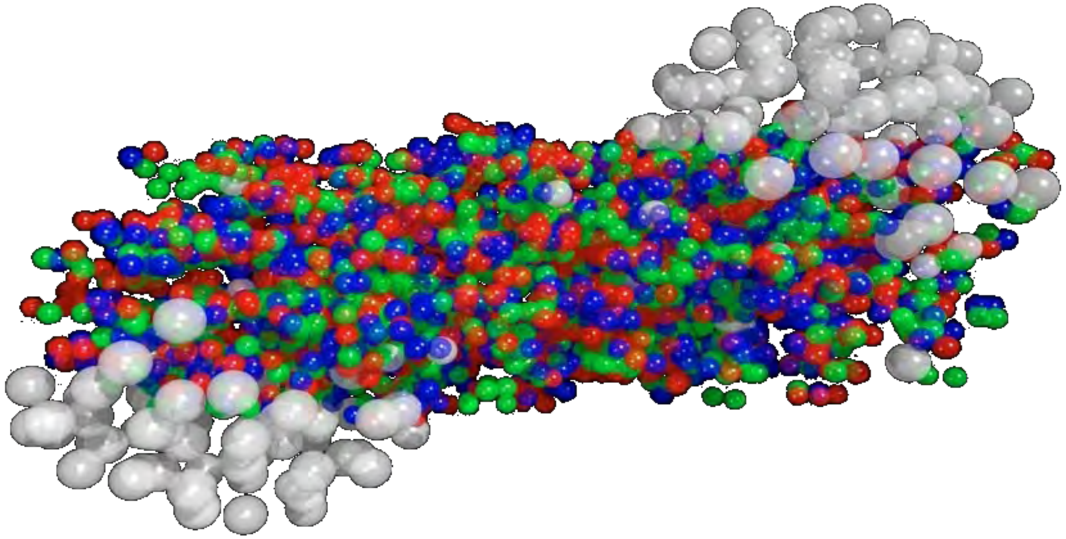
FERMILAB-CERN HADRON COLLIDER PHYSICS SUMMER SCHOOL 2024



HEAVY ION COLLISIONS

QGP introductions and Soft sector measurements

Inspired by presentations by Helen Caines, Yen-Jie Lee, Hanna Zbroszczyk

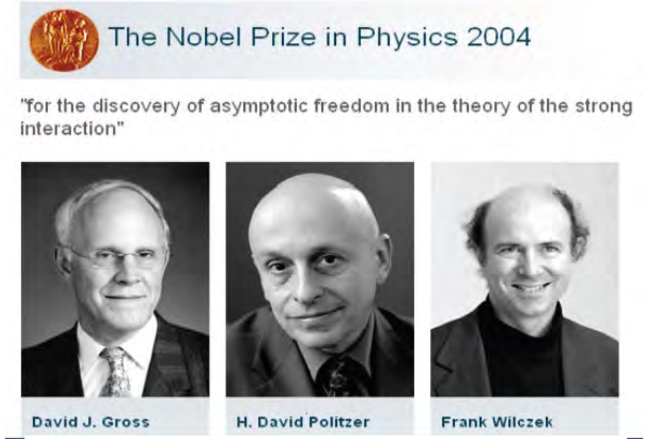
QGP – THE HISTORIC PERSPECTIVE

- 1973: Gross, Wilczek and Politzer:
- “Asymptotic freedom of QCD”

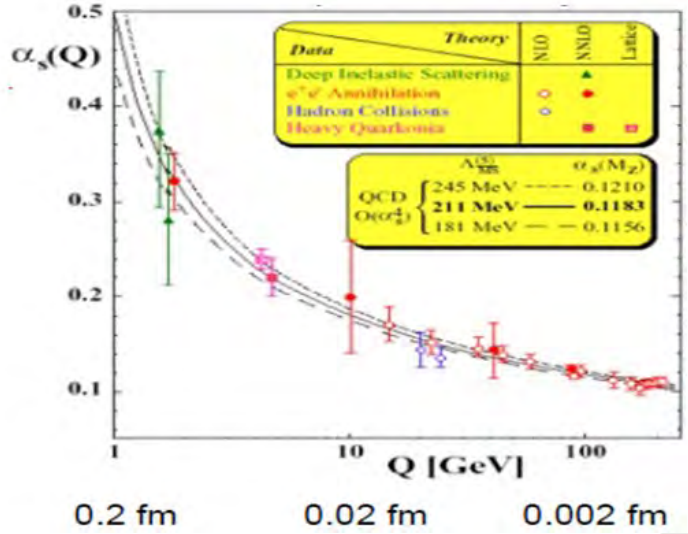
- 1974: 1st Workshop on
- “BeV/nucleon collisions of heavy ions”

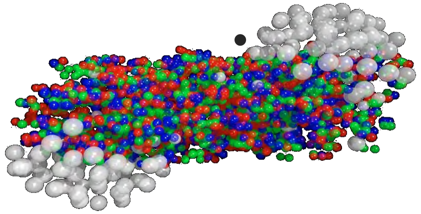
- 1975 Collins and Perry, mass of neutron stars
- “Quark Soup” at limits of T & baryon densities

- 1978: Shuryak proposed the term
- “Quark Gluon Plasma”



$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(33 - 2n_f)\log(Q^2/\mu^2)}$$





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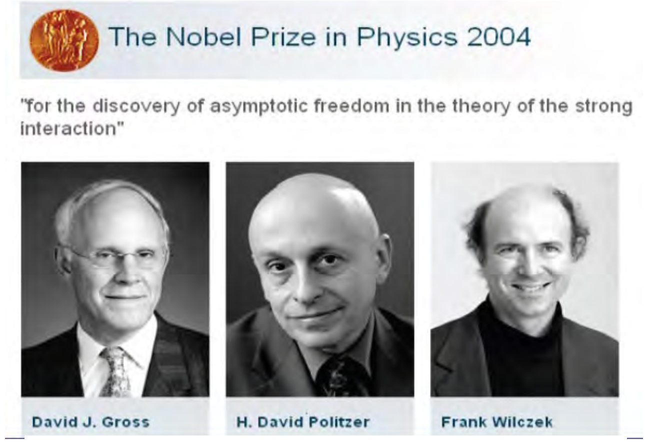

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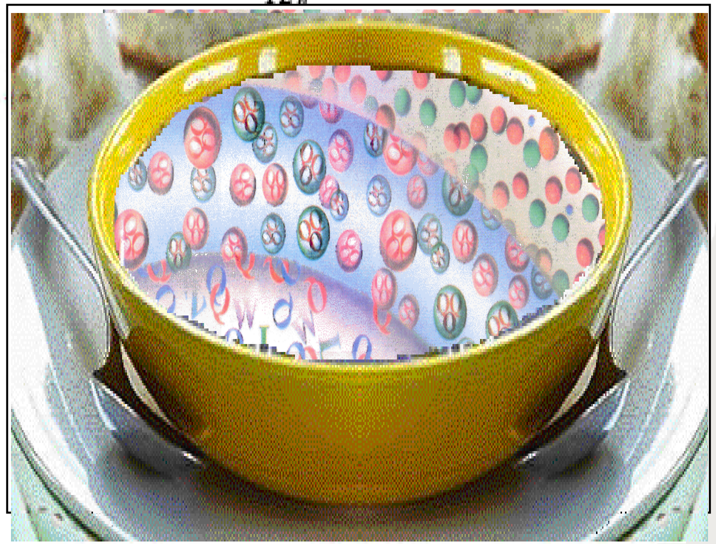
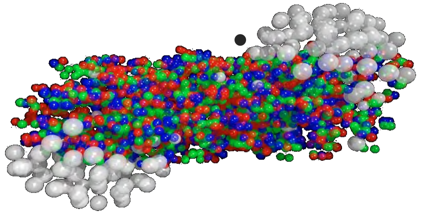


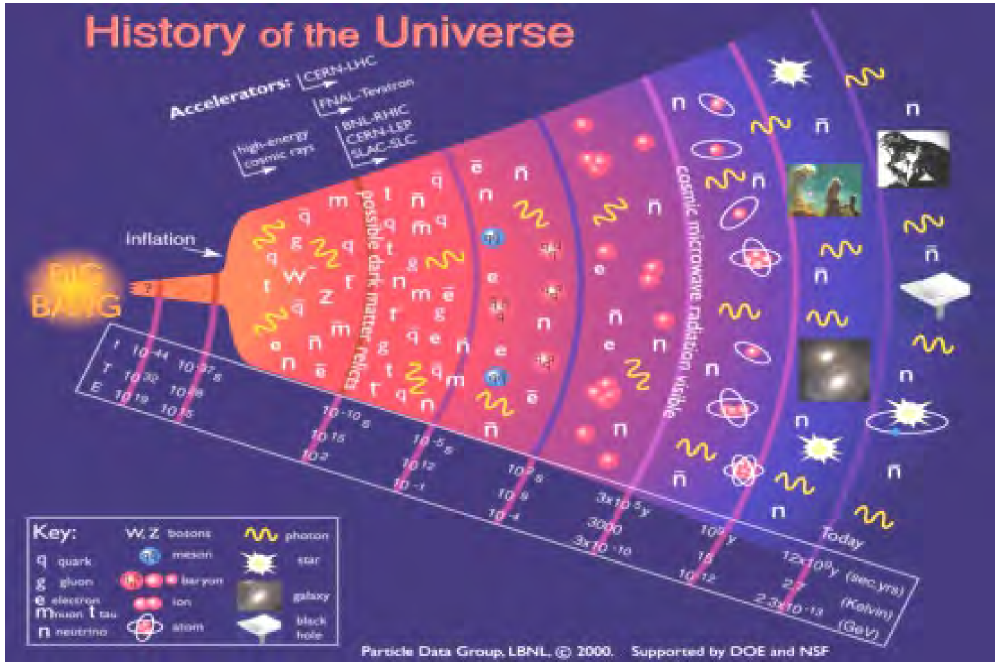


OLGA EVDOKIMOV (UIC)

AUGUST 1, 2024

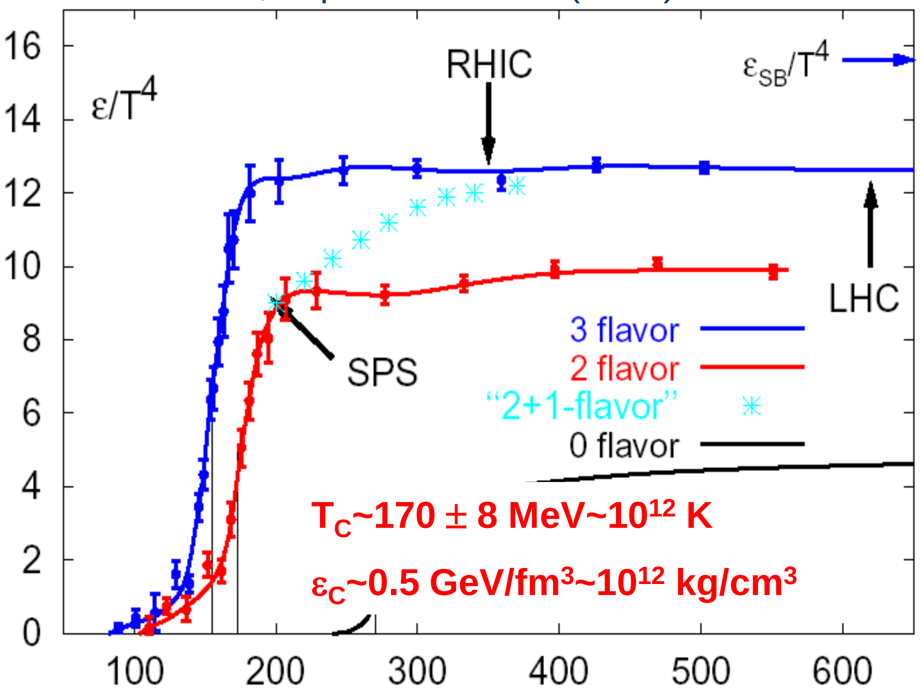
QGP – THE HISTORIC PERSPECTIVE

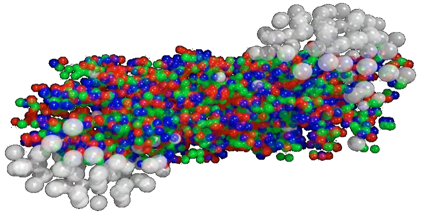
- Cosmological perspective



- Lattice QCD prediction

F. Karsch, hep-lat/0401031 (2004)





QGP ≡ a thermally equilibrated deconfined quarks and gluons, where color degrees of freedom become manifest over nuclear, rather than nucleonic, volumes.

QGP – HOW TO

- Nuclear matter:

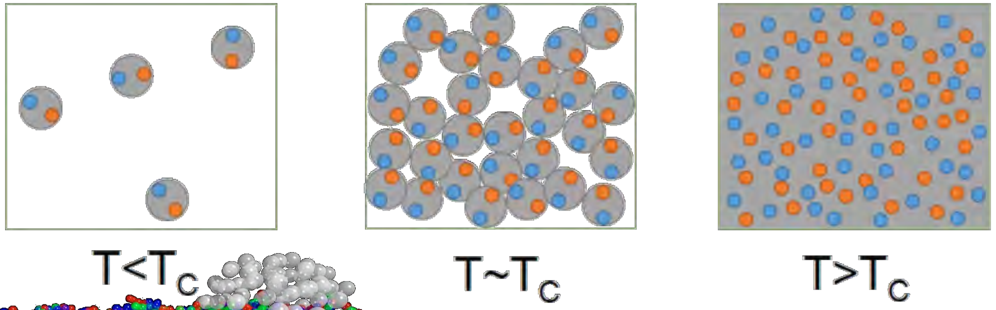
  At low color densities: q & g are confined into color singlets (baryons and mesons)

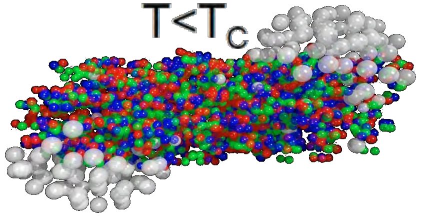
  At high color densities: q & g become unbound by Debye screening of color charge

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr \;\rightarrow V(r) \sim -\frac{4}{3}\frac{\alpha_s}{r} e^{-r/r_D}, \text{ where } \; r_D \sim \sqrt[3]{n} \text{ – Debye radius}$$

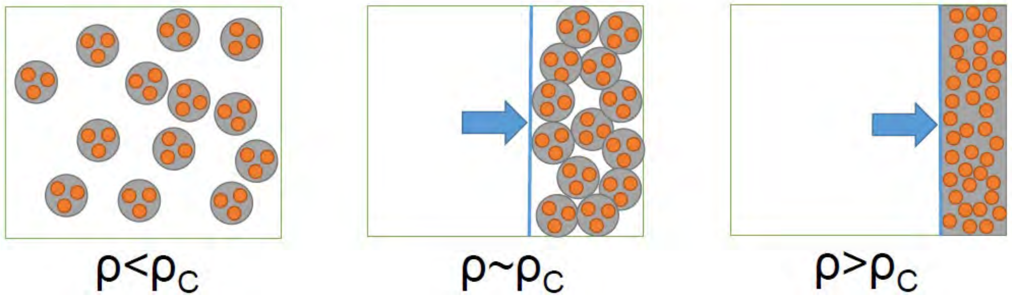
- Quark-Gluon Plasma is a color conductor!
- Need ultra-dense QCD matter for phase transition:

increase temperature

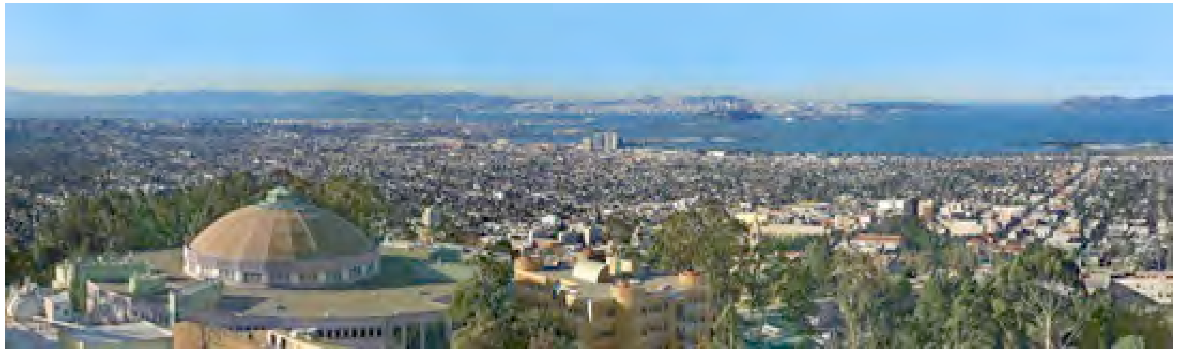




increase density



HISTORY OF HIN EXPERIMENTS



1974-1982:

