

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?

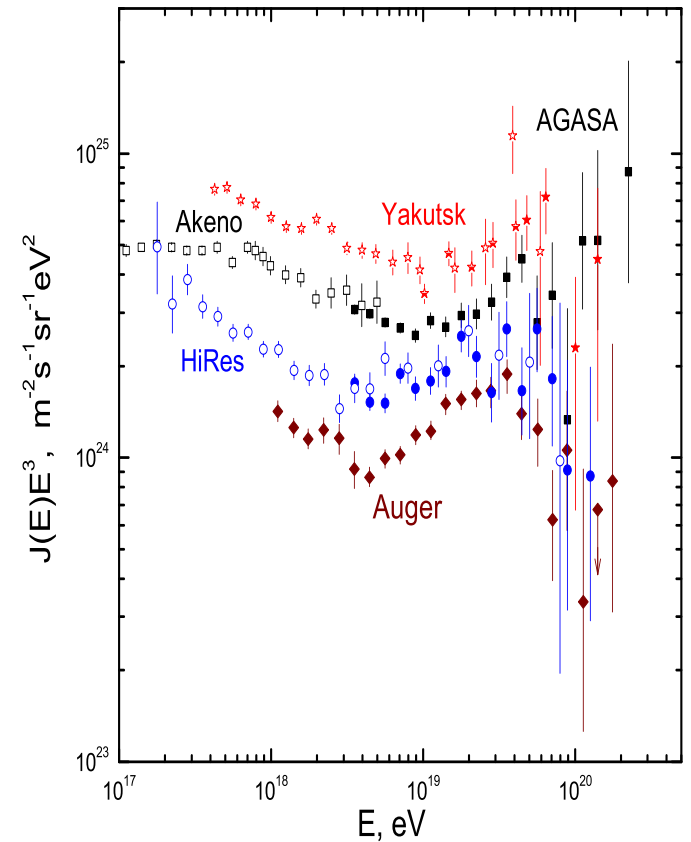
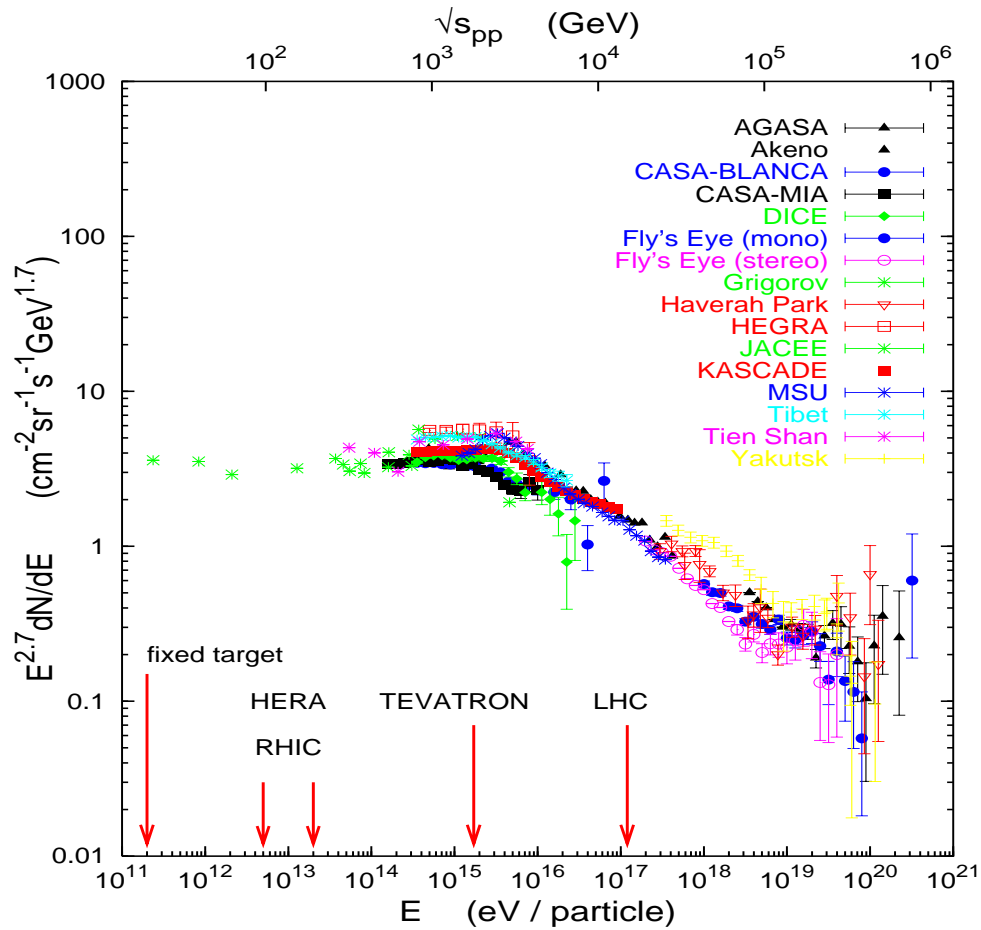
Why: to learn about

