The QCD Medium Properties at Finite Baryon Density

- Search for the QCD Critical Point in HIC

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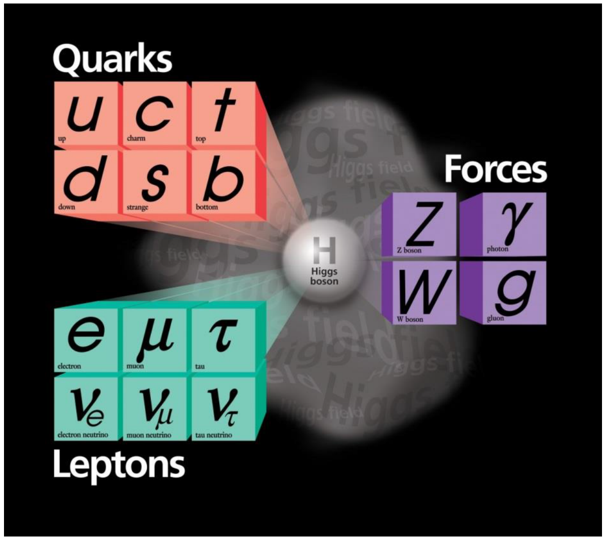
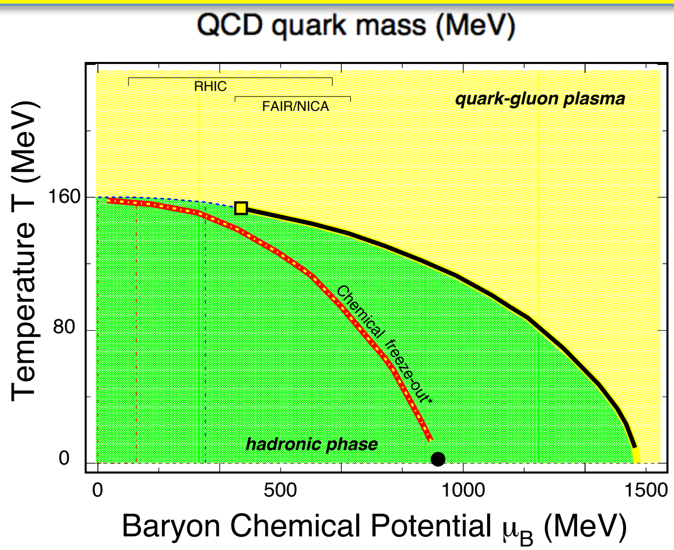
QCD in the Twenty-First Century



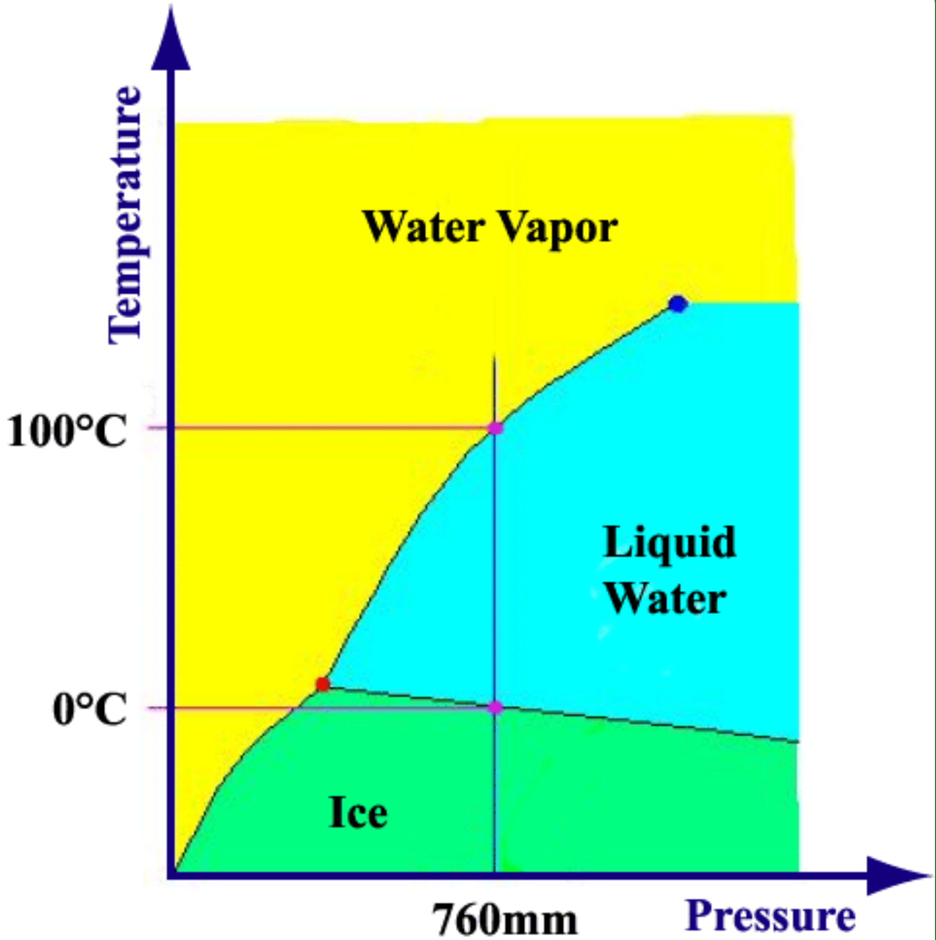
Emergent properties with QCD degrees of freedom!

(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



Phase Diagram



Phase diagram:

A ***map*** shows, at given degrees of freedom, how does matter organize itself under external conditions. New orders, regularities, properties, … emerge.

Water: H_2O

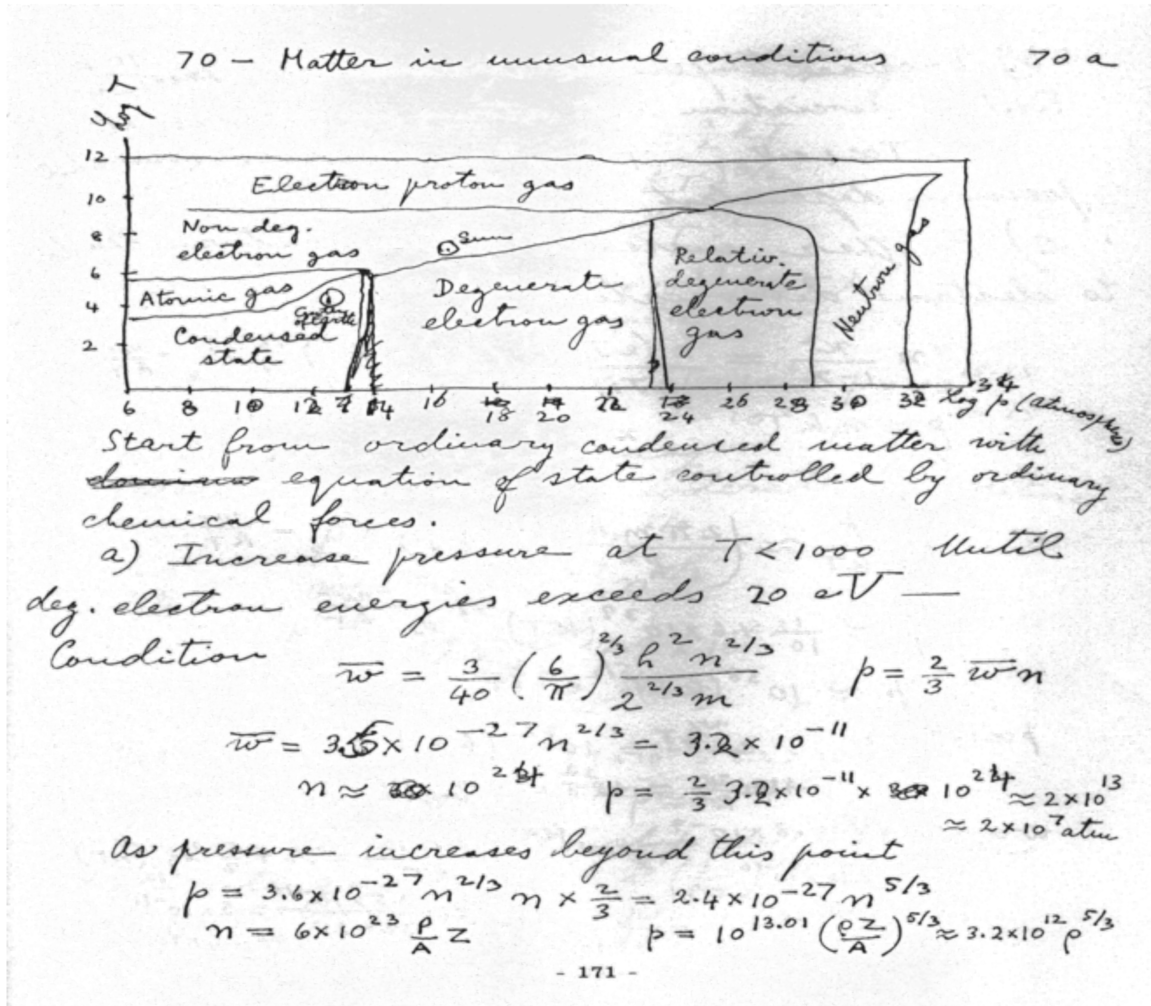
QCD Phase Diagram:

Structure of matter with color degrees of freedom, *quarks* and *gluons*.

QCD Phase Diagram (1953)

E. Fermi

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



70 — Matter in unusual conditions 70 a

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

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

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

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

$n \approx 3 \times 10^{24}$ $\quad p = \frac{2}{3} 3.2 \times 10^{-11} \times 3 \times 10^{24} \approx 2 \times 10^{13}$
$\approx 2 \times 10^{7}$ atm

As pressure increases beyond this point

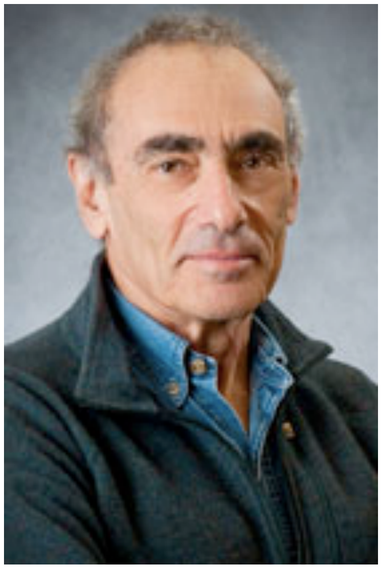
$p = 3.6 \times 10^{-27} n^{2/3} n \times \frac{2}{3} = 2.4 \times 10^{-27} n^{5/3}$

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

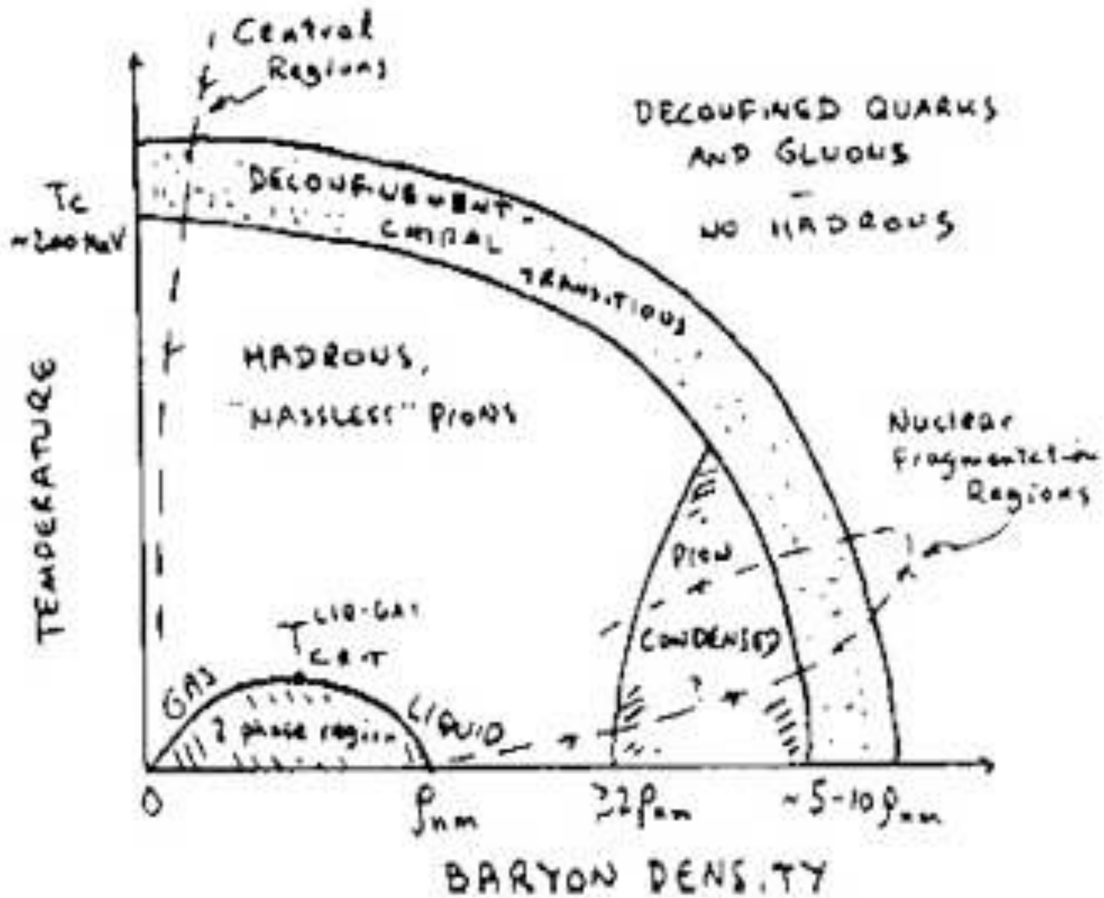
- 171 -

QCD Phase Diagram (1983)

1983 US Long Range Plan *- by Gordon Baym*

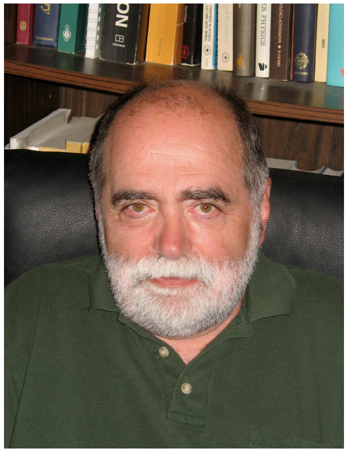


Gordon Baym

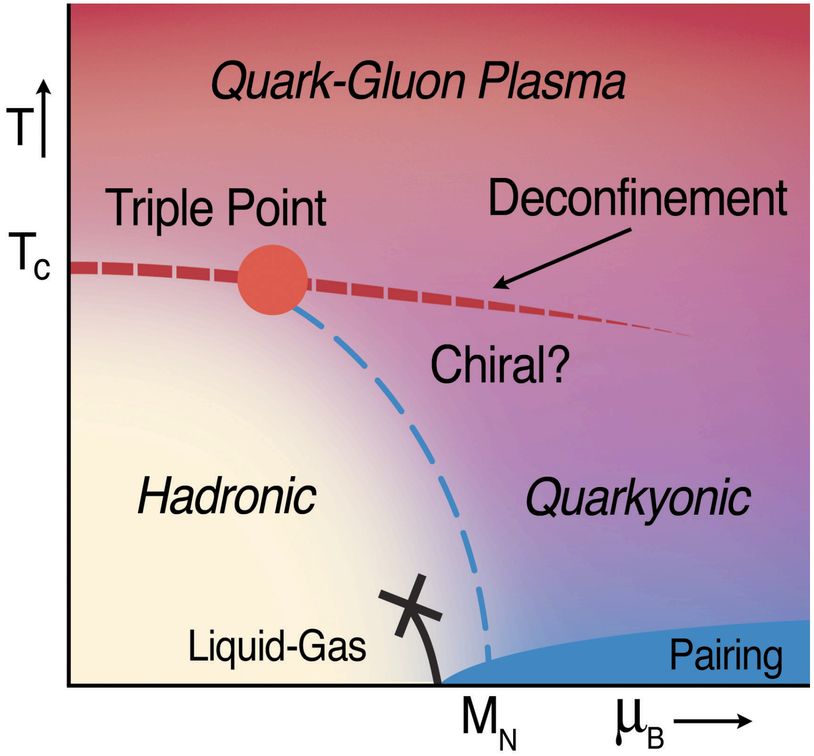


QCD Phase Diagram (2009)

