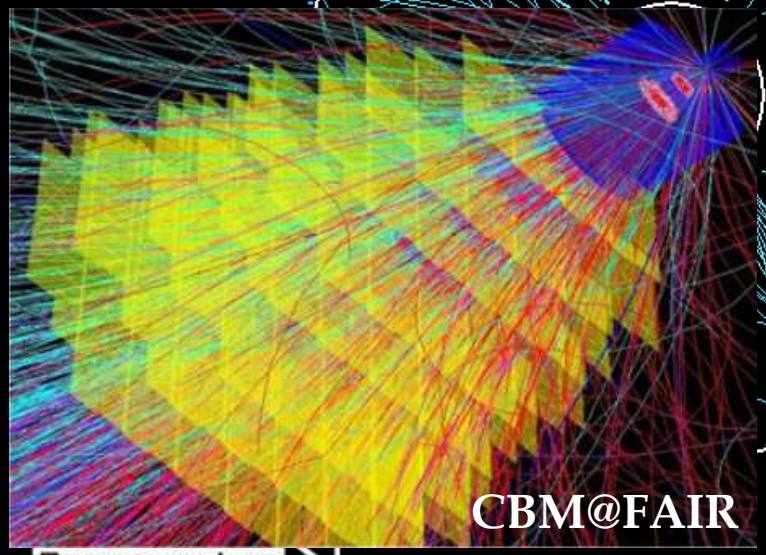
Physics at High Baryon Densities



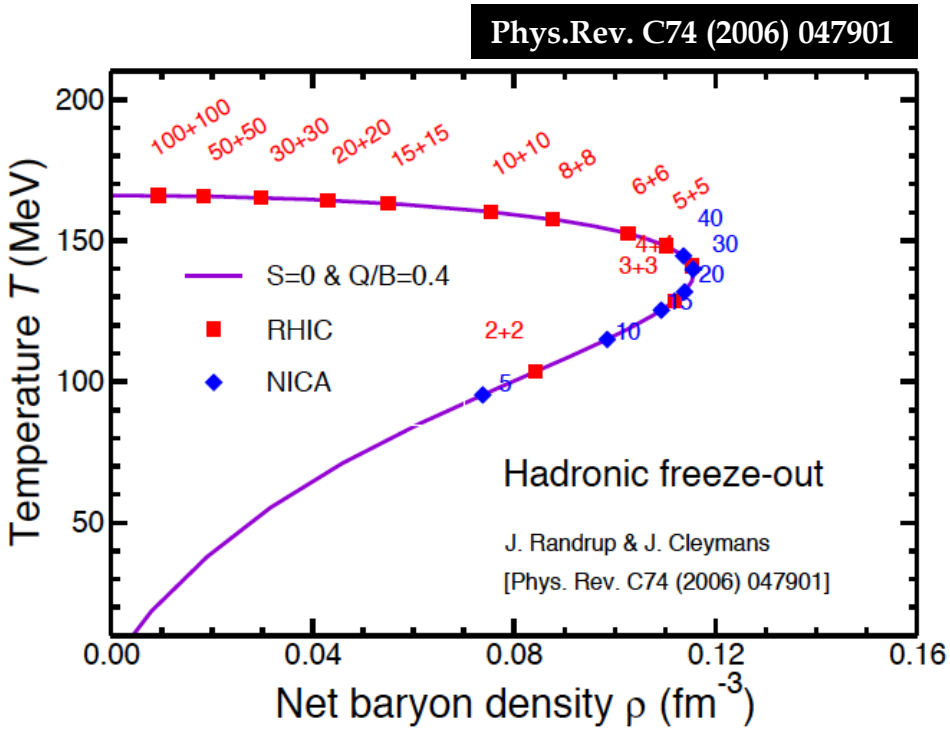
Alexander Schmah
Lawrence Berkeley National Lab
International Conference on Science and Technology for FAIR in Europe 2014

BERKELEY LAB

U.S. DEPARTMENT OF ENERGY

Outline

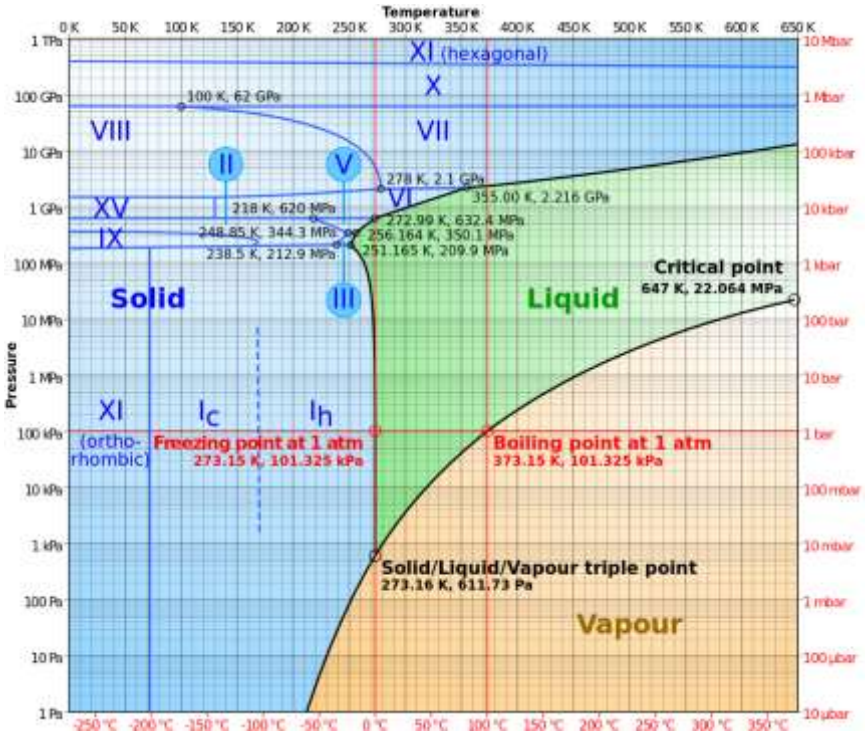
- Introduction to the physics at high baryon densities
- Some selected highlights from running experiments
- Conclusions and why we need to focus on lower energies



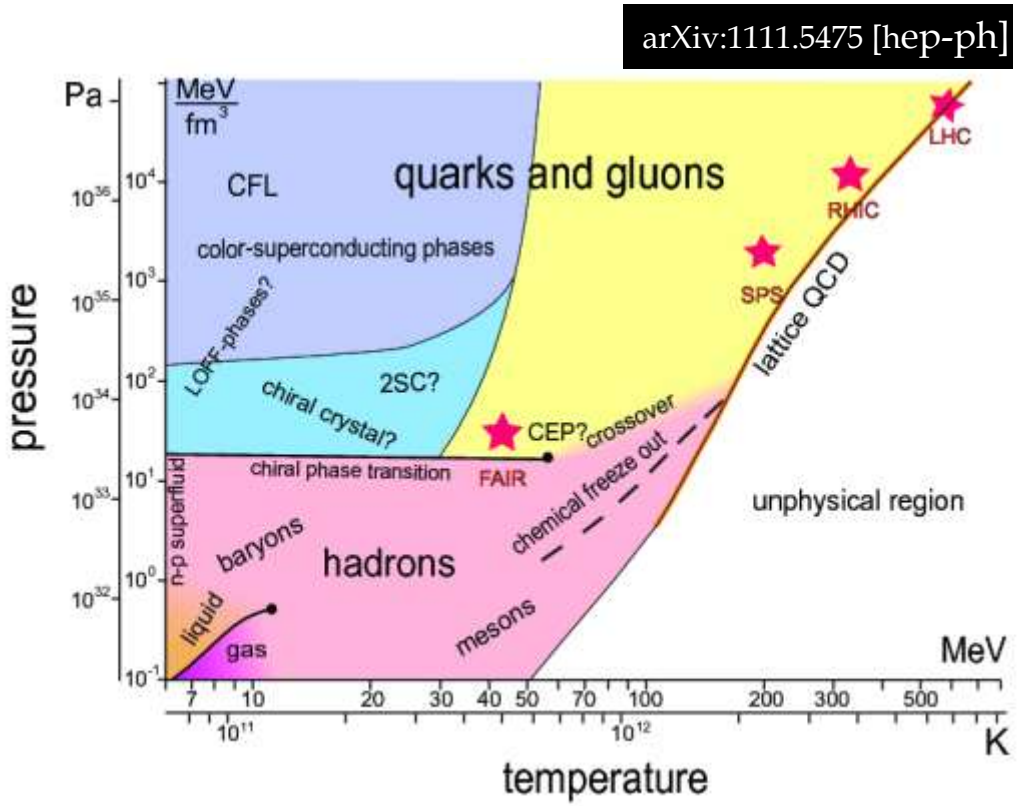
→ **Compressed Baryonic Matter!**
→ **Highest density at freeze-out at ~ $\sqrt{s_{NN}}$ = 8 GeV**

Basic Motivation: Phase Diagrams

Water (Electromagnetism)



Quark Matter (QCD)



- Can we establish/study a QCD phase diagram with

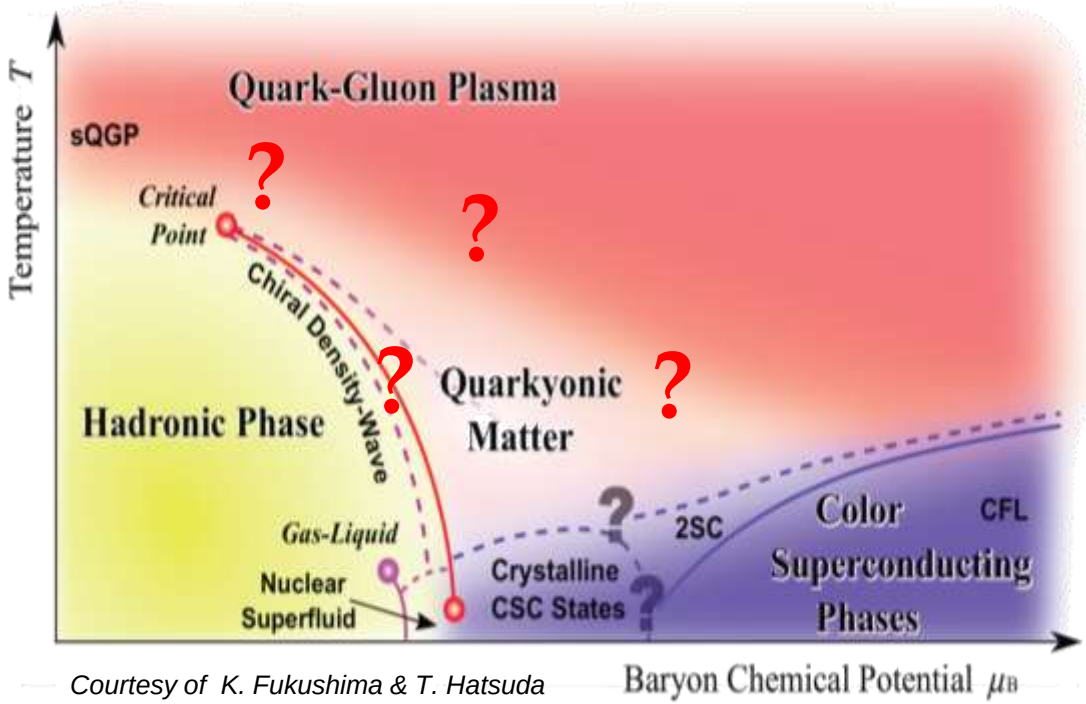
1. Phase transitions?
2. Critical point?
3. Other phases of matter, e.g. Quarkyonic?

The QCD Phase Diagram

Basic motivation: Exploration of the QCD phase diagram

- 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)
- Chiral symmetry restoration?
  → Di-leptons
- Quarkyonic matter?
  → ???

Rept.Prog.Phys. 74 (2011)

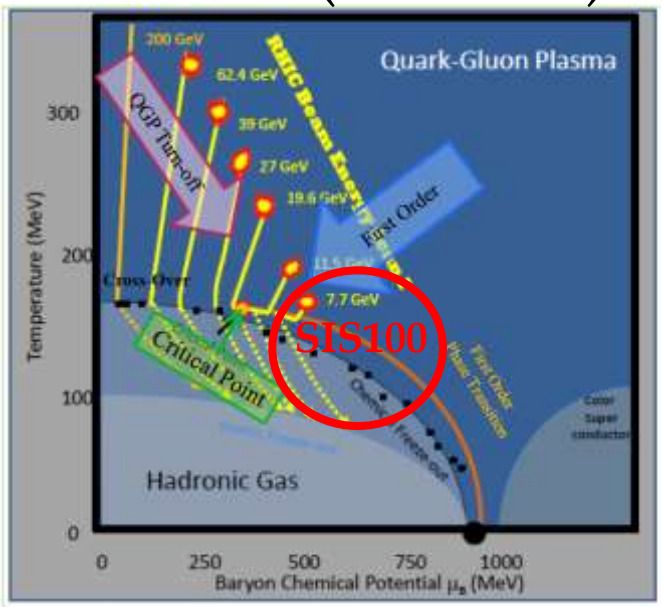


Courtesy of K. Fukushima & T. Hatsuda

? QCD critical point
? QCD phase transition
? Quarkyionic matter
? QGP phase

The Beam Energy Scan Programs

RHIC (Collider)

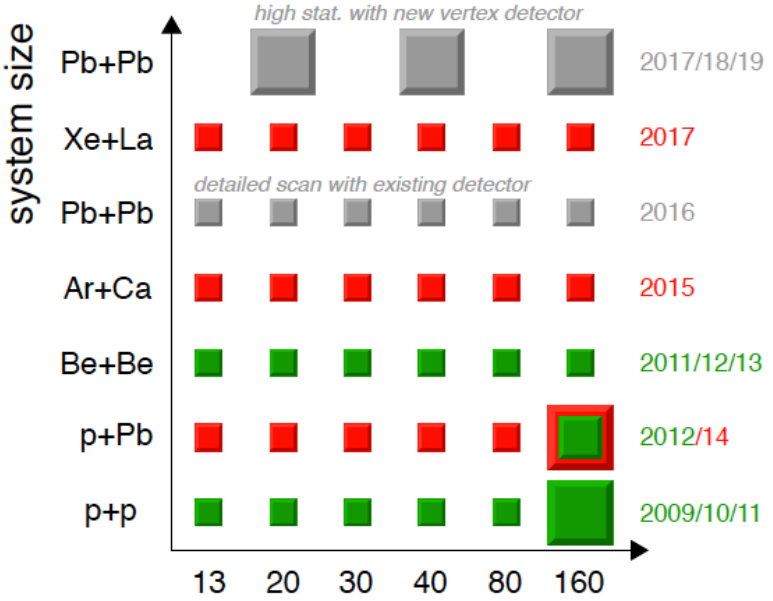


D. Cebra

$\sqrt{s_{NN}}$ (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

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

SPS (Fixed target)



