Hadronic Interactions

and

Astro-particle Physics

Paolo Lipari, INFN Roma “Sapienza”

“What's Next:
Sezione d'urto del neutrino”

Bologna 9th - 10th november 2015

Calculations of the neutrino cross sections:

$$\nu_\alpha + A \to \ldots$$

$$\overline{\nu}_\alpha + A \to \ldots$$

can be considered as an

“hadronic interaction problem”

because the Weak Interaction coupling of the neutrino to the fundamental quark fields can be considered as perfectly well known.

$$\nu_\ell + A \to \ell + \text{hadronic system}$$
$$\nu_\ell + A \to \nu_\ell + \text{hadronic system}$$

What is the physics we are studying ?

$E_\nu \sim 1\ \text{GeV}$ Nuclear Physics

$E_\nu \sim \text{few GeV}$ Resonance production

$E_\nu \sim 30\ \text{GeV}$ Parton structure ("Deep inelastic")

$E_\nu \sim 10^6\ \text{GeV}$ ... small x PDF's (saturation....)

$$\nu_\ell + A \to \ell + \text{hadronic system}$$

$$\nu_\ell + A \to \nu_\ell + \text{hadronic system}$$

What is the physics we are studying ?

$E_\nu \sim 1 \text{ GeV}$	Nuclear Physics	Crucial region for future oscillation studies
$E_\nu \sim \text{few GeV}$	Resonance production	
$E_\nu \sim 30 \text{ GeV}$	Parton structure ("Deep inelastic")	
$E_\nu \sim 10^6 \text{ GeV}$	... small x PDF's (saturation....)	

$$\nu_\ell + A \to \ell + \text{hadronic system}$$

$$\nu_\ell + A \to \nu_\ell + \text{hadronic system}$$

What is the physics we are studying ?

Develop a "deep" understanding in the entire energy range is very desirable.

$E_\nu \sim 1 \text{ GeV}$ — Nuclear Physics

$E_\nu \sim \text{few GeV}$ — Resonance production

$E_\nu \sim 30 \text{ GeV}$ — Parton structure ("Deep inelastic")

$E_\nu \sim 10^6 \text{ GeV}$ — ... small x PDF's (saturation....)

Questions:

[1.] Estimate the Systematic uncertainties
in our description of the neutrino cross section
in different energy ranges.

[2.] Impact of these theoretical uncertainties
for different topics of research
[Neutrino oscillations, Supernova physics .....]

[3.] Possibilities to construct experimental programs
to reduce these uncertainties with the direct
measurements of relevant properties.

Questions:

[1.] Estimate the Systematic uncertainties
in our description of the neutrino cross section
in different energy ranges.

[2.] Impact of these theoretical uncertainties
for different topics of research
[Neutrino oscillations, Supernova physics .....]

[3.] Possibilities to construct experimental programs
to reduce these uncertainties with the direct
measurements of relevant properties.

[0.] *Intrinsic scientific interest* of these
measurements for Particle Physics.

Uncertainties on the description of hadronic interactions are an important source of systematic error in several research topics in Astroparticle physics.

only some examples

[1.] Calculation of the **Atmospheric Neutrino fluxes**

- (*) for oscillation studies.
- (*) as a background for astrophysical neutrinos

[2.] Calculation of the **Production of secondary particles in interstellar space** (and other astrophysical environments) [positrons, antiprotons, photons] by cosmic rays

- (*) Indirect searches for Dark Matter
- (*) Cosmic Ray studies

[3.] **Modeling of Cosmic Ray showers**

$E = 10^{15} - 10^{20}$ eV for the interpretation of Extensive Air Shower observations.

[1.] Atmospheric Neutrinos

No-oscillation fluxes:

$$\phi^{[\circ]}_{\nu_j}(E,\Omega) = \phi_A(E_0) \otimes \left[\begin{array}{l} \text{Geomagnetic} \\ \text{effects} \end{array} \right] \otimes \sigma[A\, A_{\rm air} \to (\pi, K) \to \nu]$$

Fluxes modified by oscillations:

$$\phi^{[\rm osc]}_{\nu_j}(E,\Omega) = \phi^{[\circ]}_{\nu_k}(E,\Omega) \otimes P_{\nu_k \to \nu_j}\left[E, \cos\theta_{\rm zenith}; \quad \{\Delta m^2_{jk}, \theta_{jk}, \delta\}\right]$$

Observables :

$$\left[\begin{array}{c} \text{Atmospheric } \nu \\ \text{observables} \end{array} \right] = \phi^{[\rm osc]}_{\nu_j}(E,\Omega) \otimes \sigma[\nu_j + A \to \ldots]$$

$$\begin{bmatrix} \text{Atmospheric } \nu \\ \text{observables} \end{bmatrix} = \phi_A(E_0) \; \otimes$$

$$\otimes \; \sigma[A\, A_{\rm air} \to (\pi, K) \to \nu] \; \otimes \; \sigma[\nu_j + A \to \ldots]$$

$$\otimes \; P_{\nu_k \to \nu_j} \left[E, \cos\theta_{\rm zenith}; \quad \{\Delta m^2_{jk}, \theta_{jk}, \delta\}\right]$$

$$\begin{bmatrix} \text{Atmospheric } \nu \\ \text{observables} \end{bmatrix} \Longleftrightarrow \text{sign}\left[\Delta m^2_{13}\right]$$

Need *"sufficient control"*
over all elements in the chain [Cross sections!]

Note:

In some sense the situation is similar
for an “ordinary accelerator neutrino beam”

(*) Accelerator beam [perfectly known]

(*) Target region for secondary production

(*) Neutrino interactions in the detector

Note:

In some sense the situation is similar
for an “ordinary accelerator neutrino beam”

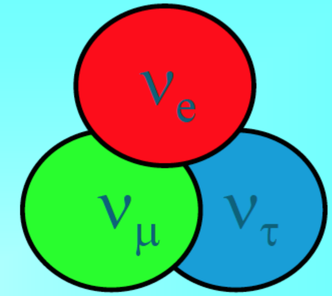
(*) Accelerator beam [perfectly known]

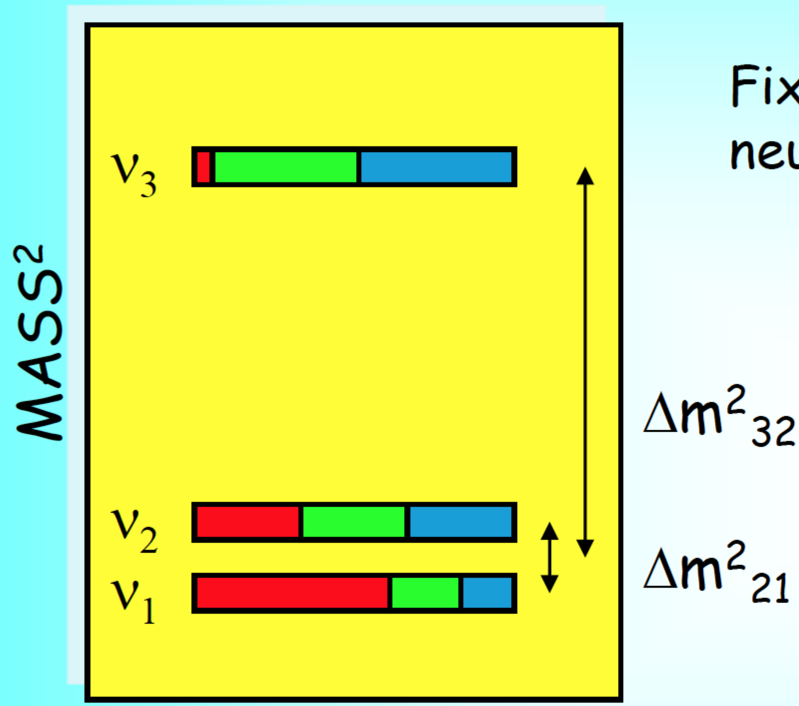
(*) Target region for secondary production

(*) Neutrino interactions in the detector

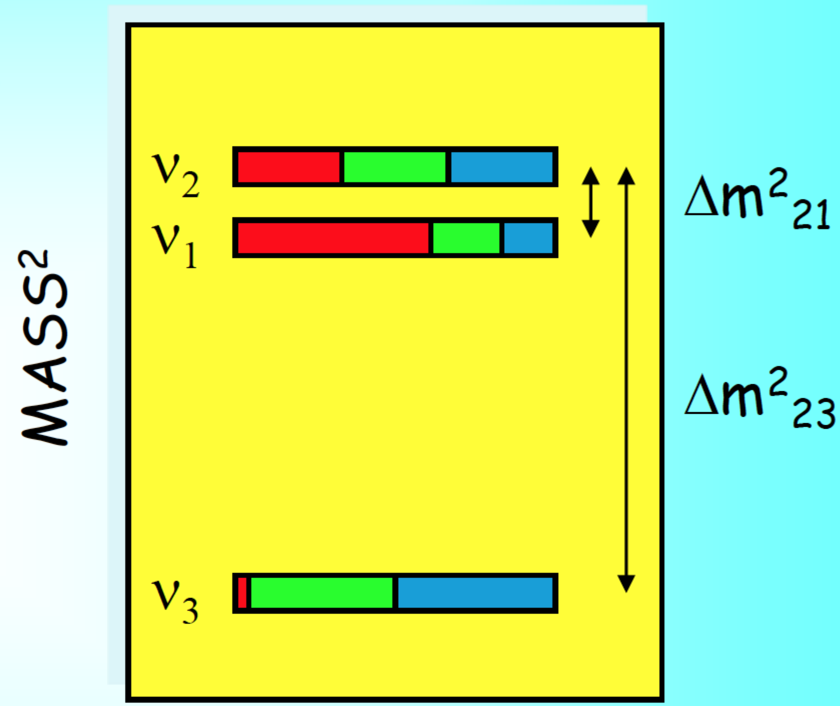
….. yes, yes I know there is the near detector
[but for atmospheric neutrinos there are muons
and “symmetries” (up/down nue/numu)
that can constrain the problem.]

Neutrino mass ordering





Fixed by solar neutrinos



Normal mass hierarchy

$\Sigma m > m_h$

$|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$

Inverted mass hierarchy

$\Sigma m > 2\, m_h$

$|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

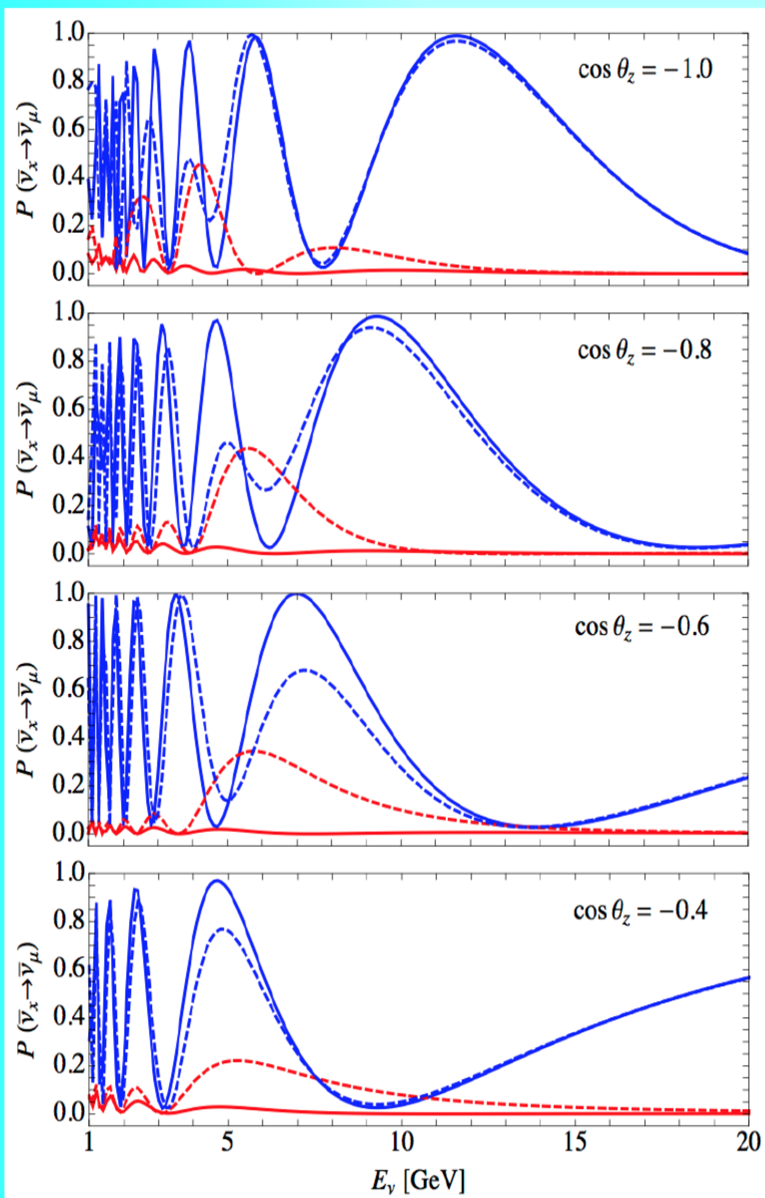
$|\Delta m^2_{ij}|$ ⇔ $D_{ij} = 4|U_{ei}|^2|U_{ej}|^2$

mass splittings — oscillation depth

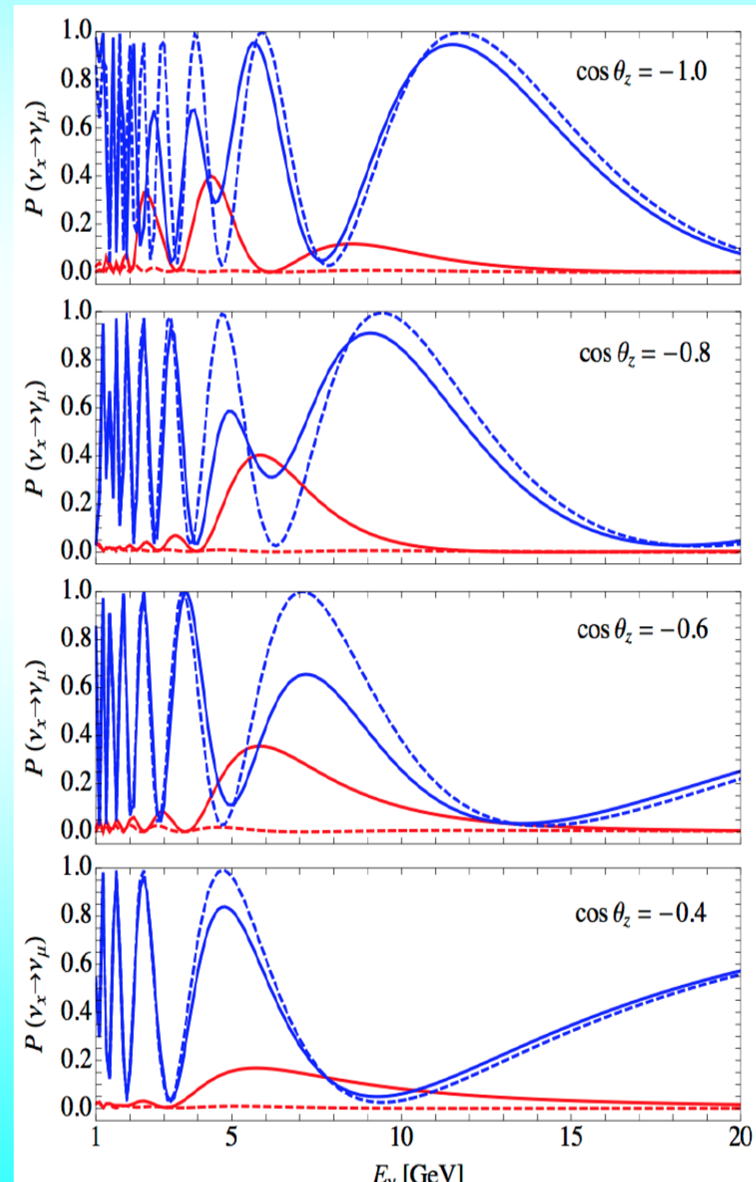
from A.

Probabilities

neutrinos



antineutrinos



NH - solid
IH - dashed
x = μ - blue
x = e - red

from A. Smirnov

Method

Measurement of E - θ distributions of different type of events.
Compare events for the normal and inverted orderings

"tracks"

$\nu_\mu + N \rightarrow \mu + h$

$\nu_\tau + N \rightarrow \tau + h$

$\rightarrow \mu + \nu + \nu$

muon track

+ cascade

Measurements

$E_\mu \quad \theta_\mu \quad E_h$ — inelasticity

$E_\nu = E_\mu + E_h$

$E_h \quad E_\mu \quad \theta_\mu \rightarrow \theta_\nu$ — reconstruction

"cascades"

$\nu_e + N \rightarrow e + h$

$\nu_\alpha + N \rightarrow \nu_\alpha + h$

$\nu_\tau + N \rightarrow \tau + h$

$\rightarrow h + \nu$

$\rightarrow e + \nu + \nu$

cascades

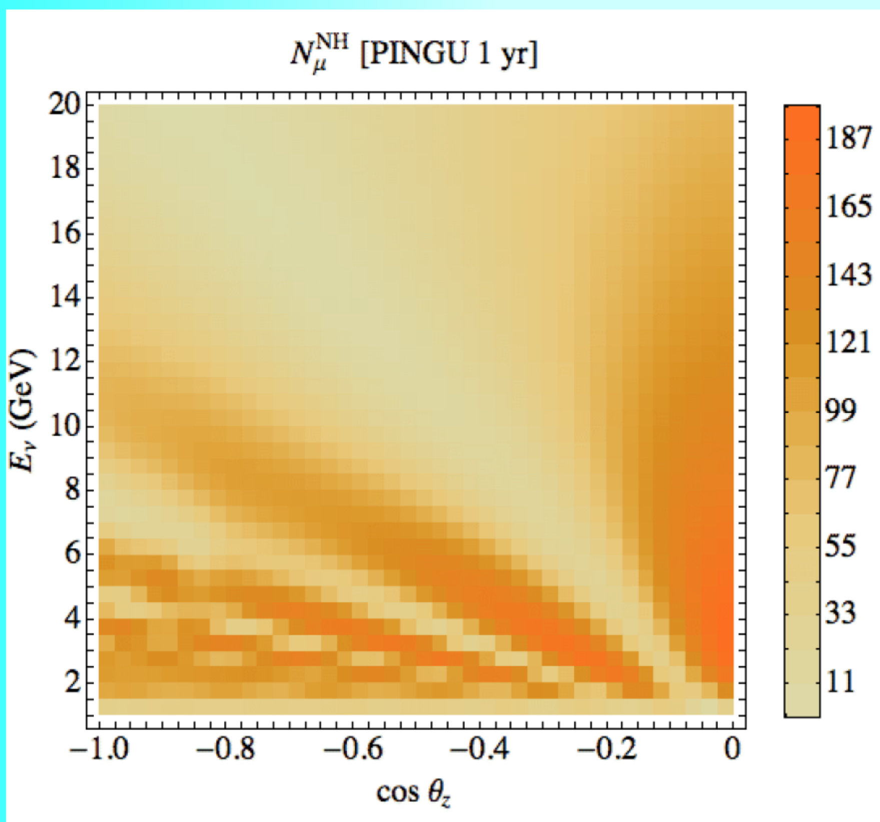
$E_\nu \quad \theta_\nu$ — reconstruction

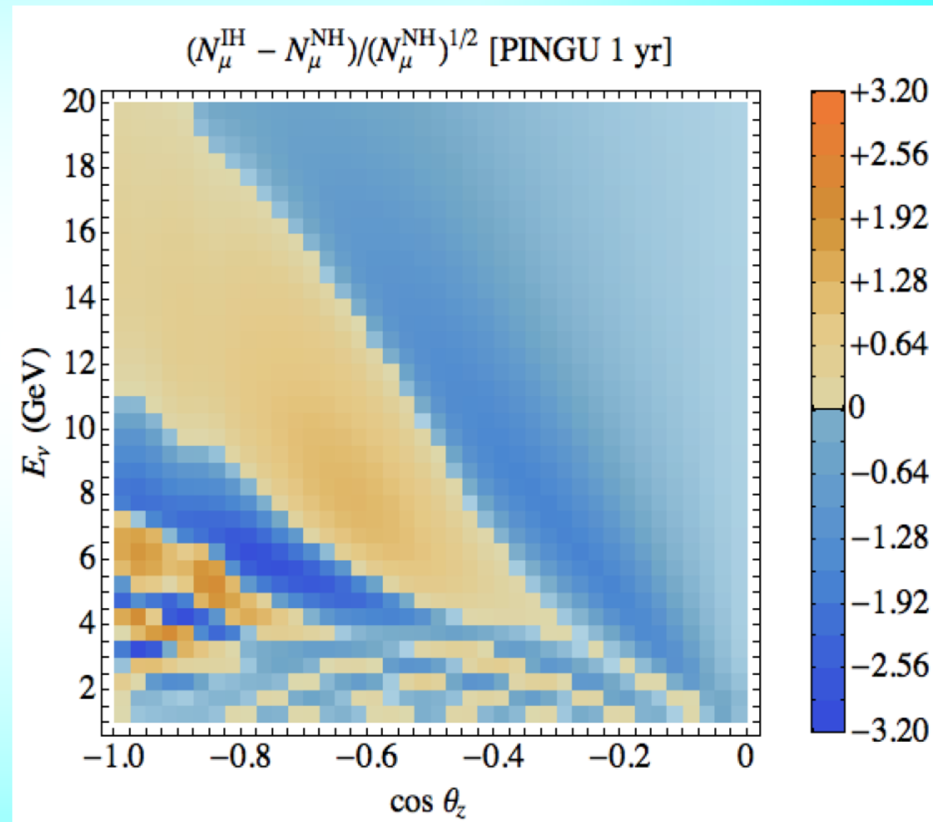
from A. Smirnov

Track events

~ 10^5 events/year

``Distinguishability"





Estimator of sensitivity
S – asymmetry
|S| - significance

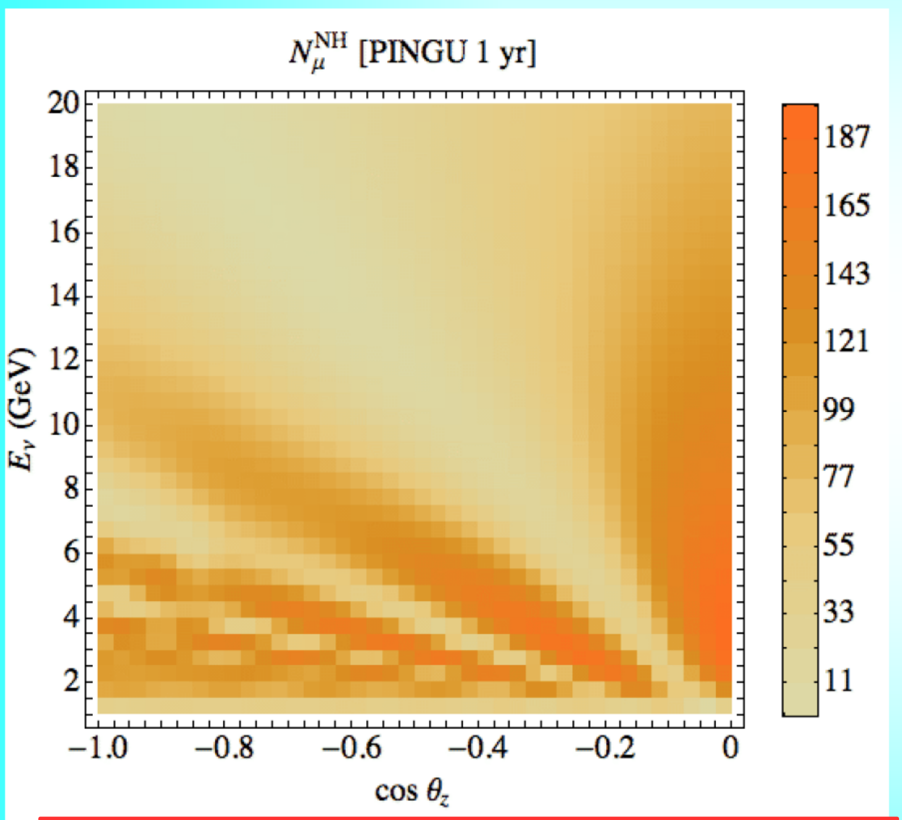
from A. Smirnov

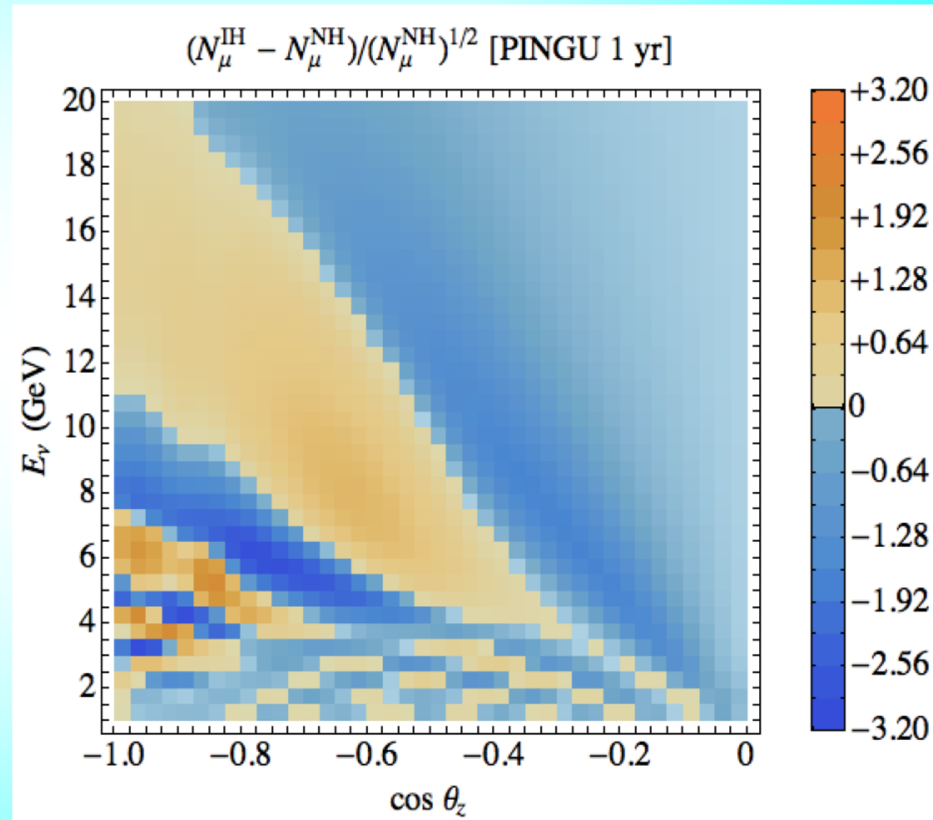
Track

~ 10^5 events

Note:

Plots in “true” Neutrino Energy and Direction
(No smearing for reconstruction).





