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Beam Energy Scan Program in STAR

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1. Introduction and motivations
2. BES-I: what have we learned so far?
3. Future

STAR

Introduction

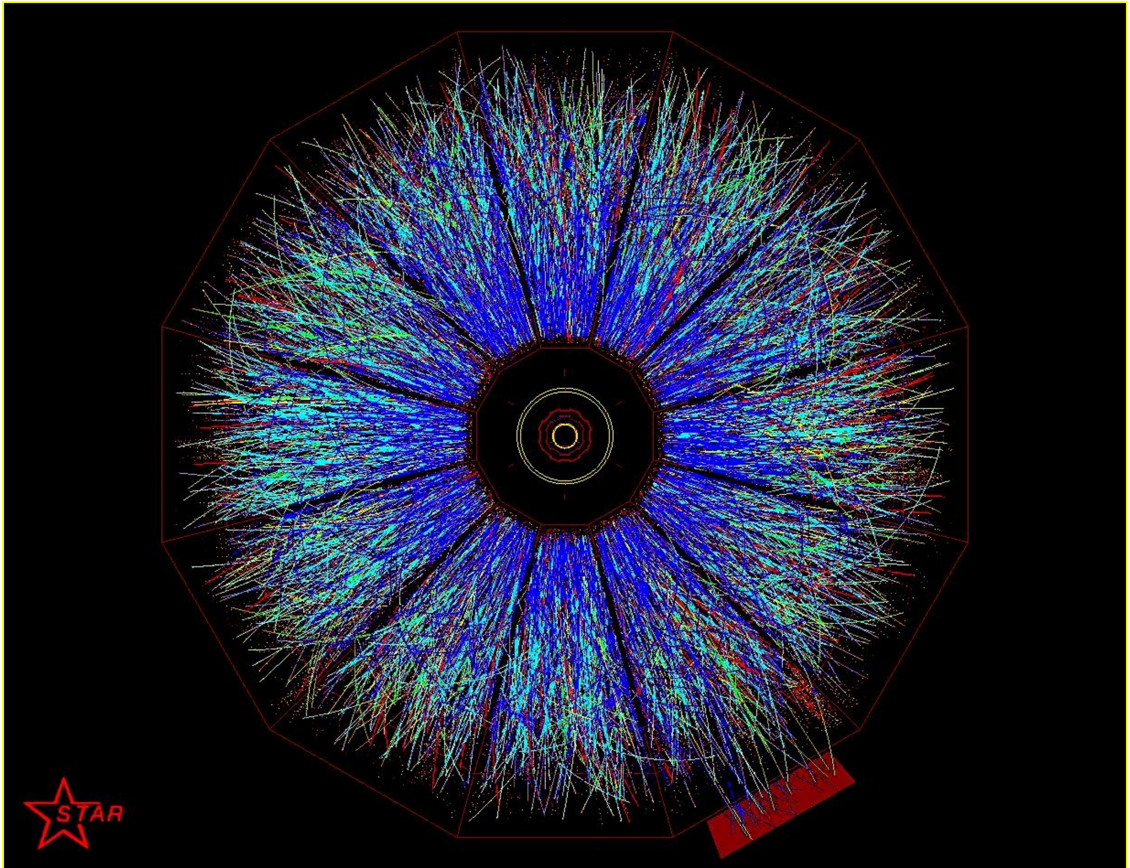
What have we learned so far?

Goal of the RHIC Heavy Ion Program:

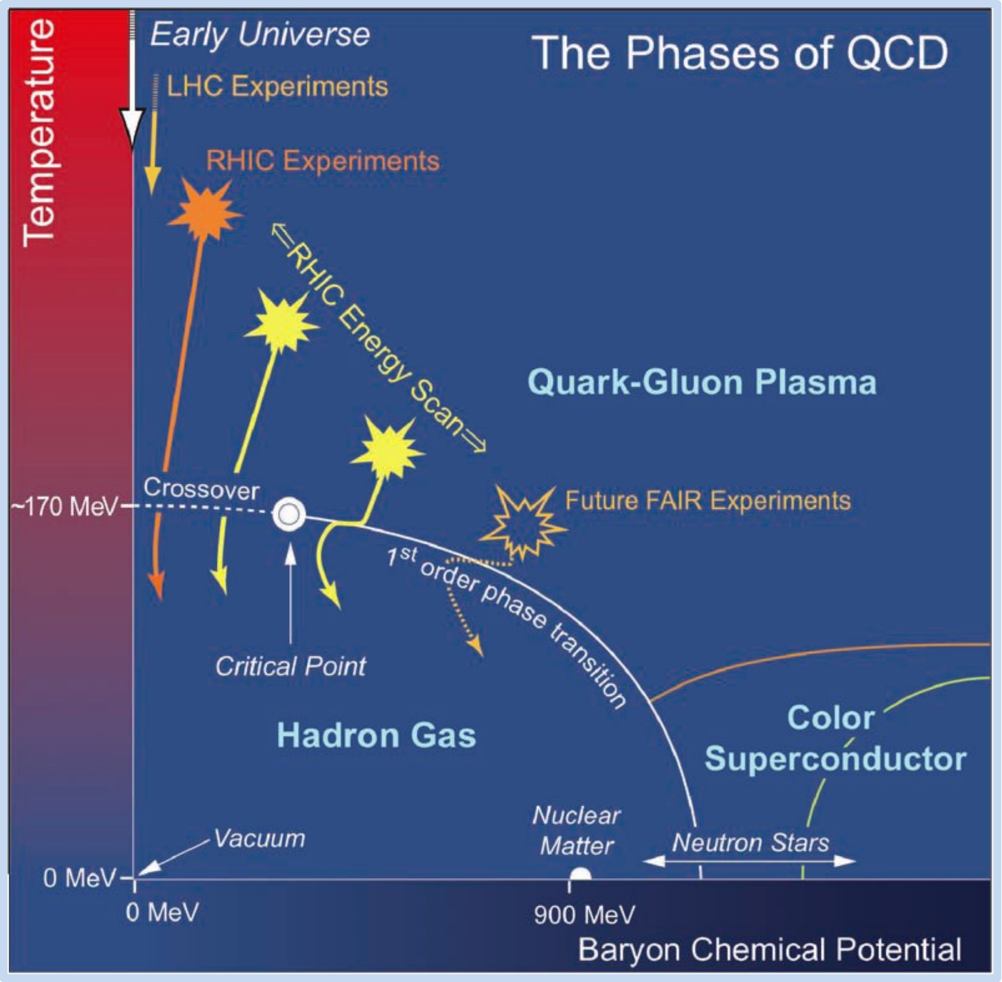
- search the QGP and measure its properties
- scan the QCD phase diagram

We learned about..

.. strongly interacting, hot, dense matter with partonic collectivity



Beam Energy Scan at RHIC



RHIC was built to find QGP.

QGP is new and complicated phase of matter

QGP exhibits unique and unexpected properties

Big progress in understanding its nature:
- high collision energy – cross over transition
- low collision energy – 1st order transition
  and the Critical Point

$\sqrt{s_{NN}} \sim 7.7 - 200$ GeV

20 MeV $< \mu_B <$ 420 MeV

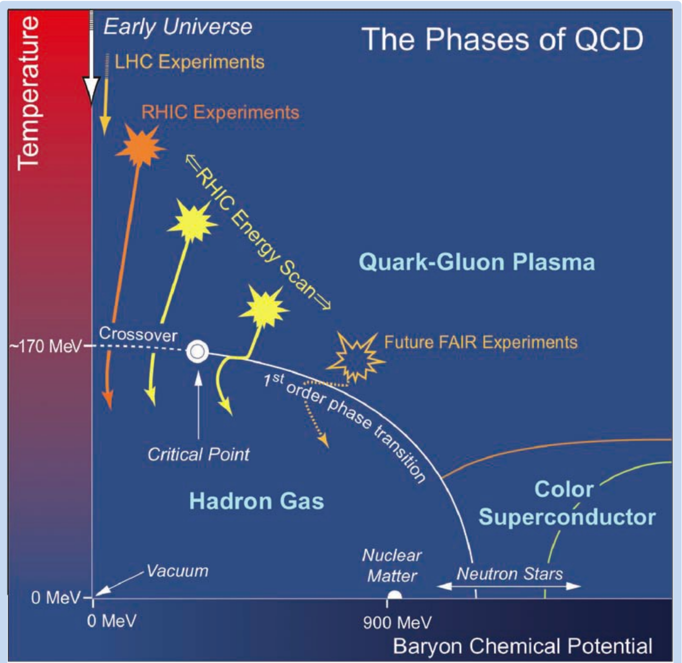
BES goals

1. Search for turn-off of sQGP signatures
2. Search for the QCD critical point
3. Search for the signals of phase transition/phase boundary

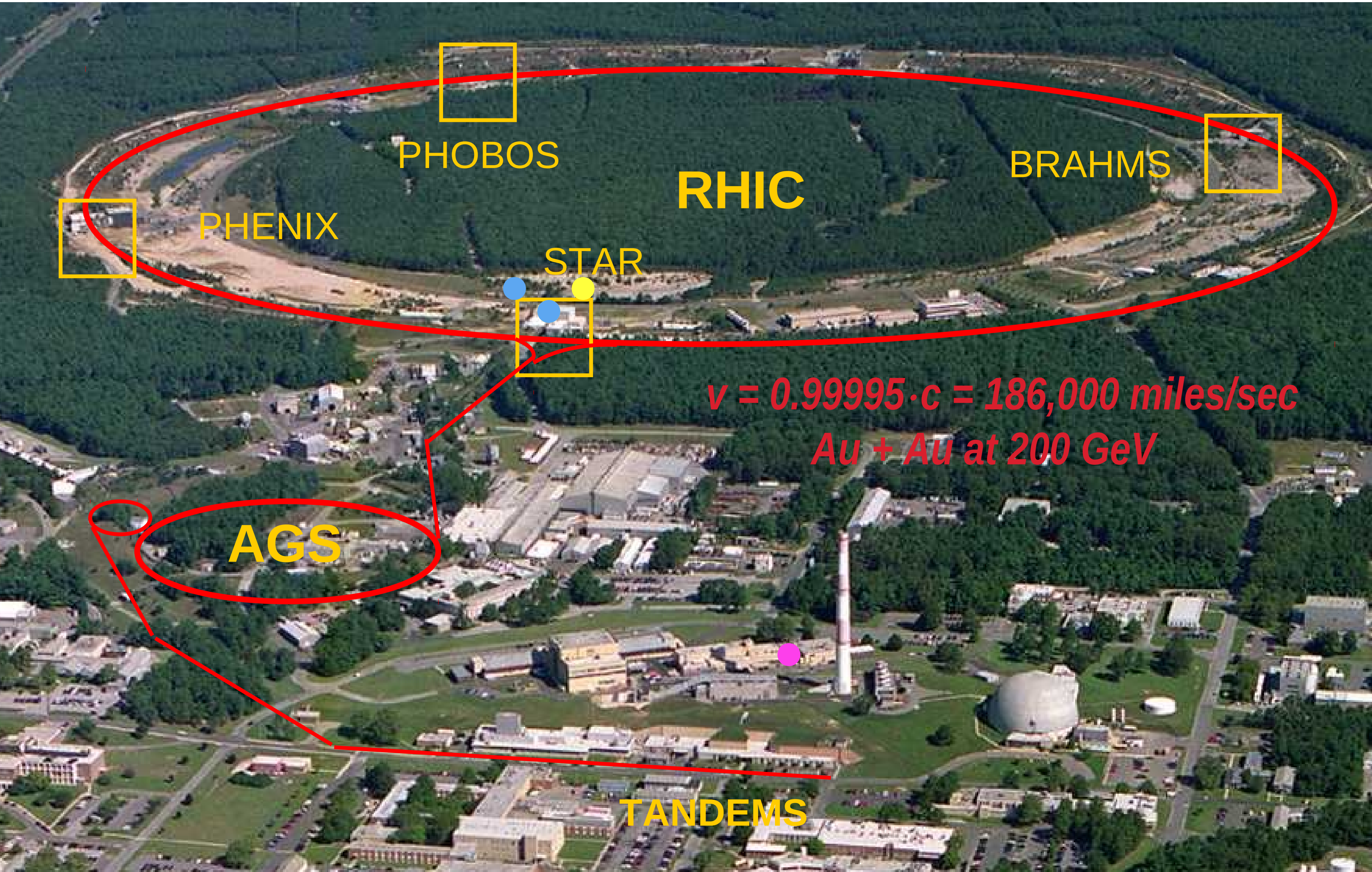
STAR: *http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493*, *arXiv:1007.2613*

Year	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Events (10^6)
2010	200	20	350
2010	62.4	70	67
2010	39	115	130
2011	27	155	70
2011	19.6	205	36
2014	14.5	260	20
2010	11.5	315	12
2010	7.7	420	4

Where are we on the QCD Phase Diagram ?



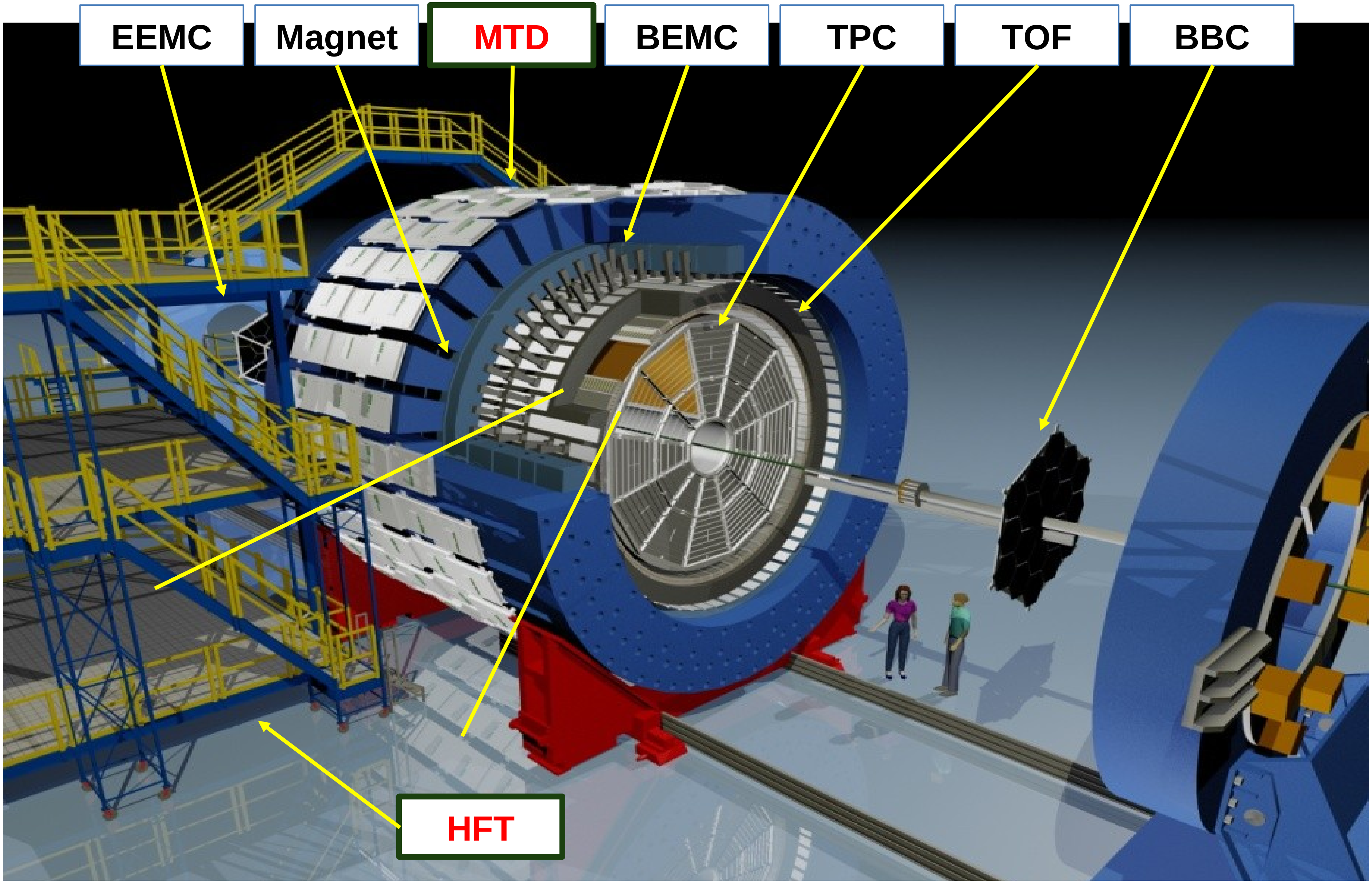
Relativistic Heavy Ion Collider (RHIC)
Brookhaven National Laboratory (BNL), Upton, NY



