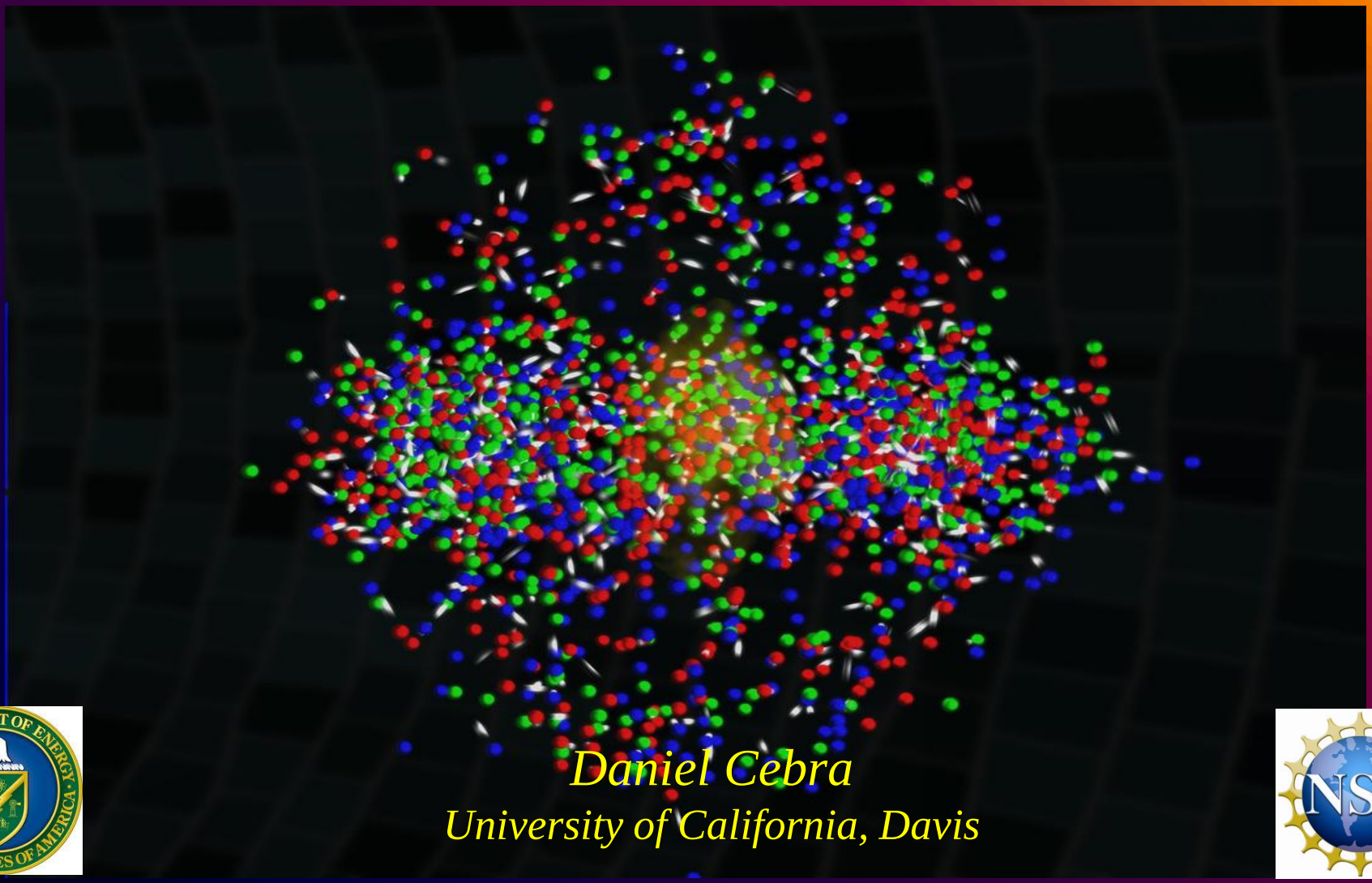
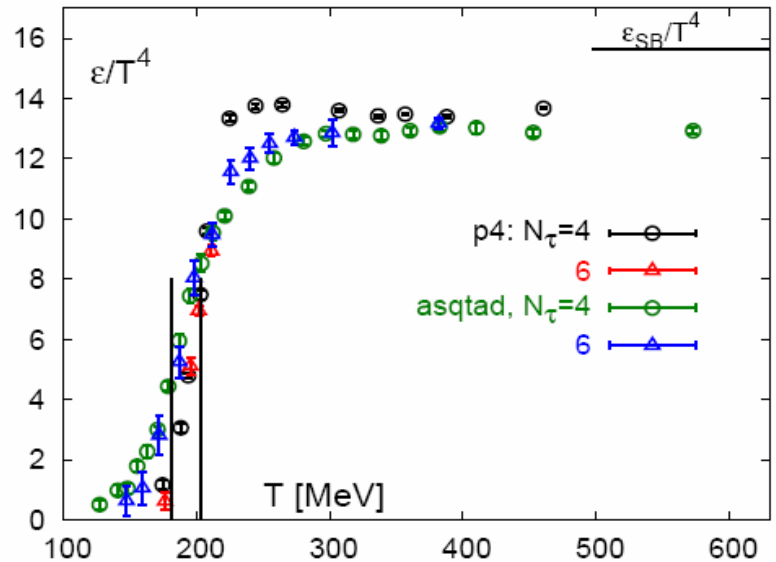
Realizing the NSAC Long Range Plan at RHIC: The QCD Phase Diagram



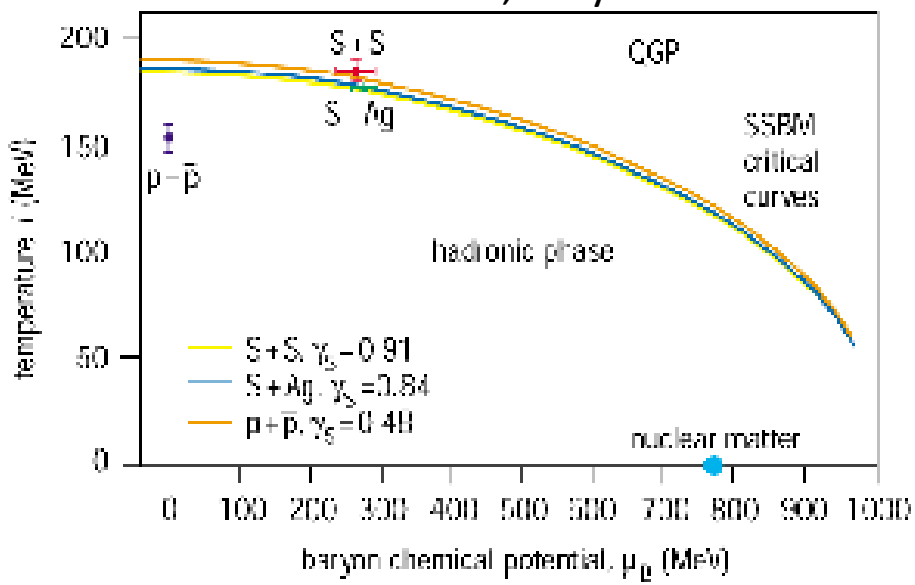
Daniel Cebra
University of California, Davis

