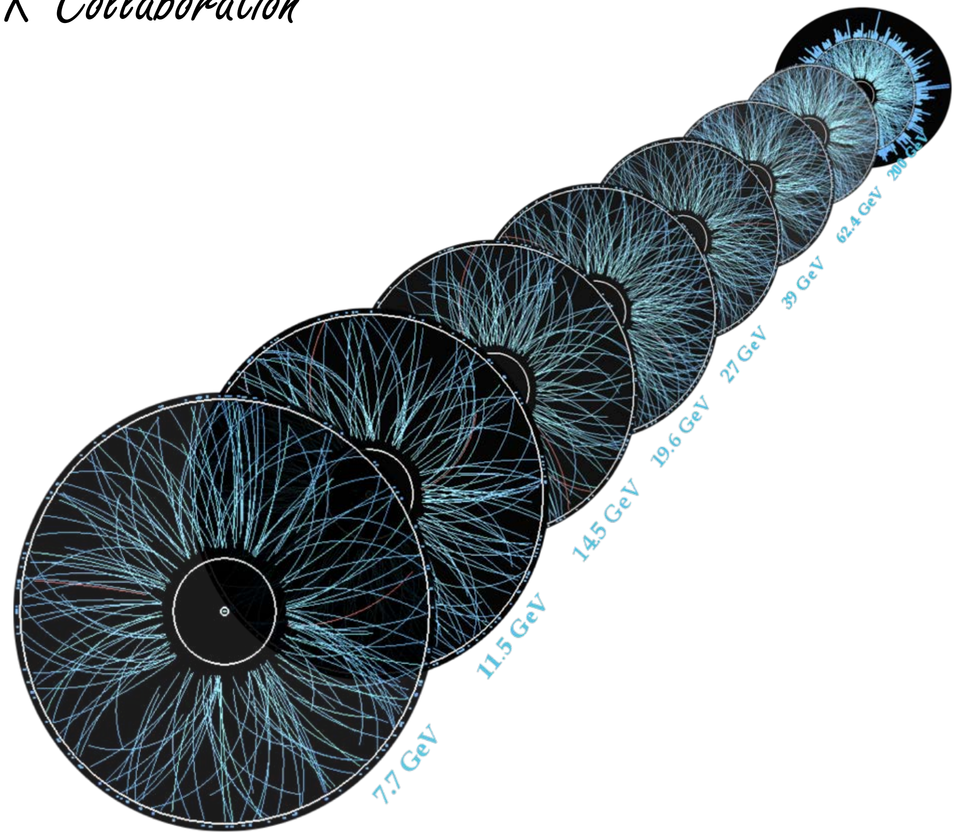
UIC UNIVERSITY OF ILLINOIS AT CHICAGO

Beam Energy Scan program at RHIC

Olga Evdokimov

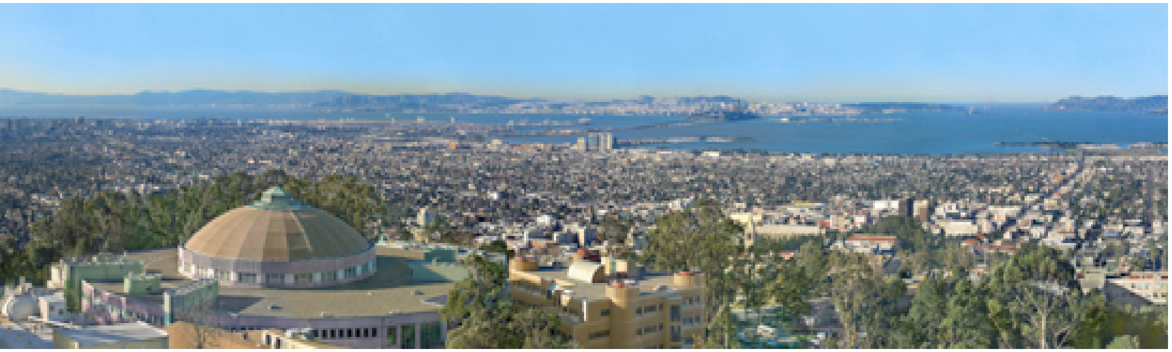
For the STAR Collaboration



Outline:

- Introduction: QGP discovery
- Beam Energy Scan program at RHIC
- RHIC BES-II – physics prospects
- Outlook

History of HI experiments



1974-1982:
Bevelac/Berkeley
$\sqrt{s_{nn}}$ = 0.1-1 GeV

1986-1994:
AGS/BNL, JINR
1-5 GeV

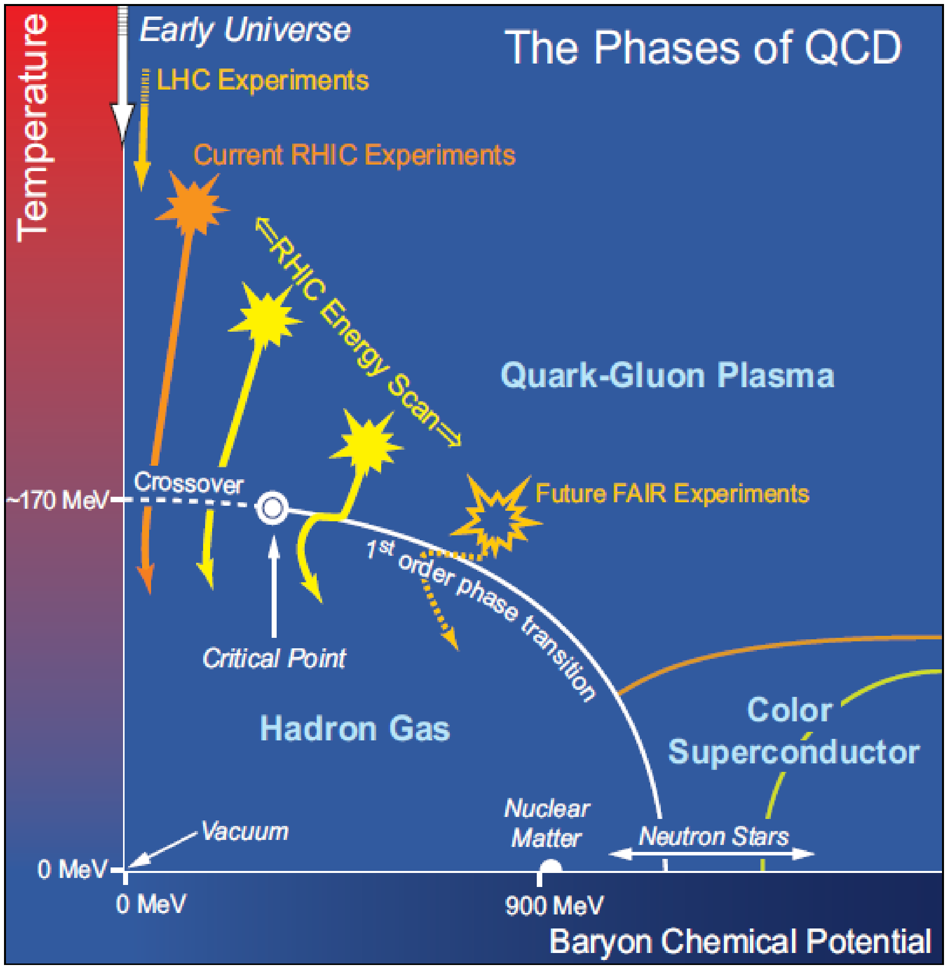
2000-
RHIC/BNL
3(?)-200 GeV

1986-1994:
SPS/CERN
10-20 GeV

2010-
LHC/CERN
2.76-5.02 TeV

The STAR Heavy-Ion Program

QCD matter under extreme conditions



Multiple theoretical models predict the existence of the Critical Point on the QCD phase diagram

Begun with:

- (s)QGP Studies
  - EoS,
  - Degrees of freedom,
  - Transport properties
  - ….

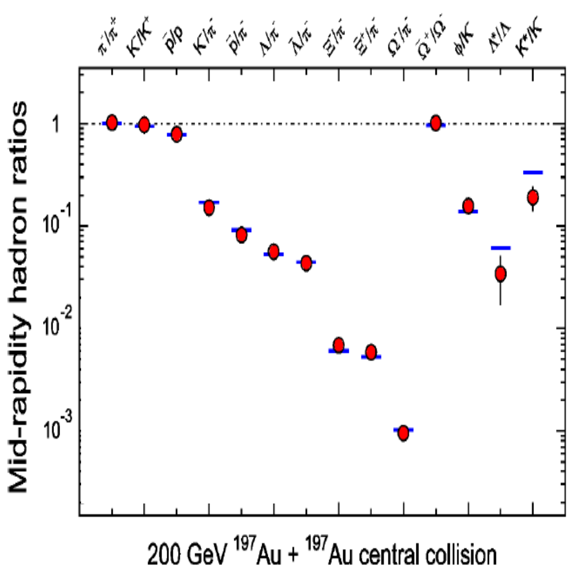
Expanded with:

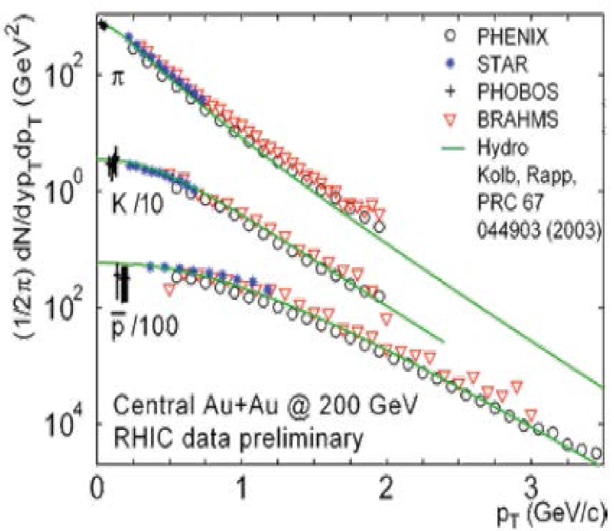
- Beam Energy Scan
  - QCD critical point search,
  - Onset of deconfinement,
  - Chiral symmetry restoration
  - …

QGP as we know it:

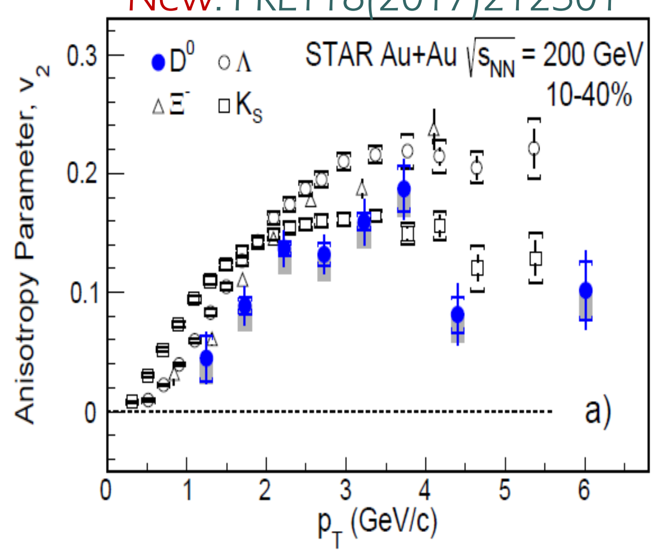
(in one sentence:)