$\sqrt{s_{NN}}$ = 5-17 GeV

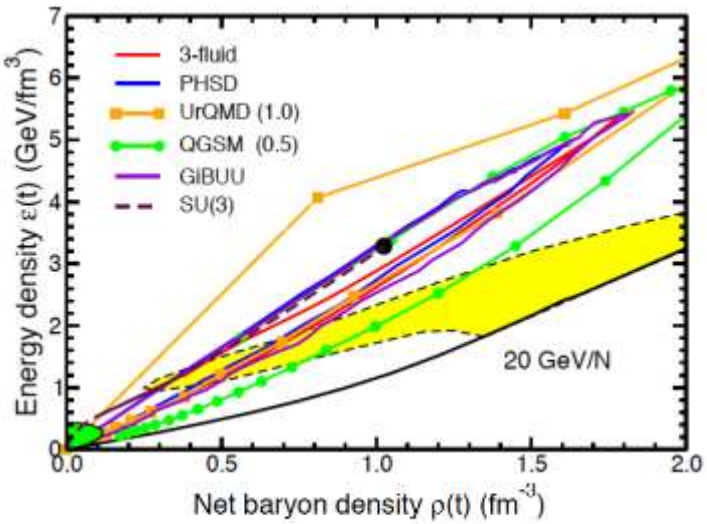
- Two dimensional scan in energy and system size
  → Criticality

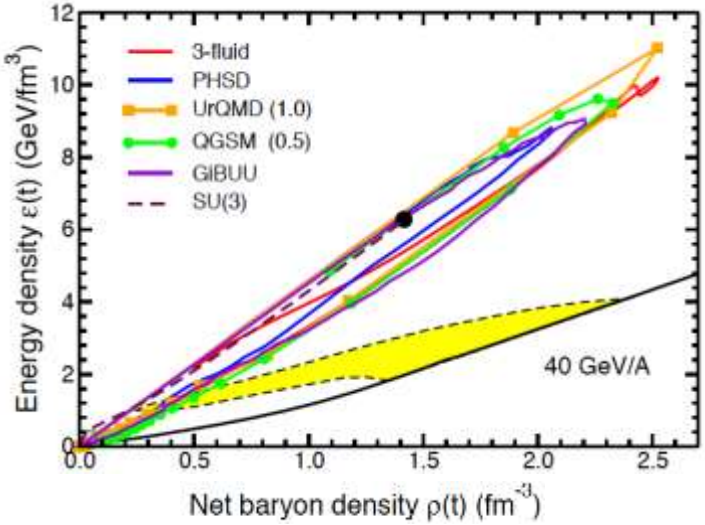
- p+p and p+Pb reference runs

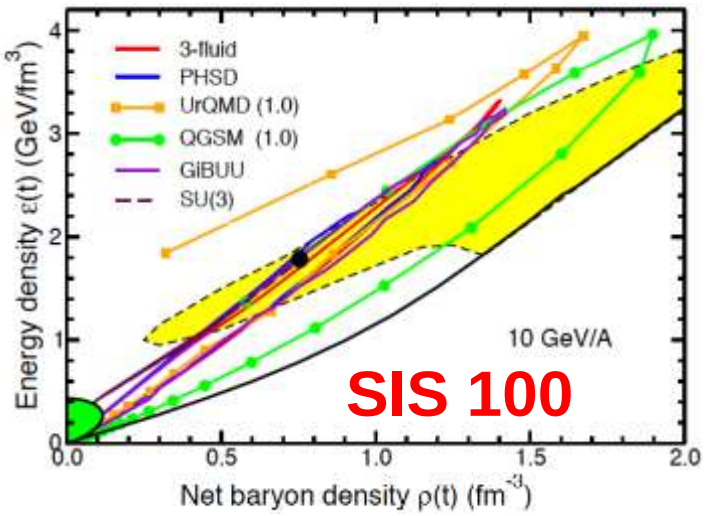
Anar Rustamov → yesterday

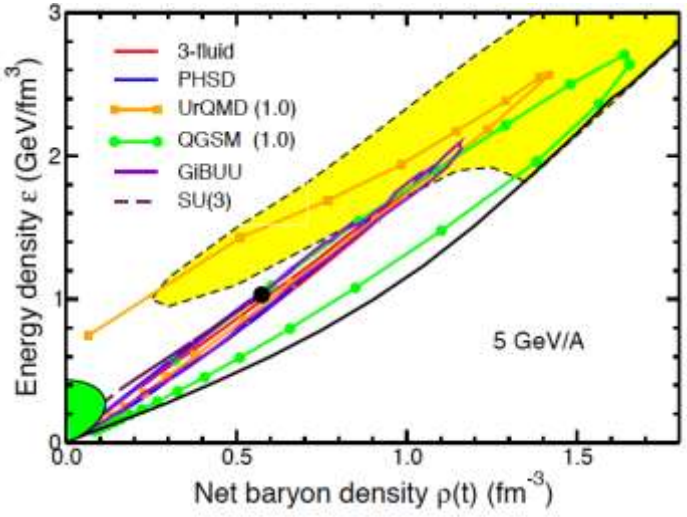
Phase Space Trajectories

Phys.Rev. C75 (2007) 034902





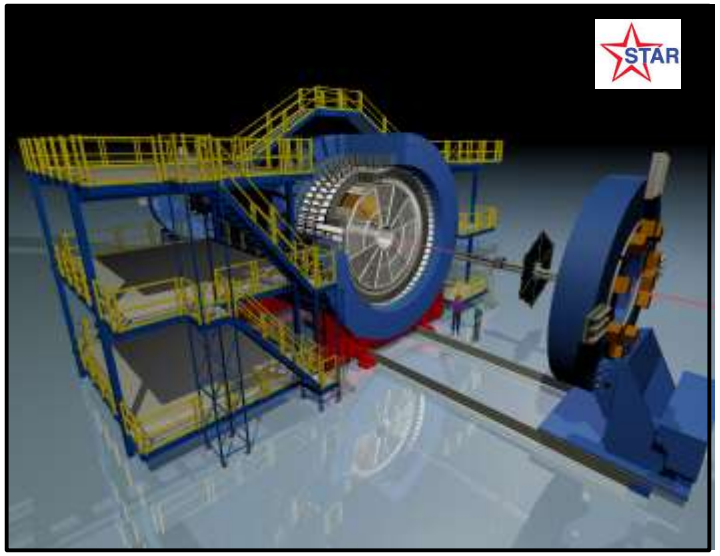




- Coexistence region not reached at energies < 5 GeV/A
- Optimal test of phase transition region at SIS100 energies!

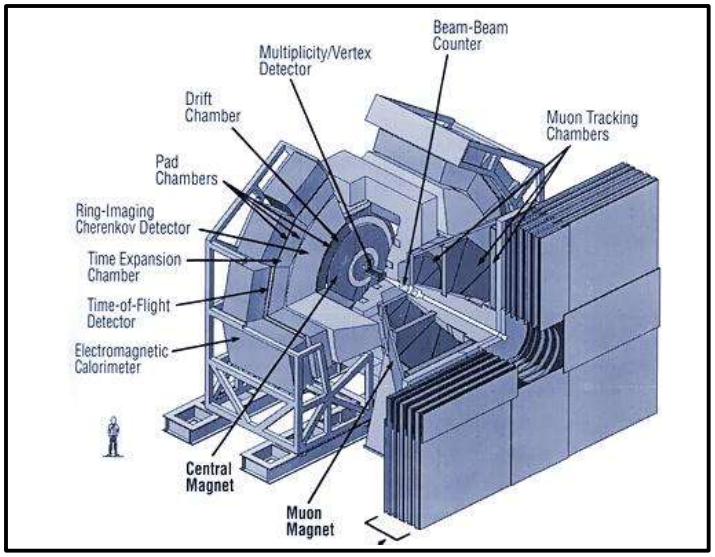
Present Experiments

STAR



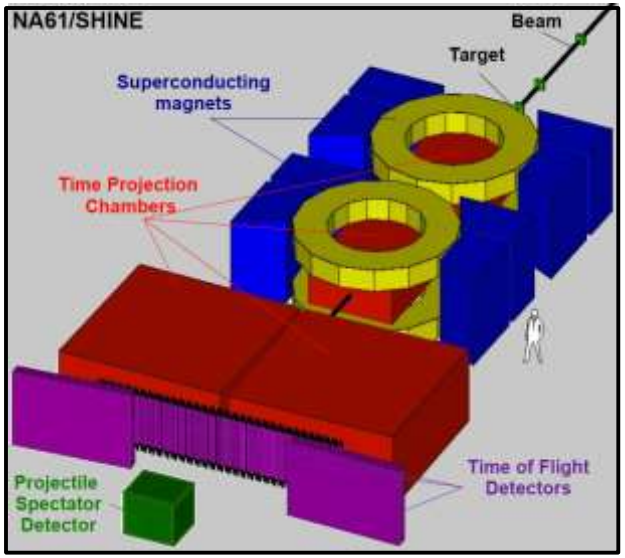
- $7.7 < \sqrt{s_{NN}} < 200$ GeV
- Excellent PID
- Full azimuthal coverage
- Energy scan started: 2010

PHENIX



- $7.7 < \sqrt{s_{NN}} < 200$ GeV
- High granularity calorimeter
- Energy scan started: 2010

NA61/SHINE

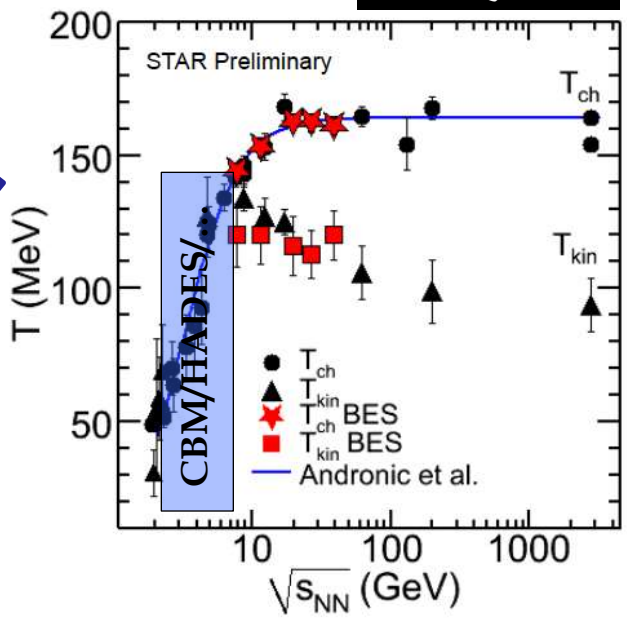


- $\sqrt{s_{NN}}$ = 5-17 GeV
- Full forward ToF
- Energy scan started: 2009

Relatively low statistics at lowest energies (~ few million events)
→Focus mainly on bulk observables
→ For rare probes and lower energies CBM/HADES/NA60+/MPD is needed!

Freeze-Out Systematics

STAR QM 2014



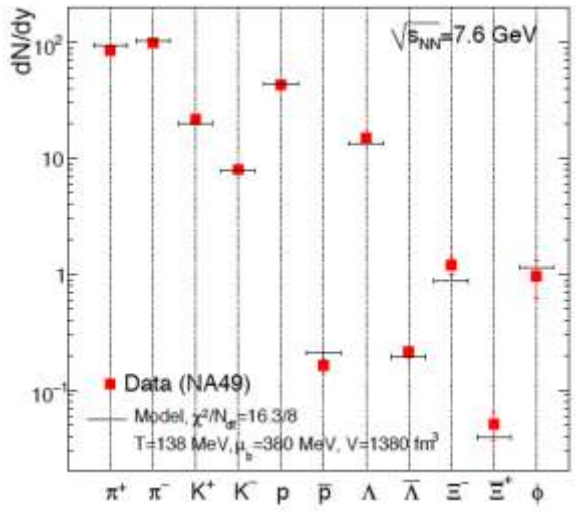
$T_{chemical}$: Statistical hadronization model

Where are we in the phase diagram?

- Saturation of T_{chem} above ~10 GeV
- Splitting between T_{chem} and T_{kin} starts at ~6 GeV

- Connected to a phase change?

