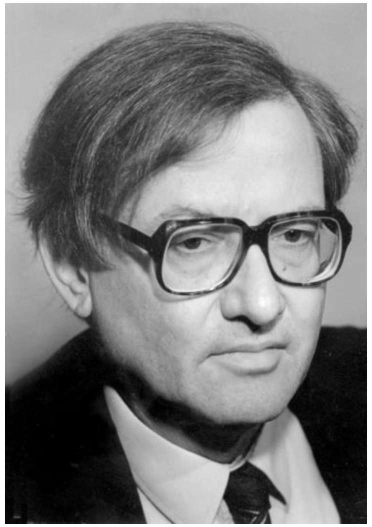

Signs of hydrodynamic scaling in pseudorapidity distributions of p+p and heavy-ion collisions

GÁBOR KASZA, TAMÁS CSÖRGŐ, MÁTÉ CSANÁD

ZIMÁNYI SCHOOL'19, BUDAPEST

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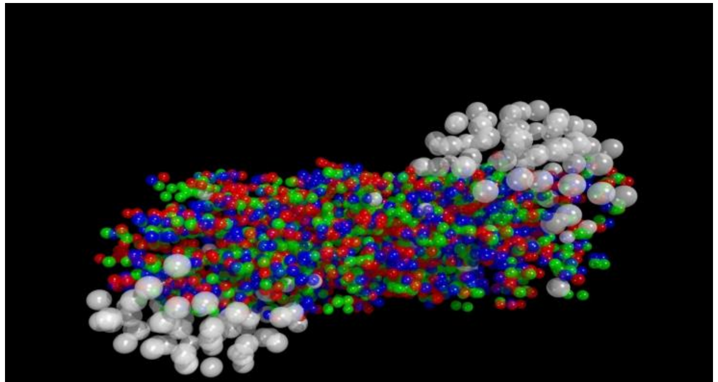
NKFIH/OTKA K 133 046

Various application of hydrodynamics

- Fluid dynamics: flow of liquid and gases
- Examples:
  - *Calculating forces and moments in aircrafts*
  - *Weather forecast*
  - *Describing nebulae*
  - *Inner structure of stars (magnetohydrodynamics)*
  - *Modelling fission weapon detonation*
  - *Describing the Quark Gluon Plazma (QGP)*
- Different systems in many aspects: however, hydro works well in all cases
- Why is hydrodynamics so effective?



Heavy-ion collision: in the overlap area, the sQGP is created

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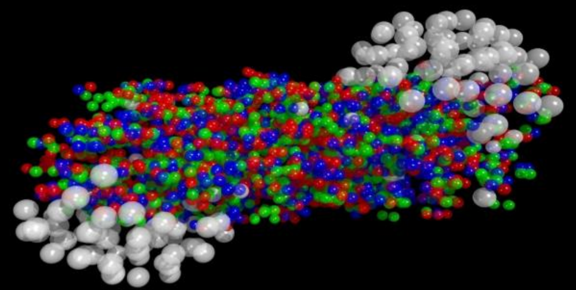

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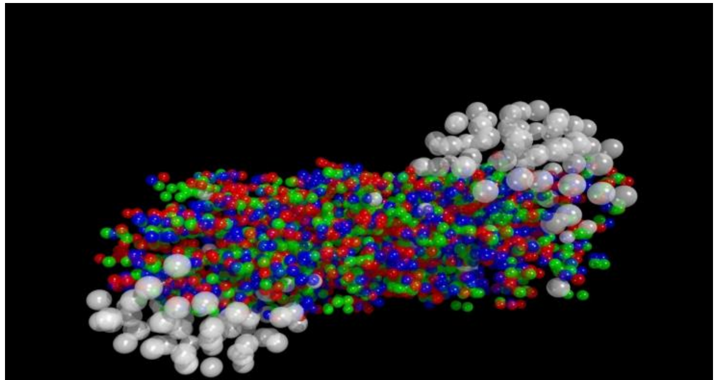

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Hydrodynamics has no internal scale!

- *Is the scaling behaviour violated on microscopic scales?*

Our recent perfect fluid solution

- Rindler coordinates, velocity field: $(\tau,\eta_x)=\left(\sqrt{t^2-r_z^2},\ \frac{1}{2}\ln\left[\frac{t+r_z}{t-r_z}\right]\right),\quad u^\mu=\left(\cosh\left(\Omega\right),\sinh\left(\Omega\right)\right)$
- 1+1 dimensional, parametric, almost self-similar solution:

Csörgő T., Kasza G., Csanád M., Jiang Z.: arXiv:1805.01427, arXiv:1806.06794

λ: acceleration parameter (Hwa-Bjorken: *λ=1*)

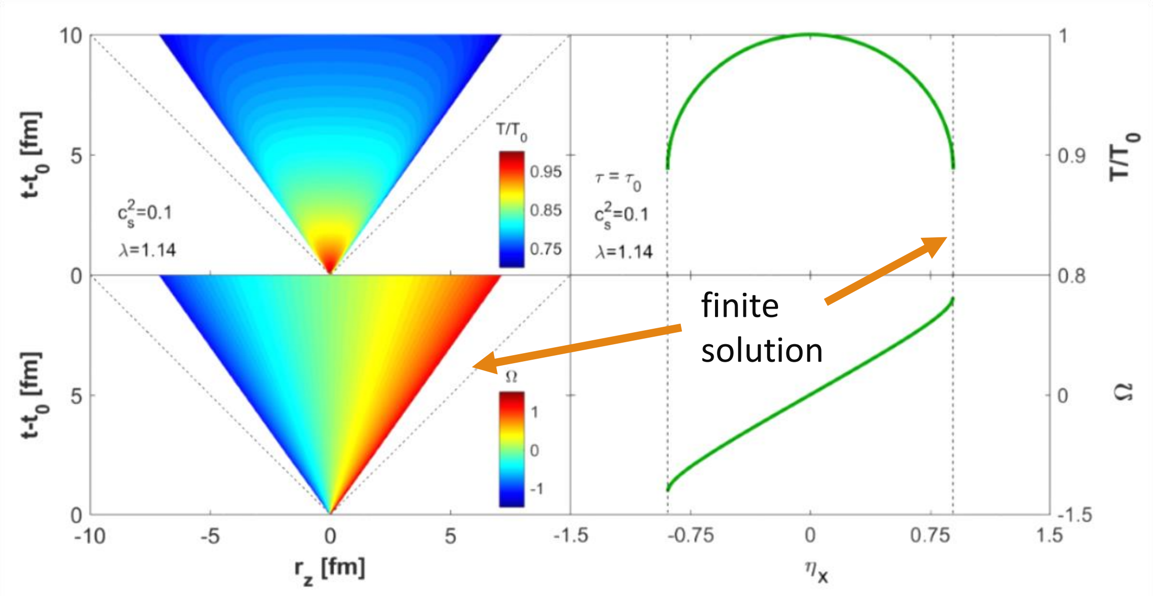
↓

accelerating solution

↓

realistic *dN/dη*

$$
\begin{aligned}
\eta_x(H) &= \Omega(H)-H,\\
\Omega(H) &= \frac{\lambda}{\sqrt{\lambda-1}\sqrt{\kappa-\lambda}}\arctan\left(\sqrt{\frac{\kappa-\lambda}{\lambda-1}}\tanh\left(H\right)\right)\\
\sigma(\tau,H) &= \sigma_0\left(\frac{\tau_0}{\tau}\right)^{\lambda}\mathcal{V}_\sigma(s)\left[1+\frac{\kappa-1}{\lambda-1}\sinh^2(H)\right]^{-\frac{\lambda}{2}},\\
T(\tau,H) &= T_0\left(\frac{\tau_0}{\tau}\right)^{\frac{\lambda}{\kappa}}\mathcal{T}(s)\left[1+\frac{\kappa-1}{\lambda-1}\sinh^2(H)\right]^{-\frac{\lambda}{2\kappa}},\\
\mathcal{T}(s) &= \frac{1}{\mathcal{V}_\sigma(s)},\\
s(\tau,H) &= \left(\frac{\tau_0}{\tau}\right)^{\lambda-1}\sinh(H)\left[1+\frac{\kappa-1}{\lambda-1}\sinh^2(H)\right]^{-\lambda/2}
\end{aligned}
$$



Scaling behaviour in high-energy physics

- *dN/dy* is obtained from the new solution (in self-similar approximation):

$$\frac{dN}{dy} \approx \left.\frac{dN}{dy}\right|_{y=0} \cosh^{-\frac{1}{2}\alpha(\kappa,\lambda)-1}\left(\frac{y}{\alpha(1,\lambda)}\right) \exp\left(-\frac{m}{T_{\mathrm{eff}}}\left[\cosh^{\alpha(\kappa,\lambda)}\left(\frac{y}{\alpha(1,\lambda)}\right)-1\right]\right)$$

Physical parameters:
λ: acceleration parameter
κ: inverse square of c_s
T_{eff}: effective temperature
m: particle mass

- If $|y| << 2+(\lambda-1)^{-1}$, Gaussian rapidity-density:

$$\frac{dN}{dy} \approx \frac{\langle N \rangle}{(2\pi\Delta^2 y)^{1/2}} \exp\left(-\frac{y^2}{2\Delta^2 y}\right) \longrightarrow \frac{1}{\Delta^2 y} = (\lambda-1)^2\left[1+\left(1-\frac{1}{\kappa}\right)\left(\frac{1}{2}+\frac{m}{T_{\mathrm{eff}}}\right)\right]$$

- Depends on the combination of the physical parameters through the width (*Δy*)
- *λ, m, T_{eff} and κ can be arbitrary, but their combination is not: Δy is determined by fits*
- Physical differences are only apparent in the width of the distribution

Csörgő, Kasza, Csanád, Jiang solution:
arXiv:1805.01427

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Beautiful example of scaling behaviour

Csörgő, Kasza, Csanád, Jiang solution:

arXiv:1805.01427

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Scaling behaviour in high-energy physics

- The pseudorapity distribution is the product of *dN/dy* and the Jakobian:

$$\left(\eta_p(y)\,,\,\frac{dN}{d\eta_p}(y)\right)=\left(\frac{1}{2}\log\left[\frac{\bar{p}(y)+\bar{p}_z(y)}{\bar{p}(y)-\bar{p}_z(y)}\right]\,,\,\frac{\bar{p}(y)}{\bar{E}(y)}\,\frac{dN}{dy}\right)$$

K. G. , Csörgő T.:

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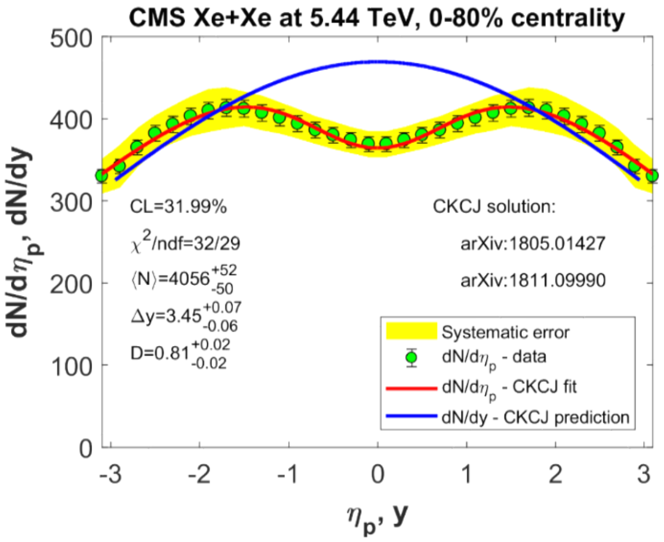
- The rapidity density is depressed at midrapidity by $\frac{1}{\sqrt{1+D^2}}$



$$D = \frac{m}{\bar{p}_T}$$

„*D*epression" or „*D*epth" parameter

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- Main question: Does this scaling behaviour appear in the data?
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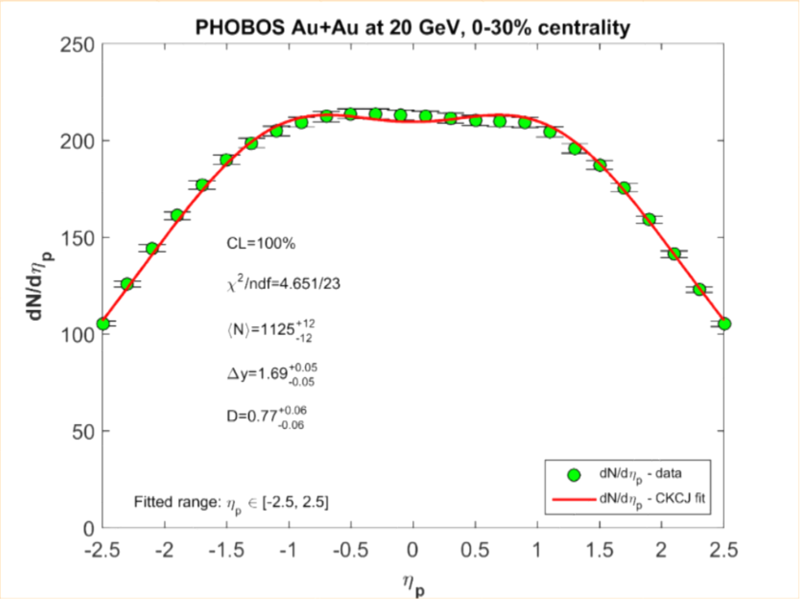