...a strongly interacting thermalized partonic matter with (near) perfect fluidity





New: PRL118(2017)212301



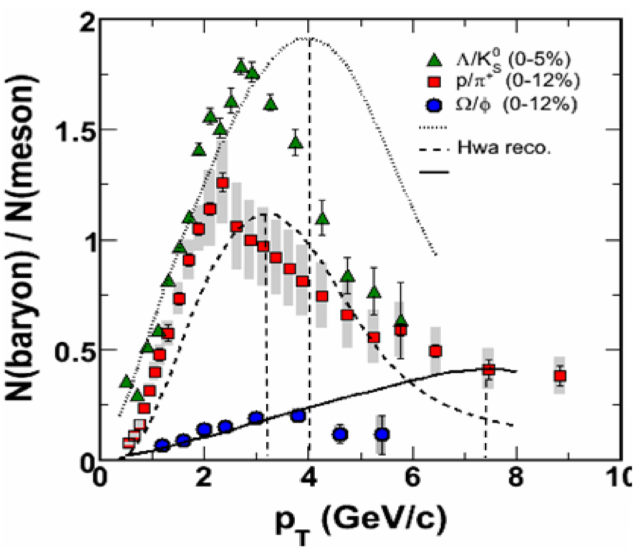
- Chemical freeze-out at the predicted phase boundary
- Strong radial and elliptic flow for hadrons (in strange and charm sectors too)

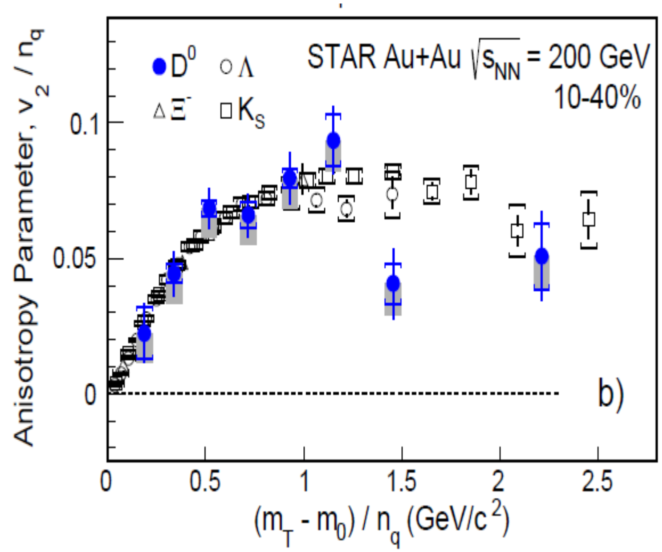
QGP as we know it:

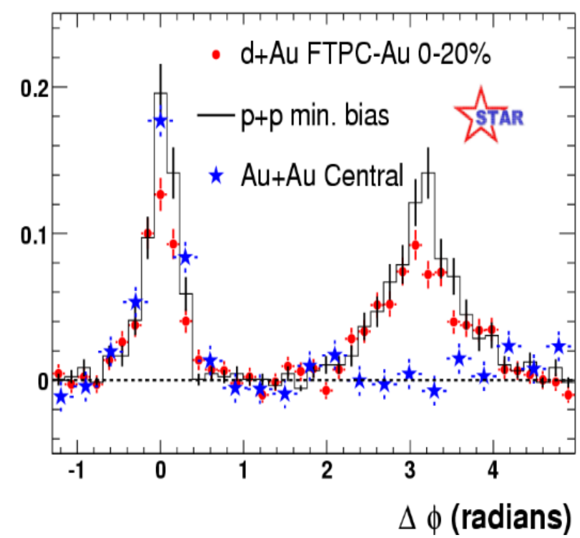
(in one sentence:)

...a strongly interacting thermalized partonic matter with (near) perfect fluidity

New: PRL118(2017)212301

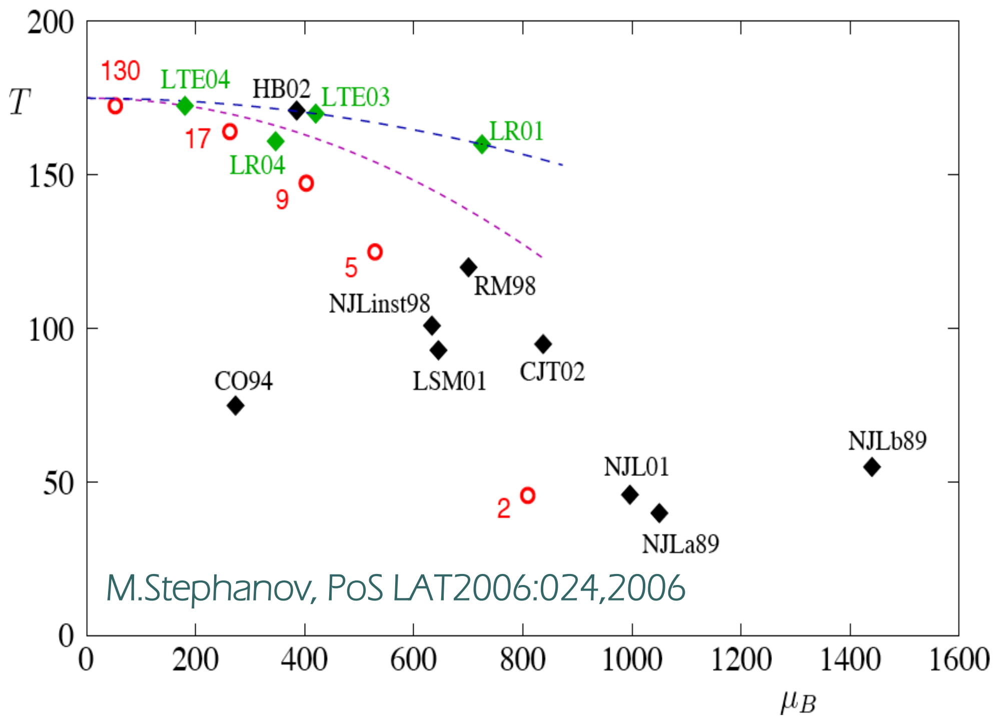






- Hadronization via quark coalescence
- Partonic energy loss in the medium

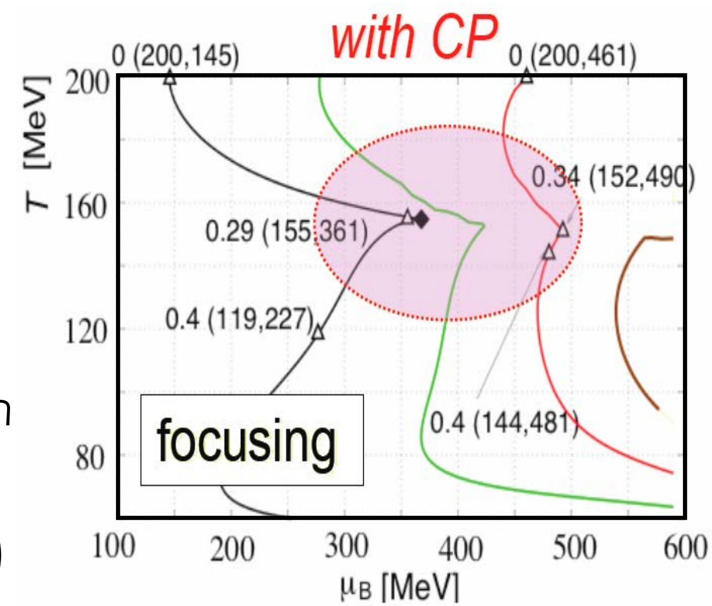
QCD Critical Point, in theory



M.Stephanov, PoS LAT2006:024,2006

Evolution of the system is attracted to the critical point

Focusing causes broadening of signal region



The "limits" of the phase diagram are well understood in theory:

smooth crossover at large T and μ_B~0 (LQCD)

1st order transition is predicted at large μ_B

Exact location is hard to determine theoretically

Search for QCD Critical point

Experimentally, one can access different regions of phase diagram by varying $\sqrt{s_{NN}}$

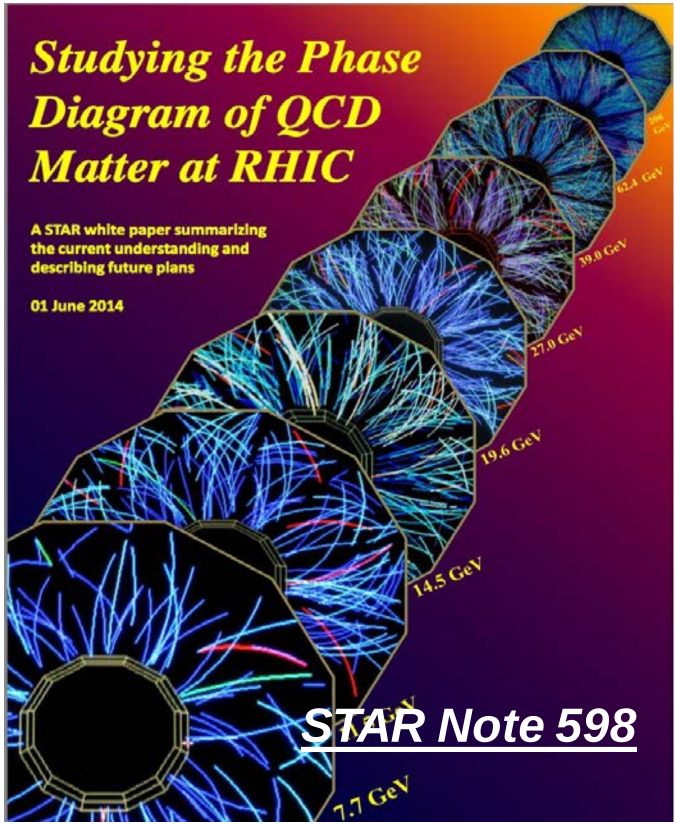
STAR BES strategy

Direct signatures of Critical Point

- Discontinuous trends in fluctuation observables

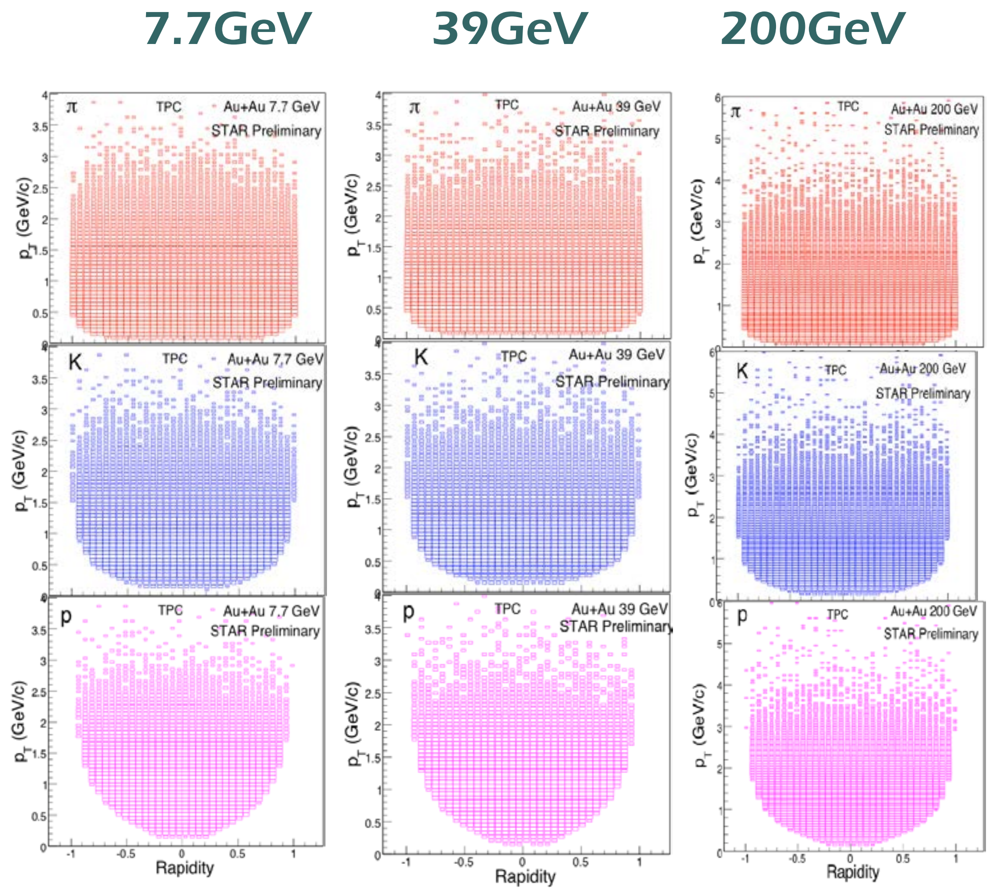
Search for onset of QGP signatures discovered at highest RHIC energy

