The Phase Diagram of QCD

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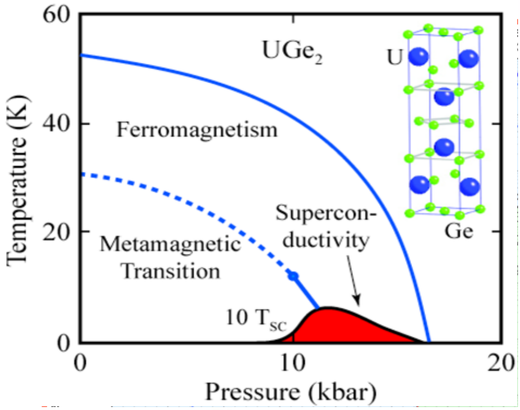
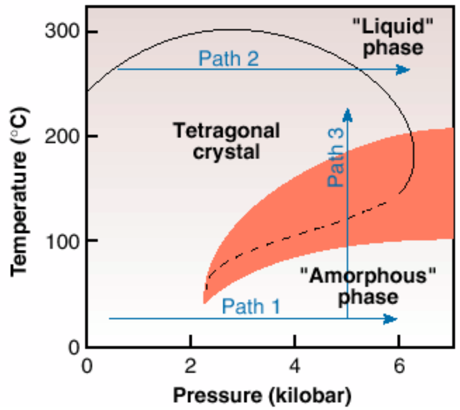
NISER

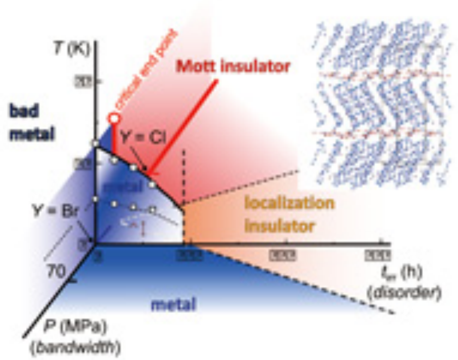
Outline:
- Phase Diagram of QCD
- Experimental Realization
- Summary

