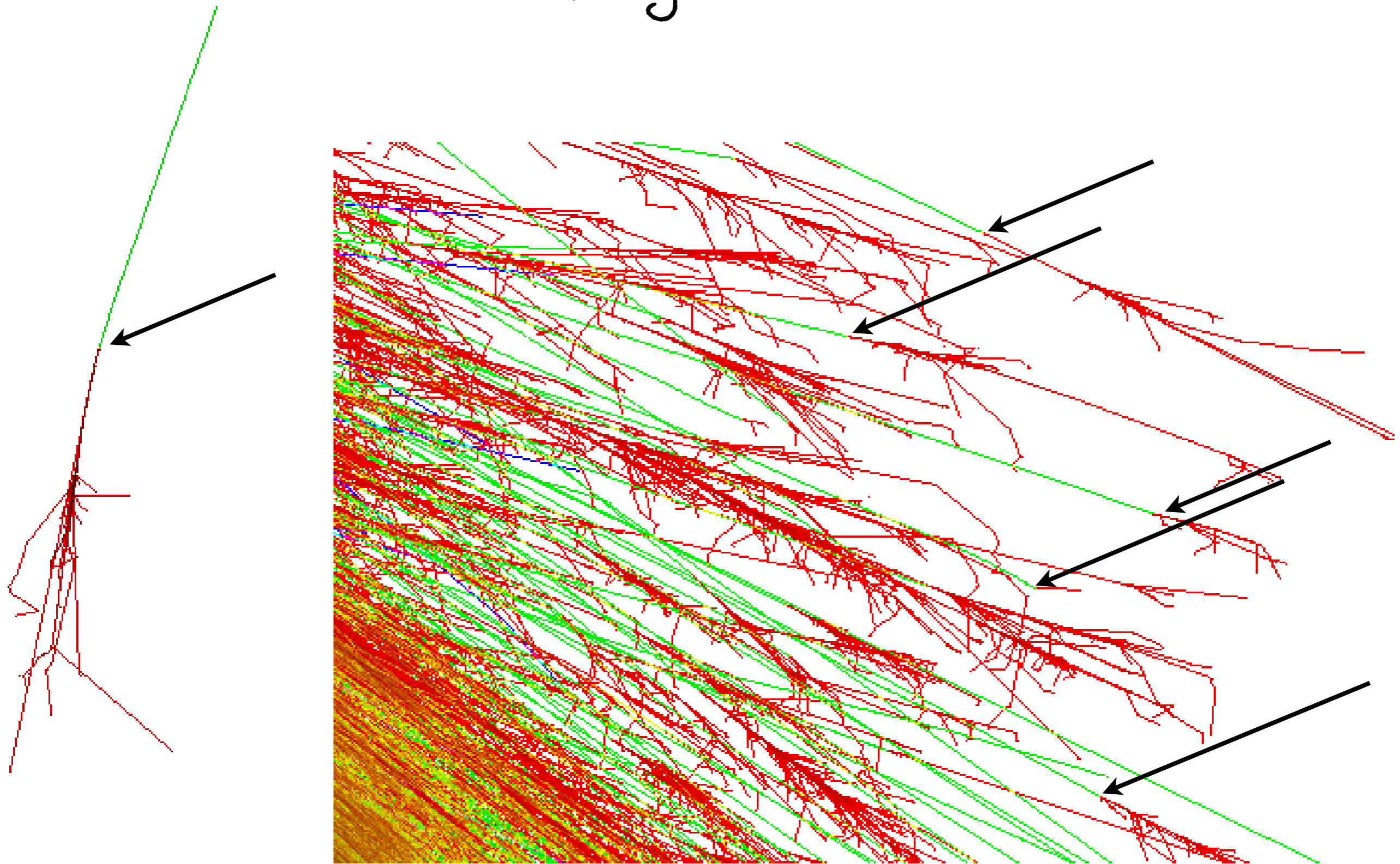




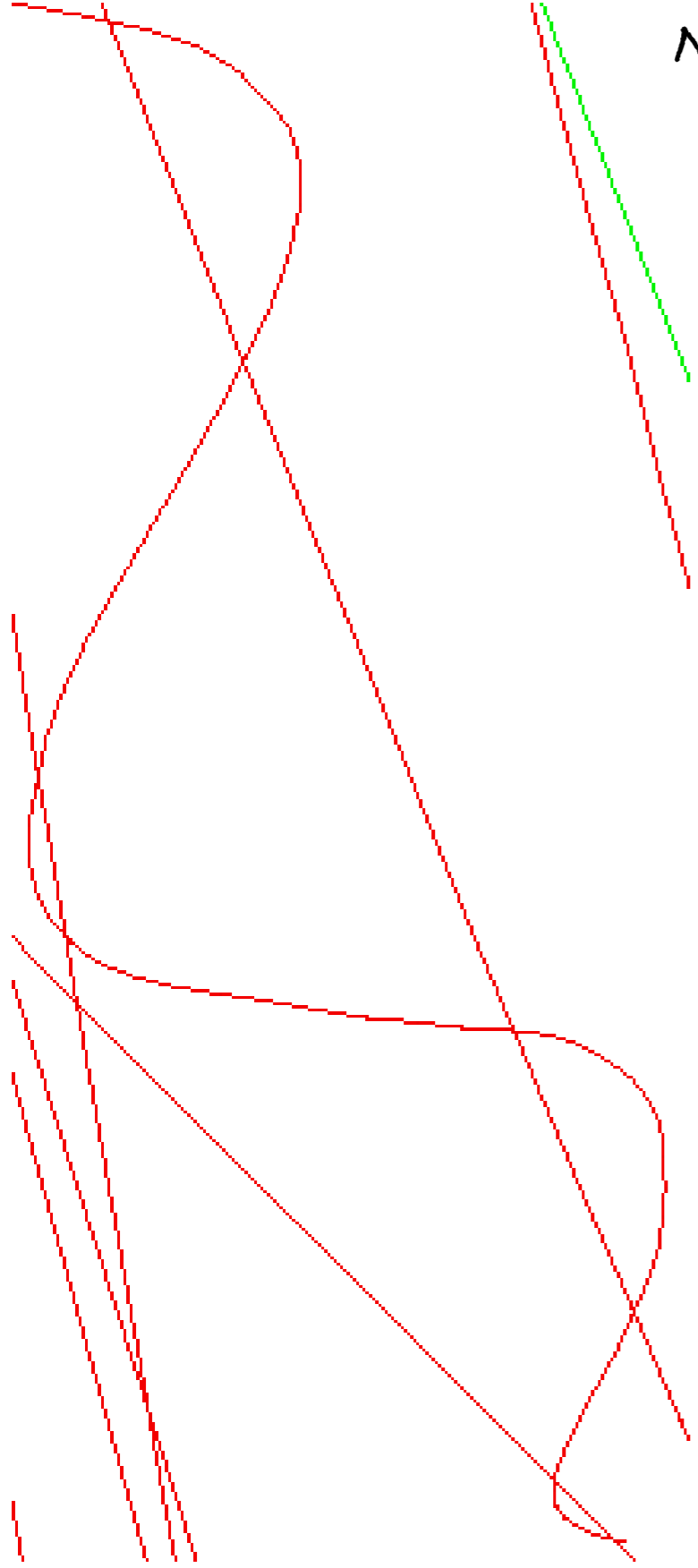
