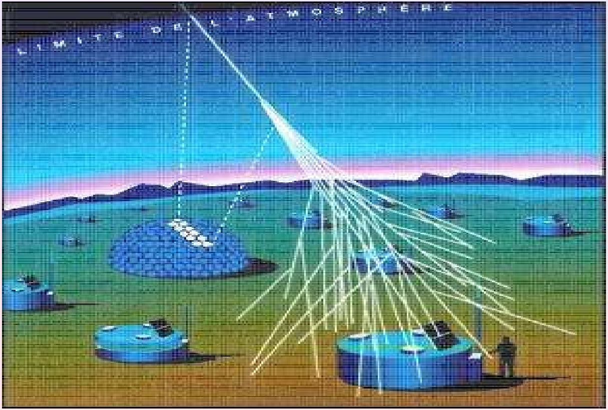
Hadronic Interactions & Air Showers

Sergey Ostapchenko (NTNU, Trondheim)

ICRR (Tokyo), October 11, 2011

Extensive Air Shower (EAS) techniques of CR detection

High energy cosmic rays – studied via measurements of air showers (nuclear-e/m cascades induced by CR particles)



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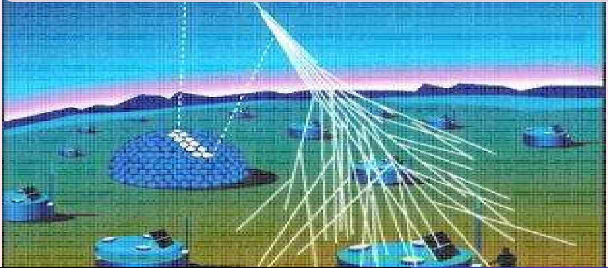
ground-based observations (= thick target experiments)

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



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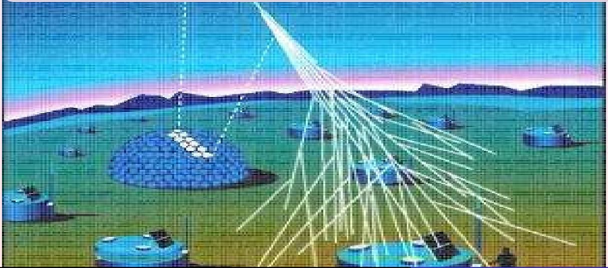

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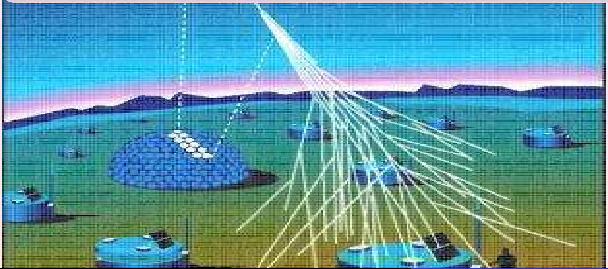

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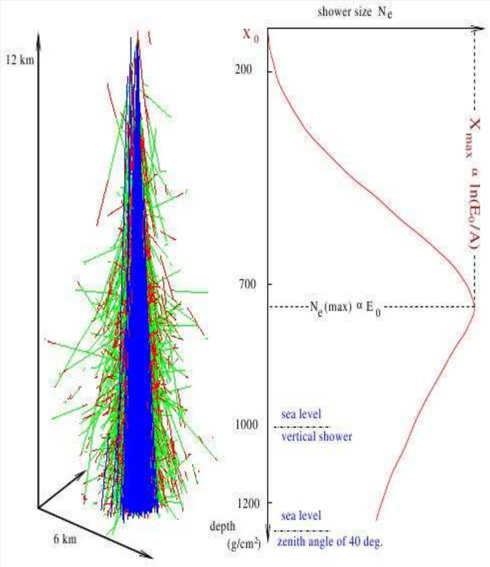

- EAS development – driven by interactions of primary / 'leading' secondary particles
- $\Rightarrow$ hadronic cascade $=$ EAS backbone
- secondary cascades – well averaged
- observables used for CR composition studies – most sensitive to hadronic physics
- e.g. $X_{\max}$: to $\sigma^{\rm inel}_{p-\rm air}$ and to 'inelasticity' $K^{\rm inel}_{p-\rm air}$
- N_μ: to $N^{\rm ch}_{\pi-\rm air}\big|_{E\sim\sqrt{E_0}}$

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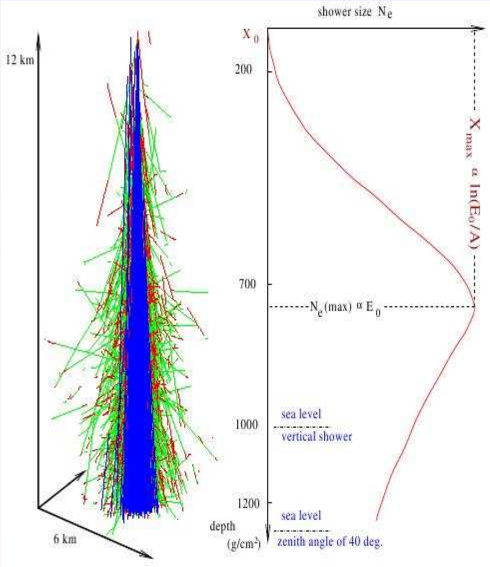

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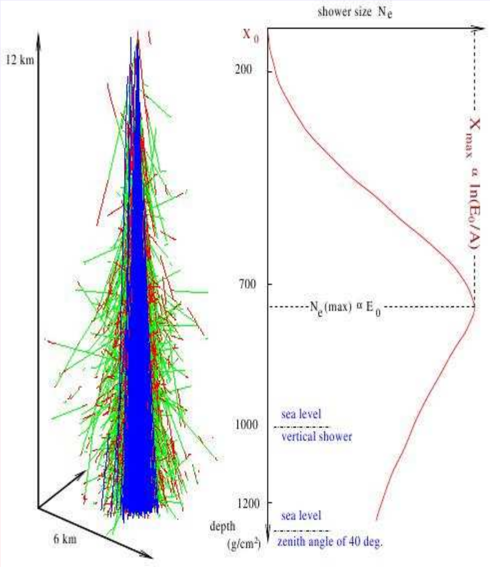

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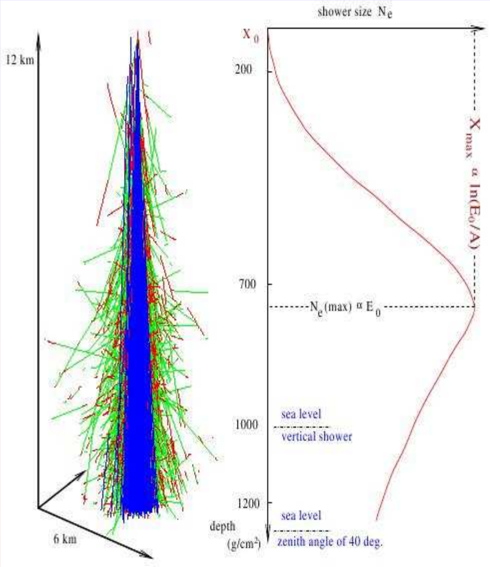

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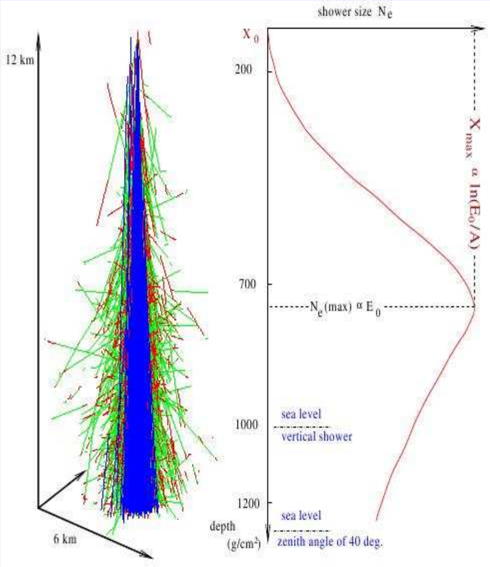

