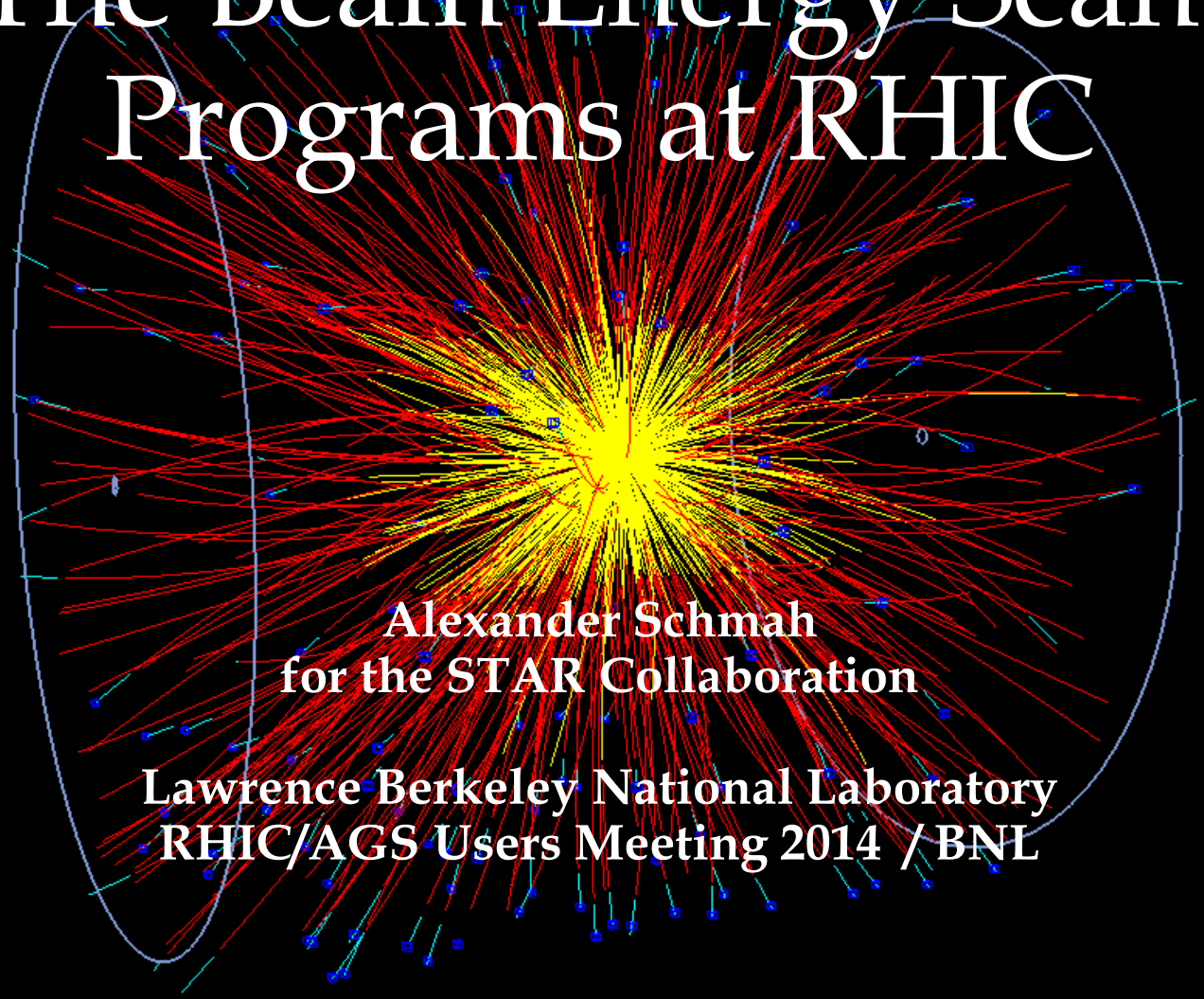
The Beam Energy Scan Programs at RHIC

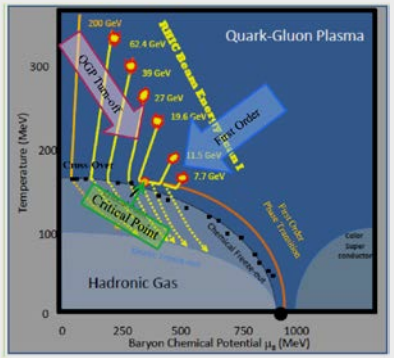


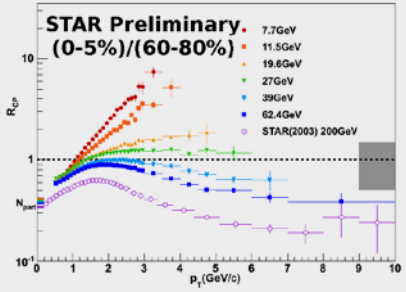
Alexander Schmah
for the STAR Collaboration

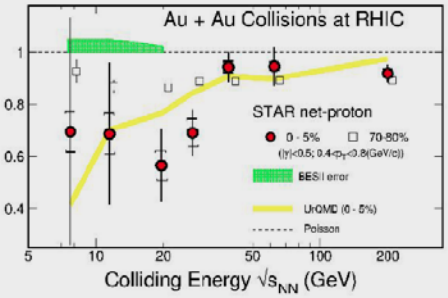
Lawrence Berkeley National Laboratory
RHIC/AGS Users Meeting 2014 / BNL

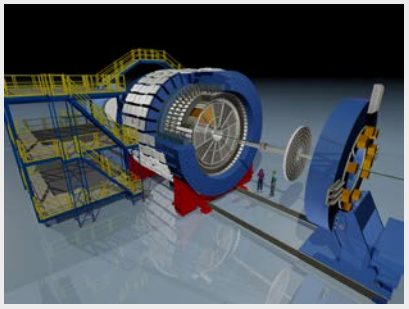
Outline

- Introduction to the beam energy scan program at RHIC
- Some selected highlights from BES phase I
- Projections and outlook to BES phase II
- Upgrades for BES phase II and fixed target program







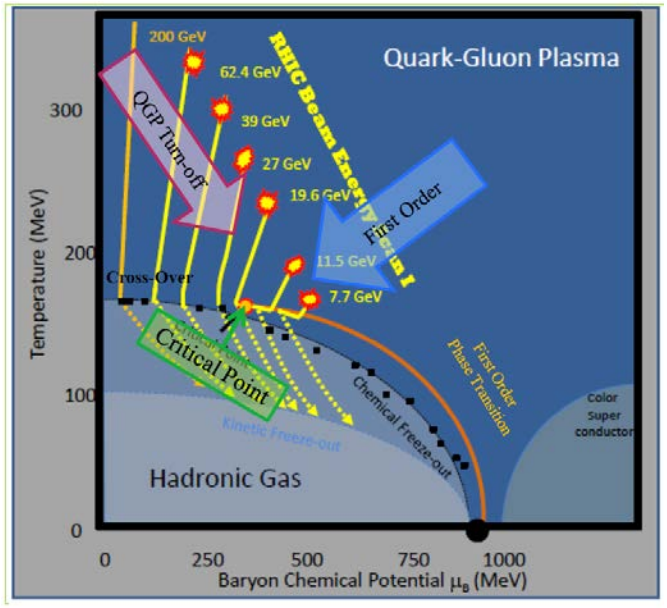


See also talks:
Jim Thomas (Tue.)
Ron Soltz (Wed.)
Evan Sangaline (Wed.)
Rene Bellwied (Wed.)
Volker Koch (Wed.)

The QCD Phase Diagram

Goals of the beam energy scans:

- Hadron gas phase at low T and/or μ_B
- We expect from QCD lattice calculations a cross over at high energies
- QGP at high T and/or μ_B
  → R_{CP}, NCQ scaling of v_2,...
- First order phase transition?
  → HBT, v_1 analyses
- Critical point?
  → Fluctuation analyses (net-protons)



D. Cebra

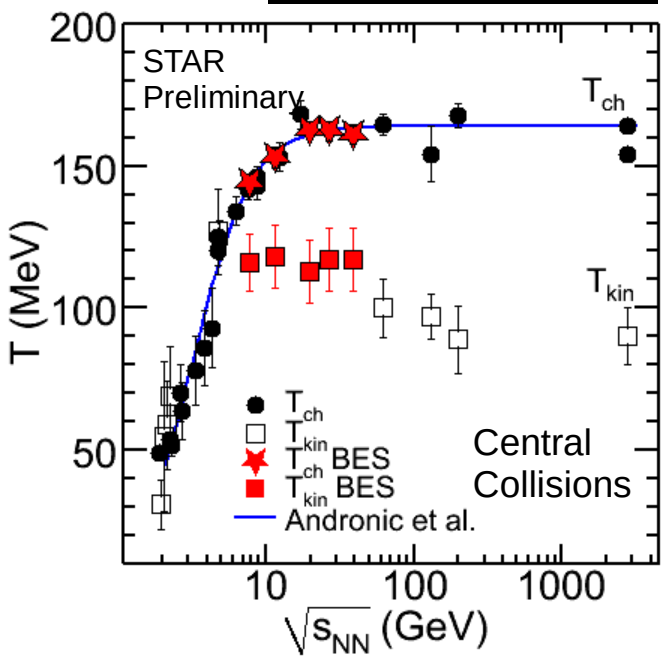
$\sqrt{s_{NN}}$ (GeV)	*MB Events in 10^6
7.7	4.3
11.5	11.7
14.5	24**
19.6	35.8
27	70.4
39	130.4
62.4	67.3

STAR BES: arXiv:1007.2613

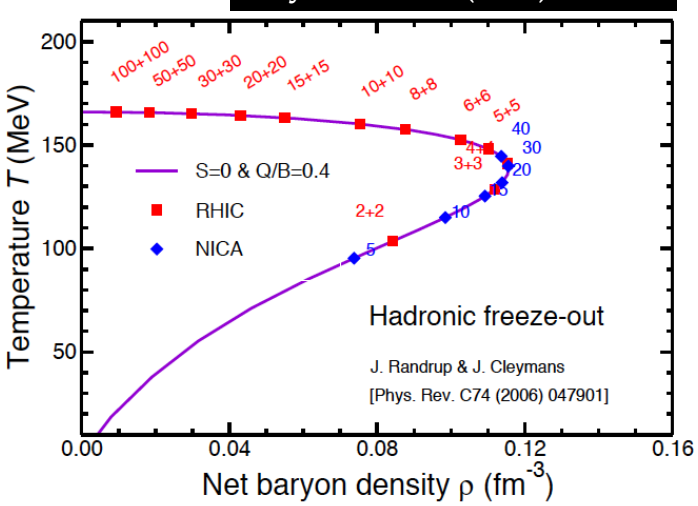
*Au+Au minimum bias events at STAR usable for analysis
** Estimated statistics

Freeze-Out Systematics

Lokesh Kumar, QM2014



Phys.Rev. C74 (2006) 047901

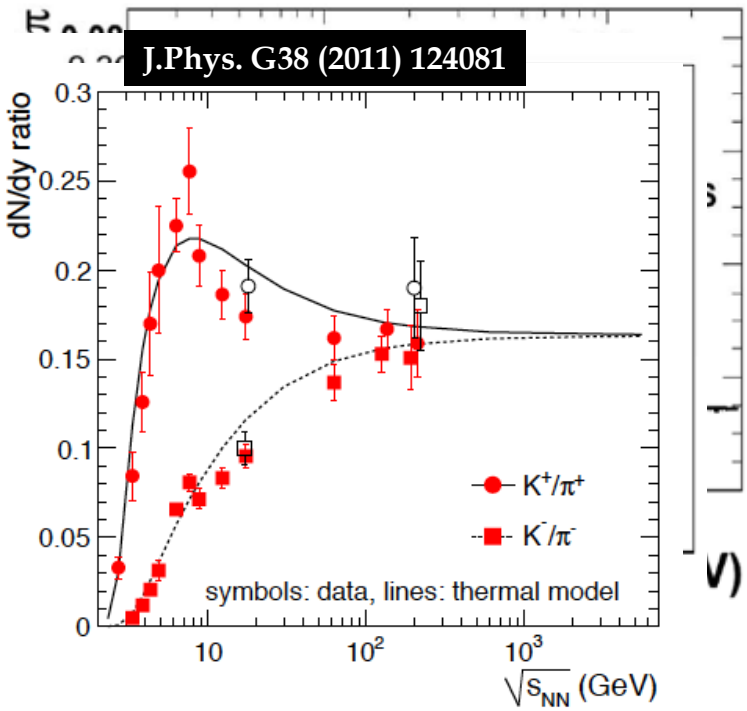


- Saturation of T_{chem} above $\sqrt{s_{NN}} \sim 10$ GeV
- Splitting between T_{chem} and T_{kin} starts at $\sqrt{s_{NN}} \sim 6$ GeV

- Connected to a phase change?

