Hadronic interaction models and interpretation of CR data

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“Avoid models as much as you can!”

“Important issues are INPUT OF REAL DATA ...”

A. Watson

Why do we need models?

- generally: to combine pieces of experimental information into a coherent picture
  ⇒ to predict observables in (yet) unstudied kinematic regions
- particularly: to provide an interface between the collider and CR fields

Cosmic rays: why & how?

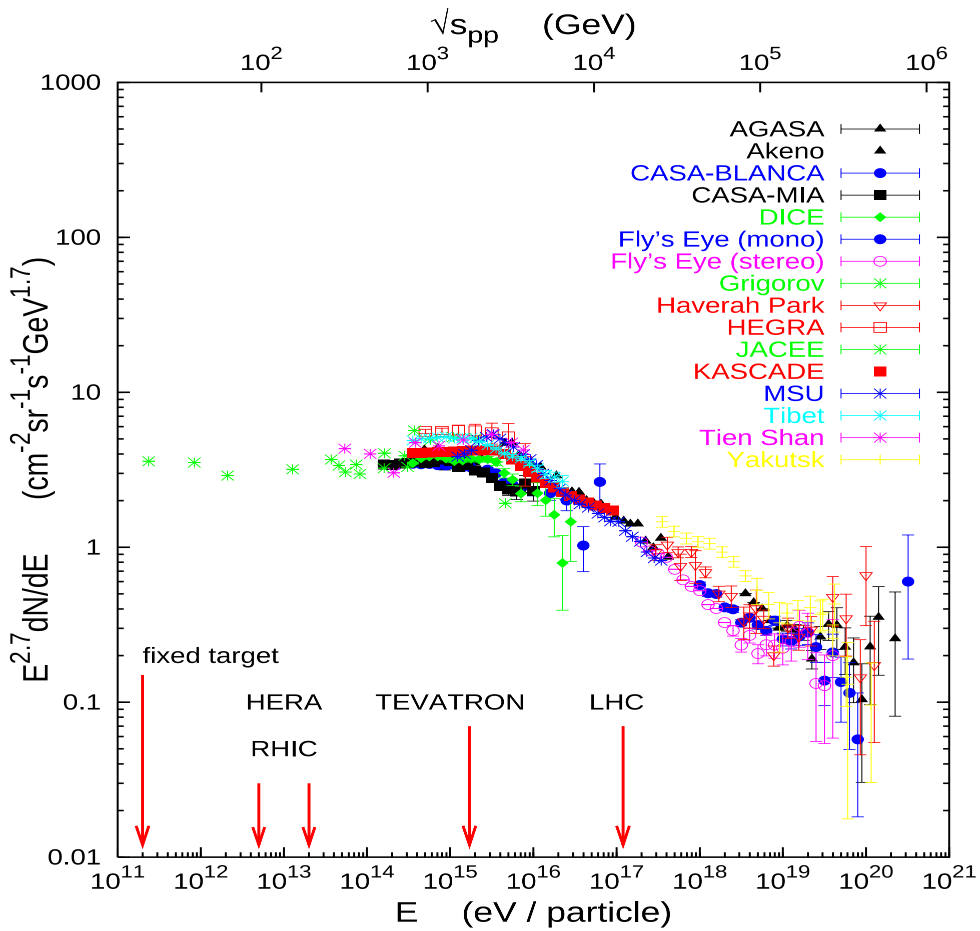
Why: to learn about

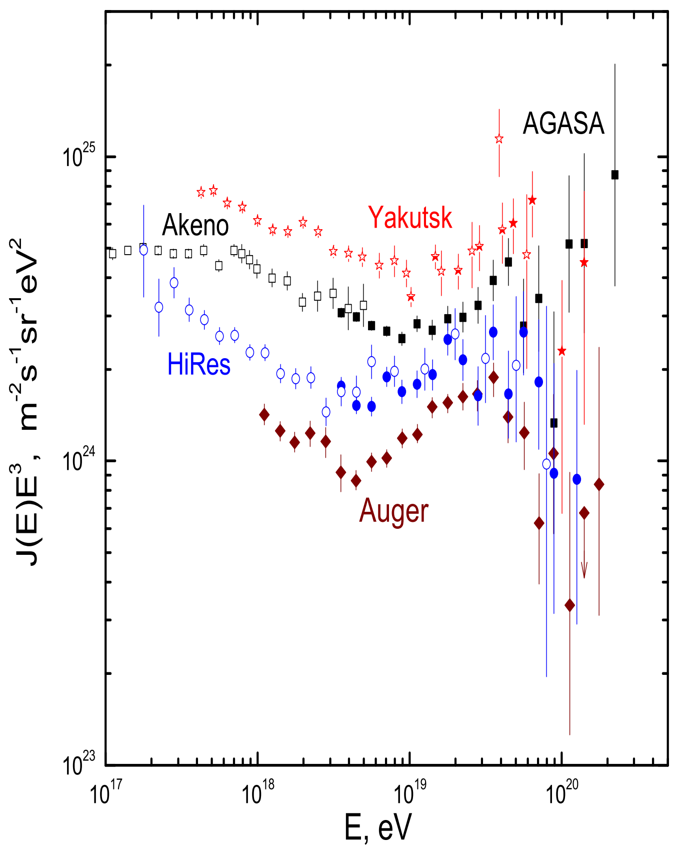
- their sources
- accelleration mechanism
- propagation ($\Rightarrow$ (extra-)galactic magnetic fields)

