Particle Production in Cosmic Ray Interactions

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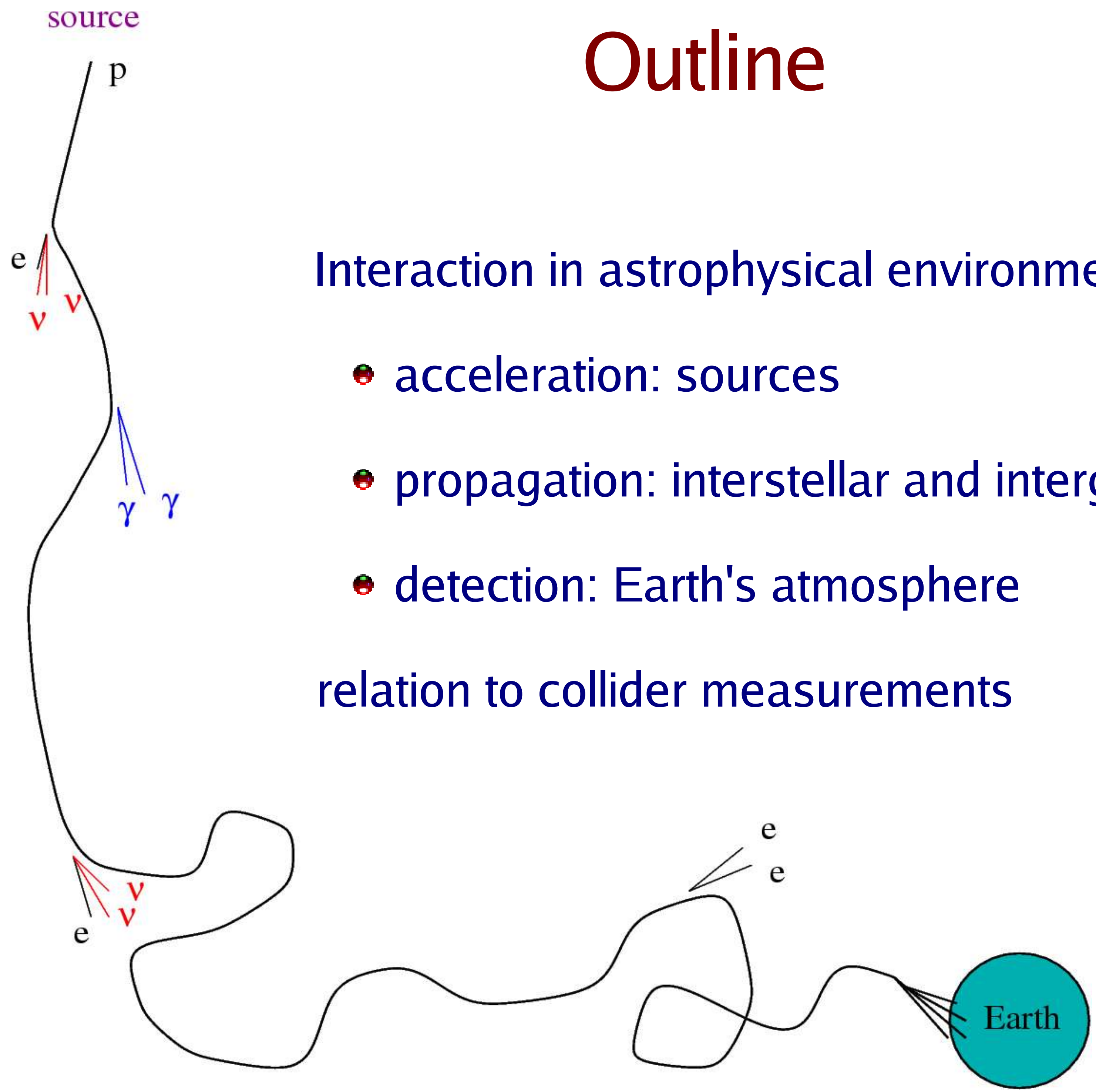
Outline

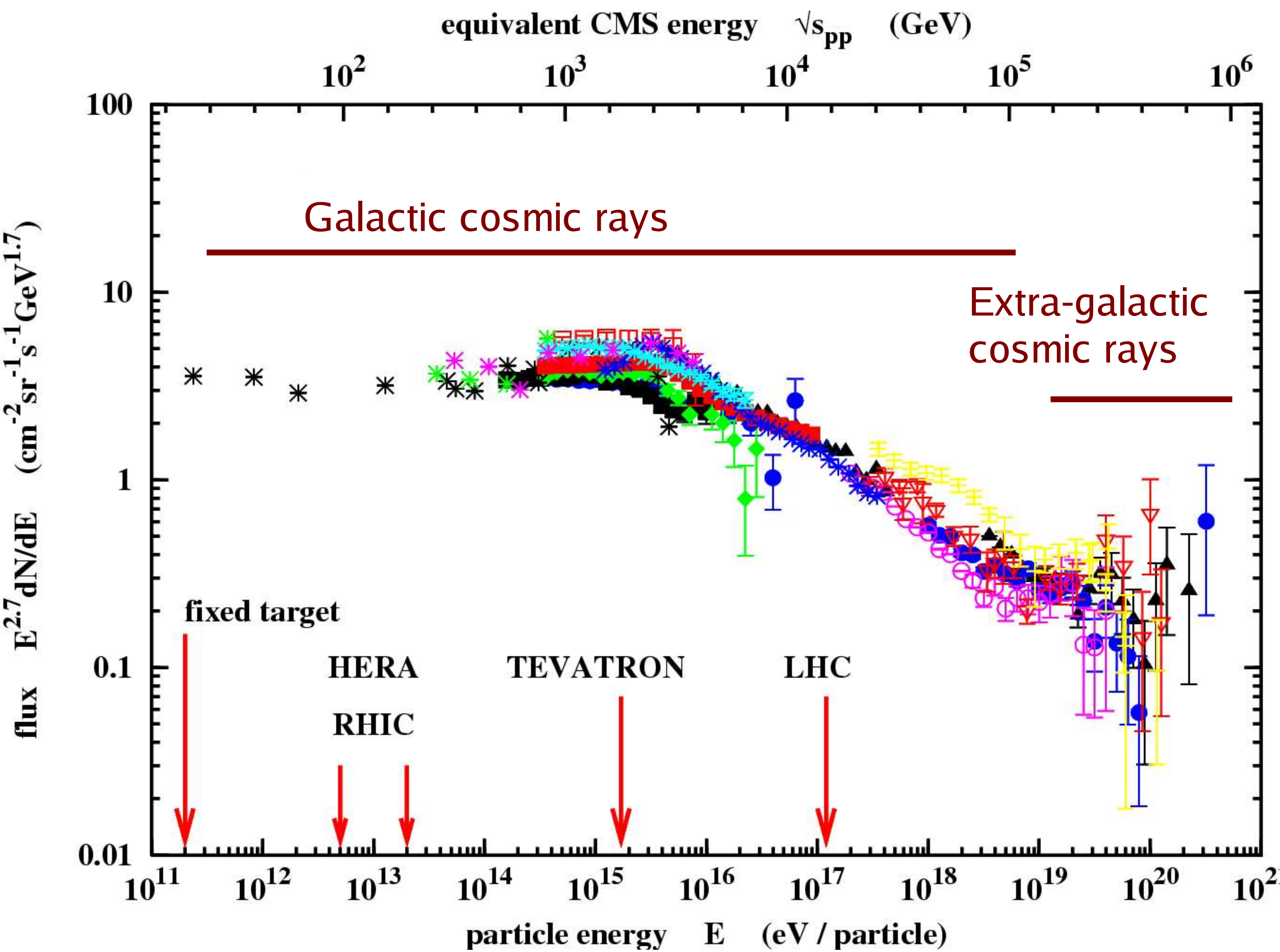
Interaction in astrophysical environments

- acceleration: sources
- propagation: interstellar and intergalactic space
- detection: Earth's atmosphere