PBM



Larry McLerran

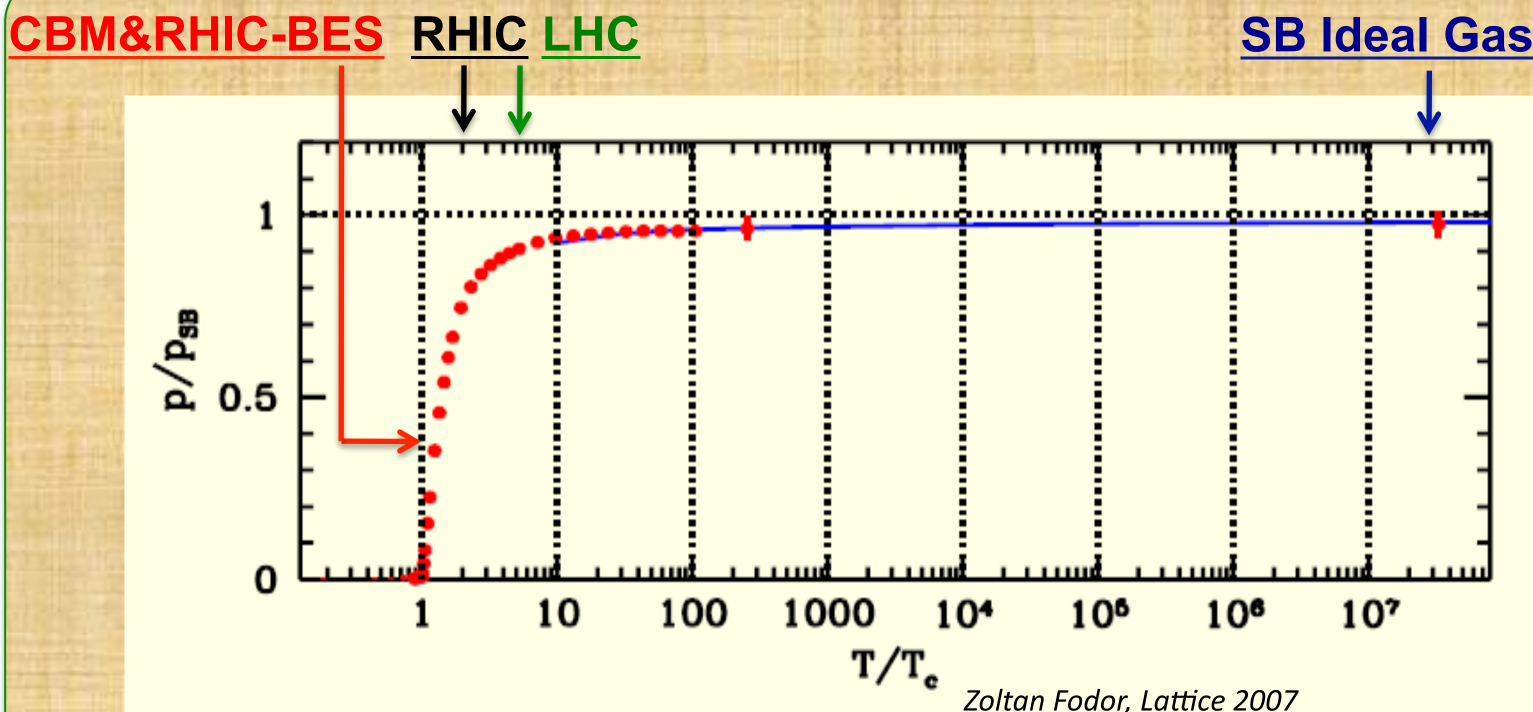


nucl-th: 0907.4489, NPA830,709(09) *L. McLerran*
nucl-th 0911.4806: *A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, and J. Stachel*

Experiments: Systematic measurements (E_{beam}, A_{size}) :

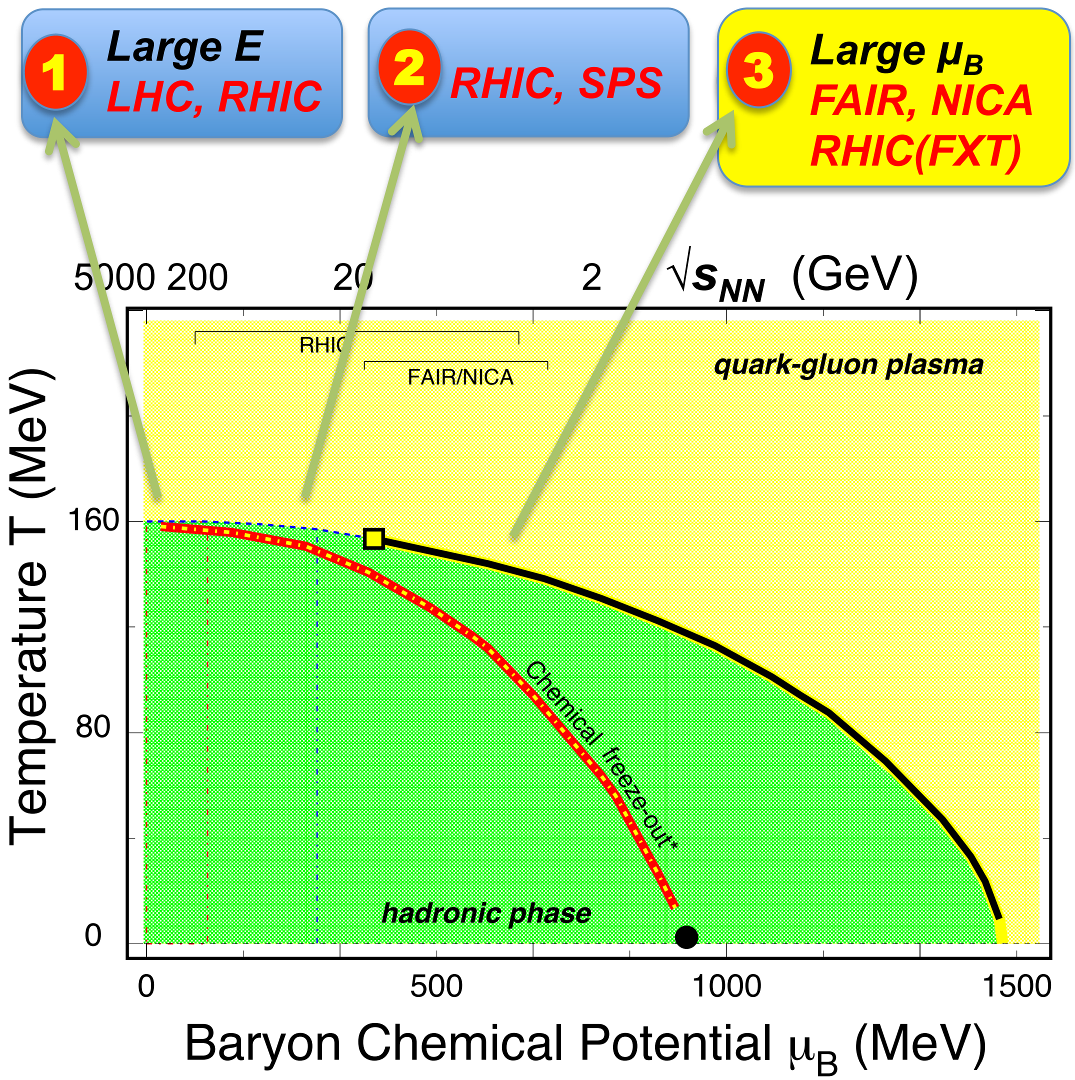
to extract **numbers** that are related to the ***phase diagram***!

QCD Thermodynamics



1) At $\mu_B = 0$: *smooth* crossover 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) , RHIC and LHC are similar
4) Dynamic changes at finite μ_B: BES@RHIC and CBM + …

The QCD Phase Diagram and the Beam Energy Scan



2000 – 2010 (2012):

Top energy programs

Discovery of sQGP

2010 – 2014:

BES-I: 7.7, 11.5, 14.5, 19.6, 27, 39 GeV

- QCD **Critical Point**
- Chiral effects

2019 – 2020:

BES-II: 7.7, 11.5, 14.5, 19.6 GeV

FXT*: 4.5, 3.9, 3.6, 3.0 GeV

2022 – 2025:

BES-III:

Fixed-target program

Outline

(1) Introduction

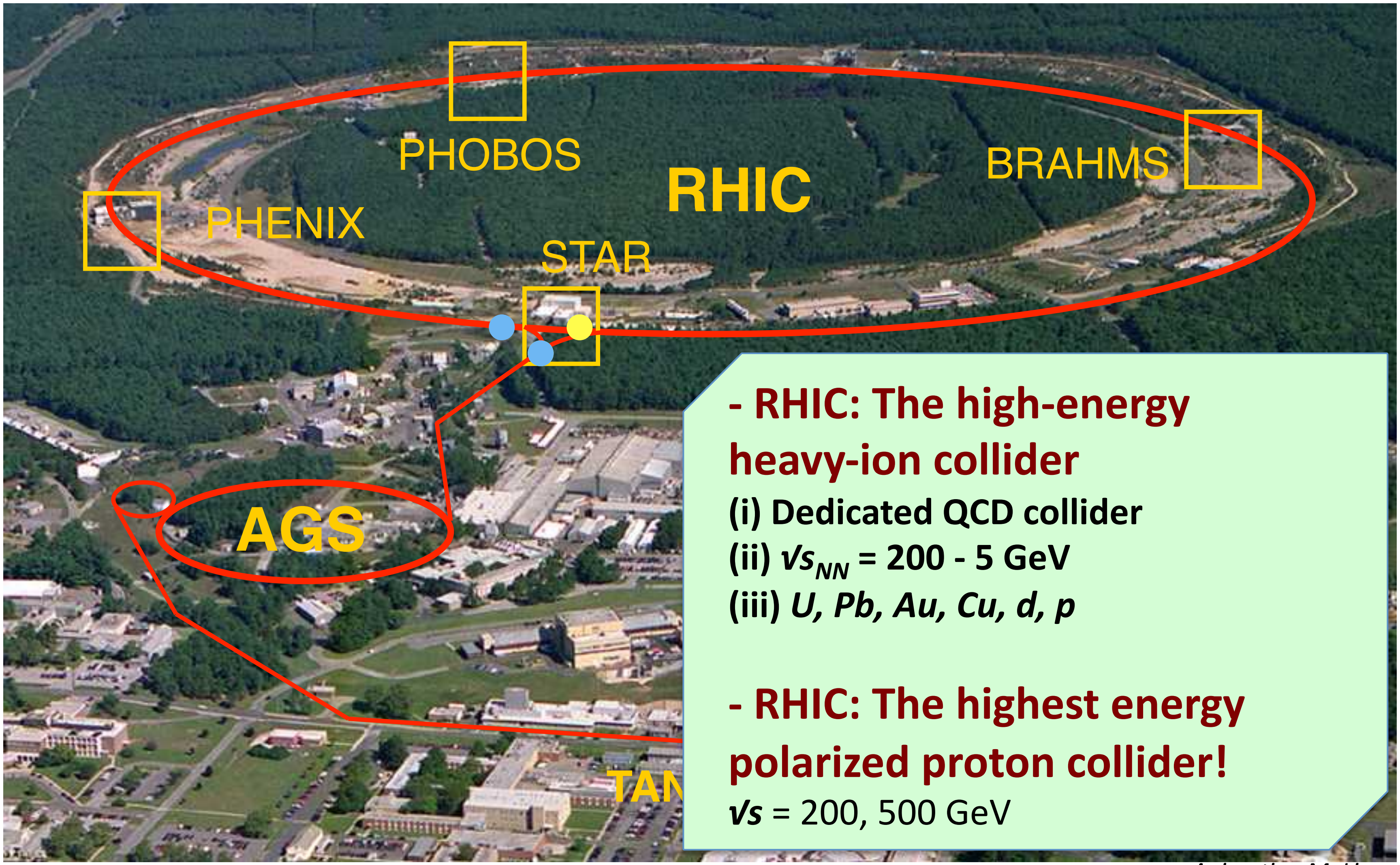
(2) Recent Results from BES-I at RHIC

(i) Collectivity; (ii) Chirality; **(iii) Criticality**

(3) Summary and Outlook

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*

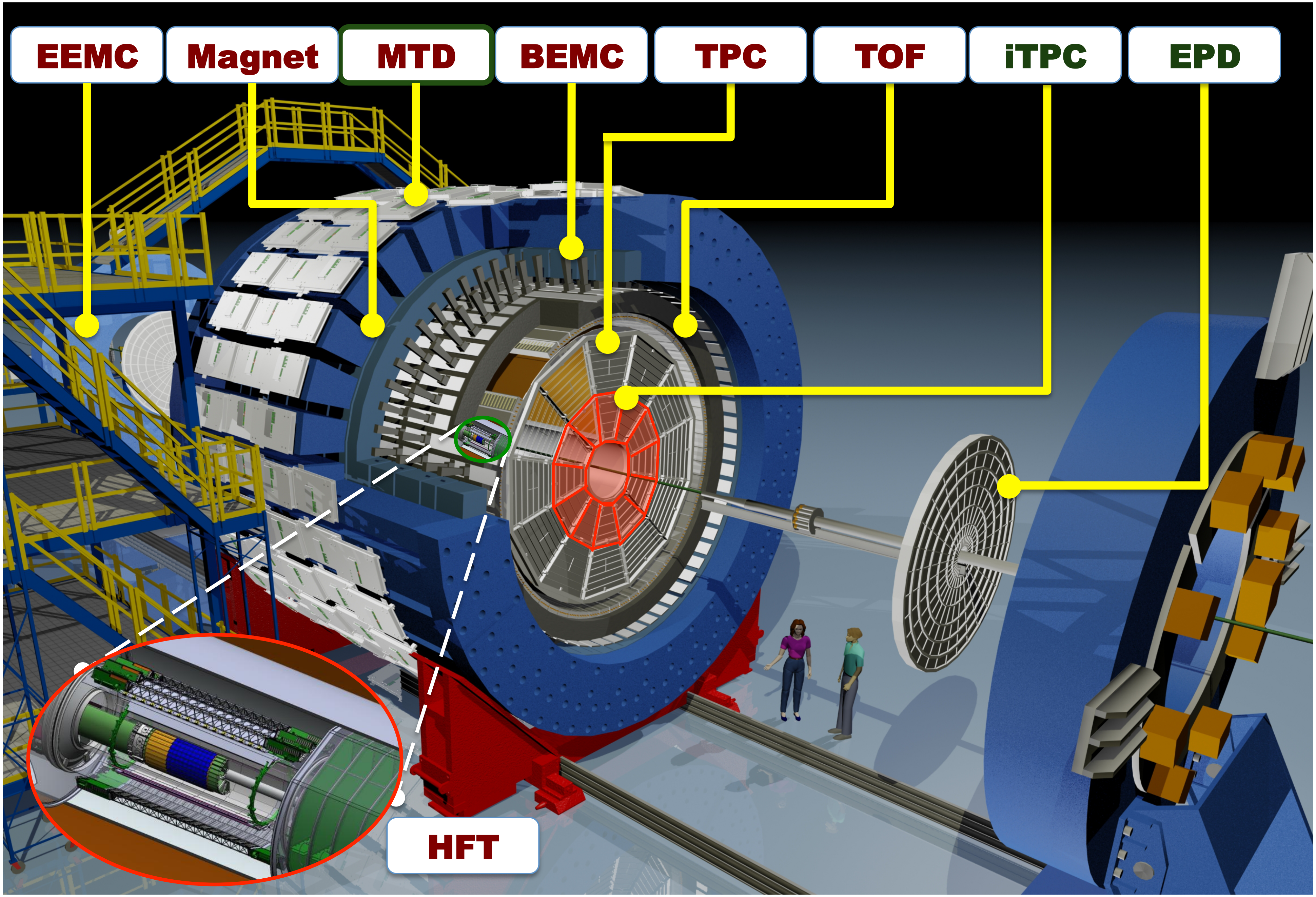
- RHIC: The highest energy polarized proton collider!

