Probing hot QCD matter in ultrarelativistic heavy-ion collisions

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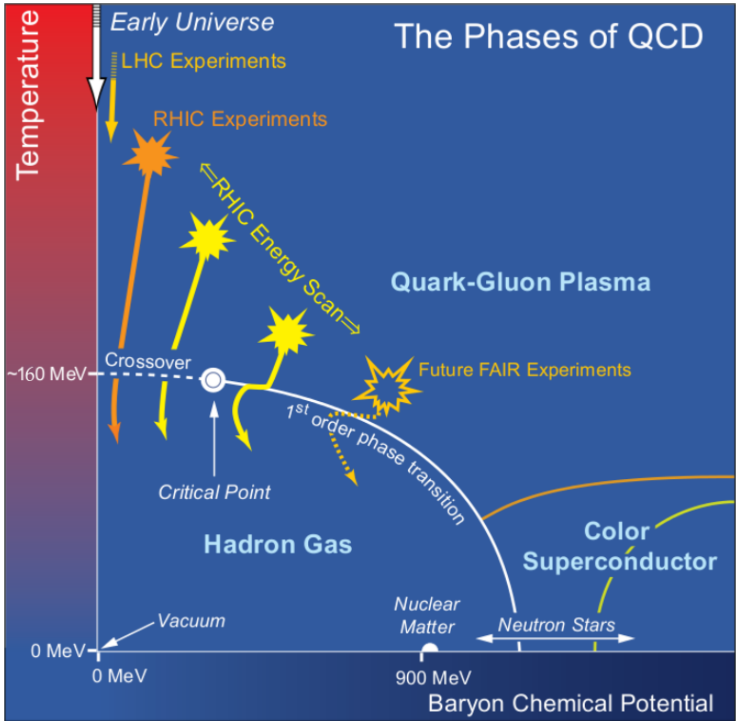
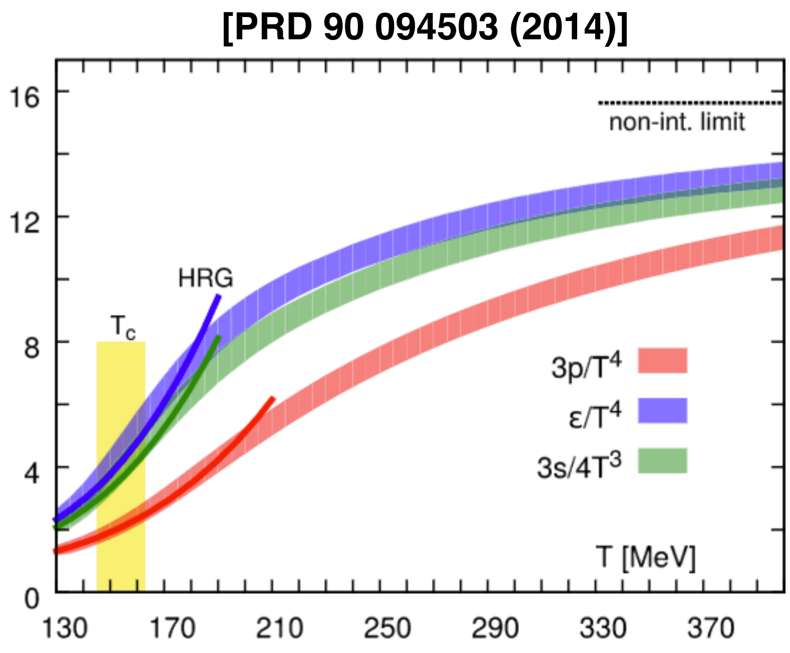
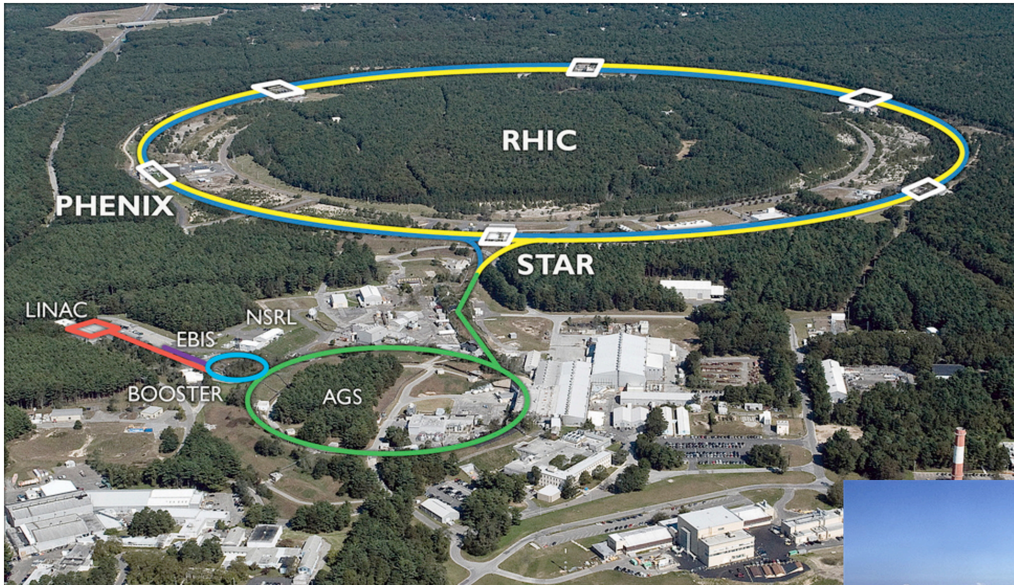
High-temperature regime of QCD

- At high temperatures and densities, quarks and gluons are no longer confined into hadrons but behave quasi-freely
  - Quark-Gluon Plasma (QGP)
- Lattice QCD indicates a crossover between phases, $T_c \sim 154 \pm 9$ MeV
- Expect a 1st order phase transition and critical point elsewhere





Heavy-ion colliders



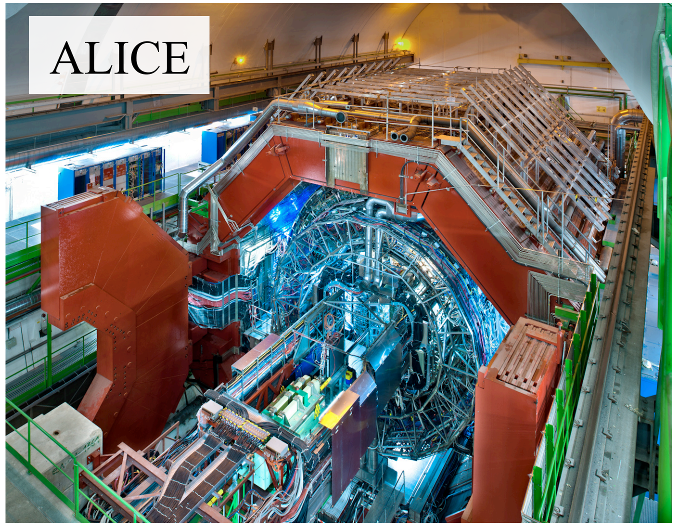
Relativistic Heavy Ion Collider

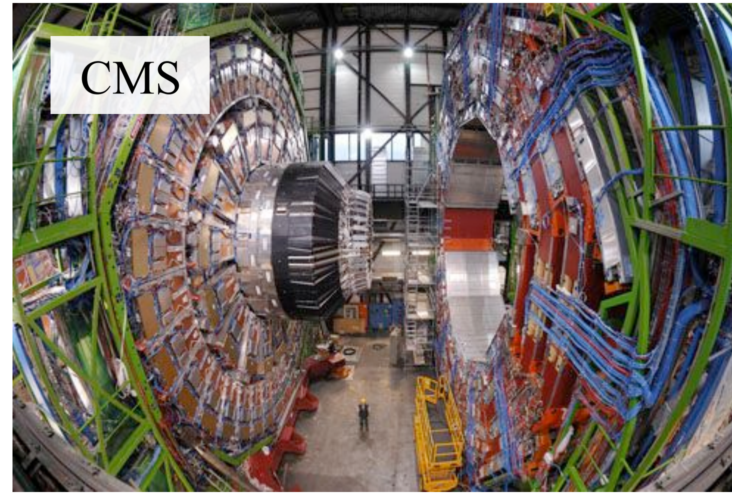
- 3.8 km circumference
- Au+Au collisions
  @ $\sqrt{s_{NN}}$ = 7.7 – 200 GeV
- also p+p, p+Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, U+U

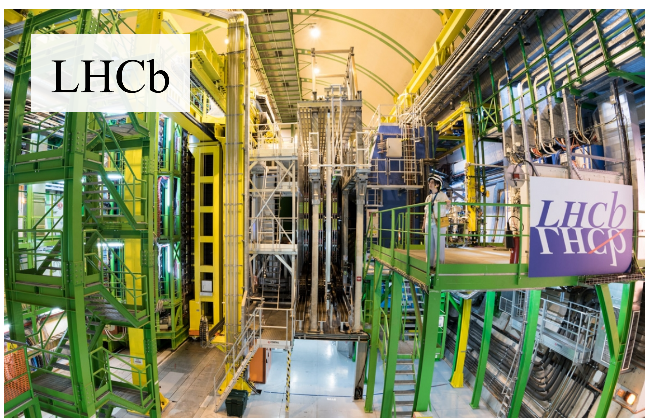
Large Hadron Collider

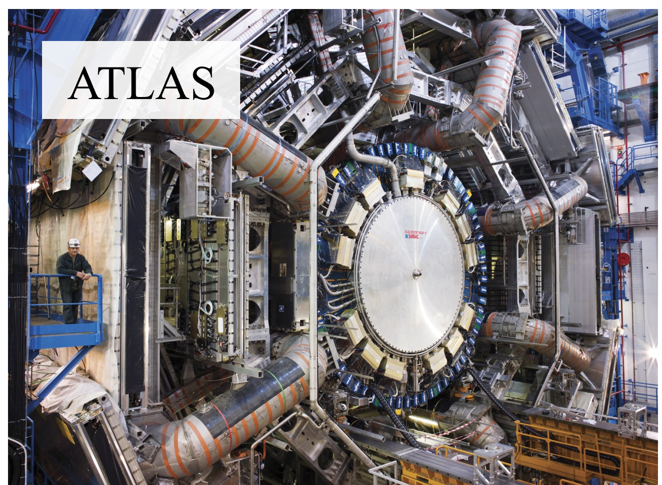
- 27 km circumference
- Pb+Pb collisions
  @ $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
- also p+p, p+Pb, Xe+Xe

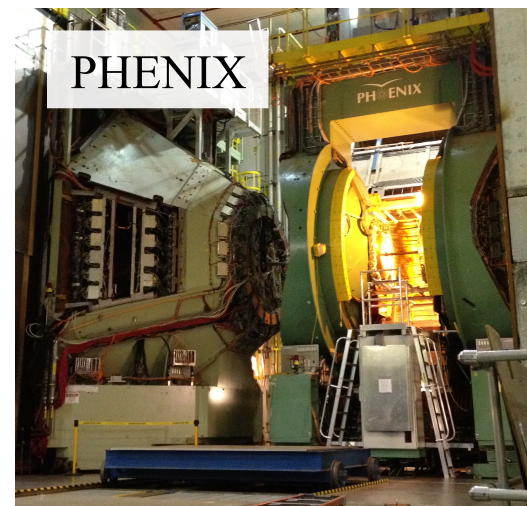
Heavy-ion experiments



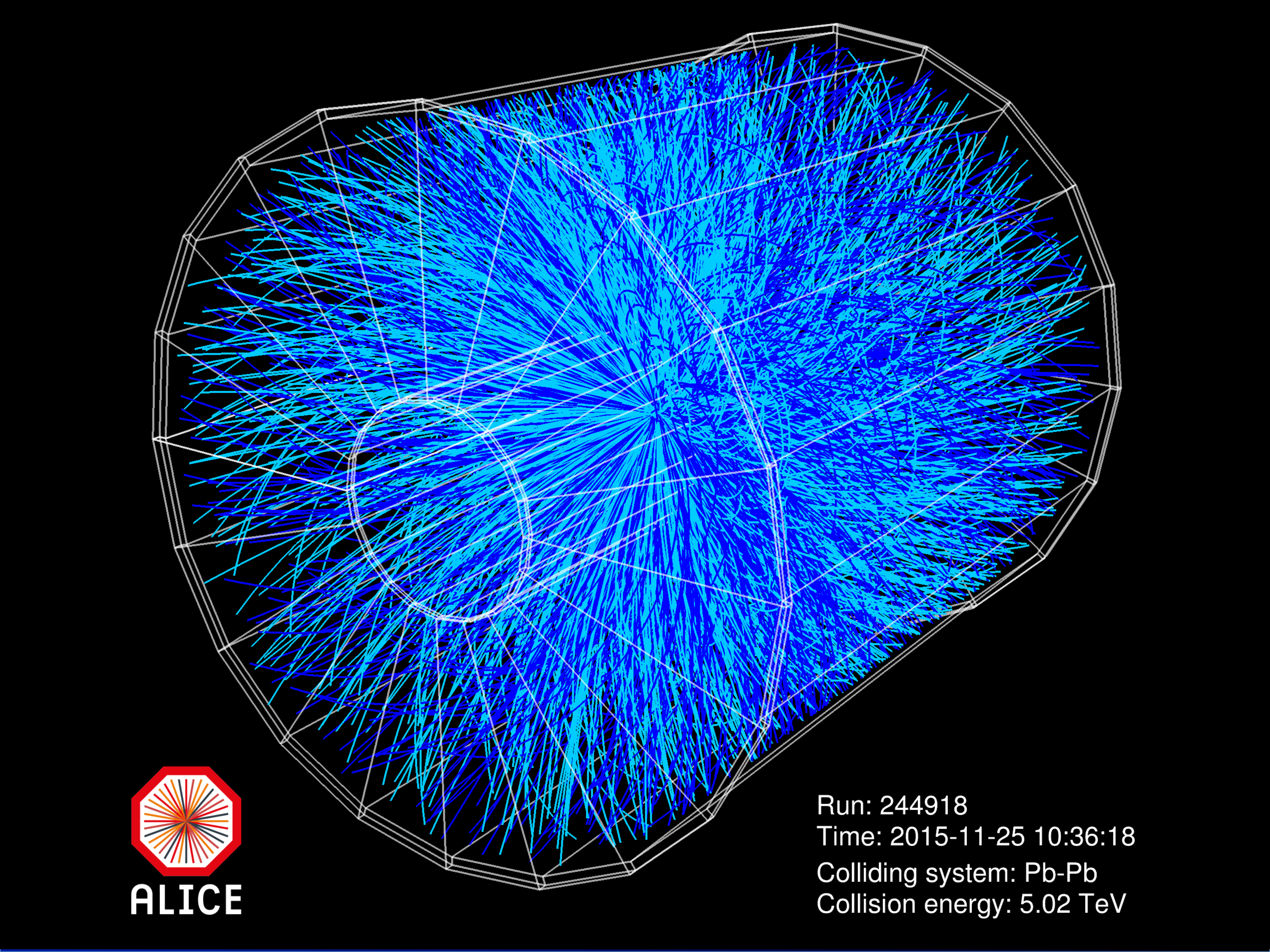








Not pictured: PHOBOS, BRAHMS, HADES, NA49, NA61/SHINE


ALICE
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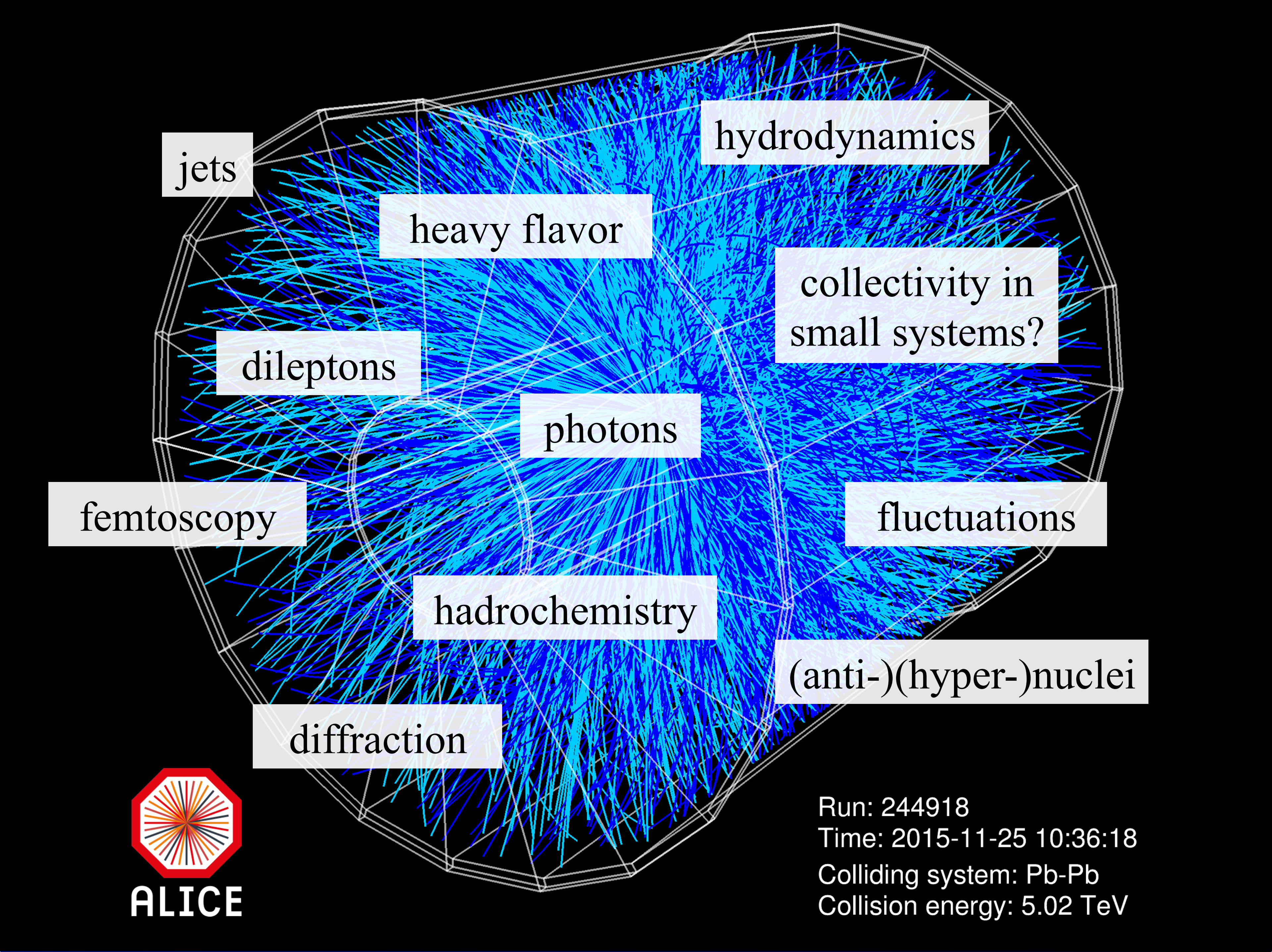
Time: 2015-11-25 10:36:18
Colliding system: Pb-Pb
Collision energy: 5.02 TeV


jets
heavy flavor
hydrodynamics
collectivity in small systems?
dileptons
photons
femtoscopy
fluctuations
hadrochemistry
(anti-)(hyper-)nuclei
diffraction
ALICE
Run: 244918
Time: 2015-11-25 10:36:18
Colliding system: Pb-Pb
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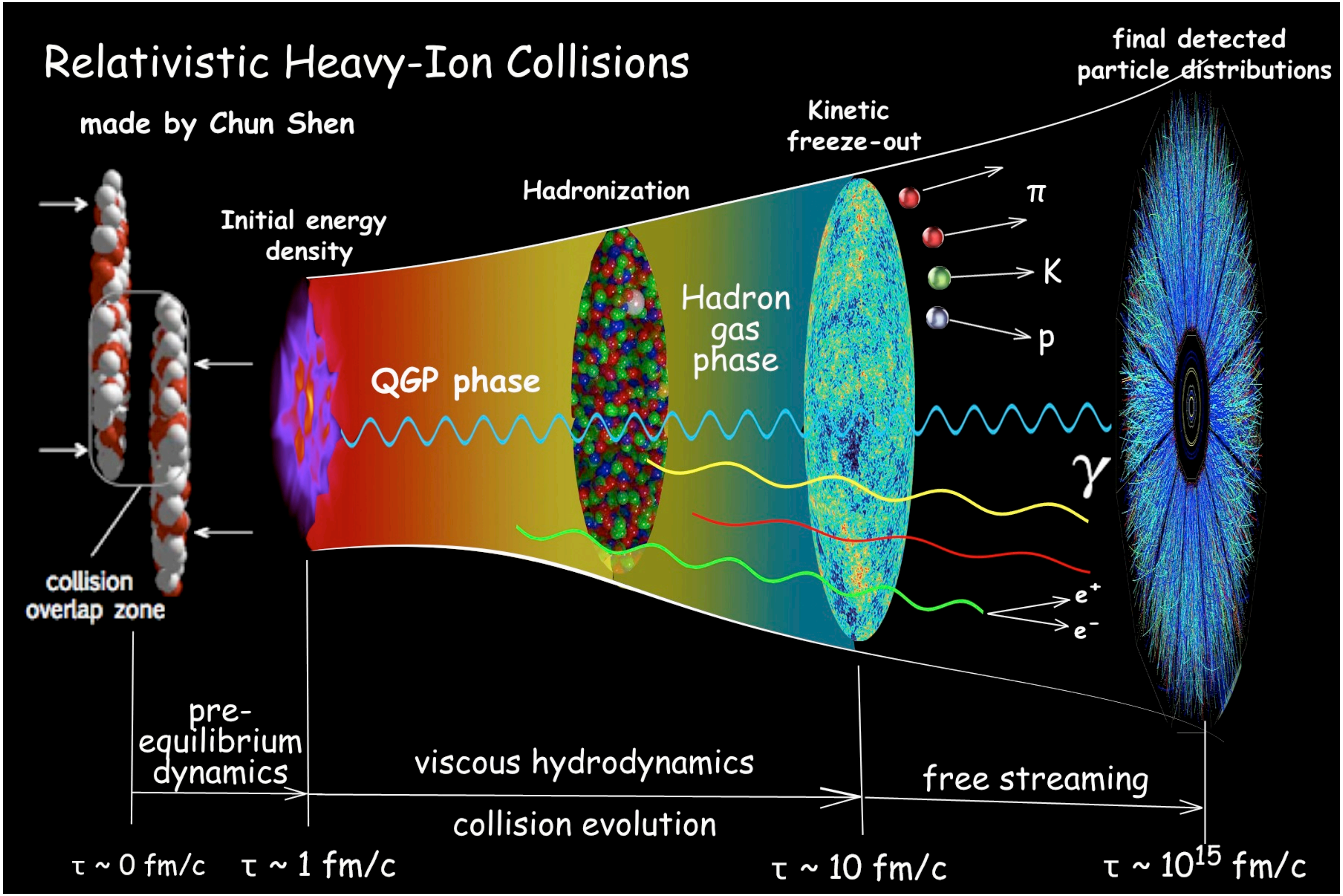
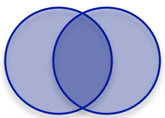
Evolution of a heavy-ion collision

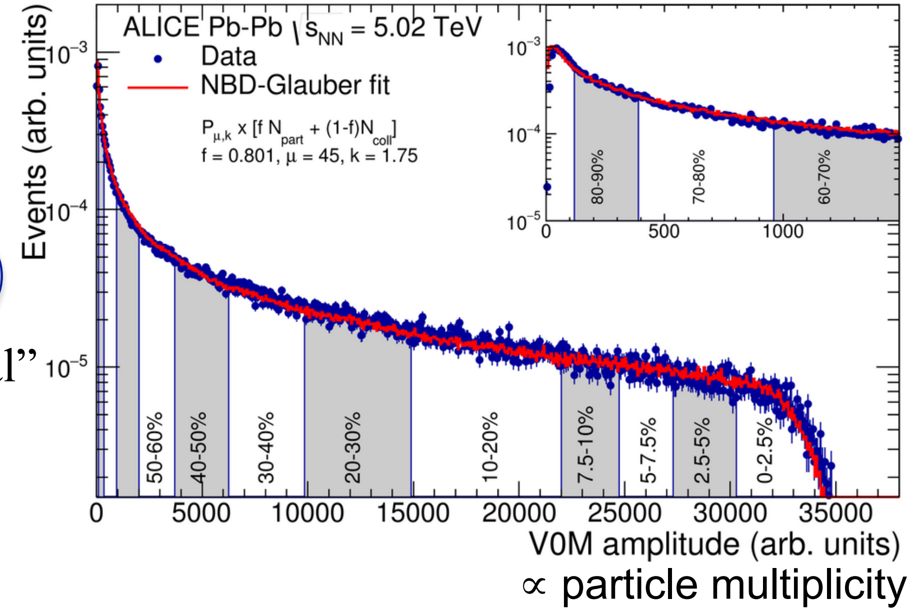


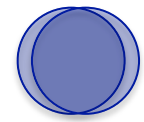
Geometry of a heavy-ion collision

- Centrality: amount of overlap of colliding nuclei



"peripheral"

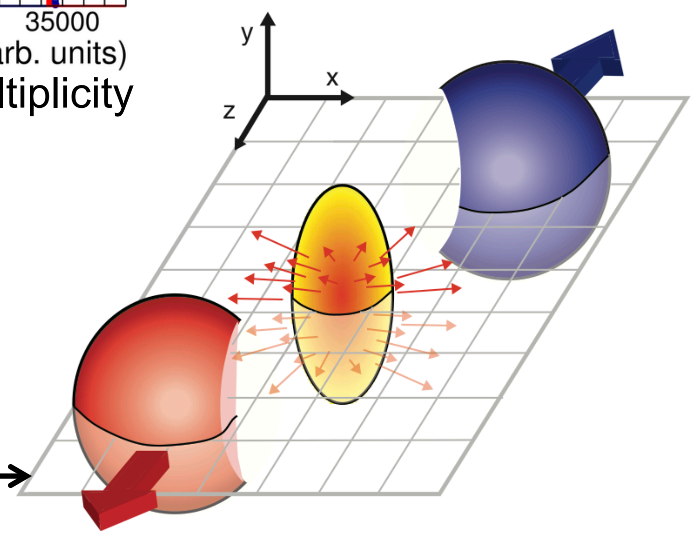




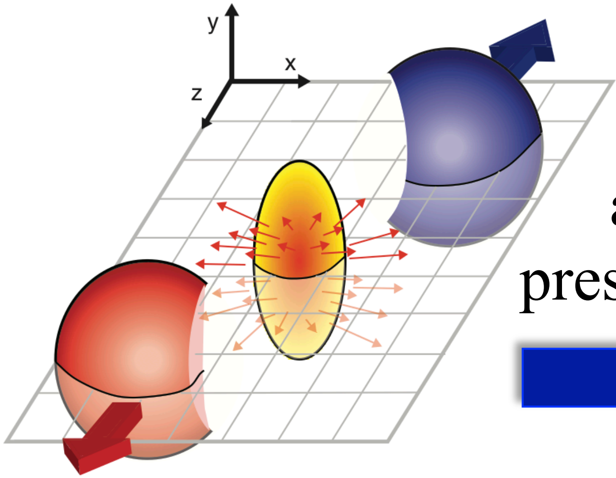
"central"

- Peripheral events are not rotationally symmetric → anisotropic interaction region

symmetry plane →

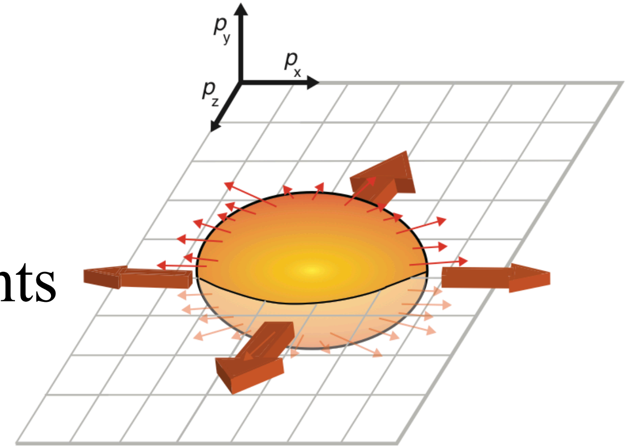


Anisotropic interaction region

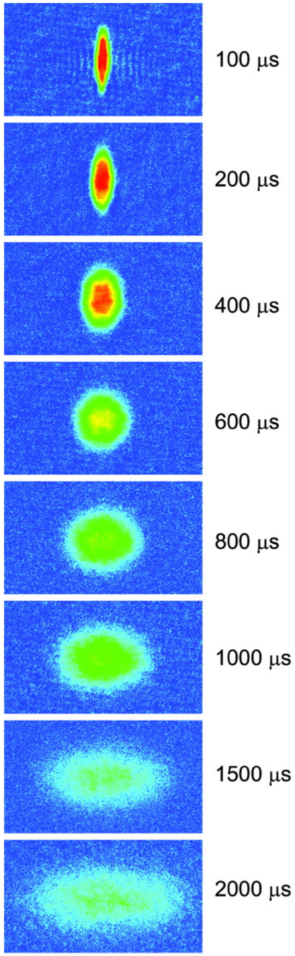


position-space anisotropy

anisotropic pressure gradients



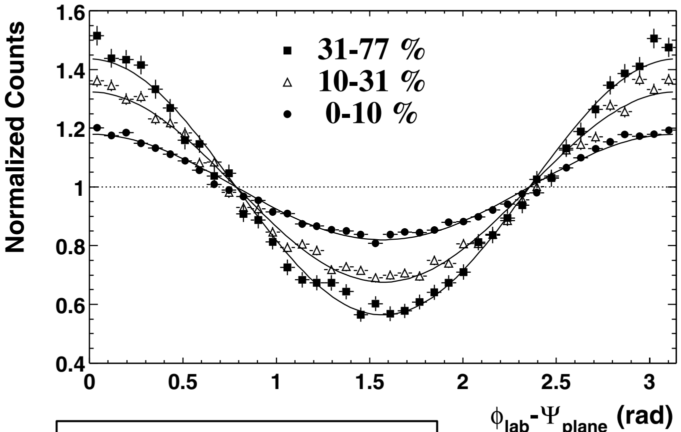
momentum-space anisotropy



Elliptic Flow in Ultracold Lithium

K.M. O'Hara et al., Science, 13 Dec 2002: 2179-2182

- Stronger in-plane pressure gradients → particles boosted in-plane more than out-of-plane

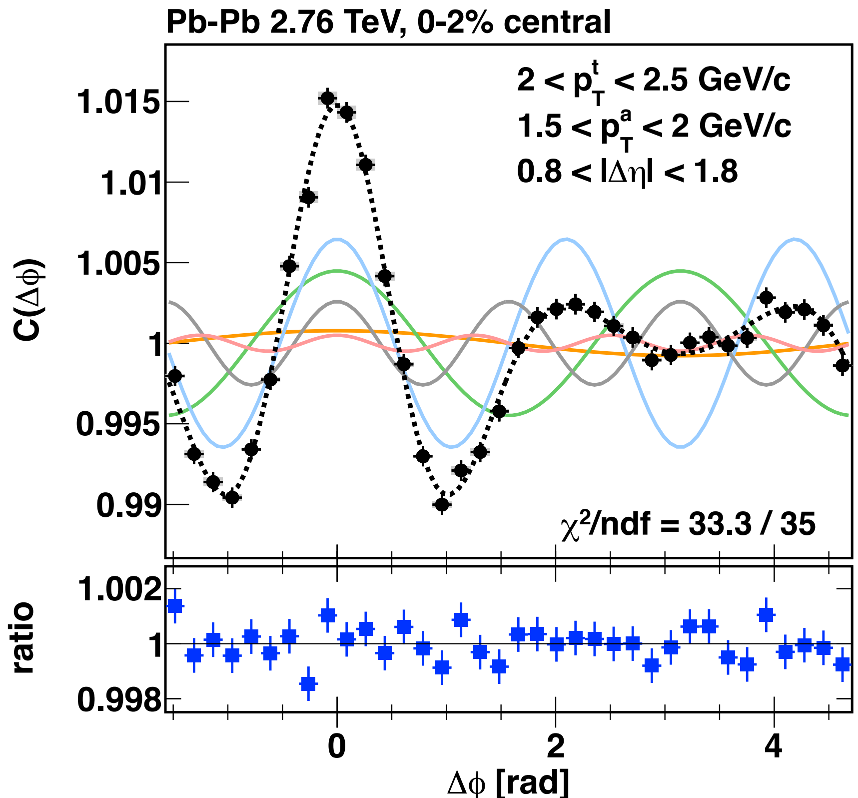


STAR, PRL 90 (2003) 032301

Anisotropic flow components v_n

- Particle distribution described by a Fourier cosine series

$$
\begin{aligned}
dN/d\varphi \sim 1 &+ 2v_1\cos(\varphi-\Psi_1) \\
&+ 2v_2\cos(2(\varphi-\Psi_2)) \\
&+ 2v_3\cos(3(\varphi-\Psi_3)) \\
&+ 2v_4\cos(4(\varphi-\Psi_4)) \\
&+ \ldots
\end{aligned}
$$

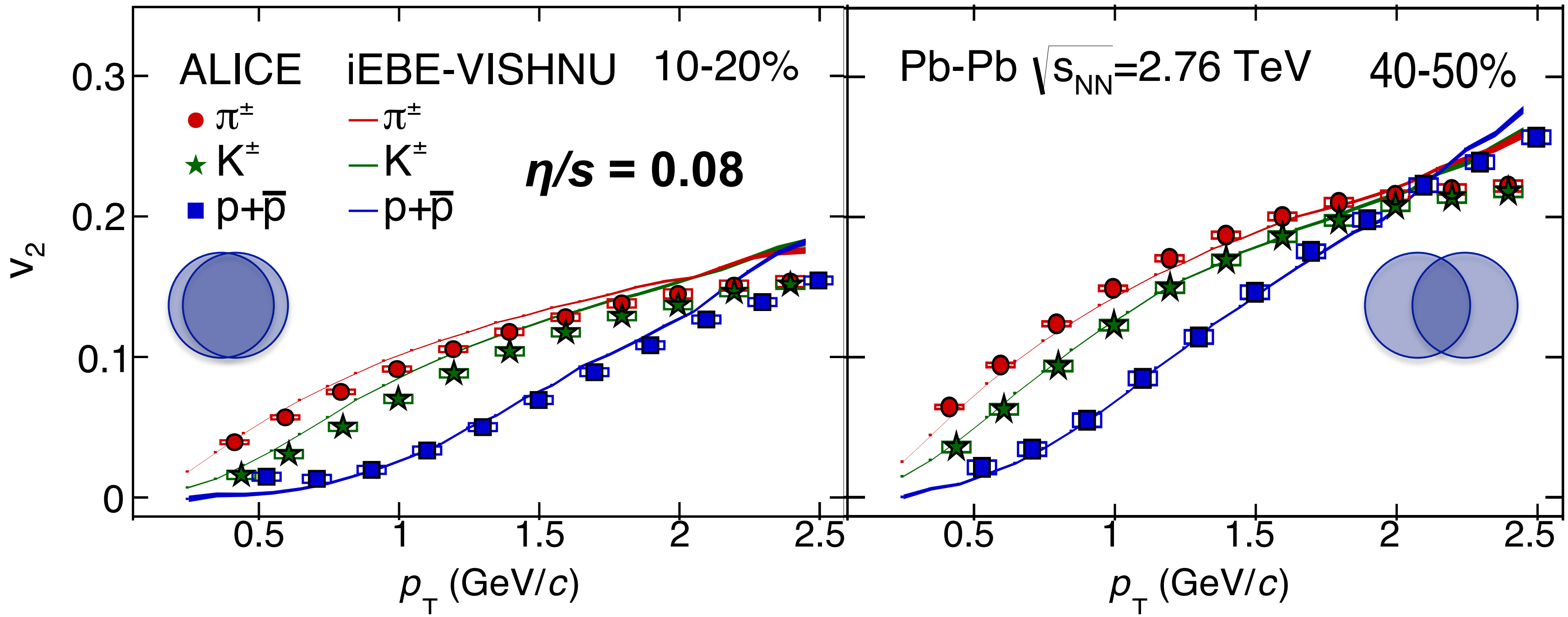


ALICE, PLB 708 (2012) 249

- Two-particle ($\Delta\varphi$) distribution described by Fourier series with coefficients v_n^2
- In non-central events, v_2 is dominant → "elliptic flow"

Hydrodynamic evolution of the system

- Measurements of v_2 are described very well by hydrodynamic models → QGP behaves as a liquid!

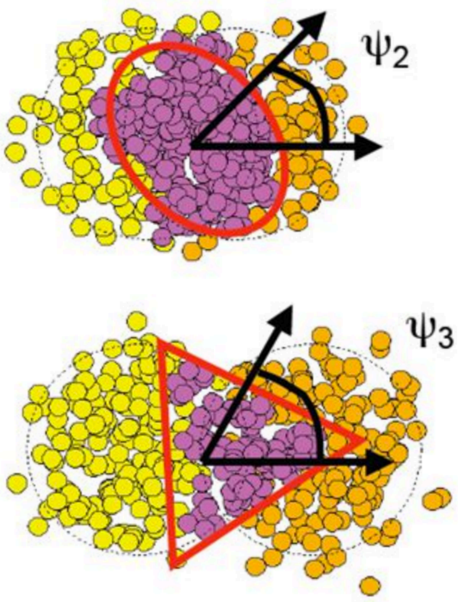


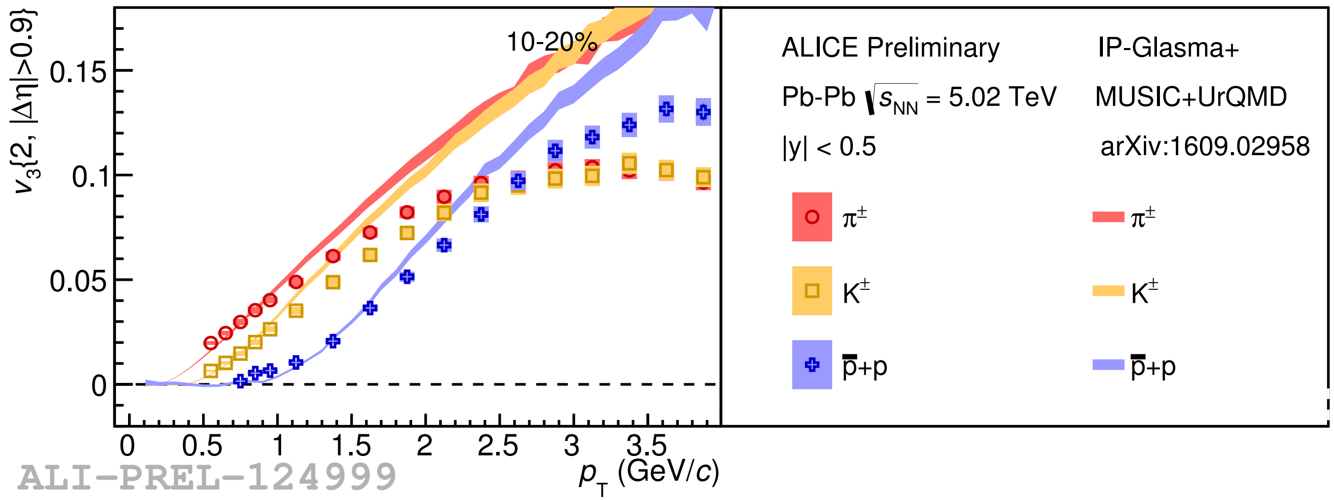
- Viscosity (η/s) is near quantum lower bound → QGP is the "perfect liquid"