Phys.Lett. B673 (2009), 142-145

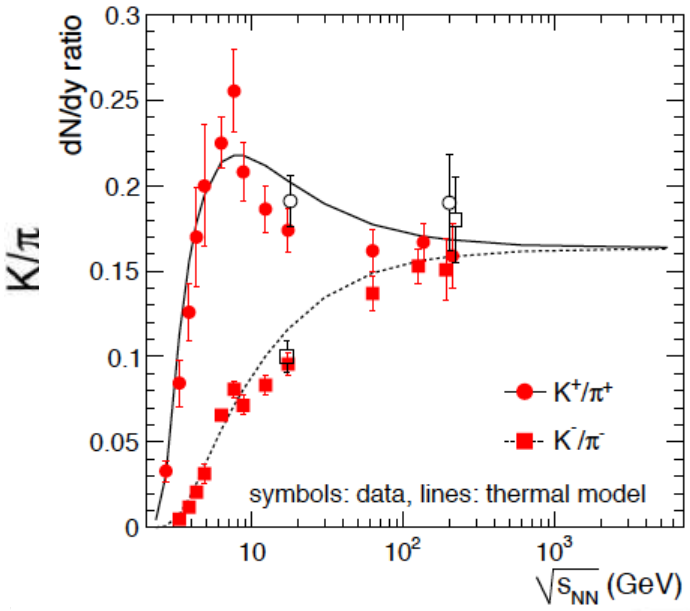


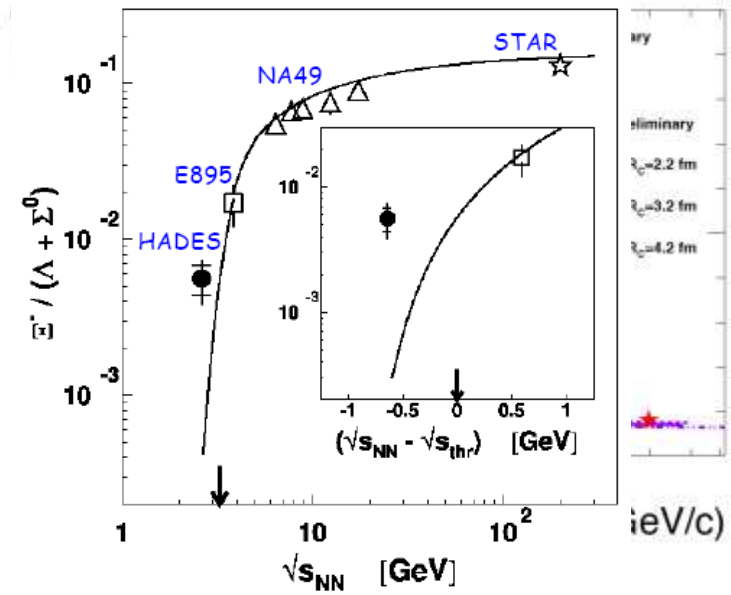
- Maximum baryon density reached at ~8 GeV
  → pions processes become more important

Lattice chemical freeze-out parameters:
S. Mukherjee. arXiv:1211.7048 [nucl-th]
A. Bazavov et al., Phys. Rev. Lett. 109,192302 (2012)
S. Borsanyi et al., Phys. Rev. Lett. 111, 062005 (2013)

Energy Dependence of Particle Ratios

J.Phys. G38 (2011) 124081





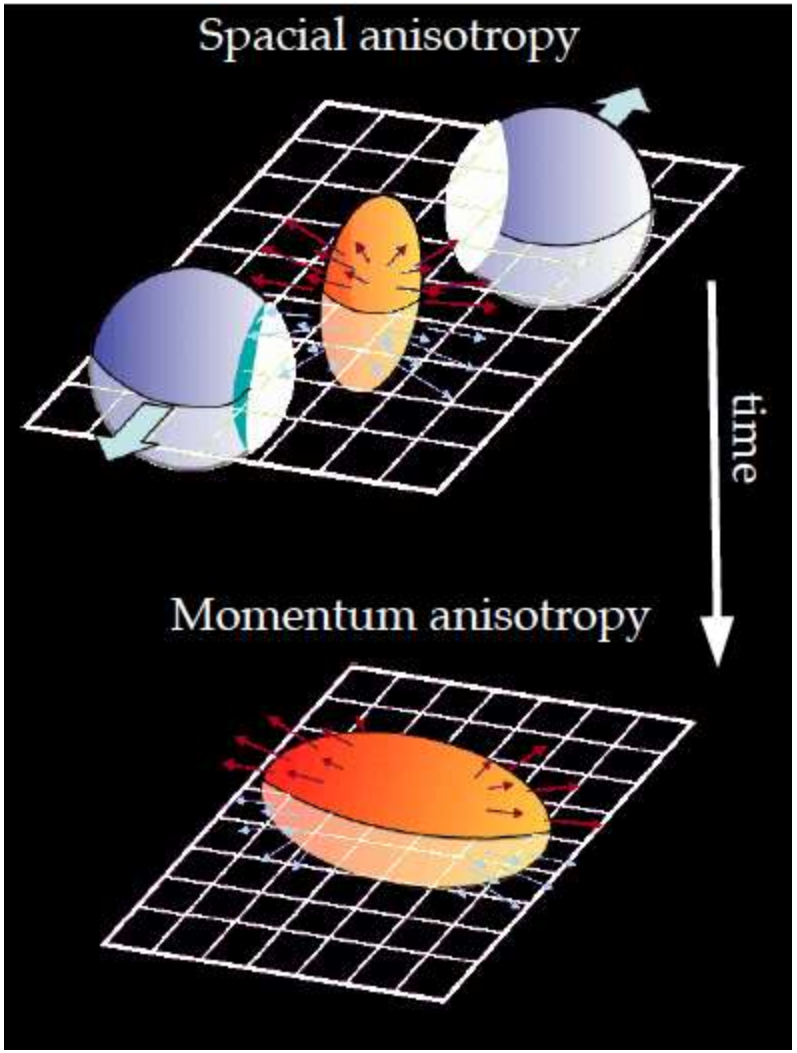
- Pronounced structures in particle ratios at ~ 5-10 GeV
  → indications for a phase transition?

- Net-baryon density has a maximum at ~ $\sqrt{s_{NN}}$ ~ 8 GeV at freeze-out (Λ/π)
  + Associate production channels like N+N → N + Λ + K^+
- Canonical strangeness suppression at low energies?
- Statistical hadronization model can describe the various structures, **EXCEPT** multi=strange particles
  → Ξ
  → What about Ω?

HADES, QM 2014

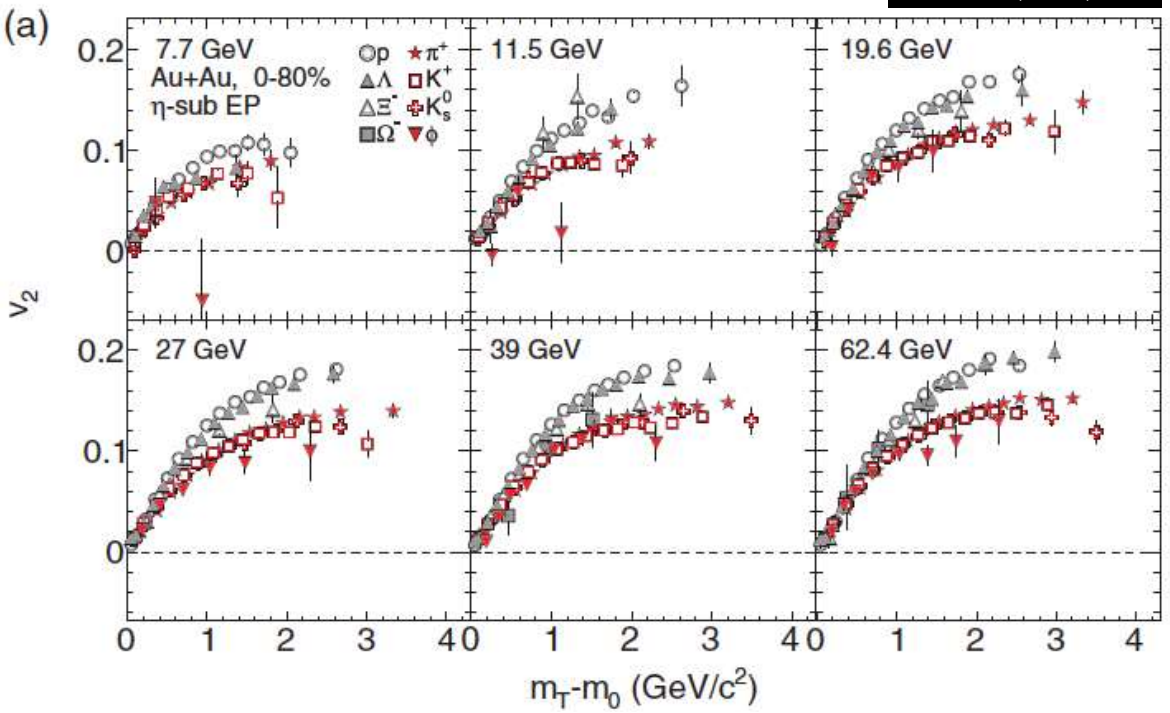
Hwa & Yang, Phys. Rev. C 75, 054904 (2007)

Collective Behavior



Hydrodynamic evolution

Phys. Rev. C 88, 014902 (2013)

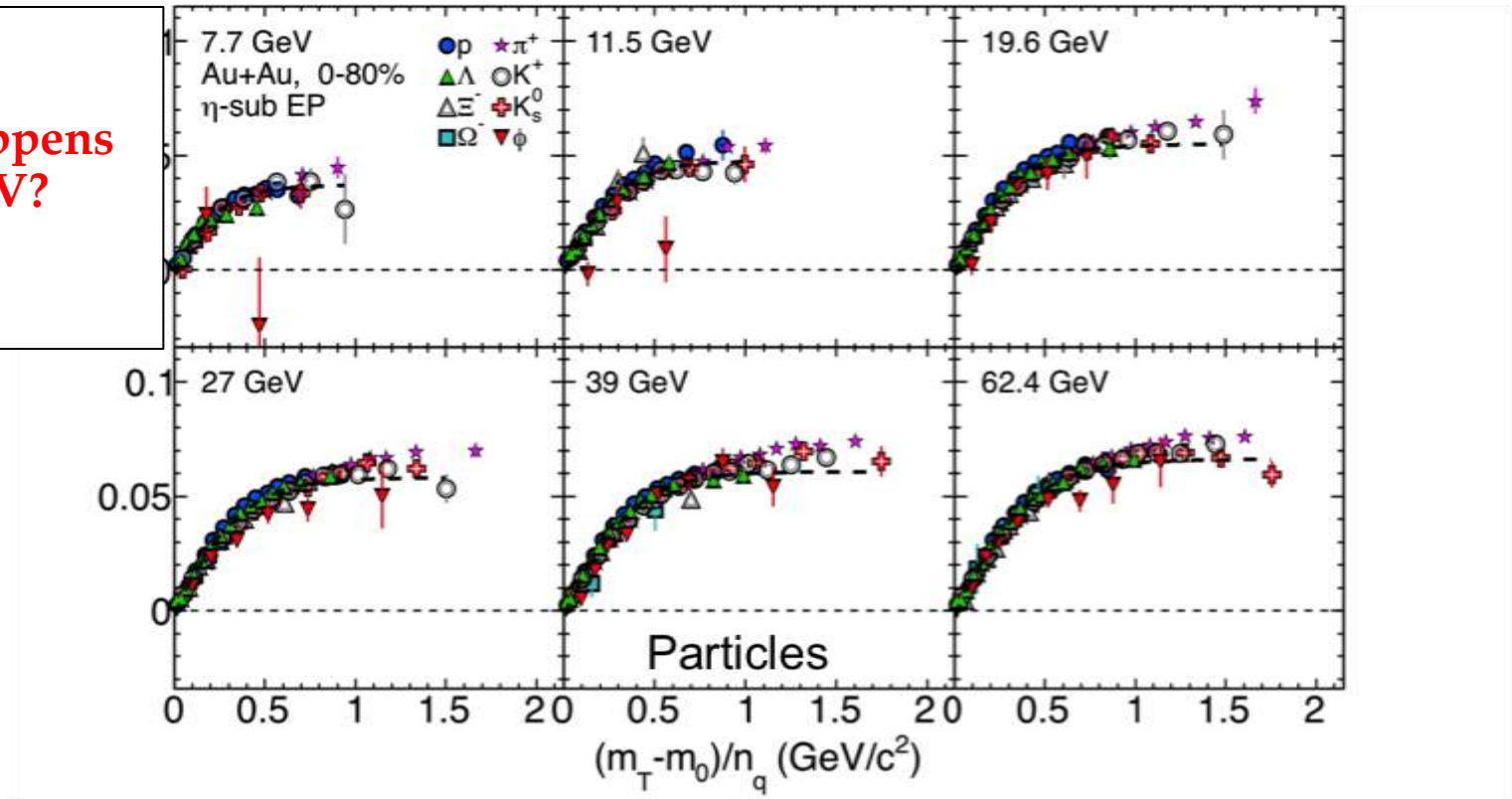


- v_2 is strength of correlation with event plane
- Baryon-**meson** splitting
  → signature for partonic degrees of freedom?
- This signature should go away in a hadronic environment
  → **SIS 100 energies**
  → **QGP at < 8 GeV?**

v_2 NCQ Scaling of Particles

Phys. Rev. C 88, 014902 (2013)

What happens at 2-8 GeV?



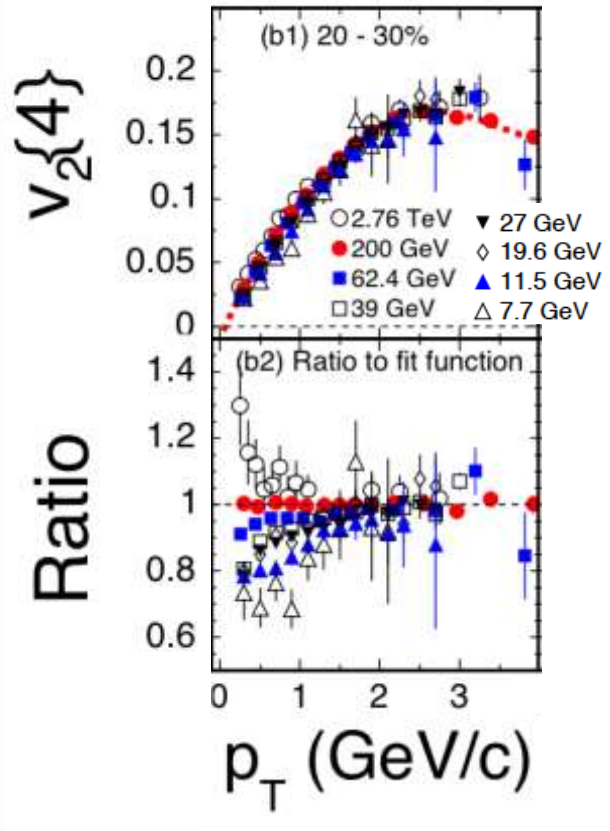
- NCQ-scaling holds for particles and anti-particles separately at all energies → Partonic degrees of freedom?

