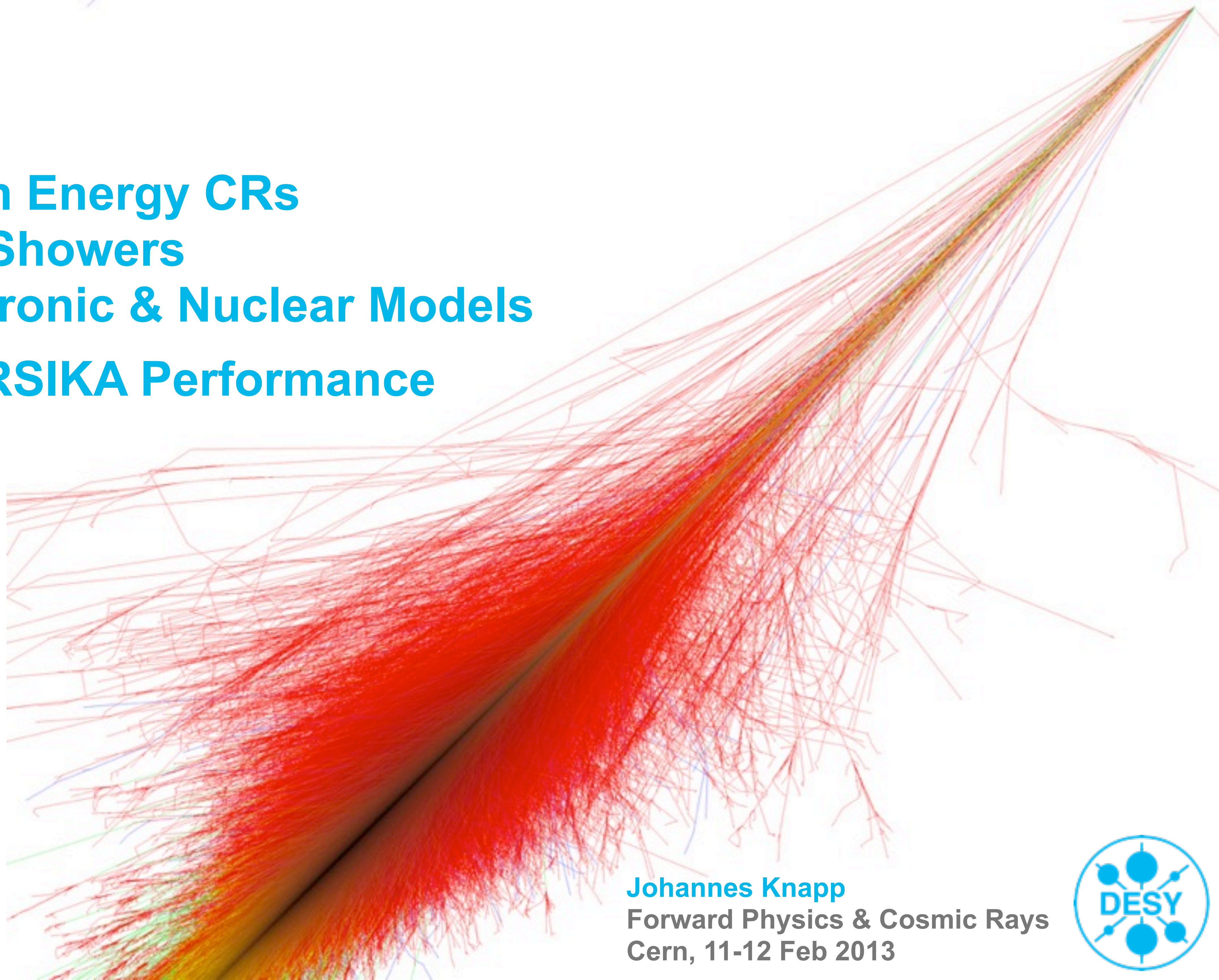
Modelling of Air Showers - An Overview.

- > High Energy CRs
- > Air Showers
- > Hadronic & Nuclear Models
- > CORSIKA Performance



HELMHOLTZ | ASSOCIATION

Johannes Knapp
Forward Physics & Cosmic Rays
Cern, 11-12 Feb 2013

DESY

Cosmic Rays:

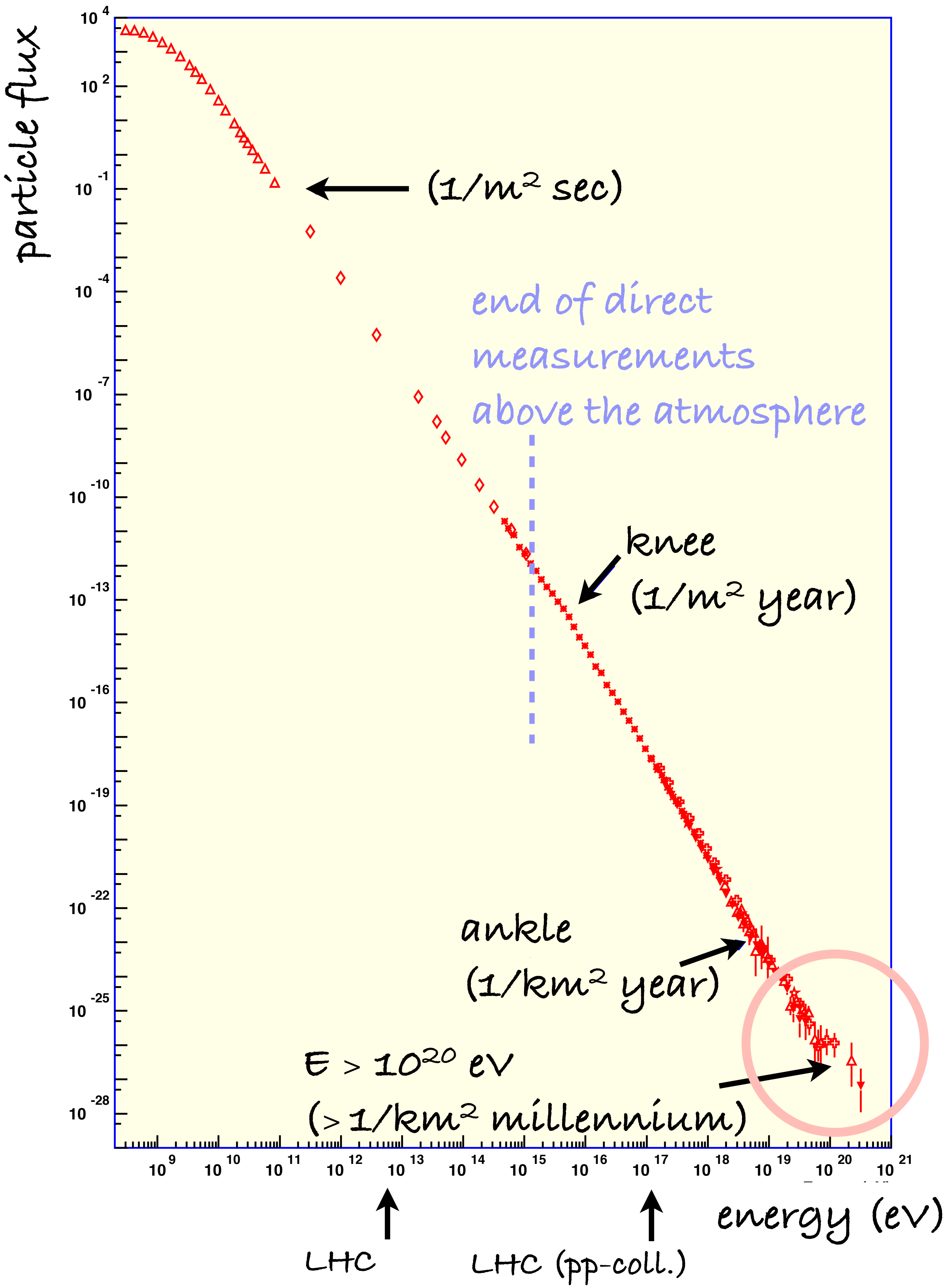
charged particles from astrophysical sources
... the highest energy particles in the universe !

Cosmic Rays: p, He, ... Fe fully ionised nuclei
electrons identified at low energies

Energies: MeV .... $\geq 10^{20}$ eV (UHE: $> 10^{18}$ eV)

Important part of the galaxy / universe

Flux of Cosmic Rays



12 orders of magnitude in energy,
33 " in flux !

10x up in energy, ≈500x down in flux

Highest energy events:
≈ 3 x 10^{20} eV

10^{20} eV particles do exist,
but are very rare.
< 1 particle / (km² millennium)

Exciting particle- and astrophysics:

There are Cosmic Particle Accelerators out there, going up to $>10^{20}$ eV !!

Where are they? How do they work?
How do UHE particles interact?

Cosmic Rays: the real
high-energy physics

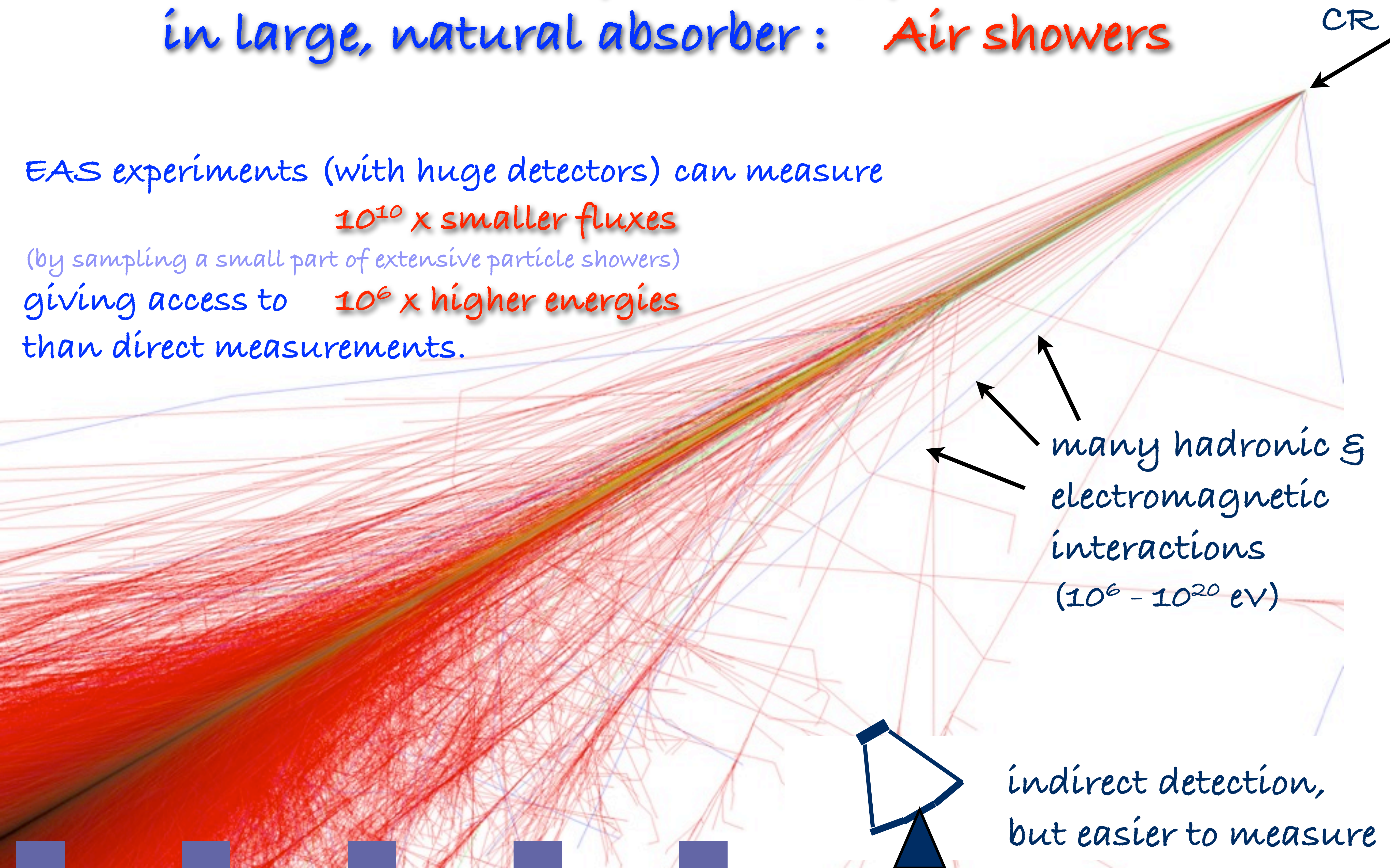
Direct measurements impossible for $E > 10^{15}$ eV.