v = 0.99995·c = 186,000 miles/sec

Au + Au at 200 GeV

STAR Detector System



EEMC

Magnet

MTD

BEMC

TPC

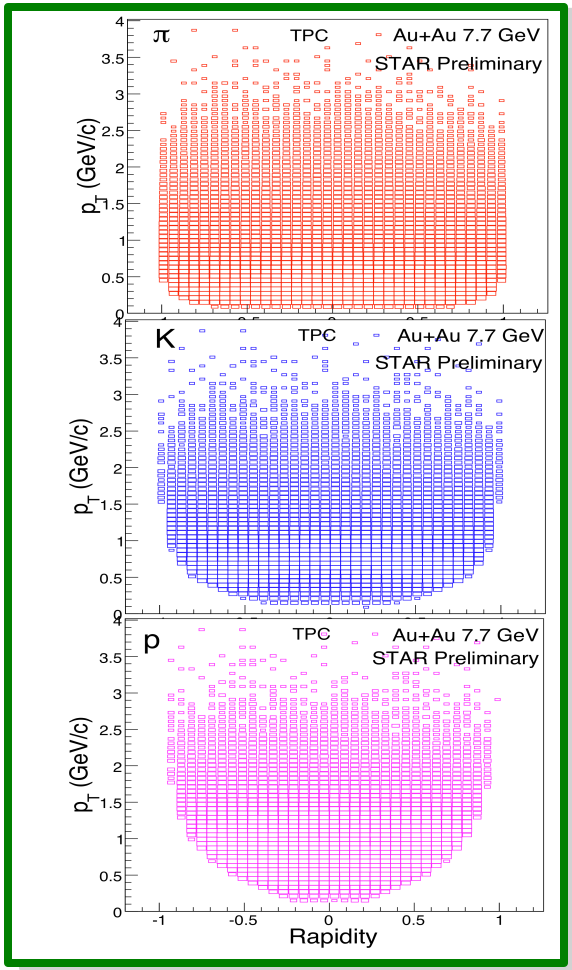
TOF

BBC

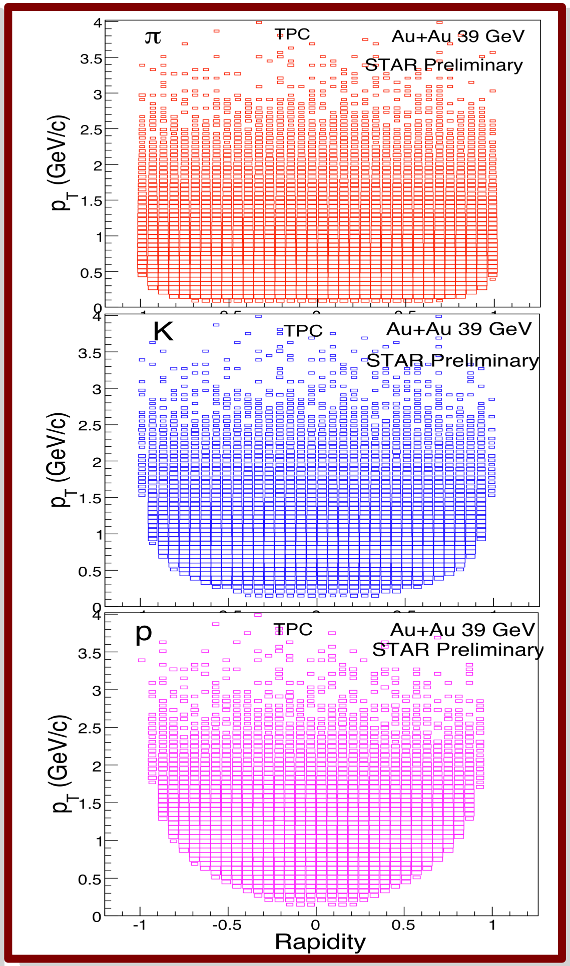
HFT

Identified Particle Acceptance at STAR

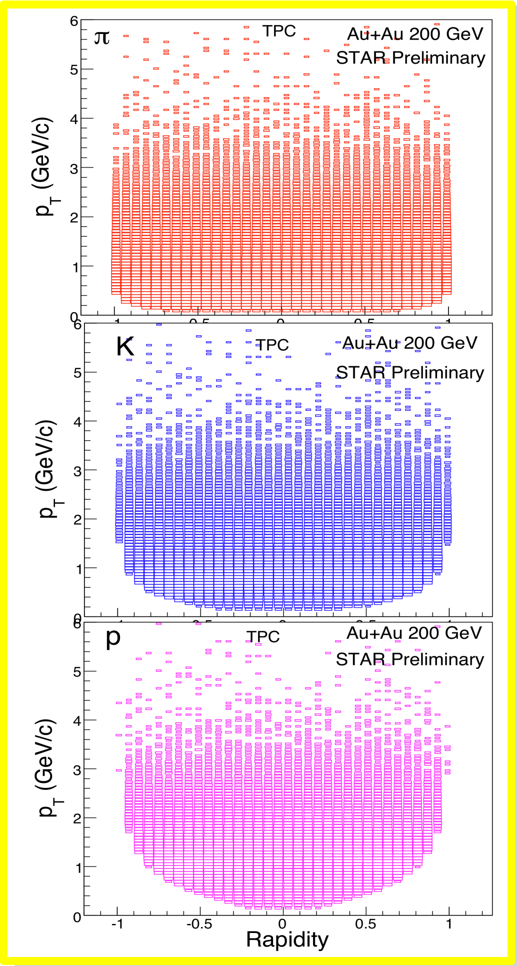
Au+Au at $\sqrt{s_{NN}}$ = *7.7* GeV



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

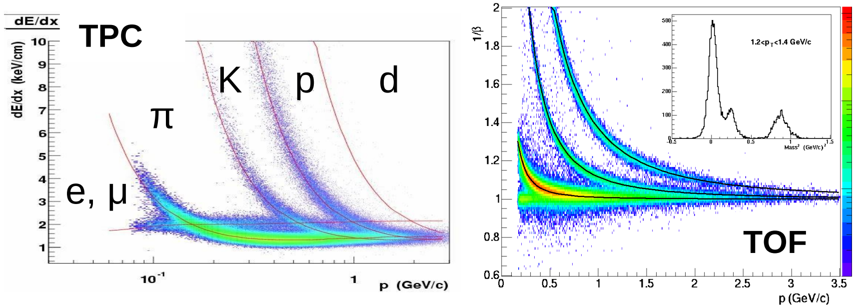


Au+Au at $\sqrt{s_{NN}}$ = *200* GeV

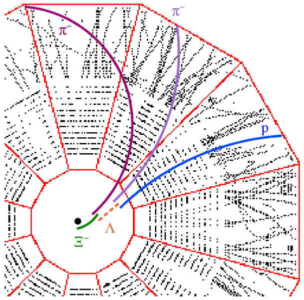


At collider geometry we got similar acceptance for all particles and energies

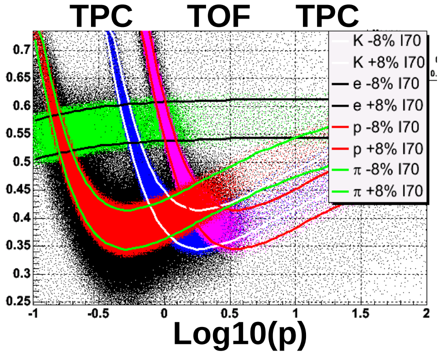
Particle Identification at STAR

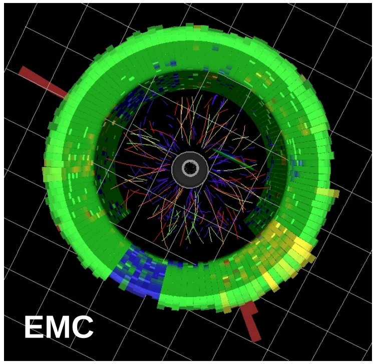


Charged hadrons

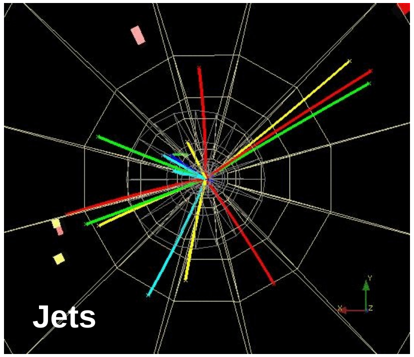


Hyperons & Hyper-nuclei

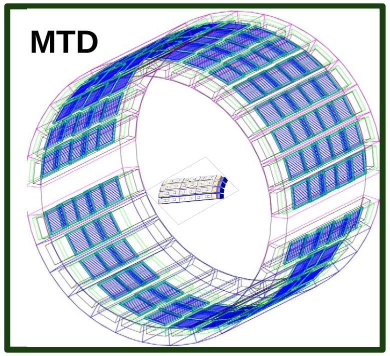




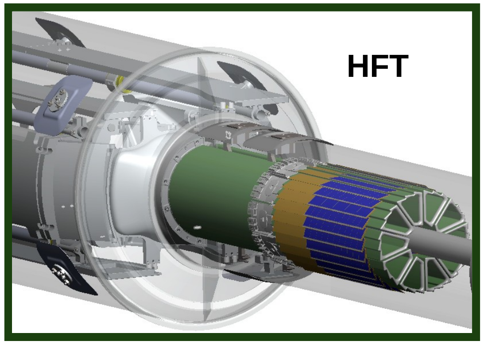
Neutral particles



Jets & Correlations



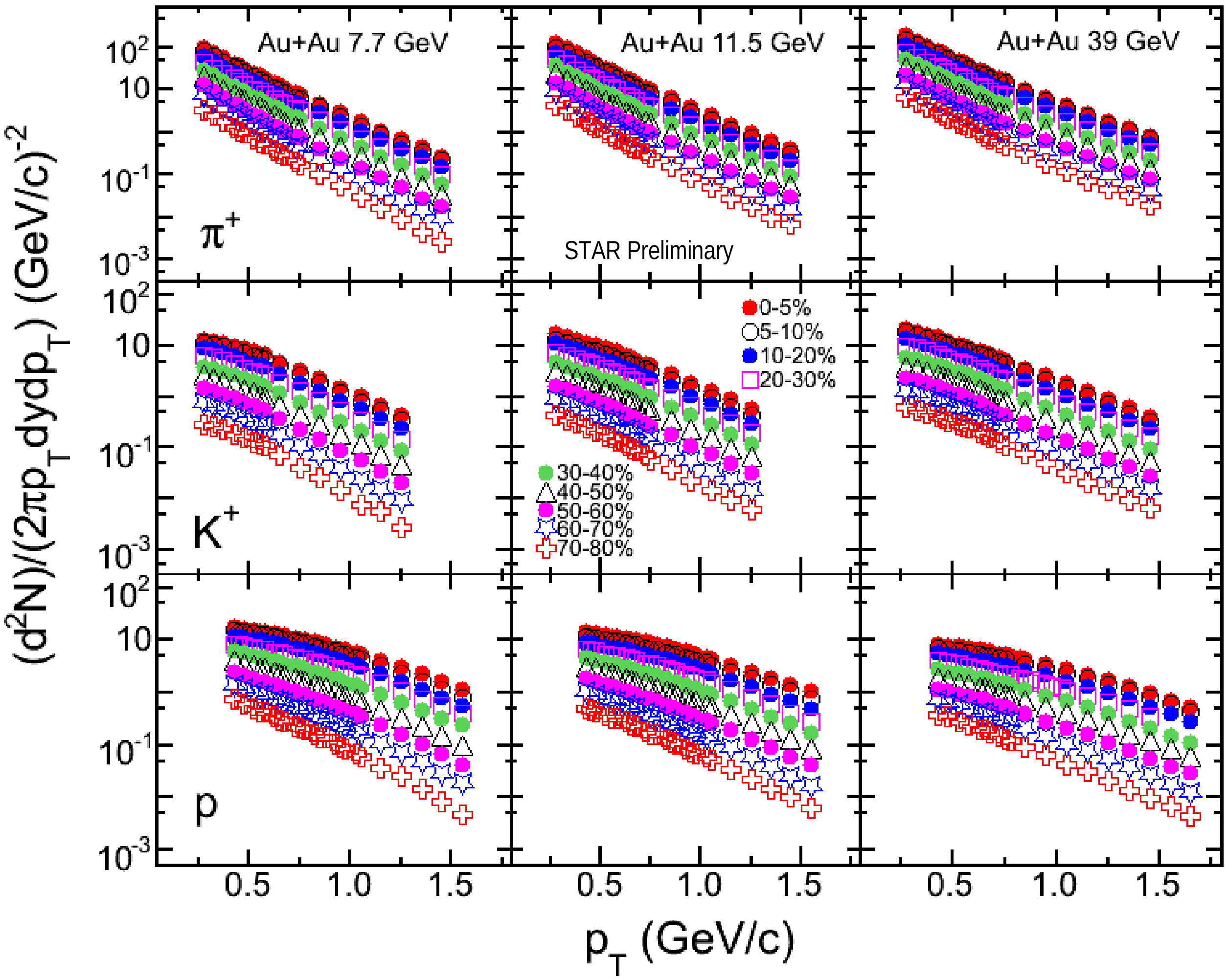
High pT muons



Heavy-flavor hadrons

Wide acceptance and excellent particle identification

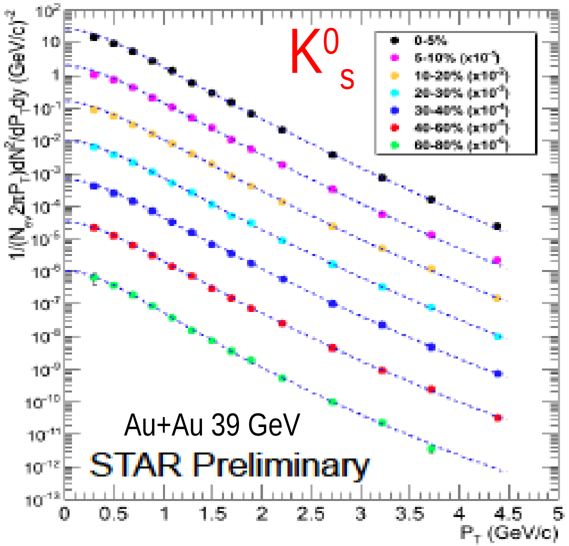
Spectra: π, K, p

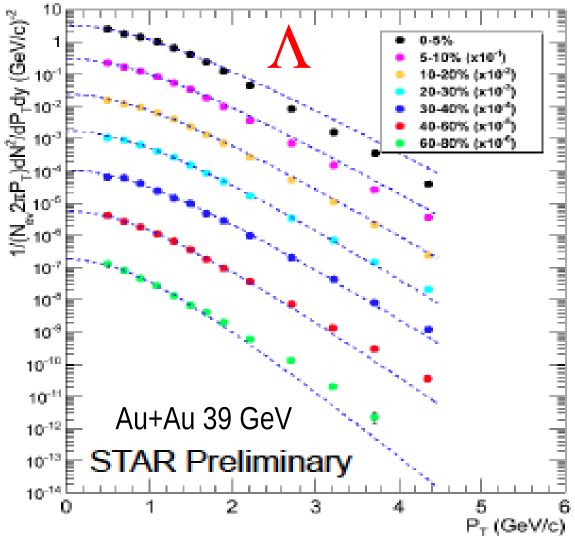


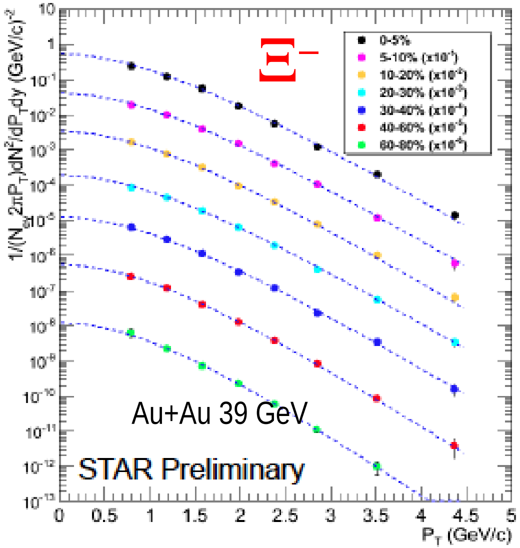
Slopes: π > K > p

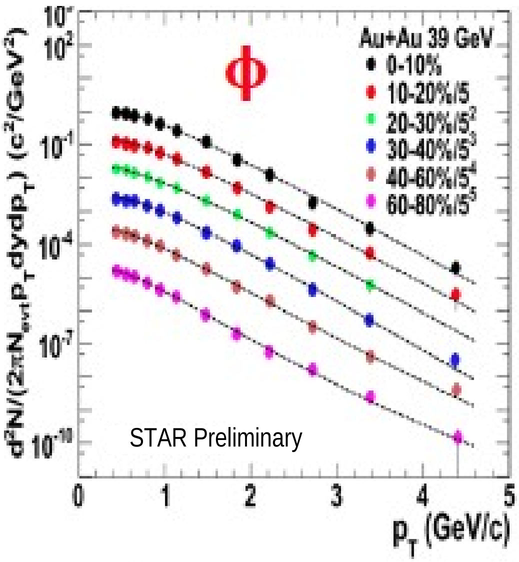
π, K, p yields within measured p_T ranges

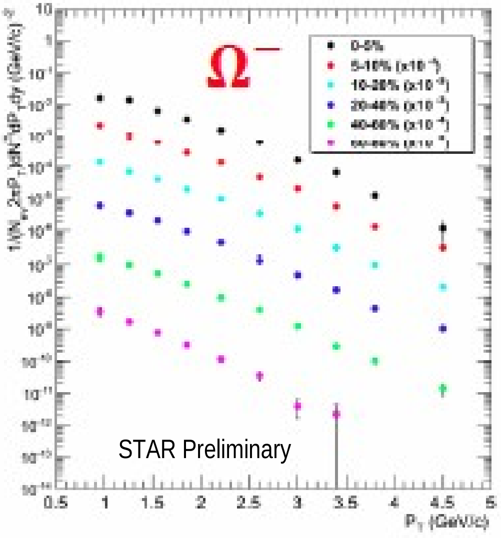
Spectra : strange hadrons



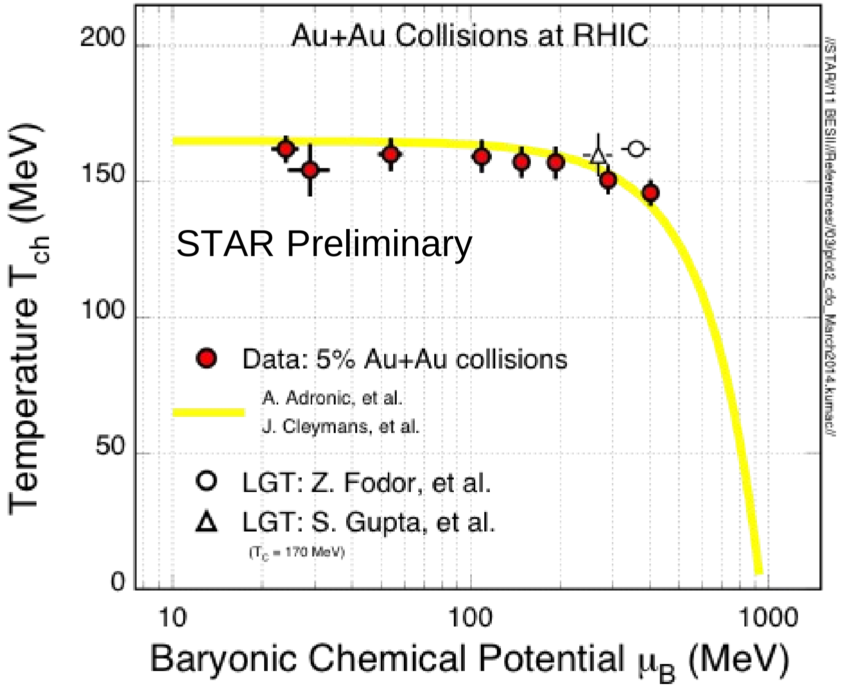


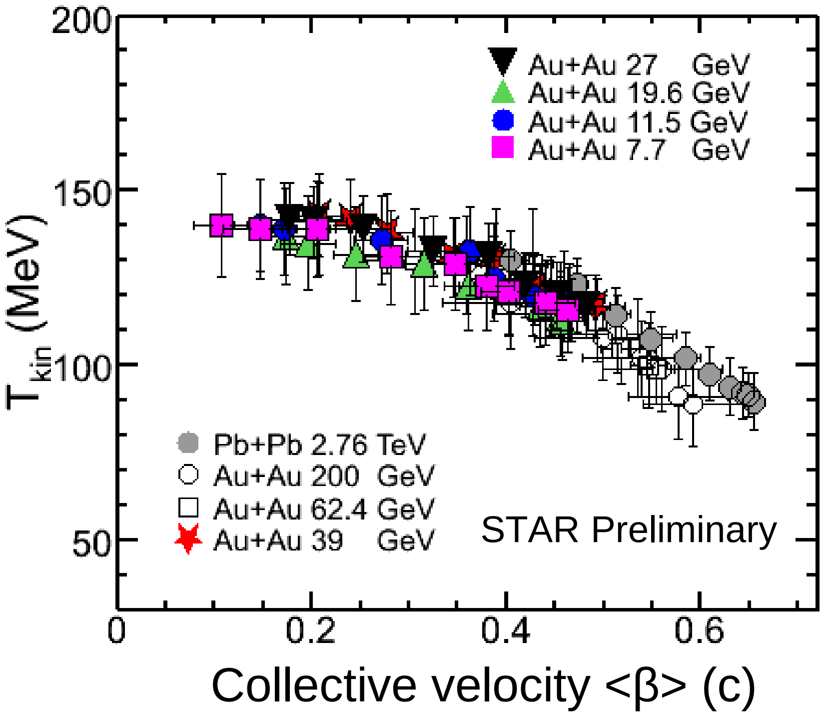






