Status of EAS simulations

S. Ostapchenko

NTNU (Trondheim)

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- Air shower physics
- Direct EAS simulation
- Numerical & hybrid procedures
- Puzzles & contradictions
- Input from the LHC
- Conclusions

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Extensive air shower physics

EAS development ⇐ high energy interactions

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

Most sensitive to hadronic physics:

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

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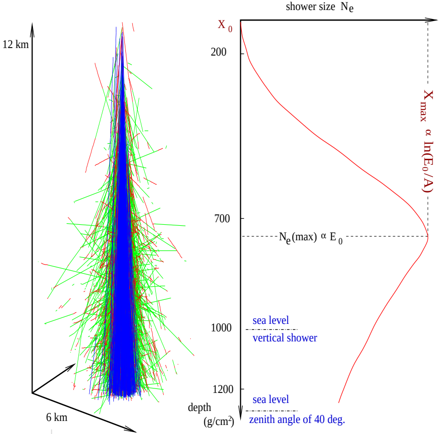
Experimental observables
- mostly from e/m cascades

- charged particle densities at ground
- fluorescence radiation
- Cherenkov radiation
- radio emission



Also muon component:

- mostly from decays of $\pi^{\pm}$, $K^{\pm}$, K_L produced in the hadronic cascade
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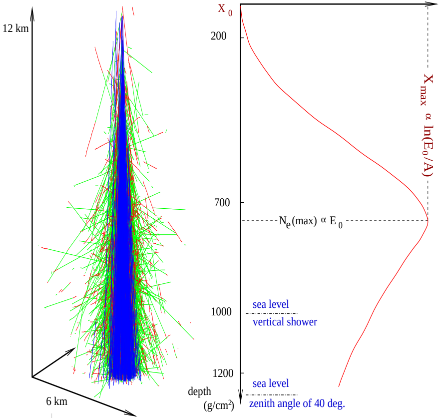

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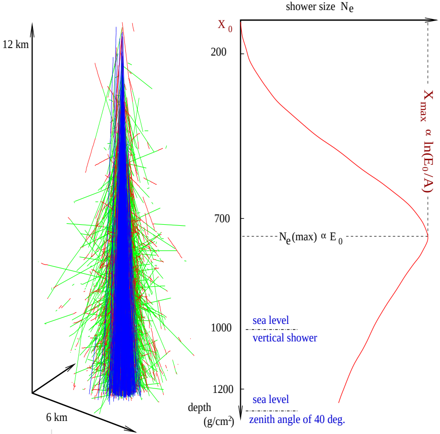

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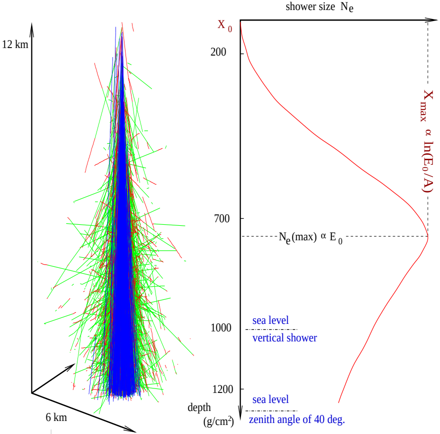

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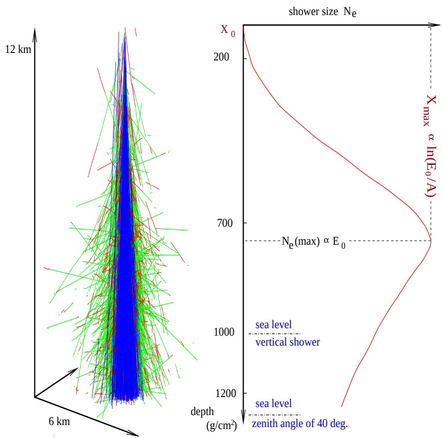

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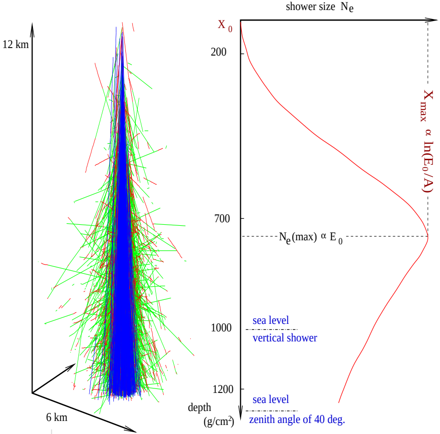