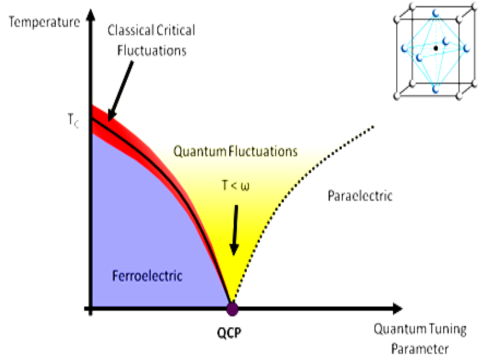
IIT Madras, Chennai – January 18, 2016

Phase diagram





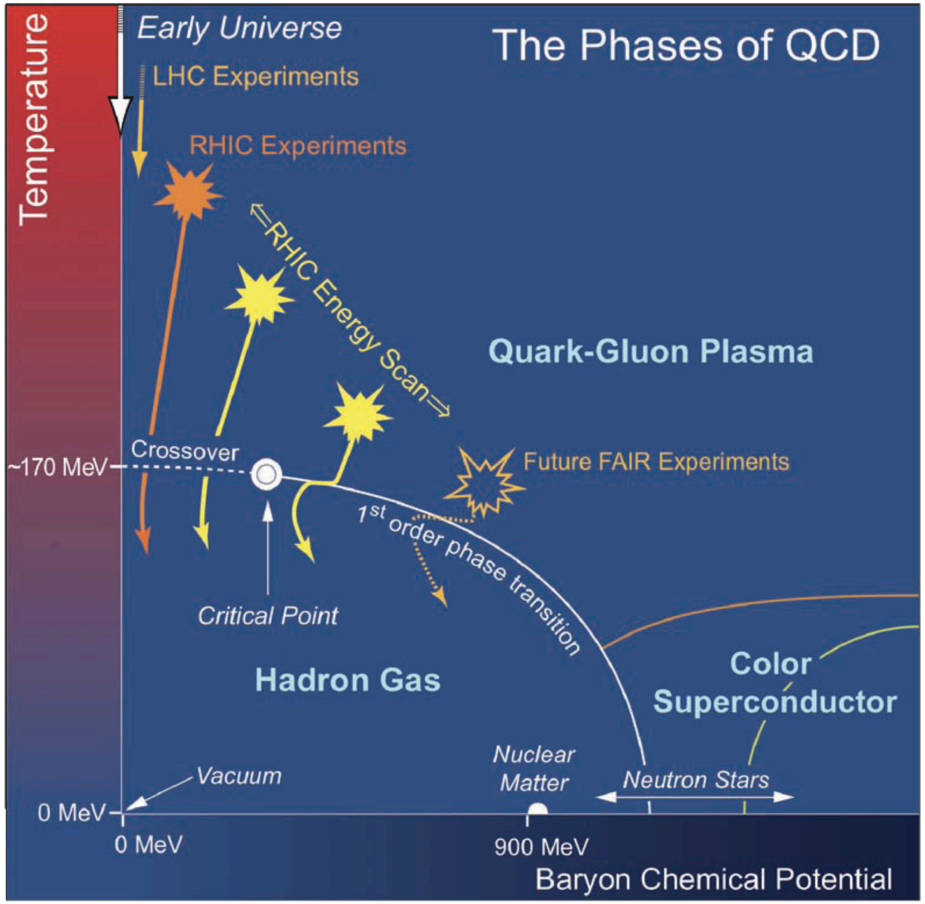




Phase diagram of Water
Electromagnetic interaction
Precisely known

http://www1.lsbu.ac.uk/water/water_phase_diagram.html

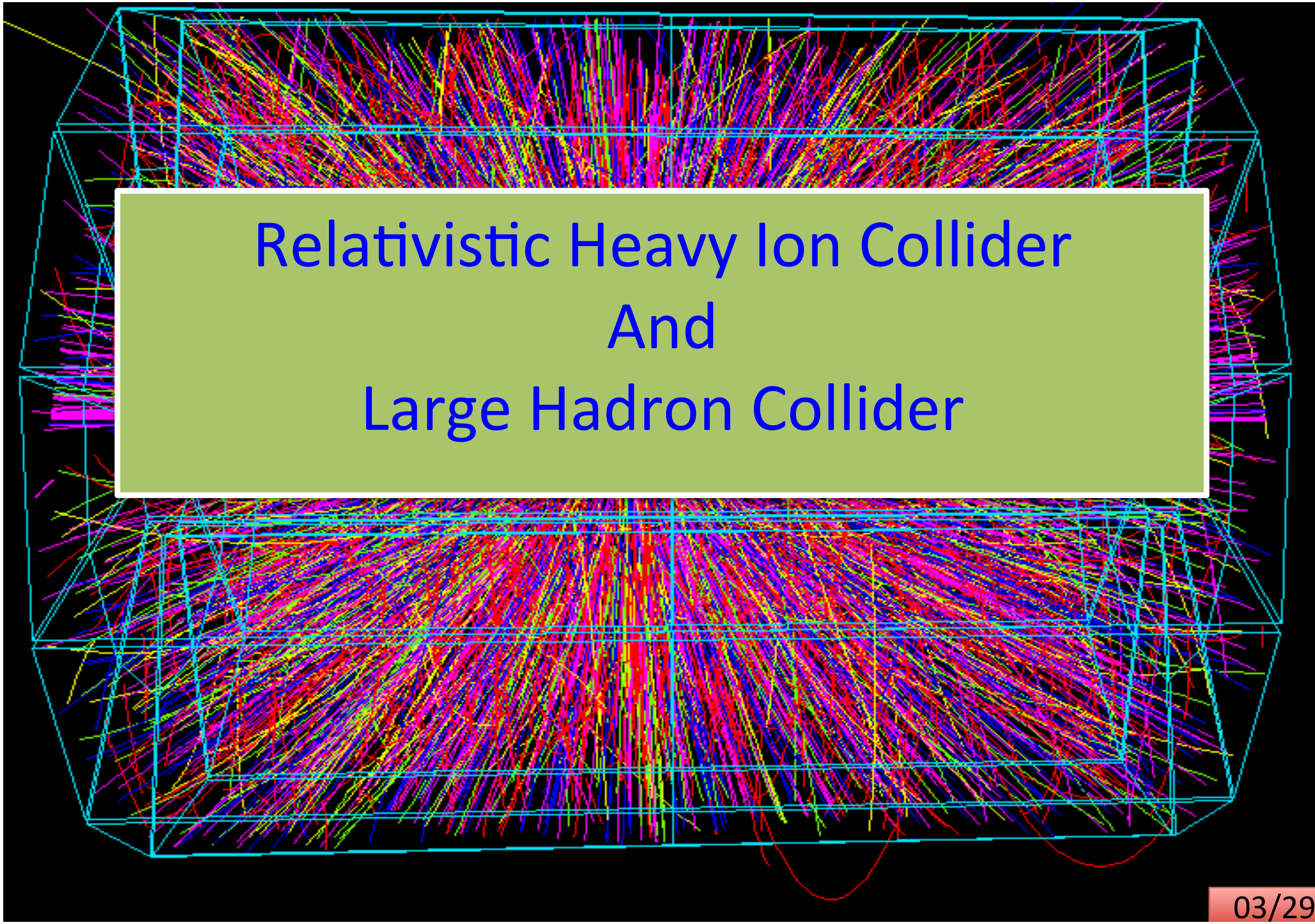
Many



Phase diagram of strong interactions
Largely still a conjecture

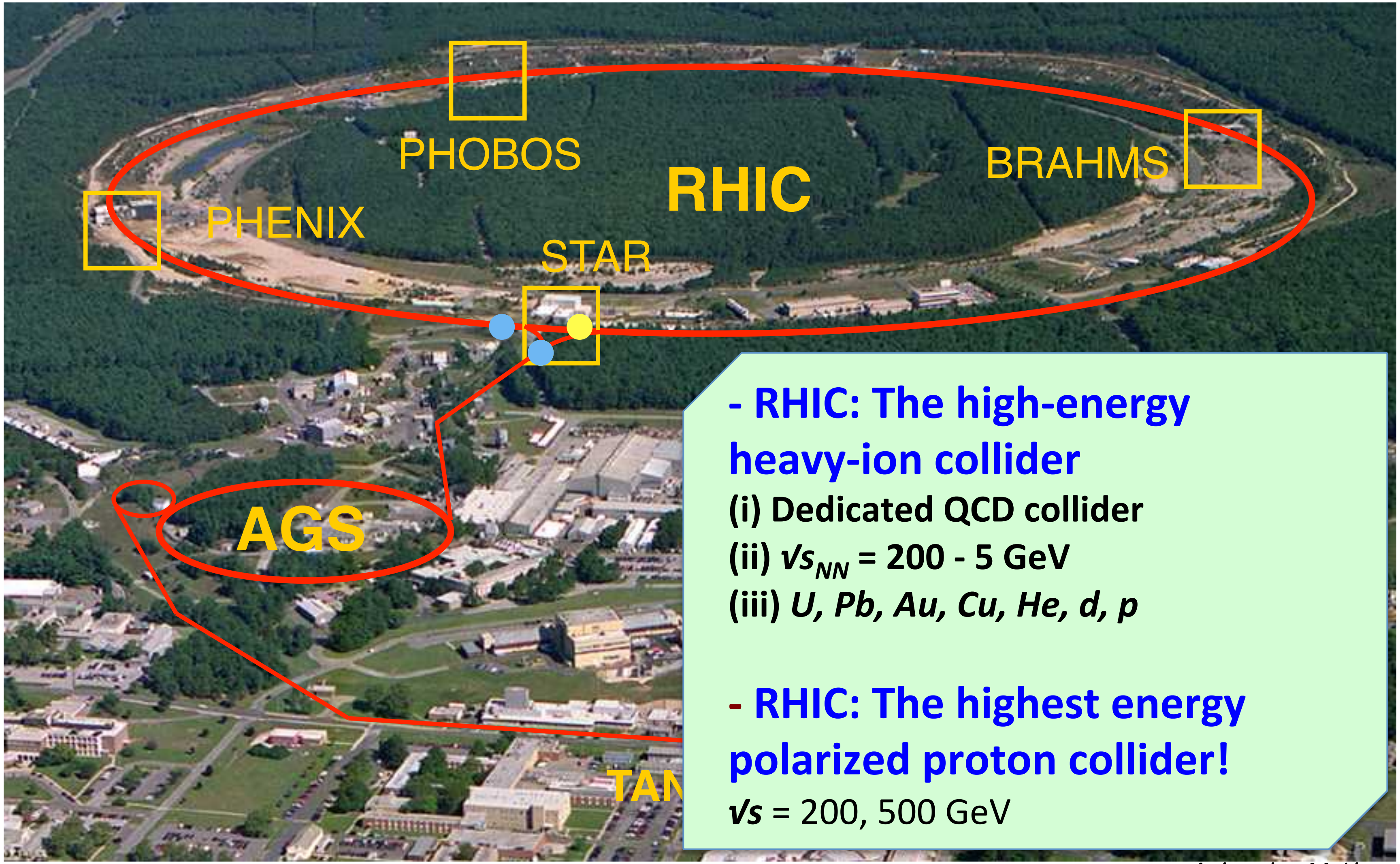
NSAC Long range plan

Unique



Relativistic Heavy Ion Collider
And
Large Hadron Collider

Relativistic Heavy Ion Collider



- **RHIC: The high-energy heavy-ion collider**

(i) Dedicated QCD collider

(ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV

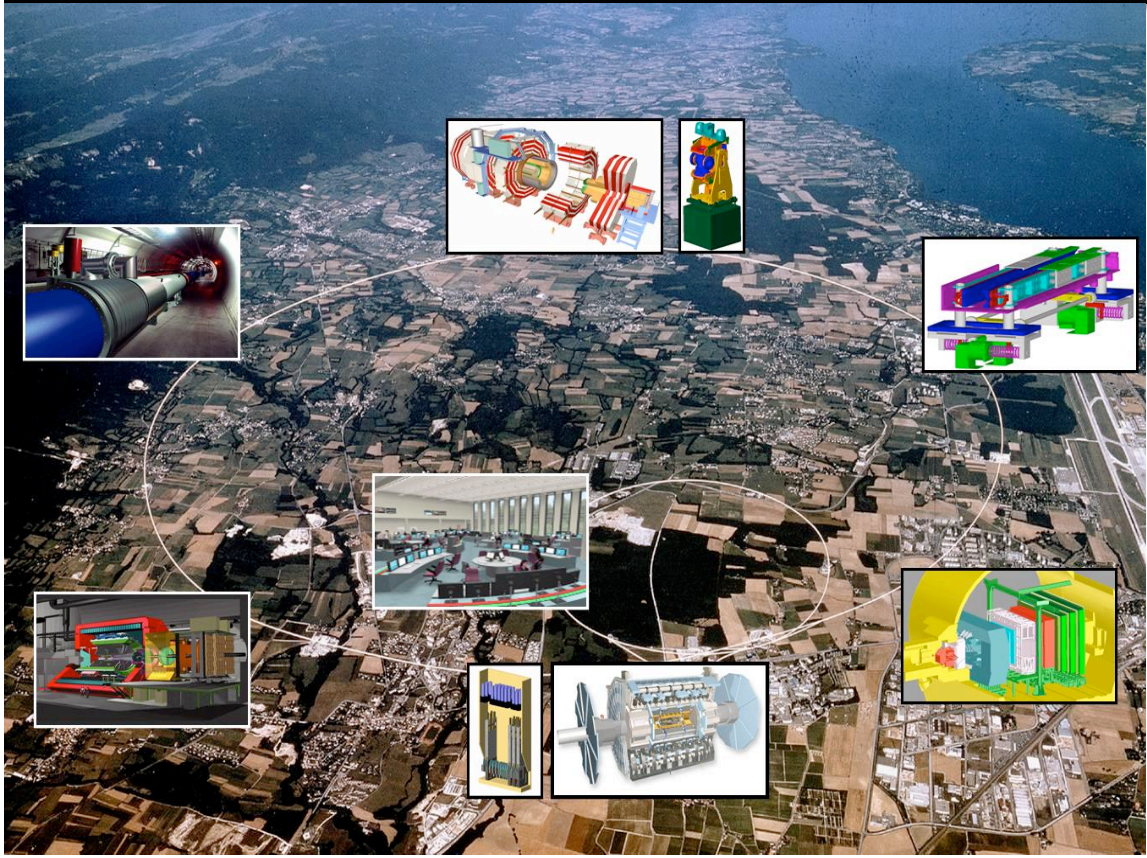
(iii) *U, Pb, Au, Cu, He, d, p*

- **RHIC: The highest energy polarized proton collider!**

$\sqrt{s}$ = 200, 500 GeV

Animation M. Lisa

Large Hadron Collider



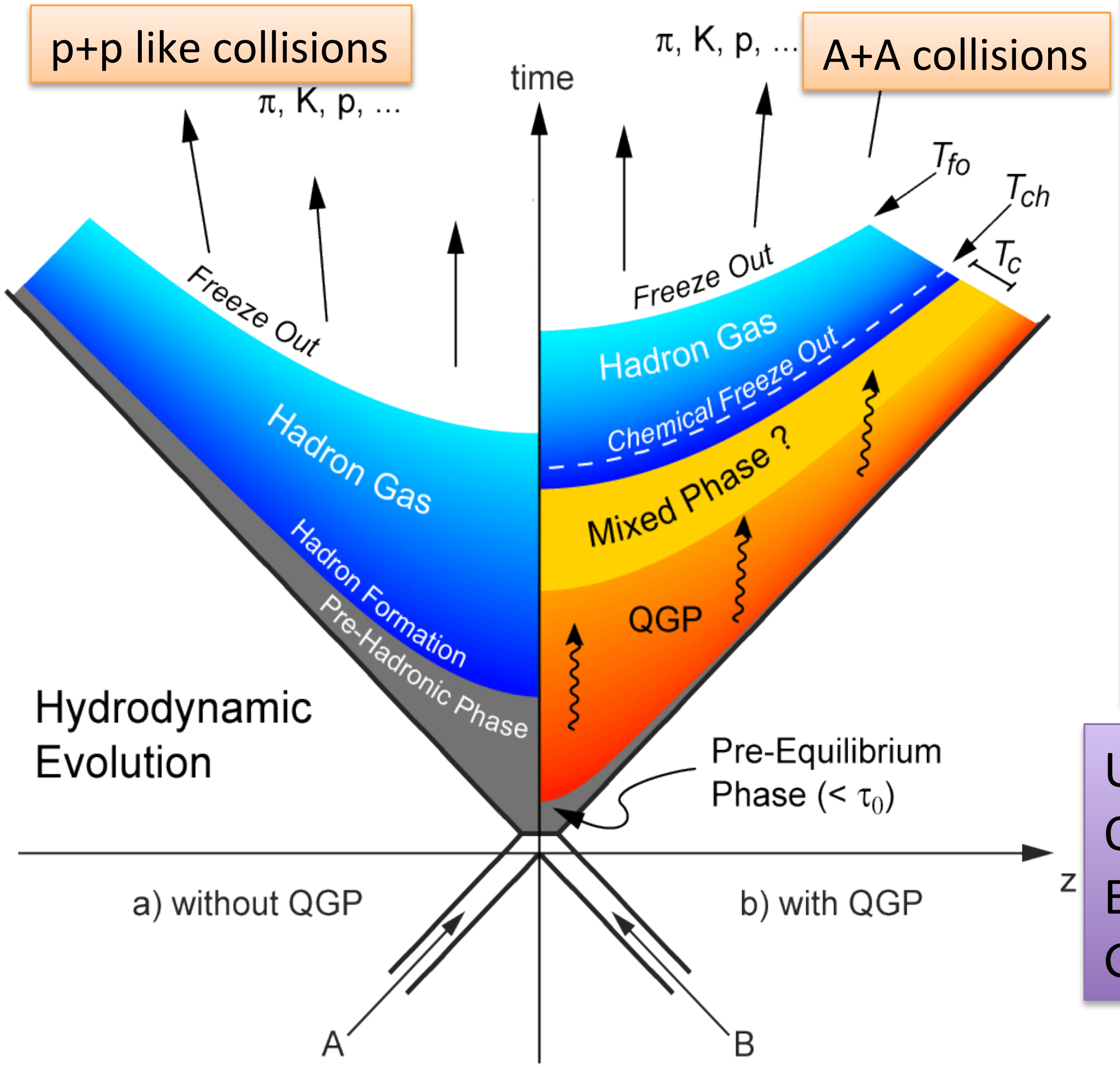
- ✧ Produces matter with temperature more than 100,000 times the temperature of Sun
- ✧ Data recorded will fill around 100,000 dual layer DVDs every year

- ✧ Largest particle accelerator: Circumference is 26.659 Km.
- ✧ Worlds Coldest place: 9300 magnets at -271.3°C (1.9 K) – Colder than outer space
- ✧ Worlds Loneliest place: Internal pressure 10^{-13} atm. 10 times less than the pressure on moon
- ✧ Fastest Race track: Trillions of protons race 11245 times a second with speed 99.9999991% speed of light

The CMS magnet system contains about 10 000 t of iron, which is more iron than in the Eiffel Tower

The Sun never sets for such experiments

Heavy-Ion Collisions and QCD Phase diagram



J. D. Bjorken Physical Review D 27 (1983) 140

Colliding two nuclei we expect to create the QCD transitions

-- De-confinement
-- Chiral Symmetry Restoration

in laboratory

Universe:
QCD Ph. Transition: T~200MeV
EW Ph. Transition: T ~ 150 GeV
GUT Ph. Transition: T ~ 10^{16} GeV

Experimental access to the Phase diagram of QCD

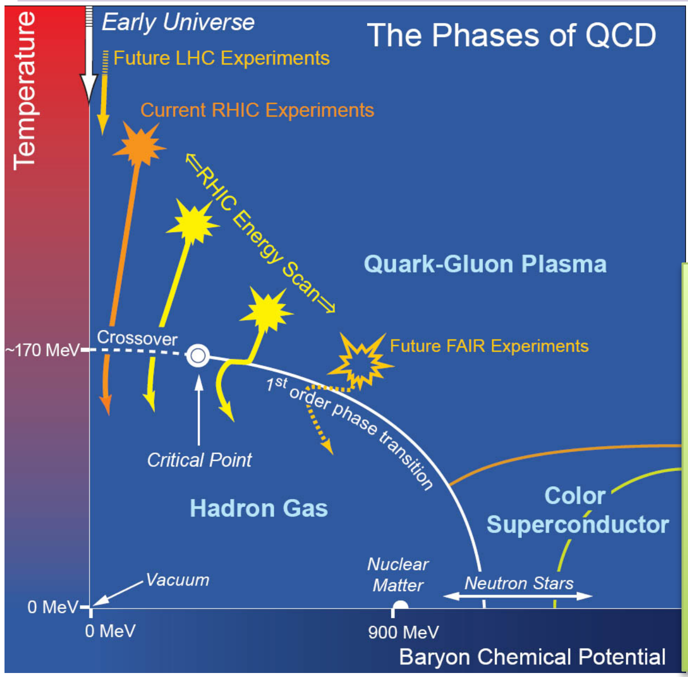
Physical systems undergo phase transitions when external parameters such as the temperature (T) or a chemical potential (μ) are tuned.

Conserved Quantities:

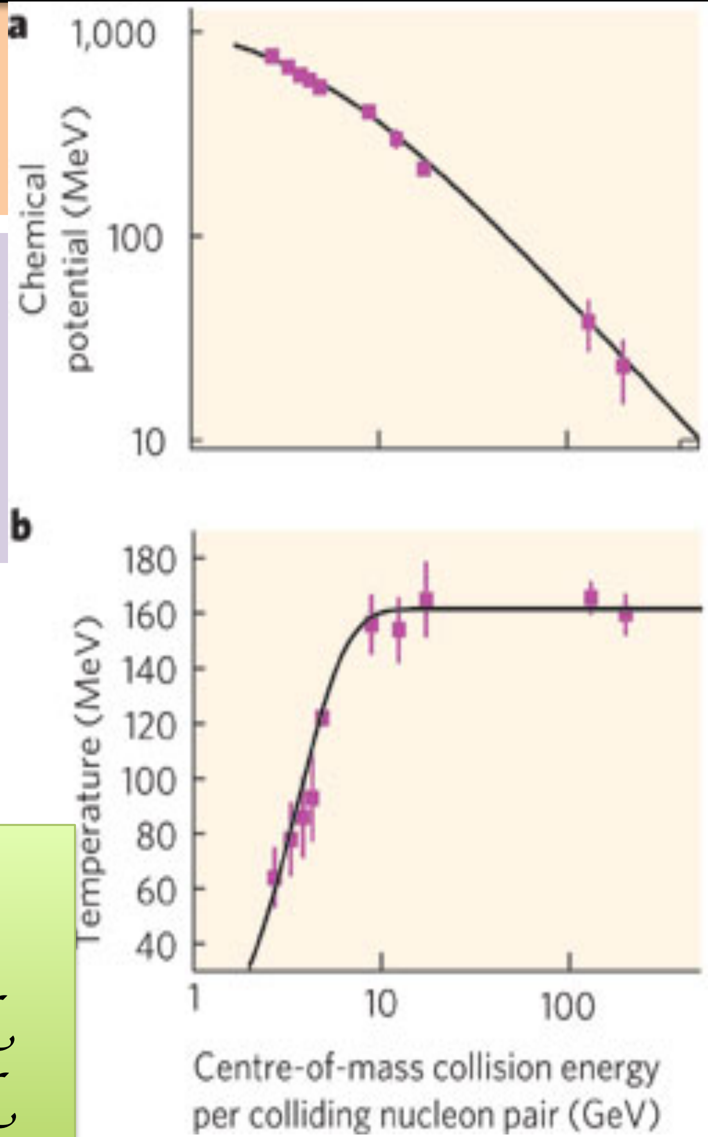
Baryon Number ~ μ_B

Electric Charge ~ μ_Q ~ small

Strangeness ~ μ_S ~ small



Varying beam energy varies Temperature and Baryon Chemical Potential



P. Braun-Munzinger, J. Stachel
Nature 448:302-309,2007

Establishing the Phase Diagram of QCD

Produce a QCD matter where Thermodynamics is applicable

Demonstrate existence of Quark-Gluon Phase

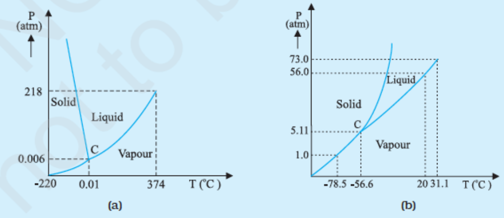
Establish cross-over at $\mu_B = 0$ MeV

Establish – QCD Critical Point and/or 1^{st} Order Phase Transition at high μ_B

Chapter – 11
Thermal Properties of Matter
NCERT - Book

Triple Point

The temperature of a substance remains constant during its change of state (phase change). A graph between the temperature T and the Pressure P of the substance is called a phase diagram or $P - T$ diagram. The following figure shows the phase diagram of water and CO_2. Such a phase diagram divides the $P - T$ plane into a solid-region, the vapour-region and the liquid-region. The regions are separated by the curves such as sublimation curve (BO), **fusion curve** (AO) and **vaporisation curve** (CO). The points on **sublimation curve** represent states in which solid and vapour phases coexist. The point on the sublimation curve BO represent states in which the solid and vapour phases co-exist. Points on the fusion curve AO represent states in which solid and liquid phase coexist. Points on the vapourisation curve CO represent states in which the liquid and vapour phases coexist. The temperature and pressure at which the fusion curve, the vaporisation curve and the sublimation curve meet and all the three phases of a substance coexist is called the **triple point** of the substance. For example the triple point of water is represented by the temperature 273.16 K and pressure $6.11 10^{-3}$ *Pa.*