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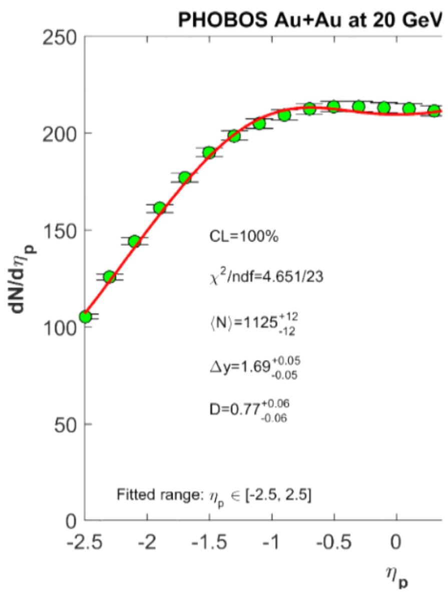

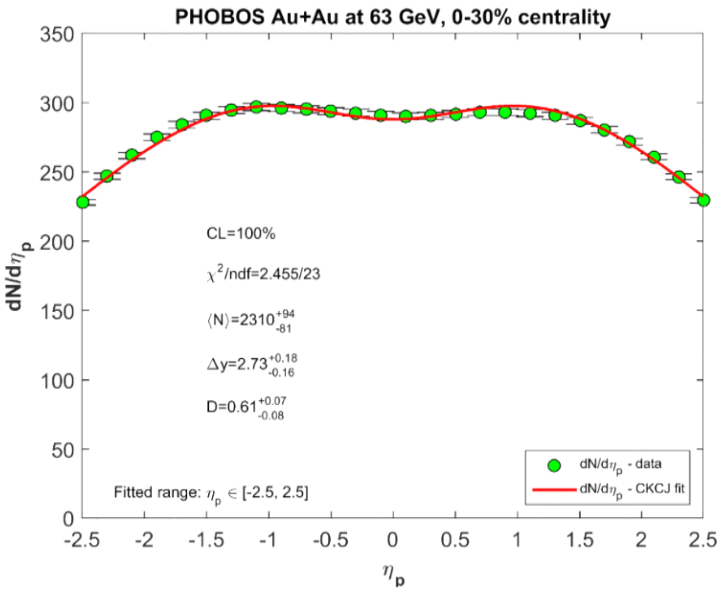

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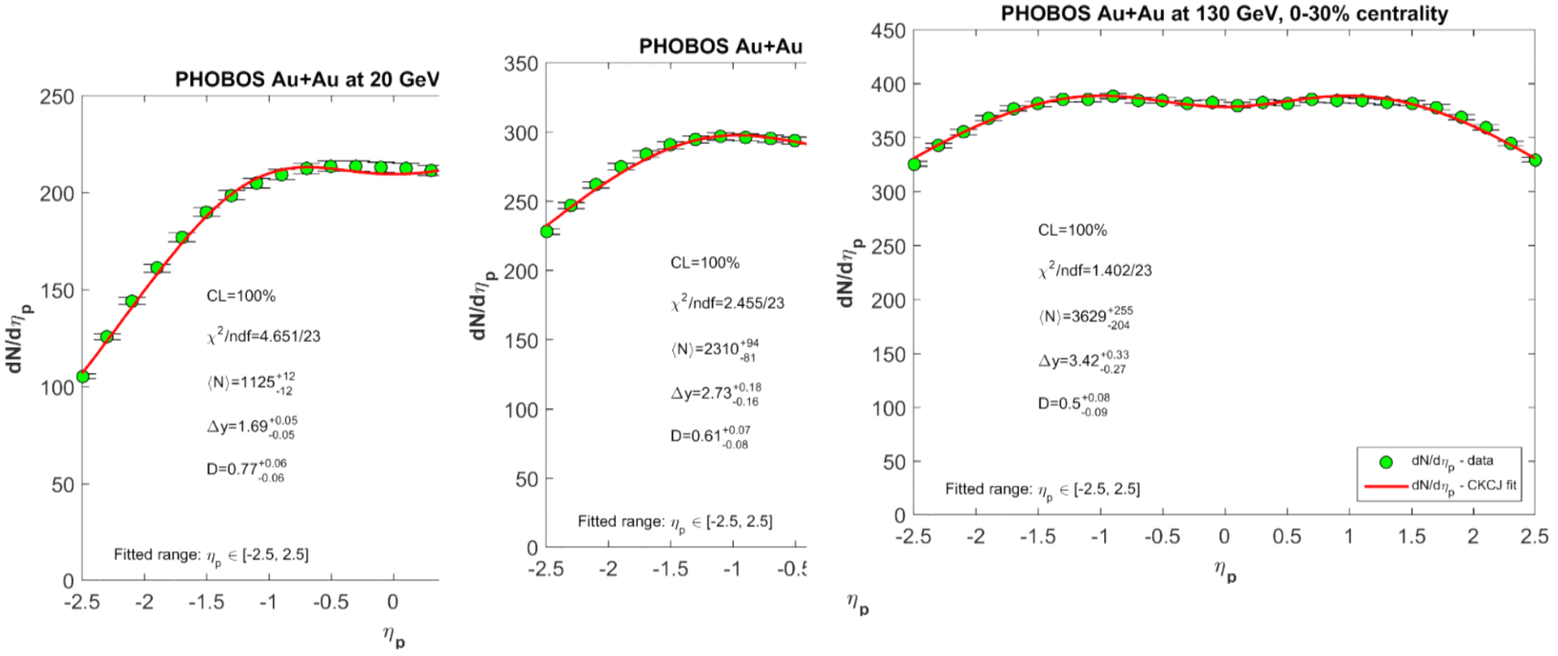

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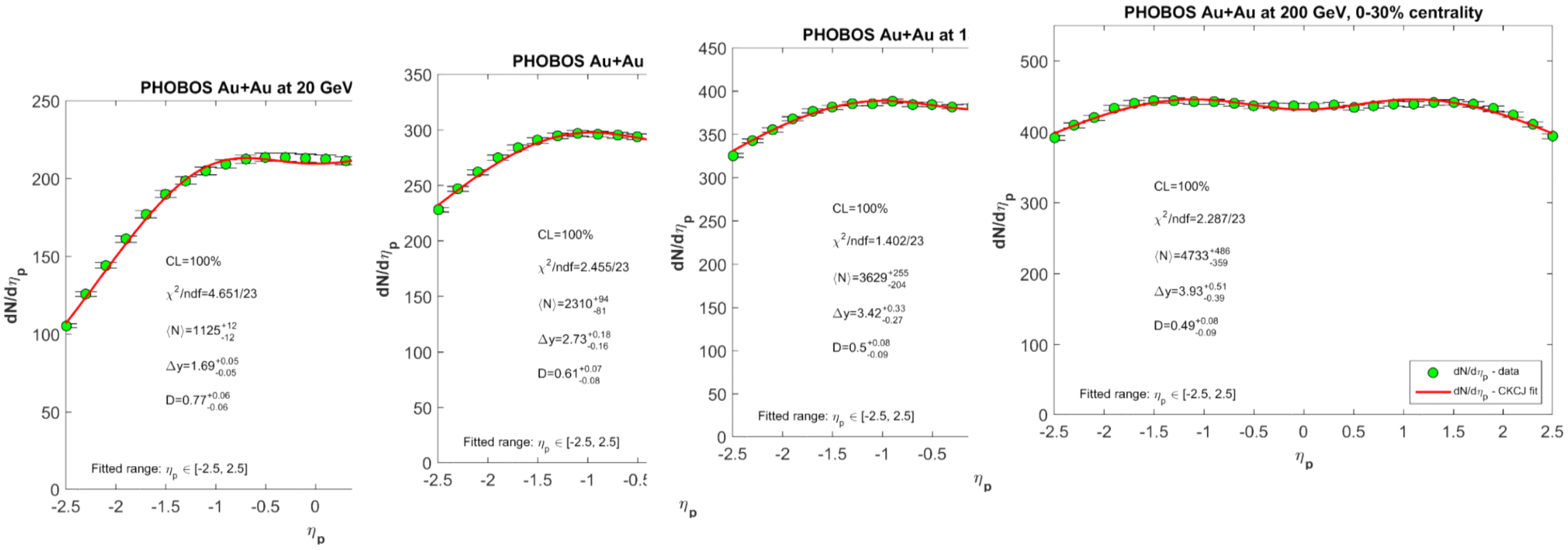

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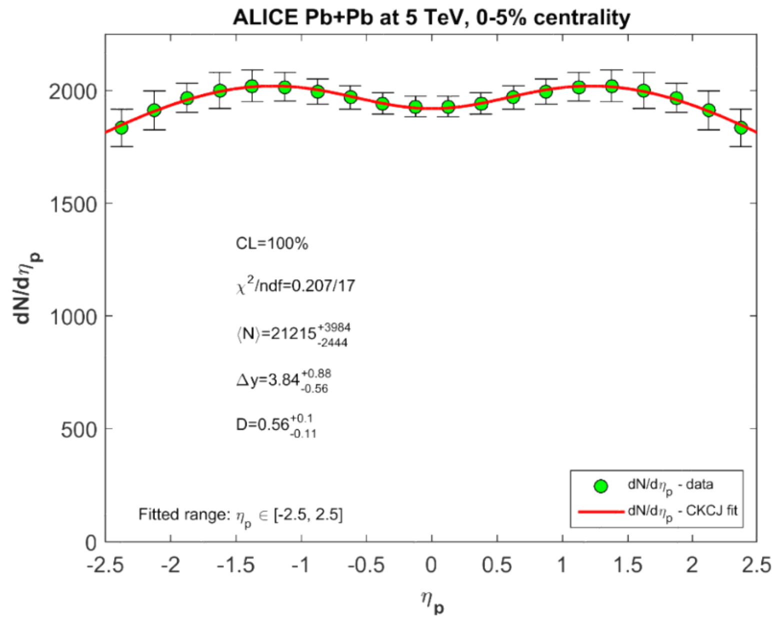

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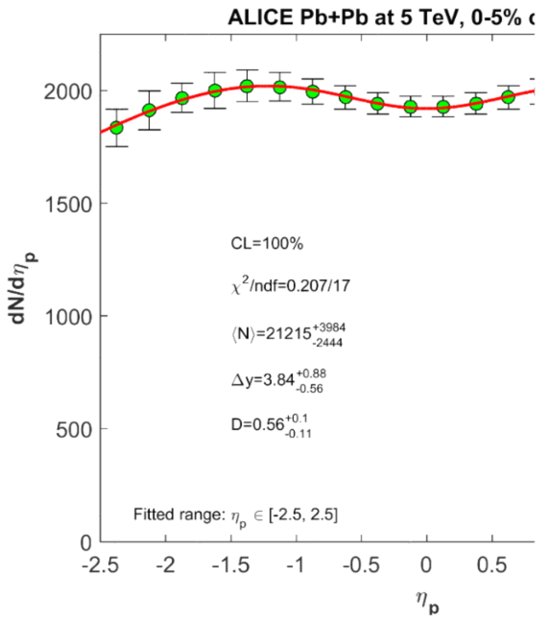