ALICE, JHEP 09 (2016) 164

Higher harmonics (n > 2)

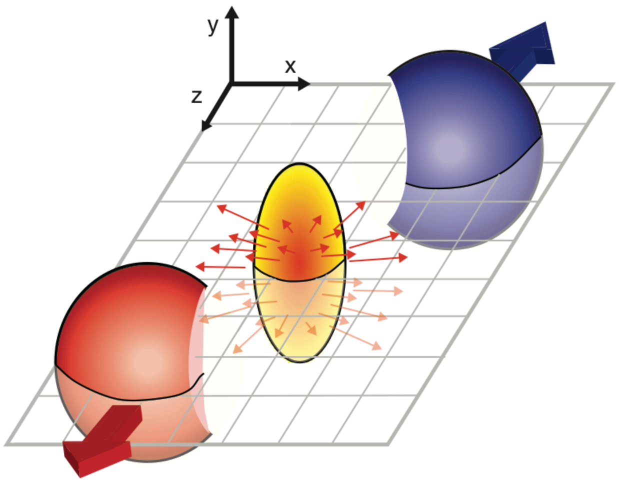
- Due to event-by-event fluctuations of the positions of nucleons, overlap region is not perfectly symmetric
  → development of triangular flow v_3, quadrangular flow v_4,...
- Higher harmonics are sensitive to hydrodynamic properties and dynamics of the QGP

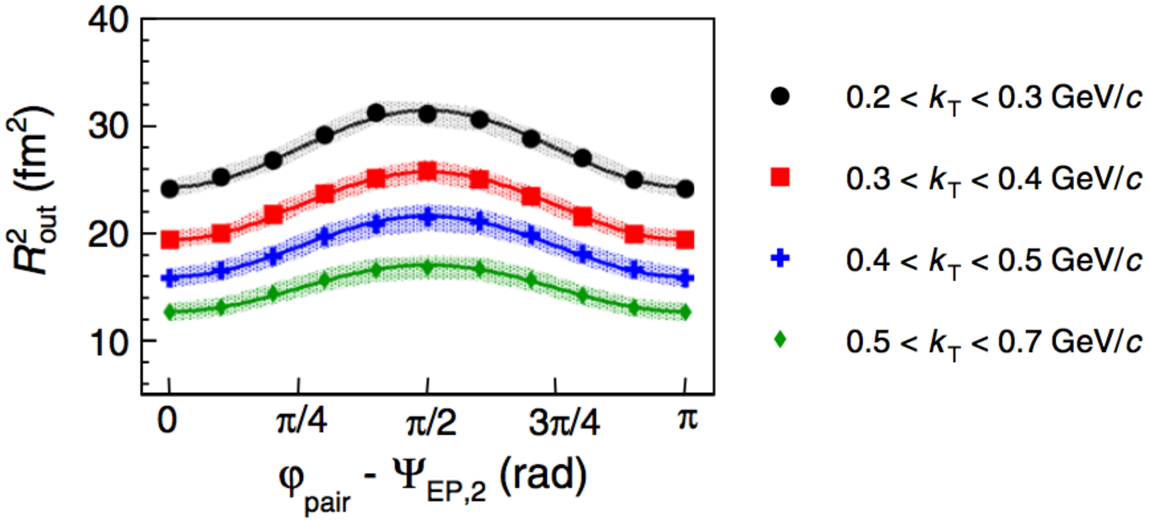




Size of the system – femtoscopy

- Hanbury Brown-Twiss (HBT) interferometry
  - quantum interference of pairs of identical particles can be used to measure (final) source size

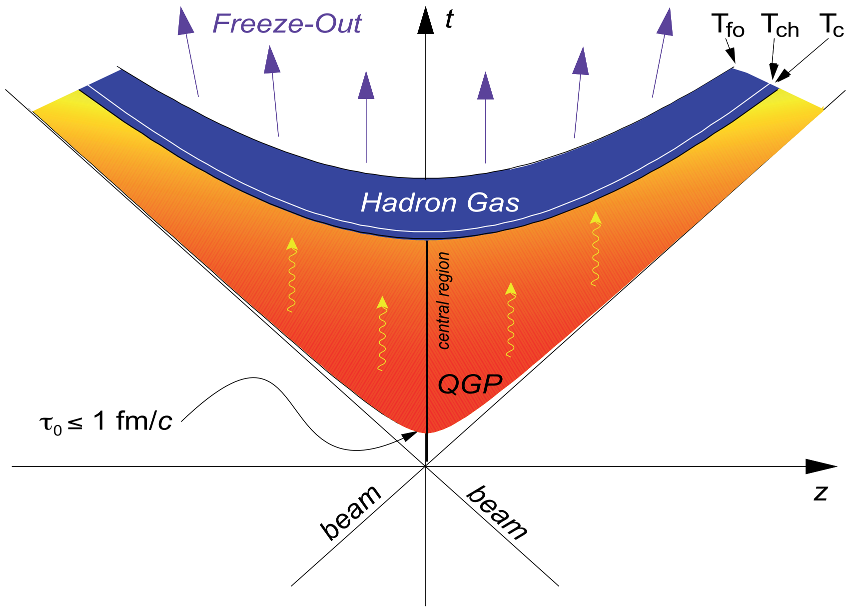




- Source region is smaller in-plane than out-of-plane at late times, although smaller eccentricity than at early times

ALICE, PRL 118 (2017) 222301

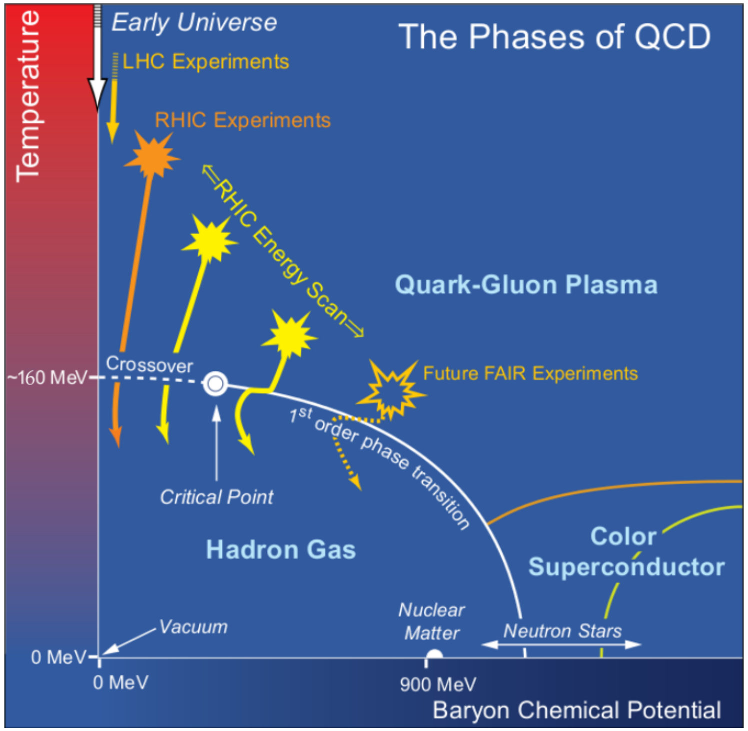
Cooldown of the QGP, hadrochemistry



- Pseudocritical temperature (T_c): transition from QGP phase to hadron gas phase
- Chemical freeze-out (T_{ch}): inelastic collisions cease, particle species ratios become fixed
- Kinetic freeze-out (T_{kin}, T_{fo}): elastic collisions cease, particles stream freely to the detector

Fluctuations in heavy ion collisions

- Event-by-event fluctuations of particle multiplicities are used to study properties and phase structure of strongly-interacting matter
- Fluctuations grow in the region near a phase transition and/or critical point



Critical opalescence in CO_2 (2nd order PT)
J.V. Sengers, A.L Sengers, Chem. Eng. News, June 10, 104–118, 1968

$T > T_c$ $T >\sim T_c$ $T <\sim T_c$ $T < T_c$

Fluctuations in heavy ion collisions

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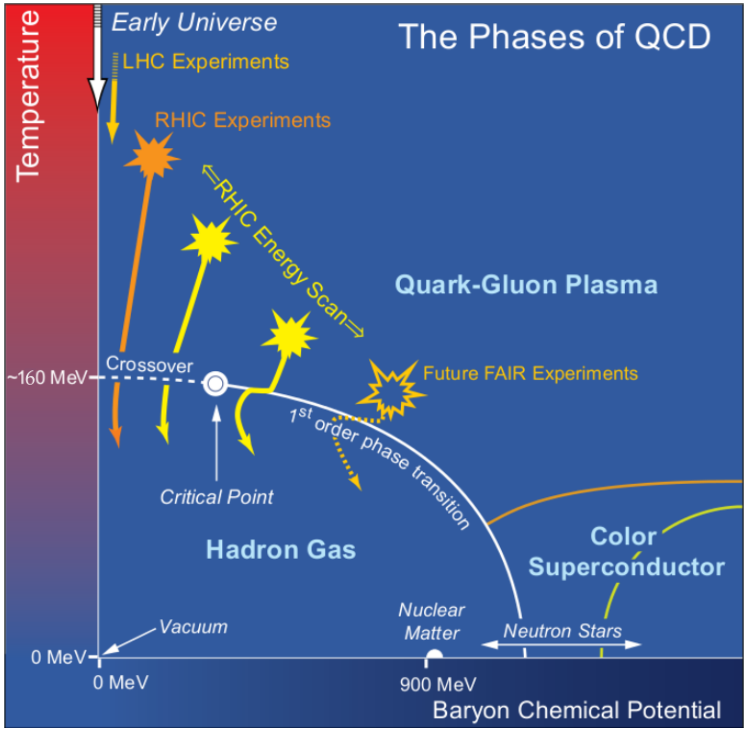


- Fluctuations grow in the region near a phase transition and/or critical point
- Fluctuations of conserved charges can be related to susceptibilities calculable in lattice QCD
  - precision test of LQCD at $\mu_B \approx 0$

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium

Theory:
calculate susceptibilities in Lattice QCD

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial \left(\mu_B / T\right)^n}$$

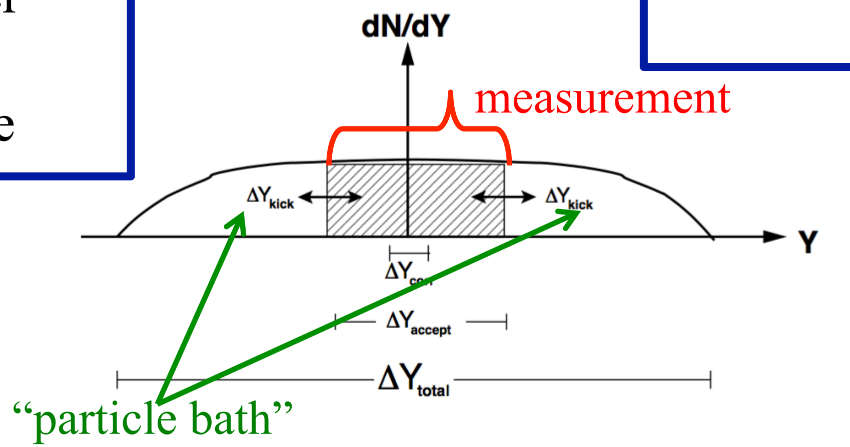
B → baryon number
S → strangeness
Q → electric charge

↔ Grand Canonical Ensemble

Experiment:
measure particle multiplicity distributions

$$\Delta N_p = N_p - N_{\bar{p}}$$

net-proton
net-kaon
net-pion



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⟷ Grand Canonical Ensemble ⟷

Experiment:
measure particle multiplicity distributions

$$\Delta N_p = N_p - N_{\bar{p}}$$

$$\langle \Delta N_B \rangle = VT^3 \chi_1^B$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^2 \right\rangle = VT^3 \chi_2^B = \sigma^2$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^3 \right\rangle \Big/ \sigma^3 = \frac{VT^3 \chi_3^B}{\left(VT^3 \chi_2^B\right)^{3/2}} = S$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^4 \right\rangle \Big/ \sigma^4 - 3 = \frac{VT^3 \chi_4^B}{\left(VT^3 \chi_2^B\right)^2} = \kappa$$

$$S\sigma = \chi_3^B / \chi_2^B$$
$$\kappa\sigma^2 = \chi_4^B / \chi_2^B$$

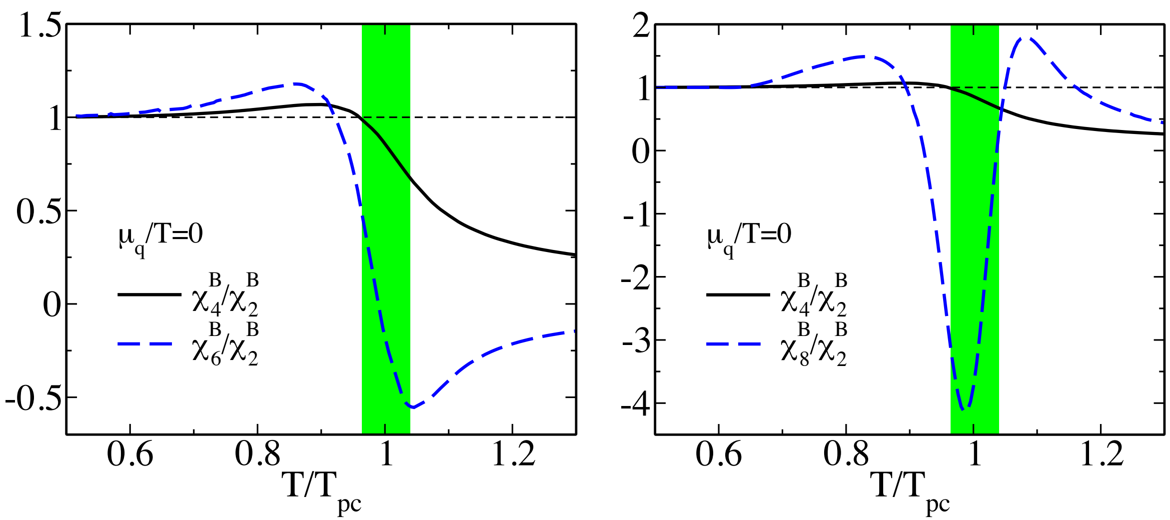
Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium

Theory: calculate susceptibilities in Lattice QCD as a function of temperature

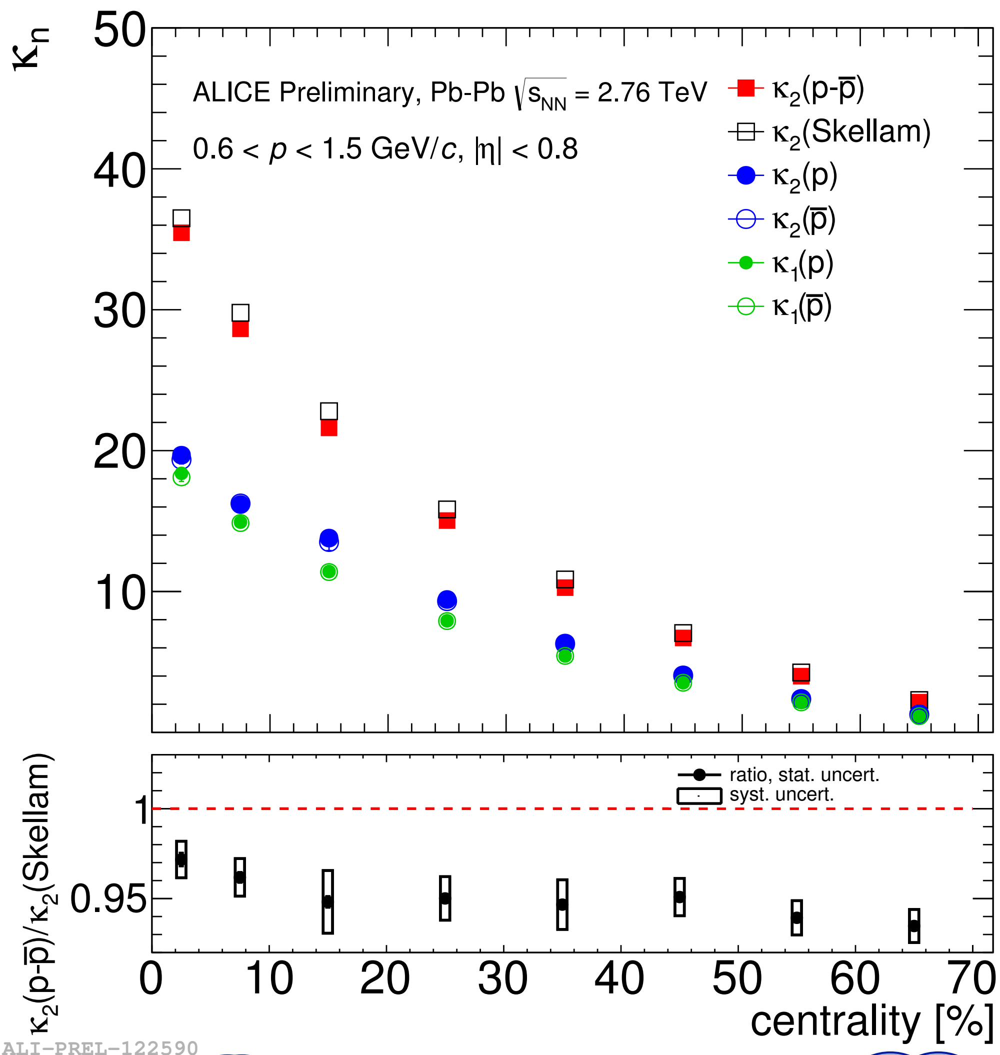
Grand Canonical Ensemble

Experiment: measure higher moments vs. $\sqrt{s_{NN}}$



Friman, B., et al.
EPJC 71 (2011) 1694

Net-proton fluctuations



$$\kappa_1(p) = \langle N_p \rangle$$

$$\kappa_2(p) = \left\langle \left(N_p - \langle N_p \rangle\right)^2 \right\rangle$$

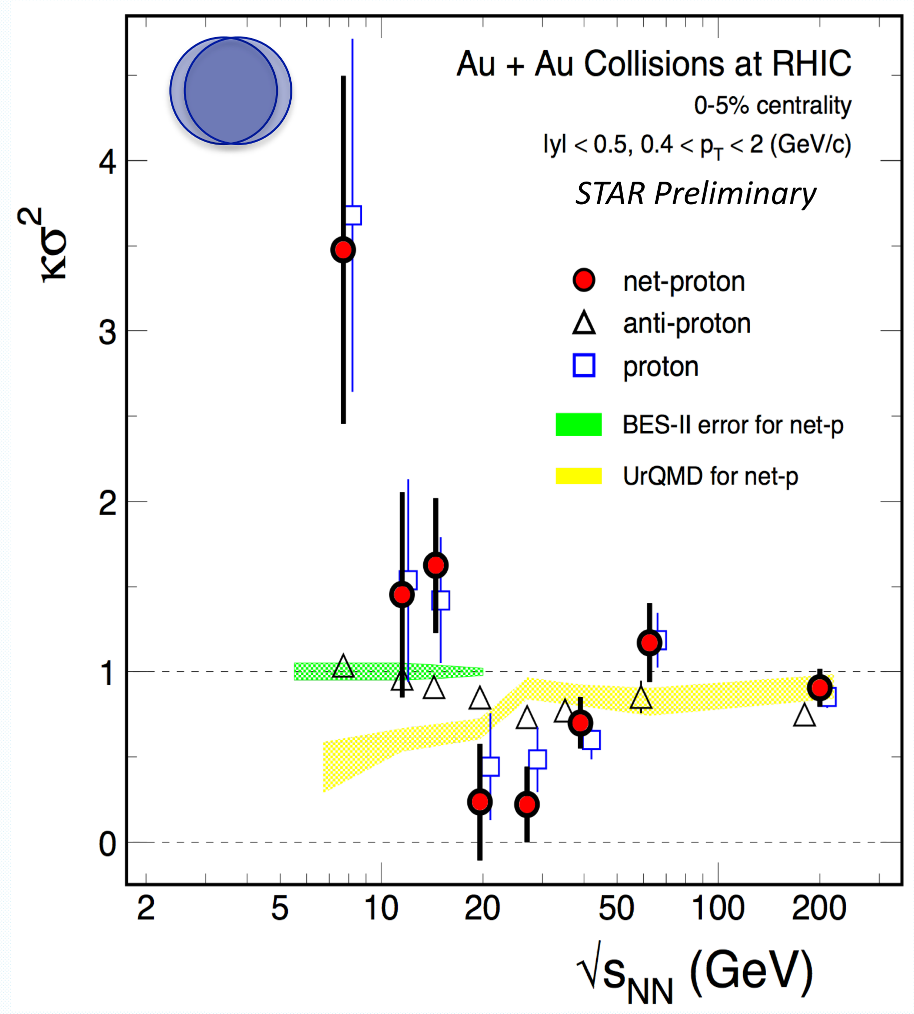
$$\kappa_2(p-\bar{p}) = \left\langle \left(\Delta N_p - \langle \Delta N_p \rangle\right)^2 \right\rangle$$

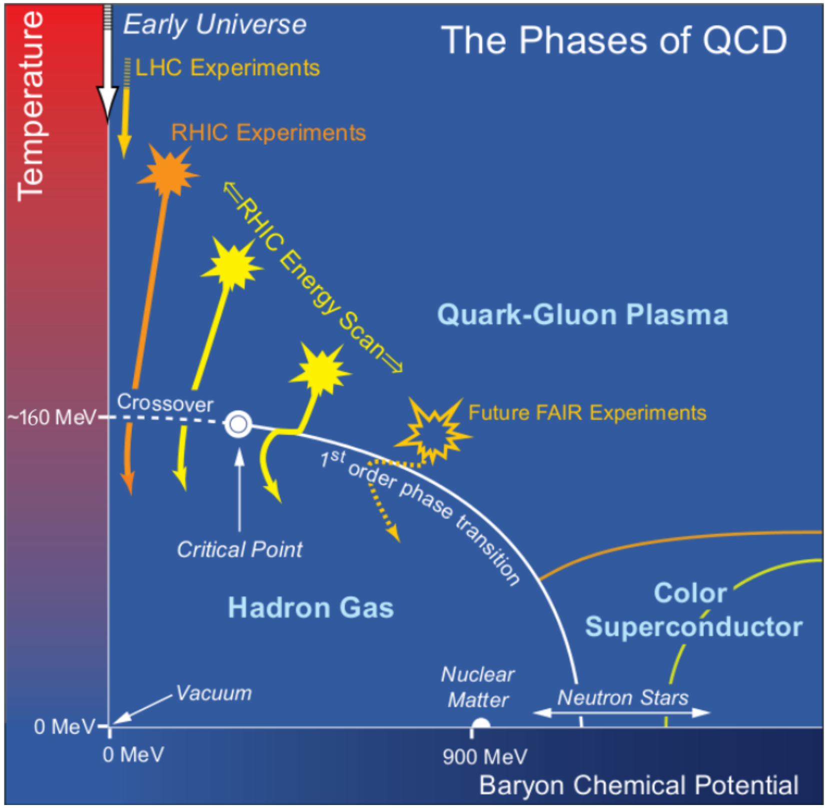
- Skellam baseline → when multiplicity distributions of protons and anti-protons are Poissonian and uncorrelated
- κ_2(p-p) shows only small deviations from Skellam prediction
  - can be fully explained by volume fluctuations and global baryon number conservation

P. Braun-Munzinger et al., NPA 960 (2017) 114

Higher moments

- Scan the phase diagram by lowering the collision energy





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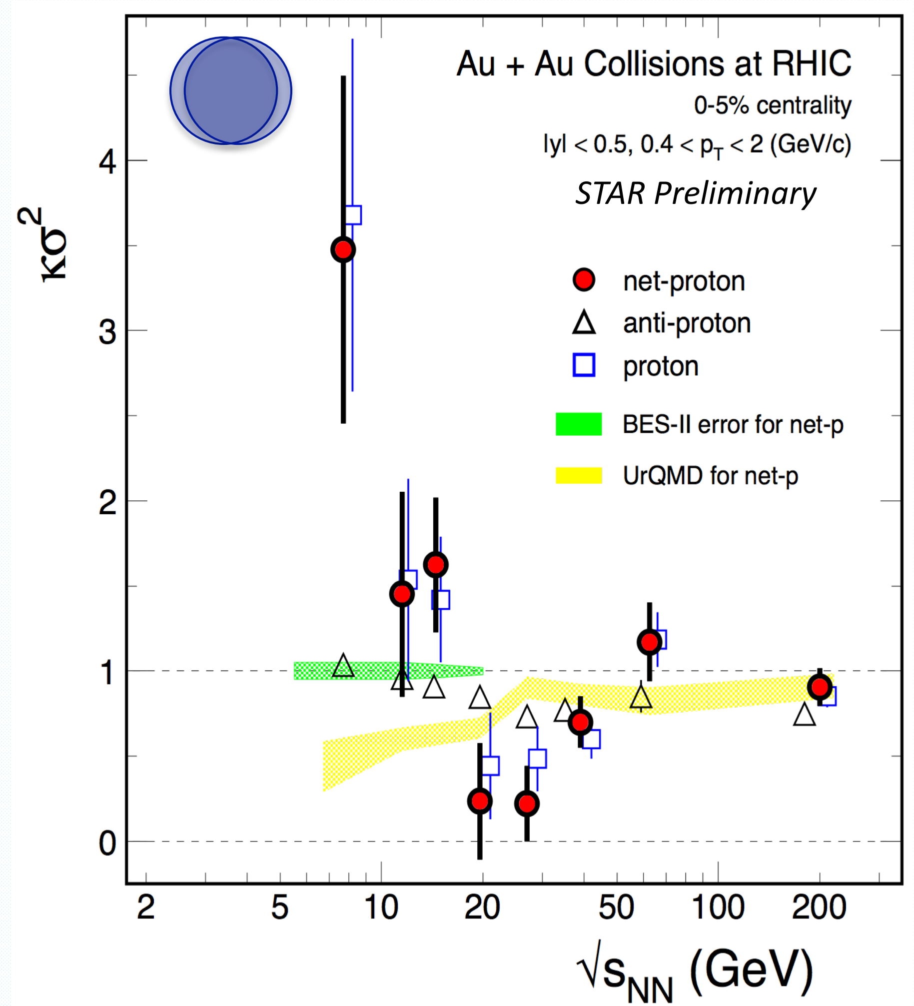
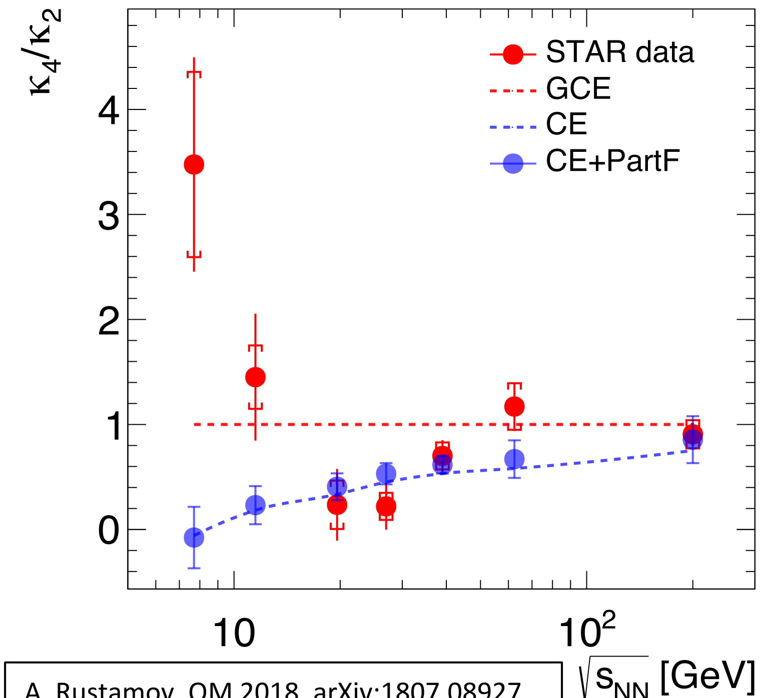


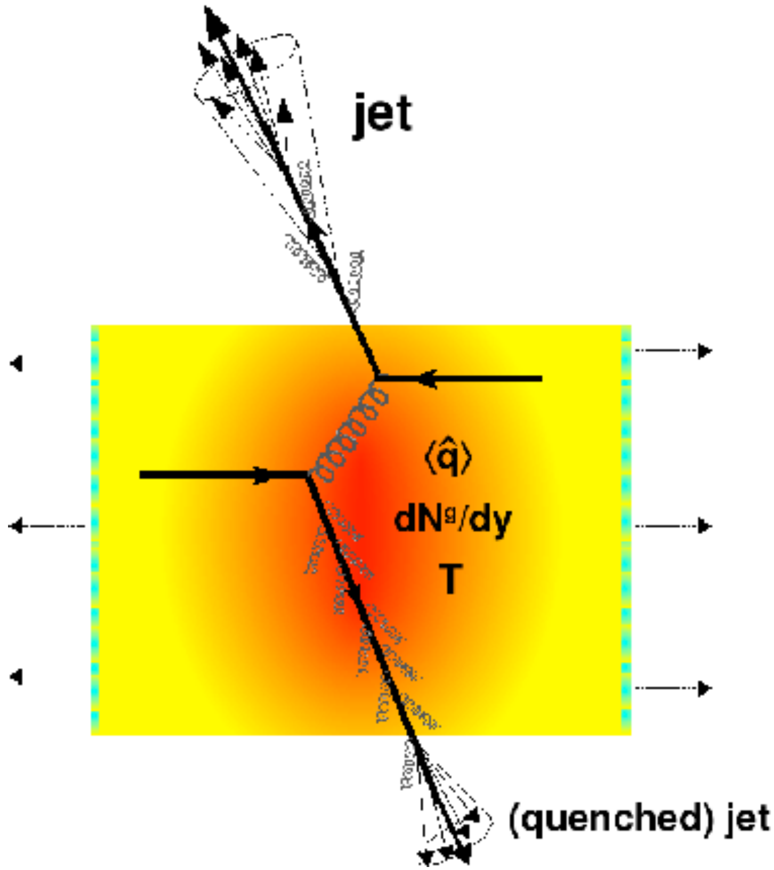


A. Rustamov, QM 2018, arXiv:1807.08927

- Deviations can be largely explained by global conservation laws and participant fluctuations

Jets: probes of the QGP

- Hard scatterings in the early stages of the collision produce back-to-back recoiling partons, which fragment into collimated clusters of hadrons

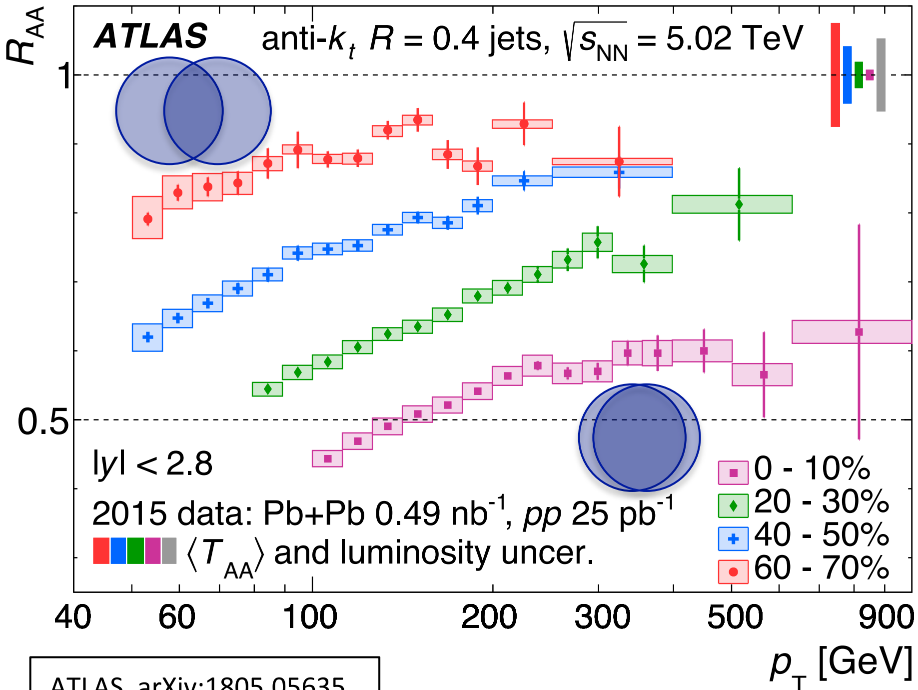


- As they traverse the QGP, partons interact with the medium → "jet quenching"
- Characterize the nature of this energy loss to understand properties of the QGP and the interactions of a colored probe with a colored medium

Jet suppression

- Compare number of reconstructed jets in AA collisions with superimposed pp collisions

$$R_{AA} = \frac{(1/N_{evt}) \left. dN_{jet}/dp_T \right|_{AA}}{\langle N_{coll} \rangle \left. dN_{jet}/dp_T \right|_{pp}}$$



ATLAS, arXiv:1805.05635

- Significant jet suppression in heavy-ion collisions over a wide momentum range

Charged particle suppression

- Compare number of charged particles in AA collisions with superimposed pp collisions

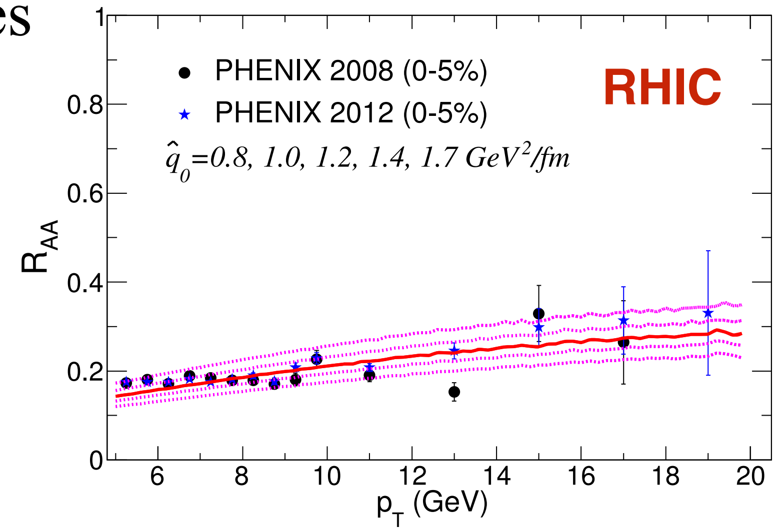
$$R_{AA} = \frac{(1/N_{evt})\, dN/dp_T \big|_{AA}}{\langle N_{coll} \rangle\, dN/dp_T \big|_{pp}}$$

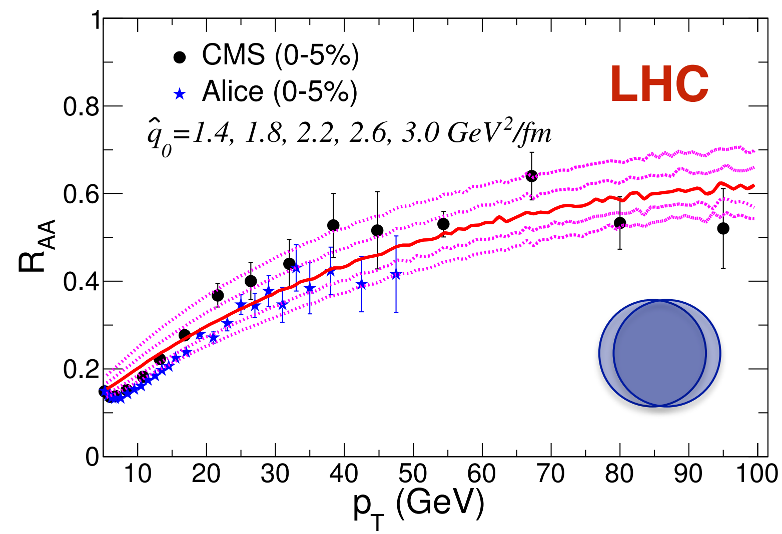
- Jet transport coefficient

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

for a quark with E = 10 GeV

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at} \begin{array}{l} \text{T=370 MeV,} \\ \text{T=470 MeV,} \end{array}$$

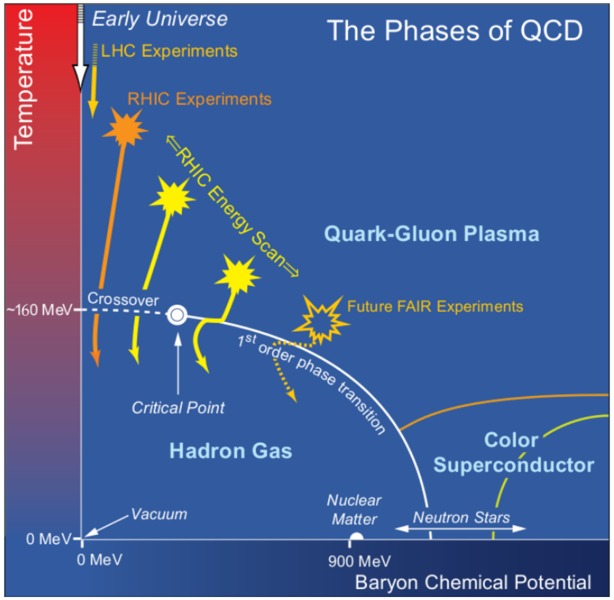




JET Collaboration, K.M. Burke et al., PRC 90 (2014) 014909

Heavy-ion collisions: Extreme QCD

- Deconfined state of quarks and gluons produced in ultrarelativistic heavy ion collisions → Quark-Gluon Plasma
- Flow measurements show very low η/s
  - QGP behaves hydrodynamically as a "perfect liquid"
- Jet transport parameter $\hat{q}$ describes large energy loss of colored probe due to interactions with a colored medium
- Higher moments related to susceptibilities χ
  - precisely test LQCD and search for critical behavior
- Future measurements at LHC, RHIC, FAIR, NICA will improve our understanding of the dynamic, thermal, and chemical properties of the QGP and the phase diagram of QCD



Thank you for your attention!

Any questions?

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