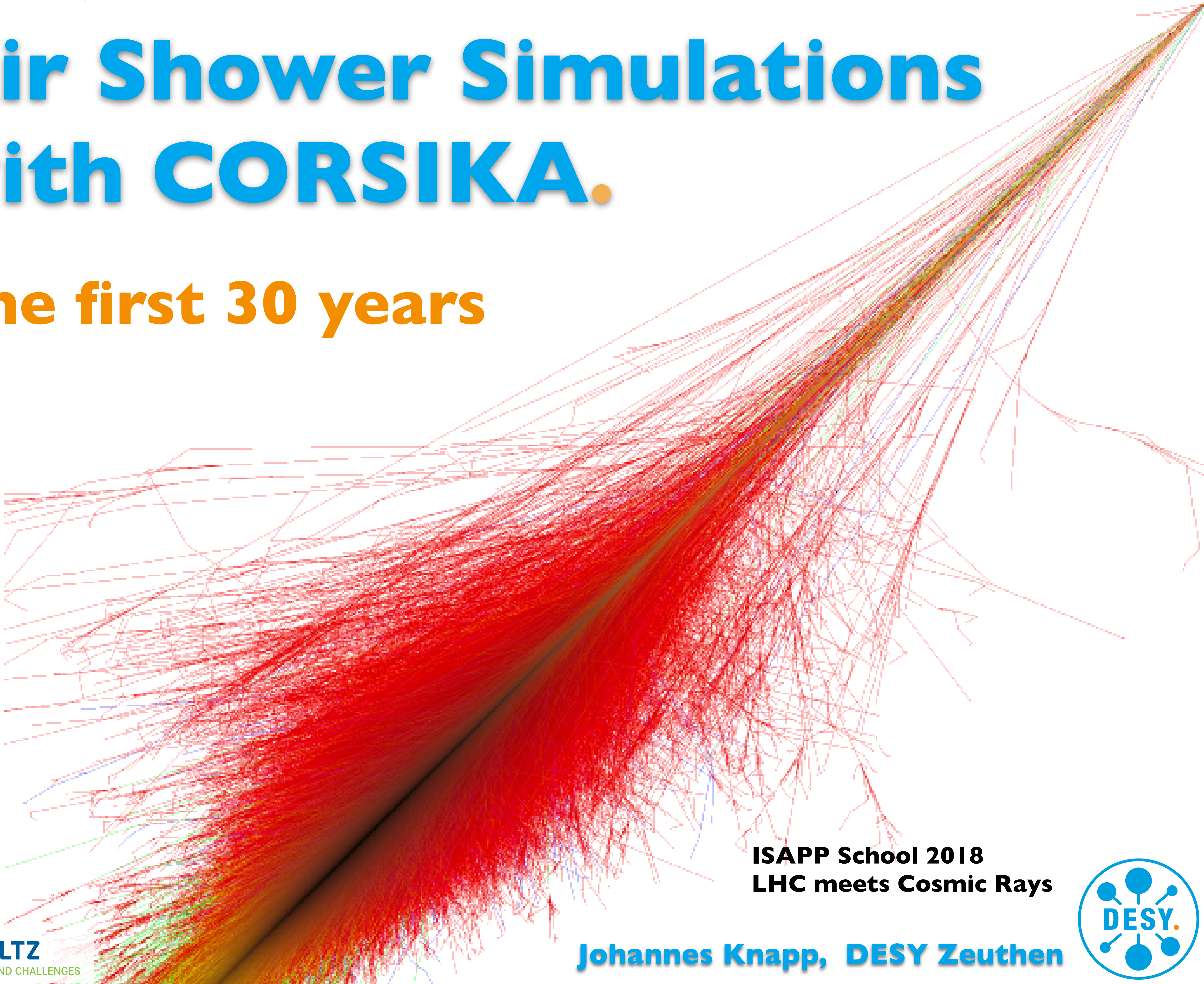
Air Shower Simulations with CORSIKA.

The first 30 years

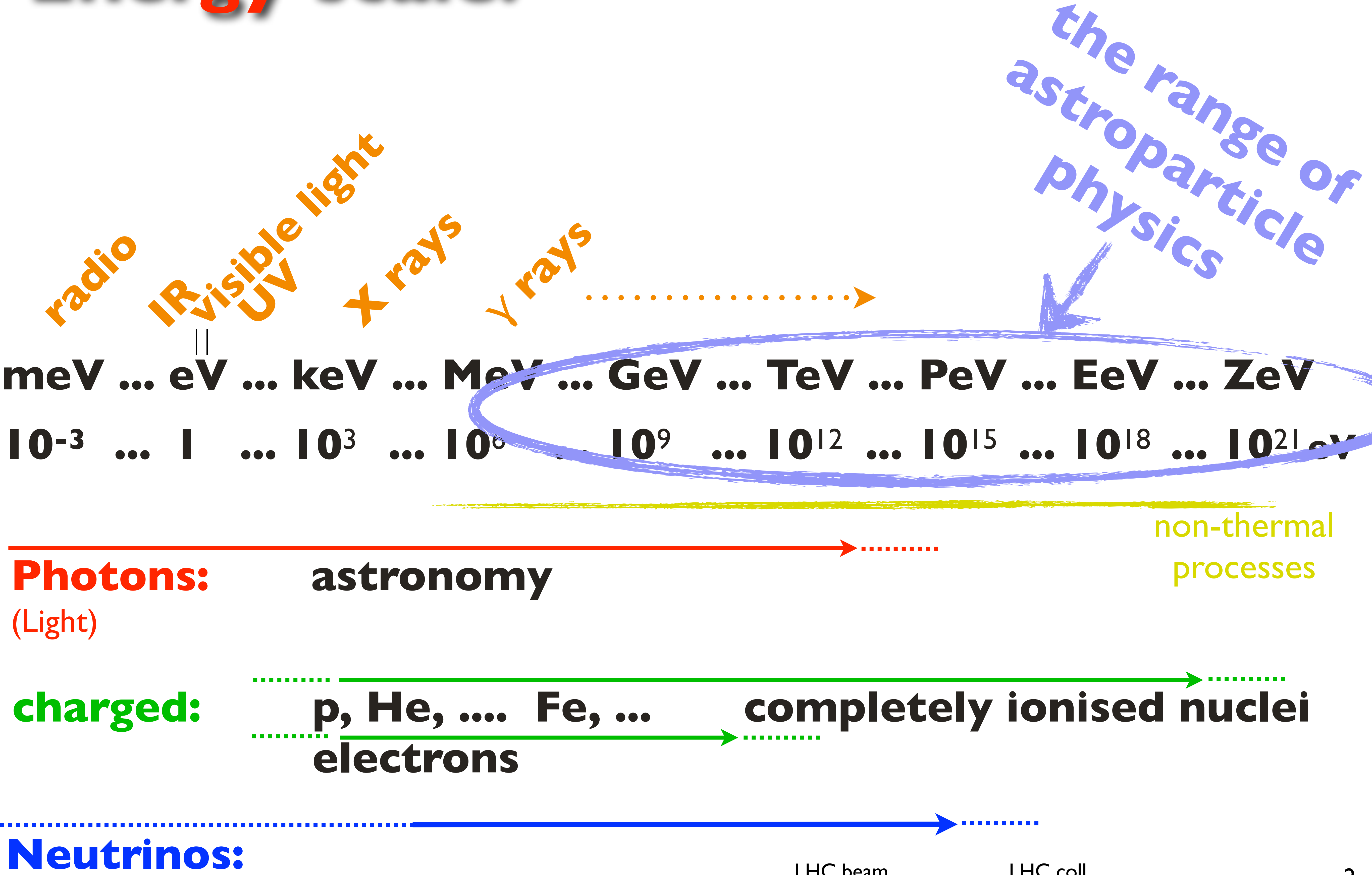


ISAPP School 2018
LHC meets Cosmic Rays

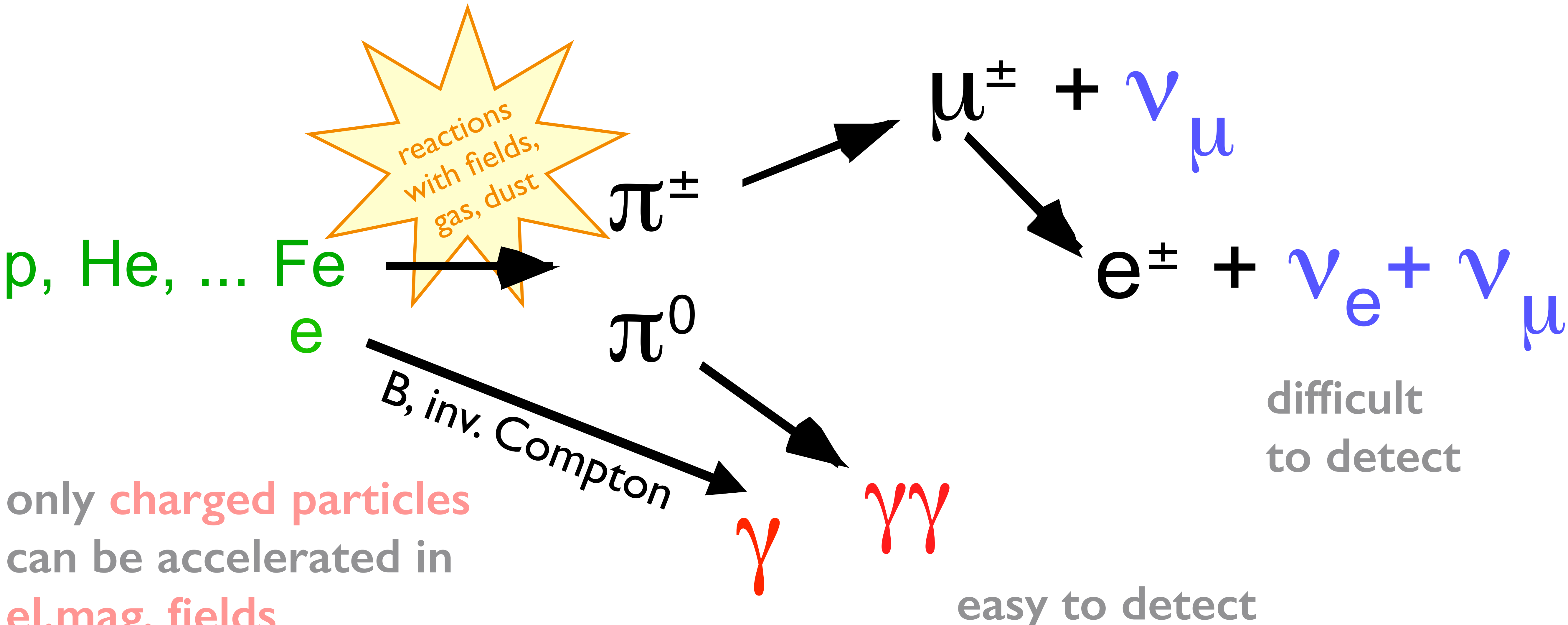
Johannes Knapp, DESY Zeuthen

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Energy scale:



Cosmic rays, gamma rays and neutrinos come likely from the same sources



only charged particles can be accelerated in el.mag. fields

γ, ν

point back to sources (good for astronomy)
but serious backgrounds

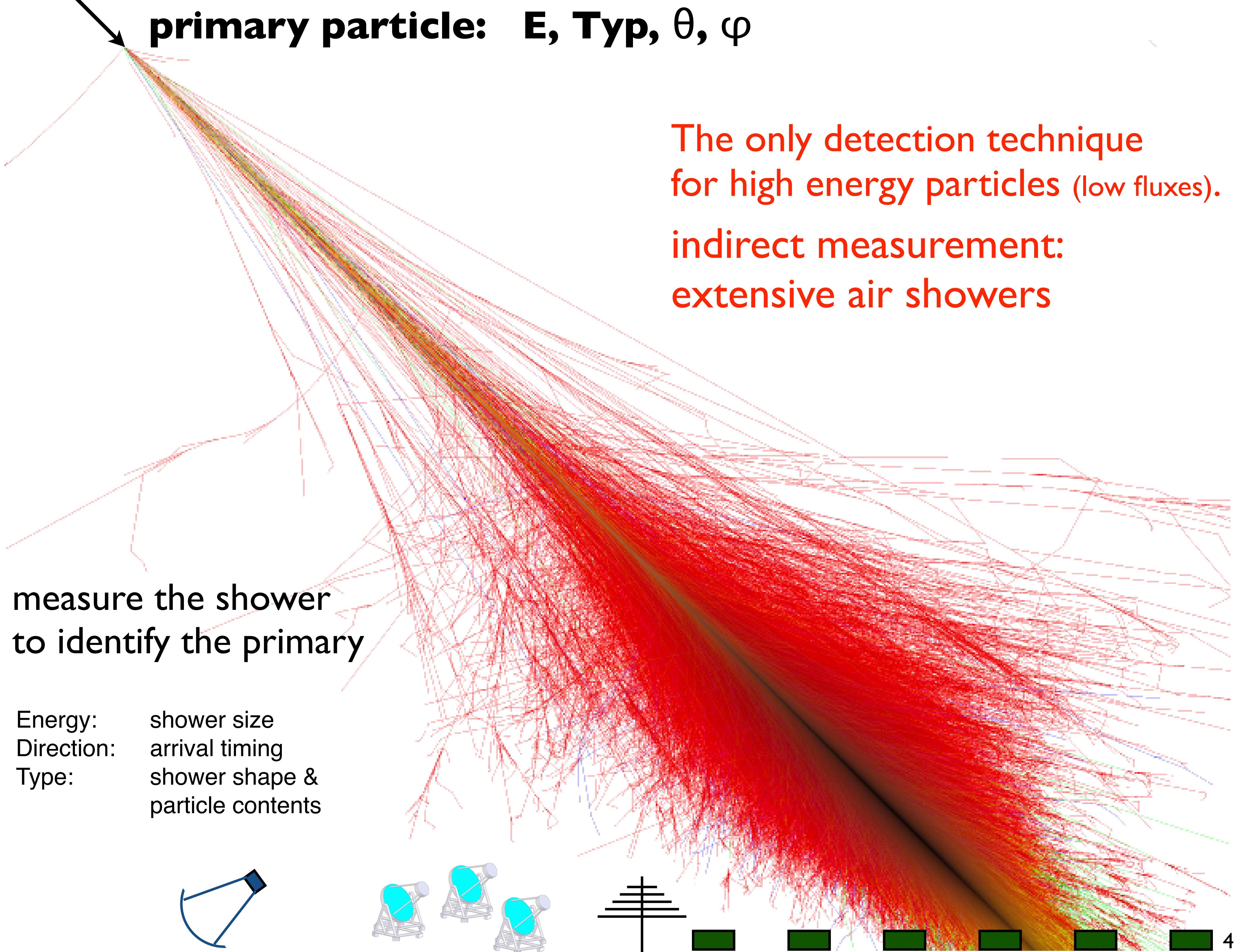
"multi-messenger astrophysics"

but gamma rays are currently the most "productive" messengers.

primary particle: E, Typ, θ, φ

The only detection technique
for high energy particles (low fluxes).

indirect measurement:
extensive air showers



measure the shower
to identify the primary

Energy:	shower size
Direction:	arrival timing
Type:	shower shape & particle contents

needed in all experiments where
showers of astroparticles are measured:

gamma rays (E $\geq$ 50 GeV) in air

distinguish γs from hadrons (cosmic rays)

cosmic rays (E $\geq$ 1 TeV) in air

distinguish p, He, O, … Fe, γ , electrons

neutrinos (E $\geq$ 10 TeV) in air, ice, water, earth

distinguish neutrinos from penetrating muons and identify ν_e, ν_μ, ν_τ

and measure energy and direction of primary particle.

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, ...

correlations between them,

statistical fluctuations,

....

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

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

(similarly: simulation for detector, electronics, trigger,
readout, & reconstruction)

A shower of 10^{20} eV contains:

~10 sub-showers of 10^{19} eV

…

~10^{6} sub-showers of 100 TeV

…

~10^{11} sub-showers of 1 GeV

A **correct** shower model
reproduces experimental data
for **all** primaries and energies,
at **all** altitudes and zenith angles

Oxford English Dictionary:

Simulation:

"Imitating the behaviour of some situation or process by means of a suitably analogous situation or apparatus" (e.g. with a computer program)

Model:

"A simplified or idealised description or conception of a particular system, situation, or process, as a basis for theoretical or empirical understanding, or for calculations, predictions, etc.;

A conceptual representation of something."

Simulation:

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

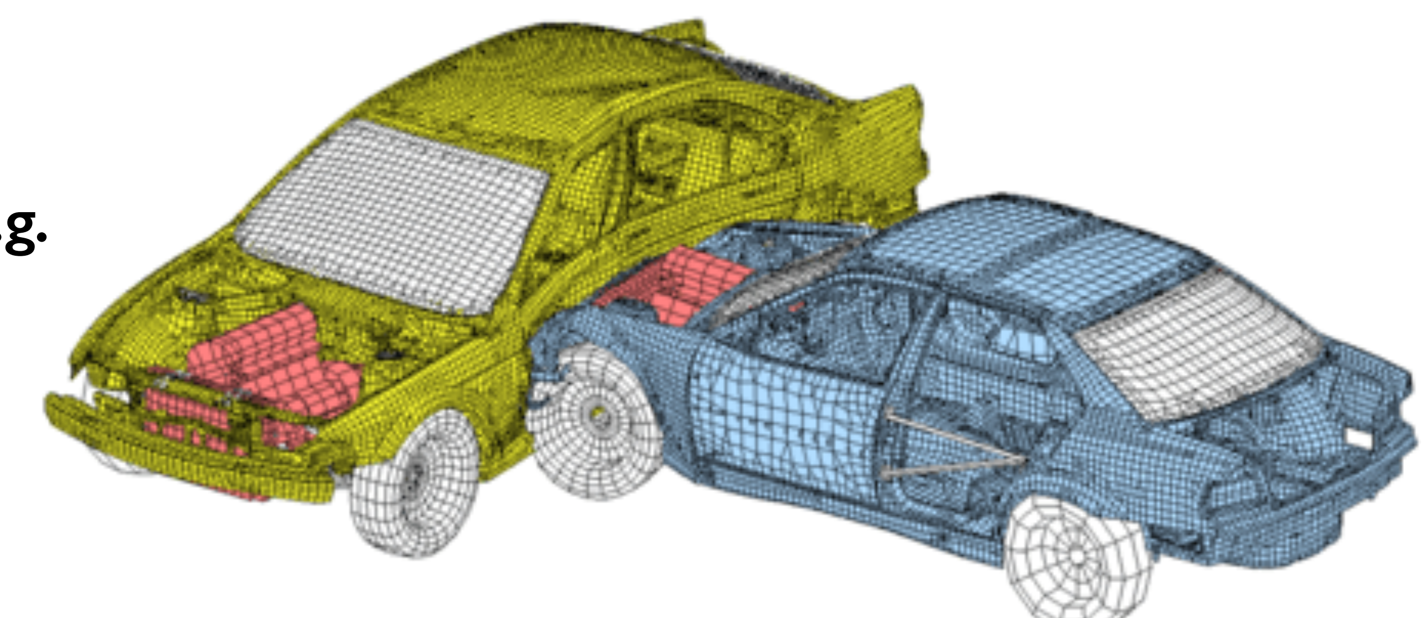
Simulation is the numerical convolution of many individual, but inter-dependent, parts to a greater and more complex whole.

("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 various sub-processes.

e.g.



Sims (on computer) are cheaper than real crashes, but initially real crashes are needed to test whether sims are correct (good enough)

Models:

simplified, conceptual

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

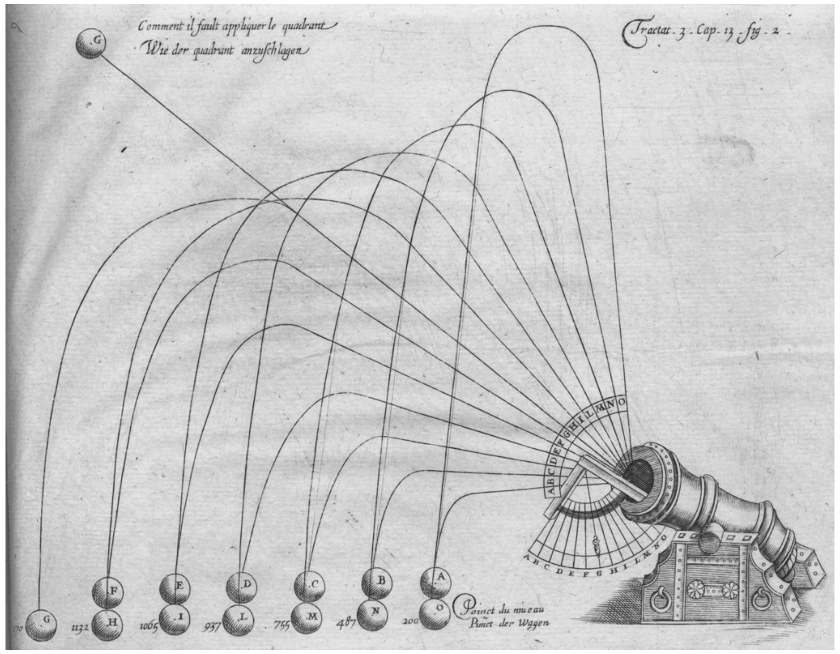
then Models of reality are used
(i.e. simplifications, assumptions, approximations, ...)

but simplifications come 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 ?

e.g.

assume: well-known velocity, no air resistance,
then: trajectories are parabolas, easy to calculate



In Practice

> the precise and complete simulation of a complex problem may be impossible (or at least very difficult / costly).

> Usually, “Simulation” and “Model” are mixed in various degrees find a good compromise:
>
> The complexity of the simulation should reflect the complexity of the problem.

> interplay between sub-parts (and emergence) still qualitatively correct, even if some of the ingredients are not right.

> statistical nature of particle interactions and transport makes Monte-Carlo simulations (with random numbers) the tool of choice.

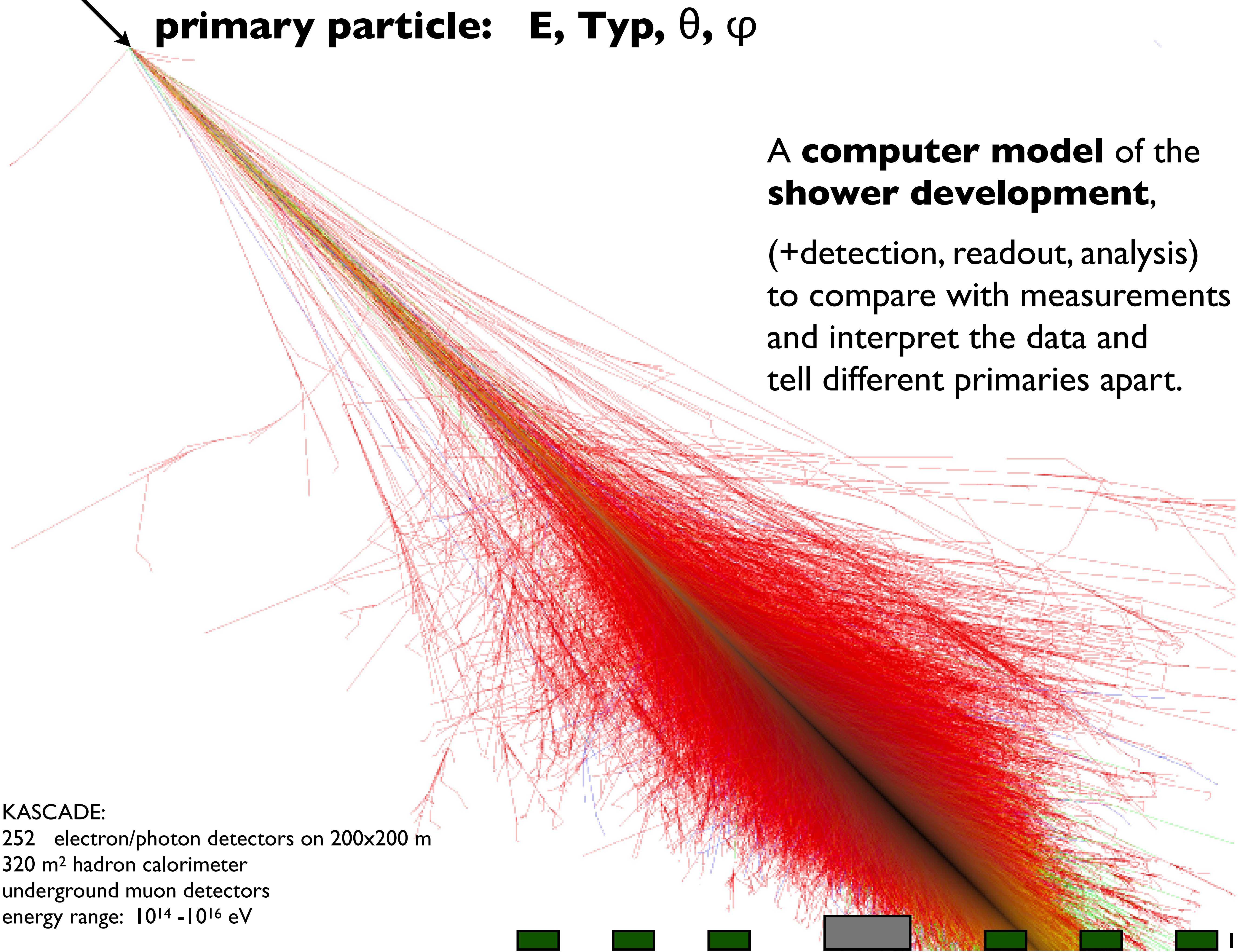
(The names “Simulation” and “Model” are often wrongly used synonymously.)

CORSIKA

Cosmic Ray Simulation for KASCADE

KASCADE: an experiment to measure cosmic ray composition
in Karlsruhe (Germany)
first ideas: 1987, first data ~1997,
KASCADE-Grande ~2003
end data taking 2009

primary particle: E, Typ, θ, φ



A **computer model** of the **shower development**,

(+detection, readout, analysis) to compare with measurements and interpret the data and tell different primaries apart.

KASCADE:
252 electron/photon detectors on 200x200 m
320 m^2 hadron calorimeter
underground muon detectors
energy range: 10^{14} - 10^{16} eV

History 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

the frame

hadronic

el.mag.