Measure reaction products of primaries in large, natural absorber : Air showers

EAS experiments (with huge detectors) can measure 10^{10} x smaller fluxes

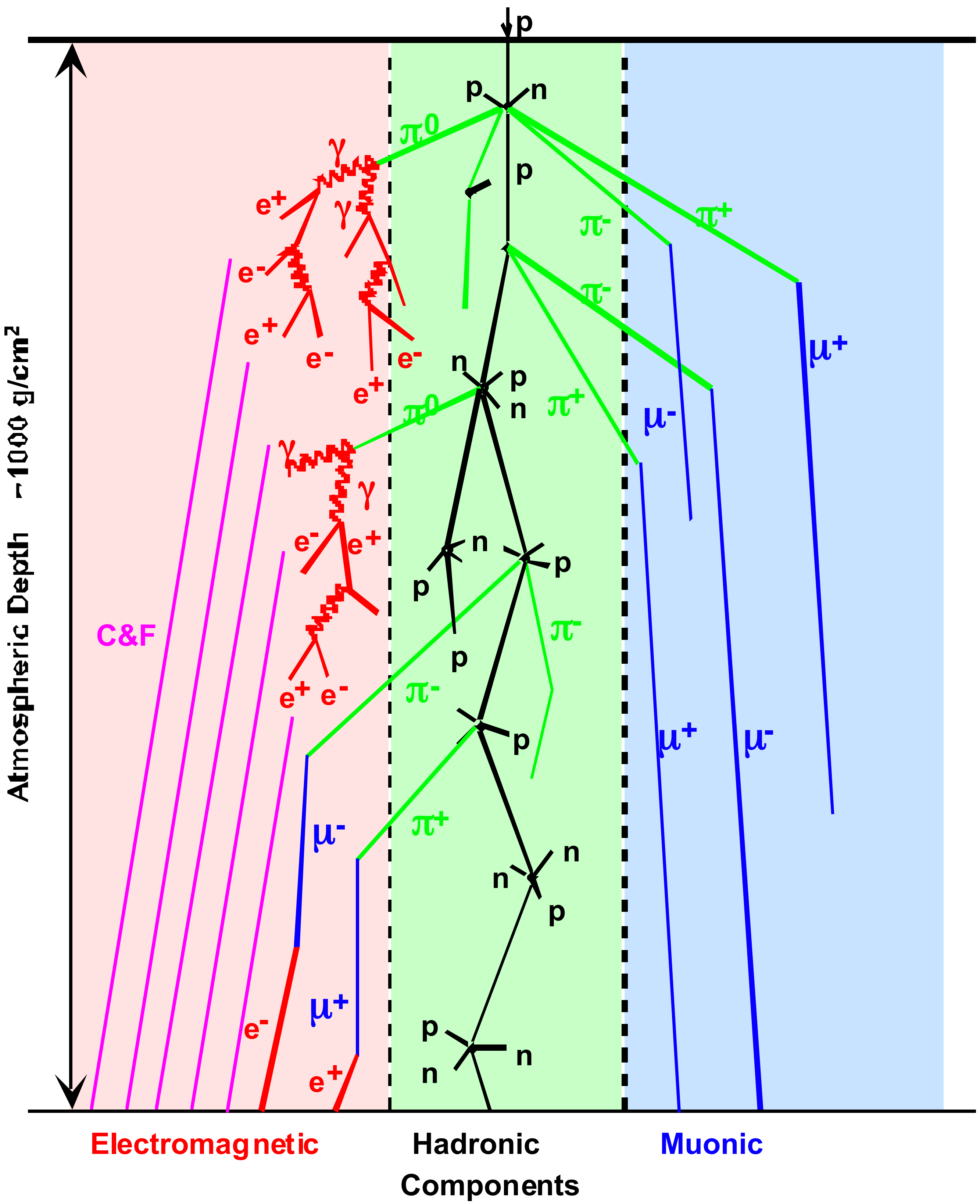
(by sampling a small part of extensive particle showers)

giving access to 10^{6} x higher energies than direct measurements.



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

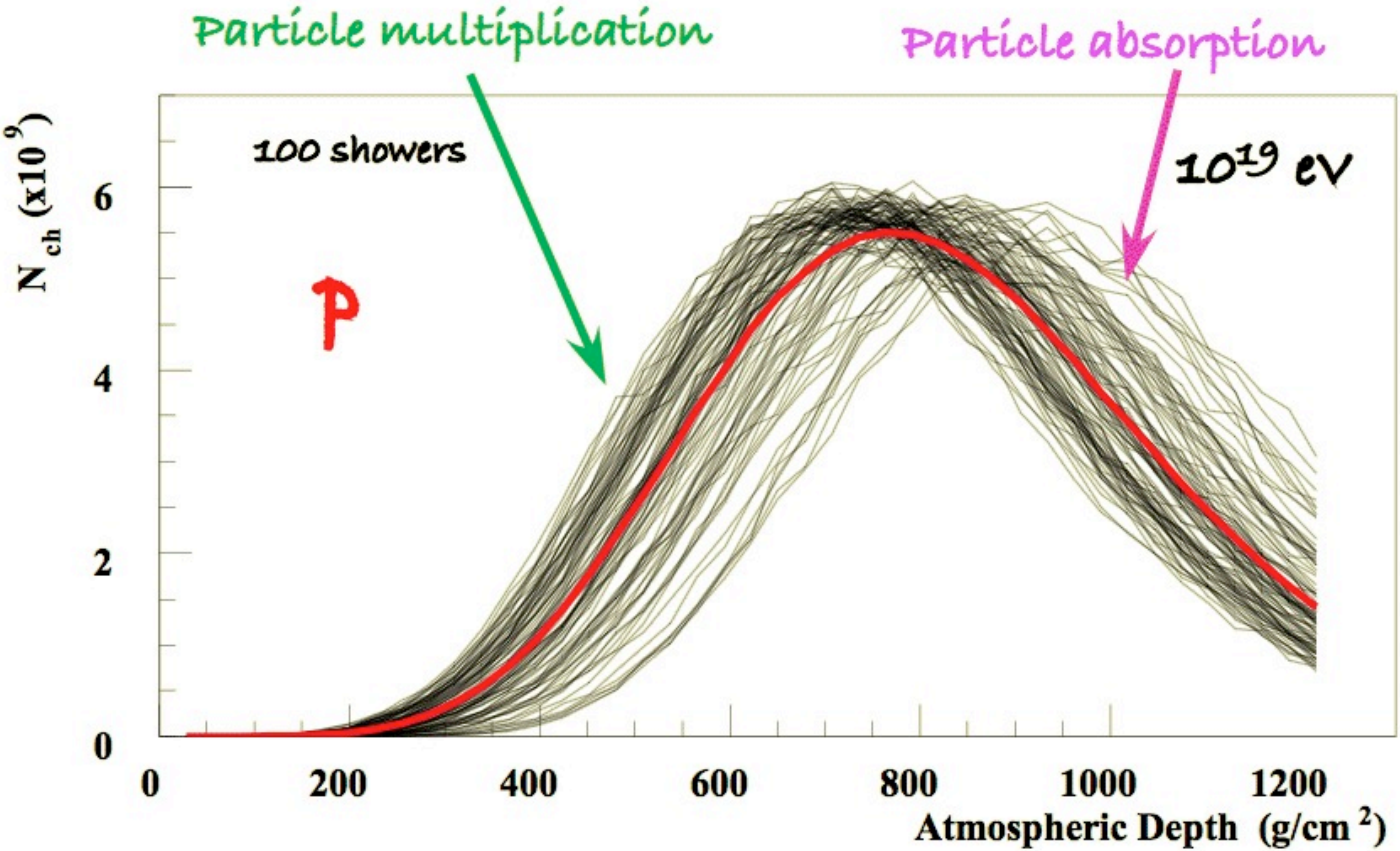
μ : from $\pi^{\pm}$, K, decays ≈ 1 GeV

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)
Earth magnetic field, ...
the ever-changing atmosphere ....

Complex interplay with many correlations



Particle multiplication
Particle absorption
100 showers
10^{19} eV
P
N_{ch} (x10^9)
0
2
4
6
0
200
400
600
800
1000
1200
Atmospheric Depth (g/cm ^{2})

Unknown at high energies :

- CR composition (p, He, O, ... Fe, γ , ν)
- energy spectrum

  get composition from magnetic deflections, features in spectrum,
  well-understood acceleration and environments
  to constrain hadronic interactions.

- details of nuclear and hadronic interactions

  Construct an **air shower model** based on
  particle physics data (ISR, SPPS, ... LHC ...) and reliable theories.
  Extrapolate to the UHECR regime (>10^{18} eV, very forward)
  to interpret EAS results (e.g. composition).

Find consistent description of
Astrophysics and Hadronic Physics
simultaneously.

A difficult problem ...

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 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.

e.g. The Pierre Auger Observatory

"What is the **origin** of the Ultra High Energy Cosmic Rays ?"

(UHECRs: > 10^{18} eV)

Measure them with unprecedented statistics and quality.

Where do UHECRs come from?

What are they?

How are they accelerated?

Does their spectrum end?

Extensive Air Shower:

indirect measurement,

shape and particle content of showers

Auger: Hybrid Detector

measure extensive air shower with:

24 Fluorescence telescopes

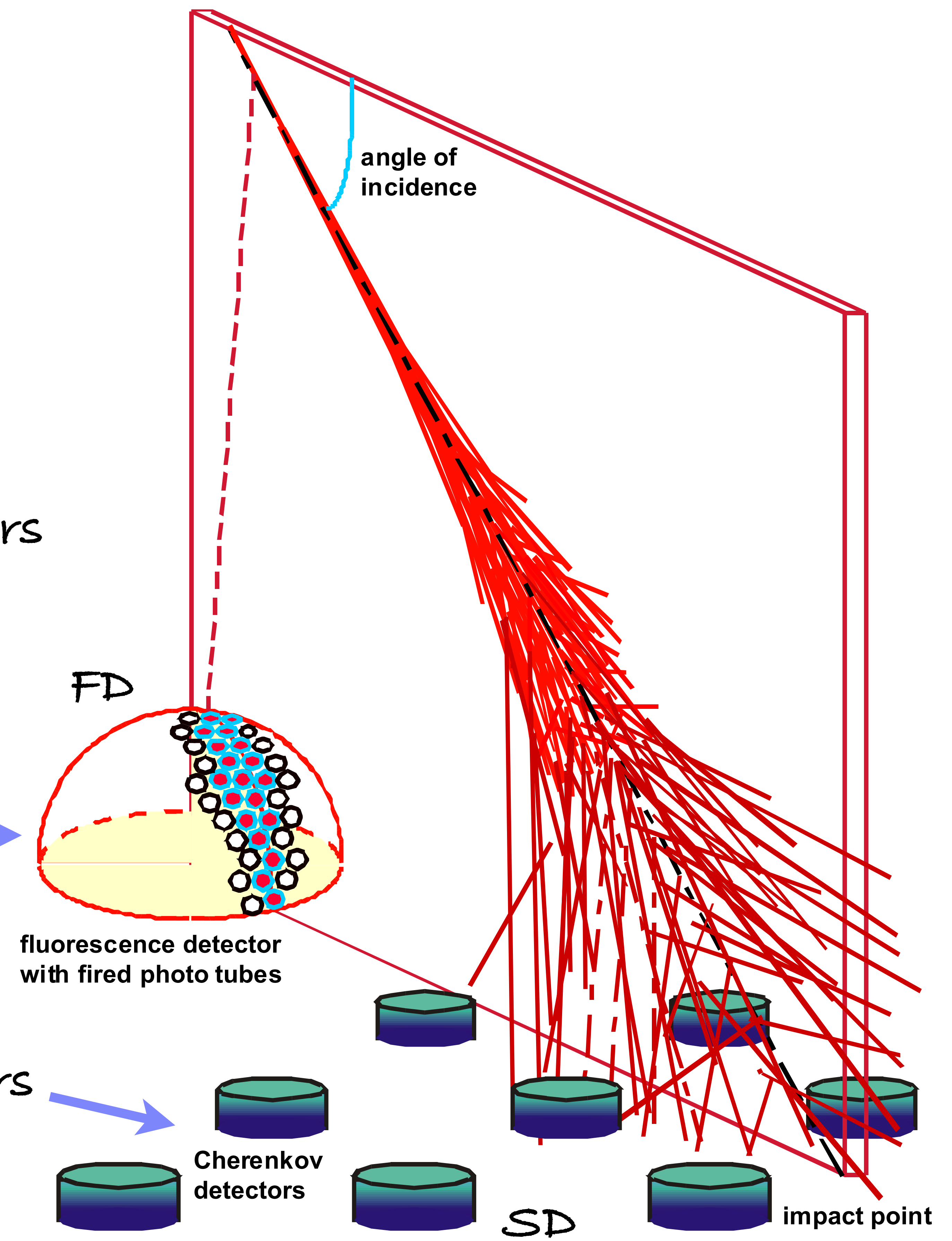
$30^0 \times 30^0$ FoV, 10% duty cycle,

good energy resolution

array of 1600 water Cherenkov detectors

on 3000 km^2, 100% duty cycle,

well-known aperture



Reconstruction (e.g. for Auger)

direction θ, φ: via arrival times

primary energy E: fluorescence tels.: from longitudinal profile

ground array: lateral particle distribution at ground

particle number $\sim E$ $\sigma E/E \approx 30\%$

mass m: subtle differences in shower form & particle contents

Fe shower develop higher than p showers.