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

Animation M. Lisa

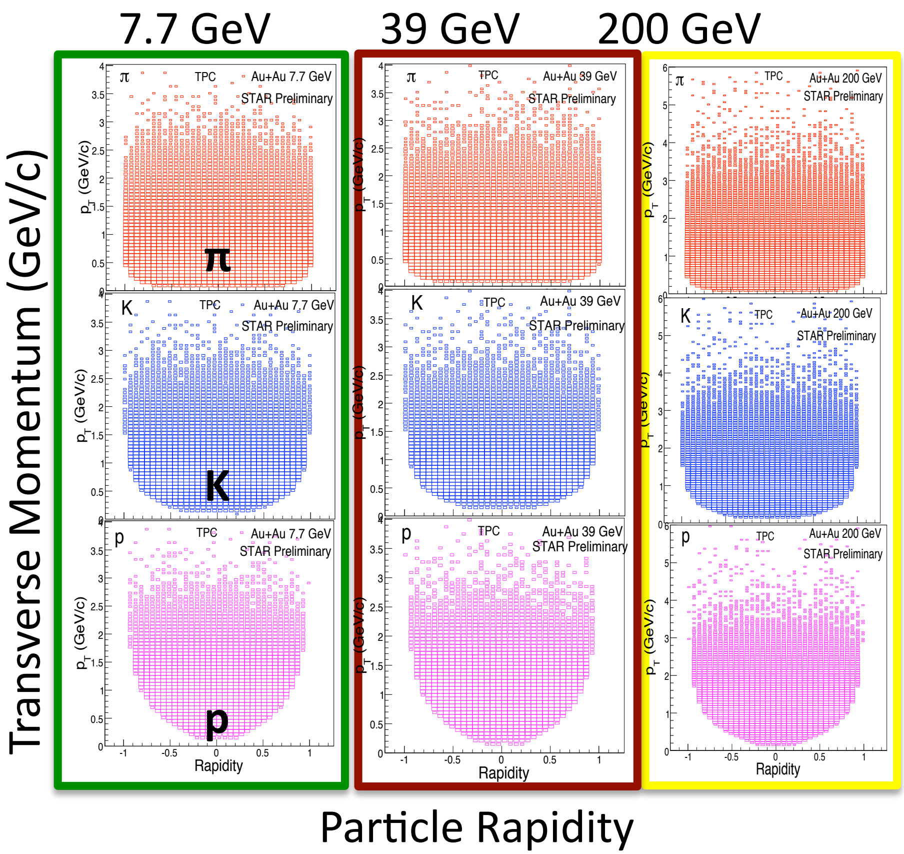
STAR Collaboration

STAR Detector System



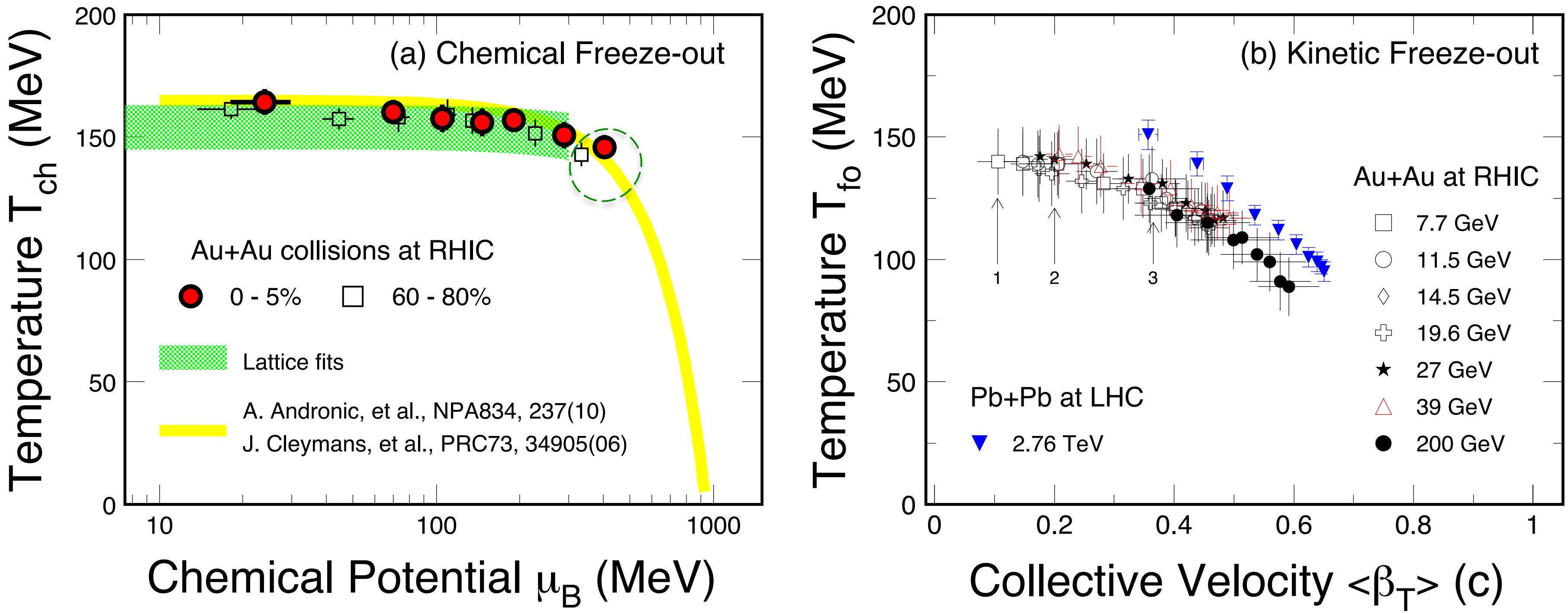
Data Sets for BES-I Program

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010



1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Especially important for fluctuation analysis

Bulk Properties at Freeze-outs



Chemical Freeze-out: (GCE)

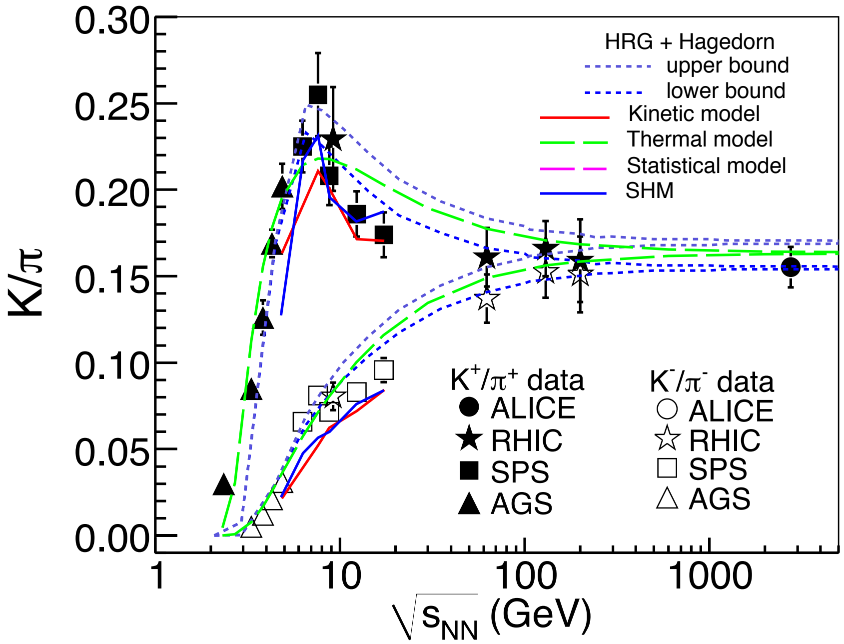
- Weak temperature dependence
- Centrality dependence μ_B!
- LGT calculations indicate Critical region above μ_B **~ 300 MeV?**

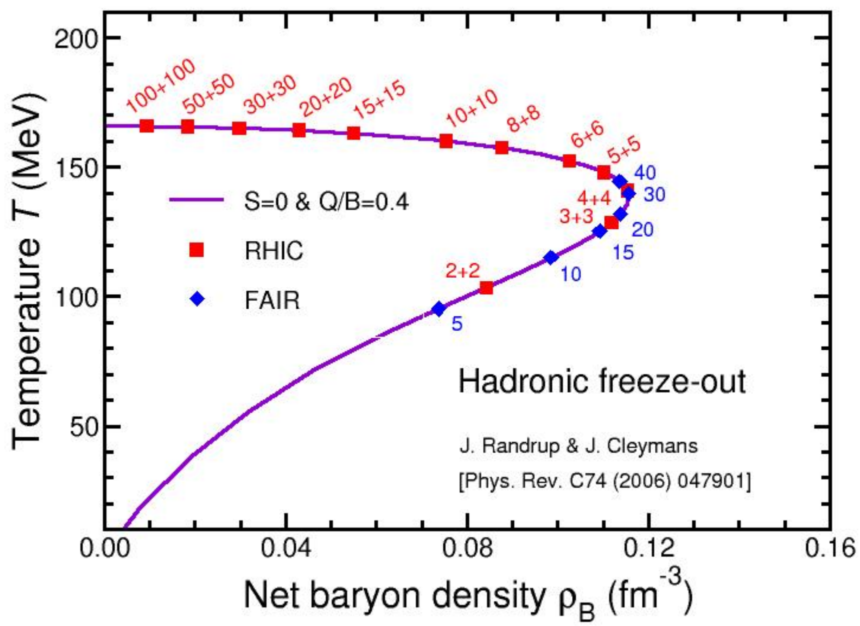
Kinetic Freeze-out:

- Central collisions => lower value of T_{fo} and larger collectivity β_T
- **Stronger collectivity at higher energy, even for peripheral collisions**

- ALICE: B.Abelev et al., PRL109, 252301(12); PRC88, 044910(2013).
- STAR: J. Adams, et al., NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)
- S. Mukherjee: Private communications. August, 2012

K/π Ratios and Baryon Density





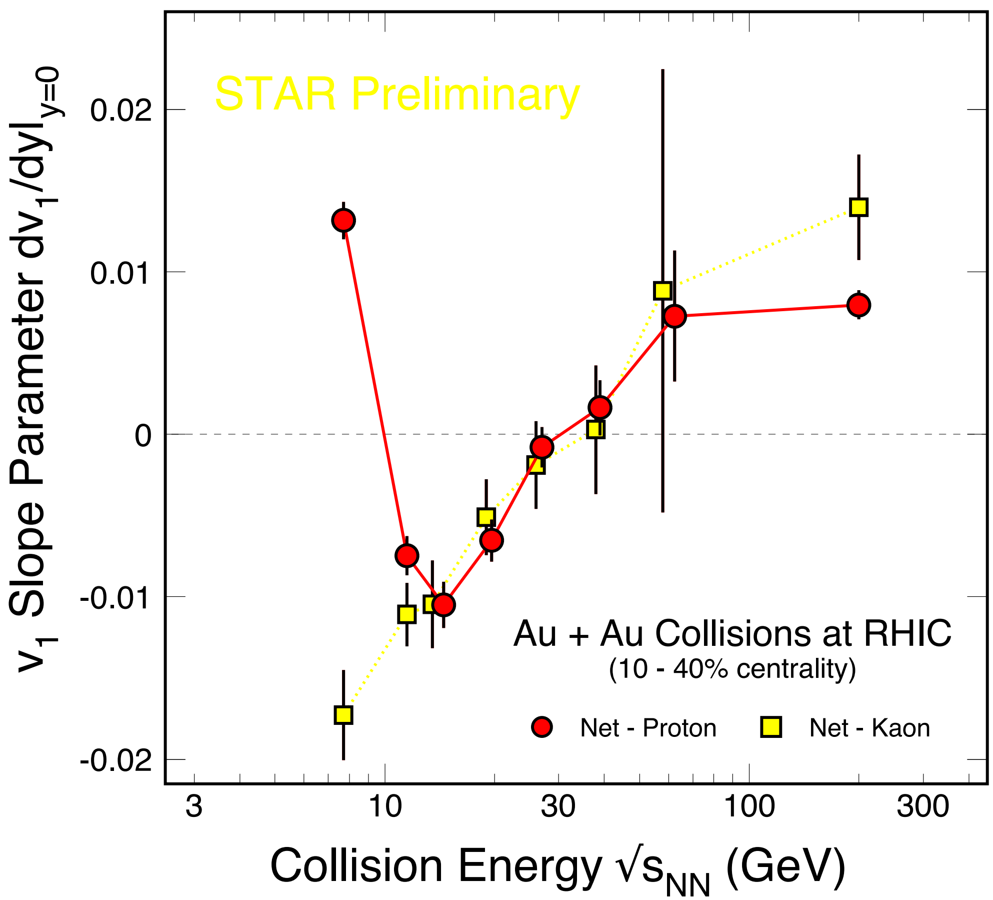
1) In heavy ion collisions **K^+/π** ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV, **K^-/π** ratio merges with **K^+/π** at higher collision energy
2) Model: Baryon density peaks at $\sqrt{s_{NN}}$ ~ 8 GeV
3) **At $\sqrt{s_{NN}}$ > 8 GeV, pair production becomes important**

L. Kumar, *et al.*1304.2969; J. Randrup and J. Cleymans, Phys. Rev. **C74**, 047901(2006)

Collectivity

$$\partial_\mu [(\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu}] = 0$$
$$\partial_\mu [s\, u^\mu] = 0$$

v_1 vs. Energy: Softest Point?

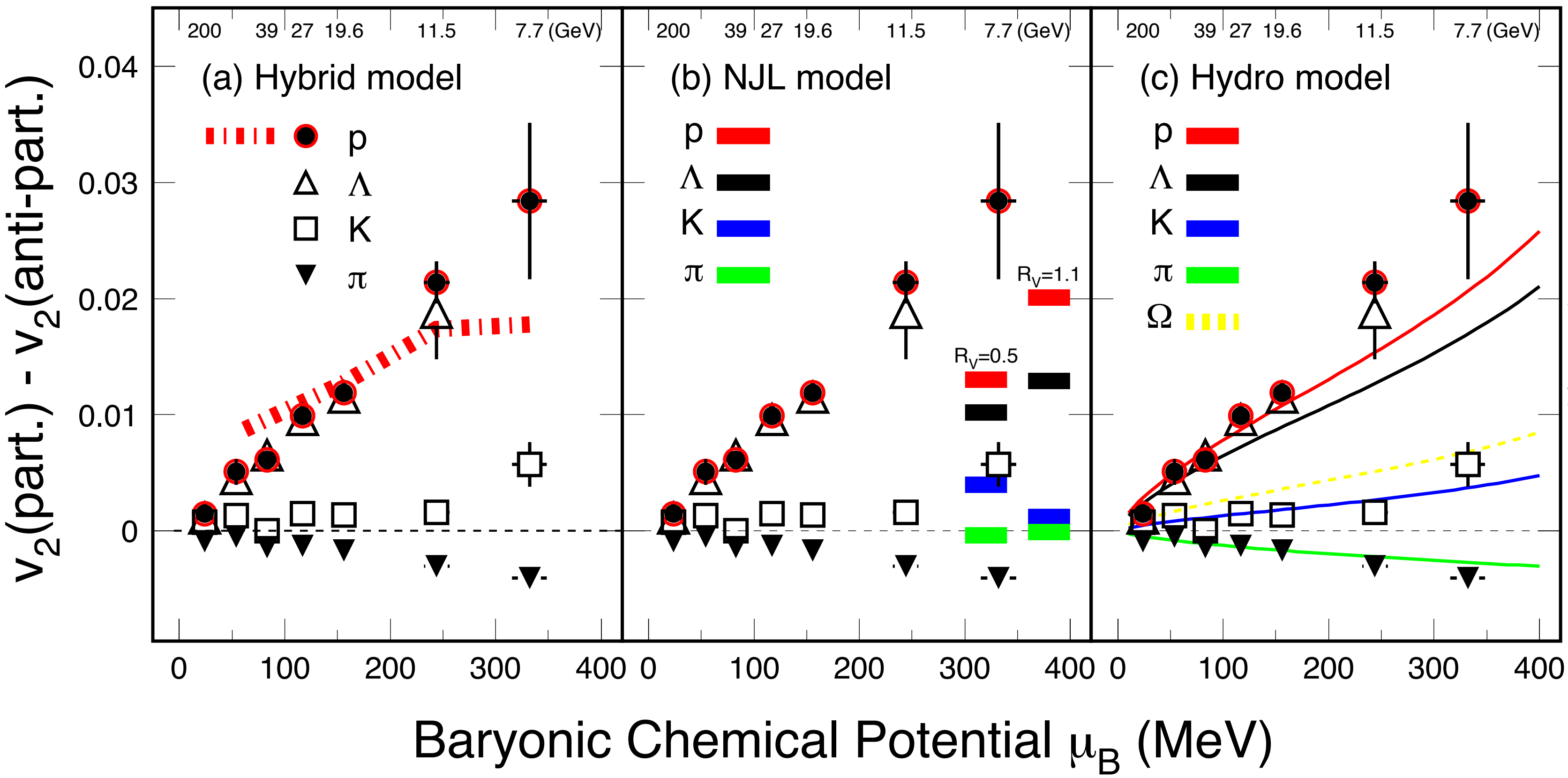


1) Mid-rapidity net-proton dv_1/dy published in 2014 by STAR, except the point at 14.5 GeV
2) Minimum at $\sqrt{s_{NN}}$ = 14.5 GeV for net-proton, but net-Kaon data continue decreasing as energy decreases
3) At low energy, or in the region where the net-baryon density is large, repulsive force is expected, v_1 slope is large and positive!
4) Softest point for baryons?

