Interaction Models:
Ultra-High Energy Cosmic Rays & LHC data

Sergey Ostapchenko (NTNU, Trondheim)

ICRR (Tokyo), October 11, 2011

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- (Ultra-)High Energy Cosmic Rays
  - CR spectrum
  - potential UHECR sources
  - detection methods: extensive air showers (EAS)

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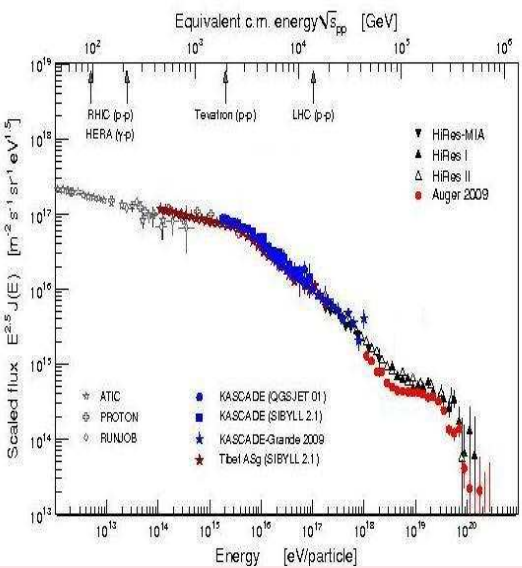
- Summary & prospects

High Energy Cosmic Rays



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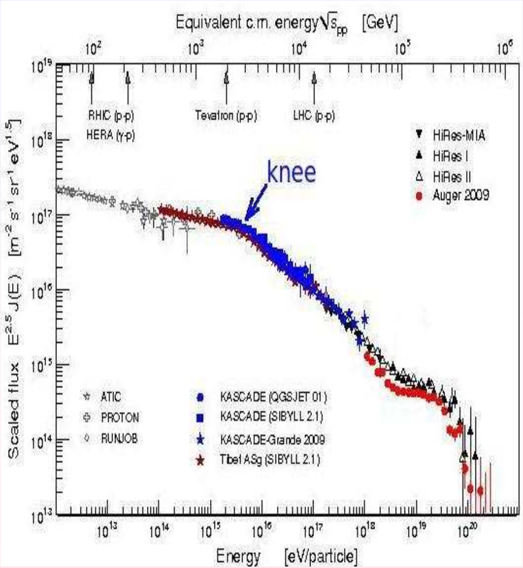

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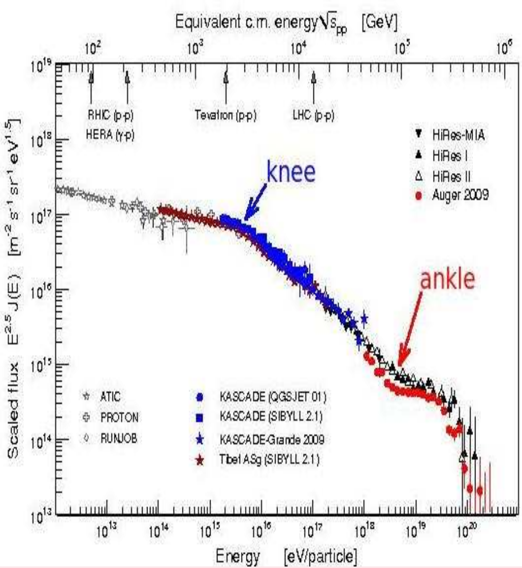

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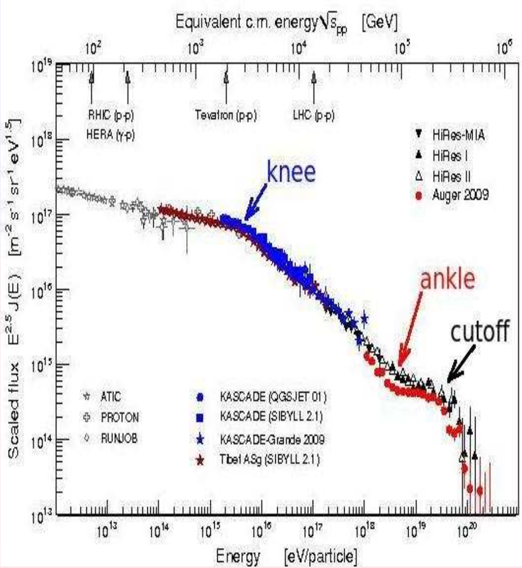

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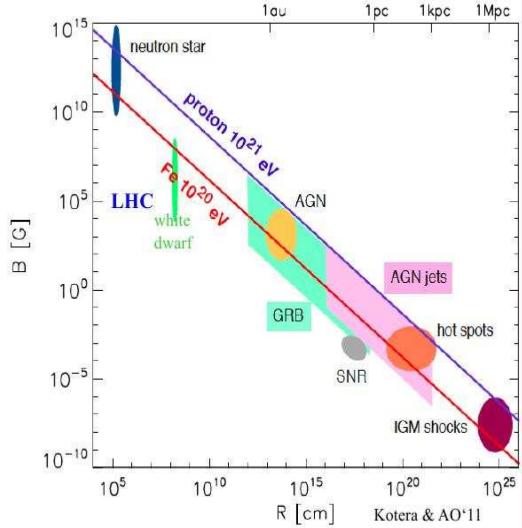
- cutoff at $\sim 10^{20}$ eV (interaction with background γs?)

Ultra-High Energy Cosmic Rays (UHECR)

Potential UHECR sources – Hillas's condition: CRs to be retained in the source for sufficiently long time $\Rightarrow E_{\max} \propto B_{\text{source}} R_{\text{source}}$



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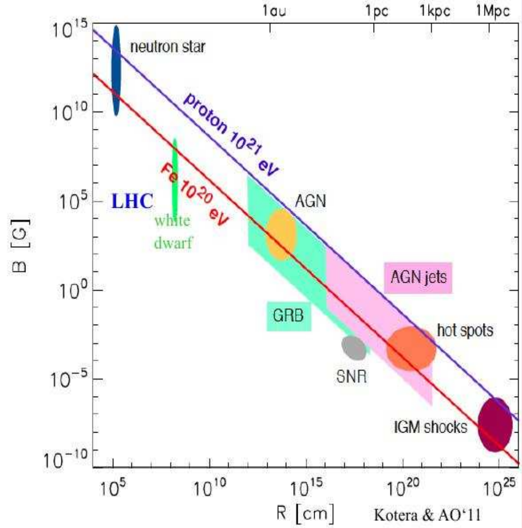

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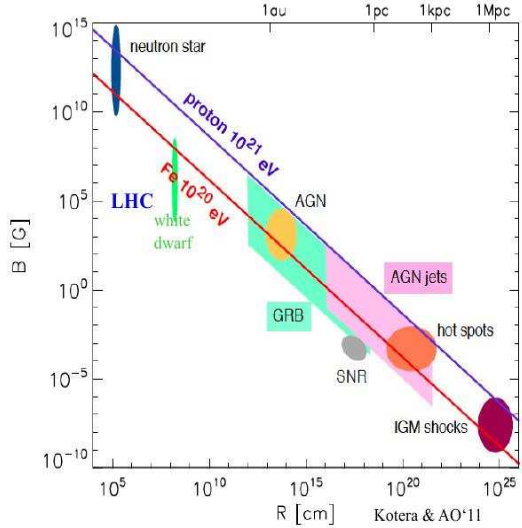

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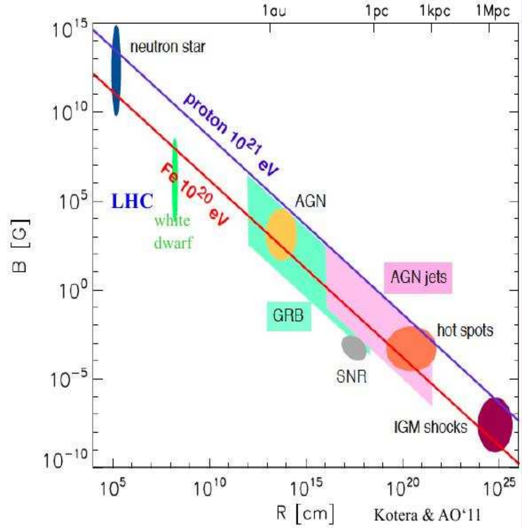

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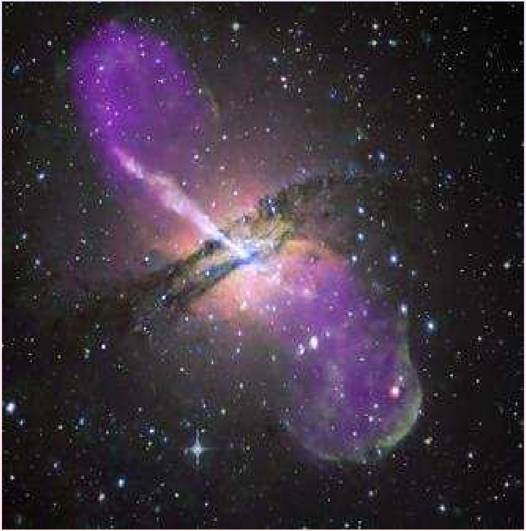

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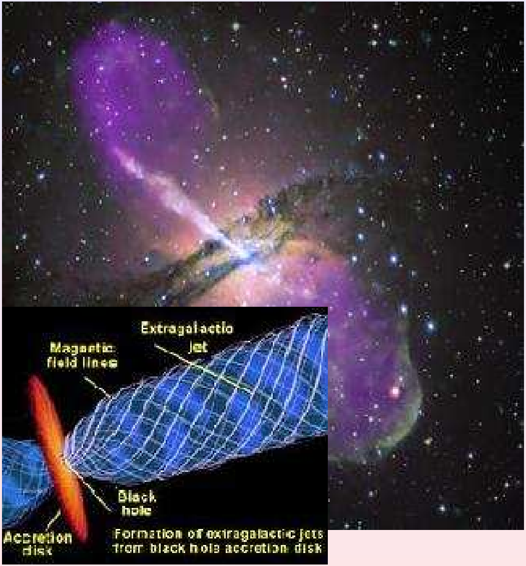

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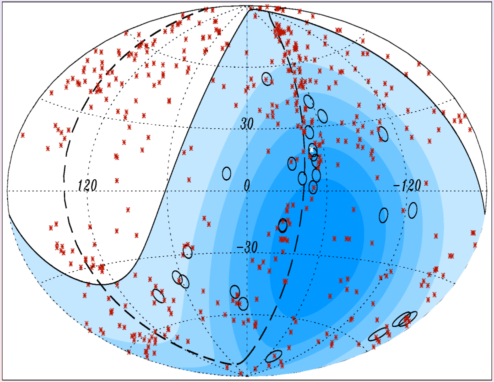
- CR acceleration possible near the black hole or in a jet/lobe

AGNs already established as UHECR sources?