- Number of constituent quark scaling
- Partonic collectivity
- Hadron suppression: opacity
- Local parity violation



RHIC BES program Phase-I

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
54.4	1300	2017
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010



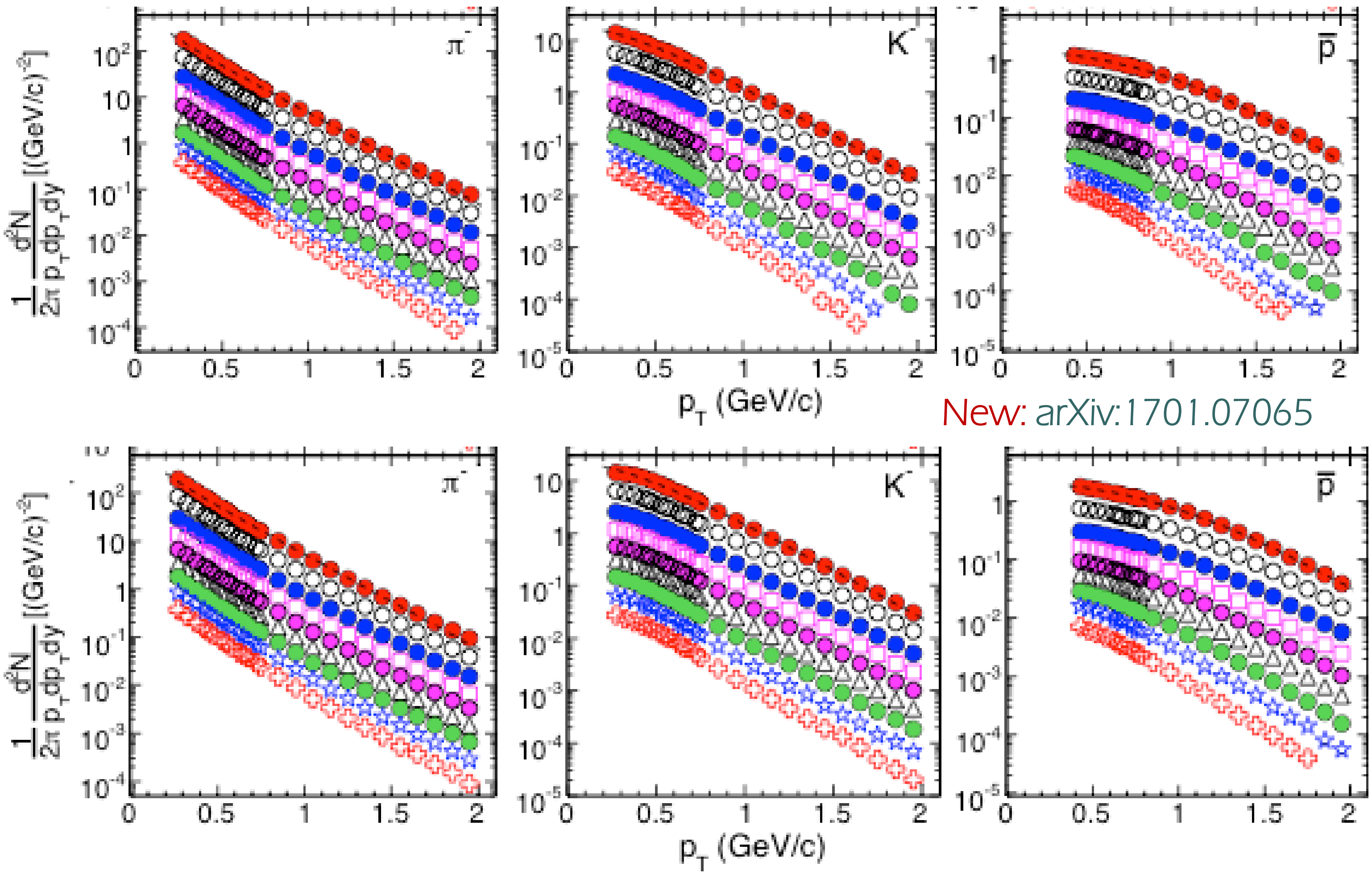
STAR advantage for Critical Point Search: RHIC versatility and particle identification over extended and uniform acceptance

Same detector: (partial) cancellation of systematic uncertainties

Particle Identification for BES

Au+Au 19.6 GeV

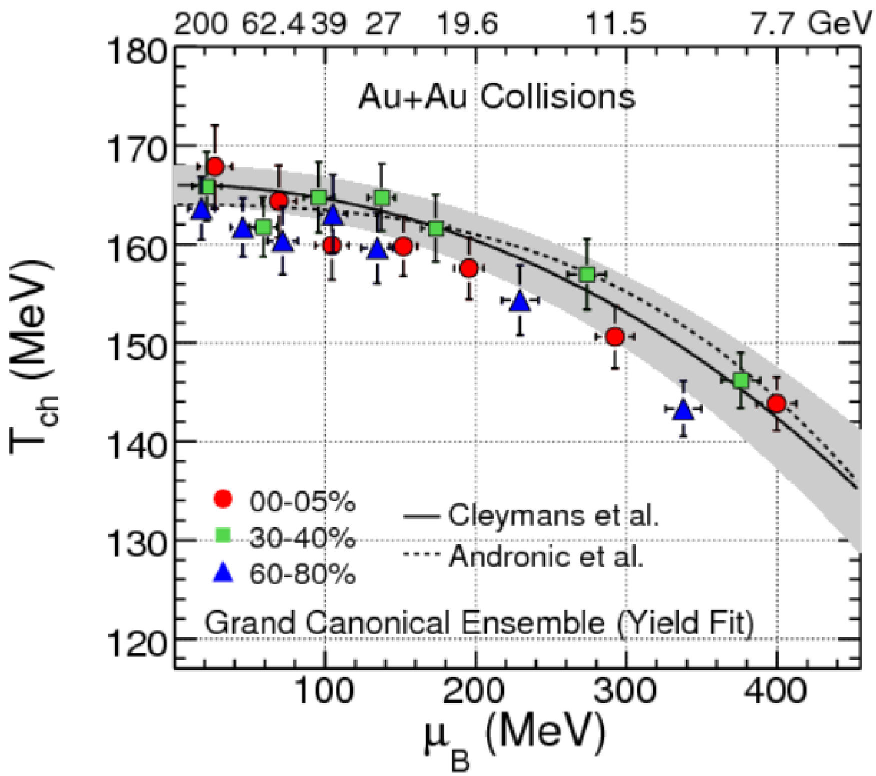
Au+Au 27 GeV



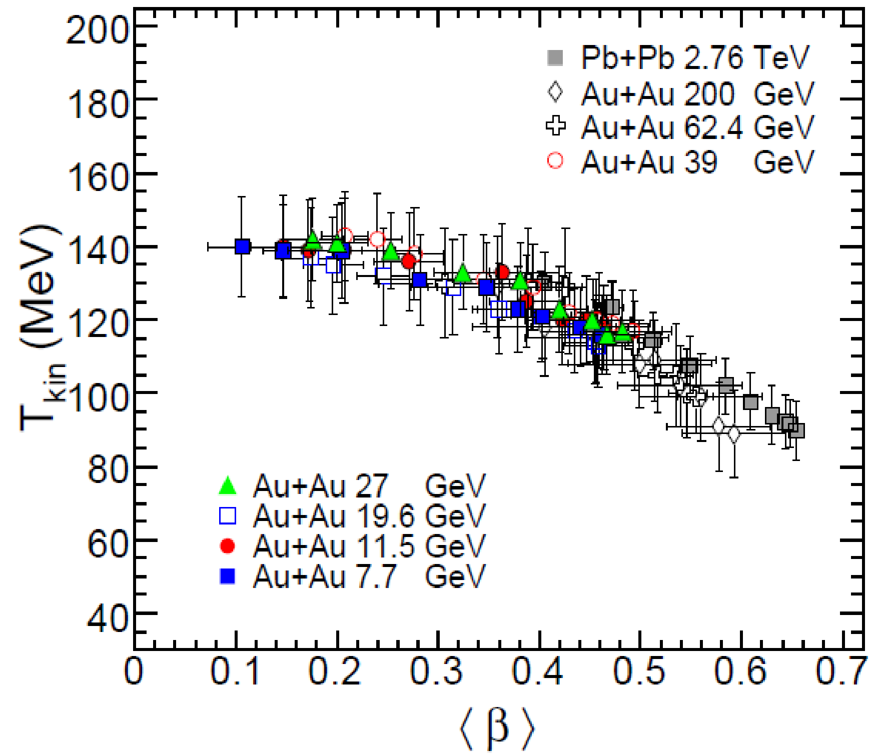
New: arXiv:1701.07065

New STAR identified particle spectra results from 19.6 and 27 GeV Au+Au collisions data

Freeze-out Dynamics



New: arXiv:1701.07065



Chemical Freeze-out:

Provides T, μ_B mapping of phase diagram

Smoothly evolving trends

Generally well described by empirical models

Kinetic Freeze-out:

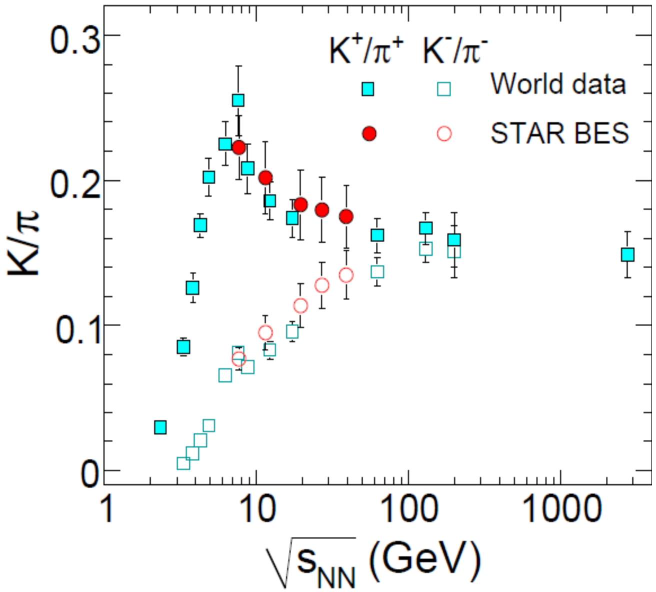
Explosive collective expansion

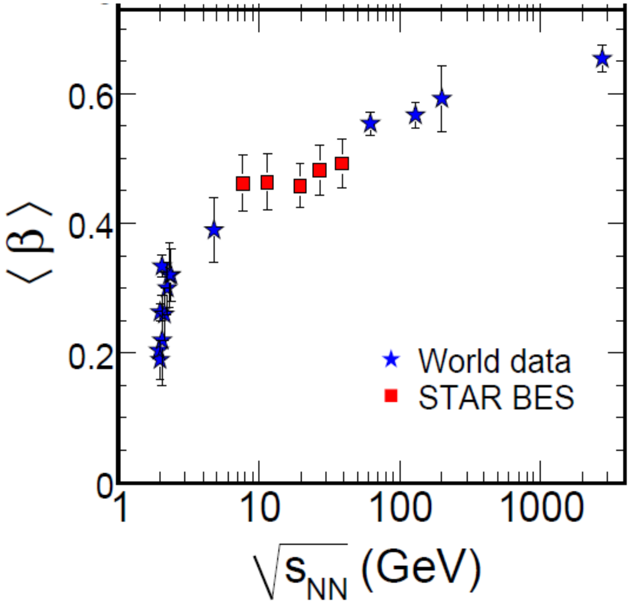
Higher radial flow for more central and higher energy collisions

Critical point search zone

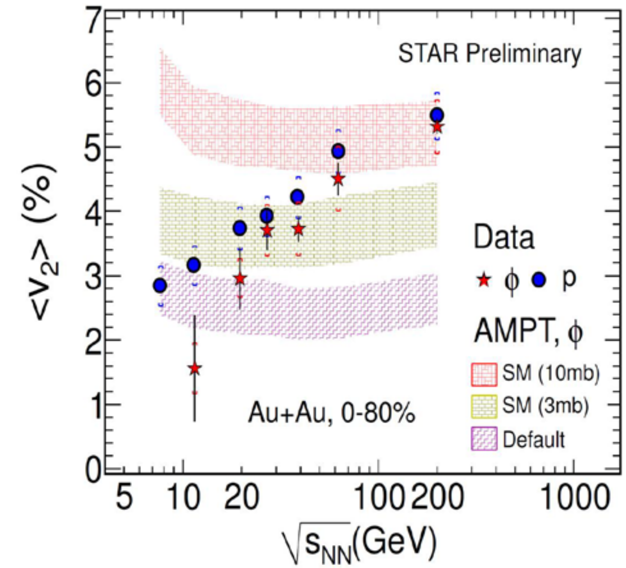
Many changing trends below ~20 GeV:

New: arXiv:1701.07065





STAR BES II White Paper



RHIC Beam Energy Scan

Phase-I (2009 – 2017)

7.7, 11.5, 14.5, 19.6, 27, 39, 54.4

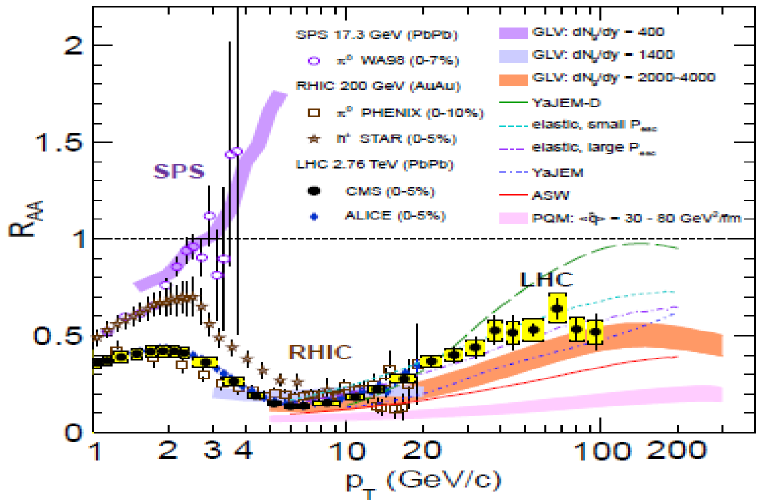
(62.4, 130,200)

Phase-II (2019 – 2020)

9.1, 11.5, 14.5, 19.6

FXT: 3.0, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7

Nuclear modification in BES-I

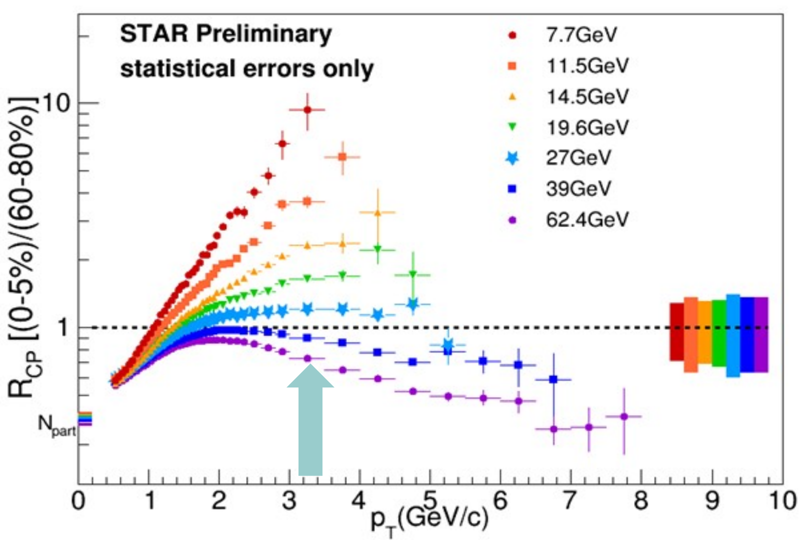


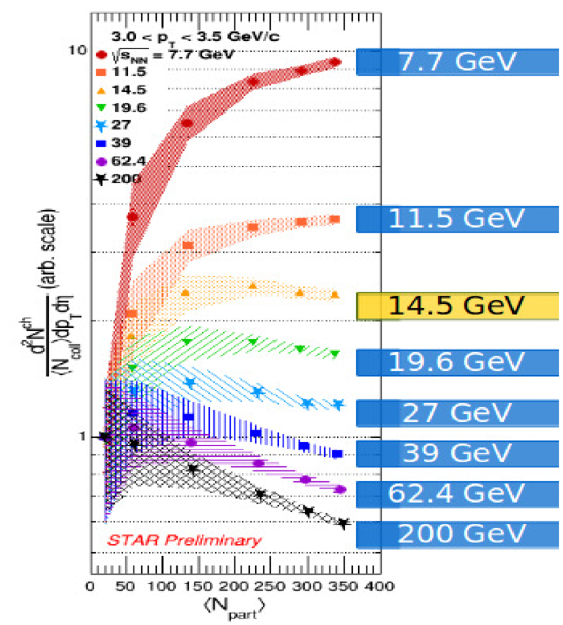
R_{CP} for hadrons and for charged particles probes partonic energy loss in the medium

BES-I results indicate disappearance of suppression bellow 14.5 GeV

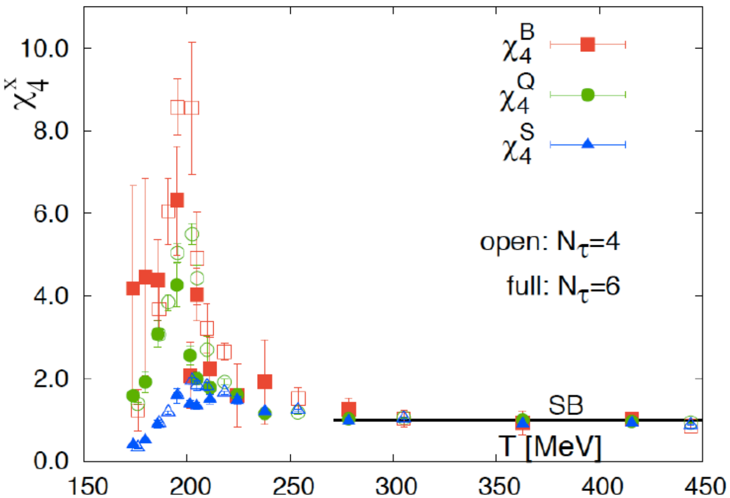
Would like to explore this with identified hadrons (to isolate baryon stopping)

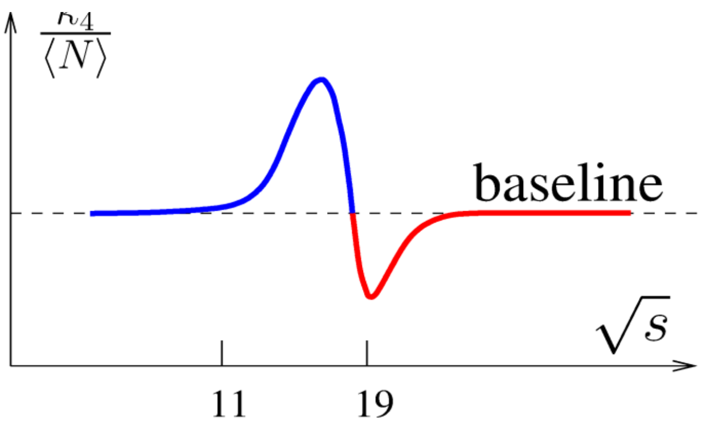
New: arXiv:1707.01988





CP signatures: theory





M.A. Stephanov, PRL107, 052301 (2011).
Schaefer&Wanger,PRD 85, 034027 (2012);

Divergence of the correlation length is expected near the QCD critical point

Should manifest itself in the non-monotonic behavior of correlations and fluctuations related to conserved quantities

$$<(\delta N)^2> \approx \xi^2, <(\delta N)^3> \approx \xi^{4.5}, <(\delta N)^4> -3<(\delta N)^2>^2 \approx \xi^7$$