How: determining

- CR arrival directions
- energy spectrum
- particle composition

(U)HECR spectrum

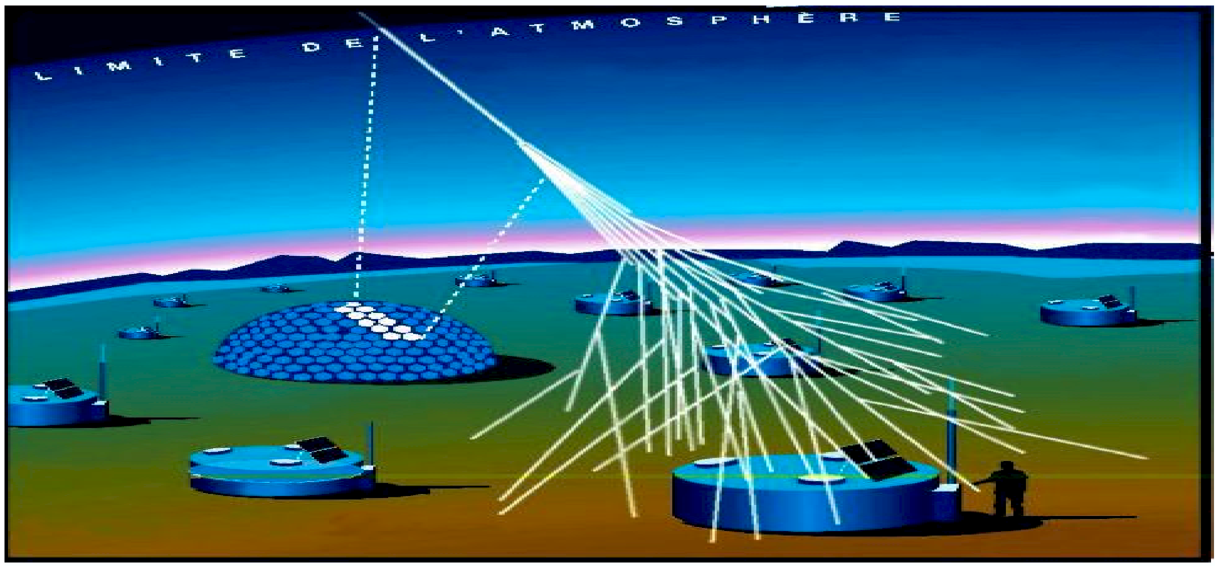




- 'knee' @ $\sim 3 \cdot 10^{15}$ eV (cutoff for galactic accelleration of protons?/propagation?)
- 'ankle' @ $\sim 10^{19}$ eV (transition to extragalactic CRs?)
- GZK cutoff (?) @ $\sim 10^{19.5}$ eV ($p + \gamma_{\rm cmb} \longrightarrow \Delta$)

Cosmic ray detection

At very high energies - indirect (extensive air showers)

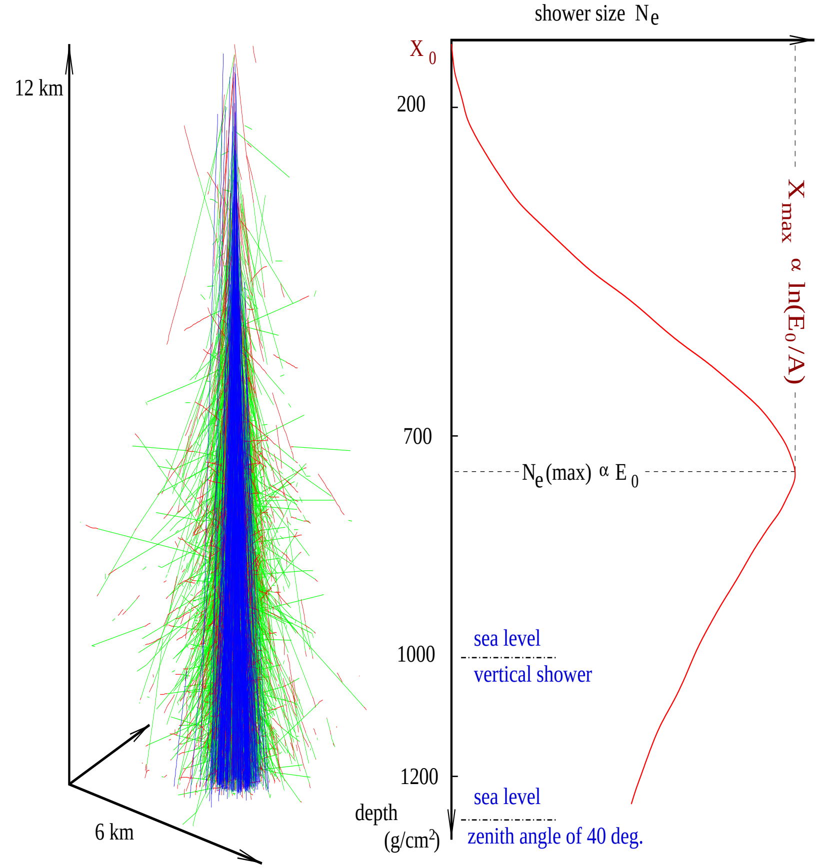


- ground observations (using the atmosphere as the target)
  - primary energy $\Longleftrightarrow$ charged particle density at ground
  - CR composition $\Longleftrightarrow$ muon density at ground
- measurements of fluorescence light
  - primary energy $\Longleftrightarrow$ integrated light
  - CR composition $\Longleftrightarrow$ shower maximum position X_{max}

Hadronic interactions in EAS: key quantities

Extensive air shower (EAS) development $\Leftarrow$ high energy interactions

- backbone - hadron cascade
- guided by few interactions of initial (fastest secondary) particle
  $\Rightarrow$ main source of fluctuations
- many sub-cascades of secondaries $\Rightarrow$ well averaged



Basic model-dependent quantities:

- shower maximum position $X_{\rm max}$
  - mainly sensitive to $\sigma_{p-{\rm air}}^{\rm inel}$ ($\sigma_{p-{\rm air}}^{\rm non-diffr}$), $K_{p-{\rm air}}^{\rm inel}$
- number of muons at ground N_μ
  - mainly depends on $N_{\pi-{\rm air}}^{\rm ch}$ (at energies $\sim \sqrt{E_0}$)

Fluorescence measurements:
- grossly depend on the primary particle interaction

Ground-based studies:

- very sensitive to pion-air interactions

Requirements to CR interaction models:

- cross section predictions
- description of minimum bias hA- and AA-collisions
- $\Rightarrow$ importance of 'forward' region
- predictive power (no re-tuning possibilities)

But:

- low sensitivity to 'fine' details (smoothed by EAS development)
- high p_t - irrelevant, e.g., $p_t = 10$ GeV, $E_0 = 10^5$ GeV $\Rightarrow \Theta \simeq p_t/E_0 = 10^{-4}$
- charm, bottom, ... new rare processes - also irrelevant:
  - much smaller inclusive cross sections $\Rightarrow$ small contribution to N_e, N_μ
  - produced mainly at central rapidities $\Rightarrow$ don't influence $X_{\max}$

