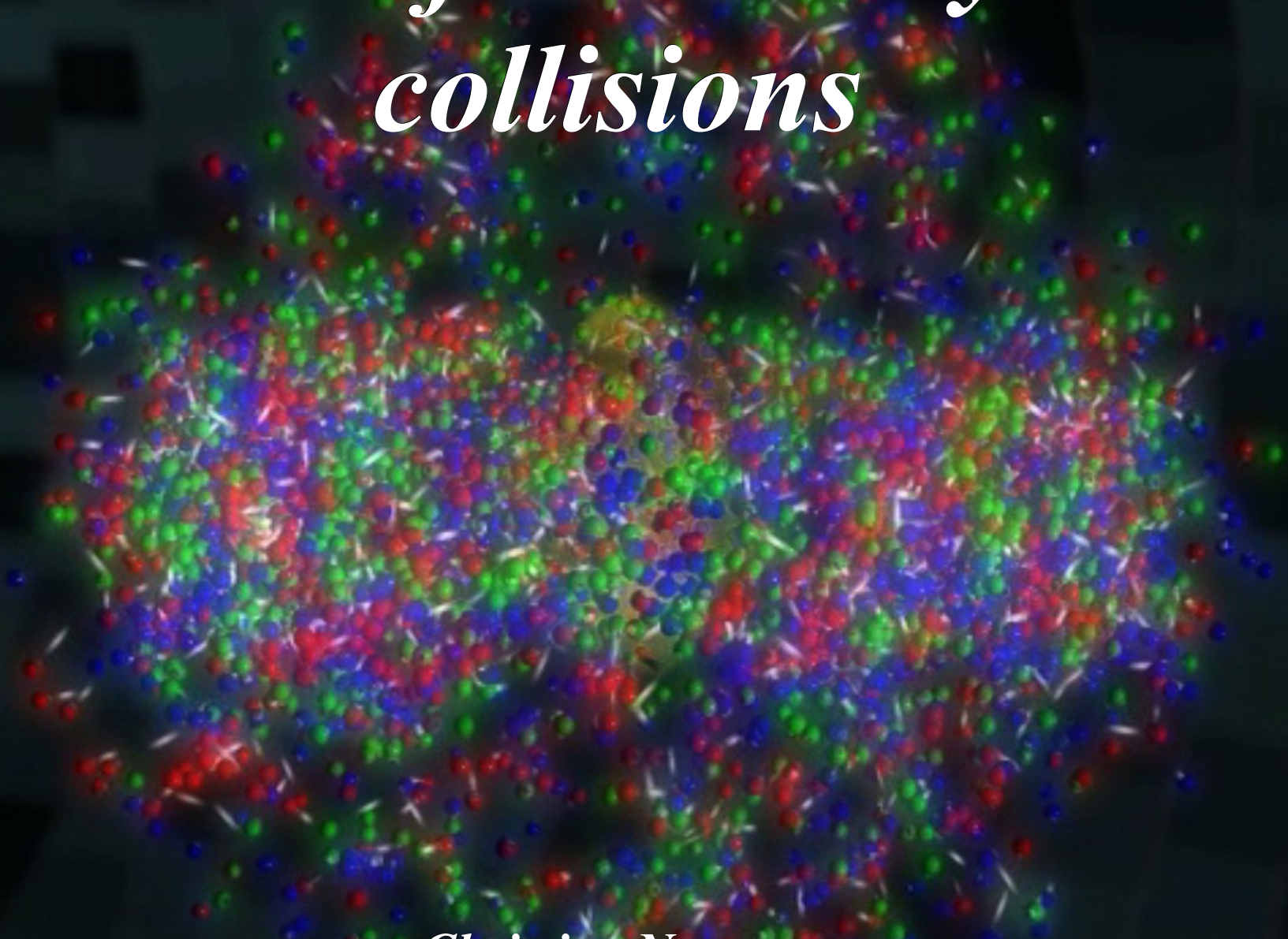
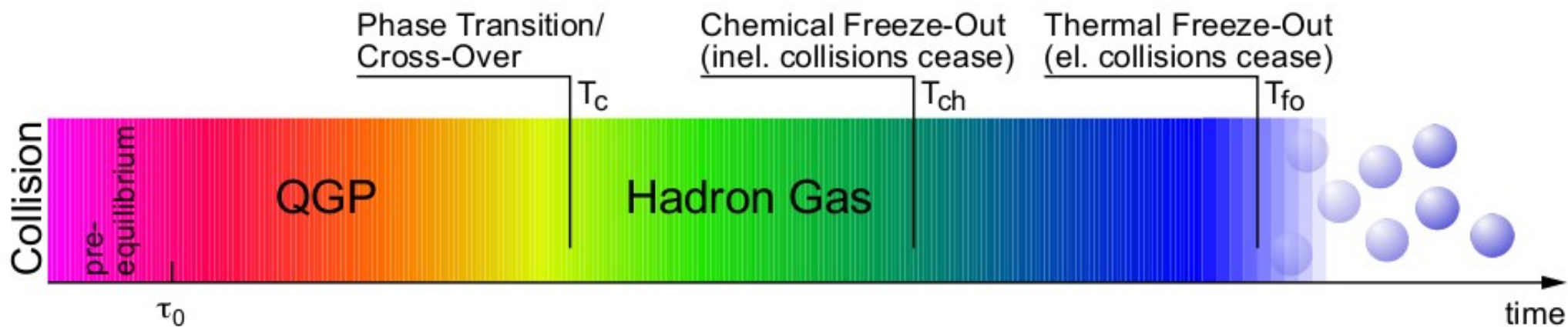
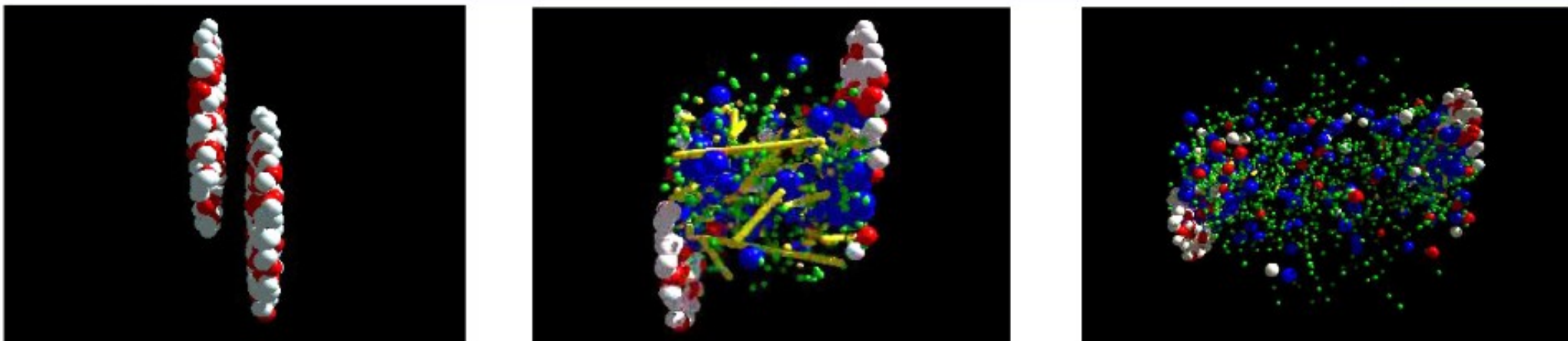


Results from heavy ion collisions



Christine Nattrass
University of Tennessee at Knoxville

Standard model of heavy ion physics

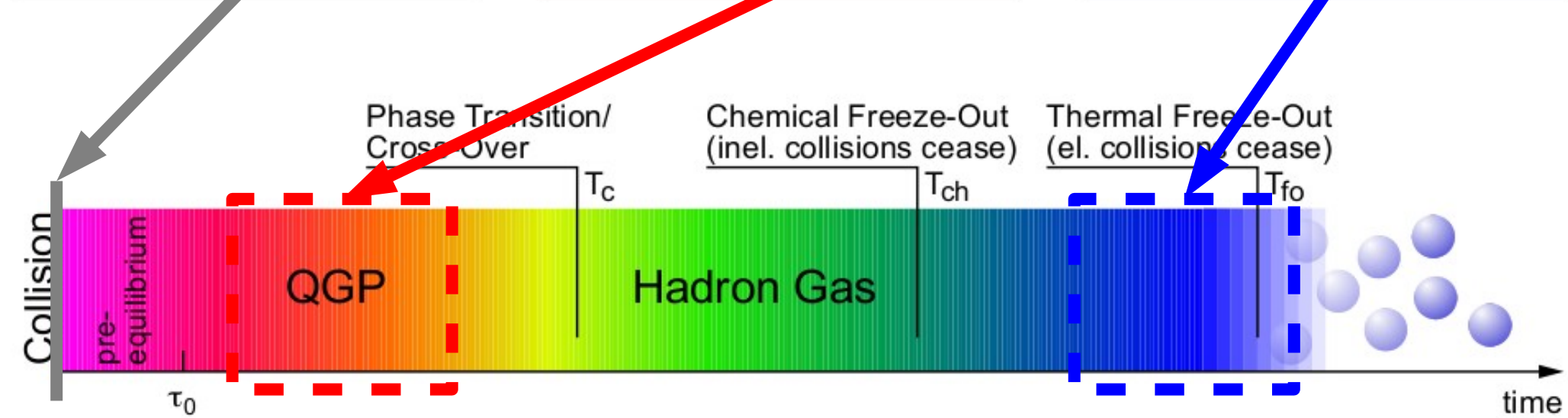
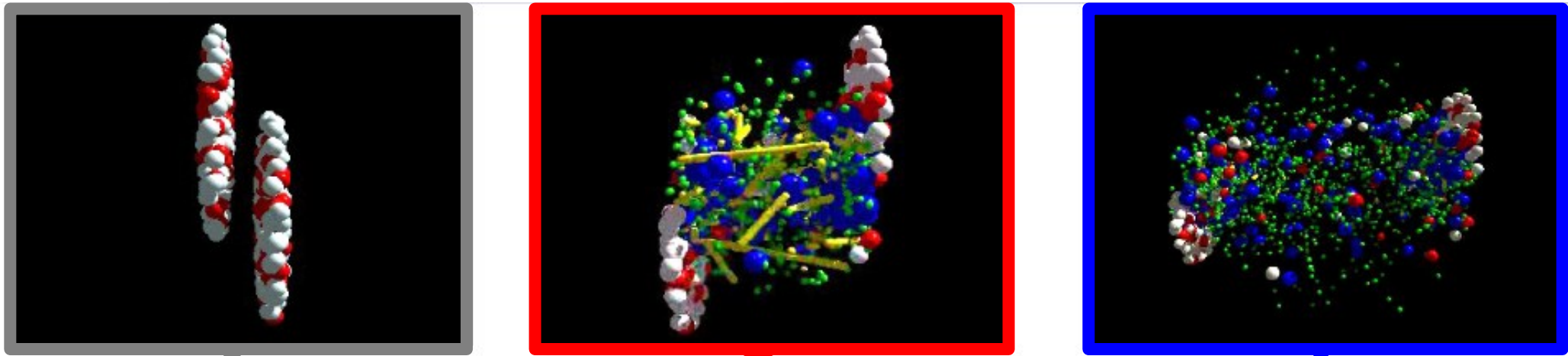


Standard model of heavy ion physics

Initial State

QGP

Freeze-out

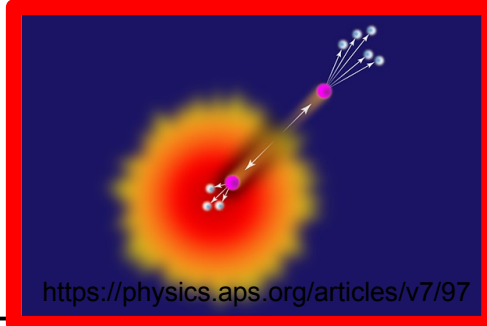
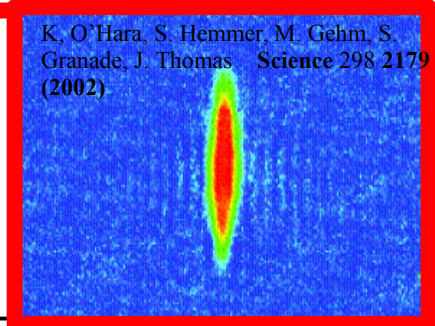
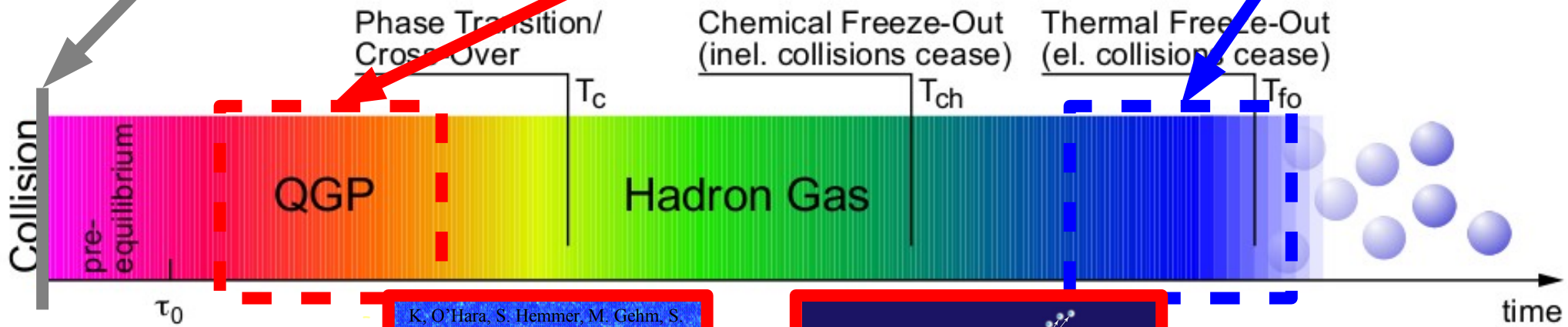
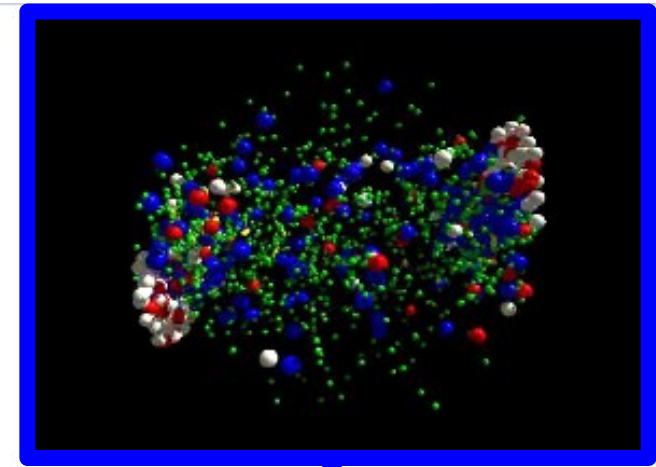
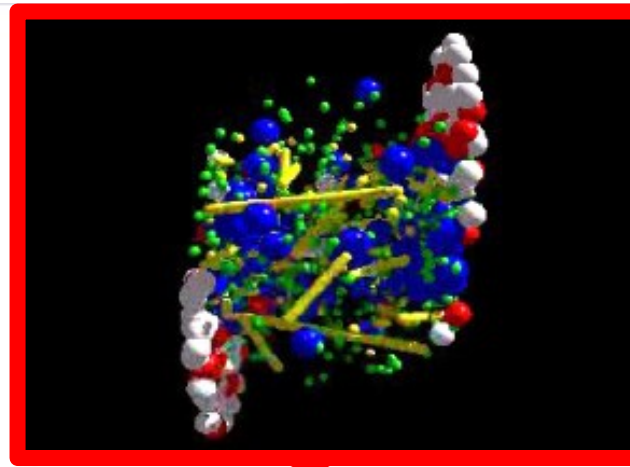
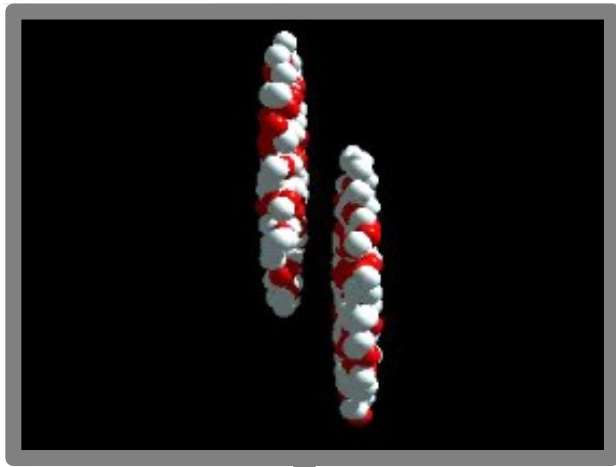