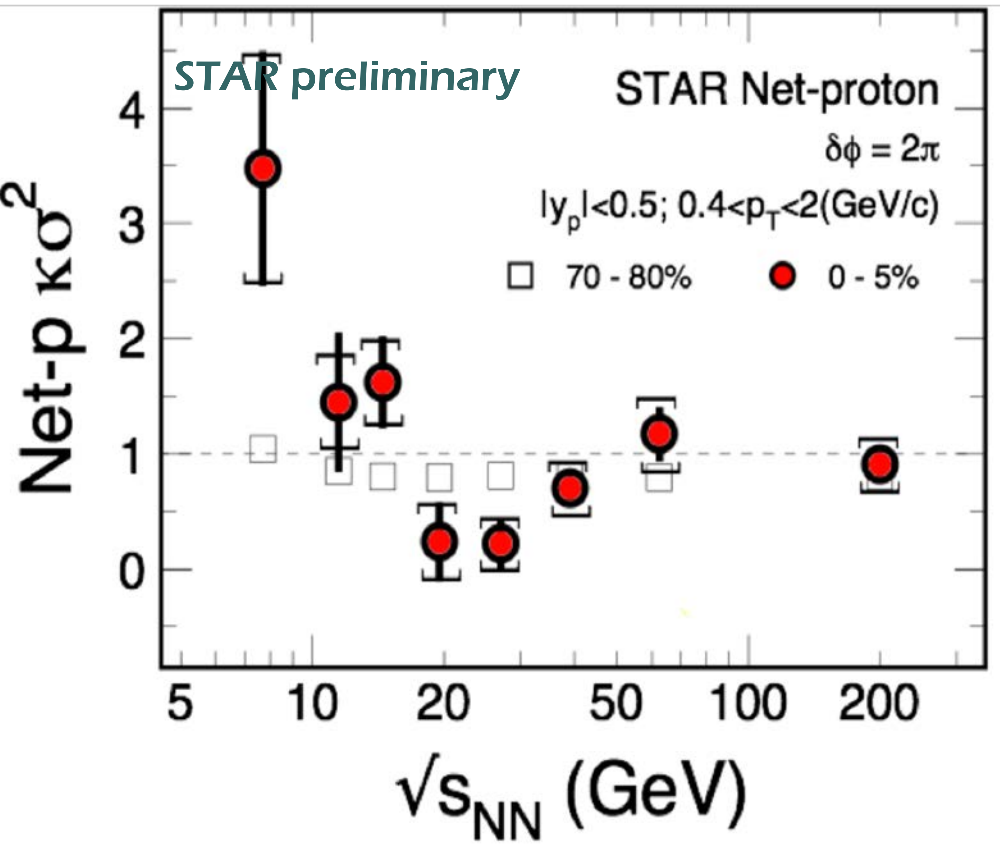
Higher moments of conserved quantum numbers (Q, S, B) are more sensitive to the correlation length

$$<(\delta N)^2> \approx \xi^2, <(\delta N)^3> \approx \xi^{4.5}, <(\delta N)^4> -3<(\delta N)^2>^2 \approx \xi^7$$

Theory predicts an oscillation pattern in the energy dependence of the higher order moments

Higher moments in BES-I

X.Luo PoS CPOD2014 (2015) 019



Excitation function for net-proton higher moments ($\kappa\sigma^2$) in 5% most central Au+Au collisions

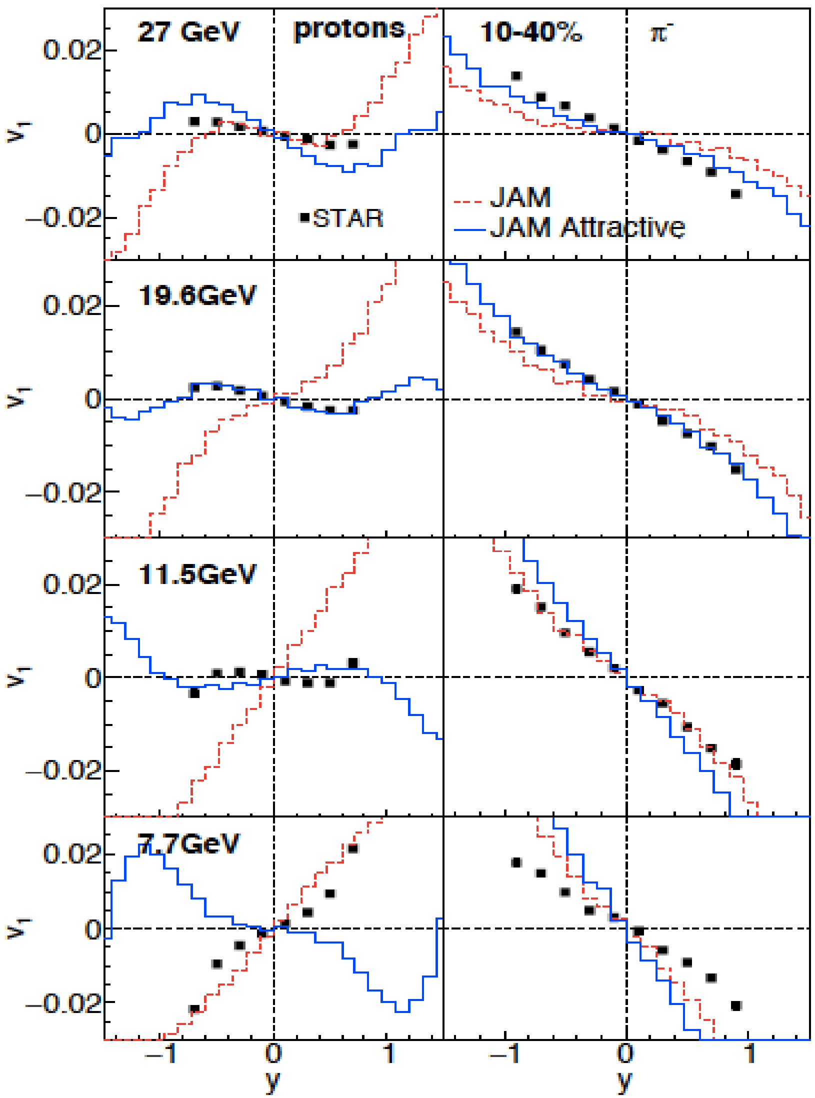
Changing trends at ~20GeV

Will the oscillation pattern emerge at lower energies?

Caveat: no such trend is seen in net-charge or net-kaon distributions

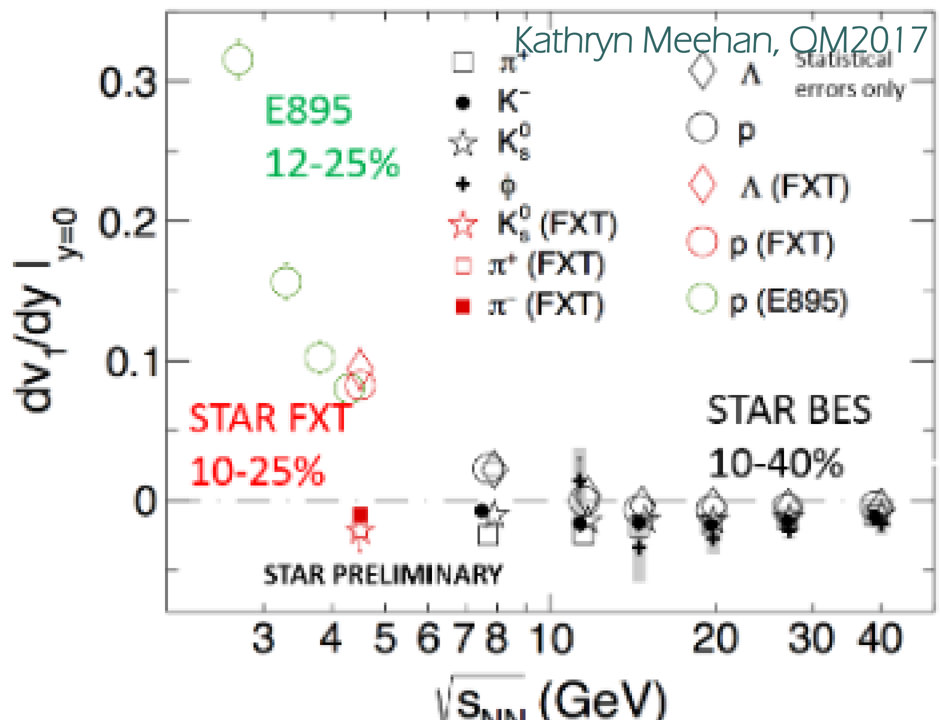
Directed flow slope in BES-I

Y. Nara, A. Ohnishi, H. Stoecker,
arXiv: **1601.07692** ; PRC94, 034906(2016)



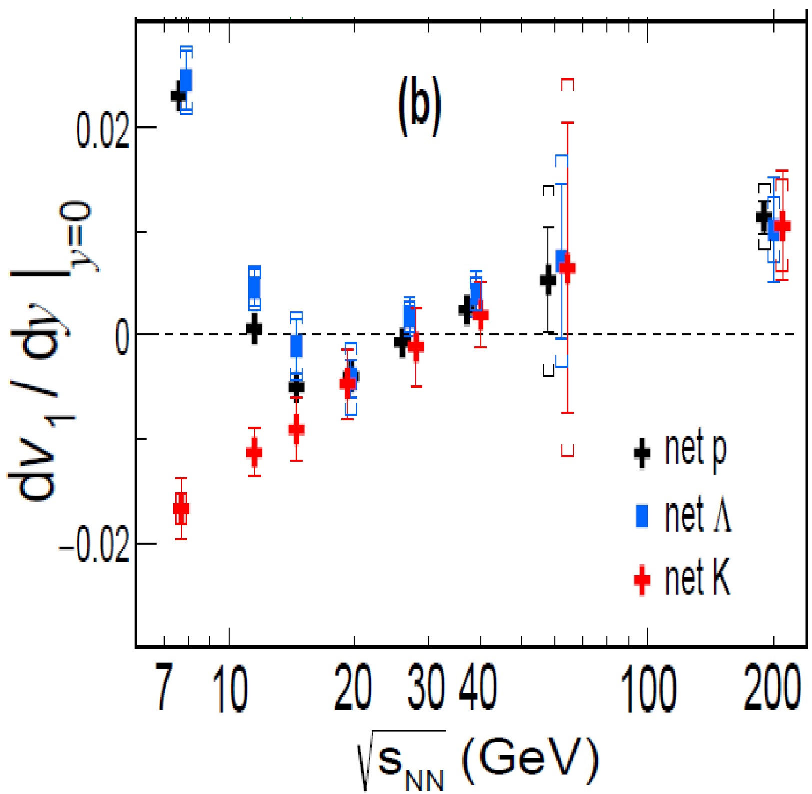
Changes in EoS due to attractive force
→ Softest point

Such softening can be interpreted as evidence for a first-order phase transition.