Bevelac/Berkeley

$\sqrt{s_{nn}}$ = 0.1-1 GeV

1986-1994:

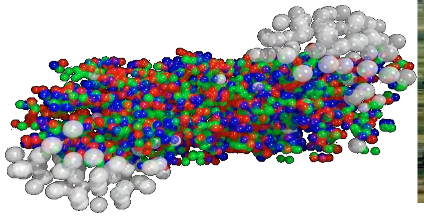
AGS/BNL, JINR

5-1 GeV

2000-

RHIC/BNL

200-3 GeV



1986-1994:

SPS/CERN

20-10 GeV

2010-

LHC/CERN

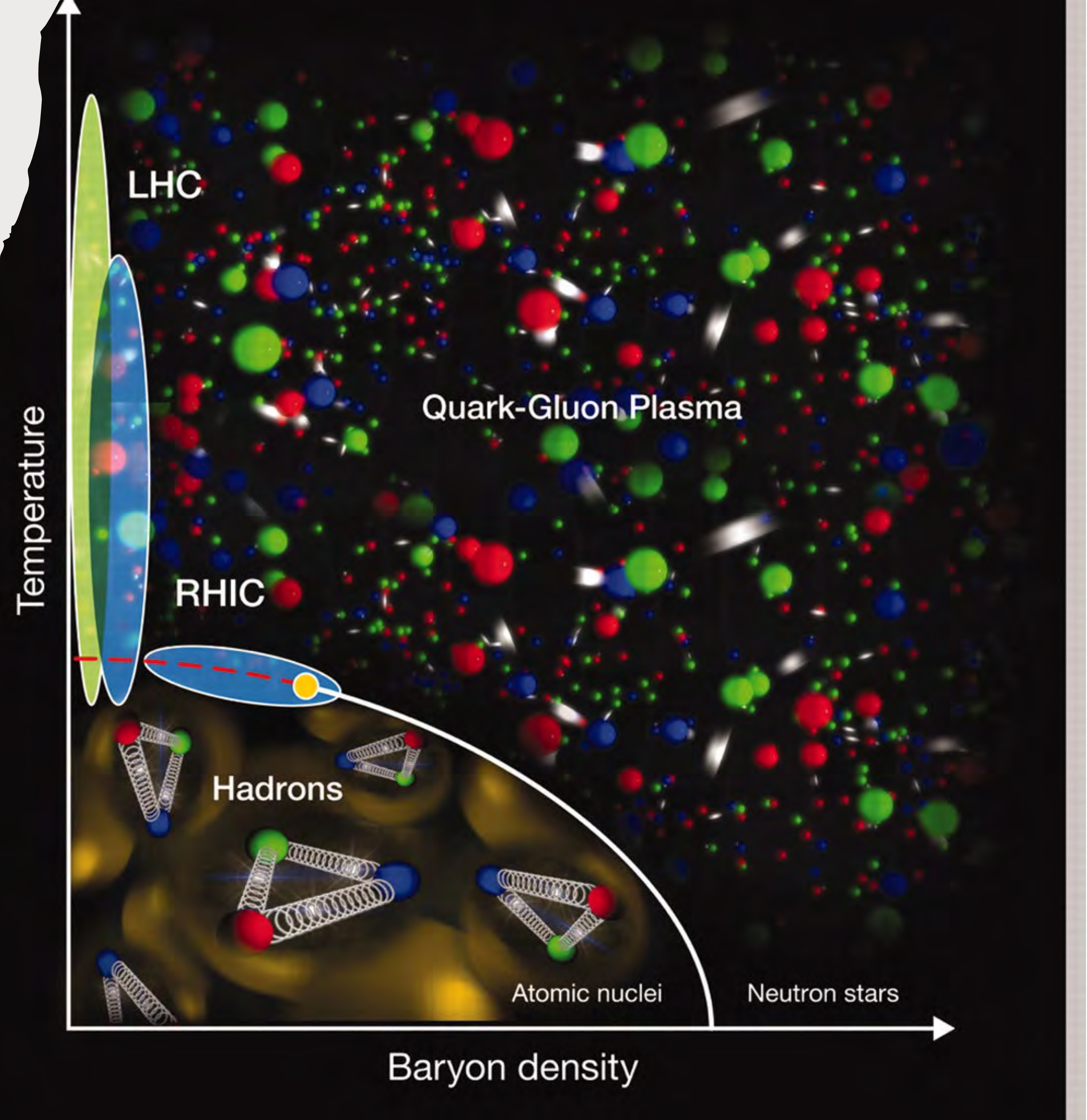
2.76-5.5 TeV

CORE HIN PROGRAM: QGP EXPLORATION

- QCD matter under extreme conditions:

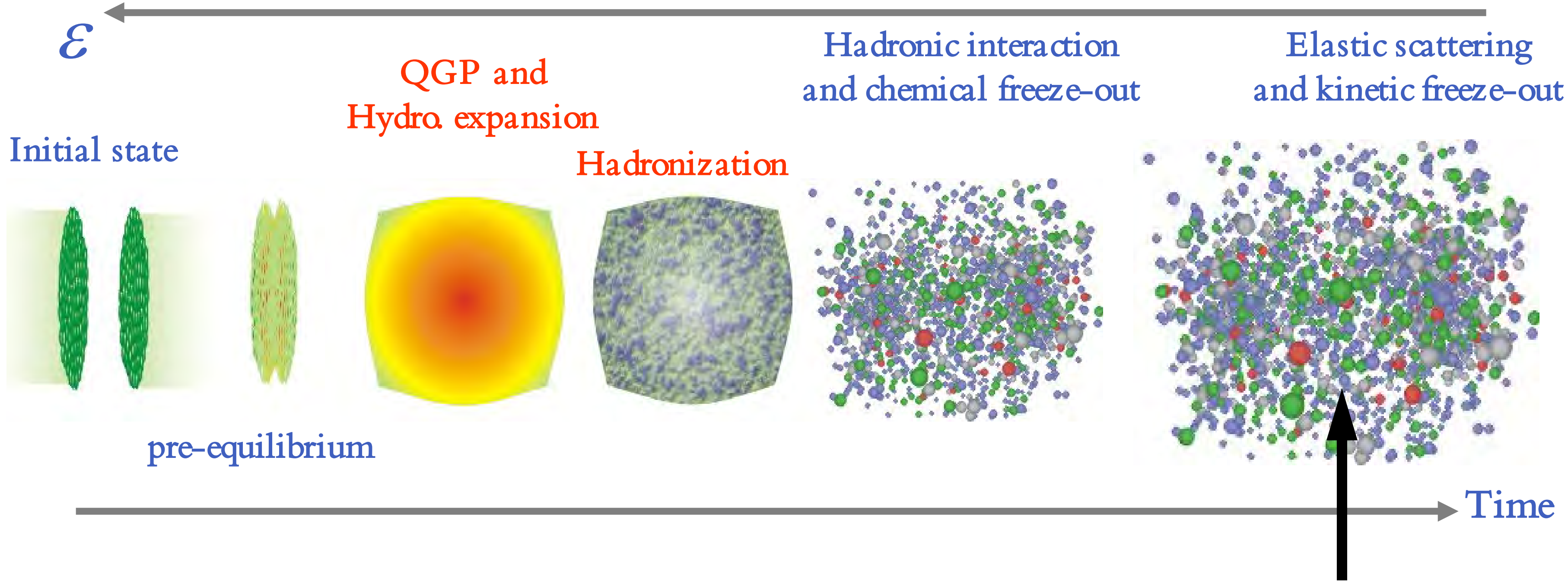
  QGP EoS,
  Degrees of freedom,
  Transport properties,
  Hadronization mechanisms,…
  but also
  QCD critical point search,
  Onset of deconfinement,
  Chiral symmetry restoration,…

- WITHOT a "standard model" for heavy ion collisions!



SOFT SECTOR MEASUREMENTS

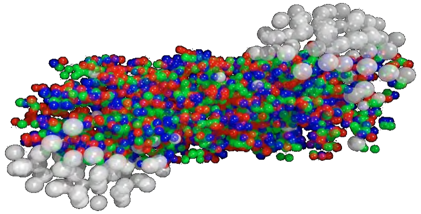
- “Standard Model” of heavy ion collisions: a complex dynamics of intrinsically many-body system



Bulk particle distributions

QGP hadronizes into soft hadrons; 99% of total yields

No direct access to details of QGP phase

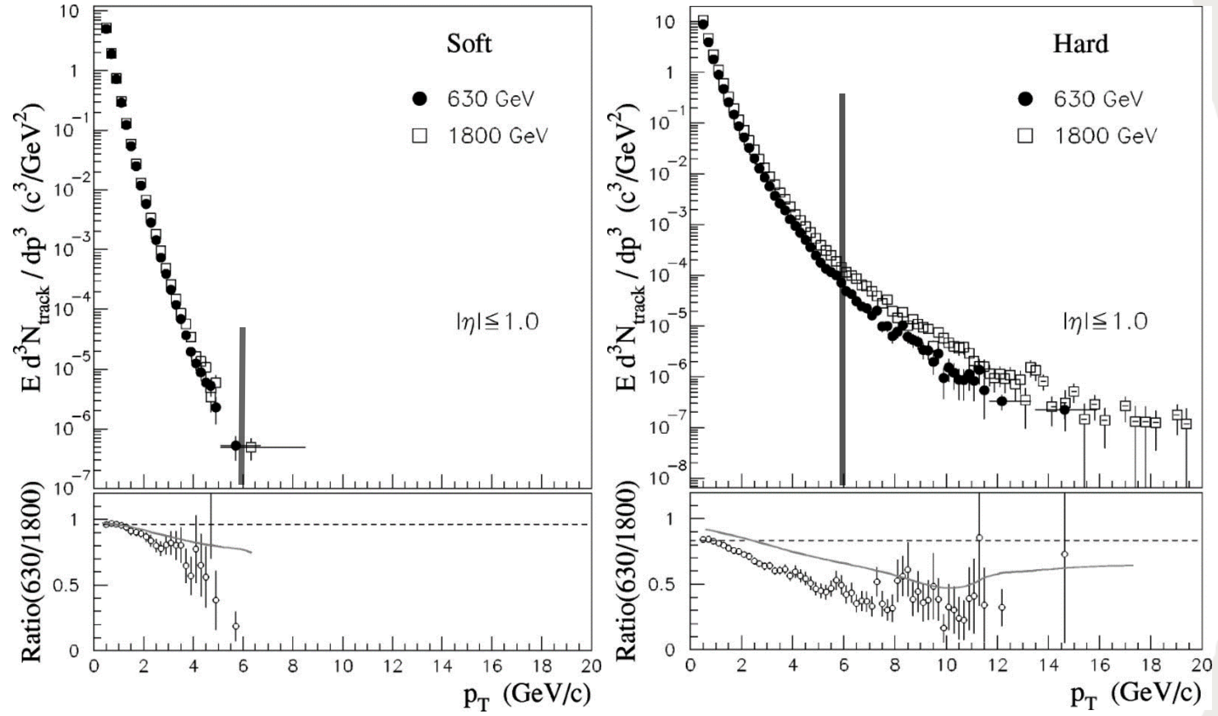


WHAT IS "SOFT" VS. "HARD"?

- In HEP studies, hadron collisions are traditionally subdivided into "soft" and "hard" by the presence of jets

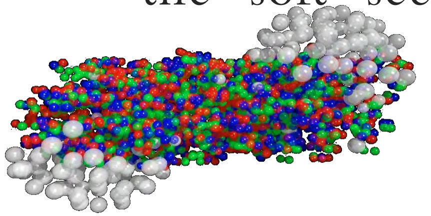
- Inclusive charged hadron cross-sections from $p\bar{p}$ collisions above 6 GeV/c are dominated by jet production

- Data from RHIC/LHC suggest similar Threshold, but conventional designation for the "soft" sector is < 2 GeV/c

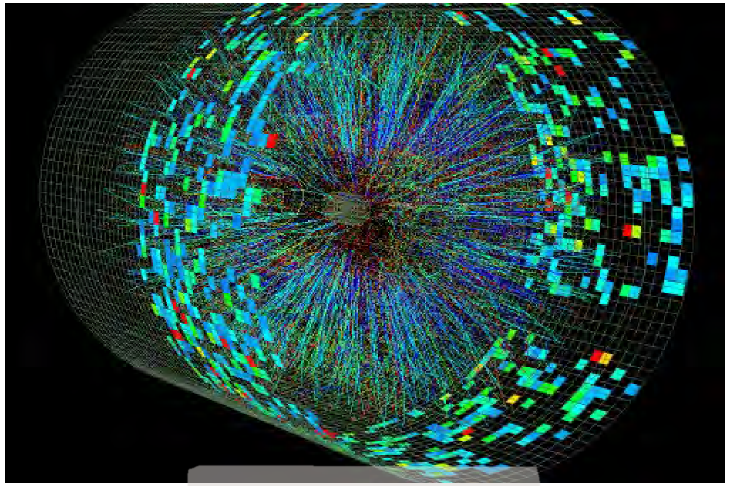


Min Bias Data, charged hadrons $|\eta|<1$

"Soft" vs "Hard" division based on calorimeter clusters E_T>1.1 GeV

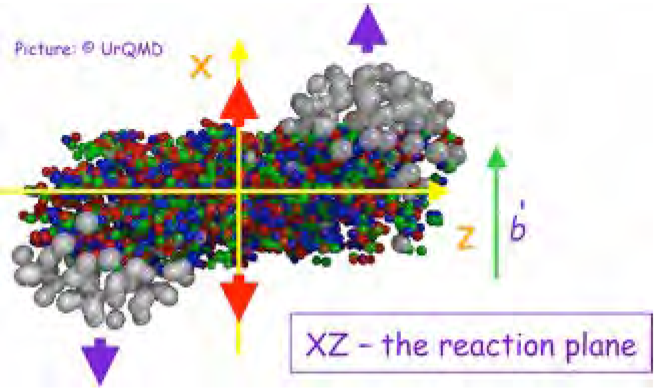


GEOMETRY IN HIN COLLISIONS

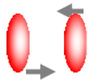


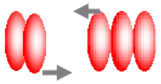
Central AA event

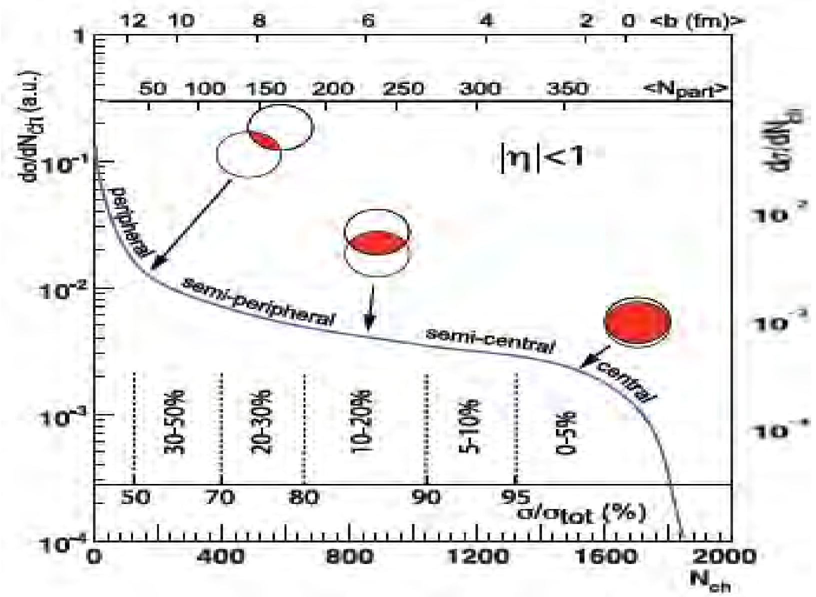
peripheral (bmax) ↔ central (b ~ 0)
~40TeV in central AA collisions at 0.2 TeV