Standard model of heavy ion physics

Initial State

QGP

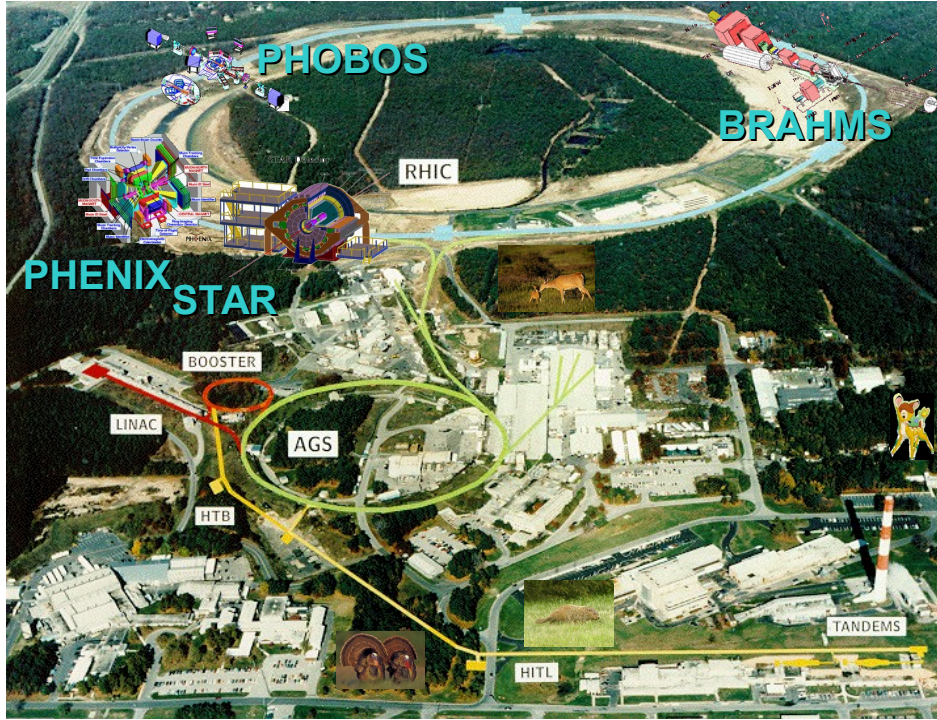
Freeze-out



Hydrodynamical flow

Jet quenching

Relativistic Heavy Ion Collider



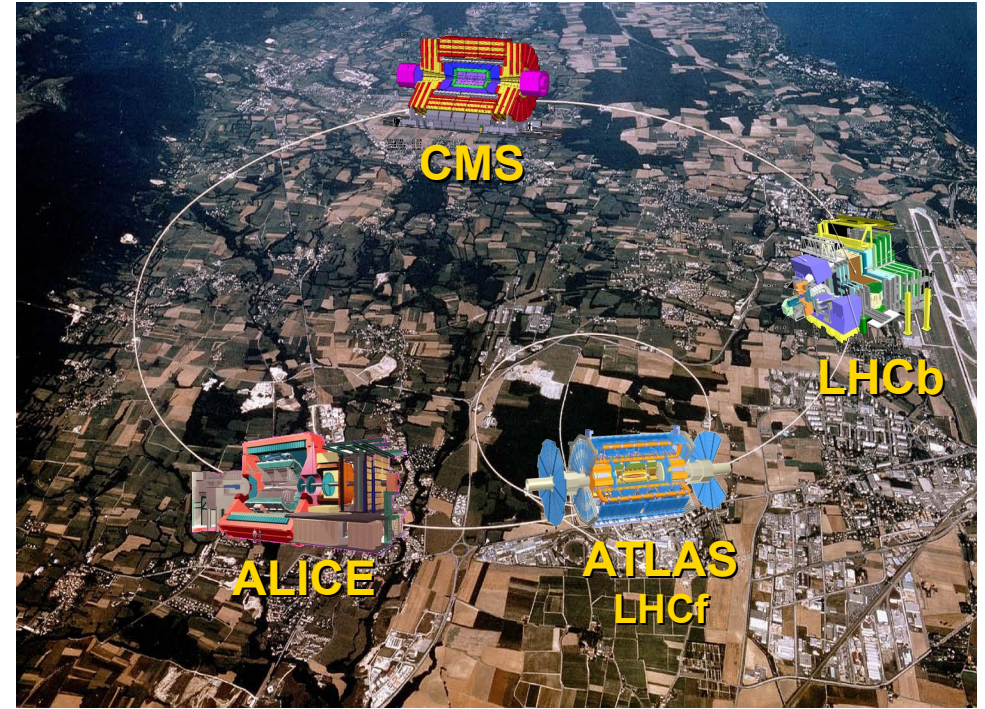
Upton, NY

1.2km diameter

$p+p$, $d+Au$, $Cu+Cu$, $Au+Au$, $U+U$

$\sqrt{s_{NN}} = 9 - 200 \text{ GeV}$

Large Hadron Collider



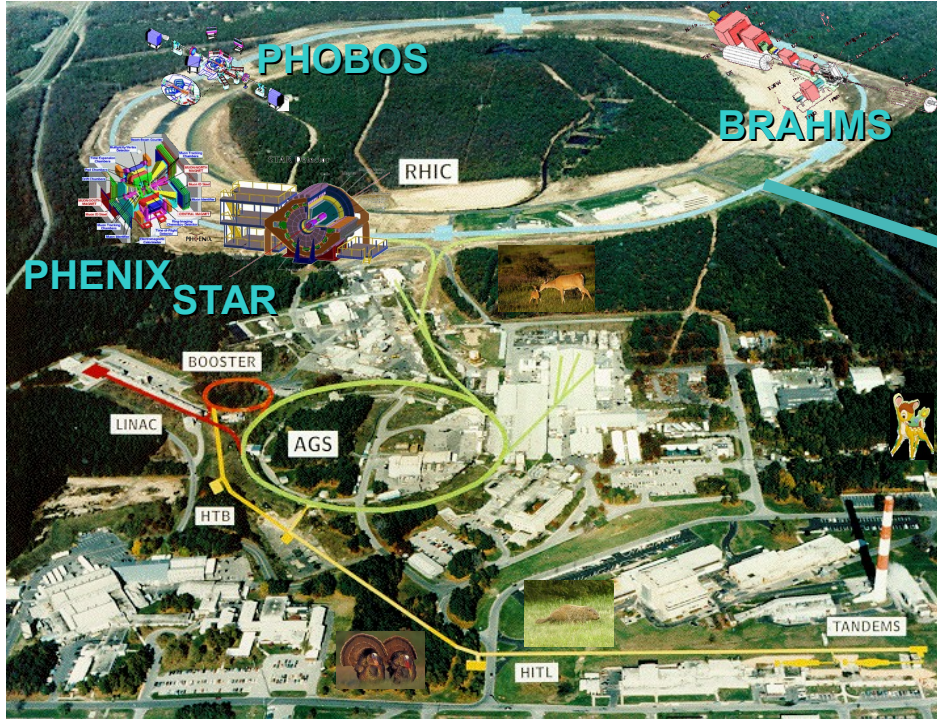
Geneva, Switzerland

8.6km diameter

$p+p$, $p+Pb$, $Pb+Pb$

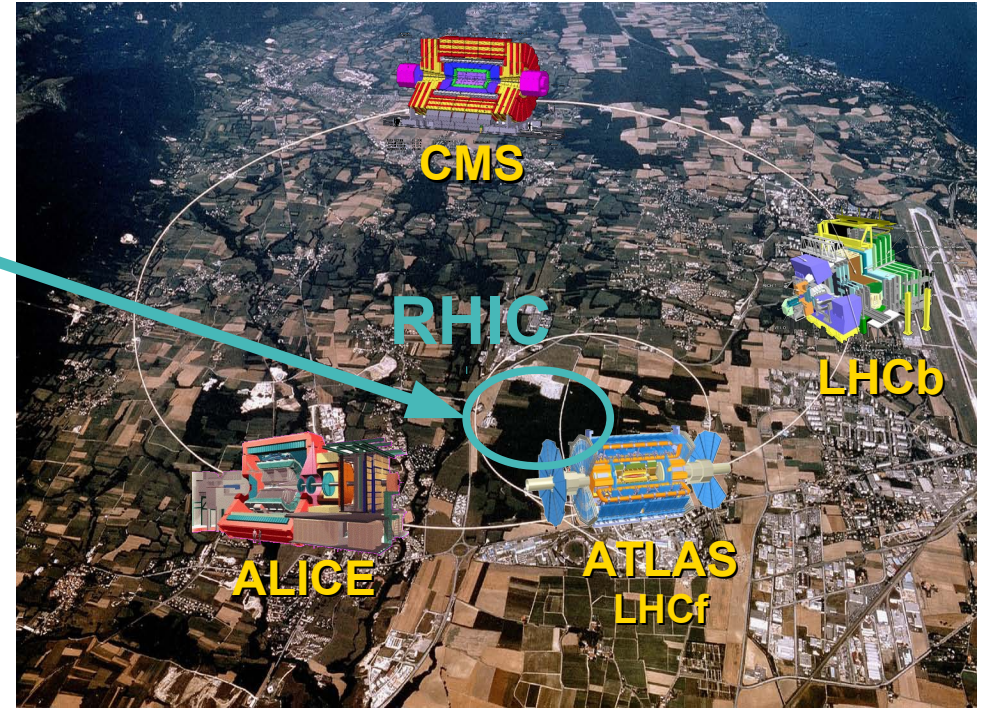
$\sqrt{s_{NN}} = 2.76 \text{ GeV}, 5.5 \text{ TeV}$

Relativistic Heavy Ion Collider



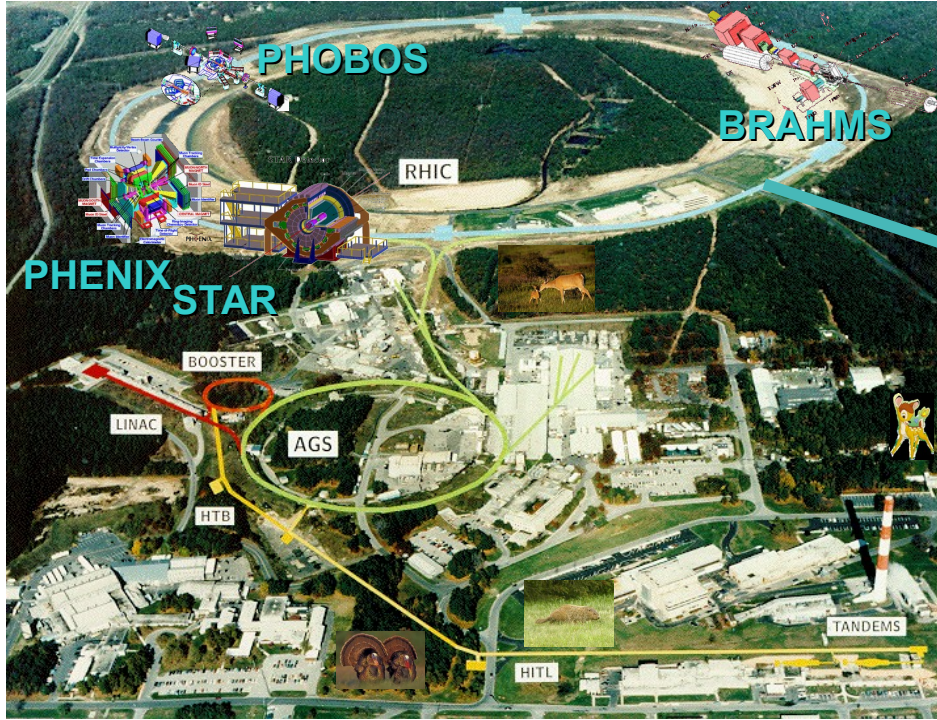
Upton, NY
1.2km diameter
 $p+p, d+Au, Cu+Cu, Au+Au, U+U$
 $\sqrt{s_{NN}} = 9 - 200 \text{ GeV}$

Large Hadron Collider



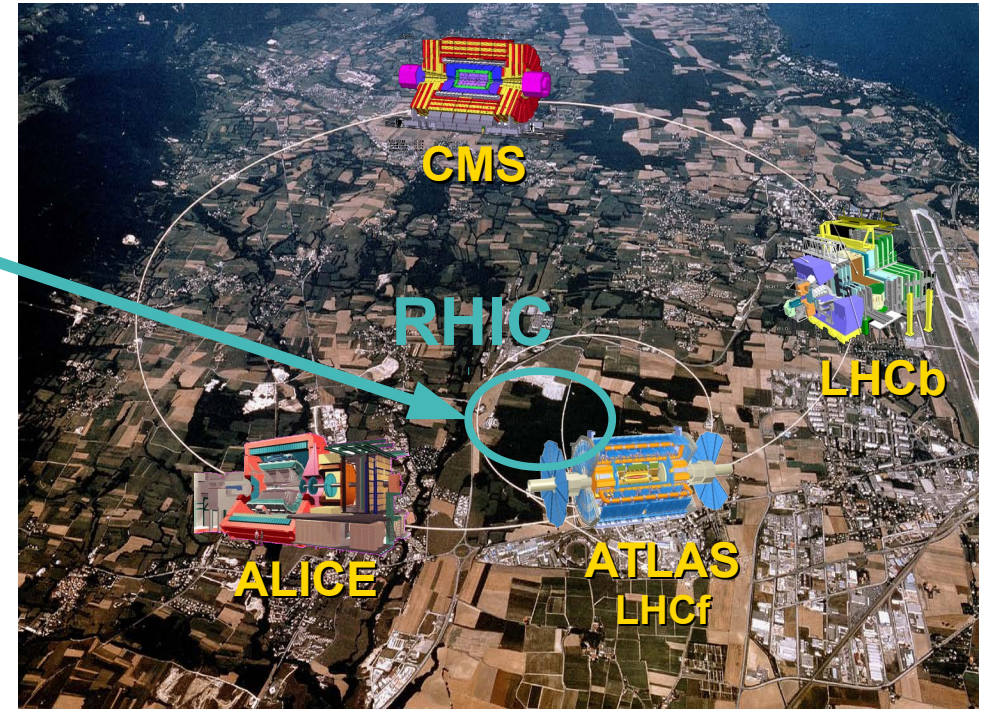
Geneva, Switzerland
8.6km diameter
 $p+p, p+Pb, Pb+Pb$
 $\sqrt{s_{NN}} = 2.76 \text{ GeV}, 5.5 \text{ TeV}$

Relativistic Heavy Ion Collider

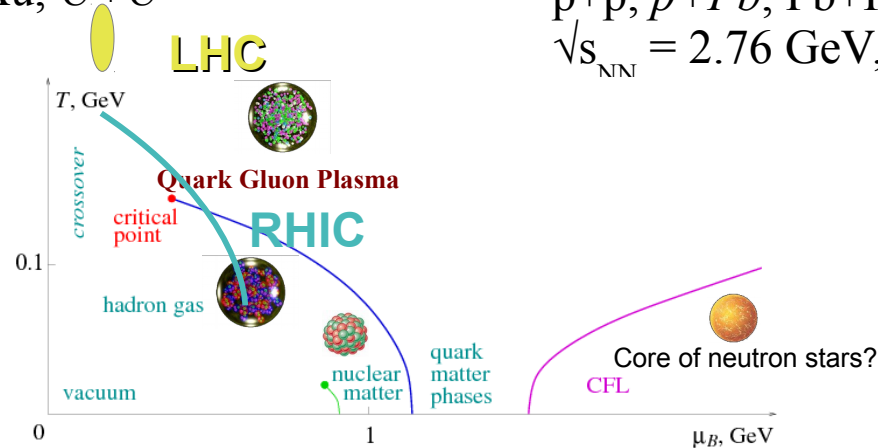


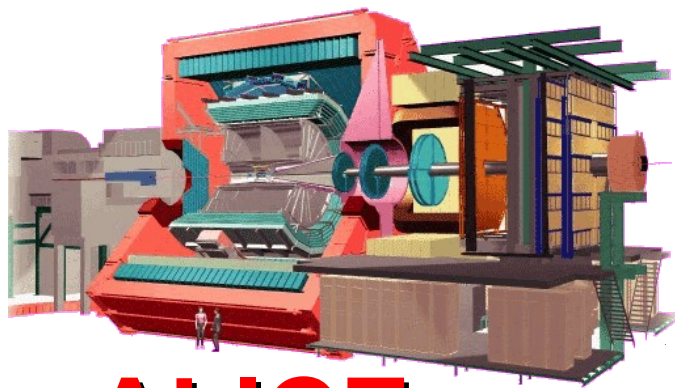
Upton, NY
 1.2km diameter
 $p+p, d+Au, Cu+Cu, Au+Au, U+U$
 $\sqrt{s}_{NN} = 9 - 200 \text{ GeV}$

Large Hadron Collider

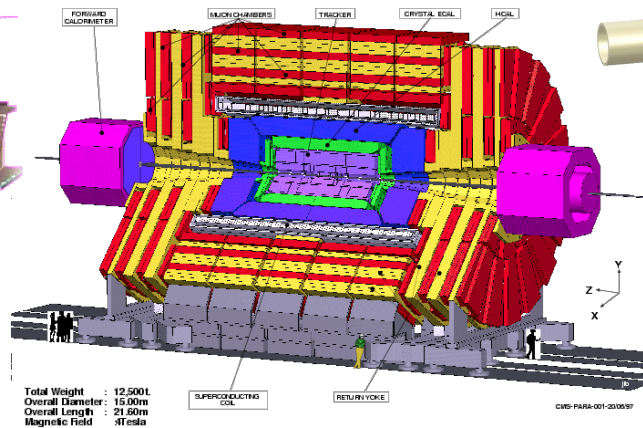


Geneva, Switzerland
 8.6km diameter
 $p+p, p+Pb, Pb+Pb$
 $\sqrt{s}_{NN} = 2.76 \text{ GeV}, 5.5 \text{ TeV}$

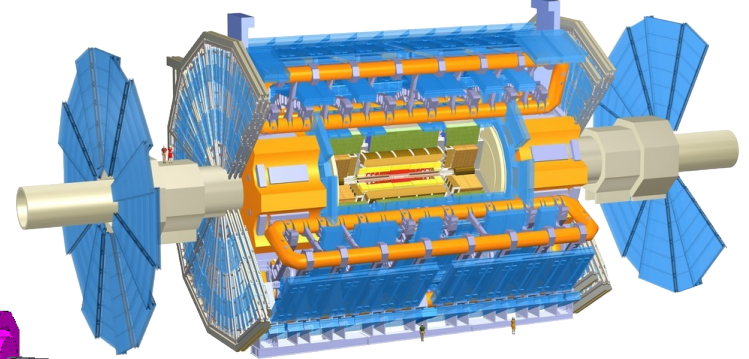




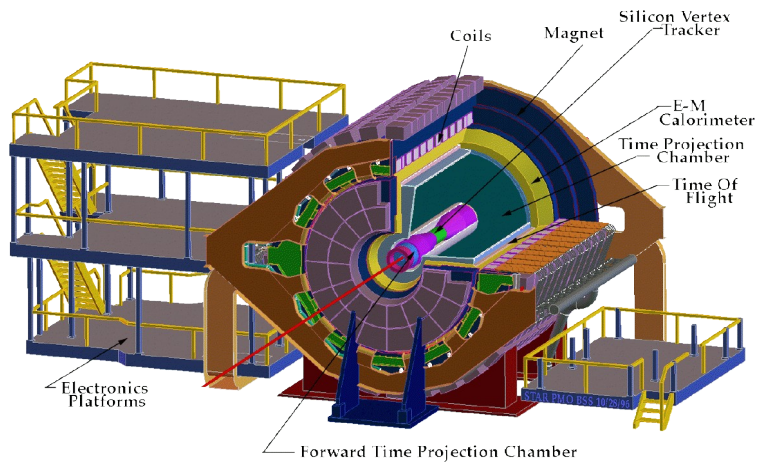
ALICE



CMS



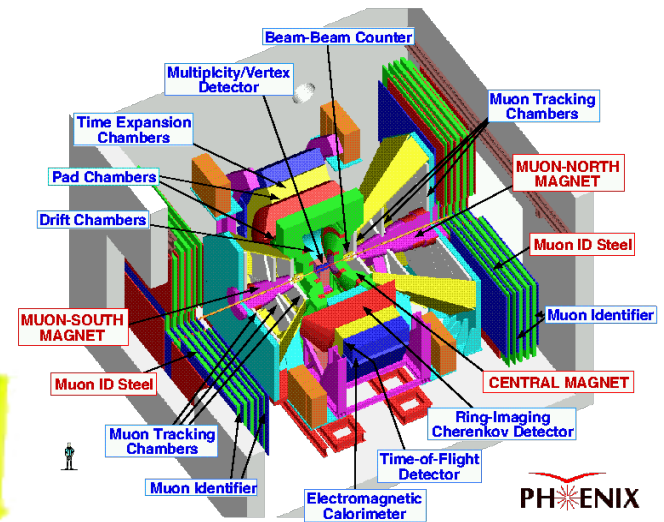
ATLAS



STAR



LHCb

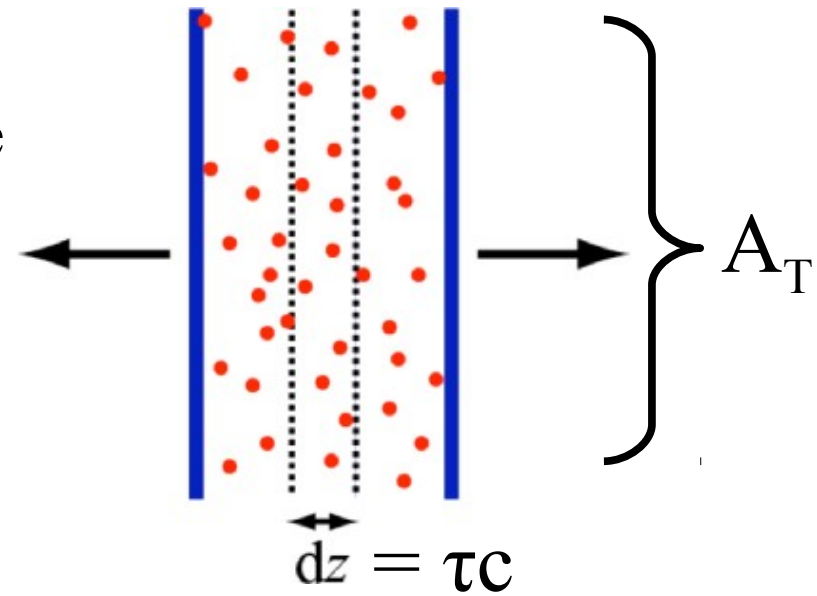


PHENIX

Forming the QGP

How can we estimate the energy density?

