Heavy Ion Physics in Future

-- *Dense Matter Physics & Critical Point Search*

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Many Thanks to the Organizers!

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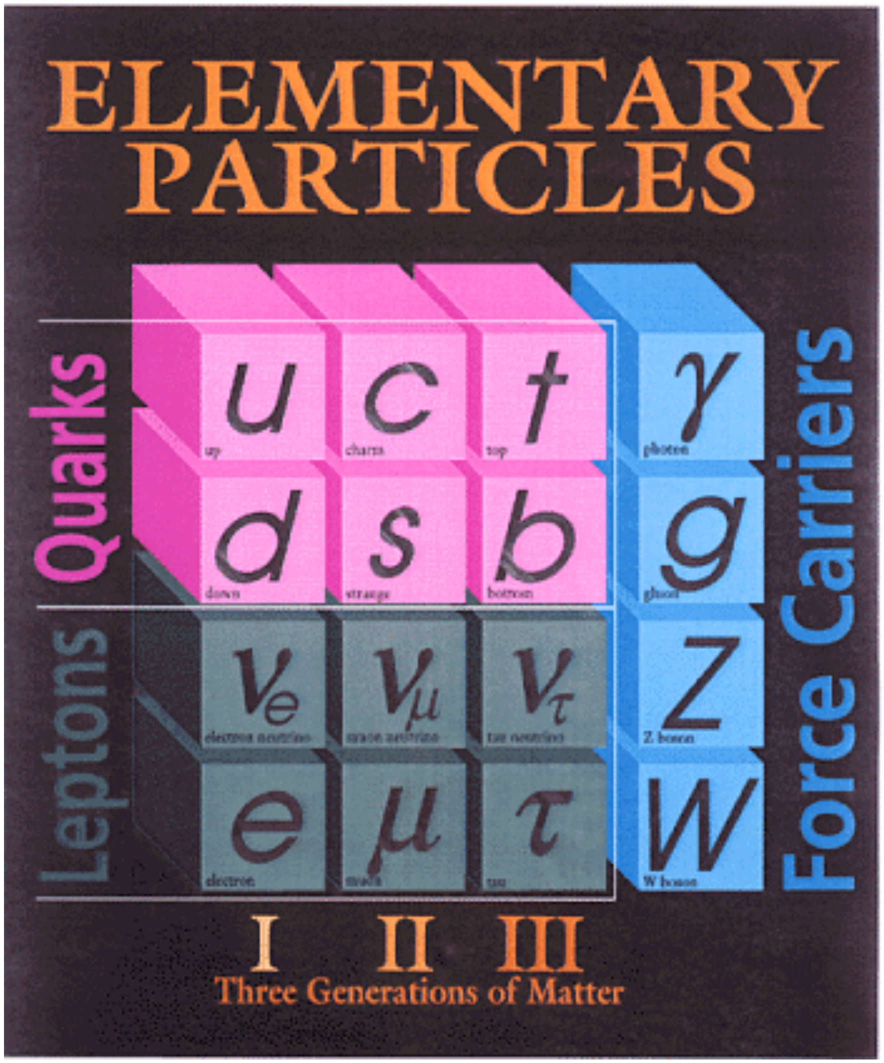
U.S. DEPARTMENT OF ENERGY

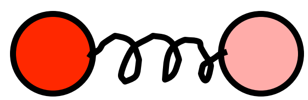
BERKELEY LAB

Basics on Quantum Chromodynamics

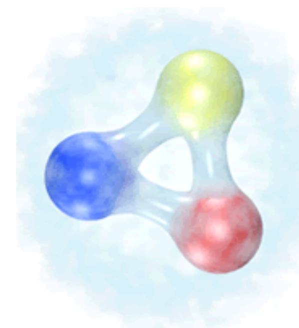


1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.
2) Gluons hold quarks together to from hadrons:

meson

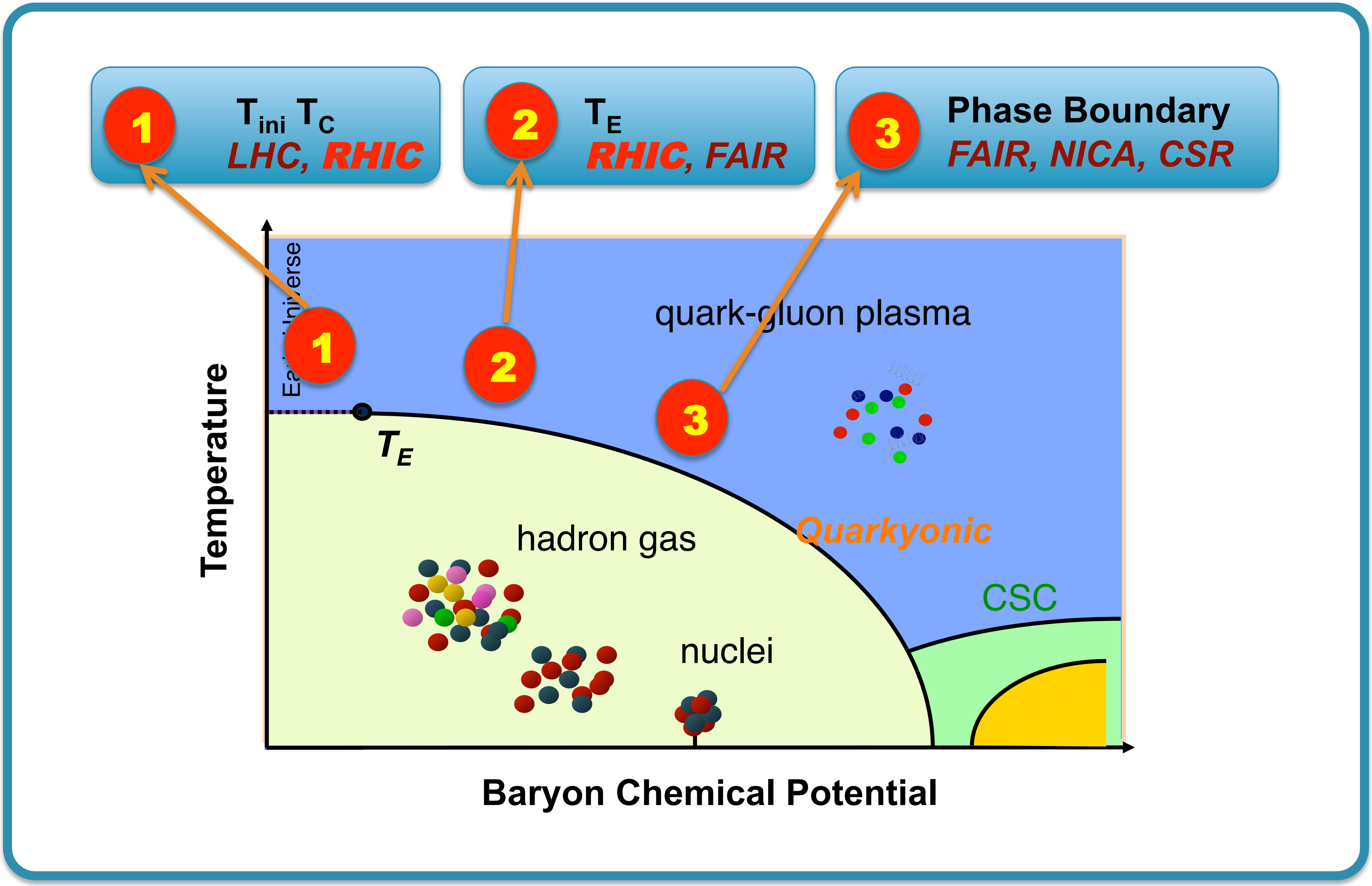


baryon

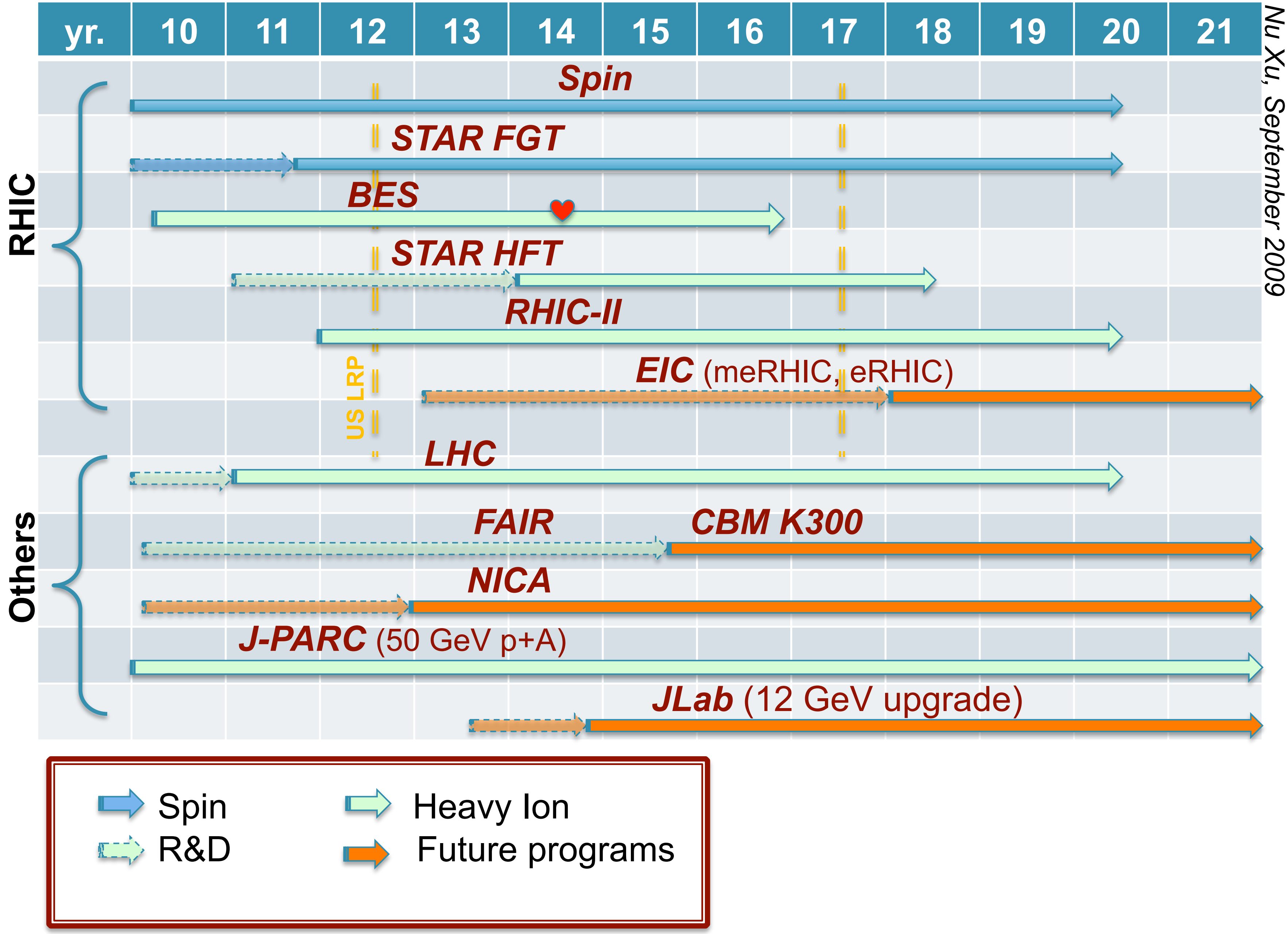


3) Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement.***

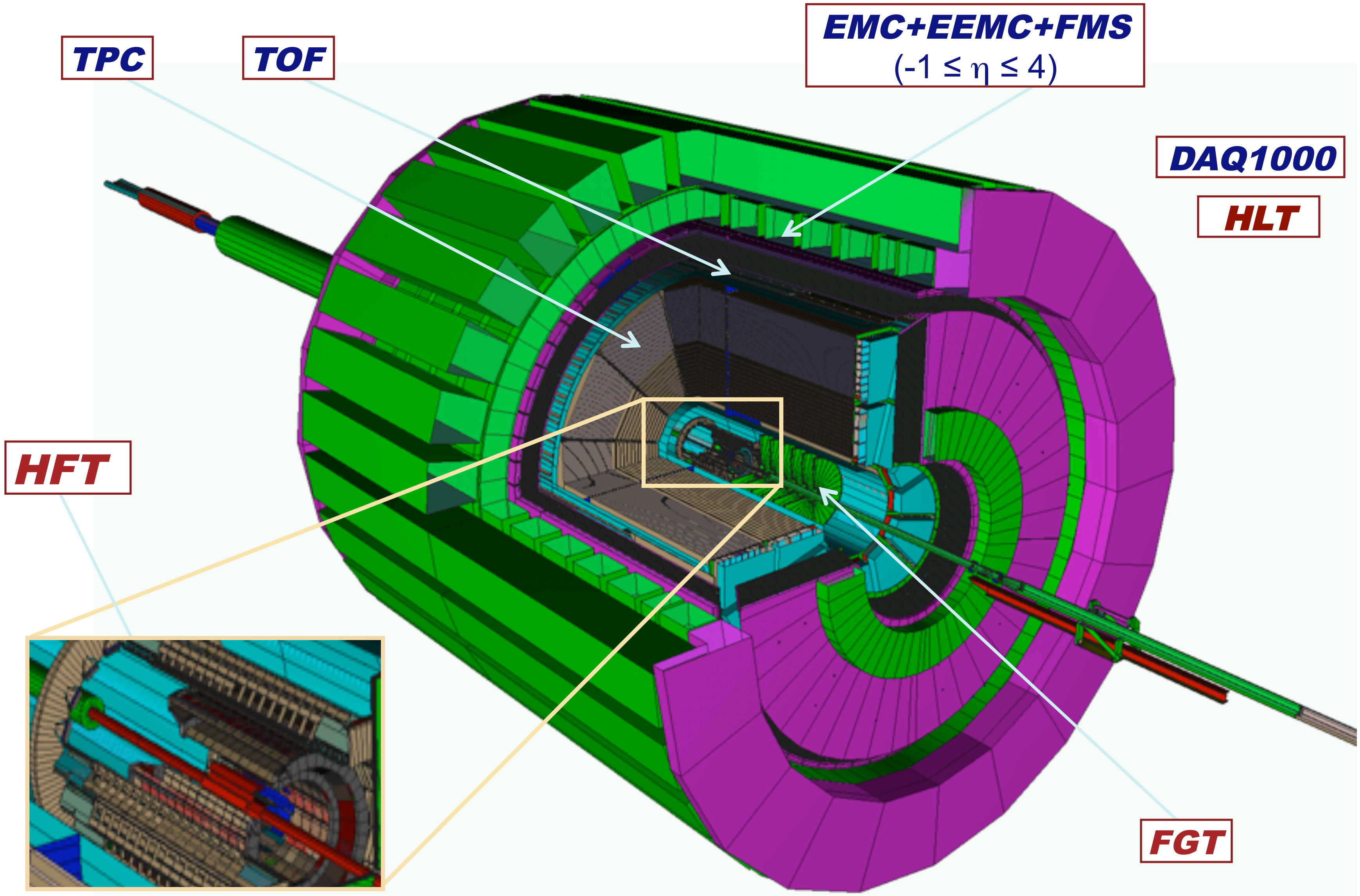
The QCD Phase Diagram and High-Energy Nuclear Collisions



Timeline of QCD and Heavy Ion Facilities



STAR Detectors: *Full 2π particle identification!*



STAR Physics Focus

Structure of Nucleon

Structure of Cold Nuclear Matter

Structure of Hot/Dense Matter

Matter with partonic degrees of freedom. Theory of QCD.

Outline

(1) Introduction

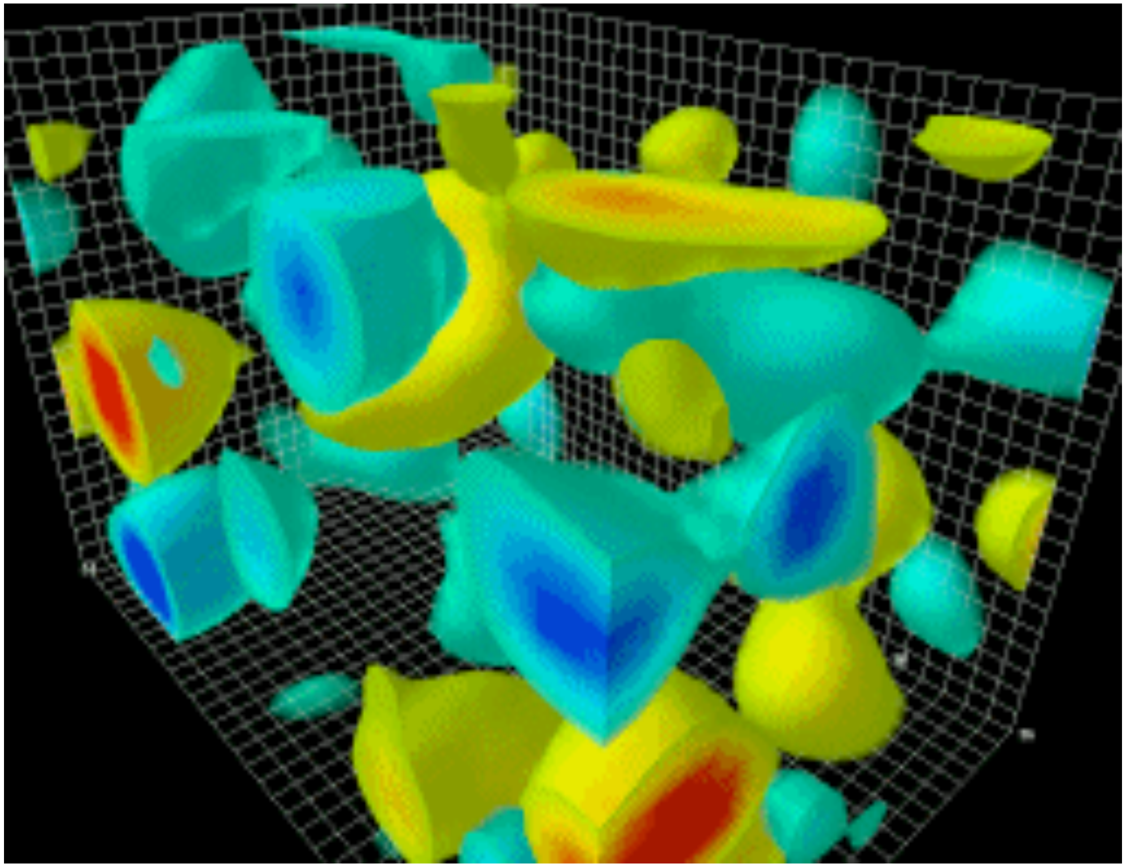
(2) Recent results from RHIC

(3) Two Proposals: for exploring the locating QCD phase diagram

(4) Summary and Outlook

Search for Local Parity Violation

in High Energy Nuclear Collisions



Animation by *Derek Leinweber*

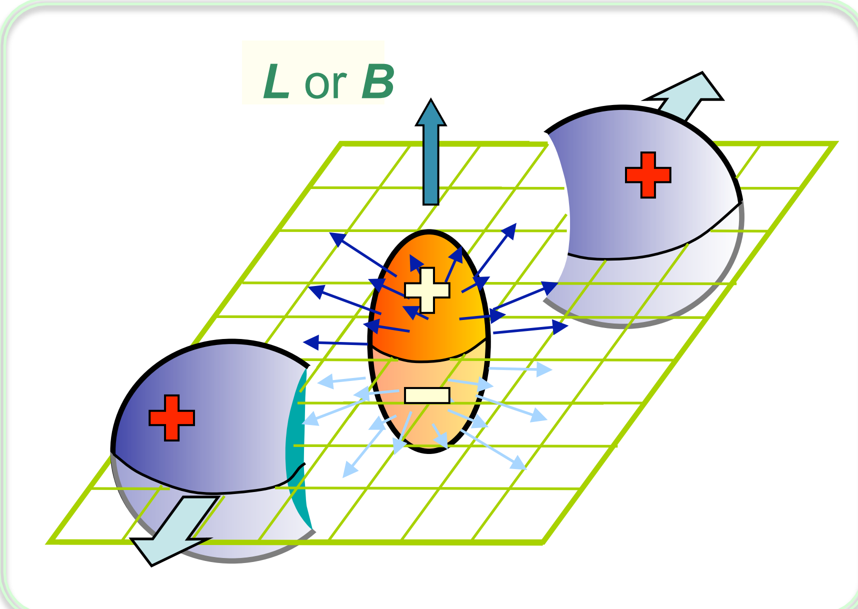
Topological transitions have never been observed *directly* (e.g. at the level of quarks in DIS). An observation of the *spontaneous* ***strong***, ***local*** **parity violation** would be a clear proof for the existence of the physics.

Chiral Magnetic Effect:

Kharzeev, PL ***B633*** 260 (06).
Kharzeev, *et al,* NP ***A797*** 67(07).
Kharzeev, *et al,* NP ***A803*** 227(08).
Fukushima, *et al,* PR***D78***, 074033(08).