Chemical freeze-out





Chemical Freeze-out:
→ only central collisions.

- **Kinetic Freeze-out:**
  → lower value of T_{kin} and larger collectivity β

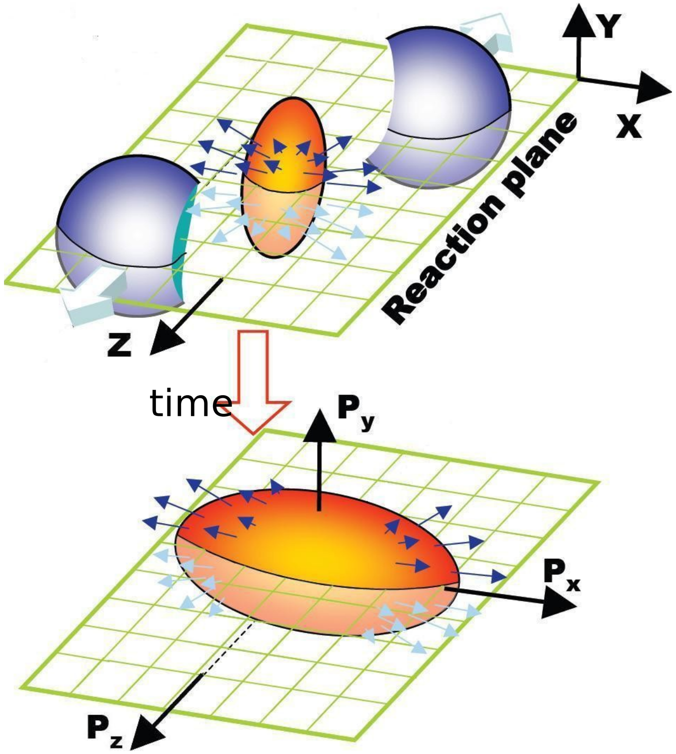
  → stronger collectivity at higher energy

1. Turn-off signatures of QGP

Dissapearance of signals of partonic degrees of freedom seen at $\sqrt{s}_{NN}$ = 200 GeV

- constituent quark number scaling
- hadron suppression in central collisions
- dynamical charge fluctuations
- …

Anisotropic flow



Initial spatial anisotropy determined by impact parameter and initial fluctuations

In early collision stages, spatial anisotropy converted by gradient pressure and scatterred to momentum anisotropy.

- **Fourier decomposition of the momentum space particle distributions in the x-y plane**
  - **v_n is the n-th harmonic Fourier coefficient of the distribution of particles with respect to the reaction plane**
    - **v_1: "directed flow"**
    - **v_2: "elliptic flow"**
    - **v_3: "triangular flow"**

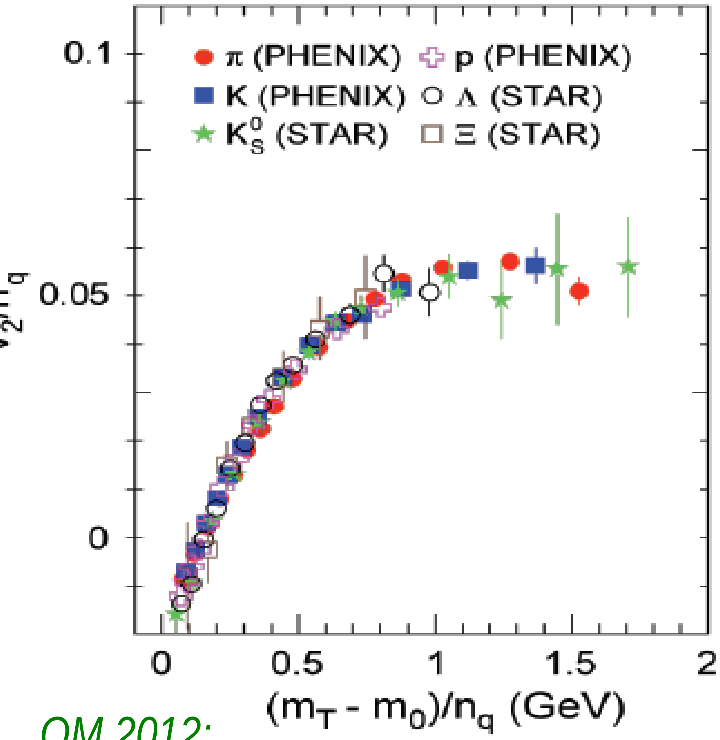
$$\frac{dN}{d\varphi} \approx \left(1+2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi-\psi_n)\right)\right)$$

$$v_n = \left\langle \cos n\left(\varphi-\psi_n\right)\right\rangle,\ n=1,2,3..,$$

Partonic degrees of freedom in Au+Au at $\sqrt{s}_{NN}$ = 200 GeV

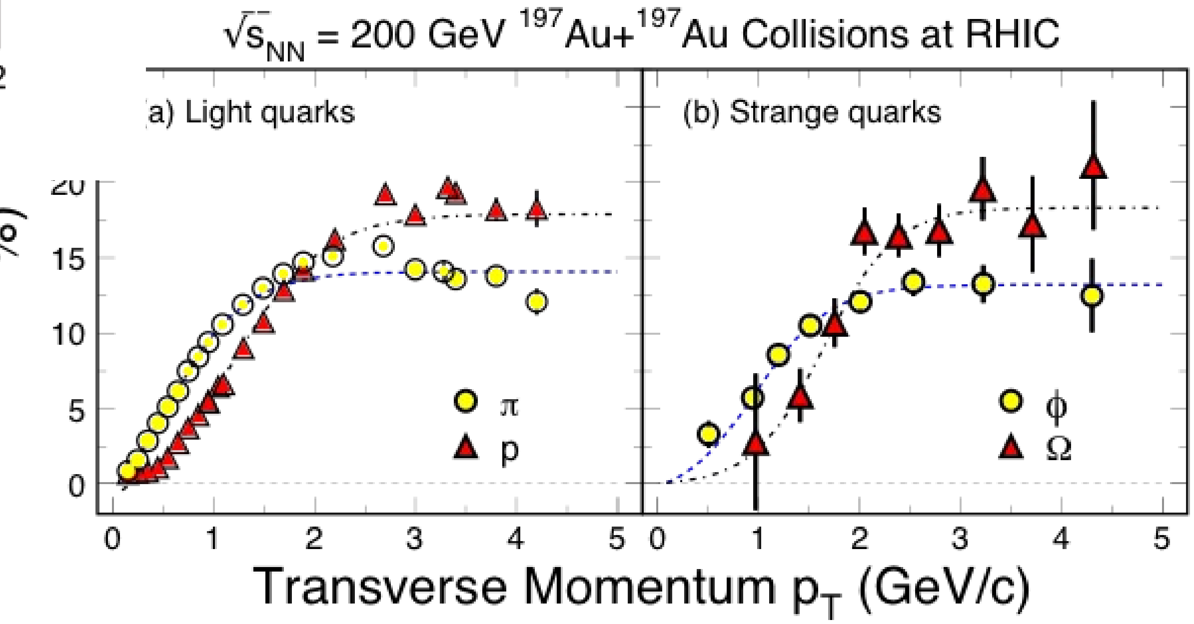
Flow developed in pre-hadronic stage
It is a signal of deconfinement at RHIC

