Perspectives on Nuclear Physics Input into High-Energy Cosmic Ray Interactions

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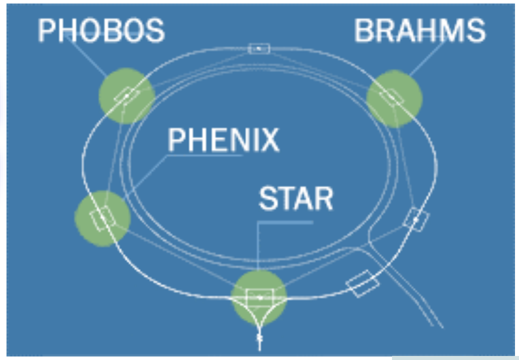
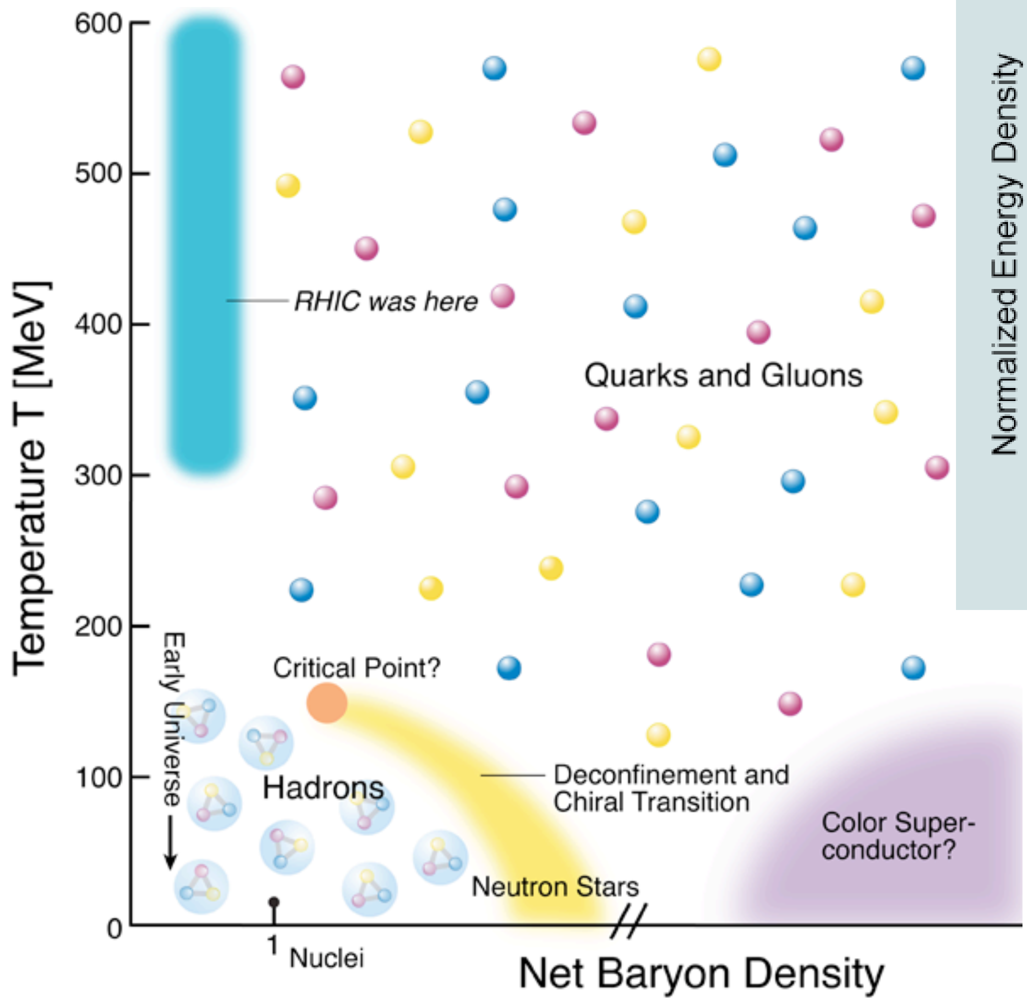
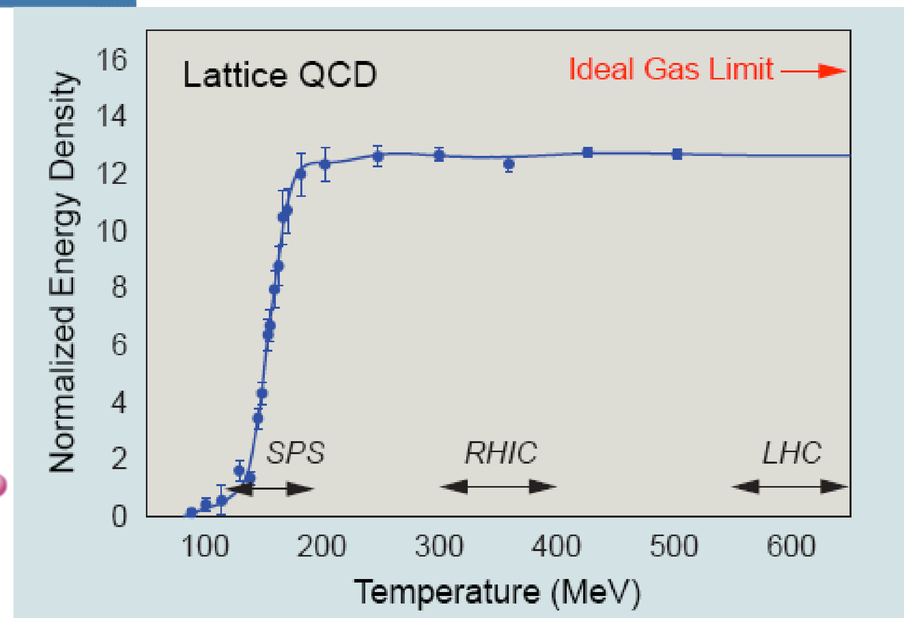
Disclaimer: My expertise in nuclear collisions is mostly at low energies; my expertise in high energies is mostly with neutrinos. So this is essentially an outsider's perspective!

