This work is supported by NKFIH K-133046 and MATE KKP (2023) grants.

Scaling behaviour of dN/dy in high energy collisions

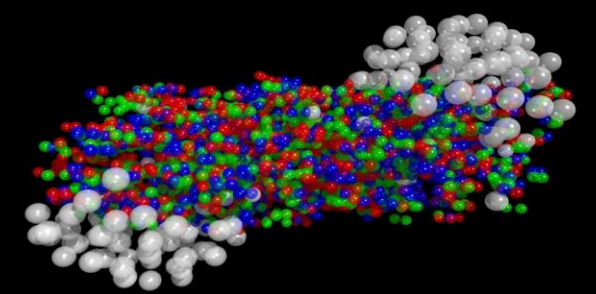
GÁBOR KASZA, TAMÁS CSÖRGŐ

52ND INTERNATIONAL SYMPOSIUM ON MULTIPARTICLE DYNAMICS

GYÖNGYÖS, 08/24/2023

Various application of hydrodynamics

- Why is hydrodynamics so effective?
- Works well on …
  - … *microscopic scales*
  - … *macroscopic scales*
  - … *cosmic scales*
- Different systems in many aspects



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

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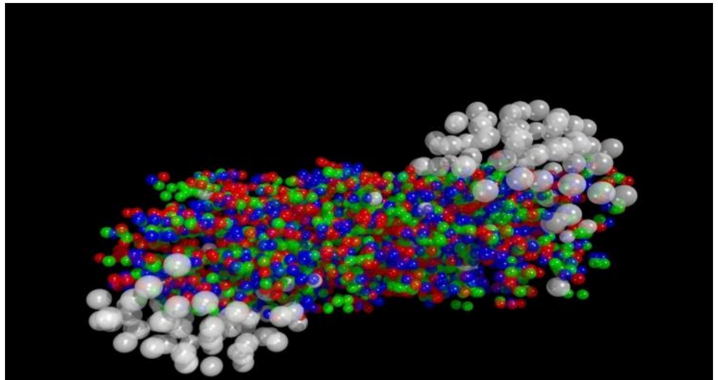
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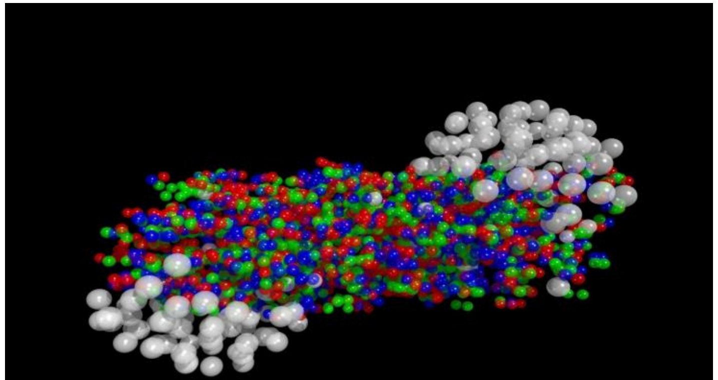

Heavy-ion collision: in the overlap area, the sQGP is created

Hydrodynamics has no internal scale!

- Today's presentation: ***a new example of hydodynamic scaling behaviour in dN/dy data***

Relativistic perfect fluid solution with accelerating velocity field

- Equation of state: $\varepsilon = \kappa_0 p \quad (\mu=0)$
- Rindler coordinates: $\tau = \sqrt{t^2 - r_z^2}$ $\qquad \eta_z = \frac{1}{2}\ln\left(\frac{t+r_z}{t-r_z}\right)$
- Velocity field: $u^\mu = \begin{pmatrix}\cosh(\Omega)\\ \sinh(\Omega)\end{pmatrix}$ $\qquad \Omega \equiv \Omega(\eta_z)$

