Air Shower simulations with CORSIKA

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Ooty, India, December 17- 20, 2010

COsmic Ray SImulations for KAscade

A simulation package for particle showers in the atmosphere.

Cosmic Rays

and

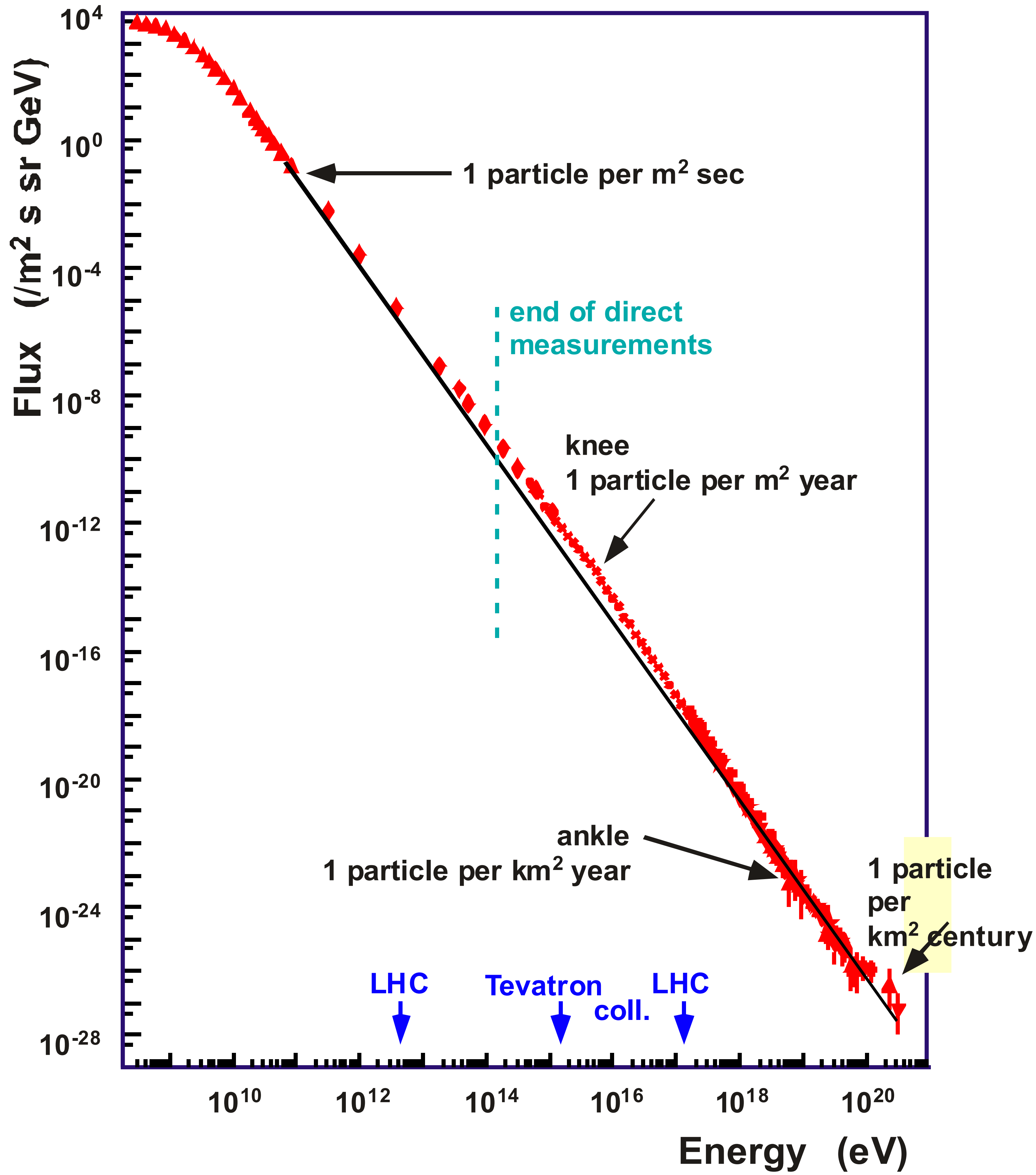
Air Showers

Cosmic Ray Flux:

steeply falling:

x 10 up in energy

1/500 down in flux



N_{evts} = flux x area x 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

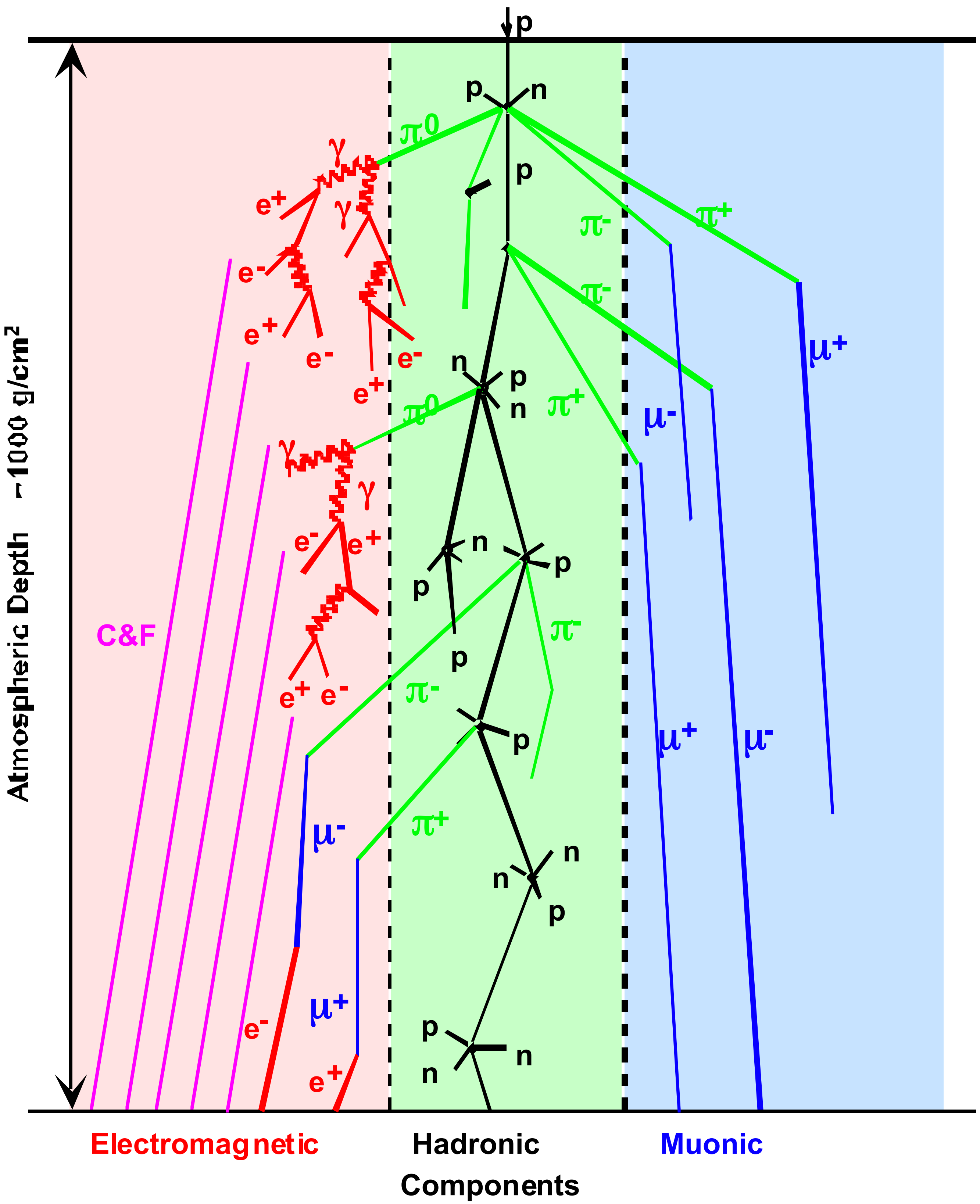
Natural detectors: atmosphere, water, ice

← 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 $\pi^\pm$, K, decays ≈ 1 GeV

Ne,γ : Nμ ≈ 10 - 100 varying with core distance, energy, mass, Θ, ...

Details depend on:

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

at energies from ≈ 10^6 ... >10^{20} eV

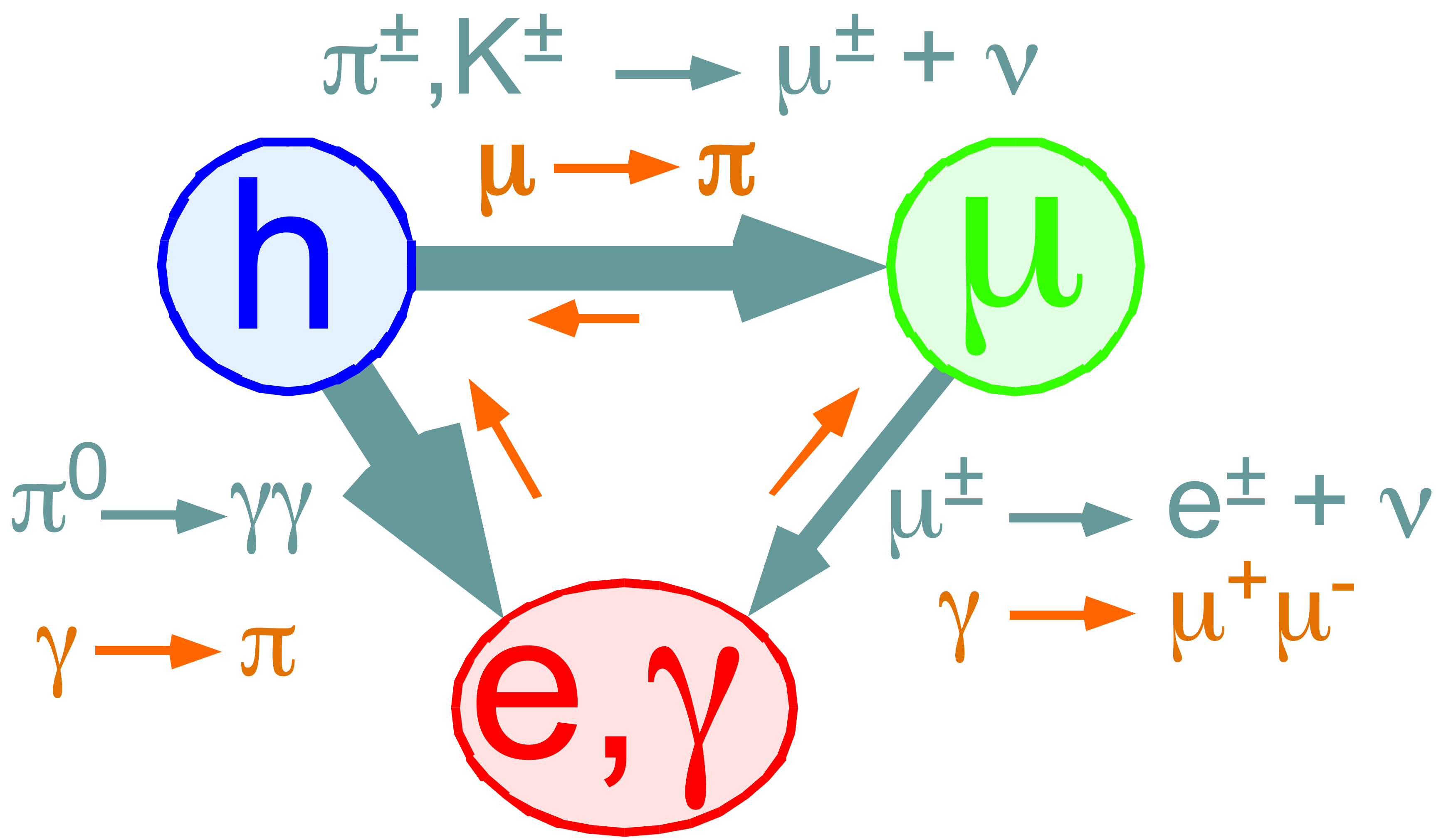
(far above man-made accelerators)

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 idealized 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, m, ϑ, r, ...

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 ← in case of discrepancy : difficult to identify origin; in case of agreement : is parameter combin. unique ?

i.e. perform a Consistency Check

Iterative process (many different experiments / variables / variable combinations)
to understand
cosmic ray physics and air shower development simultaneously.

CORSIKA

Archeology of CORSIKA

pre 1989

SH2C-60-K-OSL-E-SPEC (P Grieder):
- main structure,
- isobar model for hadronic interactions

HDPM & NKG (Capdevielle):
- high-energy hadronic interactions,
- analytic treatment of electro magnetic 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

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

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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

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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.

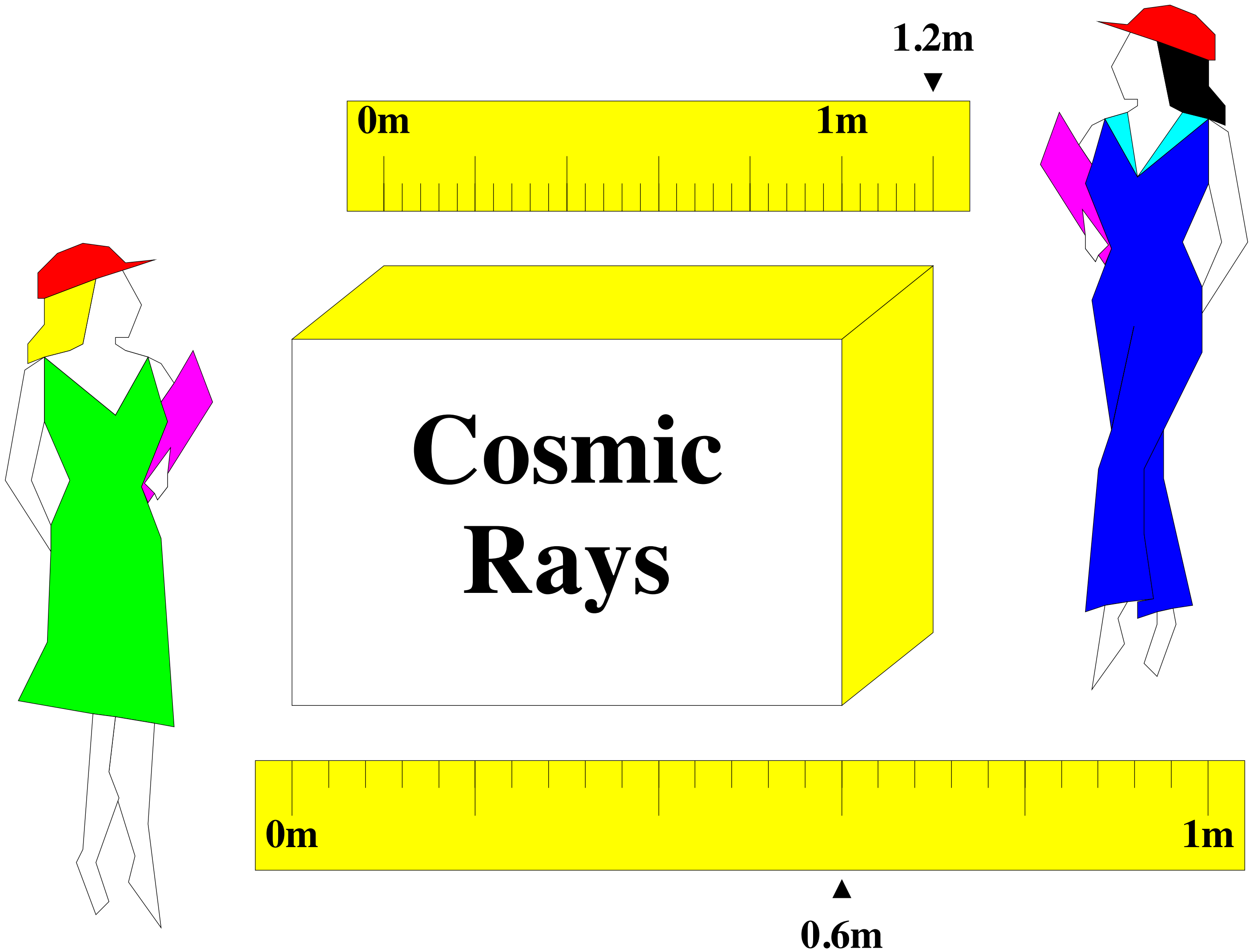

KfK 4998
November 1992
The Karlsruhe Extensive Air Shower Simulation Code CORSIKA
J. N. Capdevielle, P. Gabriel, H. J. Gils, P. Grieder,
D. Heck, J. Knapp, H. J. Mayer, J. Oehlschläger,
H. Rebel, G. Schatz, T. Thouw
Institut für Kernphysik
Kernforschungszentrum Karlsruhe
Forschungszentrum Karlsruhe
Technik 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

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



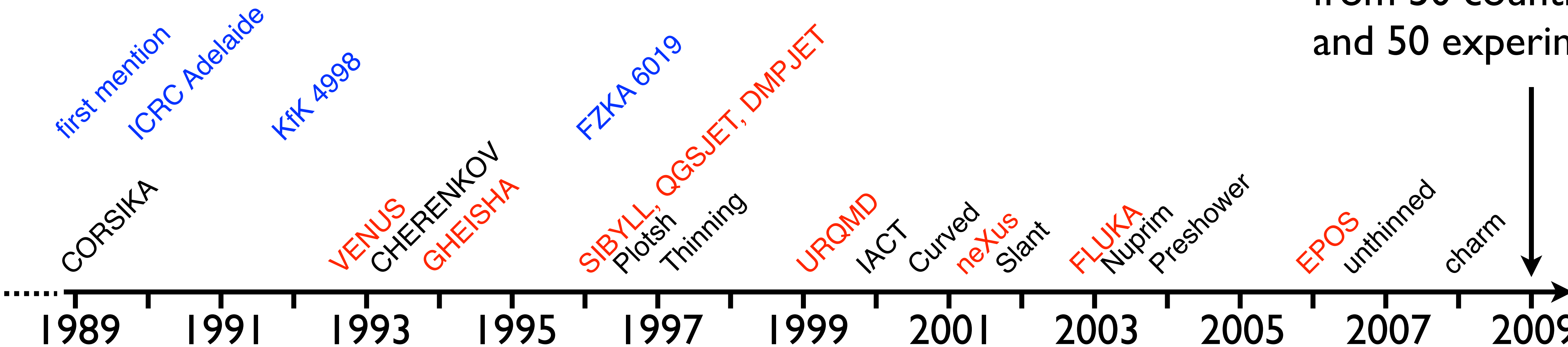
Fly's Eye:
The box is 0.6m wide
(Composition changes)

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

700 users
from 50 countries
and 50 experiments



> 1 day per
10^{15} eV shower

< 20 min per
10^{15} eV shower

KfK 4998 + FZKA 6019 > 870 citations !

by far the most cited work of its authors

The Timeline

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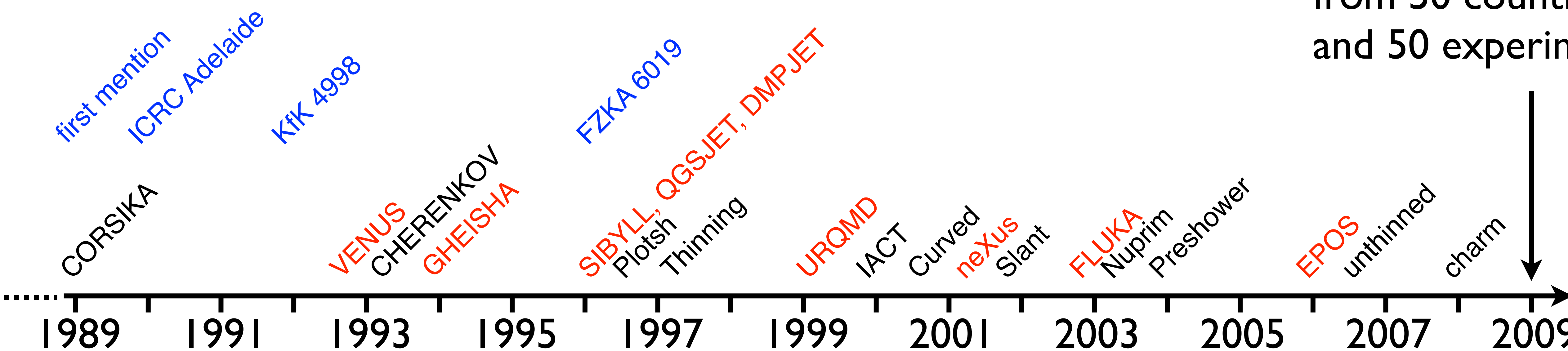

> 1 day per
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KfK 4998 + FZKA 6019 > 870 citations !