- M. Isse, A. Ohnishi et al, PR **C72**, 064908(05)
- Y. Nara, A. Ohnishi, H. Stoecker, arXiv: **1601.07692**

● STAR: PRL**112**, 162301(2014)
■ STAR: QM2015

BES v_2 and Model Comparison

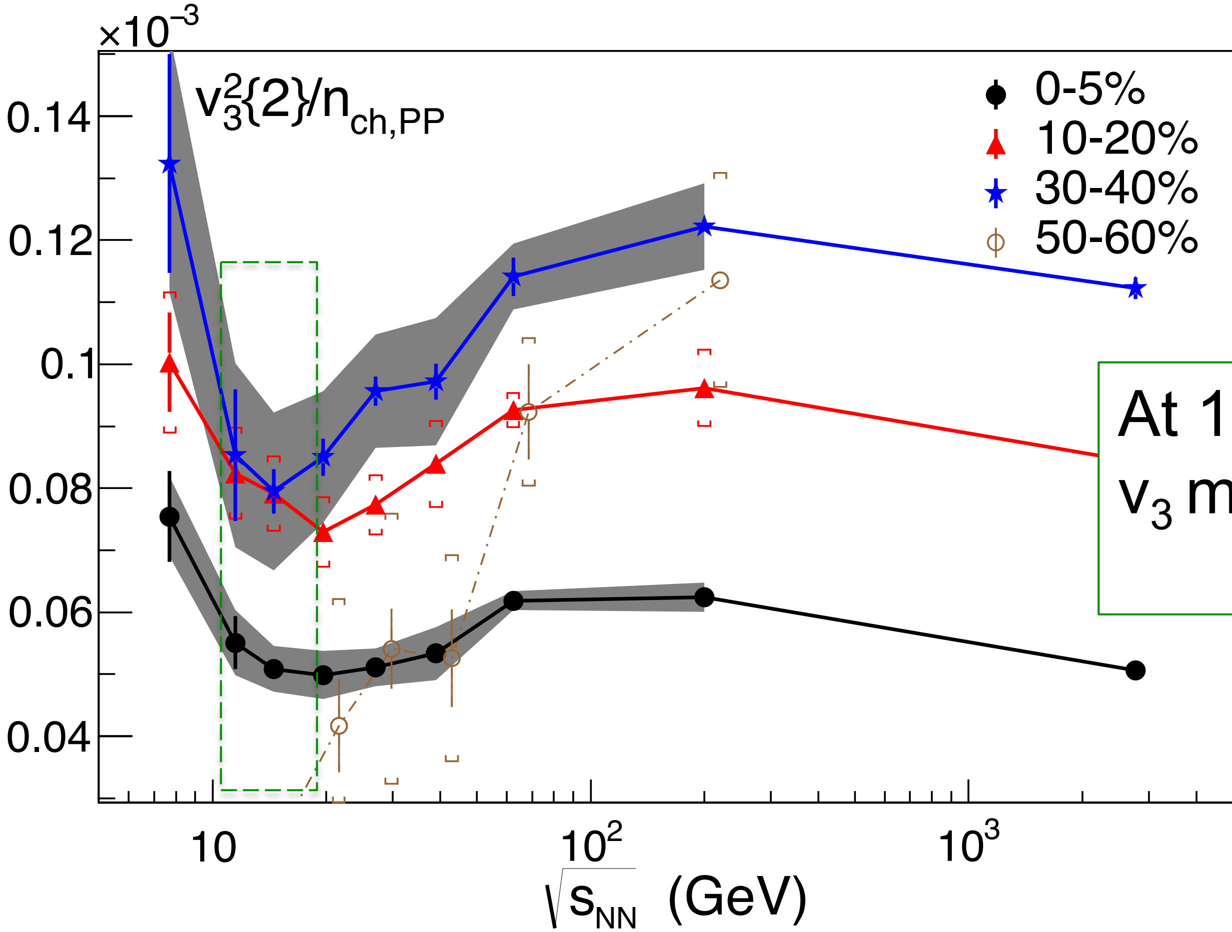


(a) Hydro + Transport: Baryon results fit [J. Steinheimer, et al. PR **C86**, 44902(13)]

(b) NJL model: Sensitive to vector-coupling, **CME, μ_B** driven.
[J. Xu, et al., PRL**112**.012301(14)]

(c) Hydro solution: **Chemical potential μ_B** and **viscosity η/s** driven!
[Hatta et al. PR **D91**, 085024(15); **D92**, 114010(15) //NP **A947**, 155(16)]

The v_3 : Energy Dependence



At $10 \le \sqrt{s_{NN}} \le 20$ GeV, v_3 minima developed

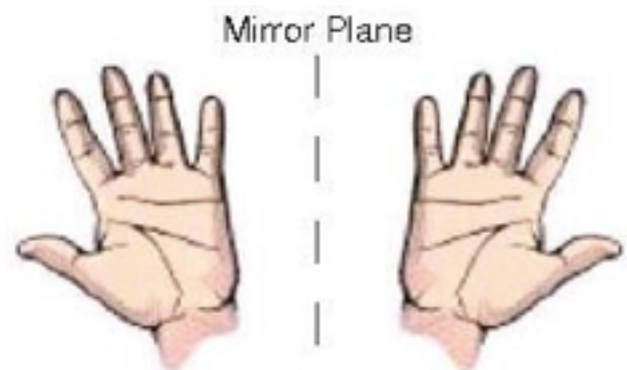
STAR: PRL**116**, 112302(2016)

Collectivity: Implies the properties change at energy below 20 GeV, i.e. partonic => hadronic

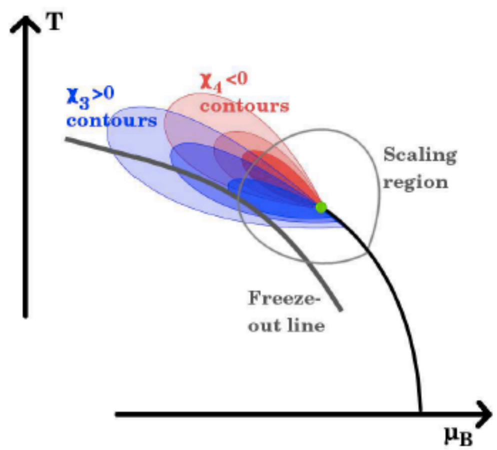
Collectivity: Summary

1) At high energy, strong collectivity and vanishing ratio of η/s => Perfect liquid of the strongly coupled plasma
2) Hadron formation via coalescence at T_C
3) At beam energy $\sqrt{s_{NN}}$ < 20 GeV, net-proton v_1 shows a dip and the break down of the number of quark scaling in v_2

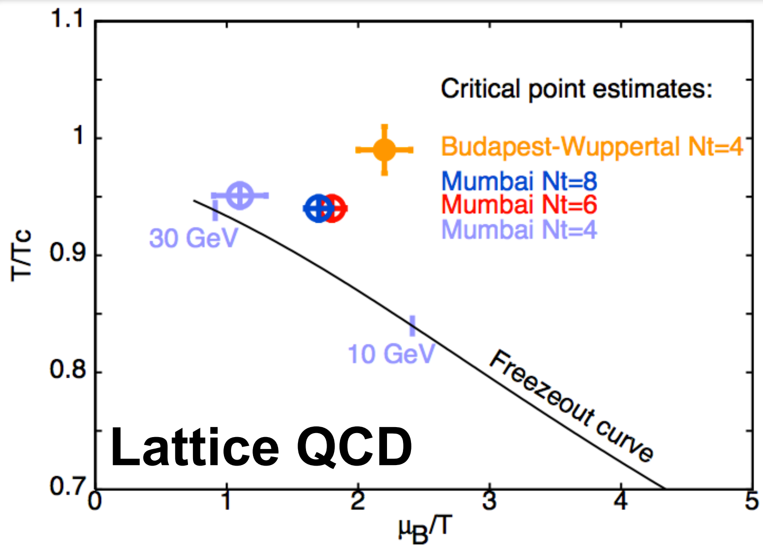
Chirality

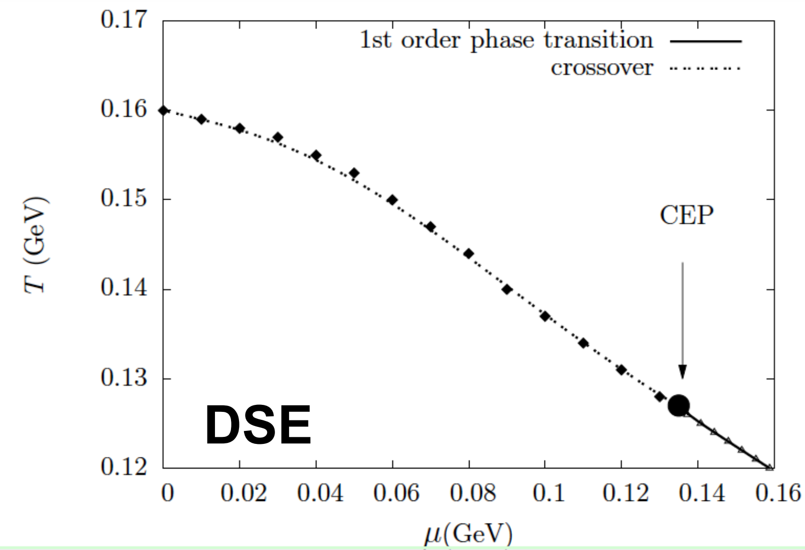


Criticality



Status on Predictions





Lattice QCD:

1): Fodor&Katz, JHEP 0404,050 (2004):
$(\mu^E_B, T_E) = (360, 162)$ MeV (Reweighting)

2): Gavai&Gupta, NPA 904, 883c (2013):
$(\mu^E_B, T_E) = (279, 155)$ MeV (Taylor Exp.)

3): F. Karsch ($\mu^E_B / T_E > 2$, CPOD2016)

DSE:

1): Y. X. Liu, et al., PRD90, 076006(2014):
$(\mu^E_B, T^E) = (372, 129)$ MeV

2): Hong-shi Zong et al., JHEP 07, 014(2014):
$(\mu^E_B, T_E) = (405, 127)$ MeV

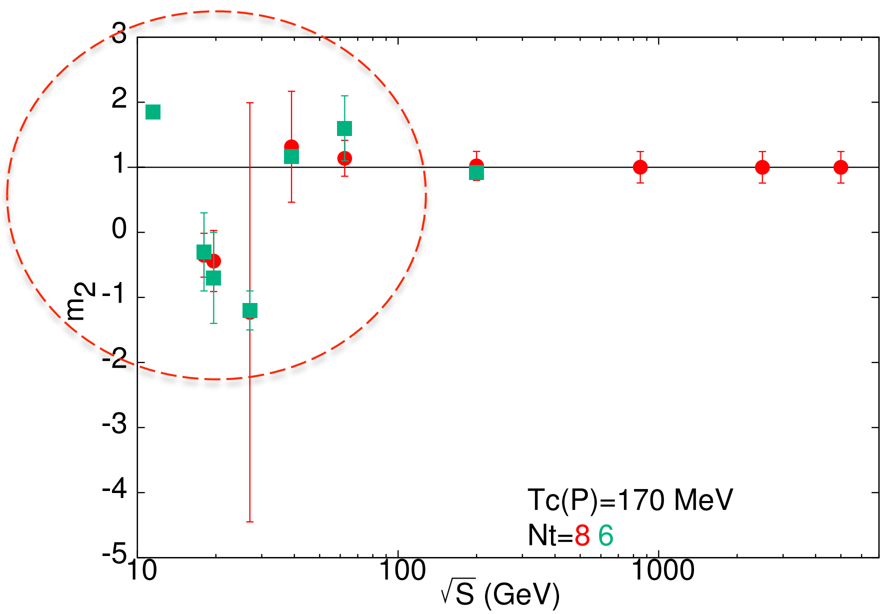
3): C. S. Fischer et al., PRD90, 034022(2014):
$(\mu^E_B, T^E) = (504, 115)$ MeV

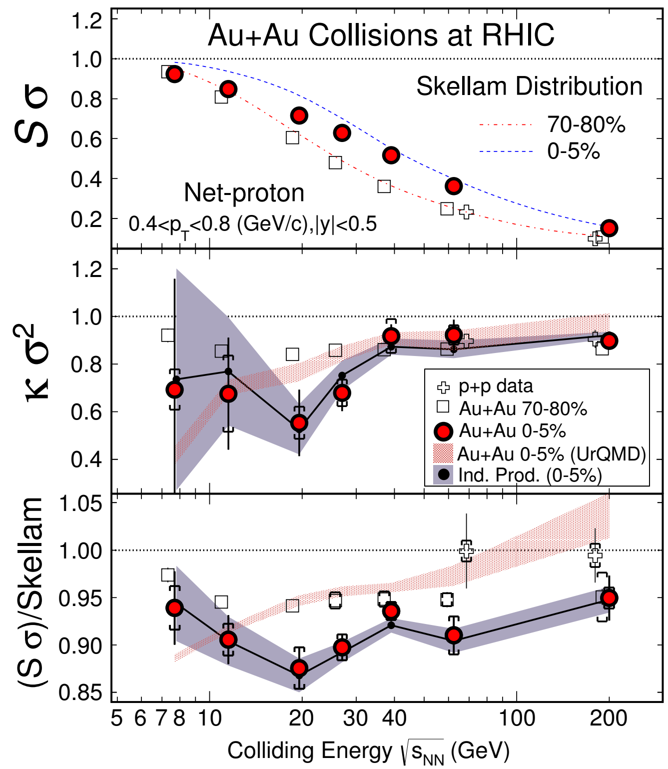
$\mu^E_B = 300 \sim 504$ MeV, $T_E = 115 \sim 162$, $\mu^E_B / T_E = 1.8 \sim 4.38$

Status on Predictions

Critical Point : Lattice & Experiments

♡ Ratios of higher moments of baryon (proton) distributions.



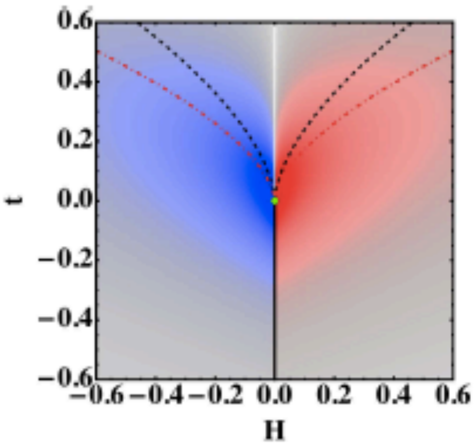


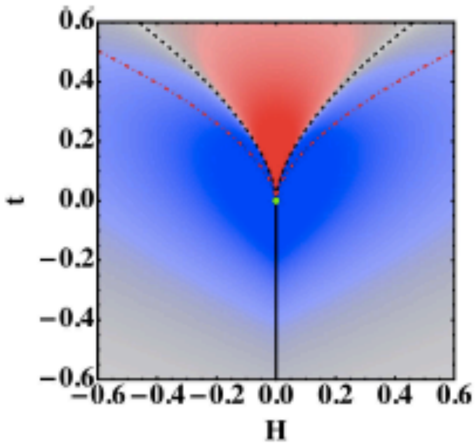
Gavai-Gupta, '10
Datta-Gavai-Gupta, Lattice 2013

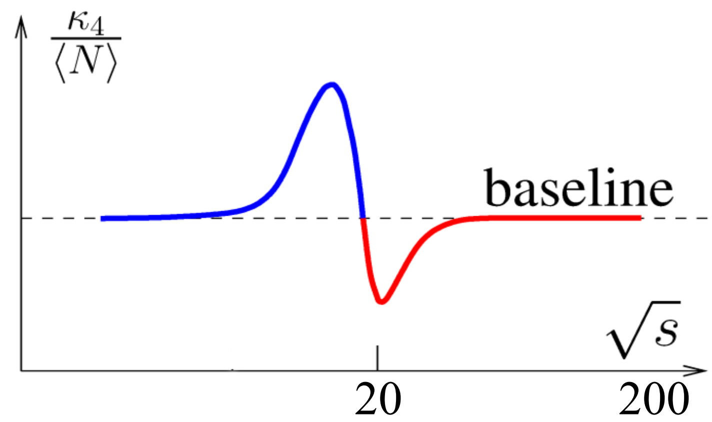
L. Adamczyk *et al.*
STAR Collaboration PRL (2014)

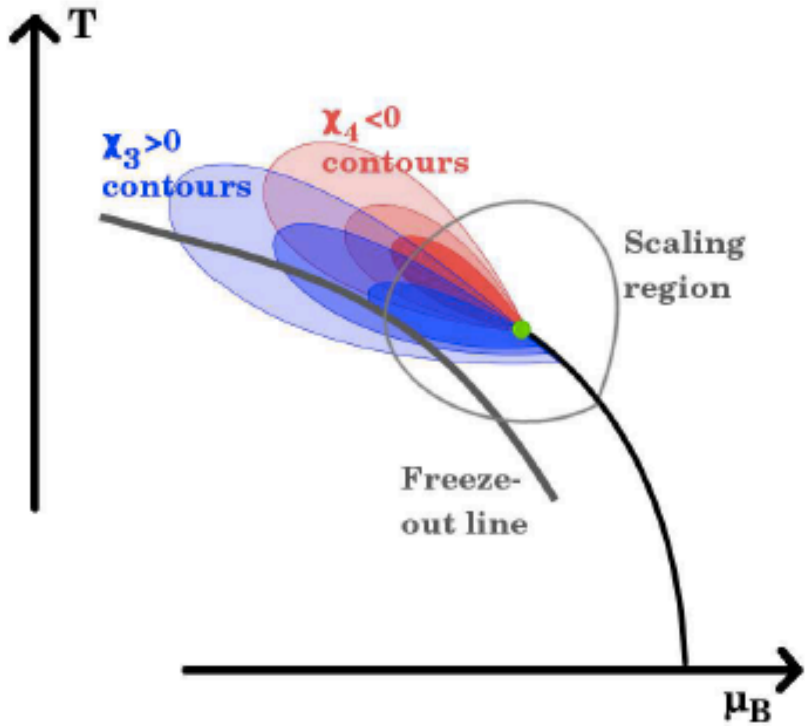
$$\mathcal{S}\sigma \equiv m_1 \text{ and } \kappa\sigma^2 \equiv m_2.$$

Expectation from Model Calculations









- Characteristic “Oscillating pattern” is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*
- Critical Region (CR)

- M. Stephanov, ***PRL107***, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, arXiv: 1603.05198, Phys. Rev. **D93** (2016) 034037

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

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

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

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

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

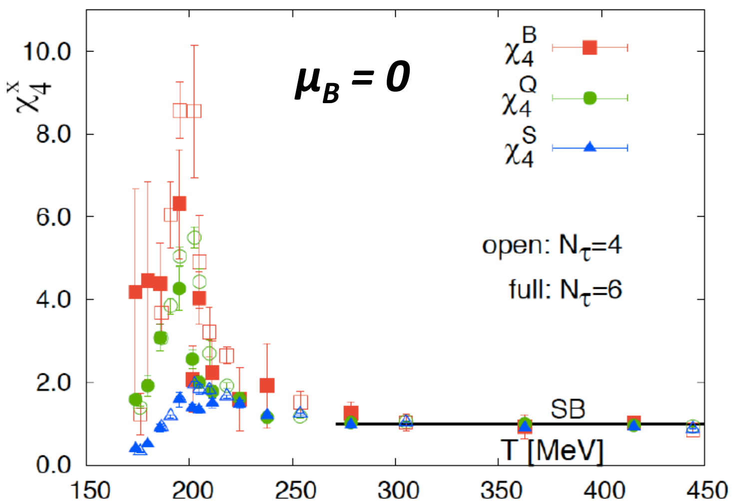
$$\frac{T^2 \chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2$$