Scaling of v_2 with n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons



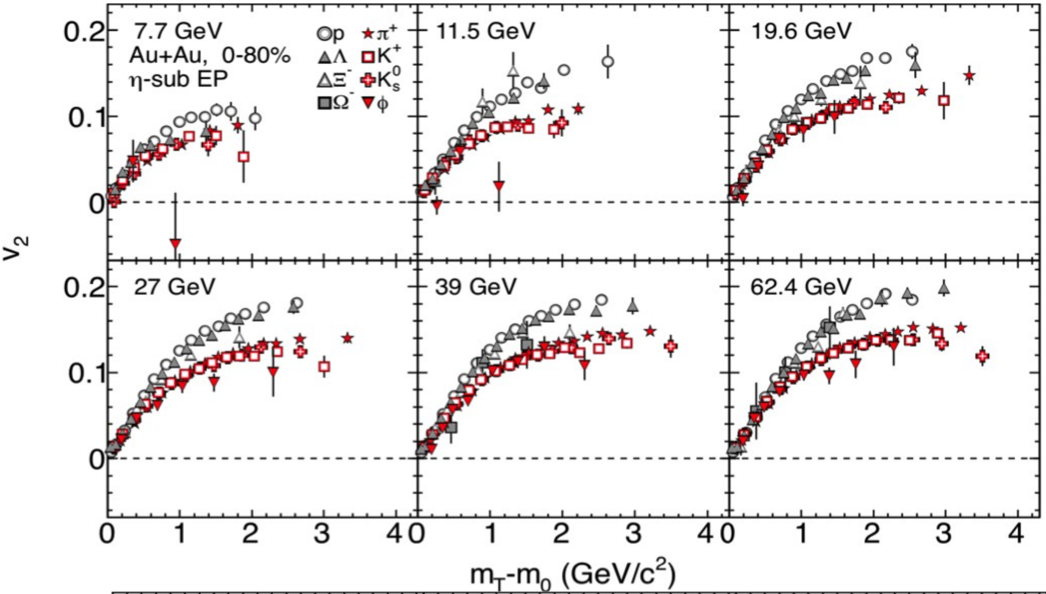
QM 2012:

Possible disappearance of n_q scaling at lower collision energies = disaperance of partonic degrees of freedom

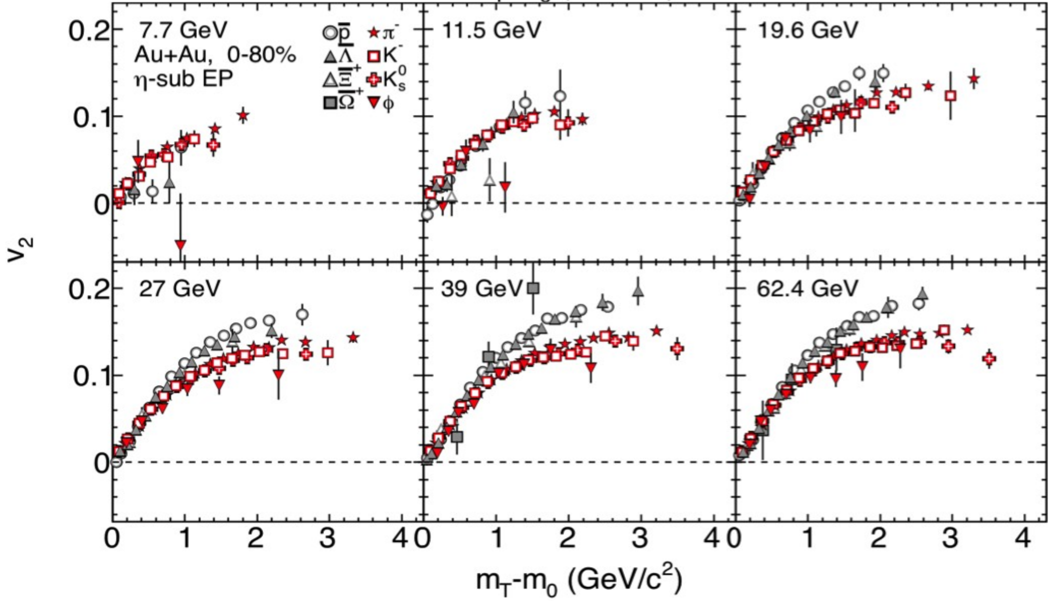


v_2 of identified (anti)particles vs energy

Phys. Rev. C 88 (2013) 14902



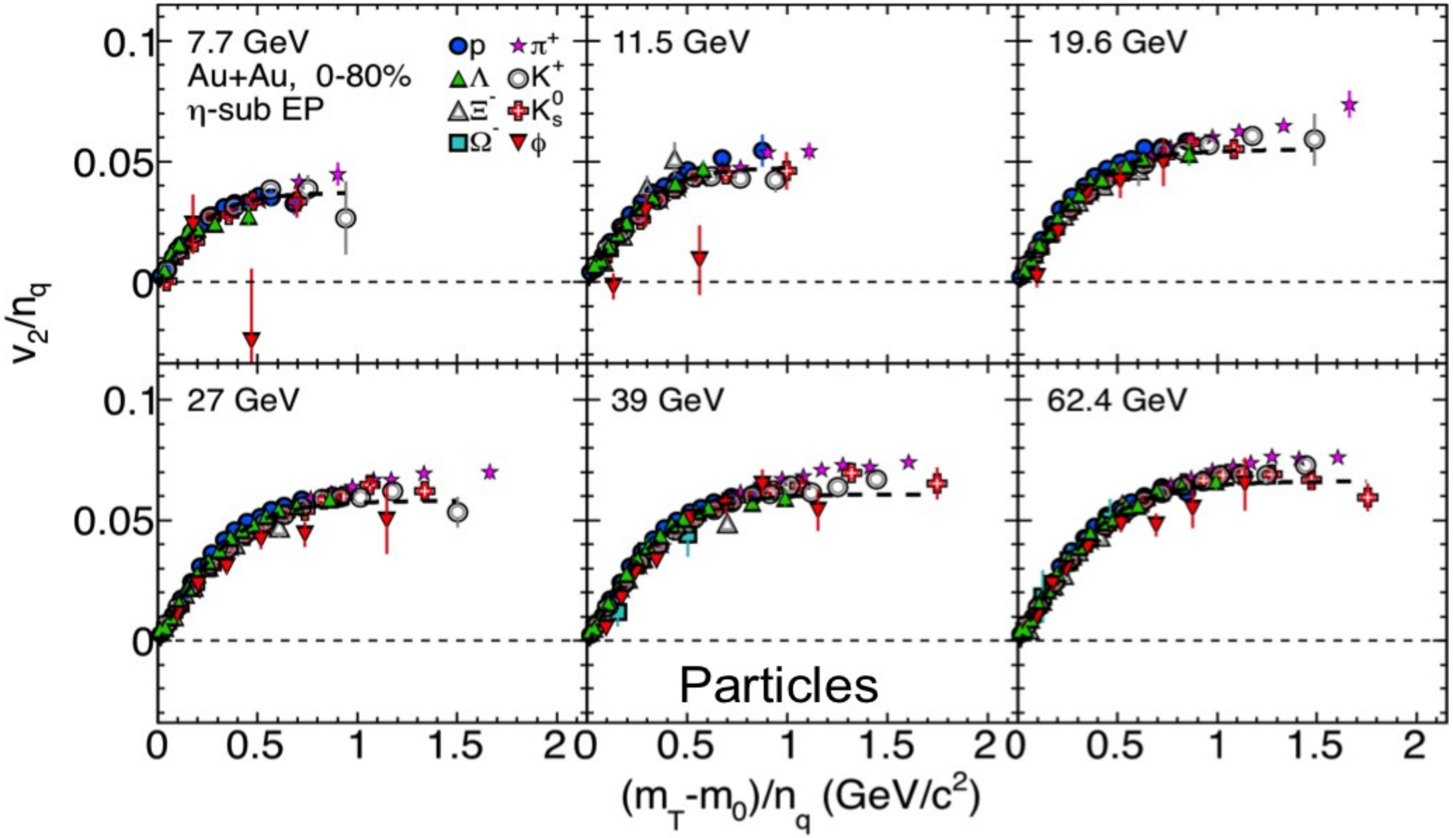
Baryons and mesons bands splitting decrease with decreasing of $\sqrt{s_{NN}}$



Baryon and meson band splitting for antiparticles disappear at $\sqrt{s_{NN}} \leq 11.5$ GeV

v_2/n_q scaling with energy - particles

Phys. Rev. C 88 (2013) 14902



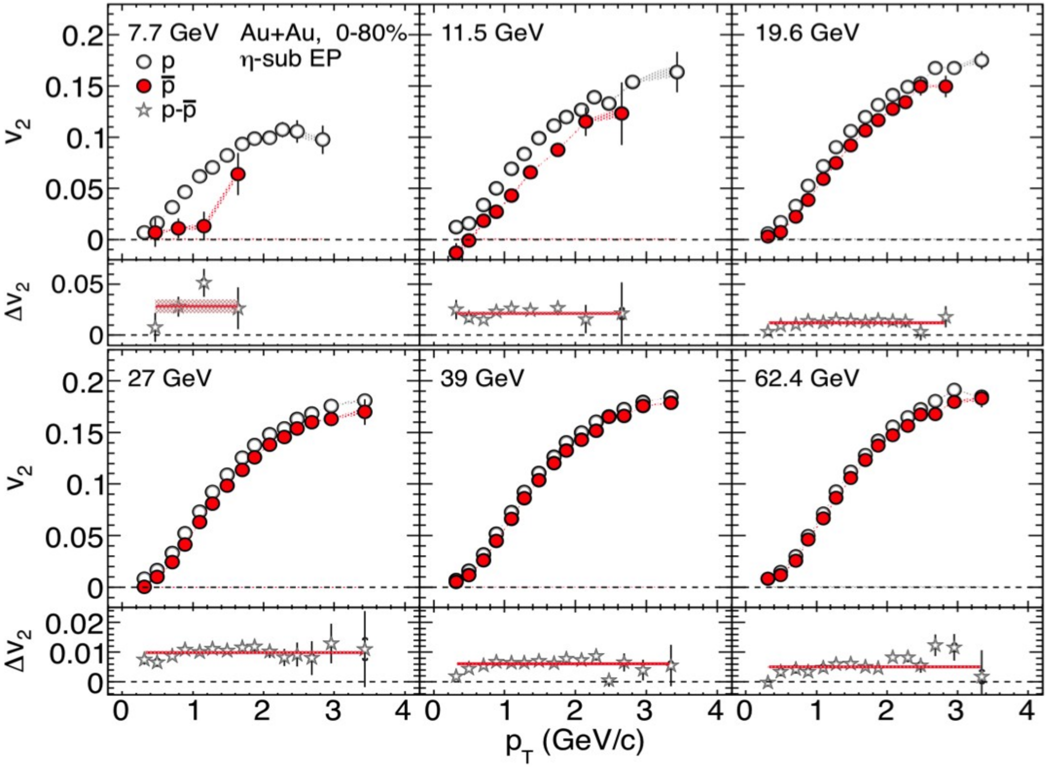
n_q scaling holds within ~10%, except ϕ

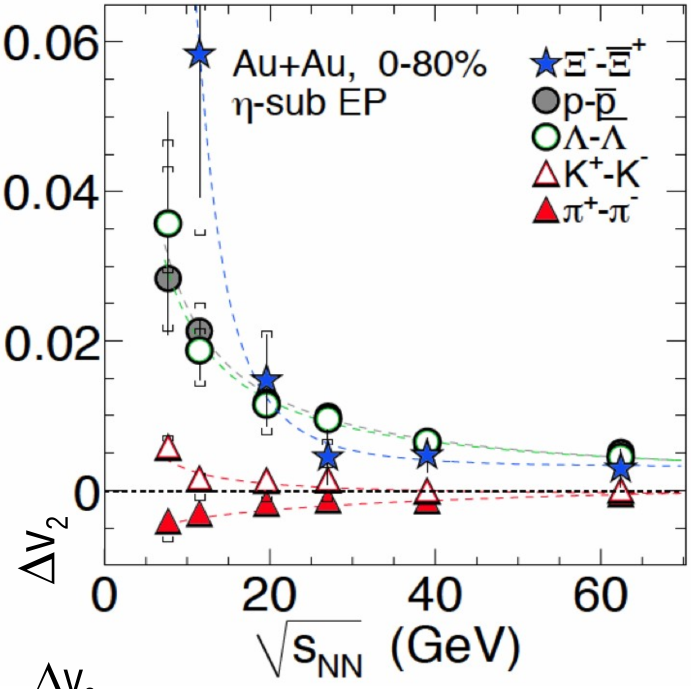
ϕ meson becomes outlier at lowest two energies (large error bars)

v_2 for protons and antiprotons

Phys. Rev. Lett. 110 (2013) 142301

$\Delta v_2 = v_2(\text{proton}) - v_2(\textbf{\textit{anti}}\text{proton})$





Δv_2:

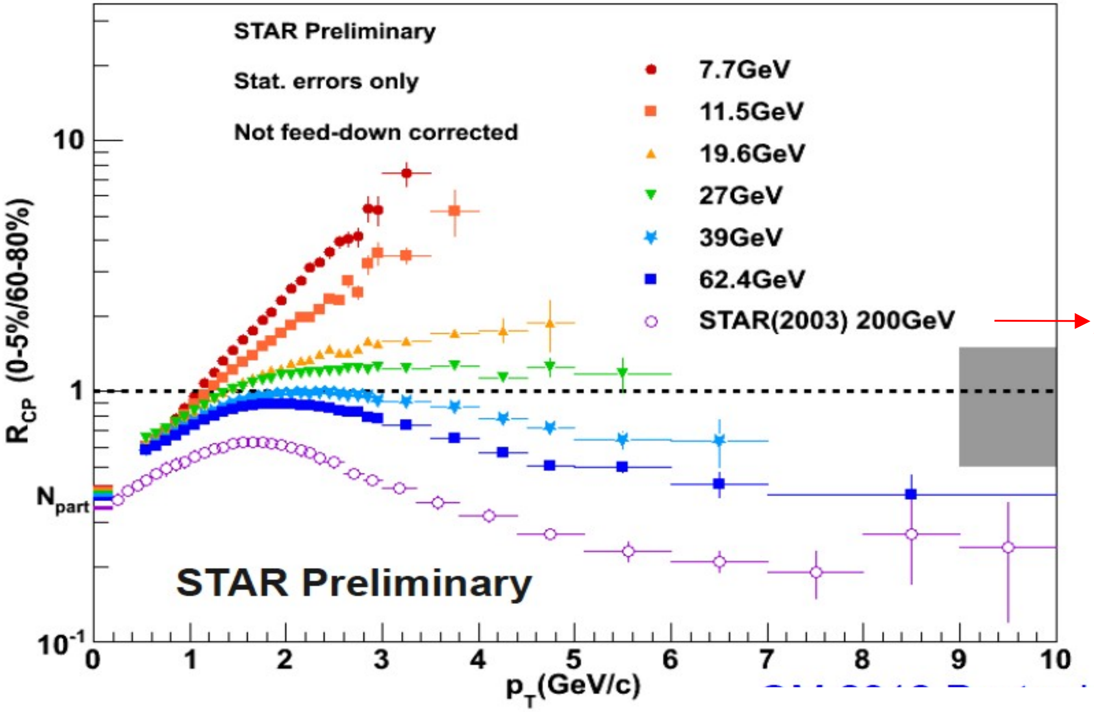
- larger for baryons than for mesons
- nonlinear increase with decrease of $\sqrt{s_{NN}}$