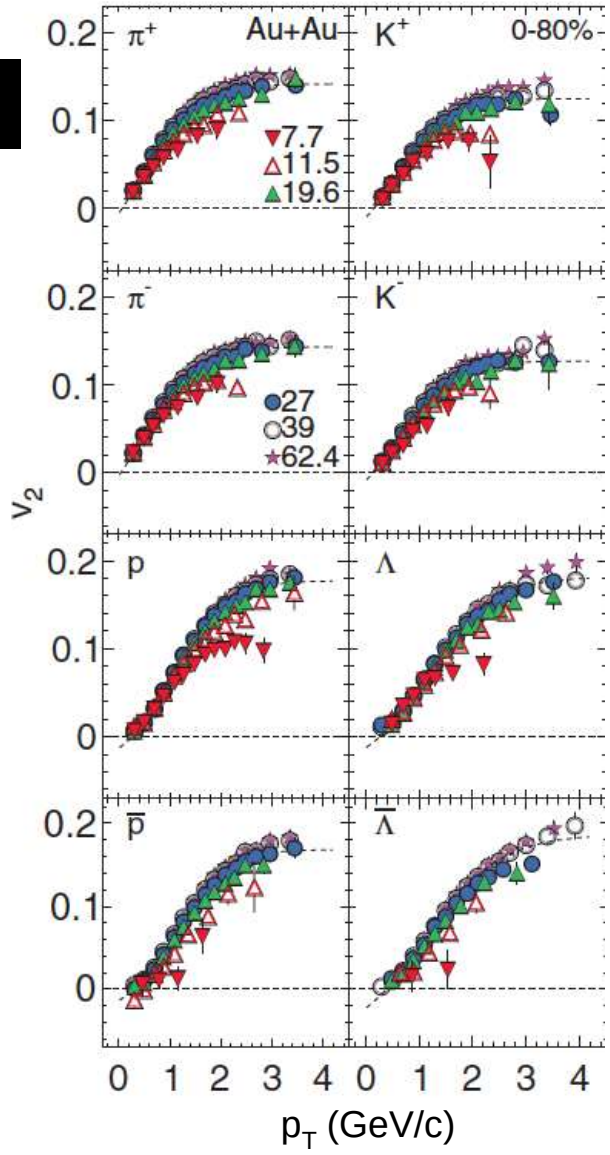
NCQ = Number of Constituent Quark

- High m_T-m_0 not measured at lower energies
- Do ϕ-mesons or multi-strange particles deviate?
- NCQ scaling should break down at even lower energies (2-5 GeV)!

Energy Dependence of Elliptic Flow (v_2)

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





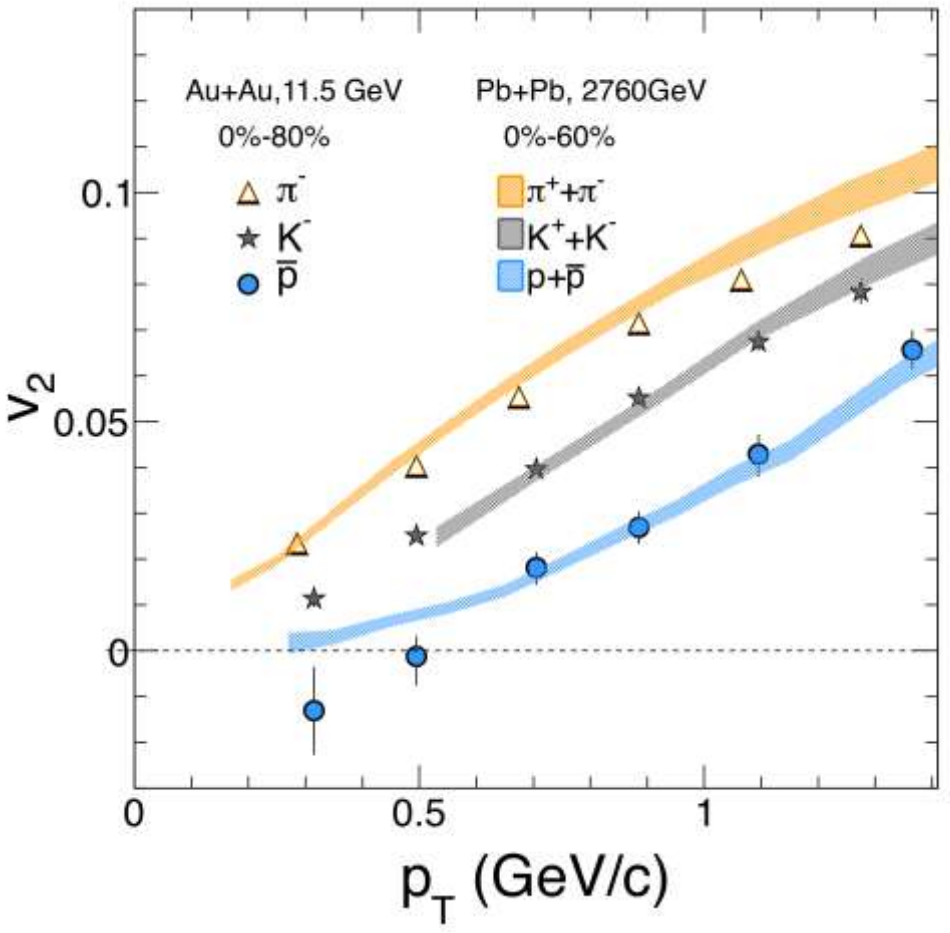
- Large (similar) collectivity at all energies?

- But particle composition changes with energy!
  → v_2 increases for every particle
- What about rare particles at low energies?
- Conclusions for hydro, η/s?
- What happens at 3-8 GeV?

Phys. Rev. C 88, 014902 (2013)

What is going on with Flow?

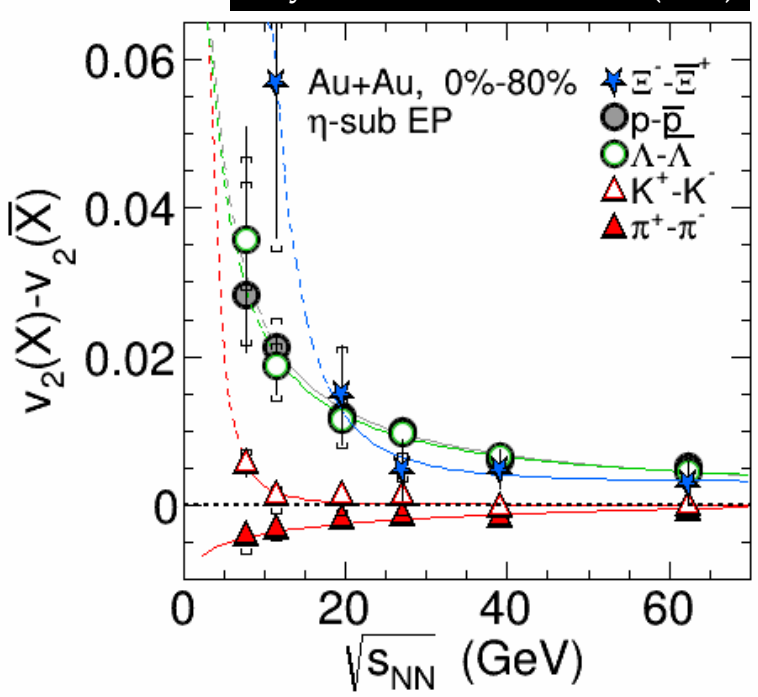
STAR: Phys. Rev. C 88, 014902 (2013)
ALICE: arXiv:1405.4632



- Anti-particle v_2 at low energies (SIS100/300 regime) seems to be very similar to v_2 at LHC energies ($\sqrt{s_{NN}}$ = 2760 GeV)!
- More detailed studies at energies below $\sqrt{s_{NN}}$ = 11.5 GeV are needed

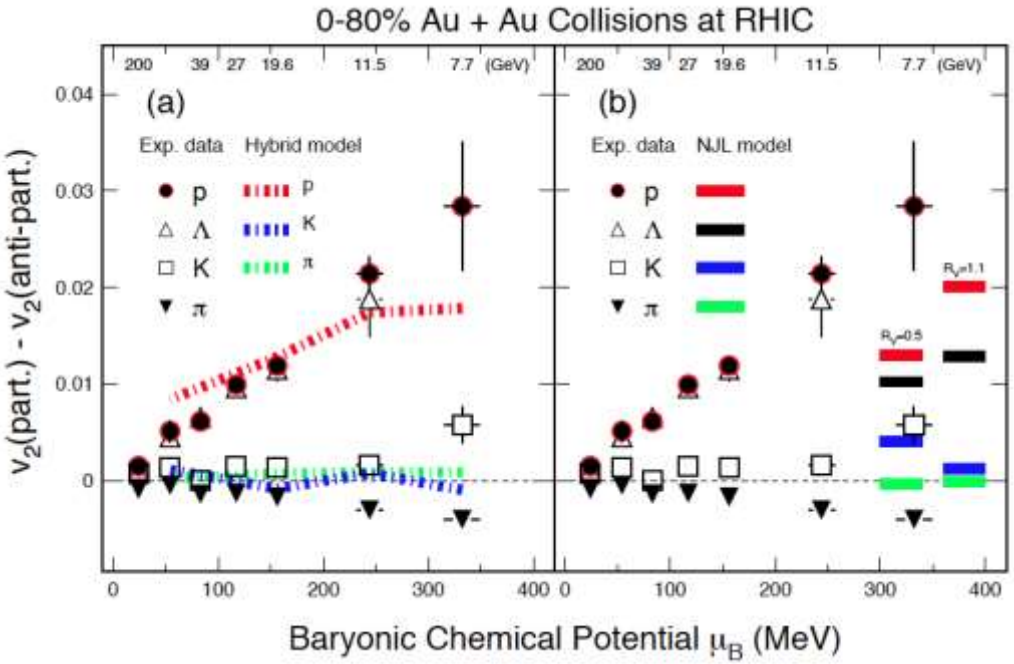
Δv_2 vs. $\sqrt{s_{NN}}$: Comparison with Theory

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



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

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

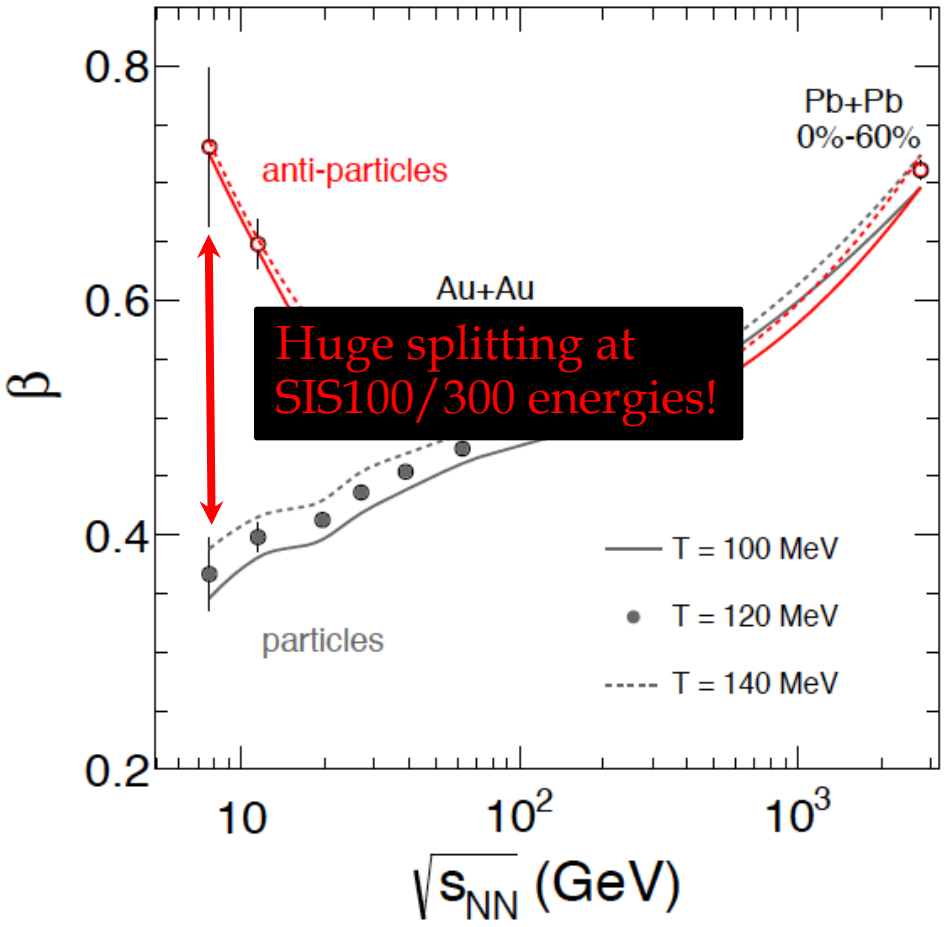


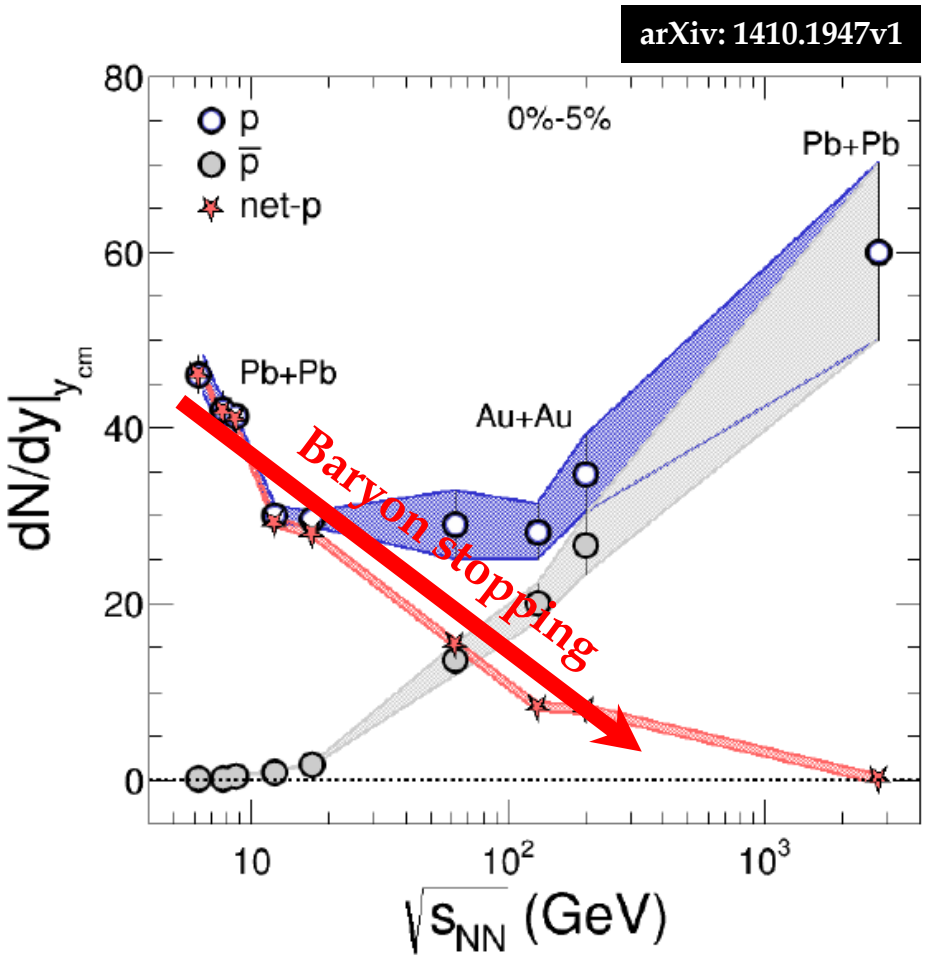
- Hydro model: Hybrid model (UrQMD + hydro) with baryon stopping
- Nambu-Jona-Lasinio (NJL): Using vector mean-field potential, repulsive for quarks, attractive for anti-quarks

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

- Good agreement of hybrid-hydro model with data
  → Mainly baryon stopping?
- What happens at even lower energies?

