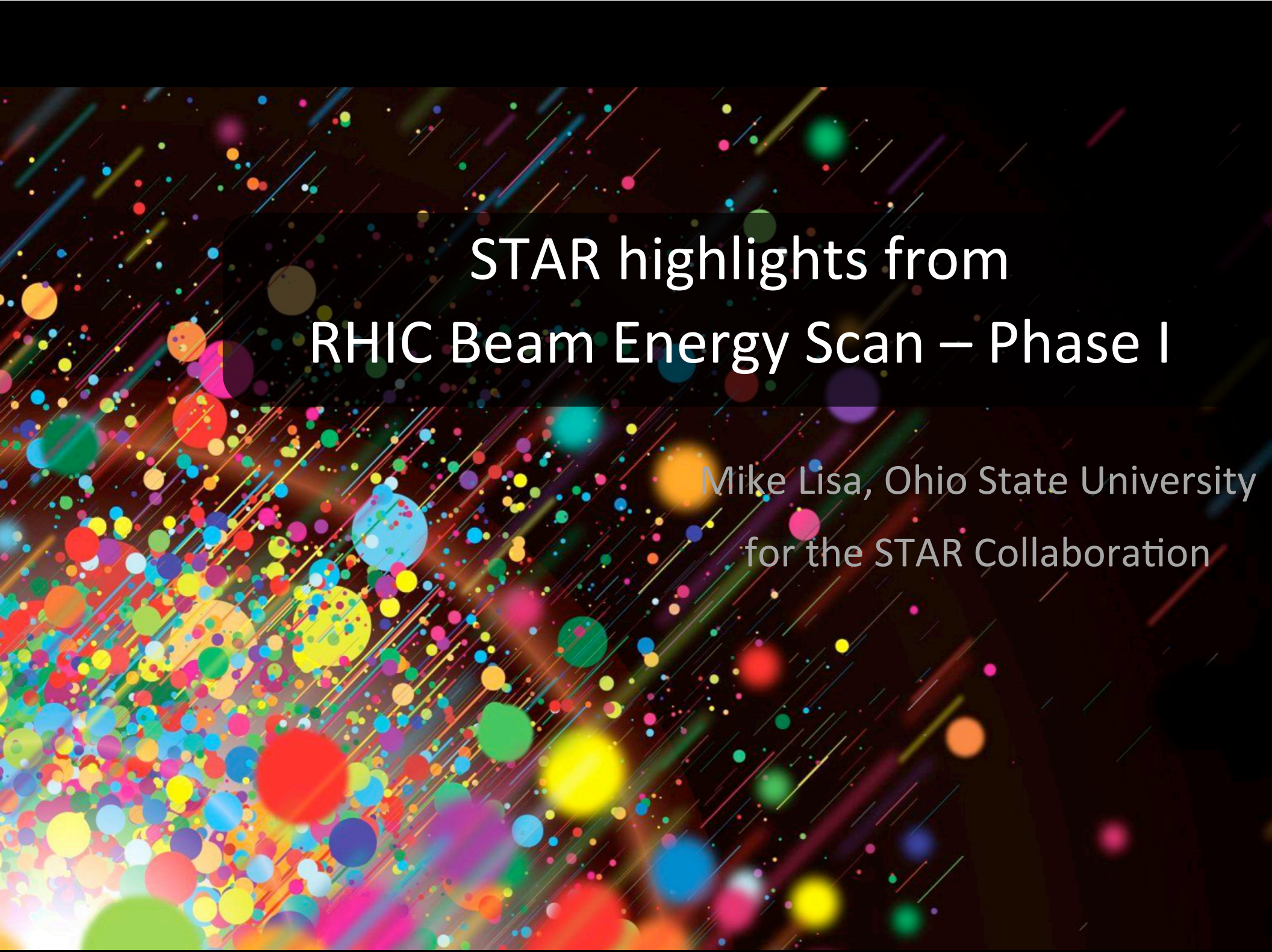
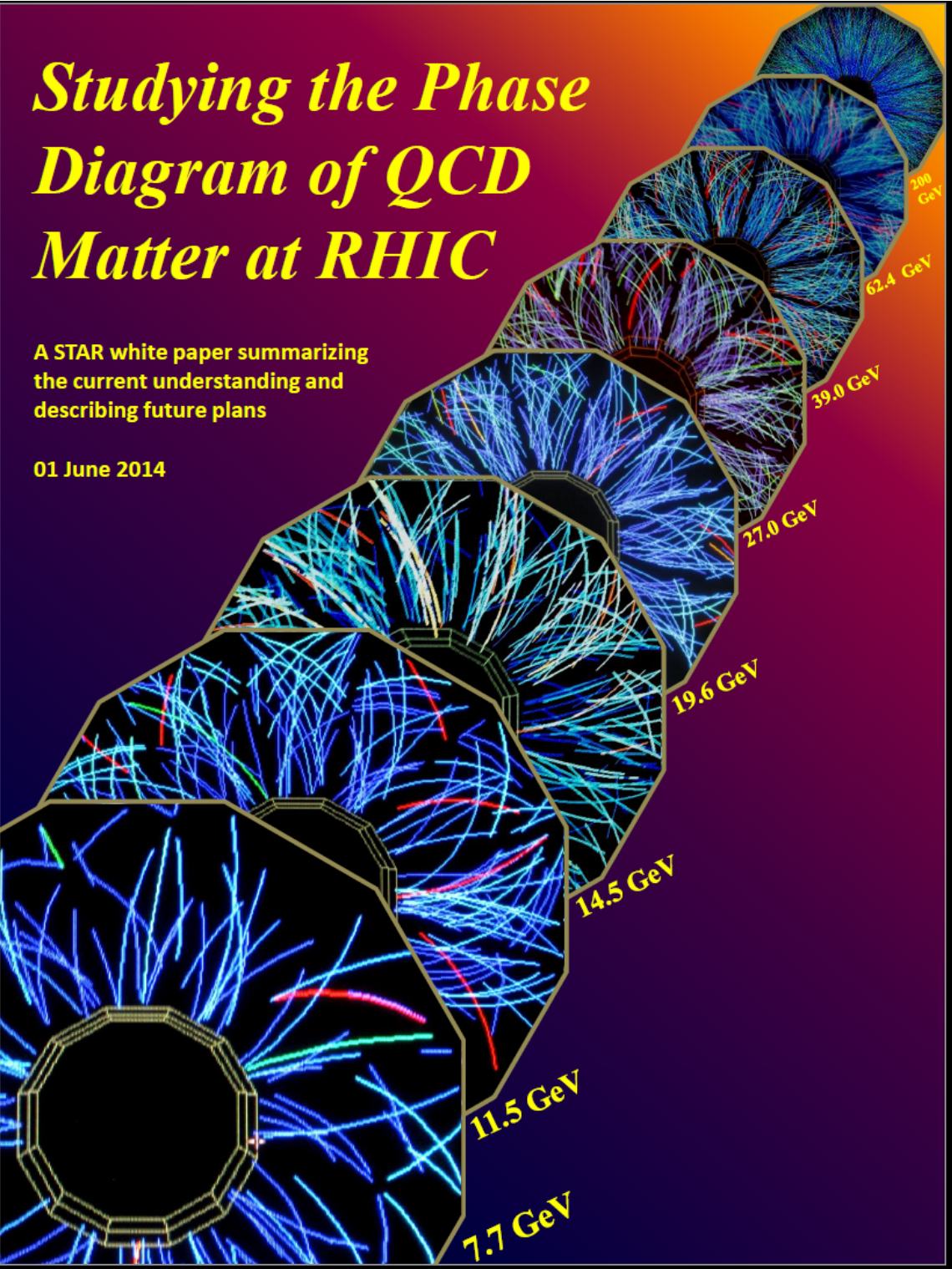