Search for Local Parity Violation

in High Energy Nuclear Collisions

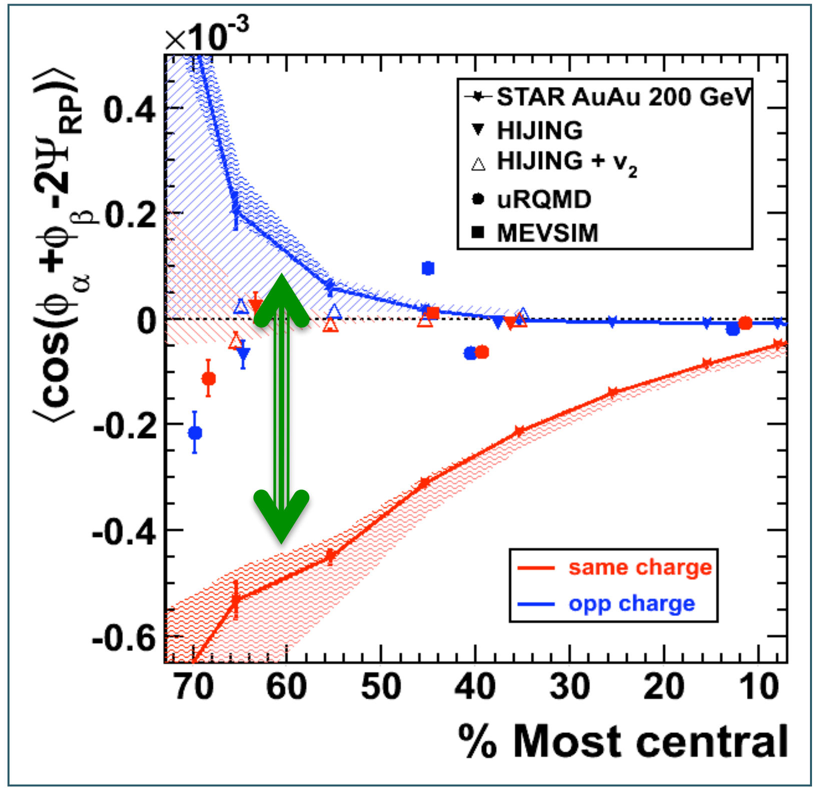


$$\left\langle \cos\left(\phi_\alpha + \phi_\beta - 2\Psi_{RP}\right)\right\rangle$$

Parity even observable

Voloshin, PR C62, 044901(00).

STAR; arXiv: 0909.1739 (PRL); 0909.1717 (PRC).

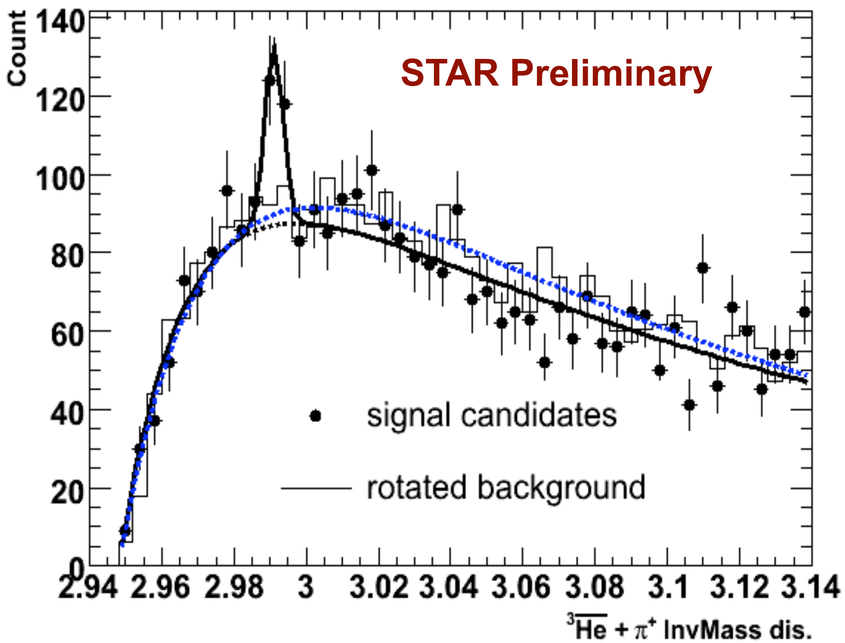


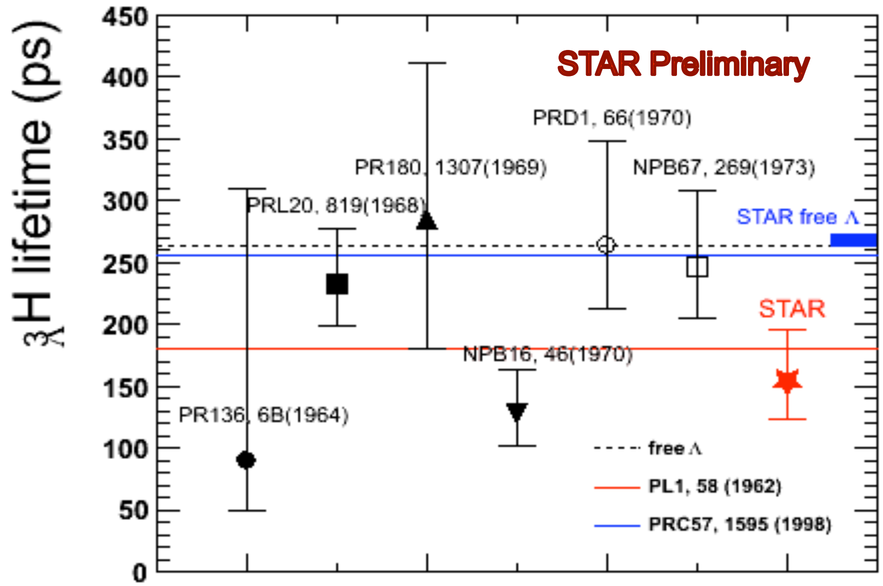
The separation between the same-charge and opposite-charge correlations.

- **Strong external EM field**
- ***De-confinement* and *Chiral symmetry restoration***

First Observation of ${}^{3}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{He} + \overline{\pi}^{-}$

200 GeV Au+Au collisions at RHIC





Particle type	Ratio
${}^{3}_{\Lambda}\bar{H}/{}^{3}_{\Lambda}H$	0.49 ± 0.18 (stat.) ± 0.07 (sys.)
${}^{3}\bar{He}/{}^{3}He$	0.45 ± 0.02 (stat.) ± 0.04 (sys.)
${}^{3}_{\Lambda}\bar{H}/{}^{3}\bar{He}$	0.89 ± 0.28 (stat.) ± 0.13 (sys.)
${}^{3}_{\Lambda}H/{}^{3}He$	0.82 ± 0.16 (stat.) ± 0.12 (sys.)

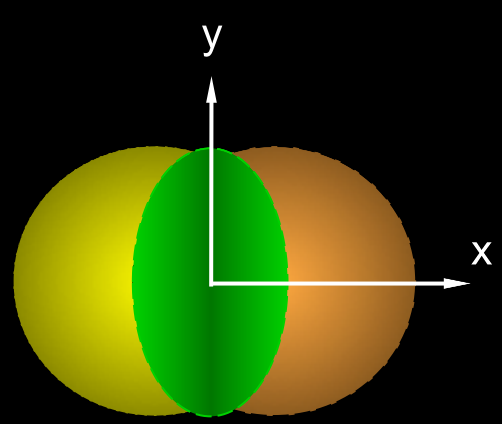
1st observation anti-hyper nucleus!

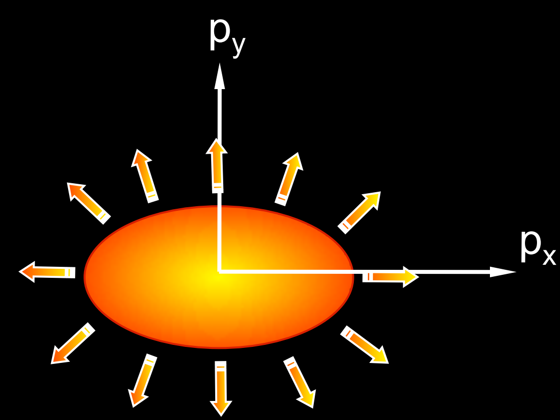
(1) Strangeness production saturated
(2) Coalescence at work