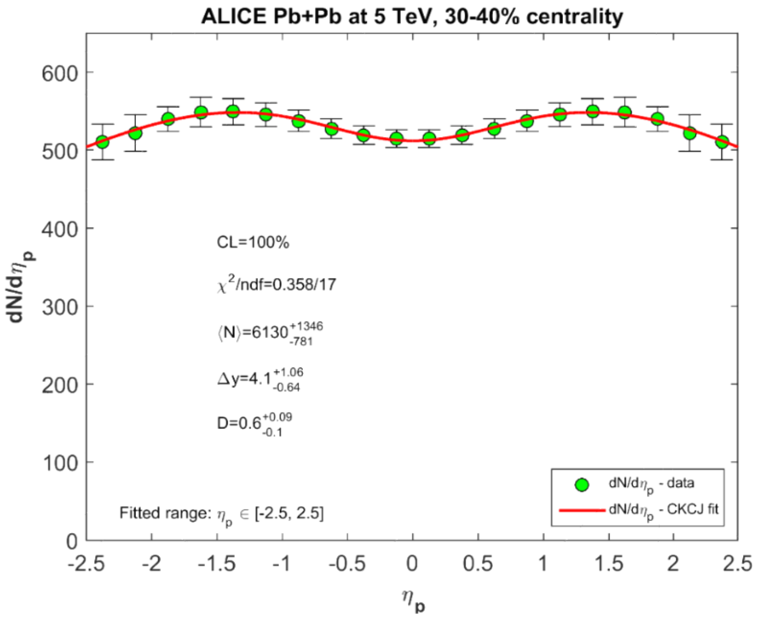

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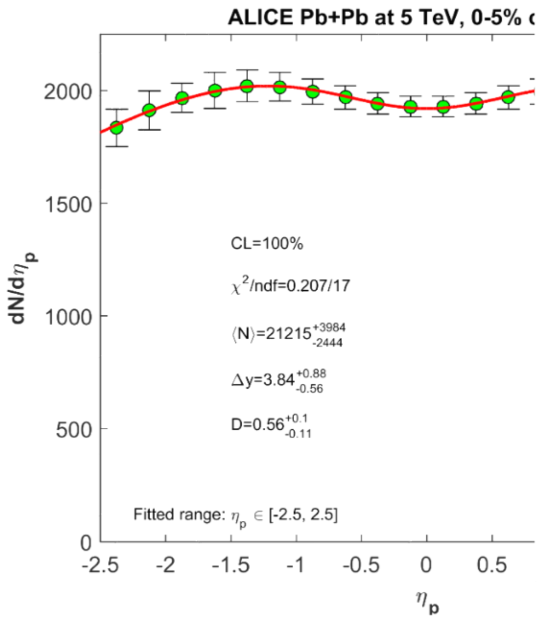

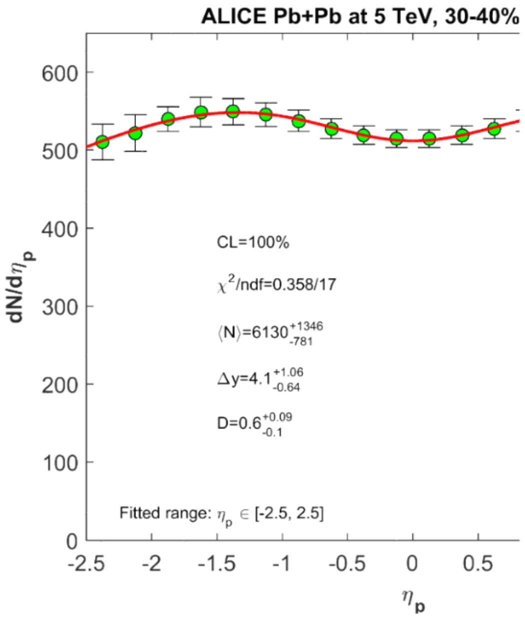

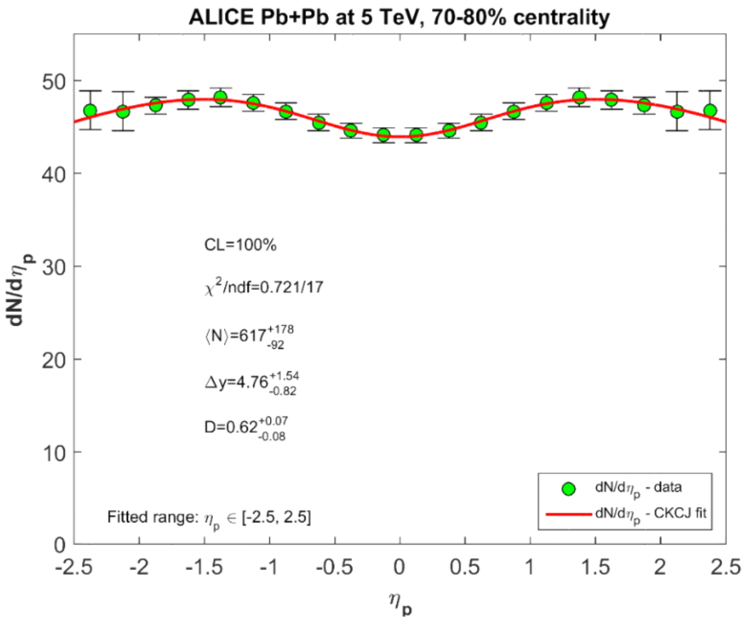

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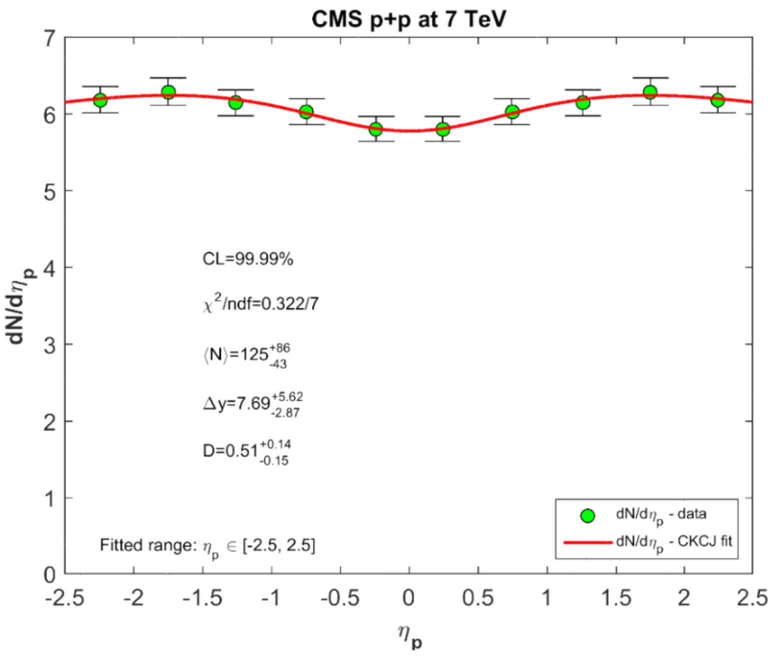

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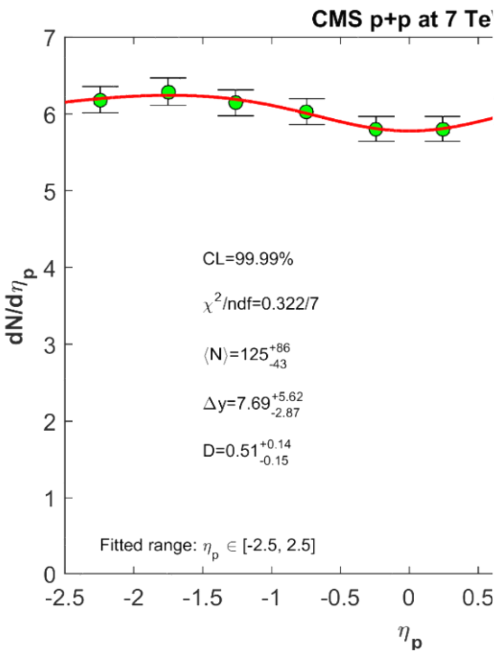

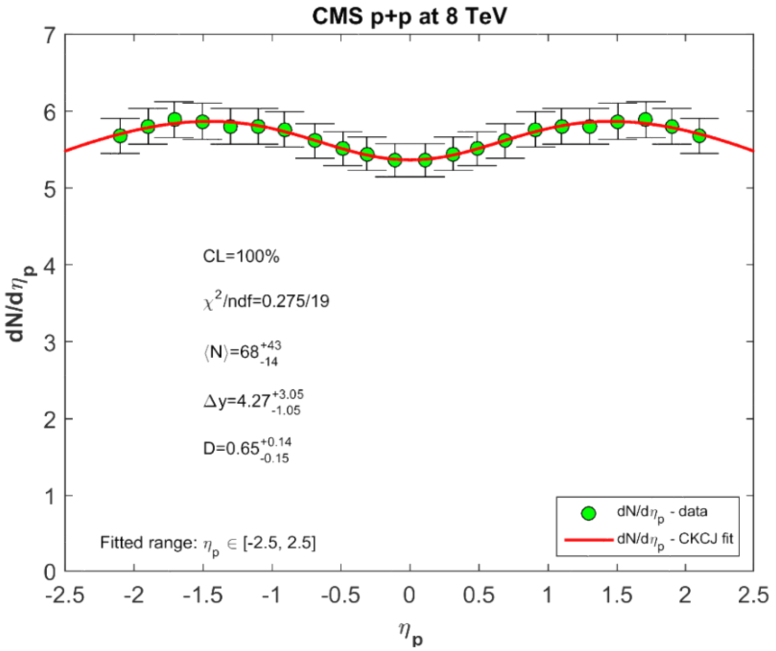

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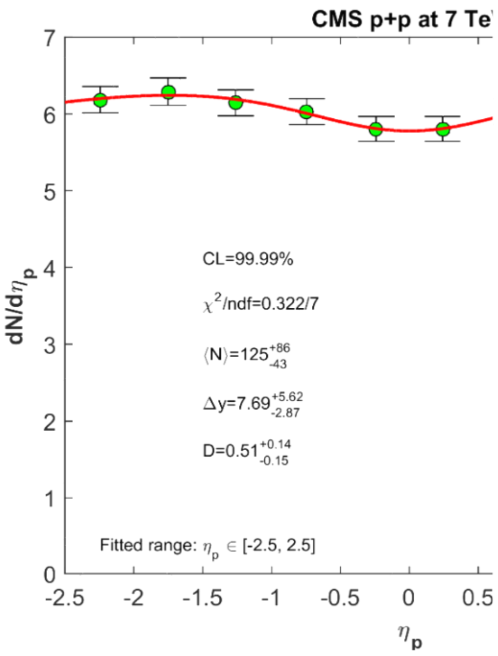