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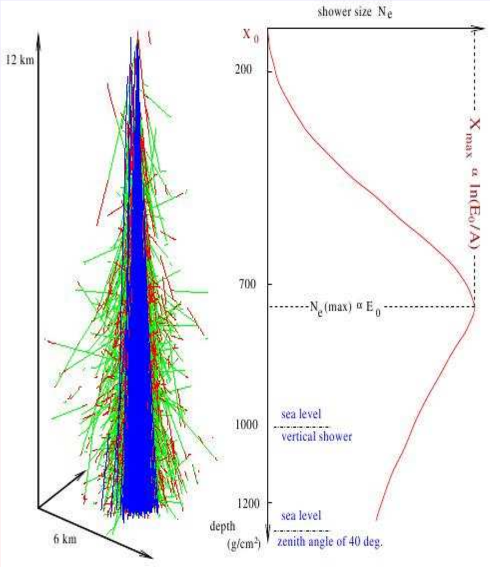

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Nucleus-induced air showers & superposition model

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

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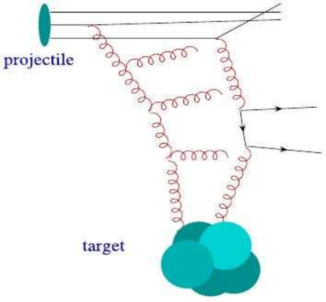
- experiments measure EAS properties for individual showers
- $\Rightarrow$ shower-to-shower fluctuations have to be described

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



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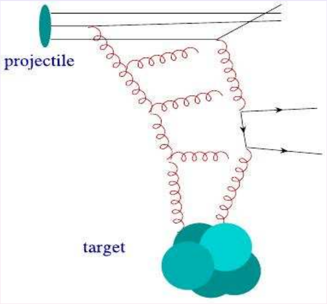

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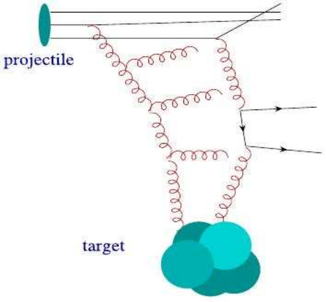

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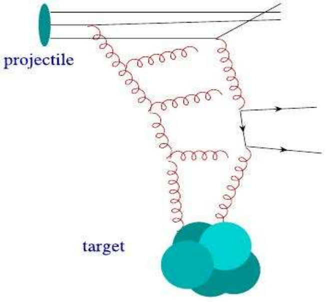

single cascade may be 'soft' (all $|q^2| < Q_0^2 \sim 1\,\mathrm{GeV}^2$)

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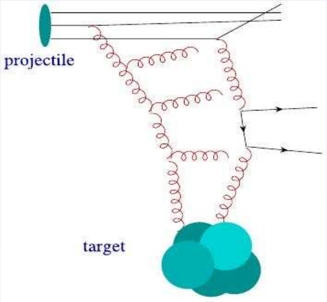

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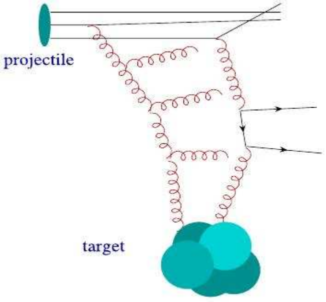

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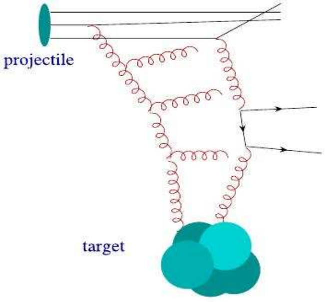

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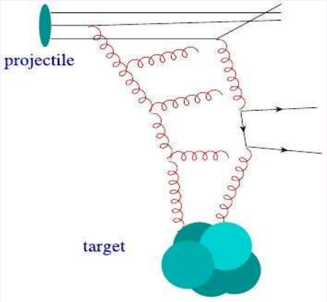

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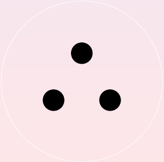

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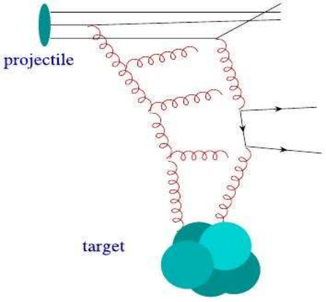

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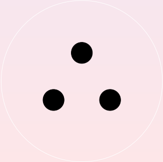

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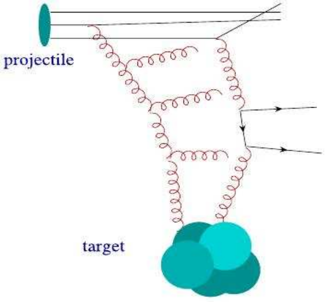

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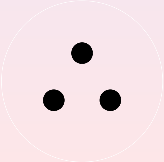

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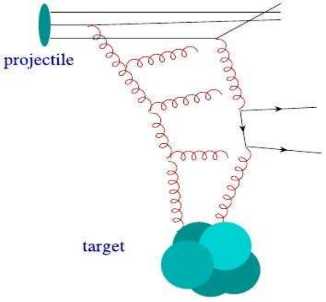

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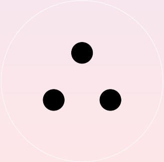
- $\Rightarrow$ important for dedicated QCD studies



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- multiple scattering picture: many parton cascades develop in parallel
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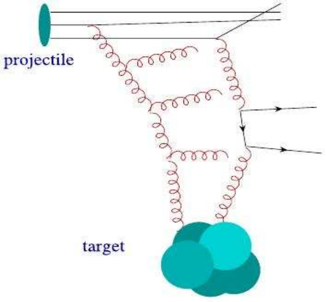

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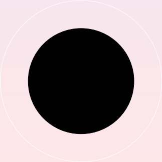

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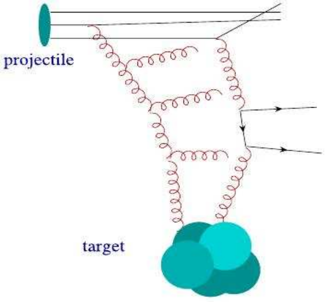

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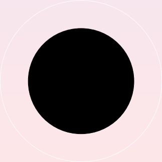

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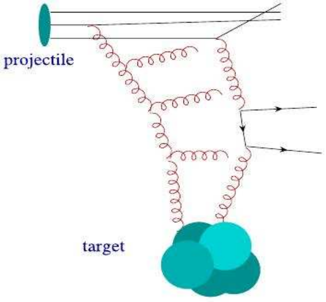

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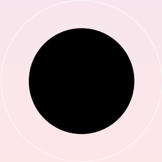

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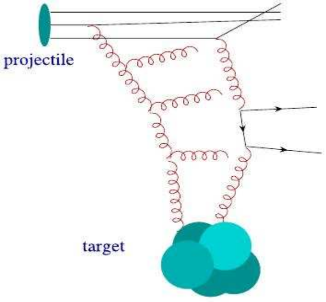

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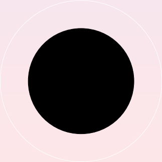

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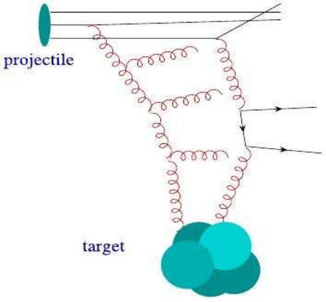

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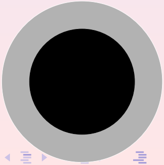