X_{max}, $\rho(r)$, e/μ ....

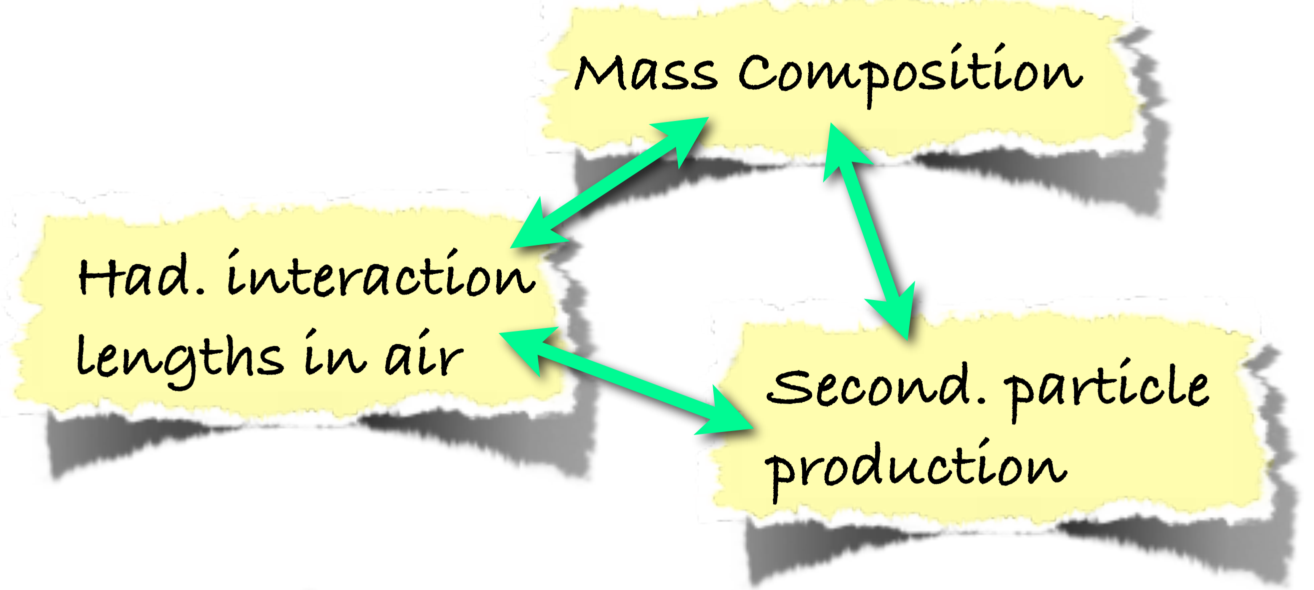
results depend strongly on EAS models

in addition: there are large shower fluctuations

remember: large air shower detectors are only sparsely sampling the showers (financial reasons).

i.e. much worse than one would wish.

Study of high-energy CRs requires detailed modelling of hadronic interactions in air.



Composition vs hadronic interaction modelling

"Particle Physics approach"

a. Obtain relevant data at accelerators (... ISR, SPPS, LHC + others)
b. Develop a sound theoretical framework to extrapolate to higher energies (well beyond accelerators)

?

Use knowledge of particle physics to interpret the CR data

"Astrophysics approach"

a. Astrophysical composition measurements from:
   - Magnetic deviations of particles from point sources
   - Features on the energy spectrum
   - Acceleration Mechanism/Environment well understood

?

Use knowledge of composition to constrain hadronic interactions

In reality: a compromise ... :
Self-consistent description of composition and interactions

The difficulties:

EAS energies go far beyond accelerator energies

Understand relevant hadronic & nuclear physics at energies < few TeV (soft interactions, diffraction, cross sections, particle production, ...)

Extrapolate to high energies (based on a reliable theory)

(The variable atmosphere)

← not topic of this meeting

understand relevant hadronic & nuclear physics
at energies < few TeV (soft interactions, diffraction,
cross sections, particle production, ...)

i.e. not the "phenomenological" type of understanding,
where each set of data gets its own "tuning"
just to fit the accelerator data,

but the type of understanding,
that allows firm extrapolation over
decades in energy.

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at energies $<$ few TeV (soft interactions, diffraction,
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where each set of data gets its own "tuning"
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but the type of understanding,
that allows firm extrapolation over
decades in energy.

Is that possible at all?

Too many free (ad-hoc) parameters
are may be ok for low energies (< accelerator energies),

but lead to exploding systematical errors
when extrapolating.

Predictions become meaningless.

How to build an air-shower model?

1. The detector medium:
   Atmospheric composition, density as function of height

2. The beam: p, He, ... Fe, γ, ν, exotics ???
   p, e, γ, μ, K, Λ, Σ, ... (all known particles)

3. Particle interactions
   cross sections & particle production
   for electromagnetic and
   for nuclear & hadronic interactions

4. Particle tracking in magnetic field,
   ionisation, energy loss, Cherenkov light
   multiple scattering, decays, absorption ...

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   cross sections & particle production
   for electromagnetic and
   for nuclear & hadronic interactions

   this is crucial

4. Particle tracking in magnetic field,
   ionisation, energy loss, Cherenkov light
   multiple scattering, decays, absorption ...

How to build a hadronic interaction model?

1. invent a model for p-p collisions (simple or elaborate)
2. tune to reproduce experimental results for p-p
3. extrapolate to higher energies

tricky!

add:

4. diffractive processes
5. hard processes
6. p-N, π-N, X-N, N_1-N_2
7. nuclear physics
8. fragmentation of strings into hadrons

....

Problems arise mostly with 4. - 8.

Agreement with p-N, π-N and N-N data is usually worse than with p-p data.

Anything to learn from Accelerator Experiments ?

In air showers:

Projectiles:

p, He, ... Fe, ... γ, (ν)

p, n, $\pi^{\pm}$, $K^{\pm,0}$, Λ, Δ, ... + any secondary

Targets:

O_2, N_2, Ar in air

Energies:

$E = 10^9 \ldots 10^{21}$ eV (= 10^9 TeV !!)

(all are important !!!)

Emission angle:

very forward ($\eta_{peak} \sim 3.2 + 1.2 \times \log_{10}(E/TeV)$ $\sim 4-14$)

"soft interactions" QCD does not work

At accelerators:

Projectiles:

p, $\bar{p}$, e^+, e^-, A, γ, ν,

n, $\pi^{\pm}$, $K^{\pm,0}$

Targets:

p, e^-, A

Energies:

$E <$ ~~1 TeV~~ 3.5 TeV (soon ~ 8 TeV)

$E < 200$ GeV for nuclei & mesons

colliding: $E_{lab,pp} = 1.7 \times 10^{15}$ eV (1.3×10^{17} eV)

$E_{lab,AA} = 8.5 \times 10^{13}$ eV

Emission angle:

high p_T ($|\eta| < 3-5$)

7: TOTEM

∞: LHCf

"hard interactions", QCD + soft

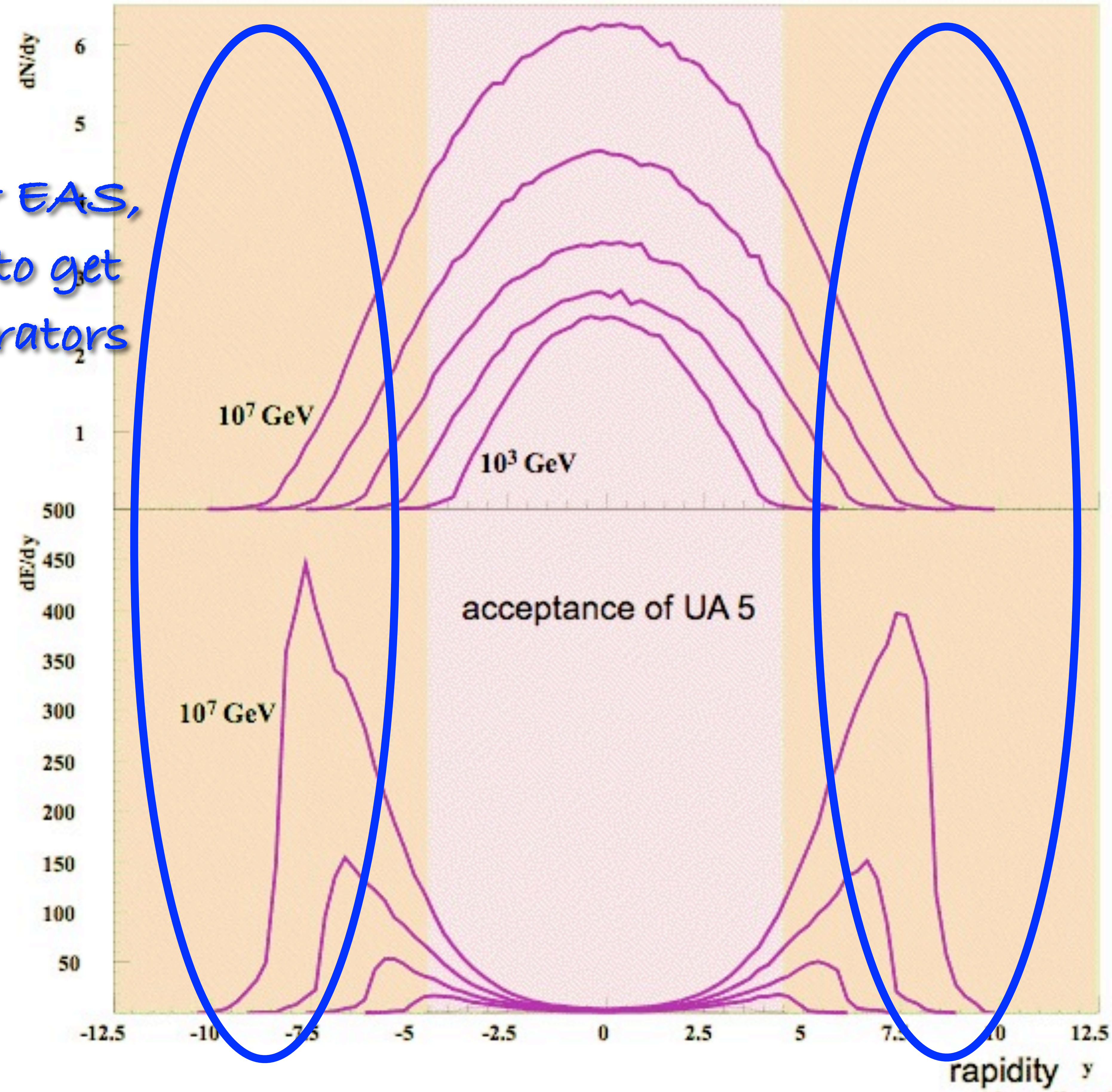
The very forward region

particle density

important for EAS, but difficult to get at with accelerators

energy density

p-p non-diffractive interactions



Cosmic Ray Models need:

cross sections: total, inelastic, diffractive...
particle production: type, energy, angular dist.
mainly in very forward direction ($\eta \approx 3 \ldots 15$)

but measurements in the very forward range become increasingly difficult:

energy flux,
particle number,
momentum,
particle type

Also needed:
Consistent calculation of

interaction cross sections and particle production
soft, hard, diffractive, nuclear interactions

of all sorts of hadrons,
over the whole energy range

Are there theoretical guidelines for soft interactions?