- Maximum baryon density reached at $\sqrt{s_{NN}} \sim 8$ GeV
  → pion processes become more important

Particle Ratios

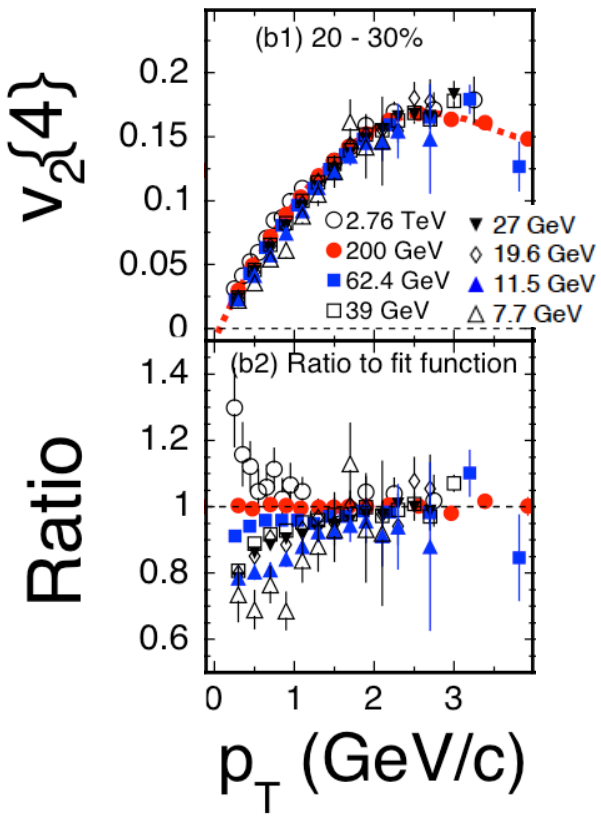


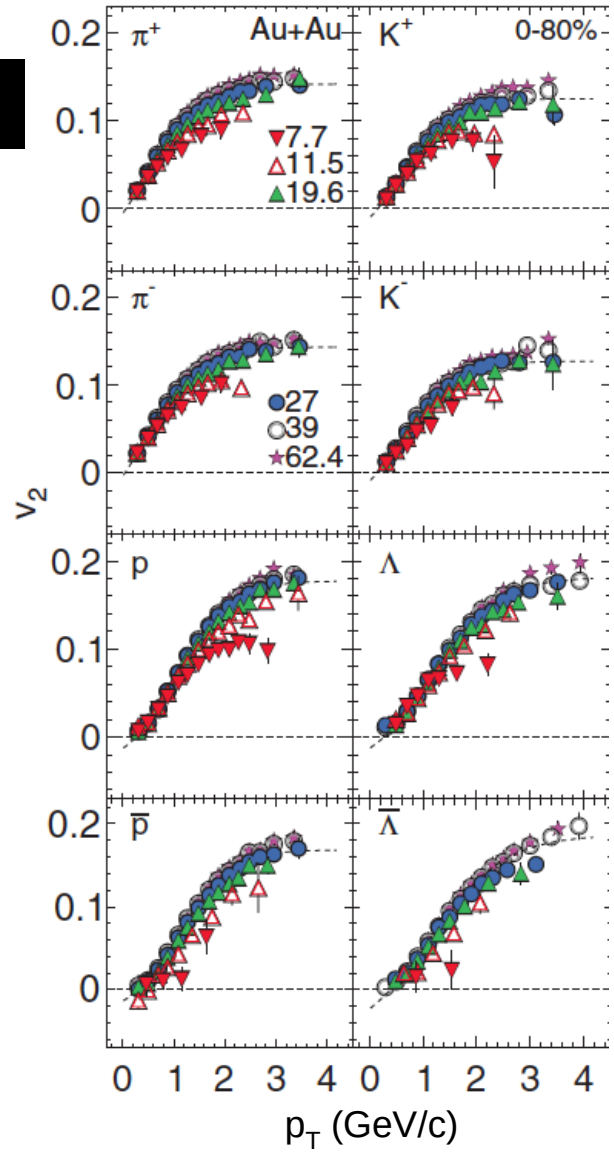
- Pronounced structures in particle ratios at $\sqrt{s_{NN}}$~ 5-10 GeV
  → indications for a phase transition?

- Net-baryon density has a maximum at ~ $\sqrt{s_{NN}}$ ~ 8 GeV at freeze-out
  + Associate production channels like $N+N \rightarrow N + \Lambda + K^+$
- Canonical strangeness suppression at low energies
- Statistical hadronization model can describe the "horn"

Elliptic Flow (v_2)

STAR: Phys.Rev. C86, 054908 (2012)
ALICE: Phys. Rev. Lett. 105, 252302 (2010)





- Large (similar) collectivity at all energies?

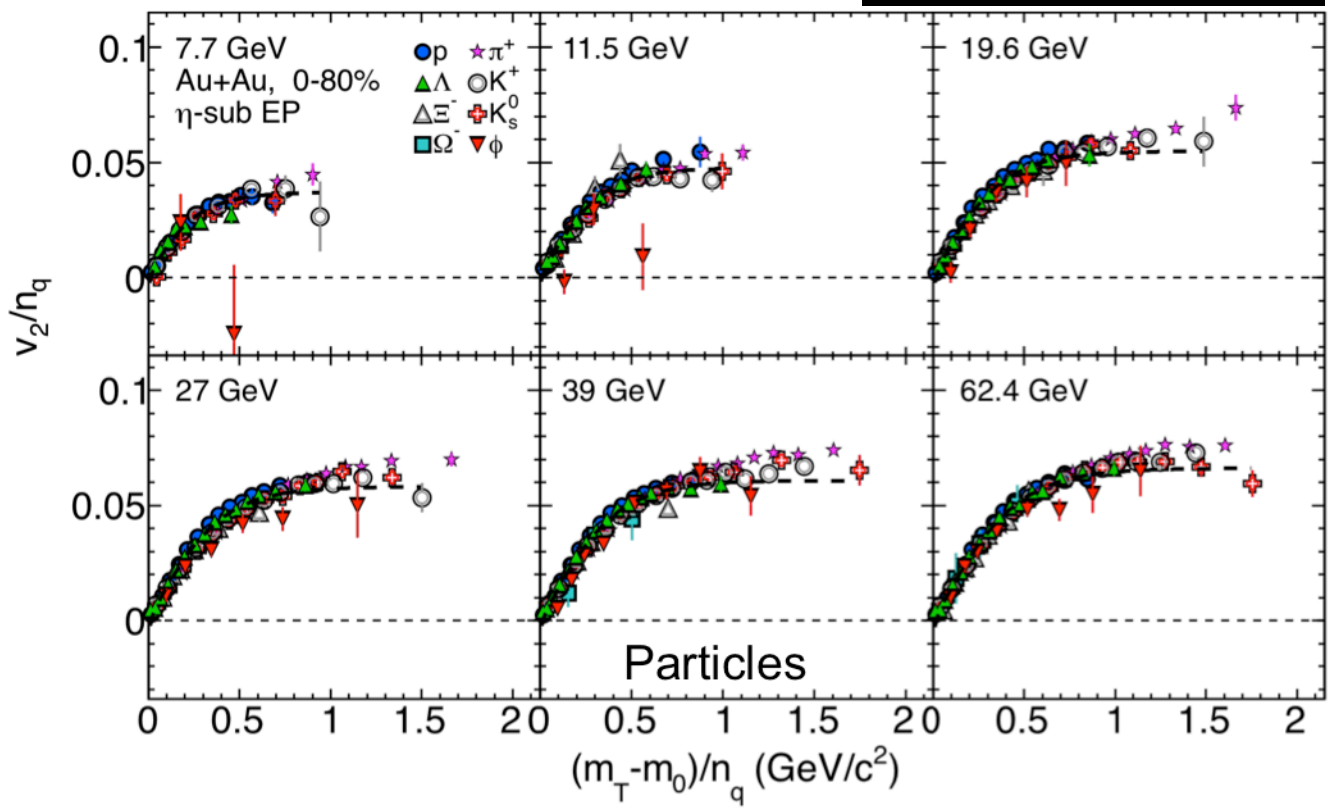
- But particle composition changes with energy!
  → v_2 increases for every particle
- What about rare particles at low energies?
- Conclusions for hydro, η/s?

Phys. Rev. C 88, 014902 (2013)

v_2 Number-of-Constituent Quark Scaling

Rihan Haque, QM 2014

Phys. Rev. C 88, 014902 (2013)

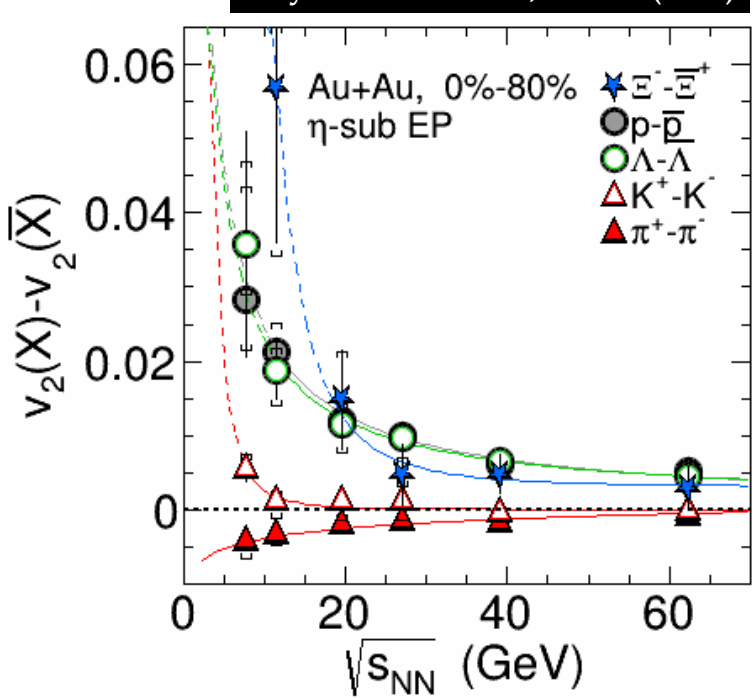


- NCQ-scaling holds for particles and anti-particles separately at all energies → Partonic degrees of freedom?

- High m_T-m_0 not measured at lower energies
- Do ϕ-mesons deviate?