π decay in μ



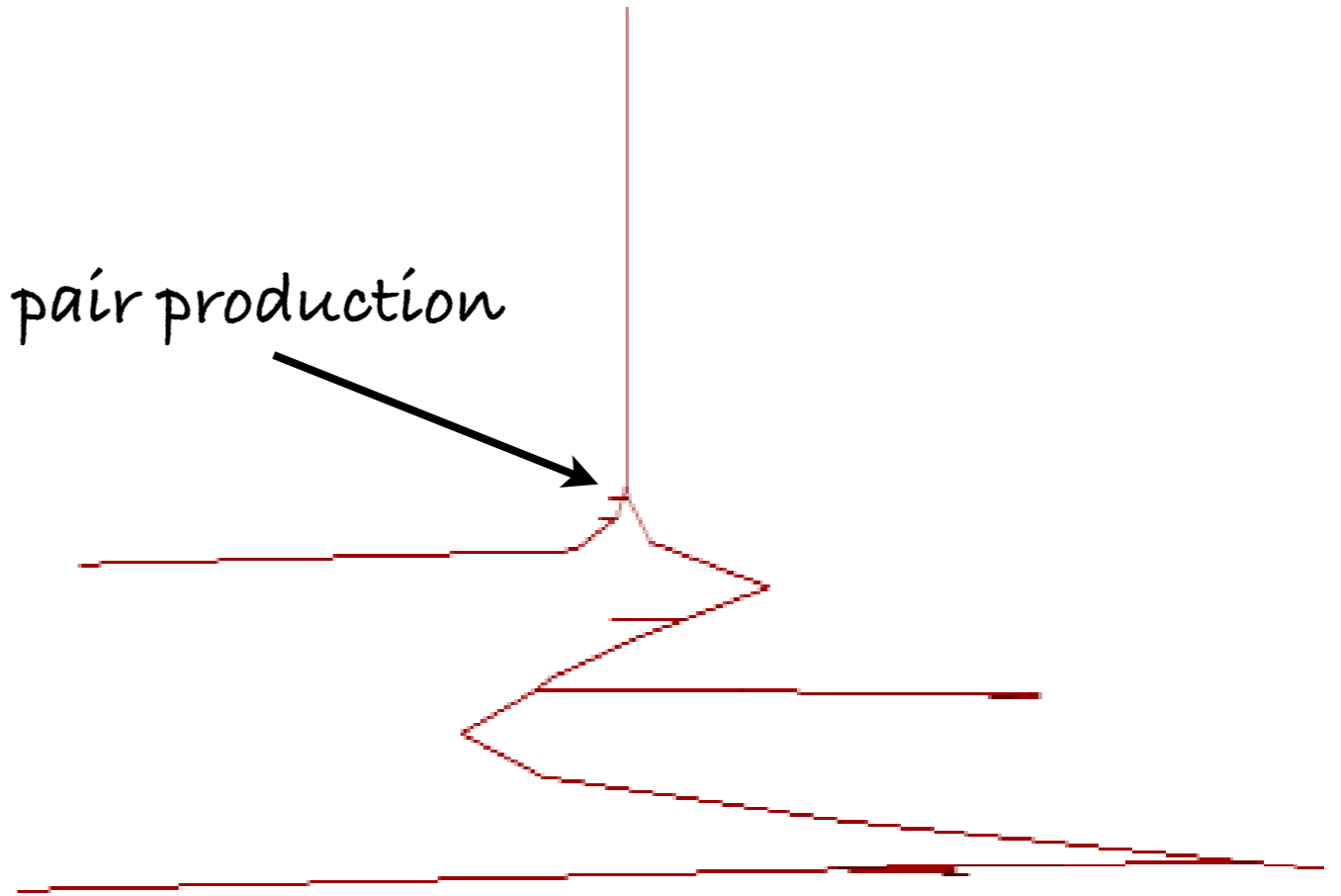