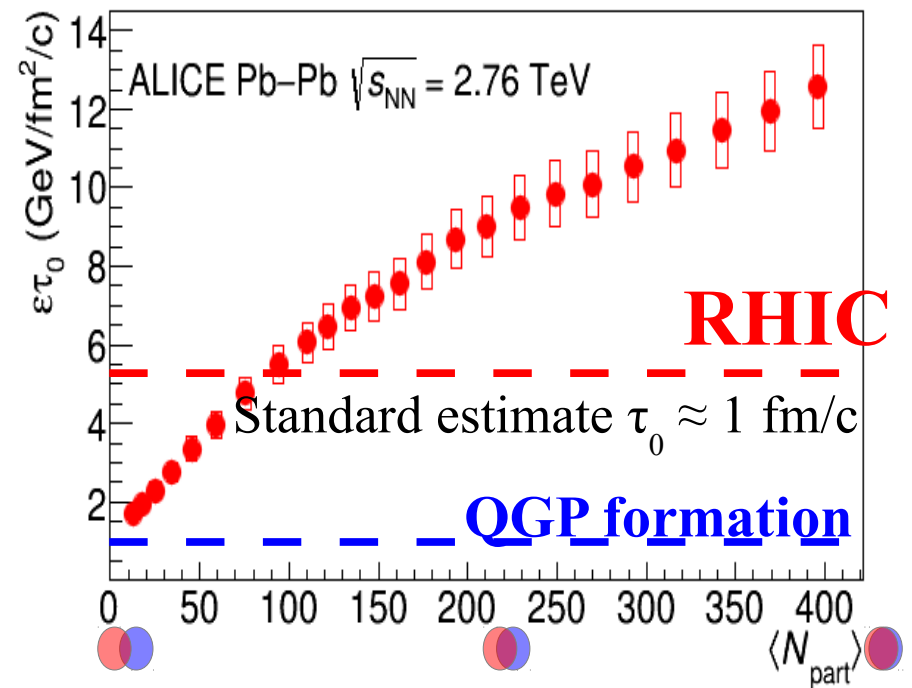
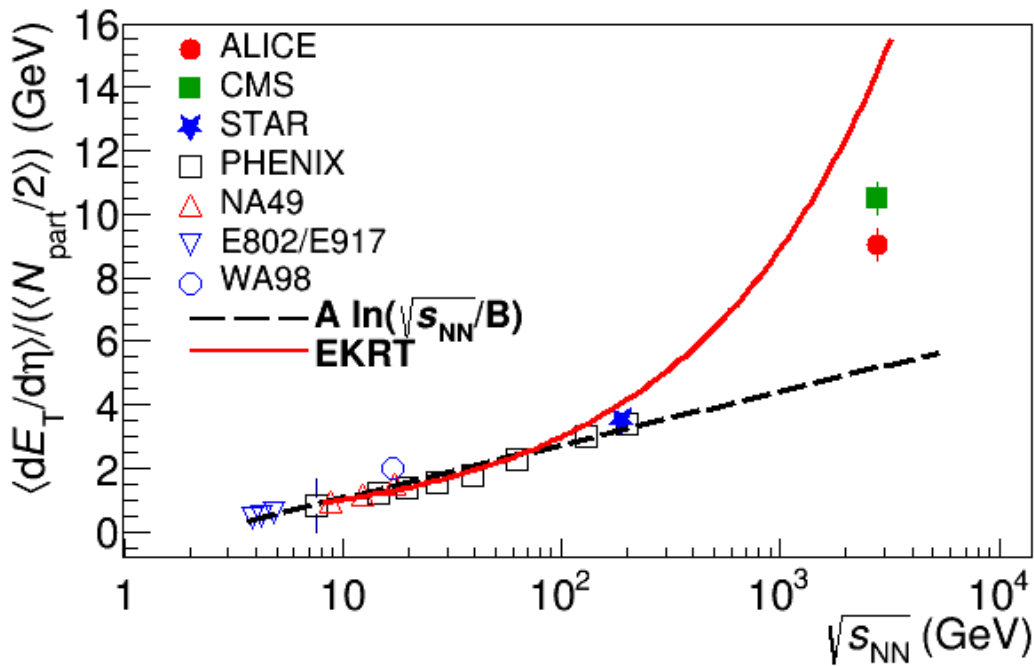
- Transverse energy (E_T)
 - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ϵ



$$\epsilon = \frac{1}{V} \frac{dE_T}{dy} = \frac{J}{A_T \tau c} \frac{dE_T}{d\eta}$$

- QGP formation for $\epsilon > 0.5 \text{ GeV}/\text{fm}^3$

Energy dependence from dE_T/dy

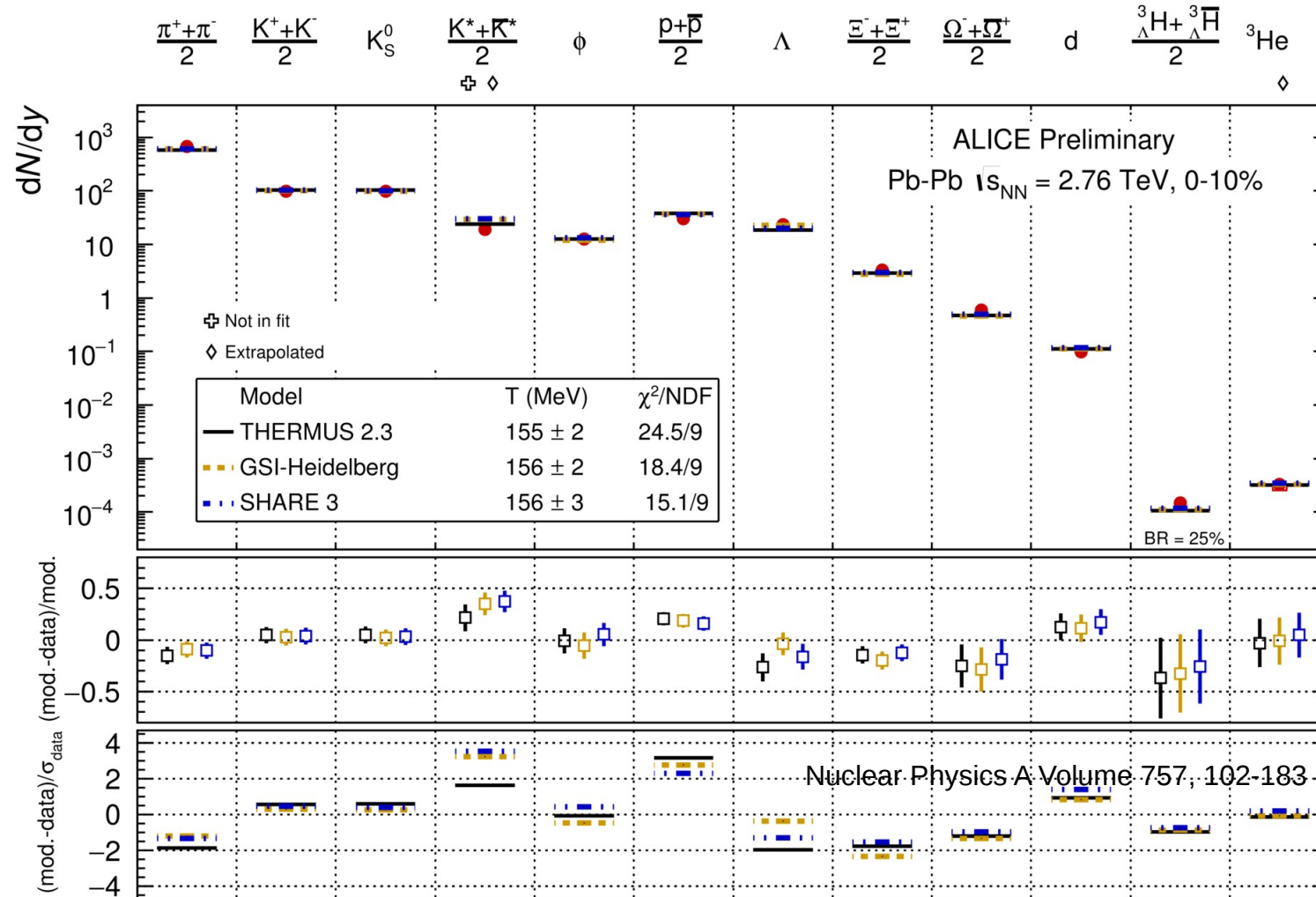


$$\epsilon = \frac{1}{Ac\tau_0} \frac{dE_T}{dy}$$

→ Higher than extrapolations of RHIC data

Where are we on the phase
diagram?