Radial Expansion Velocity



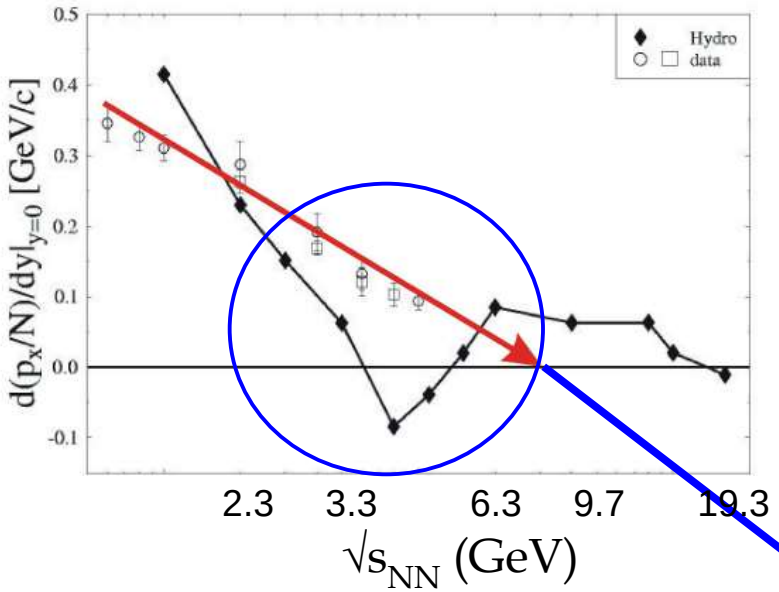


- Radial expansion velocity extracted from blast wave fits to v_2 data
- Different behavior for particles and anti-particles at lower energies
- Similarities to proton/anti-proton/net-proton curves
  → Baryon stopping? Annihilation of anti-protons?

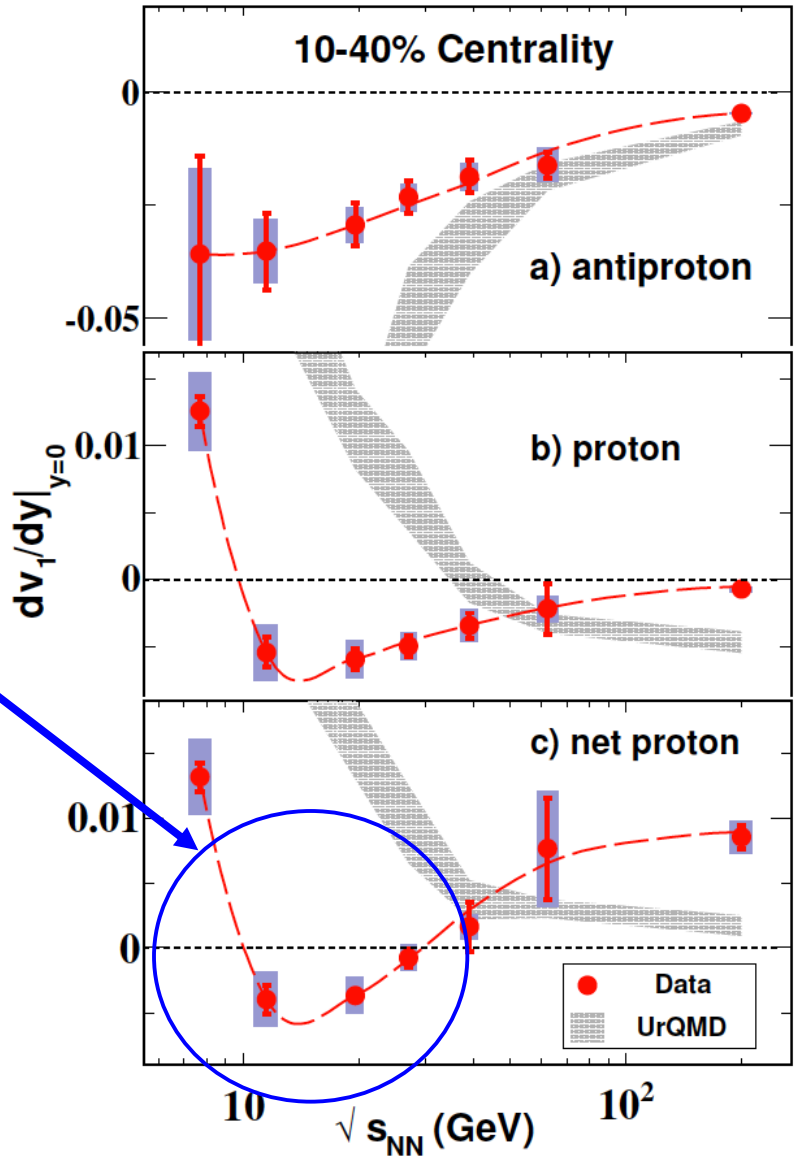
Directed Flow (v_1)

The hunt for the first order phase transition

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



PRL, 112 (2014) 162301



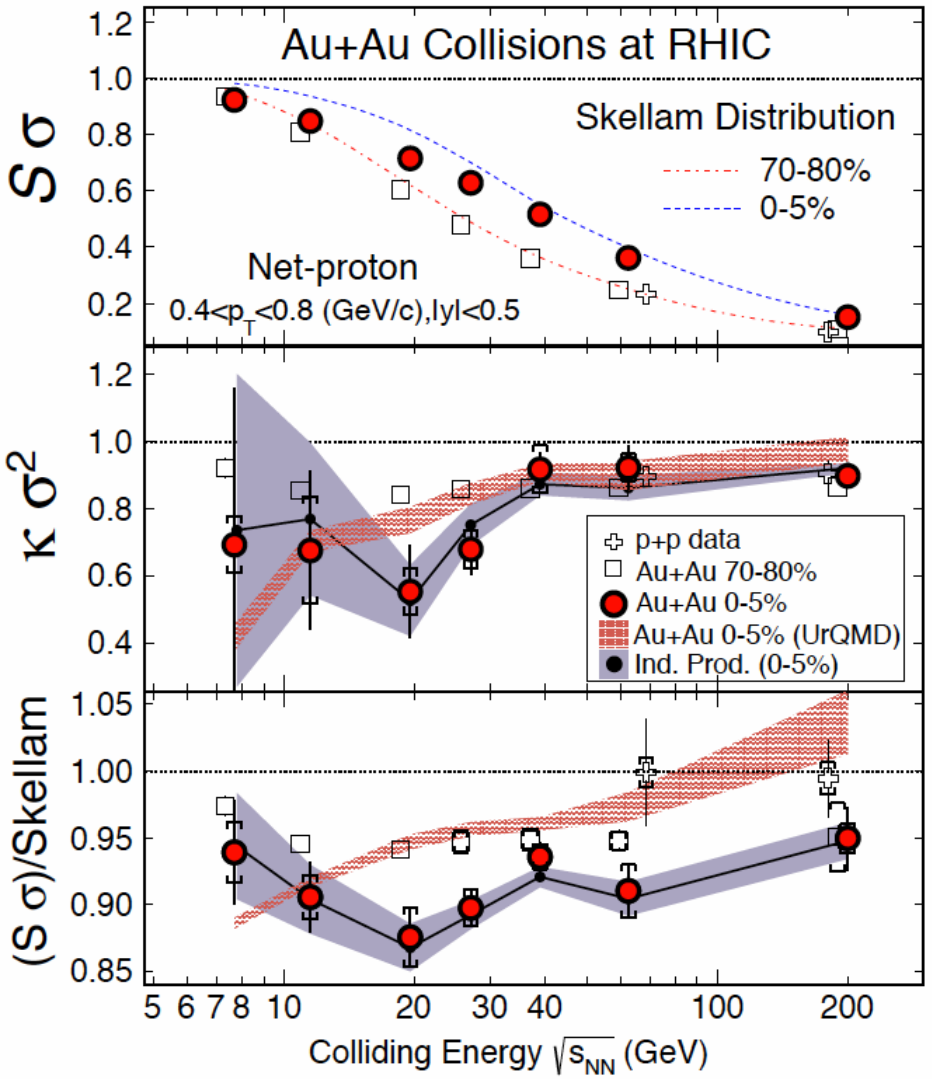
- Dip in net-proton dv_1/dy reproduces theory prediction
  → Softest point of EoS?

- Rising and falling trends of protons and anti-protons qualitatively reproduced by UrQMD
- Dip at different position than model
  → trend correlated to baryon stopping?

Higher Moments of Net-Protons

The hunt for the QCD critical point

Phys. Rev. Lett. 112 (2014) 32302



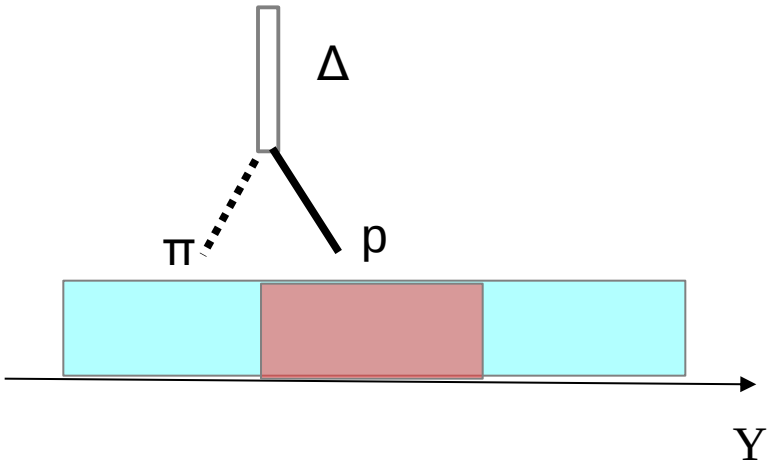
- Net-protons as proxy for net-baryons (conserved quantity)
- Non-monothonic behavior → hint for CP
- Hints of a structure around 19.6 GeV

- 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
- ...

Rare Probes: Higher order Moments

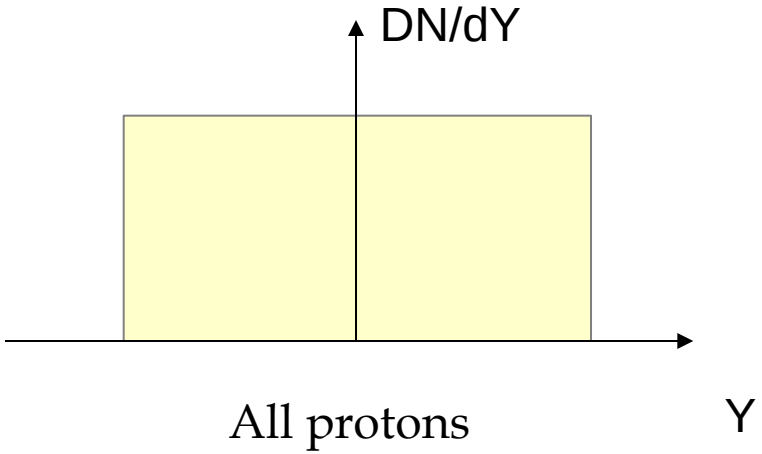
Higher order moments more sensitive to tails
→Better observable for critical point measurement
→ Much more statistics needed

Graphics: Volker Koch

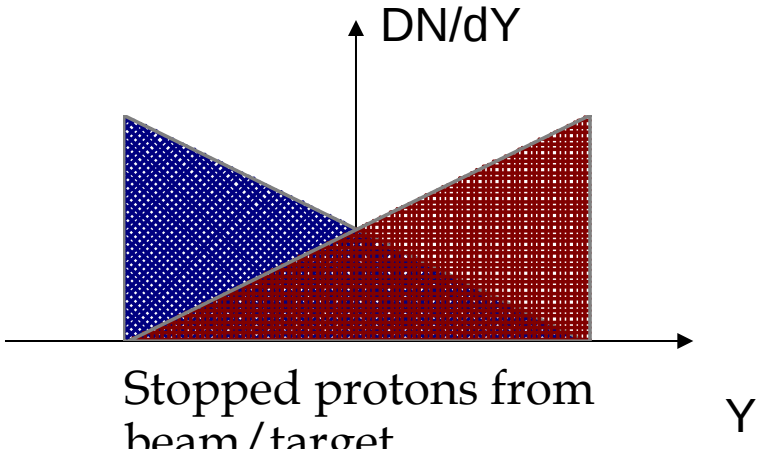


Autocorrelations:
→Centrality detector needed independent in acceptance from main detector!