Yes : Gribov - Regge Theory (GRT)
of multi - Pomeron exchange
(a relativistic quantum field theory)

successful for
elastic scattering
total cross-section

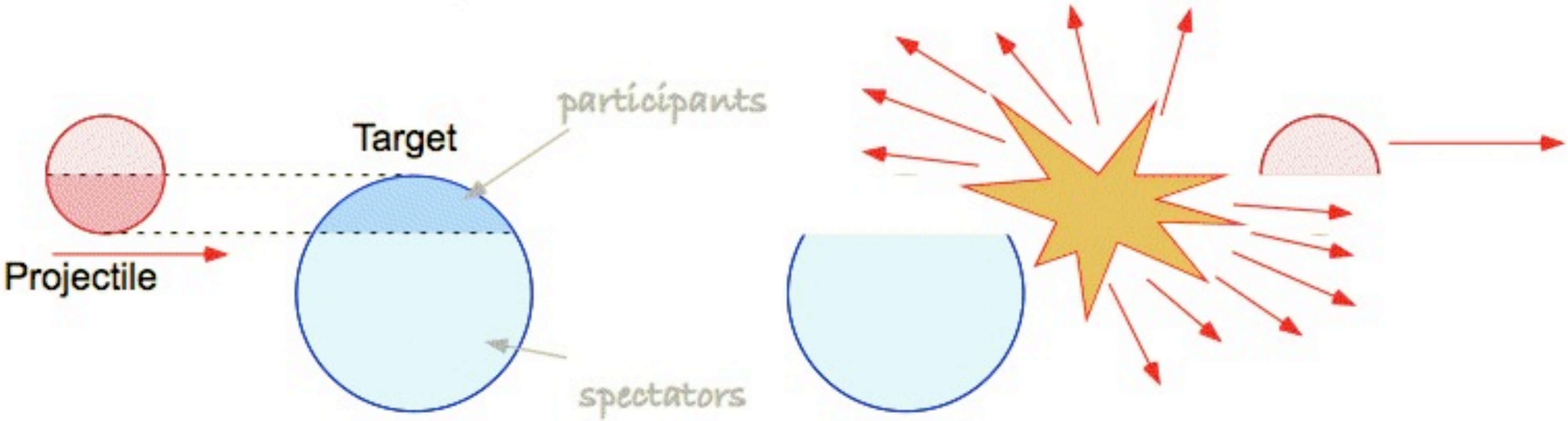
$pp, \pi p, Kp, \ldots$

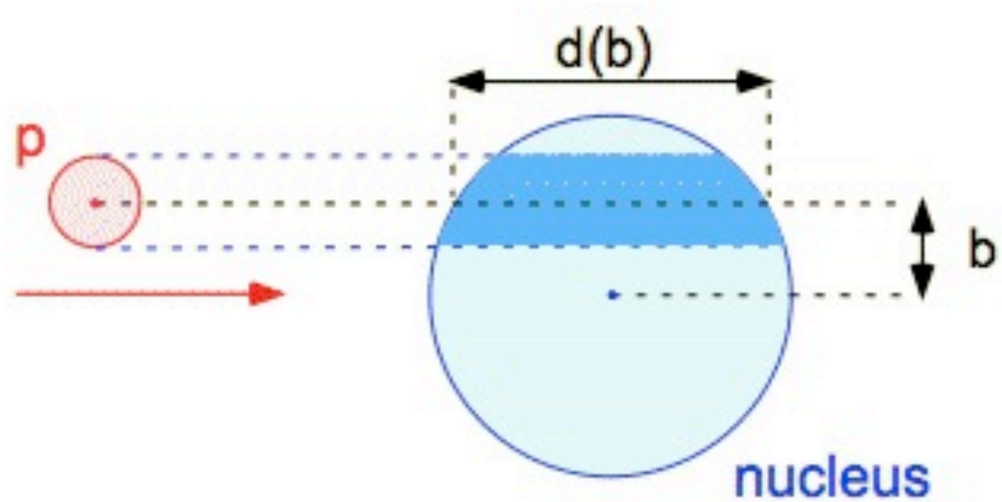
extension to particle production :
not without uncertainty but
relatively few free parameters and
seems to work fine up to highest energies

The best theoretical model we have at the moment !

Glauber Theory of nucleon-nucleus and nucleus-nucleus collisions
(a geometric model)

1^{st} collision: p, He, C, ... Fe collide with N, O, Ar
at energies: 10^{10} ... 10^{21} eV





d(b), ρ(r), σ(p-p) → σ(p-nucleus), no. of target participants

Analogous for nucleus-nucleus collisions.
Works rather well !

Problem: multiple interactions
of nucleons in one collision

much more detail on soft hadronic models
in talk of S Ostapchenko

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 with accelerator data,
then extrapolated to $>10^{20}$ eV
(≈8 orders of magnitude !!!)

+ many extensions & simplifications

Sizes and runtimes vary
by factors 2 - 40.
Total: » 10^5 lines of code
Many years of development.

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

Simulations vs Data:

... a few examples

Result:

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

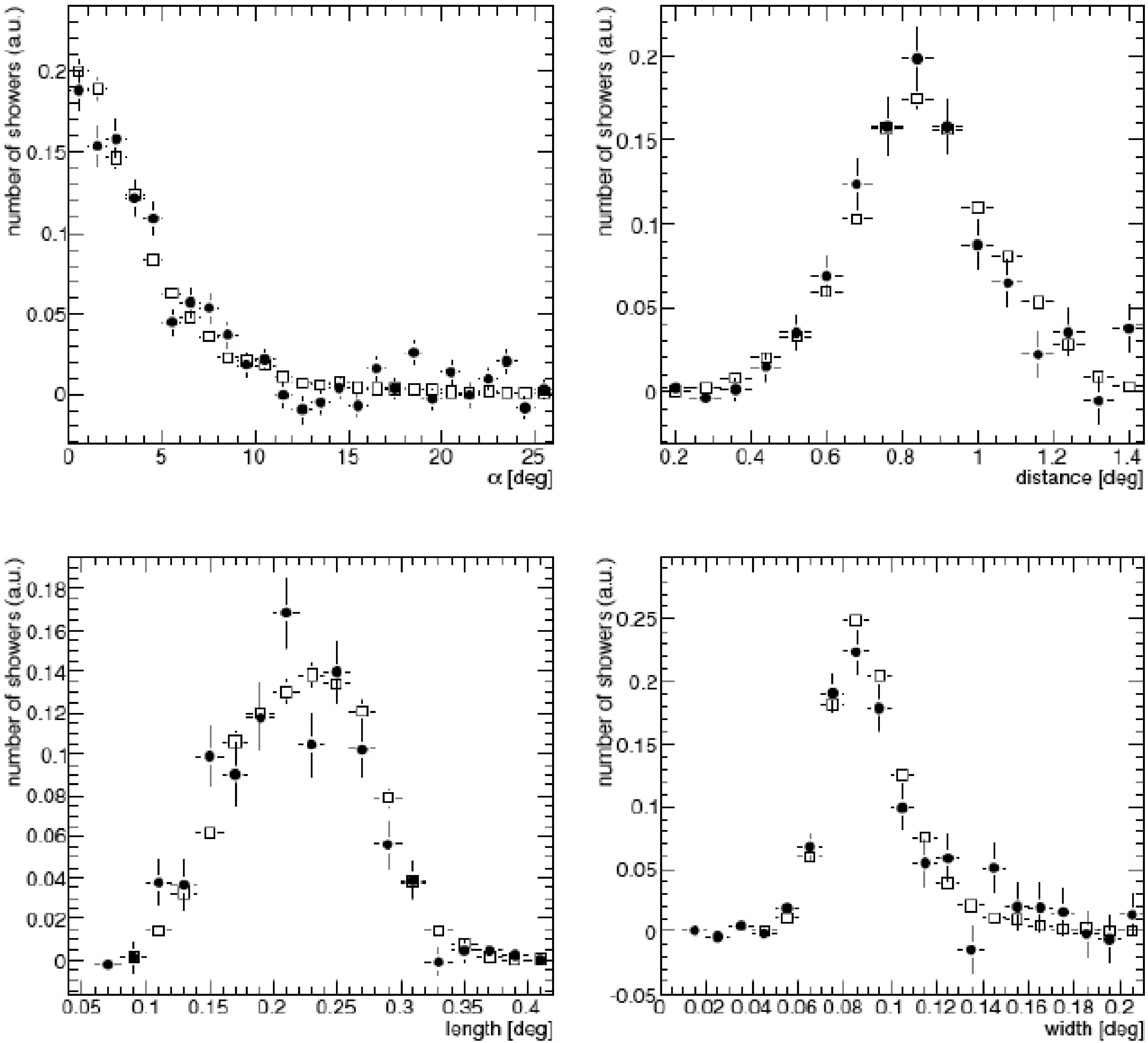
VERITAS

Telescope 1

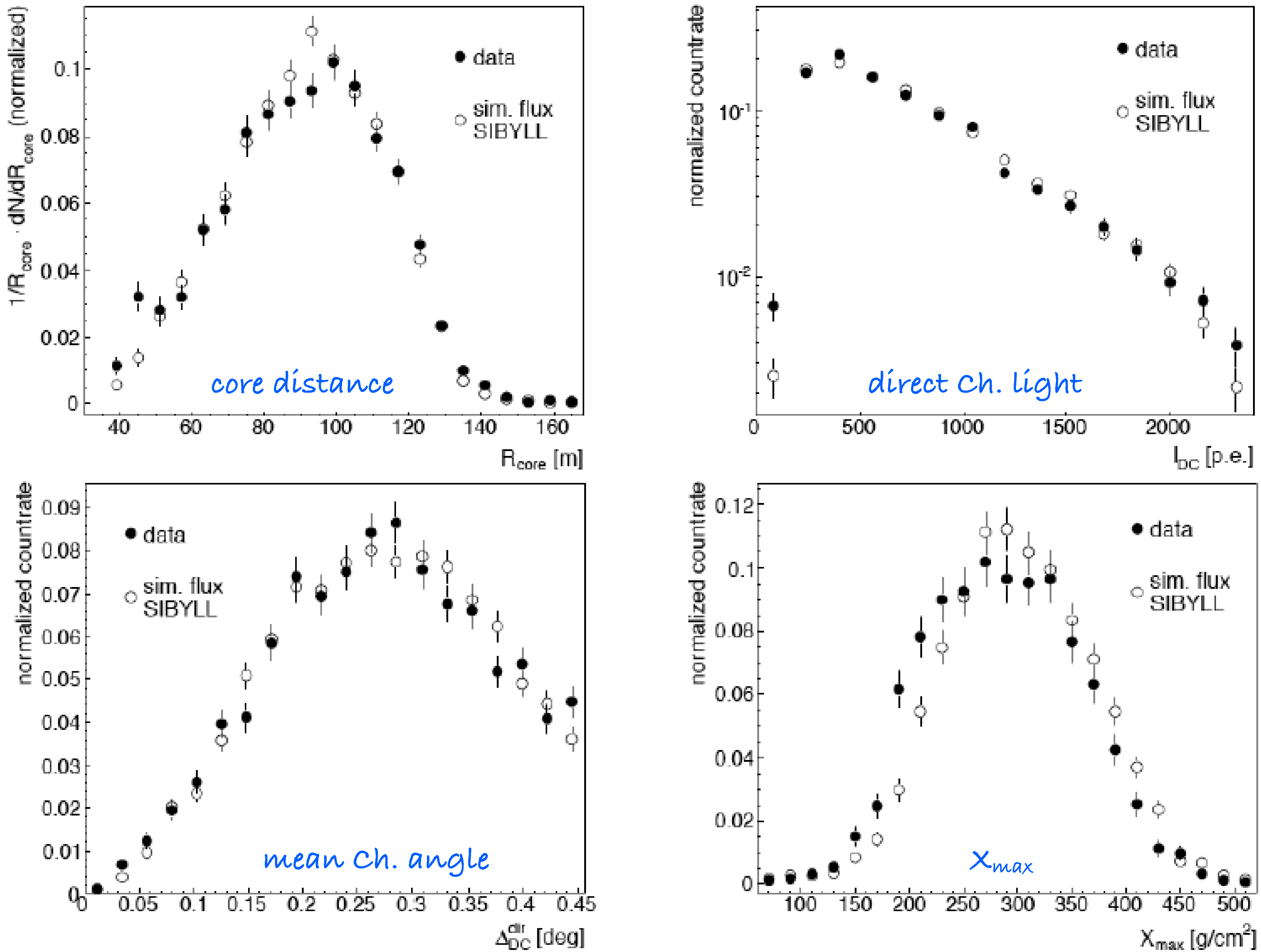
E > 150 GeV

gamma rays:
good agreement of image parameter distributions

CR background:
absolute trigger rate within 15%



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

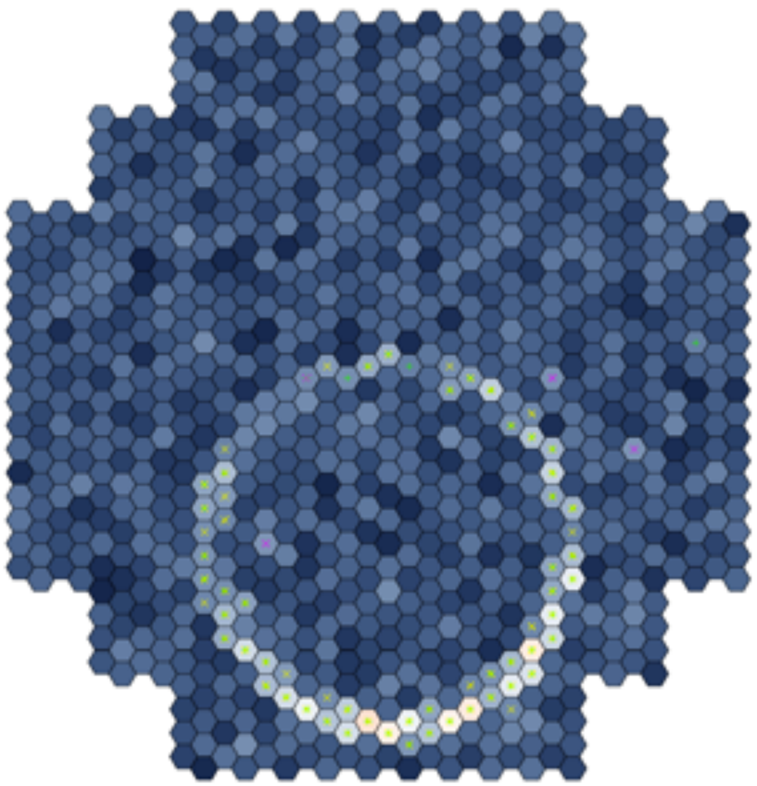


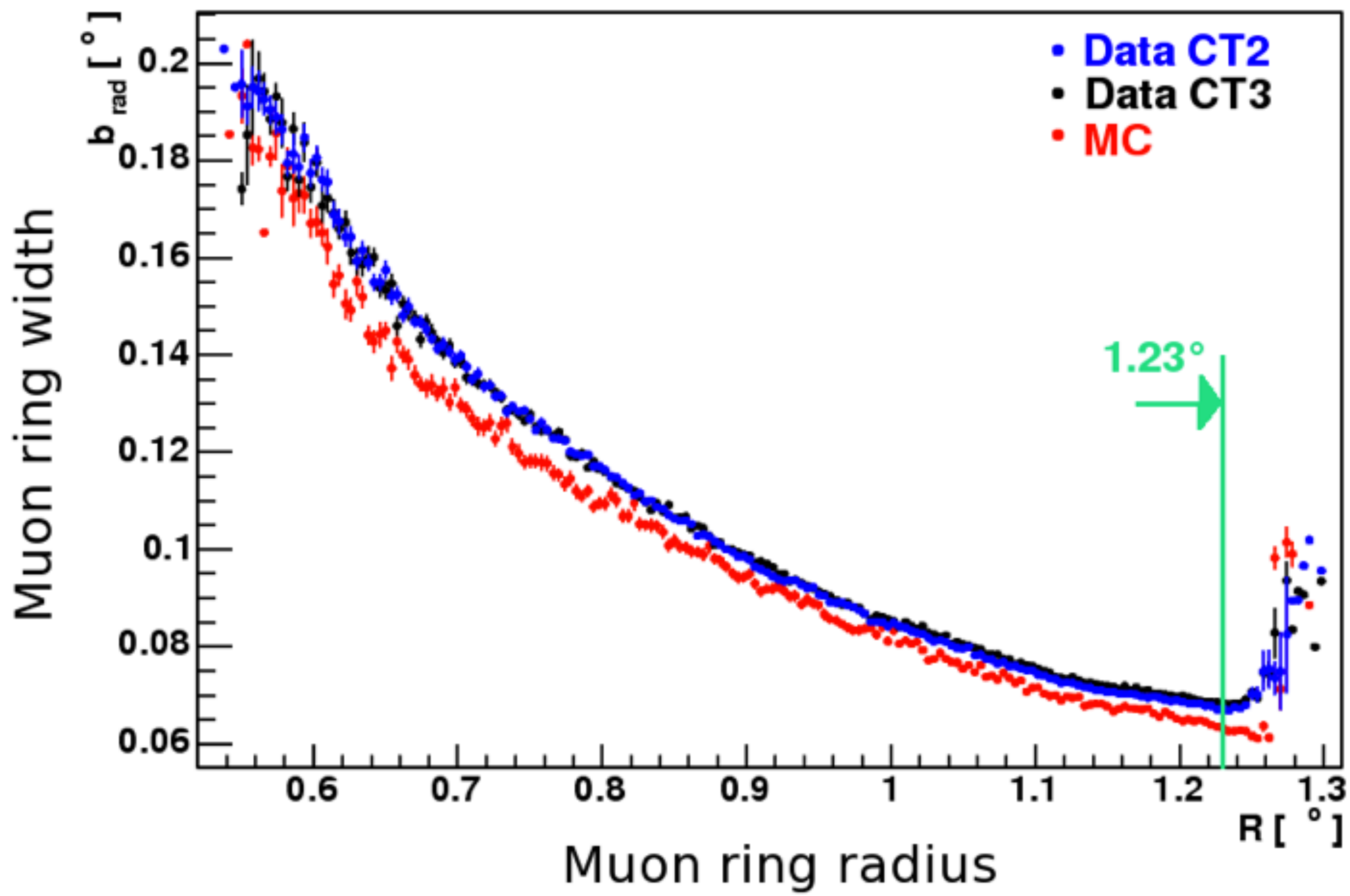
HESS 10-100 TeV mix of hadronic primaries astro-ph/0701766

Muon ring width

(in Cherenkov Telescopes)

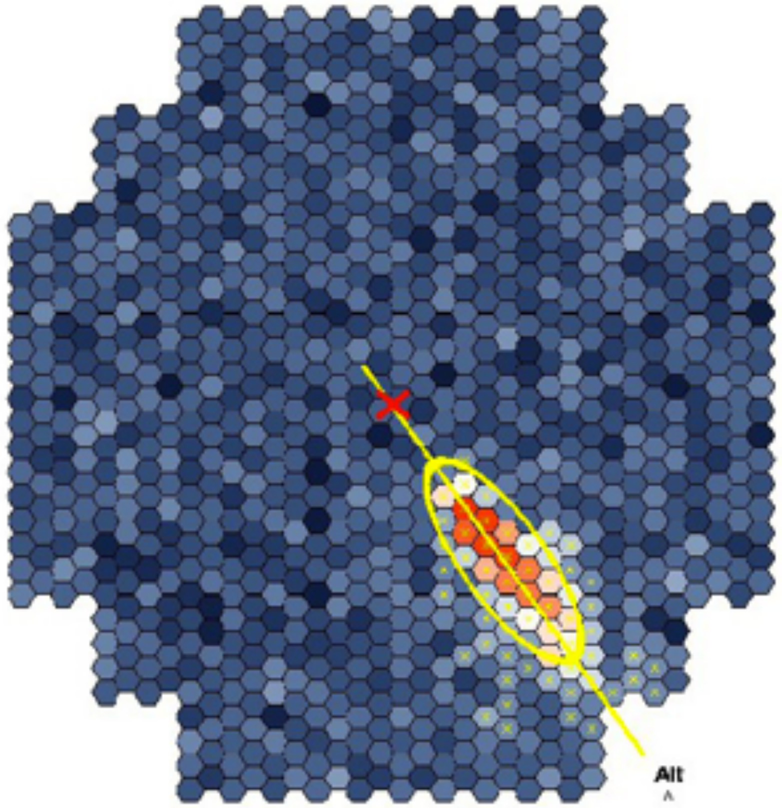
low-energy muons:
small ring radius
more multiple scattering





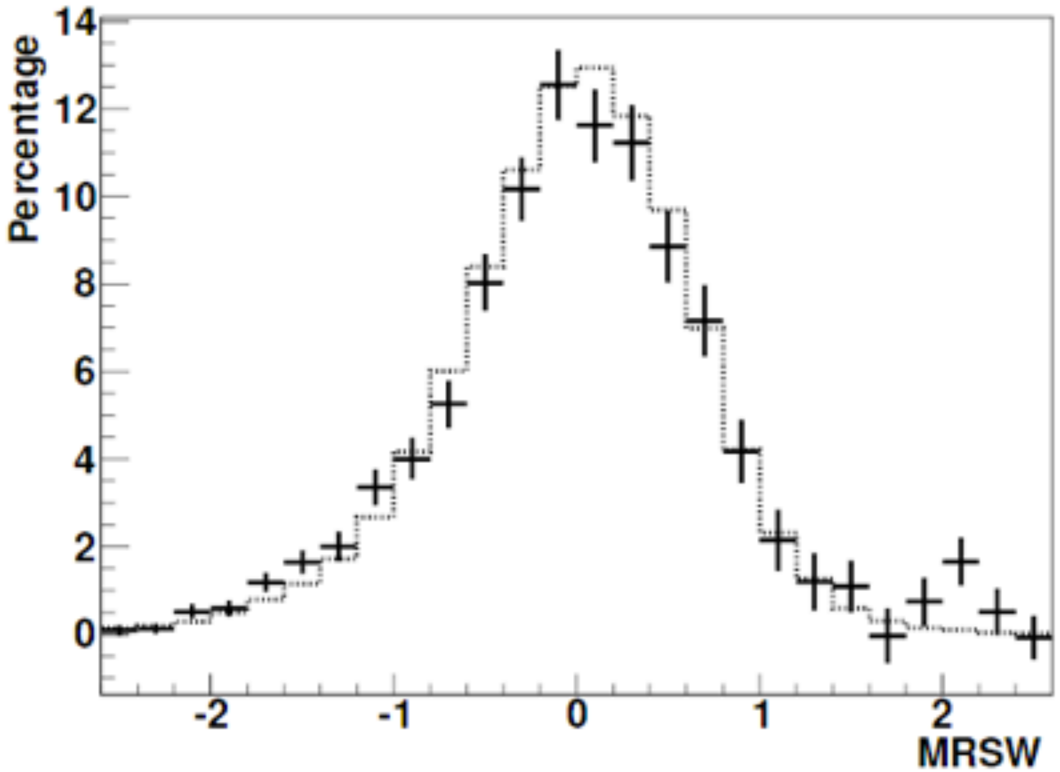
Scaled width and length

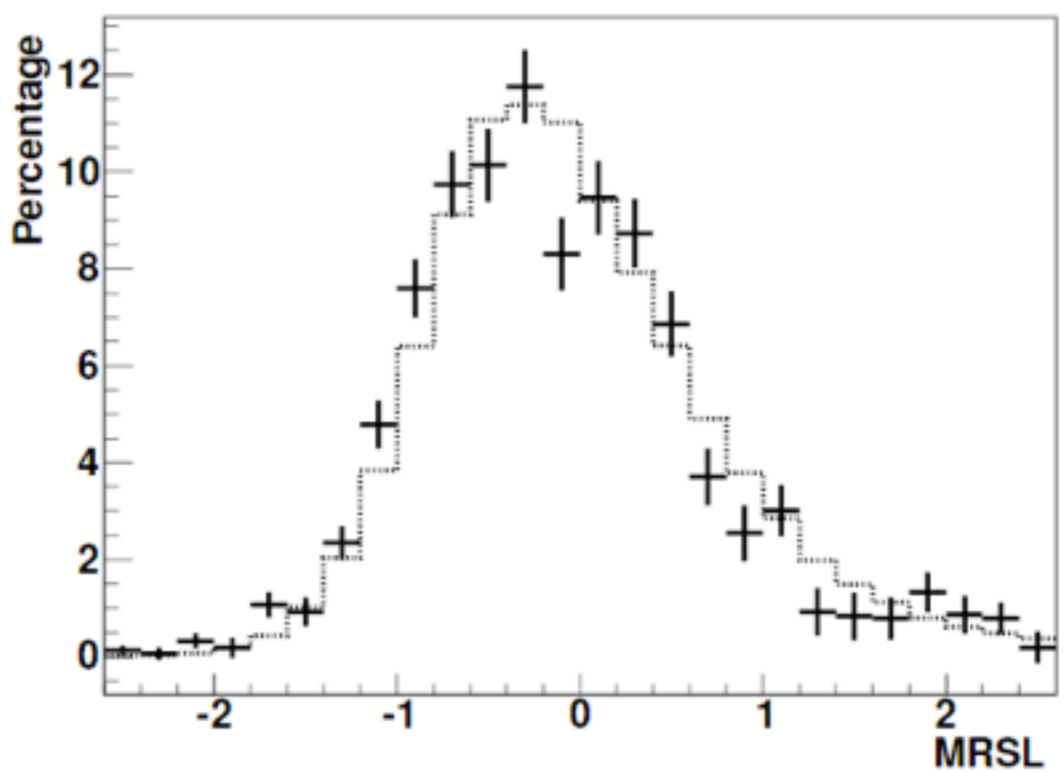
(of shower images)



