The STAR Beam Energy Scan (BES) program at RHIC

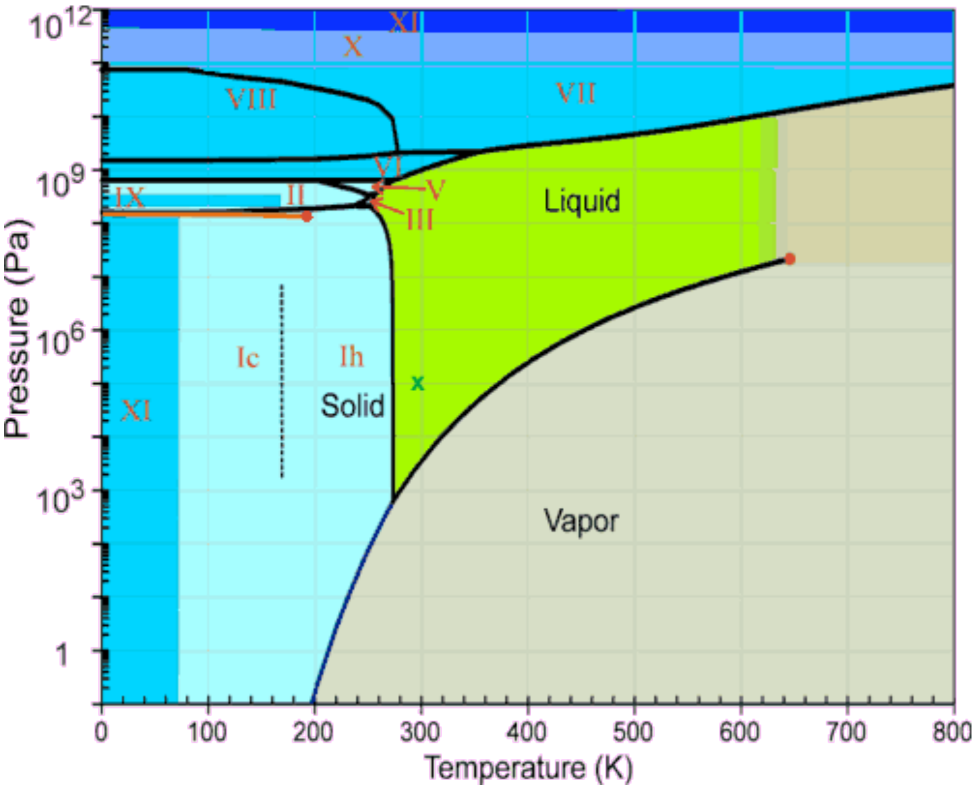
Michael K. Mitrovski
for the
STAR Collaboration

Outline

1. Introduction.
2. The STAR experiment.
3. Measurements used for an investigation into the onset of deconfinement and the nature of the phase transition
    a. Anisotropic flow
    b. Particle yields and spectra
    c. Event-by-Event fluctuations
    d. Beam Energy Scan program of STAR
4. Summary and Conclusions.

Phase Diagram of Strongly Interacting Matter

The phase diagram of water



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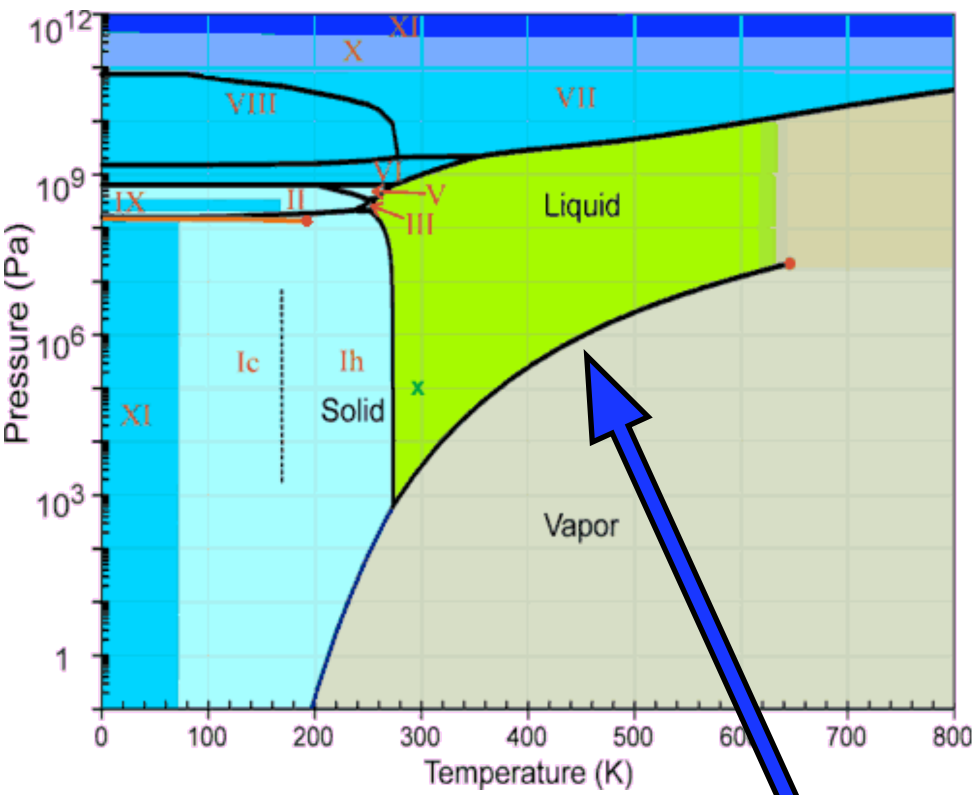

1st order phase transition

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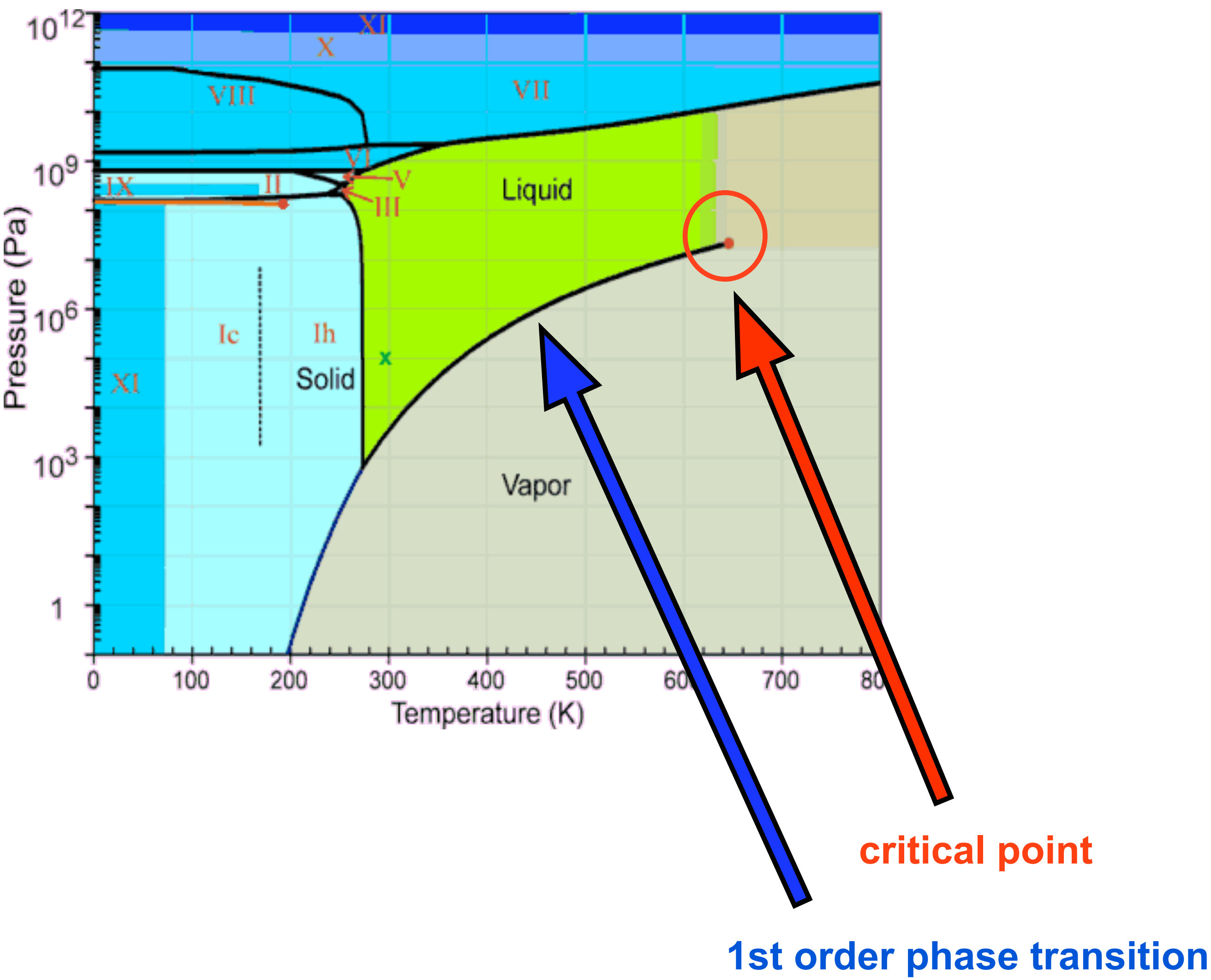

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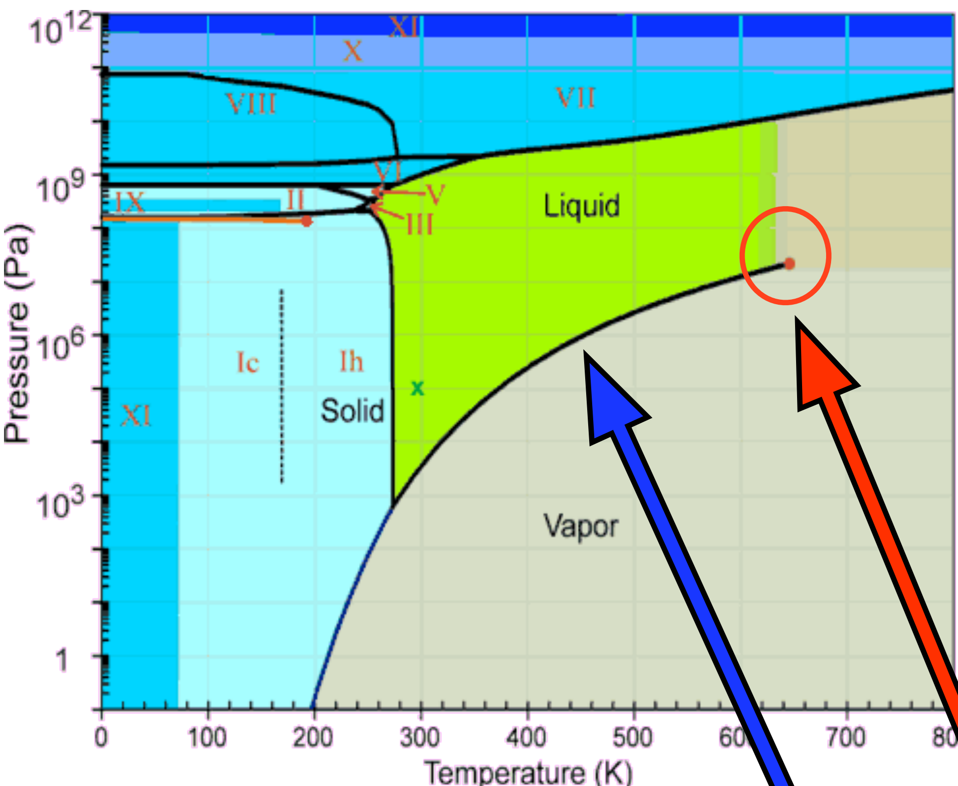
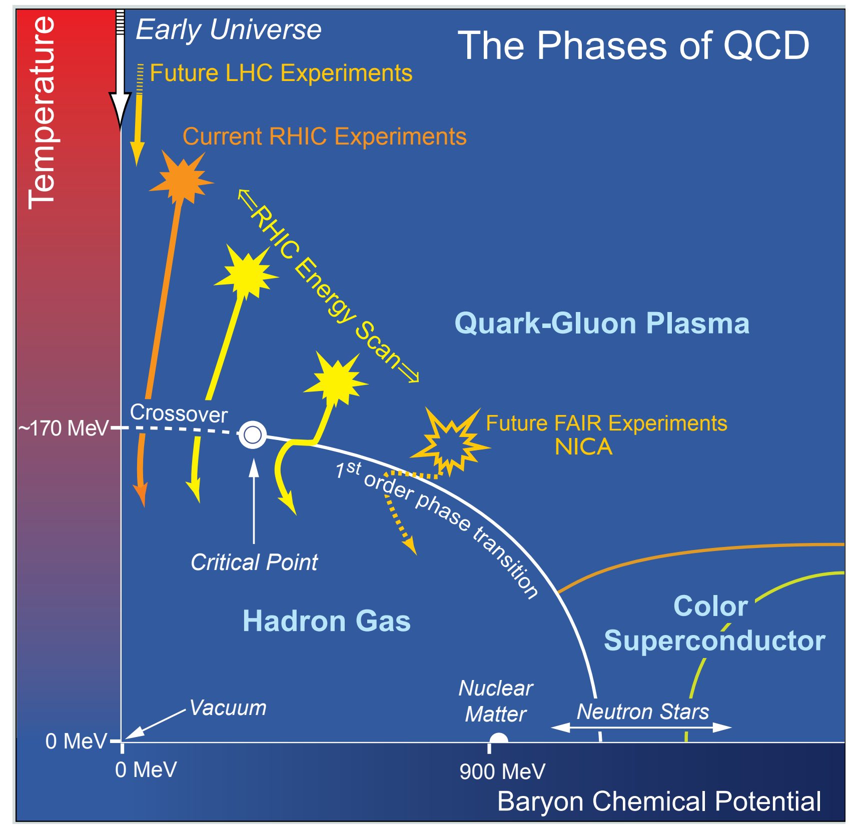


The phase diagram of strongly interacting matter is under study



critical point

1st order phase transition

USA-NSAC 2007 Long-range plan

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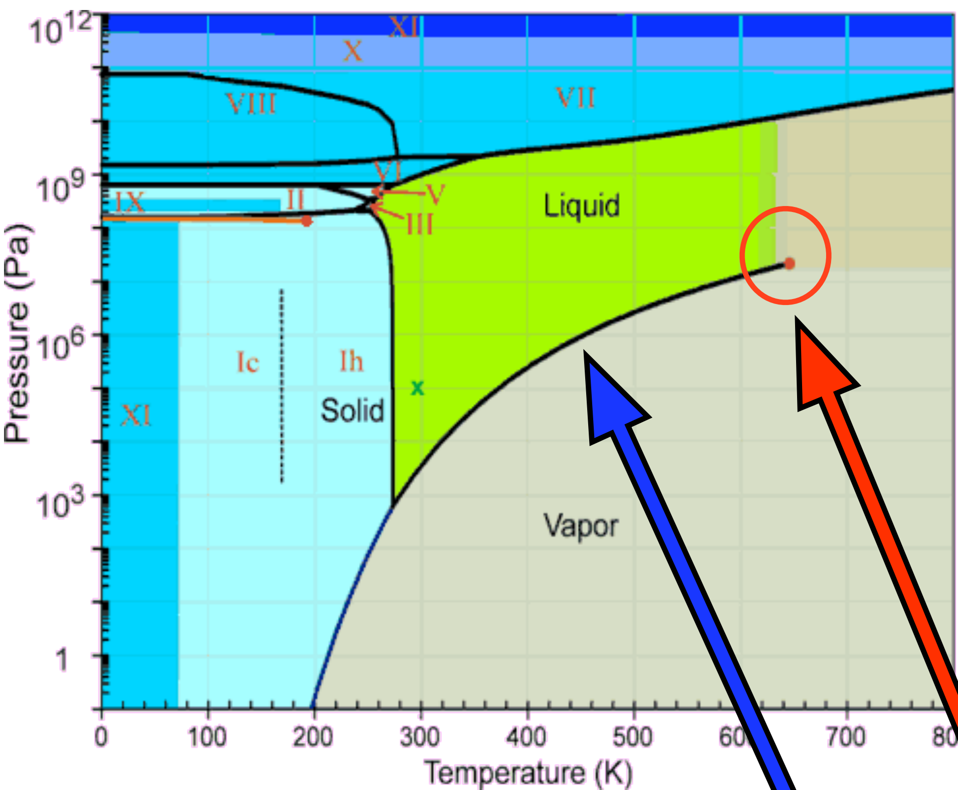