Proton – antiproton difference increases with decreasing energy

Difference between particle and antiparticle →
→ break down of N_q scaling between particles
and antiparticles at lower energies

R_{cp} for charged particles

$$R_{CP}=\frac{d^2 N dp_T \, d\eta / \langle N_{bin} \rangle (central)}{d^2 N dp_T \, d\eta / \langle N_{bin} \rangle (peripheral)}$$

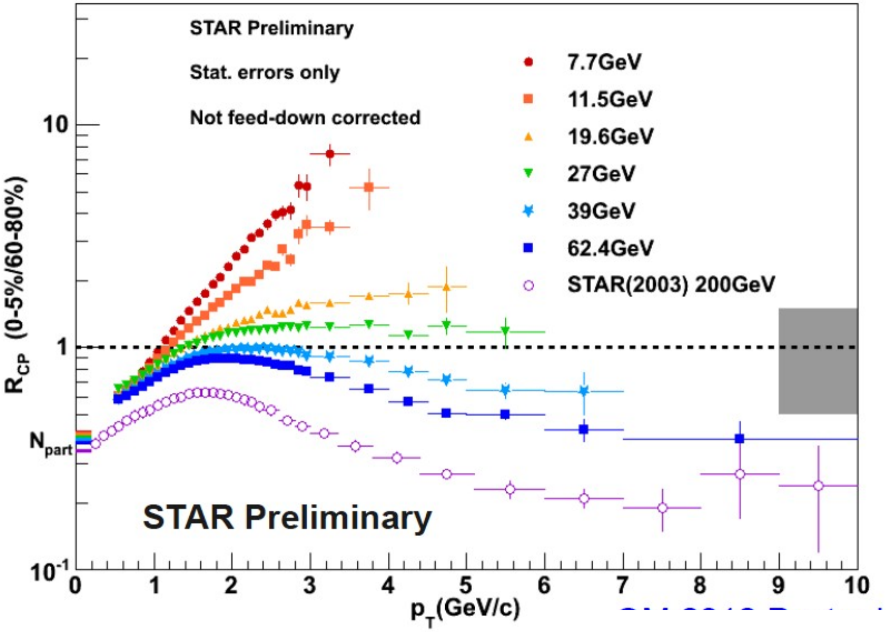


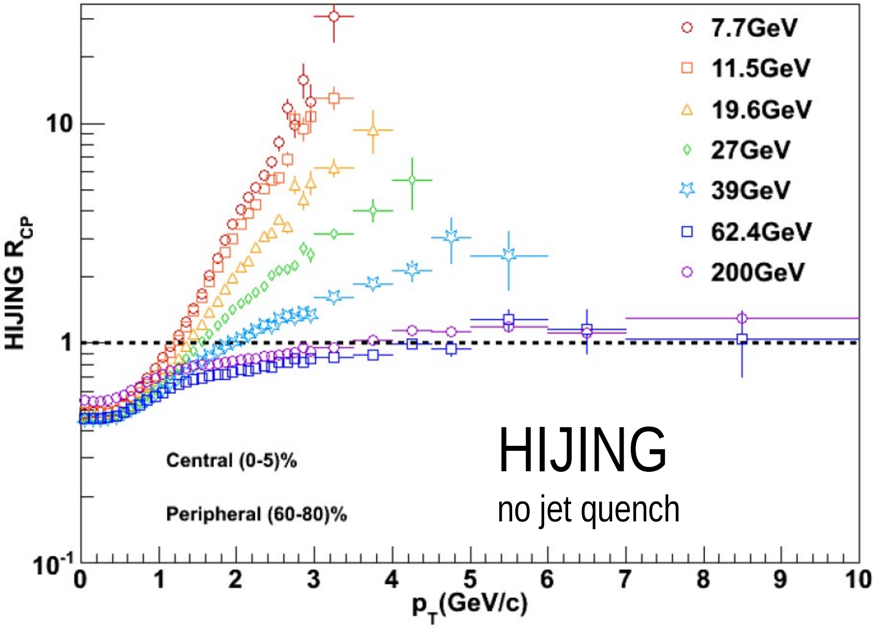
J.Adams et al., (STAR coll.
PRL 91, 172302 (2003)

$R_{CP}>1$ for $\sqrt{s_{NN}}=27$ GeV and below -
high p_t suppression seen at $\sqrt{s_{NN}}=200$ GeV is not present

R_{cp} for charged particles

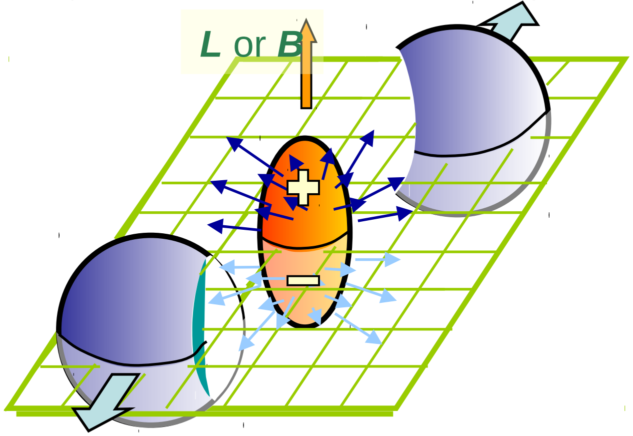
QM 2012:



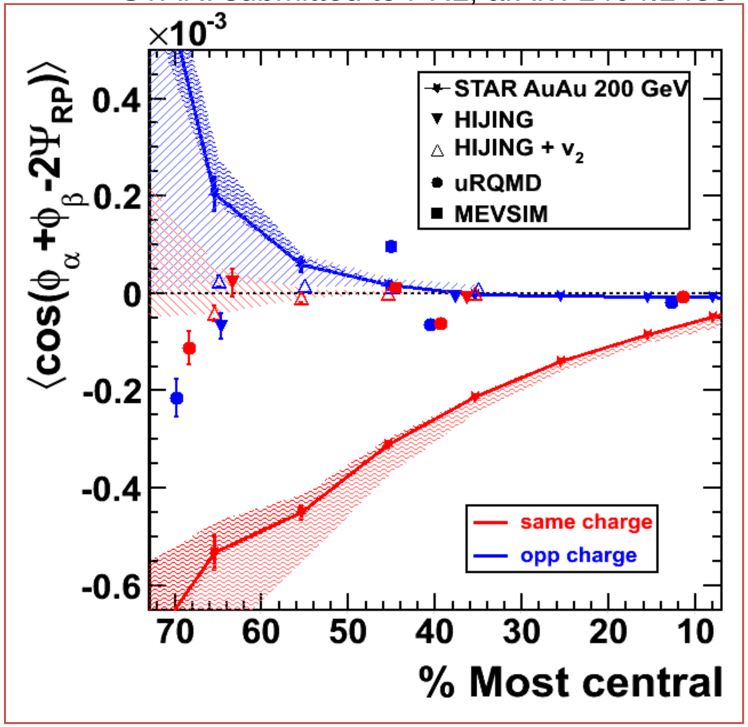


HIJING without jet quenching, including Cronin effect

Dynamical charge correlations ("local parity violation")



STAR: submitted to PRL, arXiv: 1404.1433



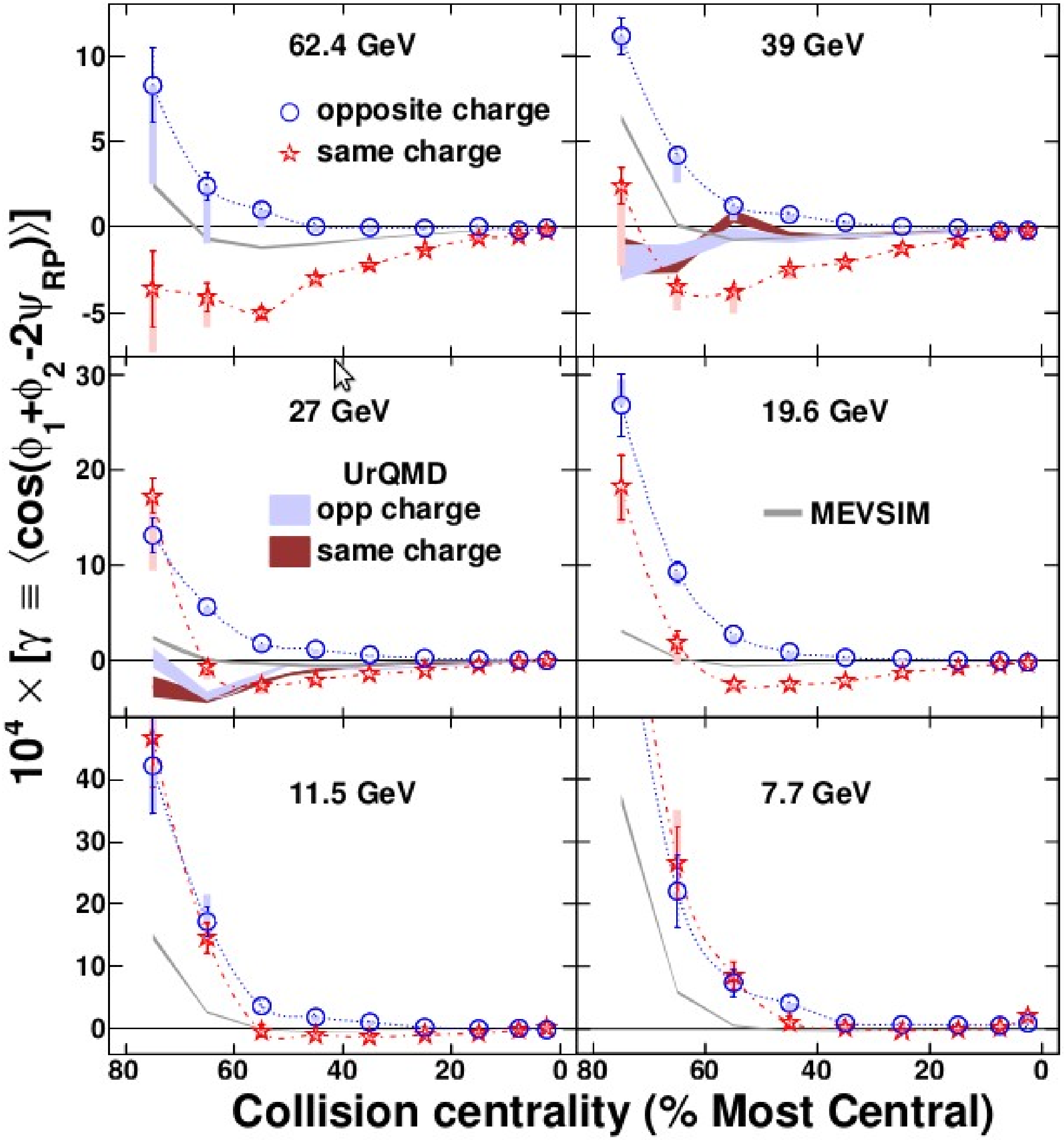
(1) Under strong magnetic field, when the system is in the state of deconfinement, local fluctuation may lead to local parity violation.

(2) Experimentally one would observe the separation of the charges in high-energy nuclear collisions.

(3) Observed signature at top RHIC energies has excellent statistical significance for AuAu, UU and CuCu at top RHIC energies

(4) If interpretation is correct, disappearance of signal would be new signature for turn-off of deconfinement

Dynamical charge correlation signal vs. $\sqrt{s_{NN}}$



Splitting between same and opposite-sign charges decreases with decreasing $\sqrt{s_{NN}}$ and disappears below $\sqrt{s_{NN}}$ = 11.5 GeV

Phys. Rev. Lett. 113 (2014) 52302

Turning-off sQGP signals:

- Baryons and mesons bands for antiparticles collapses at $\sqrt{s_{NN}} = 11.5$ GeV
- v_2/N_q scaling between particles and antiparticles breaks down
- high p_t suppression disappeared
- disappearance of charge separation
- LPV disappears at low energies

Hadronic interactions are dominant at lower beam energies

2. Critical Point

Indications of the existence of Critical Point
- fluctuation measures

Why we do measure fluctuations and correlations ?

System at the QCD critical point region is expected to show sharp increase in the correlation length

→ large non-statistical fluctuations should be observed

→ search for increase (or discontinuities) in fluctuations and correlations as function of $\sqrt{s_{NN}}$

→ fluctuations should be maximized at Critical Point

Observables:

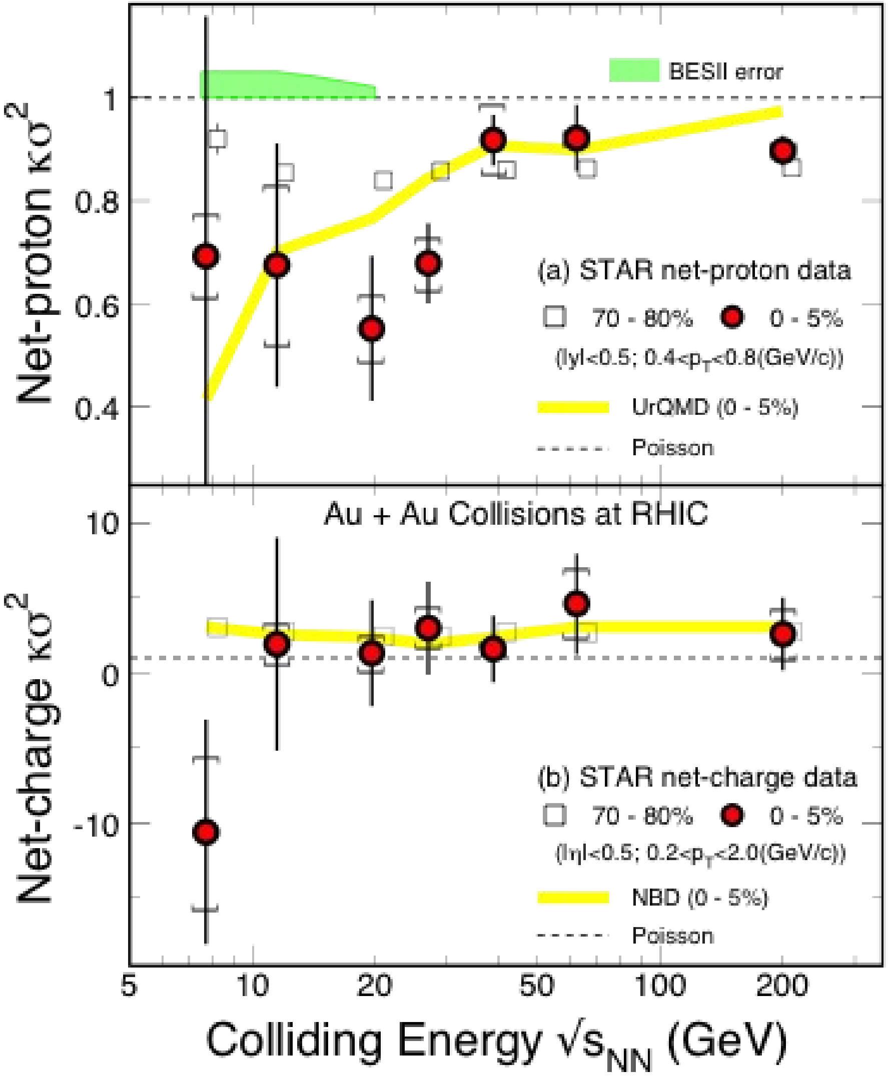
→ Particle ratio fluctuations: K/π, p/π, K/p

→ Conserved numbers (B,Q,S) fluctuations

- higher moments of net-protons and net-charge

Higher moments

$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$
$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$$



- Higher moments of conserved quantities measure non-Gaussian nature of fluctuations;
- They are more sensitive (than variance) to CP fluctuations (to correlation length)
- Non-monotonic behavior of high moments distributions vs $\sqrt{s_{NN}}$ is expected to probe CP

Net-proton:

- Similar behavior at $\sqrt{s_{NN}}$ = 39, 62 and 200 GeV
- UrQMD shows monotonic behavior vs $\sqrt{s_{NN}}$
- All data show deviations below Poisson for κσ2 at all energies.