Muon decays



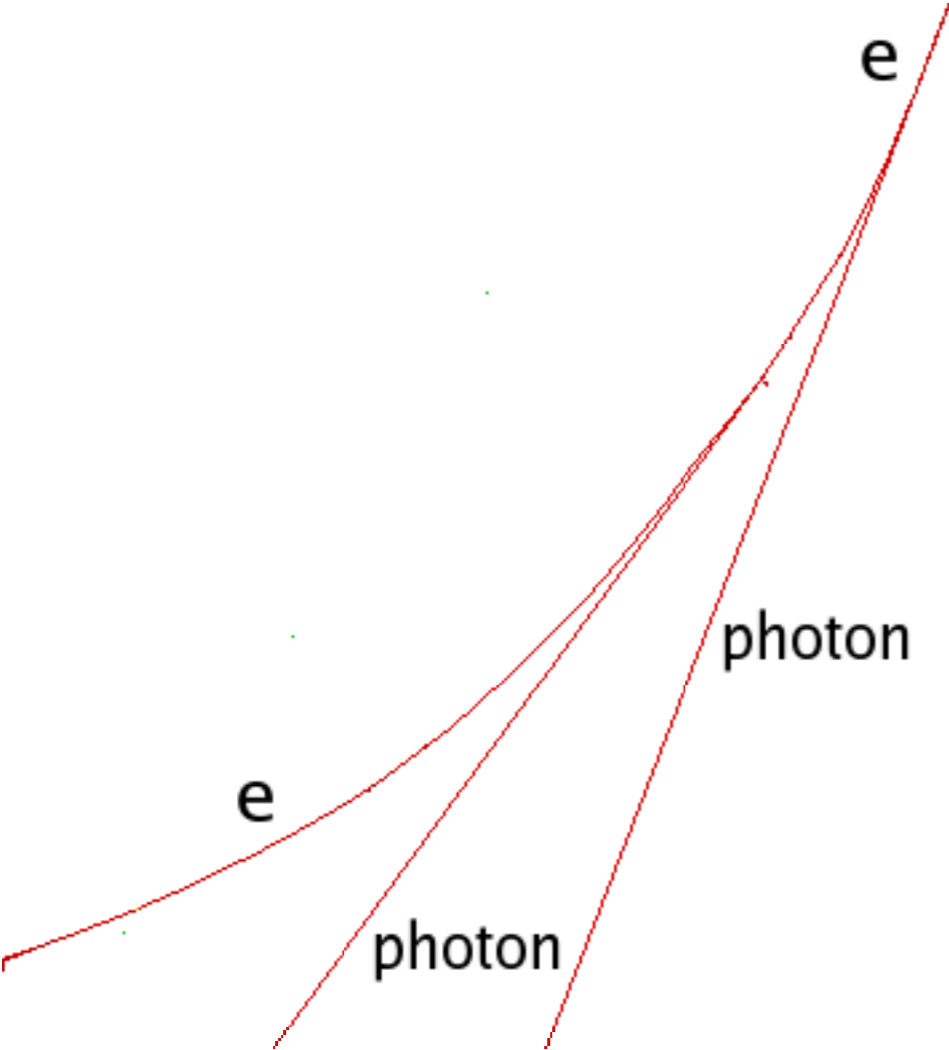
Magnetic deflection:
charged particles spiral around
Earth magnetic field.