Npart - number of participants
Nbin – number of binary collisions

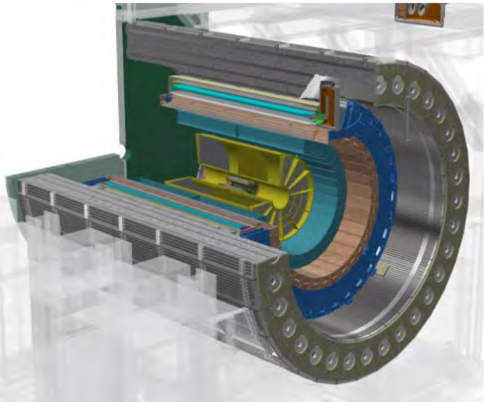
- Example:  Npart = 2, Nbin = 1

 Npart = 5, Nbin = 6



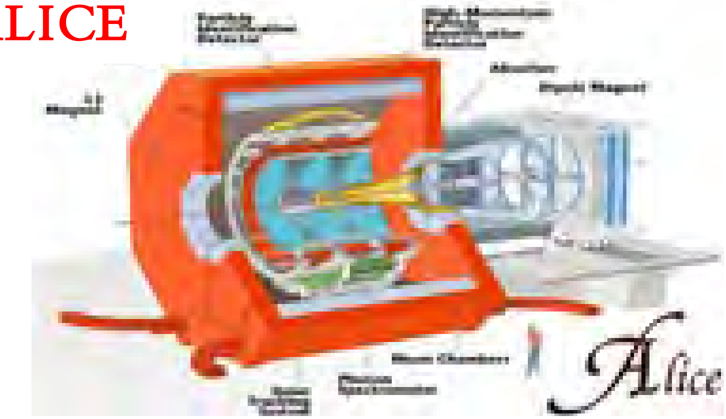
OPERATING (HIN) EXPERIMENTS

sPHENIX

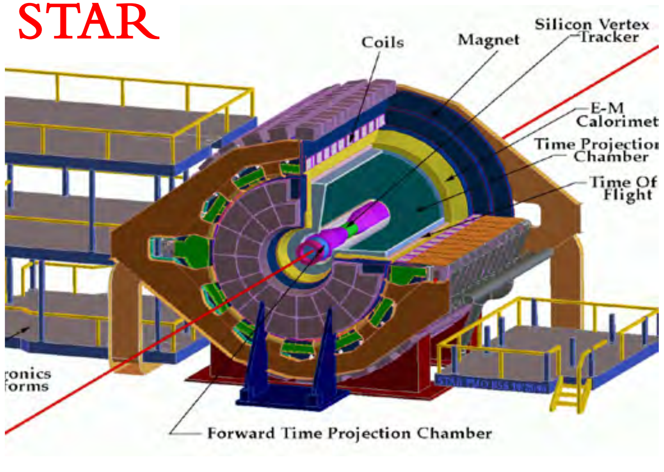


ATLAS

ALICE

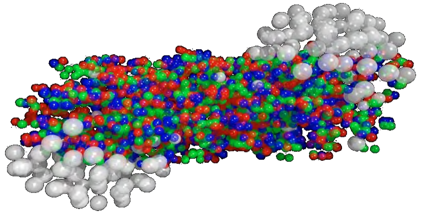


STAR



CMS

LHCb



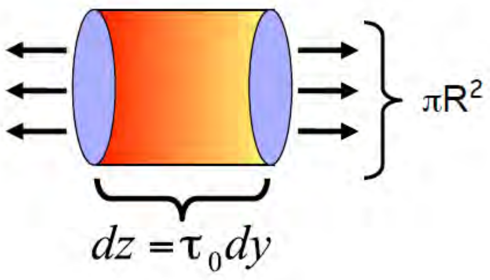
START SIMPLE: COUNTING

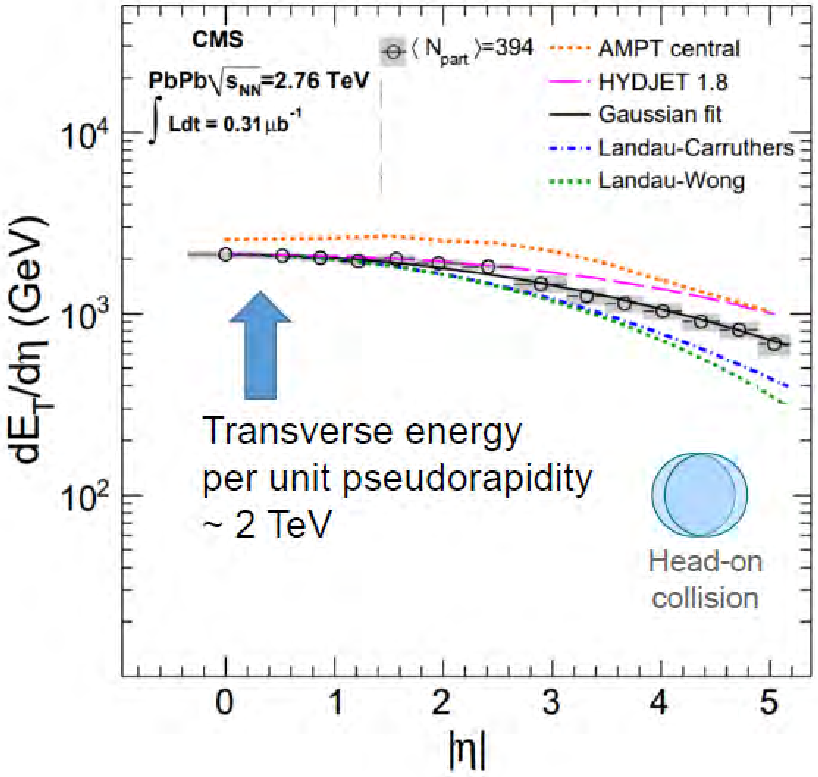
- Number of charged particles produced in the collisions:

  LHC: particle density in PbPb $\times$ 400 of pp

- Energy density? Bjorken formula:

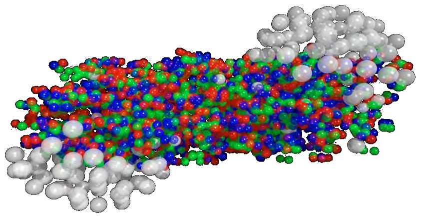
$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$





→

$$\varepsilon_{Bj} = \frac{1}{\pi(7fm)^2}\frac{1}{1\ fm/c}\ 2\text{TeV}=13\ \text{GeV}/fm^3 \gg \varepsilon_c$$



PARTICLE ABUNDANCIES AND TEMPERATURE

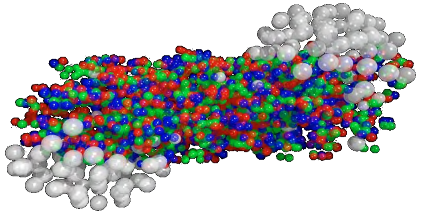
- In statistical thermal models, particle abundancies are related to temperature chemical potential:

$$dN_i(T,\mu_B) \sim e^{-(E_i-\mu_B B_i)/T} d^3p$$

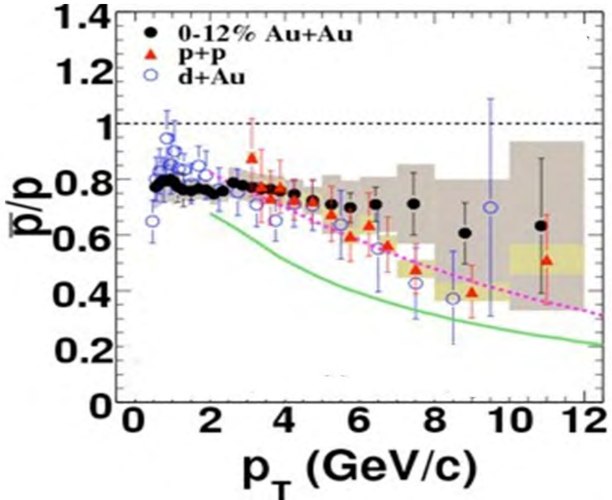
- Assume all particles occupy the same volume at chemical freeze-out and are described by same temperature T and baryon potential μ_B
- Just two ratios are needed to determine the (T , μ_B) for the system and predict abundancies for all other species to test for chemical equilibrium:

$$\frac{\bar{p}}{p} = \frac{e^{-(E_p+\mu_B)/T}}{e^{-(E_p-\mu_B)/T}} = e^{-2\mu_B/T} \quad \rightarrow \text{gives } \mu_B/T$$

$$\frac{K}{\pi} = \frac{e^{-E_K/T}}{e^{-E_\pi/T}} = e^{-(E_K-E_\pi)/T} \quad \rightarrow \text{gives } T$$

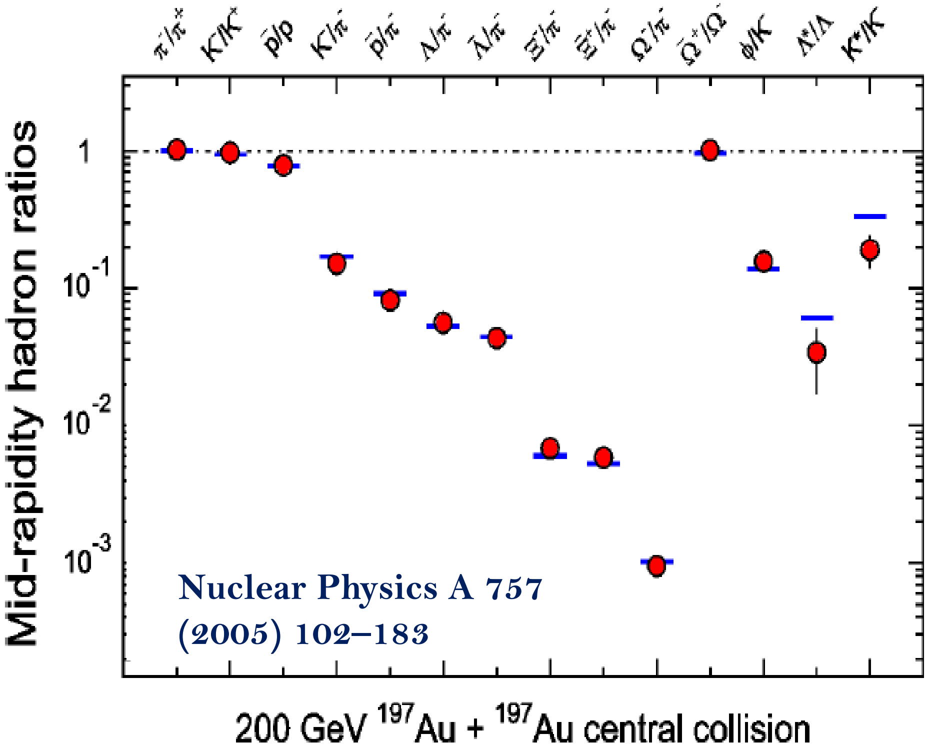


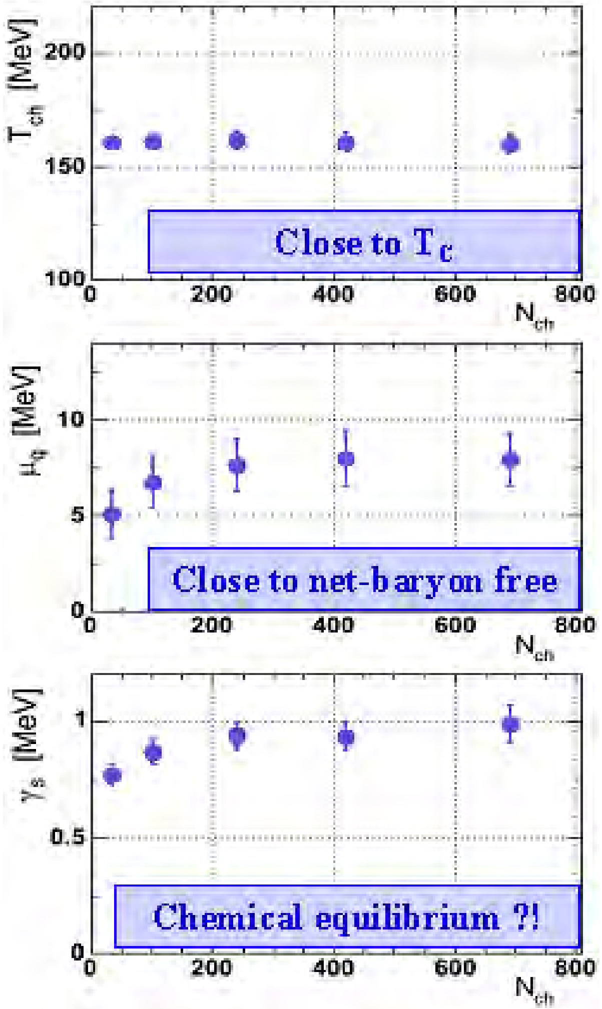
(side note: the system is close to but not net-baryon free!)

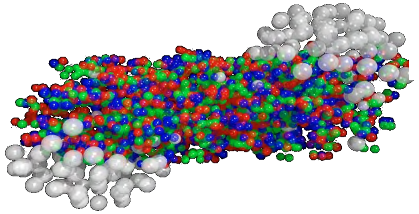


CHEMICAL EQUILIBRIUM?