*STAR: **PRL112**, 32302(14)/arXiv: 1309.5681*

Net-charge results:

- No non-monotonic behavior
- More affected by the resonance decays

STAR: arXiv: 1402.1558
P. Garg et al, PLB726, 691(13)

- Below $\sqrt{s_{NN}}$ = 19.6 GeV data points have large uncertainties

Critical Point signals:

- Deviations of moment products in central Au+Au collisions from Poisson expectations observed
- Big uncertainties prevent us from drawing conclusions

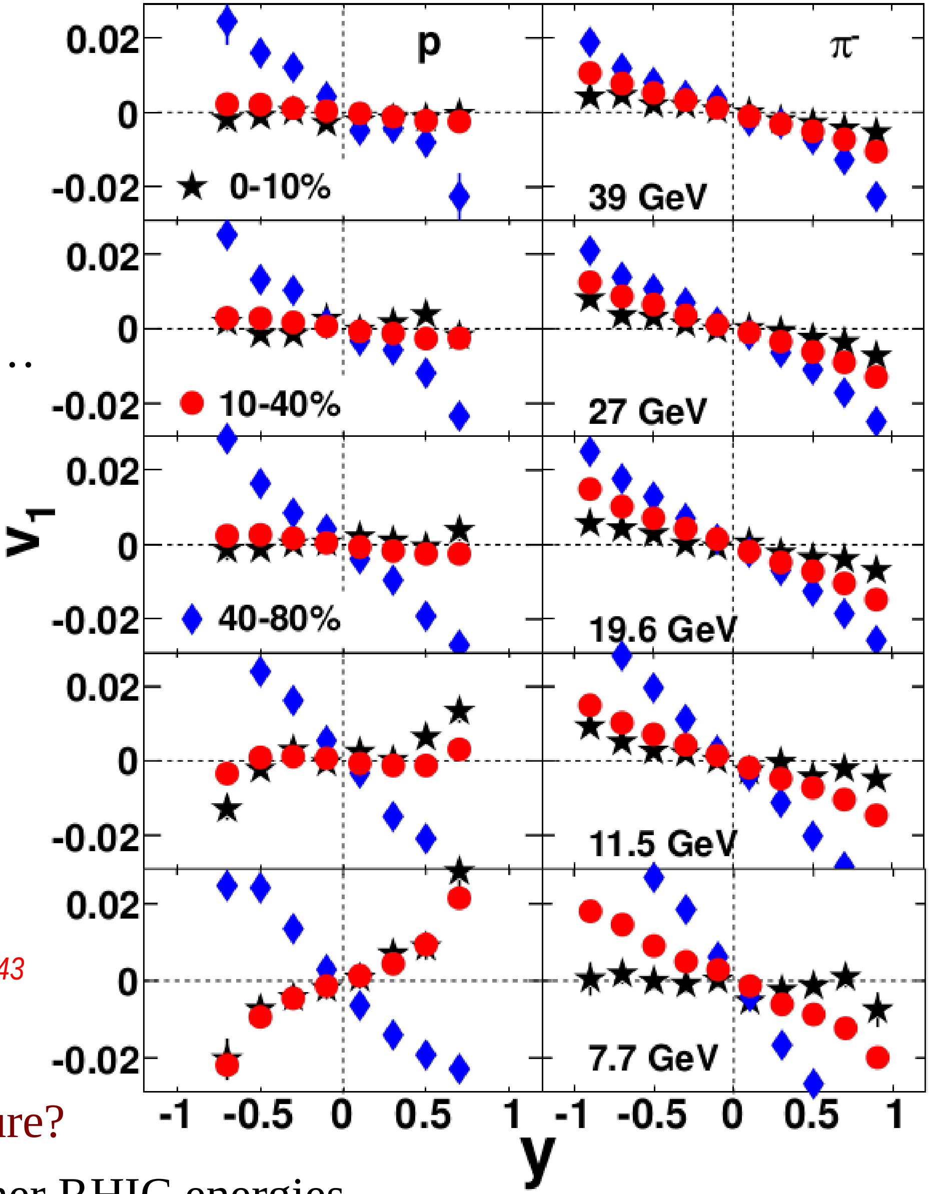
3. Phase transition

Dissapearance of phase transition

- azimuthally sensitive femtoscopy
- direct flow
- ...

Directed flow (v_1) of identified particles

- v_1 probes early stage of collision
- is a probe of early pressure
- a change of sign in the slope of dv_1/dy for protons is proposed to be a sensitive probe to the first-order phase transition …

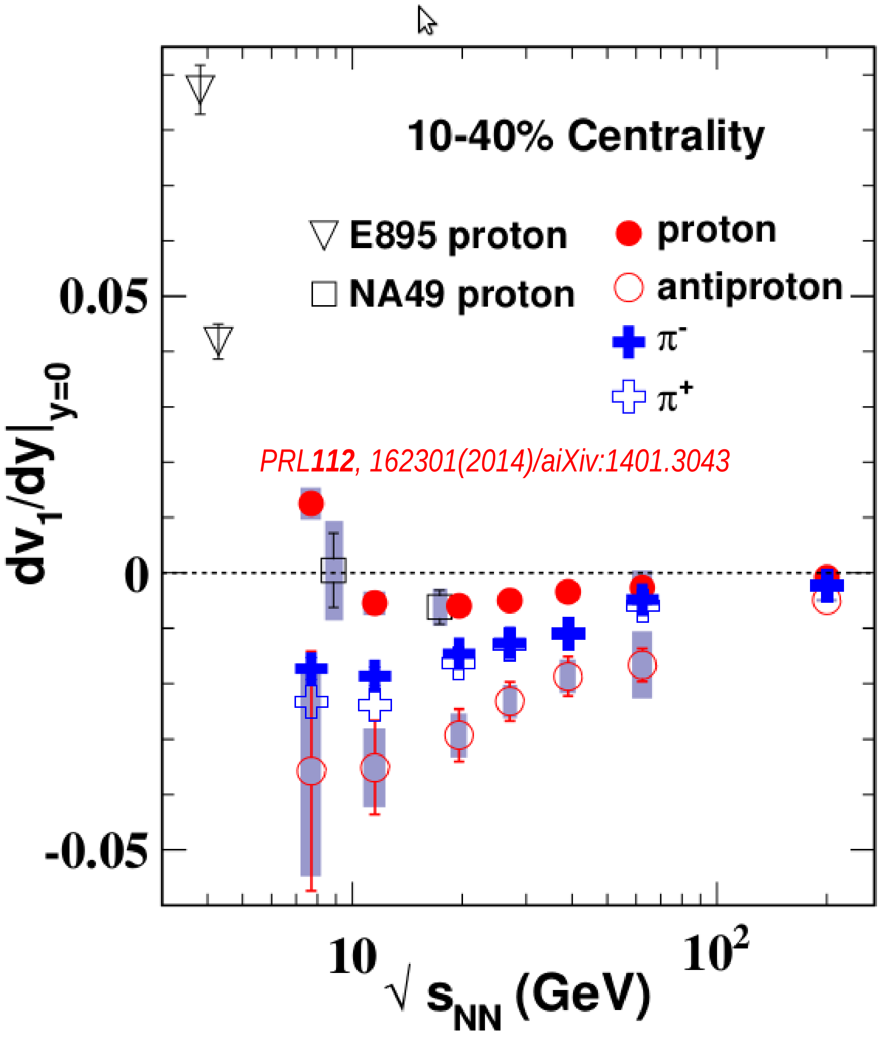


*STAR: PRL**112**, 162301(2014)/aiXiv:1401.3043*

Proton v_1 slope at midrapidity changes sign ($\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV) → 1st order PT signature?

$\sqrt{s_{NN}}$ = 39 GeV v_1 follows trend observed at higher RHIC energies

v_1 of identified particles

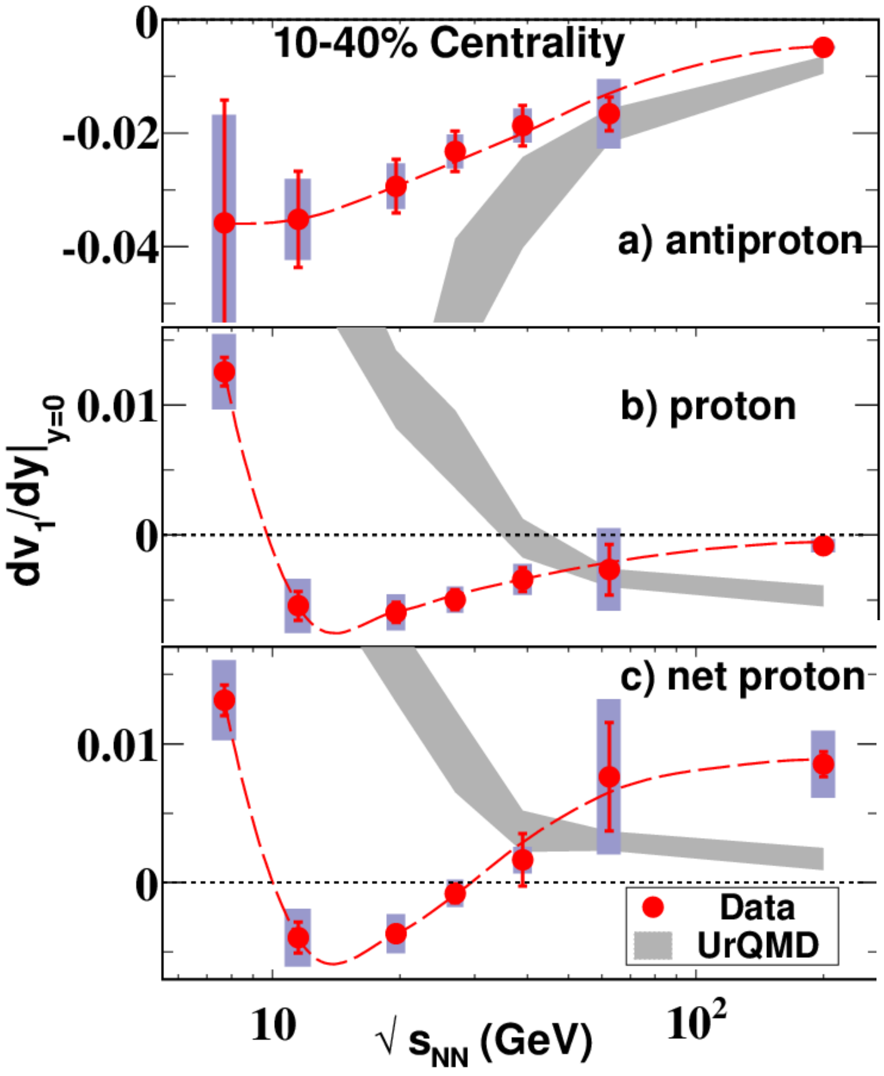


STAR data are consistent with the trend from AGS and NA49 data points for protons.

All other particle type except protons (baryons) have a negative slope.

Proton slope changes from positive to negative in the BES range (7 to 11) GeV.

v_1 of identified particles



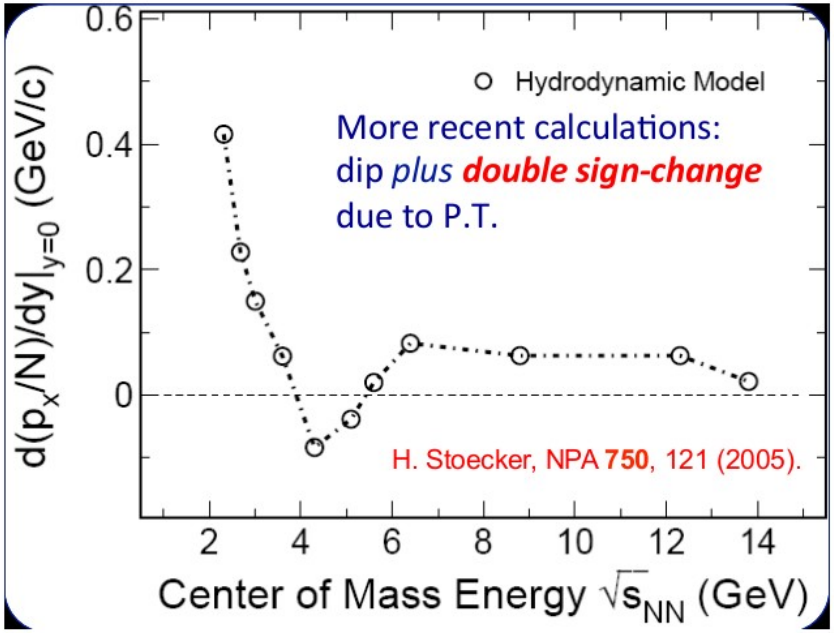
1) Antiproton slope is always negative
2) Proton slope changes sign
3) Net-proton slope changes sign twice

4) BESII improvement:

1) - improved reaction plane determination

- systematic centrality dependence analysis

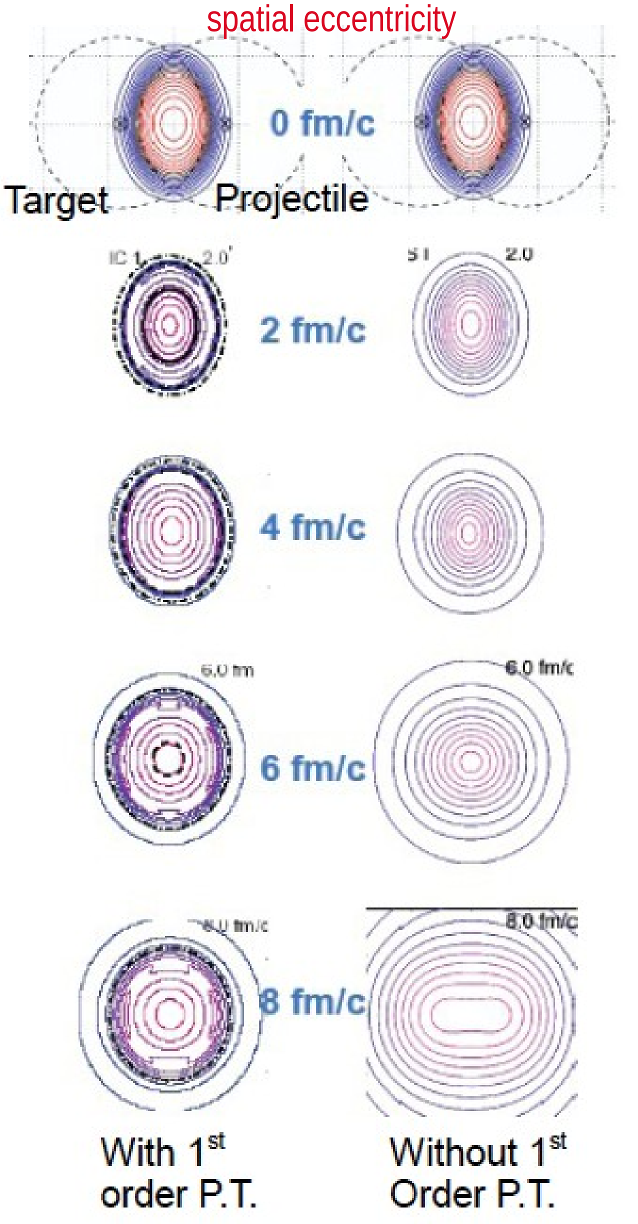
*STAR: PRL**112**, 162301(2014)/aiXiv:1401.3043*



More recent calculations: dip *plus* ***double sign-change*** due to P.T.