relation to collider measurements



Cosmic ray energies



Extra-galactic cosmic ray propagation

Gamma-ray background

$$E_p \geq 5x10^{19}\ eV$$

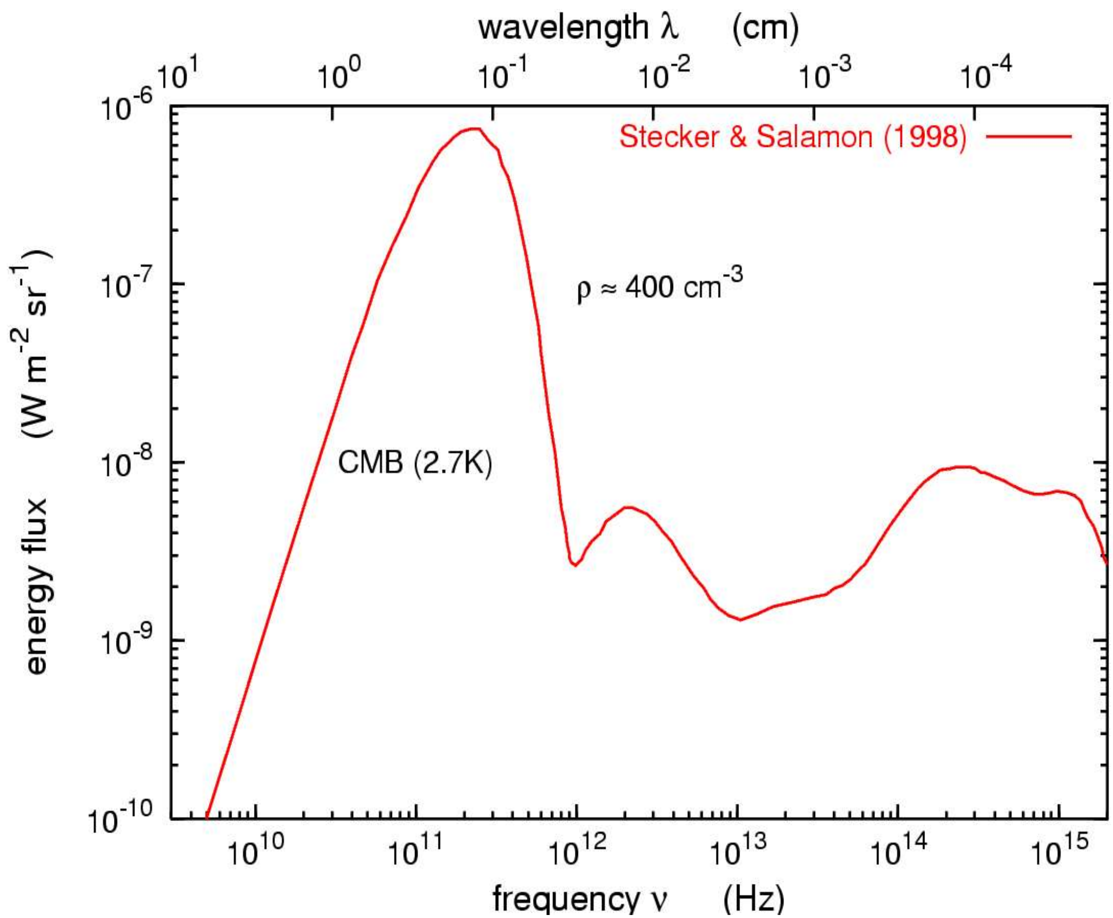
$$E_\gamma \approx 6x10^{-4}\ eV$$

CM energy close to particle production threshold

$$p\ \gamma \rightarrow \Delta^+ \rightarrow p\ \pi^0$$

$$\rightarrow n\ \pi^+$$

$$\rightarrow p\ e^+\ e^-$$



Greisen-Zatsepin-Kuz'min cutoff (1966):

energy loss ~ 20% per hadronic interaction

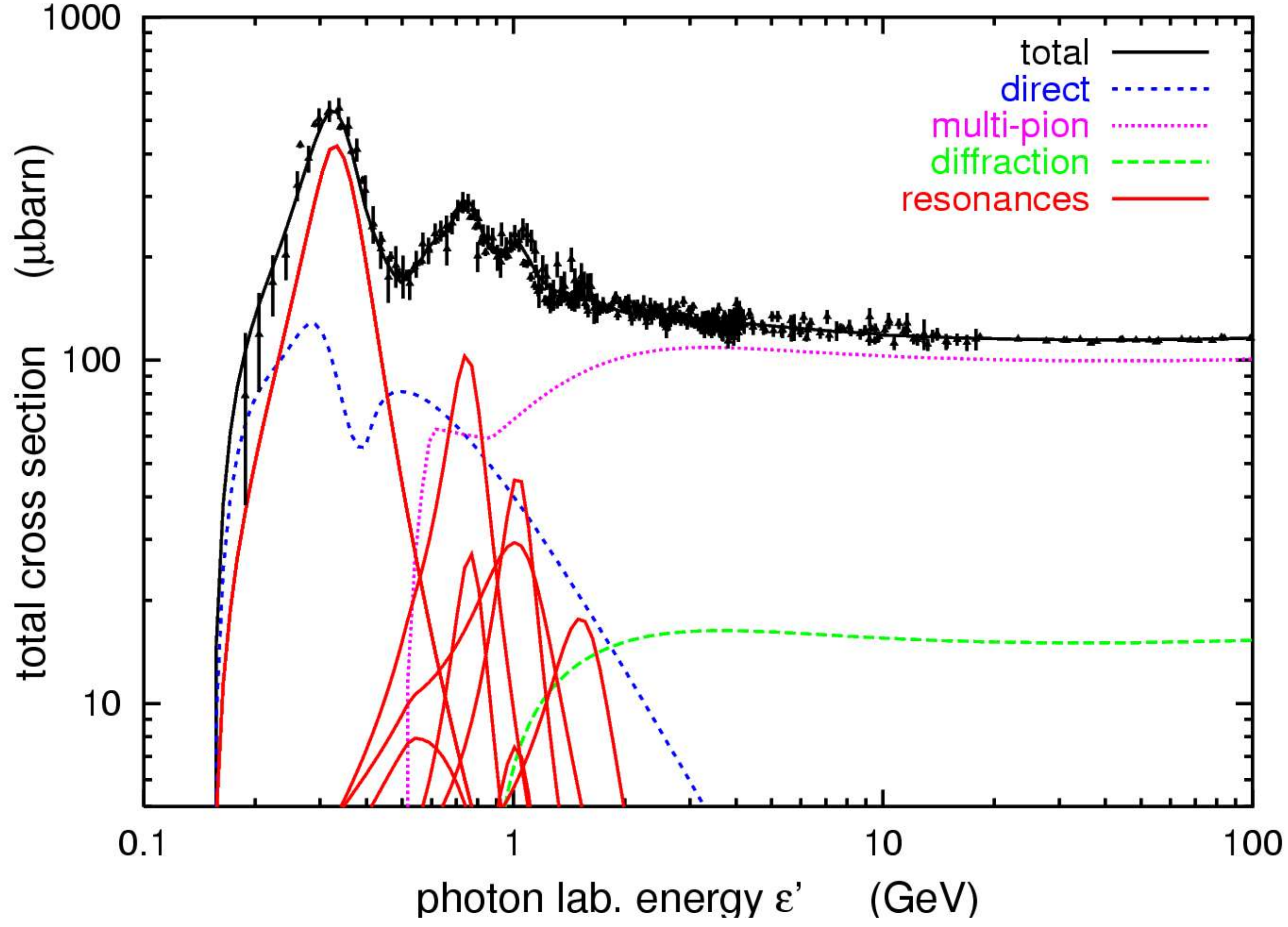
Modeling of low-energy photoproduction

SOPHIA 2.0

CPC 124 (2000) 290

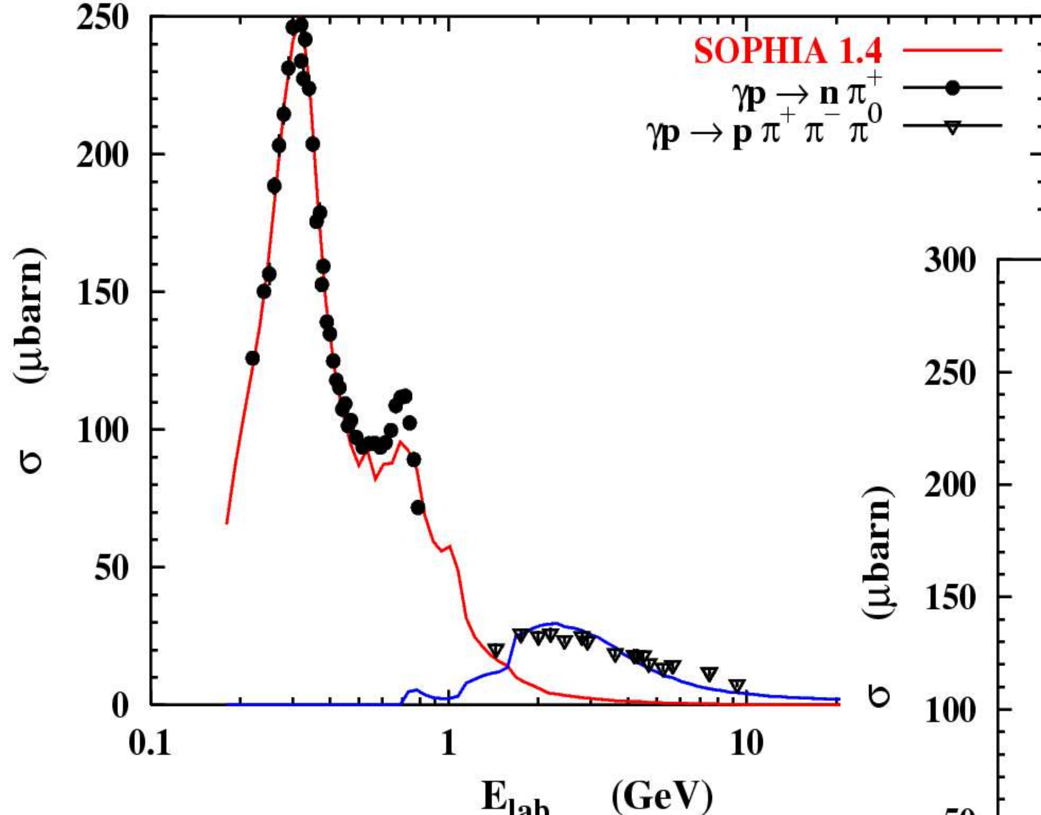
Processes:

- direct pion graph
- resonances
- multi-pion continuum
- diffraction

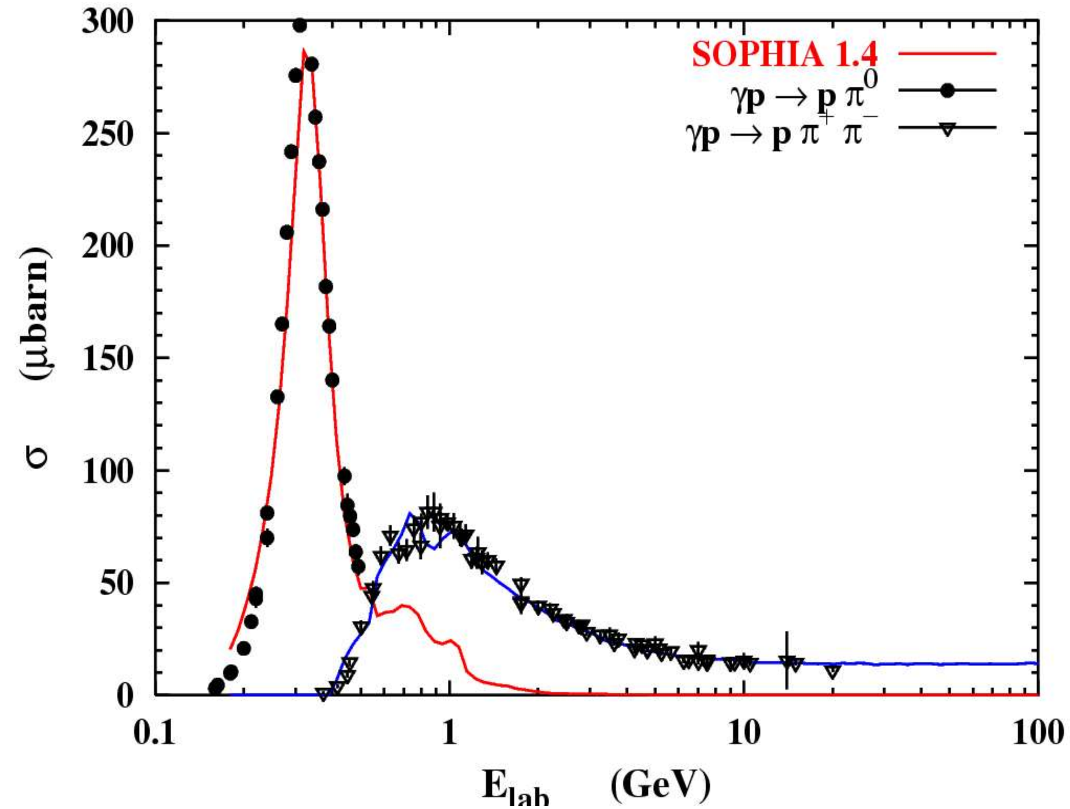


Photoproduction: well-measured in fixed-target experiments

SOPHIA: comparison to data



Mücke et al, CPC 124 (2000) 290

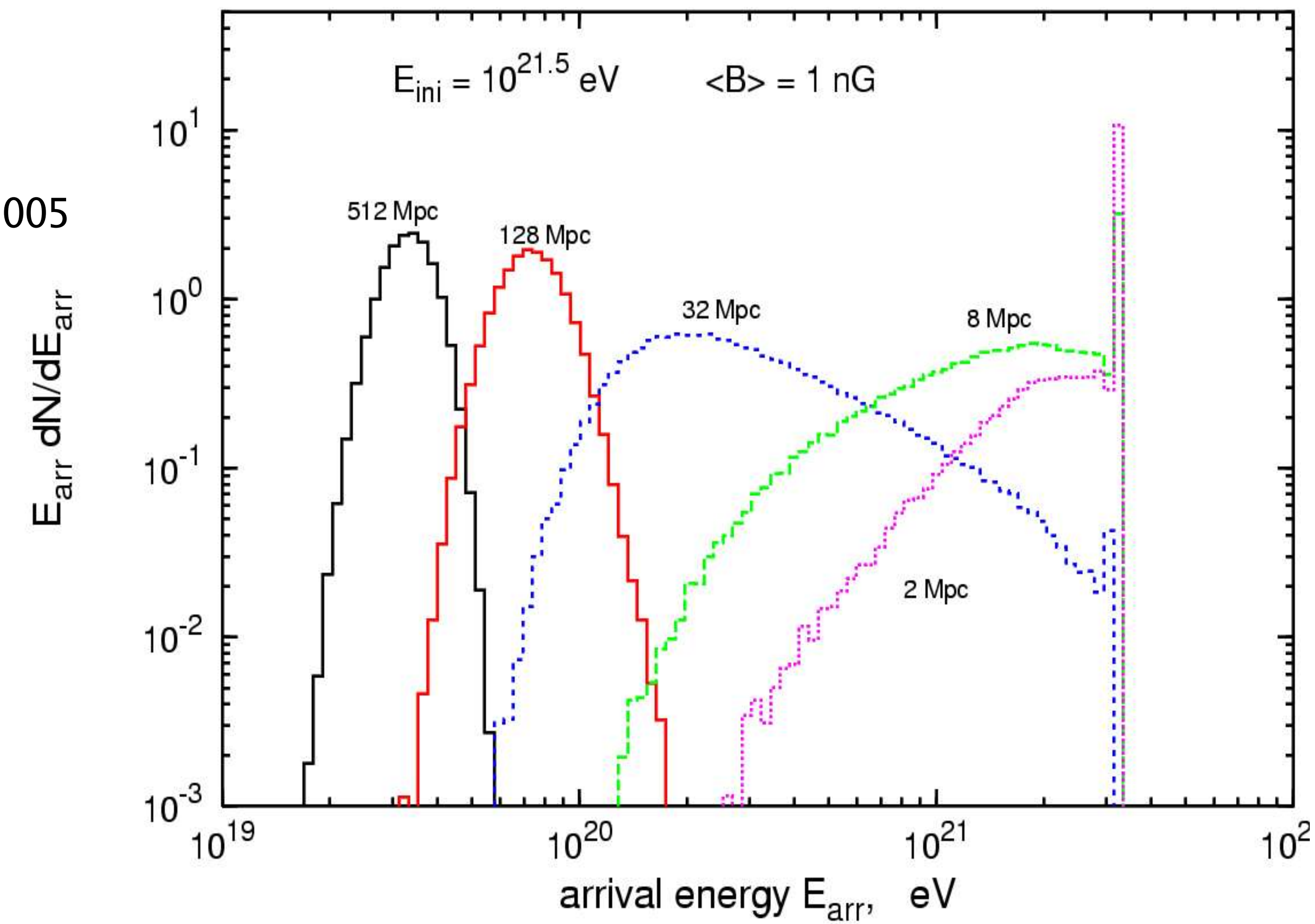


SOPHIA: accurate, phenomenological description of data at very low energy

Prediction of energy loss length

Simulation:

Stanev et al, PRD 62 (2000) 093005



GZK cutoff: stochastic energy loss process

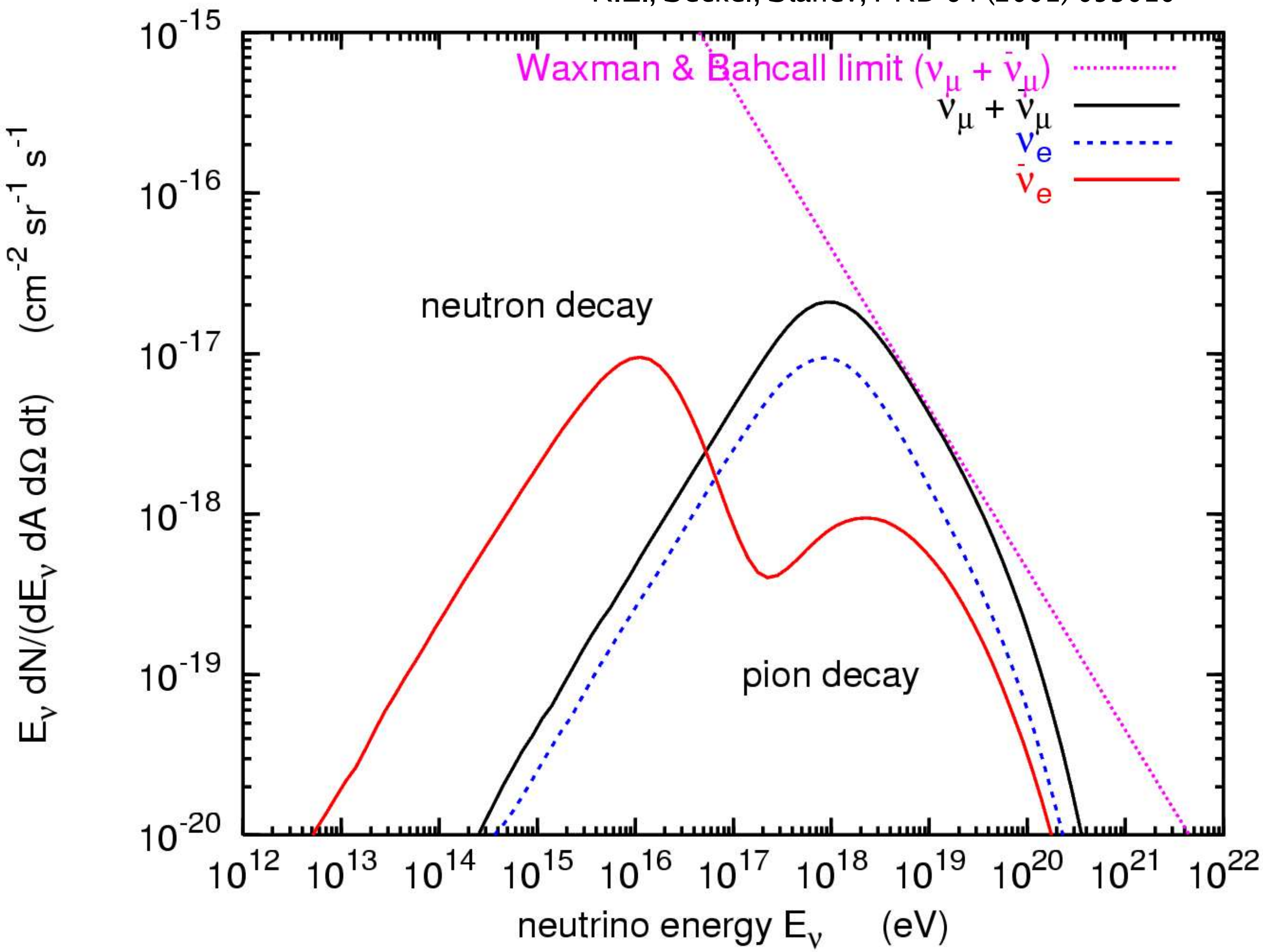
Physics well understood: good agreement between modern calculations