RHIC

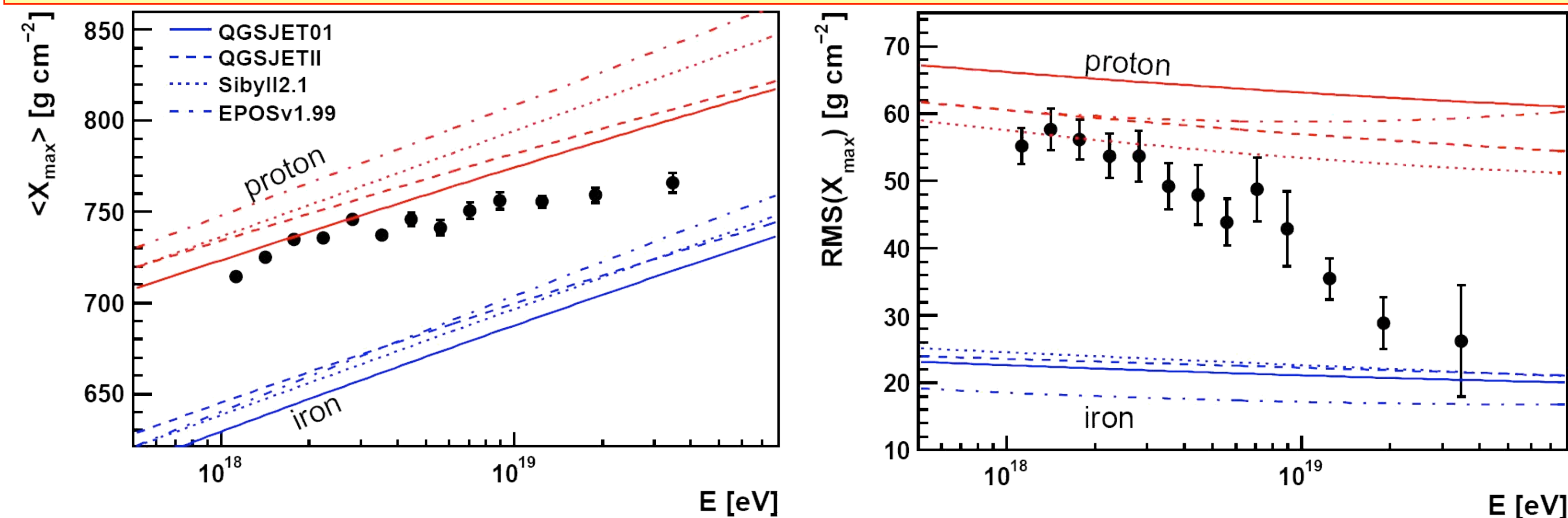




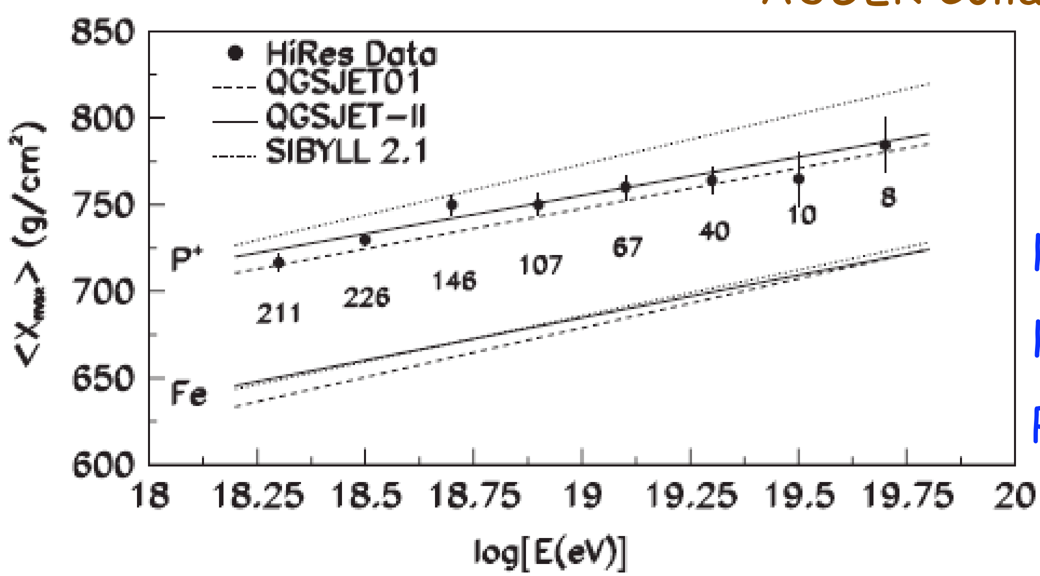


Why are laboratory nuclear experiments relevant to the cosmic-ray physics?

Recent results suggest presence of a significant nuclear component in the higher-energy cosmic-ray flux from the measurements of the depth of the shower maximum



AUGER Collaboration, PRL **104**, 091101 (2010)

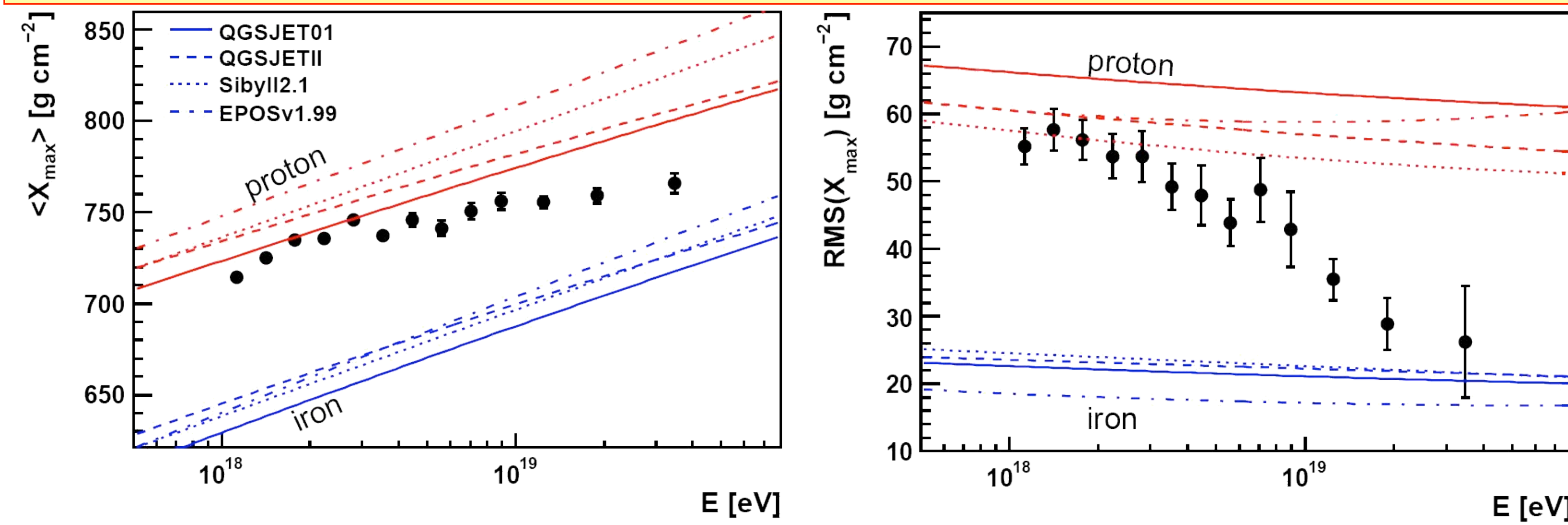


However, see

HIRES Collaboration,

PRL **104**, 161101 (2010)

Recent results suggest presence of a significant nuclear component in the higher-energy cosmic-ray flux from the measurements of the depth of the shower maximum



AUGER Collaboration, PRL **104**, 091101 (2010)

CAUTION: Heitler's original formula:

$$\langle X_{max} \rangle = \alpha\,(\ln E - \langle \ln A \rangle) + \beta$$

assumes that heavier nuclei are basically superposition of the nucleons

(see however Ulrich et al., arXiv:0906.0418)