H. Stoecker, NPA **750**, 121 (2005).

Azimuthally sensitive femtoscopy



Reference: Kolb and Heinz, 2003, nucl-th/0305084

Freeze-out shape of participant zone in non-central collisions is sensitive to EOS:

- Initial out-of-plane eccentricity

- Stronger in-plane pressure gradients drive in-plane expansion (→ more spherical freeze-out shape)

- Measure eccentricity at freeze-out as function of energy:

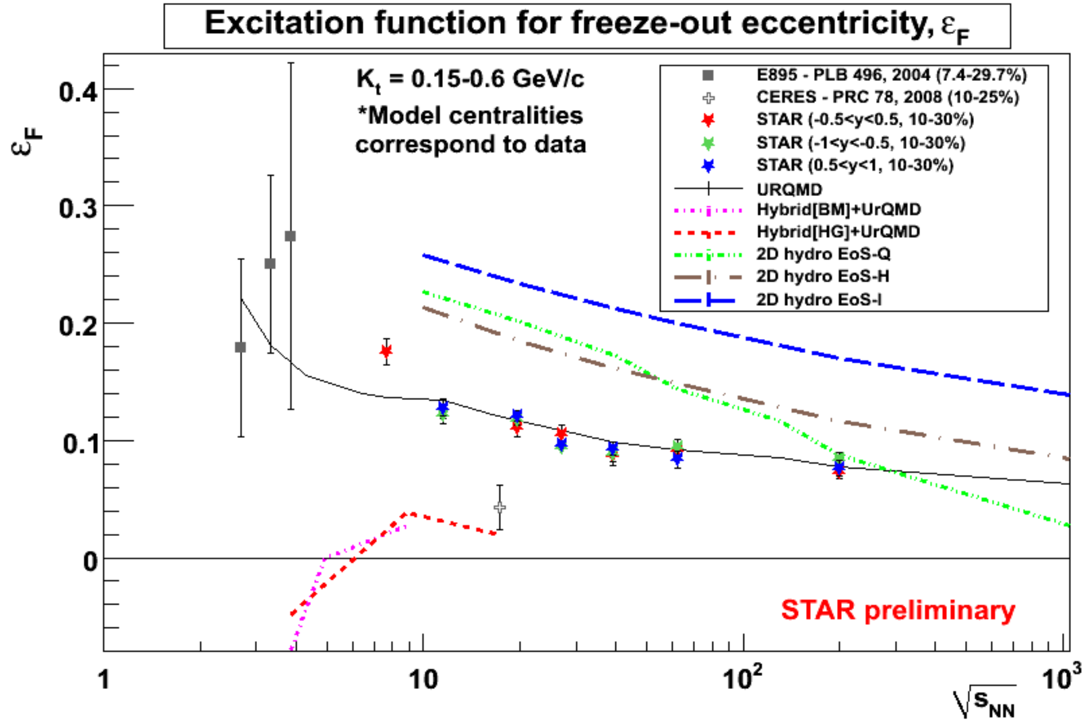
$$\varepsilon_F = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}$$

- Expectation: excitation function for freeze-out eccentricity to fall monotonically with increasing energy

Non-monotonic behavior could indicate a change in EOS → 1st order phase transition

M.Lisa et al., New J.Phys. 13 (2011) 065006

Azimuthal HBT for freeze-out eccentricity



Speculations/explanations: softening of EOS due to entrance into mixed phase above some energy, observed as plateau or minimum in excitation function

M.Lisa et al., New J.Phys. 13 (2011) 065006

Measured freeze-out eccentricity parameters show a smooth decrease from low to high collision energies

It is consistent with monotonically decreasing shape

1^{st} order Phase Transition:

- Net-protons v_1 changes sign twice and shows a minimum around $\sqrt{s_{NN}}$ = 11.5-19.6 GeV
- If the 1^{st} order phase transition takes place at all - that would be probably at lower end of the energy spectrum

Conclusions from BES-I

STAR excellent performance down to $\sqrt{s_{NN}}$ =7.7 GeV

BES-I data sets ($\sqrt{s_{NN}}$ =62.4, 39, 27, 19.6, 14.5, 11.5 and 7.7 GeV) cover important region of QCD phase diagram

Several important sQGP signatures not seen at low energies:

- $v_2(m_T - m_0)$ exhibits baryons and mesons bands splitting
- v_2 for particles & antiparticles diverges strongly at low $\sqrt{s_{NN}}$
- high p_t suppression R_{CP} disappears at low $\sqrt{s_{NN}}$, under investigation
- charge separation signal disappears at low $\sqrt{s_{NN}}$, interpretation unclear
- dv_1/dy of net-protons (directed flow) changes sign with $\sqrt{s_{NN}}$
- fluctuations are constant or monotonic with energy from 7.7 to 200 GeV
- higher moments of net-protons and net-charges deviates from Poisson baseline
- freeze-out eccentricity (asHBT) monotonically decreases with energy

RHIC's energy range is special one

Did we answer our questions ?

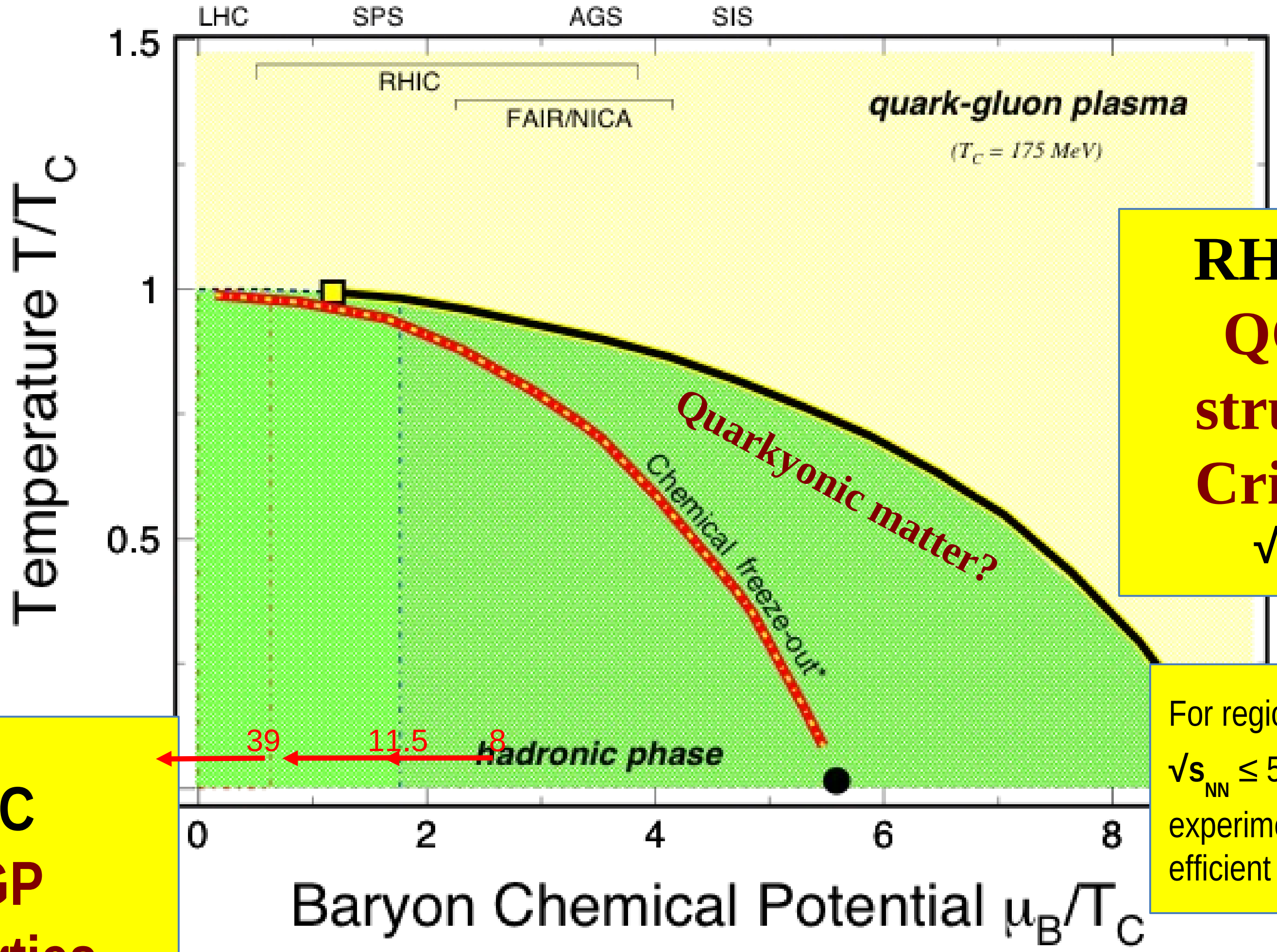
1. turn-off of QGP signatures ? **strong hints**
2. Evidence of the first order phase transition ? **strong hints**
3. Search for the critical point ? **hints** **MORE** statistics !!!

BES-II Phase

… planned for 2018-2019

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Events (10^6)
19.6	205	400
14.5	260	300
11.5	315	230
9.1	370	160
7.7	420	100

Exploring QCD Phase Diagram



RHIC BES-II
QCD phase structure and Critical Point
$\sqrt{s}_{NN} \leq 20$ GeV

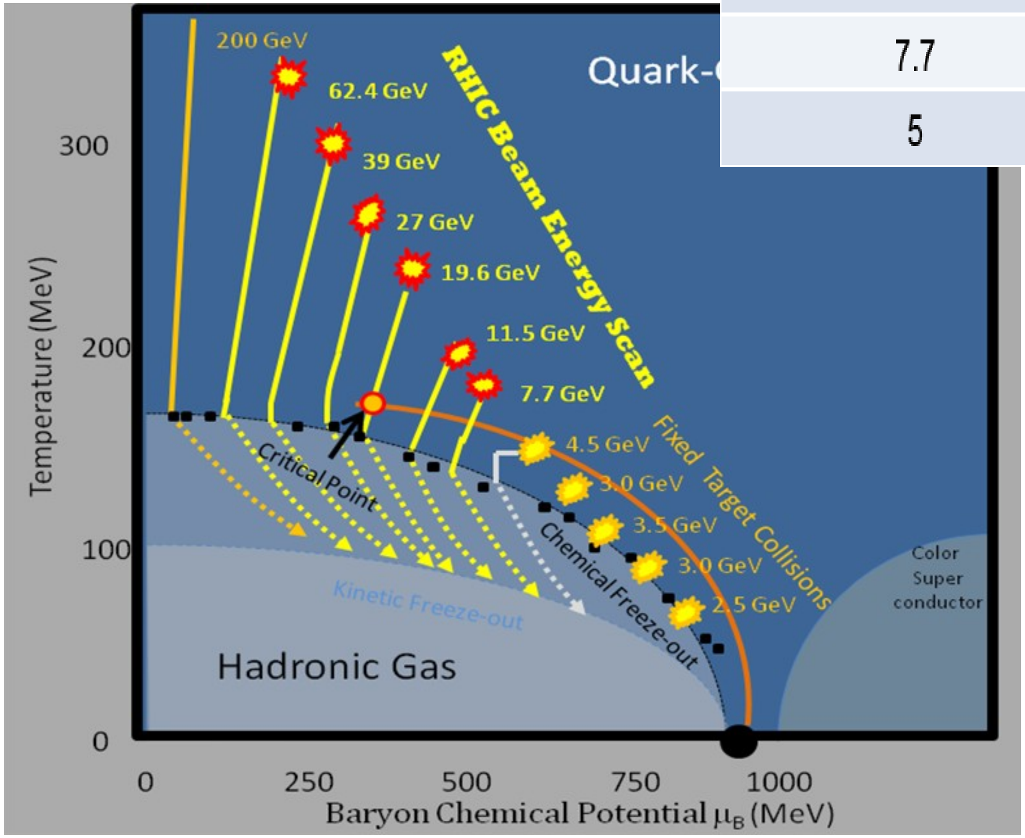
For region $\mu_B > 500$ MeV, $\sqrt{s}_{NN} \leq 5$ GeV, fixed-target experiments are much more efficient

RHIC
sQGP properties
$\sqrt{s}_{NN} = 200$GeV

Fixed-target

μ_B extended range in STAR due to fixed target program

Collider mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode μ_B (MeV)
19.6	4.5	585
15	4.0	625
11.5	3.5	670
7.7	3.0	720
5	2.5	775



Fixed target at STAR

→ STAR will have coverage from mid-rapidity to target rapidity (sufficient for some BES studies)

→ Main detectors tested

→ If successful – this may open a way for fixed target runs with other beams used in BES program in collider mode experiments ($\sqrt{s_{NN}}$= 3.5 and 3 GeV, μ_B up to 800 MeV)

→ Availabe would be the region: $20 < \mu_B < \sim 800$ MeV !

Thank you!

