Program BES w eksperymencie STAR

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BES program in STAR
and what next?

..

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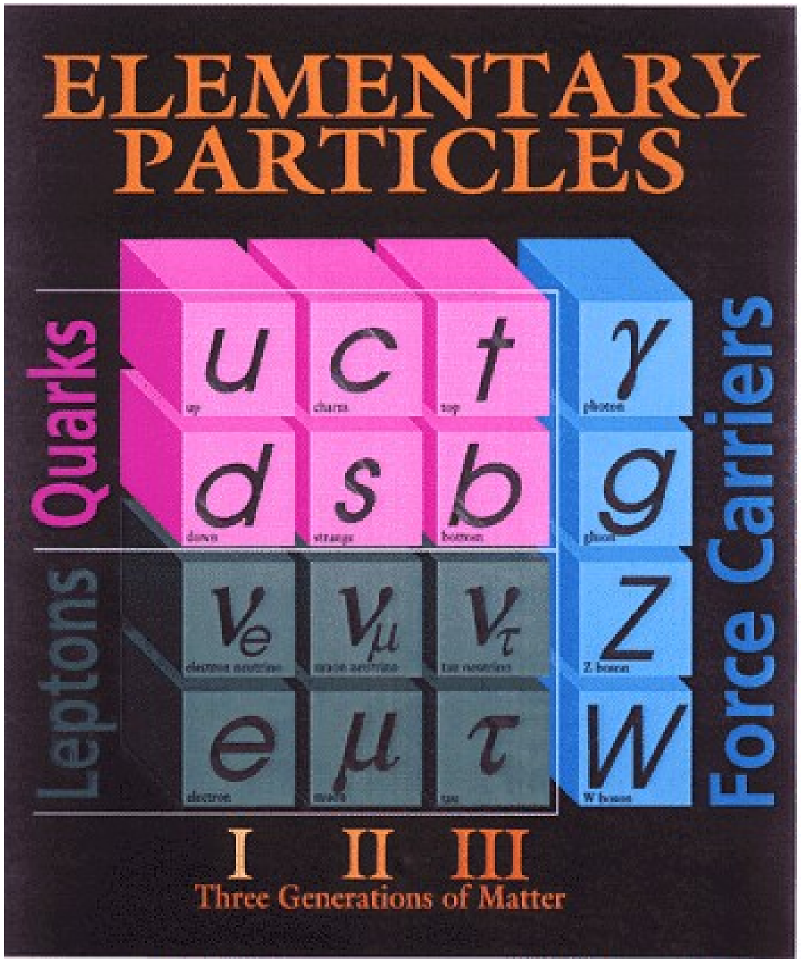
1. Introduction and motivations
2. Phase I - some results
   - what questions are we able to answer ? **
3. Phase II (completion of BES program)

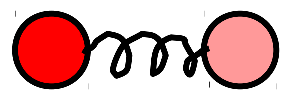
Basics on Quantum Chromodynamics



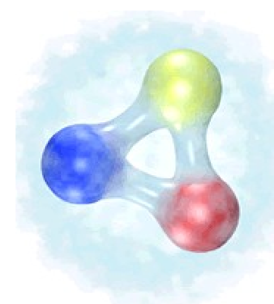
Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.

Gluons hold quarks together to from hadrons:

meson



baryon

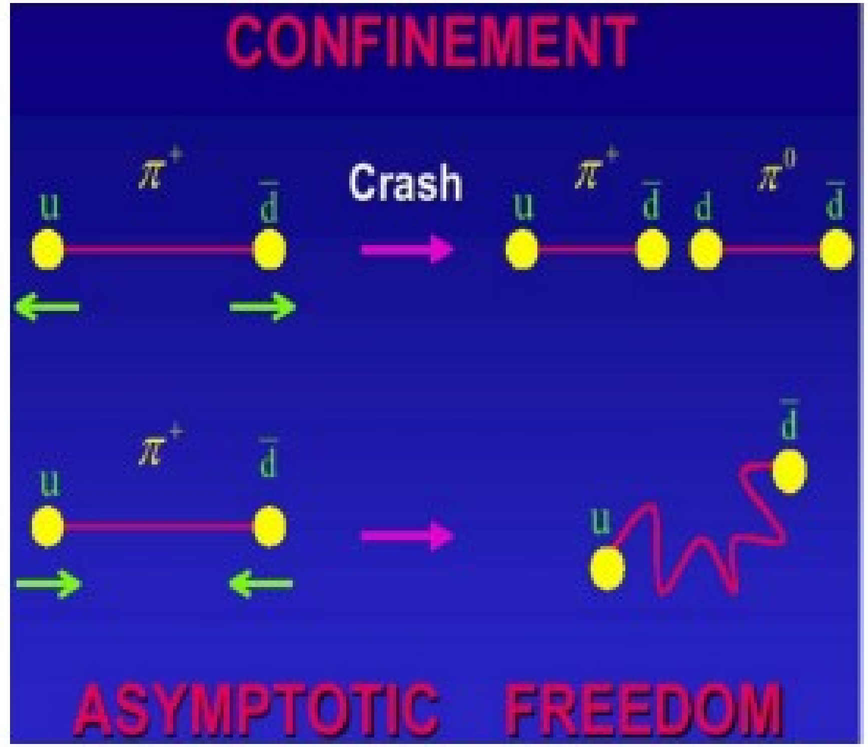


Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement.***

Quark gluon plasma (QGP)

Asymptotic freedom is the property of some gauge theories in which the interaction between the particles, such as quarks, becomes arbitrarily weak at ever shorter distances, i.e. length scales that asymptotically converge to zero.

Confinement is the physics phenomenon that color charged particles (such as quarks) cannot be isolated. The quarks are confined with other quarks by the strong interaction to form pairs or triplets so that the net color is neutral, to obey the Pauli exclusion principle. Quarks in mesons must be of a color and the corresponding anti-color to achieve color neutralism; in baryons a red-green-blue mixture (or its anti-color equivalent in an antiparticle) must be achieved.



Quark-gluon plasma (QGP) is a phase of quantum chromodynamics (QCD) which exists at extremely high temperature and/or density.
This phase consists of (almost) free quarks and gluons which are the basic building blocks of matter.

Where are we?

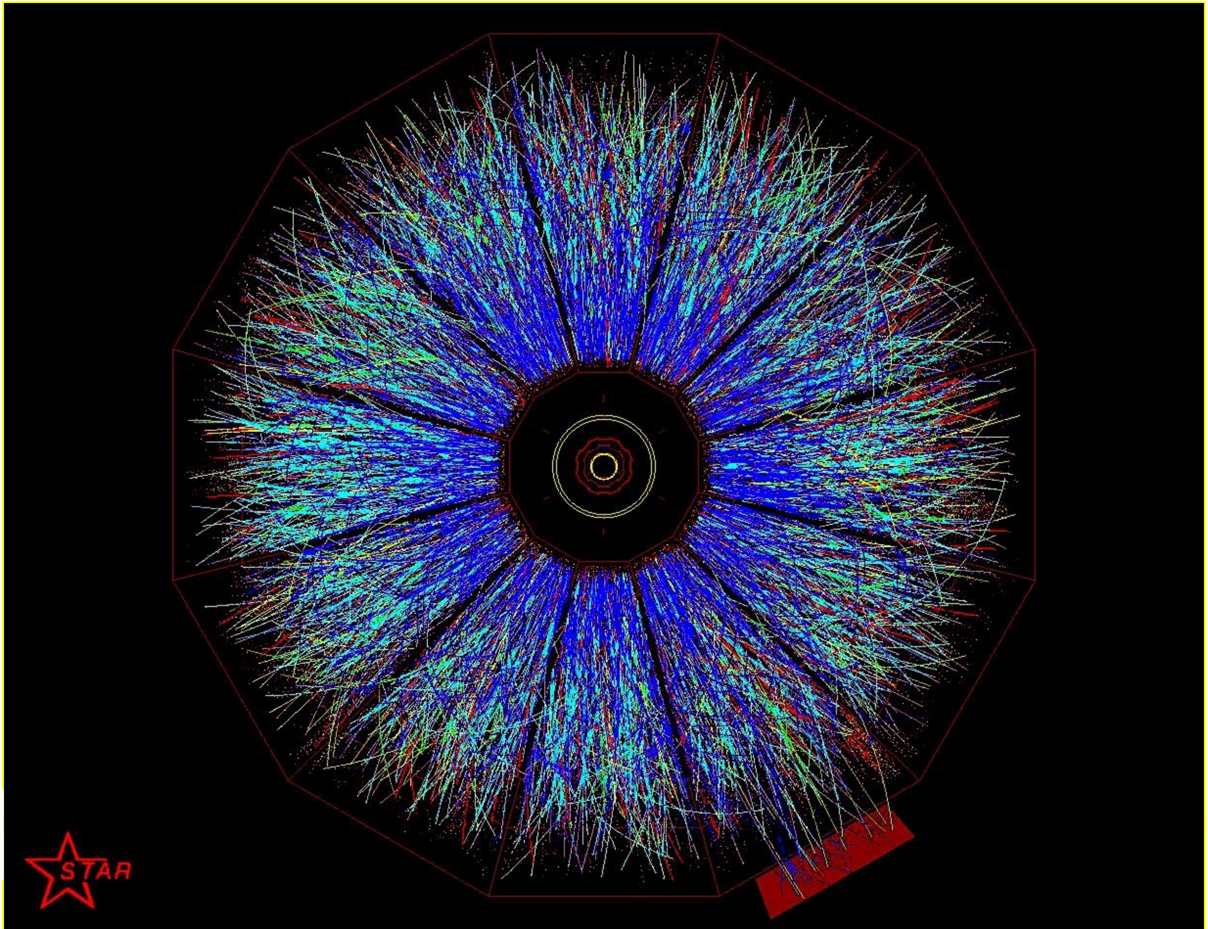
Goal of the RHIC Heavy Ion Program:

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

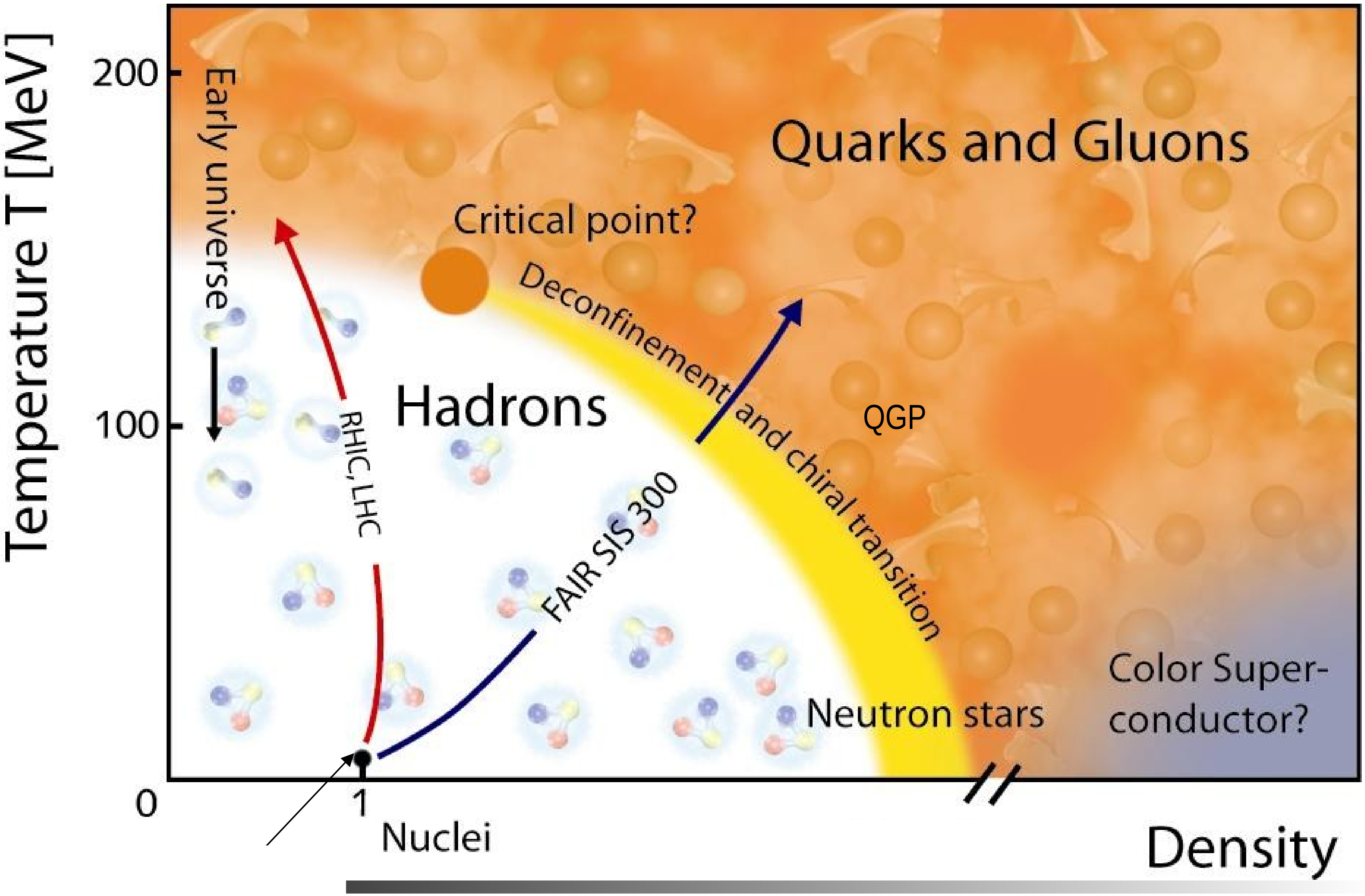
What have we learned so far?

STAR NPA 757 (2005) 102

Strongly interacting, hot, dense matter with partonic collectivity

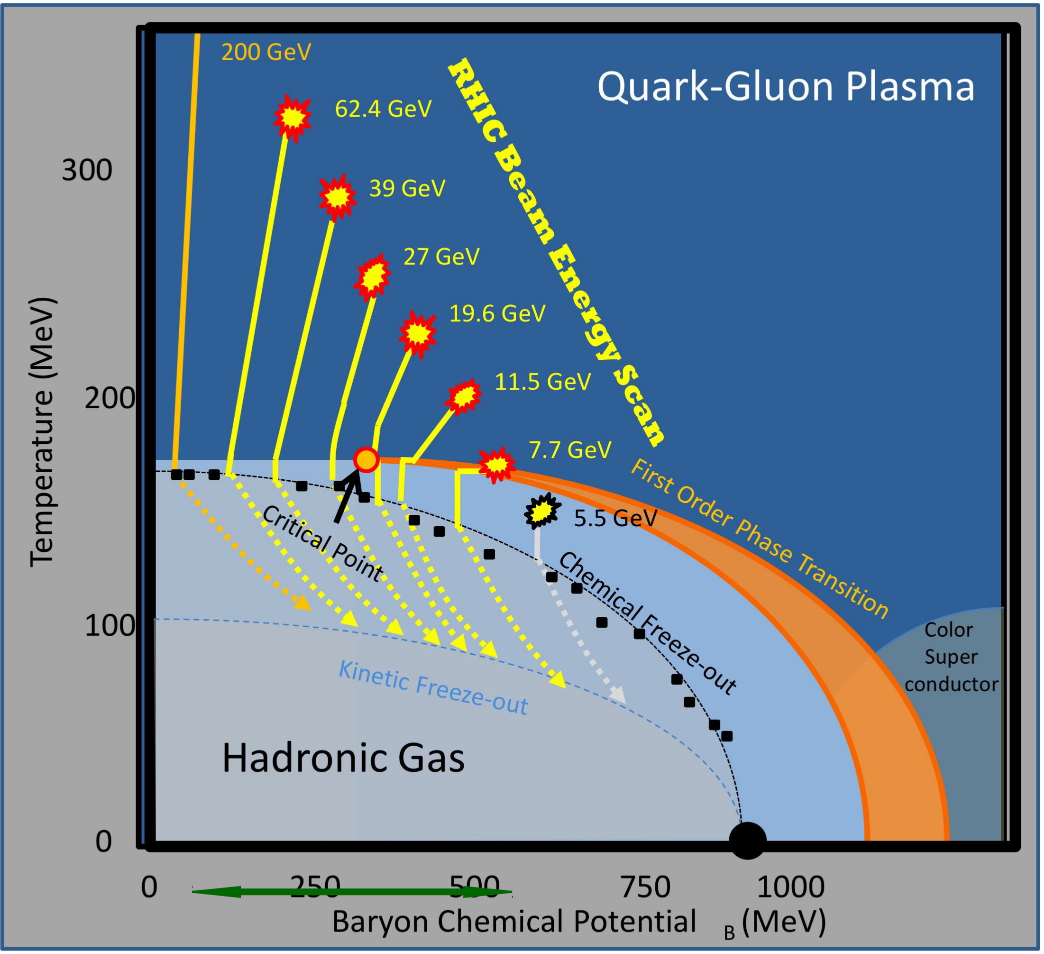


Phase Diagram



Beam Energy Scan at RHIC: $\sqrt{s_{NN}}$ ~ 5-50 GeV

160 MeV< μ_B <500 MeV



We built RHIC to find QGP.

And we did it !

but,

QGP- new and complicated phase of matter

With unique and unexpected properties

Huge progress in understanding its nature:

@high energy – cross over transition

@lower – should be 1st order transition

+ Critical point

→ **BES program was born**

With RHIC beams:

(1) Study properties of sQGP

(2) Map out QCD matter phase structure

Structure of QCD matter phase diagram is

fundamental

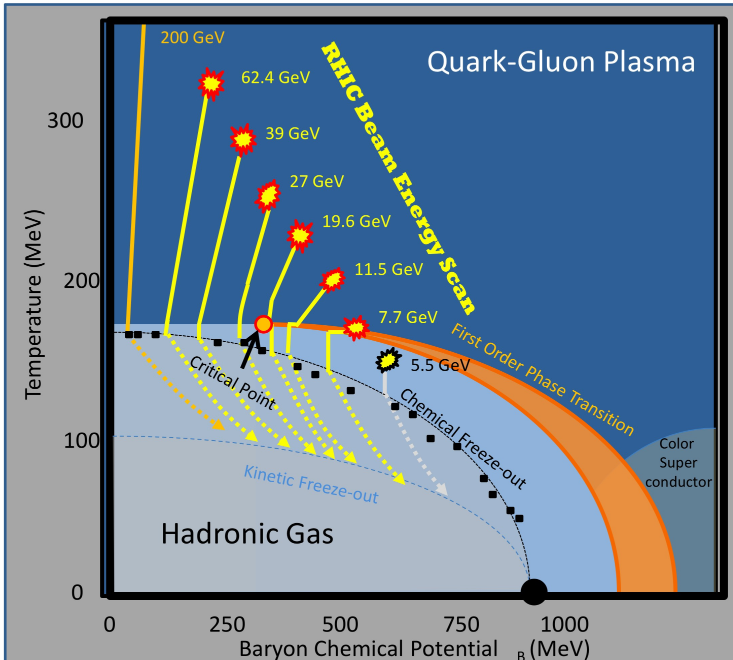
(will be in text books in future decades)

Three BES goals:

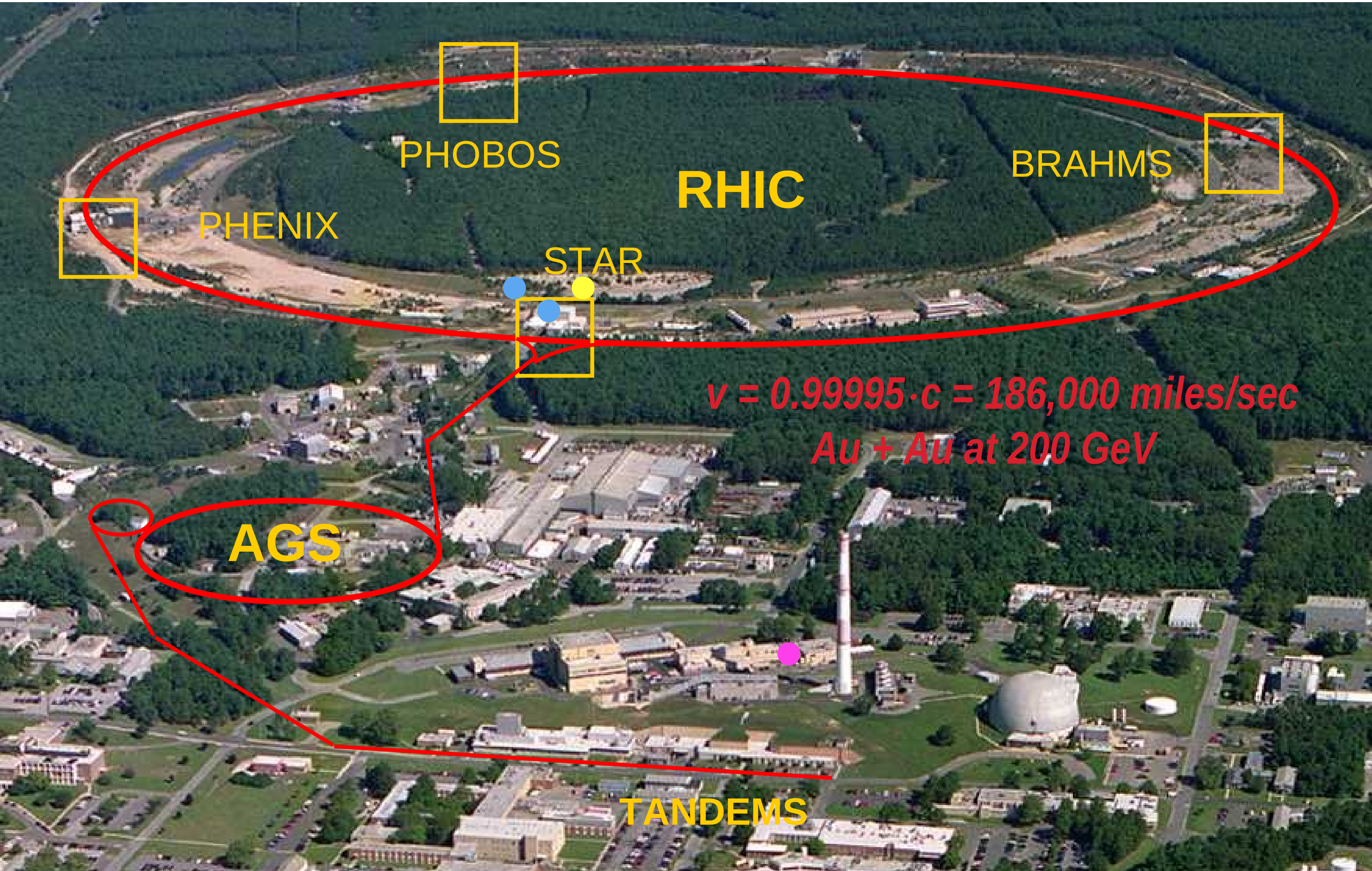
1. Search for the QCD critical point
2. Search for the signals of phase transition/phase boundary
3. Search for turn-off of sQGP signatures

Year	$\sqrt{s_{NN}}$ (GeV)	Events (10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5

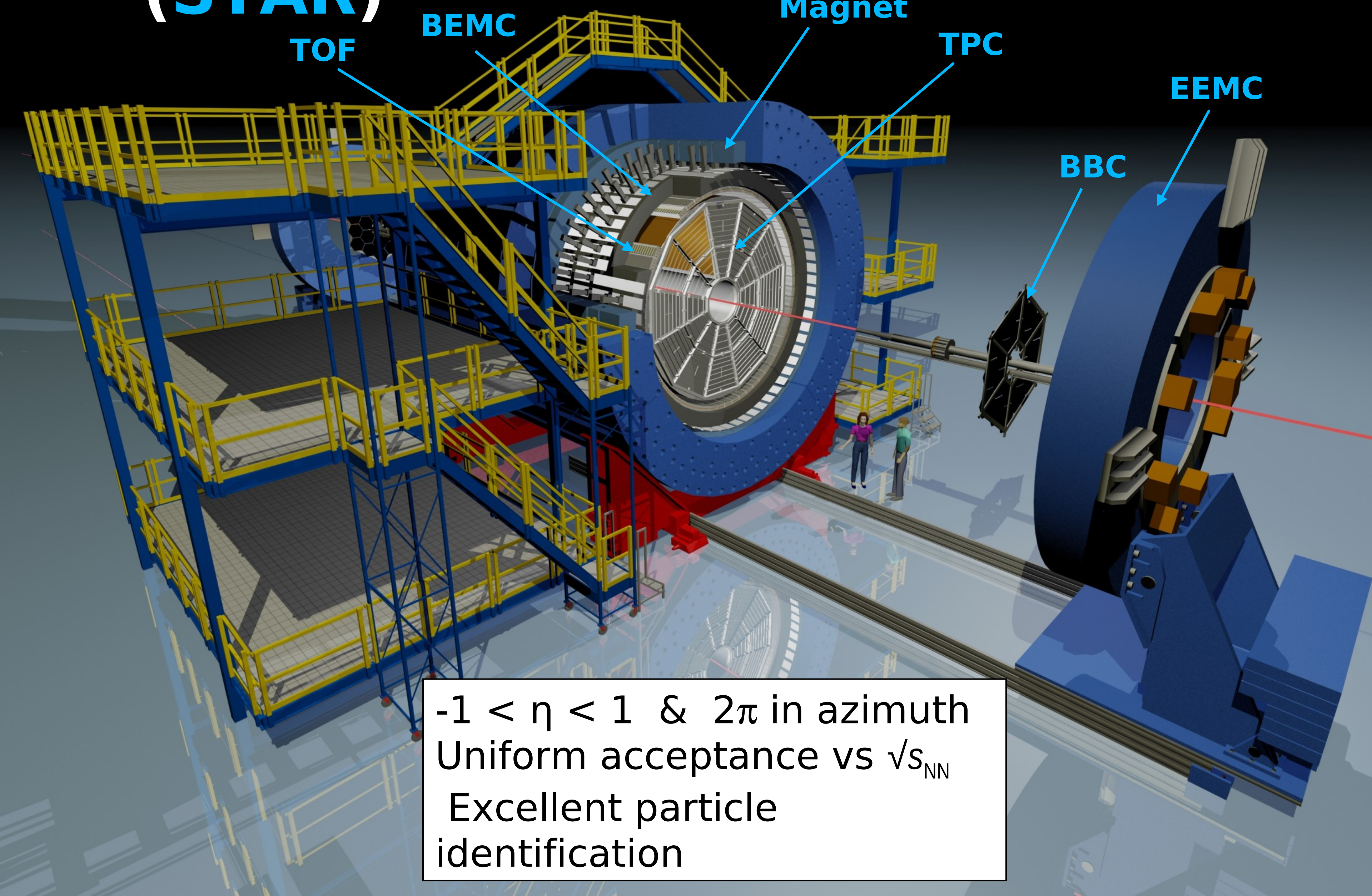
Where are we probing on the QCD Phase Diagram ?



Relativistic **H**eavy **I**on **C**ollider (RHIC)
Brookhaven National Laboratory (BNL), Upton, NY



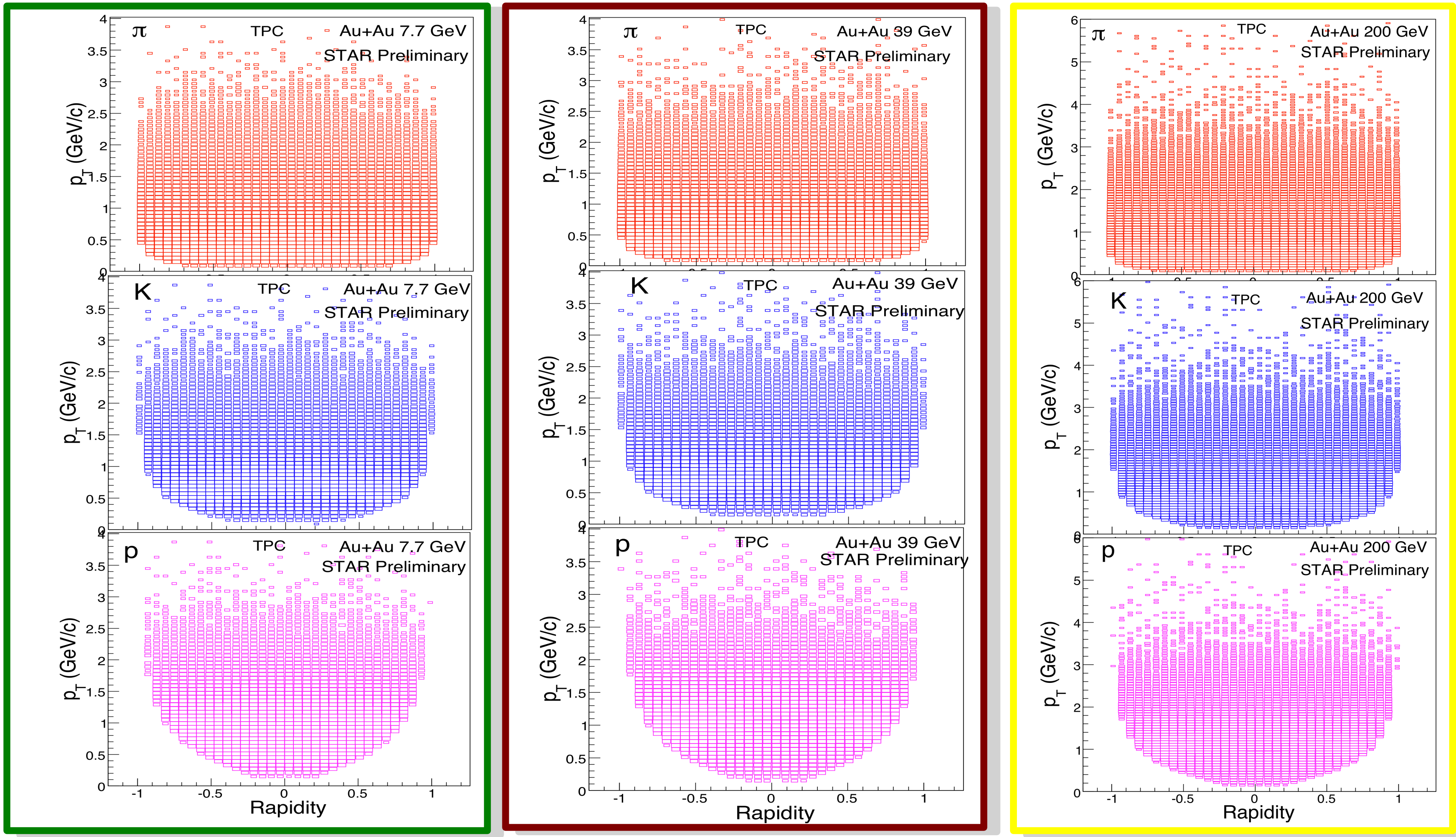
The Solenoid Tracker At RHIC (STAR)



- $-1 < \eta < 1$ & 2π in azimuth
- Uniform acceptance vs $\sqrt{s_{NN}}$
- Excellent particle identification

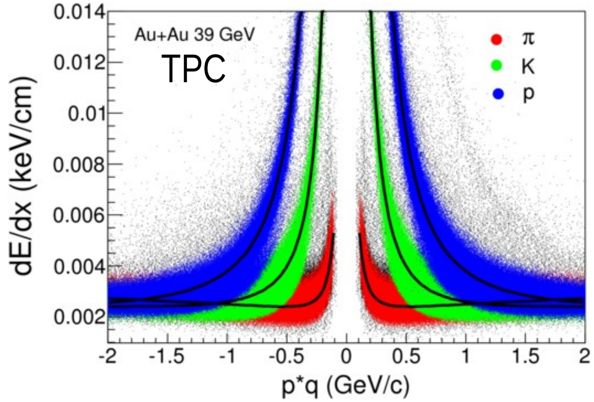
Identified Particle Acceptance at STAR

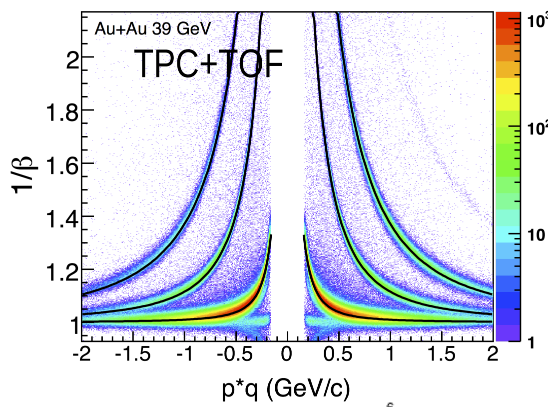
Au+Au at *7.7* GeV | Au+Au at *39* GeV | Au+Au at *200* GeV



At collider geometry - similar acceptance for all particles and energies

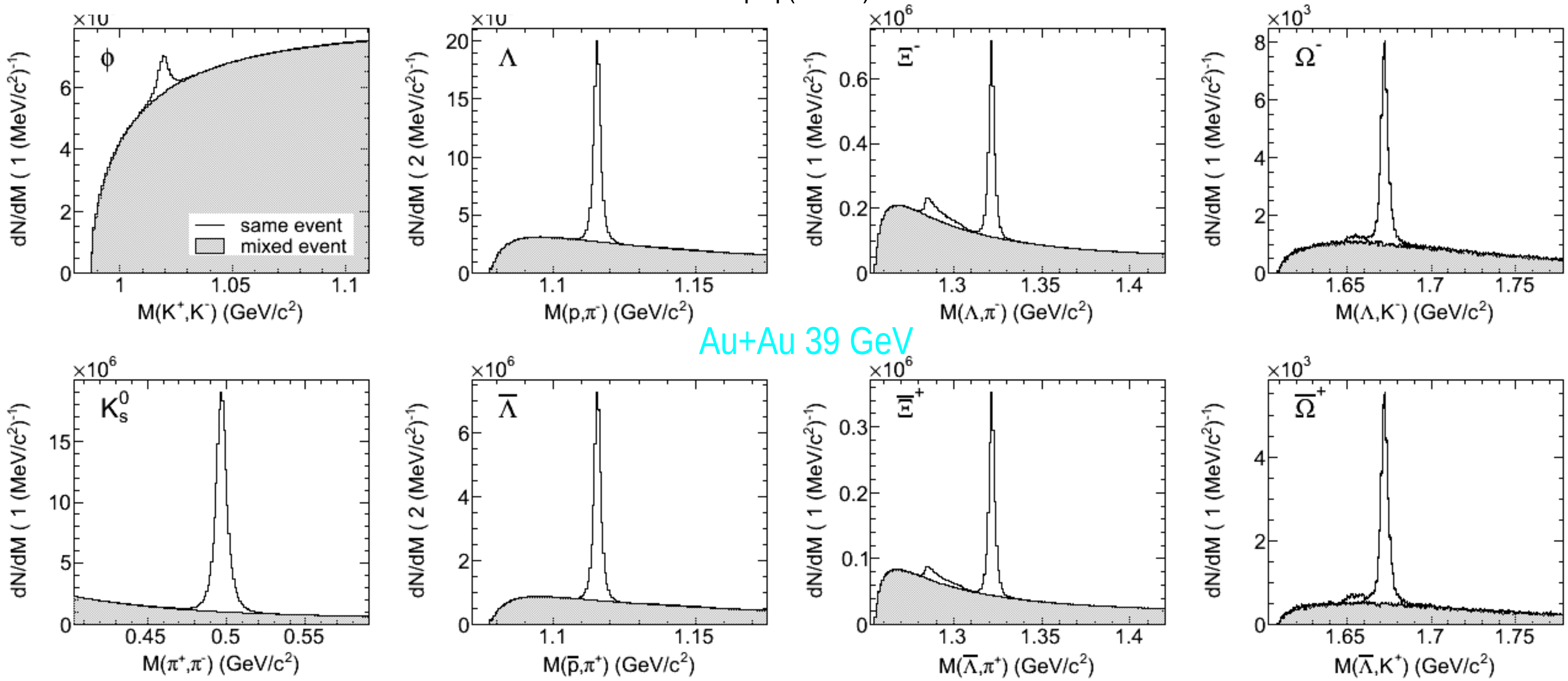
Particle Identification





PID (TPC+TOF):
pion/kaon: p_T~1.6 GeV/c
proton p_T~3.0 GeV/c

Strange hadrons: decay topology & invariant mass



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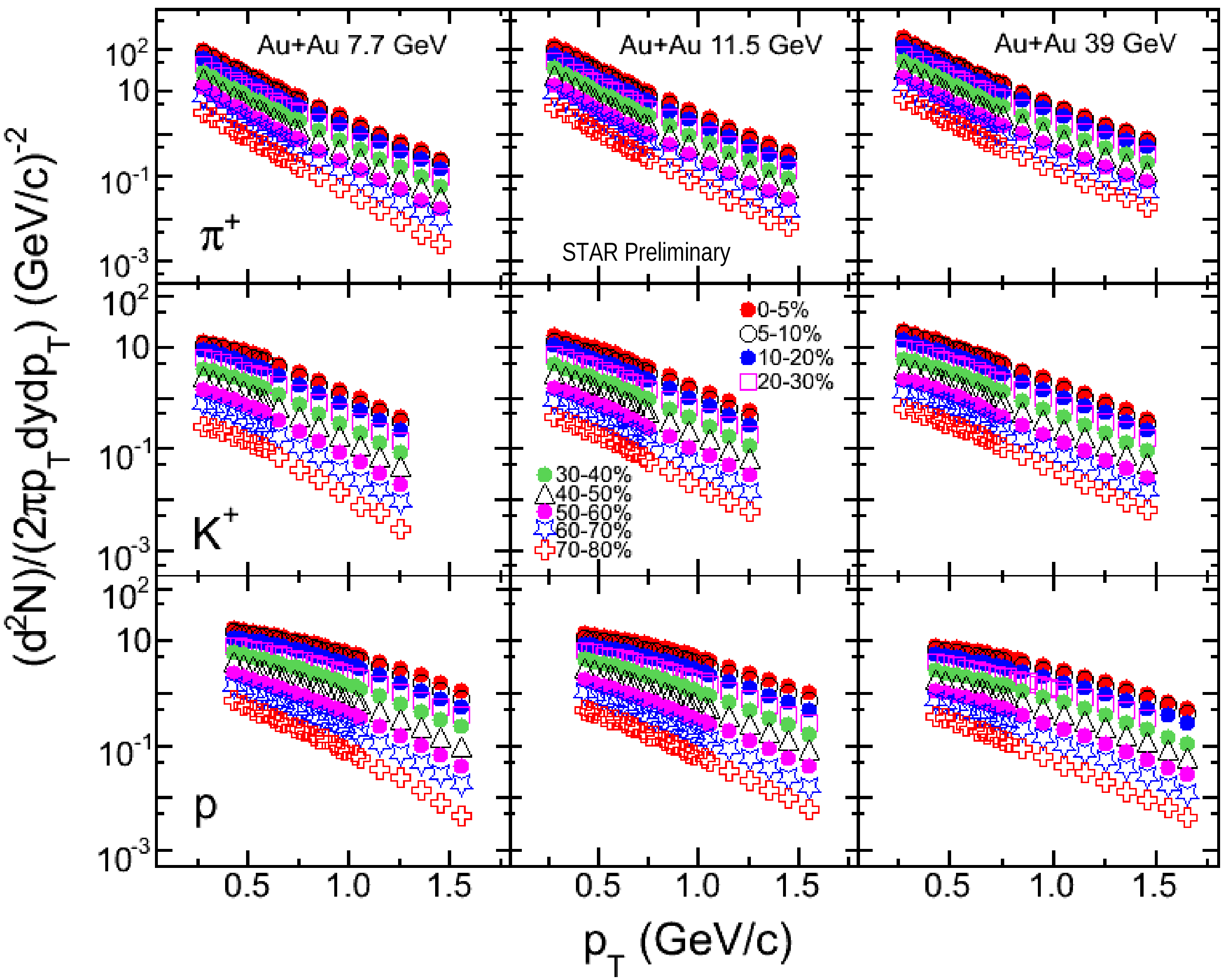
Environment

