MC generators of HE hadronic collisions: Applications for secondary CRs

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Based on collaborations with M. Kachelriess, I. Moskalenko

Why MC models (for astrophysical applications)

- Existing parametrizations (e.g. for $\bar{p}$) mostly outdated
  - tuned to old experimental data
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- Specific for $\bar{d}$: importance of phase space correlations between produced particles

HE interaction models: what is attractive?

- HE physics is more transparent
  - e.g. rising importance of perturbative QCD processes
- $\Rightarrow$ cleaner theoretical framework possible
- $\Rightarrow$ predictive power
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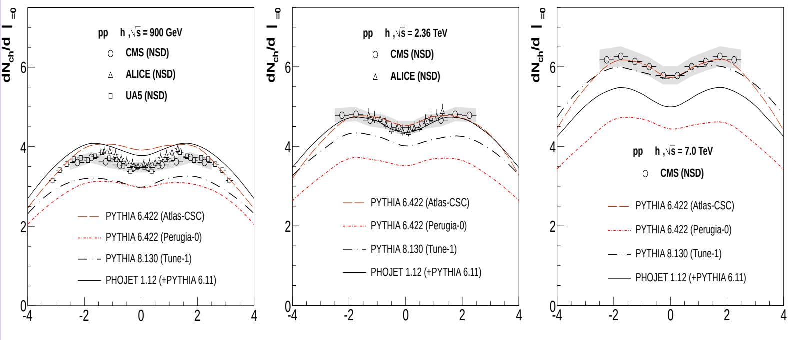
Example: comparison of pre-LHC models to first LHC data

- bad surprise for 'accelerator'-based MC generators



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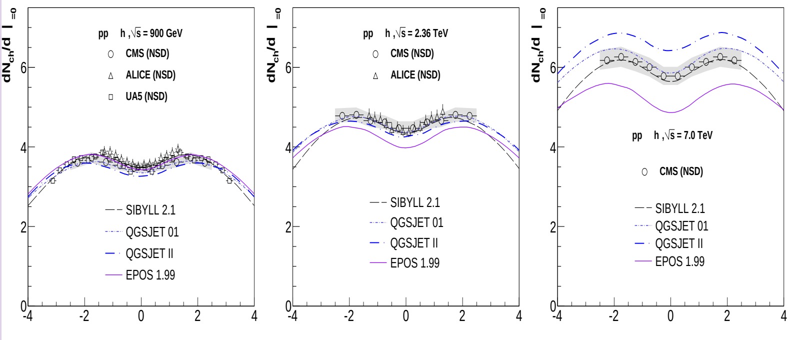
- much better agreement for CR interaction models



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- different theoretical formalism, amount of detalization

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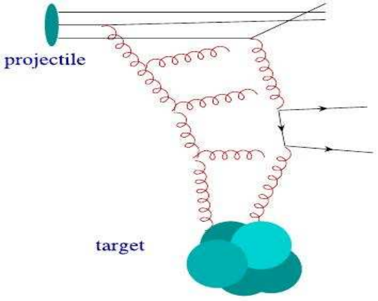
HE hadronic interactions: qualitative picture

- QCD-inspired: interaction mediated by parton cascades
- multiple scattering
  (many cascades in parallel)
- i.e. interactions between
  parton clouds prepared before
- real cascades
  ⇒ particle production
- virtual cascades
  ⇒ elastic rescattering



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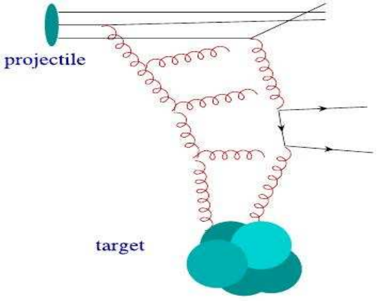

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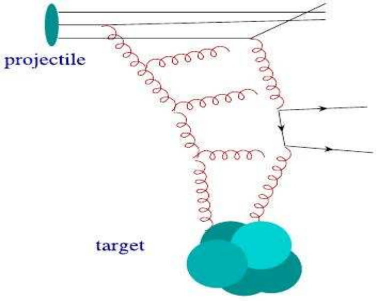