simulated gamma-rays have mean 0 and variance 1

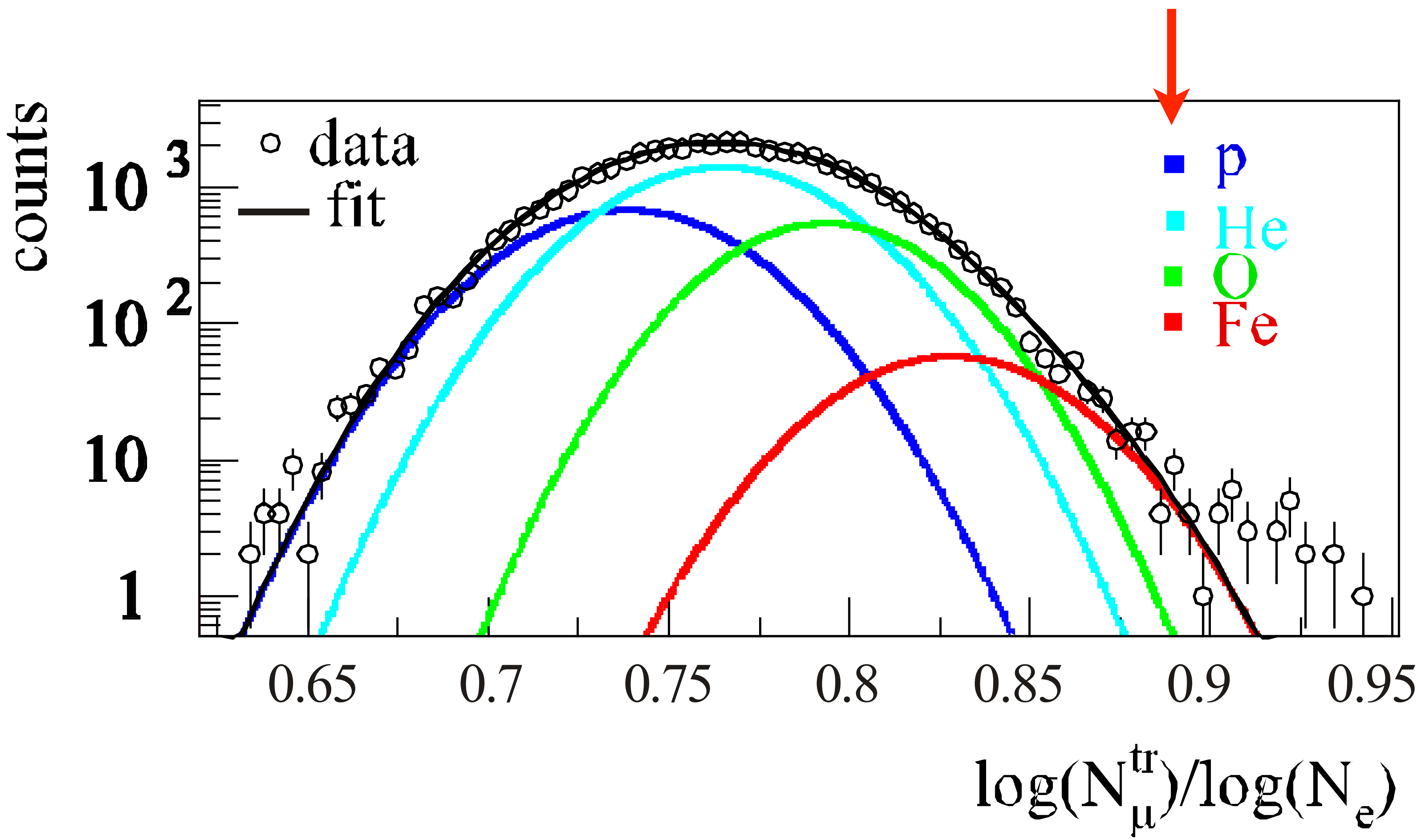
simulations and
measured H.E.S.S. data from the Crab Nebula





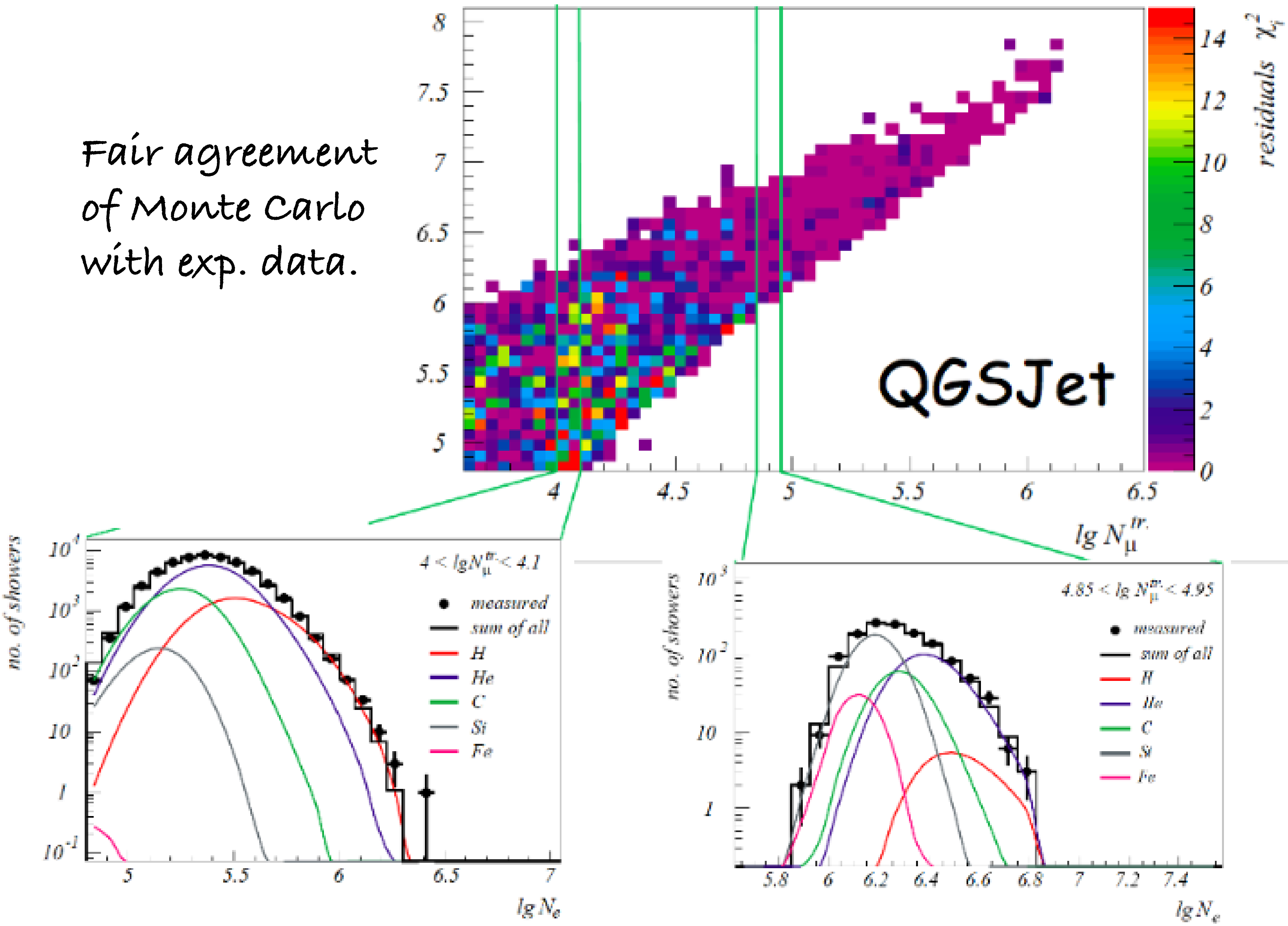
KASCADE: 10^{15} - 10^{16} eV
muon - electron ratio

CORSIKA Simulations



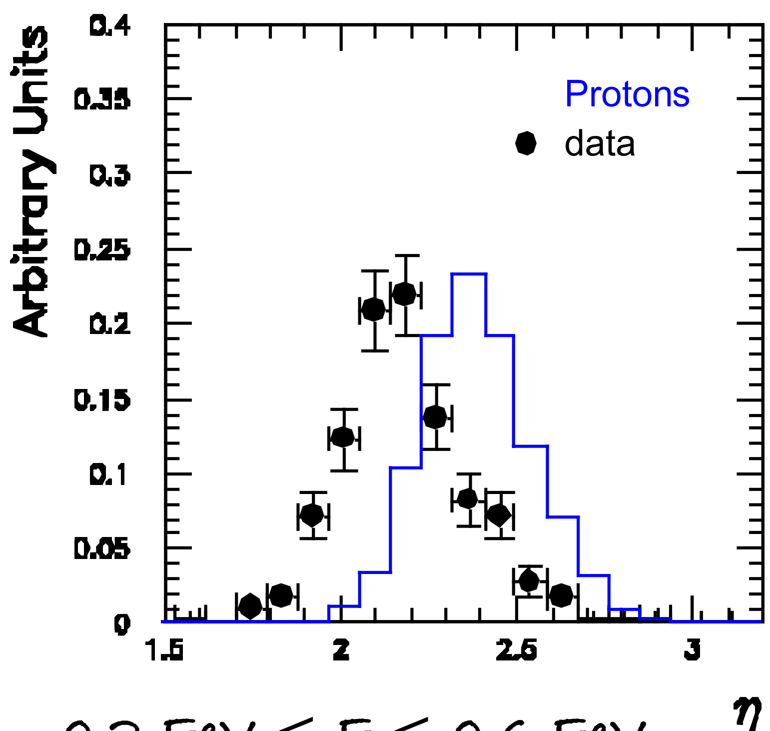
KASCADE

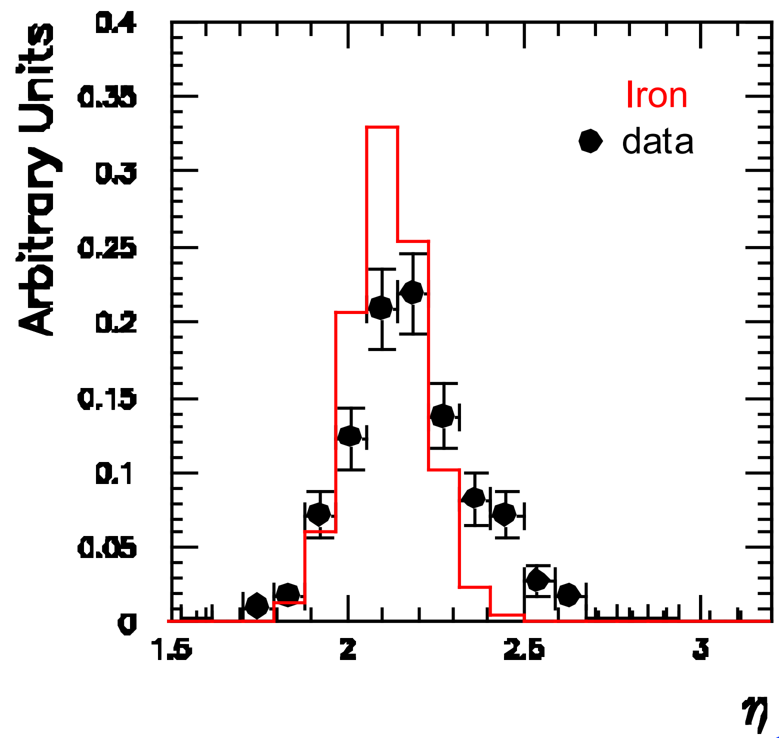
Fair agreement of Monte Carlo with exp. data.