Submitted to ***Science*** by STAR

Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

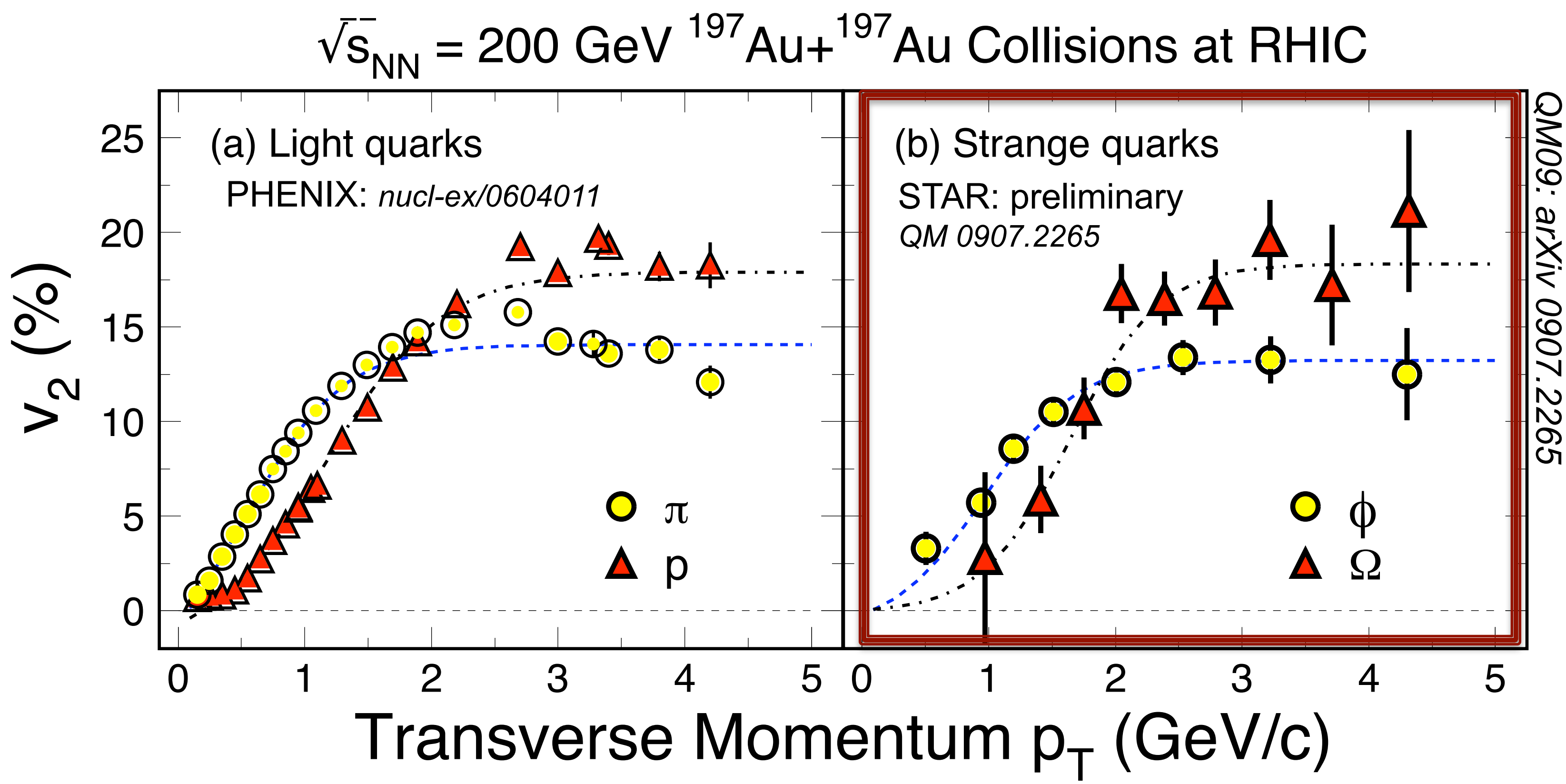




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

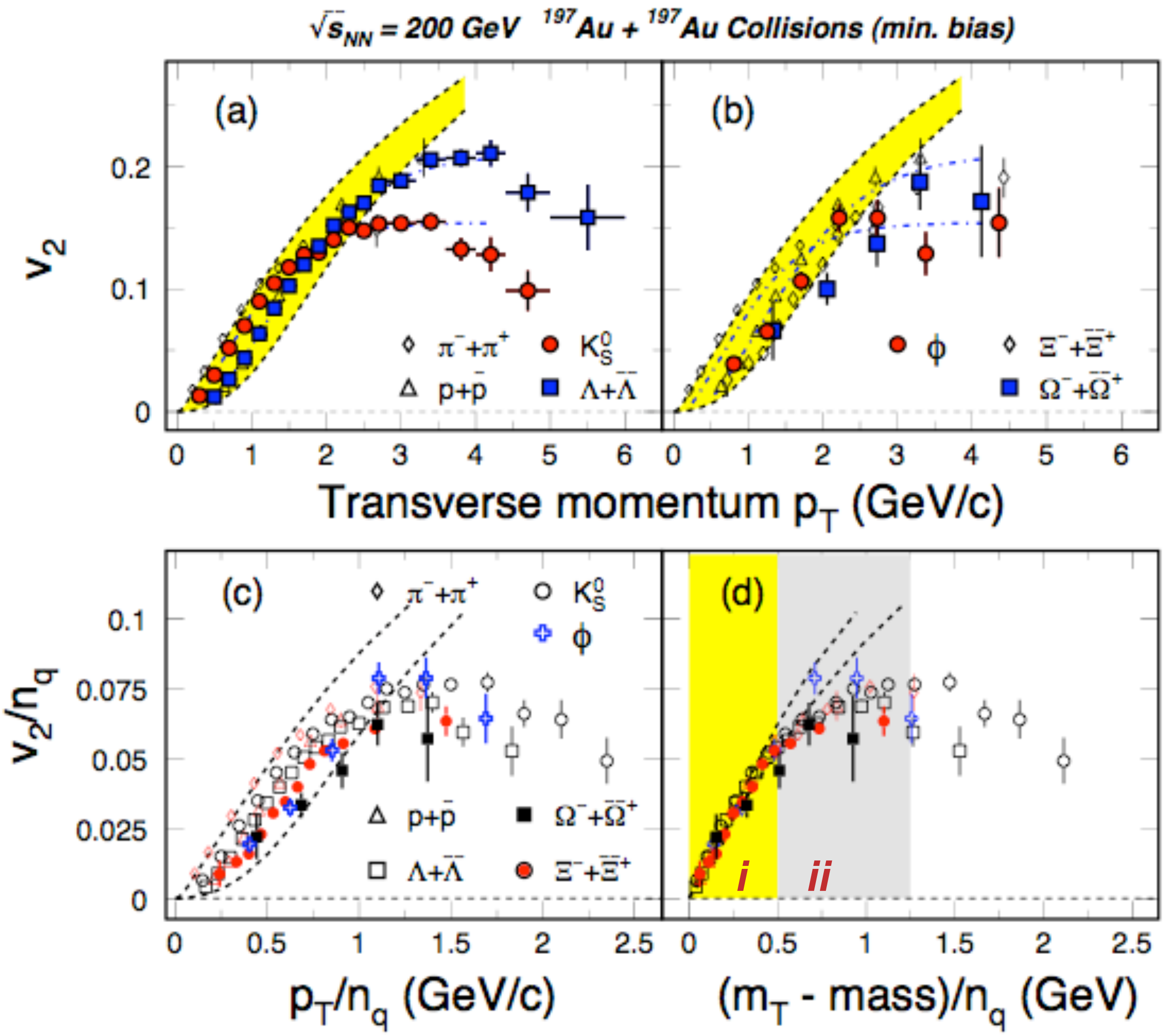
Partonic Collectivity at RHIC



Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks ordering***

=> Collectivity developed at partonic stage!
=> De-confinement in Au+Au collisions at RHIC!

Collectivity, De-confinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

➪ **n_q-scaling** novel hadronization process

➪ **Partonic flow** De-confinement

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05) nucl-ex/0405022, QM05*

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

sQGP and the QCD Phase Diagram

In 200 GeV Au+Au collisions at RHIC, strongly interacting matter formed:

- **Jet energy loss: R_{AA}**
- **Strong collectivity: v_0, v_1, v_2**
- **Hadronization via coalescence: n_q-scaling**

Questions:

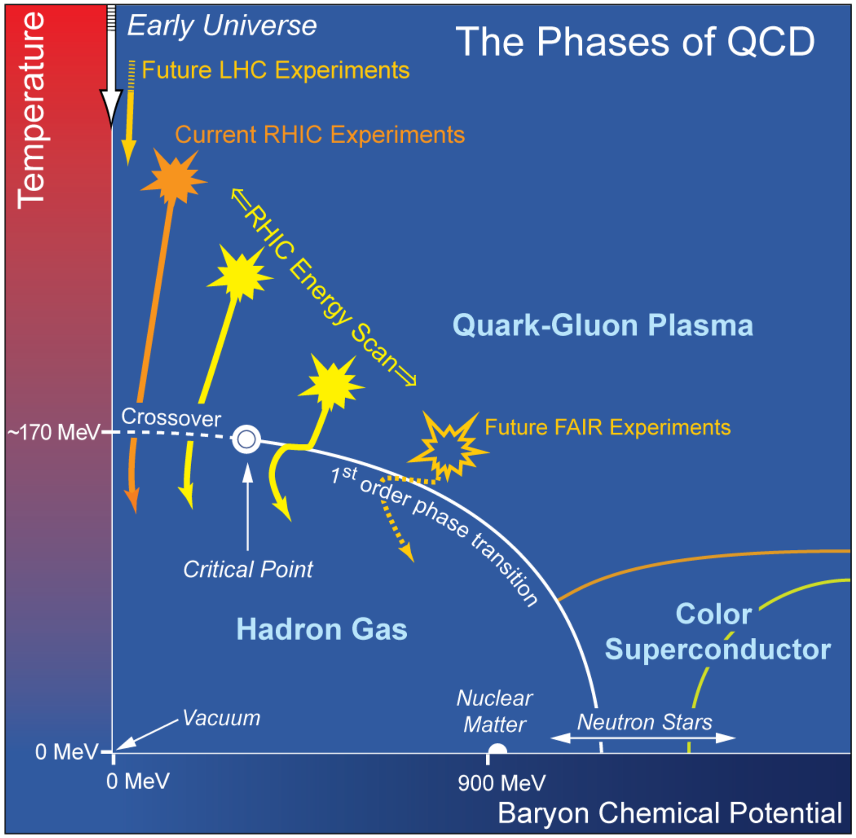
Is thermalization reached at RHIC?

- **Systematic analysis with dN/dp_T and dv_2/dp_T results…**
- ***Heavy quark and di-lepton measurements***

When (at which energy) does this transition happen?
What does the QCD phase diagram look like?

- ***RHIC beam energy scan***

The QCD Critical Point



RHIC (200) & LHC: Determine the temperature T_{ini}, T_C

BES: Explore the QCD phase diagram T_E **and the location *phase boundary***

- Low baryon density, cross over

- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram* at finite baryon chemical potential.

- Experimental evidence for either the critical point and/or 1st order transition is important for our knowledge of the QCD phase diagram*.

** Thermalization assumed*

*M. Stephanov, K. Rajagopal, and E. Shuryak, PRL **81**, 4816(98); K. Rajagopal, PR **D61**, 105017 (00)*

http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf

RHIC run10 Physics Programs

RHIC cool down early Dec.

STAR shift starts Dec. 15th

Beam Energy (GeV)	25 cryo-week	30 cryo-week	20 cryo-week CR	Physics
200	10	10	10	Thermalization J/Ψ v_2, m_{ee}
62.4	4	4	***5***	
39	1	1.5		BES programs, T_E, *phase boundary*
27	2	4.5		
18	0	1.5		
11.5	2	2.5	***2.5***	
7.7	1	1	***2.5***	

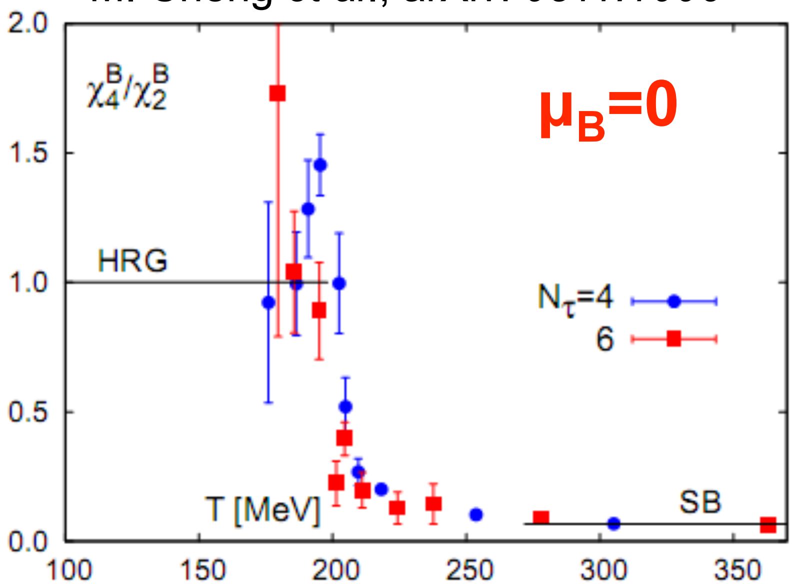
Exploring the QCD Phase Diagram

(1) Proposal II: *NQ scaling in v_2* for locating the possible QCD phase boundary