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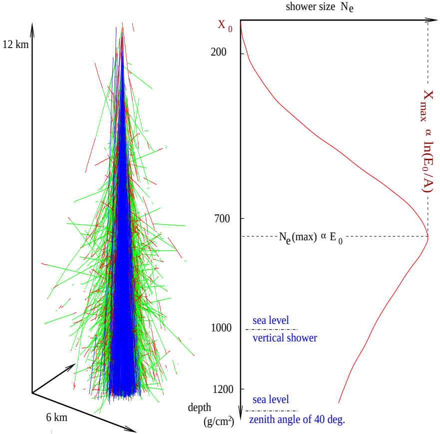

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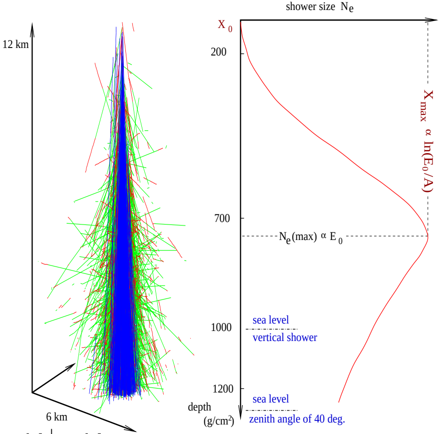

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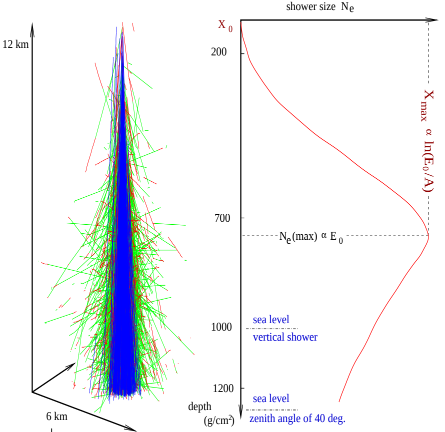

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Superposition model

For average characteristics: nucleus A induced shower of energy E_0 can be replaced by A proton-induced cascades of energy E_0/A

- follows from the number of interacting nucleons per collision:

$$\langle \nu_A \rangle = \frac{A\,\sigma_{p-\mathrm{air}}}{\sigma_{A-\mathrm{air}}}$$

- mean free pass of the nucleus is $(\sigma_{p-\mathrm{air}}/\sigma_{A-\mathrm{air}})$ times shorter
- but each nucleon interacts with the probability

$$w_{\mathrm{int}} = \frac{\langle \nu_A \rangle}{A} = \frac{\sigma_{p-\mathrm{air}}}{\sigma_{A-\mathrm{air}}}$$

- $\Rightarrow \langle X^A_{\max}(E_0)\rangle = \langle X^p_{\max}(E_0/A)\rangle = \langle X^p_{\max}(E_0)\rangle - \mathrm{ER}\ln \mathrm{A}$, $\mathrm{ER}= d\langle X^p_{\max}(E_0)\rangle / d\ln E_0$
- $\Rightarrow$ can be used for CR composition studies
- similarly: $\langle N^A_{e(\mu)}(E_0)\rangle = A\,\langle N^p_{e(\mu)}(E_0/A)\rangle \sim E_0^{\alpha_{e(\mu)}}\, A^{1-\alpha_{e(\mu)}}$

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Direct simulation of air showers

Most transparent - direct EAS simulation (e.g. CORSIKA program)

- very time-costy ⇒ impractical at very high energies
- to speed up - weighted sampling (Hillas's 'thinning'):

choose	only 1 secondary to track - with a probability $f_{\rm th}(E)$
particle	aquires a weight $w_{\rm th}(E) = 1/f_{\rm th}(E)$ (represents a bunch of particles of the same energy)
appropriate	for average EAS characteristics
creates	artificial fluctuations for EAS observables

- to restrict artificial fluctuations - impose weight restrictions (Kobal et al.): stop the 'thinning' at $w_{\rm th} \sim w_{\rm max}$
- to obtain realistic particle distributions in phase space - 'unthining' (Billiore): collect particles from a wider bin (e.g. from a large area around the detector); $w'(E) = w_{\rm th}(E)\, S_{\rm det}/S_{\rm sample}$