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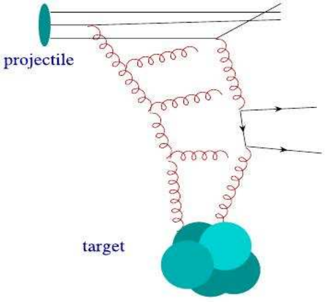

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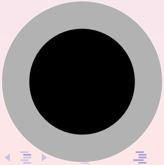

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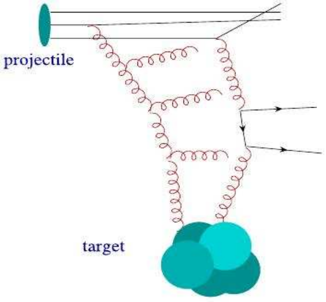

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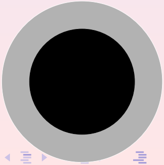

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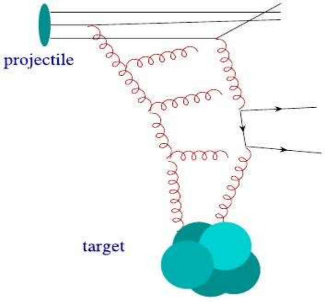

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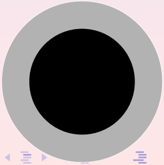

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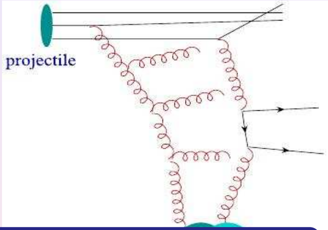

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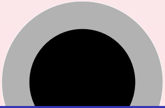

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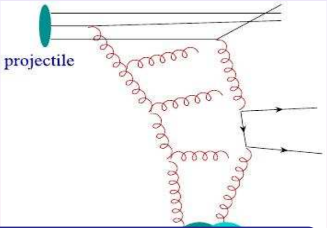

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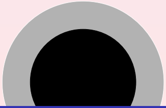

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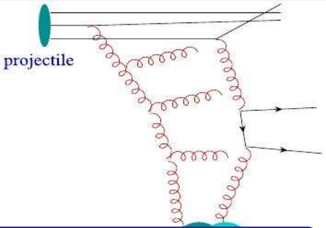

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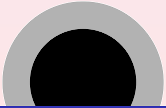

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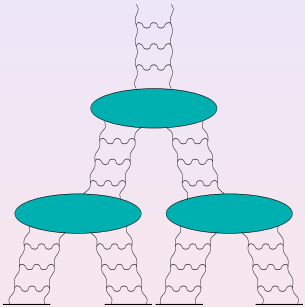

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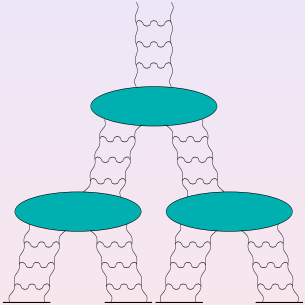

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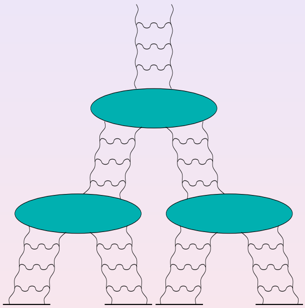

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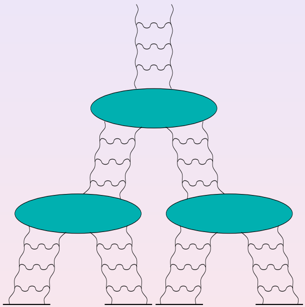

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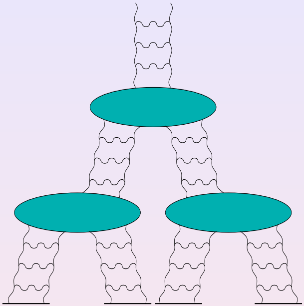

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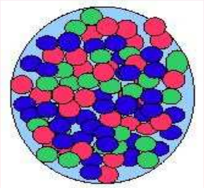

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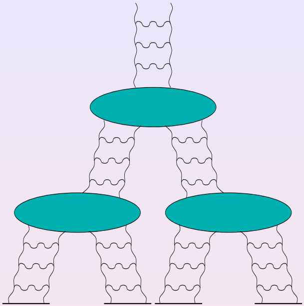

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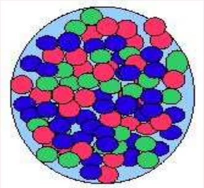

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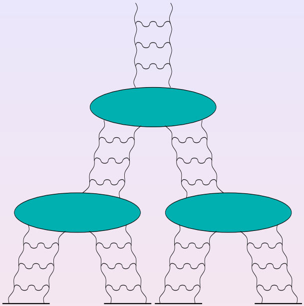

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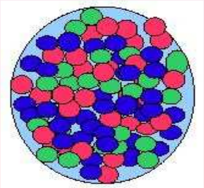

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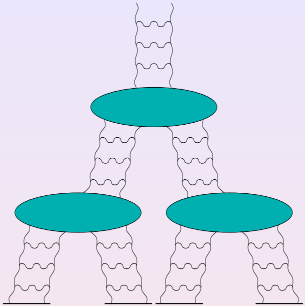

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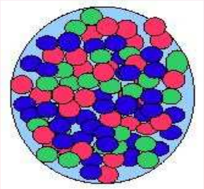

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- describe 'elementary' interaction
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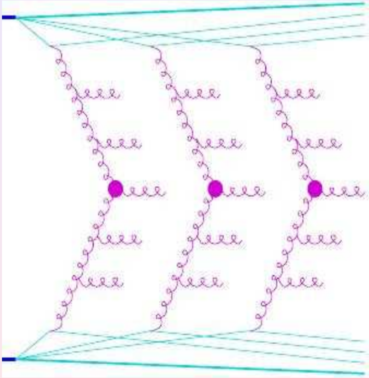

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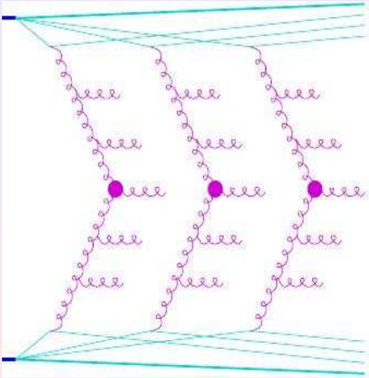

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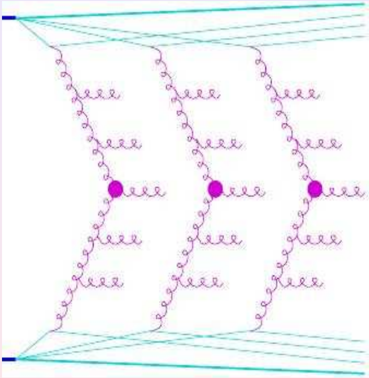

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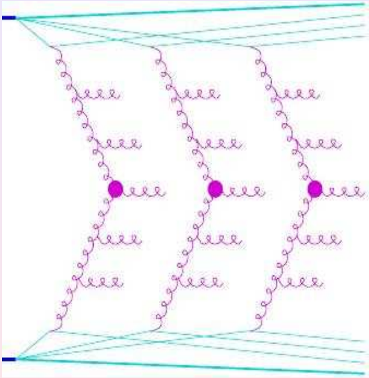

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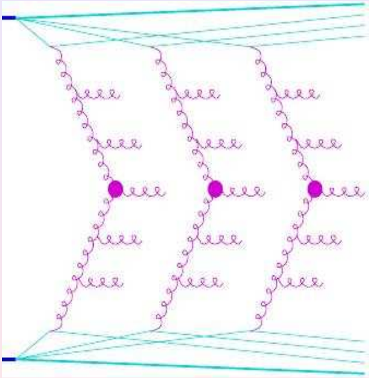