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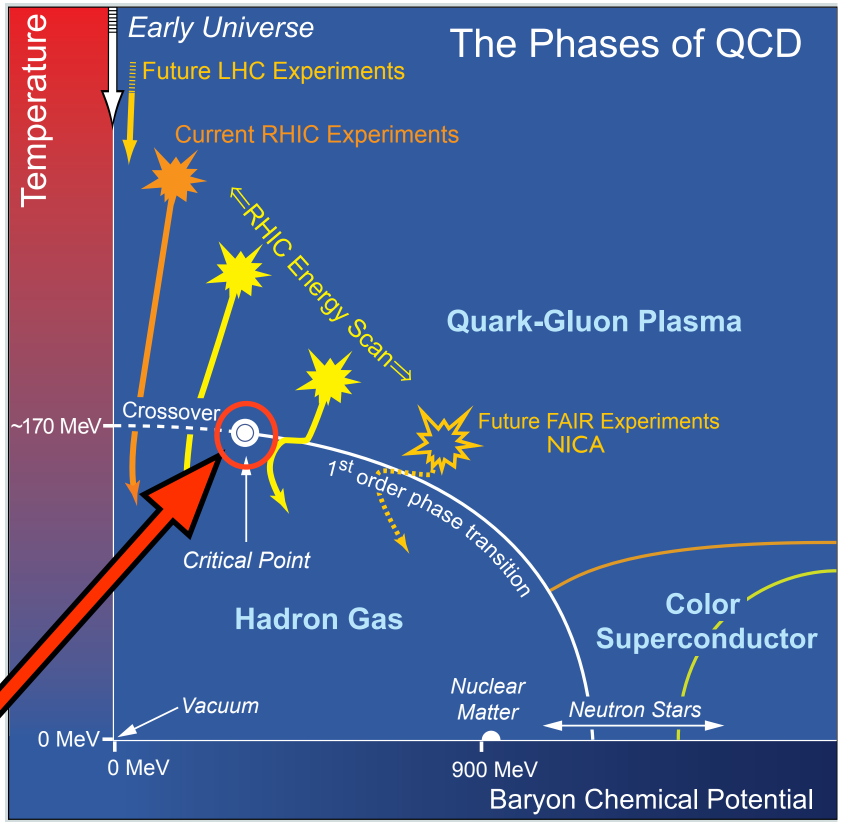

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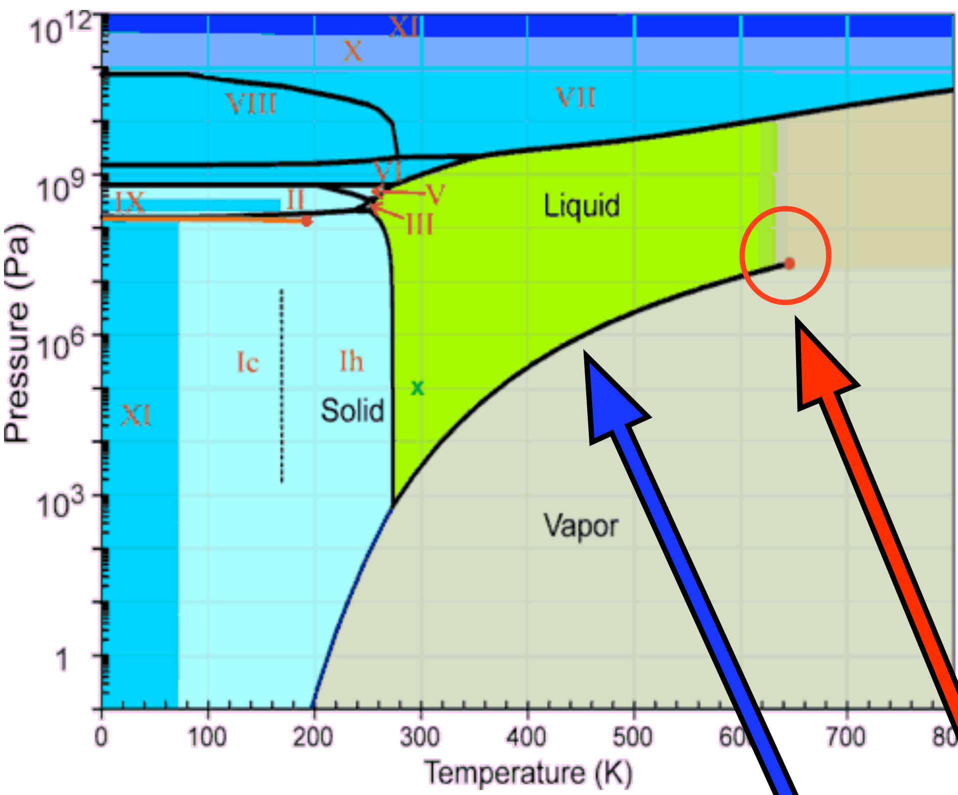

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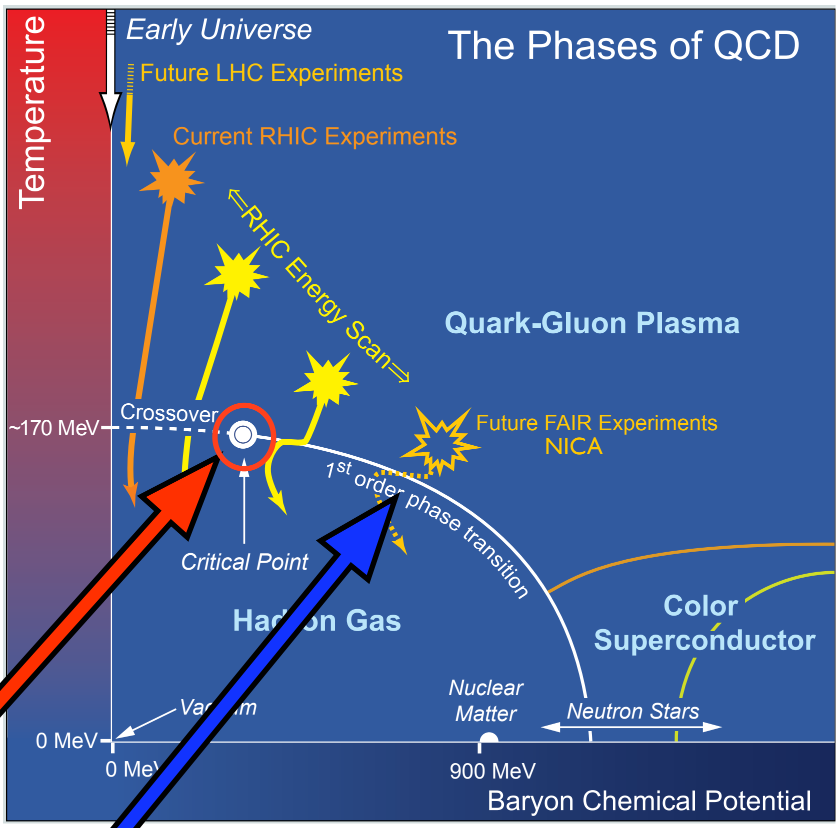

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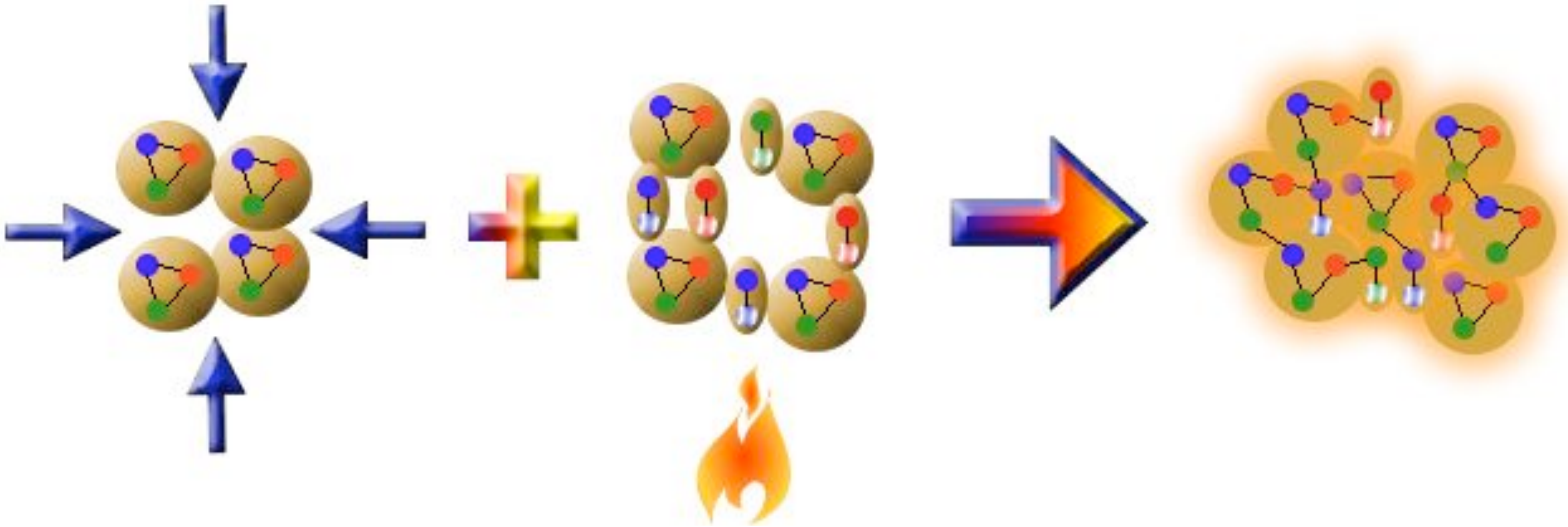
Strongly Interacting Matter in extreme conditions

Pressure + Heat → Quark-Gluon Plasma



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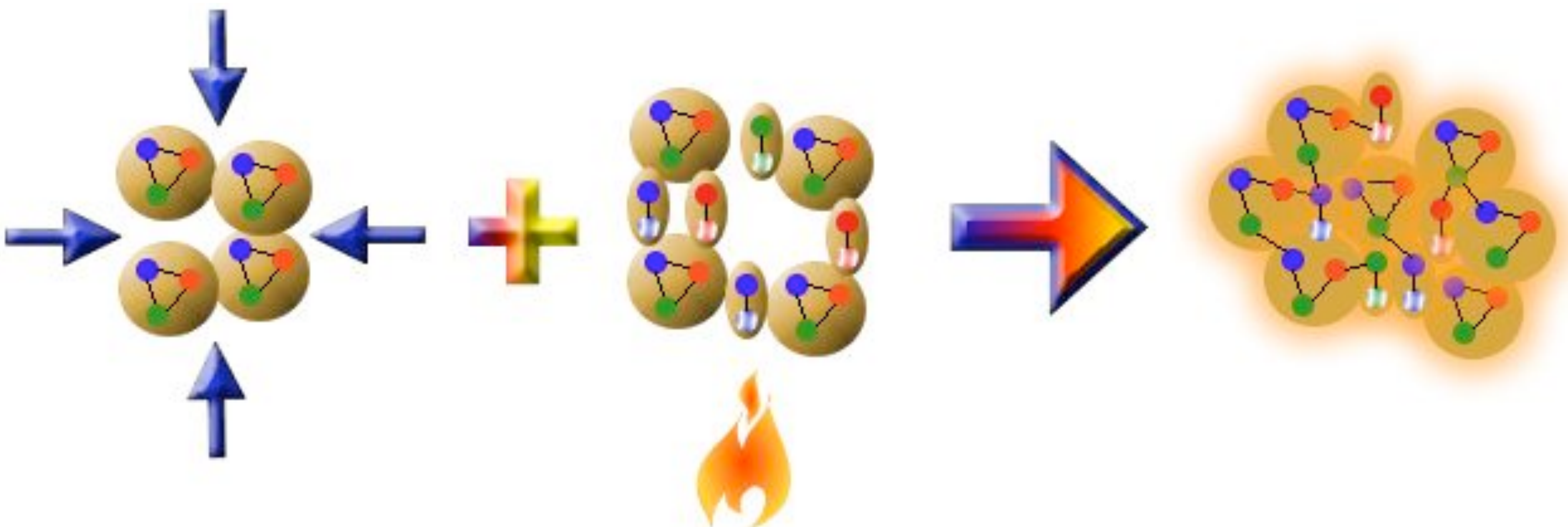
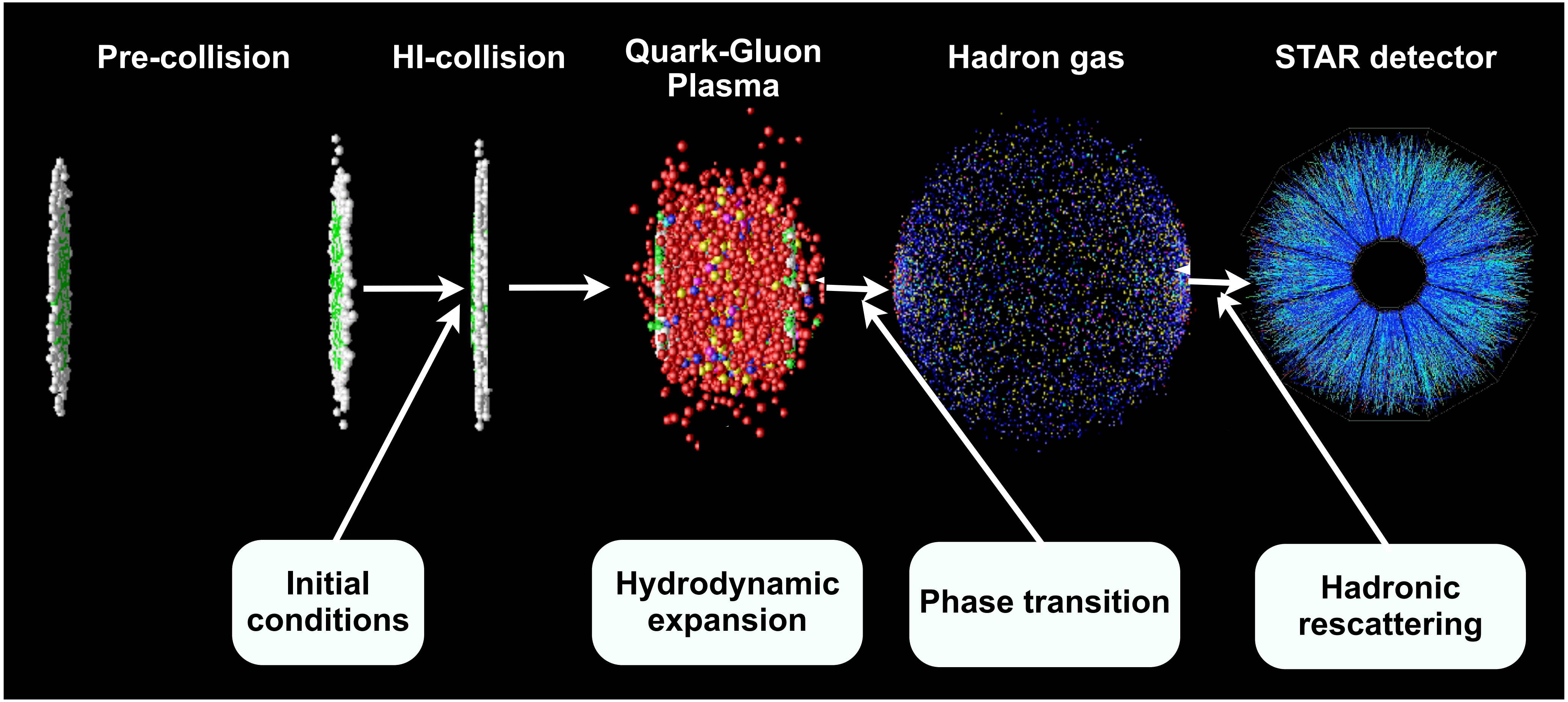


High energy densities → „Free“ quarks?

