Heavy ion collisions at lower energies: challenges and opportunities

Beam Energy Scan (BES I and II) from RHIC

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Outline:

- **Introduction and Motivation**
- **Results from BES I**
- **Future perspectives with BES II**
- **Summary**

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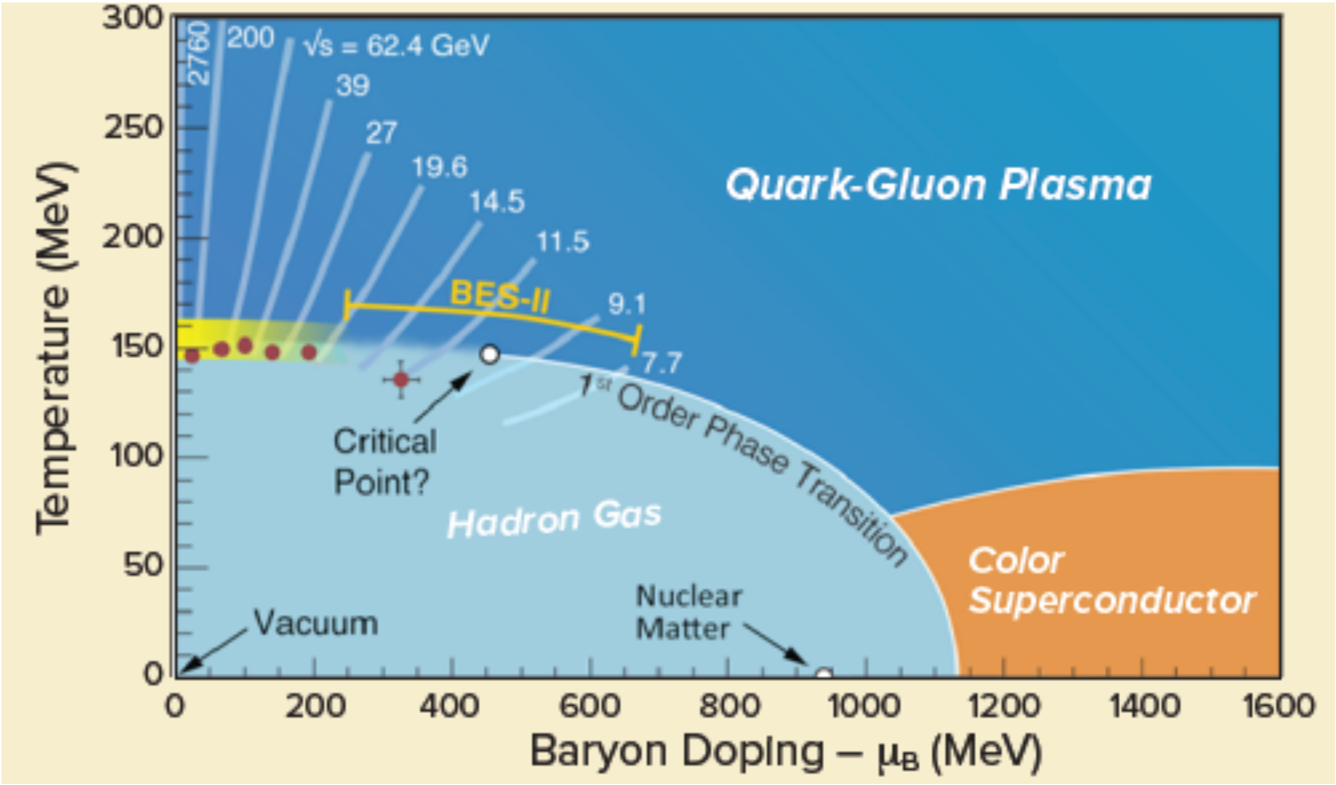
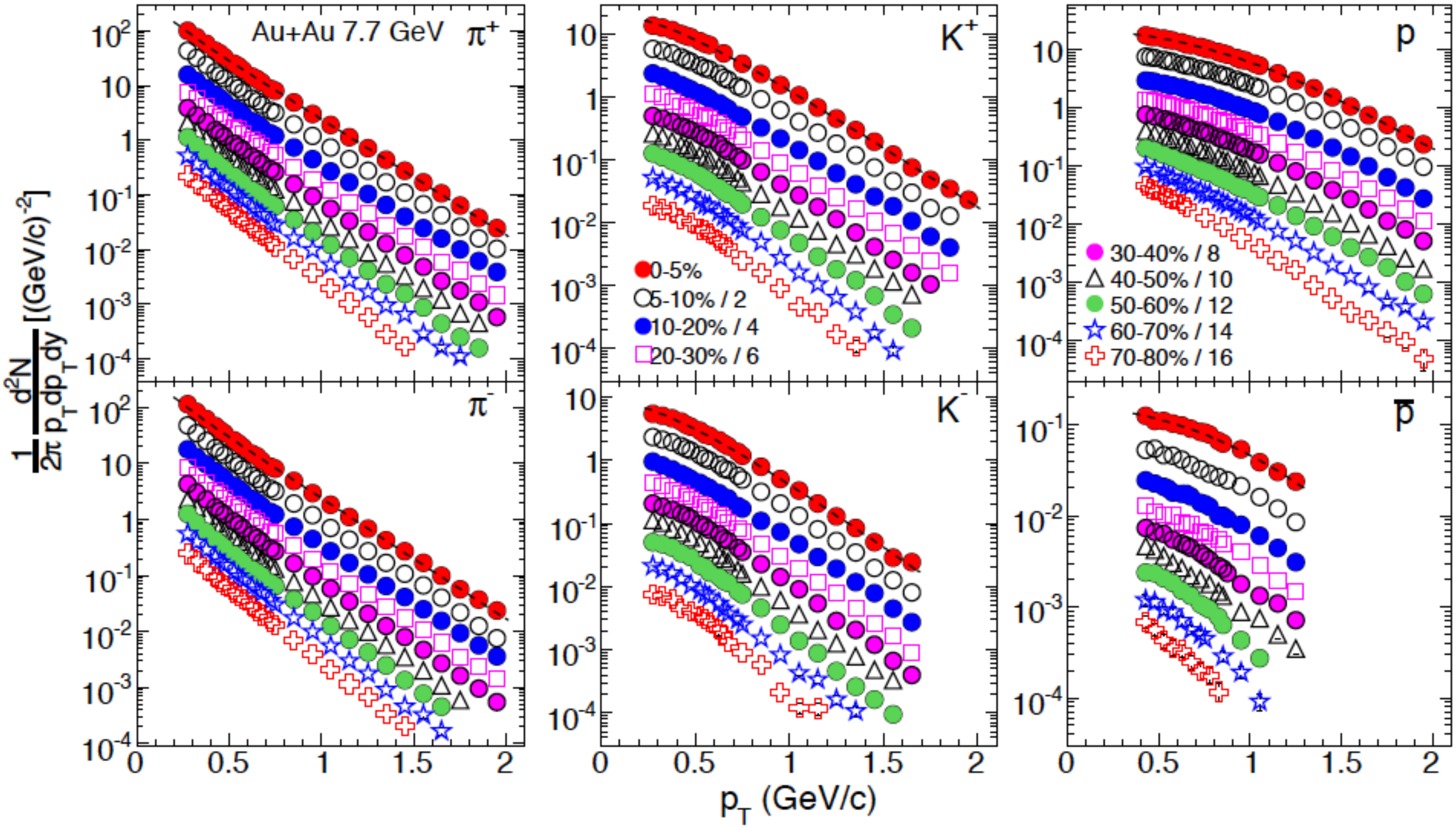
Map out the phase diagram



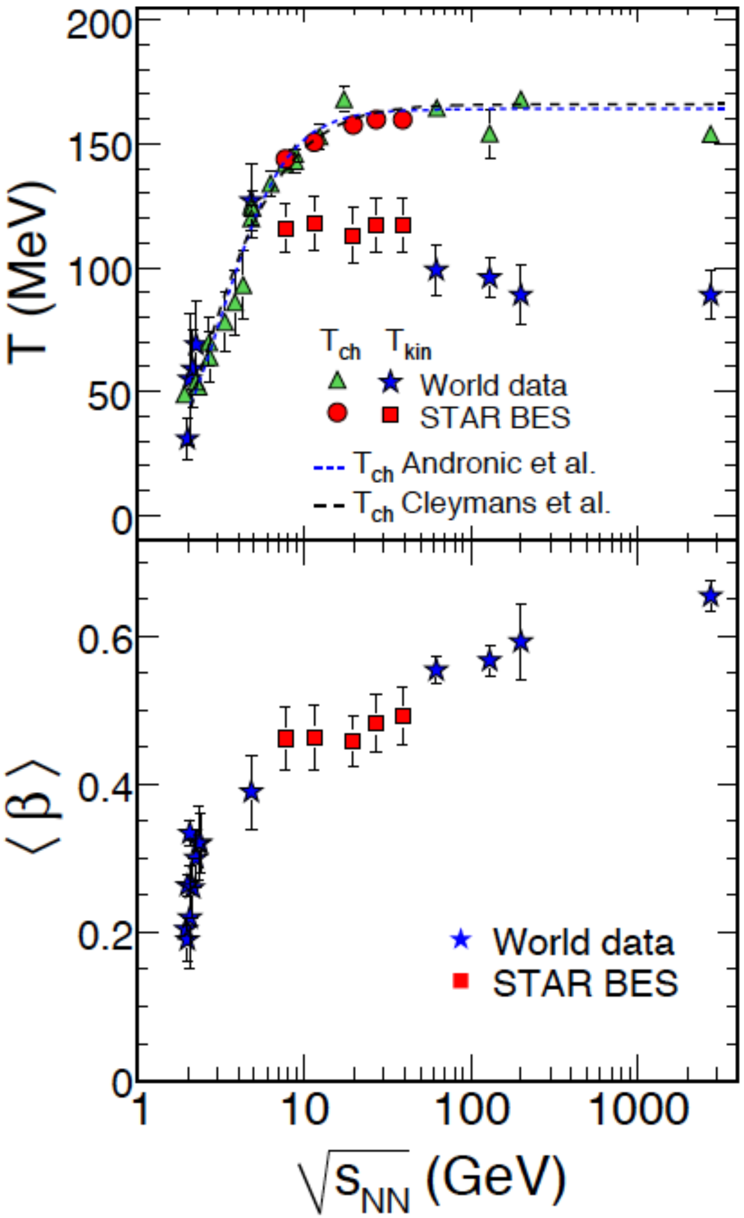
- disappearance of QGP signatures (QGP turn off)
- first order phase transition
- critical point
- chiral symmetry restoration (not covered)