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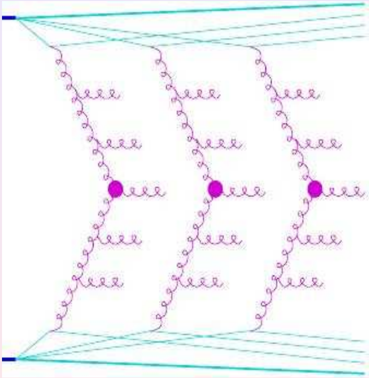

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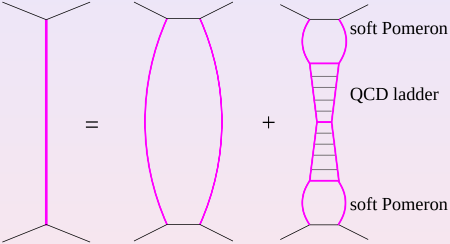
- based on combined treatment of soft & hard parton processes (implemented in QGSJET, QGSJET-II, EPOS)



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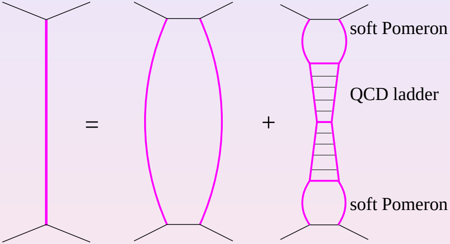

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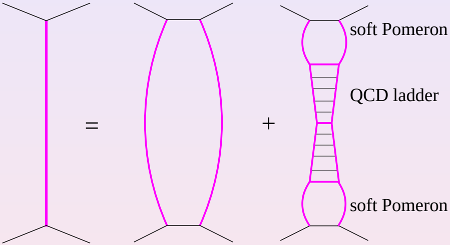

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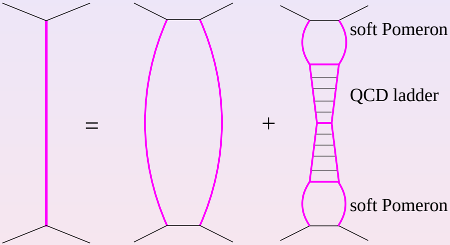

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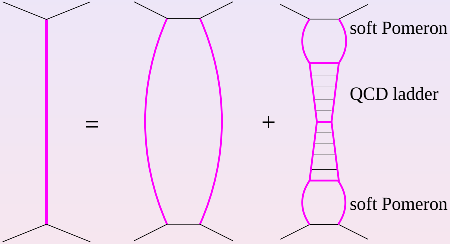

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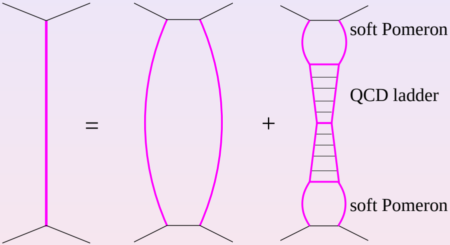

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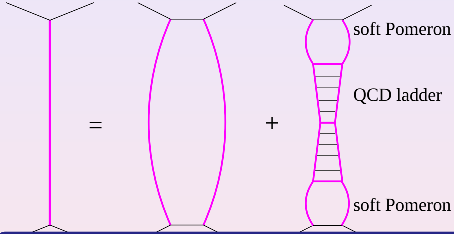

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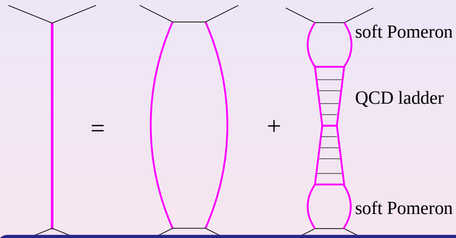

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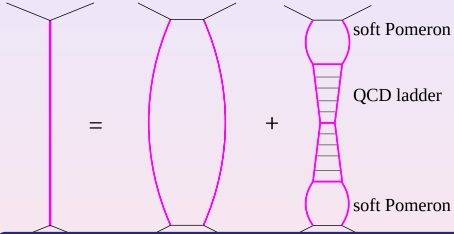

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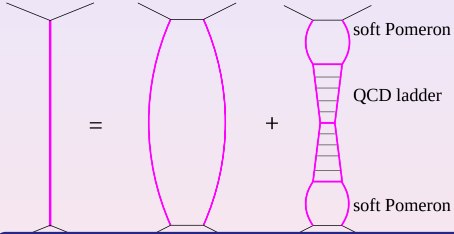

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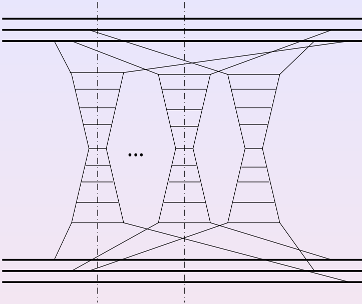

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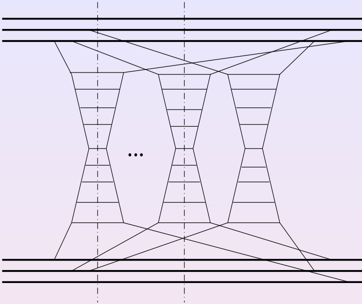

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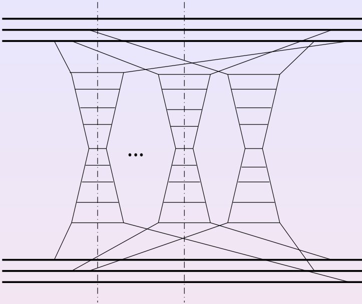

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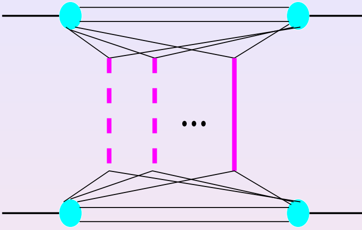

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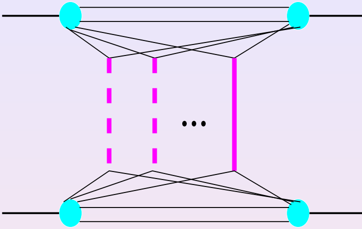

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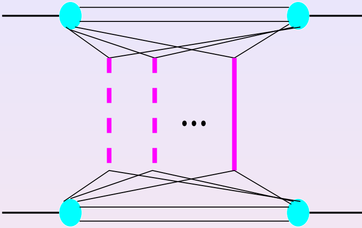

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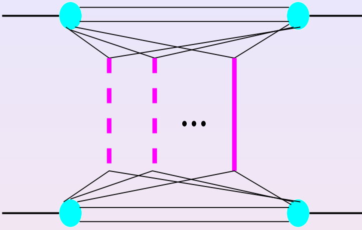

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$$\sigma_{ad}^{(n)}(s) = \int d^2b \, \frac{[2\chi_{ad}^{\mathbb{P}}(s,b)]^n}{n!} \, e^{-2\chi_{ad}^{\mathbb{P}}(s,b)}$$

($\chi_{ad}^{\mathbb{P}}$ – Pomeron exchange eikonal)

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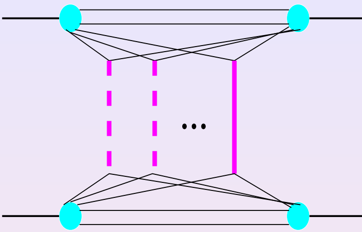

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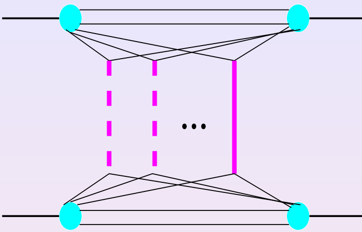

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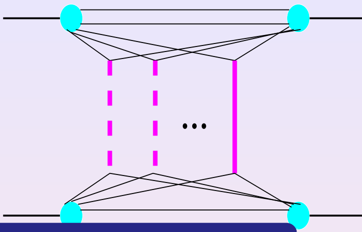