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Numerical and hybrid approaches

Fluctuations of EAS observables - 2 sources:

- fluctuations of EAS development:

  free pass of the primary hadron $X_0 \sim \lambda_a = m_{\mathrm{air}}/\sigma^{\mathrm{inel}}_{h-\mathrm{air}}$
  ($X = \int_h^\infty dh' \, \rho_{\mathrm{air}}(h')$, [g/cm^2])

  'inelasticity' of the 1st interaction

  multiplicity N_{ch} of the 1st interaction

  same for the most energetic secondaries

- measurement systematics:

  finite detector size

  finite resolution, etc.

$\Rightarrow$ to correctly catch EAS fluctuations MC treatment of the beginning of the shower ($E > E^{\mathrm{high}}_{\mathrm{thr}} \sim 10^{-2} \cdot E_0$) is sufficient

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free	pass of the primary hadron $X_0 \sim \lambda_a = m_{\rm air}/\sigma^{\rm inel}_{h-{\rm air}}$ $(X = \int_h^\infty dh'\, \rho_{\rm air}(h'),\ [{\rm g/cm^2}])$
'inelasticity'	of the 1st interaction
multiplicity	$N_{\rm ch}$ of the 1st interaction
same	for the most energetic secondaries

- measurement systematics:

finite	detector size
finite	resolution, etc.

$\Rightarrow$ to correctly catch EAS fluctuations MC treatment of the beginning of the shower ($E > E^{\rm high}_{\rm thr} \sim 10^{-2} \cdot E_0$) is sufficient

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scattering angle squared per radiation unit (37 g/cm^2 in air):

$$\langle\theta^2\rangle \sim E_s^2/E^2, \quad E_s = 21\,{\rm MeV}$$

thus, 1D-treatment could be appropriate above 1 GeV

but: π^0 which decays into gammas has non-zero p_t!

- typical p_t of secondaries in hadronic interactions < 1 GeV
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Numerical method (CONEX)

Hadronic cascade equation:

$$\frac{\partial h_a(E,X)}{\partial X} = -\frac{h_a(E,X)}{\lambda_a(X)} - h_a(E,X)\,\frac{dL/dX}{c\,\tau_a(E)} + \frac{\partial}{\partial E}\left[\beta_a^{\rm ion}(E)\,h_a(E,X)\right]$$
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- solved numerically, discretizing particle energy E and depth X

E/m cascades - similarly (without decays):

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EAS - just an instrument to study CRs

- ⇒ air shower simulations - a part of the instrument

What do we expect from a 'good' instrument?

- allows to measure a quantity A
- with an accuracy B
- if the measurement was performed correctly
  - following the instruction C

Cosimic ray studies:

- $A = \{$primary energy, CR composition, arrival direction$\}$
- C - main subject of experimental EAS techniques
- B - always properly estimated by each single experiment
  (but disagreement with another experiment $> \sqrt{B_1^2 + B_2^2}$)

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Shower simulations - an external ingredient for an exper. analysis

- $\Rightarrow$ source of doubt: is C is a correct way to measure A?
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  involve phenomenological interaction models

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- $\Rightarrow$ least certain results

Two biggest puzzles:

- EAS muon content
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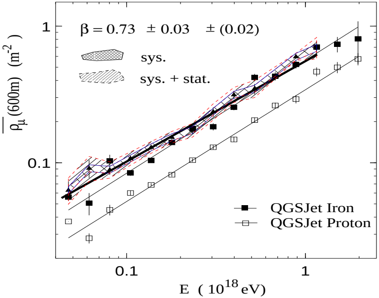
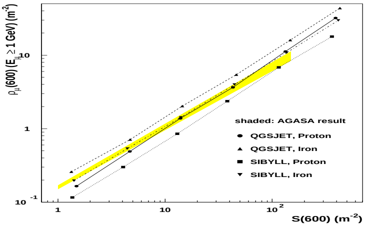
EAS muon puzzle