Let's Remind Ourselves of Where We Started

2000



CERN Courier, May 2000

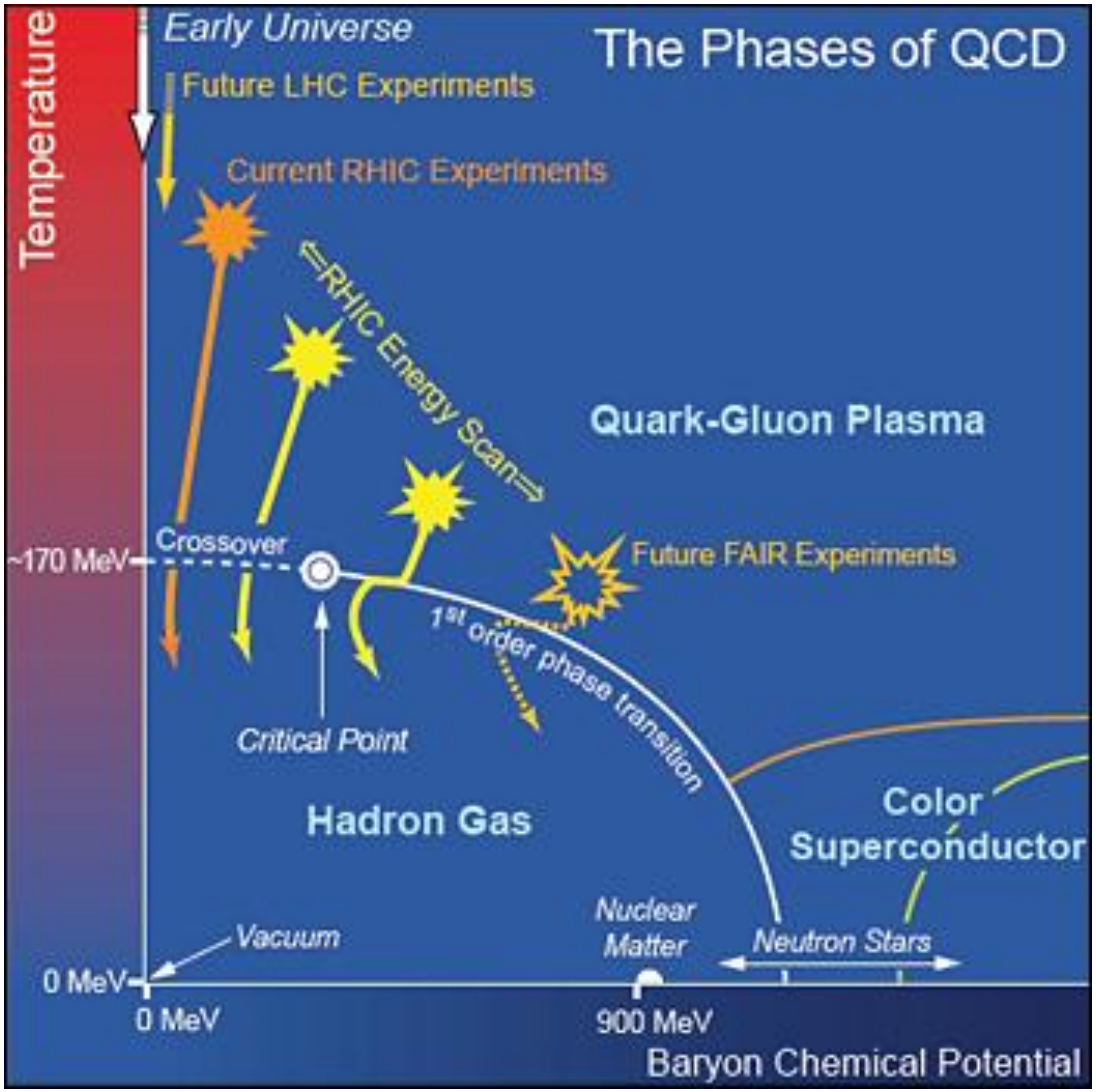


- The critical temperature was expected to be around 200 MeV
- The phase transition was expected to be "sharp" for all baryon chemical potential
- Data were sparse

We Made Progress in both theory and Experiment

2008

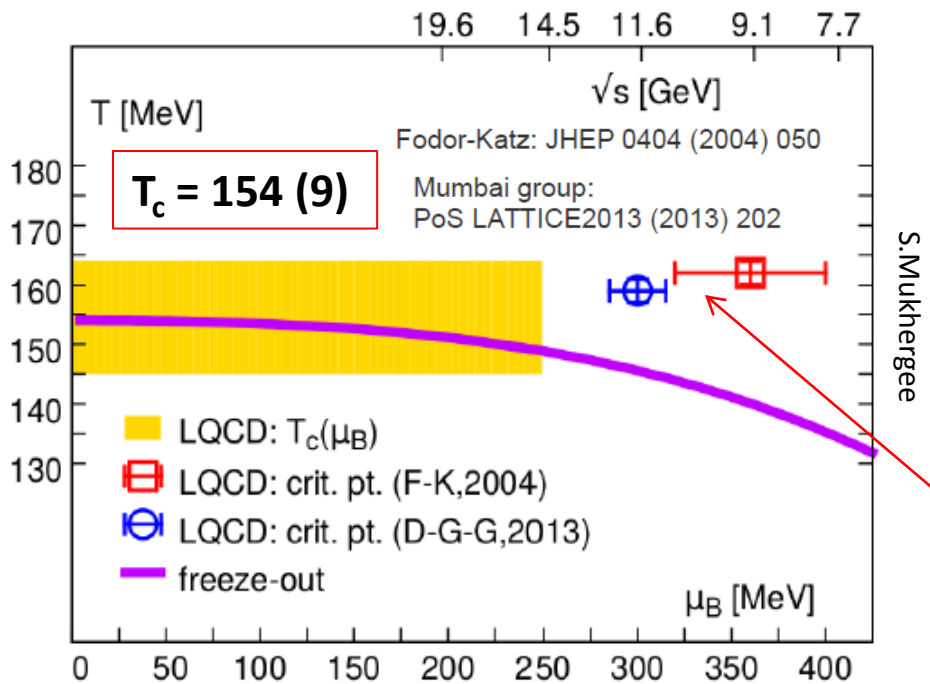
- Estimates of the critical temperature dropped and came close to chemical equilibrium model fits to data
- The transition is understood to be a crossover at $\mu_B = 0$
- Additional phases at high μ_B expected
- Energy scans proposed create systems with a range of initial conditions to explore the phase diagram



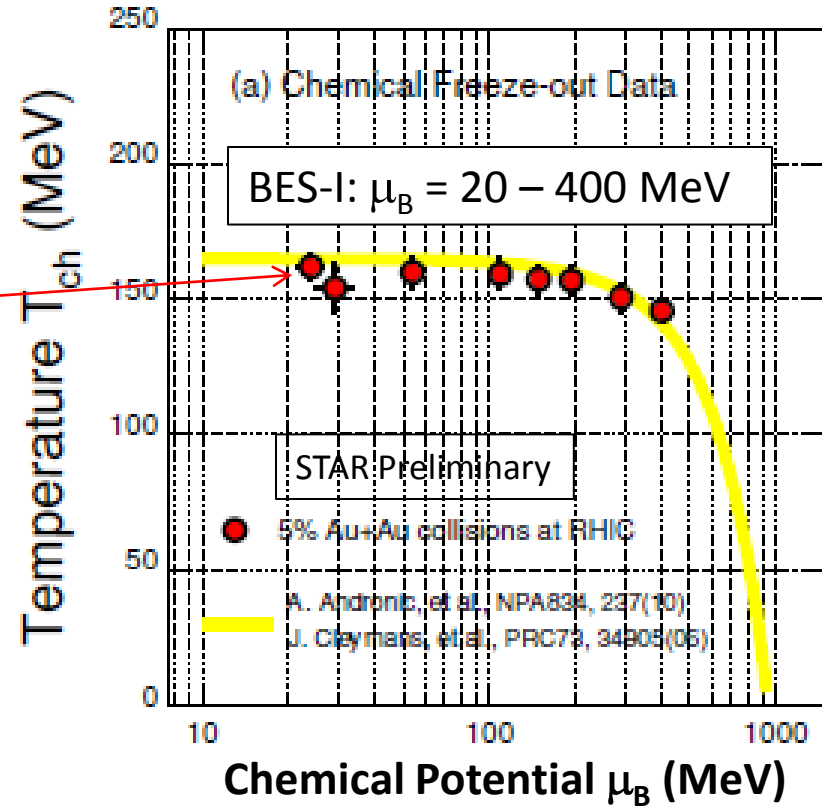
Further Refinements

Using a statistical equilibrium model and the measured particle yields (π, K, p, Λ, Ξ, ϕ, Ω), one can estimate the location in the phase diagram.

$$N_i/V = \frac{g_i}{(2\pi)^3}\gamma_S^{S_i}\int \frac{1}{\exp\left(\frac{E_i-\mu_B B_i-\mu_S S_i}{T_{ch}}\right)\pm 1}d^3p$$



S.Mukhergee



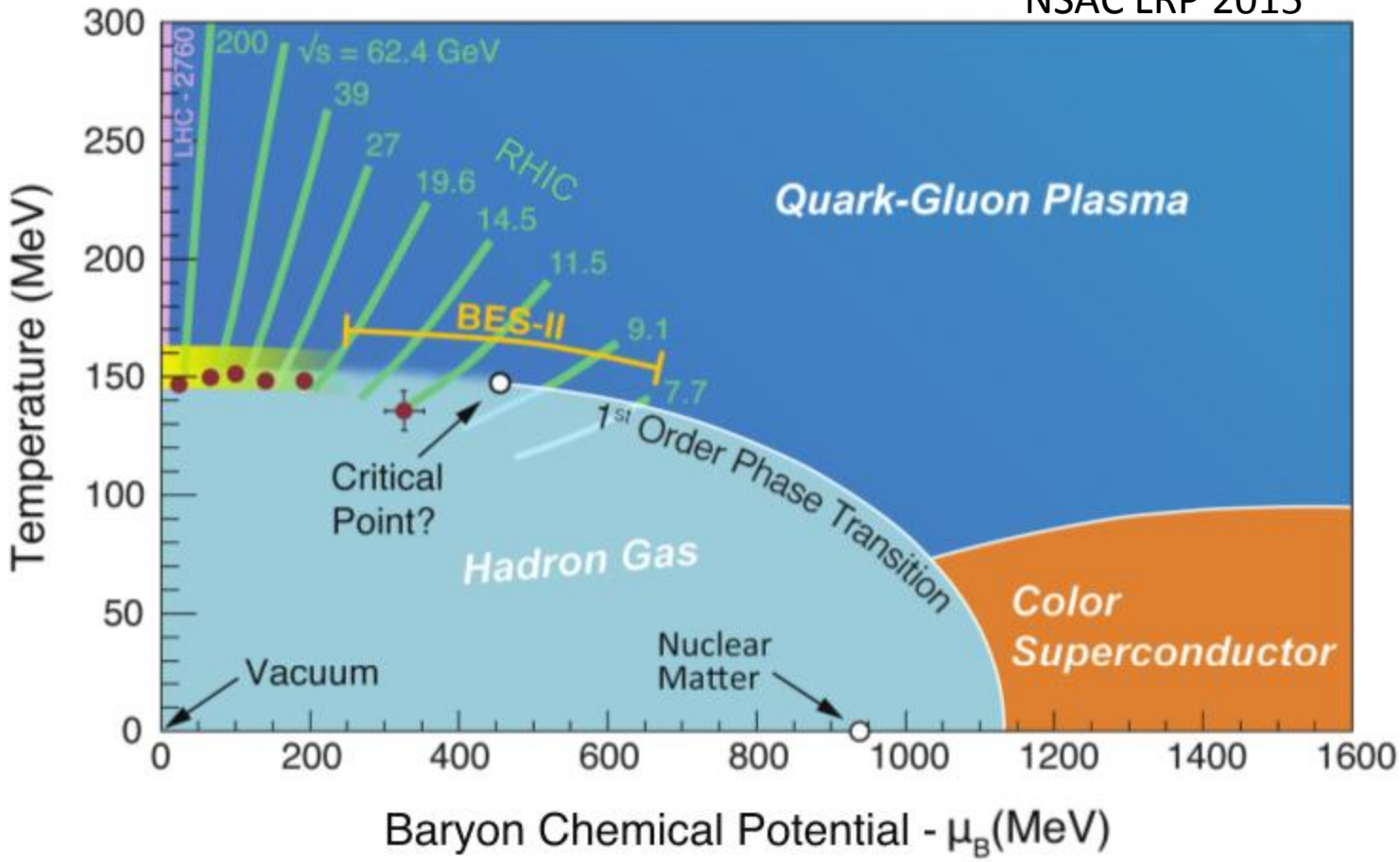
BES-II White Paper

Some Lattice Gauge Theory predictions suggest that the low end of the BES-I scan one may find the critical point

We Are We Today?