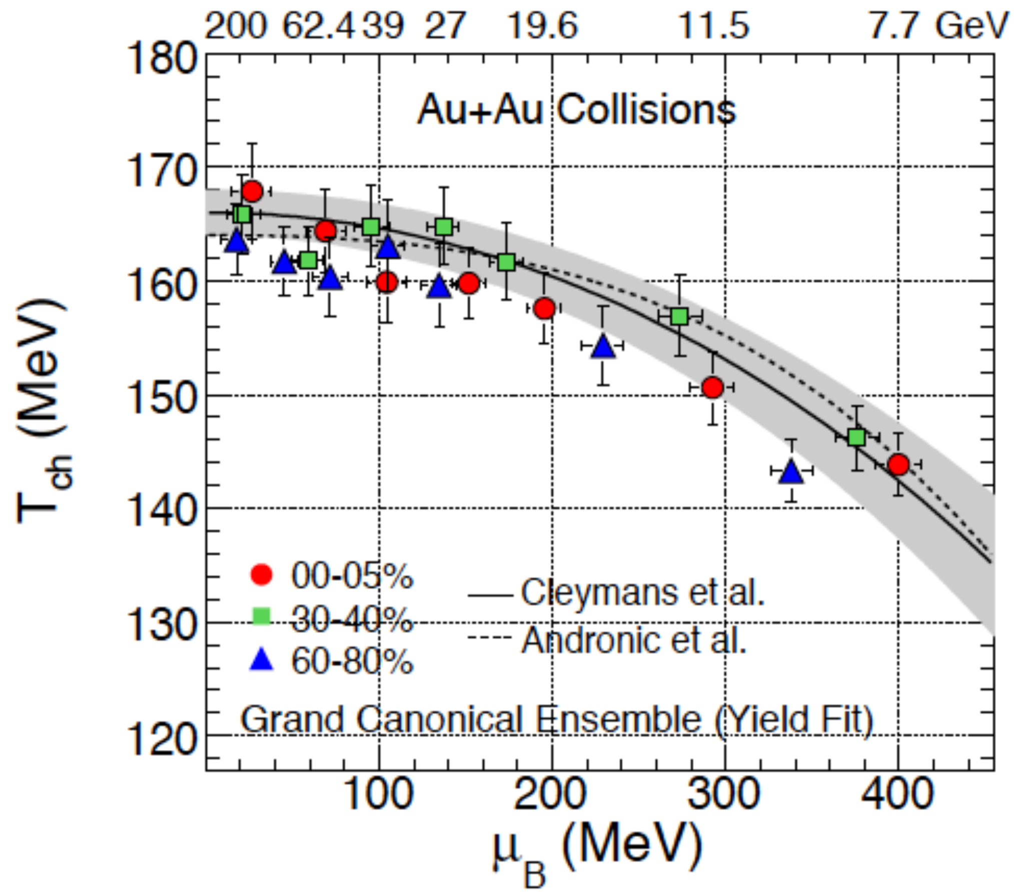
Particle spectra



- Global quantities: T_{ch}, T_{kin}, μ_B, energy density, freeze-out volume… arXiv: 1701.07065

Freeze-out parameters

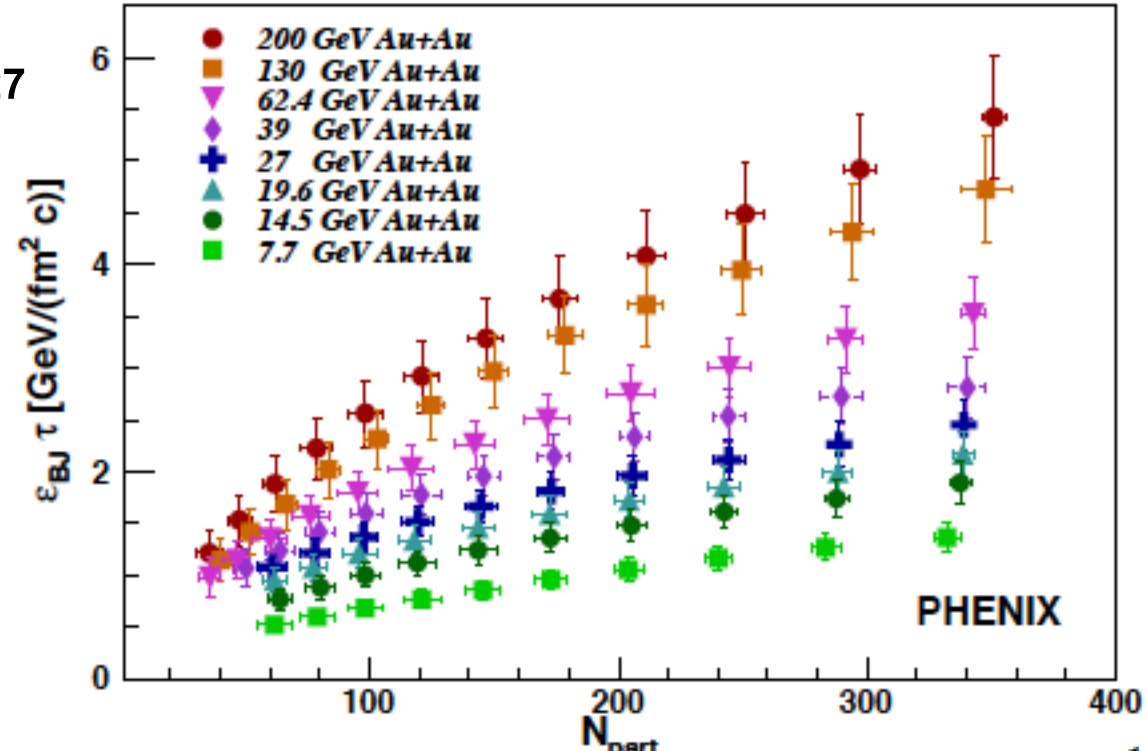




- At √sNN > 7 GeV, $T_{ch} > T_{kin}$
- At √sNN < 7 GeV, $T_{ch} \sim T_{kin}$
- Collective velocity increases as a function of √sNN.

Energy density

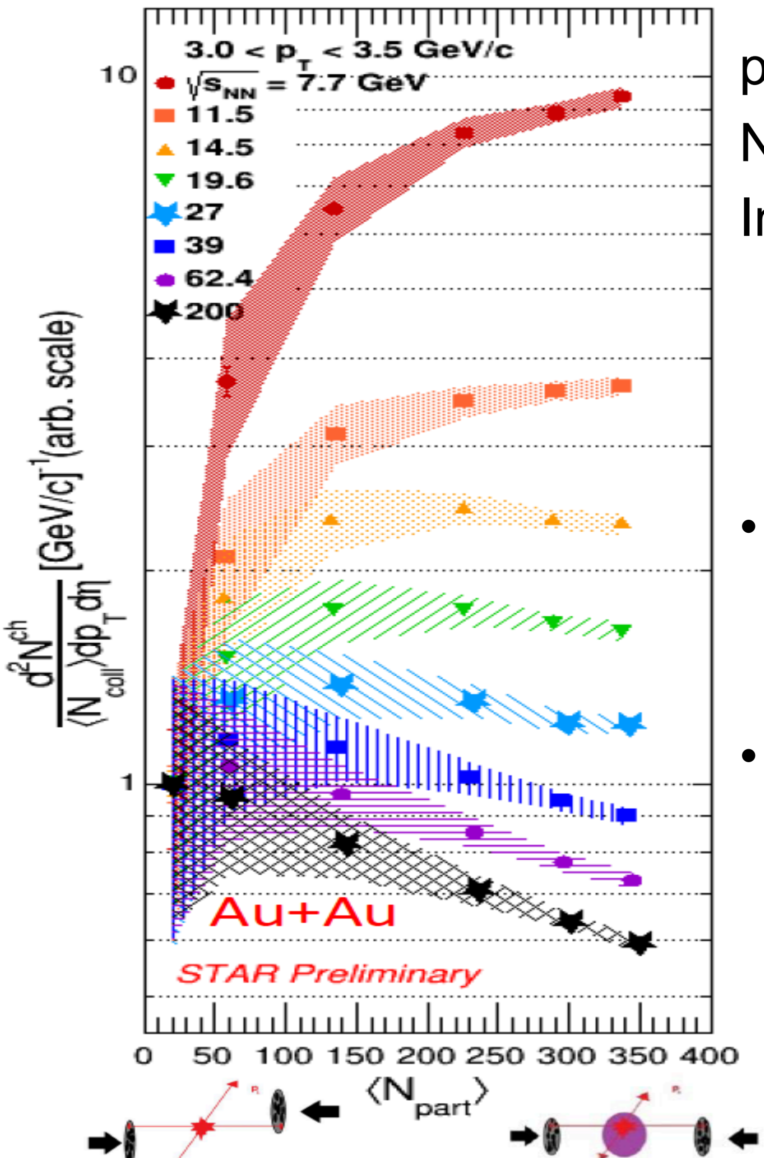
arXiv: 1509.06727



- Bjorken Energy density assuming boost invariant $\epsilon_{Bj} = \frac{1}{A_\perp \tau}\frac{dE_T}{dy}$
- $\varepsilon_{Bj}\,\tau$ > 1 GeV/(fm^2 c) in central 7.7 GeV collisions

- From lattice, critical ε_c=0.34 ± 0.16 GeV/fm^3 : central lowest energy 7.7 GeV might be above transition region. A. Bazavov et al. (hotQCD) ,Phys. Rev. D90 (2014) 094503