Heavy-Ion Collisions



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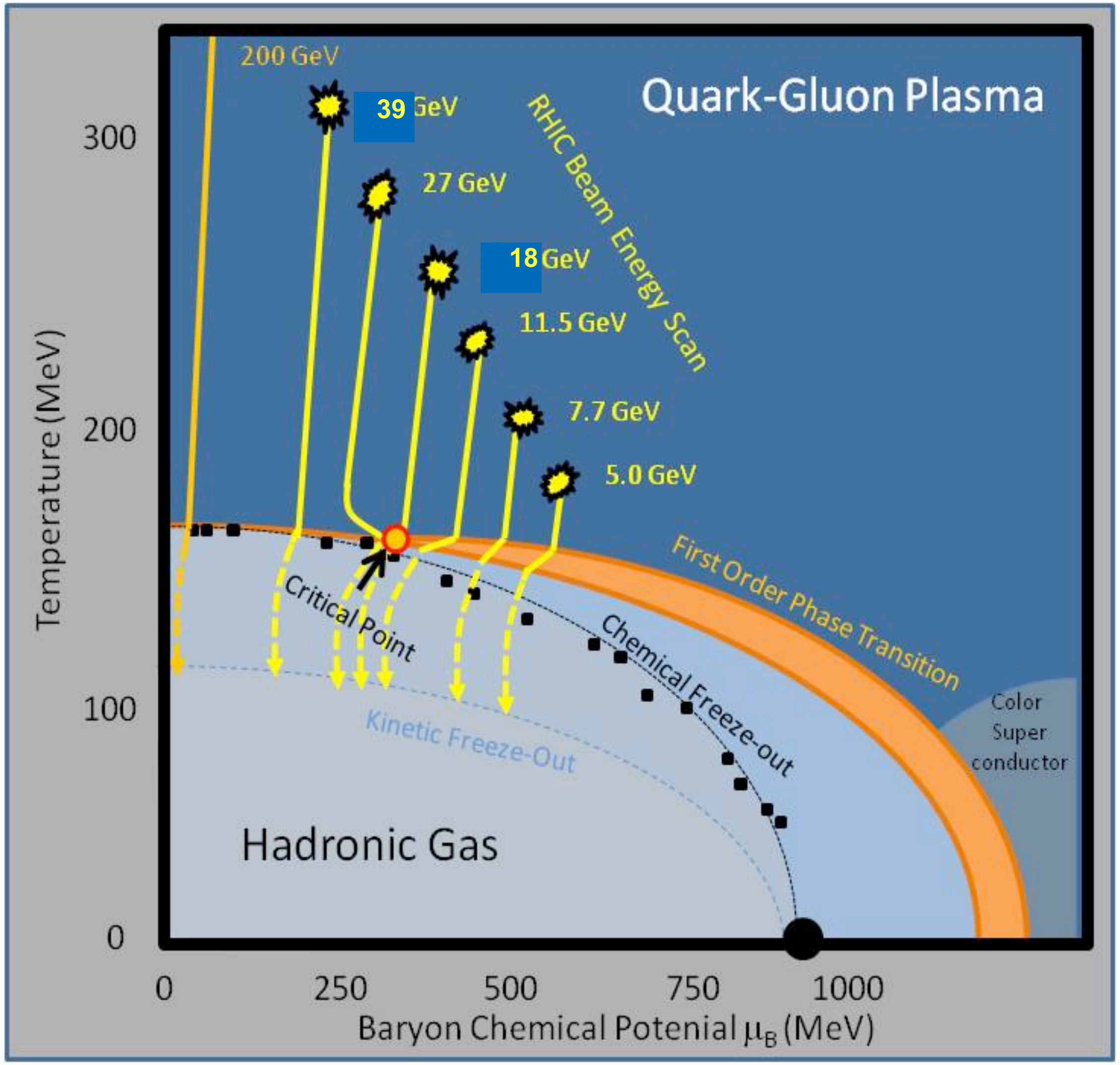

- The chemical freeze-out points extracted from the existing STAR data approaches the crossover region and are close to a possible prediction of the critical point from Lattice Theory.
- The location for the onset of deconfinement (OoD) and the critical point (CP) is theoretically not well constrained and the BES program will look for signatures for the OoD and the CP.
- Is a phase transition/critical point reflected in hadronic observables?
  - In order to search for the onset of deconfinement and the critical point RHIC started 2010 the „Beam Energy Scan" (BES) program.

  - $\sqrt{s_{NN}}$ = 7.7, 11.5, 18*, 27*, 39 GeV

USA-NSAC 2007 Long-range plan

*Will be taken in Run 2011

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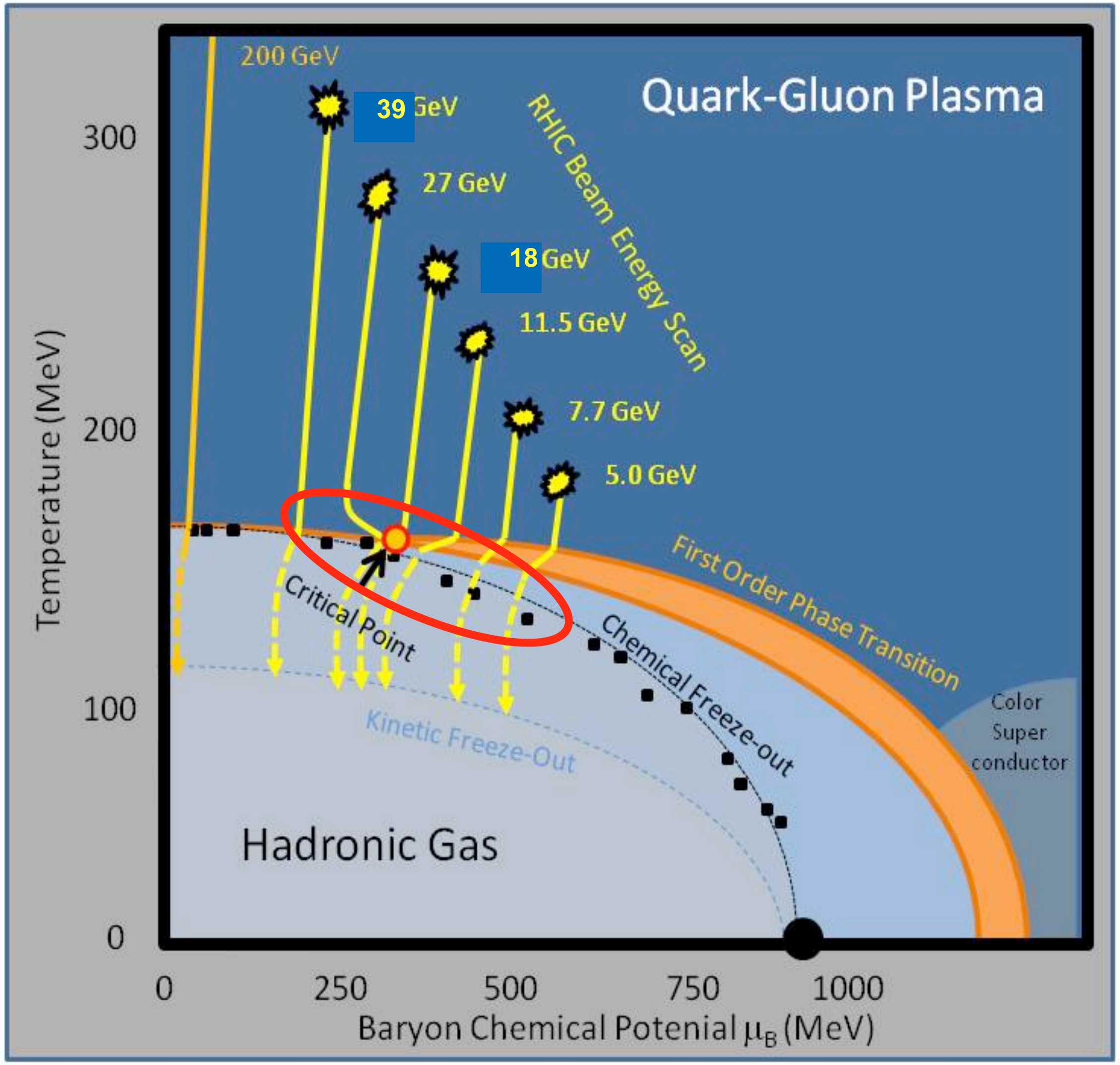

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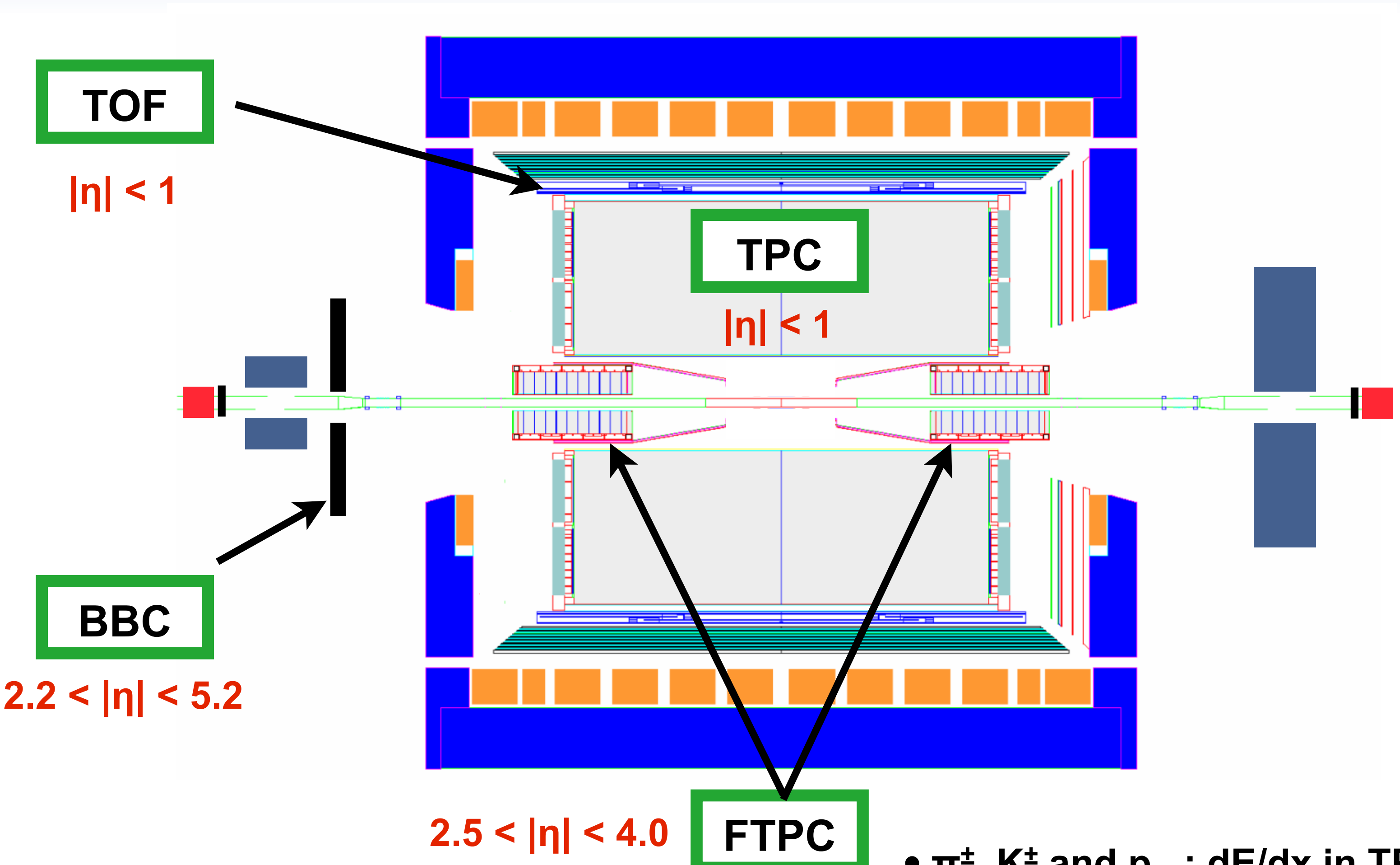
  - $\sqrt{s_{NN}}$ = 7.7, 11.5, 18*, 27*, 39 GeV
  - The BES program covers the region in the red circle

The BNL Accelerator Complex

- Beam species from p to $^{197}Au^{79+}$ (2011 with Electron Beam Ion Source (EBIS) up to U).
- Beam energy from $\sqrt{s_{NN}}$ = 7.7 - 200 GeV at RHIC.

The STAR Experiment



- $\pi^{\pm}$, $K^{\pm}$ and p : dE/dx in TPCs
- K^0_S, Λ, Ξ, Ω : decay topology + inv. mass. + dE/dx
- φ : inv. mass. + dE/dx

- TPC: Q, $\vec{x}$, $\vec{p}$, dE/dx
- TOF: time of flight

STAR Ref.: K. H. Ackermann et al.: NIM A 499 (2003) 624

Scenarios for the OoD and CP

a) Anisotropic flow

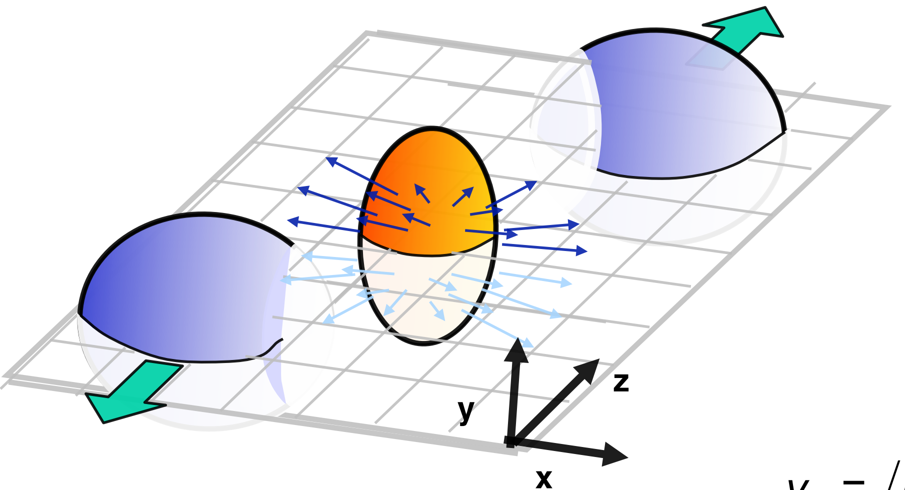
- Do we see partonic collectivity at top RHIC energies?
- Will we see a change of the EOS in the RHIC Beam Energy Scan (BES)?

b) Particle yields and spectra

c) Event-by-Event fluctuations

d) Beam Energy Scan program of STAR

Elliptic Flow



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

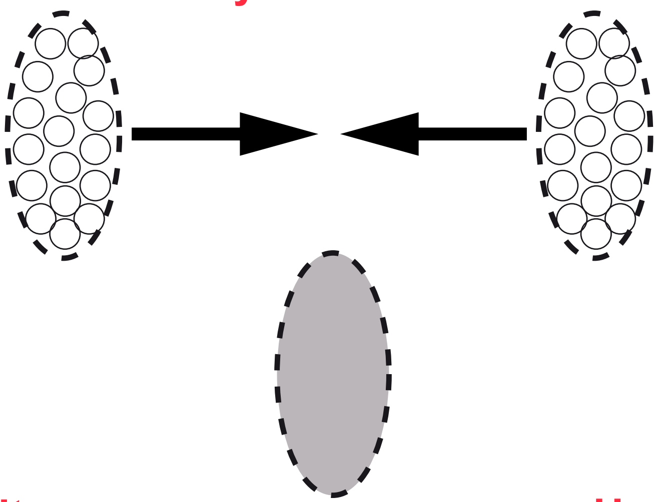
$$v_2 = \langle \cos 2\phi \rangle, \ \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

- In non central collisions the coordinate space configuration is anisotropic, but the initial momentum distribution is isotropic.
- Interaction among constituents generate a pressure gradient which transforms the initial coordinate space anisotropy into the observed momentum space anisotropy → anisotropic flow
- Elliptic flow is sensitive to the early stage of collision dynamics.