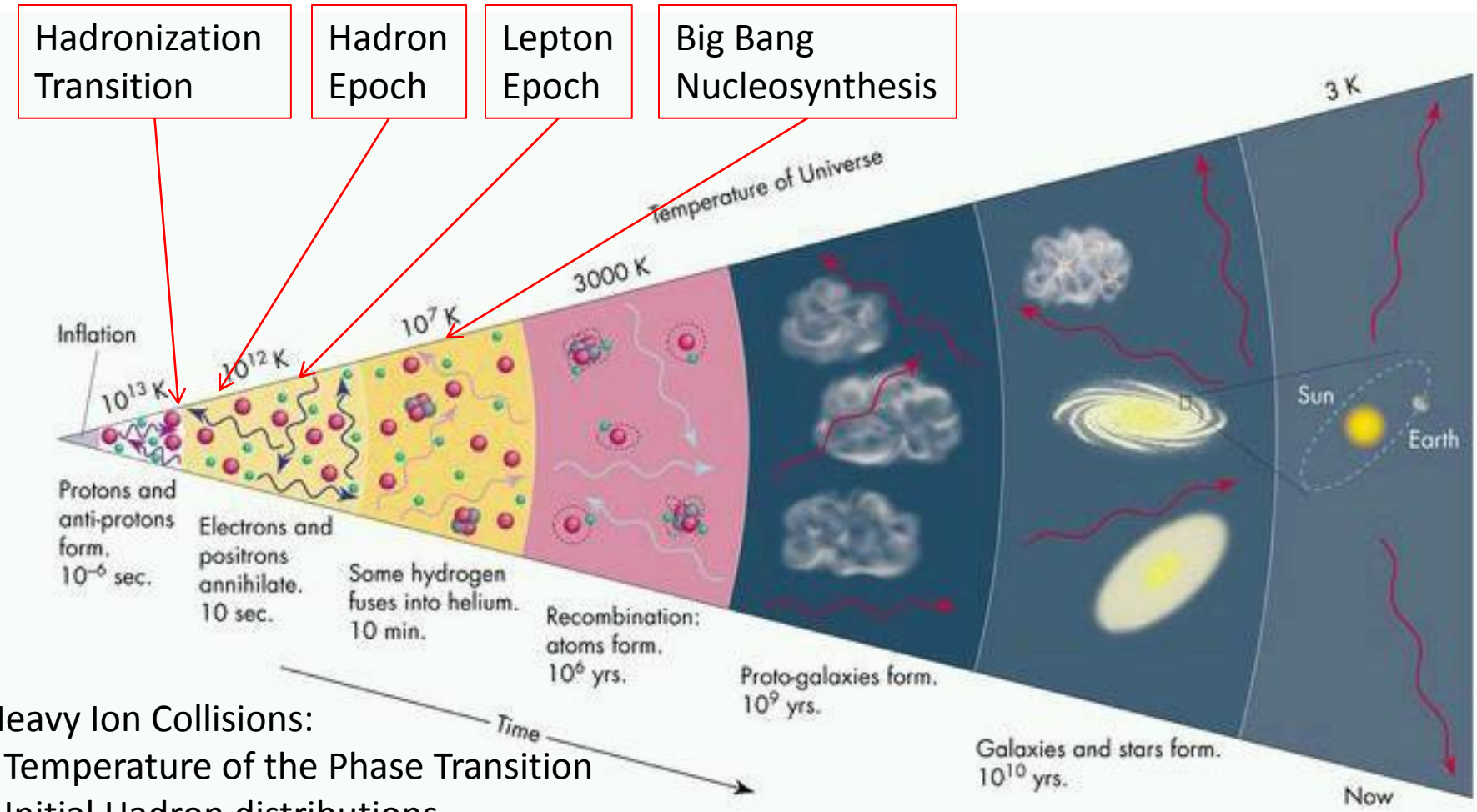
- Good agreement better experiment and theory at top RHIC energy
- Still not clear as to the nature of the phase transition at higher μ_B

NSAC LRP 2015



➔ These still open questions are important, and have motivated BES-II

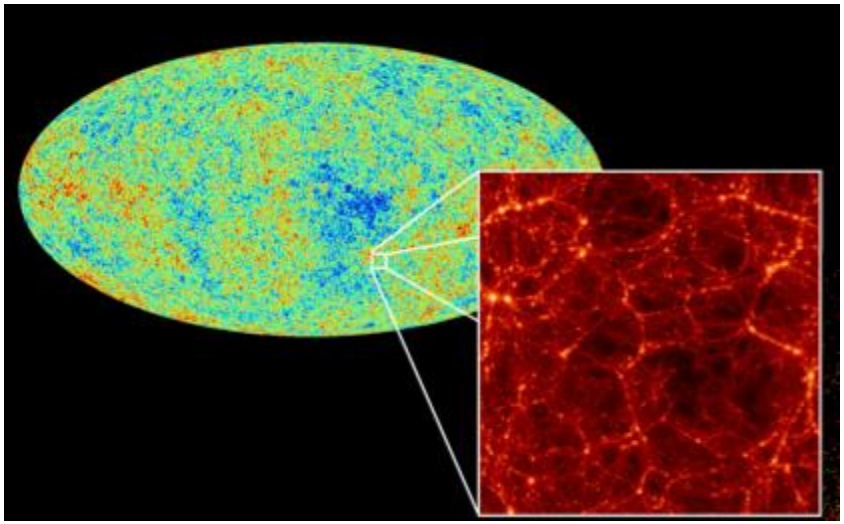
What do Heavy Ion Collisions Tell us about the Big Bang?



Heavy Ion Collisions:

- Temperature of the Phase Transition
- Initial Hadron distributions
- Evolution of hot hadron gas

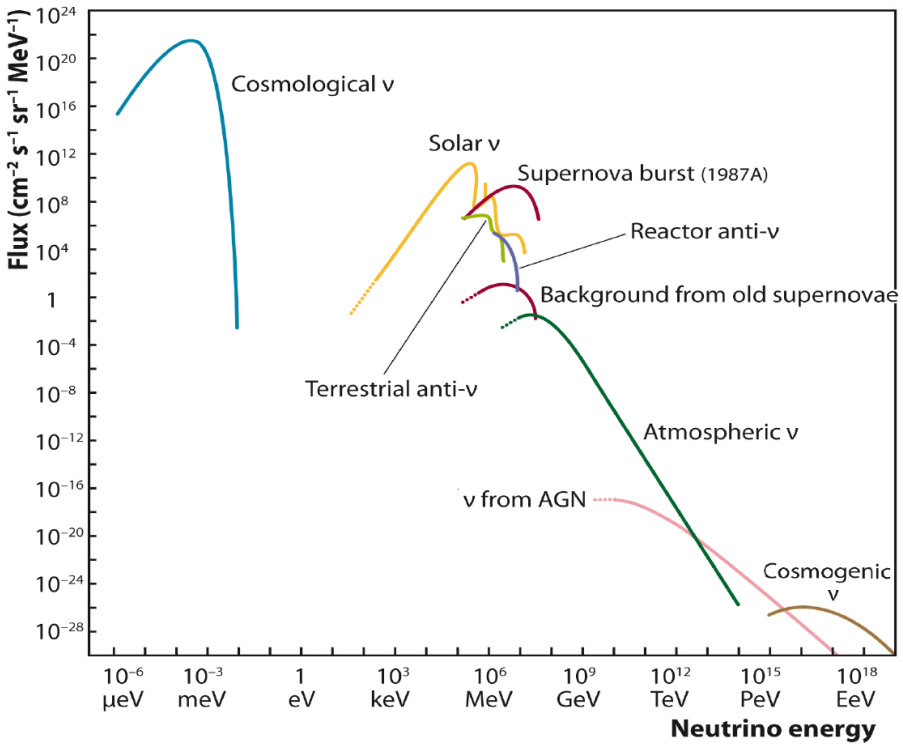
What Could We Learn from details of the Hadron Epoch