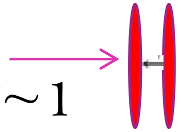
- Statistical model: $\frac{N_i(T,\mu)}{V} = \frac{g_i}{2\pi^2}\gamma_s^{|S_i|}\int_0^\infty \frac{p^2 dp}{e^{(E_i-\mu_B B_i-\mu_S S_i)/T}\pm 1}$







$T_c \sim 160$ MeV, $\mu_B \sim 20$ MeV, $\gamma \sim 1$

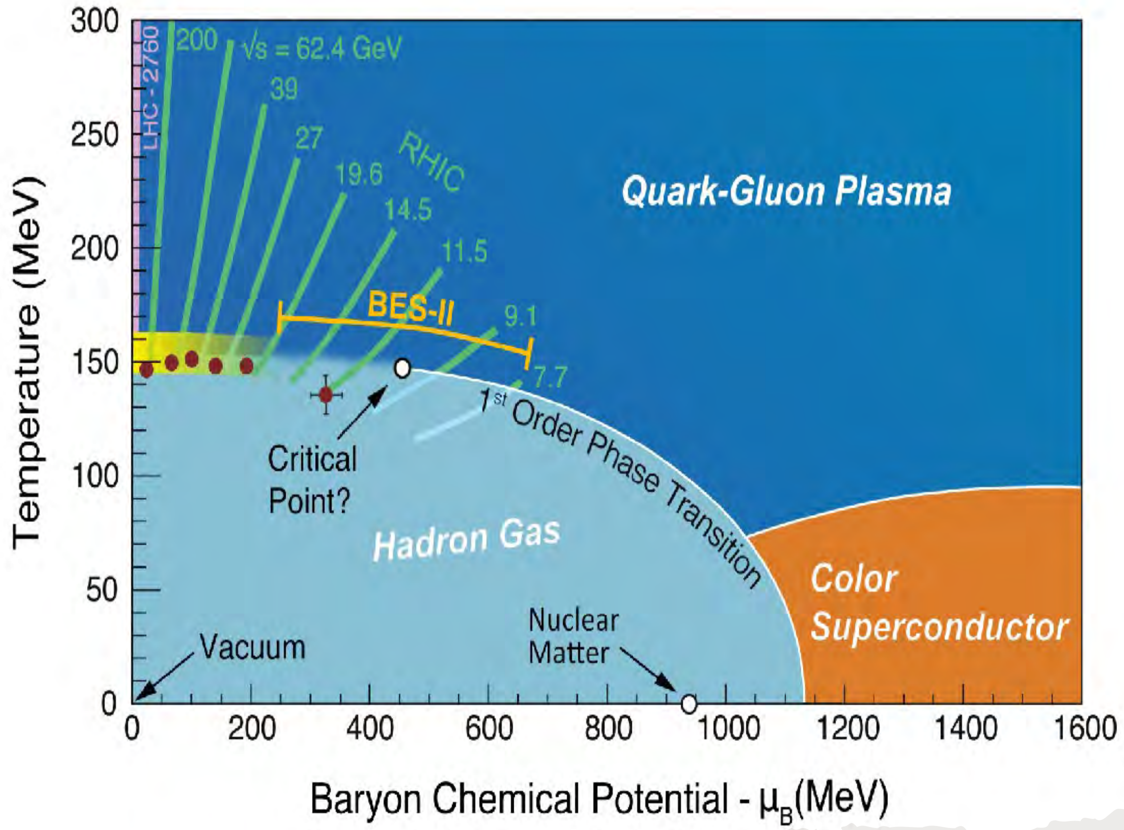


CHEMICAL FREEZEOUT MAP

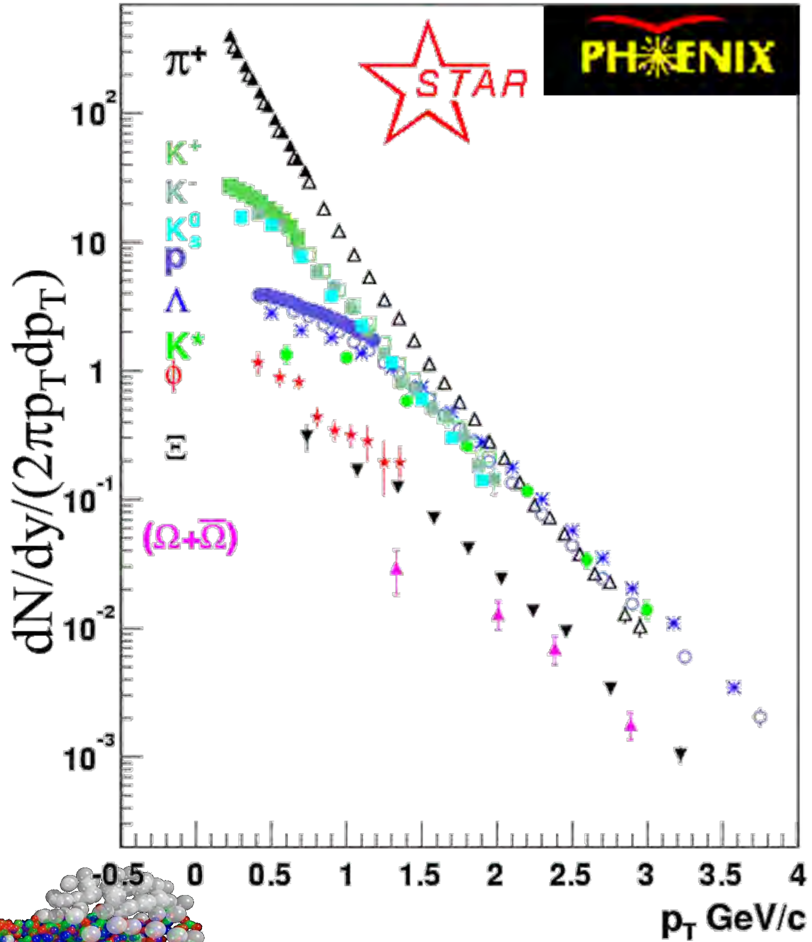
- At (upper) RHIC and LHC energies the extracted chemical freeze-out temperatures maps closely the predicted phase transition boundary.

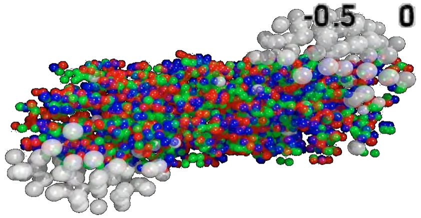
- *Important note:* success of statistical models alone does not prove the system is in equilibrium. Anything producing hadrons evenly populating the free particle phase space will mimic a microcanonical ensemble!

- Need other evidence for thermalization/collectivity!

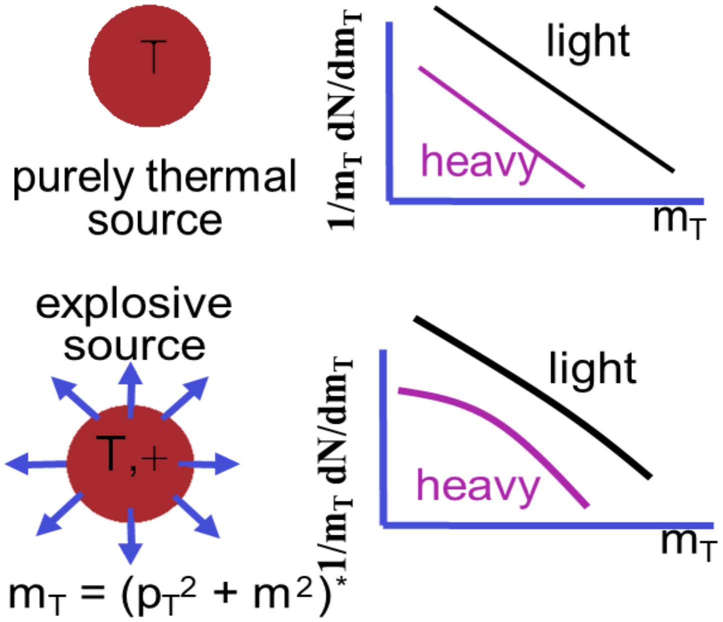


SPECTRAL DISTRIBUTIONS IN HIN





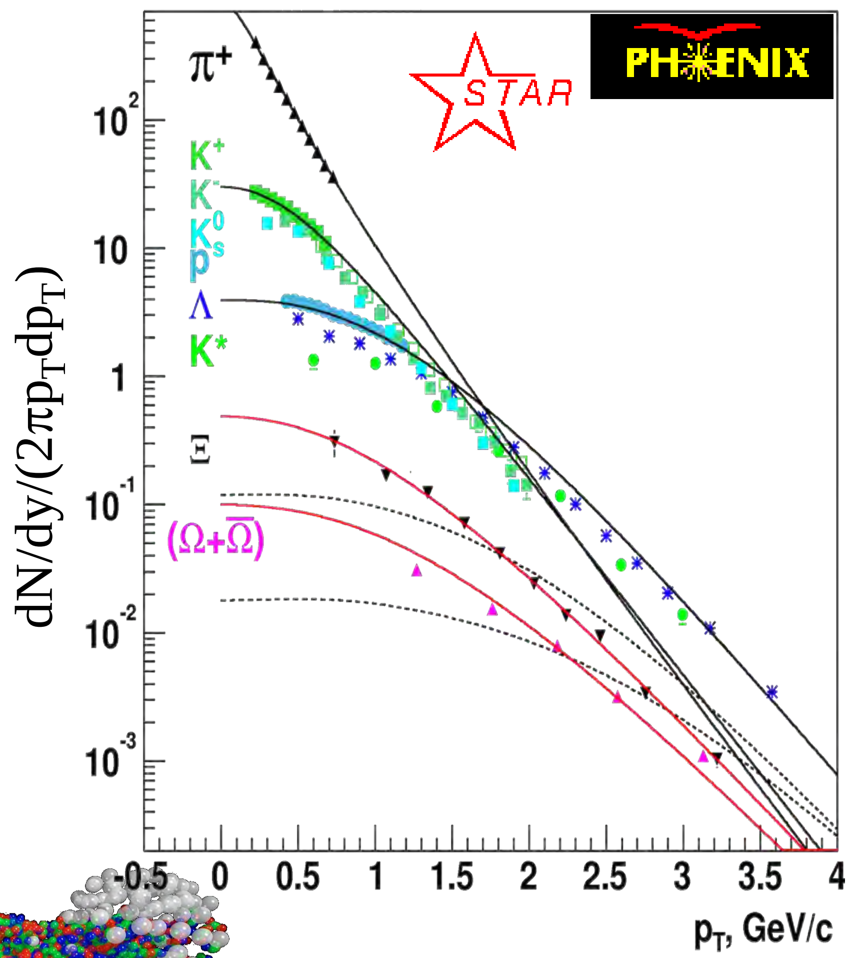
- Different spectral shapes: "flattening" with increasing particle mass

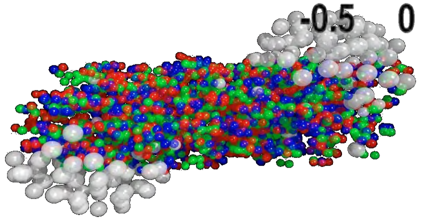


- With pressure buildup in the center, large pressure gradient → collective expansion:

Radial flow

SPECTRAL DISTRIBUTIONS IN HIN





Blast-wave model:

PRC48 (1993) 2462

$$\frac{dn}{m_T\, dm_T} \propto \int_0^R r\, dr\, m_T\, K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right) ,$$

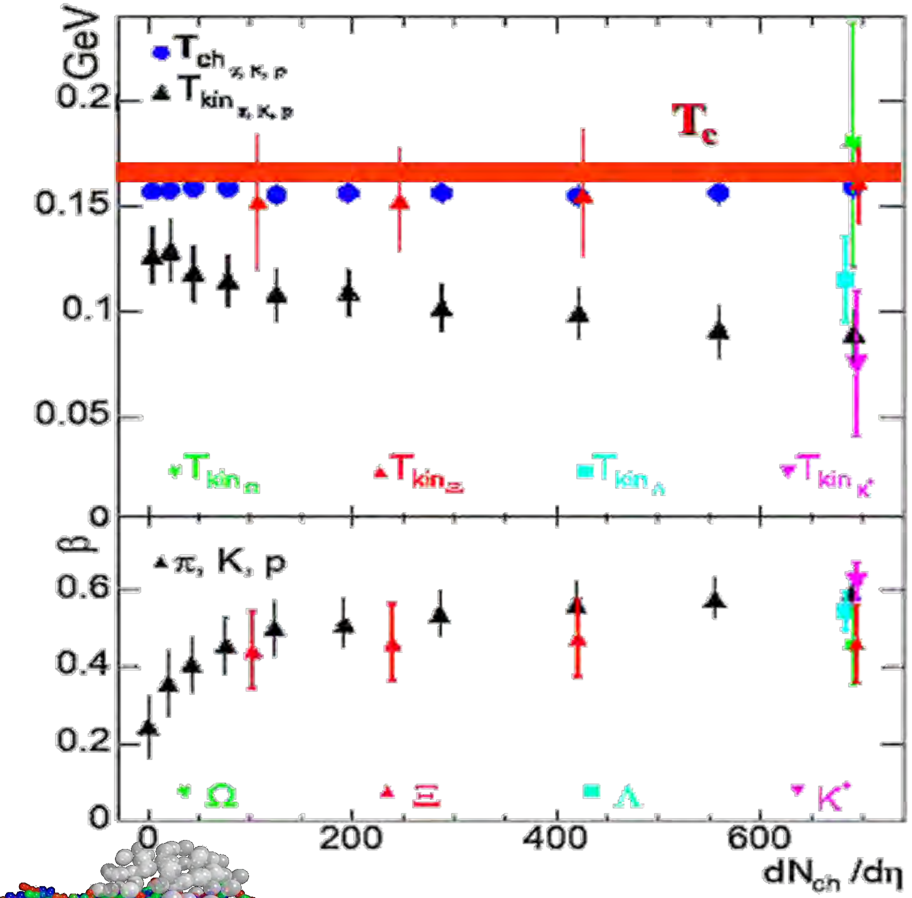
where $\rho = \tanh^{-1}\beta_r$ and $\beta_r = \beta_s f(r)$

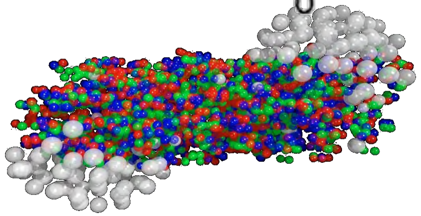
π, K, p → T= 90MeV, β=0.6 c

Ξ, Ω → T=160MeV, β=0.45 c

Explosive medium with hints of partonic collectivity

PARTONIC COLLECTIVITY?





- T_{kin}↓, β↑ with centrality: higher pressure gradients in more central events
- T_{ch} ~ const
- Chemical freeze-out may probe the phase boundary: real T_C must be close T_{ch}!

- Multi-strange baryons: early freeze-out
  Constant T_{kin}, β
- No additional flow build-up due to small hadronic interaction cross-sections
- Probe early-stage flow:

T_{kin} ~ T_{ch} ~ 160 MeV, β ~ 0.45 at hadronization

↓ via rescattering

T_{kin} ~ 90 MeV, β ~ 0.6

HADRONIC PHASE

We have:

$T_{kin} \sim T_{ch} \sim 160$ MeV, $\beta \sim 0.45$ at hadronization

↓ via rescattering

$T_{kin} \sim 90$ MeV, $\beta \sim 0.6$

- Can do a back-of-an-envelope estimate of hadronic phase life-span:

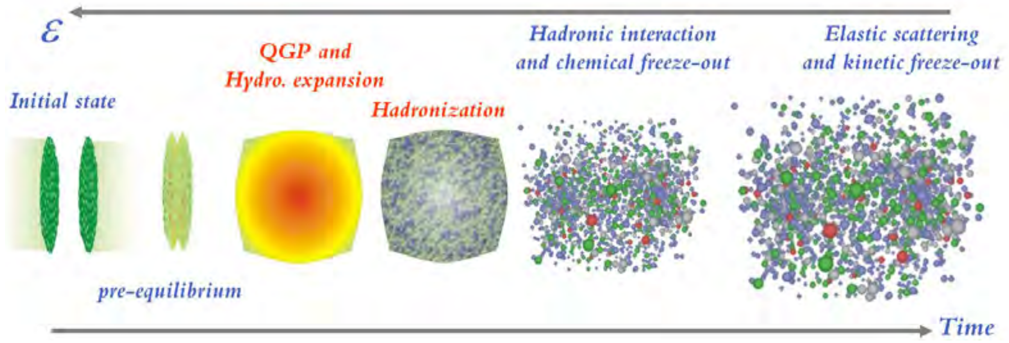
Massless particles in equilibrium: entropy density $\sim T^3$

$$T_{kin}^3 R_{kin}^3 \geq T_{ch}^3 R_{ch}^3$$

$$\Delta R = R_{kin} - R_{ch} \geq \left(\frac{T_{ch}}{T_{kin}} - 1\right) R_{ch} \geq \left(\frac{T_{ch}}{T_{kin}} - 1\right) R_A$$

$$\Delta t \geq \frac{\Delta R}{\beta_s} \geq \left(\frac{T_{ch}}{T_{kin}} - 1\right) \frac{R_A}{\beta_s} \approx 6 fm/c$$