CORSIKA Vers. 1.0 Oct 1989

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

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[2]Physikalisches Institut der Universität Bern,
CH-3012 Bern, Switzerland

Abstract

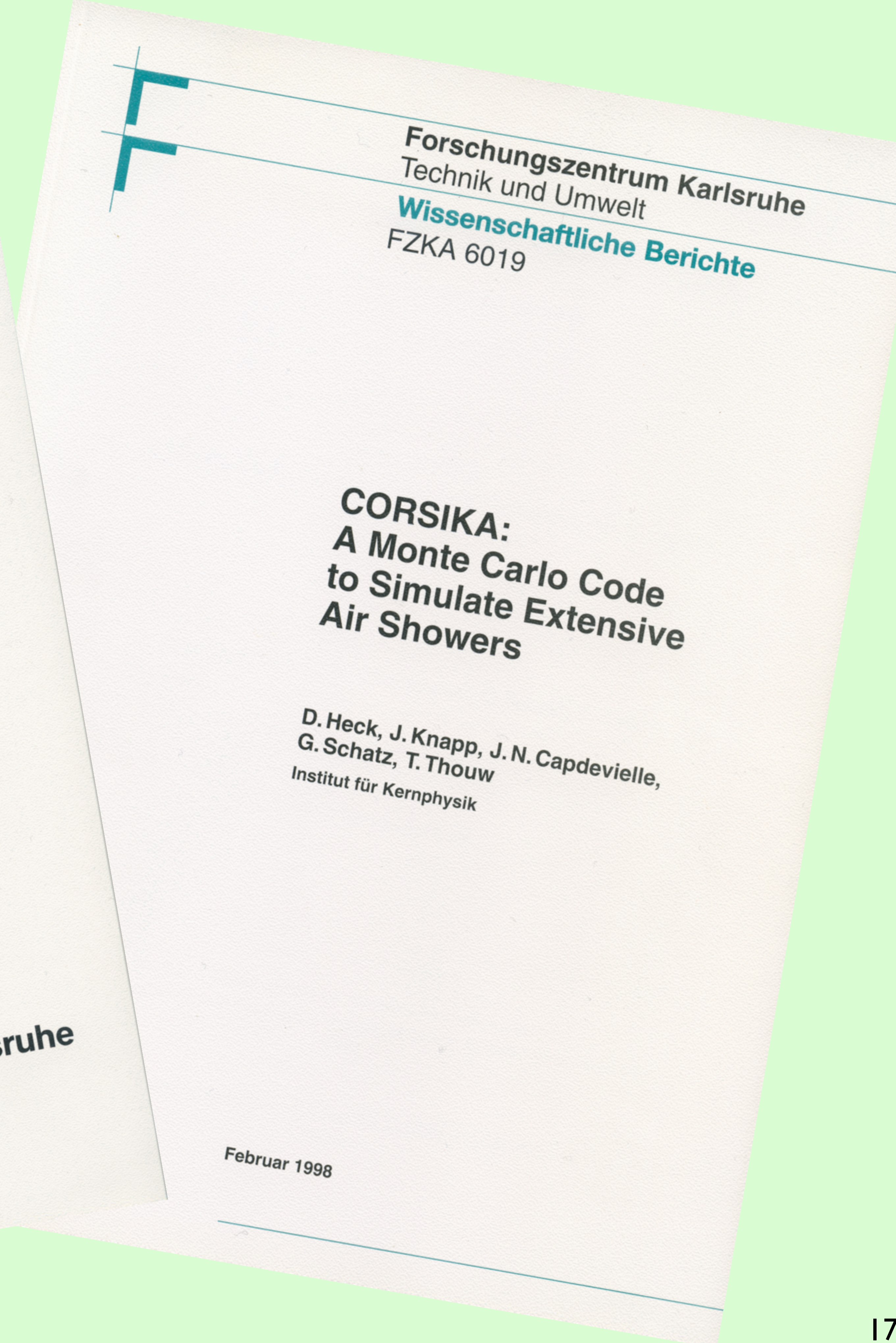
A detailed simulation program for extensive air showers and first results are presented. The mass composition of cosmic rays with $E_0 \geqq 10^{15}$eV can be determined by measuring electrons, muons and hadrons simultaneously with the KASCADE detector.

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

User’s Manual
(continuously updated)


KARLSRUHER INSTITUT FÜR TECHNOLOGIE (KIT)

Extensive Air Shower Simulation
with CORSIKA:
A User’s Guide
(Version 7.6400 from April 20, 2018)

D. Heck and T. Pierog

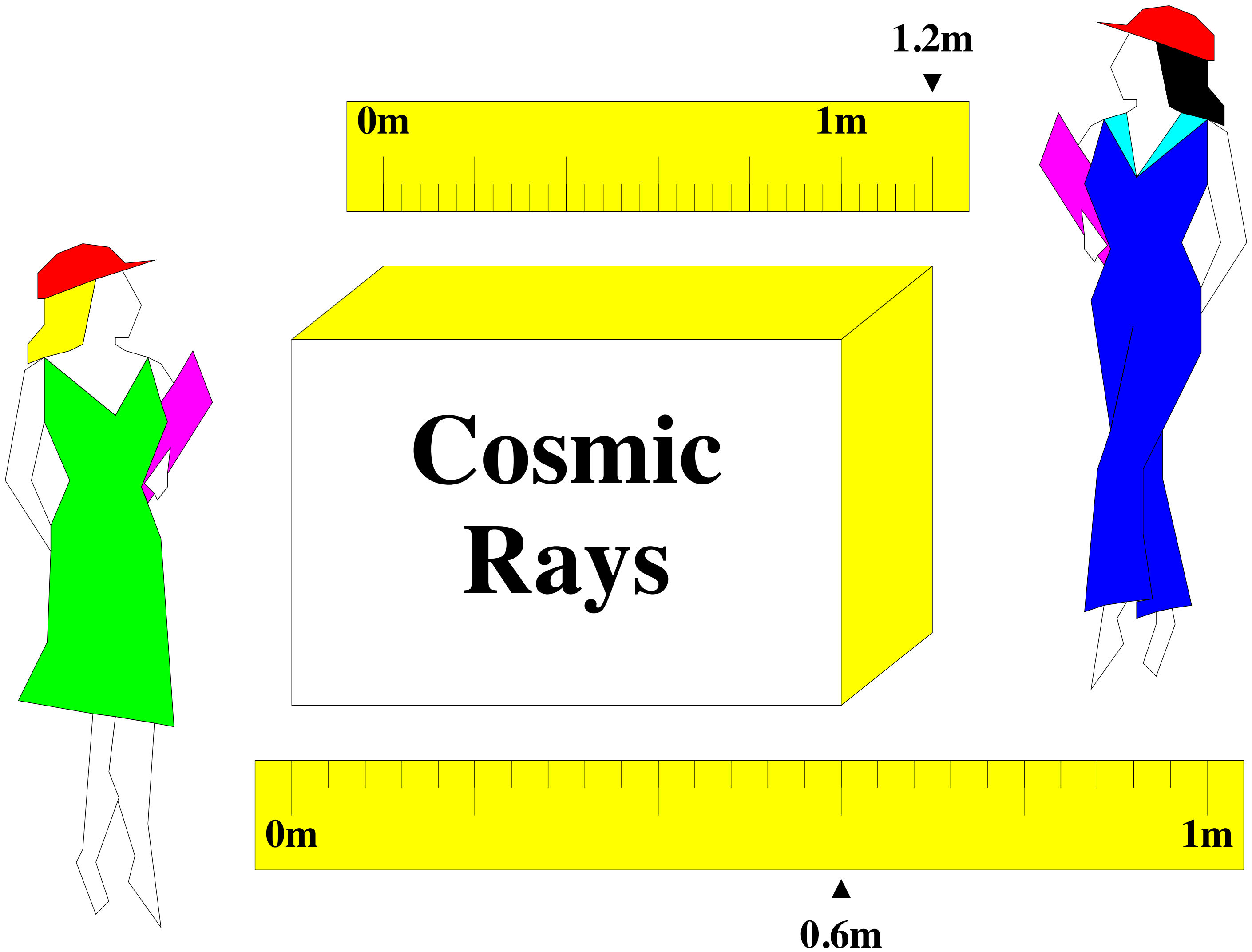
Institut für Kernphysik

KIT - Universität des Landes Baden-Württemberg und
nationales Forschungszentrum in der Helmholtz-Gemeinschaft

Preface to KfK 4998 (1992)

Analysing experimental data on Extensive Air Showers (EAS) or planning corresponding experiments requires a detailed theoretical modelling 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.

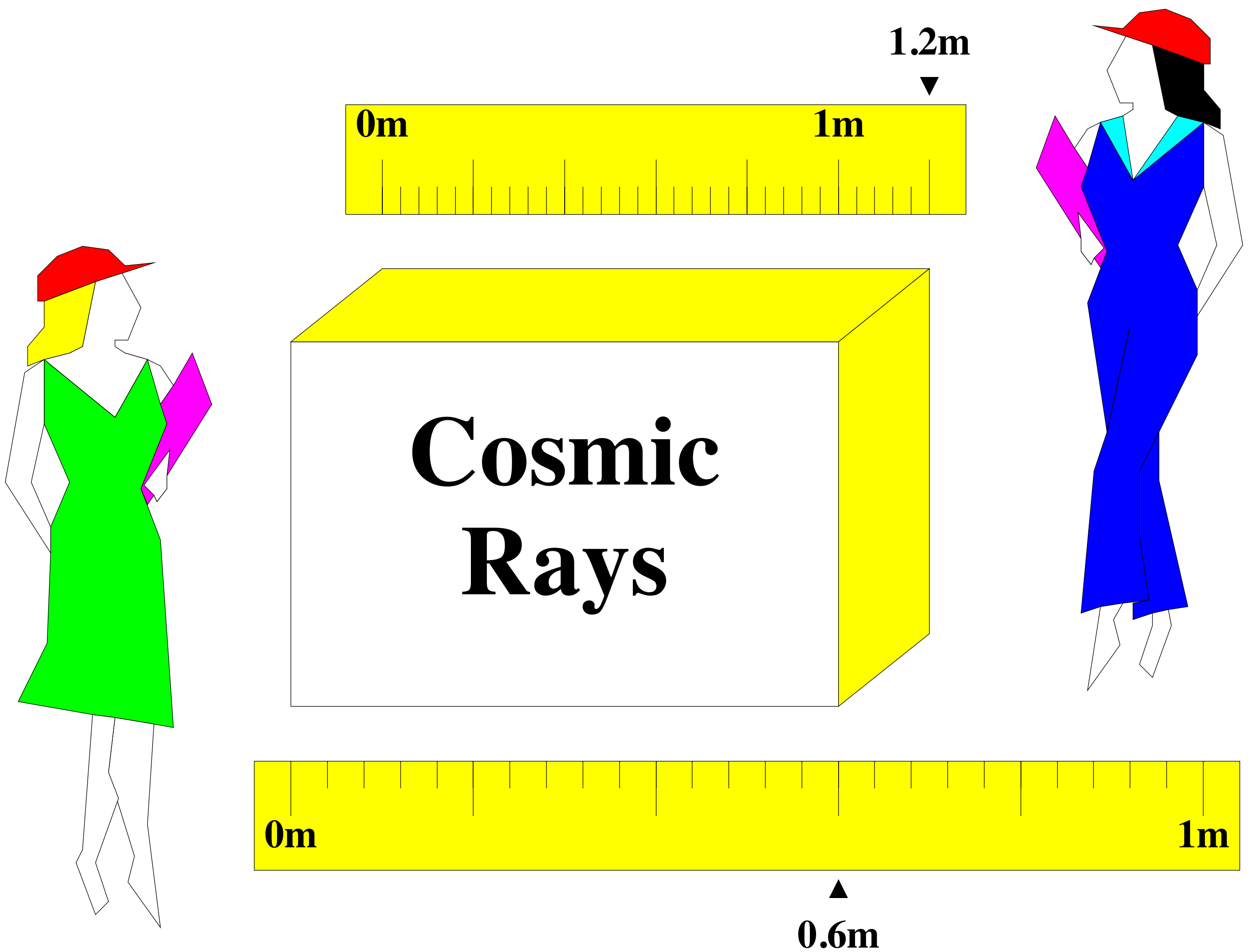
1997



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

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

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.

CORSIKA:

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

tracking, decays, atmospheres, ...

* recommended
* based on Gribov-Regge theory
* source of systematic uncertainty

el.mag.	EGS4 *
low-E.had.*	FLUKA *
	UrQMD
	GHEISHA
high-E.had. **	QGSJET **
	EPOS-LHC *
	DPMJET *
	SIBYLL

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

+ many extensions & simplifications

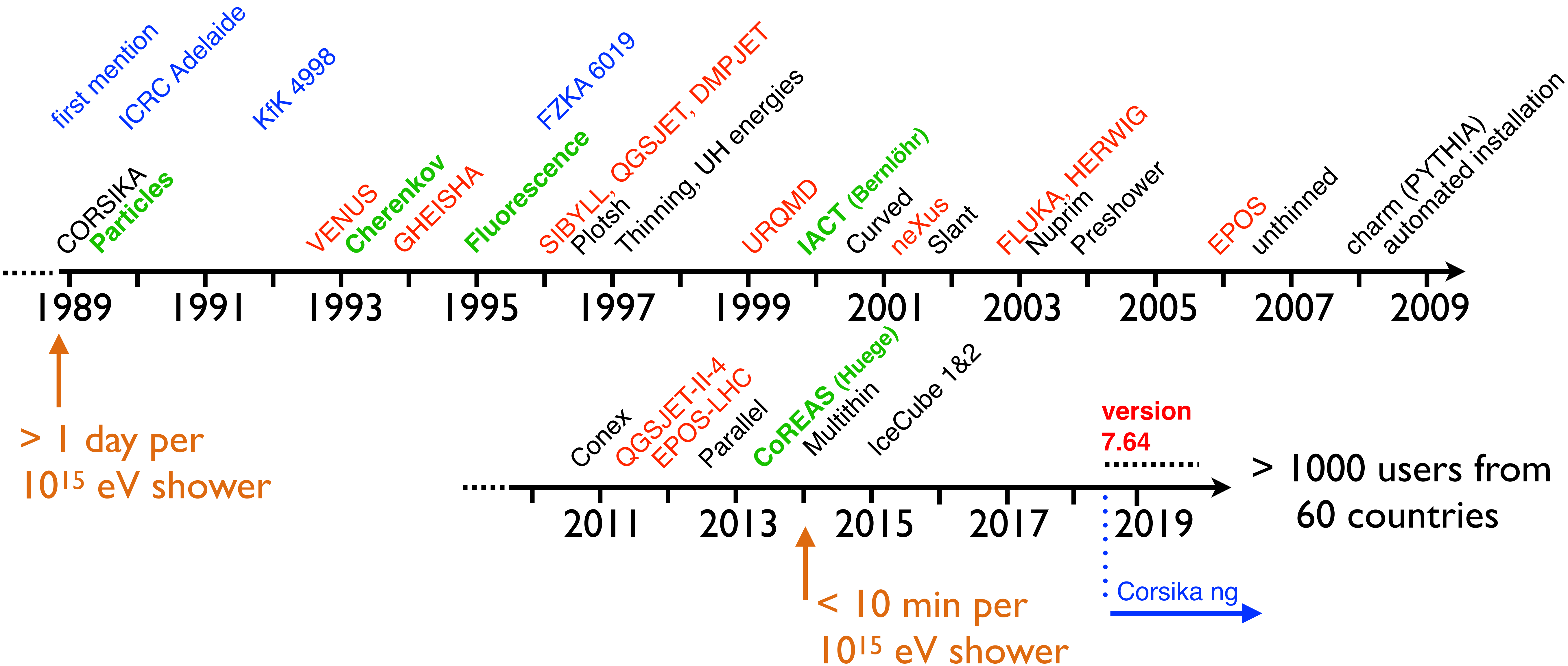
Sizes and runtimes vary by factors 2 - 40.

Total: >> 10^5 lines of code

many person-years of development.

https://www.ikp.kit.edu/corsika/

The Timeline



KfK 4998 + FZKA 6019 ~2300 citations

Google Scholar

by far the most cited work of its authors

(and more citations than all KASCADE papers together)

from Google Scholar:

CORSIKA: A Monte Carlo code to simulate extensive air showers

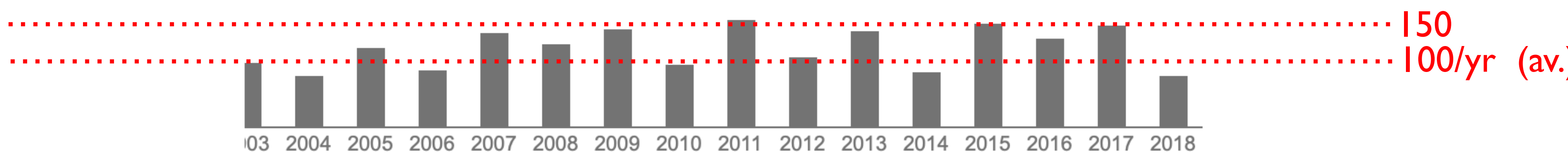
Authors Dieter Heck, G Schatz, J Knapp, T Thouw, JN Capdevielle

Publication date 1998

Issue FZKA-6019

Description CORSIKA is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries. The particles are tracked through the atmosphere until they undergo reactions with the air nuclei or-in the case of instable secondaries-decay. The hadronic interactions at high energies may be described by ve reaction models alternatively: The VENUS, QGSJET, and DPMJET models are based on the Gribov-Regge theory, while SIBYLL is a minijet model. HDPM is a phenomenological generator and adjusted to experimental data wherever possible. Hadronic interactions at lower energies are described either by the more sophisticated GHEISHA interaction routines or the rather simple ISOBAR model. In particle decays all decay branches down to the 1 level are taken into account. For electromagneti the …

Total citations Cited by 2294



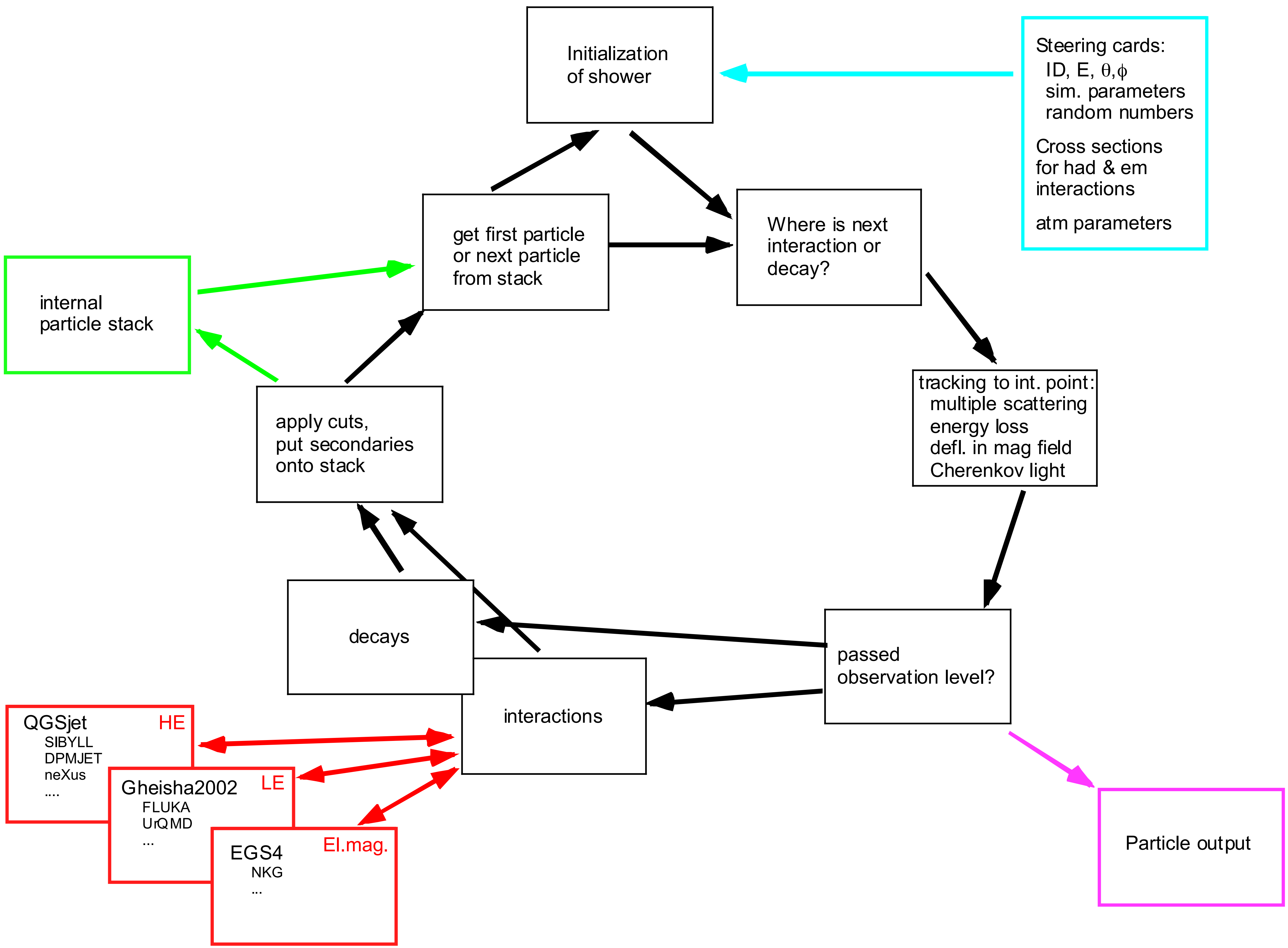
Scholar articles CORSIKA: A Monte Carlo code to simulate extensive air showers
D Heck, G Schatz, J Knapp, T Thouw, JN Capdevielle - 1998
Cited by 1284 Related articles All 11 versions

report FZKA 6019 *
D Heck, J Knapp, JN Capdevielle, G Schatz, T Thouw - Forschungszentrum Karlsruhe, 1998
Cited by 458 Related articles

Upgrade of the Monte Carlo code CORSIKA to simulate extensive air showers with energies> 10** 20-eV *
D Heck, J Knapp - 1998
Cited by 417 Related articles All 3 versions

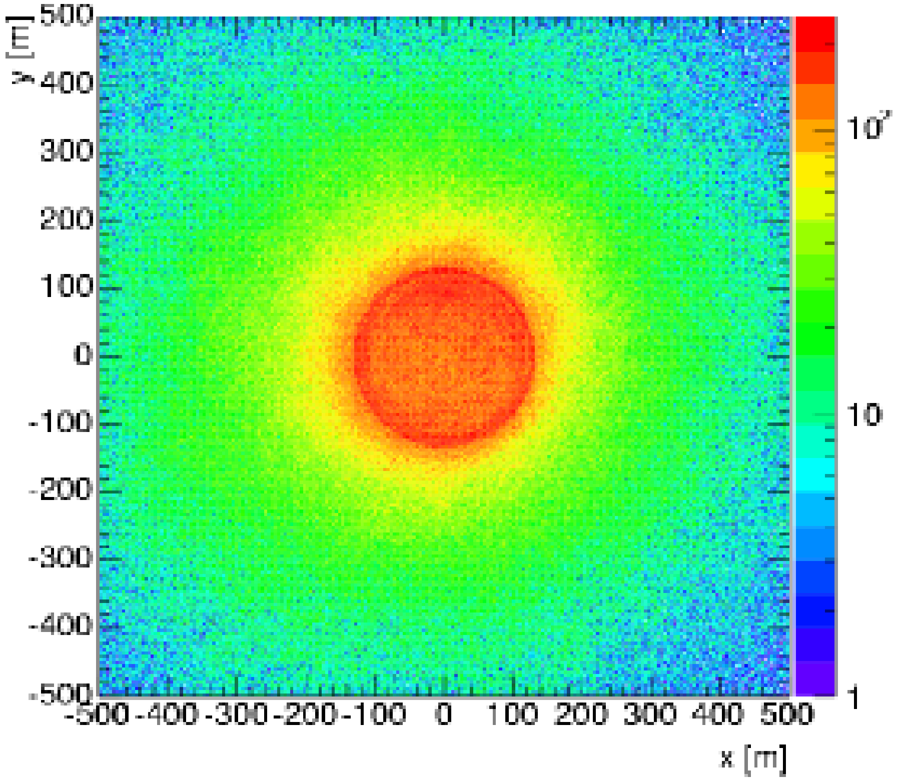
Report FZKA 6019 (1998) *
D Heck, J Knapp, JN Capdevielle, G Schatz, T Thouw - Forschungszentrum Karlsruhe, 1997
Cited by 229 Related articles

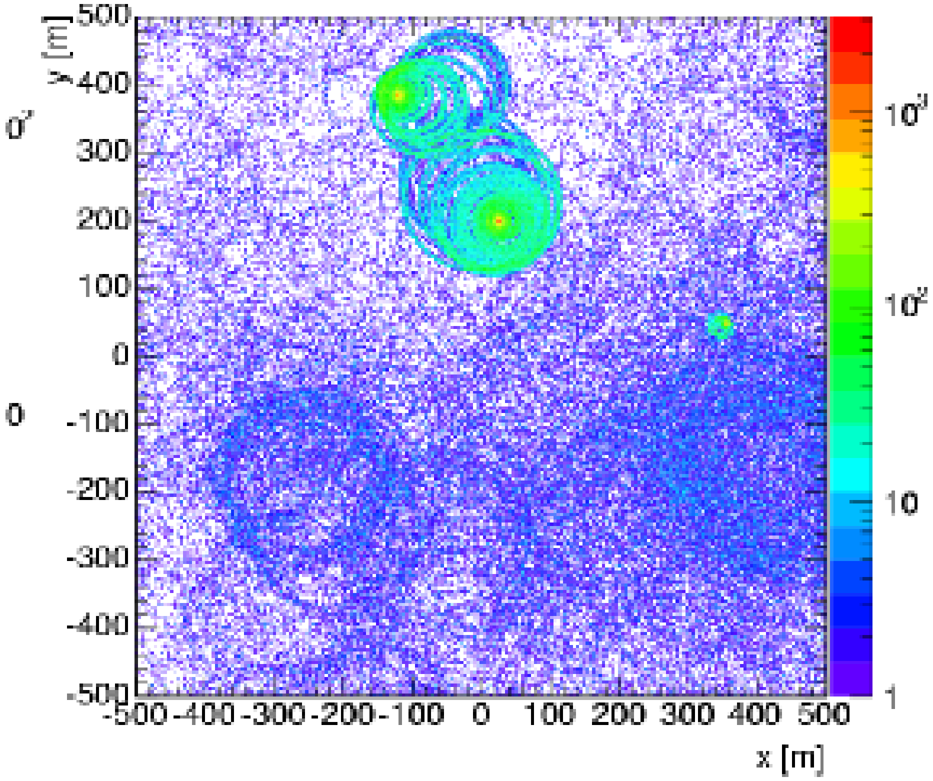
CORSIKA flow diagram

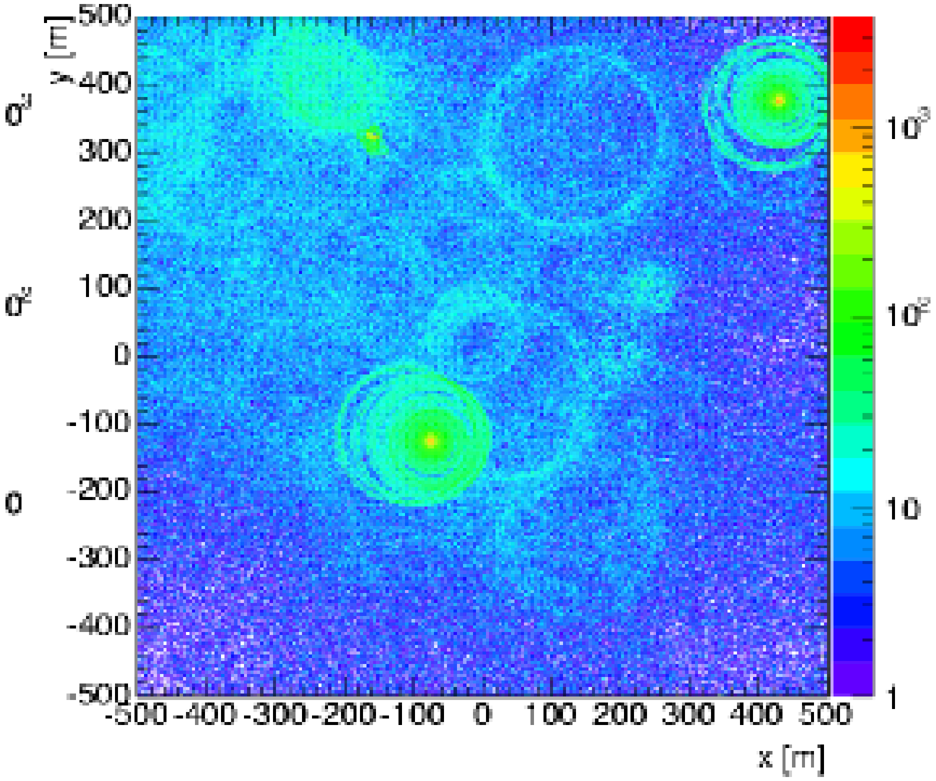


Examples of emerging features in detailed simulations:

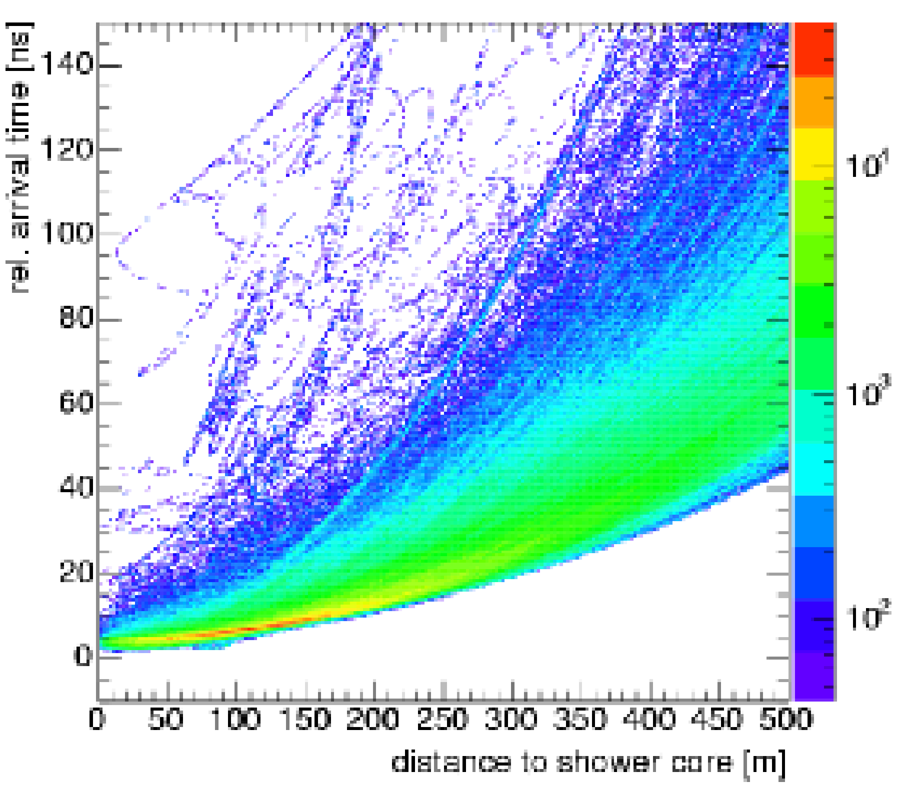
Cherenkov light:

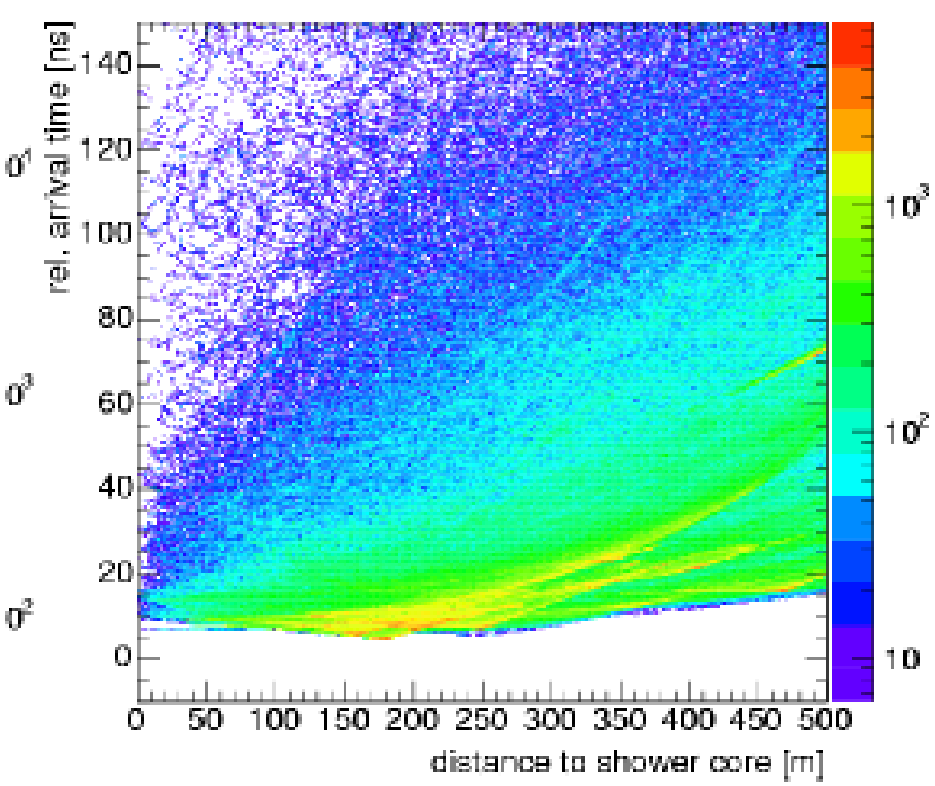


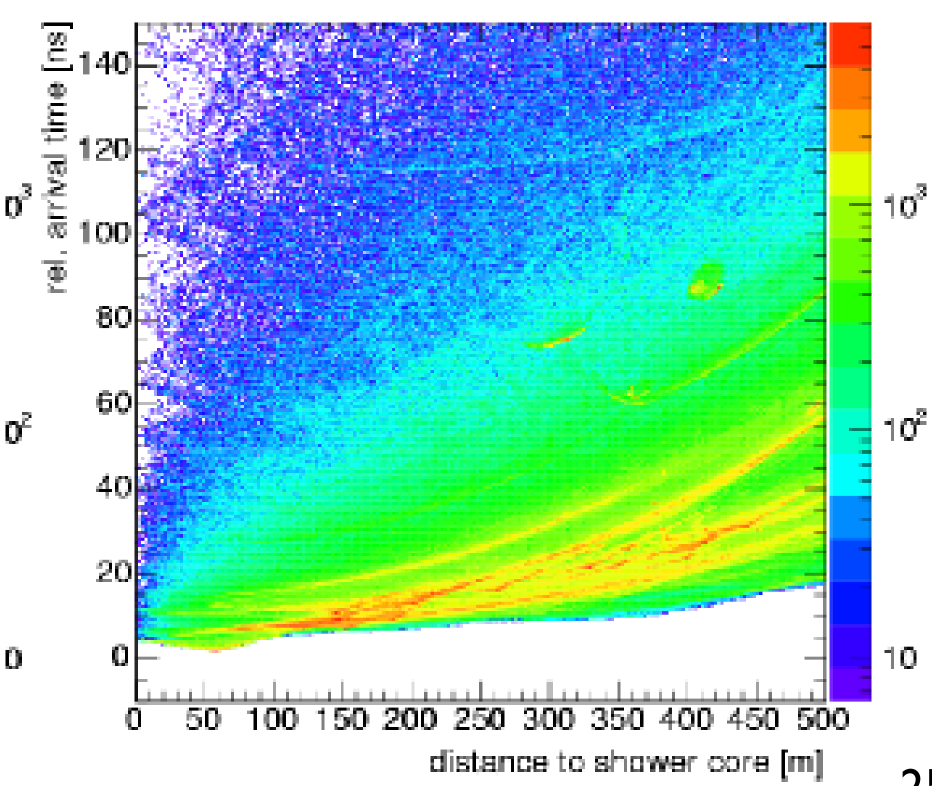


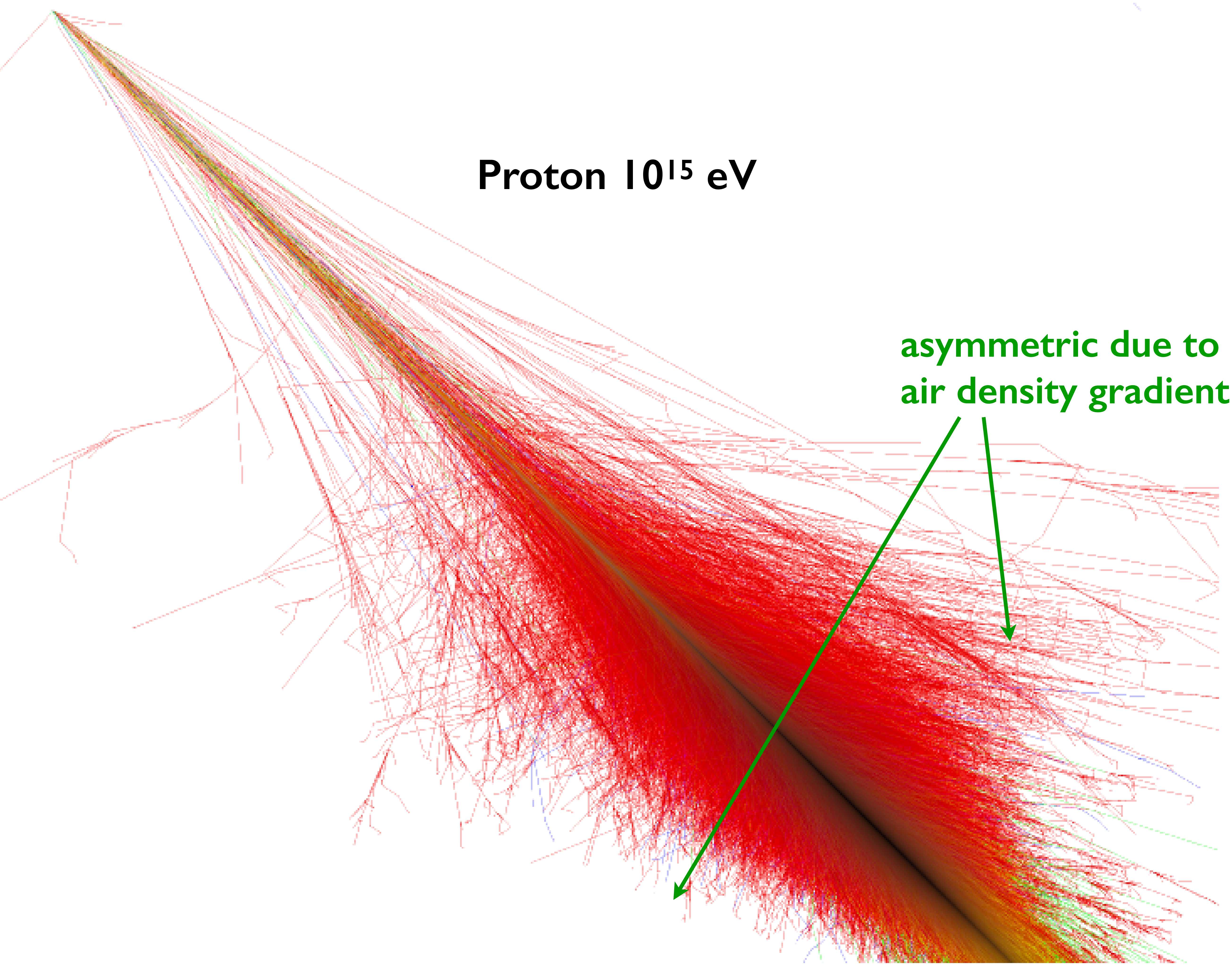


gamma 300 GeV **proton 90 GeV** **iron 50 GeV**








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

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

- change in a complex way,
- are correlated,

and this is important for analysis

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

Many such effects in EAS physics.

Therefore:

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

Simulations vs Data:

Result:

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

Simulated showers look very much like measured ones.

– Considerable convergence of models since 1990

– 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 ones,
i.e. CORSIKA is not far off the truth.

(uncertainties < 30% for most observables)

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– Simulations with hadronic interaction models

- based on Gribov-Regge Theory
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  heavy mesons, baryons ....

produce showers that look very much like real ones,
i.e. CORSIKA is not far off the truth.

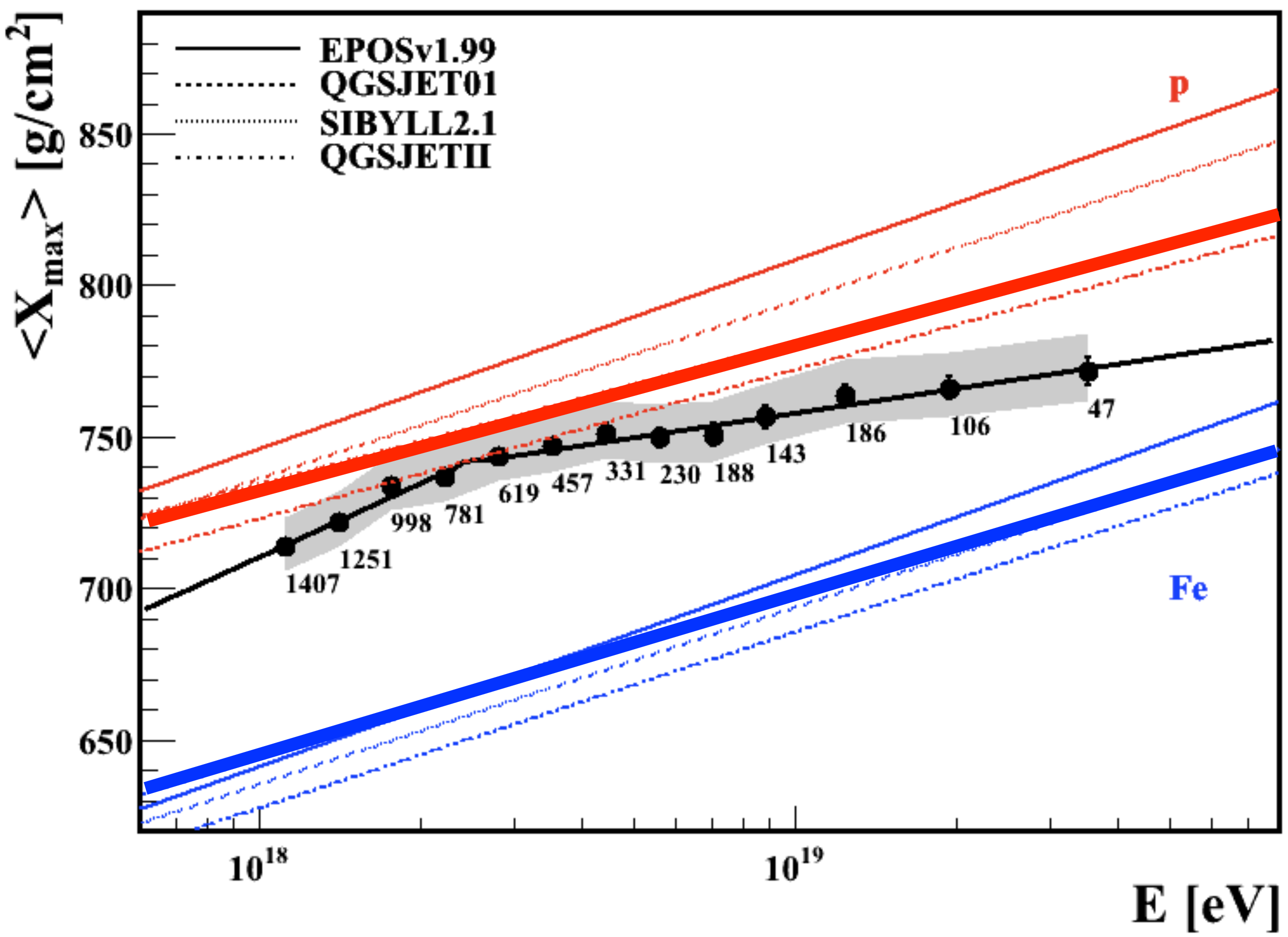
(uncertainties < 30% for most observables)

– much better agreement at lower energies
(where collider data constrain extrapolations)

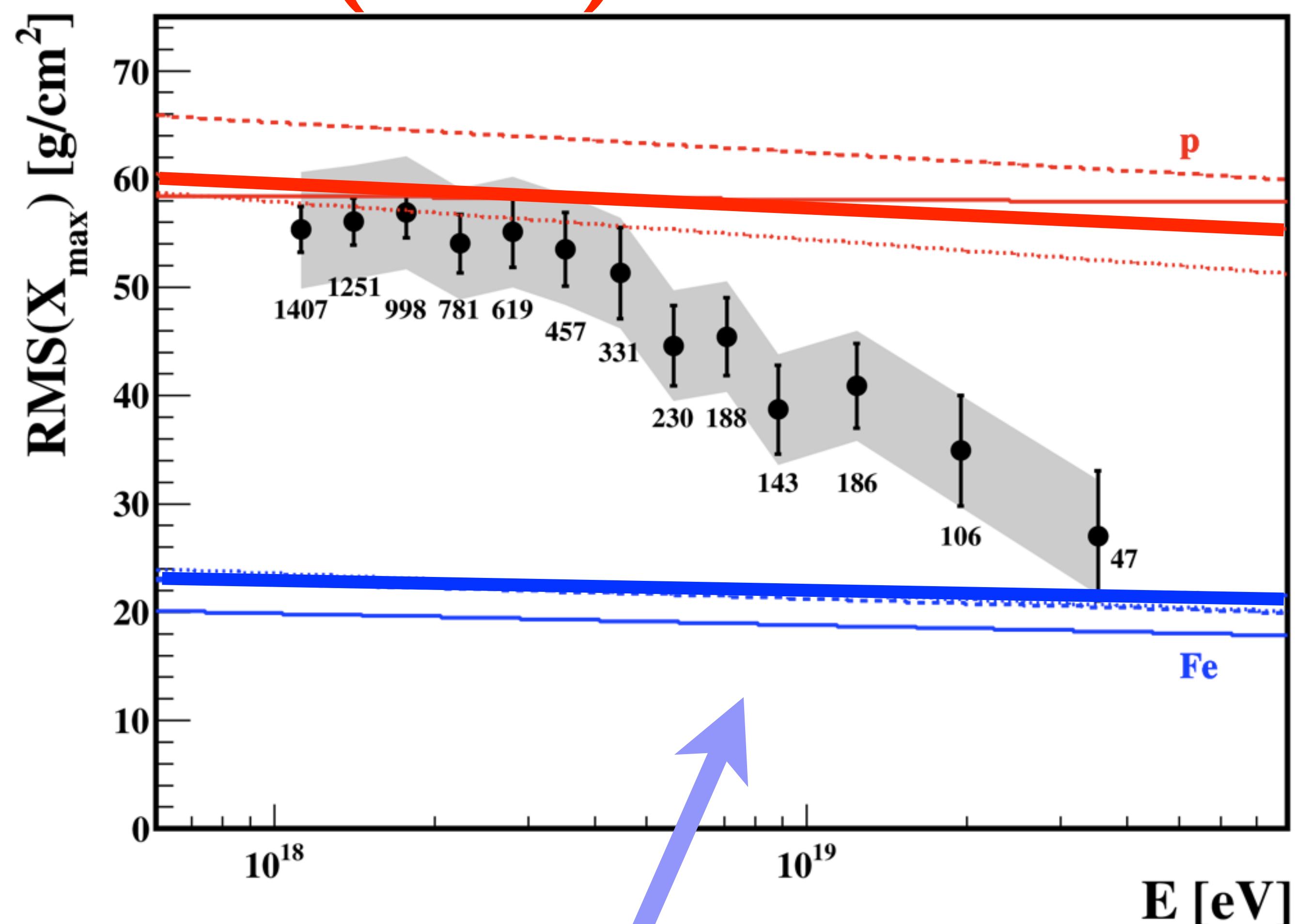
– for highest energies ($>10^{18}$ eV)
considerable extrapolation beyond collider data is needed.
Without firm theoretical guidelines as to how
to extrapolate, uncertainties are exploding.
Pure phenomenology is not good enough.

Current limitations:

X_{max} Auger: composition



RMS(X_{max})



model dependent
interpretation

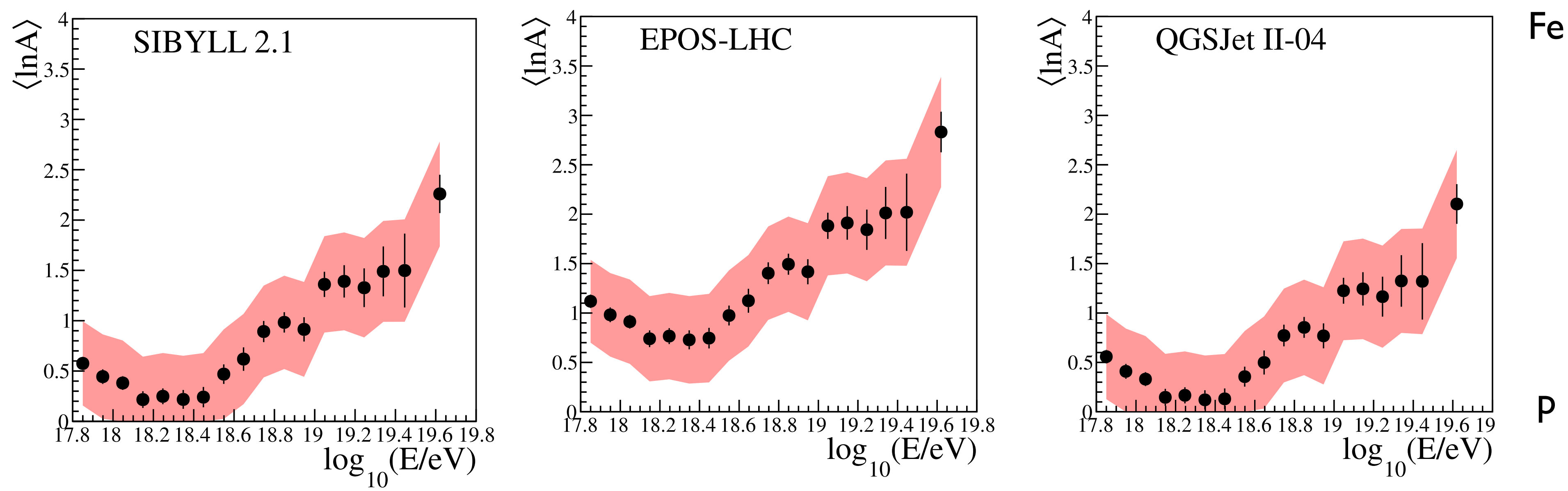
whatever we do to models
(within limits),
data do not fit to
primary proton sims.

If one trusts the models,
then composition turns heavier
(but the **two plots are not consistent**) :(

mixed/heavy ?
(10^{19} eV < E < 4×10^{19} eV)

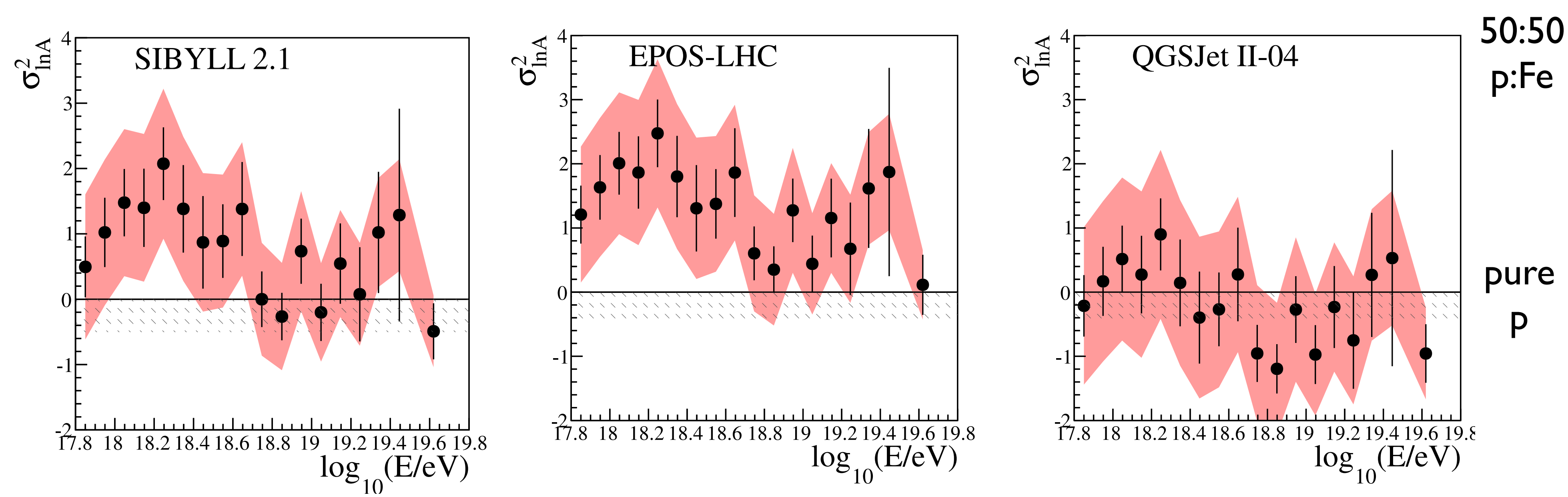
Composition data: transition to heavier primaries

$$\langle X_{\max} \rangle \approx \langle X^{p}_{\max} \rangle - D_p \langle \ln A \rangle$$



⟨ln A⟩: Transition from medium → light → heavy ?