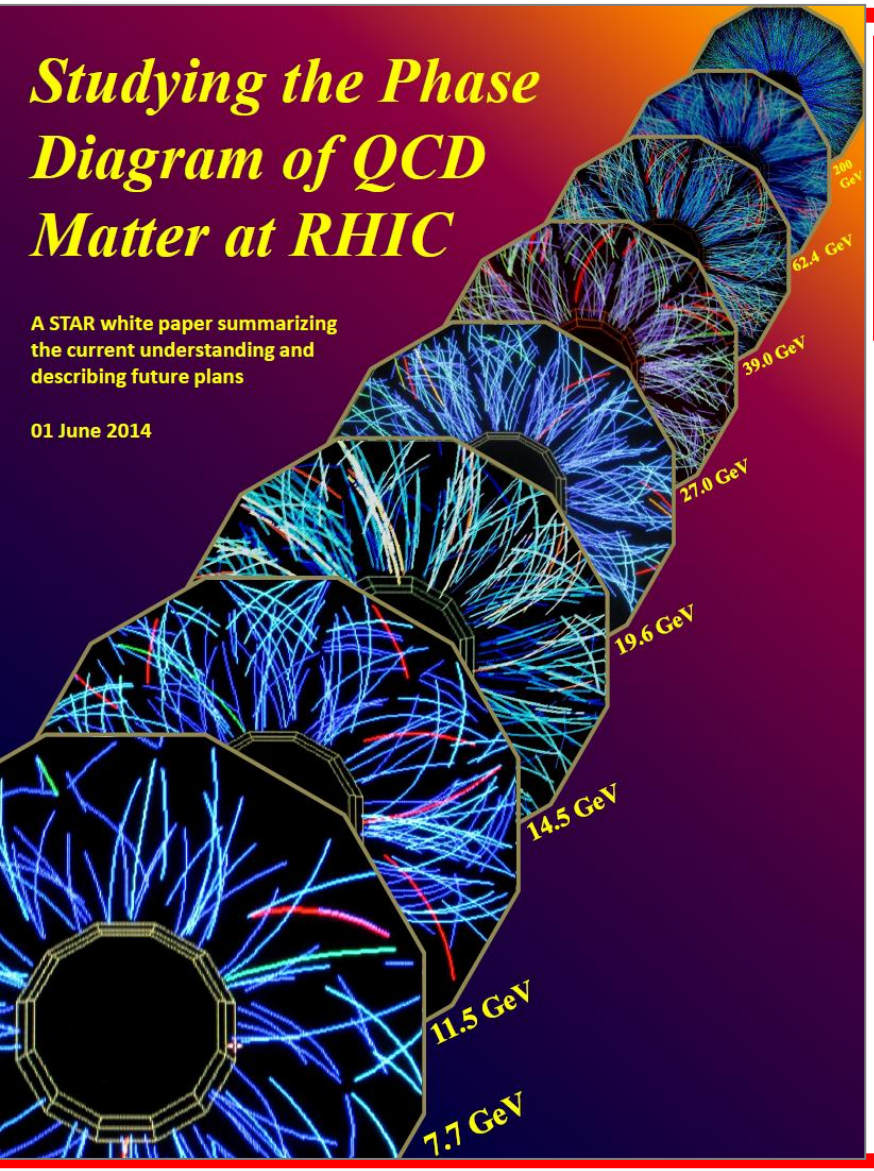
•Cosmic microwave background only takes us back 300,000 years, after the big bang.

•The hadonization transition took place rough one microsecond after the big bang.

•We now know the temperature of the hadronization transition
•We know the initial ratios of hadrons
•We know the pathways by which mesons decay into neutrinos, allows higher precision estimate of the CνB
•Better initial particle ratios place tighter constraints on baryogenesis.
• The better initial conditions could influence estimates of BBN



Can We Make Further Progress?



Beam Energy Scan II (2019-2020)

Select the most important energy range
➔ 5 to 20 GeV

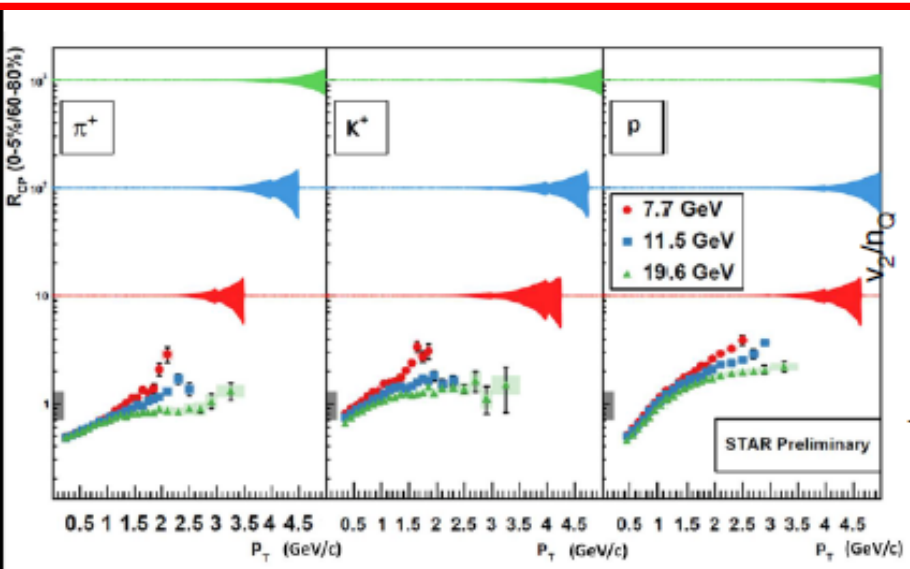
Improve significance
➔Long runs, higher luminosity (eCooling)

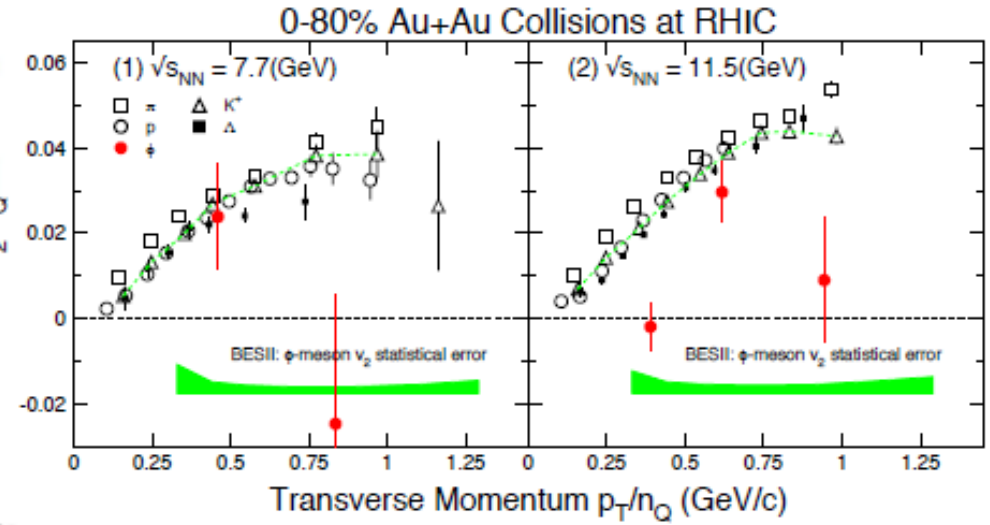
Refine the signals
➔Detector improvements

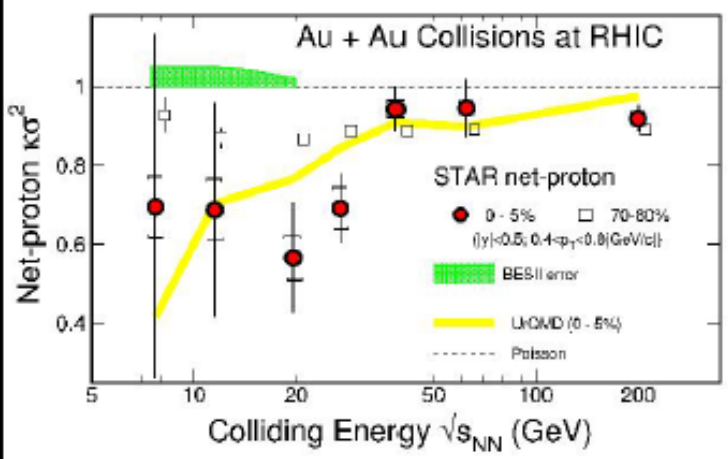
Extend Range
➔Fixed Target Opportunity

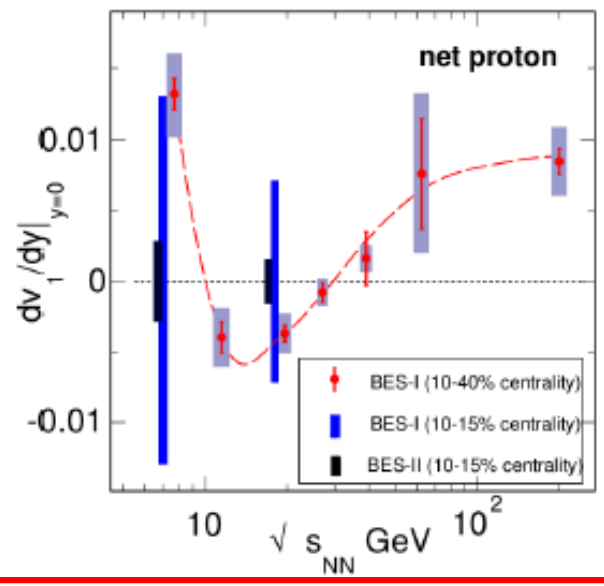
Concurrent Theory Initiative
➔Beam Energy Scan Theory Collaboration

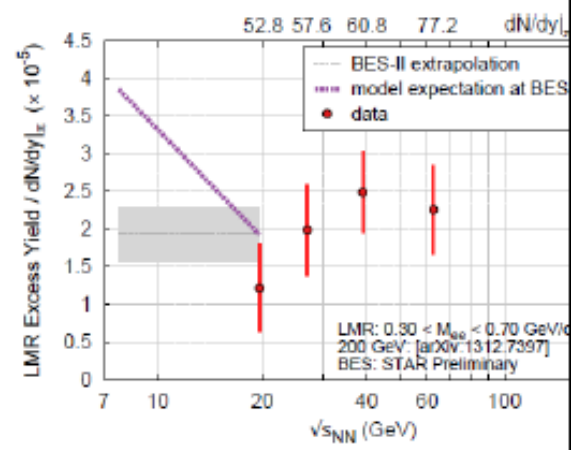
Reduction in Errors with Improved Statistics