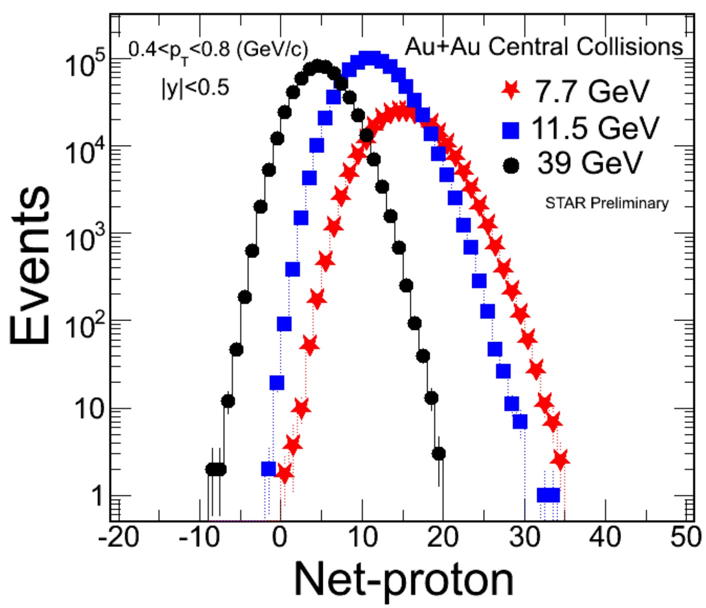
$$\frac{T\, \chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma$$

Thermodynamic function ⇔ Susceptibility ⇔ Moments

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

Higher Moments and Criticality





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:

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

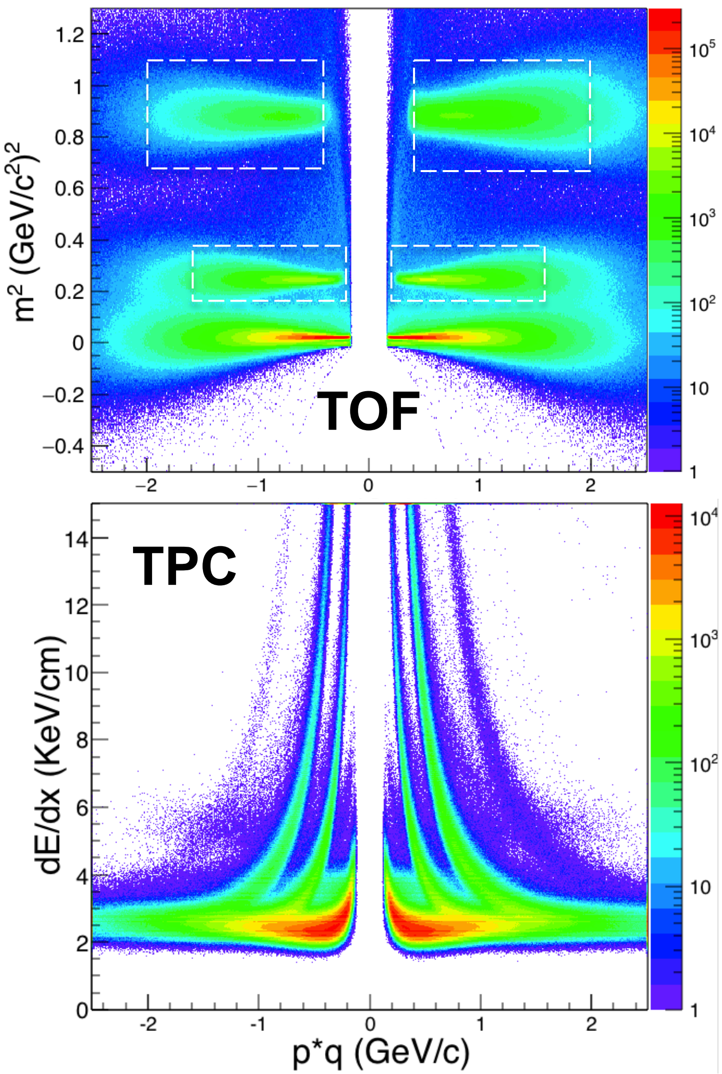
4) **Extract susceptibilities and freeze-out temperature**. An independent/important test of thermal equilibrium in heavy ion collisions.

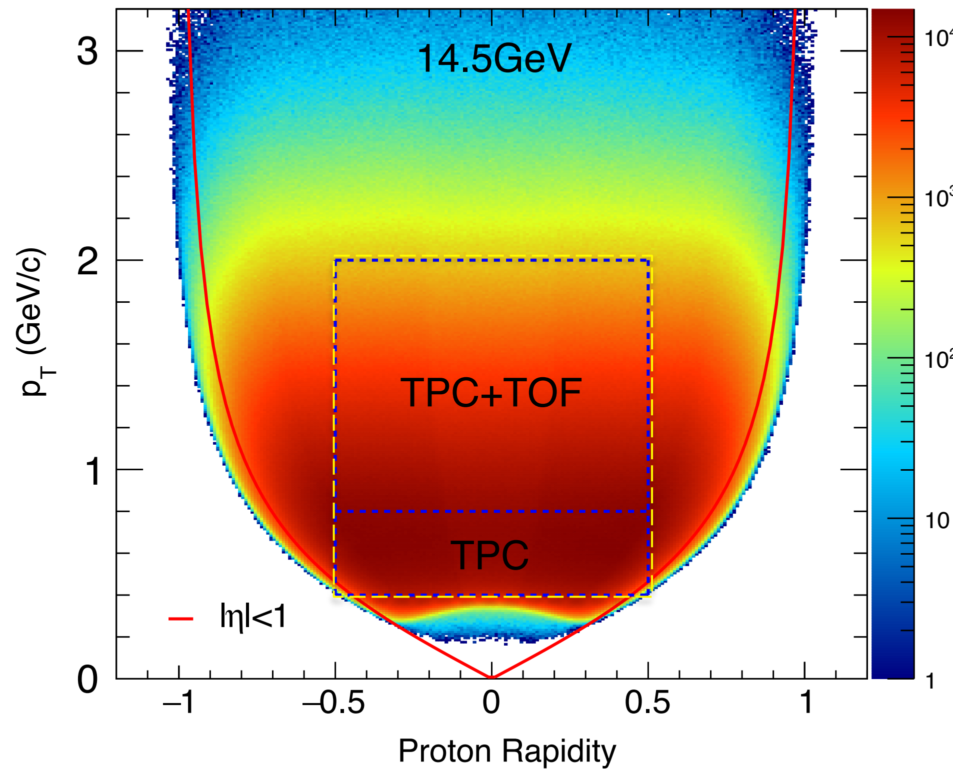
References:

- STAR: *PRL* **105**, 22303(10); *ibid*, **112**, 032302(14)
- S. Ejiri, F. Karsch, K. Redlich, *PLB633*, 275(06) // M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB696*, 459(11) // F. Karsch et al, *PLB695*, 136(11),
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // V. Skokov et al., PRC88, 034901(13)
- PBM, A. Rustamov, J. Stachel, arXiv:1612.00702

Proton Identification with TOF

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





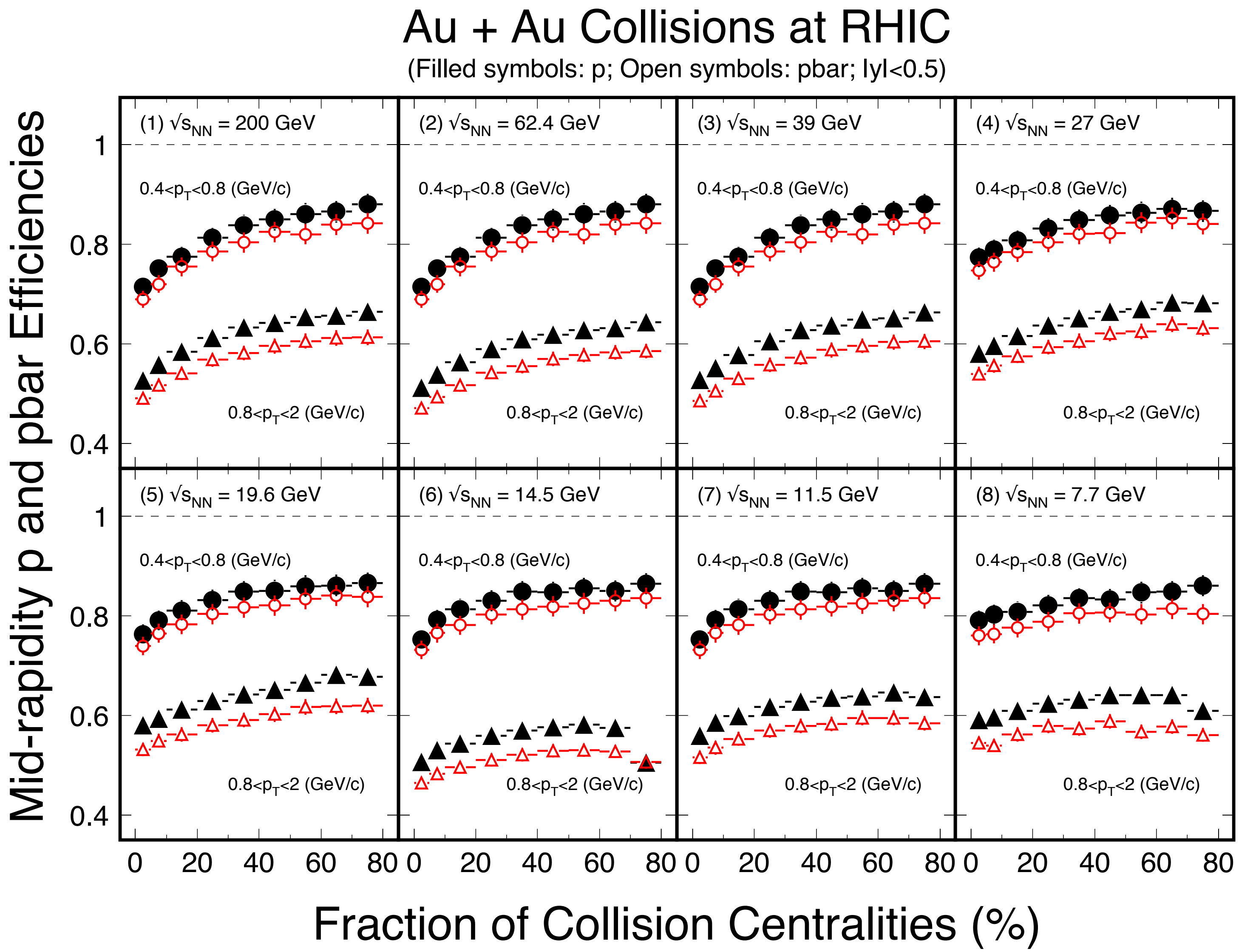
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

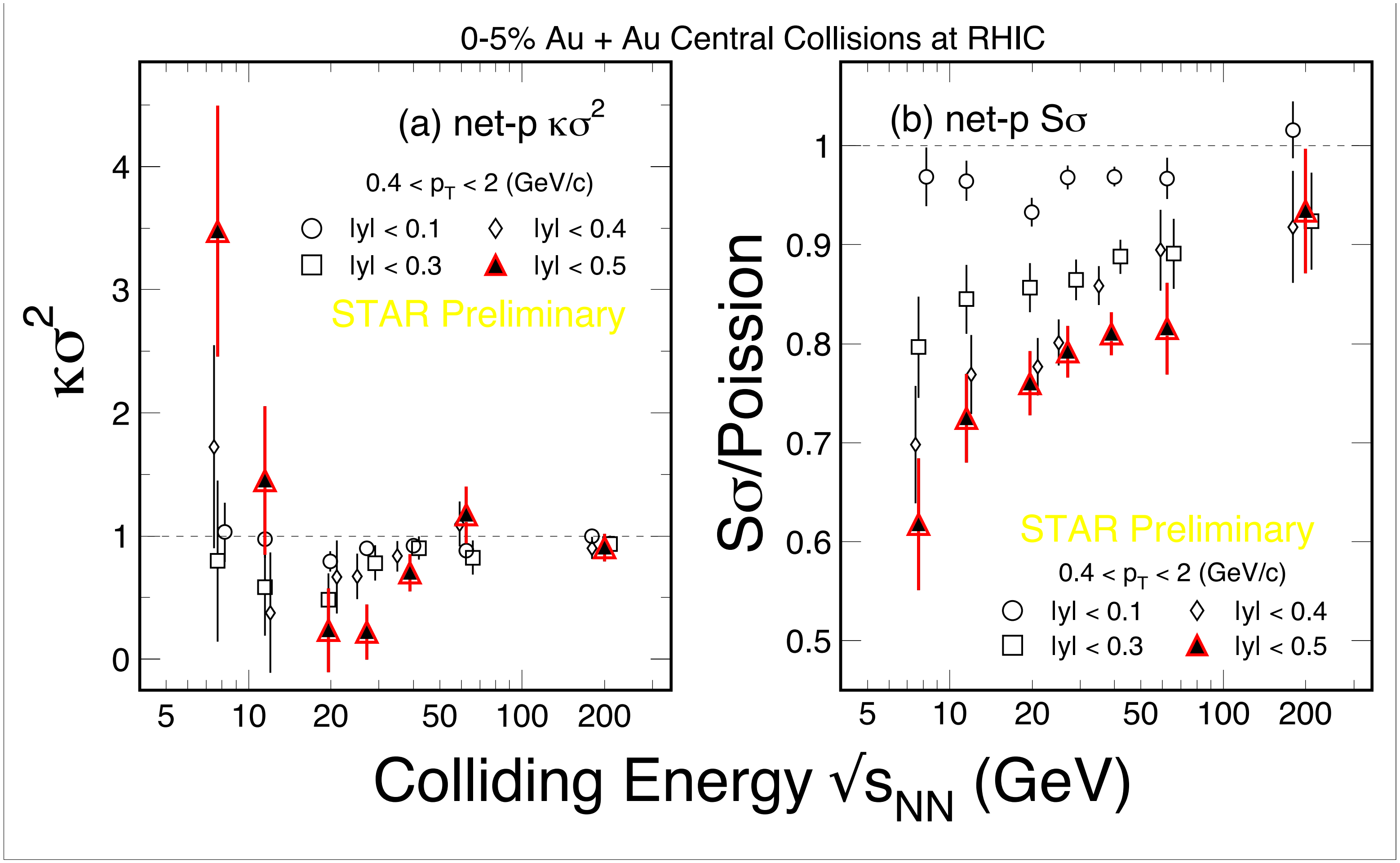
TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): $\varepsilon_{TPC} \sim 0.8$

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

Efficiency Corrections

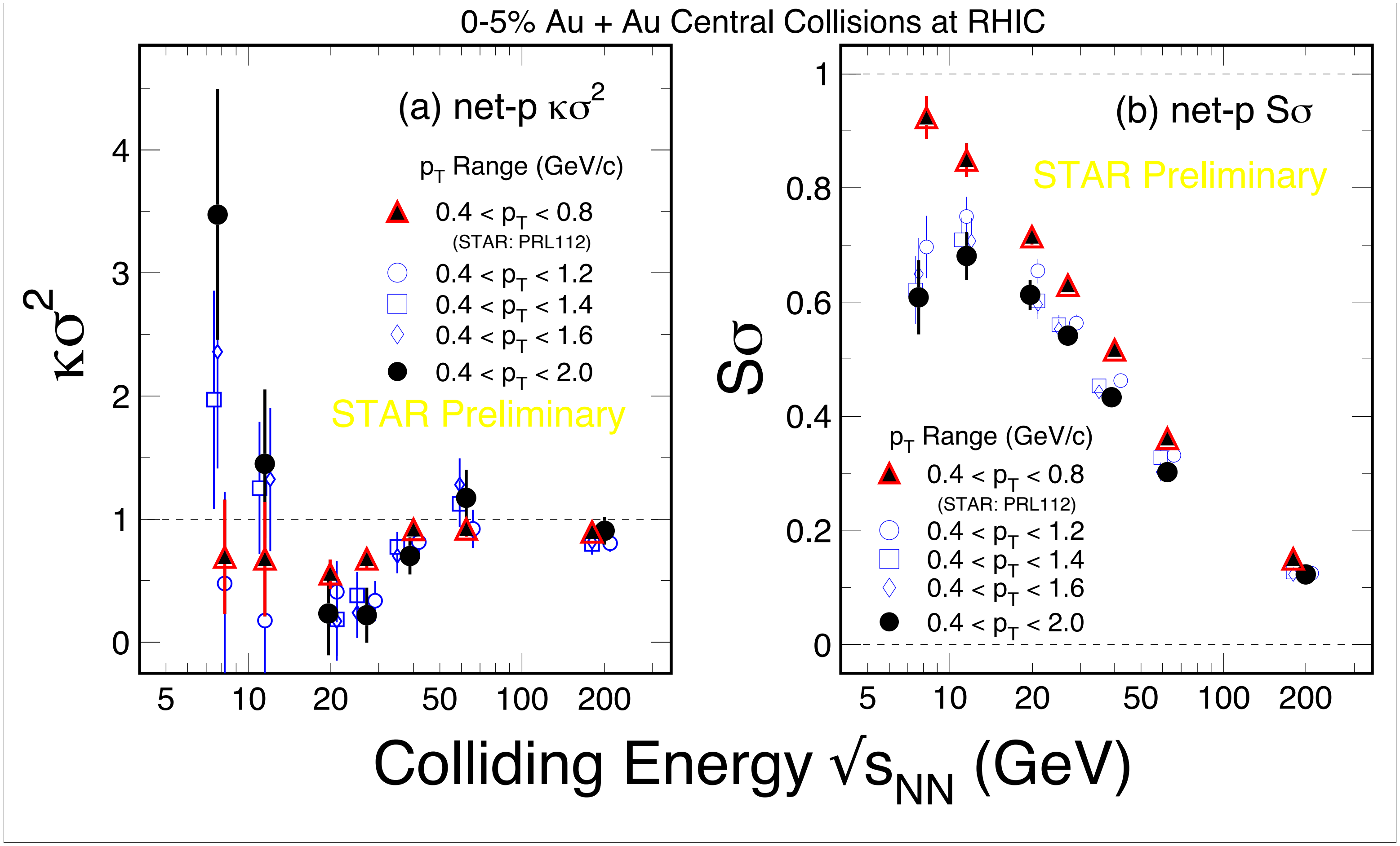


Rapidity Dependence



Sensitive to rapidity coverage!