Pierre Auger Collaboration: correlation of UHECR arrival directions with nearby AGNs at 3σ level *[Science 318 (2007) 938]*



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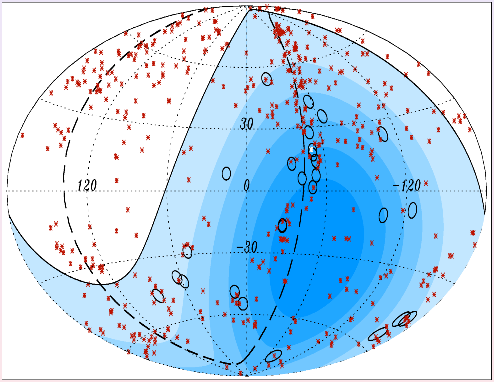

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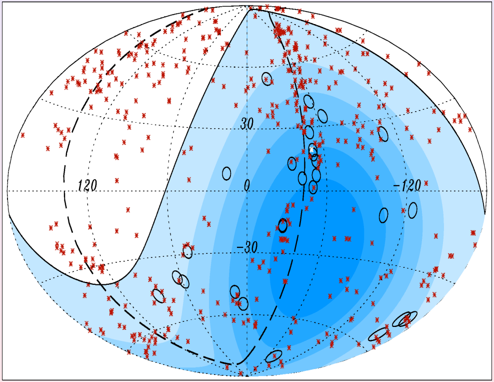

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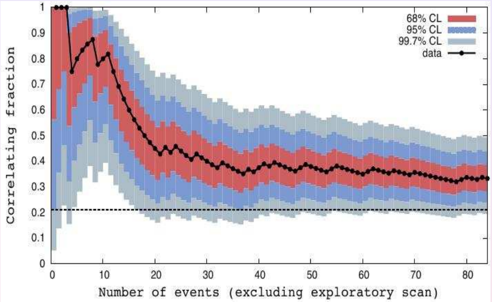

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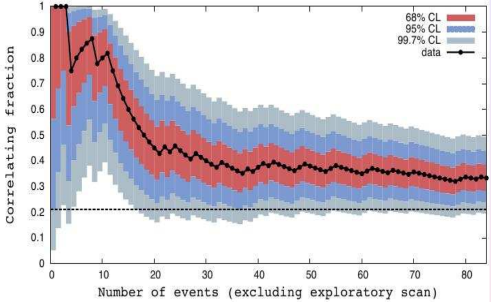

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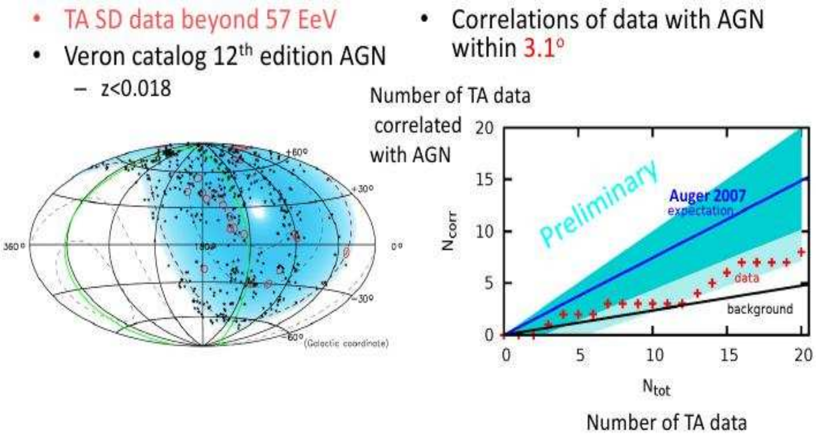

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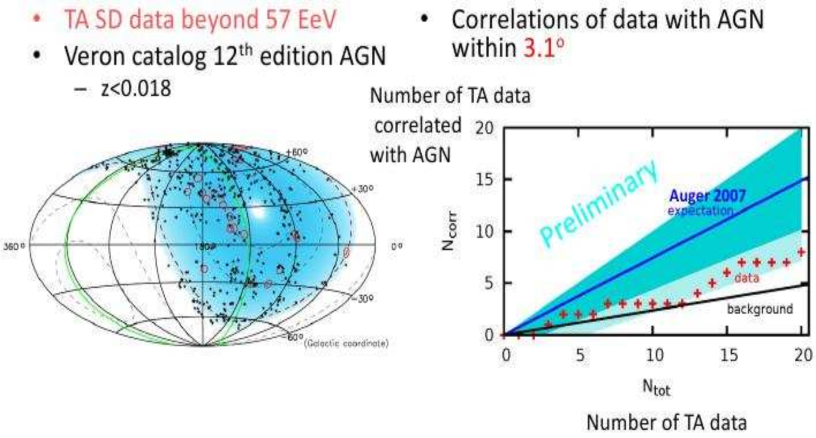

- ⇒ consistent both with the isotropy and with the AGN correlation hypothesis

Propagation in extragalactic space & GZK cutoff

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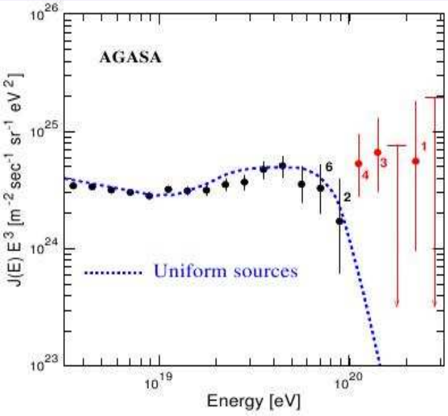
- in turn, UHE nuclei loose energy via photodisintegration on IR photons: $A + \gamma \rightarrow (A-1) + p/n \Rightarrow$ similar cutoff

Trans-GZK events & physics beyond the Standard Model?

Observation of trans-GZK events by the AGASA Collaboration *[PRL 81 (1998)]*



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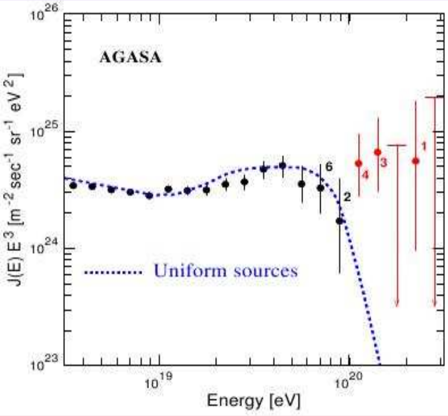

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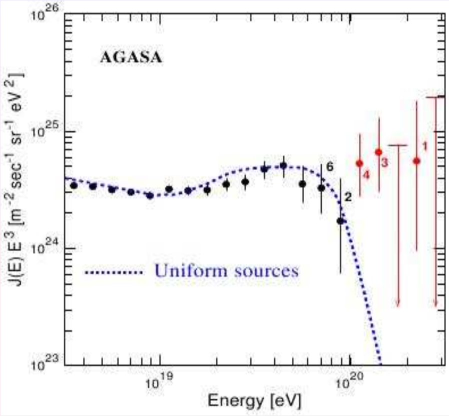

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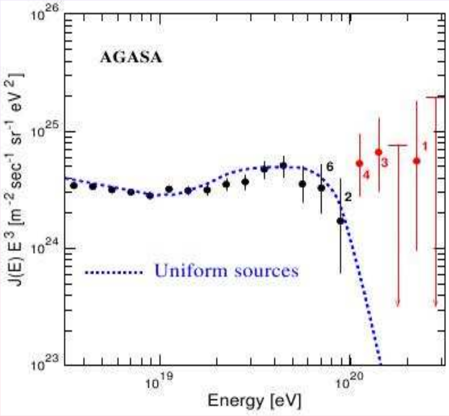

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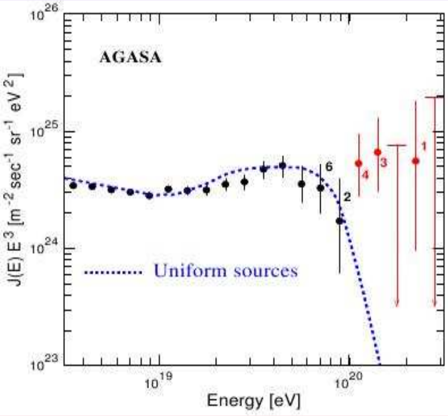

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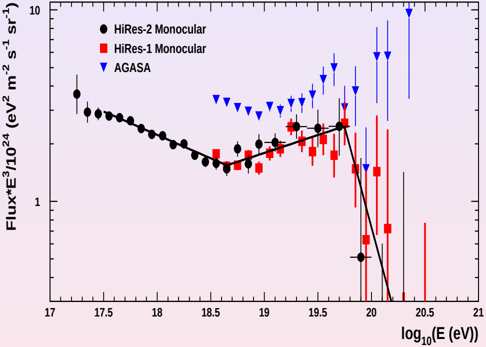

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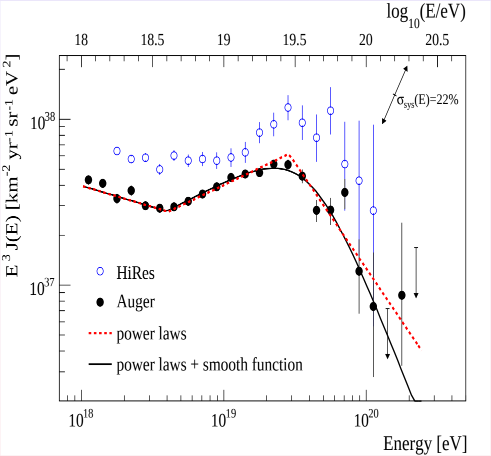

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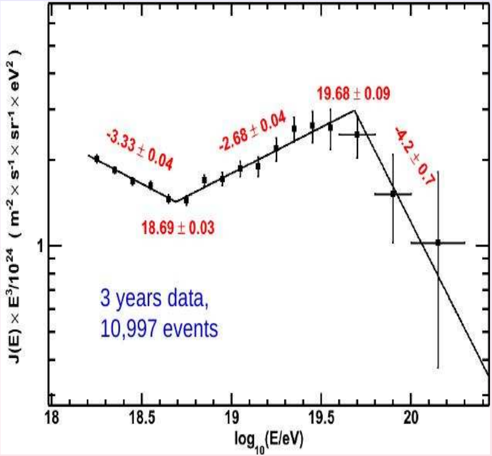