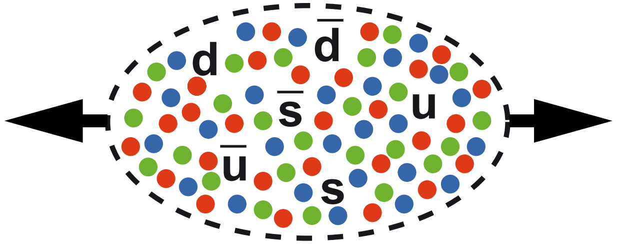
  ⇒ A unique hadronic probe of the early stage

Partonic Collectivity

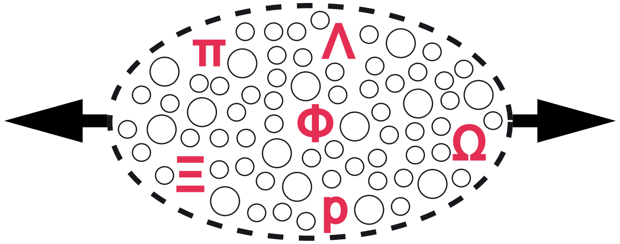
Heavy Ion collision



Partonic collectivity



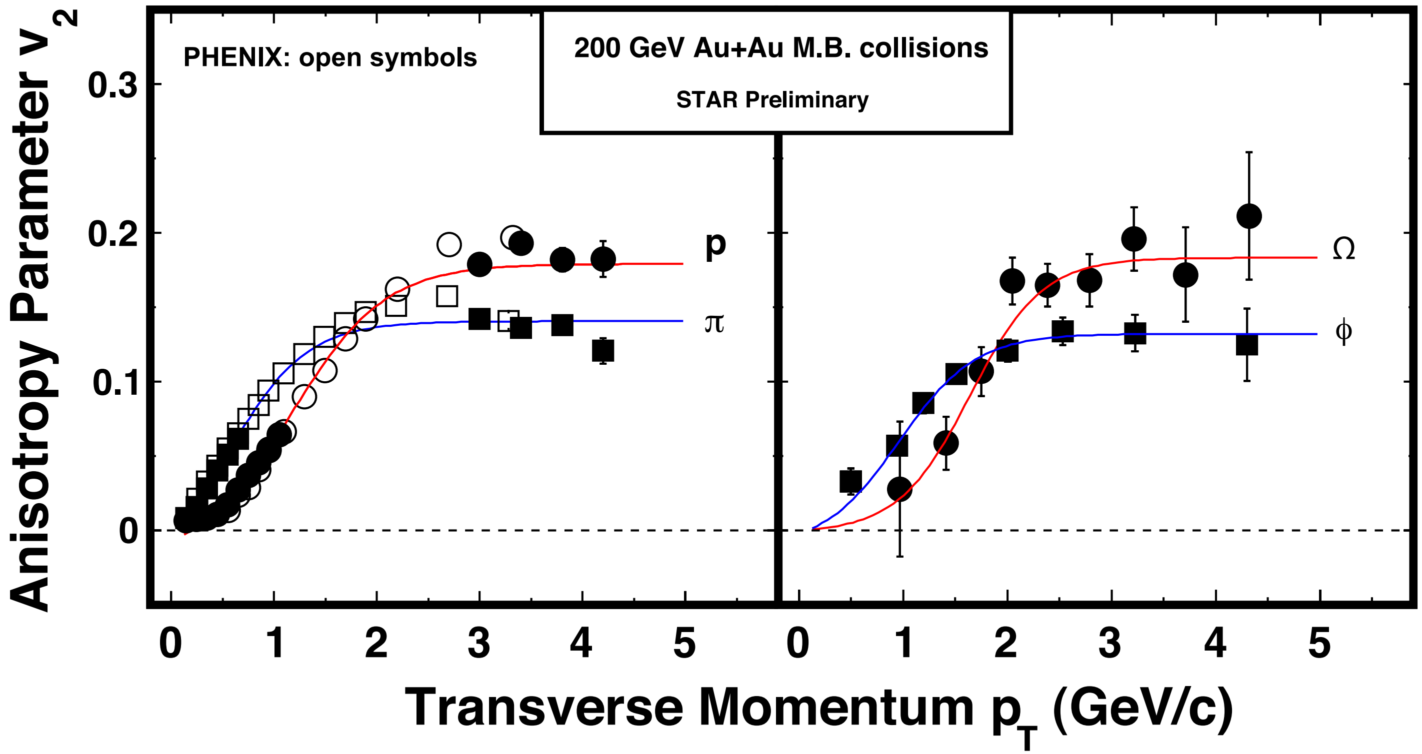
Hadronic collectivity



- Collectivity develops on the quark level and persists after hadronization.

- Collectivity develops on the hadronic level and will be different for every hadron species due to differing cross-section.

Partonic Collectivity



- At low p_t (≤ 2 GeV/c) hadronic mass ordering effect is visible.
- At high p_t (> 2 GeV/c) number of quarks ordering.

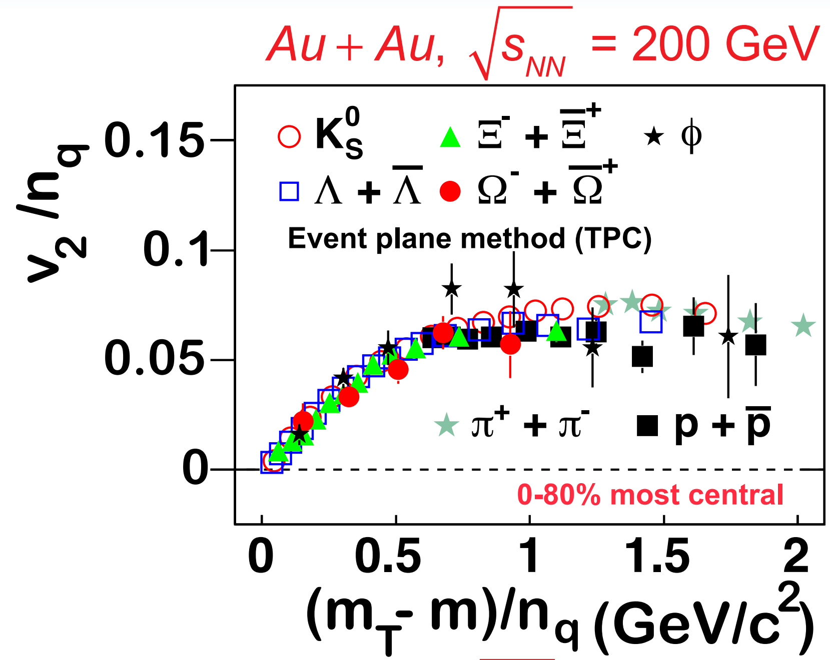
⇒ Collectivity develops at the partonic stage

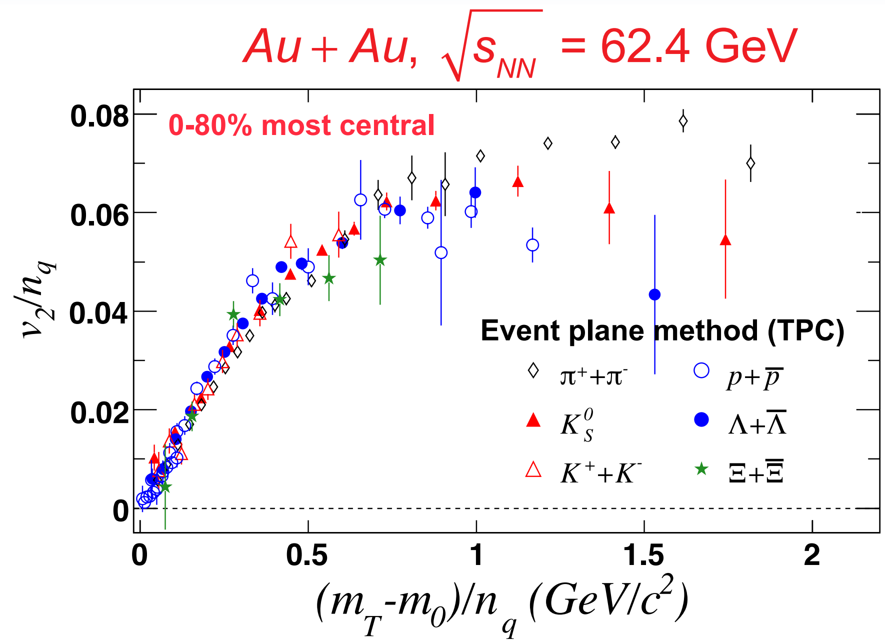
STAR Ref.: S. Shi for the STAR Collaboration: NPA 830 (2009) 187

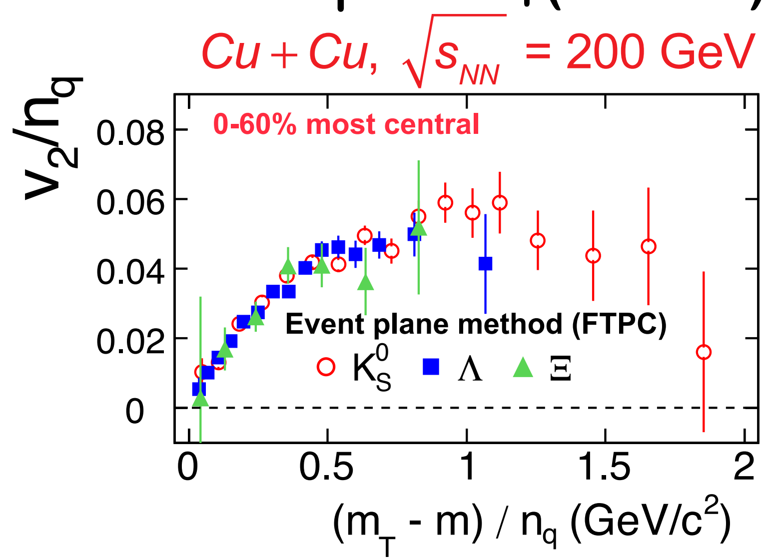
PHENIX: Issah and Tarenko, nucl-ex/0604011
NQ inspired fit: Dong et al., PLB 597 (2004) 328

a) Anisotropic flow

Partonic Collectivity





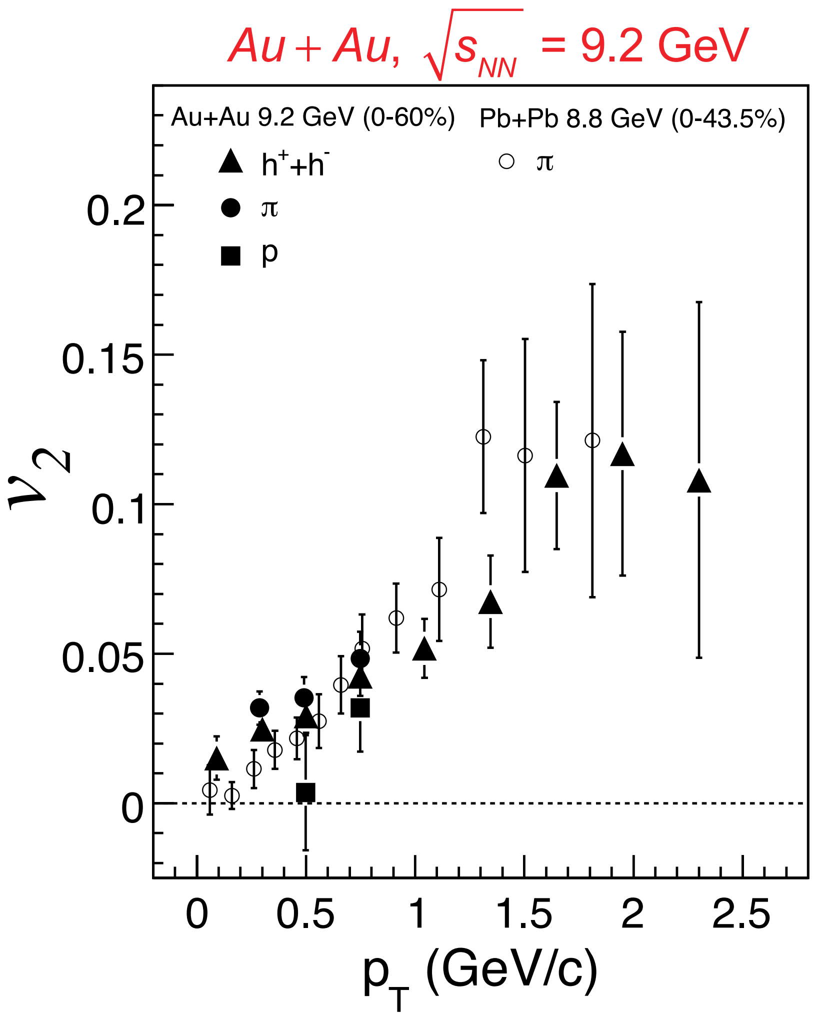


- v_2 of light and multi-strange hadrons are scaling by the number of quarks

  ⇒ also visible for Φ and Ω which indicates that the collectivity develops at the partonic level

STAR Ref.: B. I. Abelev et al.: PRC 75 (2007) 054906
B. I. Abelev et al.: PRC 99 (2007) 112301
B. I. Abelev et al.: PRC 77 (2008) 054901
B. I. Abelev et al.: PRC 81 (2010) 044902

Signatures for a Phase Transition - BES Program



- v_2 results from 9.2 GeV test run with 3k good events.
- STAR recorded in the BES program several million events at 3 energies.

STAR Ref.: B. I. Abelev et al.: PRC 81 (2010) 024911

Alt:PRC 68 (2003) 034903

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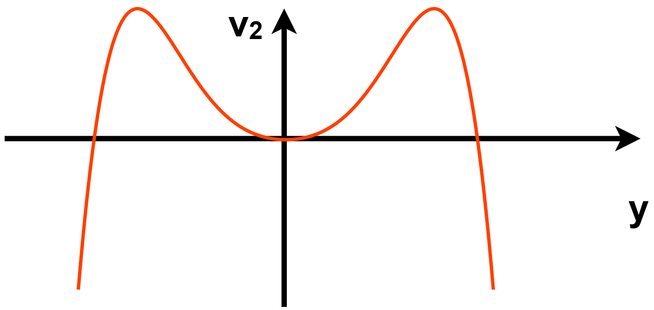

- At the phase transition from hadronic matter to quark-gluon plasma the EOS is softer in a mixed phase.
- This should be visible in a deep minimum of proton v2 at midrapidity known as softest point.

Stöcker:NPA 750 (2005) 121
Kolb et al.:PRC62 (2000) 054909

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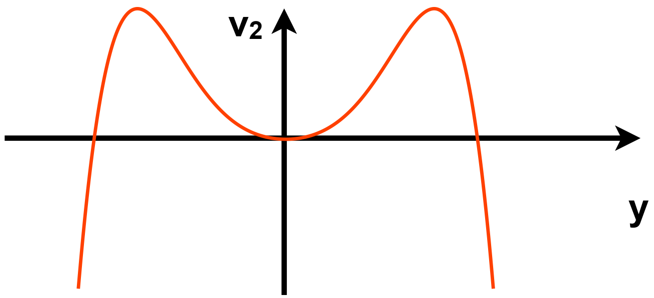

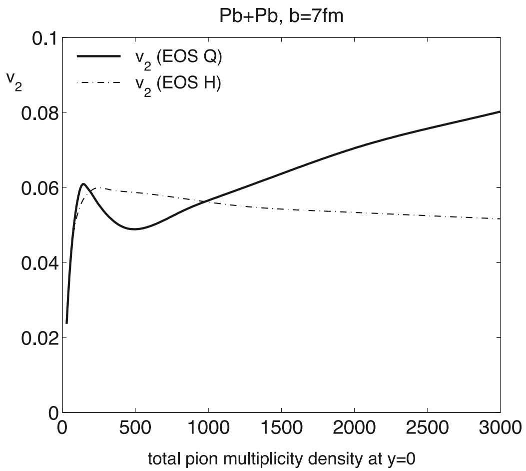

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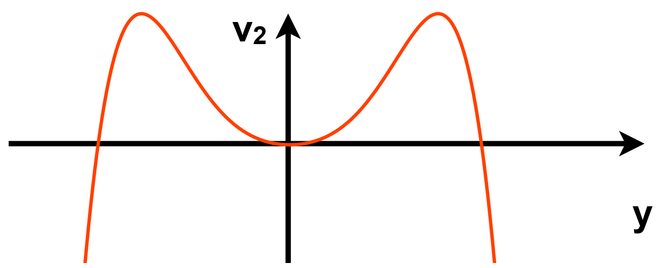

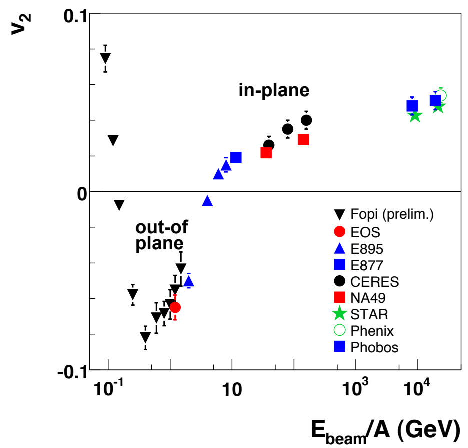

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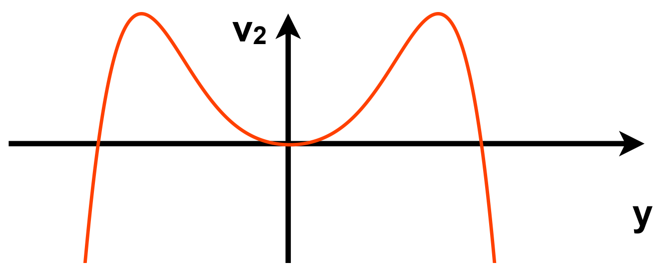

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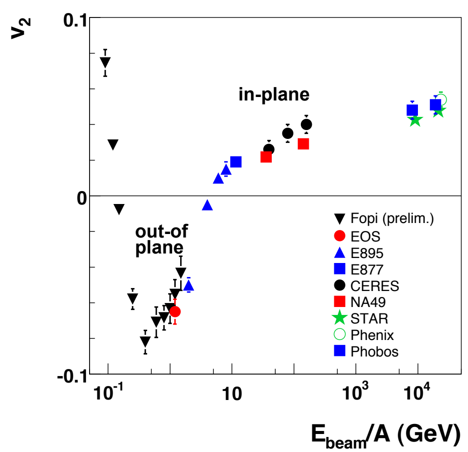

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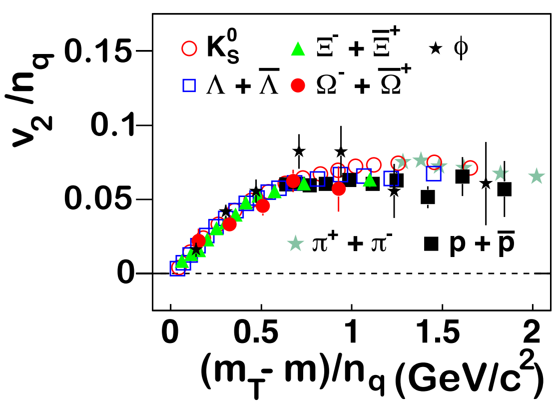


- The breaking of v_2 number of quark scaling will indicate a transition from partonic to hadronic world.