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CORSIKA:

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

tracking, decays, atmospheres, ...

el.mag.	EGS4 *
low-E.had.*	GHEISHA
	FLUKA *
	UrQMD
high-E.had.**	QGSJET **
	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: » 10^5 lines of code
Many years of development.

CORSIKA:

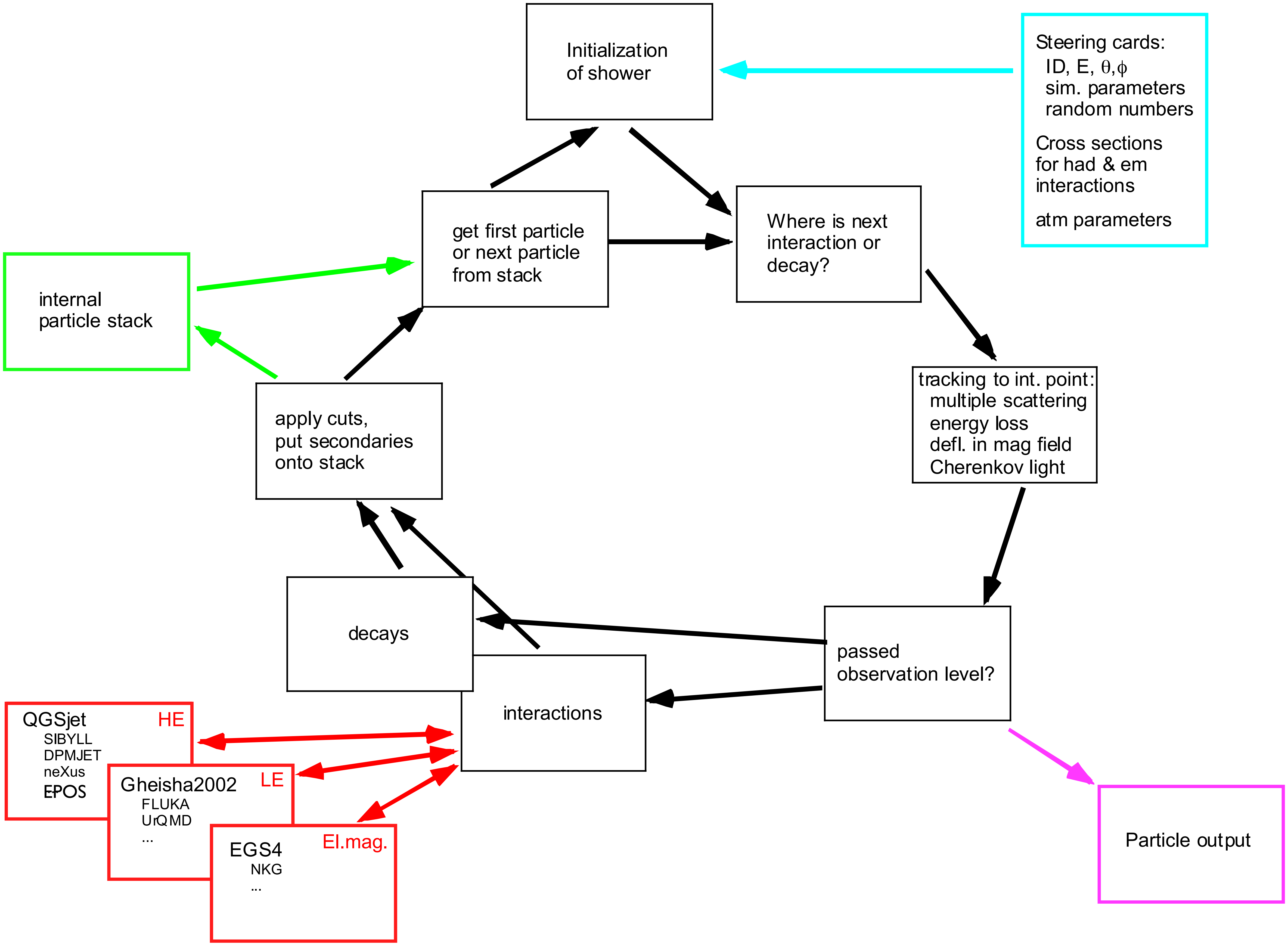
http://www-ik.fzk.de/corsika/

Free download (after registration)
Installation instructions
Detailed User's Guide

papers & talks

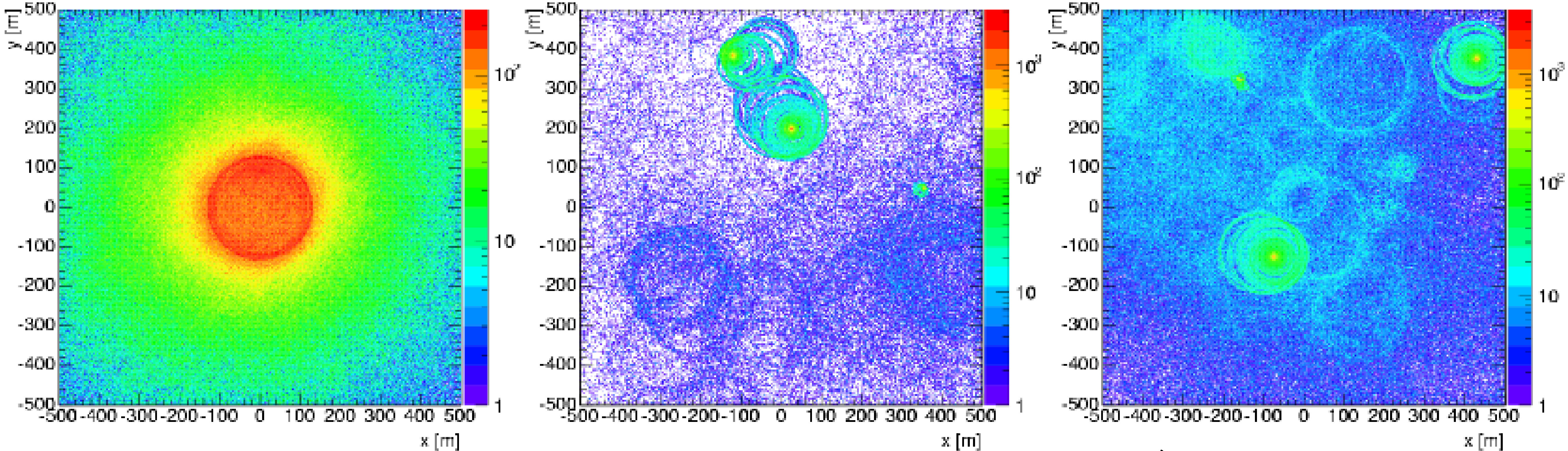
mostly Fortran code + some C routines,
self contained (no external packages needed),
runs on (virtually) all machines.

CORSIKA flow diagram

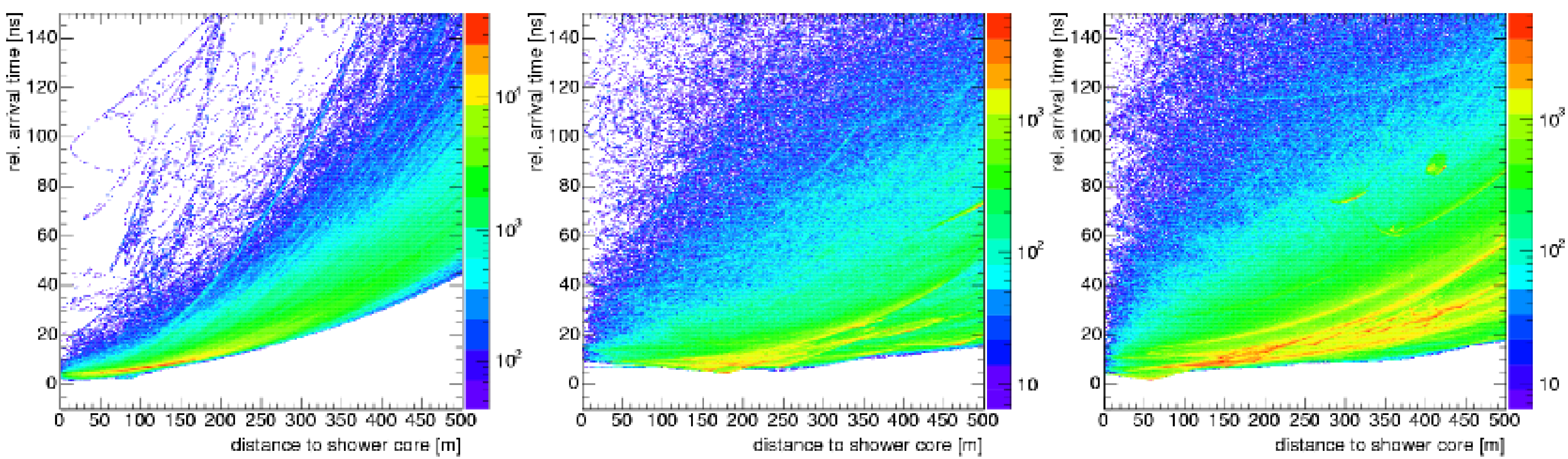


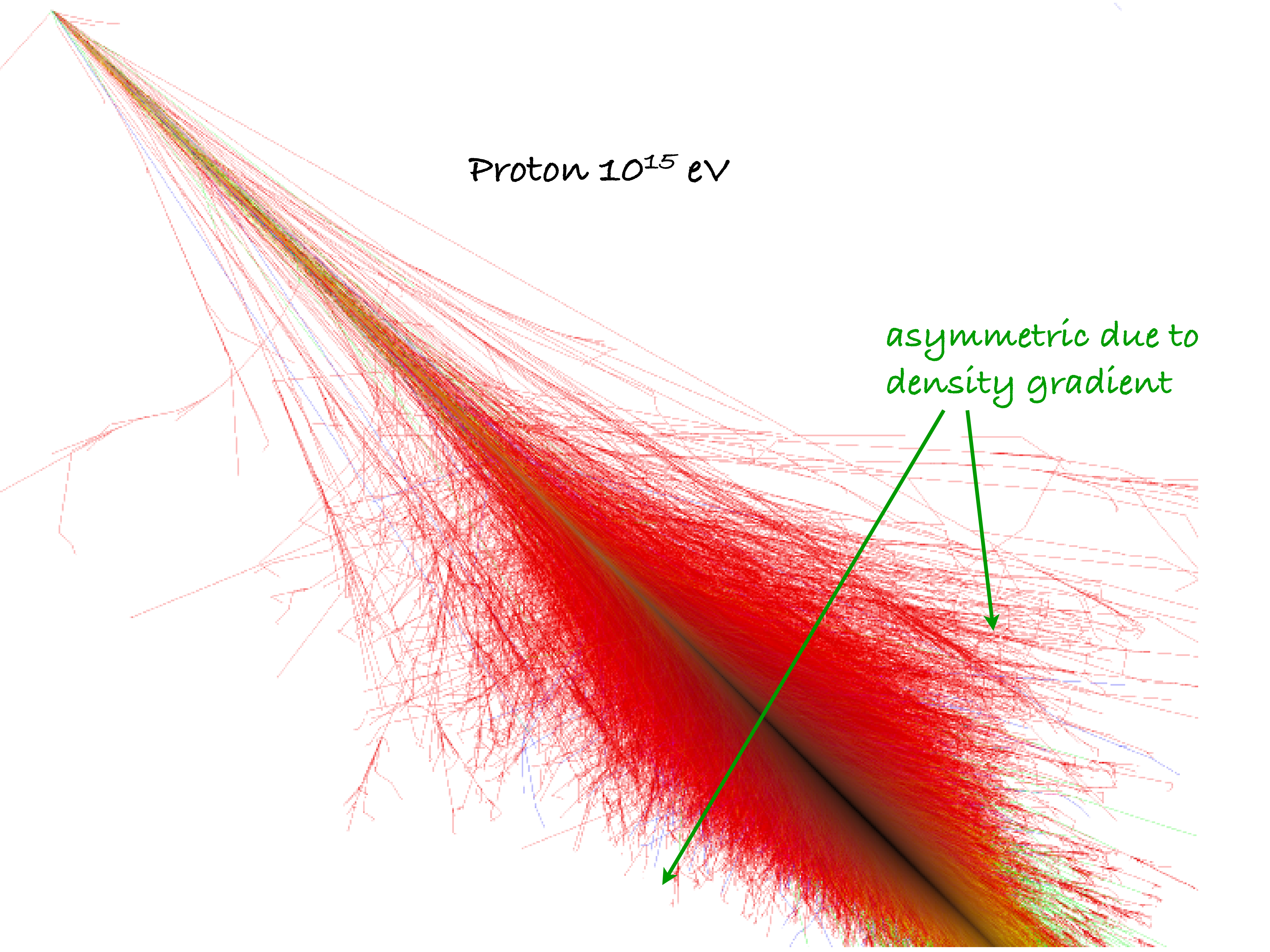
Examples of emerging features in detailed simulations:

Cherenkov light:



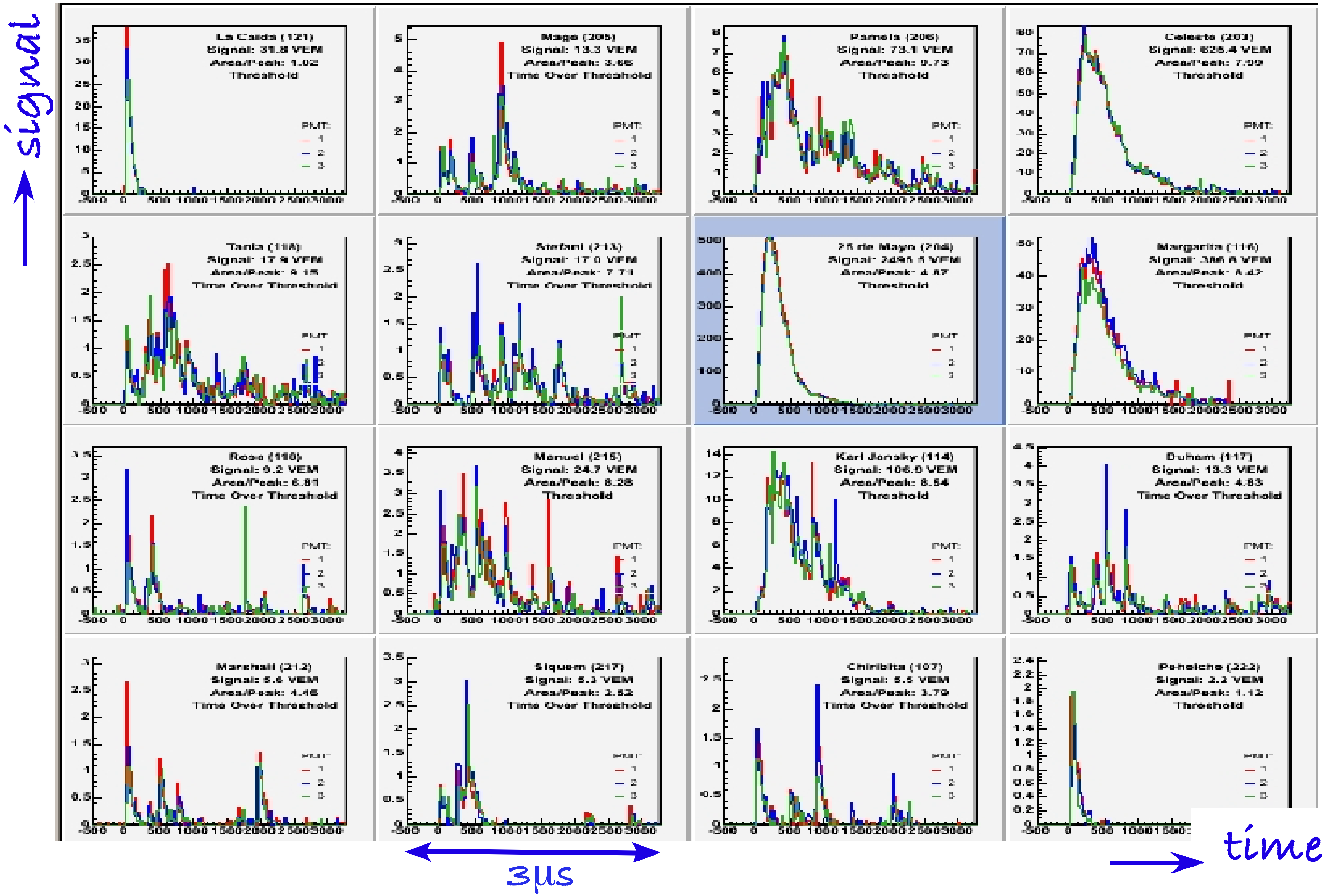
gamma 300 GeV　　proton 90 GeV　　iron 50 GeV





