Study the QCD Phase Structure in High-Energy Nuclear Collisions

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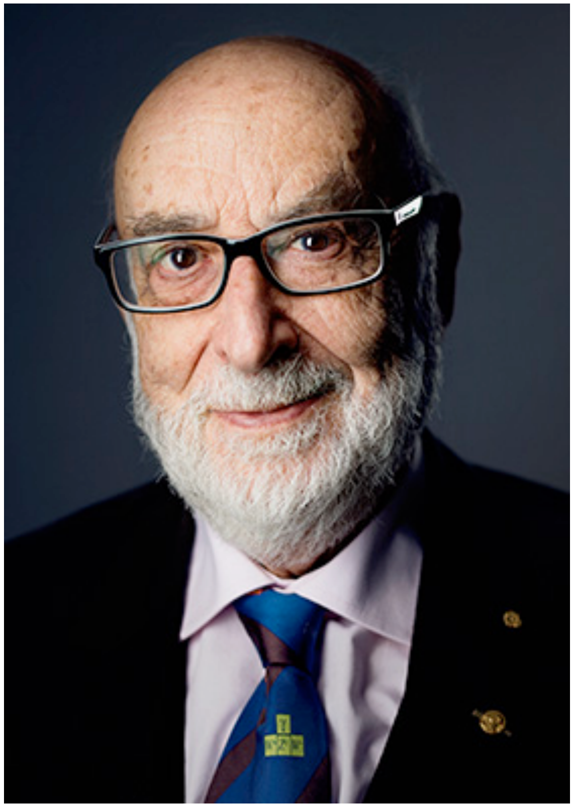
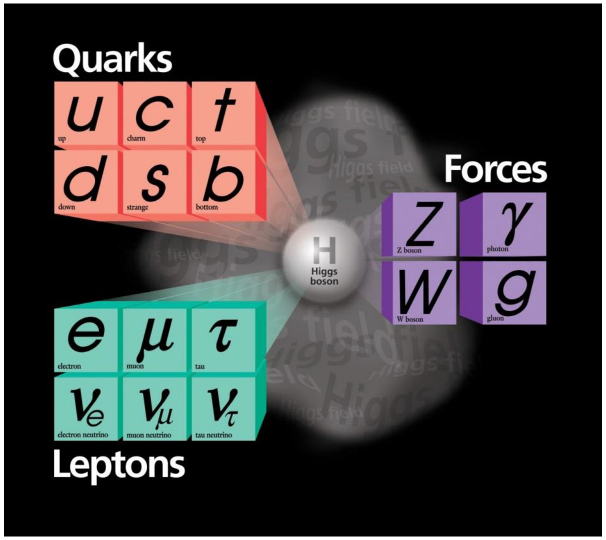
2013 NOBEL PRIZE IN PHYSICS

Francois Englert and Peter Higgs,



"for the theoretical discovery of a mechanism that **contributes to our understanding of the origin of mass of subatomic particles**, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

QCD in the Twenty-First Century

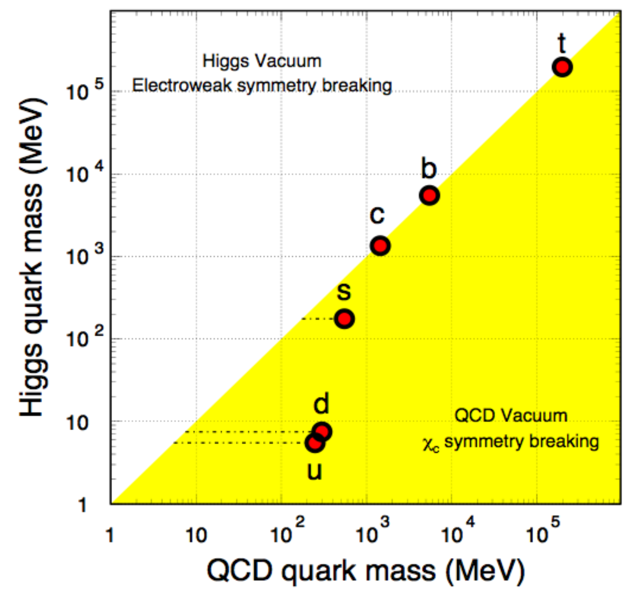


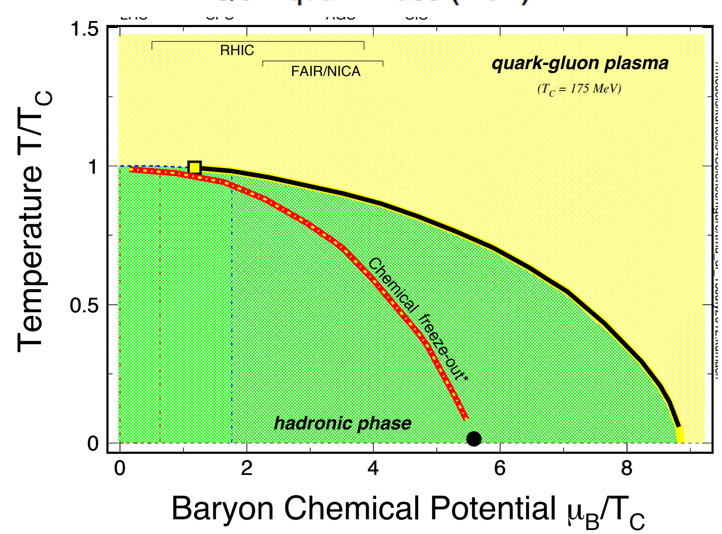
(1) Higgs Particle –

- **Origin of Mass**, **QCD dof**
- Standard Model ➔ The *Theory*

(2) QCD Emergent Properties:

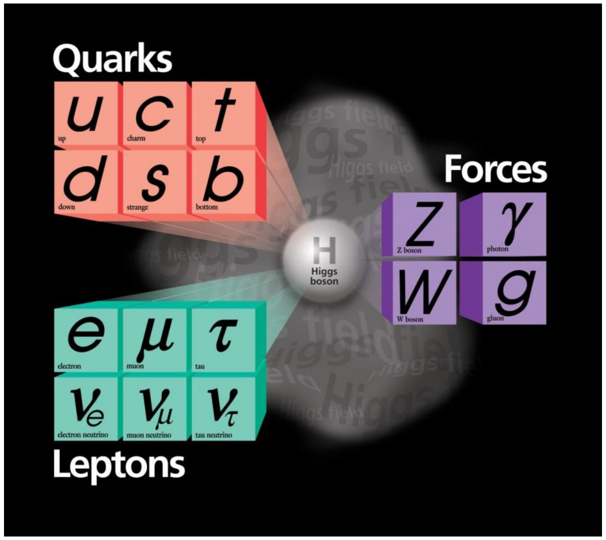
- Confinement
- χ_C symmetry
- QCD Phase Structure
- Nucleon helicity structure
- Non-linear QCD at small-x





QCD in the Twenty-First Century

2015 KOBE JAPAN



Emergent properties with QCD degrees of freedom!

(1) Higgs Particle –
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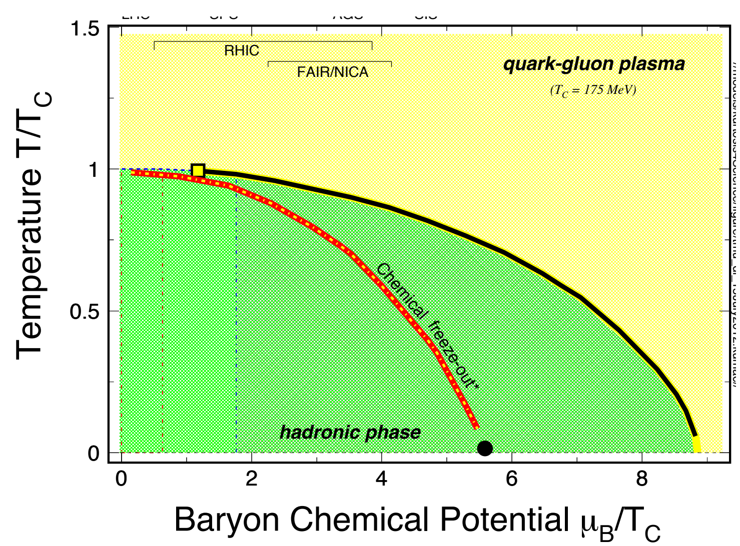
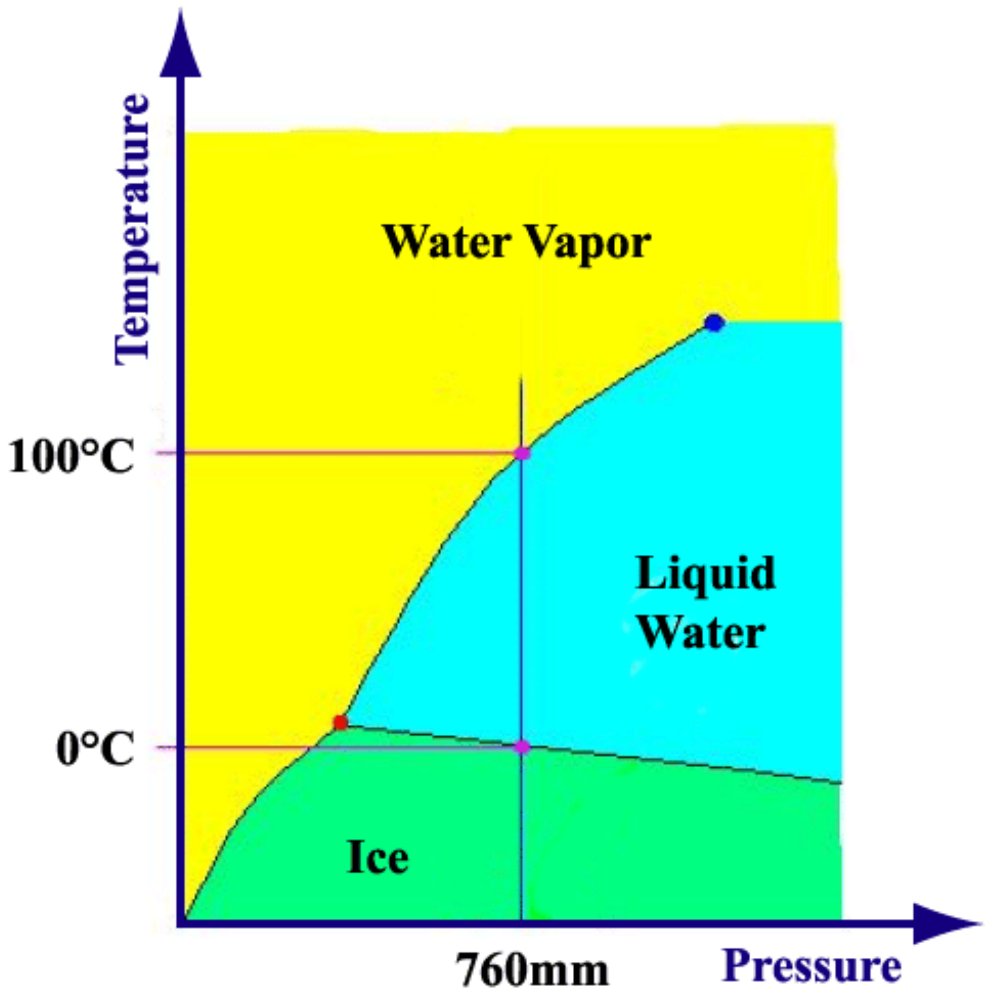


Phase Diagram: Water

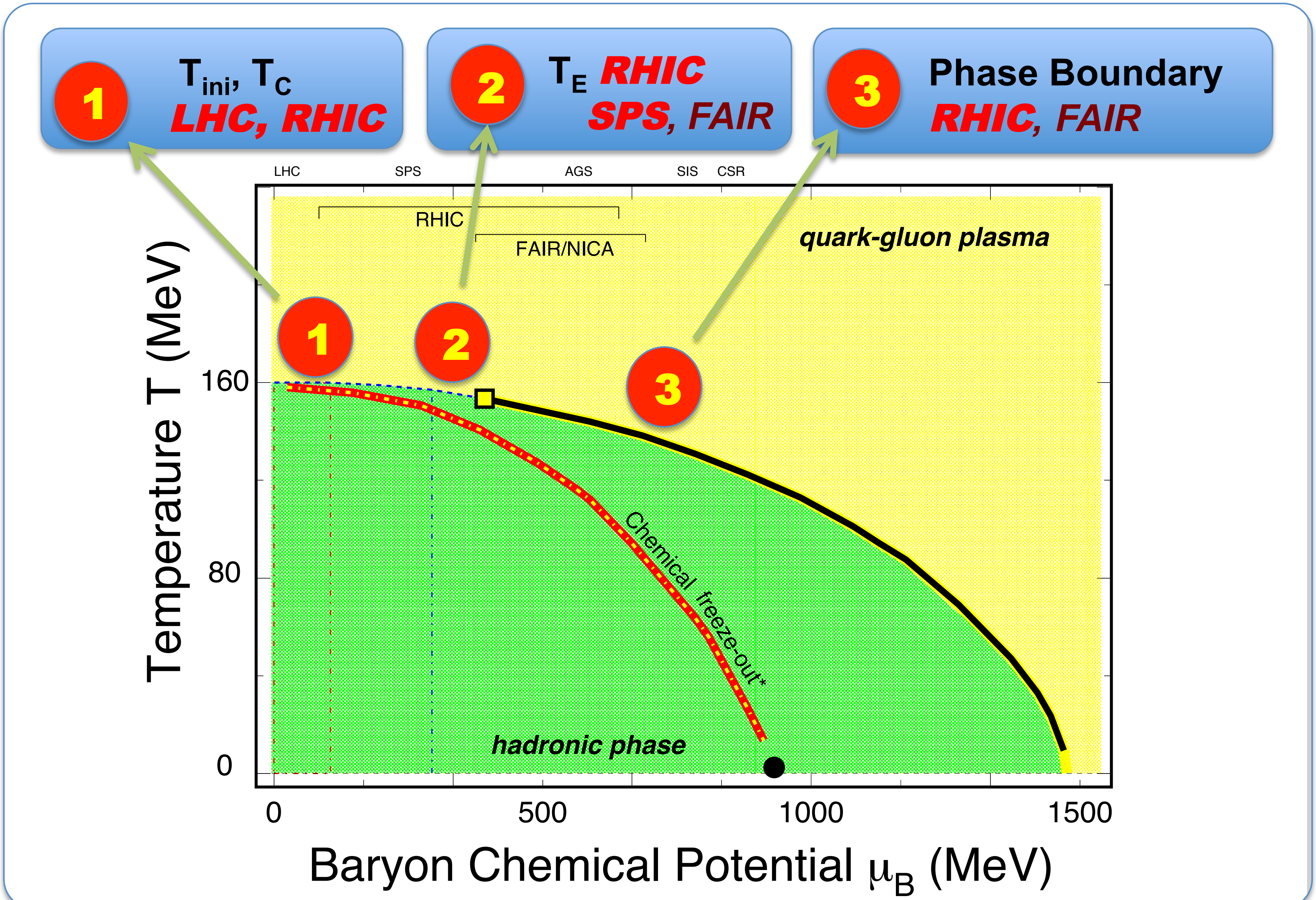


Phase diagram: A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

Water: H_2O

The QCD phase diagram: structure of matter with quark-, gluon-degrees (color degrees) of freedom.

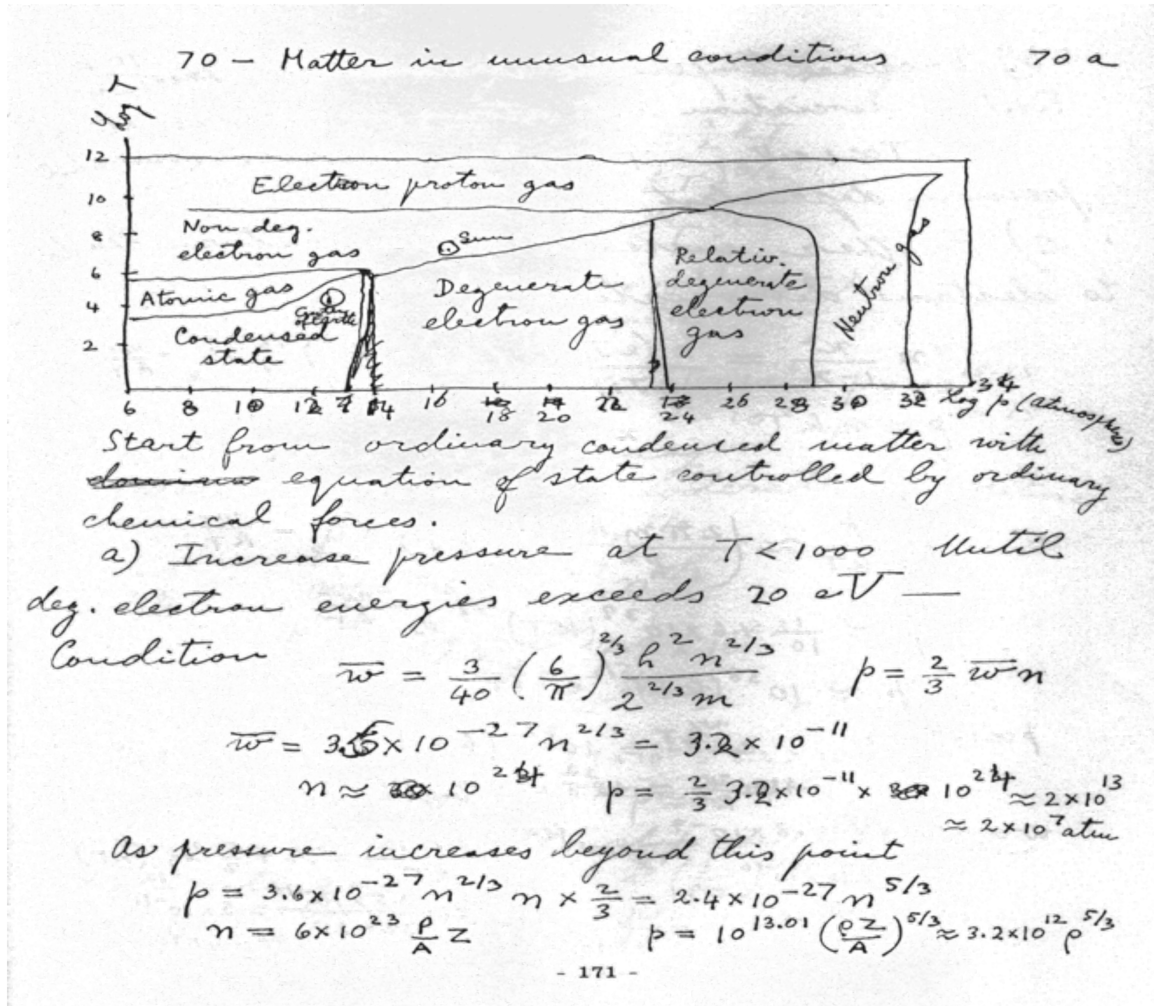
The QCD Phase Diagram and High-Energy Nuclear Collisions



QCD Phase Diagram (1953)

E. Fermi: *"Notes on Thermodynamics and Statistics " (1953)*

E. Fermi



70 — Matter in unusual conditions 70 a

Start from ordinary condensed matter with equation of state controlled by ordinary chemical forces.

a) Increase pressure at T < 1000 until deg. electron energies exceeds 20 eV —

Condition $\bar{w} = \frac{3}{40}\left(\frac{6}{\pi}\right)^{2/3} \frac{h^2 n^{2/3}}{2^{2/3} m}$ $\qquad p = \frac{2}{3}\bar{w} n$

$\bar{w} = 3.5 \times 10^{-27} n^{2/3} = 3.2 \times 10^{-11}$

$n \approx 10^{24}$ $\qquad p = \frac{2}{3} 3.2 \times 10^{-11} \times 10^{24} \approx 2 \times 10^{13}$

$\approx 2 \times 10^{7}$ atm

As pressure increases beyond this point

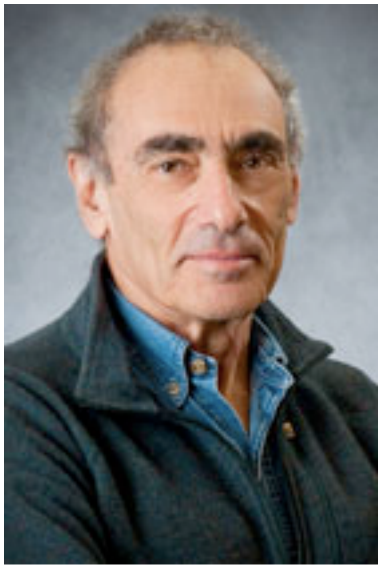
$p = 3.6 \times 10^{-27} n^{2/3} n \times \frac{2}{3} = 2.4 \times 10^{-27} n^{5/3}$