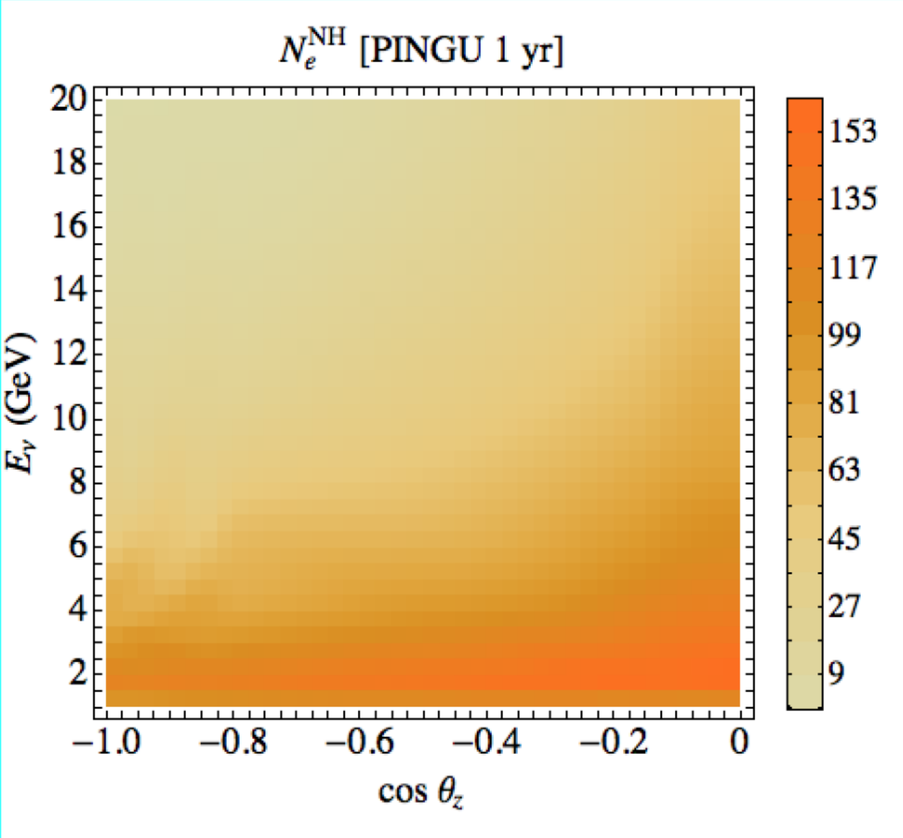
Note energy range:

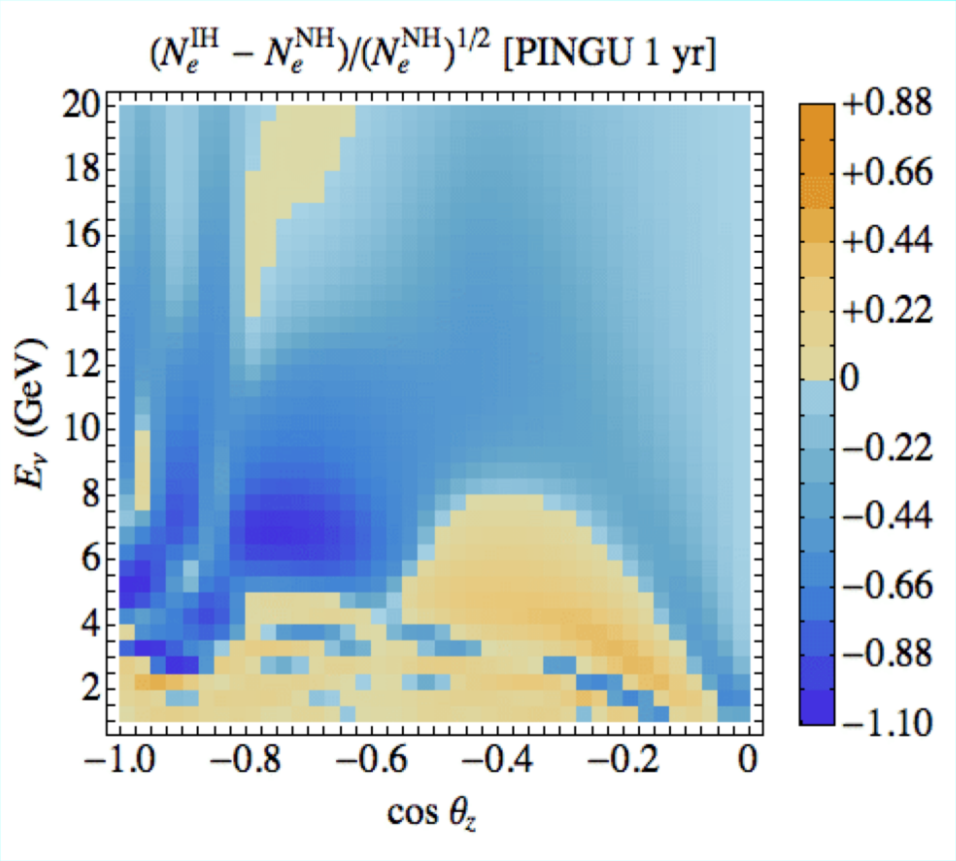
$$E_\nu \sim \text{few GeV}$$

Estimator of sensitivity
S – asymmetry
|S| - significance

Cascade events

``Distinguishability"





Statistical significance

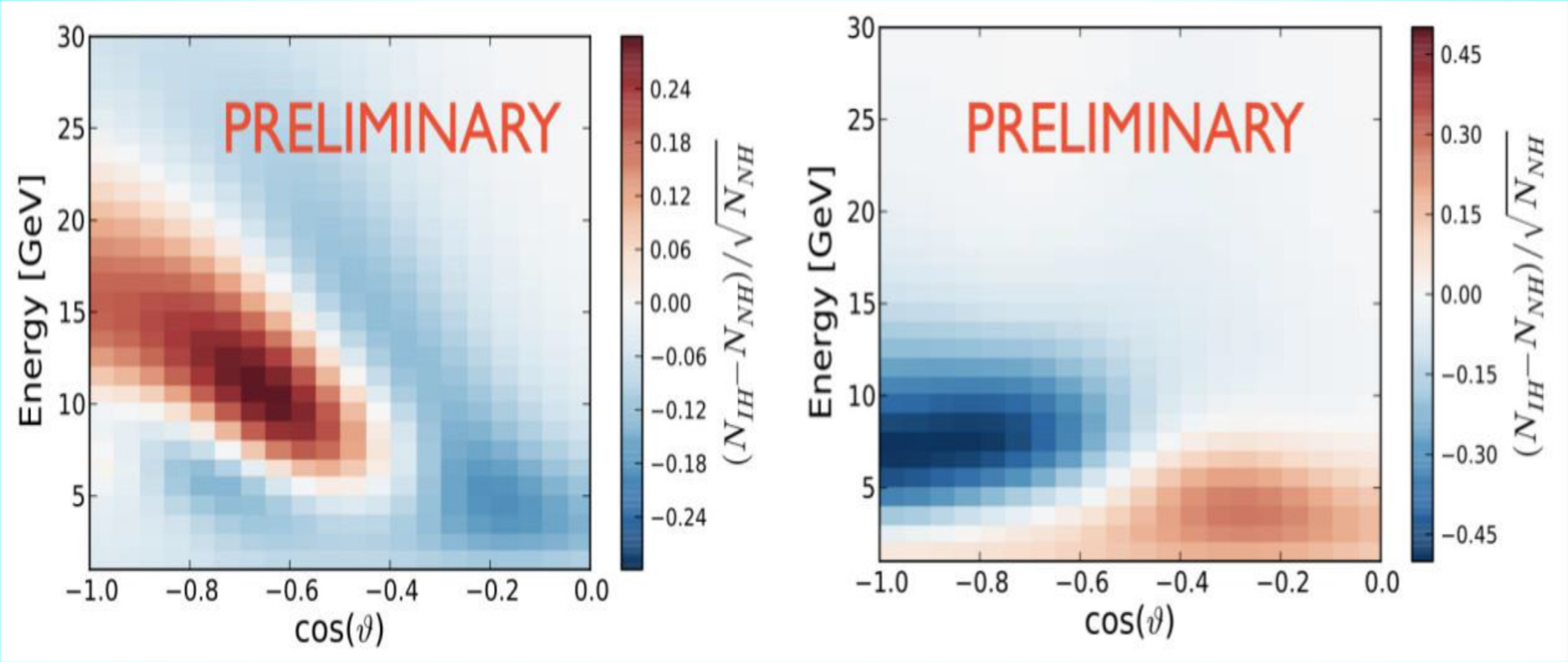
from A. Smirnov

Smeared

Over energy and an
resolution functions

Note:

Plots in "true" Neutrino Energy and Direction
(No smearing for reconstruction).



tracks

cascades

distinguishability

from A. Smirnov

Measuring CP-phase

Global fit

T2K + NOvA + reactors

J-PARC- SK

750 kw upgrade

at 2- 3 σ

$3\pi/2$ from 0

Dedicated experiments

J-PARC- HK

DUNE LBNF

ESS

Europeanspalation source Lund

~ 5 - 7 σ

result in 2030 - 2035

~ 2 bln US$

Long term and expensive commitment

Alternative?

All possible alternatives must be explored and scenarios of developments in the next 20 years should be considered

from A. Smirnov

Measuring CP-phase

Global fit

T2K + NOvA + reactors

J-PARC- SK

750 kw upgrade

at 2- 3 σ

3π/2 from 0

Dedicated experiments

J-PARC- HK

DUNE LBNF

ESS

Europeanspalation source Lund

~ 5 - 7 σ

result in 2030 - 2035

~ 2 bln US$

Long term and expensive commitment

Potential of atmospheric Neutrinos for the study of the Dirac phase : delta

Alternative?

All possible alternatives must be explored and scenarios of developments in the next 20 years should be considered

from A. Smirnov

What role (if any) the uncertainties in:

(a) the Neutrino-nucleus cross sections
(b) the calculation of the [no oscillation] atmospheric neutrino flux

play in a program of determination of the neutrino mass hierarchy [and for a more difficult and more ambitious attack to the problem of the CP violation phase] ?

What role (if any) the uncertainties in:

(a) the Neutrino-nucleus cross sections
(b) the calculation of the [no oscillation] atmospheric neutrino flux

play in a program of determination of the neutrino mass hierarchy [and for a more difficult and more ambitious attack to the problem of the CP violation phase] ?

[In my personal opinion] these questions are important, but (to my knowledge) they have not been addressed with the required critical attention, and deserve further studies.

What role (if any) the uncertainties in:

(a) the Neutrino-nucleus cross sections
(b) the calculation of the [no oscillation] atmospheric neutrino flux

play in a program of determination of the neutrino mass hierarchy [and for a more difficult and more ambitious attack to the problem of the CP violation phase] ?

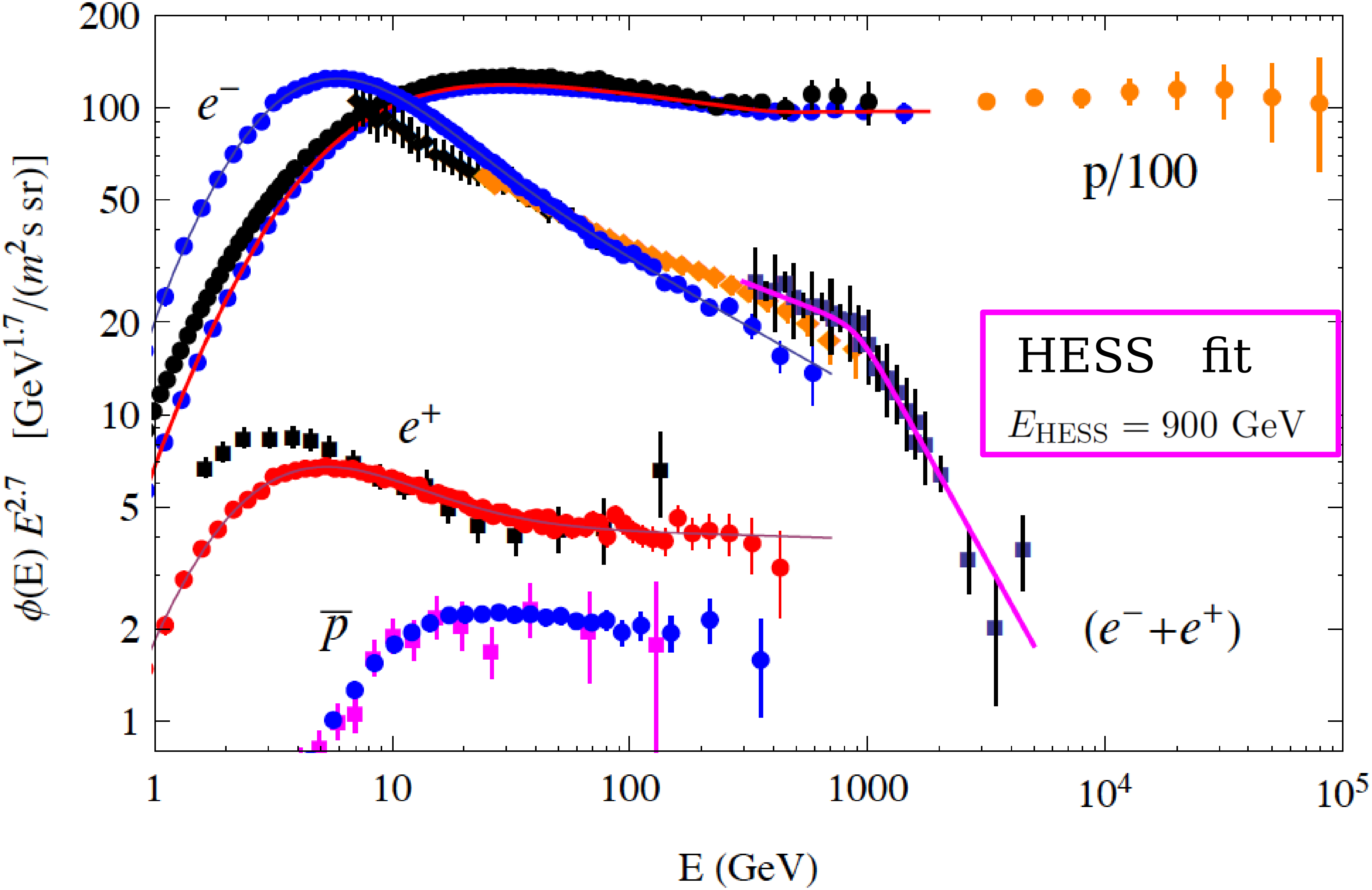
[In my personal opinion] these questions are important, but (to my knowledge) they have not been addressed with the required critical attention, and deserve further studies.

BUT: If it is desired it is possible to plan studies to reduce the existing systematic uncertainties that are (qualitatively) of order 10%

[2.] Production of secondaries by Cosmic Rays in interstellar space

AMS-02 data

PAMELA, CREAM, FERMI, HESS



“Standard mechanism”
(the only one “certainly known to exist”
and not negligibly small)

for the production of positrons and anti-protons
in cosmic rays.

Interactions of primary cosmic ray particles

in interstellar space $\langle n_{\rm ism} \rangle \approx 1~{\rm cm}^{-3}$

(or perhaps inside the astrophysical accelerators).

The existing populations of relativistic particles
are determined by an “injection rate”, and by
the properties of the Milky Way magnetic field that
“quasi-confines” charged particles in the Galaxy.

Calculation of the *injection spectra* of secondary particles in the Milky Way

$$n_A(E) \simeq \frac{4\pi}{\beta c} \, \phi_A(E)$$

$$q_j(E, \vec{x}, t) = n_{\rm target}(\vec{x}) \sum_{\rm A} \int_E^\infty dE_0 \, n_{\rm A}(E_0, \vec{x}, t) \, \beta \, c \sum_{{\rm A}_t} f_{{\rm A}_t} \, \sigma_{{\rm AA}_t}(E_0) \, \frac{dN(E, E_0)}{dE} \bigg|_{{\rm AA}_t \to j}$$

Dominant source of positrons:

$$\pi^+ \to \mu^+ + \nu_\mu \to [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu$$

Additional sources [kaon decay]

$$K^+ \to e^+ + \nu_e + \pi^\circ$$

$$K^+ \to \mu^+ + \nu_\mu \to [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu$$

$$K^+ \to \mu^+ + \nu_\mu + \pi^\circ \to [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu + \pi^\circ$$

$$K^+ \to \pi^+ + \pi^\circ \to \nu_\mu \to e^+$$

$$K^+ \to \pi^+ + \pi^\circ + \pi^\circ \to e^+ + \ldots$$

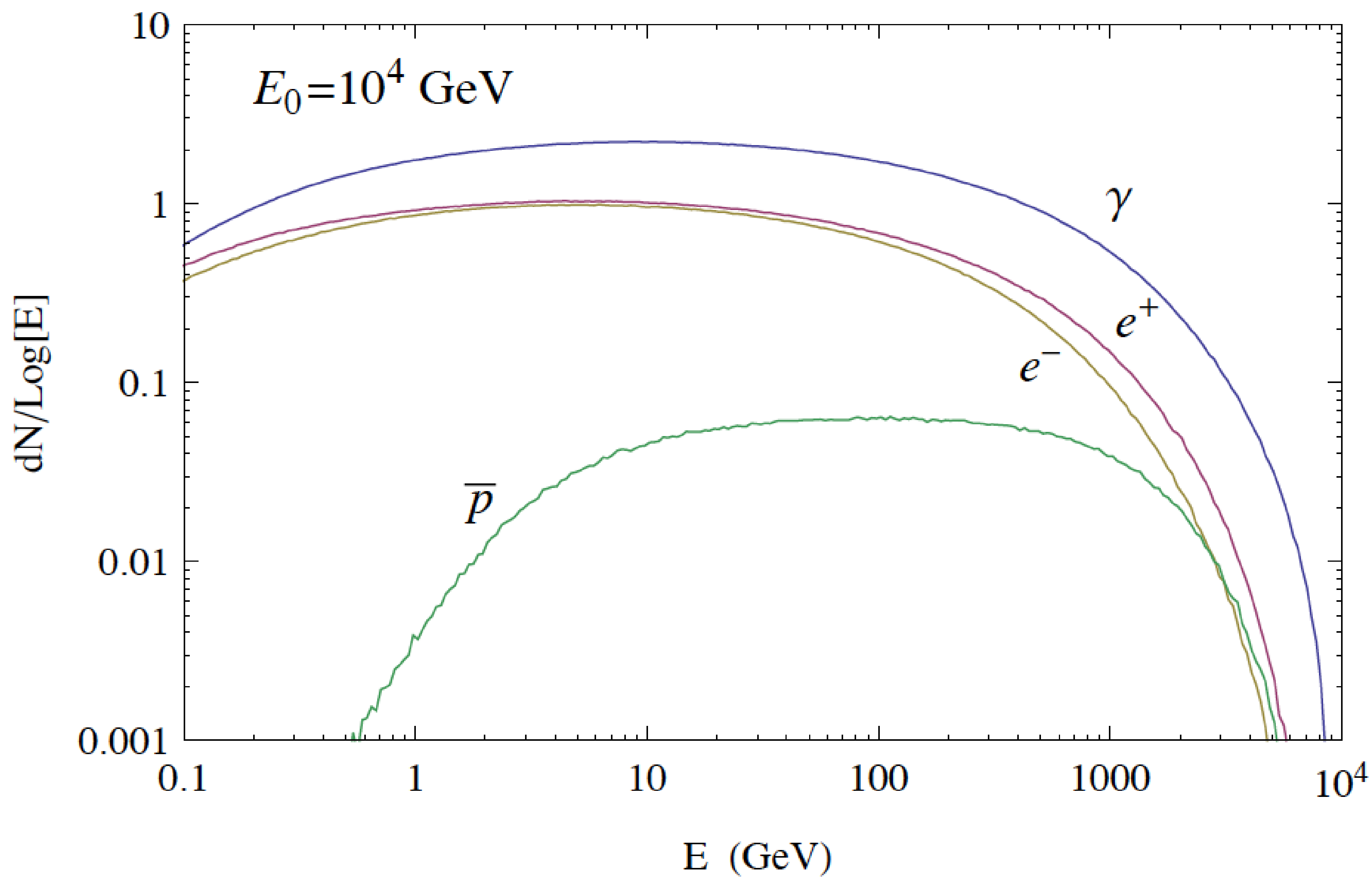
$$K^+ \to \pi^+ + \pi^+ + \pi^- \to e^+ + \ldots$$

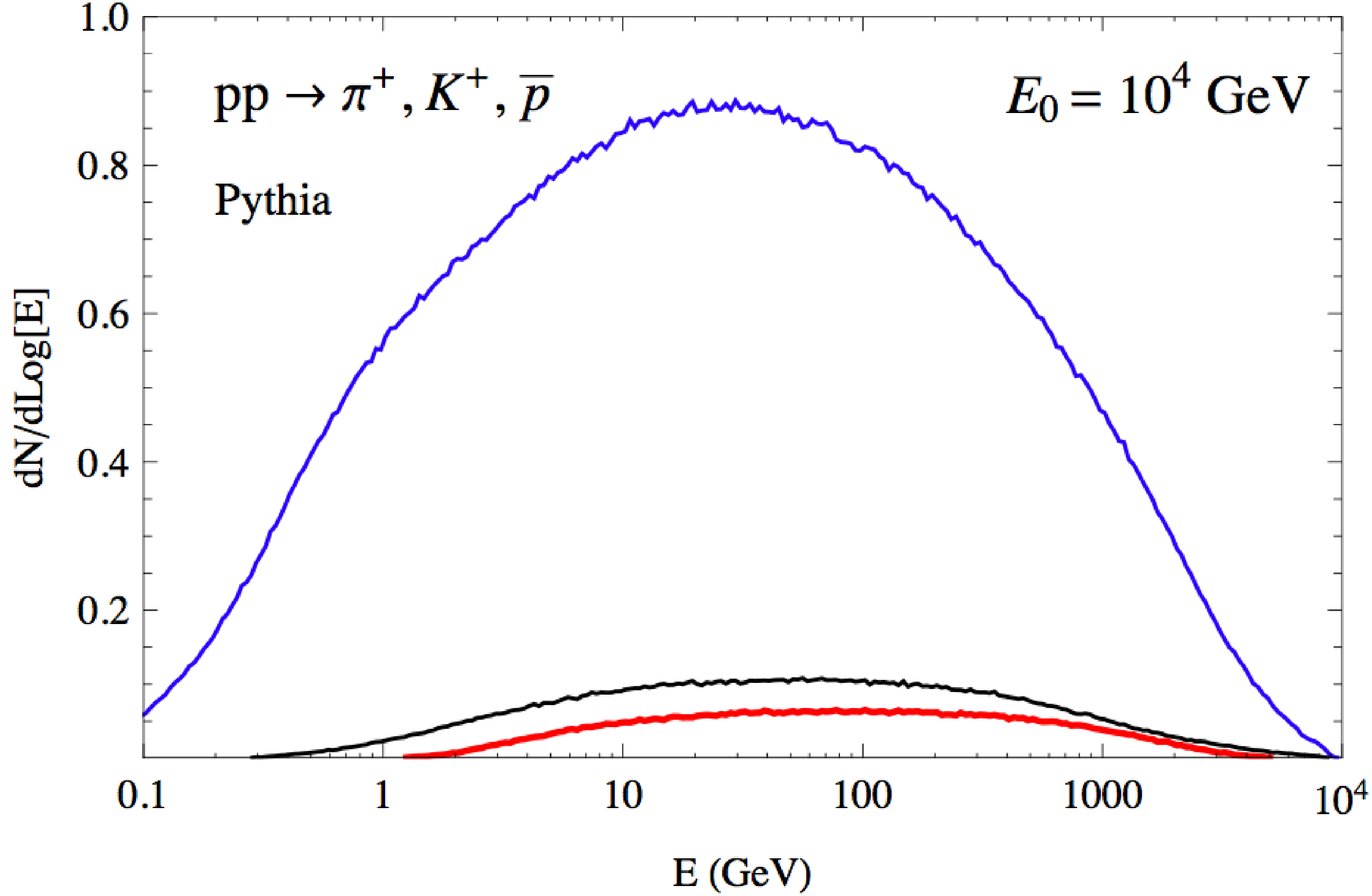
$$K_L \to \pi^- + e^+ + \nu_e$$

$$K_L \to \pi^- + \mu^+ + \nu_\mu \to \pi^- + [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu$$