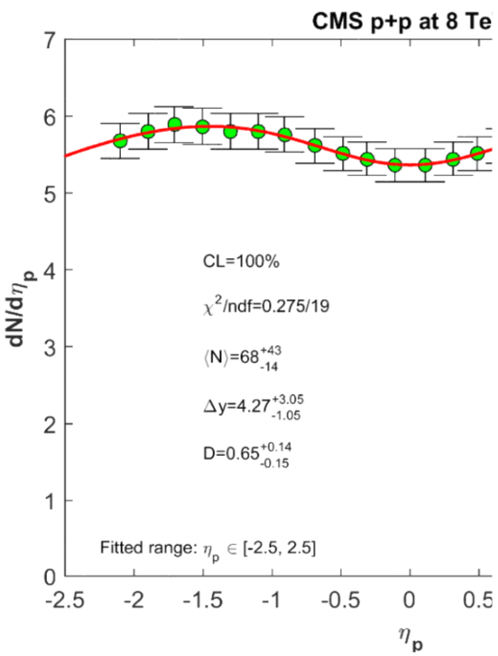

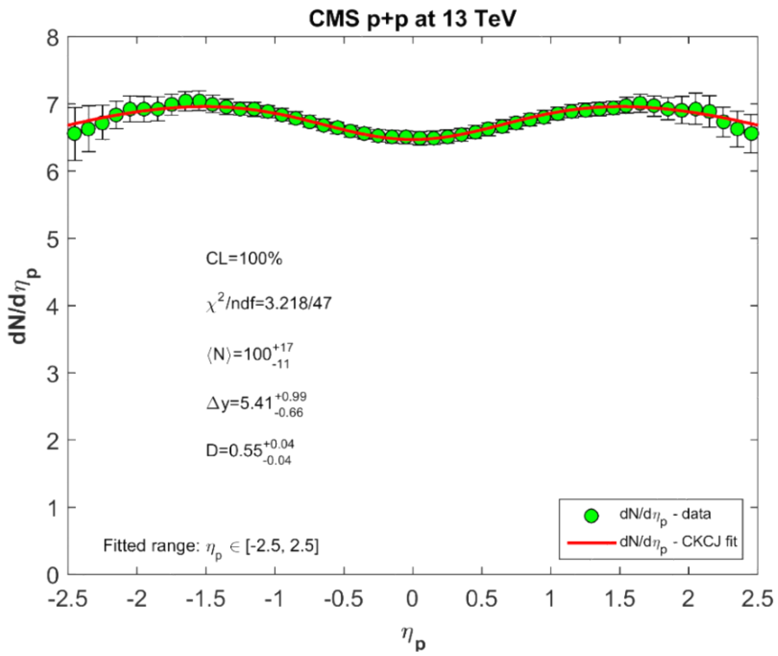

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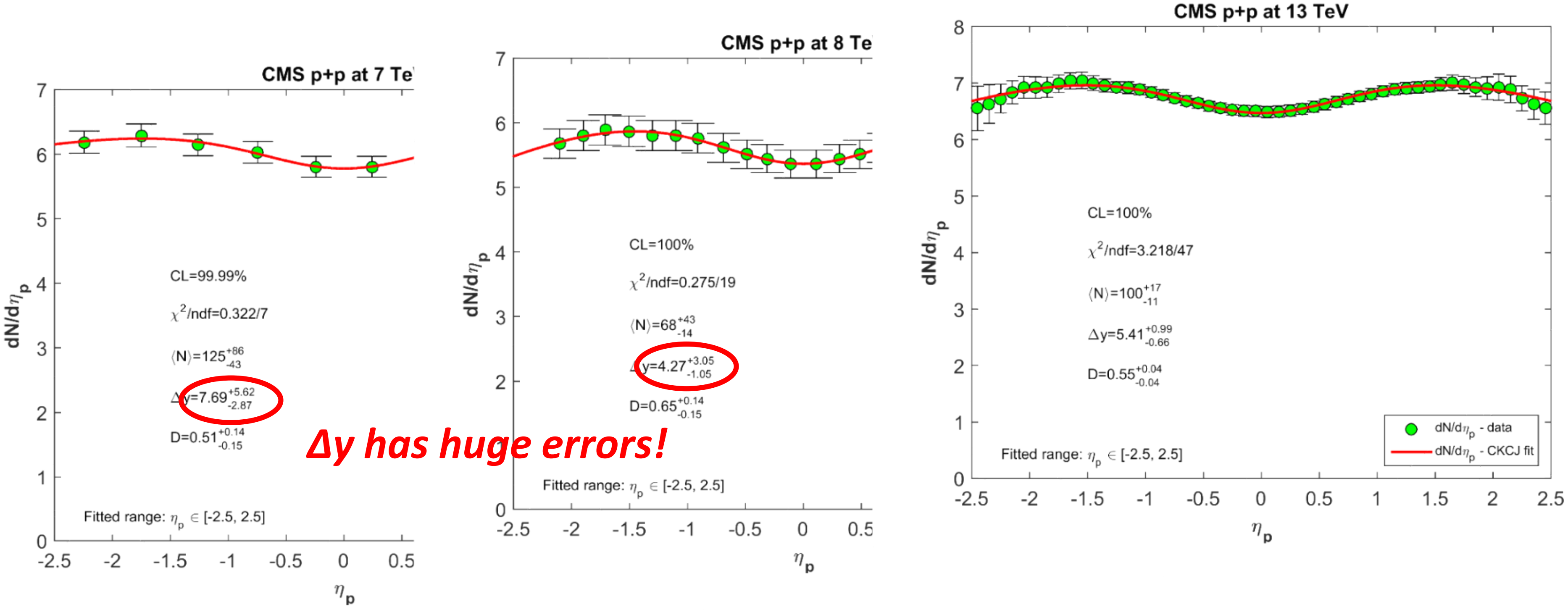

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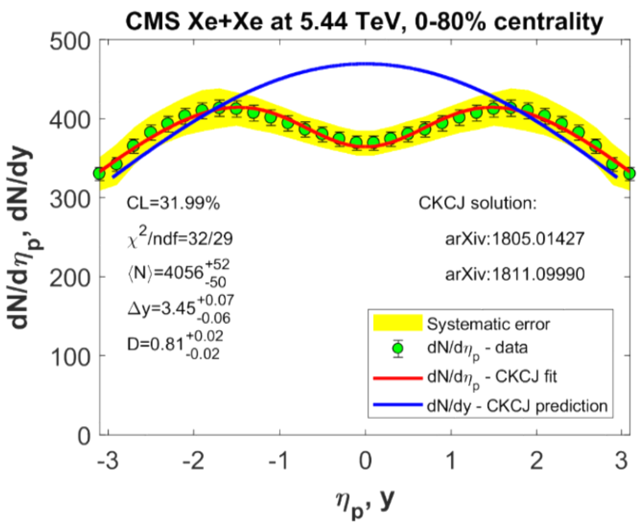
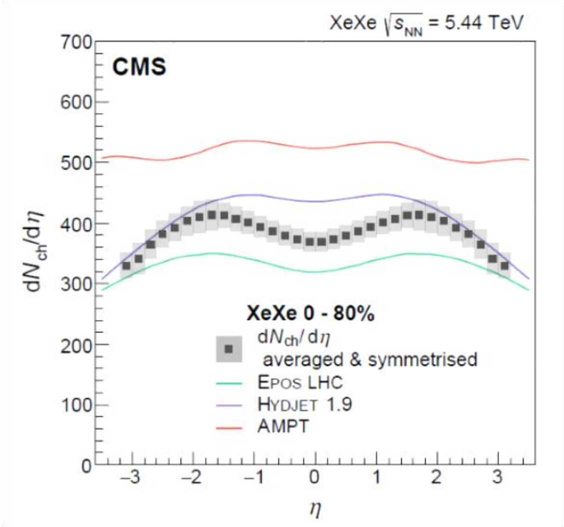




Our self-similar hydrodynamic calculations are succesful in such cases where other models fail.

CMS collab.: arXiv:1902.03603

Werner, Liu, Pierog: arXiv:hep-ph/0506232

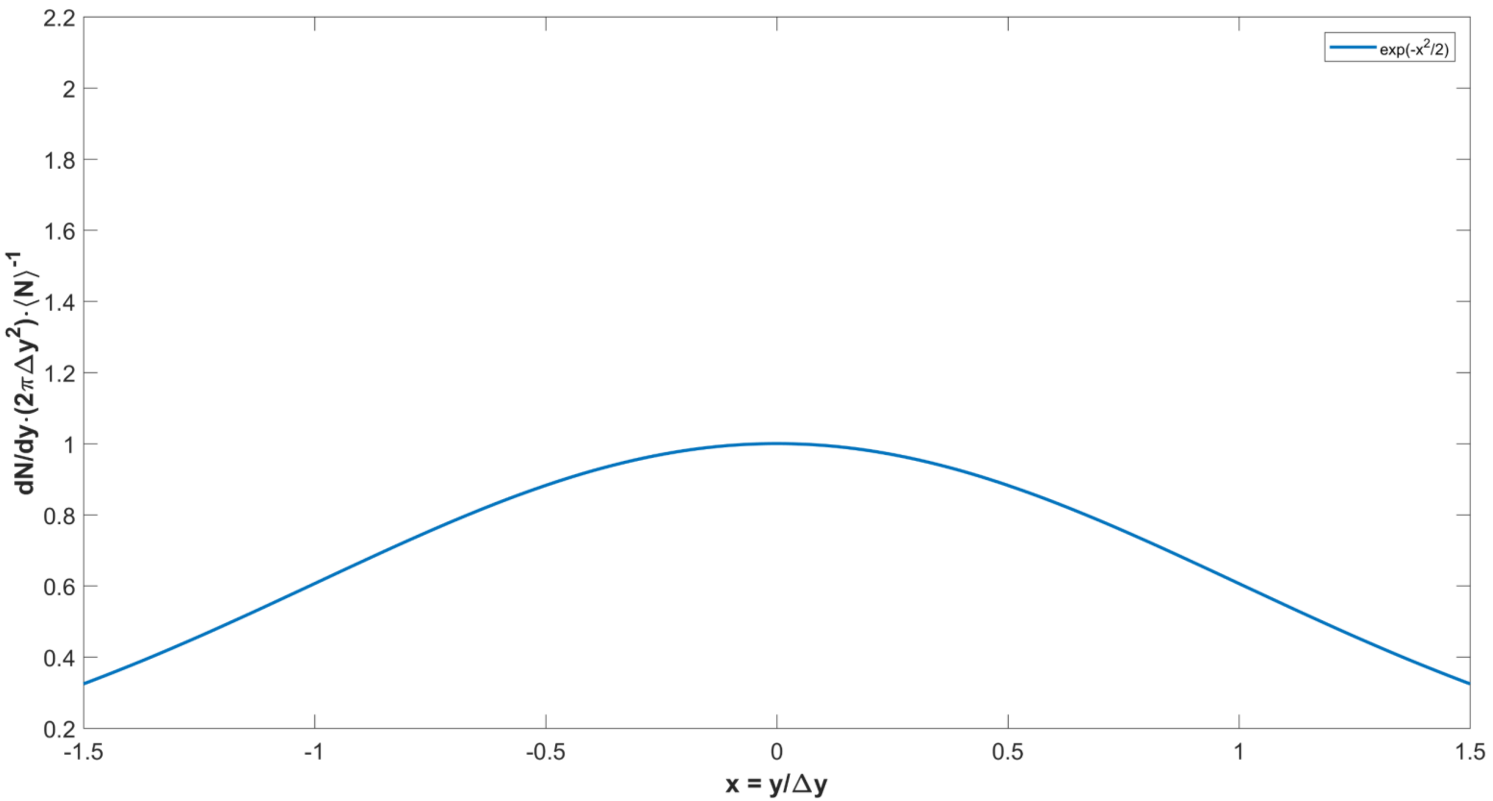
Pierog, Karpenko, et all.: arXiv:1306.0121

Lokhtin, Snigirev: arXiv:hep-ph/0506189

Lin, Ko, et all.: arXiv:nucl-th/0411110

Representation of scaling behaviour

- All the fitted dataset can be described by a normalized Gaussian:



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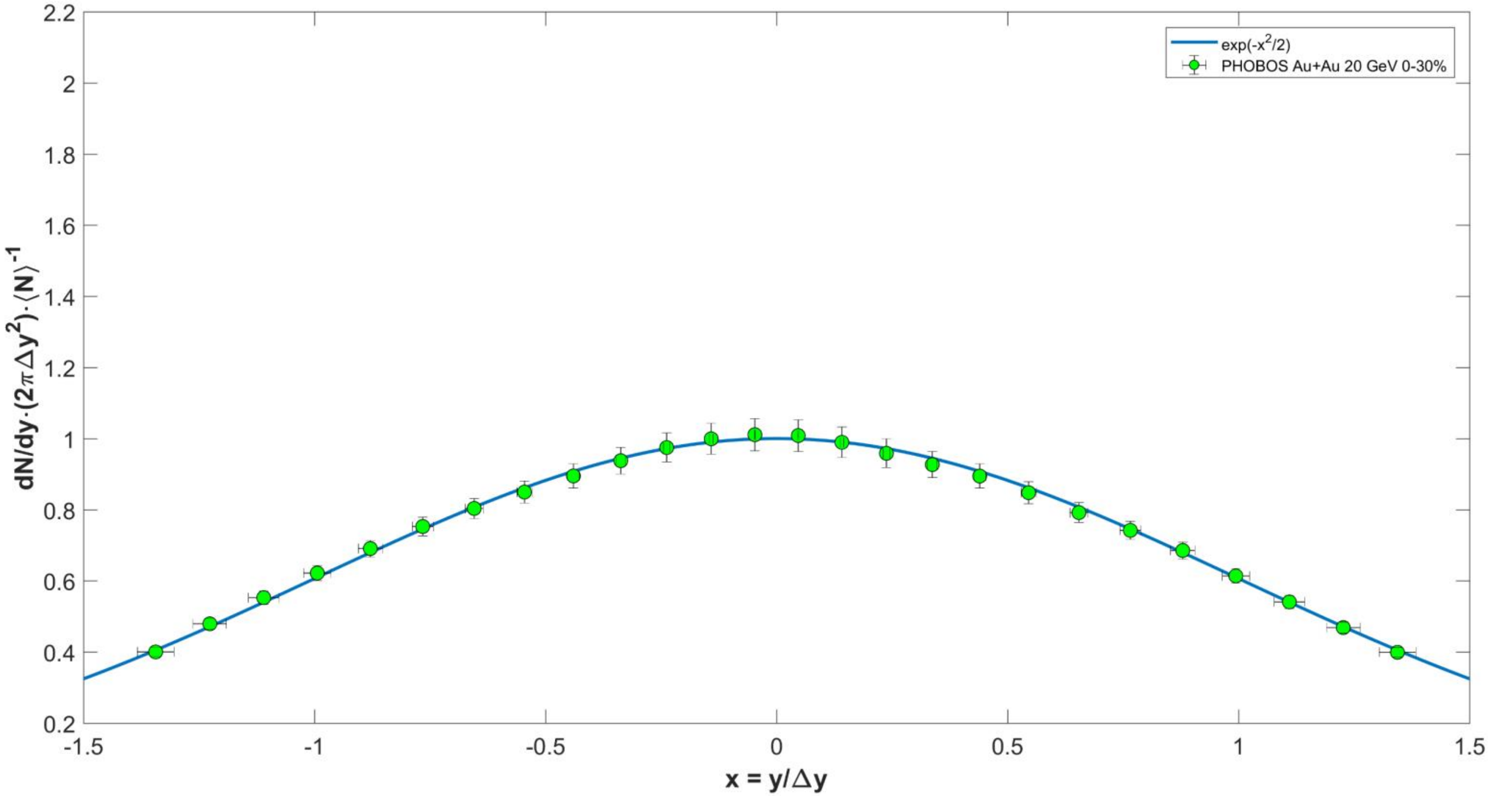

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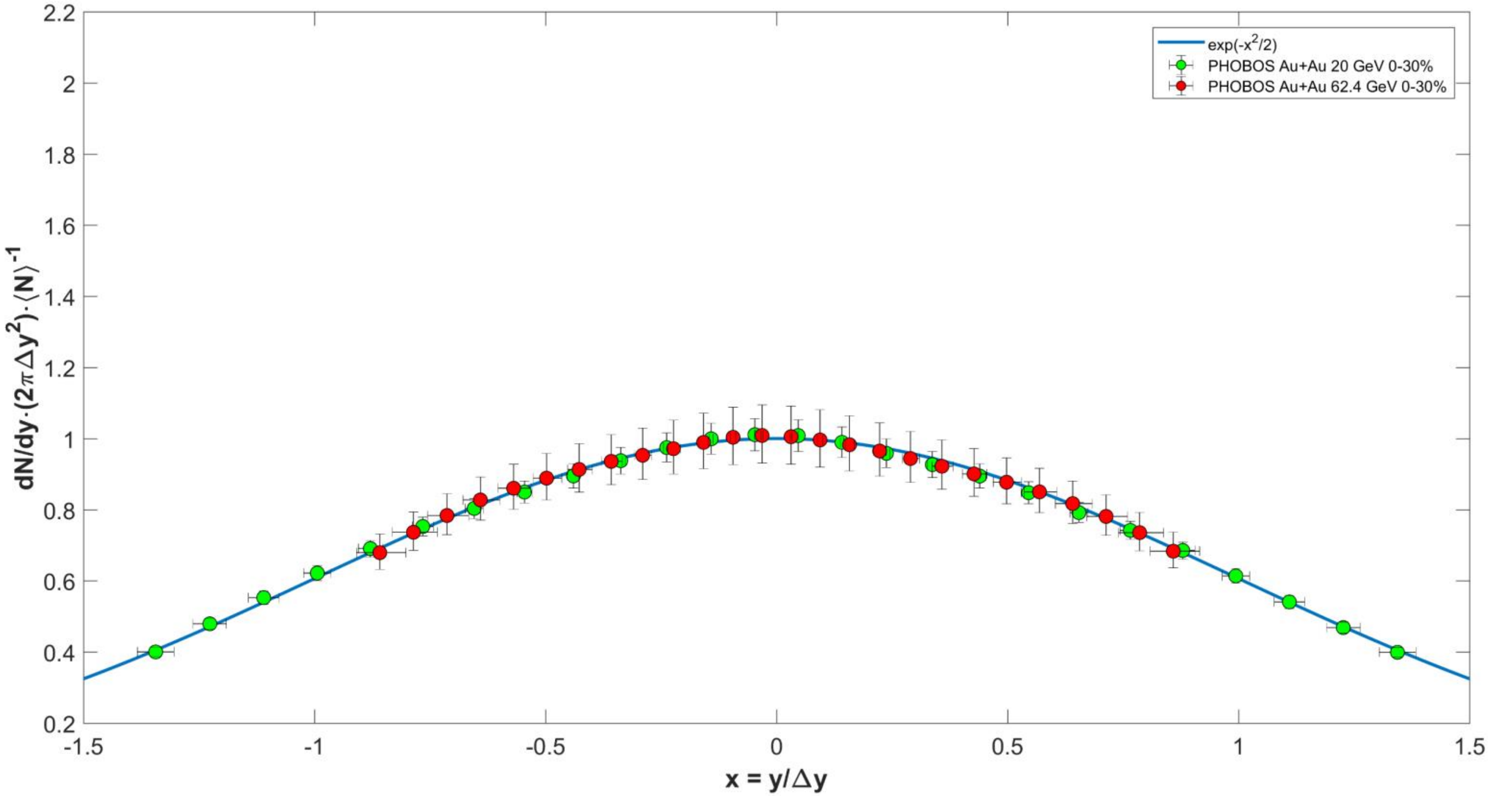

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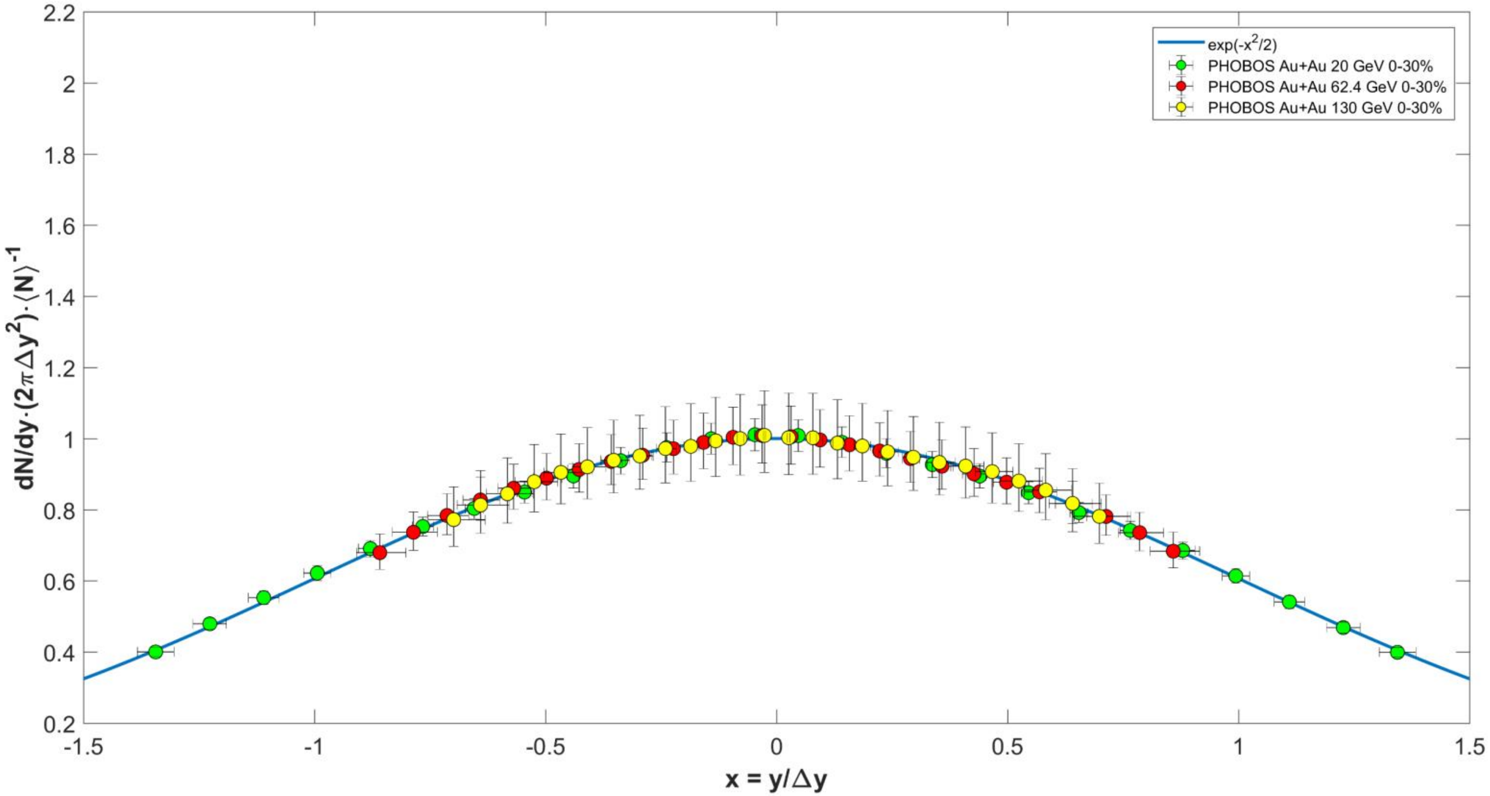