QGP turn off: jet quenching



p_T range 3.0-3.5 GeV/c

N_{bin} scaled particle yields as a function of N_{part}

Interplay of

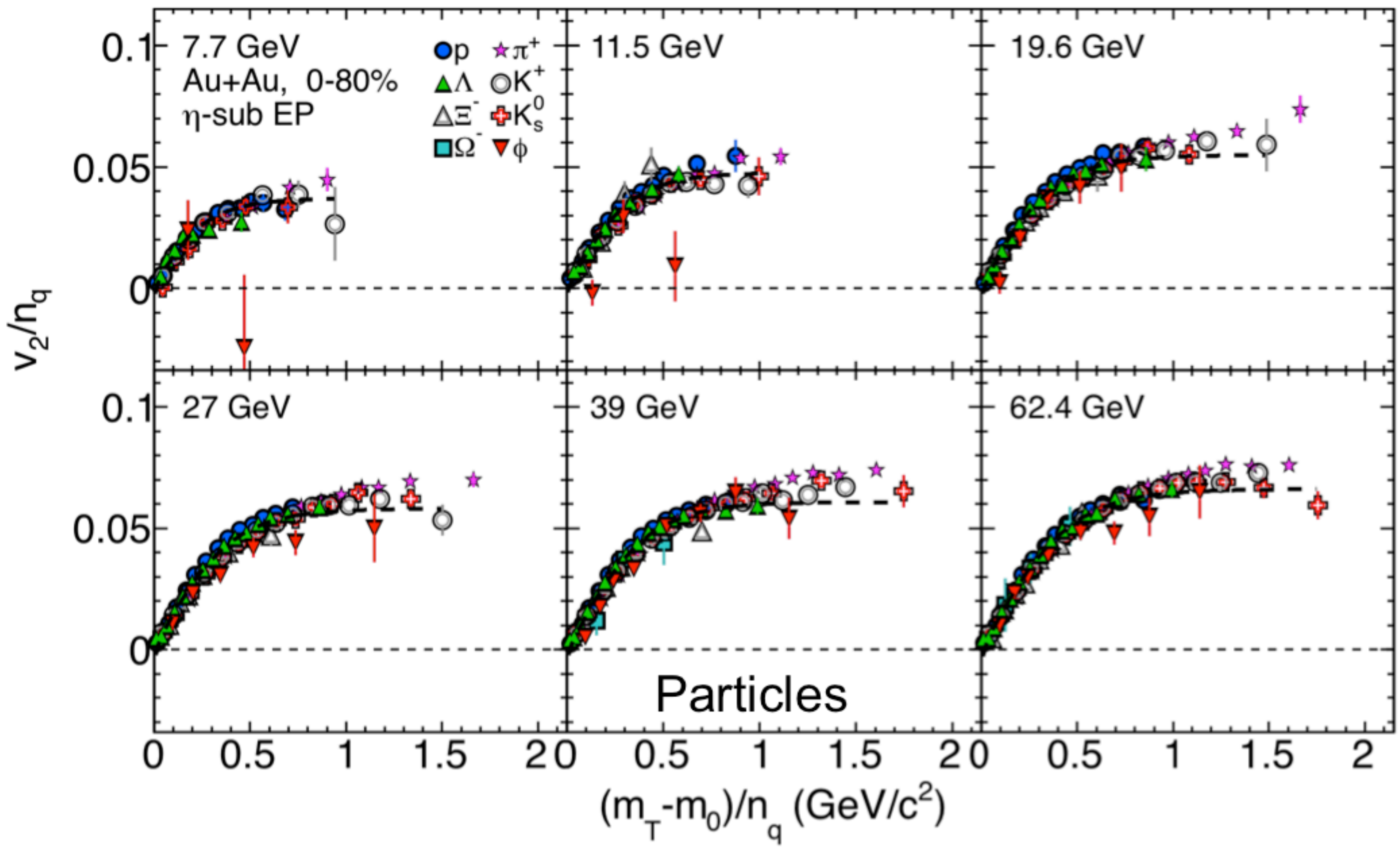
Cronin effect, radial flow, coalescence

Jet quenching

- At √sNN > 14.5 GeV/c,
  jet quenching has to be there

- At √sNN < 14.5 GeV/c, the jet quenching feature is gone but we can not rule out jet quenching.

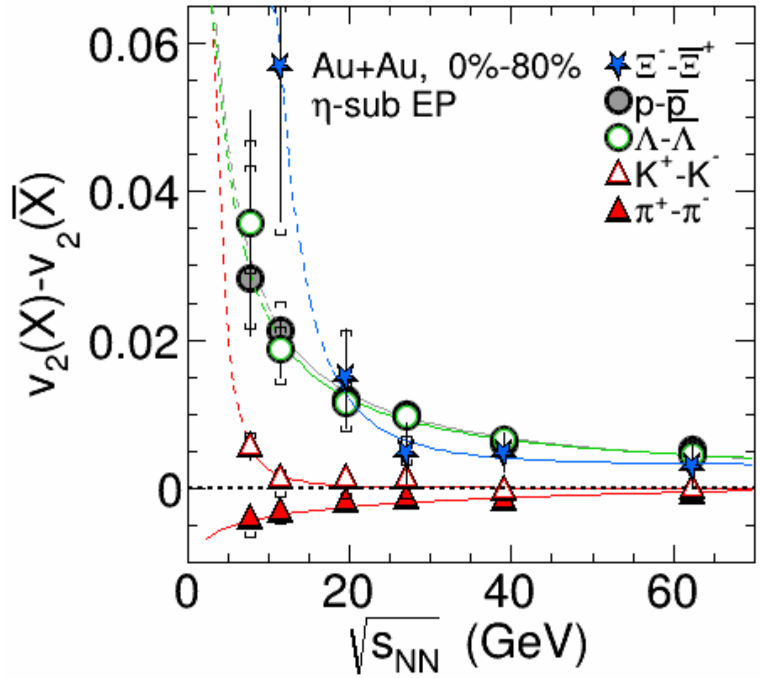
QGP turn off: NCQ scaling and ϕ meson v_2



- NCQ scaling holds for particle and anti-particle separately.
- ϕ meson v_2, sensitive to QGP, close to zero with large uncertainty at $\sqrt{s_{NN}}$ = 11.5 GeV and below.

QGP turn off: particle and anti-particle v_2

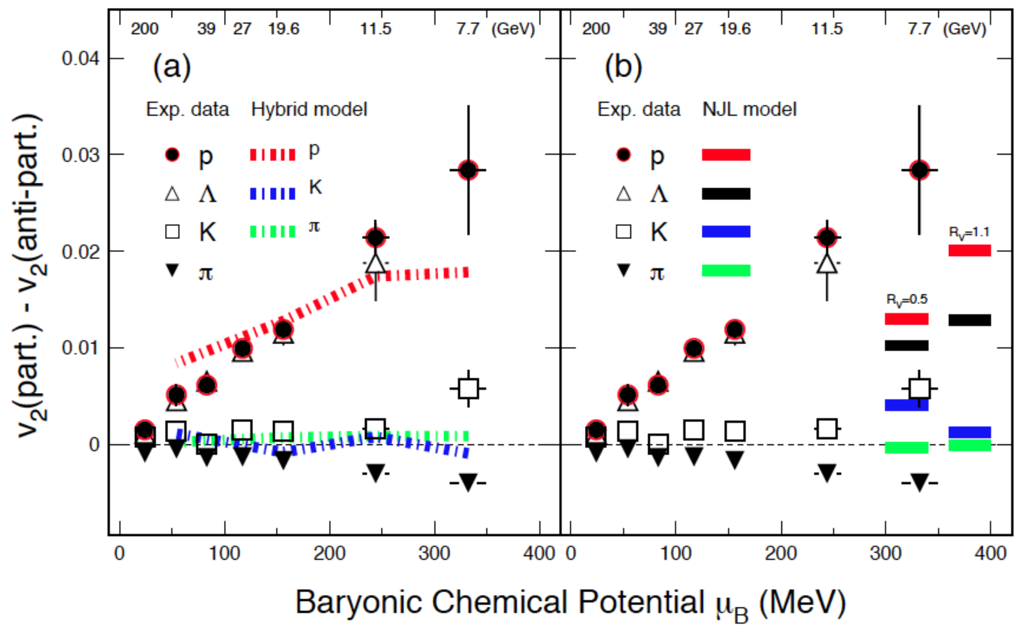
Phys. Rev. Lett. 110, 142301 (2013)



Hybrid: Phys. Rev. C 86, 044903 (2012)

NJL: Acta Phys.Polon.Supp. 7 (2014) 1, 183

0-80% Au + Au Collisions at RHIC



v_2 for particle is different from that for anti-particle at lower energies.

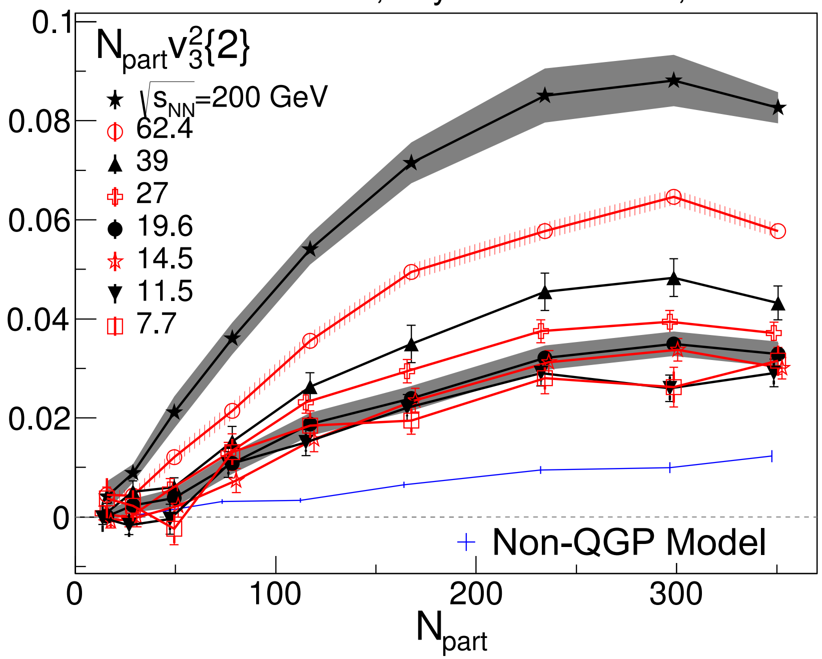
Hadronic dynamics becomes more and more important at lower energies.

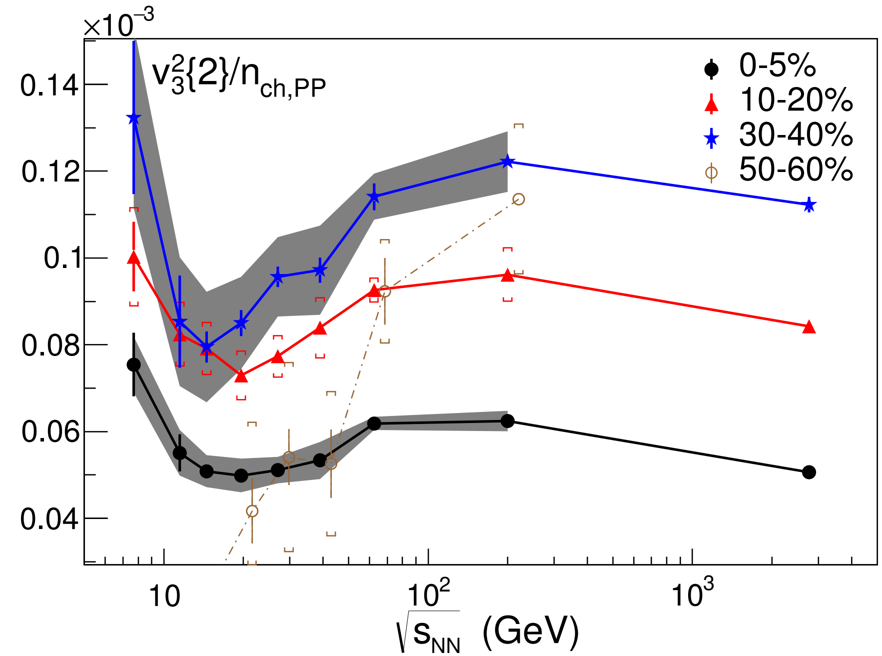
Hydro model: Hybrid model (UrQMD + hydro) with baryon stopping

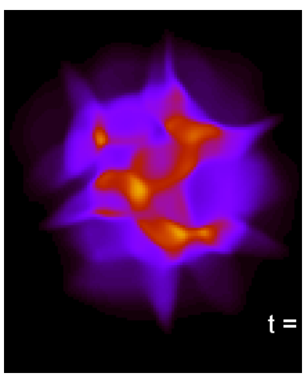
Nambu-Jona-Lasinio (NJL): Using vector mean-field potential, repulsive for quarks, attractive for anti-quarks