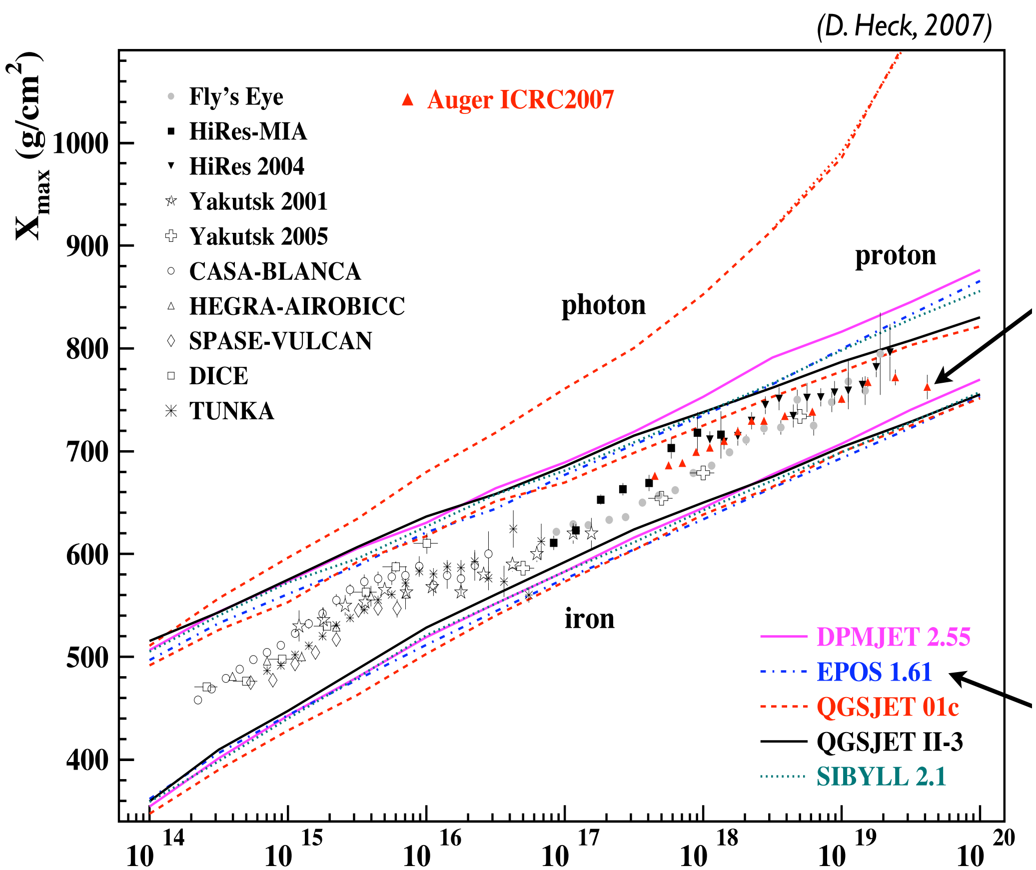
$\Rightarrow$ CR interaction models $\equiv$ models of 'typical' (mb level) interactions

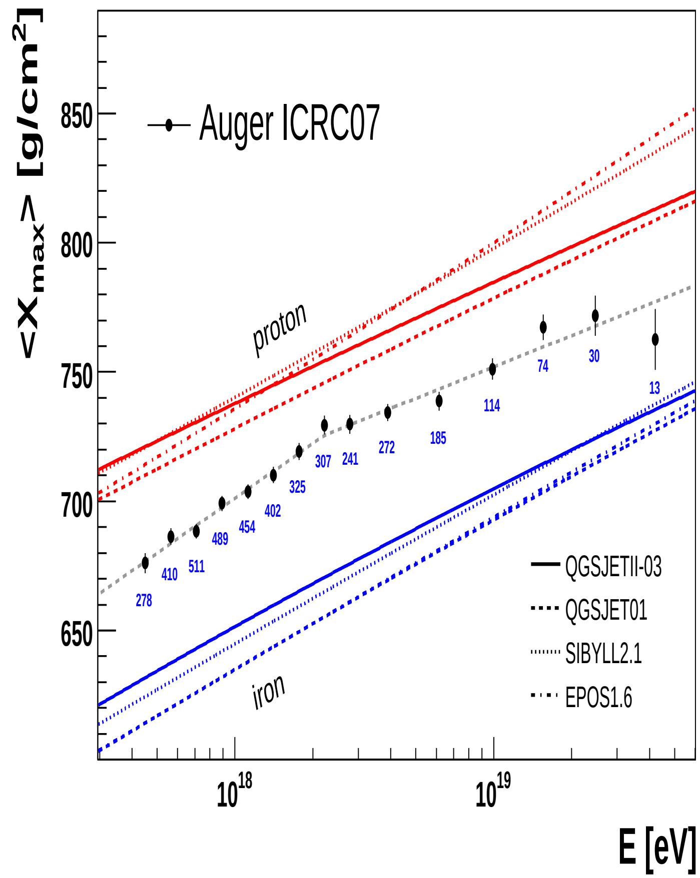
$\Rightarrow$ based on Reggeon techniques (Pomeron approach)

Example models:

- SIBYLL 2.1 (Engel, Gaisser, Lipary & Stanev): CR analog of PITHYA
- QGSJET / QGSJET-II (Kalmykov & SO / SO): Pomeron-Pomeron interactions
- EPOS (Pierog & Werner): separate treatment of 'dense' (central 'core') and 'dilute' (peripheral 'corona') interaction regions