Proton 10^{15} eV
asymmetric due to density gradient

Pulse Shapes in Water-Cherenkov Detectors

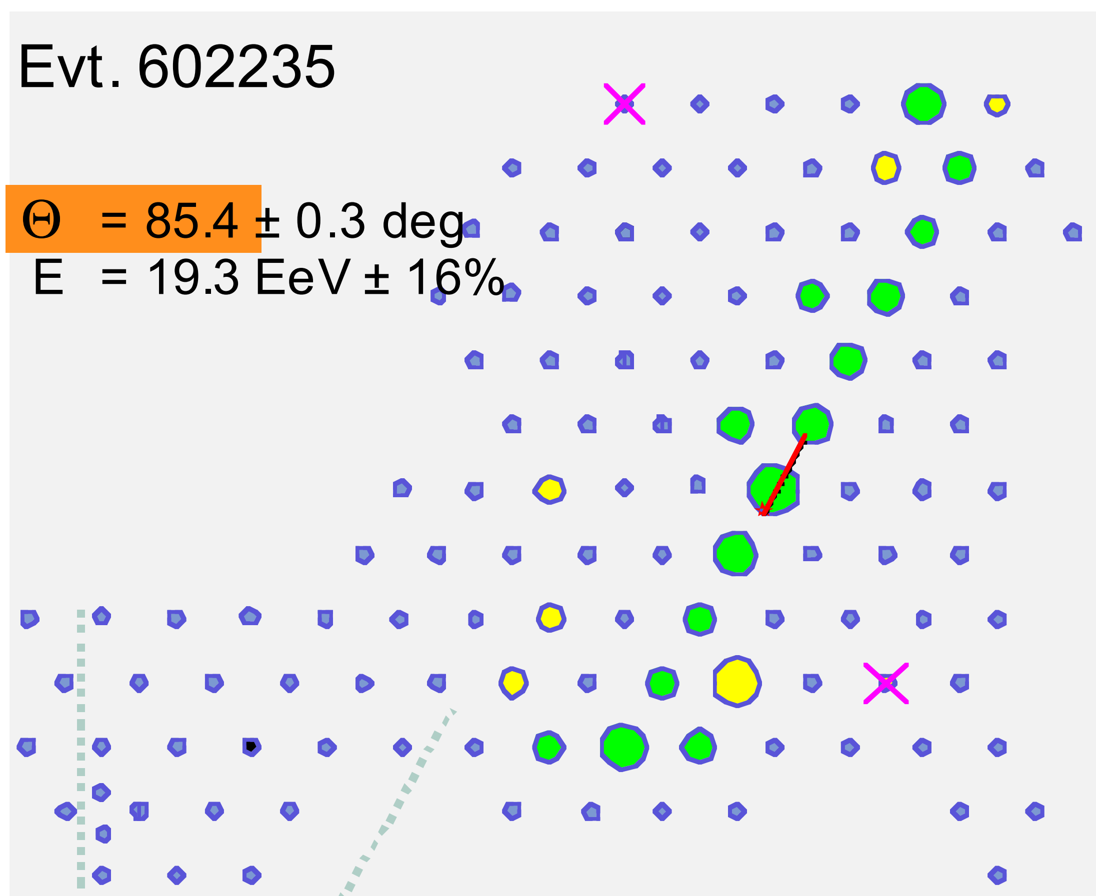


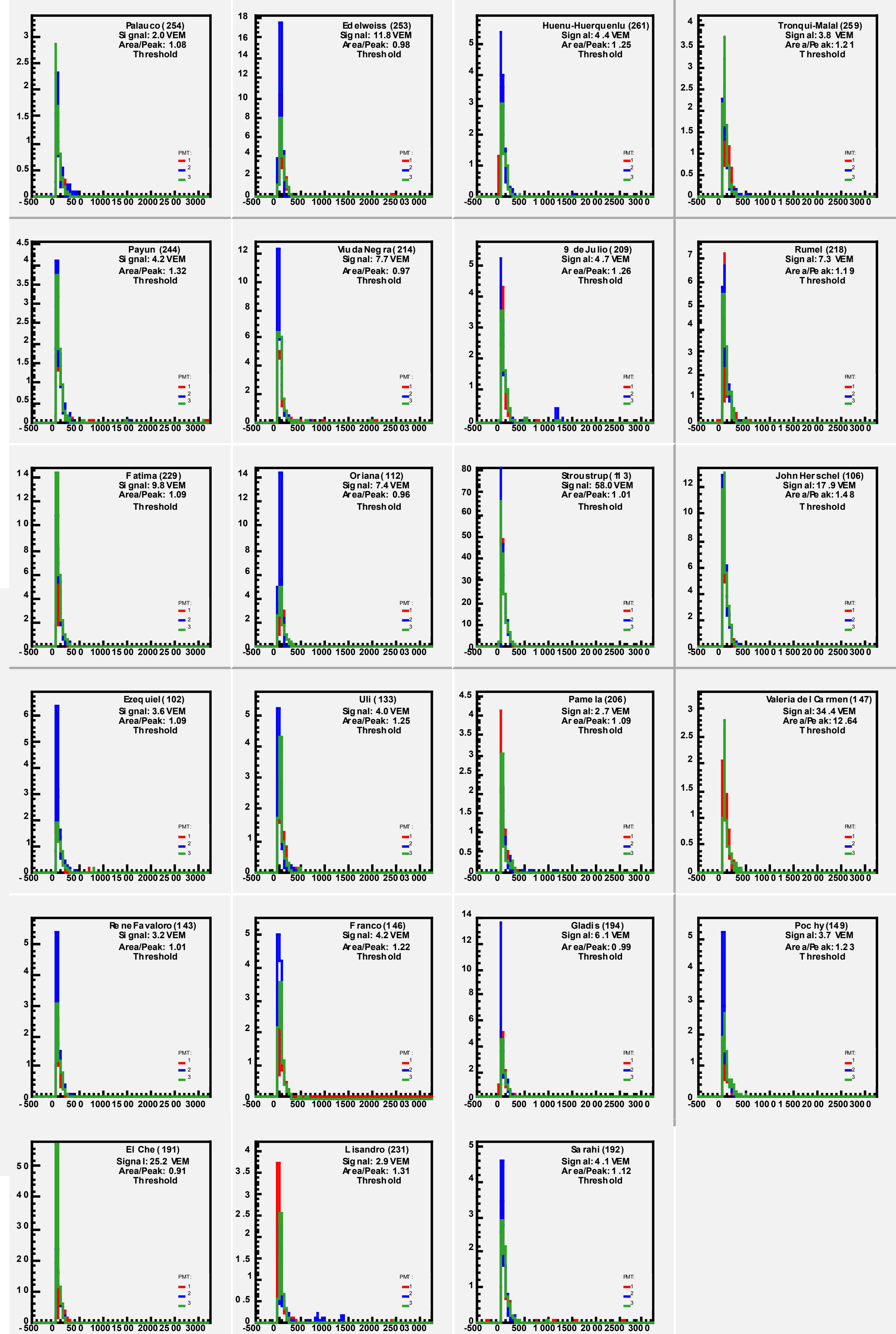
High, smooth pulses close to shower core, low, spiky pulses far away.

Horizontal showers

Only muons left in air shower.
Very narrow time traces.

Crucial for neutrino search with Auger.





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**

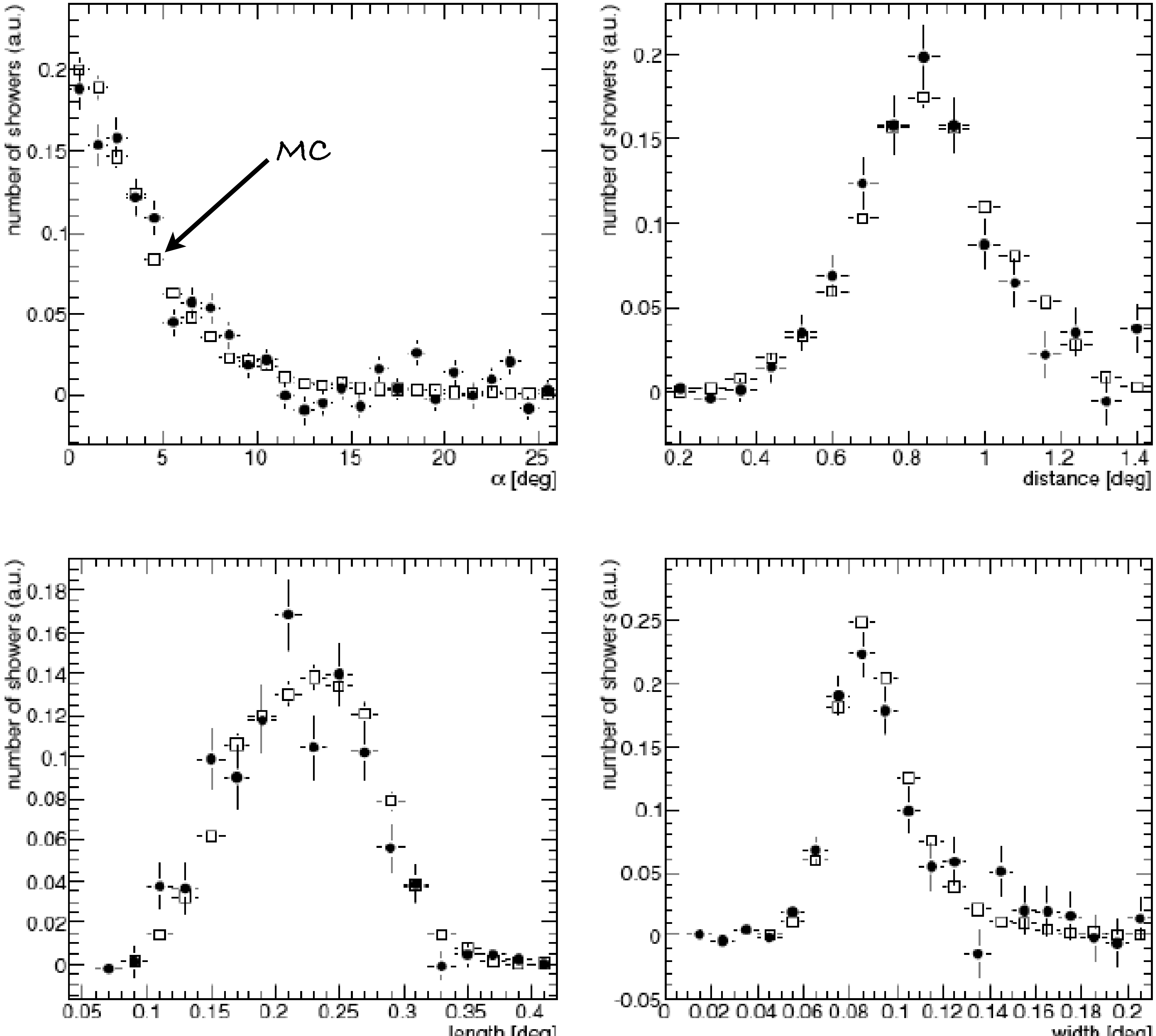
VERITAS

Telescope 1

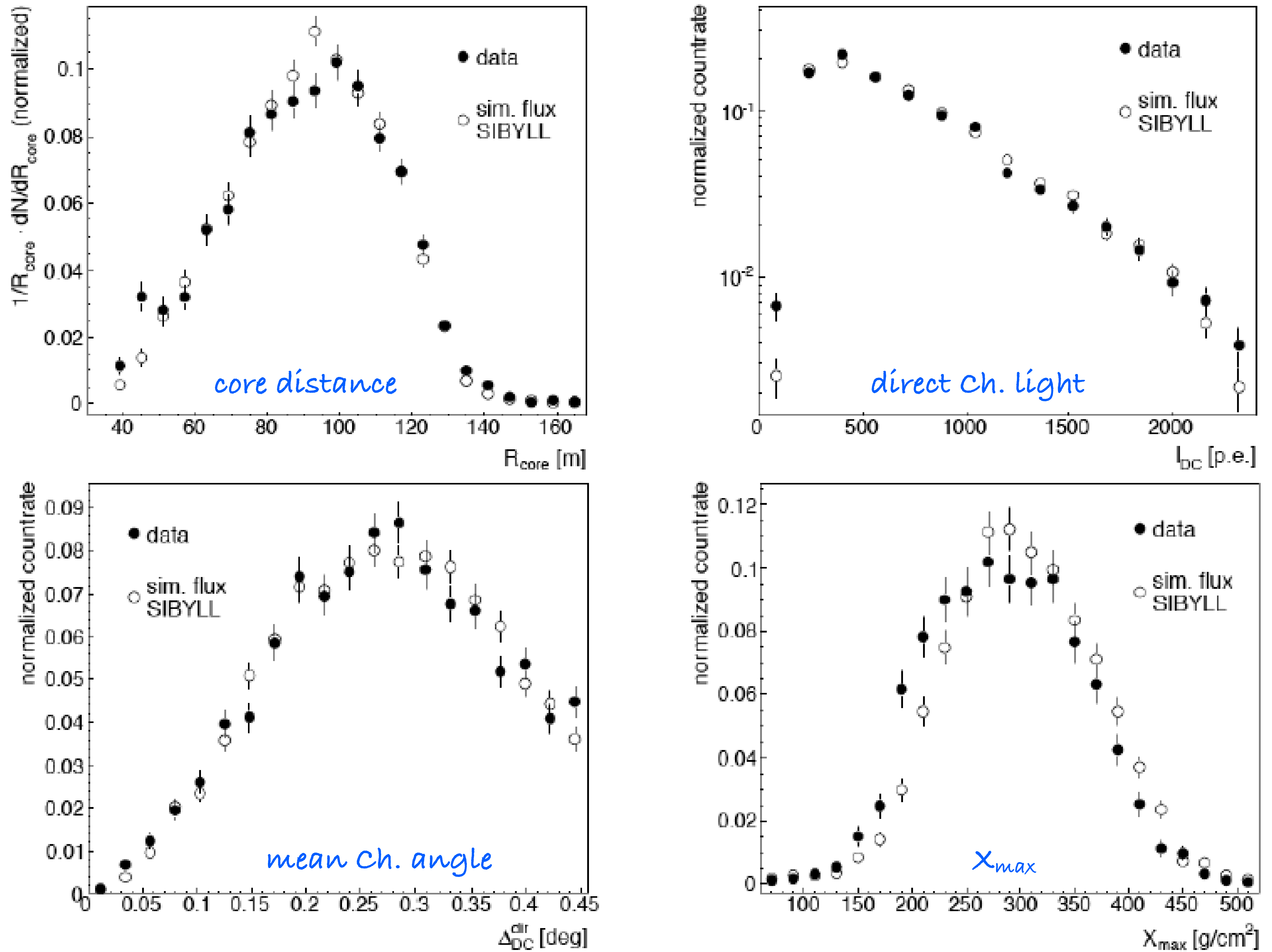
E > 150 GeV

gamma rays:
good agreement of image param. distributions

CR background:
absolute trigger rate within 15%



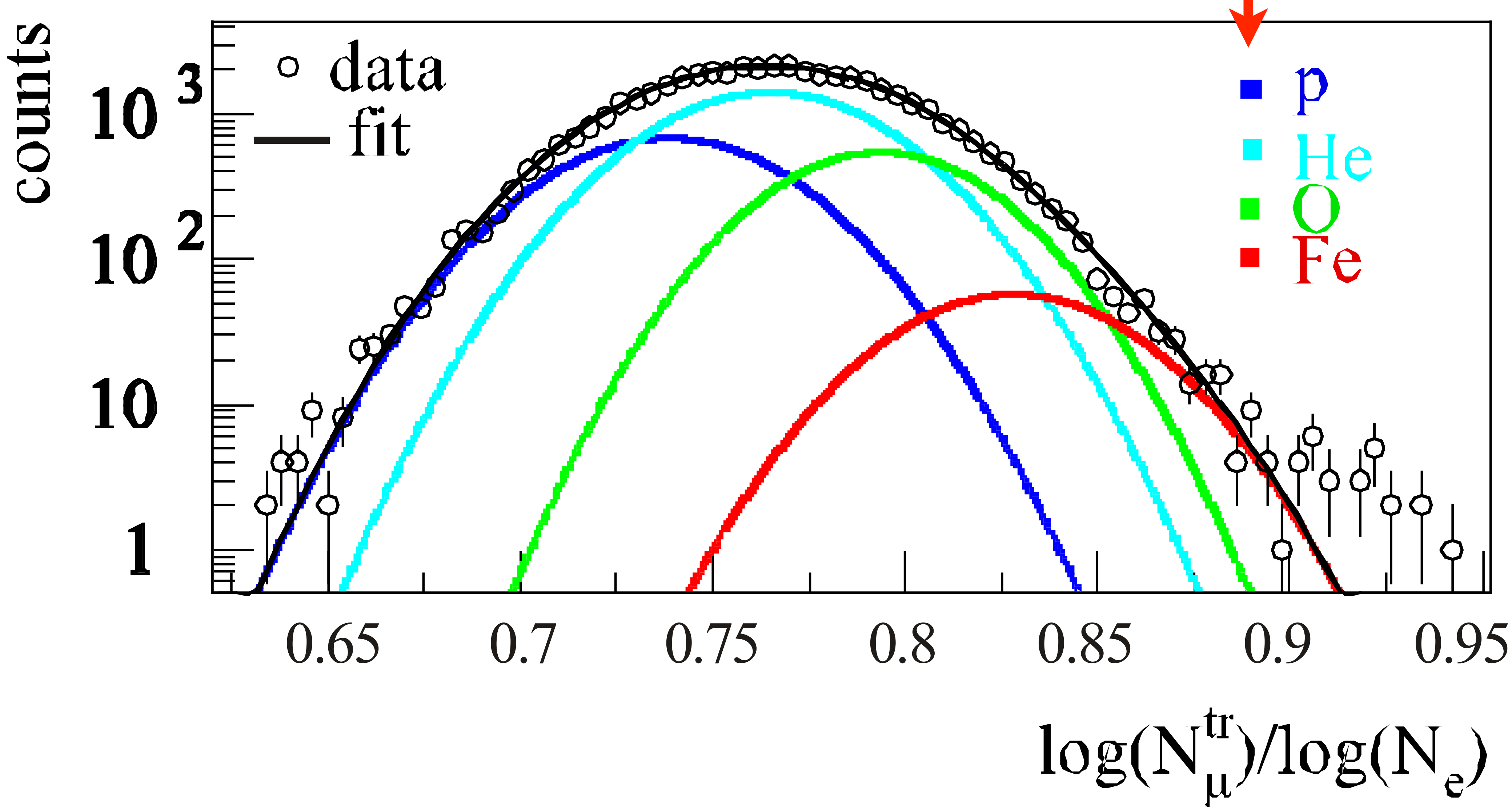
G Maier,
29th ICRC Pune (2005)
astro-ph/0507445



HESS 10-100 TeV mix of hadronic primaries astro-ph/0701766

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

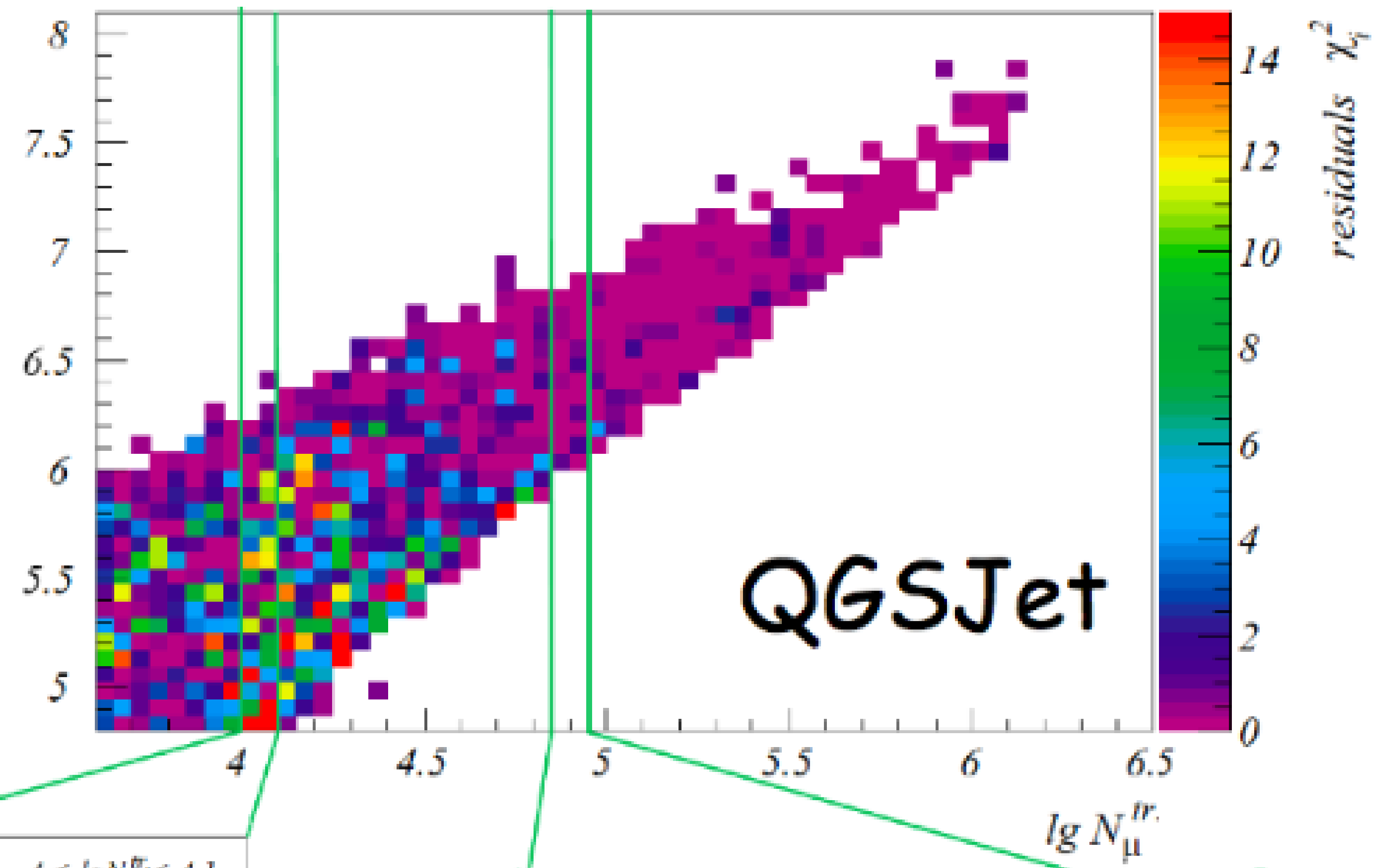
CORSIKA Simulations

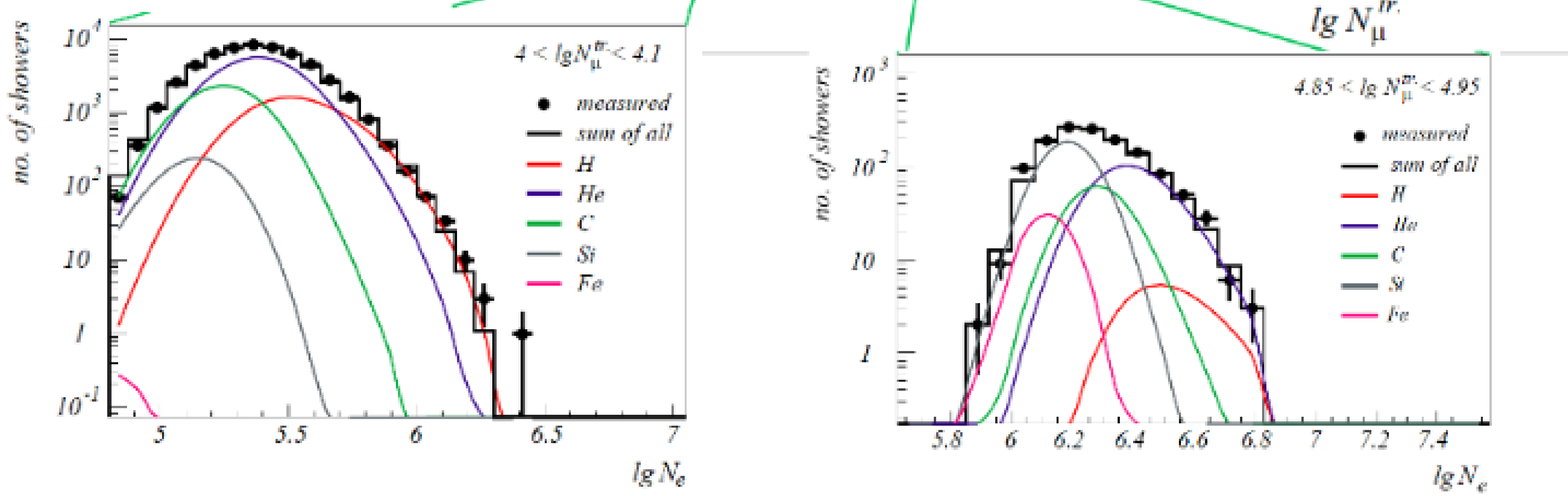


QGSJet - description of data

KASCADE

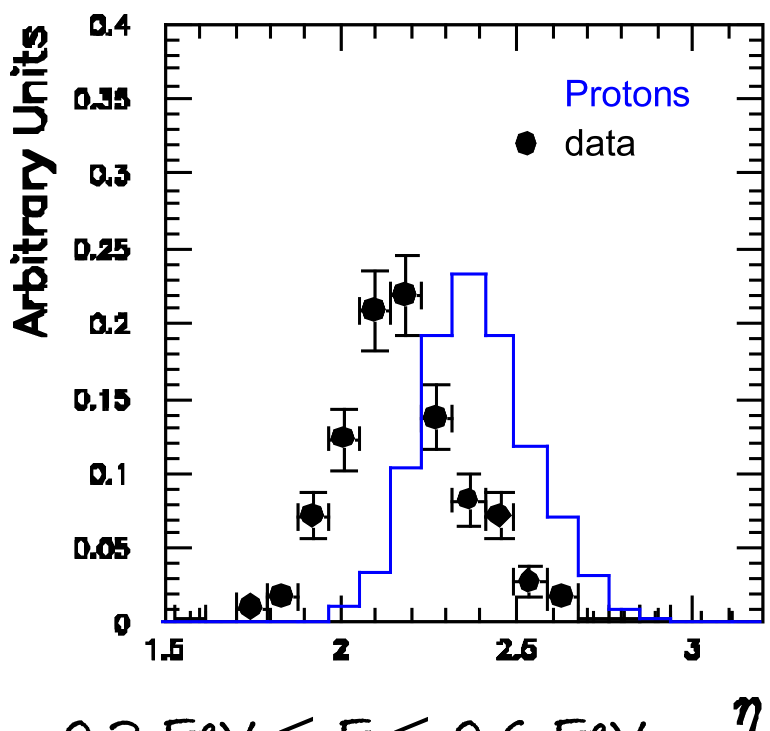
Fair agreement of Monte Carlo with exp. data.