Old HiRes-Mia result: more muons than predicted by similations

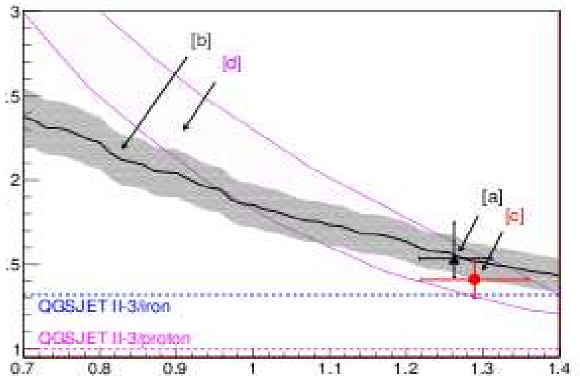


- not suppoted by AGASA:
  $\rho_\mu(600\ \text{m}) \sim \rho_\mu(p\ /\ \text{QGSJET})$



EAS muon puzzle & Auger data

Pierre Auger collaboration - models underestimate ρ_μ by 50%:



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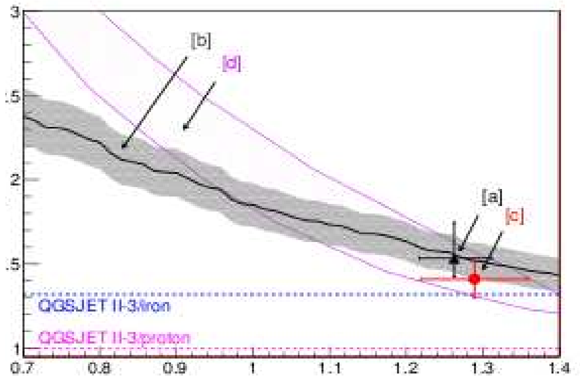

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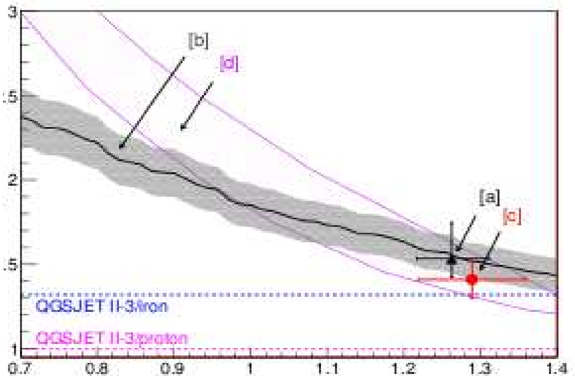

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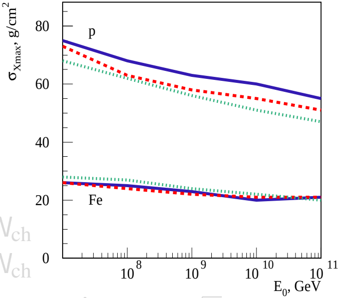

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  mean free pass λ_p: $\Delta\sigma_X^p = \lambda_p \sim 1/\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$ (~ 50 g/cm^2)

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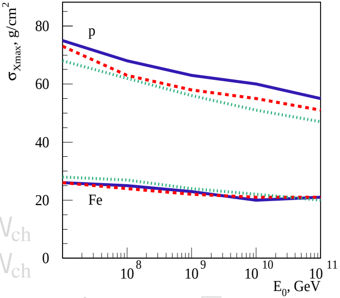

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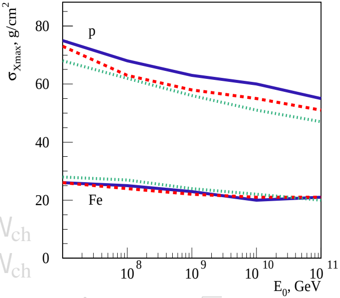

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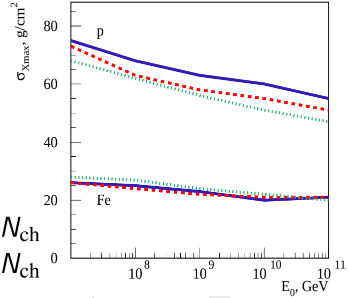

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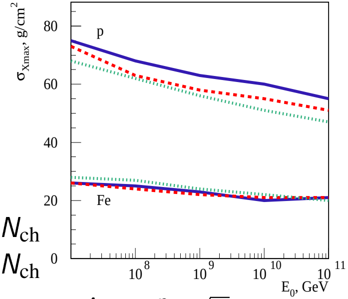