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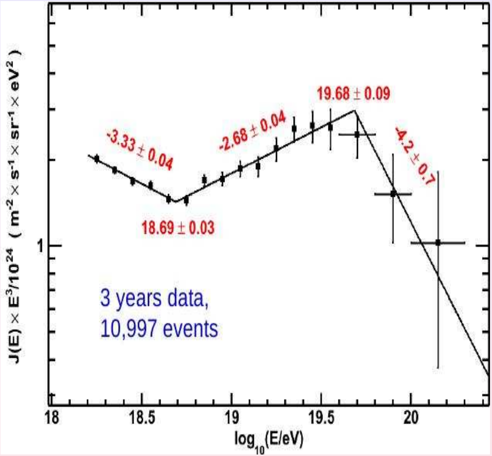

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- trans-GZK story - finally over

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$\Rightarrow$ measurements of CR composition – key to the UHECR puzzle

Extensive Air Shower (EAS) techniques of CR detection

observations of nuclear-e/m cascades induced by CR particles:

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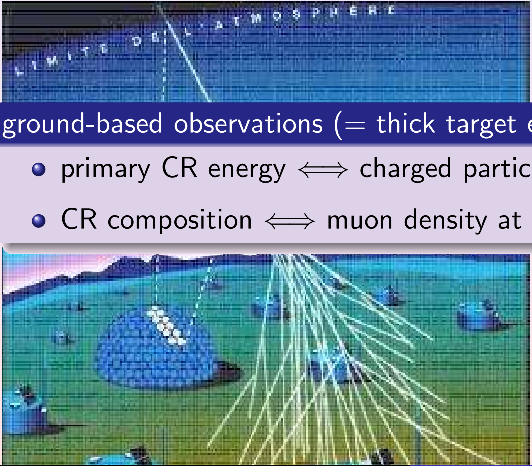

ground-based observations (= thick target experiments)

- primary CR energy $\Longleftrightarrow$ charged particle density at ground
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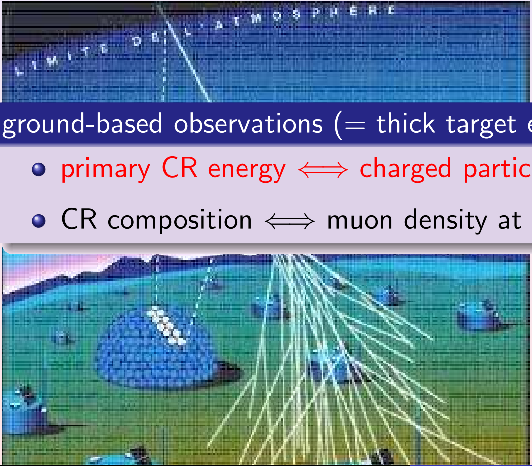

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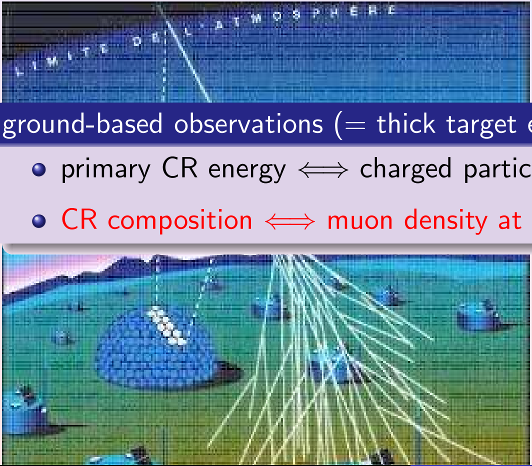

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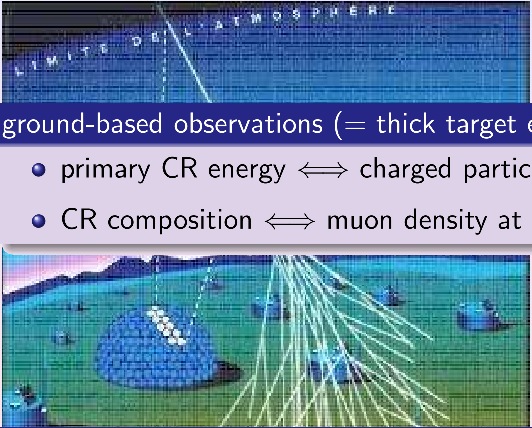

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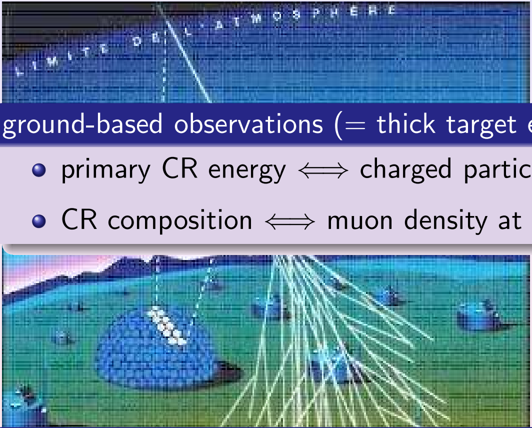

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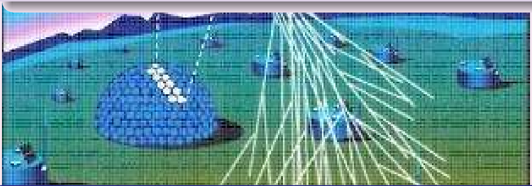

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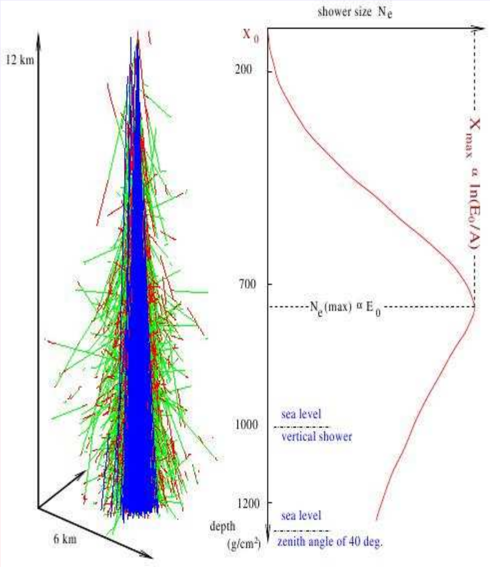

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- e.g. $X_{\max}$: to $\sigma^{\rm inel}_{p-\rm air}$ and to 'inelasticity' $K^{\rm inel}_{p-\rm air}$
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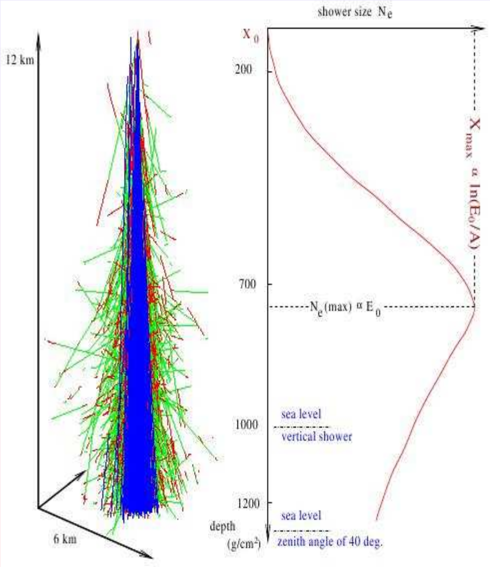

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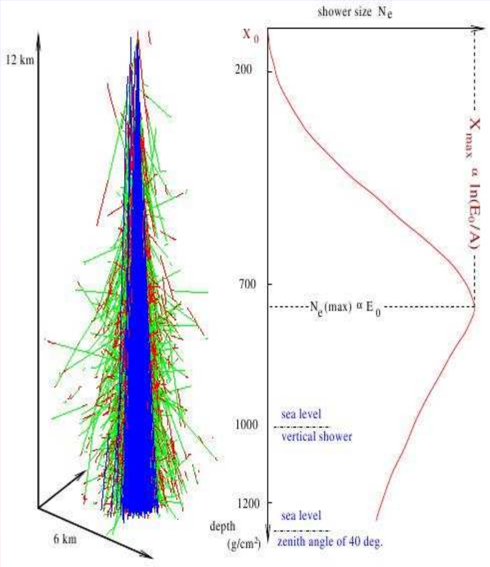

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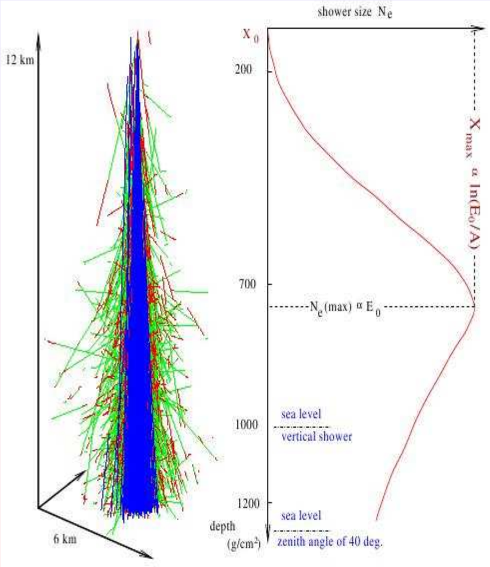

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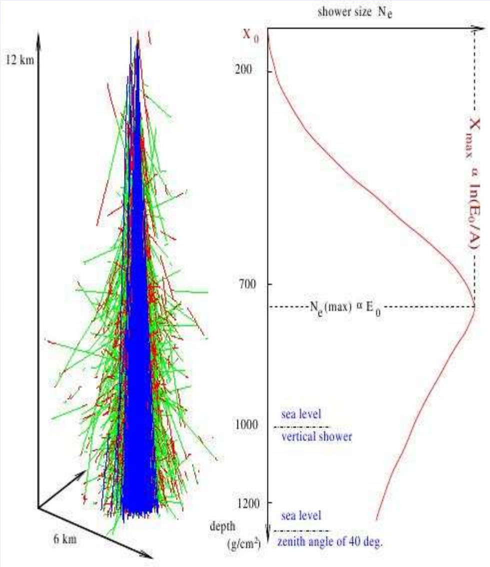

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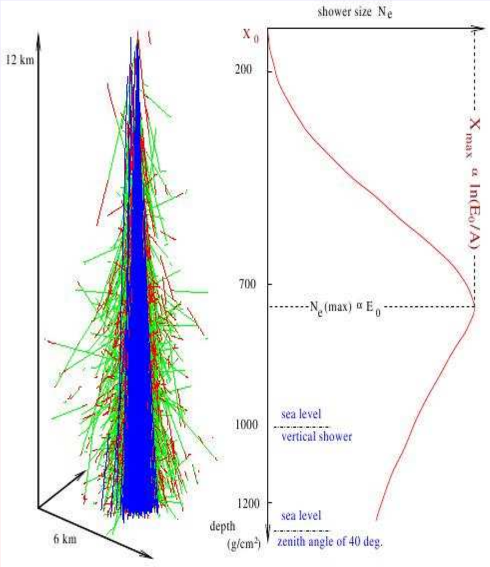