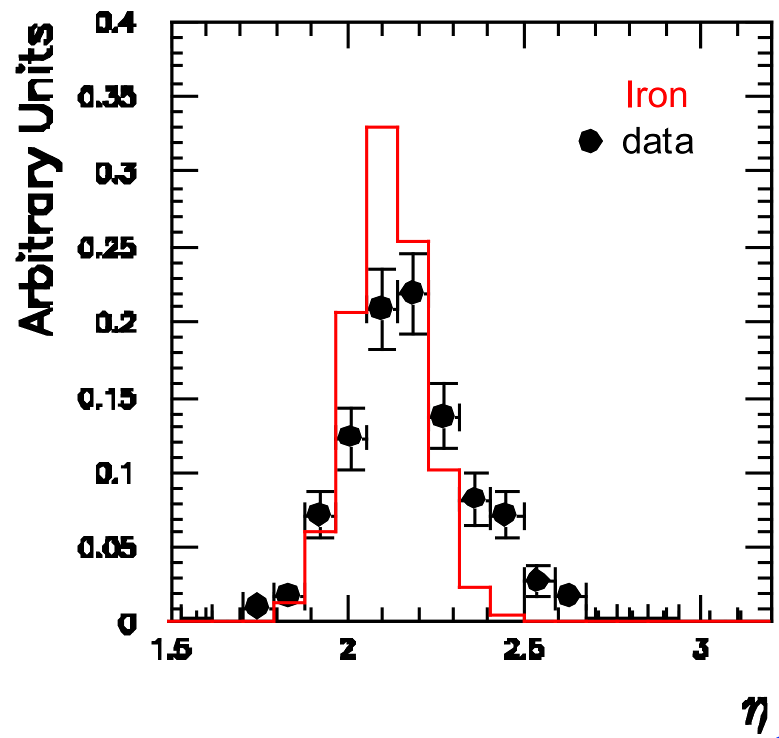


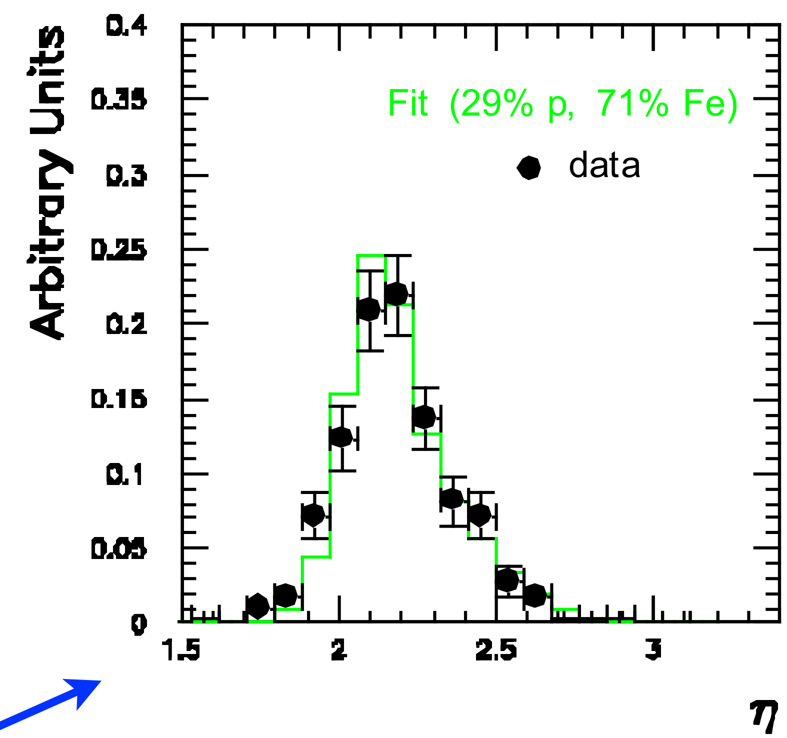


H Ulrich (KASCADE)

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

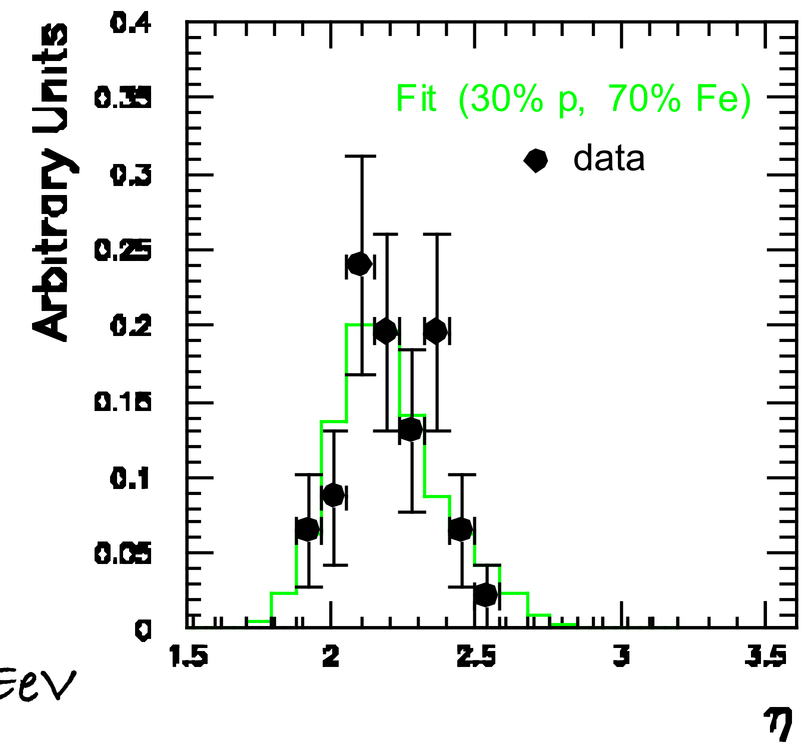






0.2 EeV < E < 0.6 EeV
292 events

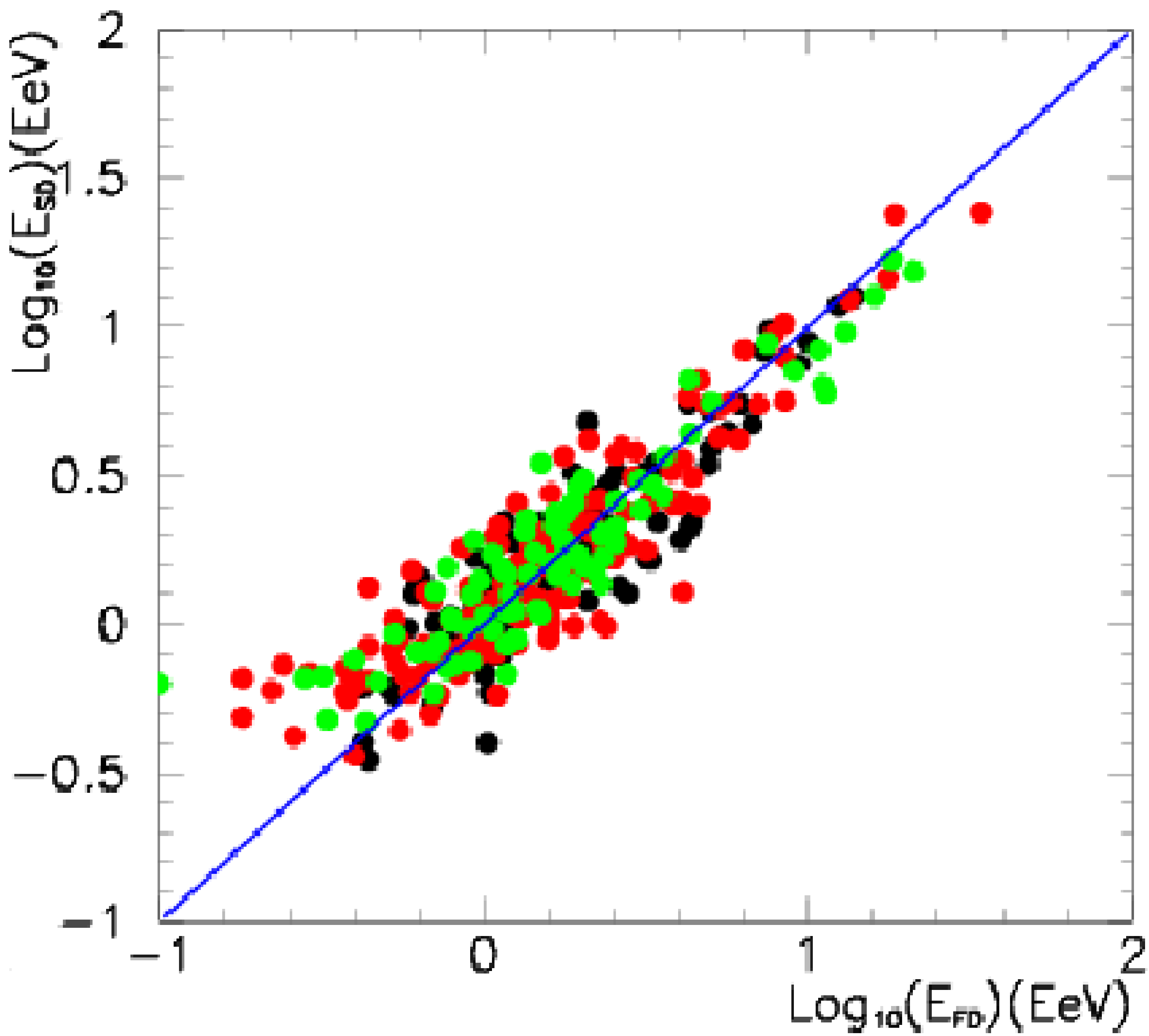
Models can describe data



0.6 EeV < E < 1 EeV
46 events

FD vs SD energy

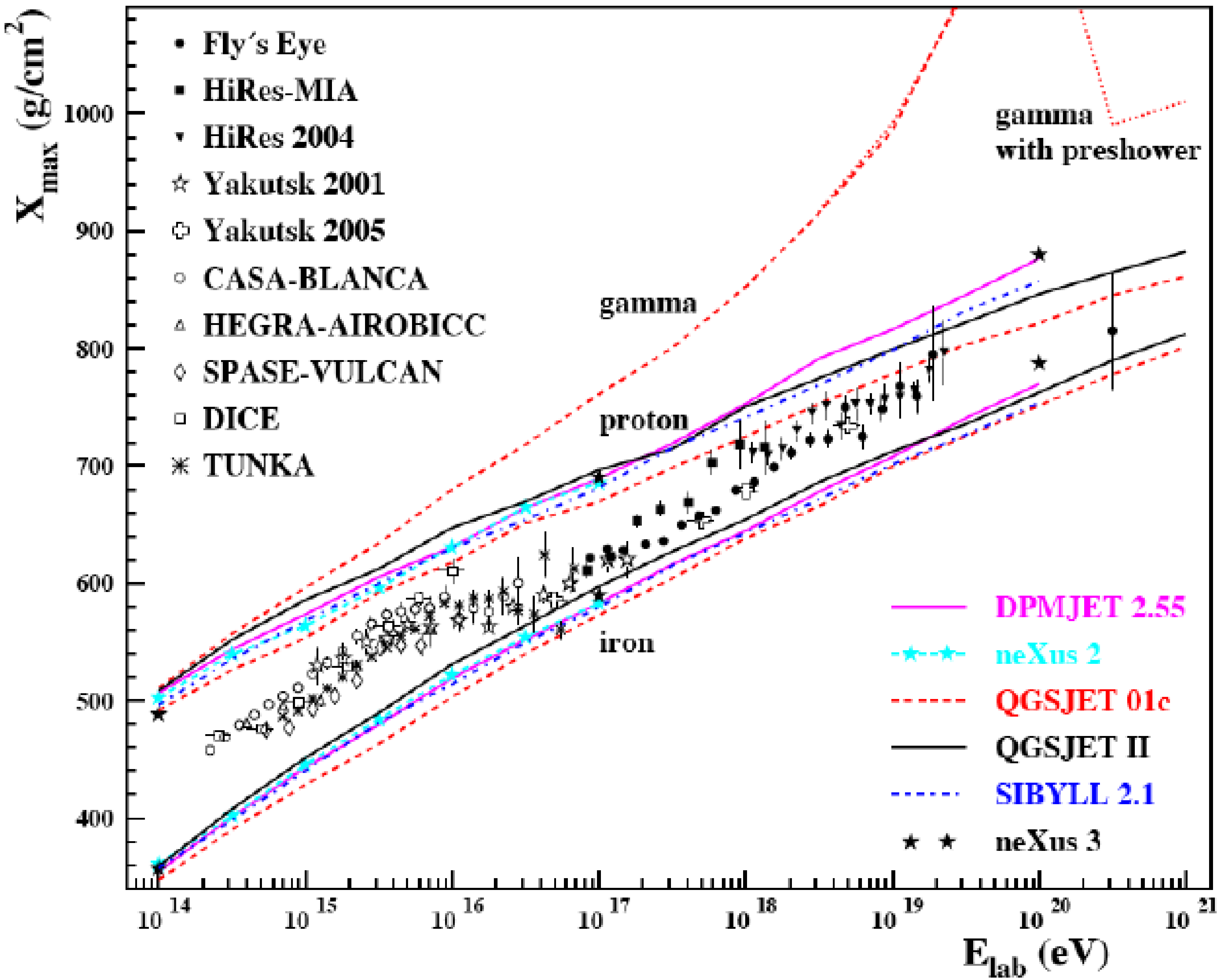
Auger ($E > 10^{18}$ eV)



- 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%)

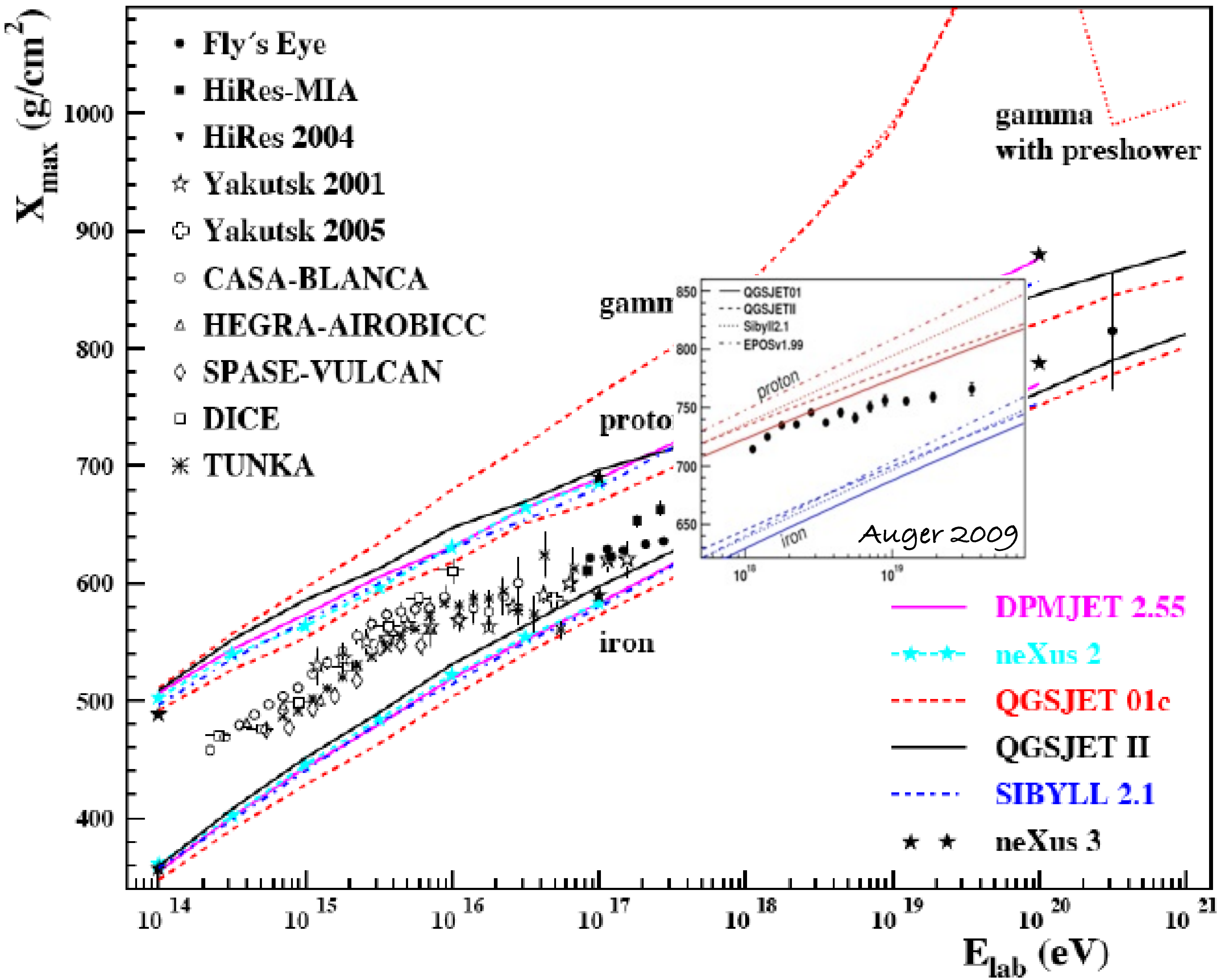
X_{max} as fct. of energy



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 .... $>10^{20}$ 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.