Mapping the phase diagram: higher harmonics

STAR Collaboration, Phys. Rev. Lett. **116**, 112302





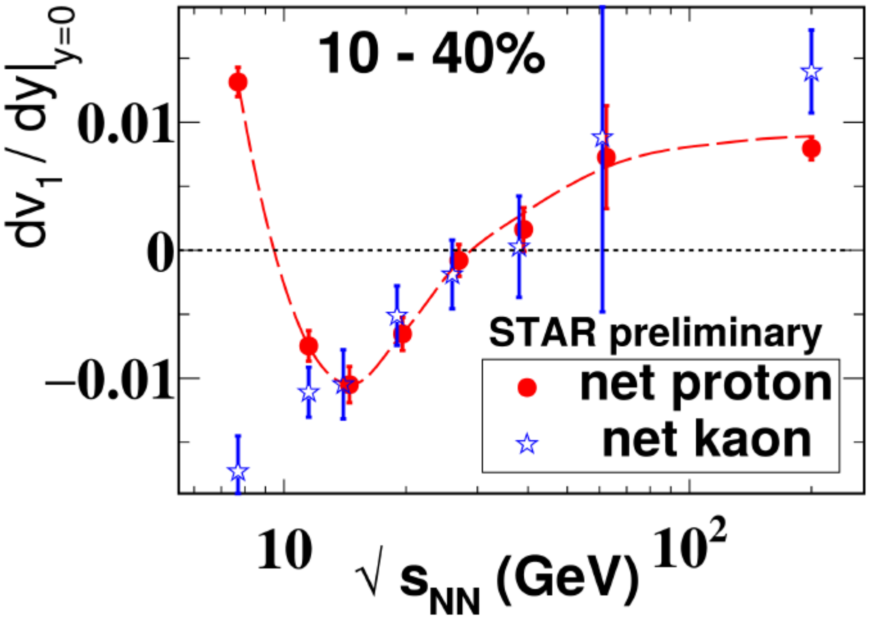


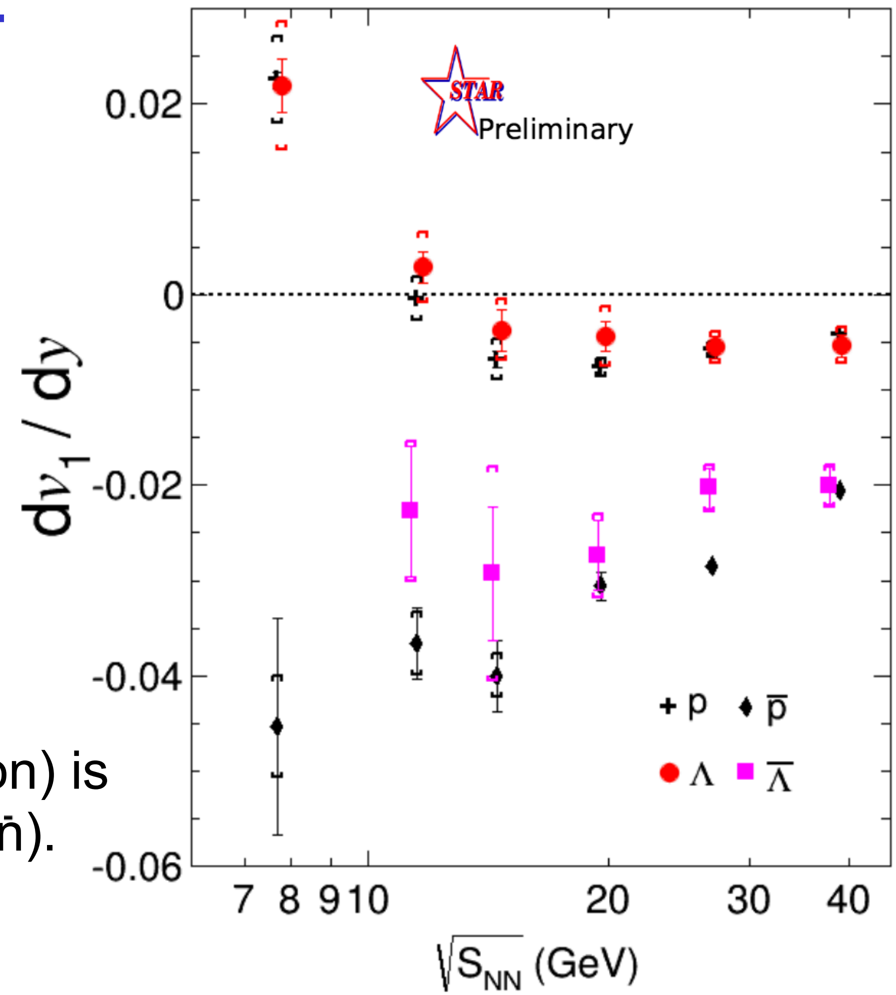
Models show that higher harmonic ripples are sensitive to the presence of a QGP: v_3 goes away when the QGP goes away

In more central collisions, v_3 is present at the lowest energies, but disappears at lower energies for N_{part}<50 (turn-off of QGP)

When scaled by entropy density, v_3 shows a minimum near 15 GeV consistent with an increased bulk viscosity and decreased effective pressure

Softening of EOS: v_1 slope





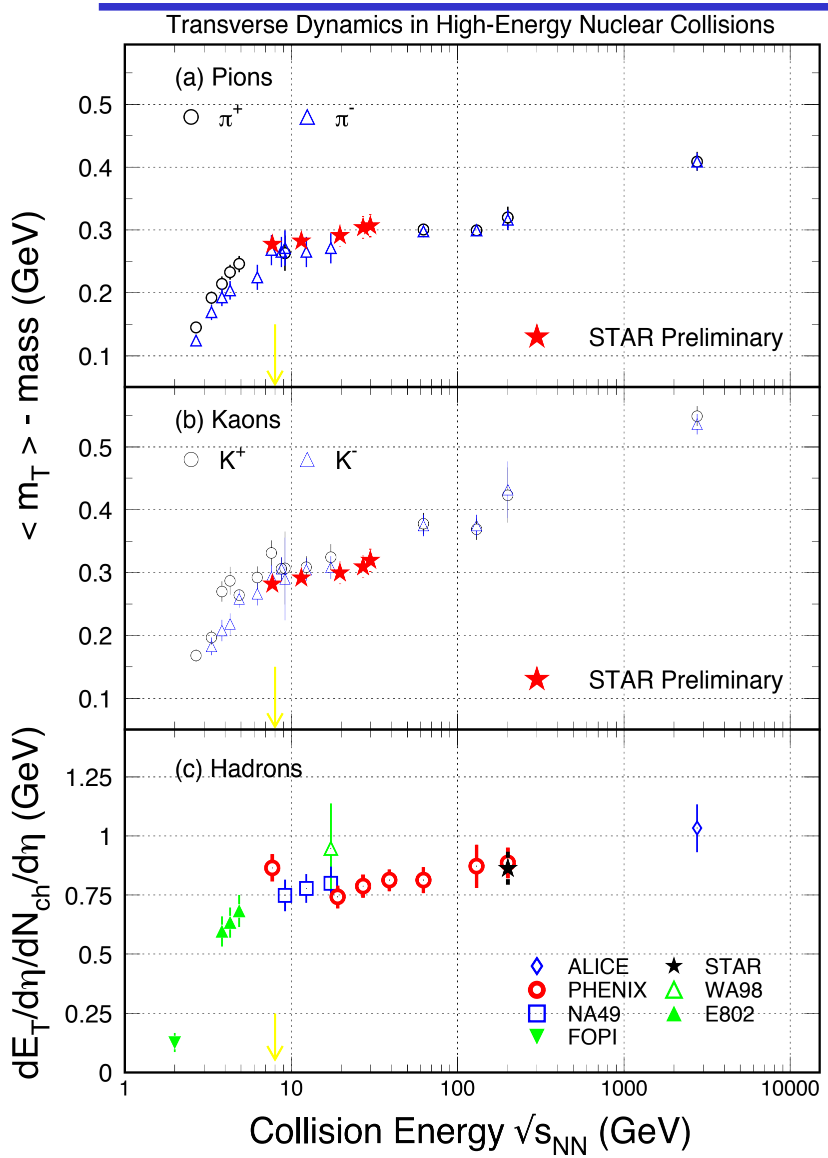
v_1 slope:

Proton (baryon stopping + pair production) is different from anti-proton (pair production).

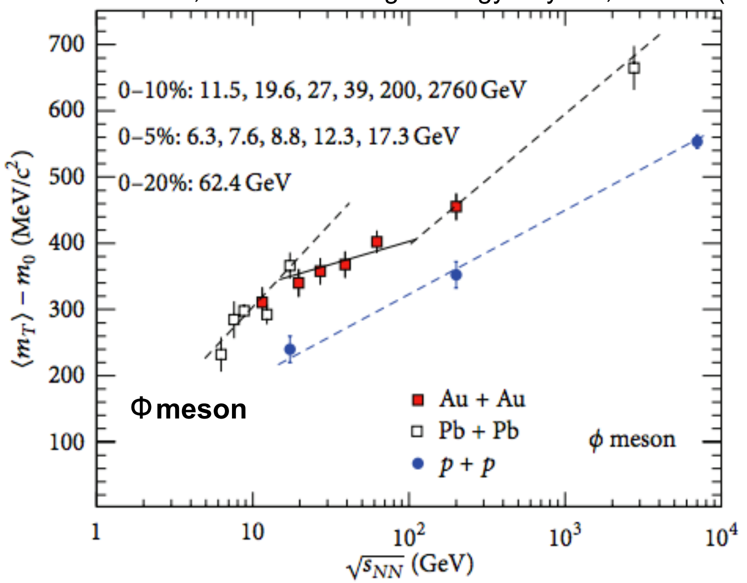
So is the Lambda.

Non-monotonic behavior seen in net-proton v_1 slope as a function of collision energy. First order phase transition? softening of EOS? but not for net-kaon.

Softening of EOS: transverse mass or energy



NA49: Phys. Rev. C 78, 4 (2008), Physics Lett. B 491, 59 (2000).
STAR: Phys. Rev. C 49, 064903 (2009).
ALICE: Phys. Rev. C91, 024609 (2015).
M. Nasim et al., Advances in High Energy Physics, 197930 (2015).