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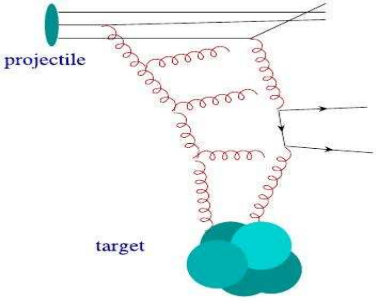

Universal interaction mechanism

- different hadrons (nuclei) $\Rightarrow$ different initial conditions (parton Fock States) but same mechanism
- energy-evolution of the observables (e.g. $\sigma_{pp}^{\mathrm{tot}}$): due to a larger phase space for cascades to develop

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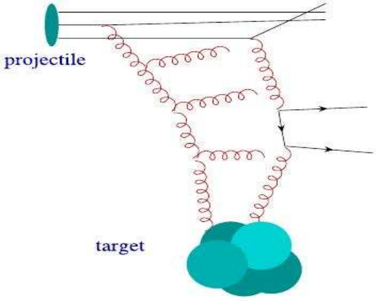

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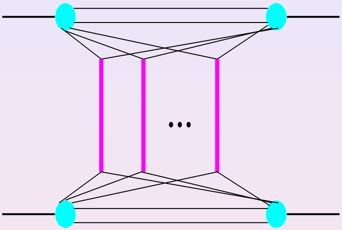
- multiple scattering = multi-Pomeron exchanges (Pomeron - universal object with vacuum quantum numbers)
- allows to calculate: cross sections & partial probabilities of final states



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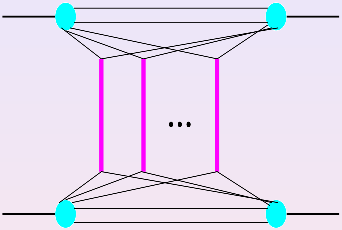

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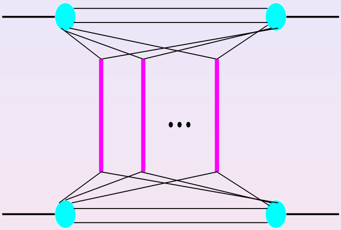

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- e.g. relative yields & properties of different hadrons - defined by hadronization procedures

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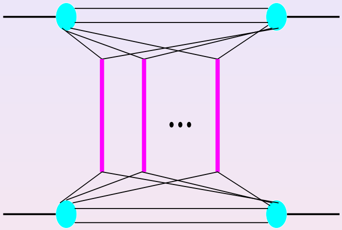

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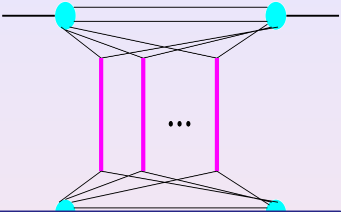

Relative strengths of the two models

- QGSJET-II: explicit treatment of nonlinear processes: splitting & merging of parton cascades
  - based on all-order resummation of the underlying diagrams
  - ⇒ advanced treatment of interaction configurations
- EPOS: much more advanced hadronization treatment
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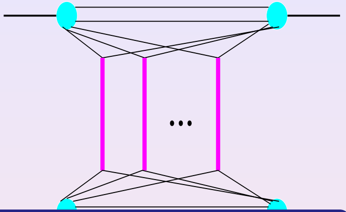

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If we plug it all in, with dozens of new parameters...

- no warranty it will work properly
  (the model will remain a phenomenological one)

- Most of available data dates back to 70s

$\bar{p}$ production at low energies: experimental data & models

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- Typically, spectrometer (fixed angle $\vartheta_{\rm lab}$) measurements
  - $\Rightarrow p_{\rm t}-$ & $p_{\rm l}-$dependences folded together ($p_{\rm t} \simeq \vartheta_{\rm lab}\, p_{\rm l}$)
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- As LE benchmark I'll use pp & pBe data for $p_{\rm lab} = 19.2$ GeV/c *[Allaby et al. 1970]*