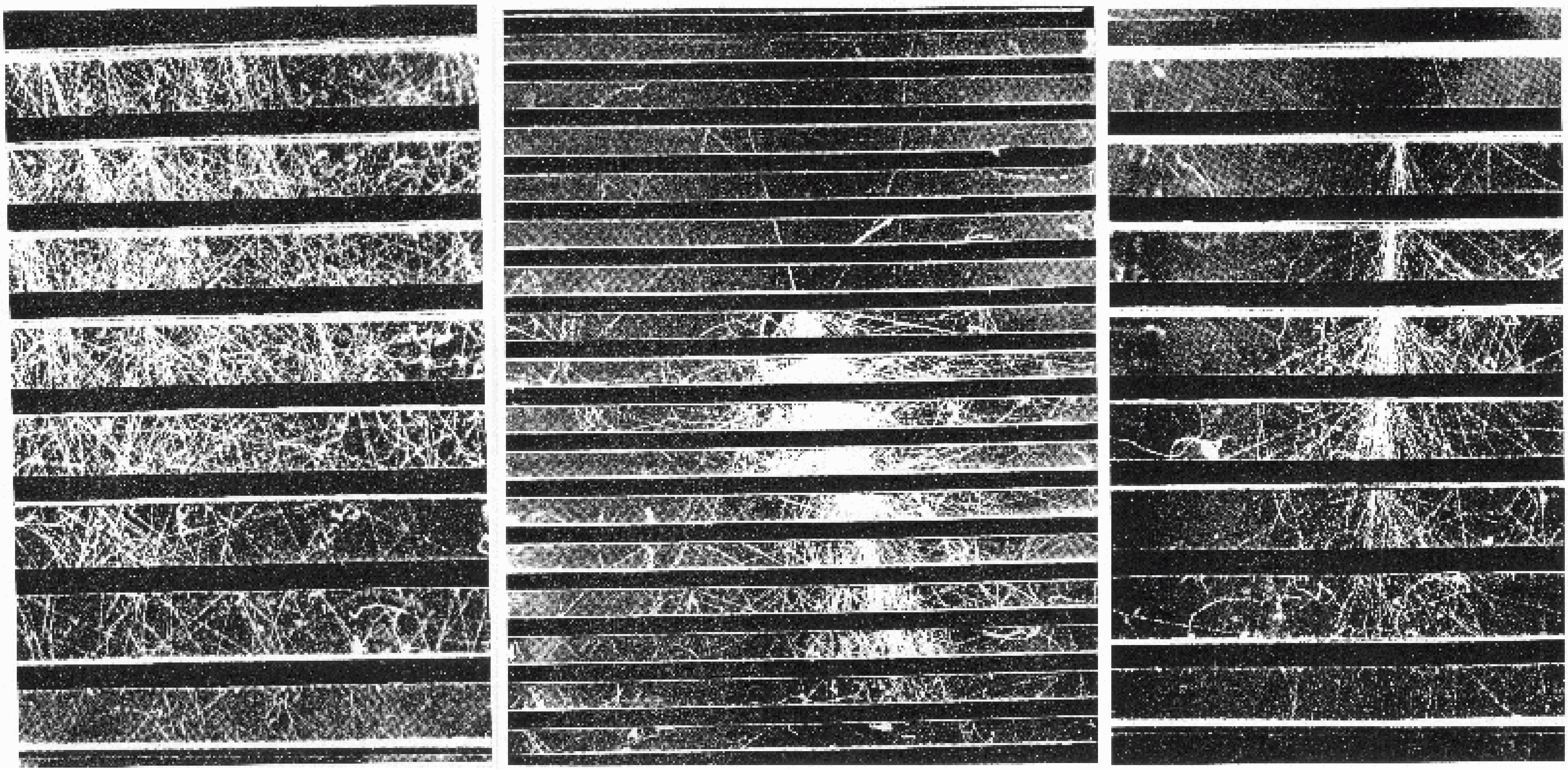
(uncertainties < 30% for most observables)

- Everyone uses the same code.

THIS IS A REMARKABLE SUCCESS!

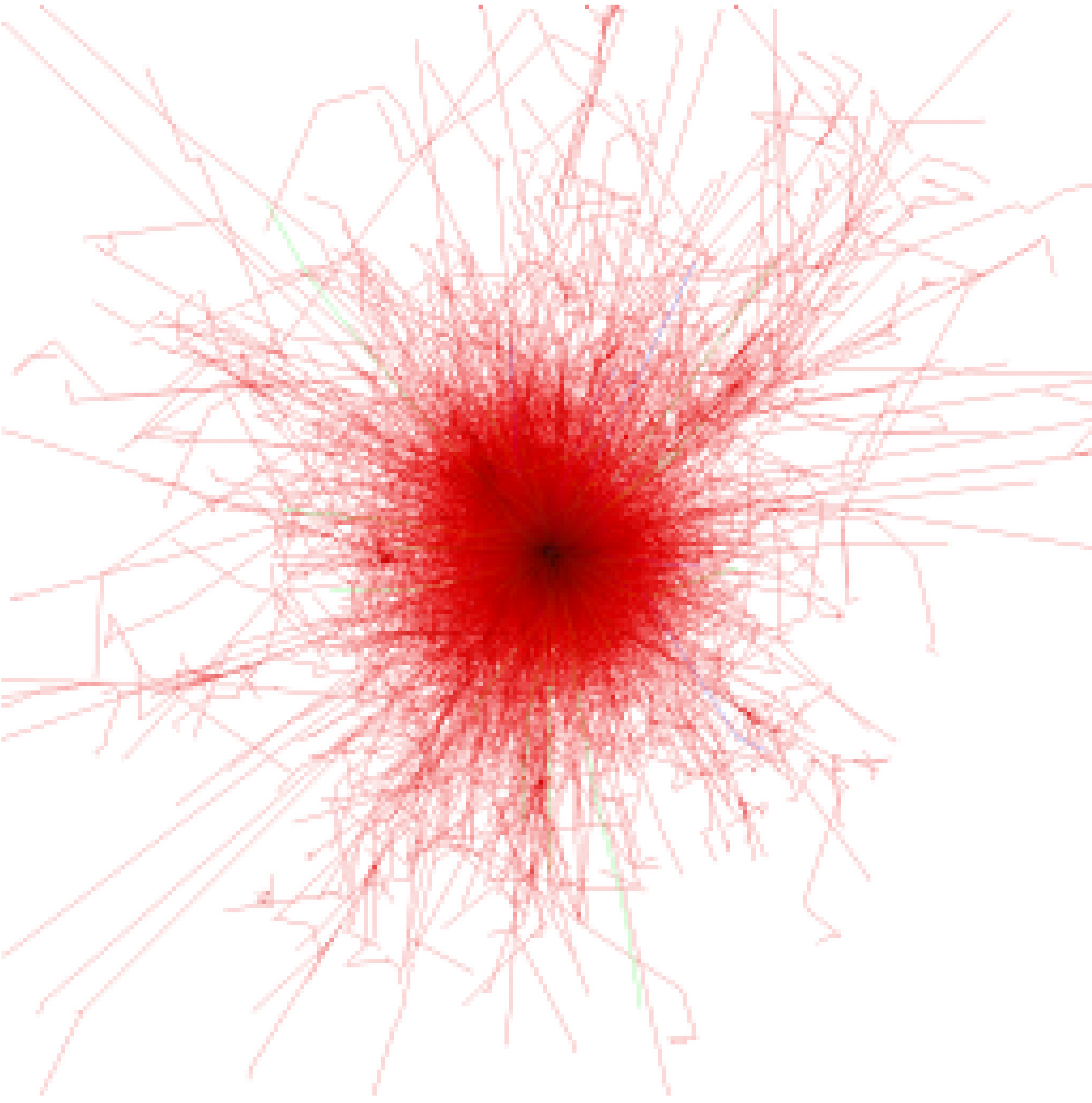
Educational Images

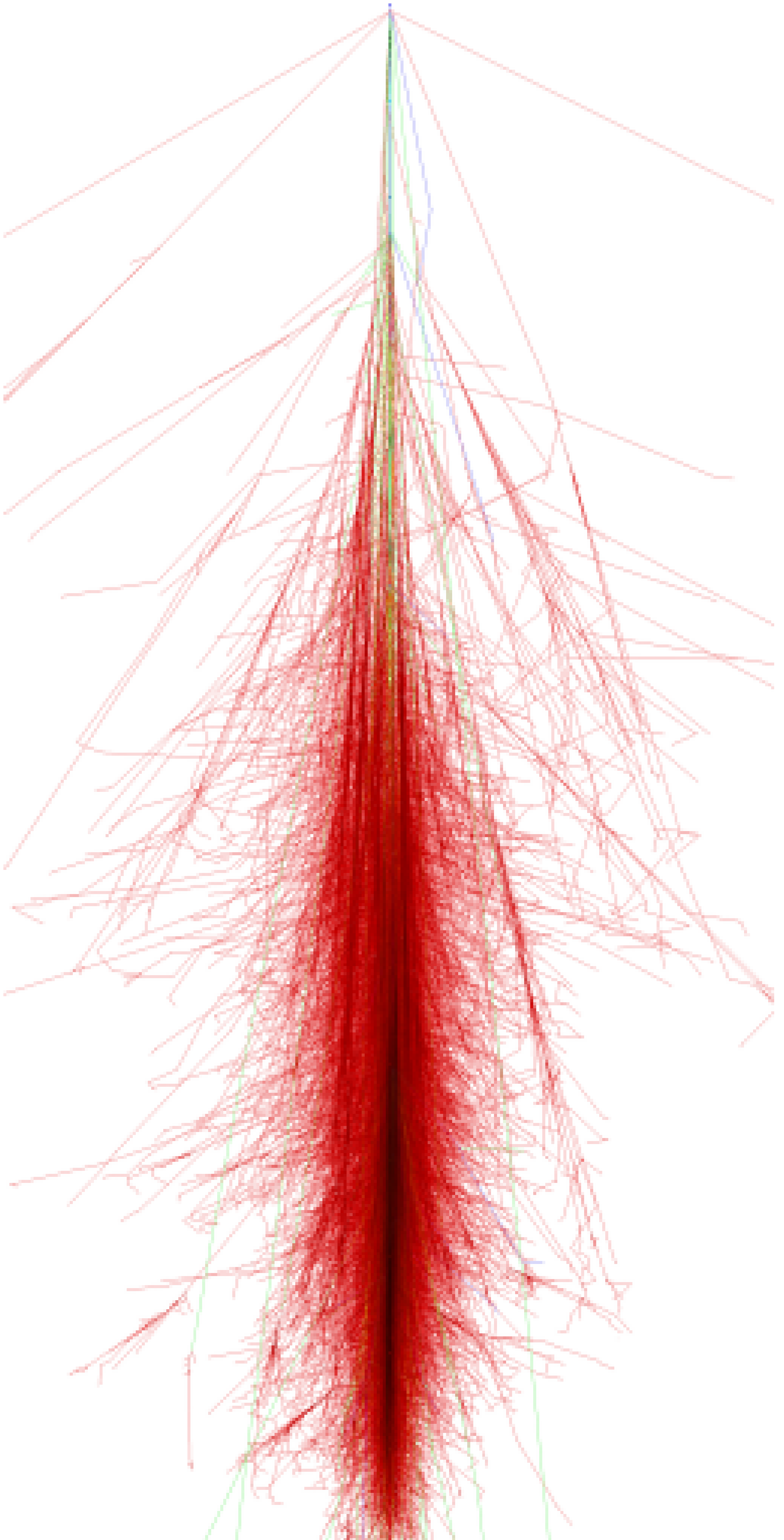
Visualise and understand what is going on ...



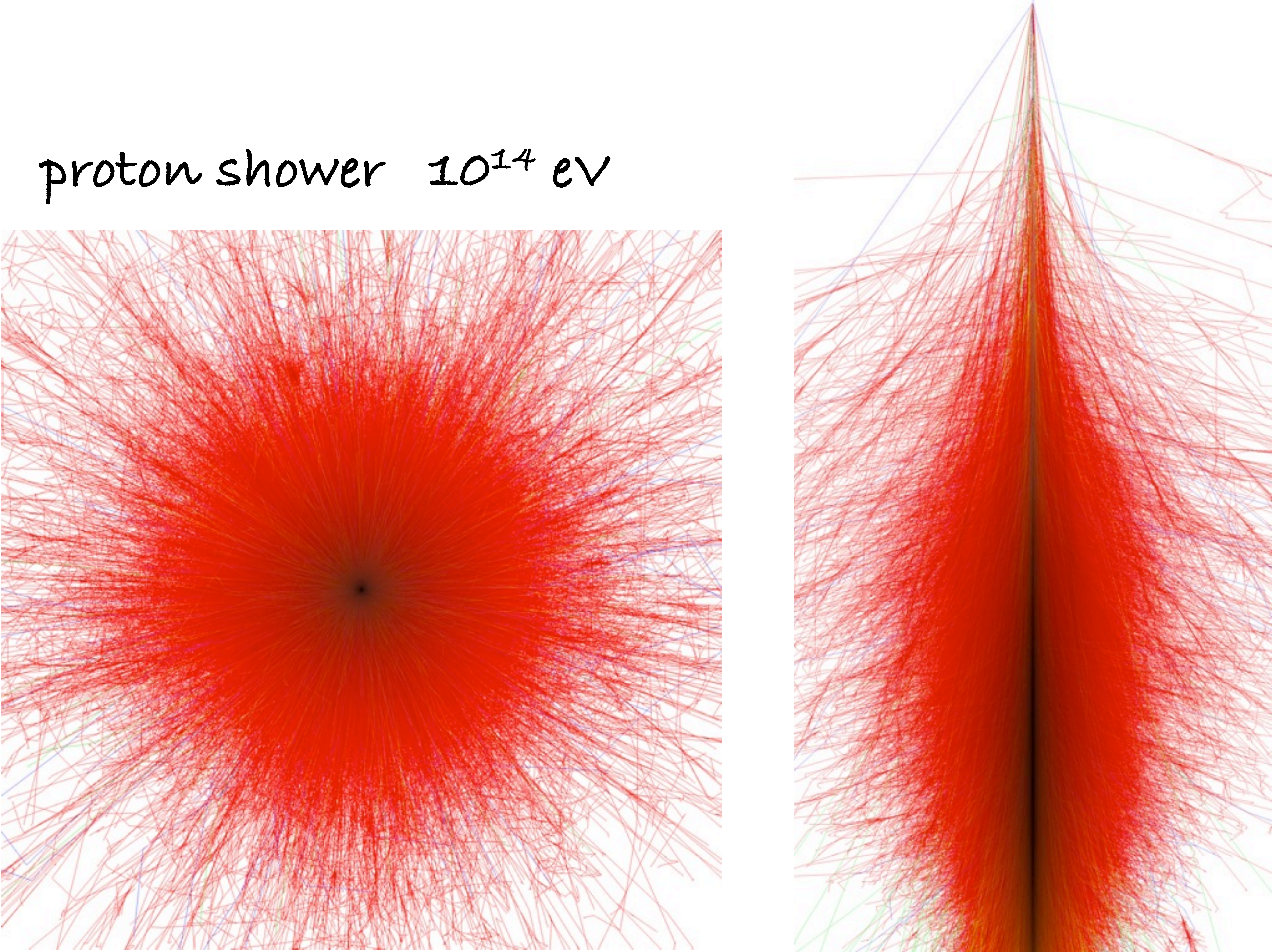
... as with early bubble and cloud chamber photos.