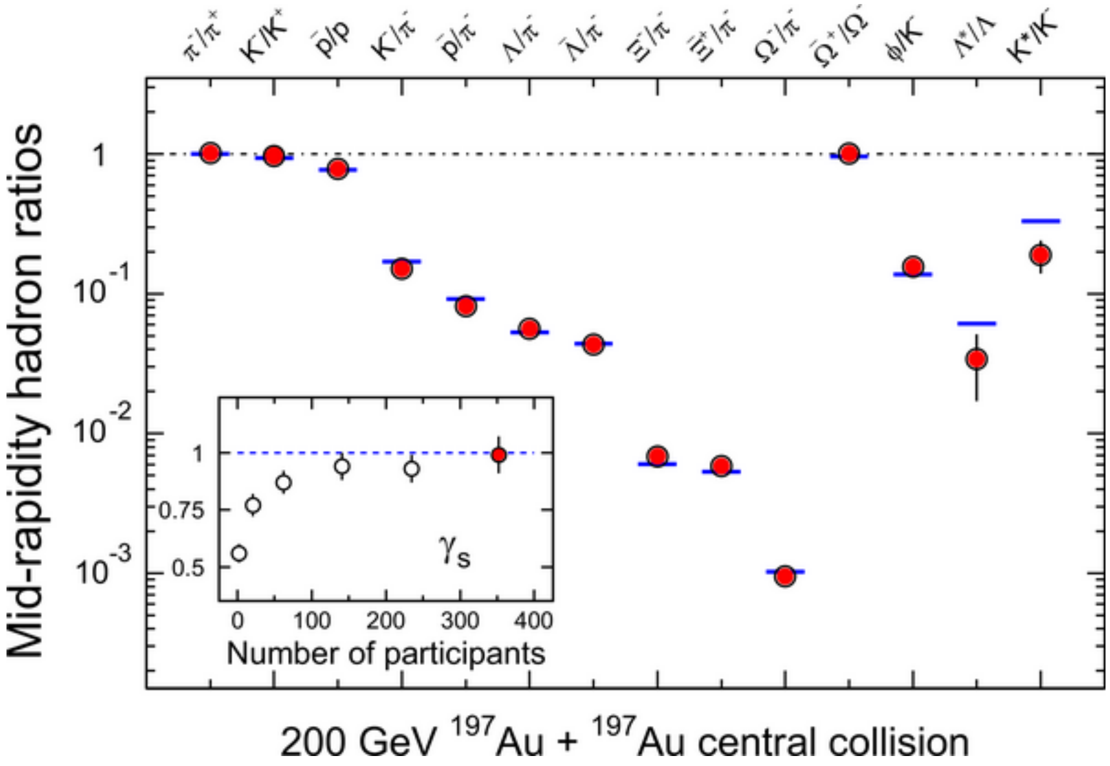


Pressure-temperature phase diagrams for (a) water and (b) CO_2 (not to the scale).

If successful QCD PD could also find place a in text books

Particle Production – Thermalized Source

STAR PRL : 2004
STAR NPA : 2005



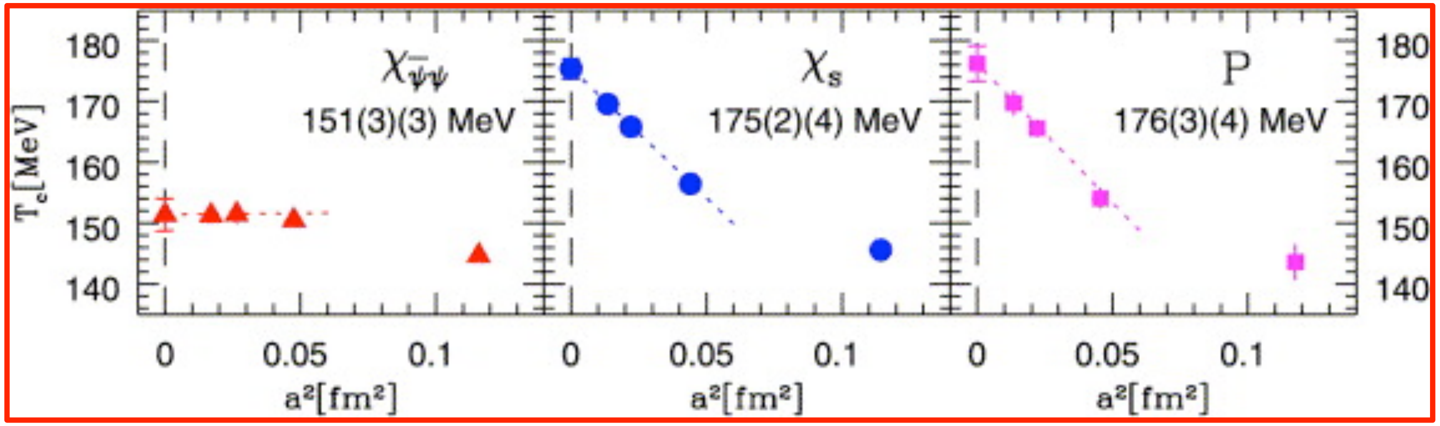
T_{ch} = 163 ± 4 MeV
μ_B = 24 ± 4 MeV

$$n = \frac{1}{V}\frac{\partial (T \ln Z)}{\partial \mu} = \frac{V.T..m_i^2 g_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm 1)^{k+1}}{k}\left(e^{\beta k \mu_i}\right)K_2\left(\frac{km_i}{T}\right)$$

Statistical Model with Grand Canonical Ensemble.
Incorporates the various conservation laws.
Assumes thermal and chemical equilibrium.

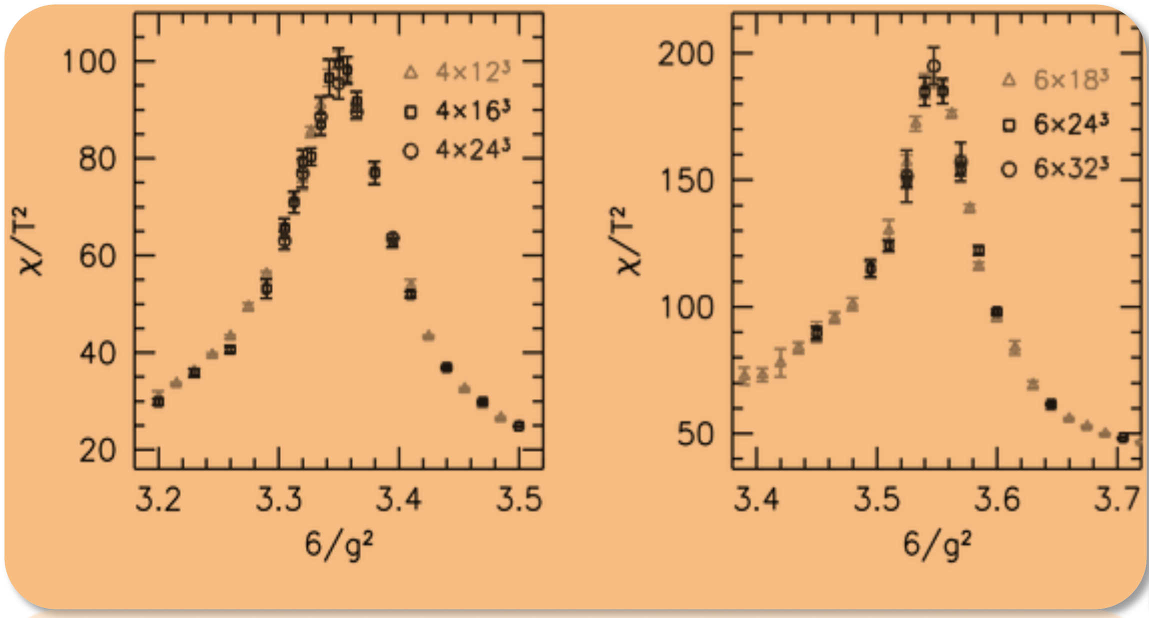
In central collisions, the system is thermalized at RHIC

QCD Phase Structure & Transition Temperature at μ_B = 0 MeV



PRD85 (2012) 054503

NPA 830 (2009) 805c



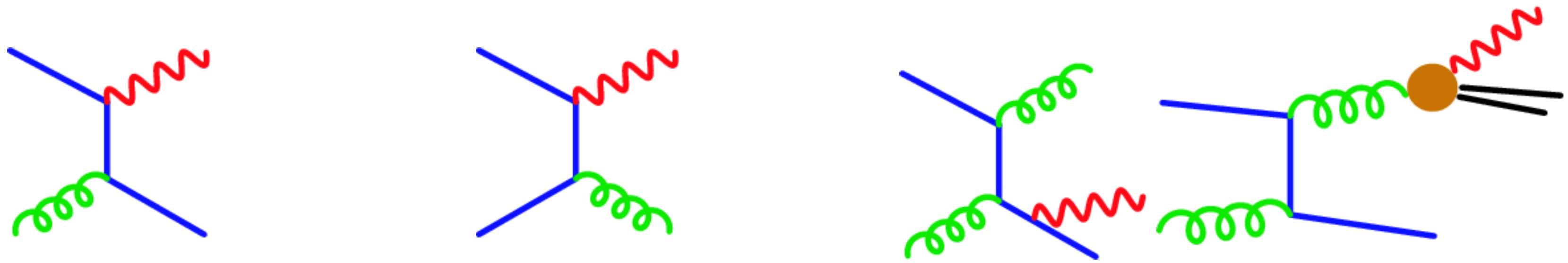
Nature443:675-678,2006

Transition temperature and Cross Over established at zero baryon chemical potential

Establishing Quark-Gluon Plasma

If there is system of free quarks and gluons – Photons can be produced through:

Compton **Annihilation** **Bremsstrahlung**

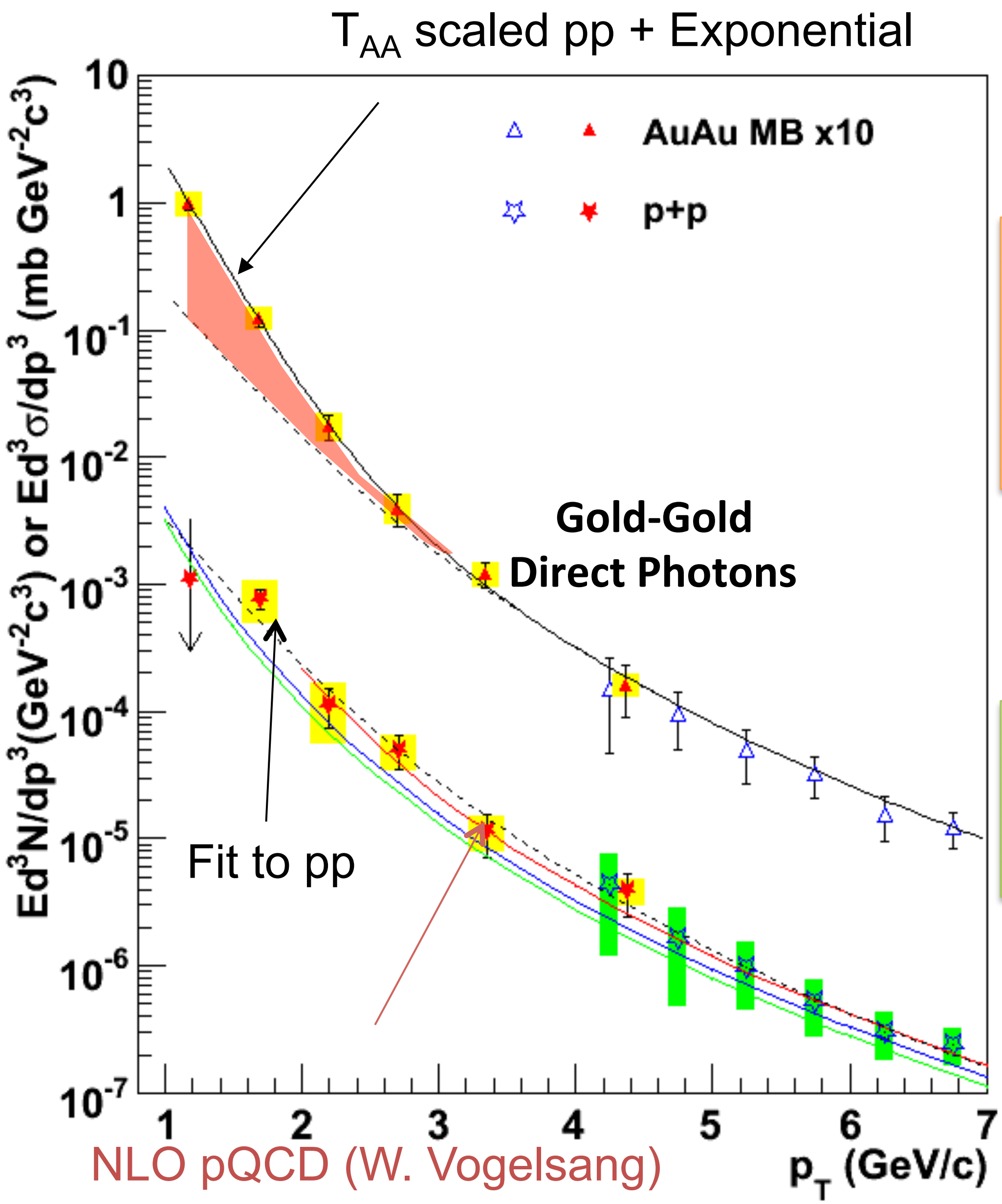


In a hydrodynamic picture: Slope of momentum distribution of these photons

$$T_{eff} = T_{th} + \frac{1}{2} m v_r^2$$

T_c ~ 150 MeV ~ 10^{12} Kelvin
Temperature for QCD transition from Lattice QCD

Establishing Quark-Gluon Plasma



T_i = 300-600 MeV > T_c

Sinha, Srivastava, Alam, Sarkar, Gale, Turbide, Rasanen, Liu, d'Enteria

Deconfined state of quarks And Gluons

Proton-Proton Direct Photons

Perspective of Temperature Reached in Heavy-ion Collisions

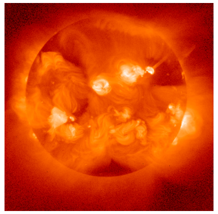
~10^{12} K — Nucleus-Nucleus collisions — ~ **150 MeV**

~10^{9} K — Neutron Star Thermonuclear Explosion

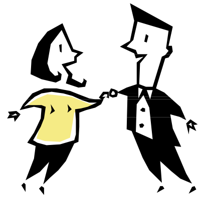
(Terrestrial Nuclear explosions)

~10^{6} K — Solar Interior

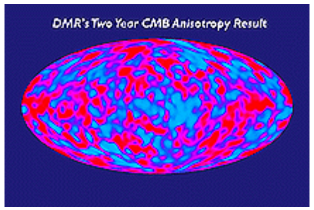
~6000 K — Solar Surface



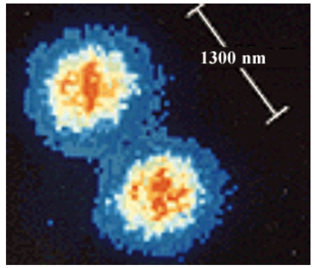
~300 K — Room Temperature ~ **1/40 eV**



~3 K — Cosmic Microwave Background



~10^{-6} K — Trapped Ions

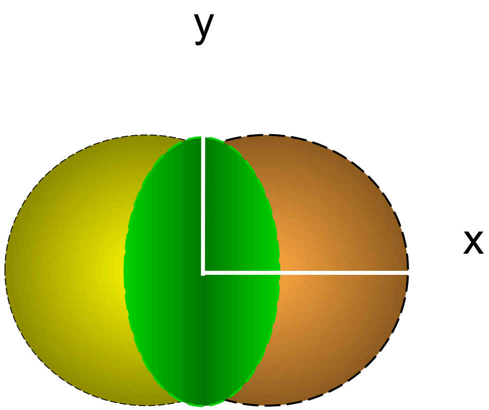


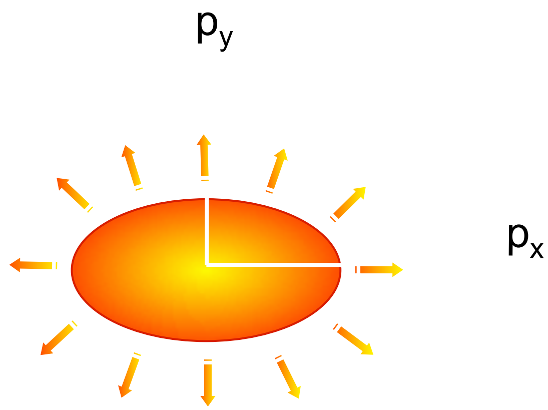
~10^{-10} K — Rhodium metal spin cooling (2000)

(Low-T World Record!)

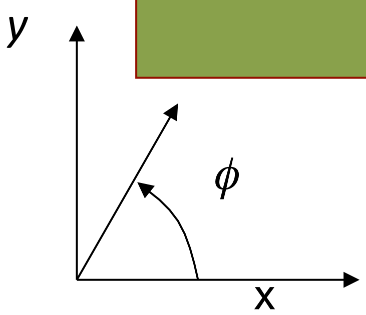
Collectivity

coordinate-space-anisotropy ⇨ momentum-space-anisotropy





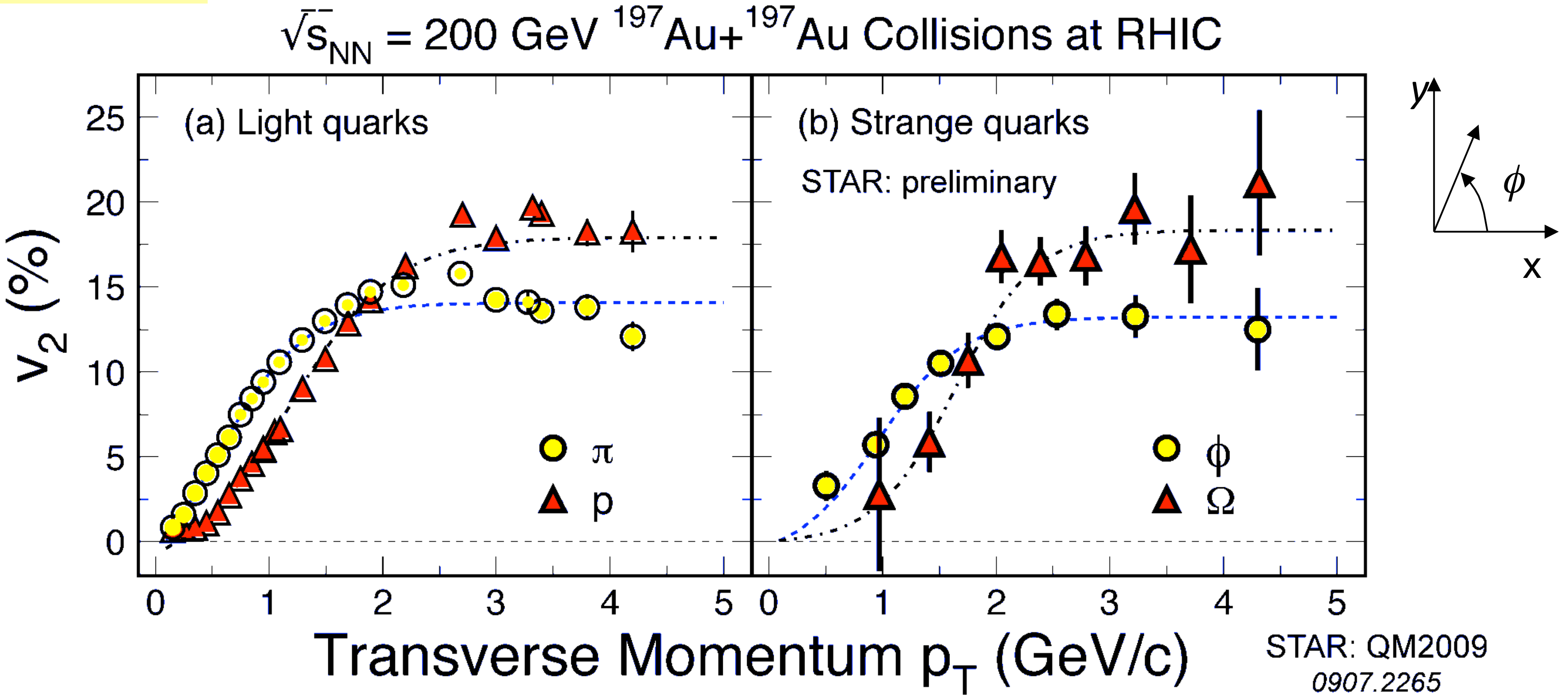
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \qquad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$



Strong Collectivity

$v_n = \langle \cos n\phi \rangle$

STAR PRL : 2016

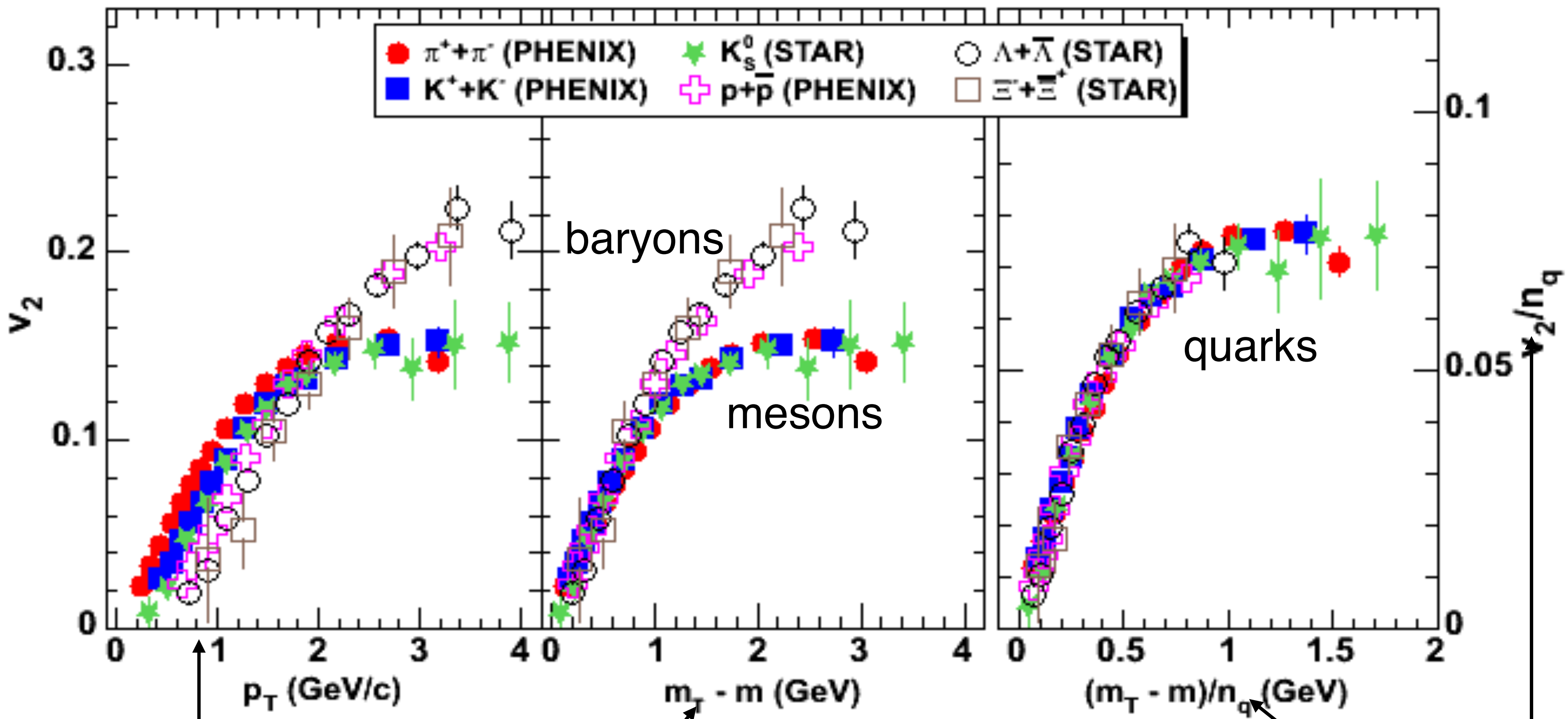


Low p_T : Heavier hadrons have lower v_2 (~ hydrodynamic pattern)

High p_T : Collectivity grouped along baryon-meson lines
(~ Hadronization by partonic recombination)

All p_T : Collectivity similar for hadrons with strange and light quark
(~ developed at partonic stage)