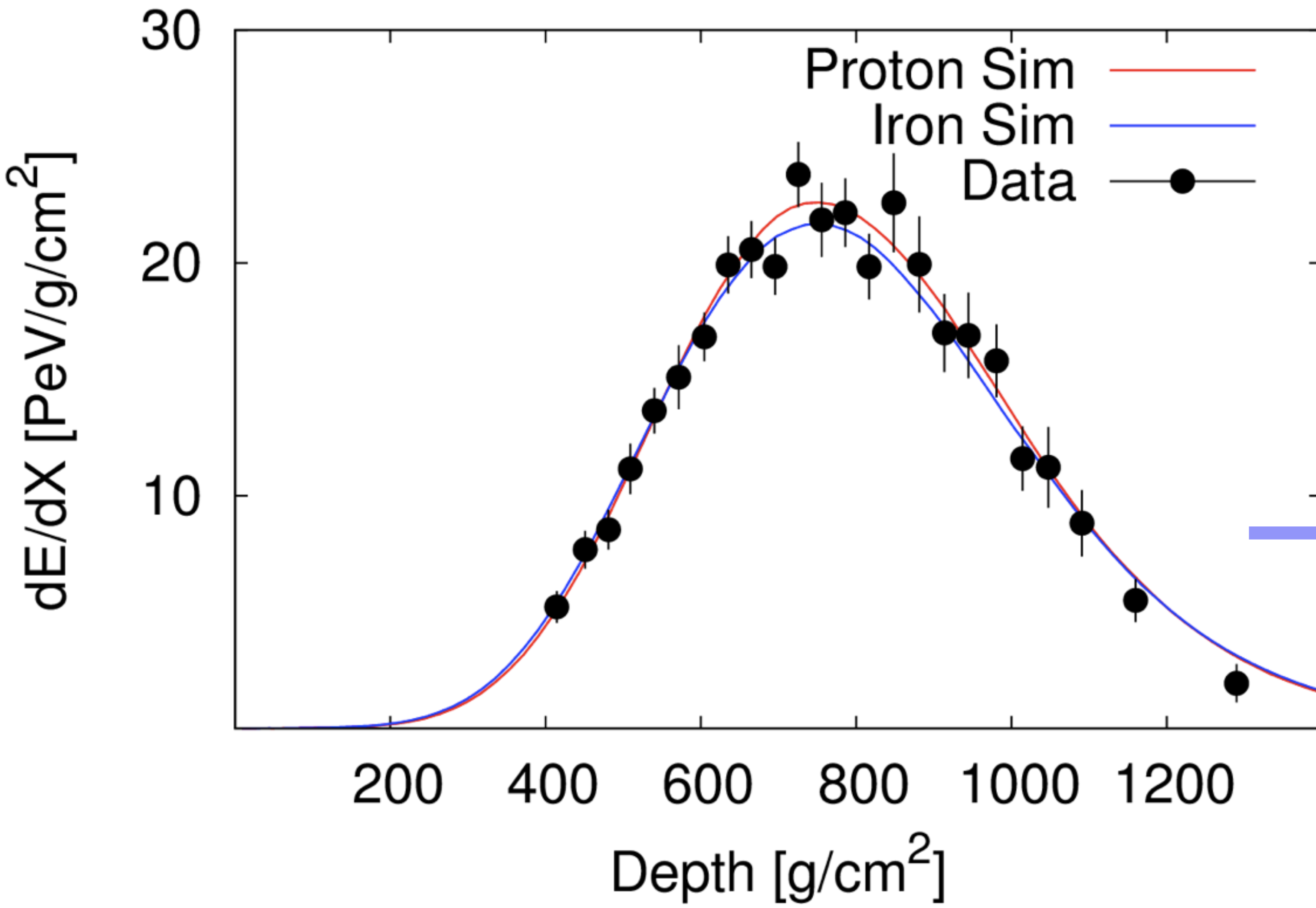
$$\sigma(X_{\max})^2 \approx \langle \sigma_i^2 \rangle + D_p^2\, \sigma(\ln A)^2$$



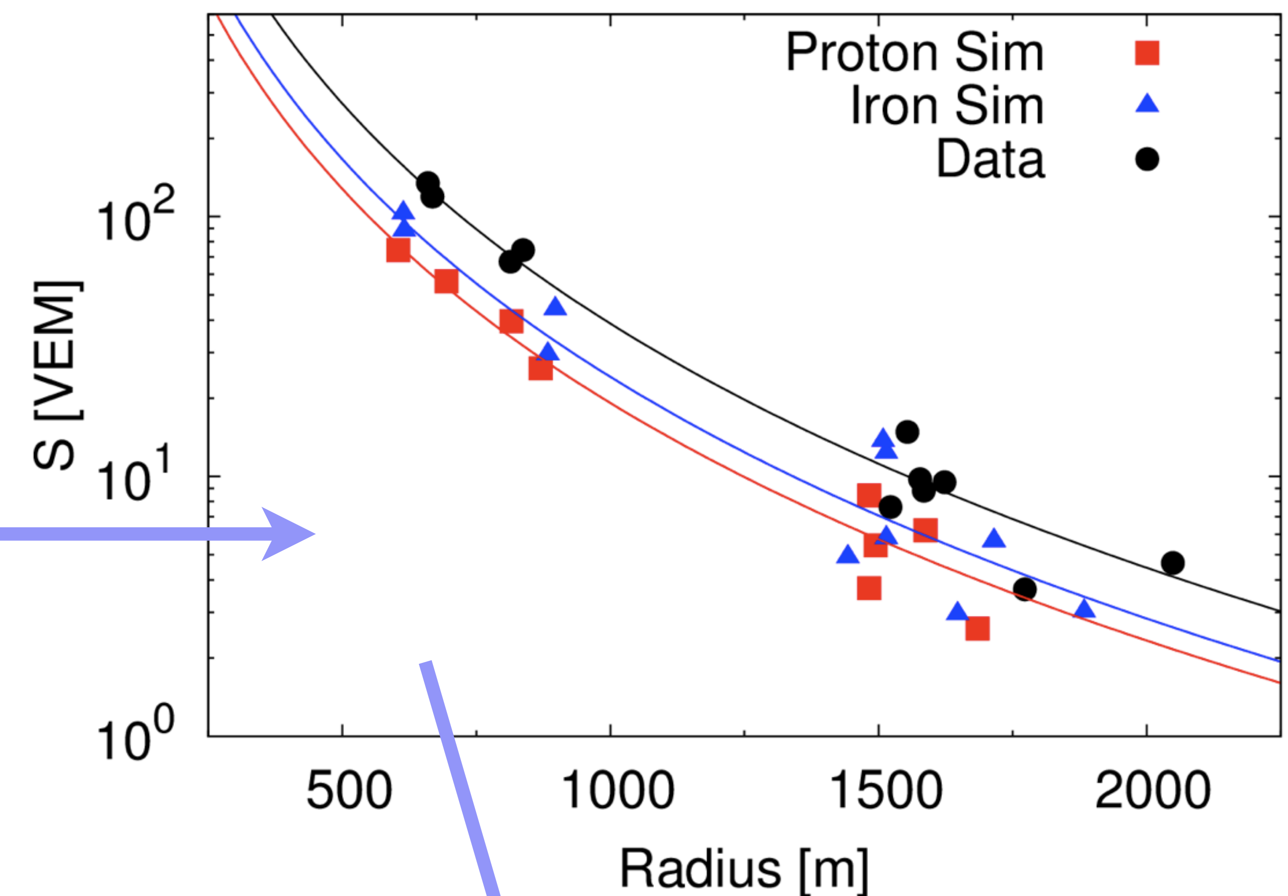
σ(ln A): Transition from proton dominated or mixed → approx. pure ?

differences between models, inconsistencies between ⟨ln A⟩ and σ(ln A)

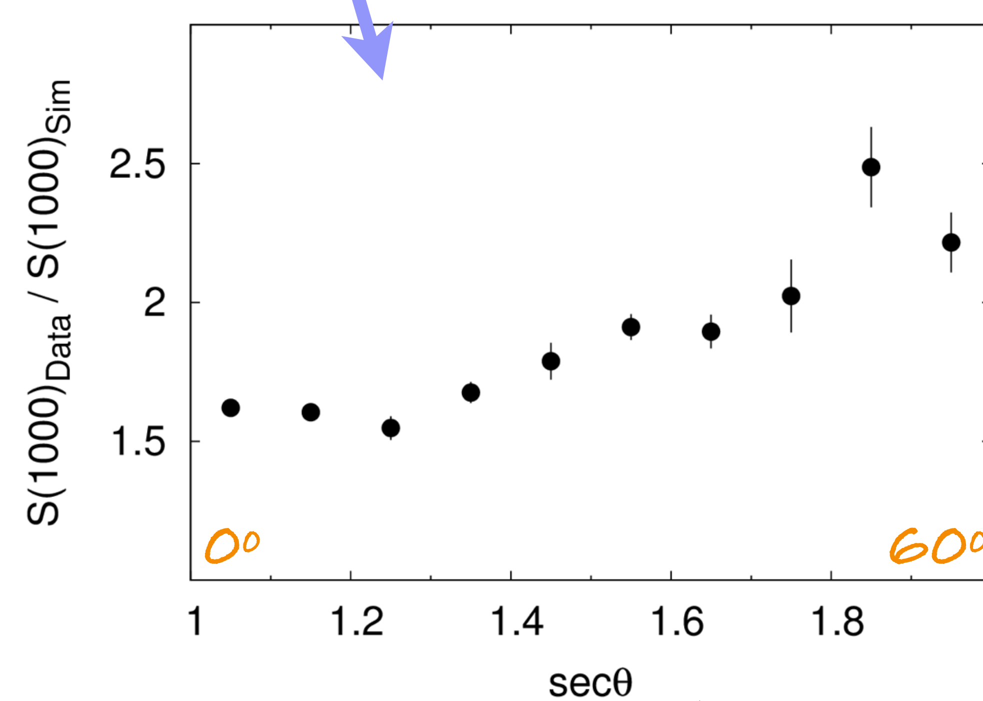
Are the EAS models right ?



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

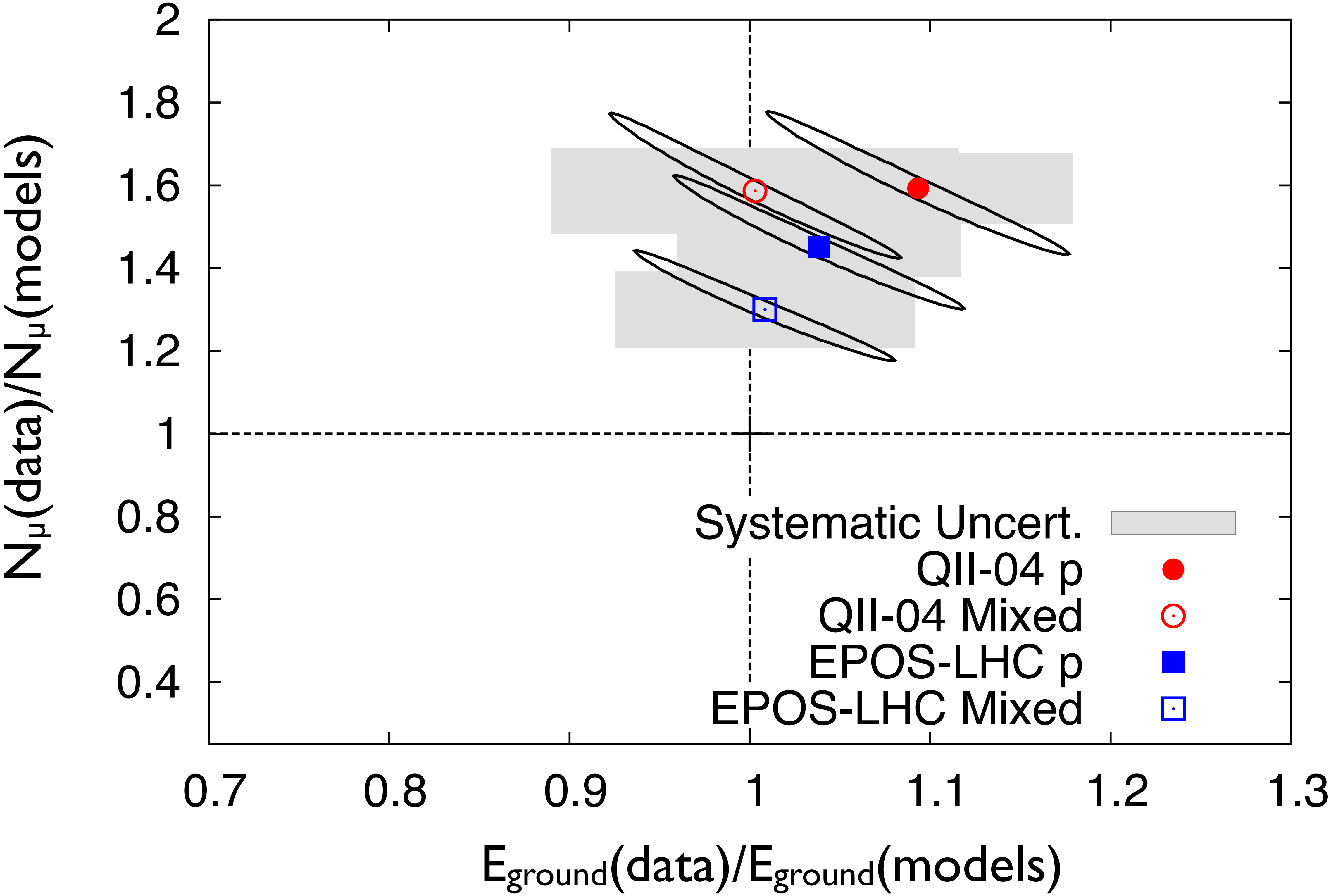


match the long. shower profile (as seen in FD) of a measured event with p and Fe simulations

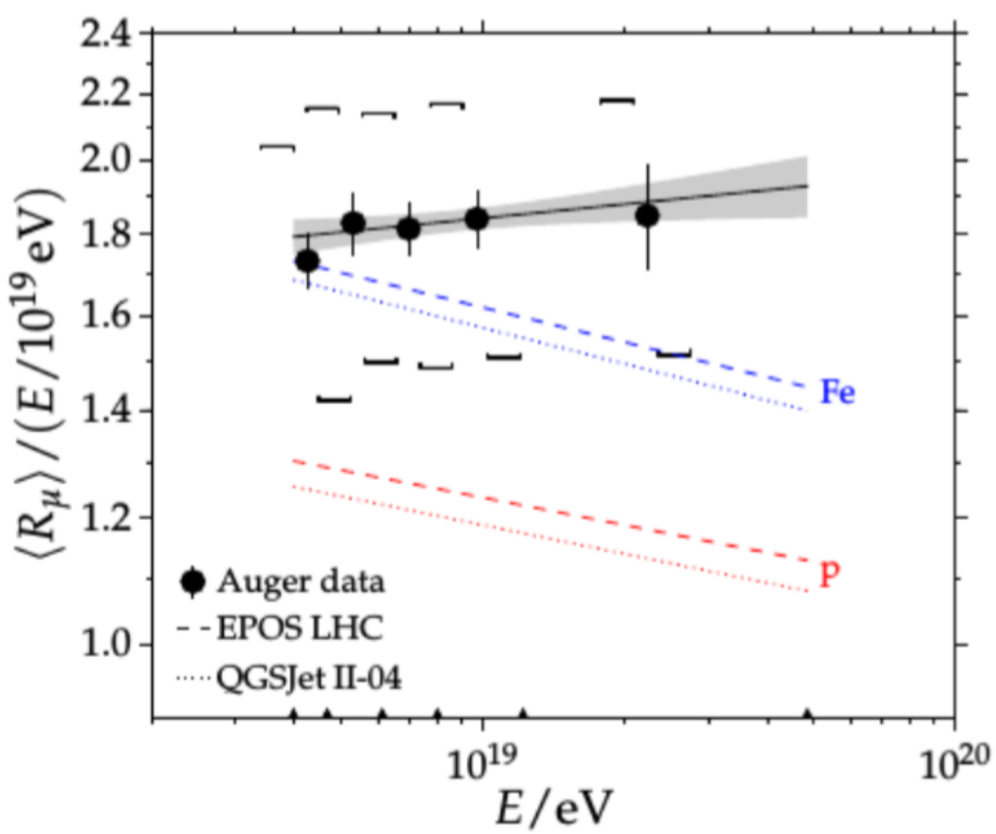


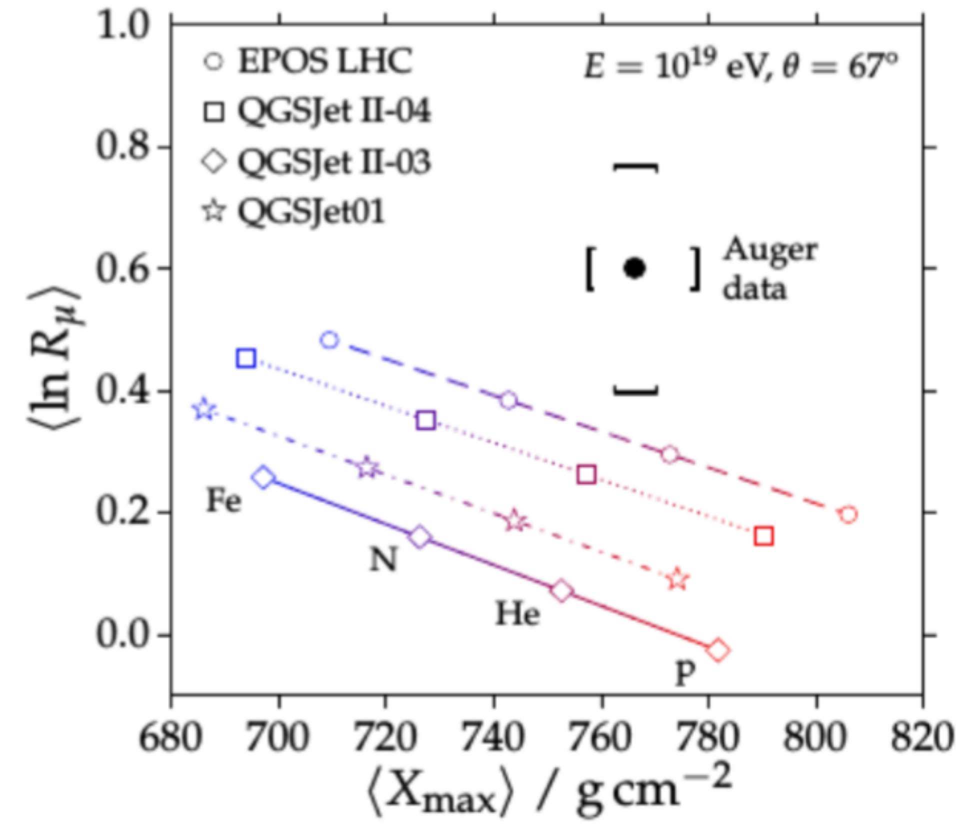
models underestimate ground signal by 1.5 - 2x

μ content rises with θ



in all models muon number is 30-60% too small





Auger, arXiv-1408.1421

- More muons in air shower data than expected
- No consistency between different observables can be achieved

$\rightarrow$ Interaction physics in air shower models still not accurate

Something is still wrong

Air shower models require modifications:

hadronic model ?

fluorescence yield ?

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

Auger is doing
Particle physics at $>10^{19}$ eV with cosmic rays !!

Note: an air shower model must work well
for all energies from MeV to 10^{20} eV

(as in a shower interactions occur at all energies)

for all primaries at all angles and altitudes

Good agreement at one energy / primary / angle / altitude
is no guarantee for good agreement at another one.

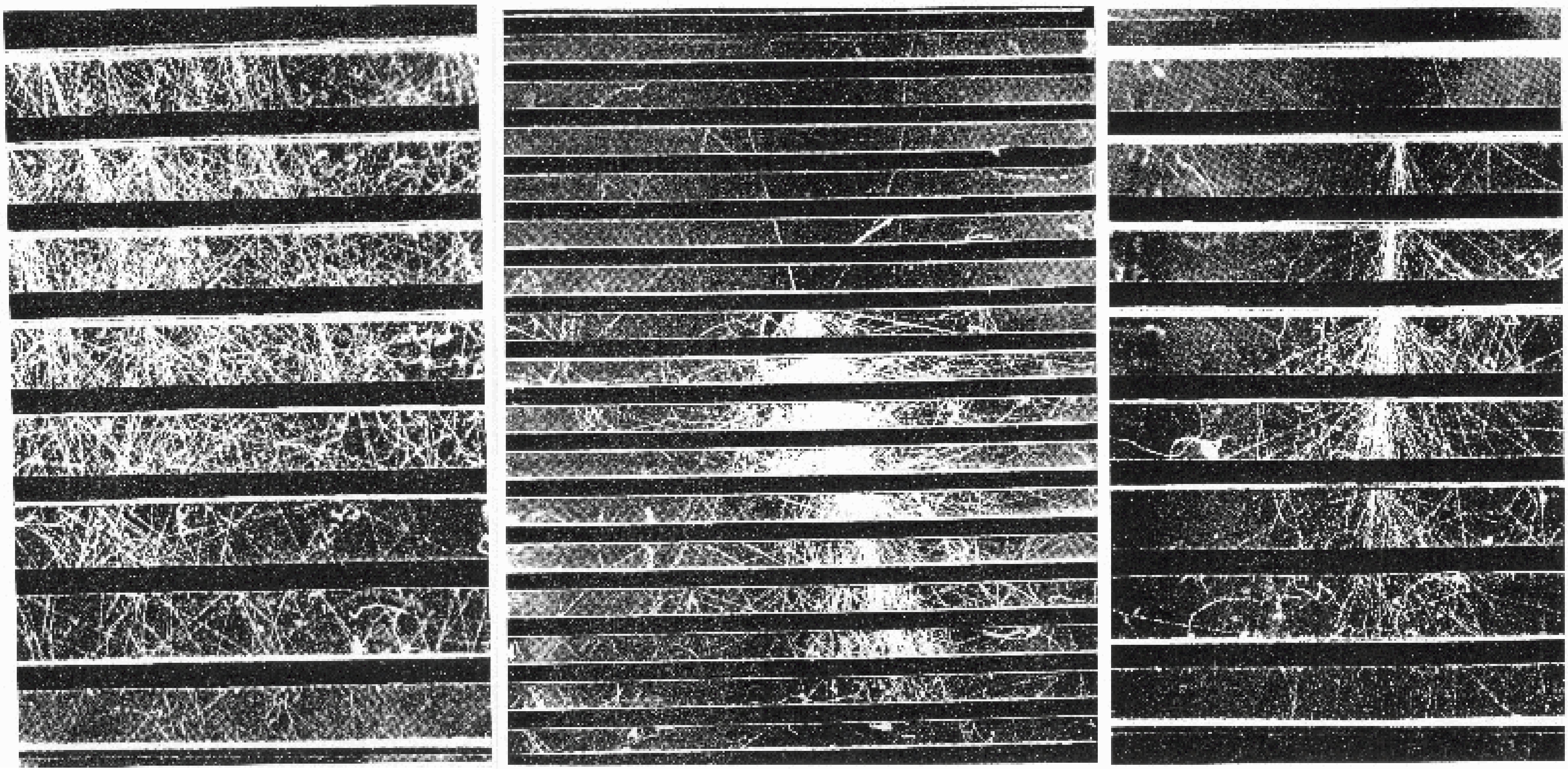
Need to tune models always with all available
sets of data:

air showers, direct CR measurements,
colliders, fixed target expts., underground muons, …

… a long and tedious process

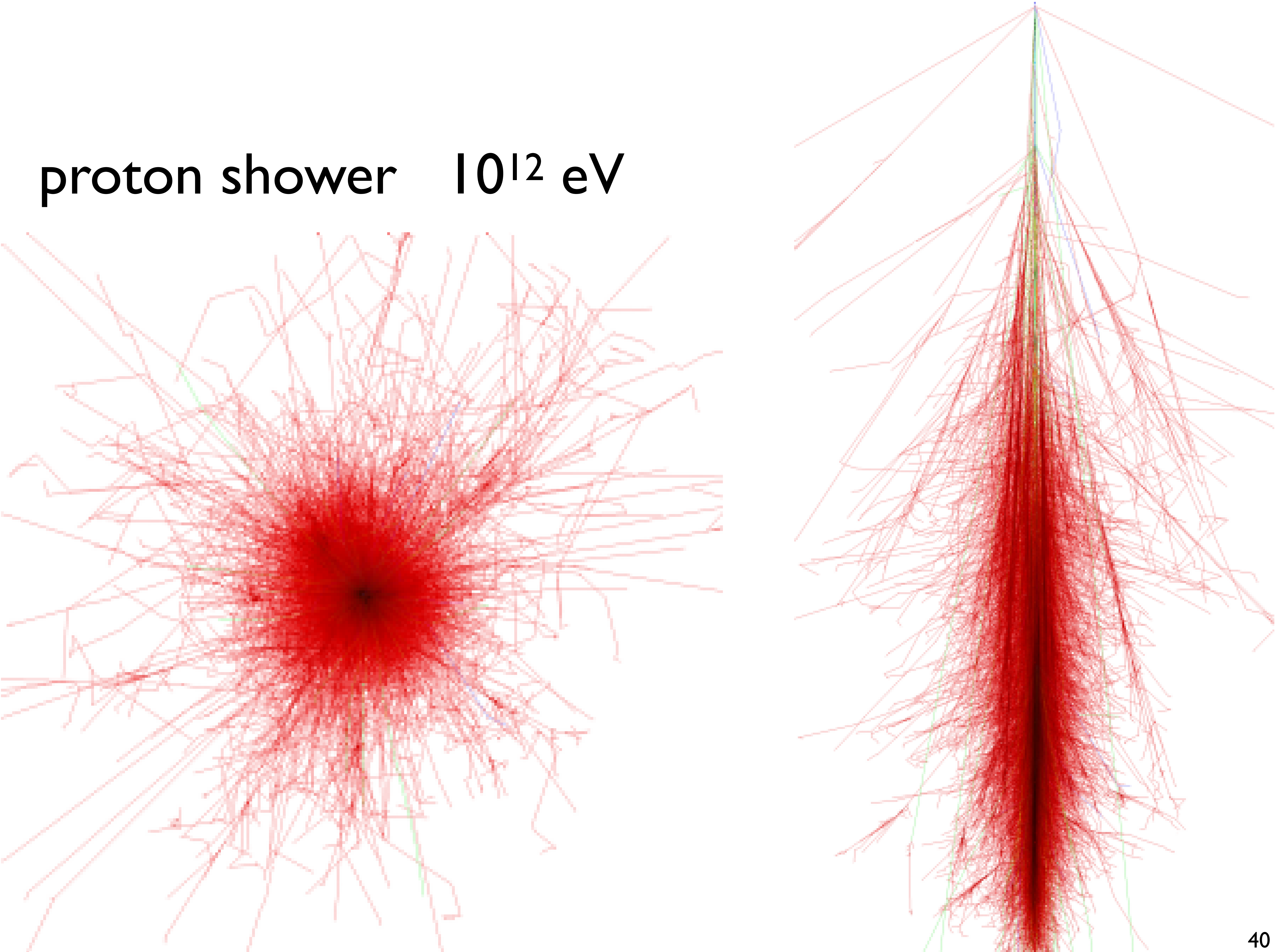
Educational Images

Visualise and understand what is going on ...