$n = 6 \times 10^{23} \frac{\rho}{A} Z$ $\qquad p = 10^{13.01} \left(\frac{\rho Z}{A}\right)^{5/3} \approx 3.2 \times 10^{12} \rho^{5/3}$

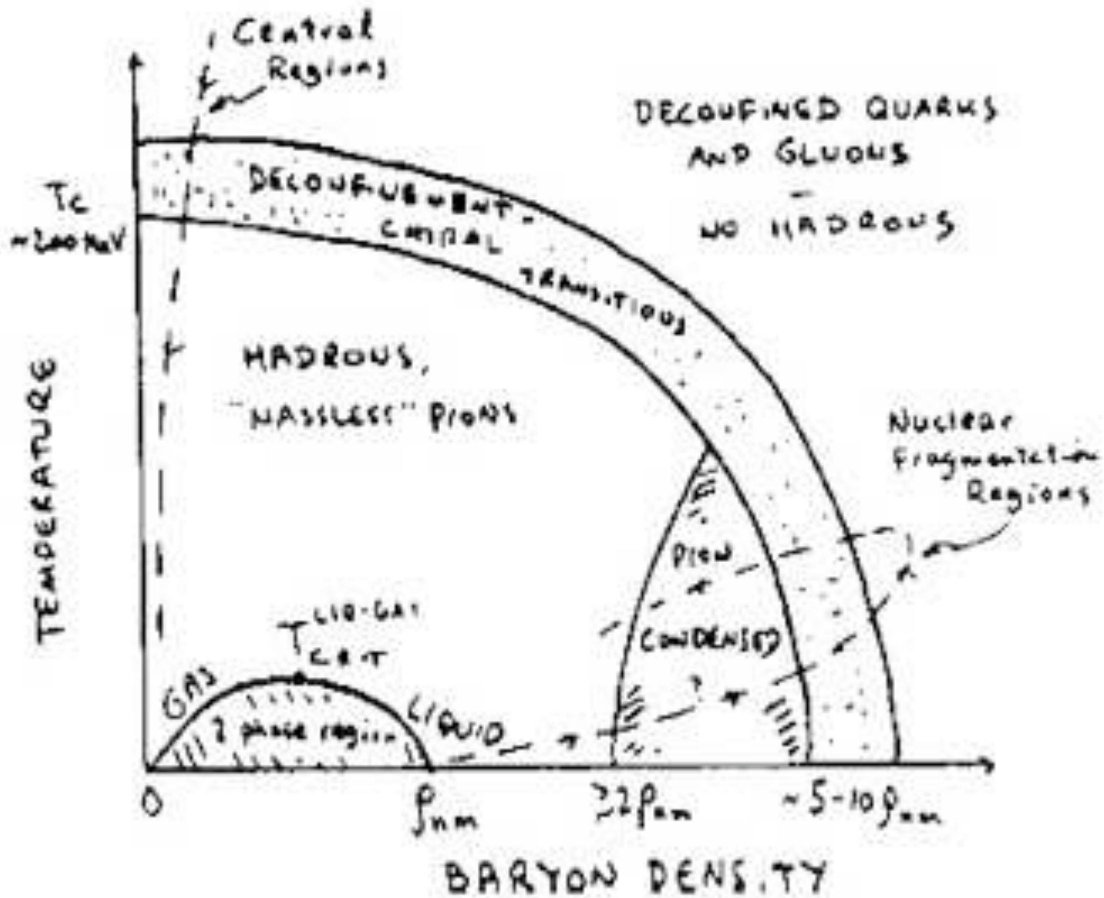
- 171 -

QCD Phase Diagram (1983)

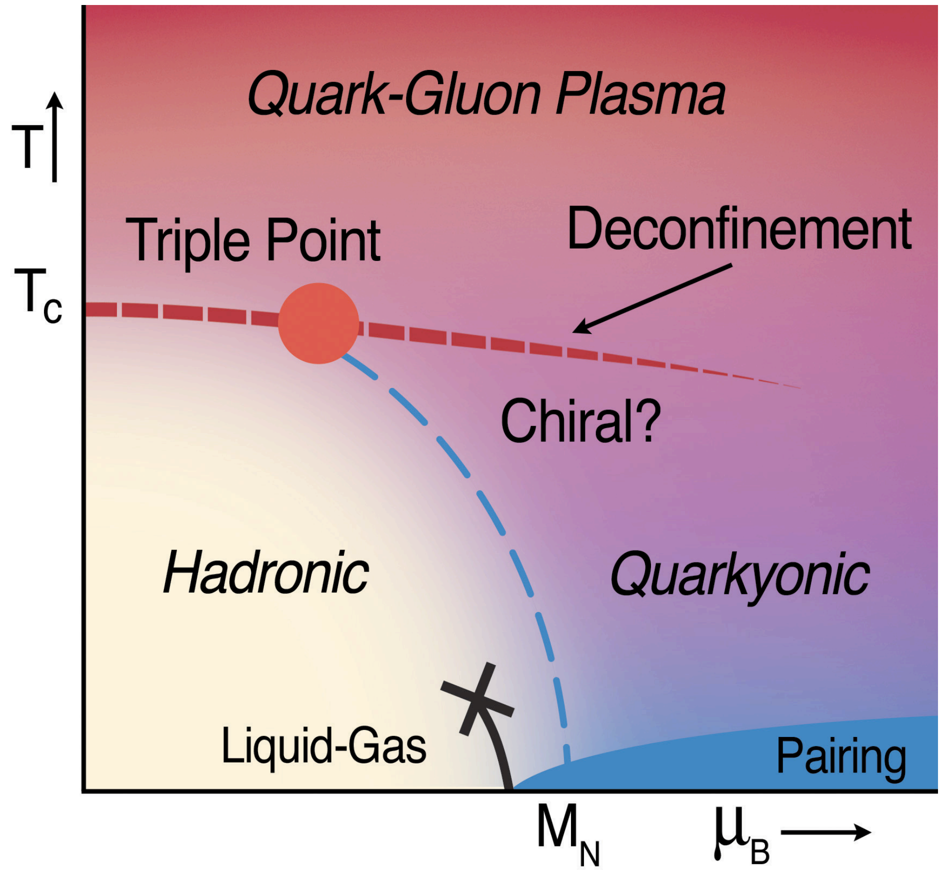
1983 US Long Range Plan *- by Gordon Baym*



Gordon Baym



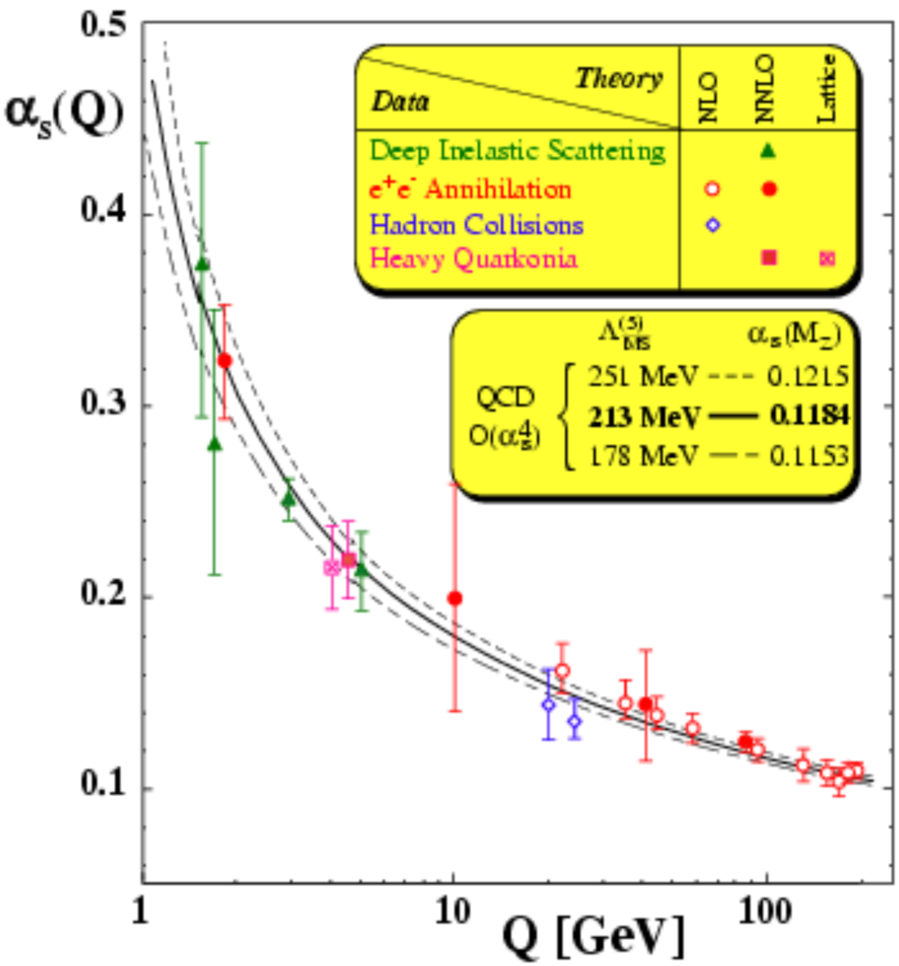
QCD Phase Diagram (2009)



nucl-th: 0907.4489, ***NPA830***,709(09) *L. McLerran*

NPA837, 65(2010) nucl-th 0911.4806: *A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, and J. Stachel*

Running Coupling Constant: α_s



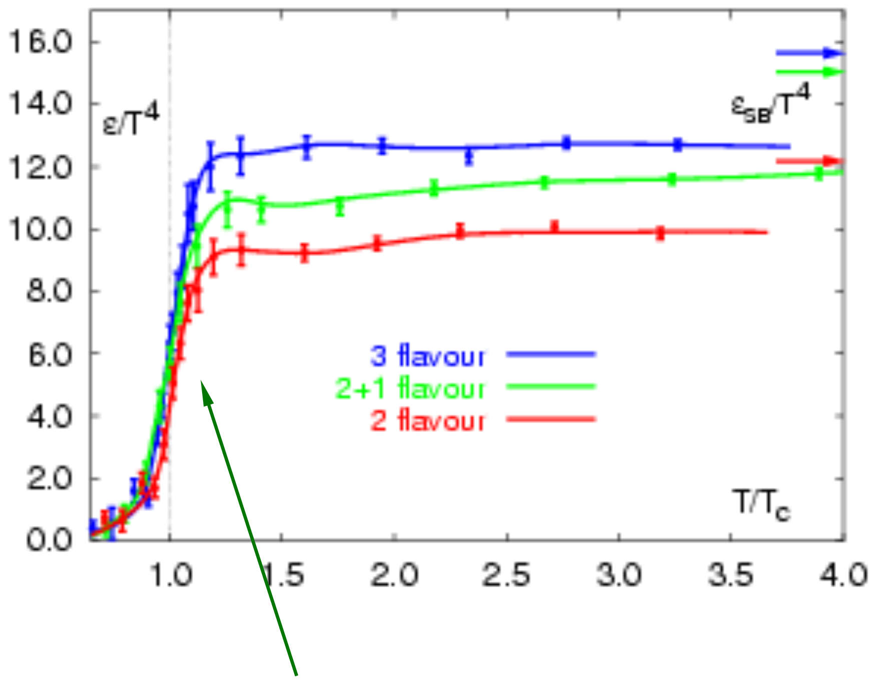
α_s: strong coupling constant
Q: momentum transfer

QCD models provide reasonable results on the Q-dependence of the strong coupling constant, especially at high Q.

As a function of the momentum transfer, the strong coupling constant α_s decreases exponentially, but never goes to zero, meaning STRONG interactions are always there!

Reference:
S.Bethke, hep-ex/0004021

QCD on Lattice



Lattice calculations predict
$T_c \sim 160$ MeV

1) Large increase in ε
a fast cross cover !

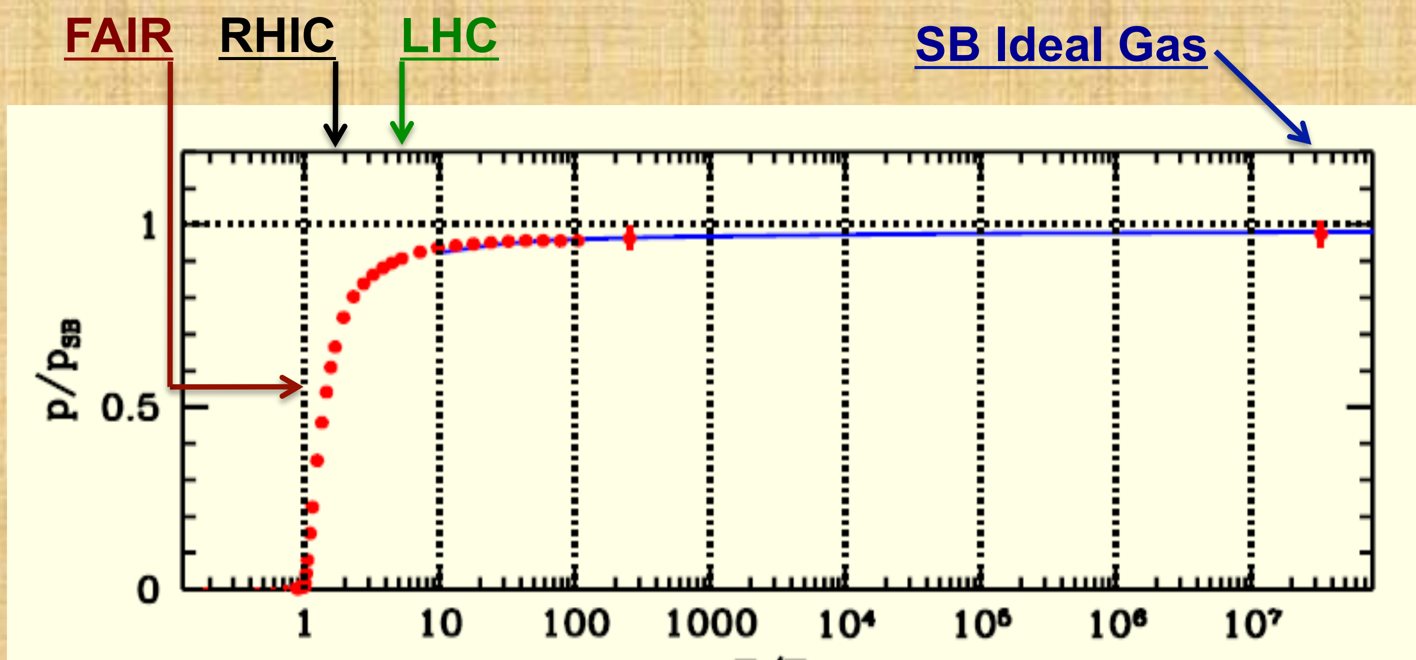
2) Does not reach ideal, non-interaction S. Boltzmann limit !

⇒ many body interactions
⇒ Collective modes
⇒ Quasi-particles are necessary

3) $T_c \sim 160$ MeV!

*Z. Fodor et al, **JHEP** 0203:014(02)*
Z. Fodor et al, hep-lat/0204001
C.R. Allton et al, hep-lat/0204010
F. Karsch, Nucl. Phys. A698, 199c(02).

QCD Thermodynamics



Zoltan Fodor, Lattice 2007

1) At $\mu_B = 0$: cross over transition, $150 < T_c < 170$ MeV
2) The SB ideal gas limit: $T/T_c \sim 10^7$
3) T_{ini}(LHC) ~ 2-3*T_{ini}(RHIC)
4) Thermalized, evolutions are similar for RHIC and LHC
5) At FAIR, system change dramatically

Outline

(1) Introduction

(2) Experimental Setup

(3) Recent Results:

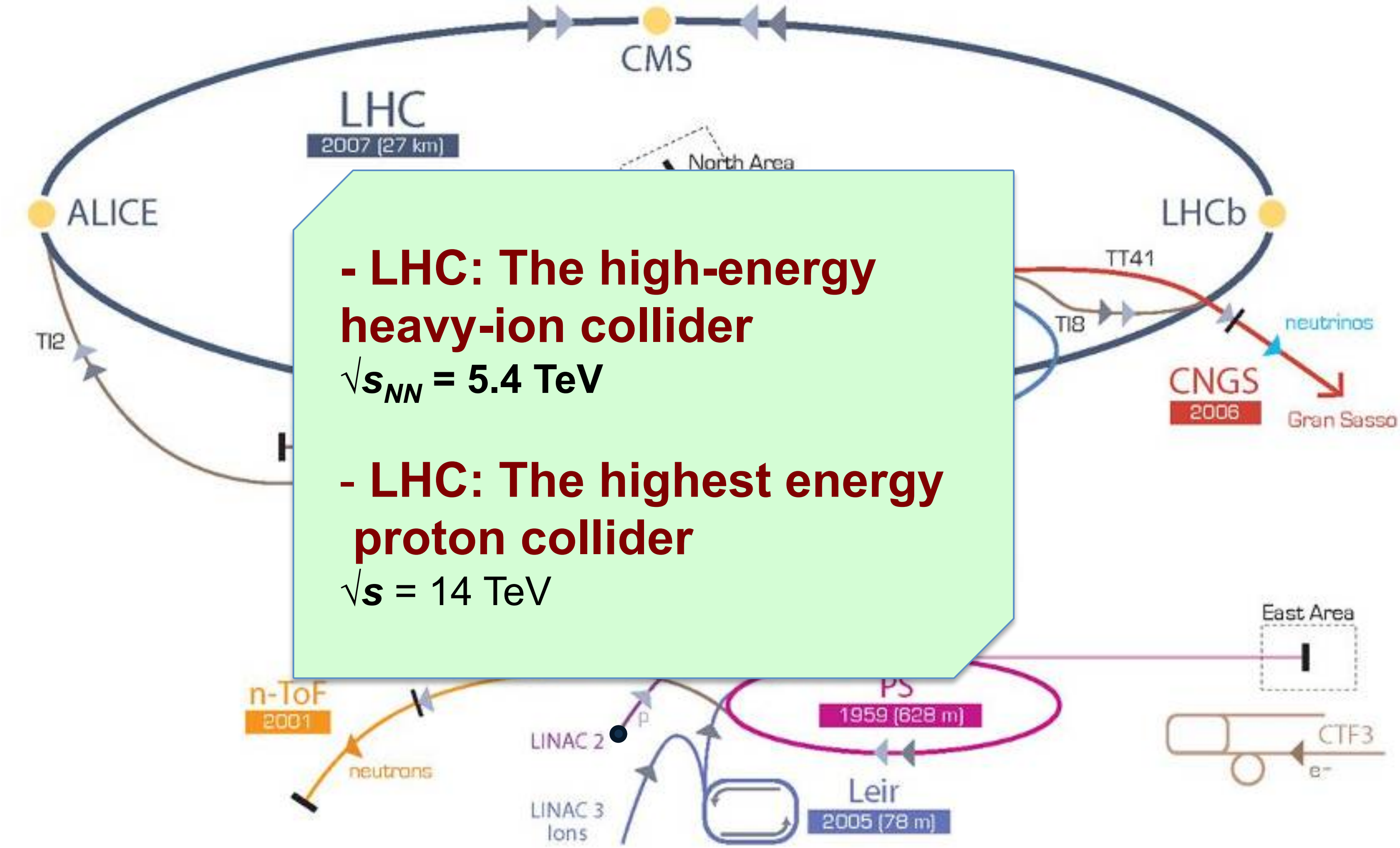
- Collectivity

- Criticality

- Chirality

(4) Summary and Outlook

Large Hadron Collider



- LHC: The high-energy heavy-ion collider

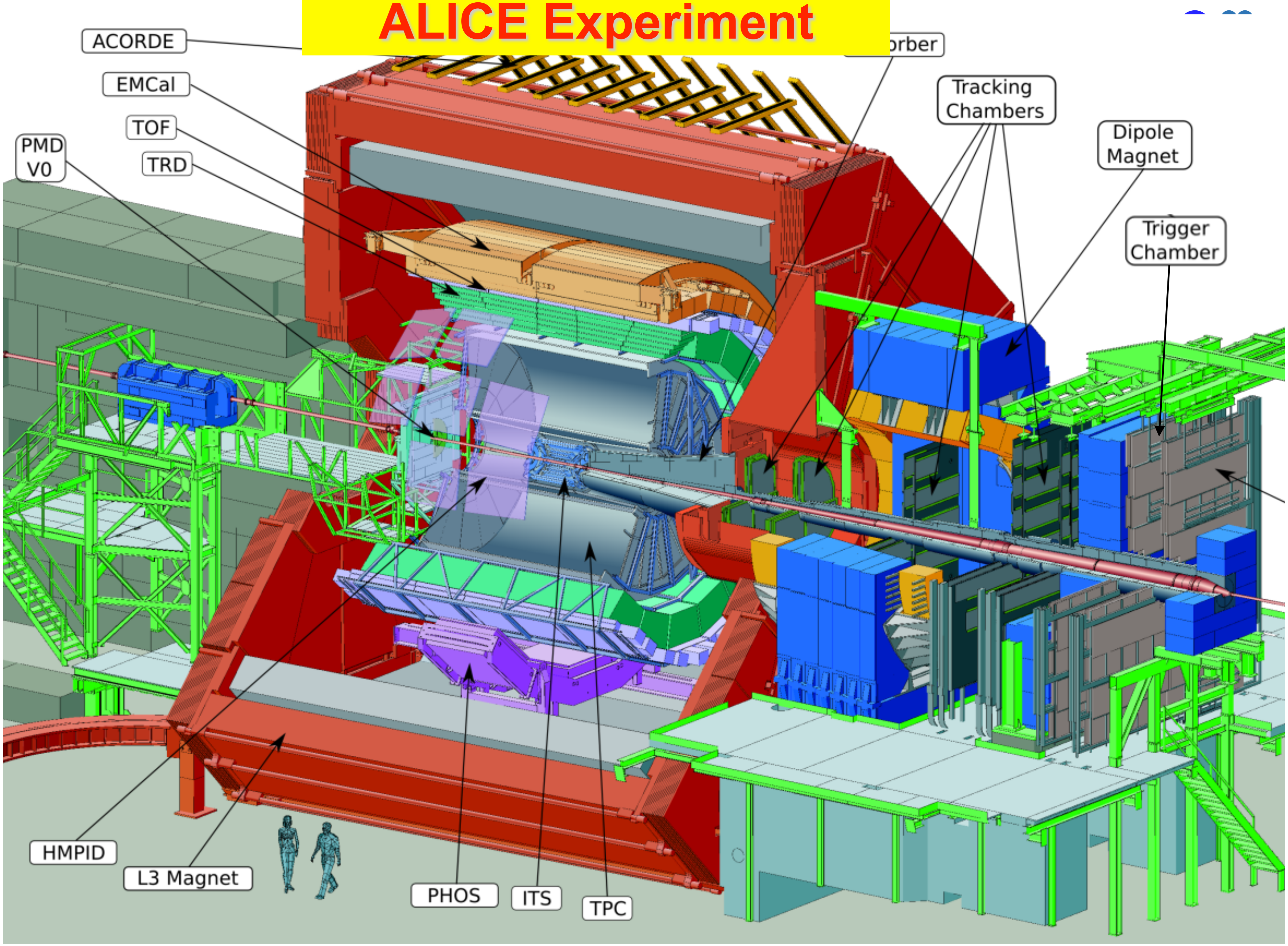
$\sqrt{s_{NN}}$ **= 5.4 TeV**

- LHC: The highest energy proton collider

$\sqrt{s}$ = 14 TeV

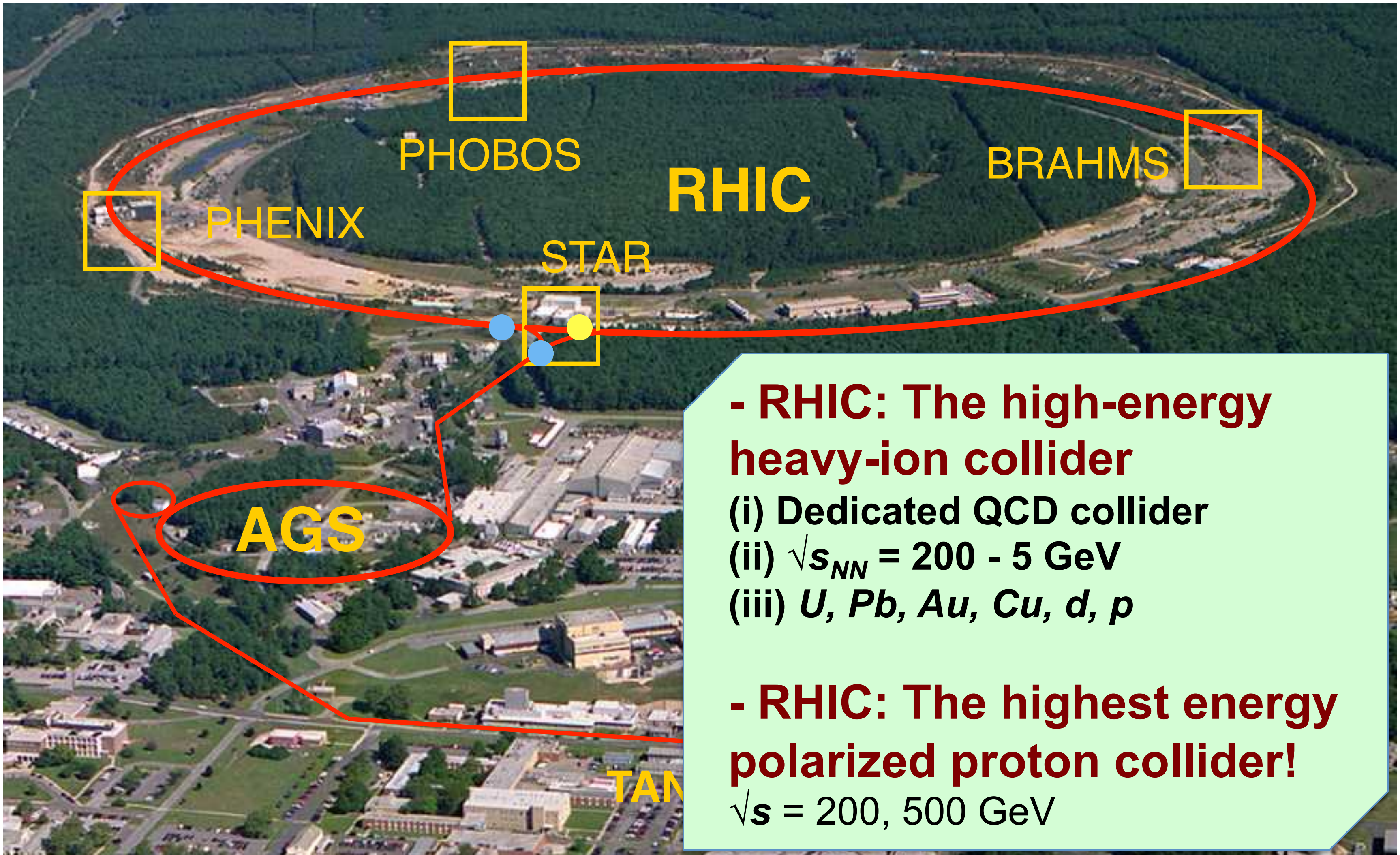
ALICE Experiment

ALICE Experiment



Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY



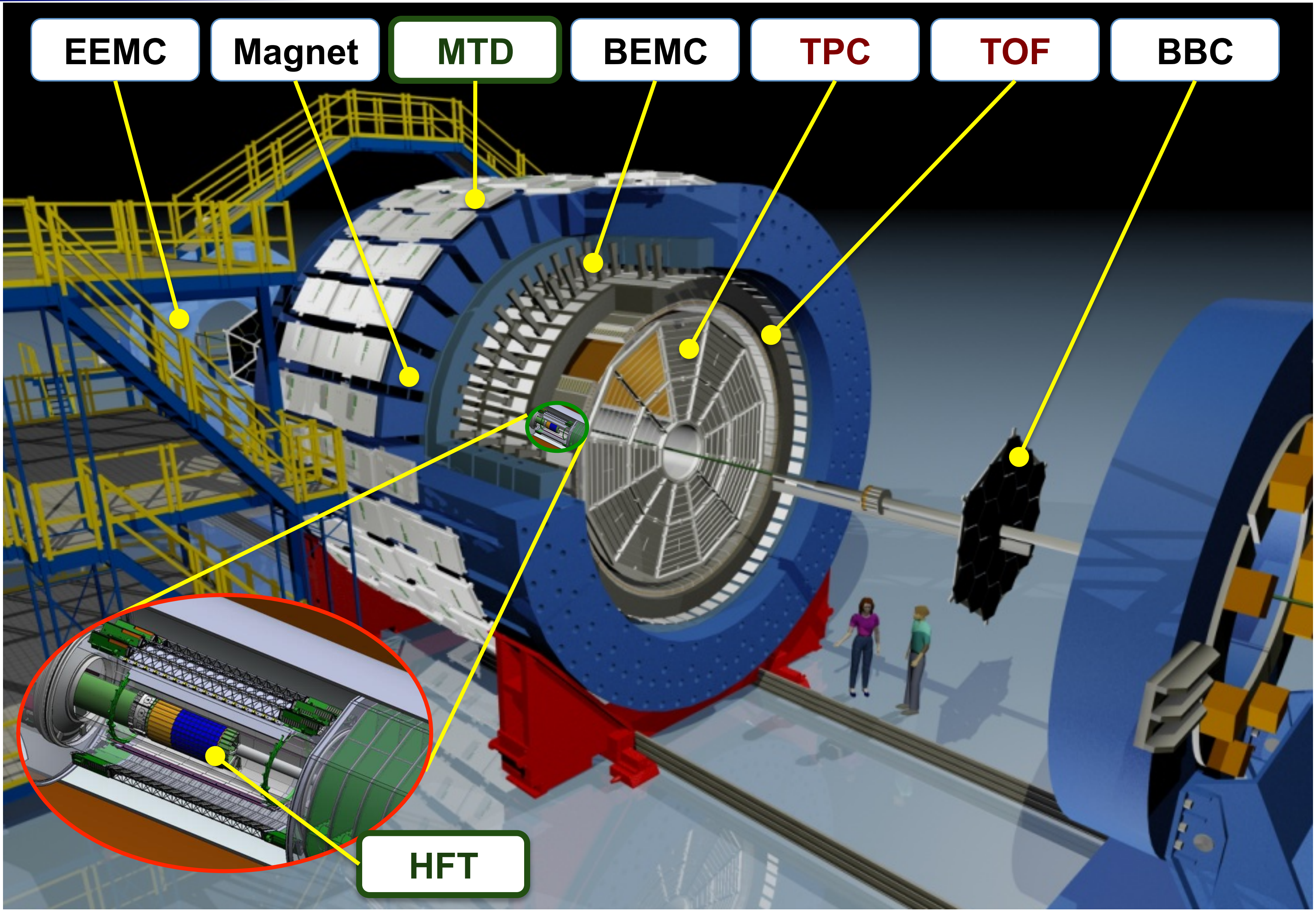
- **RHIC: The high-energy heavy-ion collider**
  (i) Dedicated QCD collider
  (ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV
  (iii) *U, Pb, Au, Cu, d, p*

- **RHIC: The highest energy polarized proton collider!**
  $\sqrt{s}$ = 200, 500 GeV

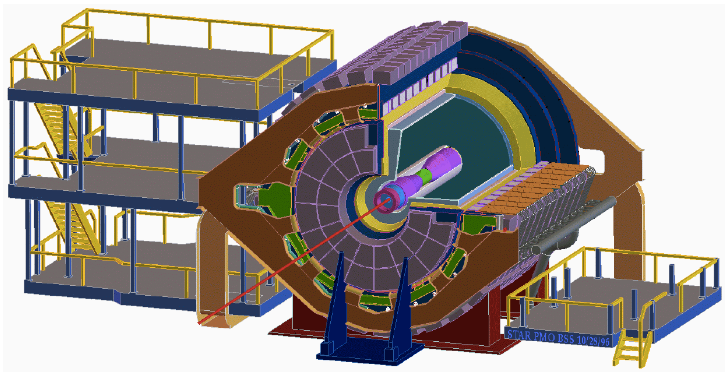
Animation M. Lisa


STAR Collaboration

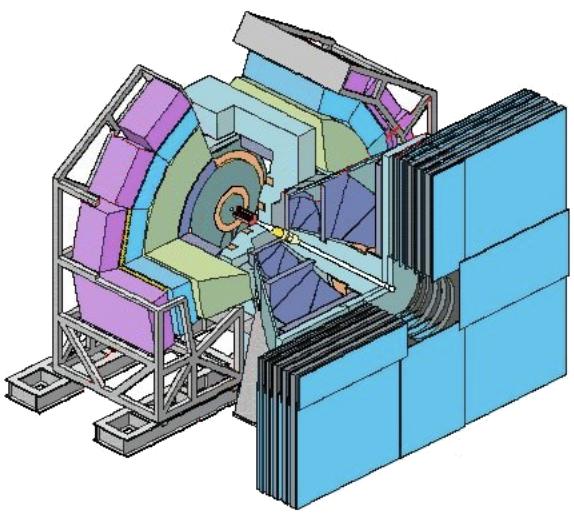
STAR Detector System



High-Energy Nuclear Collider Experiments

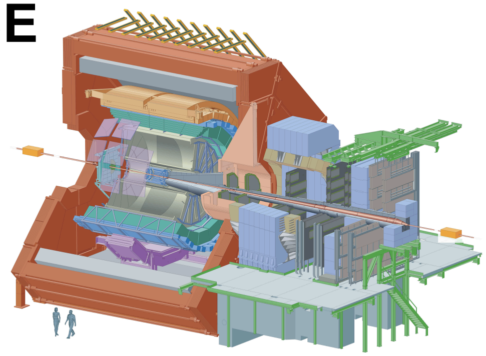


STAR

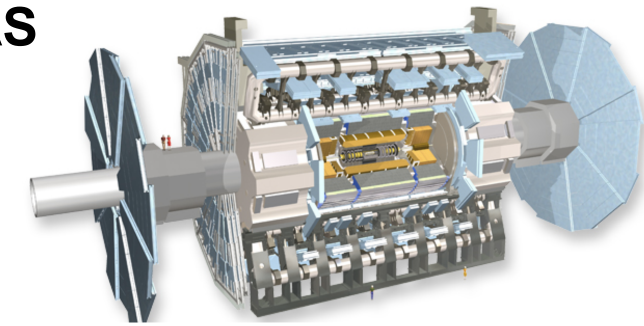


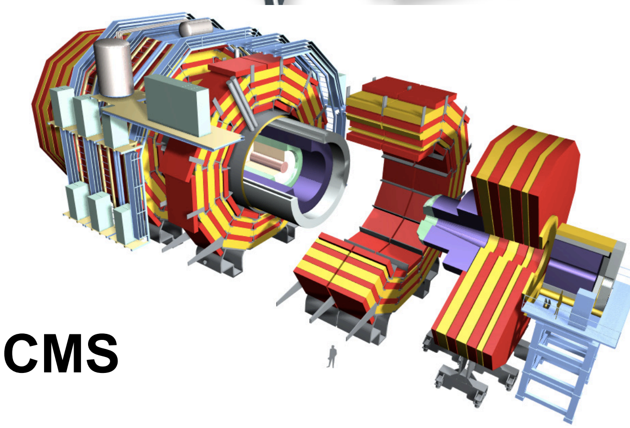
PHENIX

ALICE



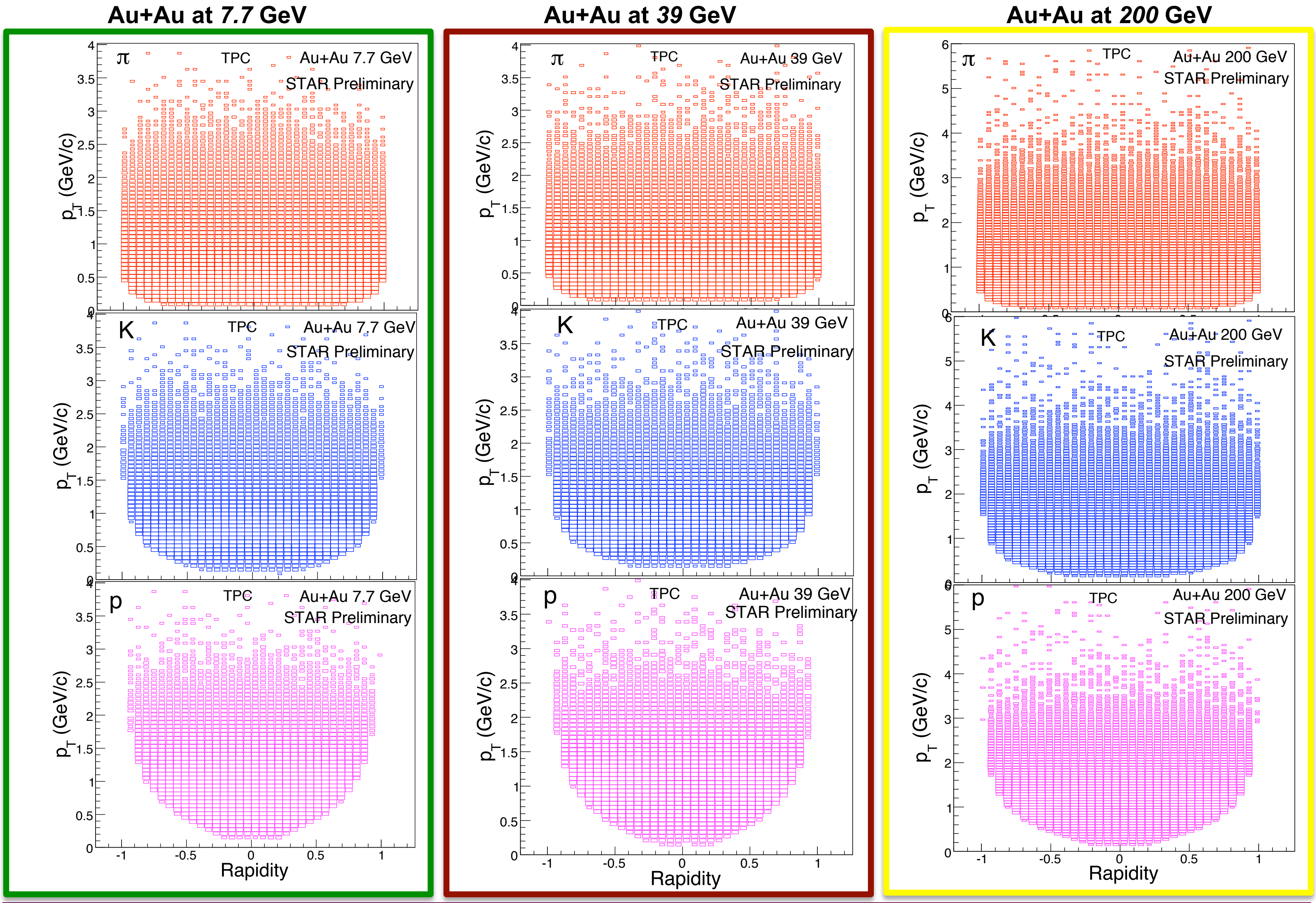
ATLAS



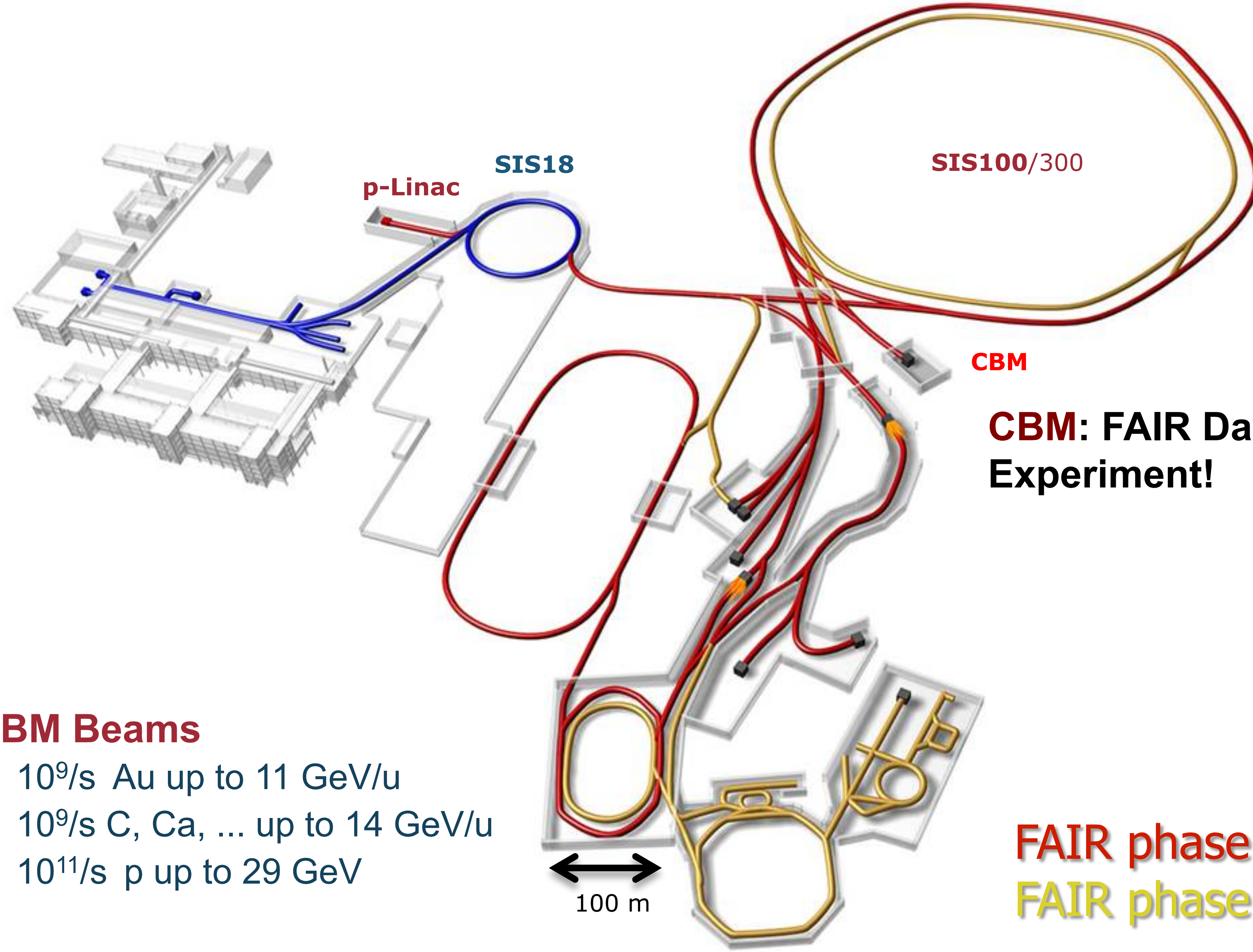


CMS

PID: 7.7, 39, 200 GeV ($\pi^{\pm}$, $K^{\pm}$, p)