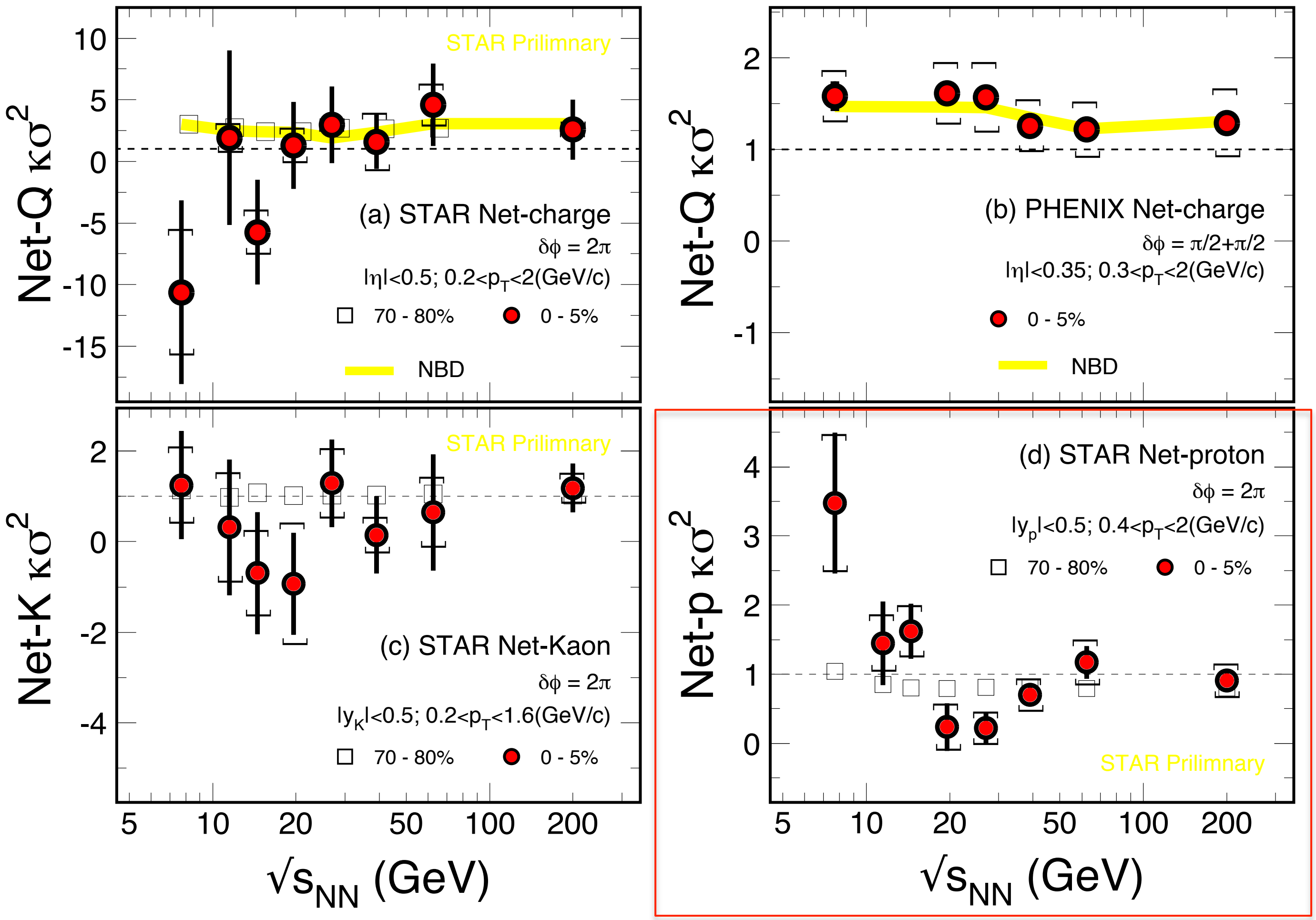
Transverse Momentum Dependence



Sensitive to p_T coverage!

Phase space coverage is important!!!

Higher Moments of Net-Q, -K, -p



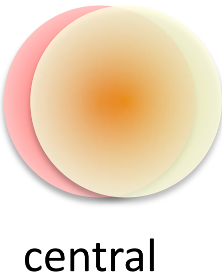
$$error(\kappa * \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

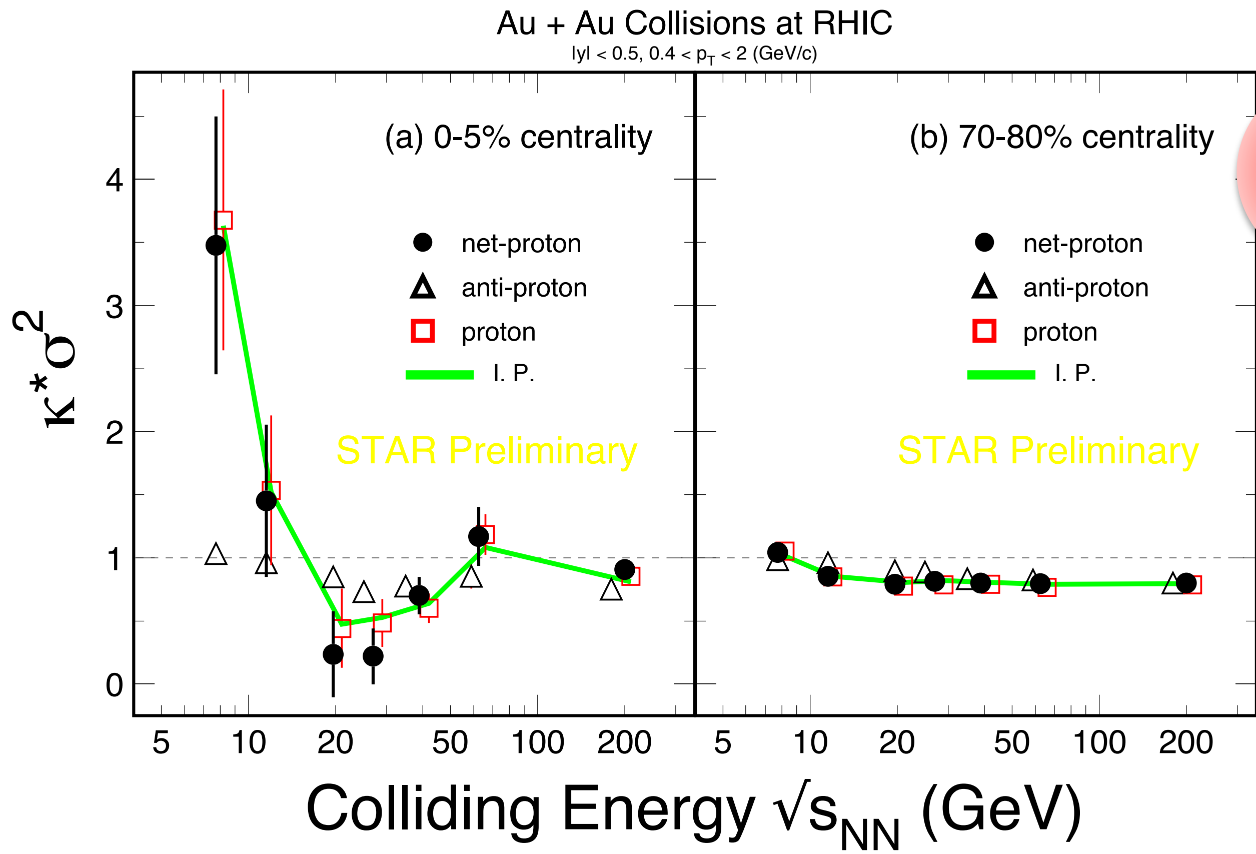
In STAR:

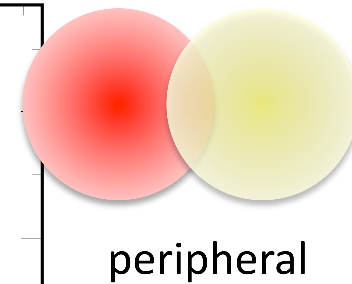
σ(Q) > σ(K) > σ(p)

1) The results of net-Q and net-Kaon show flat energy dependence.
2) Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions starting at $\sqrt{s_{NN}}$ < 27 GeV!

Net-proton Higher Moment



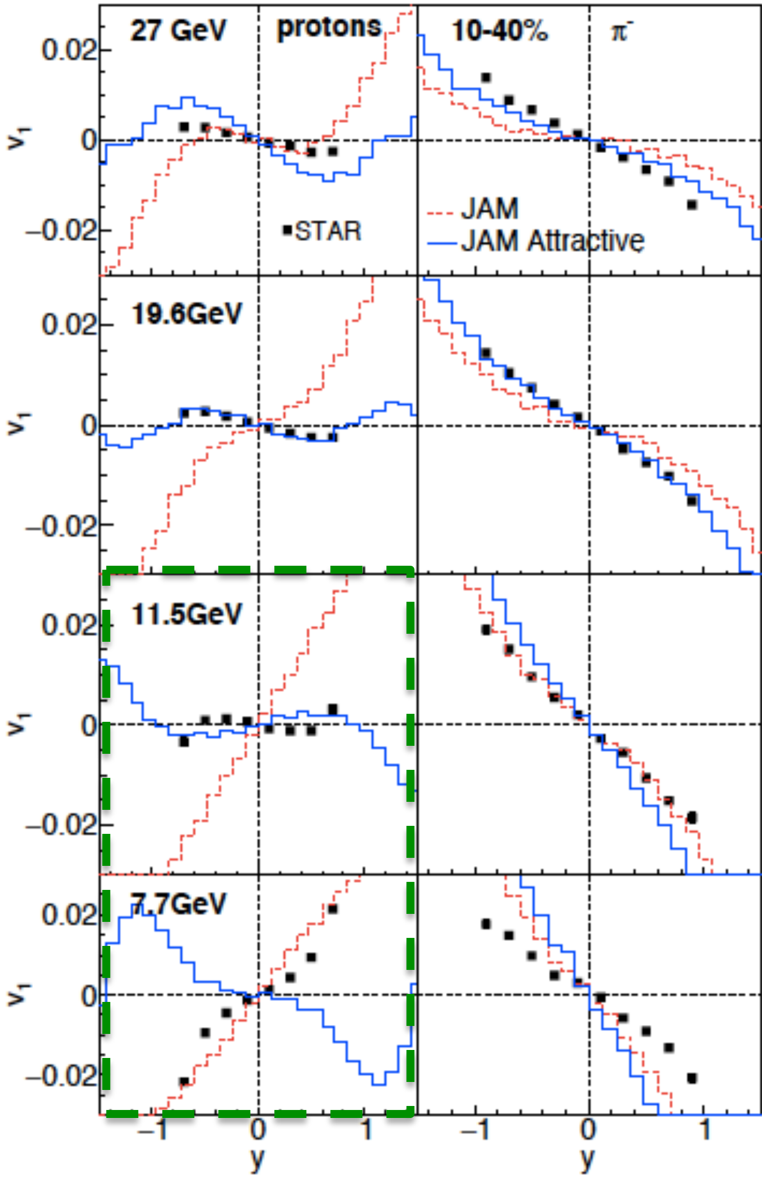




1) Flat energy dependence for 70-80% peripheral collisions
2) Non-monotonic behavior in the most central 0-5%, and 5-10% collisions. Net-p follow protons, especially at lower collision energies

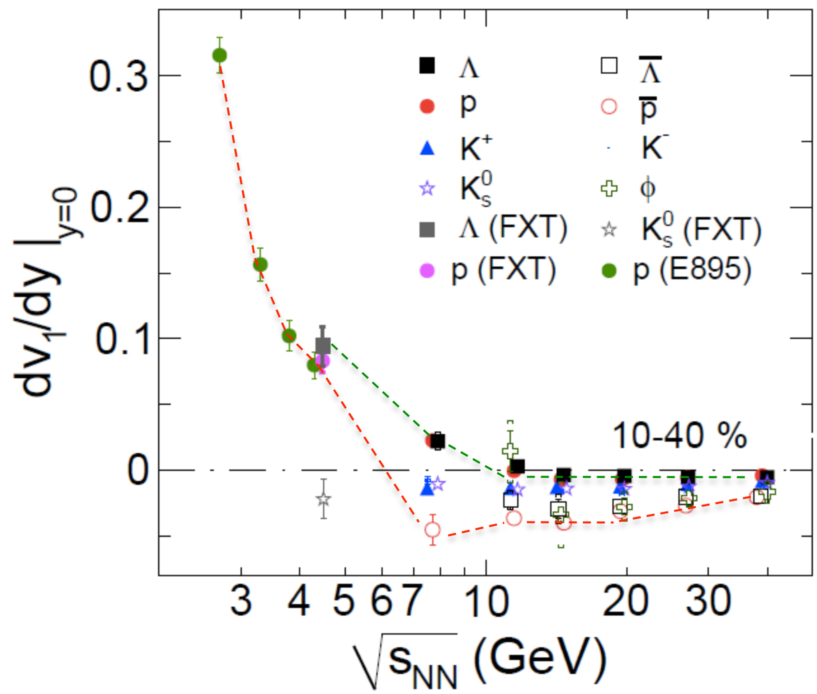
X.F. Luo, CPOD2014, QM2015

v_1 vs. Energy: Softest Point?



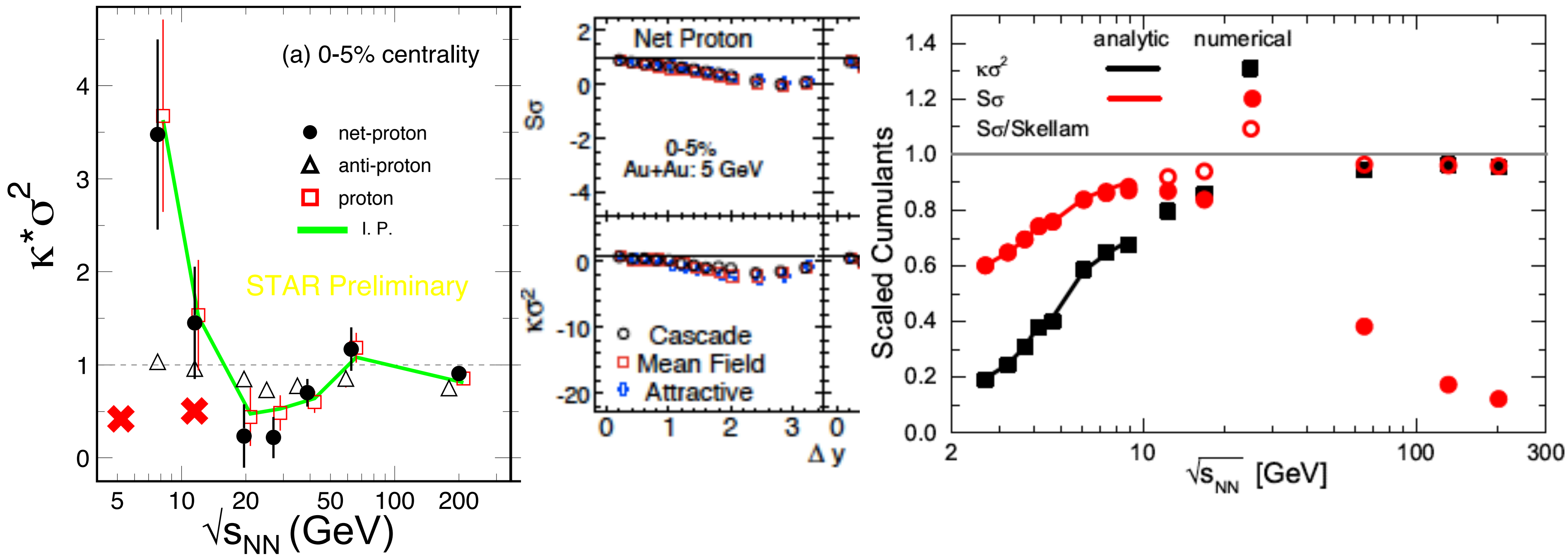
"Attractive force" → Change of the EOS ~ "softest point"

- Y. Nara, A. Ohnishi, H. Stoecker, arXiv: **1601.07692** ; PRC94, 034906(2016)



Kathryn Meehan, QM2017

All Model Are Wrong!