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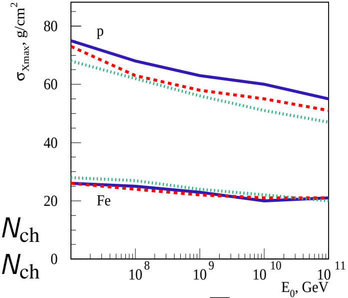

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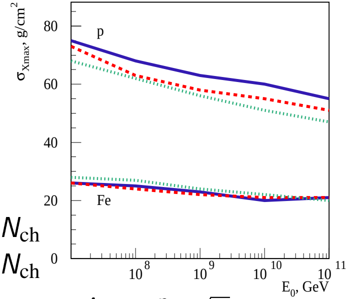

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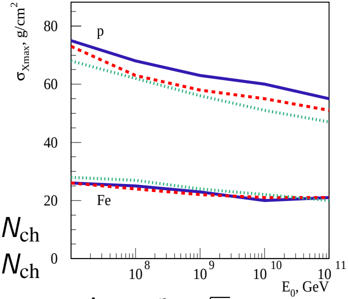

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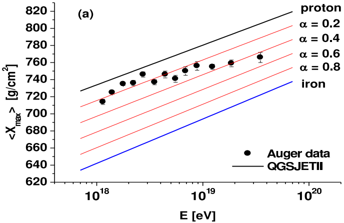

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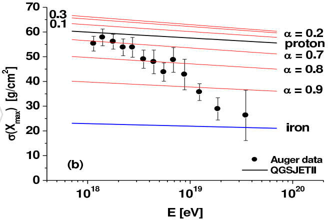

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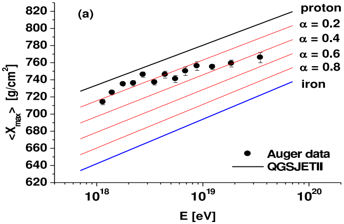

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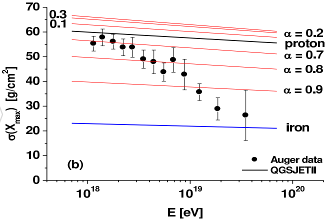

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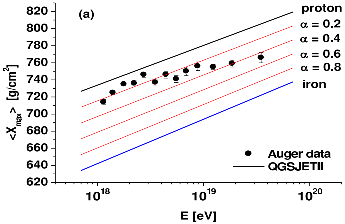

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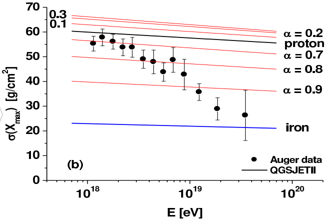

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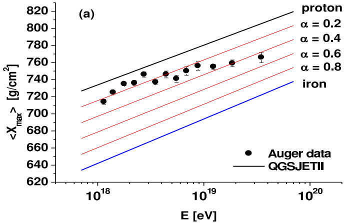

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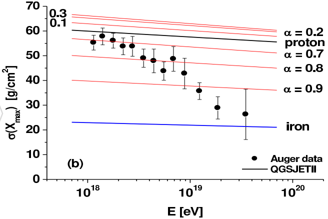

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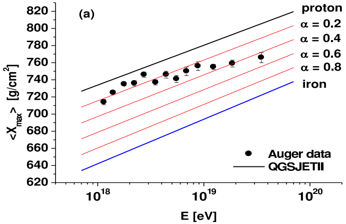

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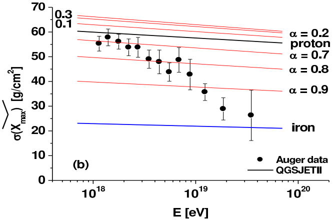

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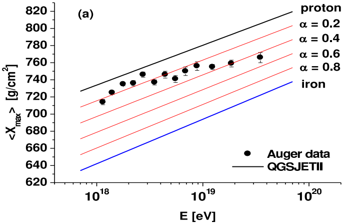

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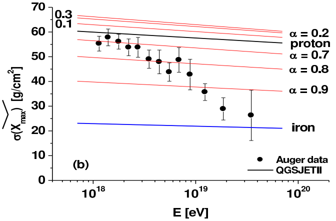

(figures from Wilk & Wlodarszik 2010)