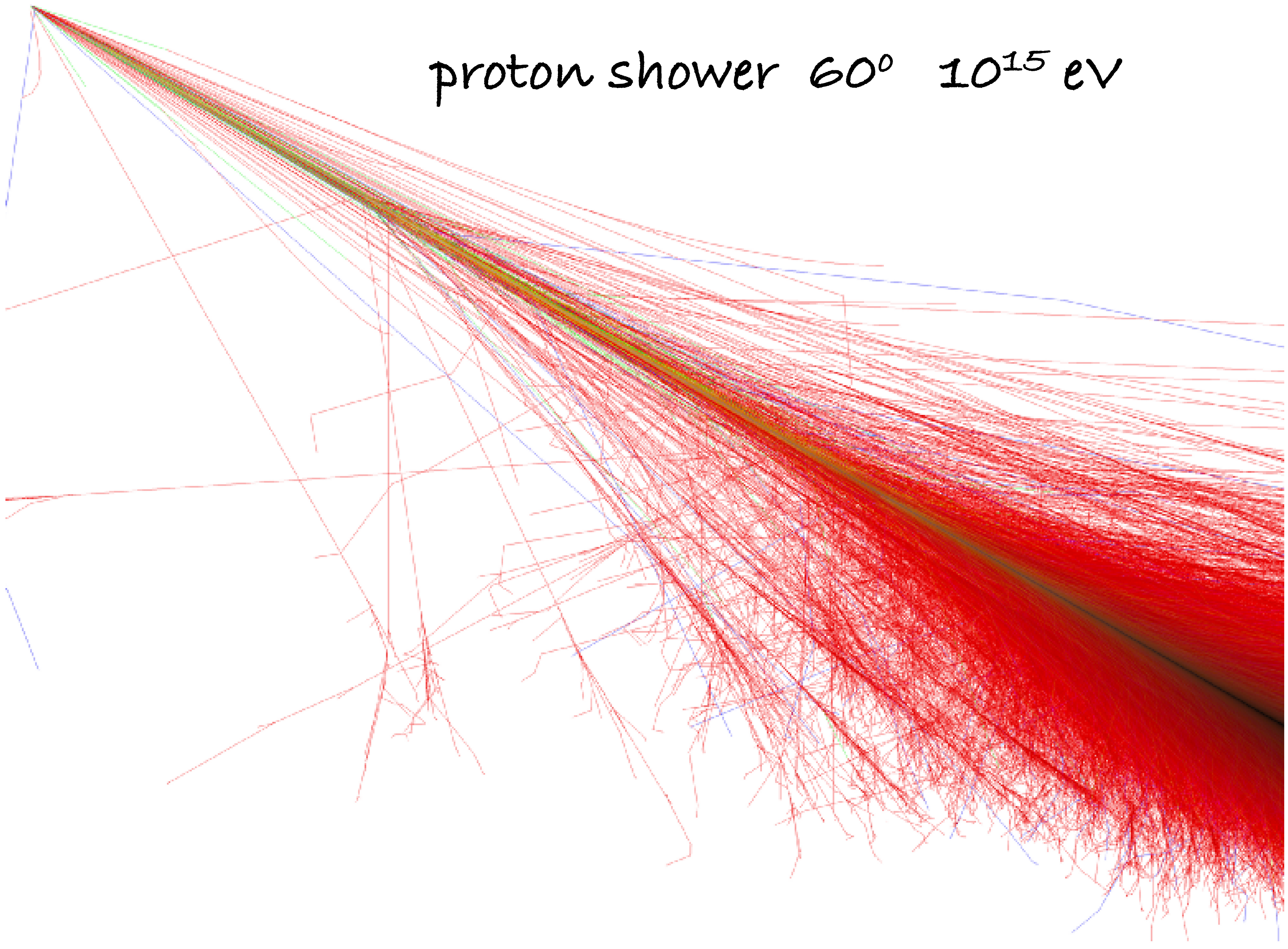
proton shower 10^{12} eV





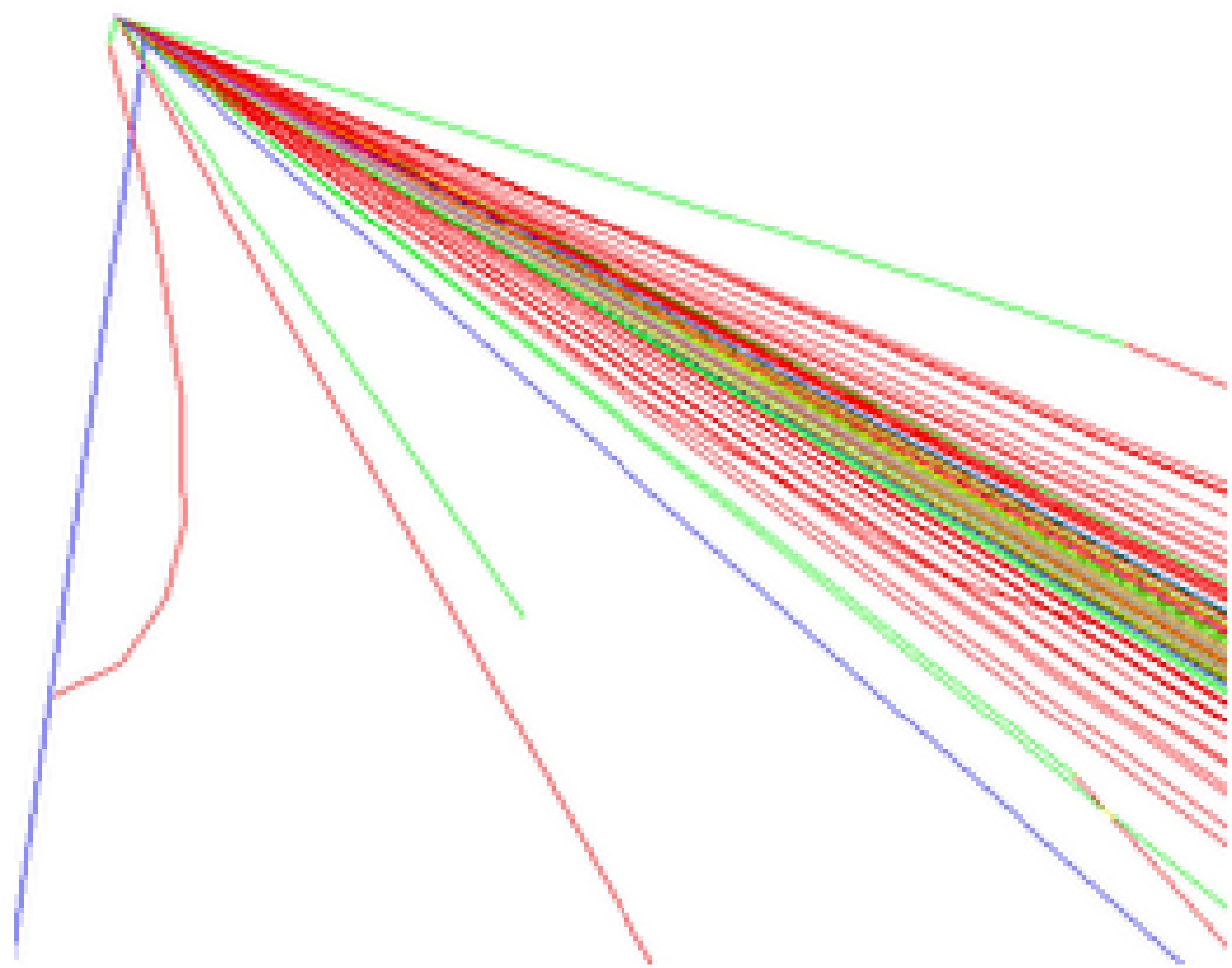
proton shower 10^{14} eV




proton shower 60° 10^{15} eV

proton 10^{15} eV

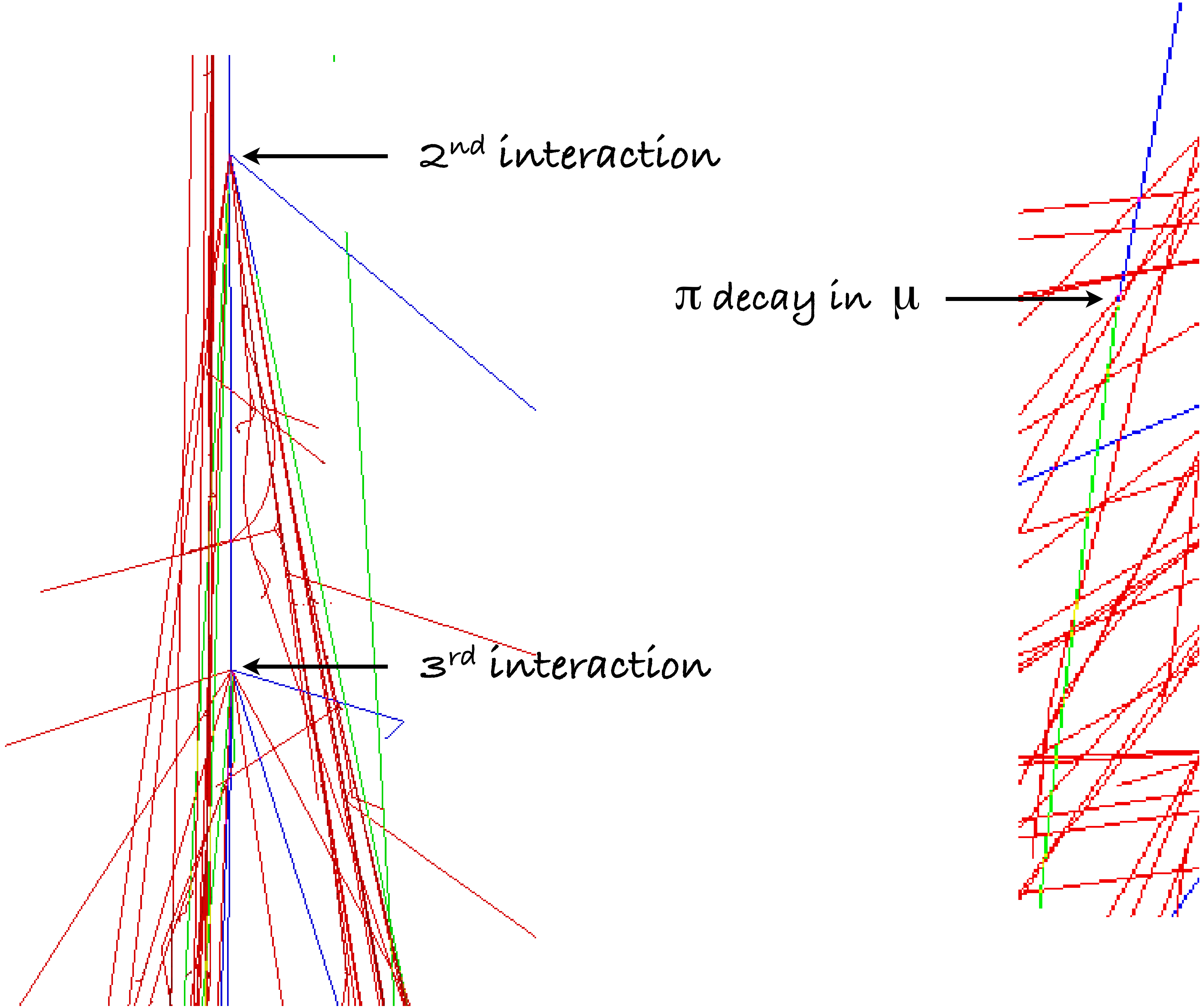
1^{st} interaction



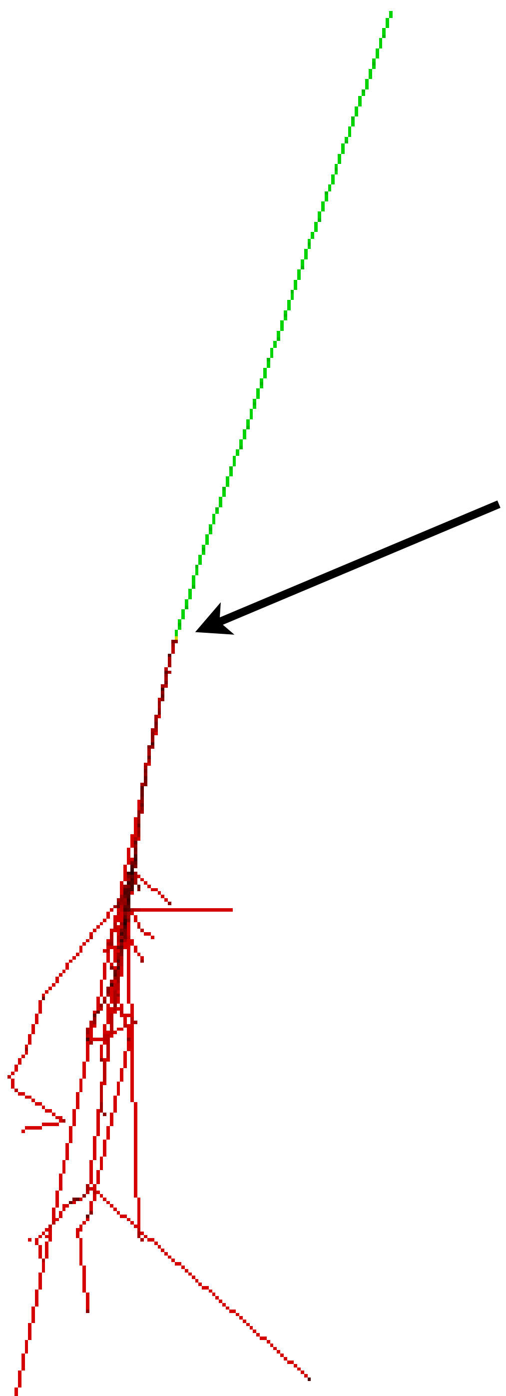
electrons/photons

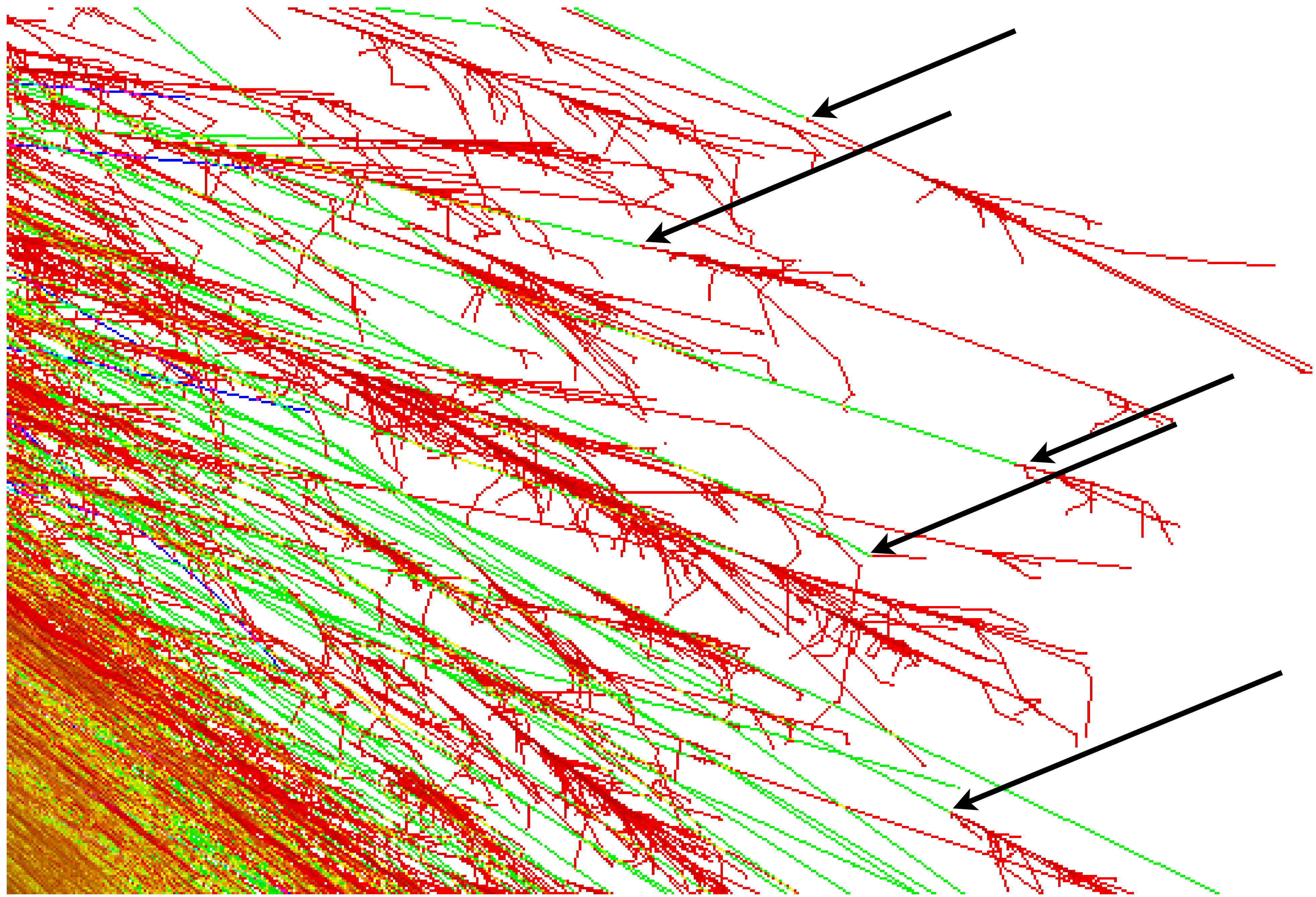
muons

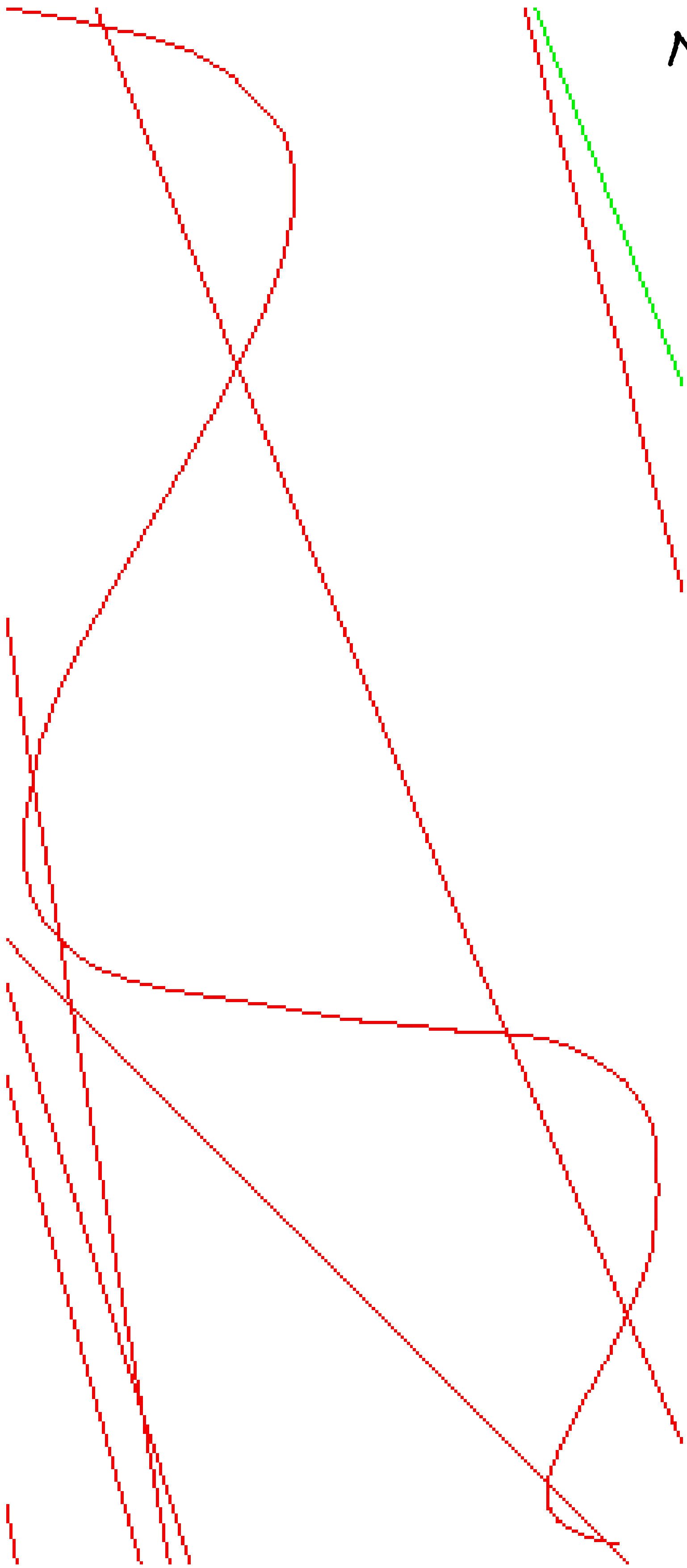
hadrons


2nd interaction
π decay in μ
3rd interaction

Muon decays

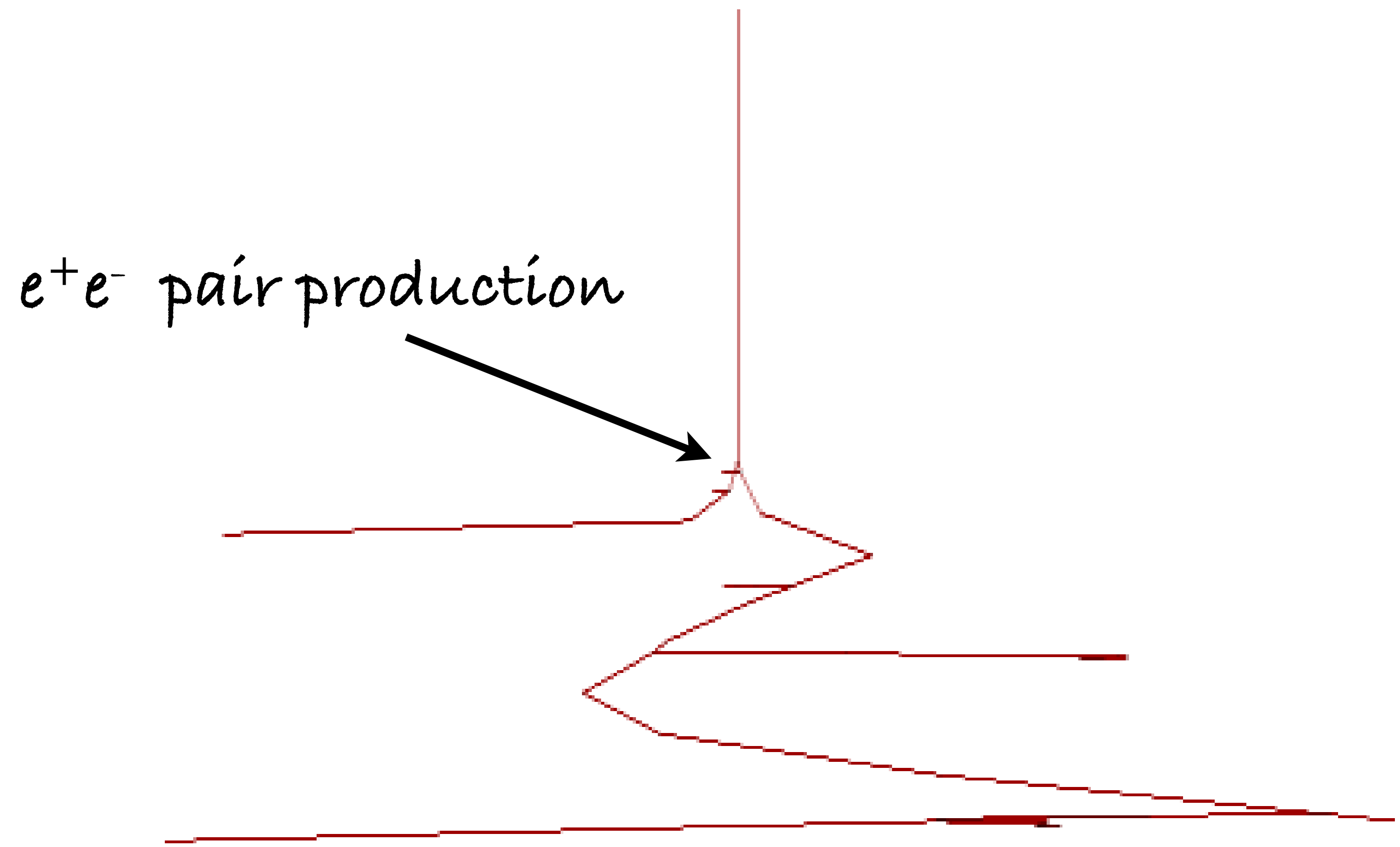




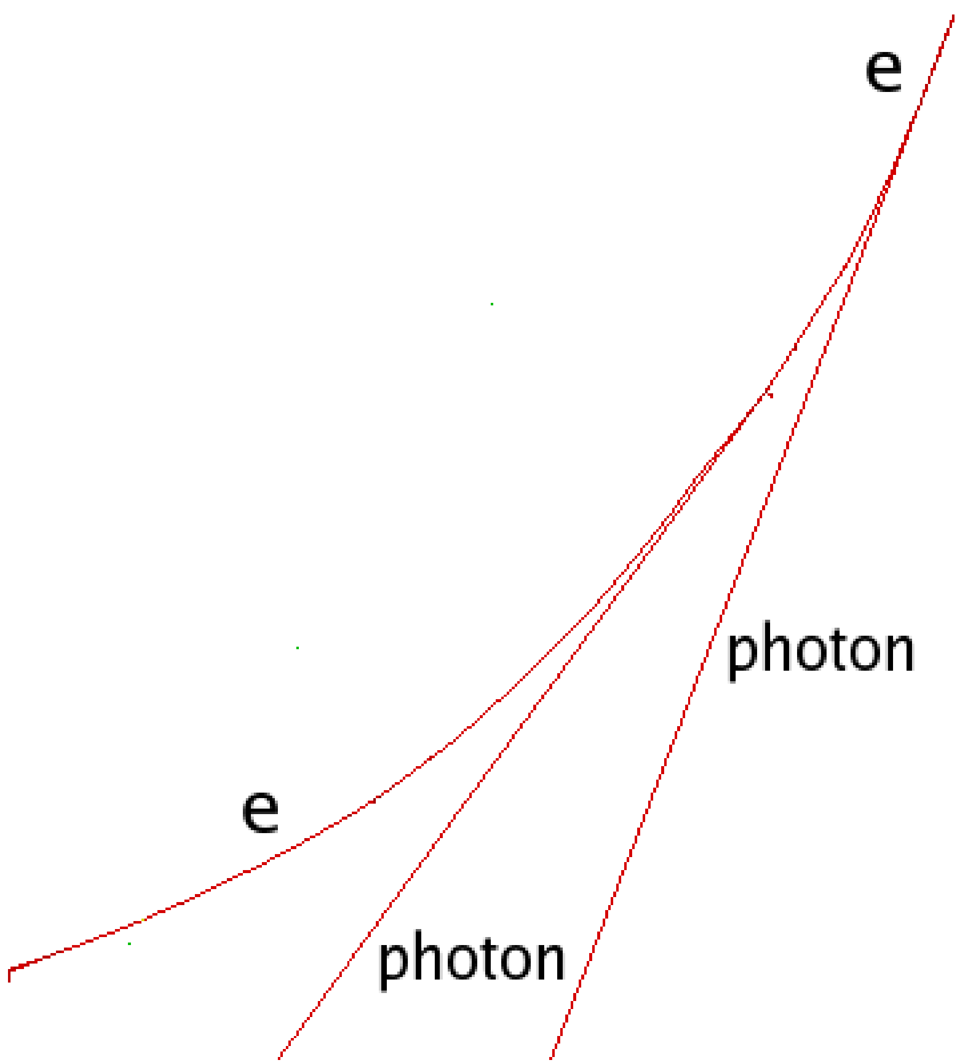


Magnetic deflection:

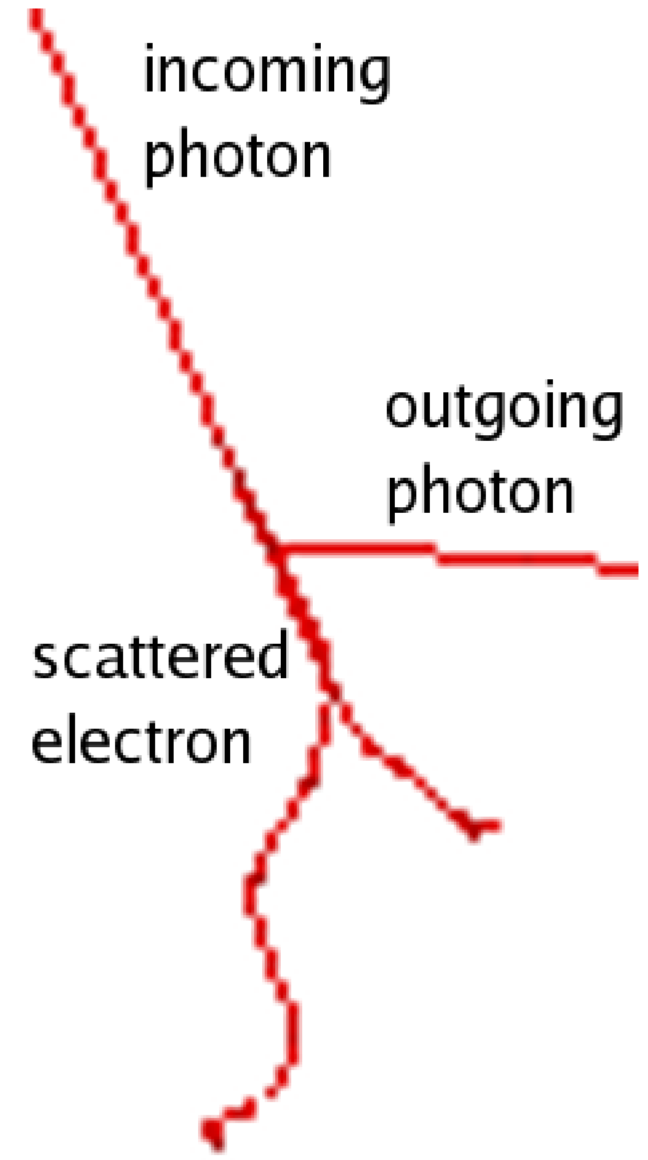
charged particles spiral around Earth magnetic field.