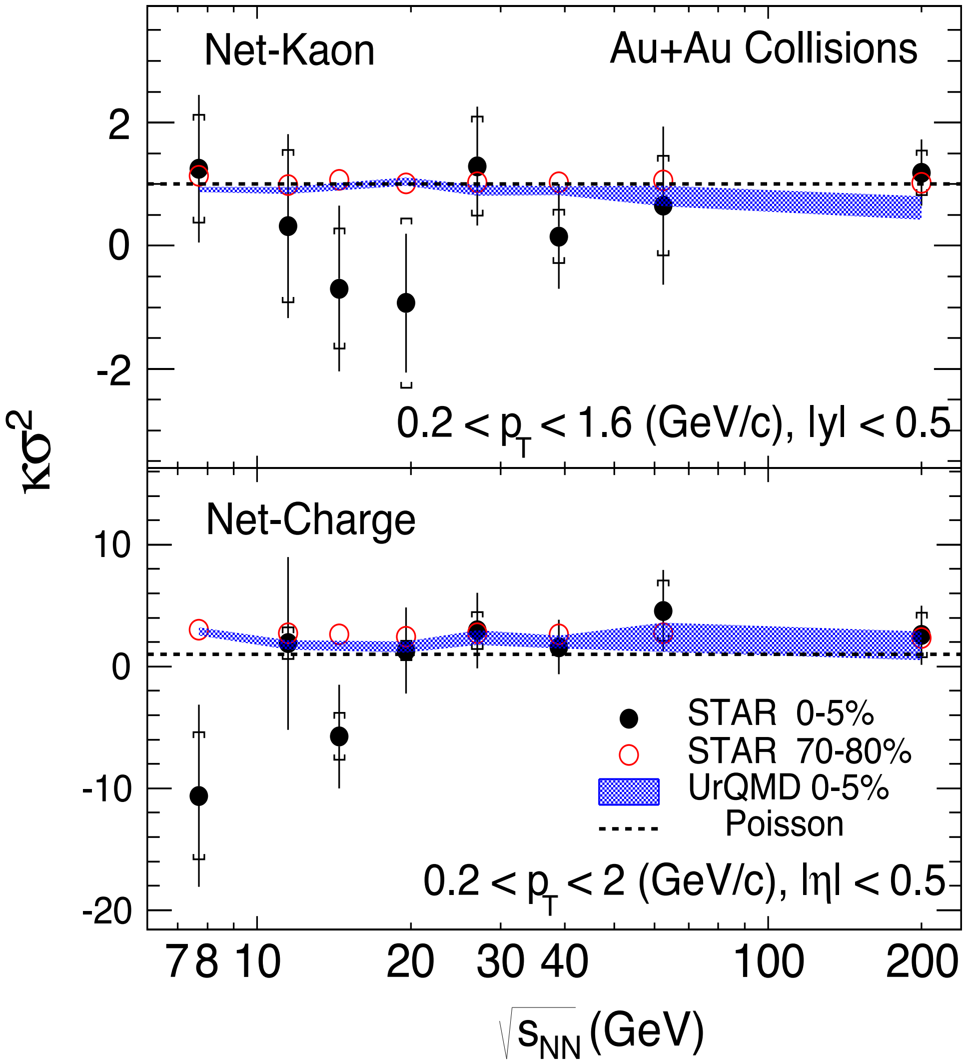


Particle $<m_T>-m_0$ and transverse energy per particle show a flat pattern above ~8 GeV and then increase again

L. van Hove, PLB 118, 138 (1982).

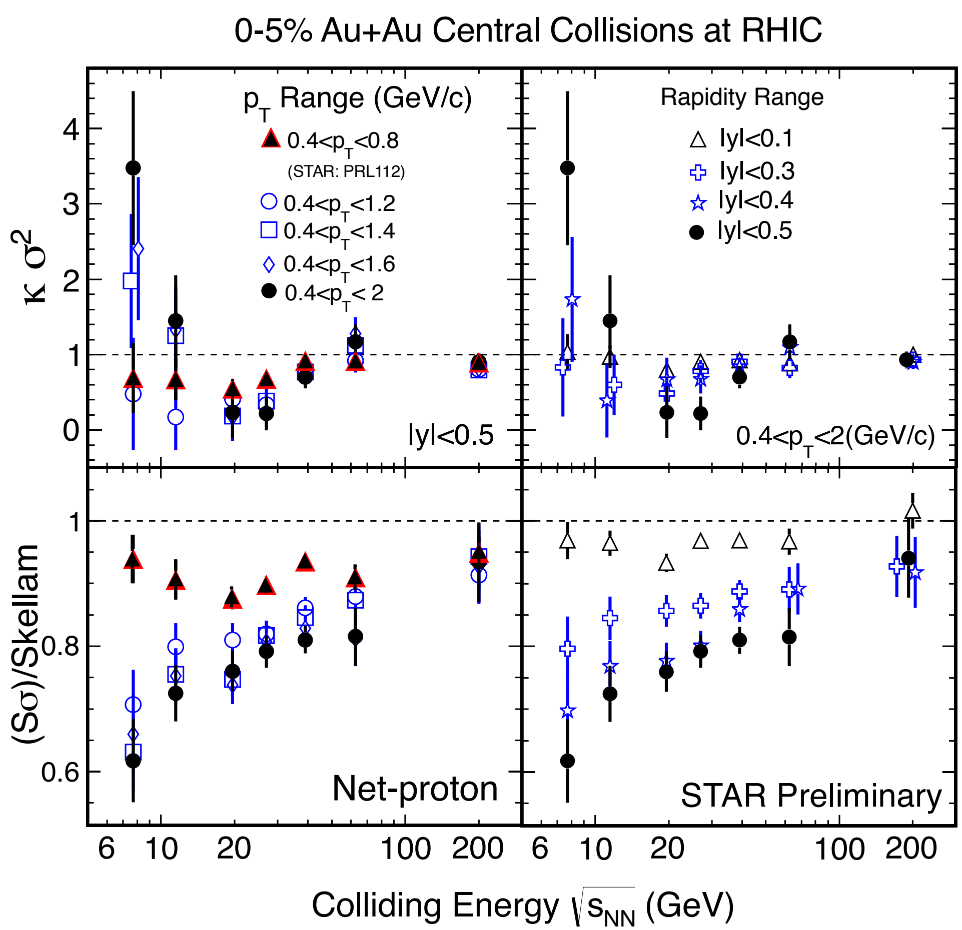
Indication of 1st order phase transition ?

Critical point: moments of net charge and net-kaon distributions



- Net-kaon and net-charge $k\sigma^2$ are consistent with unity .
- More statistics are needed to draw a conclusion.
- UrQMD without critical point, shows no energy dependence.

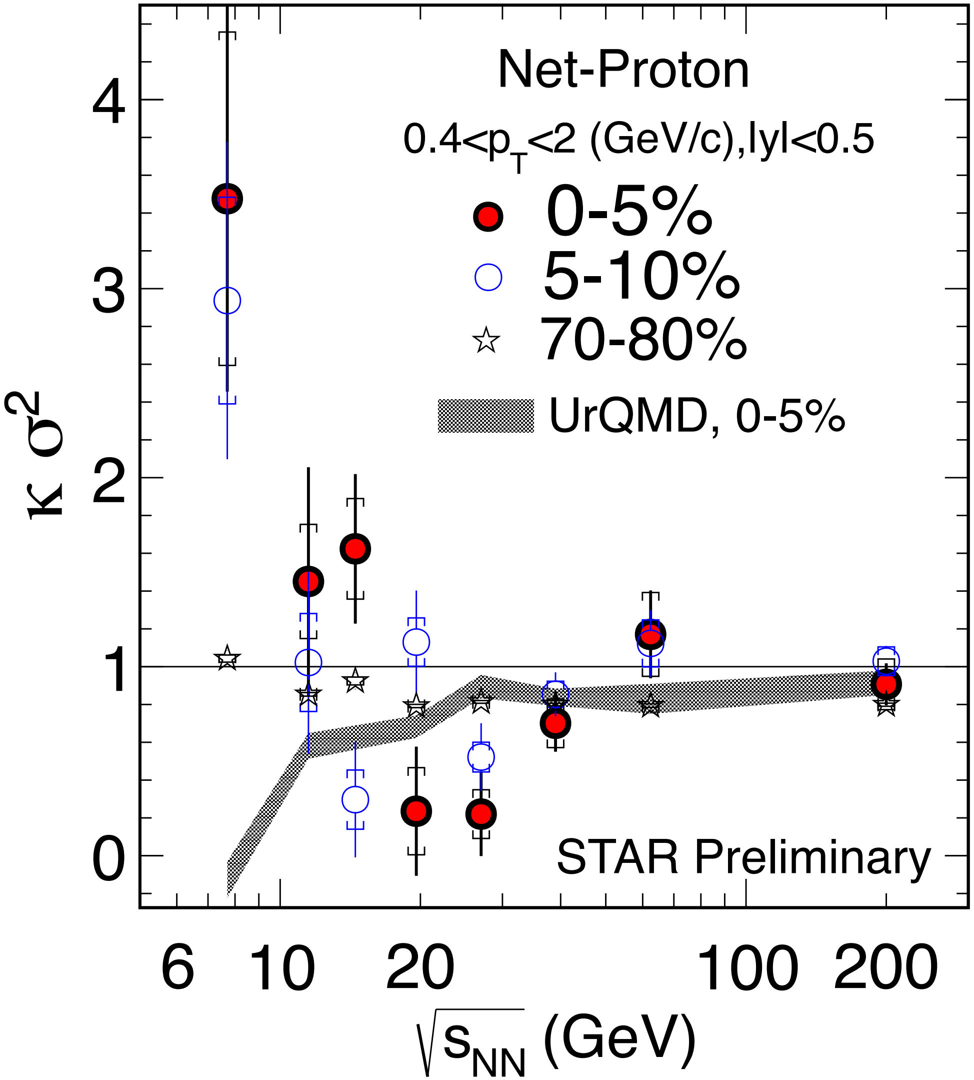
Moments of net proton distributions



Results sensitive to kinematic cuts (p_T range and rapidity range).

With Large acceptance, non-monotonic behavior is seen as a function of √sNN.

Moments of net proton distributions as a function of √sNN



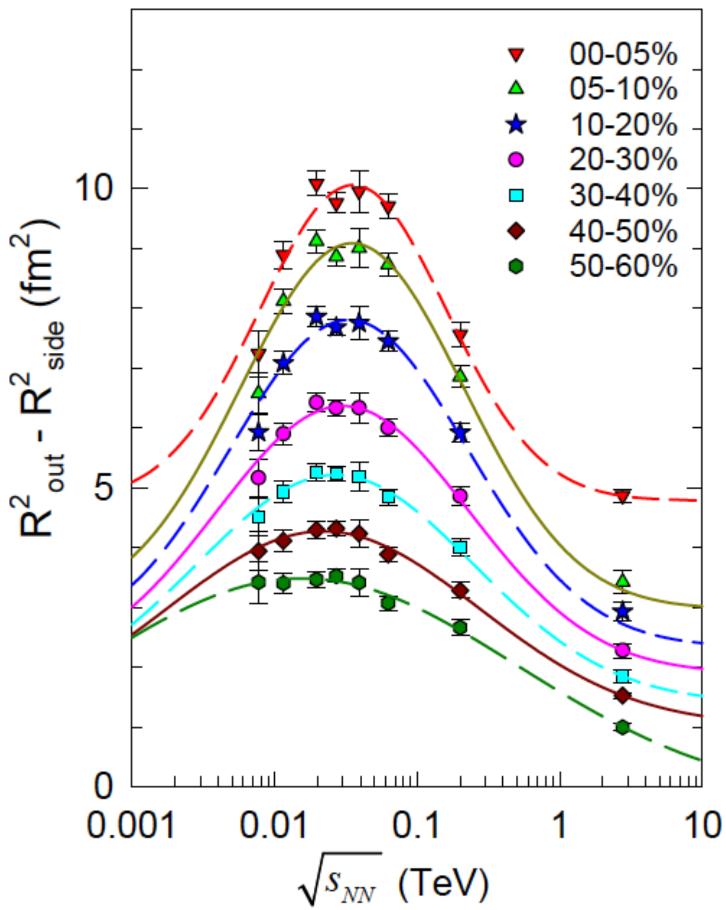
Non-monotonic trend is observed in central 0-5% collisions