Input from the LHC

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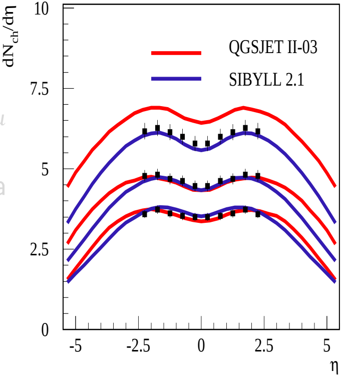
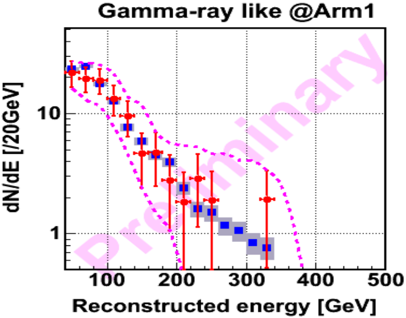
- yet no indication in the LHCf data





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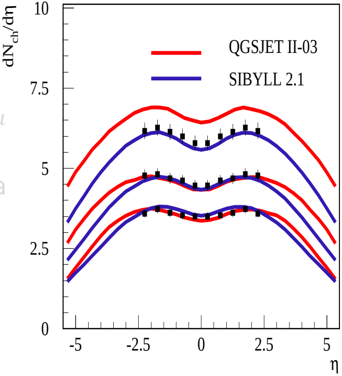

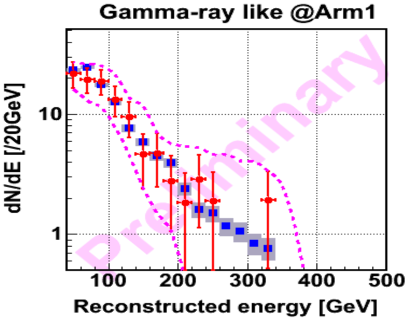

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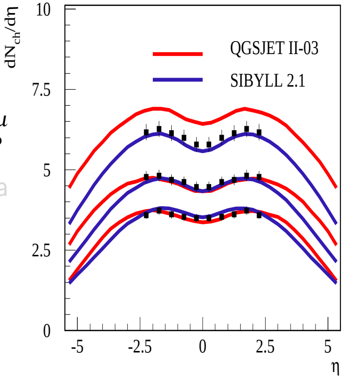

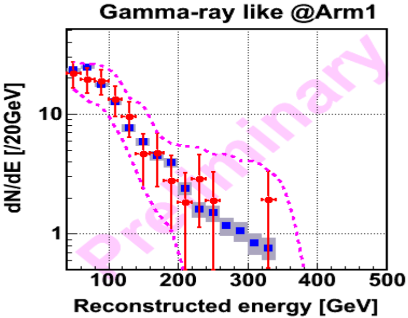

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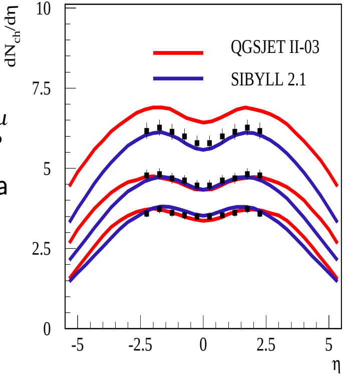

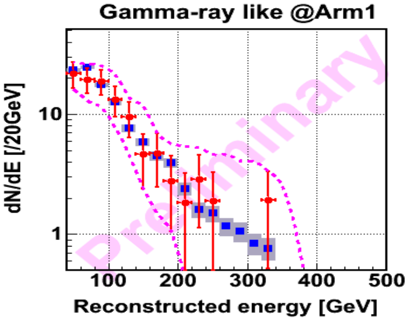

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Conclusions

EAS simulations - considerable progress over the last two decades

- standard EAS simulation packages are wide-spread in the field, compared to various measurements
- unlike 20 years ago, good overall description of EAS data
- wide range of applications: 'standard' EAS techniques, fluorescence, Cherenkov & radio emission

New efficient approaches to EAS simulation - 'hybrid' procedures: combination of MC & numerical techniques

Still puzzles in CR composition studies - related to hadronic models

- muon puzzle - no indication that models are wrong from LHC
- $X_{\max}$ puzzle - crucial LHC measurement (σ_{pp}^{tot}) ahead

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