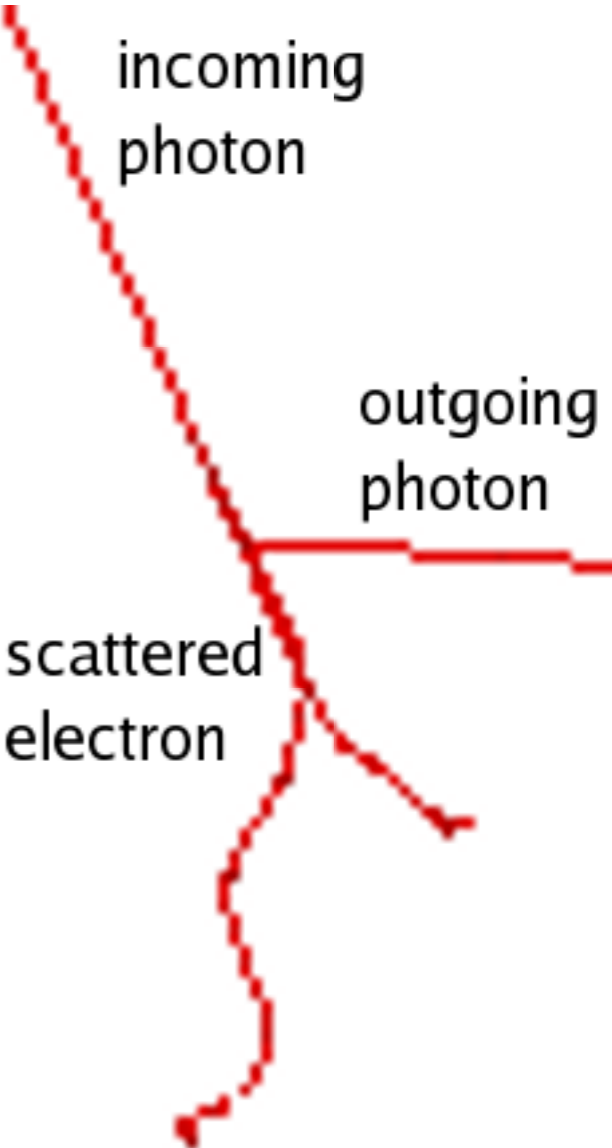
e^+e^- pair production