(2) Proposal I: *high moments* for locating the possible QCD critical point

Susceptibilities and High Moments

M. Cheng *et al*., arXiv: *0811.1006*



(I) Susceptibilities from the lattice QCD calculations

$$\chi_2^X = \frac{1}{VT^3}\left\langle \delta N_X^2 \right\rangle$$

$$\chi_4^X = \frac{1}{VT^3}\left[\left\langle \delta N_X^4 \right\rangle - 3\left\langle \delta N_X^2 \right\rangle^2\right]$$

$$\chi_4^X / \chi_2^X \Rightarrow \kappa^X$$

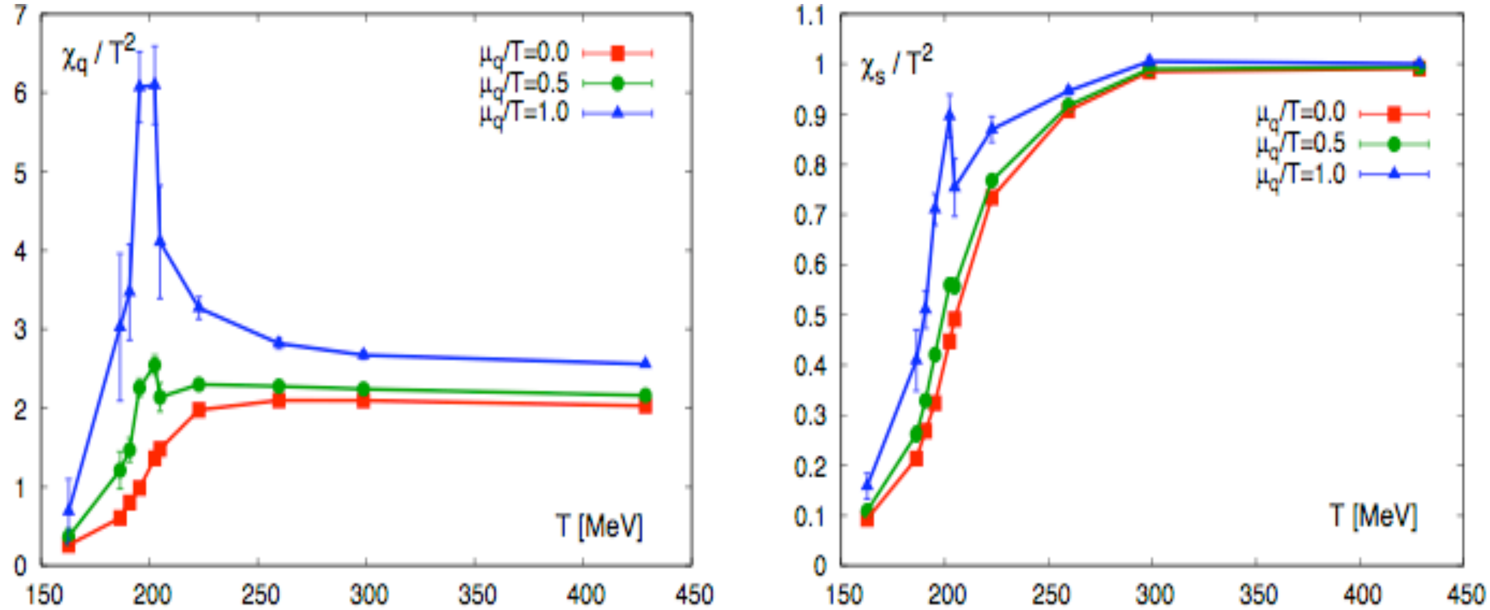
(II) At the CP at finite value of μ_B, the power of the correlation length of the system is proportional to the order of the moments:

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

Increase of the ***non-Gaussian*** fluctuation at the critical point

M. Stephanov, PRL ***102***, 032301(09)

Observables: χ_q, χ_S



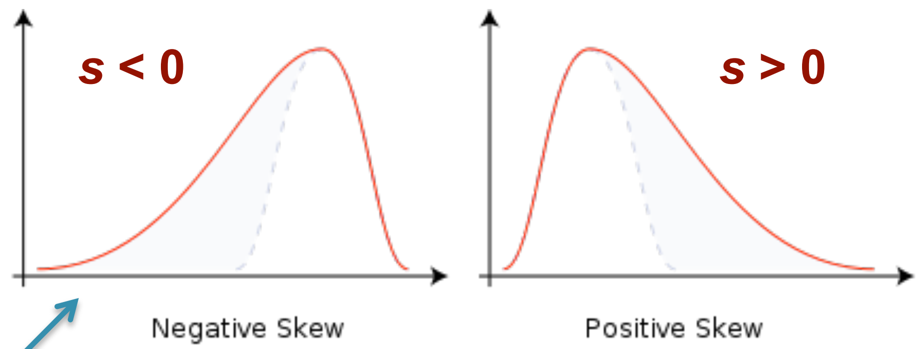
Event by Event:

1. net-proton Kurtosis $K_p(E)$
2. two proton correlation function $C_2(E)$
3. ratio of the d/p
4. ratio of K/p

$$K_p = \frac{\langle N_p^4 \rangle - 3\langle N_p^2 \rangle^2}{\langle N_p^2 \rangle}$$

M. Cheng et al., PRD79, 074505(09);arXiv:0811.1006
F. Karsch, INT, 08
M. A. Stephanov, PRL ***102****, 032301(09)*

Basics on Skewness and Kurtosis

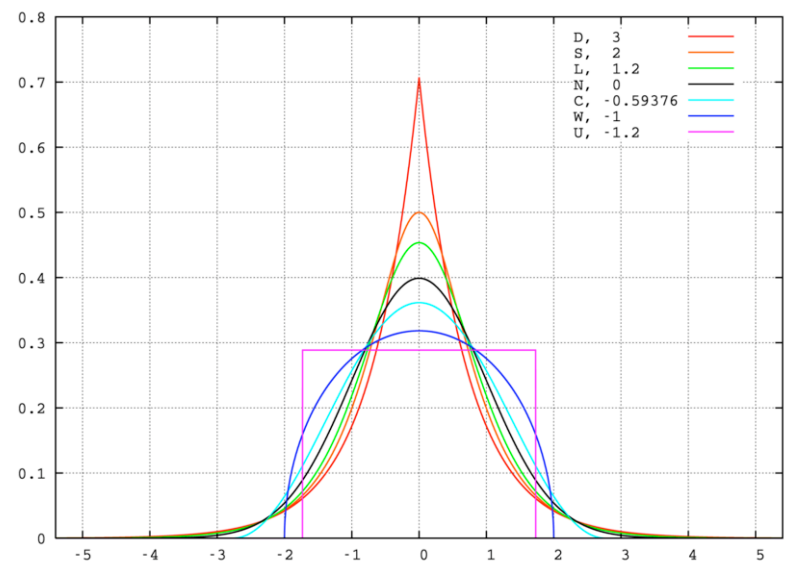


Mean: $M = \langle N \rangle$

Variance: $\sigma^2 = \left\langle \left(N - \langle N \rangle\right)^2 \right\rangle$

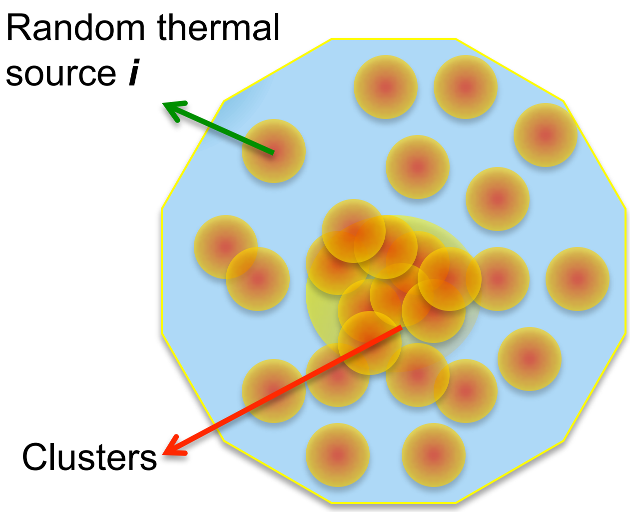
Skewness: $s = \dfrac{\left\langle \left(N - \langle N \rangle\right)^3 \right\rangle}{\sigma^3}$

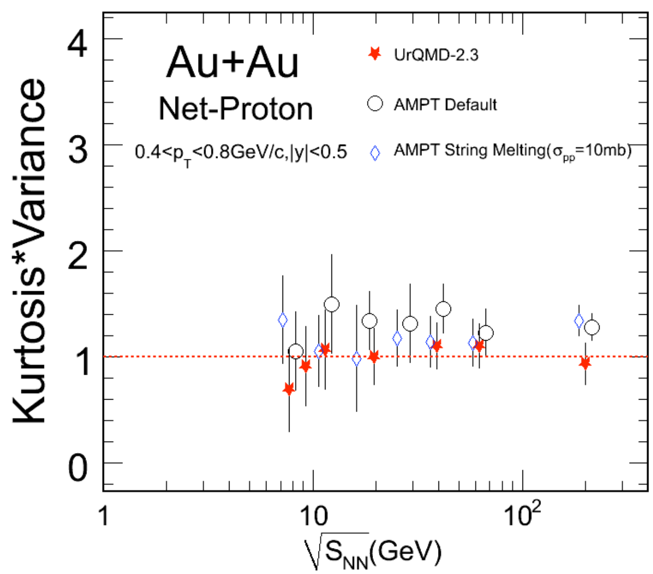
Kurtosis: $\kappa = \dfrac{\left\langle \left(N - \langle N \rangle\right)^4 \right\rangle}{\sigma^4} - 3$



s(Gaussian) = ***κ***(Gaussian)=0, ***Probe of non-Gaussian fluctuation.***

Random Sources and Critical Point





(1) The sum of independent thermal sources is also a random thermal source. The multiplicity distribution is *Possion* and follows the CLT.