Directed flow slope vs. energy

New: arXiv:1708.07132



A minimum in the dv_1/dy could indicate the Softest point in EOS

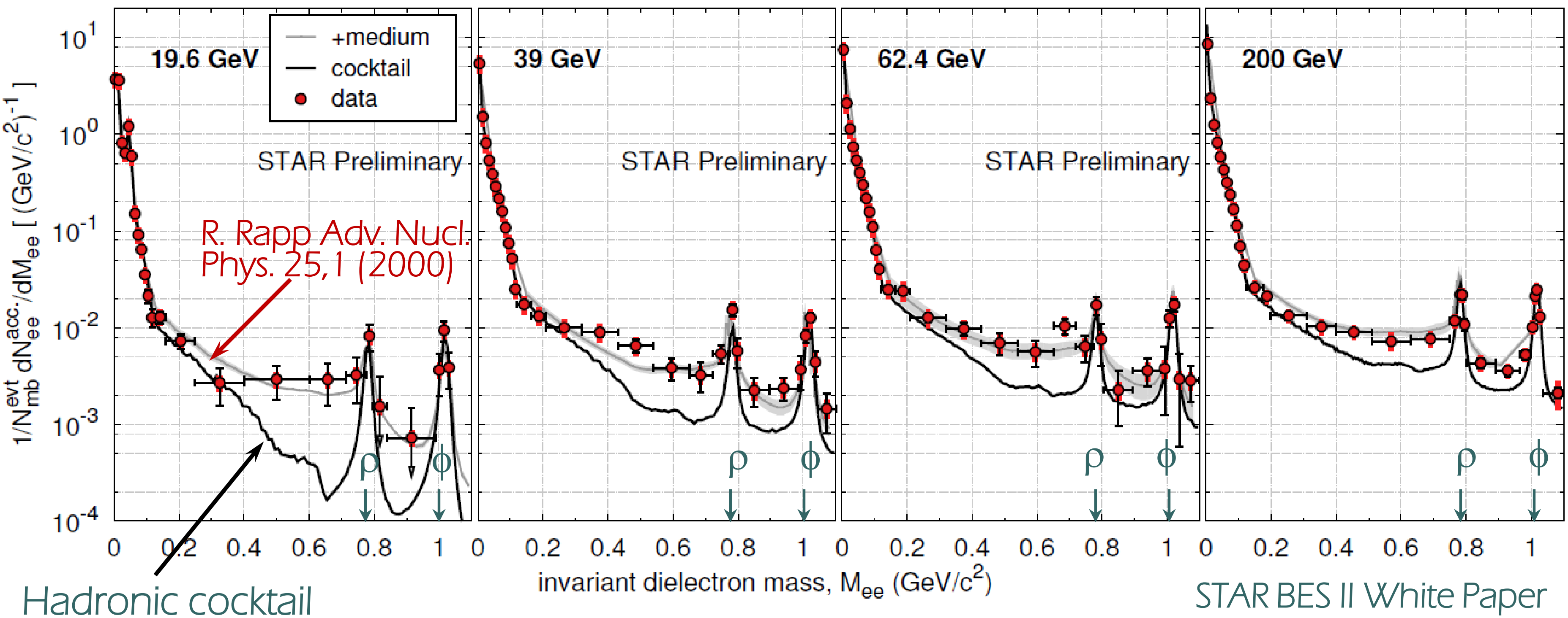
A “dip” is observed for net-proton (and net-Lambdas), but not for net-kaon

Puzzling to have the “Softest point” for only baryons

To date no model reproduces the trend

Need detailed studies extending to low energies

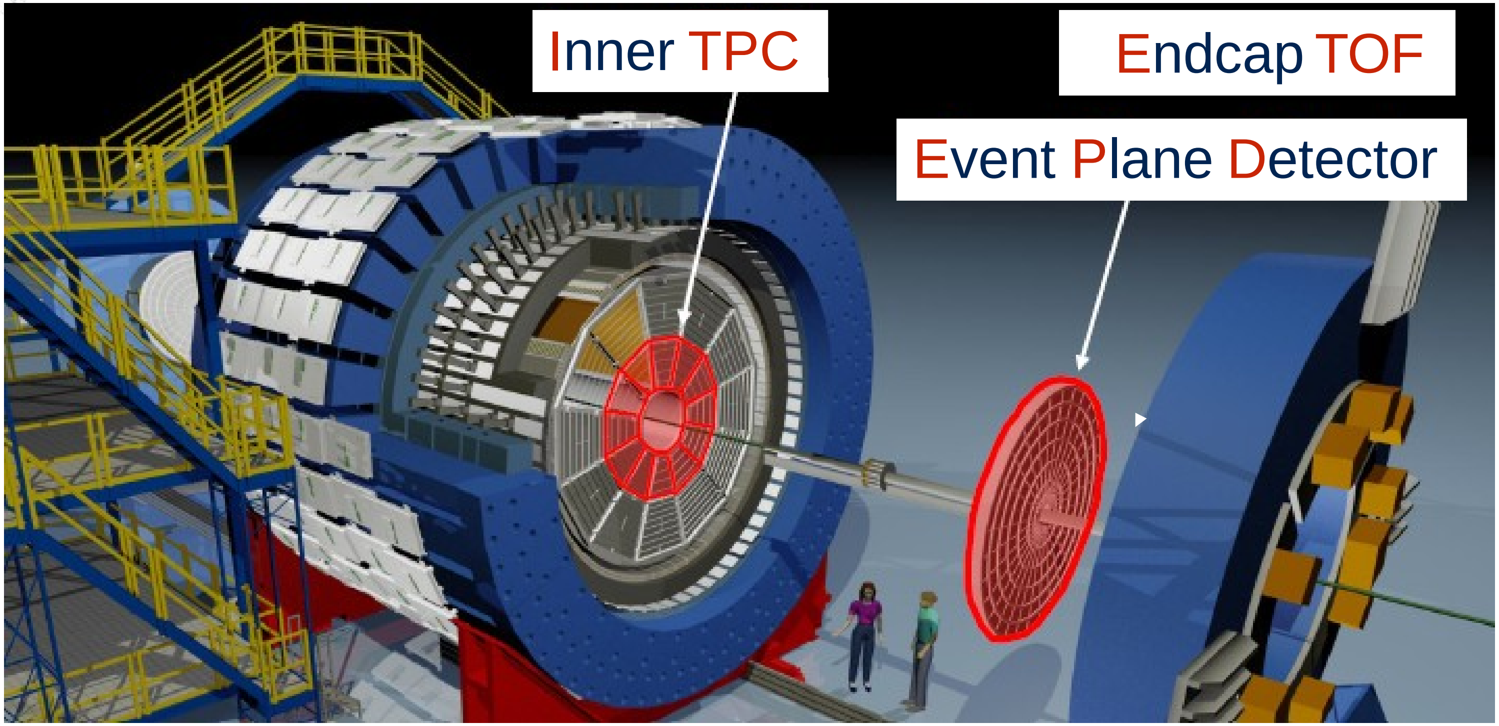
Chiral Phase transition



Dilepton mass spectra can be described by model with QGP+HG phases which include in-medium ρ broadening

Need to extend this measurement to low energies

Detector upgrades for BES-II



iTPC	EPD	eTOF
Continuous pad rows Replace all inner TPC sectors	Replace Beam-Beam Counter	Add CBM TOF modules and electronics
$\|\eta\|<1.0 \rightarrow \|\eta\|<1.5$	$2.1<\|\eta\|<5.1$	$-1.6 < \eta < -1.1$
Better dE/dx and momentum resolution	Better triggering and greatly improved EP resolution	Extend forward PID capability, Extended reach for FXT

Detector upgrades for BES-II

BES-II Detector upgrades promises many analysis improvements

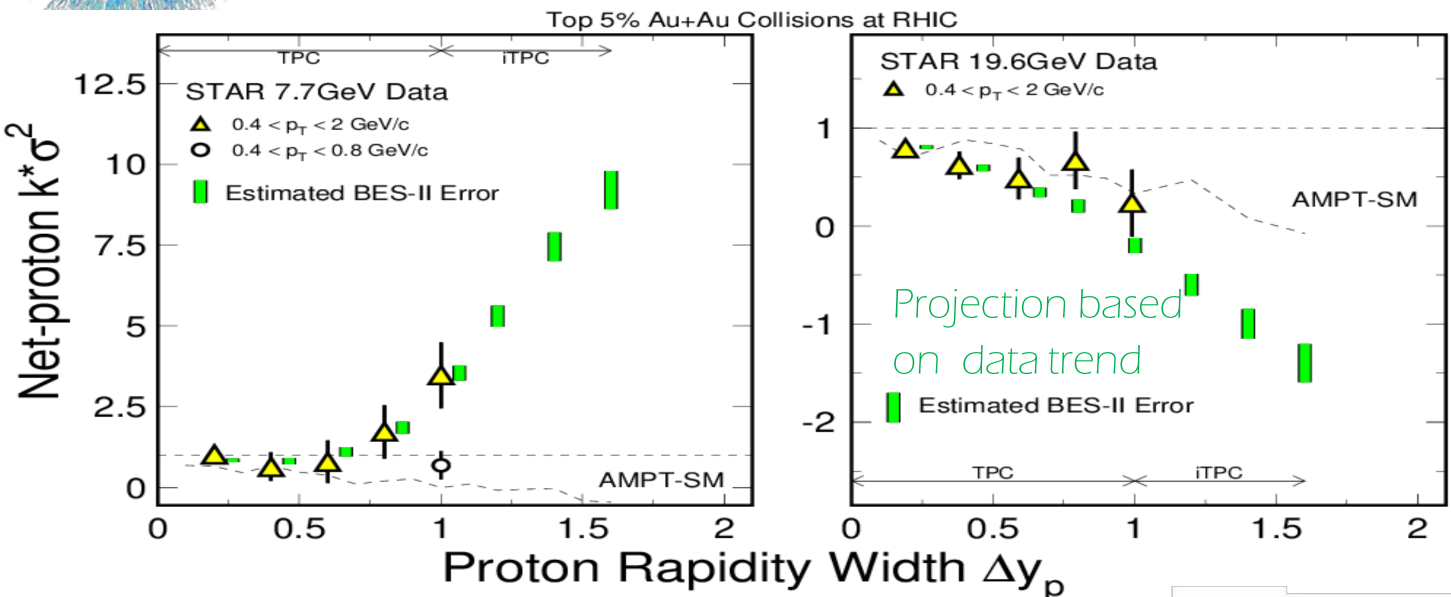
Significant improvements in terms of statistical and systematic uncertainties
Advanced PID capability
Broader kinematic coverage

RHIC Upgrade

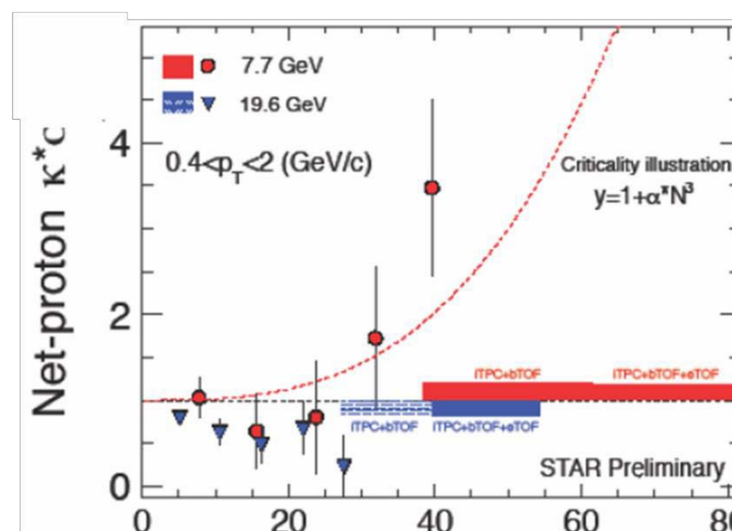
Low Energy Electron Cooling at RHIC
Expected luminosity increase by factors 3-10 for BES collision energies

	iTPC	EPD	eTOF
2017	-	1/8 installed	1 prototype
2018	One sector	Full Installation	3 modules at one sector
2019	Full Installation	Full Installation	Full Installation