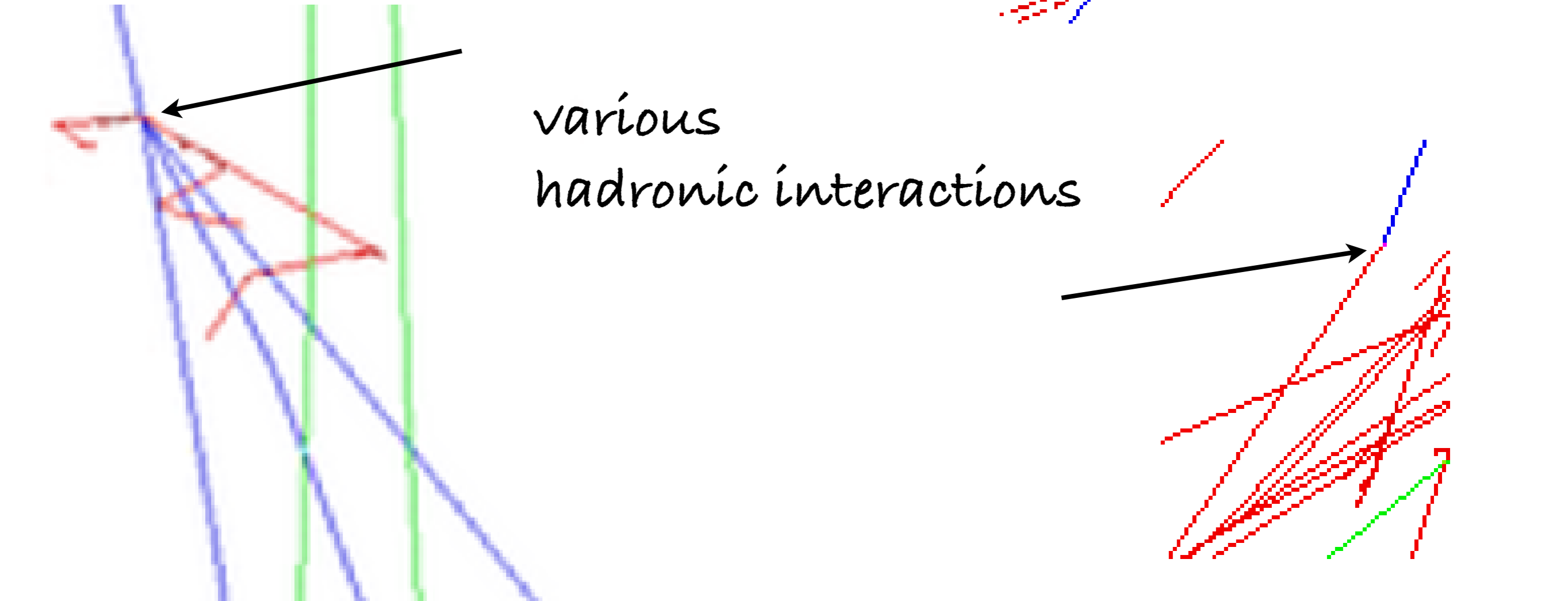
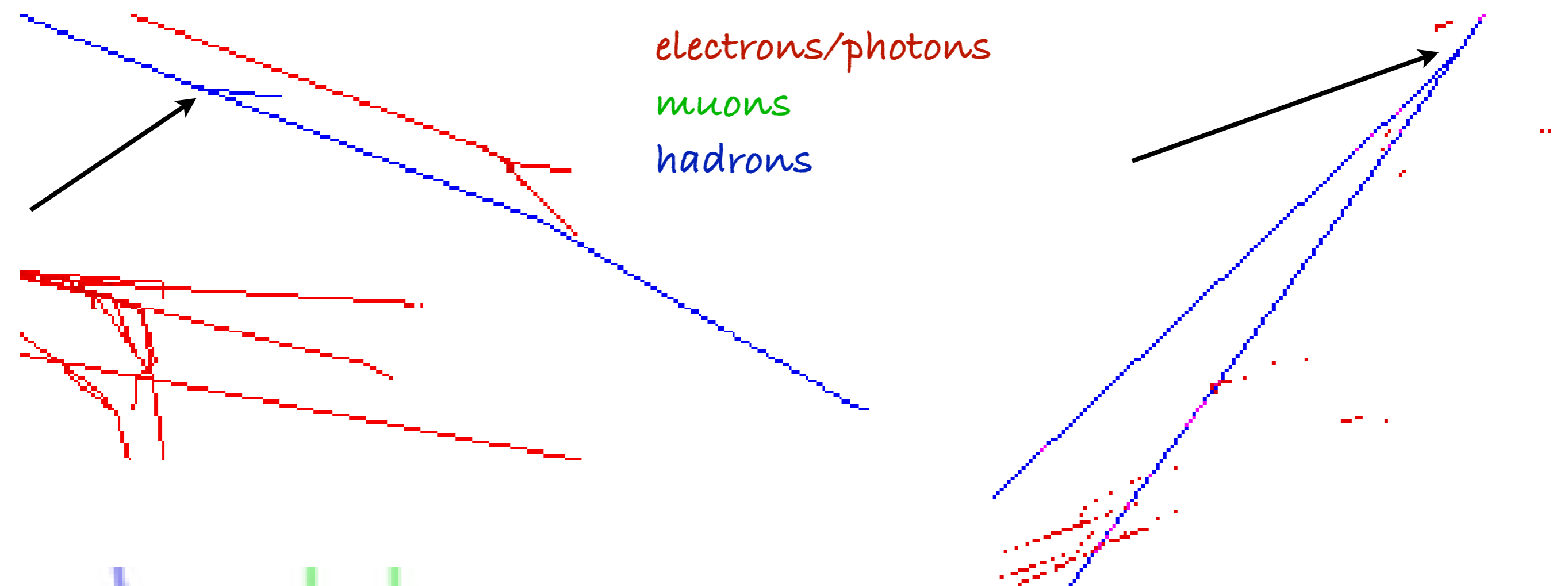