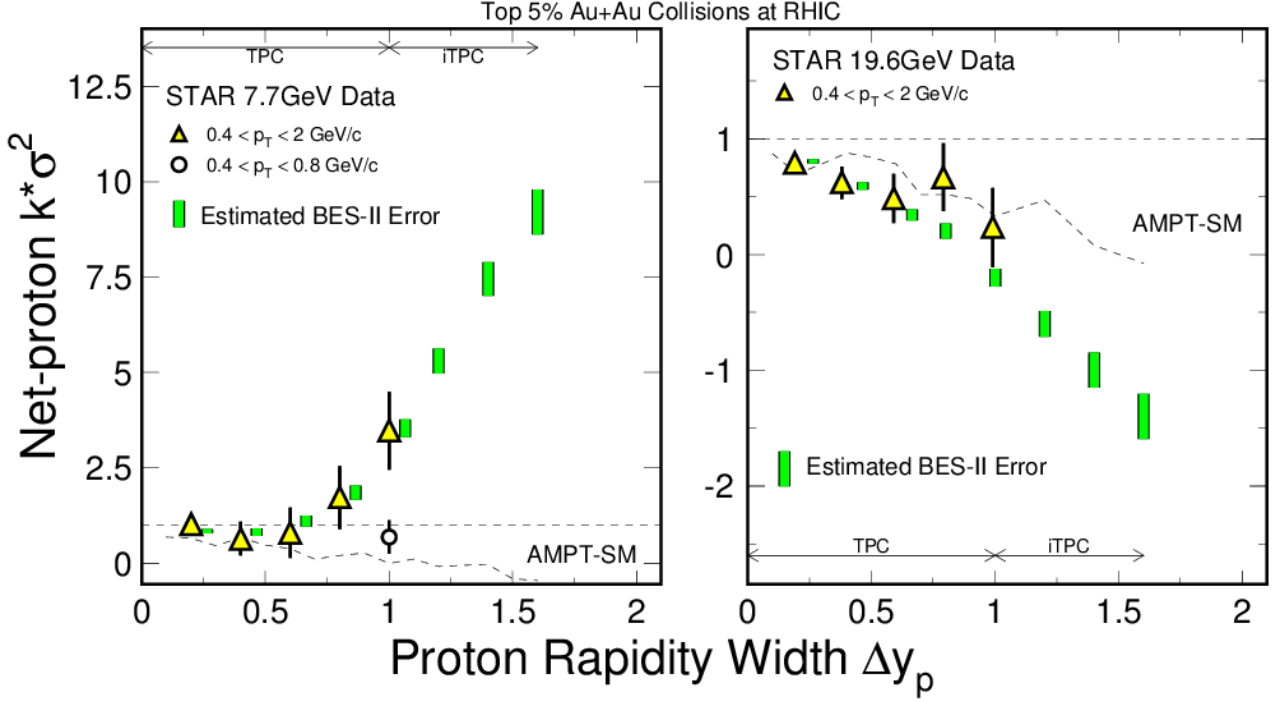




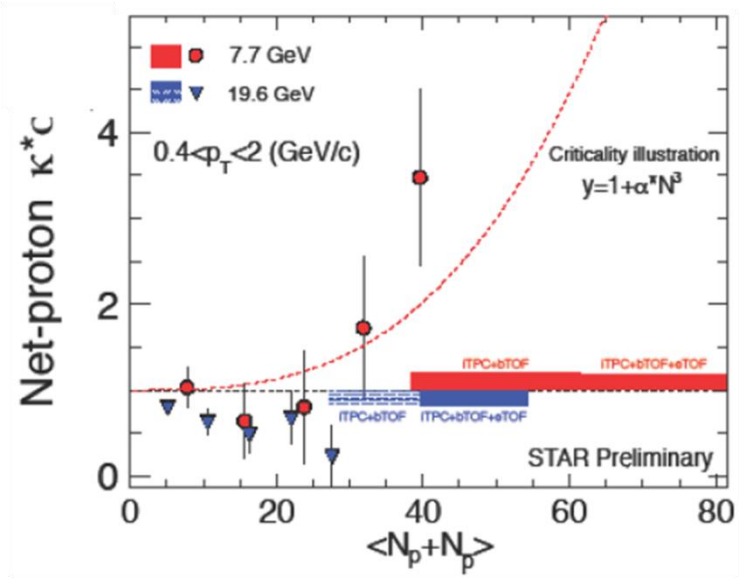


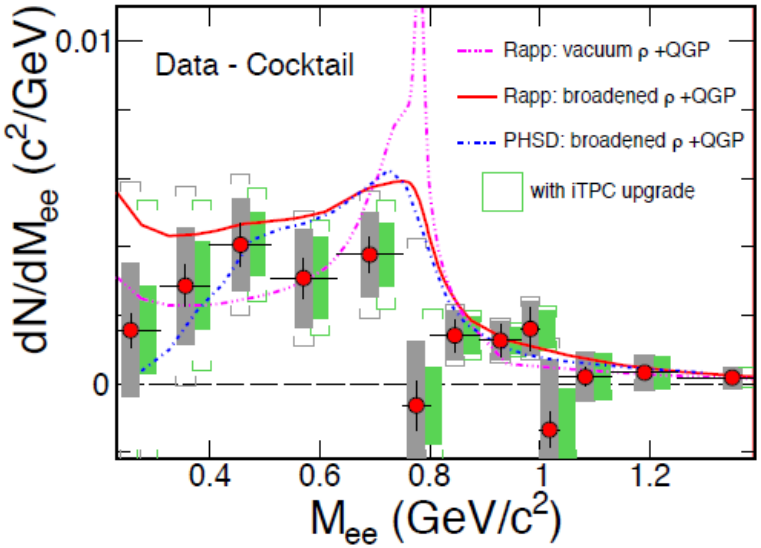






Improvements due to Upgrades





Conclusions

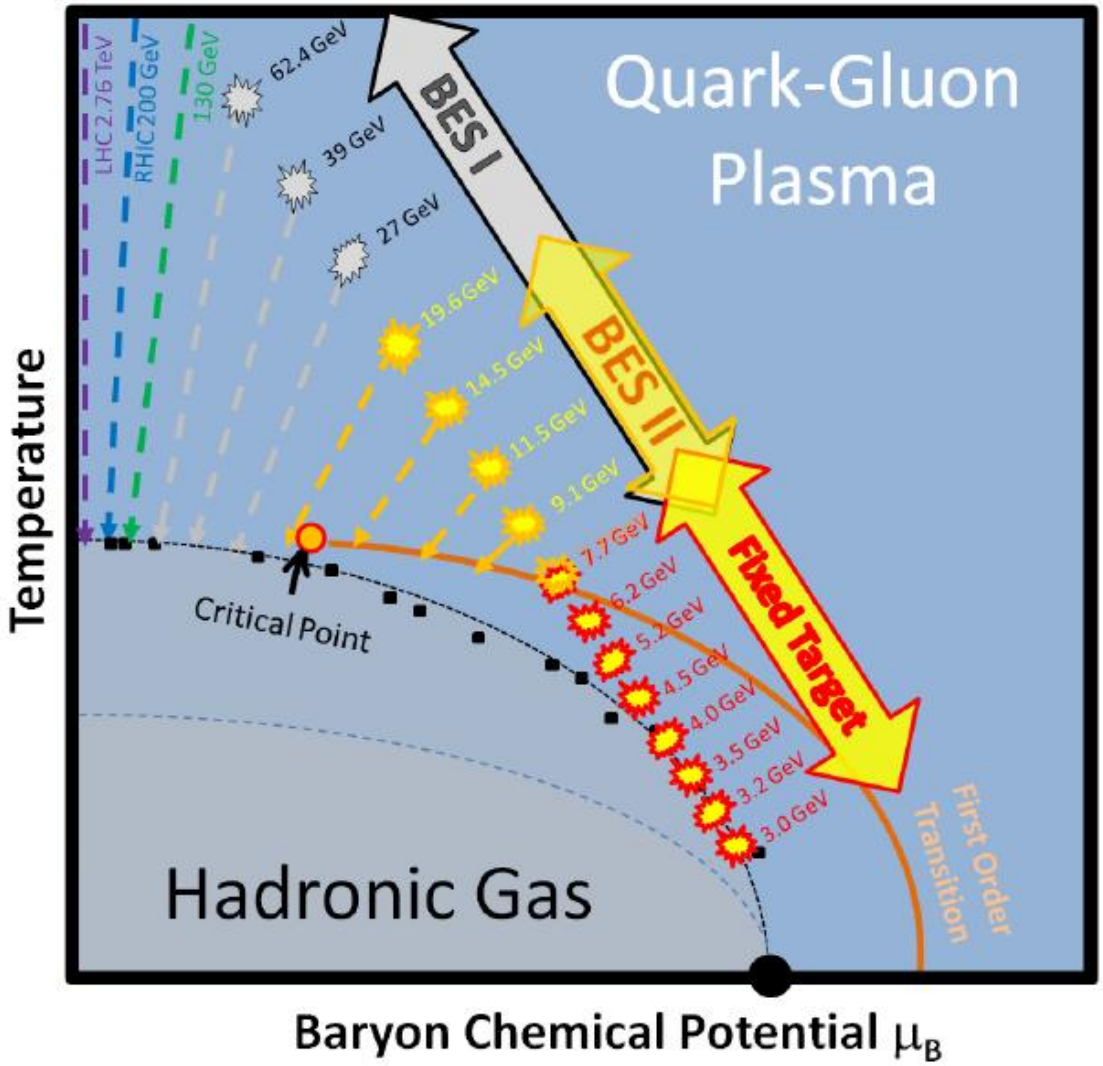
- There has been much progress in our understanding of the phase diagram of QCD matter.