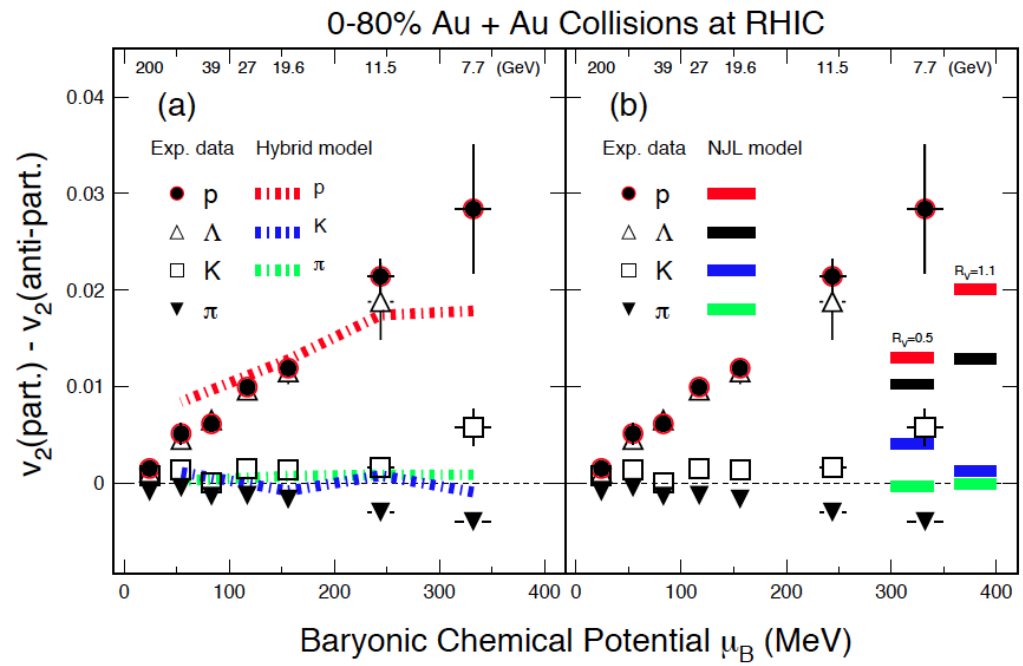
Particle-anti-Particle Δv_2 vs. $\sqrt{s_{NN}}$

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



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

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



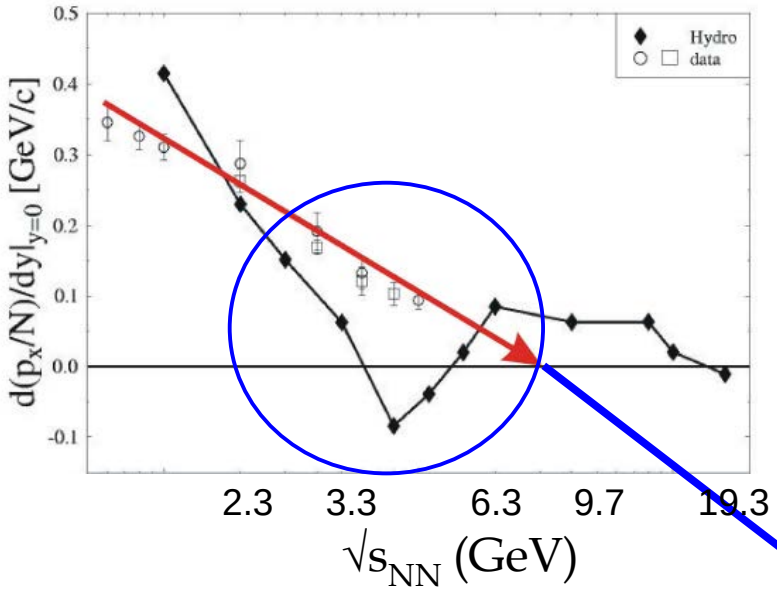
- Hydro model: Hybrid model (UrQMD + hydro) with baryon stopping
- Nambu-Jona-Lasinio (NJL): Using vector mean-field potential, repulsive for quarks, attractive for anti-quarks

- NCQ scaling for particles/anti-particles broken
  → Indication for a phase transition?

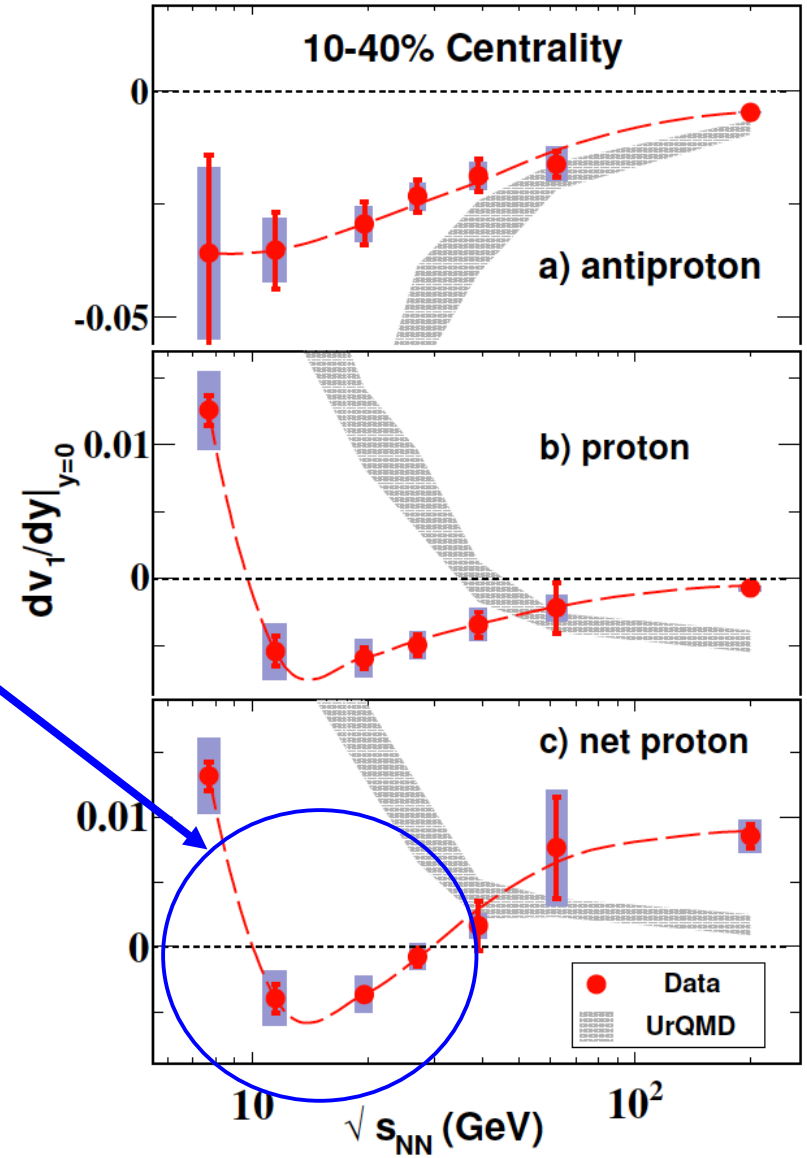
- Good agreement of hybrid-hydro model with data
  → Mainly baryon stopping?
- How is the agreement for other centralities?

Directed Flow (v_1)

H. Stoecker, Nucl. Phys. A 750 (2005)



PRL, 112 (2014) 162301



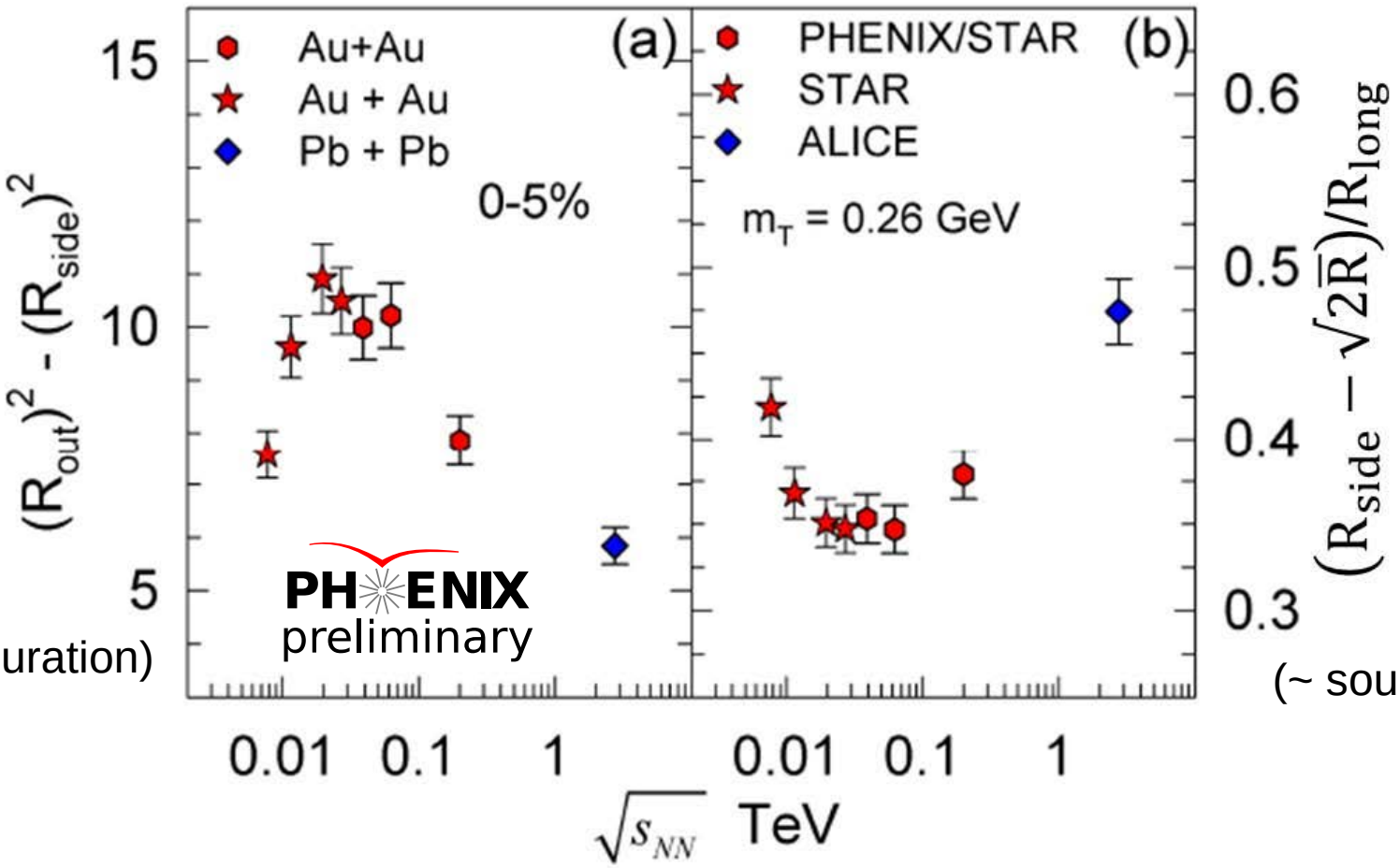
- Dip in net-proton dv_1/dy reproduces theory prediction
  → Softest point of EoS?

- Rising and falling trends of protons and anti-protons qualitatively reproduced by UrQMD
- Dip at different position than model
- Centrality dependence important
- How does it look like for other particles?

Emission Duration and Expansion/Lifetime

Roy Lacey, QM2014
Ron Soltz, QM2014

(~ emission duration)

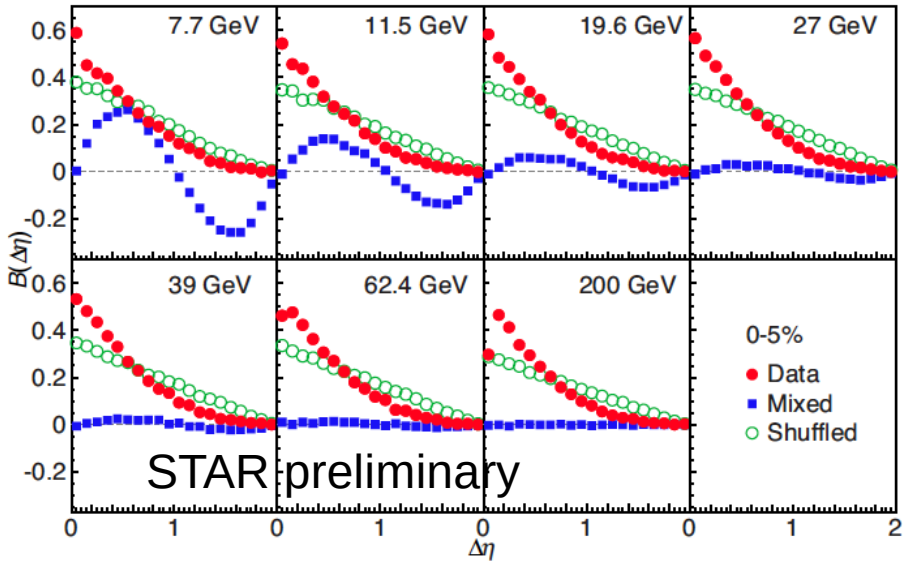


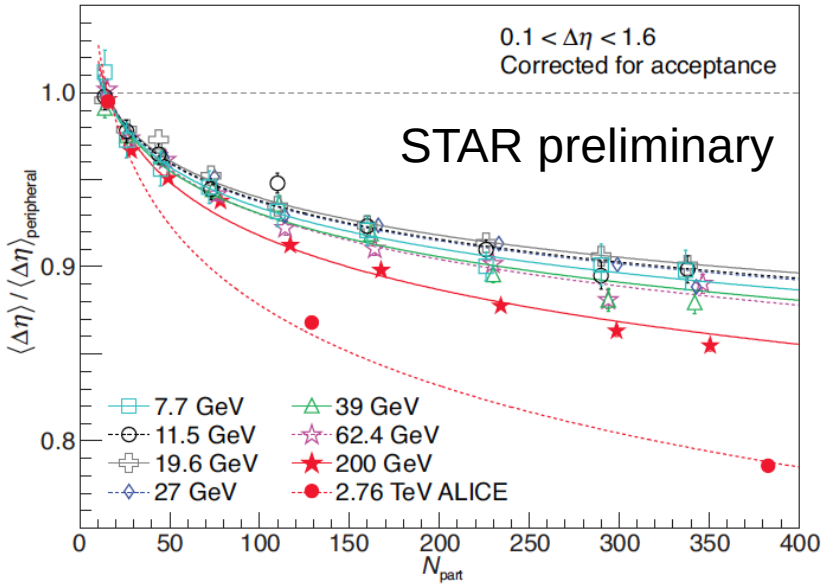
(~ sound speed)

- Non-monotonicity in $(R_{out})^2 - (R_{side})^2$
- R_{side}/R_{long} indicative of expansion/lifetime

- Softest point of EoS?
- Indication for critical point?

Balance Functions

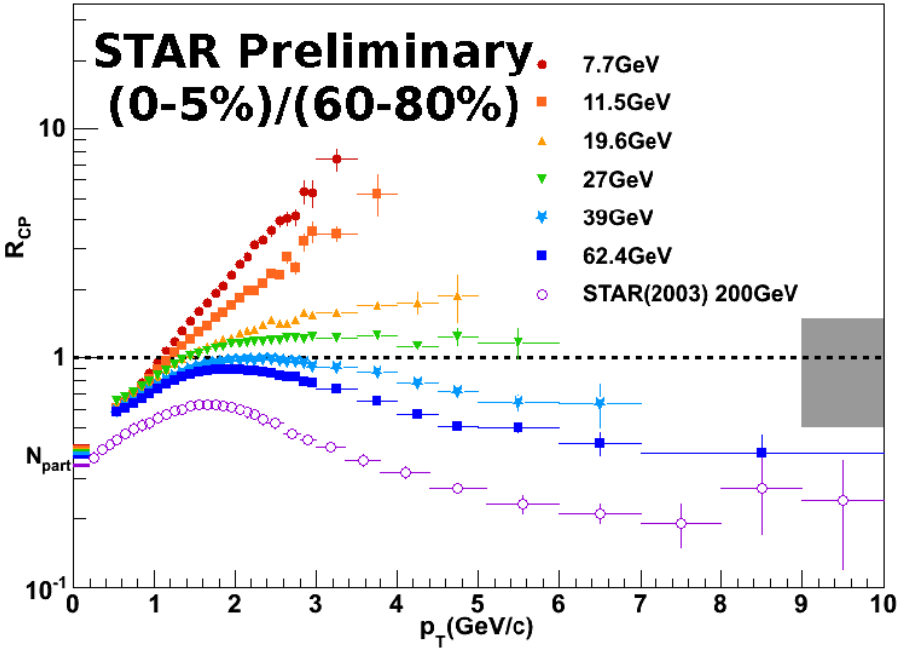




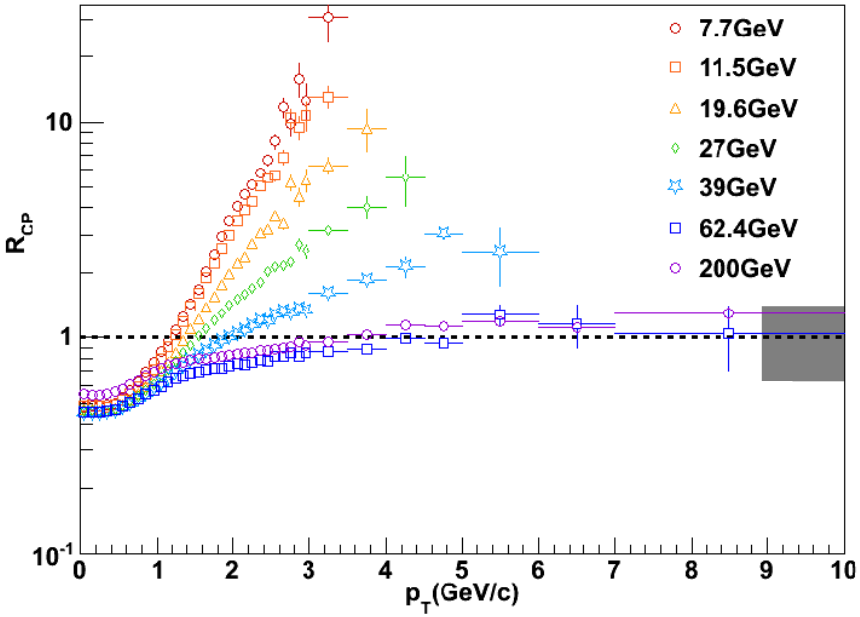
- Balance functions are sensitive to the correlation of balanced charges:
  → study dynamics of hadronization
- Narrowing of balance functions with increasing energy and increasing centrality at all energies:
  → hint for delayed hadronization after QGP phase

Nuclear Modification Factor: R_{CP}

Data



Hijing



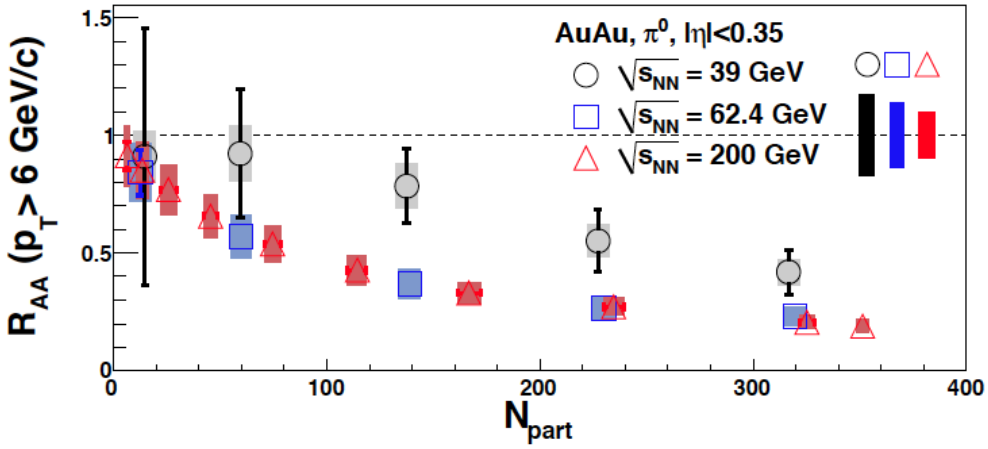
Stephen Horvart, QM2014

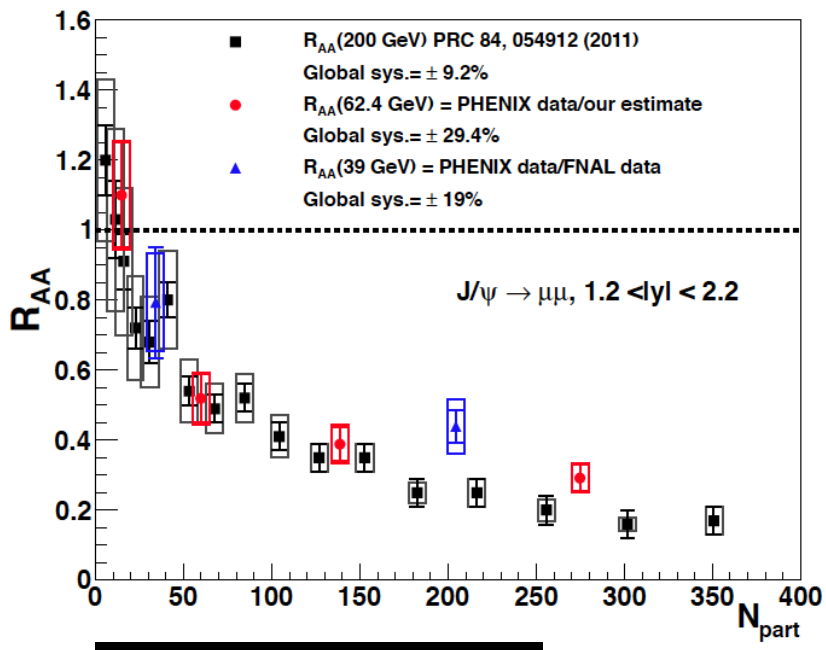
- R_{CP} suppression at high p_T for $\sqrt{s_{NN}}$ >= 39 GeV
  → signature for partonic energy loss
- R_{CP} is increasing towards lower energies
  → change of energy loss?