STAR highlights from RHIC Beam Energy Scan – Phase I

Mike Lisa, Ohio State University

for the STAR Collaboration



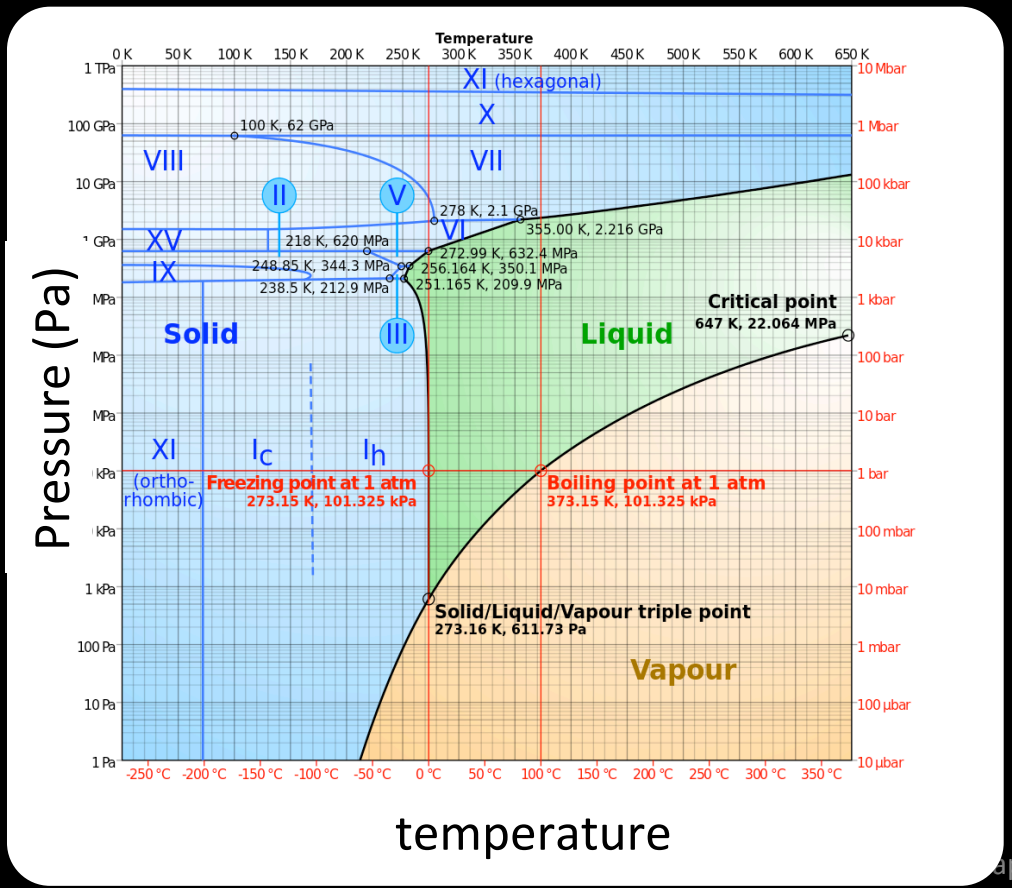
- Motivation
- Observations
- Discussion
- Perspectives