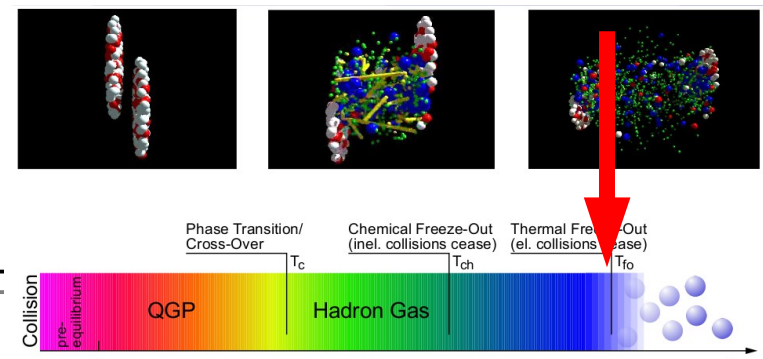
Chemistry - equilibrium



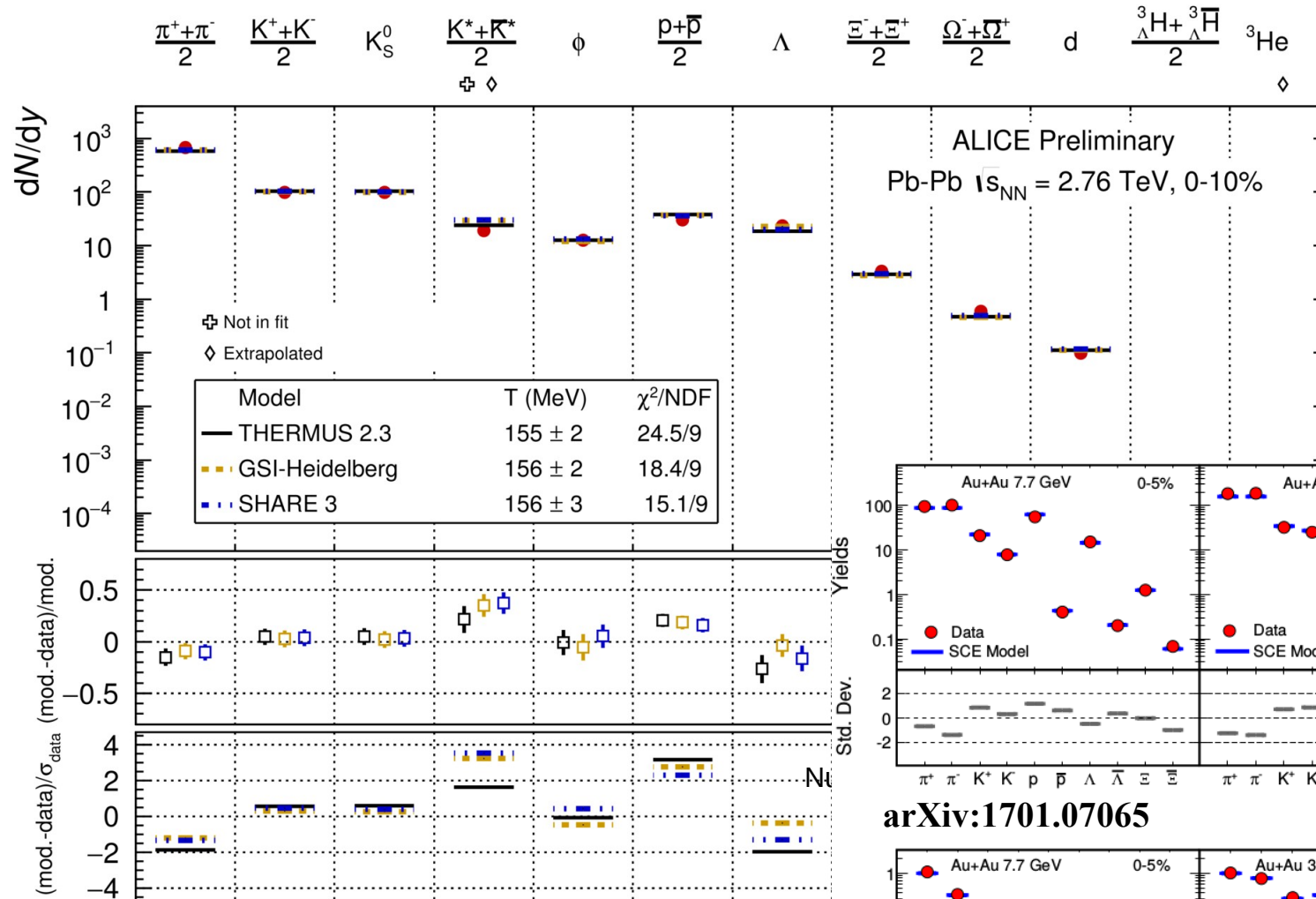
ALI-PREL-94600

Nuclear Physics A Volume 757, 102-183

- Ratios of particles expected from a model

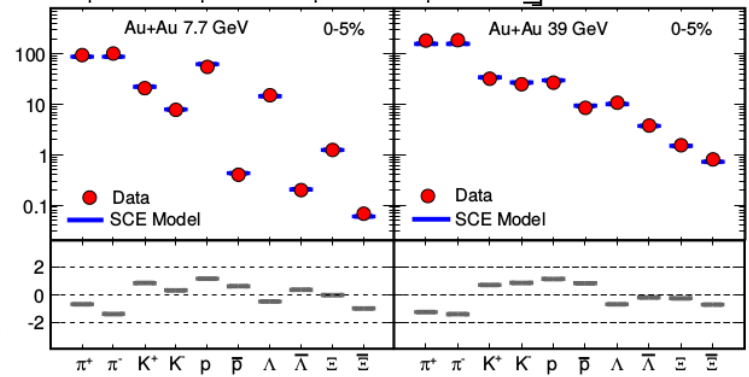


Chemistry - equilibrium

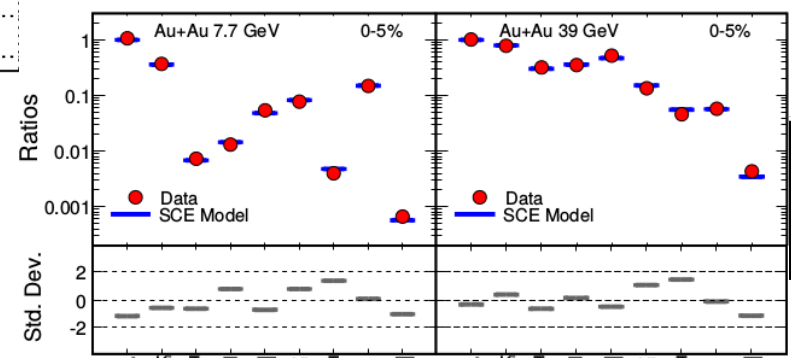


ALI-PREL-94600

ALICE Preliminary
Pb-Pb $1S_{NN} = 2.76$ TeV, 0-10%



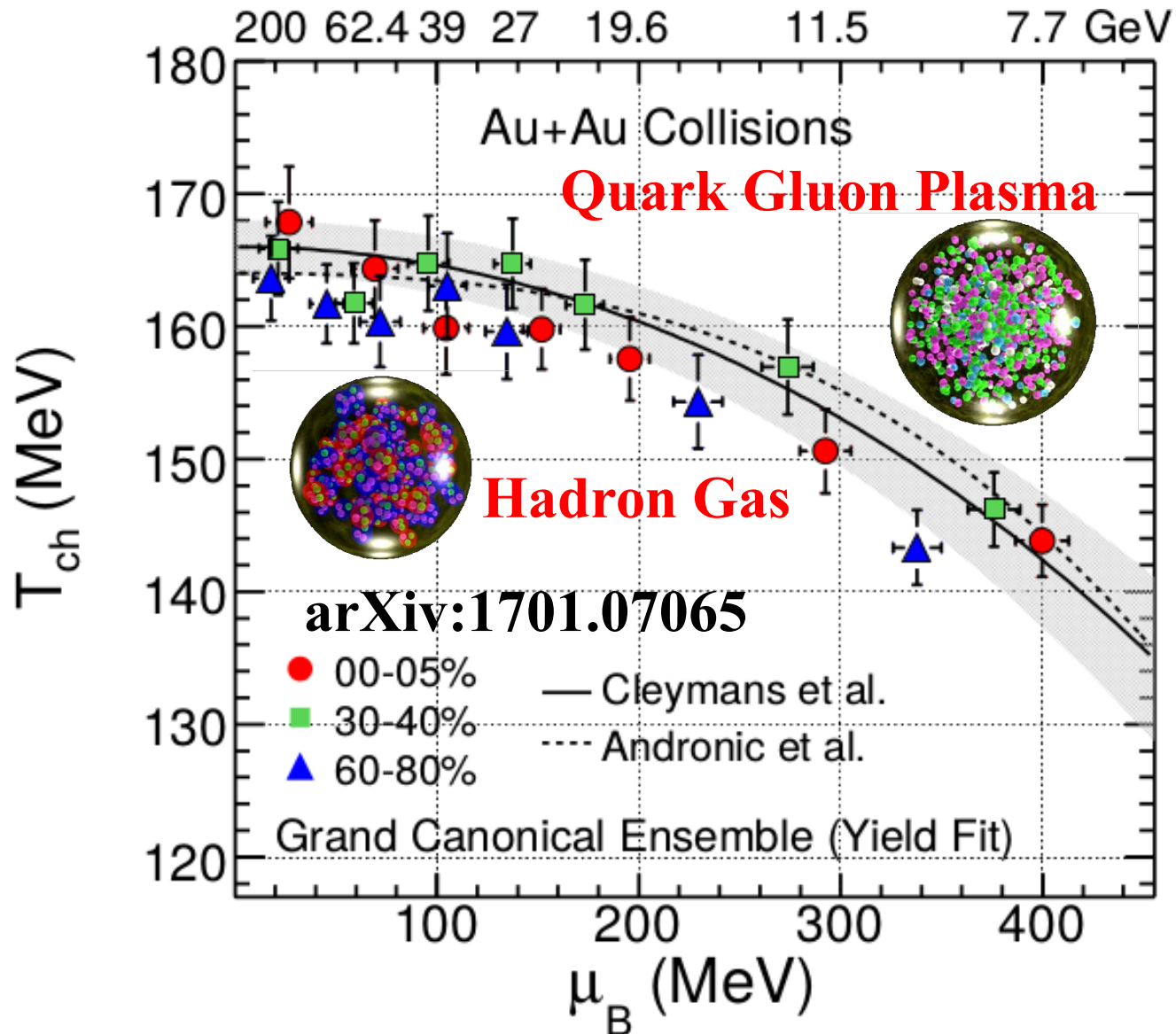
arXiv:1701.07065

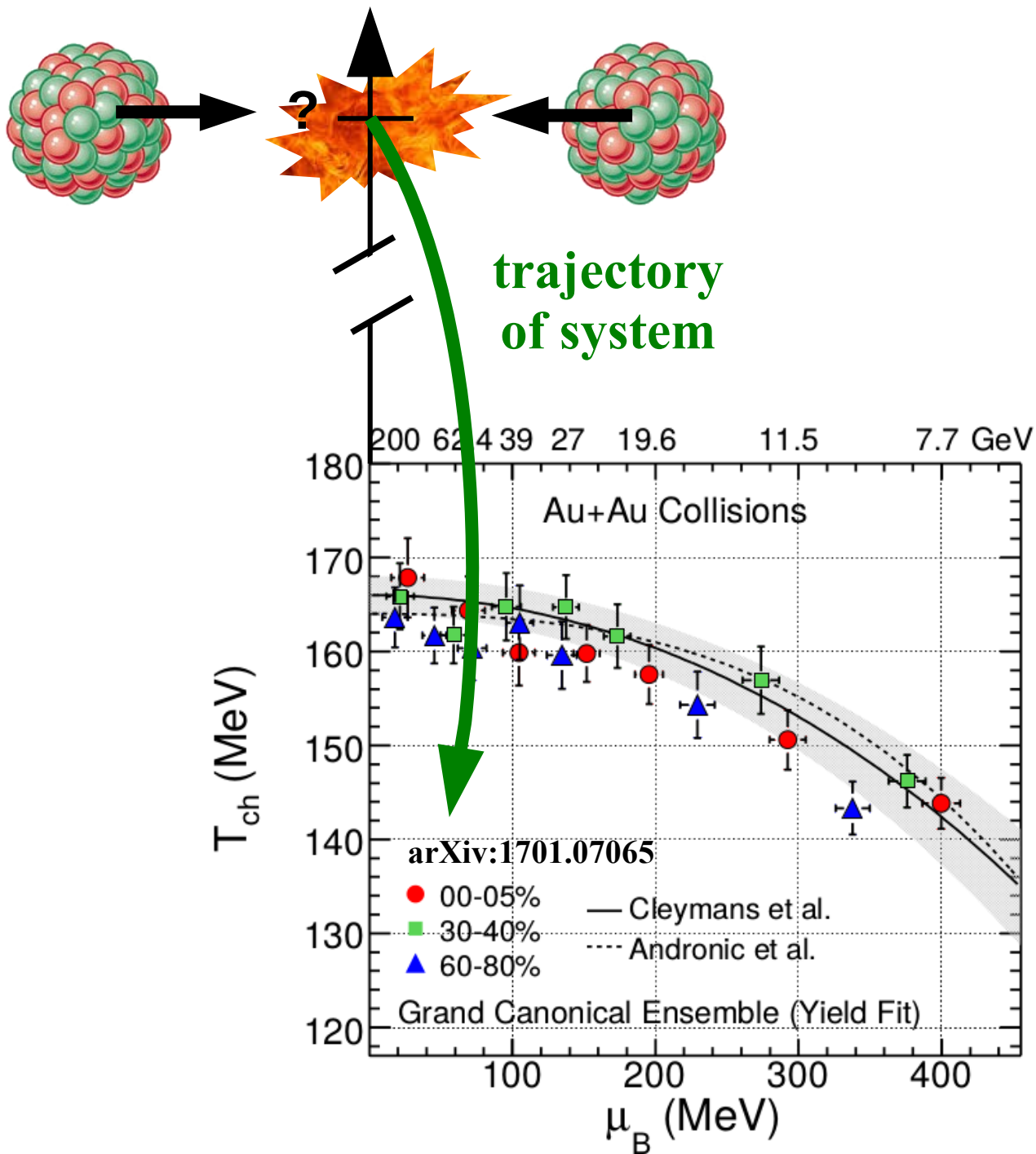


- Ratios of particles expected from a model



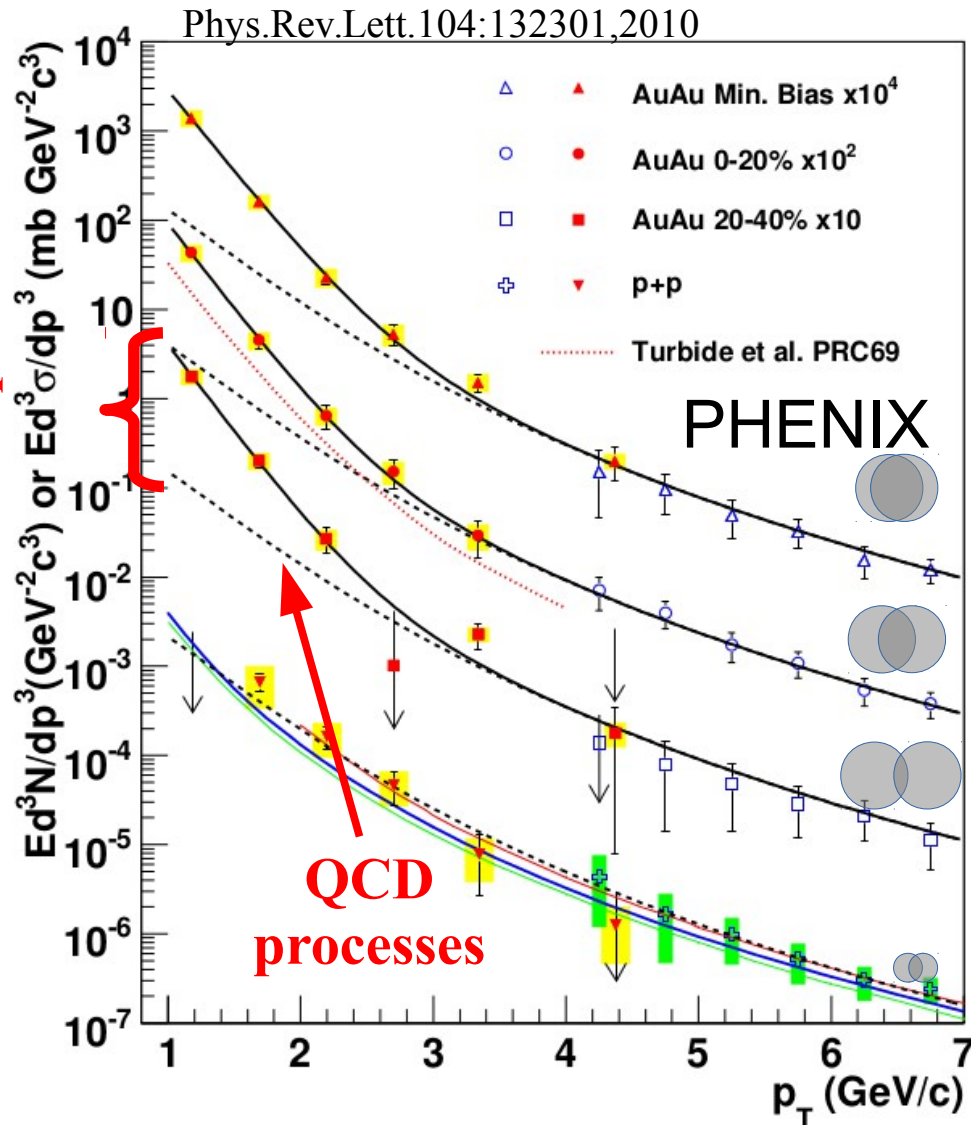
QCD Phase Diagram





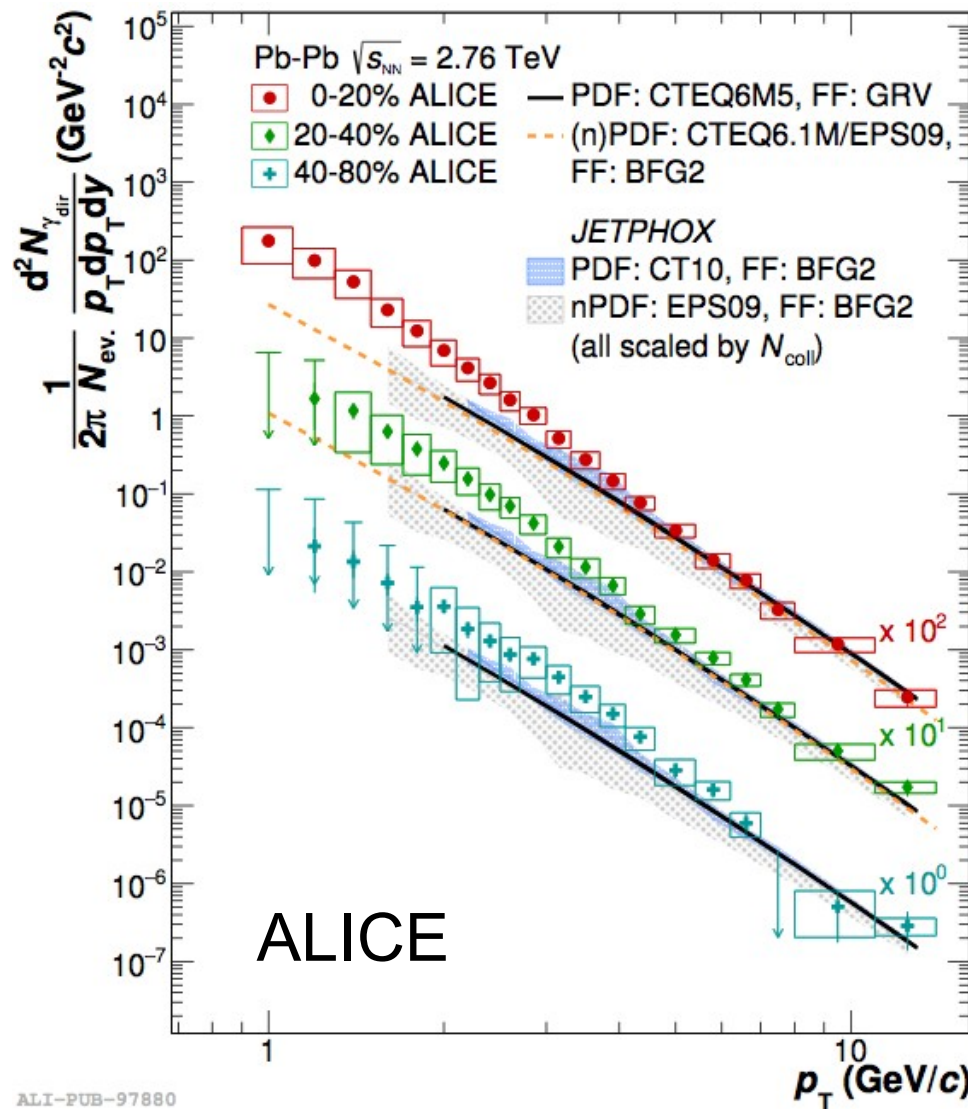
Thermal photons

Thermal photons



Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$

Inverse slope: $T = 221 \pm 19 \text{ (stat)} \pm 19 \text{ (syst) MeV}$

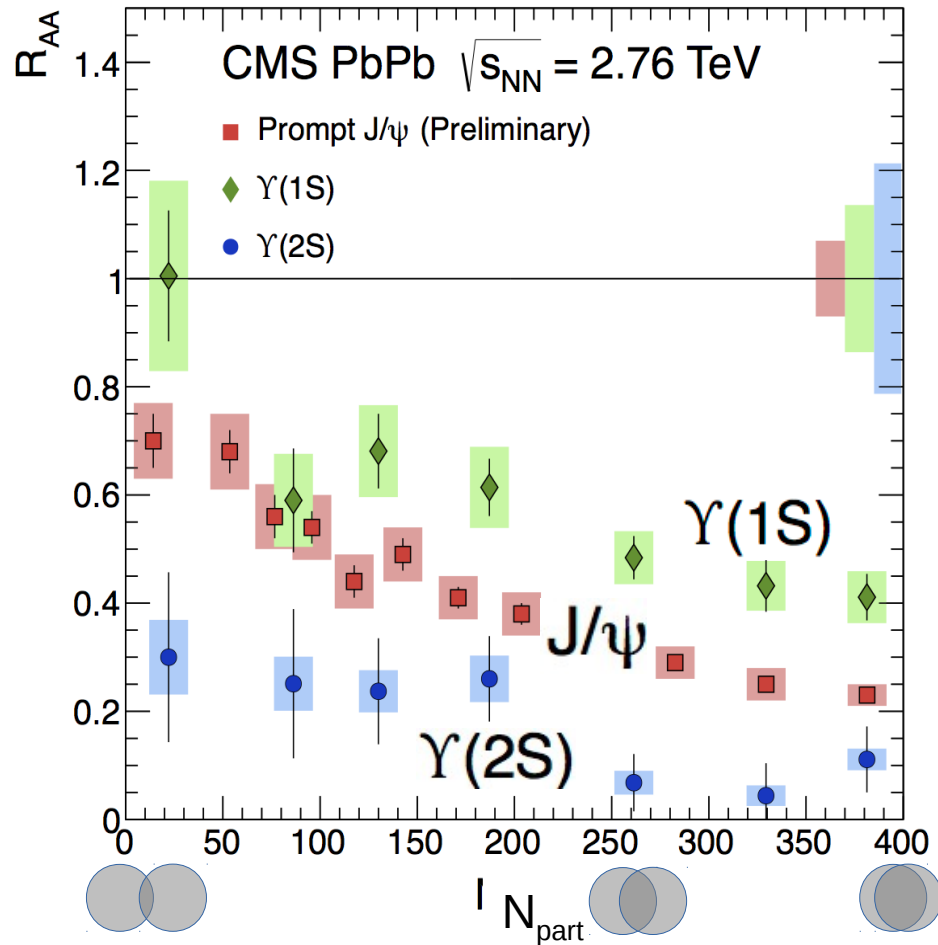


Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$

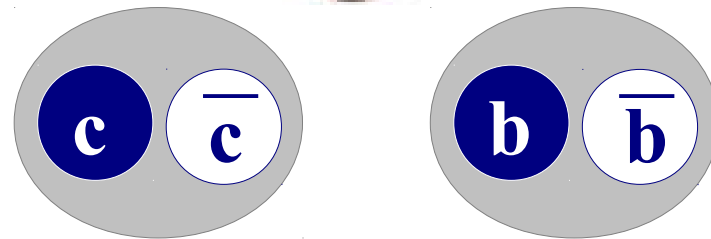
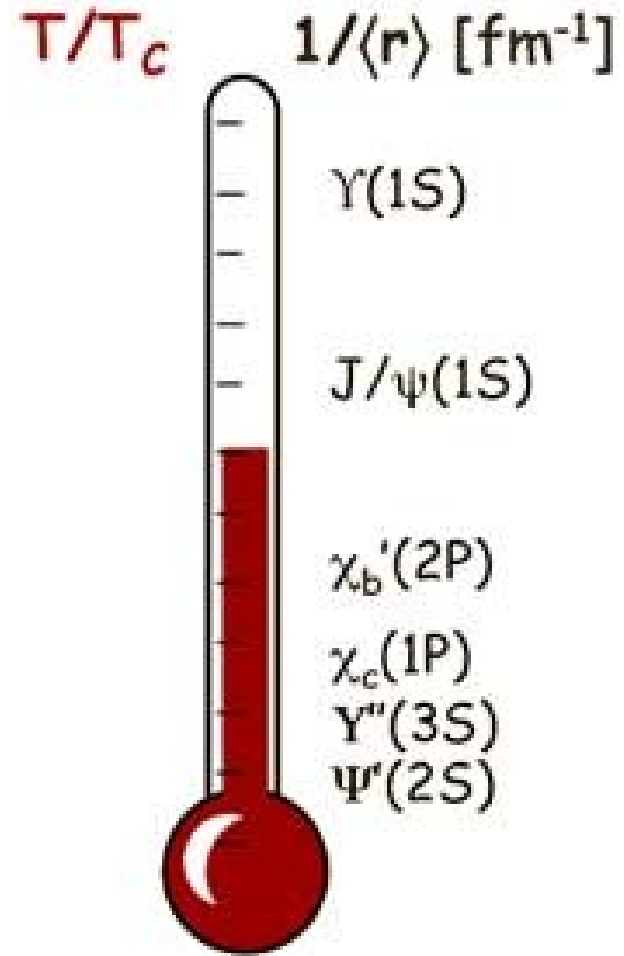
Inverse slope: $T = 304 \pm 51 \text{ MeV}$

A quarkonium-thermometer

CMS-PAS HIN-11-011
arXiv:1708.04962 [nucl-ex]

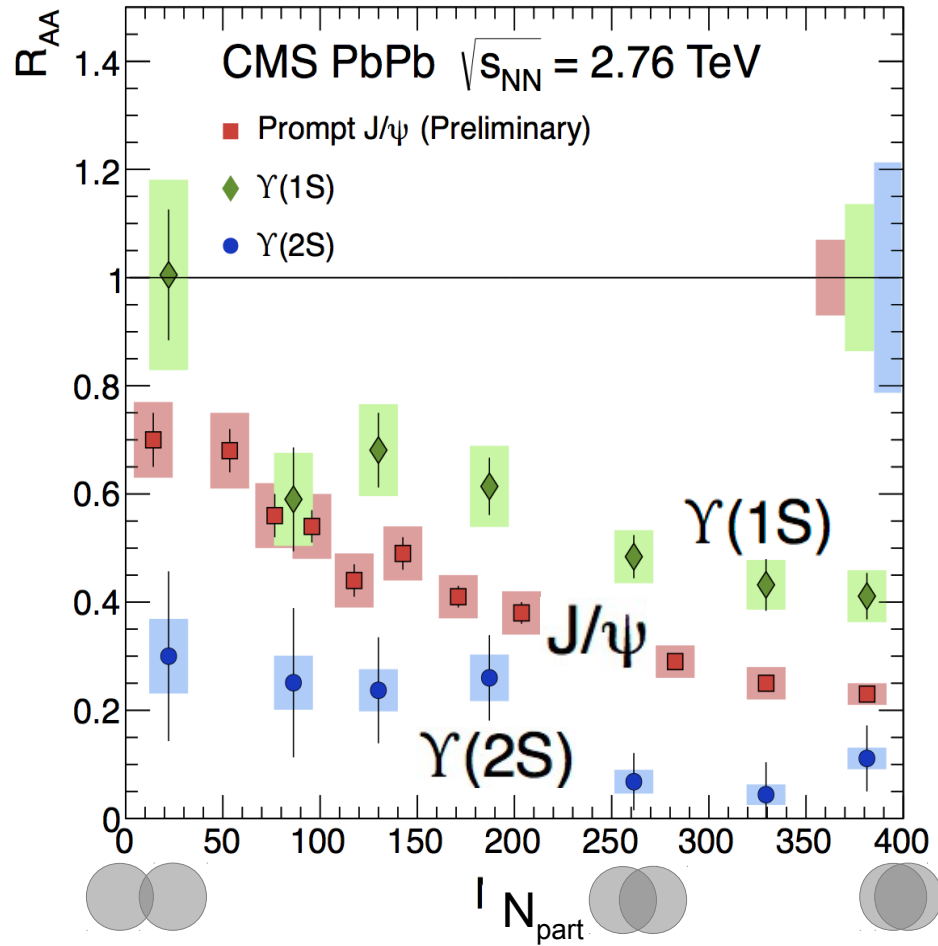


Clear hierarchy in R_{AA} of different quarkonium states



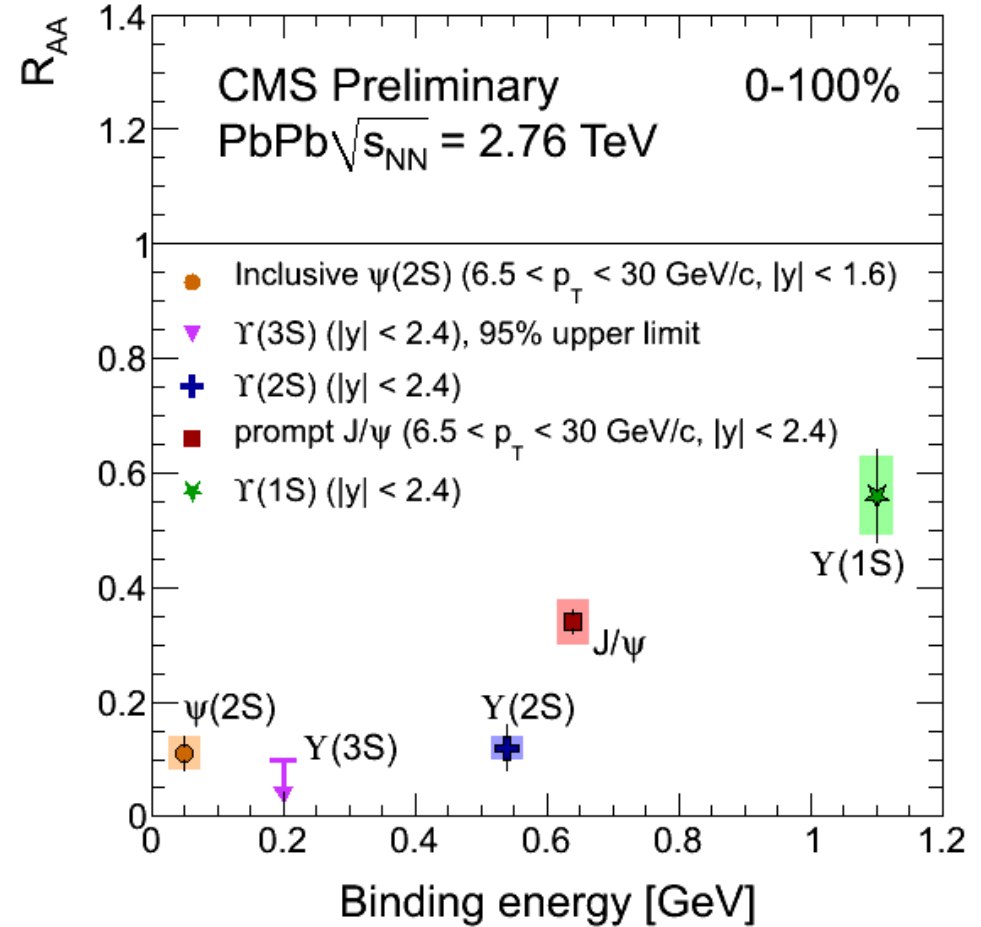
A quarkonium-thermometer

CMS-PAS HIN-11-011
arXiv:1708.04962 [nucl-ex]