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

How: determining

- CR arrival directions
- energy spectrum
- particle composition

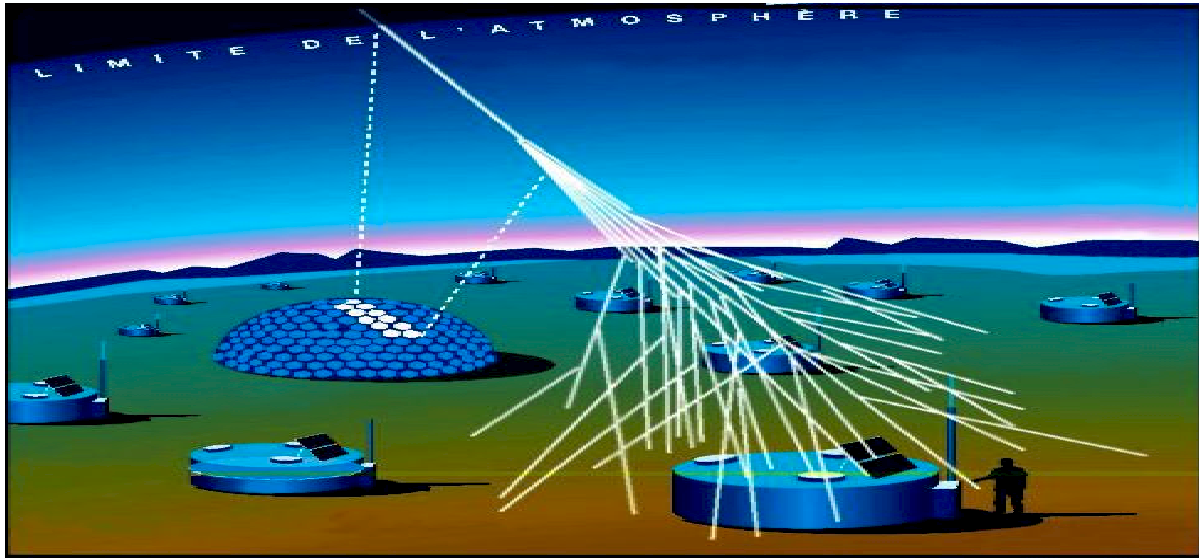
(U)HECR spectrum



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

Cosmic ray detection

At very high energies - indirect (extensive air showers)



- ground observations (using the atmosphere as the target)
 - primary energy \iff charged particle density at ground
 - CR composition \iff muon density at ground
- measurements of fluorescence light
 - primary energy \iff integrated light
 - CR composition \iff 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:

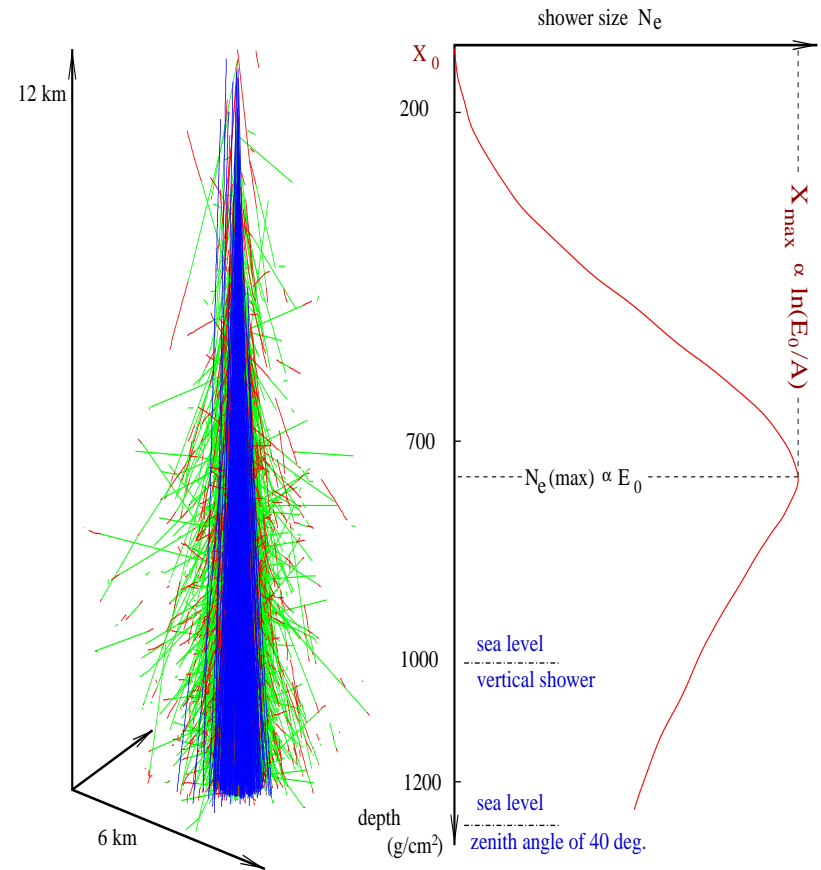
- shower maximum position X_{\max}
 - mainly sensitive to $\sigma_{p\text{-air}}^{\text{inel}}$ ($\sigma_{p\text{-air}}^{\text{non-diffr}}$), $K_{p\text{-air}}^{\text{inel}}$
- number of muons at ground N_{μ}
 - mainly depends on $N_{\pi\text{-air}}^{\text{ch}}$ (at energies $\sim \sqrt{E_0}$)