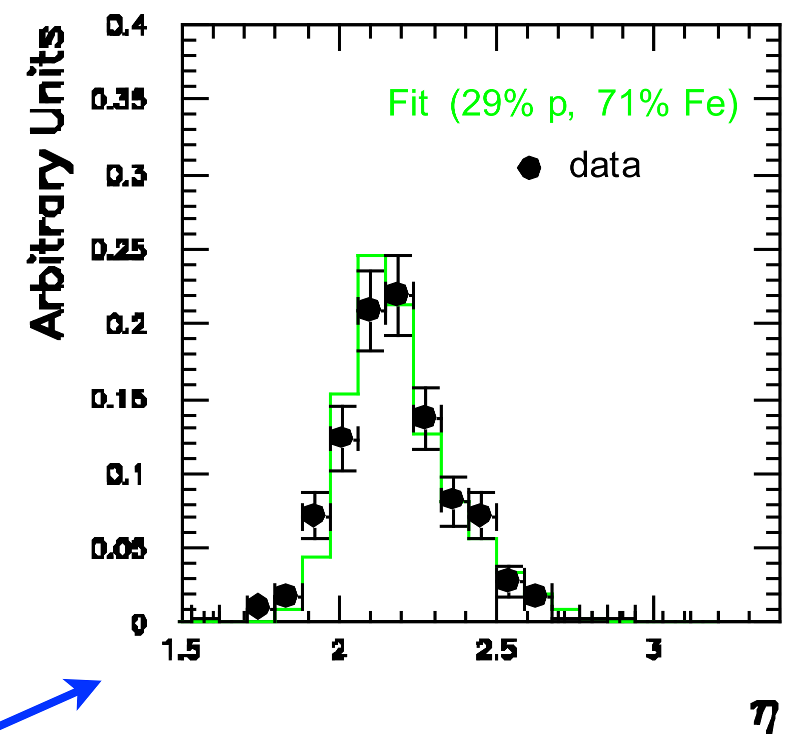


H Ulrich (KASCADE)

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



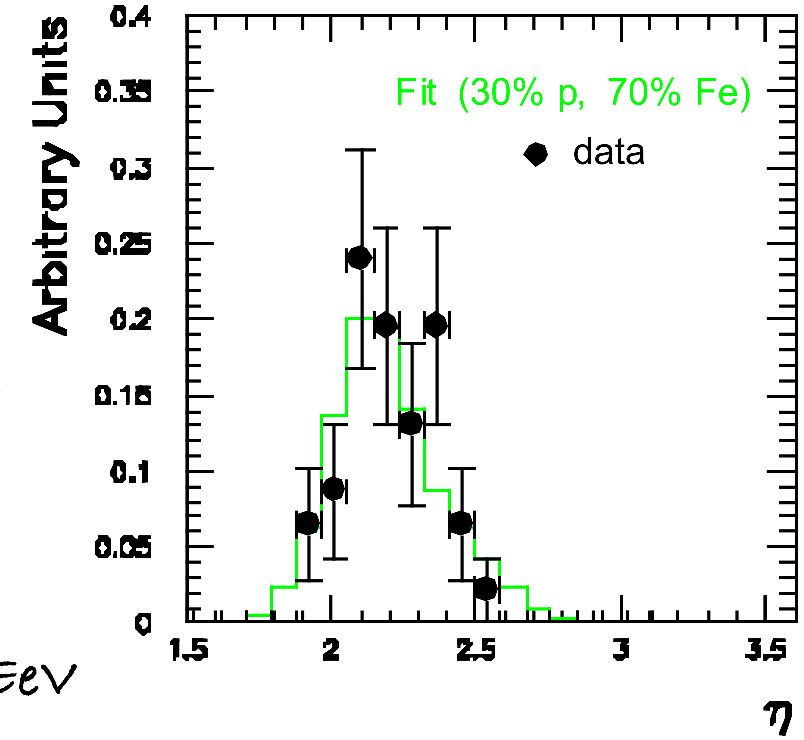




0.2 EeV < E < 0.6 EeV

292 events

Models can describe data



0.6 EeV < E < 1 EeV

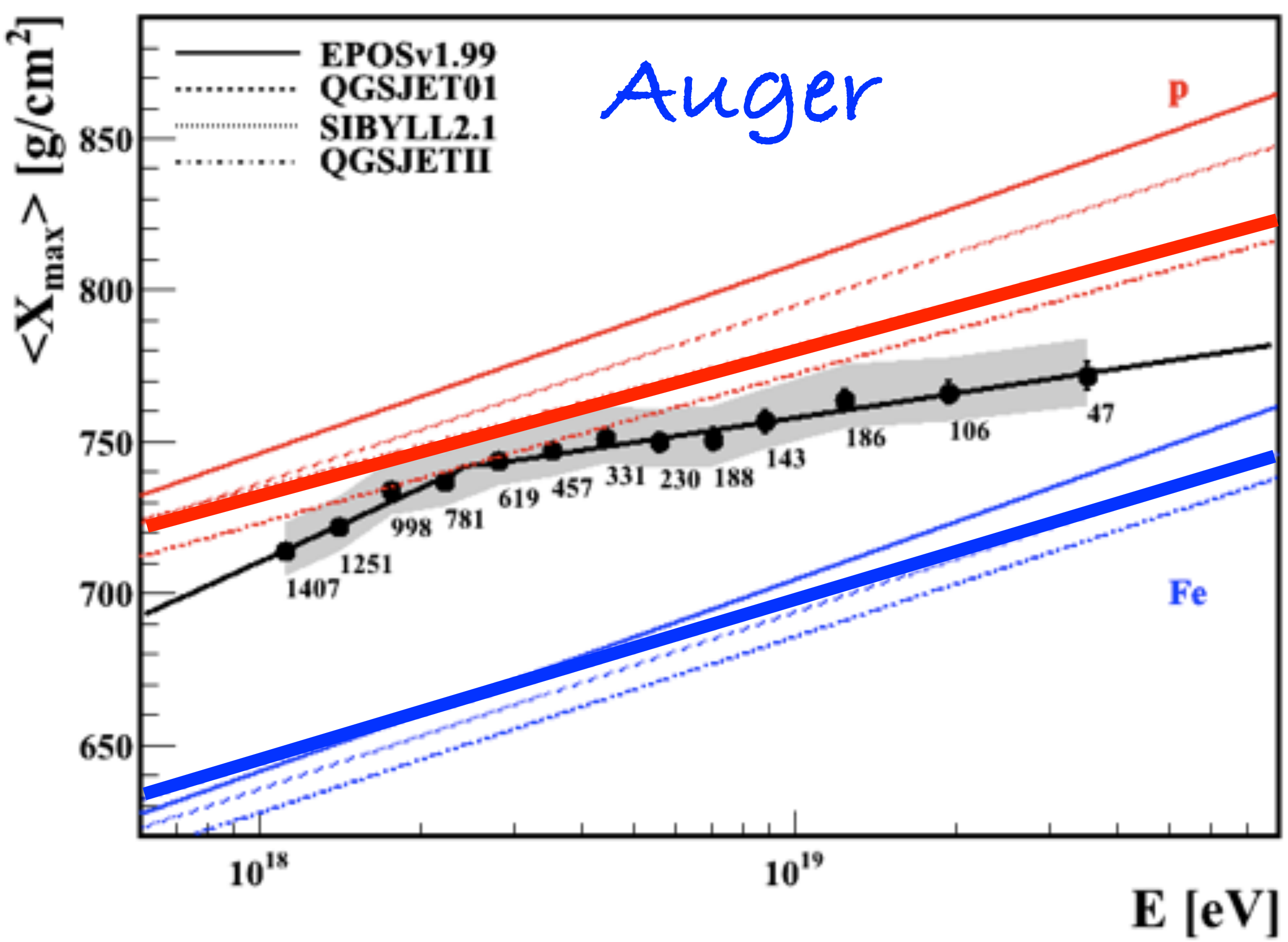
46 events

X_{max} as fct. of energy

10^{18} - 5×10^{19} eV

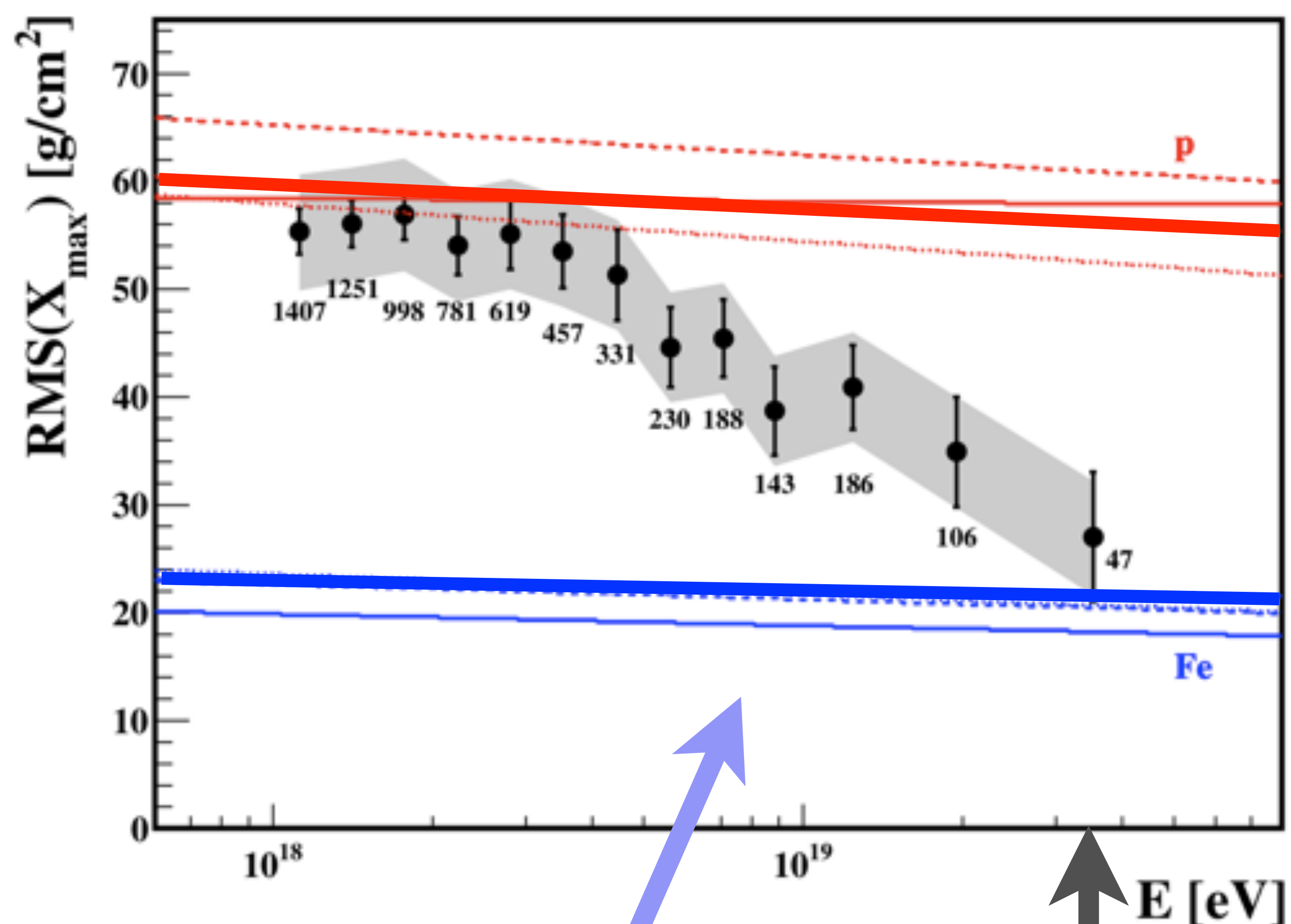
MCs for mixed hadronic comp. are consistent with data.
γ, ν showers look very different.