Net-proton moments in BES-II



arXiv:1609.05102



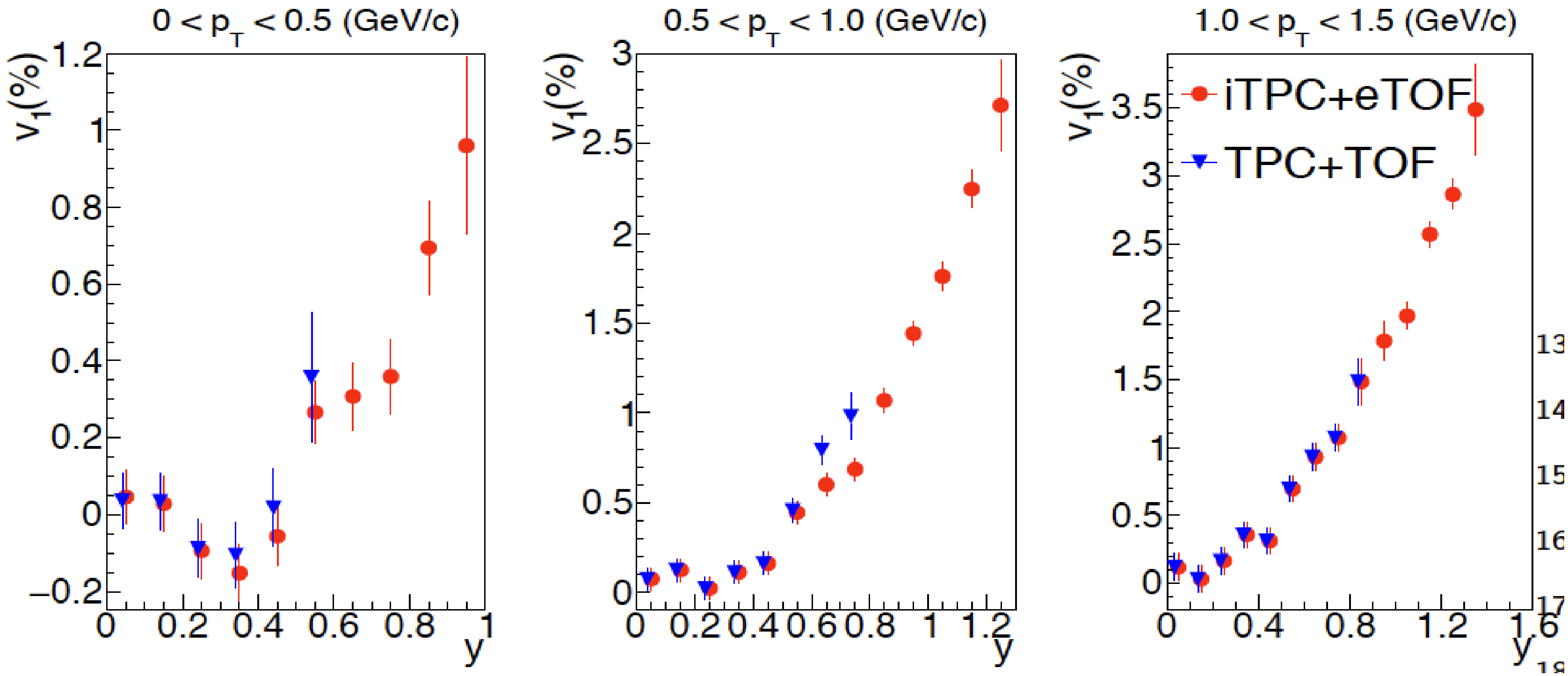
Non-monotonic behavior observed in BES-I data demands further studies

Extending rapidity range Δyp will help establishing the nature of correlation

Directed flow in BES-II

Modeled with UrQMD at 19.6 GeV

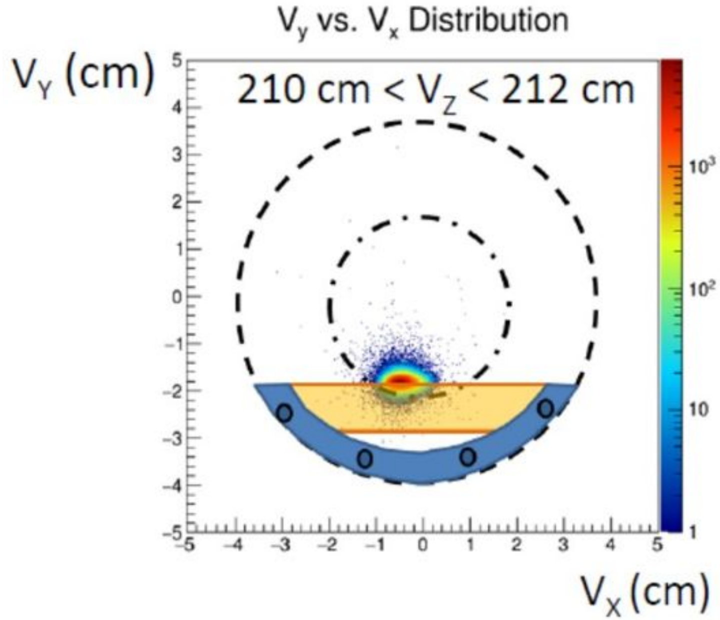
arXiv:1609.05102

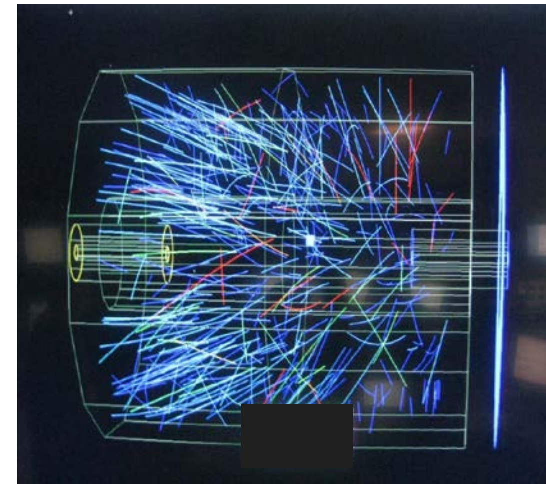


Possible softening of EoF – a standing prediction for 1st-order phase transition

Exploring broader rapidity range in BES-II – dynamics could be different in forward region

STAR in the Fixed Target mode



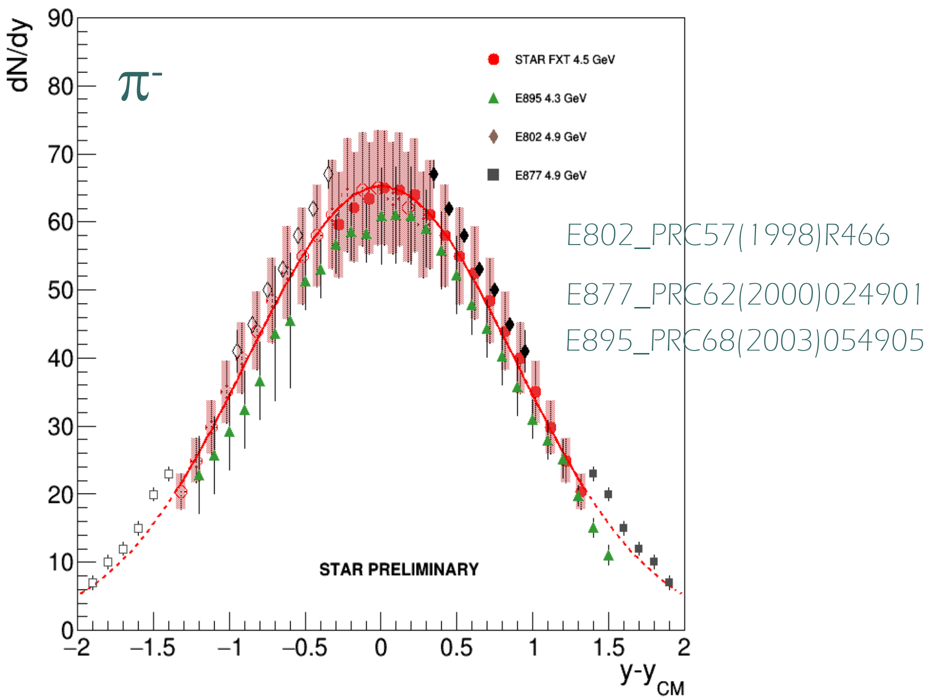


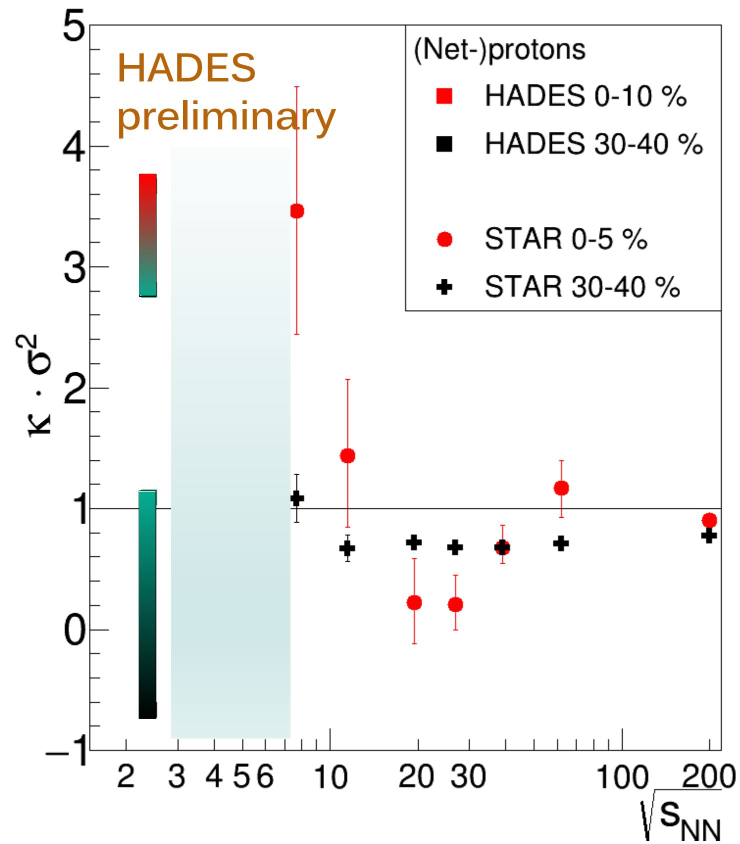
Proposed Fixed target program will be able to explore $\sqrt{s_{NN}}$ energy range between 3.0 and 7.7 GeV

The target is located just outside the STAR TPC at ~210cm

STAR in the Fixed Target mode

Au+Au @ 4.5 GeV





"Proof of principle" results presented at QM2017, many more underway (Lambdas, Kaons, HBT, v_n,...)