- Radial flow is changing a lot over the BES energy range
- Hijing calculation with Cronin effect but without partonic energy loss shows similar trends
- High p_T particles not measured at lower energies

Nuclear Modification Factor: R_{AA}

Phys. Rev. Lett. 109 (2012) 152301





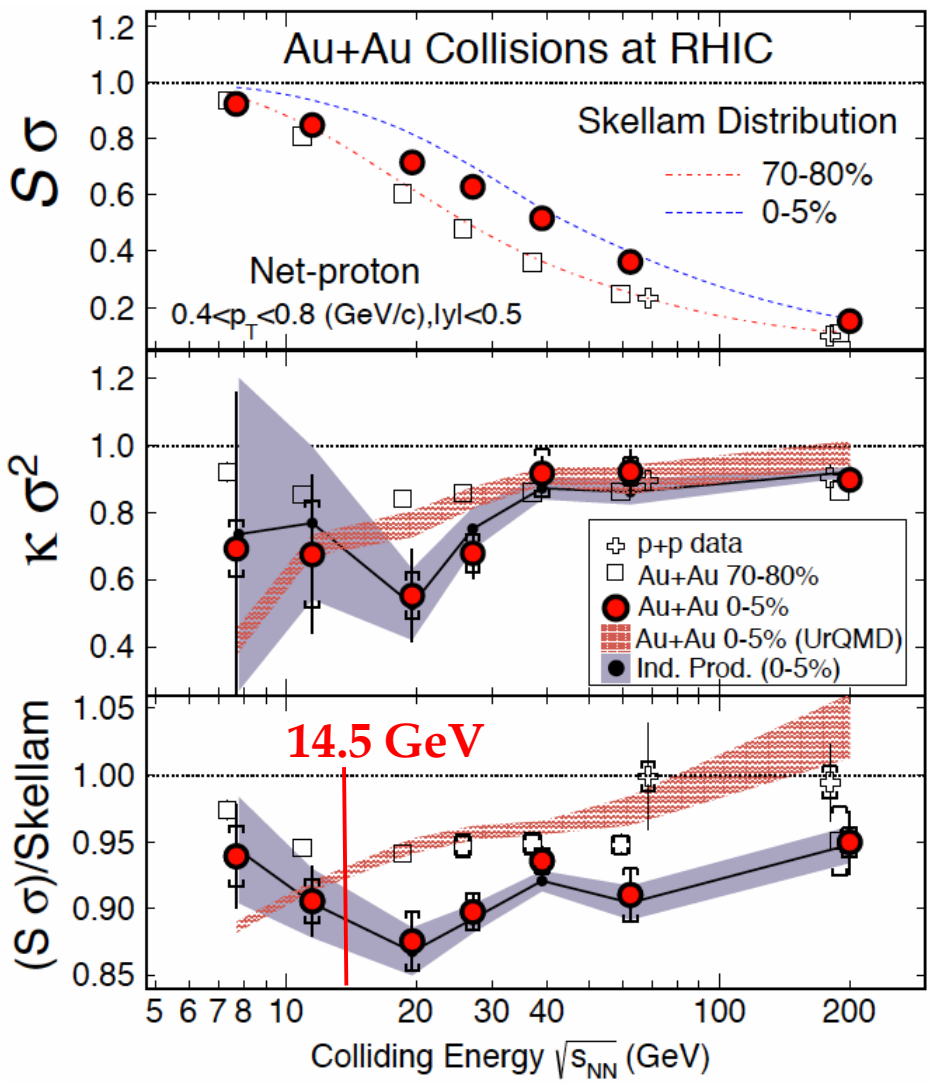
Phys.Rev. C86 (2012) 064901

- R_{AA} suppression of π^0 at high p_T for $\sqrt{s_{NN}}$ >= 39 GeV
- R_{AA} suppression of J/ψ at forward rapidity for $\sqrt{s_{NN}}$ >= 39 GeV
- Similar suppression for 39, 62.4, and 200 GeV

Higher Moments of Net-Protons

The hunt for the QCD critical point

Phys. Rev. Lett. 112 (2014) 032302



- Net-protons as proxy for net-baryons (conserved quantity)

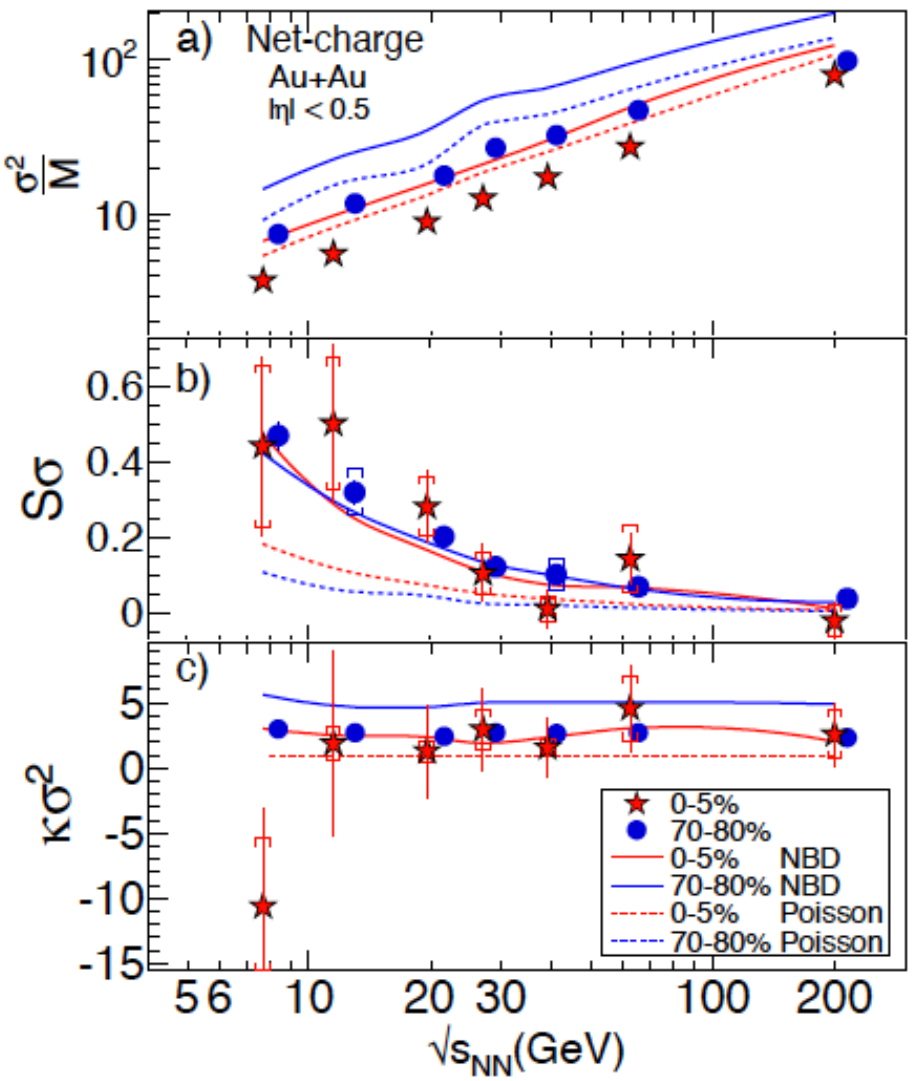
- Hints of a structure around 19.6 GeV

- UrQMD model shows similar trends as data and similar magnitude at 0-5%
- More statistics and better control of systematic is needed to make a conclusion
- Additional energies needed
  → 14.5 GeV already taken by STAR/PHENIX

Higher Moments of Net-Charge

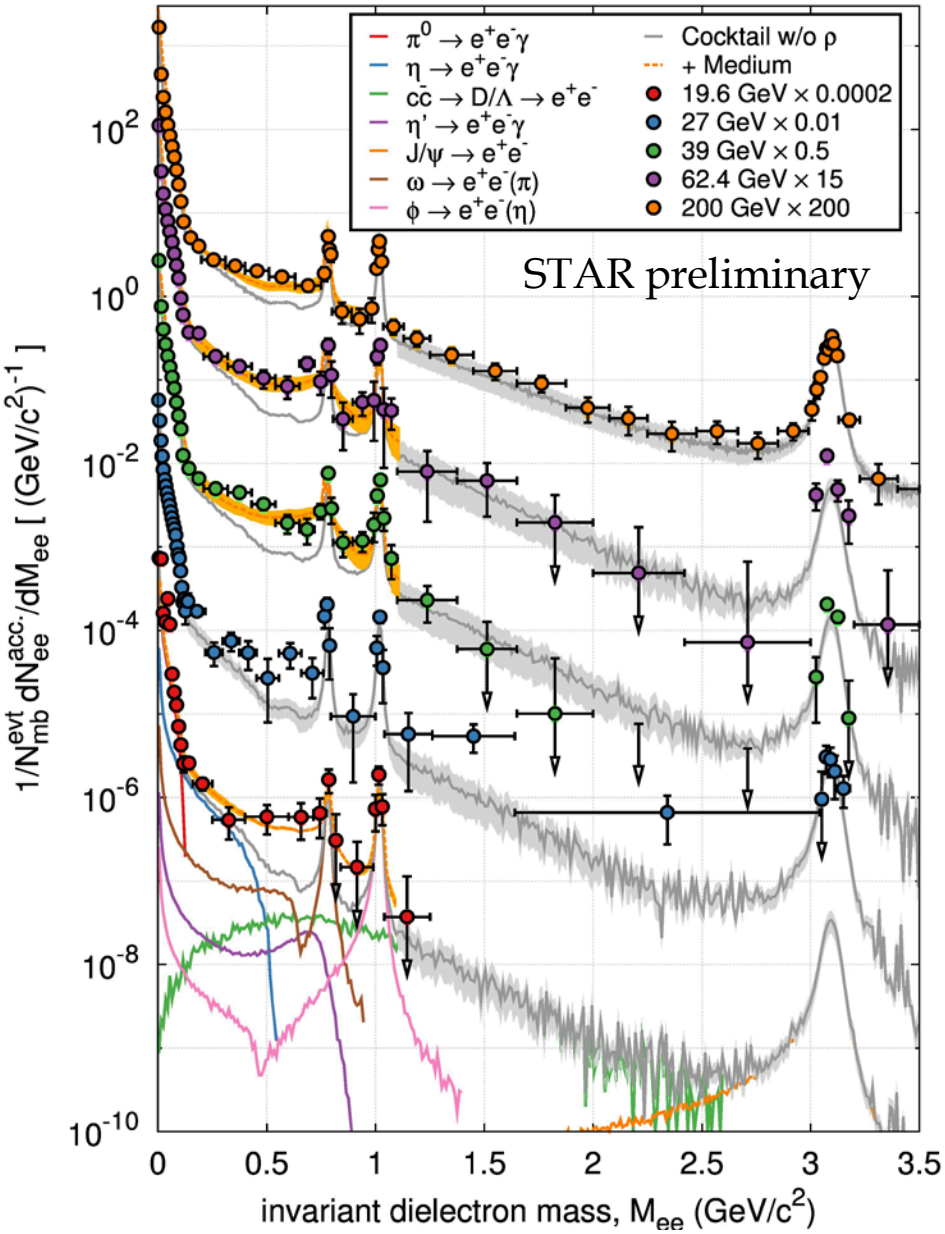
The hunt for the QCD critical point

arXiv:1402.1558



- No non-monotonic behavior observed so far
- Error bars significant → BES II

Di-Electron Spectra



- Fair agreement of di-lepton data and cocktail over the whole mass range for all energies
- The scenario of a broadened rho spectral function can consistently describe the LMR excess yield from $\sqrt{s_{NN}}$=19.6 up to 200 GeV

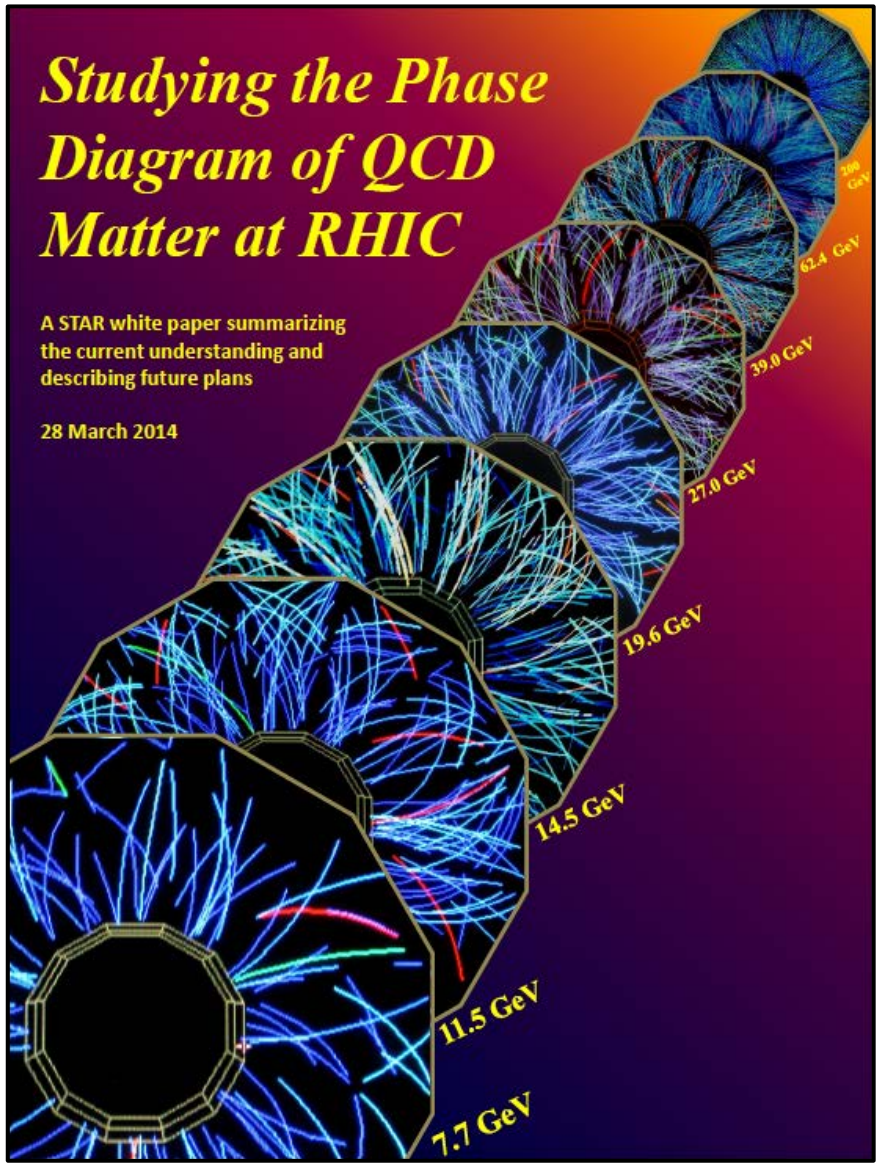
- Charm cross sections not known at lower energies
- **Lower energies needed (total baryon density is increasing)**
- Systematic errors for model?
- Connect vector meson modification in LMR to chiral symmetry restoration?
- What about QGP radiation (IMR)?

R. Rapp, private communication,
R. Rapp Adv. Nucl. Phys. 25,1 (2000)

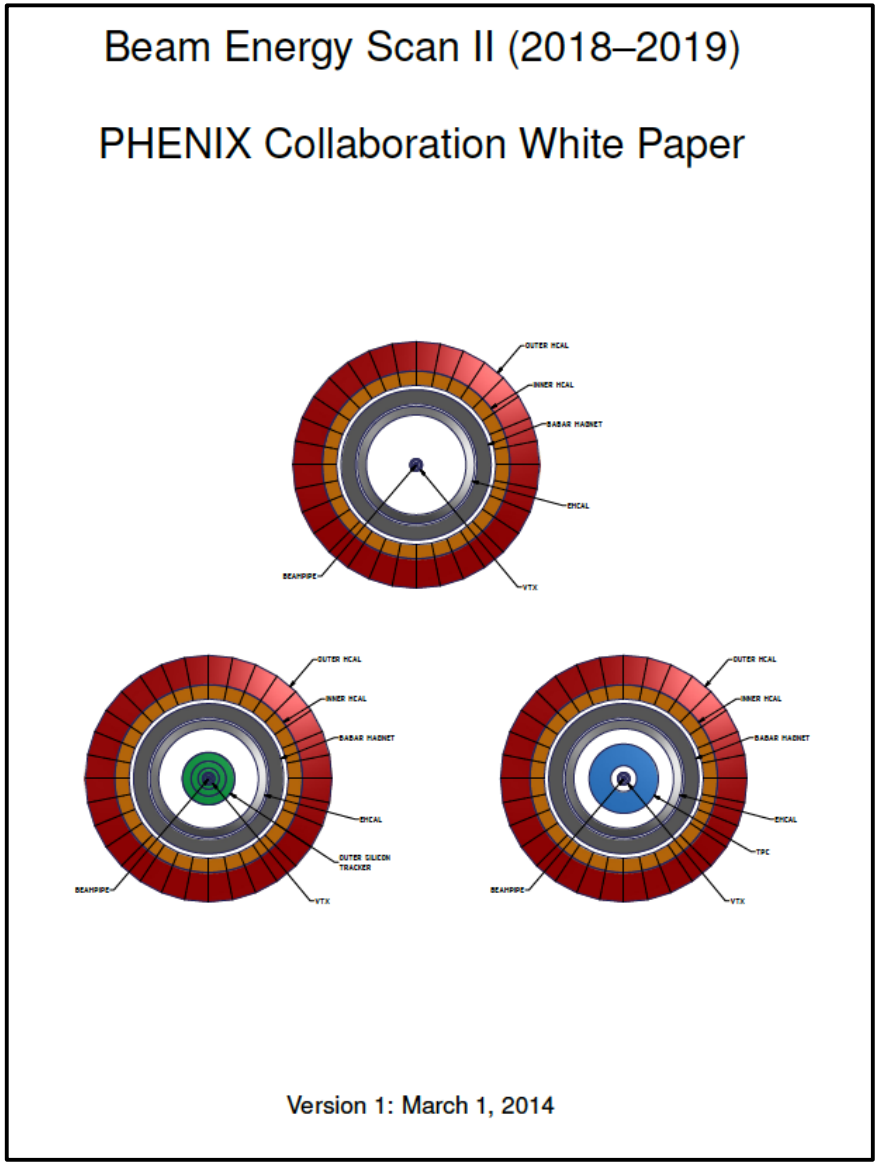
Patrick Huck, QM2014

RHIC BES Phase II White Papers

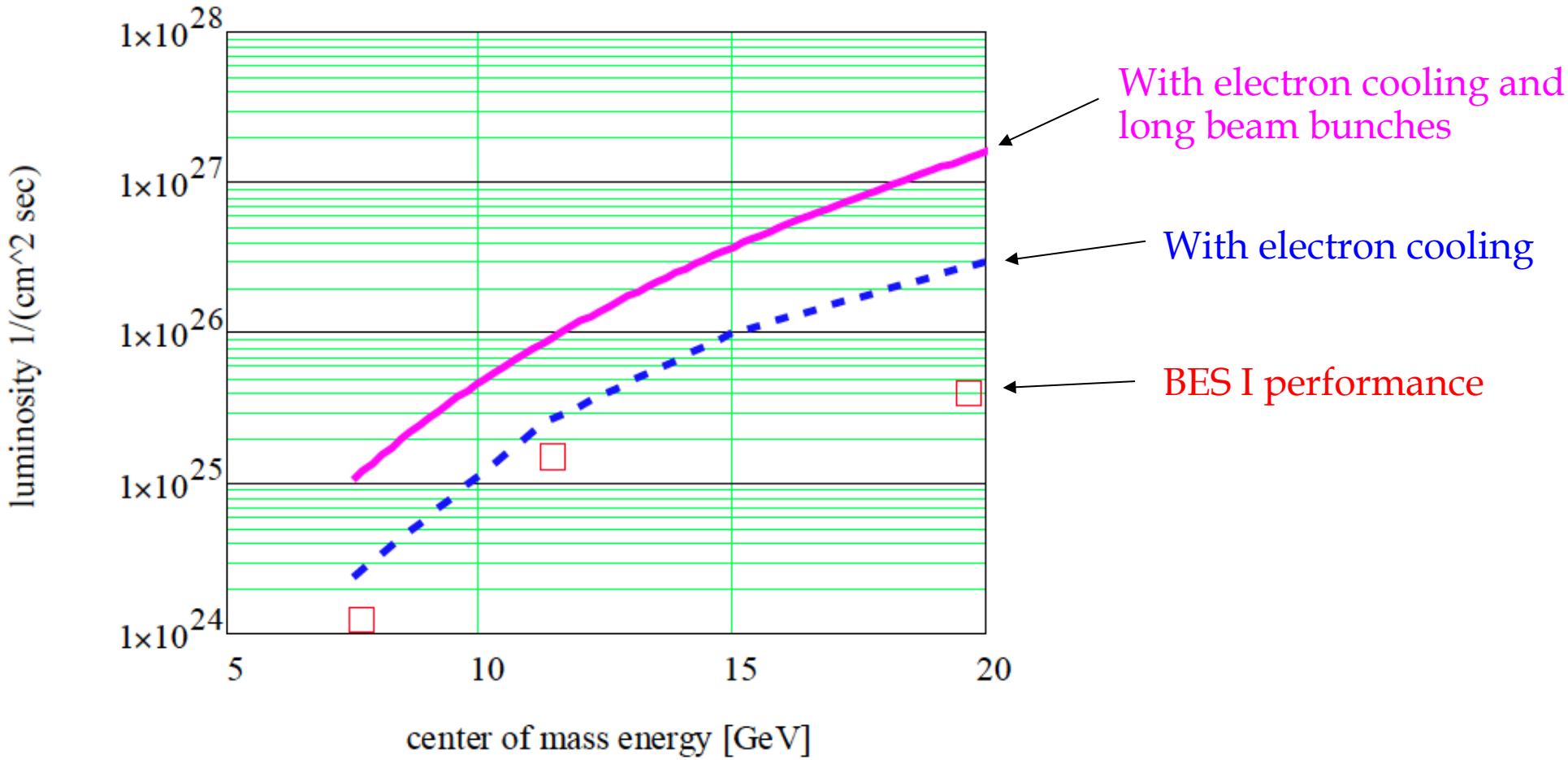
STAR



PHENIX



Luminosity Improvements for BES II



- Electron cooling + longer beam bunches for BES II
  → Factor 4-15 improvement in luminosity compared to BES I

- Every energy available with electron cooling!

BES II Requested Beamtime

- PHENIX request based on only one year
- STAR request driven by di-lepton, R_{CP} and ϕ-meson v_2 measurements

PHENIX (only 2019)

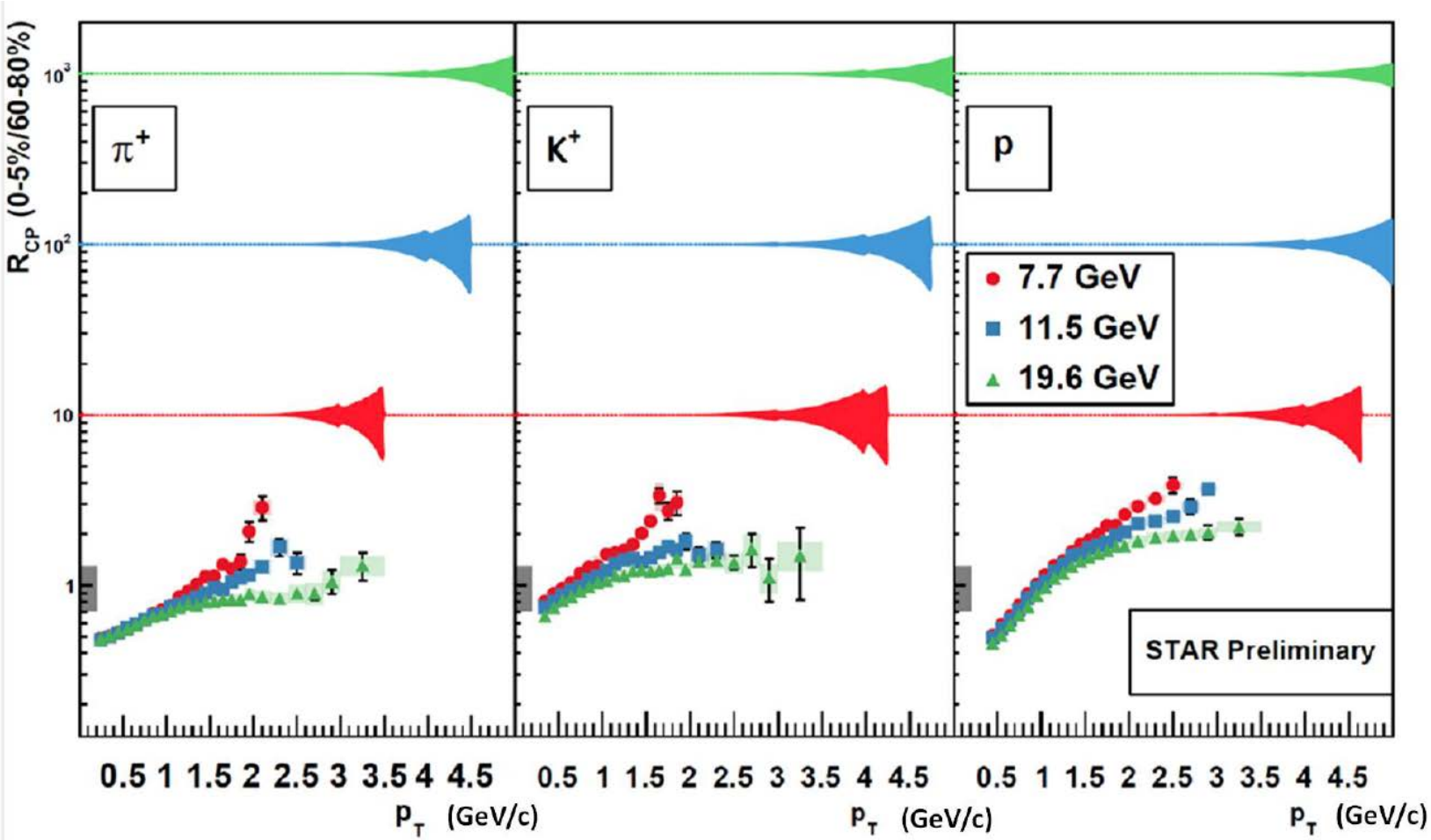
Species	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time (Days)	Events(M) $\lvert z_{vtx}\rvert < 10$cm	Events(M) $\lvert z_{vtx}\rvert < 30$cm	Events(M) $\lvert z_{vtx}\rvert < 1$ m
Au+Au	11.5	315	45	15	45	112.5
	13.0	281	23	17	50	125
	9.0	376	41	6	17	42.5
	19.6	205	4	33	100	2500
	200	20	10	1200	3600	9000
p+p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

STAR (2018/2019)

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+

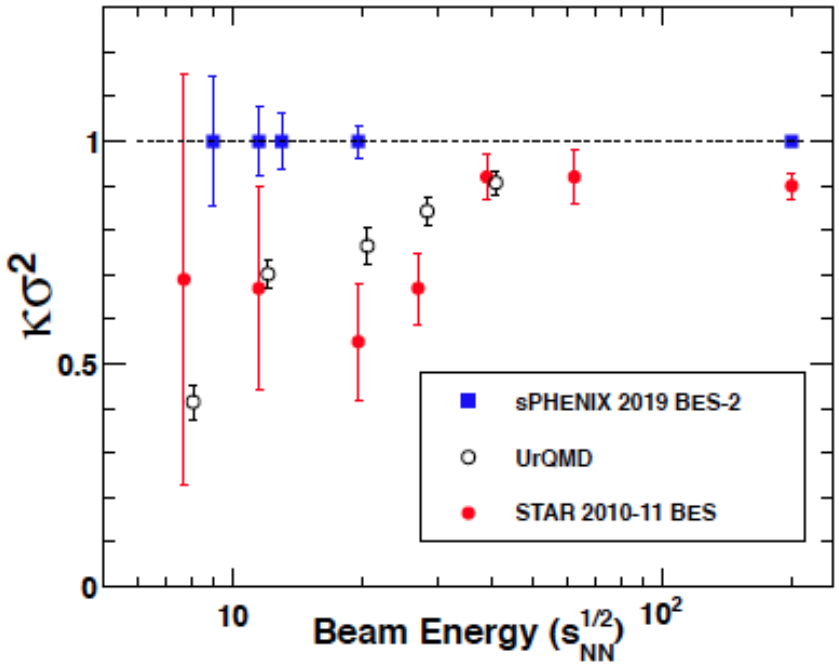
BES II Projections: R_{CP}



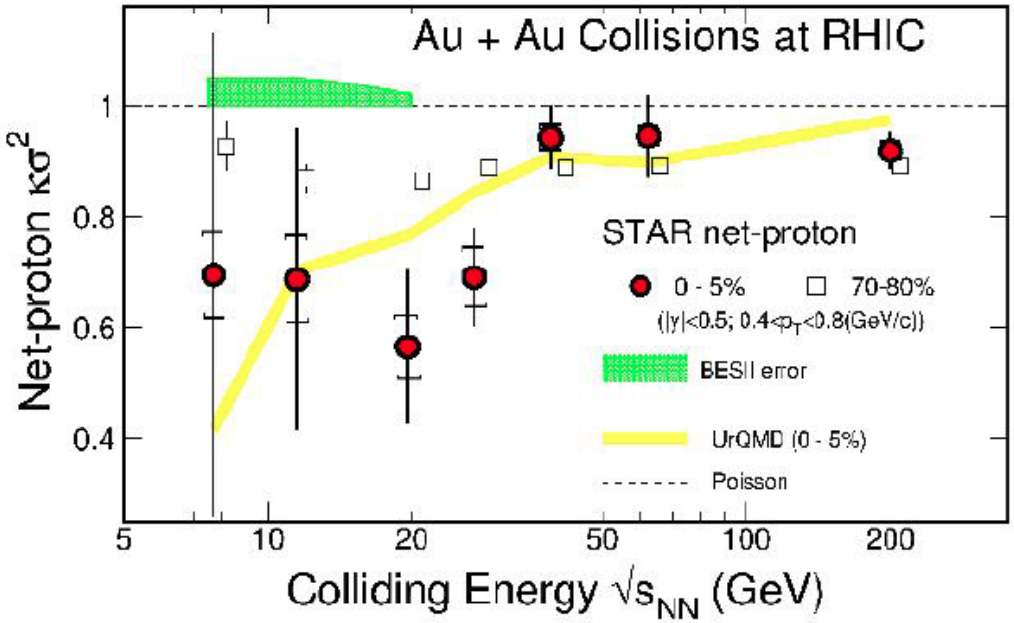
• Protons will cover p_T ~4.5 GeV down to $\sqrt{s_{NN}}$ = 7.7 GeV

BES II Projections: Net-Proton Higher Moments

PHENIX

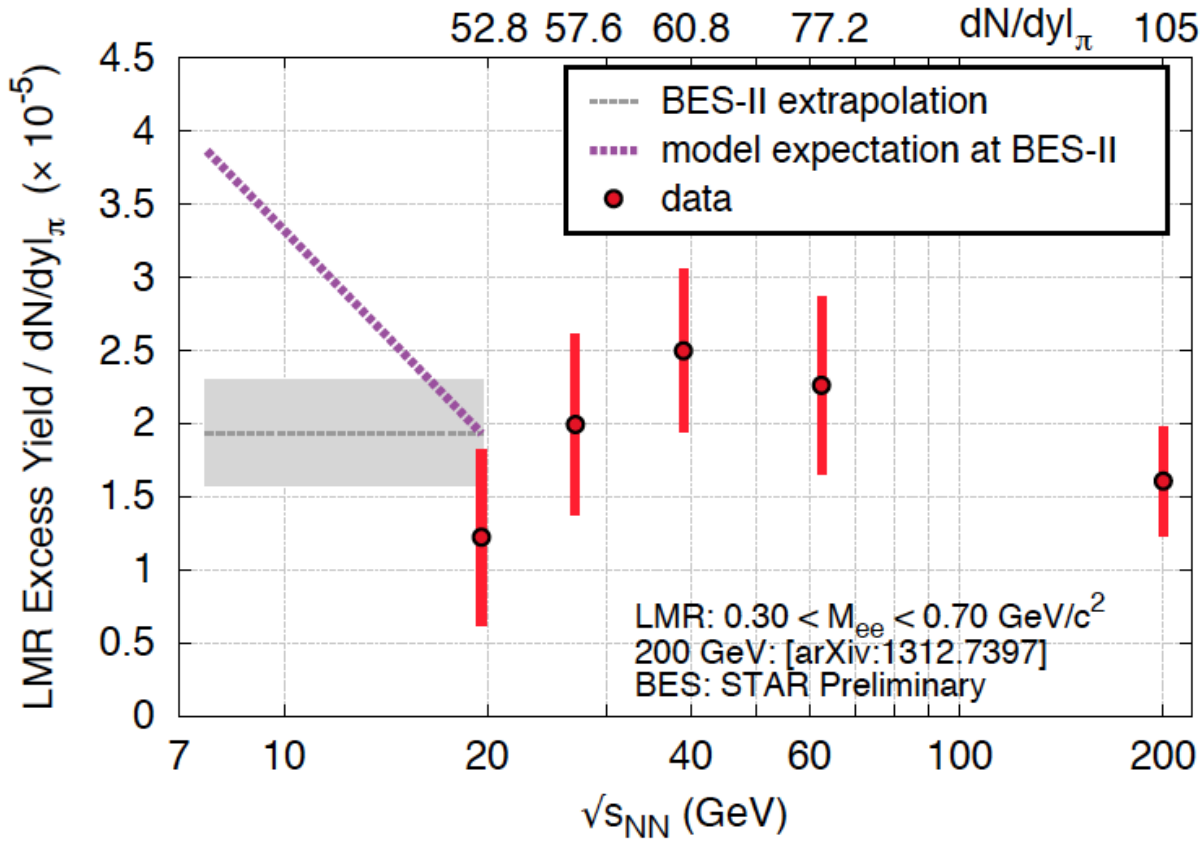


STAR (2018/2019) Phys. Rev. Lett. 112 (2014) 032302



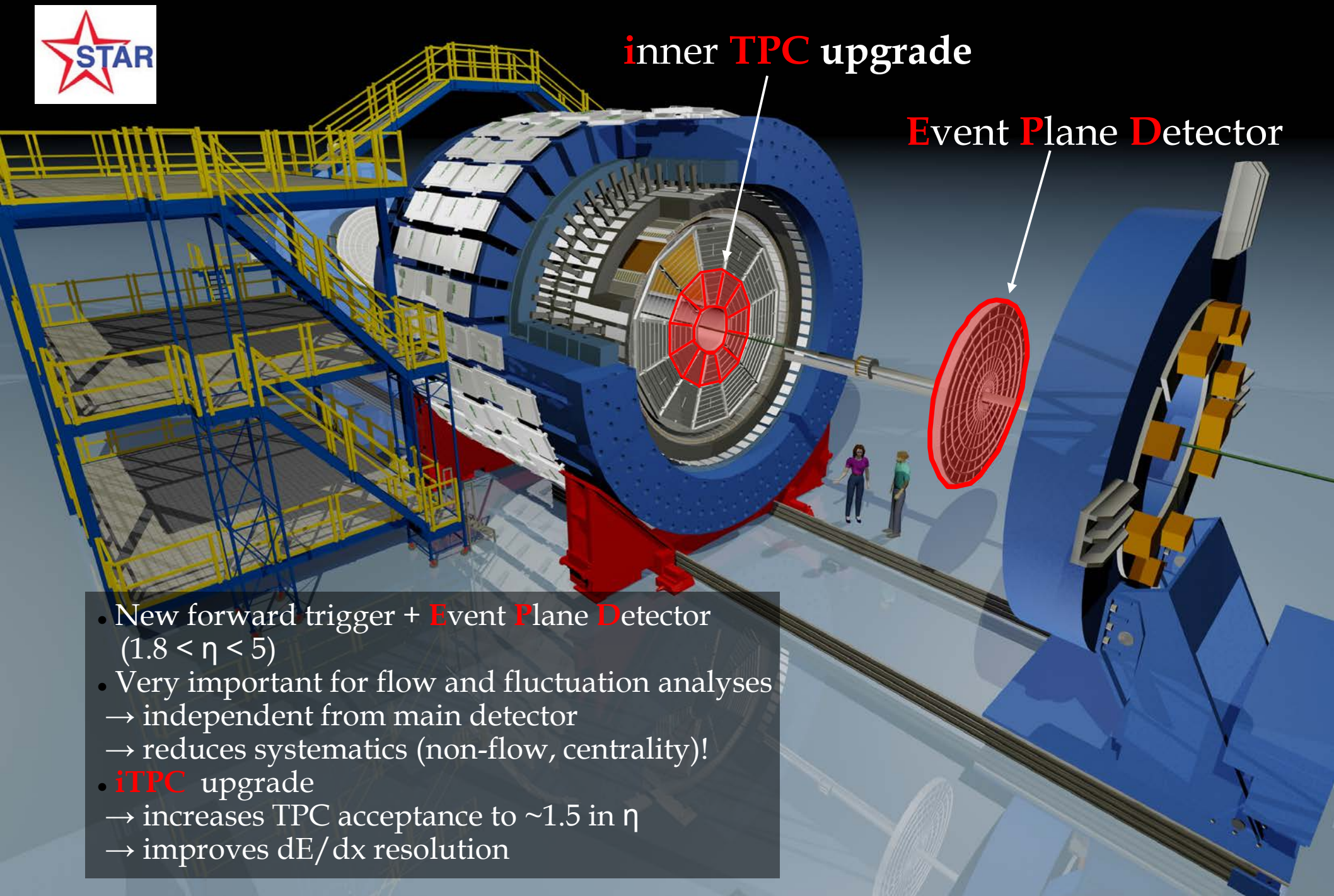
- PHENIX (with TPC) and STAR will have similar (small) error bars at energies below $\sqrt{s_{NN}} < 19.6$ GeV
  → Important cross check!

BES II Projections: Di-Leptons



- Total baryon density is going to increase to lower energies
  → LMR excess will most likely increase
  → Projected error bars are similar to higher energies

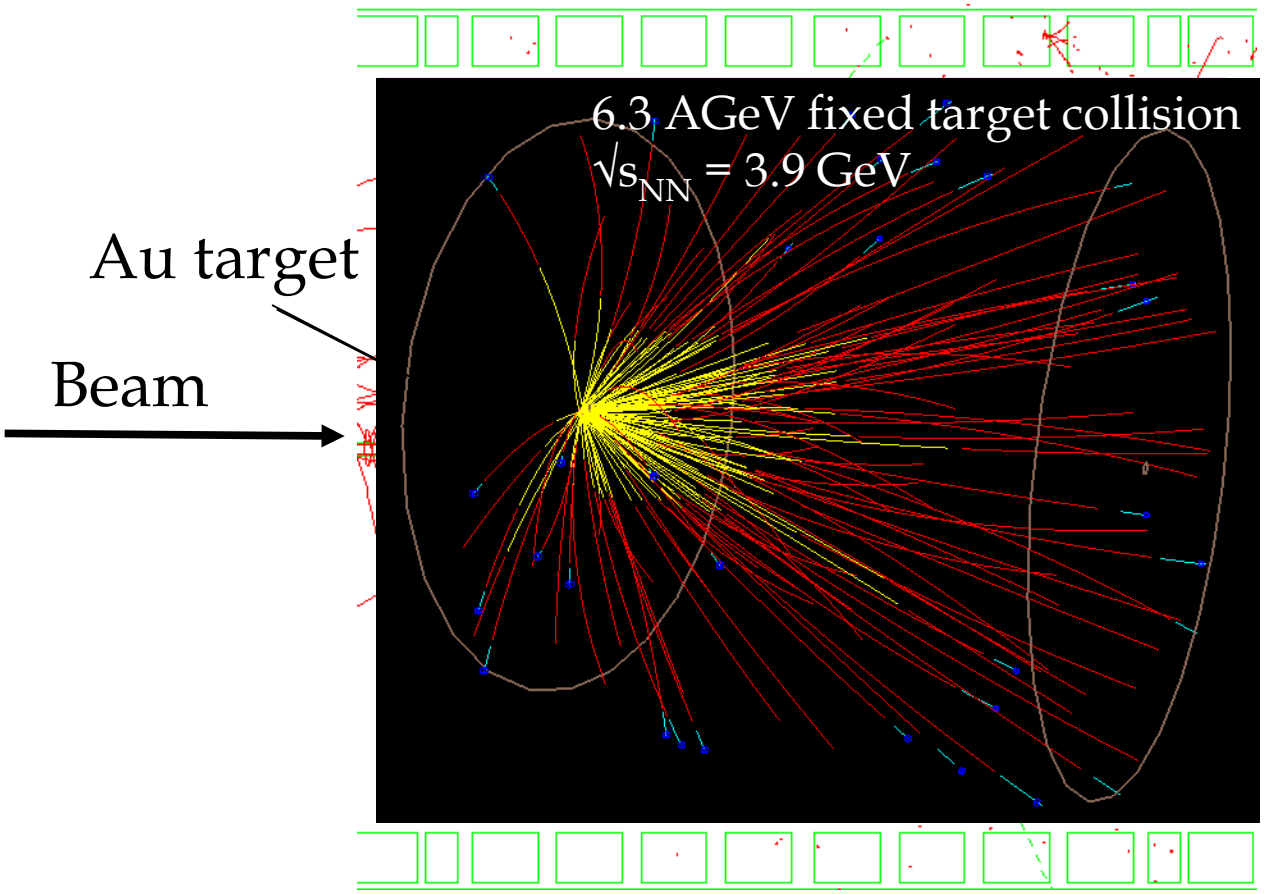
Detector Developments for BES II

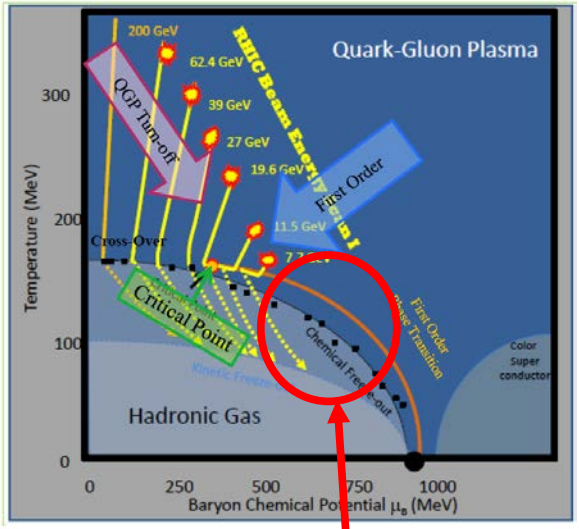


- New forward trigger + Event Plane Detector ($1.8 < \eta < 5$)
- Very important for flow and fluctuation analyses
  → independent from main detector
  → reduces systematics (non-flow, centrality)!
- iTPC upgrade
  → increases TPC acceptance to ~1.5 in η
  → improves dE/dx resolution

Fixed Target Program for BES II

Brooke Haag, QM2014



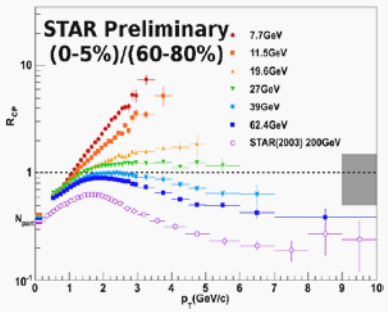


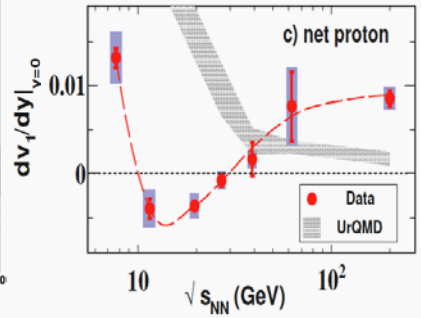
Access to low T, high μ_B (similar to CBM/FAIR)

- Fixed target program extends STAR's physics reach to region of compressed baryonic matter
- Simultaneous run with collider mode (ions from the halo, main program will not be affected)

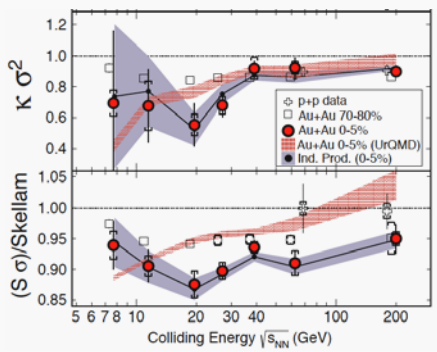
but much lower luminosity compared to CBM!

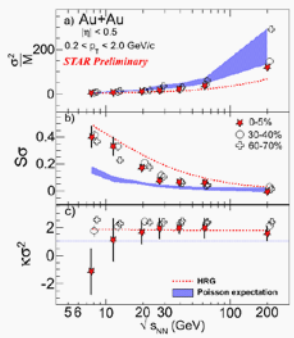
BES II: Key Questions



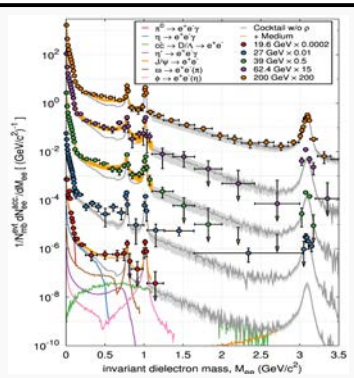


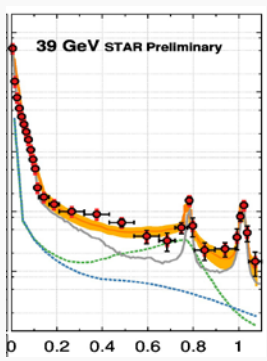
- **Is there a first order phase transition and where is it?**
  - → R_{CP} not measured at high p_T for low energies!
  - → v_1 measurement for different centralities, EPD detector to control systematics





- **Where is the critical point and can we find it?**
  - → Error bars (stat. + syst.) too large!
  - → More energies/systems (SPS)





- **Study of QGP radiation and chiral symmetry restoration for different μ_B**
  - → Multi-differential di-lepton spectroscopy at large M_{ee}

Thanks!

PHENIX BES II Detector Requirements

- De-comissioning of PHENIX in the shutdown period 2016-2017 → **sPHENIX**
- Only participation in 2019 run
- 25% of EMCAL ready for 2019 run
- No di-lepton capabilities for BES II
- **VTX <u>or</u> TPC enough for most of the analyses!**

Physics Analysis	N_{evt} ($\times 10^6$)	Required Detectors
Charged Particle Multiplicity	5	VTX and/or TPC
Multiplicity Fluctuations	5	VTX and/or TPC
Charged Particle p_T Spectra	10	VTX and/or TPC
p_T Fluctuations	10	VTX and/or TPC
Moments of Net Charge	10	VTX and/or TPC
Charged Particle Flow	10	VTX and/or TPC
Charged Particle R_{CP}	30	VTX and/or TPC
Di-hadron Correlations	50	VTX and/or TPC
Chiral Magnetic Effect	10	VTX and/or TPC
Transverse Energy	5	EMCal
Neutral Pion Spectra	10	EMCal
Neutral Pion R_{CP}	30	EMCal
Identified Particle Spectra	10	TPC
Identified Particle Ratios	10	TPC
Identified Particle Flow	30	TPC
Identified Particle HBT	50	TPC
Moments of Net Protons	100	TPC
Particle Ratio Fluctuations ($K/\pi, \bar{p}/p$)	100	TPC