Baryon stopping:
→Fluctuations might bias critical point measurement

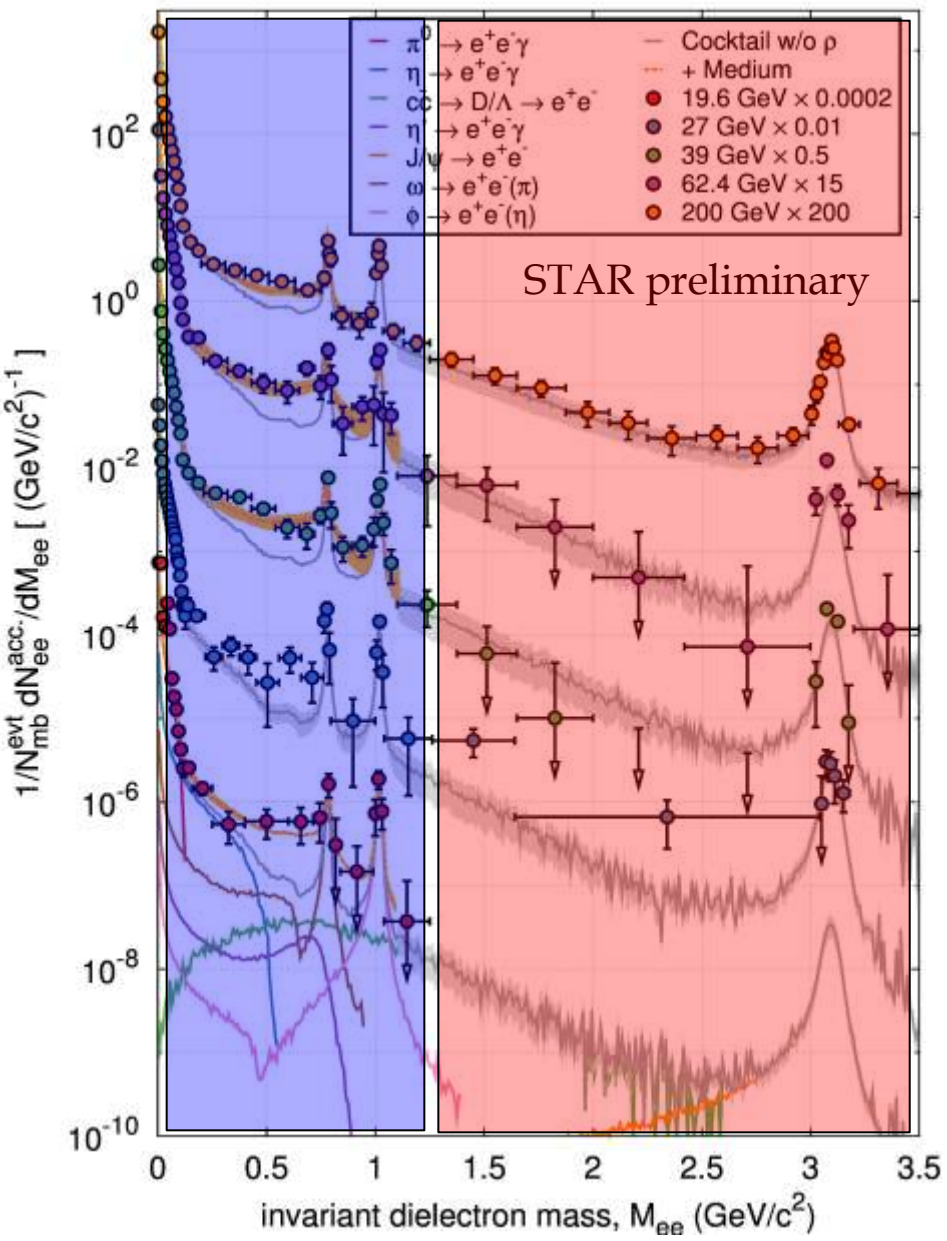


All protons



Stopped protons from beam/target

Rare Probes: Di-Electron Spectra



Good probes of created matter
→ No strong interaction!

- 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 larger)**
- Chiral symmetry restoration?
- What about QGP radiation?
  → We need **MUCH** more statistics at the lowest energies!

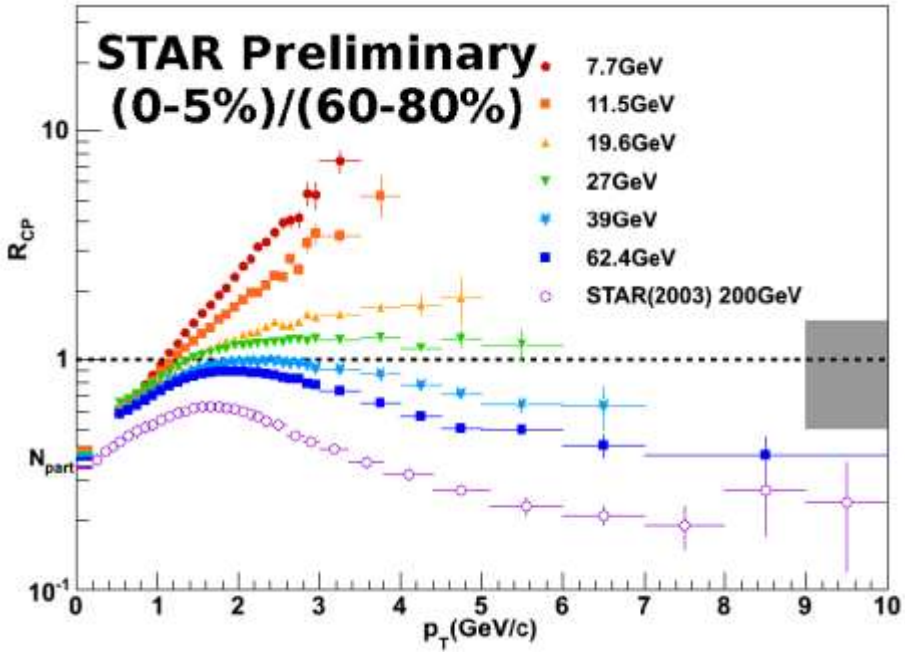
R. Rapp, private communication,
R. Rapp Adv. Nucl. Phys. 25,1 (2000)

Ralf Rapp → yesterday
Xangbu Xu → next talk

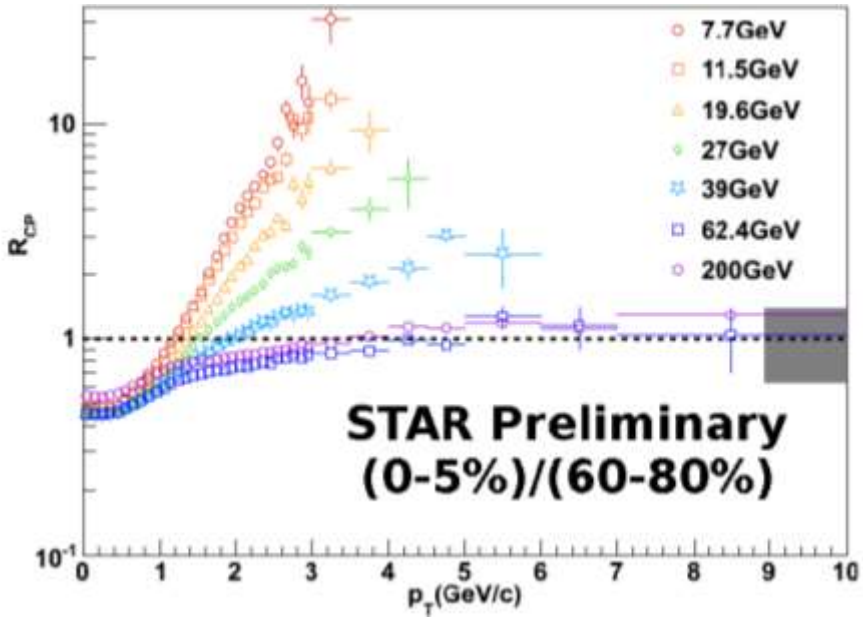
Rare Probes: High p_T R_{CP}

RCP: "Normalized p_T spectra ratio Central to Peripheral"

Data



Hijing



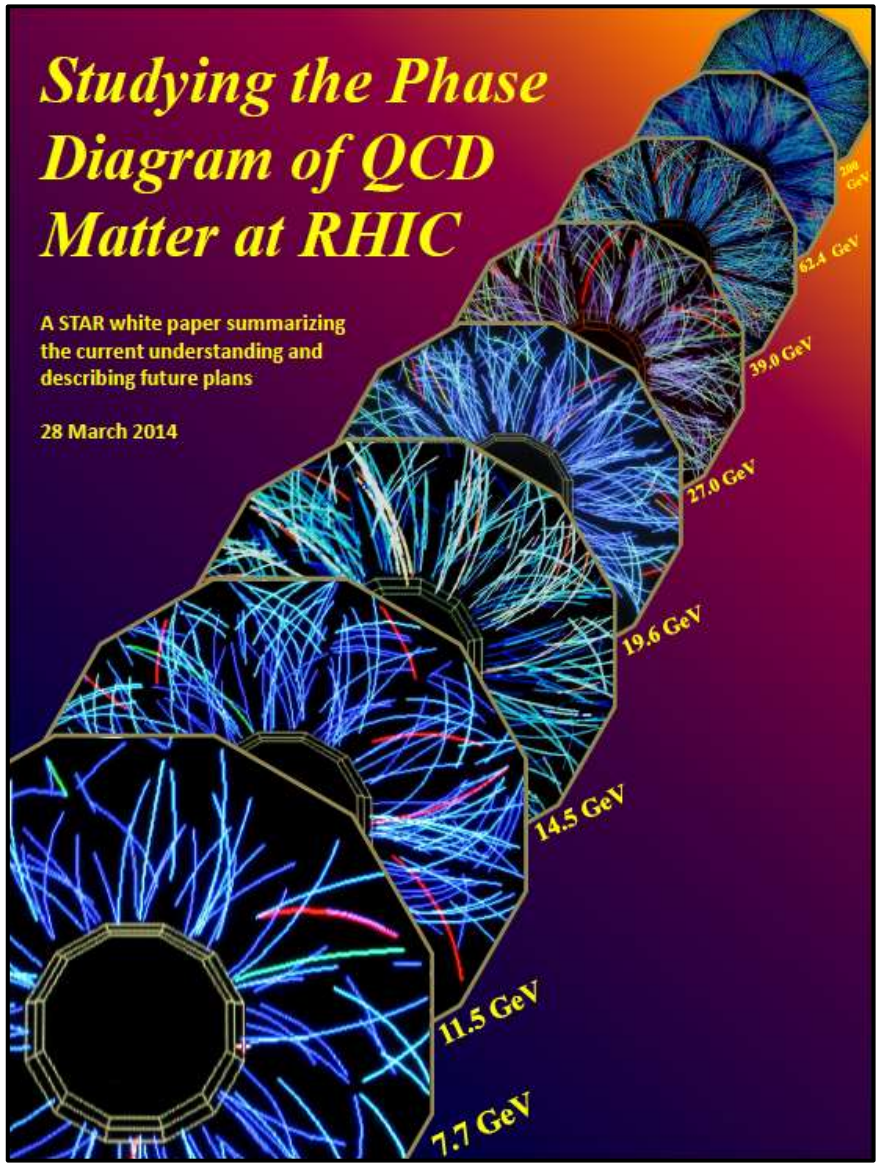
QM 2014 poster

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

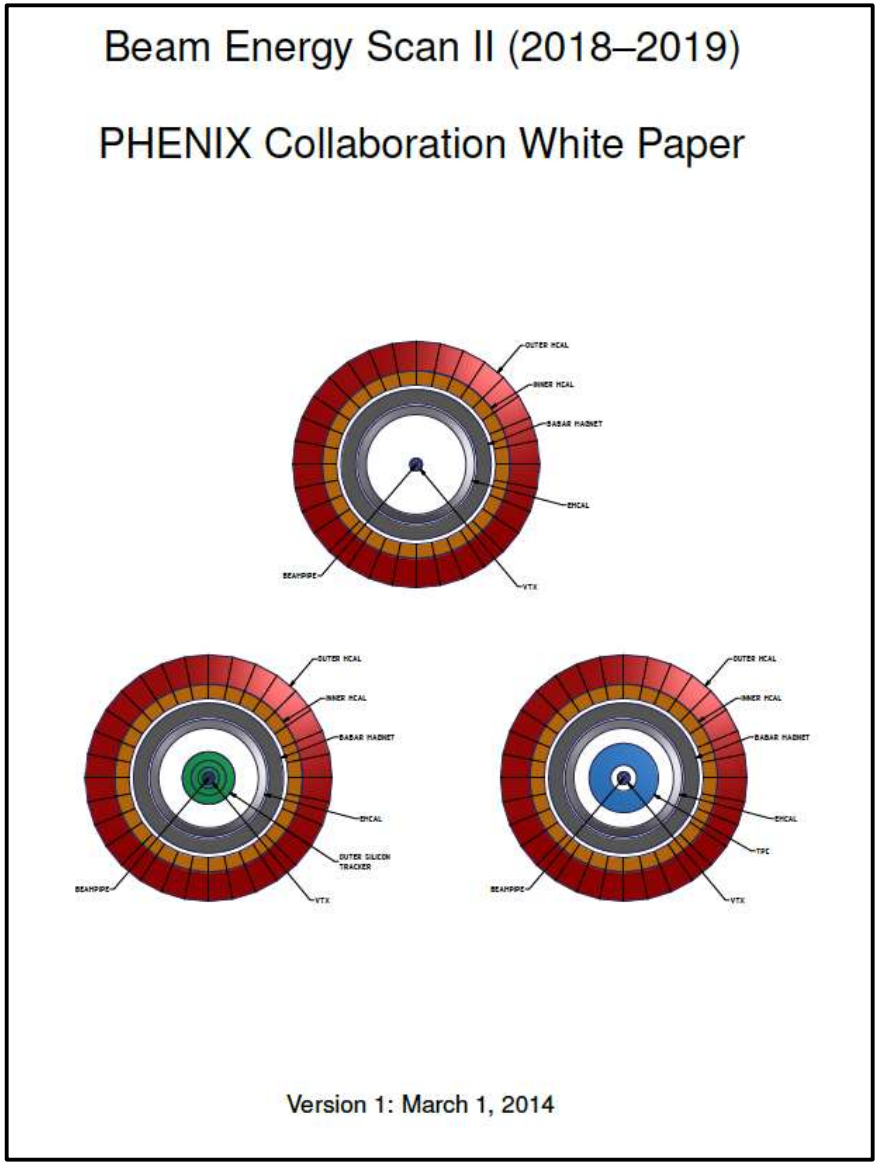
- Radial flow is changing a lot over the BES energy range
- Hijing calculation with Cronin effect but without partonic energy loss shows similar trends
- High p_T particles not measured at lower energies