Partonic Collectivity



particle mass dependence

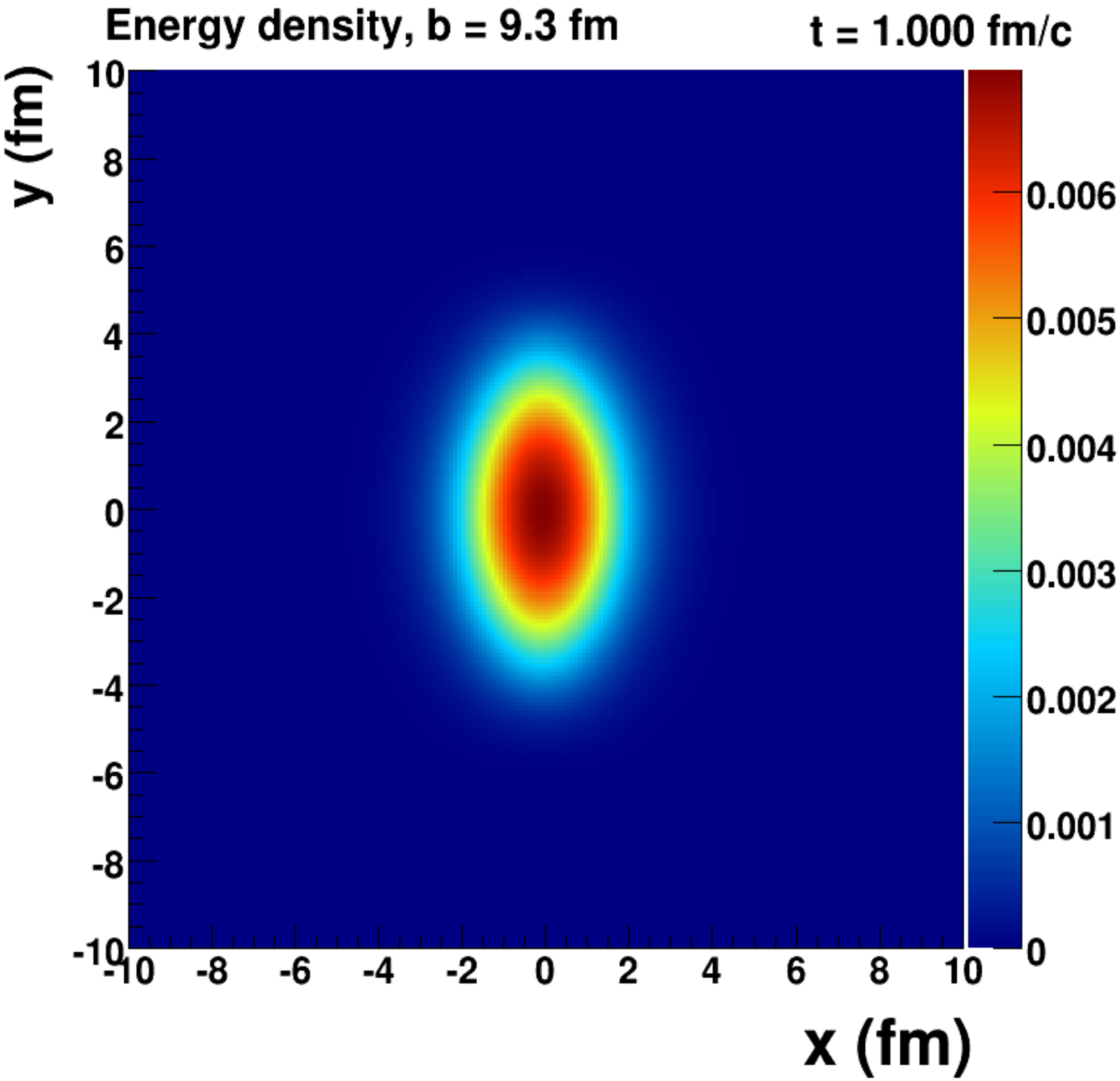
plotted vs. trans. kinetic energy

both axes scaled by number of constituent quarks

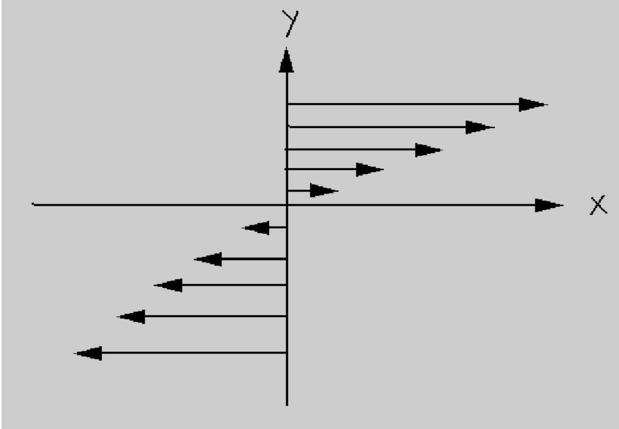
n_q = 2 for mesons
n_q = 3 for baryons

recombination of quarks
quarks have v_2 before hadronization

Properties of QGP



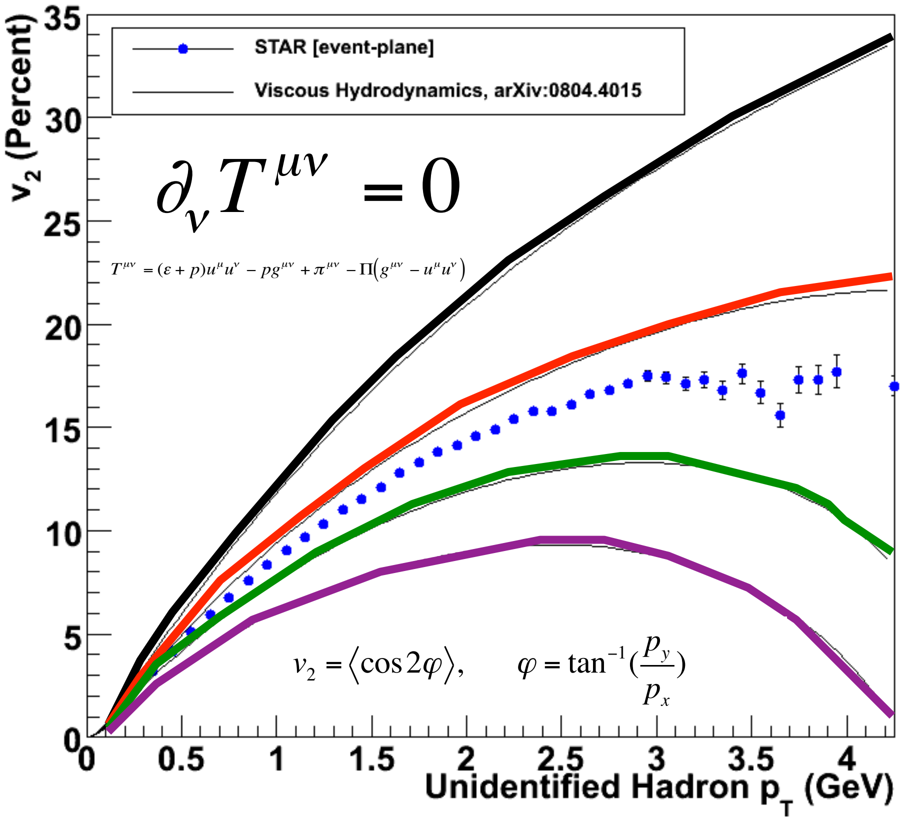
$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$