- Data and Theory have both advanced and resolved some questions (T_C at $\mu_B = 0$)

- Open Questions: Is there a 1st order phase transition and a critical point?

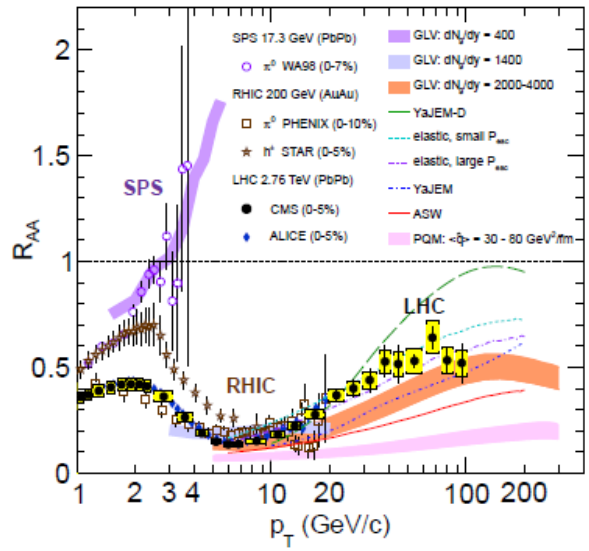
- BES-II and the BES-T Collaboration will complete a detailed and focused study

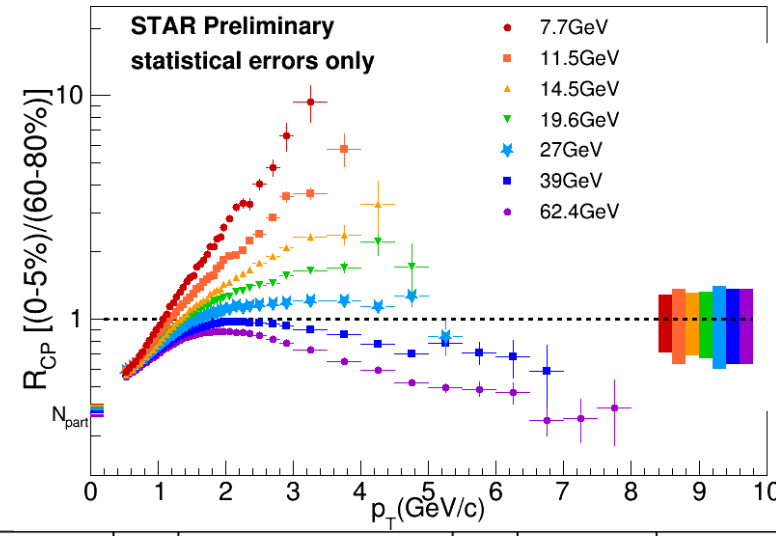
EXTRA SLIDES


Quark-Gluon Plasma
Hadronic Gas
BES I
BES II
Fixed Target
LHC 2.76 TeV
RHIC 200 GeV
130 GeV
62.4 GeV
39 GeV
27 GeV
19.6 GeV
14.5 GeV
11.5 GeV
9.1 GeV
7.7 GeV
6.2 GeV
5.2 GeV
4.5 GeV
4.0 GeV
3.5 GeV
3.2 GeV
3.0 GeV
Critical Point
First Order Transition
Temperature
Baryon Chemical Potential μ_B

Disappearance of QGP Signatures - R_{CP}

- R_{CP} for hadrons and for identified particles can provide a measure of partonic energy loss in the medium.
- Not sufficient reach to search for evidence of high p_T suppression below 19.6 GeV
- Stopped Baryons complicate inclusive R_{CP} measurements
- pQCD calculations show high p_T suppression
- Hybrid calculations describe the low p_T behavior

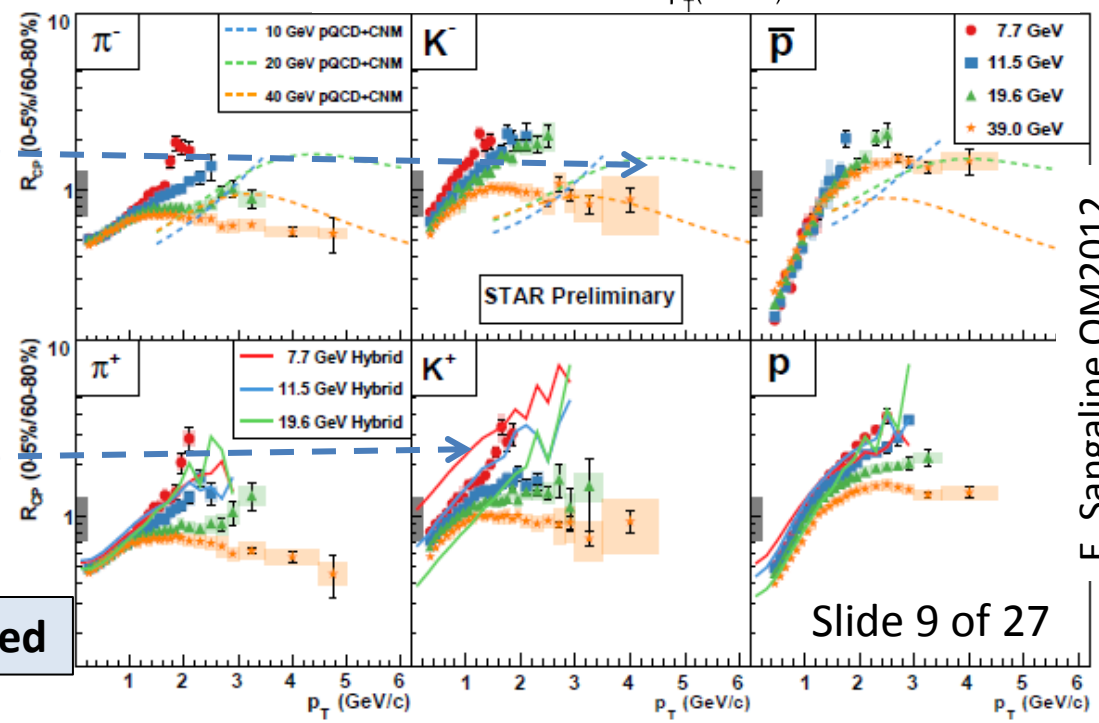




S. Horvat QM2015

pQCD calculations

Hybrid calculations



E. Sangaline QM2012

More p_T reach is needed

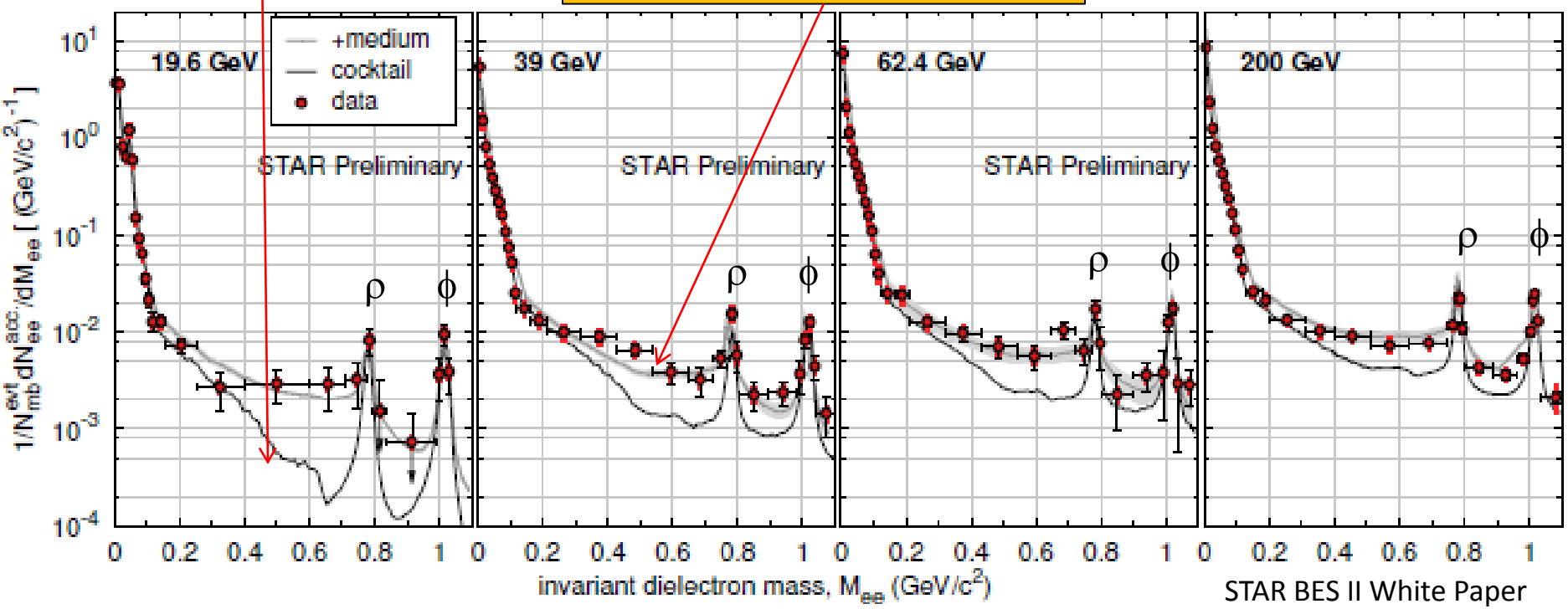
Chiral Phase Transition

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

Low Mass Region:
Black lines are the Cocktail (excluding the ρ meson)