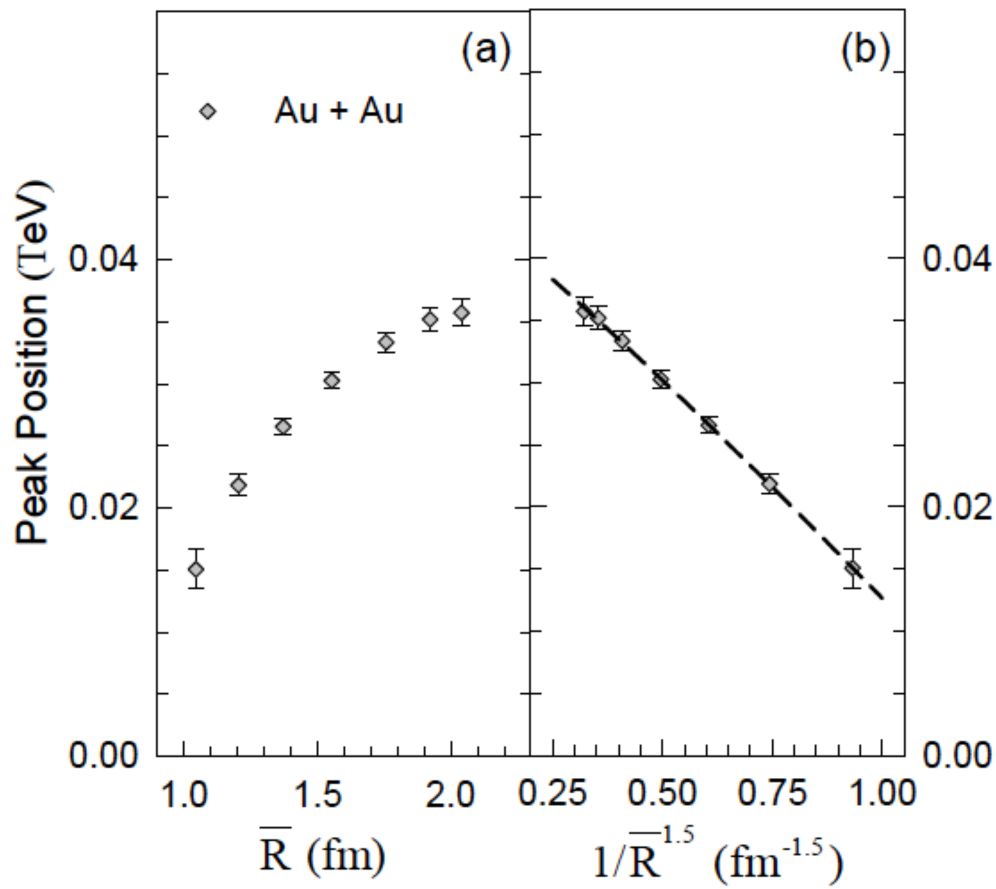
UrQMD without critical point can not explain data, decreases towards lower energy, consistent with baryon number conservation.

X. Luo CPOD2014

HBT radii: finite-size scaling

R.Lacey, PRL114,142301(2015)





R^2_{out}-R^2_{side} sensitive to the emission duration, shows a non-monotonic trend as a function of collision energy

Finite-size scaling analysis indicates a second order phase transition with T^{cep} ~165 MeV and μ^{cep}_B ~ 95 MeV for the location of the critical end point.

What has been achieved from BES I

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QGP turn off signatures

- jet quenching feature is gone for N_{bin} scaled particle yields as a function of N_{part} at $\sqrt{sNN}$ < 14.5 GeV.
- ϕ meson $v_2 \sim 0$ at $\sqrt{sNN}$=11.5 and 7.7 GeV with large uncertainties.
- Higher harmonics $v_3 \sim 0$ at $N_{part} < 50$ at 7.7 GeV.

First order phase transition

- When scaled by entropy density, v_3 shows a minimum near 15 GeV consistent with an increased bulk viscosity and decreased effective pressure.
- Non-monotonic behavior seen in net-proton v_1 slope as a function of $\sqrt{sNN}$.
- Particle $\langle m_T \rangle - m_0$ and transverse energy per particle show a flat pattern At $\sqrt{sNN}$ > 8 GeV and increases again.

Critical point:

- Non-monotonic trend is seen in moments of net proton distributions in central Au+Au as a function of collision energy
- Non-monotonic trend is seen in the HBT radii as a function of collision energy

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Towards BES II

In 2019 & 2020

7.7, 9.1, 11.5, 14.5 and 19.6 GeV

μ_B from 205 to 420 MeV

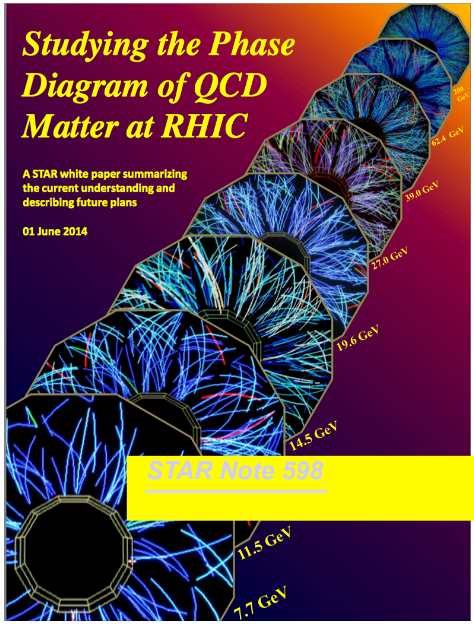
10~25 times more statistics

Detector upgrade

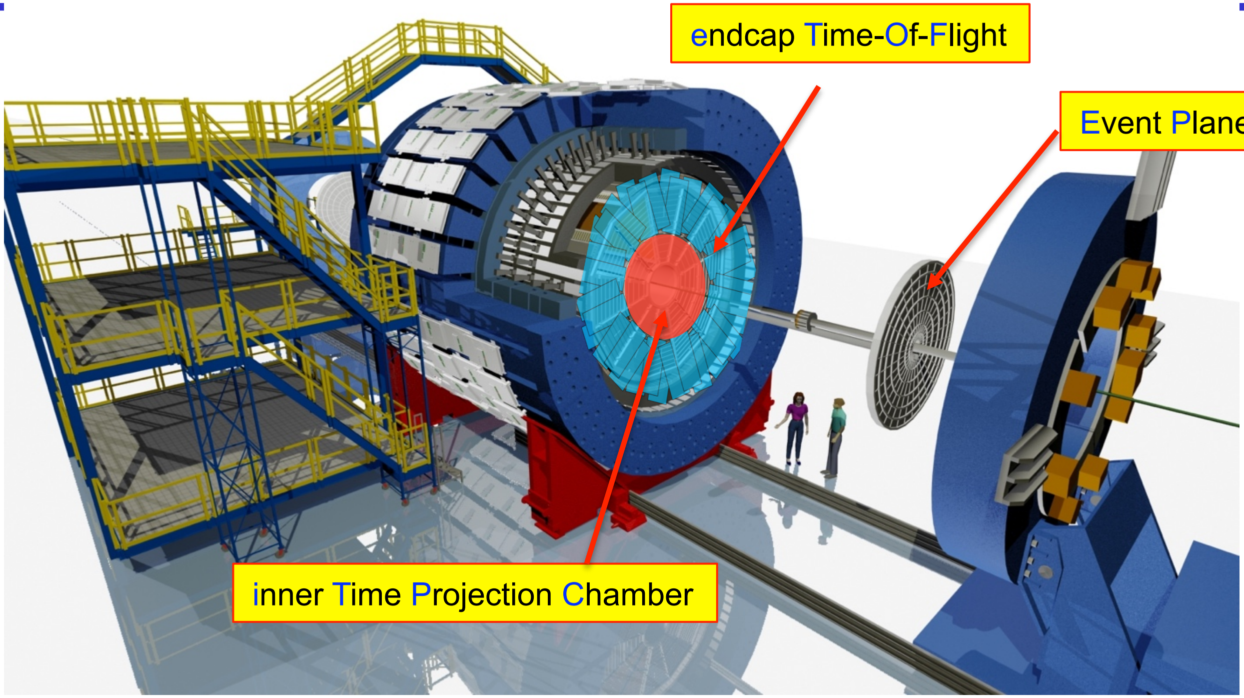
- inner Time Projection Chamber
- Event Plane Detector
- endcap Time-Of-Flight

Low Energy Electron Cooling at RHIC

Collision Energies (GeV)	Proposed Event Goals (M)	BES I Event (M)
7.7	100	4
9.1	160	N/A
11.5	230	12
14.5	300	20
19.6	400	36

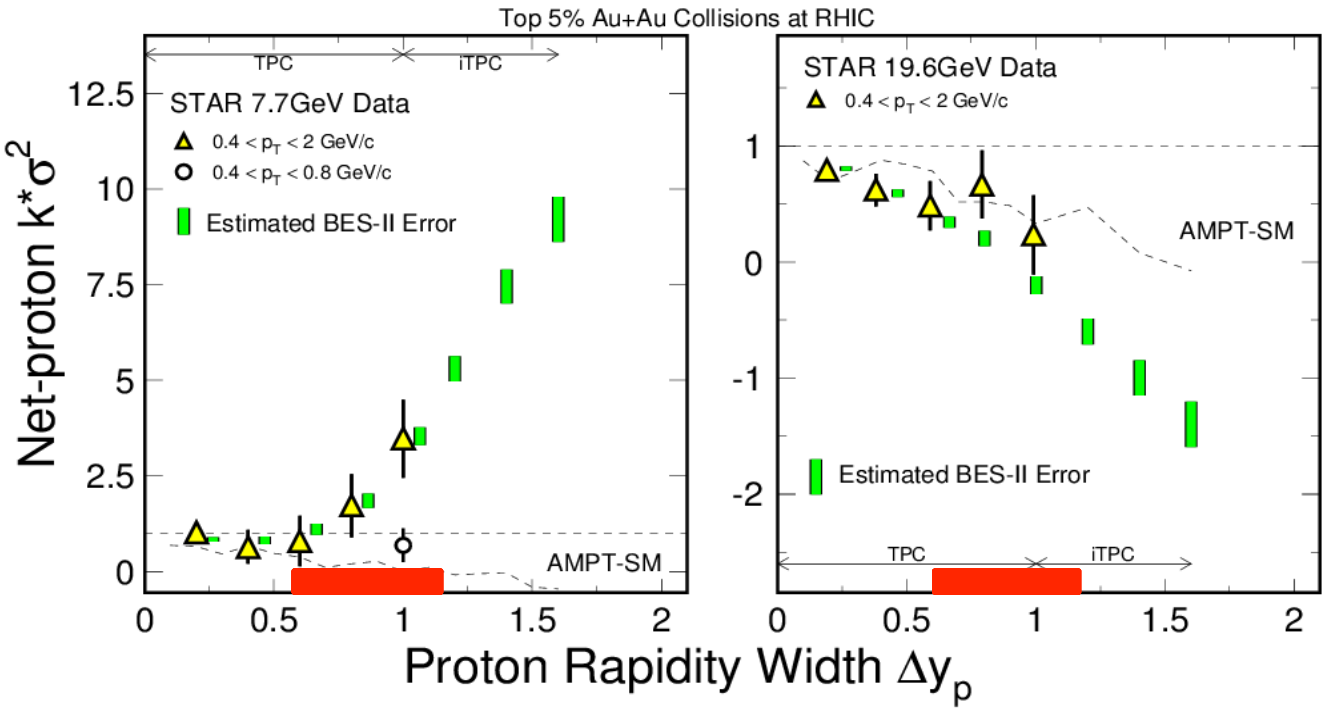


Upgrade plan for BES II



iTPC upgrade	EPD upgrade	eTOF upgrade
Continuous pad rows Replace all inner TPC sectors	**Replace Beam Beam Counter**	**Add CBM TOF modules and electronics (FAIR Phase 0)**
$\|\eta\|<1.5$	**$2.1<\|\eta\|<5.1$**	**$-1.6<\eta<-1.1$**
p_T >60 MeV/c	Better trigger & b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resolution	Greatly improved Event Plane info (esp. 1st-order EP)	Allows higher energy range of Fixed Target program
Fully operational in 2019	**Fully operational in 2018**	**Fully operational in 2019**

Net-proton cumulants in BES II with iTPC



Net-proton cumulants revealed a non-trivial energy dependence from BES I.