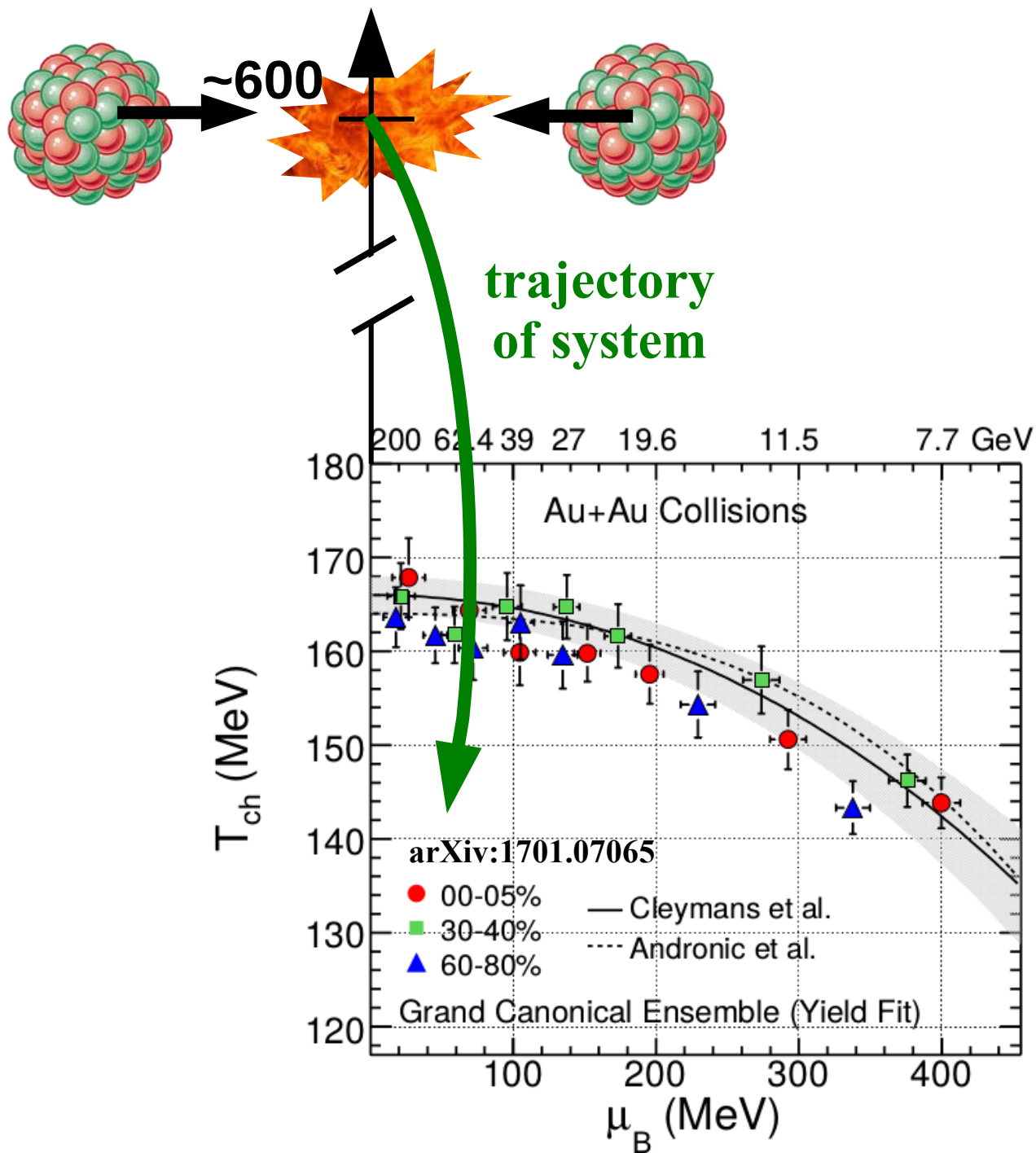
Clear hierarchy in R_{AA} of different quarkonium states

Note: $6.5 < p_T < 30$ GeV for J/ψ and ψ(2s)



Expected in terms of binding energy

CMS-PAS HIN-12-014, HIN-12-007

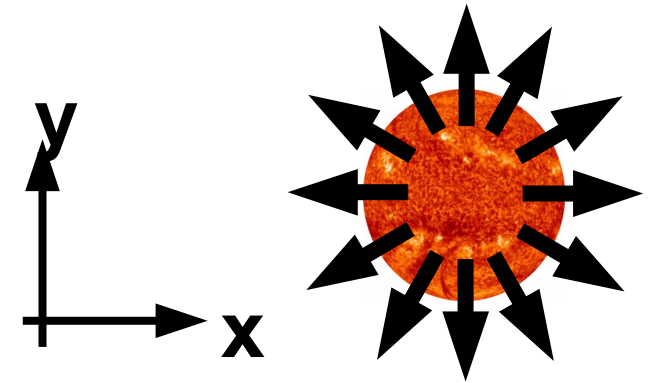


Hydrodynamical flow

Hydrodynamical flow

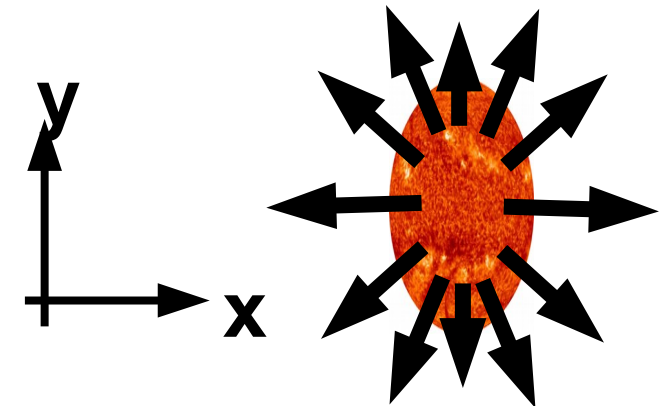
- Radial Flow

- Affects shape of low p_T particle spectra



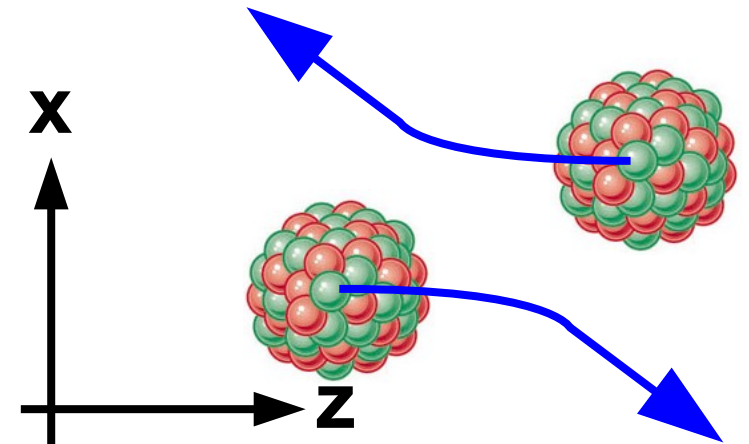
- Elliptic Flow

- Sensitive to initial geometry
- Requires early thermalization of the medium

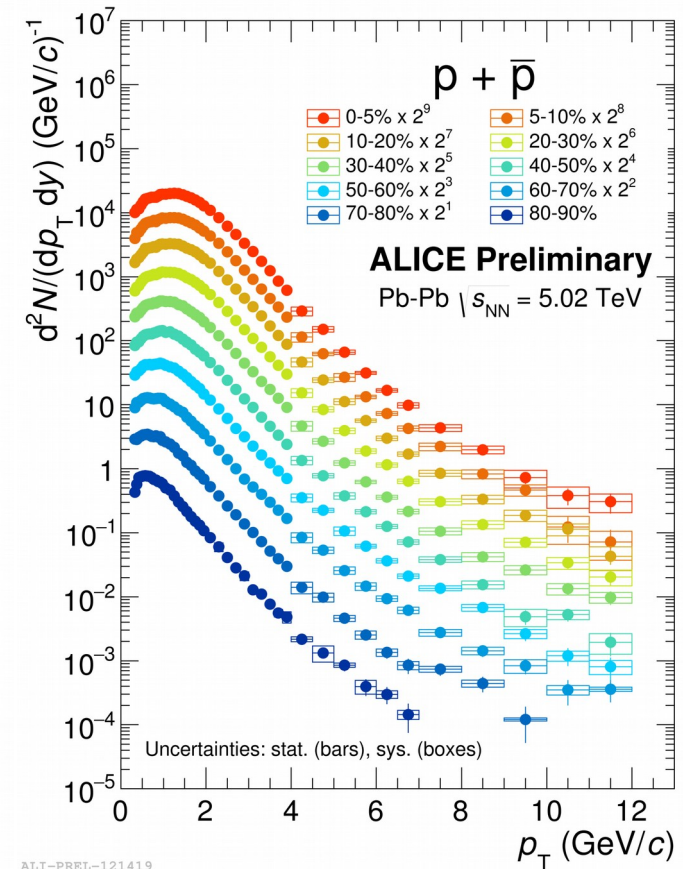
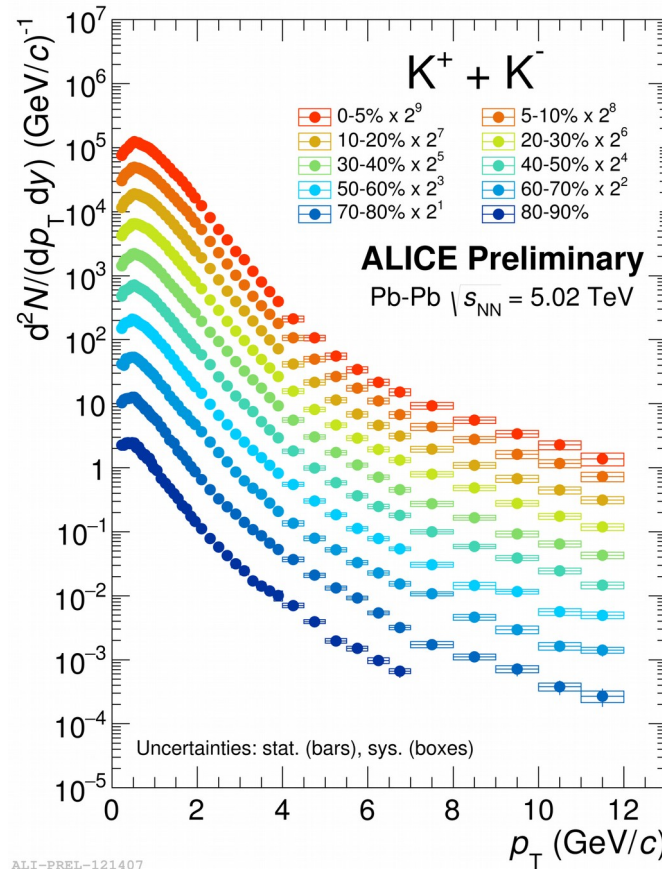
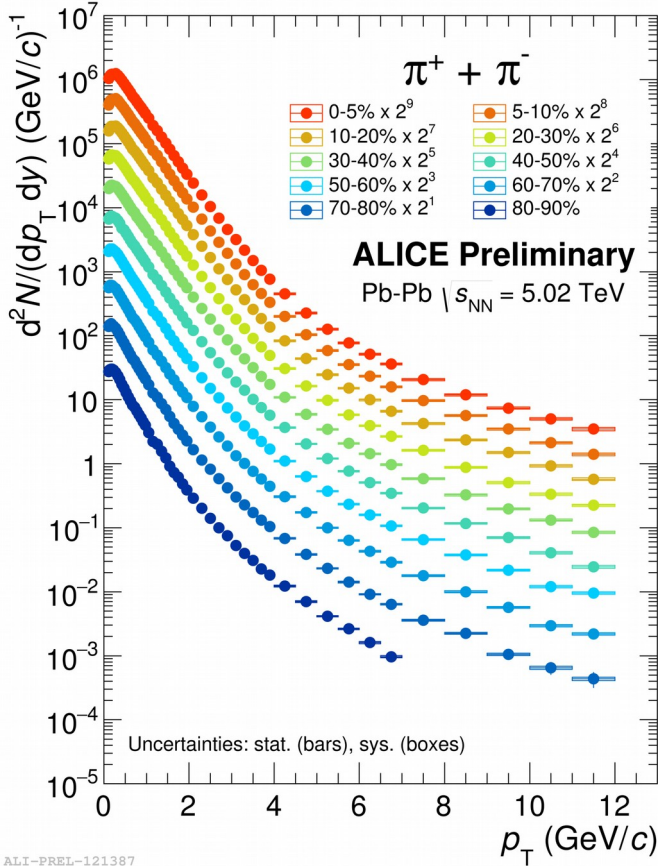


- Directed Flow

- Produced in the pre-equilibrium phase of the collision
- Decreases with increasing \sqrt{s}_{NN}



Hadron spectra

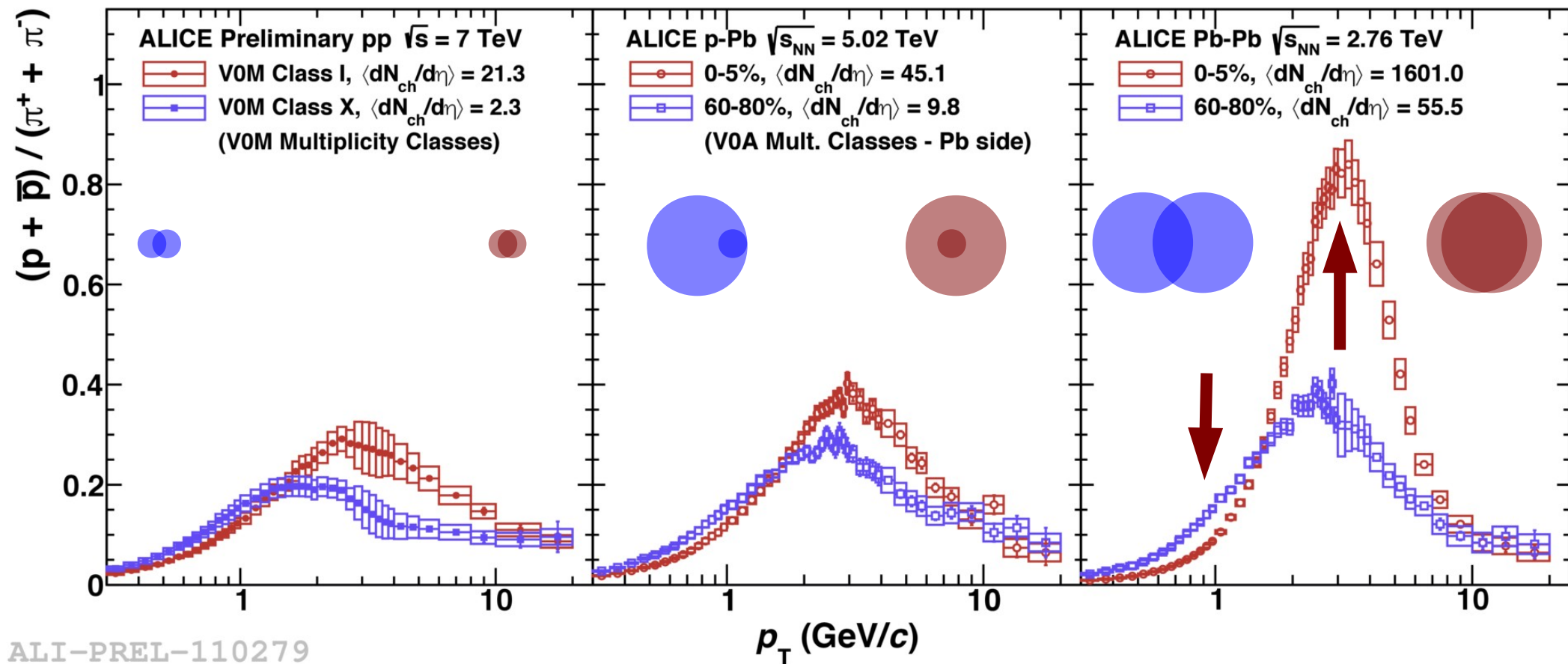


- Radial flow boosts hadrons
 - low p_T : mass dependent slope
 - high p_T : common hardening of p_T spectra

$$T_{eff} \approx T_f + \frac{1}{2} m \beta_T^2 \quad p_T \ll m$$

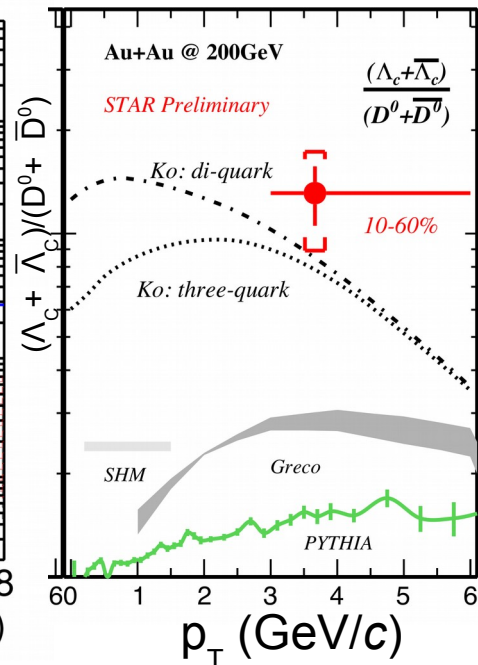
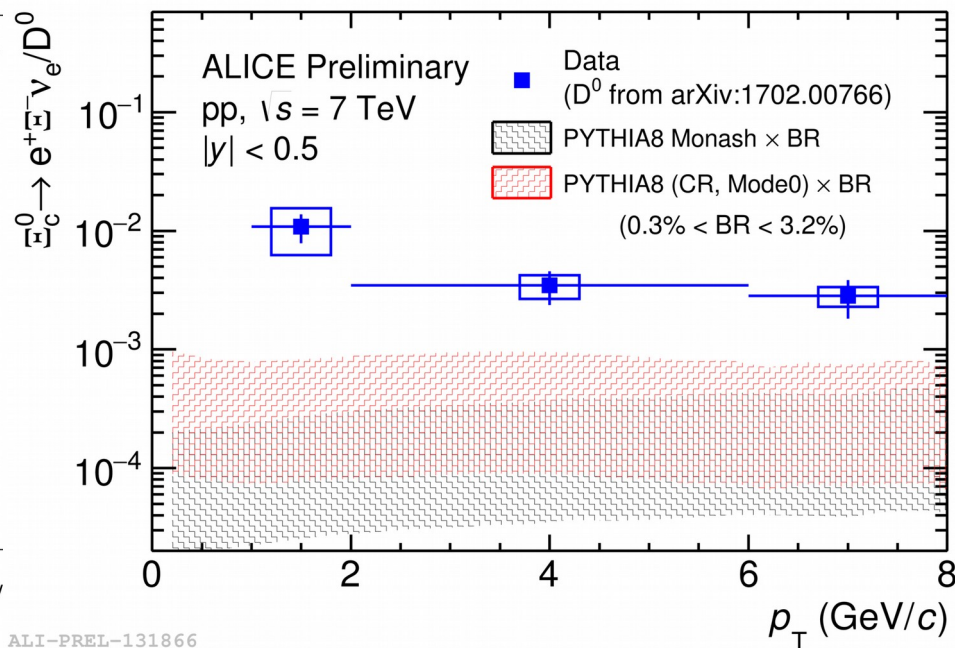
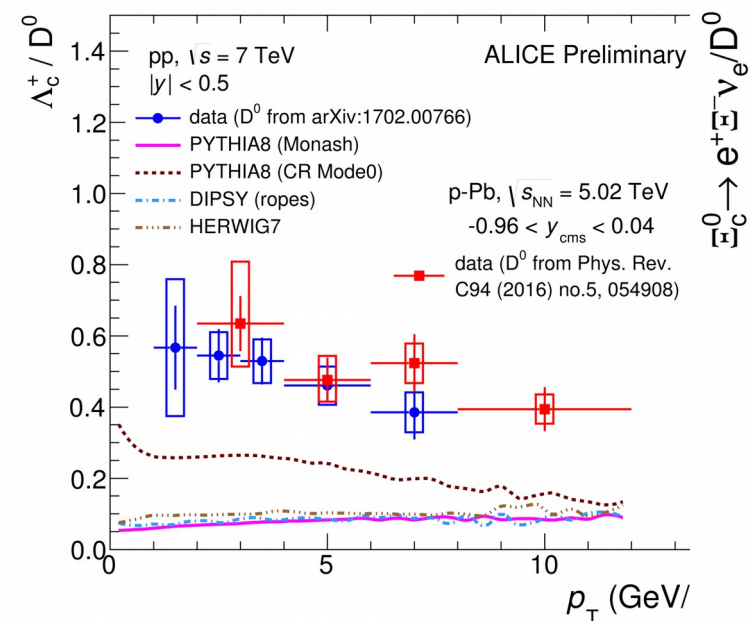
$$T_{eff} \approx T_f \sqrt{\frac{1 - \beta_T}{1 + \beta_T}} \quad p_T \gg m$$