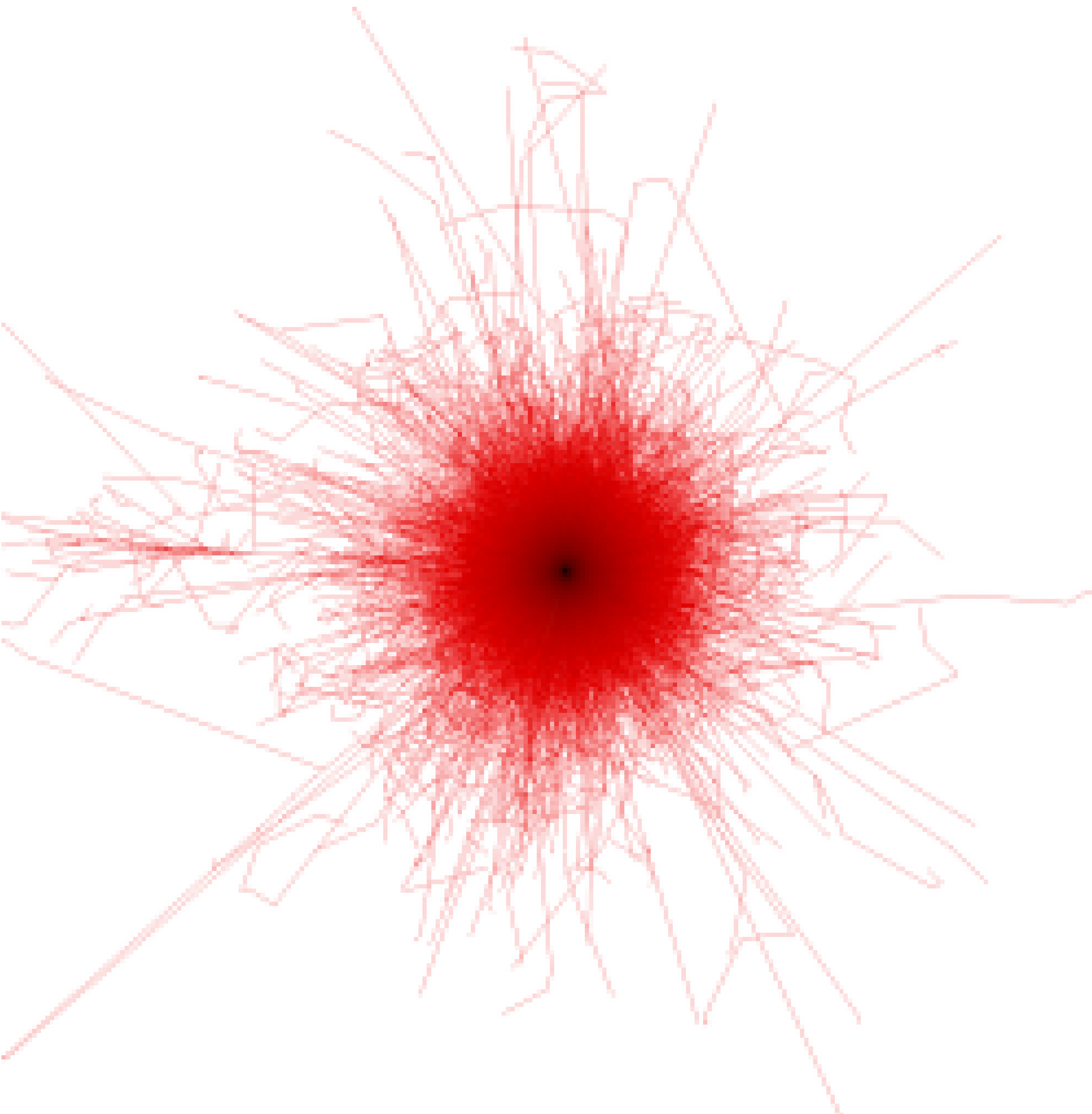


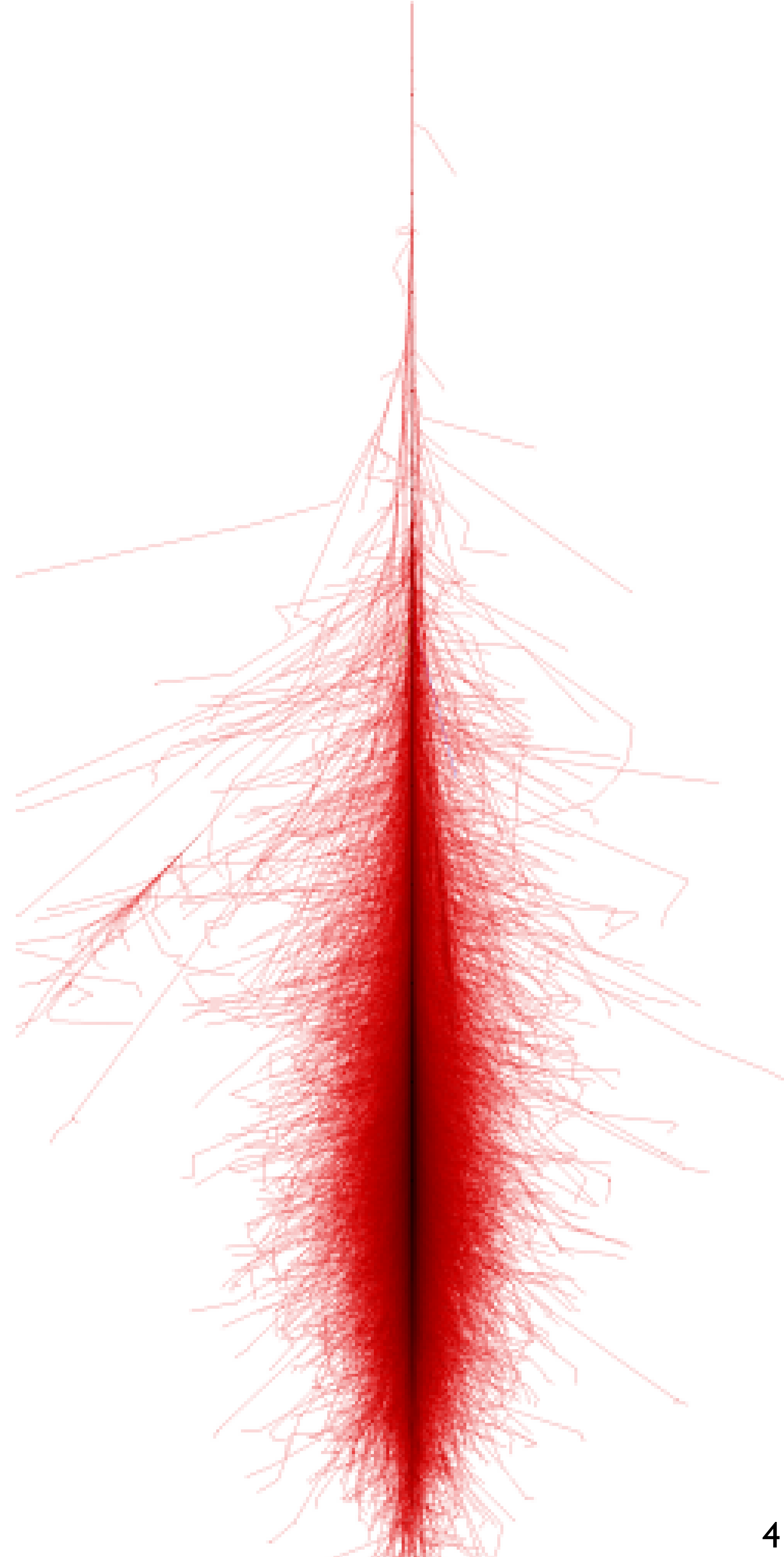
... as with early bubble and cloud chamber photos.