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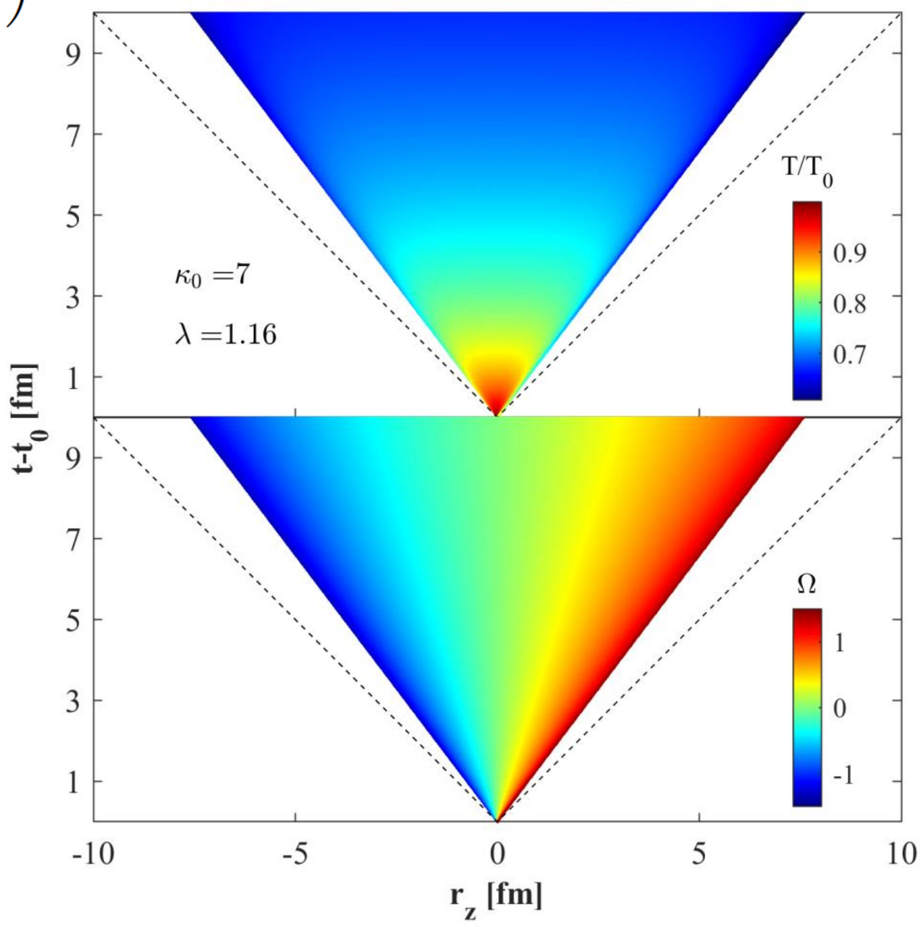
- 1+1 dimensional, parametric, almost self-similar, finite solution

λ: rate of acceleration (Hwa-Bjorken: *λ=1*) → *accelerating expansion* → realistic $dN/d\eta_p$



Pseudorapidity distribution

- Starting from the rapidity distribution, we calculated the pseudorapidity distribution
- Parametric curve:

$$\left(\eta_{\mathrm{p}}(y), \frac{dN}{d\eta_{\mathrm{p}}}(y)\right) = \left(\frac{1}{2}\ln\left[\frac{\langle|p(y)|\rangle + \langle p_z(y)\rangle}{\langle|p(y)|\rangle - \langle p_z(y)\rangle}\right], \frac{\langle|p(y)|\rangle}{\langle E(y)\rangle}\frac{dN}{dy}\right)$$

- We compared this curve with experimental data :
  - PHOBOS Au+Au 130 GeV, 200 GeV
  - ALICE Pb+Pb 5.02 TeV
  - CMS p+p 7 TeV, 8 TeV, 13 TeV
  - CMS Xe+Xe 5.44 TeV