Radial Flow and Baryon/Meson Ratio



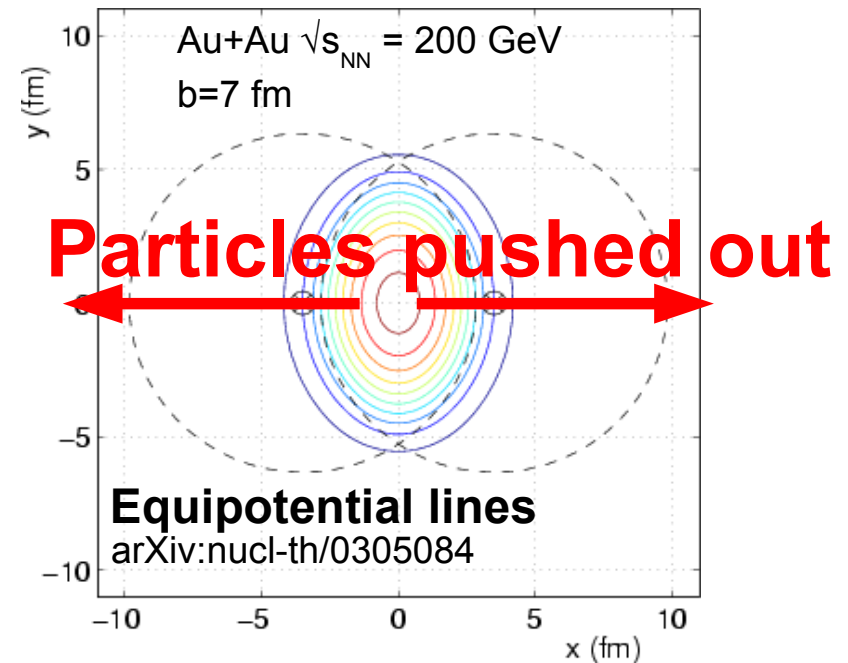
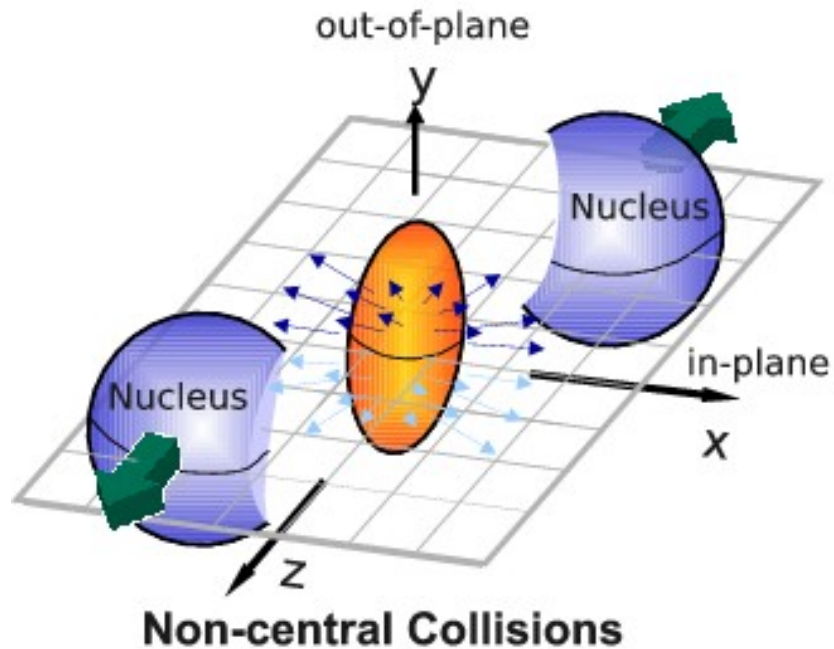
- Radial flow pushes protons to intermediate p_T and depletes low p_T
 - Stronger radial flow in central Pb–Pb collisions
- Similar effects observed in high-multiplicity pp and p–Pb collisions

Charmed baryons

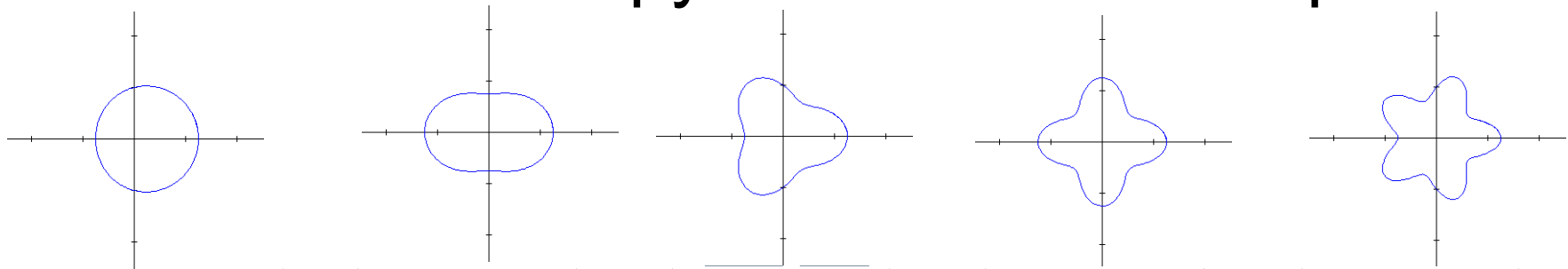


- First midrapidity measurement of Λ_c in pp and p–Pb collisions
 - Charmed baryon/meson ratio not reproduced by event generators
- First measurement of Ξ_c in pp collisions
- Constraints of charm hadronization
- Benchmark for measurements in heavy ion collisions

Anisotropic flow

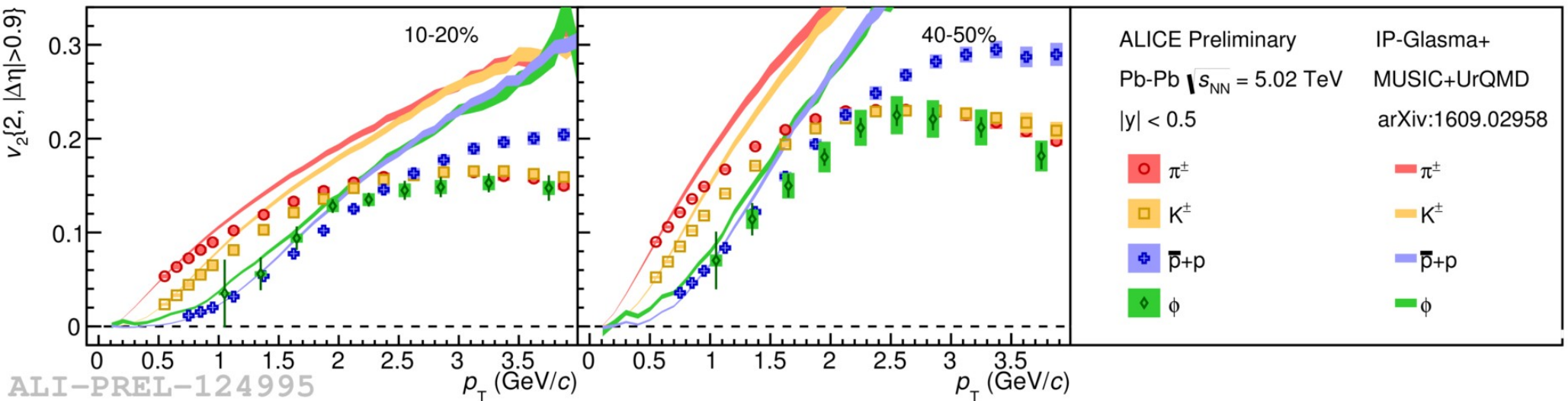


- Initial overlap asymmetric \rightarrow pressure gradients
- Momentum anisotropy \rightarrow Fourier decomposition:



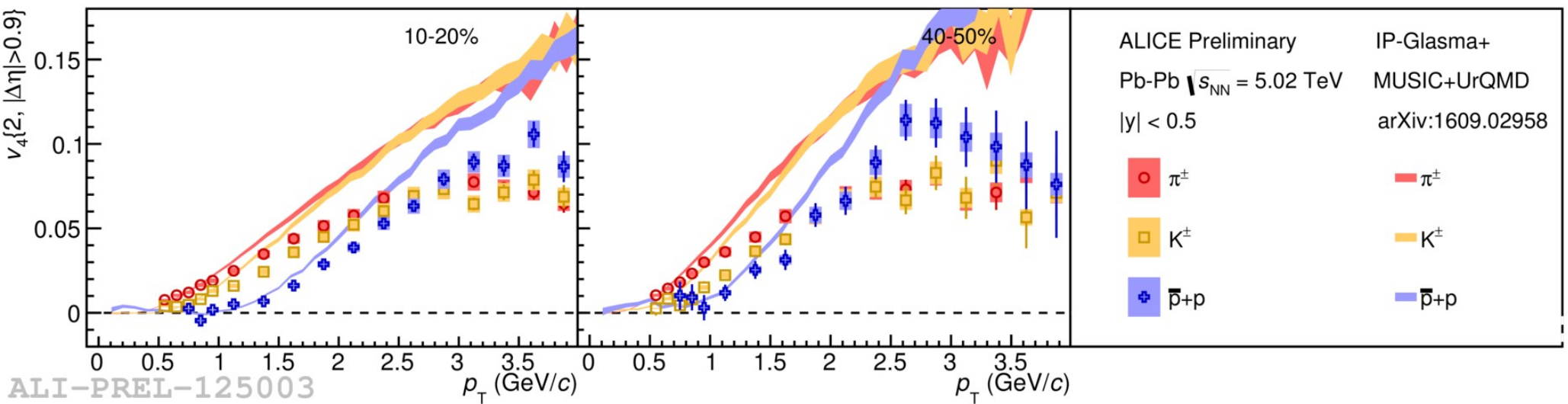
$$\frac{d^2 N}{dp_T d\phi} \approx 1 + 2v_1 \cos(d\phi) + 2v_2 \cos(2d\phi) + 2v_3 \cos(3d\phi) + 2v_4 \cos(4d\phi) + 2v_5 \cos(5d\phi) + \dots$$

Anisotropic flow - v_2



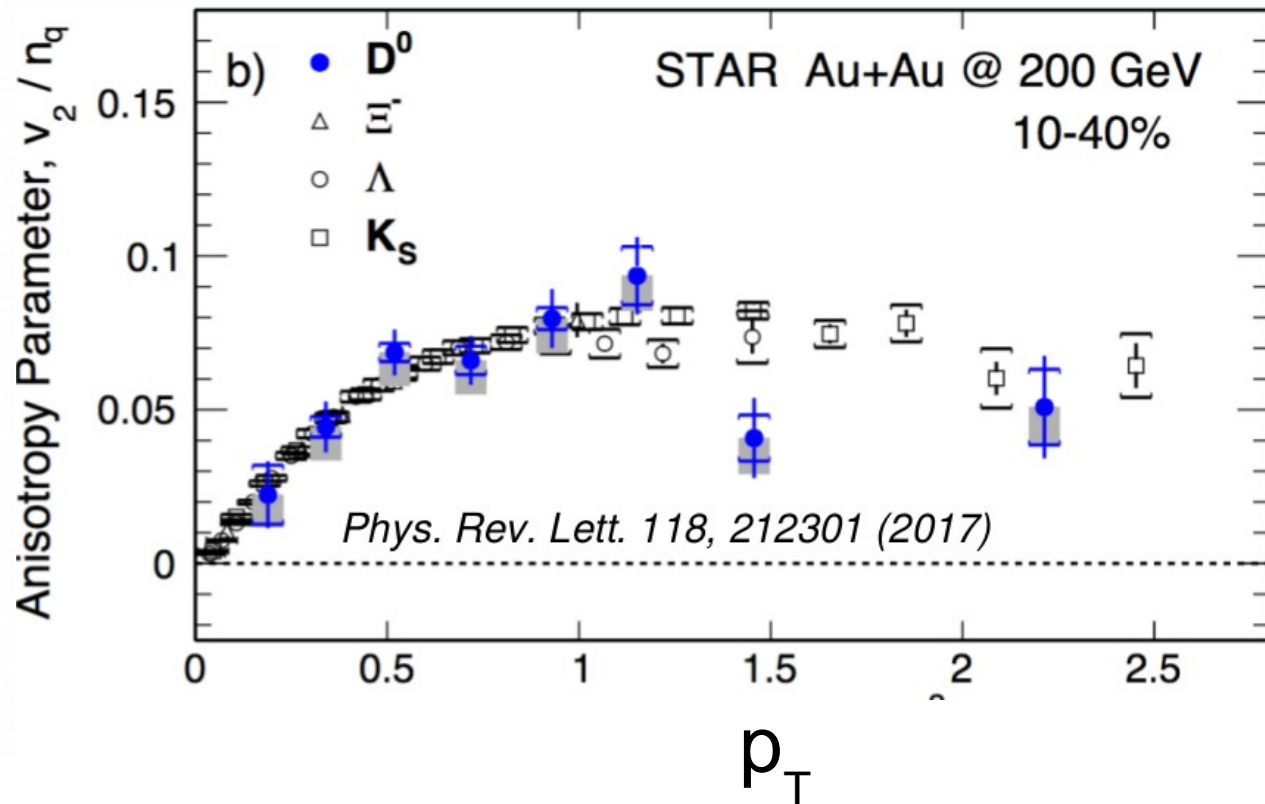
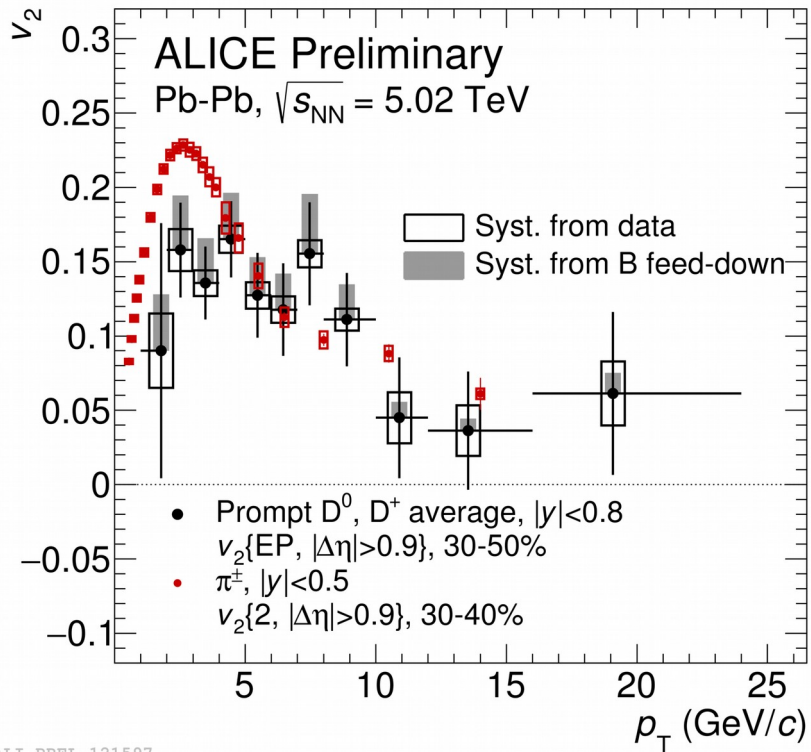
- v_2 sensitive to:
 - initial conditions: geometry
 - final state: particle interactions (medium properties, e.g. shear viscosity)
- Data in agreement with hydrodynamic models at low p_T

Anisotropic flow - v_4



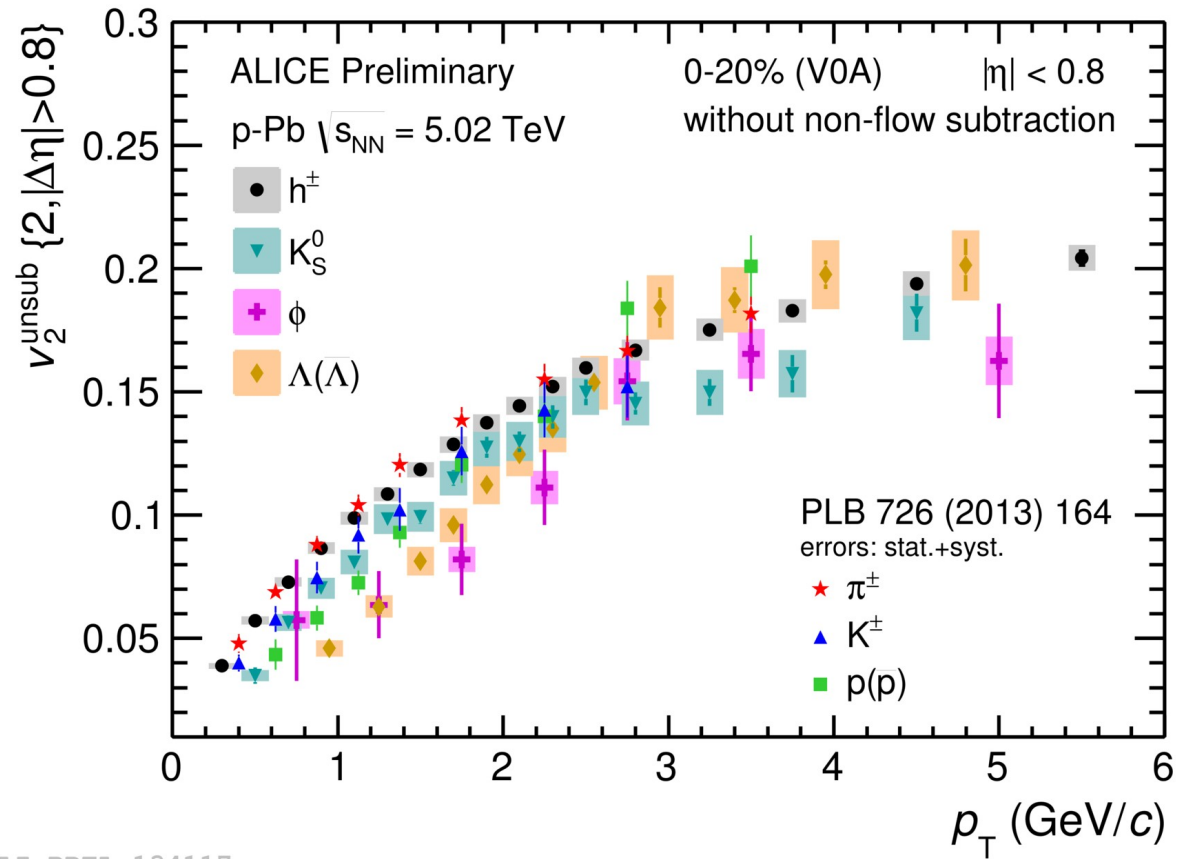
- v_4 more sensitive to interactions and less to initial state
 - hydrodynamic models work at low p_T ($p_T < 1$ GeV/c)
 - only describes trend at intermediate p_T ($1 < p_T < 2$ GeV/c)

D meson v_2



- Even heavy quarks flow!

v_2 in p—Pb



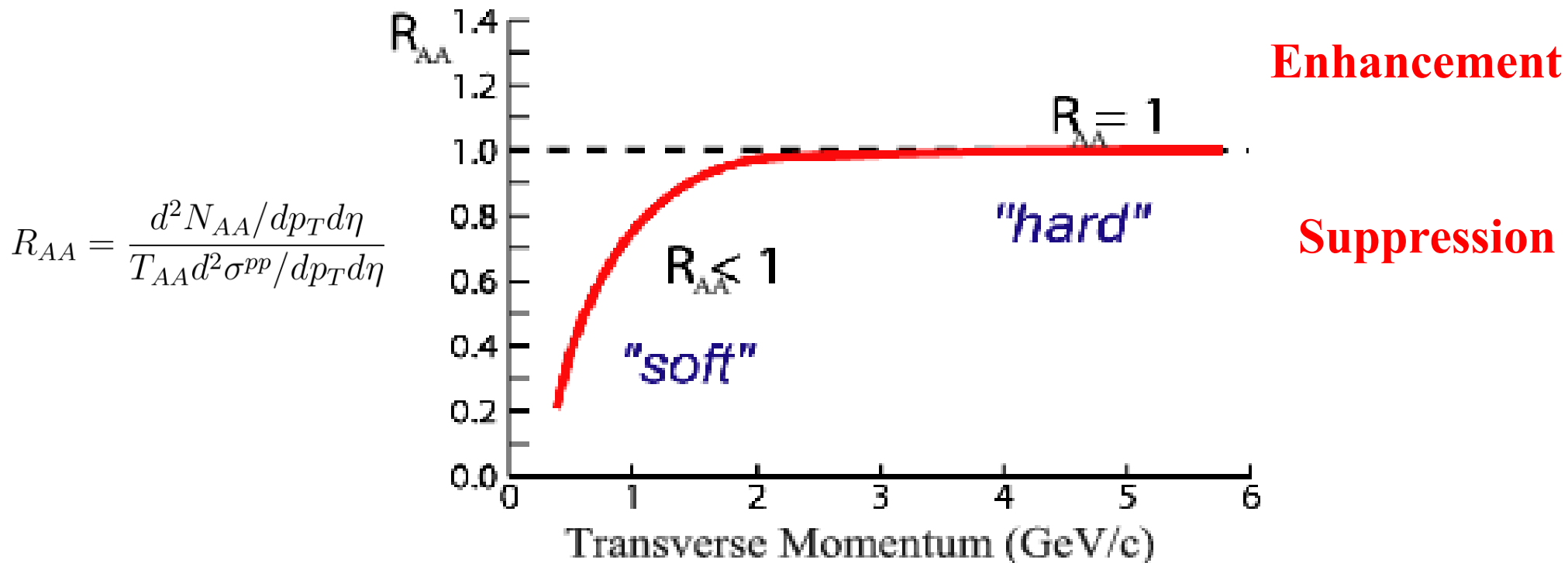
ALI-PREL-134117

- mass ordering like in Pb—Pb

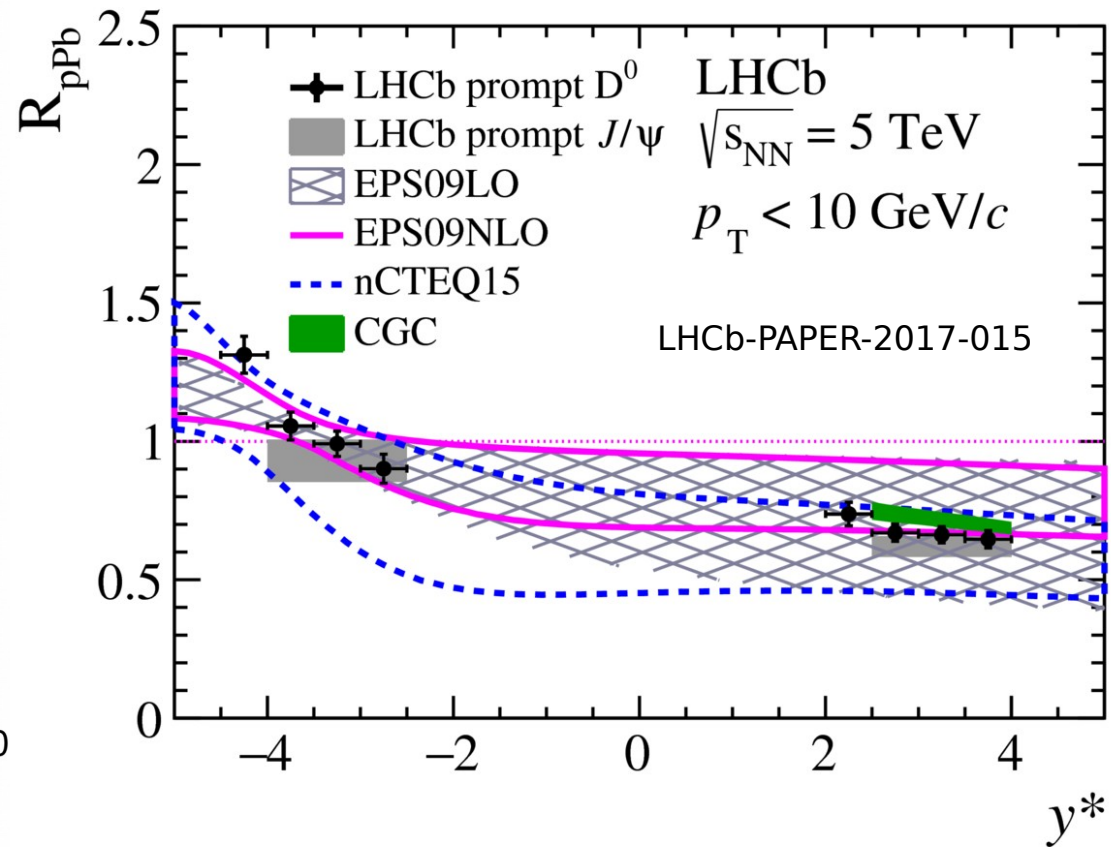
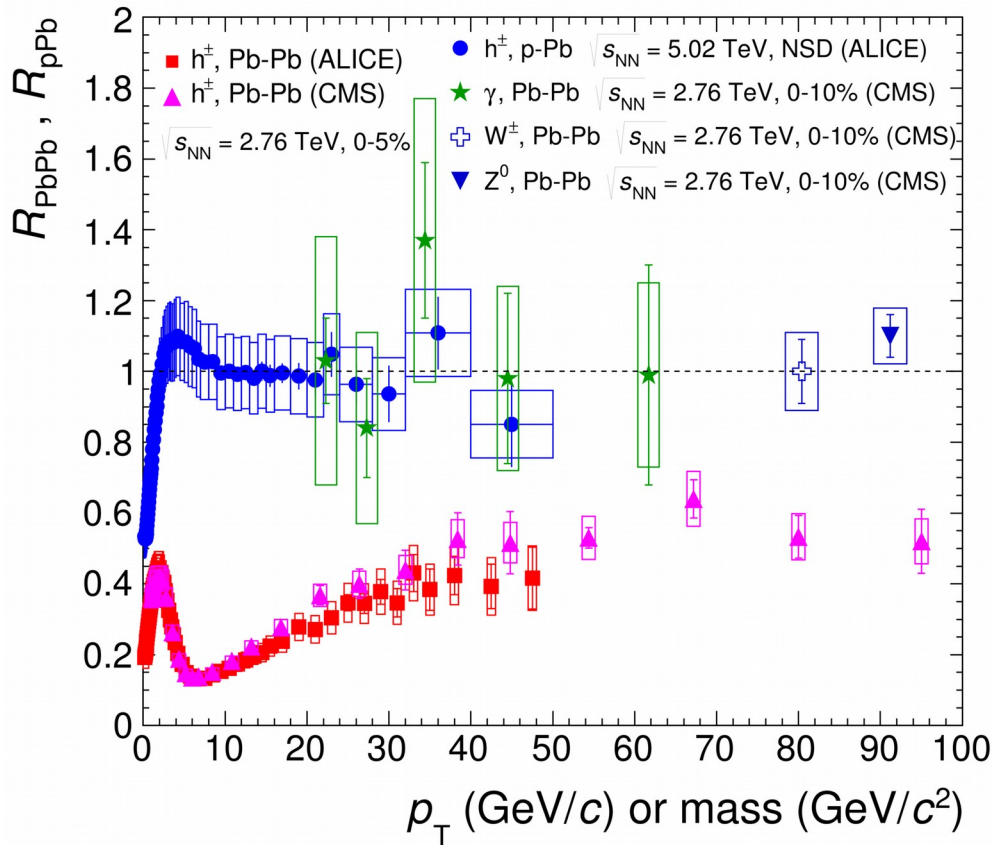
Energy loss in the medium

Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high- p_T probes (jets) are suppressed, this is evidence of jet quenching

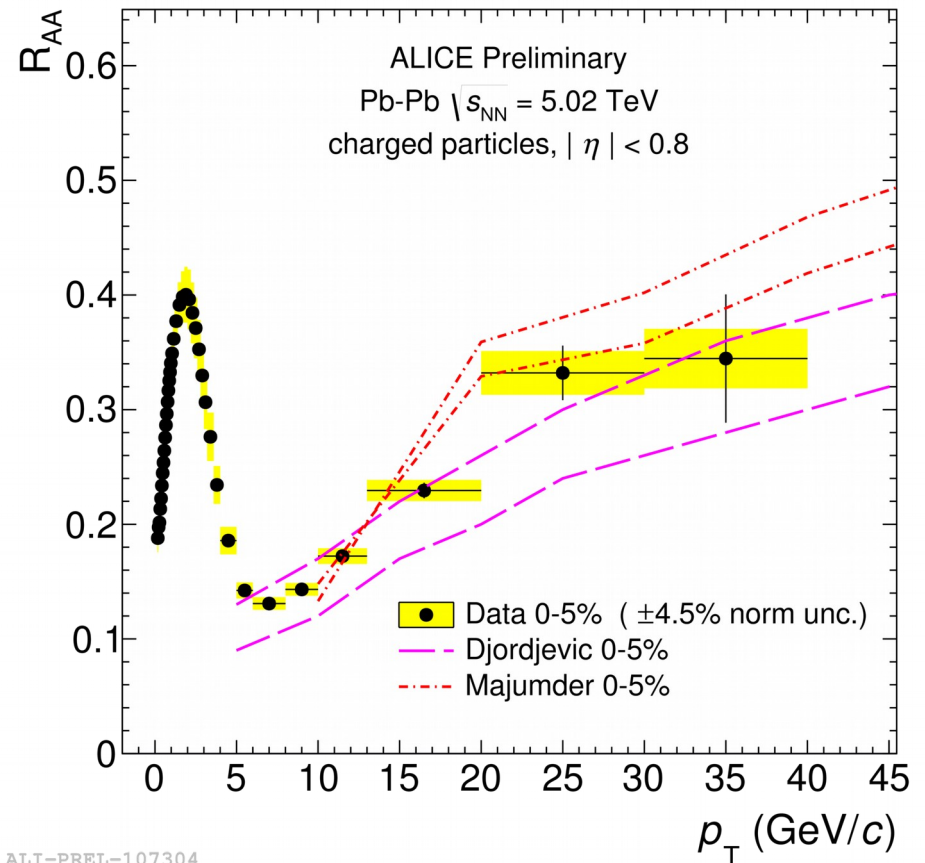
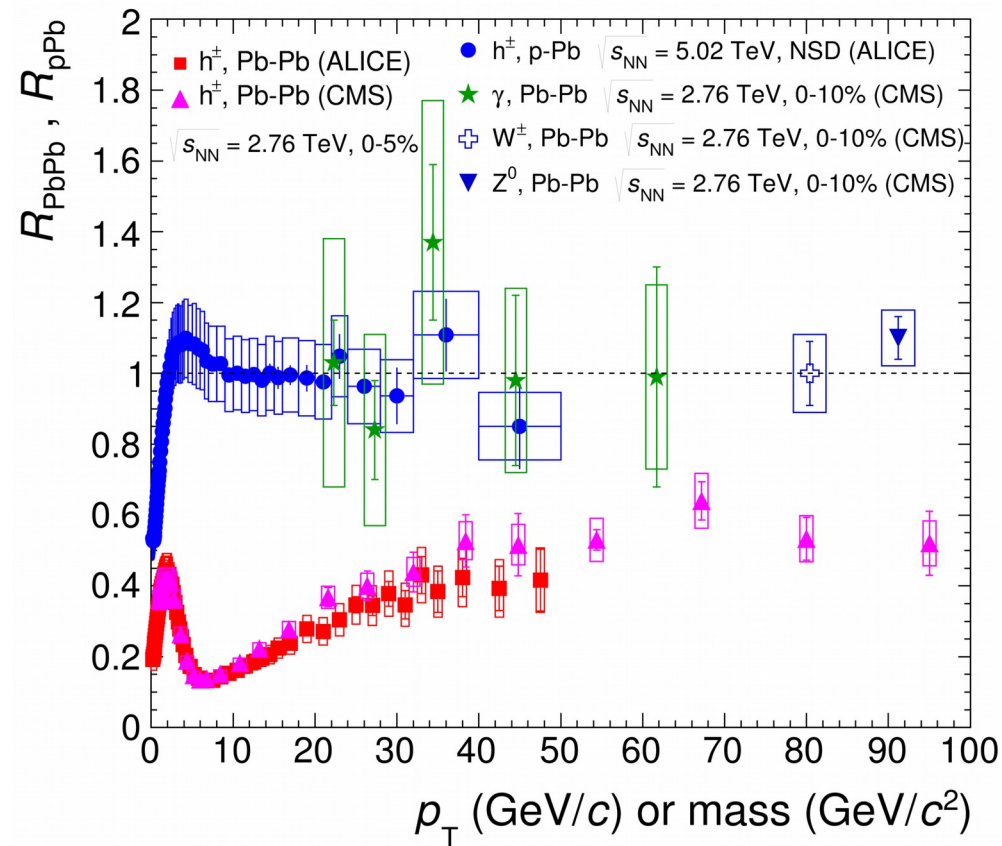


Nuclear modification factor



- Charged hadrons (colored probes)
 - Suppressed in Pb—Pb
 - Not suppressed in p—Pb at midrapidity
 - Some cold nuclear matter effects at forward rapidities
- Electroweak probes not suppressed

Nuclear modification factor

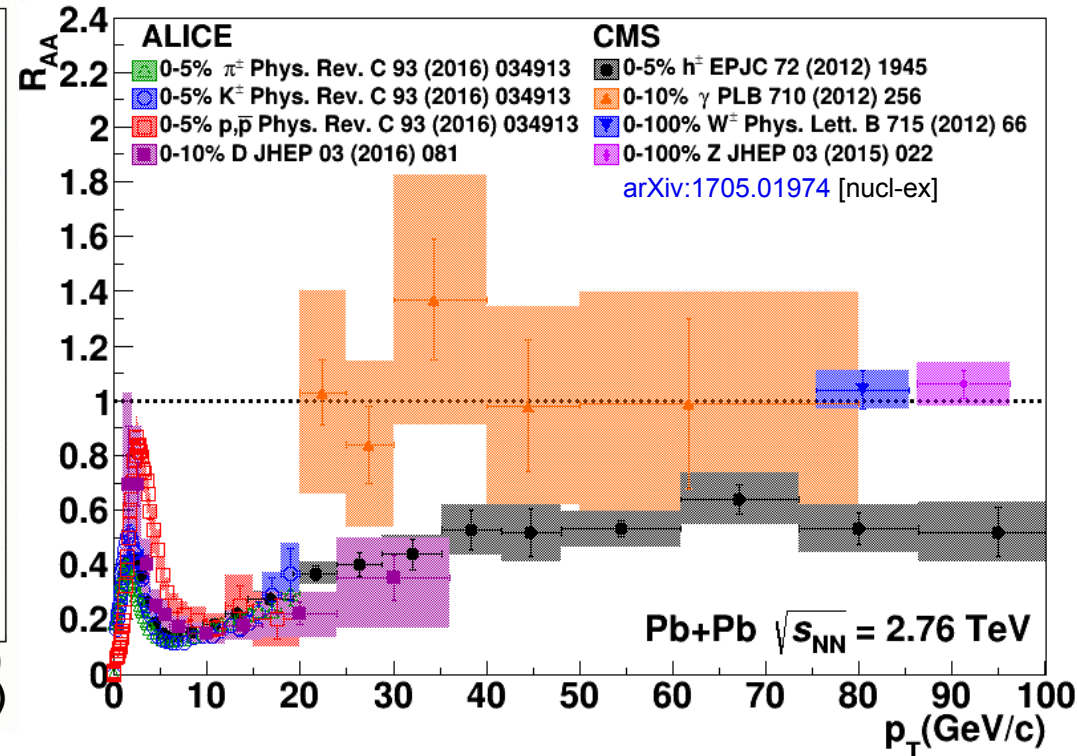
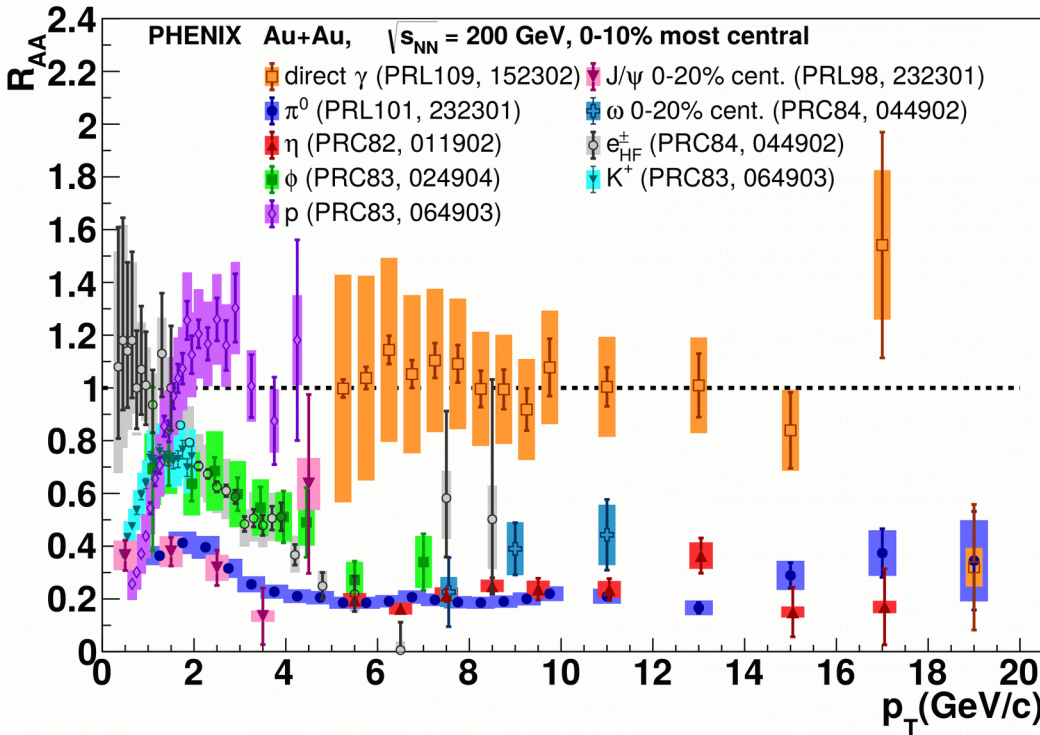