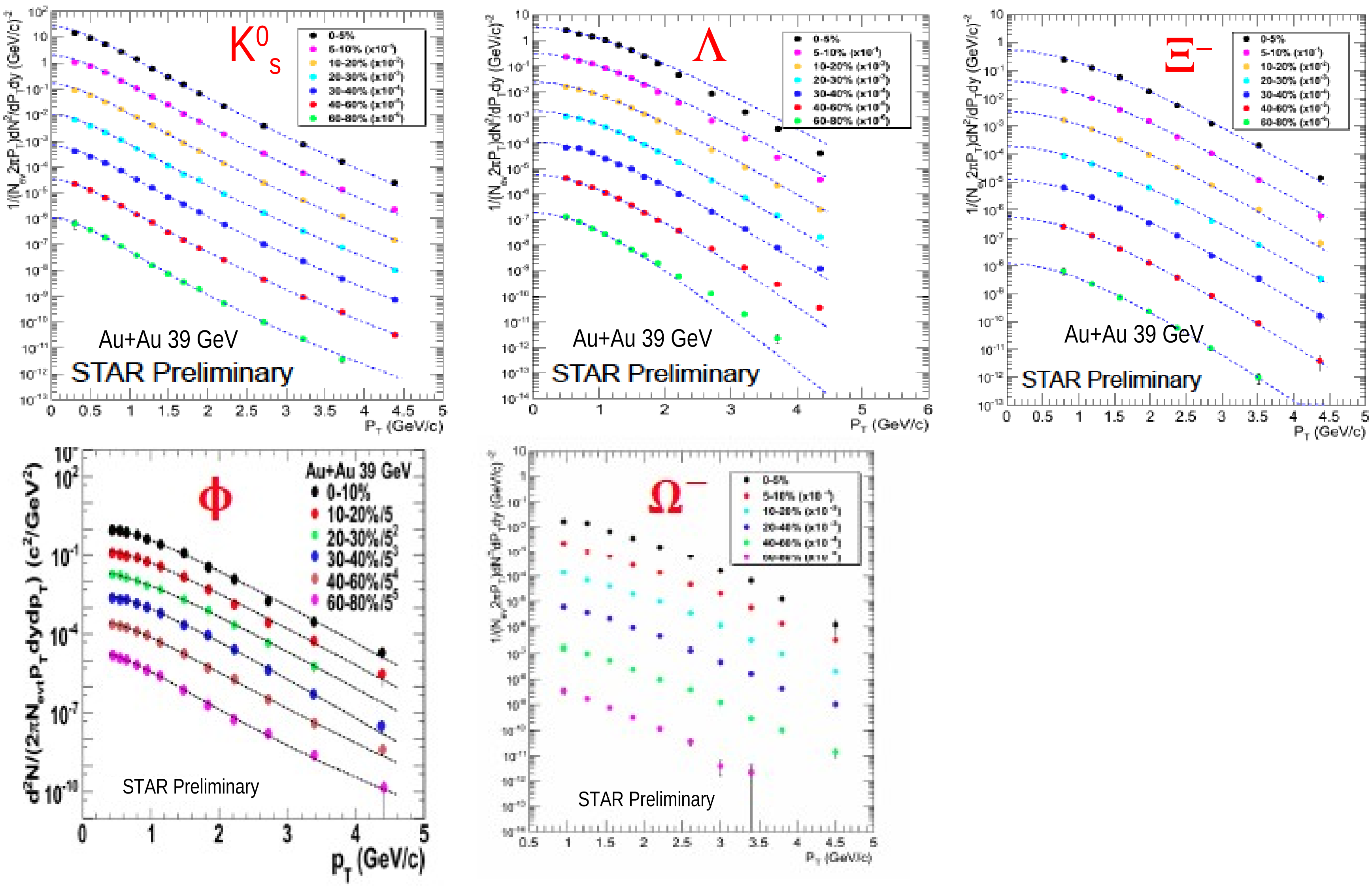
Spectra: π, K, p



Slopes: π > K > p

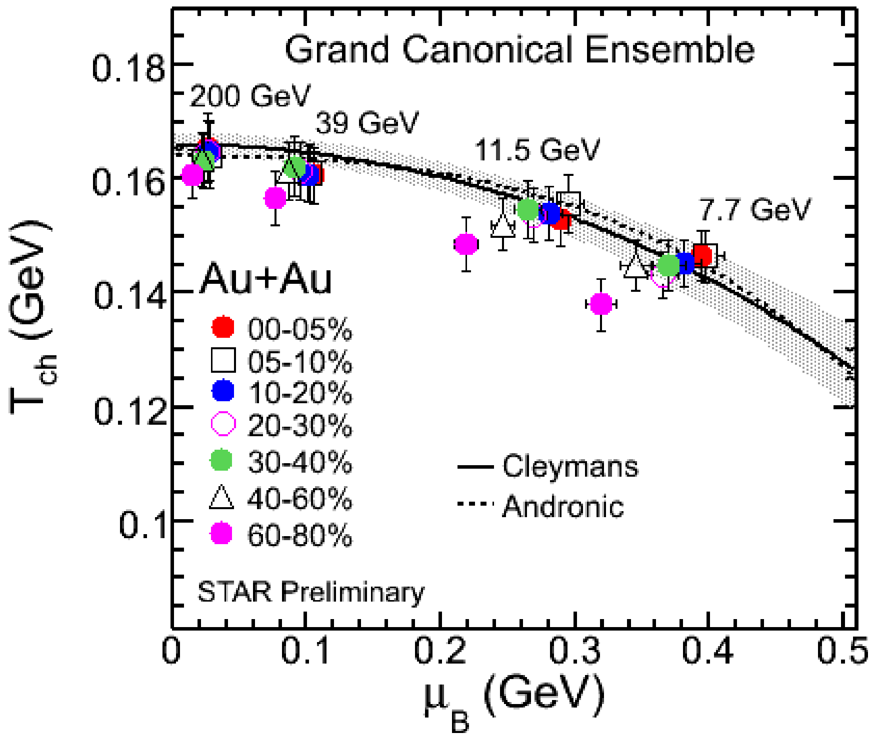
π, K, p yields within measured p_T ranges: 70-80% of total yields

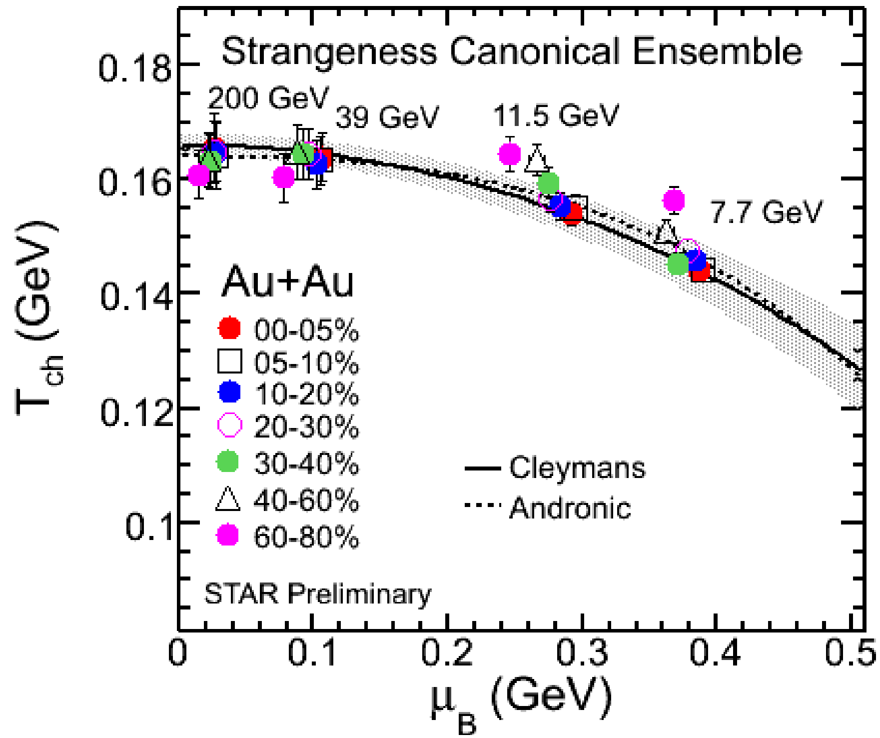
Spectra : strange hadrons



Chemical freeze-out parameters extracted from spectra and ratios of measured particles with THERMUS fits

(Wheaton and Cleymans, Comput. Phys. Commun. 180, 84 (2009))





BES data (Phase I) extends relevant region of QCD Phase Diagram from μ_B= 20 MeV to ~ 400 MeV ($\sqrt{s_{NN}}$ =7.7 GeV)

centrality dependence of μ_B still under study

BES: Experimental Program

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

Observables:

(1) indications of the existence of Critical Point

- fluctuation measures
  - higher moments of conserved quantities (net proton distribution -> kurtosis)
  - particle ratio fluctuations

(2) signatures of phase transition (softening of EOS)

- azimuthally-sensitive femtoscopy
- direct flow v_1
- …

(3) disappearance of signals of partonic degrees of freedom seen at 200 GeV

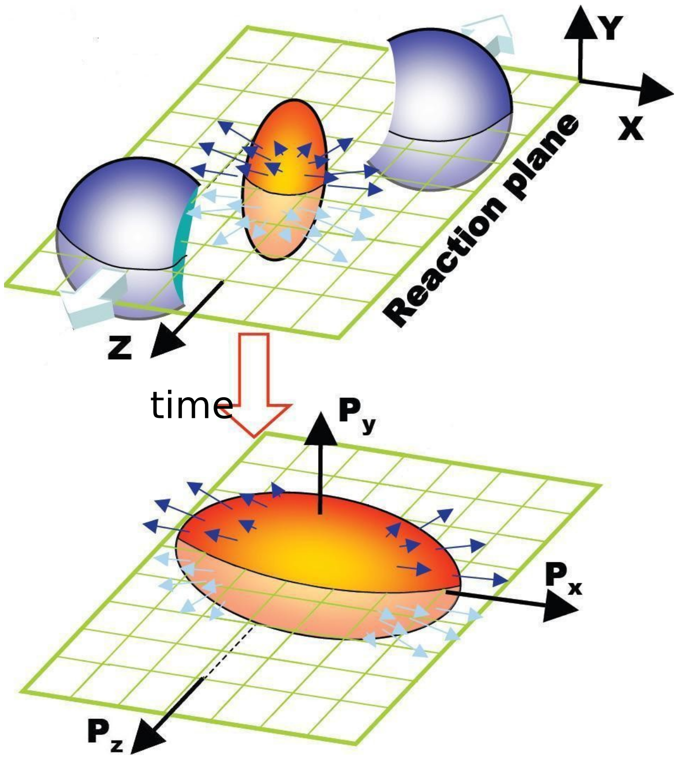
- disappearance of constituent-quark-number scaling of v_2
- disappearance of hadron suppression in central collisions
- dynamical charge fluctuations ('local parity violation')
- …

the easiest one …

3. Turn off signatures of QGP

Do QGP signatures (v_2, R_{cp}, …) turn-off ?

Anisotropic flow



Initial spatial anisotropy is determined by impact parameter and initial fluctuations

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

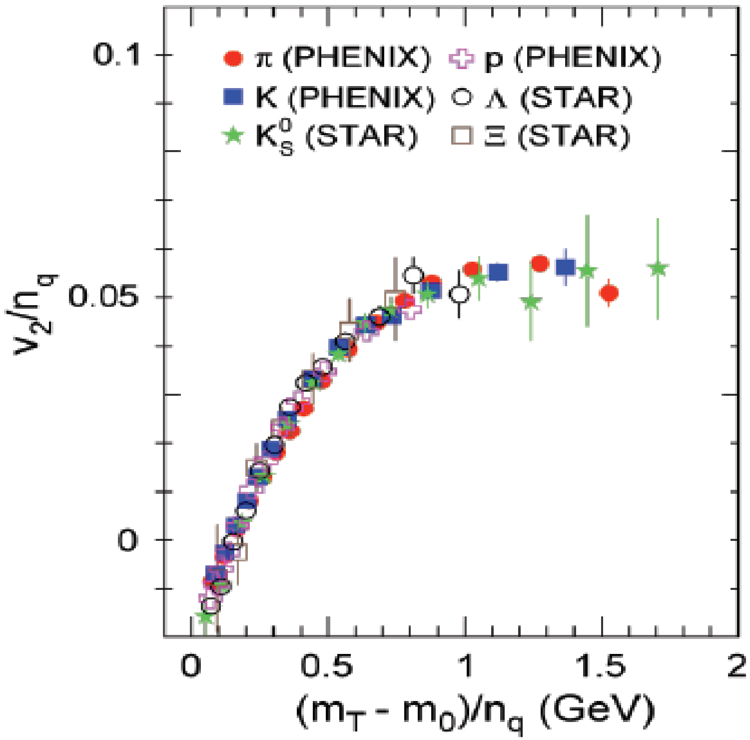
- **Fourier decomposition of the momentum space particle distributions in the x-y plane**
  - **v_n is the n-th harmonic Fourier coefficient of the distribution of particles with respect to the reaction plane**
    - **v_1: “directed flow”**
    - **v_2: “elliptic flow”**
    - **v_3: “triangular flow”**

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

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

one of the main finding at RHIC:

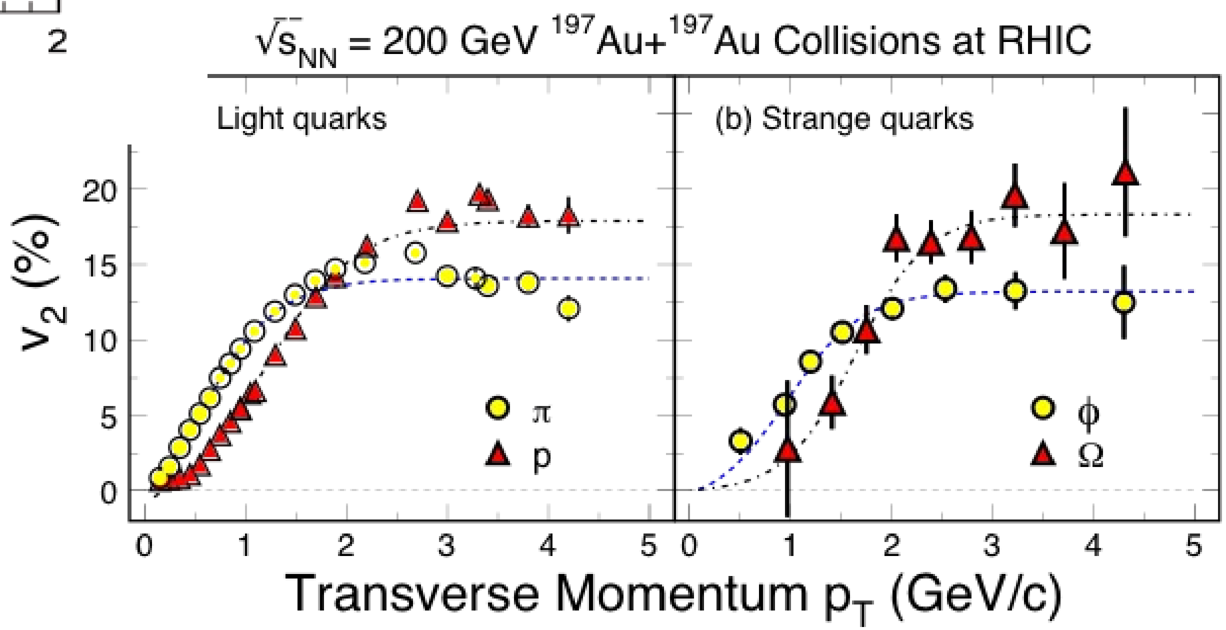
partonic degrees of freedom in Au+Au at 200 GeV



Scaling flow parameters by quark content n_q (baryons=3, mesons=2) resolves meson-baryon separation of final state hadrons

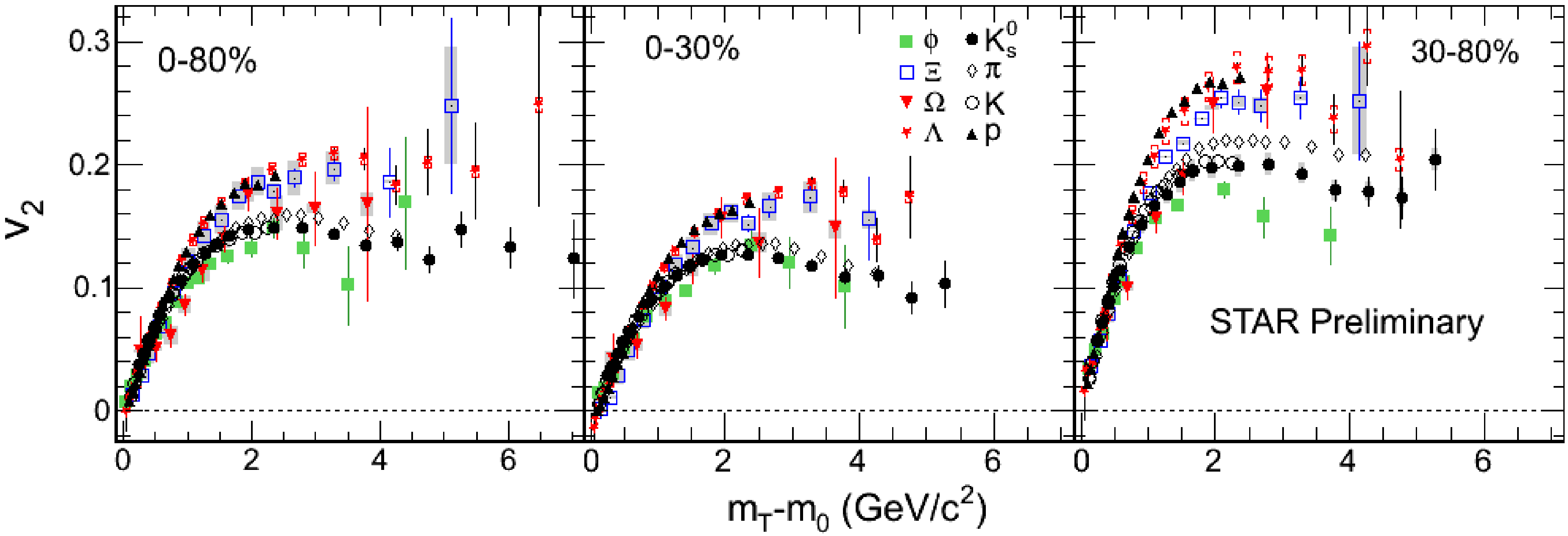
flow developed in pre-hadronic stage

DECONFINEMENT at RHIC



Identified Particle Elliptic Flow @ 200 GeV

QM 2012: π^+, π^-, K_s^0, p, $\bar{p}$, ϕ, Λ, $\bar{\Lambda}$, Ξ^-, $\bar{\Xi}^+$, Ω^-, $\bar{\Omega}^+$



Refinement due to precision measurements on identified particle v_2 (high stat.):

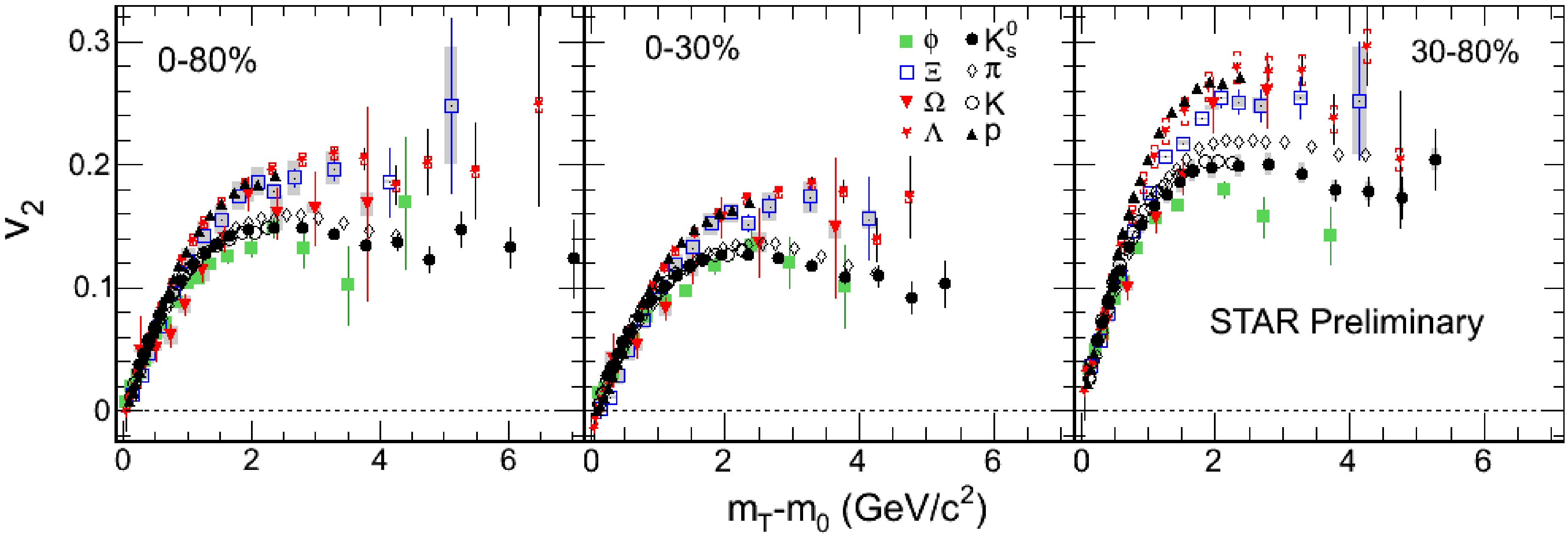
0-30%: baryon-meson grouping / NCQ scaling holds (within 10%)

30-80%: Multi-strange hadron v_2 deviate from NCQ scaling at m_T-m_0>1 GeV/c^2

Precision identified particle v_2 data → constraints on studies of sQGP properties

Identified Particle Elliptic Flow @ 200 GeV

QM 2012: π^+, π^-, K_S^0, p, $\bar{p}$, ϕ, Λ, $\bar{\Lambda}$, Ξ^-, $\bar{\Xi}^+$, Ω^-, $\bar{\Omega}^+$



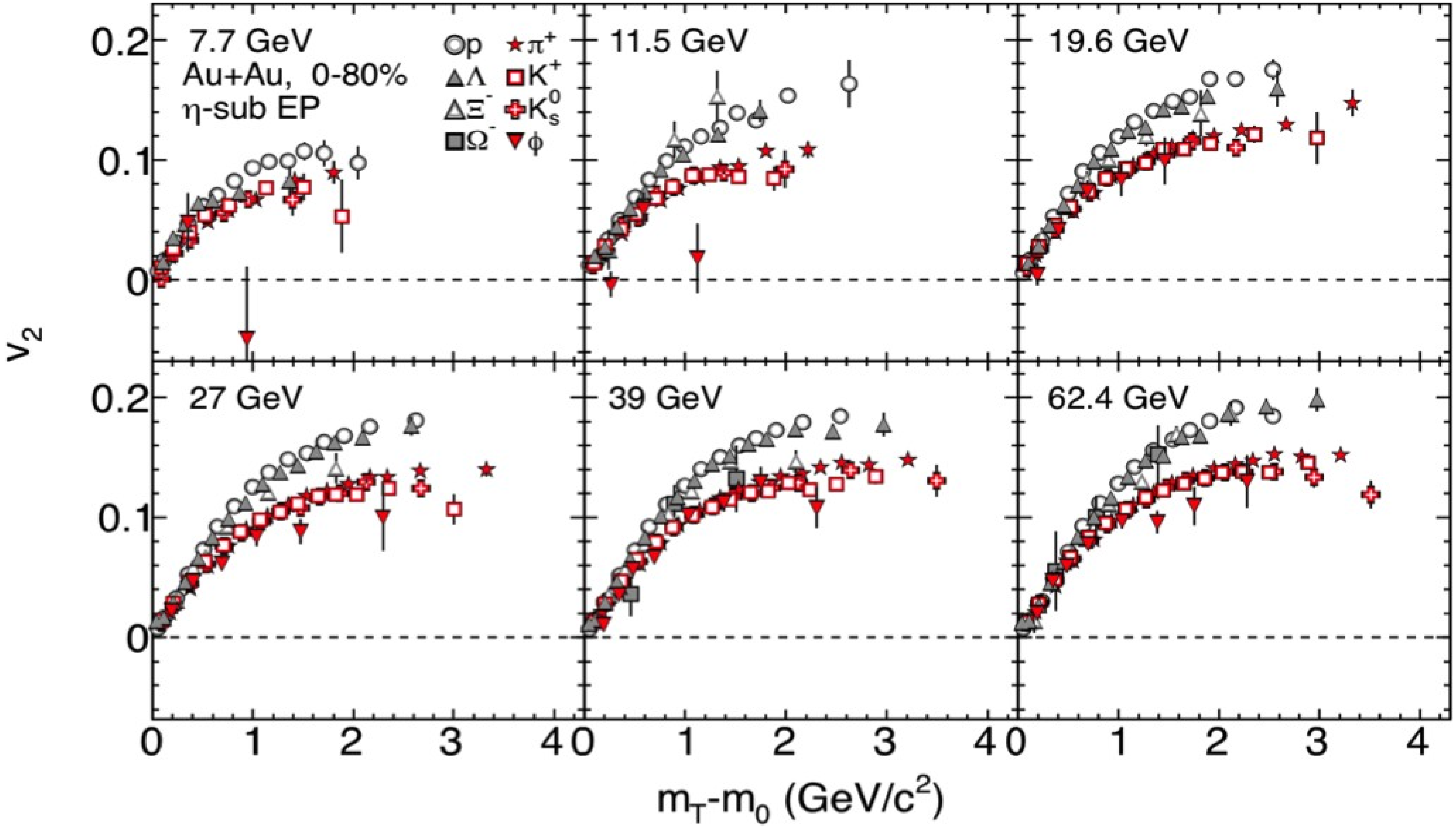
with lowering energy, disappearance of n_q scaling

(≈disaperance of partonic degree of freedom)

would suggest that we exit partonic world

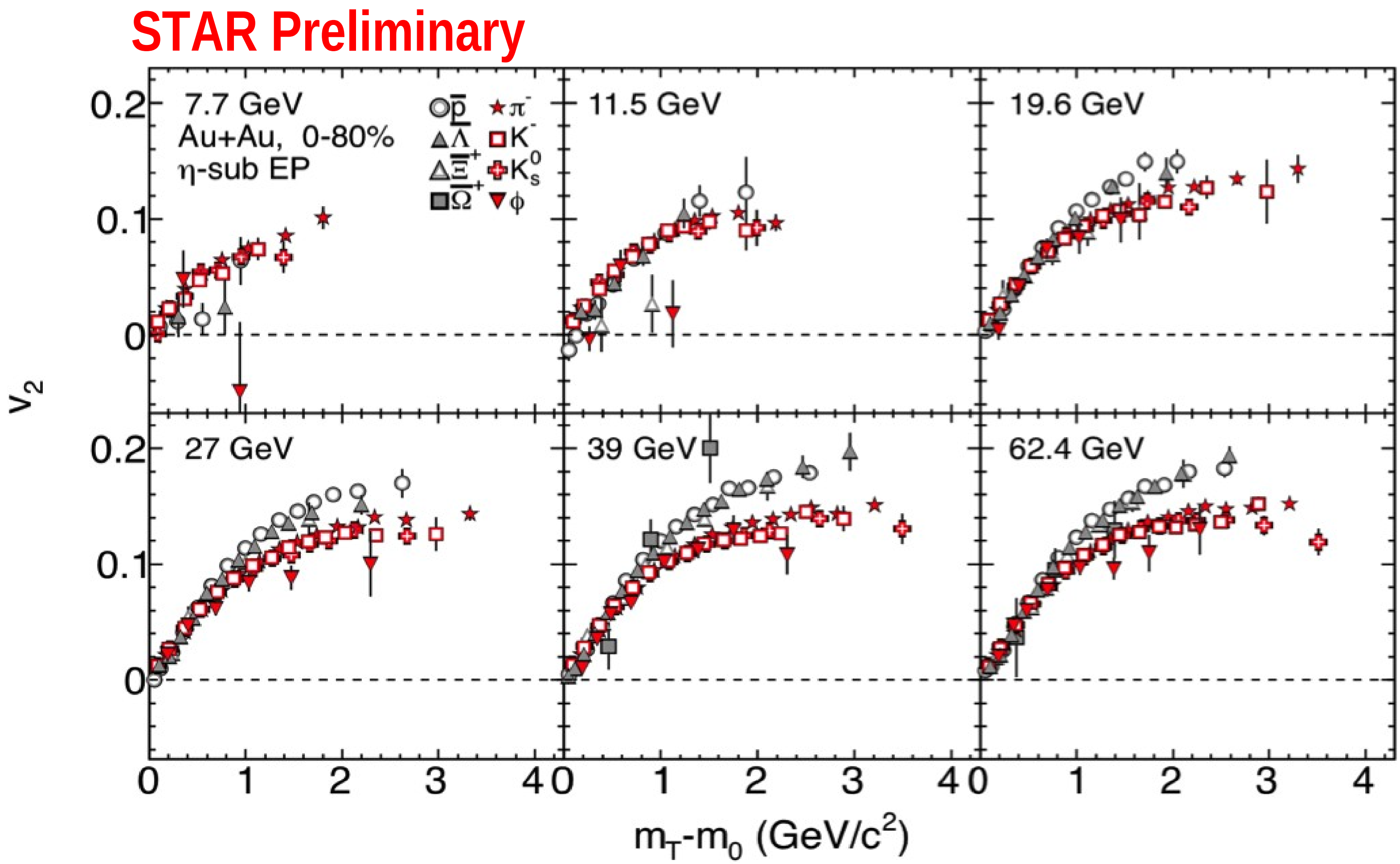
BES: v_2 of identified particles vs energy

STAR Preliminary



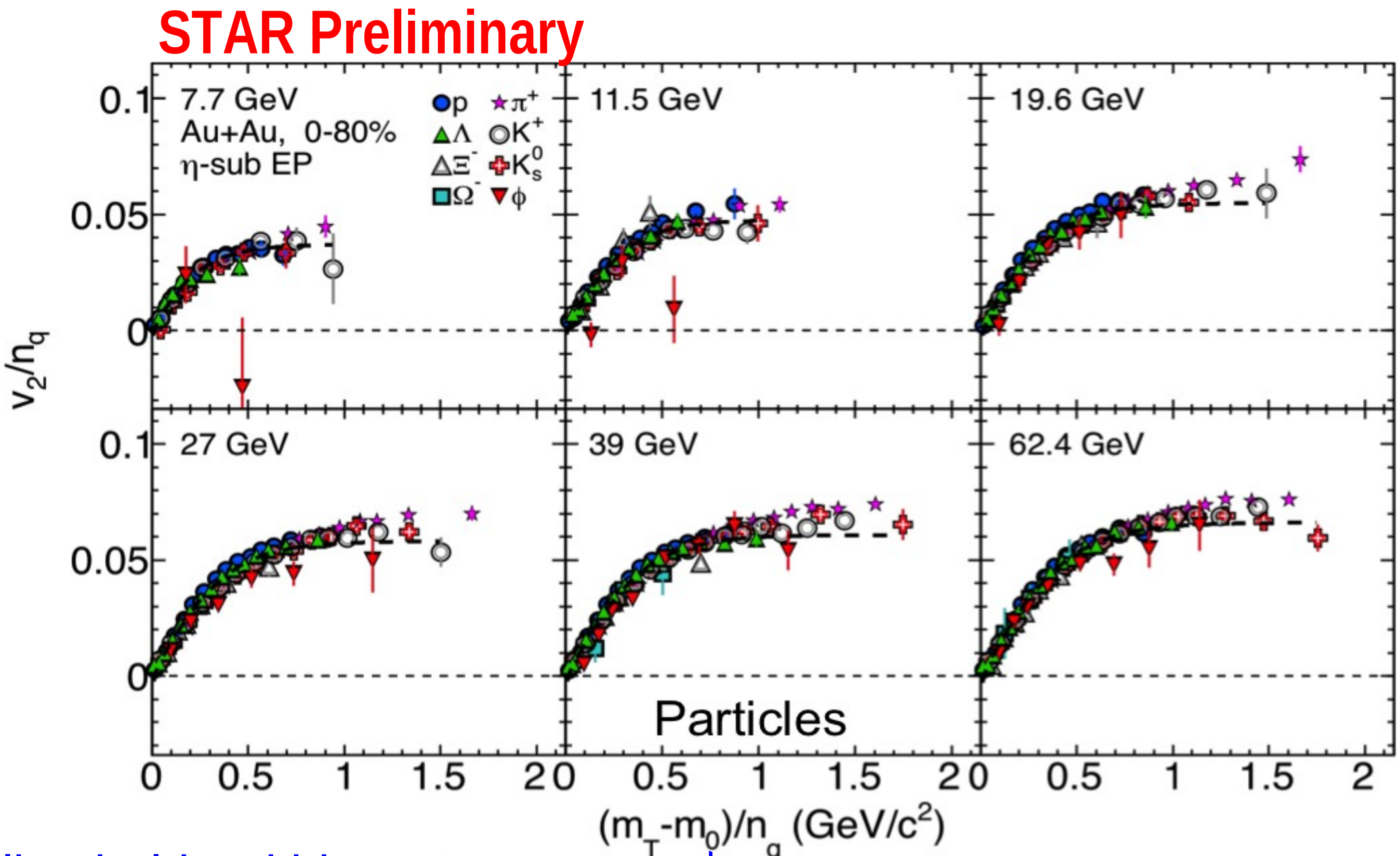
Baryon vs. meson splitting for particles decreases as we go down in $\sqrt{s_{NN}}$