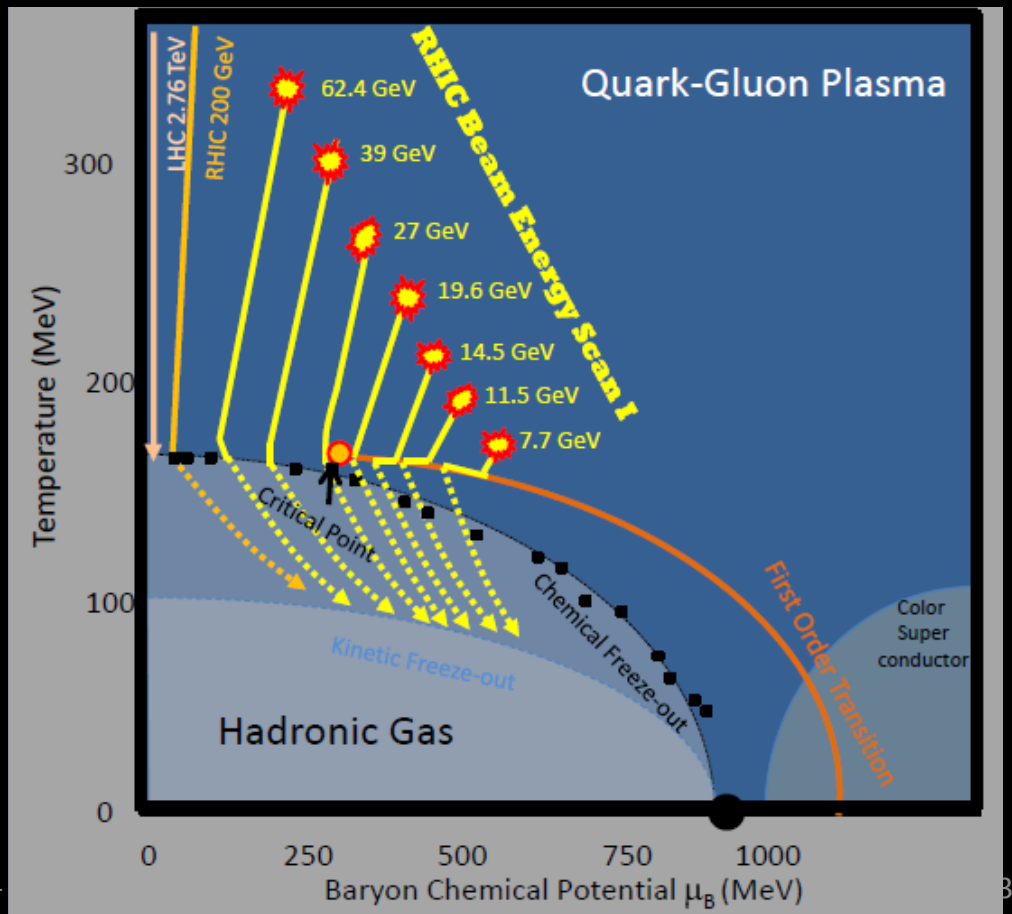
← Much more detail in STAR White paper

http://www.bnl.gov/npp/pac.asp
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

The RHIC Beam Energy Scan

- Experimental exploration of the QCD phase diagram
  - understanding the fundamental theory through its phase structure
- Focus on the transitions
  - a condensed matter approach to the partonic condensed matter system
    → vary μ_B and T by varying collision energy





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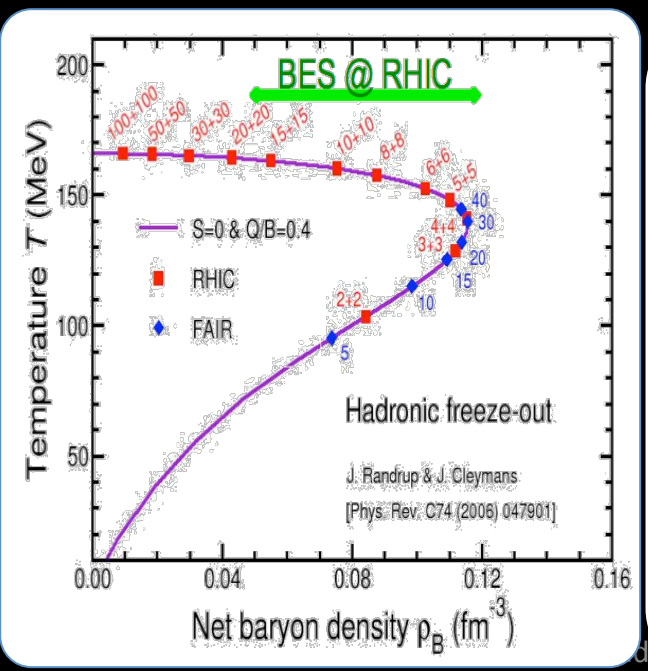
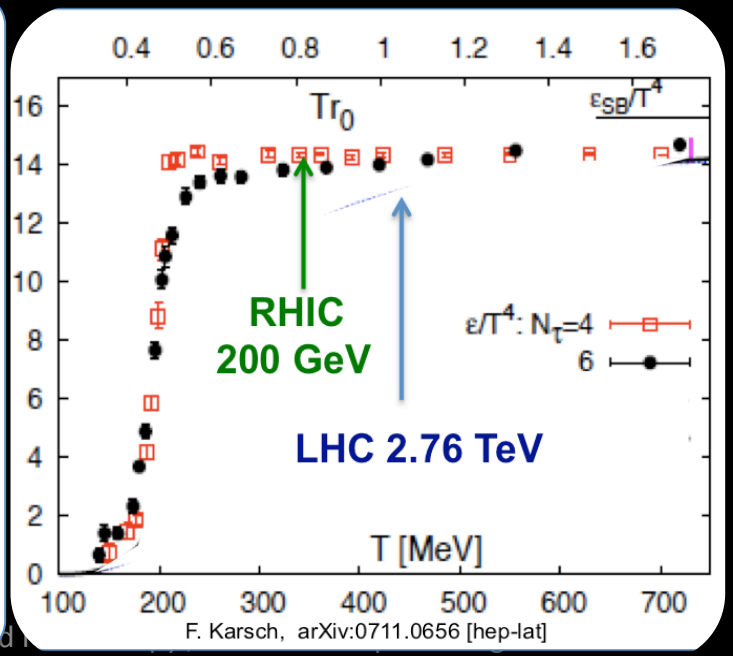
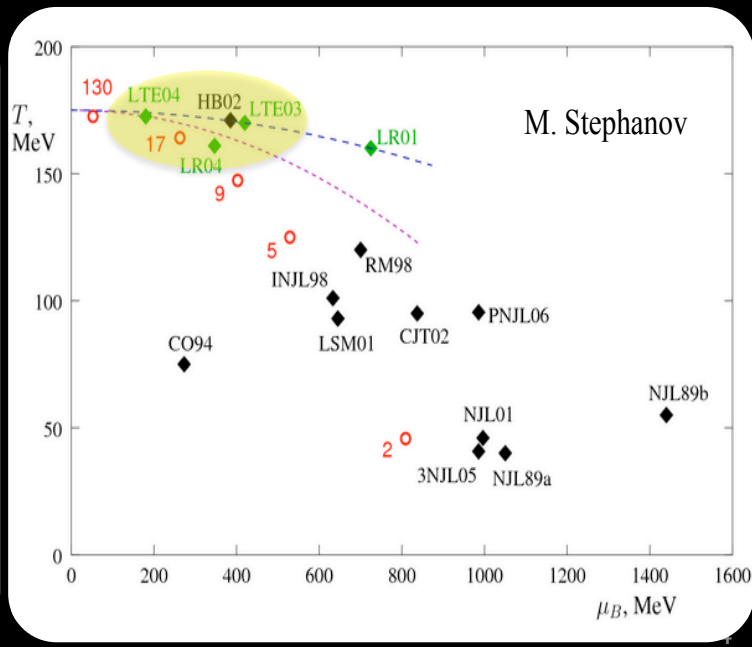
- Focus on the right energy – QCD sets the scale
  - theory, models, data systematics: $\sqrt{s_{NN}}$=5-50 GeV