Instead of the simple eikonal formula one has

$$\Omega_{AB}^{(s_{NN},b)}(m,X^+,X^-) =$$
$$\prod_{k=1}^{AB}\left\{\frac{1}{m_k!}\prod_{\mu=1}^{m_k} G_k(x^+_{k,\mu},x^-_{k,\mu},s_{NN},b_k)\right\}\Phi_{AB}\left(x^{\mathrm{proj}},x^{\mathrm{targ}},s_{NN},b\right),$$

$$\Phi_{AB}\left(x^{\mathrm{proj}},x^{\mathrm{targ}},s_{NN},b\right) = \sum_{l_1}\ldots\sum_{l_{AB}}$$
$$\times\ \int\prod_{k=1}^{AB}\left\{\prod_{\lambda=1}^{l_k} d\tilde{x}^+_{k,\lambda}d\tilde{x}^-_{k,\lambda}\right\}\prod_{k=1}^{AB}\left\{\frac{1}{l_k!}\prod_{\lambda=1}^{l_k} -G_k(\tilde{x}^+_{k,\lambda},\tilde{x}^-_{k,\lambda},s_{NN},b_k)\right\}$$
$$\times\ \prod_{i=1}^{A} F_{\mathrm{remn}}\left(x_i^{\mathrm{proj}}-\sum_{\pi(k)=i}\tilde{x}^+_{k,\lambda}\right)\prod_{j=1}^{B} F_{\mathrm{remn}}\left(x_j^{\mathrm{targ}}-\sum_{\tau(k)=j}\tilde{x}^-_{k,\lambda}\right).$$

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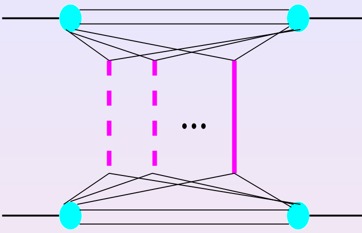

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- energy-momentum correlations between multiple rescatterings taken into account
- results in harder spectra of secondary hadrons (e.g. π^0s)

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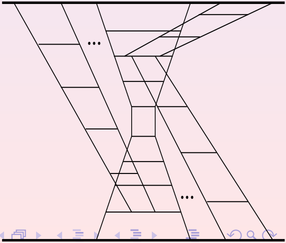

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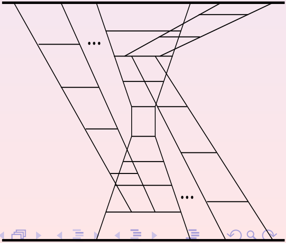

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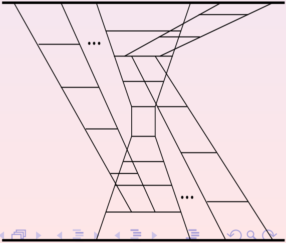

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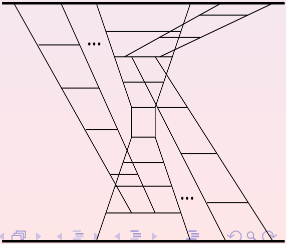

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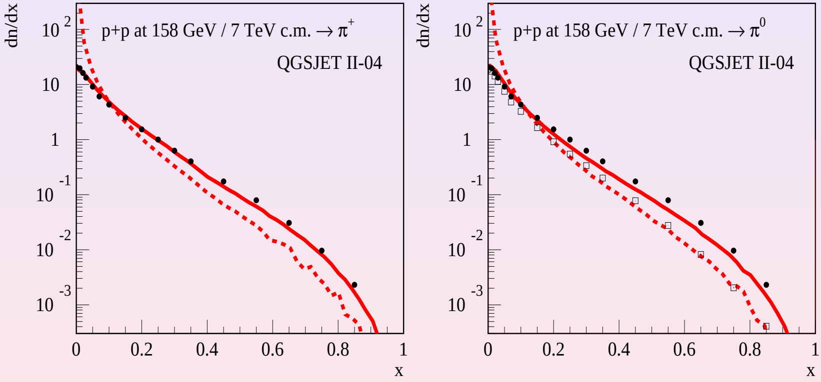

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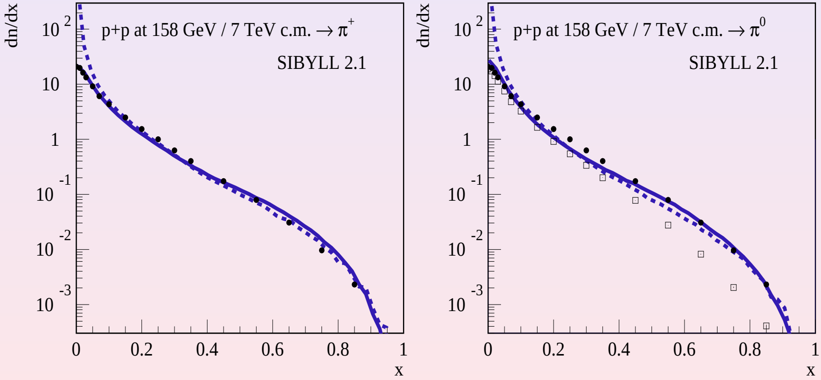

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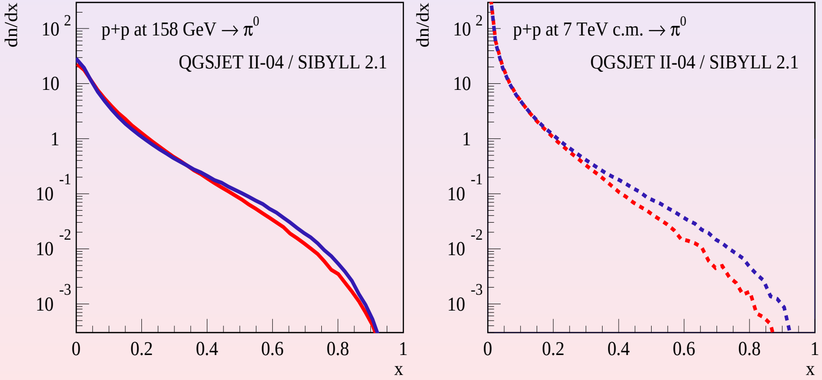

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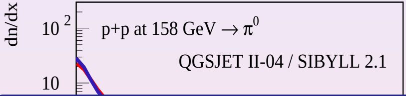

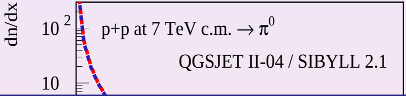

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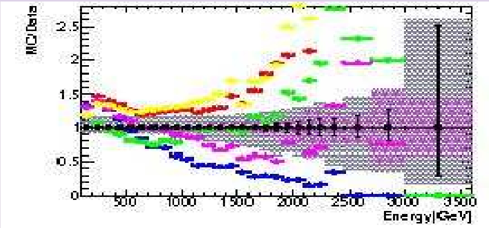

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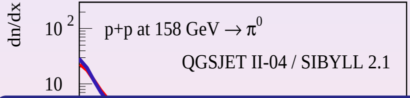

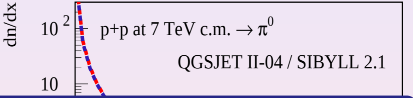

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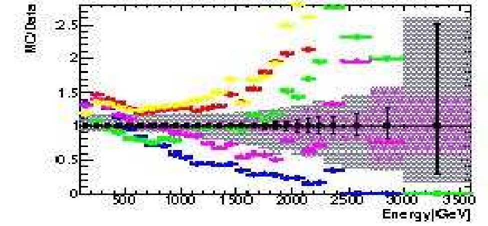
- why it is important?