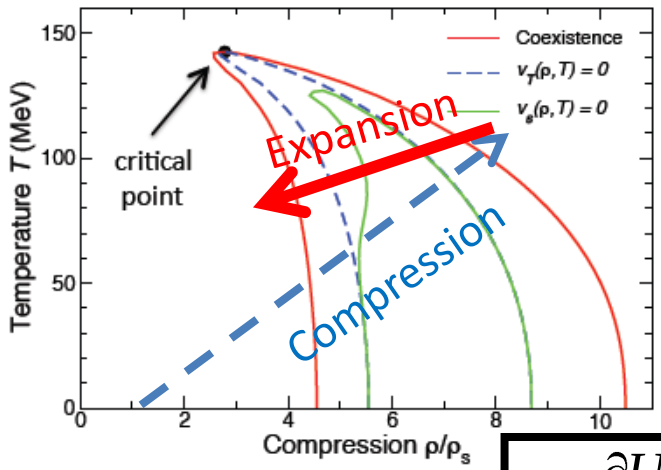
Grey lines are in medium calculations from R. Rapp which include both HG and QGP components (including medium broadened ρ meson). Model is able to match the data

Low Mass Region:
Emission depends on T, total baryon density, and lifetime



STAR BES II White Paper

Search for 1st Order Phase Transition – v_1

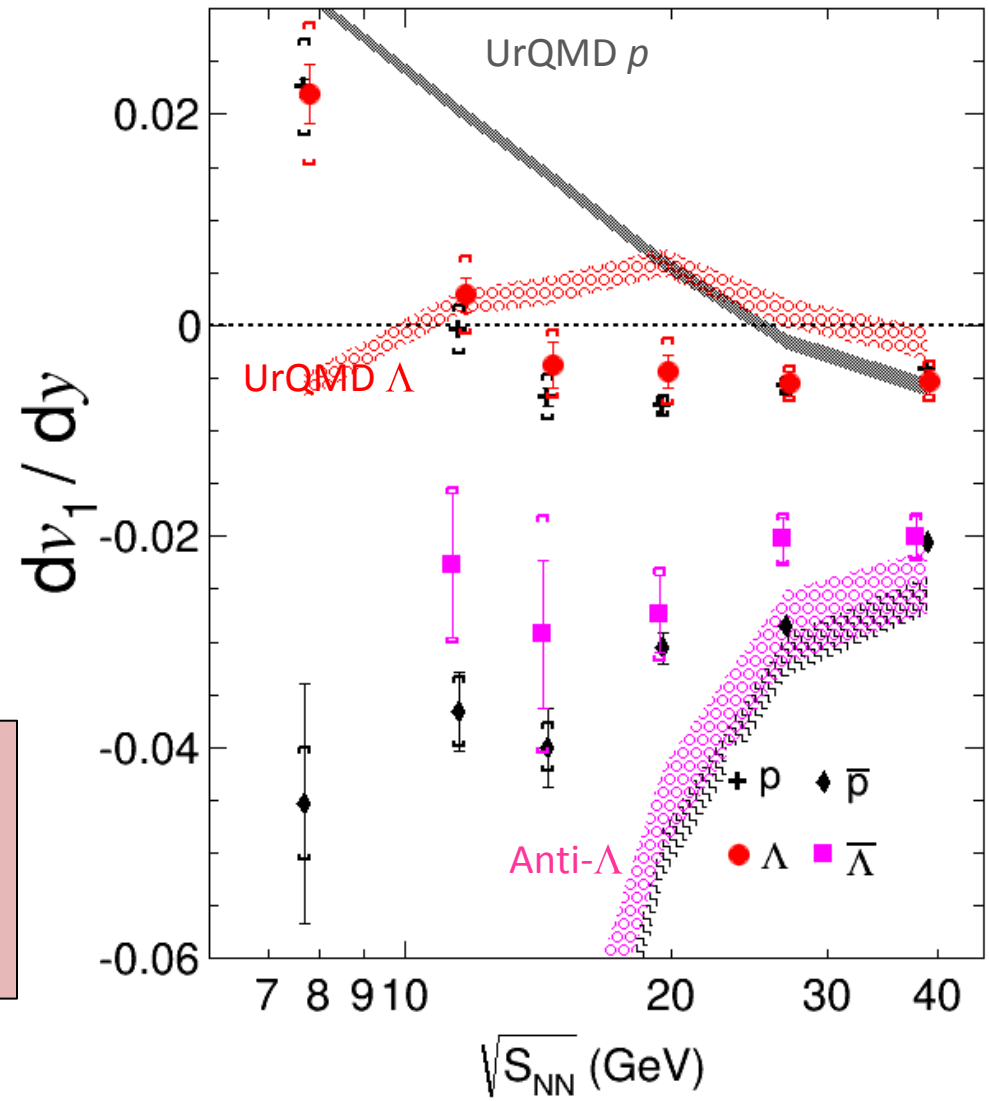


$v_T = 0$: isothermal spinodal

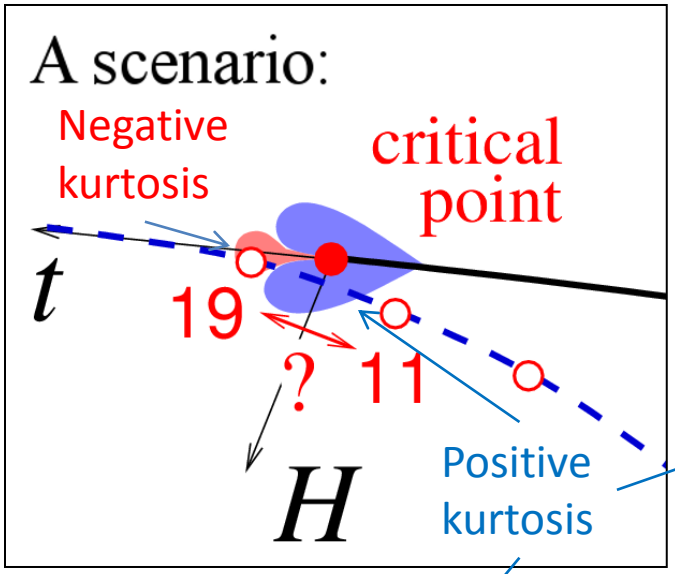
$v_s = 0$: isentropic spinodal

$$\mu = \frac{\partial U}{\partial N}$$

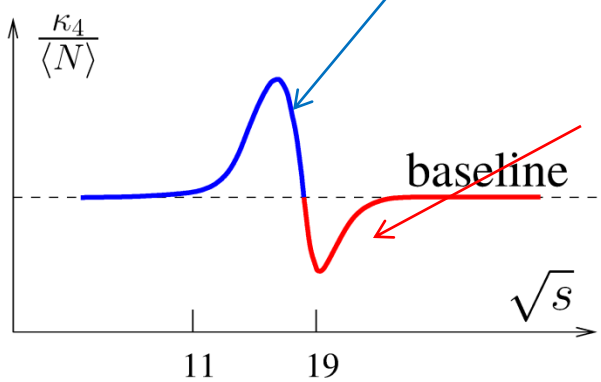
- First order phase transition is characterized by unstable coexistence region. This spinodal region will have the softest Equation of State
- v_1 is a manifestation of early pressure in the system



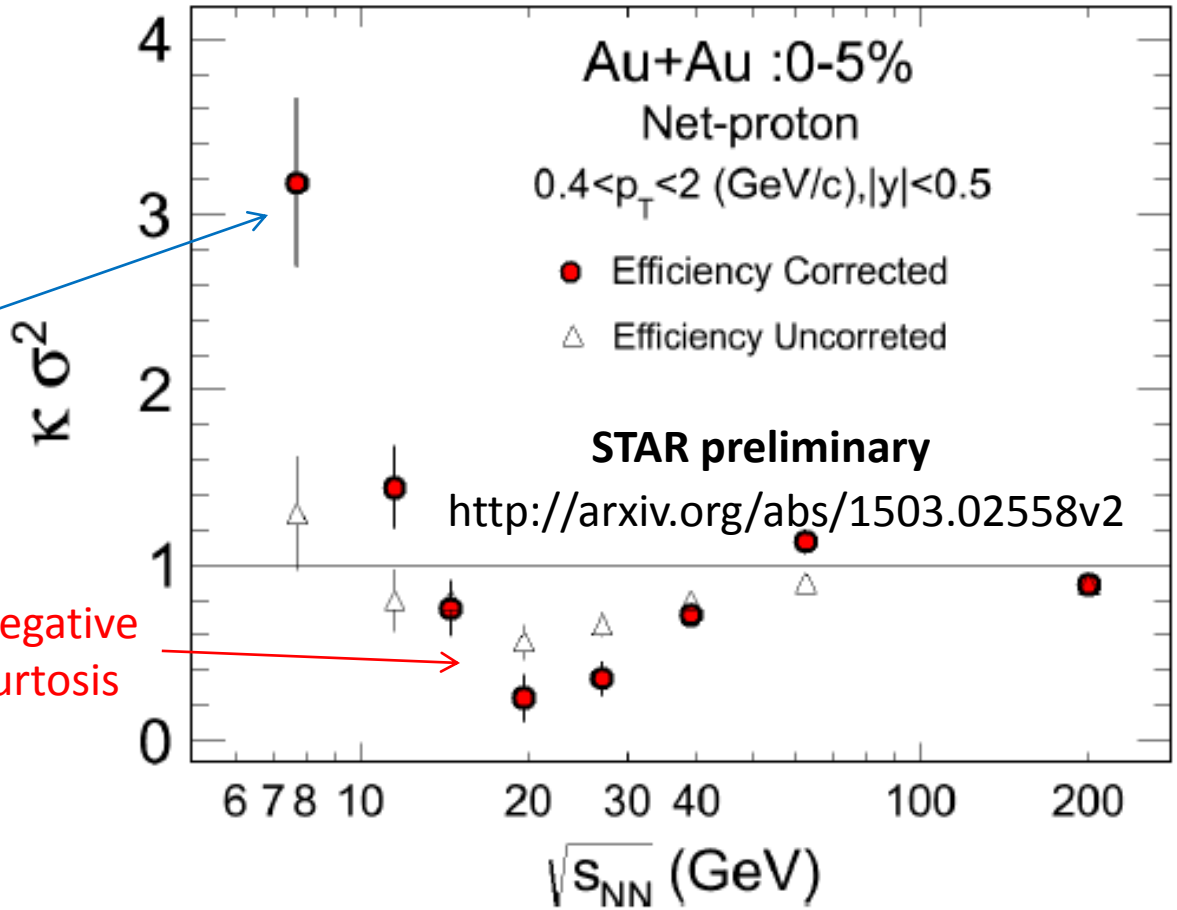
Search for the Critical Point – $\kappa\sigma^2$