Condensed matter QCD is not Energy Frontier science - Steve Vigdor







The RHIC Beam Energy Scan

- Experimental exploration of the QCD phase diagram
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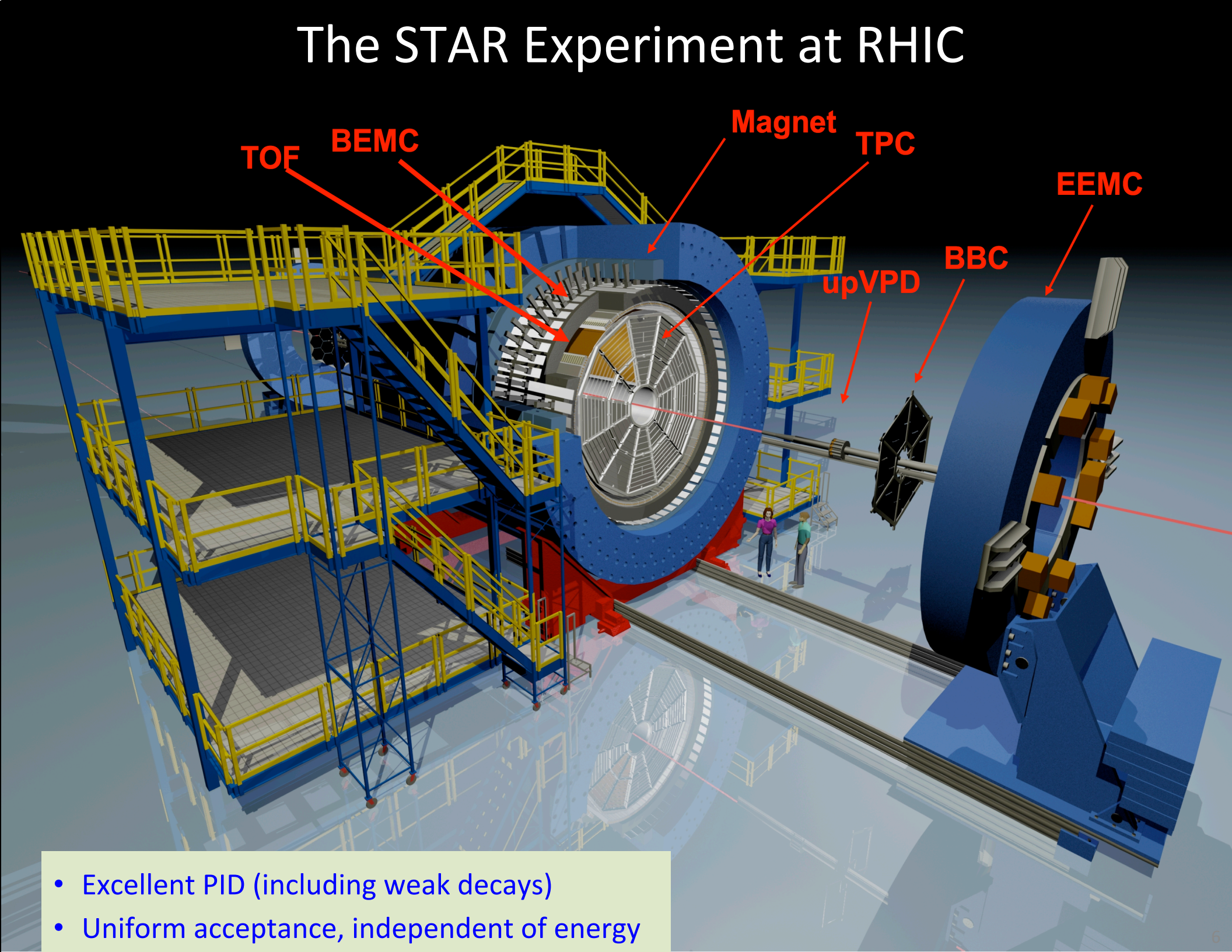
- Focus on the transitions
  - a condensed matter approach to the partonic condensed matter system → vary μ_B and T by varying collision energy
- Focus on the right energy – QCD sets the scale
  - theory, models, data systematics: $\sqrt{s_{NN}}$=5-50 GeV
- Limited theory guidance: watch for possibly subtle systematics
  - uniform, unchanging detector acceptance crucial → collider
  - highly variable control of energy & colliding species