$$K_L \to \pi^+ + \pi^\circ + \pi^\circ \to e^+ + \ldots$$

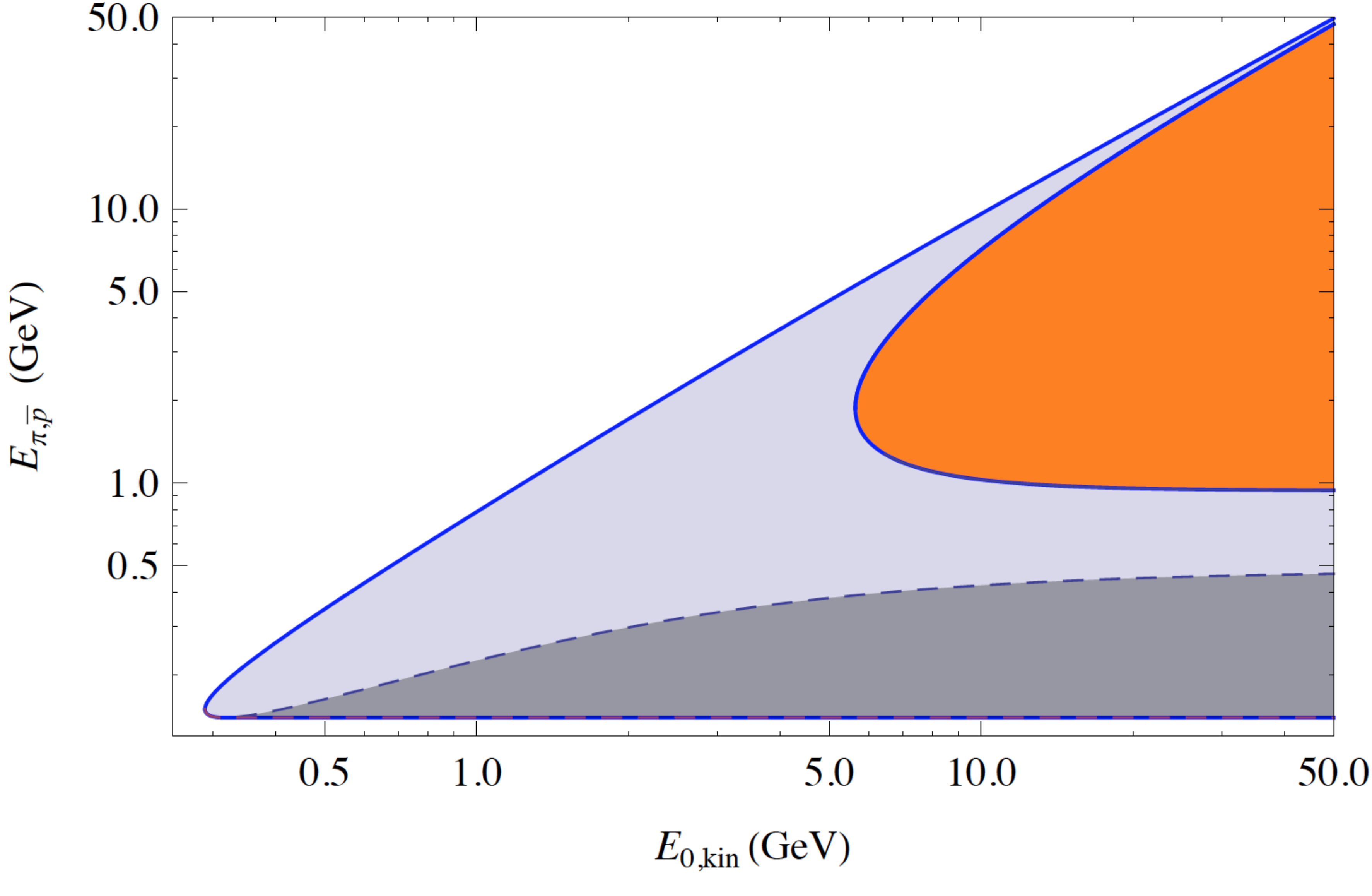
Production of different particles



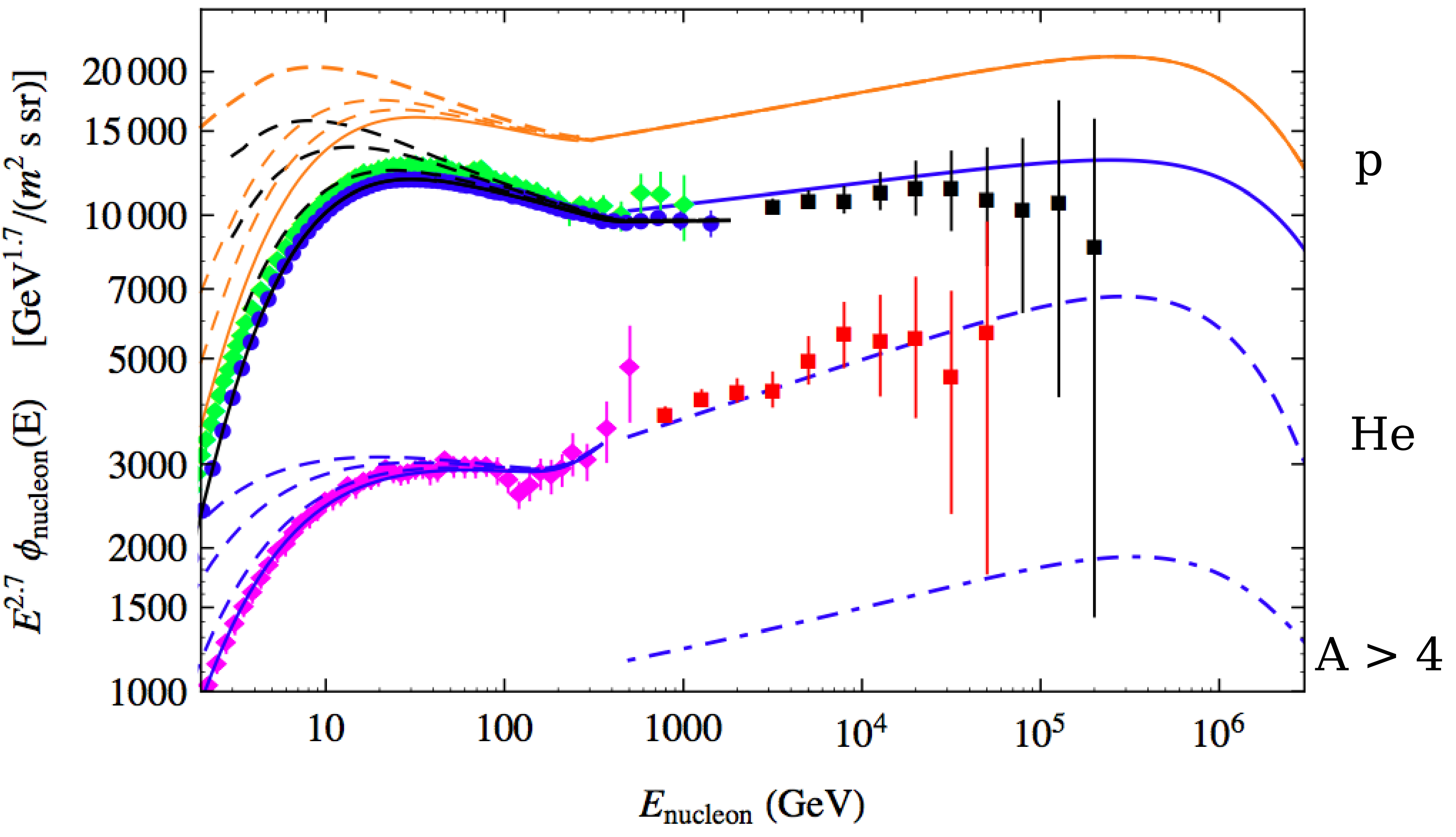


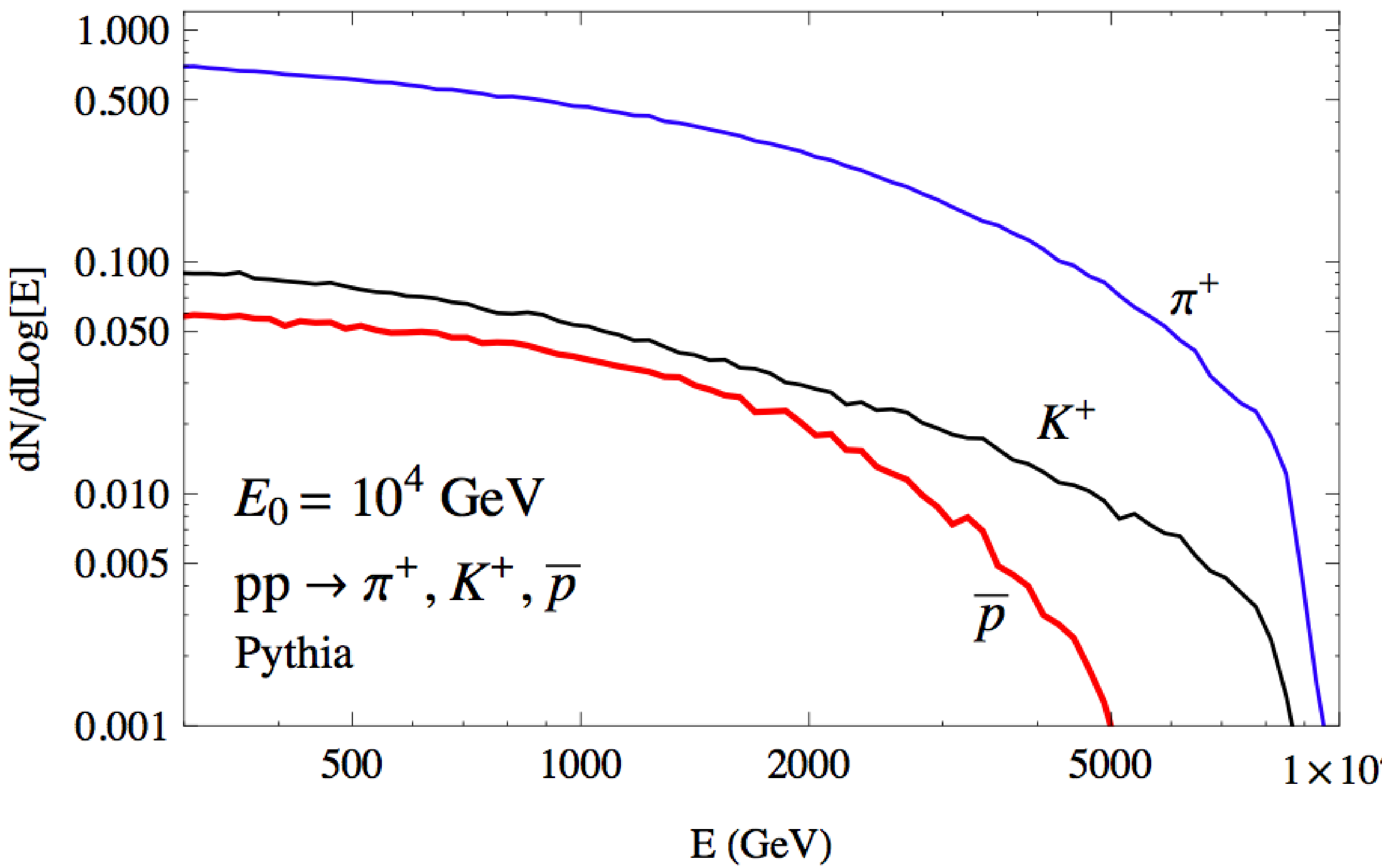
$pp \to \pi^+, K^+, \overline{p}$
$E_0 = 10^4$ GeV
Pythia
dN/dLog[E]
1.0
0.8
0.6
0.4
0.2
0.1
1
10
100
1000
10^4
E (GeV)

Kinematics of production for pions and anti-protons

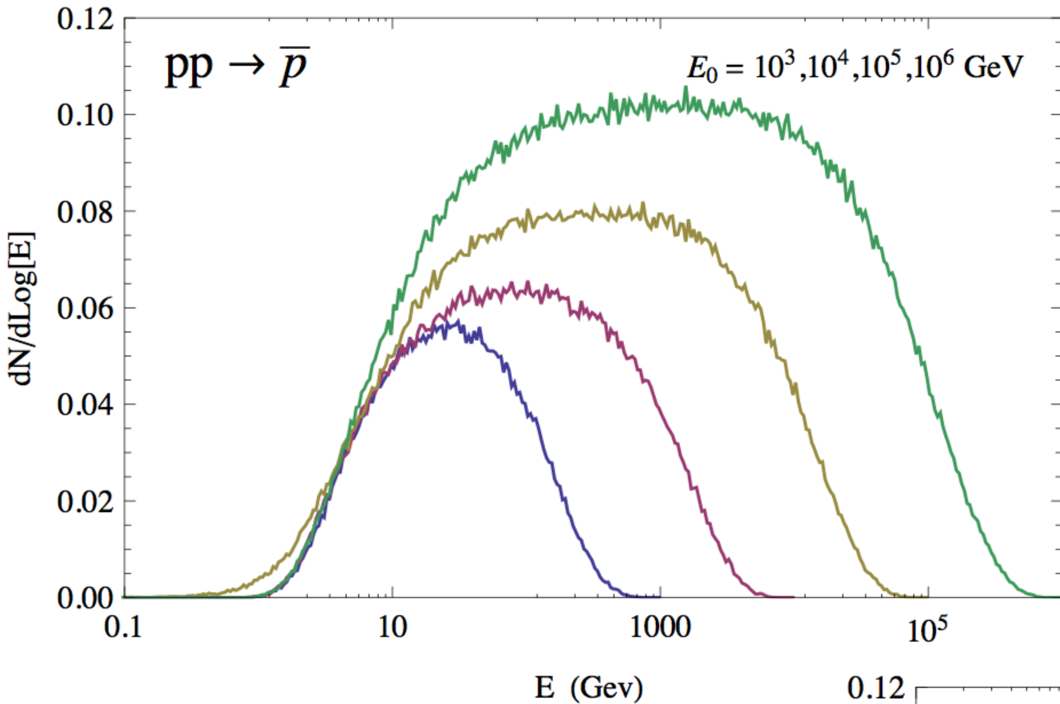


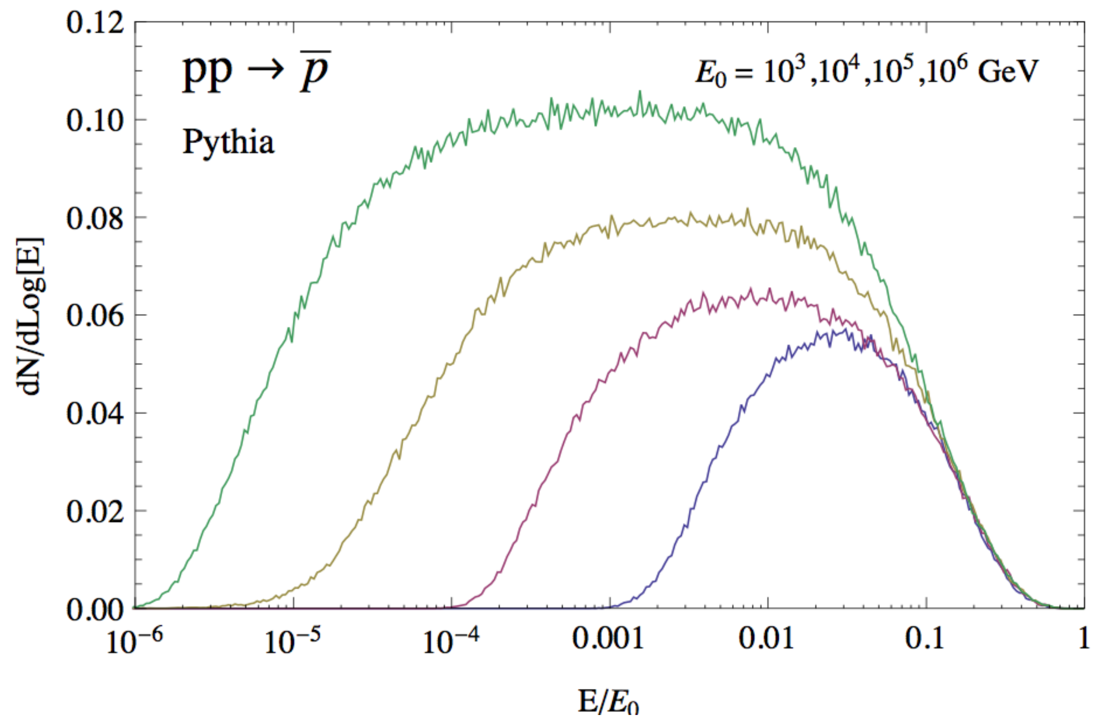
Nucleon Fluxes

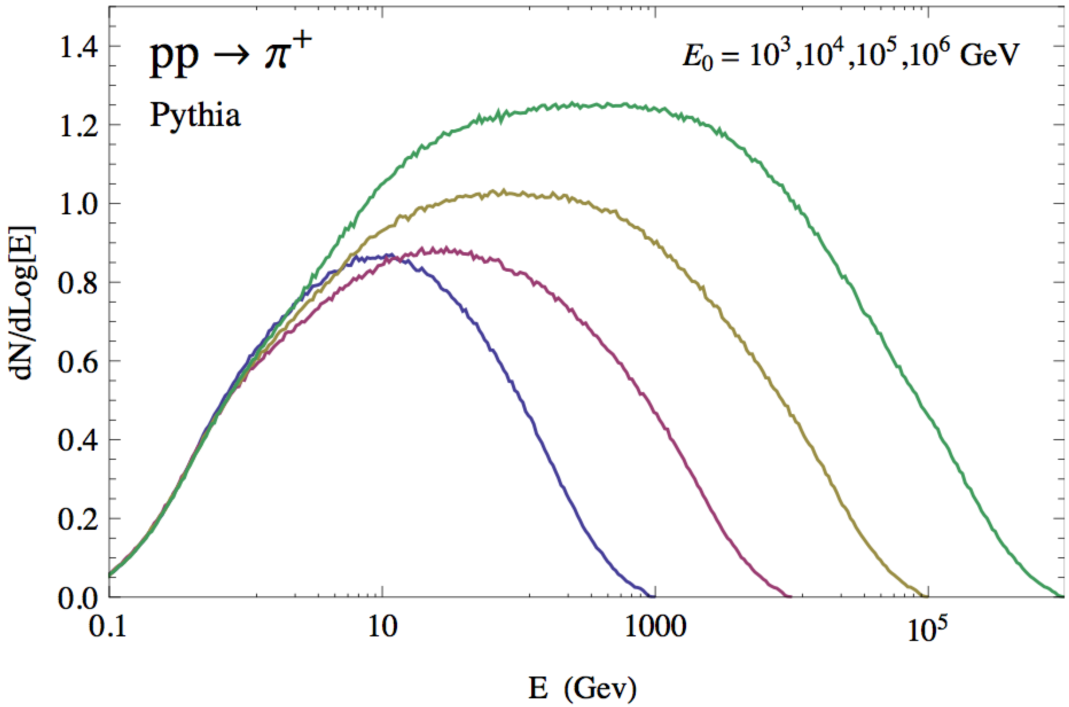


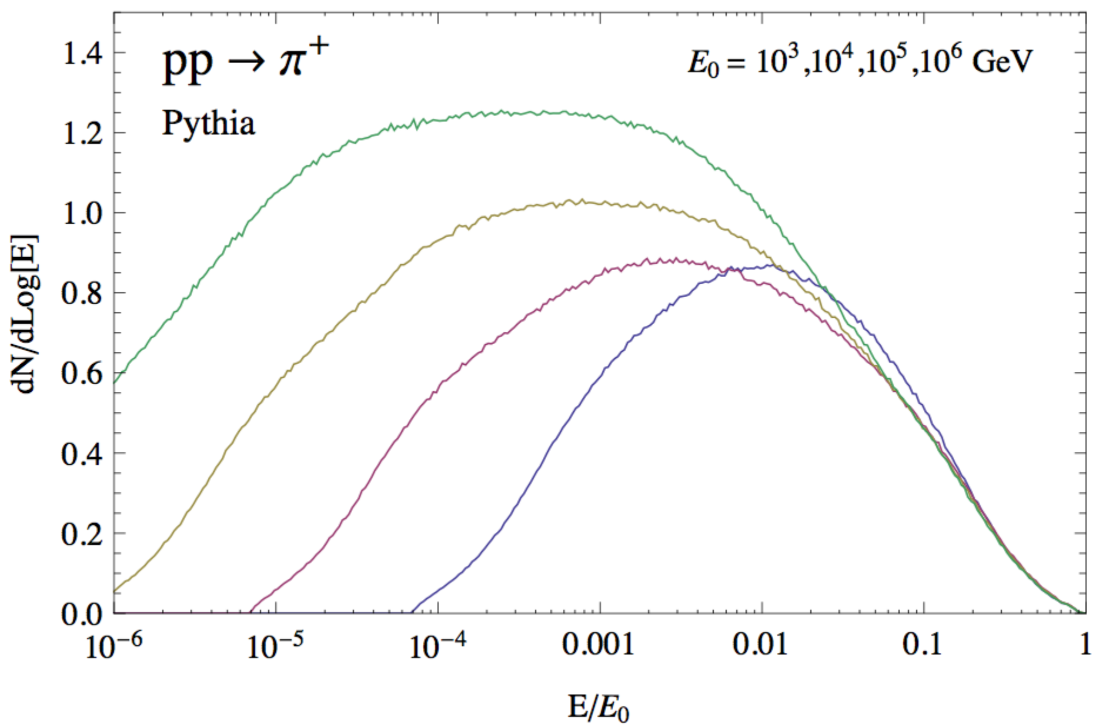


1.000
0.500
0.100
0.050
0.010
0.005
0.001
dN/dLog[E]
500
1000
2000
5000
1×10^4
E (GeV)
π^+
K^+
$\overline{p}$
$E_0 = 10^4$ GeV
pp $\rightarrow \pi^+, K^+, \overline{p}$
Pythia


pp → $\overline{p}$
$E_0 = 10^3, 10^4, 10^5, 10^6$ GeV
dN/dLog[E]
E (Gev)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.1
10
1000
10^5

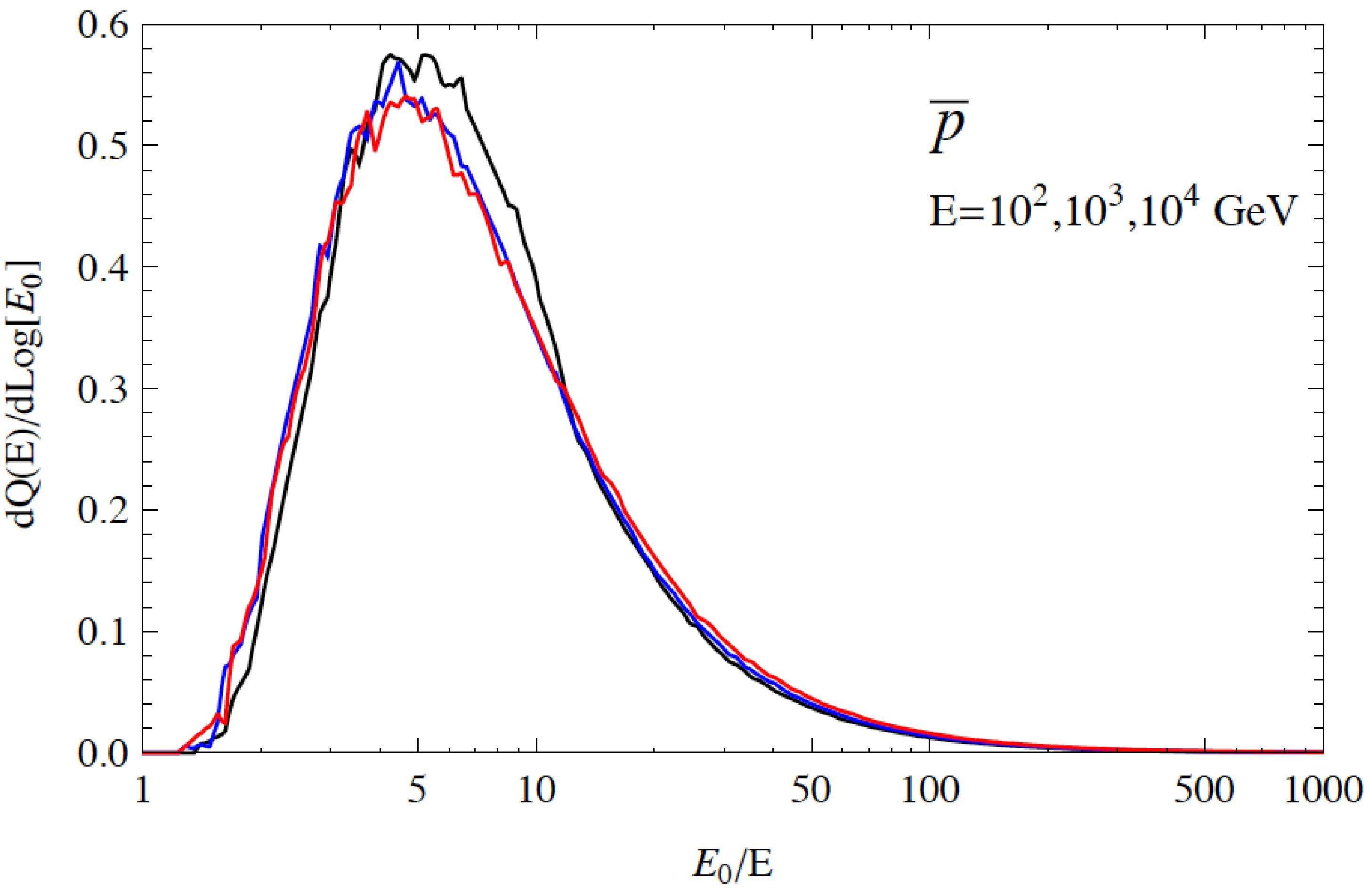

pp → $\overline{p}$
$E_0 = 10^3, 10^4, 10^5, 10^6$ GeV
Pythia
dN/dLog[E]
E/E_0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
10^{-6}
10^{-5}
10^{-4}
0.001
0.01
0.1
1