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- most sensitive to interactions of secondary pions (also kaons & (anti-)nucleons) at intermediate energies ($E \sim \sqrt{E_0}$)

Nucleus-induced air showers & superposition model

For average (only!) air shower characteristics: $A-$induced EAS of energy E – equivalent to A proton-induced showers of energy E/A

- N of 'wounded' nucleons per collision: $\langle \nu_A \rangle = A\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ (valid up to target diffraction)
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- $\Rightarrow \langle X^A_{\max}(E)\rangle \simeq \langle X^p_{\max}(E)\rangle - ER\ln A$
  $\langle N^A_e(E)\rangle \simeq \langle N^p_e(E)\rangle A^{0.1}; \quad \langle N^A_\mu(E)\rangle \simeq \langle N^p_\mu(E)\rangle A^{-0.1}$
  – nucleus-induced air showers reach their maxima earlier, have less $e^{\pm}$ and more muons

EAS maximum position $X_{\max}$ – the key to the UHECR composition

UHECR composition from $X_{\max}$ observations

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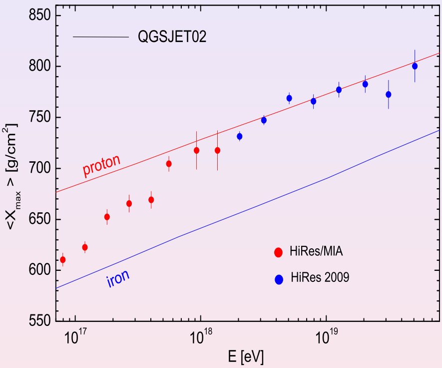

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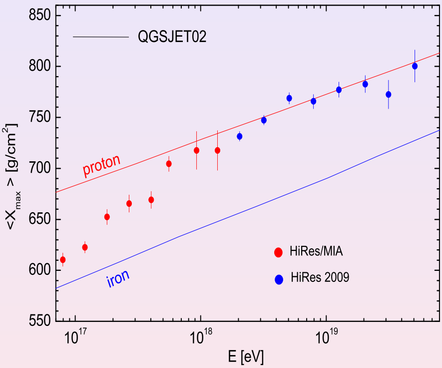

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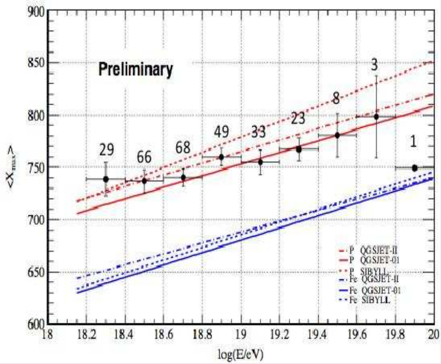

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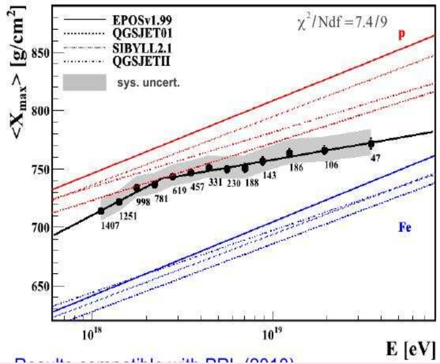

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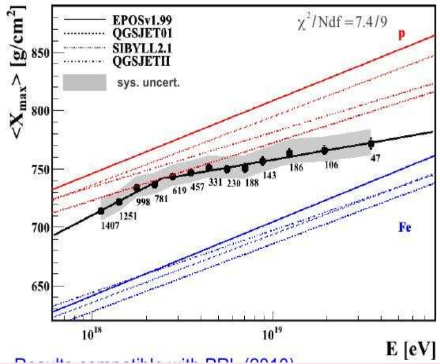

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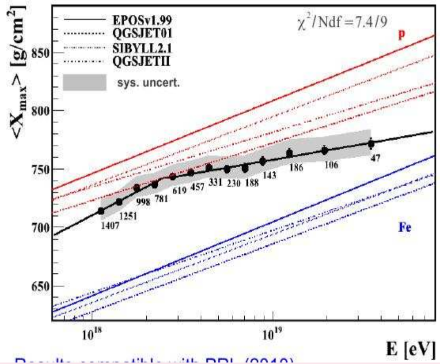

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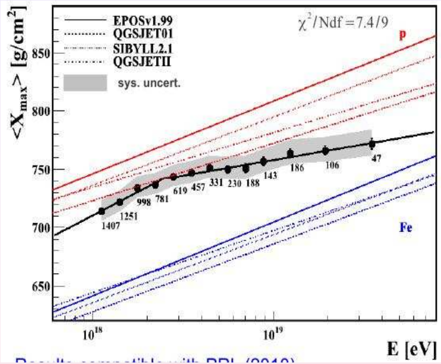

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- yes, by studying shower fluctuations, e.g. RMS($X_{\max}$) *[Aloisio, Berezinsky, Blasi & SO, PRD 77 (2008)]*

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- RMS($X_{\max}$) for proton-induced showers
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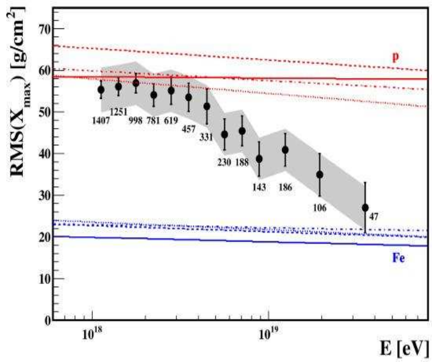

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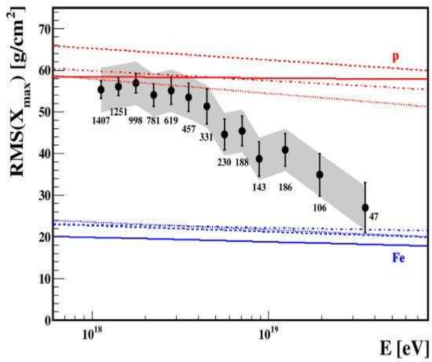

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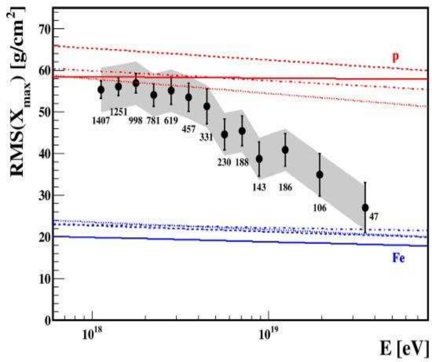

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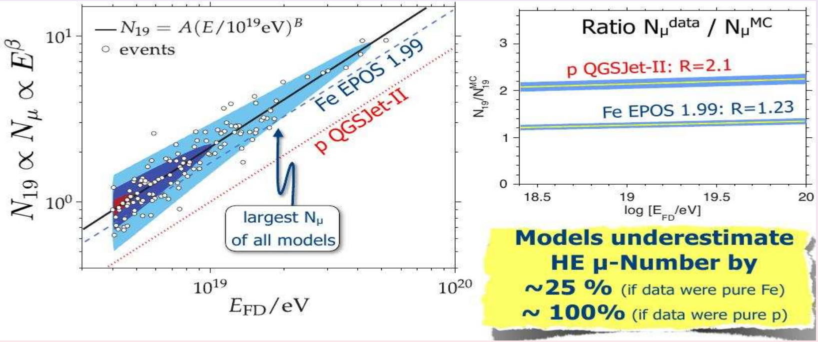

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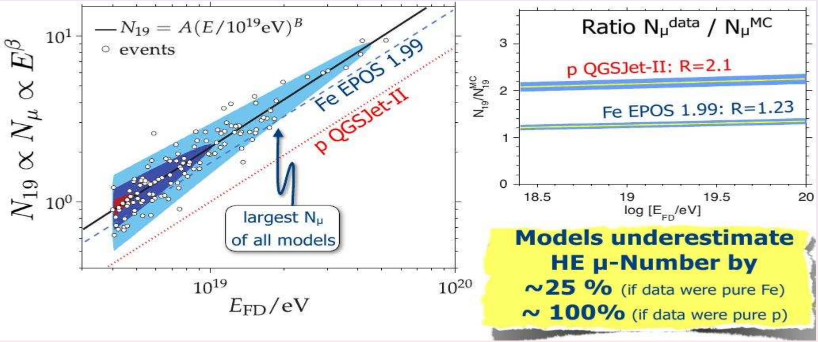

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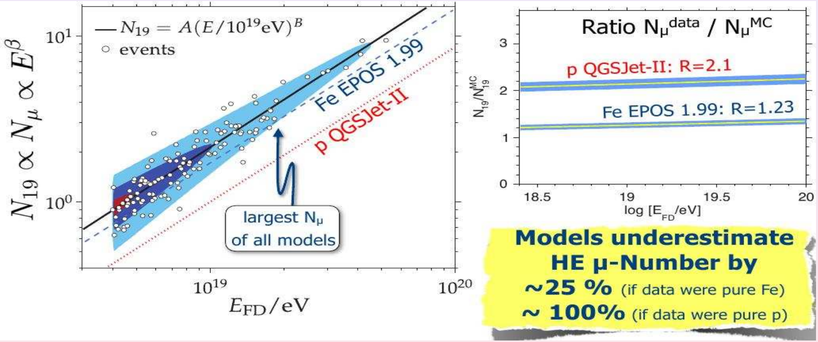
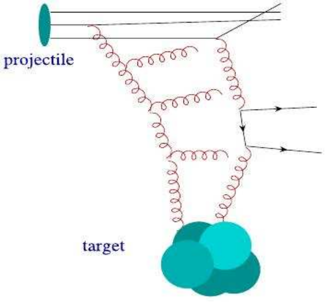


- may be UHECR are gold nuclei?!
- highly unlikely, rather CR interaction models should be wrong

High energy interactions: qualitative picture

- multiple scattering picture: many parton cascades develop in parallel
- generally required for unitarity
- allows to explain multiple (mini-)jet production



[picture from R. Engel]

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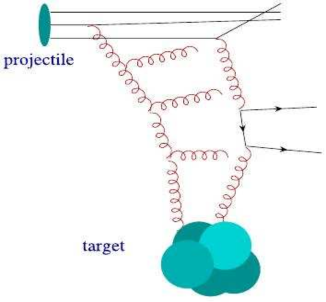