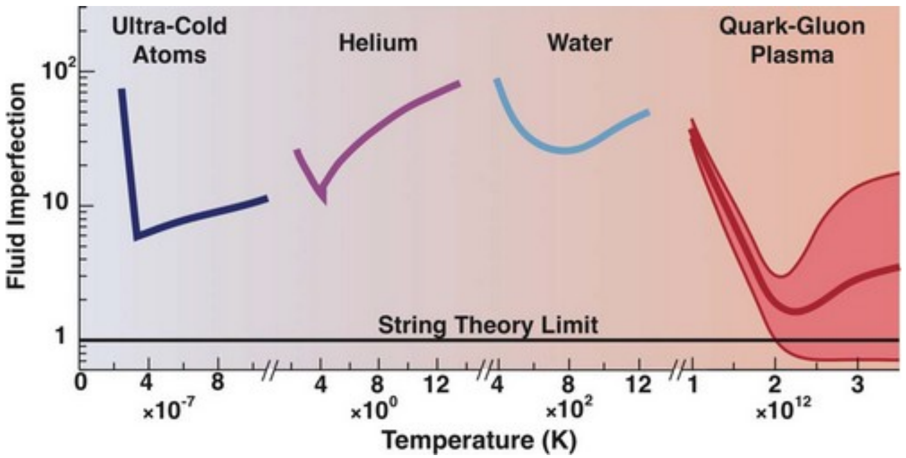


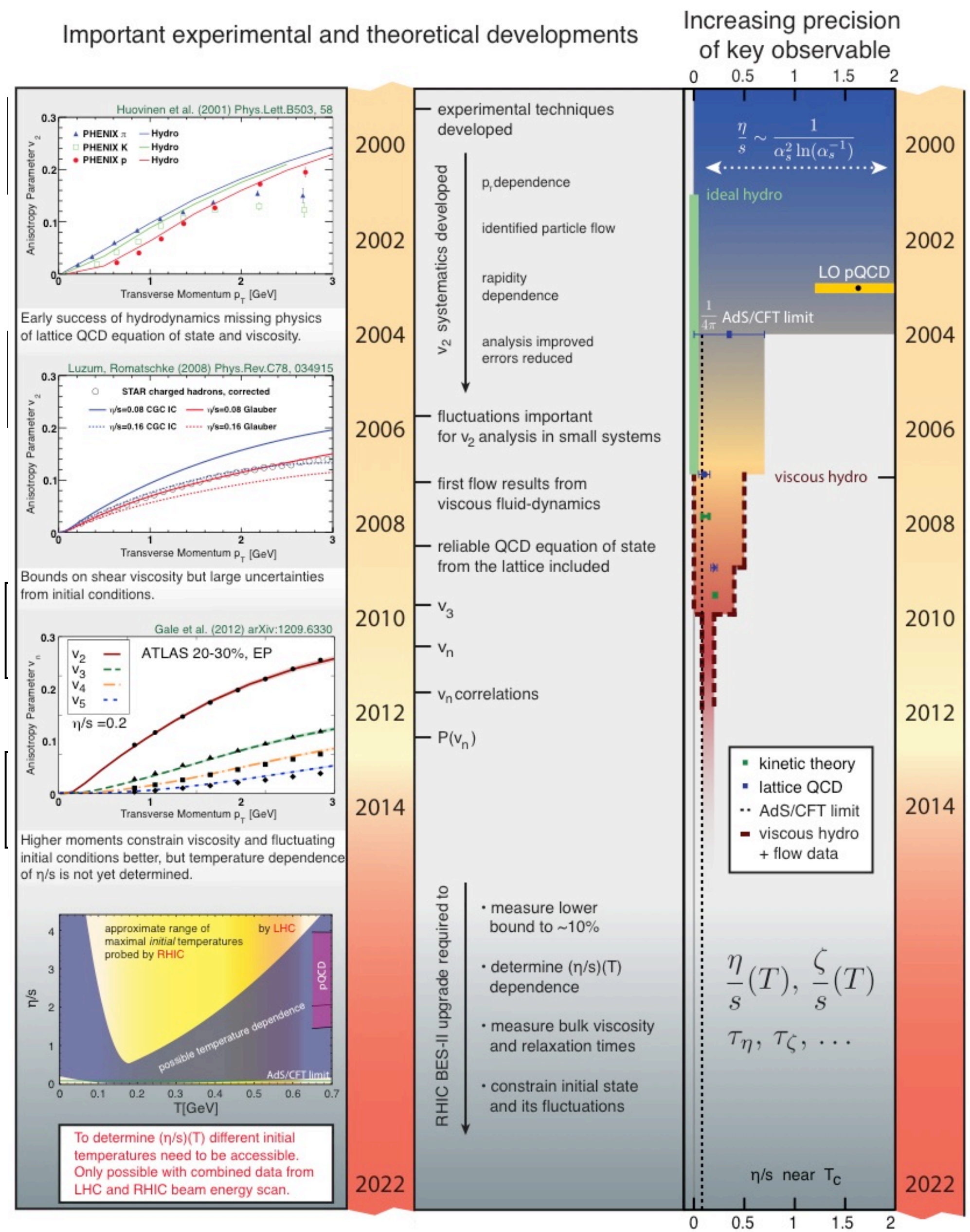
$$v_n = \langle \cos n\phi \rangle$$

Viscosity:
Resistance to Flow

Viscosity





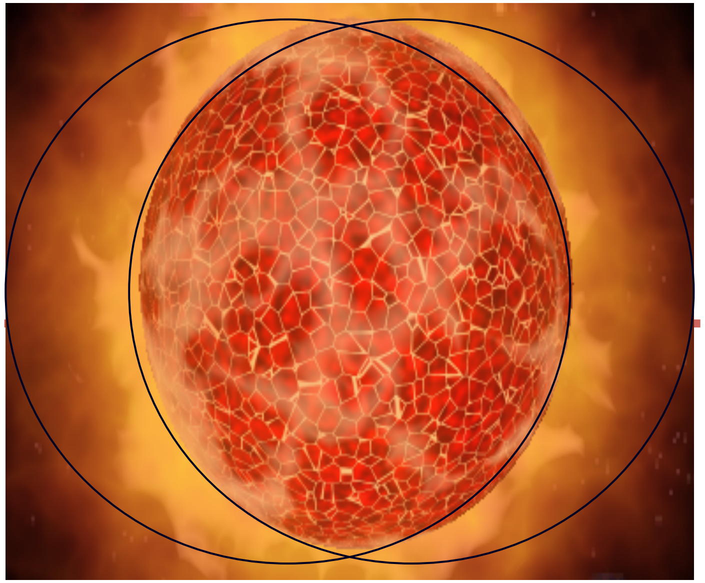


Perfect Fluid

Opacity

Matter we want to study

Calibrated LASER

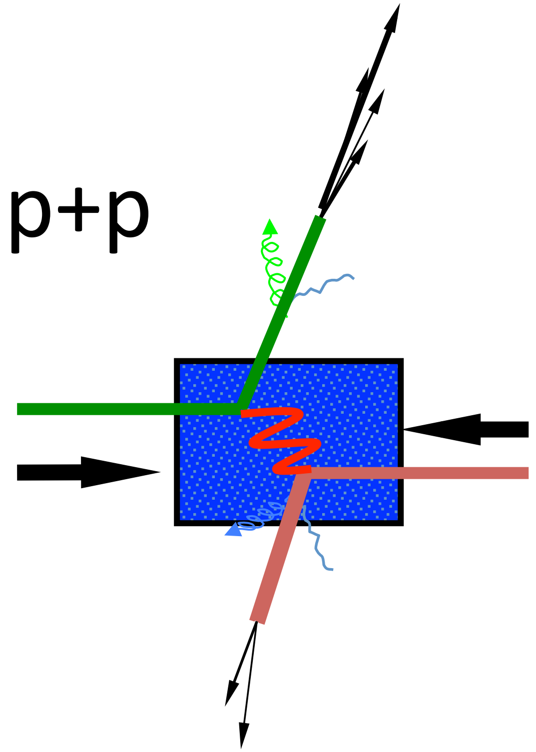


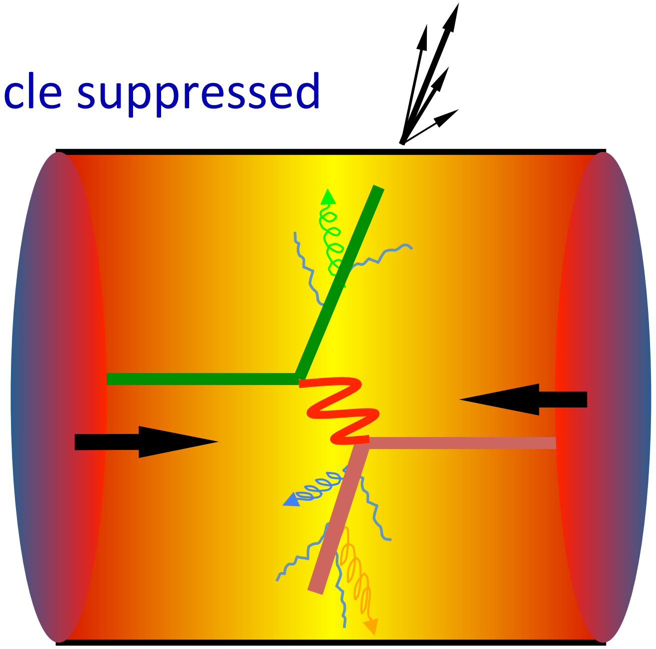
Calibrated Light Meter

Jets

Calibrated Heat Source

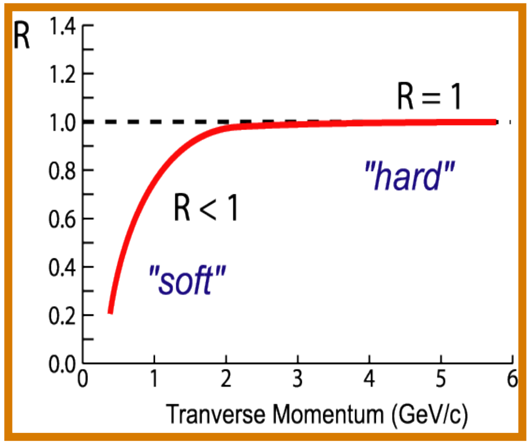
Quenching of Jets



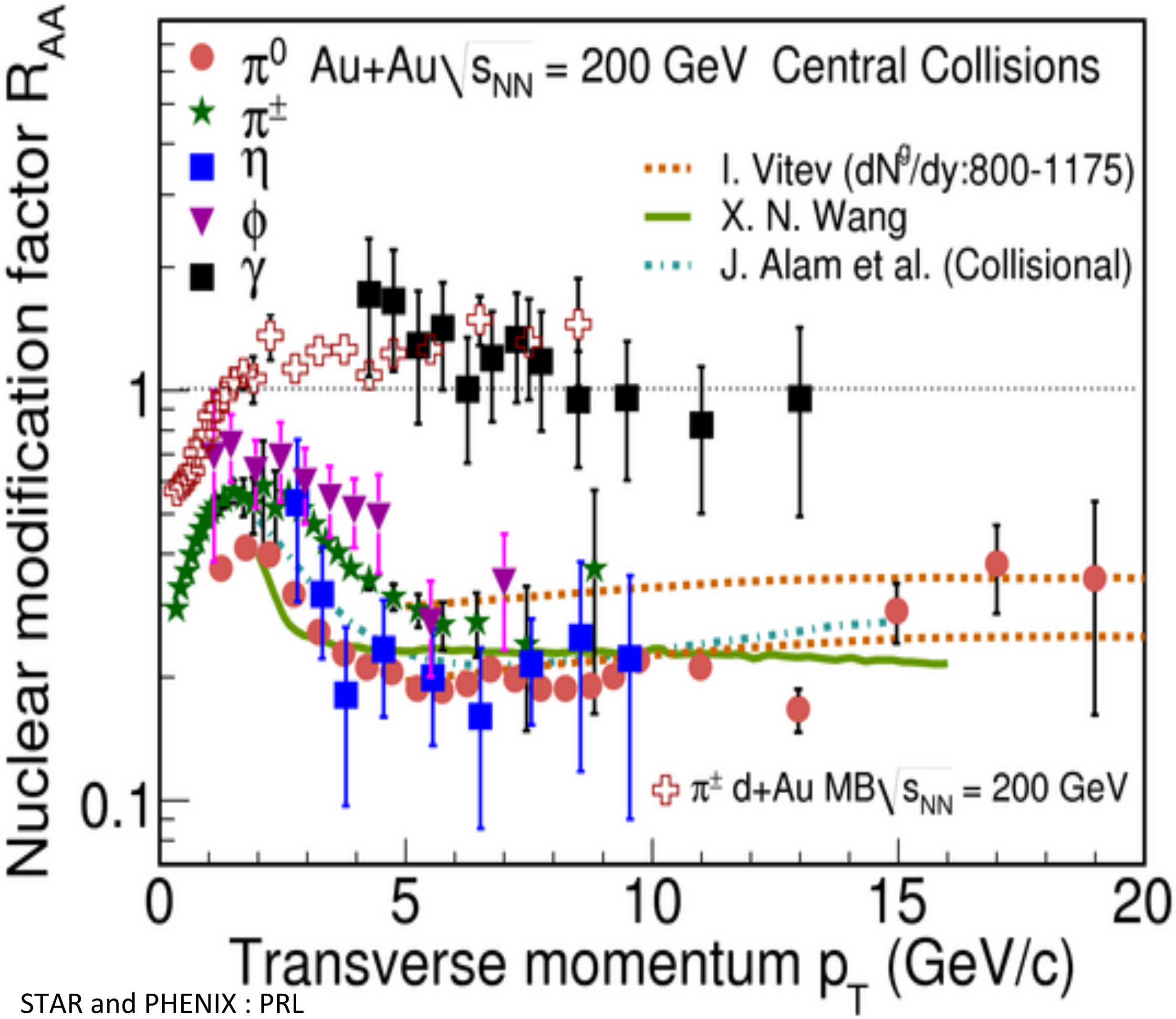


Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$



Experimental Evidence: Quenching of Jets



STAR and PHENIX : PRL
New J.Phys. 13 (2011) 065031

High p_T hadron production suppressed

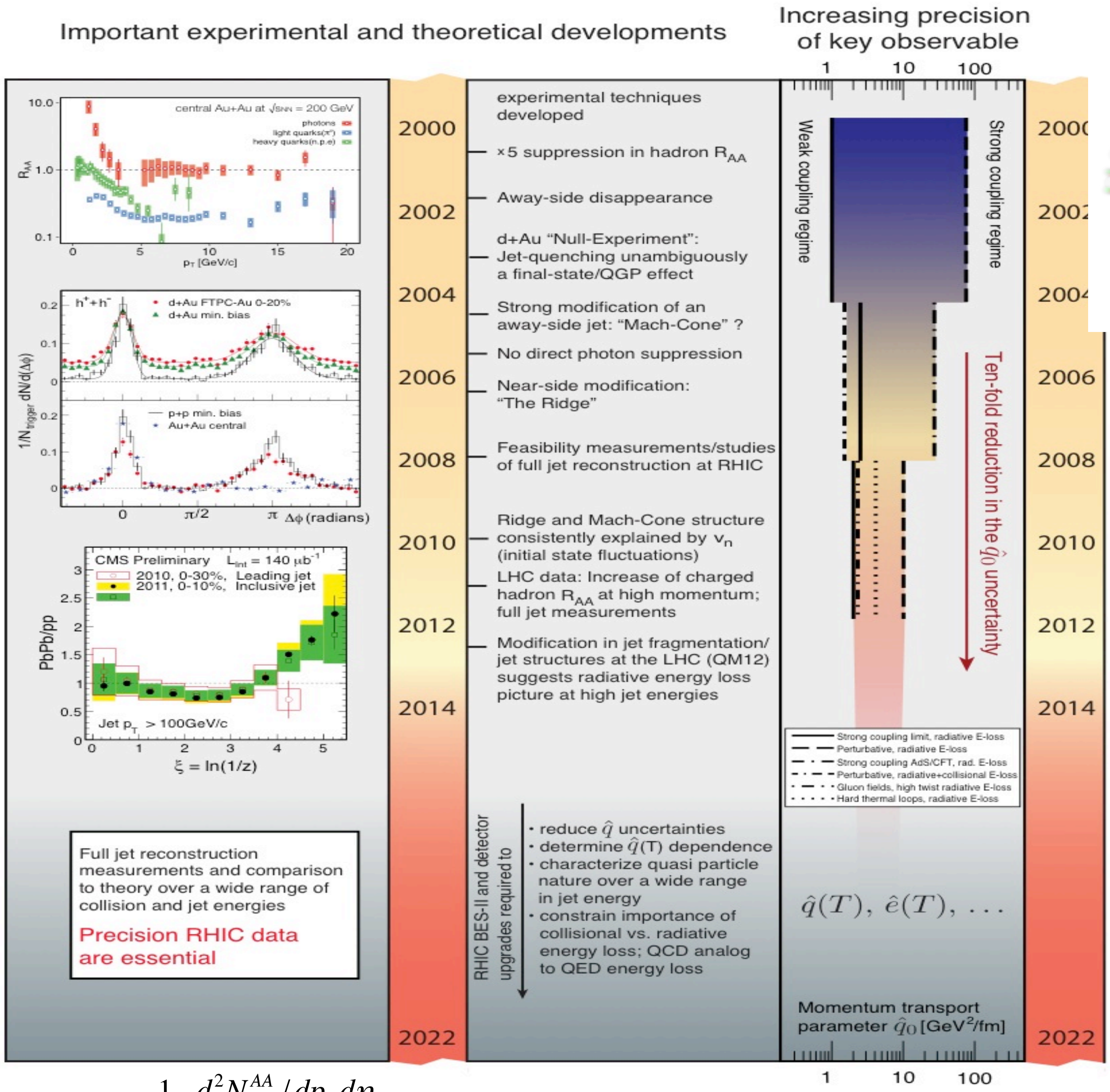
Production of photons which do not participate in strong interactions is not suppressed

No suppression in d+Au collisions

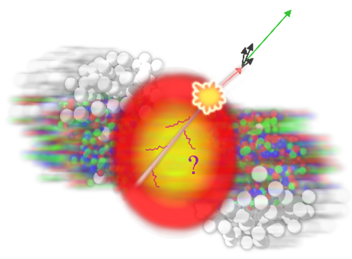
$\varepsilon_{initial} > \varepsilon_C$ (Lattice)

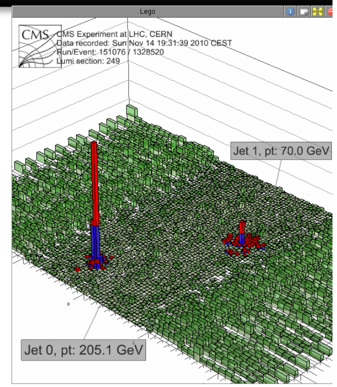
Interpretation : Energy loss of partons in a dense medium