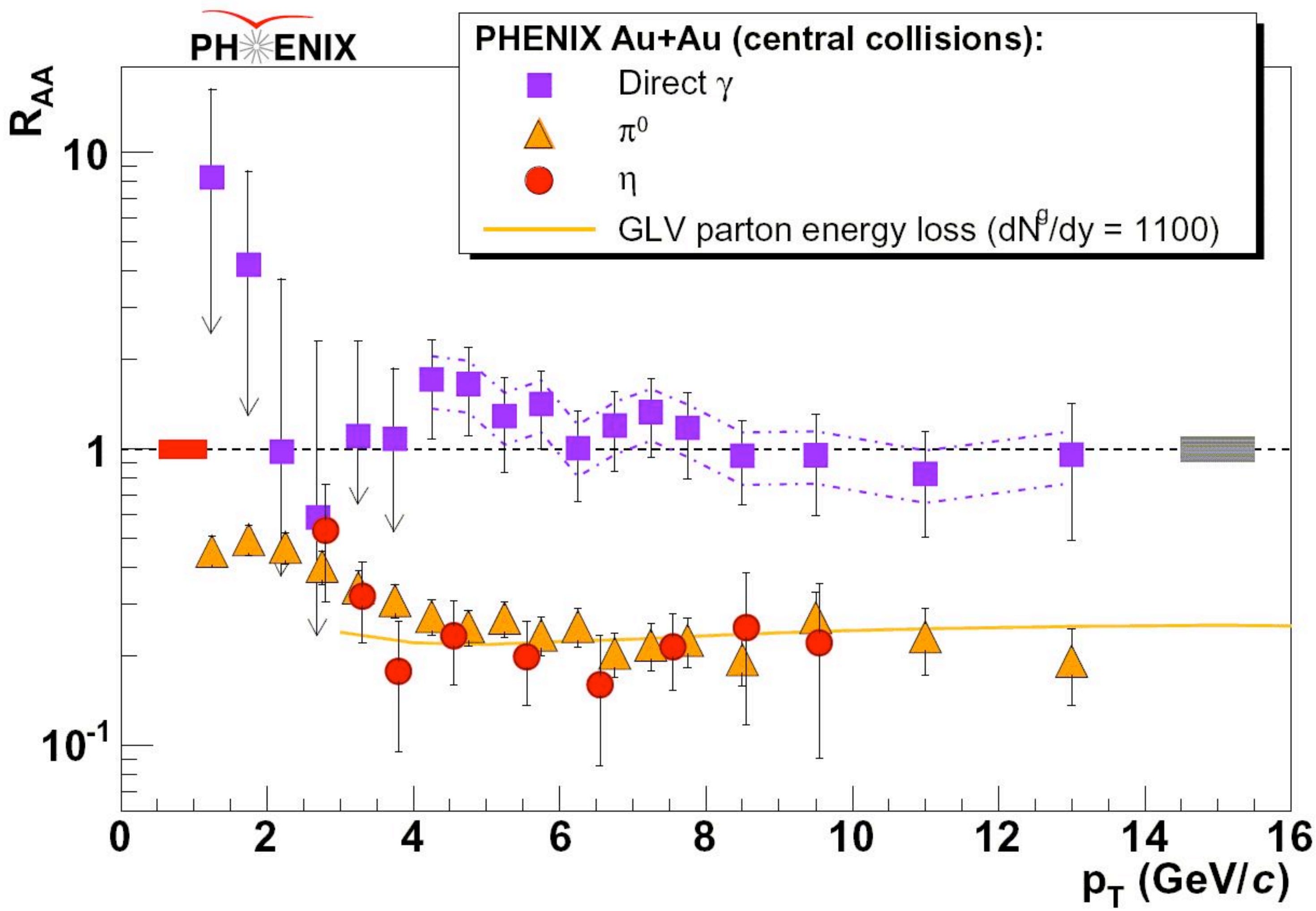
Are nuclear collisions simply a superposition of nucleon collisions?

$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{\mathrm{coll}}\,(dN_{pp}/dp_T)}$$

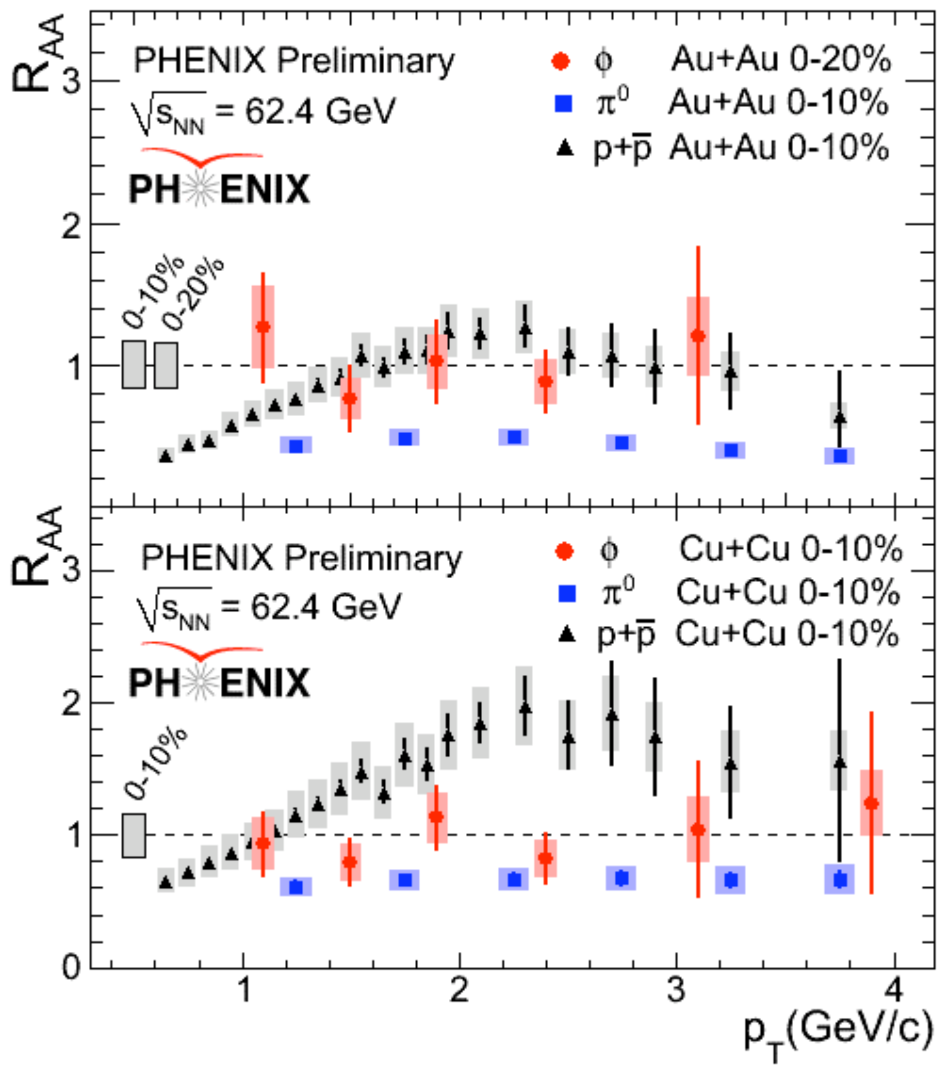
N_{coll} = number of binary collisions

Absence of nuclear medium interactions (i.e. γ's) $\Rightarrow R_{AA} \approx 1$

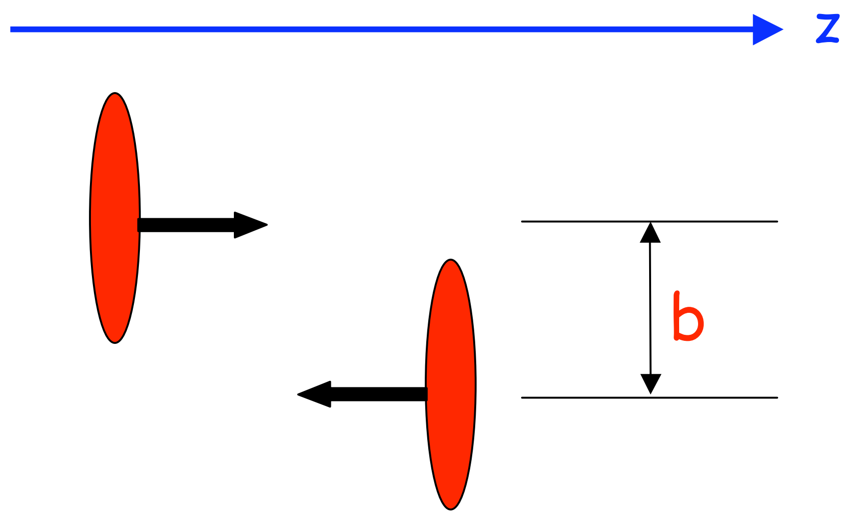
Energy loss in the medium $\Rightarrow$ reduction of p_T



PRL 96, 202301 (2006)



QCD jets are quenched by the nuclear medium. Nuclear collisions are NOT simply a superposition of pp collisions!

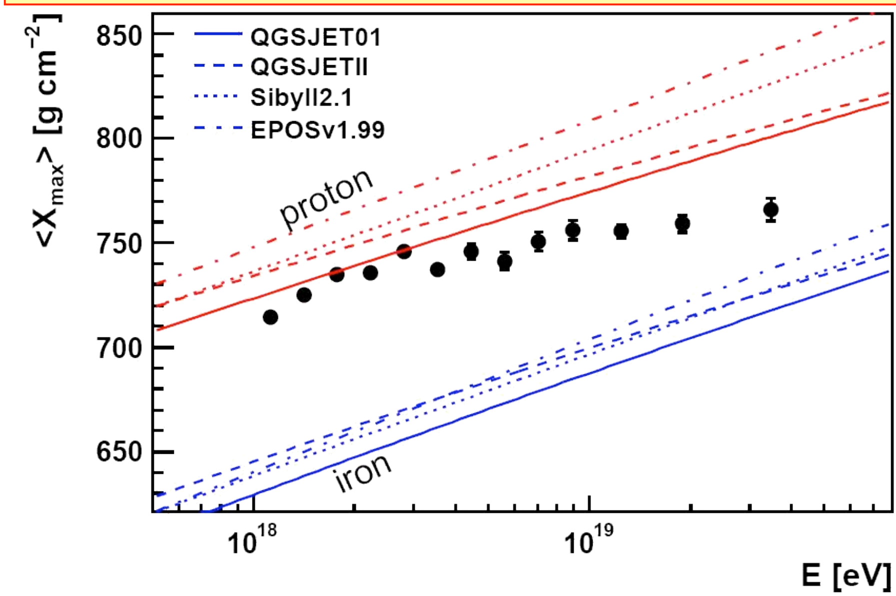


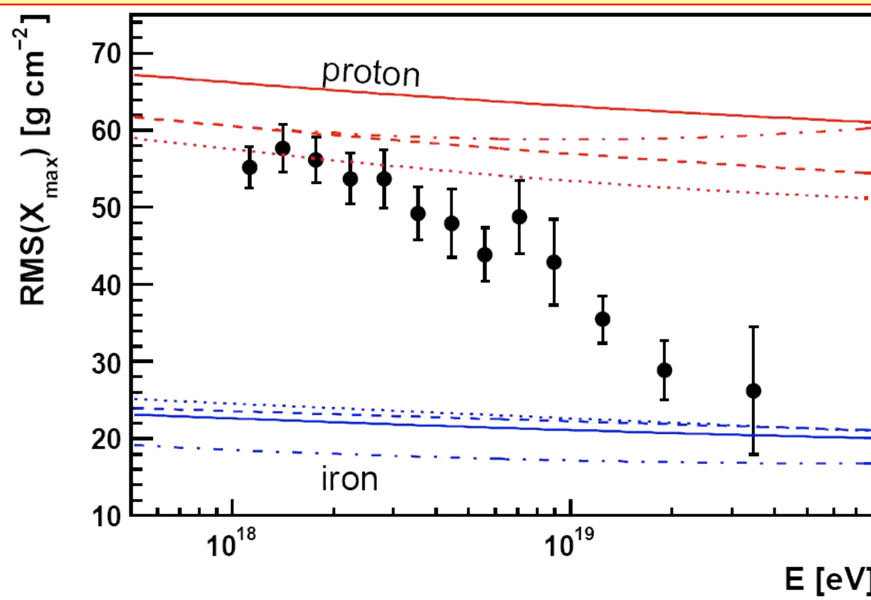
Glauber formula

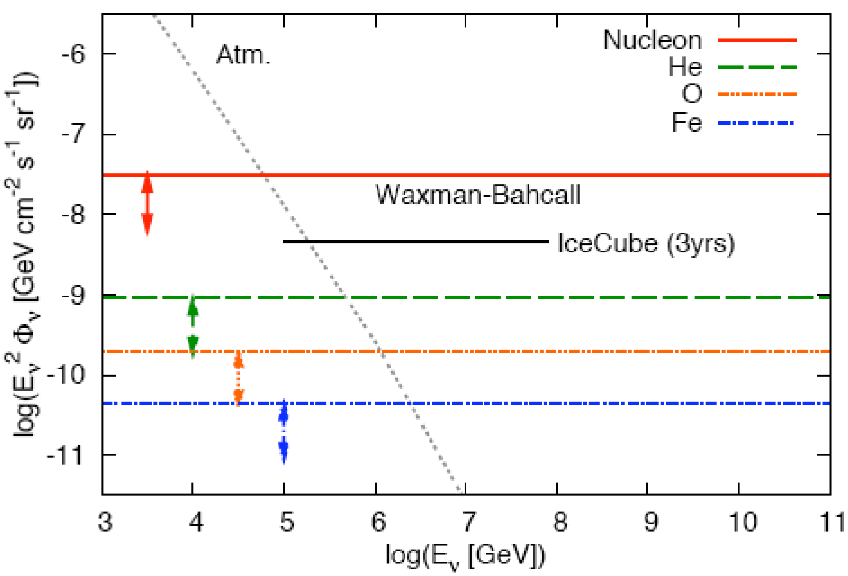
$$\sigma_{AA} = \int d^2b \left(1 - \exp\left[-\sigma_{pA} \int \rho_A(b) dz\right]\right)$$

Glauber formula and its extensions represent multiple scatterings in the target, but do not take into account the emergent properties of the quark-gluon system for which there are strong experimental hints.

Recent results suggest presence of a significant nuclear component in the higher-energy cosmic-ray flux from the measurements of the depth of the shower maximum







If there are sources of ultra-high energy cosmic-ray nuclei, these sources should also produce neutrinos!

Murase & Beacom,
PRD **81**, 123001 (2010).

What have we recently learned from relativistic heavy-ion experiments?

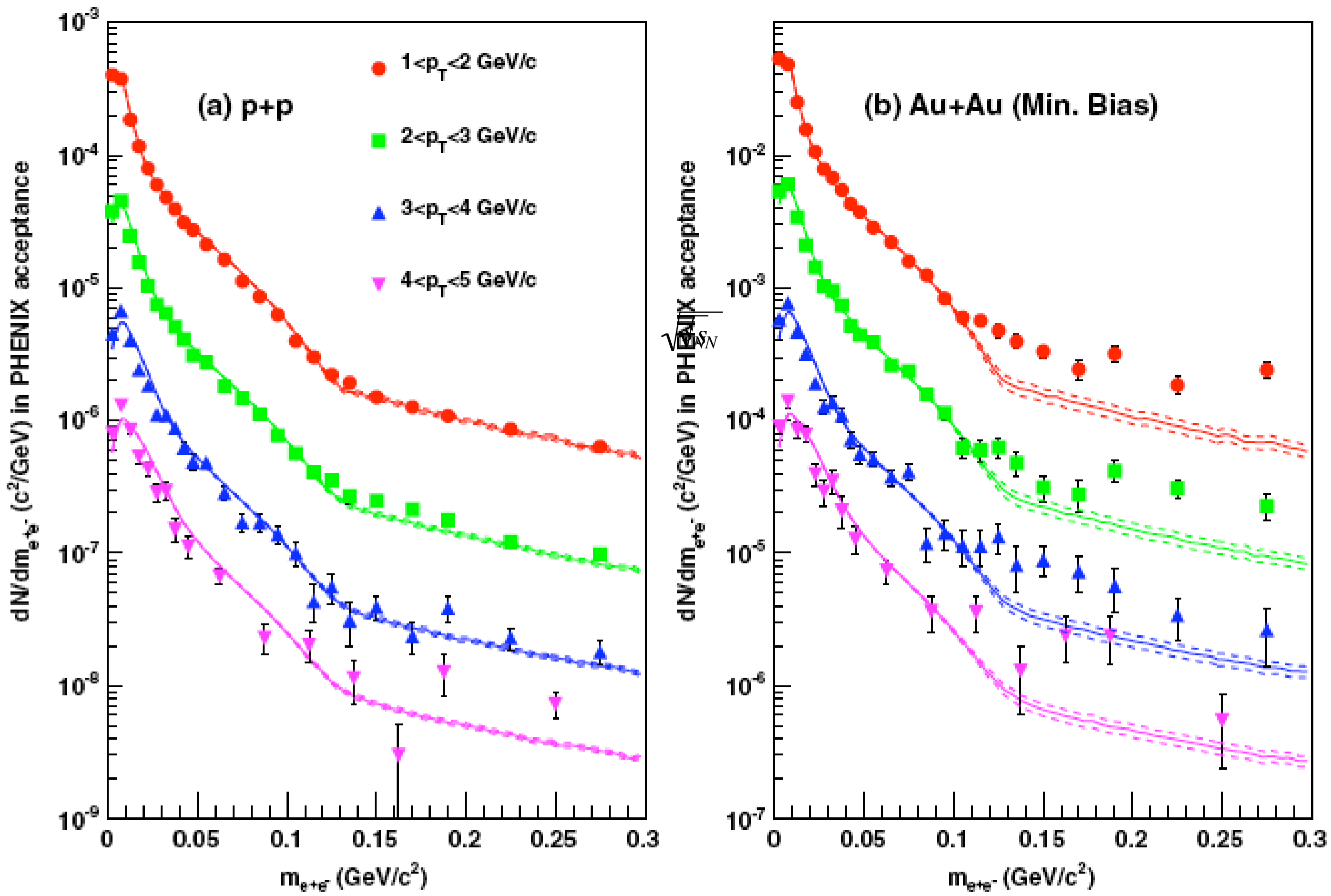
❶ An effective "temperature" in 200 GeV Au-Au collisions has been measured. Result is not exactly what we expected.

❷ Negative Binomial Distributions continue to fit the data well.

❸ There are strong experimental indications that the quark-gluon system formed in relativistic heavy-ion collisions is not a gas, but *almost* a perfect liquid.

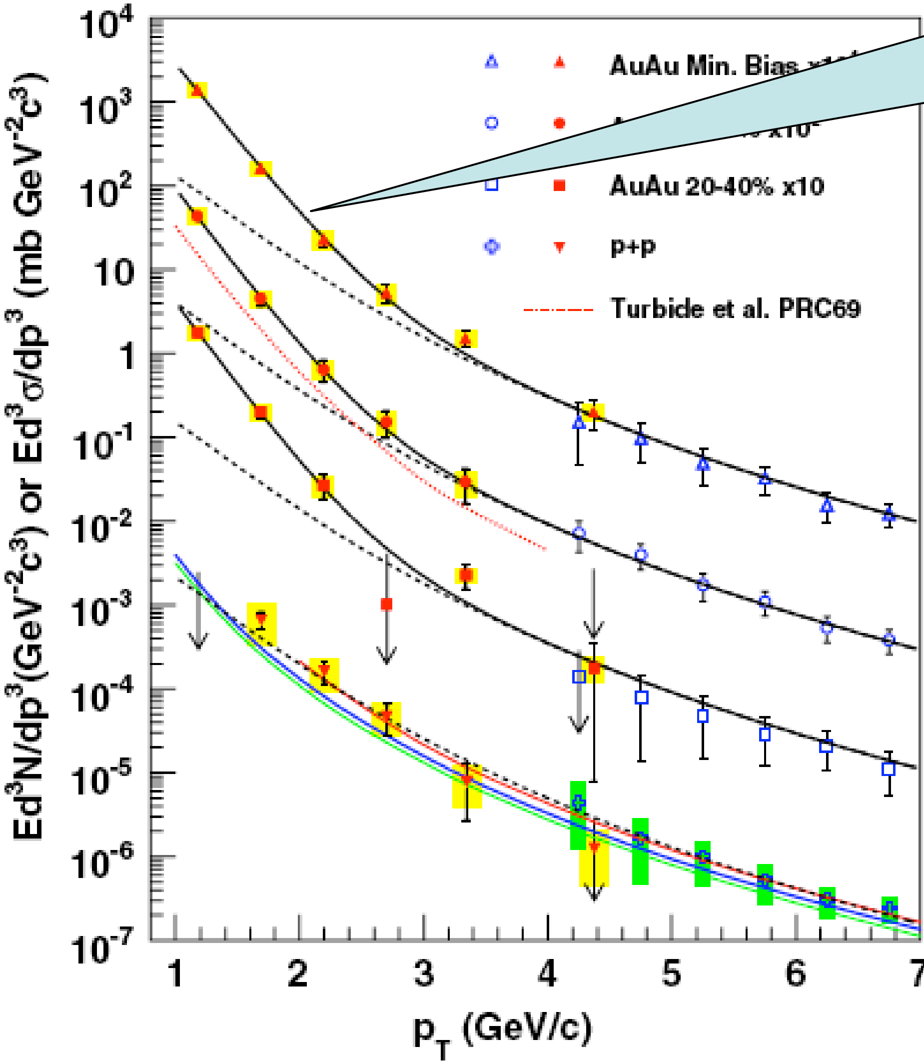
❶ Measuring the "temperature" at $\sqrt{s_{NN}}$ ~ 200 GeV Au-Au collisions

First measure opposite-charge lepton pairs



PRL **104**, 132301 (2010)

…then convert to real photons by going to zero invariant mass



T_{eff} =221±19±19 MeV (effective because γ's are emitted as the temperature evolves)

+

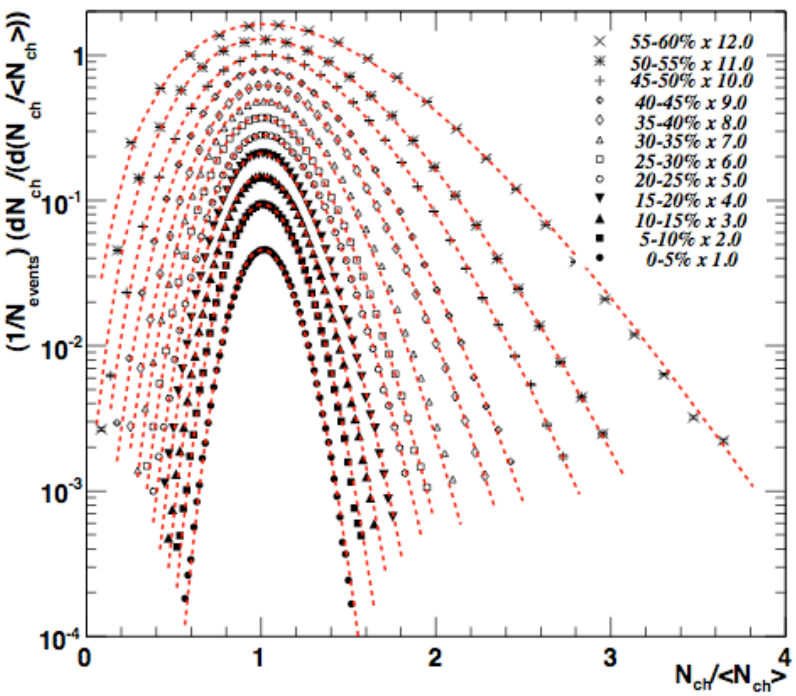
theoretical input

300 MeV < $T_{initial}$ < 600 MeV

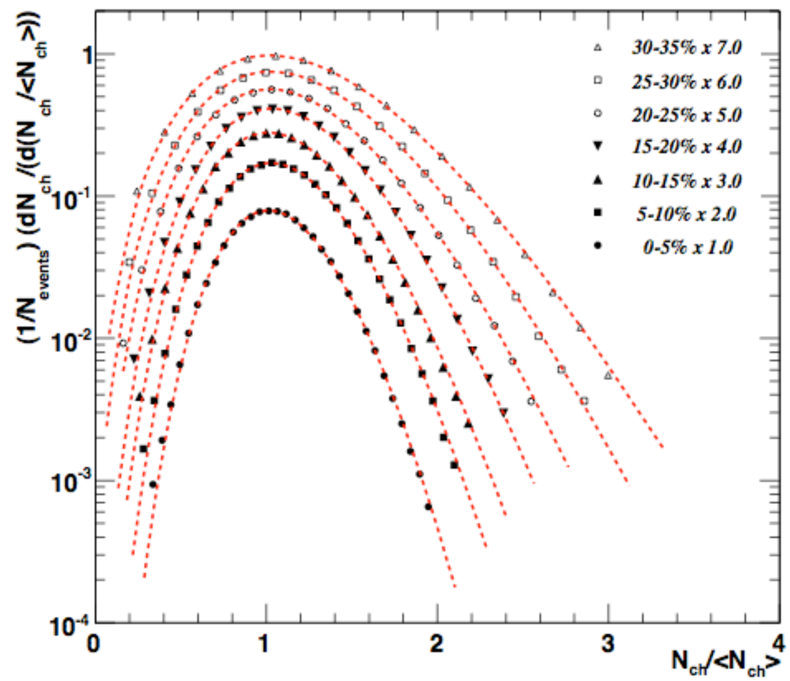
as opposed to the QCD prediction of ~ 170 MeV !