$T_{ch} \sim 160$ MeV

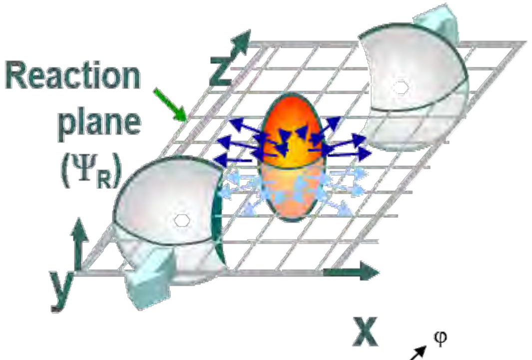


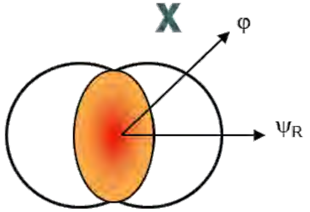
$T_{kin} \sim 90$ MeV

COLLECTIVITY IN HIN COLLISIONS

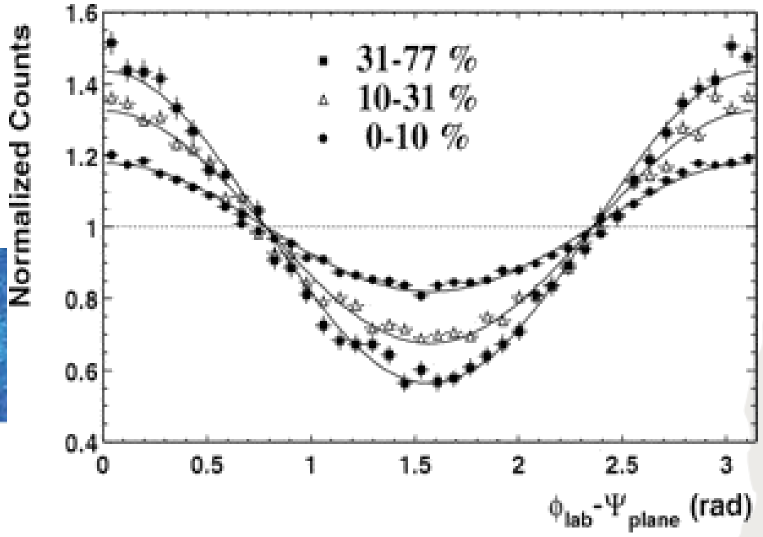
- Another signature HIN result: *elliptic flow (v_2)*
- Initial state spatial anisotropy → Pressure gradient anisotropy → Final state momentum anisotropy
- Fourier expansion for angular distributions:

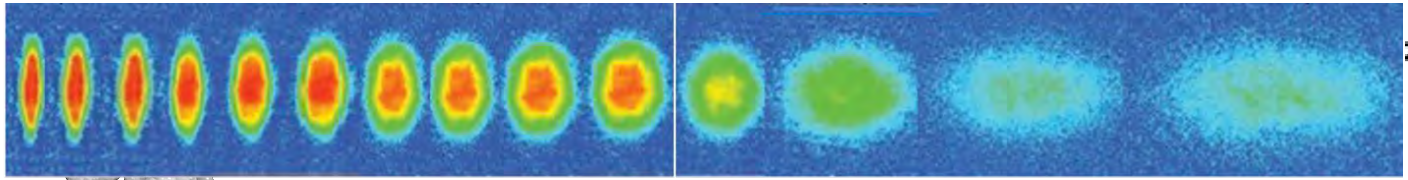
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi)\right)$$

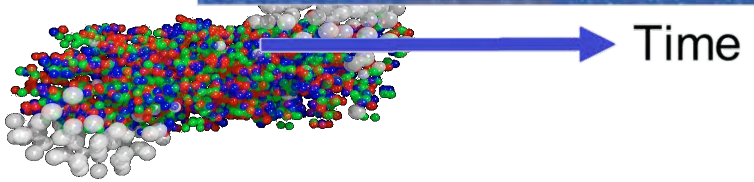




Elliptic flow develops at early stage
Large v_2 is an indication of early thermalization



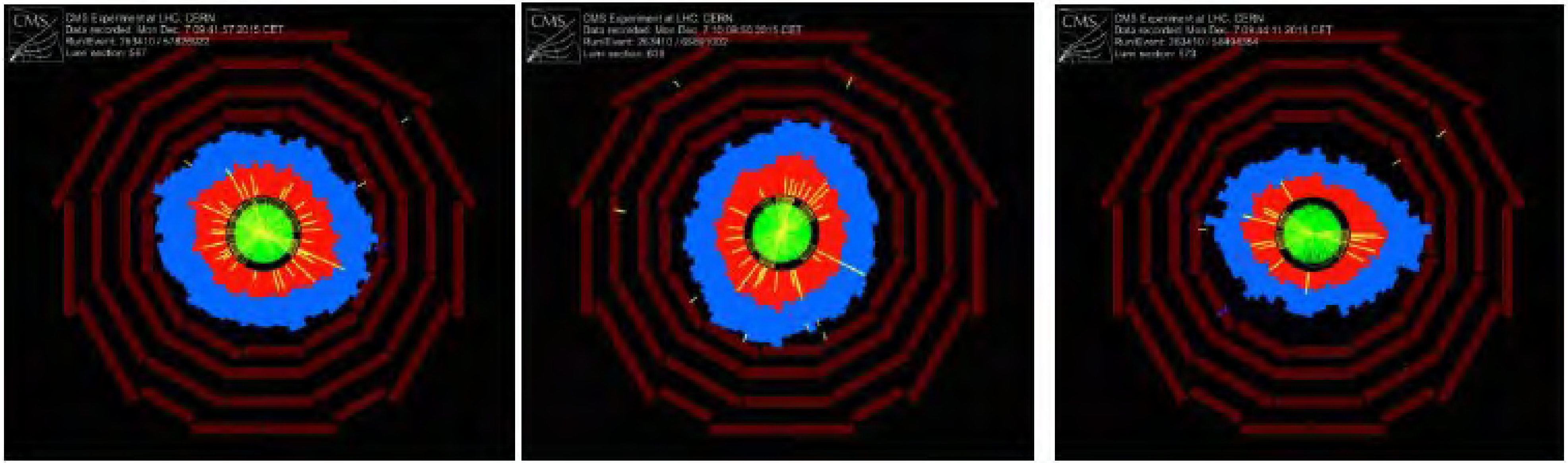


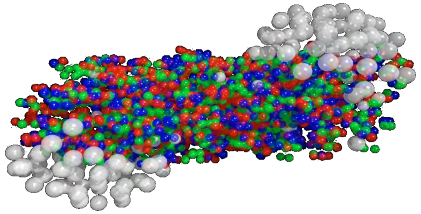


–M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

COLLECTIVITY IN HIN COLLISIONS

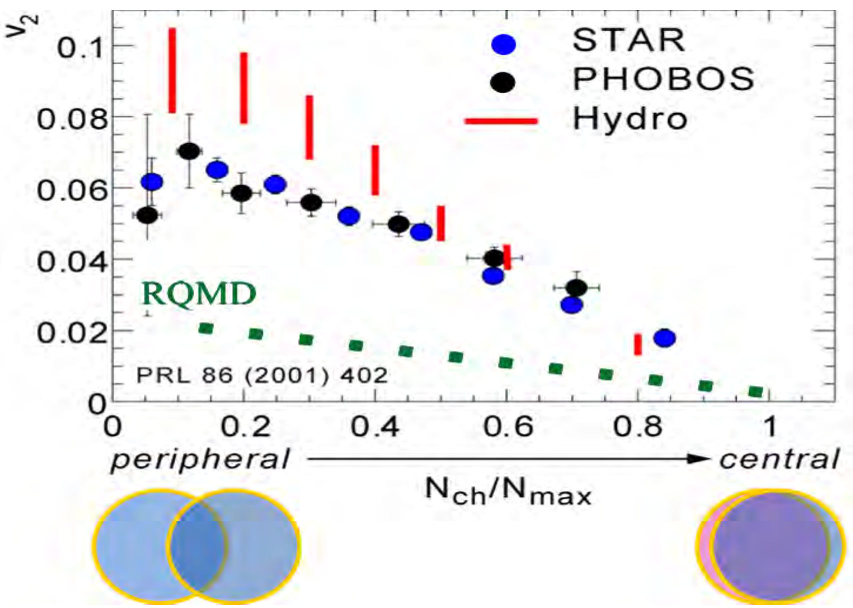
- Elliptic flow anisotropy is visible in raw hadronic and electromagnetic energy distributions and charged particle track densities!

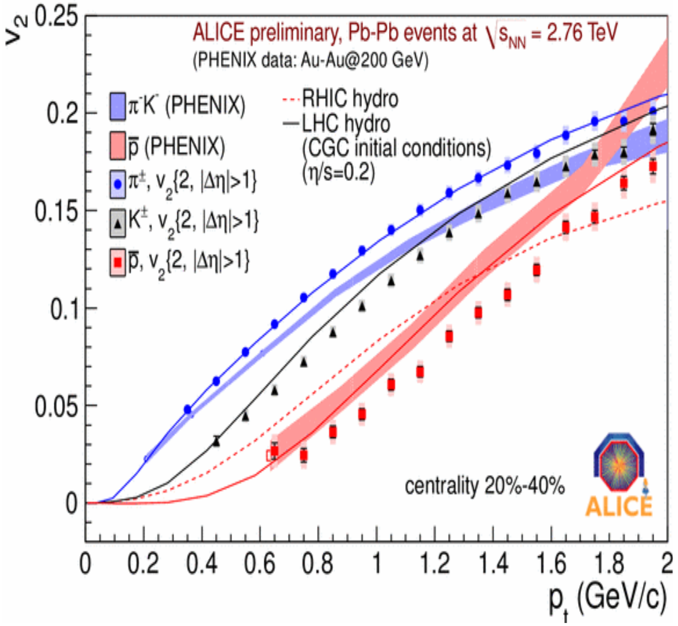


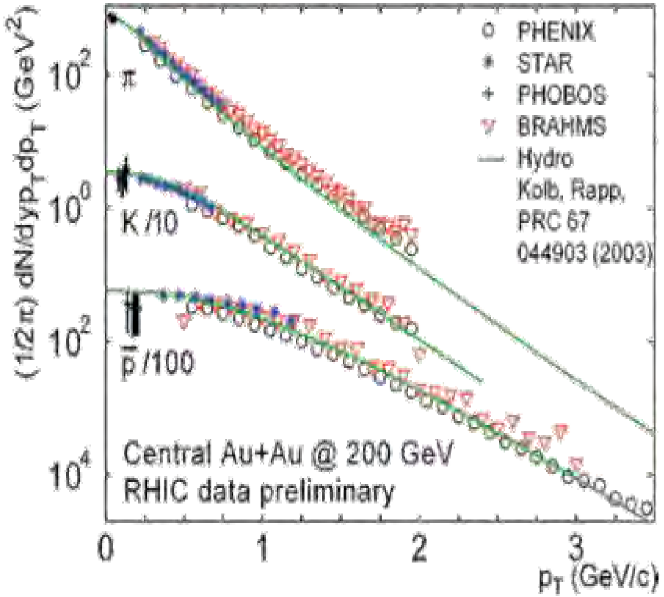


QGP AS A PERFECT LIQUID

- Very strong elliptic flow is observed in relativistic HIN collisions

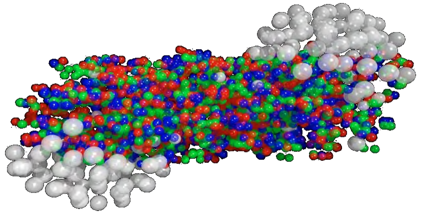






- $v_2(p_T)$ and mass dependence (as well as radial flow) – well described by ideal hydrodynamics!

  Ideal hydro == "*Perfect liquid*": equilibrium, zero mean free path, low viscosity

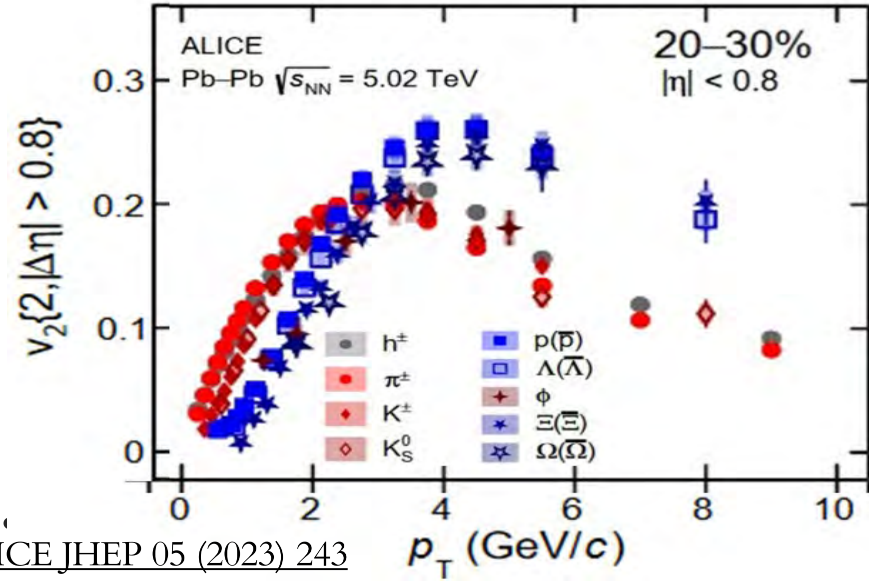


⋆Hydrodynamical calculations: thermalization time $t \sim 0.6\ fm/c$

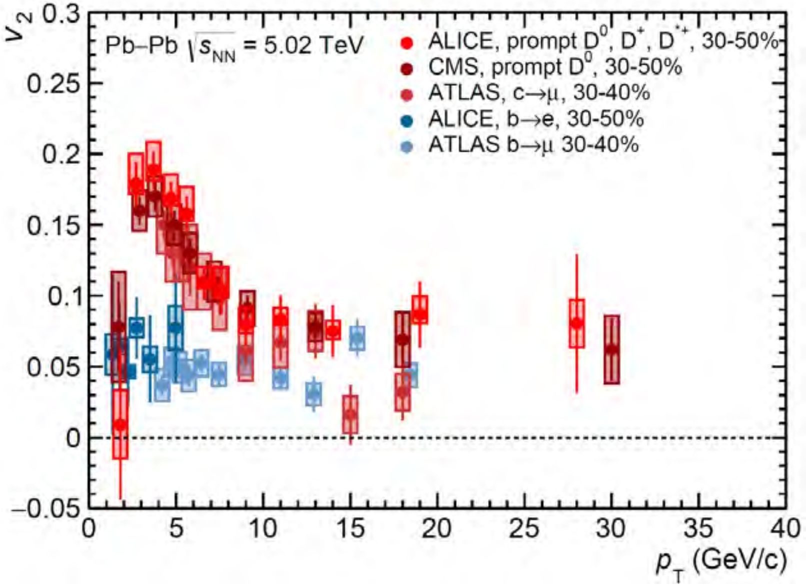
⋆Hadronic transport models fail to describe the data

MORE ON COLLECTIVITY

- Thermalization for strangeness and charm: elliptic flow for identified particle species

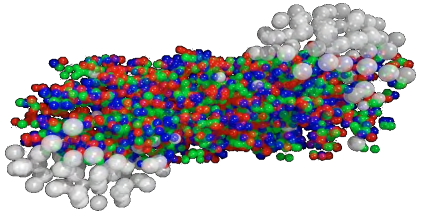


ALICE JHEP 05 (2023) 243



- Strange, multi-strange, charm hadrons – everything flow!