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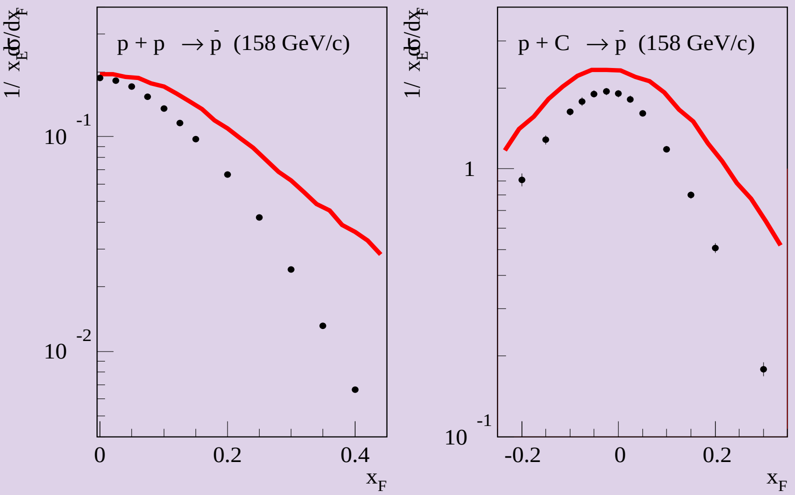
Just one popular LE interaction model compared to NA49 data



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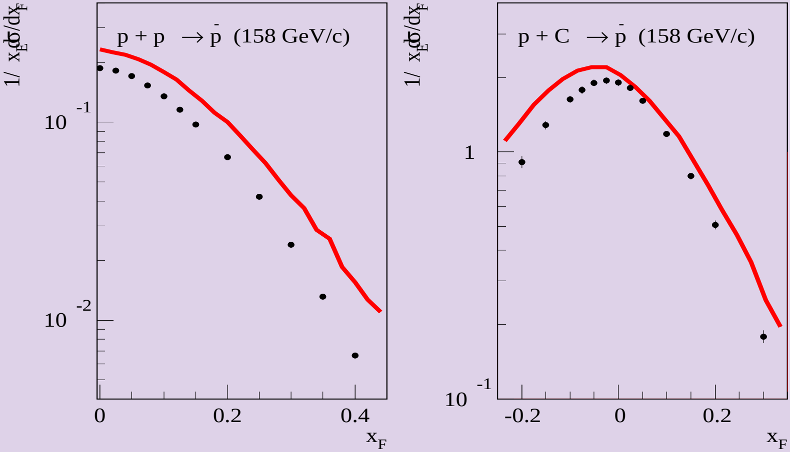
HE models: QGSJET-II-04 compared to NA49 data



- the model overestimates $\bar{p}$-production already at 158 GeV/c
- things get much worse at lower energies

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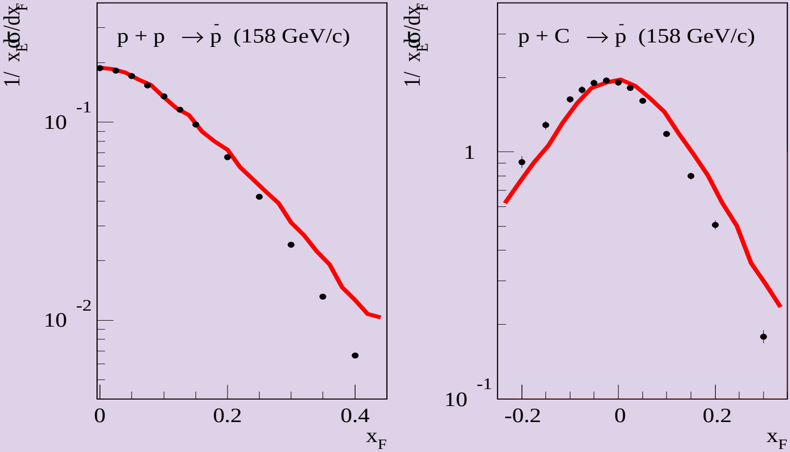
HE models: EPOS-LHC compared to NA49 data



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- LE behavior - best among the models I tried!