proton shower 10^{12} eV

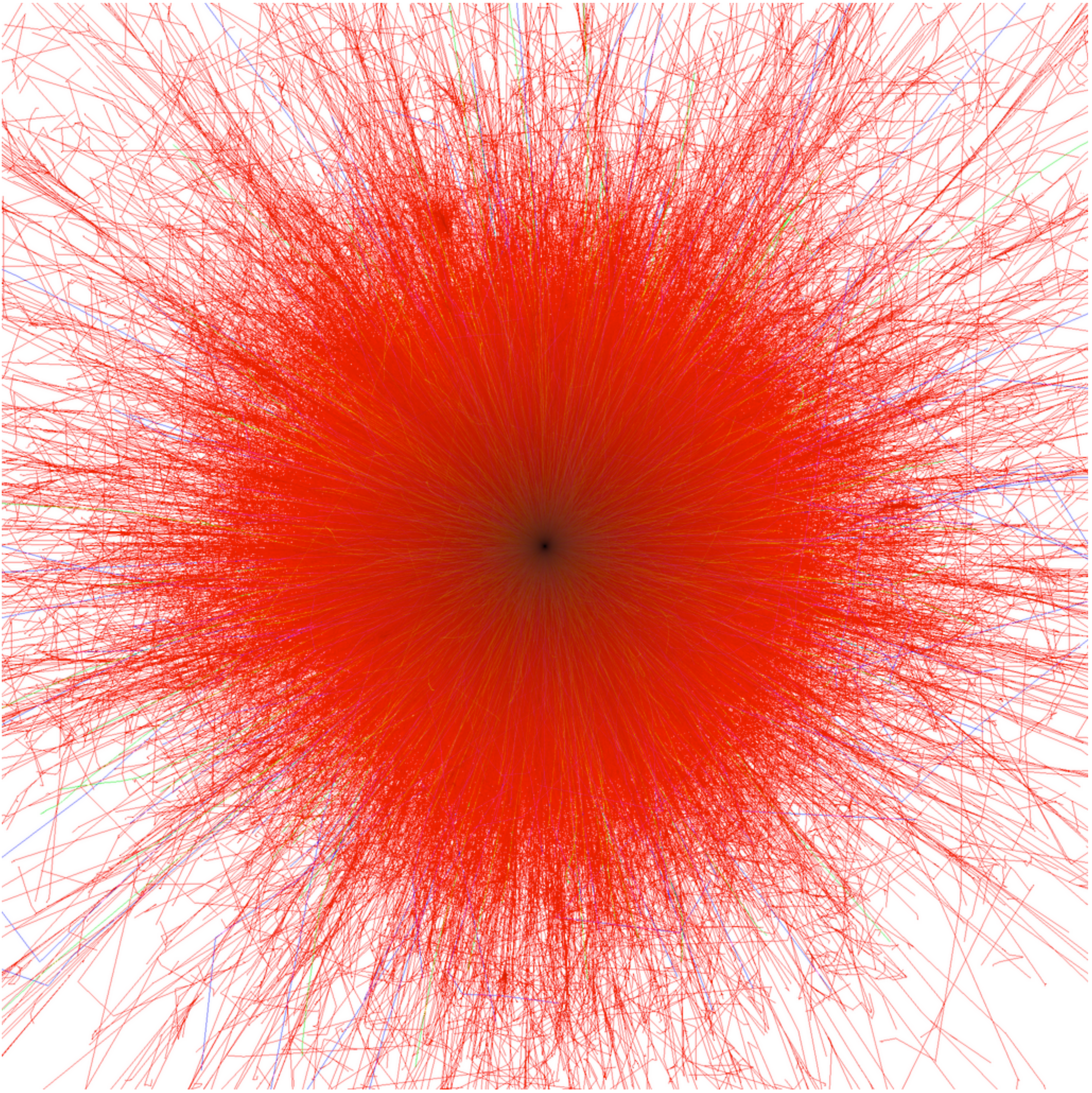


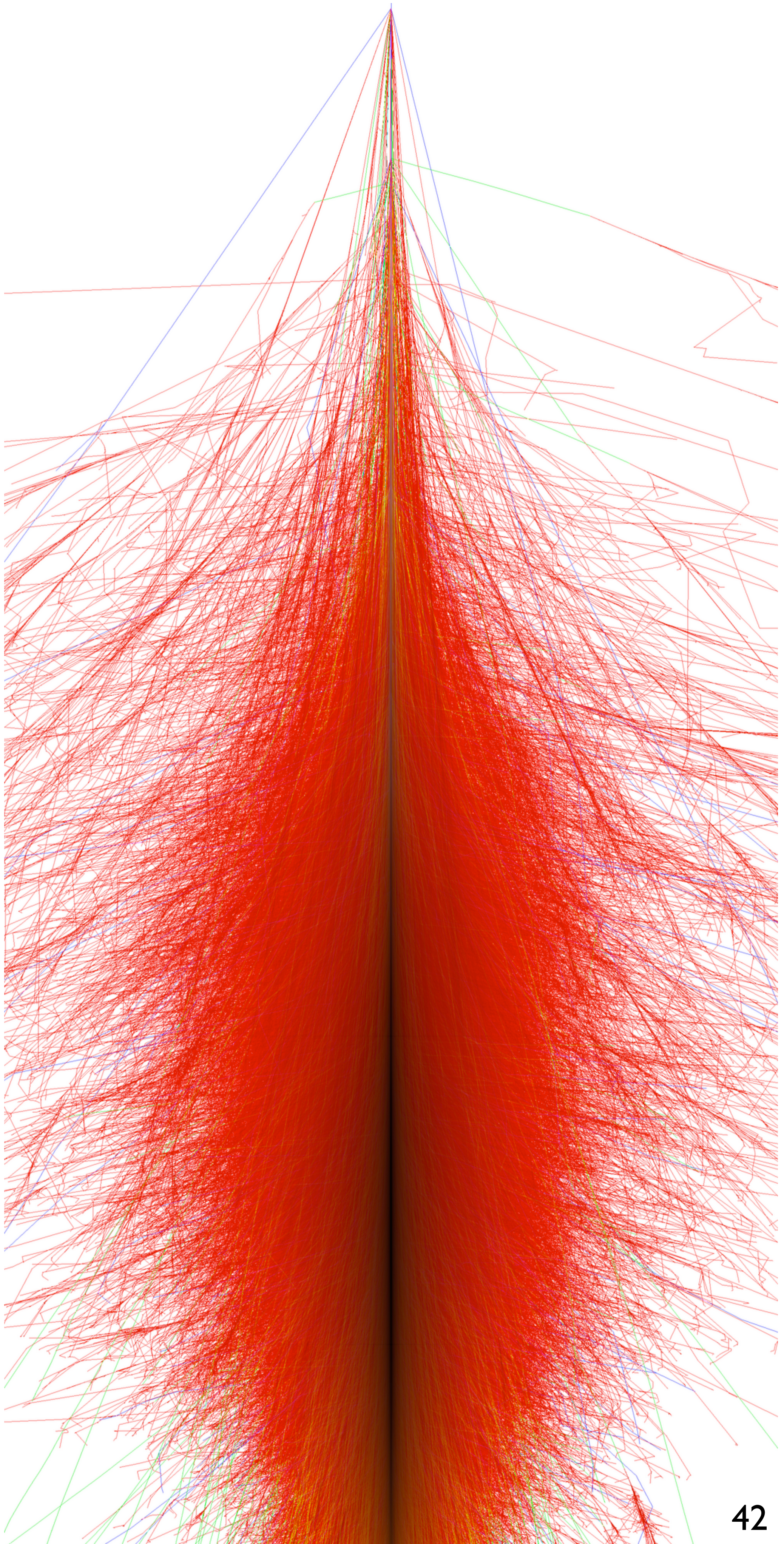
photon shower 10^{12} eV



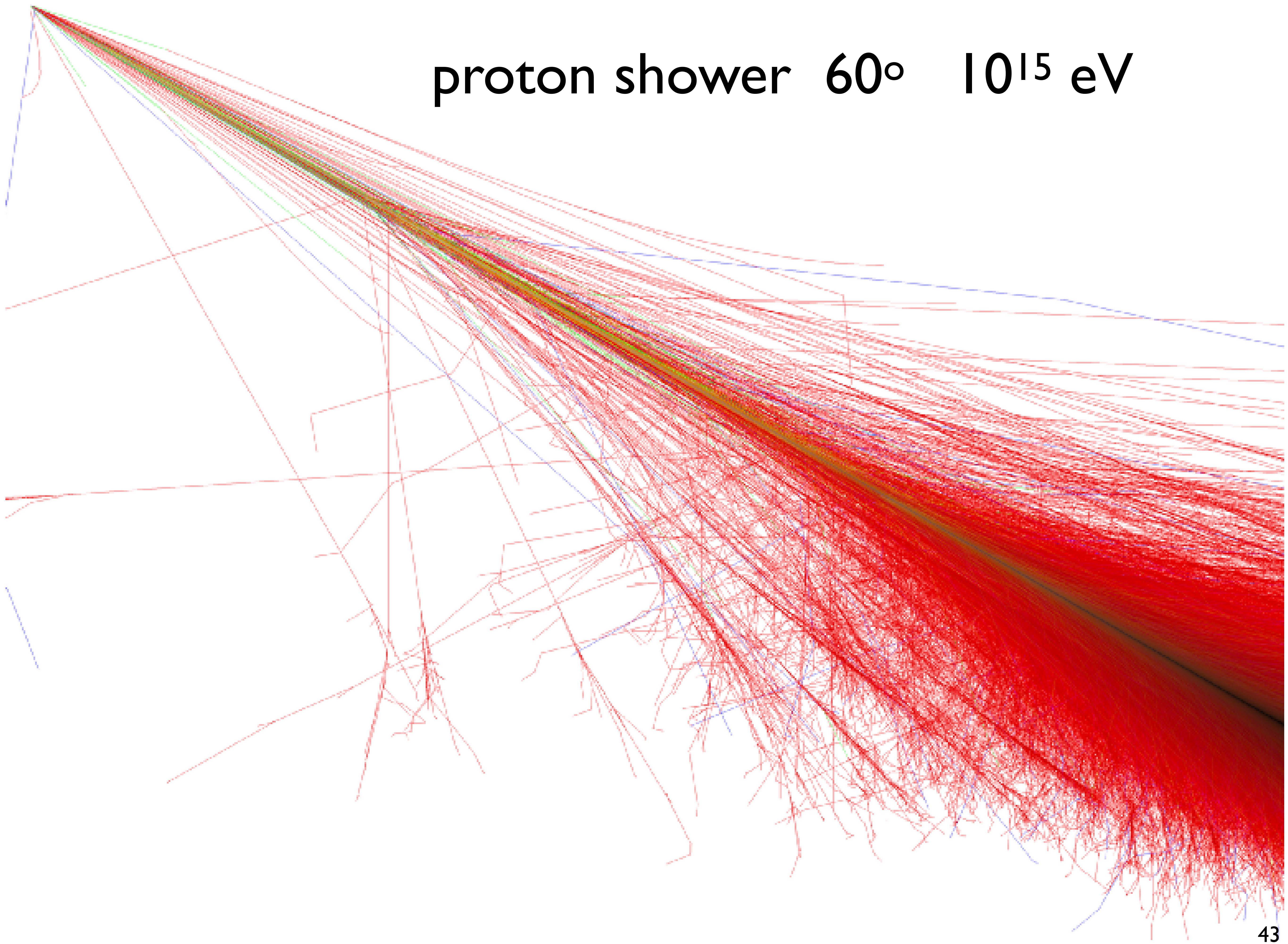


proton shower 10^{14} eV

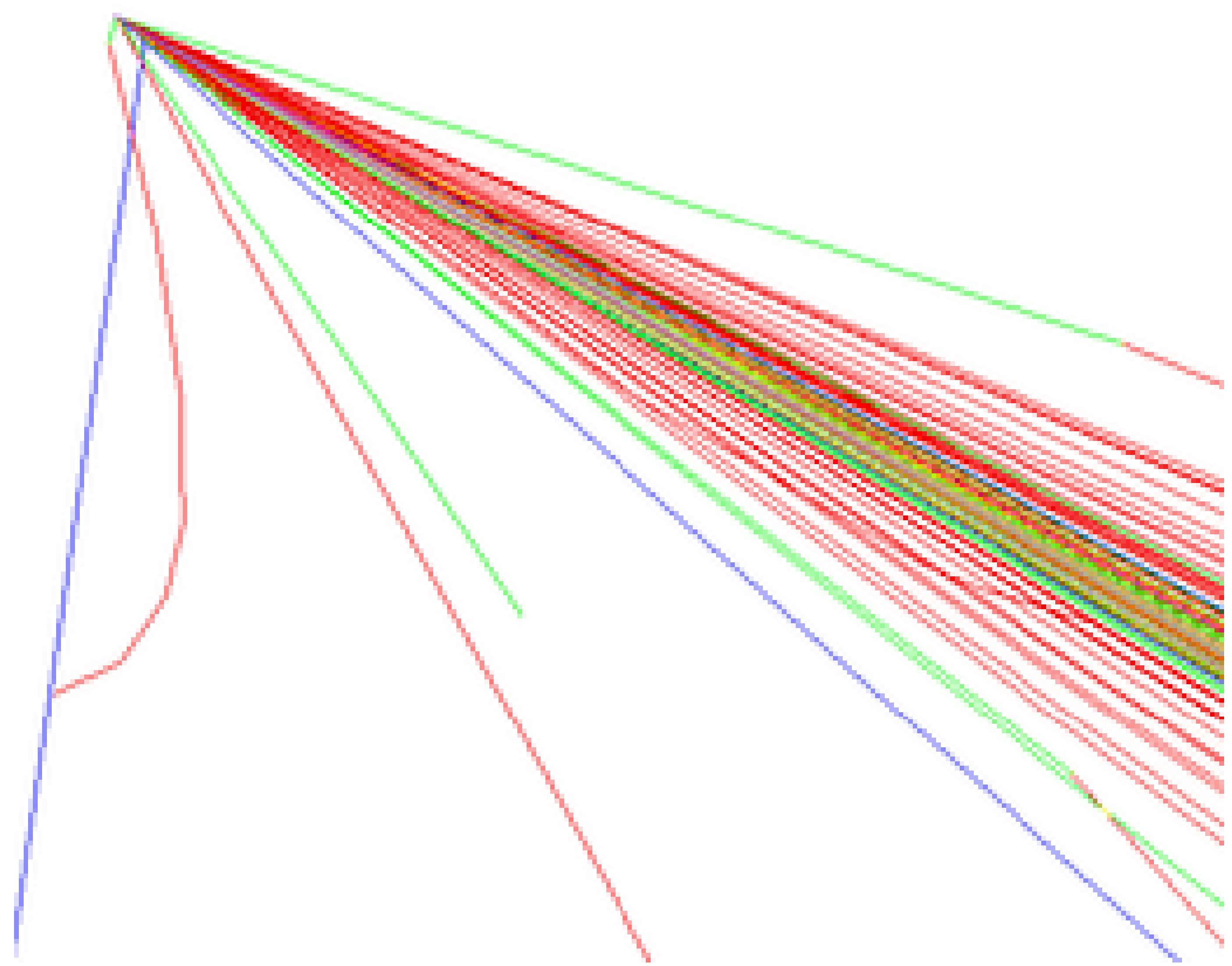




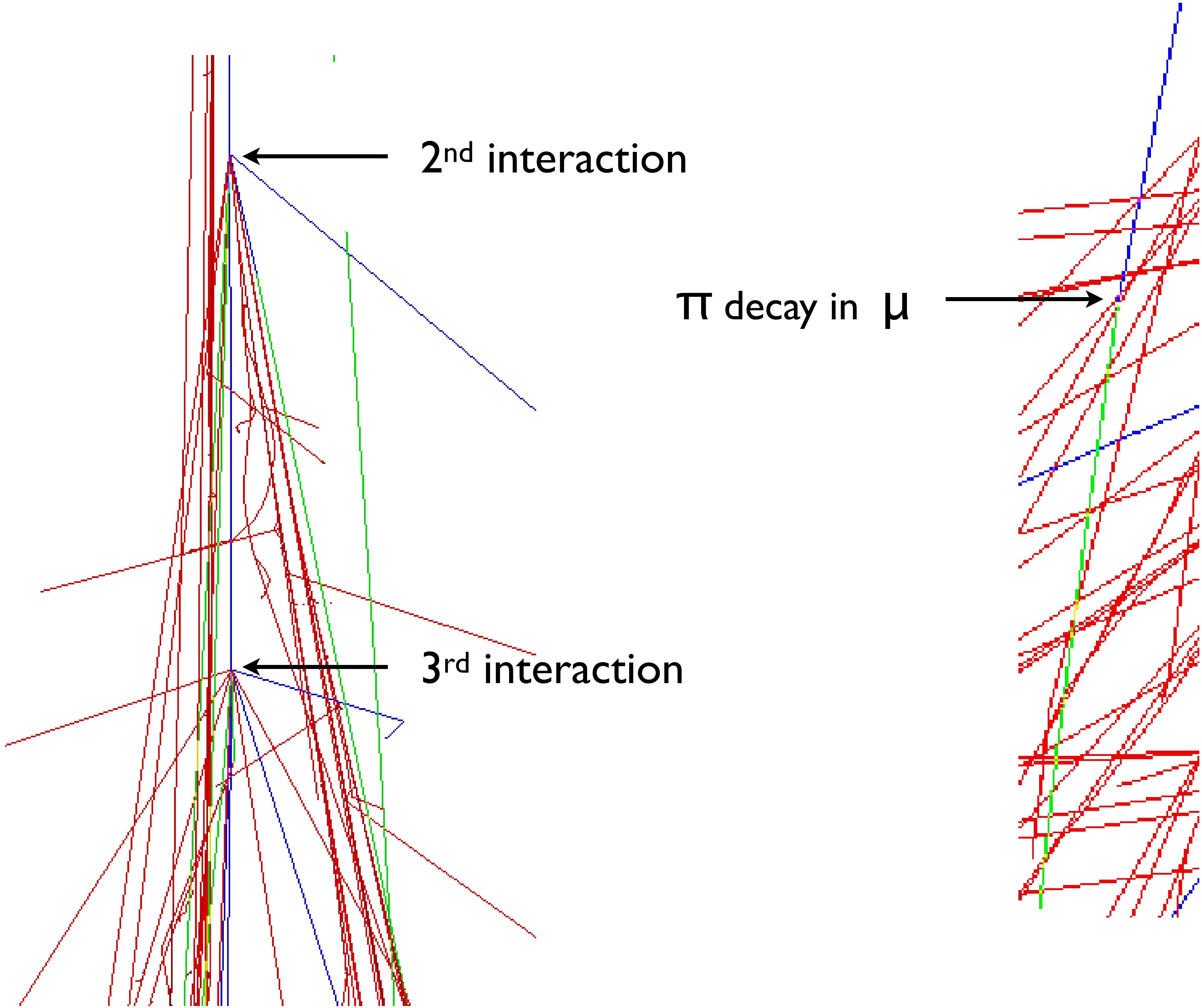
proton shower 60° 10^{15} eV



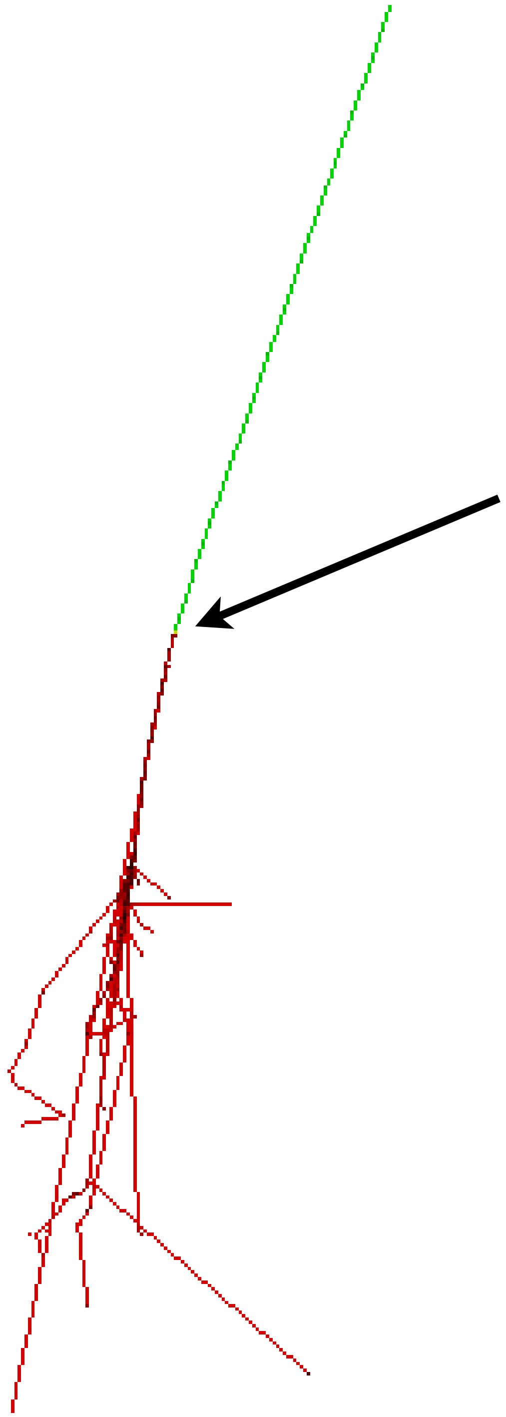
proton 10^{15} eV
1^{st} interaction

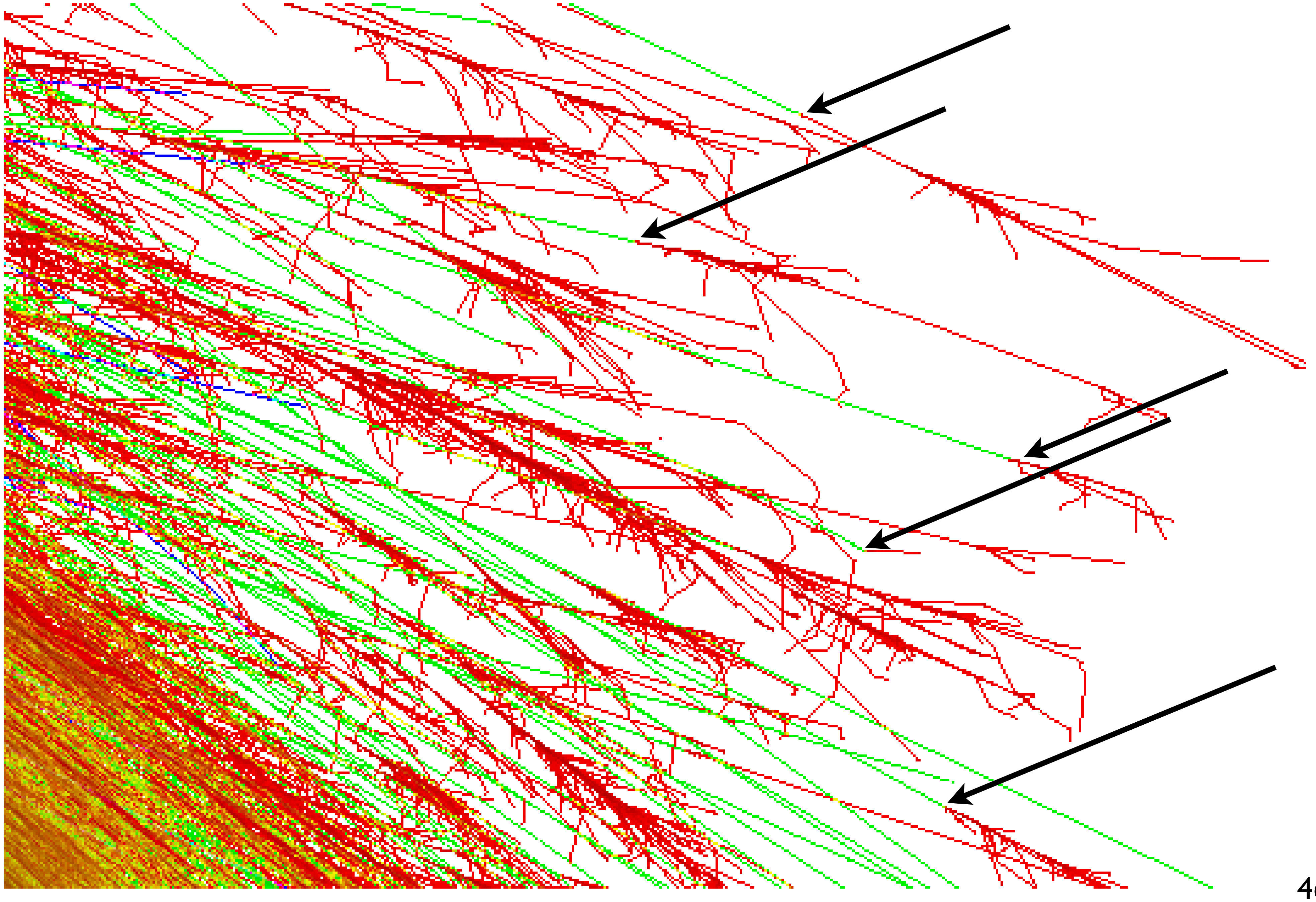


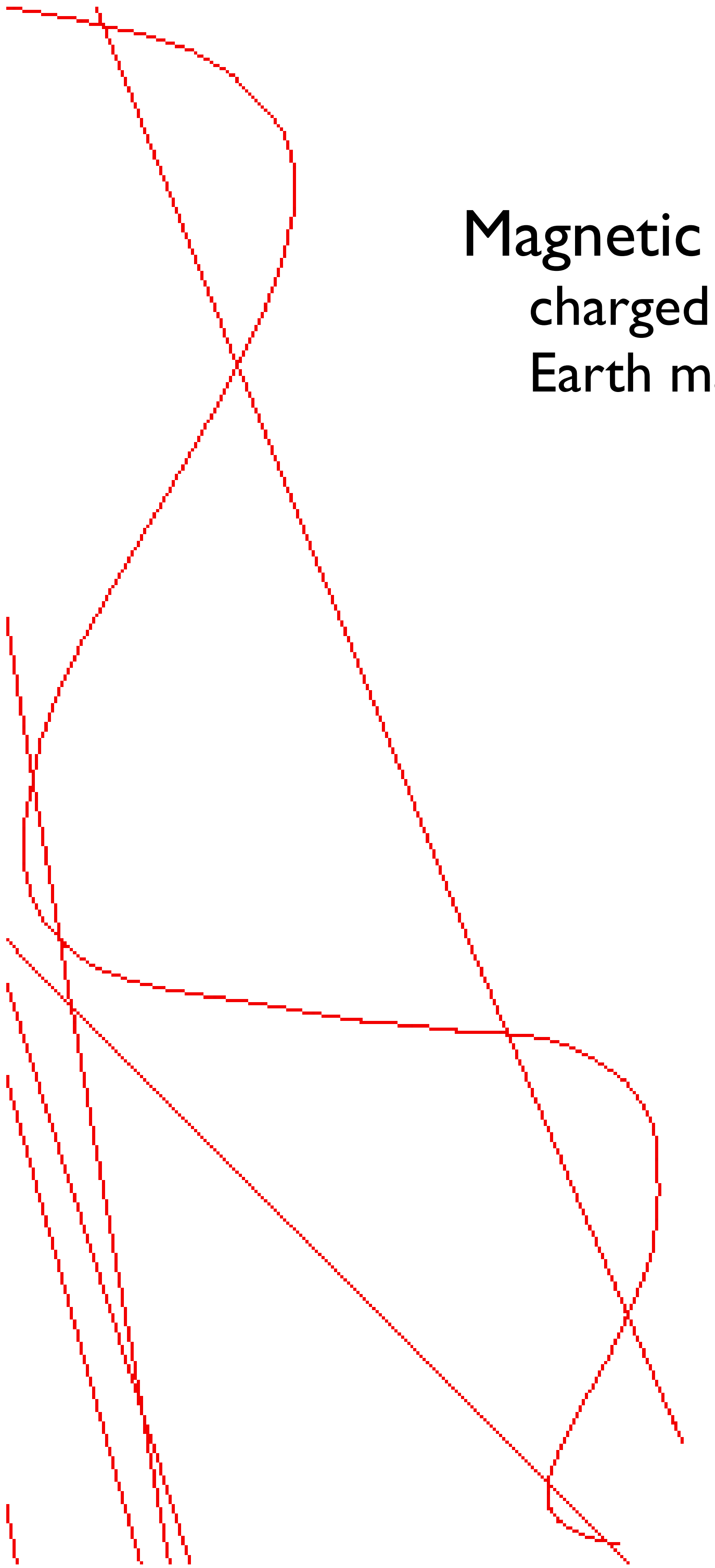
electrons/photons
muons
hadrons


2nd interaction
π decay in μ
3rd interaction

Muon decays



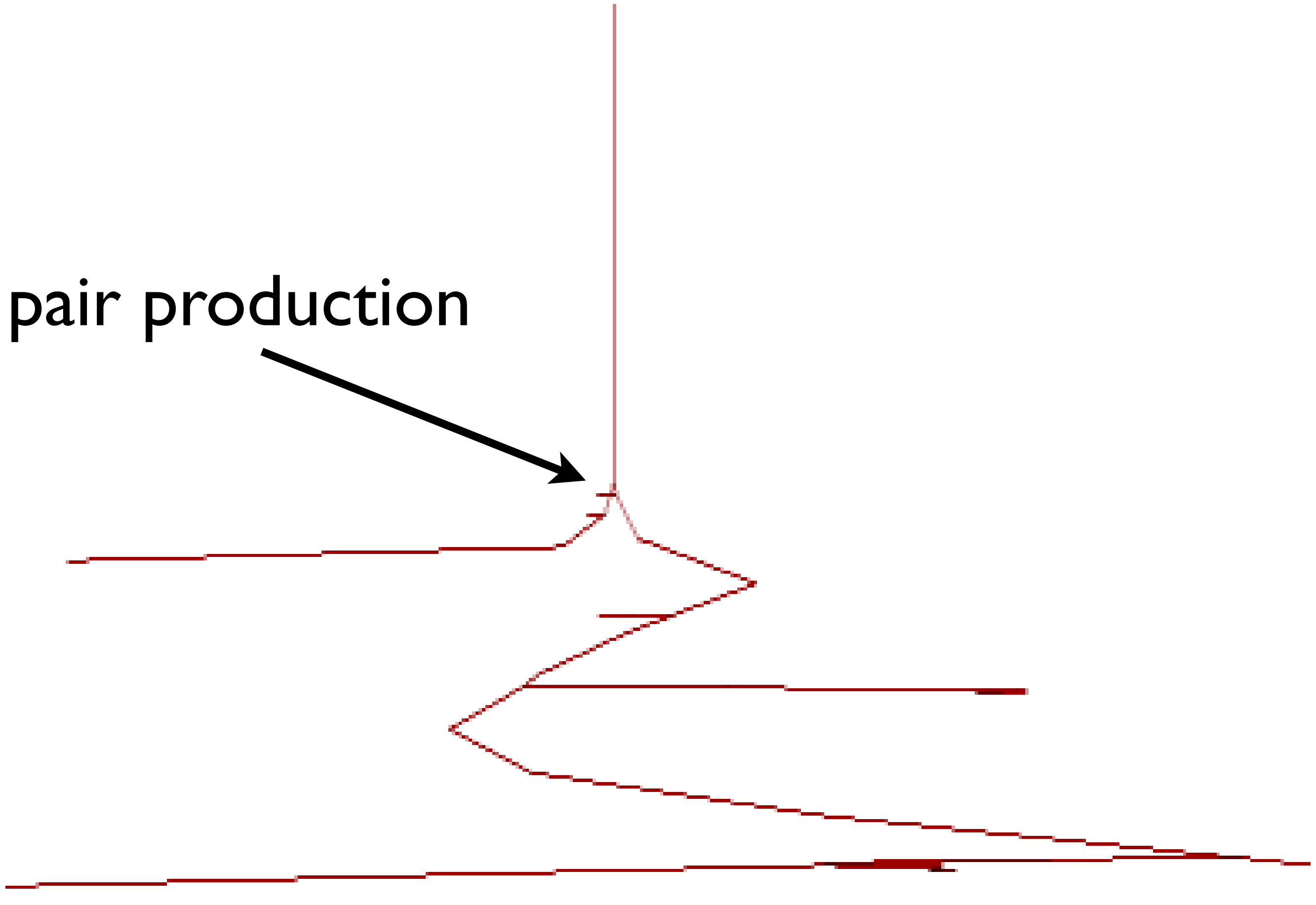




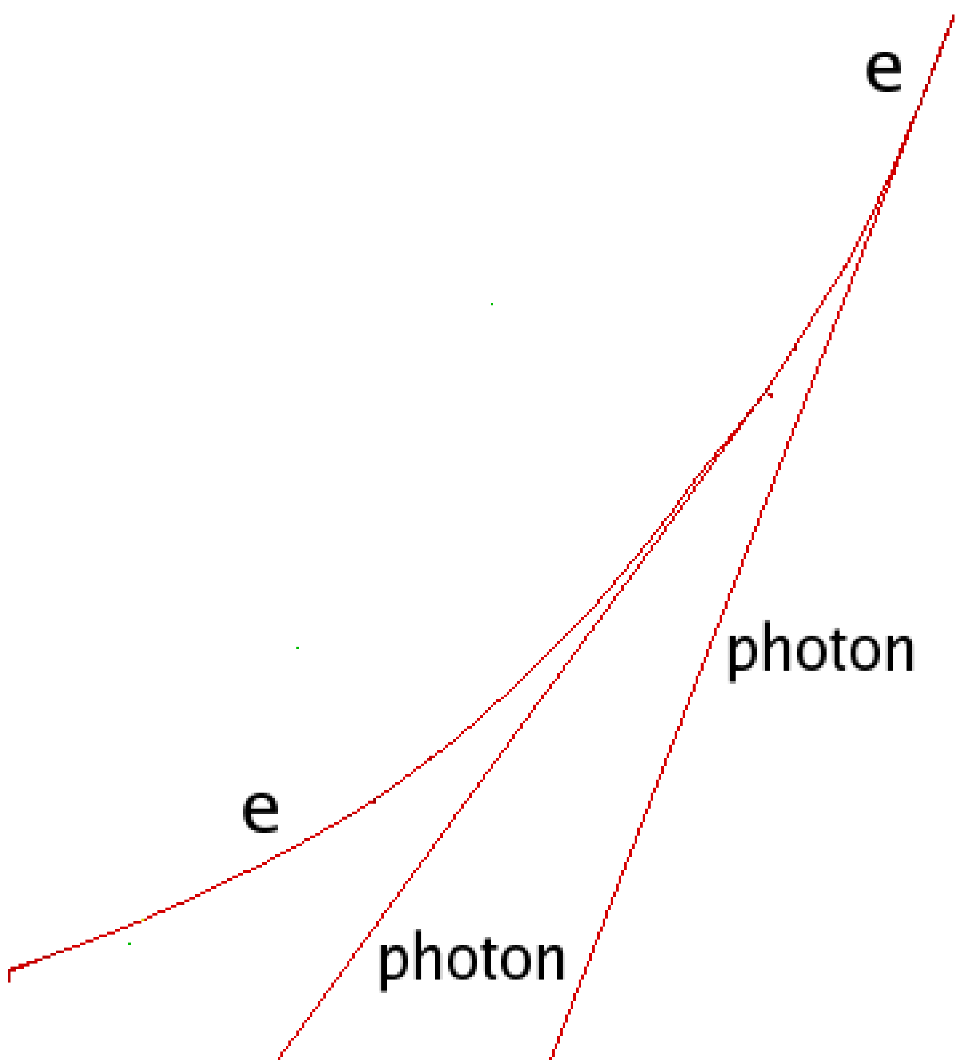
Magnetic deflection:

charged particles spiral around
Earth magnetic field.