⇒ Important to measure multi-strange particles especially Ω and φ v_2

Stöcker:NPA 750 (2005) 121
Kolb et al.:PRC62 (2000) 054909

Scenarios for the OoD and CP

a) Anisotropic flow

b) Particle yields and spectra

- "Horn" and "Step": Equilibration at early stage of both hadron gas and QGP.
  (Gazdzicki, Gorenstein:APP B30 (1999) 2705)

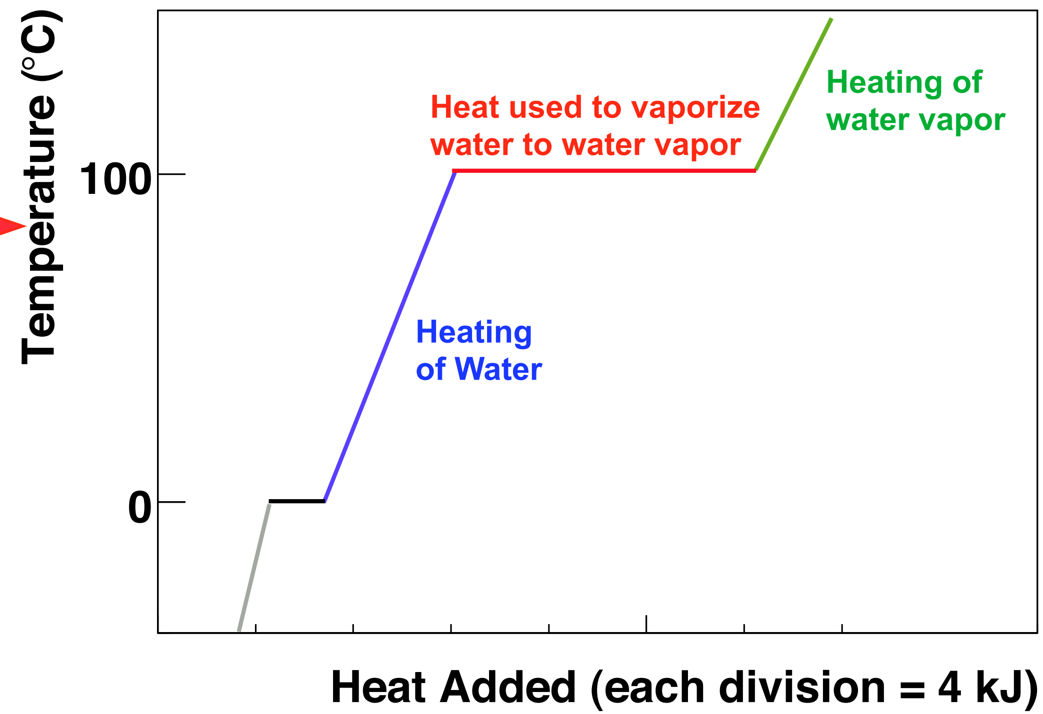
c) Event-by-Event fluctuations

d) Beam Energy Scan program of STAR

$\langle m_t \rangle - m_0$

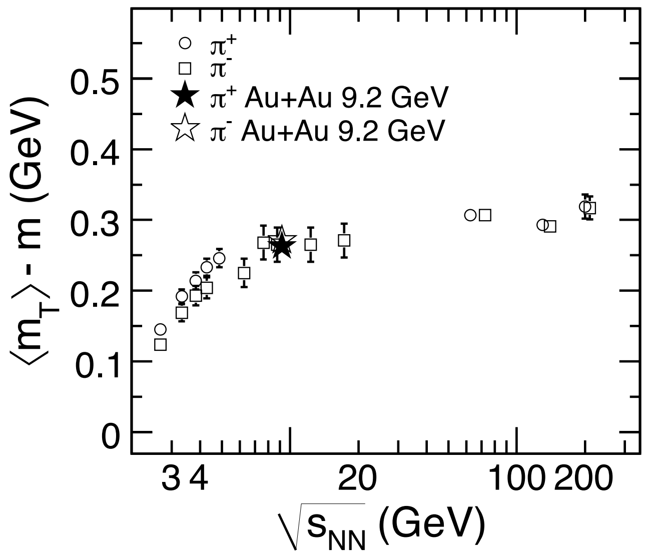
The basic idea - heating curve of water

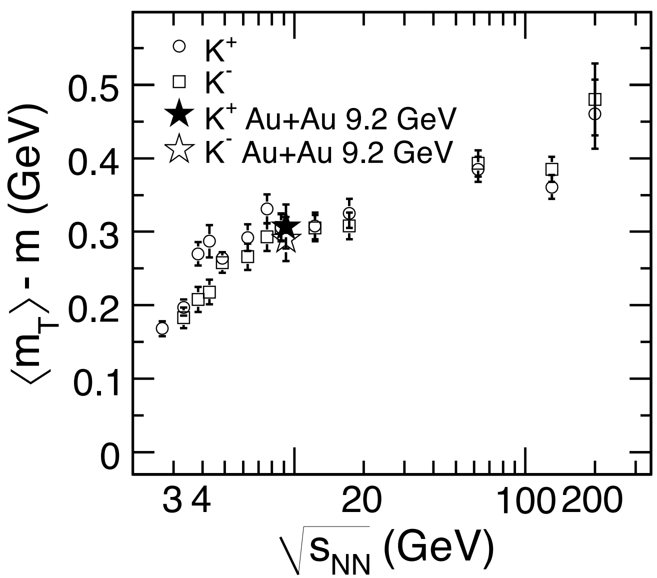
Hadronic observable



Collision energy

$\langle m_t \rangle - m_0$





- $\langle m_t \rangle - m_0$ results from 9.2 GeV test run with 3k good events.
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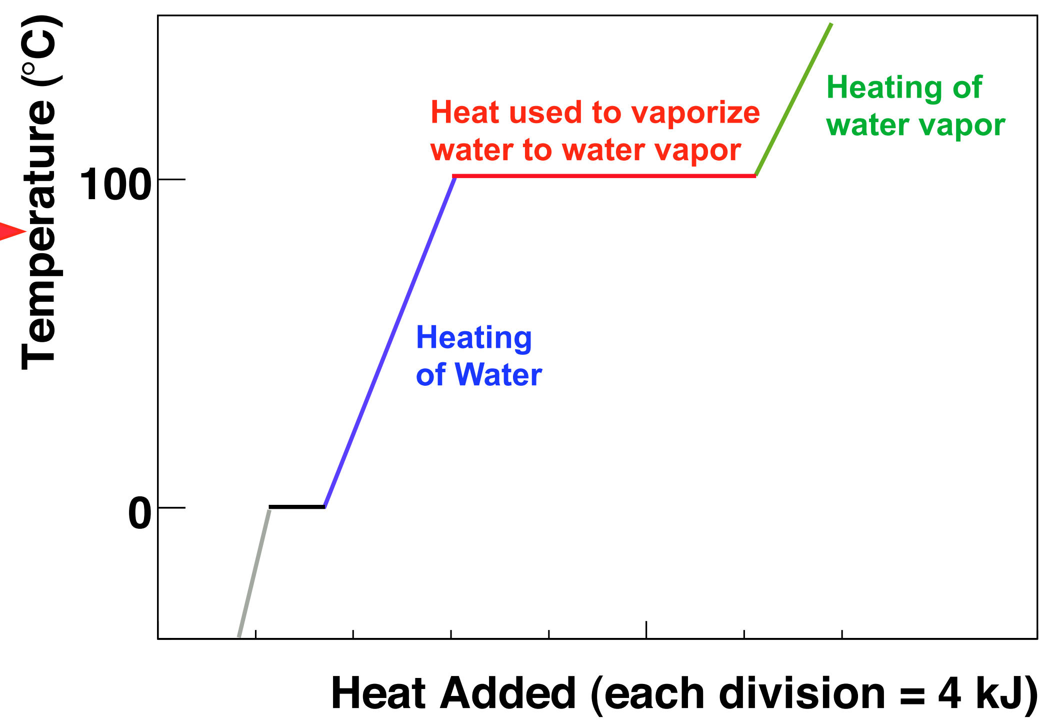

Collision energy

STAR Ref.: B. I. Abelev et al.: PRC 81 (2010) 024911

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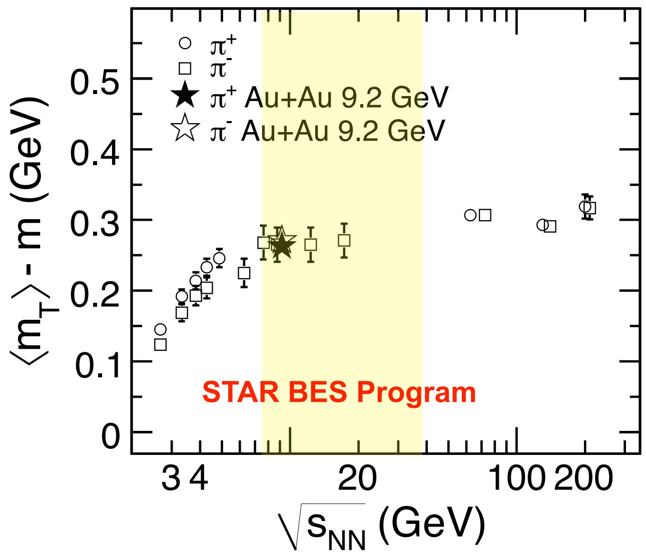

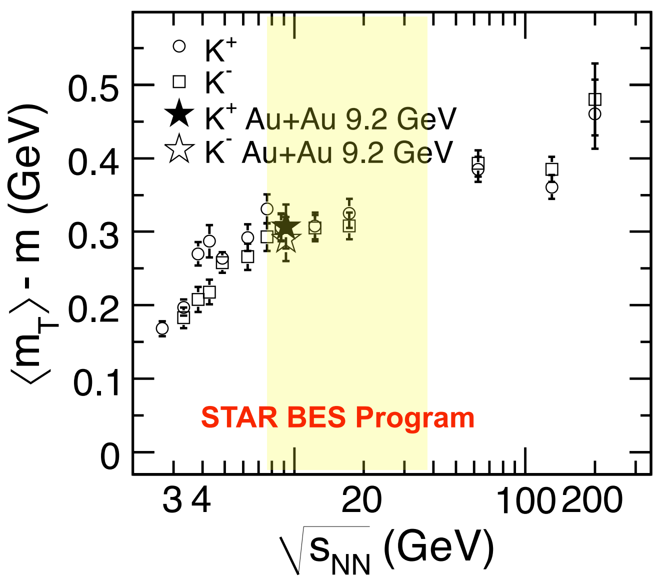

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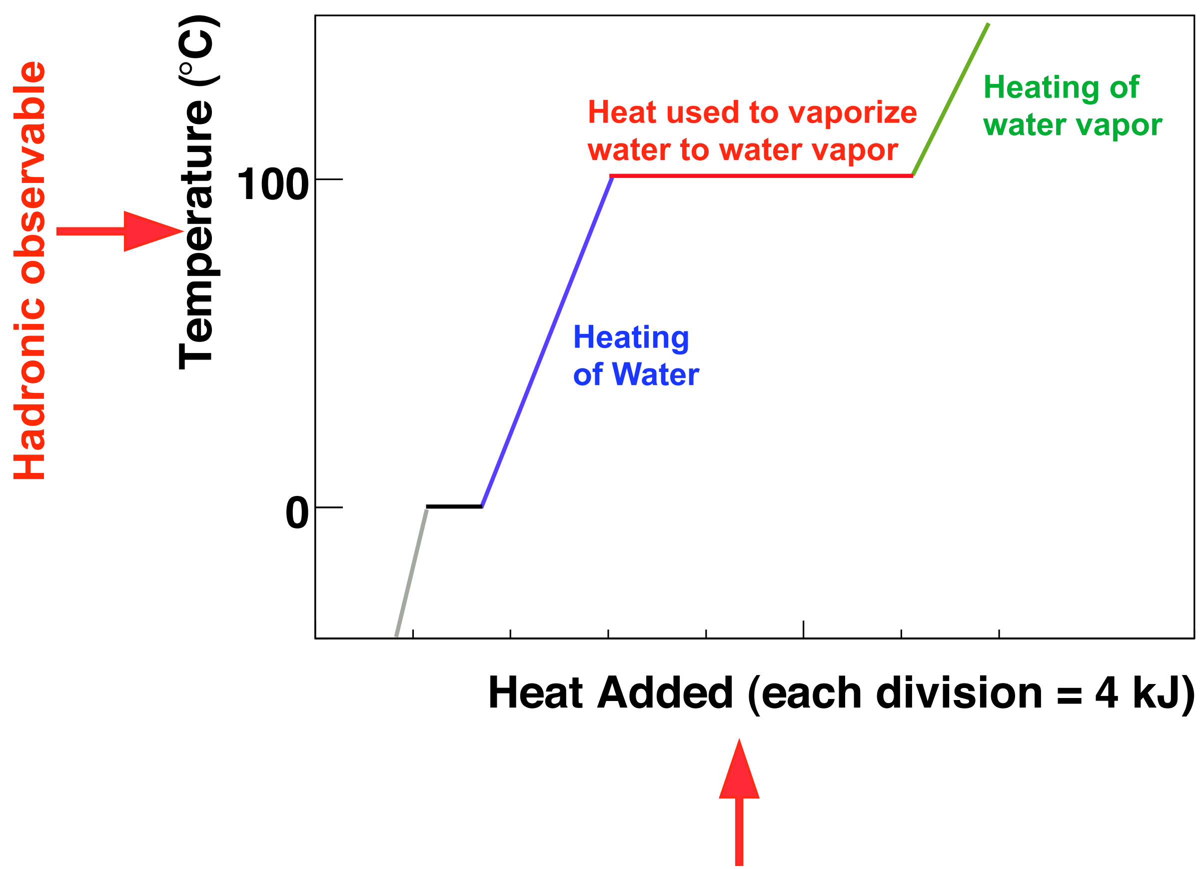