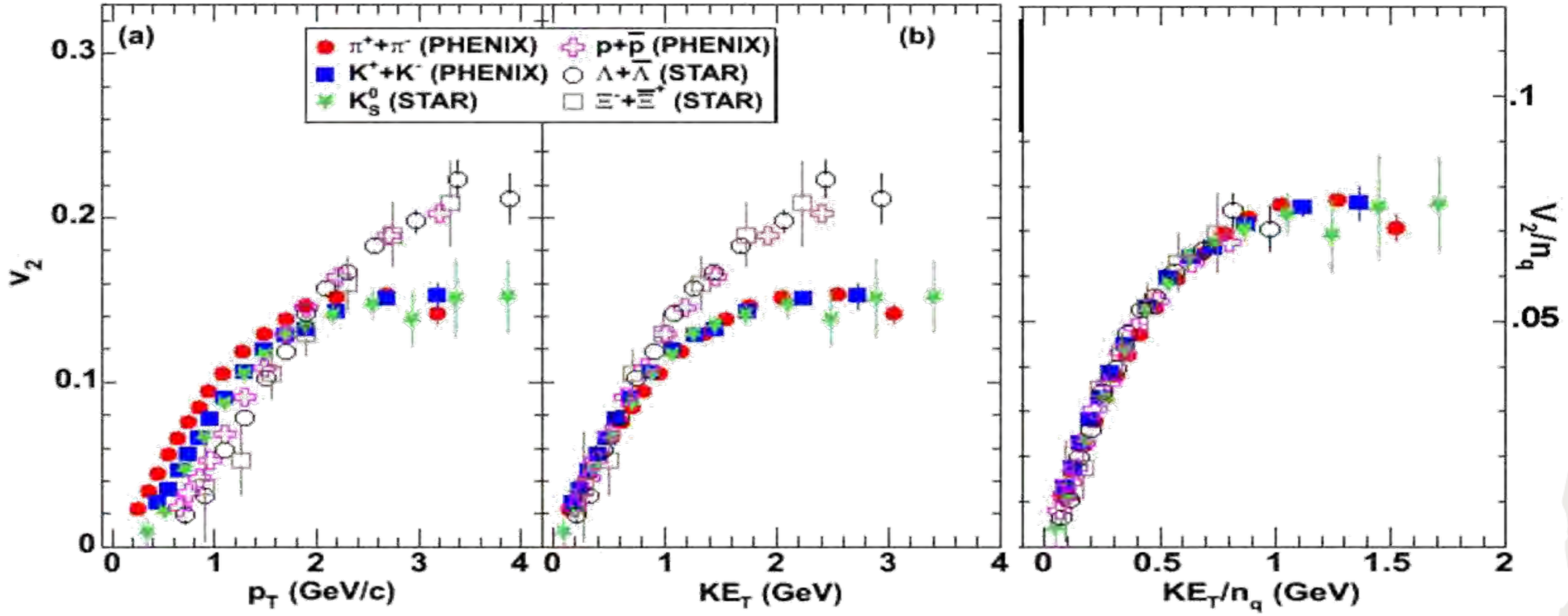
Evidence for thermalization in strange and charm sector

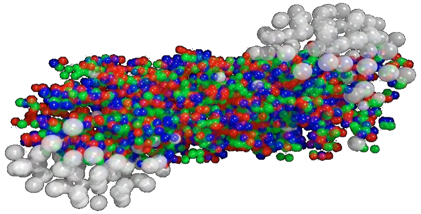


PARTONIC DEGREES OF FREEDOM

- Pressure gradients converting work into kinetic energy: $KE_T = m_0(\gamma_T - 1) = m_T - m_0$
- If partons are flowing, the $v_2(p_T)$ flow pattern in for hadrons can be expressed at a constituent quark level as:

$$\frac{dN}{d\varphi} \propto [1 + 2v_2(p_T)\cos(2\varphi) + \cdots] = \left[1 + 2v_2^q(p_T^q)\cos(2\varphi) + \cdots\right]^{n_q} \approx 1 + 2n_q v_2^q\left(\frac{p_T}{n_q}\right)\cos(2\varphi) + \cdots$$





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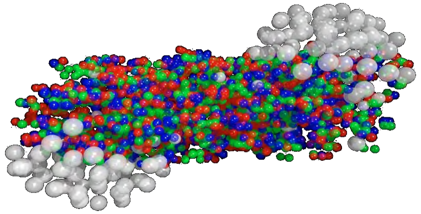
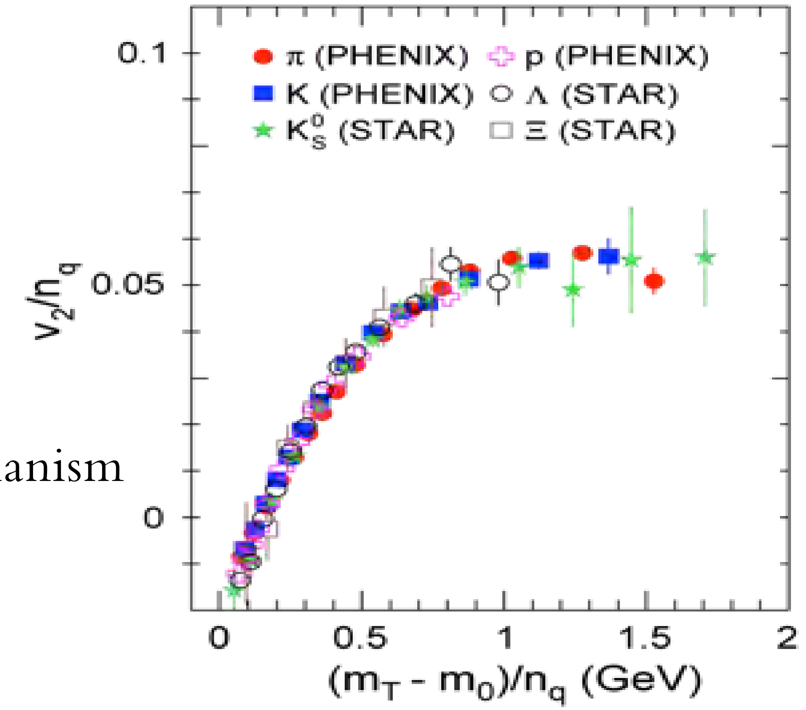
- Switching to KE_T/n and v_2/n

  with $n = 2$ for mesons and $n = 3$ for baryons

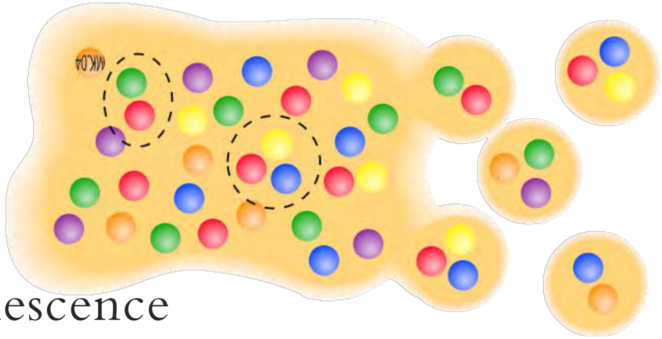
- Hadronization of flowing quarks by a coalescence mechanism

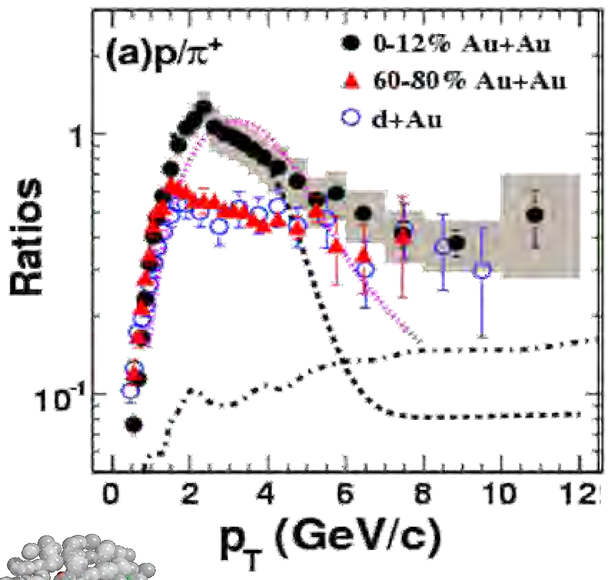


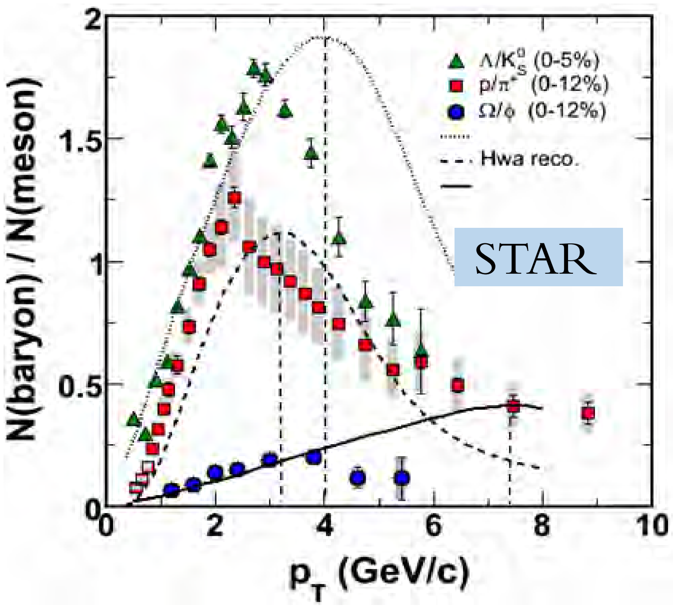


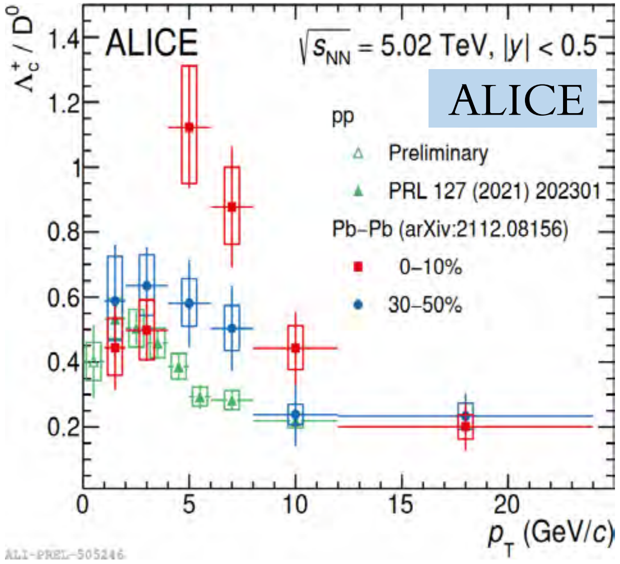
QUARK COALESCENCE

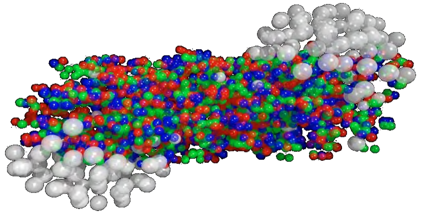
- Signature HIN result: baryon to meson ratios
  RHIC and LHC: enhancements in $p/\pi, \Lambda/K, \Omega/\varphi, \Lambda_c/D$
- QGP hadronization through partonic recombination/coalescence





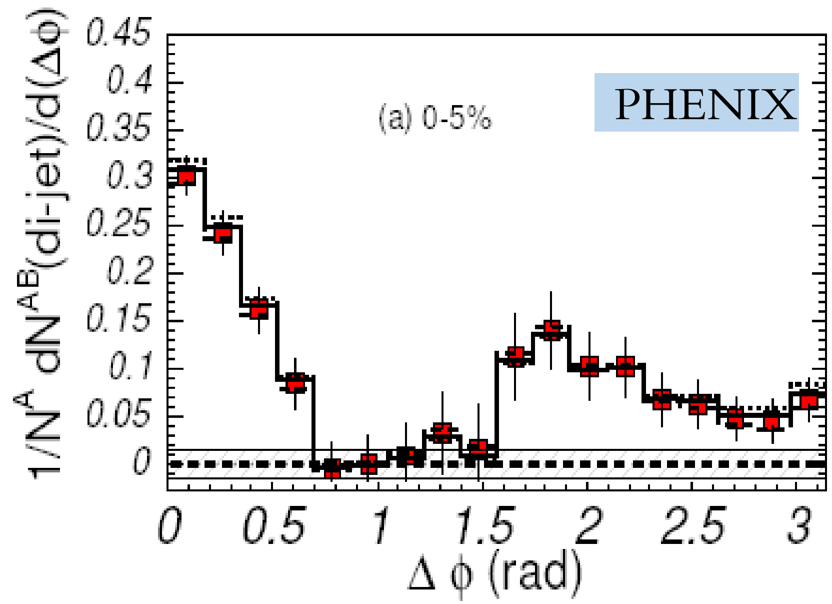


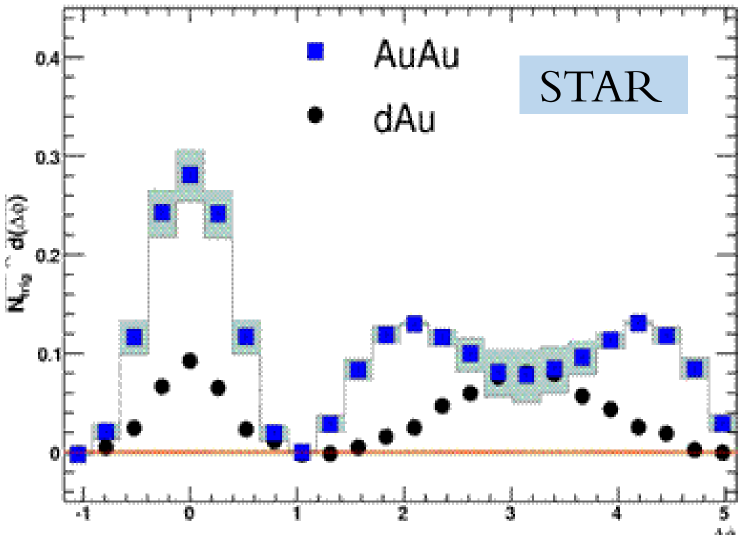


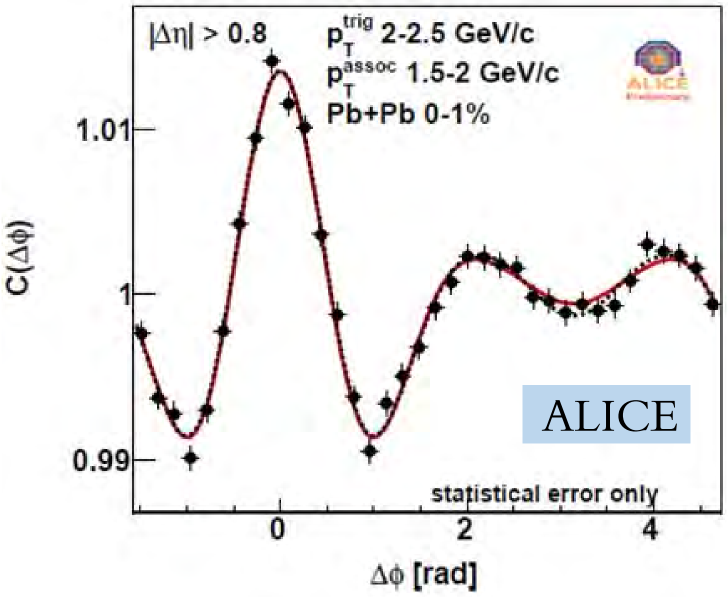


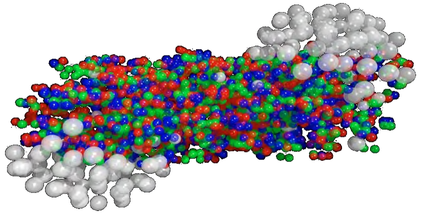
BACK TO AZIMUTHAL ANISOTROPIES

- Two-particle correlation studies revealed a complex landscape of azimuthal anisotropies:
  Reemergence of away side peak, double-hump structures.



