RHIC Beam Energy Scan

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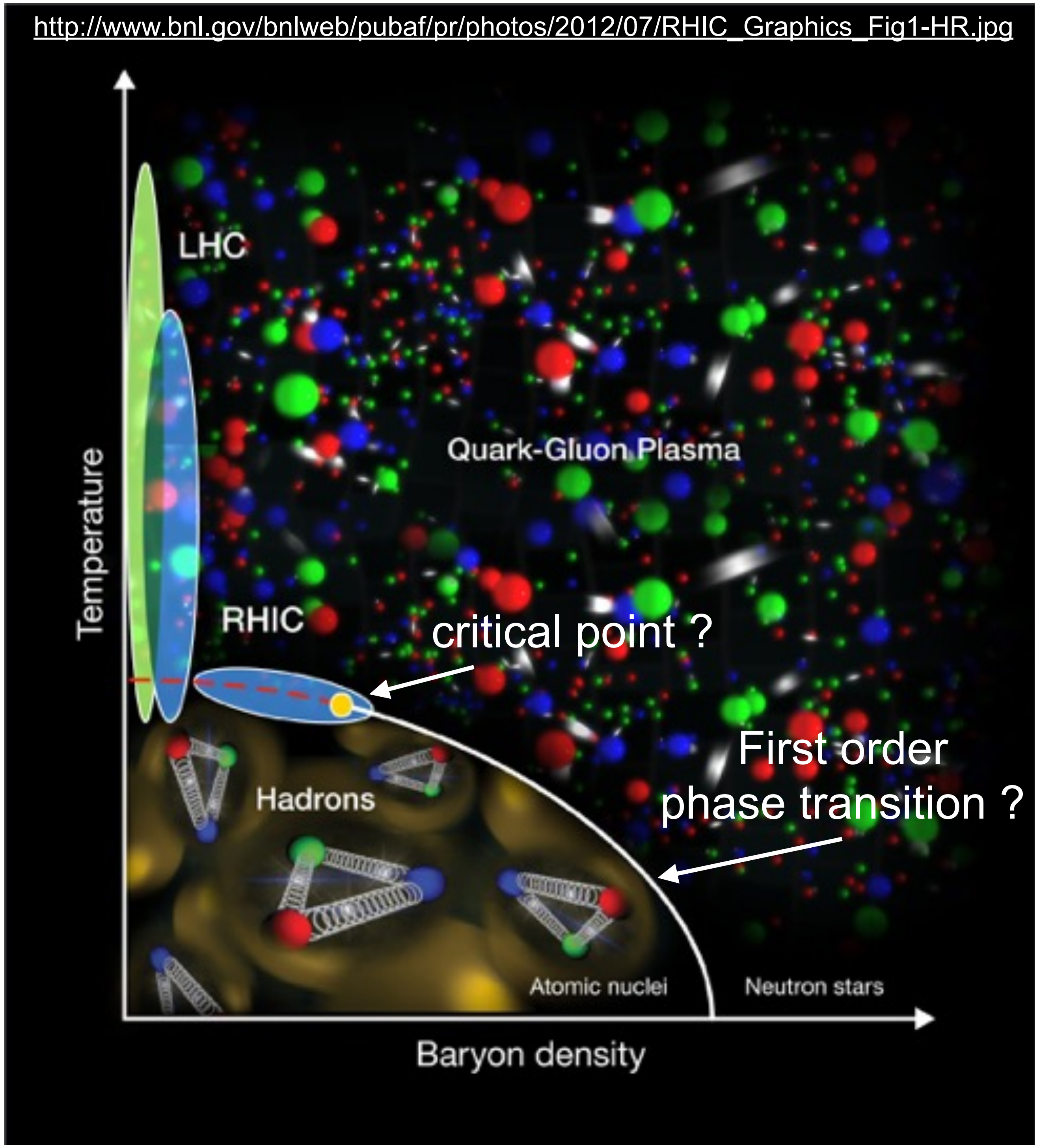
Hadrons and Hadron Interactions in QCD 2015,
Symposium: QCD phase diagram and heavy ion collisions,
Kyoto, Mar/4/2015

Outline

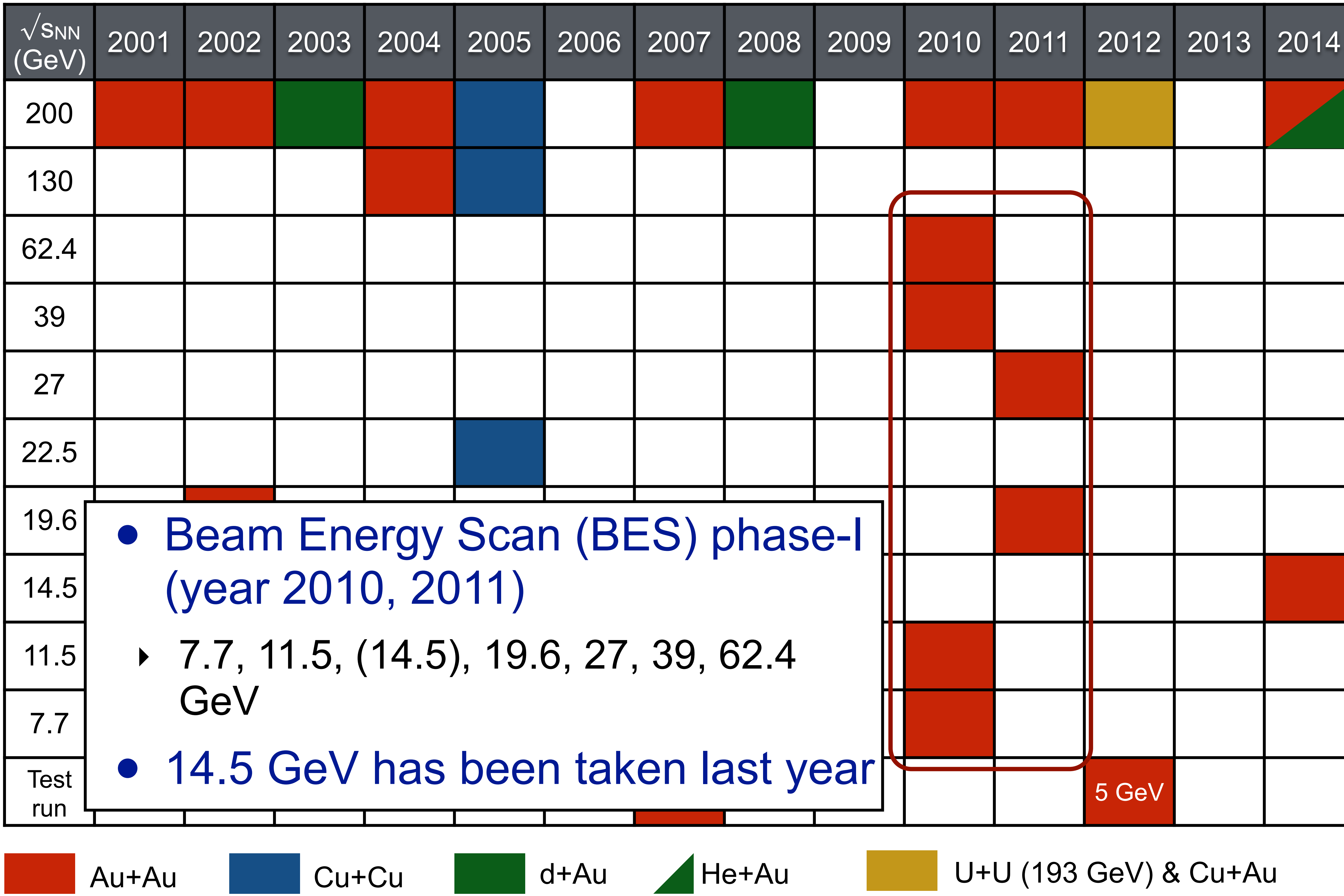
- Introduction
  - RHIC Beam Energy Scan (BES) phase-I
  - PHENIX & STAR experiments
- Review selected results from year 2010 & 2011
- Future upgrade for BES phase-II
- Summary

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



- 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 been taken last year

Relativistic Heavy Ion Collider

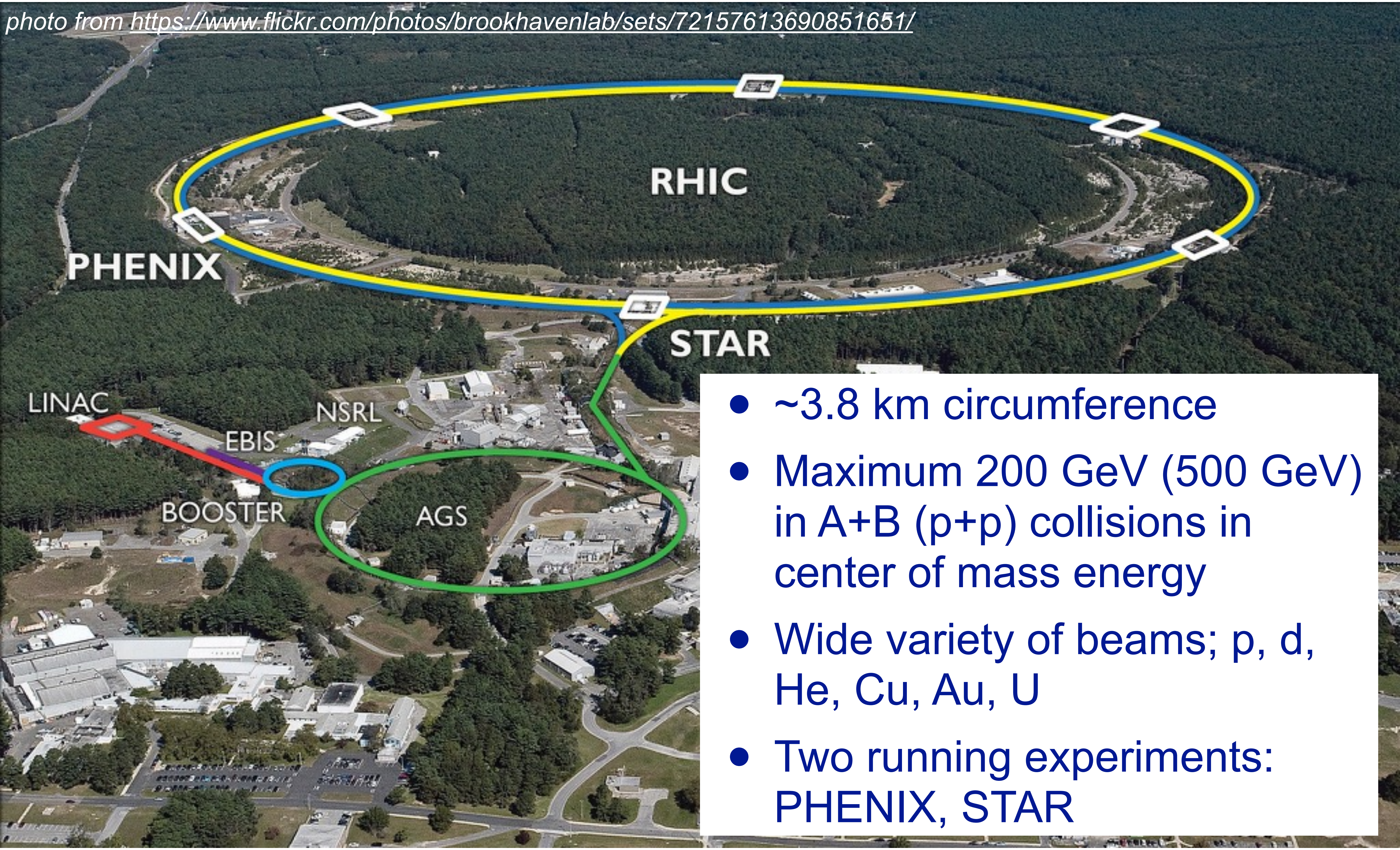
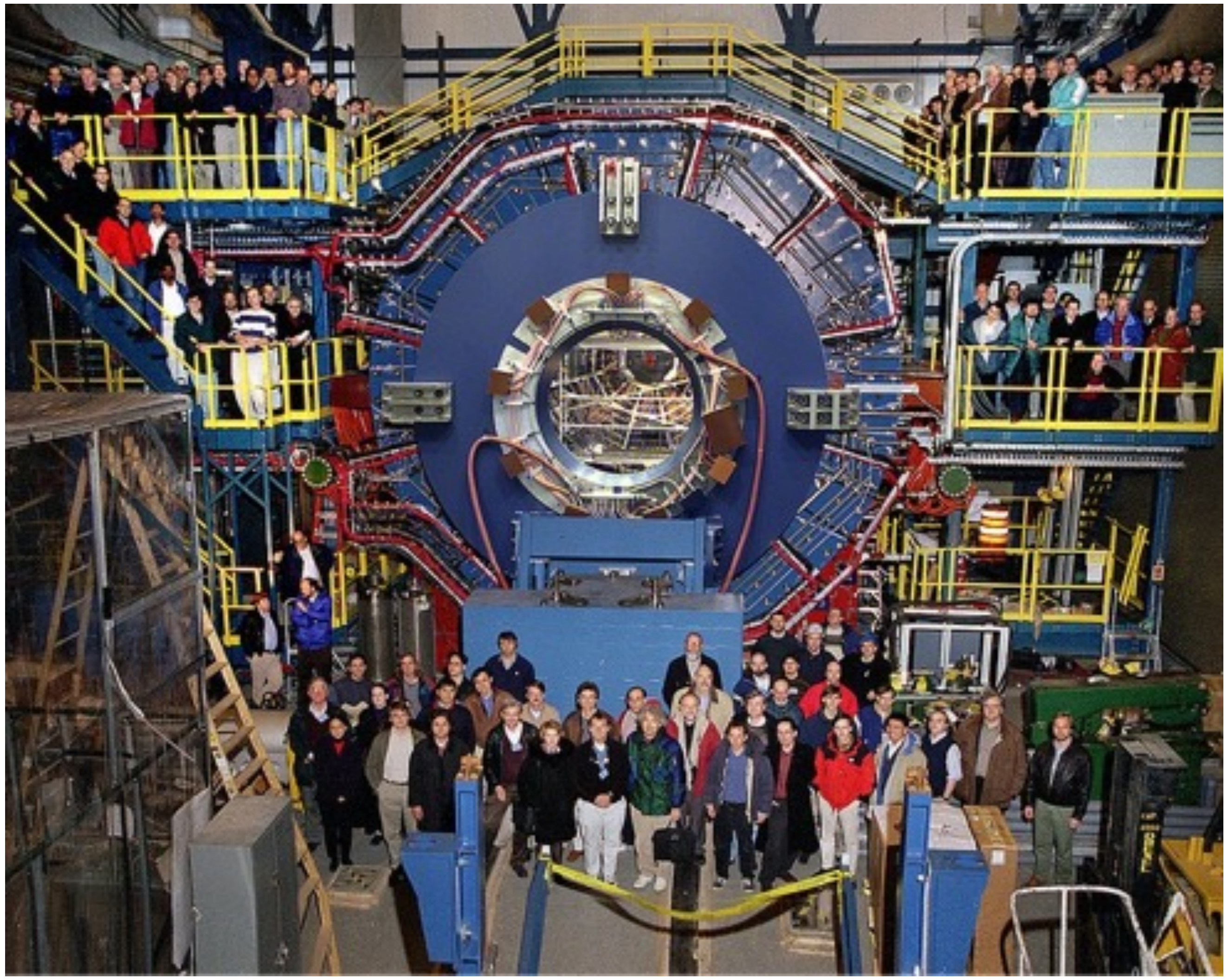


photo from https://www.flickr.com/photos/brookhavenlab/sets/72157613690851651/

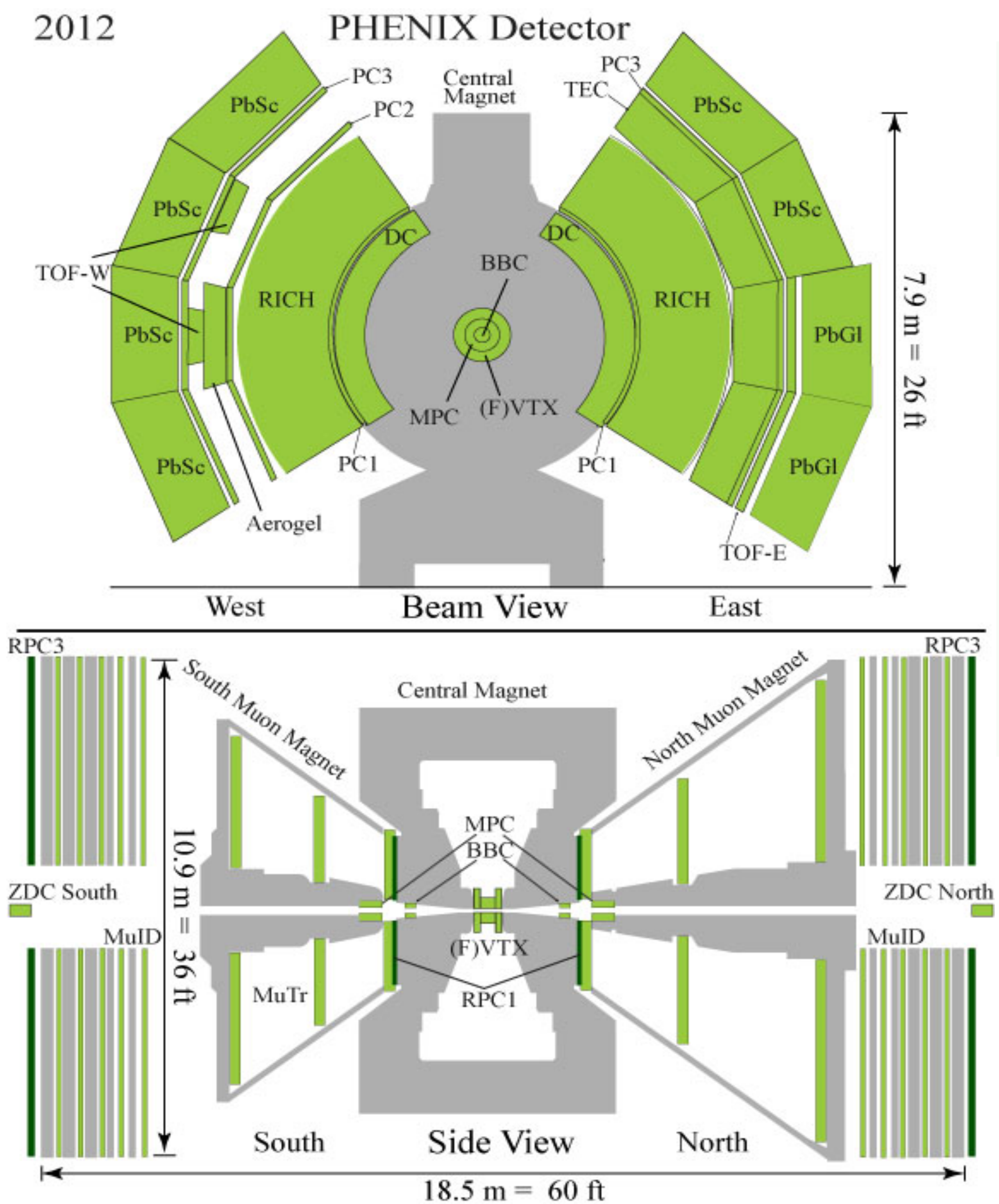
- ~3.8 km circumference
- Maximum 200 GeV (500 GeV) in A+B (p+p) collisions in center of mass energy
- Wide variety of beams; p, d, He, Cu, Au, U
- Two running experiments: PHENIX, STAR

PHENIX & STAR experiments

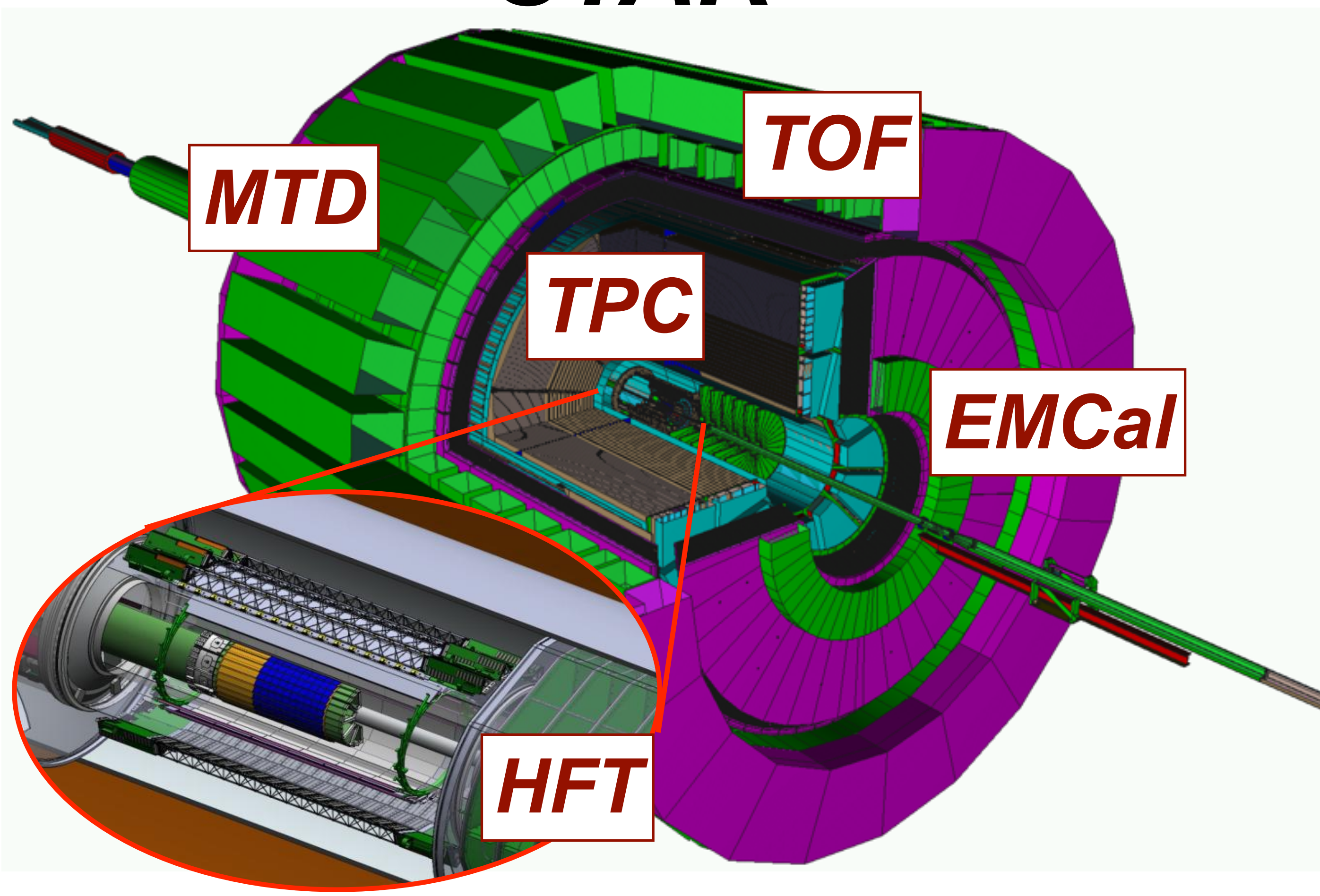


- PHENIX: the *P*ioneering *H*igh *E*nergy *N*uclear *I*nteraction e*X*periment
  - Rare probes by electrons & photons with fast triggers
- STAR: *S*olenoidal *T*racker *A*t *R*HIC
  - Hadrons with large acceptance

PHENIX & STAR experiments

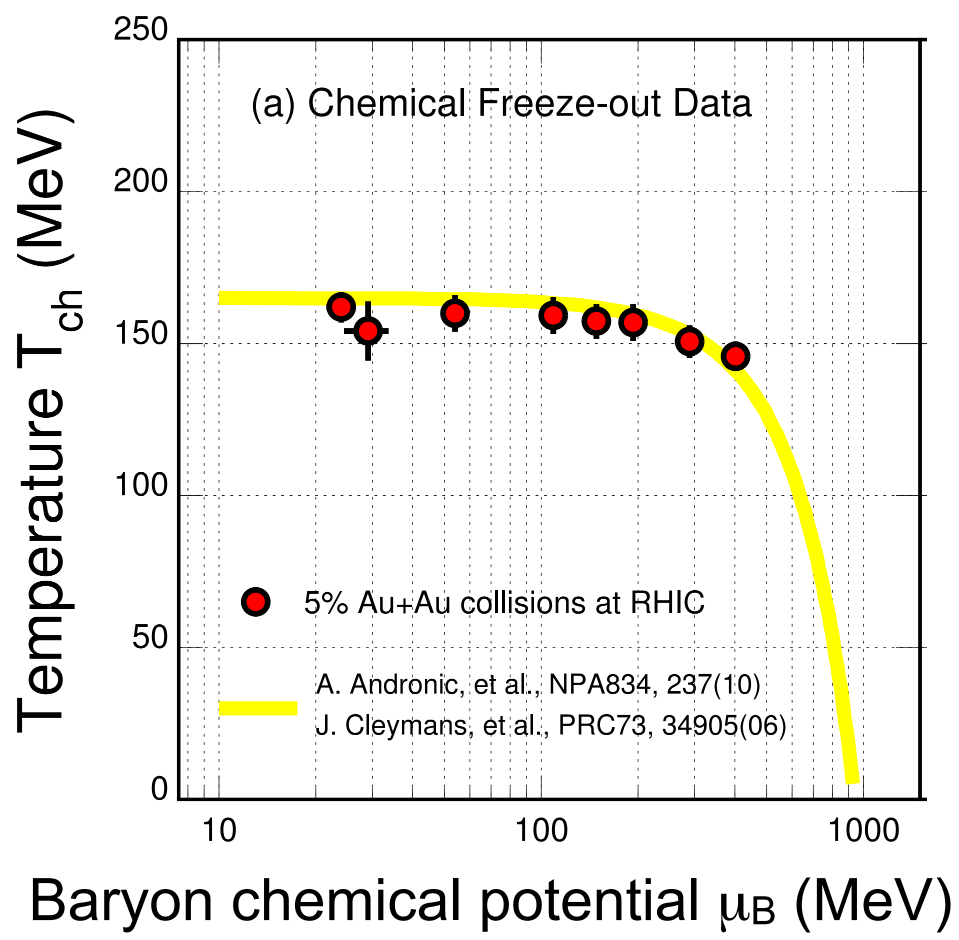


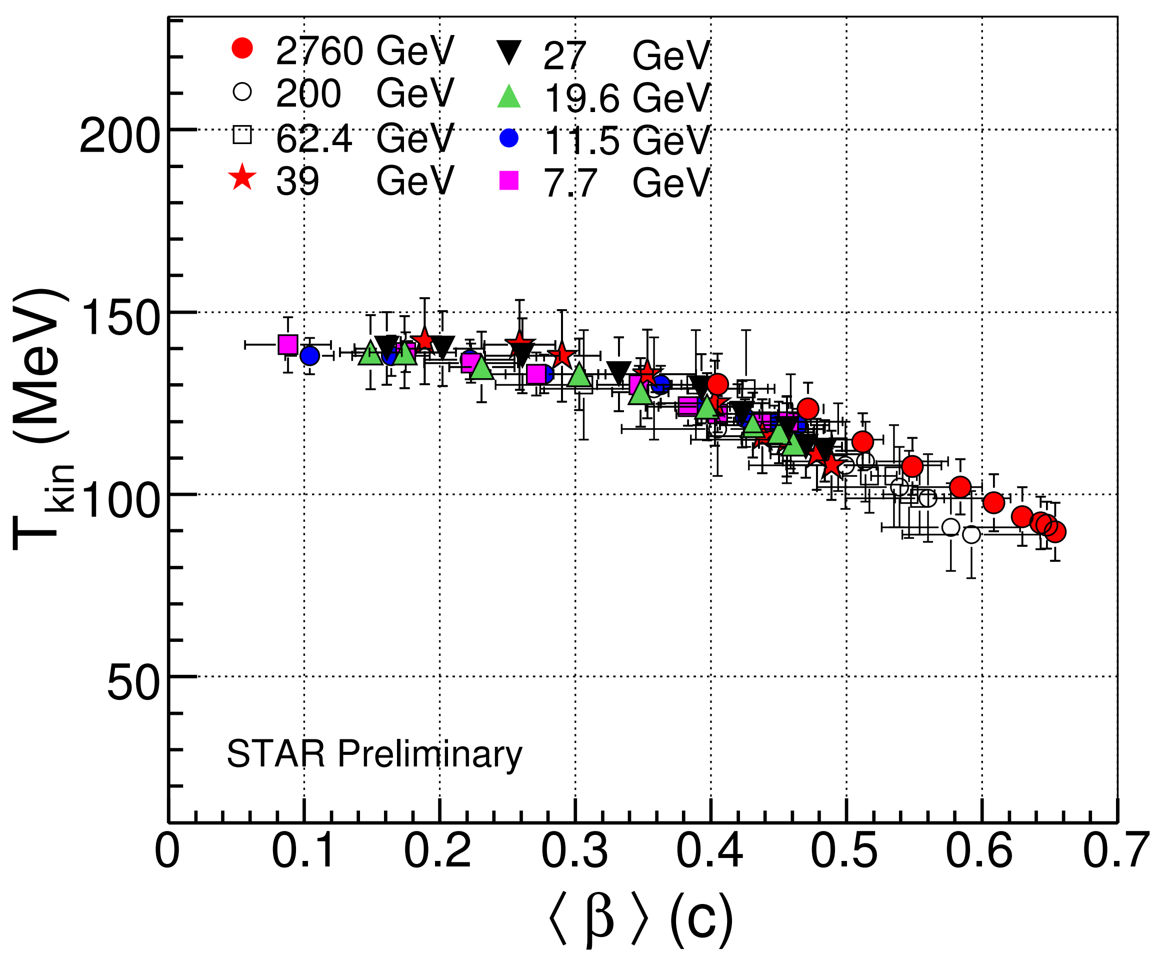
STAR



- Detector upgrades made two experiments similar
  - in terms of observables
- sPHENIX upgrade is considered around 2017

Where are we in QCD phase diagram ?



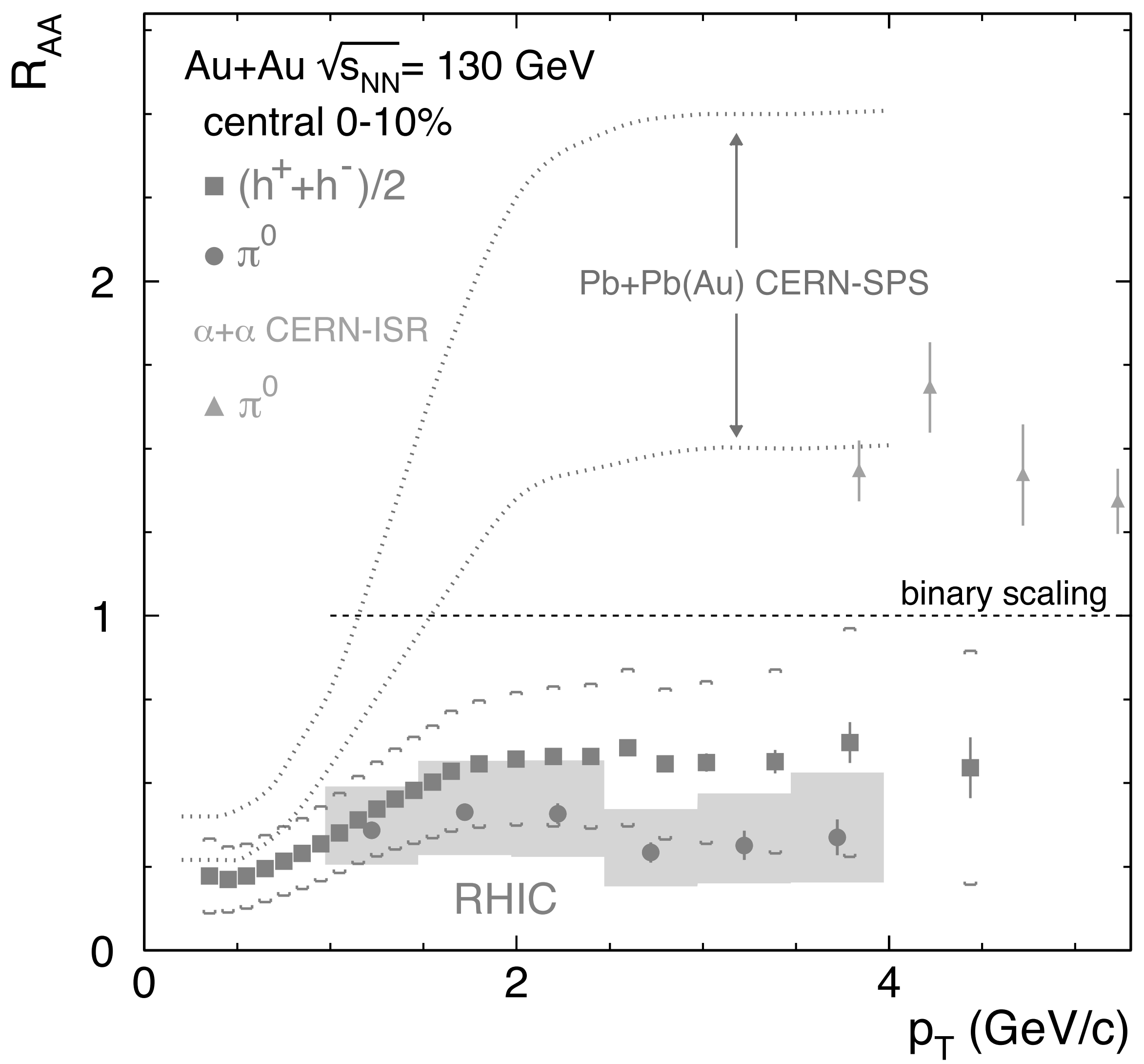


- RHIC BES phase-I covers up to ~ 400 MeV in μ_B
  - Chemical freeze-out temperature & baryon chemical potential from particle ratio
  - Kinetic freeze-out temperature from p_T spectra
- Can we observe onset (turn-off) of QGP at high μ_B ?

Search for turn-off QGP signals

Jet quenching

*PHENIX: **PRL88**, 022301 (2002)*



$$R_{AA} = \frac{dN^{AA}/dp_T d\eta}{\langle N_{coll}\rangle\, dN^{p+p}/dp_T d\eta}$$

N_{coll} : Number of binary collisions

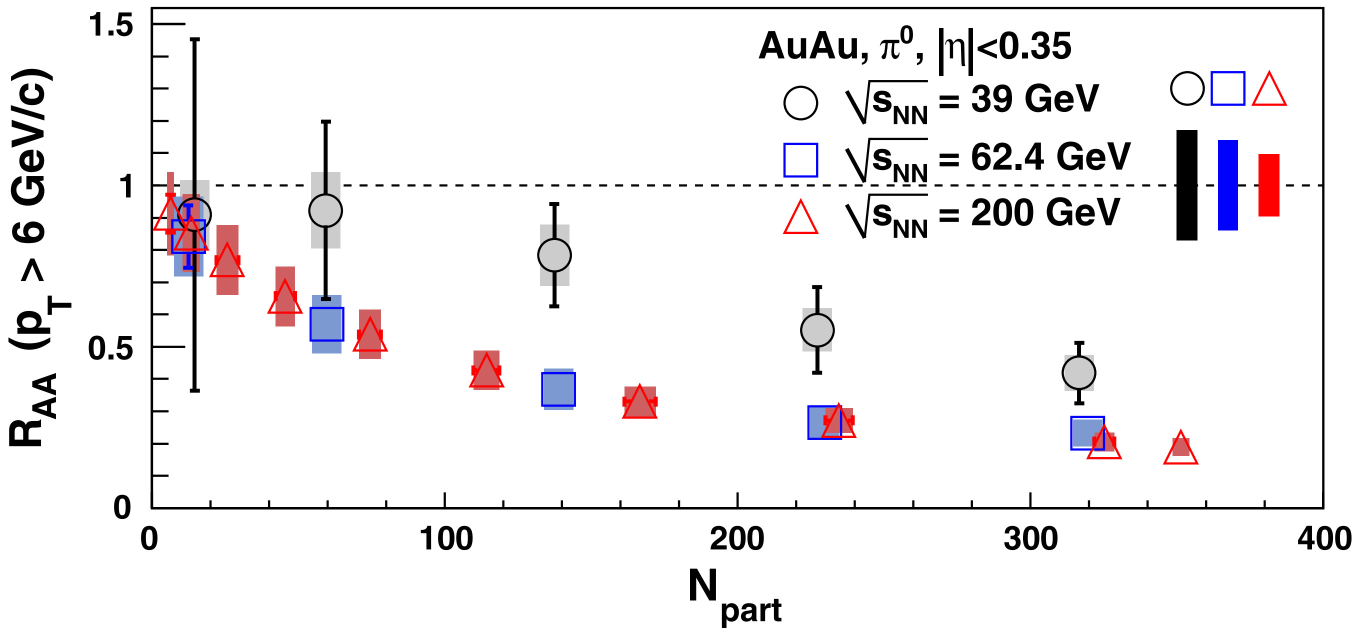
R_{AA} = 1
if A+A is superposition of p+p

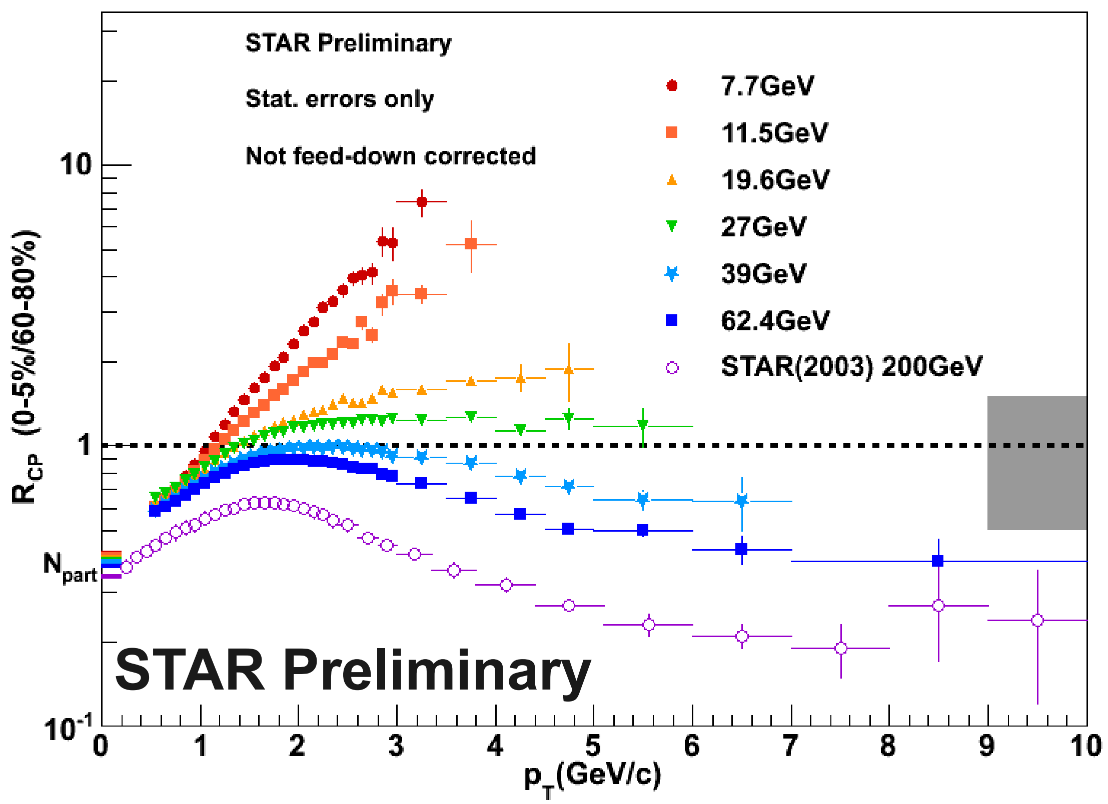
Initial hard scattering - Binary collision scaling

- Suppression of hadron yields at high p_T
  - Energy loss of partons in the medium
  - Very opaque medium in terms of color charge
- What happens in lower energies ?

R_{AA} at low energies

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





- Exhibit suppression down to 39 GeV
  - 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
- R_{AA} > 1 below 39 GeV

Quark (parton) coalescence

Coalescence

$$\frac{dN^r}{dp_T}(p_T) \sim C_r \times \left(\frac{dN^q}{dp_T}(p_T/n)\right)^n$$

Hadrons from coalescence have larger momentum than the quark momentum

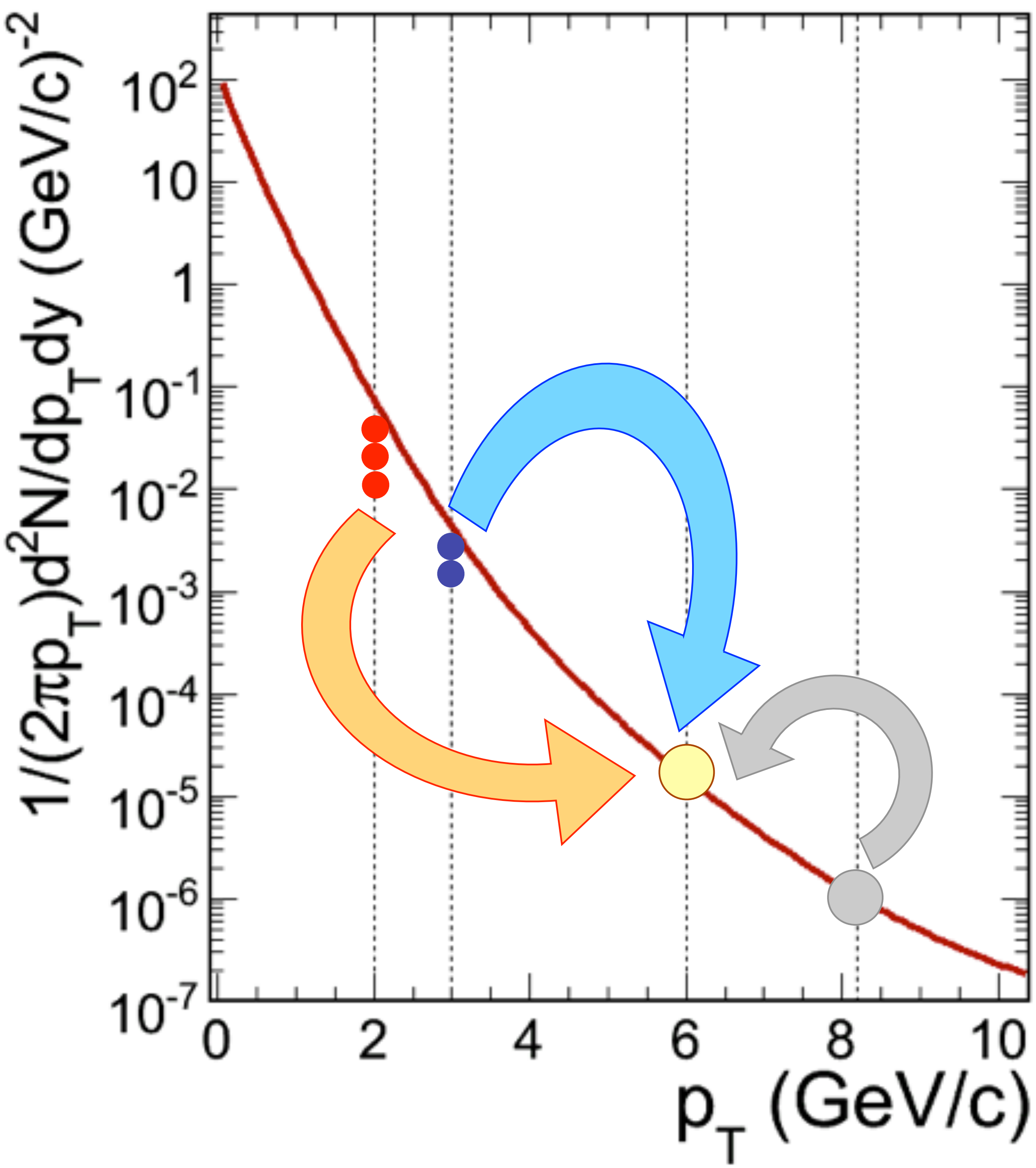
$$p_T^h > p_T^q$$

Fragmentation

$$\frac{dN^f}{dp_T}(p_T) \sim \frac{dN^q}{dp_T}(p_T/z)(z < 1)$$

Carry only a fraction (z < 1) of the initial quark momentum

$$p_T^h < p_T^q$$



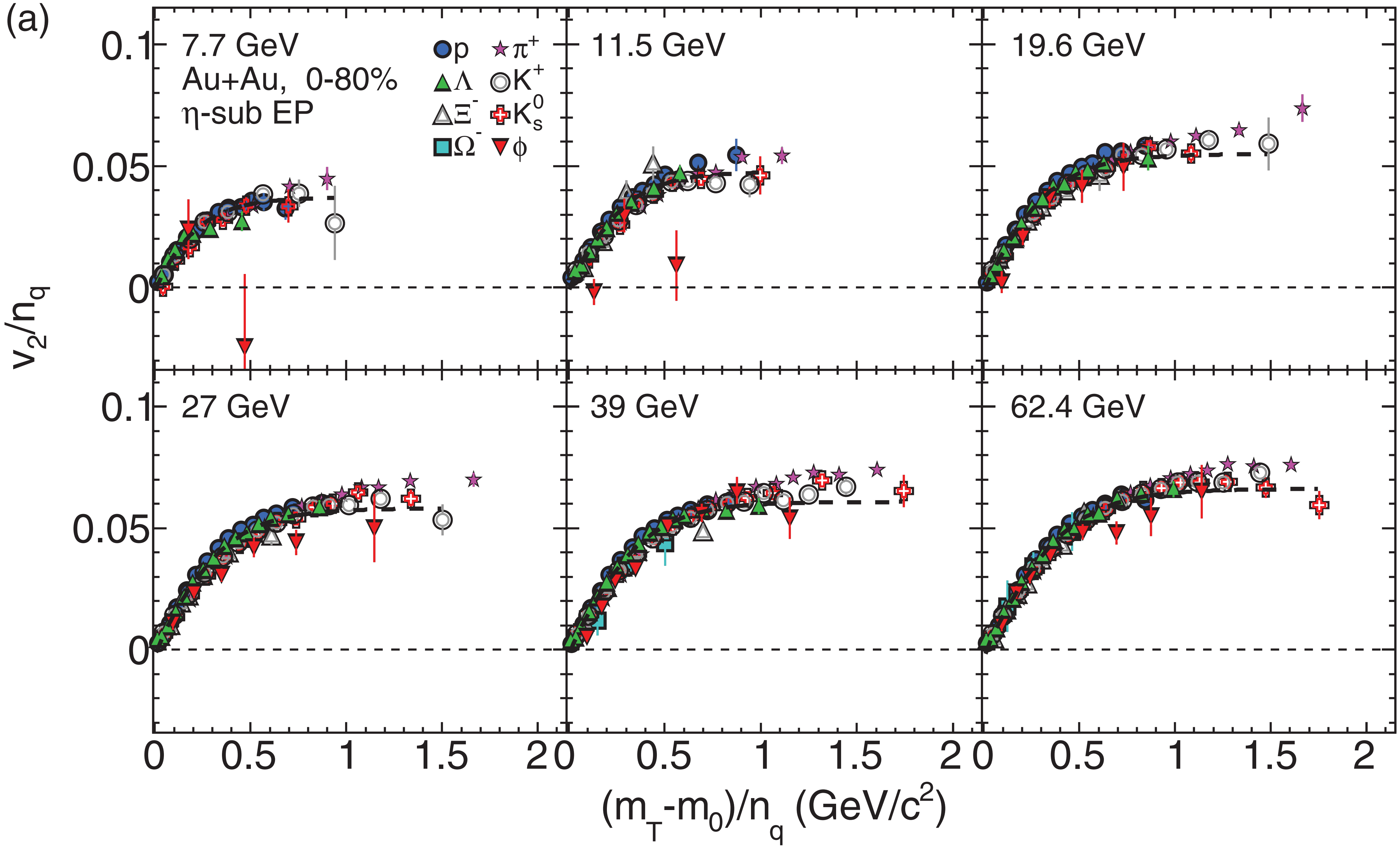
D. Molnar and S. A. Voloshin, ***PRL91****, 092301 (2003), R. C. Hwa and C. B. Yang,* ***PRC66****, 025205 (2002), V. Greco et al,* ***PRL90****, 202302 (2003), R. J. Fries et al,* ***PRL90****, 202303 (2003), ...*

$$v_2^h(p_T) \approx n_q v_2^q(p_T/n_q)$$

- Hadron productions by quark coalescence picture
- Specific scaling pattern for meson and baryon v_2

Elliptic flow v_2

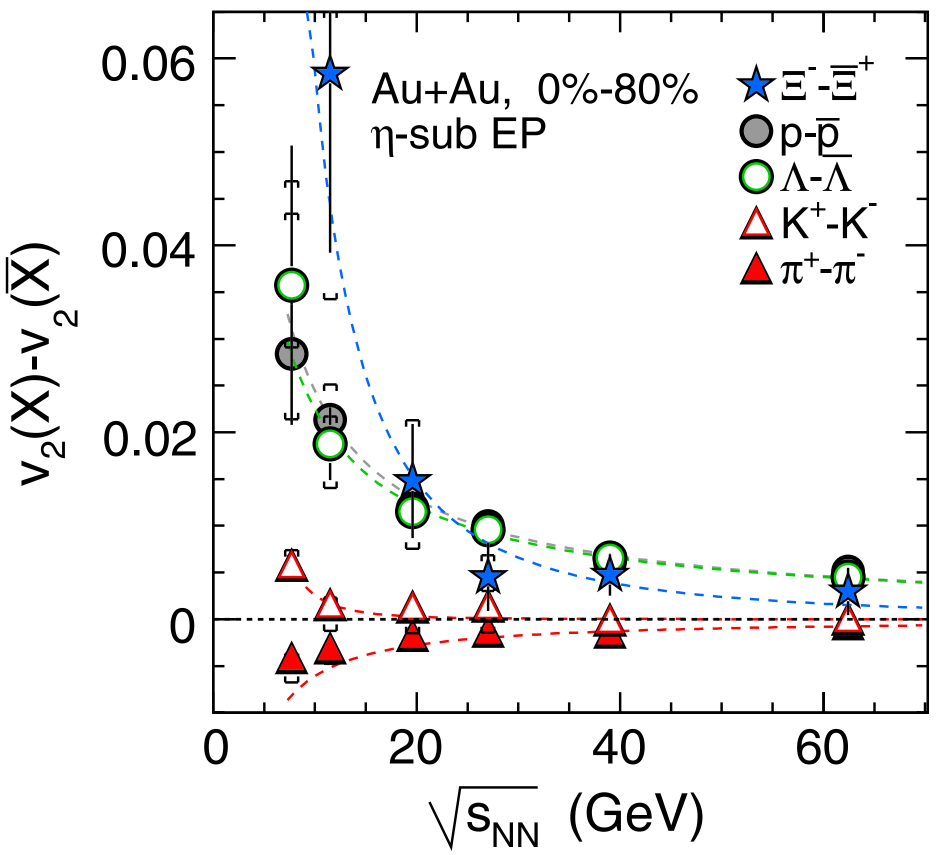
STAR: ***PRC88***, *014902 (2013)*



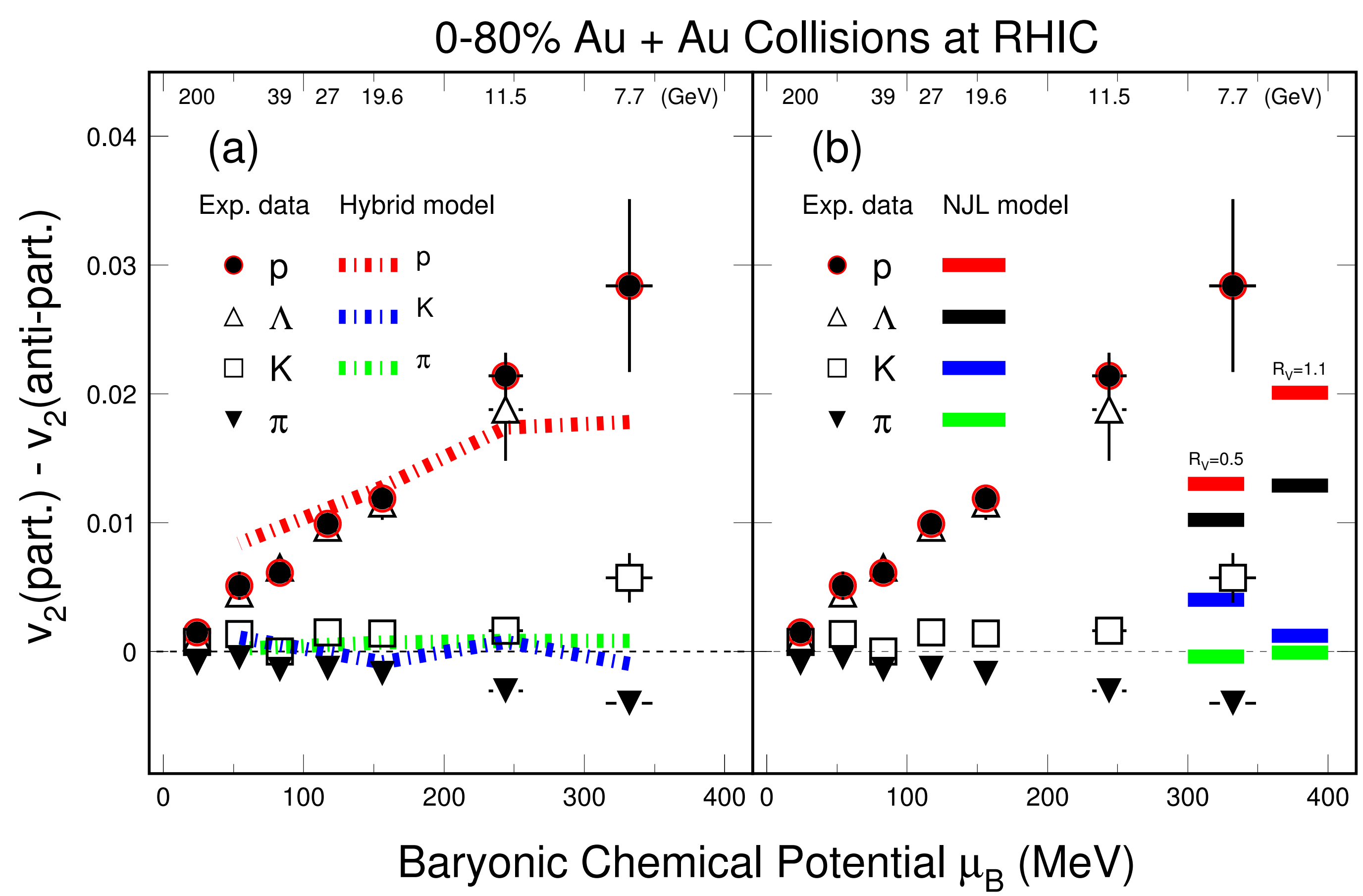
- Number of constituent quark (NCQ) scaling - partonic d.o.f
  - Hold separately for particles and anti-particles
  - Need more statistics in high m_T-m_0 at lower energies

v_2; particles vs anti-particles

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



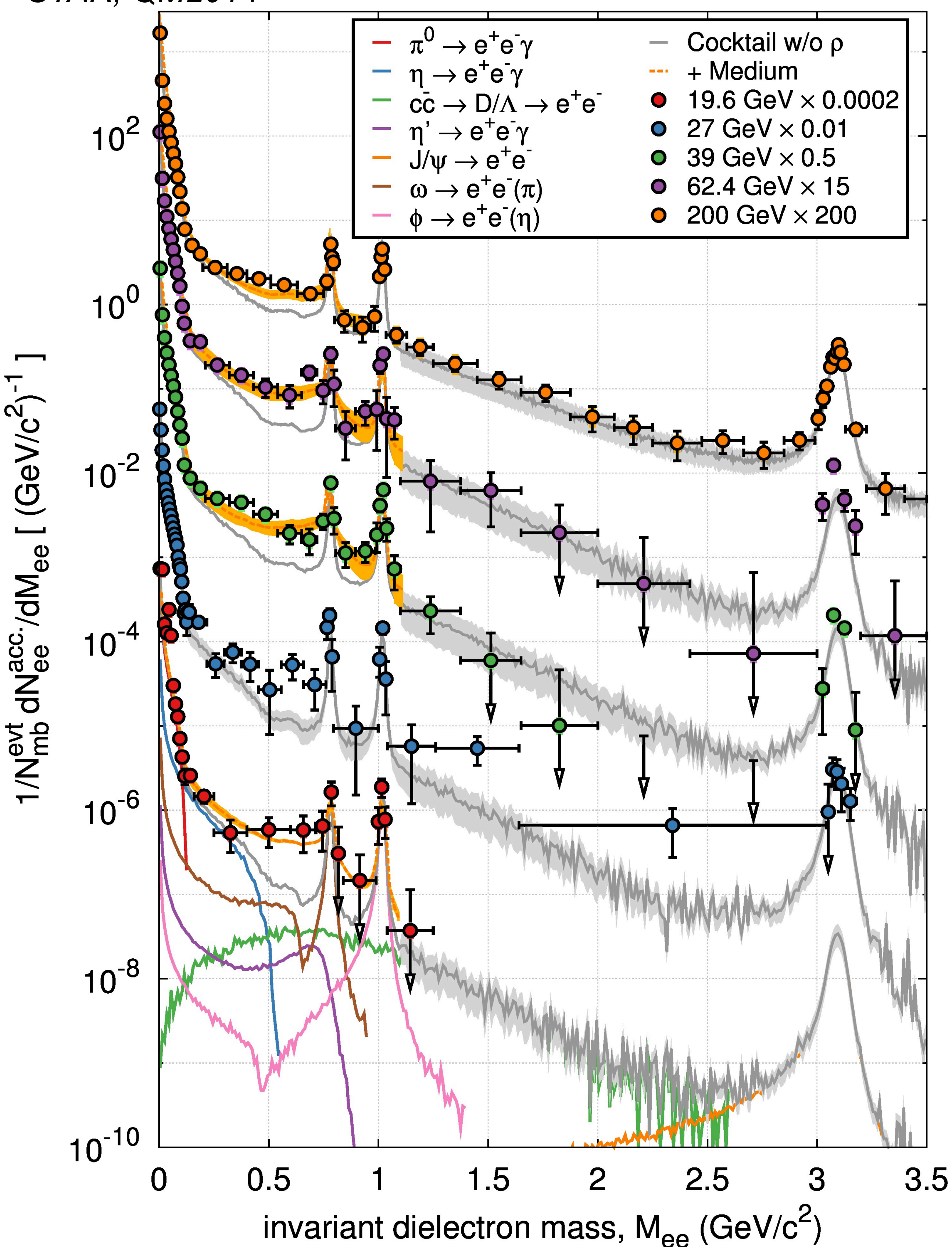
*Hybrid model: **PRC86**, 044903 (2012)*
*NJL model: **PRL112**, 012301 (2014)*



- Relative difference of v_2 between particles and anti-particles increase in lower beam energies
  - NCQ scaling breaks down between particles and antiparticles
- Qualitative agreement with several models
  - No quantitative explanations on the difference of v_2

Di-electron mass spectra

STAR, QM2014

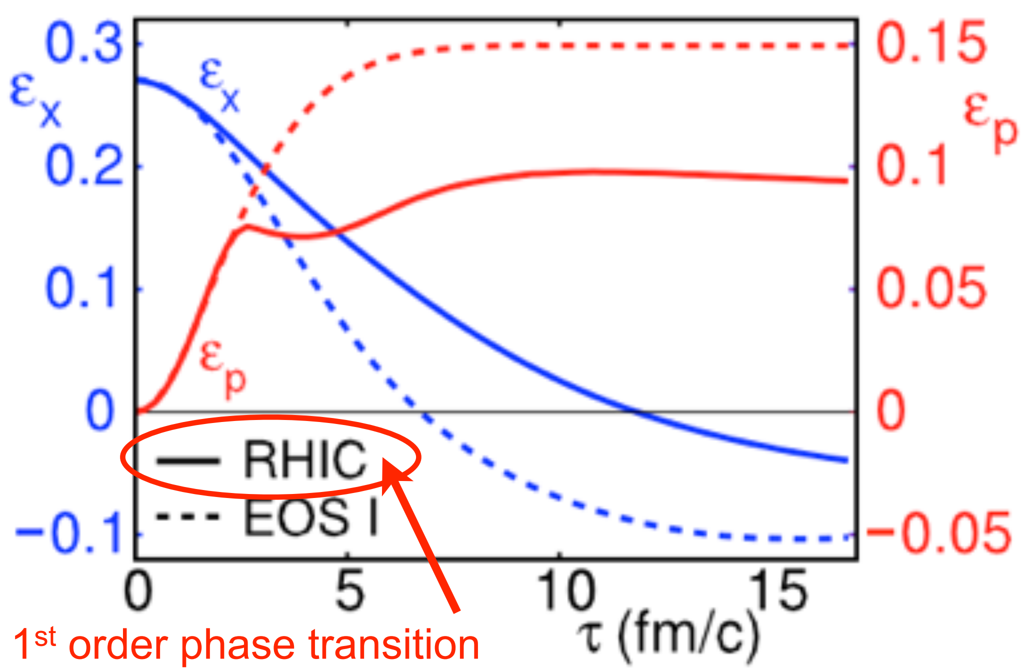


- Chiral symmetry restoration, thermal radiation
  - STAR measured di-electron spectra in $\sqrt{s_{NN}}$ = 19.6 - 200 GeV
  - Excess in M_{ee} < 1.1 GeV/c^2 (LMR) observed at all energies
  - In-medium modification of ρ spectral function describe LMR enhancement
  - No energy dependence of LMR excess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

Search for signals of 1st order phase transition

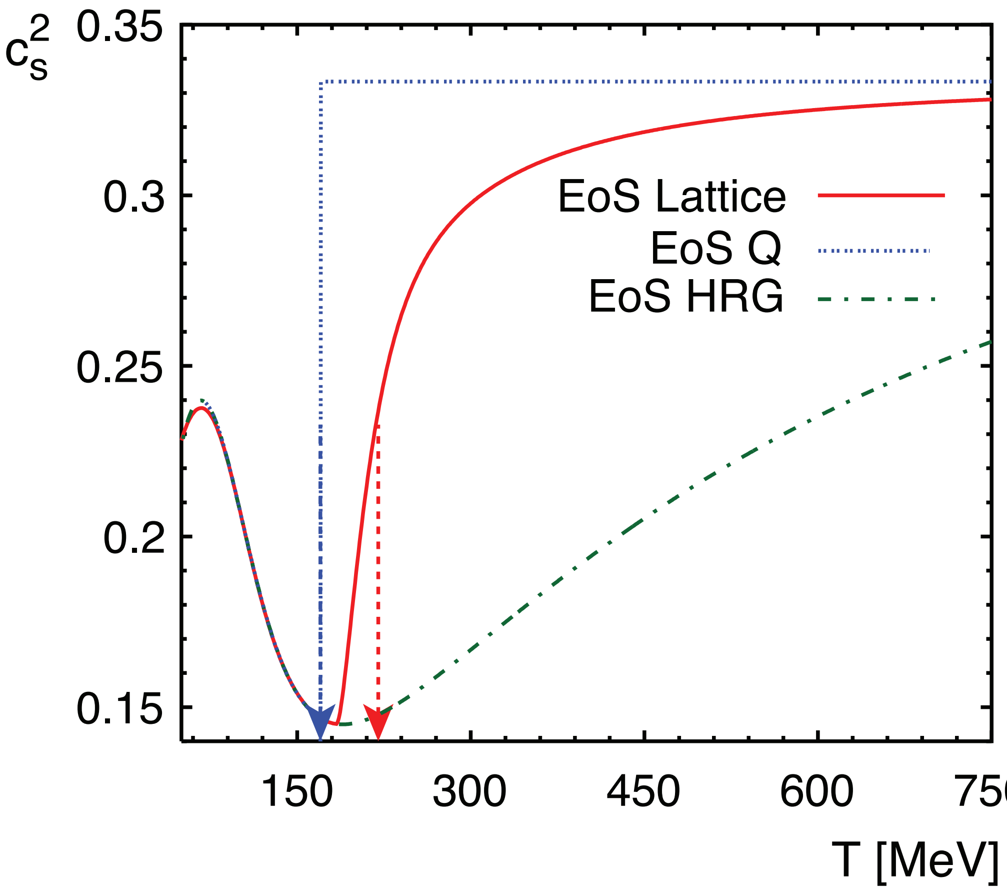
Equation of state → flow systematics

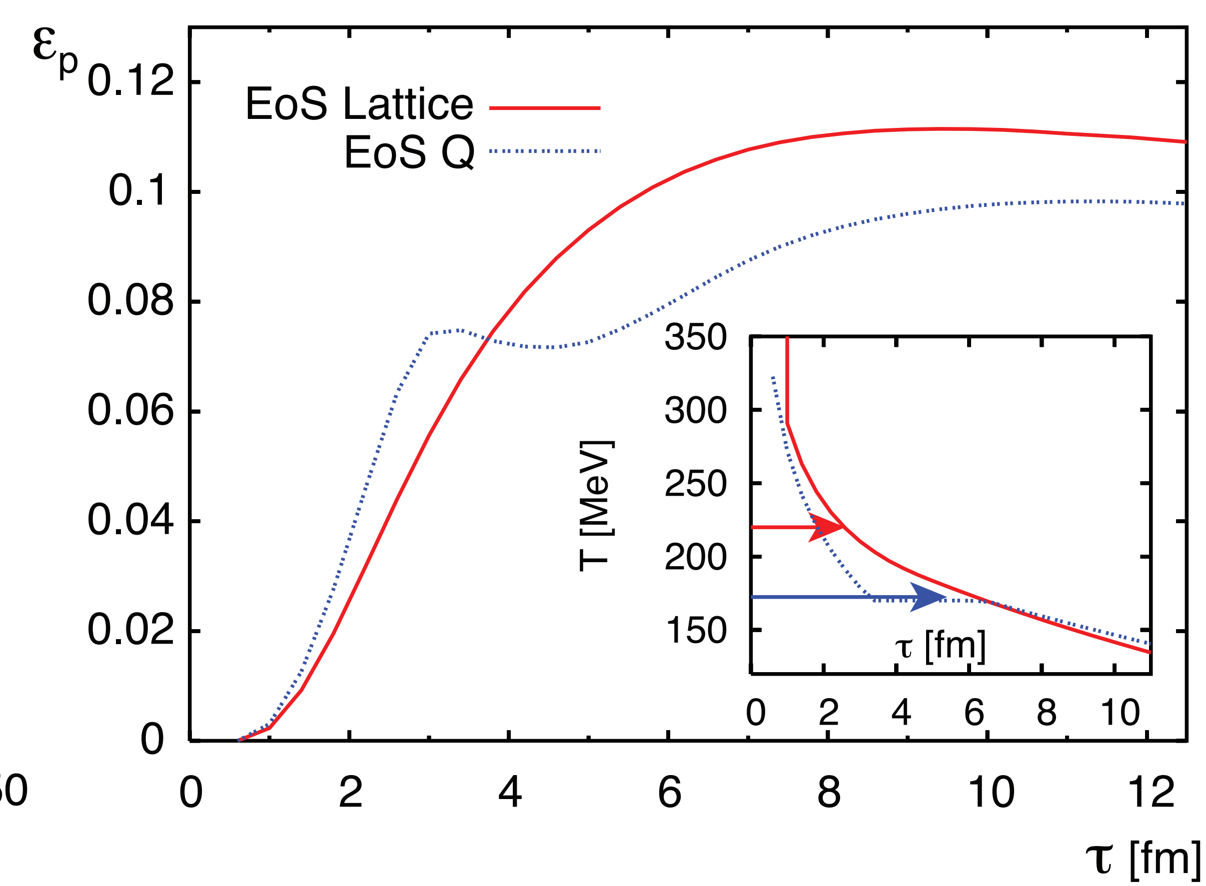
*P. F. Kolb et al, **PRC62**, 054909 (2000)*



- 1st order phase transition affects the build up of spatial & momentum anisotropy

➡ Look at flow systematics

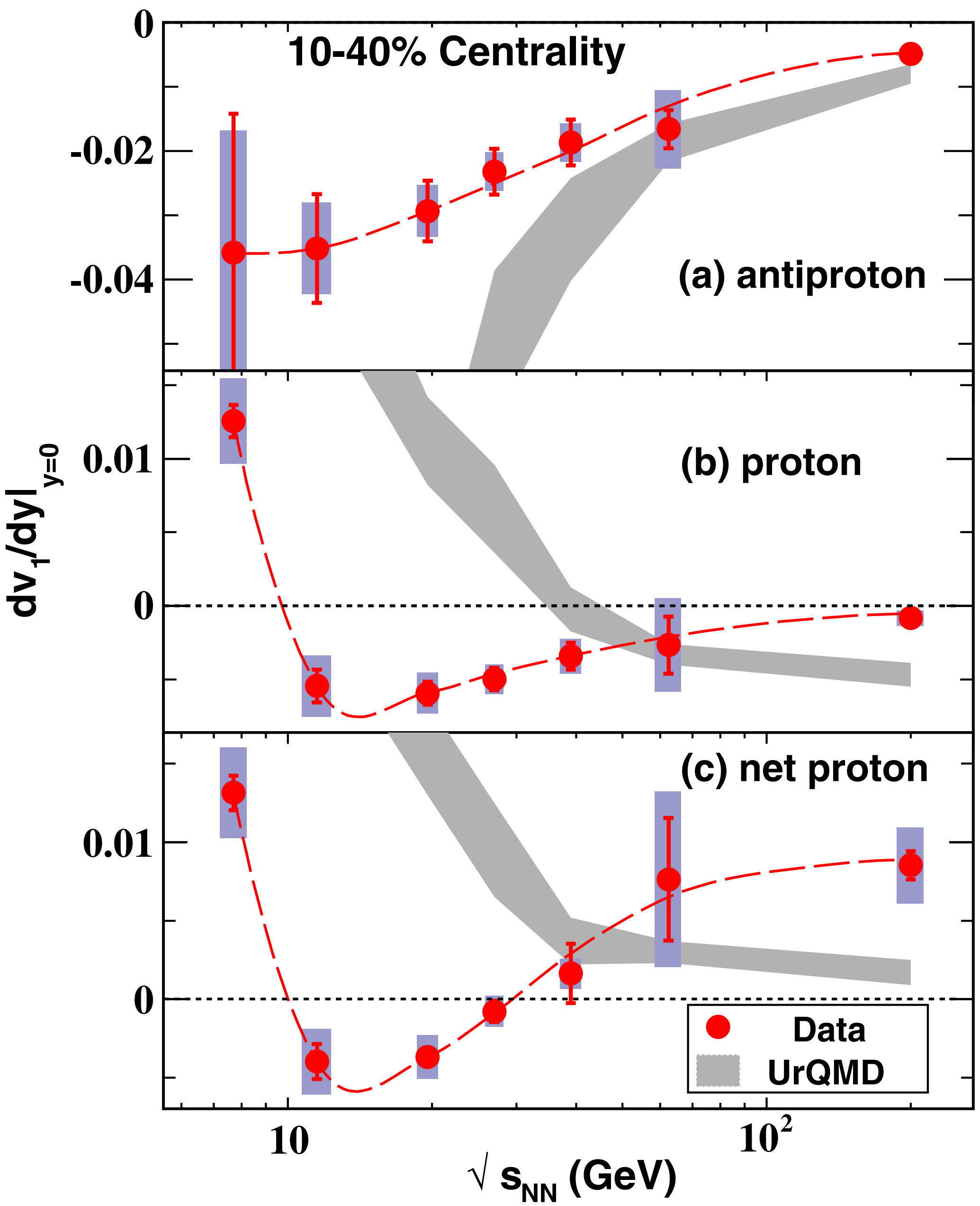




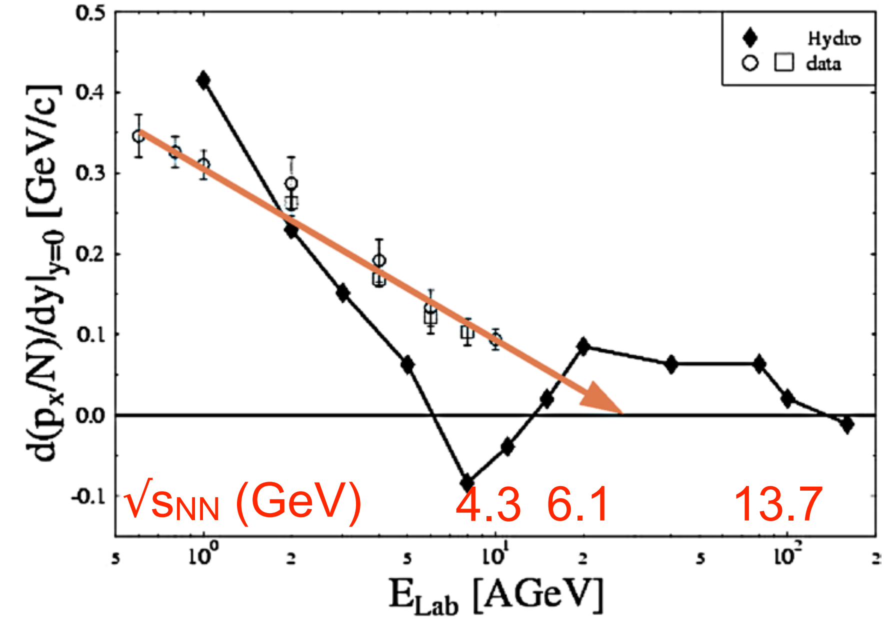
R. Snellings, New J. Phys.13, 055008 (2011)

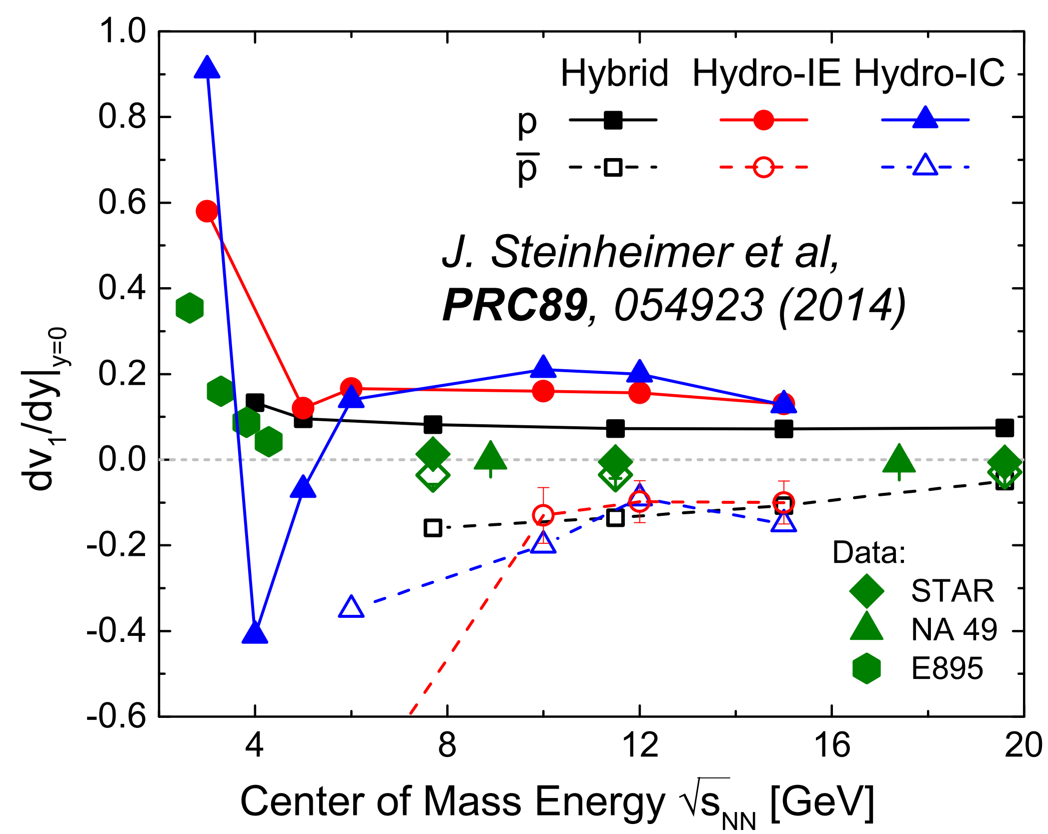
Directed flow v_1

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



H. Stocker: **NPA750** (2005) 121-147

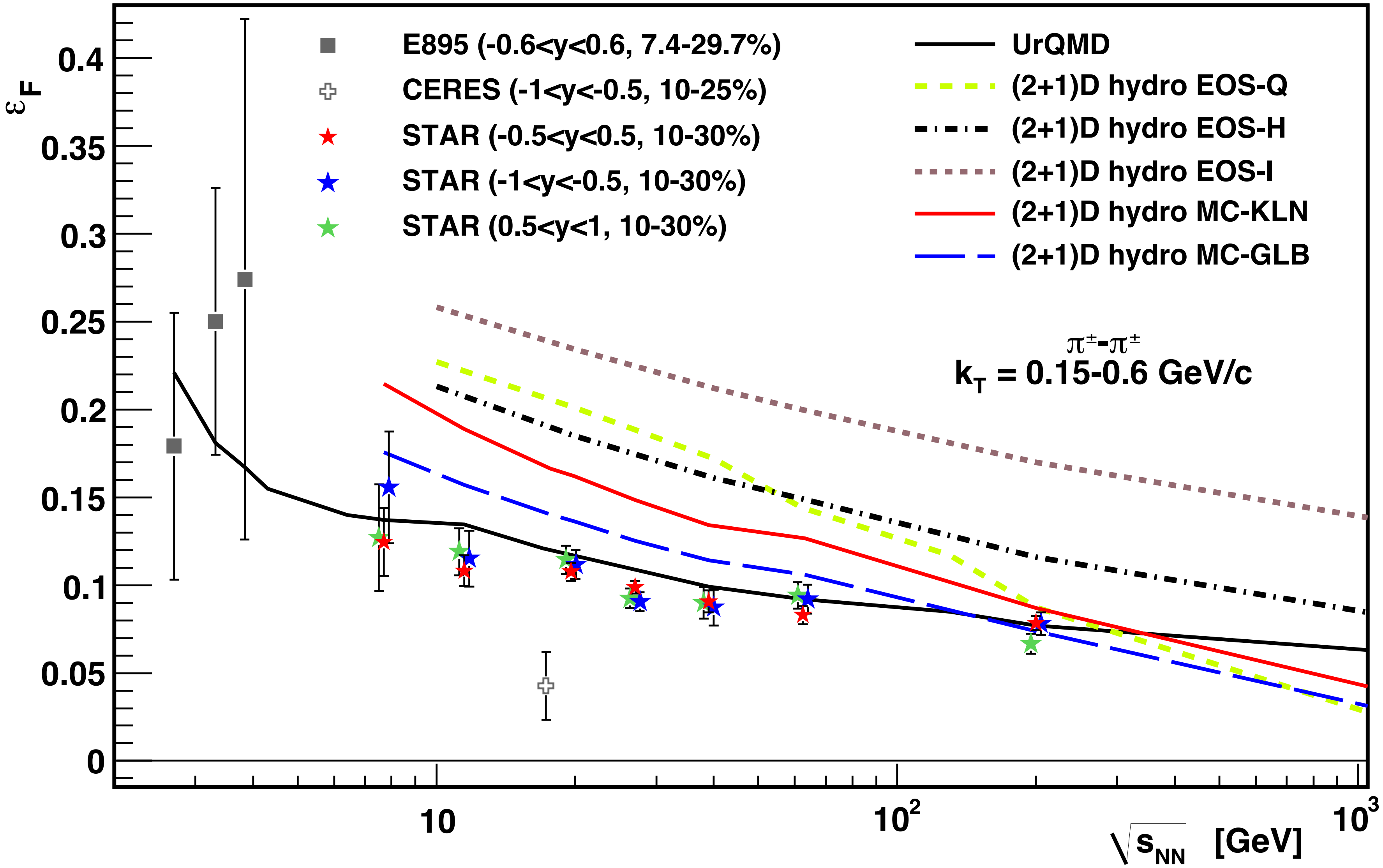




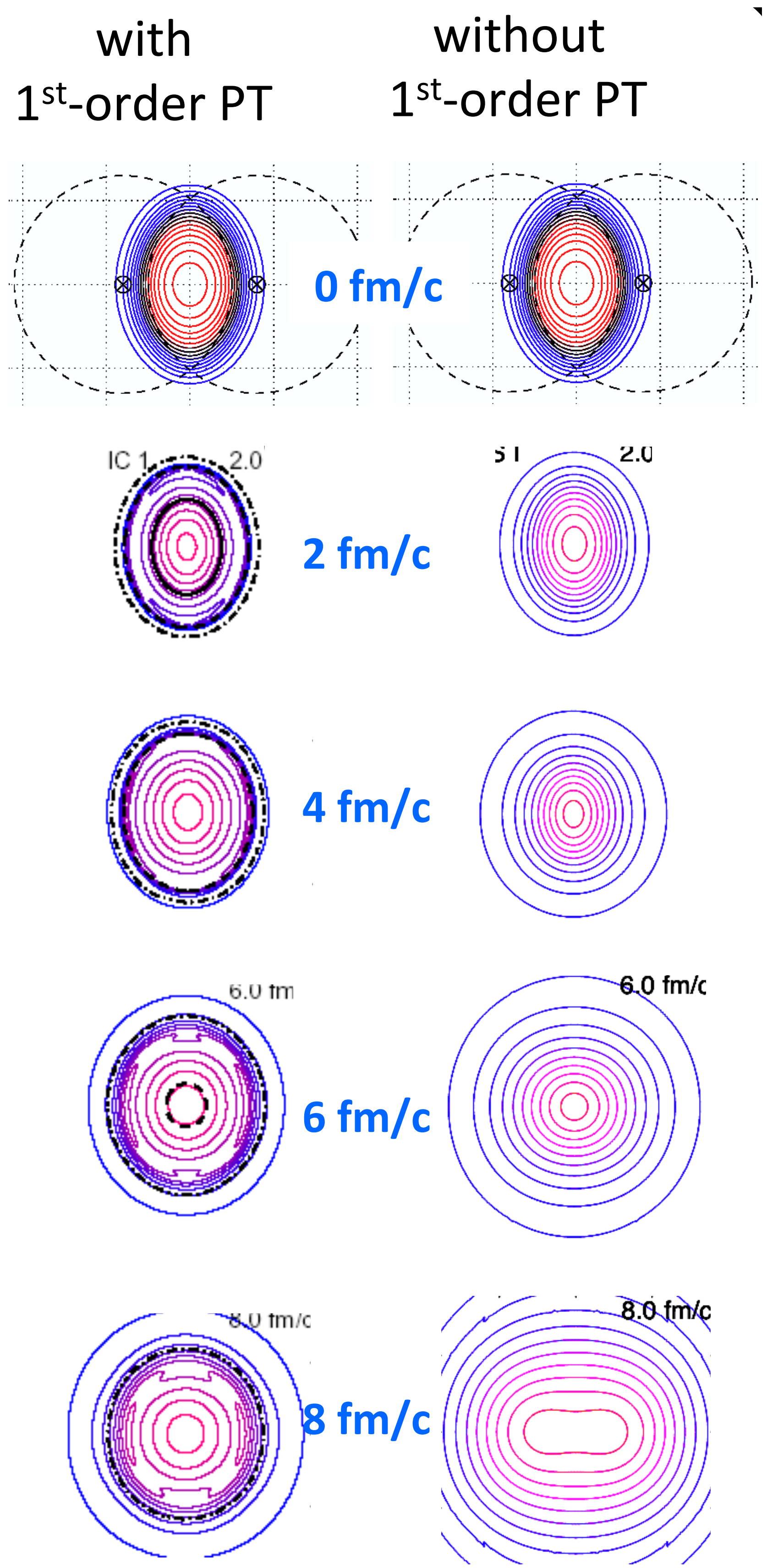
- Early prediction shows the minimum around ~ 5 GeV
  - Non-monotonic behavior, trend is similar with early prediction
  - Recent more realistic hybrid calculation can’t reproduce the data

Azimuthal sensitive HBT

STAR: arXiv:1403.4972 [nucl-ex]



by M. Lisa

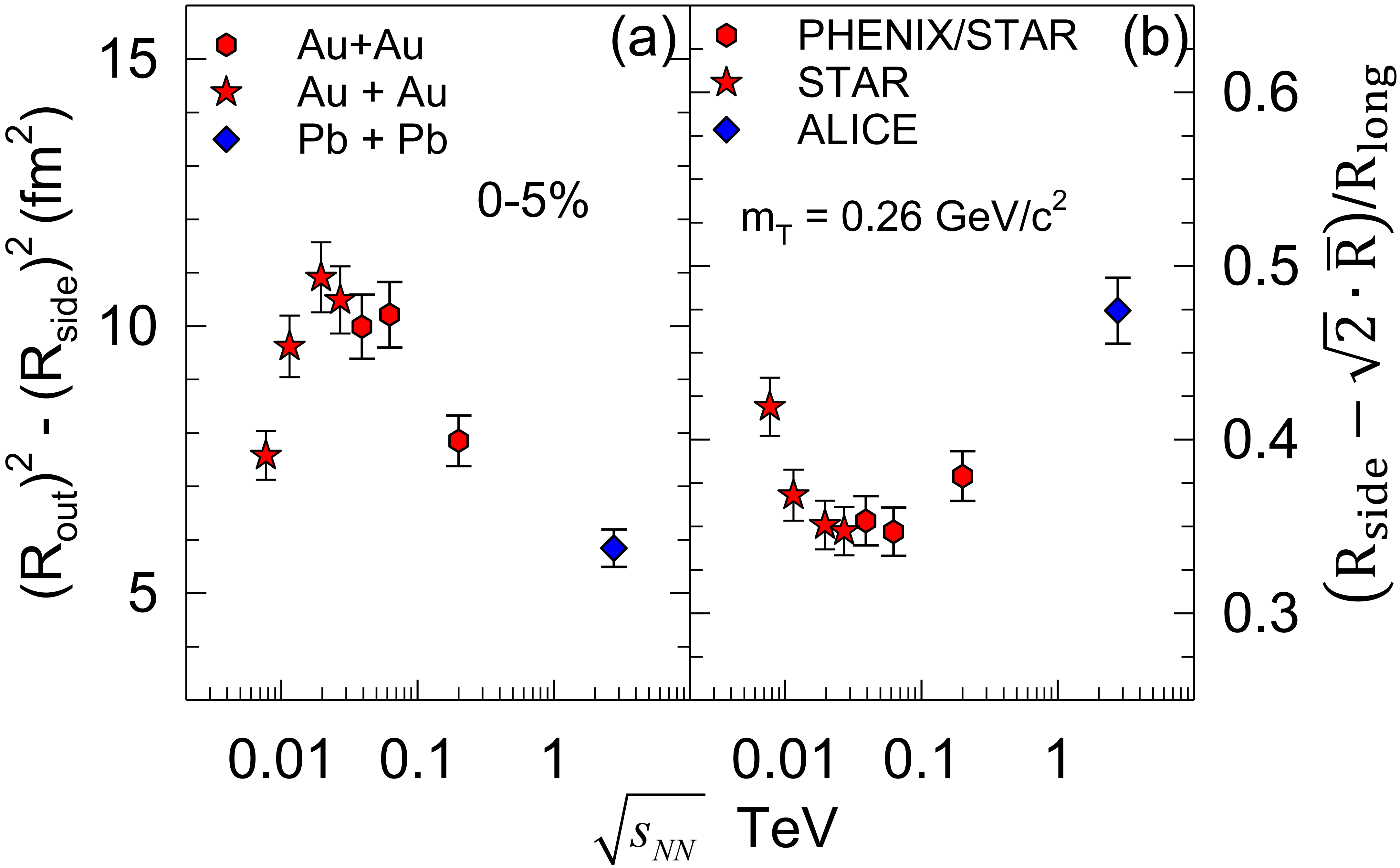


Ideal hydro calculations - Kolb & Heinz

- STAR results show monotonic decrease of freeze-out eccentricity
  - No sudden change on the STAR data

HBT radii

PHENIX: arXiv:1410.2559 [nucl-ex]



- 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

Search for signals of QCD critical point

Fluctuation of conserved charges

- At critical point (with infinite volume)
  - susceptibilities and correlation length diverge
  - but both quantities cannot measure directly in the experiments
- Observables
  - Moment (or cumulant) of conserved quantities: e.g. net-baryons, net-charge, net-strangeness
  - Product of moments (ratio of cumulants) ↔ ratio of susceptibilities

$$\kappa_2 = \left\langle (\delta N)^2 \right\rangle \sim \xi^2, \kappa_3 = \left\langle (\delta N)^3 \right\rangle \sim \xi^{4.5}, \kappa_4 = \left\langle (\delta N)^4 \right\rangle - 3 \left\langle (\delta N) \right\rangle^2 \sim \xi^7$$

$$S\sigma = \frac{\kappa_3}{\kappa_2} \sim \frac{\chi_3}{\chi_2}, \;\; K\sigma^2 = \frac{\kappa_4}{\kappa_2} \sim \frac{\chi_4}{\chi_2}$$

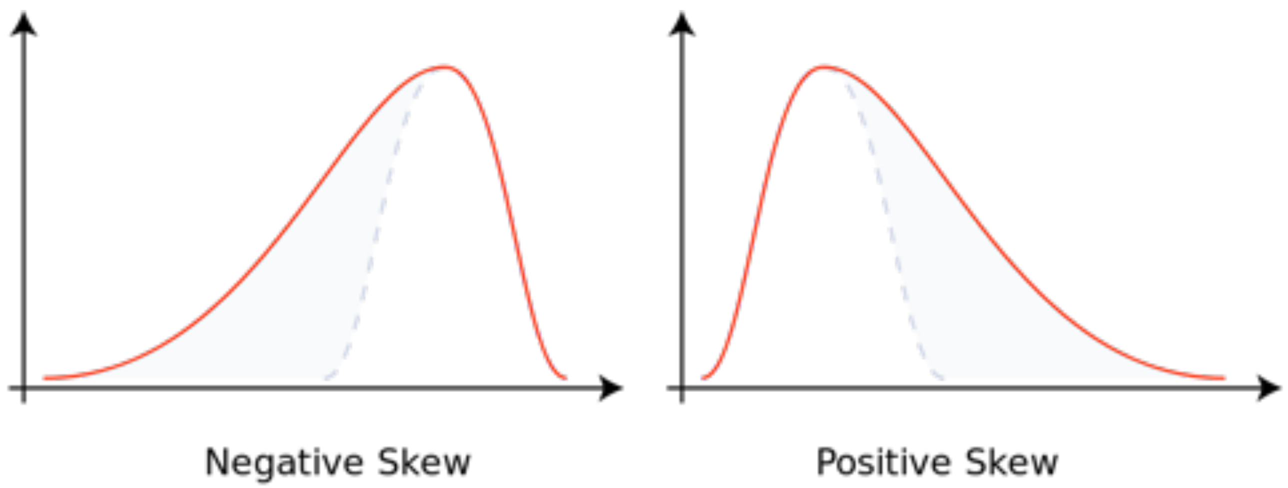
- directly related to the susceptibility ratios (Lattice QCD)
- higher moments (cumulants) have higher sensitivities to correlation length*

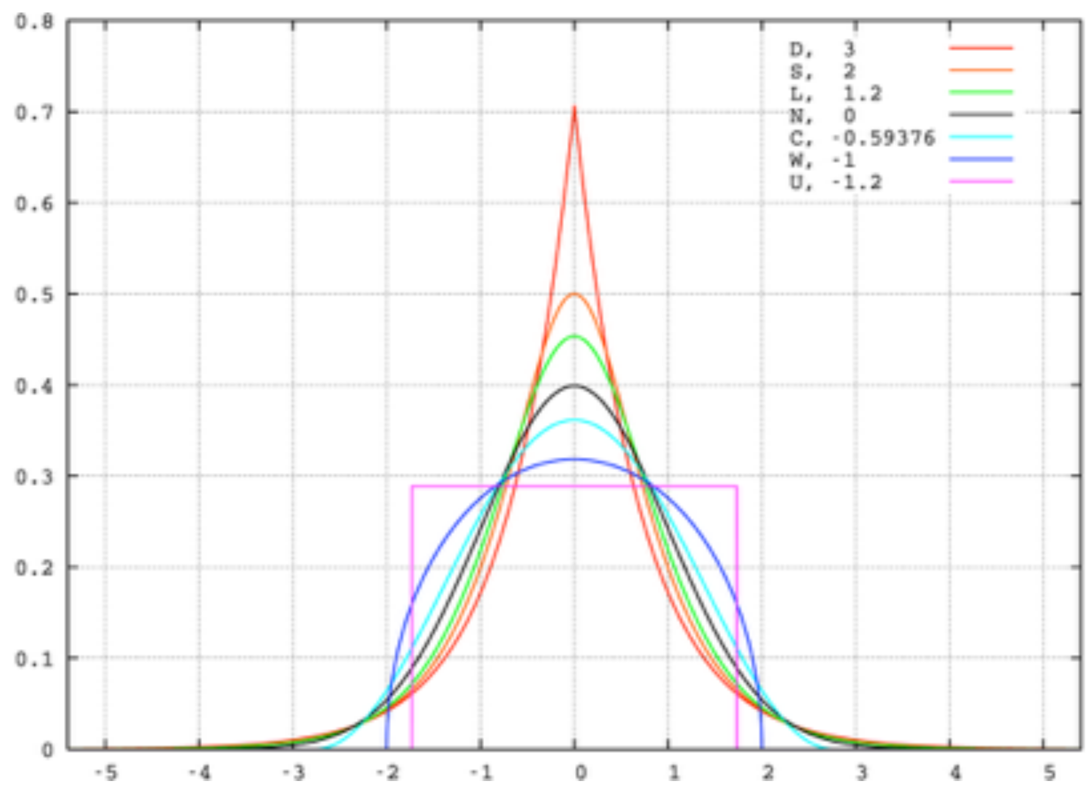
** M. A. Stephanov, **PRL102**, 032301 (2009)*

- Signal = non-monotonic energy dependence of moment products (cumulant ratios) for conserved charges vs $\sqrt{s_{NN}}$

Non-gaussian fluctuations

From Wikipedia

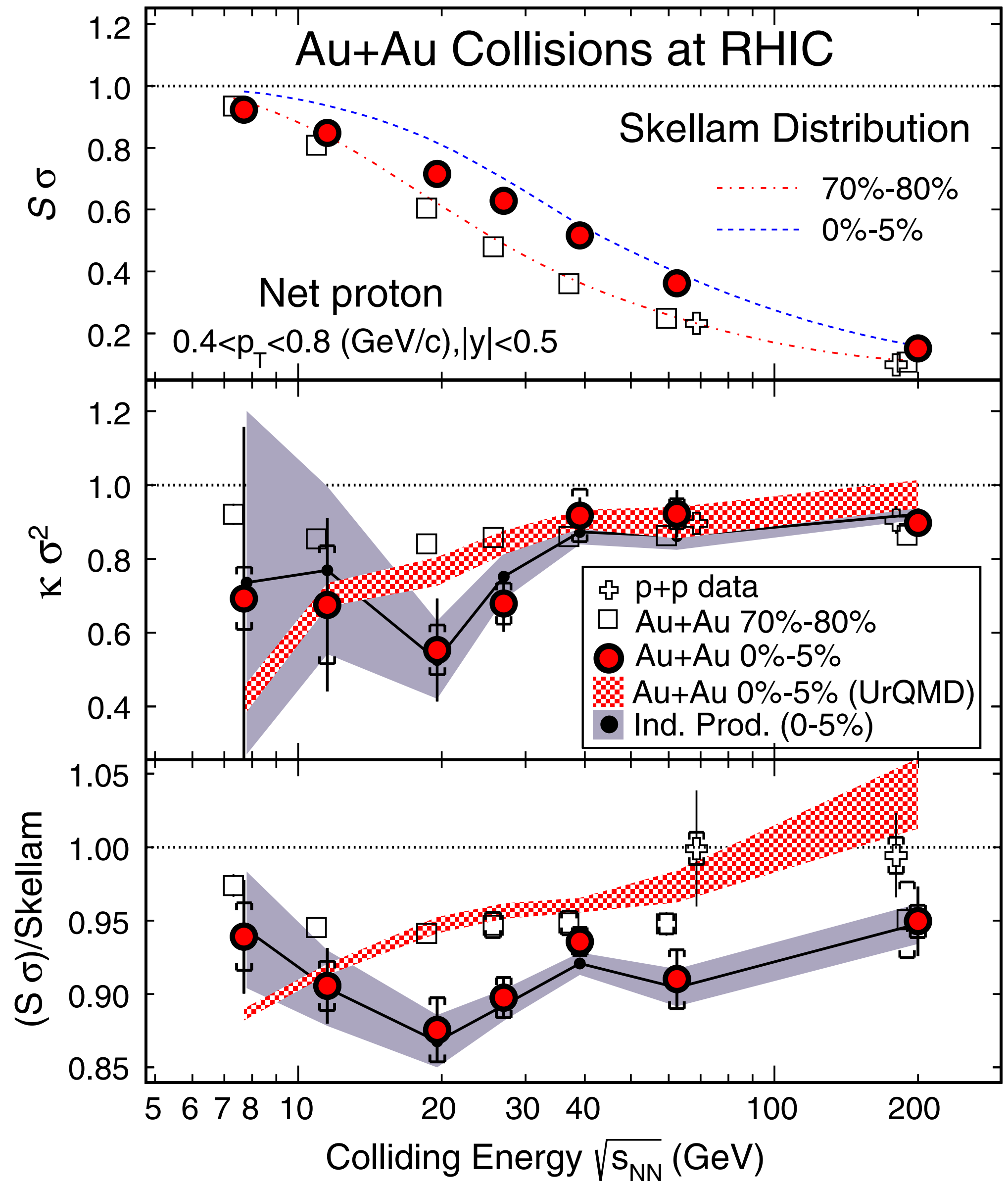




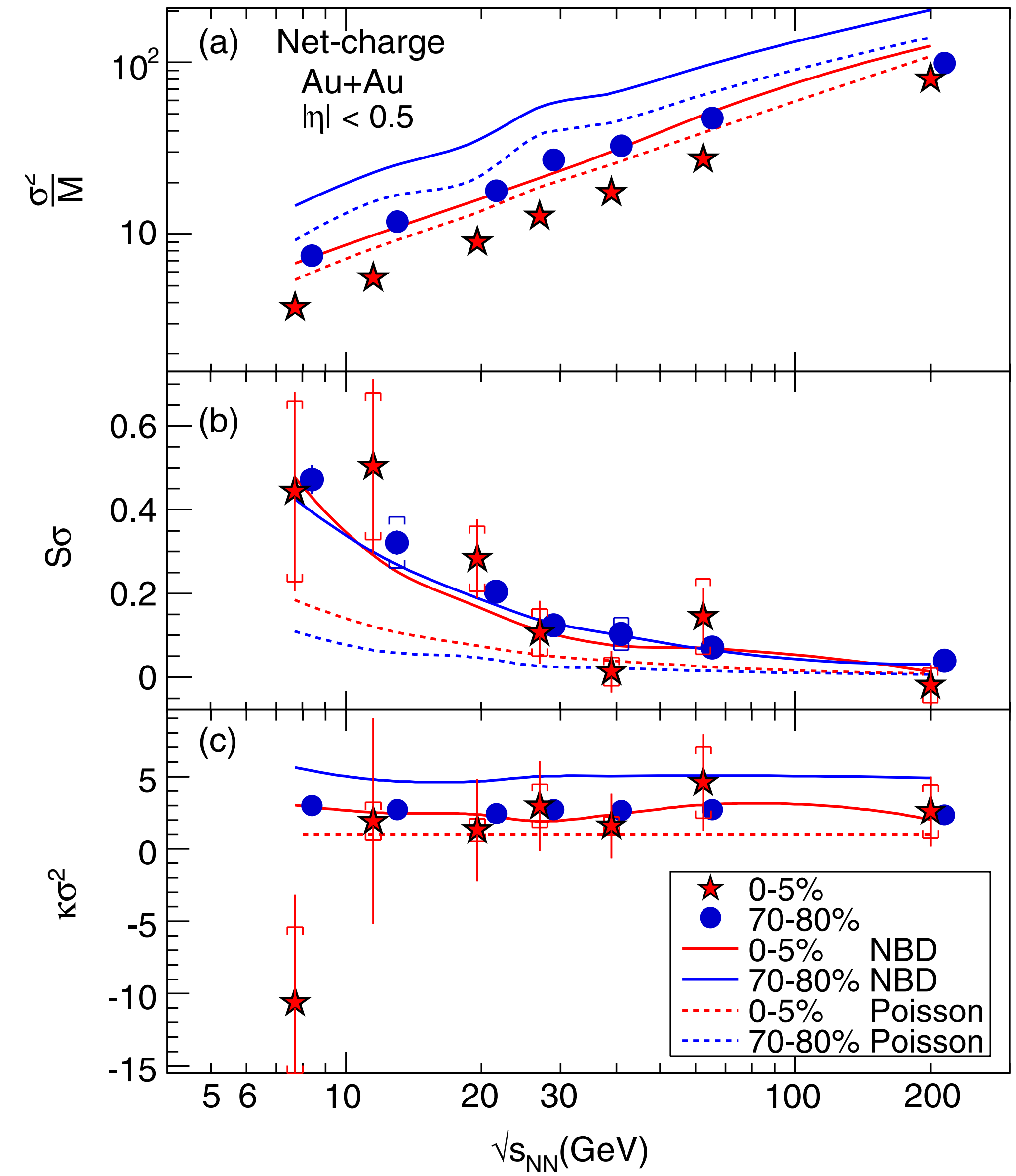
- 3rd moment = skewness
  - asymmetry
- 4th moment = kurtosis
  - peakedness
- Both moments = 0 for gaussian distribution
- Critical point search → non-gaussian fluctuations

Net-proton & net-charge fluctuations

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



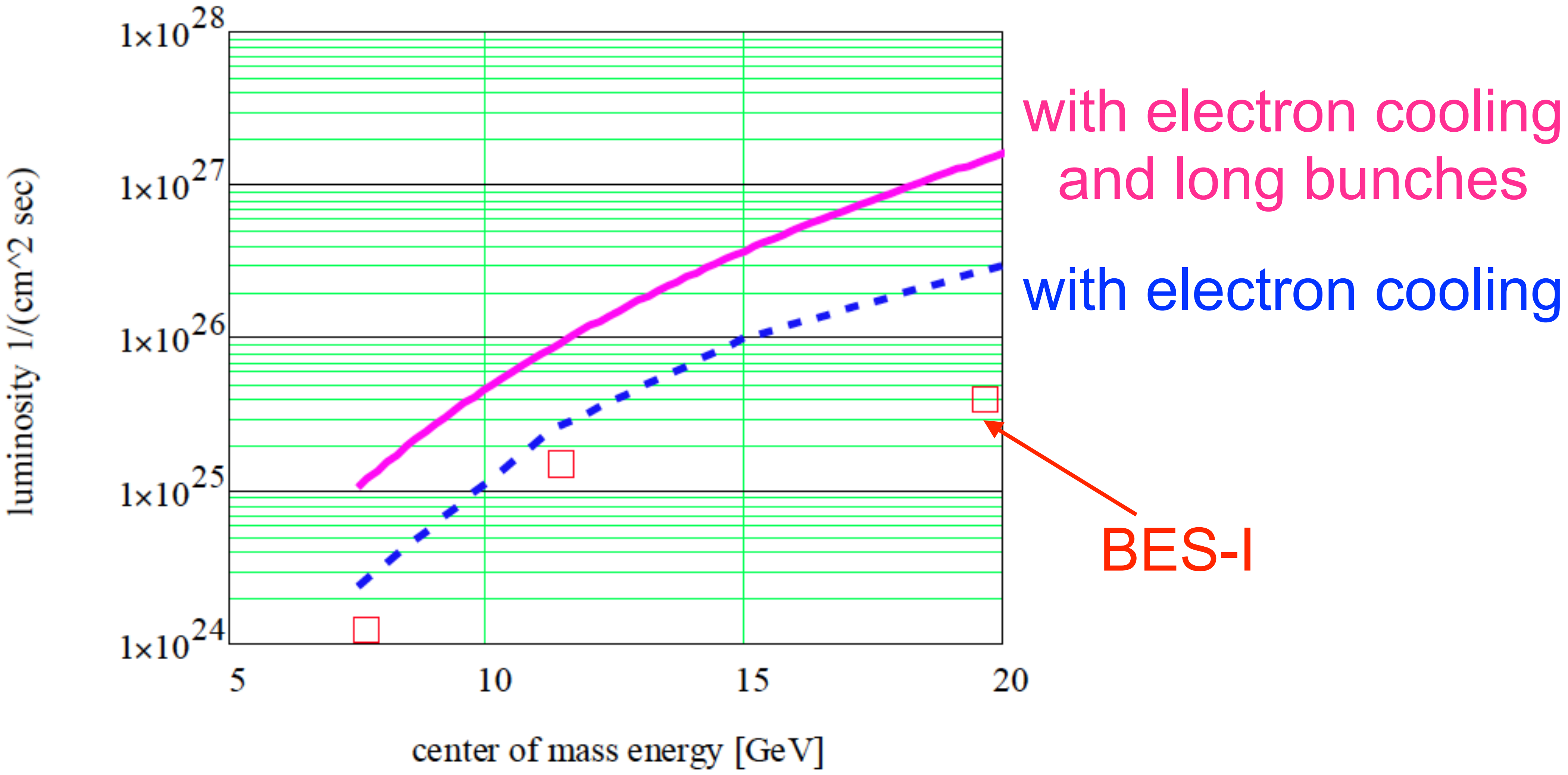
STAR: **PRL113**, 092301 (2014)



- Largest deviation around 19.6 GeV for net-proton
  - But only ~20% deviation from poisson baseline
- Need more precise measurements below 20 GeV

Upgrade plans for BES phase-II

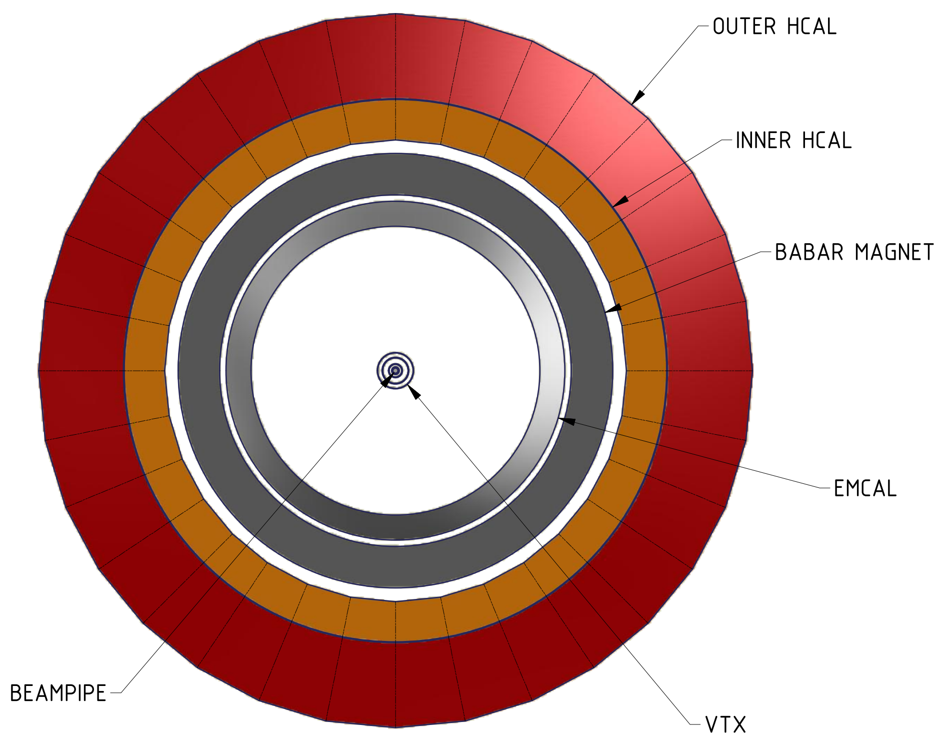
RHIC luminosity improvements



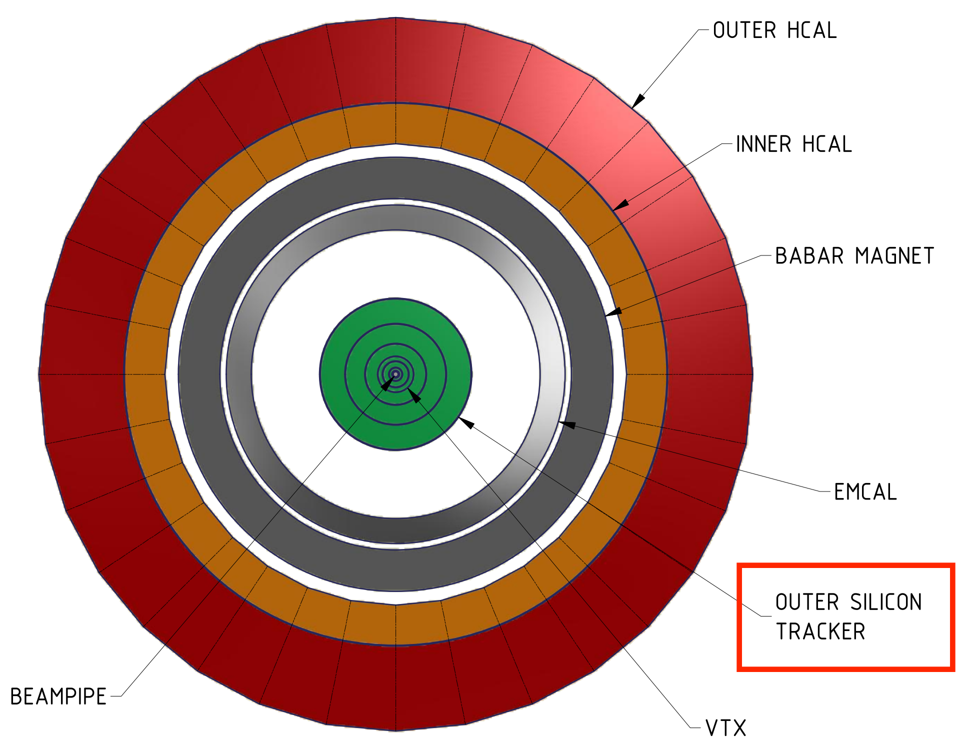
- Electron cooling will be available for BES-II
  - Electron cooling: by a factor of 3-10 increase in 5-20 GeV
  - Electron cooling + long bunches: by a factor of 2-5

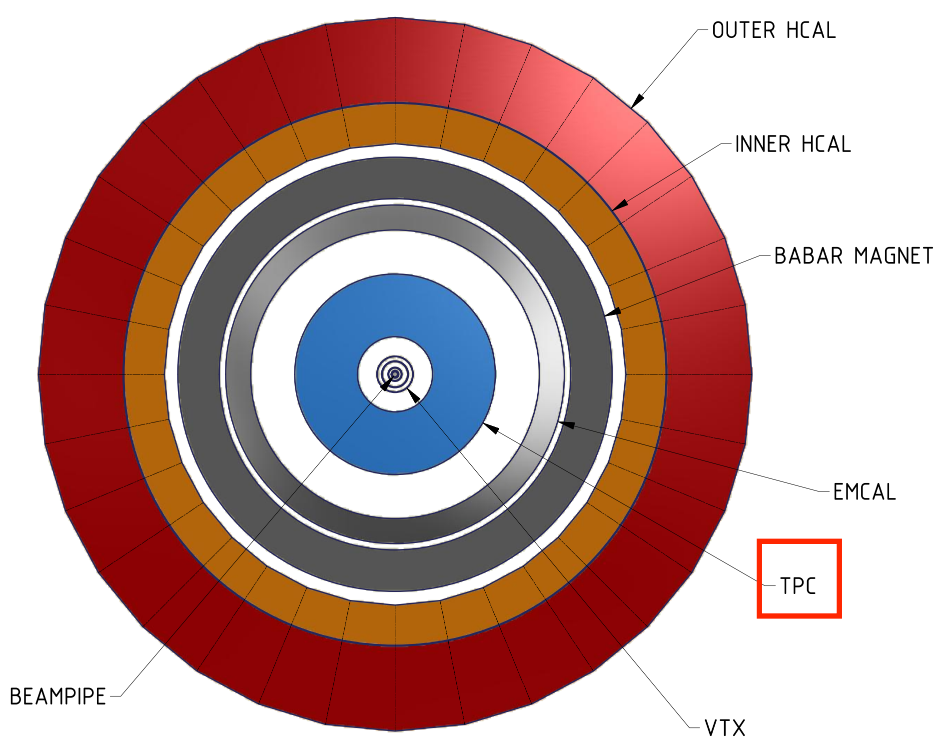
sPHENIX upgrade for BES-II

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

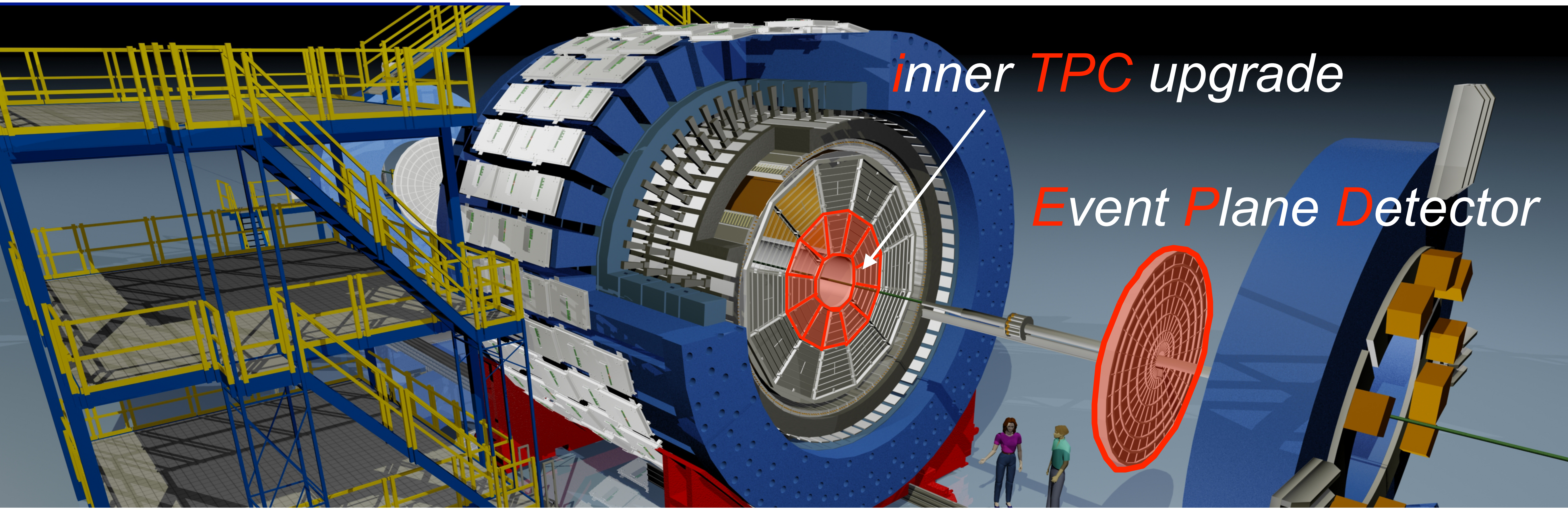


Acceptance:
- |η| < 1
- Full azimuth





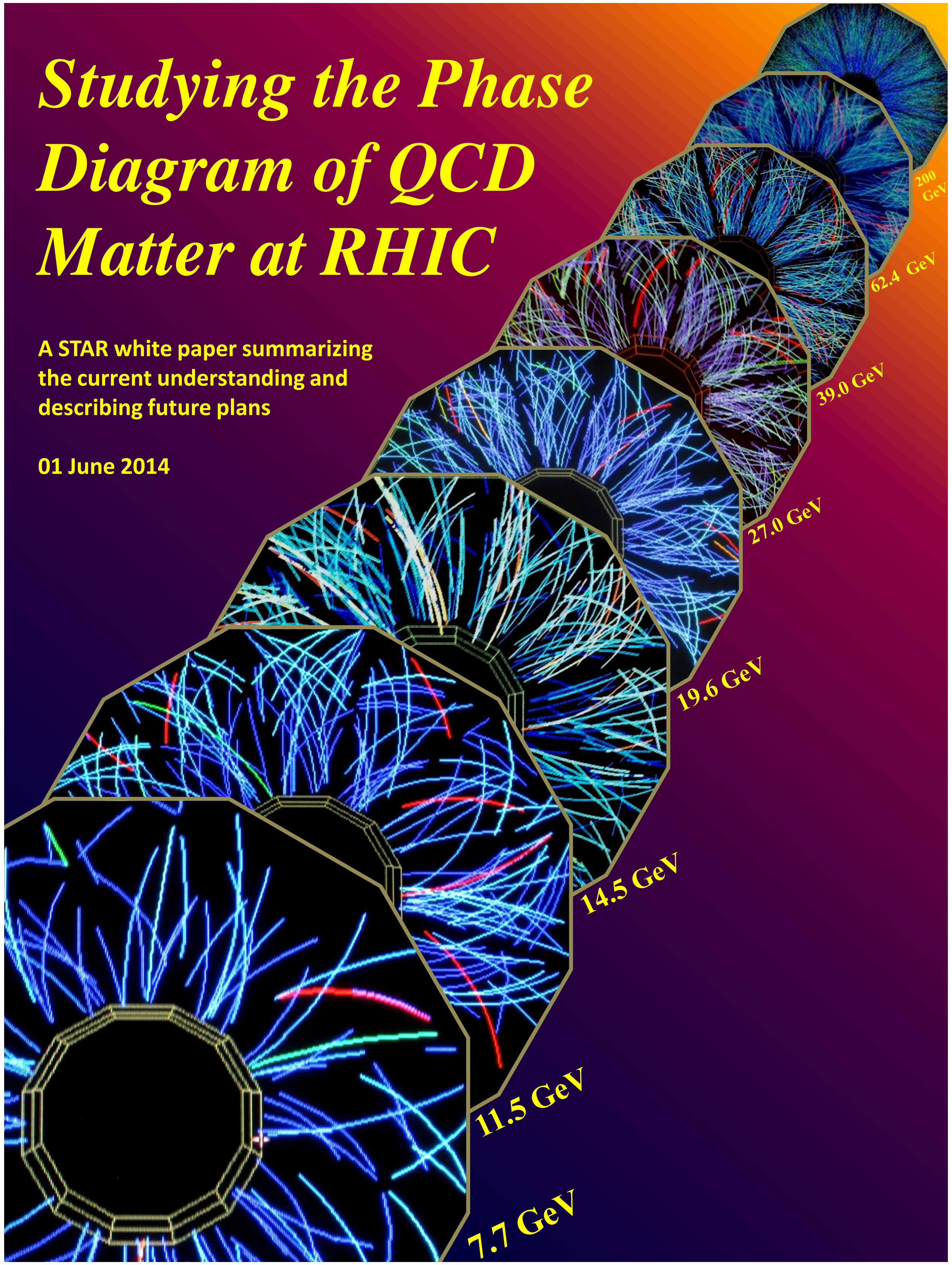
STAR upgrade for BES-II



- Event Plane Detector, 1.8 < |η| < 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

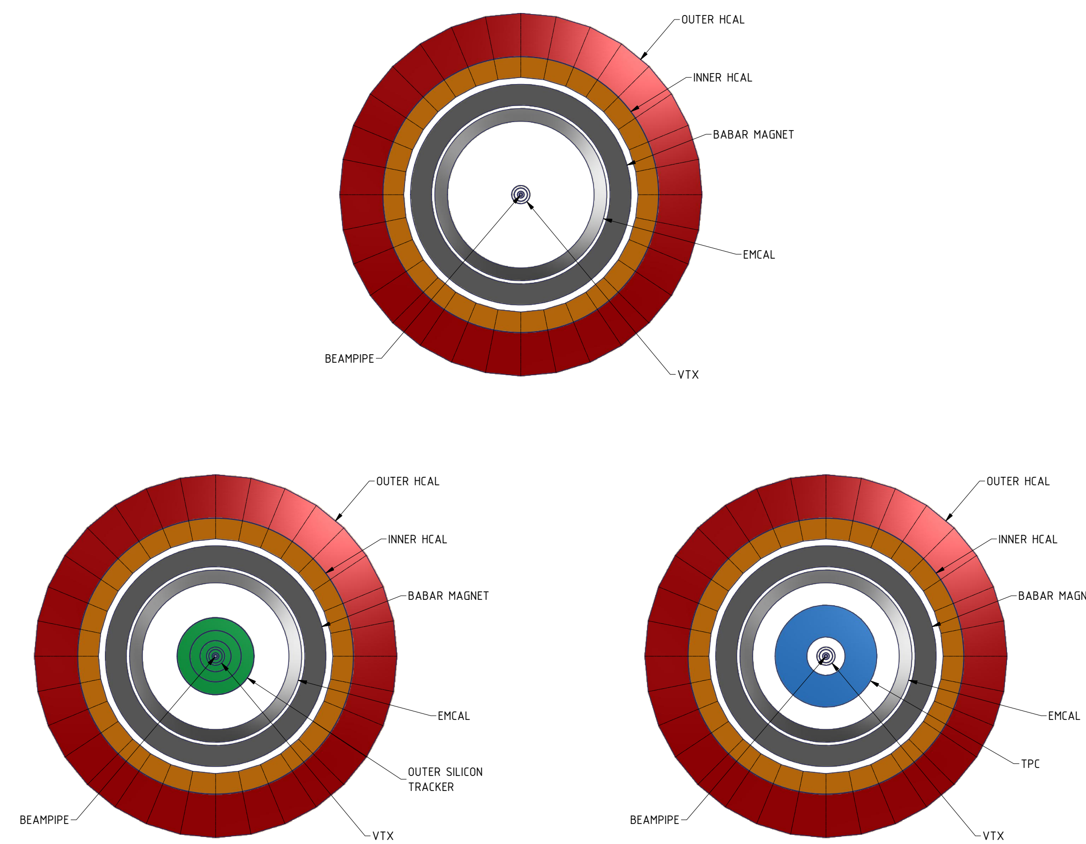
https://drupal.star.bnl.gov/STAR/system/files/BES_WPII_ver6.9_Cover.pdf



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

Beam Energy Scan II (2018–2019)

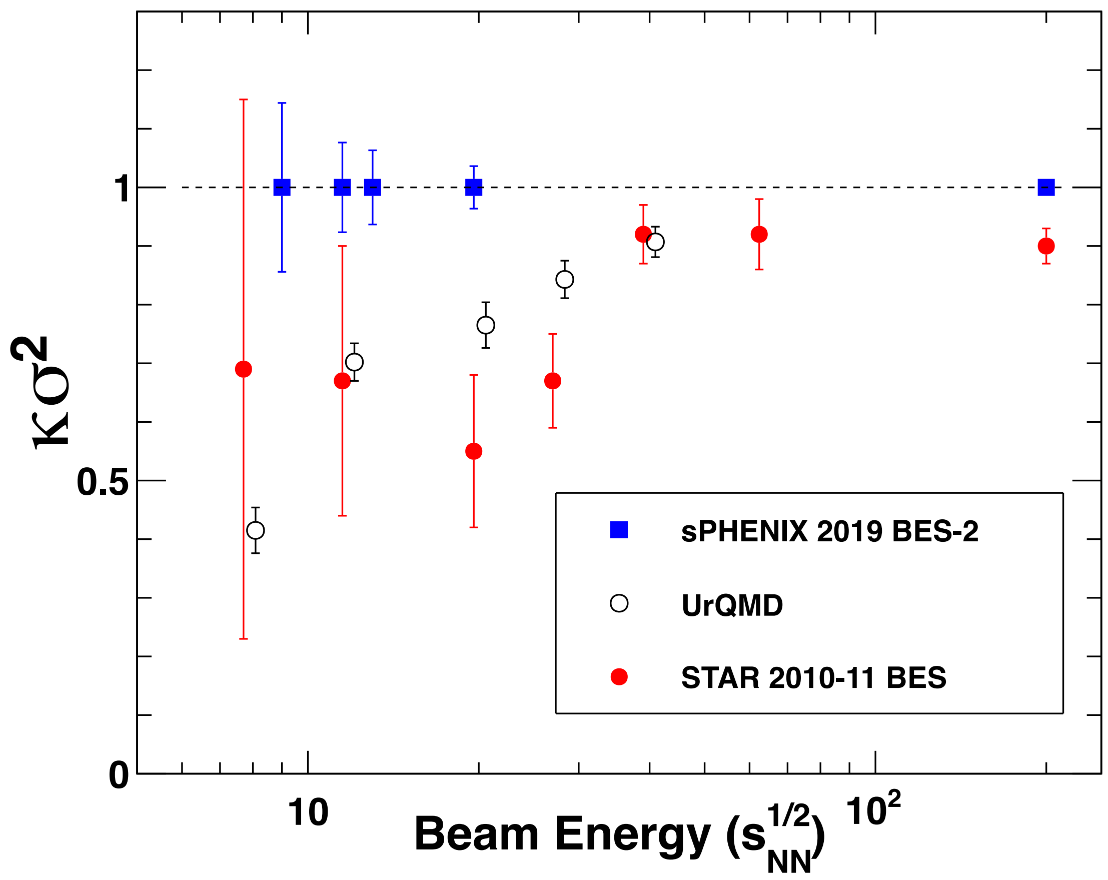
PHENIX Collaboration White Paper



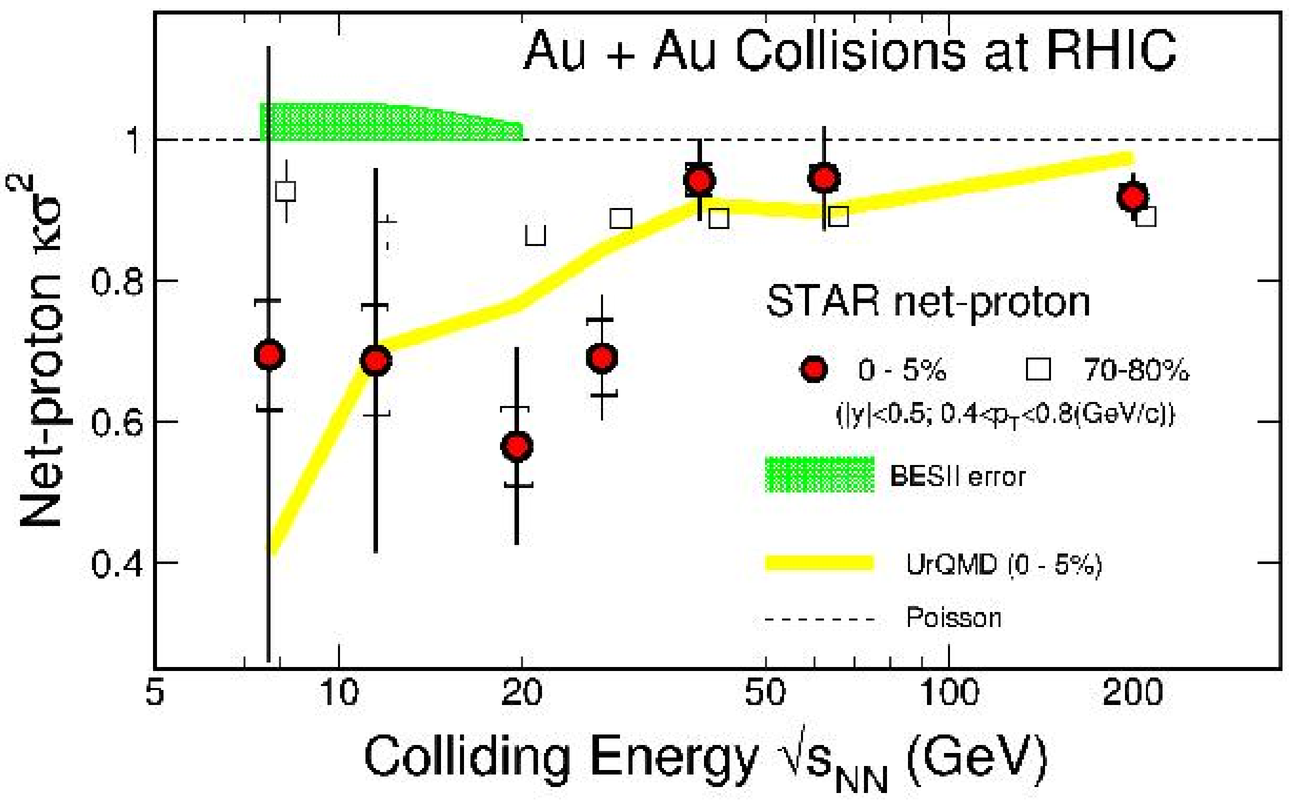
Version 1: March 1, 2014

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 HBT 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 calculations
- We need precision measurements below 20 GeV
  - BES phase-II
  - 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

2015 KOBE JAPAN

QUARK MATTER 2015

The 25th International Conference on Ultra-relativistic Nucleus-Nucleus Collisions

Kobe Fashion Mart, Rokko Island, Kobe, Japan

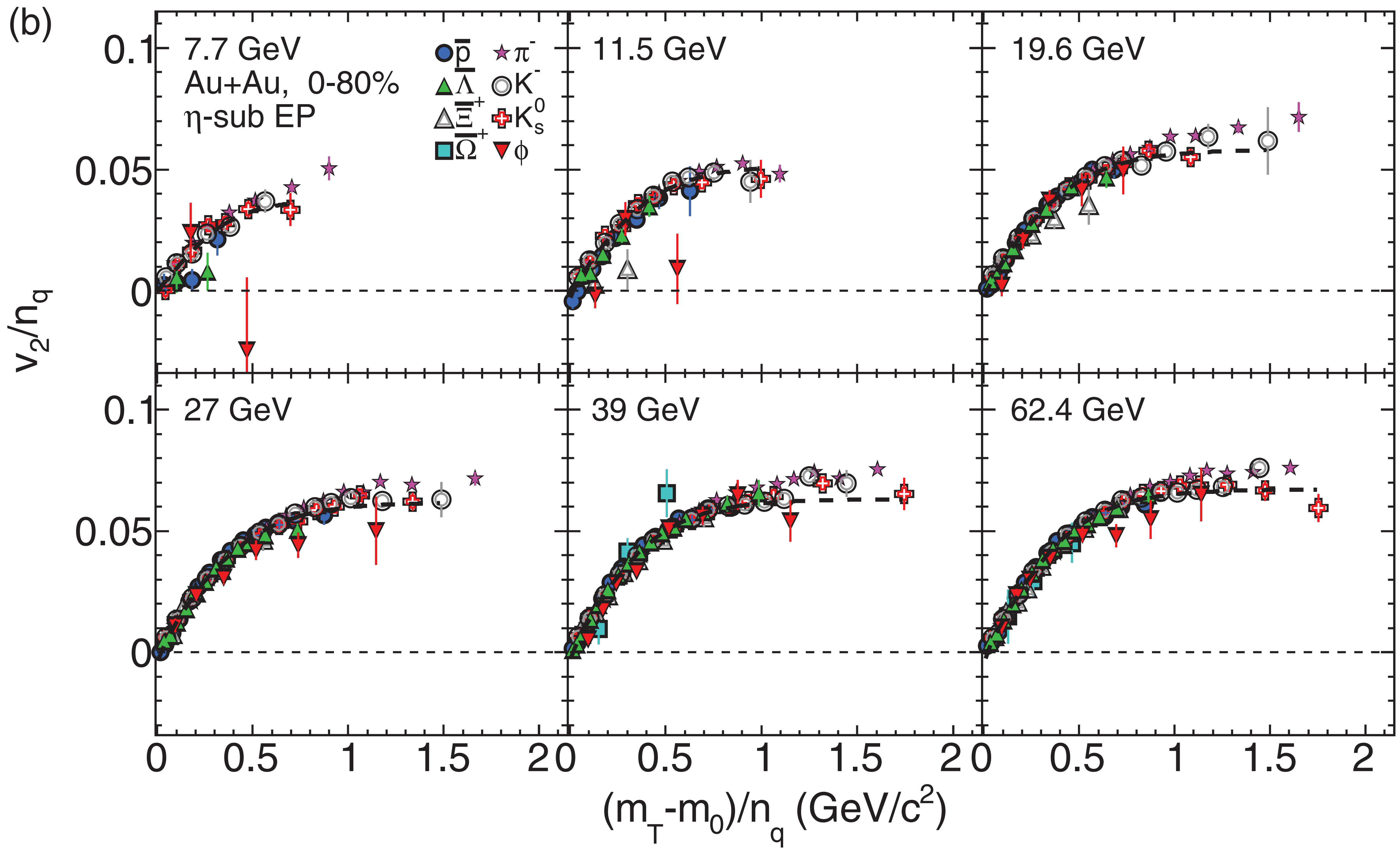
Sep. 27 (Sun) – Oct. 3 (Sat), 2015

[Registration will start from April 27, 2015]

Back up

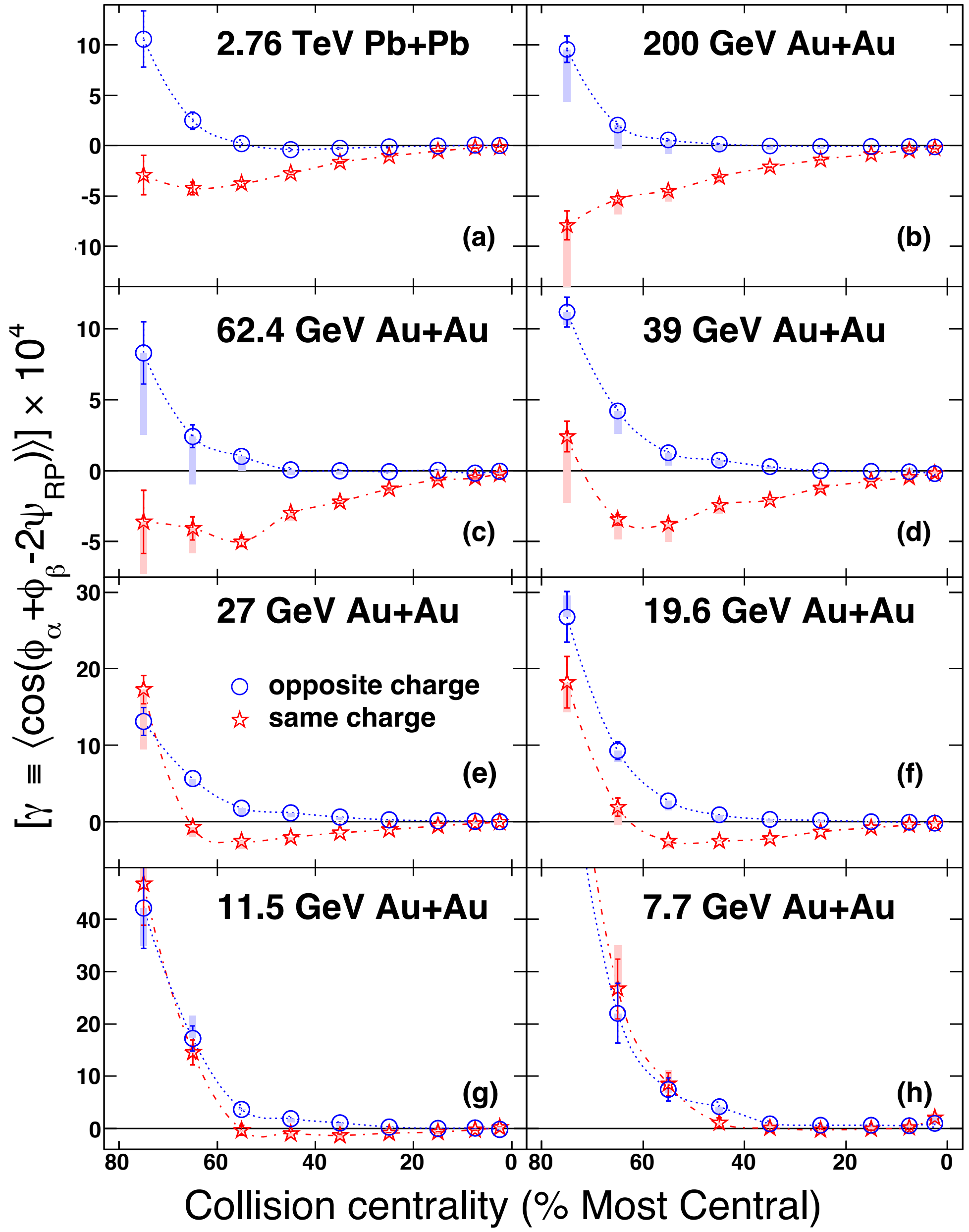
NCQ scaling of v_2 for anti-particles

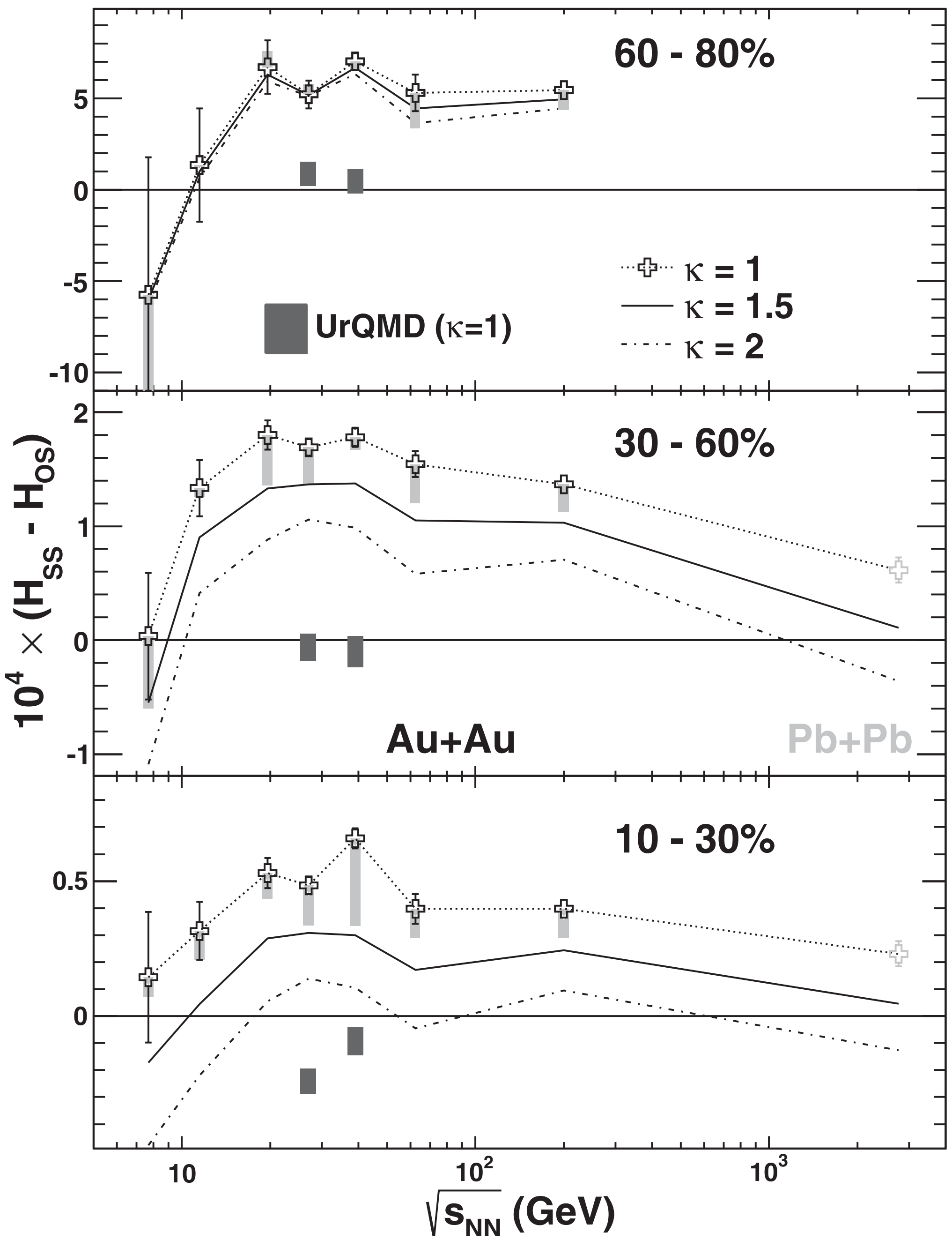
STAR: **PRC88**, 014902 (2013)



Charge separation w.r.t. event plane

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

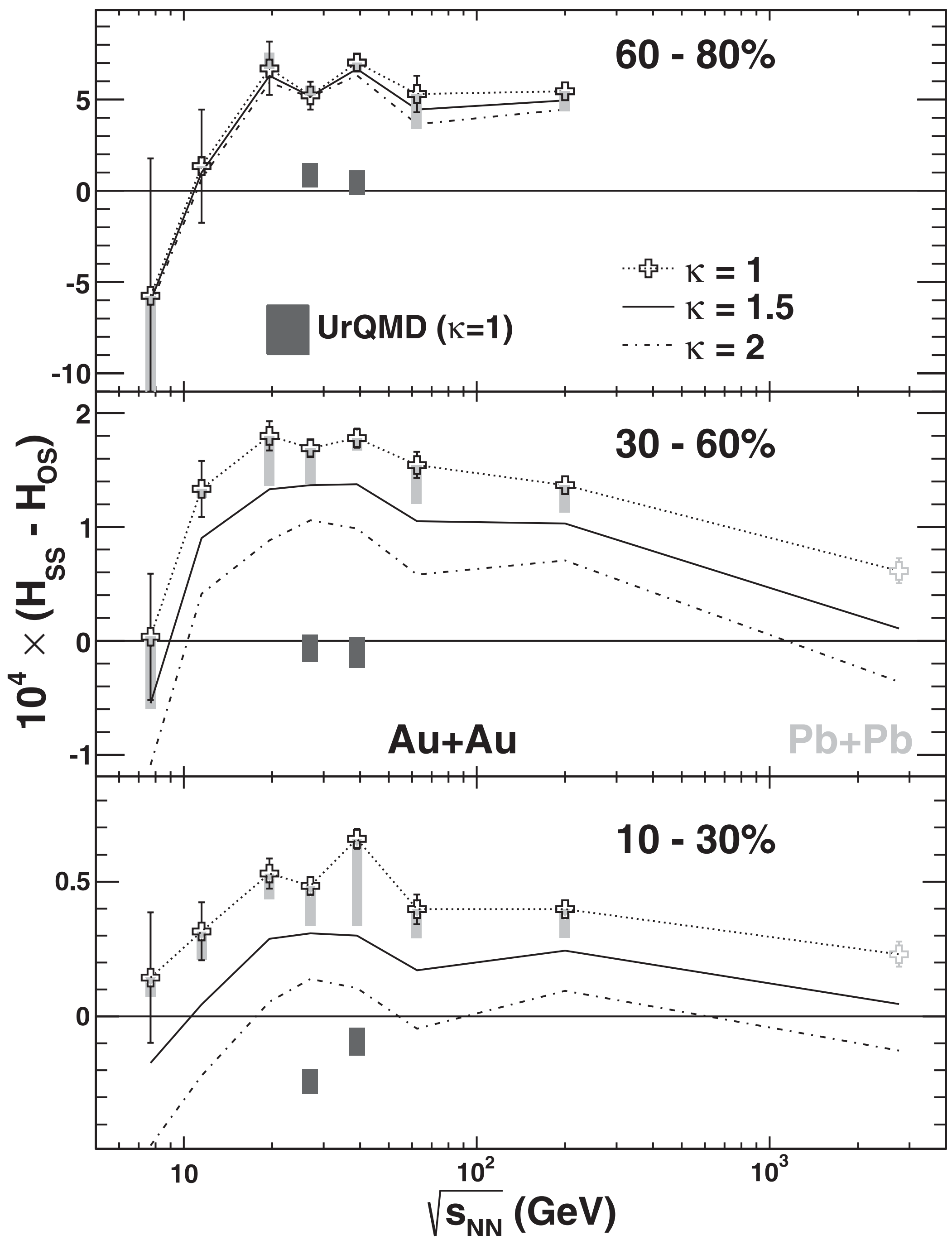




- Chiral magnetic effect + Local parity violation
  - Signal ~ 0 in $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV
  - Need better estimate of κ & precision measurements below 20 GeV

CME signal

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



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

$$\delta \equiv \langle \cos(\phi_1 - \phi_2) \rangle = F + H,$$

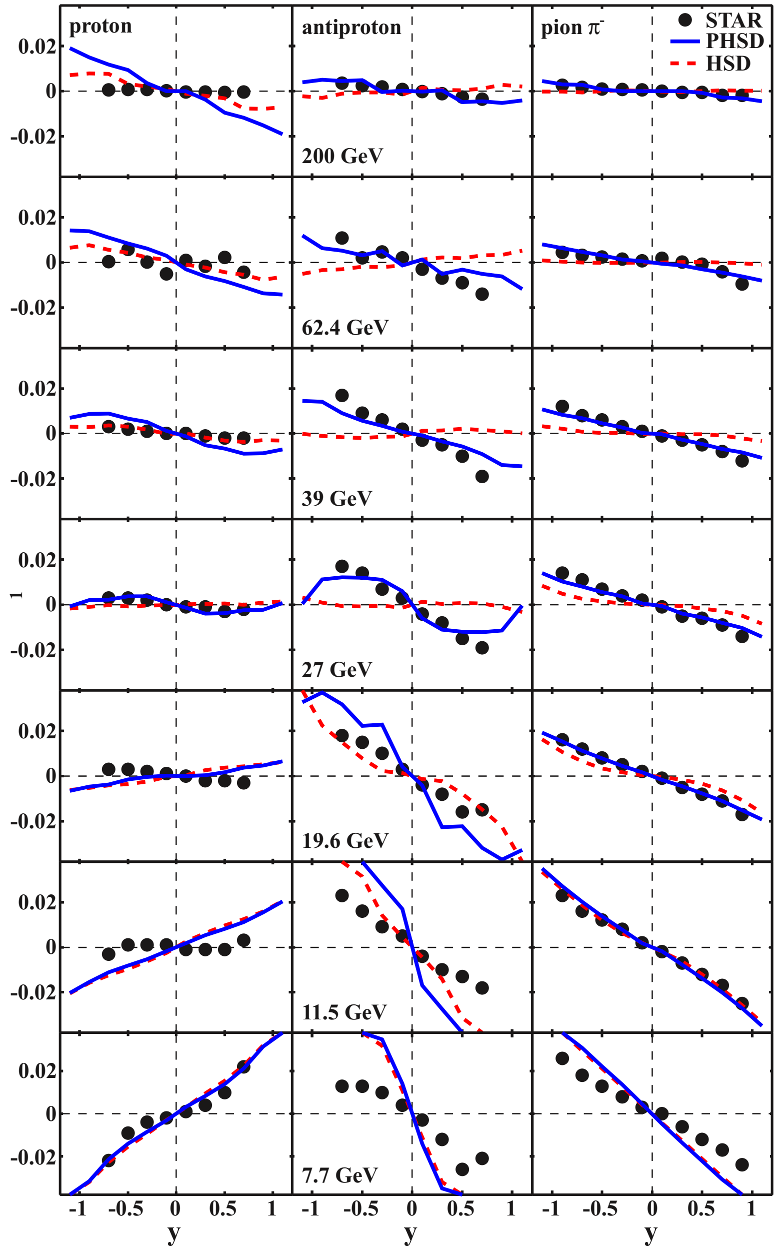
H: CME contribution,

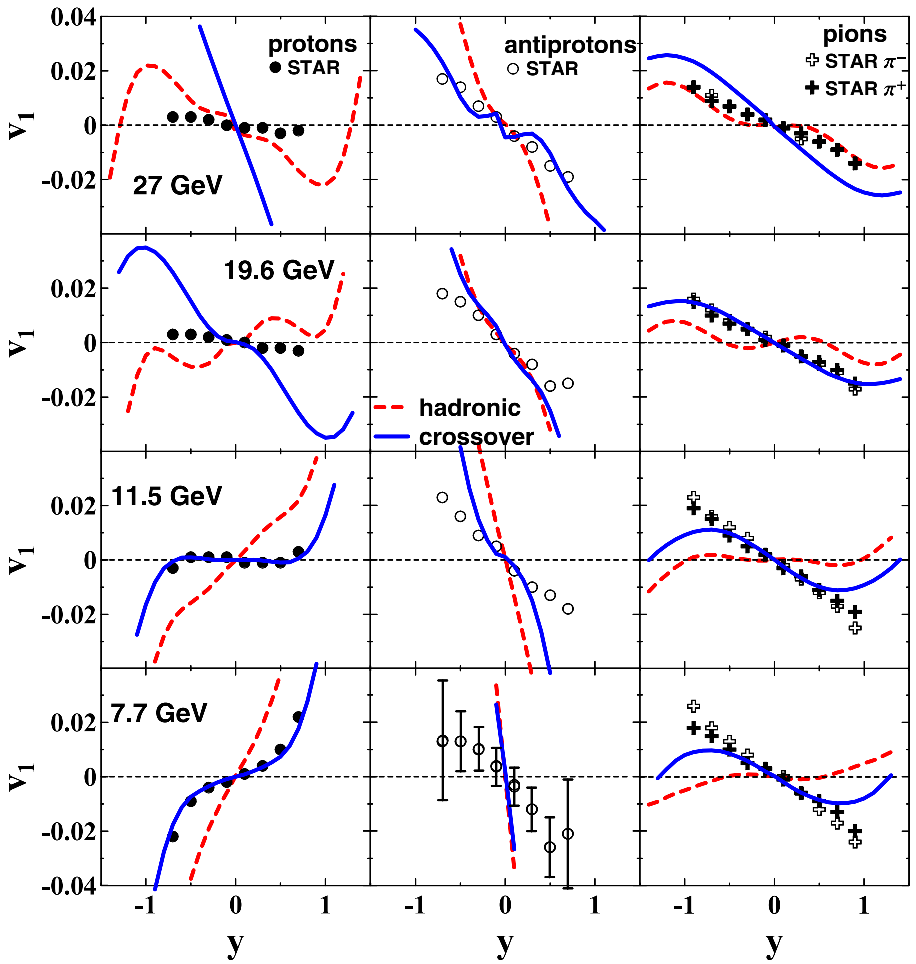
F: background contribution, κ: parameter

- 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

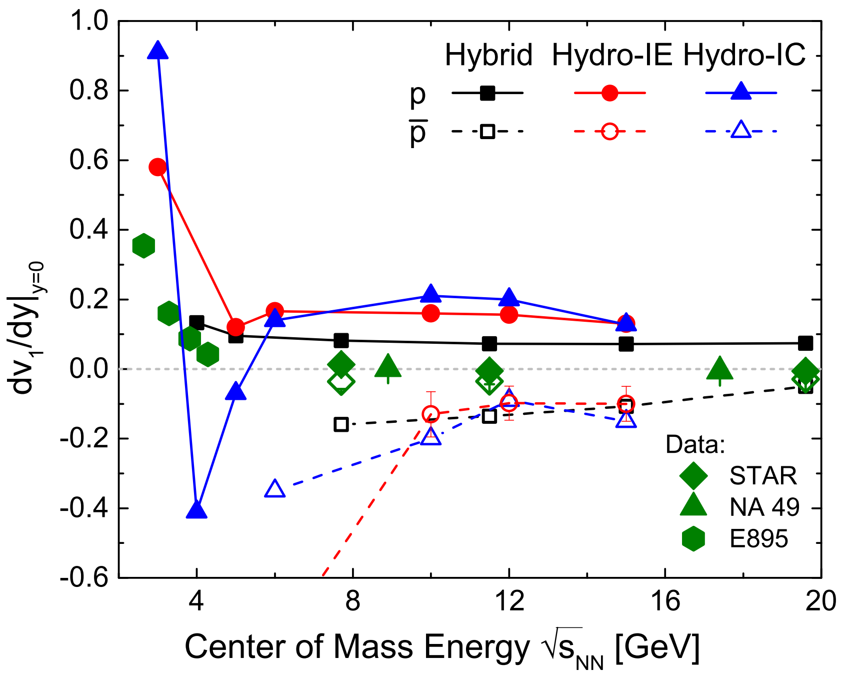
Directed flow, model calculations

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) $\|z_{vtx}\| < 10$cm	Events(M) $\|z_{vtx}\| < 30$cm	Events(M) $\|z_{vtx}\| < 1$ 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

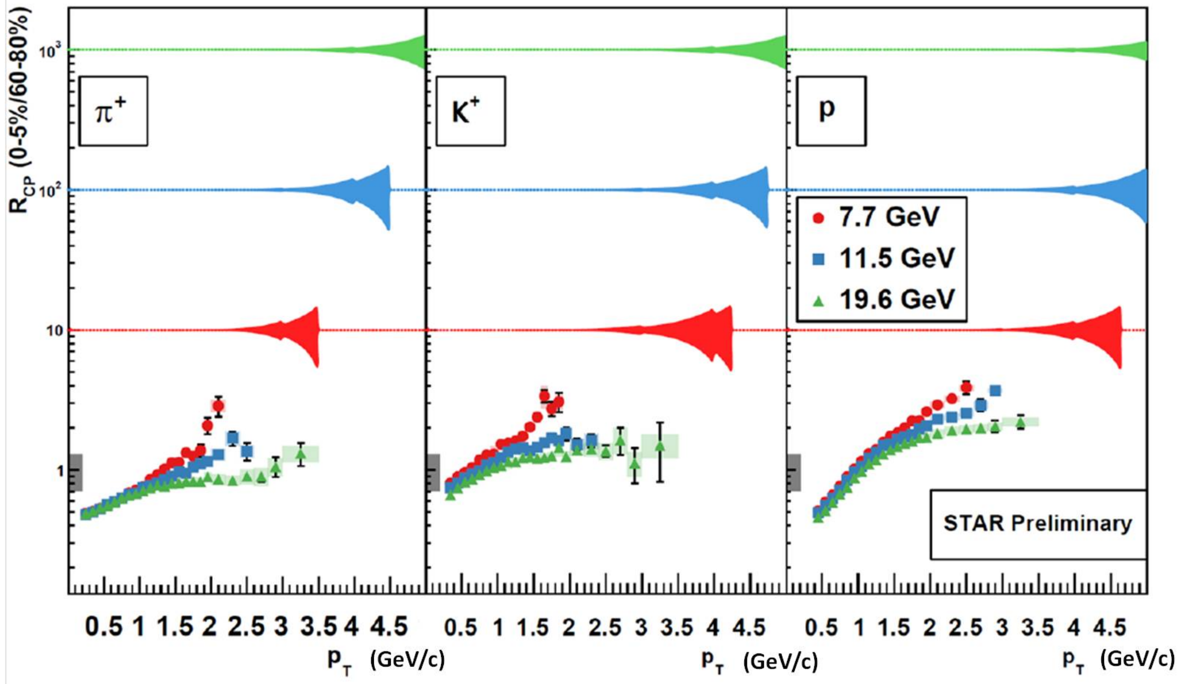
Table 3. Beam Energy Scan Phase-II proposal for 22 weeks of RHIC running in each of the years 2018 and 2019.

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+

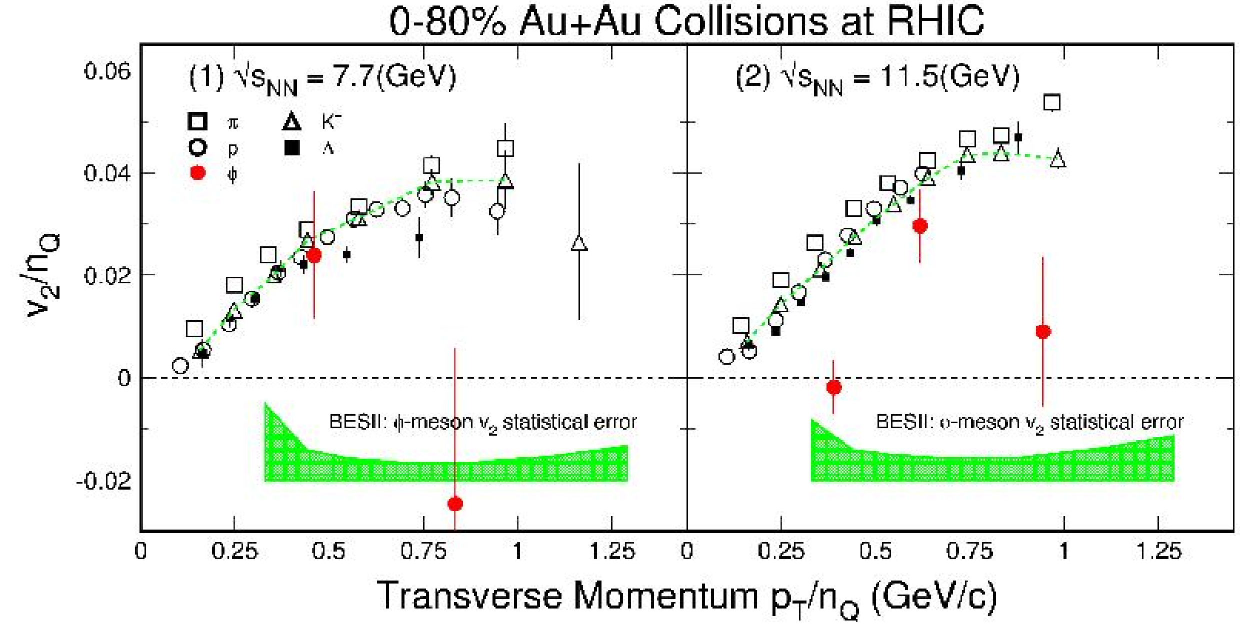
- Focused on $\sqrt{s_{NN}} < 20$ GeV
  - One year (2019) request from PHENIX
  - Two year (2018, 2019) request from STAR

BES-II projections

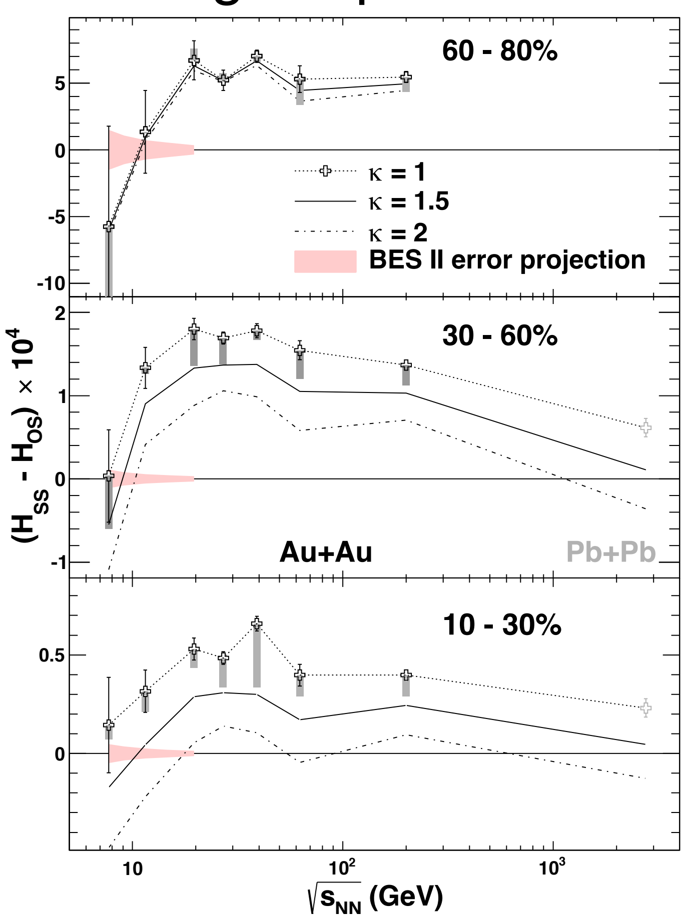
Rcp



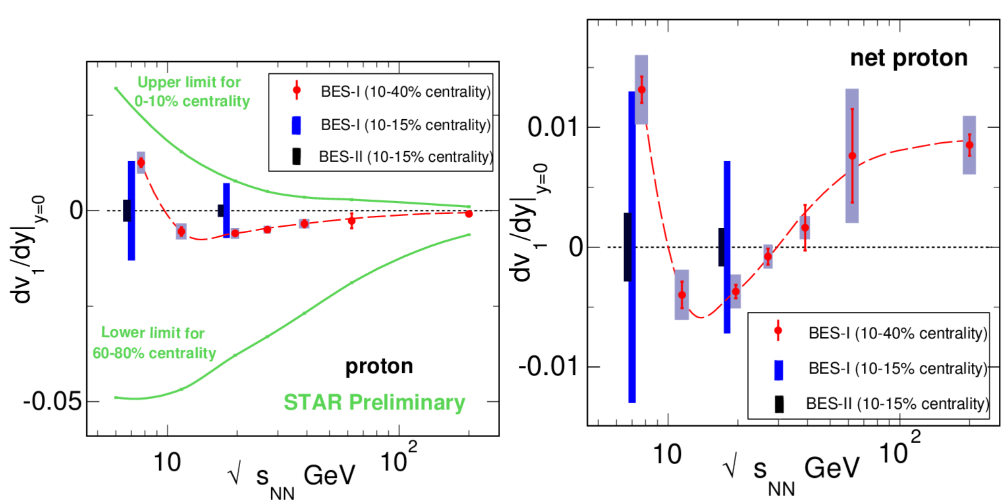
v_2



charge separation



Directed flow



Di-lepton LMR excess