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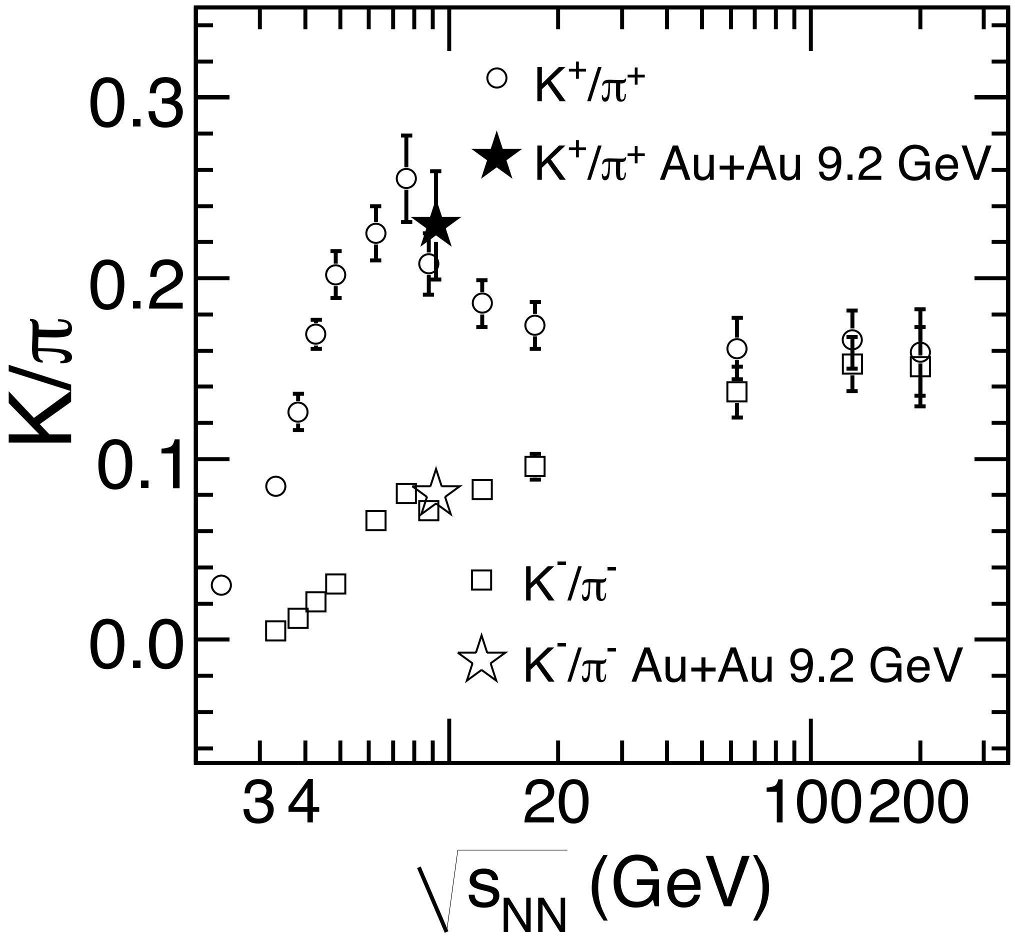
K/π Ratio



- Non-monotonic structure in K^+/π^+ ratio visible.
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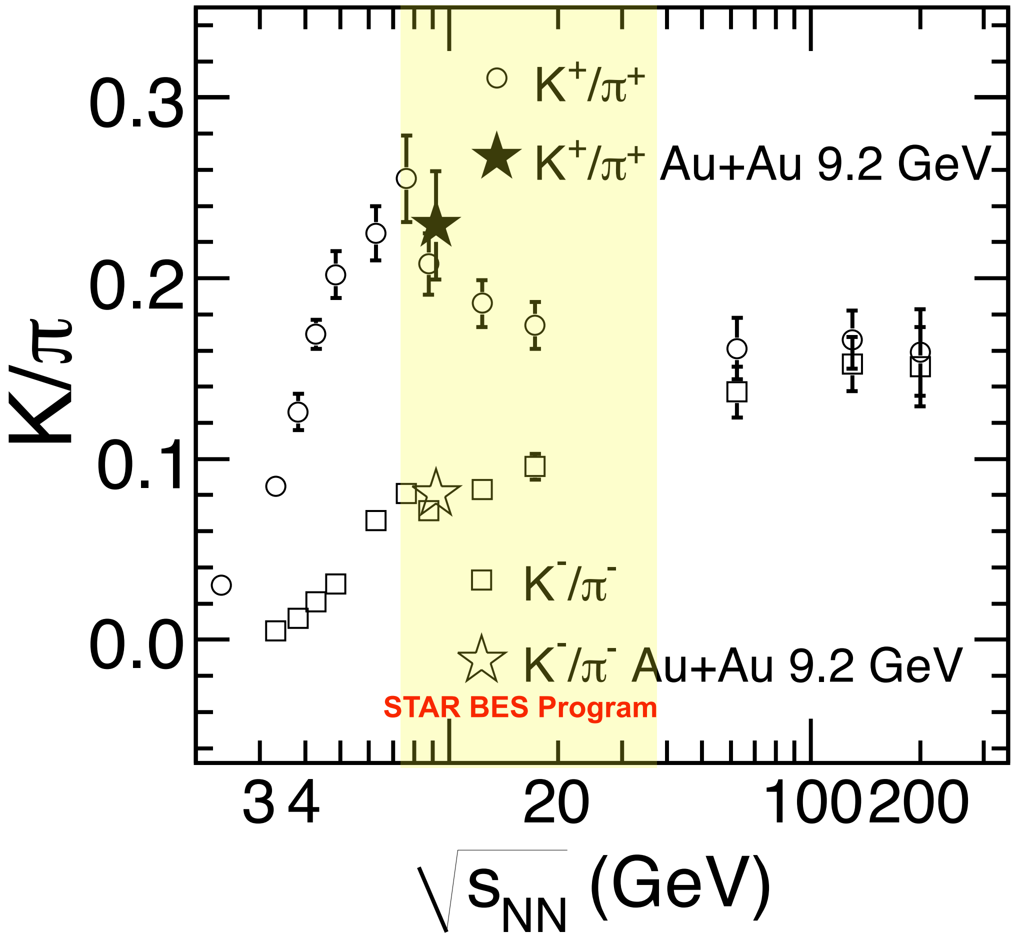

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Scenarios for the OoD and CP

a) Anisotropic flow

b) Particle yields and spectra

c) Event-by-Event fluctuations

- Diverging susceptibilities near the critical point are connected to fluctuations.
  (Stephanov et al:PRD 60 (1999) 114028,
  Gorenstein et al.:PLB 585 (2004) 237)

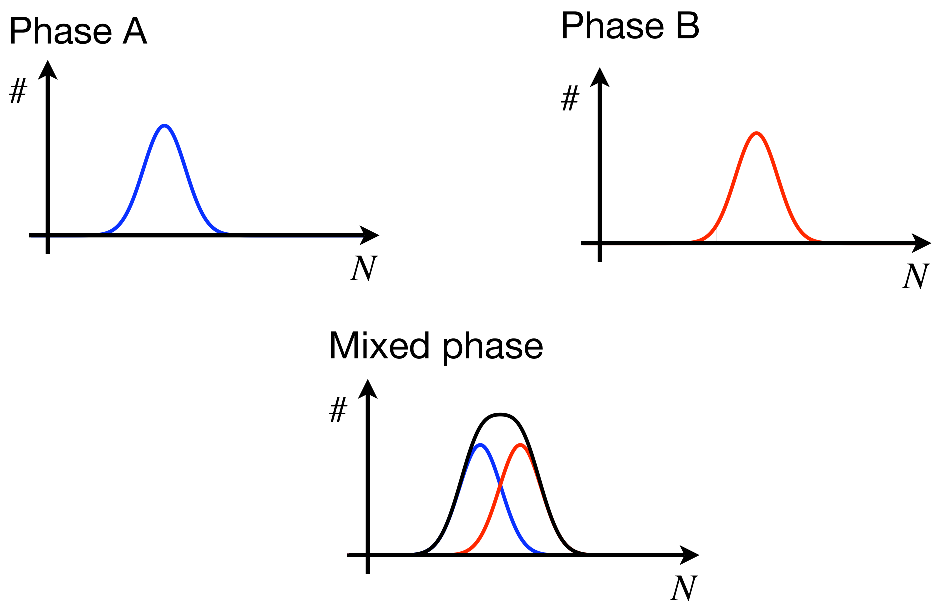
- Baryon number and strangeness correlation in a QGP.
  (Koch et al:PRL 95 (2005) 182301)

- Higher moments are more sensitive to diverging sigma field.
  (Stephanov:PRL 102 (2009) 032301)

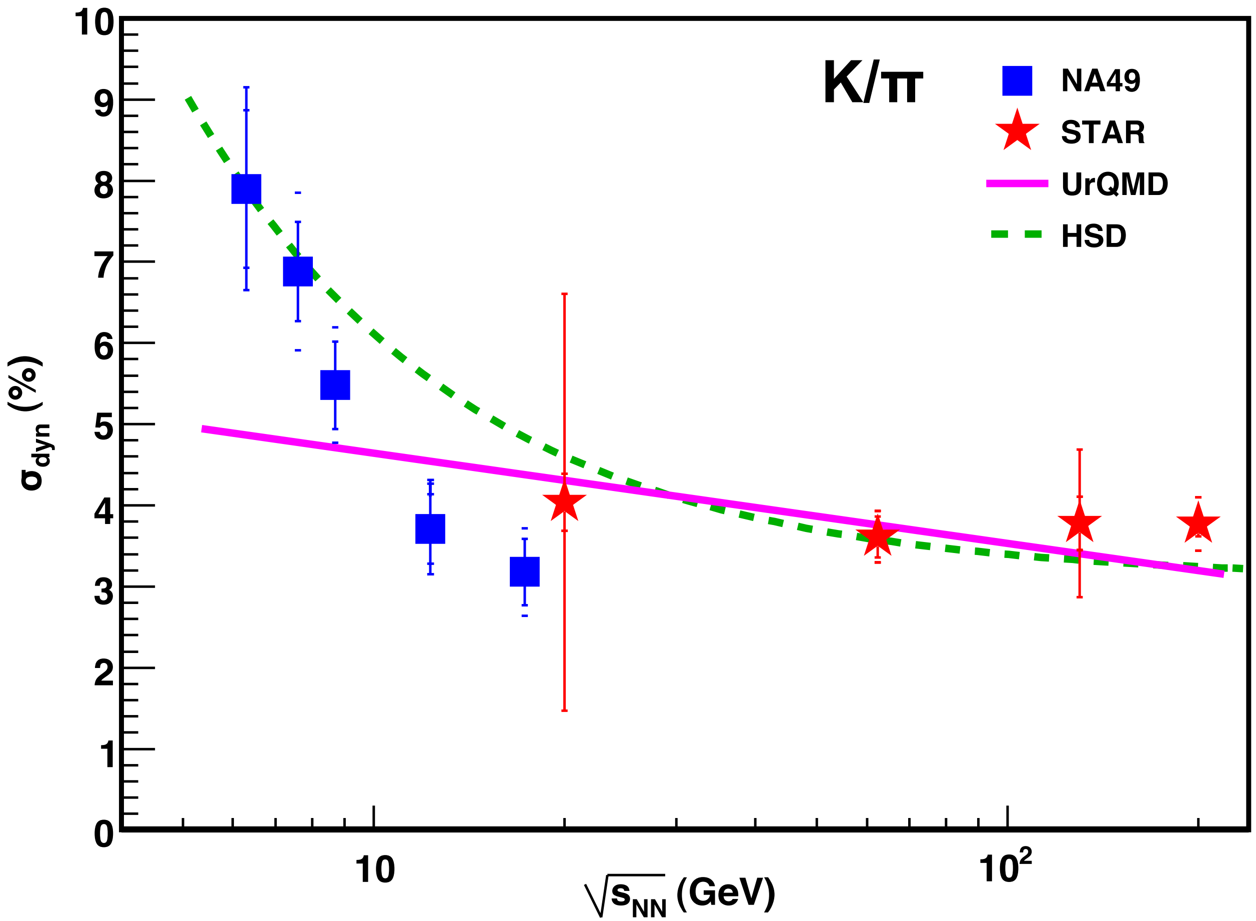
d) Beam Energy Scan program of STAR

Introduction in Ratio Fluctuations

- **Hadron ratios...**
  - **... are an intensive quantity**
  - **... characterize the chemical composition of the fireball**
  - **... are not affected by hadronic re-interaction when looking at conserved quantities (baryon number, strangeness)**
- **Change of particle (e.g. strangeness) production properties at the phase transition**
  - **Two event classes**
  - **Larger fluctuations in the mixed phase**



K/π Ratio Fluctuations



- Steep rise towards low SPS energies.
- No variation from top SPS to RHIC energies.
- Rise towards low energies not reproduced by UrQMD.
- HSD catches the trend, but over-predicts the data at high SPS energies.

STAR Ref.: B. I. Abelev et al.: PRL 103 (2009) 92301

NA49 Ref.: Alt et al.: PRC 79 (2009) 044910
UrQMD Ref.:Bleicher et al.: arXiv:0805.0567
HSD Ref.: Gorenstein et al. PRC 79 (2009) 024907

$$\sigma_{dyn} = sign\left(\sigma^2_{data} - \sigma^2_{mix}\right)\sqrt{\left|\sigma^2_{data} - \sigma^2_{mix}\right|}$$, relative width $\sigma = RMS / Mean \times 100$ [%]

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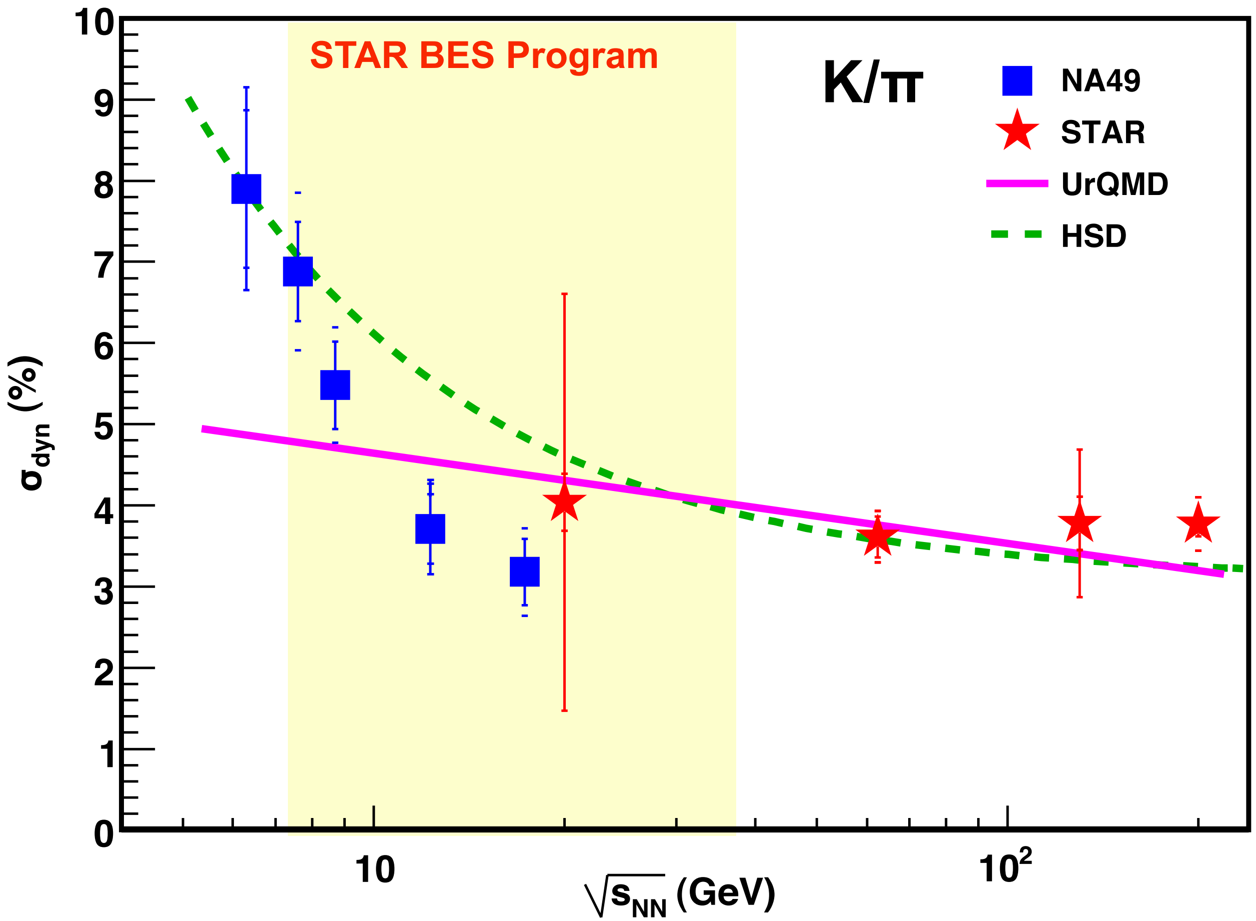