BES: v_2 vs energy for ***anti***particles



Baryon vs. meson splitting for ***anti***particles disappears at energies ≤11.5 GeV (within errors)

BES: n_q scaling with energy - particles



n_q scaling holds within ~10%, except ϕ

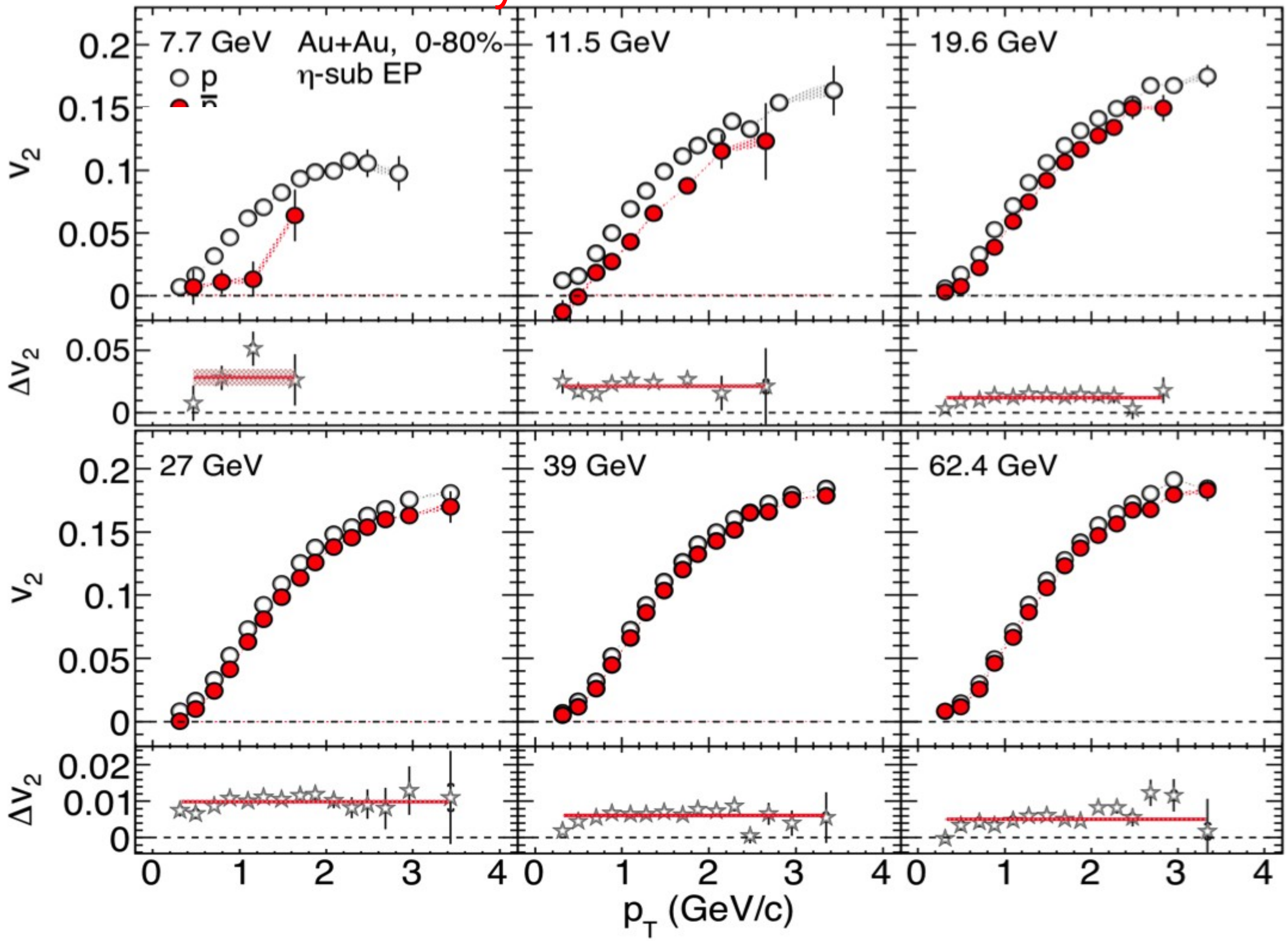
– ϕ meson becomes outlier at lowest two energies – but large error bars

anti-particles: n_q scaling within ~10%

BES: v_2 for p and anti-p

STAR Preliminary

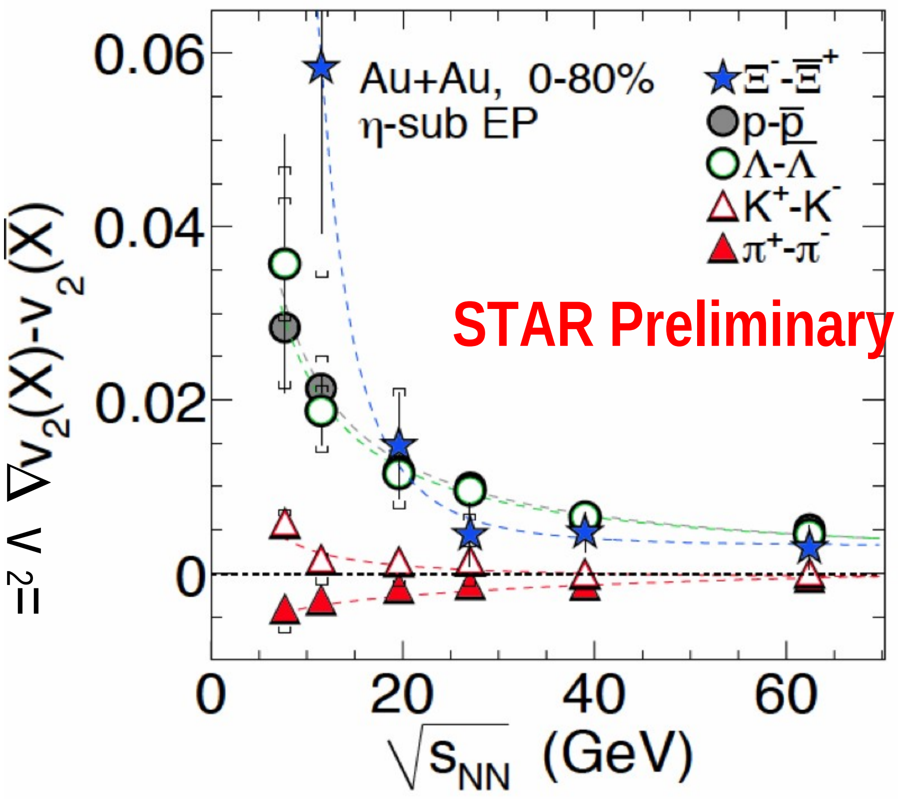
$\Delta v_2 = (v_2^{proton} - v_2^{antiproton})$



Proton – antiproton difference increases with decreasing energy

(very little p_T dependence)

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



difference between particle and antiparticle is observed -> break down of N_q scaling between particles and *anti*particles at lower energies

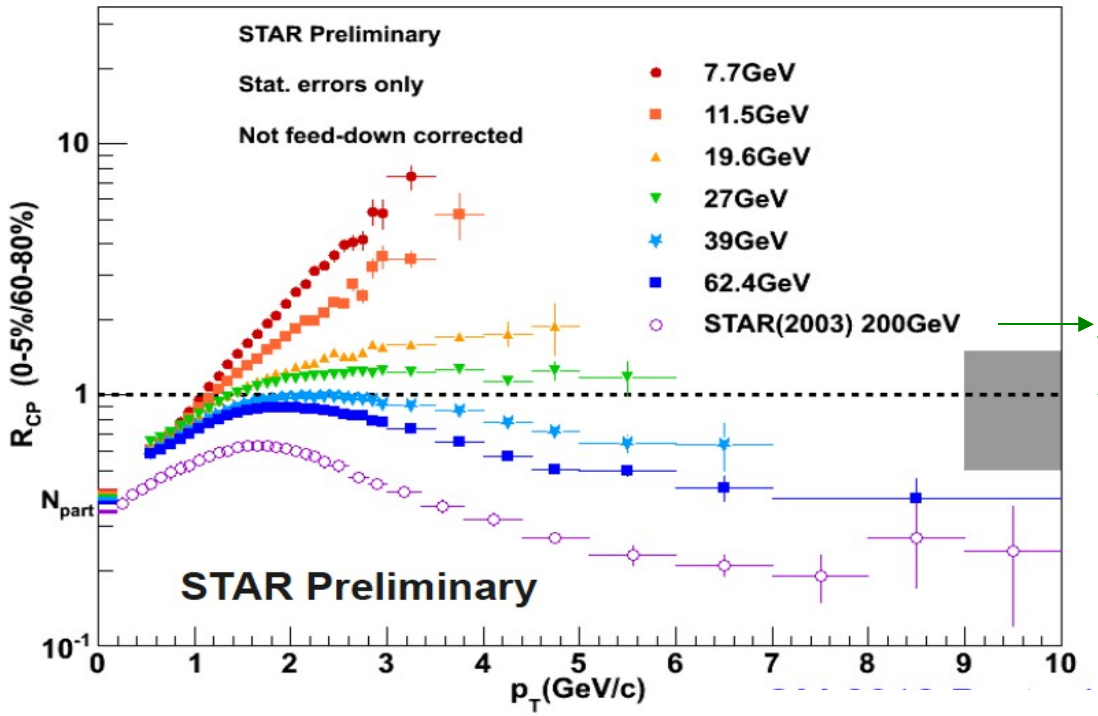
Δv_{2}:

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

*J. Xu et al., PRC **85**, 041901 (2012)*
*J. Dunlop et al., PRC **84**, 044914 (2011).*

BES: R_{cp} for charged particles

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

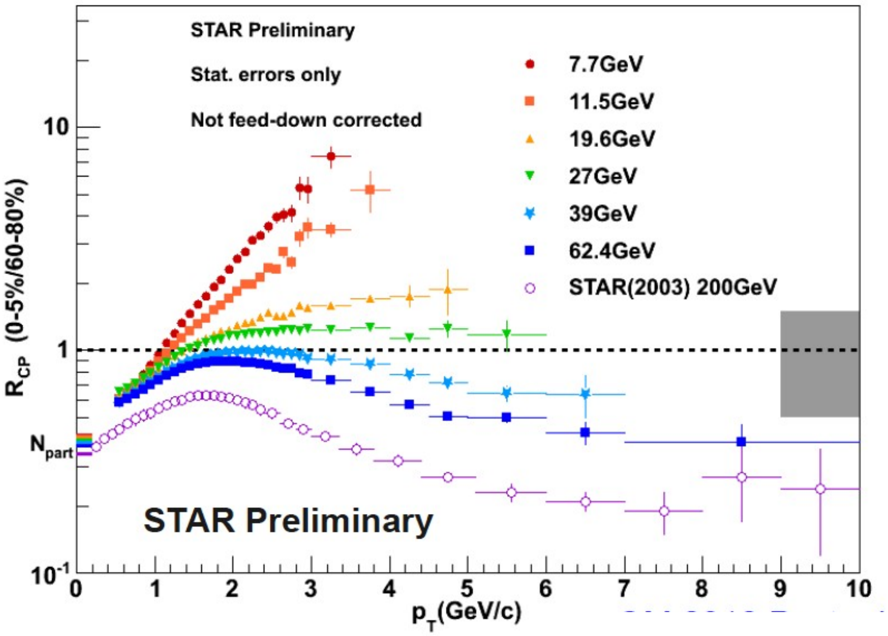


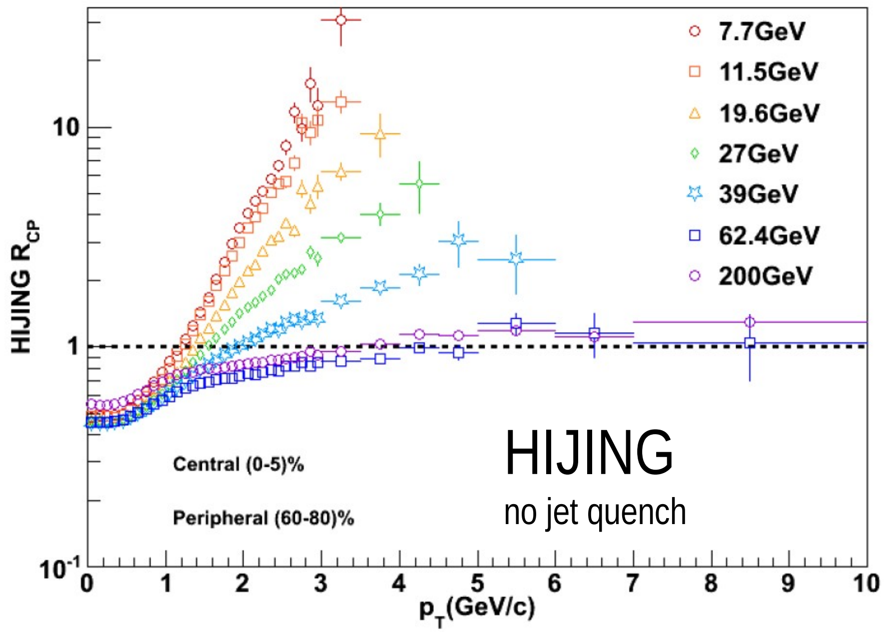
J.Adams et al., (STAR coll.) PRL 91, 172302 (2003)

R_{CP}>1 for 27 GeV and below - high p_t suppression seen at 200 GeV is gone

BES: R_{cp} for charged particles

QM 2012:

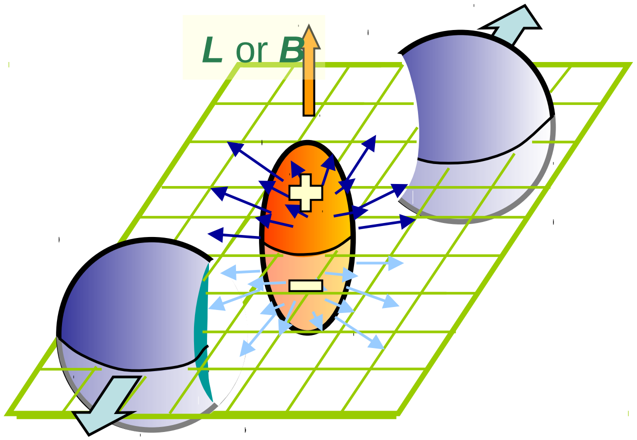


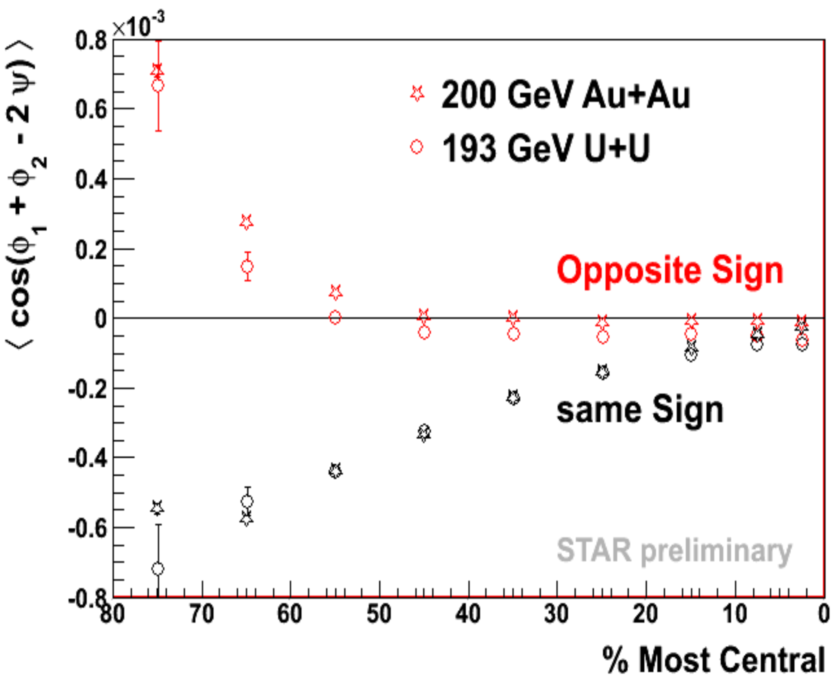


HIJING <u>without jet quenching, but including Cronin effect </u>(though k_T broadening) resembles $\sqrt{s_{NN}}$ dependence at low energies

role of Cronin effect under investigation

Dynamical charge correlations ("local parity violation")





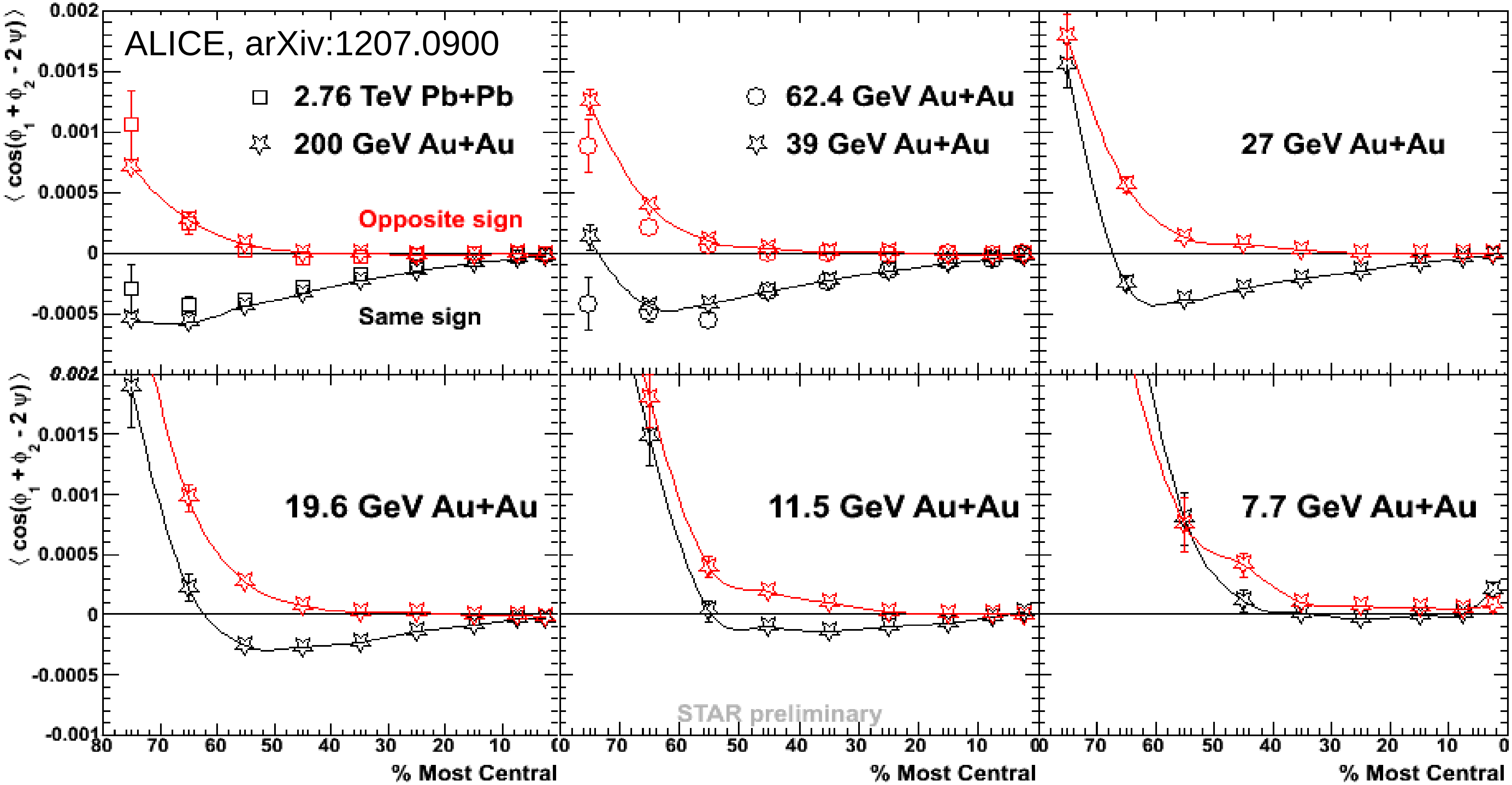
(1) Under strong magnetic field, when the system is in the state of deconfinement, local fluctuation may lead to local parity violation.

(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

Ad #3 (Turn off signatures of QGP):

These observations:

- baryon/meson grouping for *anti*particles stars to collapse at 11.5 GeV
- disappearance of high p_t suppression
- disappearance of charge separation
- break down of N_q scaling between particles and *anti*particles
- local parity violation decreases with decrease of $\sqrt{s_{NN}}$
- ...

indicate that hadronic interactions become dominant at lower beam energies the most exciting …

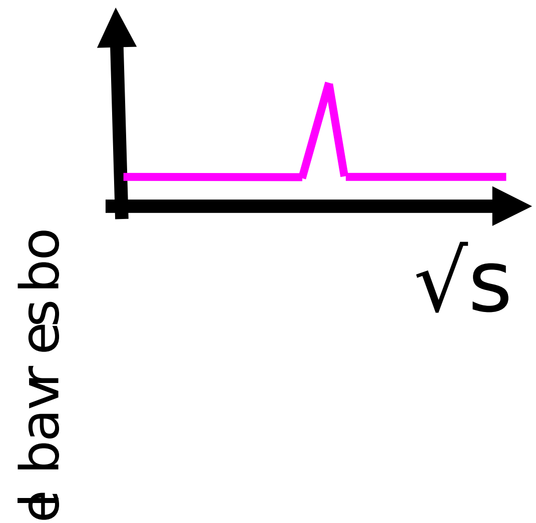
1. Critical Point

CP: Why fluctuations and correlations ?

Theory:

System at the QCD critical point region is expected to show a sharp increase in the correlation length, thus large non-statistical fluctuations

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

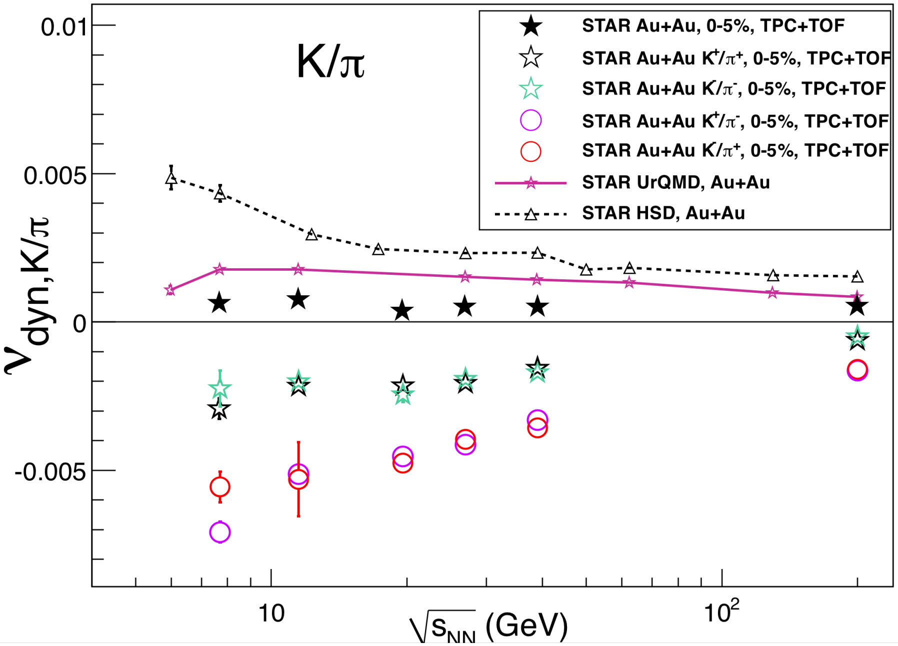


Fluctuations maximized at Critical Point

Promising observables:

- Particle ratio fluctuations: K/π, p/π, K/p
- Conserved numbers (B,Q,S) fluctuations
  - higher moments of net-protons and net-charge

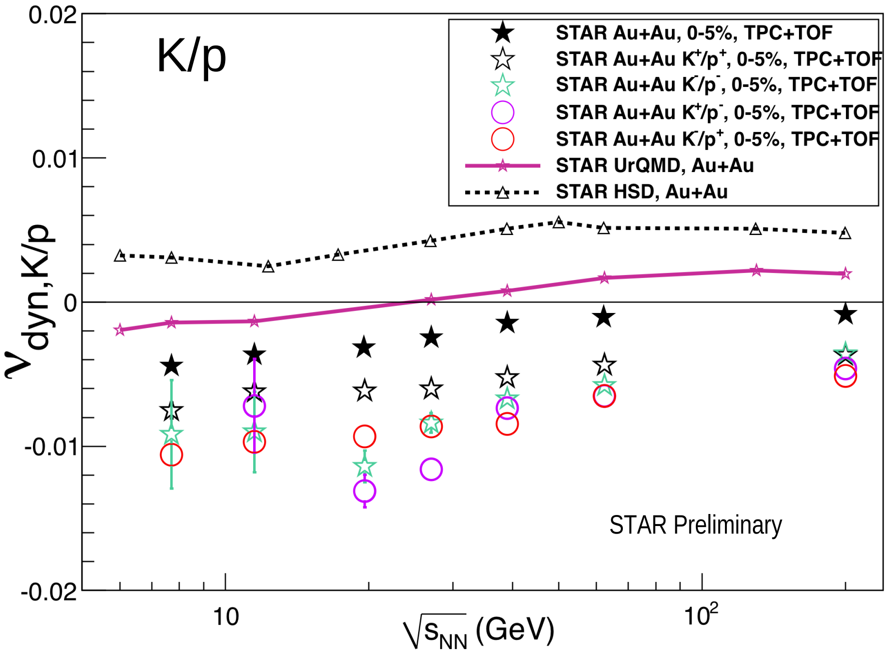
event-by-event particle ratio fluctuations

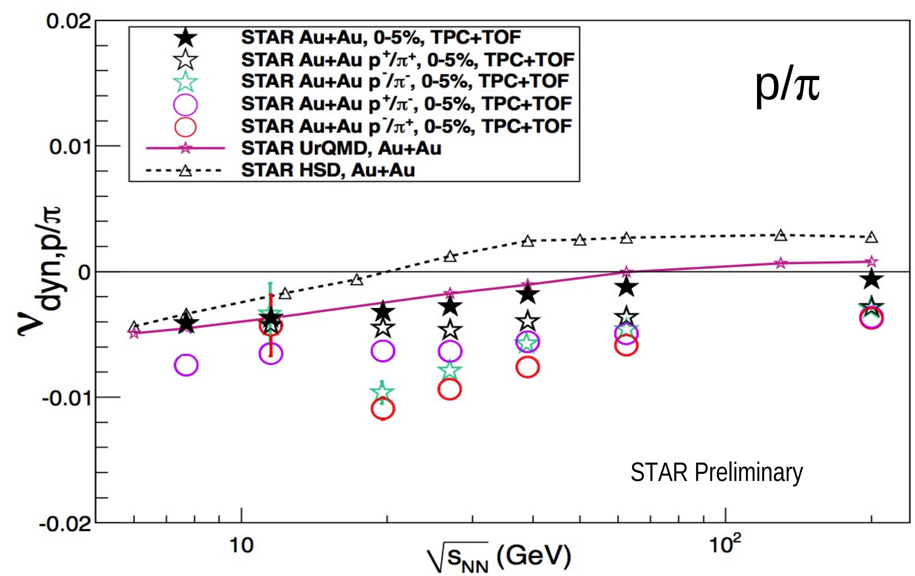


$$\nu_{dyn,K\pi} = \frac{\langle N_K(N_K-1)\rangle}{\langle N_K\rangle^2} + \frac{\langle N_\pi(N_\pi-1)\rangle}{\langle N_\pi\rangle^2} - 2\frac{\langle N_K N_\pi\rangle}{\langle N_K\rangle\langle N_\pi\rangle}$$

$$s_{dyn} = sign\left(s^2_{data} - s^2_{mixed}\right)\sqrt{\left|s^2_{data} - s^2_{mixed}\right|}$$

$$s^2_{dyn} » \nu_{dyn}$$

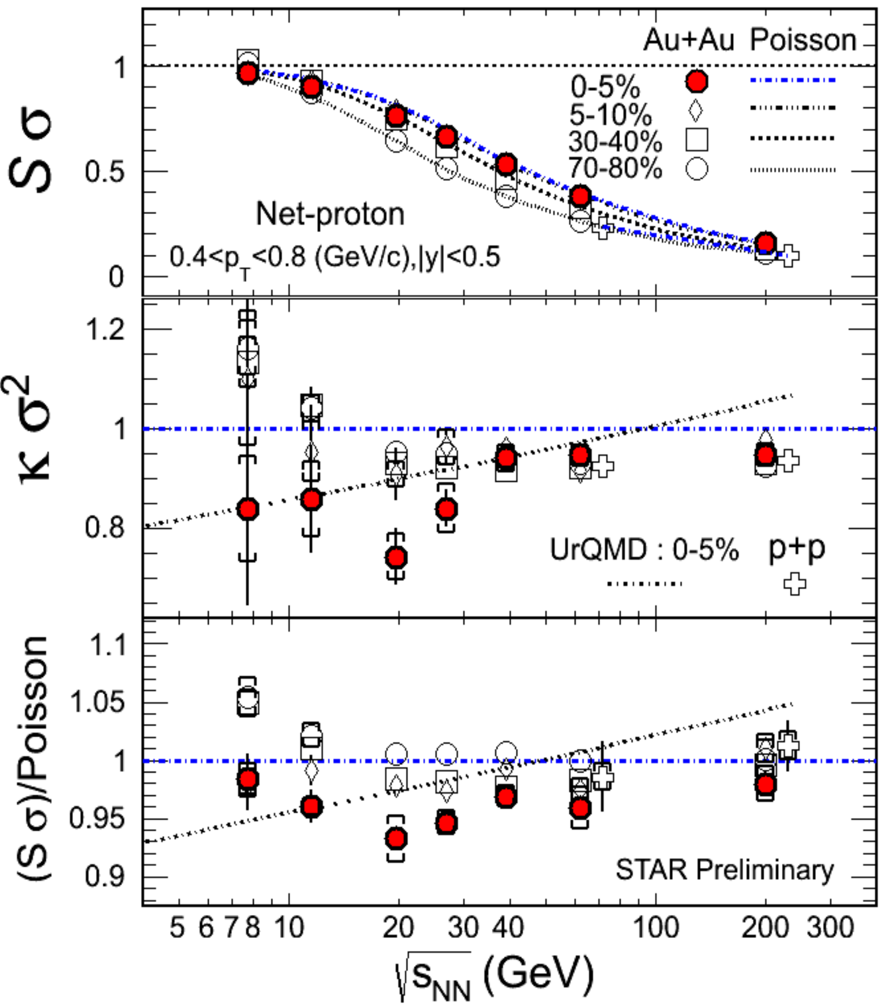




Constant or monotonic trends observed in particle ratio fluctuations with energy

Higher moments: net-protons

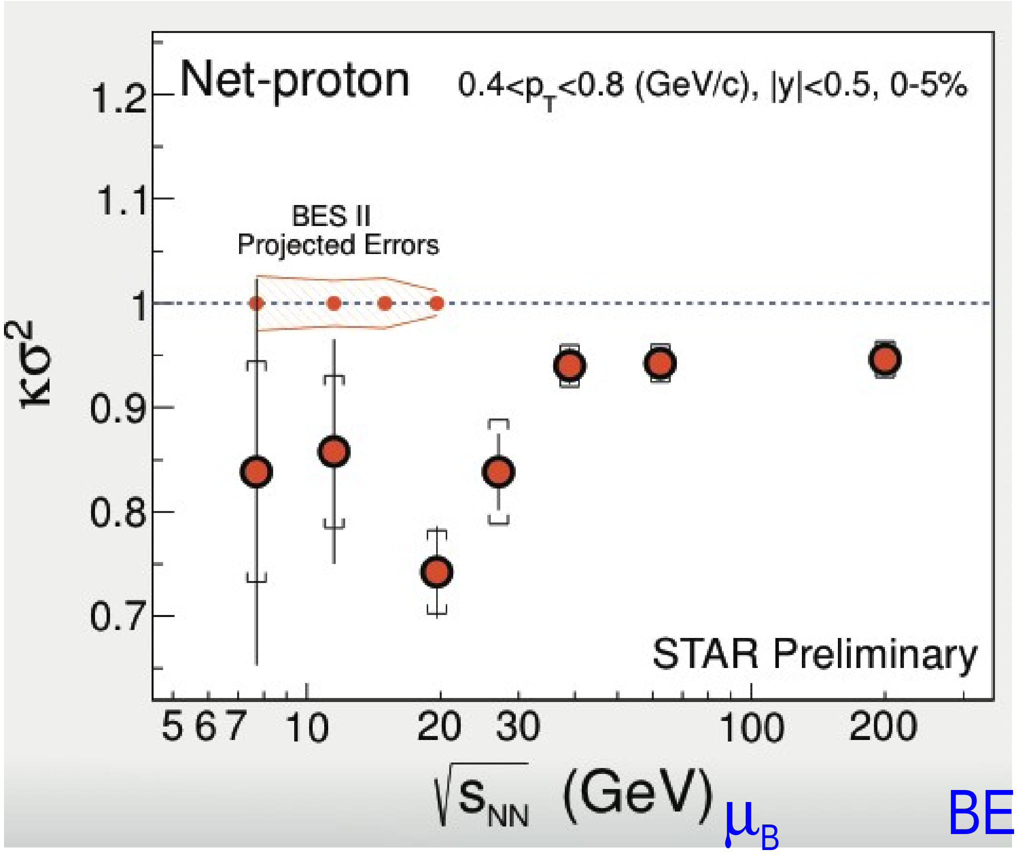
$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$
$$S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3$$
$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$$



- Higher moments of conserved quantities measure non-Gaussian nature of fluctuations and are more sensitive (than variance σ^2) to CP induced fluctuations (to correlation length)
- Non-monotonic behavior of high moments distributions vs energy are expected to signal CP

- Similar behavior at 39, 62 and 200 GeV
- Deviations below Poisson baseline in 0-5% central collisions
- Above Poisson baseline in peripheral collisions below 19.6 GeV
- UrQMD shows monotonic behavior vs √s
- Data points below 19.6 GeV have large uncertainties -> prevents conclusions (presently)
→ for BES phase-II

Current and projected uncertainties on net-proton kurtosis x variance



BES phase II:

	μ_B	BES I	BES II
19.6	206	36 (M)	400 (M)
15	250		100 (M)

Ad #1 (Critical Point):

Deviations of moment products in central Au+Au collisions from Poisson expectations are observed

Uncertainties of current results on higher moments (particularly at 19.6 GeV and bellow) prevents us from drawing conclusions

2. Phase transition

can we demonstrate the softening of EOS ?