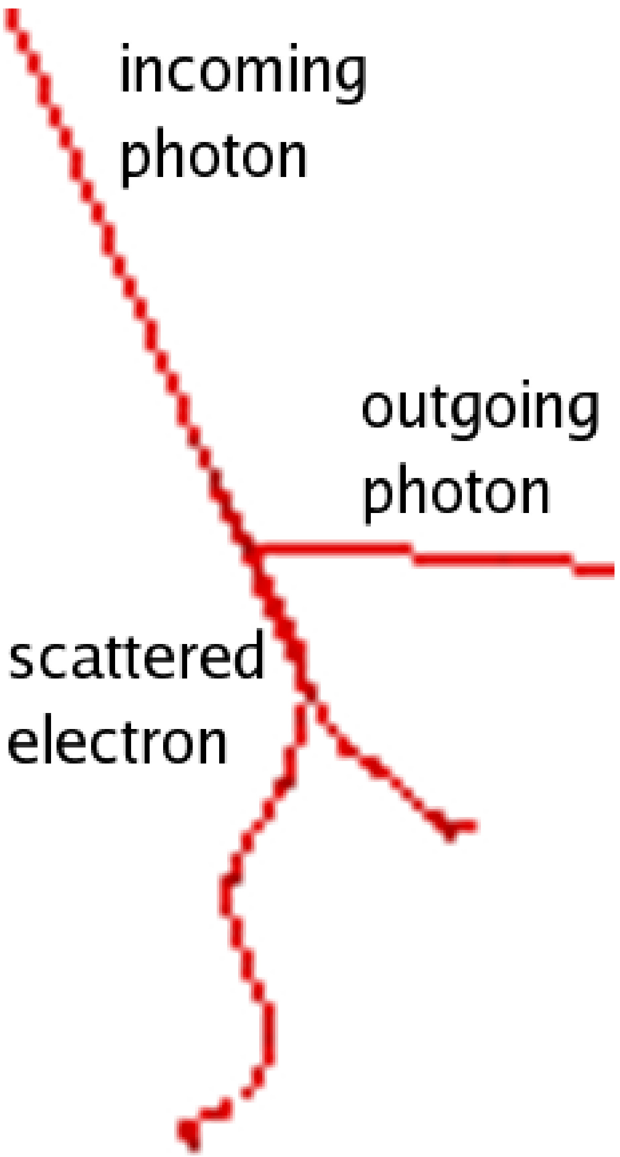
e^+e^- pair production

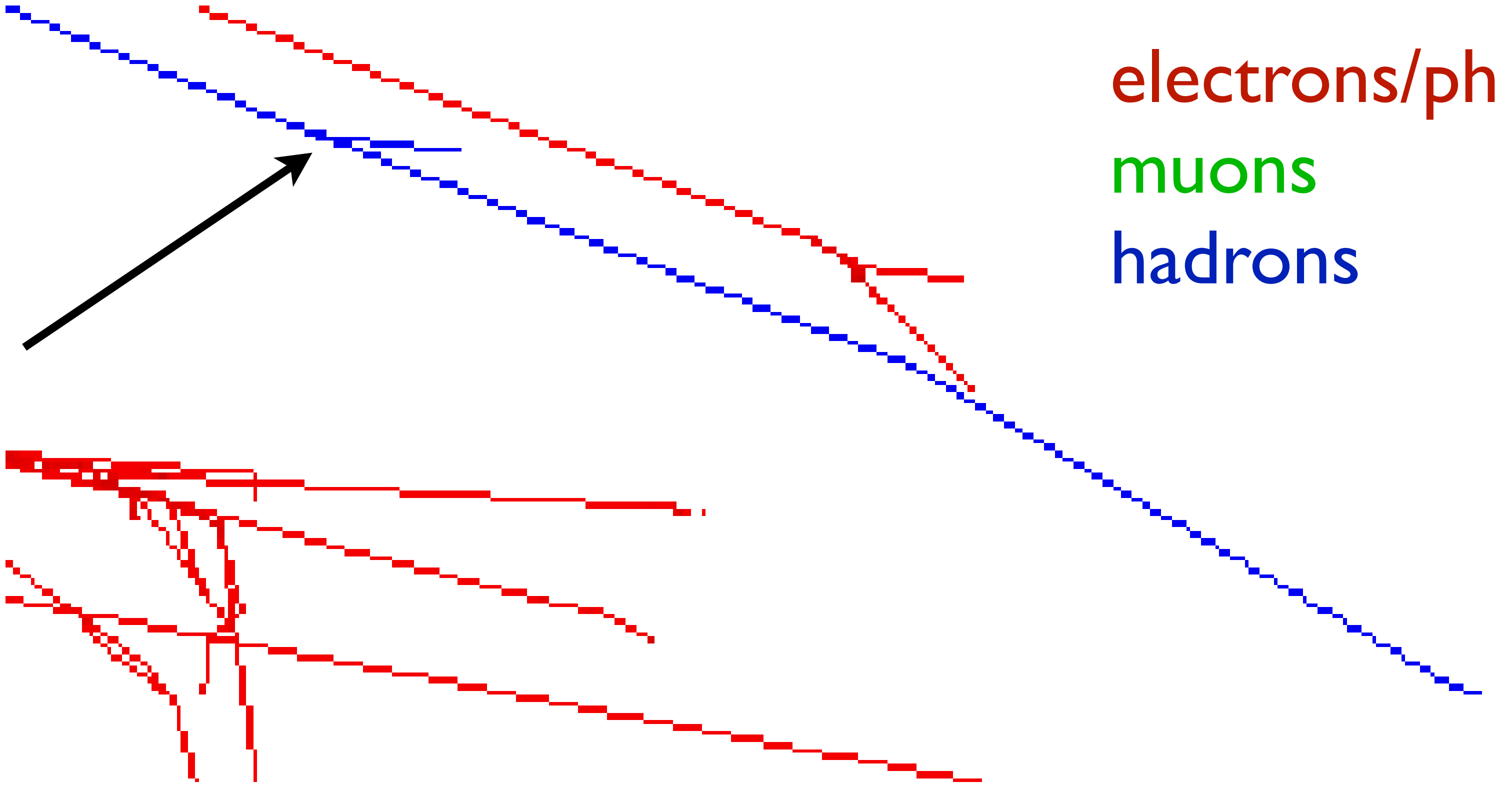


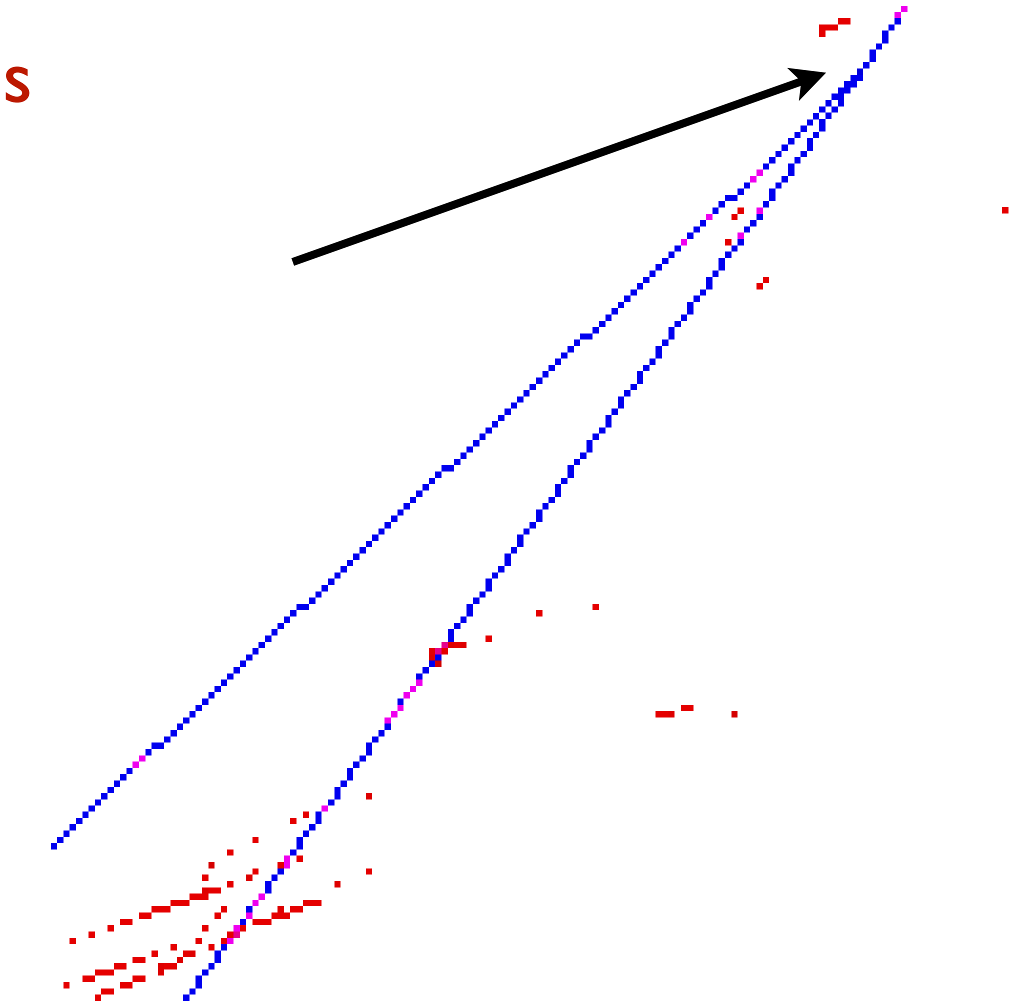
Bremsstrahlung



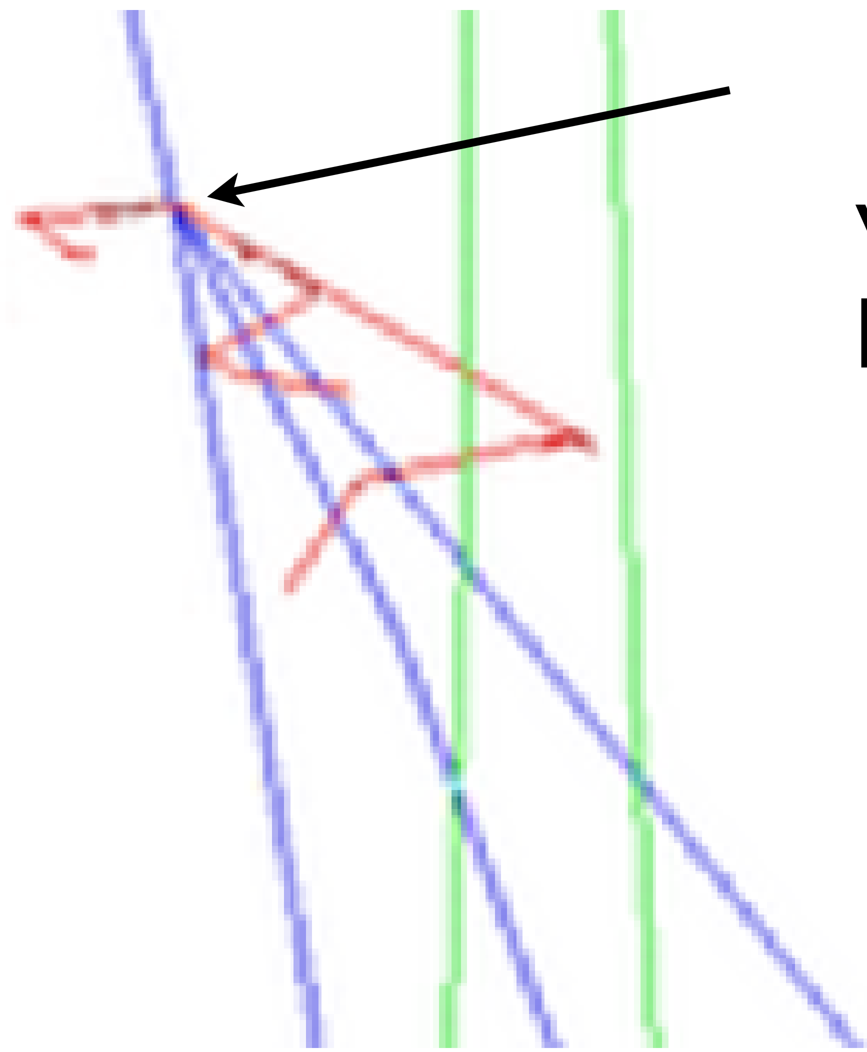
Compton scattering



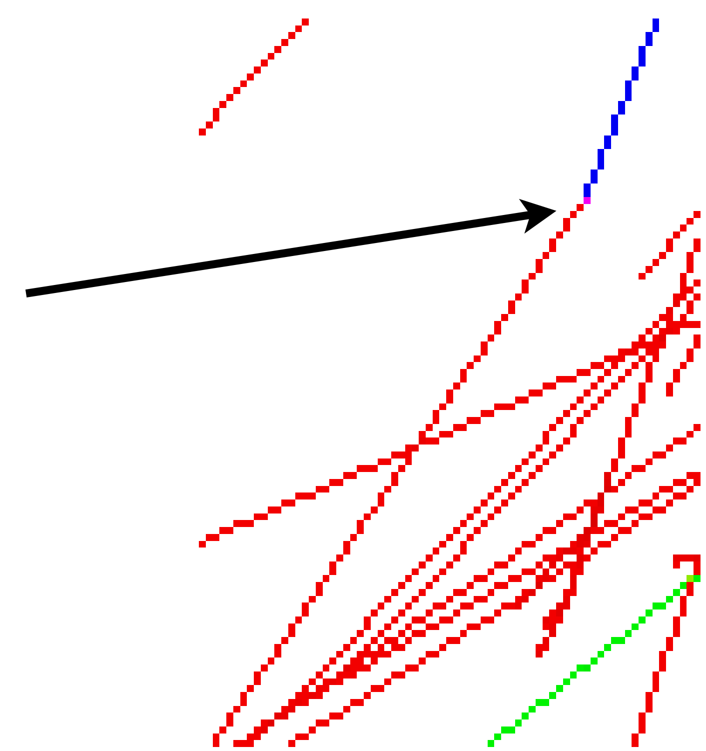


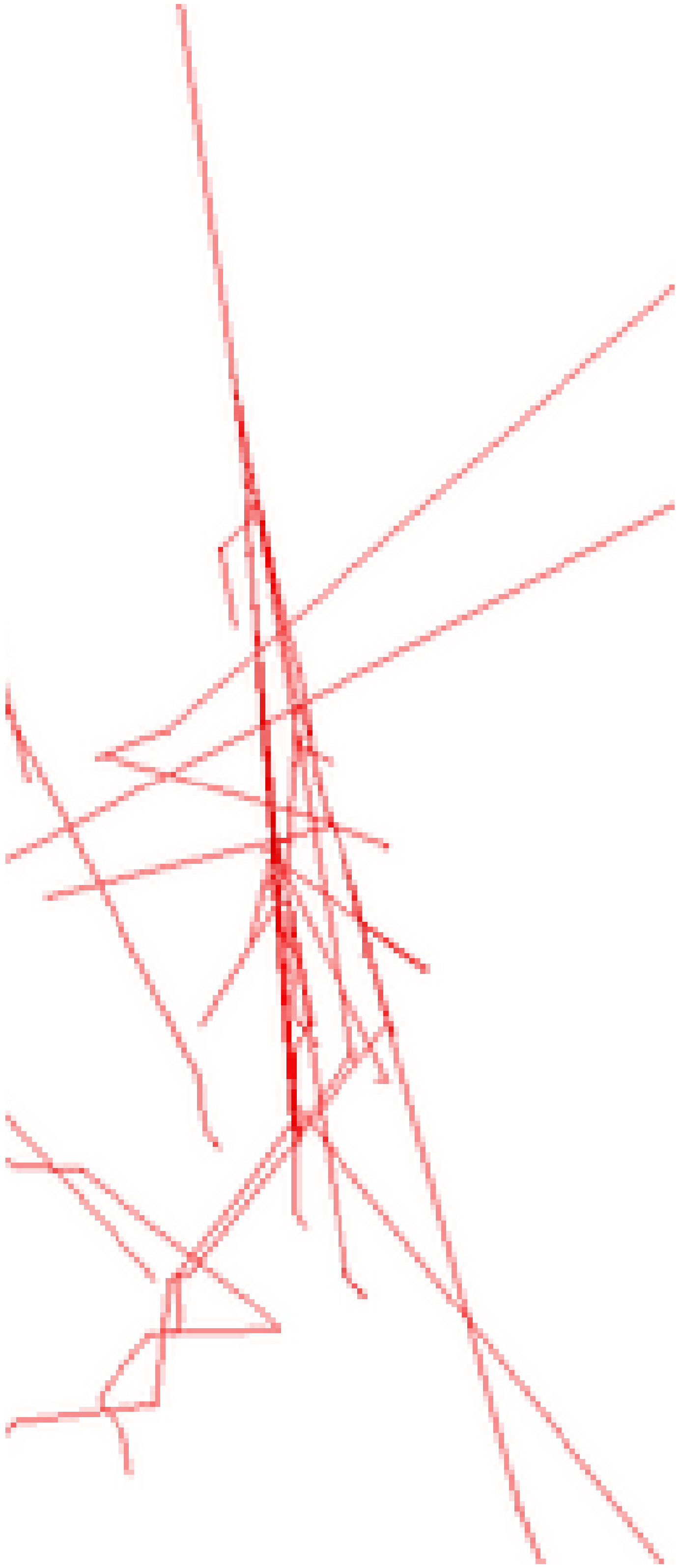


electrons/photons
muons
hadrons

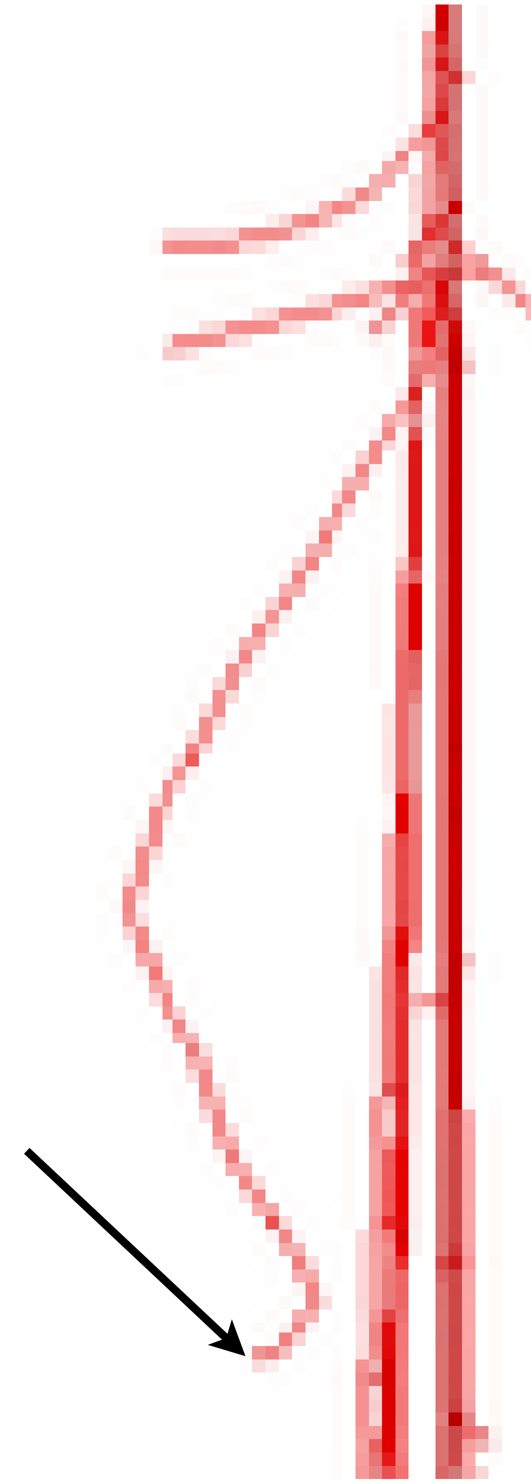


various
hadronic interactions





protons (or neutrons)
are absorbed

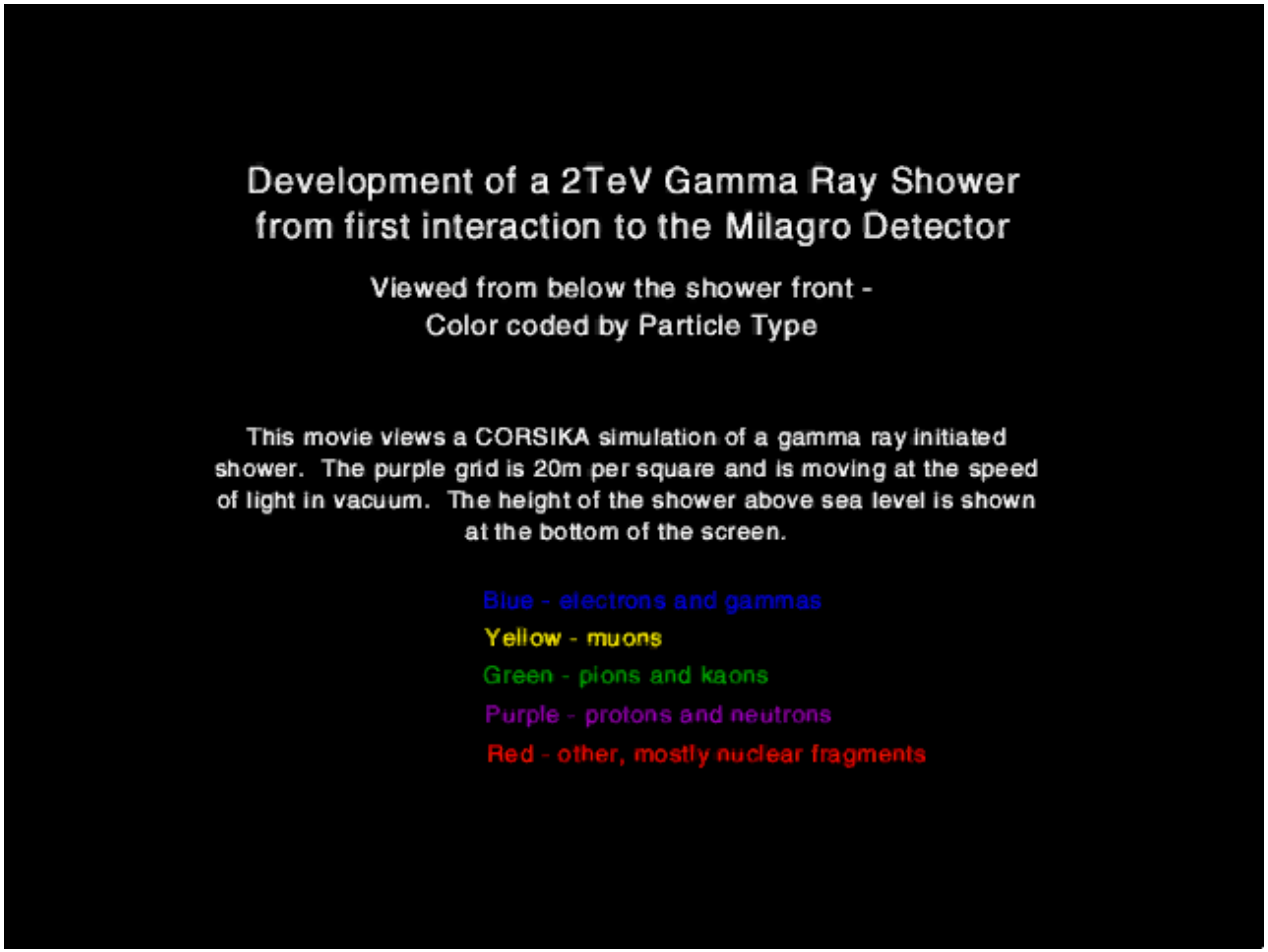


photon induces
electromagnetic sub-shower

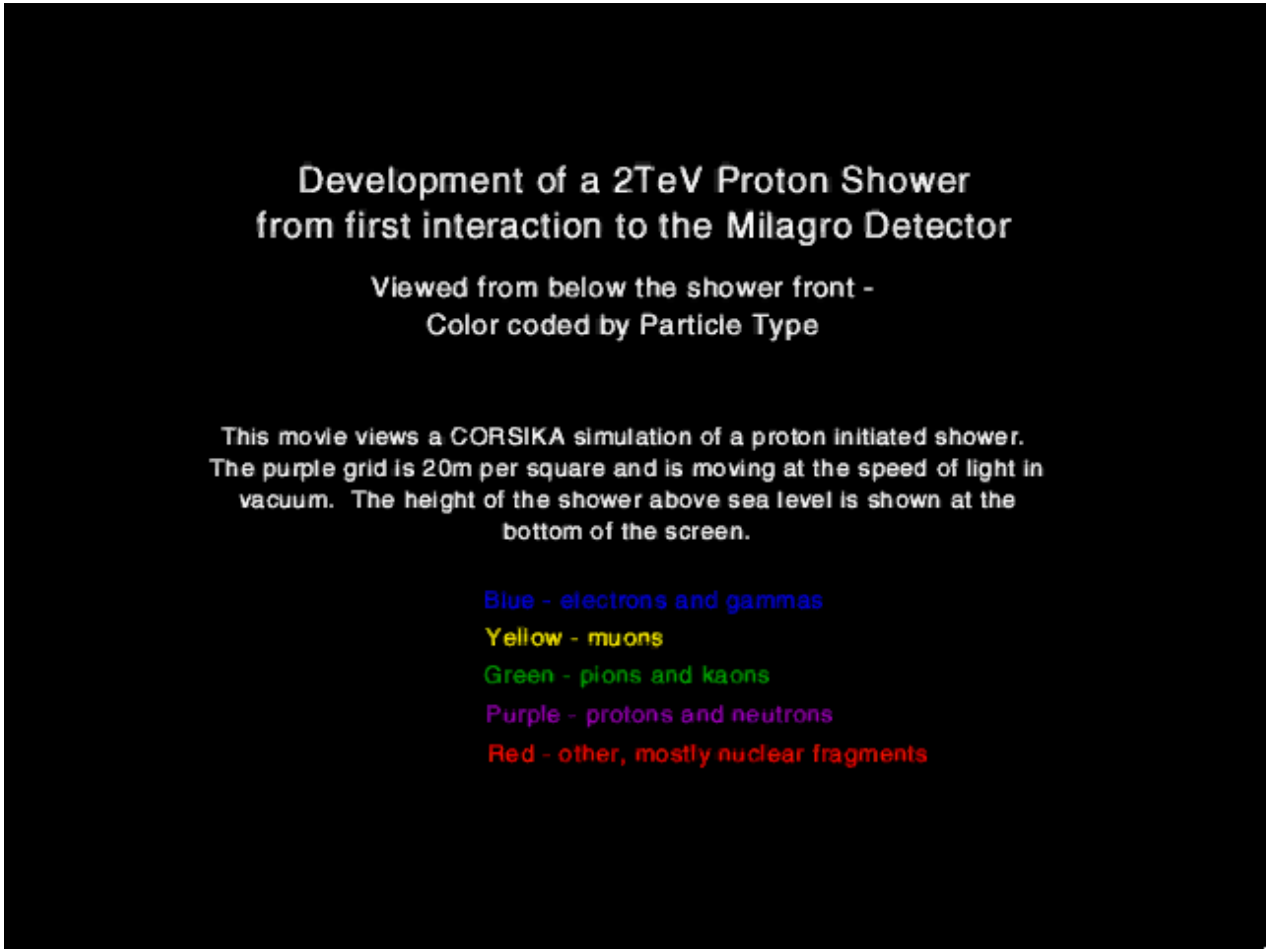
electron slowed down
and absorbed

2 TeV gamma shower, bottom view

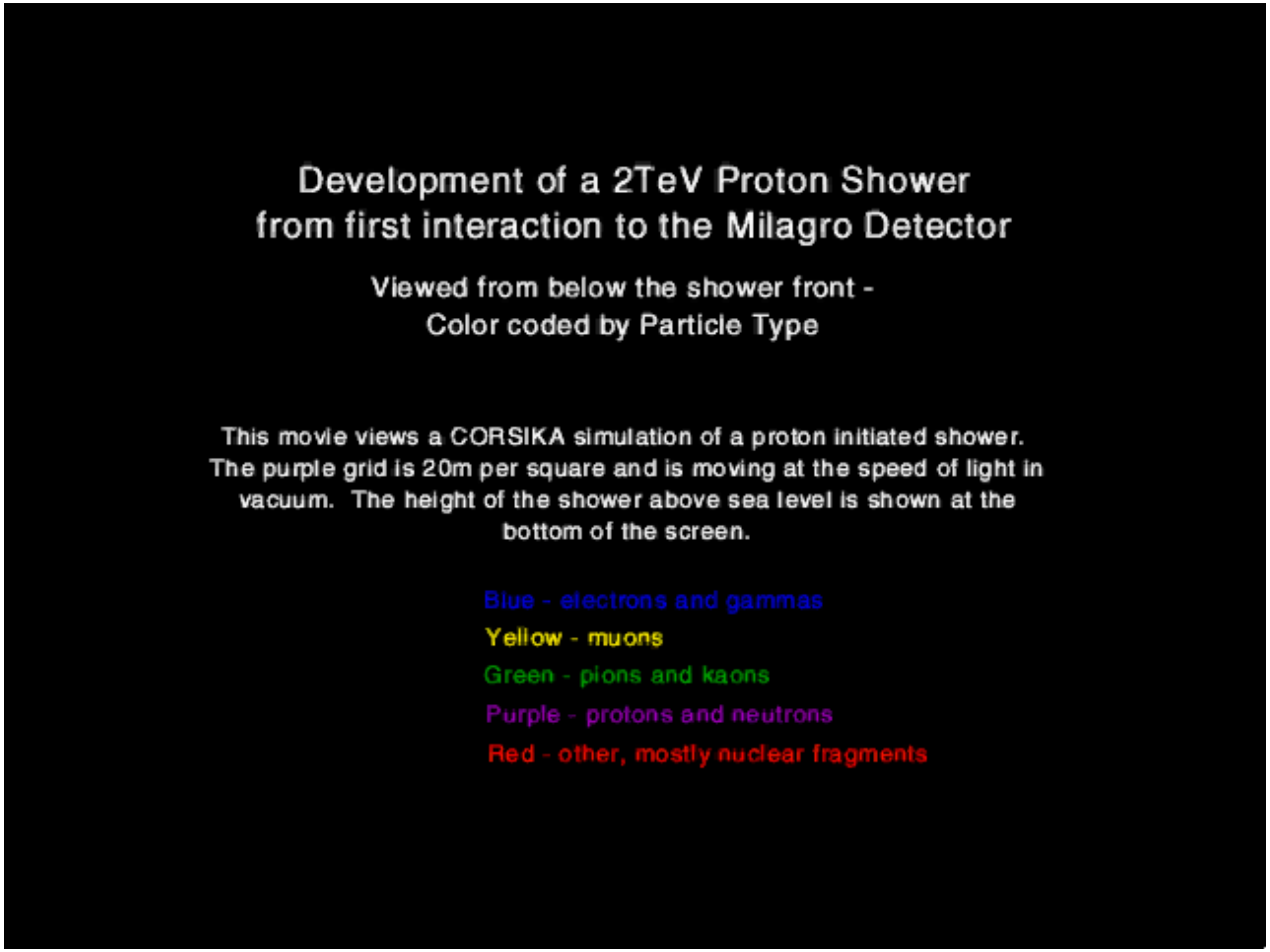
2 TeV gamma shower, bottom view



2 TeV proton shower,   bottom view



2 TeV proton shower, bottom view



2 TeV gamma shower onto Milagro, side view

Shower from a vertical 2TeV Gamma Ray Primary

Side View

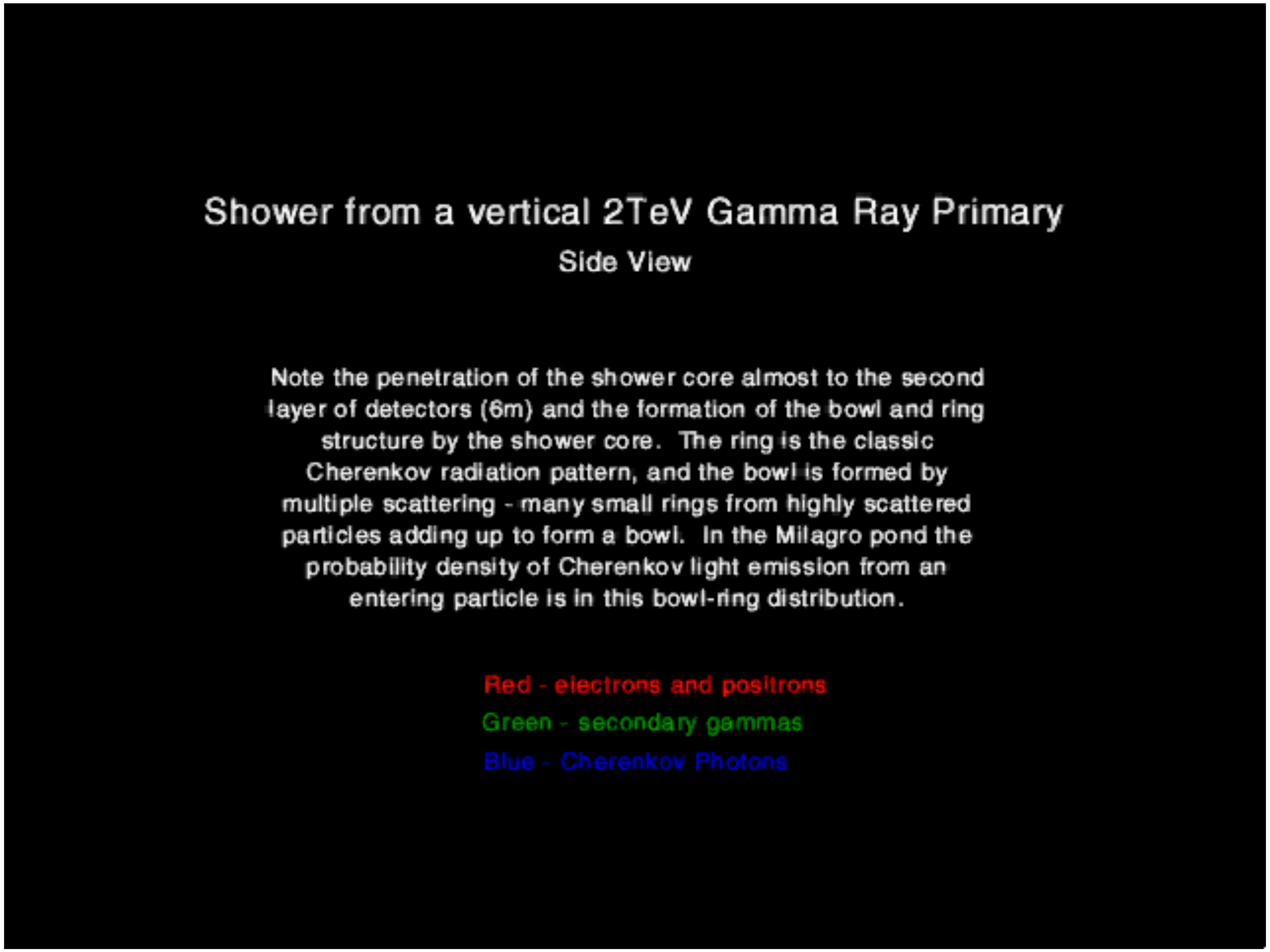
Note the penetration of the shower core almost to the second layer of detectors (6m) and the formation of the bowl and ring structure by the shower core. The ring is the classic Cherenkov radiation pattern, and the bowl is formed by multiple scattering - many small rings from highly scattered particles 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