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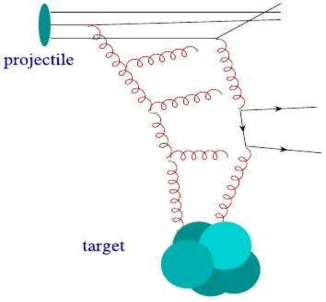

[picture from R. Engel]

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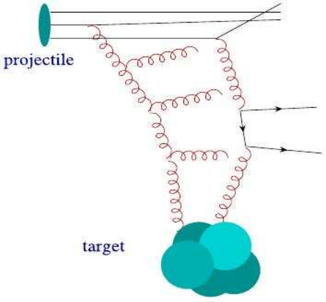

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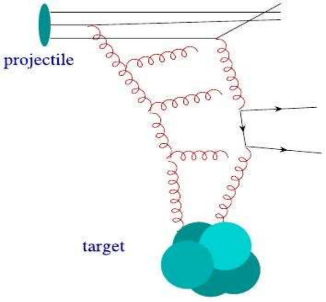

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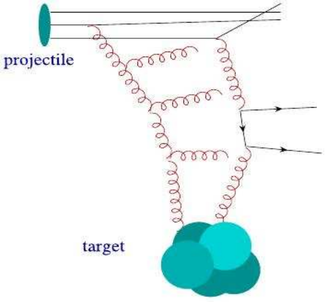

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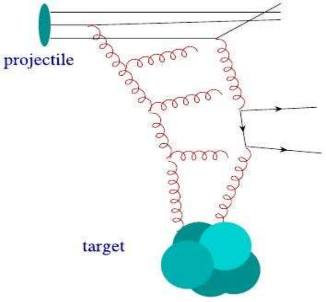

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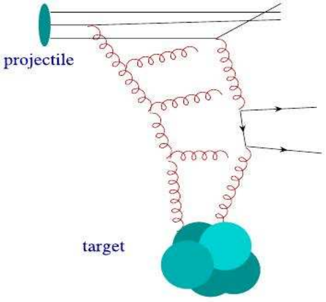

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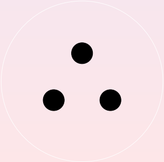

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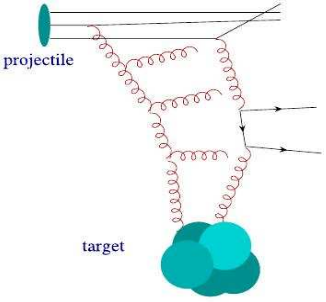

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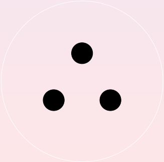

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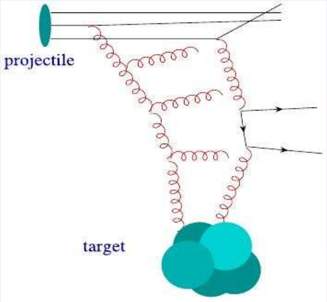

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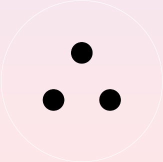

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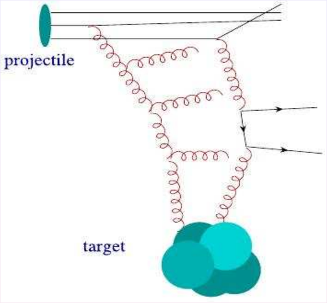

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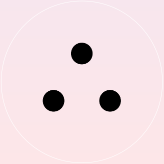

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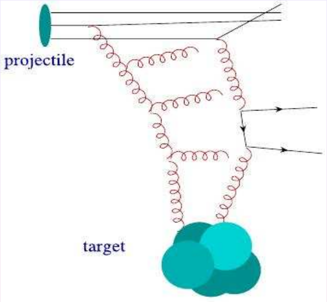

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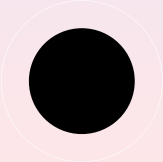

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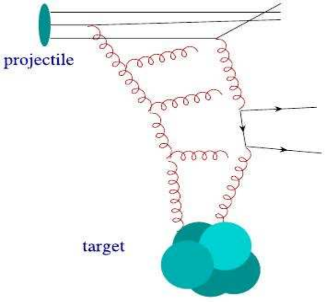

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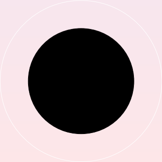

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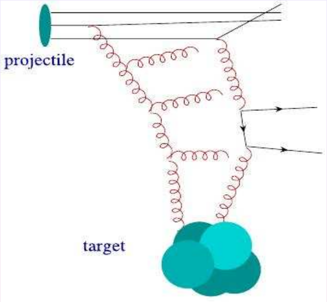

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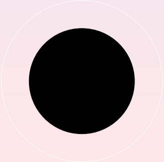

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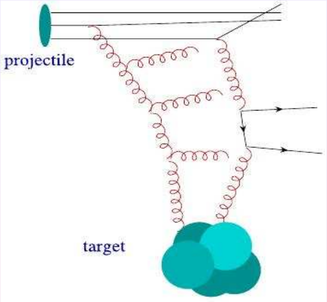

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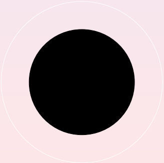

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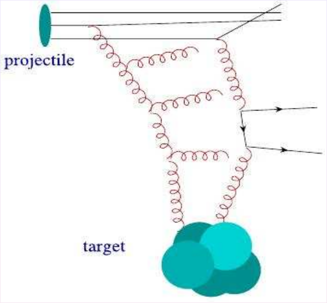

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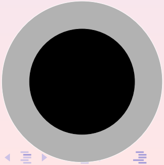

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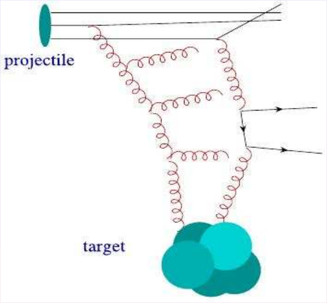

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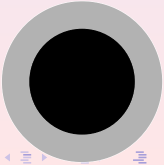

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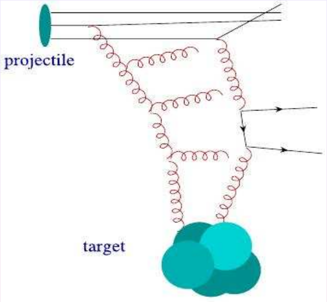

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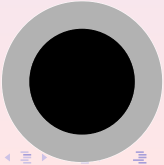

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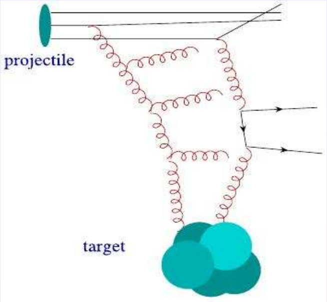

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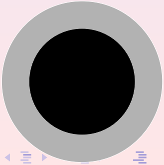

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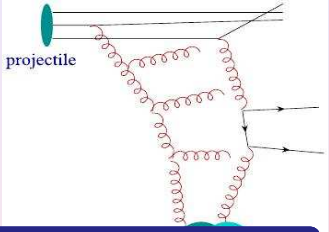

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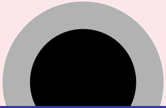

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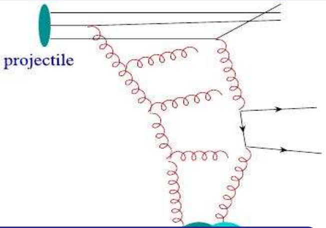

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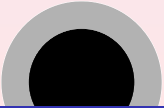

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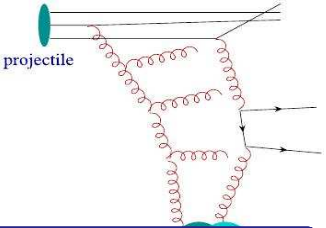

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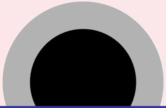

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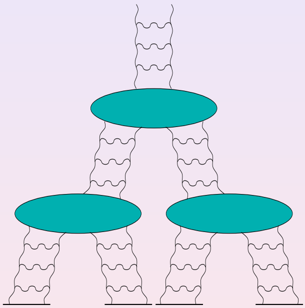

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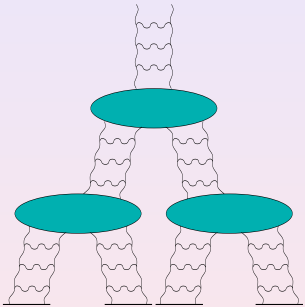

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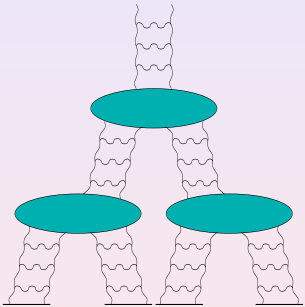

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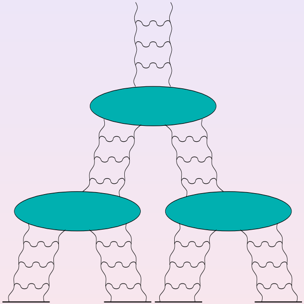

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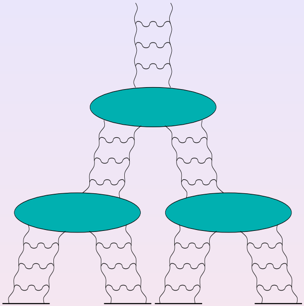

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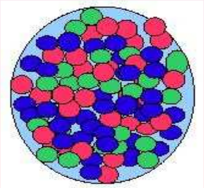

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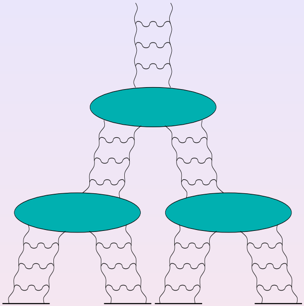

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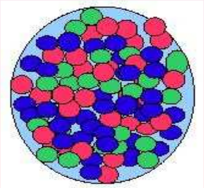

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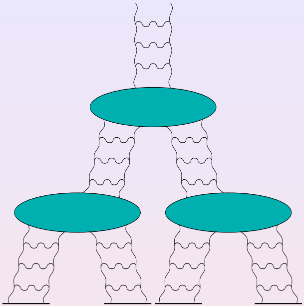

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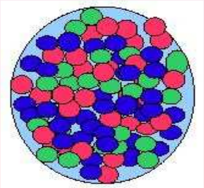

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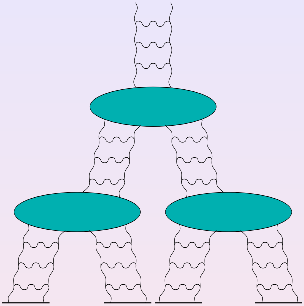