STAR: Near Future Plans

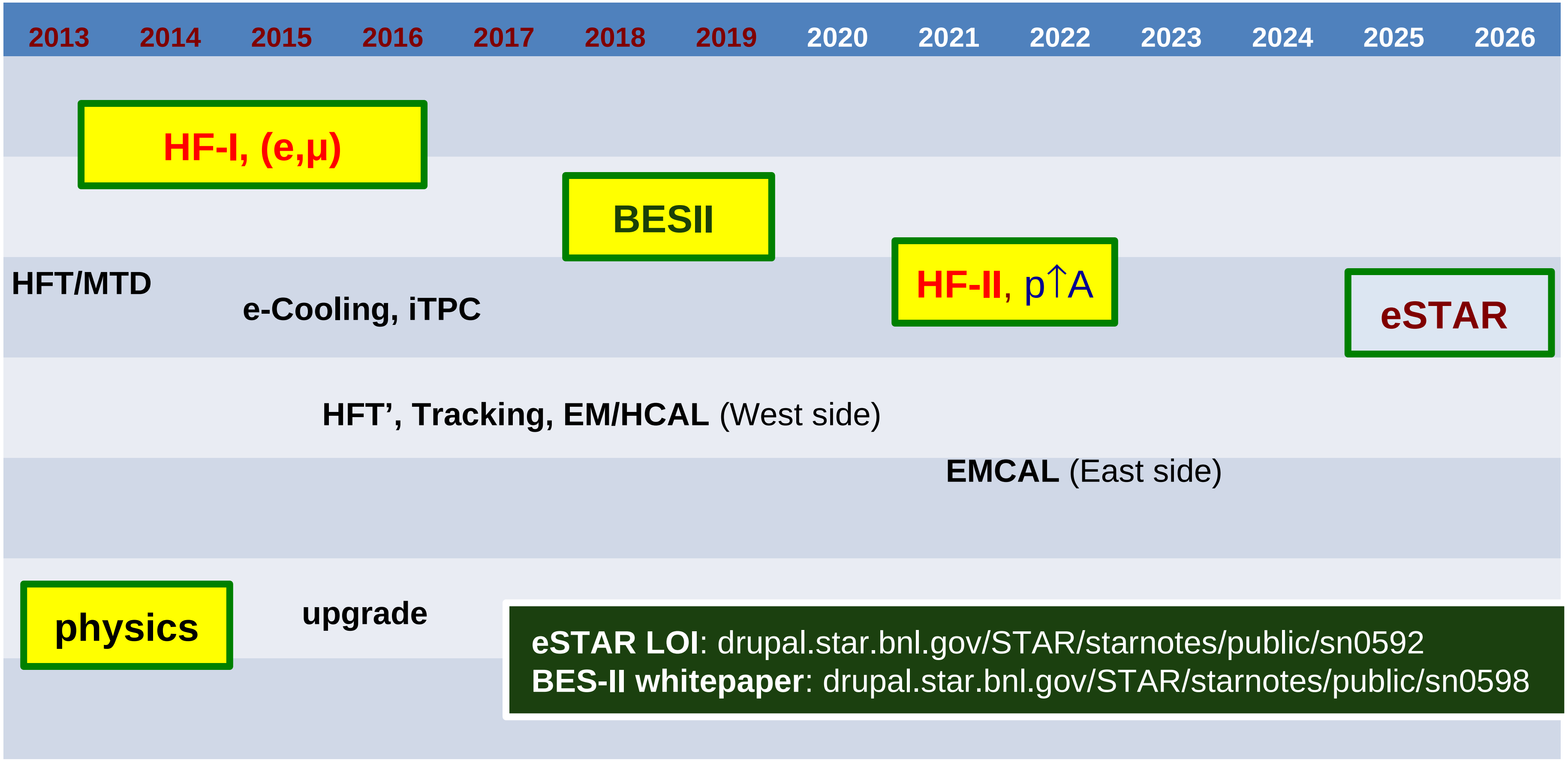
- HFT: Charm
- Di-lepton

sQGP properties

- QCD phase structure
- Critical Point

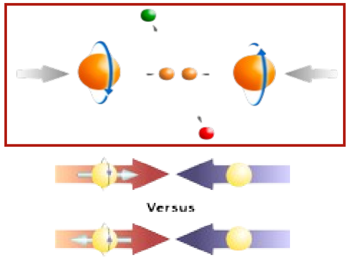
AA: HFT': B, **ΛC**
Jet, γ-jet
pA: *CNM, p-spin*

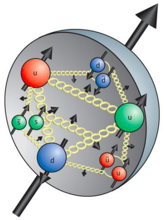
Phase structure with dense gluon



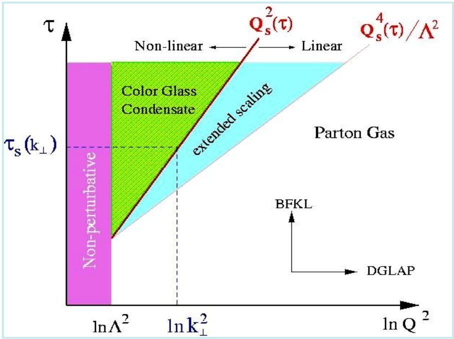
eSTAR LOI: drupal.star.bnl.gov/STAR/starnotes/public/sn0592
BES-II whitepaper: drupal.star.bnl.gov/STAR/starnotes/public/sn0598

STAR Physics Focus





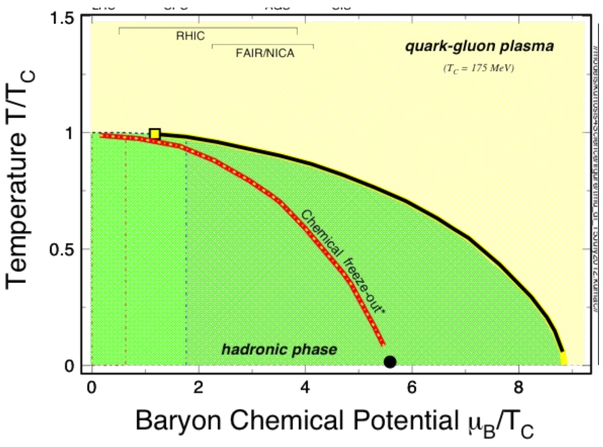
Polarized *p+p* Program
- Study ***proton intrinsic properties***



Small-x Physics Program
- Study low-x properties, initial condition, search for ***CGC***
- Study elastic and inelastic processes in pp2pp

eSTAR

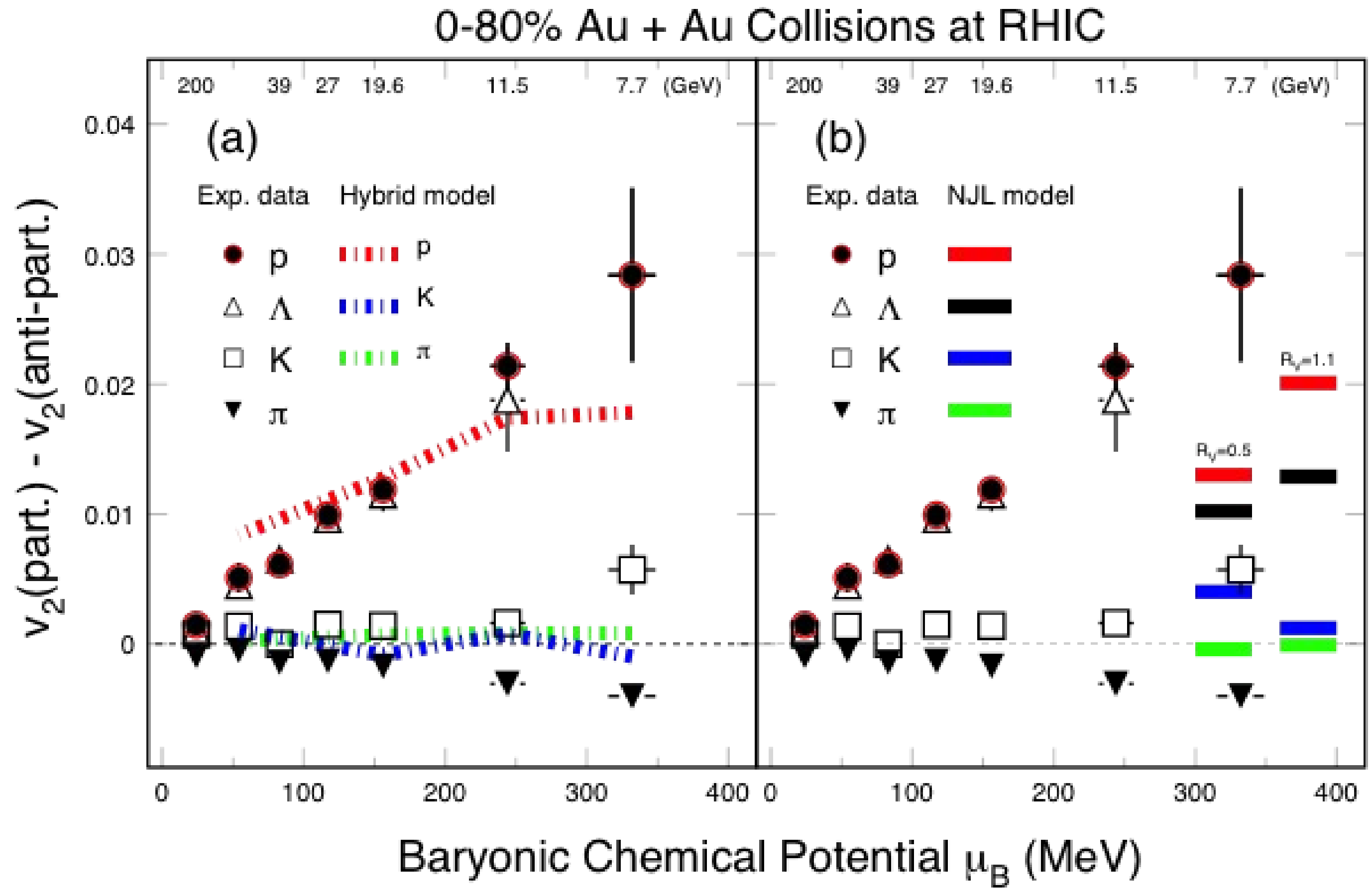
Since 2010



1) At 200 GeV at RHIC
- Study ***medium properties, EoS***
- pQCD in hot and dense medium

2) RHIC Beam Energy Scan (BES)
- Search for the ***QCD critical point***
- Chiral symmetry restoration

Model comparison for v_2

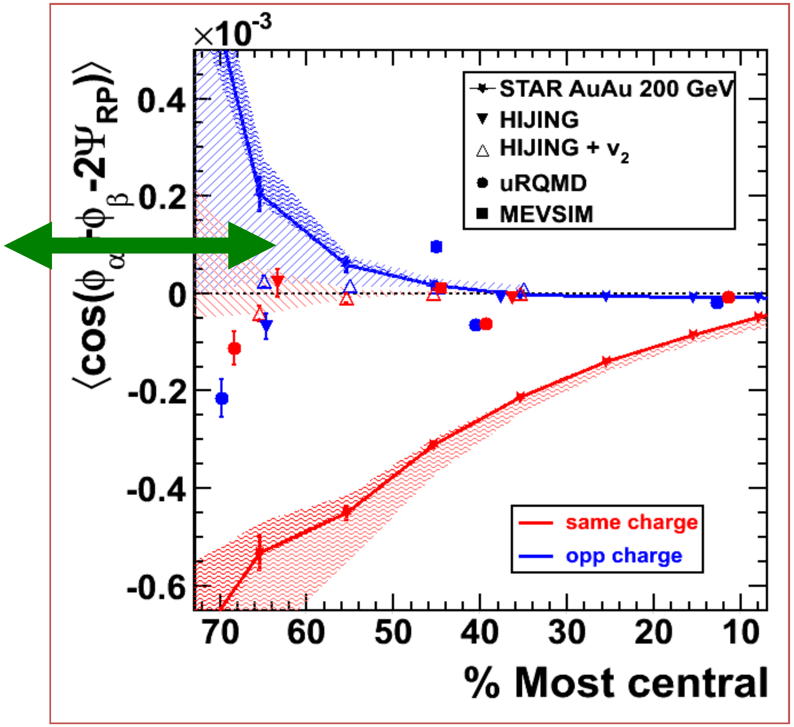


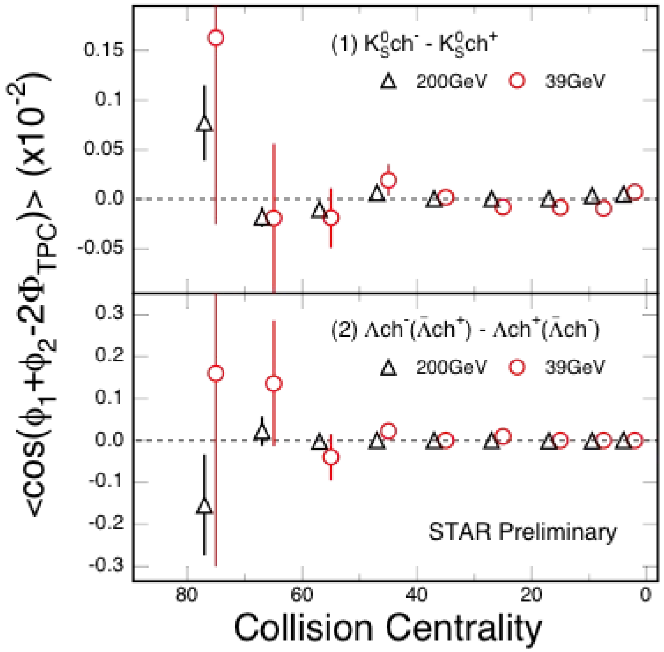
(a) Hydro + Transport: consistent with baryon data.

[J. Steinheimer, V. Koch, and M. Bleicher PRC86, 44902(13).]

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

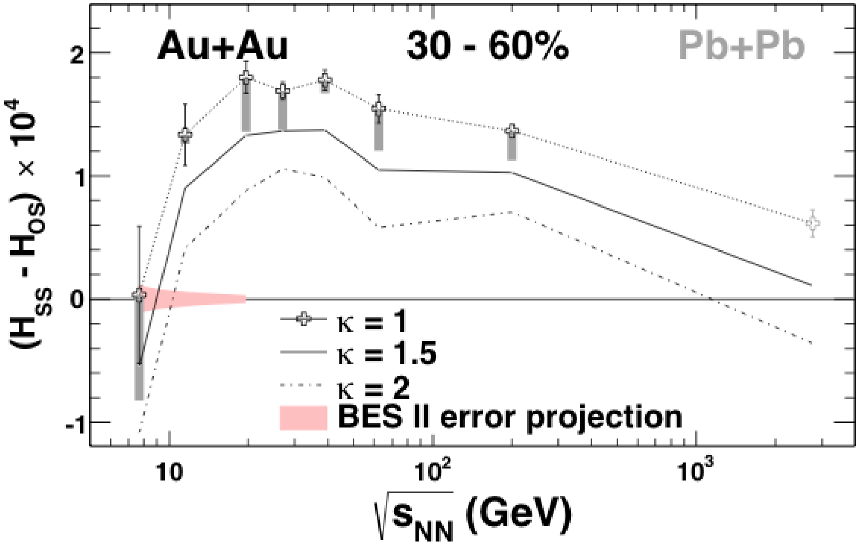
Charge Separation and Event Plane





LPV disappears with neutral hadrons:

Phys. Rev. Lett. 113, 052302 (2014)



LPV disappears at low energy:

hadronic interactions dominant at $\sqrt{s_{NN}} \leq 11.5$ GeV

STAR: PRL. 103, 251601(09)
PLB633, 260 (06)
NPA803, 227(08)