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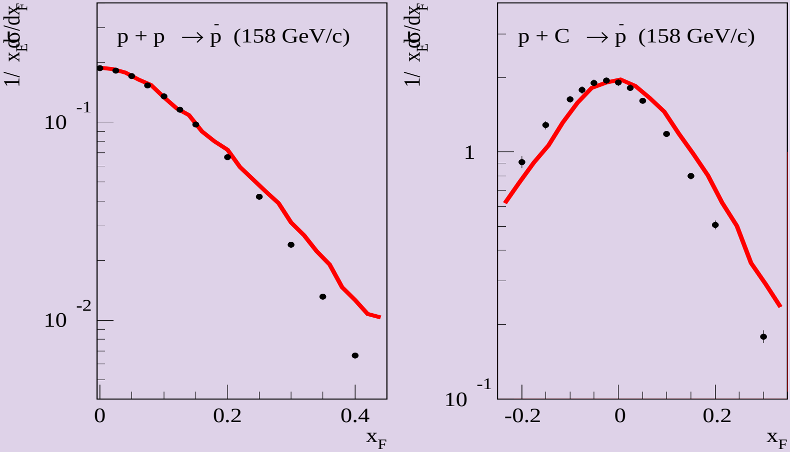

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- NB: A model is not a parametrization:
  - $\Rightarrow$ can not describe everything perfectly
  - otherwise predictive power is lost

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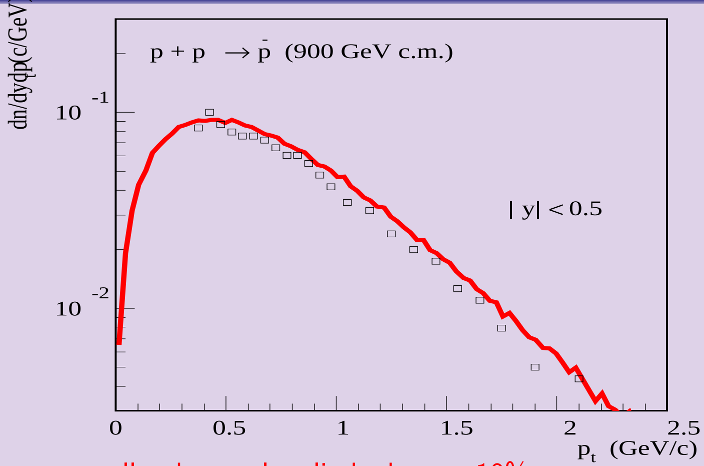
$\bar{p}$: cross-check wrt. ALICE data at LHC (900 GeV c.m.)



- actually, the results climbed some 10% up

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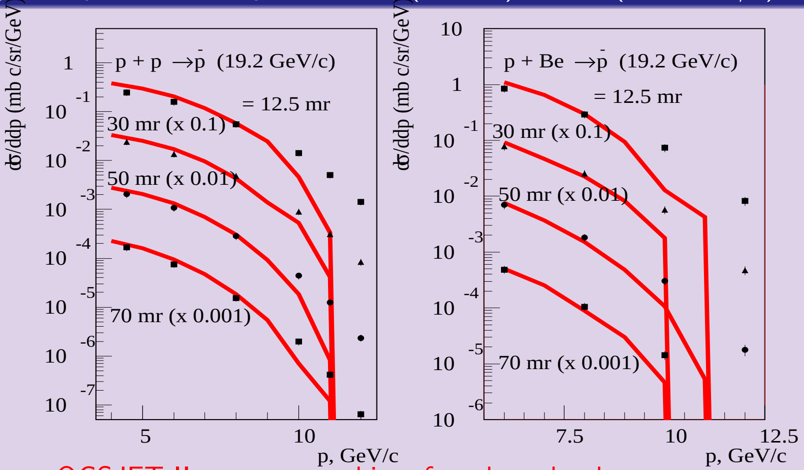
$\bar{p}$: comparison with spectrometer (fixed ϑ) results (19.2 GeV/c)



- QGSJET-IIm: spectra a bit softer than the data
- NB: statistics (10^8 events) insufficient for the tails