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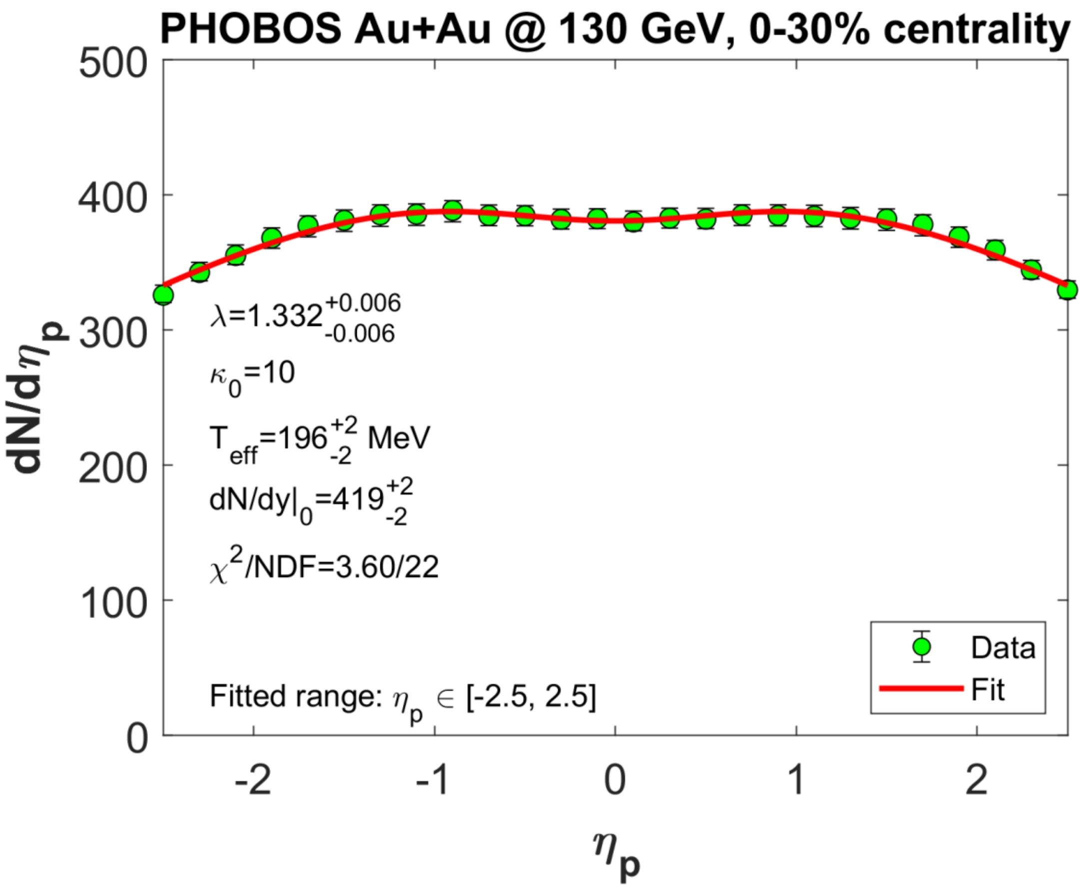
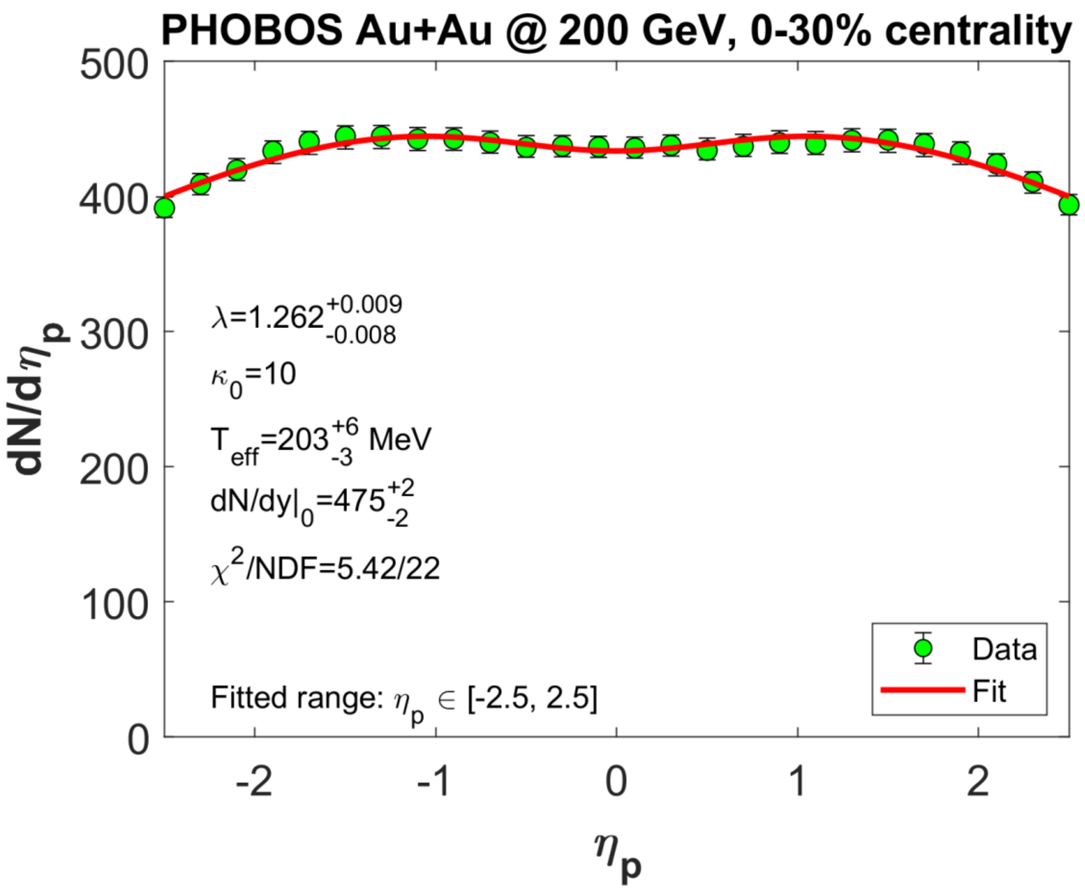
- Different sizes (p+p, A+A), different centralities, different collision energies

Fits to PHOBOS data (Au+Au)





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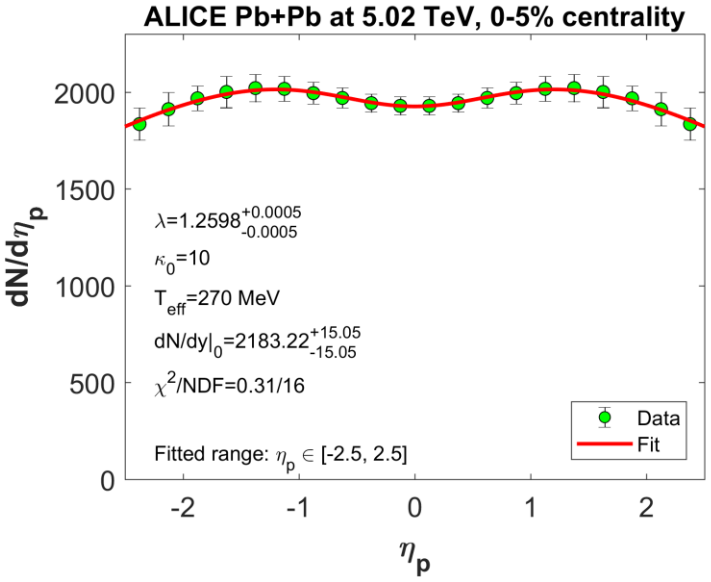
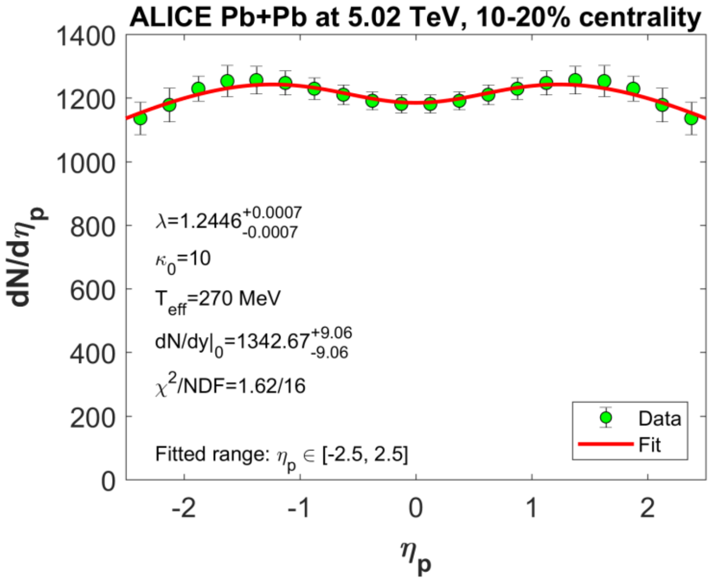
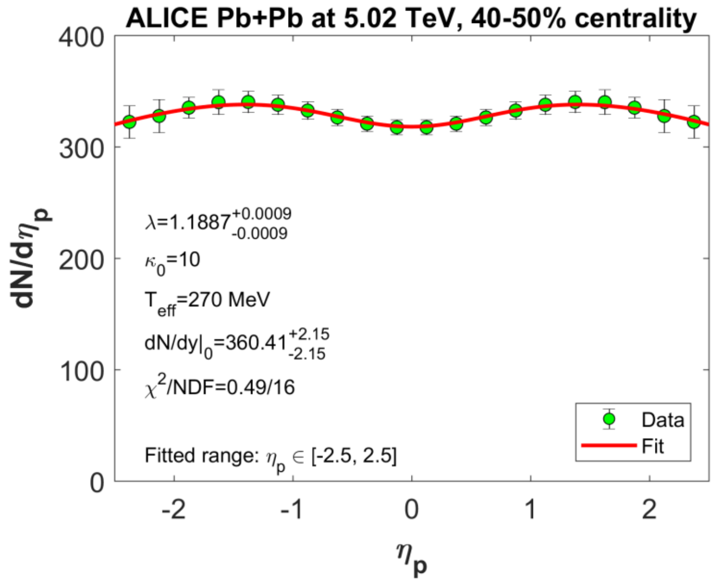
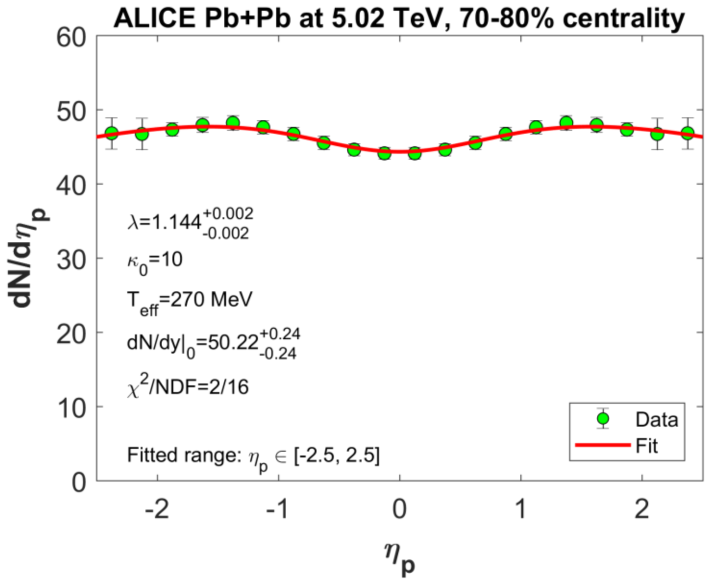
Fits to ALICE data (centrality dependence)

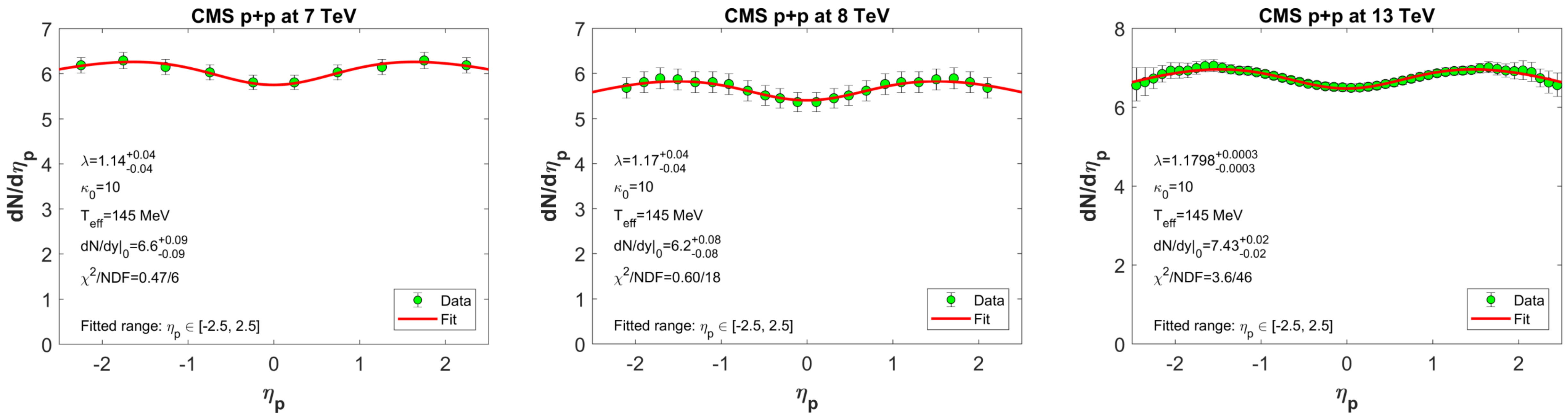








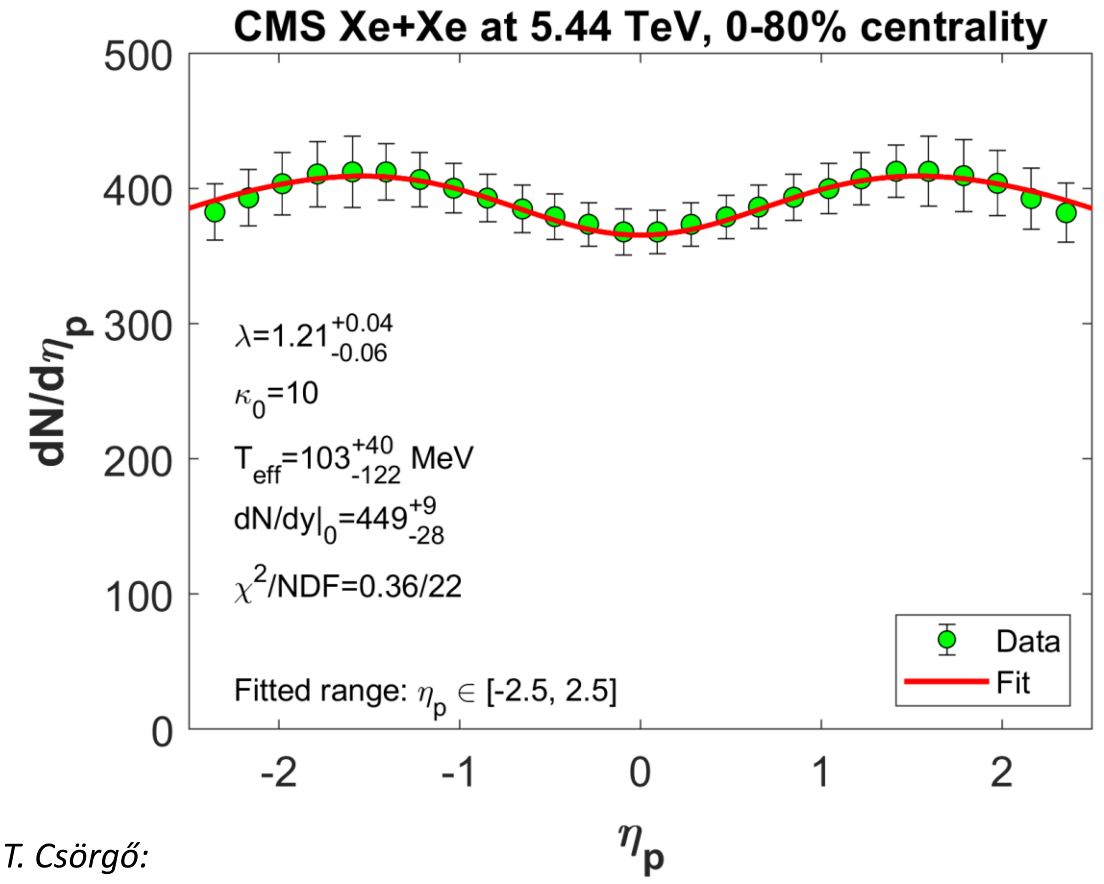
Fits to CMS data (p+p)

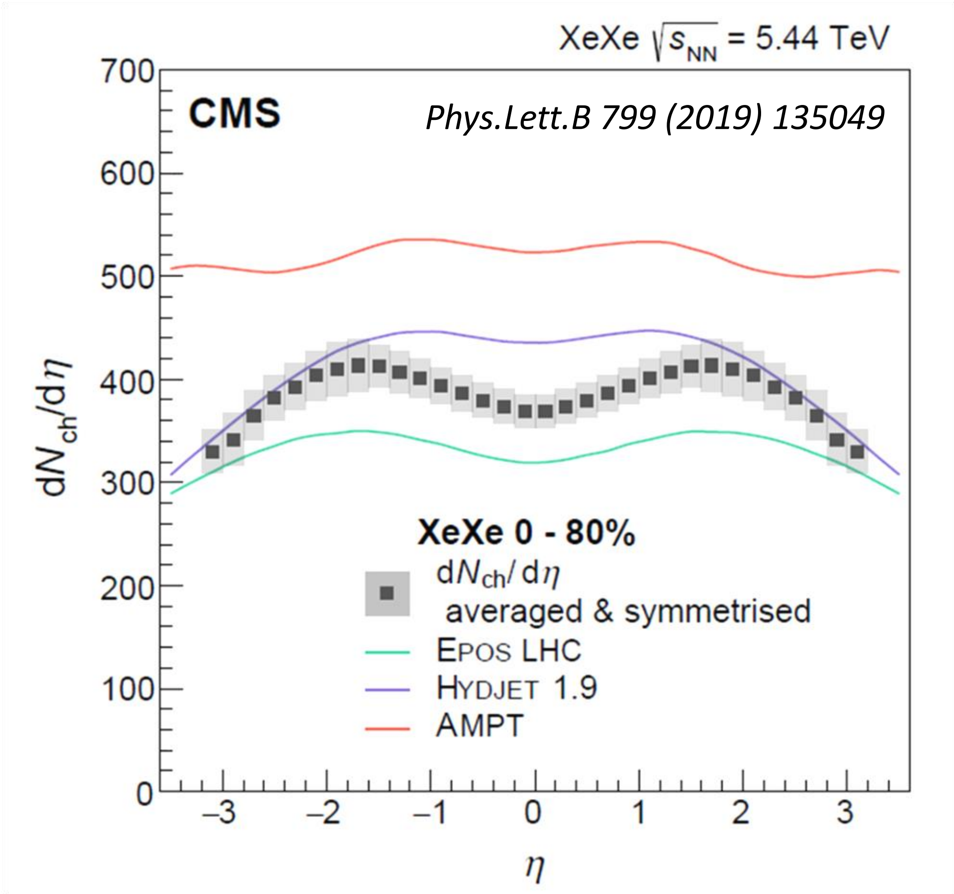


***Collectivity* in p+p collisions?**

Fits to CMS data (Xe+Xe)

- The parametric formula works well in such cases where other models fail:





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A reasonable approximation of the rapidity distribution

- If ***|y| << 2+1/(λ-1)***, then the rapidity distribution becomes Gaussian:

$$\frac{dN}{dy} \approx \frac{\langle N \rangle}{(2\pi\Delta y^2)^{1/2}} \exp\left(-\frac{y^2}{2\Delta y^2}\right)$$

- Manifest of the hydrodynamic scaling behaviour:

$$\frac{1}{\Delta y^2} = (\lambda - 1)^2 \left[1 + \left(1 + \frac{1}{\kappa_0}\right)\left(\frac{1}{2} + \frac{m}{T_{\text{eff}}}\right)\right]$$

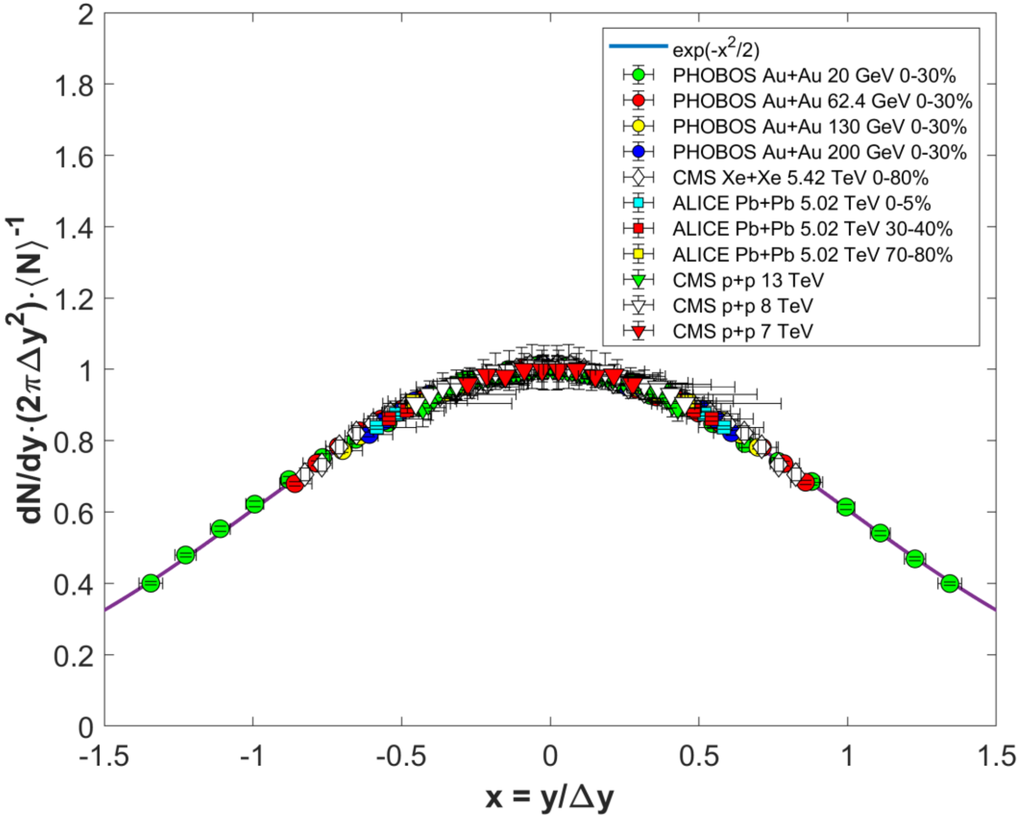
$$\langle N \rangle = (2\pi\Delta y^2)^{1/2} \left.\frac{dN}{dy}\right|_{y=0}$$

- The physical properties of different collisions (√s, centrality, size) are scaled out:

$$\frac{dN}{dy} = \left.\frac{dN}{dy}\right|_{y=0} \exp\left(-\frac{y^2}{2\Delta y^2}\right) \longrightarrow f(x) = \exp\left(-\frac{x^2}{2}\right)$$

Data collapsing

- Pseudorapidity distributions were transformed into rapidity distributions → fits to the *dN/dy* data series



For each dataset, the fit range satisfies:

$|y| << 2+1/(\lambda-1)$

This condition is the strictest in the case of *PHOBOS Au+Au@20 GeV* → $|y| << 3$, $|x| << 1.8$

- Data collapsing on the $f(x)=exp(-x^2/2)$ curve of the scale function

Another prediction for Gaussian dN/dy from Landau hydrodynamics:
C-Y. Wong: Phys. Rev. C 78, 054902
C-Y. Wong et al.: Phys.Rev.C 90 (2014) 6, 064907
A. Sen et al.: J.Phys.Conf.Ser. 630 (2015) 1, 012042

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

Thank you for your attention!

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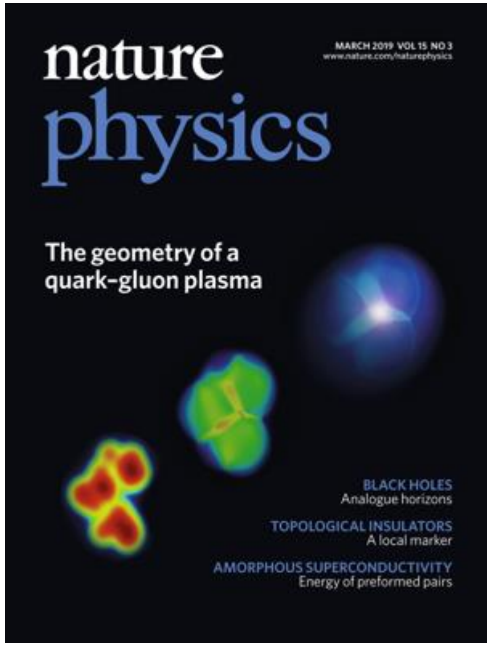
Is the hydrodynamic description well-accepted?

- A+A collisions: become a major trend since 2005
- p+A, d+A and He+A collisions: accepted since 2019
- p+p collisions: not widely accepted yet



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- p+p collisions: not widely accepted yet
- However, describing H+H systems by hydro is *not* a recent idea

arXiv:hep-ex/9711009v2 19 Dec 1997

Nijmegen preprint
HEN-405
Dec. 97

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

EHS/NA22 Collaboration

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[b] Institute of Physics and Nuclear Techniques of Academy of Mining and Metallurgy and Institute of Nuclear Physics, PL-30055 Krakow, Poland
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[e] Centro Brasileiro de Pesquisas Fisicas, BR-22290 Rio de Janeiro, Brazil
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[h] KFKI, Hungarian Academy of Sciences, H-1525 Budapest 114, Hungary

Abstract: The invariant spectra of π^- mesons produced in $(\pi^+/K^+)p$ 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.

Rapidity distribution

- We applied the Cooper-Frye formula
- Temperature is determined on the freeze-out hypersurface
- Integrals were calculated by saddle-point approximation
- Fluid rapidity could be well approximated by a linear function: $\Omega \approx \lambda \eta_z$
- The 1+1 dimensional rapidity distribution was embedded in 1+3 dimension

$$\frac{dN}{dy} \approx \left.\frac{dN}{dy}\right|_{y=0} \cosh^{-\frac{\alpha(\kappa_0)}{2}-1}\left(\frac{y}{\alpha}\right) \exp\left(-\frac{m}{T_{\text{eff}}}\left[\cosh^{\alpha(\kappa_0)}\left(\frac{y}{\alpha}\right)-1\right]\right)$$

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$$\eta_{\mathrm{p}}(y) = \tanh^{-1}\left(\mathcal{J}^{-1}\tanh(y)\right) = \tanh^{-1}\left(\frac{\tanh(y)}{\sqrt{1-\frac{m^2}{\langle m_{\mathrm{T}}(y)\rangle^2\cosh^2(y)}}}\right)$$

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