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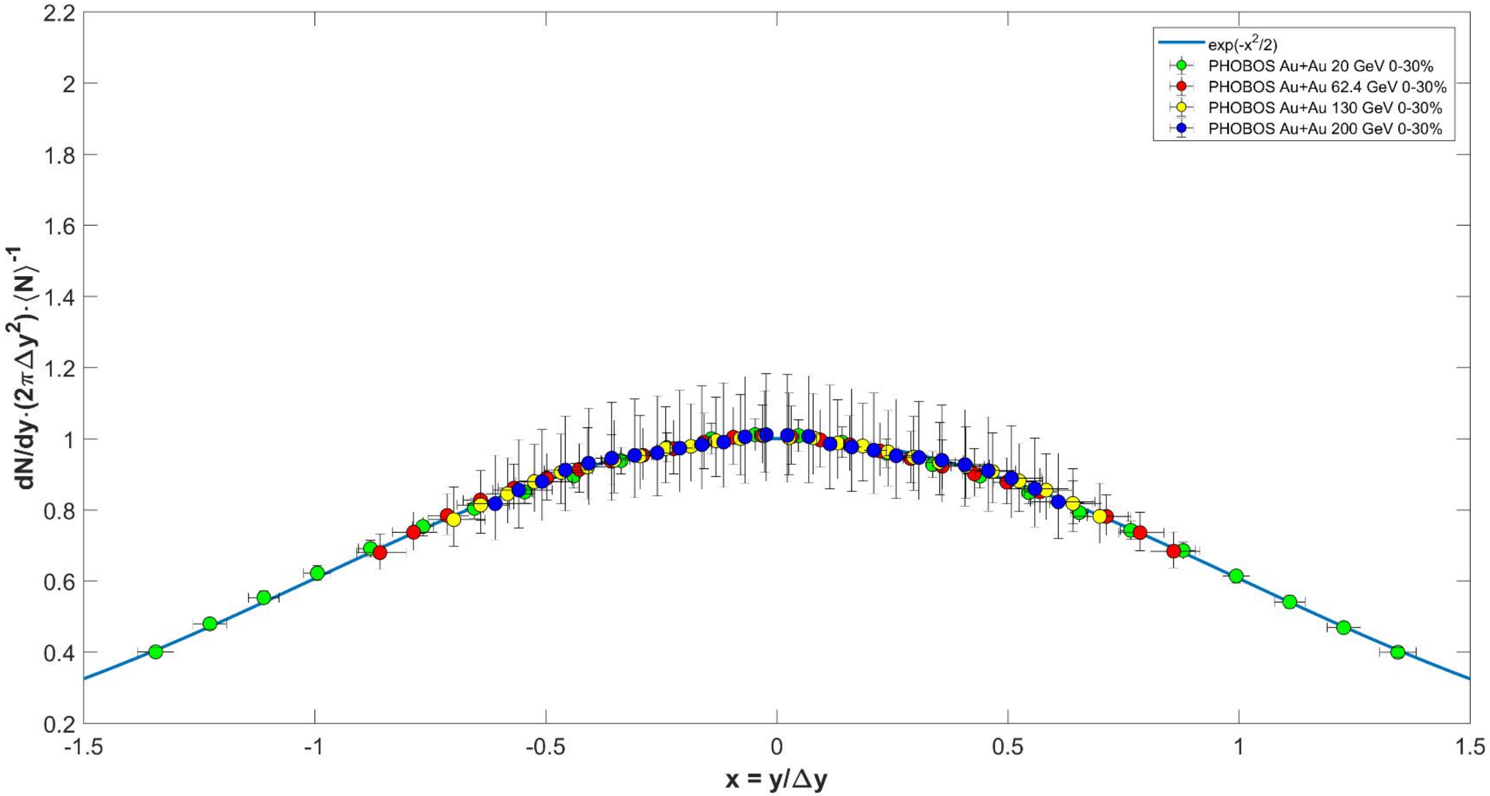

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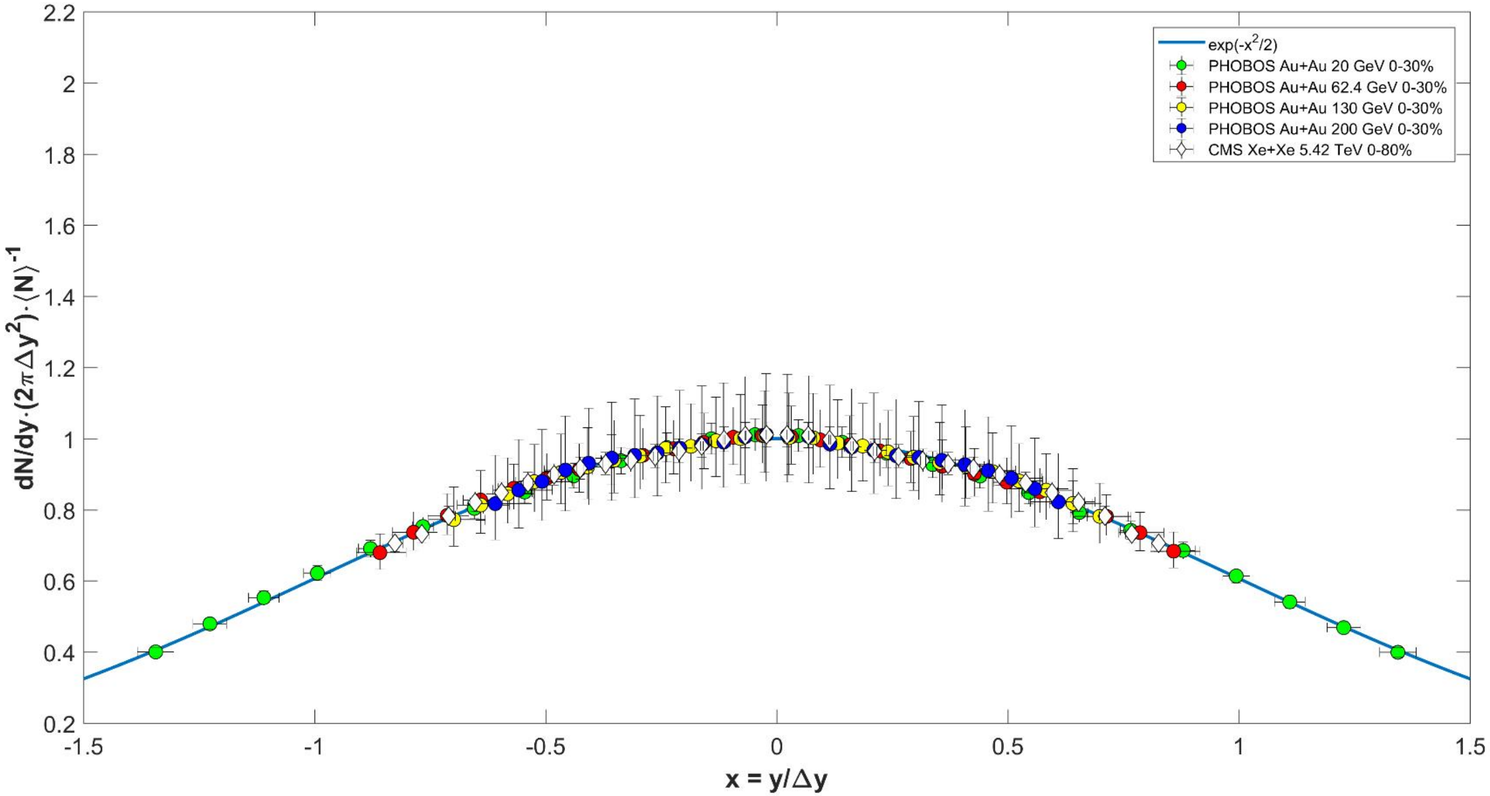

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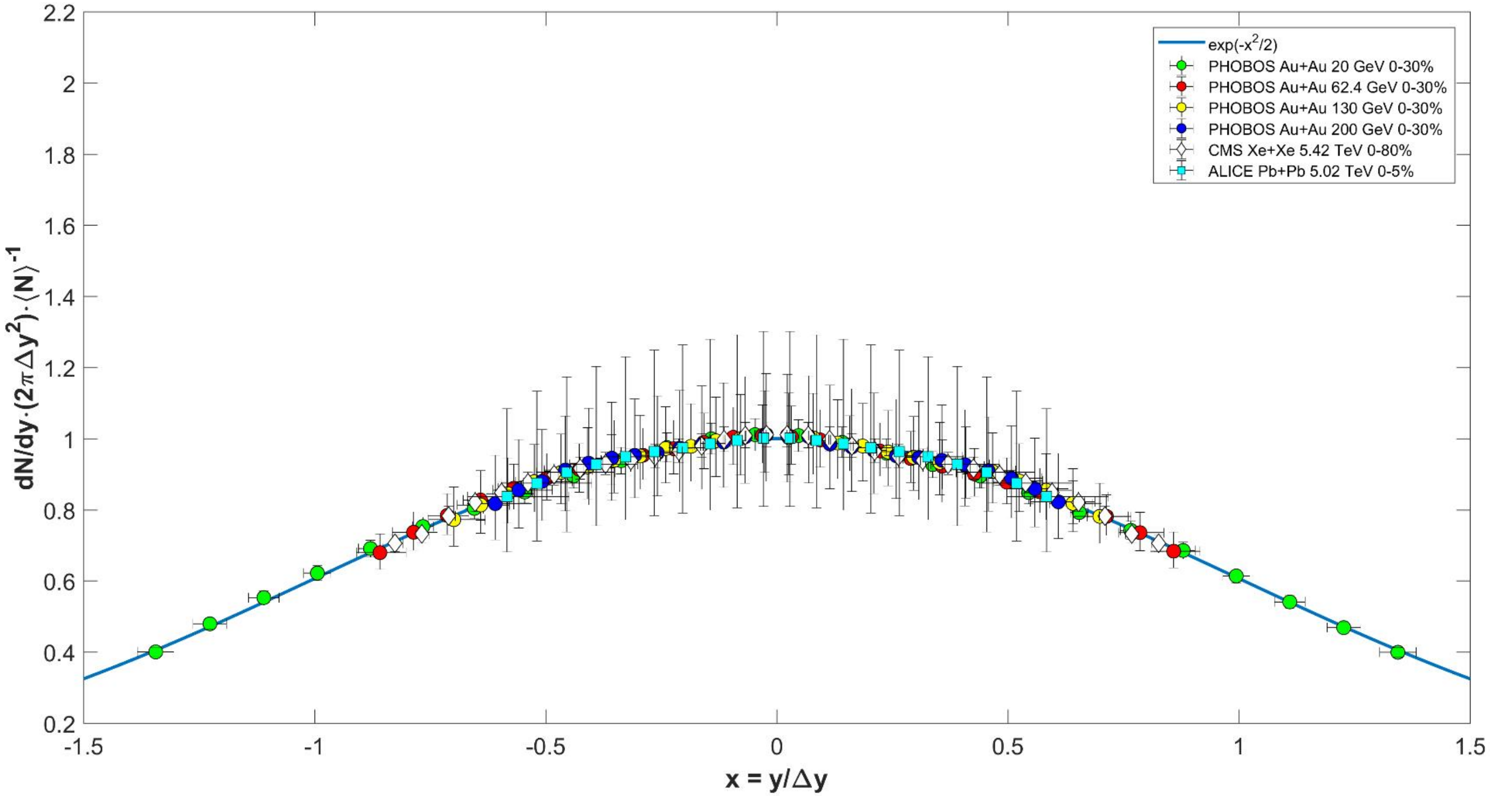