Secondary particle production: GZK neutrinos

R.E., Seckel, Stanev, PRD 64 (2001) 093010

Assumptions:

- all CR at 10^{19} eV extragalactic
- injection spectrum *$dN/dE \sim E^{-2}$*
- uniform distribution of sources
- redshift evolution of source density



Waxman & Bahcall limit (PRD 59 (1998) 023002)

optically thin sources, each proton interacts once before leaving source

Galactic cosmic ray propagation

Cosmic Rays:
mainly p, He, ... Fe

Interstellar medium:
density $\rho \sim 1\,/\mathrm{cm}^3$,
mainly p, He

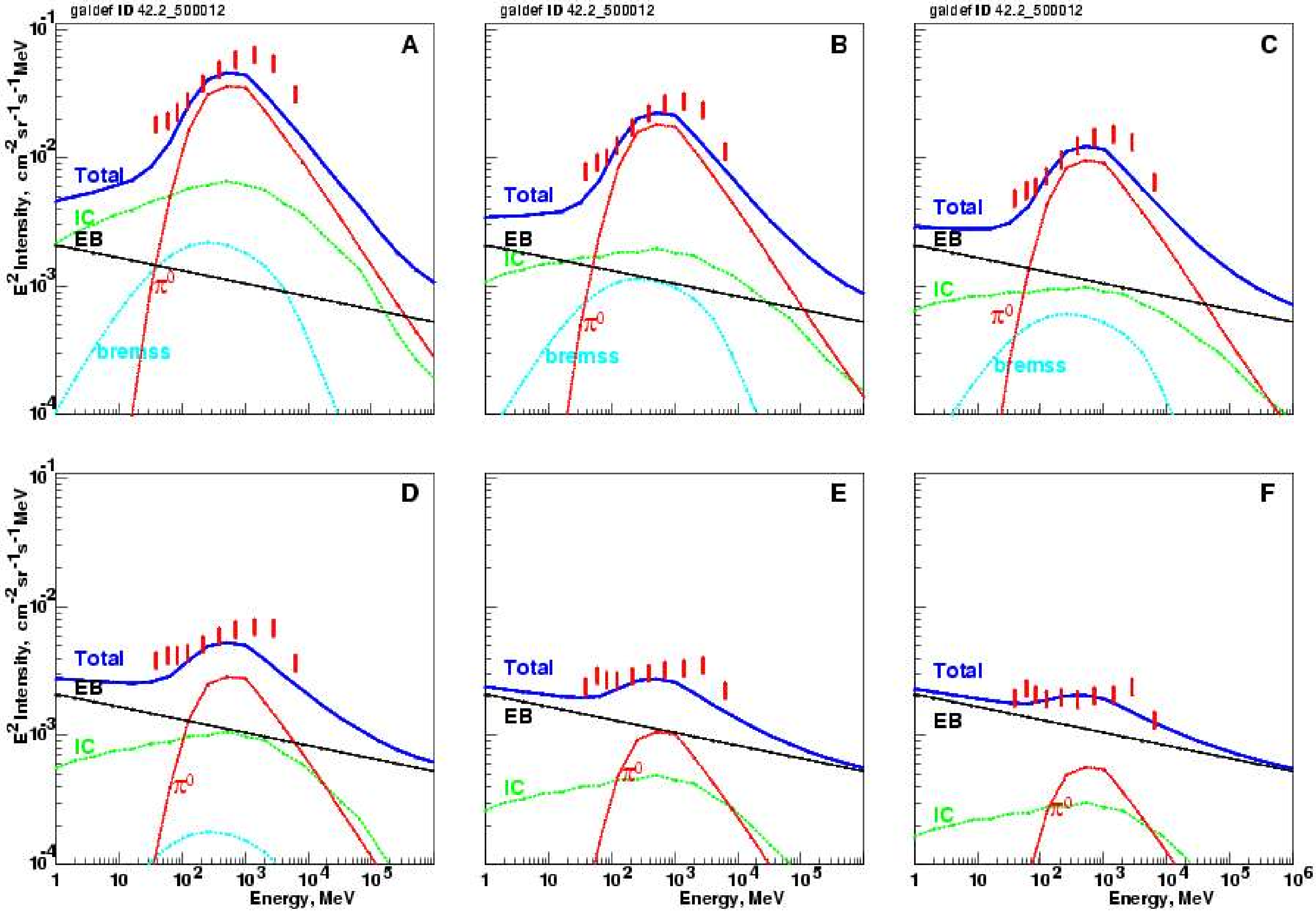
Interaction of cosmic rays with ISM:

- spallation processes of nuclei (B/C ratio etc.)
- gamma-ray production
    - directional information: acceleration sites
    - new physics
- antiproton production
    - antimatter, new physics

Modeling of had. gamma-ray production

- hadronic gamma-ray production via π^0 decay
- characteristic peak in γ-ray spectrum at 70 MeV
- relevant energy range: 1 GeV and up (typical: 100 GeV)
- models: parametrizations of pion production data and Monte Carlo codes
- accelerator data (p-p collisions):
  - secondary photon multiplicity
  - π^0 distributions only at very low energy

Example: diffuse gamma-ray emission

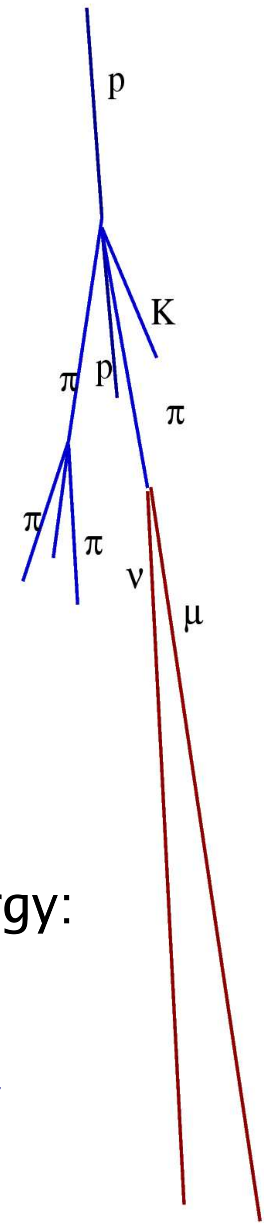


Strong, Moskalenko & Reimer, astro-ph/0306346

diffuse flux: identified point sources subtracted

γ-ray excess?

Cosmic ray interactions in the atmosphere

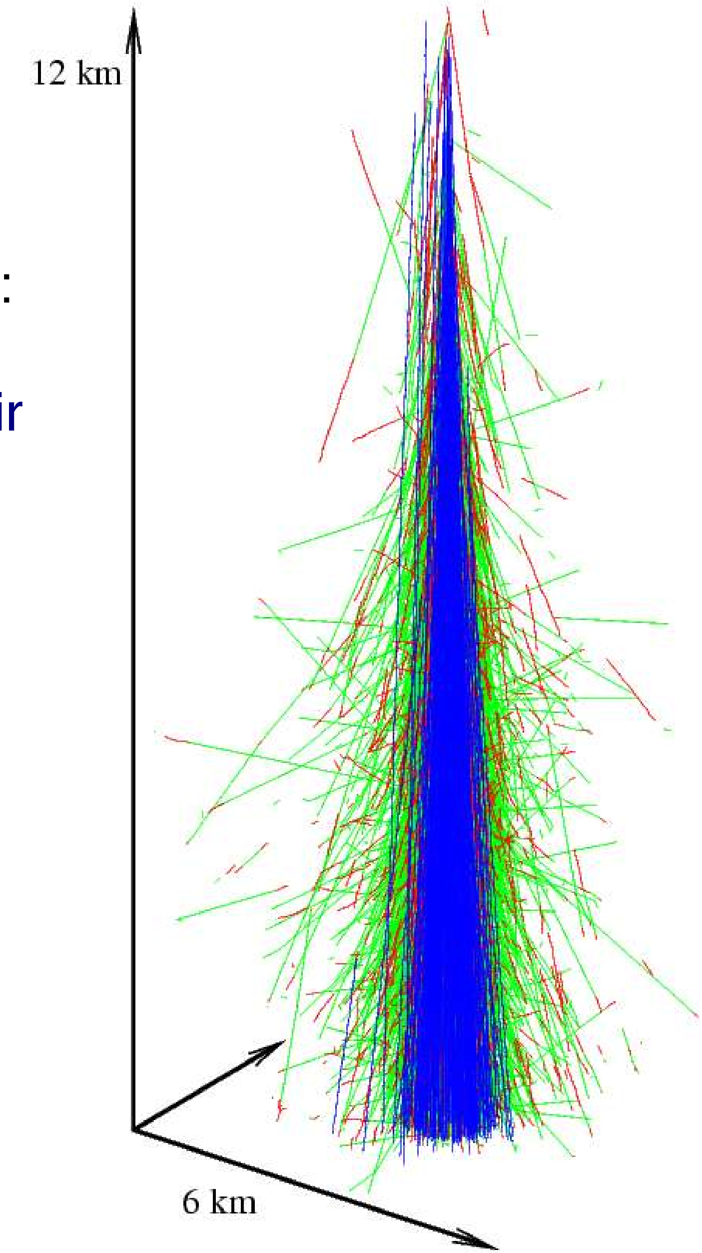


low- and
medium energy:

inclusive flux
of secondary
particles

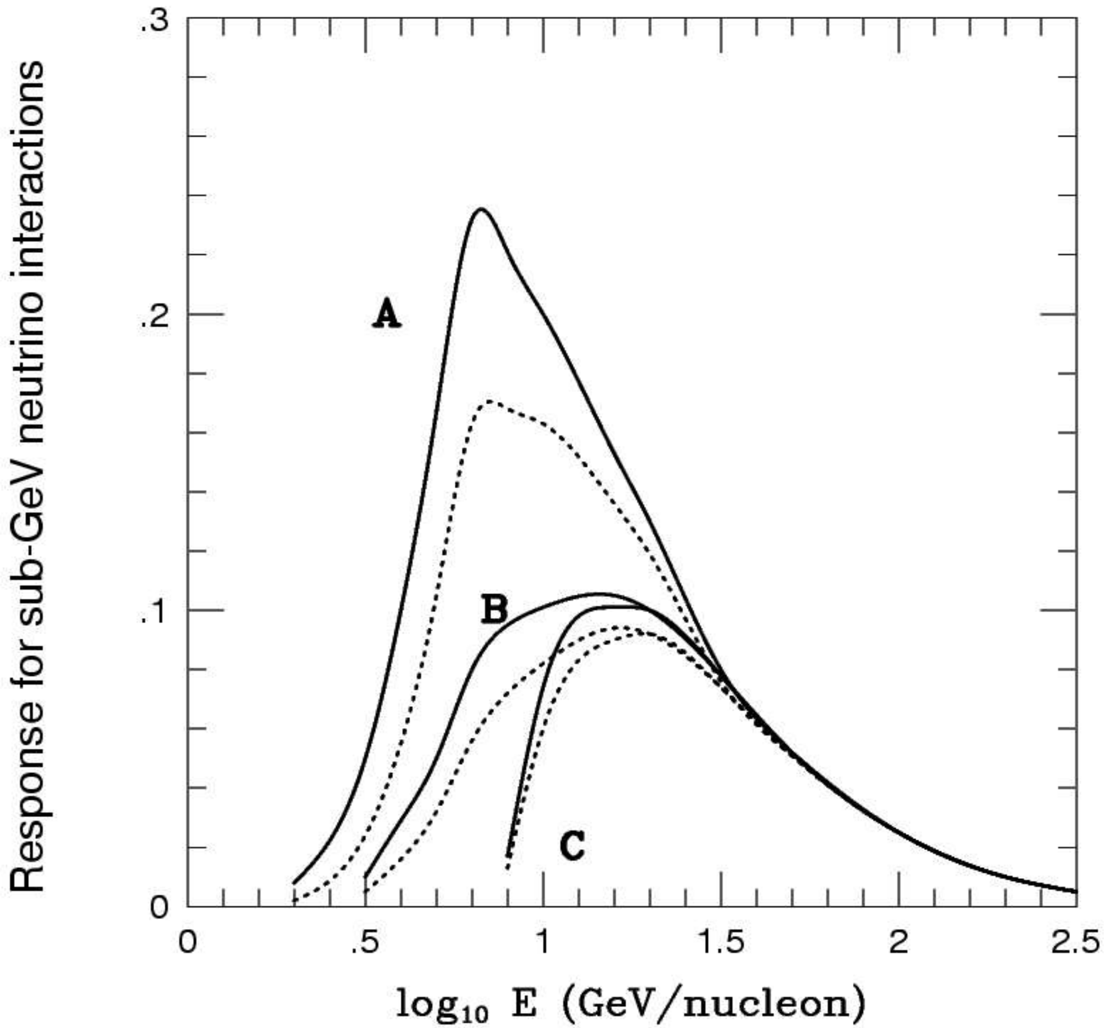
high energy:

extensive air
shower



SuperKamiokande: sub-GeV neutrinos

R.E., Gaisser, Stanev, PLB 472 (2000) 113



primary cosmic ray energy:

A ... no geomagnetic cutoff

B ... upward going ν's

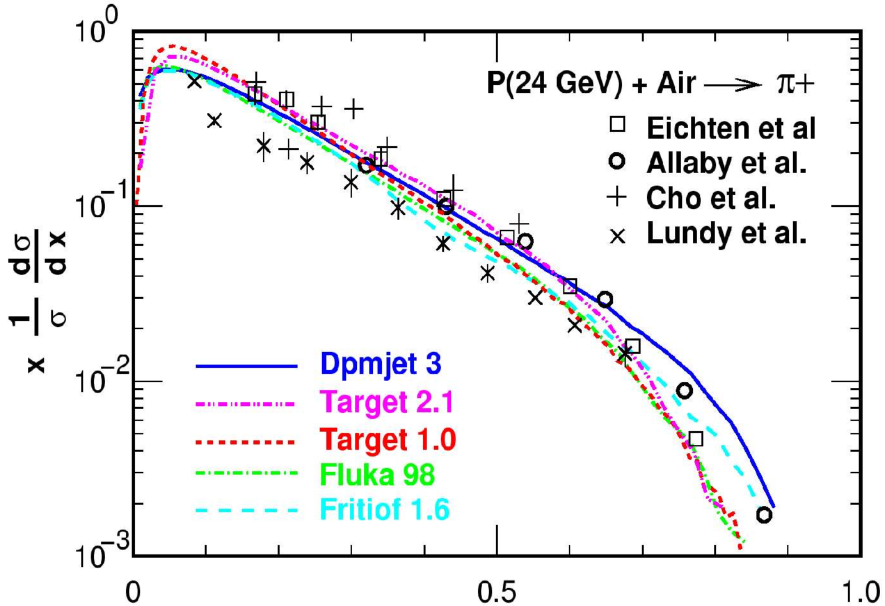
C ... downward going ν's

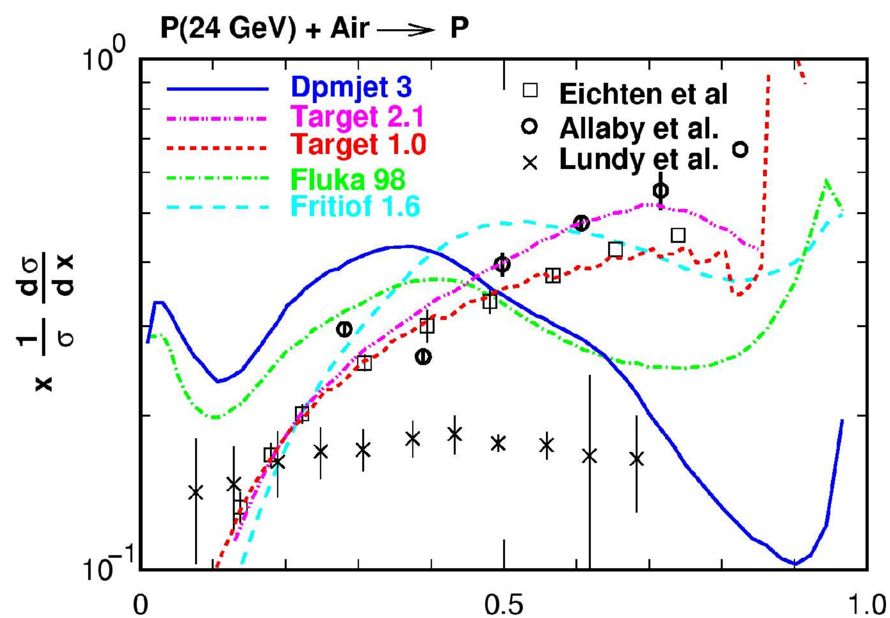
similar energy range for low-energy muons

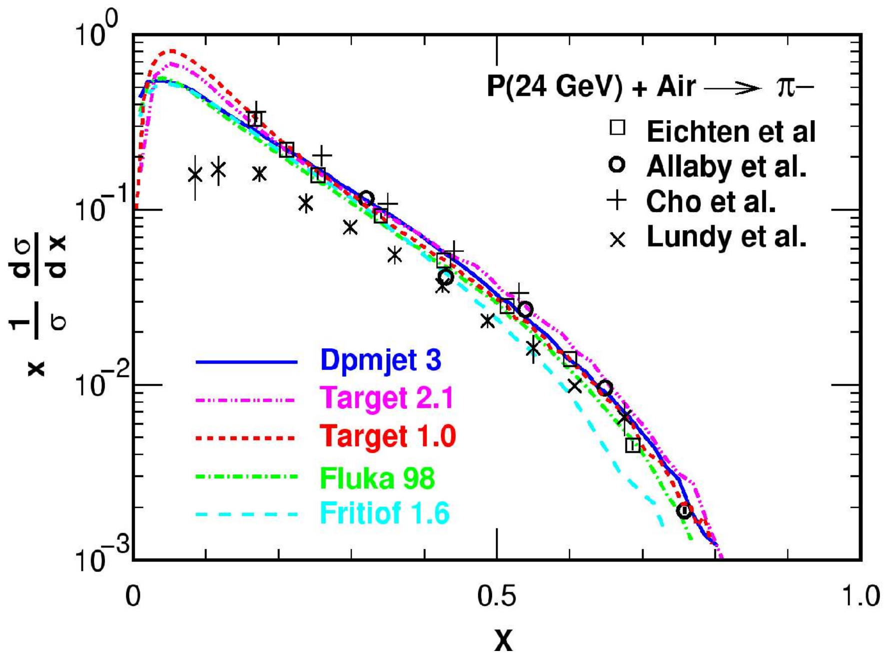
p-air collisions important: charged pions and kaons