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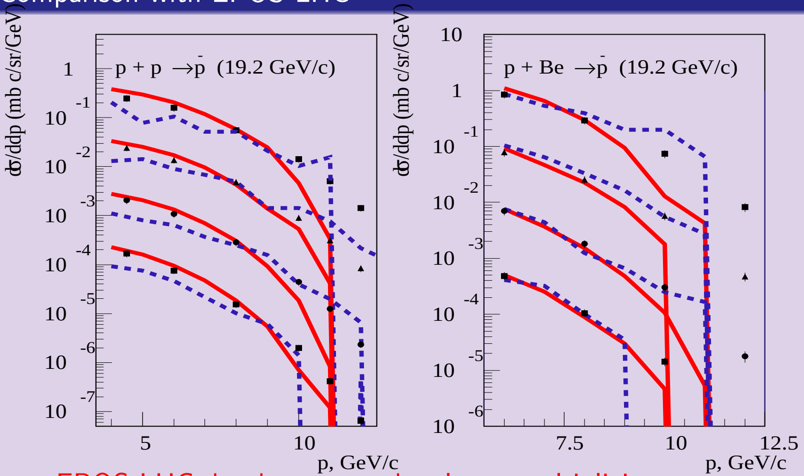
Comparison with EPOS-LHC



- EPOS-LHC: harder spectra but lower multiplicity

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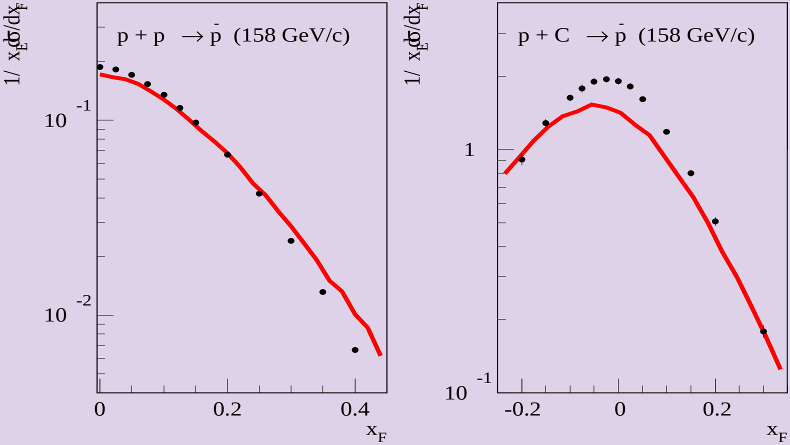
QGSJET-IIm compared to NA49 data



- now the spectra a bit hard
- just a compromise description over a wide energy range

Secondary CR fluxes & Z-moments

- General formula for the yield of particle X (e.g. $\bar{p}$):

$$q_X^{ij}(E_X) = n_j \int_{E_X}^{\infty} dE \, \frac{d\sigma^{ij\to X}(E, E_X)}{dE_X} \, I_i(E)$$

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- For power-law primary fluxes $(I_i(E) \propto E^{-\alpha_i})$ – Z-moments:

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Secondary CR fluxes & Z-moments

- General formula for the yield of particle X (e.g. $\bar{p}$):

$$q_X^{ij}(E_X) = n_j \int_{E_X}^{\infty} dE \, \frac{d\sigma^{ij\to X}(E, E_X)}{dE_X} \, I_i(E)$$

  - $I_i(E)$ - flux of primary nuclei of type i
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  - all the information about production (e.g. model-dependence) – 'hidden' in $Z_X^{ij}(E_X, \alpha_i)$

Z-moments for $\bar{p}$ production by protons

- Let us be more specific and consider $p + p \to \bar{p}$:

$$Z_{\bar{p}}^{pp}(E_{\bar{p}}, \alpha) = \int_0^1 dz\, z^{\alpha-1}\, \frac{d\sigma^{p+p\to\bar{p}}(E_{\bar{p}}/z, z)}{dz}$$

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    - $\Rightarrow$ decreases for 'softer' production spectrum (smaller energy fraction $z = E_{\bar{p}}/E_p$ taken by $\bar{p}$)
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- NB: Z-moments are defined wrt secondary particle energy (here $E_{\bar{p}}$), NOT the interaction energy!

Z-moments for $\bar{p}$ production by protons

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$$\tilde{Z}_{\mathrm{norm}}(E_{\max}, E_{\bar{p}}, \alpha) \equiv \frac{1}{Z_{\bar{p}}^{pp}(E_{\bar{p}}, \alpha)} \int_0^1 dz\, z^{\alpha-1} \frac{d\sigma^{p+p\to\bar{p}}(E_{\bar{p}}/z, z)}{dz} \times \Theta(E_{\max} - E_{\bar{p}}/z)$$

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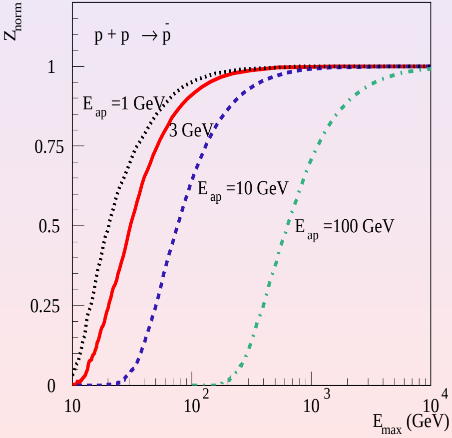

- let us use $\alpha = 2.8$
- typically, $z_{\bar{p}} = E_{\bar{p}}/E_p \sim 0.1$
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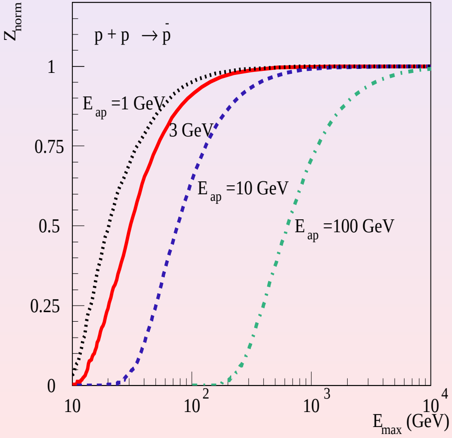

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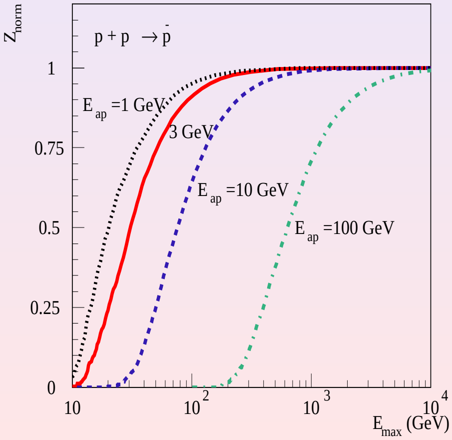

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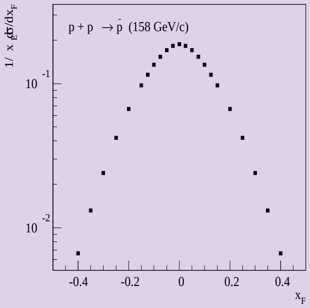

- for small $E_{\bar{p}}$: $z_{\bar{p}} \to 1$ is forbidden by kinematics ($E_p > E_{\rm thr}$)
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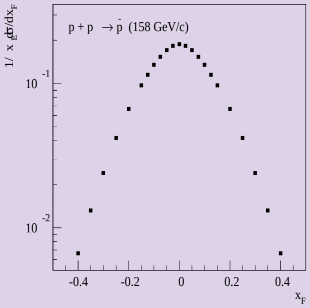

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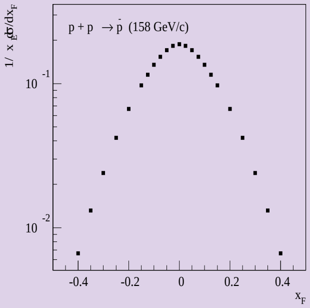

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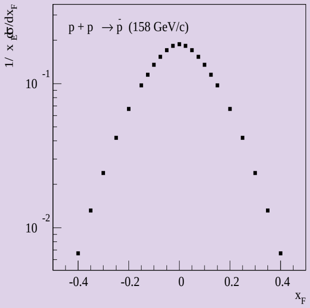

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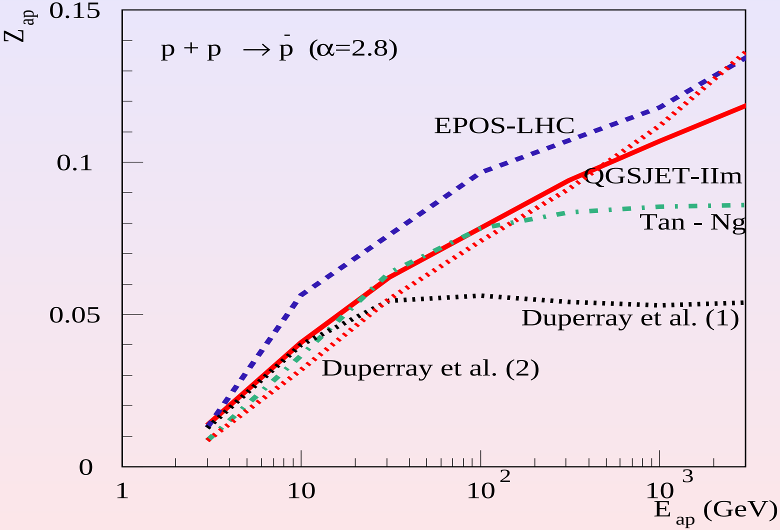

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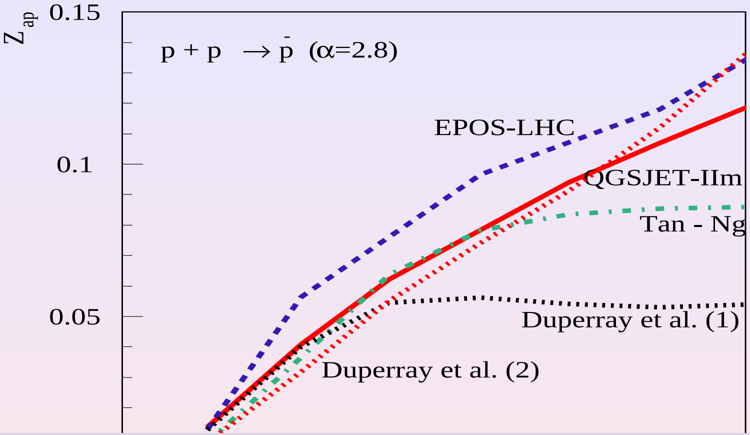

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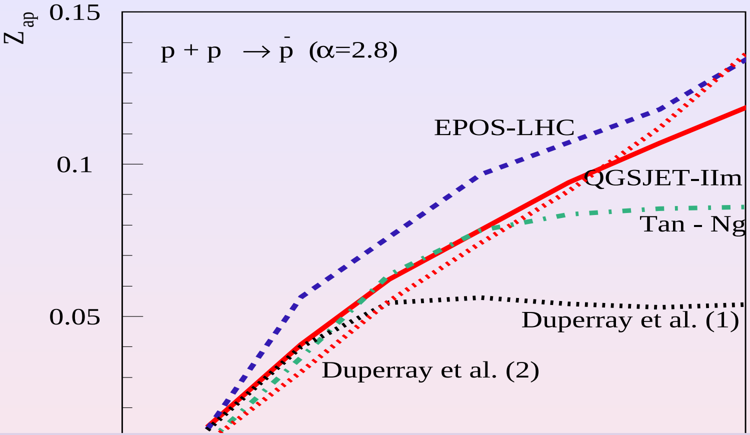

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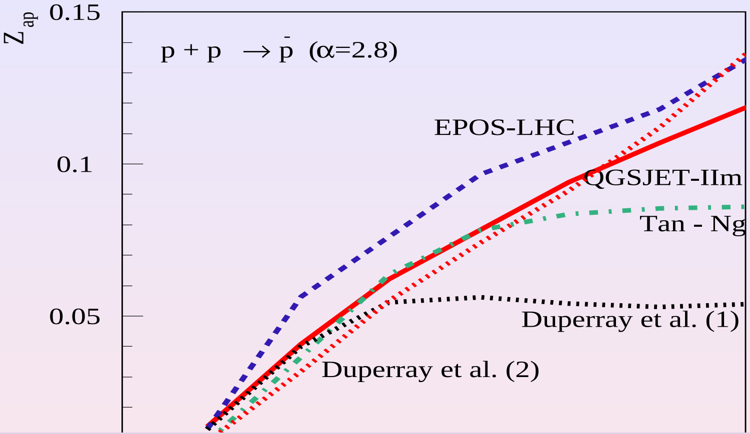