Condensed matter QCD is not Energy Frontier science - Steve Vigdor

If RHIC did not exist, we would have to build it. - Berndt Mueller

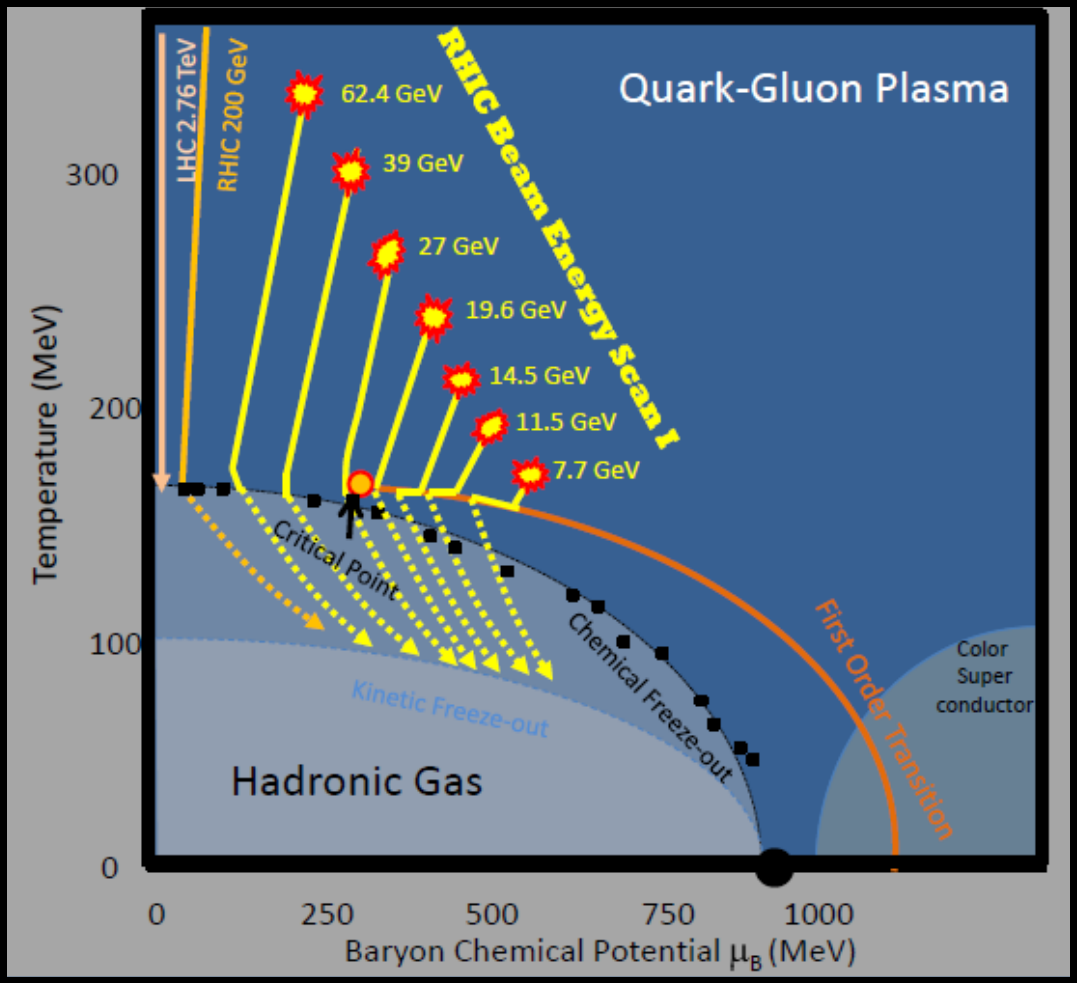
The STAR Experiment at RHIC



- Excellent PID (including weak decays)
- Uniform acceptance, independent of energy

RHIC BES Phase I

- 2009: Detailed plan for BES
  - arXiv:1007.2613
  - specific energies & stats for specific questions



0) location on the phase diagram?
1) sQGP signatures turn off/on?
2) critical fluctuations?
3) evidence of mixed phase?