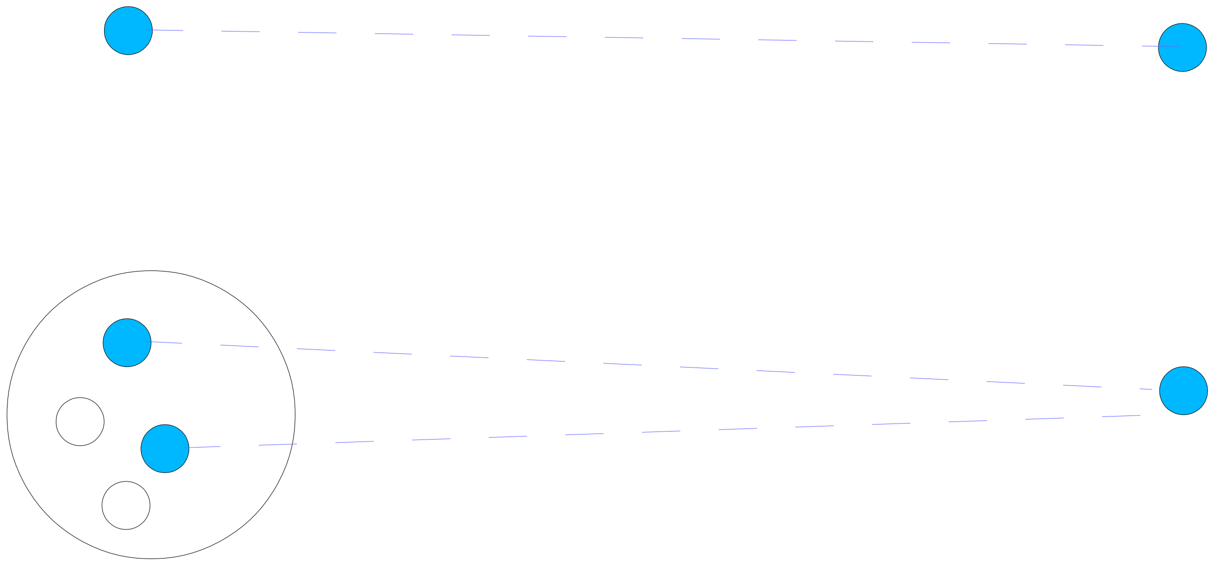

pp → π^+
Pythia
$E_0 = 10^3, 10^4, 10^5, 10^6$ GeV
dN/dLog[E]
E (Gev)


pp → π^+
Pythia
$E_0 = 10^3, 10^4, 10^5, 10^6$ GeV
dN/dLog[E]
E/E_0

Response function for anti-proton production.
[Primary particle energy that contributes
to the flux at energy E]

$$q_j^{(\mathrm{ism})}(E,\vec{x},t) = \sum_A \int dE_0 \; n_A(E_0,\vec{x},t)\; n_{\mathrm{ism}}(\vec{x})\,\beta c\,\frac{d\sigma_{A\to j}}{dE}(E,E_0)$$





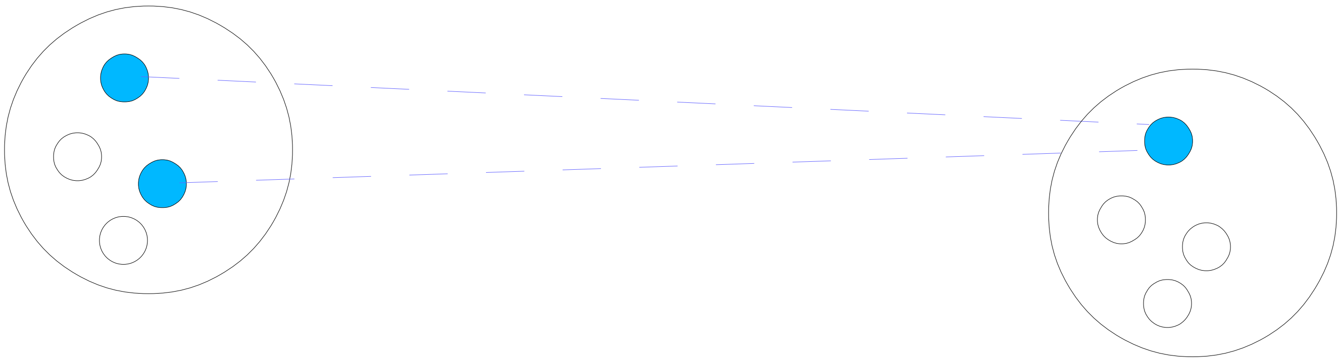
Laboratory frame:

$$\left[\frac{dN}{dE}\right]_{pp}$$

$$\left[\frac{dN}{dE}\right]_{\mathrm{A}p}$$

Spectra moderately softer
in projectile hemisphere

$$\mathrm{A}_1 \ \mathrm{A}_2$$



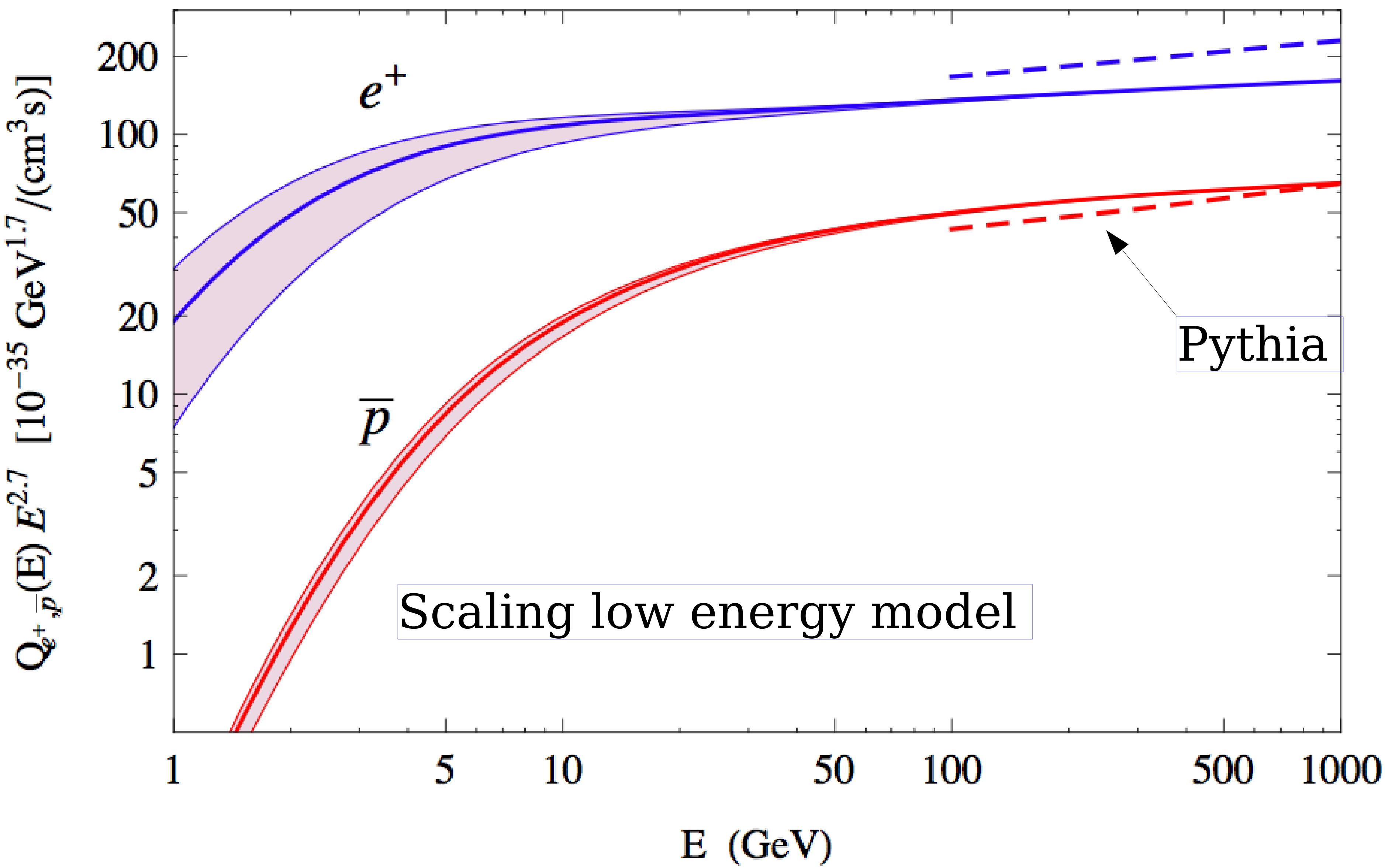
Decomposition of the cross section into partial cross sections

$$1 \leq N_{\mathrm{projectile}} \leq \mathrm{A}_1$$

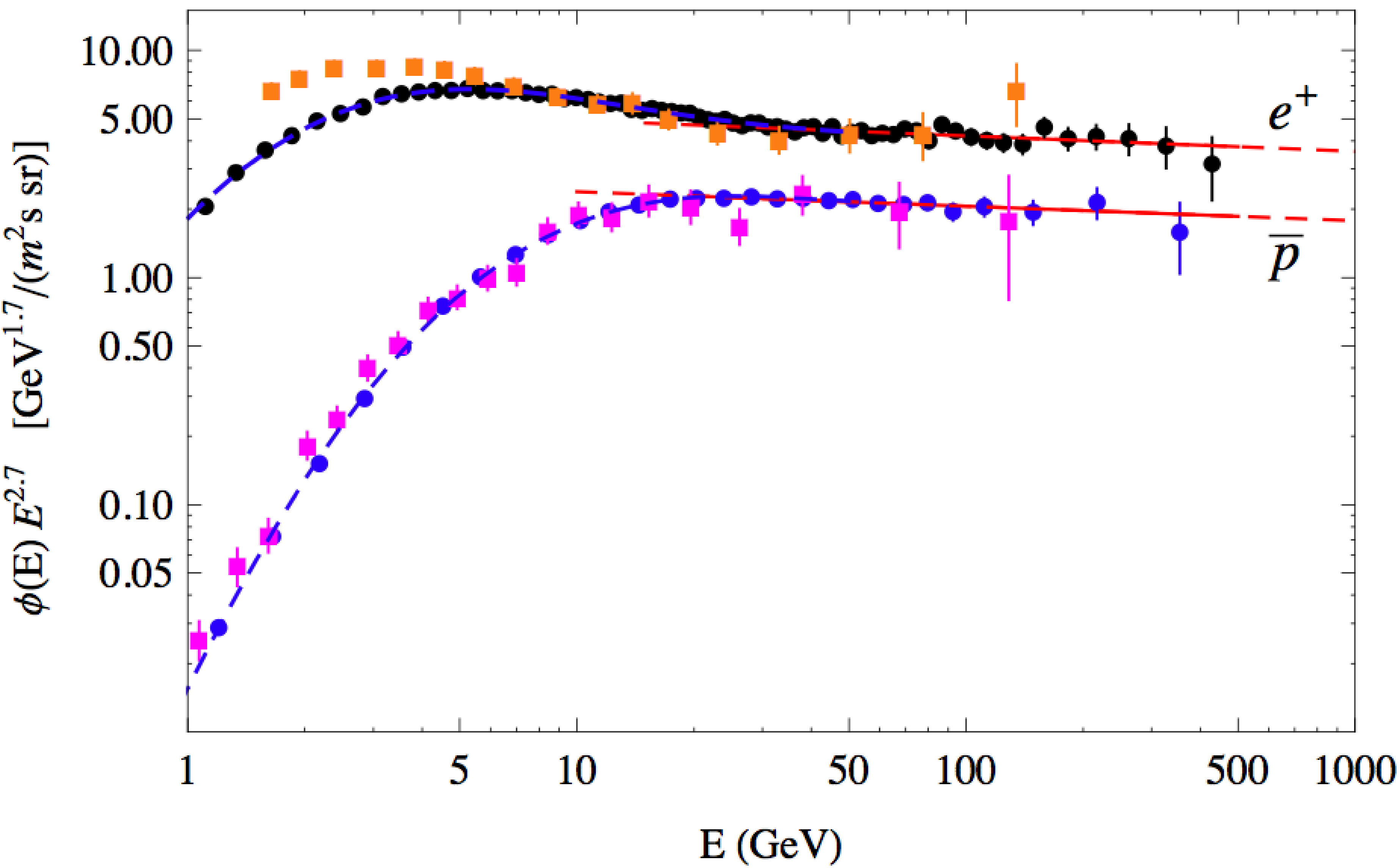
$$1 \leq N_{\mathrm{target}} \leq \mathrm{A}_2$$

$$\left[\frac{dN}{dE}\right]_{\mathrm{A}_1 \ \mathrm{A}_2} \simeq \langle N_{\mathrm{A}_1} \rangle \left[\frac{dN}{dE}\right]_{p\mathrm{A}_2}$$

Injection Spectra of positrons and anti-protons



Anti-proton and Positron Cosmic Ray Fluxes



Very desirable to measure
in a *broad energy range*
and *more precisely*
the inclusive cross sections for the production
different particles in the final state

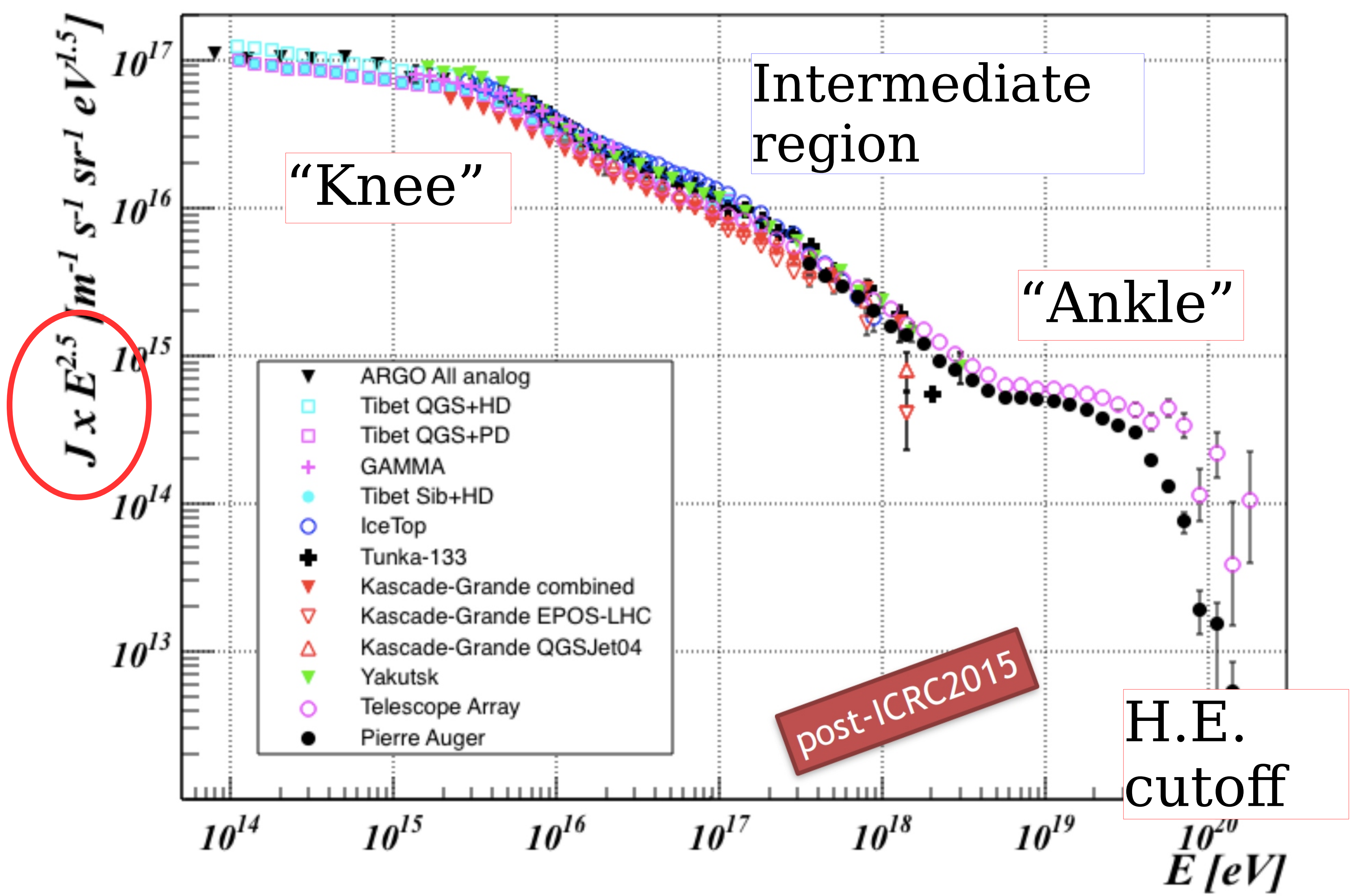
Pions, kaons, anti-nucleons.

7 TeV of laboratory energy [LHC extracted beam]
is of great value to study the production]
of particles around 1 TeV of observed energy

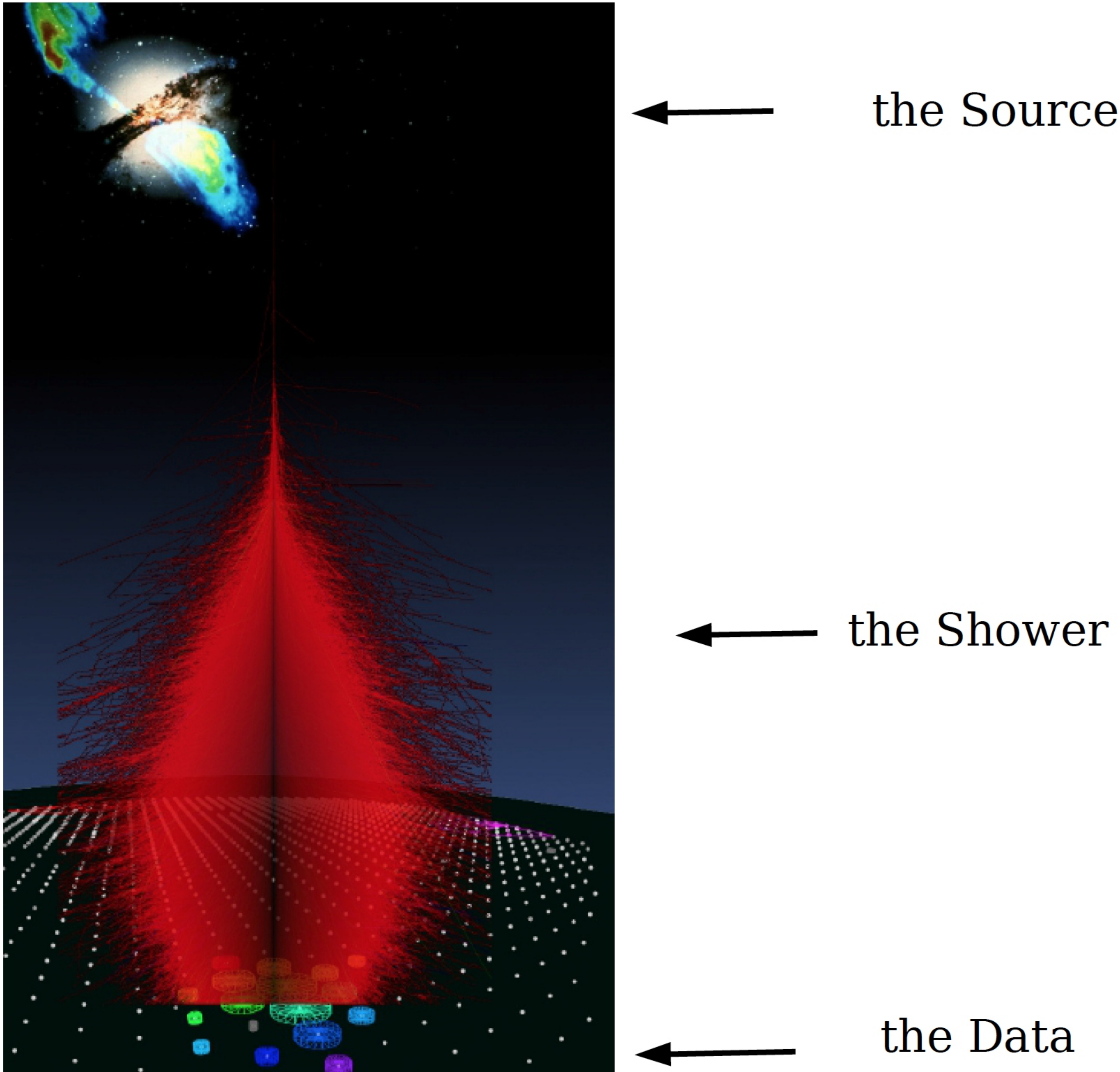
[3.] High Energy Cosmic Ray Interactions

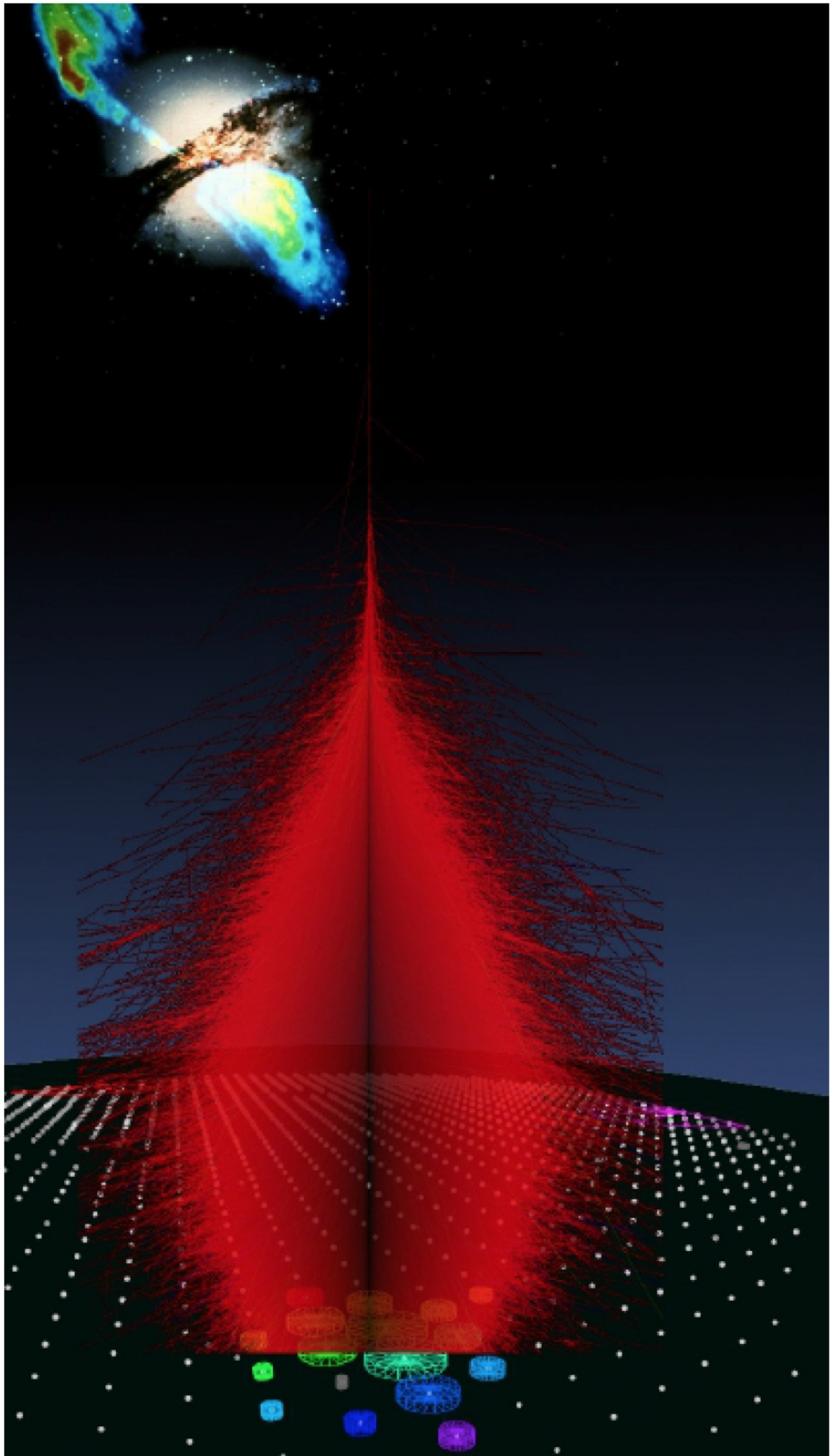
Spectrum of high energy Cosmic Rays $\phi(E) \times E^{2.5}$

All particle spectrum



Proton laboratory energy	Nucleon-nucleon c.m. energy
$E_0 \simeq 3 \times 10^{15}$ eV	$\sqrt{s} \simeq 2.37$ TeV
$E_0 \simeq 10^{17}$ eV	$\sqrt{s} \simeq 13.7$ TeV
$E_0 \simeq 10^{18}$ eV	$\sqrt{s} \simeq 43.3$ TeV
$E_0 \simeq 10^{19}$ eV	$\sqrt{s} \simeq 137$ TeV
$E_0 \simeq 10^{20}$ eV	$\sqrt{s} \simeq 433$ TeV


the Source
the Shower
the Data



the Source

the Shower

[The estimate of the Energy and Mass of the shower requires the detailed modeling of shower development]

the Data

Measurement of Spectrum and Composition:

Two techniques:

1. Fluorescence Light Telescopes

Measure the
Longitudinal development of an Air shower

2. "Surface Detector"

[A single layer of the shower]
Measure the particles that reach the ground, separating if possible the difference components [*Muon component + electromagnetic component*]

Shower Components at Ground Level:

Electromagnetic
Component

$e^{\mp}, \ \gamma$

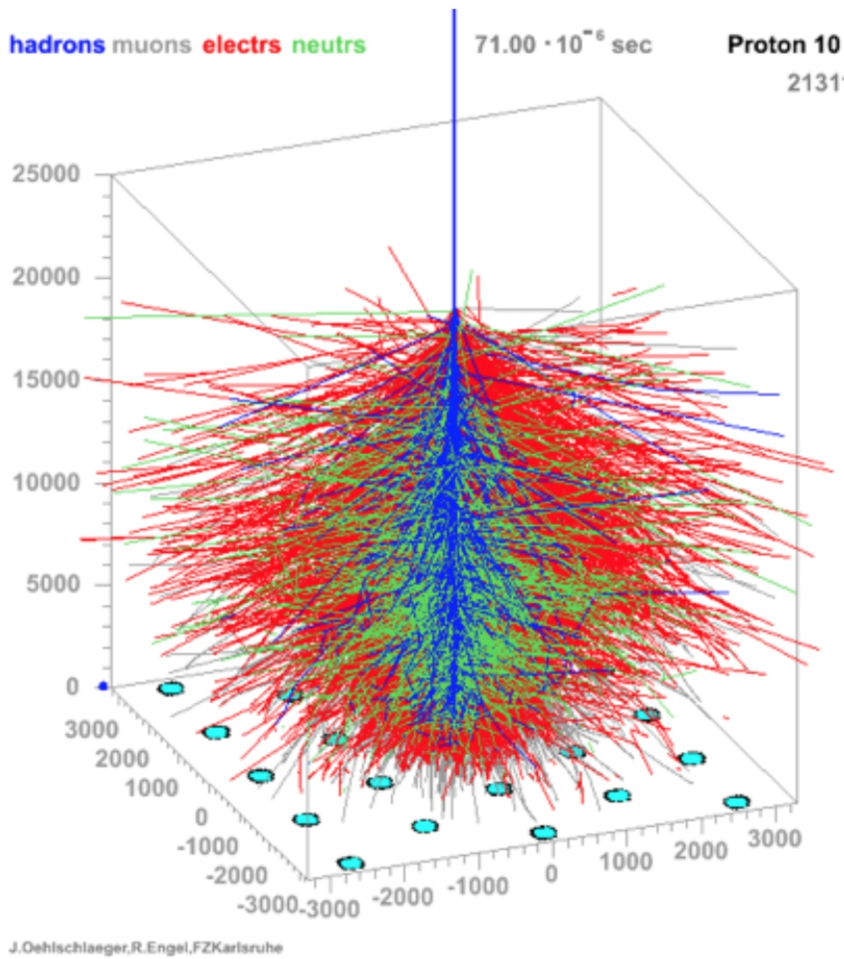
Muon Component

$\mu^{\mp}$

(Invisible) Neutrino component

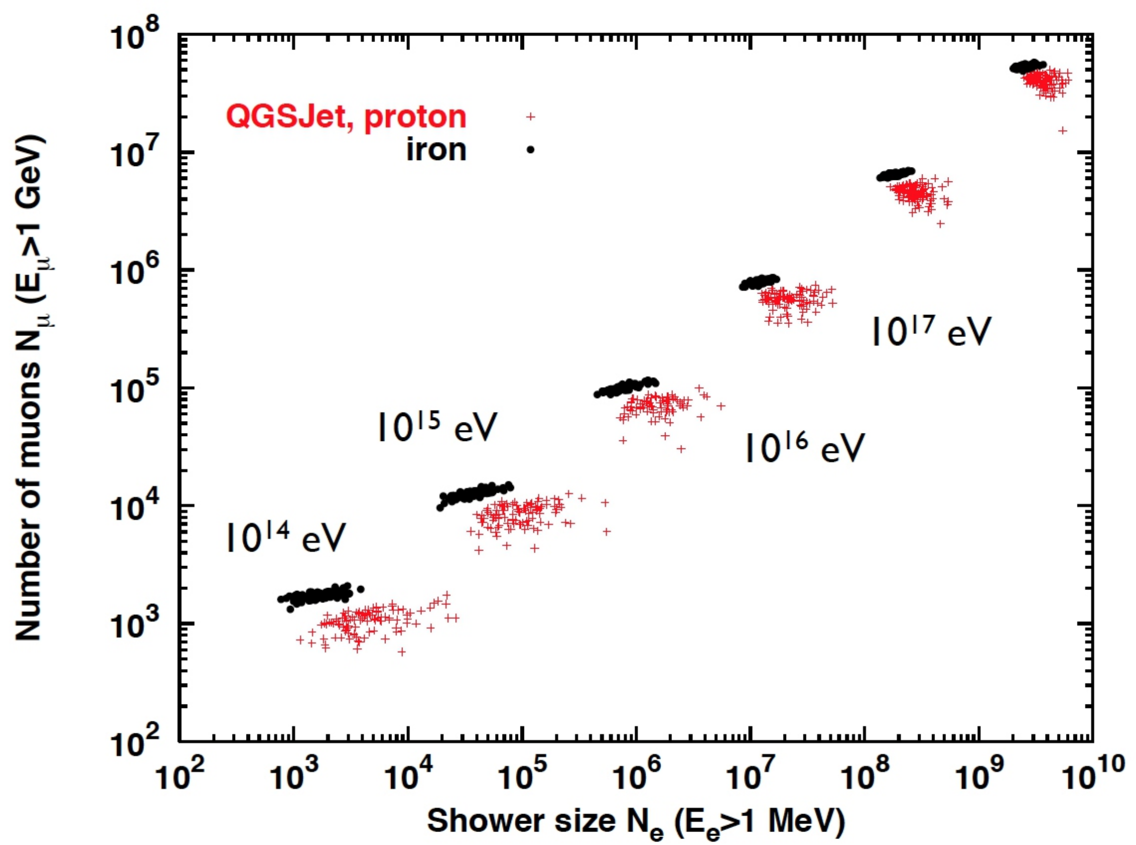
Hadronic component
[small and close to the shower axis]

Electron-muon shower size correlation

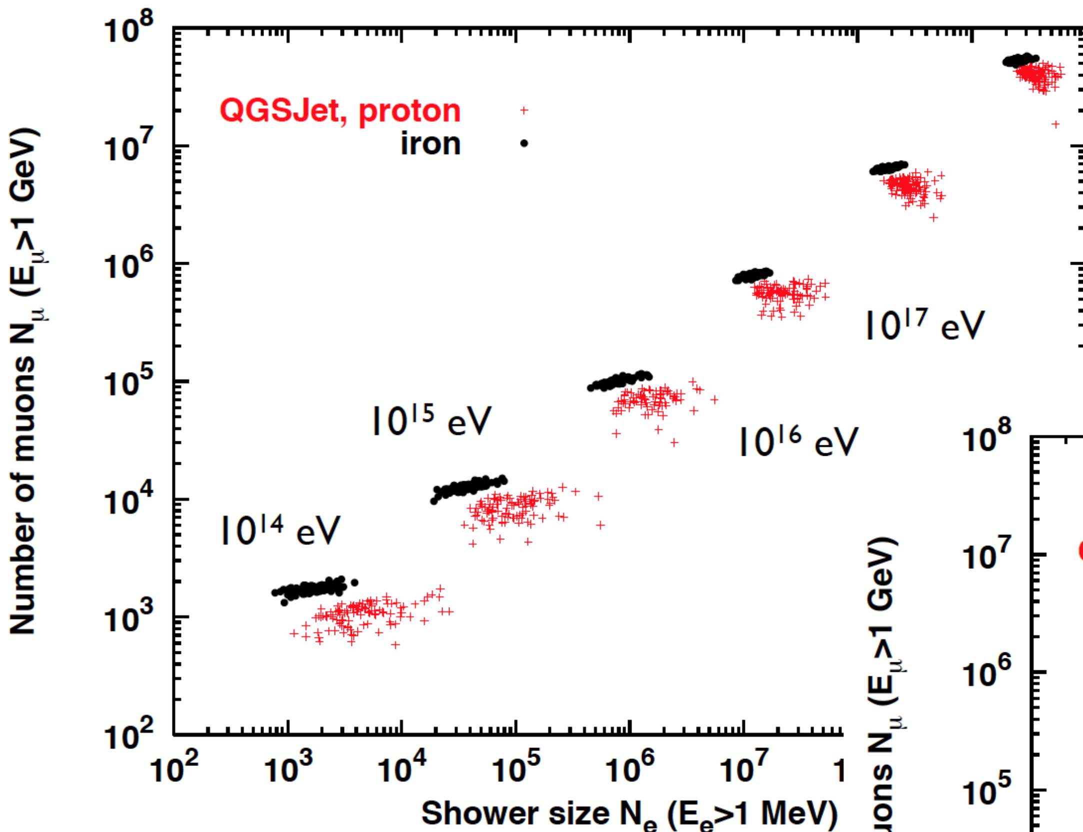


Example: KASCADE-Grande

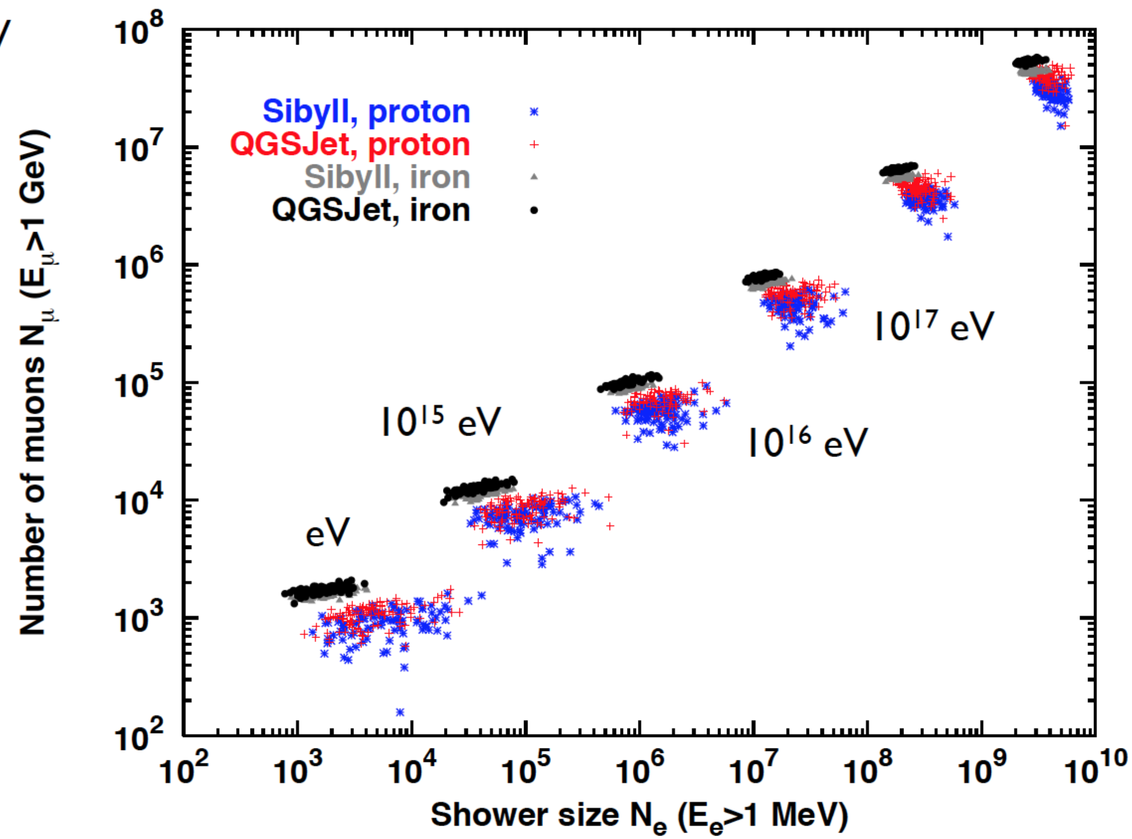
Combined energy-composition analysis



Model dependence of predictions

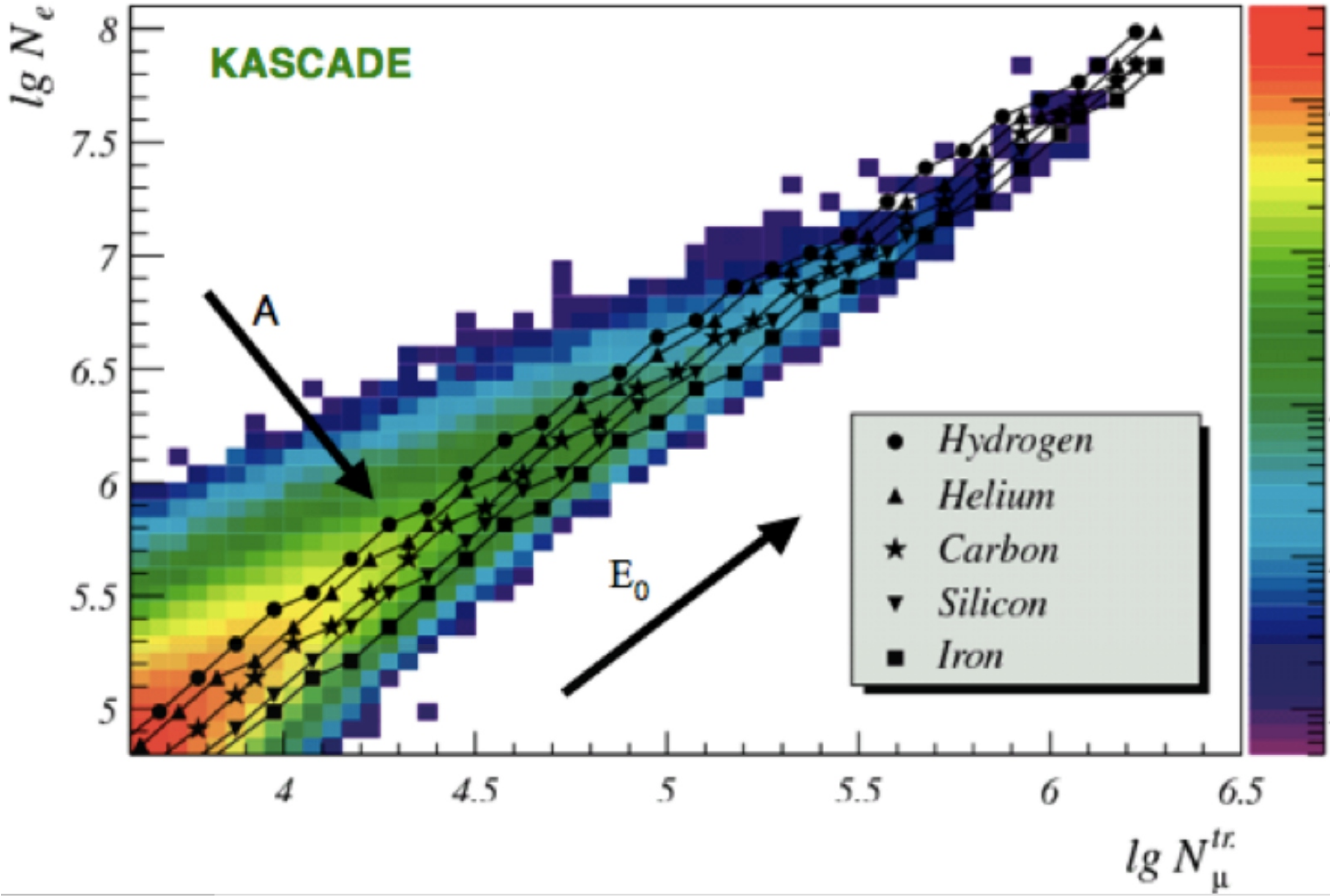


Strong model dependence !

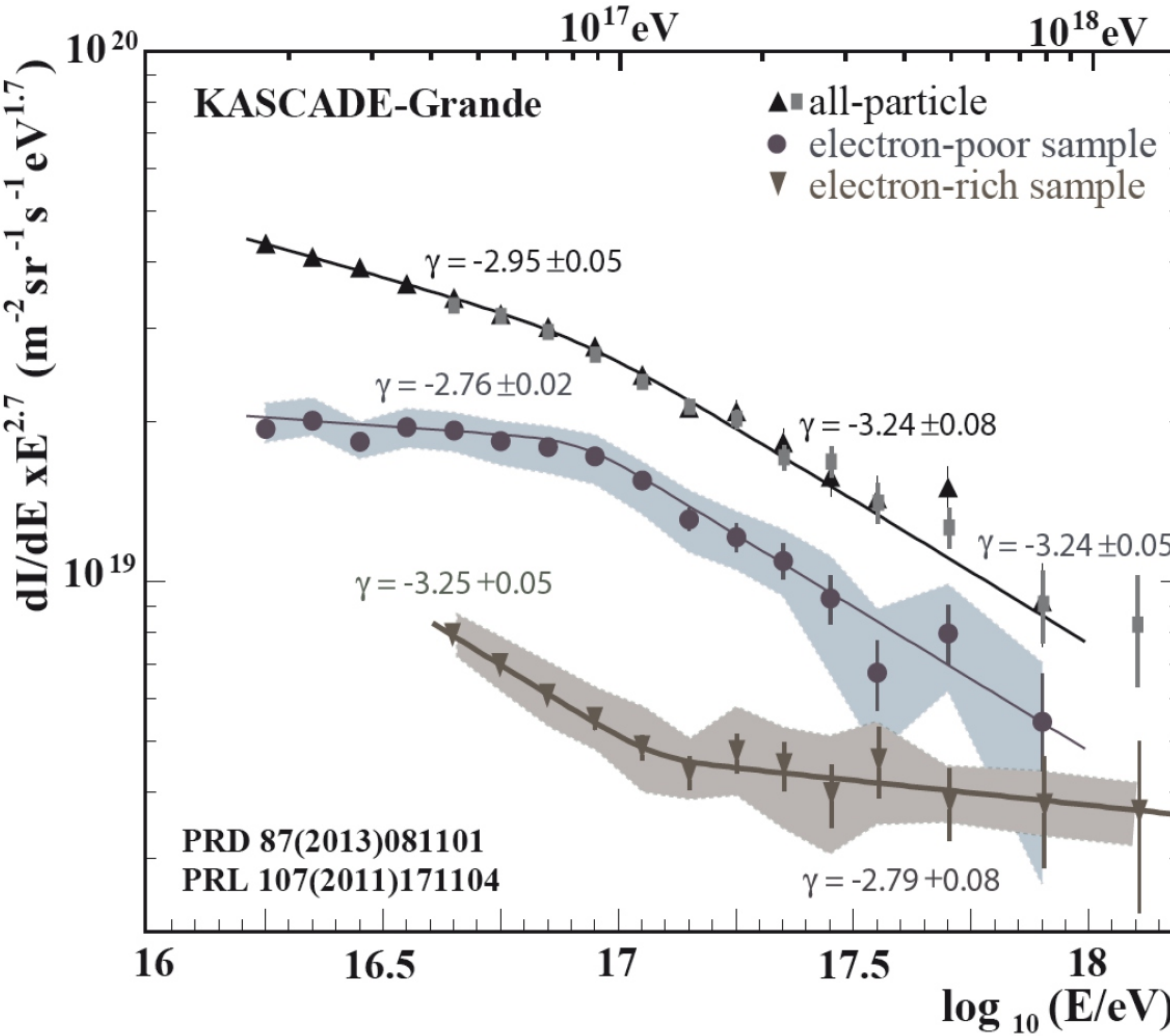


- Composition (muon number)
- Energy (distance to X_{max})