(2) In the absence of CP, it can be shown:

$$\kappa * \sigma^2 = const. \quad \propto \quad \frac{\chi_4}{\chi_2} T^2$$

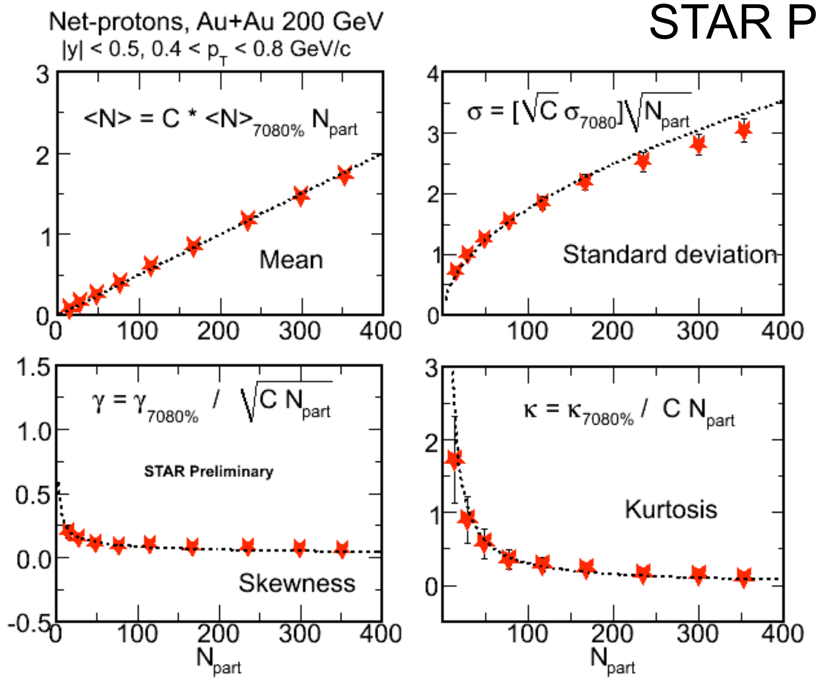
$$s * \sigma = const. \quad \propto \quad \frac{\chi_3}{\chi_2} T$$

Lattice results

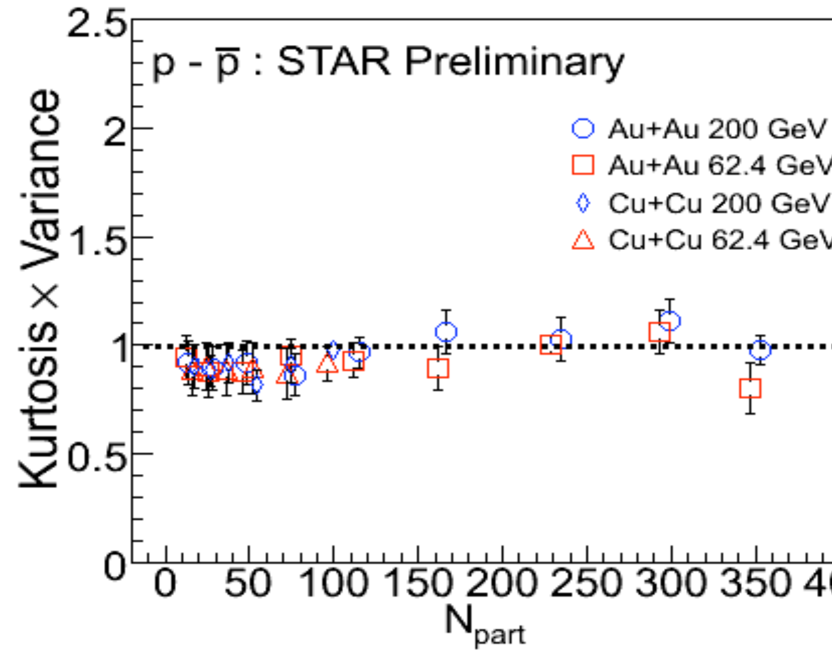
(3) Energy and centrality (volume) dependence of the non-Gaussian behavior => ***Critical Point!***

(4) Extract thermodynamic ***properties of the medium!***

Higher Moments Analysis (BES)



STAR Preliminary, QM09

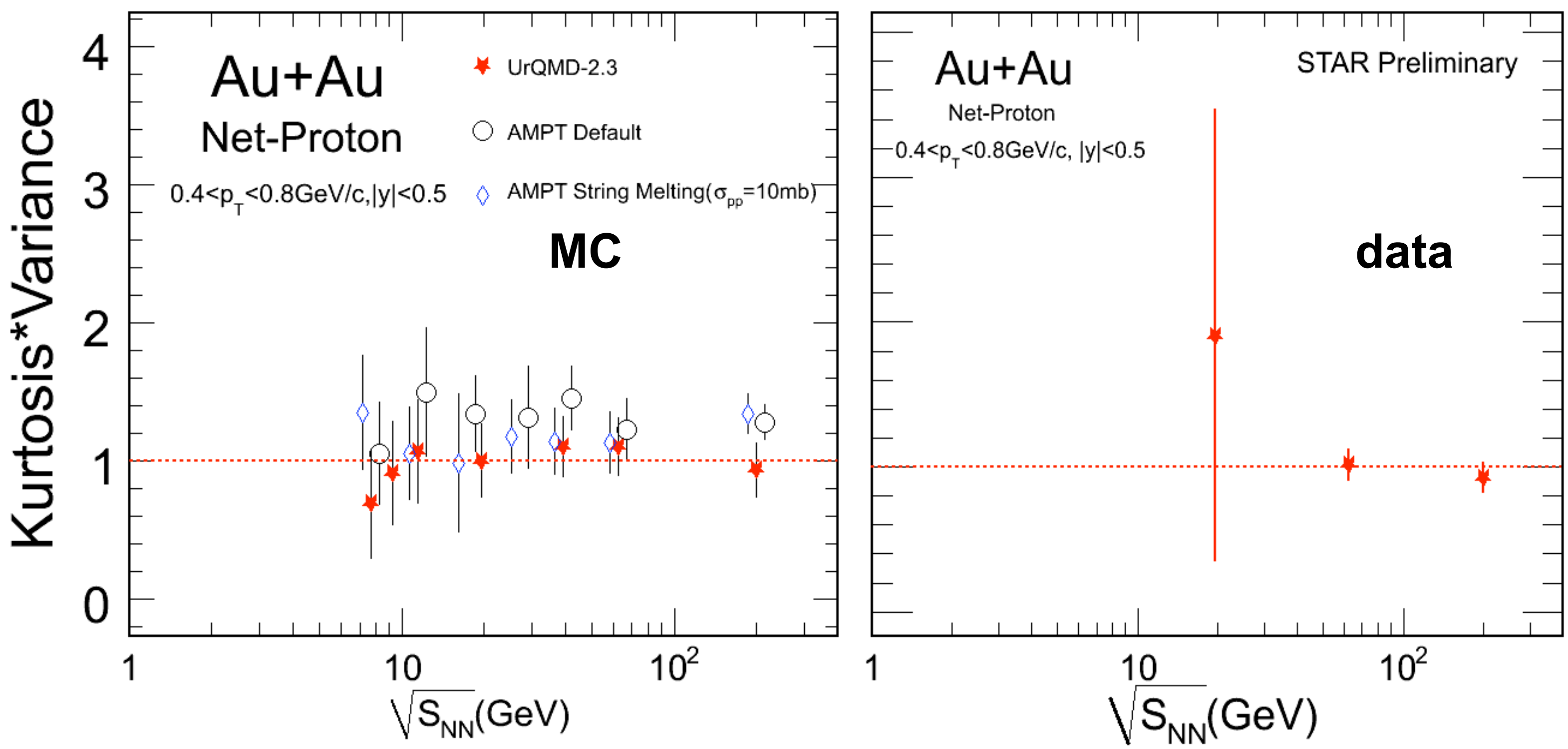


QM09: arXiv 0907.4542

1) Higher moments are more sensitive to QCD critical point related fluctuation.

2) The 4th moment, Kurtosis, is directly related to the corresponding thermodynamic quantity: susceptibility of conserved quantum numbers such as Baryon number and strangeness.

$\kappa\bullet\sigma^2$ vs. Collision Energy



- Energy and centrality dependence of $\kappa\bullet\sigma^2$
- Flat results from models without the CP

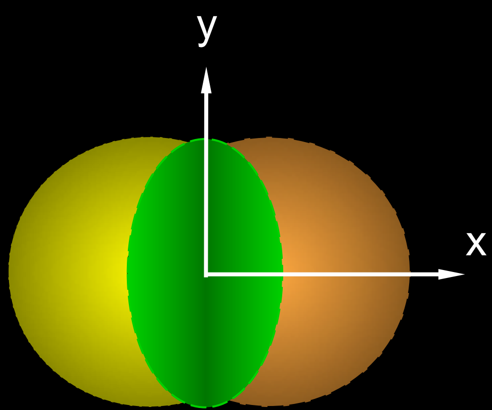
Summary I

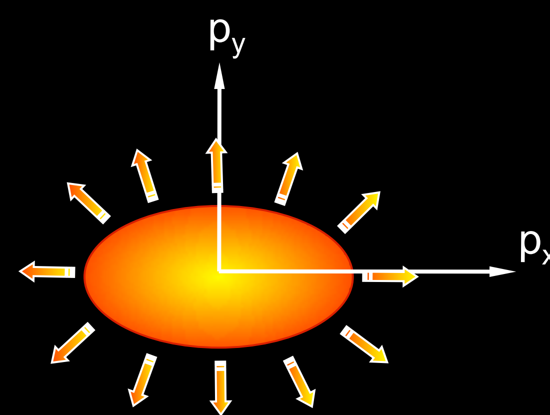
1) Beam energy scan (BES) at RHIC is an important/ necessary step forward for exploring the QCD phase diagram with high-energy nuclear collisions
2) LGT predicts a spike at finite value of μ_B indicating the existence of CP

3) $\kappa \times \sigma^2$ for net-protons are consistent with unity for the beam energy range: $\sqrt{s_{NN}}$ = 200 - 62.4 -19.6 GeV at RHIC. Other conventional observables should also be studied.

Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

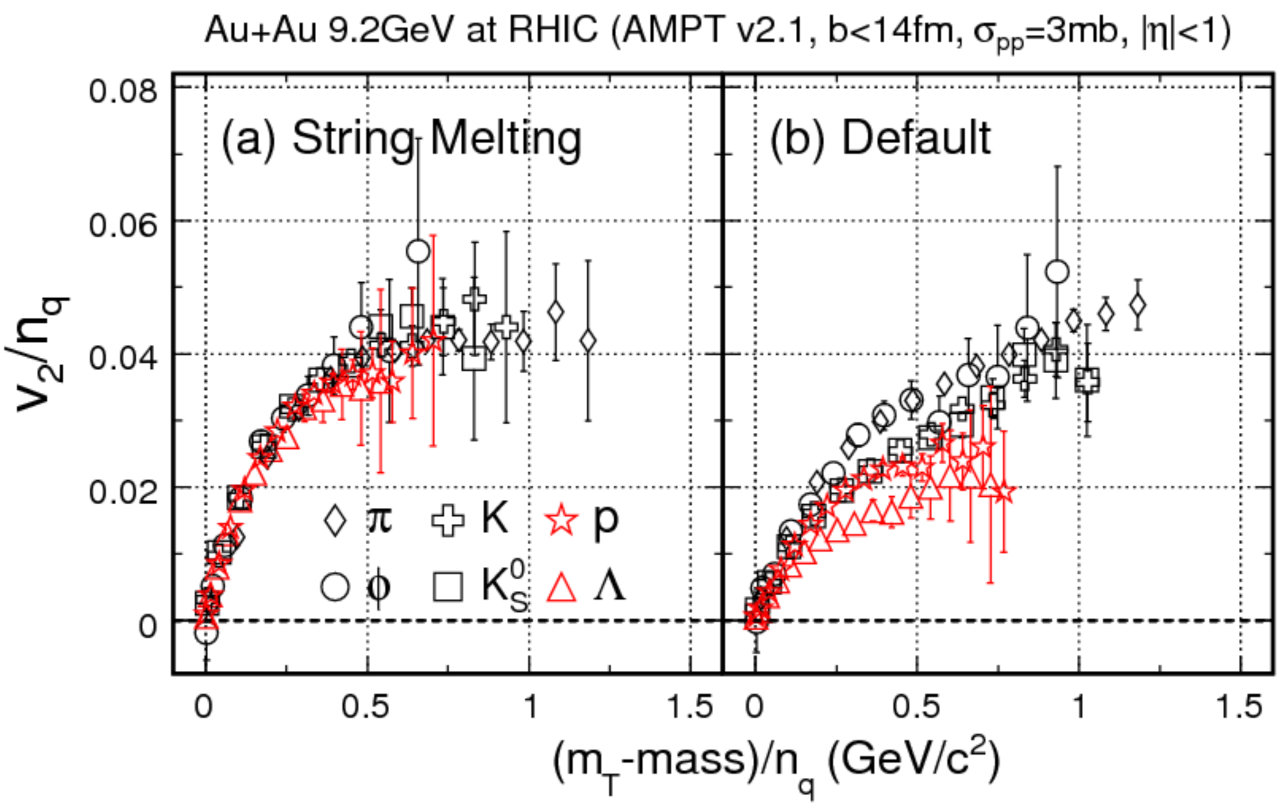




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

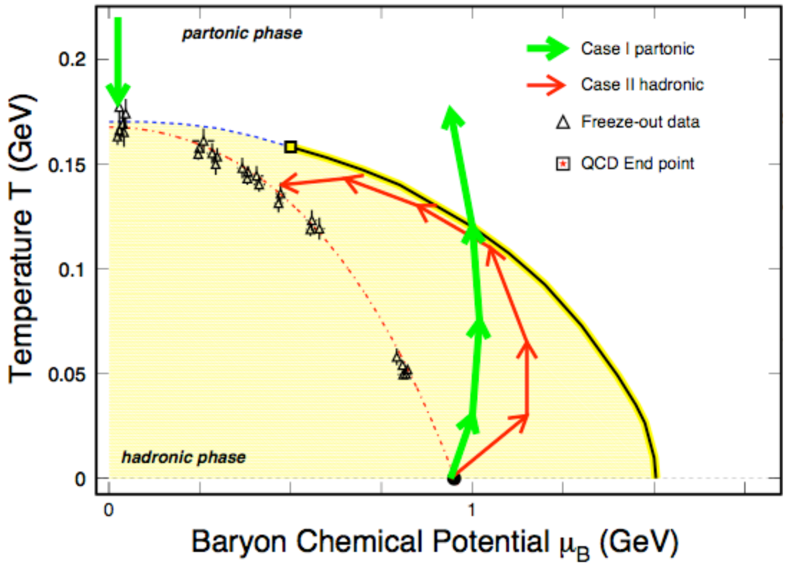
Au+Au Collisions at 9.2 GeV AMPT (v2.1)

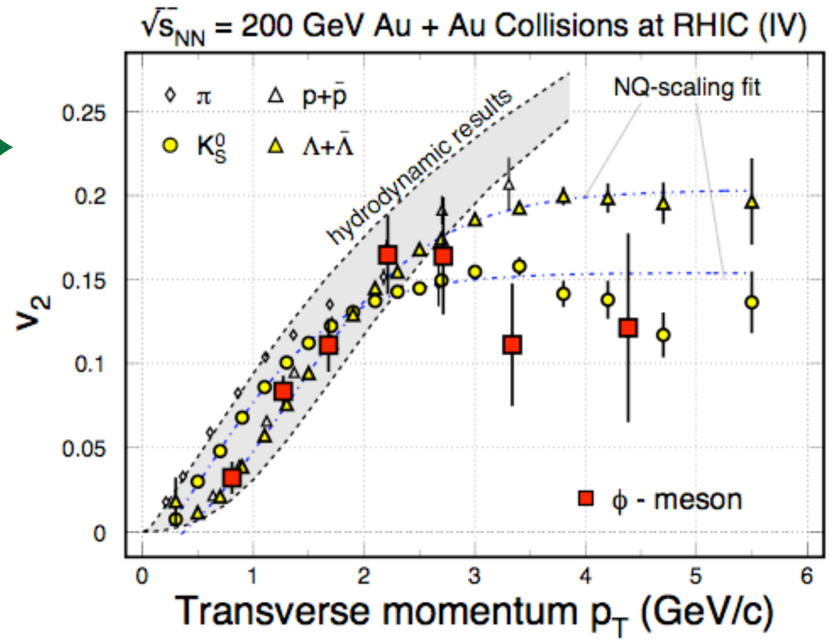


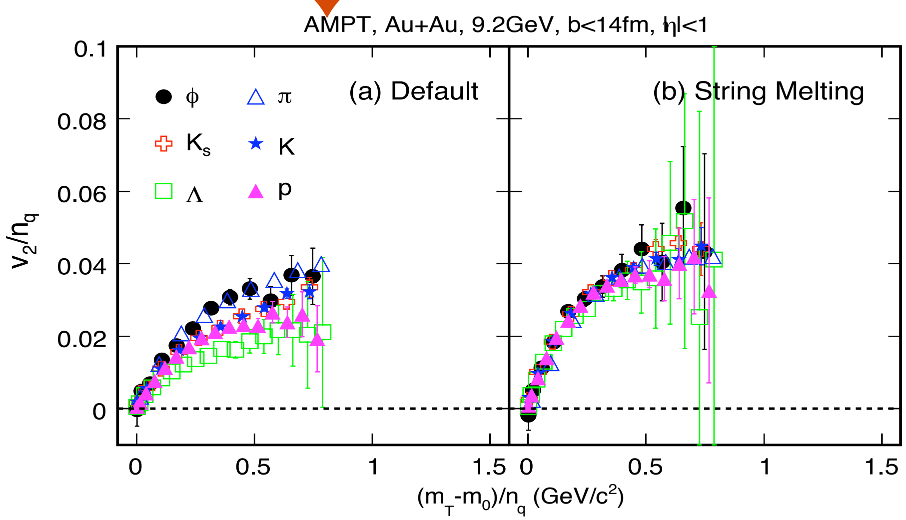
J. Tian *et al,* Phys. Rev. **C79**, 067901(2009).

(a) Patonic matter: coalescence of massive quarks for hadronization ➔ Clear NQ scaling in v_2 !	***(b) Hadronic matter:*** rescatterings amongst hadrons ➔ No NQ scaling in v_2 !

Observable*: Quark Scaling in v_2







- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi, \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

Summary II

1) NQ scaling in v_2: partonic collectivity & de-confinement in high-energy nuclear collisions.
2) Scaling in v_2: partonic dof dominants
   No scaling in v_2: hadronic dof dominants
3) The multi-strange hadrons are particularly clean for the search, φ, for example.

Other Observables

(1) Local parity violation

(2) Event-by-Event fluctuations:

N(K)/N(pion), *N(K)/N(p)*, $<p_T>$, …

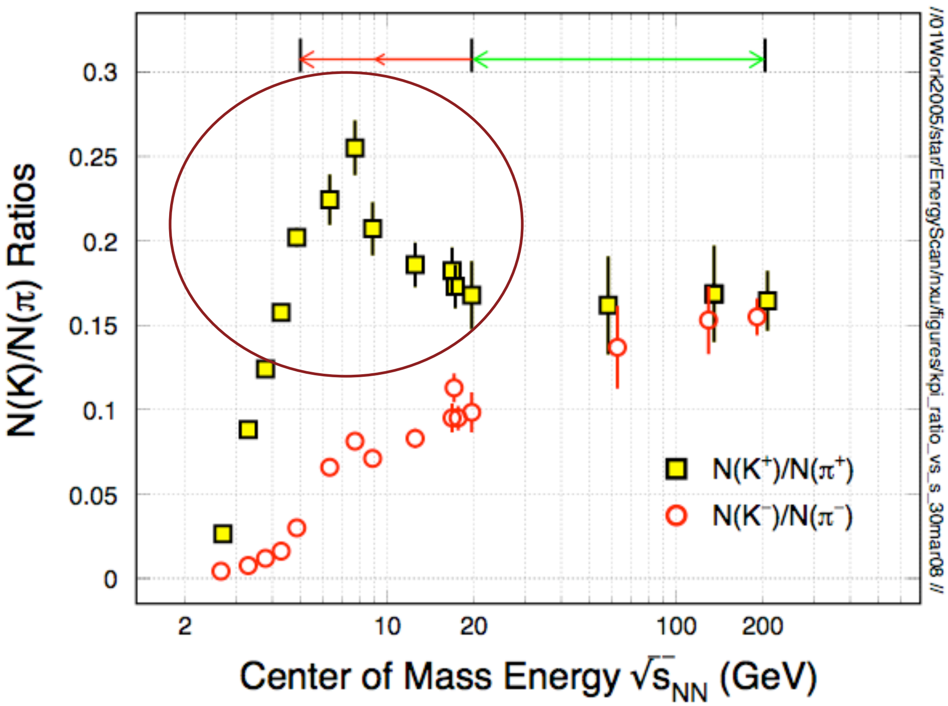
(3) Correlation functions:

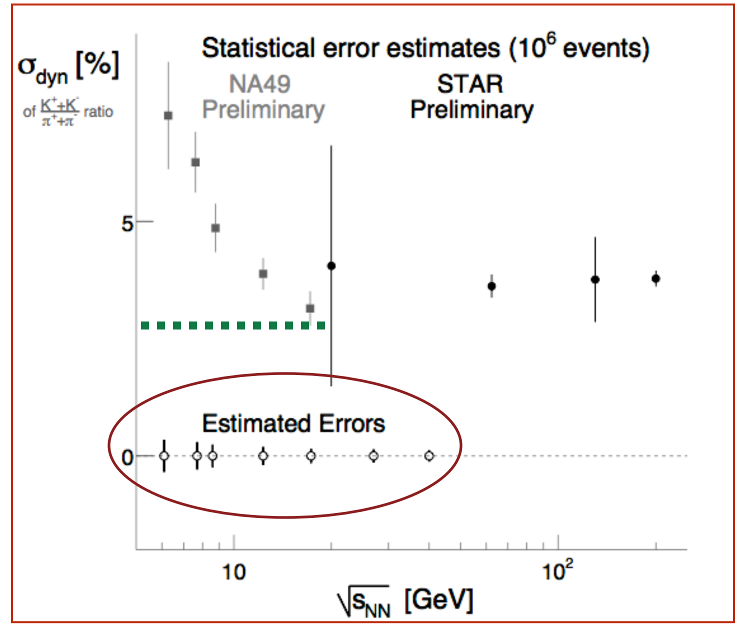
BB, MM, MB, clusters, light nuclei

(4) … *Chiral* properties (?)