CR composition with $X_{\max}$



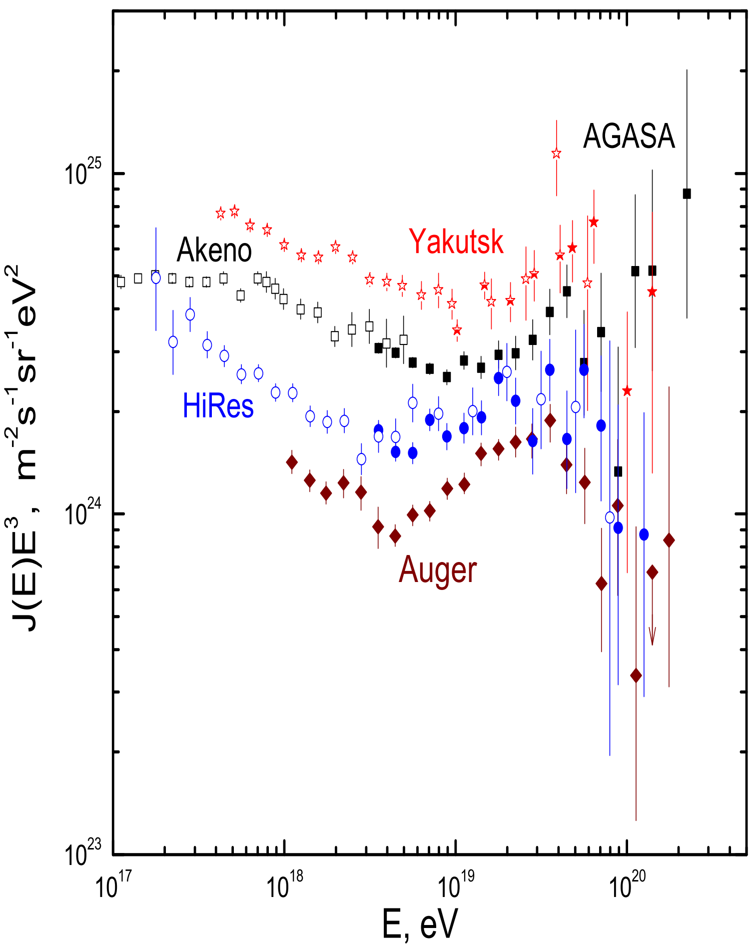


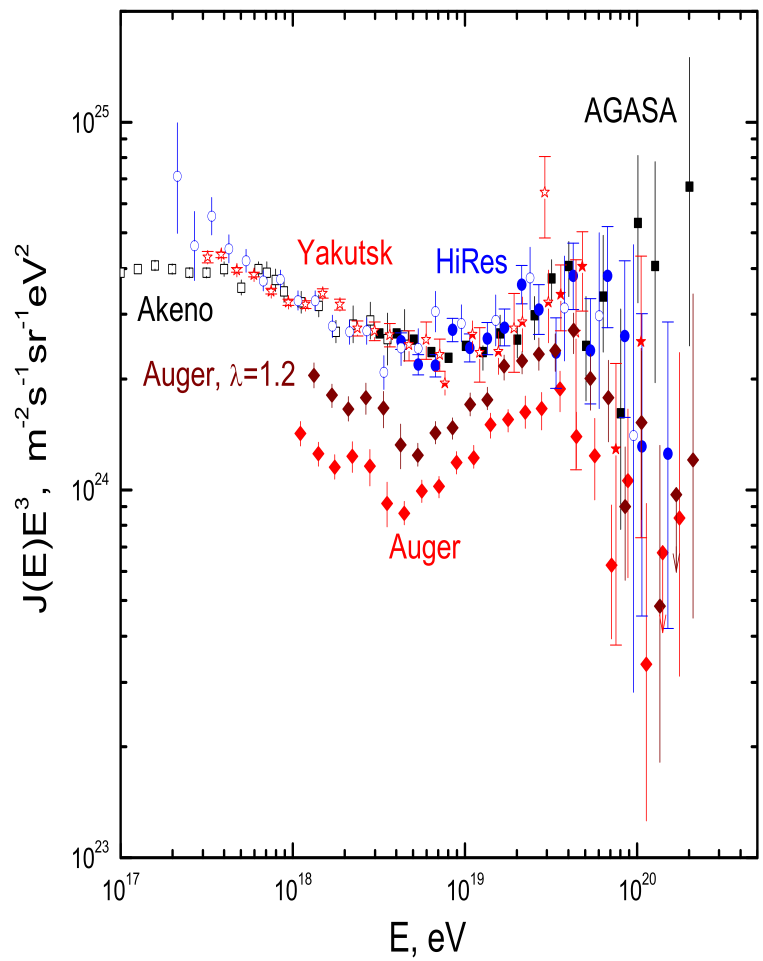
Crucial question - CR composition above 10^{18} eV:

- reliable way to find the transition to extragalactic CRs
- a key to understanding accelleration / propagation mechanisms

Example: 'dip' model (Berezinsky et al.) predicts proton composition
('dip' caused by $p + \gamma_{\rm cmb} \rightarrow p e^+ e^-$)

Calibrating the energies of different experiments by the 'dip' position brings them together:





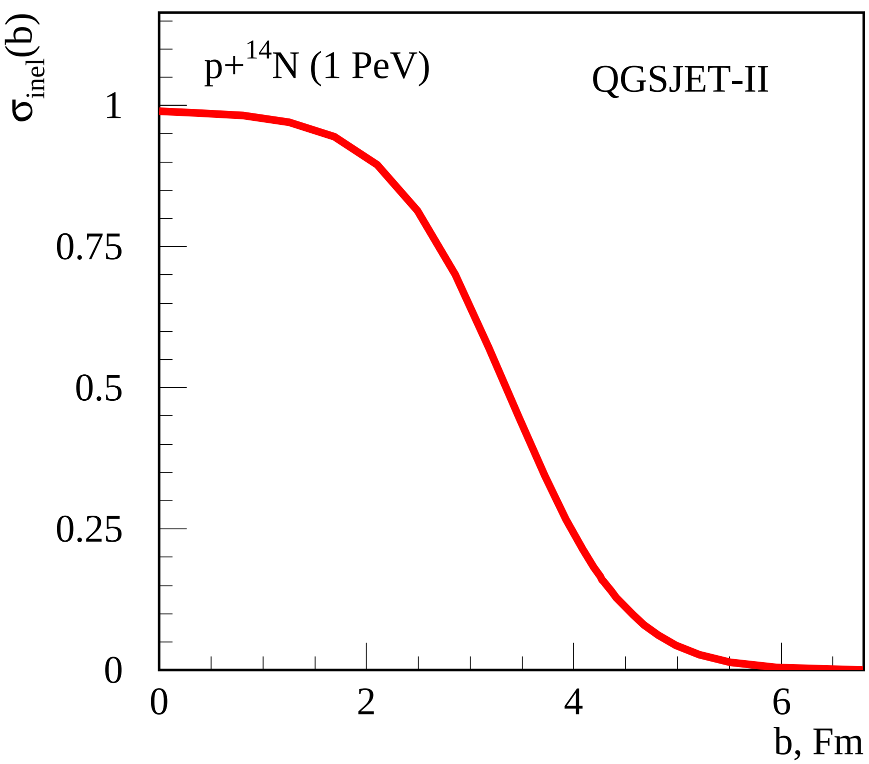
'Central' & peripheral collisions:

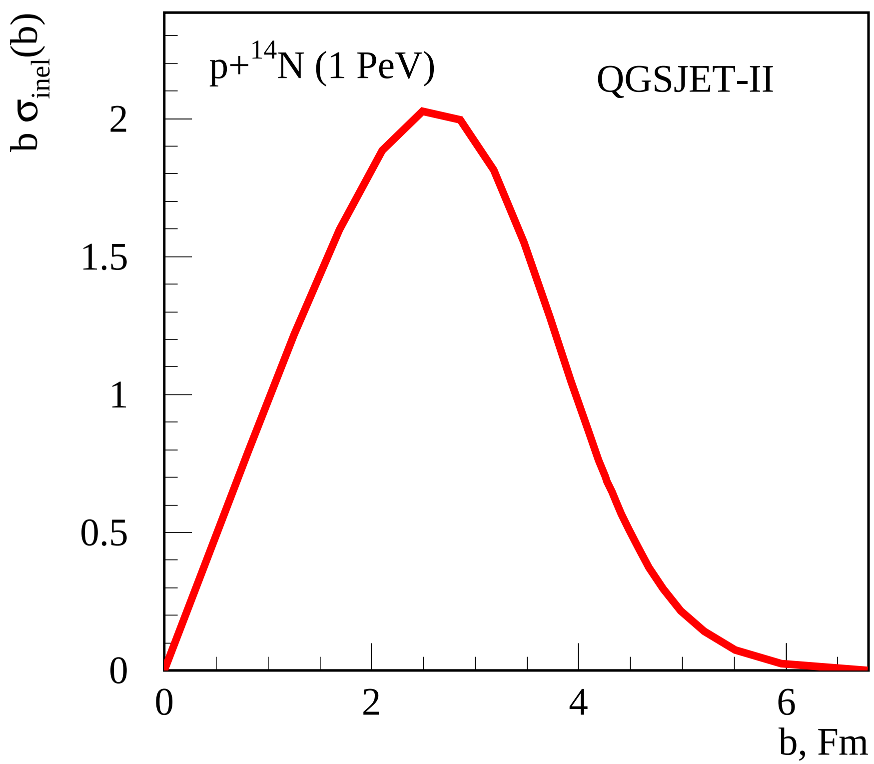
relative importance for $\sigma^{\rm inel}_{h-{\rm air}}$, $K^{\rm inel}_{h-{\rm air}}$, $N^{\rm ch}_{h-{\rm air}}$?

What is 'central'?

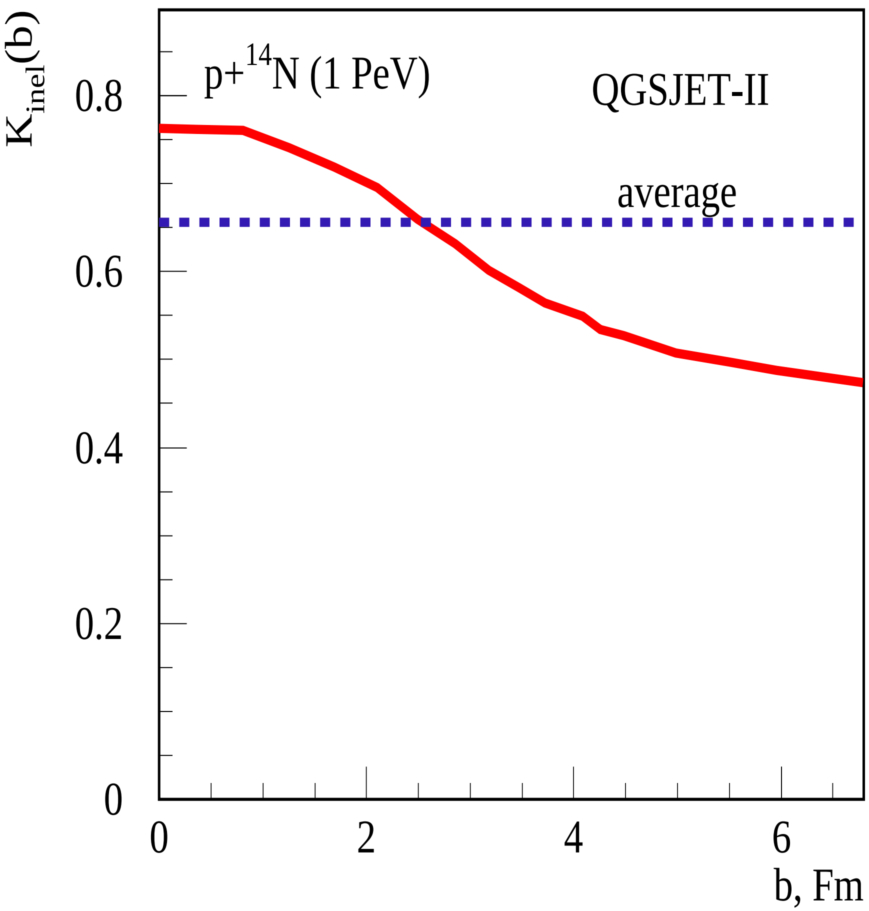
- 'black disc' limit: $\sigma^{\rm inel}(b) \sim 1 \Rightarrow \sigma^{\rm el}/\sigma^{\rm tot} \simeq 1/2$
- experiment: $\sigma^{\rm el}_{pp}/\sigma^{\rm tot}_{pp} \simeq 1/4$ @ $\sqrt{s} = 1.8$ TeV

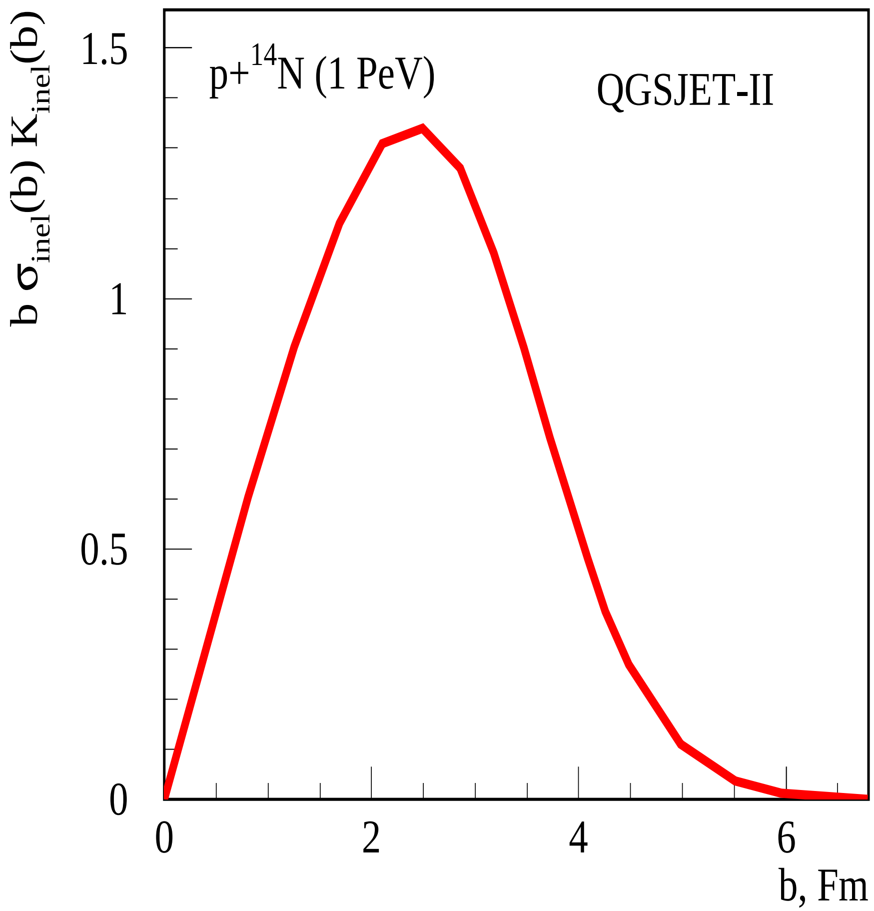
Interaction profile & b-contributions to $\sigma^{\rm inel}_{p-{\rm air}}$ @ $E_0 = 10^6$ GeV:





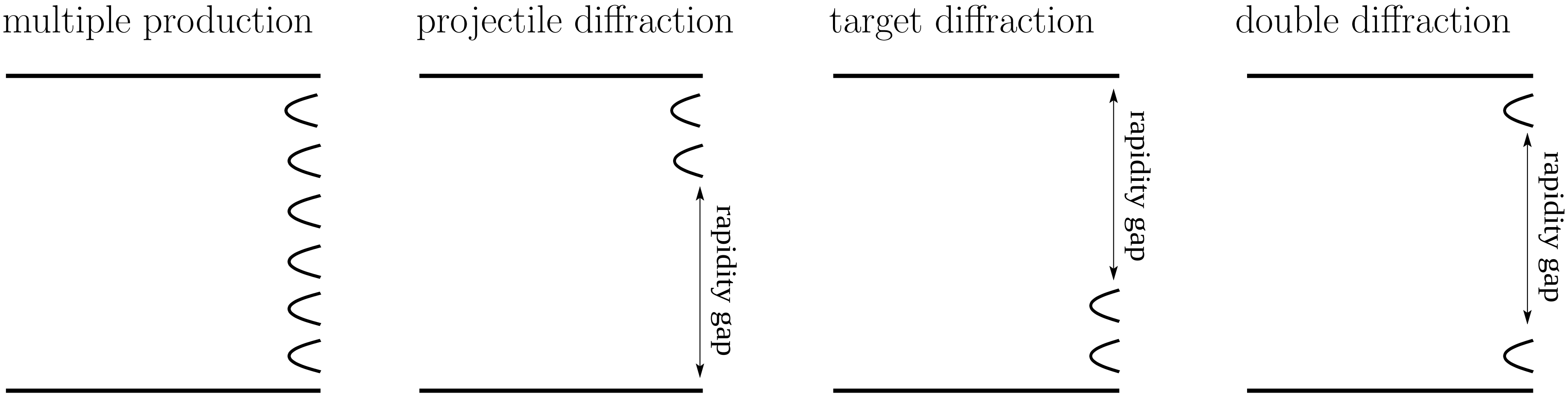
b-dependence & b-contributions to $K^{\rm inel}_{p-{\rm air}}$ @ $E_0 = 10^6$ GeV:



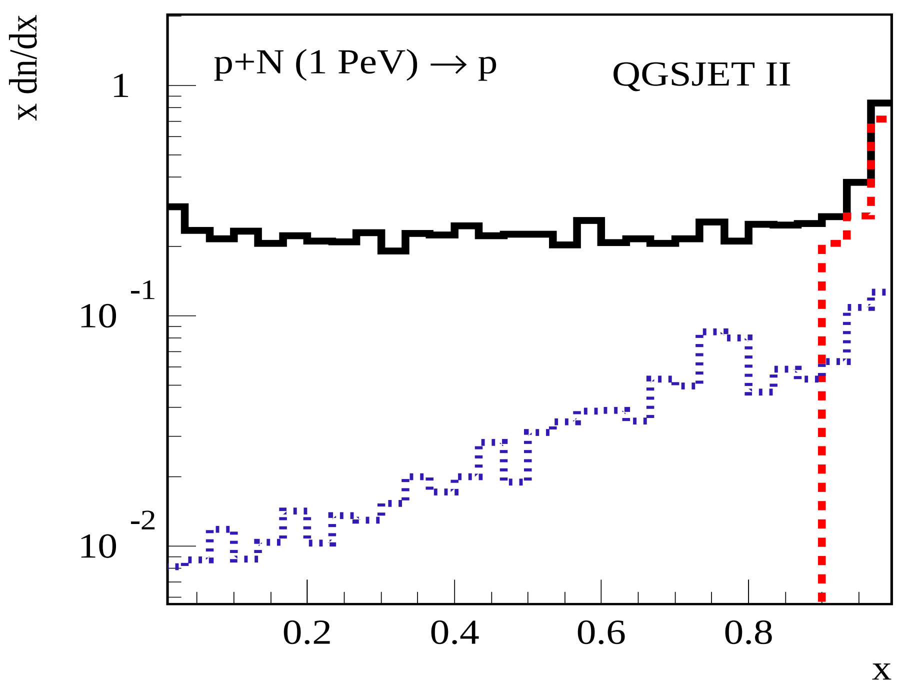


Peripheral contribution: decisive for cross sections & energy losses $\Rightarrow$ for $X_{\max}$

Diffraction dissociation



Leading proton spectrum & diffraction contributions



LHC input

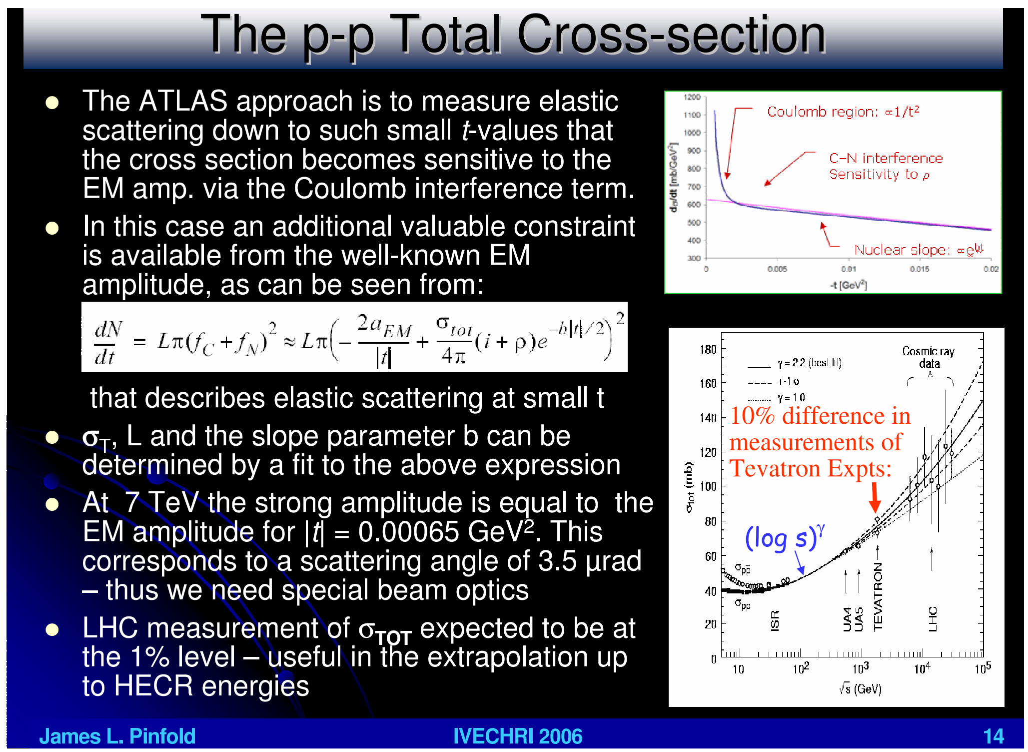
Hadronic cross sections - of crucial importance for EAS applications

- $\sigma^{\rm inel}_{h-{\rm air}}$ - direct impact on $X_{\max}$
- model calibration:
  - particle production: mainly with fixed target hp data
  - energy extrapolation: mainly inferred from $\sigma^{\rm tot}_{pp}(s)$ behavior

$\Rightarrow$ measurement of $\sigma^{\rm tot}_{pp}$ with 1% accuracy (~ 10 mb) - most important LHC contribution:

- allows to obtain $\sigma^{\rm inel}_{p-{\rm air}}$ (Glauber + inelastic screening)
- significantly improves model calibration

Not sufficient for $X_{\max}$: $\sigma^{\rm diffr}_{p-{\rm air}}$ & $K^{\rm inel}_{p-{\rm air}}$?

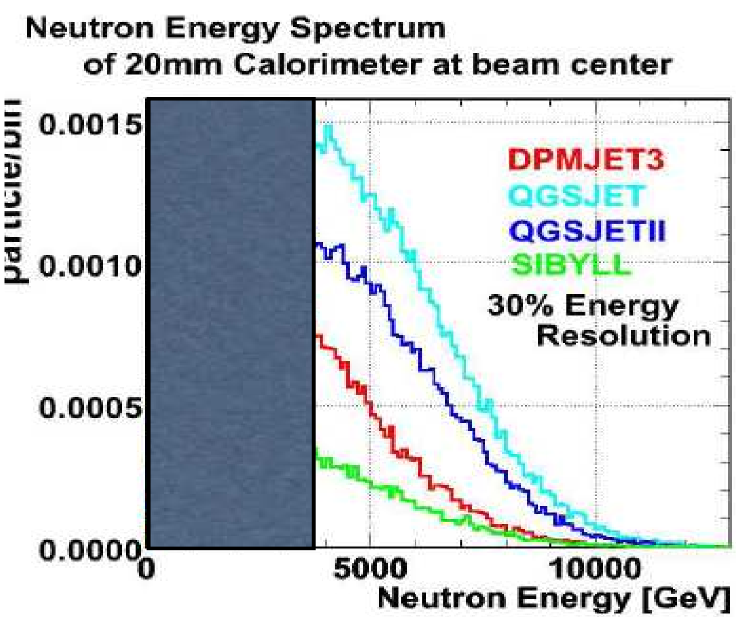


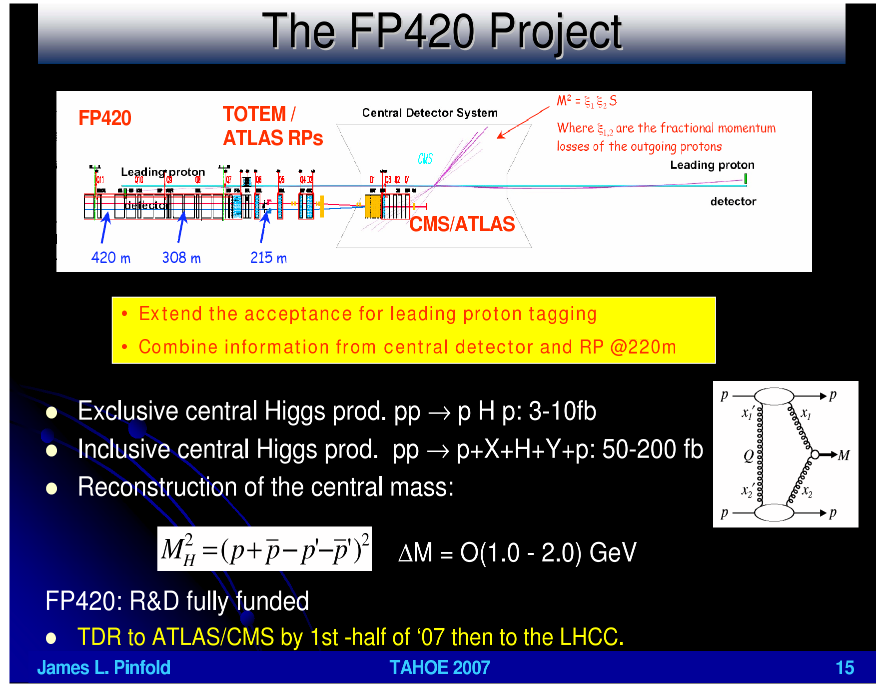
FP420 experiment:

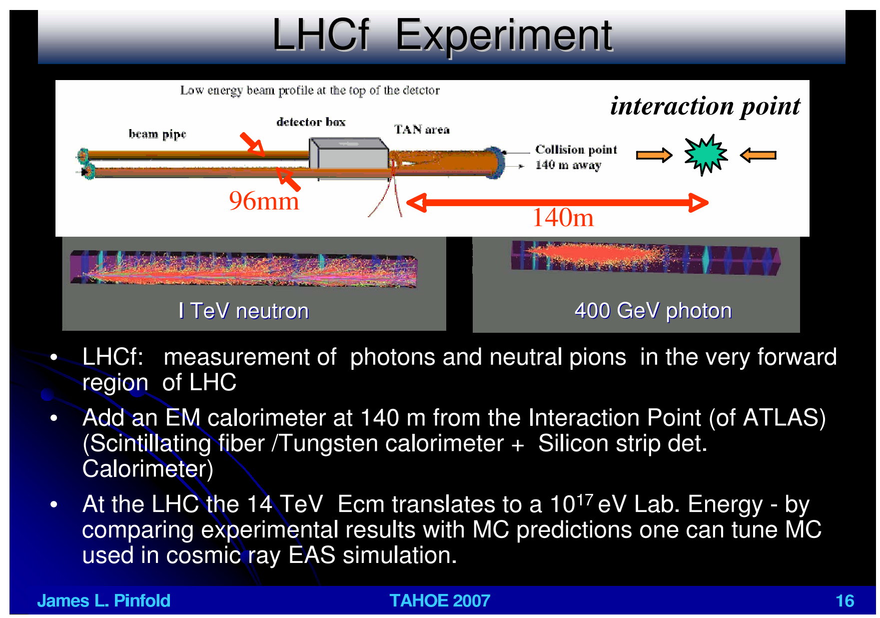
- designed to study diffractive Higgs production
- can measure 'soft' diffraction - interesting by itself and of vital importance for CRs

LHCf experiment:

- measurement of forward neutrons and gammas
- allows to test inelasticity at 0.1 EeV!
- sensitive to projectile diffraction
- $\Rightarrow$ powerful discriminator between models!



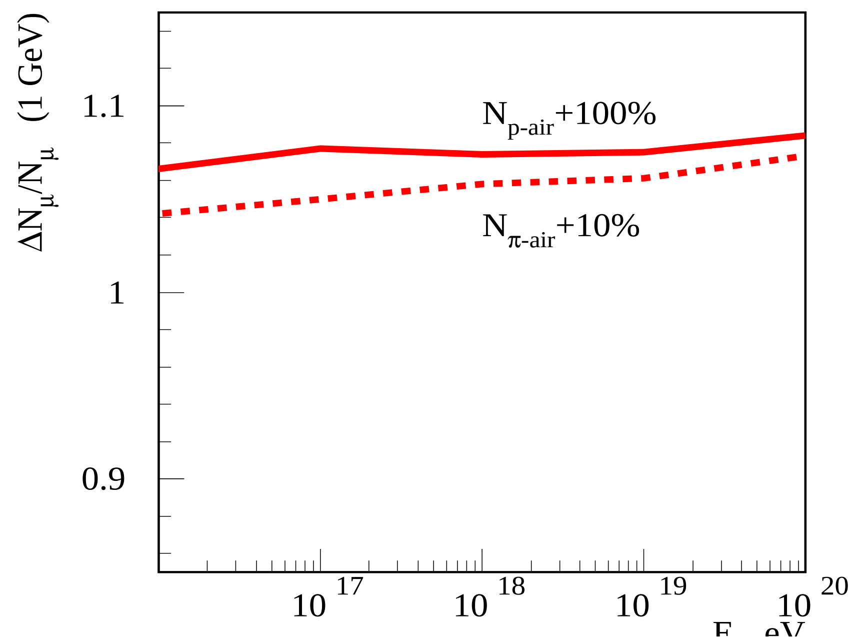




CR composition with muons

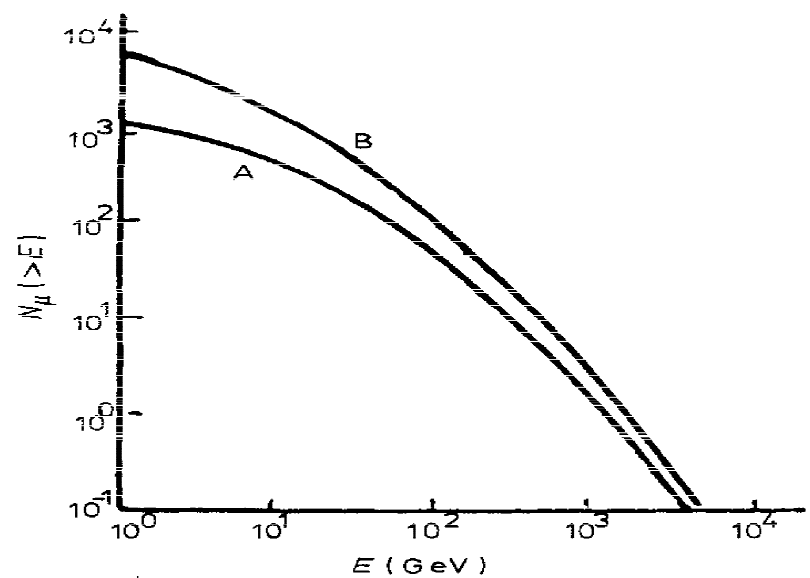
Muon number N_μ - main model dependence via $N^{\rm ch}_{\pi-{\rm air}}$

Example: increase $N^{\rm ch}_{p-{\rm air}}$ by 100% (QGSJET) or $N^{\rm ch}_{\pi-{\rm air}}$ by 10% - nearly same effect



But:

- shape of meson spectra important
- special role of (anti-) baryons (Grieder, 1973): don't decay⇒ increase number of 'generations' - important effect in EPOS model



Wide spread of model predictions ⇒ composition studies difficult