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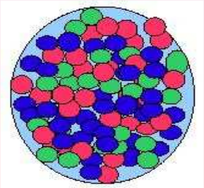

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- similar physics content for all MC generators used in CR field:
  - multiple scattering
  - soft & hard processes
  - nonlinear effects, e.g. parton shadowing (not in all models)

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  - EPOS (Liu, Pierog & Werner, 2006-2011)

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- model updates / cross checks with new data - necessary

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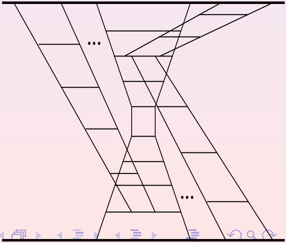

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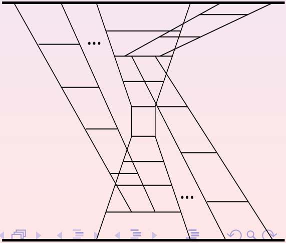

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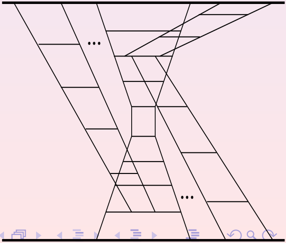

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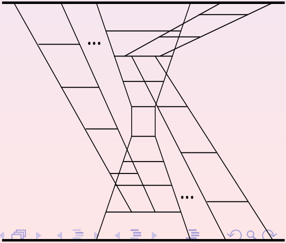

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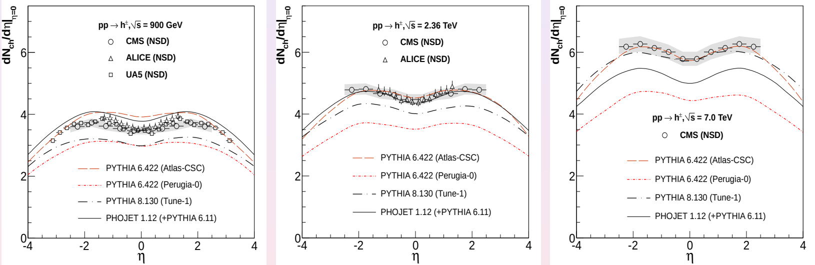
MC generators & LHC data

- LHC data: $N_{\rm ch}(s)$ rises quicker than predicted by most MCs



[plots from d'Enterria et al., Astrop. Phys. 35 (2011)]

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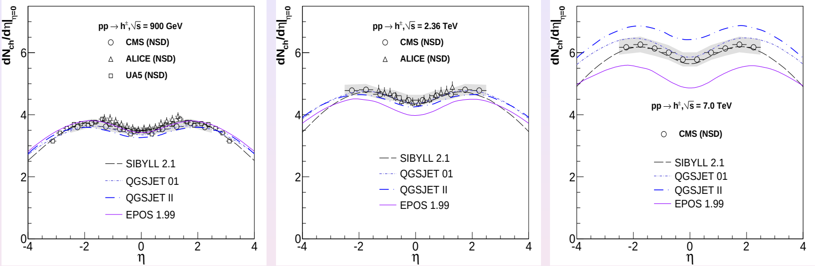

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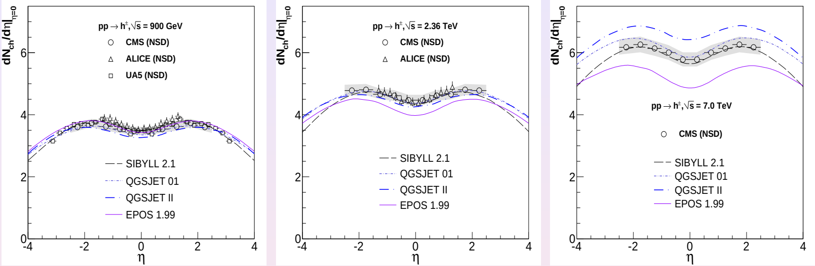

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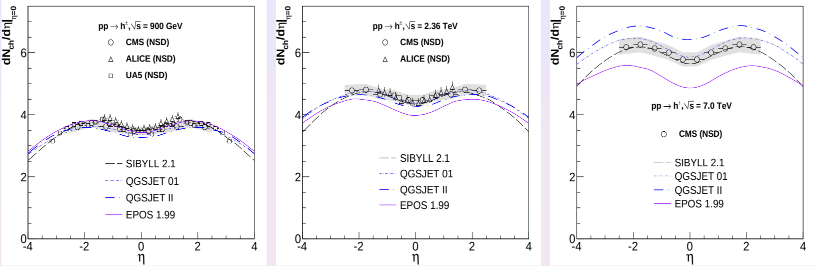

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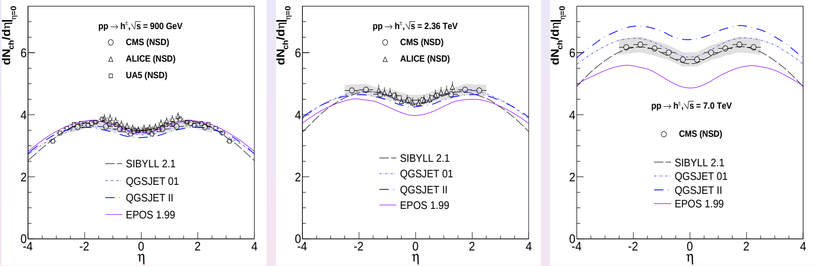

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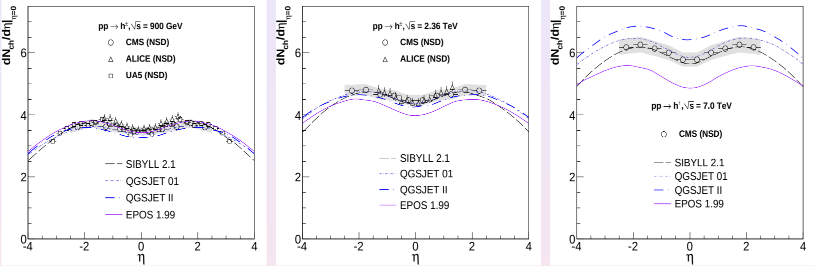

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Effect of model retuning to LHC data?

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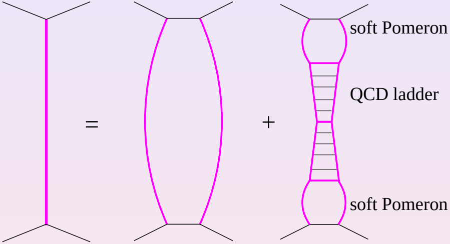
QGSJET-II model

- based on combined treatment of soft & hard parton processes



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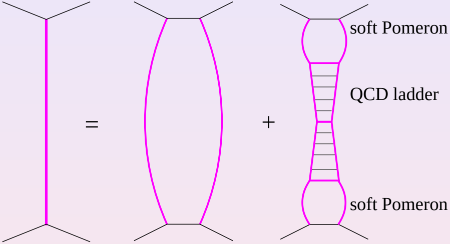

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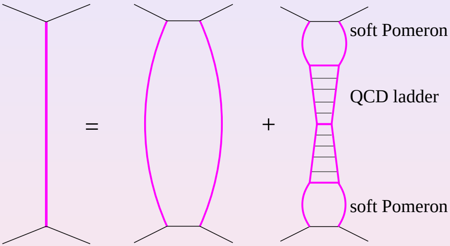

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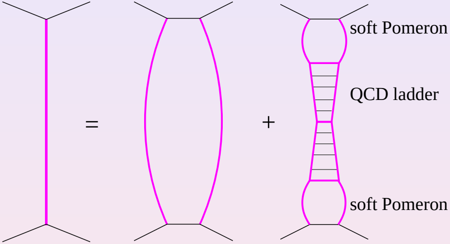

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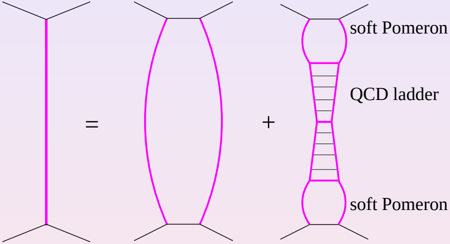

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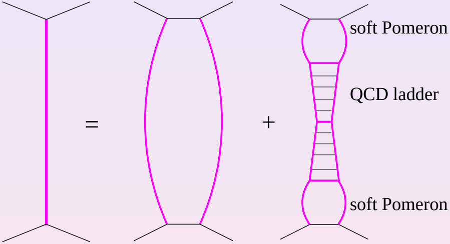

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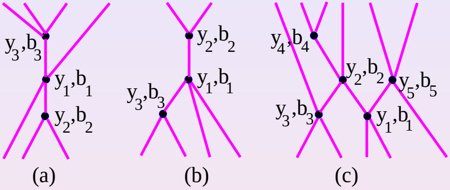

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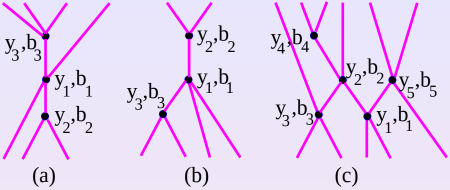

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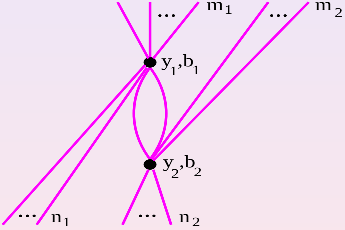

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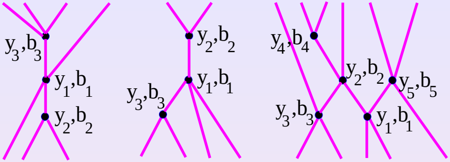

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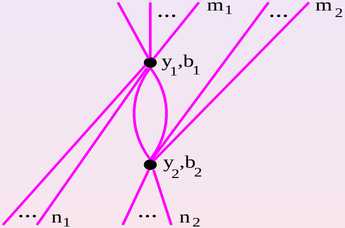

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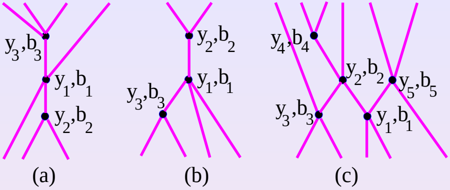

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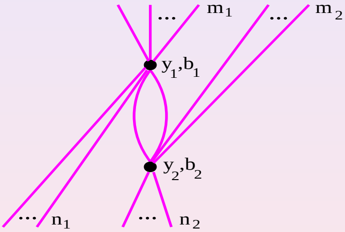