M. Stephanov



STAR results show a fall and rise of the fluctuation variable



Negative kurtosis

BES Phase I – What have We Learned

- The BES at RHIC spans a range of μ_B that could contain features of the QCD phase diagram.

- Signatures consistent with a parton dominated regime either disappear, lose significance, or lose sufficient reach at the low energy region of the scan.

- Dilepton mass spectra show a broadening consistent with models including hadron gas and quark-gluon plasma components

- There are indicators pointing towards a softening of the equation of state which can be interpreted as evidence for a first order phase transition.

- The higher moment fluctuation is sensitive to critical phenomena, but these analyses place stringent demands on the statistics.

BES Phase II Proposal

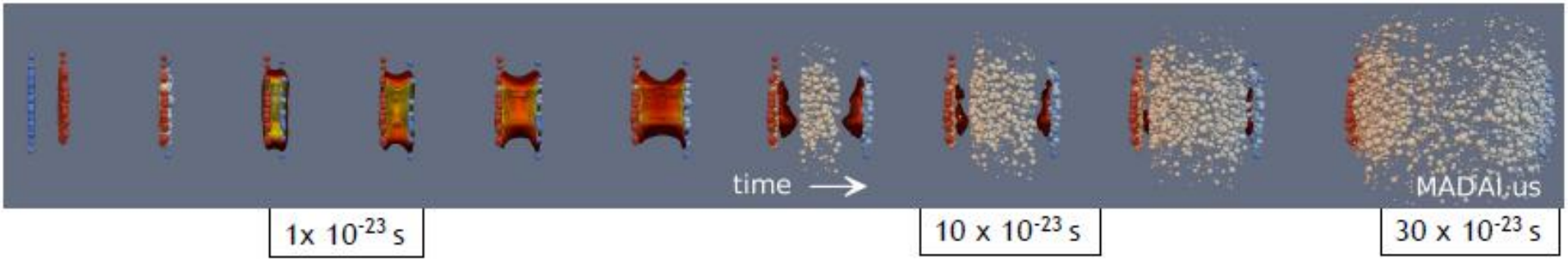
BES Phase II is planned for two 24 cryo-week runs in 2019 and 2020

$\sqrt{S_{NN}}$ (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV)	420	370	315	250	205
BES I (MEvts)	4.3	---	11.7	24	36
Rate(MEvts/day)	0.25		1.7	2.4	4.5
BES I $\mathcal{L}$ (1×10^{25}/cm^{2}sec)	0.13		1.5	2.1	4.0
BES II (MEvts)	100	160	230	300	400
eCooling (Factor)	4	4	4	3	3
Beam Time (weeks)	**12**	**9.5**	**5.0**	**5.5**	**4.5**

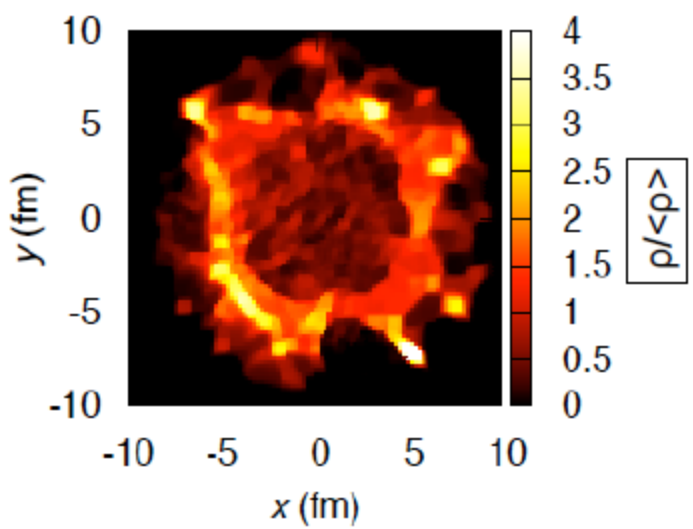
Revised estimates

Creating Little Bangs in the Laboratory

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

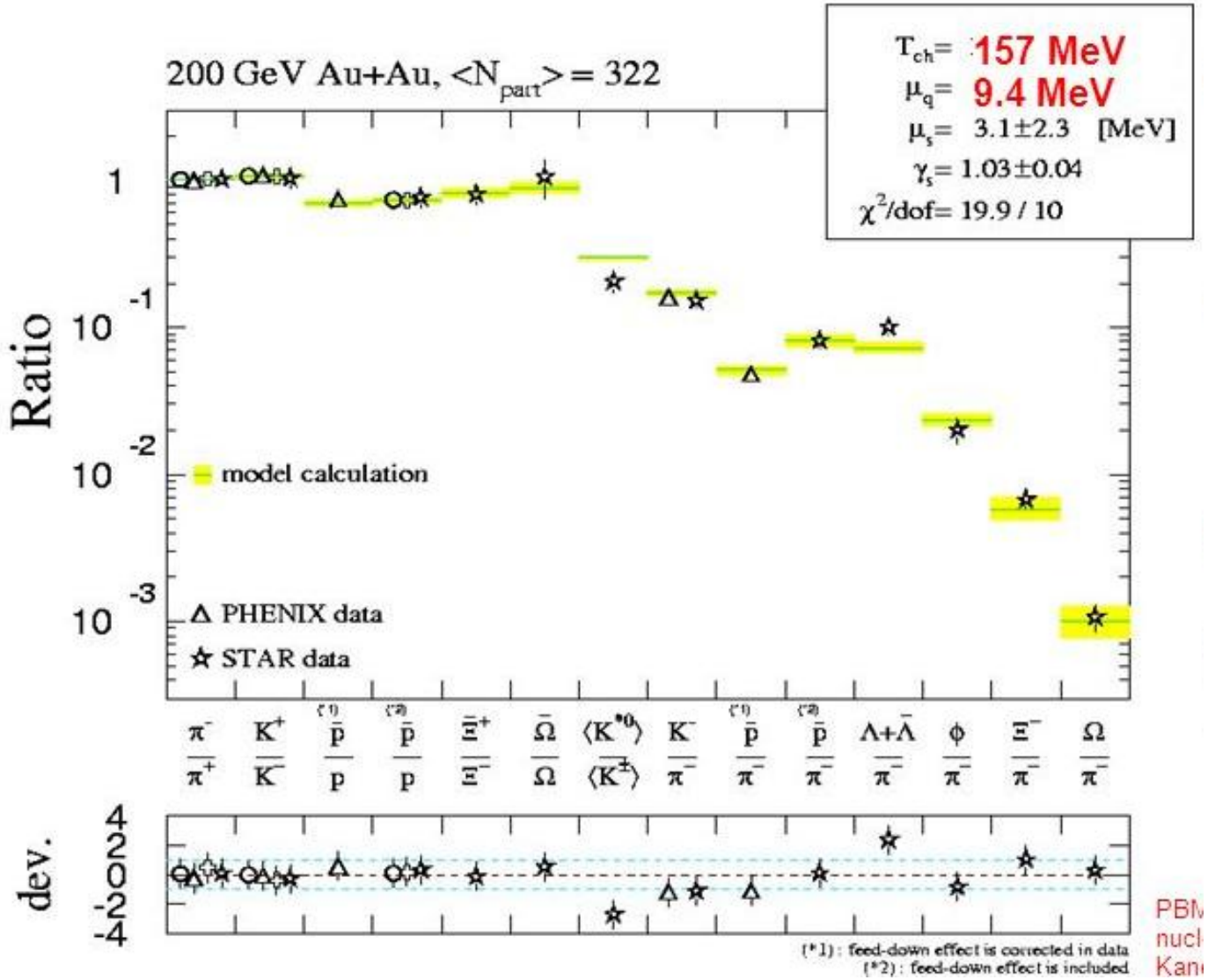


Chiral fluid dynamics



Herold, Nahrgang et al, Nucl.Phys. A925 (2014) 14-24

- Rapid thermalization during compression
- Local equilibrium in Quark-Gluon Plasma
- Cooling during Hubble-type expansion
- Hadronization at phase transition
- Continued cooling through elastic scattering
- Kinetic freeze-out


200 GeV Au+Au, <N_part> = 322
T_ch= 157 MeV
μ_q= 9.4 MeV
μ_s= 3.1±2.3 [MeV]
γ_s= 1.03±0.04
χ²/dof= 19.9 / 10
Ratio
model calculation
PHENIX data
STAR data
dev.
(*1) : feed-down effect is corrected in data
(*2) : feed-down effect is included