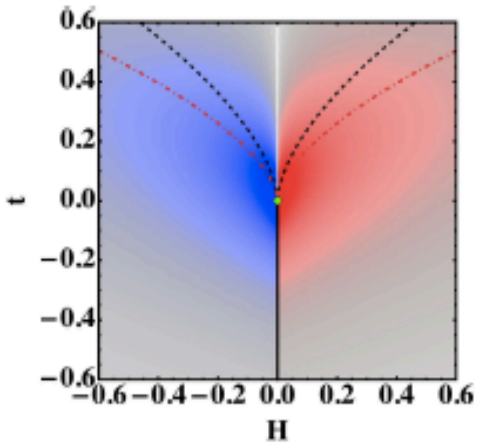
At $\sqrt{s_{NN}} \leq 10$ GeV: Data: **$\kappa\sigma^2 > 1$!** Model: **$\kappa\sigma^2 < 1$!**

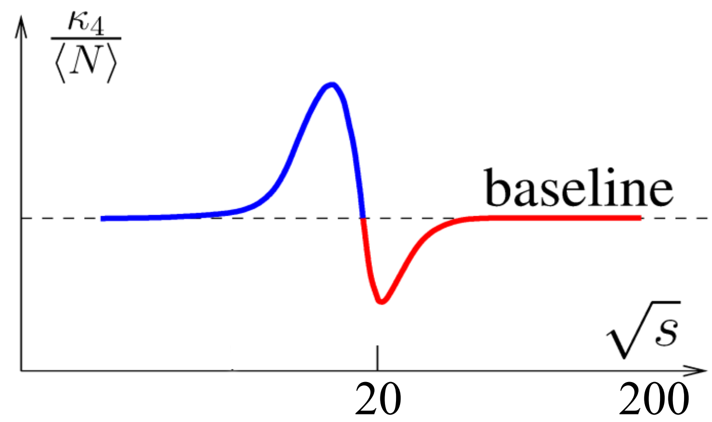
*All models: **suppress higher order net-proton fluctuations***

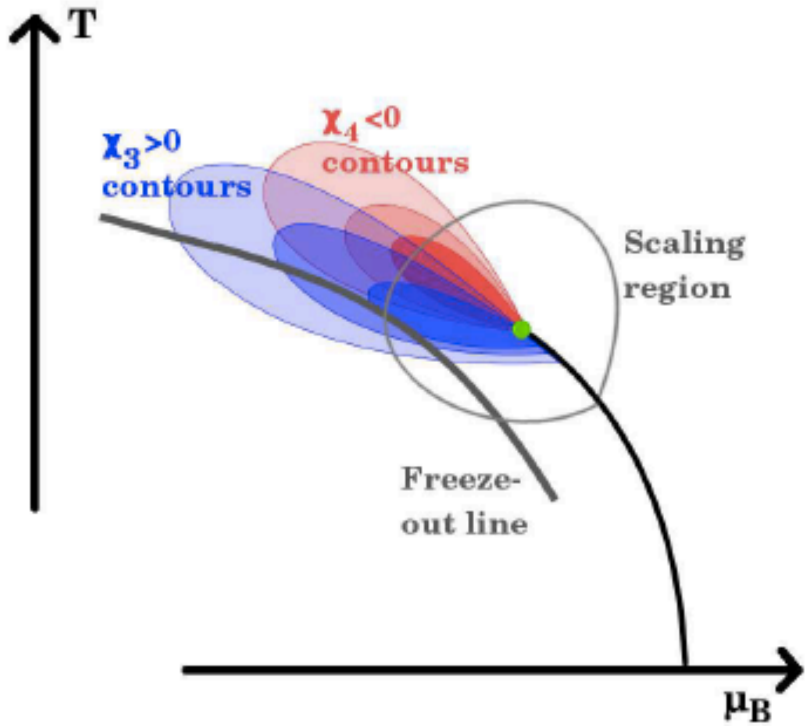
(UrQMD, AMPT, HRG and JAM do not reproduce data)

1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, 1510.05519, PR**C92**, 064908(15)
2) X.F. Luo *et al*, NP **A931**, 808(14)
3) P.K. Netrakanti *et al.* 1405.4617, NP **A947**, 248(16)
4) P. Garg *et al.* Phys. Lett. **B726**, 691(13)
5) Baryon mean-field (**attractive**): Shu He et al., 1607.07276

Expectation from Model Calculations



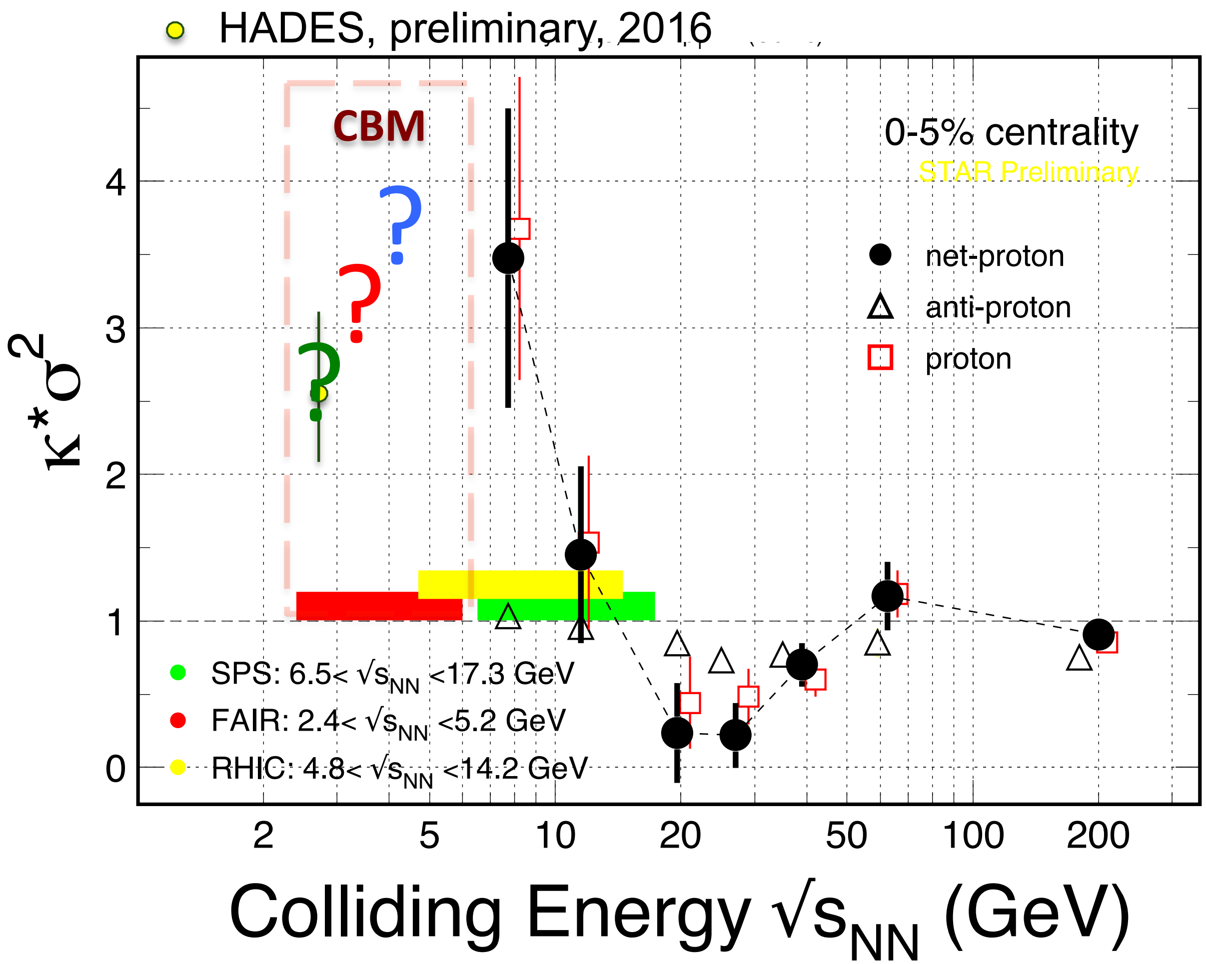


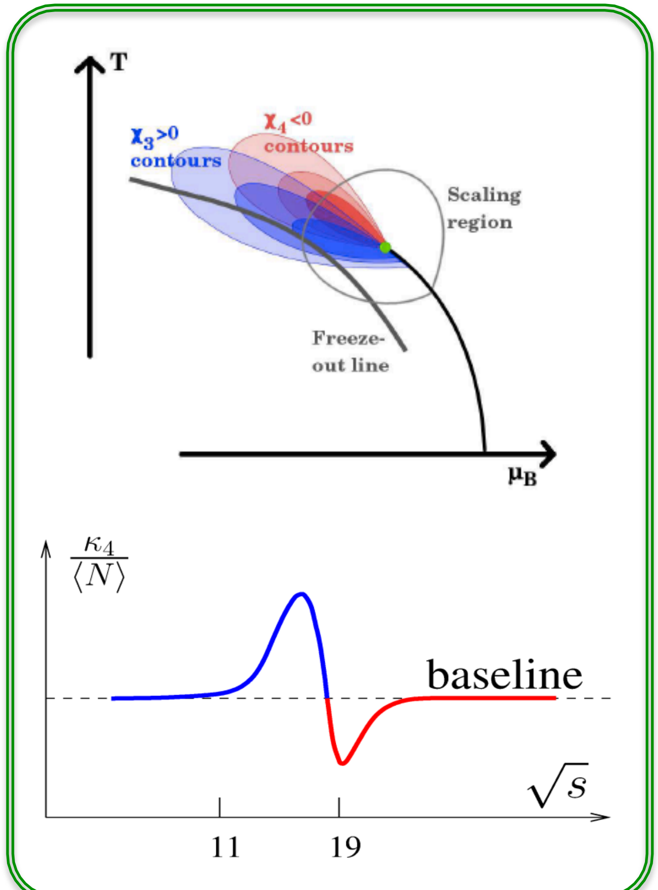


- Characteristic "Oscillating pattern" is expected for the QCD critical point but *the exact shape depends on the location of freeze-out with respect to the location of CP*
- Critical Region (CR)

- M. Stephanov, ***PRL107***, 052301(2011)
- V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyyama, arXiv: 1603.05198, Phys. Rev. **D93** (2016) 034037

Search at Large μ_B is Critical



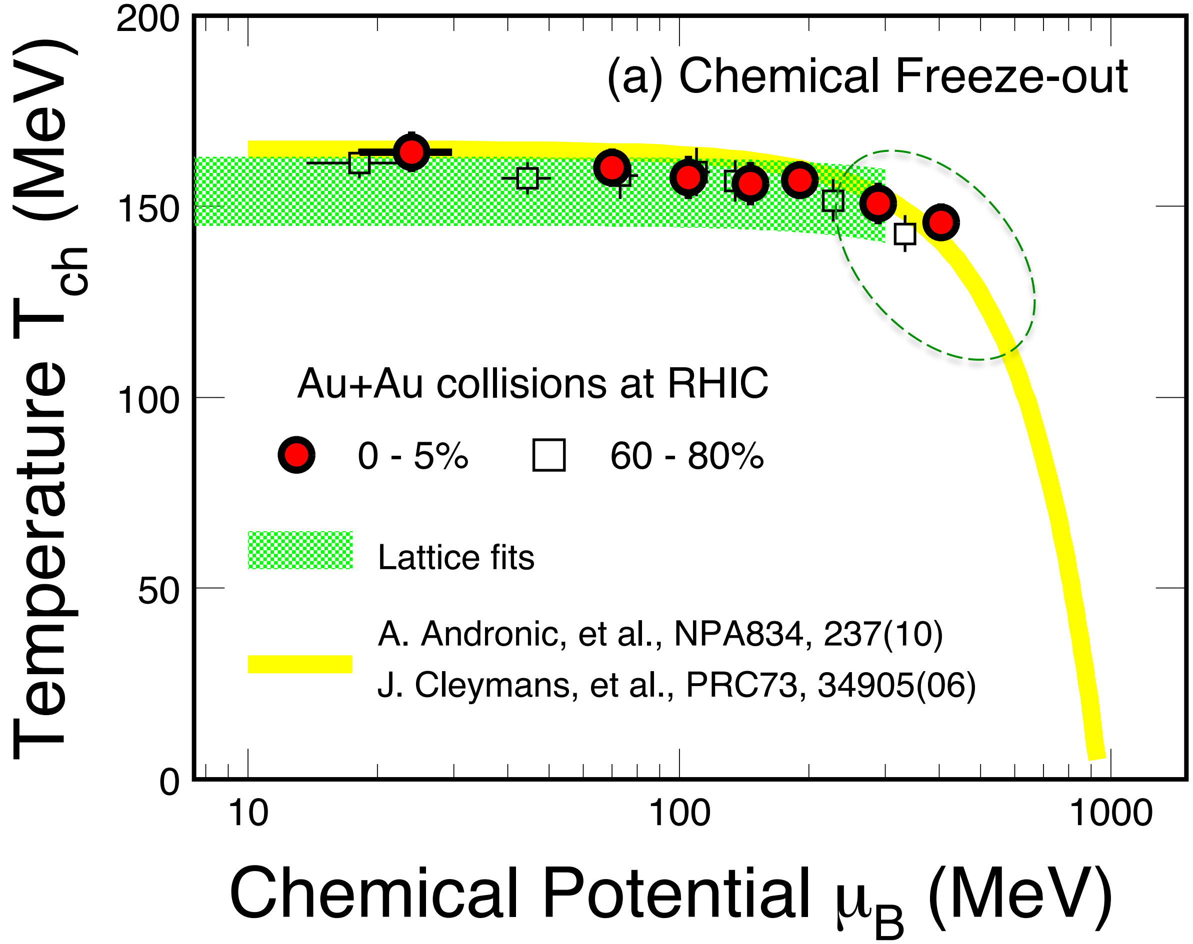


CBM/HADES Experiment (2.5 < $\sqrt{s_{NN}}$ < 8 GeV) :

Key region for CP search

STAR Data: X.F. Luo et al, PRL**112** (2014) 32302; X.F. Luo, PoS(CPOD14)019; QM plenary (15)

Critical Region



CP: 300 < μ_B < 700 MeV, 15 < $\sqrt{s_{NN}}$ < 2 GeV
BES-III (STAR FXT and CBM are required)

Summary: CP Search

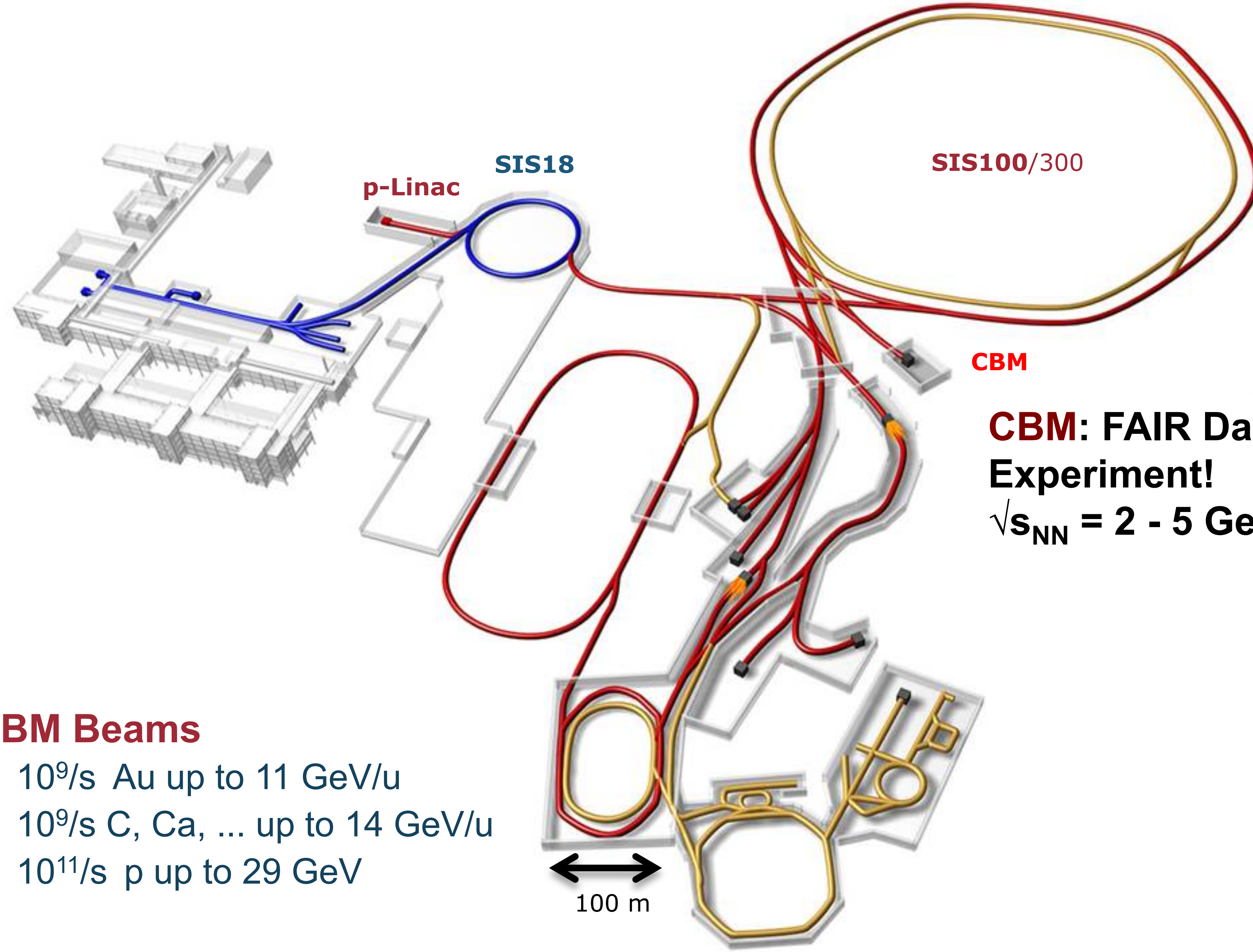
1) Below $\sqrt{s_{NN}}$ ~ 15 GeV the slope of net-p v_1 > 0 implies repulsive interactions. But, net-p Kurtosis > 1, indicating attractive force.