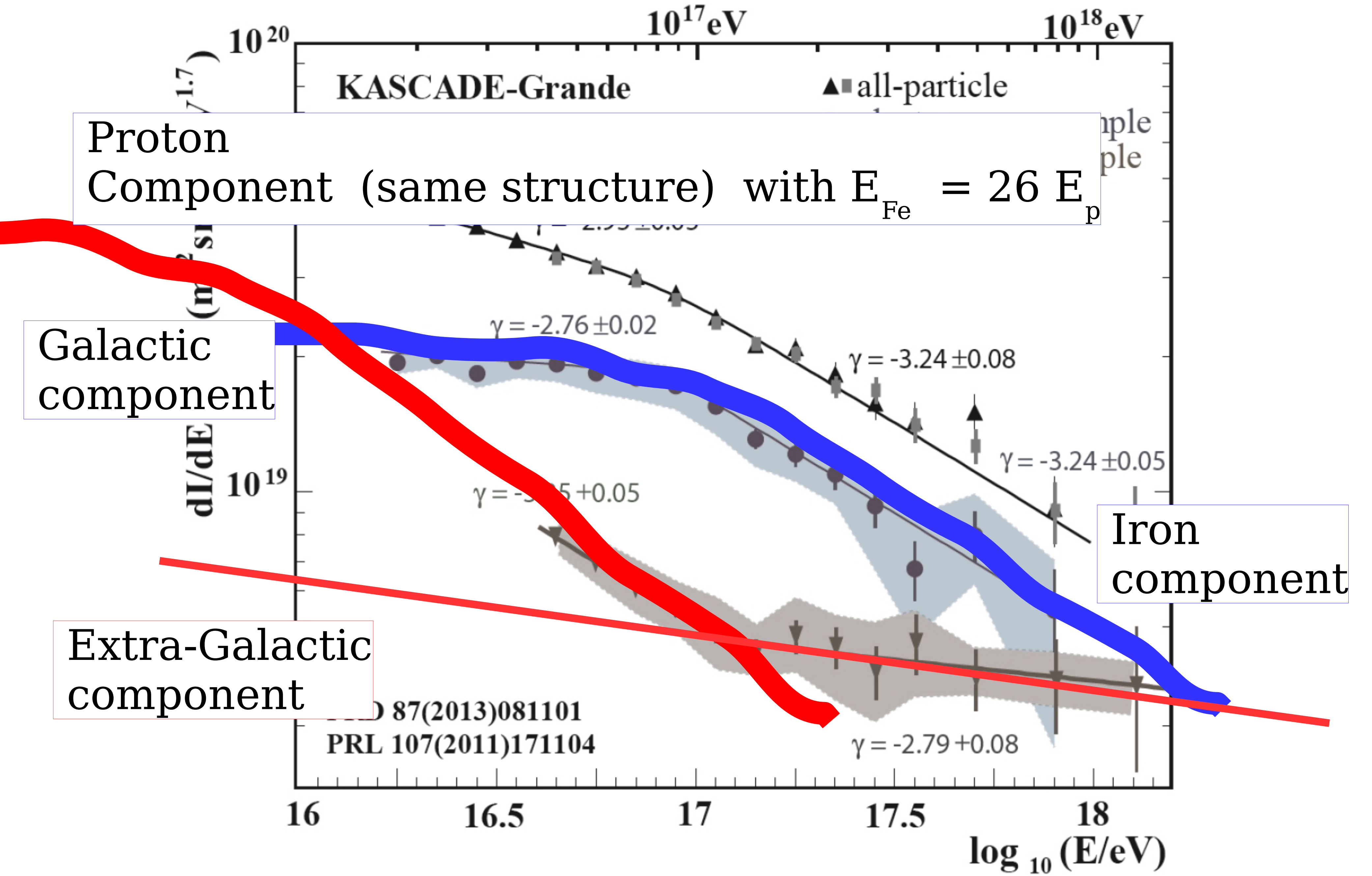
Interpretation of the DATA

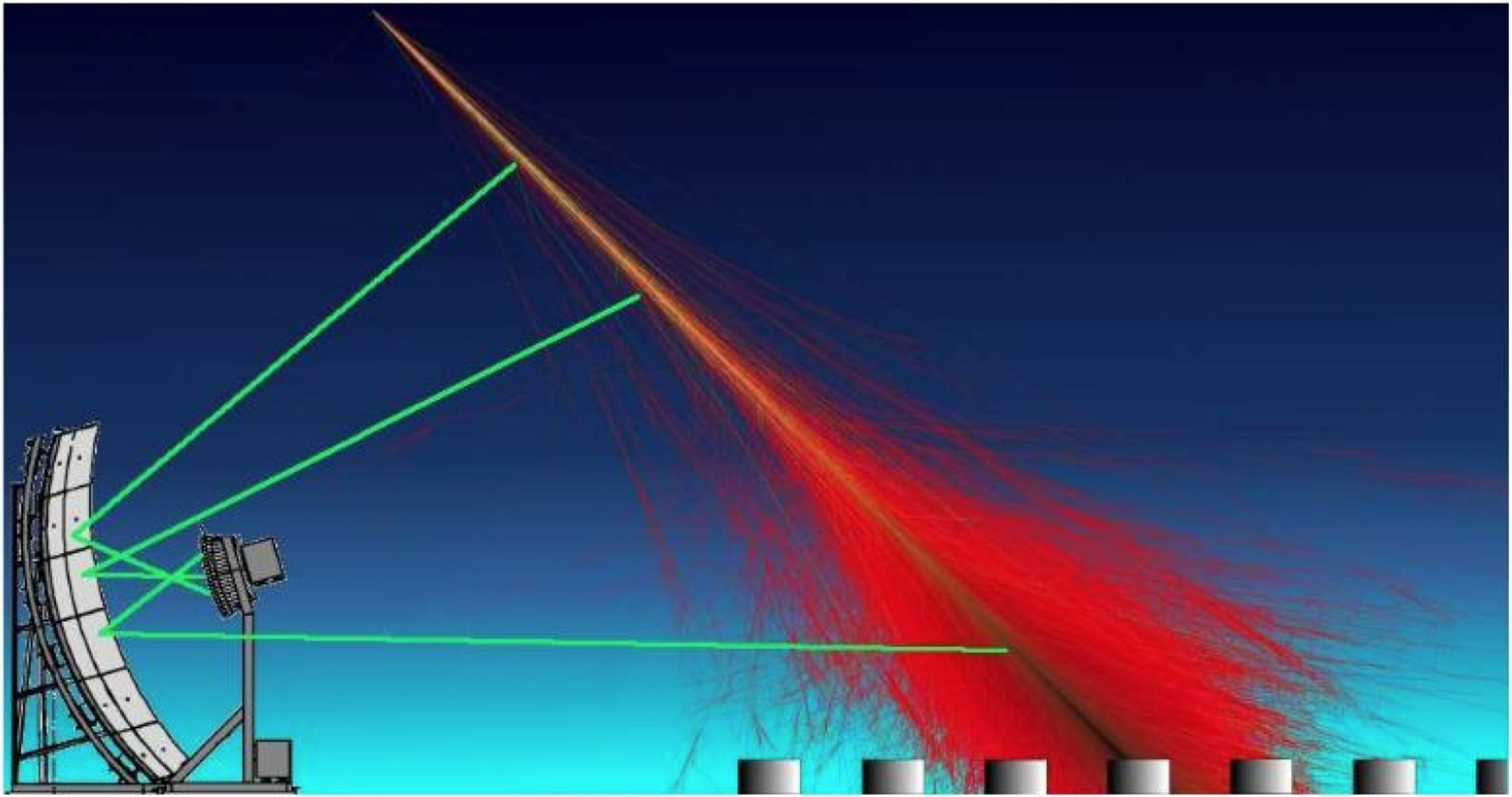


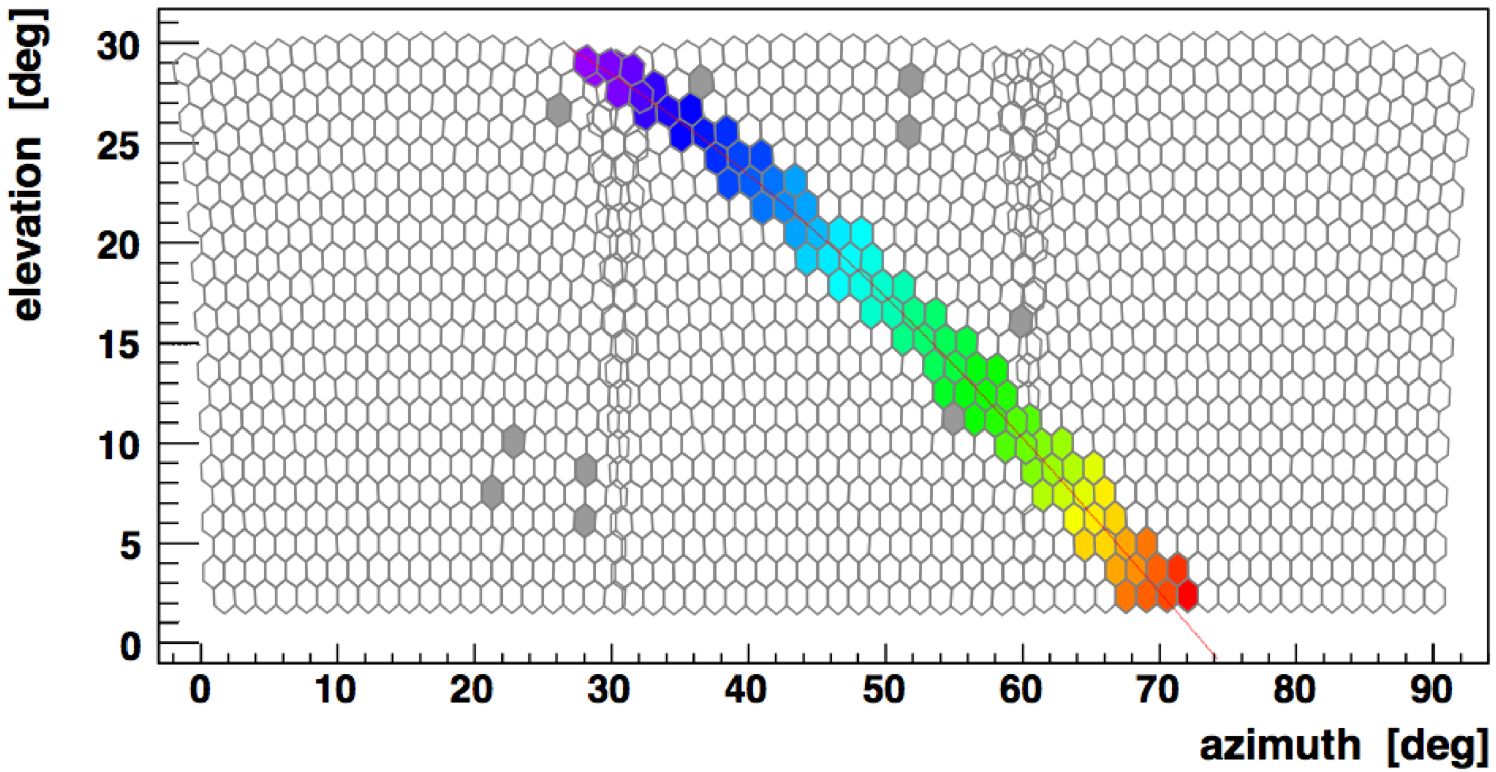
Kascade Grande “ankle” in the light component.



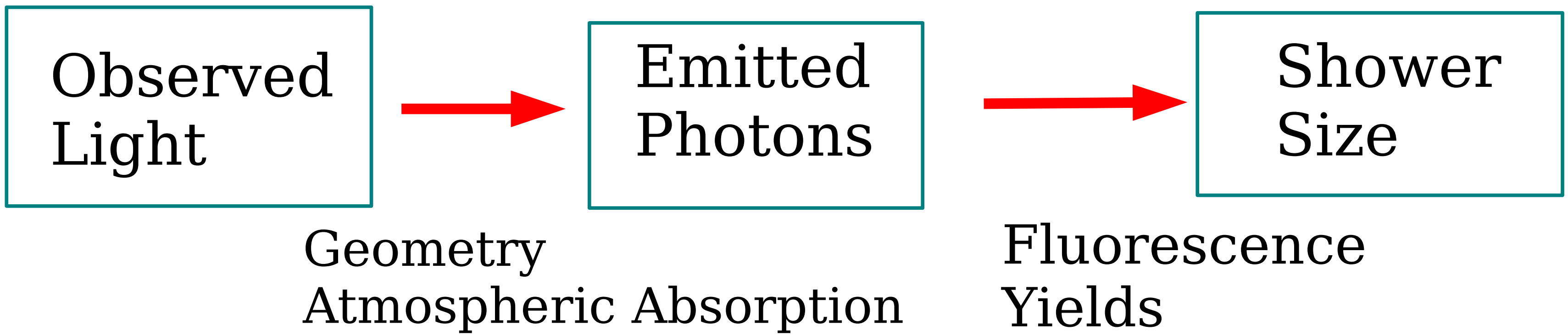
Kascade Grande “ankle” in the light component.

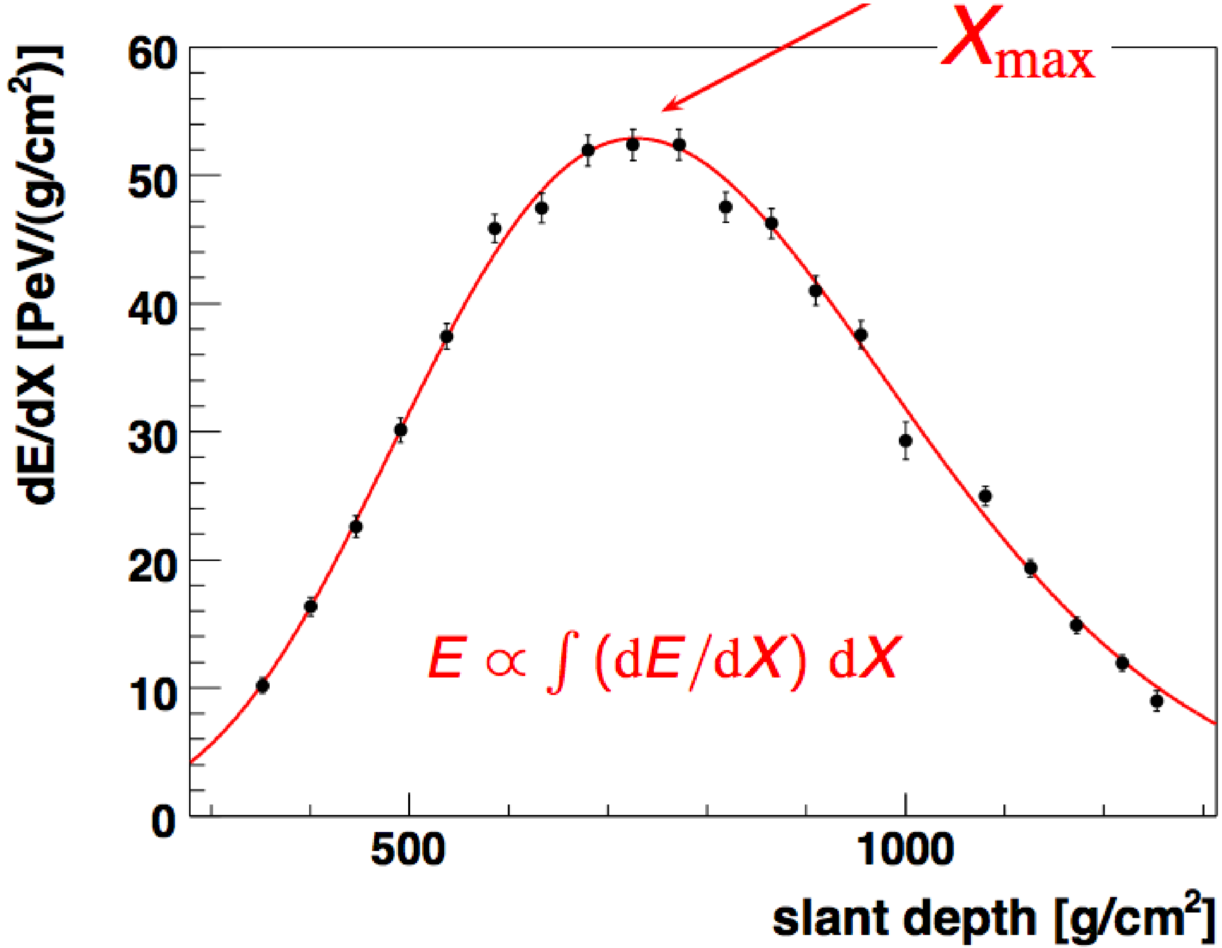






$$L(\Omega) \to F_\gamma(X) \to N_{e^\pm}(X)$$

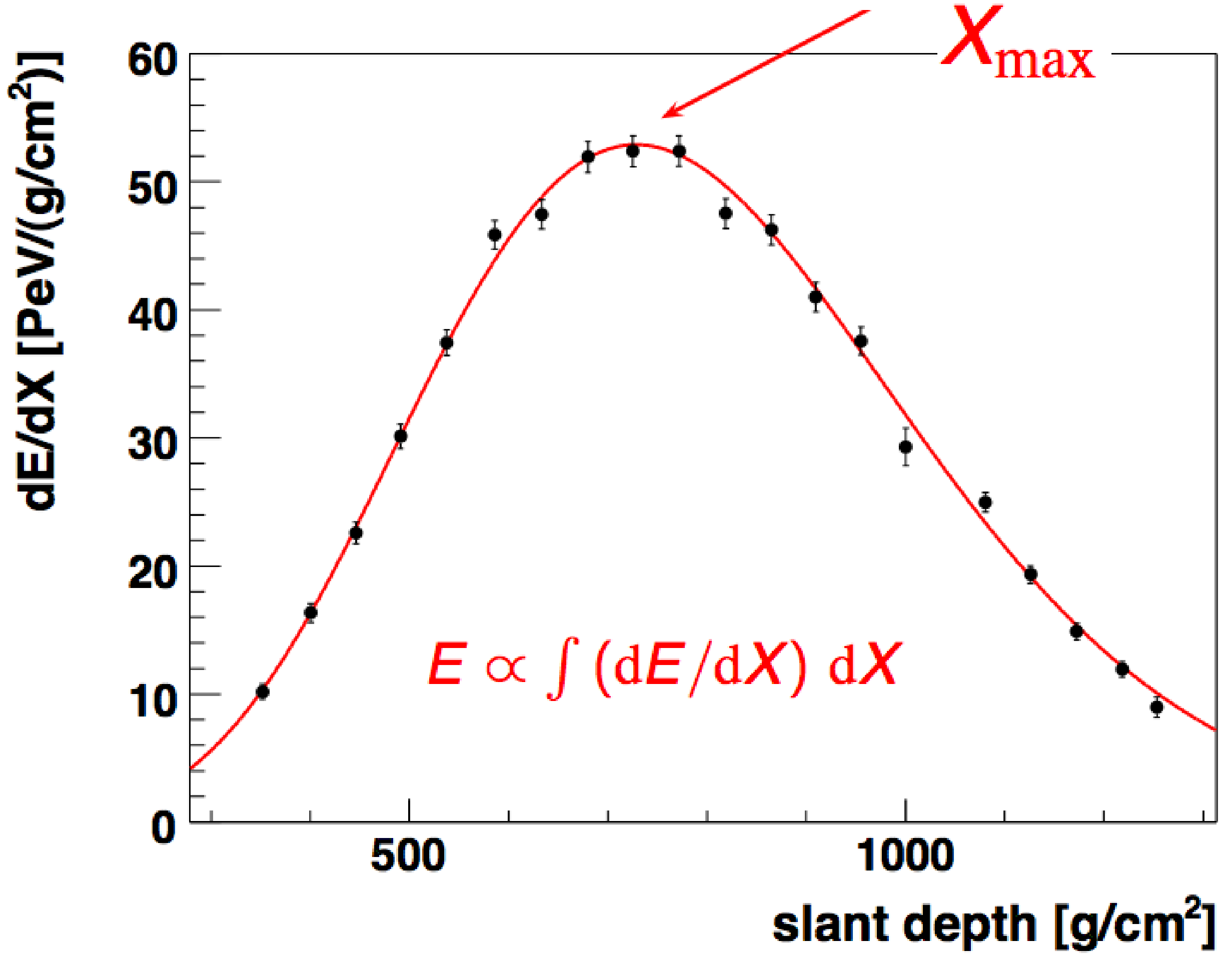




$$E_{\text{ionization}} = \int dX \; N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

Small Model dependence

$$E_{\text{tot}} = E_{\text{ionization}} + E_{\nu} + E_{\mu} + E_{\text{ground}}$$



Area $\propto$ Energy

Shape depends on :

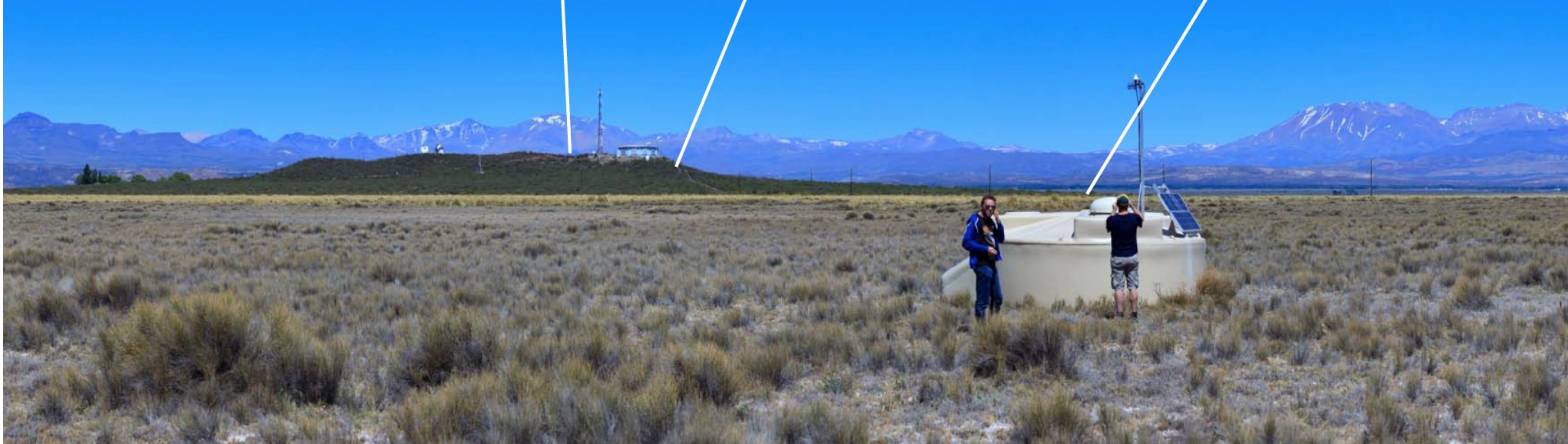
- Primary Identity
- Interaction Model

S. Coutu

Hybrid design

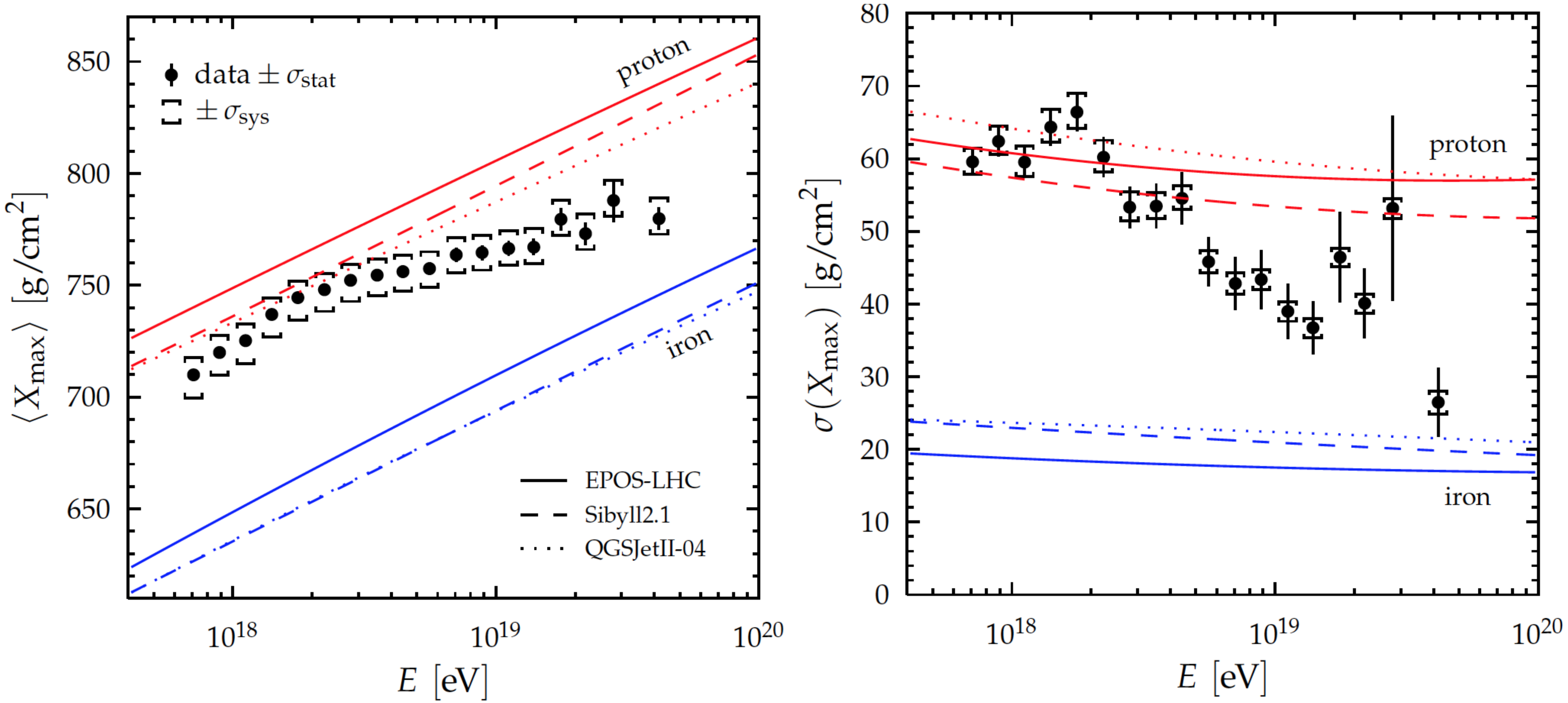
~500 collaborators;
16 countries;
86 institutions;
> 50,000 km^2 sr yr

A multi-component
hybrid Observatory;
study of UHECRs >10^{17} eV.