Facility for Antiproton & Ion Research



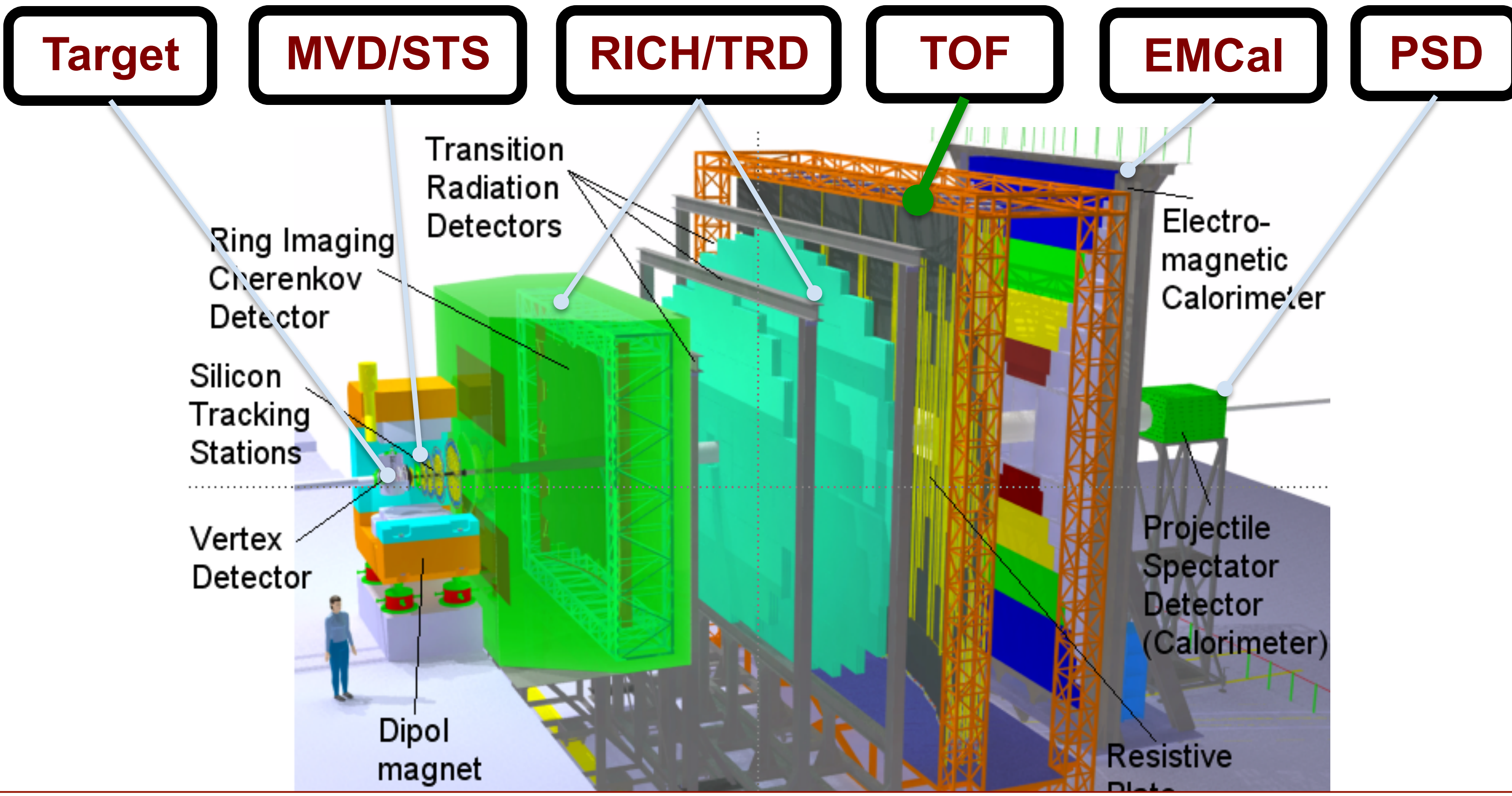
CBM: FAIR Day-1 Experiment!

CBM Beams

- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

FAIR phase 1
FAIR phase 2

The CBM Experiment at FAIR

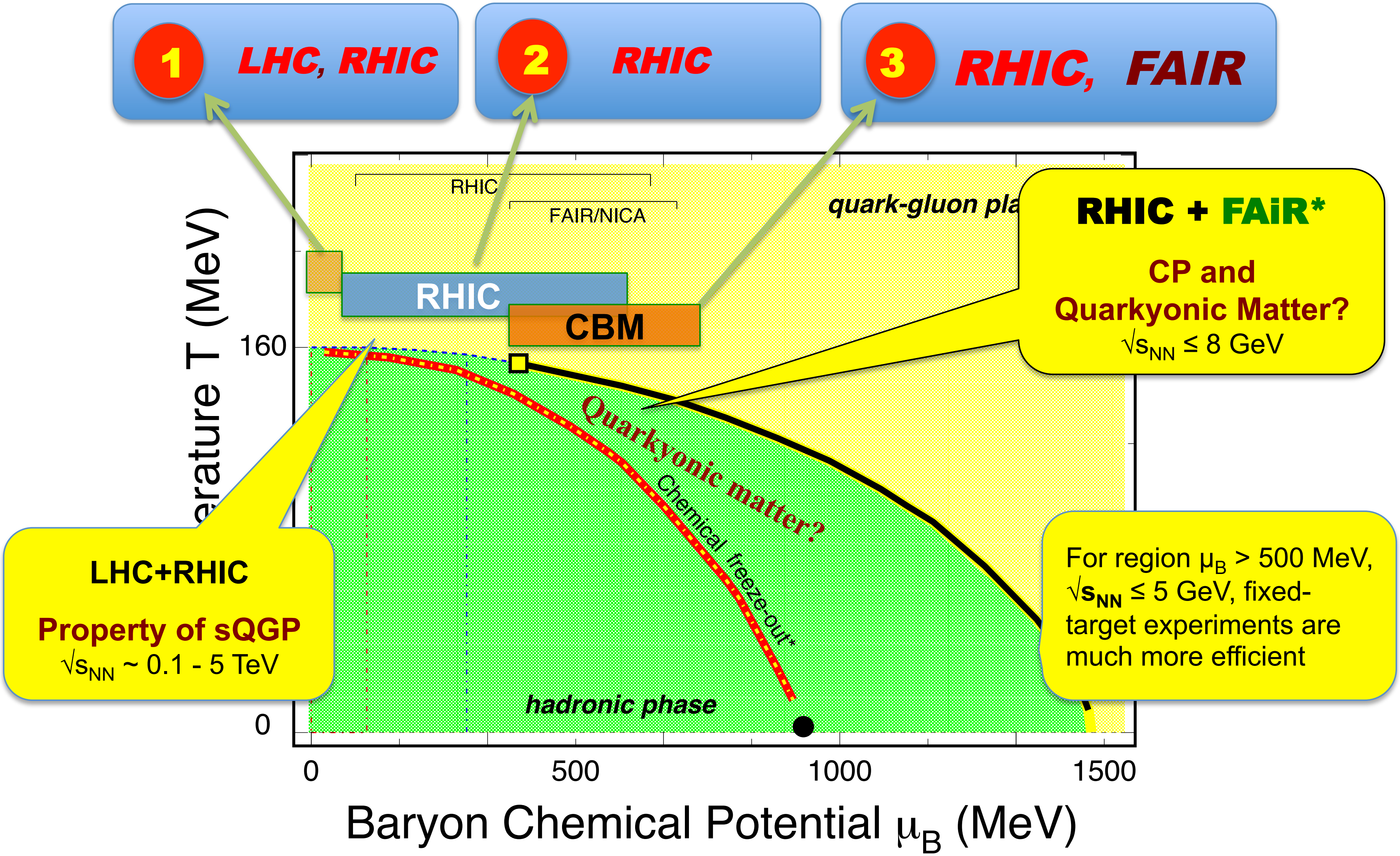


FAIR: One of the highest intensity accelerator complex in the 21st century

Precision measurements at high baryon density region for:

(i) Dileptons (***e, μ***); (ii) High order correlations; (iii) Flavor productions (***s, c***)

Exploring QCD Phase Structure

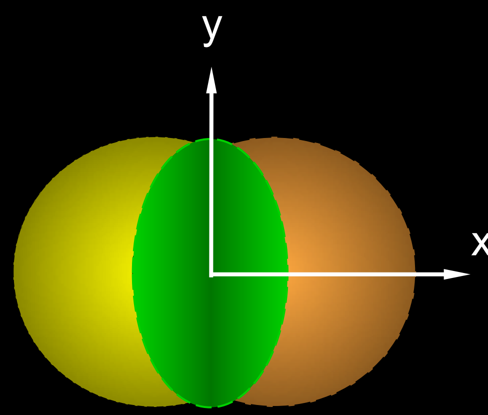


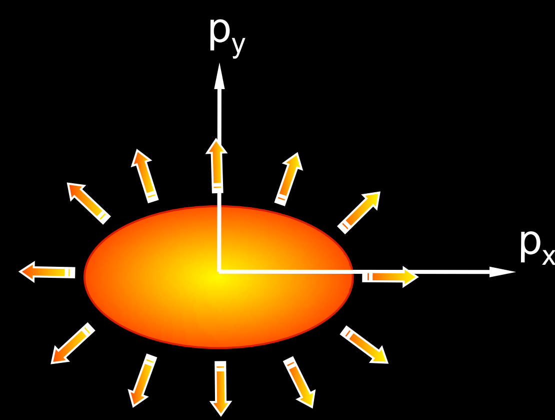
Collectivity

More see talks by B. Schenke, J-Y. Ollitrault

Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

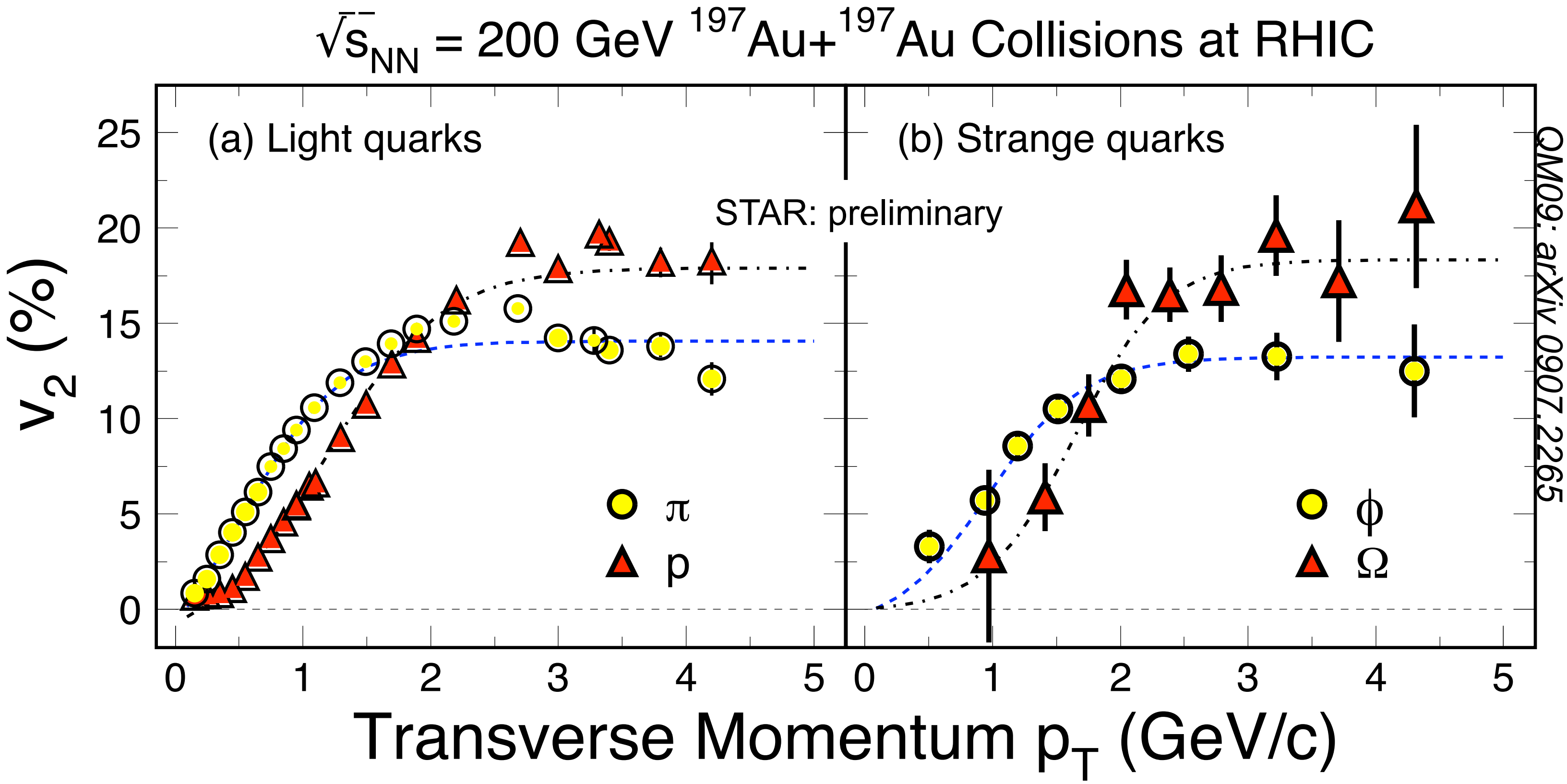




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

Partonic Collectivity at RHIC



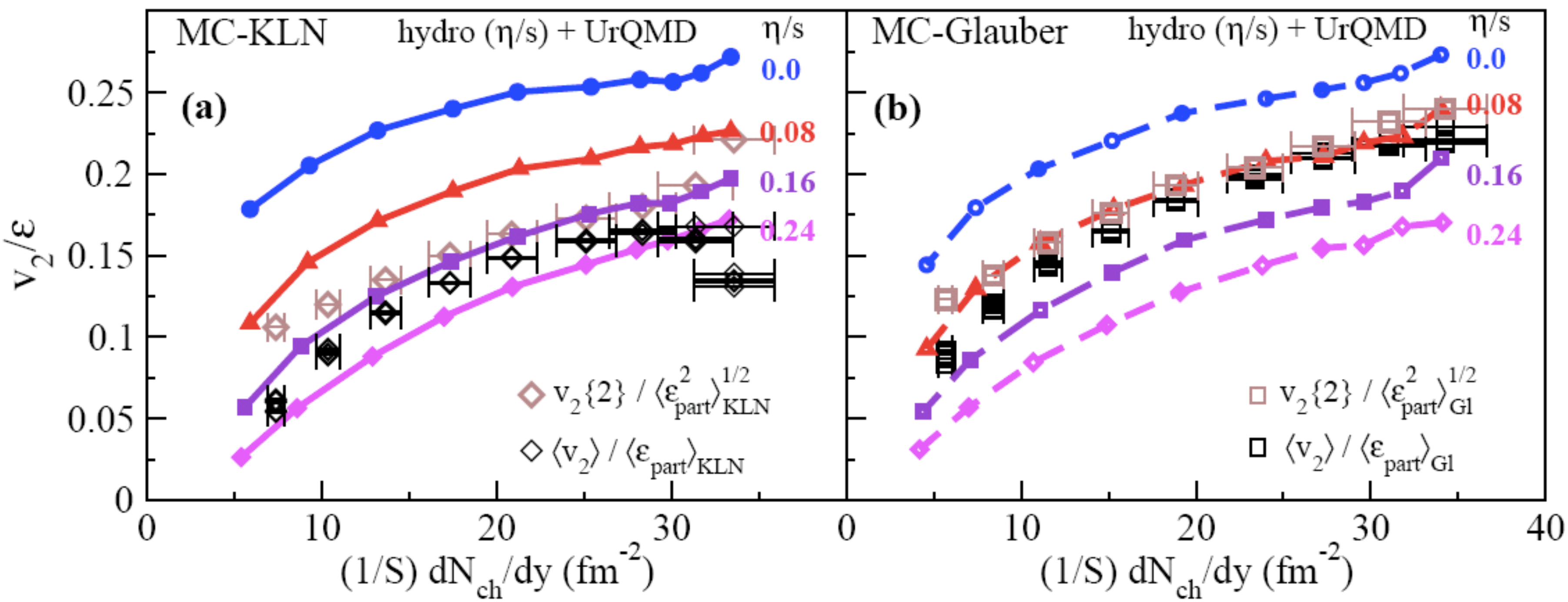
Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering

High p_T (> 2 GeV/c): ***number of quarks scaling (NCQ)***

➔ ***Partonic Collectivity, necessary for QGP!***

➔ ***De-confinement in Au+Au collisions at RHIC!***

Comparison with Model Results

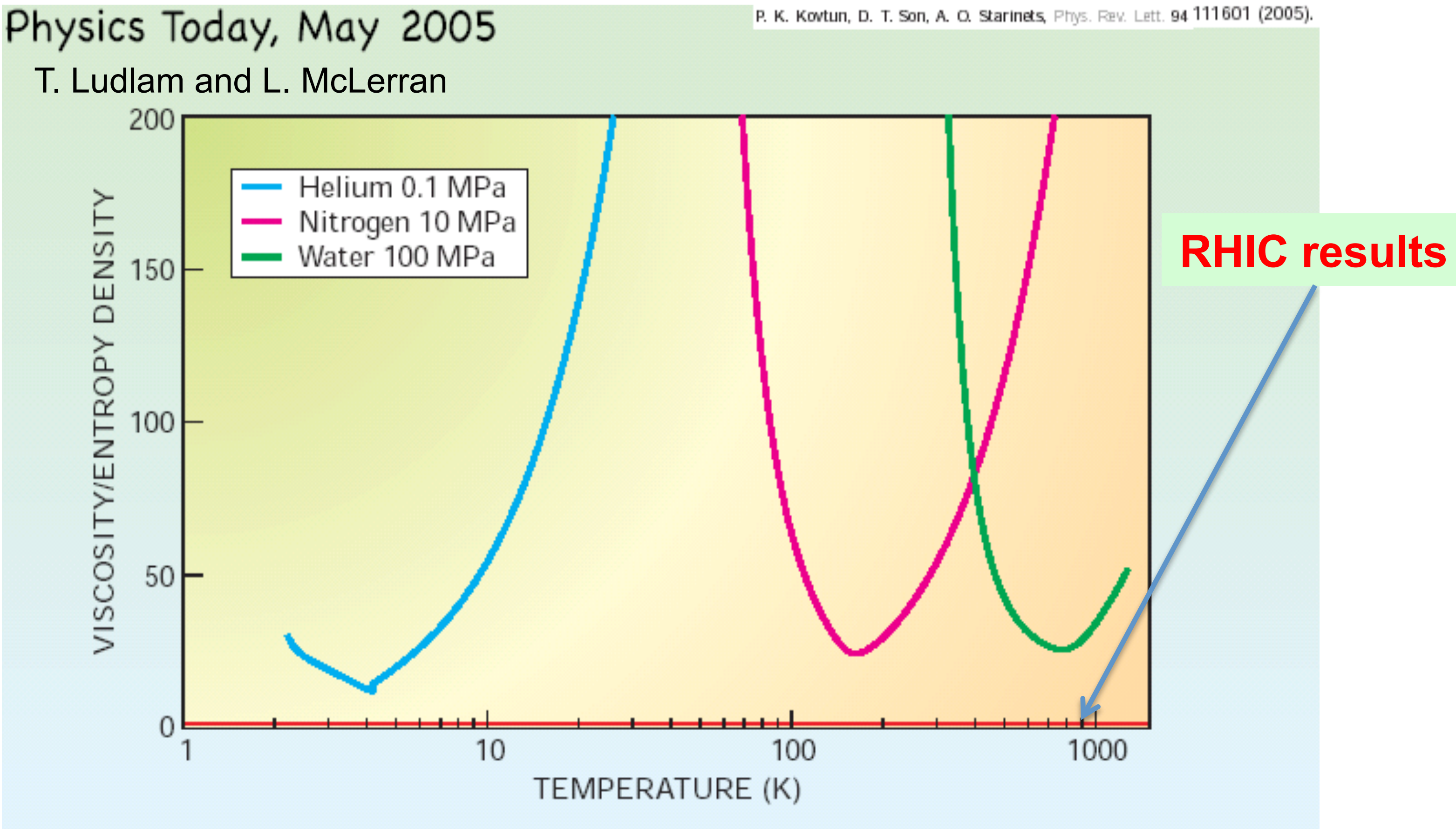


➔ ***Small value*** of specific viscosity over entropy ***η/s***

➔ Model uncertainty dominated by ***initial eccentricity ε***

Model: Song *et al.* ***PRL106****, 192301(2011), arXiv:1011.2783*

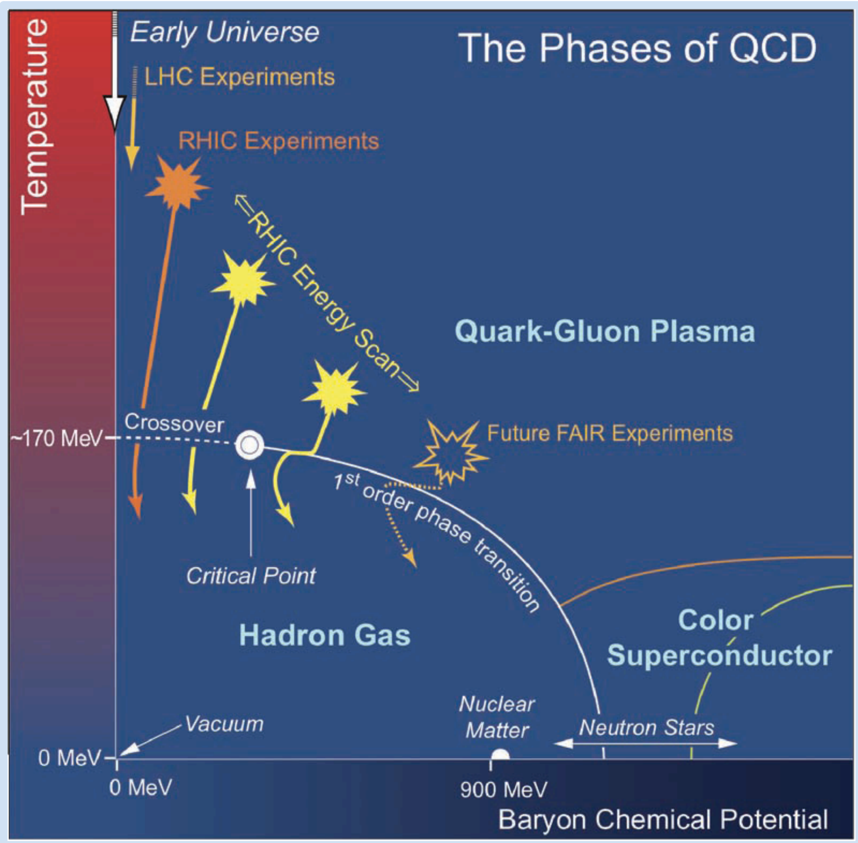
Low *η/s* for QCD Matter at RHIC



1) $\eta/s \geq 1/4\pi$, ***'perfect liquid'***

2) η/s(QCD matter) << η/s(QED matter)

Beam Energy Scan at RHIC



Study QCD Phase Structure

- Onset of sQGP
- Phase boundary and critical point
- Chiral symmetry

BES-I:

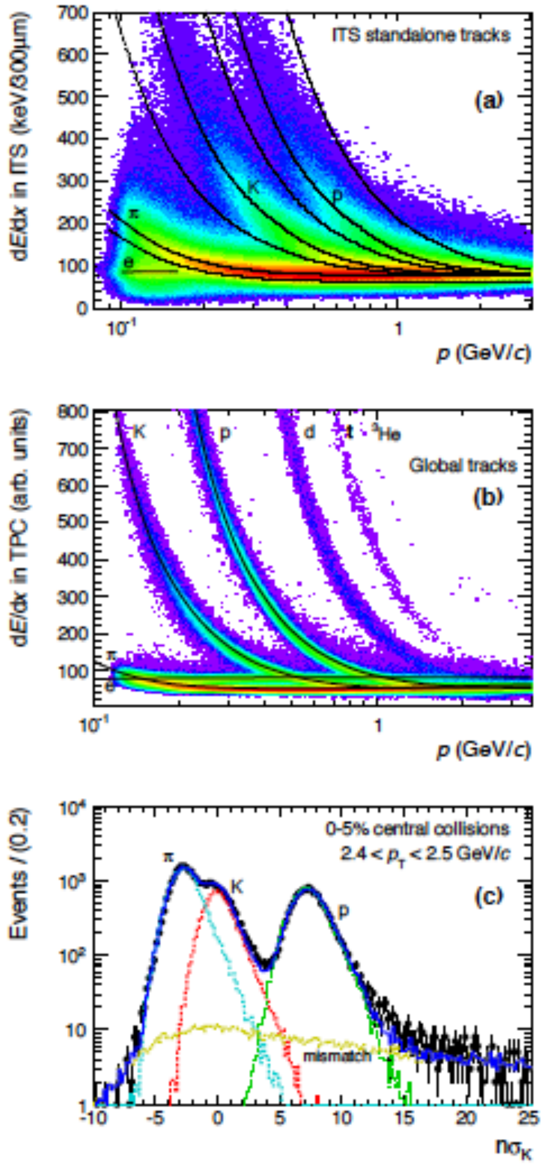
$\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39GeV

BES-II: $\sqrt{s_{NN}} \leq$ 20GeV

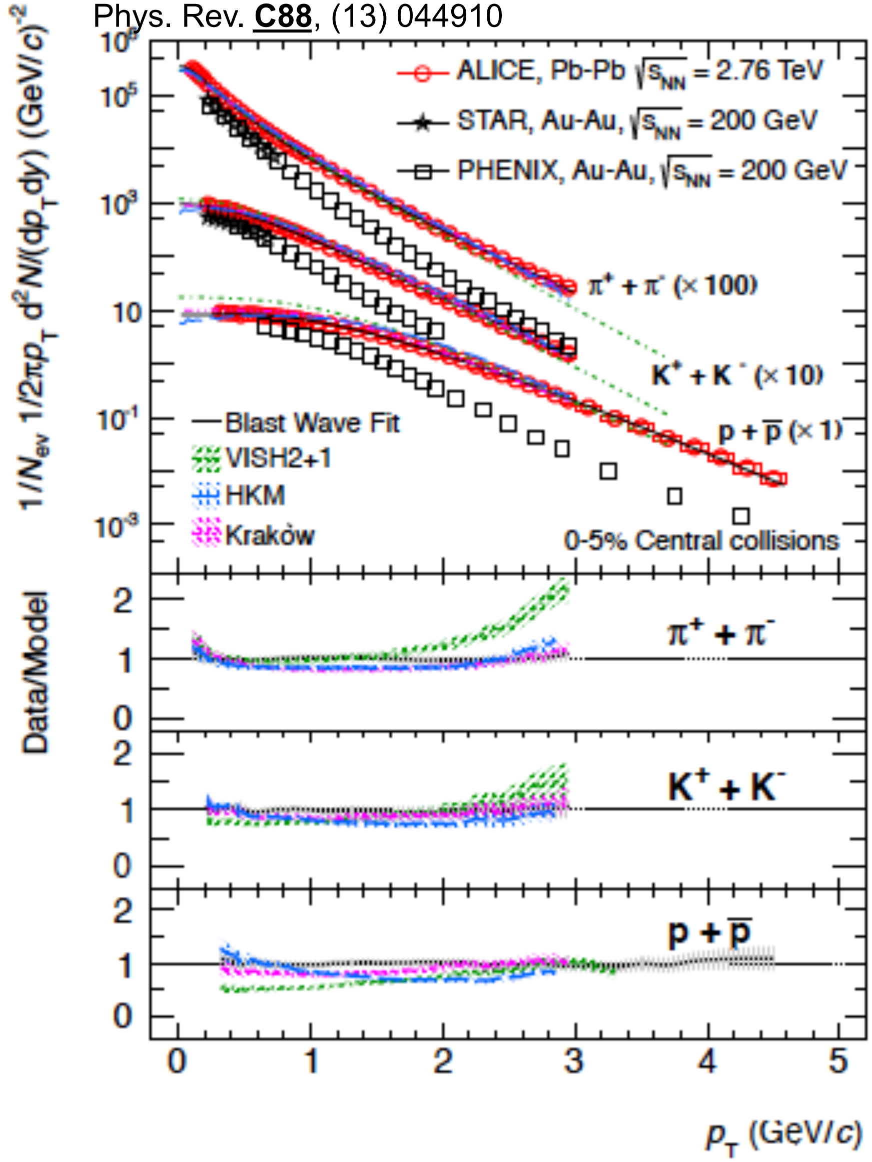
(1) Collectivity: **EOS of the system**

(2) Critical point* (critical region): **High order cumulants**

Identified Hadron Spectra

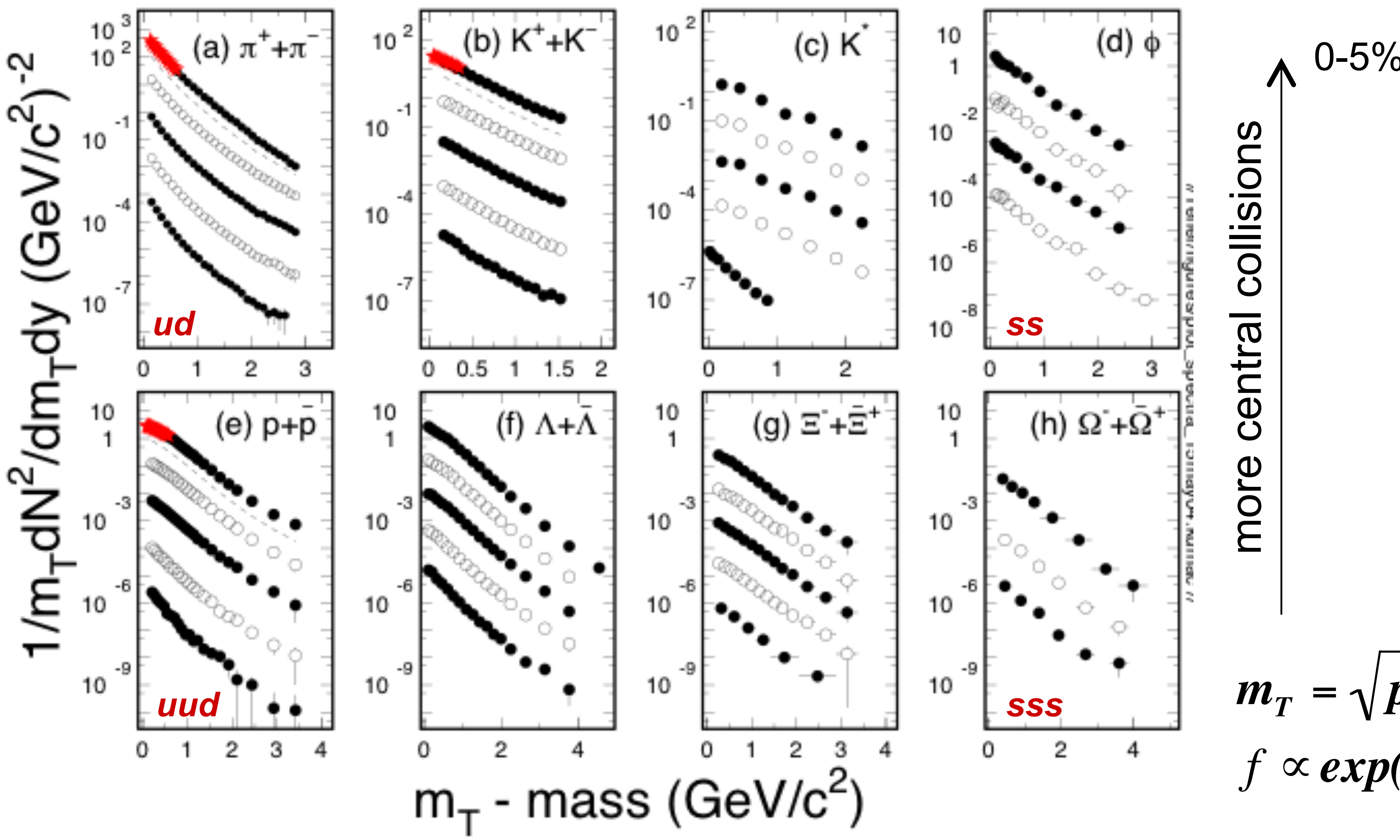


ALICE: B. Abelev et al, Phys. Rev. Lett. **109**, (12) 252301; Phys. Rev. **C88**, (13) 044910



Hadron Spectra from RHIC

p+p and Au+Au collisions at 200 GeV



$$m_T = \sqrt{p_T^2 + m^2}$$

$$f \propto exp(-m_T/T_{slope})$$

Multi-strange hadron spectra are exponential in their shapes.

STAR white papers - Nucl. Phys. A757, 102(2005).

Thermal Model Fits (Blast-Wave)

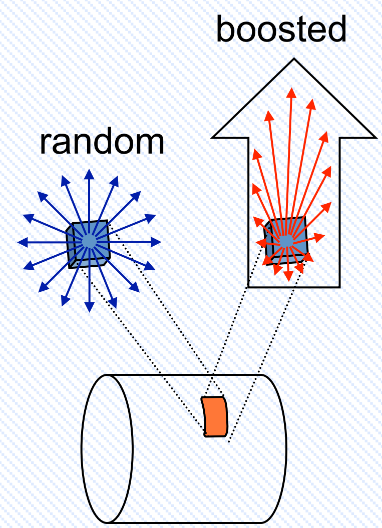
Source is assumed to be:
- Locally thermal equilibrated
- Boosted in radial direction

E.Schnedermann, J.Sollfrank, and U.Heinz, Phys. Rev. ***C48****, 2462(1993)*

$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}} p d\sigma_\mu \Rightarrow$$

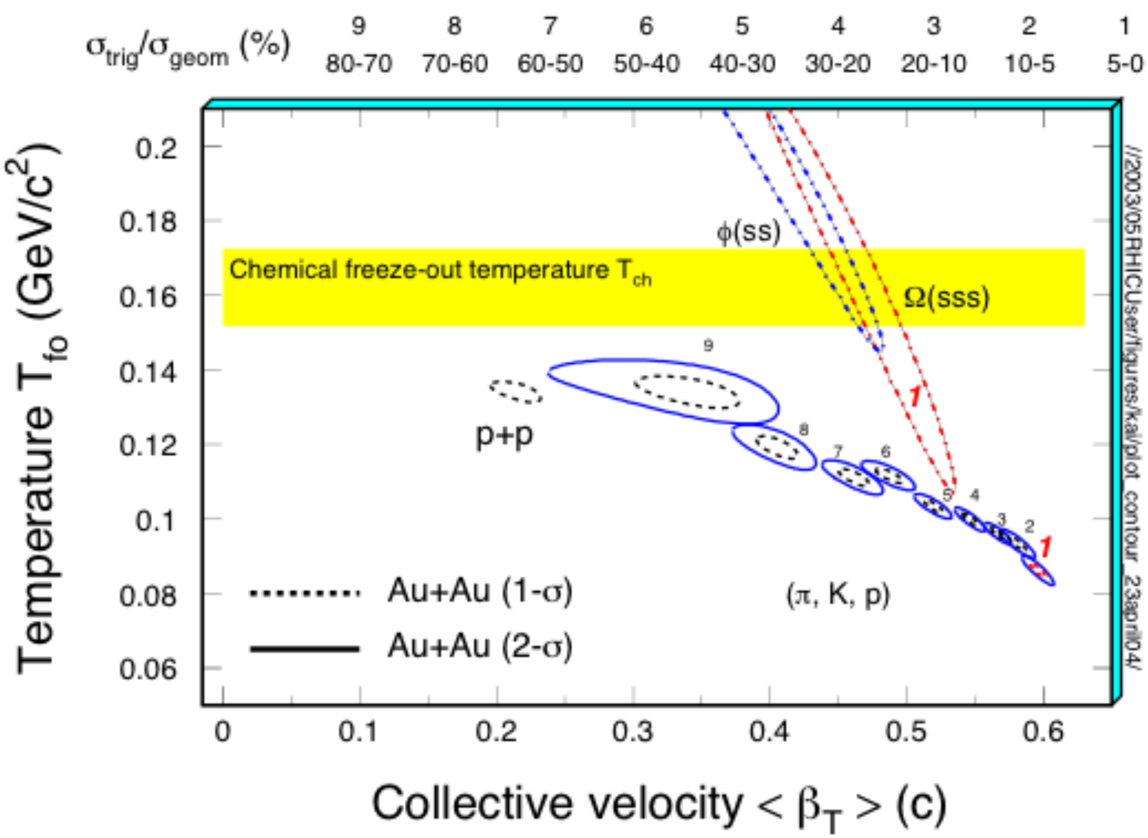
$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

$$\rho = \tanh^{-1}\beta_T \qquad \beta_T = \beta_S\left(\frac{r}{R}\right)^\alpha \qquad \alpha = 0.5,\ 1,\ 2$$



Extract thermal temperature T_{fo} and velocity parameter $\langle\beta_T\rangle$

Blast Wave Fits: *RHIC*



1) π, K, and p change smoothly from peripheral to central collisions.

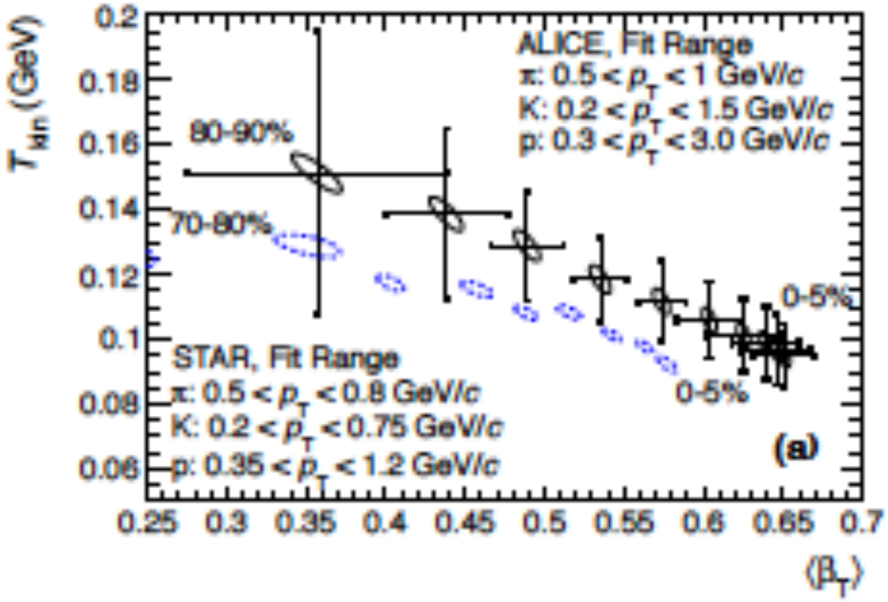
2) At the most central collisions, $\langle \beta_T \rangle$ reaches 0.6c.