Will be able to extend high-moments measurements to HADES energies

Summary

- BES-I results indicated turn-off of QGP signatures and hints of critical behavior
- Many critical measurements require larger data samples (higher moments of net-proton distributions, ϕ-meson flow, di-leptons, …)
- BES-II program provides a well define plan for the phase diagram exploration:

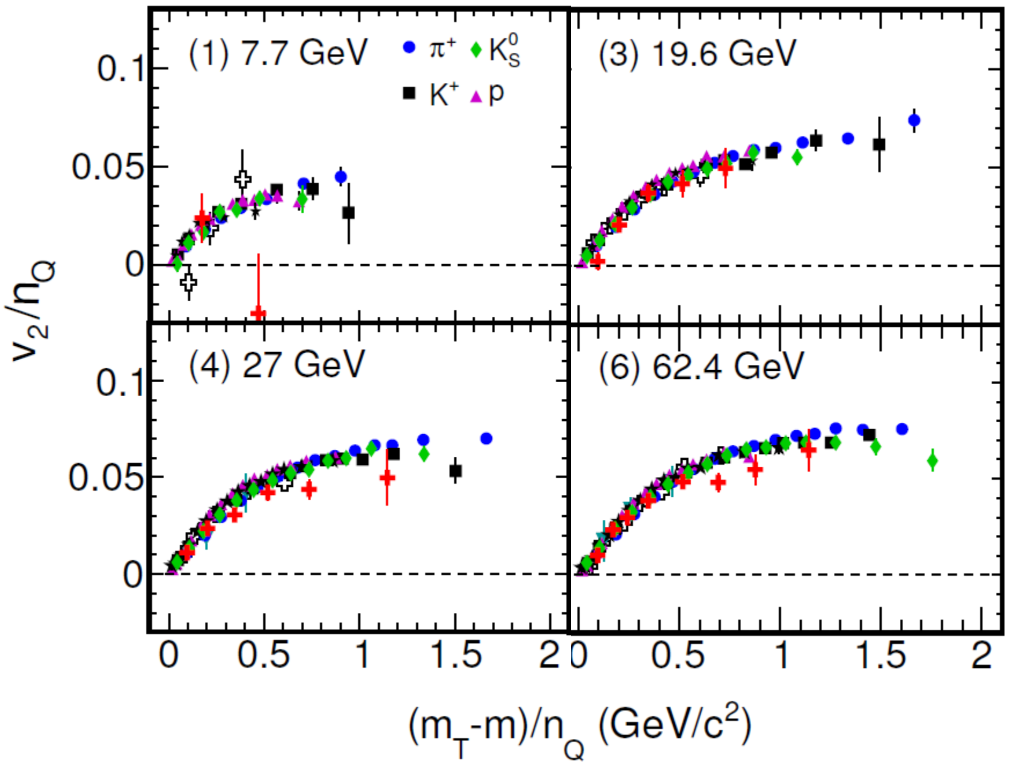
  Ongoing detector/facility upgrades will extend kinematic coverage and physics reach

  Fixed-target program will further extend μ_B reach of the energy scan

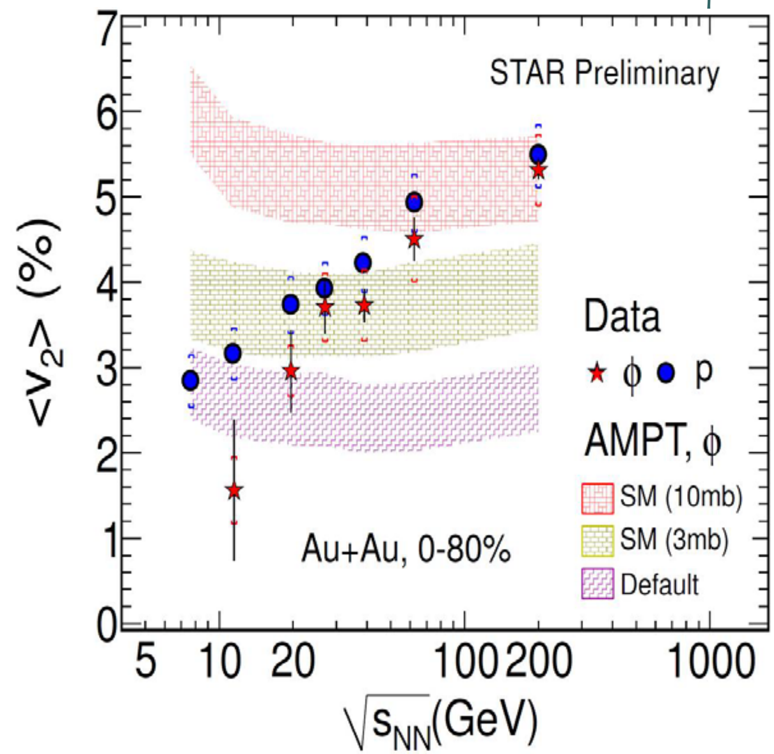
Looking forward to new measurements revealing signs of the first-order phase transition and pin-pointing location of the QCD critical point!

Thank you!

ϕ-meson elliptic flow



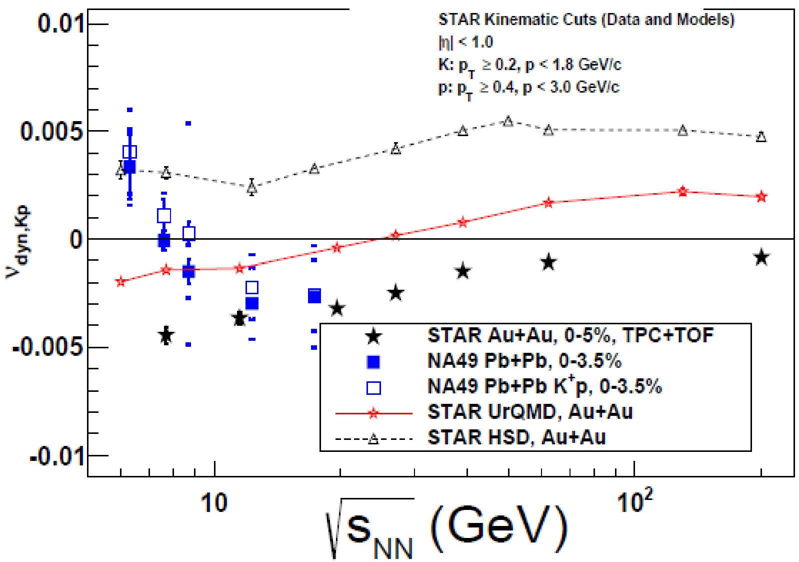
STAR BES II White Paper

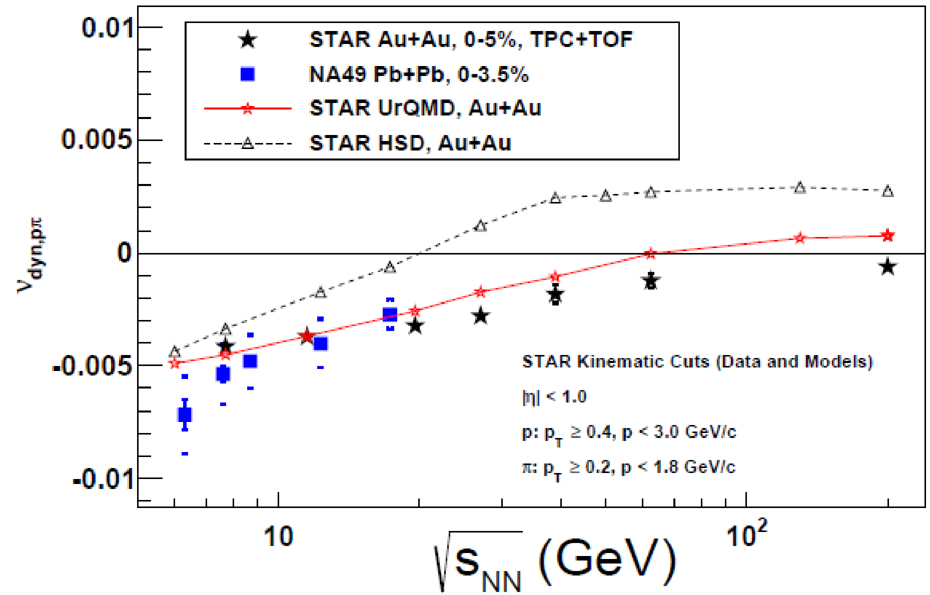


Non-zero ϕ-meson v_2 is indicative of partonic nature of elliptic flow.
Departure of the ϕ-meson p_T-integrated v2 values from the ones of protons?

Identified Particle fluctuations

PRC 92(2015)21901





Kπ **fluctuations:** tensions between STAR and NA49 results (no energy dependence in STAR measurements, disagreement at 7.7GeV)

pπ **fluctuations:** consistent across entire explored energy range

Predictions for higher moments

Connections with thermodynamics susceptibilities in LQCD and other models (e.g. HRG)

arXiv: 0811.1006
arXiv:1007.2581
arXiv:1001.3796

$$\chi_B^{\ 2} = \frac{1}{VT^3} < \delta N_B^{\ 2} >$$

$$\chi_B^{\ 3} = \frac{1}{VT^3} < \delta N_B^{\ 3} >$$

$$\chi_B^{\ 4} = \frac{1}{VT^3} (< \delta N_B^{\ 4} > - 3 < \delta N_B^{\ 2} >^2)$$

→

Kurtosis x Variance^2 = χ^4 / χ^2
Skewness x Variance = χ^3 / χ^2

Y.Hatta et al., PRL 91, 102003 (2003)

net-baryon fluctuations ~ net-proton number fluctuations

Probe correlation length (ξ)

High moments sensitive to high power of the correlation length

$$< (\delta N)^2 > \approx \xi^2, < (\delta N)^3 > \approx \xi^{4.5}, < (\delta N)^4 > - 3 < (\delta N)^2 >^2 \approx \xi^7$$

at or near CP non-Gaussian fluctuations expected to dramatically increase

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)

STAR BUR for 2019

Assuming 24 cryo-weeks

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Number Events	Priority	Sequence
9.8	19.6	4.5 weeks	Au+Au	400M MB	1	1
7.3	14.5	5.5 weeks	Au+Au	300M MB	1	3
5.75	11.5	5 weeks	Au+Au	230M MB	1	5
4.6	9.1 [1]	4 weeks	Au+Au	160M MB	1	7
9.8	4.5 (FXT)	2 days	Au+Au	100M MB	2	2
7.3	3.9 (FXT)	2 days	Au+Au	100M MB	2	4
5.75	3.5 (FXT)	2 days	Au+Au	100M MB	2	6
31.2	7.7 (FXT)	2 days	Au+Au	100M MB	2	8
19.5	6.2 (FXT)	2 days	Au+Au	100M MB	2	9
13.5	5.2 (FXT)	2 days	Au+Au	100M MB	2	10

Event number estimates assume low-energy electron cooling ready mid-way through run & performs at design for 11.5 & 9.1 GeV running

Comparison of the facilities

Facilty	RHIC BESII	SPS	NICA	SIS-100 SIS-300	J-PARC HI
Exp.:	STAR +FXT	NA61	MPD + BM@N	CBM	JHITS
Start:	2019-20 2018	2009	2020 2017	2022	2025
Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6 2.5-7.7	4.9-17.3	2.7 - 11 2.0-3.5	2.7-8.2	2.0-6.2
Rate: At 8 GeV	100 HZ 2000 Hz	100 HZ	<10 kHz	<10 MHZ	100 MHZ
Physics:	CP&OD	CP&OD	OD&DHM	OD&DHM	OD&DHM
	Collider Fixed Target	Fixed Target Lighter ion collisions	Collider Fixed Target	Fixed Target	Fixed Target

CP = Critical Point
OD = Onset of Deconfinement
DHM = Dense Hadronic Matter

Compilation by Daniel Cebra