Violation of Feynman scaling & EAS properties

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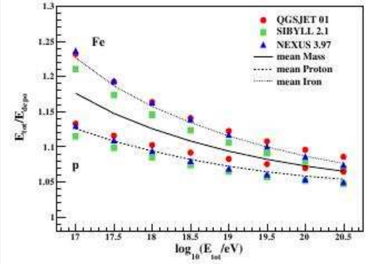

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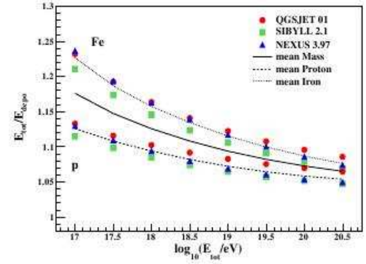

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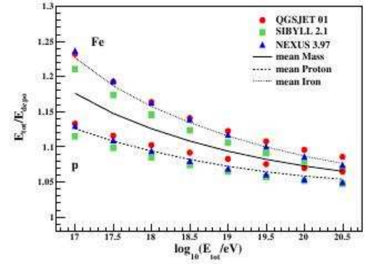

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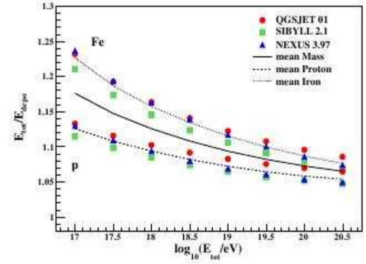

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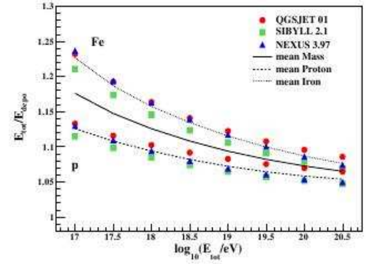

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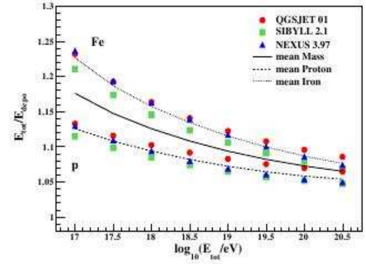

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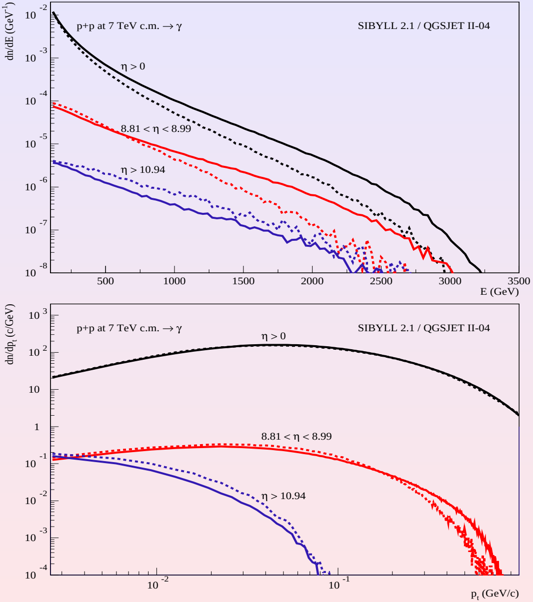

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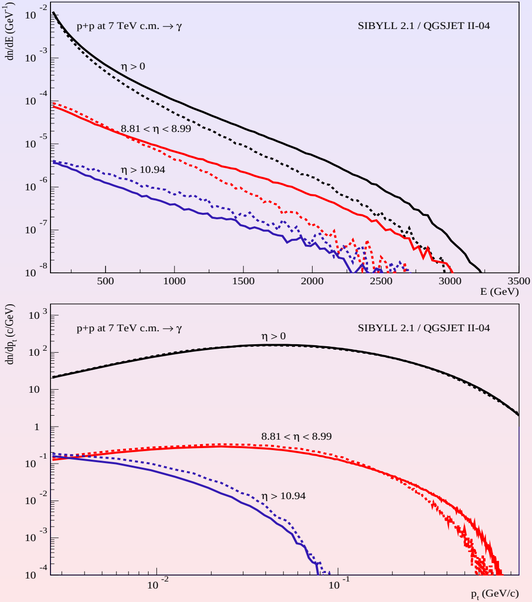

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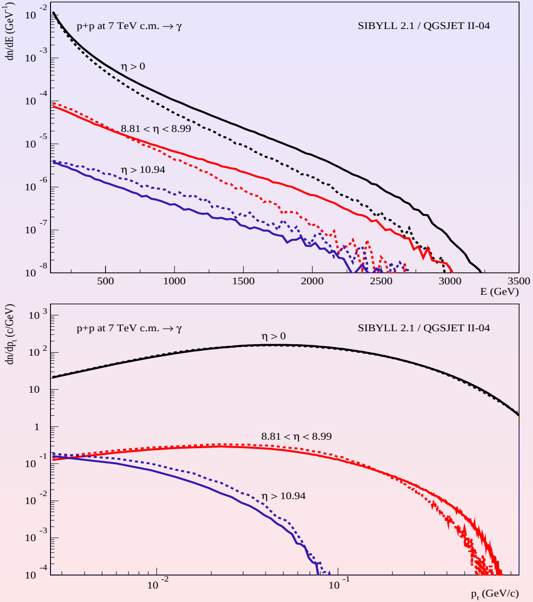

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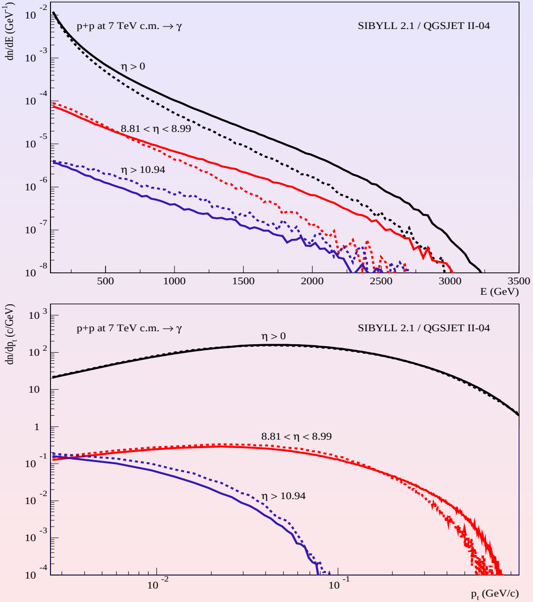

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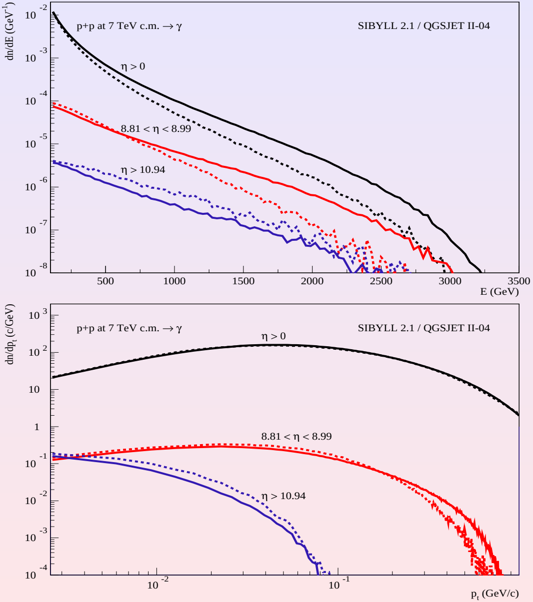

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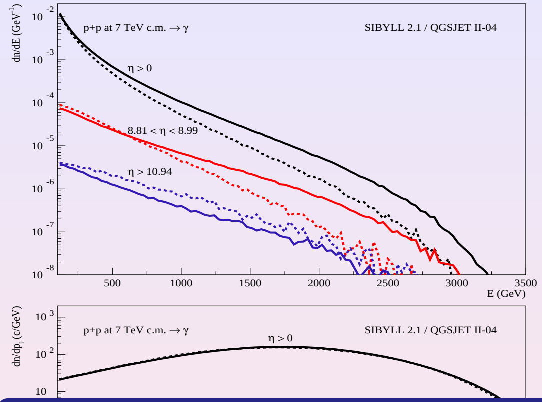