Auger results: Markus Roth

Average Shower Maximum

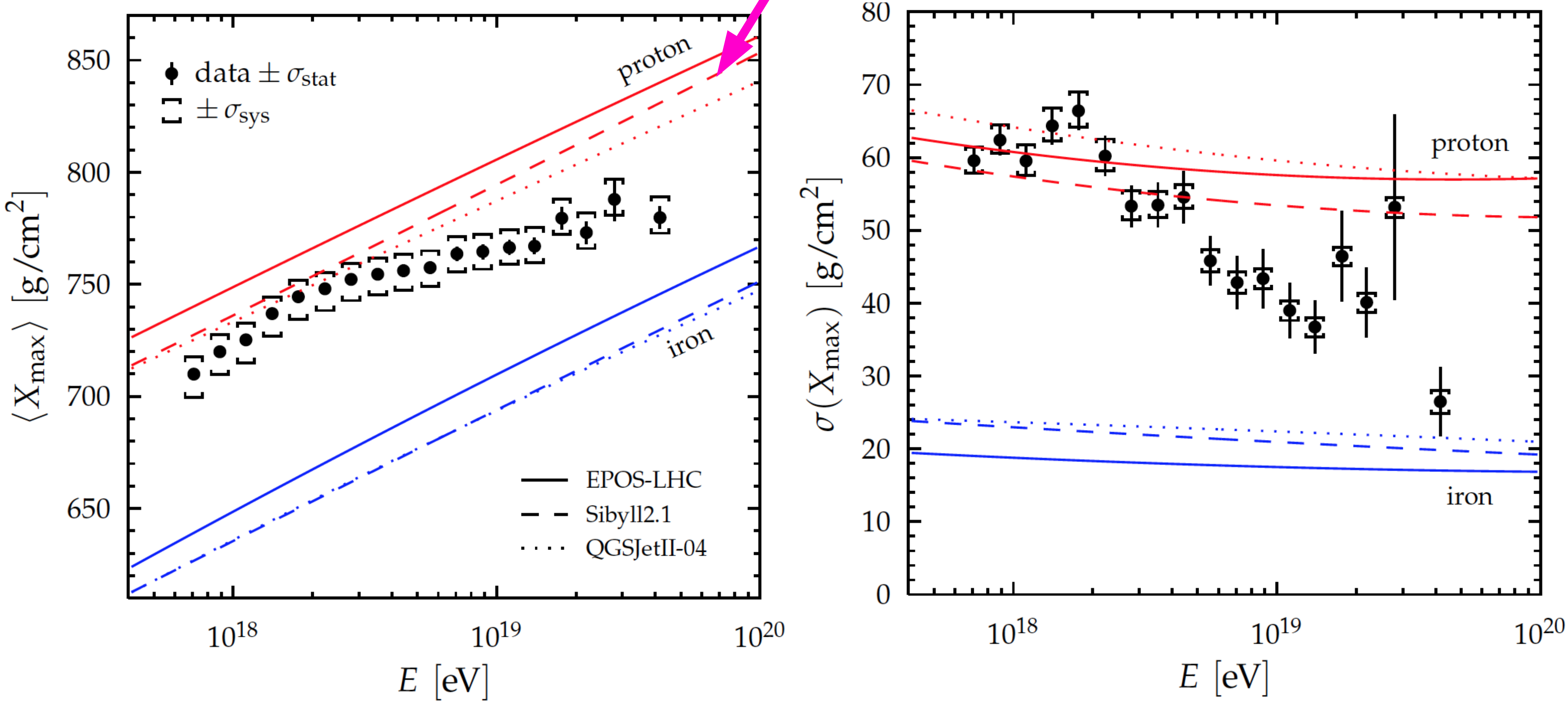


Pierre Auger Collaboration, PRD 90 (2014) 12, 122005

Auger results: Markus Roth

Average Shov

Model dependence
crucial for the interpretation



Pierre Auger Collaboration, PRD 90 (2014) 12, 122005

Planned upgrade of Auger

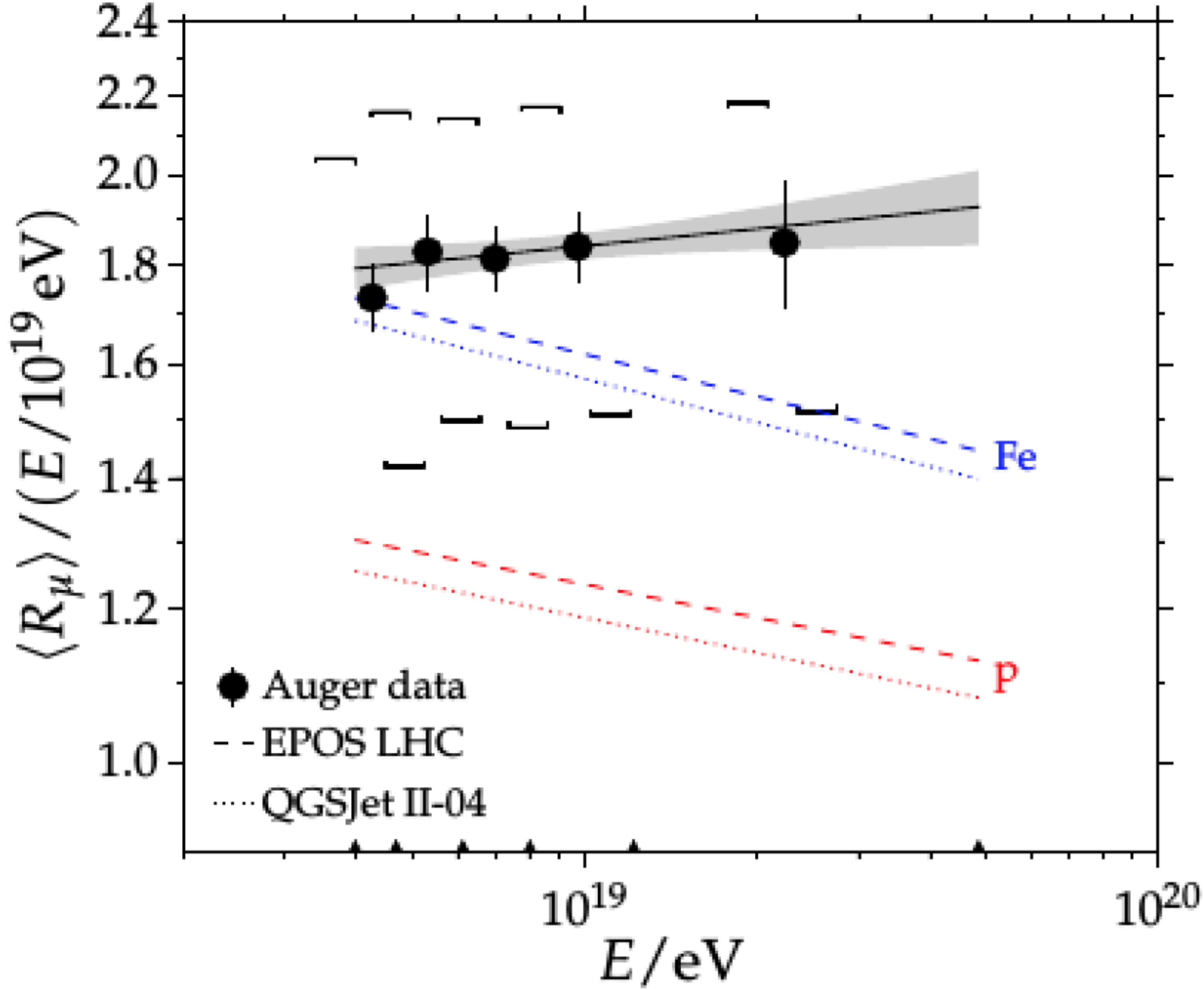
Prototype

Scintillator
Detector

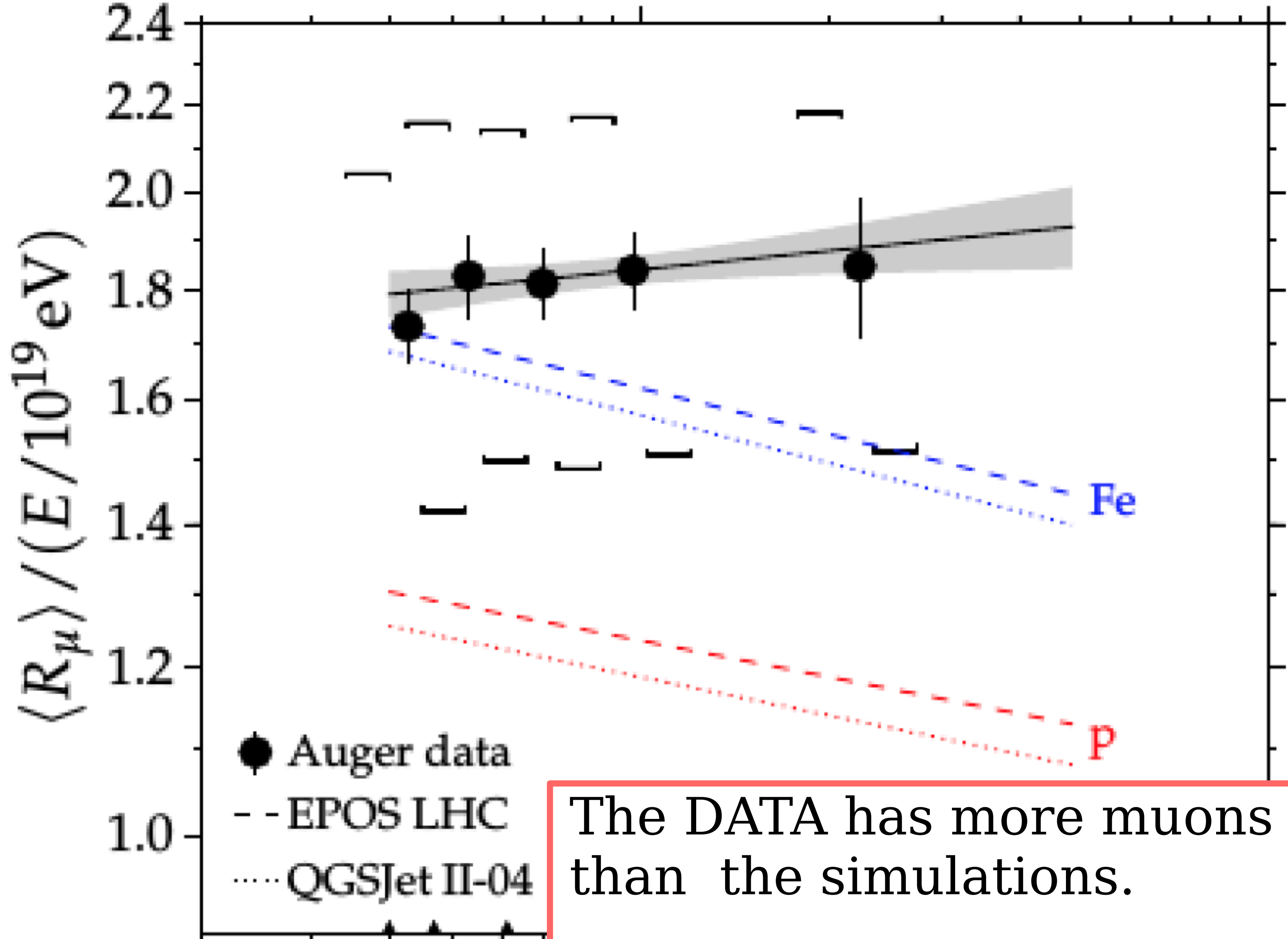
Combine:
Tank
Scintillator

to separate
muon / e.m.
components

Study of Composition with muons (inclined showers)



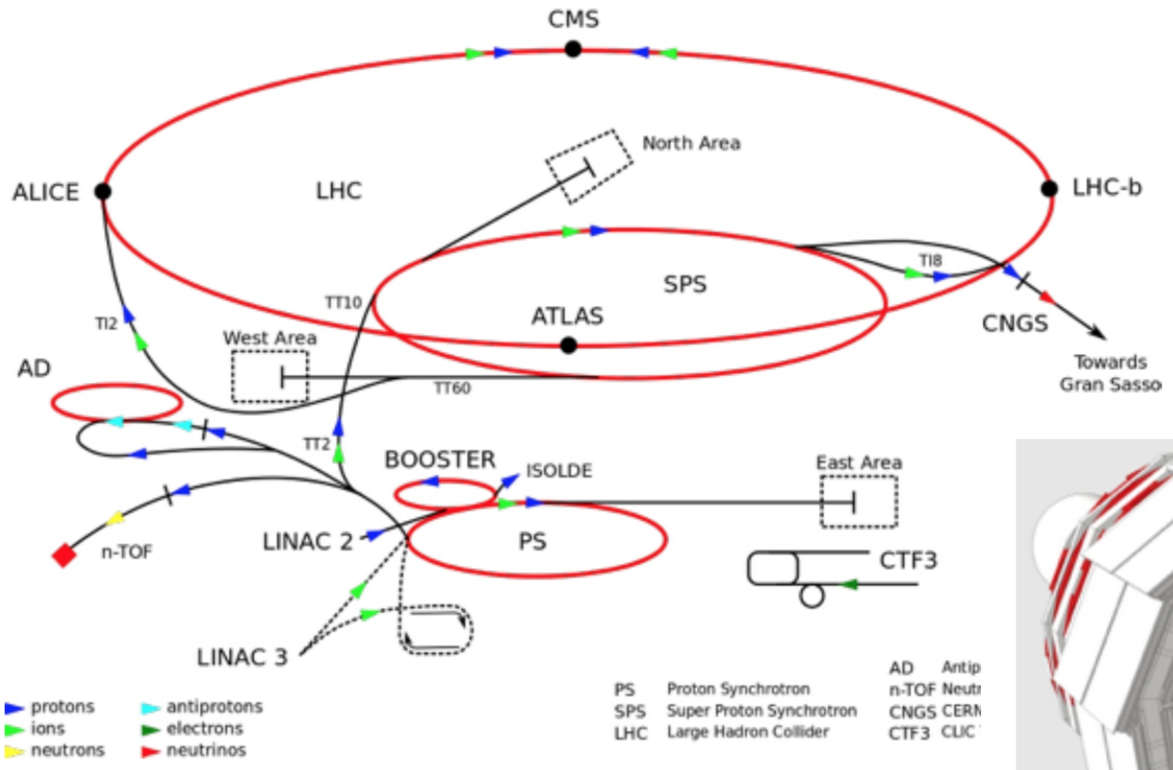
Study of Composition with muons (inclined showers)

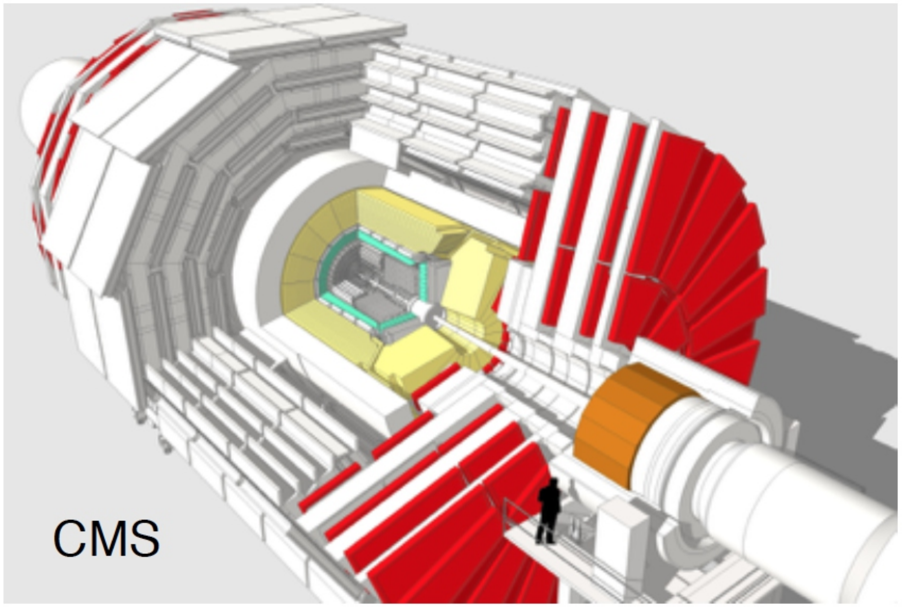


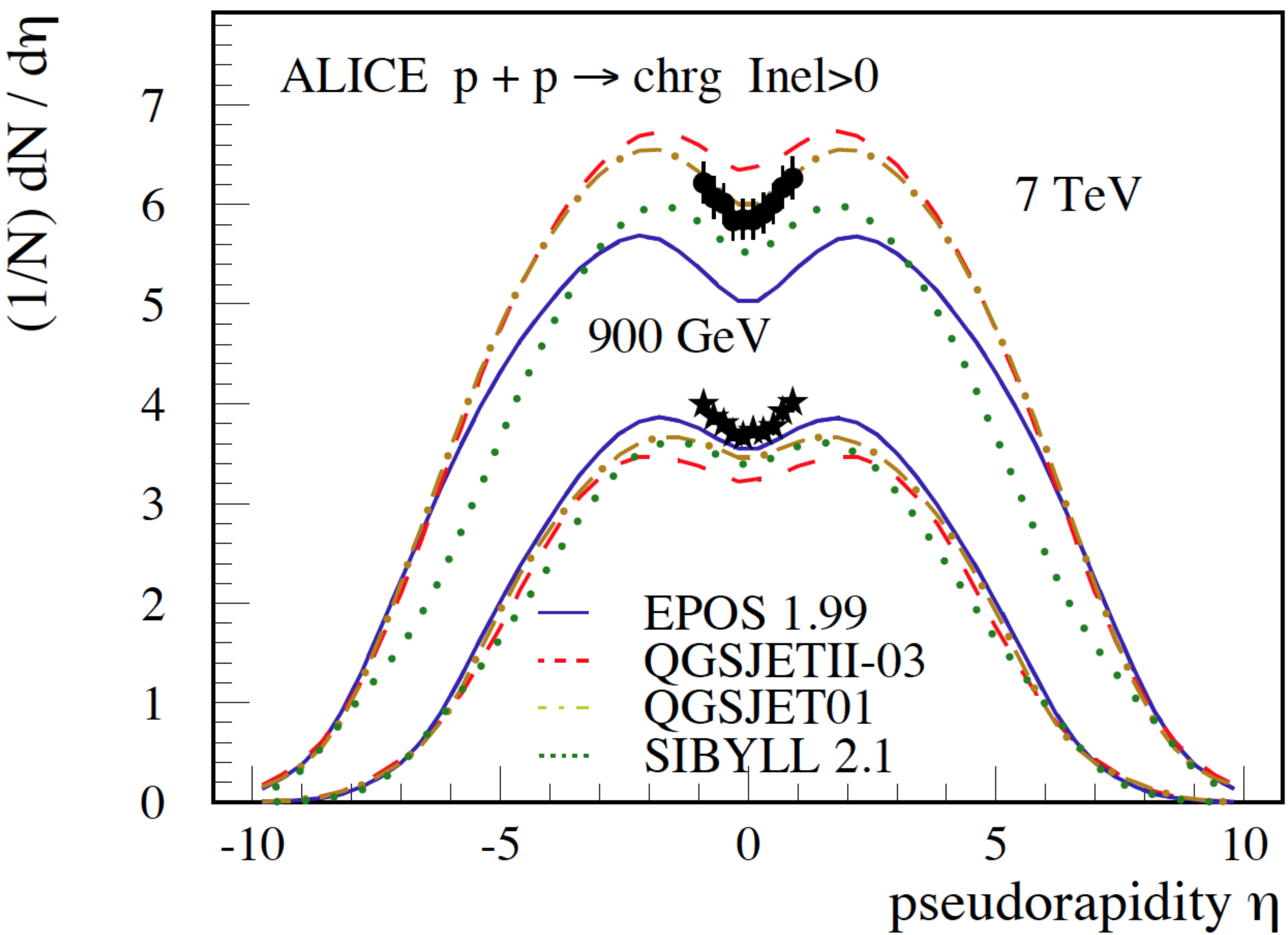
The DATA has more muons than the simulations.

Why ? What are the implications ?

LHC data to constrain the modeling of the interaction

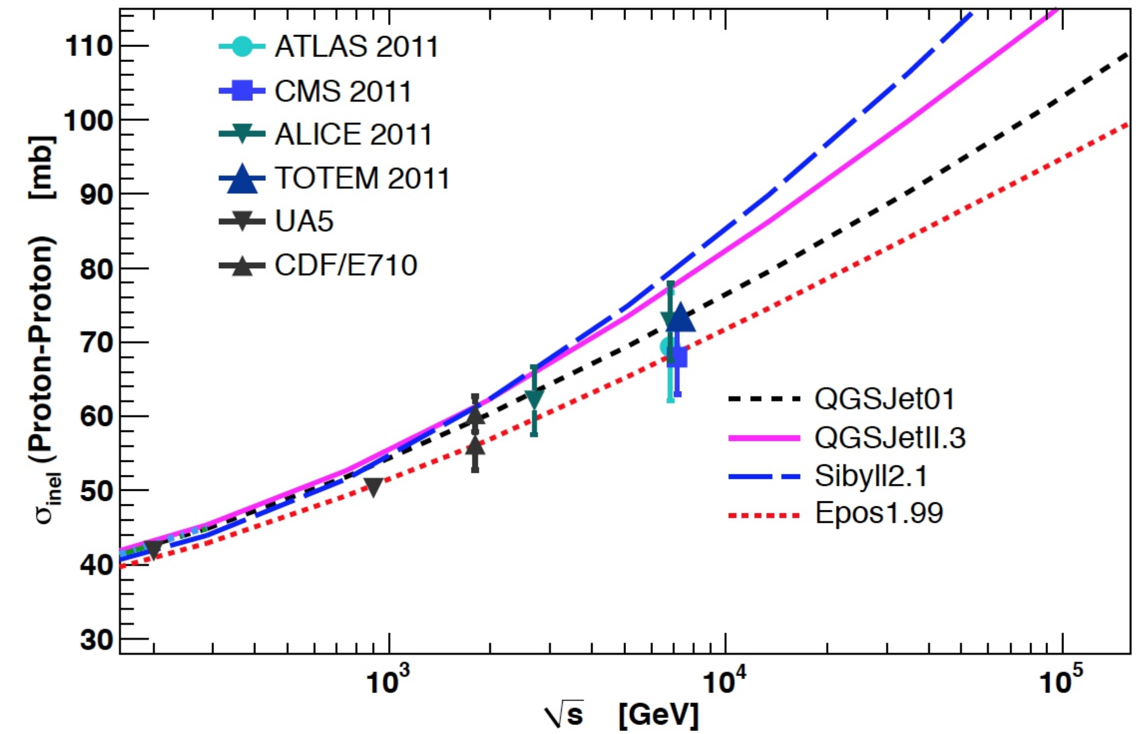


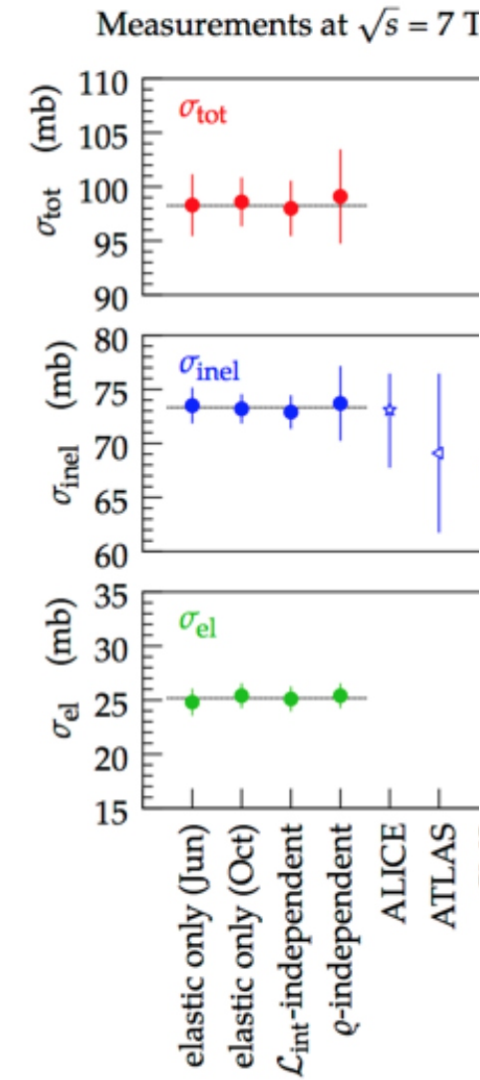


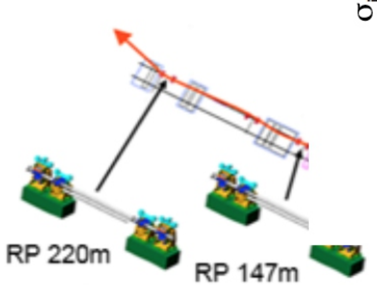


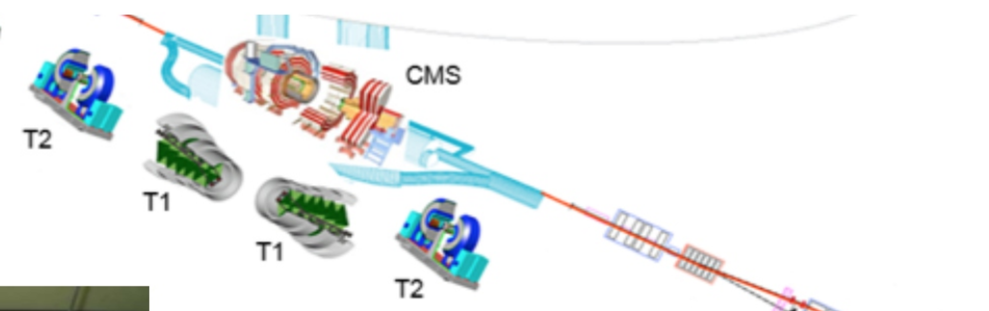
ALICE p + p → chrg Inel>0
7 TeV
900 GeV
EPOS 1.99
QGSJETII-03
QGSJET01
SIBYLL 2.1
(1/N) dN / dη
pseudorapidity η
0
1
2
3
4
5
6
7
-10
-5
0
5
10

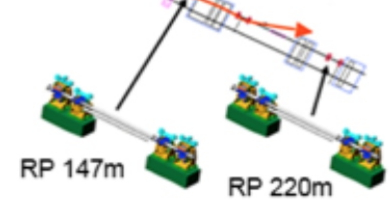
Proton-proton cross section

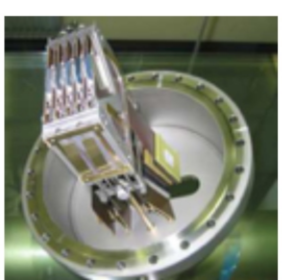






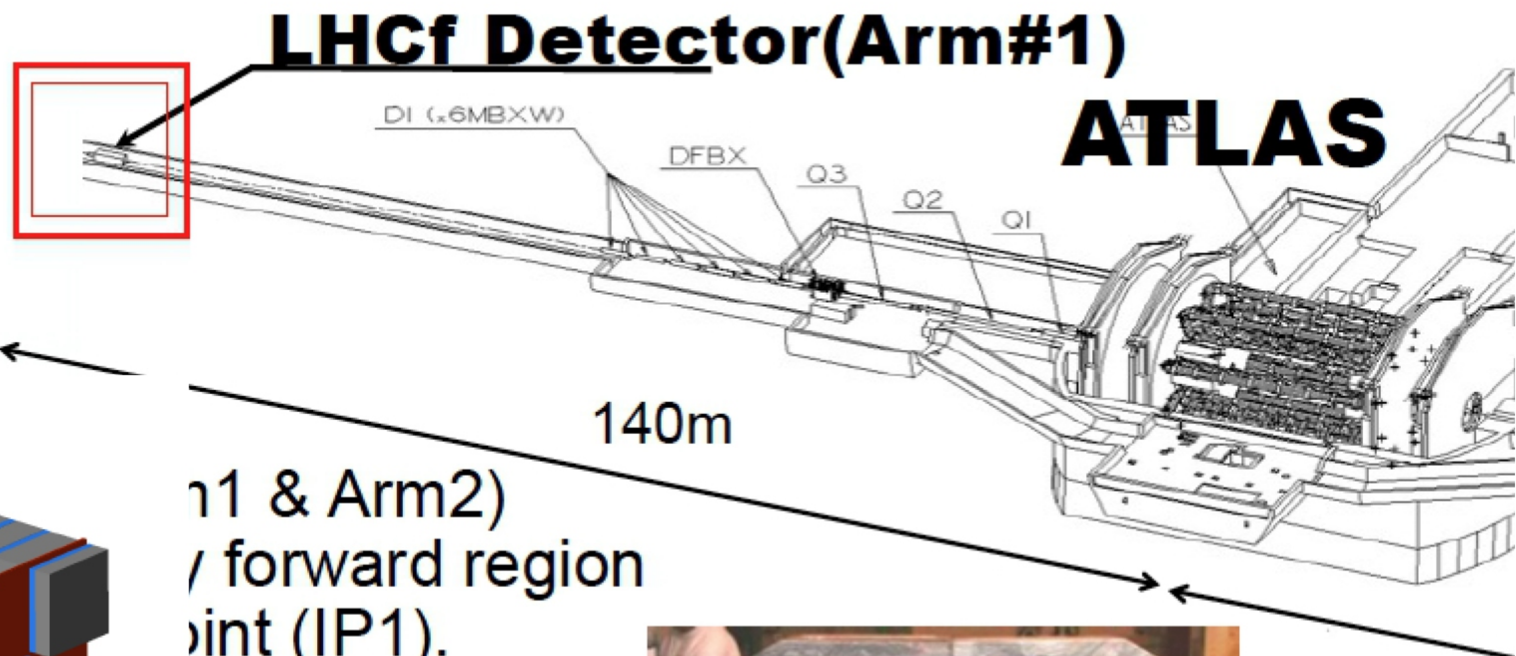


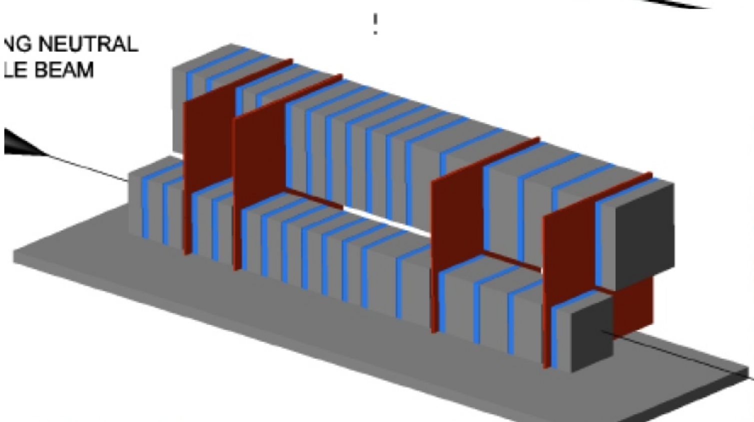




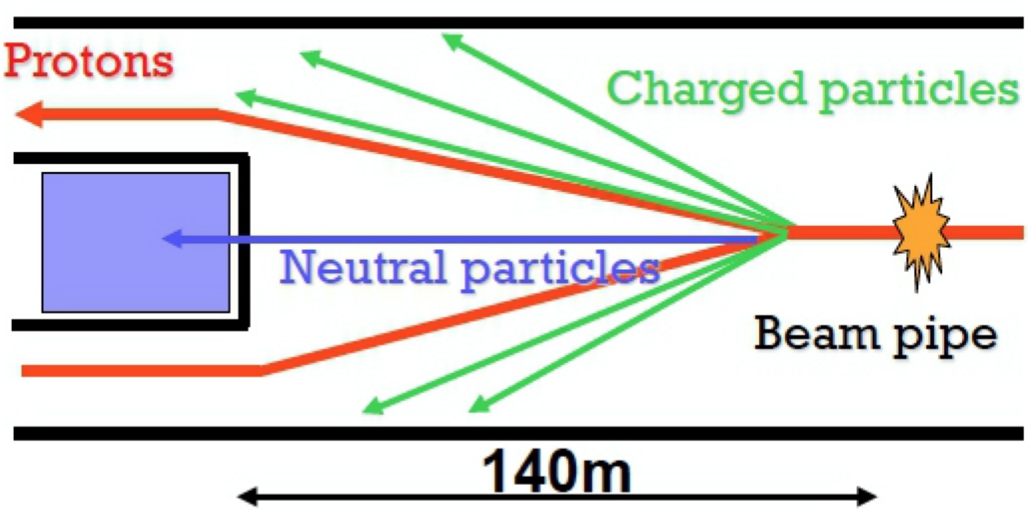
(Cafagna, ICRC 2015)