RHIC BES Phase II White Papers

STAR

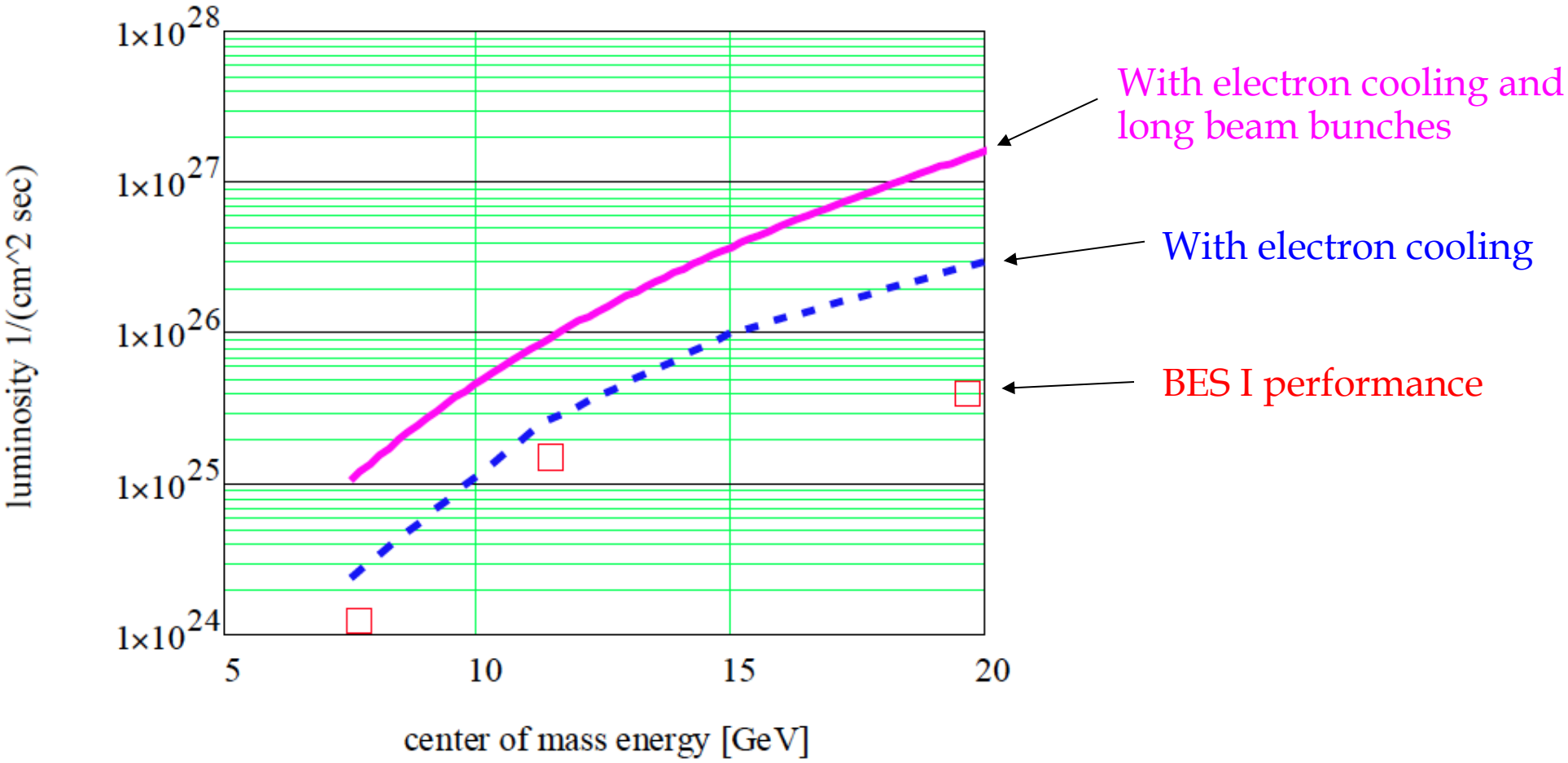


PHENIX



BES II workshop: http://besii2014.lbl.gov/Program/bes-ii-talk-files

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!

Requested Statistics for BES II

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

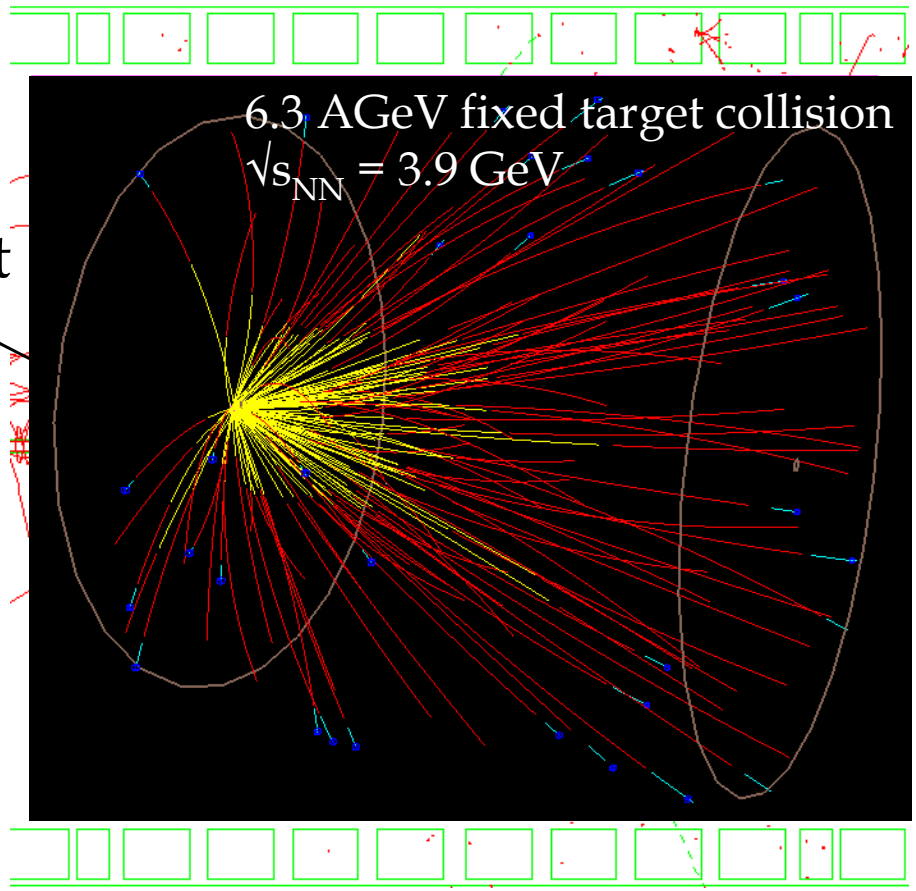
Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% Central Collisions	420	370	315	260	205
BES-I (Million Events)	4	–	12	20	36
BES-I Event Rate (Million Events/Day)	0.25	0.6	1.7	2.4	4.5
BES-I Int. Luminosity (1×10^{25}/cm^2 s)	0.13	0.5	1.5	2.1	4.0
e-Cooling Luminosity Improvement Factor	4	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+

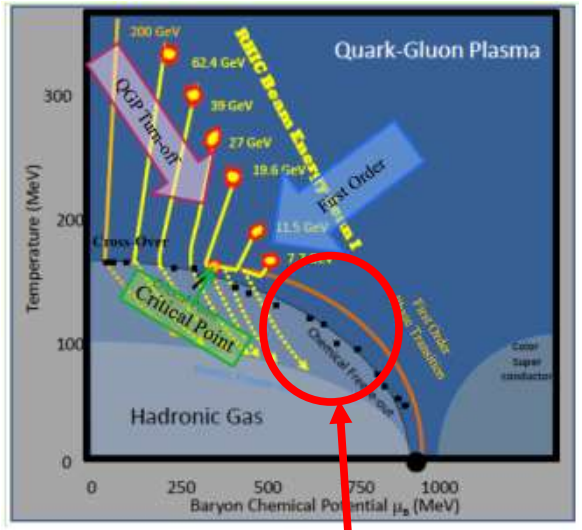
*From STAR BES II white paper

- Factor 25 more statistics (10^8 events) at $\sqrt{s_{NN}}$ = 7.7 GeV (~ SIS300 energy)

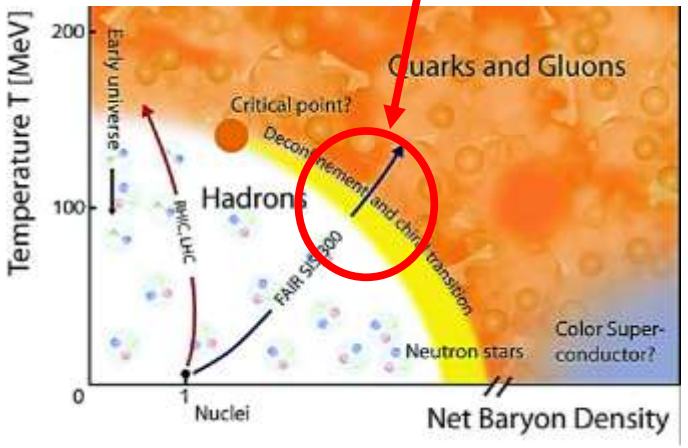
Fixed Target Program for BES II

STAR QM 2014



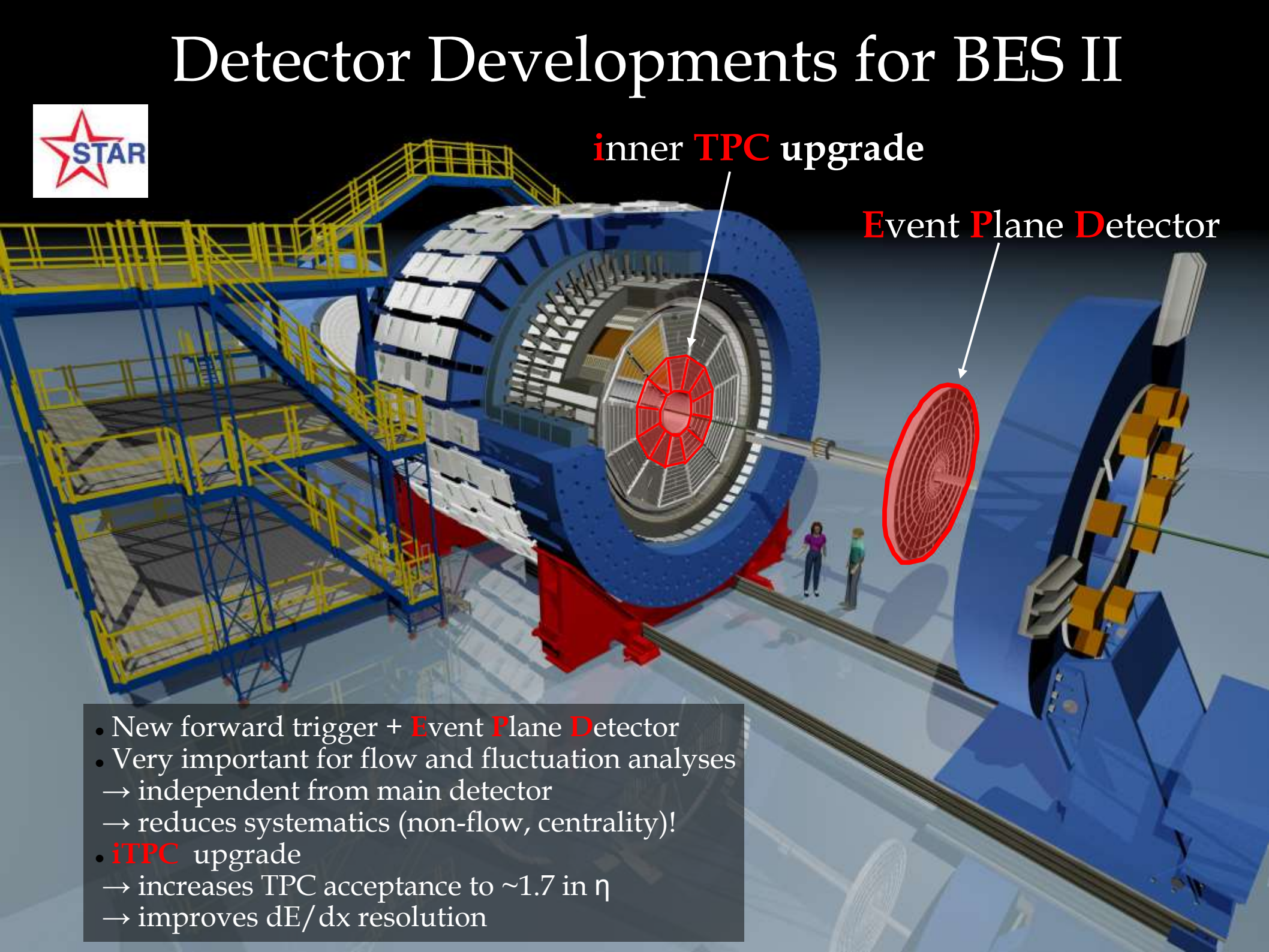


Access to low T, high μ_B



- Fixed target program extends STAR's physics reach to region of compressed baryonic matter
- Simultaneous run with collider mode (ions from the halo) **but** much lower luminosity compared to CBM!