2) No model can reproduce both results. Especially, all predictions show suppression for net-p κ.

3) BES-II at RHIC: reduce error bars.

4) FTX experiments needed to 'contain' the possible critical region below $\sqrt{s_{NN}}$ ~ 8 GeV.

Facility for Antiproton & Ion Research: FAIR

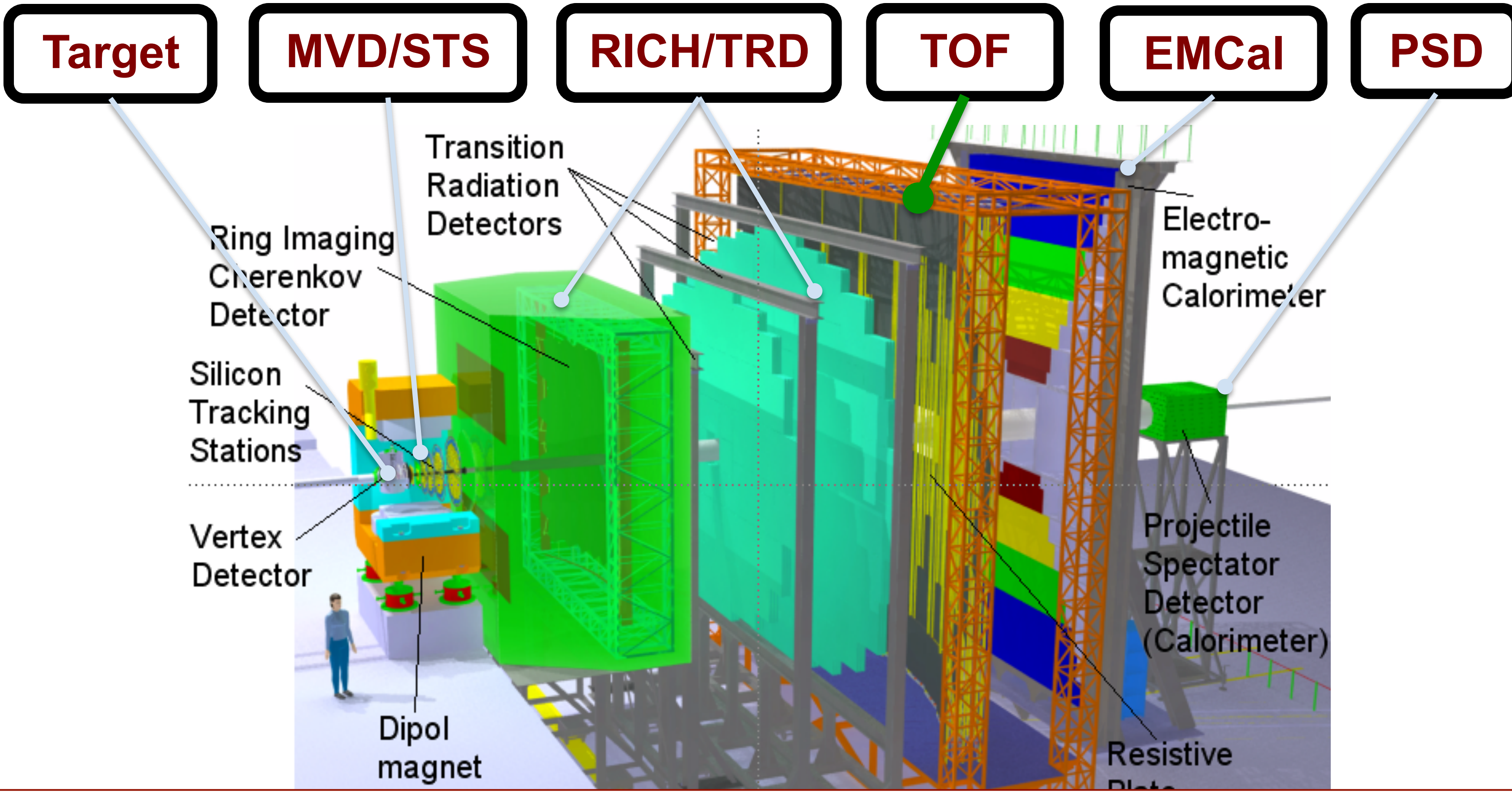


CBM: FAIR Day-1 Experiment!
$\sqrt{s_{NN}}$ = 2 - 5 GeV

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

CBM Experiment at FAIR

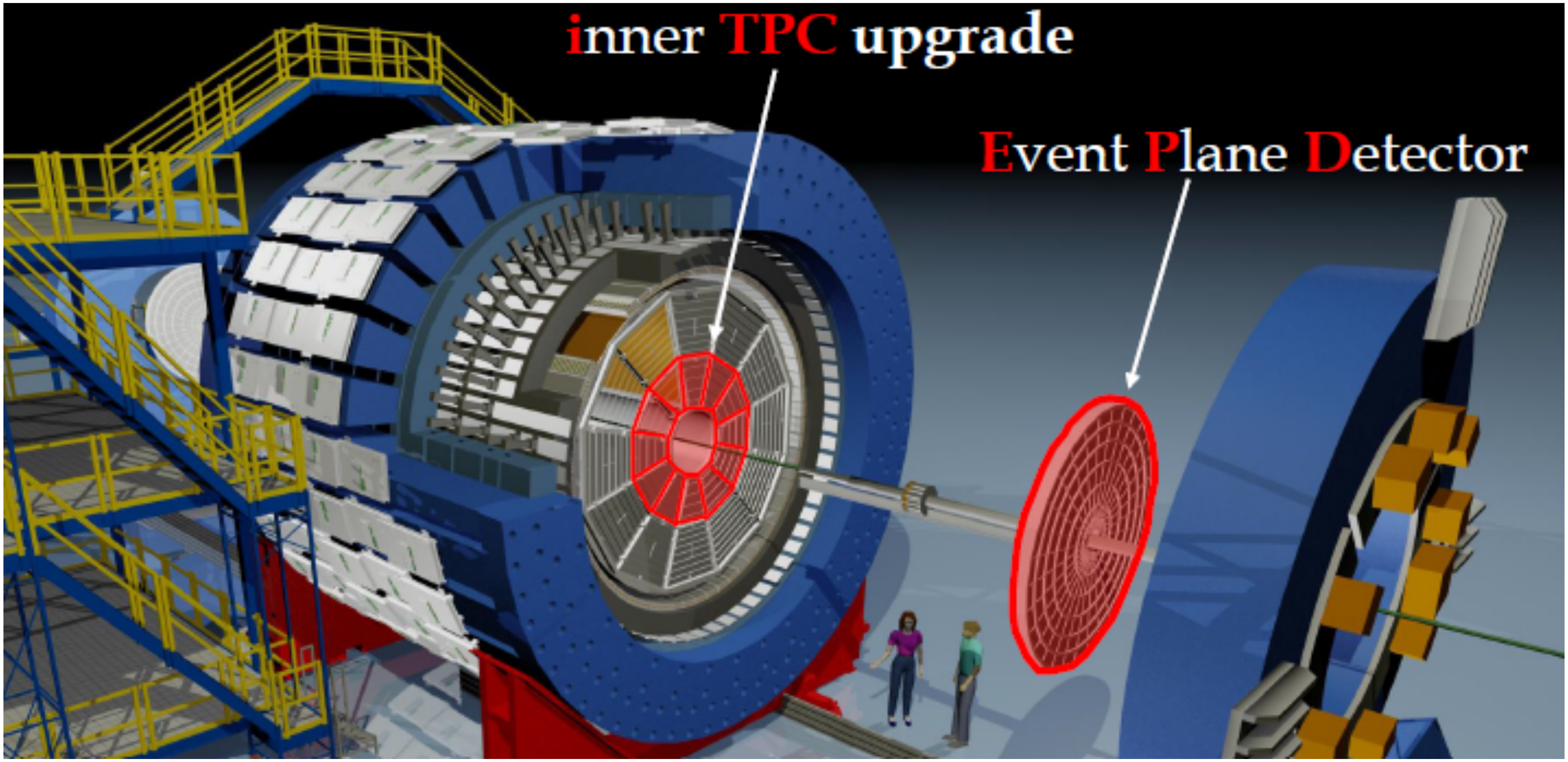


FAIR: One of the highest intensity accelerator complex in the 21st century

Precision measurements at high baryon density region for:

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

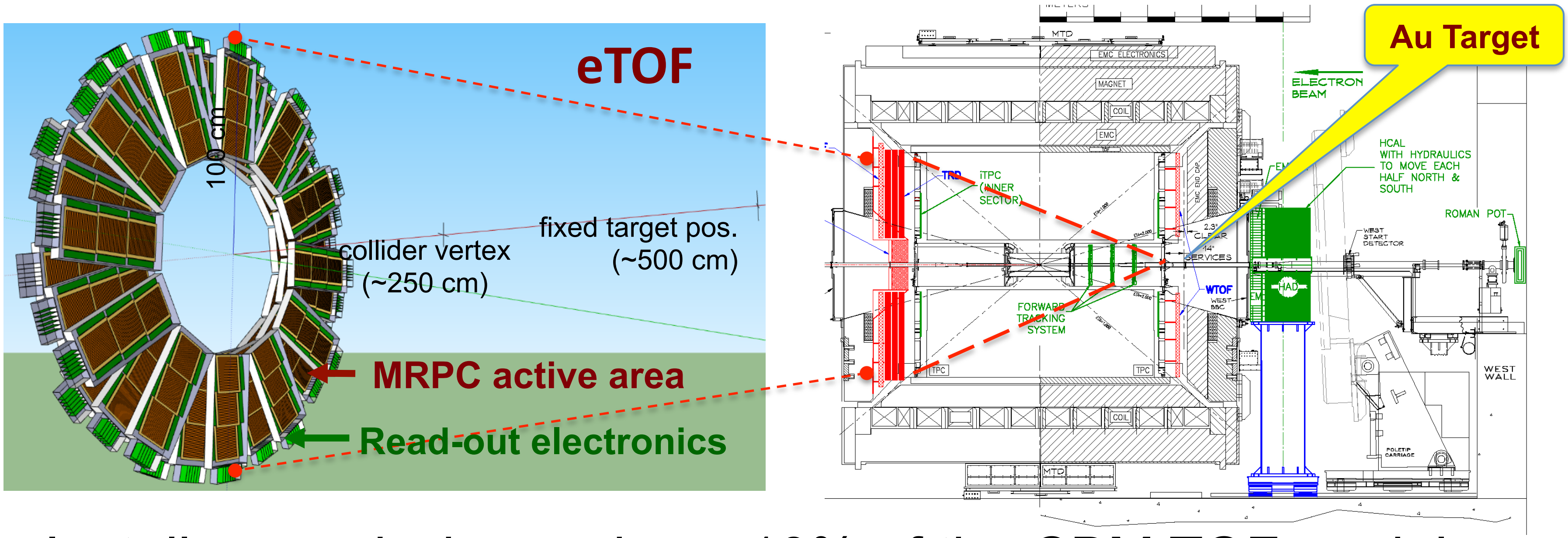
STAR Upgrades for BES Phase-II



1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance event plane resolution

iTPC, EPD, eTOF
Dedicated two runs at RHIC: 2019 & 2020

CBM Phase-0 Exp: eTOF at STAR



Install, commission and use 10% of the CBM TOF modules, including the read-out chains at STAR, starting in 2019

CBM participating in RHIC Beam Energy BES-II in 2019-2020:

- Complementary to part of CBM's physics program:
  $\sqrt{s_{NN}}$ = **3**, **3.6**, **3.9**, **4,5**, 7.7 GeV (750 ≤ μ_B ≤ 420 MeV)
  especially for ***B-*** & ***s-hadrons*** production and fluctuations

FAIR (CBM) construction starts 17, beam on target in 2025!

2019-2020: BES II at RHIC

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
39	39	2010		112	164
27	70	2011		156	162
19.6	**400** / 36	**2019-20** / 2011	**3**	206	160
14.5	**300** / 20	**2019-20** / 2014	**2.5**	264	156
11.5	**230** / 12	**2019-20** / 2010	**5**	315	152
9.2	**160** / 0.3	**2019-20** / 2008	**9.5**	355	140
7.7	**100** / 4	**2019-20** / 2010	**14**	420	140

Precision measurements, map the QCD phase diagram **$200 < \mu_B < 420$MeV**

RHIC HI Physics Programs

BES-I 2014

HF: QGP properties

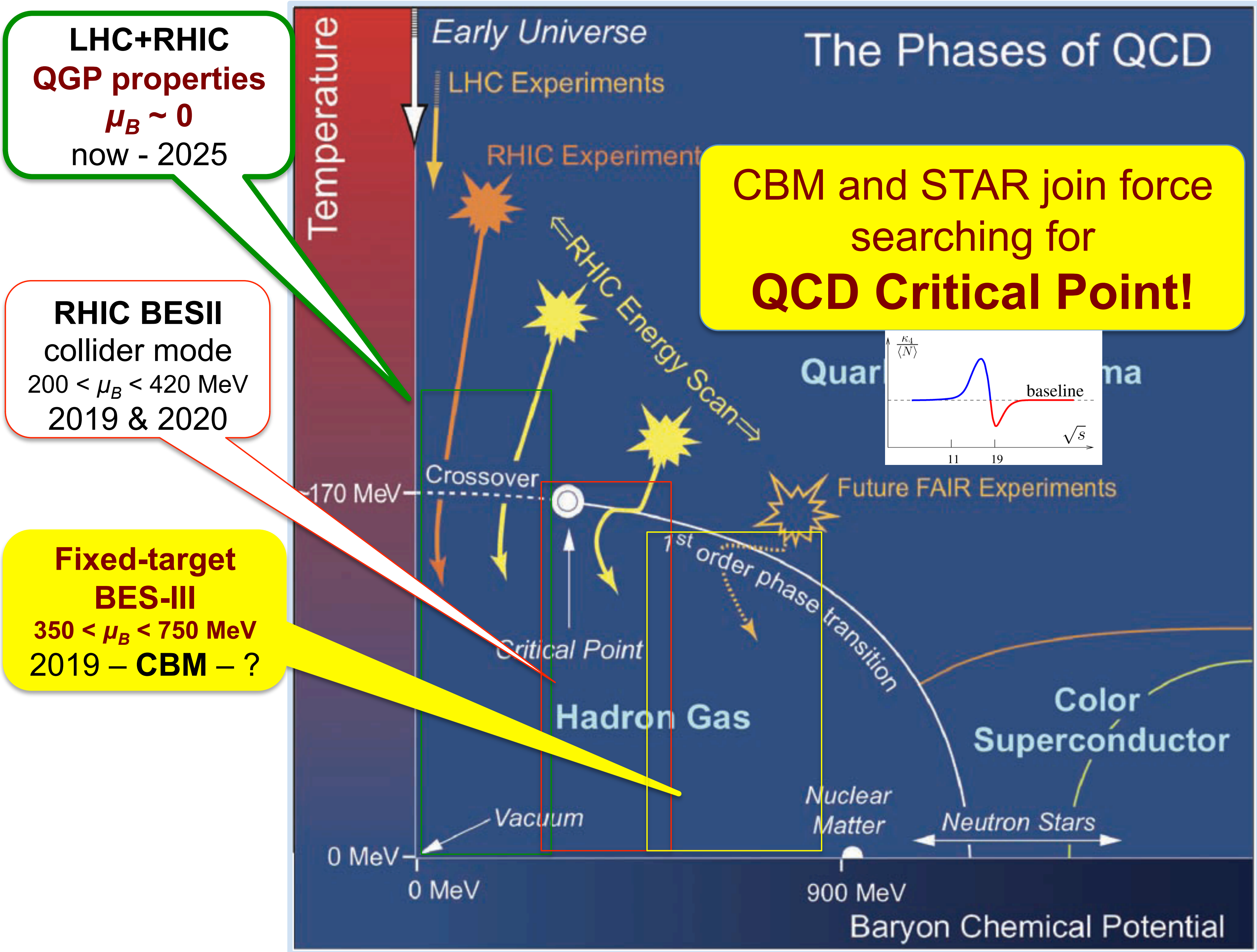
Isobaric: CME/CVE

BES-II: Critical Region

QGP Properties

2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
STAR HFT analysis			BES-II data taking and data analysis						
		Ru+Ru vs. Zr+Zr							
BES-I data analysis & upgrades						sPHENIX: HF jets & Bottom hadrons			
			STAR fixed-target (FXT) data					CBM at FAIR	

FXT programs for QCD properties at high baryon density and the critical region



LHC+RHIC
QGP properties
$\mu_B \sim 0$
now - 2025
RHIC BESII
collider mode
$200 < \mu_B < 420$ MeV
2019 & 2020
Fixed-target
BES-III
$350 < \mu_B < 750$ MeV
2019 – CBM – ?
Temperature
Early Universe
LHC Experiments
RHIC Experiments
The Phases of QCD
CBM and STAR join force
searching for
QCD Critical Point!
RHIC Energy Scan
Quark Gluon Plasma
baseline
$\sqrt{s}$
11
19
Crossover
170 MeV
Future FAIR Experiments
1st order phase transition
Critical Point
Hadron Gas
Color
Superconductor
Vacuum
Nuclear
Matter
Neutron Stars
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential