Beam Energy Scan at RHIC

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Quark Gluon Plasma and Future Directions in Heavy Ion Physics at RHIC and LHC,
4th joint meeting of APS-DNP and JPS,
Hawaii, Oct 7-11

筑波大学
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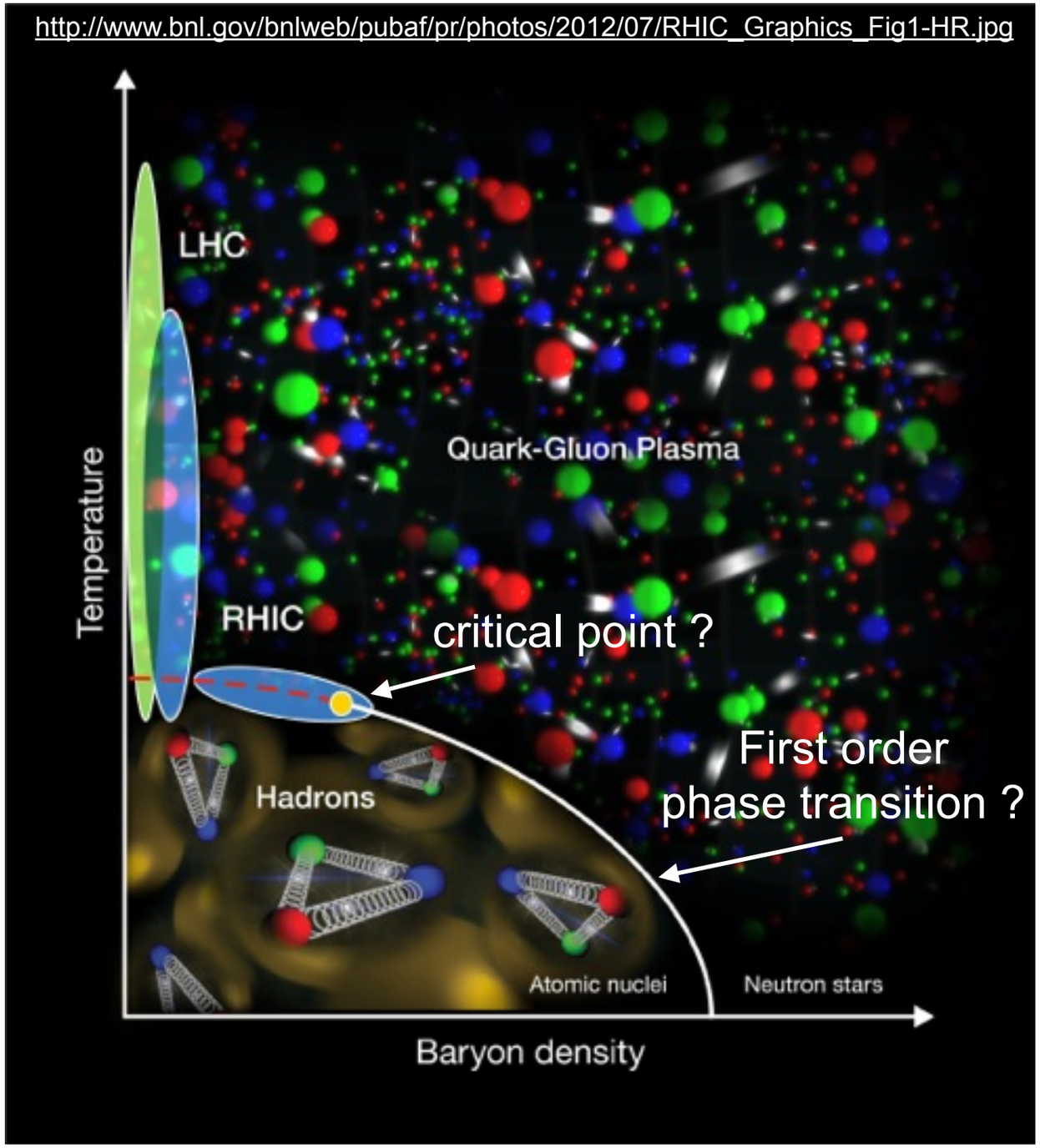
Outline

- Introduction
  - RHIC Beam Energy Scan (BES) phase-I
- Review selected results
- Future upgrade for BES phase-II
  - RHIC luminosity upgrade, sPHENIX & STAR upgrade
- Summary

RHIC Beam Energy Scan (BES)



- Cross-over transition at μ_B=0
  - from 1st principle Lattice QCD calculations
- If phase transition is 1st order at high baryon density, the end point is QCD critical point
- Beam energy scan → reach high baryon density
- Goals of BES at RHIC:
  - Search for turn-off QGP signals
  - Search for signals of 1st order phase transition
  - Search for signals of QCD critical point

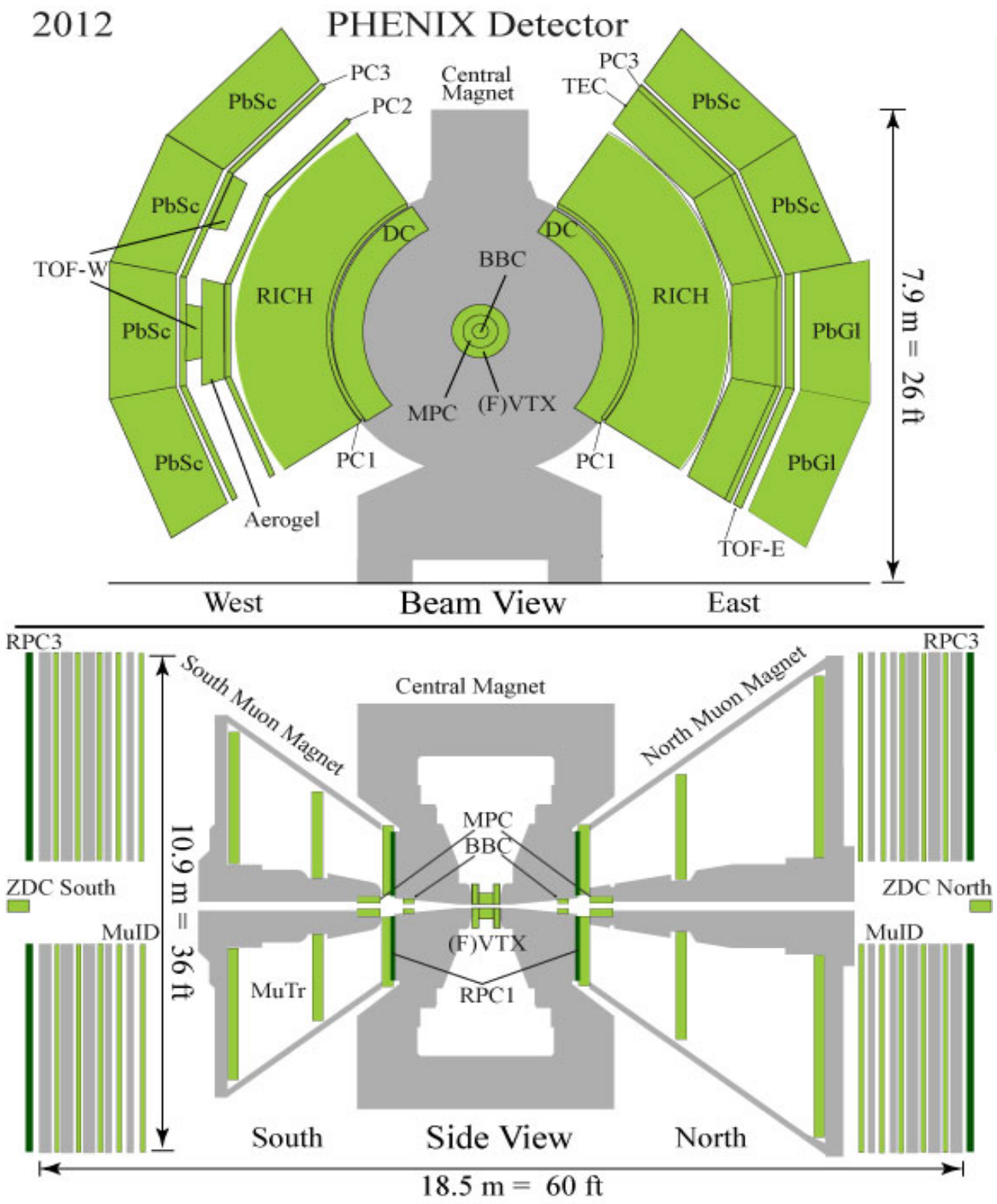
RHIC heavy ion collisions

√ (GeV	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
200	Au+Au	Au+Au	d+Au	Au+Au	Cu+Cu		Au+Au	d+Au		Au+Au	Au+Au	U+U & Cu+Au		He+Au
130				Au+Au	Cu+Cu									
62.4										Au+Au				
39										Au+Au				
27											Au+Au			
22.					Cu+Cu									
19.											Au+Au			
14.														Au+Au
11.										Au+Au				
7.7										Au+Au	Au+Au			
Test run							9.2 GeV					5 GeV		

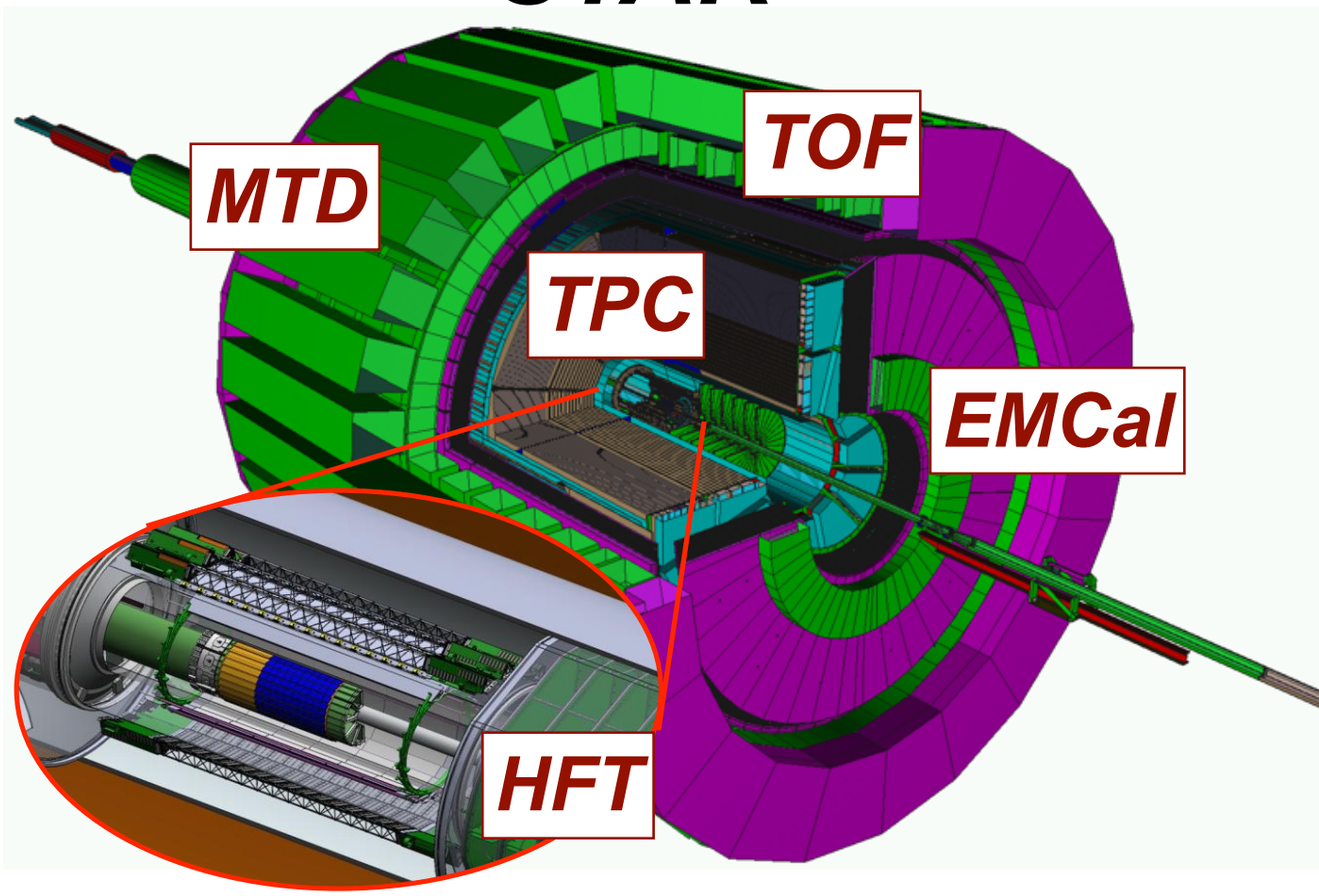
- Beam Energy Scan (BES) phase-I (year 2010, 2011)
  - 7.7, 11.5, (14.5), 19.6, 27, 39, 62.4 GeV
- 14.5 GeV has just taken this year

Au+Au Cu+Cu d+Au He+Au U+U (193 GeV) & Cu+Au

PHENIX & STAR experiments

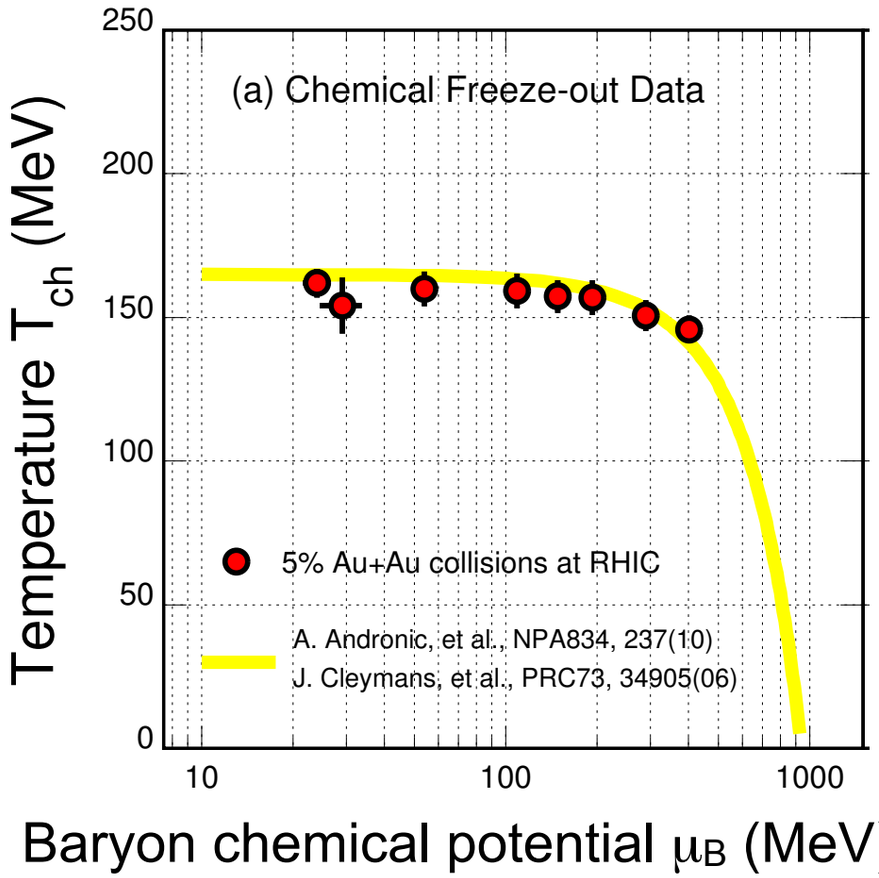


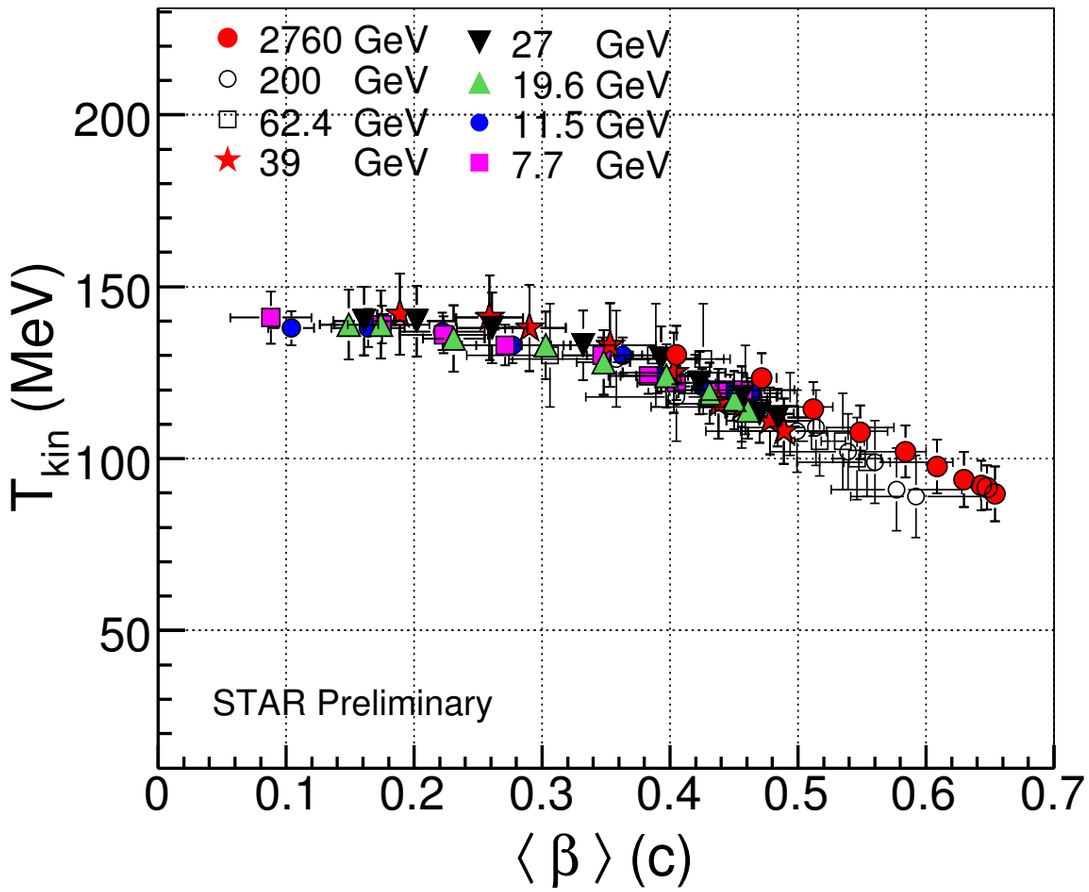
STAR



- Good acceptance in STAR
- Fast trigger, good forward counters in PHENIX
- Similar PID capabilities

Where are we in QCD phase diagram ?

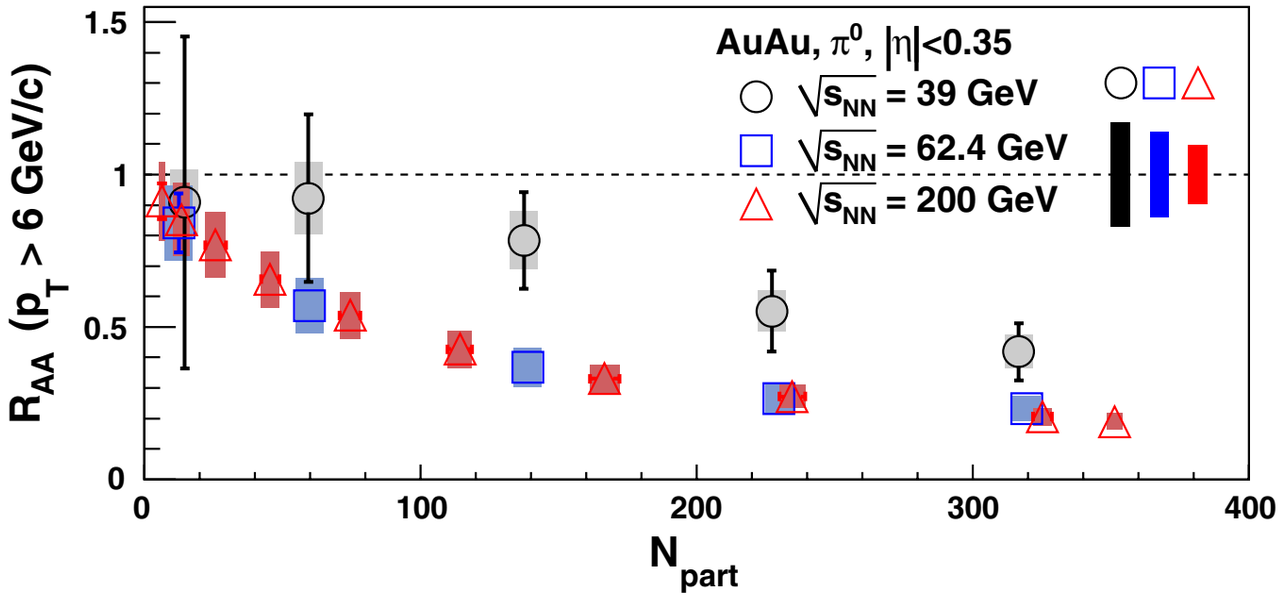




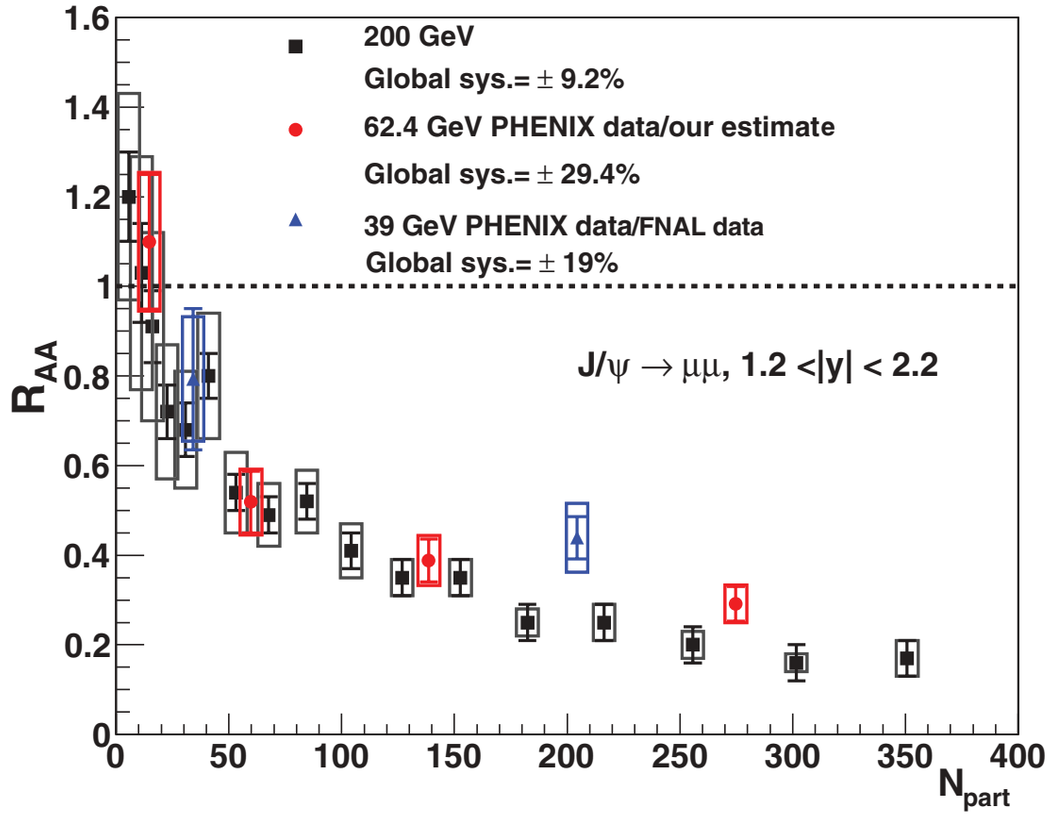
- RHIC BES phase-I covers up to ~ 400 MeV in μ_B
  - Chemical freeze-out temperature & baryon chemical potential from particle ratio
  - Kinetic freeze-out temperature from p_T spectra

Nuclear modification factor R_{AA}

PHENIX: ***PRL109****, 152301 (2012)*



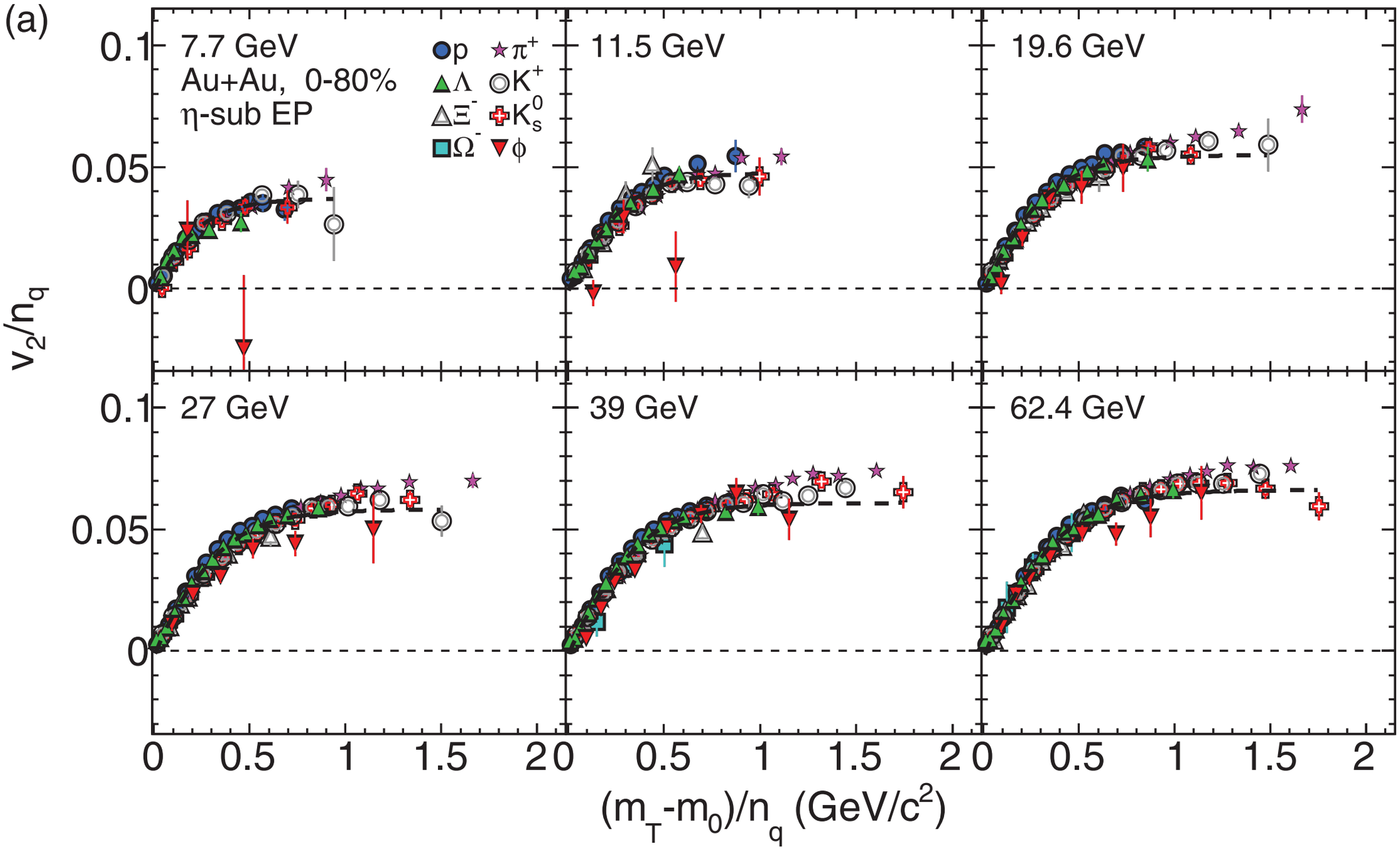
PHENIX: ***PRC86****, 064901 (2012)*



- Parton energy loss in colored medium
  - π^0 R_{AA} is suppressed in most central 0-10% at $\sqrt{s_{NN}}$ = 39 GeV
    - Results in Cu+Cu 22.5 GeV show enhancement in p_T = 4 GeV/c
  - J/ψ R_{AA} is also suppressed at 39 GeV, similar with 62.4 and 200 GeV

Elliptic flow v_2

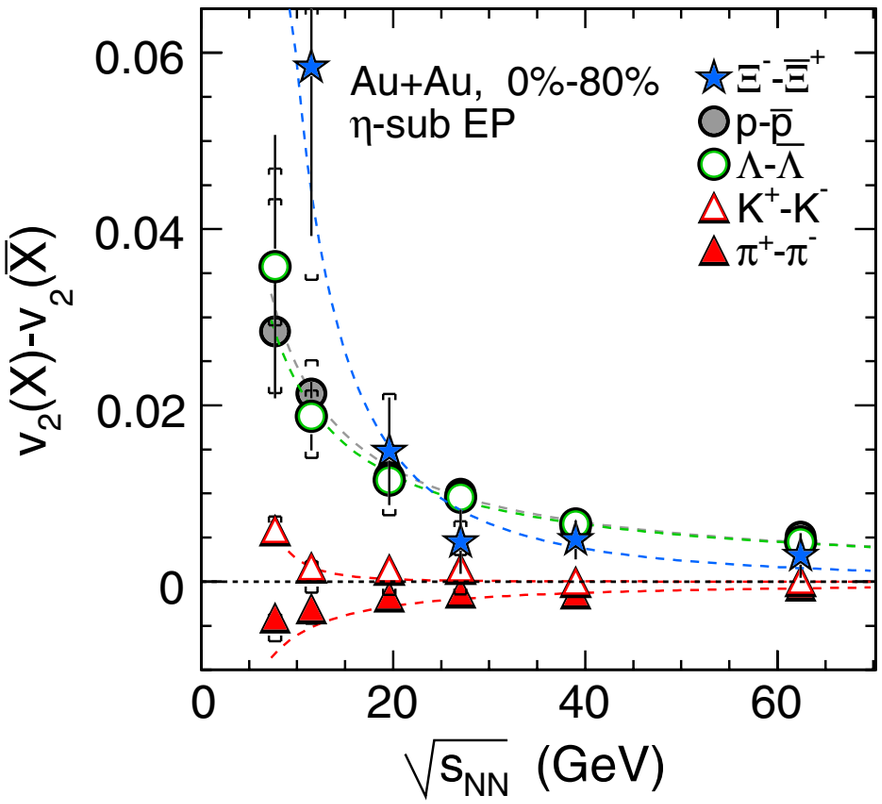
STAR: **PRC88**, 014902 (2013)



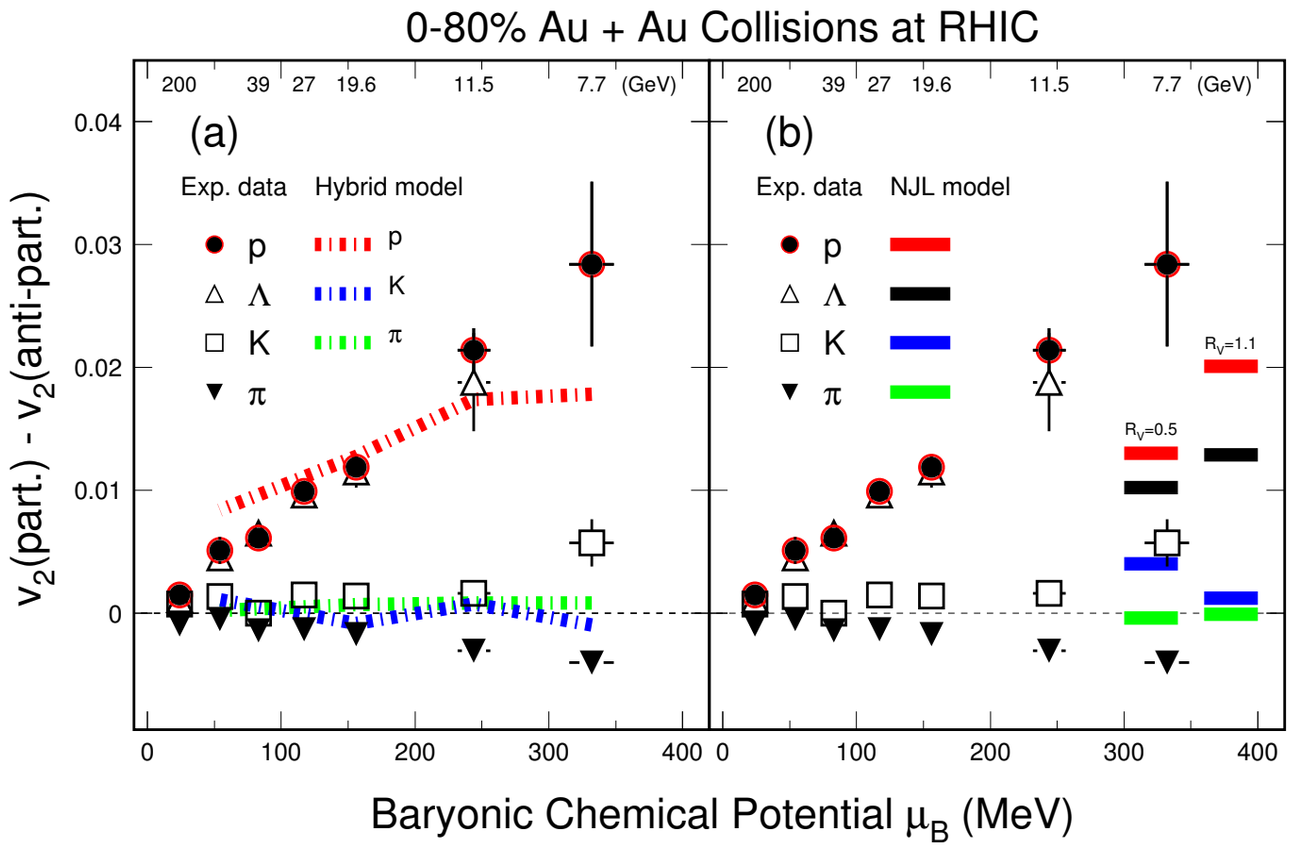
- Number of constituent quark (NCQ) scaling - partonic d.o.f
  - Hold separately for particles and anti-particles
  - Need more statistics in high m_T-m_0 at lower energies

v_2; particles vs anti-particles

STAR: ***PRL110****, 142301 (2013),*
PRC88*, 014902 (2013)*



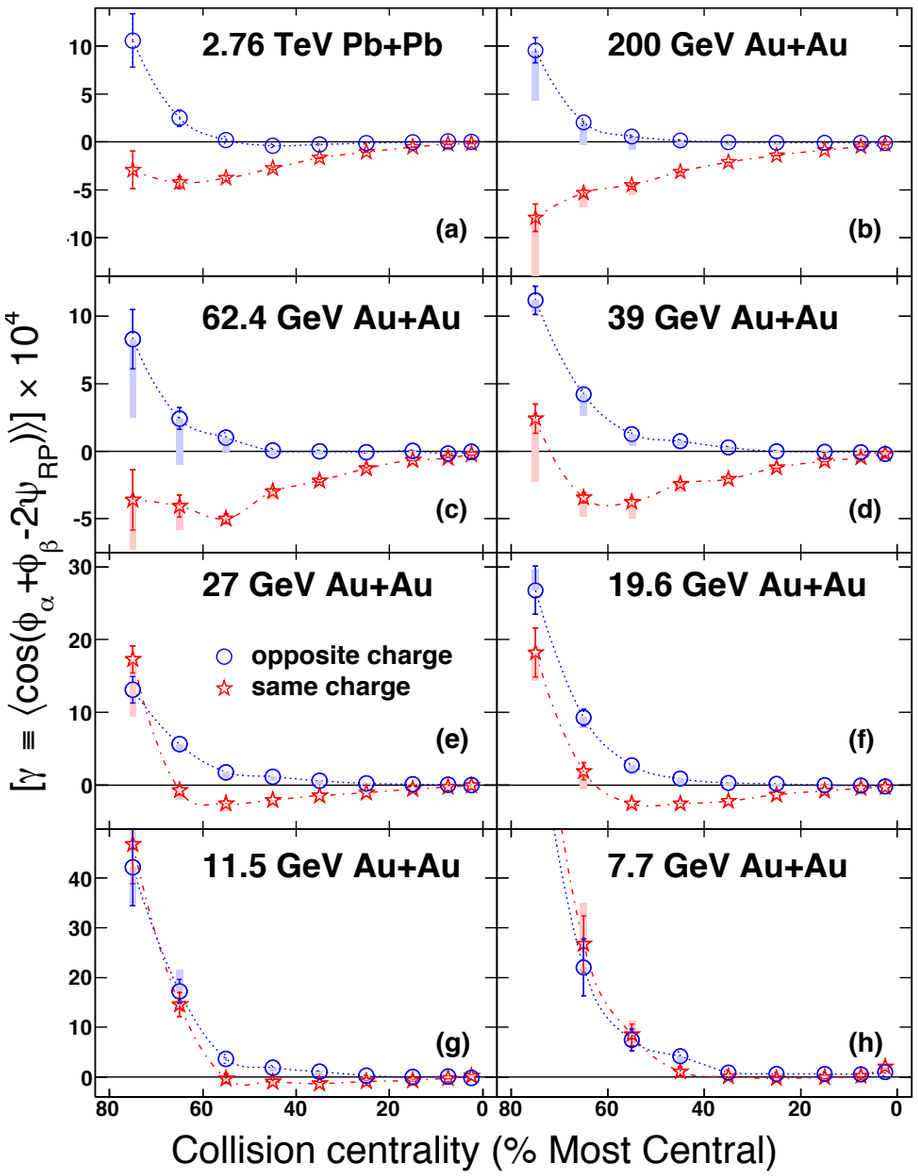
Hybrid model: ***PRC86****, 044903 (2012)*
NJL model: ***PRL112****, 012301 (2014)*

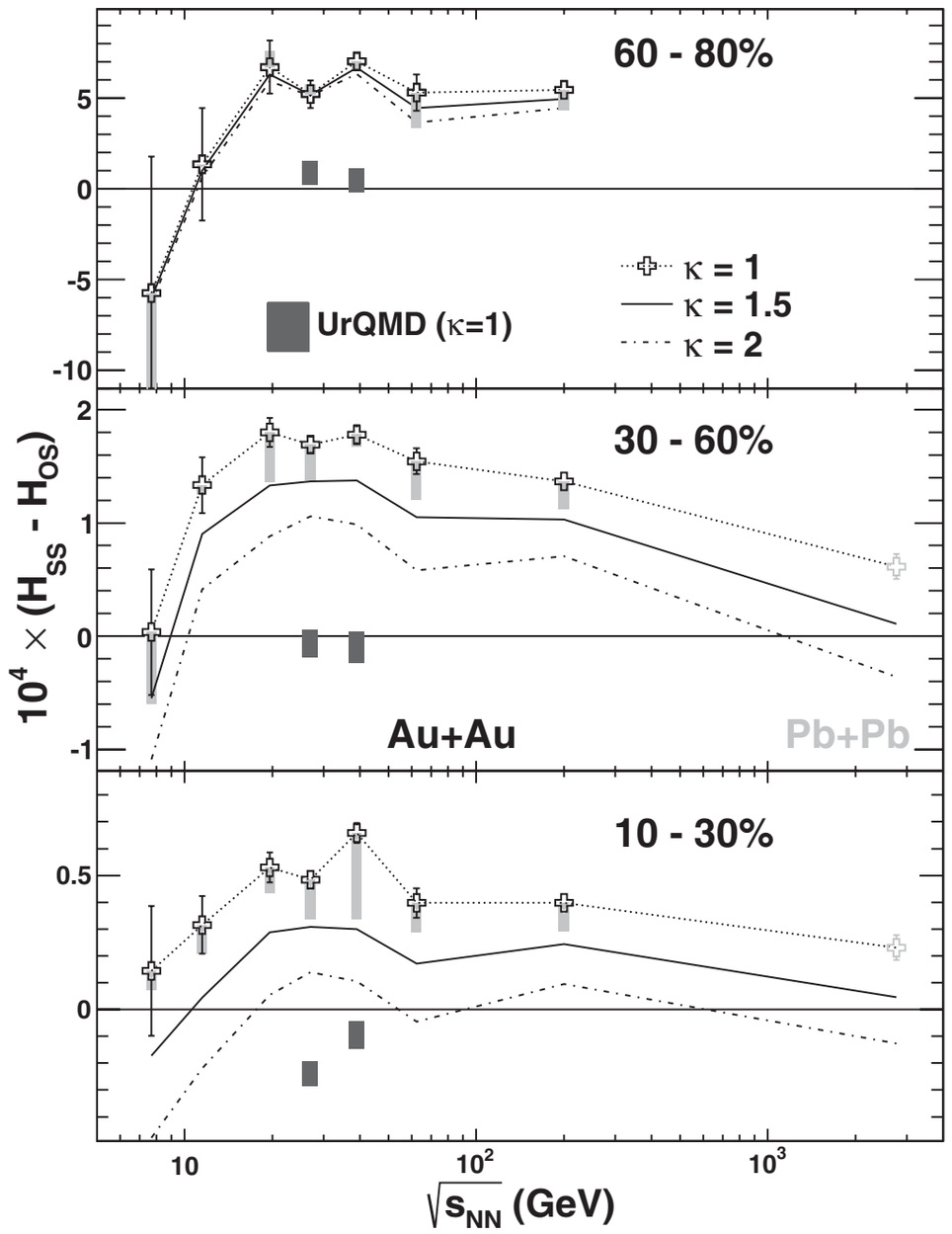


- Relative difference of v_2 between particles and anti-particles increase in lower beam energies
  - Difference increase linearly with baryon chemical potential
  - Reasonable agreement with hybrid hydro model → baryon stopping ?
  - NJL model also qualitatively reproduce the data

Charge separation w.r.t. event plane

*STAR: **PRL103**, 251601 (2009), **PRL113**, 052302 (2014),*
*ALICE: **PRL110**, 012301 (2013)*

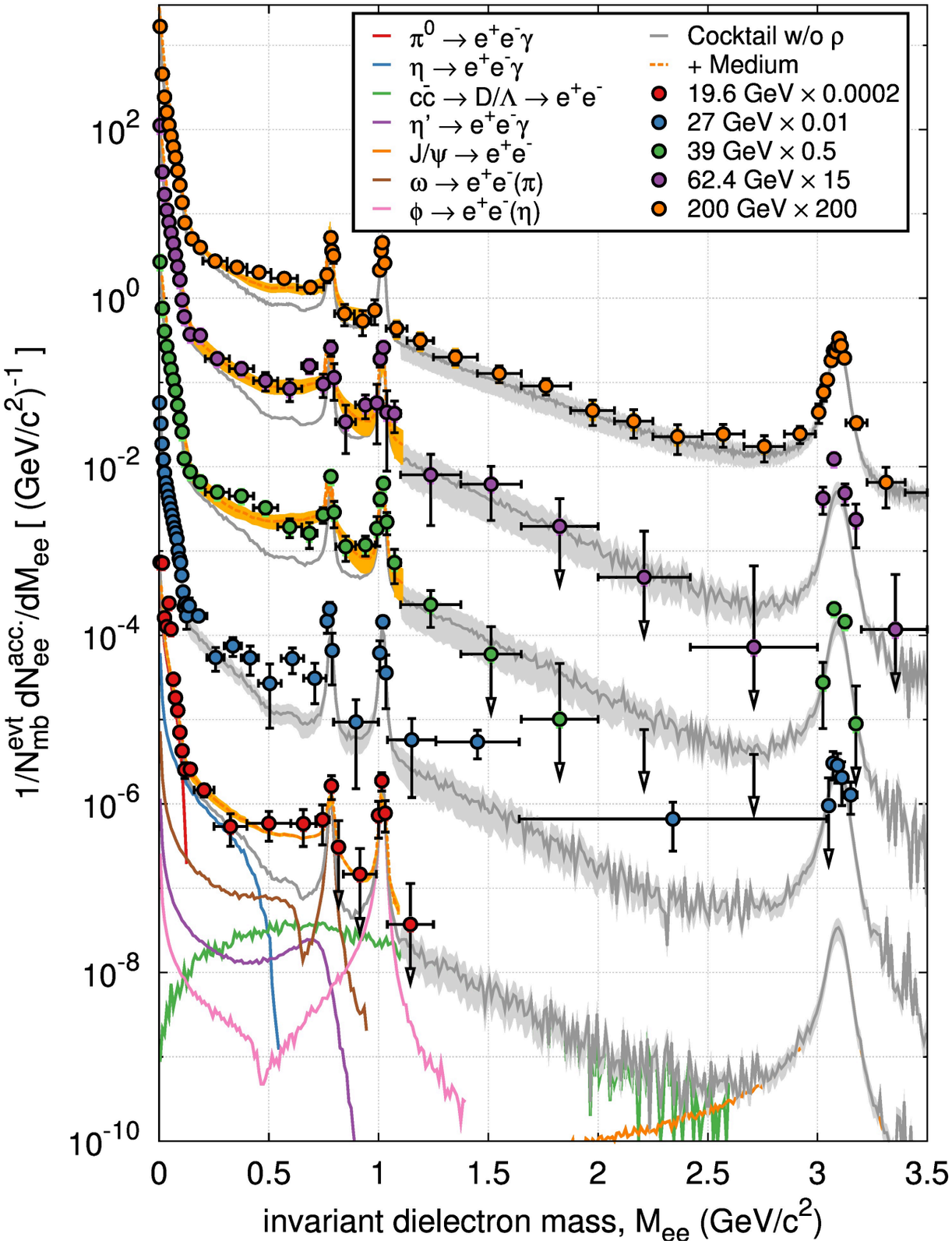




- Chiral magnetic effect + Local parity violation
  - Signal ~ 0 in $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV
  - Need better estimate of κ & precision measurements below 20 GeV

Di-electron mass spectra

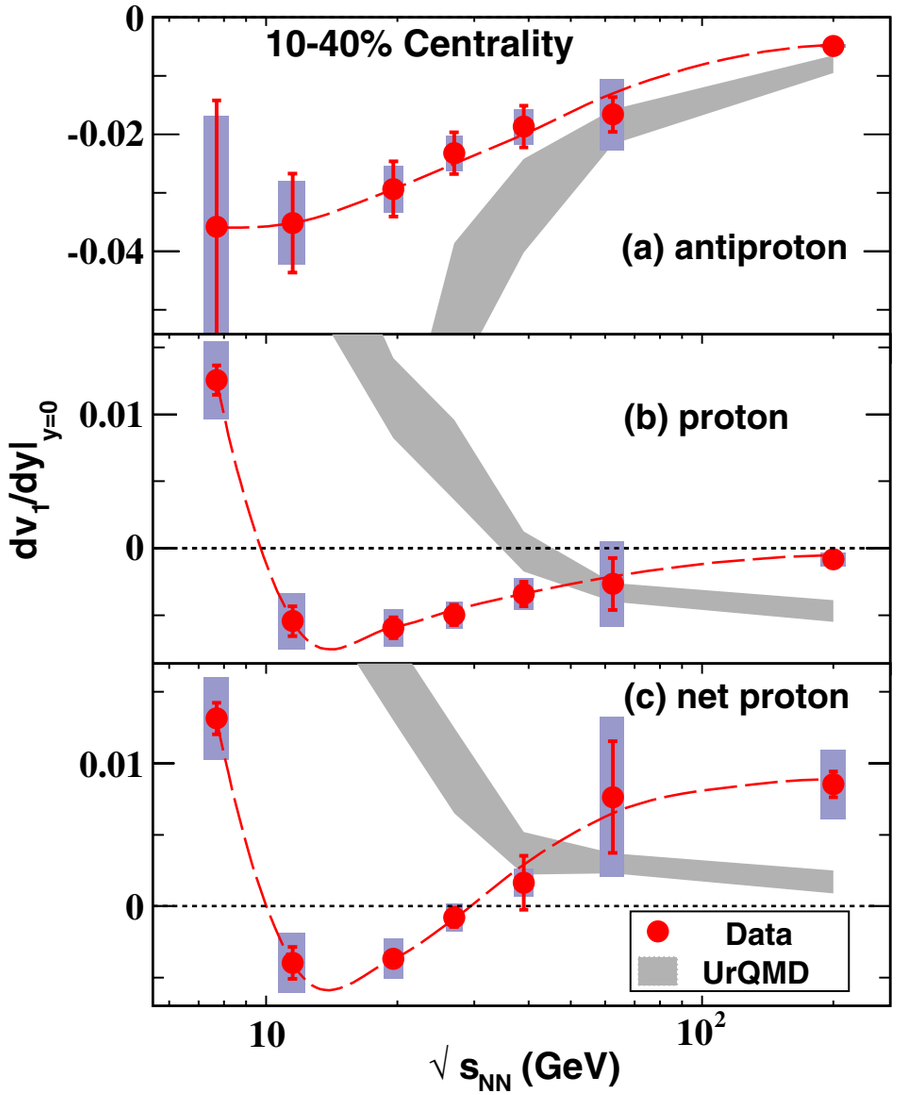
STAR, QM2014

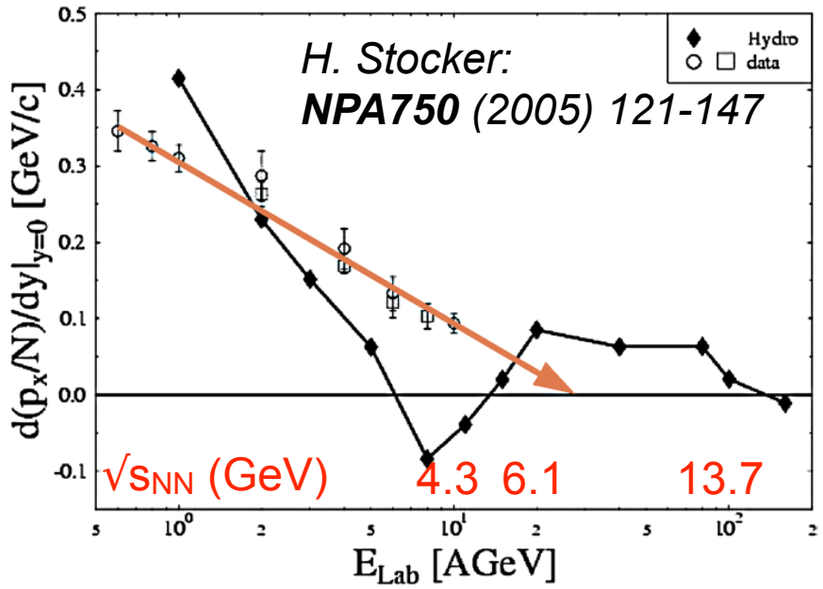


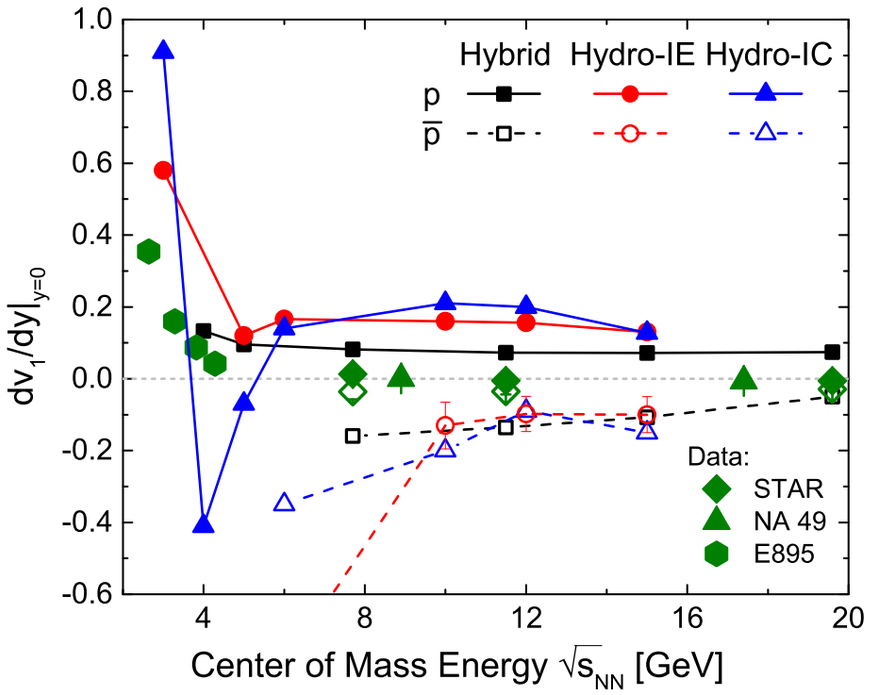
- Chiral symmetry restoration, thermal radiation
  - STAR measured di-electron spectra in $\sqrt{s_{NN}}$ = 19.6 - 200 GeV
  - Excess in M_{ee} < 1.1 GeV/c^2 (LMR) observed at all energies
  - In-medium modification of ρ spectral function describe LMR enhancement
  - No energy dependence of LMR excess
- Need more statistics below 20 GeV

Directed flow v_1

STAR: ***PRL112****, 162301 (2014)*





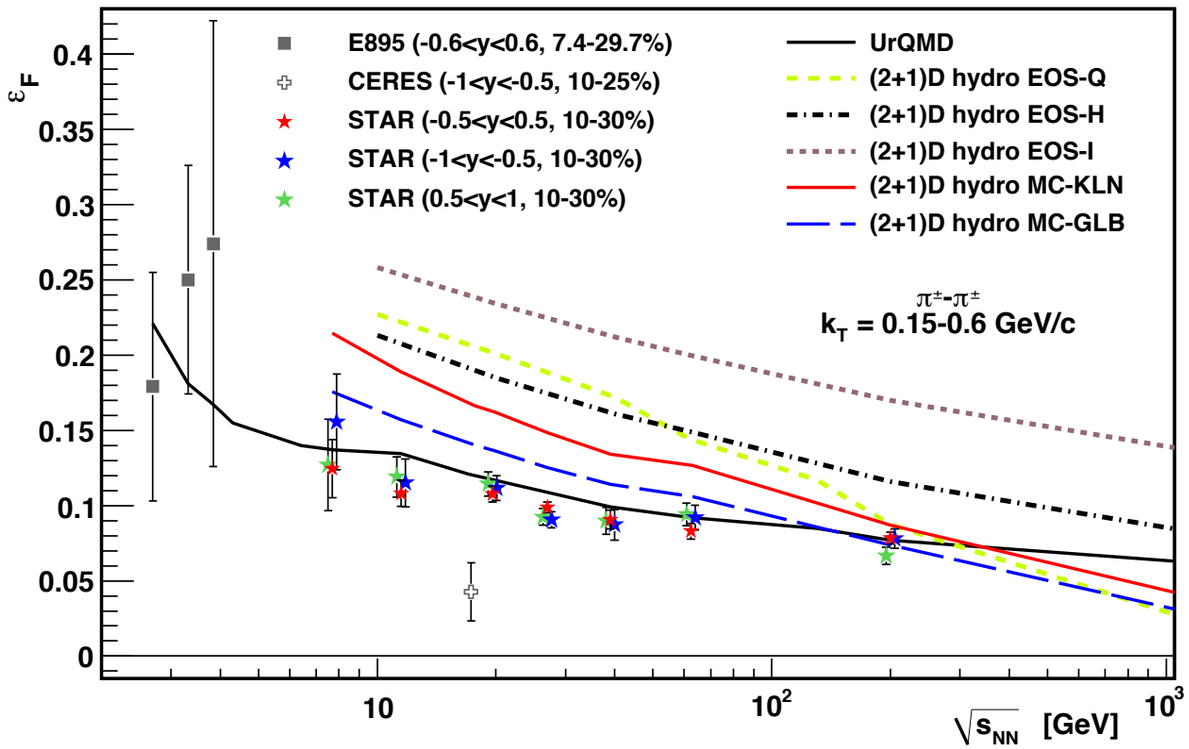


J. Steinheimer et al, ***PRC89****, 054923 (2014)*

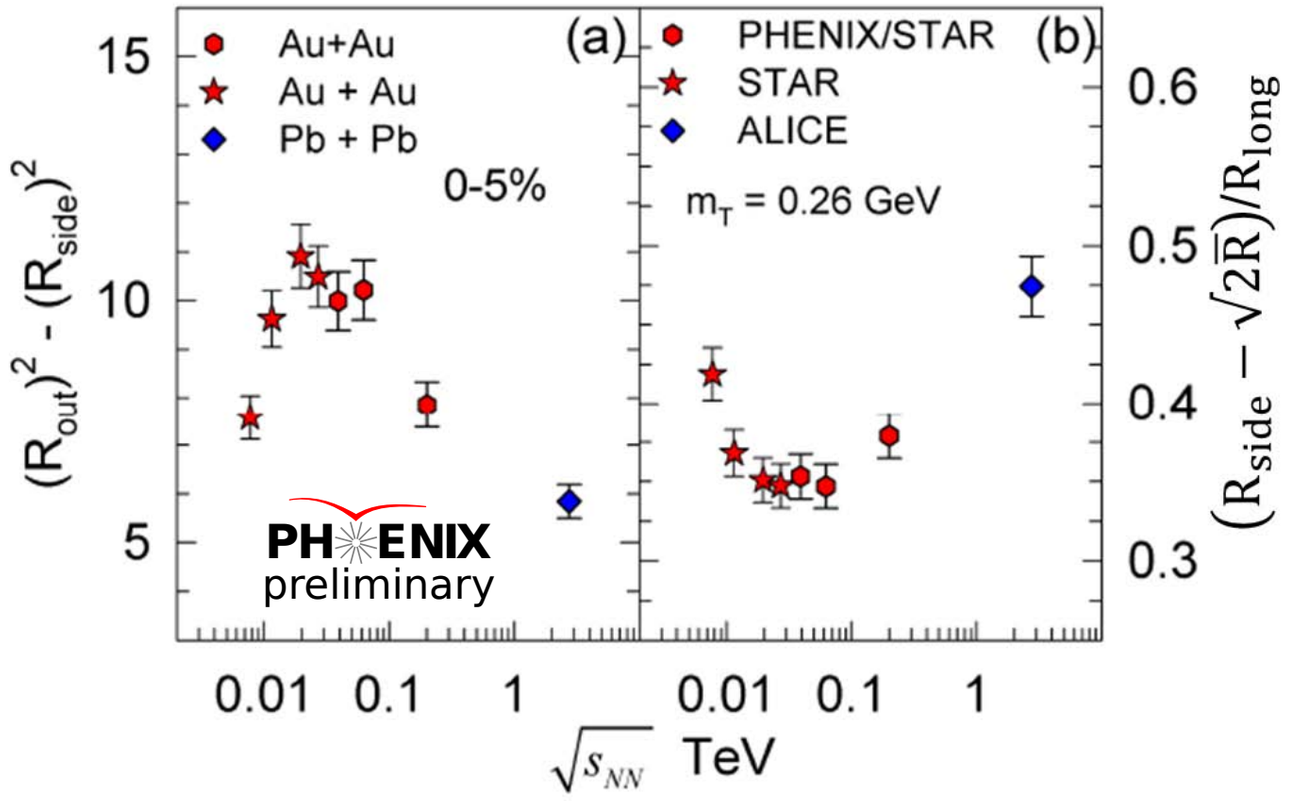
- Possible signature of first order phase transition
  - Non-monotonic behavior, trend is similar with early prediction
  - Recent more realistic hybrid calculation can't reproduce the data

Azimuthal sensitive HBT

STAR: arXiv:1403.4972 [nucl-ex]



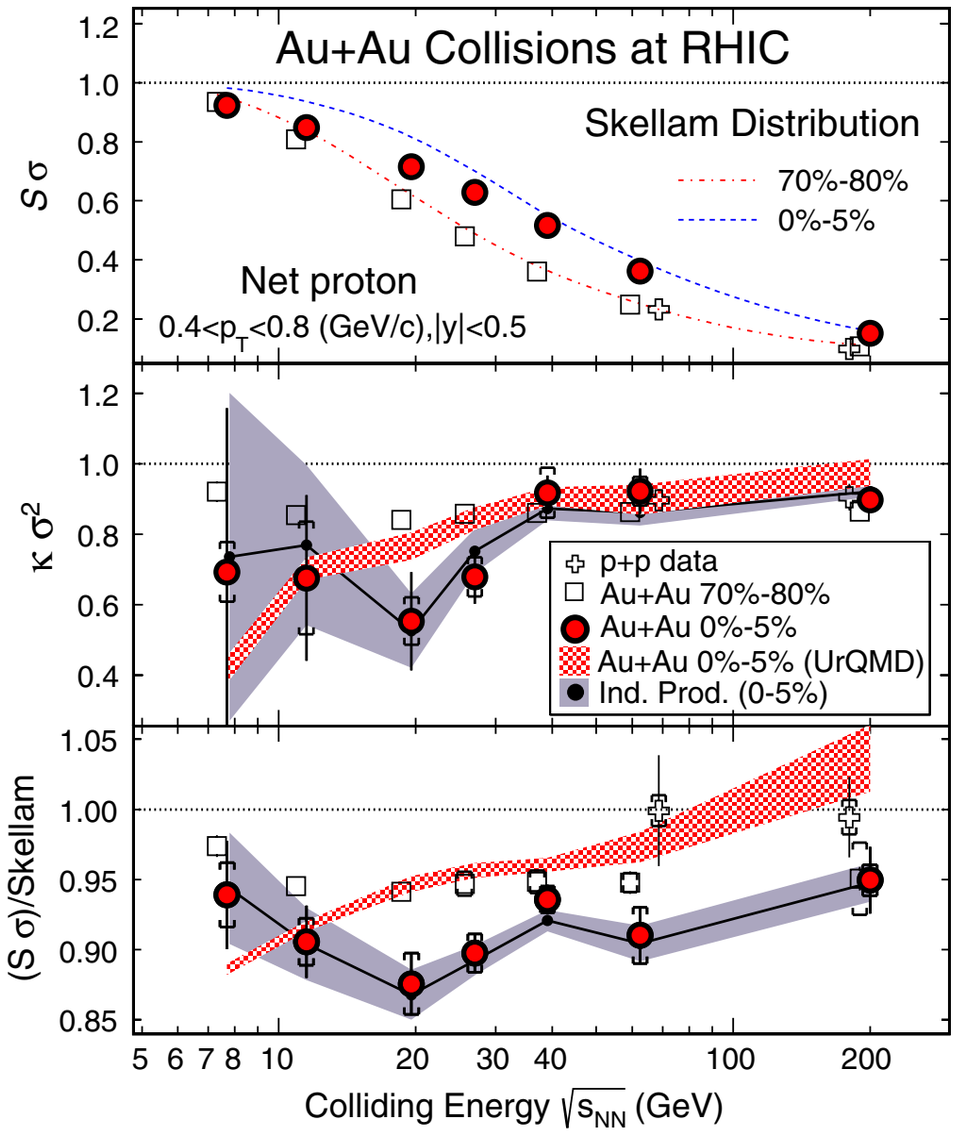
PHENIX, QM2014



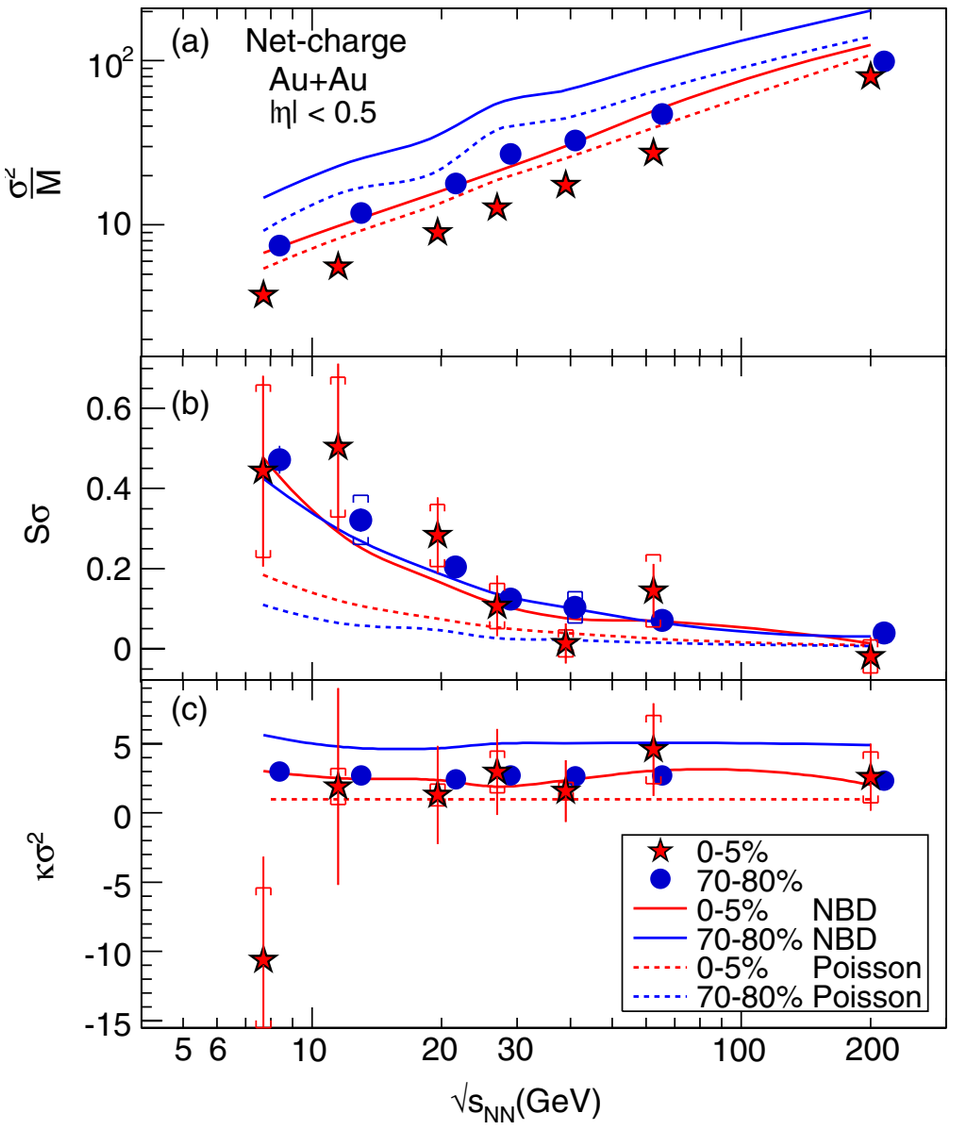
- First order phase transition → small freeze-out eccentricity
  - STAR results show monotonic energy dependence
- Non-monotonic behavior on $(R_{out})^2$-$(R_{side})^2$, R_{side}/R_{long}
  - $(R_{out})^2$-$(R_{side})^2$ ~ emission duration, R_{side}/R_{long} ~ proxy of sound speed

Net-proton & net-charge fluctuations

STAR: ***PRL112****, 032302 (2014)*

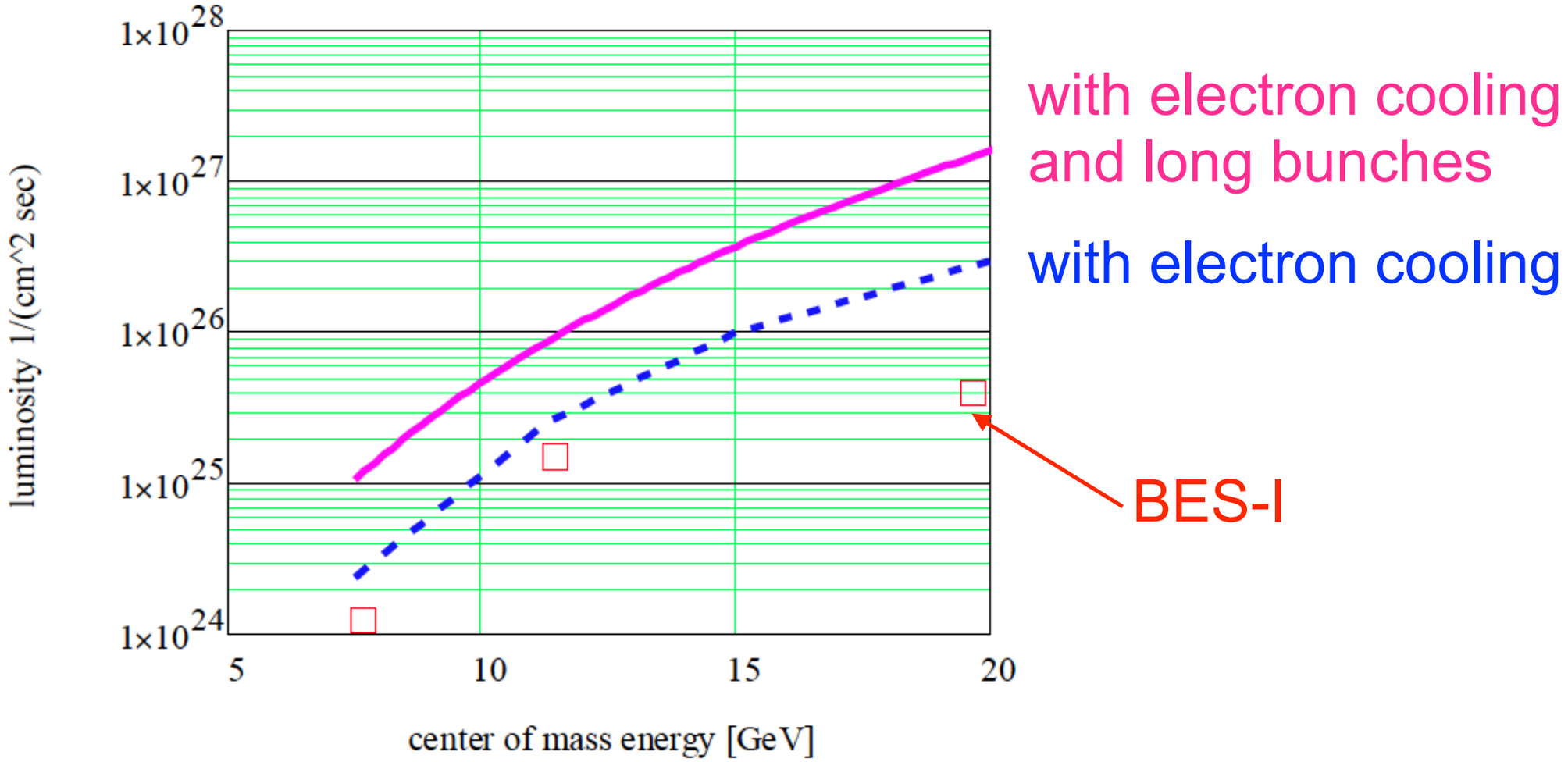


STAR: ***PRL113****, 092301 (2014)*



- Sensitive to fluctuations induced by QCD critical point
- Largest deviation around 19.6 GeV for net-proton
- Need more precise measurements

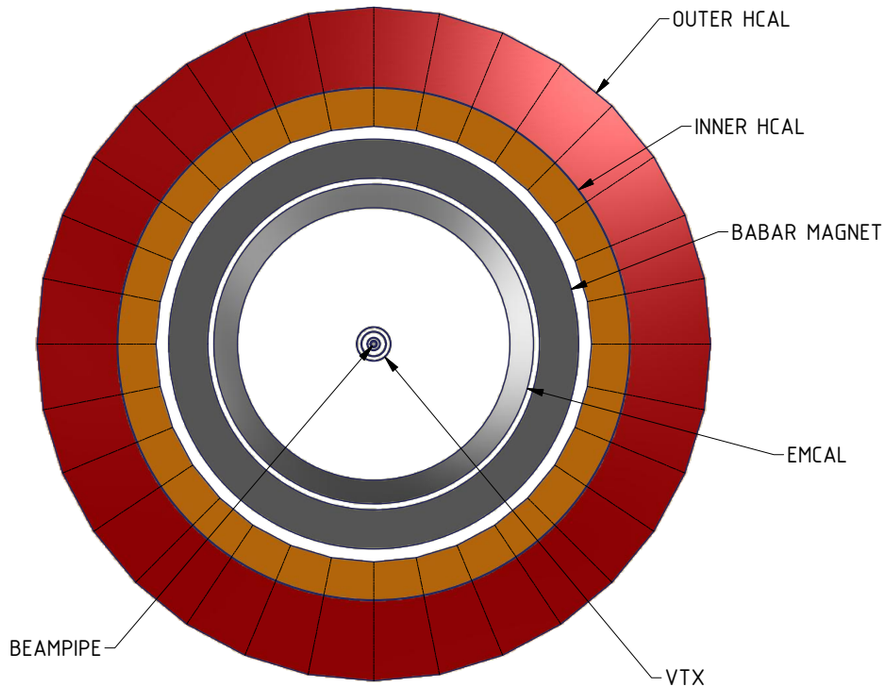
RHIC luminosity improvements



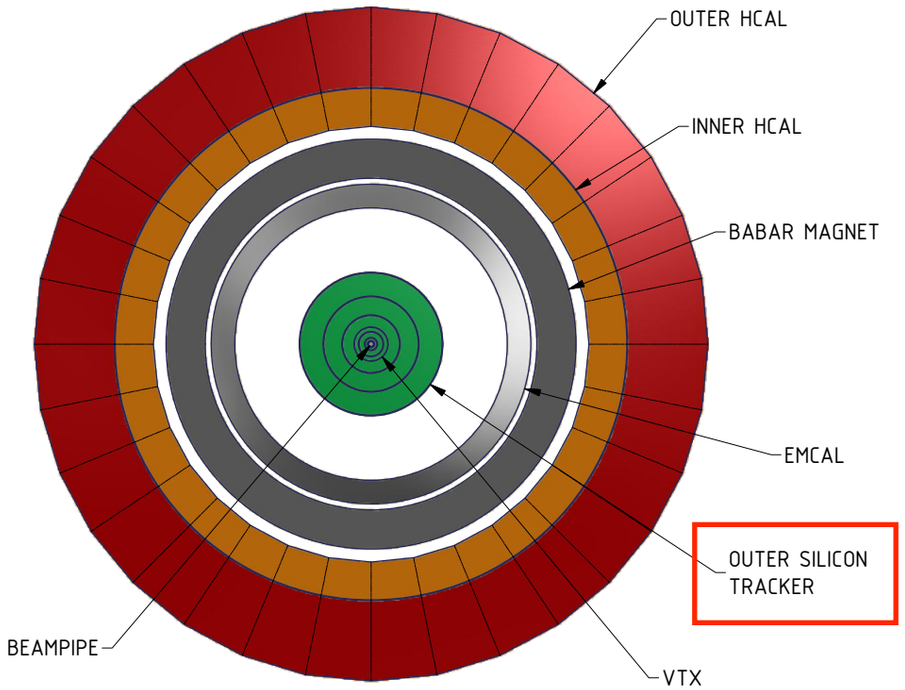
- Electron cooling will be available for BES-II
  - Electron cooling: by a factor of 3-10 increase in 5-20 GeV
  - Electron cooling + long bunches: by a factor of 2-5

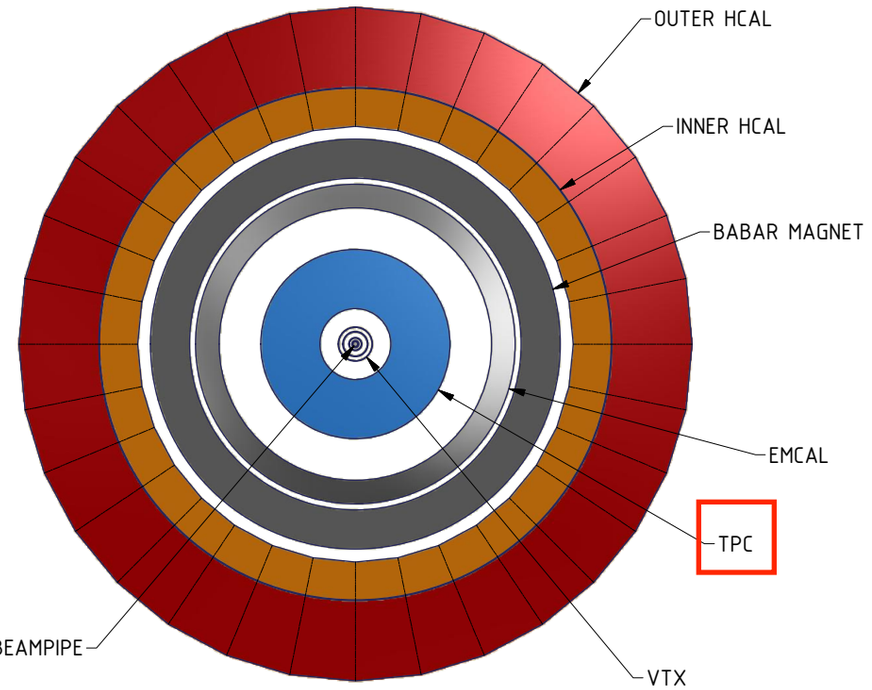
sPHENIX upgrade for BES-II

- Possible configurations in year 2019
- Option 1: EMCAL+VTX
- Option 2
  - Option 1+ Additional silicon trackers
- Option 3
  - Option 1+ TPC

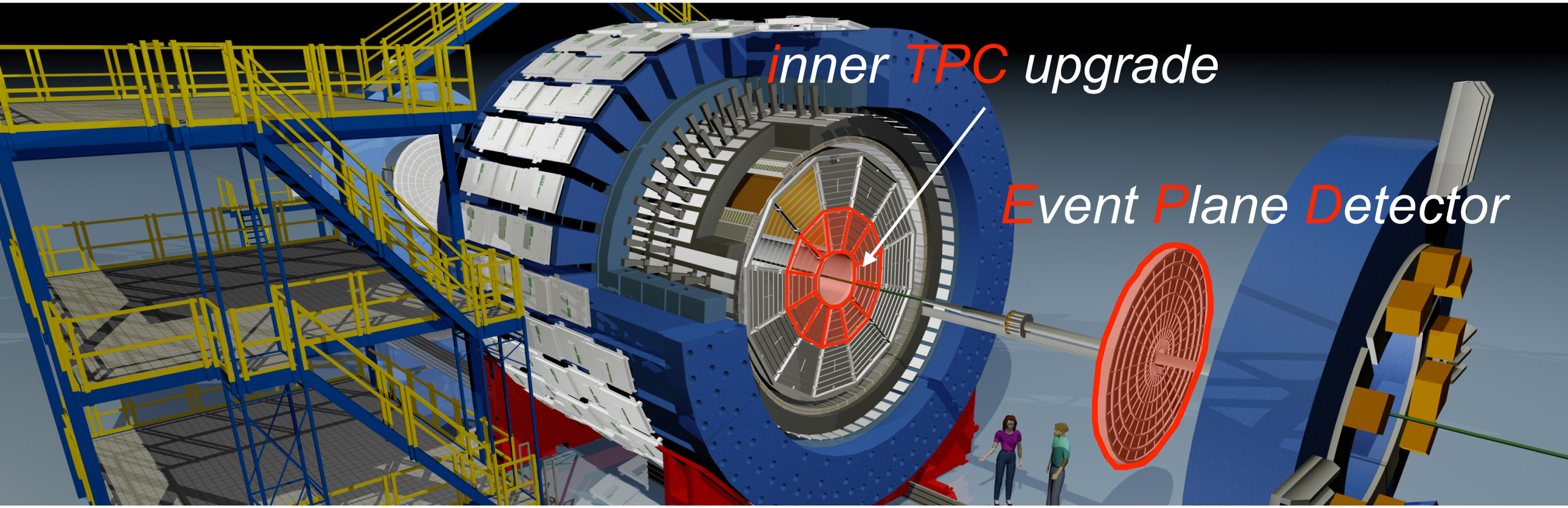


Acceptance:
- $|\eta| < 1$
- Full azimuth





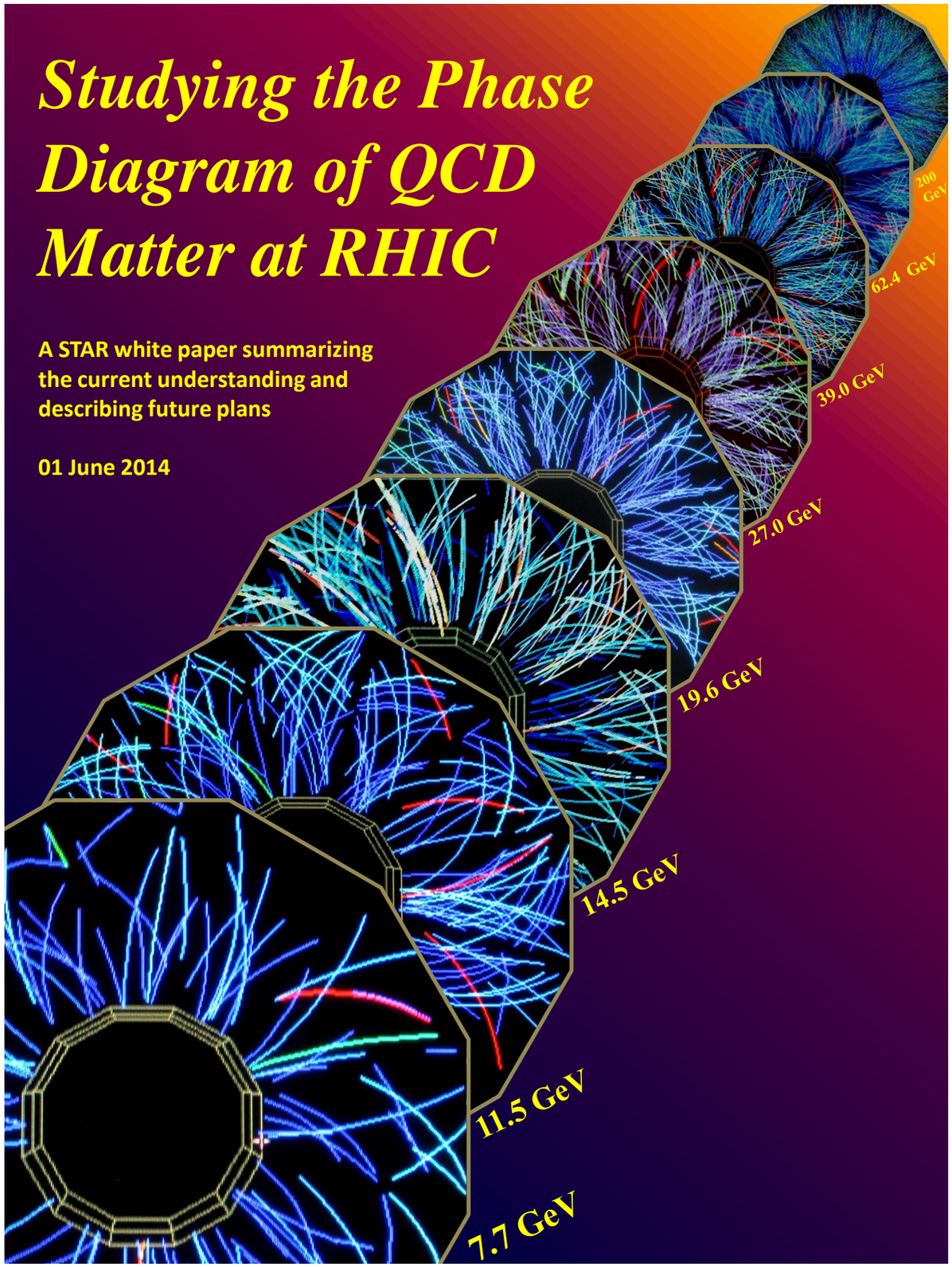
STAR upgrade for BES-II



- Event Plane Detector, $1.8 < |\eta| < 5$
  - Trigger, event plane, centrality
    - suppress backgrounds on flow measurements, independent centrality determination
- inner TPC upgrade
  - increase TPC acceptance from 1 to 1.5 in η
  - improve dE/dx resolution → better PID

BES-II white papers

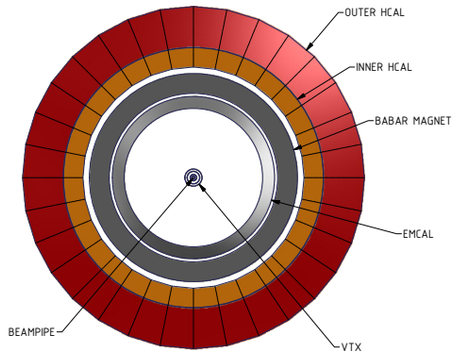
https://drupal.star.bnl.gov/STAR/system/files/BES_WPII_ver6.9_Cover.pdf

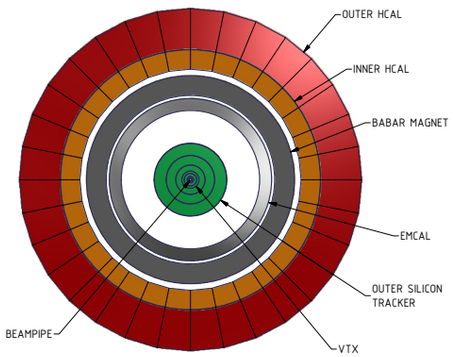


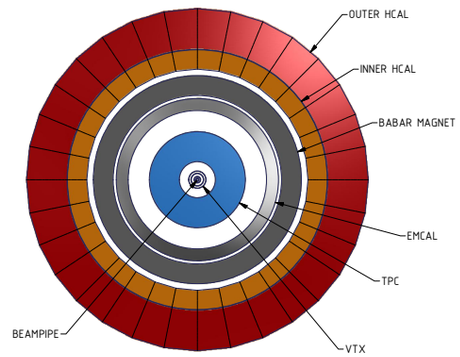
http://www.phenix.bnl.gov/phenix/WWW/publish/dave/sPHENIX/BES_II_whitepaper.pdf

Beam Energy Scan II (2018–2019)

PHENIX Collaboration White Paper



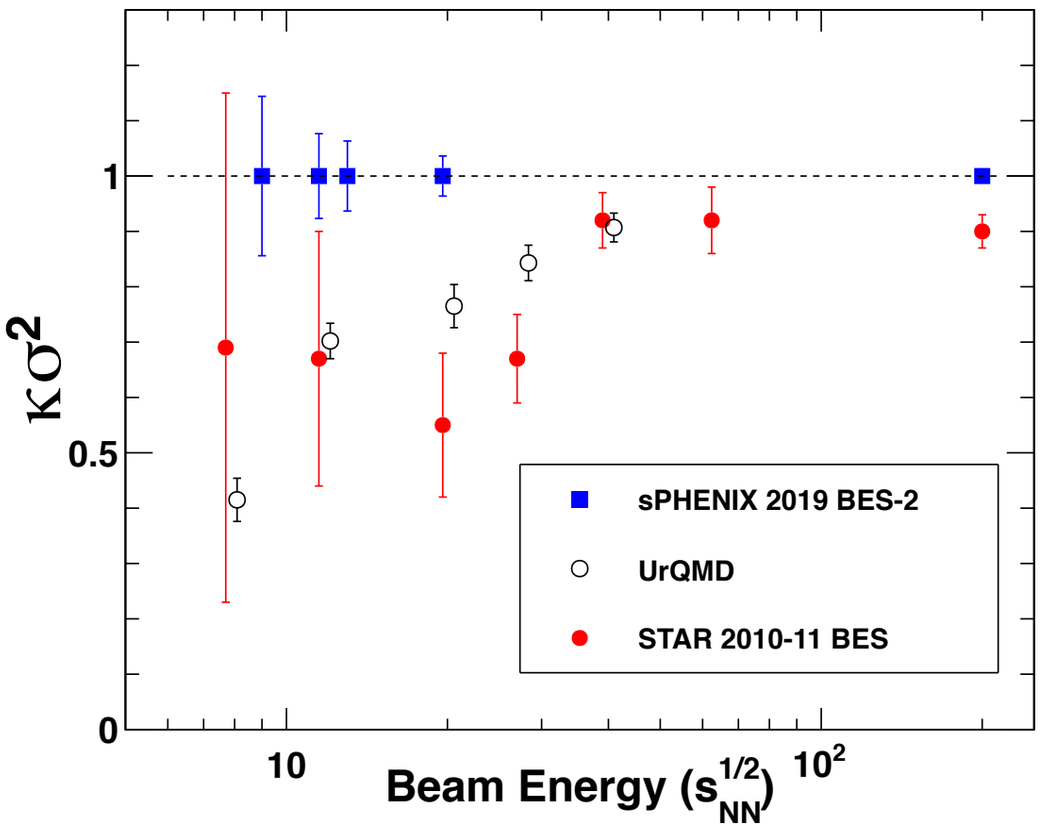




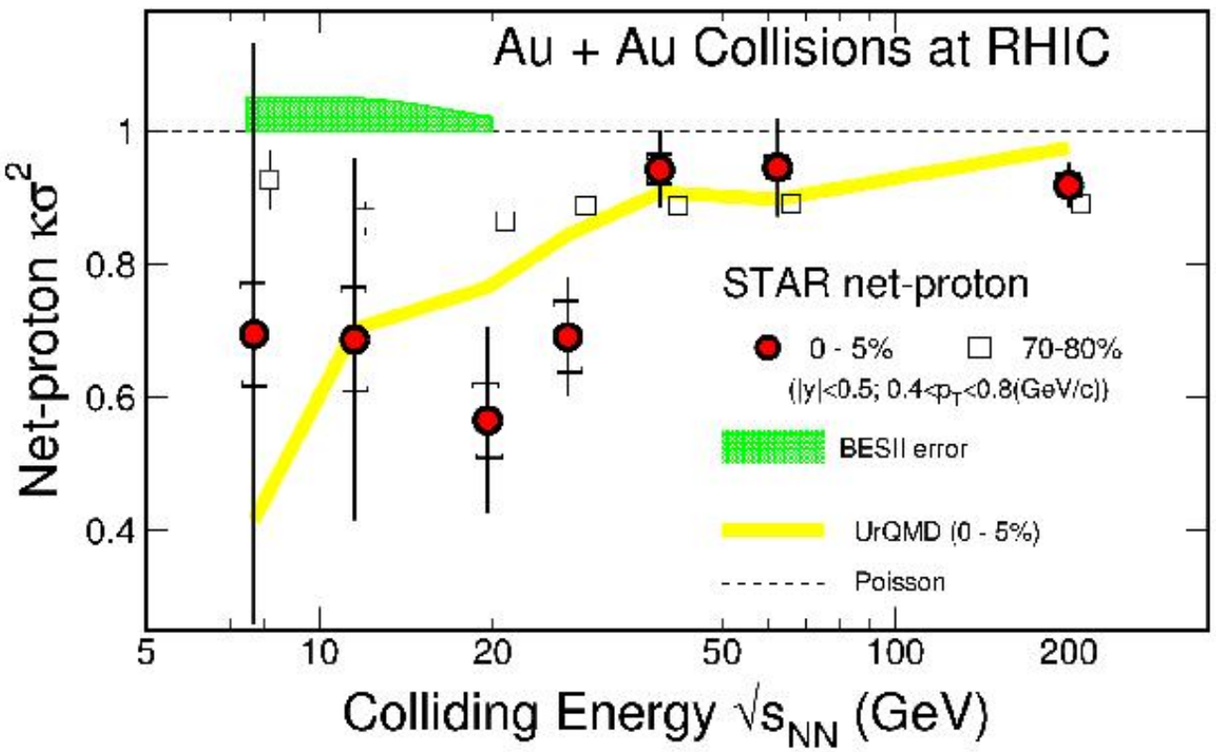
Version 1: March 1, 2014

Projections for BES-II; fluctuations

sPHENIX



STAR



- Net-proton moments
  - By a factor of 2-4 improvements on statistical precision below 20 GeV
  - Similar statistical errors for sPHENIX (with TPC) and STAR

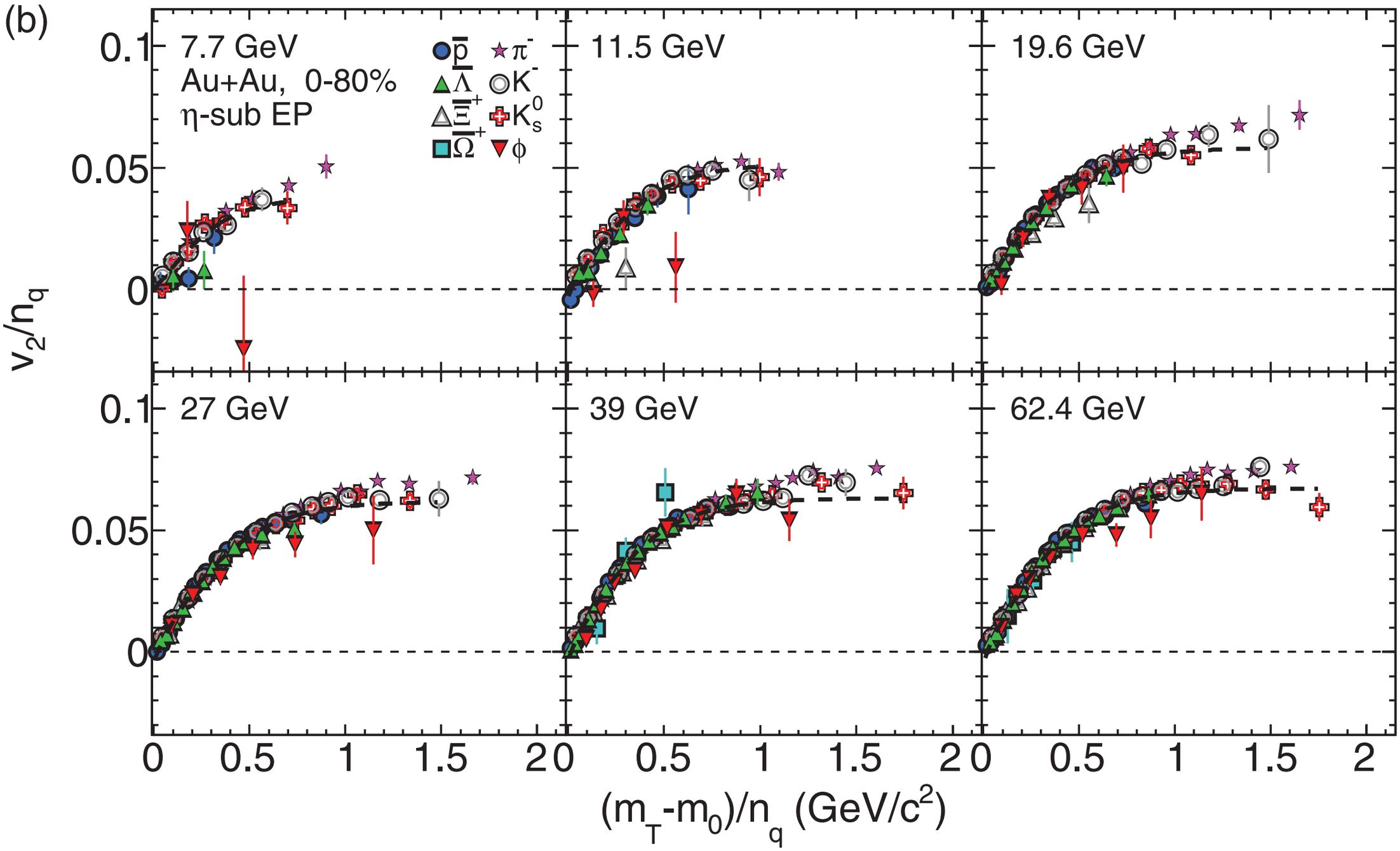
Summary

- Success of RHIC Beam Energy Scan phase-I
  - Several observables show a hint of possible turn-off signature of QGP
    - Turn-off/onset of QGP ? → BES phase II, future FAIR, J-PARC heavy ion programs
  - Non-monotonic behavior of directed flow and asHBT radii
    - 1st order phase transition ? → Quantitative and systematic model comparisons
  - Possible non-monotonic behavior of conserved charge fluctuations
    - QCD critical point ? → Precision measurements & Lattice QCD calculation
- We need precision measurements below 20 GeV
  - BES phase-II in 2018, 2019
  - Significant improvements on statistical precisions by RHIC luminosity & sPHENIX/STAR detector upgrades
  - BES-II white papers
    - sPHENIX: http://www.phenix.bnl.gov/phenix/WWW/publish/dave/sPHENIX/BES_II_whitepaper.pdf
    - STAR: https://drupal.star.bnl.gov/STAR/system/files/BES_WPII_ver6.9_Cover.pdf

Back up

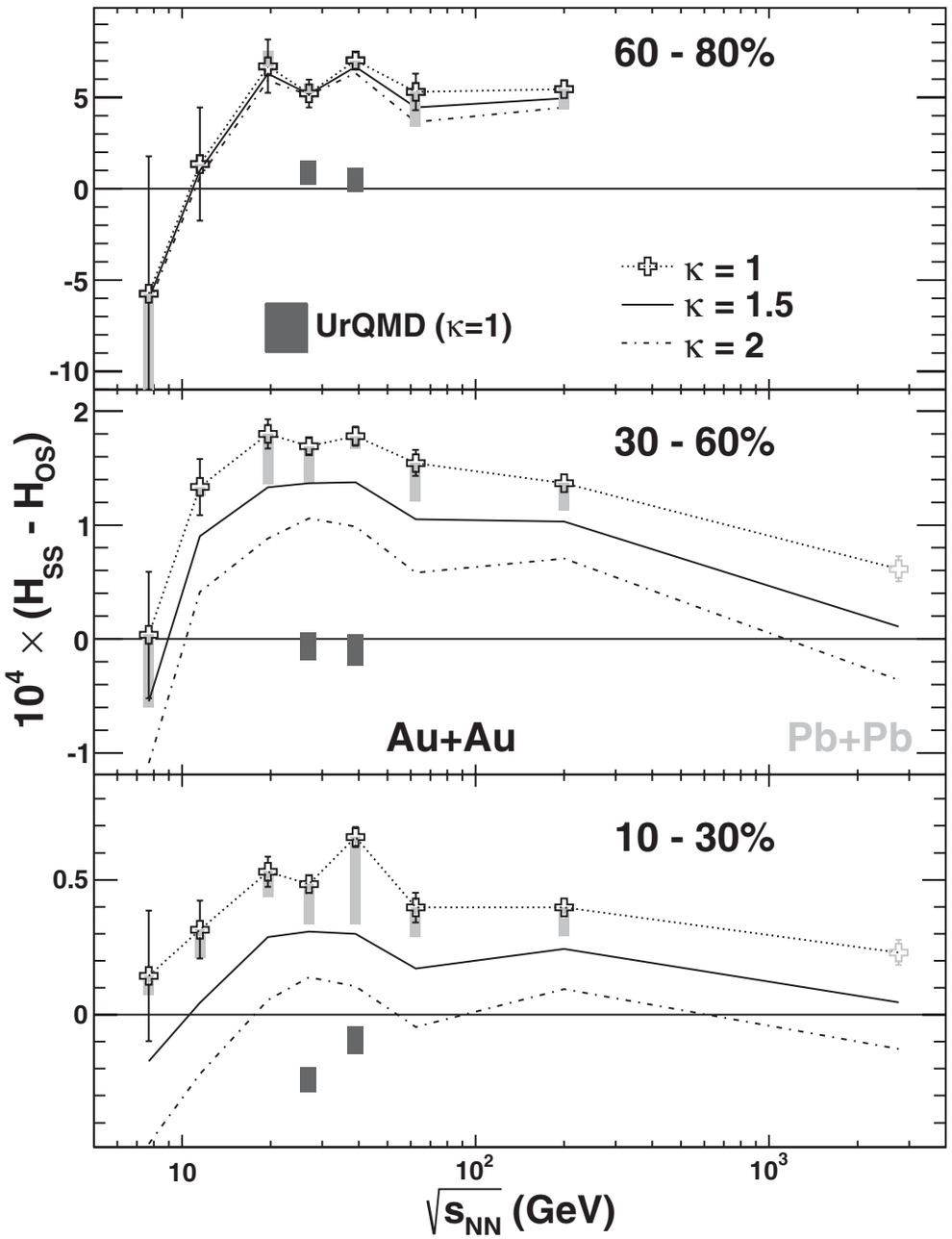
NCQ scaling of v_2 for anti-particles

STAR: ***PRC88***, *014902 (2013)*



CME signal

*STAR: **PRL103**, 251601 (2009), **PRL113**, 052302 (2014),*
*ALICE: **PRL110**, 012301 (2013)*



$$\gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{\mathrm{RP}}) \rangle = \kappa v_2 F - H,$$
$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$

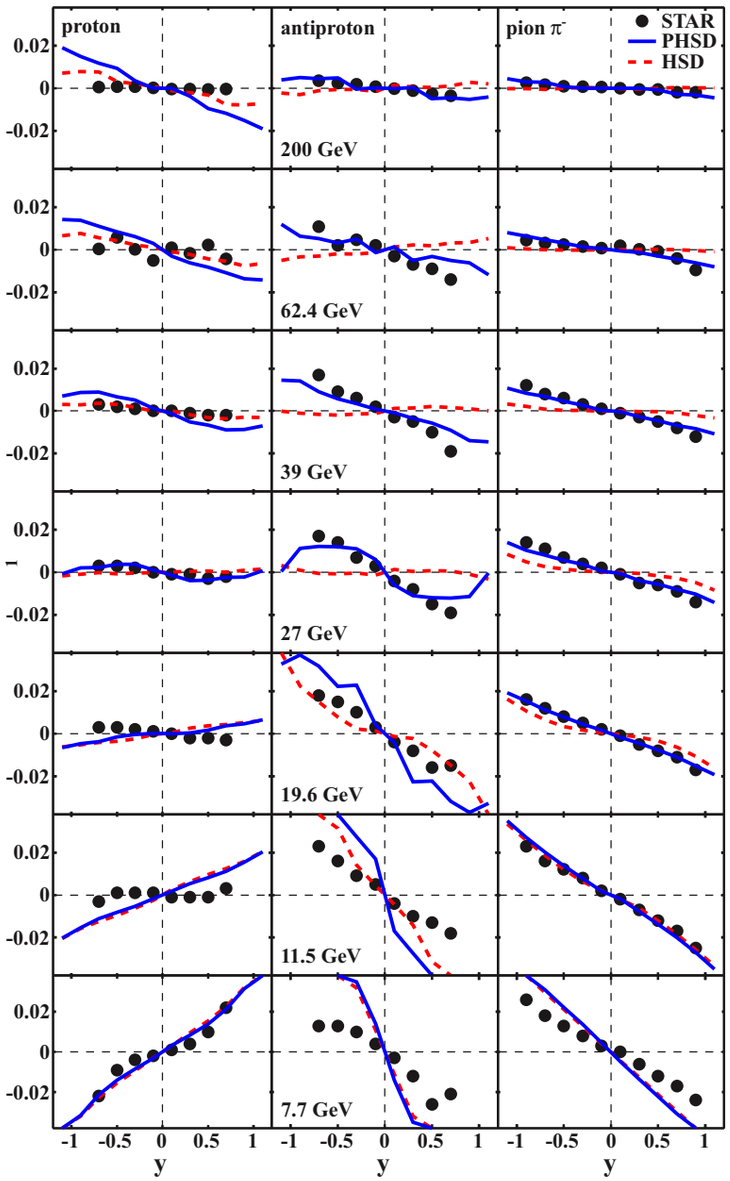
H: CME contribution,

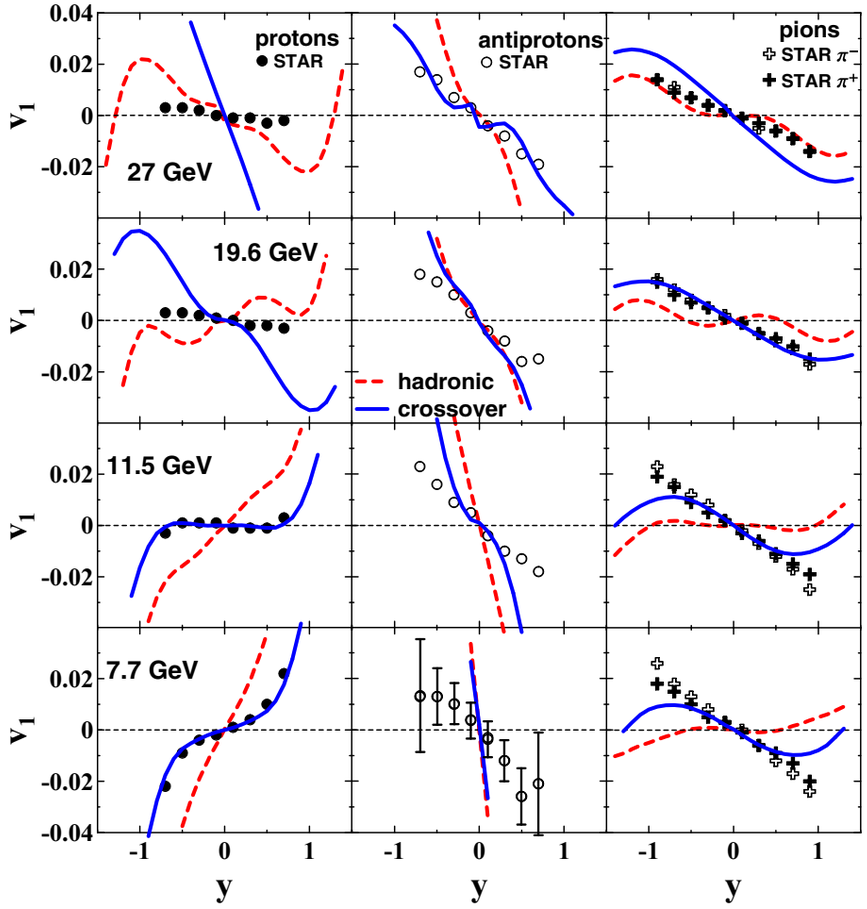
F: background contribution, κ: parameter

- Decompose measured correlation to CME (H) and background (F) contributions
  - based on A. Bzdak et al, Lect. Notes Phys. 871, 503 (2013)
- assume γ is linearly proportional to v_2

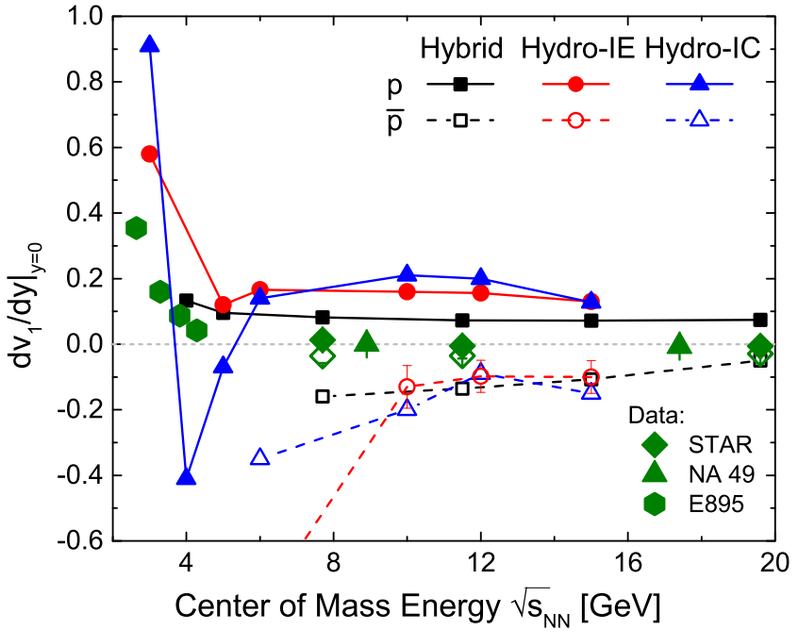
Directed flow, model calculations

V. P. Konchakovski et al, ***PRC90****, 014903 (2014)*





J. Steinheimer et al, ***PRC89****, 054923 (2014)*



- PHSD (or HSD) vs hydro with hadronic, crossover EOS
- Hybrid (UrQMD IS + Hydro + UrQMD hadronic phase) vs hydro only with different freeze-out

Beam time request for BES-II

PHENIX

Table 4.2: An outline of the PHENIX run request for the BES II program. The running time is integrated to cover a single year of RHIC running that spans 22 cryo-weeks, or 19 weeks of physics running depending on ramp-up and switching times. Higher priority is given to the data sets listed first. The number of events refers to good events within the baseline sPHENIX configuration requiring $|z_{vertex}| < 10$ cm including the PHENIX and RHIC duty factor. Also included are event estimates with a wider $|z_{vertex}| < 30$ cm and $|z_{vertex}| < 1$ m cut that could be applied if a TPC is installed.

Species	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time (Days)	Events(M) $\lvert z_{vtx}\rvert < 10$cm	Events(M) $\lvert z_{vtx}\rvert < 30$cm	Events(M) $\lvert z_{vtx}\rvert < 1$ m
Au+Au	11.5	315	45	15	45	112.5
	13.0	281	23	17	50	125
	9.0	376	41	6	17	42.5
	19.6	205	4	33	100	2500
	200	20	10	1200	3600	9000
p+p	200		10	1.2 pb^{-1}	3.6 pb^{-1}	9 pb^{-1}

STAR

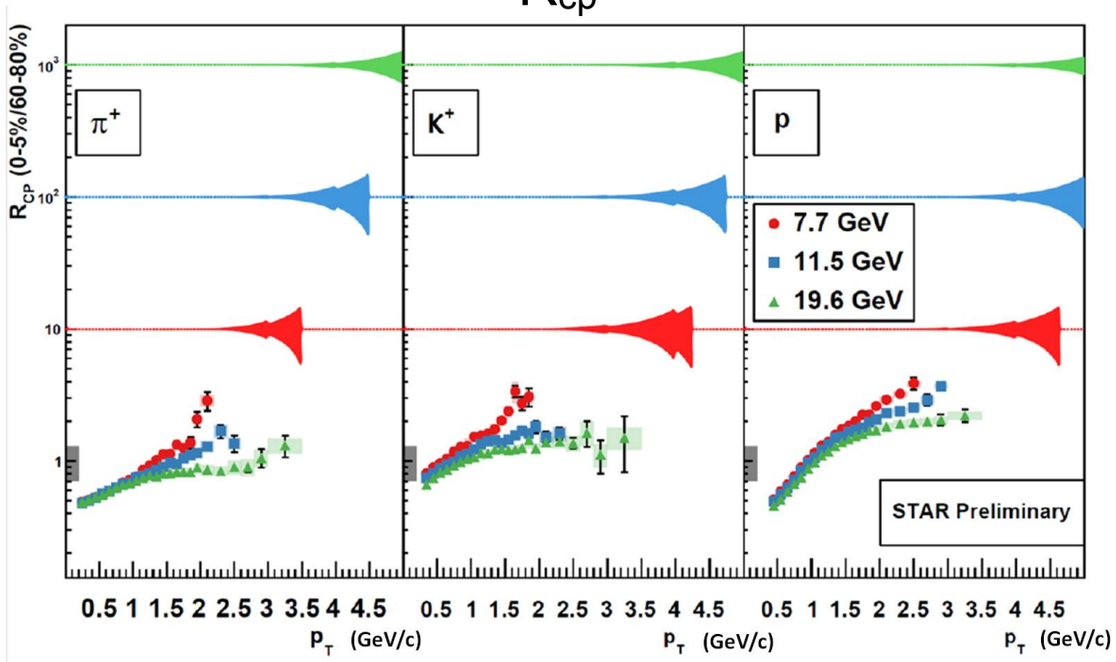
Table 3. Beam Energy Scan Phase-II proposal for 22 weeks of RHIC running in each of the years 2018 and 2019.

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% Central Collisions	420	370	315	260	205
BES-I (Million Events)	4	–	12	20	36
BES-I Event Rate (Million Events/Day)	0.25	0.6	1.7	2.4	4.5
BES-I Int. Luminosity (1×10^{25}/cm^2 s)	0.13	0.5	1.5	2.1	4.0
e-Cooling Luminosity Improvement Factor	4	4	4	8	15(4)
BES Phase-II (Million Events)	100	160	230	300	400
Required Beam Time (Weeks)	14	9.5	5.0	2.5	4.0+

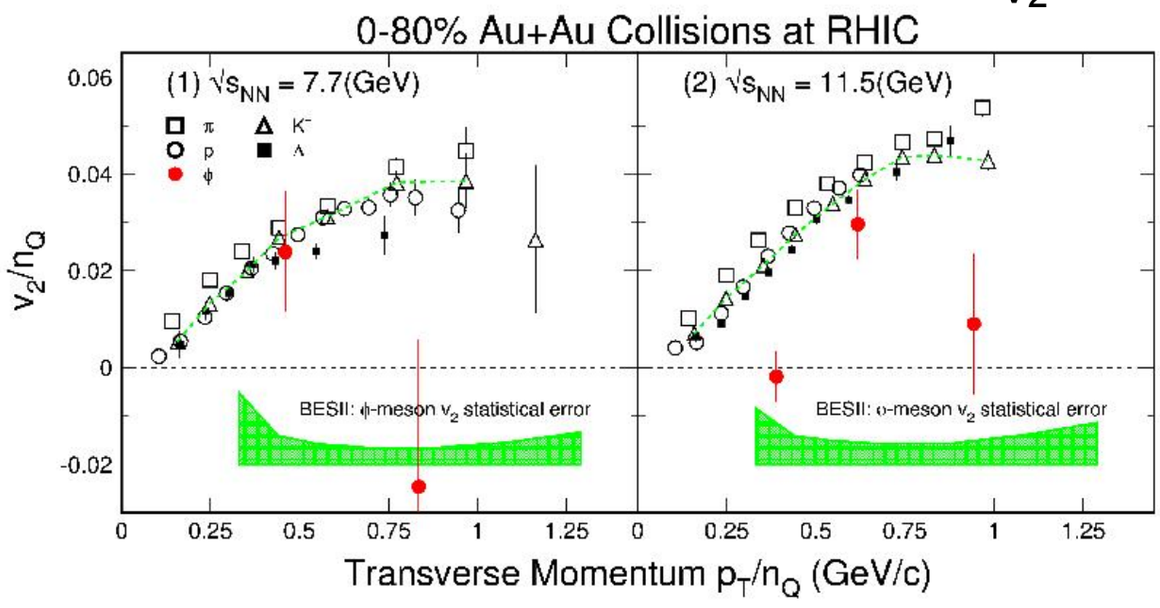
- Focused on $\sqrt{s_{NN}}$ < 20 GeV
  - One year (2019) request from PHENIX
  - Two year (2018, 2019) request from STAR

BES-II projections

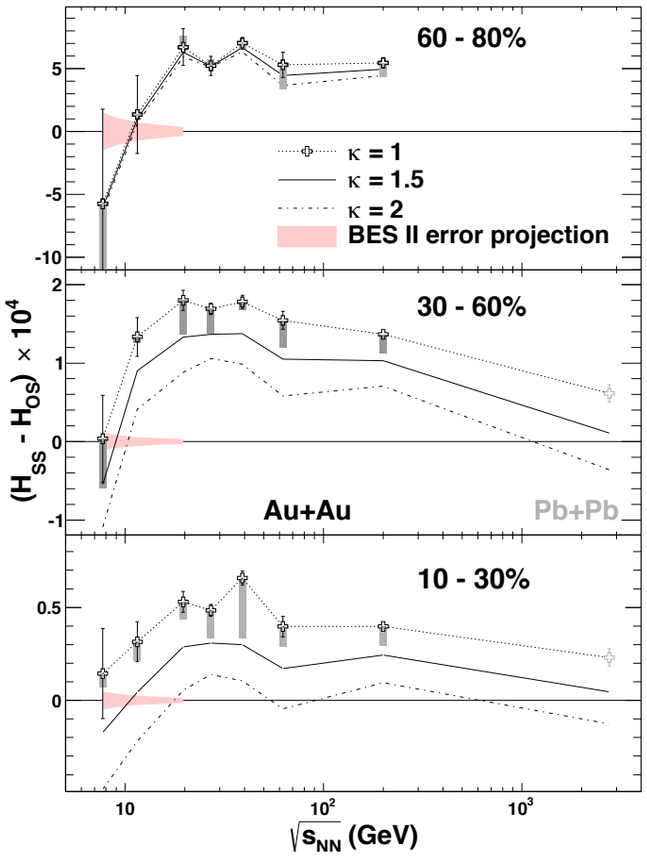
R_{cp}



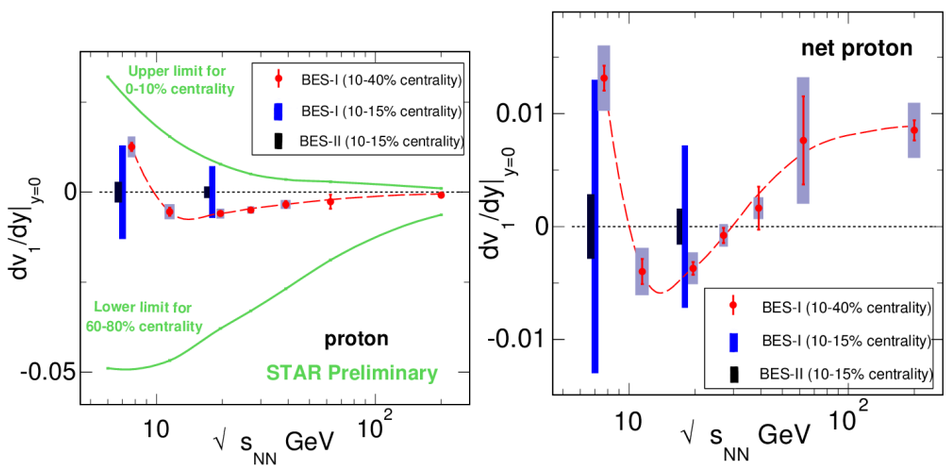
v_2



charge separation



Directed flow



Di-lepton LMR excess