→ *theory feedback & further exploration*

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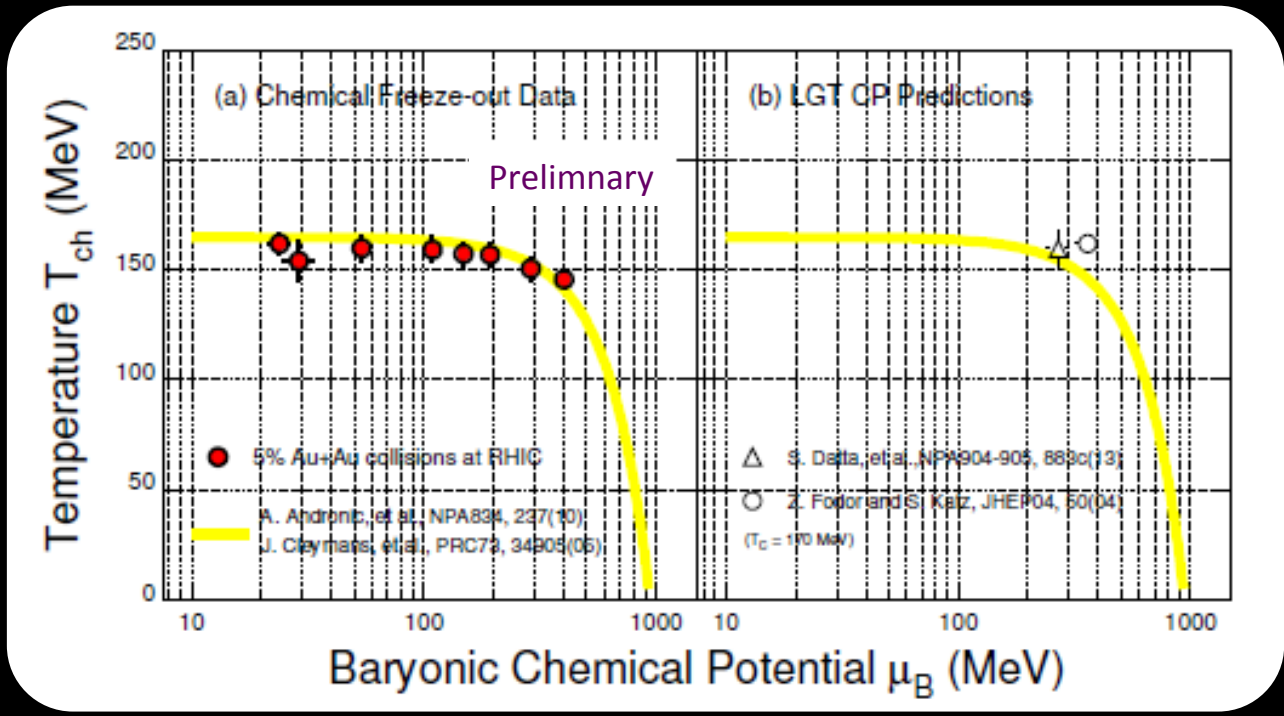
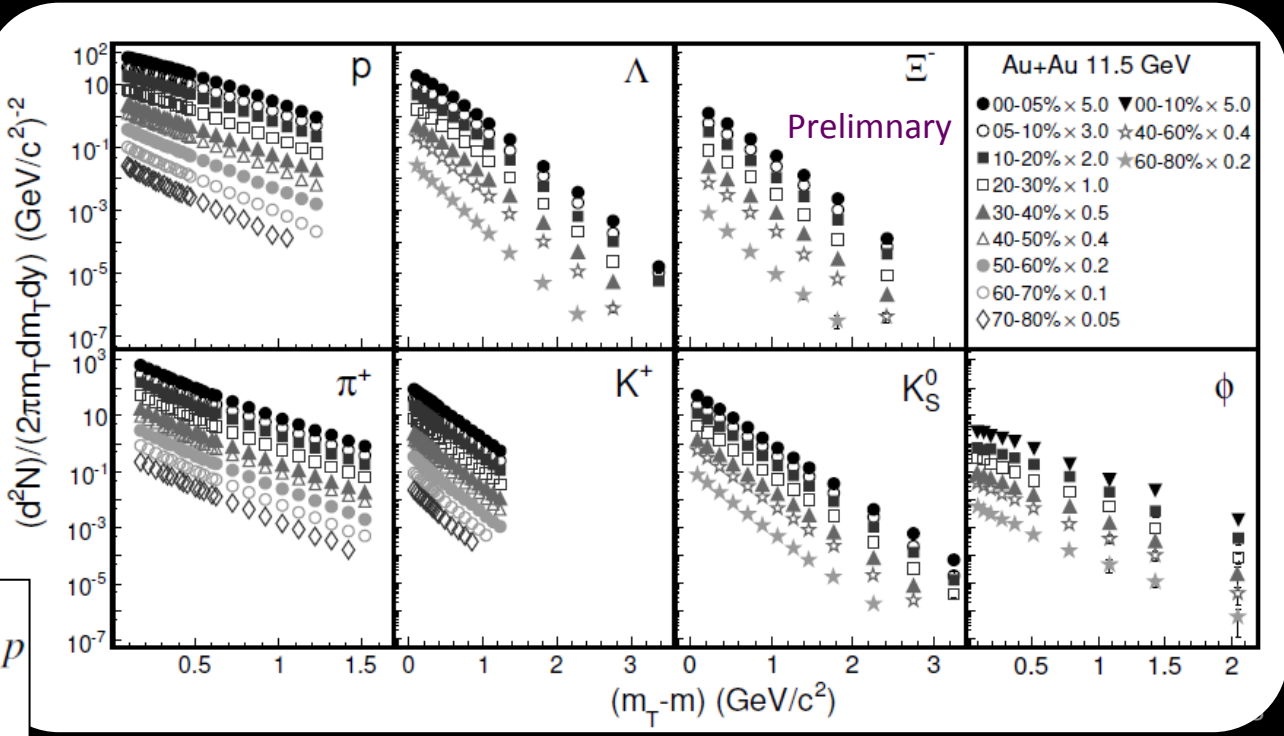
7.7	420	4	4	2010

0 – Where are we?



Uniform coverage & good PID

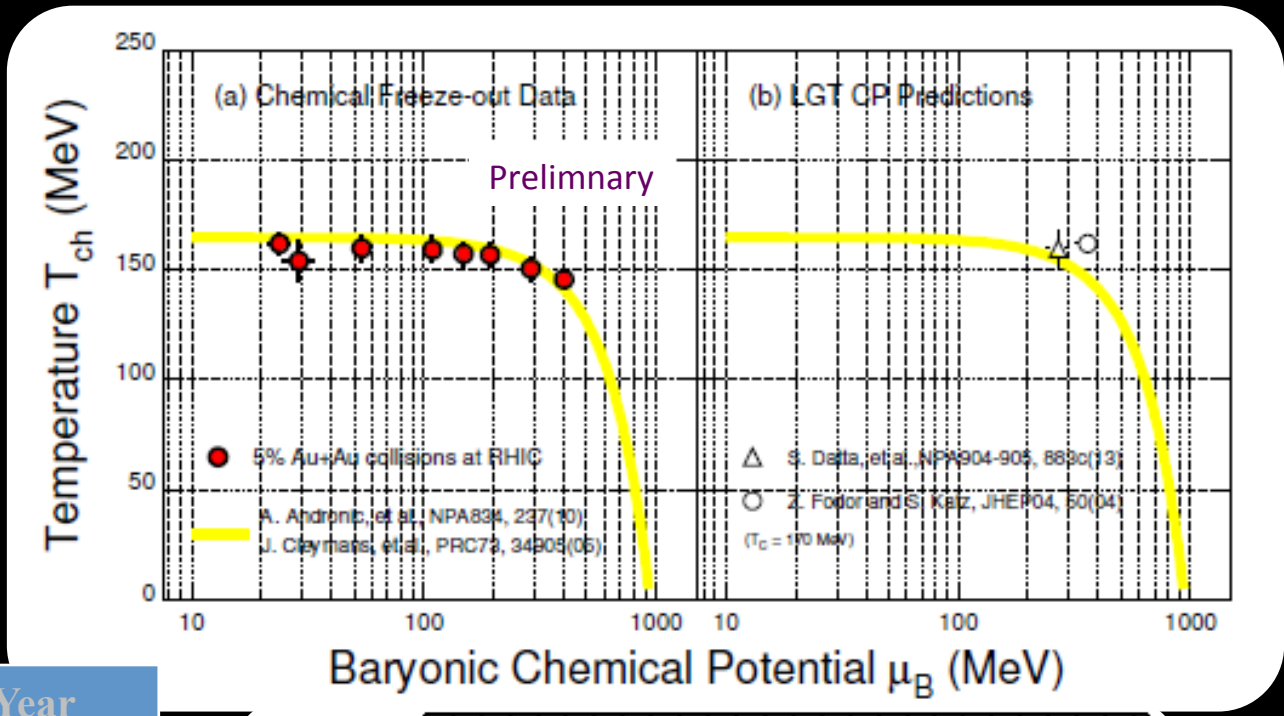
Lattice and QCD-inspired models suggest critical point near low end of BES



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

0 - Caveat

$\sqrt{s_{NN}} \leftrightarrow \mu_B$ correspondence somewhat model- and centrality-dependent



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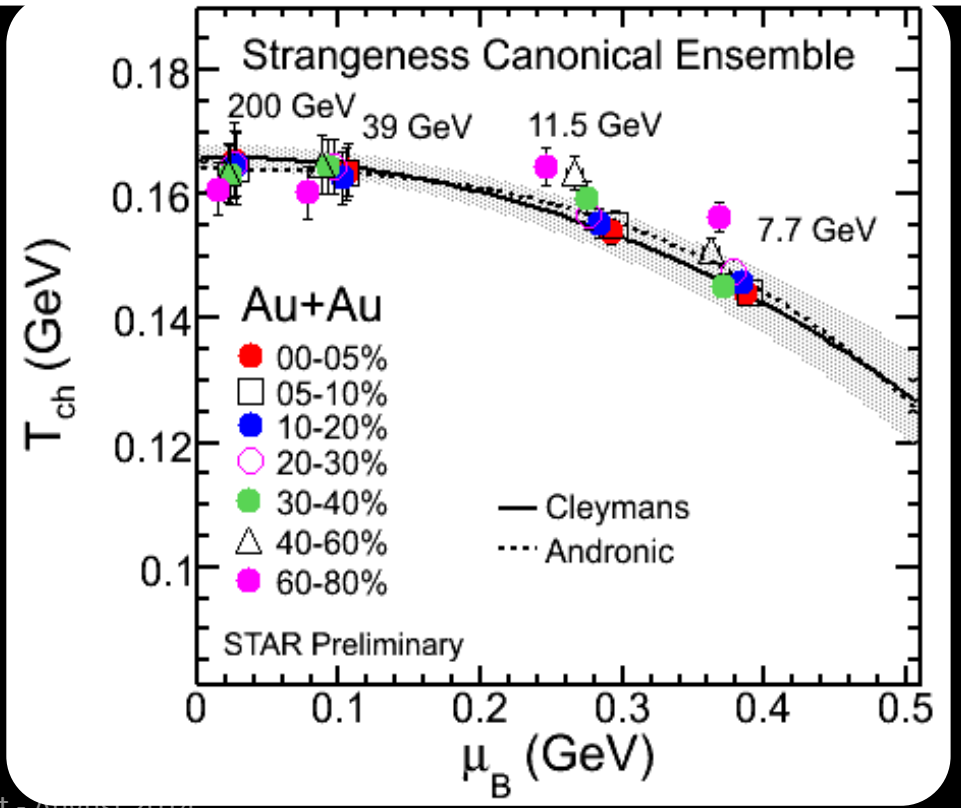