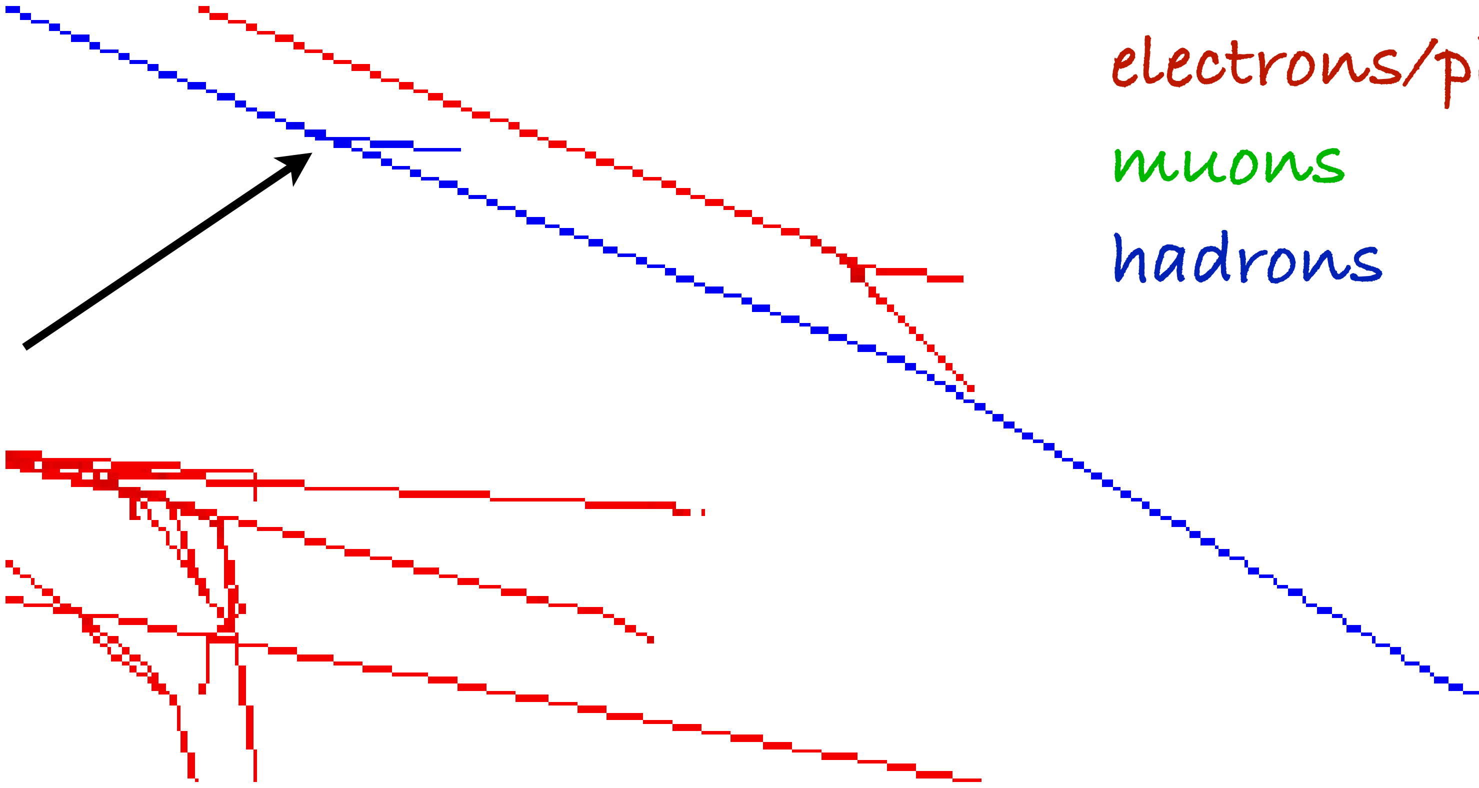


Bremsstrahlung



Compton scattering

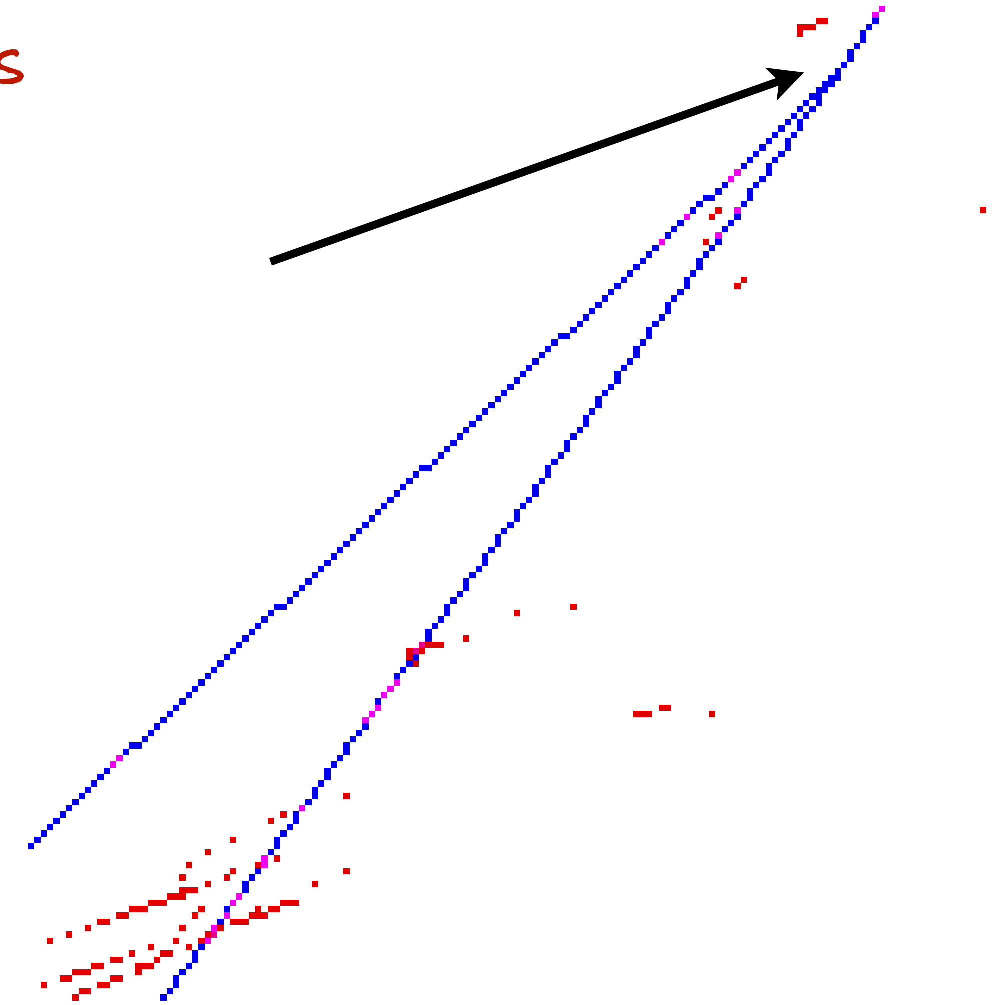


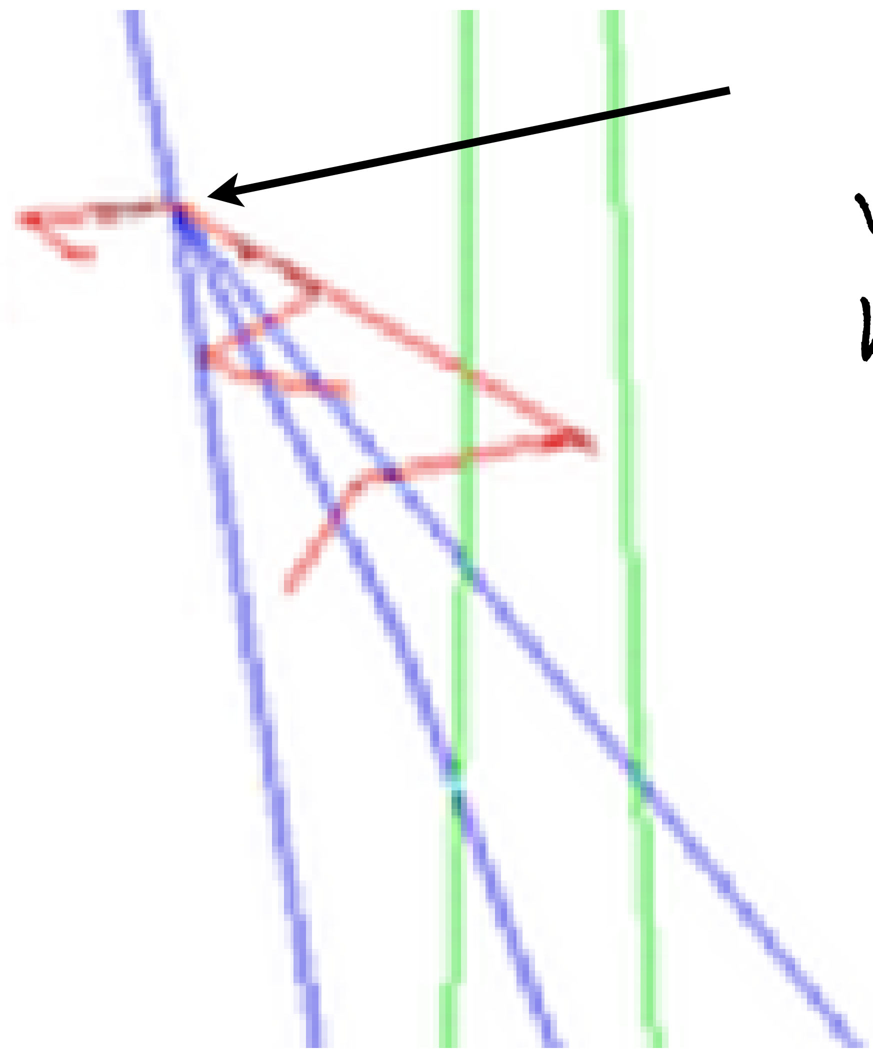


electrons/photons

muons

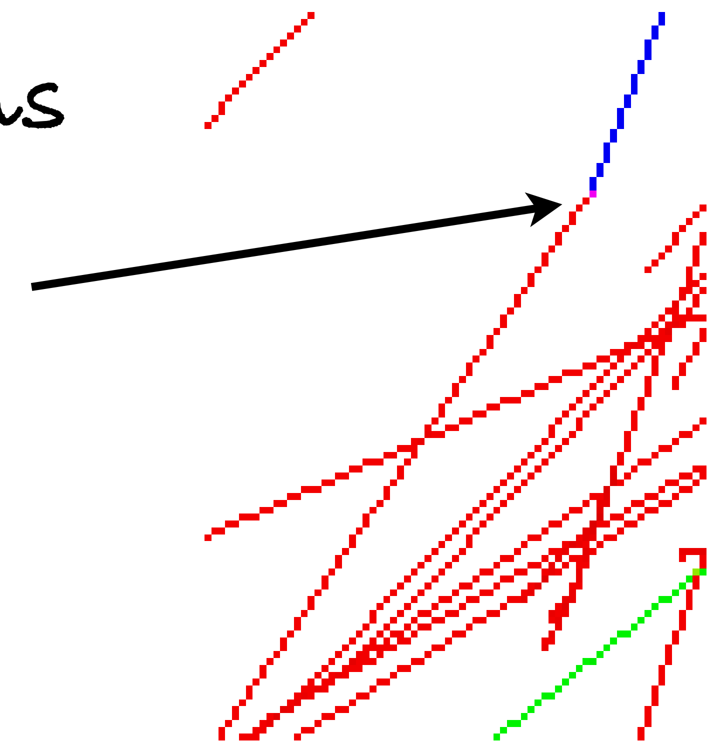
hadrons

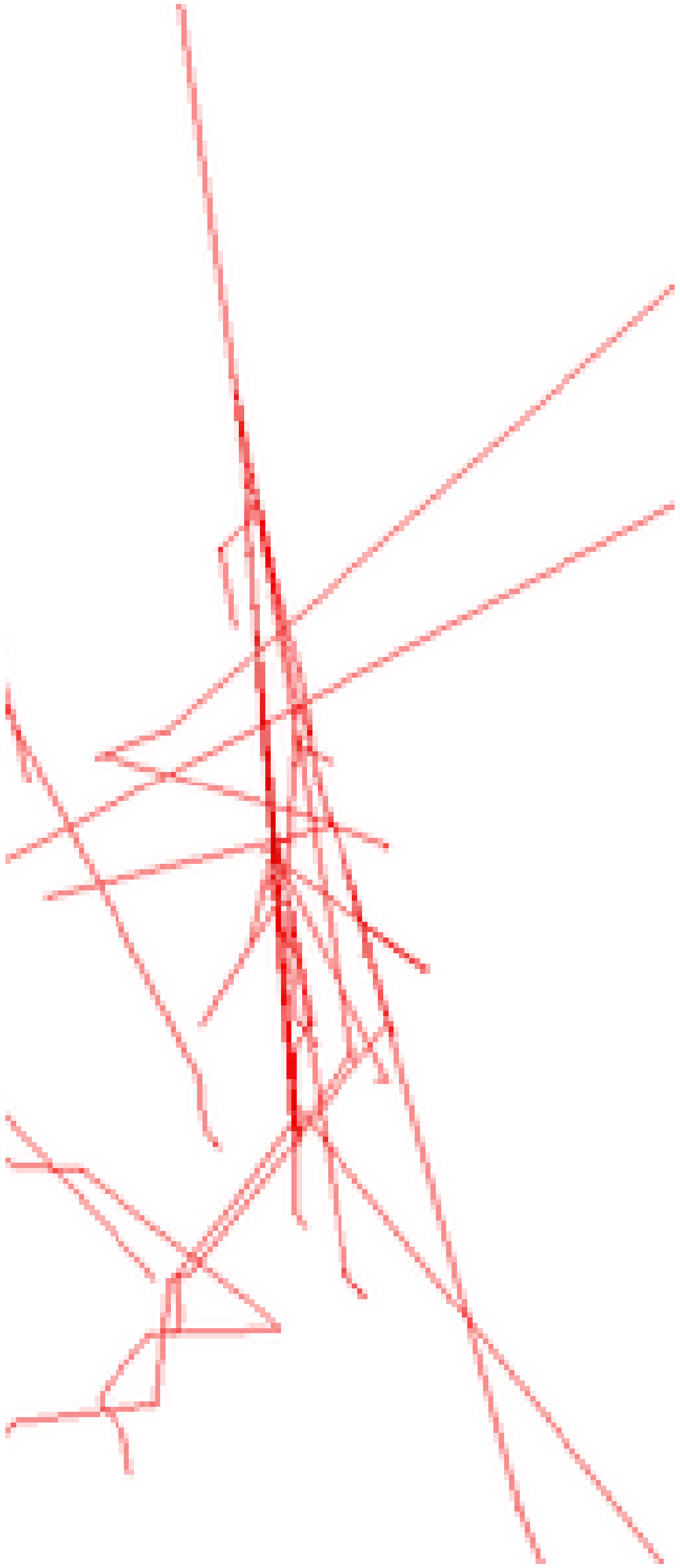




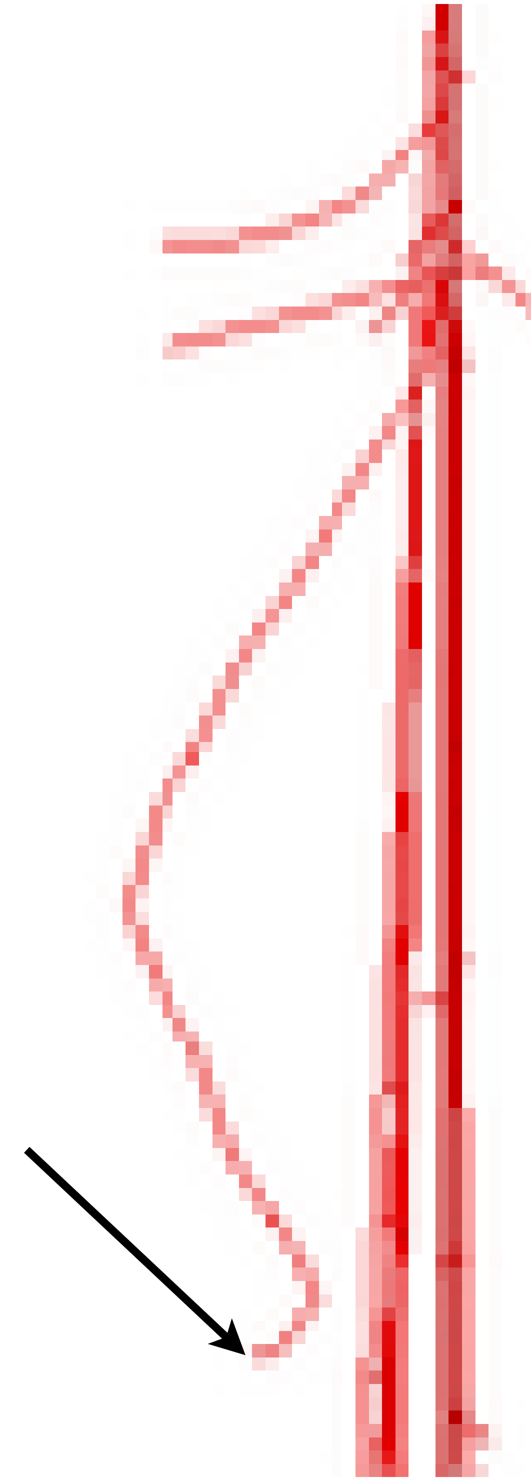
various

hadronic interactions





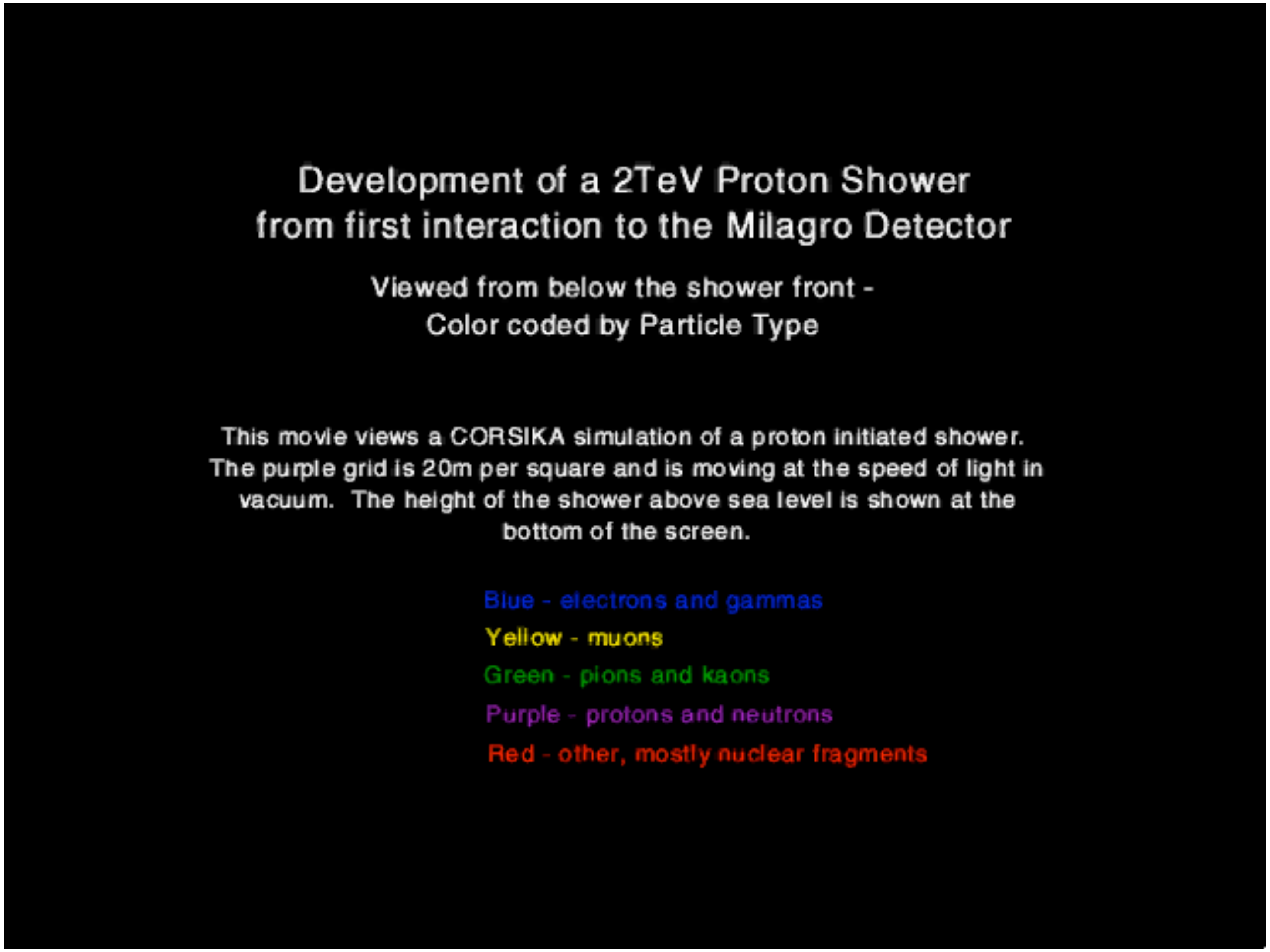
protons (or neutrons) are absorbed



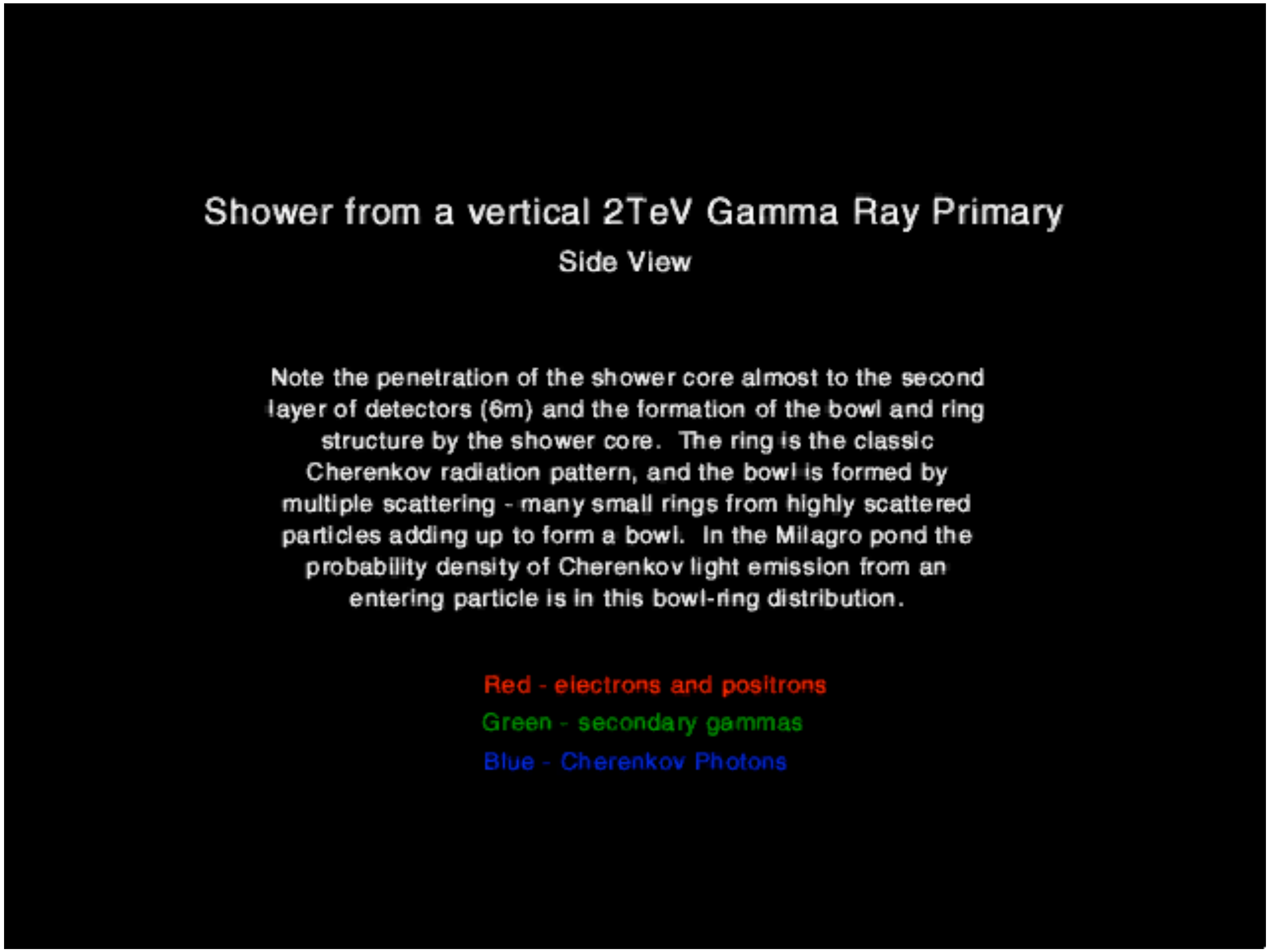
photon induces electromagnetic sub-shower

electron slowed down and absorbed

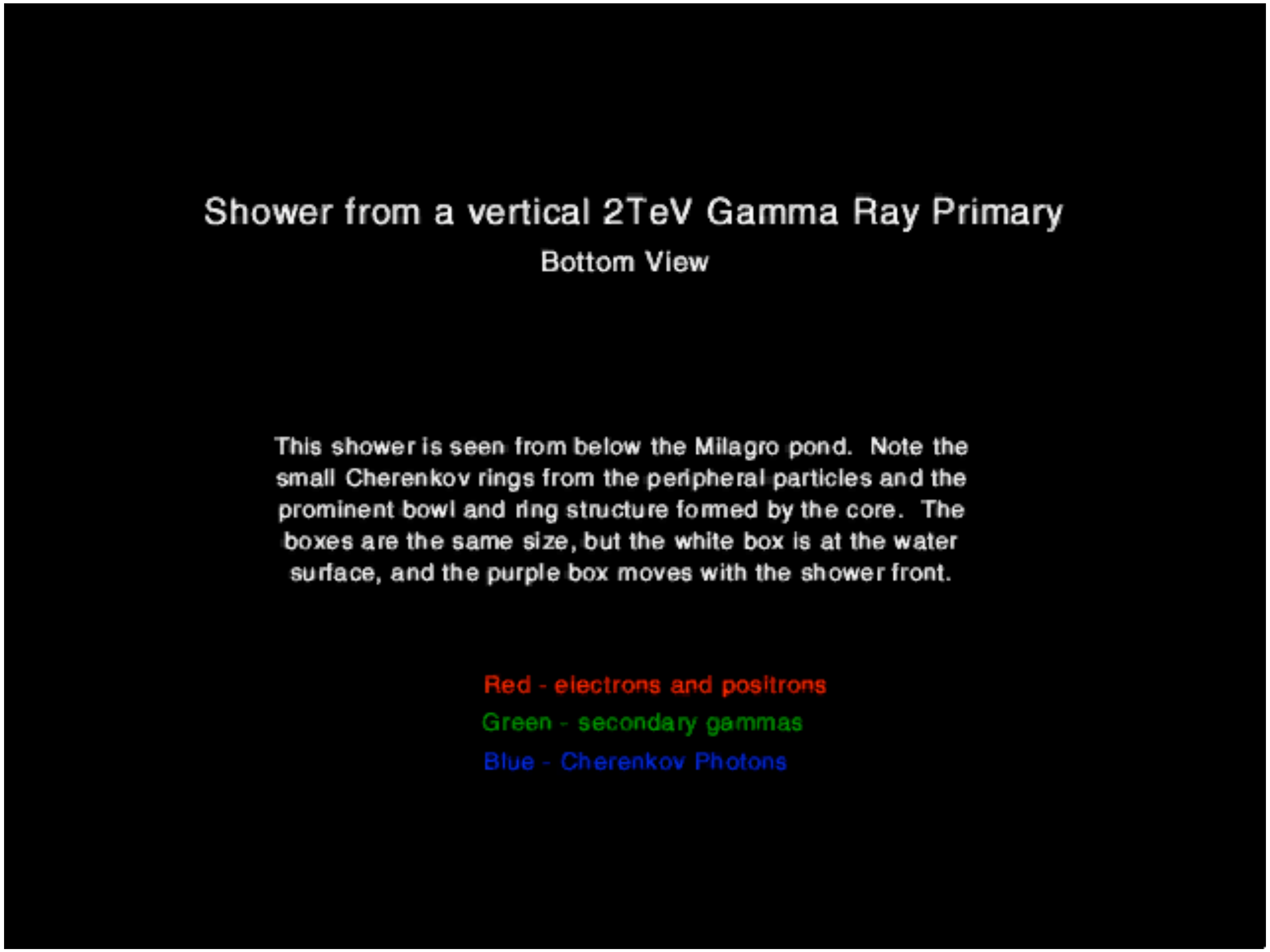
2 TeV proton shower,   bottom view



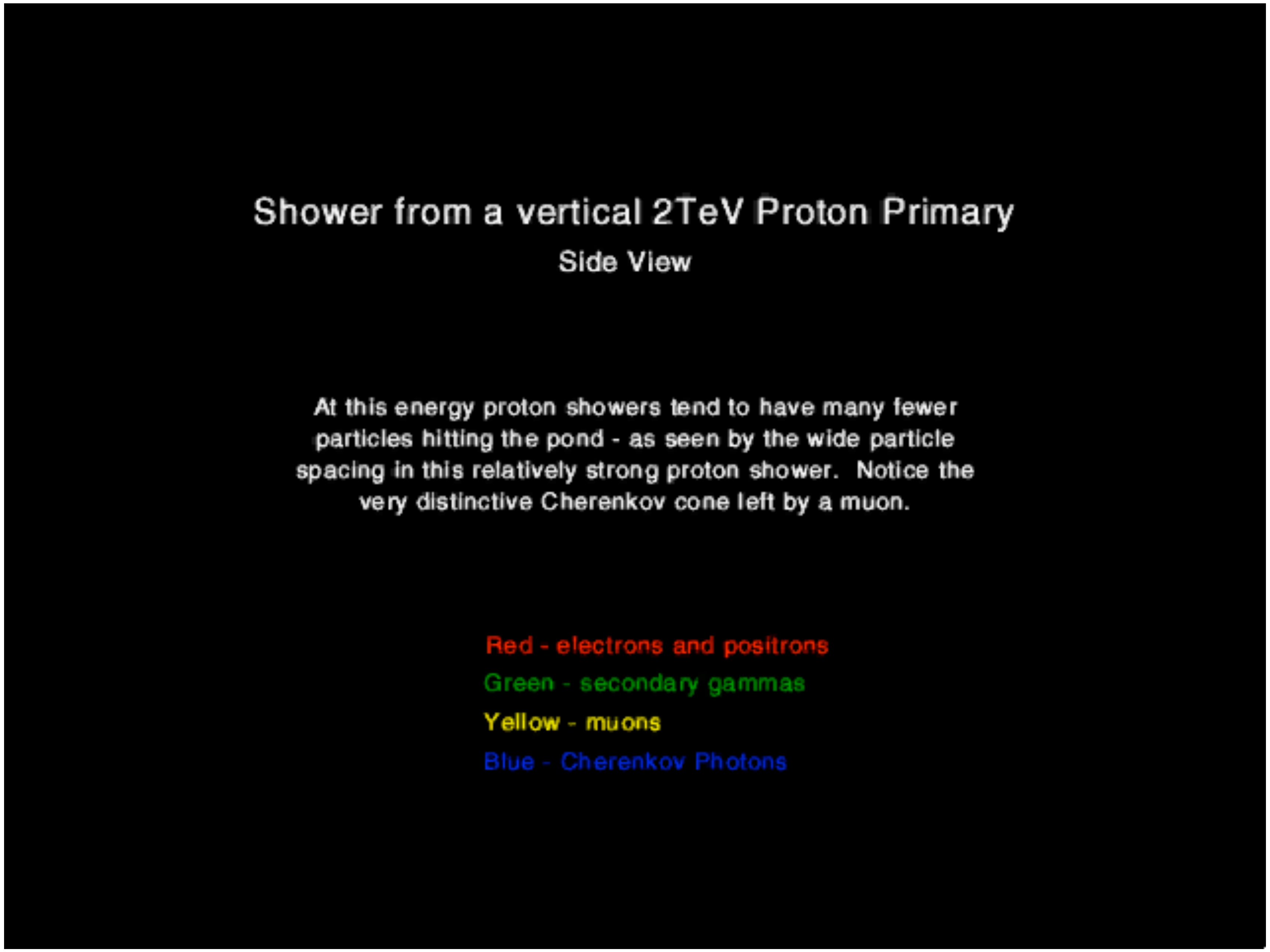
2 TeV gamma shower onto Milagro,   side view



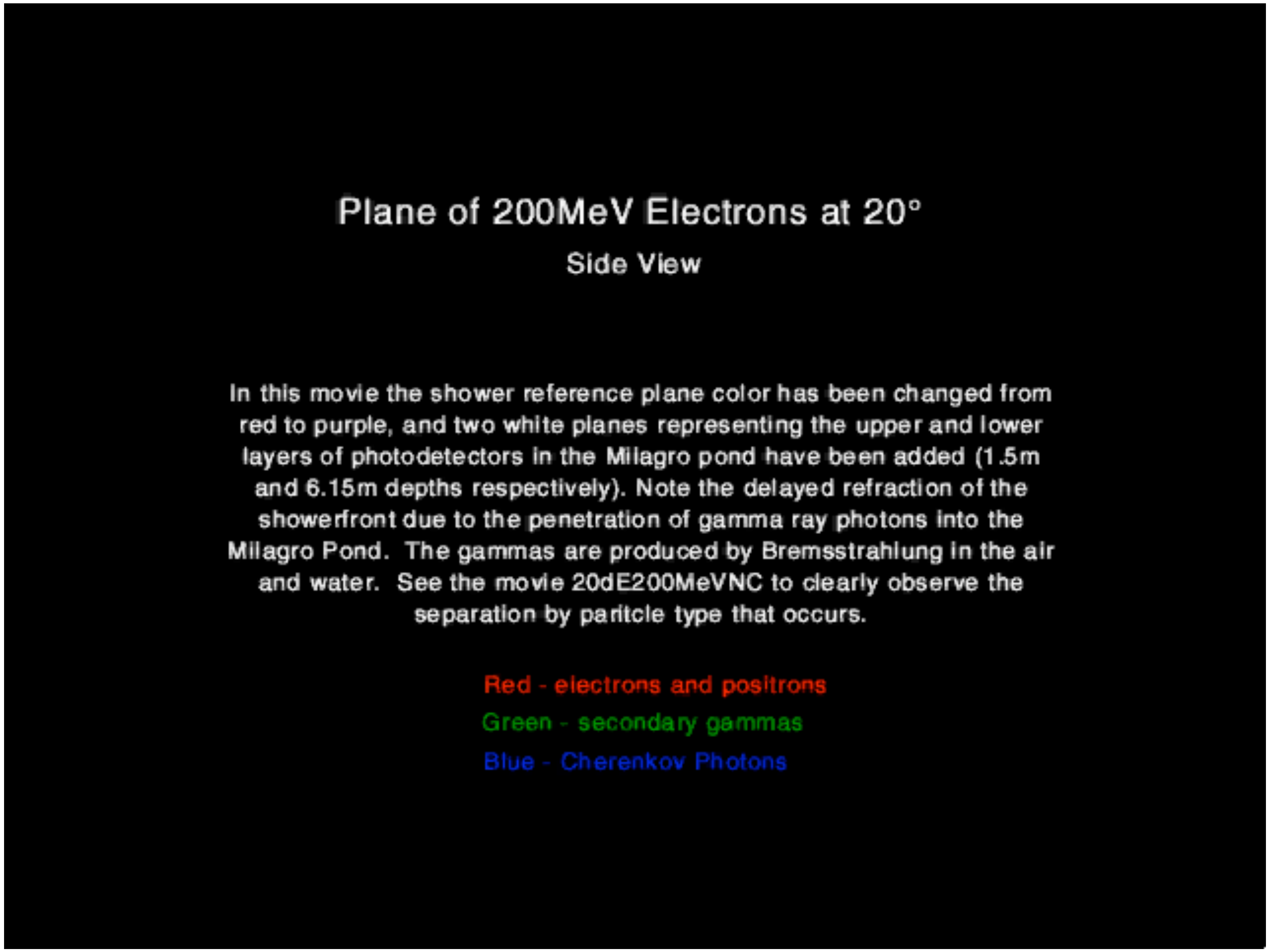
2 TeV gamma shower onto Milagro,   bottom view



2 TeV proton shower onto Milagro, side view



200 MeV electrons onto Milagro, side view



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 is a great tool
  to study and visualise air showers,
  to analyse data from air shower experiments
  and to design new experiments.

- CORSIKA has revolutionised the field and
  is now the "Gold Standard"
  of the EAS community.

- CORSIKA is not (yet) perfect,
  but approximately correct.

The End