X_{max}



model dependent interpretation

RMS(X_{max})



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

E < 4 x 10^{19} eV

If one trusts the models, then composition turns heavier

(but the two plots are not consistent)

~ 30% level for $<10^{18}$ eV
more for $>10^{18}$ eV

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 astronomy;	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

Auger data constrain Particle Physics (at $>10^{18}$ eV):

- p-air, p-p cross section @ $2x10^{18}$ eV
- Hadronic interaction models in CORSIKA need adaption ...
- More muons & ground signal needed for same fluorescence light.

But at about $>10^{18}$ eV:

muon deficit

model deficiencies appear.

Is this ....

a change of mass composition

or

a change of hadronic interaction physics
(from what we extrapolate)

or

a mix of both ??

Recent new data from

— Relativistic Heavy Ion Collider (RHIC)

nucleus-nucleus collisions,
partly with O, N beams

STAR, PHENIX,
PHOBOS, BRAHMS

— LHC

p-p, p-A, A-A,
cross sections
forward particle production,
up to 4 (soon 8) TeV / beam

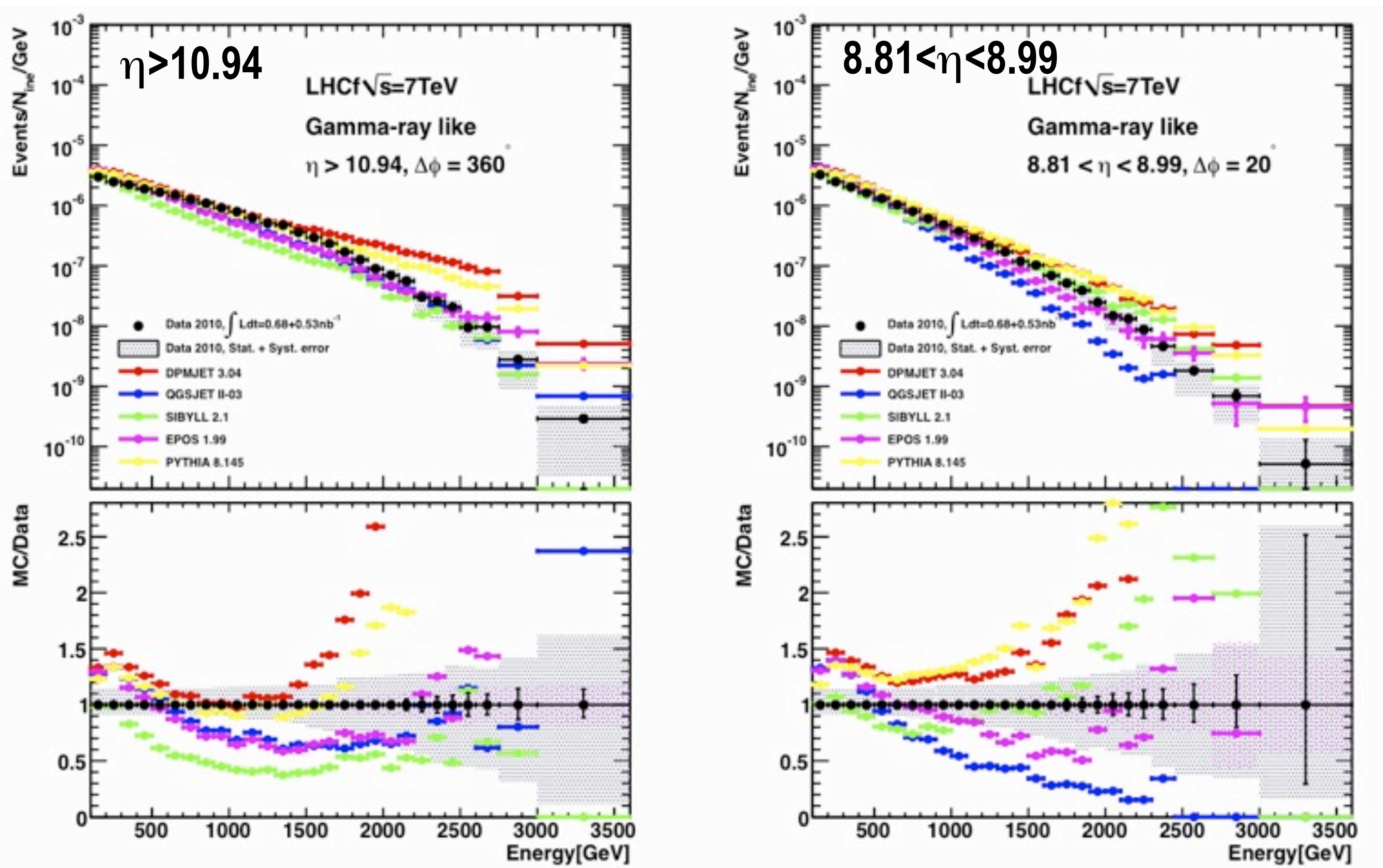
ATLAS, CMS, ALICE,
TOTEM, LHCf

Almost all new results require some modification of models!

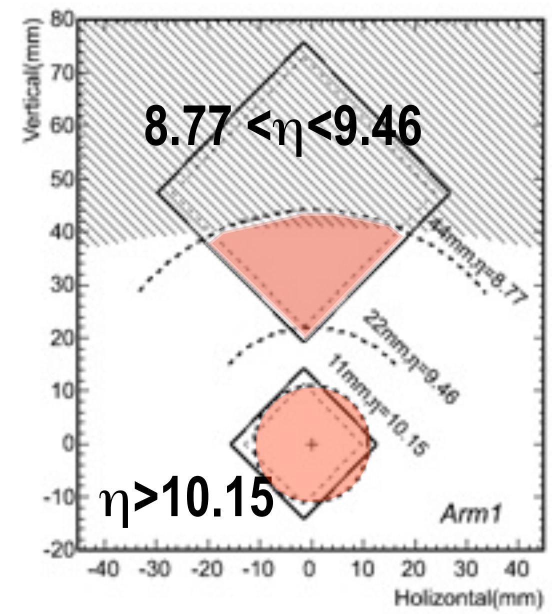
The more data is available,
the more the models will be constrained
and, possibly,
the better the extrapolations to CR energies.

Single γ spectra at 7 TeV

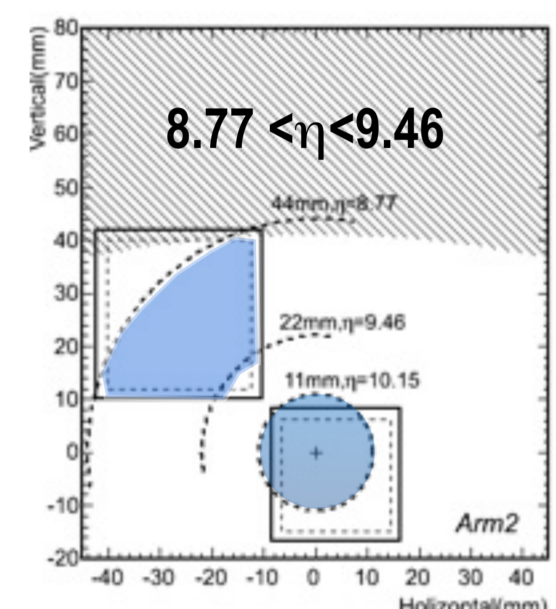
DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145



Arm 1



Arm 2



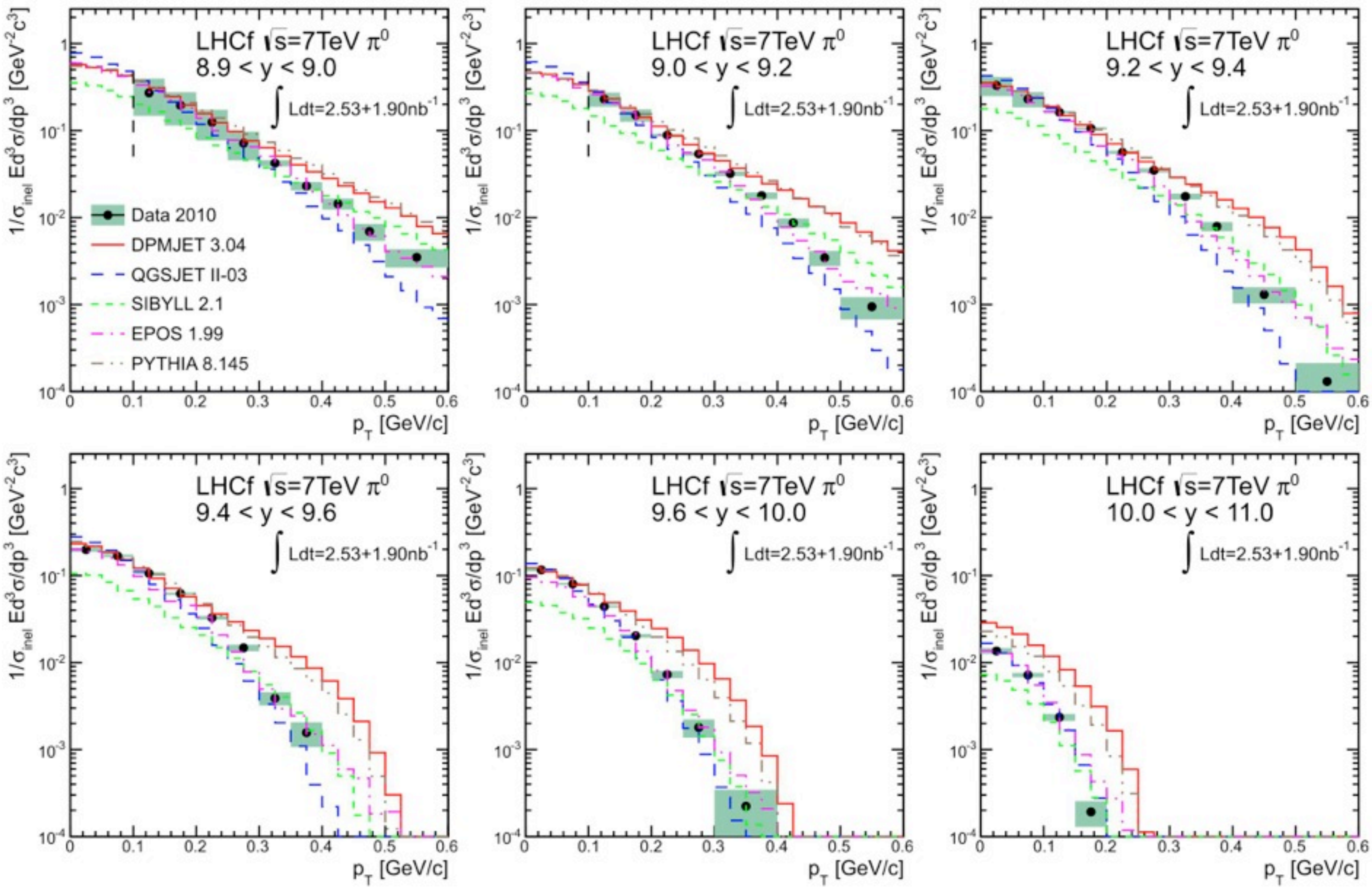
η>10.15

None of the models agrees well with data.

Data within the range of the model spread.

LHCf π^0 P_T spectra at 7 TeV

DPMJET 3.04 QGSJETII-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145



Challenge now:

Can the model builders tune their models
to capture all these differences ??

don't add just random free parameters
preserve the "predictive power"

Is an incremental change enough or
is a radically new approach needed?

much more detail: talk of T Pierog

Summary:

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)

This is a remarkable success ...

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This is a remarkable success ...

... yet, to analyse the composition at $>10^{18}$ eV (and other details)
better predictions (<10-15% precision) are needed.

The Future ...

- 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, TA ....
- modification of models
- progress in theory ?

The End