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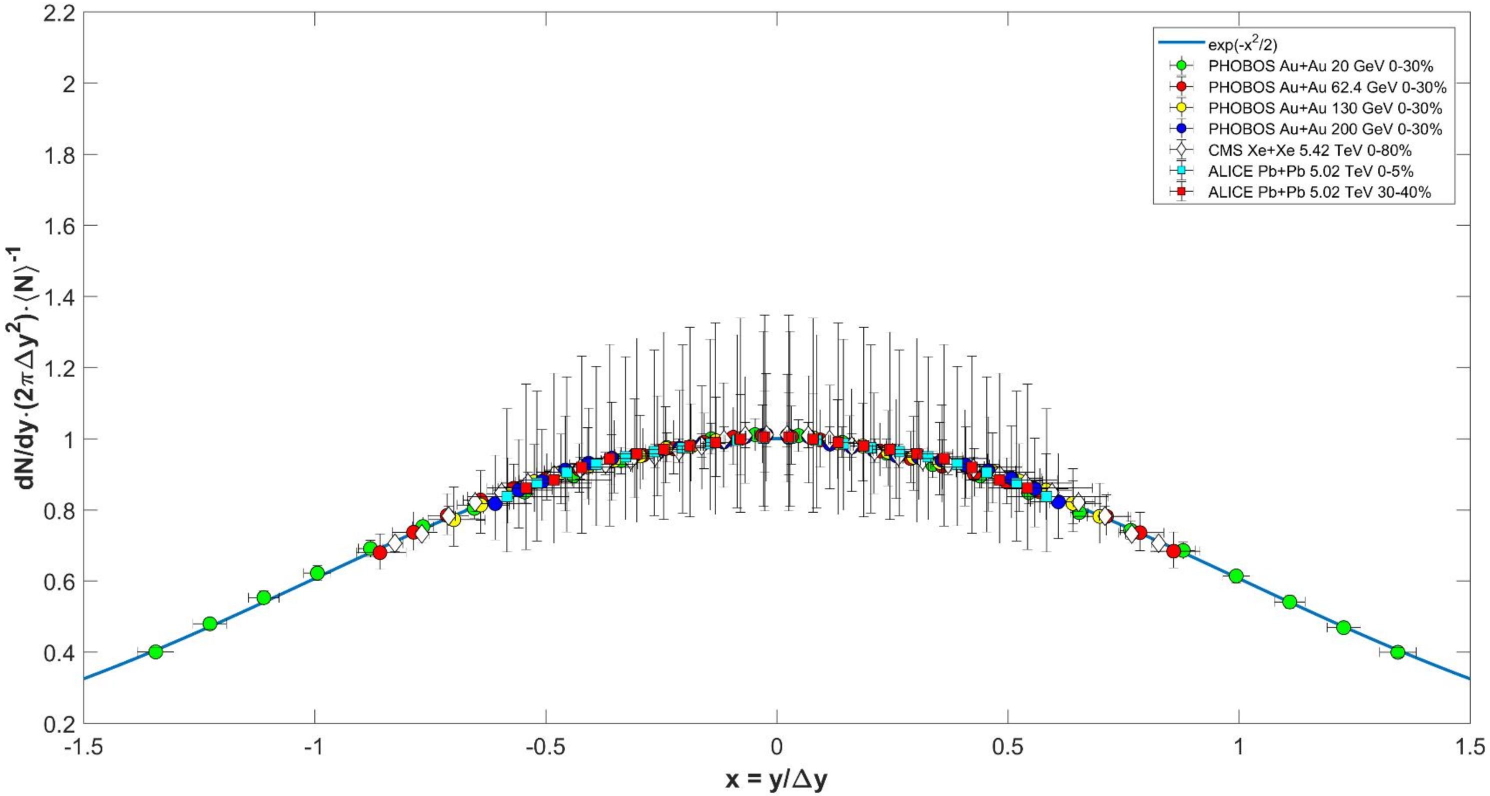

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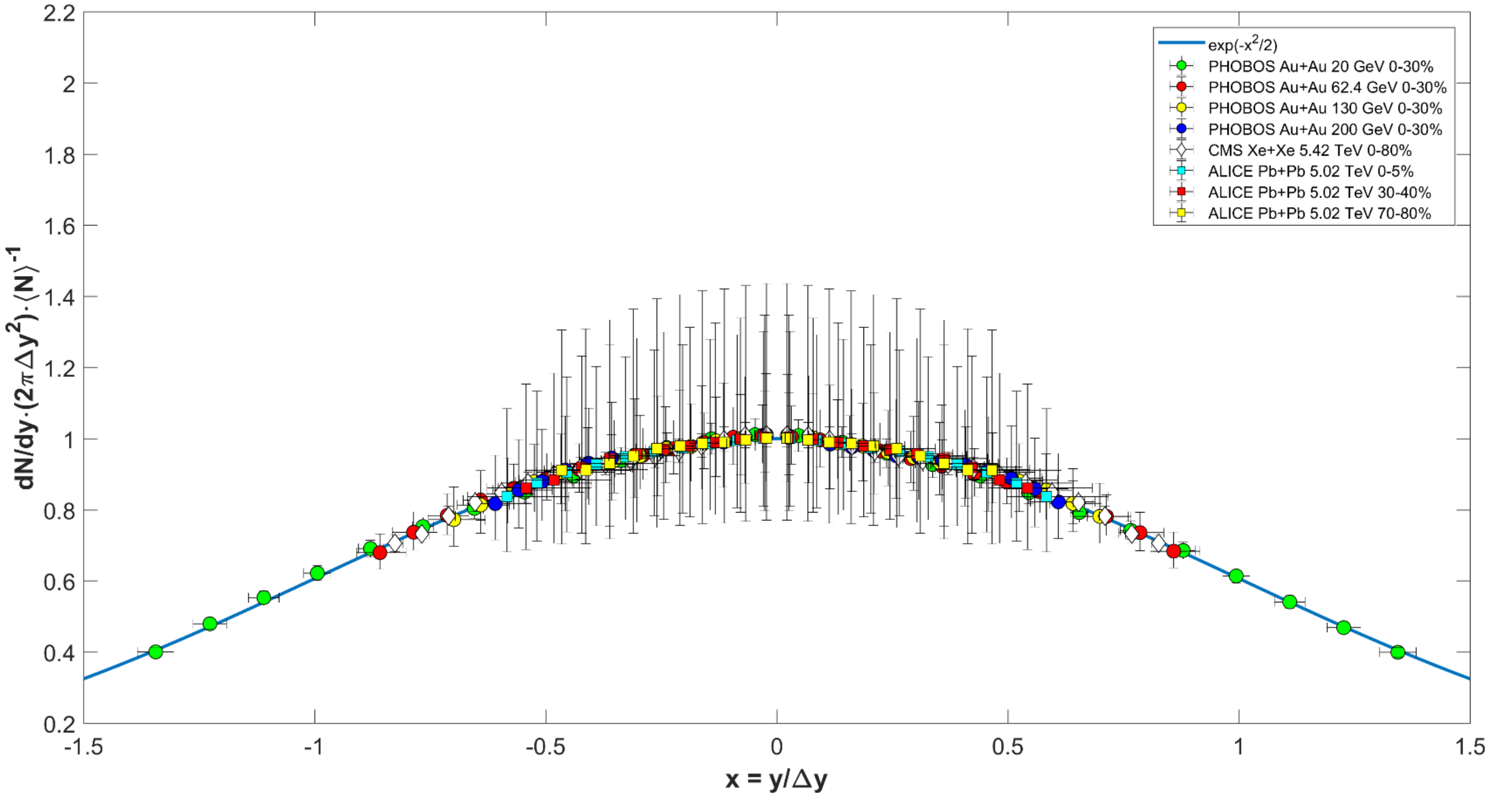

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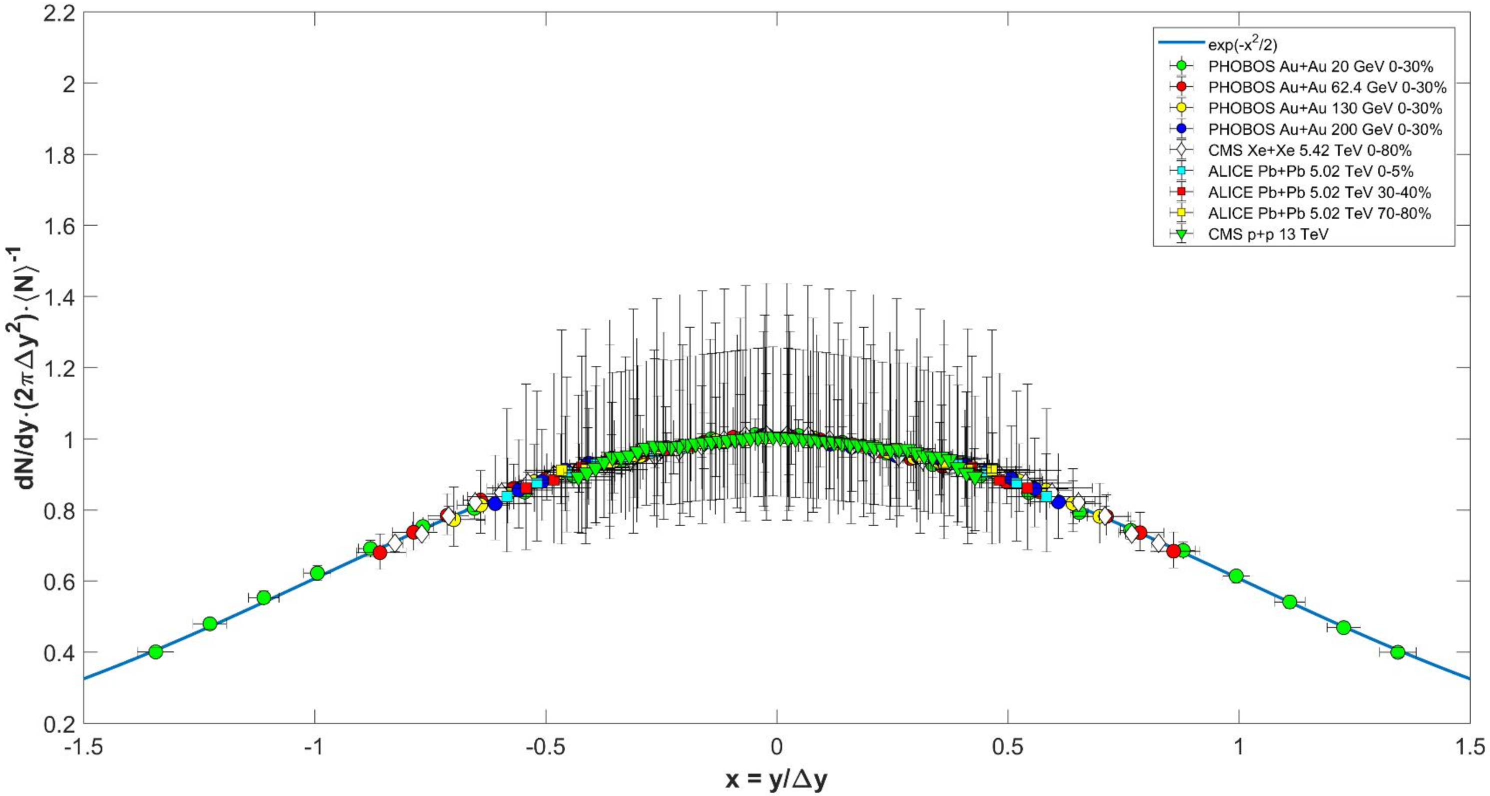

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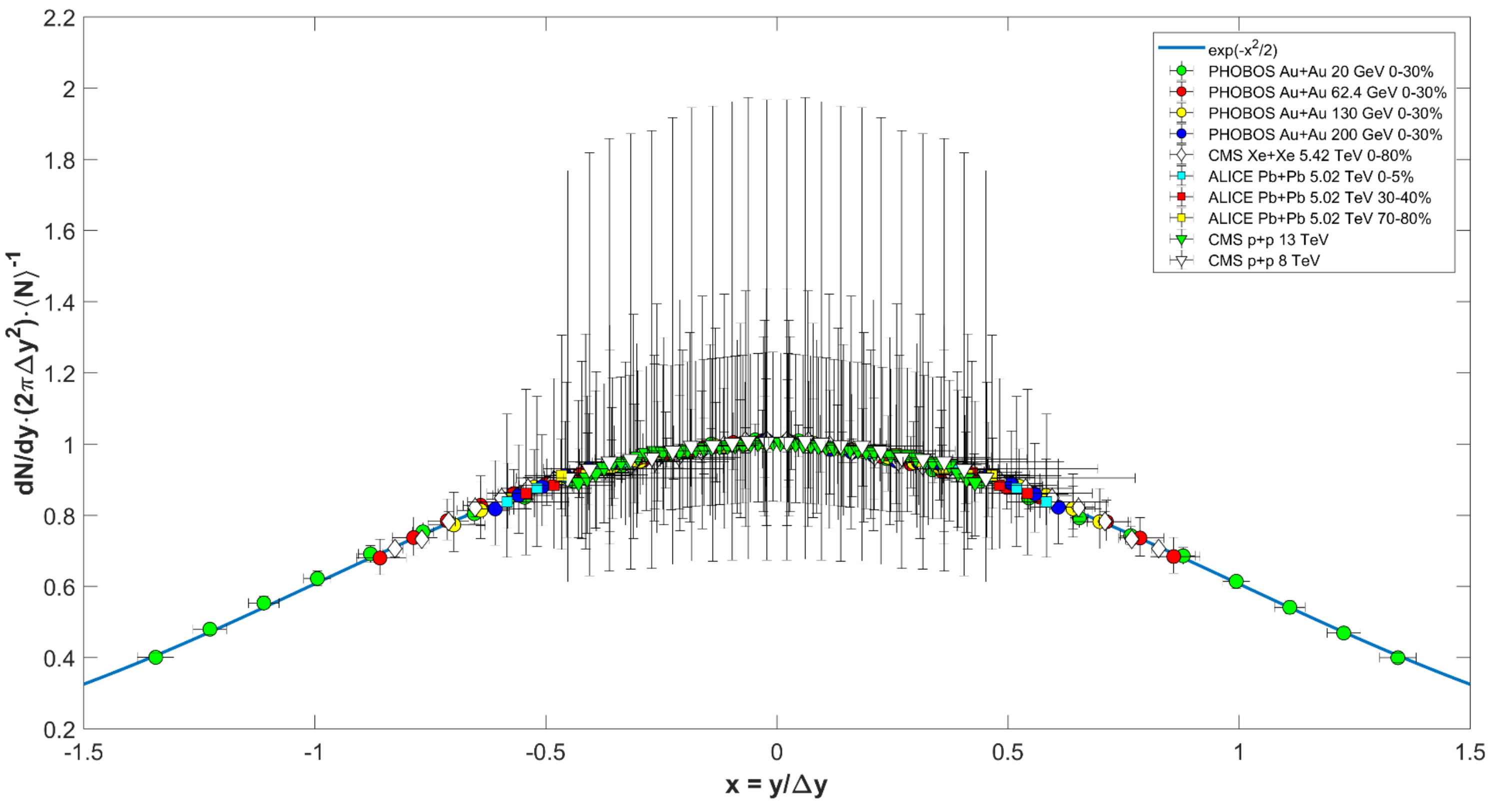