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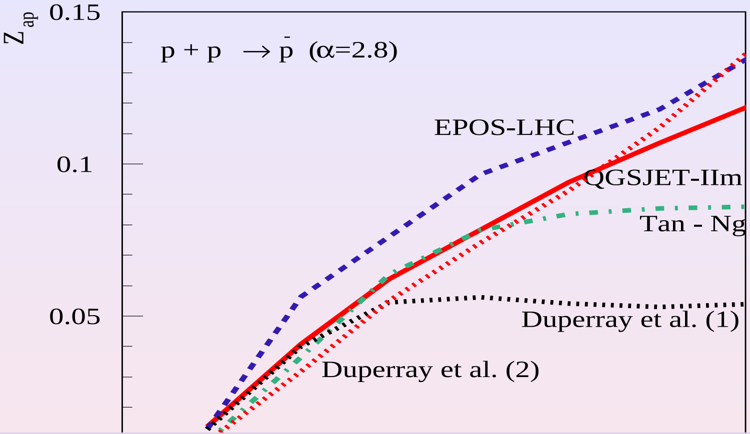

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- $f_{pA\to X}(E,z) \simeq f_{pp\to X}(E,z)$ for $z \to 1$
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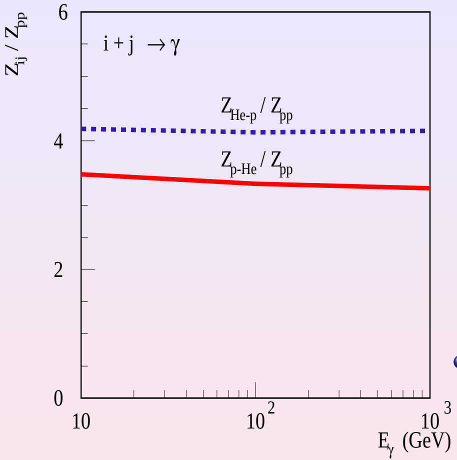
Nuclear enhancement for γ & $\bar{p}$



- the picture works well for γ
  - e.g. $Z_\gamma^{\mathrm{He}-p} / Z_\gamma^{pp} \simeq 4$

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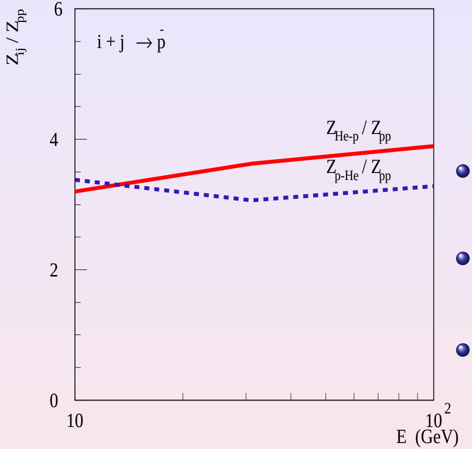

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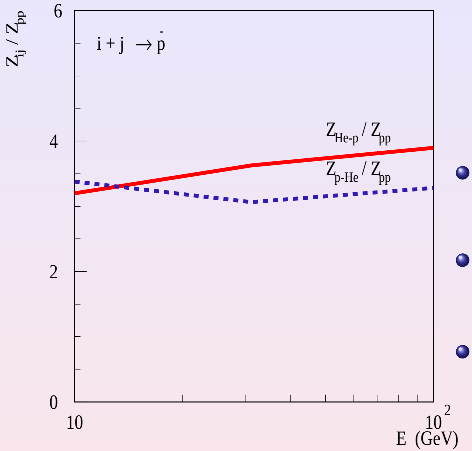

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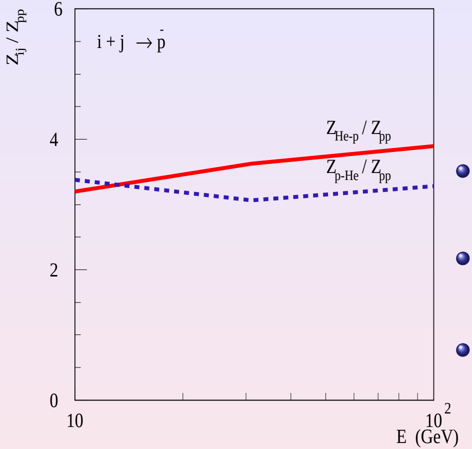

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