Opacity



$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

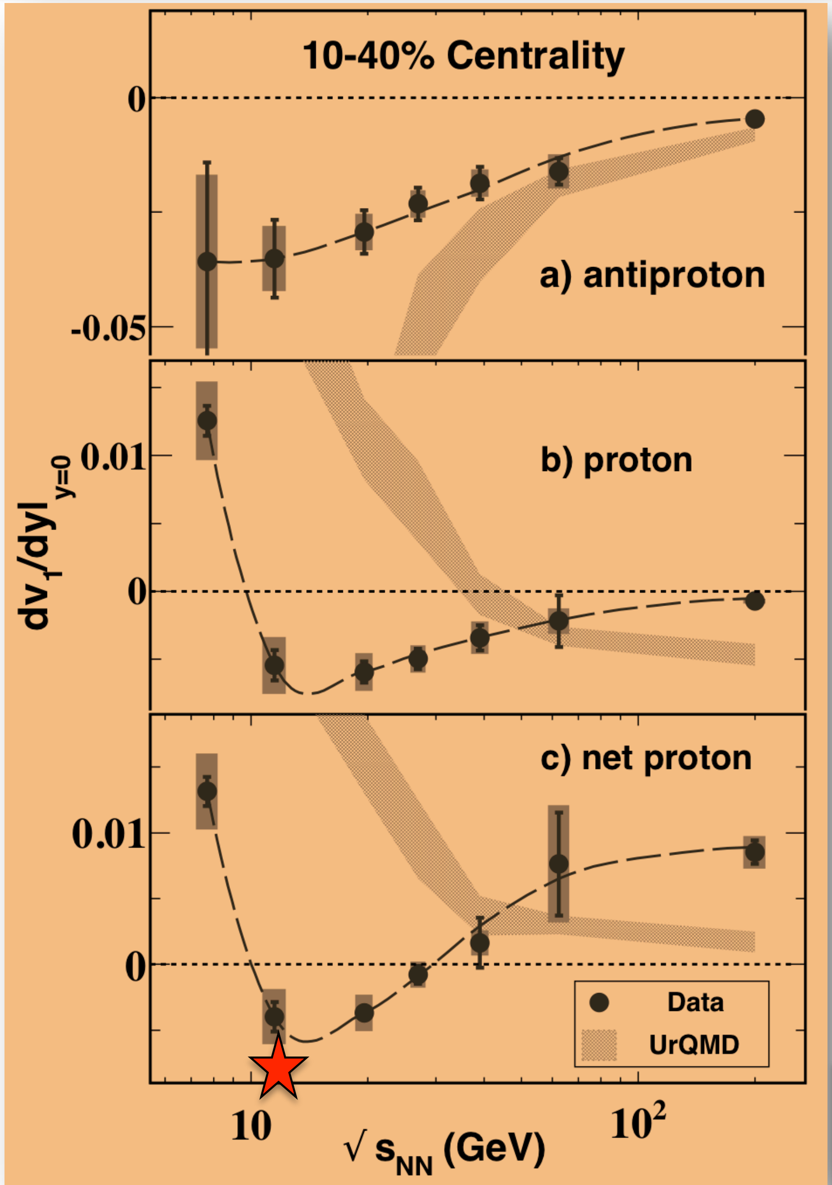




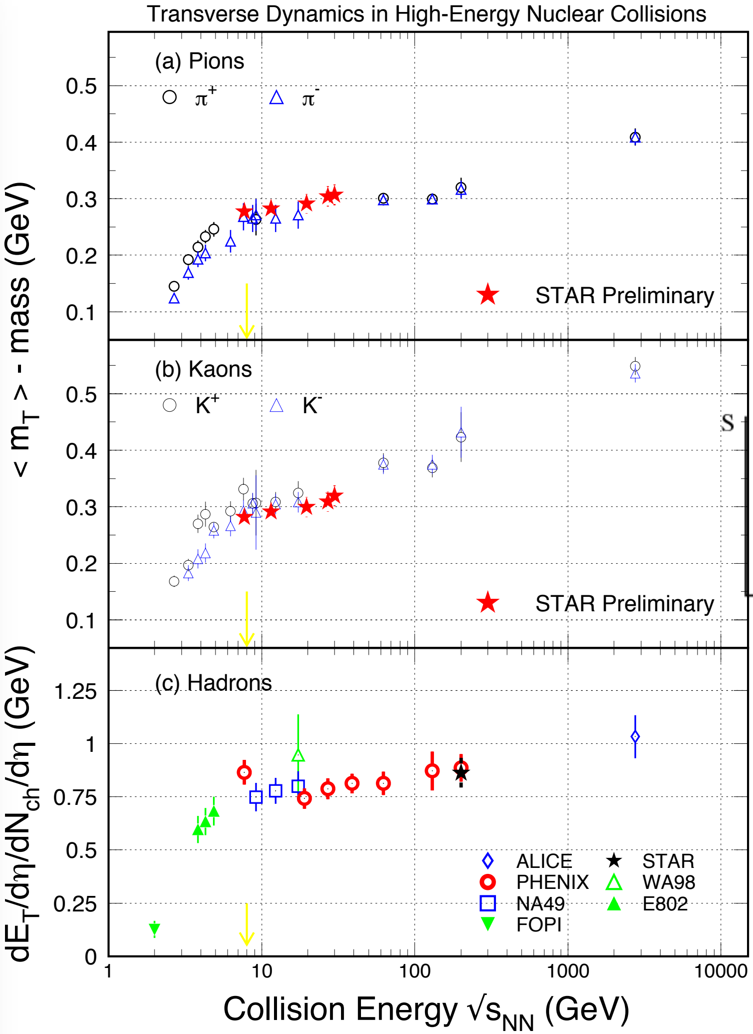
Jets Quenched

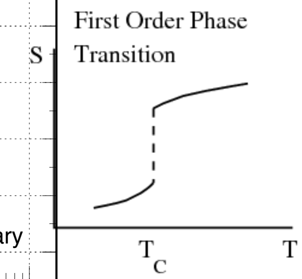
The shear viscosity to entropy density ratio is found to lie between (1-2)/4π and that reflecting the stopping power was observed to be between 2-10 GeV²/fm.

Experimental Result: 1st Order PT



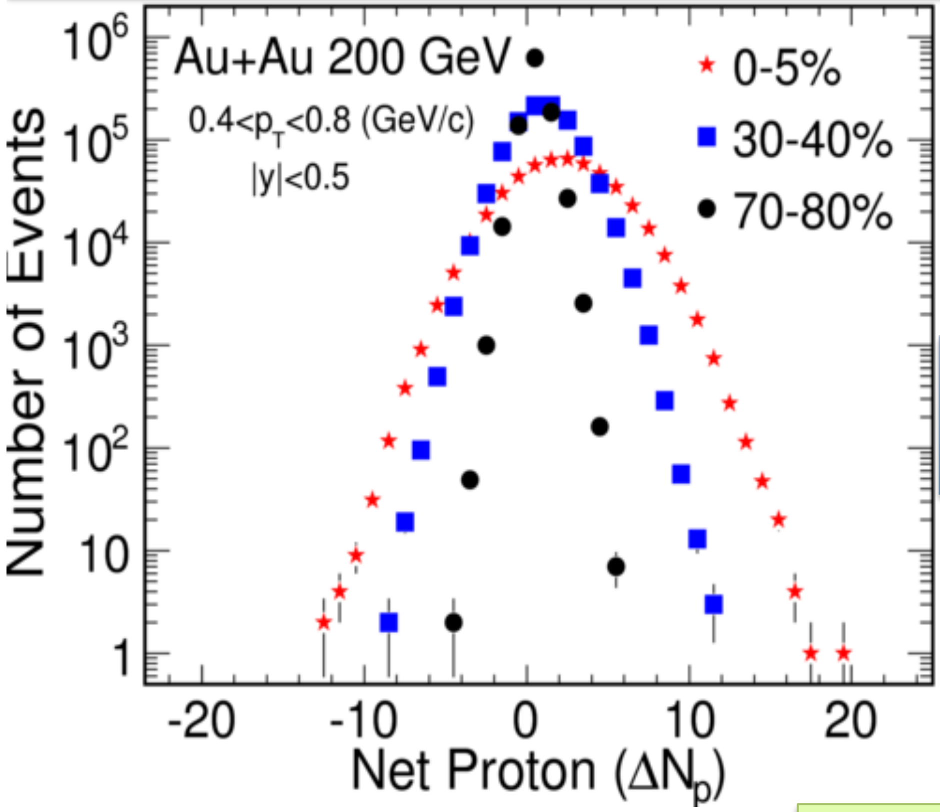
STAR: Physical Review Letters 2014





Observations consistent with 1st order Phase transition expectations

Experiment and Theory Direct Link



Shape of distribution

$\leftrightarrow$

Correlations

Moments relates to Correlation length (ξ):
Study phase transition and Critical Point

$<(\delta N)^2> \sim \xi^2$

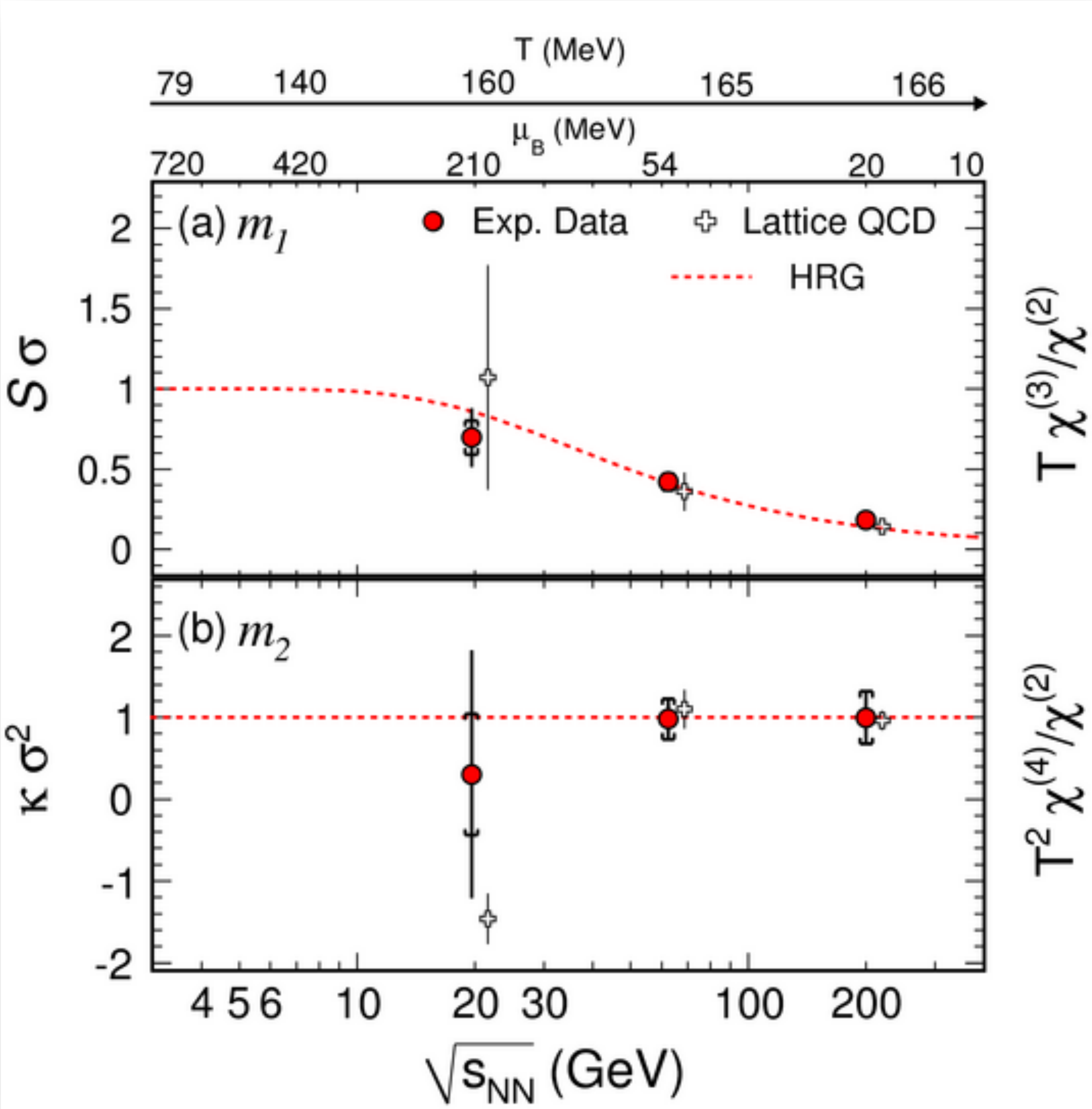
$<(\delta N)^3> \sim \xi^{4.5}$

$<(\delta N)^4> - 3<(\delta N)^2>^2 \sim \xi^7$

STAR: Physical Review Letters 2010& 2014
M. Stephanov: Physical Review Letters 2009;2011
S. Gupta and R. Gavai : Physics Letters B 2011
M. Cheng .. F. Karsch ..: Physical Review D 2009

Moments relates to Susceptibility (χ) :
Study Bulk properties of QCD matter
Kurtosis x Variance $\sim \chi^{(4)}/ [\chi^{(2)} T^2]$
Skewness x Sigma $\sim [\chi^{(3)} T]/ [\chi^{(2)} T^2]$

Data and QCD (Non-Zero T) 1st Comparison



1st comparison of high energy nuclear collision data to 1st principle QCD calculations

