Thermodynamic Probe of Collective Behavior in Small Systems

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based on arxiv: 2212.11710

In collaboration with R. Krupczak & T. Nunes

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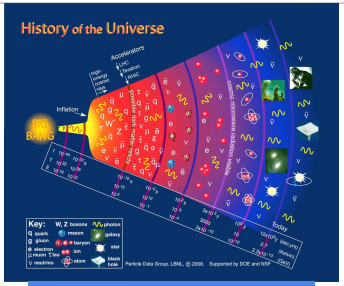
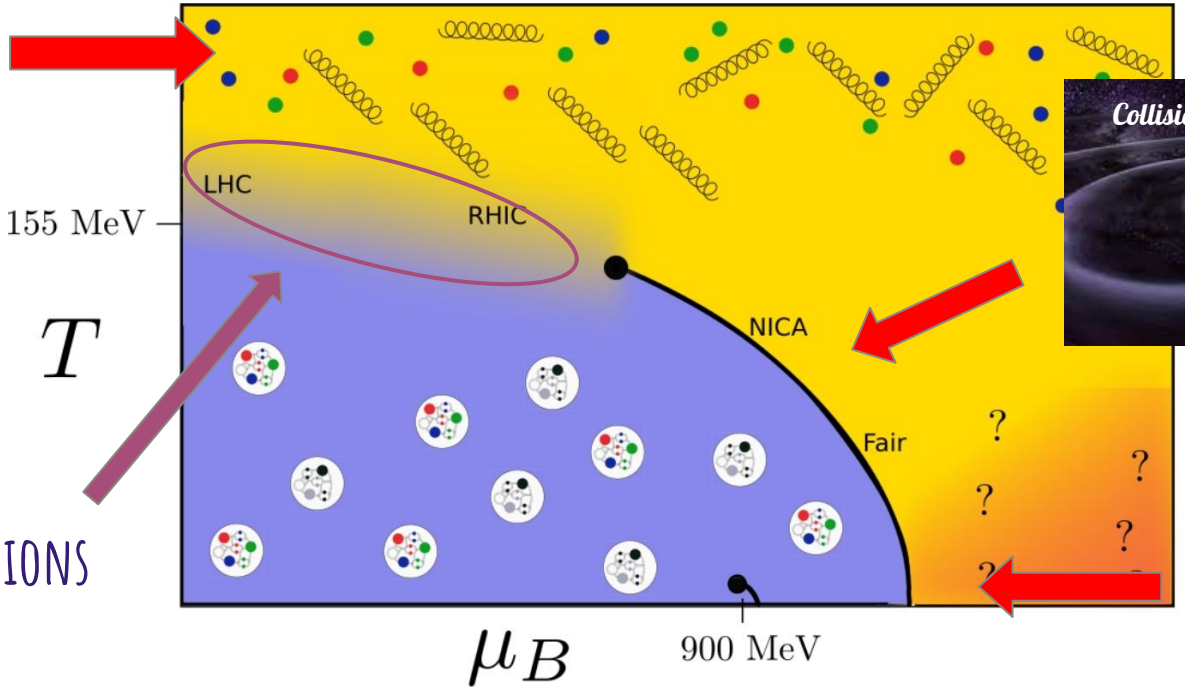
Gyöngyös, Hungary

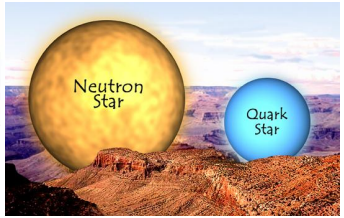
Where can we find the Quark-Gluon Plasma?