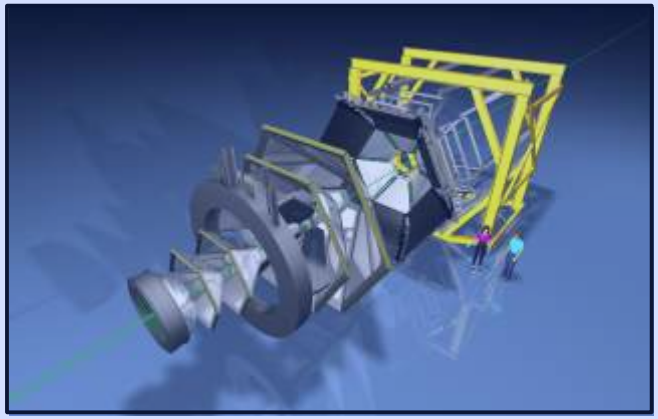
Detector Developments for BES II



- New forward trigger + Event Plane Detector
- Very important for flow and fluctuation analyses
  → independent from main detector
  → reduces systematics (non-flow, centrality)!
- iTPC upgrade
  → increases TPC acceptance to ~1.7 in η
  → improves dE/dx resolution

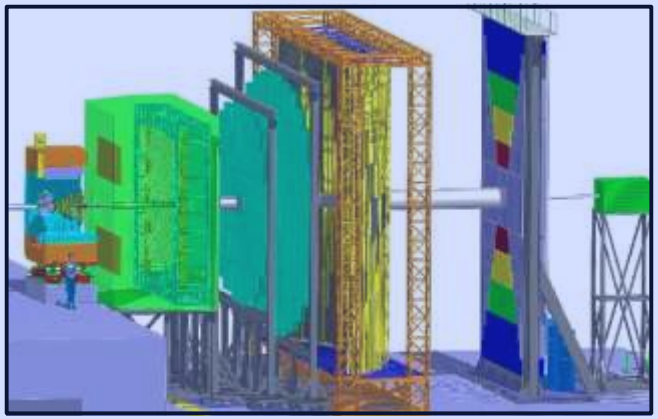
Future Experiments at High Baryon Densities

HADES@FAIR



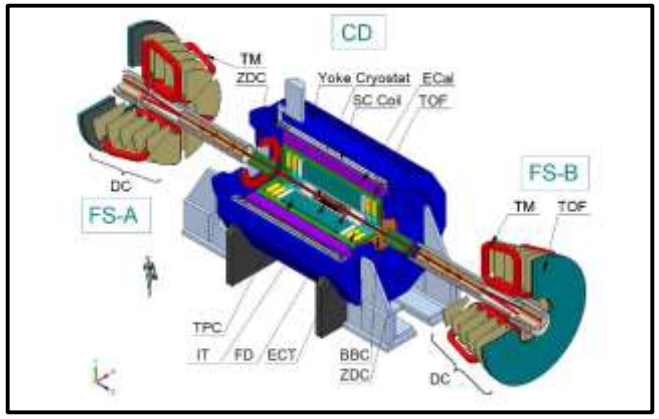
- Fixed target experiment
- SIS18/SIS100
  → $\sqrt{s_{NN}}$ = 2-3 GeV
- Di-leptons + multi-strange hadrons
- EMCAL upgrade for π^0 and η
- But: limited by occupancy, data rate and acceptance at higher energies
  → CBM

CBM@FAIR



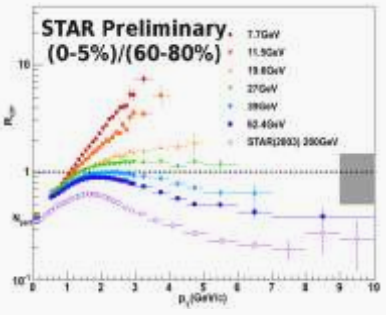
- Fixed target experiment
- SIS100/SIS300
  → $\sqrt{s_{NN}}$ = 2-8 GeV
- Differential measurements of rare probes (Ξ, J/ψ, D^0, di-leptons,...)
- Phase transition to quarkyonic and partonic matter
- Charm production,
- hypernuclei,…

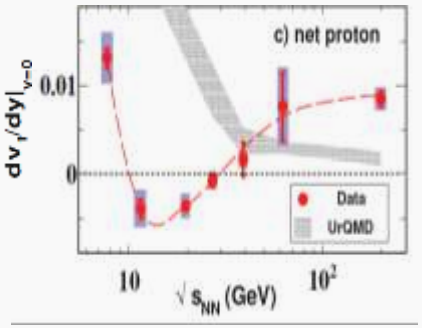
MPD@NICA



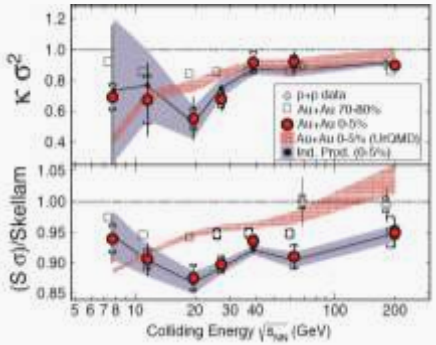
- Collider experiment
- $\sqrt{s_{NN}}$ = 4-11 GeV
- Study of in-medium properties of hadrons
- Nuclear EoS
- Phase transition, critical point search

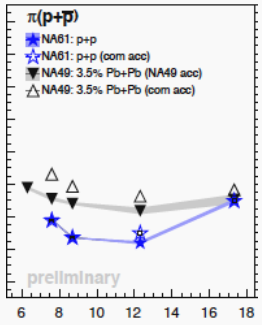
The Future of Low Energy Runs



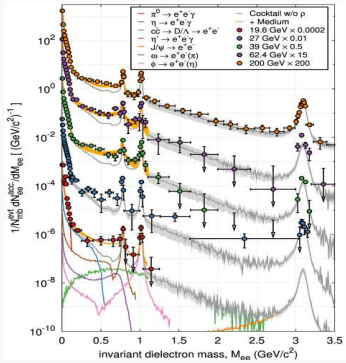


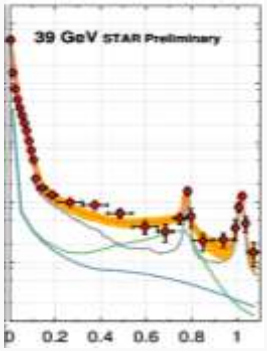
- **Is there a first order phase transition and where is it?**
  → R_{CP} not measured at high p_T for low energies!
  → v_1 measurement for different centralities, EPD detector to control systematics





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

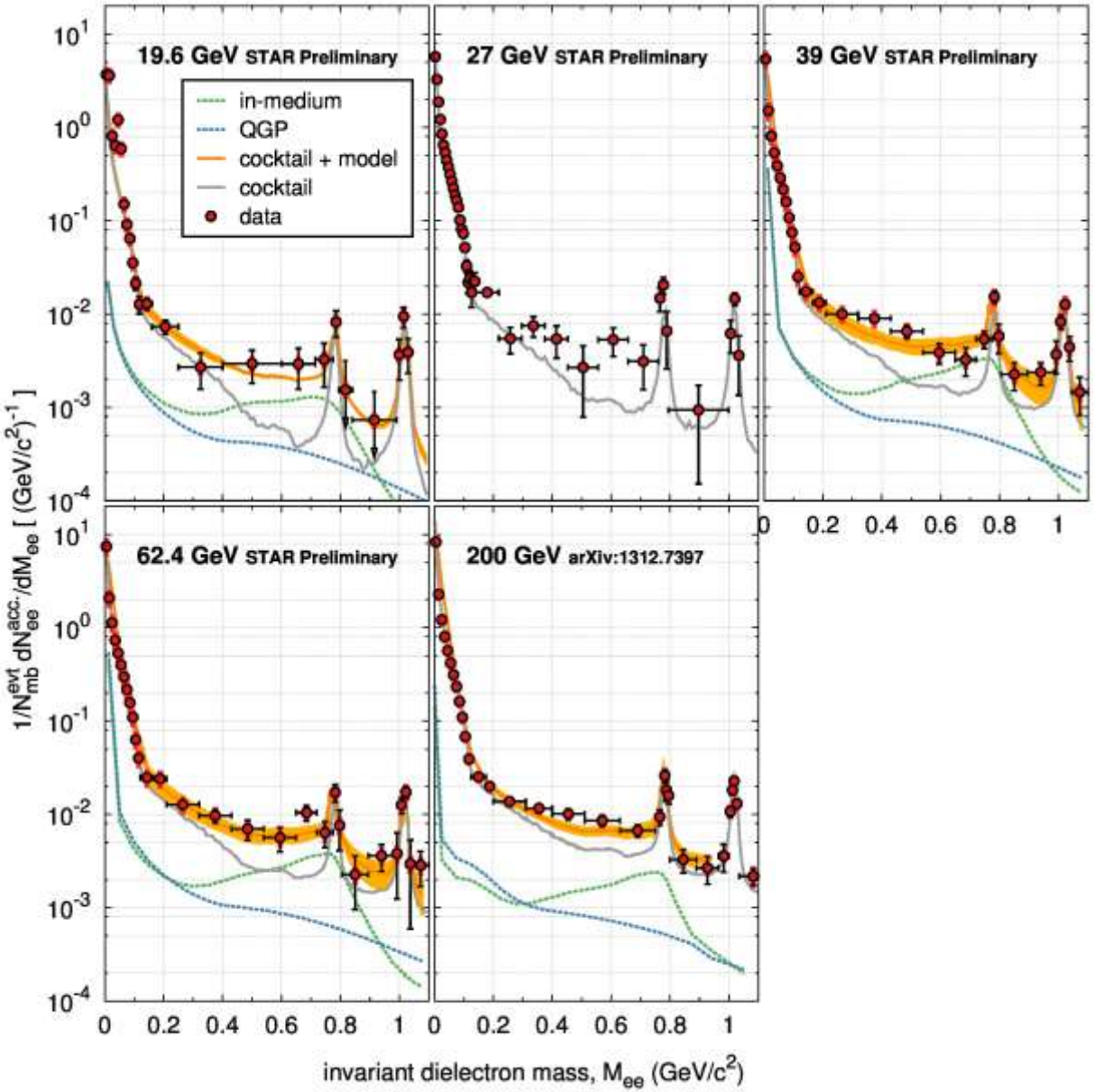




- **Study of QGP radiation and chiral symmetry restoration for different μ_B**
  → Multi-differential di-lepton spectroscopy at large M_{ee}


Thanks!

Di-Electron Spectra: Low Mass Region



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

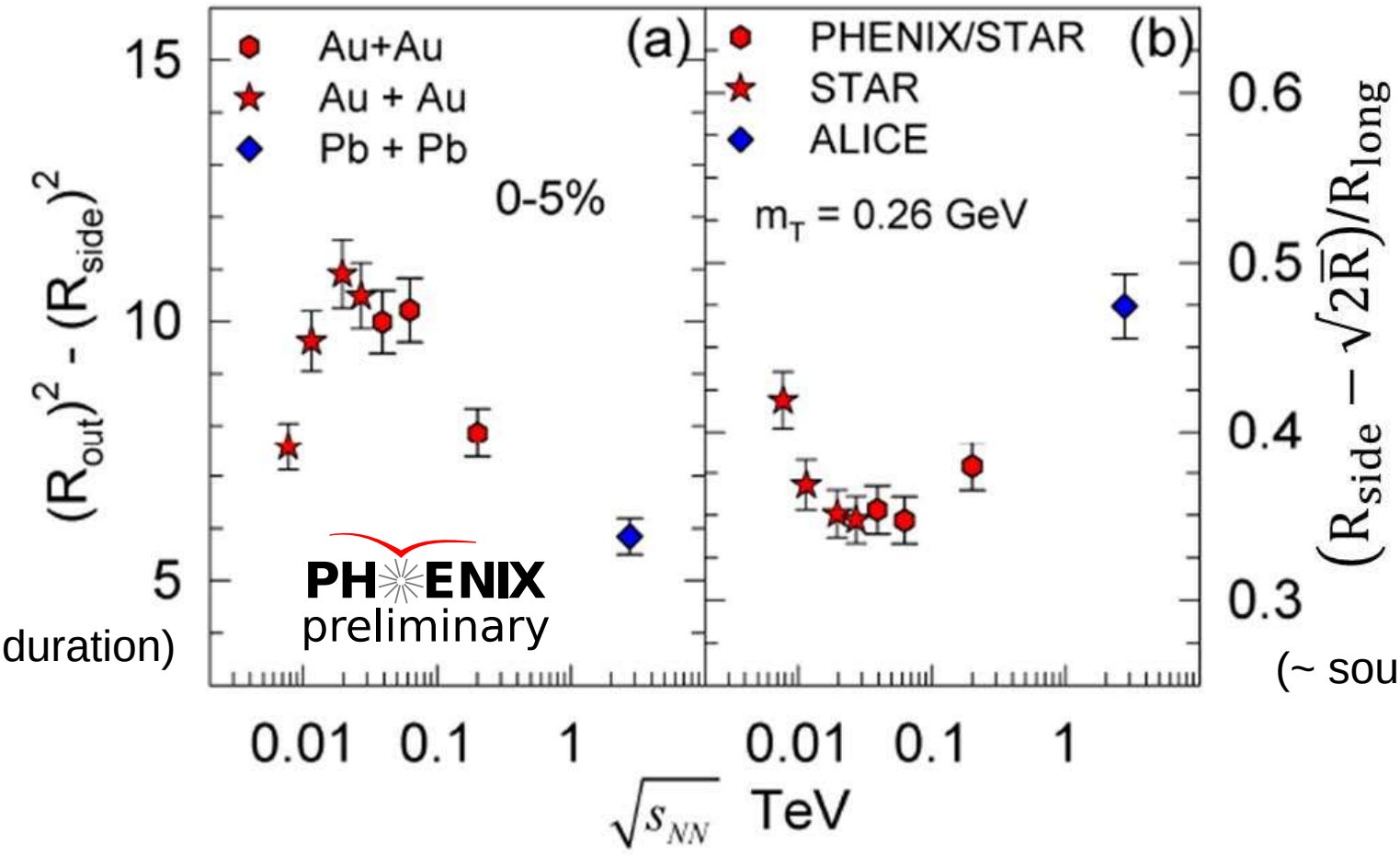
- The scenario of a broadened rho spectral function can consistently describe the LMR excess yield from $\sqrt{s_{NN}}$=19.6 up to 200 GeV

- What about the p_T dependence of model/data? (first results shown)
- Systematic errors for model?
- Chiral symmetry restoration?

Emission Duration and Expansion/Lifetime

The hunt for the first order phase transition

QM 2014



(~ 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 CEP?