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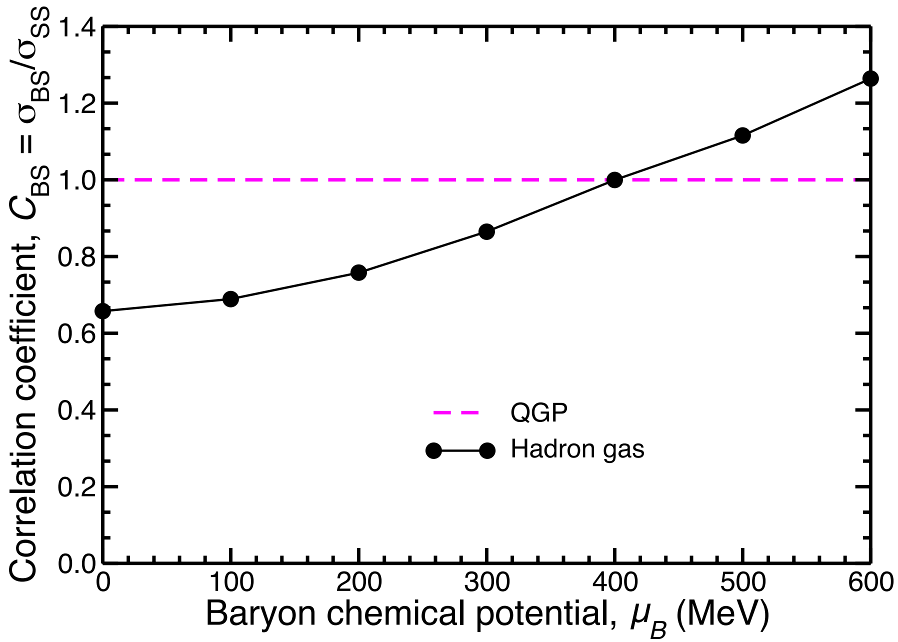
K/p Ratio Fluctuations



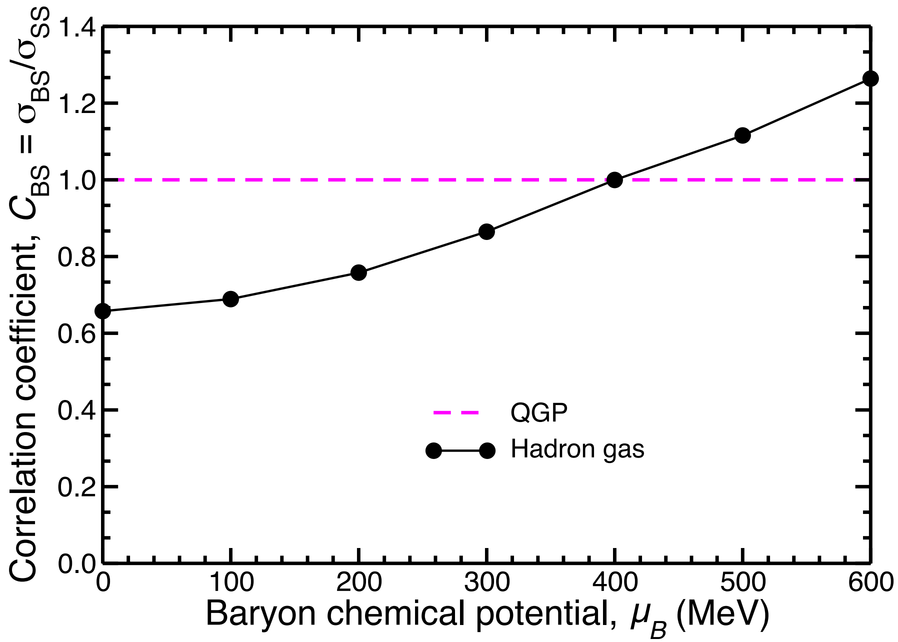
- **QGP: strangeness is carried by strange quarks, baryon number and strangeness is correlated.**
- **HG: strangeness is carried by K and Λ, baryon-strangeness correlation changes with μ_B.**

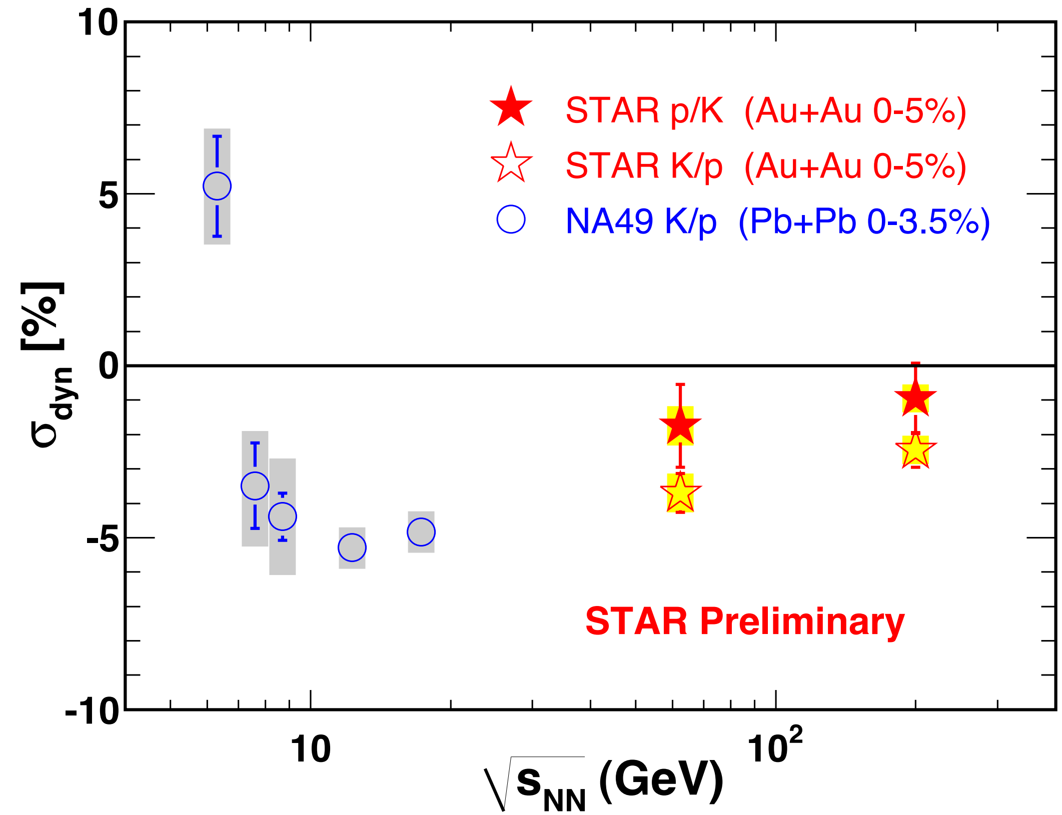
- **K/p is an approximation for C_{BS}?**
- **Sign change at low energies.**

STAR Ref.: J. Tian et al.: SQM09

Koch et. al.:PRL 95 (2005) 182301
Schuster et al.: PoS CPOD09 2009

K/p Ratio Fluctuations





- **QGP: strangeness is carried by strange quarks, baryon number and strangeness is correlated.**
- **HG: strangeness is carried by K and Λ, baryon-strangeness correlation changes with μ_B.**

- **K/p is an approximation for C_{BS}?**
- **Sign change at low energies.**

STAR Ref.: J. Tian et al.: SQM09

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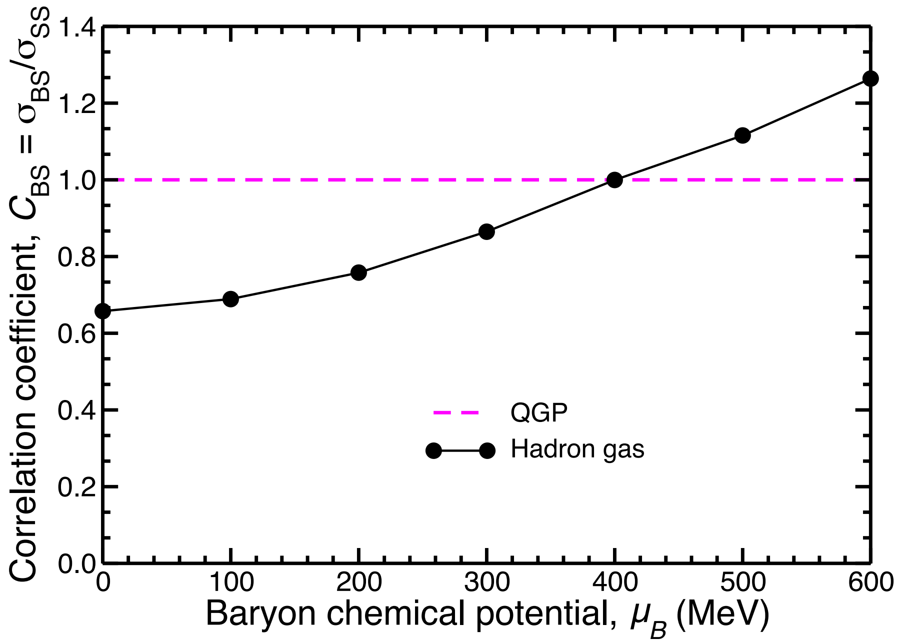

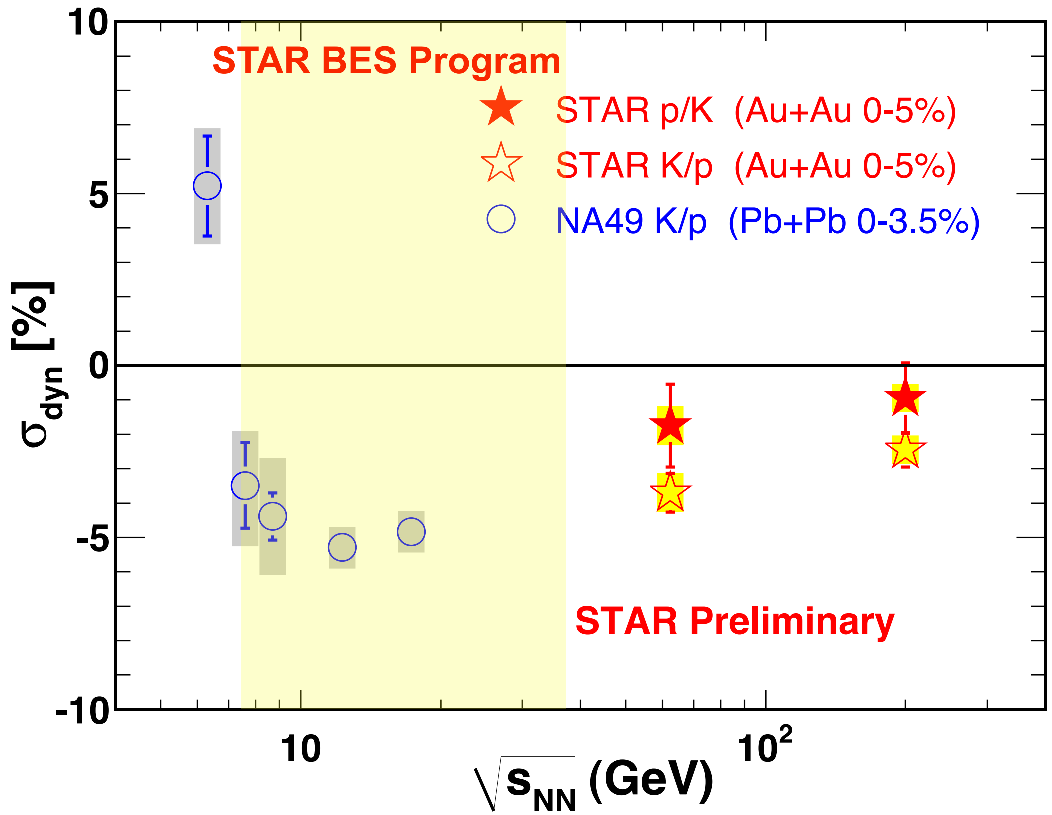

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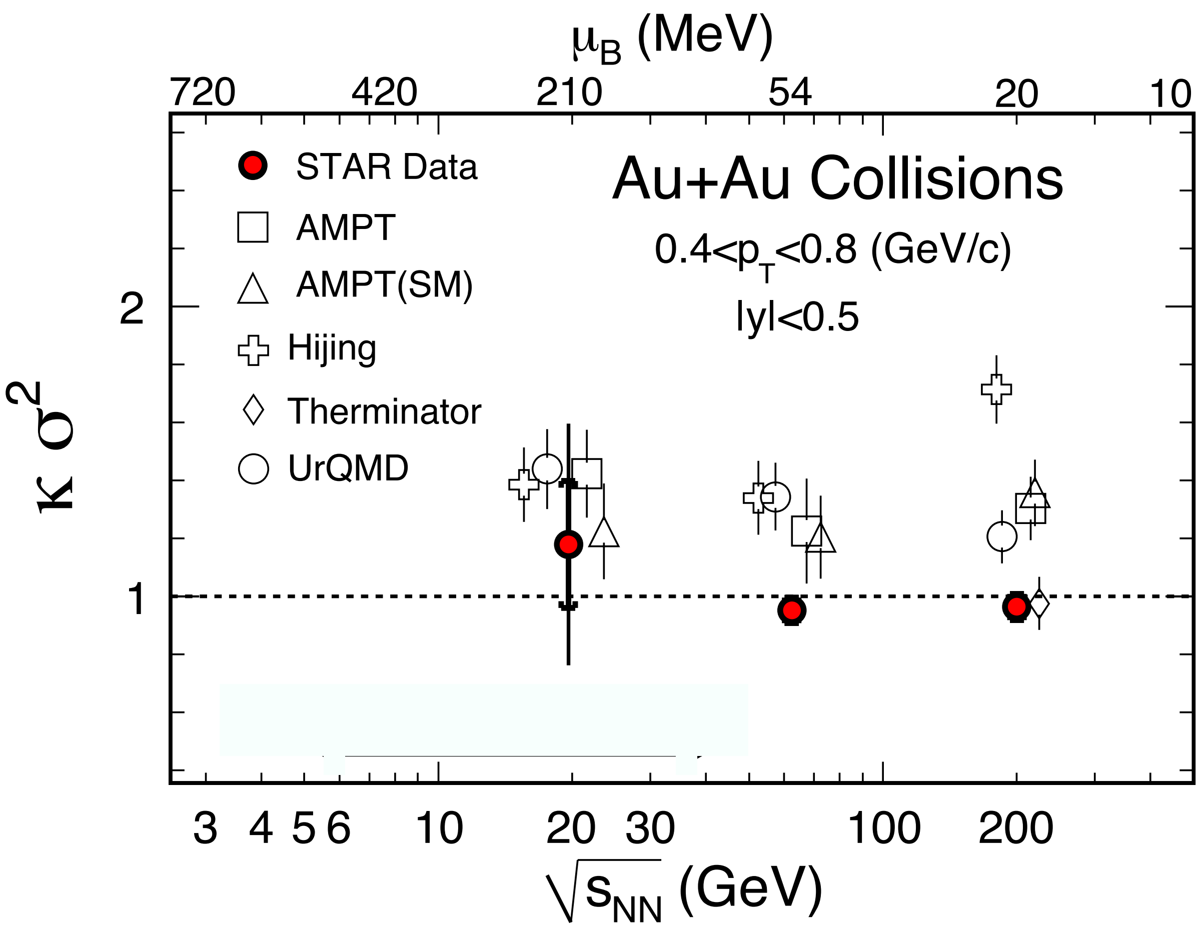
Higher Moments: Net-Proton Kurtosis



- **Critical point effect**
  - **Higher moments are more sensitive to diverging sigma field:**

    $\langle N^2 \rangle \approx \xi^2, \quad \langle N^4 \rangle \approx \xi^7$

  - **Divergence should be reflected in net-baryon and net-proton kurtosis**
  - **Kurtosis*Varince = 1 for Poisson distribution, if not close to the critical point**
- **Phase transition effect**
  - **net-proton kurtosis as proxy for net-baryon**