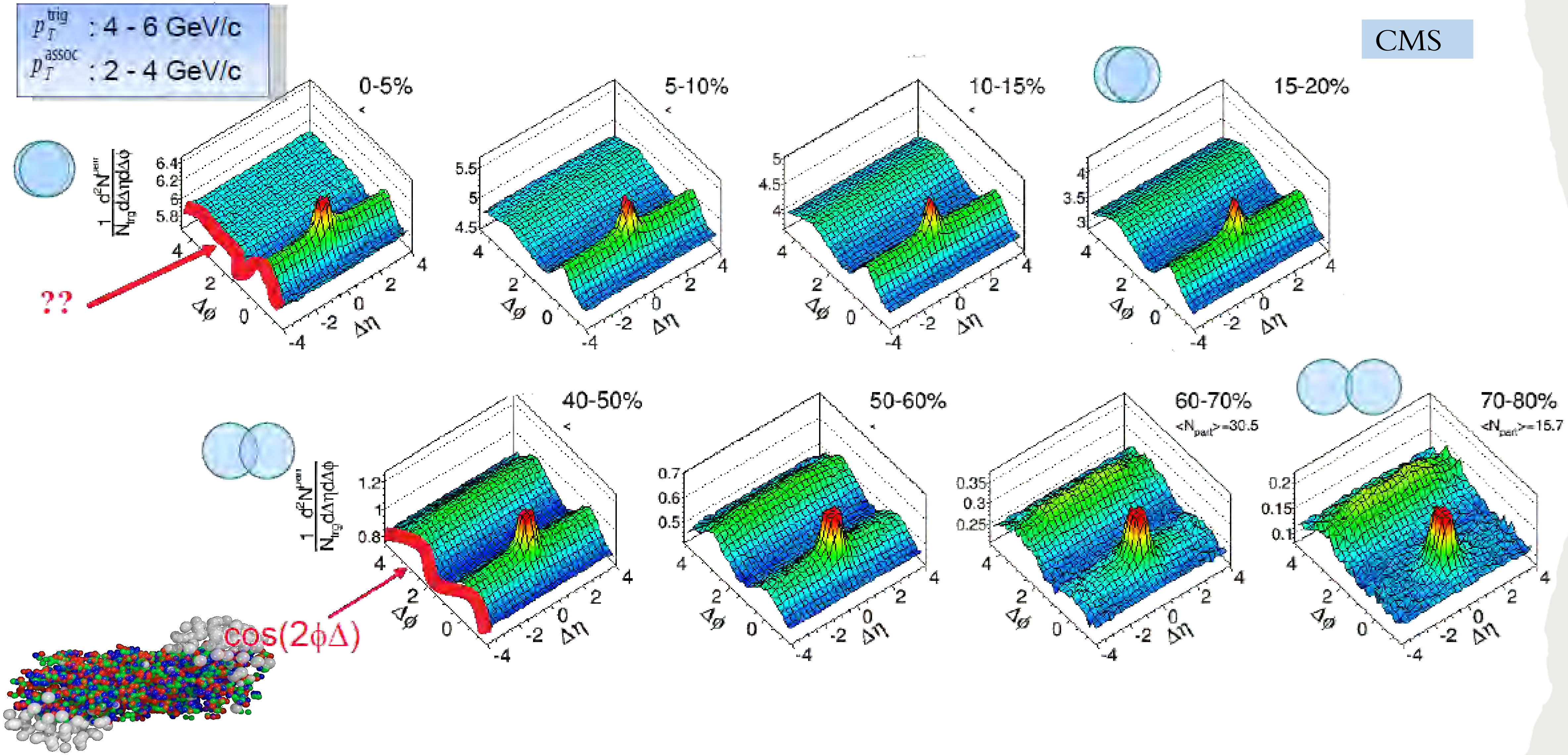






Since these features prominently appear in high-/low-p_T correlations, originally it generated many speculations about “Mach cone” like effect induced by a hard probe

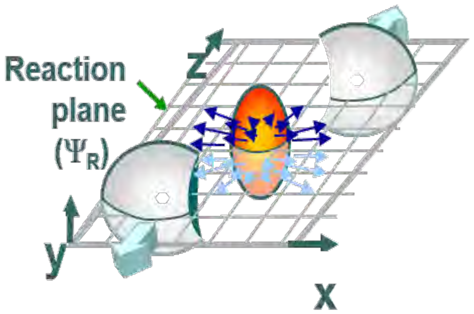
CENTRALITY EVOLUTION IN 2D



OLGA EVDOKIMOV (UIC)

AUGUST 1, 2024

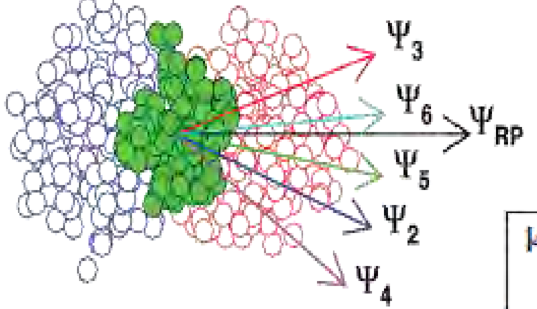
UNDERSTANDING THE INITIAL STATE



Early picture of collision geometry

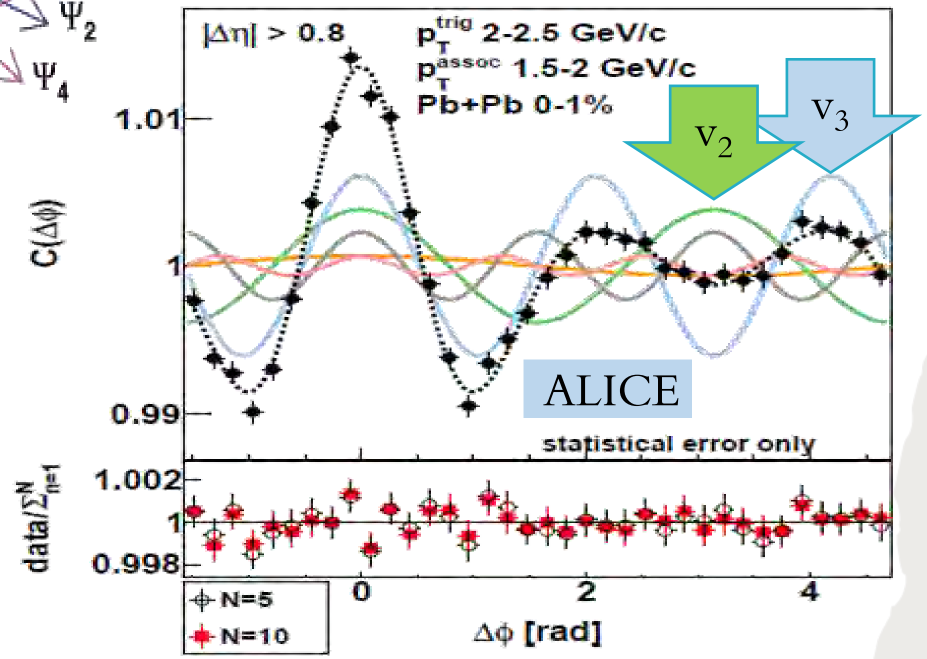
- Current Glauber-based picture:

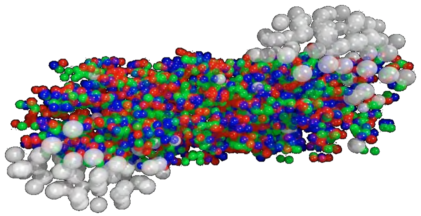
PRC 81 (2010)054905



$$\Psi_m^{pp} = \frac{1}{m}\tan^{-1}\left\{\frac{\sum_{i=1}^{N_{part}} r_i^m \sin(m\phi_i)}{\sum_{i=1}^{N_{part}} r_i^m \cos(m\phi_i)}\right\} - \frac{\pi}{m}$$

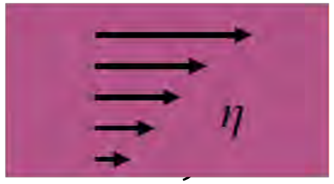
- Full correlation structure needs Fourier terms
- Very central events: $v_2 \sim v_3$, sizable v_4
- Geometry dominates the elliptic flow term; higher harmonics reflect fluctuation in initial conditions

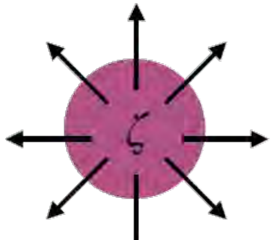




MODELING THE FLOW HARMONICS

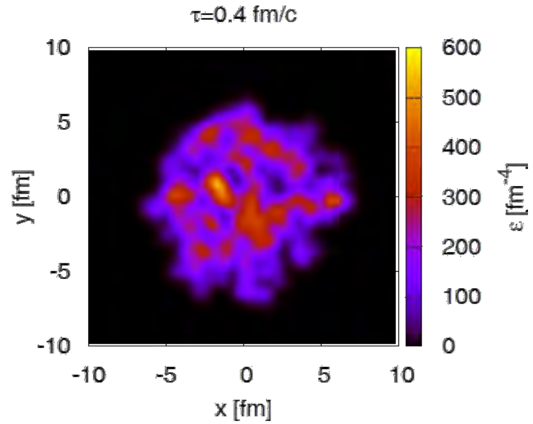
- Full hydrodynamics calculations: hierarchy of harmonics agrees with theory expectations
- Higher order anisotropies are more sensitive to η/s (shear viscosity to entropy density) variations

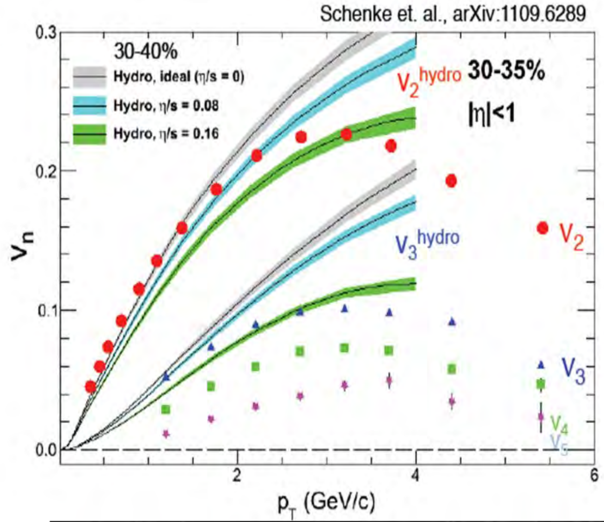


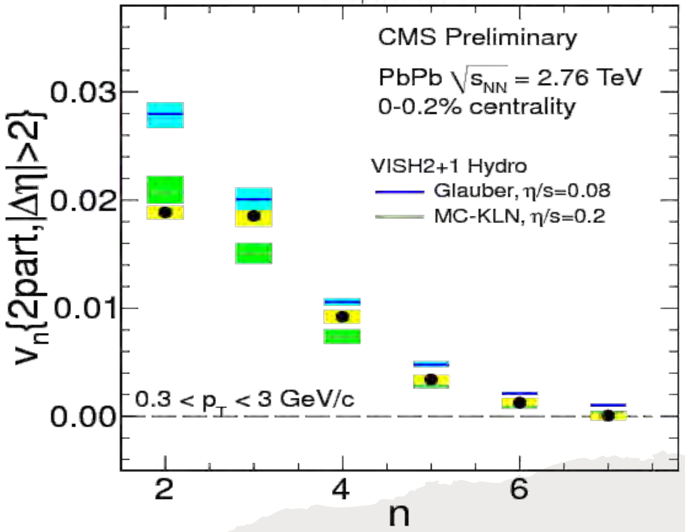


shear viscosity bulk viscosity

3+1D viscous hydrodynamics

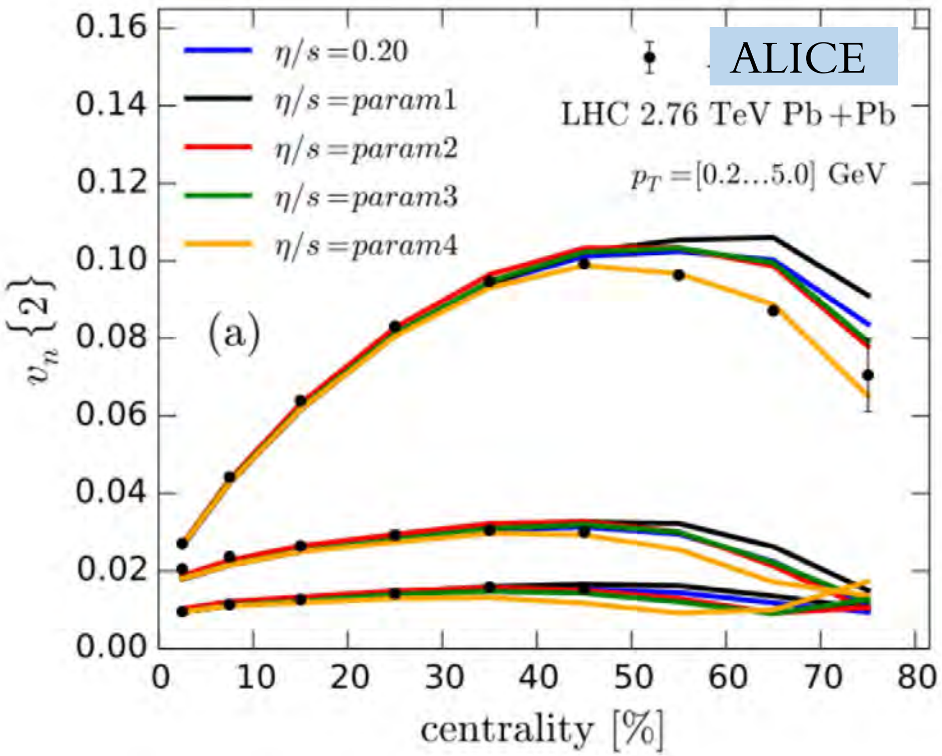


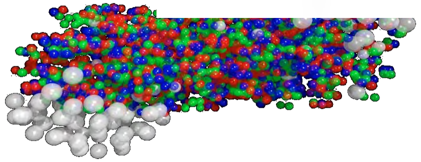


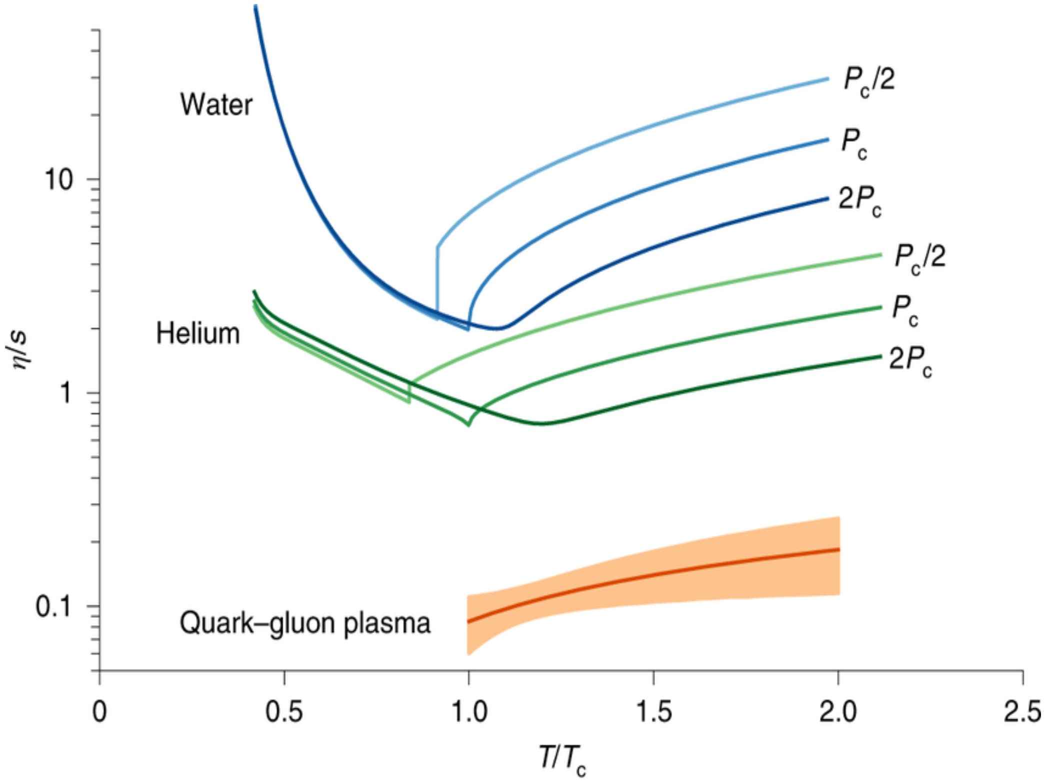


THE MOST PERFECT FLUID CREATED

- Estimates of η/s are finite, close to quantum limit $\eta/s \geq \hbar/(4\pi)$ limit is provided by the AdS/CFT correspondence







Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma; Nature Physics, 15 (2019) 1113

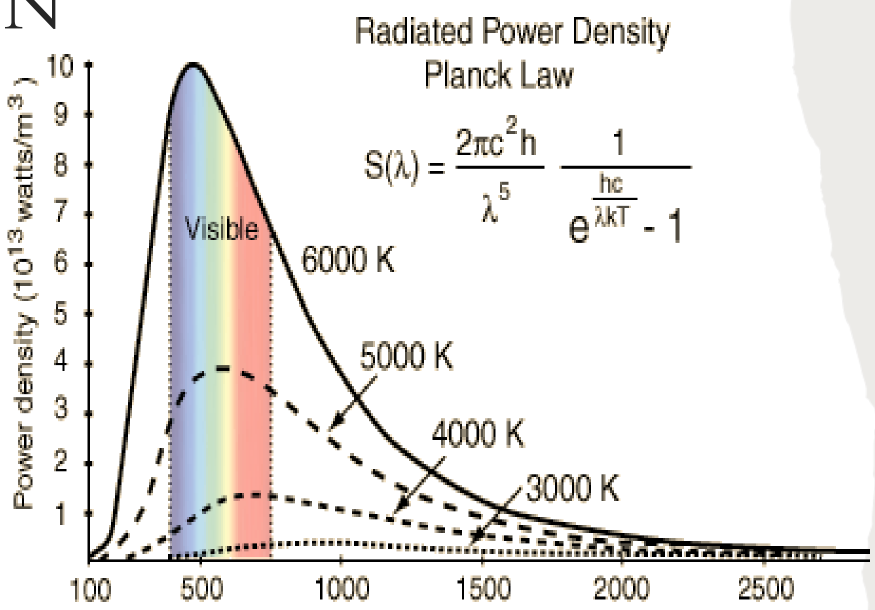
QGP TEMPERATURE, AGAIN

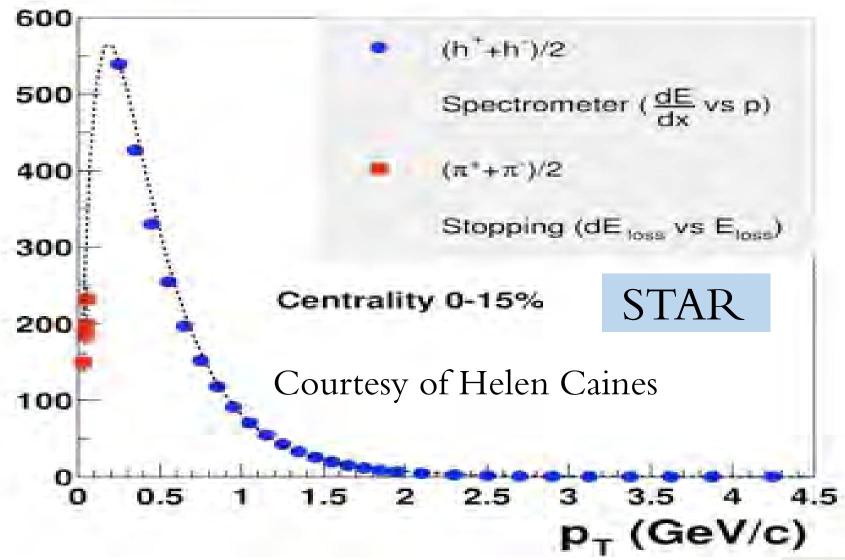
- Ideally, want a direct measure of the QGP temperature while in QGP phase: think about "blackbody" radiation

- From transverse momentum distribution of pions deduce temperature ~120 MeV

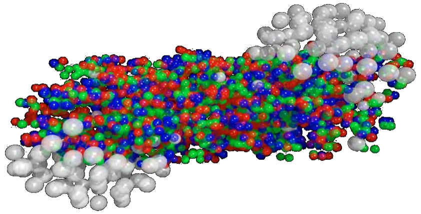
  – not the QGP temperature! The system lives substantial time in hadronic phase

  – we've already seen $T_{ch} > T_{kin}$





Courtesy of Helen Caines



OLGA EVDOKIMOV (UIC)

AUGUST 1, 2024

QGP TEMPERATURE, AGAIN

- Direct photons!

    Thermally produced by QGP (plus those from initial hard parton-scatterings)

    Mean-free path much larger than nuclear scales → leave the reaction zone unaffected

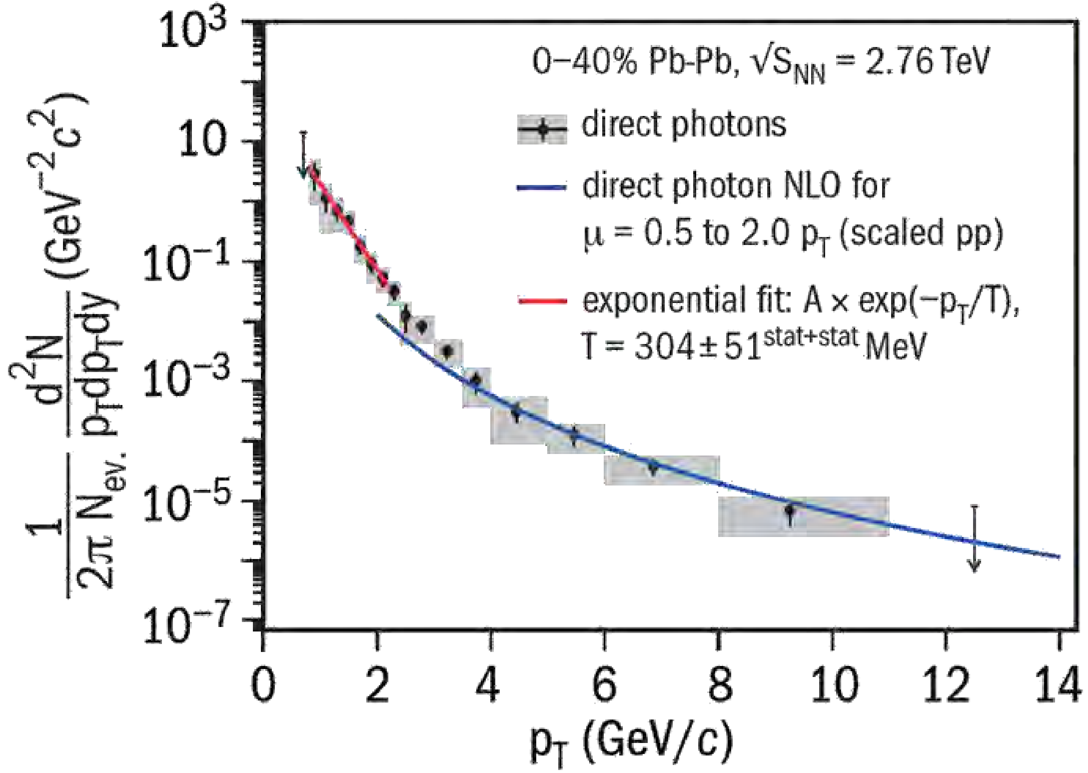
- Caveat: thermal photons are produced throughout the evolution of the system

- Extracted QGP temperatures*:

$$T_{RHIC} \sim 220\ MeV, T_{LHC} \sim 300\ MeV$$

*effective temperatures averaged over collision evolution

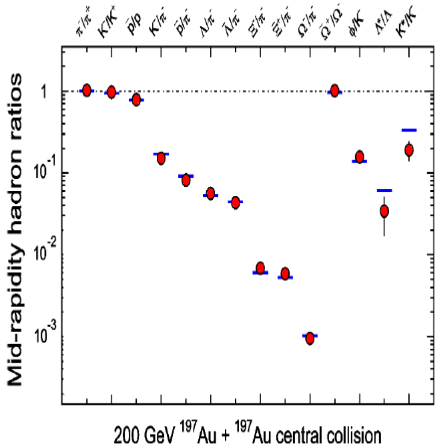
ALICE

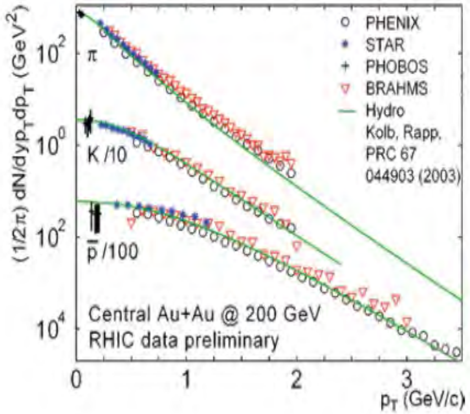


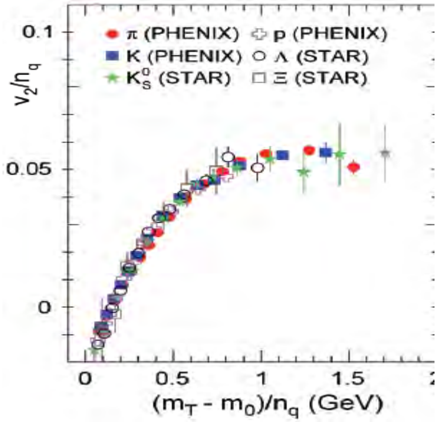
Final results in PLB 754 (2016) 235

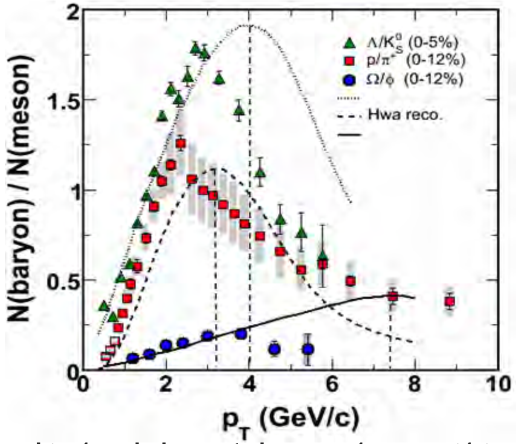
"TAKE-HOME" POINTS:

- Bulk measurements provide experimental evidence QGP formation in ultra-relativistic HIN collisions: a strongly interactive thermalized partonic matter with (near) perfect fluidity







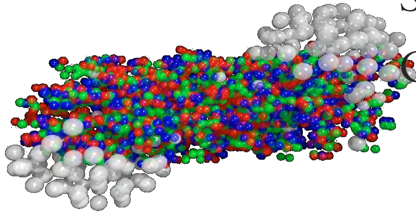


Initial temperature/energy density are above the critical values predicted for phase transition

Chemical freeze-out at predicted phase boundary

Strong radial and elliptic flow for hadrons (in strange and charm sectors too!)

Constituent quark degrees of freedom are important at hadronization



BONUS SLIDES

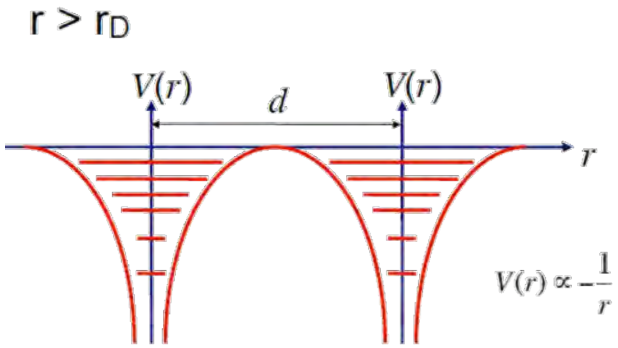
The UIC HENP Group's work is supported by US DOE-NP

QGP – HOW TO

- Asymptotic freedom occurs at very high $Q^{2,}$ not readily achievable in lab. How to make the QGP? Consider Debye screening:
- Consider high color charge density n, the short-range term of the strong potential is modified: $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr \rightarrow V(r) \sim -\frac{4}{3}\frac{\alpha_s}{r} e^{-r/r_D}$, where $r_D \sim \sqrt[3]{n}$ - Debye radius
- In QED, Debye screening radius is connected to Mott transition in condensed matter:

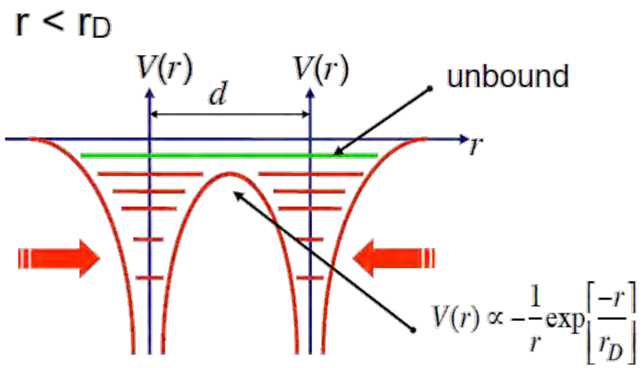
e^- separation > e^- binding radius

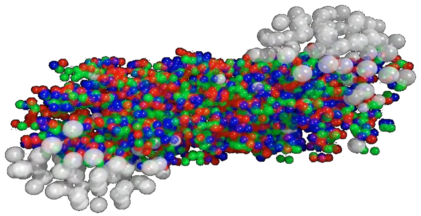
insulator



e^- separation < e^- binding radius

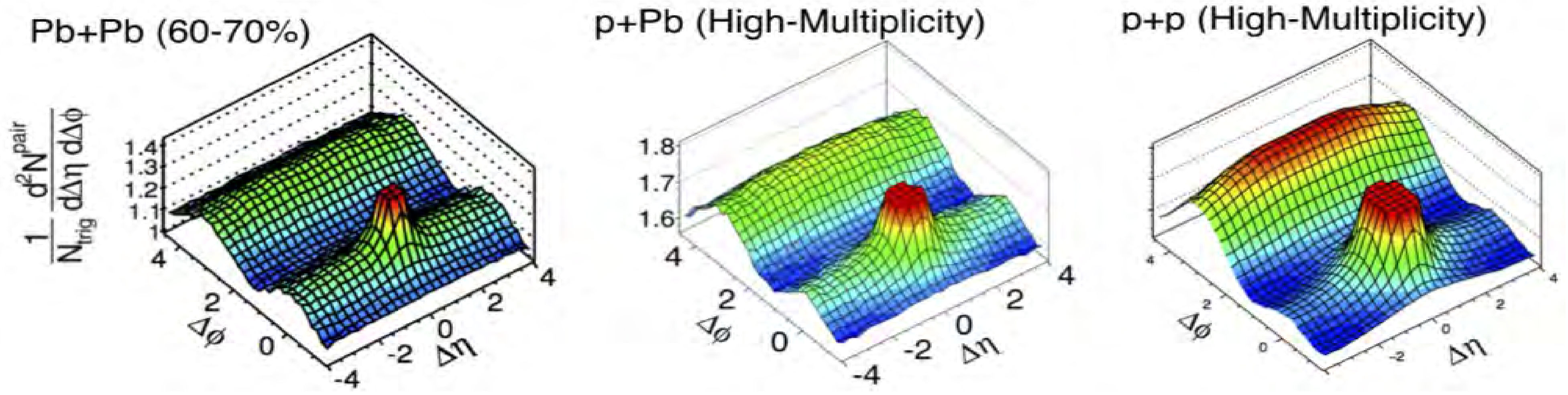
conductor





SIDE NOTE ON "RIDGE"

- Discovery of collective phenomena in small collision systems:



Long range correlations are everywhere! Yes, even in pp
Can the system that small reach an equilibrium? Could this be an initial state phenomena?
NOT reproduced for pp in any established MC generators!