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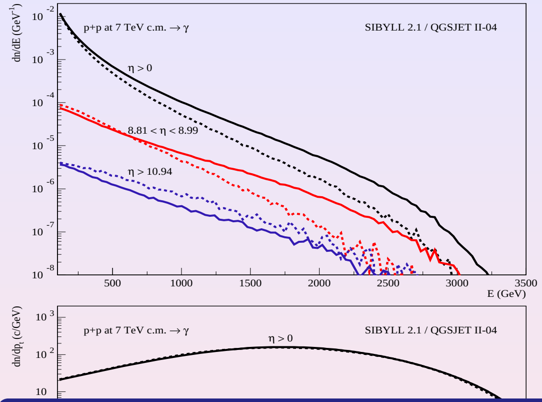

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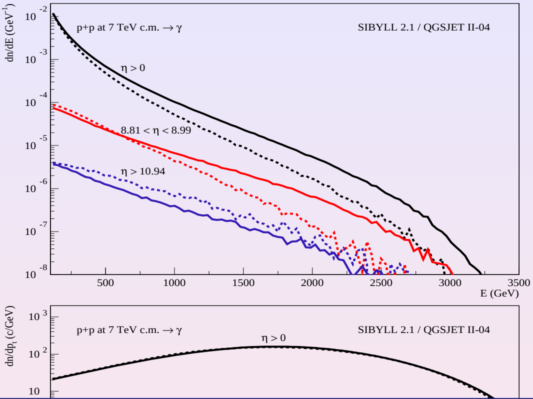

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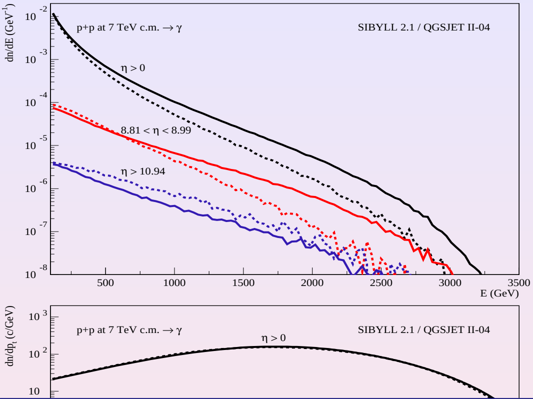

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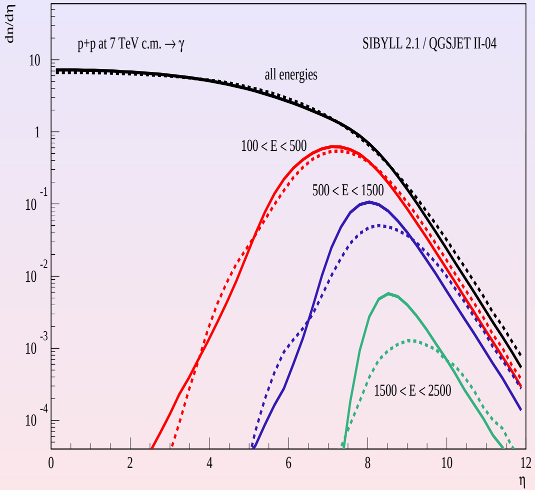

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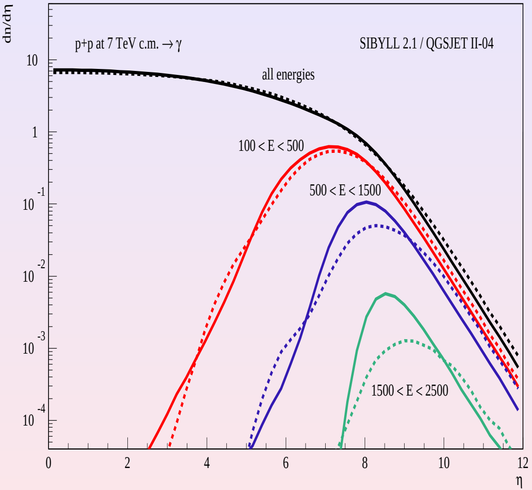

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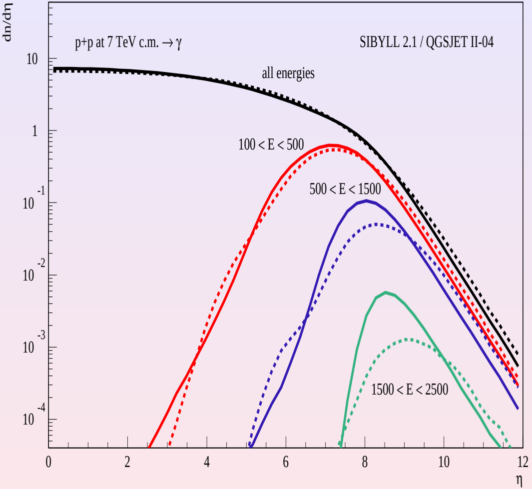

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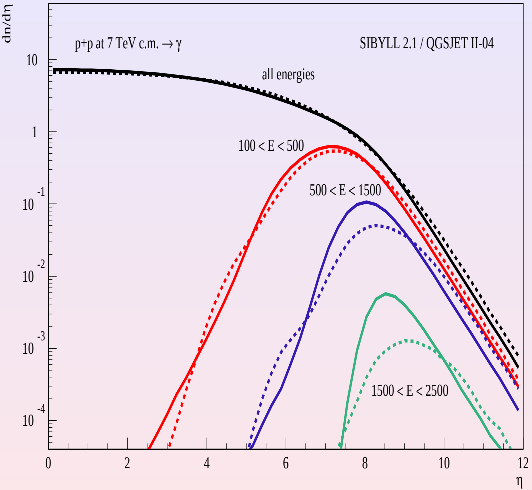

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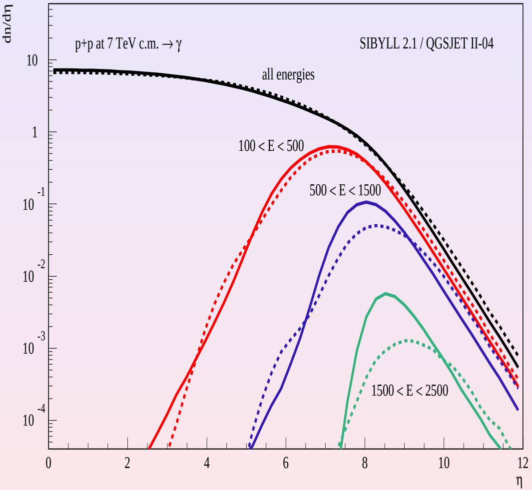

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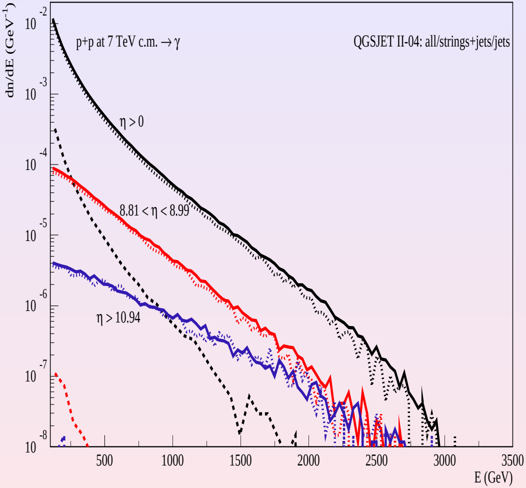
- however: p_t- (η-) integration desirable to improve the comparison with/between the models

LHCf: partial contributions to forward spectra of γs



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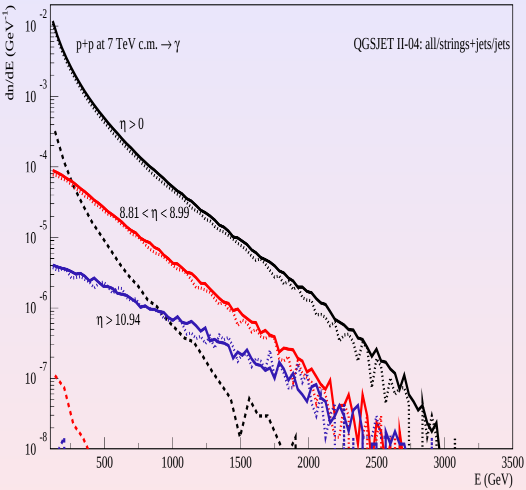

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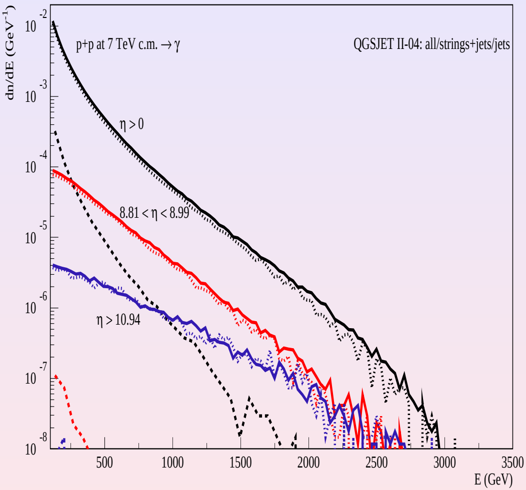

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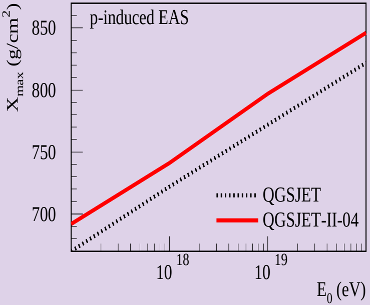

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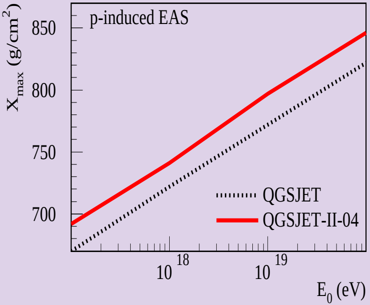

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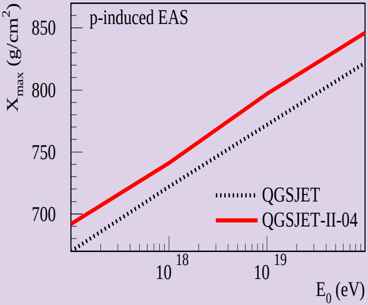
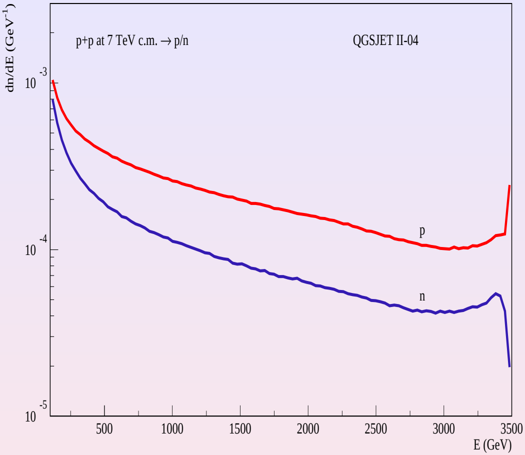


Leading nucleon 'stopping' & LHCf



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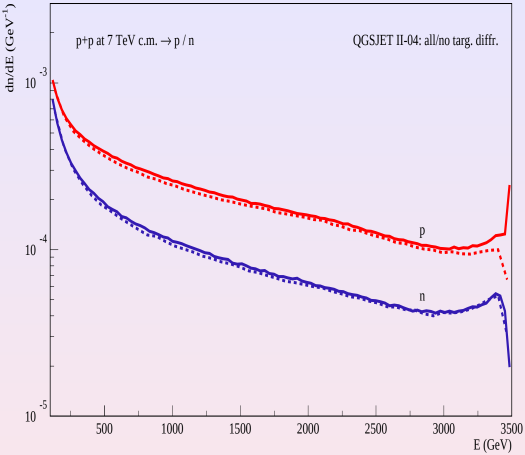

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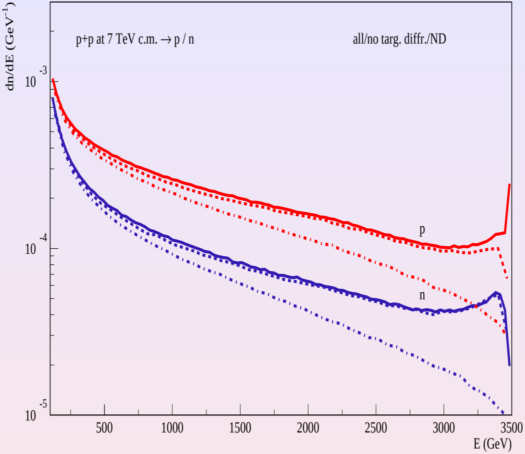

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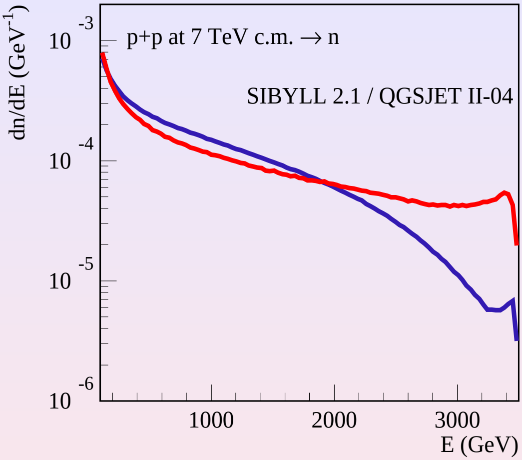

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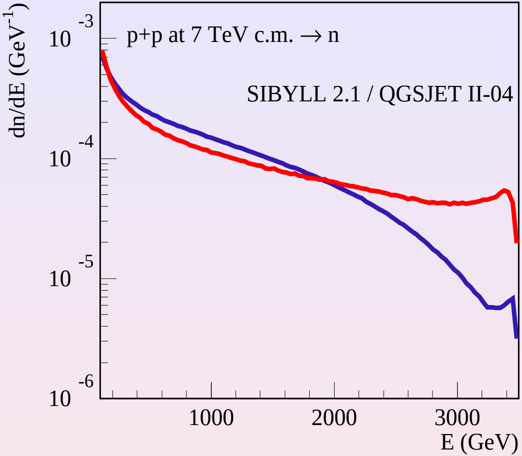

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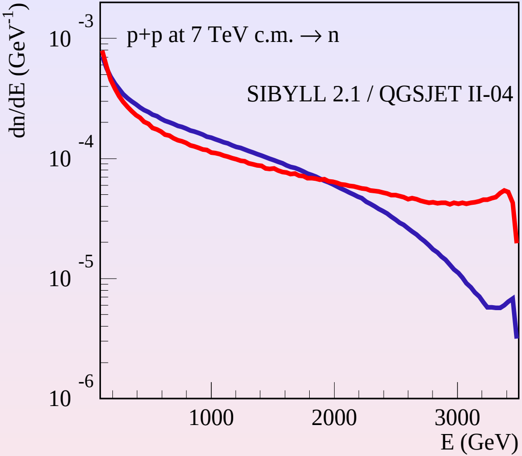

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4. future theoretical progress: from perturbative treatment of 'dense' parton systems (e.g. using saturation/ CGC models)