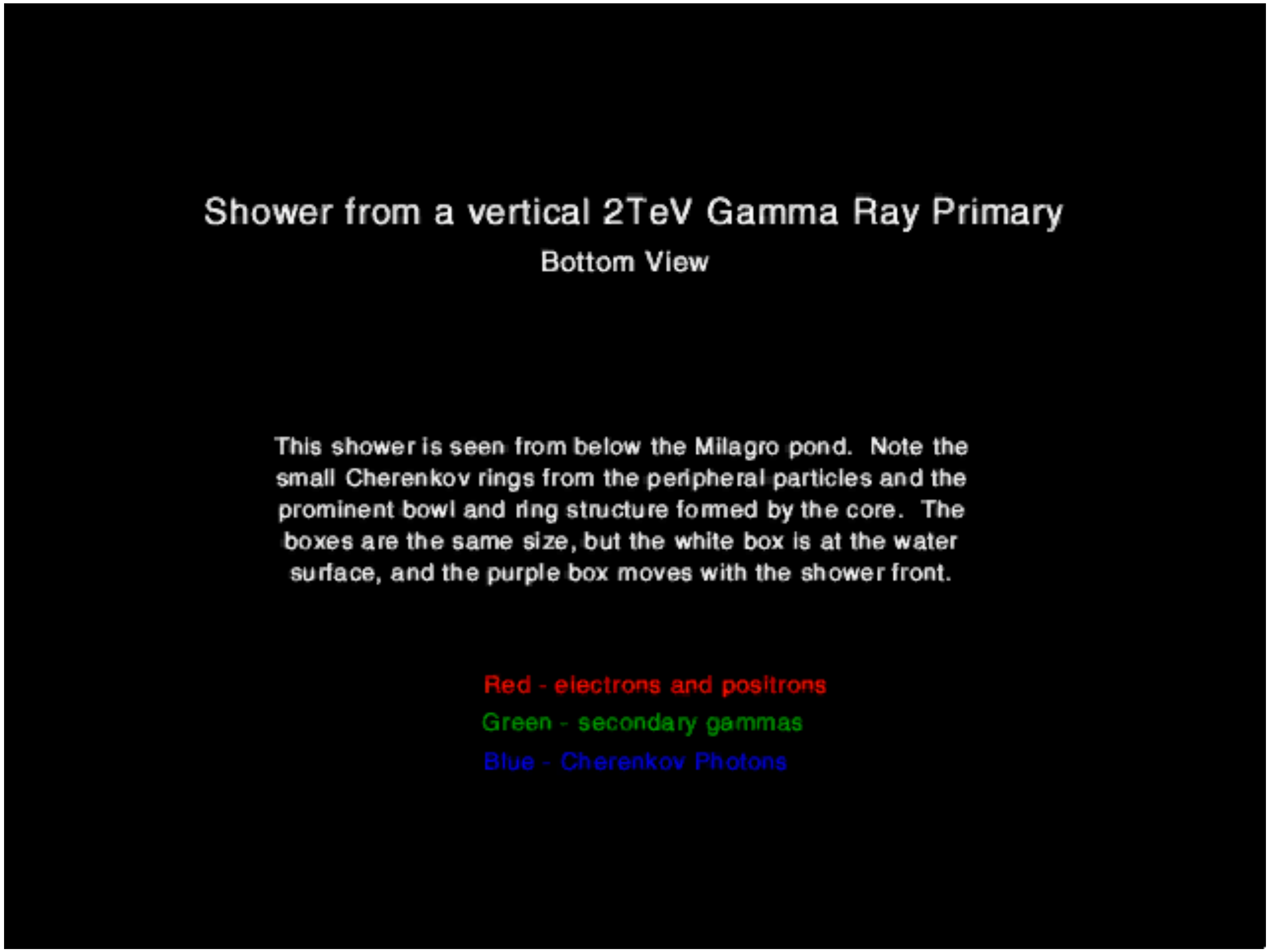
Green - secondary gammas

Blue - Cherenkov Photons

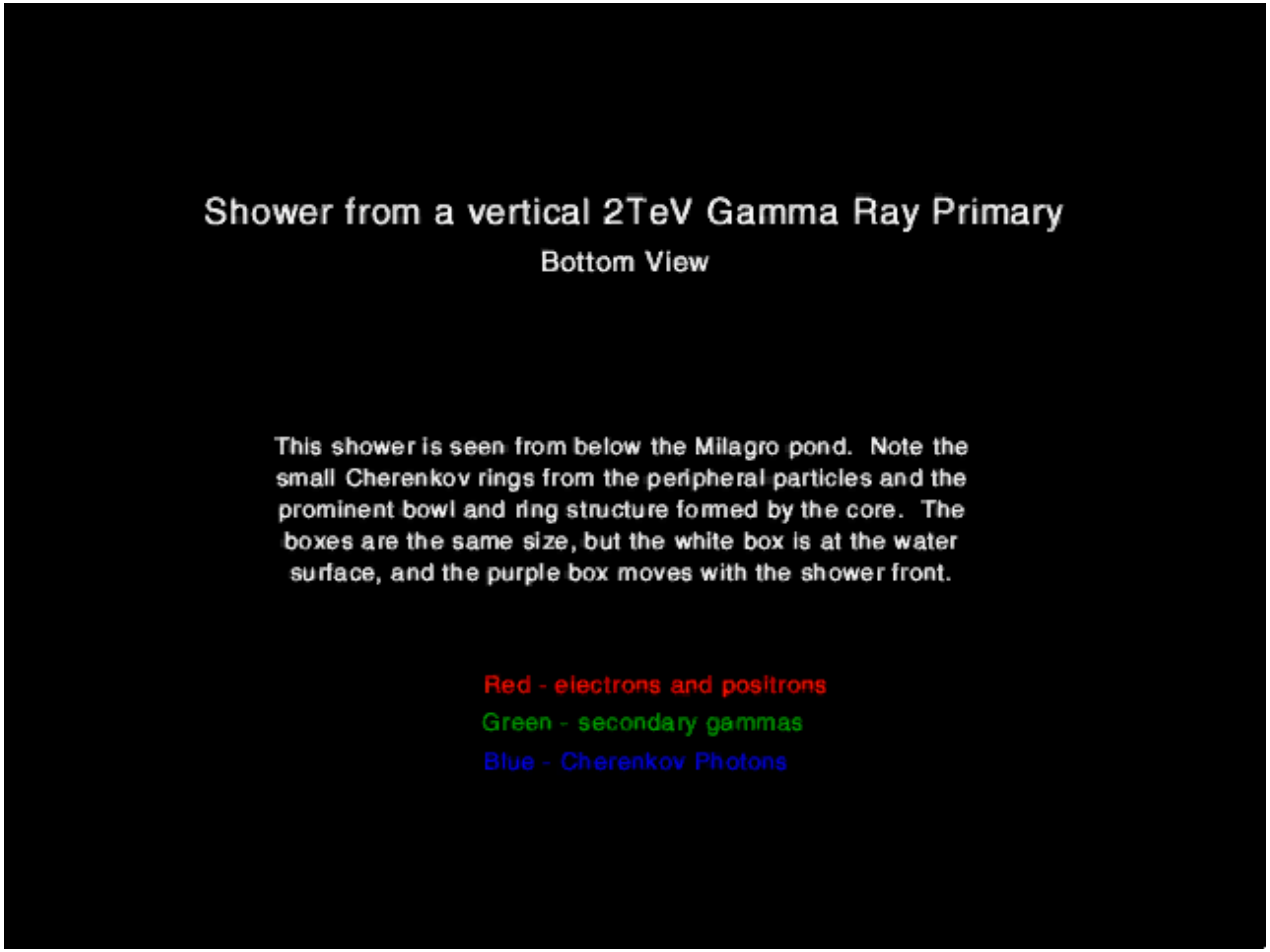
2 TeV gamma shower onto Milagro, side view



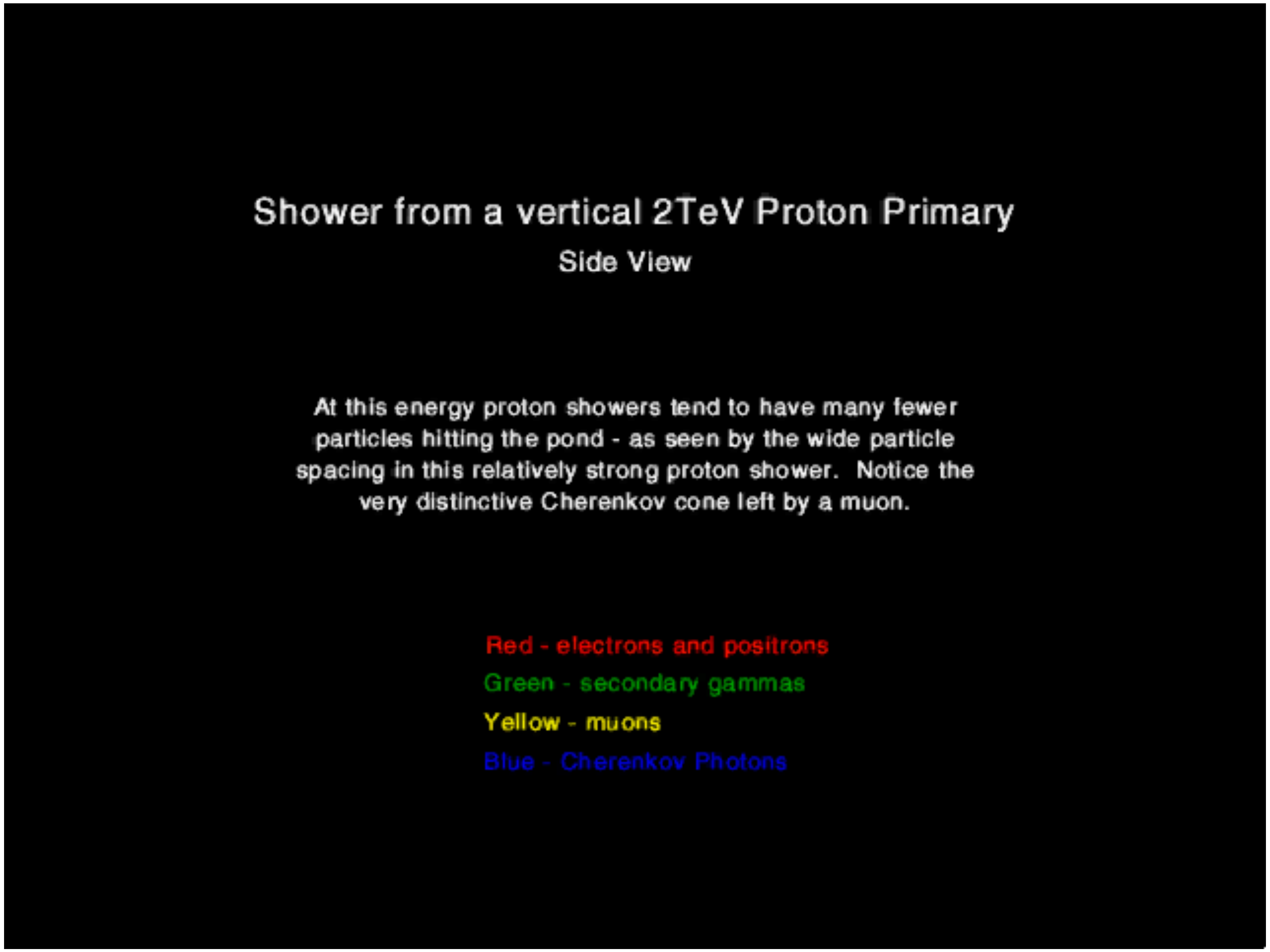
2 TeV gamma shower onto Milagro, bottom view



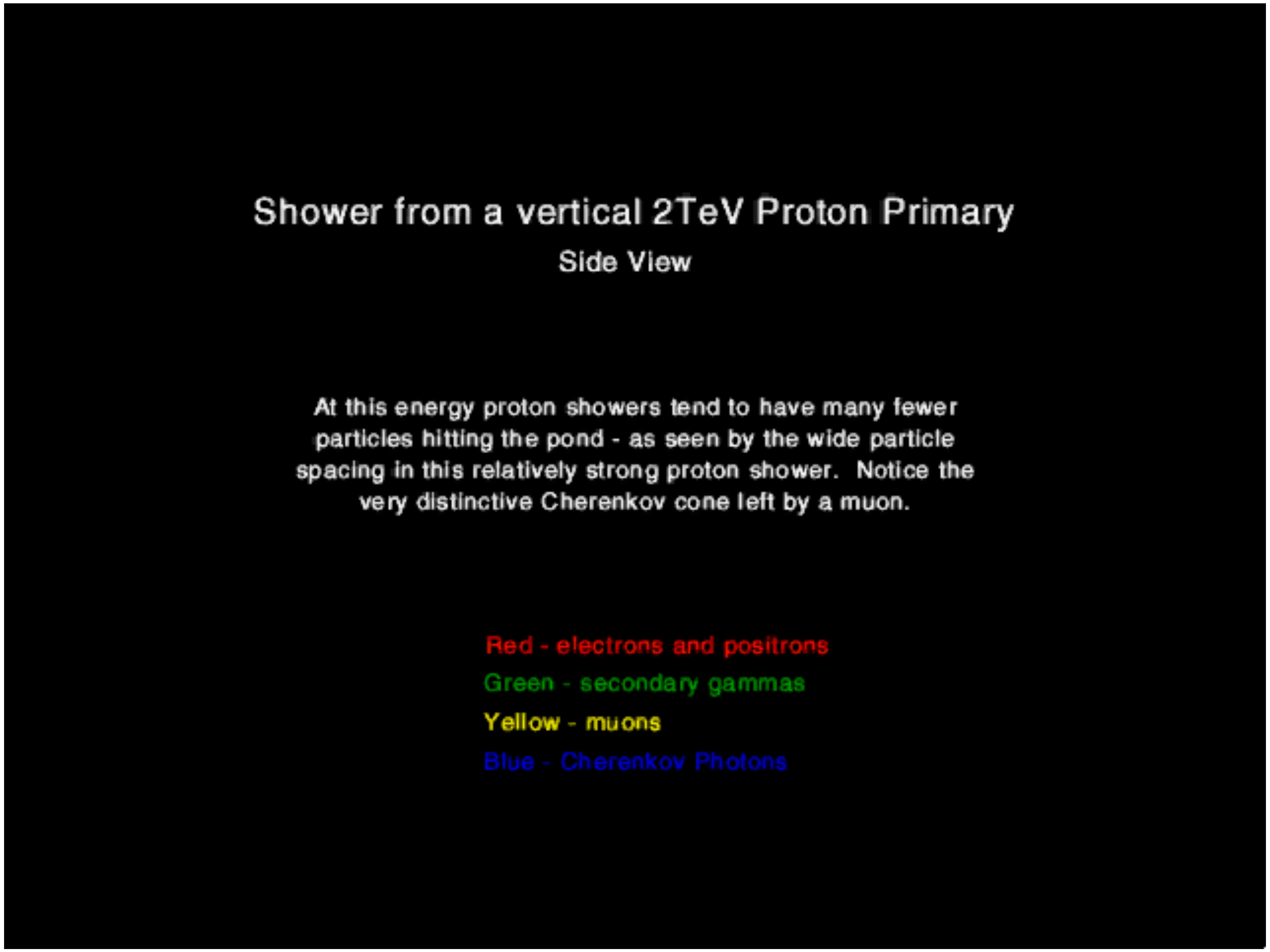
2 TeV gamma shower onto Milagro, bottom view



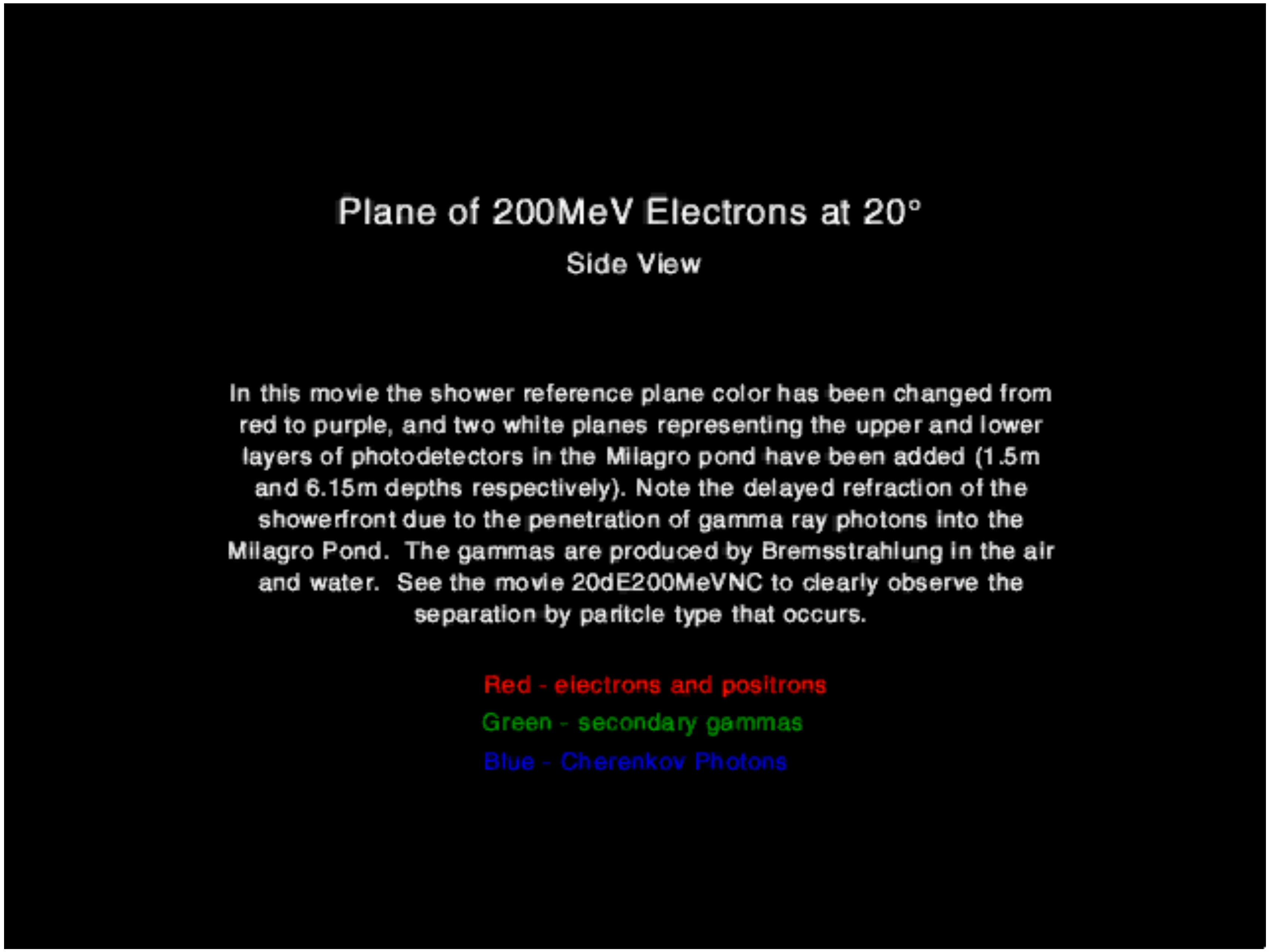
2 TeV proton shower onto Milagro,   side view



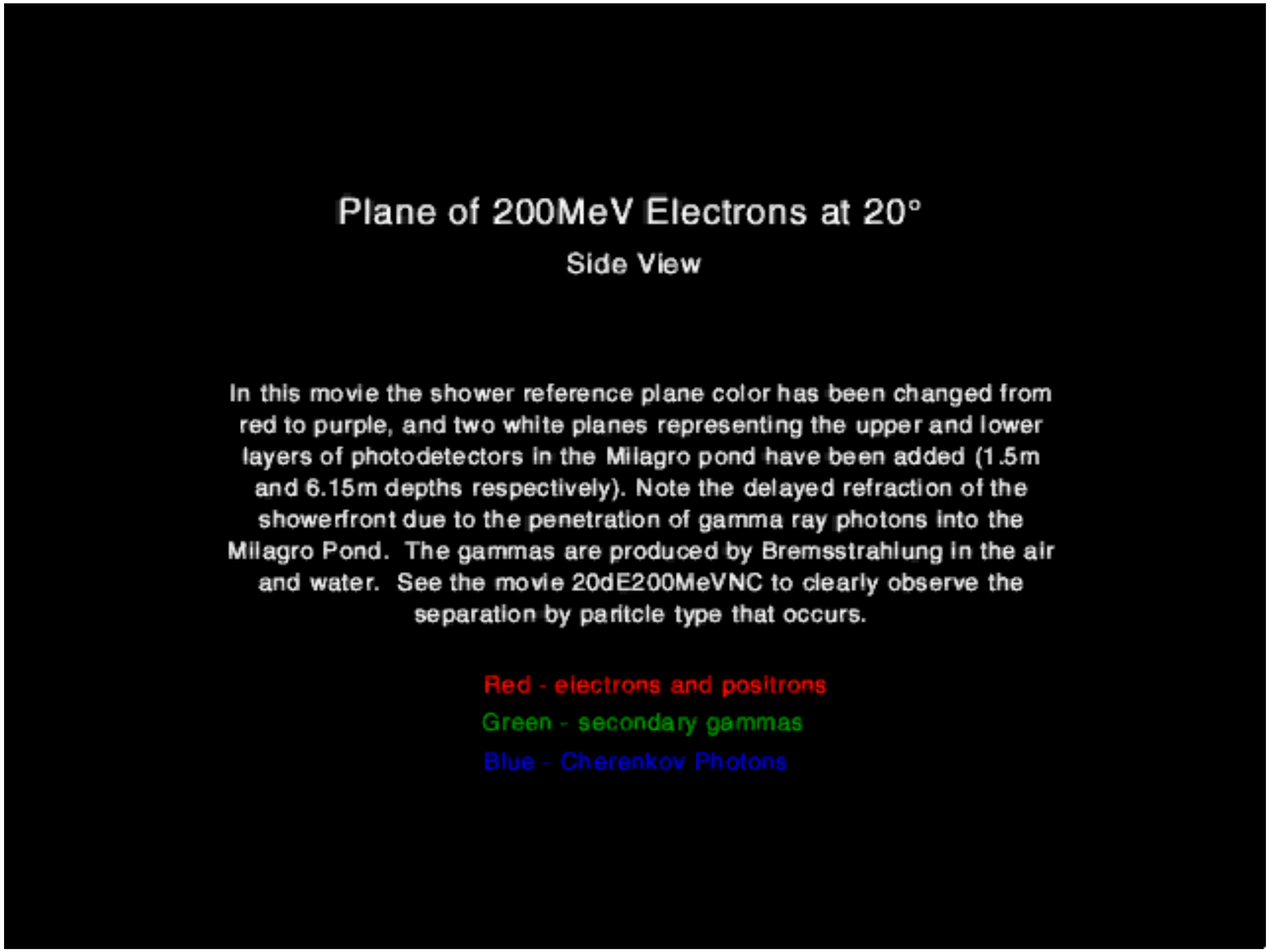
2 TeV proton shower onto Milagro, side view



200 MeV electrons onto Milagro,   side view



200 MeV electrons onto Milagro, side view



Summary:

Extensive air showers are complicated.

Monte Carlo simulations (based on random numbers)
are the right tool for simulating EAS.

Beware the details:

The more details are simulated,

the more reliable / correct is the result,

but also

the longer it takes / the more it costs.

Summary:

Shower simulations are indispensable
in high-energy astroparticle physics.

Accelerator data & theory provide valuable constraints.

Weak point: hadronic interactions @ high energies.
The higher the energy the larger the uncertainties.

CORSIKA & its models are
reasonably correct (on the 10-50% level)
and improving…

CORSIKA @ 30

- a great success, has revolutionised the field.
- prime tool of astroparticle physics

  (helps to understand shower formation in subtle detail)
- the **gold standard**, work horse for CR related physics,
- essentially all experiments are using it,
- a great and lasting legacy of the KASCADE project.

… and we want to keep it like this.

The future

CORSIKA is needed for at least another 30 years:

Auger, TA, LHAASO, EUSO, …
HESS, MAGIC, VERITAS, HAWC, CTA, Taiga, …
IceCube, KM3Net, VLVND, …
Lofar, ANITA, ARIANNA, ARA, SKA, …

A serious upgrade is underway:

clearer structure, better description, modern software technology,
remove historical baggage, re-write with many improvements,
easier to understand, debug, maintain, **extend,** (less of a black box)
diagnostics, diagnostics, diagnostics, … of all aspects of simulations
ensure the availability of the **best possible simulation tool.**
Needs also progress on the hadronic interactions!

Next Generation CORSIKA Workshop, KIT, June 2018
https://indico.scc.kit.edu/event/426/

"Towards the next generation of CORSIKA:
A framework for the simulation of particle
cascades in astroparticle physics"
https://arxiv.org/abs/1808.08226

https://www.ikp.kit.edu/corsika/

www.ikp.kit.edu/corsika/

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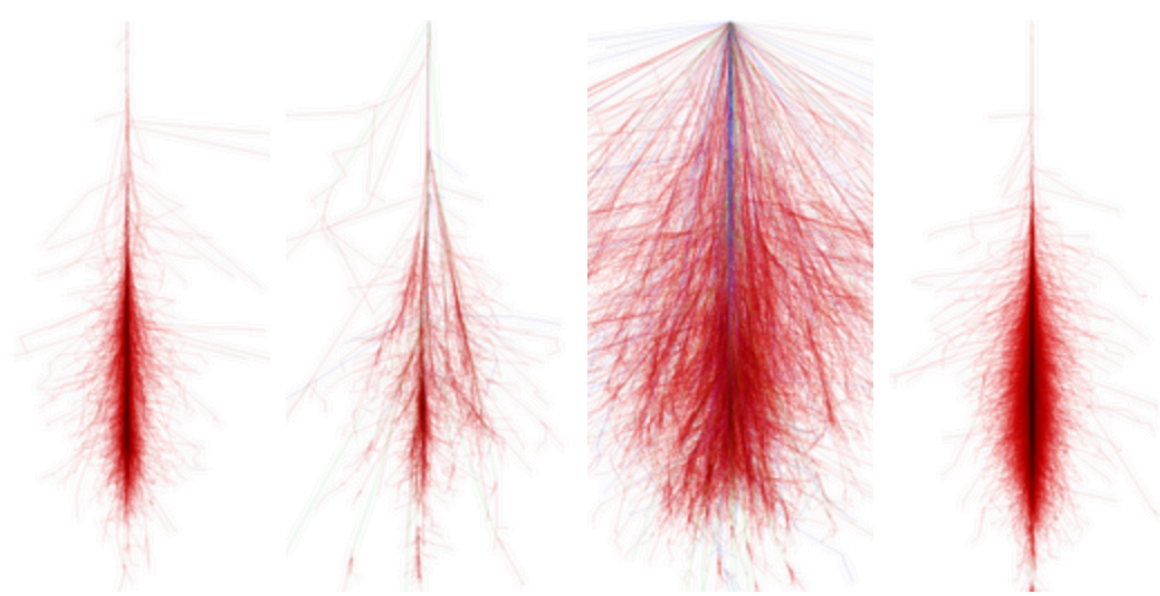
KIT Karlsruhe Institute of Technology

CORSIKA – COsmic Ray SImulations for KAscade

- Home
- Philosophy
- Visualizations
- Downloads
- Documentation
- CORSIKA Schools
- CoREAS (radio)
- COAST
- KCETA
- KSETA

CORSIKA – an Air Shower Simulation Program



Photon shower | Proton shower | Iron shower | Muon shower

(Compiled by Fabian Schmidt, University of Leeds, UK)

CORSIKA (**CO**smic **R**ay **SI**mulations for **KAscade**) is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries.

The particles are tracked through the atmosphere until they undergo reactions with the air nuclei or - in the case of instable secondaries - decay. The hadronic interactions at high energies may be described by several reaction models alternatively:The VENUS, QGSJET, and DPMJET models are based on the Gribov-Regge theory, while SIBYLL is a minijet model. The neXus model extends far above a simple combination of QGSJET and VENUS routines. The most recent EPOS model is based on the neXus framework but with important improvements concerning hard interactions and nuclear and high-density effect. HDPM is inspired by findings of the Dual Parton Model and tries to reproduce relevant kinematical distributions being measured at colliders.

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