almost no data available from accelerators

Low-energy models vs. data





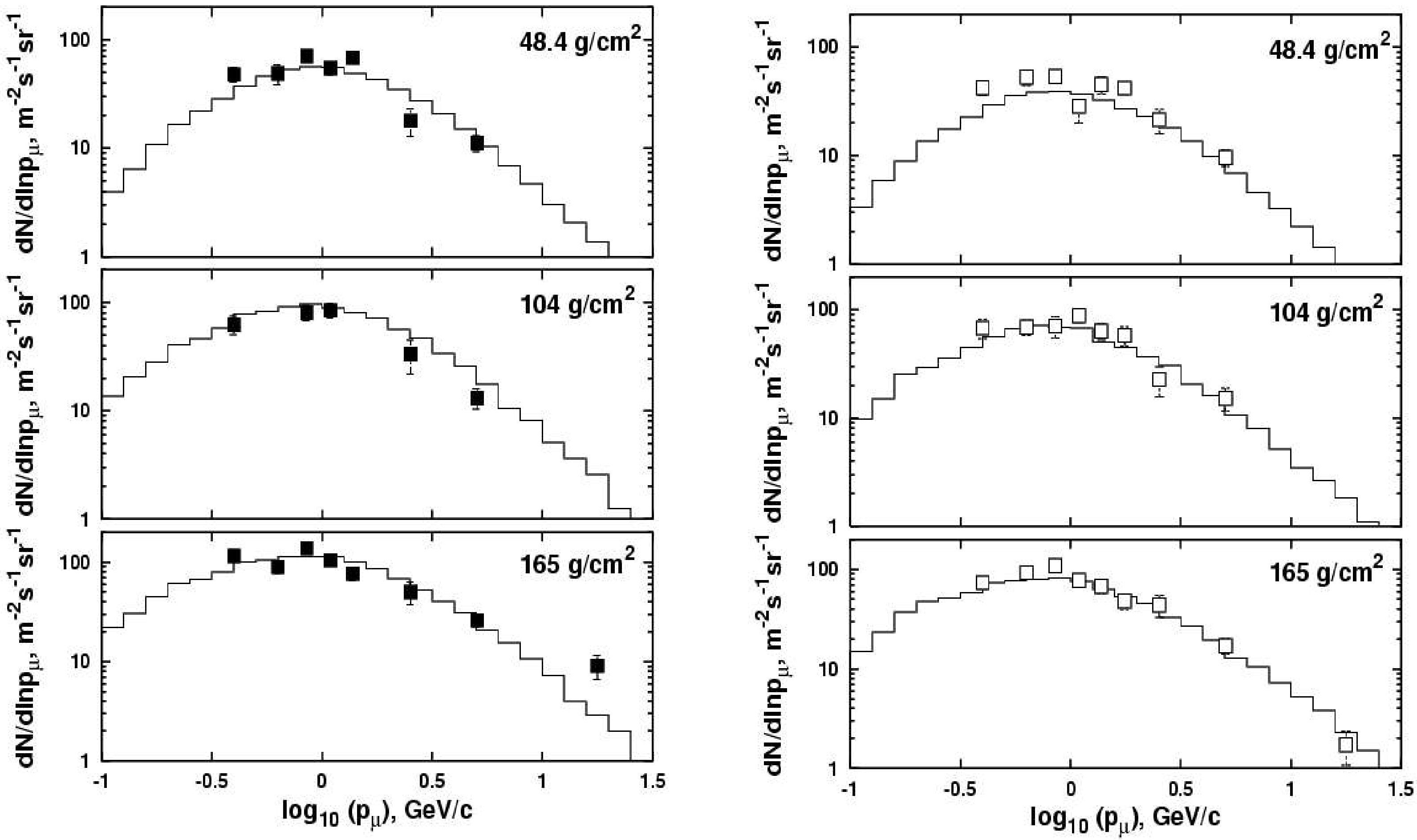


- pion and kaon production:
  general picture clear
  precision measurements
- leading nucleon production:
  data and models inconsistent
- new experiments:
  HARP, NA49, MIPP, ...

Gaisser & Honda, Ann. Rev. Nucl. Part. Sci. 52 (2002) 153

Cross-check: inclusive muon data

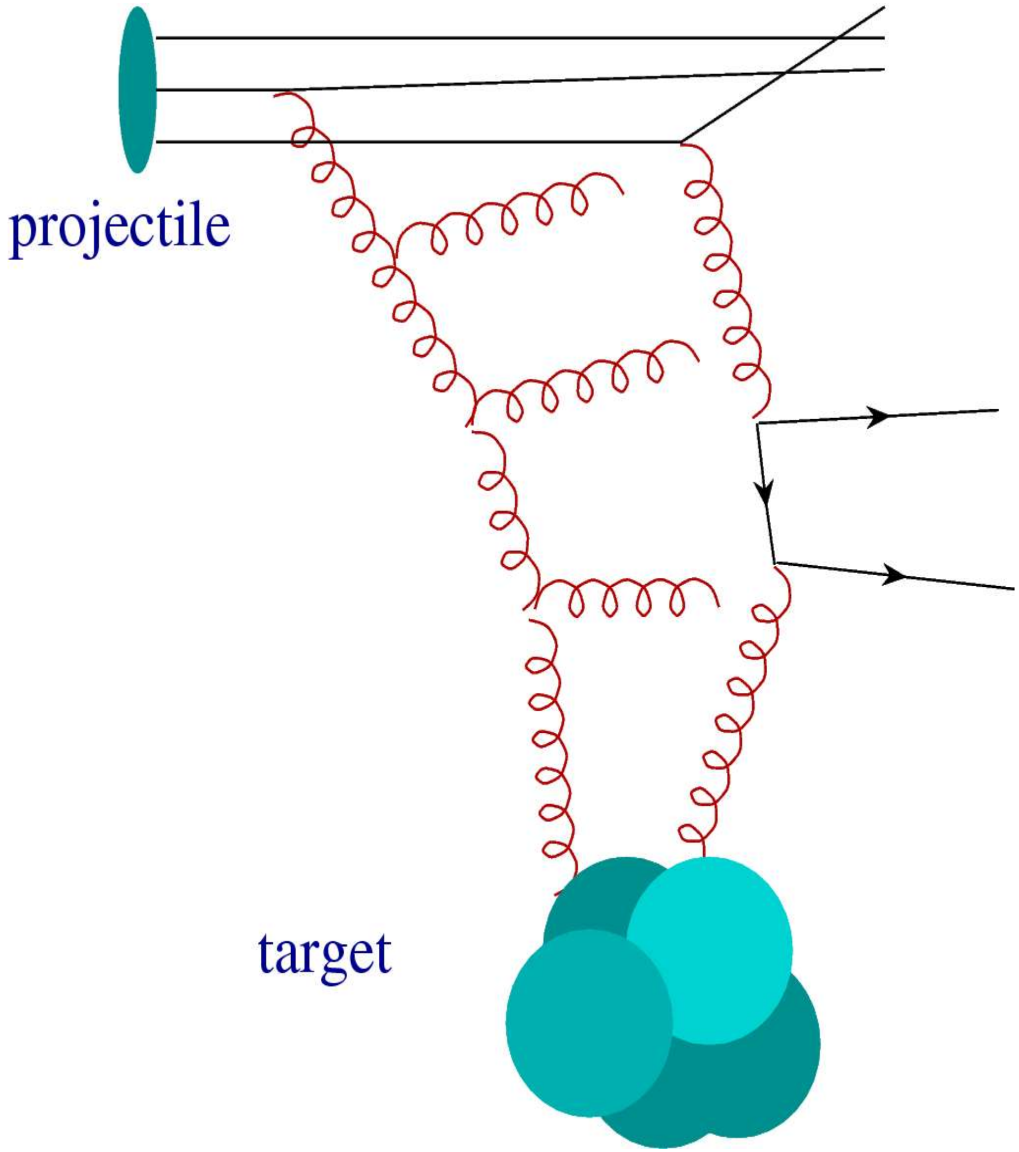
CAPRICE '98: measurement of cosmic ray flux and muons at different altitudes



Boezio et al. ICRC 2003

example: comparison to 3D calculation with TARGET 2.1

Particle production at (ultra-)high energy



extensive air showers:
up to $\sqrt{s} \sim 400{,}000$ GeV

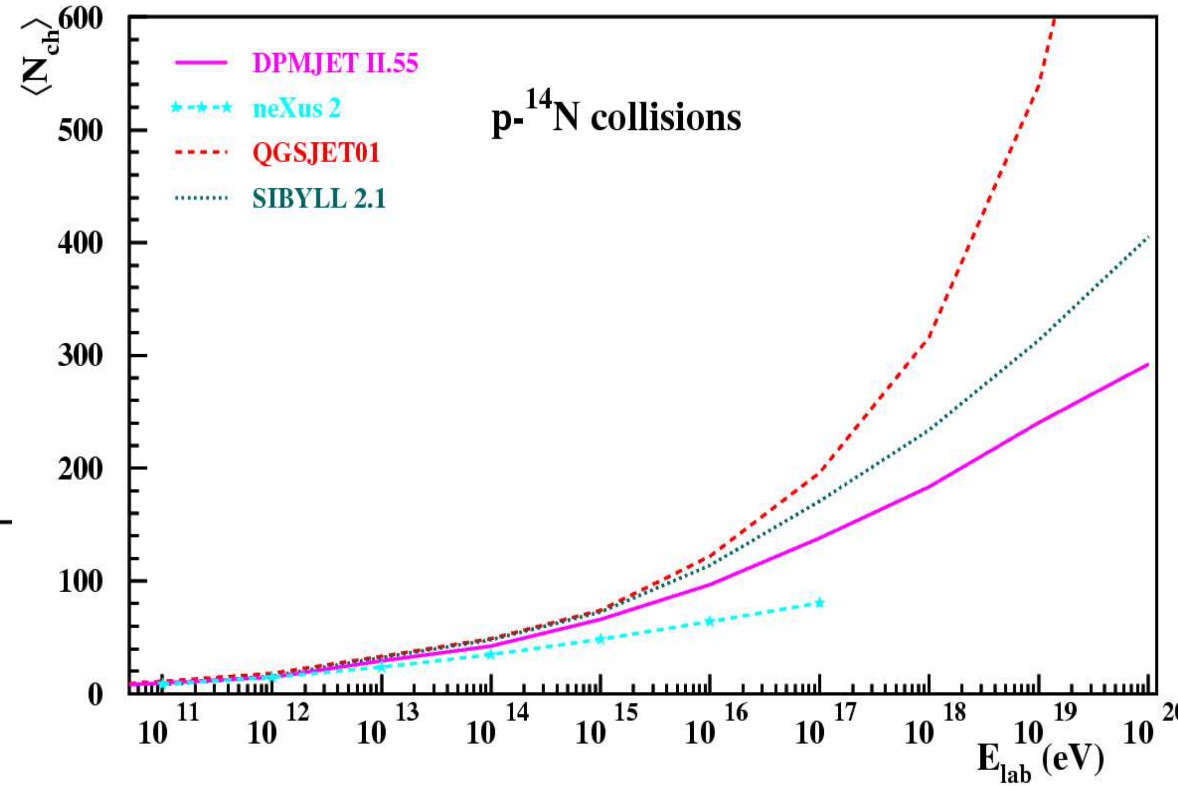
QCD-inspired models

- central particle production:
  QCD minijets
- forward particle production:
  fragmentation region scaling
- generalization to nuclei:
  Glauber approximation