Measure as a function of Δy_p in a wide range is needed to establish true nature of correlation

iTPC upgrade will enable this measurement in a wider range

Fixed target program

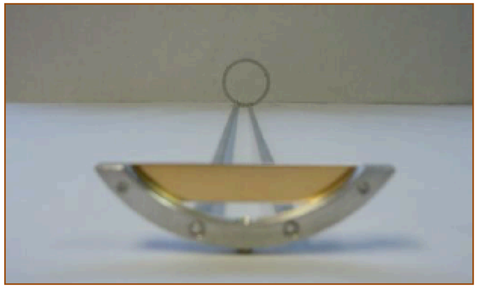
Fixed target program proposed during RHIC BES II will extend the energy down to $\sqrt{s_{NN}}$ = 3.0 GeV (μ_B = 721 MeV)

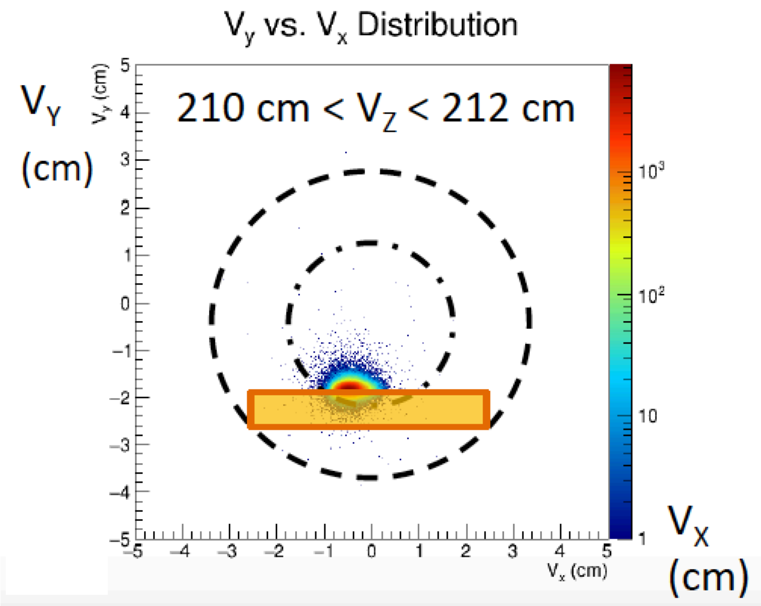
The fixed target is outside the STAR TPC at 210 cm

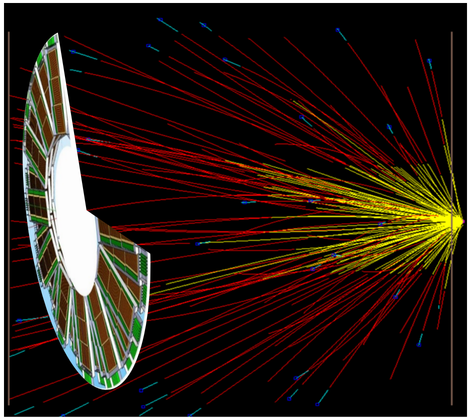
Only single beam is used

$\sqrt{s_{NN}}$ = 3.0 ~ 7.7 GeV

~100M events needed per energy

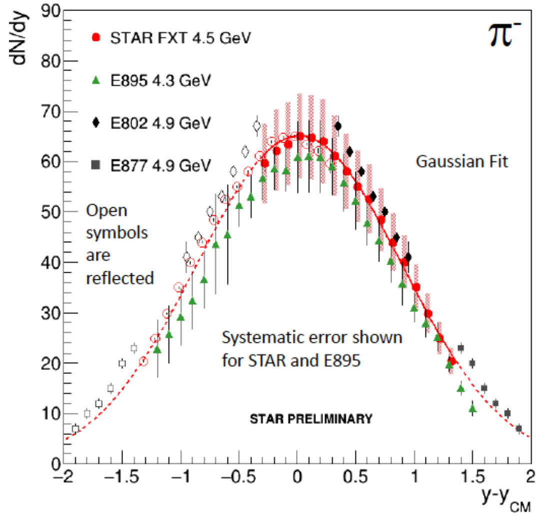


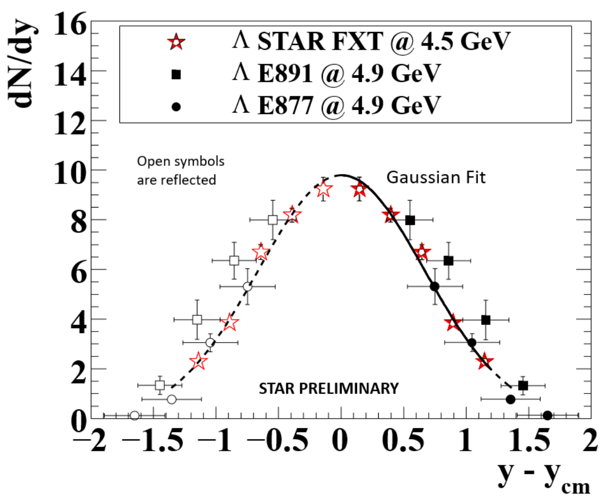


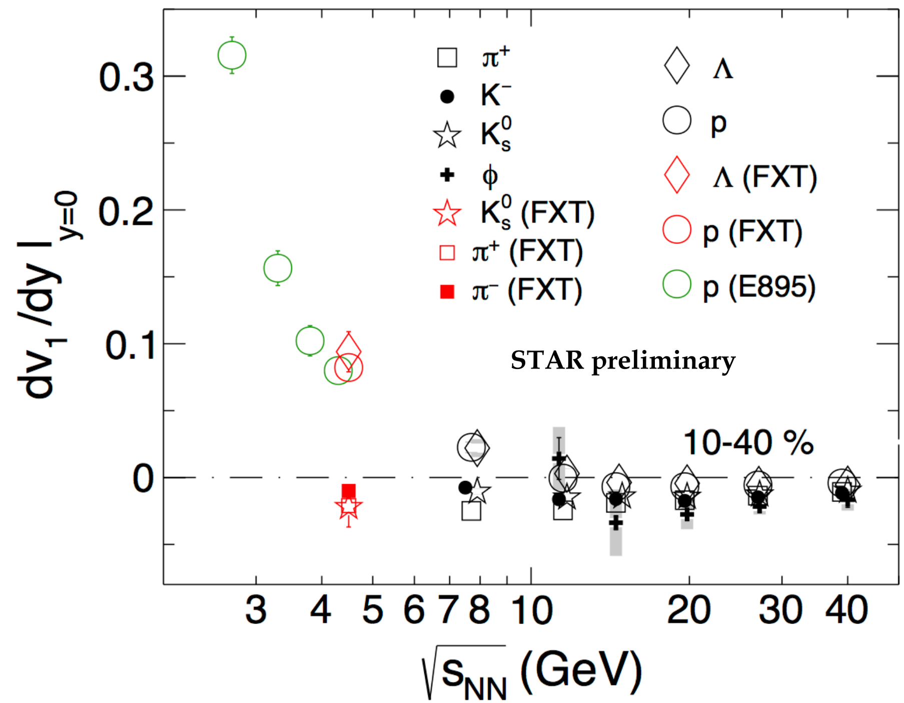


Reconstructed 3.9 GeV Au+Au event

Spectra and flow from fixed target







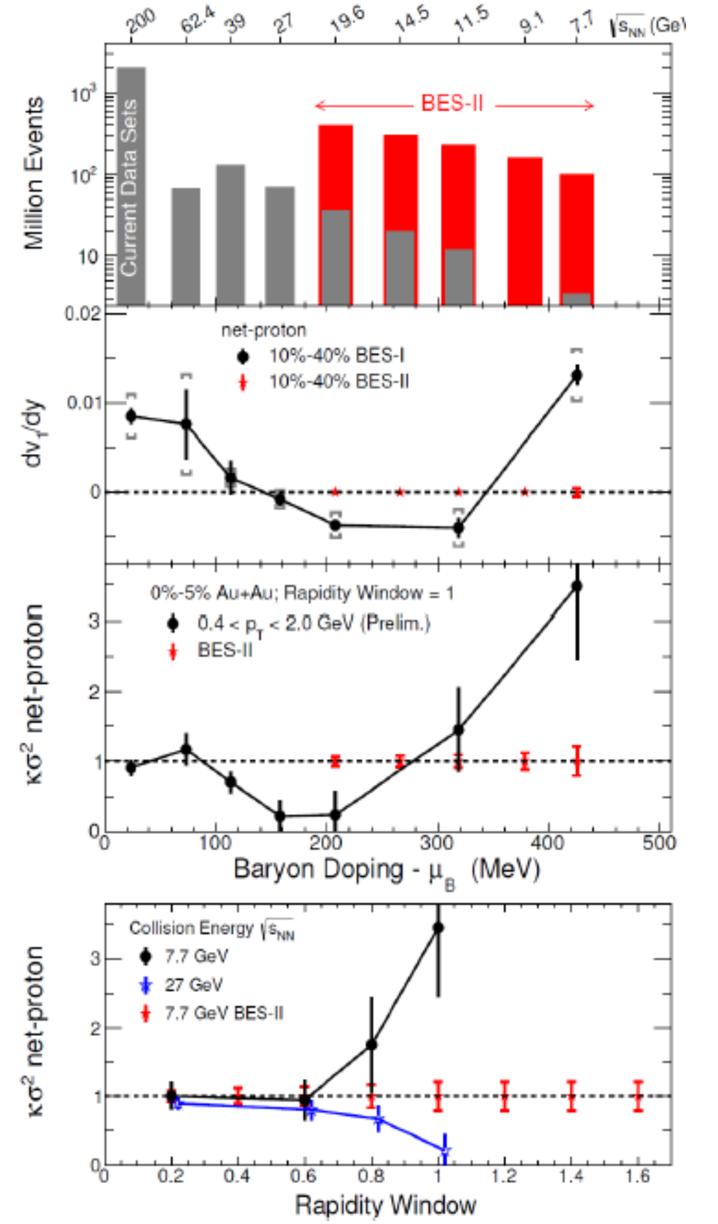
Dedicated fixed-target run in 2015: √sNN = 4.5 GeV