Observables and Advantages

SPS RHIC

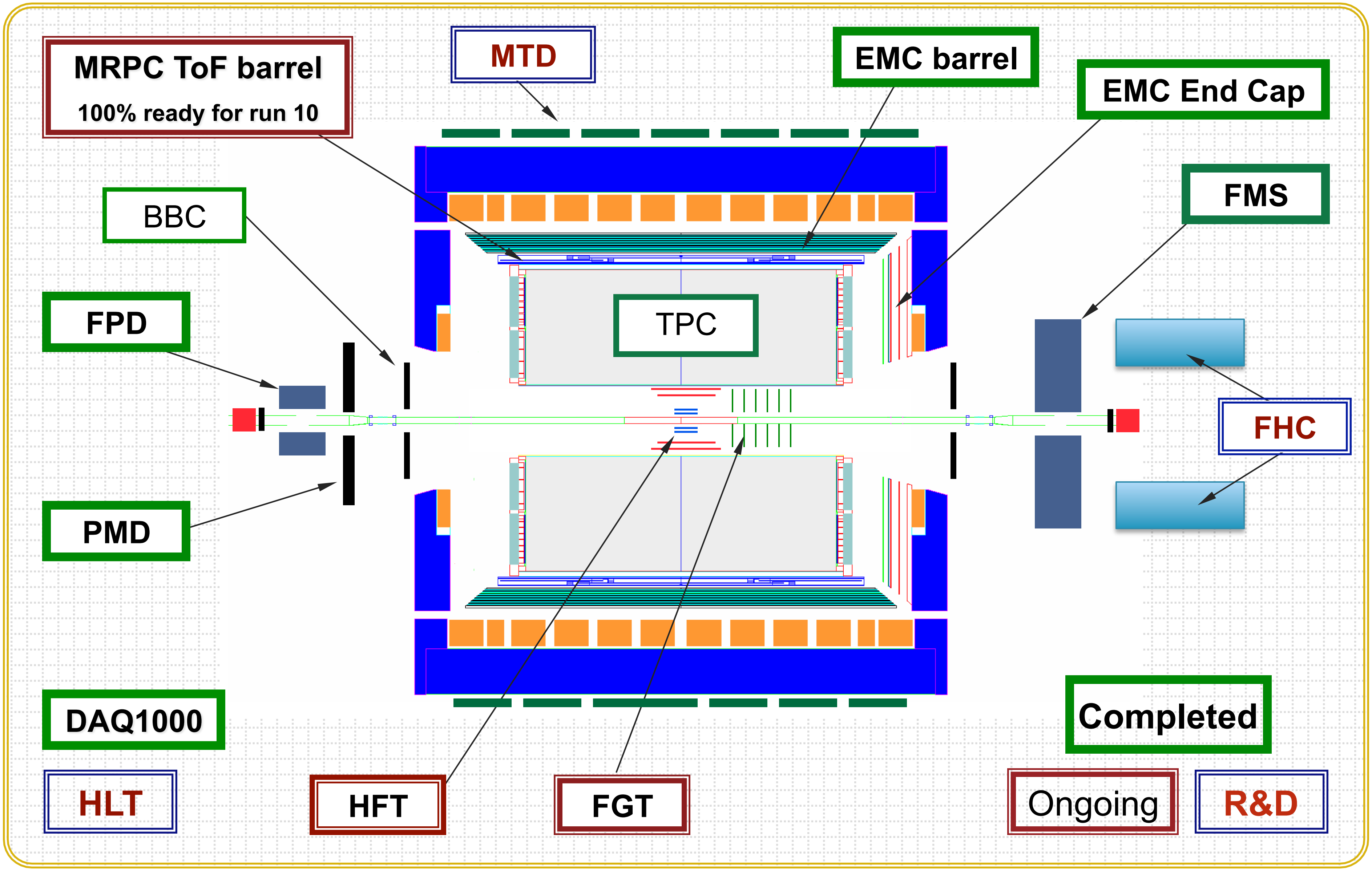




Torrieri

For STAR:
- Large acceptance: full azimuthal coverage and |y| < 1.0
- Clean particle identification: (TPC, ToF, EMC)
- Acceptance does ***not*** change with beam energy, systematic errors under control
- *Lower luminosity* at lower beam energies. Fixed target exp. will be better

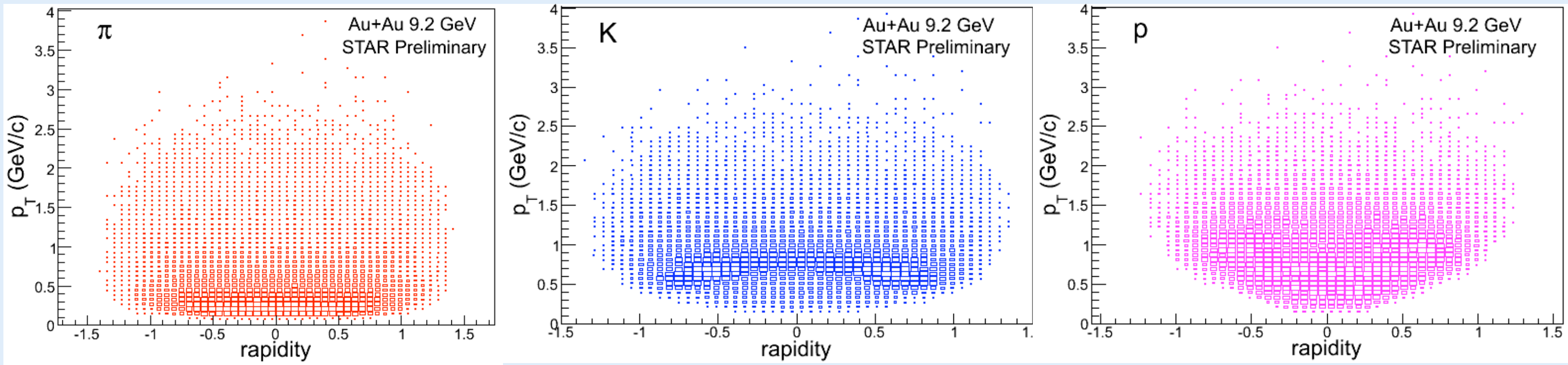
STAR Detector



Collider Acceptance

Collider Mode STAR

$\sqrt{s_{NN}}$ = 9.2 GeV Au+Au Collisions at RHIC

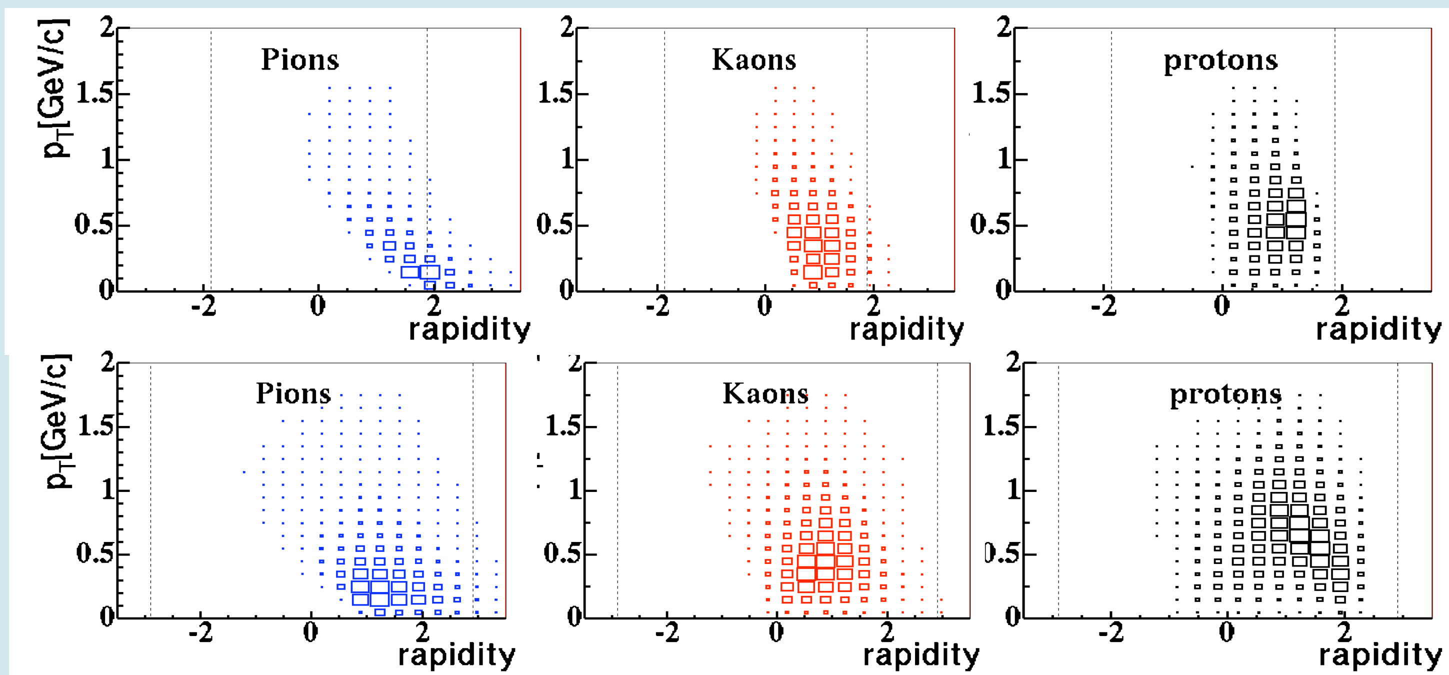


Fix-target Mode NA49

$\sqrt{s_{NN}}$

6 GeV

17 GeV



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