Early Universe $t<10^{-5}s$

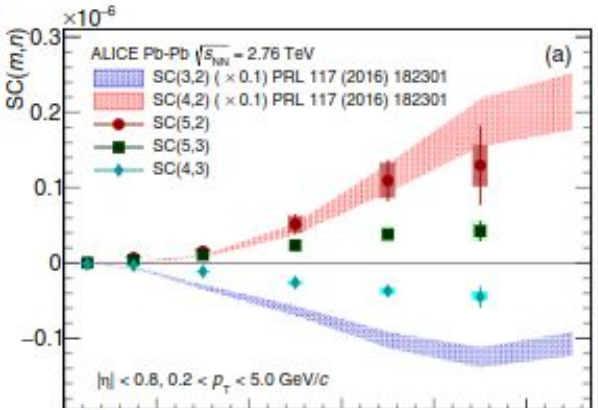


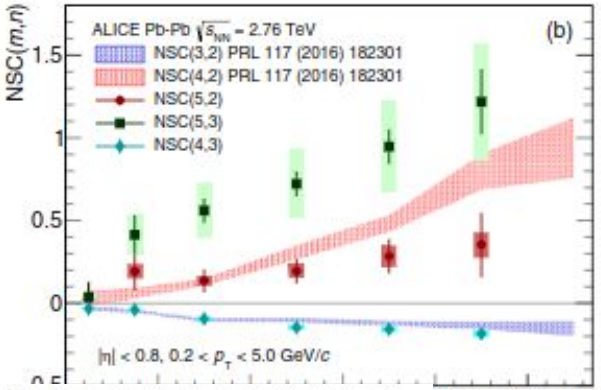
Heavy-Ion Collisions

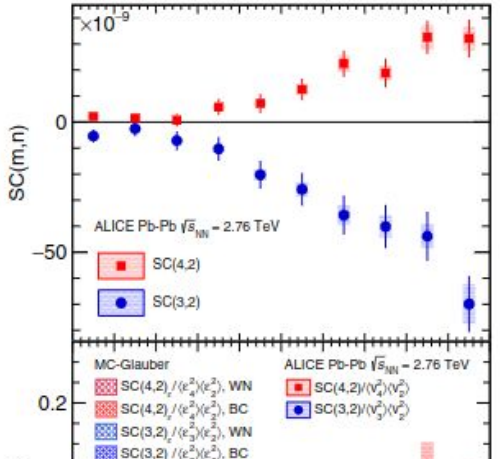


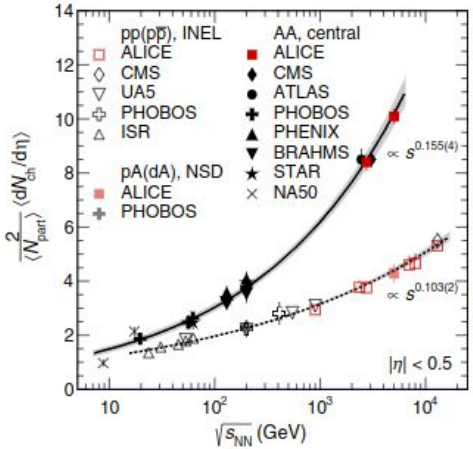
J.N Gunther, Eur.Phys.J.A 57 (2021) 4, 136

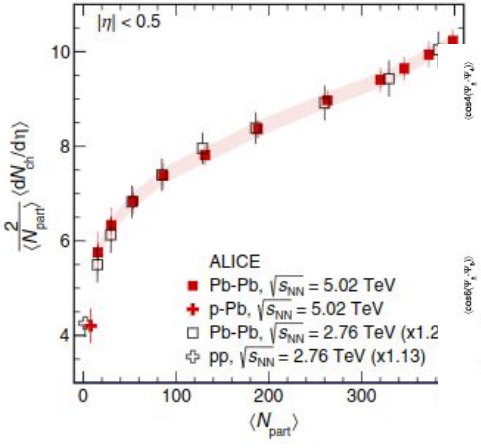
The theory is supported by several experimental findings

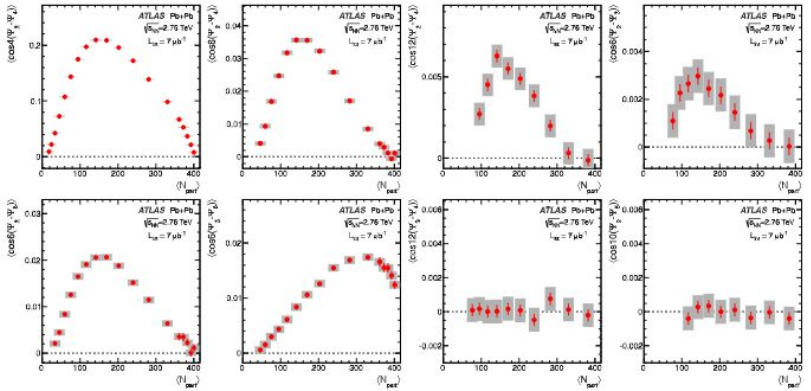




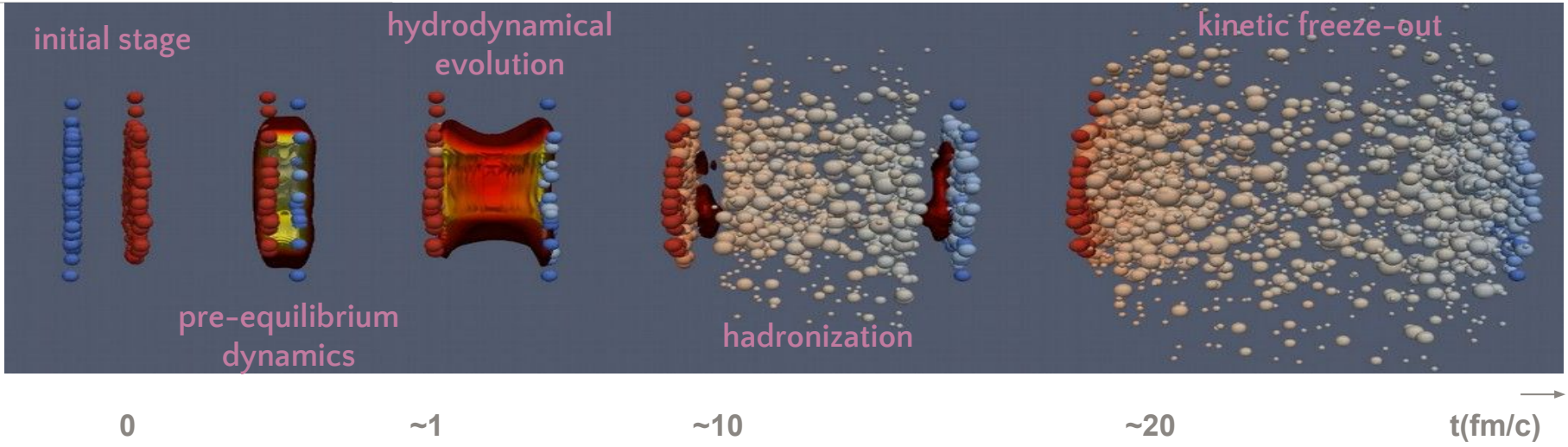








Standard Model of Nuclear Collisions



Hybrid Simulation in Nuclear Collisions

TrENTO → free streaming → MUSIC → freeze-out → URQMD

What we known about the matter created in heavy-ion collisions? *large* system

- Behaves like a Relativistic Fluid

  U.Heinz & R. Snellings Annu. Rev. Nucl. Part. Sci. 63 (2013) 123-151

- Small fluid: ~14 fm (PbPb)

- low viscosity: almost perfect fluid

  F.G e JY Ollitrault PRC 103 (2021) 4, 044907

- Anisotropic Flow: signature of collective behavior

  S. Acharya et al. [ALICE], JHEP 05, 085 (2020) arXiv:2002.00633

- Deconfinement Observed and Temperature

  FG, Giacalone, Luzum, Ollitrault Nature Physics 16, 615 (2020

J.E. Bernhard, J. S. Moreland & S. A. Bass
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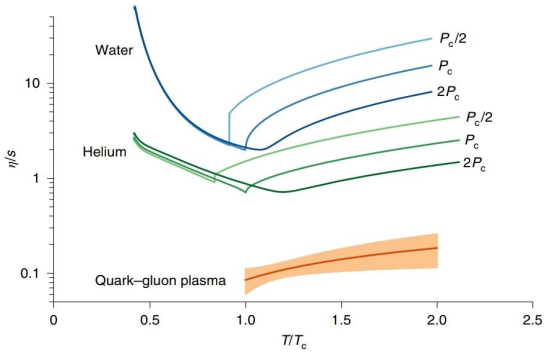

$$\frac{dN}{d\phi} \propto (1 + 2v_1 \cos\phi + 2v_2 \cos 2\phi + \cdots)$$

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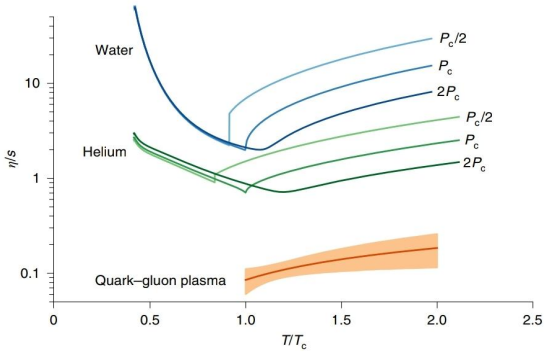


$$T_{eff} = \frac{\langle p_t \rangle}{3.07} = 222 \pm 9\text{MeV}$$

(Pb-Pb 5.02 TeV)

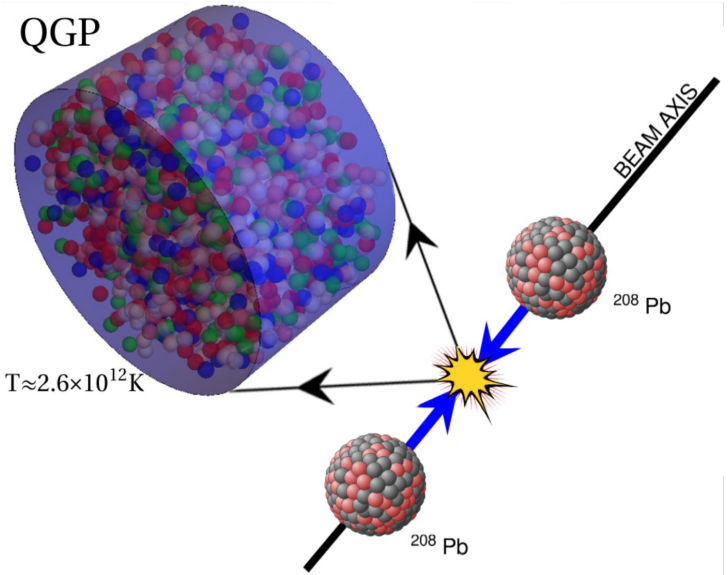
How to obtain a QGP's temperature?

1908.09728

Effective Temperature and Volume

$$E_f = \int_{f.o.} T^{0\mu} d\sigma_\mu = \epsilon(T_{eff}) V_{eff}$$

$$S_f = \int_{f.o.} s u^\mu d\sigma_\mu = s(T_{eff}) V_{eff}$$



$$\frac{E_f}{S_f} = \frac{\epsilon(T_{eff})}{s(T_{eff})}$$

T_{eff} : from the EoS

QGP as a uniform fluid at rest having the same energy and entropy at the end (freeze-out)

Hydro Simulations: Pb-Pb 5.02 TeV

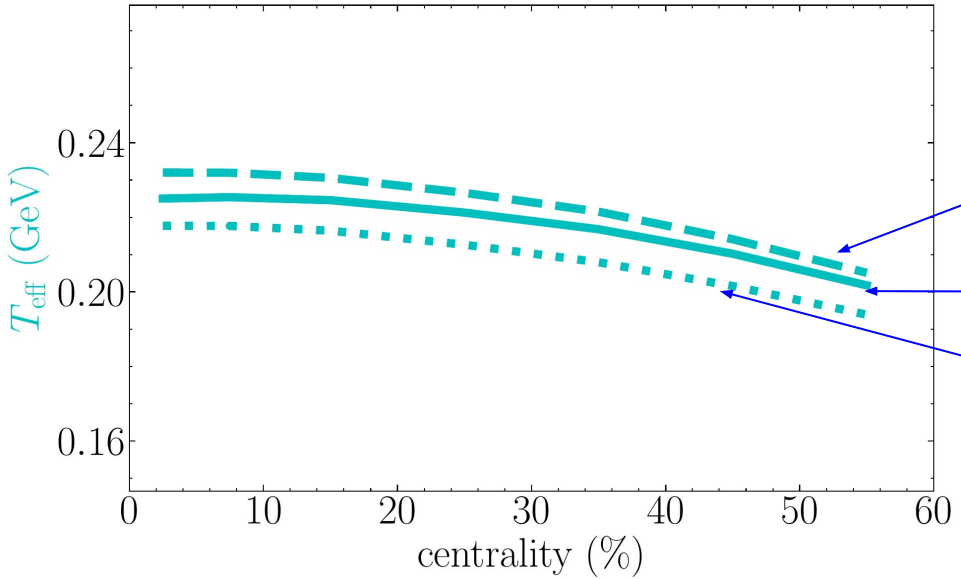
Part I

Initial Condition: **TRENTO**
Hydro Evolution: **MUSIC**
EoS: **Lattice QCD**

T_{eff}

hydro simulation!!

$T_{f.o} = 156.5\text{MeV}$ (Hot-QCD Collaboration: 1812.08235)



Shear viscous hydro

Ideal hydro

Bulk viscous hydro

Hydro Simulations: Pb-Pb 5.02 TeV

Part I

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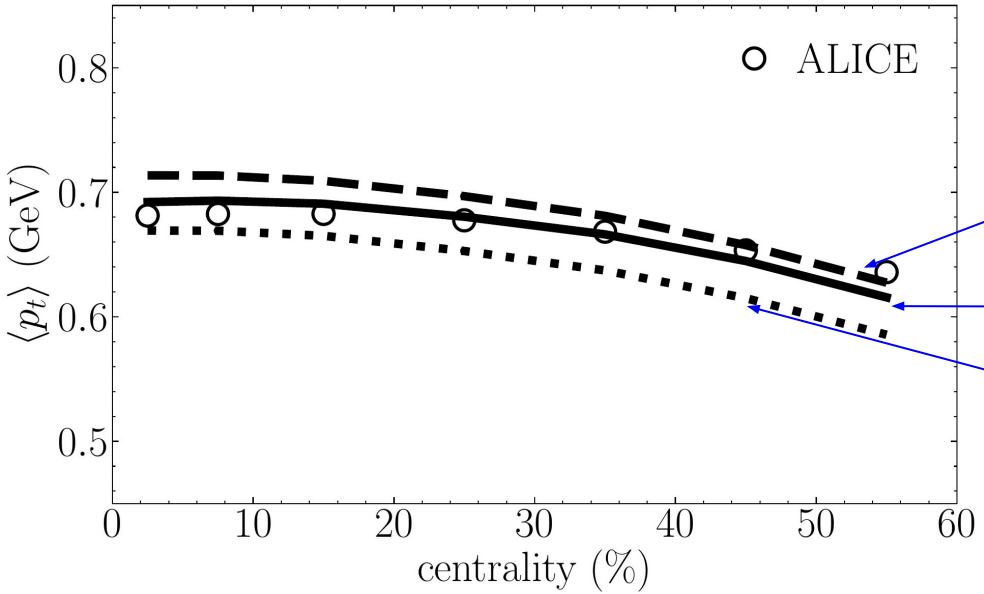
Hydro Evolution: **MUSIC**
EoS: **Lattice QCD**

$\langle p_t \rangle$



Shear viscous hydro

Ideal hydro

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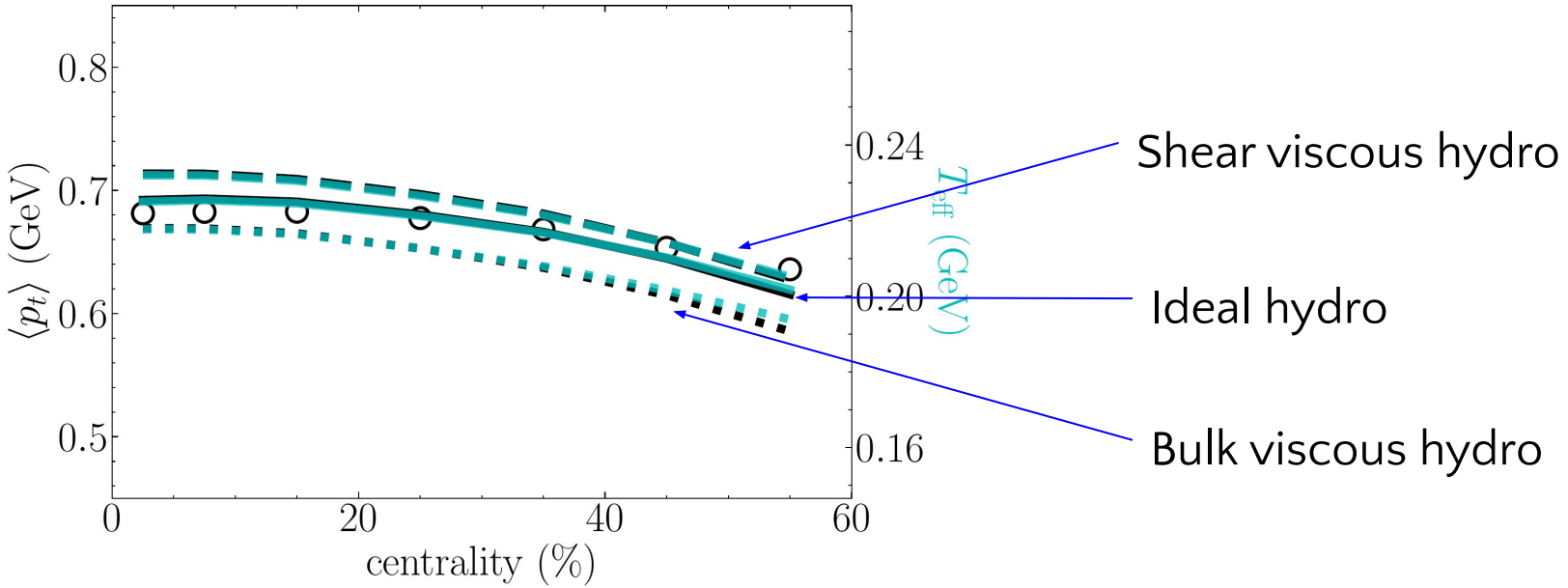
Hydro Simulations: Pb-Pb 5.02 TeV

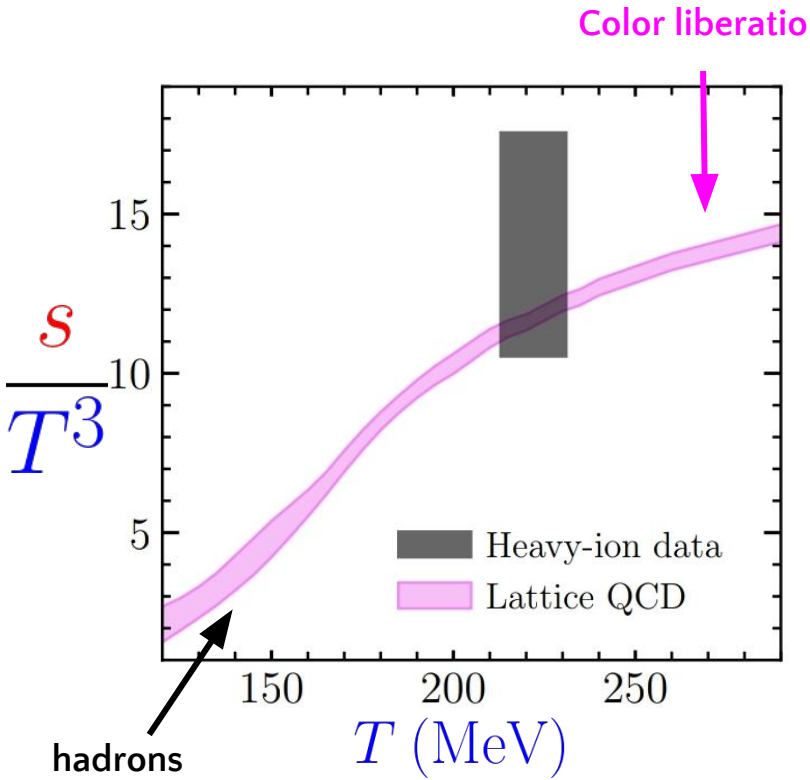
Part I

$$\langle p_t \rangle = 3.07 T_{eff}$$

Independent of hydro modeling (IC, transport coefficients, EoS)

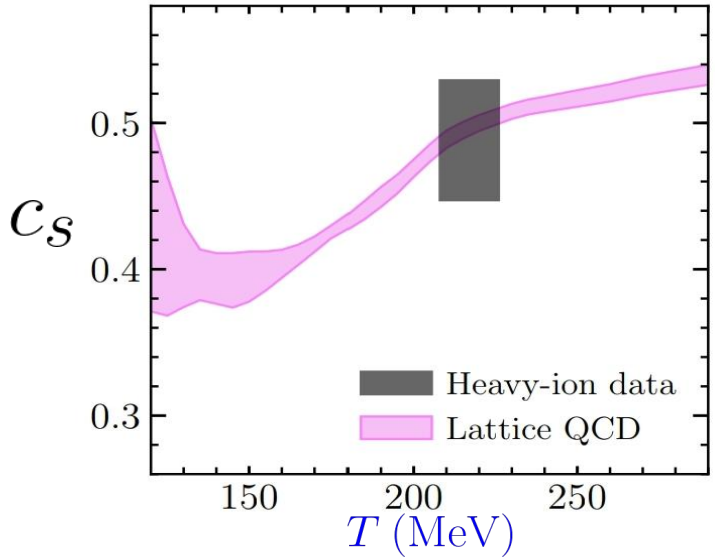


Accessing the Equation of State



- Agree with Lattice QCD
- QGP is created in these experiments
- Large number of degrees of freedom
- **Deconfinement Observed**

Lattice QCD: Borsanyi et. al, 1309.5258

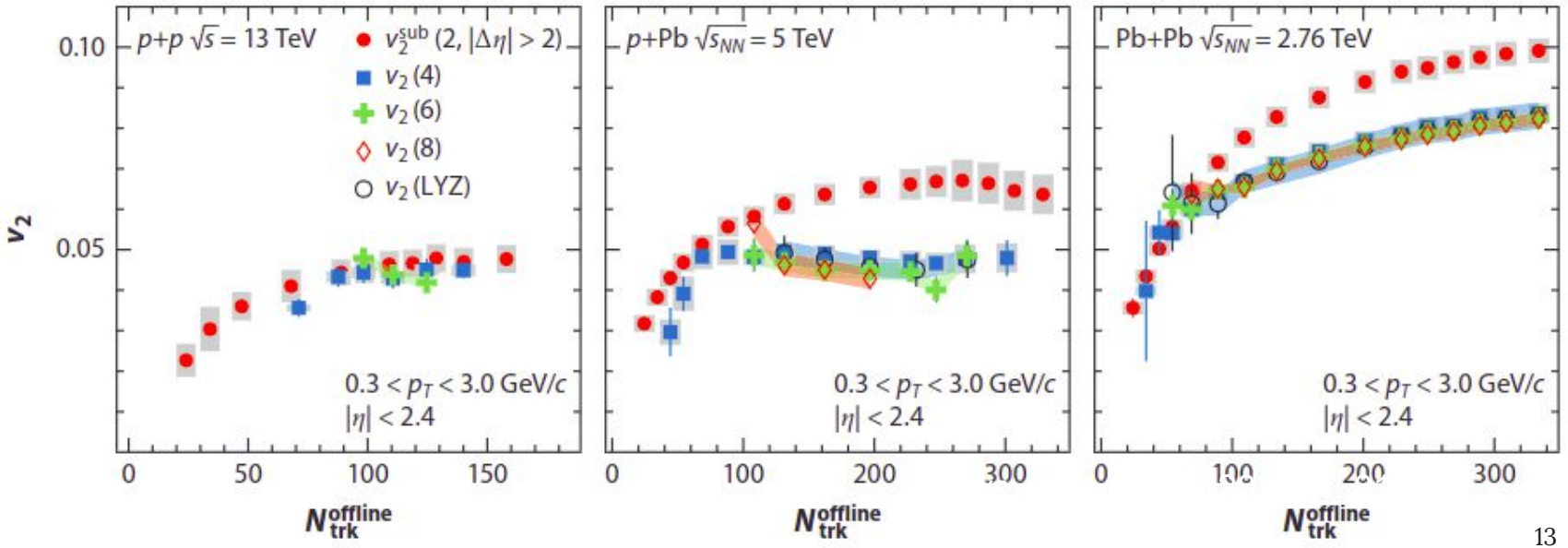


Is QGP formed in small systems?

arxiv 2212.11710

Small System Experiment

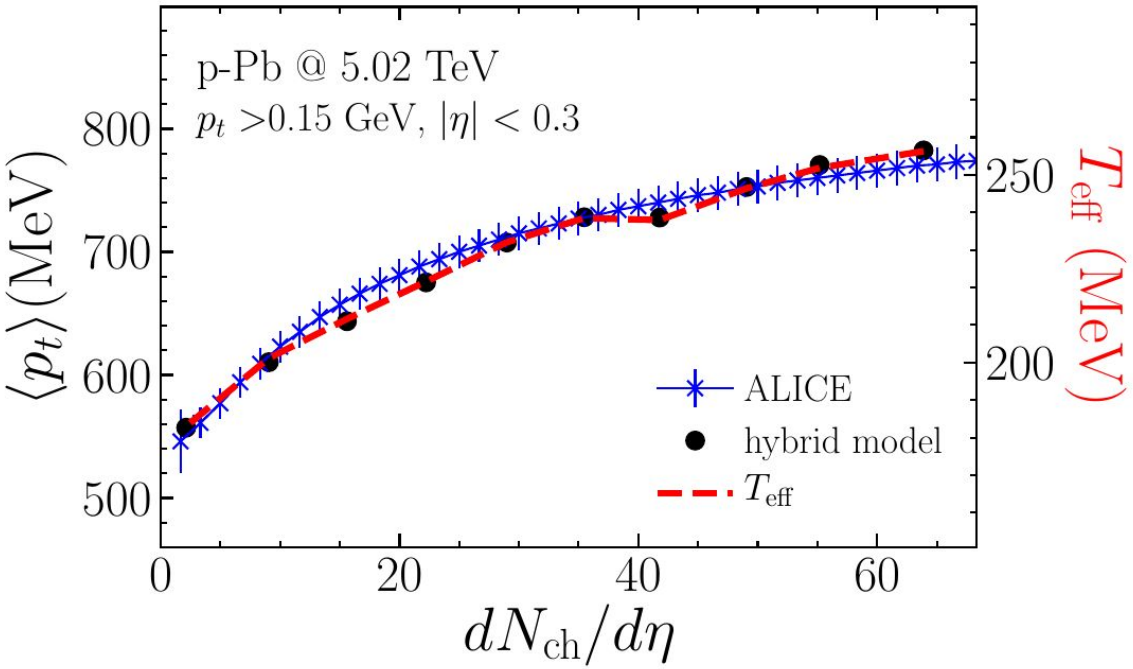
- Collectivity evidence for small system – p+Pb.
- Do these correlations have hydrodynamical origin?

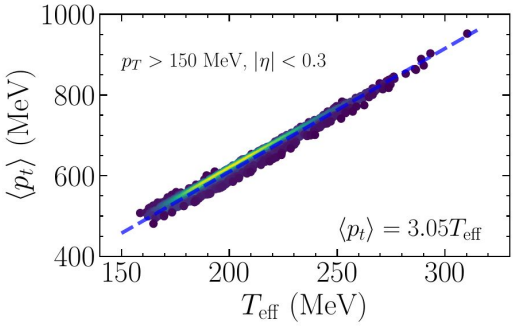


What is the temperature of the p-Pb? Part II

First time: Hybrid simulation p-Pb @ 5.02 TeV

Duke's Bayesian Analysis: arXiv:1808.02106





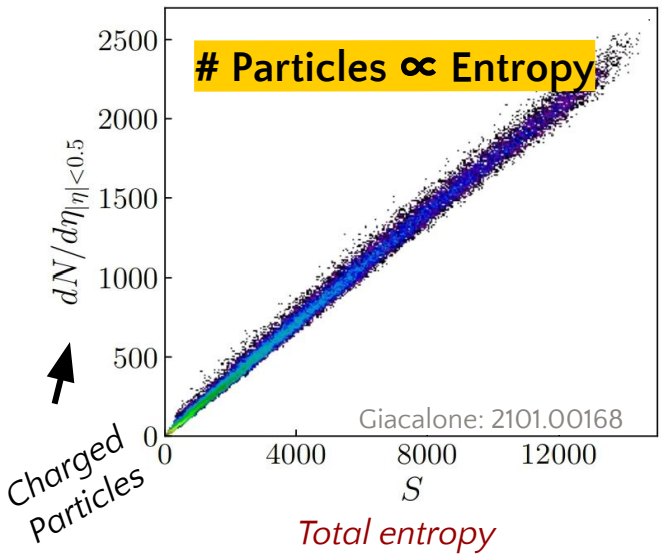
$$\langle p_t \rangle \approx 3.05 T_{\rm eff}$$

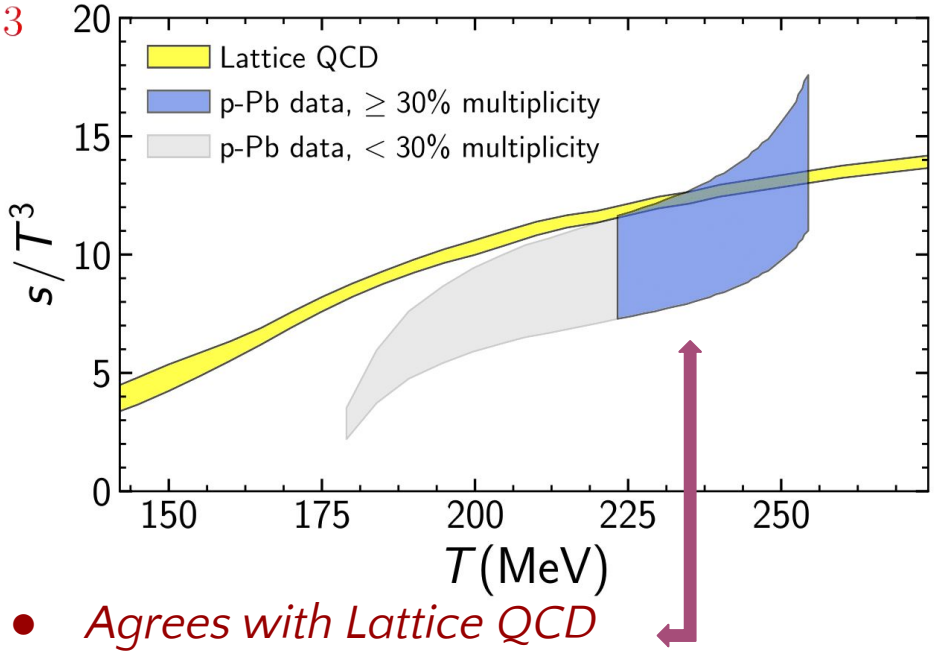
ASSUMING p-Pb behaves like a QGP fluid

Extracting thermodynamics from data Part II

p-Pb 5.02 TeV

$$\frac{s(T_{\rm eff})}{T_{\rm eff}^3} = \frac{\frac{1}{V_{\rm eff}}\frac{S}{N_{ch}}\frac{dN}{dy}}{\left(\frac{\langle p_T\rangle}{3.05}\right)^3}$$

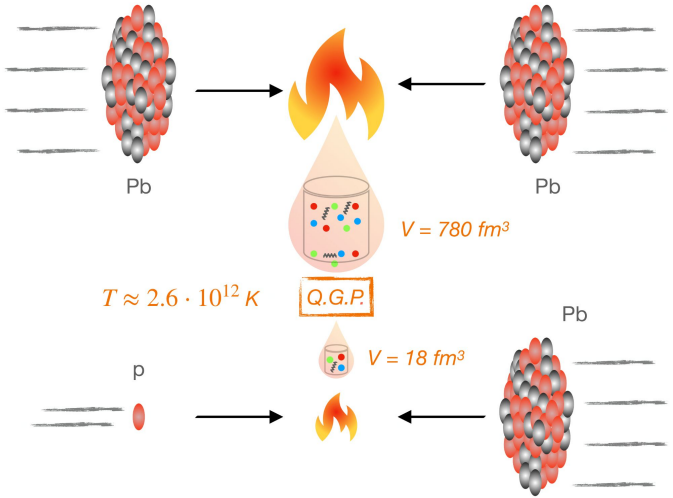




- *Agrees with Lattice QCD*
- *QGP is formed for high-multiplicity, >30%*
- *Smallest drop of QGP*

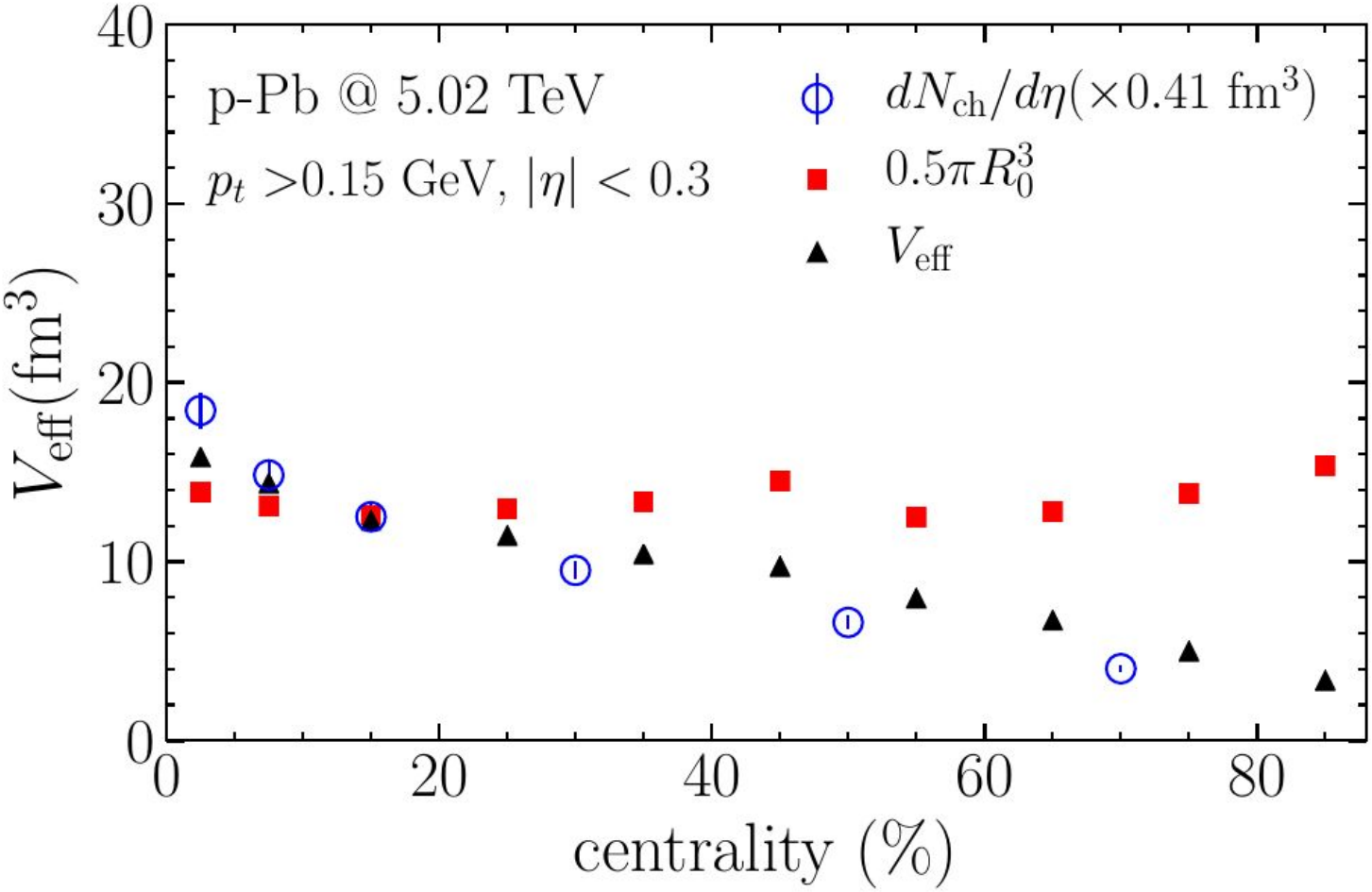
Summary

- *First time* thermodynamics is obtained in hybrid, event-by-event simulation.
- *First time* thermodynamics is studied for small systems, p-Pb.
- In a fluid system, T_{eff} is proportional to the mean momentum. $\langle p_t \rangle \approx 3.05 T_{\mathrm{eff}}$
- The thermodynamics inferred from data are consistent with Lattice QCD for small-system collisions with a high multiplicity.



Thank you for your attention.

Backup Slide


p-Pb @ 5.02 TeV
p_t >0.15 GeV, $|\eta| < 0.3$
$dN_{\rm ch}/d\eta(\times 0.41\ {\rm fm}^3)$
$0.5\pi R_0^3$
$V_{\rm eff}$
$V_{\rm eff}({\rm fm}^3)$
centrality (%)
0
10
20
30
40
0
20
40
60
80