- 1 M events in 30 minutes!
- Excellent PID using dE/dx and ToF
- dN/dy and v_1 for charged particles and V0s are in good agreement with published results

Summary

Many interesting features have been observed for the signatures of

- QGP turn off
- First-order phase transition
- Critical point

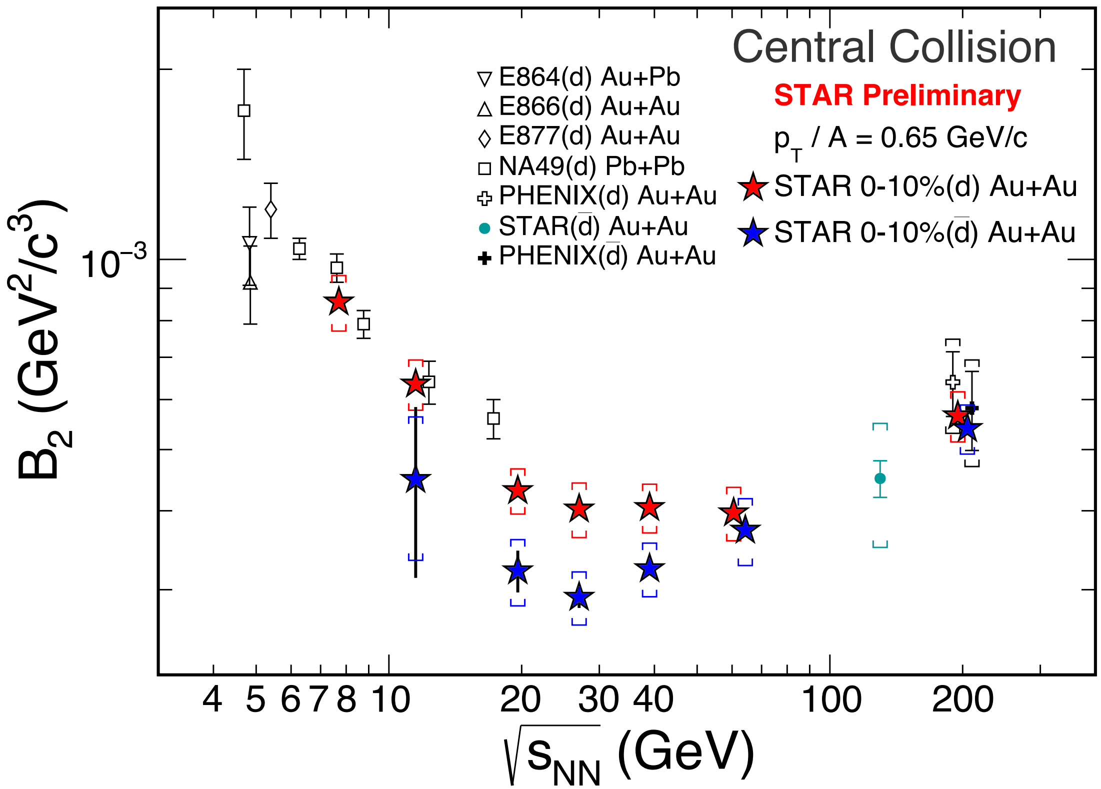


Turn the qualitative features to quantitative understandings.

- exciting results from the future BESII program
- BEST Theory Collaboration

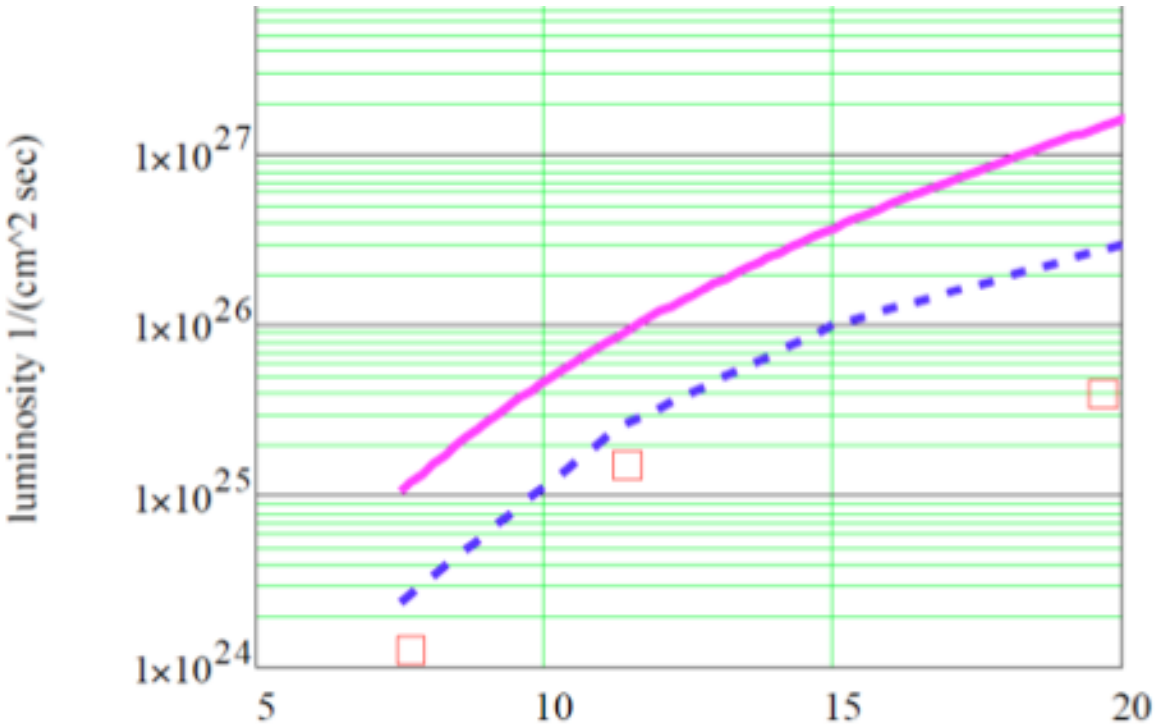
Backup

Light nucleus production at BES I



The coalescence parameter B_2 is decreasing with energy and flattening out at about 20 GeV → change in EOS?

Beam Energy Scan II in 2019-2020



RHIC is unique to study chiral symmetry restoration:

Beam energy scan II: collision energies 7.7, 9.1, 11.5, 14.5, 19.6 GeV.

Electron cooling from CAD will increase collision rate from 3-10.

Physics impact for the detector upgrade in BES II

Low Energy Electron Cooling at RHIC:

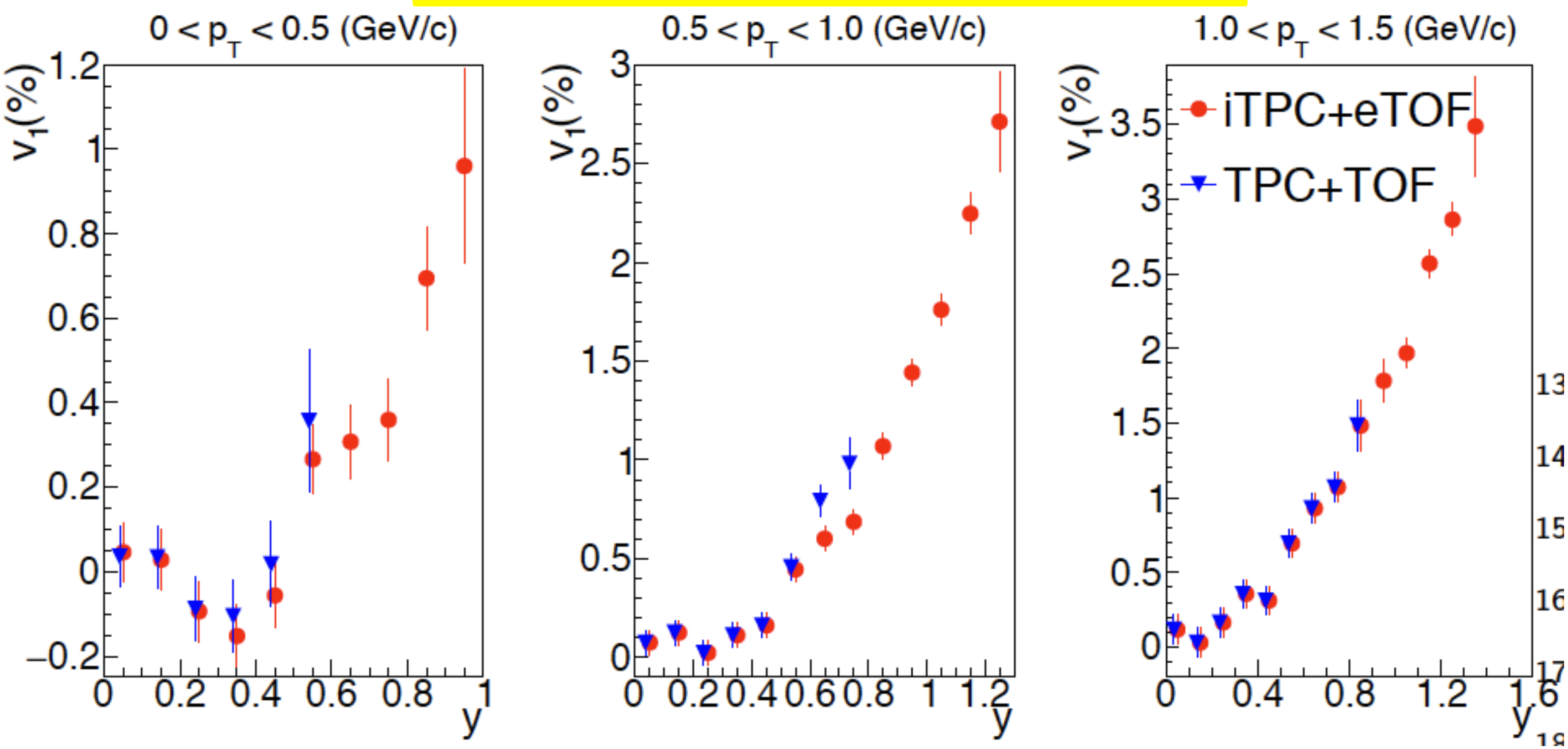
- Electron Cooling can raise the luminosity by a factor of 3-10 in the range from 5 – 20 GeV
- Long Bunches increase luminosity by factor of 2-5

The upgrade for BES II will improve many of the STAR analyses

- Better statistics
- Better resolution
- Smaller systematic uncertainty
- Wider rapidity range
- Wider p_T coverage

Directed flow v_1 in BES II

Based on 19.6 GeV UrQMD model events



The net proton v_1 slope at 11.5 GeV might indicate softening of EOS

Possible signature of a 1st-order phase transition

Softening would occur at different energies at forward rapidity