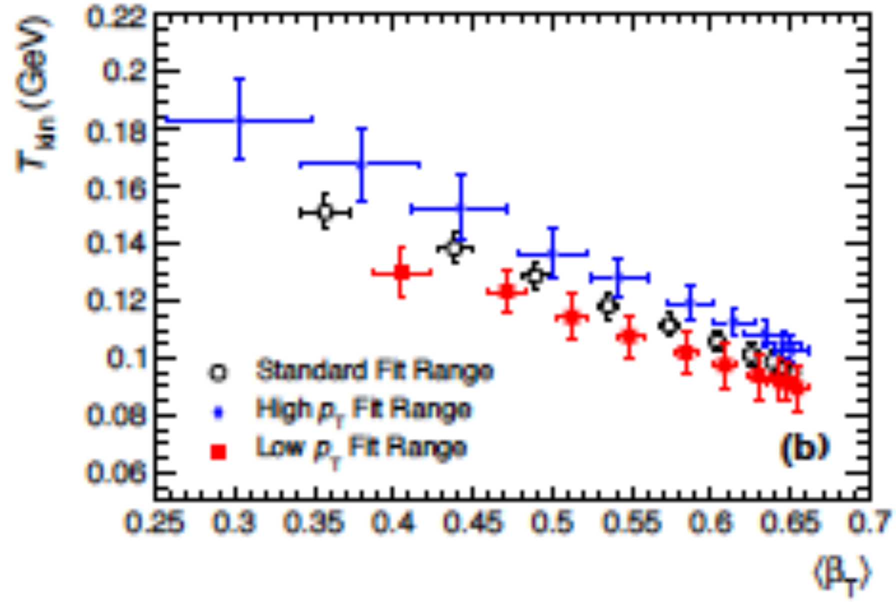
3) Multi-strange particles ϕ, Ω are found at higher T_{fo} and lower $\langle \beta_T \rangle$

⇨ **light hadrons move with higher velocity compared to strange hadrons**

STAR: NP**A715**, 458c(03); *PRL* ***92**, 112301(04);* ***92**, 182301(04).*

Blast Wave Fits: LHC





Kinetic Freeze-out at LHC similar to that from RHIC. Collective velocity parameter ***β*** is stronger in the most central collisions => Stronger collective expansion at LHC!

ALICE: B. Abelev et al, Phys. Rev. Lett. **109**, (12) 252301; Phys. Rev. **C88**, (13) 044910

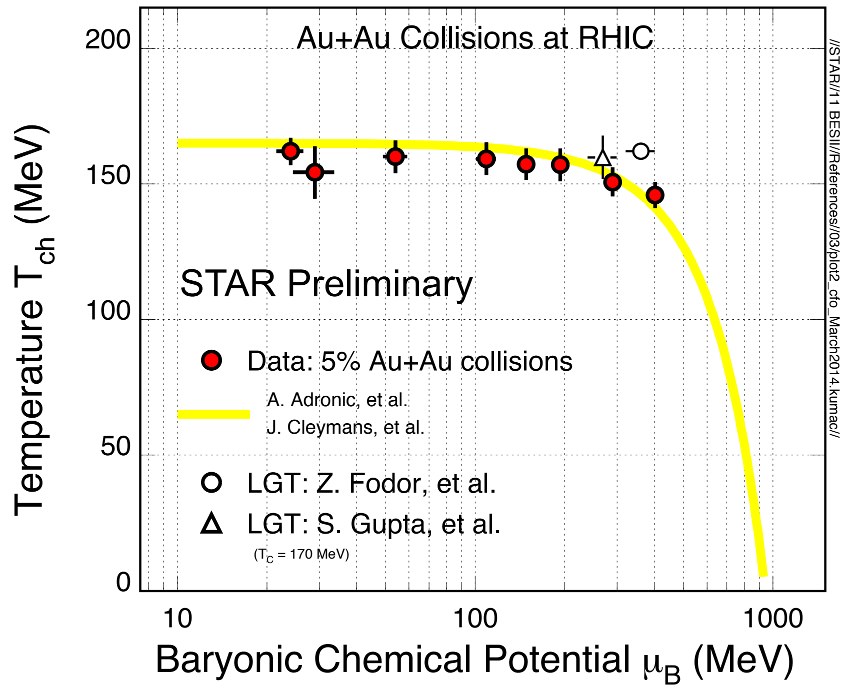
Statistical Model Fits

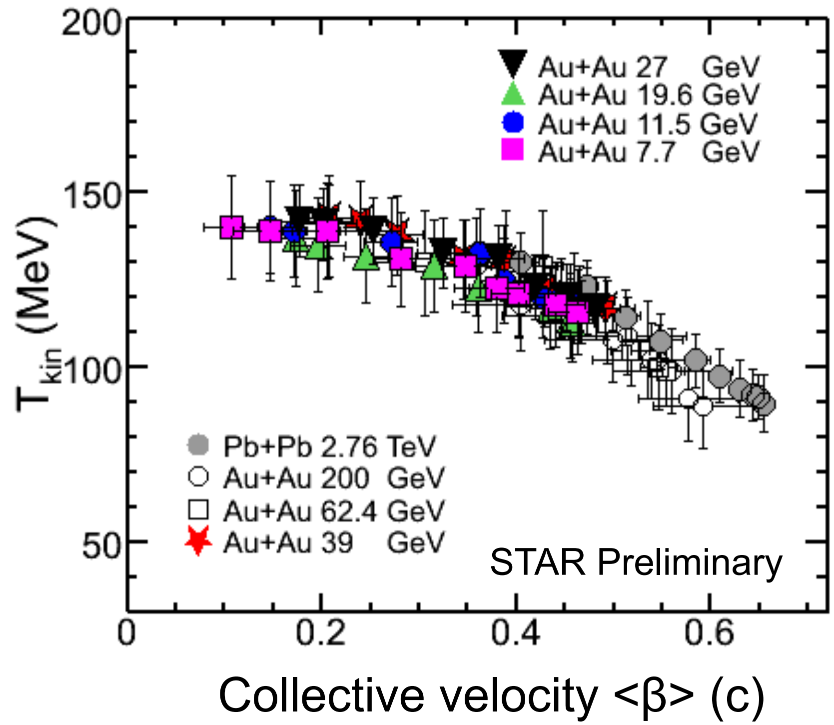
- Assume thermally (constant T_{ch}) and chemically (constant n_i) equilibrated system at chemical freeze-out
- System composed of non-interacting hadrons and resonances
- Given T_{ch} and μ_i 's (+ system size), n_i's can be calculated in a grand canonical ensemble

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

- T_{ch} and μ_i ***i*=B, Q, S**
- Obey conservation laws: Baryon Number, Strangeness, Isospin
- Short-lived particles and resonances need to be taken into account

Bulk Properties at Freeze-out

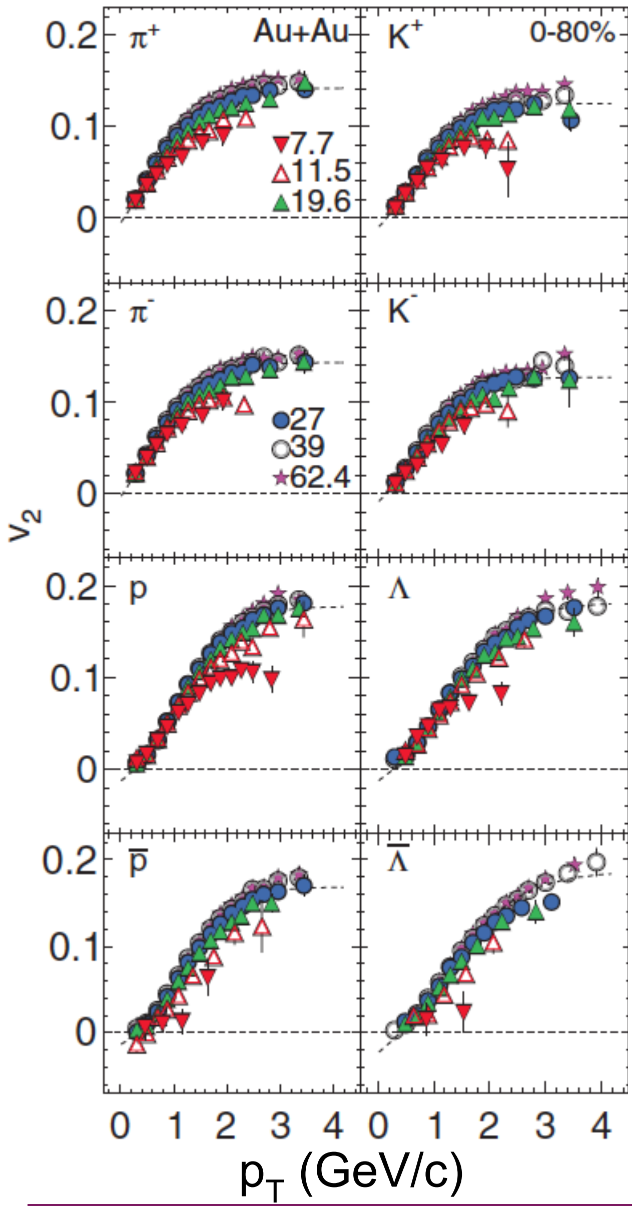


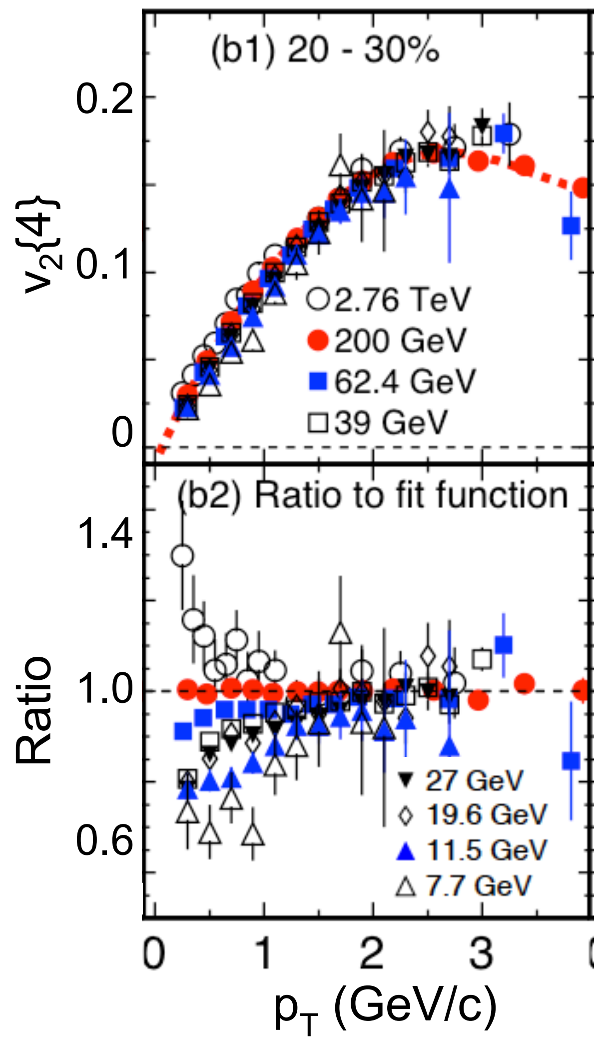


Chemical Freeze-out: (GCE)
- Central collisions.
- Centrality dependence, not shown, of T_{ch} and μ_B!

Kinetic Freeze-out:
- Central collisions => lower value of T_{kin} and larger collectivity β
- Stronger collectivity at higher energy

Charged and PID Hadron v_2 Results





1) Normalized to 200 GeV results

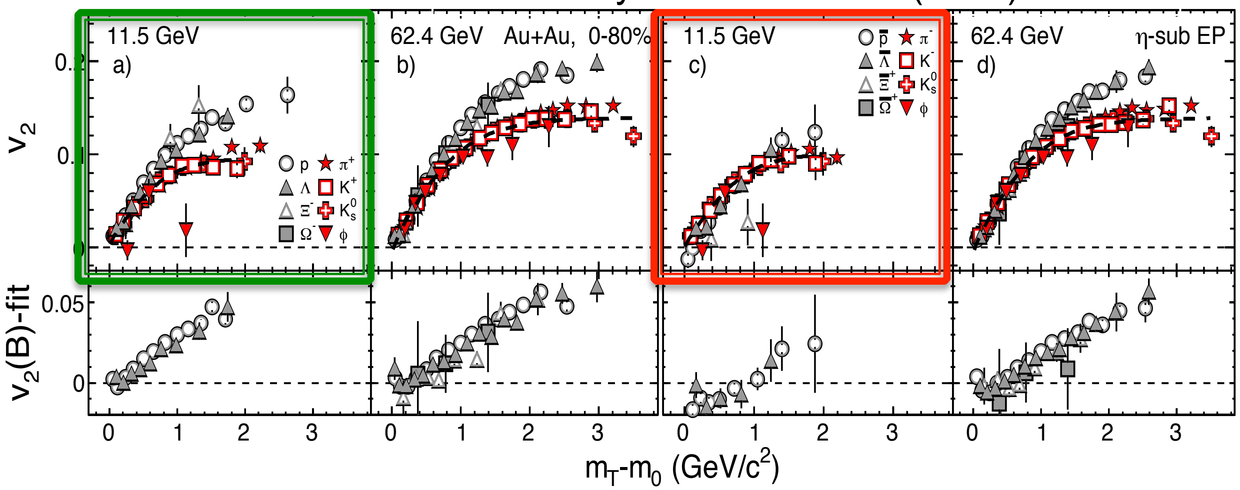
2) Stronger collectivity at higher collision energy

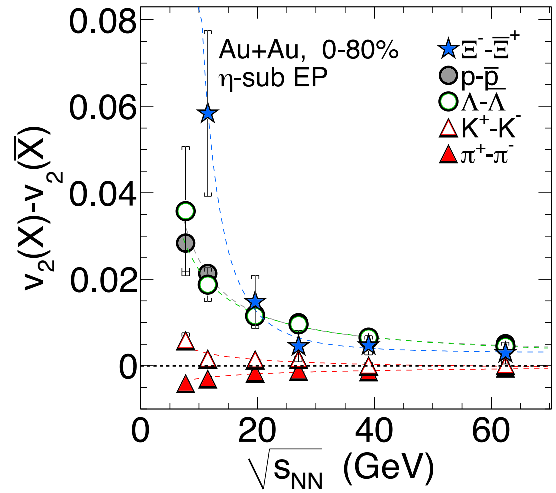
3) Particle and anti-particle display different behavior as a function of collision energy

STAR: **PRC86**, 054908 (2012); **PRC88**, 014902 (2013)
ALICE: **PRL105**, 252302 (2010)

Collectivity v_2 Measurements

STAR: Phys. Rev. Lett. **110** (2013) 142301

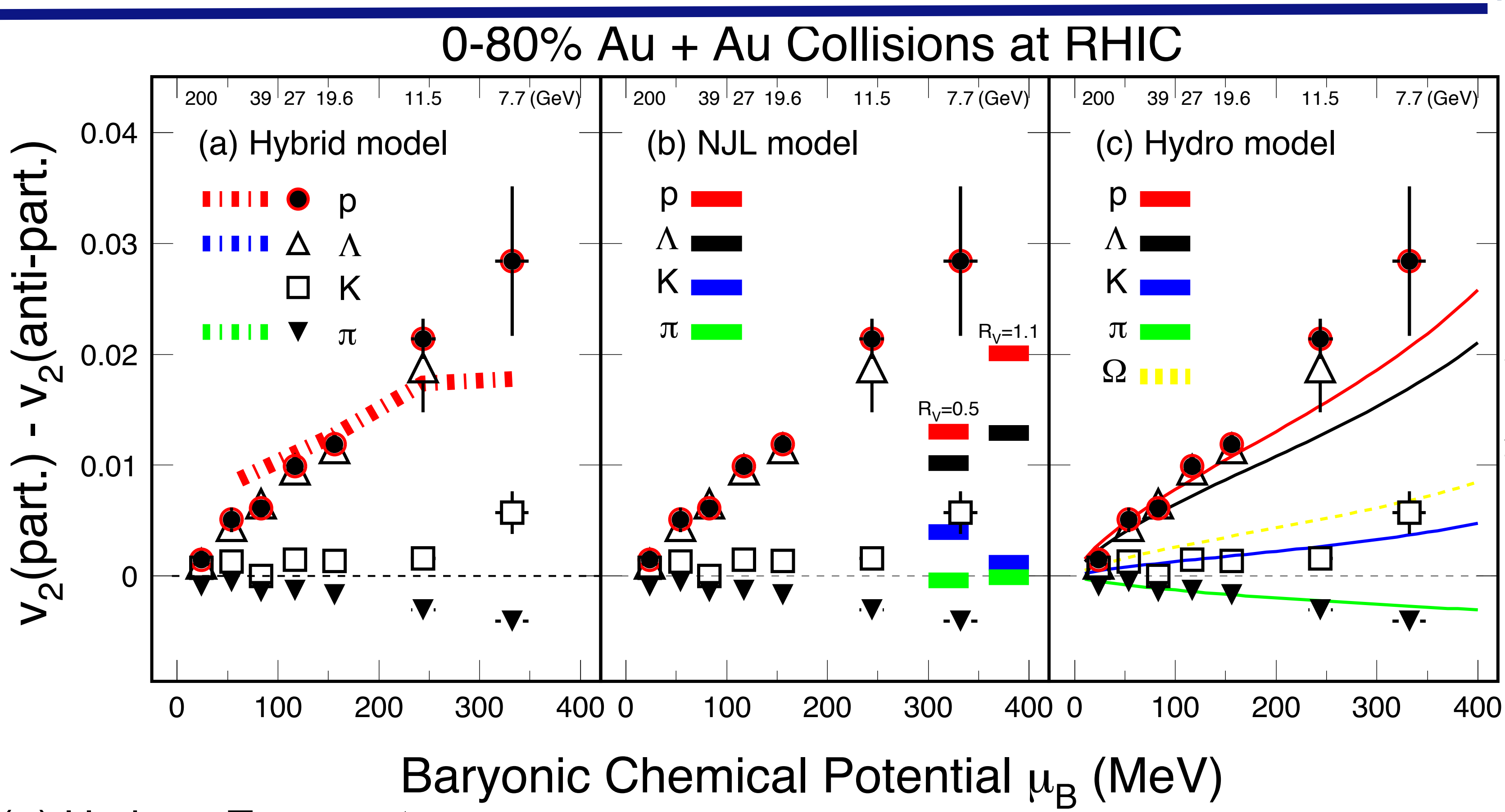




1) Number of constituent quark (NCQ) **scaling** in v_2 => **partonic collectivity** => ***deconfinement*** in high-energy nuclear collisions

2) At $\sqrt{s_{NN}}$ < 11.5 GeV, the universal v_2 **NCQ scaling is broken,** consistent with hadronic interactions becoming dominant.

BES v_2 and Model Comparison



(a) Hydro + Transport: [J. Steinheimer, et al. PRC86, 44902(13).]

(b) NJL model: Hadron splitting consistent. Sensitive to vector-coupling, **CME, net-baryon density** driven. [J. Xu, et al., arXiv:1308.1753/PRL112.012301]

(c) Pure Hydro solution with μ_B, viscosity: [Hatta et al. arXiv:1502.05894//1505.04226// 1507.04690 //]. **Chemical potential μ_B** and **viscosity η/s** driven!

Summary I

1) At high energy-nuclear collisions liquid-like quark-gluon plasma formed, η/s small

2) Current experiments, RHIC BES, cover $0 < \mu_B < 420$ MeV

3) The v_2 show strong dependence on μ_B! At high baryon (low energy) region, NCQ-scaling in v_2 disappeared and v_2(particle) > v_2(anti-particle).