❷

Negative Binomial Distribution continues to fit multiplicity fluctuations well



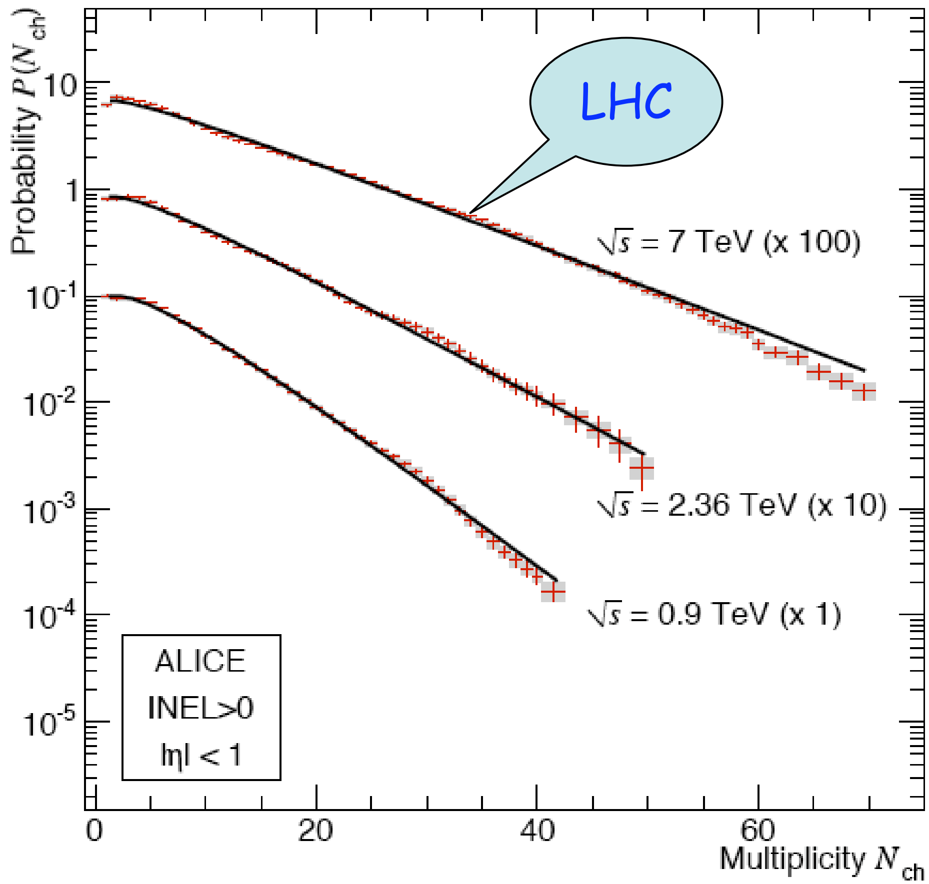
200 GeV Au+Au

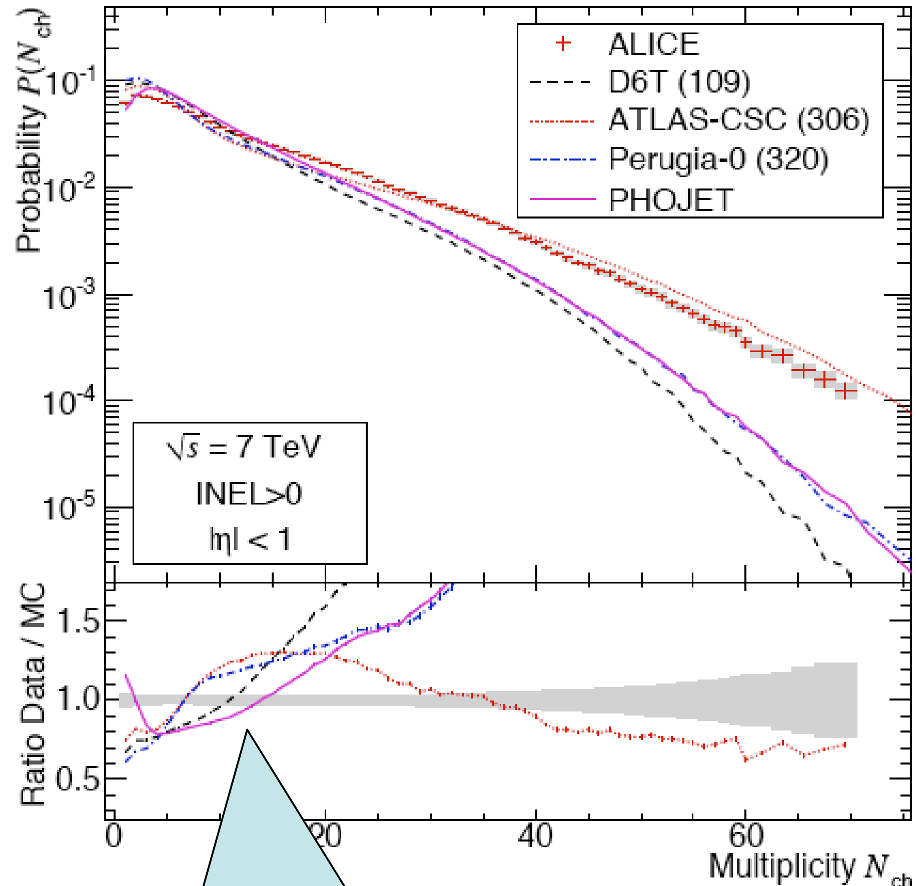


200 GeV Cu+Cu

PHENIX Collaboration, PRC 78, 044902 (2008)

Negative Binomial Distribution continues to fit multiplicity fluctuations well





ALICE Collaboration,
arXiv:1004.3514

The charged-particle density is higher than theoretical expectations!

Negative Binomial Distribution

Basic assumption: Probability of emitting n particles by the ith source is b_i^n.

$$\Rightarrow F(\lambda) = \sum_{n=0}^{\infty} P_n \lambda^n = \prod_{i}^{k_{NBD}} \frac{1-b_i}{1-\lambda b_i}$$

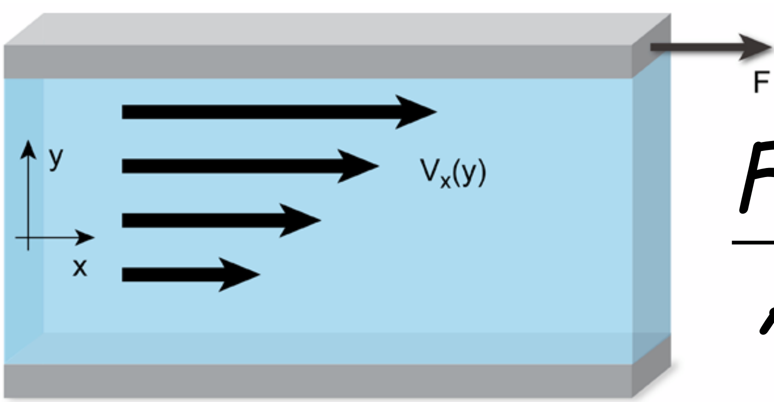
All b_i's are the same $\Rightarrow$ Negative Binomial Distribution:

$$\sum_{n=0}^{\infty} P_n \lambda^n = \left(\frac{1-b}{1-\lambda b}\right)^{k_{NBD}}$$

Note: In fits k_{NBD} is not constrained to be an integer.

Note: P_n is the complete symmetric function of degree n in the arguments b_i. The ubiquity of negative binomial distribution is likely to be statistical.

❸ What is a perfect fluid?



$$\frac{F_x}{A} = \eta \frac{\partial v_x}{\partial y}$$

"good" fluid ⇒
low viscosity, η

Is there a lower bound on shear viscosity, η? - Heuristic argument

$$F_x = \eta A \frac{\partial v_x}{\partial y}$$

For a dilute (weakly-interacting) gas of quasi-particles:

$$\eta = \frac{1}{3} n \langle p \rangle L_{\mathrm{mean}},$$

n: density, $\langle p \rangle$: ave. momentum, $L_{\mathrm{mean}} = 1/n\sigma$: mean free path
Uncertainty principle:

$$\langle p \rangle L_{\mathrm{mean}} \geq \hbar \quad \Rightarrow \quad \frac{\eta}{n} \geq \hbar$$

Danielewicz & Gyulassy, 1985

Relativistic fluids

For relativistic fluids it is more appropriate to normalize the viscosity to the entropy density

Entropy: $S \propto k_B N$; Entropy density: $s = \frac{S}{V} \propto k_B n$

Is there a lower limit to $\frac{\eta}{s} k_B$?

Kovtun, Son, Starinets, 2005

AdS/CFT duality

Large N conformal field theory in 4D	$\Longleftrightarrow$	String theory on 5D Anti deSitter space $\times S_5$
Thermal CFT	$\Longleftrightarrow$	AdS_5 *Black Hole*
CFT entropy	$\Longleftrightarrow$	Hawking entropy of the black hole
Shear viscosity	$\Longleftrightarrow$	$\sigma_{graviton\ absorption}$

Then one can calculate the viscosity in the strong coupling limit:

$$\frac{\eta}{s} = \frac{1}{4\pi}\frac{\hbar}{k_B}$$

Policastro, Son, Starinets, 2001

Hydrodynamic behavior of the quark-gluon system

Hydrodynamic evolution:

Initial state pressure gradient $\Rightarrow$ Final state velocity gradient

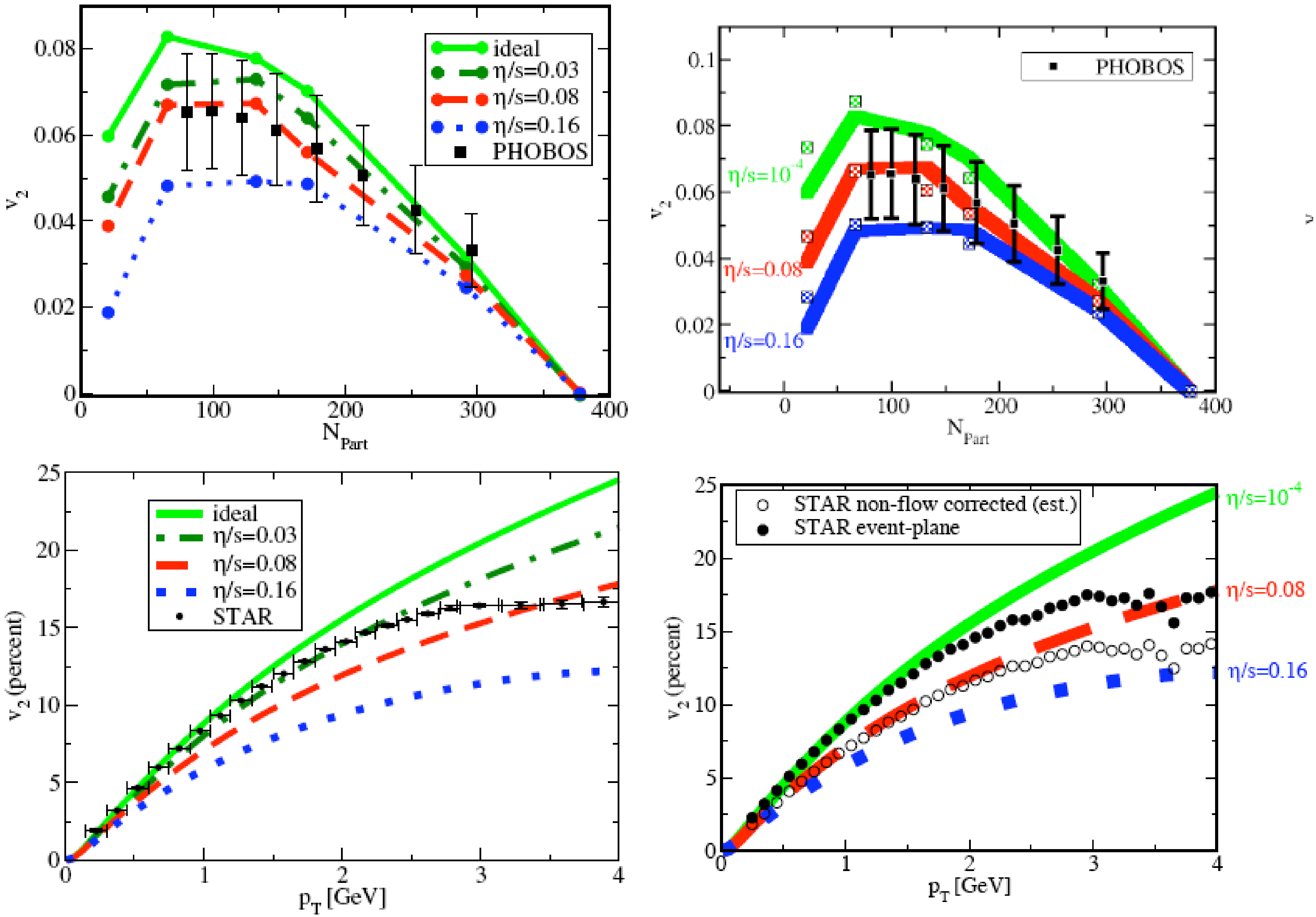
$$\frac{dN_i}{p_T dp_T dy d\phi_p}(b) = \frac{1}{2\pi}\frac{dN_i}{p_T dp_T dy}(b)\left(1 + 2\sum_i \nu_n^i \cos(n\phi_p)\right)$$

ϕ_p: azimuthal emission angle relative to the reaction plane

midrapidity, y=0 $\Rightarrow$ $\nu_{n=\mathrm{odd}} = 0$

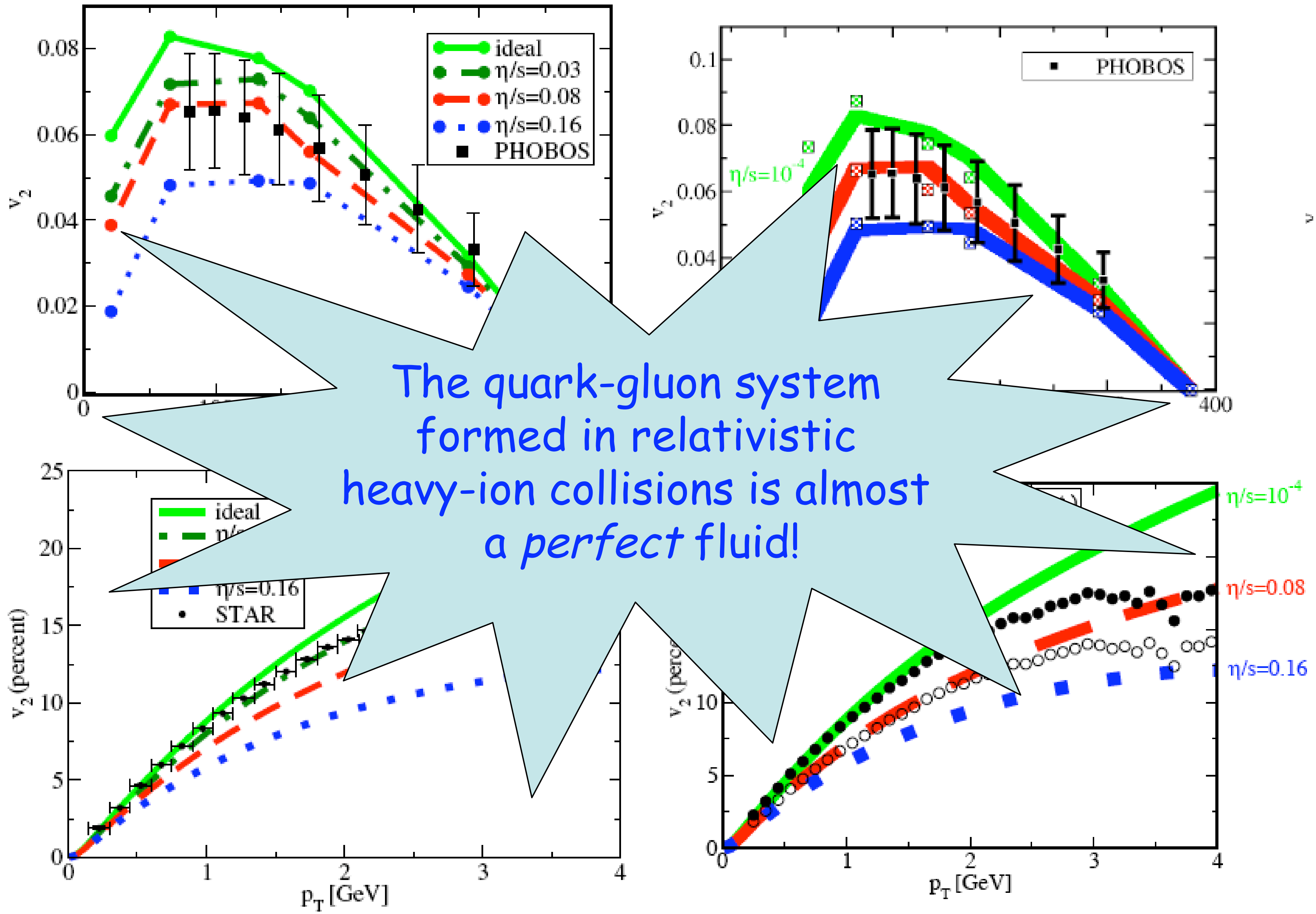
$\nu_2 > 0$ $\Rightarrow$ elliptic flow

The larger the shear velocity, η, is the more transverse expansion of the system slows down.



Romatschke & Romatschke, PRL **99**, 172301 (2207)

Heinz, arXiv:0901.4355



The quark-gluon system formed in relativistic heavy-ion collisions is almost a *perfect* fluid!

Romatschke & Romatschke, PRL **99**, 172301 (2207)

Heinz, arXiv:0901.4355

Concluding remarks

- At higher energies nuclei are not simply a "collection" of nucleons. Much interesting physics comes into play!
- Recent relativistic heavy-ion experiments found a broad spectrum of interesting phenomena, ranging from the observation of the quark-gluon system as a "perfect fluid" to measuring its temperature.
- Some of the recent cosmic ray experiments suggest an increase in the nuclear component of the cosmic-ray flux at higher energies. Insight gained from recent relativistic heavy-ion experiments could help to understand this nuclear component.