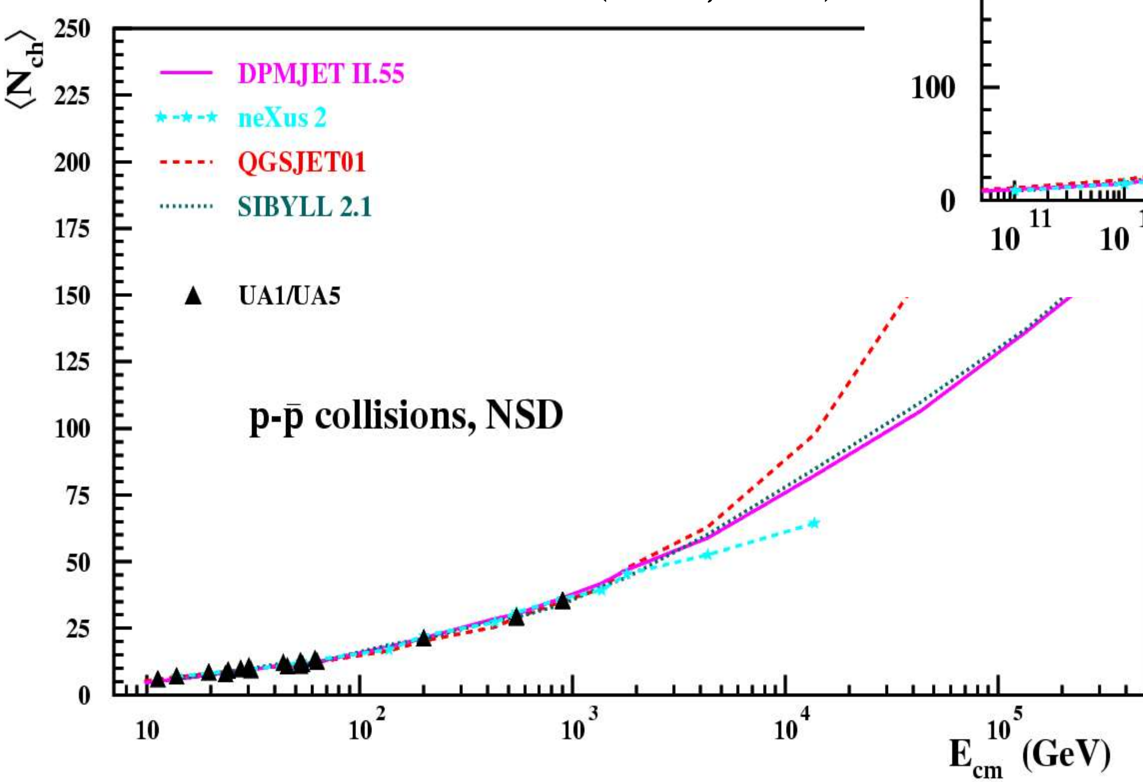
Example: multiplicity extrapolation

Large uncertainties:

- no calculable theory
- limited data available



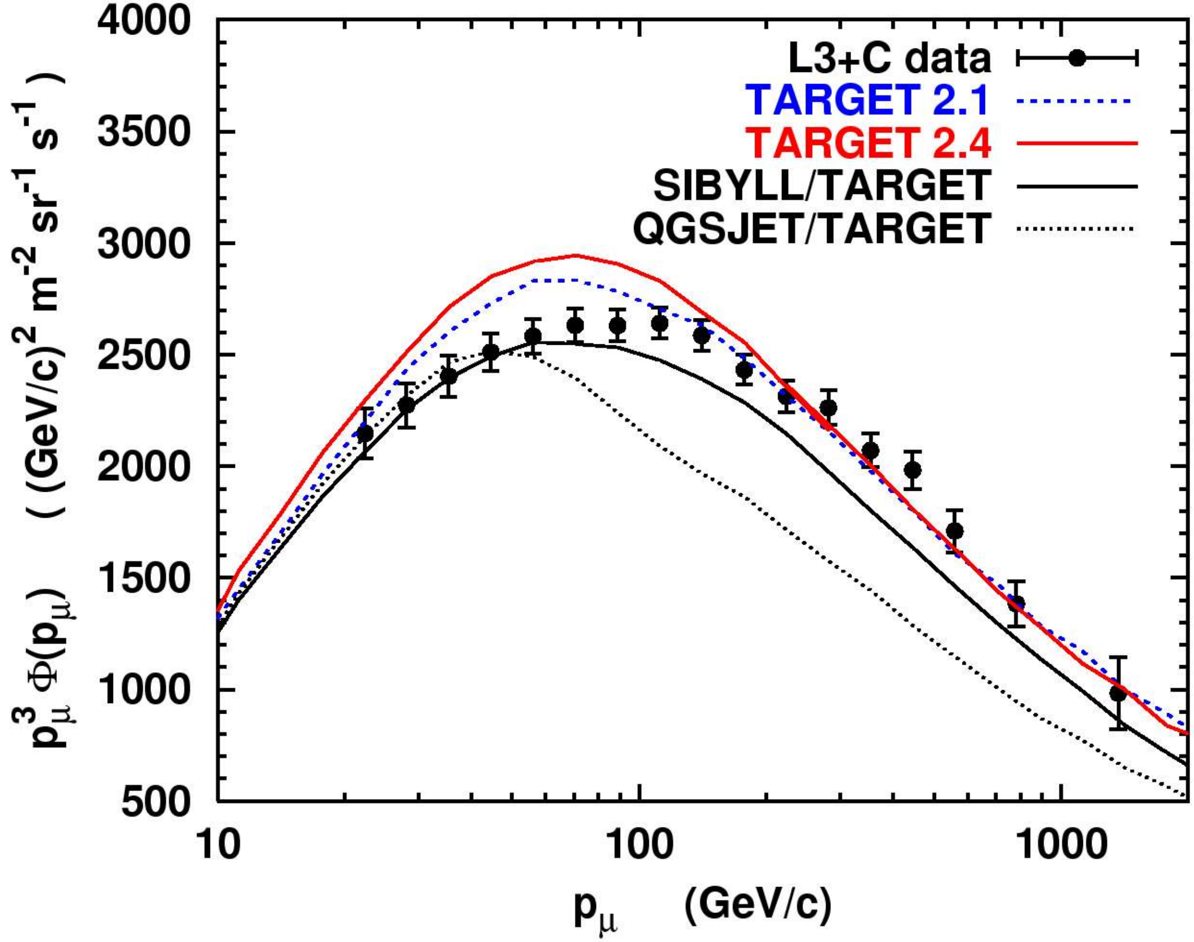
(Heck, 2004)



problems start already at medium energy

L3+C inclusive muon measurement

R.E. et al, ICRC 2003



Data: L3 Collab., M. Unger et al, ICRC 2003

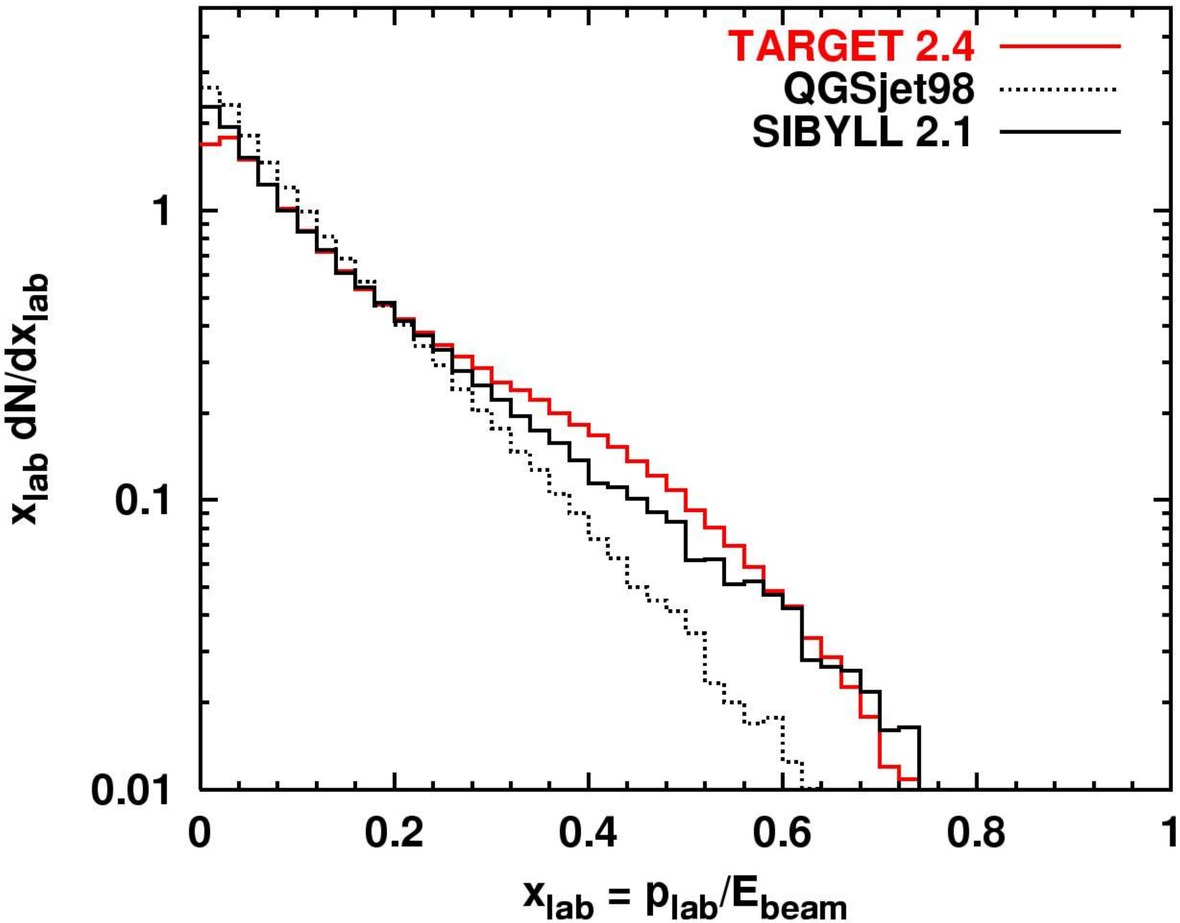
Simulation

- E < 200 GeV: TARGET
- E > 200 GeV: high-energy model

Paradox:

model with higher multiplicity predicts fewer muons

Comparison of charged pion distributions



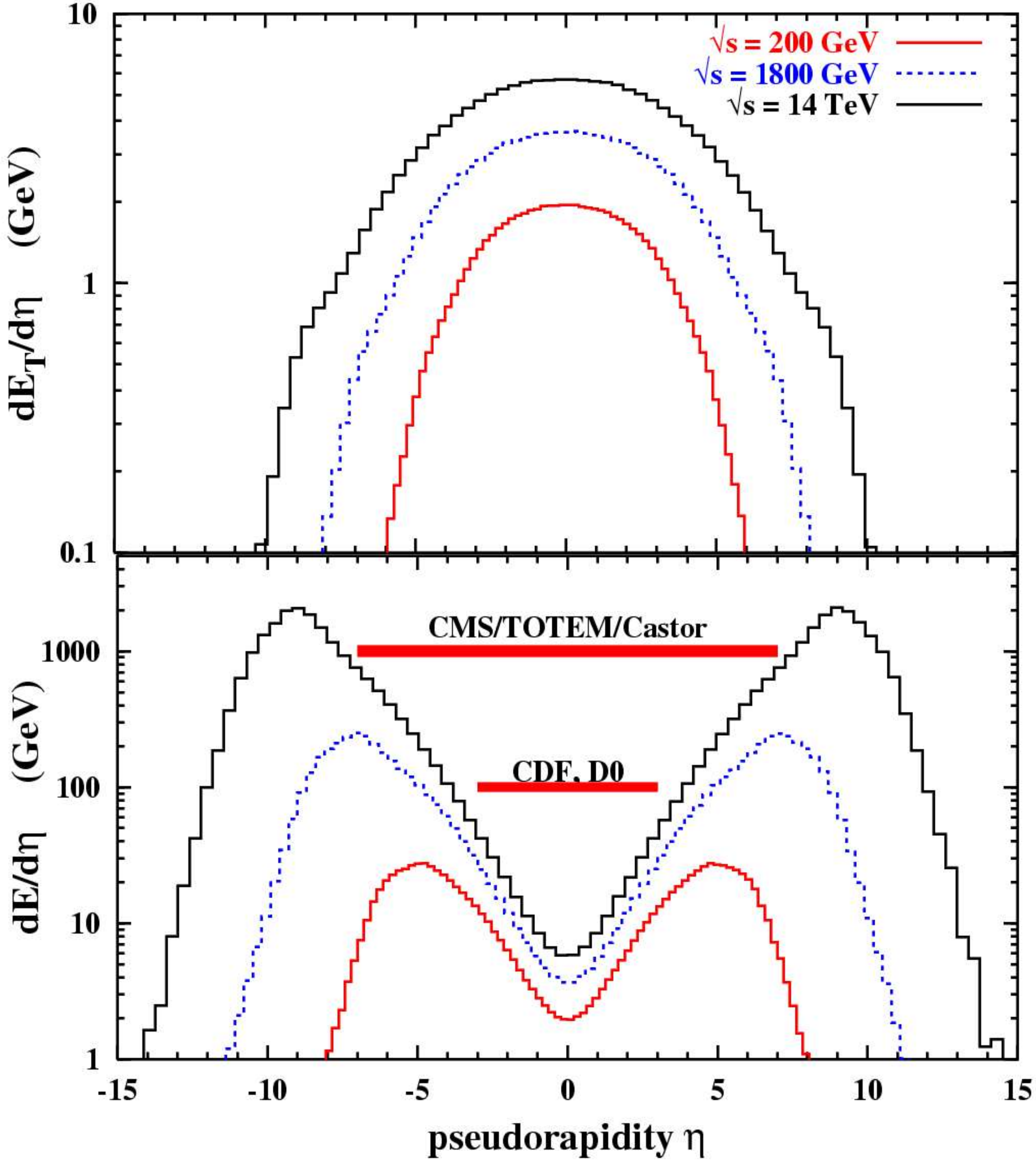
Simulation:

- p-air collisions at Elab = 500 GeV
- charged secondaries

Interpretation:

- QGSJET: multiplicity significantly higher
- SIBYLL: pion spectrum harder

Central vs. forward particle production



HEP:
multiplicity and
transverse energy

Cosmic rays:
total energy

forward particle
production difficult to
measure at colliders

Summary & outlook

- low-energy processes well understood (GZK cutoff)
- extrapolation to high-energy uncertain (extensive air showers)
- leading particle production of prime importance
- cosmic ray measurements complementary to collider data
- increasing interaction between HEP and CR communities
- several dedicated experiments running or planned (HARP, NA49, MIPP, ...)

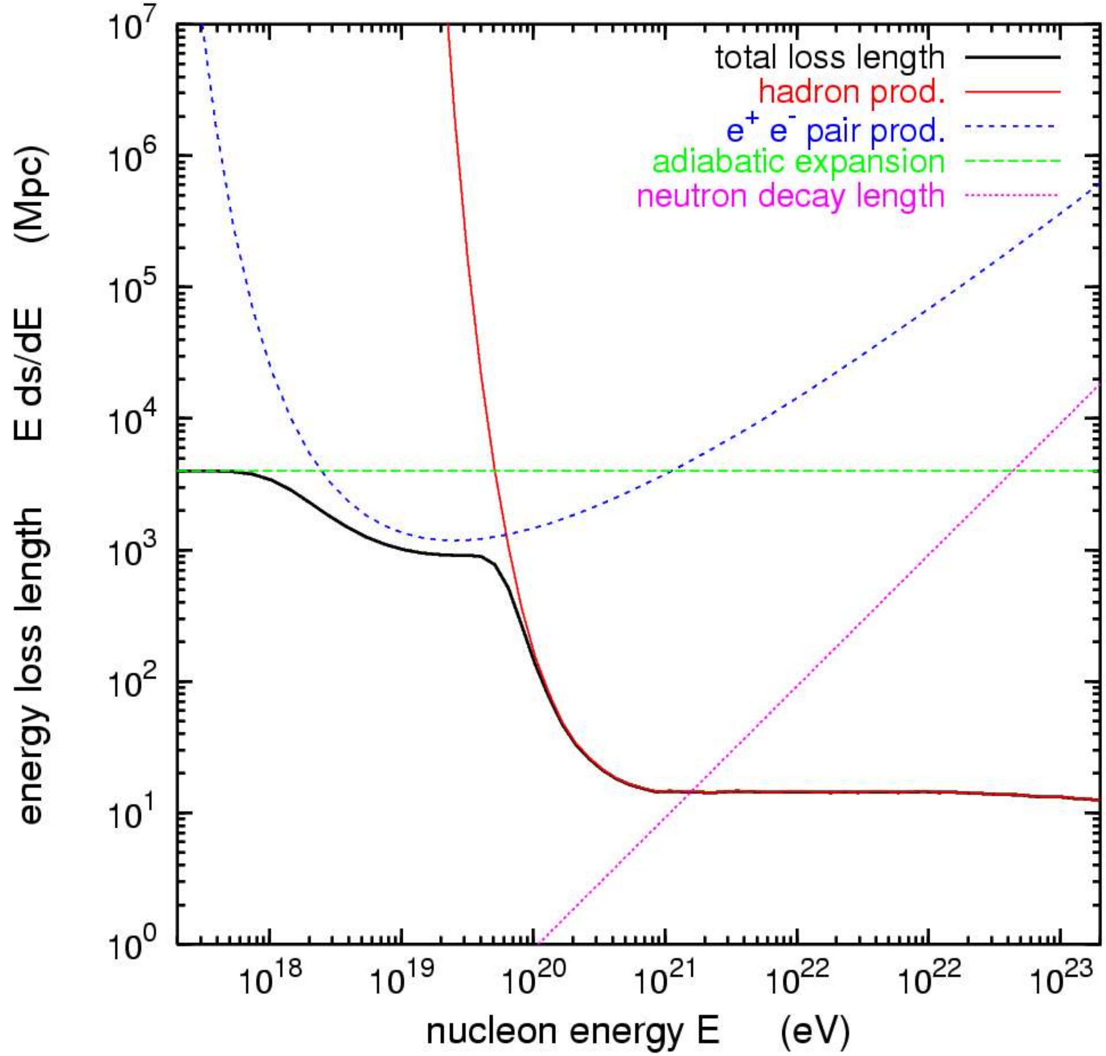
Prediction of energy loss length

Simulation:

PRD 62 (2000) 093005

GZK cutoff: stochastic energy loss process

Energy loss length: average of many propagations



Energy loss length: other particles

nuclei:

- photodissociation
- sensitivity to IR and CMB background

gamma-rays:

- pair production
- sensitivity to CMB and radio background

ApJ 512 (1999) 521