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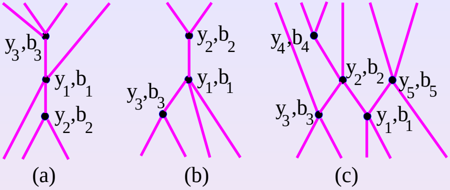

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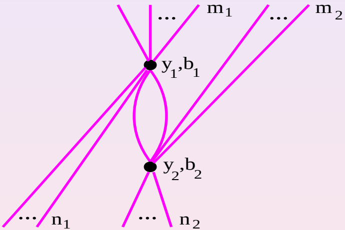

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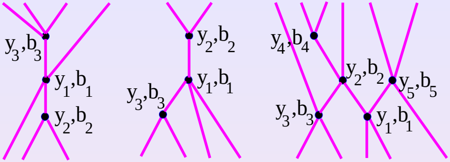

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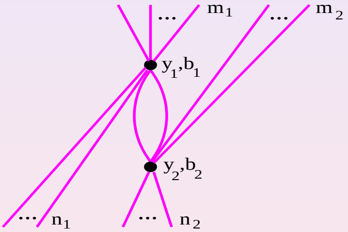

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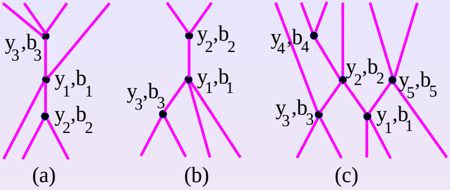

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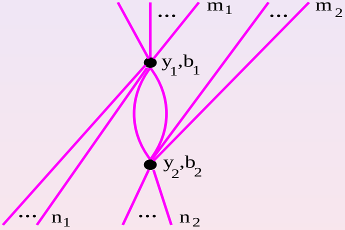

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- here: impact of calibration to LHC data

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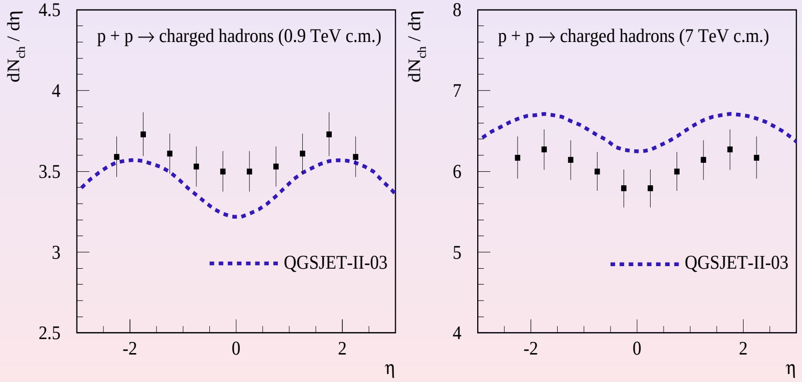

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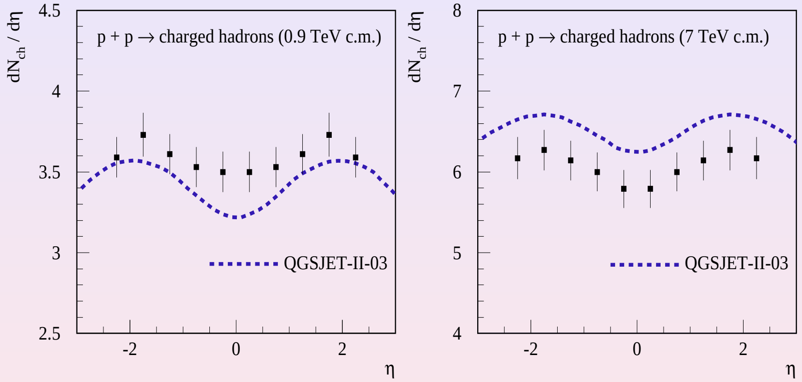

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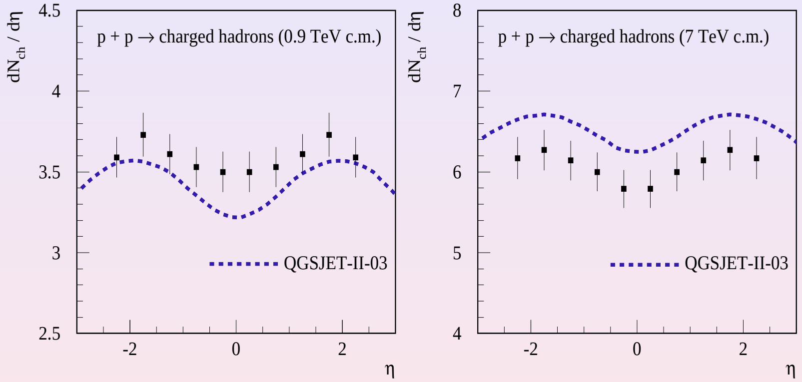

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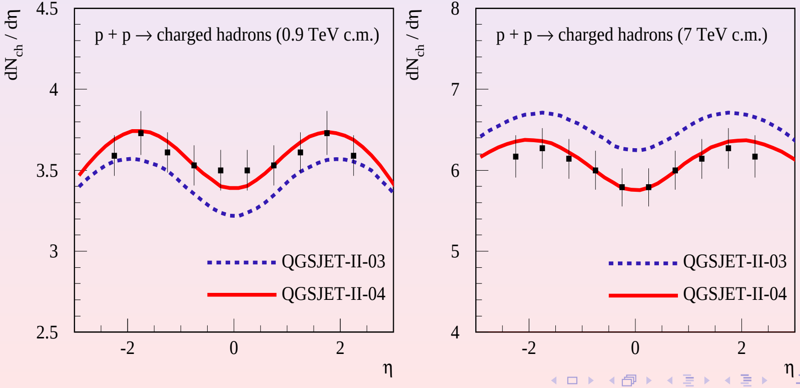

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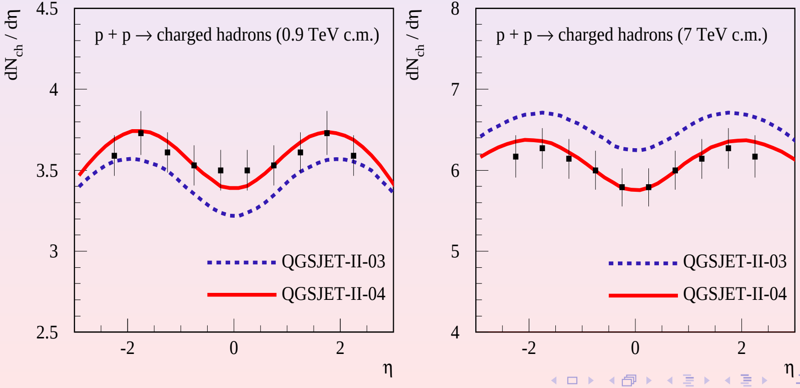

Multiplicity adjustment

changing the cutoff Q_0^2 between soft & hard processes ($2.5 \rightarrow 3$ GeV^2)

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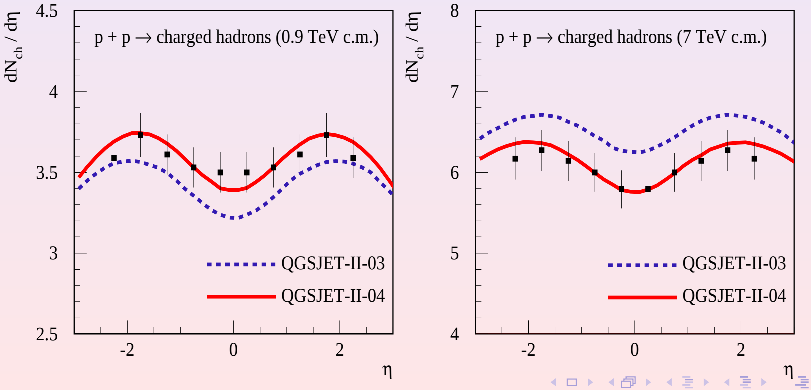

Multiplicity: cross check with ATLAS data

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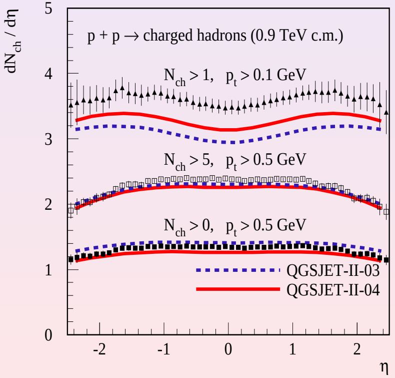

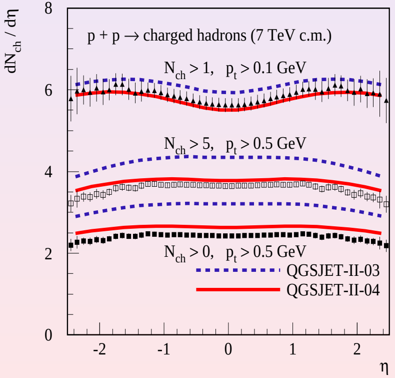

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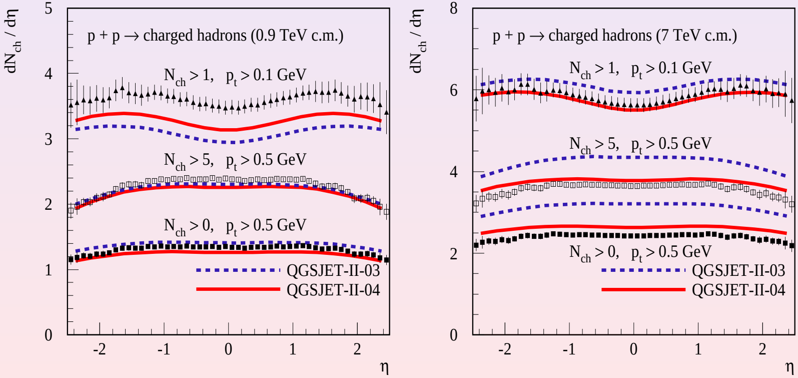

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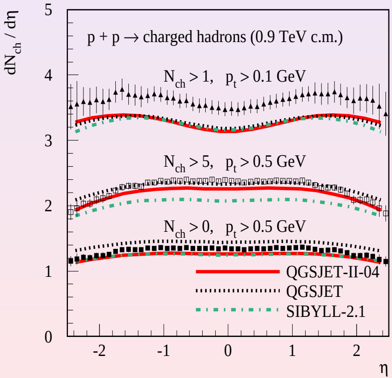