- Charged hadrons (colored probes)
 - Suppressed in Pb—Pb
 - Not suppressed in p—Pb at midrapidity
 - Some cold nuclear matter effects at forward rapidities
- Electroweak probes not suppressed
- Qualitatively in agreement with models

Nuclear modification factor R_{AA}

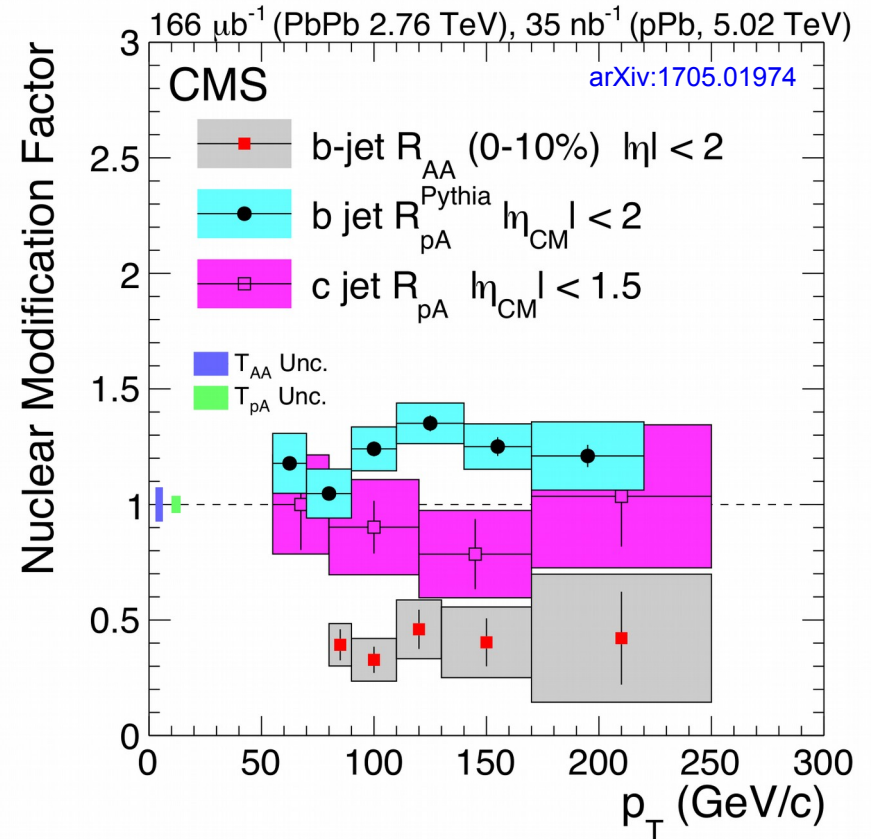
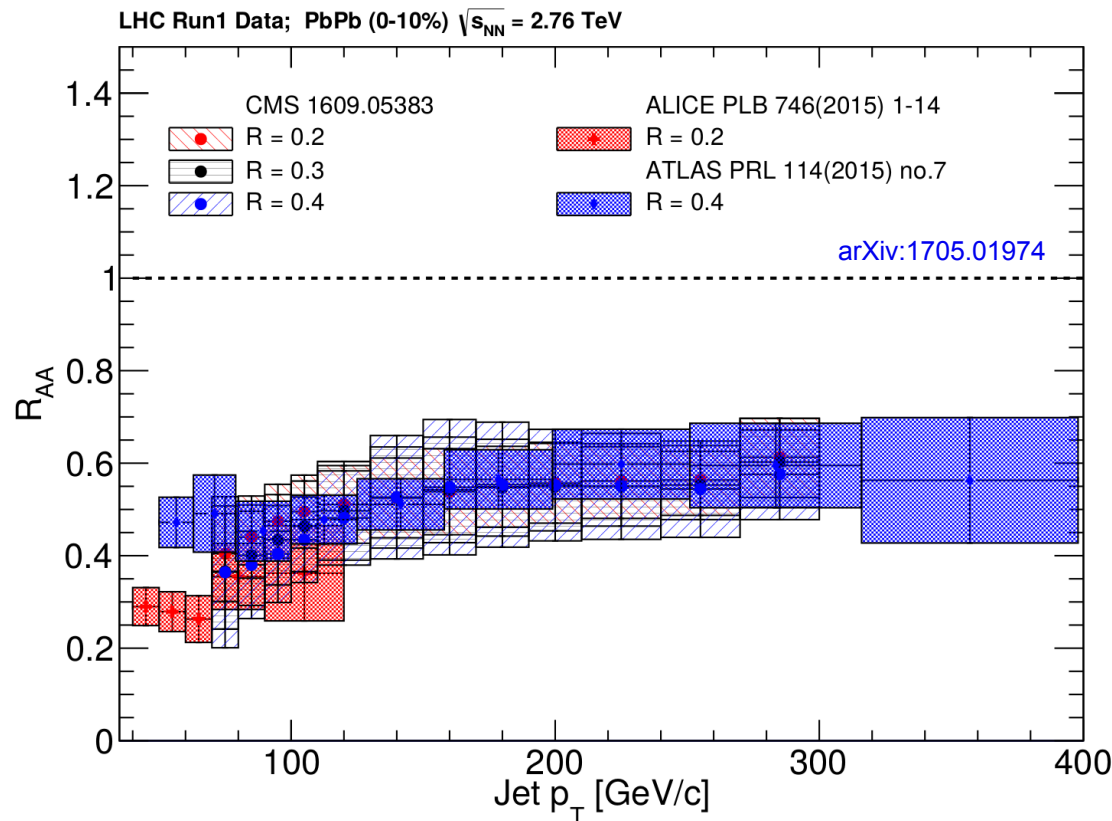
RHIC

LHC



- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them - even heavy quarks!

Jet R_{AA}



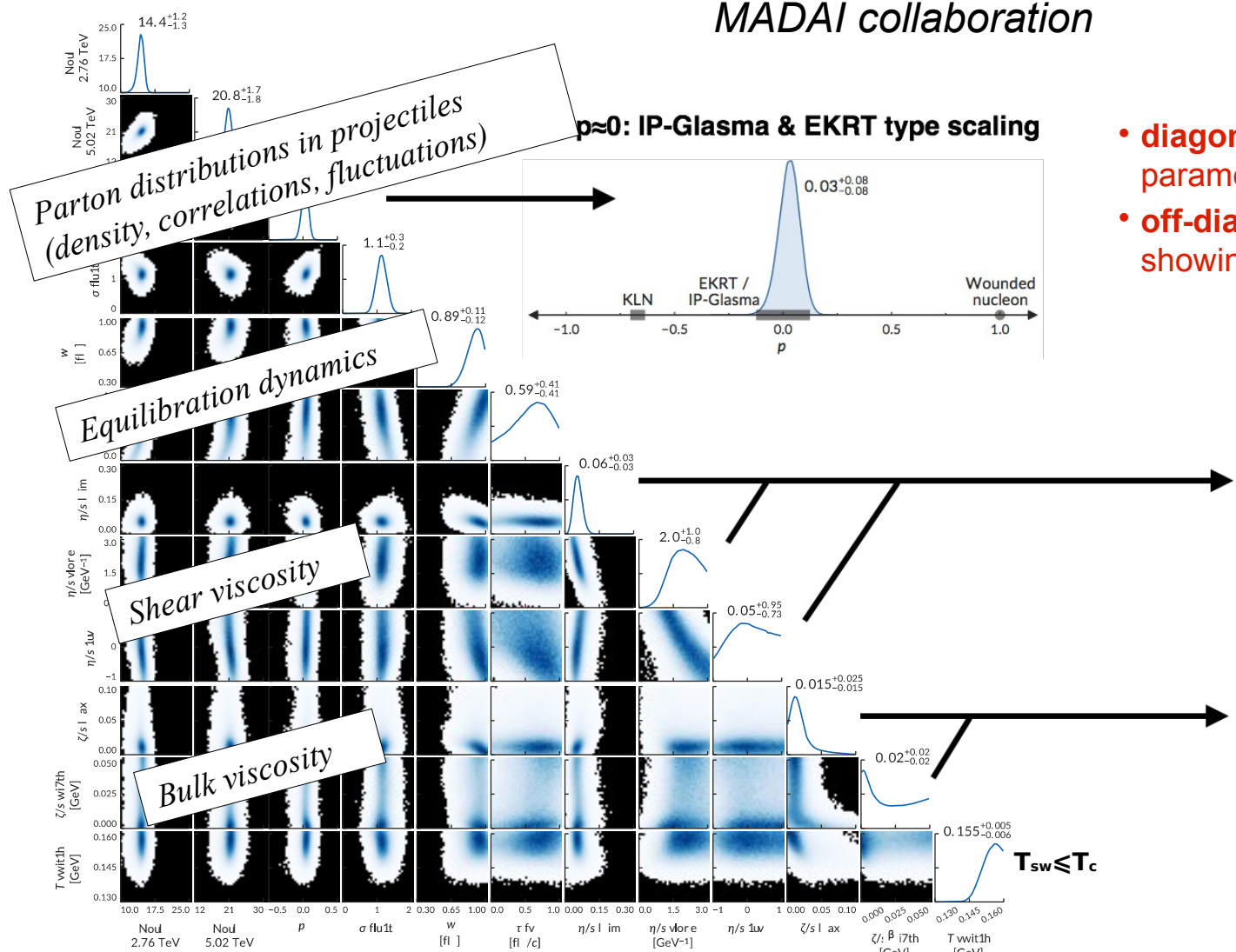
- Jet R_{AA} also demonstrates suppression
- Less suppression of heavy quark jets

Conclusions

- Mapping out the phase diagram
- Evidence for hydrodynamical flow
 - Some indications of similar phenomena in small systems
- Evidence for jet quenching
 - No evidence of similar phenomena in small systems
- Need for systematic extraction of QGP properties

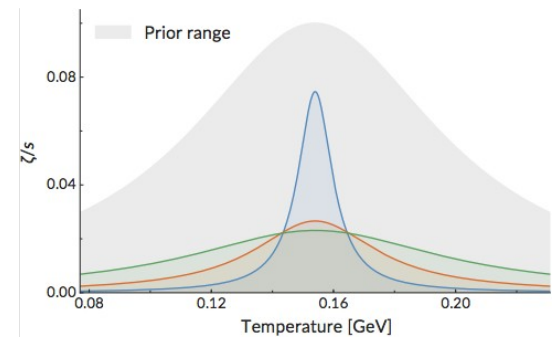
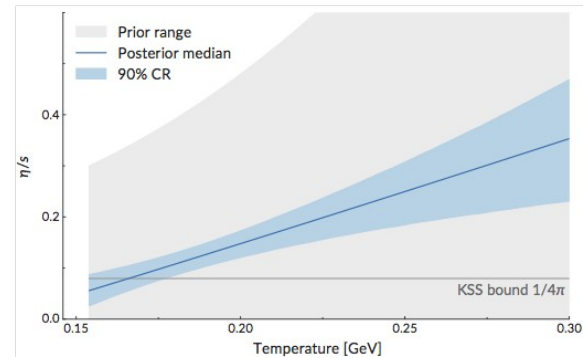
Next step: global fits of models to wide array of heavy ion collision data

Global Bayesian Analysis; S. Bass, Quark Matter 2017
MADAI collaboration



- **diagonals:** probability distribution of each parameter, integrating out all others
- **off-diagonals:** pairwise distributions showing dependence between parameters

temperature-dependent viscosities:



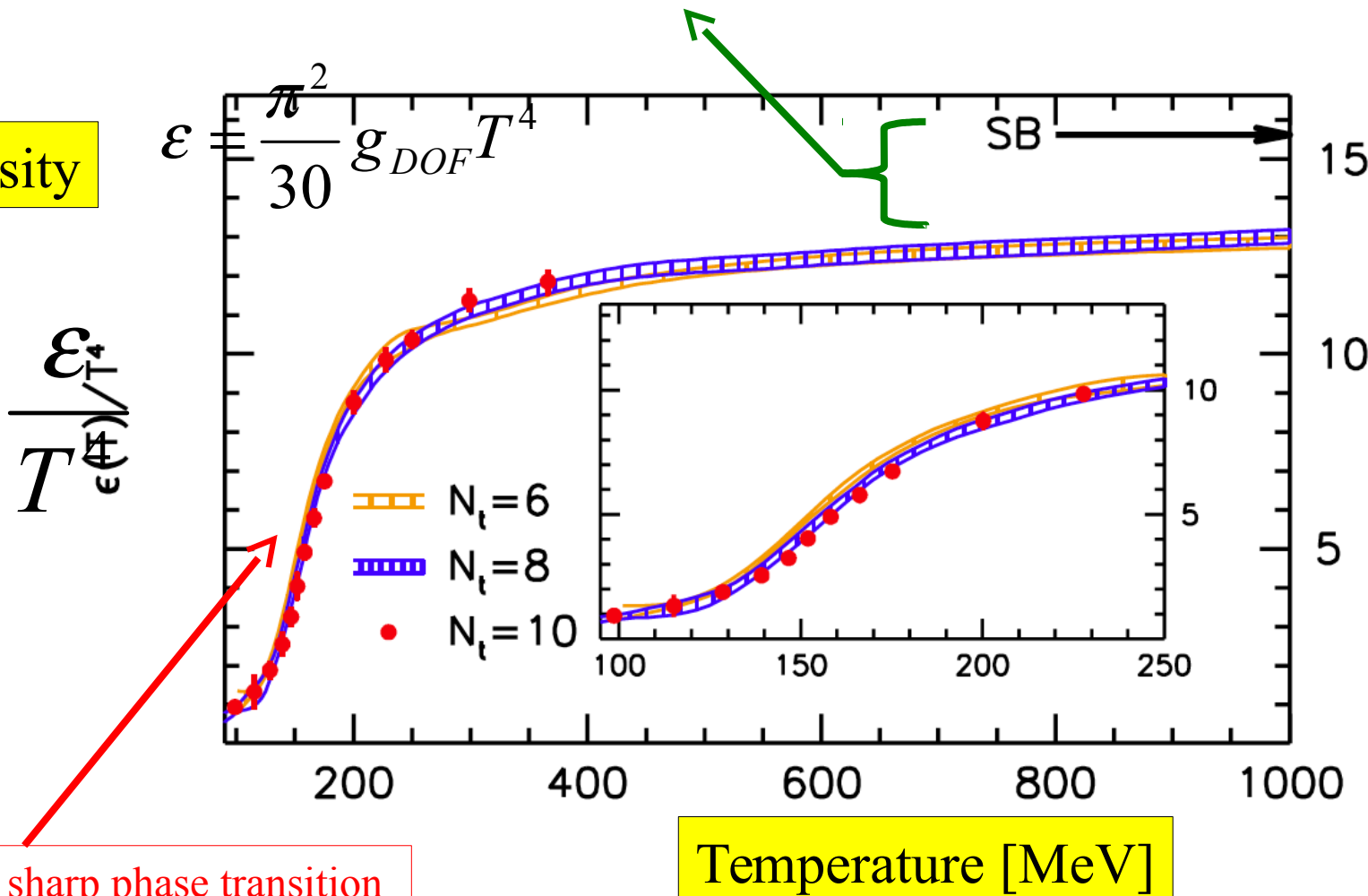
arXiv:1706.03666, Phys. Rev. C 94, 024907 (2016)

Backup

Finite Temperature QCD on the Lattice ($\mu_B=0$)

Slow convergence to non-interacting Steffan-Boltzmann limit
 What carries energy - complex bound states of q+g? “strongly-coupled” plasma?

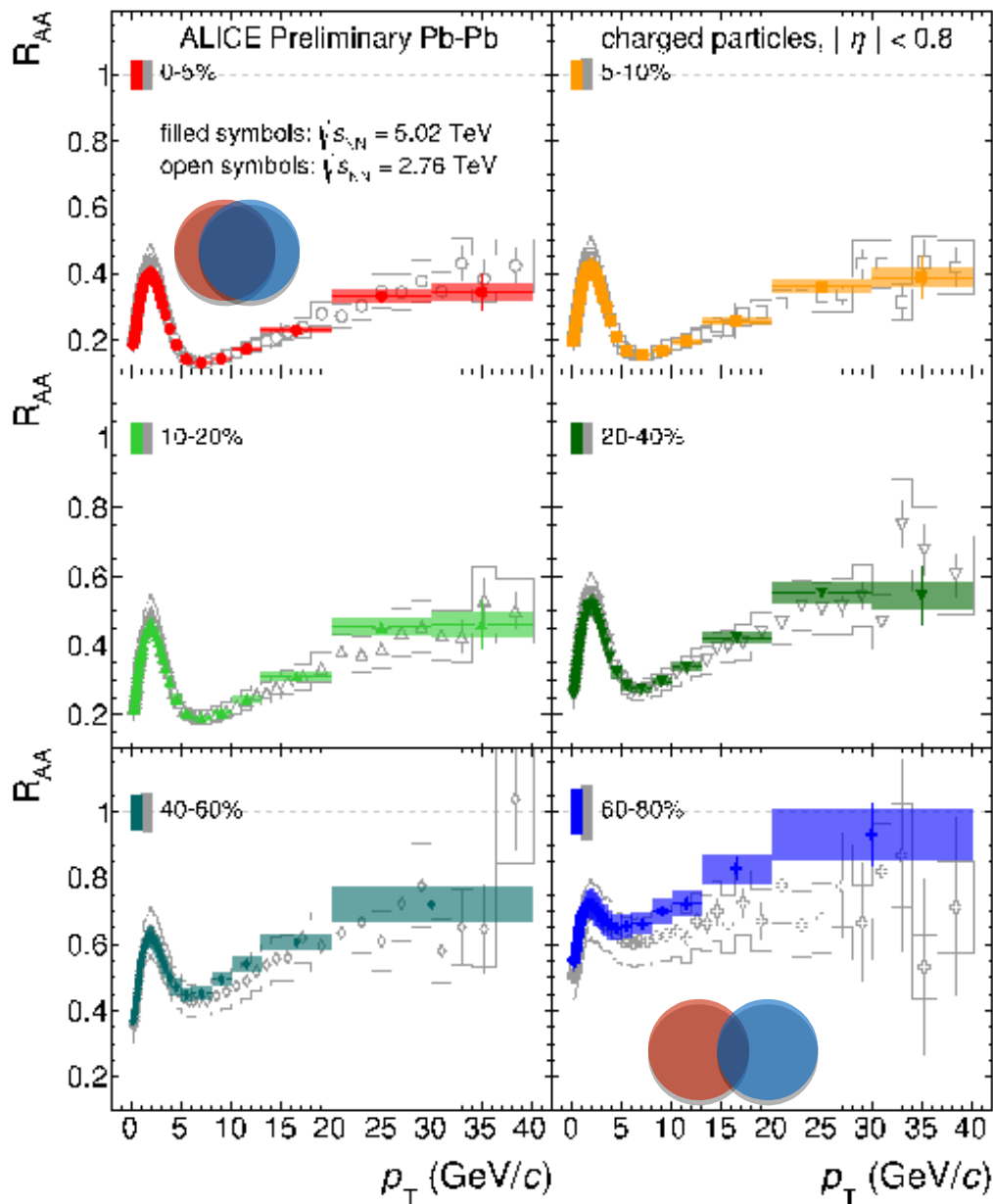
Energy density



Cross-over, not sharp phase transition
 (like ionization of atomic plasma)

S. Borsanyi et al., JHEP 1011, 077 (2010)

Charged particle R_{AA}



$$R_{AA} = \frac{d^2 N_{AA} / dp_T d\eta}{T_{AA} d^2 \sigma^{pp} / dp_T d\eta}$$

- $R_{AA} > 1$: enhancement
- $R_{AA} < 1$: suppression
- Strong modification of the spectrum shape in most central collisions
- Strong centrality dependence
- R_{AA} at 5.02 TeV similar to 2.76 TeV

Light-by-light scattering

First evidence of light-by-light scattering