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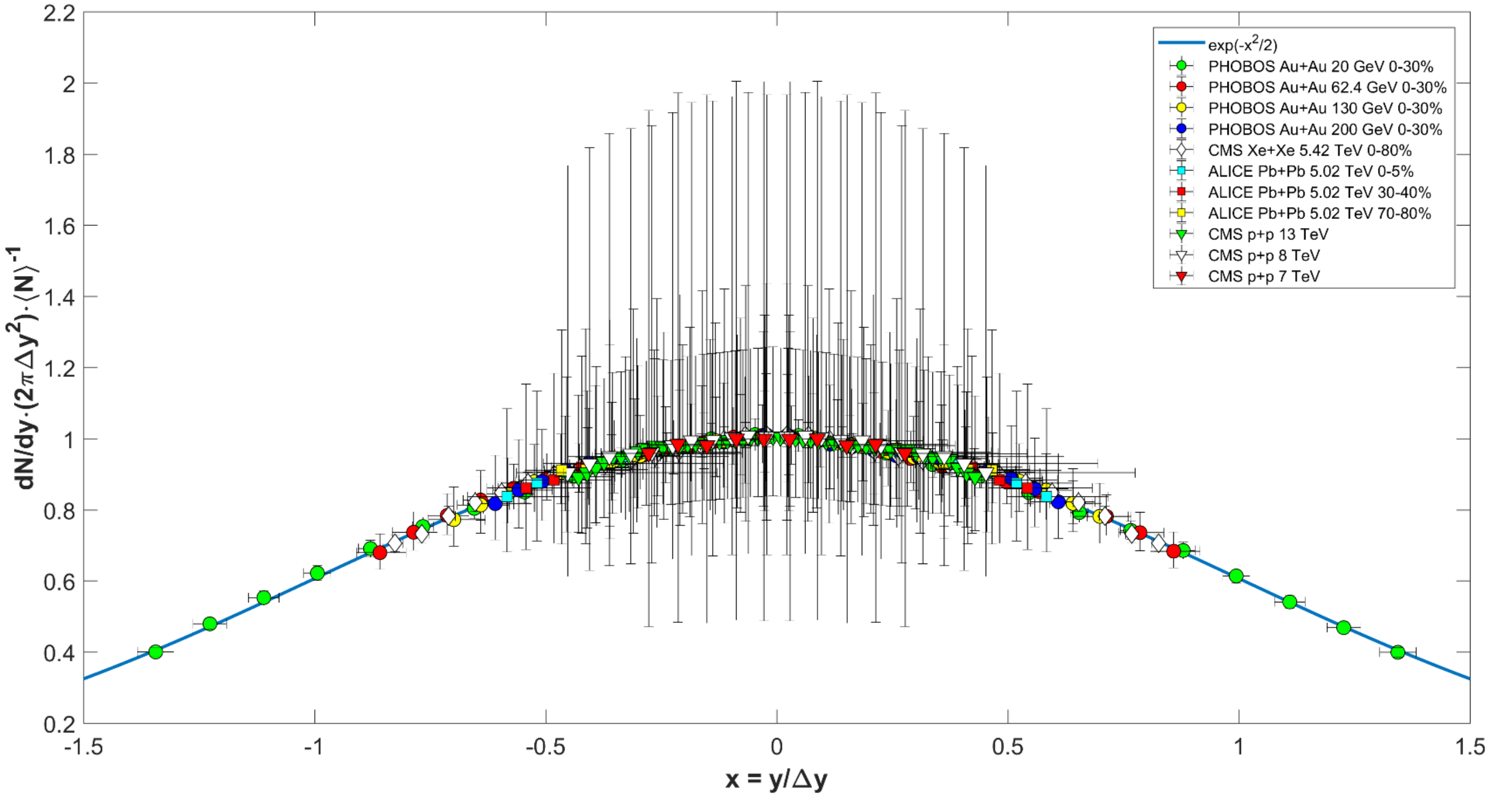

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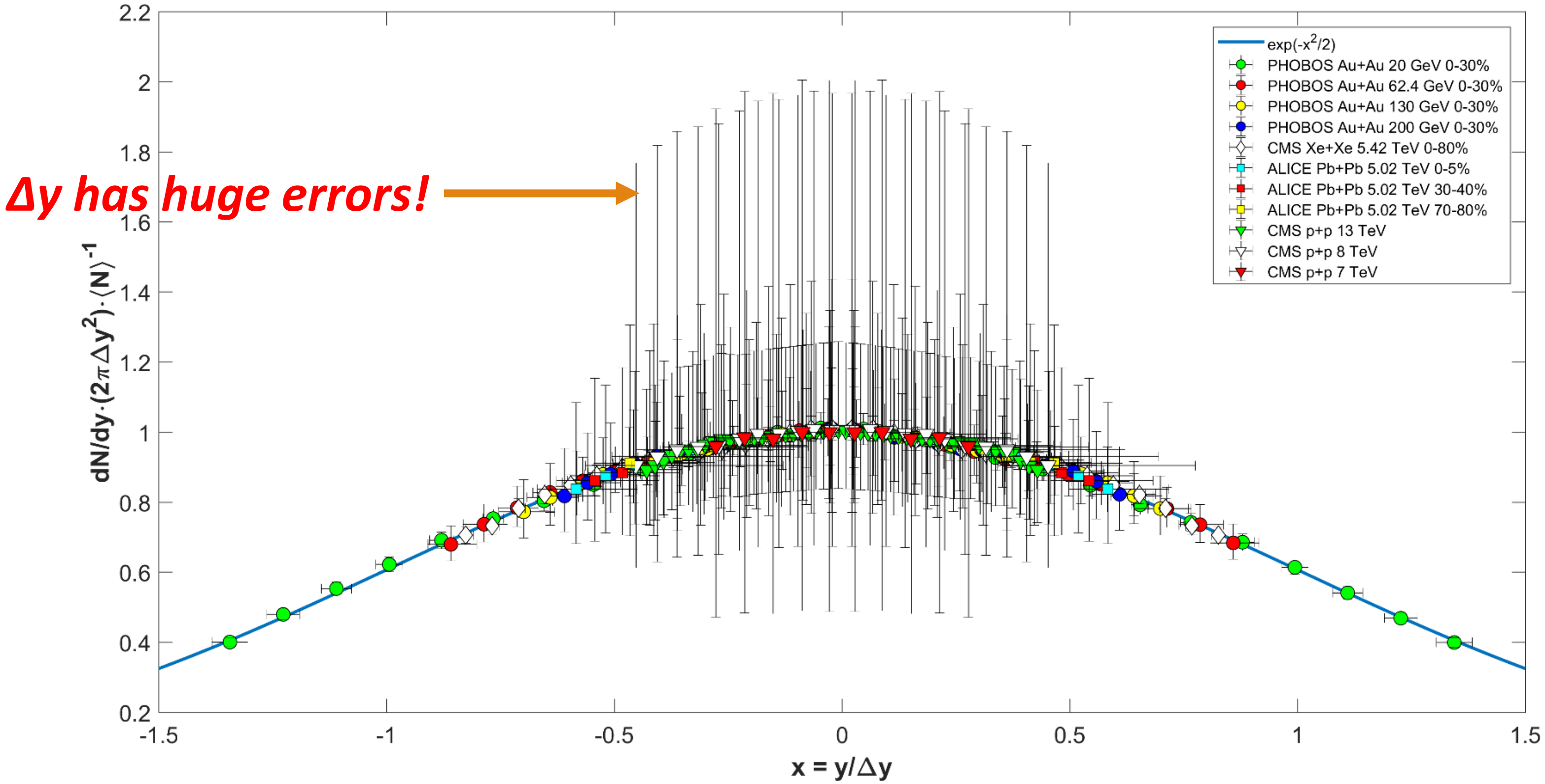

In conclusion…

- p+p collisions can be described as collective systems
- Our fits indicate low c_s value (≈0.35)
- Low c_s value indicate the presence of fluid, so the presence of QGP
- p+p and A+A collisions: *self-similar* systems

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We hope that these results help to confirm the legitimacy of hydro in p+p collisions!

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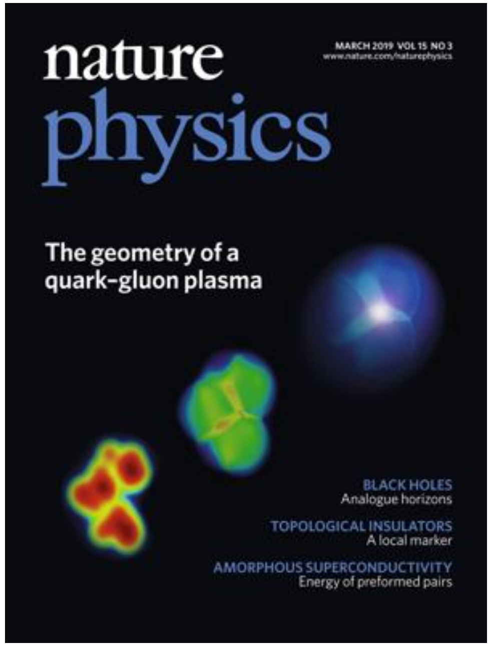

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- However, describing H+H systems by hydro is *not* a recent idea

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ESTIMATION OF HYDRODYNAMICAL MODEL PARAMETERS FROM THE INVARIANT SPECTRUM AND THE BOSE-EINSTEIN CORRELATIONS OF π^- MESONS PRODUCED IN (π^+/K^+)p INTERACTIONS AT 250 GeV/c

EHS/NA22 Collaboration

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Abstract: The invariant spectra of π^- mesons produced in (π^+/K^+)p interactions at 250 GeV/c are analysed in the framework of the hydrodynamical model of three-dimensionally expanding cylindrically symmetric finite systems. A satisfactory description of experimental data is achieved. The data favour the pattern according to which the hadron matter undergoes predominantly longitudinal expansion and non-relativistic transverse expansion with mean transverse velocity $\langle u_t \rangle = 0.20 \pm 0.07$, and is characterized by a large temperature inhomogeneity in the transverse direction: the extracted freeze-out temperature at the center of the tube and at the transverse rms radius are 140 ± 3 MeV and 82 ± 7 MeV, respectively. The width of the (longitudinal) space-time rapidity distribution of the pion source is found to be $\Delta\eta = 1.36 \pm 0.02$. Combining this estimate with results of the Bose-Einstein correlation analysis in the same experiment, one extracts a mean freeze-out time of the source of $\langle \tau_f \rangle = 1.4 \pm 0.1$ fm/c and its transverse geometrical rms radius, $R_G(\text{rms}) = 1.2 \pm 0.2$ fm.