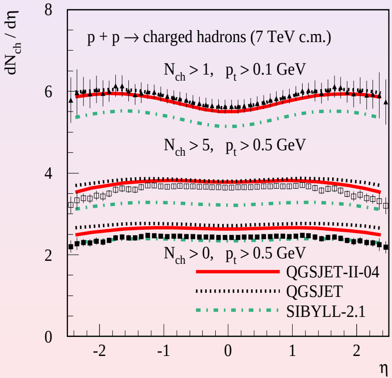

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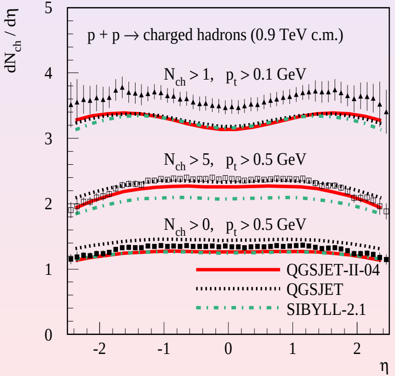

Production of (anti-)baryons

Generally, enhanced production of (anti-)baryons may increase EAS muon content *[Pierog & Werner, PRL (2008)]*

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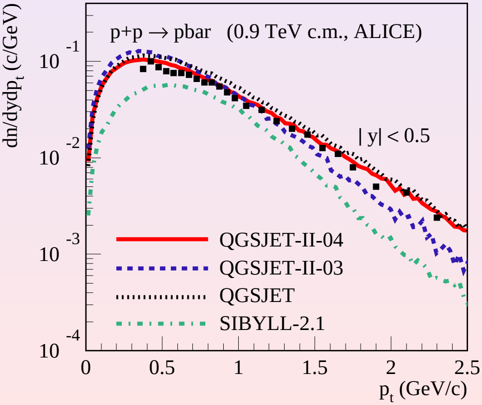

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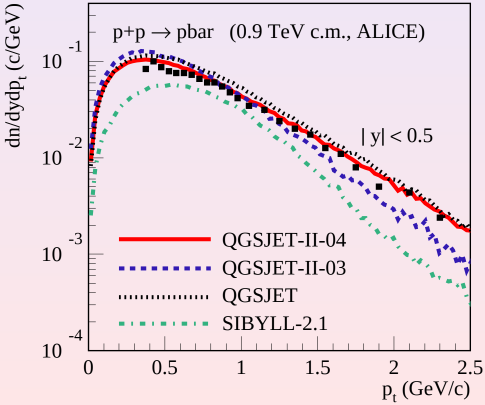

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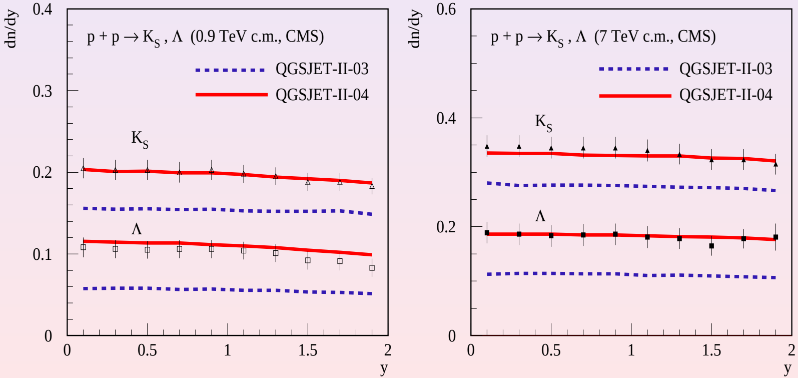

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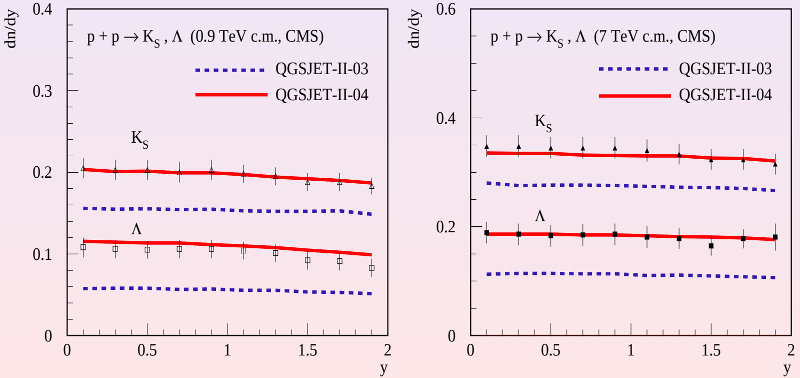

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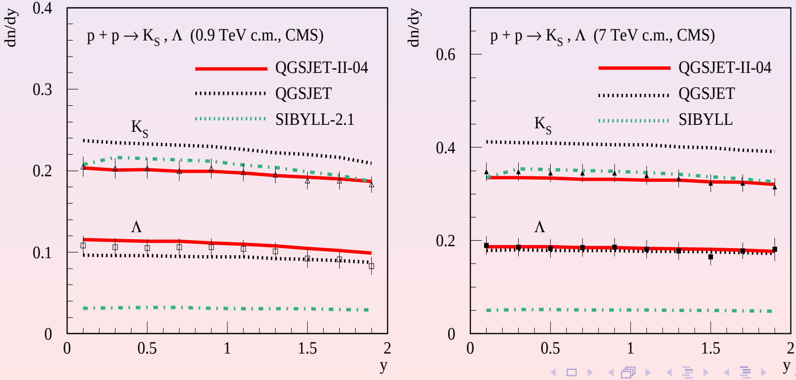
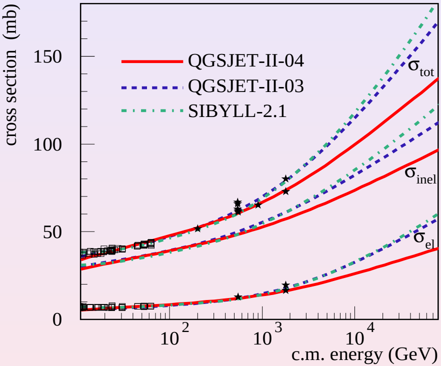


Inelastic cross section



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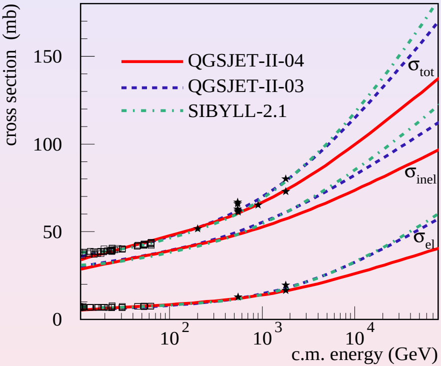

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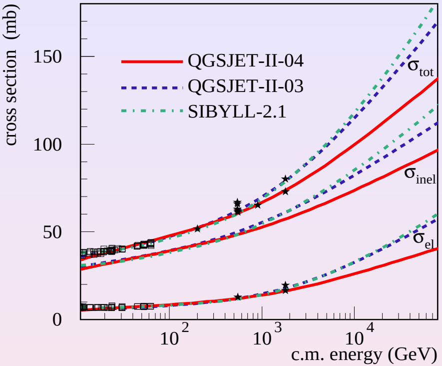

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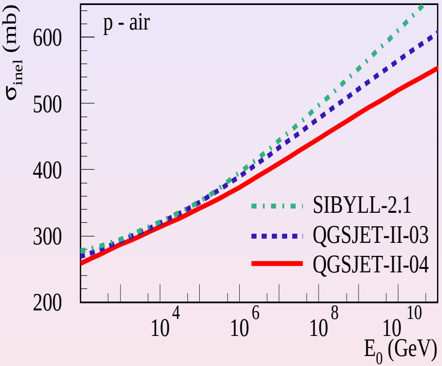
- lower cross sections now supported by LHC data

	QGSJET-II-04	QGSJET-II-03	SIBYLL	ATLAS
$\mathrm{MBTS_{AND}}$	54.1	62.3	68.4	51.9 ± 5.7
$\mathrm{MBTS_{OR}}$	60.8	69.8	74.7	58.7 ± 6.5

Table: Model predictions for "visible" cross sections (in mb) at $\sqrt{s} = 7$ TeV for ATLAS MB triggers: at least one charged hadron at $-3.84 < \eta < -2.09$ and/or at $2.09 < \eta < 3.84$ ($\mathrm{MBTS_{AND/OR}}$).

Proton-air cross section & X_{max}



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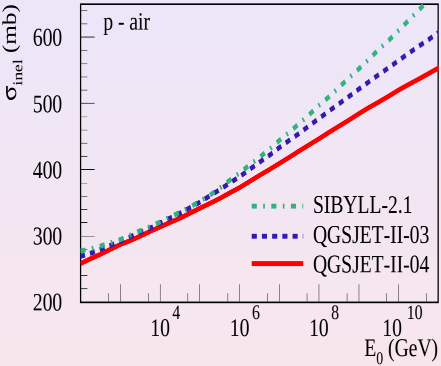

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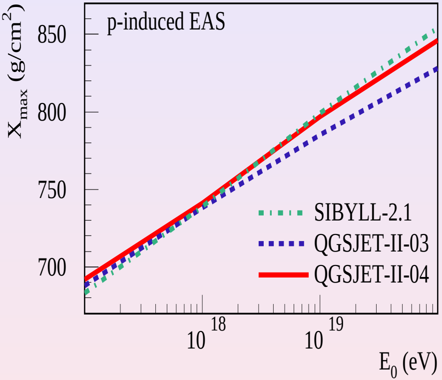

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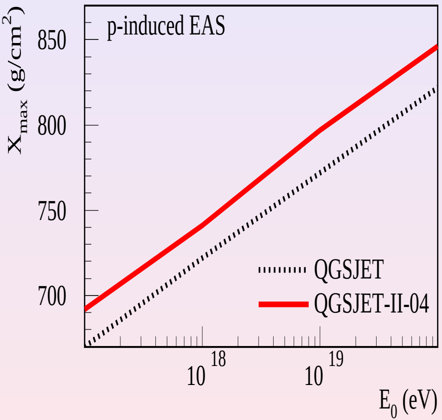

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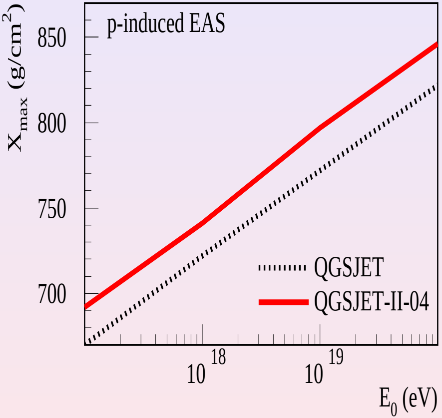

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- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)

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