STAR Ref.: M. M. Aggarwal et al.: arXiv:1004.4959, accepted for publication in PRL

c) Event-by-Event fluctuations

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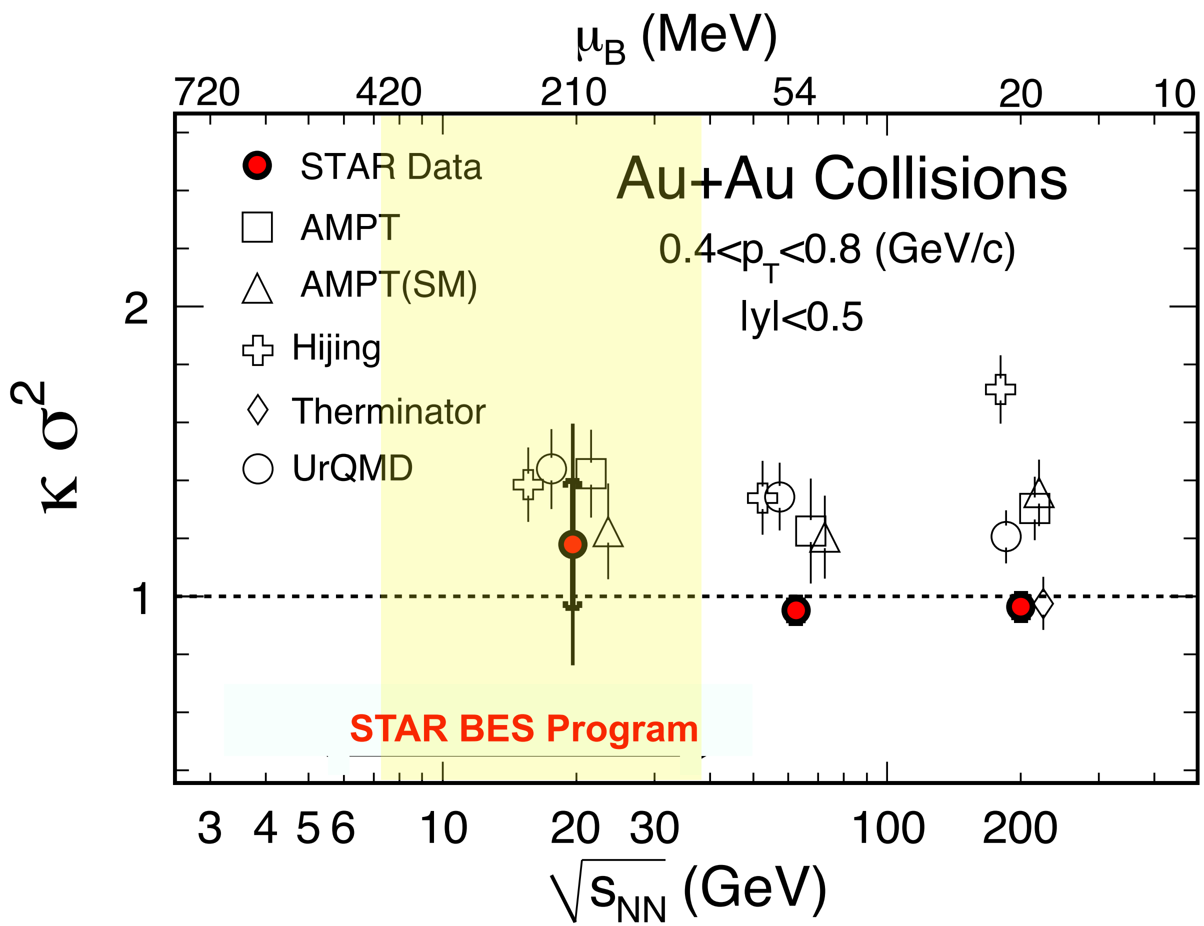

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Scenarios for the OoD and CP

a) Anisotropic flow

b) Particle yields and spectra

c) Event-by-Event fluctuations

d) Beam Energy Scan program of STAR

Collected Data for BES

E_{CM}	System	Centrality	Statistics
39 GeV	Au+Au	min. bias	169M
11,5 GeV	Au+Au	min. bias	≥ 7,5M
7,7 GeV	Au+Au	min. bias	5M

Observables

E_{CM} (GeV)	7,7	11,5	39
Statistics	2,5M	3,8M	52,5M
Observables	Millions of Events		
horn/step/kink	0,1	0,1	0,1
v_2 (up to ~ 1,5 GeV)	0,2	0,1	0,1
n_q scaling π/K/p/Λ (m_t-m_0/n_q < 2 GeV)	6	5	4,5
n_q scaling Φ/Ω (p_t/n_q = 2 GeV/c)	56	25	12
PID fluctuations (K/π, K/p)	1	1	1
Kurtosis	5	5	5

OoD

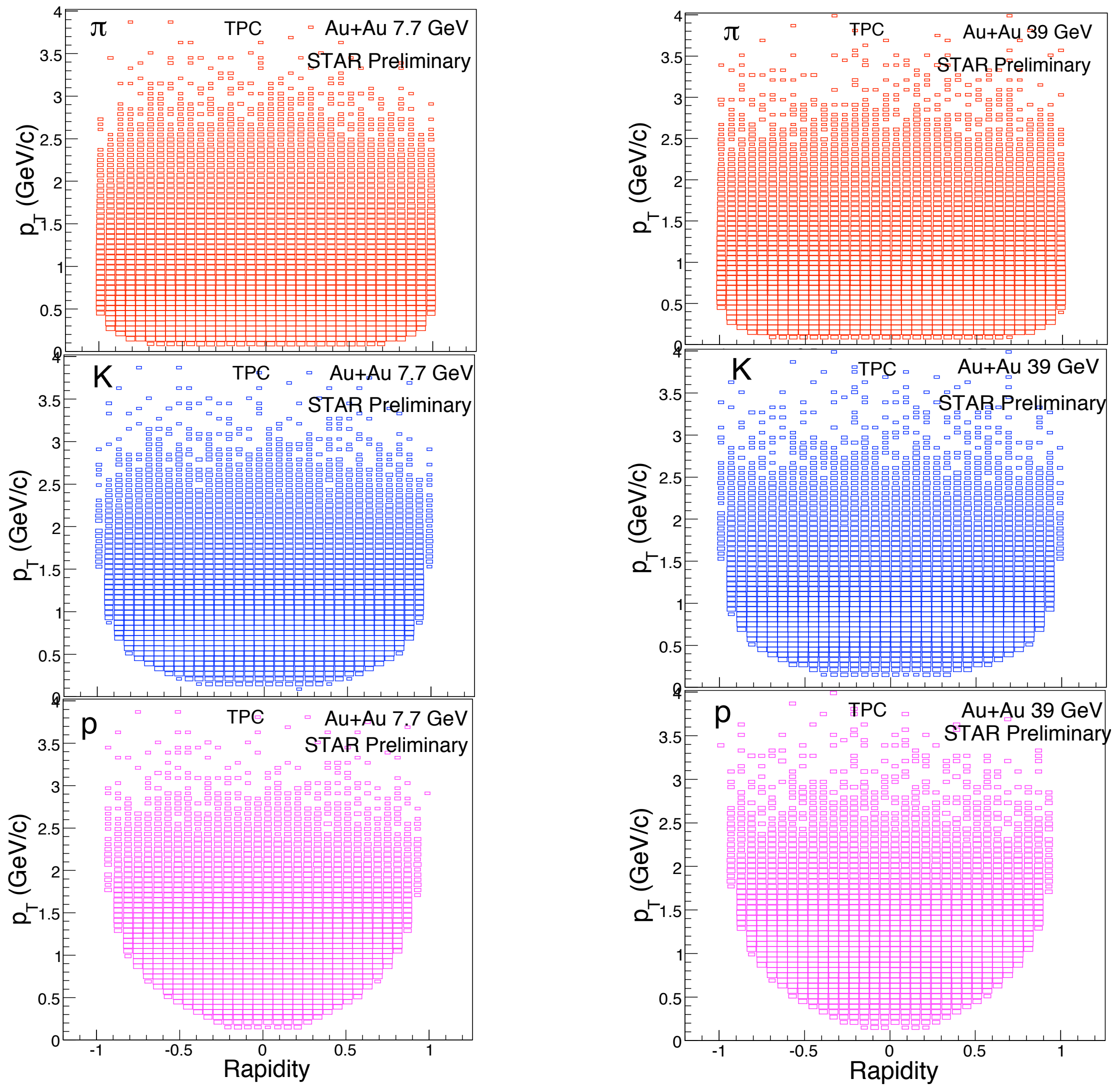
CP

- ... and many more.

http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493

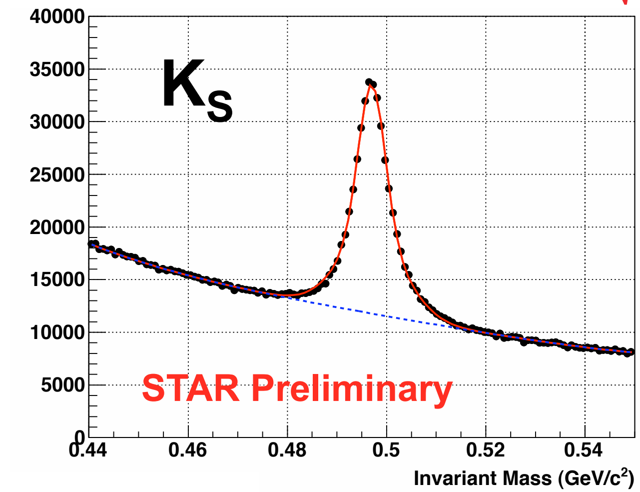
Particle Identification and Acceptance of STAR

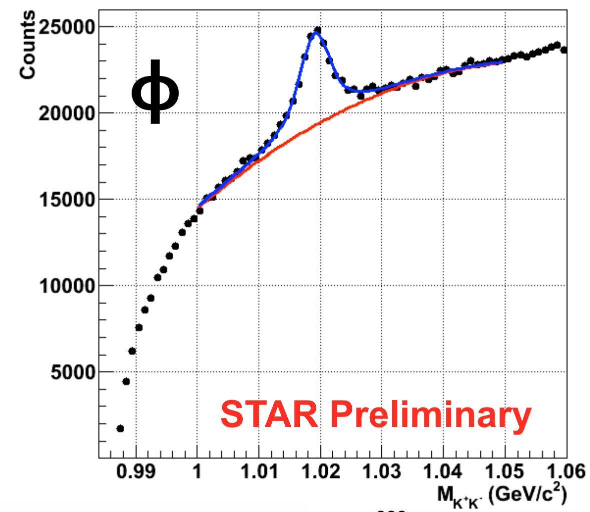
$Au+Au, \sqrt{s_{NN}}$ = 7.7 GeV $Au+Au, \sqrt{s_{NN}}$ = 39 GeV

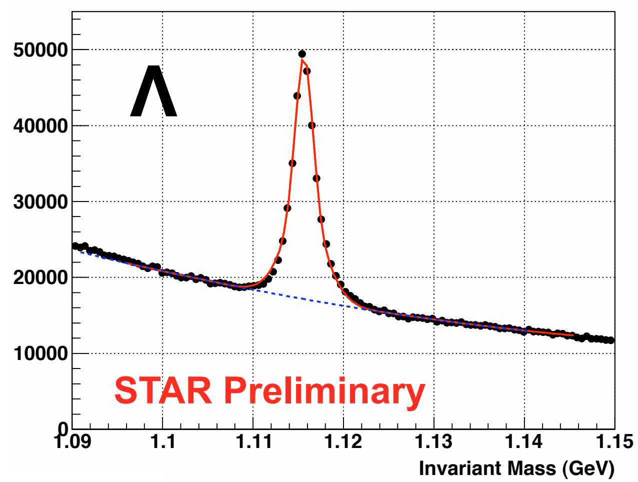


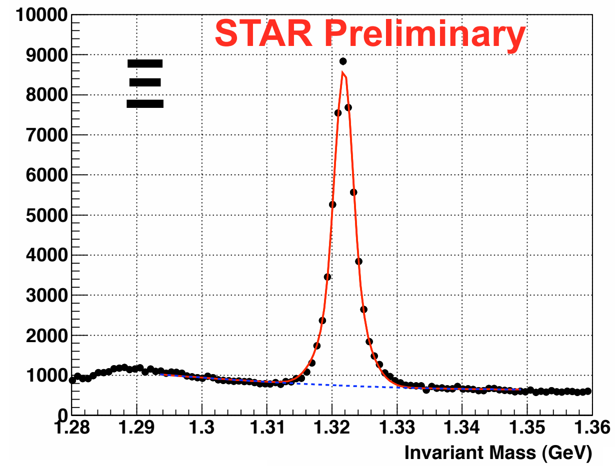
Particle Identification at STAR

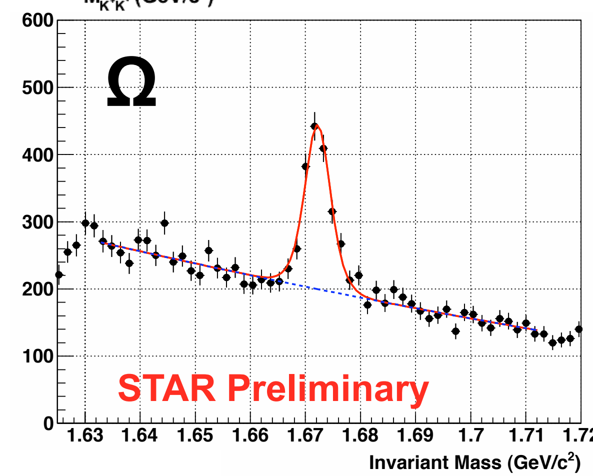
$Au + Au,\ \sqrt{s_{NN}} = 39$ GeV











Summary and Conclusions

a) Anisotropic flow

- NQ scaling works for Au+Au $\sqrt{s_{NN}}$ = 62.4/200 GeV and Cu+Cu at $\sqrt{s_{NN}}$ = 200 GeV collisions.
- The EOS may be softer in a mixed phase. This should be visible:
  - Collapse of proton v_2 at midrapidity
  - Minimum of v_2 for charged particles for a change of the EOS
- v_2 NQ scaling will break in a hadronic scenario.

b) Particle yields and spectra

- "Step" structure observed in $\langle m_t \rangle - m_0$.
- The K^+ to π^+ ratio shows a "Horn" at low SPS energies.

c) Event-by-Event fluctuations

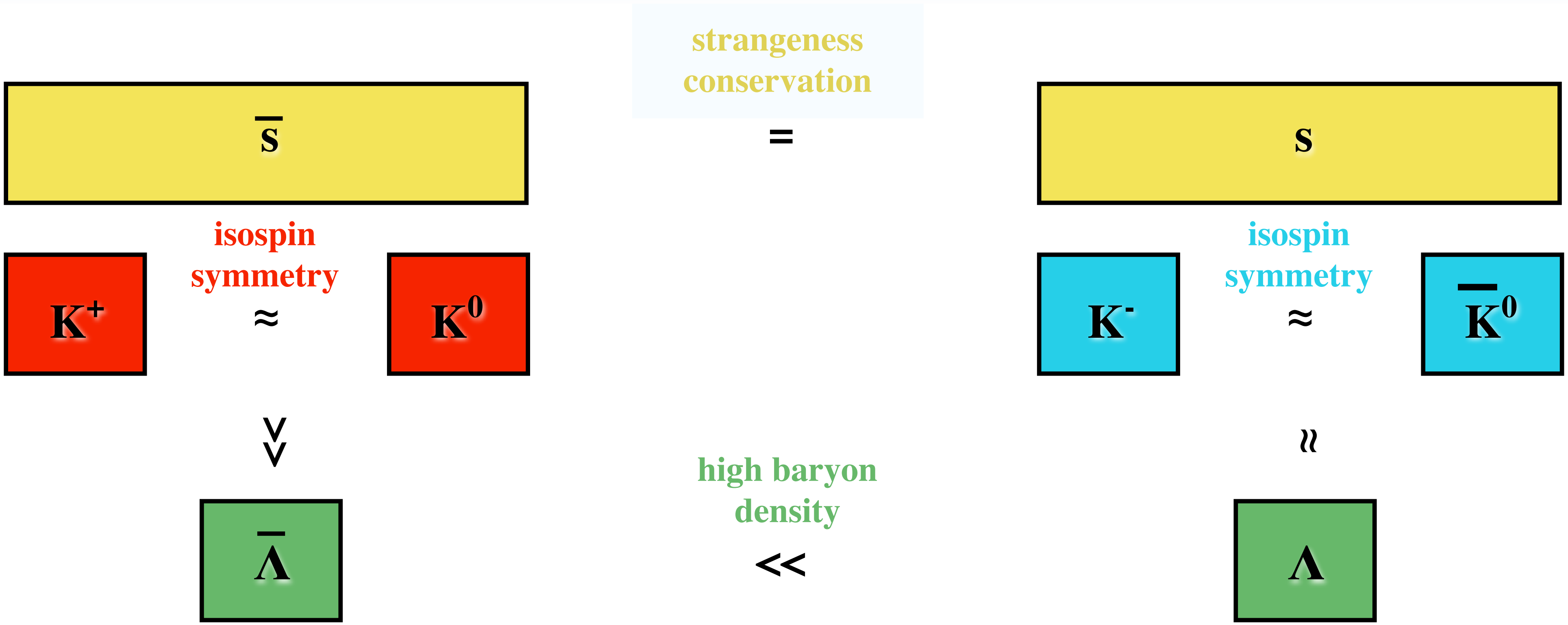
- K/π interpretation still not conclusive.
- K/p shows non-trivial excitation function.
- Kurtosis*Variance shows = 1, not close to CP.

d) Beam Energy Scan program of STAR

- Great Success.
- Will attempt all the propsed measurements to search for the „Onset of Deconfinement“ and „Critical Point“.

The End and
Thanks for
Your Attention

Main Strangeness Carrier



Sensitive to strangeness content only

Sensitive to strangeness content and baryon density