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}

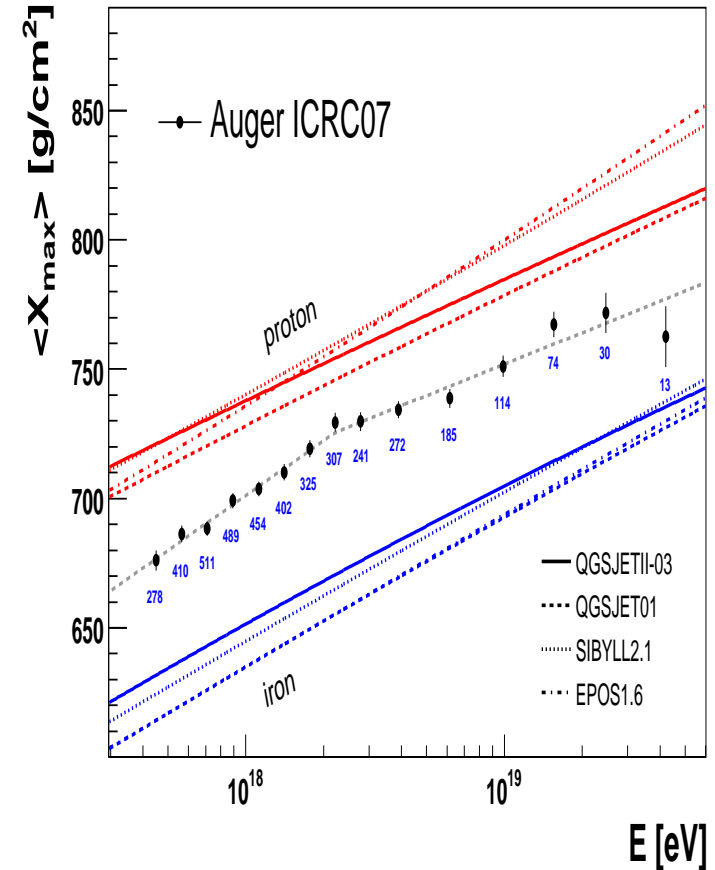
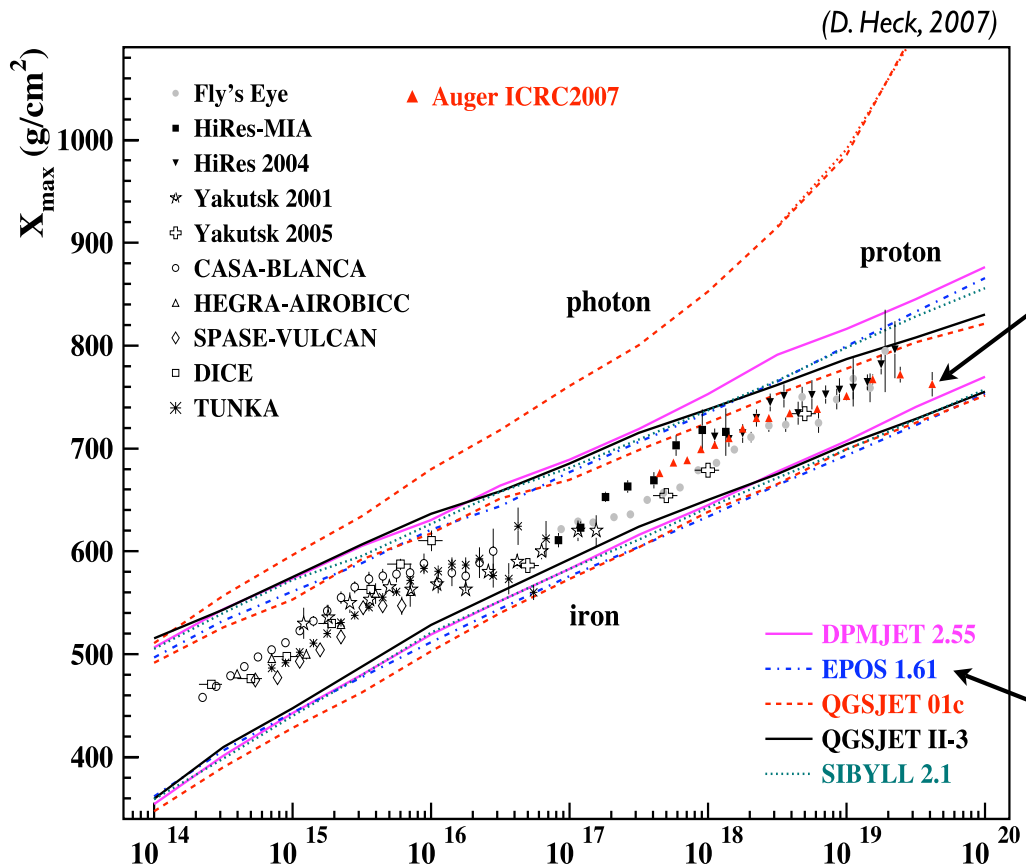
\Rightarrow CR interaction models \equiv models of **'typical'** (mb level) interactions

\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}



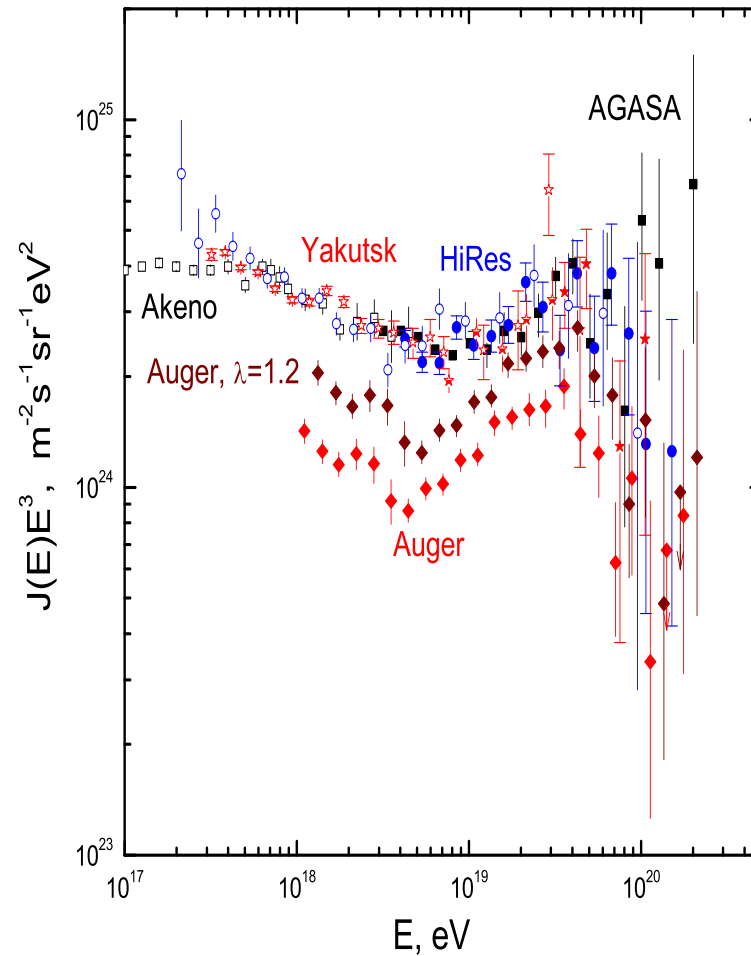
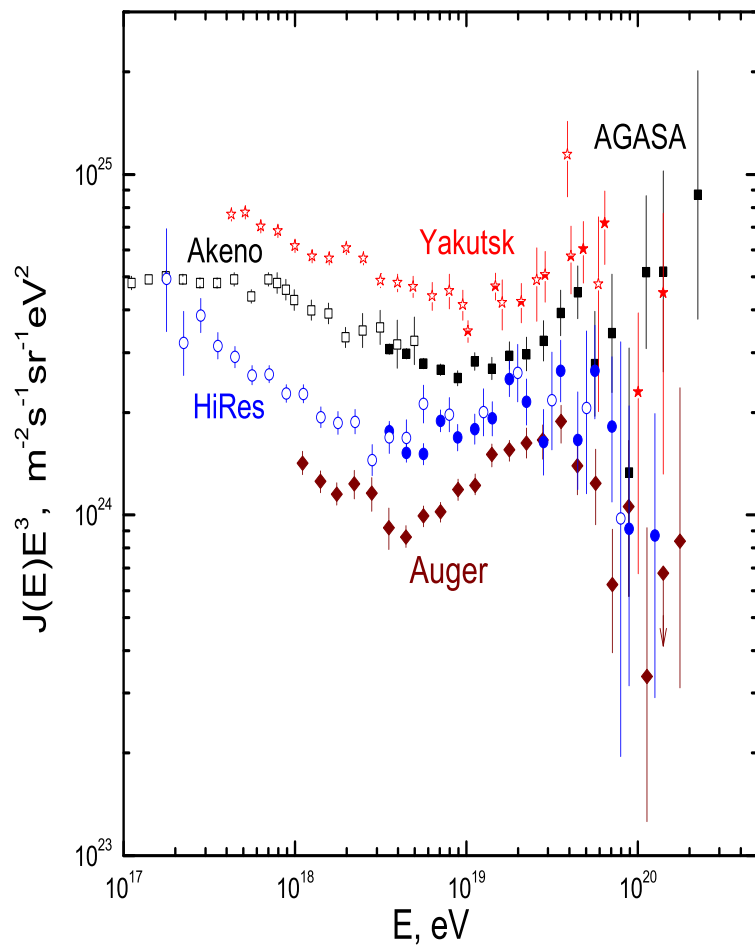
Crucial question - CR composition above 10^{18} eV:

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

Example: 'dip' model (Berezinsky et al.) predicts proton composition

('dip' caused by $p + \gamma_{\text{cmb}} \rightarrow pe^+e^-$)

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



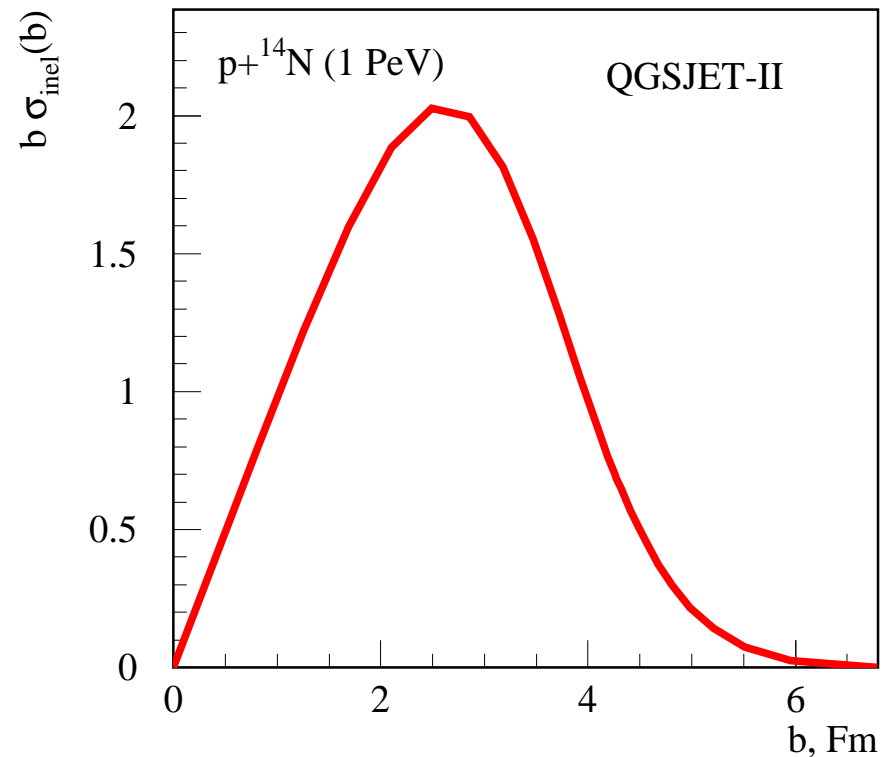
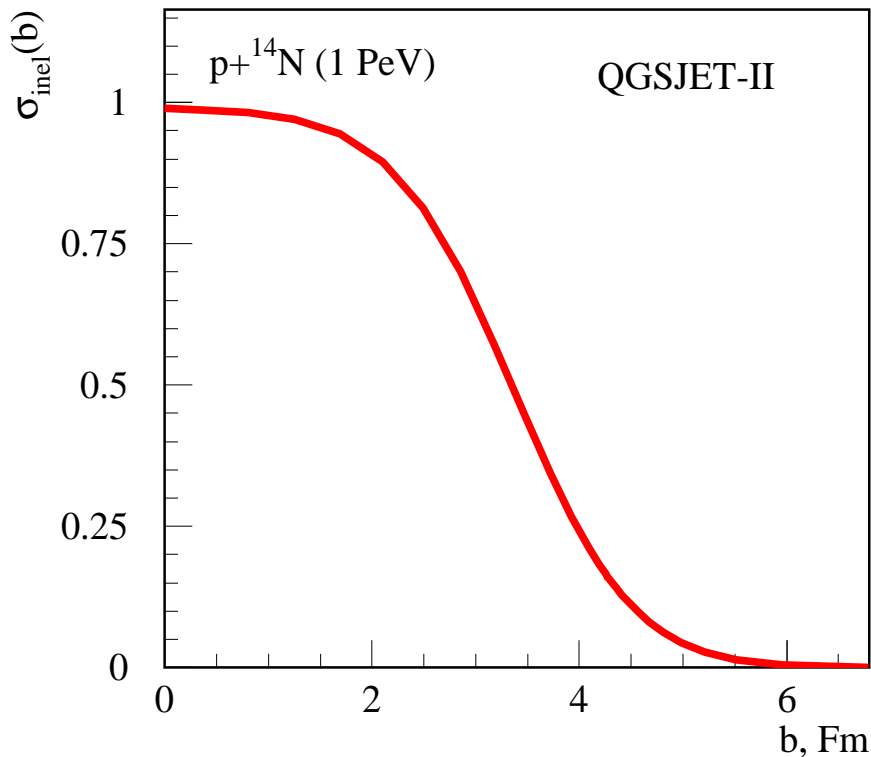
'Central' & peripheral collisions:

relative importance for $\sigma_{h\text{-air}}^{\text{inel}}$, $K_{h\text{-air}}^{\text{inel}}$, $N_{h\text{-air}}^{\text{ch}}$?

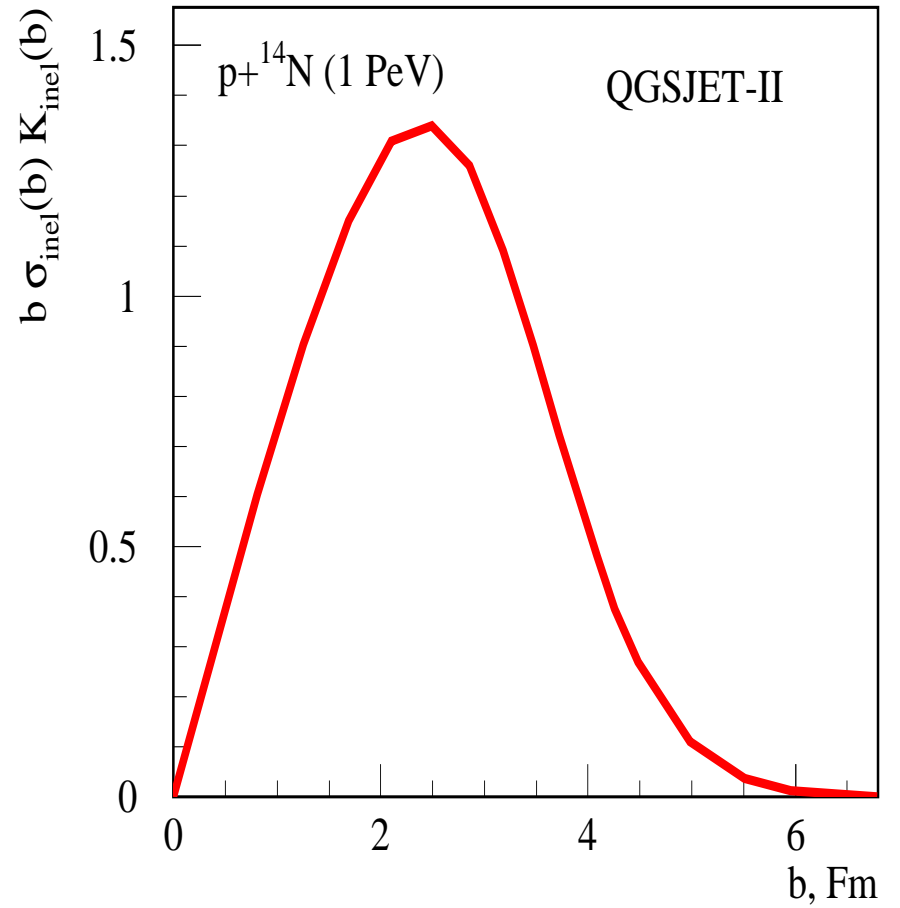
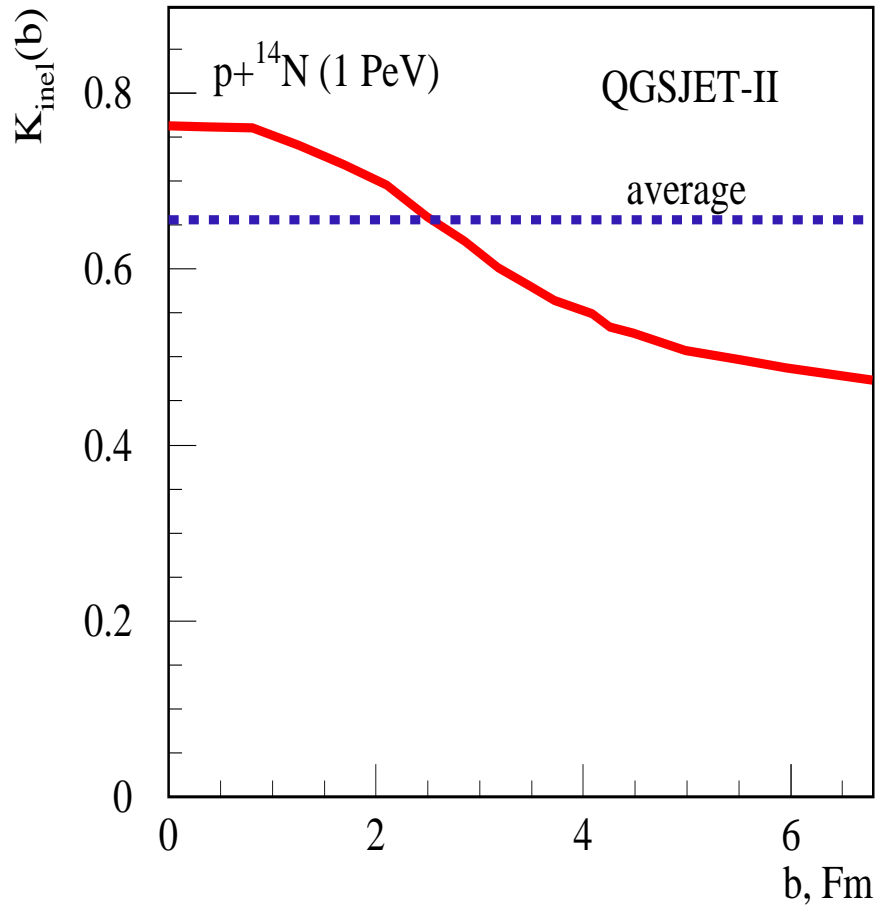
What is 'central'?

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

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



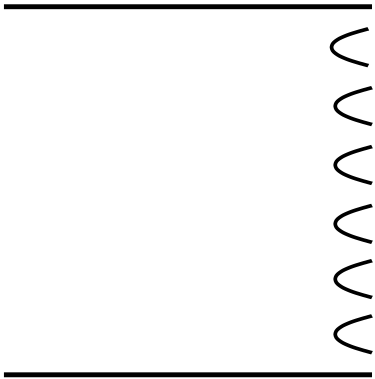
b -dependence & b -contributions to $K_{p\text{-air}}^{\text{inel}}$ @ $E_0 = 10^6$ GeV:



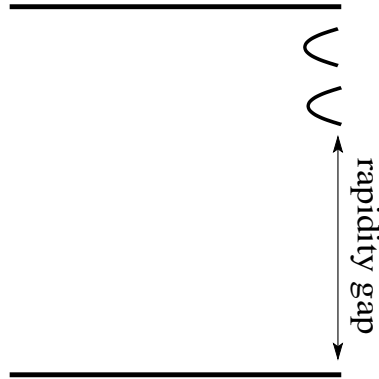
Peripheral contribution: [decisive for cross sections & energy losses](#) \Rightarrow for X_{max}

Diffraction dissociation

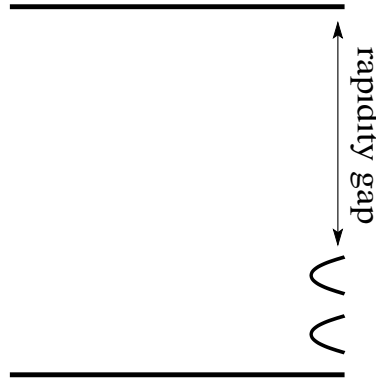
multiple production



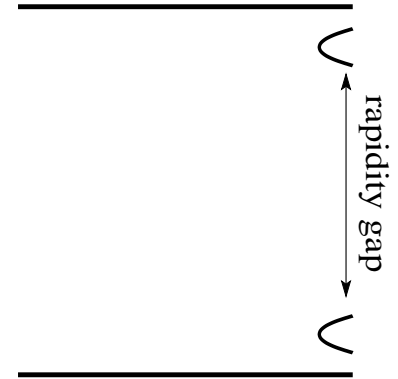
projectile diffraction



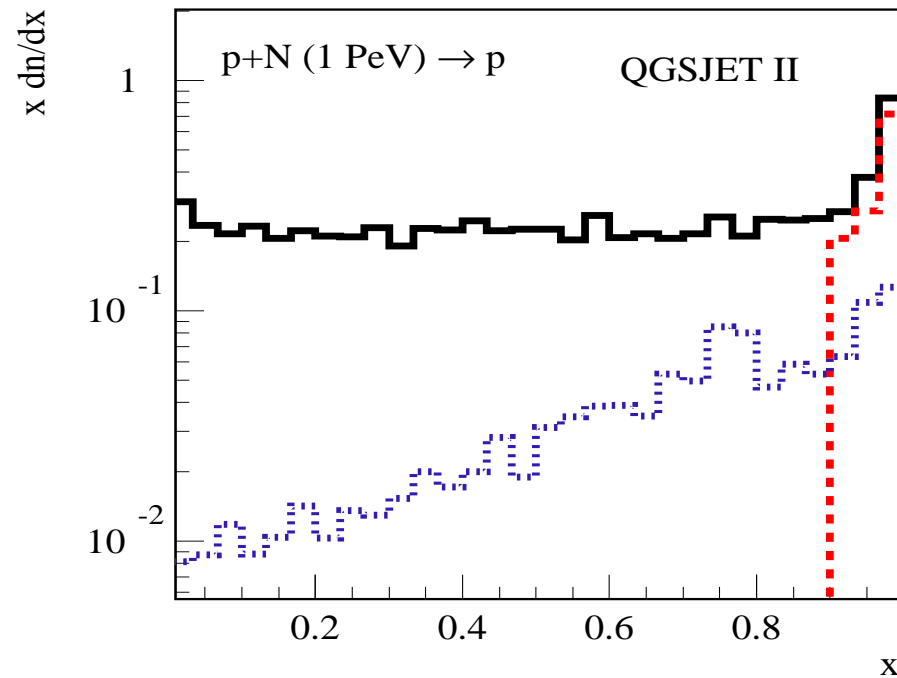
target diffraction



double diffraction



Leading proton spectrum & diffraction contributions



LHC input

Hadronic cross sections - of crucial importance for EAS applications

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

⇒ measurement of σ_{pp}^{tot} with 1% accuracy (~ 10 mb) - most important LHC contribution:

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

Not sufficient for X_{max} : $\sigma_{p\text{-air}}^{\text{diff}}$ & $K_{p\text{-air}}^{\text{inel}}$?

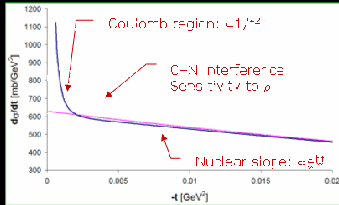
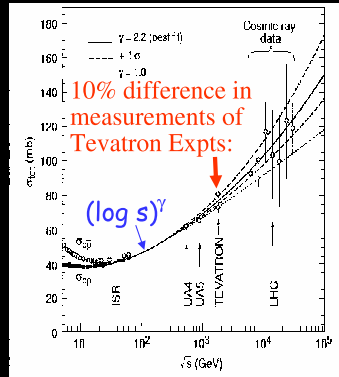
The p-p Total Cross-section

- The ATLAS approach is to measure elastic scattering down to such small t -values that the cross section becomes sensitive to the EM amp. via the Coulomb interference term.
- In this case an additional valuable constraint is available from the well-known EM amplitude, as can be seen from:

$$\frac{dN}{dt} = L\pi(f_C + f_N)^2 \approx L\pi\left(-\frac{2a_{EM}}{|t|} + \frac{\sigma_{tot}}{4\pi}(i + \rho)e^{-b|t|/2}\right)^2$$

that describes elastic scattering at small t

- σ_T , L and the slope parameter b can be determined by a fit to the above expression
- At 7 TeV the strong amplitude is equal to the EM amplitude for $|t| = 0.00065$ GeV². This corresponds to a scattering angle of 3.5 μ rad – thus we need special beam optics
- LHC measurement of σ_{TOT} expected to be at the 1% level – useful in the extrapolation up to HECR energies

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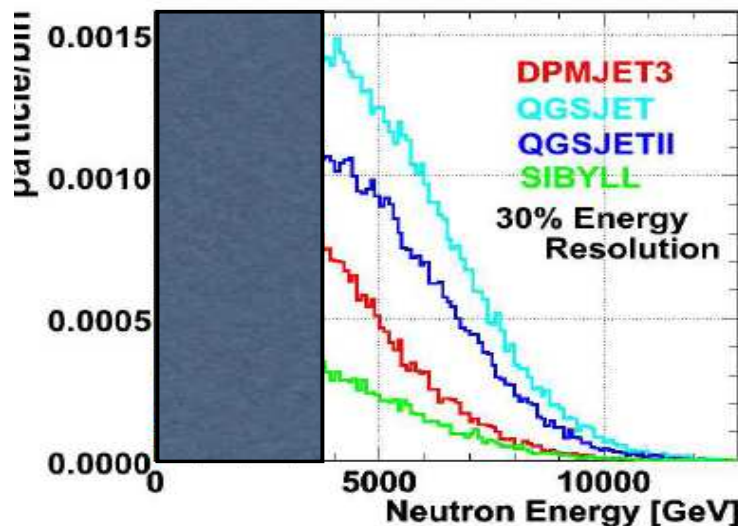
FP420 experiment:

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

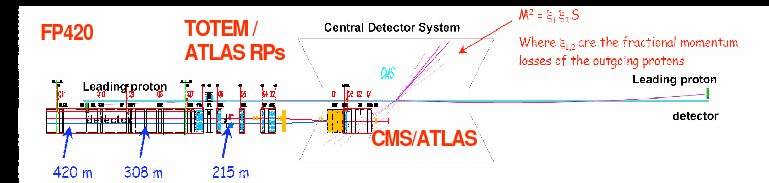
LHCf experiment:

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

Neutron Energy Spectrum
of 20mm Calorimeter at beam center



The FP420 Project



- Extend the acceptance for leading proton tagging
- Combine information from central detector and RP @220m

- Exclusive central Higgs prod. $pp \rightarrow p H p$: 3-10fb
- Inclusive central Higgs prod. $pp \rightarrow p+X+H+Y+p$: 50-200 fb
- Reconstruction of the central mass:

$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2 \quad \Delta M = O(1.0 - 2.0) \text{ GeV}$$

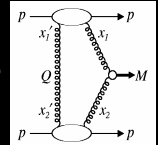
FP420: R&D fully funded

- TDR to ATLAS/CMS by 1st -half of '07 then to the LHCC.

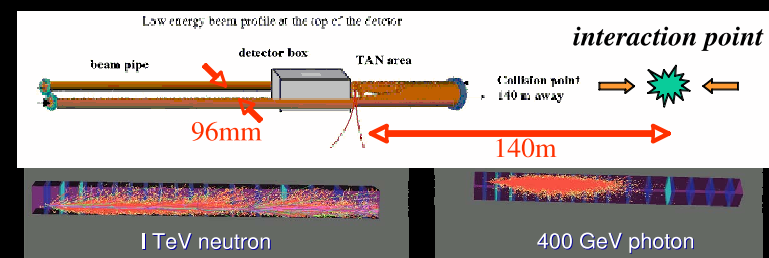
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LHCf Experiment



- LHCf: measurement of photons and neutral pions in the very forward region of LHC
- Add an EM calorimeter at 140 m from the Interaction Point (of ATLAS) (Scintillating fiber /Tungsten calorimeter + Silicon strip det. Calorimeter)
- At the LHC the 14 TeV E_{cm} translates to a 10^{17} eV Lab. Energy - by comparing experimental results with MC predictions one can tune MC used in cosmic ray EAS simulation.

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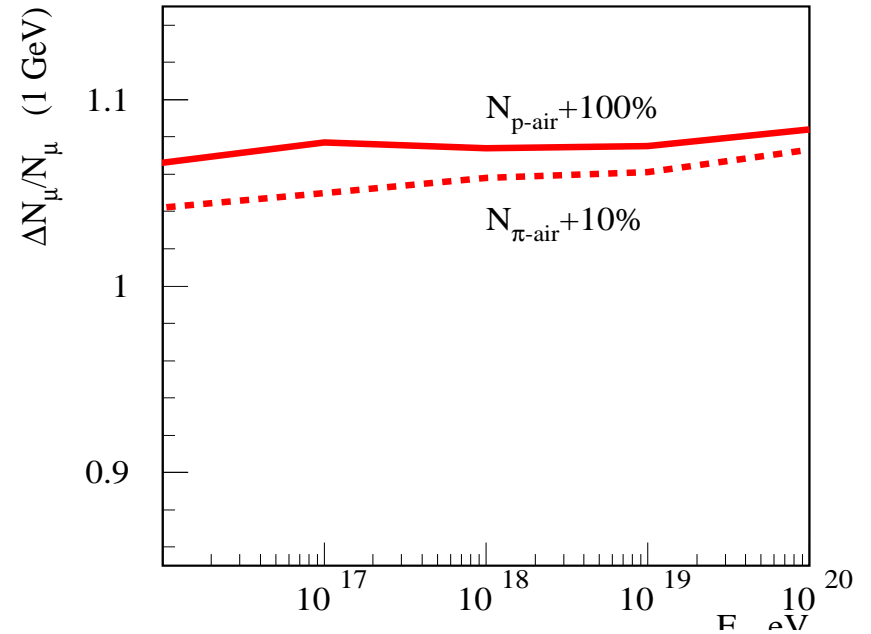
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CR composition with muons

Muon number N_μ - main model dependence via $N_{\pi\text{-air}}^{\text{ch}}$

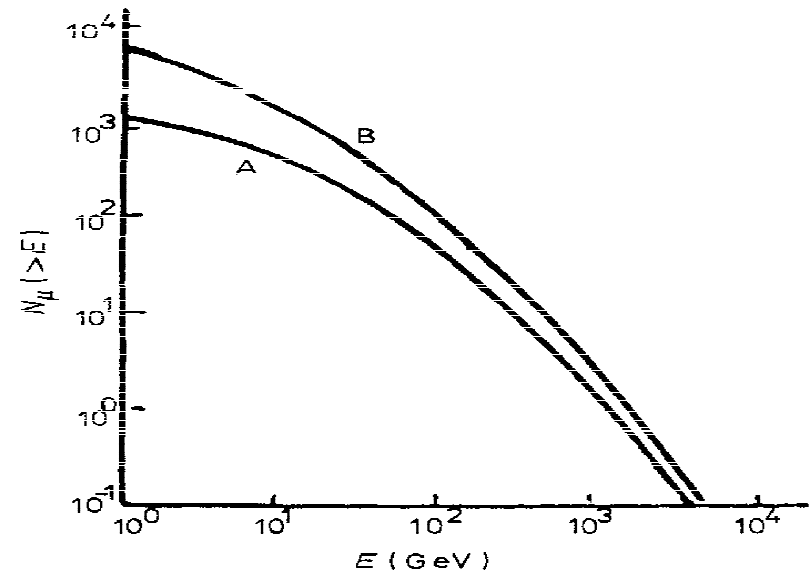
Example: increase $N_{p\text{-air}}^{\text{ch}}$ by 100% (QGSJET)

or $N_{\pi\text{-air}}^{\text{ch}}$ by 10% - nearly same effect



But:

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



Wide spread of model predictions \Rightarrow composition studies difficult