Confirms formation of QGP

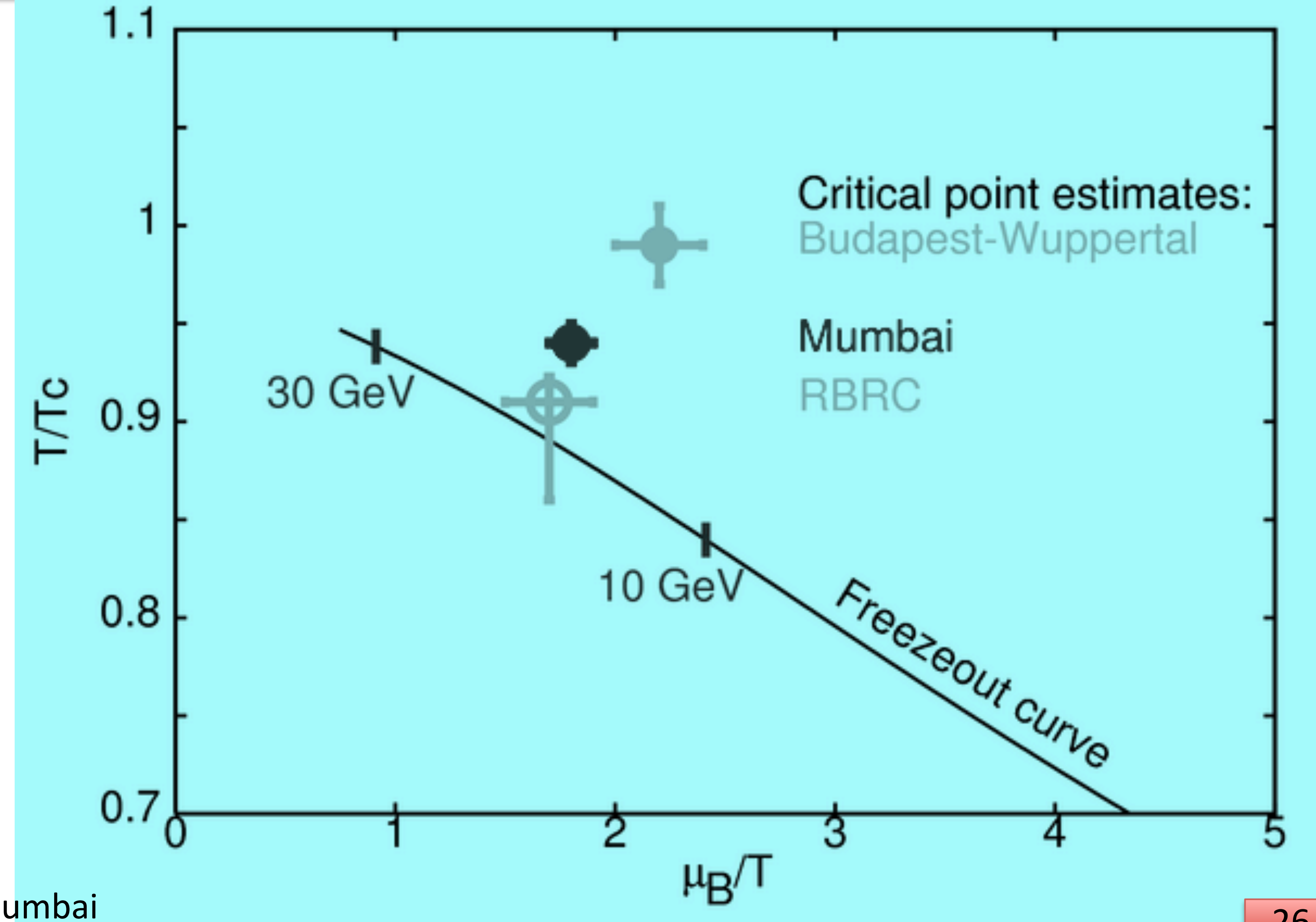
Quark-Hadron transition is a cross over

Science AAAS

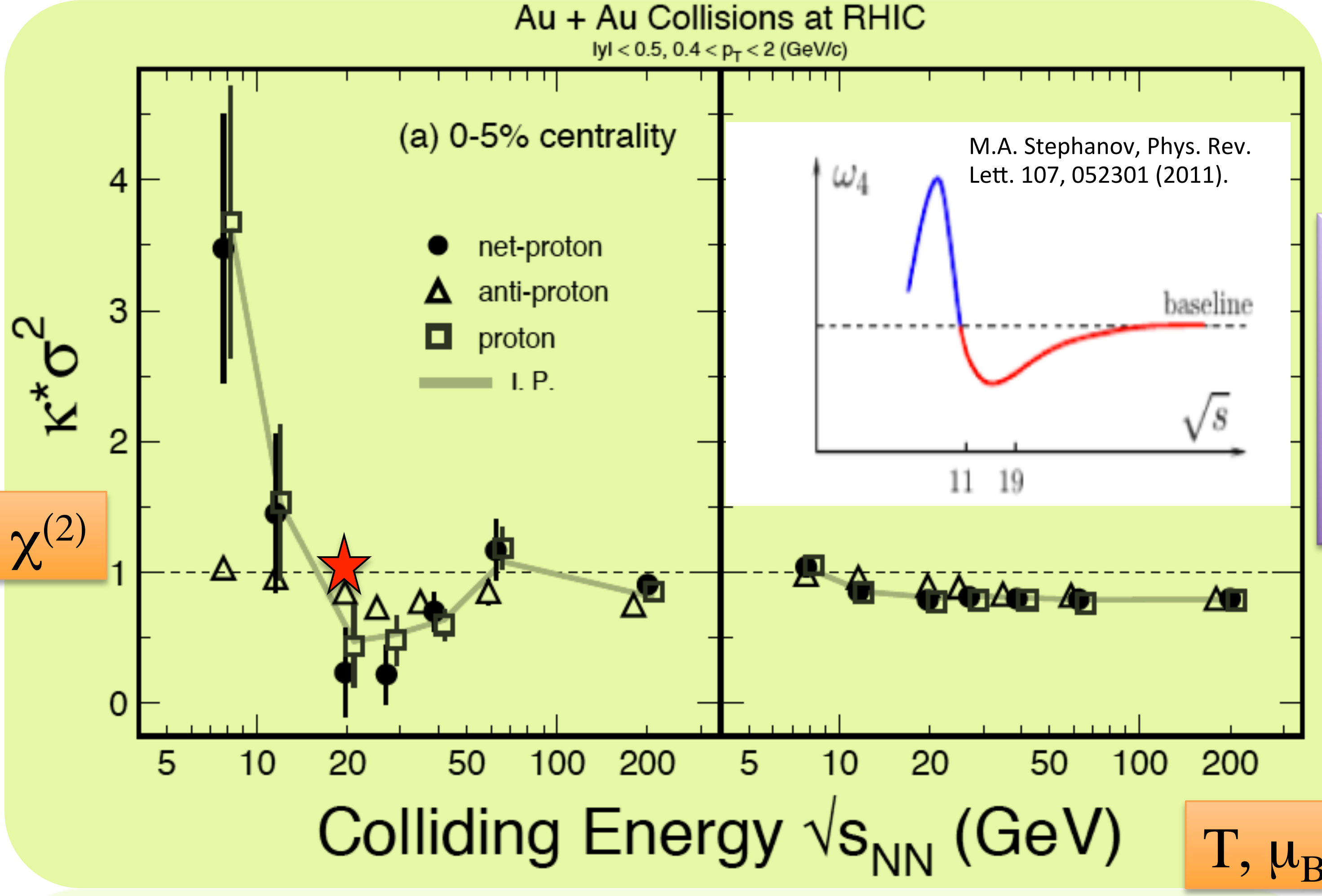
"Scale for the Phase Diagram of Quantum Chromodynamics"

Science*, *332, 1525(2011)

Theory : Critical Point



Experimental Result: Critical Point



$\chi^{(4)}/\ \chi^{(2)}$

$T,\ \mu_B$

Exciting Period !!

- *BES-II (2018-2020)*
- *CBM*
- *(2024- ..)*

STAR: Physical Review Letters 2014
And STAR Preliminary

Summary

QCD phase transition and primordial matter created in Laboratory. System of de-confined quarks and gluons formed.

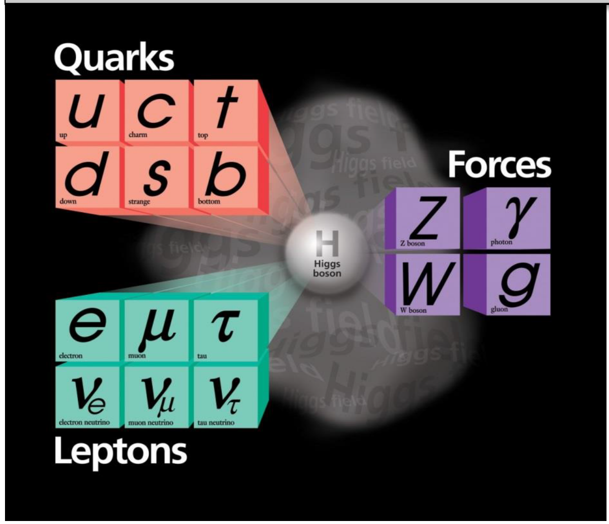
The de-confined quarks and gluons (fundamental constituent of any visible matter) exhibits the property of perfect fluidity with high degree of opacity.

Phase Diagram of Strong Interactions being laid out. Transition temperature and order of phase transition established at zero baryon chemical potential.

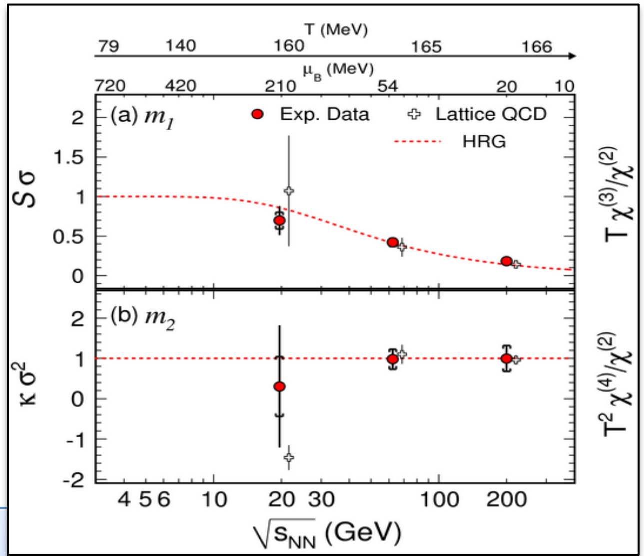
Exciting experimental results on critical point and phase boundary. Susceptibility has a non-monotonic variation with beam energy.

QCD in 21st Century

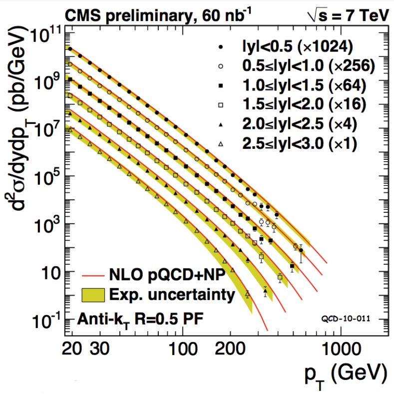
Standard Model & Origin of Mass



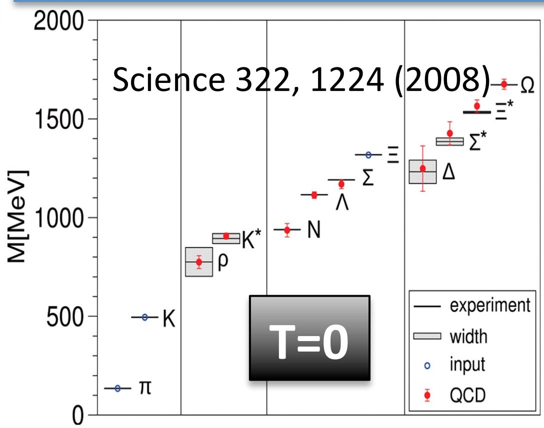
Test of QCD
Non-perturbative T>0
&
Phase structure of QCD
Phase diagram



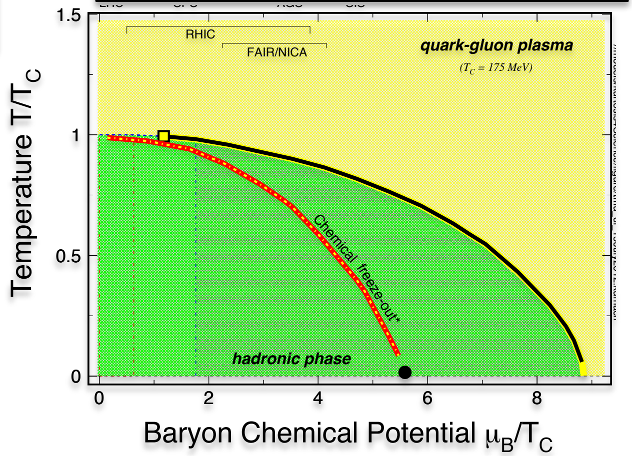
Test of QCD, Short distance scales, perturbative regime



Test of QCD, Long distance scales, Non-perturbative regime



Science 332, 1525 (2011)



Towards a complete test of QCD as a theory