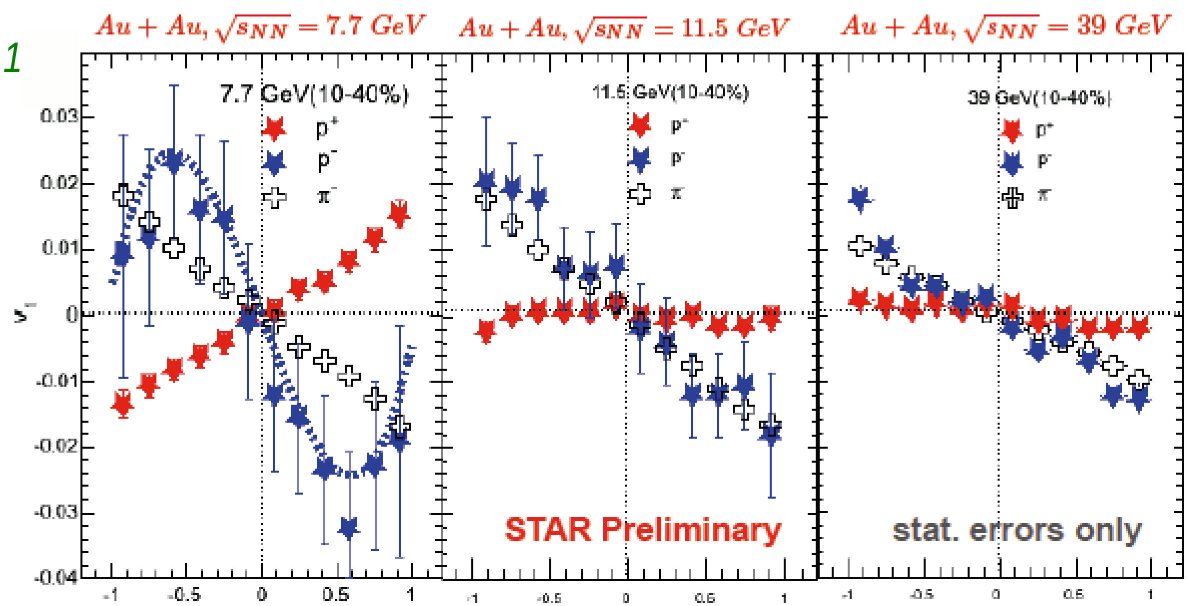
Directed flow (v_1) of identified particles

v_1 probes early stage of collision

a change of sign in the slope of dv_1/dy for protons has been proposed to be a sensitive probe to the first-order phase transition …

L.P.Csernai, D.Rohrich, PLB 458,454 (1999)
H.Stocker, NP A750, 121 (2005)
J.Brachmann et al., PRC 61, 24909(2000)

STAR, QM 2011



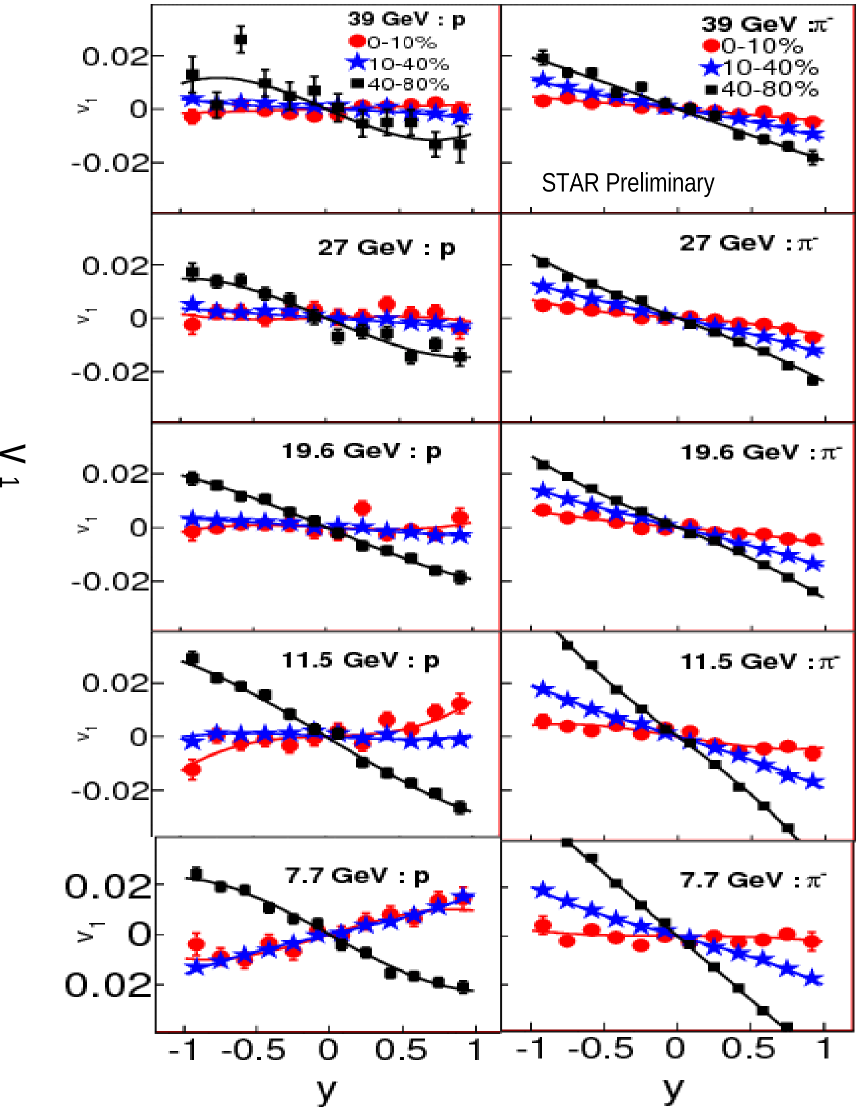
Proton v_1 slope at midrapidity changes sign (7.7 and 11.5 GeV) → 1st order PT?

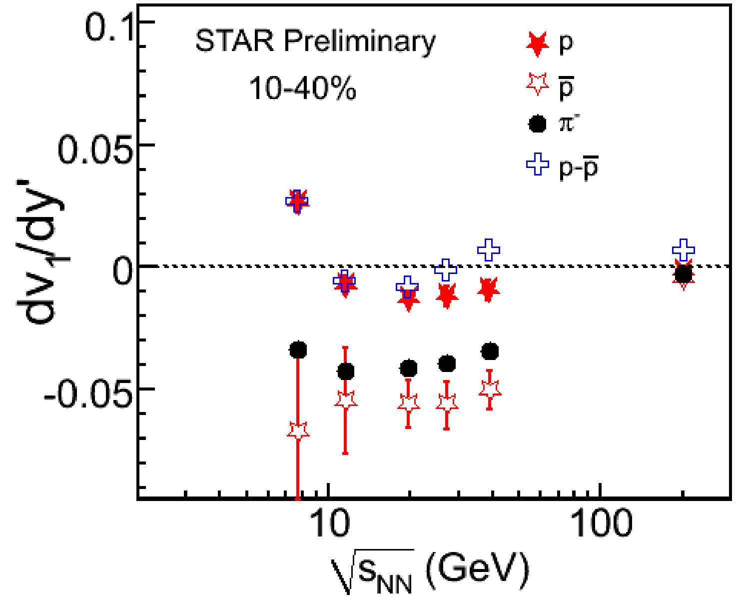
@ 39 GeV all measured v_1 values follow trend observed at higher RHIC energies

Note. the difference between protons and antiprotons

STAR, QM 2012

Search for softening of EOS – directed flow

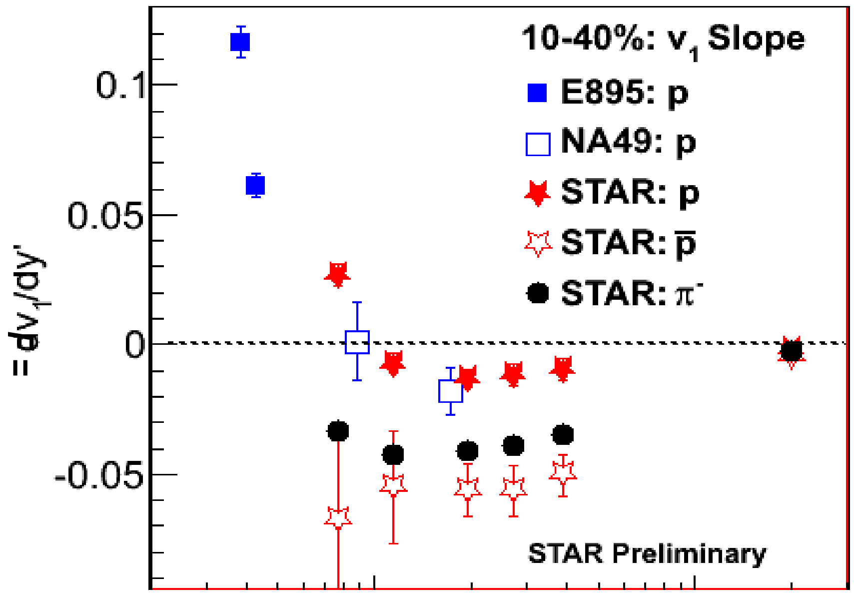




@ mid-central (10-40%) Au+Au collisions :
pions (+,-), kaons (+,-) and anti-p slope is always negative (7.7-39 GeV)
proton slope changes sign from positive to negative between 7.7 and 11.5 GeV, it remains small but negative up to 200 GeV
Non-monotonic net-proton slope, qualitatively like hydro "collapse" predictions … (?)

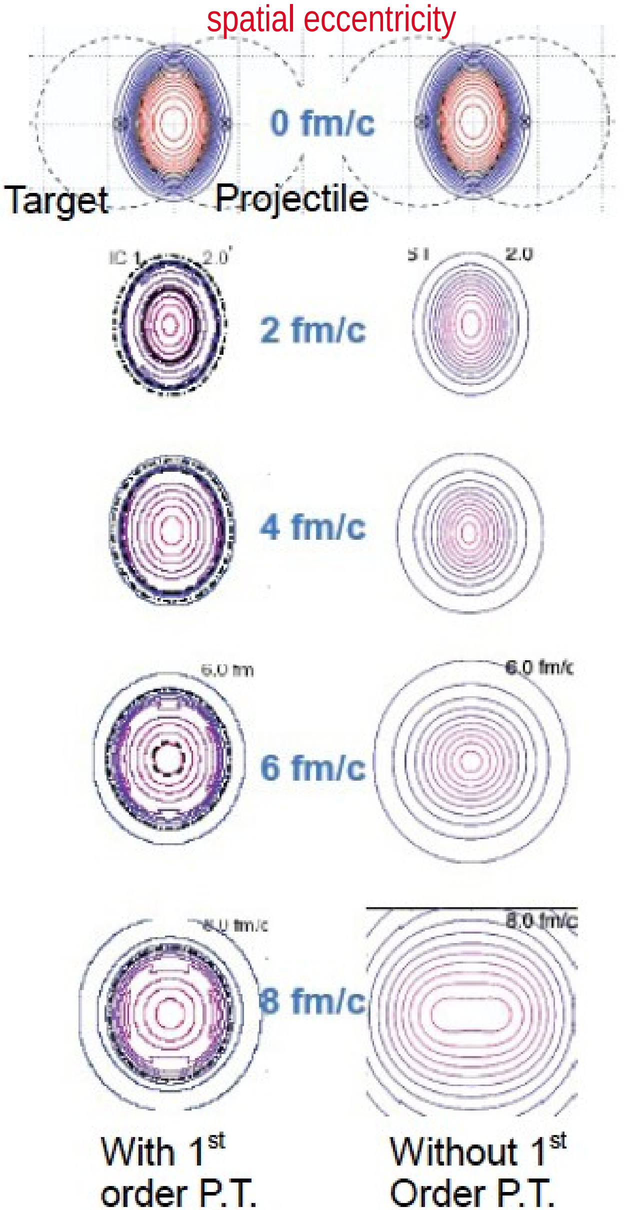
EOS softening ? – comparison with transport models

F = net-protons ($p-\bar{p}$) v1 slope: dv_1/dy



- Protons v_1 consistent with "collapse" hydro predictions
-Net-protons v_1 changes sign twice in the measured energy region, and shows a minimum around 11.5-19.6 GeV
- Physics sources are under investigation

Theory: more input
Experiment: BES Phase II – more statistics, centrality dependence, …



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

azimuthal – HBT

provides info about shape of particle emitting source

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:

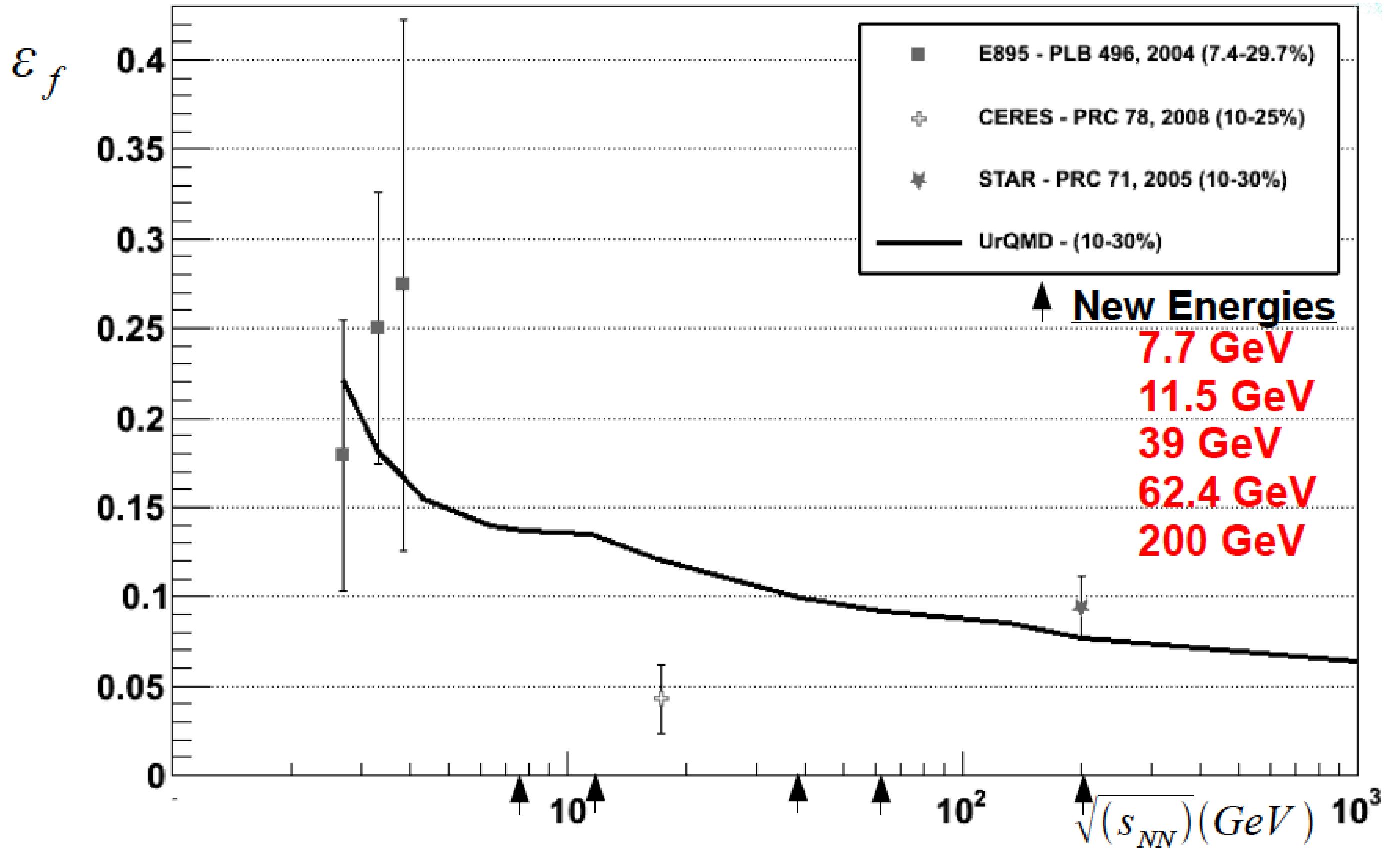
$$\varepsilon_F = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}$$

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

Non-monotonic behavior could indicate a change in EOS (softening ?) -> 1st order phase transition

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

Measurements prior to BES



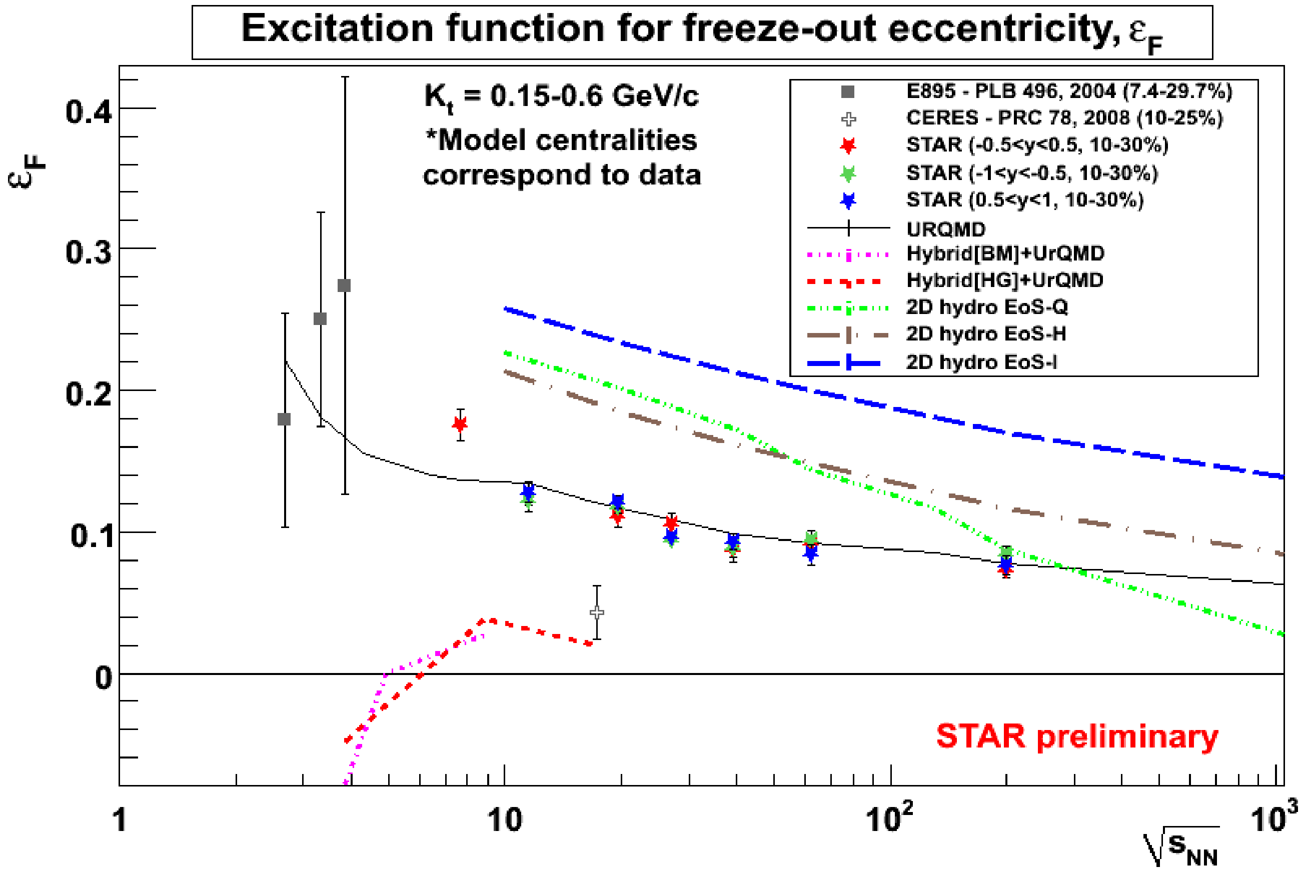
possible minimum follow by the rise ?

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)

Excitation function (BES points included)

Azimuthal HBT for freeze-out eccentricity



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

consistent with monotonically decreasing shape

Ad #2 (1st order Phase Transition):

Net-protons v_1 changes sign twice in the measured energy region, and shows a minimum around 11.5-19.6 GeV

If the 1st order phase transition takes place at all - that would be probably at lower end of the energy spectrum

So, what have we learned from BES Phase-I

STAR and RHIC excellent performance down to 7.7 GeV

BES Phase-I data sets (39, 27, 19.6, 11.5 and 7.7 GeV) cover important region of QCD phase diagram with sufficient statistics for initial survey

but it is rather coarse coverage

Several key sQGP signatures NOT seen at low energies:

- $v_2(m_T - m_0)$ exhibits well-known baryon-meson splitting, but splitting is smaller at low $\sqrt{s_{NN}}$
- 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 $\sqrt{s_{NN}}$: softening of EOS ?
- fluctuations are constant or monotonic with energy from 7.7 to 200 GeV
- higher moments of net-protons deviates from Poisson baseline
- freeze-out eccentricity (aHBT) monotonically decreases with energy

RHIC's energy range is special ...

RICH (BES): rapid changes occur in a number of signatures for energies up to approximately 30 GeV, while remaining surprisingly stable beyond that over the two orders of magnitude to the LHC

→ so, did we answer our "three" questions ?

1. turn-off of QGP signatures ? **clear evidence** no need to search above 19.6
2. Evidence of the first order phase transition ? **strong hints** lower end of range
3. Search for the critical point ? **hints** **MORE** statistics !!!

Answering remaining questions - BES II

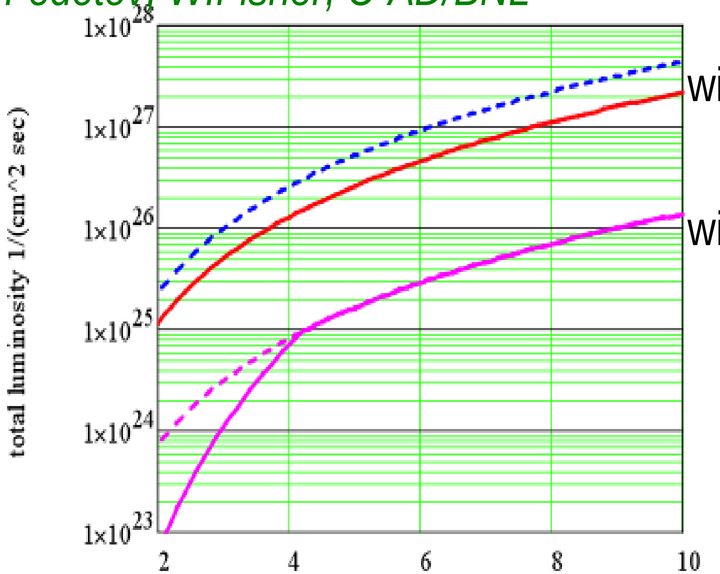
$\sqrt{S_{NN}}$ (GeV)	19.6	15	11.5	7.7
μ_B (GeV)	205	250	315	420
BES I (MEvts)	36	---	11.7	4.3
BES II (MEvts)	**400**	**100**	**120**	**80**

STAR will have BES Phase-II program of precision measurements to map out QCP phase structure with order of magnitude increase in data samples

Good chance for Au Au at $\sqrt{s_{NN}}$ = 15 GeV in 2013.

Improvements for BES phase II

A.Fedotov, W.Fisher, C-AD/BNL



(1) Electron cooling at RHIC will raise luminosity by factor 3-10 in range $\sqrt{s_{NN}}$ 5-20 GeV

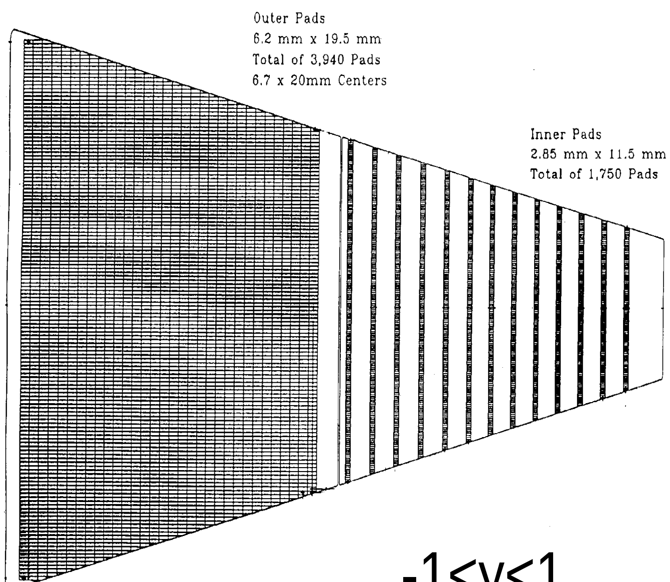
Phase I (2017) $\sqrt{s_{NN}}$ = 5-9 GeV

Phase II (2018+) $\sqrt{s_{NN}}$ = 9-20 GeV

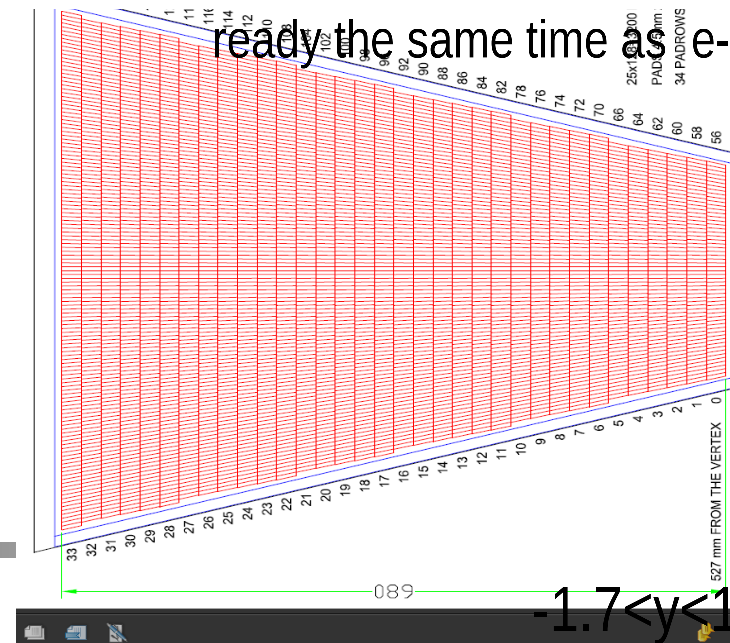
~5 M $ and would not be ready before 2017

(2) iTPC: extends y range to 1.7

ready the same time as e-cooling

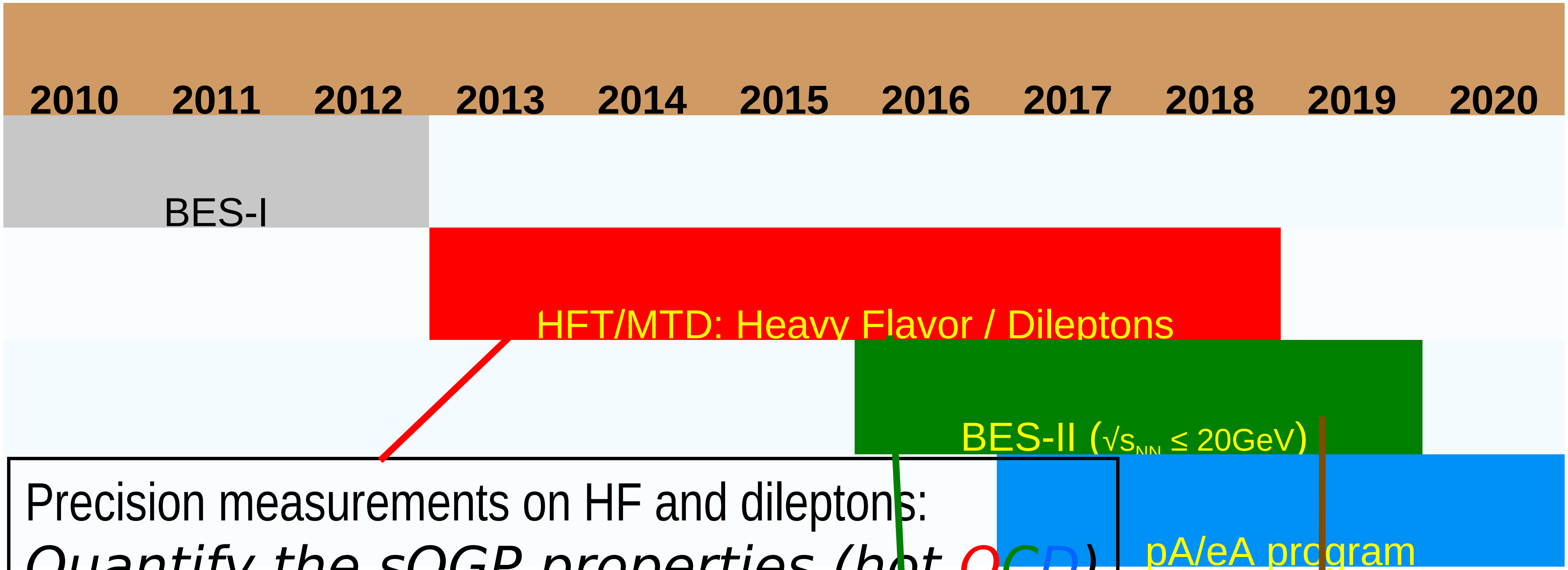


-1<y<1



-1.7<y<1.7

but, BES Phase-II will **not** happen very soon …

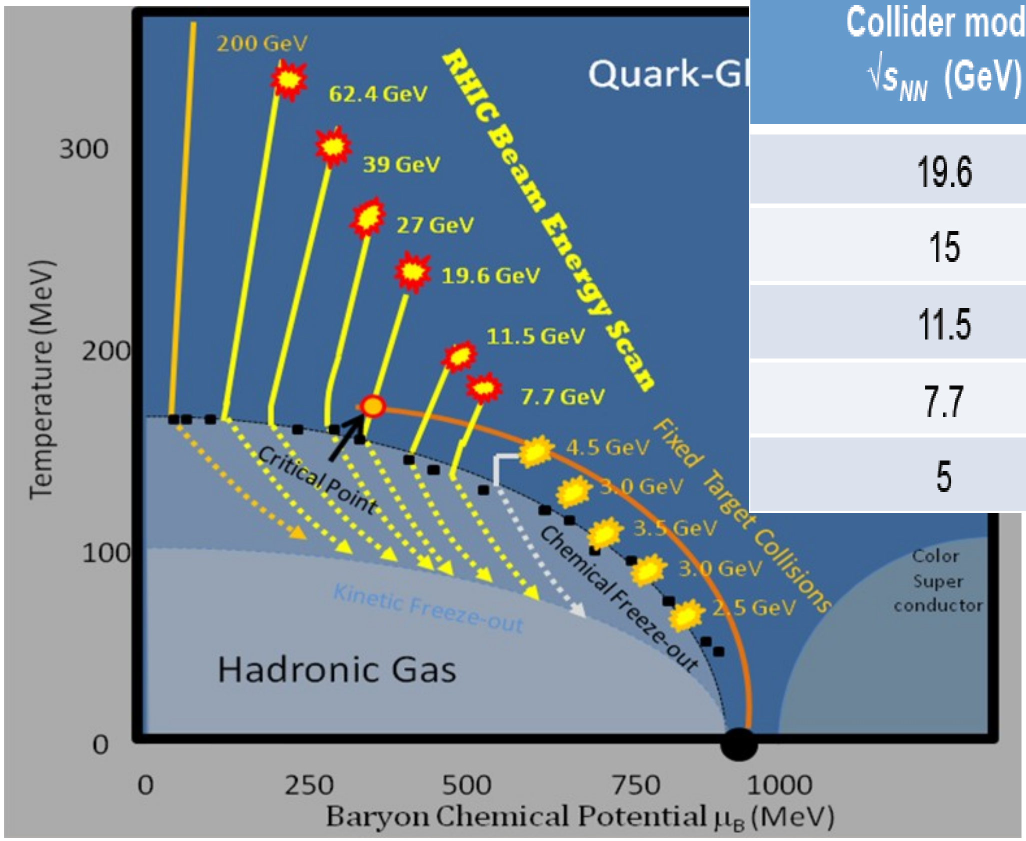


Precision measurements on HF and dileptons:
Quantify the sQGP properties (hot QCD)

Precision measurements on focused energies
Map out the QCD phase structure

Precision measurements on pA and eA
Study QCD in cold matter

μ_B extended range in STAR due to fixed target program

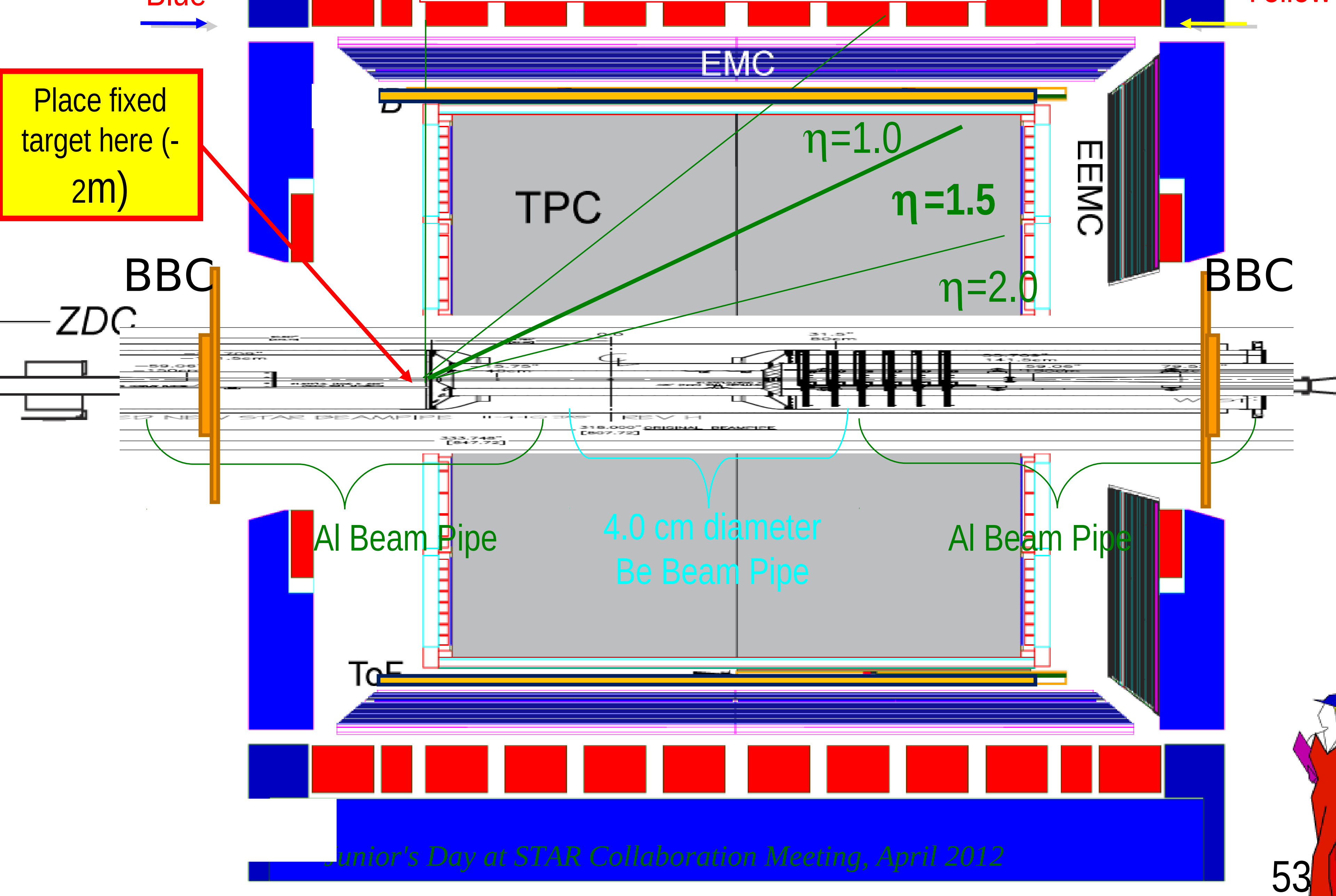


Collider mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode μ_B (MeV)
19.6	4.5	585
15	4.0	625
11.5	3.5	670
7.7	3.0	720
5	2.5	775

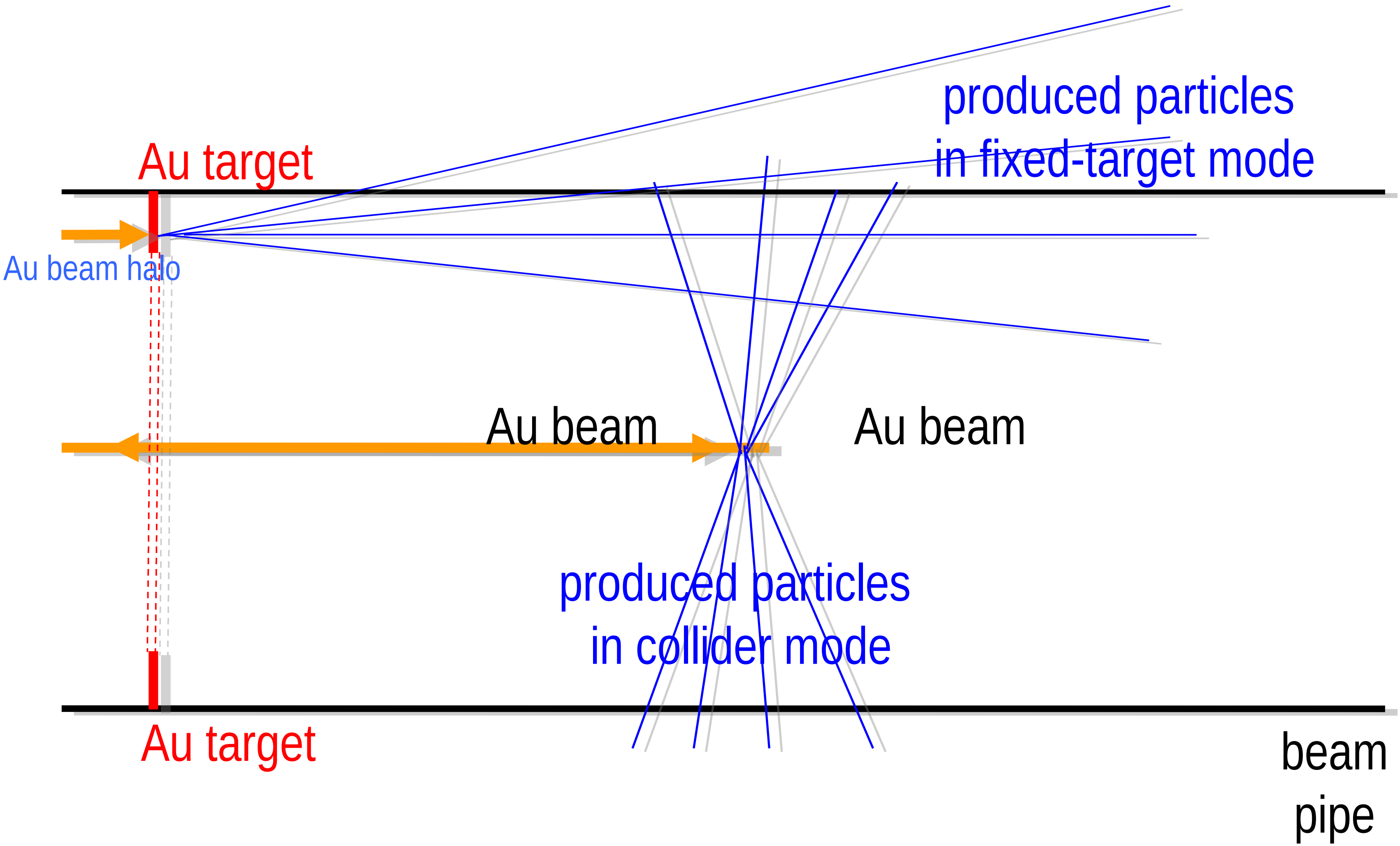
Fixed-target running allows much higher rates without e-cooling at lower energies

Minimal impact on concurrent operation

Location of Fixed Target



Concurrent running in STAR



fixed-target events taken while waiting for collider mode collisions

Fixed-target

we already have experience with running STAR in the fixed-target mode (!) and with analyzing data

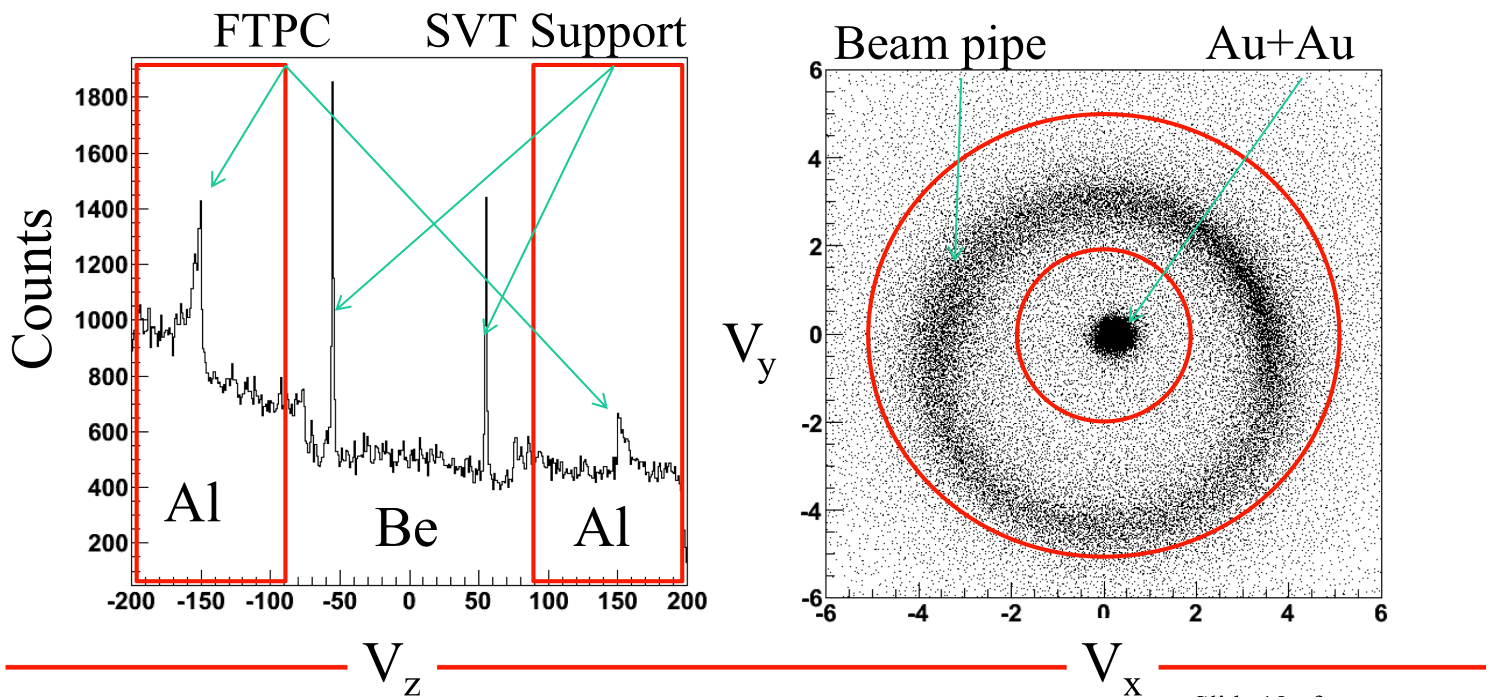
STAR capabilities

Data driven performance study

Au+Al at 3.85 GeV/c (from data set Au+Au at 7.7 GeV) – Samantha Brovko/UC Davis

Samantha's studies: Acceptance, PID, Spectra, vertexing, etc

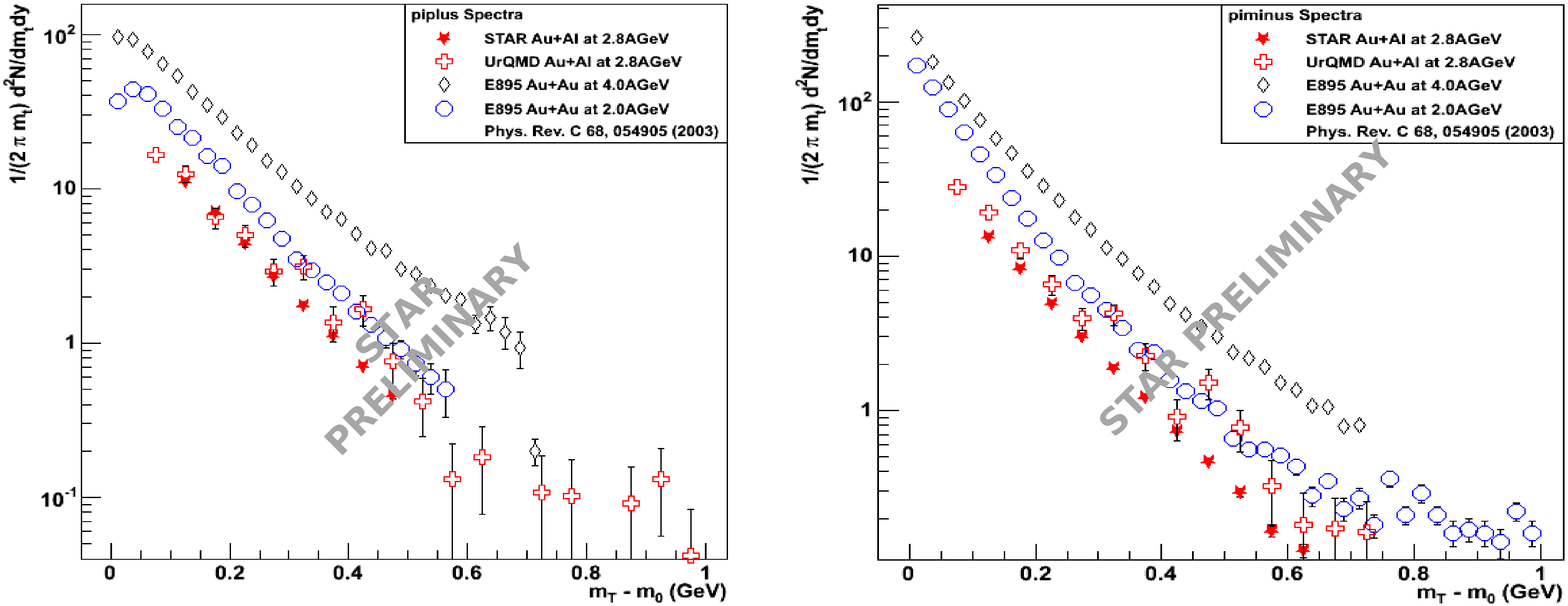
"7.7 GeV" Data set:
Select Events with $100 < |V_z| < 200$ and $2 < V_r < 5$ cm



Remember, the BES trigger was designed to eliminate triggers like Au+Al events
BBC coincident should not allow for it

Au+Al (Au of 3.85 GeV on beam-pipe) -> $\sqrt{s}_{Fixed\text{-}Target}$ =2.98 GeV

2.8 AGeV Au+Al: Spectra π^+ and π^-



- No efficiency or acceptance corrections
  - Currently in progress
- Comparison to UrQMD suggests high efficiency for $\pi^{+/-}$

Sam Brovko

needs embedding for fixed target

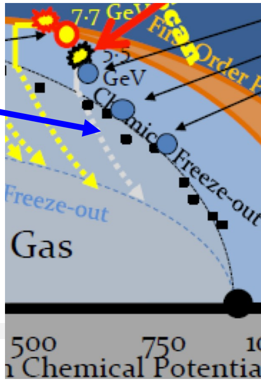
Fixed target at STAR

STAR will have adequate coverage (from mid-rapidity to target rapidity) in fixed-target mode, which is sufficient for some BES studies (detailed analysis of limitations in progress)

Main detectors TPC and TOF tested, work in progress on EEMC/BEMC, and trigger
Tracking, vertexing, PID reasonable, may be improved with optimization

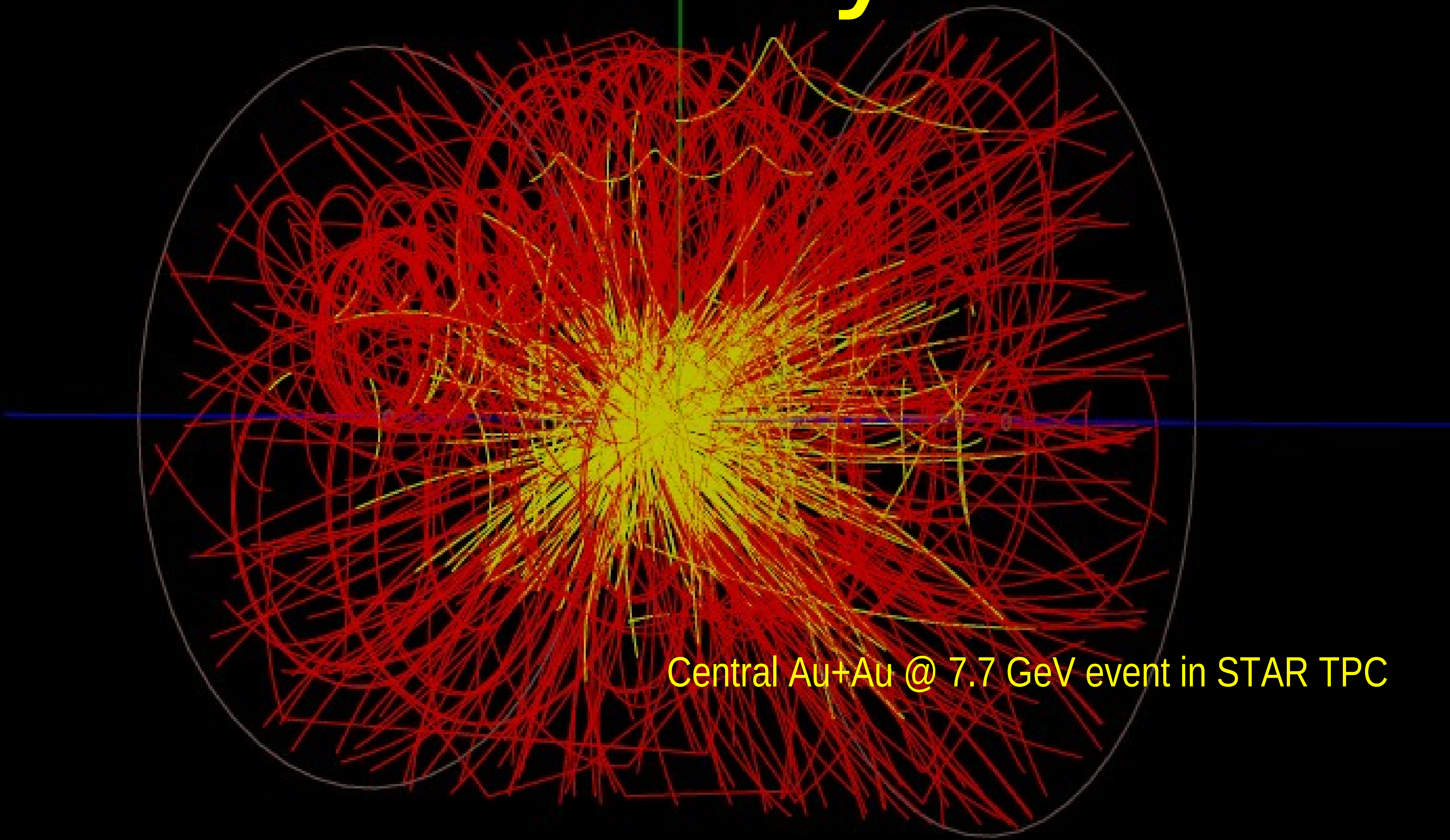
An internal fixed target can be used to take collisions with beam halo at injection energy, which will provide collisions at approximately $\sqrt{s_{NN}}$ of 5 GeV (data point missing from existing BES data)

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)



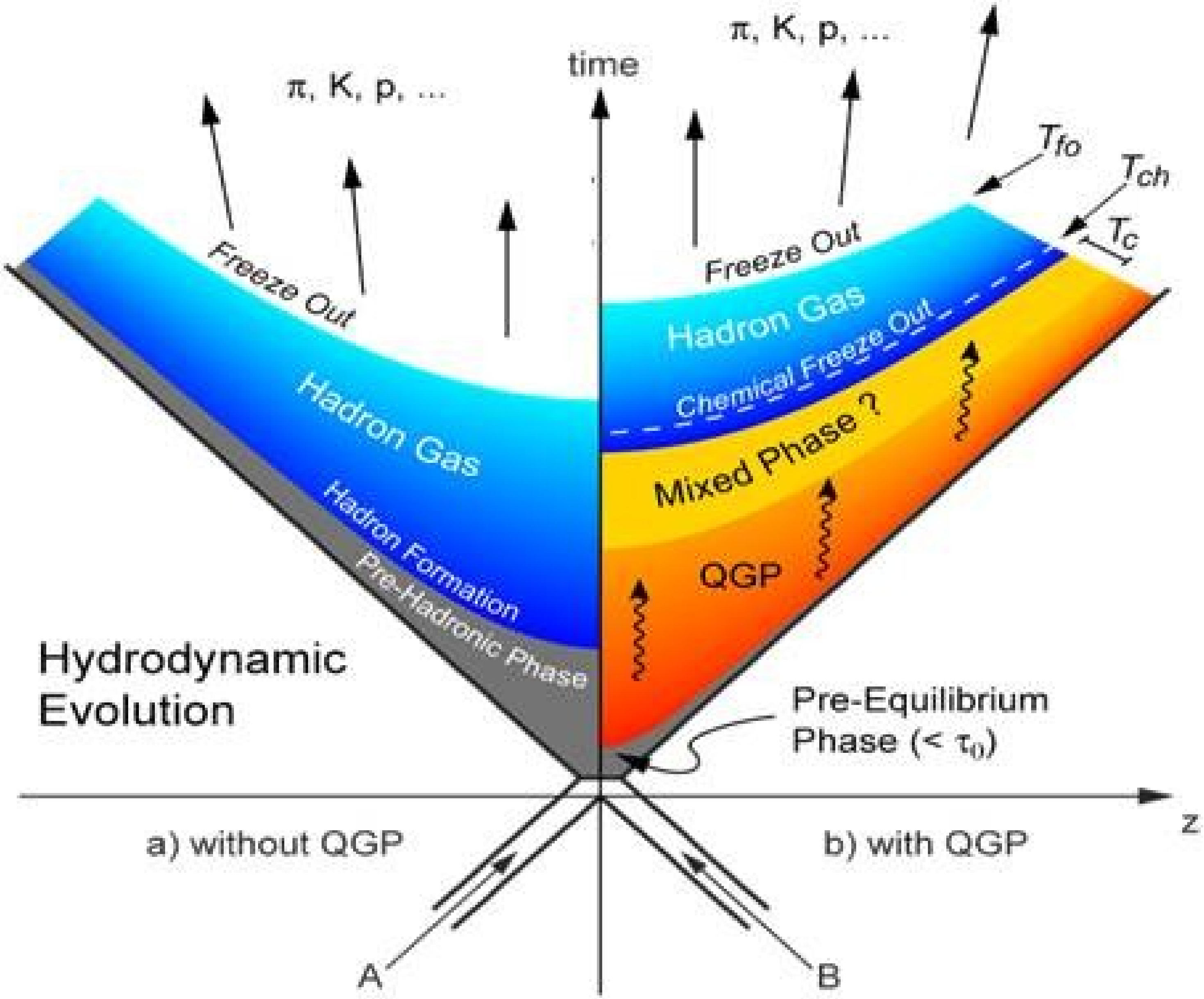
BES: analysis focused on evolution of trends with $\sqrt{s_{NN}}$ (not a single energy results)
with fixed target runs: $0 < \mu_B < \sim 800$ MeV !

Thank you !



Central Au+Au @ 7.7 GeV event in STAR TPC

Hadronization – two scenarios..

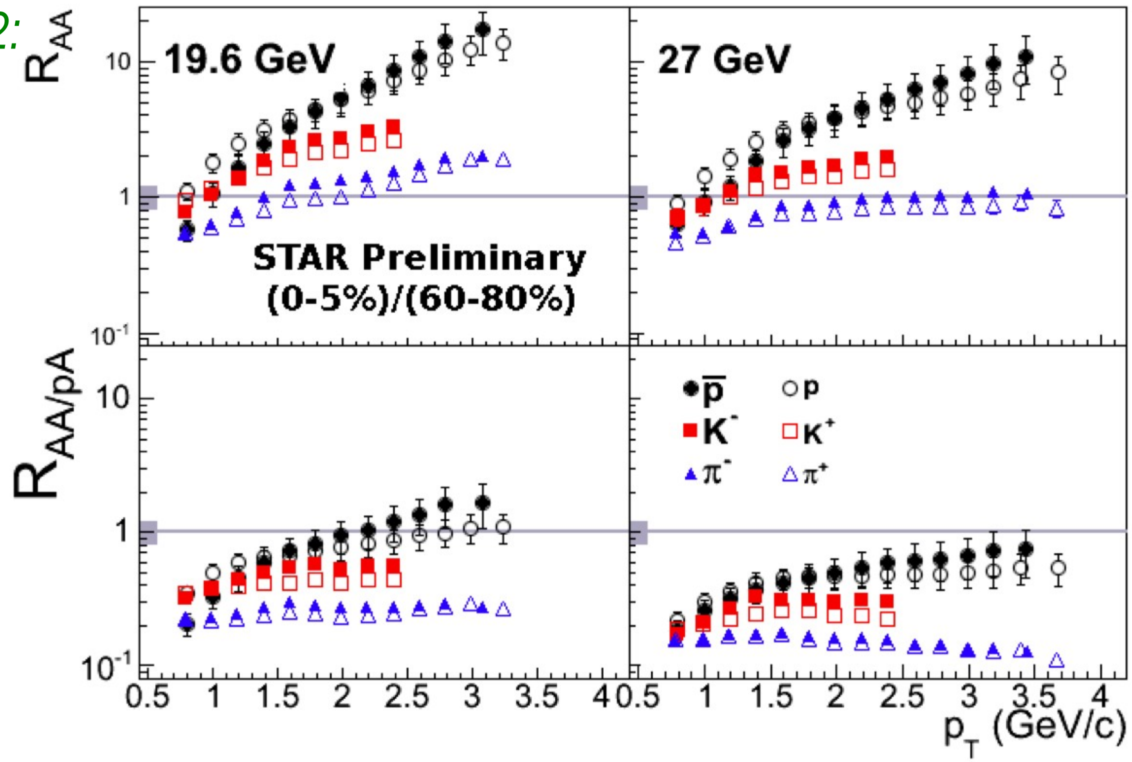


impact of Cronin effect on nuclear modification factor ...

(a qualitative illustration)

Particle ratios scaled by p+p(R_{AA}) and p+W ($R_{AA/pA}$):

QM 2012:



p+p, p+W data (Fermilab):
D.Antreasyan et al.,
Phys.Rev.D19, 764 (1979)

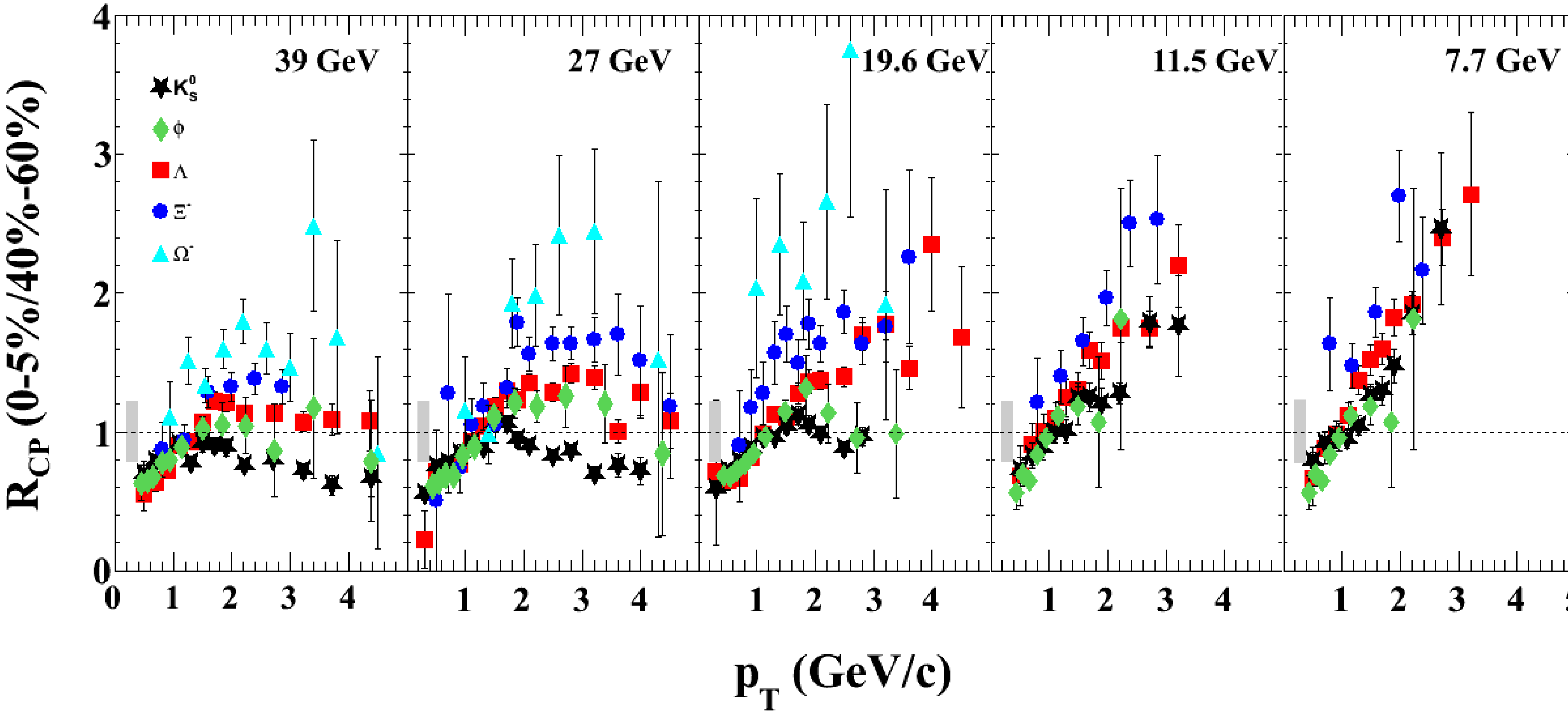
Cronin effect leads to apparent enhancement of R_{AA} at high pt

Similar effect on nuclear modification factor as lack of QGP energy loss

Work in progress

R_{CP} of various strange hadrons

QM 2012 :



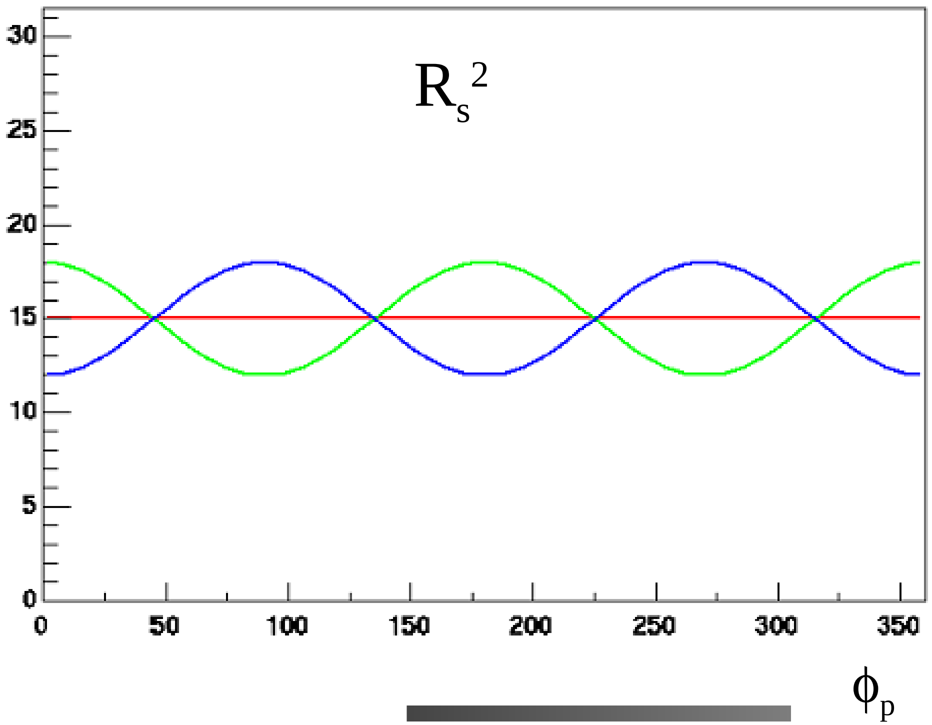
Baryon-meson splitting reduces with decrease of energy and at 7.7 is gone, Indicating decreasing partonic effects at lower energies

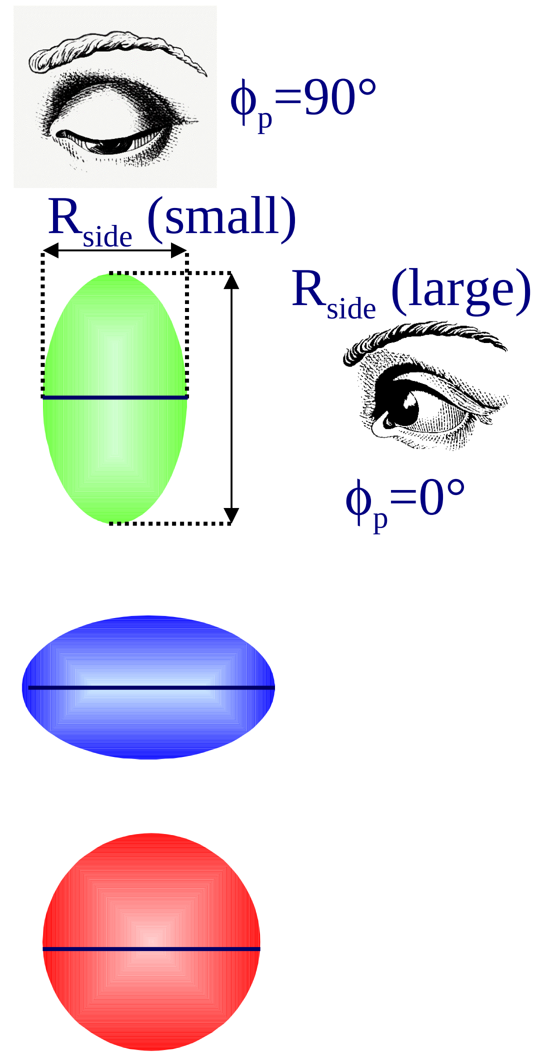
For $K^0_{pt>2\ GeV/c}$: R_{CP}<1 for $\sqrt{s_{NN}}$> 19 GeV and >1 for $\sqrt{s_{NN}}$<11.5 GeV

HBT relative to reaction plane

- for out-of-plane-extended source, expect
  - large R_{side} at 0°
  - small R_{side} at 90°

} 2^{nd}-order oscillation

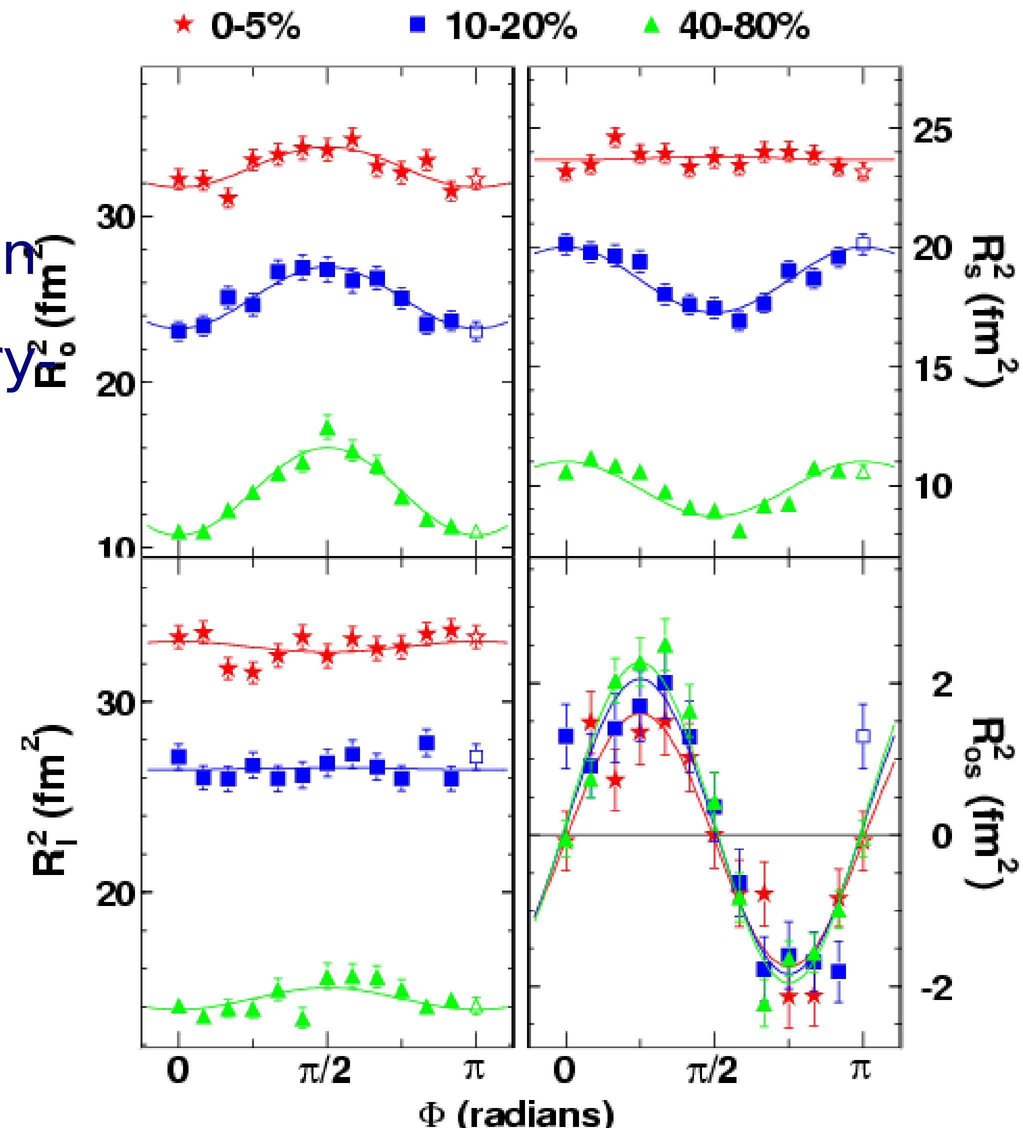




asHBT at 200 GeV in STAR – R(Φ) vs centrality

12 (!) Φ-bins b/t 0-180°
(k_T-integrated)

- clear oscillations observed in transverse radii of symmetry-allowed type
- centrality dependence reasonable



Computing Fourier Coefficients

Fourier coefficients computed from radii:

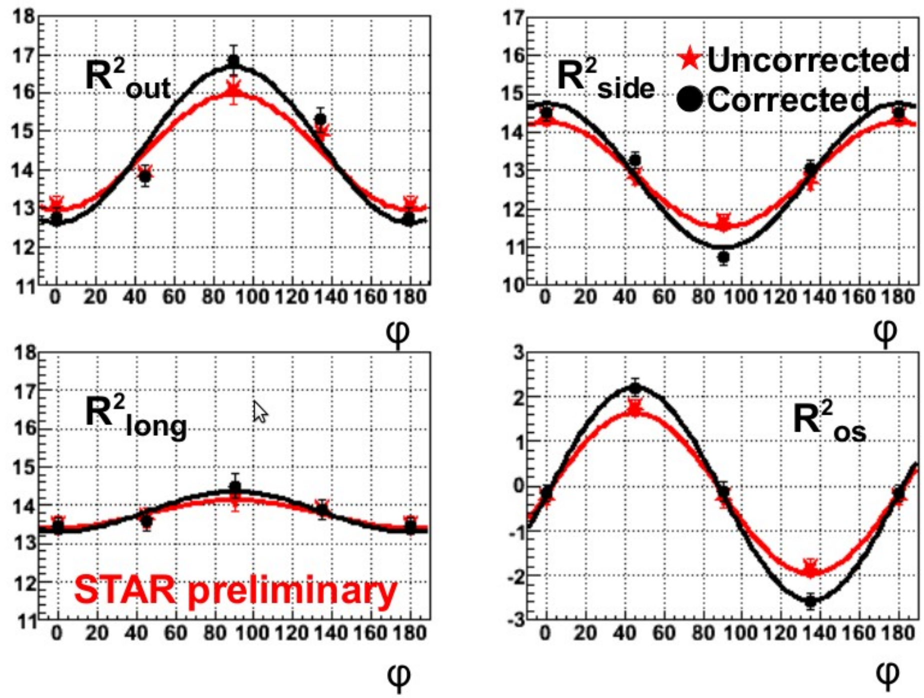
$$R_{0,i}^2 = \frac{1}{N_{bins}} \sum_{j=1}^{N_{bins}} R_i^2(\Phi_j) \qquad i = o, s, l, os$$

$$R_{2,i}^2 = \frac{1}{N_{bins}} \sum_{j=1}^{N_{bins}} R_i^2(\Phi_j) \cos(2\Phi_j) \qquad i = o, s, l$$

$$R_{2,i}^2 = \frac{1}{N_{bins}} \sum_{j=1}^{N_{bins}} R_i^2(\Phi_j) \sin(2\Phi_j) \qquad i = os$$

$$\varepsilon_F = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} \approx 2 \frac{R_{2,s}^2}{R_{0,s}^2}$$

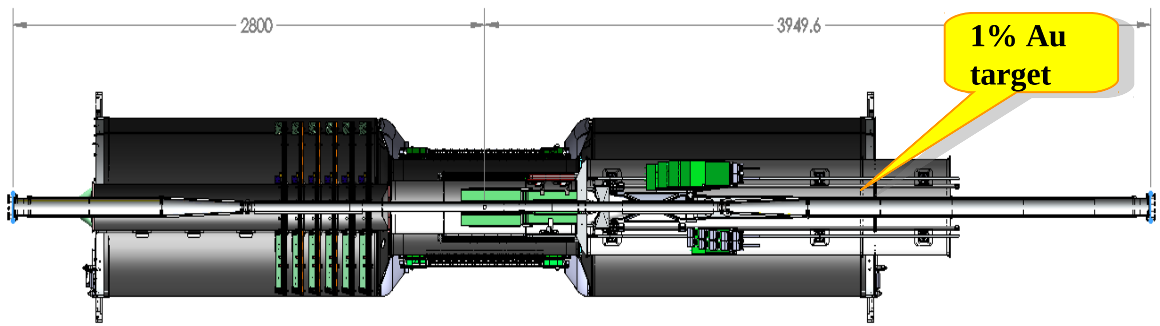
Au+Au 200 GeV
Oscillations for 20-30% Centrality and K_t = 0.35-0.60 GeV/c

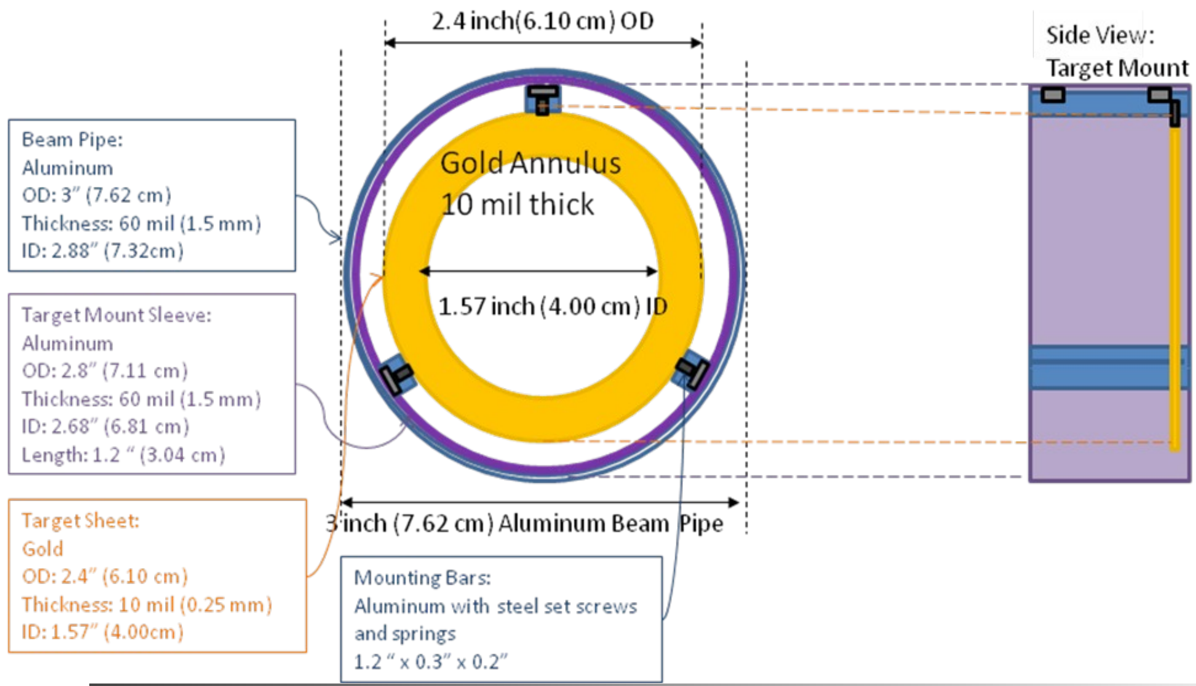


Reference: Lisa, Retiere, *Phys. Rev. C*, 70, 044907

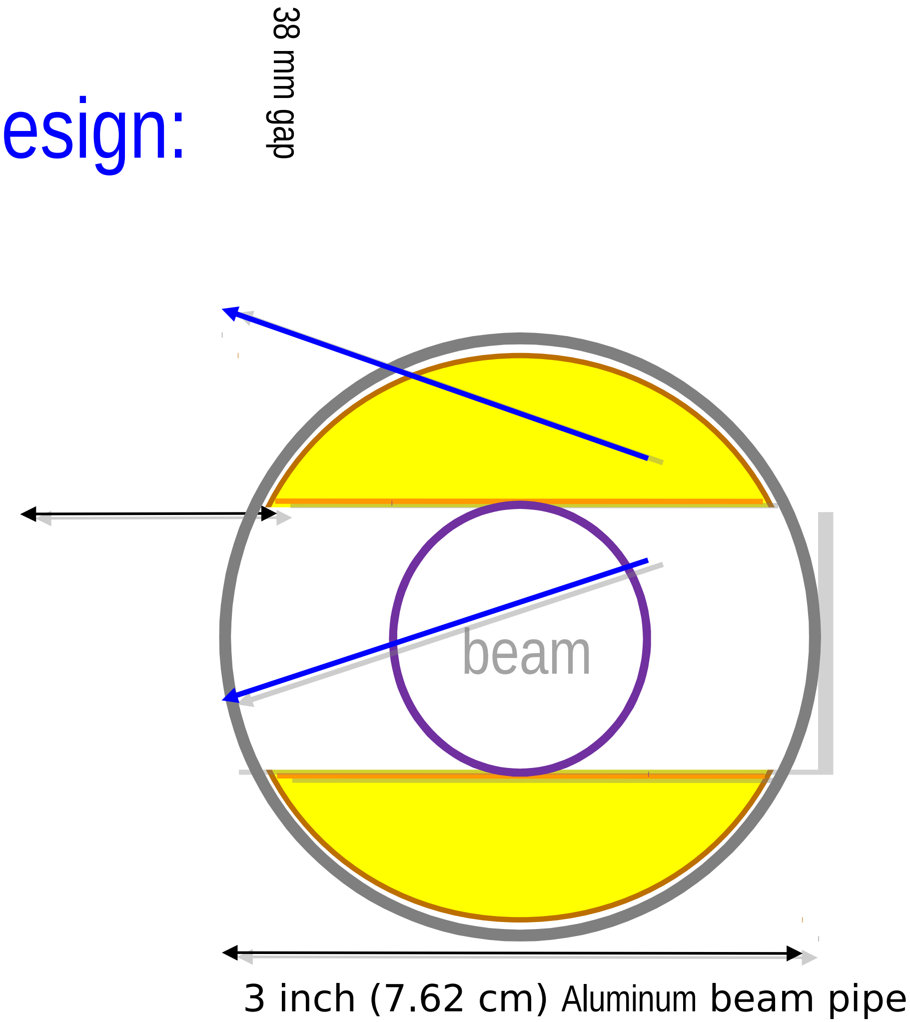
Junior's Day at STAR Collaboration Meeting, April 2012

On much faster scale: Fixed target in STAR





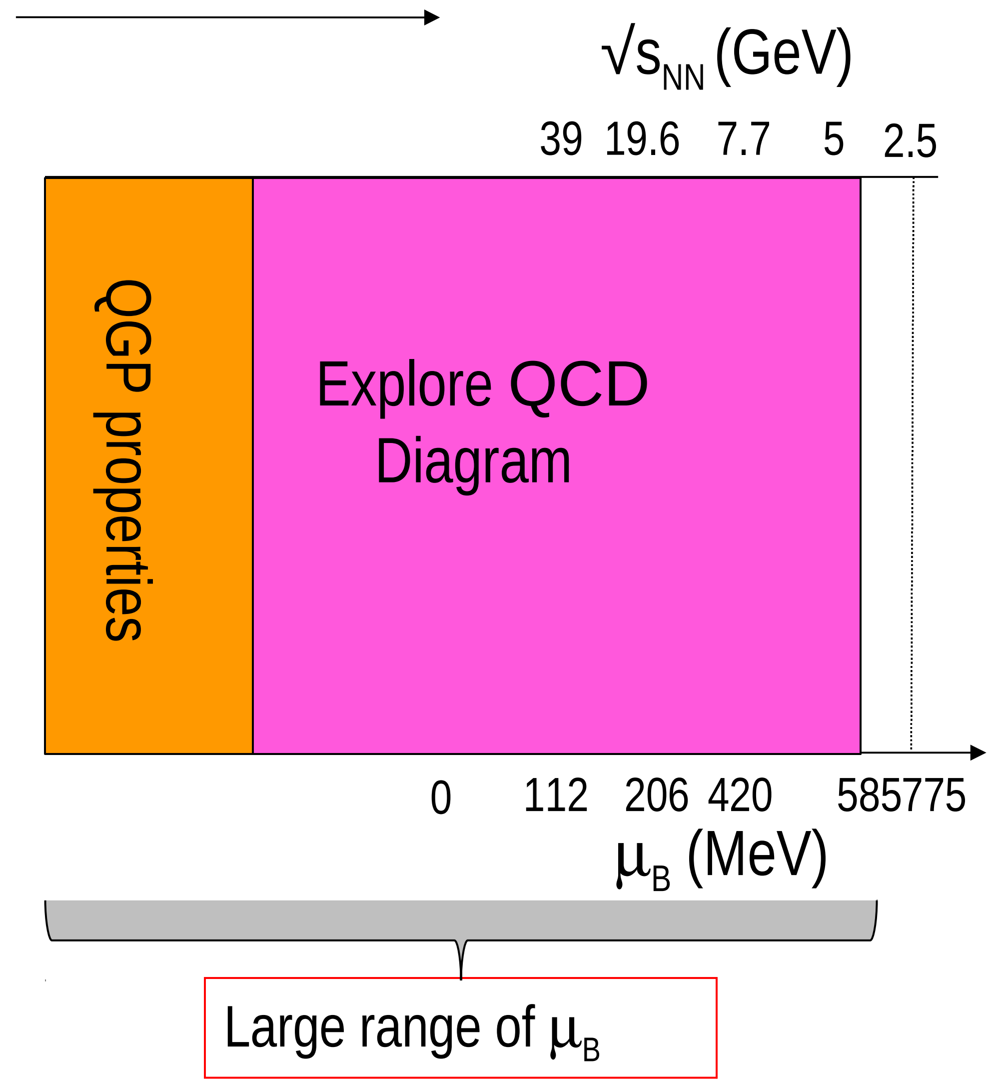
the real design:



Au targets

because kicker magnet, used to dump the beam, works in horizontal plane

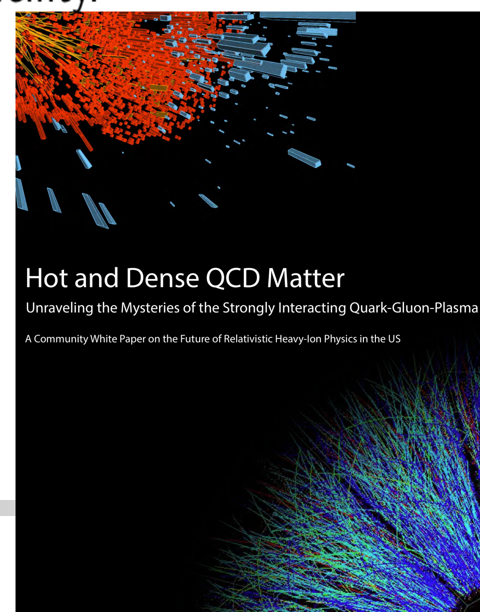
STAR Beam Energy Scan in STAR is in VERY good shape !



The next 5–10 years of the US relativistic heavy-ion program will deliver:

- a beam-energy scan program to establish the properties and location of the QCD critical point.
- the quantitive determination of the transport coefficients of the Quark Gluon Plasma, such as the temperature dependent shear-viscosity to entropy-density ratio $\eta/s(T)$, and the energy loss transport coefficients $\hat{q}$ and $\hat{e}$.
- a jet physics program to study parton energy loss and the quasi-particle nature of the QGP.
- a heavy-flavor physics program to probe the nature of the surprisingly strong interactions of heavy quarks with the surrounding medium
- a systematic forward physics program to study the nature of gluon saturation and establish the foundation for the future Electron Ion Collider research program and facility.

from Executive Summary of White Paper, Oct.24,2012



Program BES
w eksperymencie STAR

Hanna Zbroszczyk
Faculty of Physics, Warsaw University of Technology

BES program in STAR

and what next?

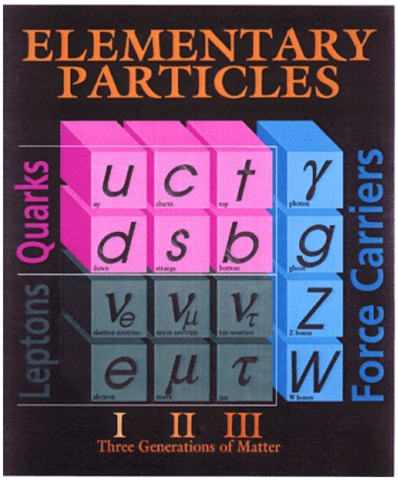
..

Hanna Zbroszczyk
Faculty of Physics, Warsaw University of Technology

Grazyna Odyniec
Lawrence Berkeley National Laboratory , Berkeley, Ca 94720, USA

1. Introduction and motivations
2. Phase I - some results
   - what questions are we able to answer ? **
3. Phase II (completion of BES program)

Basics on **Q**uantum **C**hromo**d**ynamics

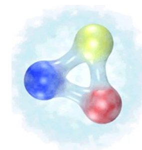


Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.

Gluons hold quarks together to from hadrons:

meson

baryon

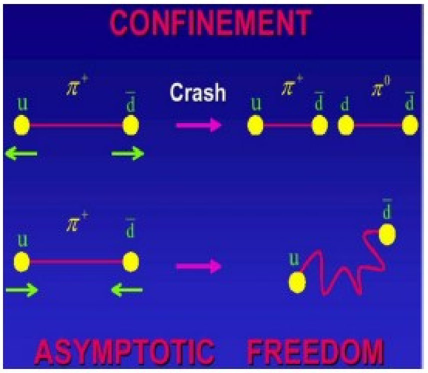


Gluons and quarks, or partons, typically exist in a color singlet state: ***confinement.***

Quark gluon plasma (QGP)

Asymptotic freedom is the property of some gauge theories in which the interaction between the particles, such as quarks, becomes arbitrarily weak at ever shorter distances, i.e. length scales that asymptotically converge to zero.

Confinement is the physics phenomenon that color charged particles (such as quarks) cannot be isolated. The quarks are confined with other quarks by the strong interaction to form pairs or triplets so that the net color is neutral, to obey the Pauli exclusion principle. Quarks in mesons must be of a color and the corresponding anti-color to achieve color neutralism; in baryons a red-green-blue mixture (or its anti-color equivalent in an antiparticle) must be achieved.



Quark-gluon plasma (QGP) is a phase of quantum chromodynamics (QCD) which exists at extremely high temperature and/or density.
This phase consists of (almost) free quarks and gluons which are the basic building blocks of matter.

Where are we?

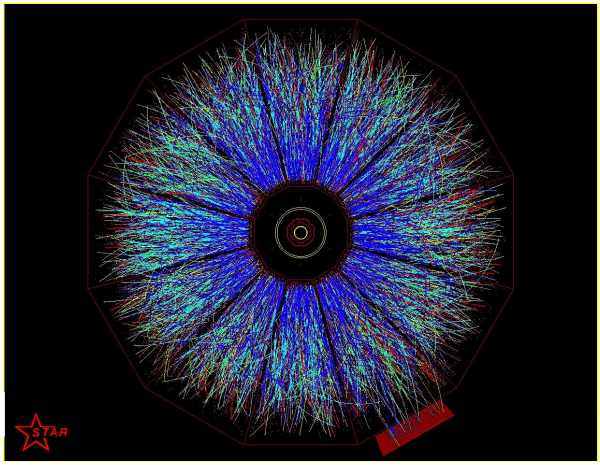
Goal of the RHIC Heavy Ion Program:

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

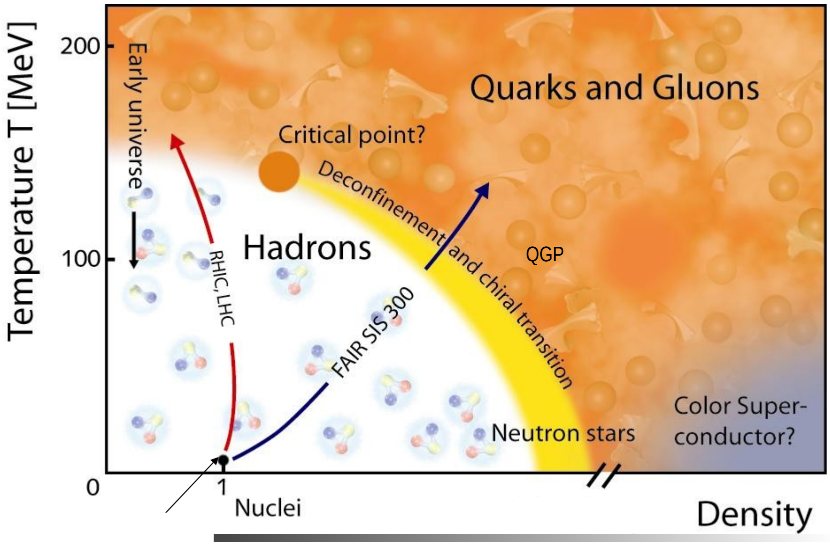
What have we learned so far?

STAR NPA 757 (2005) 102

Strongly interacting, hot, dense matter with partonic collectivity

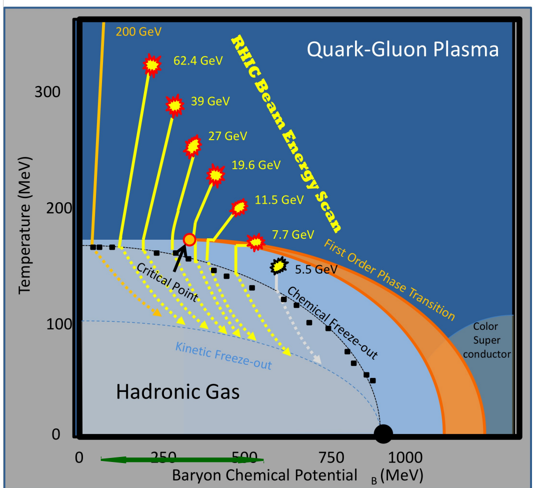


Phase Diagram



Beam Energy Scan at RHIC: $\sqrt{s_{NN}}$ ~ 5-50 GeV

160 MeV< μ_B <500 MeV



We built RHIC to find QGP.
And we did it !

but,
QGP- new and complicated phase of matter
With unique and unexpected properties
Huge progress in understanding its nature:
@high energy – cross over transition
@lower – should be 1st order transition
+ Critical point

→ **BES program was born**

With RHIC beams:
(1) Study properties of sQGP
(2) Map out QCD matter phase structure

Structure of QCD matter phase diagram is
fundamental
(will be in text books in future decades)

7

Phase diagram of nuclear matter i.e. T vs. mu_B is largely speculative

At top RHIC energies the transition between QGP and HG is cross-over (mu_B~0).

There is indirect evidence in QCD of the first order phase transition at high value of mu_B

Thus , a CP could exist (=point where the first order ph.transition ends).

Beam delivered by RHIC allowed us to systematically study the properties of strongly-coupled QCD matter at the top RHIC energies, as well as to map out the QCD matter phase structure by scanning the phase diagram with variable collision energies (diff.mu_B and T)

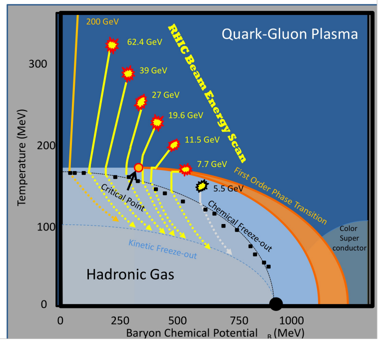
ONLY RHIC can do it, not LHC (no range needed)

Three BES goals:

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

Year	$\sqrt{s_{NN}}$ (GeV)	Events (10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5

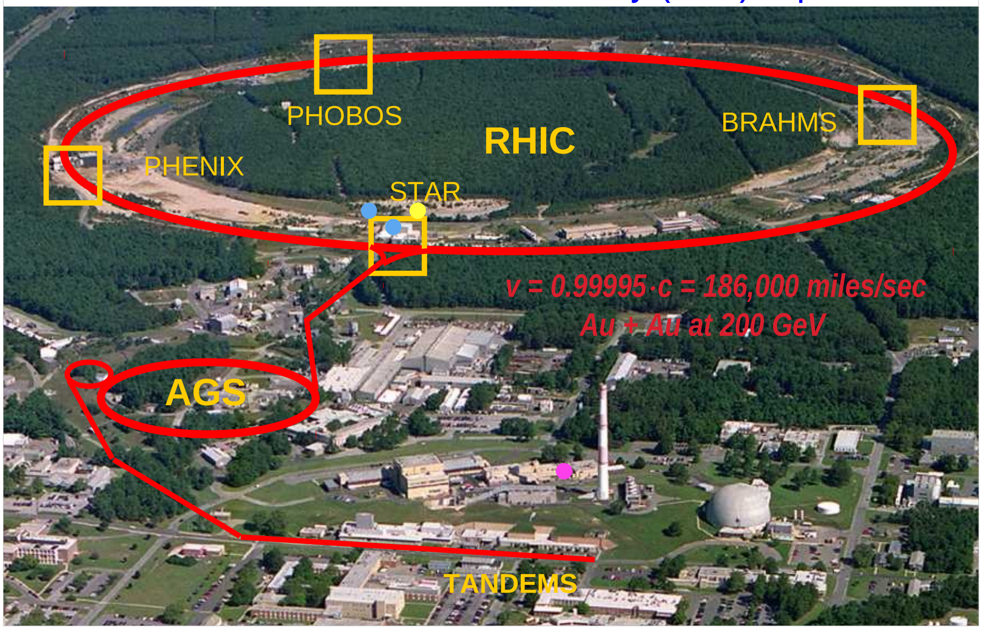
→ Where are we probing on the QCD Phase Diagram ?

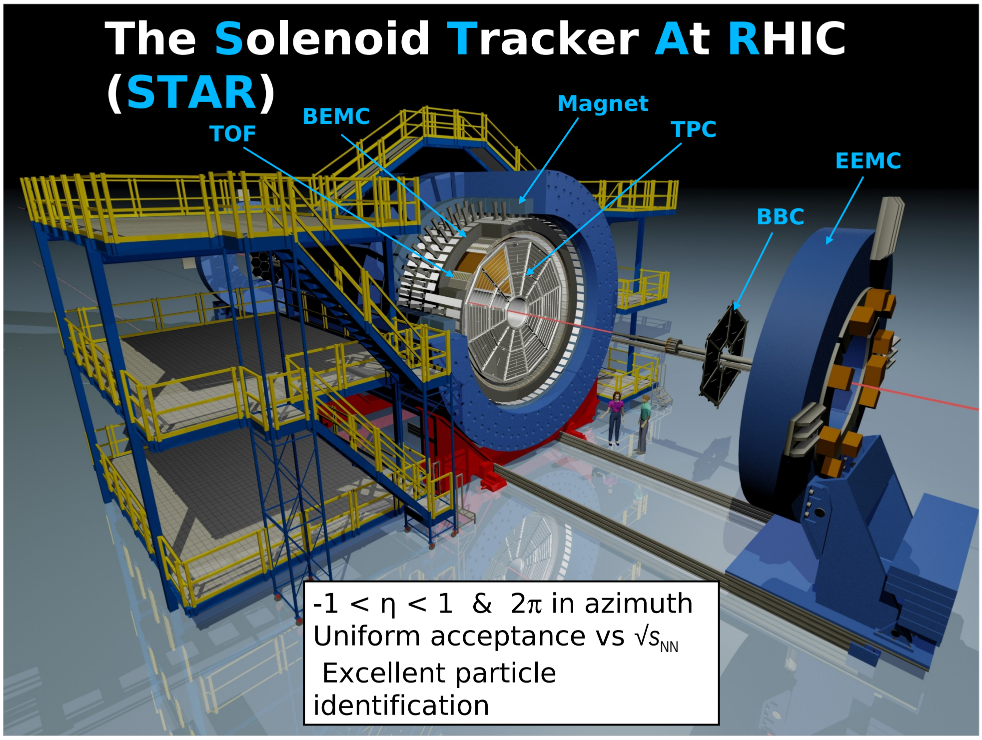


First question is when we lower the collision energies whether these key sQGP signatures observed at the top RHIC energy have been turned off

Relativistic **H**eavy **I**on **C**ollider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY





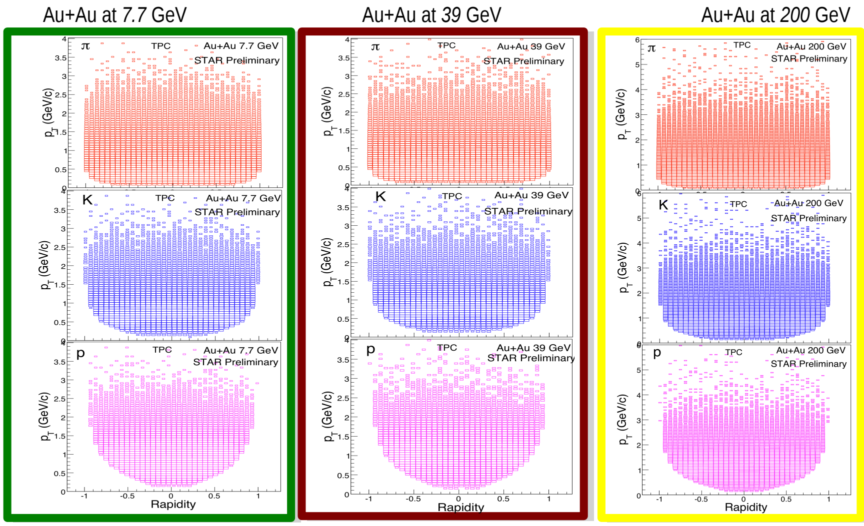
STAR detector has a large and uniform acceptance with excellent particle identification at mid-y (-1<eta<1)

across all collision energies

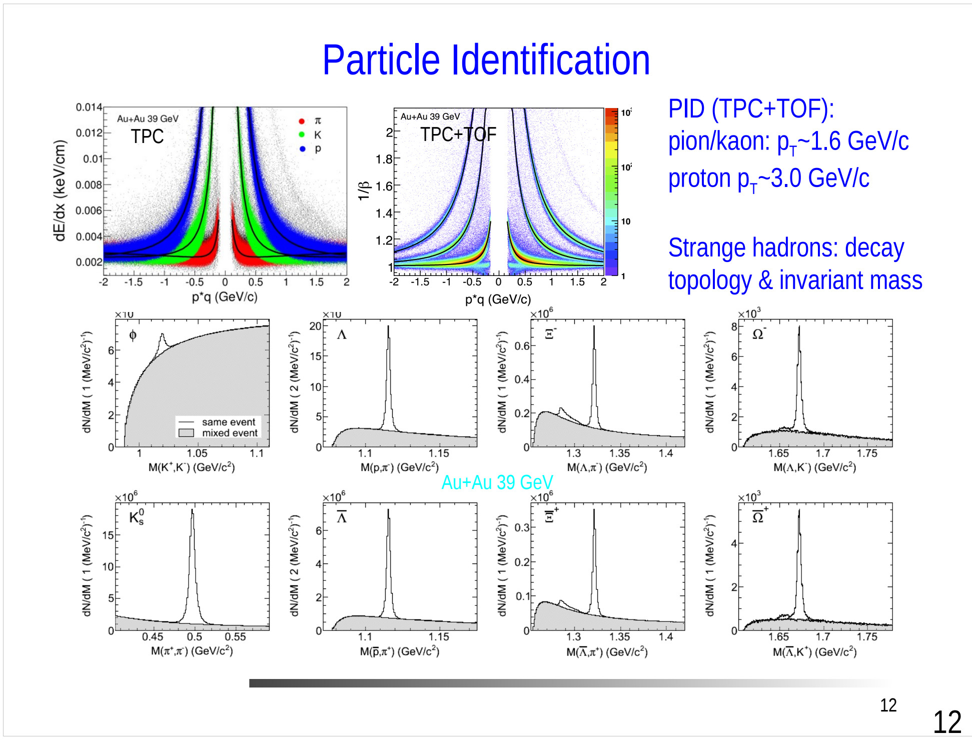
Main tracking device: TPC

PID:TPC or TPC+TOF(lower pt) or TPC+EMC (higher pt)

Identified Particle Acceptance at STAR



At collider geometry - similar acceptance for all particles and energies



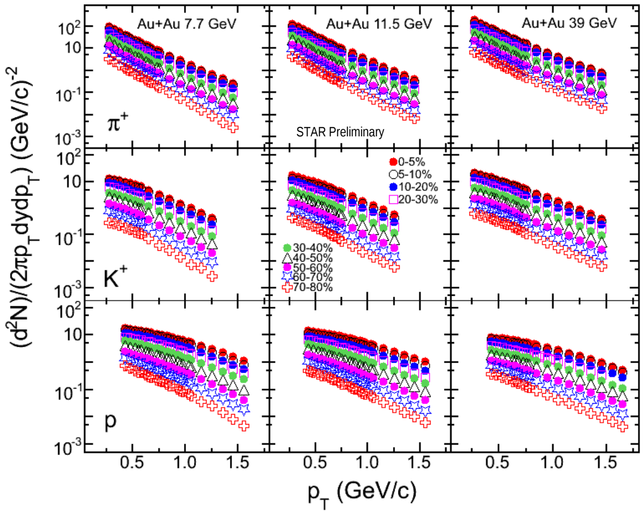
With installed in 2012 full TOF we can identify …

Environment

13

but let us first check our environment …

Spectra: π, K, p



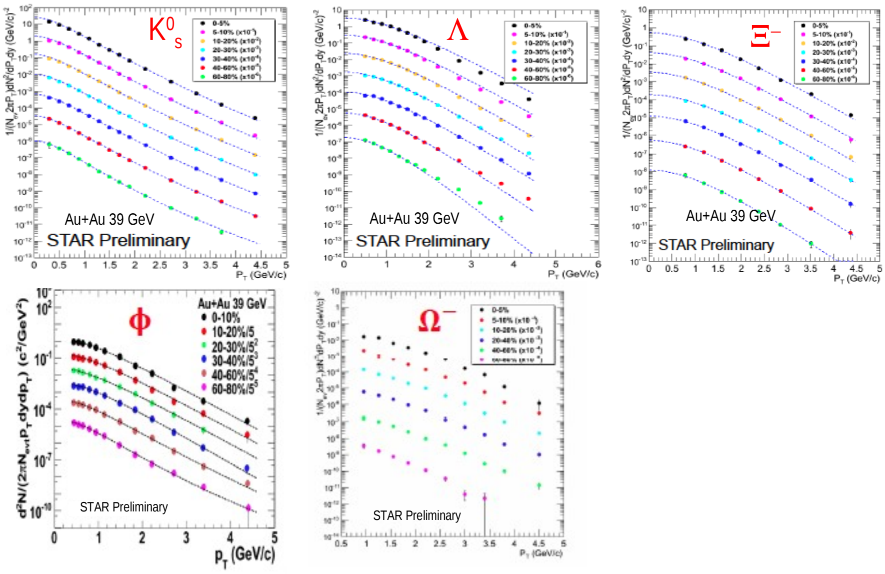
Slopes: π > K > p

π, K, p yields within measured p_T ranges: 70-80% of total yields

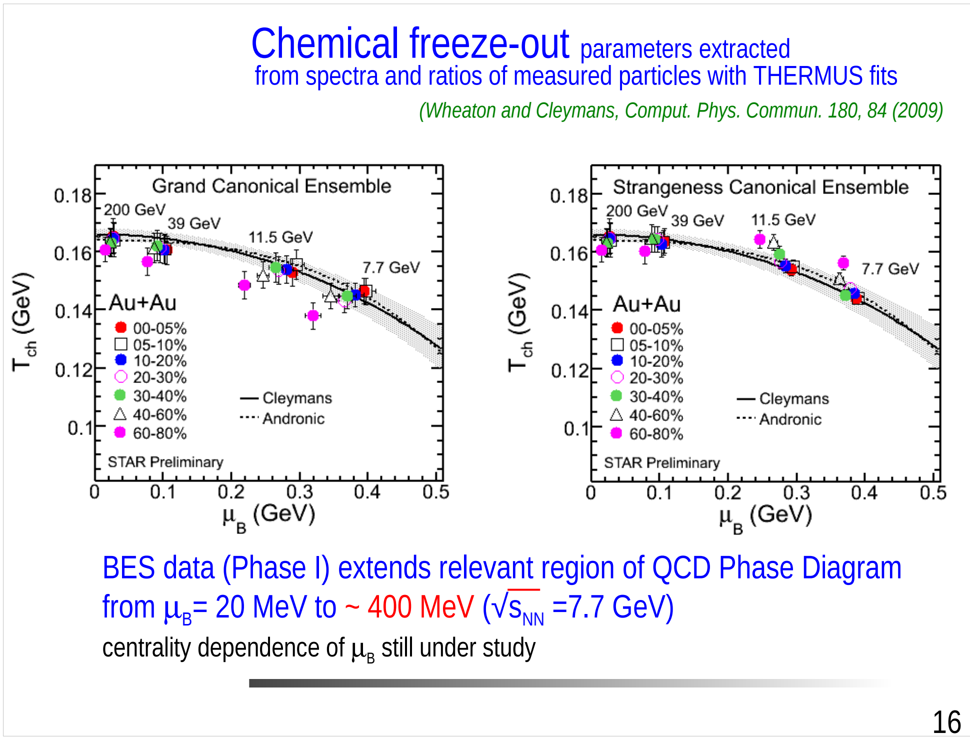
14

Proton spectra: without feed-down correction

Spectra : strange hadrons



15



Particles used: π, K, p, Λ, K^0_s, Ξ

variation of extracted parameters: T and mu_B

Left: Grand Canonical Ensemble = energy and quantum numbers or particle numbers are conserved on average

Right: Strange Canonical Ensemble = strangeness is fixed exactly by initial value of S, while baryon and charge is treated like GCE

Particle spectra can be used to extract kinetic freeze-out parameters with BW model

BES: Experimental Program

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

Observables:

(1) indications of the existence of Critical Point
- fluctuation measures
  - higher moments of conserved quantities (net proton distribution -> kurtosis)
  - particle ratio fluctuations

(2) signatures of phase transition (softening of EOS)
- azimuthally-sensitive femtoscopy
- direct flow v_1
- …

(3) disappearance of signals of partonic degrees of freedom seen at 200 GeV
- disappearance of constituent-quark-number scaling of v_2
- disappearance of hadron suppression in central collisions
- dynamical charge fluctuations ('local parity violation')
- …

17

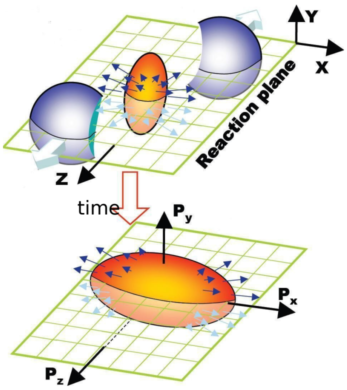
We have selected the observables which would have the best resolving power given realistic constraints on total available beam time
Dynamical charge fluctuations – przedtem sie nazywalo :local parity violation

the easiest one …

3. Turn off signatures of QGP

Do QGP signatures (v_2, R_{cp}, ...) turn-off ?

Anisotropic flow



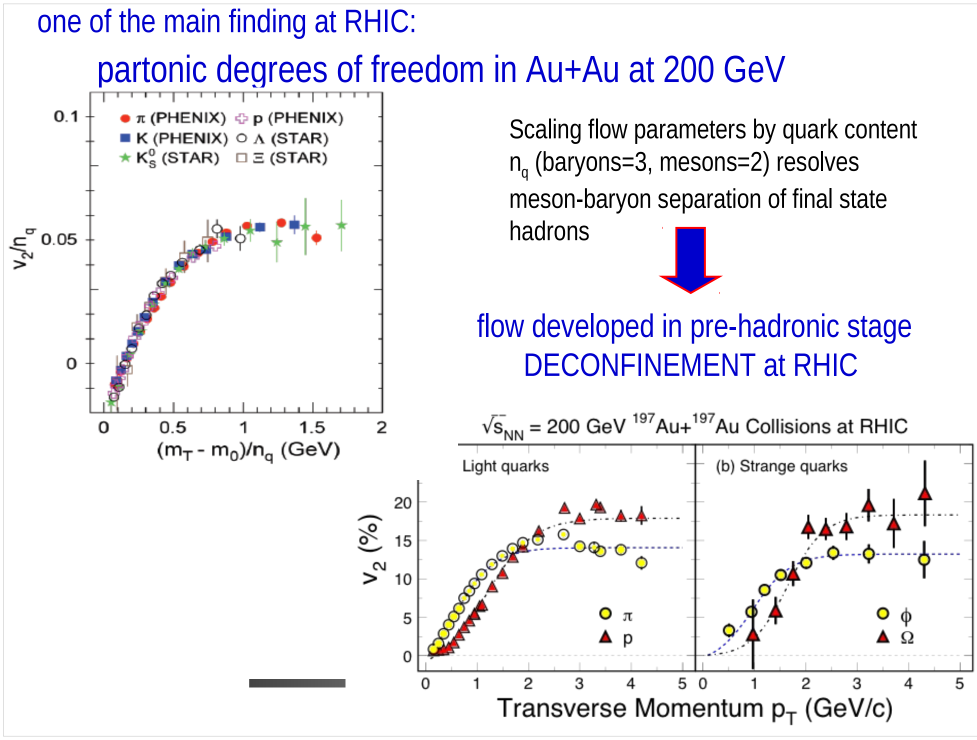
Initial spatial anisotropy is determined by impact parameter and initial fluctuations

In early collision stages, spatial anisotropy is converted by gradient pressure and scattering 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"**

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

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



V2 probes early stages of colision

V2=<cos2(phi-Psi2)>, Psi2 –orientation of the second order reaction plane

At the top RHIC energy Au+Au elliptic flow v2 scaled by the number of constituant quarks (N_q) vs. (m_T_m)/n_q shows scaling behavior -> NCQ scaling

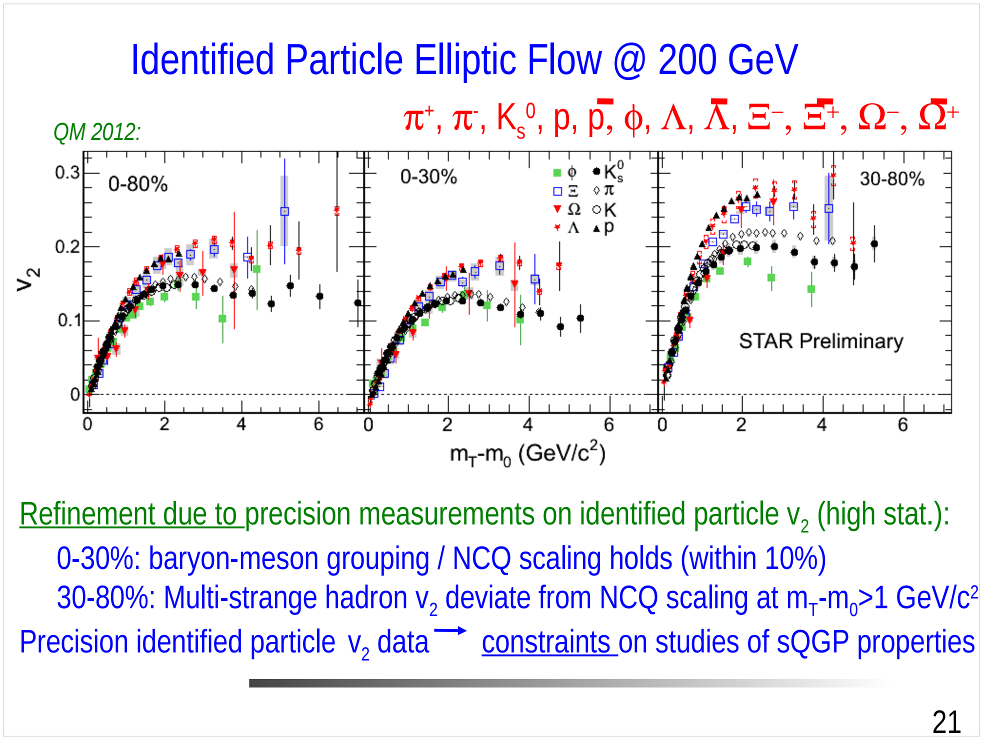
It is established signature of partonic matter formed at Au+Au at RHIC

Dotyczy tego z 2009 z animacji:

(1) Mass separation at low p_T

(2) Light and heavy quarks have similar magnitude of flow

(3) In intermediate p_T: separation between baryon and meson band



Min.bias central 30-80 %

Strong elliptic flow v2 and number of constituent quark scaling found for multi-strange hadrons at RHIC

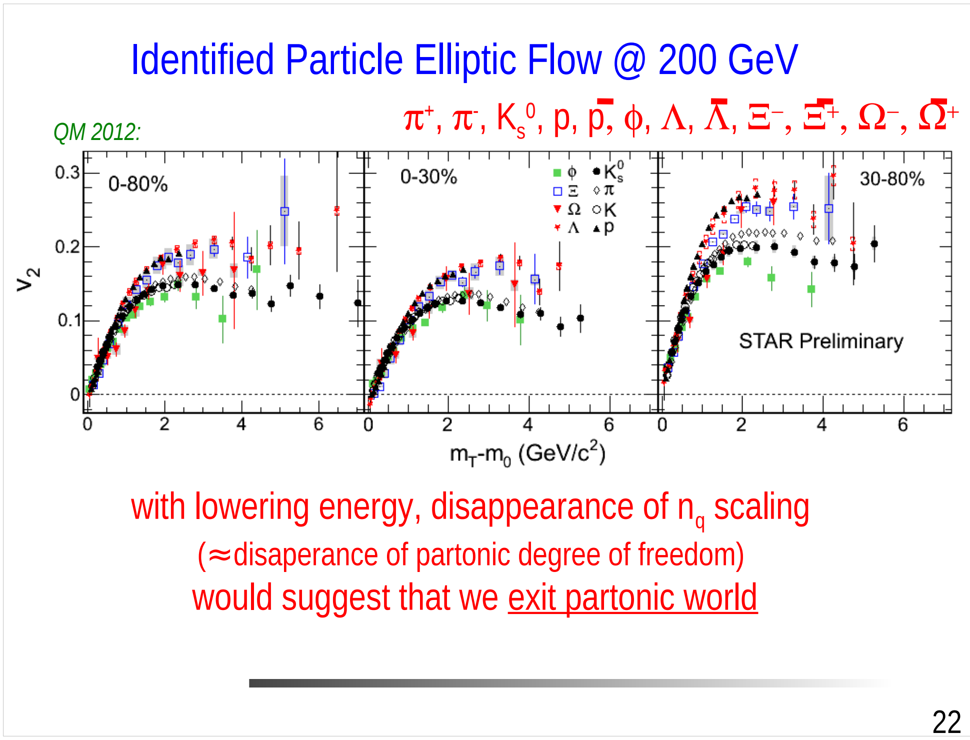
Top energy are clear evidence of partonic collectivity

In MB and centrals – clear meson/baryon grouping and QCQ scaling holds within 10 %

-> suggesting that partonic collectivities dominate the final observed v2

In 30-80 % - baryon/meson grouping starts to collapse , and v2/n_q for multi-strange hadrons (xi and omega) deviates from that of K0 beyond 10-15 %, suggesting smaller contributions from partonic phase to the final collectivity

How this will behave at lower energies ?



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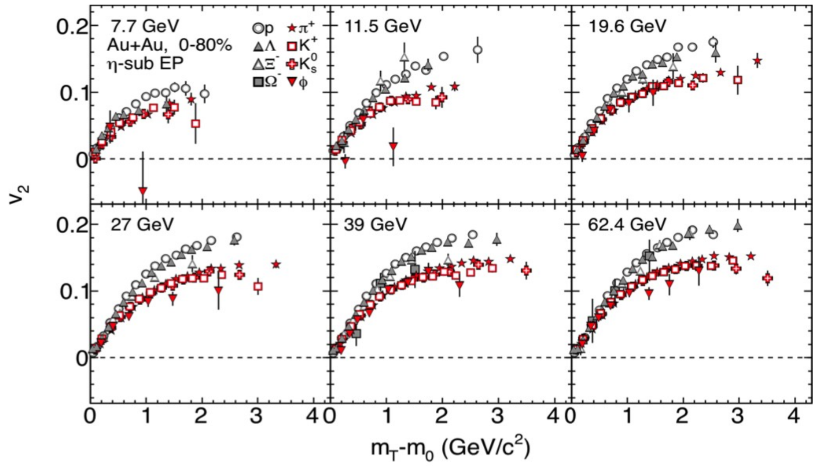
How this will behave at lower energies ?

BES: v_2 of identified particles vs energy

STAR Preliminary

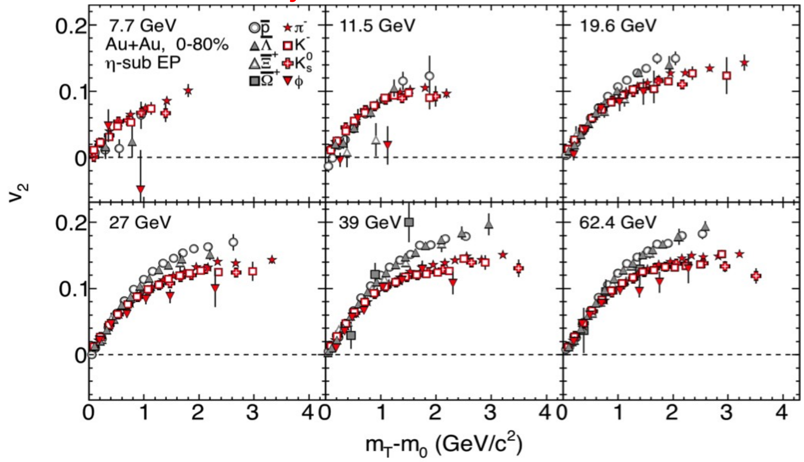


Baryon vs. meson splitting for particles decreases as we go down in $\sqrt{s_{NN}}$

23

BES: v_2 vs energy for ***anti***particles

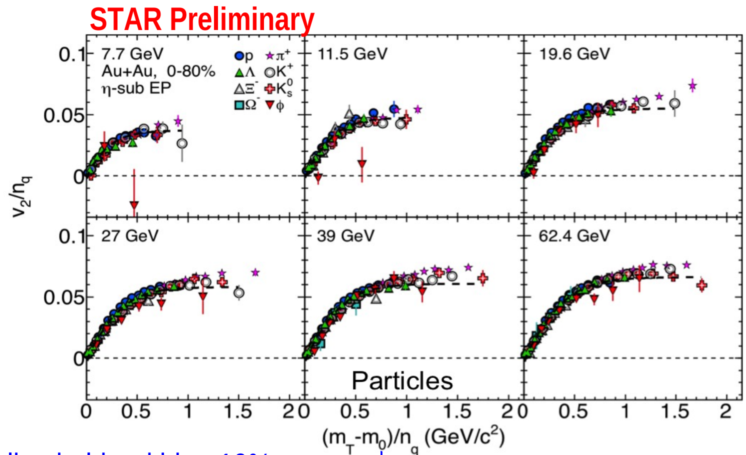
STAR Preliminary



Baryon vs. meson splitting for ***anti***particles disappears at energies ≤11.5 GeV (within errors)

24

BES: n_q scaling with energy - particles



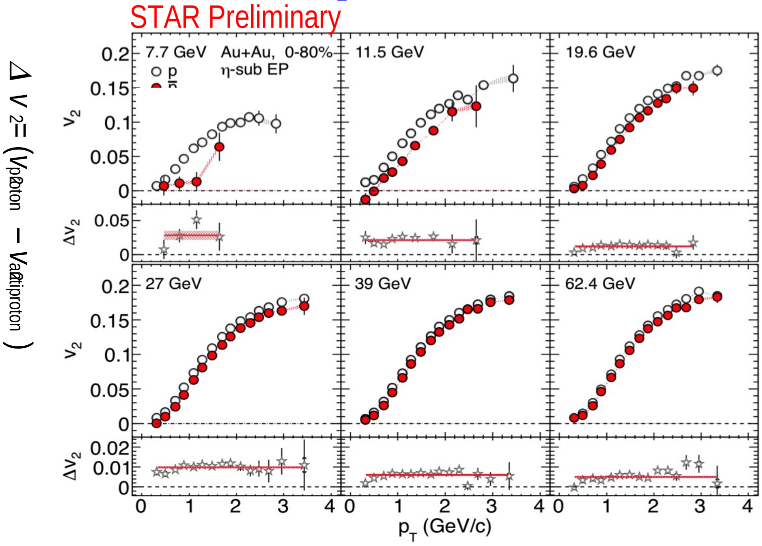
n_q scaling holds within ~10%, except φ

– φ meson becomes outlier at lowest two energies – but large error bars

anti-particles: n_q scaling within ~10%

25

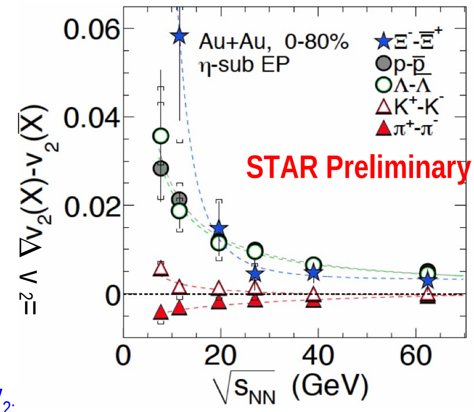
BES: v_2 for p and anti-p



Proton – antiproton difference increases with decreasing energy

(very little p_T dependence)

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



difference between particle and antiparticle is observed -> break down of N_q scaling between particles and *anti*particles at lower energies

$\Delta v_{2:}$

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

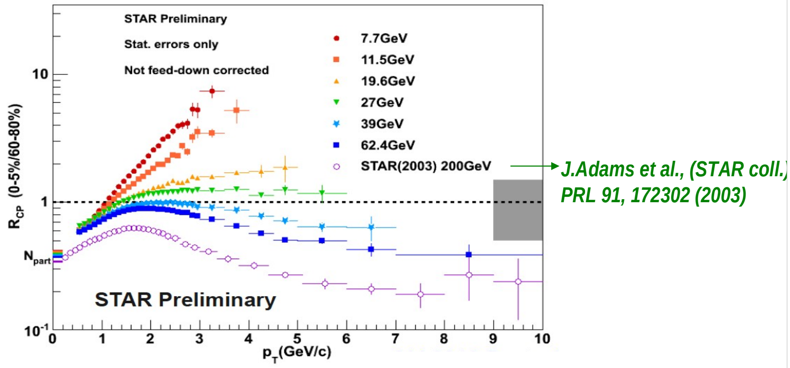
*J. Xu et al., PRC **85**, 041901 (2012)*
*J. Dunlop et al., PRC **84**, 044914 (2011).*

27

Negligible at top RHIC energies

BES: R_{cp} for charged particles

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



R_{CP}>1 for 27 GeV and below - high p_t suppression seen at 200 GeV is gone

28

One of the key QGP signature is suppression of high pt particles due to energy loss from interactions in a color medium.

This is quantified by nuclear modification factor:= ratio of particle yields at central A+A to either p+p (R_AA) or peripheral A+A (R_CP) coll. (where QGP is not expected), scaled by the corresponding number of binary coll. N_bin from MC Glauber model.

R_cp=1 if AA is a superposition of N-N. Deviation will imply contribution from nuclear or medium effects

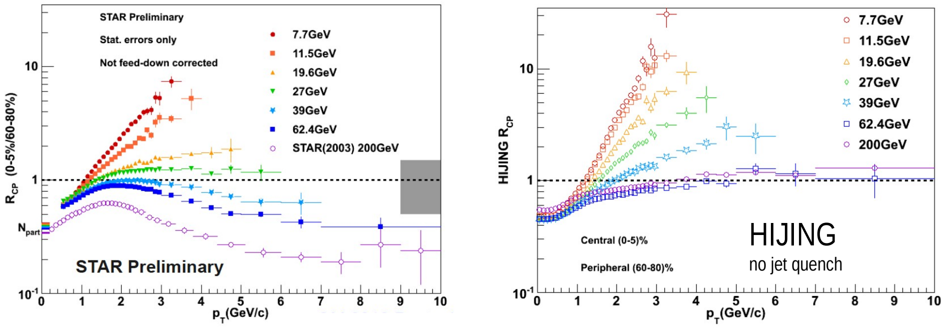
Early results from 200 GeV (puste kolka) at RHIC found clear suppression of high pt particles in R_CP which is atributed to parton energy loss in dense medium.

In the absence of dense medium , there may not be suppression at high pt particles, which can serve as indication of “turn-off” of QGP signatures

Study R_CP evolution with energy … better understanding the nuclear phase diagram …

BES: R_{cp} for charged particles

QM 2012:



HIJING without jet quenching, but including Cronin effect (though k_T broadening) resembles $\sqrt{s_{NN}}$ dependence at low energies

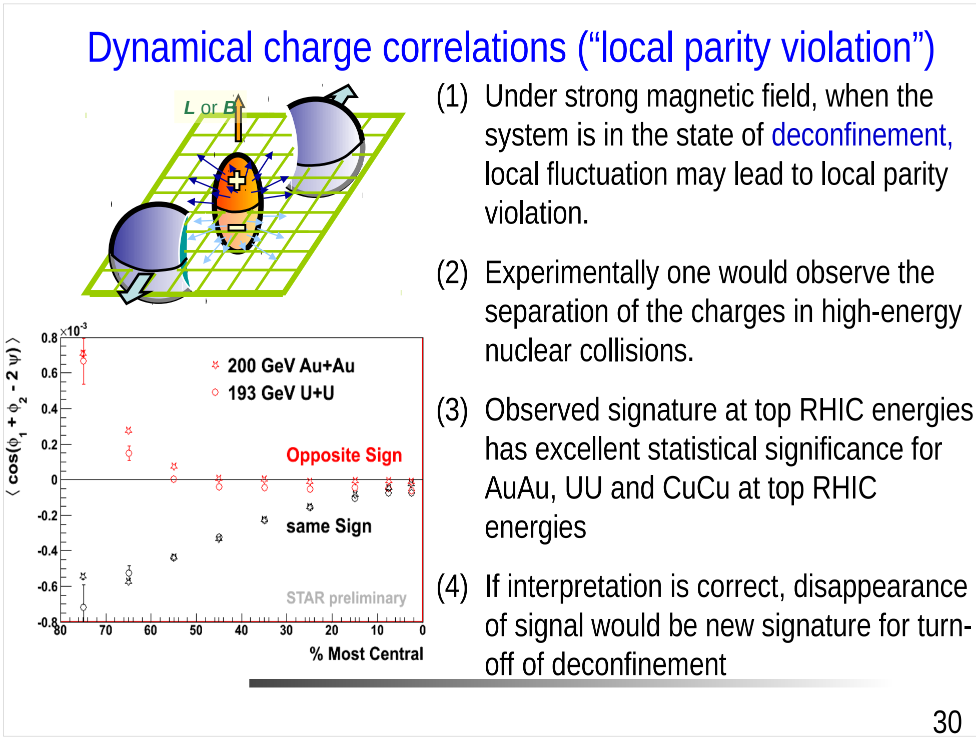
role of Cronin effect under investigation

29

HIJING: R_CP flattens out to 1 at high pt for 62.4 and 200 GeV as expected for jets that do not experience in-medium effects, but at lower energies we see a significant enhancement that is quantitatively very similar to data. This supports that for lower energies the Cronin effect becomes more dominant and makes it more difficult to draw conclusions about magnitude of partonic energy loss

Possible change in QGP opacity cannot be inferred until hard component of spectrum vs. $\sqrt{s_{NN}}$ is fully understood

Opacity – conditions of lacking transparency



In non-central collisions: large angular momentum perp.to RP + large localized B fields + deconfined phase -> strong P violating domains with diff. no. of left & right handed quarks -> preferential emission of like sign particles in the direction of the angular momentum i.e. opposite sides of the RP

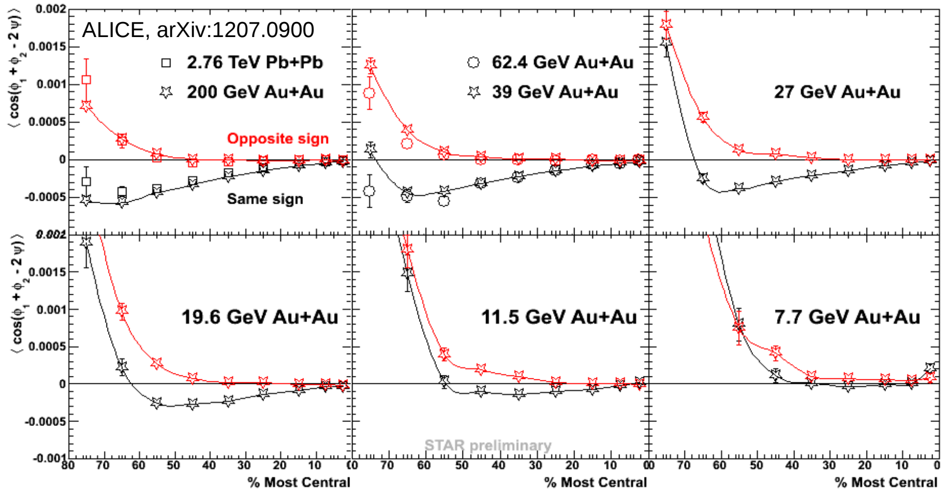
P-even may contain other effects : several investigated (resonances, jets) none result in observed magnitude and centrality dependence of signal

<cos(phi …)> – 3 particle mixed harmonic azimuthal correlator

Do poczatku: difference in correlation between SS and OS charges in HI could be related to local parity violation, if there is econfinement & chiral symm. Restoration.

It is also referred as Chiral Magnetic Effect.

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

31

For comparison, Pb+Pb results from ALICE are shown, consistent with RHIC

Ad #3 (Turn off signatures of QGP):

These observations:

- baryon/meson grouping for *anti*particles stars to collapse at 11.5 GeV
- disappearance of high p_t suppression
- disappearance of charge separation
- break down of N_q scaling between particles and *anti*particles
- local parity violation decreases with decrease of $\sqrt{s_{NN}}$
- …

indicate that hadronic interactions become dominant at lower beam energies the most exciting …

1. Critical Point

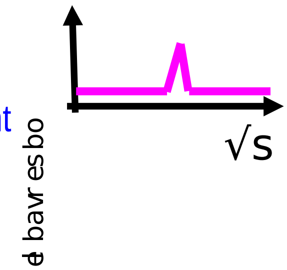
33

CP: Why fluctuations and correlations ?

Theory:

System at the QCD critical point region is expected to show a sharp increase in the correlation length, thus <u>large non-statistical fluctuations</u>

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



Fluctuations <u>maximized</u> at Critical Point

Promising observables:

- Particle ratio fluctuations: K/π, p/π, K/p
- Conserved numbers (B,Q,S) fluctuations
  - higher moments of net-protons and net-charge

34

Lattice & phenomenological calculations suggest that the presence of CP might result in divergences

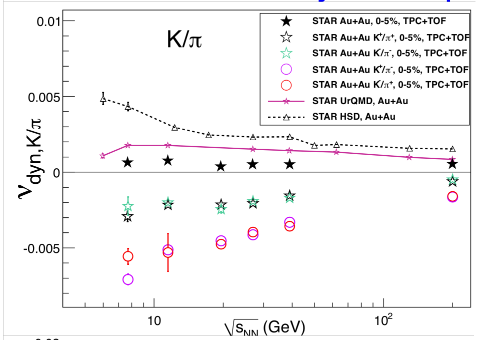
of thermodynamical susceptibilities and corr. length.

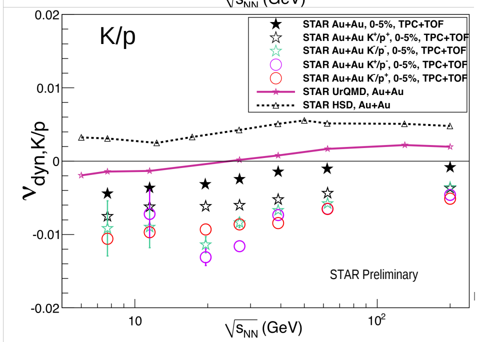
Predictions are that the behavior of fluctuations/correlations in

deconfined phase are different than that in hadron gas ->

search for discontinuities in fluctuations and correlations as function of $\sqrt{s_{NN}}$

event-by-event particle ratio fluctuations

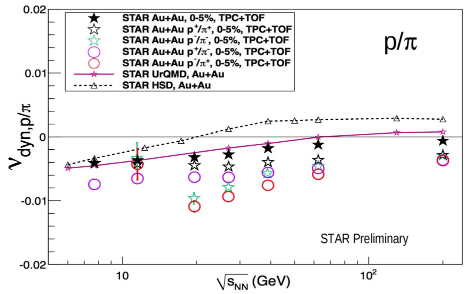




$$\nu_{dyn,K\pi} = \frac{\langle N_K(N_K-1)\rangle}{\langle N_K\rangle^2} + \frac{\langle N_\pi(N_\pi-1)\rangle}{\langle N_\pi\rangle^2} - 2\frac{\langle N_K N_\pi\rangle}{\langle N_K\rangle\langle N_\pi\rangle}$$

$$\sigma_{dyn} = sign(\sigma^2_{data} - \sigma^2_{mixed})\sqrt{|\sigma^2_{data} - \sigma^2_{mixed}|}$$

$$\sigma^2_{dyn} \approx \nu_{dyn}$$



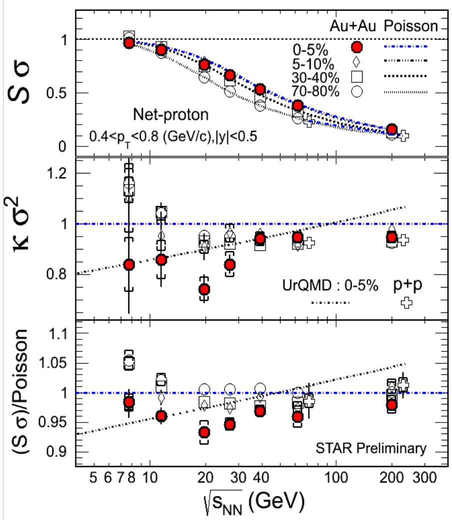
Constant or monotonic trends observed in particle ratio fluctuations with energy

Sensitive to particle number at chemical freeze-out (not at kinetic !)
Sigma dynamics represents dynamic fluctuations with statistical fluctuations removed, it is a measure of the event-by-event fluctuations in K/π ratio: measure K/p ratio e-by-e and study width (sigma) of the resulting distribution.
Fluctuations (in K/pi,p/pi, ..) are expected to be maximized at CP.

TPC+TOF: piony: 0.2-1.4; protony: 0.4-1.8, kaony: 0.2 – 1.4, includes systematic and statistical error from e contamination
Pion contamination of kaon < 3% (using TPC and TOF)

Higher moments: net-protons

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



- Higher moments of conserved quantities measure non-Gaussian nature of fluctuations and are more sensitive (than variance σ^2) to CP induced fluctuations (to correlation length)
- Non-monotonic behavior of high moments distributions vs energy are expected to signal CP

- Similar behavior at 39, 62 and 200 GeV
- Deviations below Poisson baseline in 0-5% central collisions
- Above Poisson baseline in peripheral collisions below 19.6 GeV
- UrQMD shows monotonic behavior vs √s
- Data points below 19.6 GeV have large uncertainties -> prevents conclusions (presently) → for BES phase-II

36

Ideal probe

We present S*sigma and k* sigma**2

Also plotted are Poisson expectation lines (=1) in the two upper panels and the ratio of S*sigma over Poisson expectations is shown in the bottom panel

Shown centrality and energy dependence, 0.4<pt<0.8 and -0.5<y<0.5 – bo najczystrza probka tam

UrQMD included to show non-CP effects, like baryon number conservation and hadron scattering

Cumulants are related to susceptibilities – connection to Lattice !

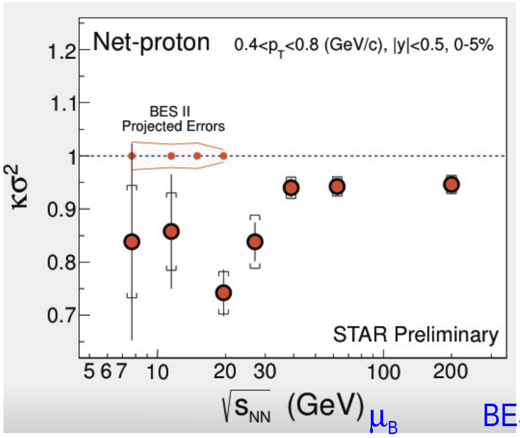
Note, that due to dynamical evolution of the system, the signature observed could be smaller then the real one

Takze analizowalismy 6-ty cumulant: C6/C2, tam przewiduje sie zmane znaku

I cos widac, tzn nie ma zmiany znaku w centralnych (0-40%) ale jest w preryferycznych (40-80 %) przy ~ 20 GeV

(albo mniej niz to) – tylko za wielkie bledy na konkluzje

Current and projected uncertainties on net-proton kurtosis x variance



BES phase II:

	μ_B	BES I	BES II
19.6	206	36 (M)	400 (M)
15	250		100 (M)

Ad #1 (Critical Point):

Deviations of moment products in central Au+Au collisions from Poisson expectations are observed

Uncertainties of current results on higher moments (particularly at 19.6 GeV and bellow) prevents us from drawing conclusions

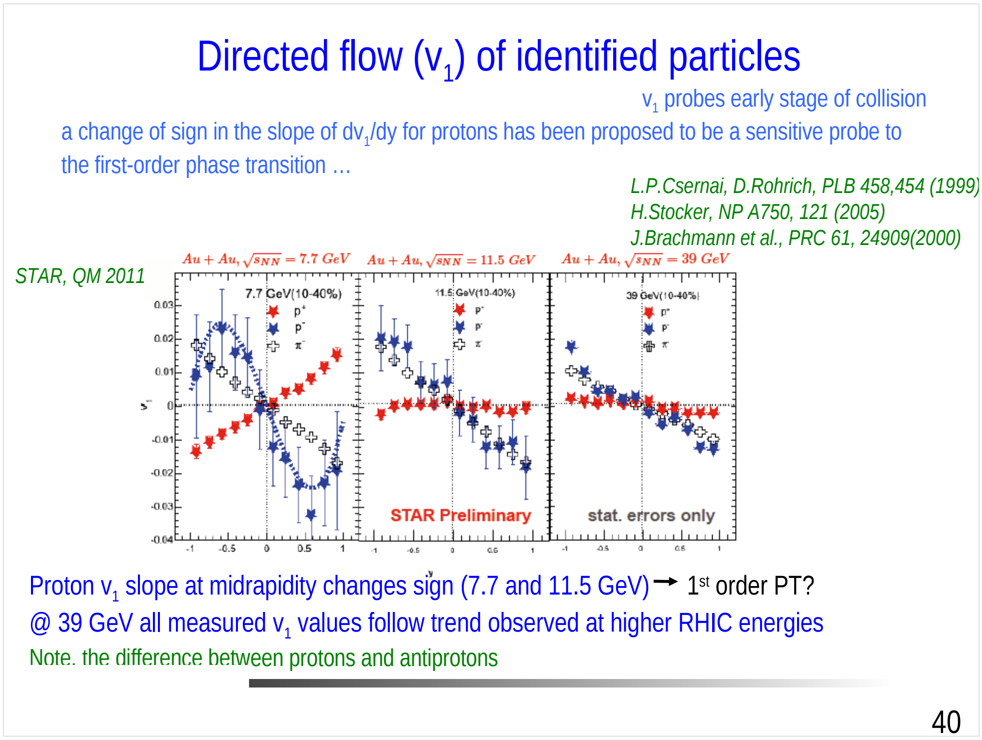
38

the equivalent of CP … (!)

2. Phase transition

can we demonstrate the softening of EOS ?

39



v1=<cos(Phi-psi1)> where Phi – azimuthal angle of particle and psi – orientation of 1-order RP .

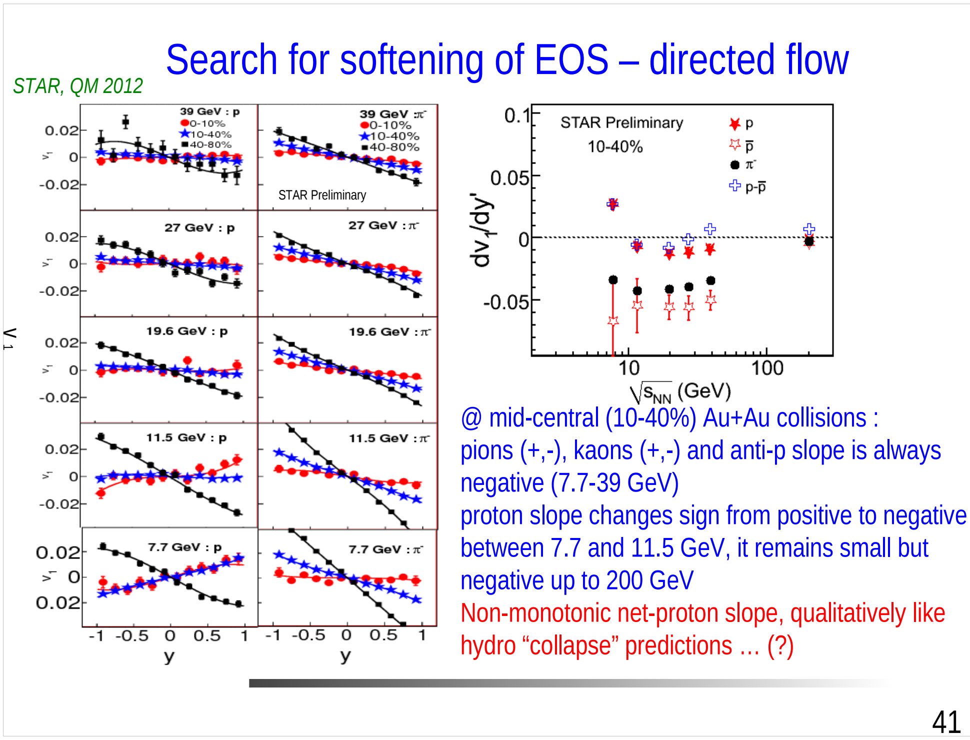
Rapidity dependence of particle v1 often quantified as the slope parameter dv1/dy' (y'= y/y_beam) vs. coll. energy in Au+Au

At lower beam energies (AGS and below) proton slope is positive at mid rapidity (that of pion is negative), which is well described by most of the transport and hydro models.

At higher beam energies proton v1 slope either flat or is negative (like pions).

Ideal hydro model as well as transport models fail to predict such exotic proton flow (anti flow).

However, hydro models with first order phase transition to QGP do predict the negative flow of protons.



Left: systematic studies in all BES energies here

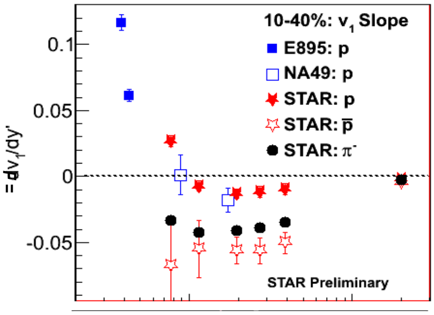
A phase transition would lead to a local minimum in directed flow as f(E)

Right: (tekst na slide’zie dotyczy rysunku po prawej stronie) – centrality bin 10-40 %

p-p_bar = “net – protons” = we take the difference in the slope parameters between protons and anti-protons weighted by their relative production yields, i.e. “net-protons v1 slope and it is plotted with crosses (open)_ on the next slide

EOS softening ? – comparison with transport models

F = net-protons ($p-\bar{p}$) v1 slope: dv_1/dy



- Protons v_1 consistent with "collapse" hydro predictions
-Net-protons v_1 changes sign twice in the measured energy region, and shows a minimum around 11.5-19.6 GeV
- Physics sources are under investigation

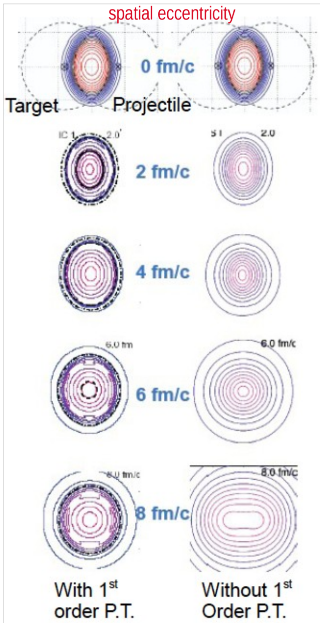
<u>Theory:</u> more input
<u>Experiment</u>: BES Phase II – more statistics, centrality dependence, …

42

Gorny rysunek – to samo co poprzednio tylko dodane E895 i NA49

Non-monotonic net-proton v_1 slope, qualitatively like hydro "collapse" prediction.

Transport models UrQMD & AMPT cannot explain even the sign of the net-proton v_1.



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

azimuthal – HBT

provides info about shape of particle emitting source

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 (softening ?) -> 1st order phase transition

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

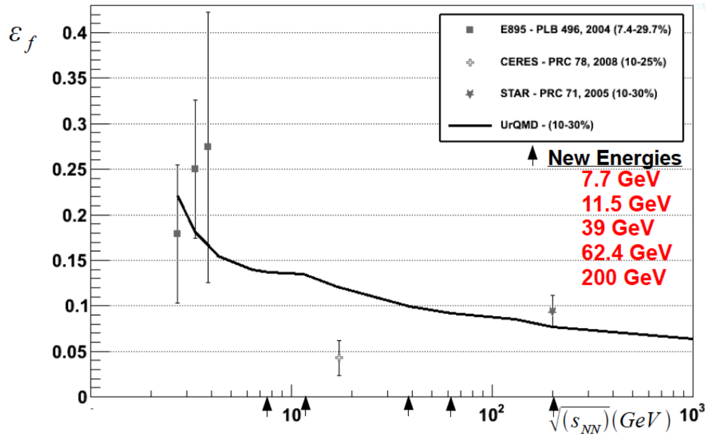
43

In initial state – participant zone = elipsoid extended out-of-plane in non-central coll. (initial eccentricity in the transverse lane)

Matter being more compressed in the reaction plane experience larger gradient pressure in pane compare to out-of plane

Preferential in-plane expansion -> more circular freeze-out shape

Measurements prior to BES



possible minimum follow by the rise ?

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

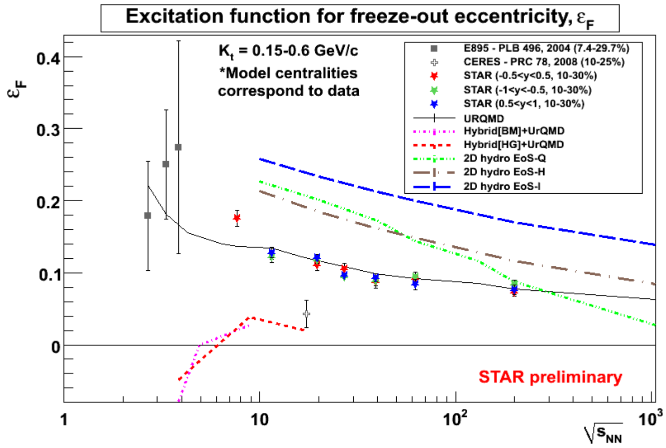
M.Lisa et al., New J.Phys. 13 (2011)

44

A pressure gradient vanish in a mixed phase, the shape would not change during this period of the lifetime

Excitation function (BES points included)

Azimuthal HBT for freeze-out eccentricity



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

consistent with monotonically decreasing shape

45

•Evolution of the initial shape depends on the pressure anisotropy.

- Freeze-out eccentricity sensitive to the 1st order phase transition.

Ad #2 (1st order Phase Transition):

Net-protons v_1 changes sign twice in the measured energy region, and shows a minimum around 11.5-19.6 GeV

If the 1st order phase transition takes place at all - that would be probably at lower end of the energy spectrum

So, what have we learned from BES Phase-I

STAR and RHIC excellent performance down to 7.7 GeV

BES Phase-I data sets (39, 27, 19.6, 11.5 and 7.7 GeV) cover important region of QCD phase diagram with sufficient statistics for initial survey

but it is rather coarse coverage

Several key sQGP signatures NOT seen at low energies:

- $v_2(m_T - m_0)$ exhibits well-known baryon-meson splitting, but splitting is smaller at low $\sqrt{s_{NN}}$
- 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 $\sqrt{s_{NN}}$: softening of EOS ?
- fluctuations are constant or monotonic with energy from 7.7 to 200 GeV
- higher moments of net-protons deviates from Poisson baseline
- freeze-out eccentricity (aHBT) monotonically decreases with energy

RHIC's energy range is special …

RICH (BES): rapid changes occur in a number of signatures for energies up to approximately 30 GeV, while remaining surprisingly stable beyond that over the two orders of magnitude to the LHC

→ so, did we answer our "three" questions ?

1. turn-off of QGP signatures ? **clear evidence** no need to search above 19.6
2. Evidence of the first order phase transition ? **strong hints** lower end of range
3. Search for the critical point ? **hints** **MORE** statistics !!!

48

1.Key QGP signatures dispaear, no need to search above 19.6

2.2 low energy performqnce critical (1st oreder from v1 between 7 and 11 ?)_3. for CP – additional question: do we need finer steps ?

mB (19.6)= 185 MeV

-> there is more than 100 MeV gap in mu_B between 11.7 and 19.6

mB (11.7) = 320 MeV

mB (7.7) = 400 MeV

mB (27) = 140 MeV

mB(39) = 110 MeV

E-cooling: increase in luminosity by factor 3-5 at 7.7

And ~10 around 20 GeV

Another possible improvement by operating with longer bunches

-> overall improvement ~ 10 fold

Answering remaining questions - BES II

$\sqrt{S_{NN}}$ (GeV)	19.6	15	11.5	7.7
μ_B (GeV)	205	250	315	420
BES I (MEvts)	36	---	11.7	4.3
→ BES II (MEvts)	**400**	**100**	**120**	**80**

STAR will have BES Phase-II program of precision measurements to map out QCP phase structure with order of magnitude increase in data samples

Good chance for Au Au at $\sqrt{s_{NN}}$ = 15 GeV in 2013.

49

Pierwsze dwa:19 – 15 -> CP

Drugie dwa: 11.5-7.7 -> onset of deconfinement, 1st order PT

Finner steps ?

HIGH STATISTICS

But that's a lot of data… at current rates, this would take ~70 weeks of RHIC operations!

Isn't there a better way? ➔ Yes! We can cool the beams!

mB (19.6)= 185 MeV

-> there is more than 100 MeV gap in mu_B between 11.7 and 19.6

mB (11.7) = 320 MeV

mB (7.7) = 400 MeV

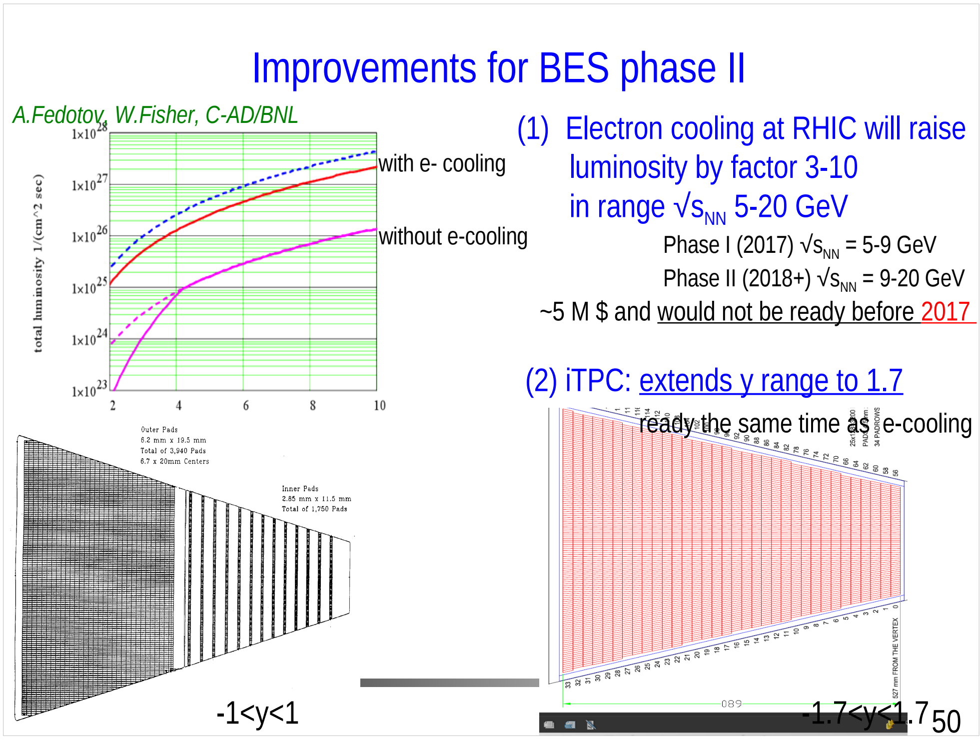
mB (27) = 140 MeV

mB(39) = 110 MeV

E-cooling: increase in luminosity by factor 3-5 at 7.7

And ~10 around 20 GeV

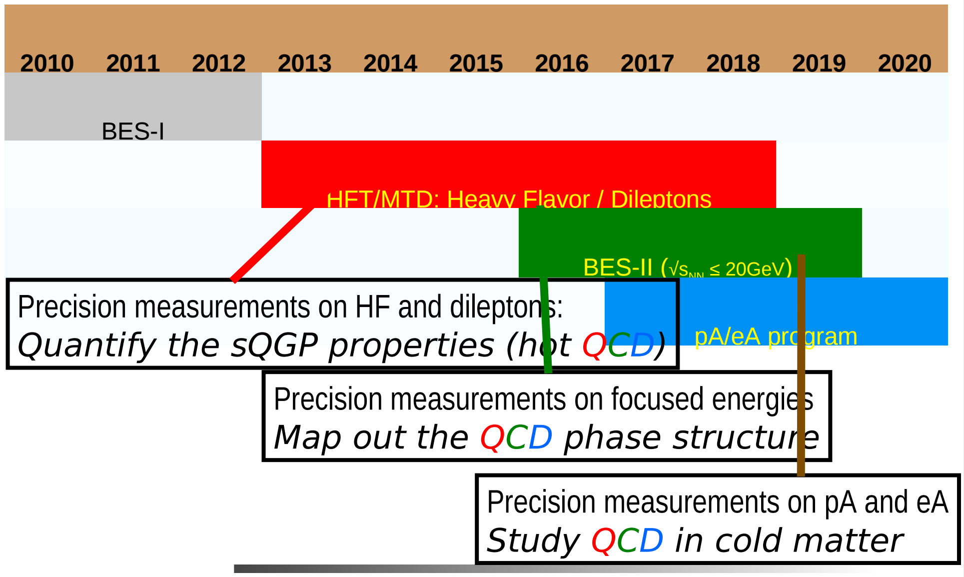
Another possible improvement by operating with longer bunches



Without e-colling – BES II would take 70 weeks

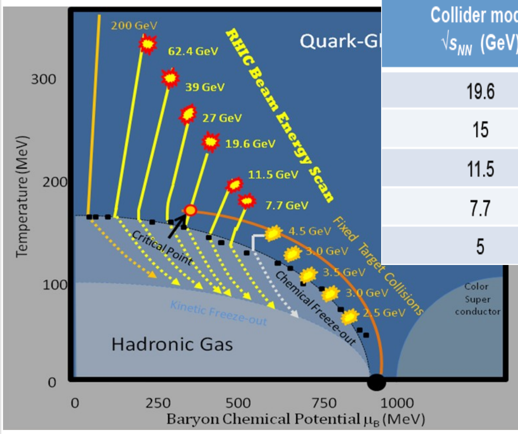
With e-cooling 17 weeks (allowing one week between energies)

but, BES Phase-II will **not** happen very soon …



51

μ_B extended range in STAR due to fixed target program

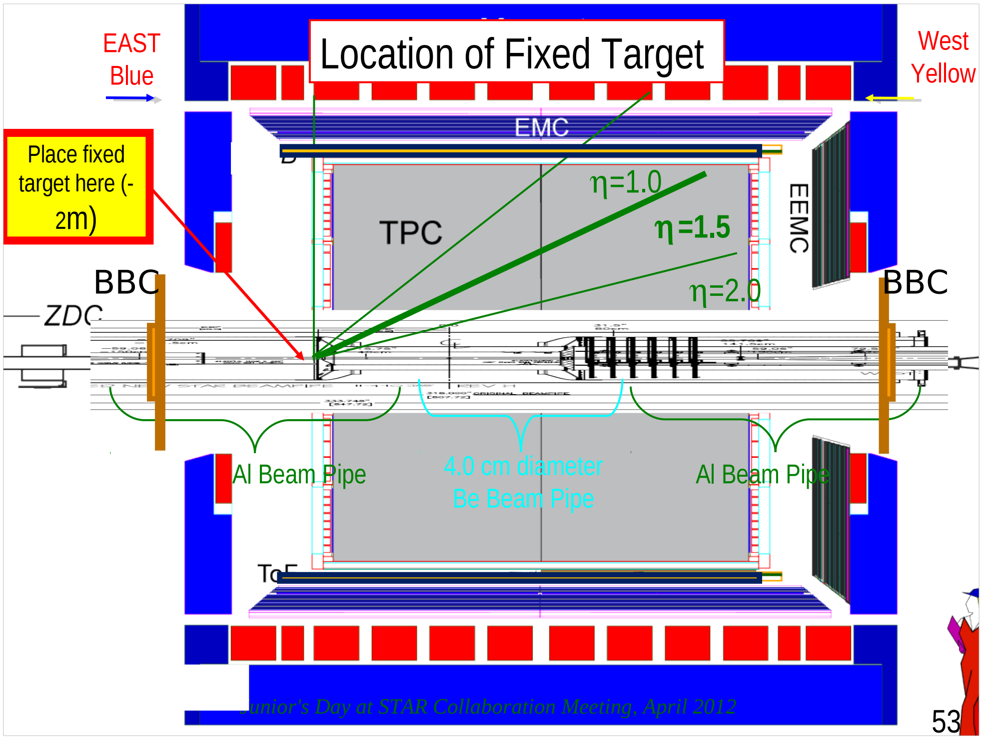


Collider mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode μ_B (MeV)
19.6	4.5	585
15	4.0	625
11.5	3.5	670
7.7	3.0	720
5	2.5	775

Fixed-target running allows much higher rates without e-cooling at lower energies

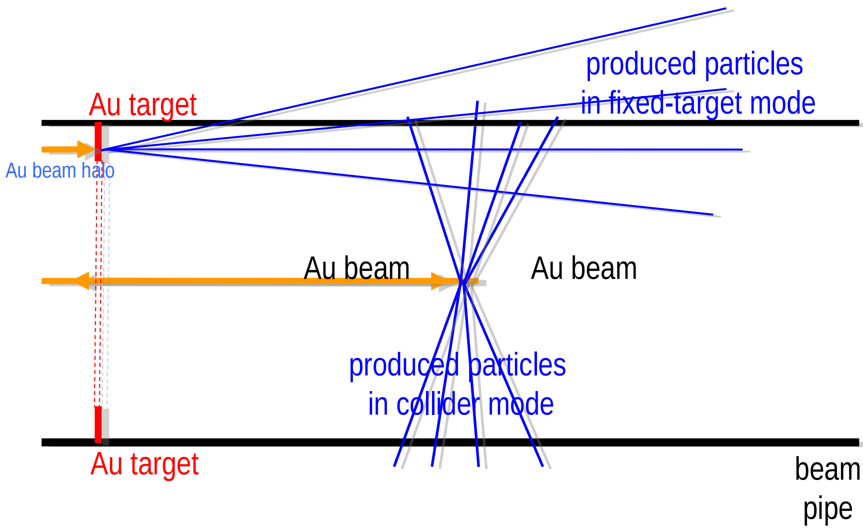
Minimal impact on concurrent operation

52



Location of Fixed Target
EAST
Blue
West
Yellow
Place fixed target here (-2m)
EMC
TPC
EEMC
η=1.0
η=1.5
η=2.0
BBC
BBC
ZDC
Al Beam Pipe
4.0 cm diameter
Be Beam Pipe
Al Beam Pipe
ToF
Junior's Day at STAR Collaboration Meeting, April 2012
53

Concurrent running in STAR



fixed-target events taken while waiting for collider mode collisions

54

Fixed-target

we already have experience with running STAR in the fixed-target mode (!) and with analyzing data

STAR capabilities

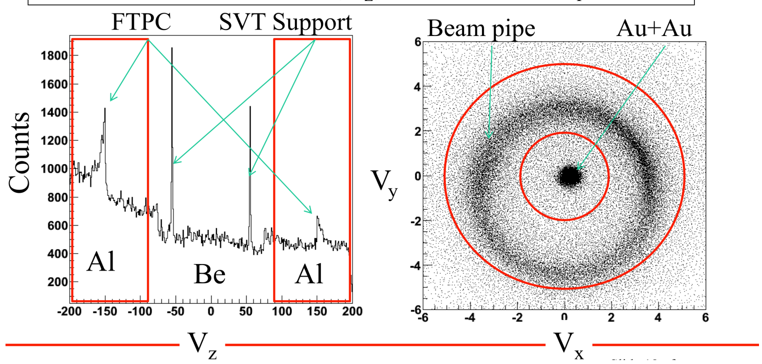
55

Data driven performance study

Au+Al at 3.85 GeV/c (from data set Au+Au at 7.7 GeV) – Samantha Brovko/UC Davis

Samantha's studies: Acceptance, PID, Spectra, vertexing, etc

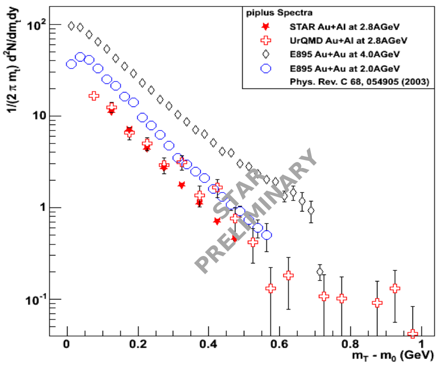
"7.7 GeV" Data set:
Select Events with $100 < |V_z| < 200$ and $2 < V_r < 5$ cm

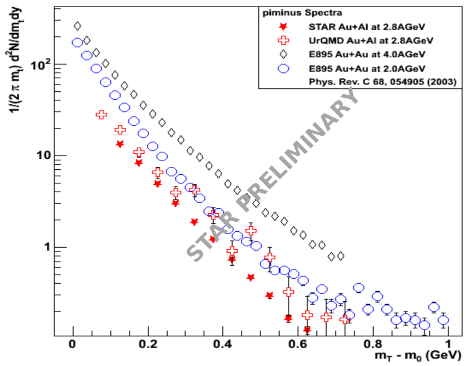


Remember, the BES trigger was designed to eliminate triggers like Au+Al events
BBC coincident should not allow for it

Au+Al (Au of 3.85 GeV on beam-pipe) -> $\sqrt{s}_{Fixed\text{-}Target}$ =2.98 GeV

2.8 AGeV Au+Al: Spectra π^+ and π^-





- No efficiency or acceptance corrections
  - Currently in progress
- Comparison to UrQMD suggests high efficiency for $\pi^{+/-}$

Sam Brovko

needs embedding for fixed target

57

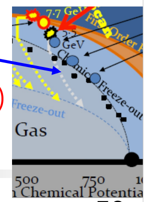
Fixed target at STAR

STAR will have adequate coverage (from mid-rapidity to target rapidity) in fixed-target mode, which is sufficient for some BES studies (detailed analysis of limitations in progress)

Main detectors TPC and TOF tested, work in progress on EEMC/BEMC, and trigger
Tracking, vertexing, PID reasonable, may be improved with optimization

An internal fixed target can be used to take collisions with beam halo at injection energy, which will provide collisions at approximately $\sqrt{s_{NN}}$ of 5 GeV (data point missing from existing BES data)

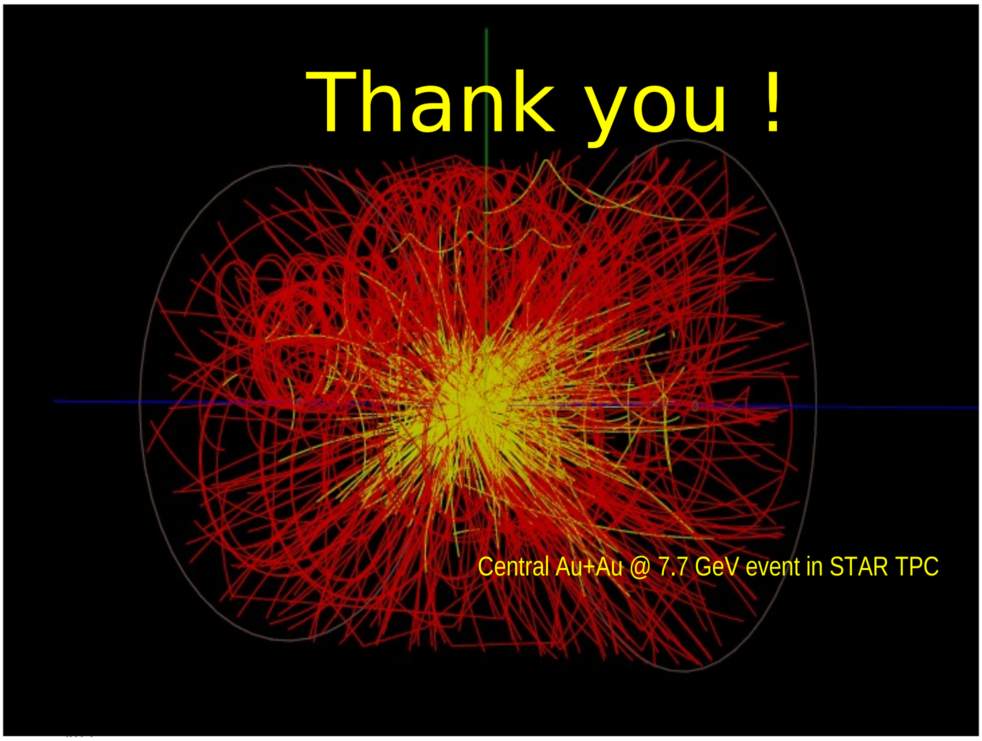
If successful – this may open a way for fixed target runs with other beams used in BES program in collider mode experiments ($\sqrt{s_{NN}}$= 3.5 and 3 GeV, μ_B up to 800 MeV)



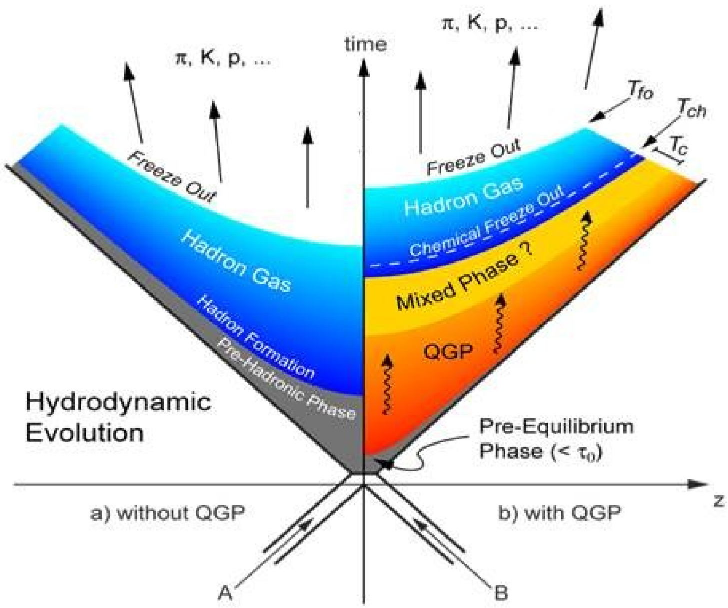
BES: analysis focused on evolution of trends with $\sqrt{s_{NN}}$ (not a single energy results)
with fixed target runs: $0 < \mu_B < \sim 800$ MeV !

58

Altough STAR was not optimized for fixed target experiment


Thank you !
Central Au+Au @ 7.7 GeV event in STAR TPC

Hadronization – two scenarios..

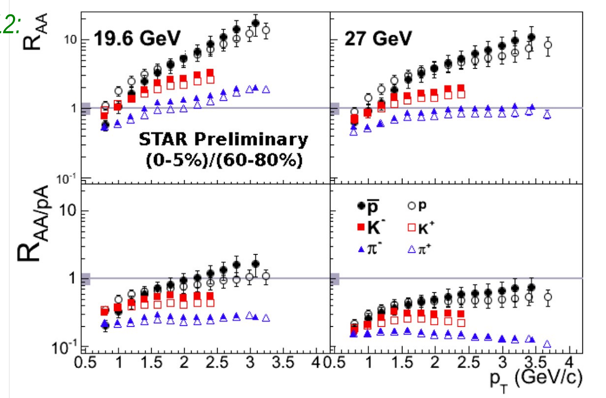


impact of Cronin effect on nuclear modification factor …

(a qualitative illustration)

Particle ratios scaled by p+p(R_{AA}) and p+W ($R_{AA/pA}$):

QM 2012:



p+p, p+W data (Fermilab): D.Antreasyan et al., Phys.Rev.D19, 764 (1979)

Cronin effect leads to apparent enhancement of R_{AA} at high pt

Similar effect on nuclear modification factor as lack of QGP energy loss

Work in progress

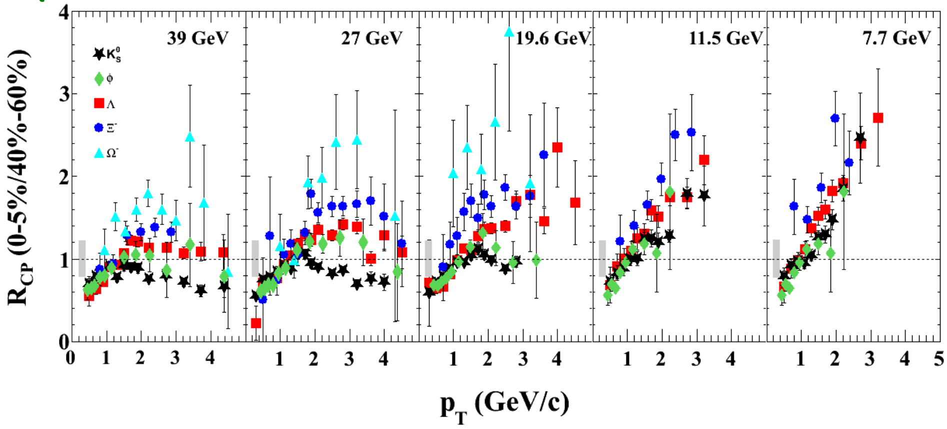
61

The efficiency corrected yields scaled using p+p(R_AA) or p+W(R_AA/pA)

Difficult to distinguish one from another

R_{CP} of various strange hadrons

QM 2012 :



Baryon-meson splitting reduces with decrease of energy and at 7.7 is gone,
Indicating decreasing partonic effects at lower energies
For $K^0_{pt>2\ GeV/c}$: R_{CP}<1 for $\sqrt{s_{NN}}$> 19 GeV and >1 for $\sqrt{s_{NN}}$<11.5 GeV

62

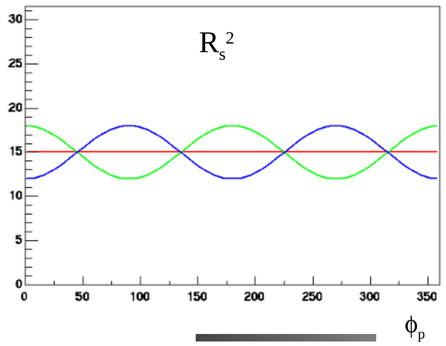
General comm: strangeness always interesting – originally enhancement suggested as a signature of QGP

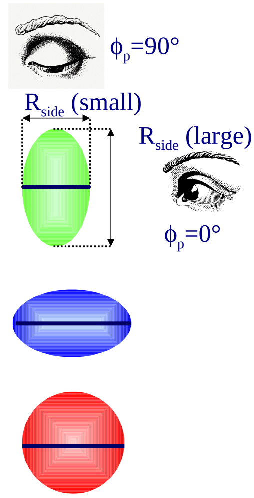
Cold Nuclear Effects – mainly Cronin starts to take over at 11.5 and 7.7 GeV, and enhances hadrons' yields at mi- pt

HBT relative to reaction plane

- for out-of-plane-extended source, expect
  - large R_{side} at 0°
  - small R_{side} at 90°

  } 2^{nd}-order oscillation

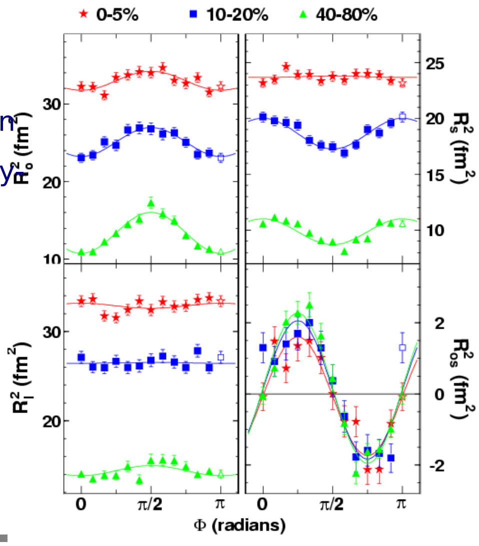




asHBT at 200 GeV in STAR – R(Φ) vs centrality

12 (!) Φ-bins b/t 0-180˚
(k_T-integrated)

- clear oscillations observed in transverse radii of symmetry allowed type
- centrality dependence reasonable



Computing Fourier Coefficients

Fourier coefficients computed from radii:

$$R^2_{0,i} = \frac{1}{N_{bins}} \sum_{j=1}^{N_{bins}} R_i^2(\Phi_j) \qquad i = o, s, l, os$$

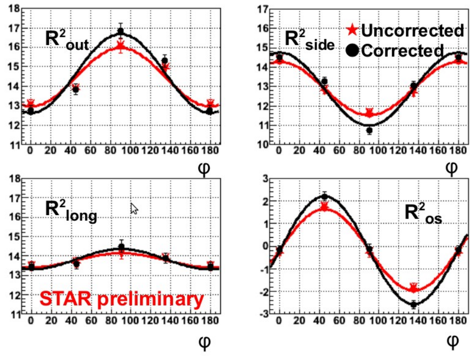
$$R^2_{2,i} = \frac{1}{N_{bins}} \sum_{j=1}^{N_{bins}} R_i^2(\Phi_j)\cos(2\Phi_j) \qquad i = o, s, l$$

$$R^2_{2,i} = \frac{1}{N_{bins}} \sum_{j=1}^{N_{bins}} R_i^2(\Phi_j)\sin(2\Phi_j) \qquad i = os$$

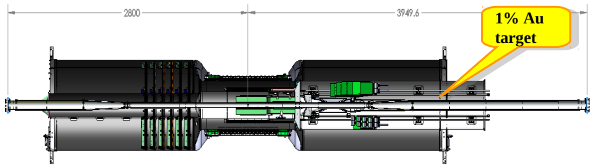
$$\varepsilon_F = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2} \approx 2\frac{R^2_{2,s}}{R^2_{0,s}}$$

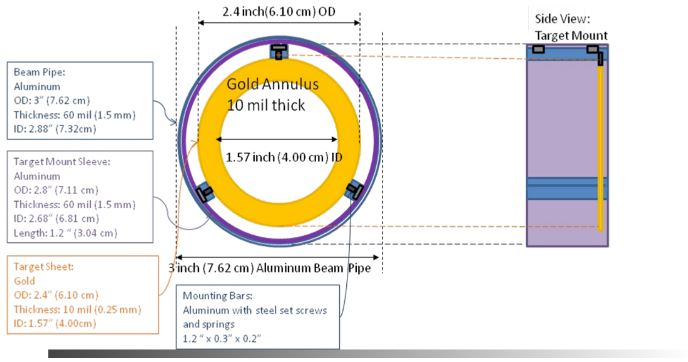
Reference: Lisa, Retiere, *Phys. Rev. C*, 70, 044907

Au+Au 200 GeV
Oscillations for 20-30% Centrality
and K_t = 0.35-0.60 GeV/c



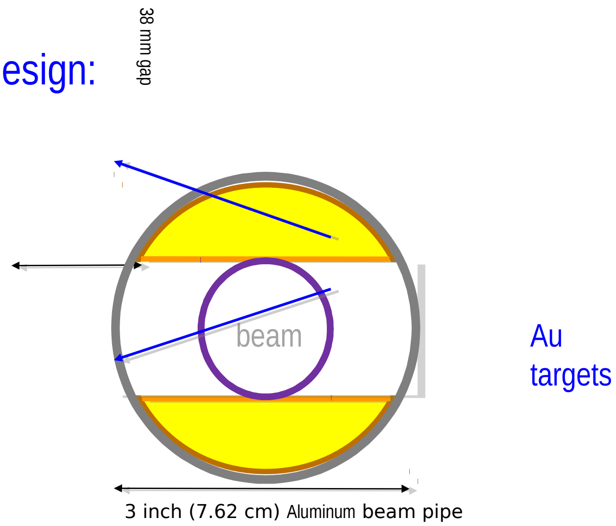
On much faster scale: Fixed target in STAR





66

the real design:



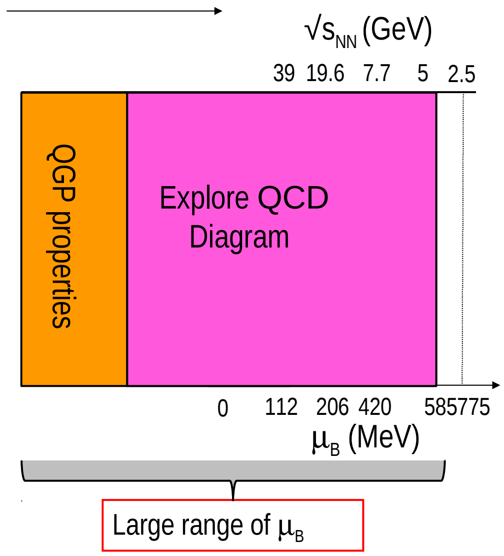
because kicker magnet, used to dump the beam, works in horizontal plane

67

Kicker magnet (responsible for beam dump) works in horizontal plane

So, t avoid beam dump on fixed target – those areas (in horizontal direction: left &right) left free

STAR Beam Energy Scan in STAR is in VERY good shape !



The next 5–10 years of the US relativistic heavy-ion program will deliver:

- a beam-energy scan program to establish the properties and location of the QCD critical point.
- the quantitive determination of the transport coefficients of the Quark Gluon Plasma, such as the temperature dependent shear-viscosity to entropy-density ratio $\eta/s(T)$, and the energy loss transport coefficients $\hat{q}$ and $\hat{e}$.
- a jet physics program to study parton energy loss and the quasi-particle nature of the QGP.
- a heavy-flavor physics program to probe the nature of the surprisingly strong interactions of heavy quarks with the surrounding medium
- a systematic forward physics program to study the nature of gluon saturation and establish the foundation for the future Electron Ion Collider research program and facility.

from Executive Summary of White Paper, Oct.24,2012