Criticality

More see talk by K. Fukushima

Susceptibilities and Moments

Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2}\sum_i d_i (m_i/T)^2 K_2(m_i/T)\cosh[(B_i\mu_B + S_i\mu_S + Q_i\mu_Q)/T]$$

The susceptibility: $T^{n-4}\chi_q^{(n)} = \frac{1}{T^4}\frac{\partial^n}{\partial(\mu_q/T)^n} P\left(\frac{T}{T_C},\frac{\mu_q}{T}\right)\Big|_{T/T_C}$, $\quad q = B,Q,S$

Conserved Quantum Number

$$\chi_q^{(1)} = \frac{1}{VT^3}\langle \delta N_q \rangle$$

$$\chi_q^{(2)} = \frac{1}{VT^3}\left\langle (\delta N_q)^2 \right\rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3}\left\langle (\delta N_q)^3 \right\rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3}\left(\left\langle (\delta N_q)^4 \right\rangle - 3\left\langle (\delta N_q)^2 \right\rangle^2\right)$$

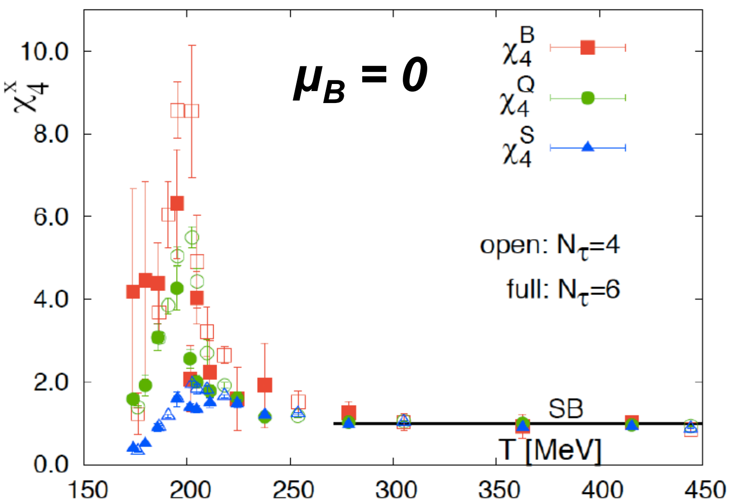
$$\frac{T^2\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2$$

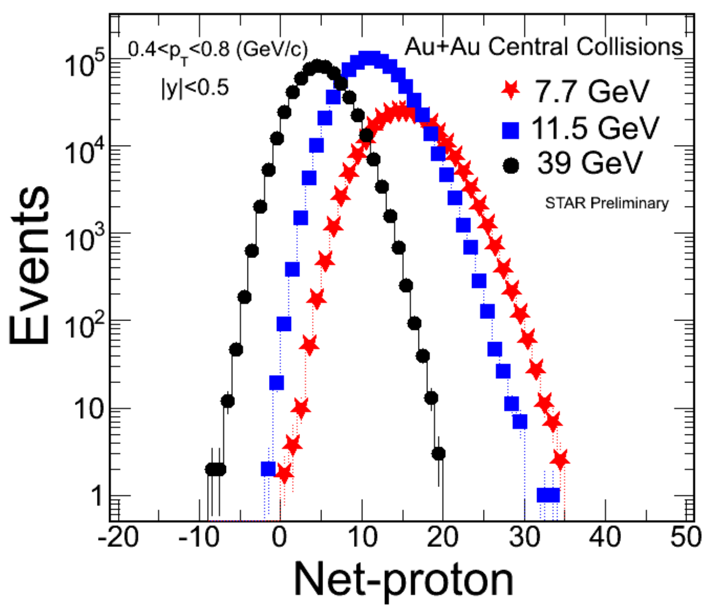
$$\frac{T\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma$$

Thermodynamic function ⇔ Susceptibility ⇔ Moments

Model calculations, *e.g.* LGT, HRG ⇔ Measurements

Higher Moments





1) Higher moments of conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \quad \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \quad \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

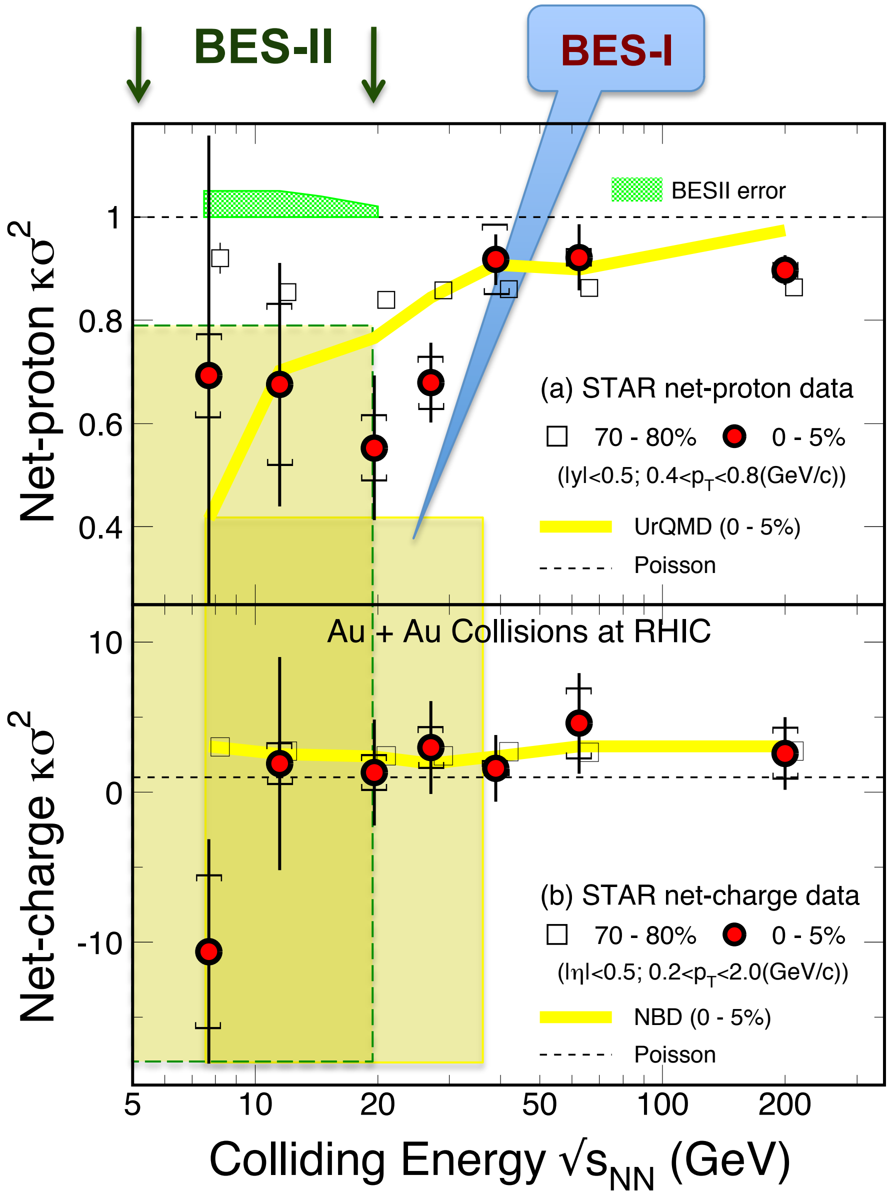
$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

4) Extract susceptibilities and freeze-out temperature. An independent/important test of thermal equilibrium in heavy ion collisions.

References:

- STAR: *PRL*105, 22303(10); *ibid*, 032302(14)
- M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB*696, 459(11) // F. Karsch et al, *PLB*695, 136(11) // S.Ejiri et al, PLB633, 275(06)
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // V. Skokov et al., PRC88, 034901(13)

Higher Moments Results



Net-proton results:

1) All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}}$~20GeV
2) UrQMD model shows monotonic behavior in the moment products

*STAR: **PRL112**, 32302(14)*

Net-charge results:

1) No non-monotonic behavior
2) More affected by the resonance decays

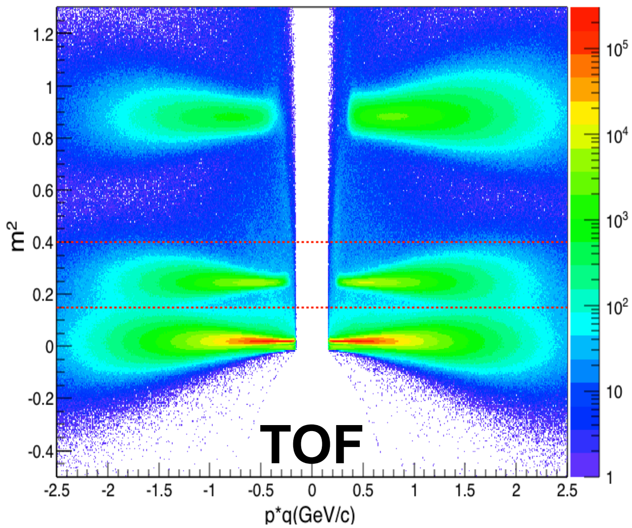
*STAR: **PRL113**, 92301(14)*
P. Garg et al, PLB726, 691(13)

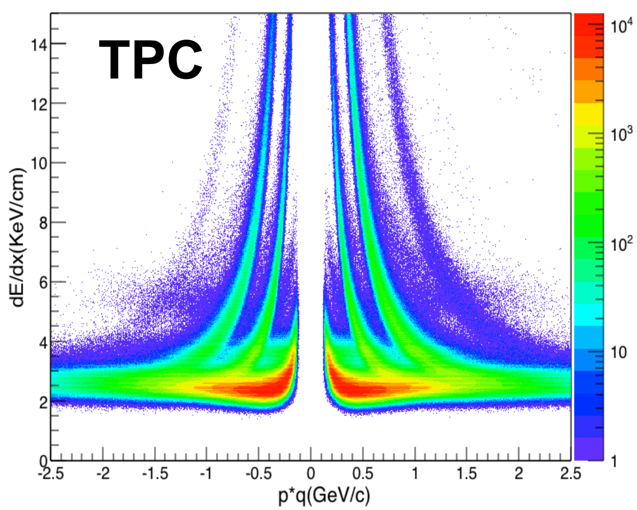
BES-II:

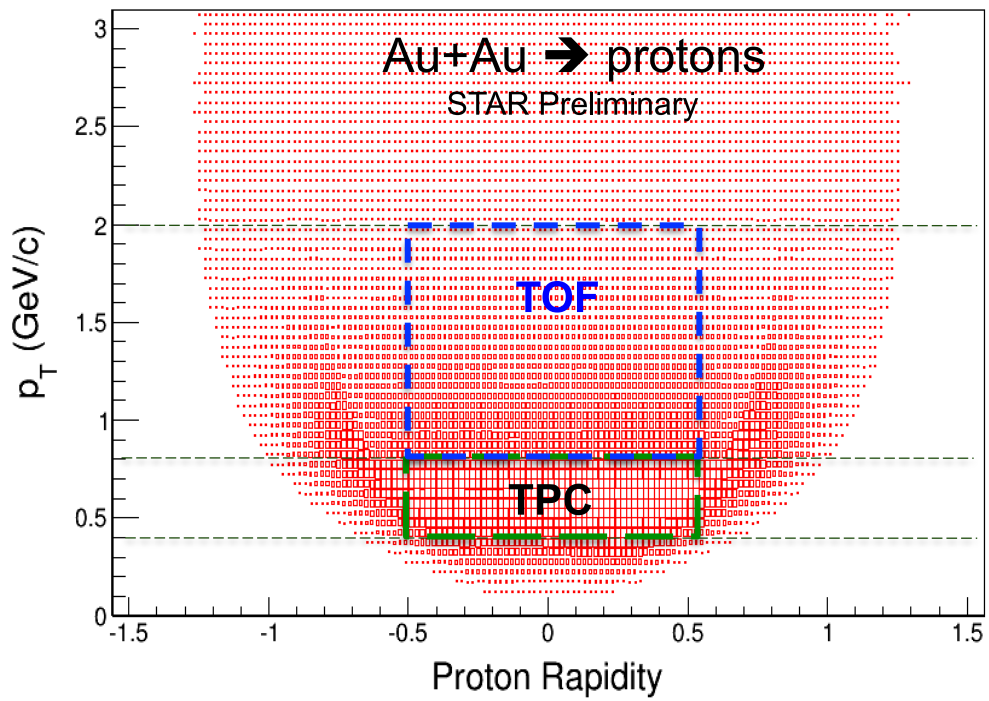
Higher statistics needed for collisions at $\sqrt{s_{NN}}$ < *20 GeV*

Extend Proton Identification with TOF

Published net-proton results: Only TPC used for proton/anti-proton PID. TOF PID extends the phase space coverage.







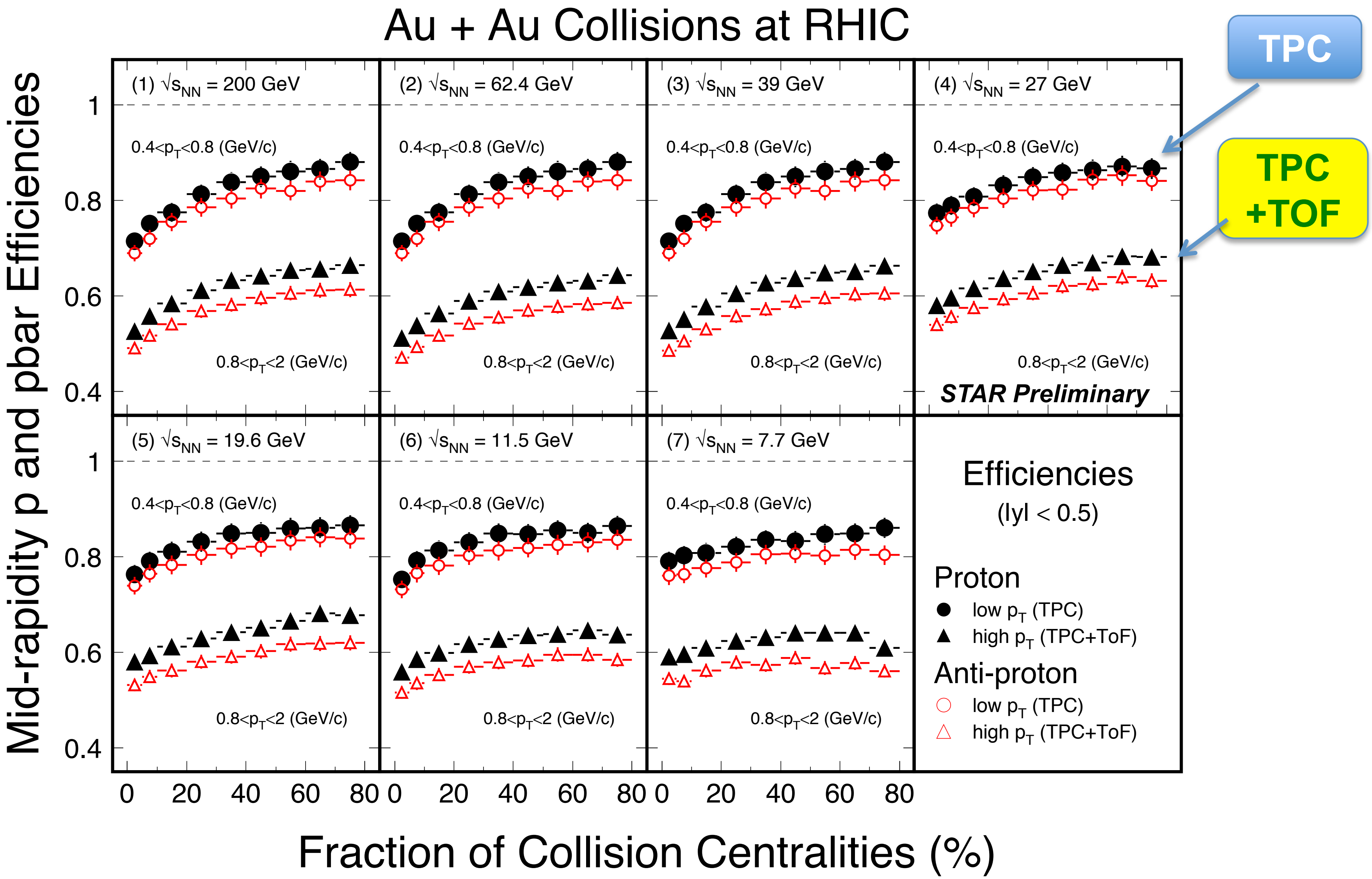
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

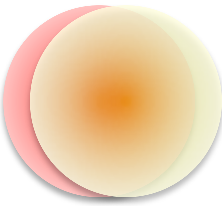
TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): $\varepsilon_{TPC} \sim 0.8$

TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): $\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$

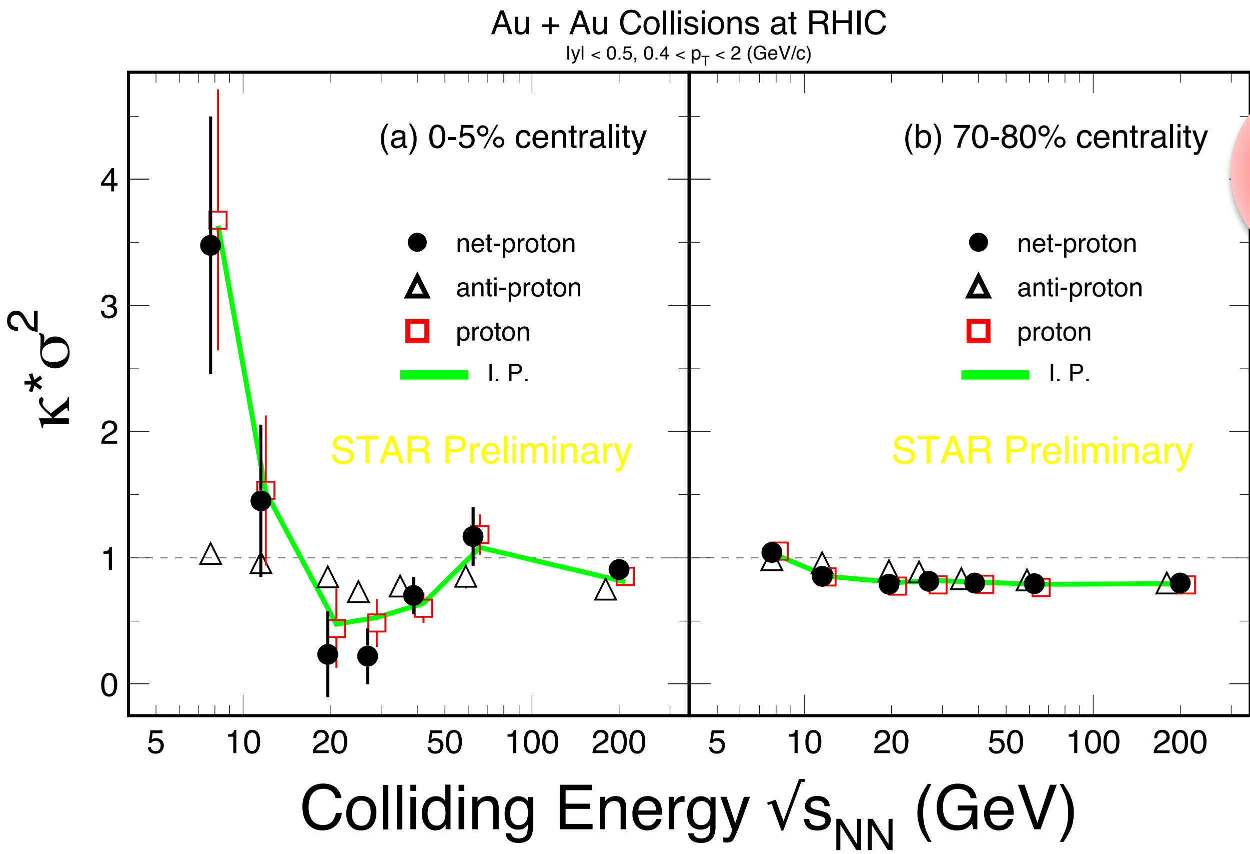
Efficiencies for (anti-)Protons

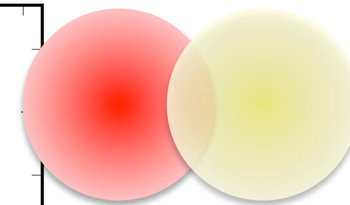


Net-proton Higher Moment



central





peripheral

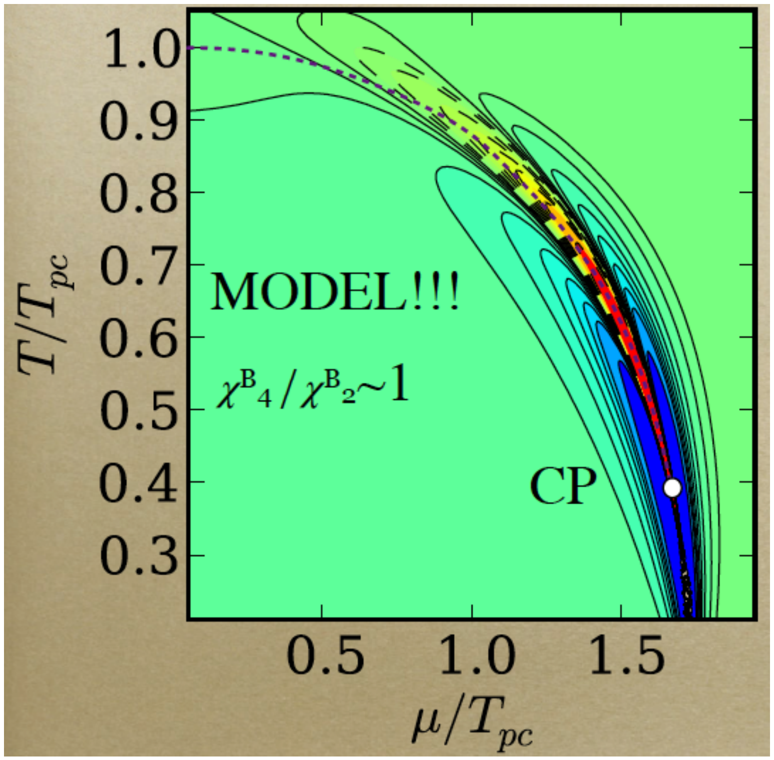
Net-proton results: All data show deviations below Poisson for $\kappa\sigma^2$ at all energies. Larger deviation at $\sqrt{s_{NN}}$ ~ 20 GeV.