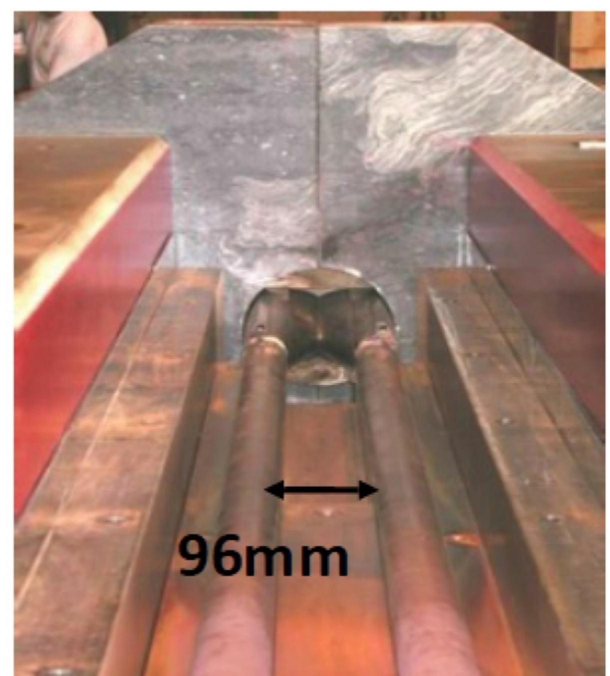
LHCf Experiment





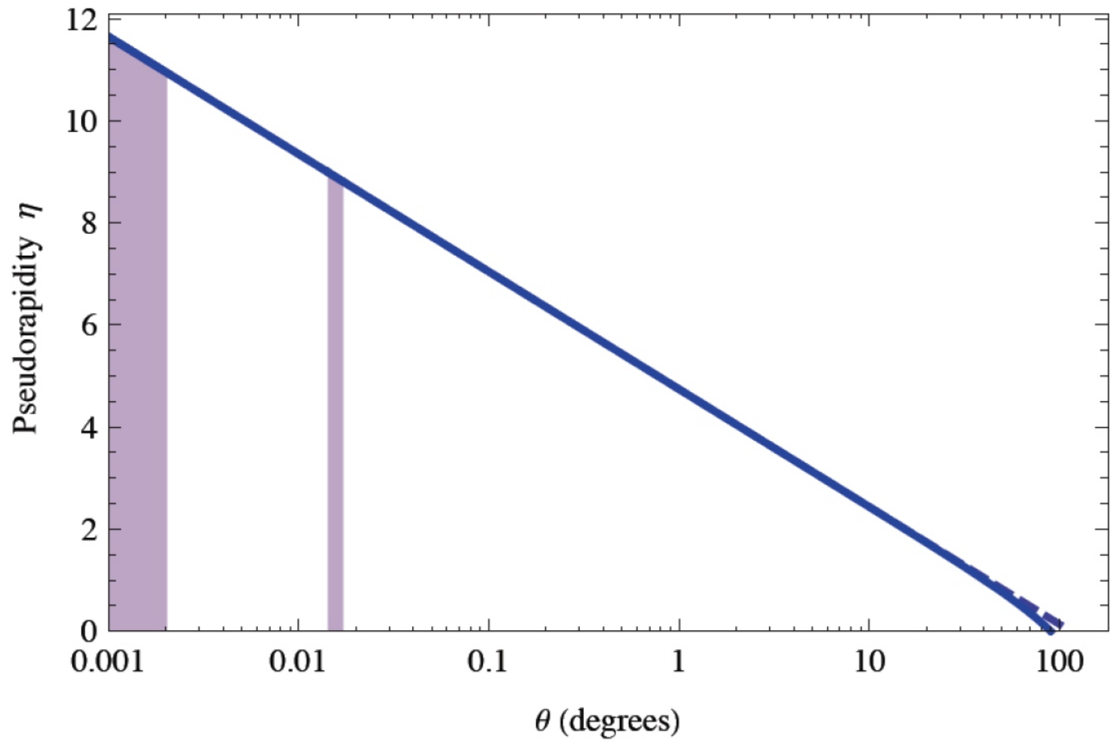
n1 & Arm2)
/ forward region
oint (IP1).
al particles
e η > 8.4.

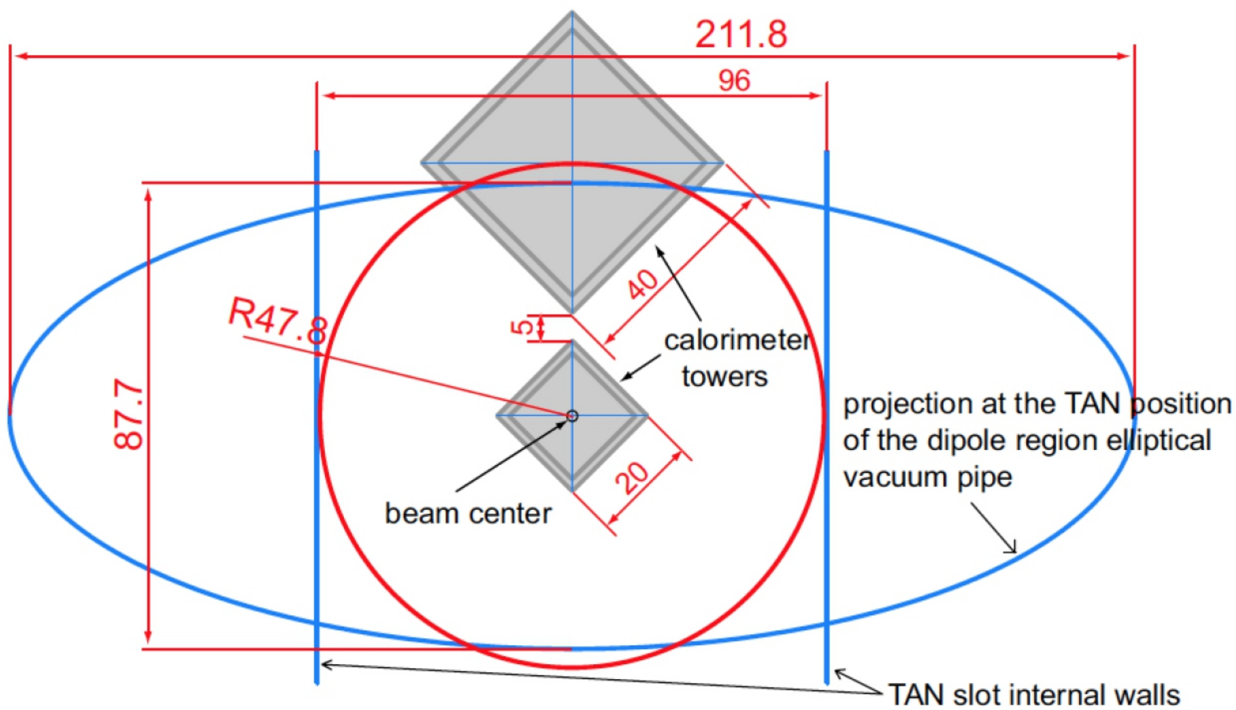




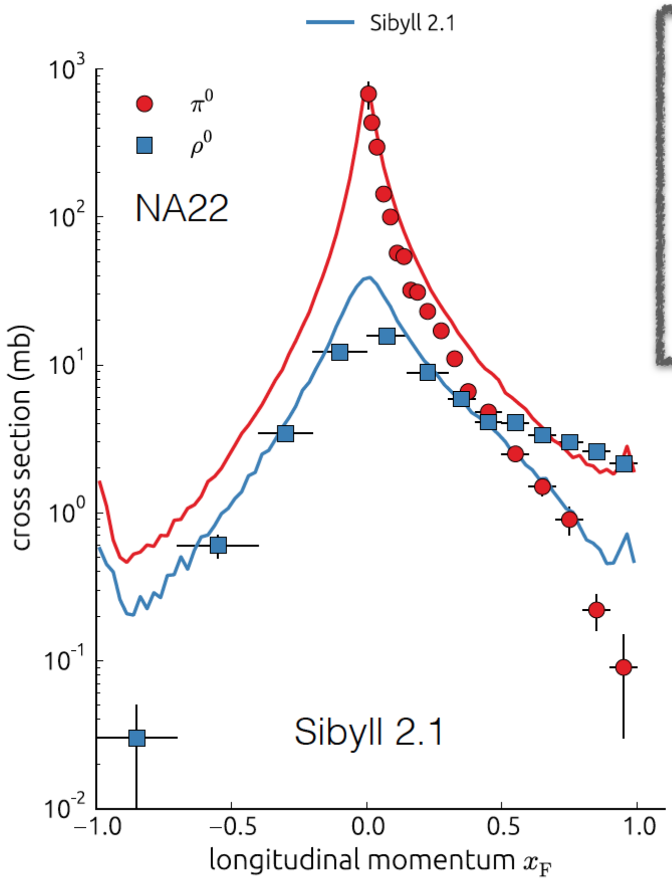
Pseudo-Rapidity versus angle:

Very small angle production:





Rho production in pion-proton interactions (i)

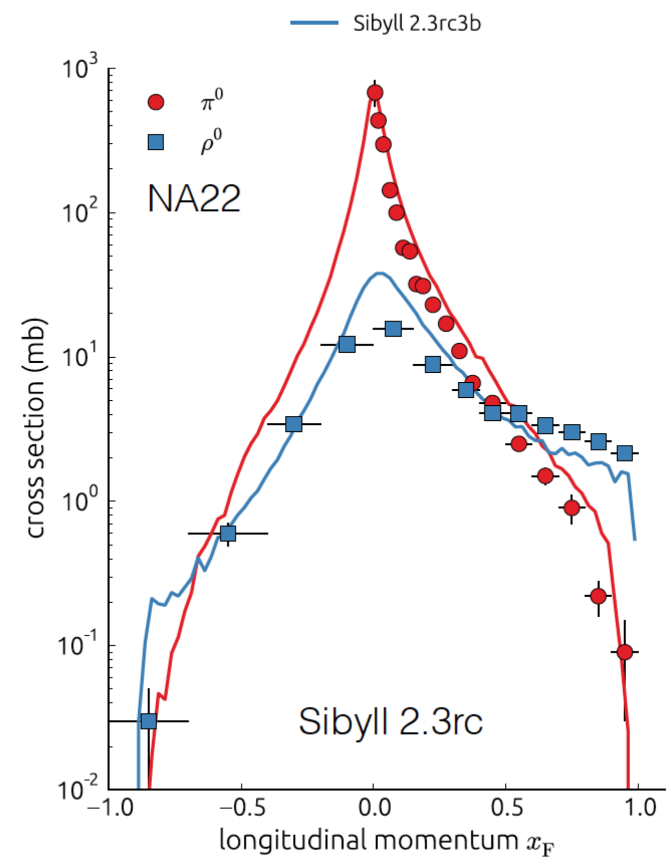


$$\pi^+ p \to \pi^0 \to 2\gamma$$

$$\pi^+ p \to \rho^0 \to \pi^+ \pi^-$$

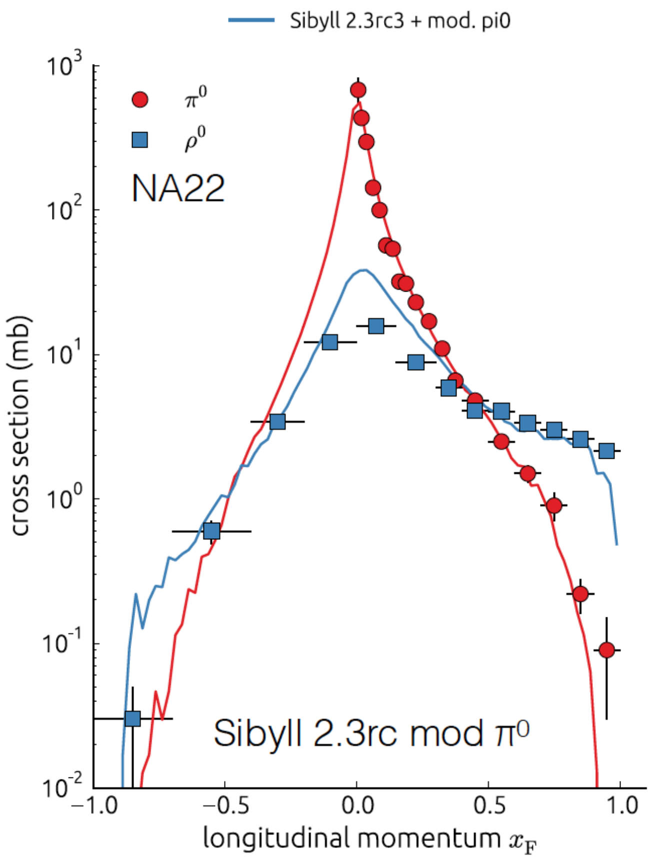
$$E_{lab} = 250\,\mathrm{GeV}$$

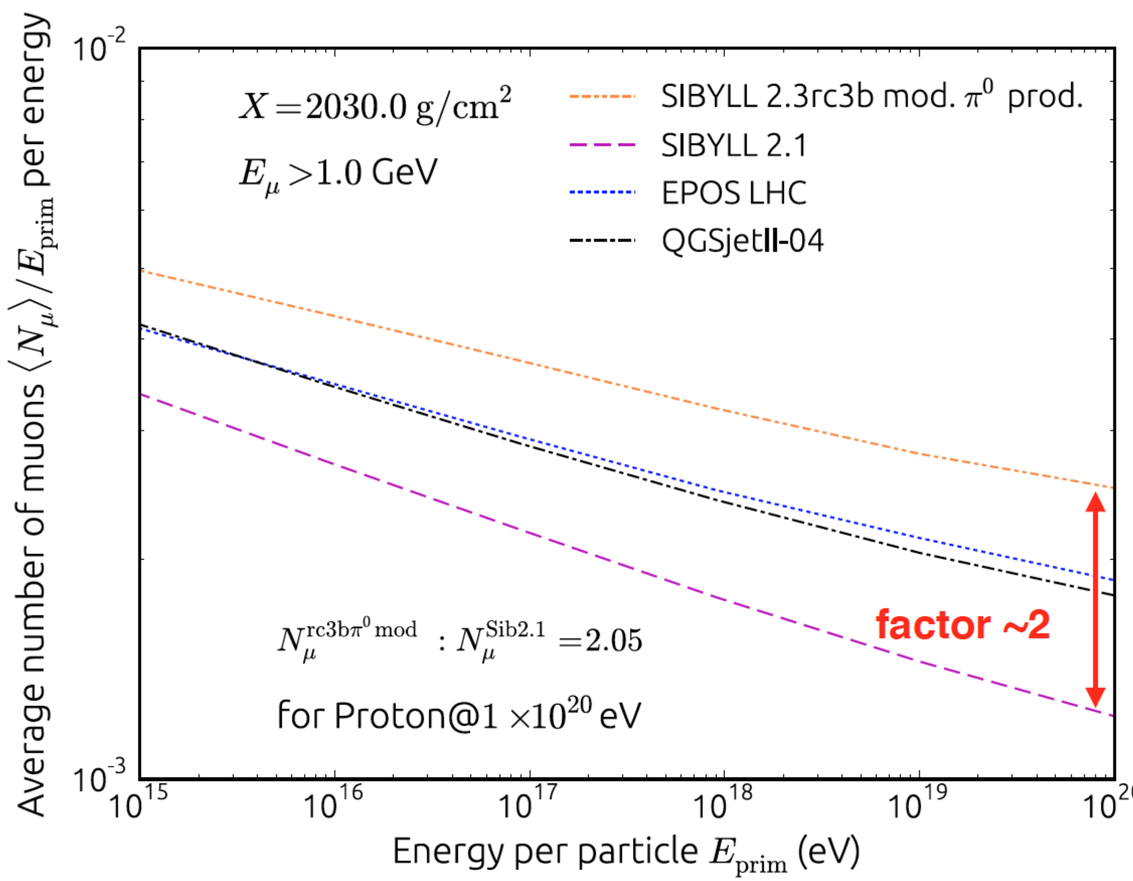
$$x_F = p_{\|} / p_{max}$$



"Low Energy" data Elab = 250 GeV
with a very important implications for shower development

Rho production in pion-proton interactions (iii)





The largest effect in the post LHC
Version of QGSJET

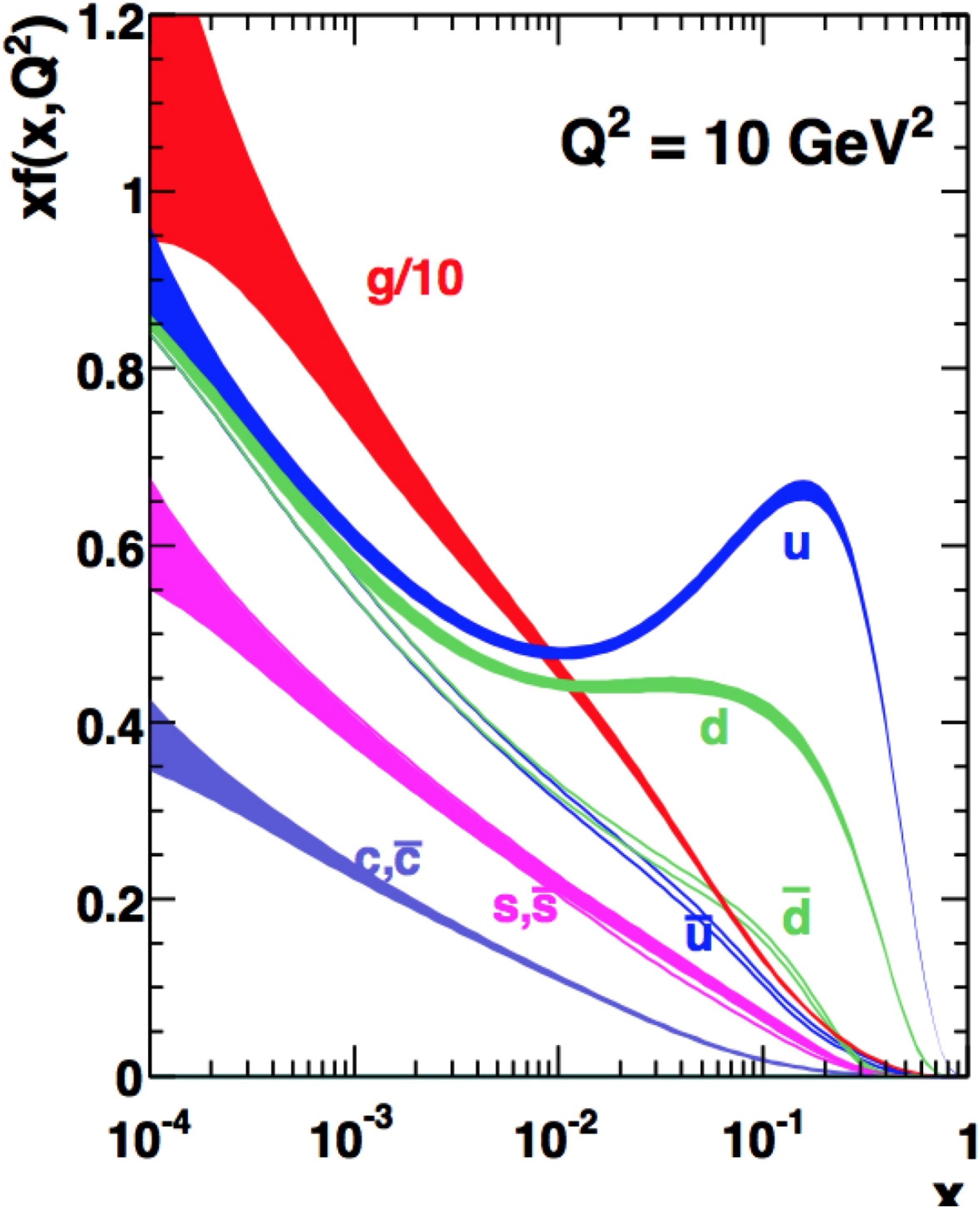
Very desirable to:

[*] Have new studies at LHC
enlarging the phase space coverage.

[*] Develop programs at lower energy
(LHC extracted beam, but also at lower energy
Where only very old data are available)

Quantum Chromo Dynamics

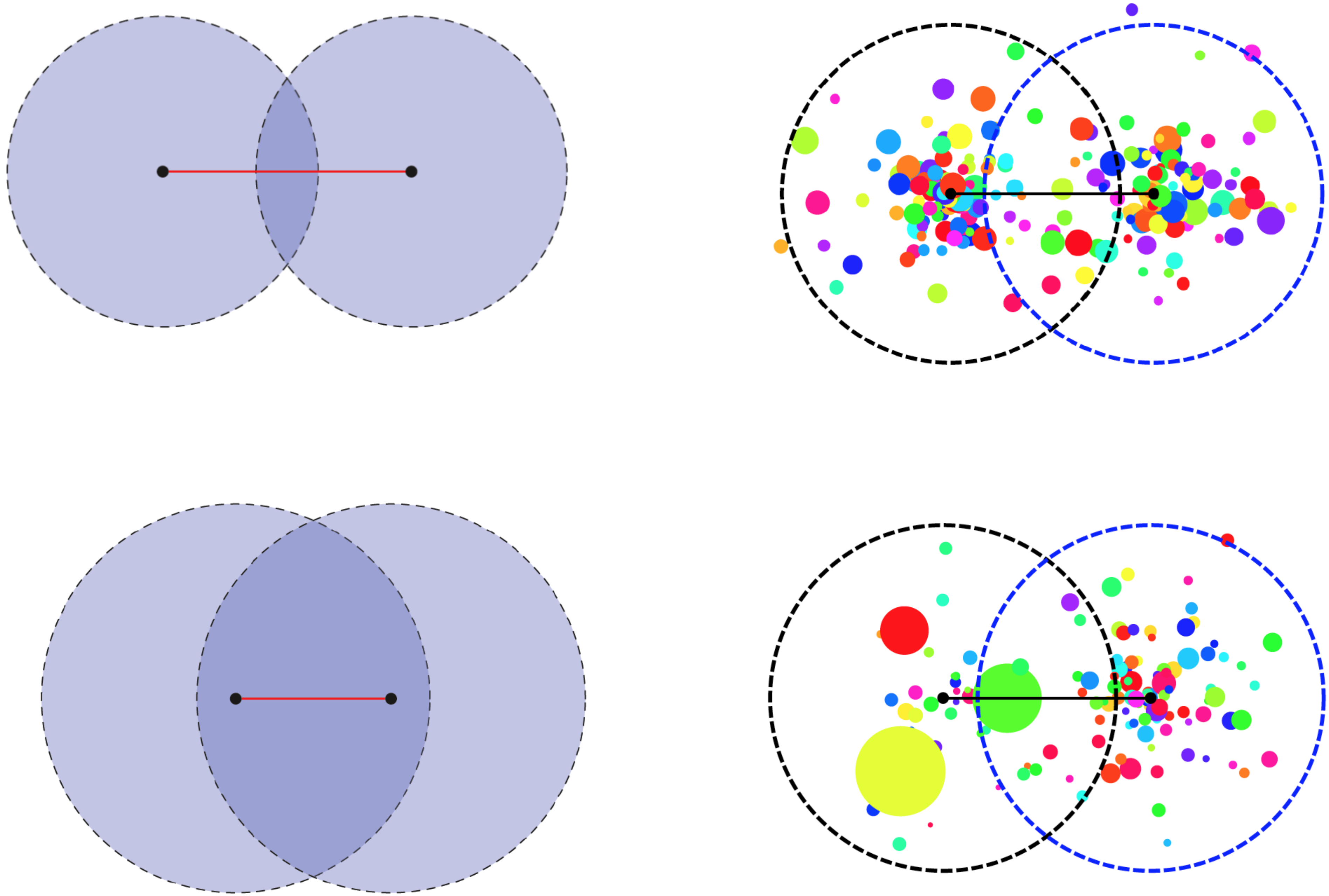
The “Dark Side” of the Standard Model



Parton Distribution Functions

$$f_j(x) \propto \frac{1}{x^{1+\delta}}$$

Rapid growth for $x \rightarrow 0$



Hadron-Hadron interactions.
Multiple Parton interactions in an essential element for the modeling of the interaction.

Problem of “correlated PDF's
(energy conservation + dynamics)

“b-dependence” of the PDF's

[*] Developing a deeper understanding of the structure of hadrons and of the behavior of the the strong interactions is a very important and very valuable field for future theoretical and experimental studies.

[*] INFN (and more in general the community of Particle Physics should support with appropriate resources this topic as an important field of research for the next decade.

[*] Developing a deeper understanding
of the structure of hadrons and of
the behavior of the the strong interactions
is a very important and very valuable field
for future theoretical and experimental studies.

[*] INFN (and more in general the community
of Particle Physics should support
with appropriate resources
this topic as an important
field of research for the next decade.

[*] A [very important] "bonus"
is that these studies requires a programs
of experiments that can be a laboratory
of development of detectors and methods
and an arena of formation for young experimental
scientists

Bridging the Gap

between

Soft and Hard
Hadronic Interactions

Problem of CONFINEMENT