Bremsstrahlung



Compton scattering



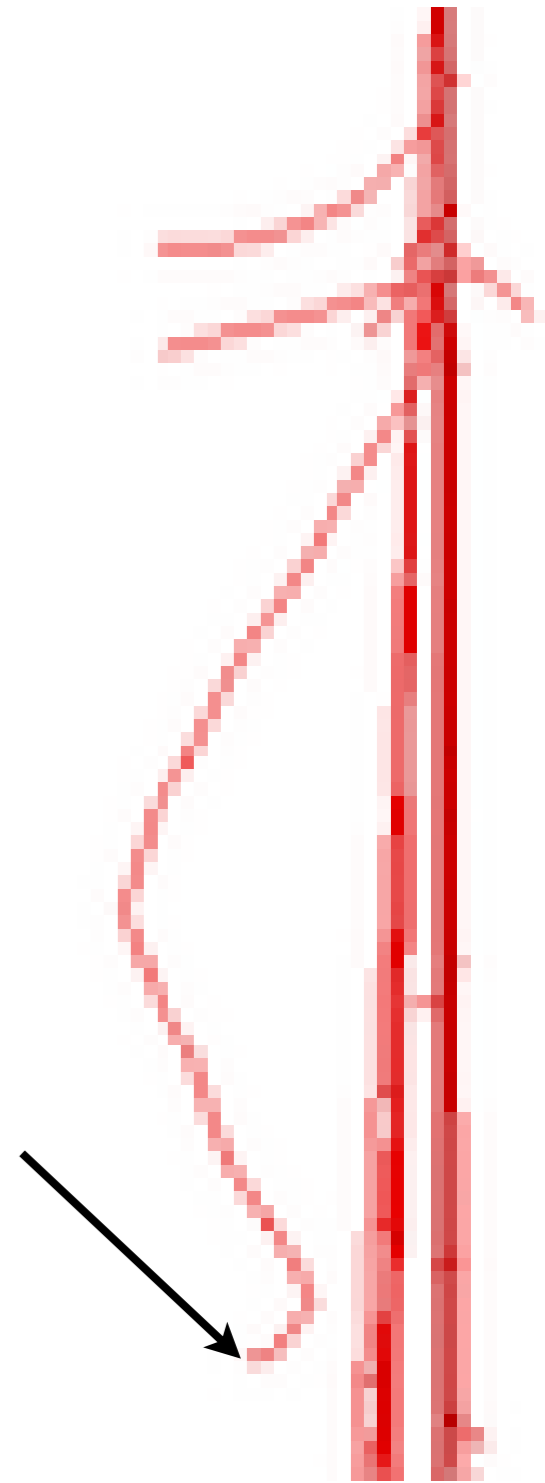




photon induces
electromagnetic sub-shower



protons (or neutrons)
are absorbed



electron slowed down
and absorbed

2 TeV gamma shower, bottom view

Development of a 2TeV Gamma Ray Shower from first interaction to the Milagro Detector

Viewed from below the shower front -
Color coded by Particle Type

This movie views a CORSIKA simulation of a gamma ray initiated shower. The purple grid is 20m per square and is moving at the speed of light in vacuum. The height of the shower above sea level is shown at the bottom of the screen.

Blue - electrons and gammas

Yellow - muons

Green - pions and kaons

Purple - protons and neutrons

Red - other, mostly nuclear fragments

2 TeV proton shower, bottom view

Development of a 2TeV Proton Shower from first interaction to the Milagro Detector

Viewed from below the shower front -
Color coded by Particle Type

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2 TeV gamma shower onto Milagro, side view

Shower from a vertical 2TeV Gamma Ray Primary Side View

Note the penetration of the shower core almost to the second layer of detectors (6m) and the formation of the bowl and ring structure by the shower core. The ring is the classic Cherenkov radiation pattern, and the bowl is formed by multiple scattering - many small rings from highly scattered particles adding up to form a bowl. In the Milagro pond the probability density of Cherenkov light emission from an entering particle is in this bowl-ring distribution.

Red - electrons and positrons

Green - secondary gammas

Blue - Cherenkov Photons

2 TeV gamma shower onto Milagro, bottom view

Shower from a vertical 2TeV Gamma Ray Primary Bottom View

This shower is seen from below the Milagro pond. Note the small Cherenkov rings from the peripheral particles and the prominent bowl and ring structure formed by the core. The boxes are the same size, but the white box is at the water surface, and the purple box moves with the shower front.

Red - electrons and positrons

Green - secondary gammas

Blue - Cherenkov Photons

2 TeV proton shower onto Milagro, side view

Shower from a vertical 2TeV Proton Primary Side View

At this energy proton showers tend to have many fewer particles hitting the pond - as seen by the wide particle spacing in this relatively strong proton shower. Notice the very distinctive Cherenkov cone left by a muon.

Red - electrons and positrons

Green - secondary gammas

Yellow - muons

Blue - Cherenkov Photons

200 MeV electrons onto Milagro, side view

Plane of 200MeV Electrons at 20°

Side View

In this movie the shower reference plane color has been changed from red to purple, and two white planes representing the upper and lower layers of photodetectors in the Milagro pond have been added (1.5m and 6.15m depths respectively). Note the delayed refraction of the showerfront due to the penetration of gamma ray photons into the Milagro Pond. The gammas are produced by Bremsstrahlung in the air and water. See the movie 20dE200MeVNC to clearly observe the separation by particle type that occurs.

Red - electrons and positrons

Green - secondary gammas

Blue - Cherenkov Photons

The Future of CORSIKA ... is bright.

- new results from RHIC, LHC on cross sections, very forward data, particle production, ...
- model-constraining cosmic ray results from AMS, Tracer, PAMELA, IACTs, KASCADE-Grande, Auger-S,
- progress in theory ?
- Many new results on the Origin of Cosmic Rays ahead.

Summary :

- **CORSIKA** has revolutionised the field and is now the "Gold Standard" of the EAS community.
- **CORSIKA** is not perfect, but approximately correct

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- **CORSIKA** has revolutionised the field and is now the "Gold Standard" of the EAS community.
- **CORSIKA** is not perfect, but approximately correct
- This is a great and lasting legacy of the KASCADE activity.

The End