Non-monotonic behavior in central collision! *X.F. Luo, CPOD2014*

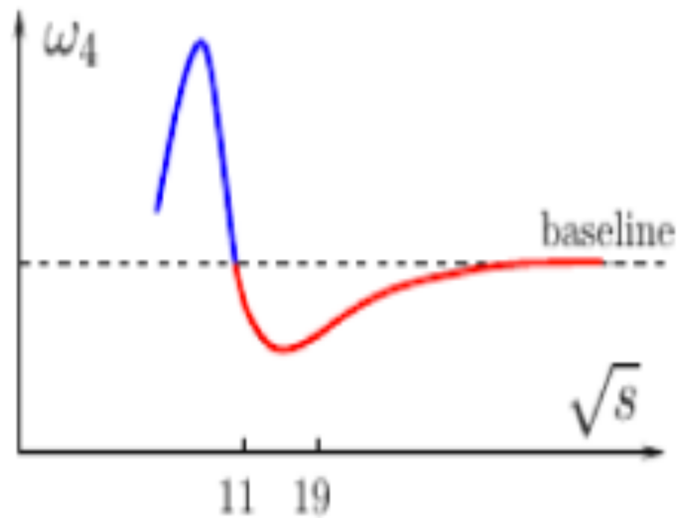
Question: What will happen at even lower collision energy?

Expectation from Calculations

V. Skokov, Quark Matter 2012



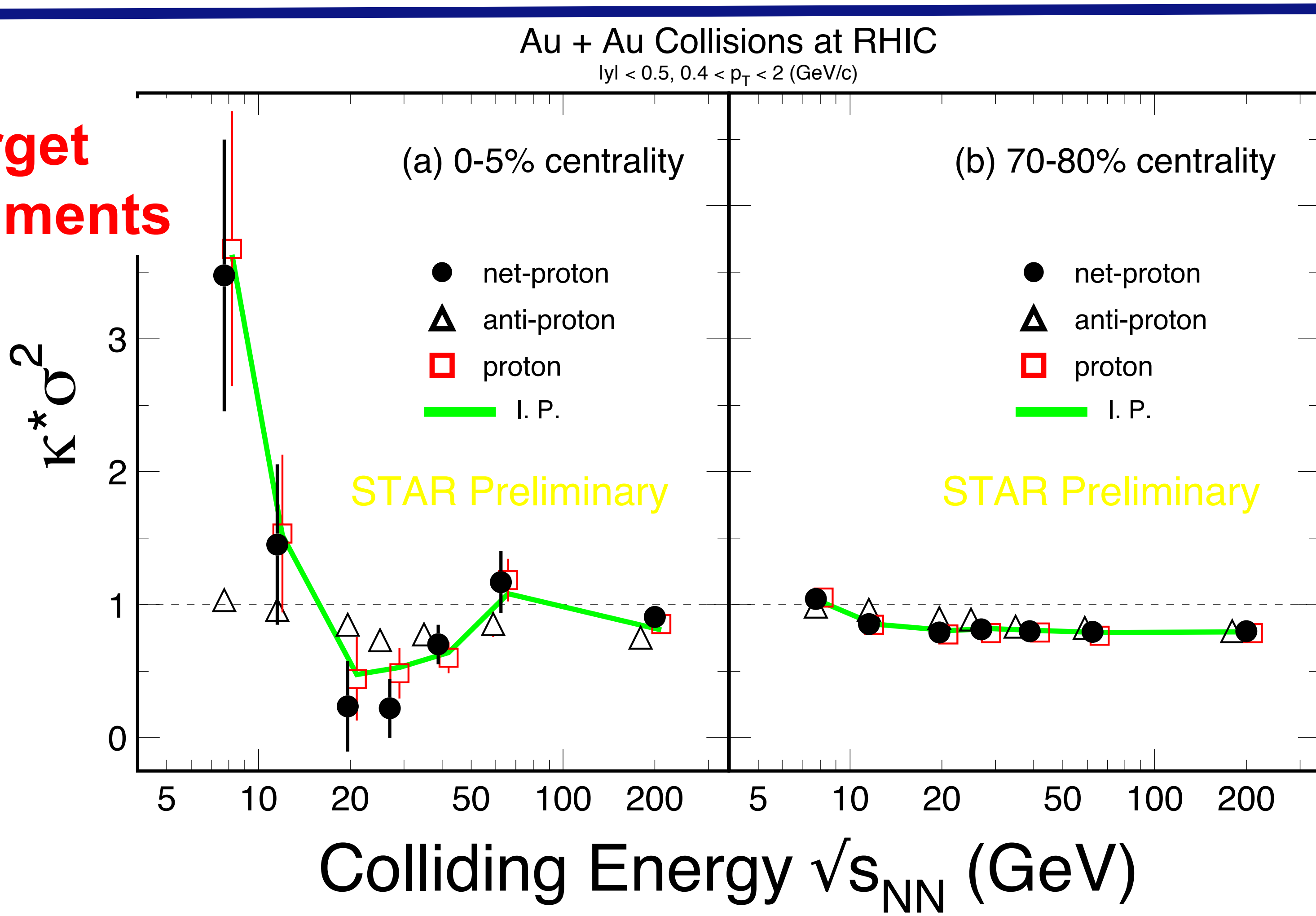
M. Stephanov, ***PRL107***, 052301(2011)



"Oscillating pattern" around the reference is expected.

Net-proton Higher Moment

Fix-target Experiments



Question: What will happen at even lower collision energy?

Summary II

RHIC BES-I preliminary results show properties of matter changes around $\sqrt{s_{NN}}$ = 20 GeV *i.e.* μ_B ~ 250 MeV: non-monotonic energy dependence in net-proton high moments =>

Hint of QCD criticality!

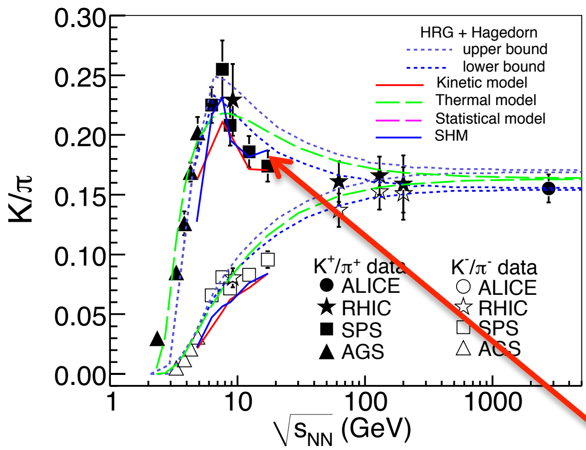
Need high statistics data at $\sqrt{s_{NN}} \leq$ 20 GeV!

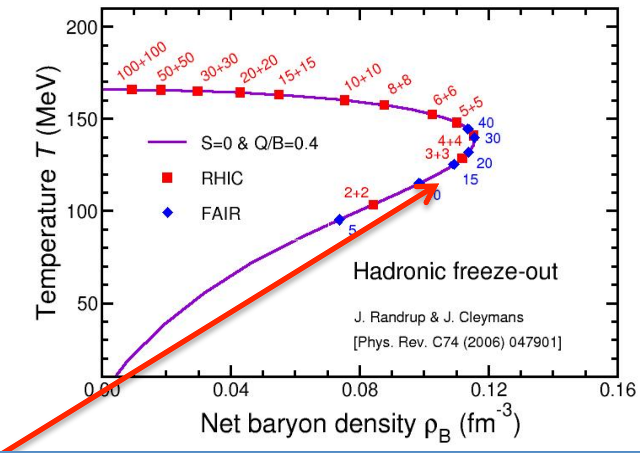
Outlook

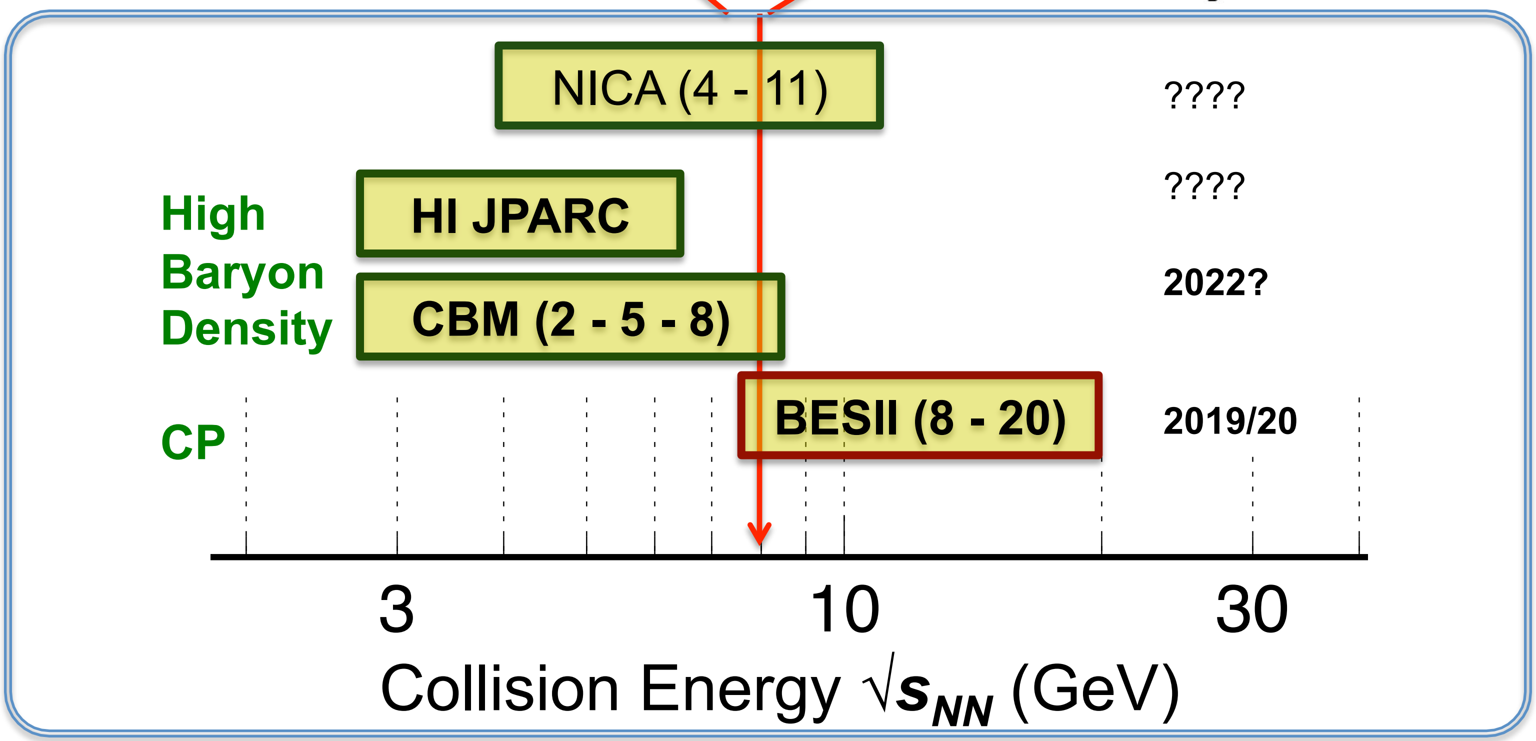
More see talk by B. Jacak

Baryon Density Peaks at $\sqrt{s_{NN}}$ ~ 8GeV

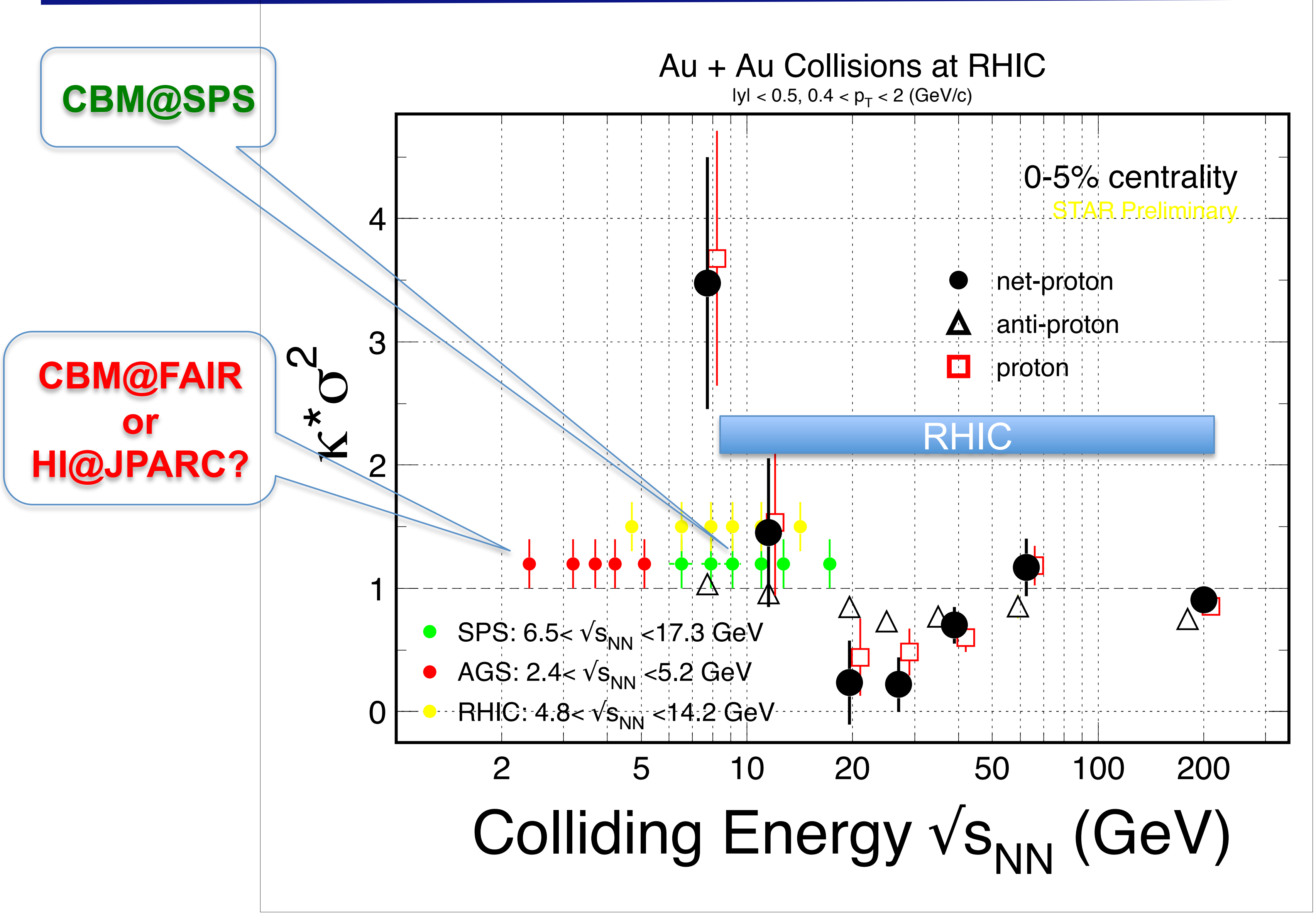
L. Kumar *et al.*
1304.2969



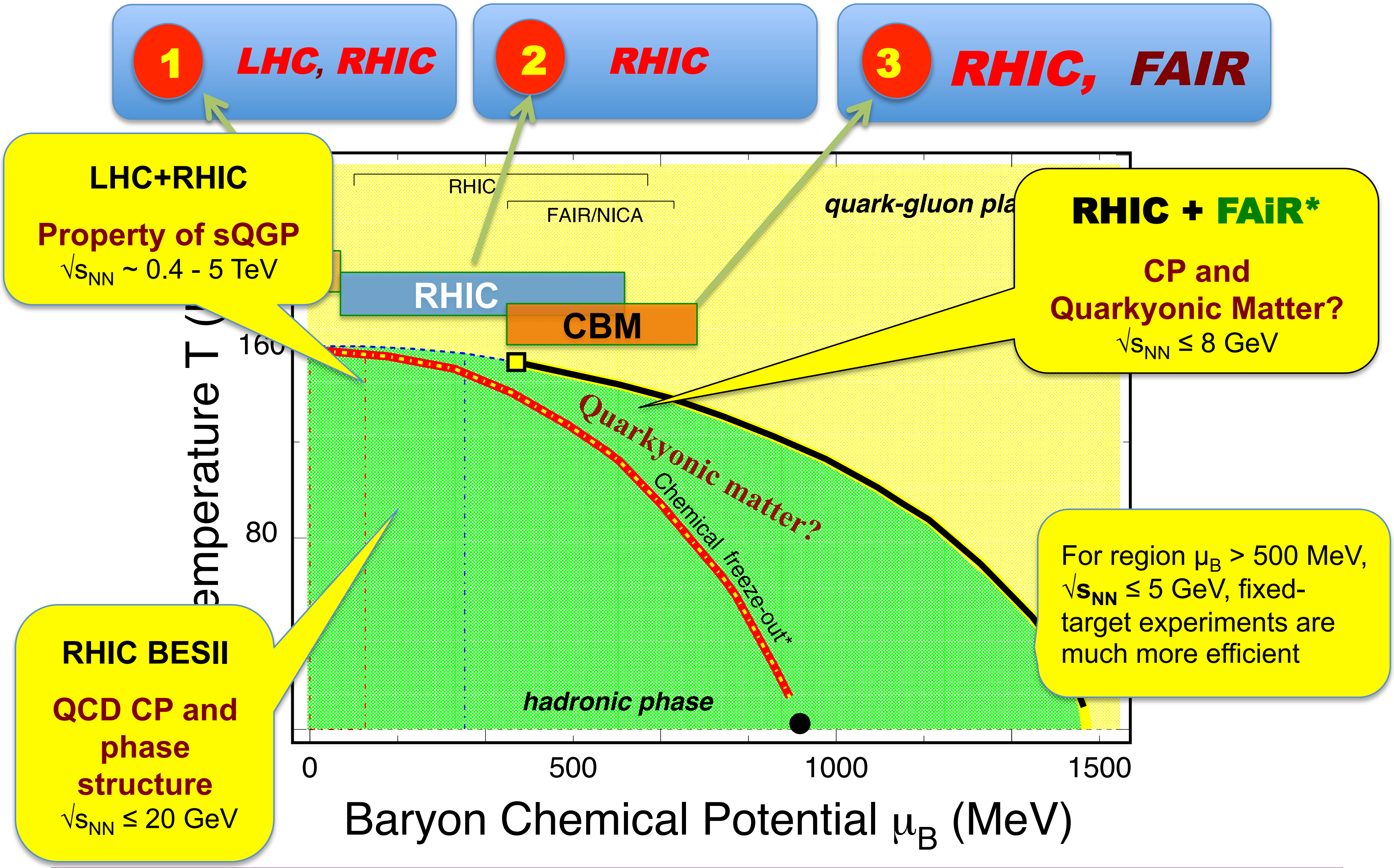




Fix-Target Experiments for Critical Point



Exploring QCD Phase Structure



Summary

1) At high energy-nuclear collisions liquid-like quark-gluon plasma formed, η/s small

2) Current experiments cover $0 < \mu_B < 420$ MeV. Fix-target experiments will extend to much higher baryon region

3) RHIC BES-I results show properties of matter changes around $\sqrt{s_{NN}}$ = 20 GeV. ***Hint of QCD criticality***

4) Need high statistics data at **$\sqrt{s_{NN}} \leq$ 20 GeV: RHIC BES-II** and fix-target experiments at **$\sqrt{s_{NN}} \leq$ 8 GeV**!

2000 – 2015: QGP at $\mu_B \sim 0$ discovered
2015 – : 1st order phase boundary
QCD Critical Point at large μ_B

Thank you!

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