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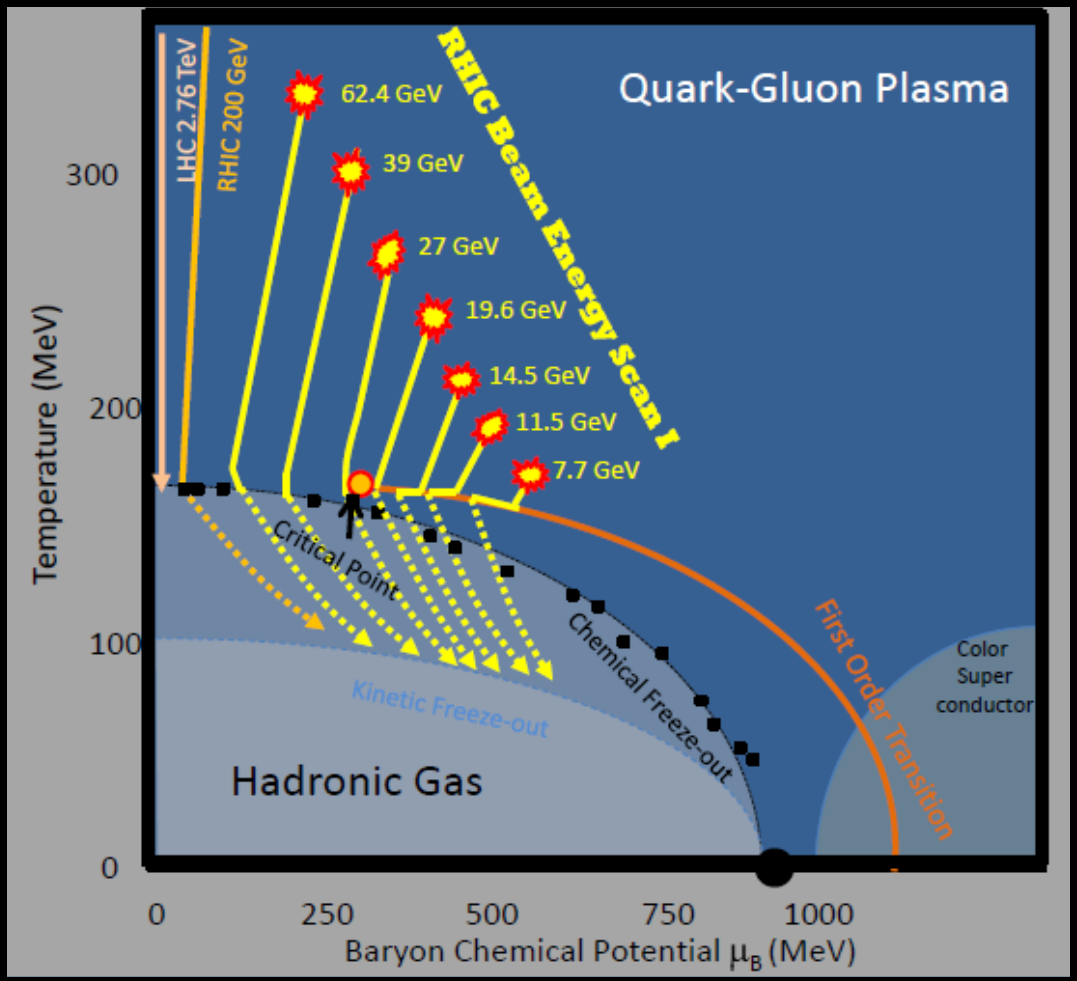

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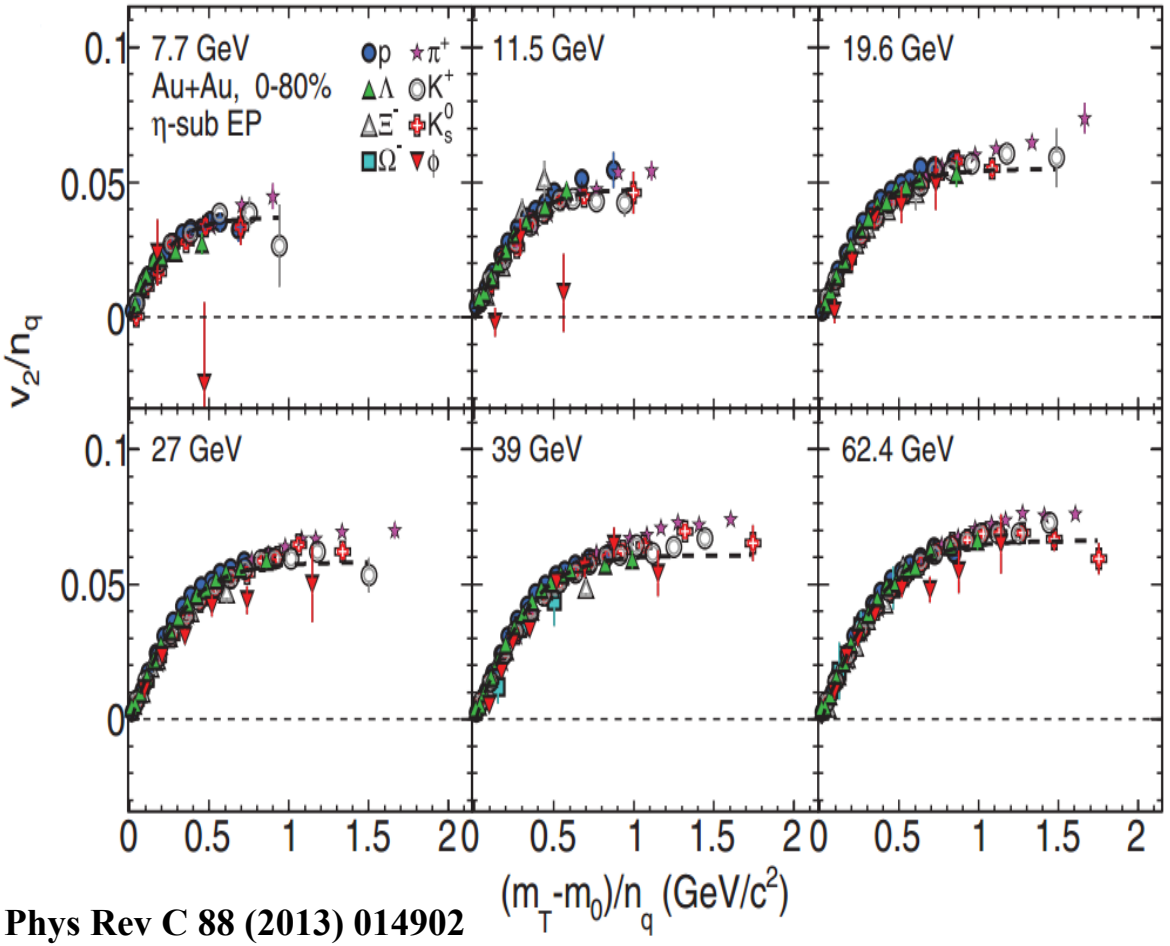
1a – NCQ scaling



Phys Rev C 88 (2013) 014902

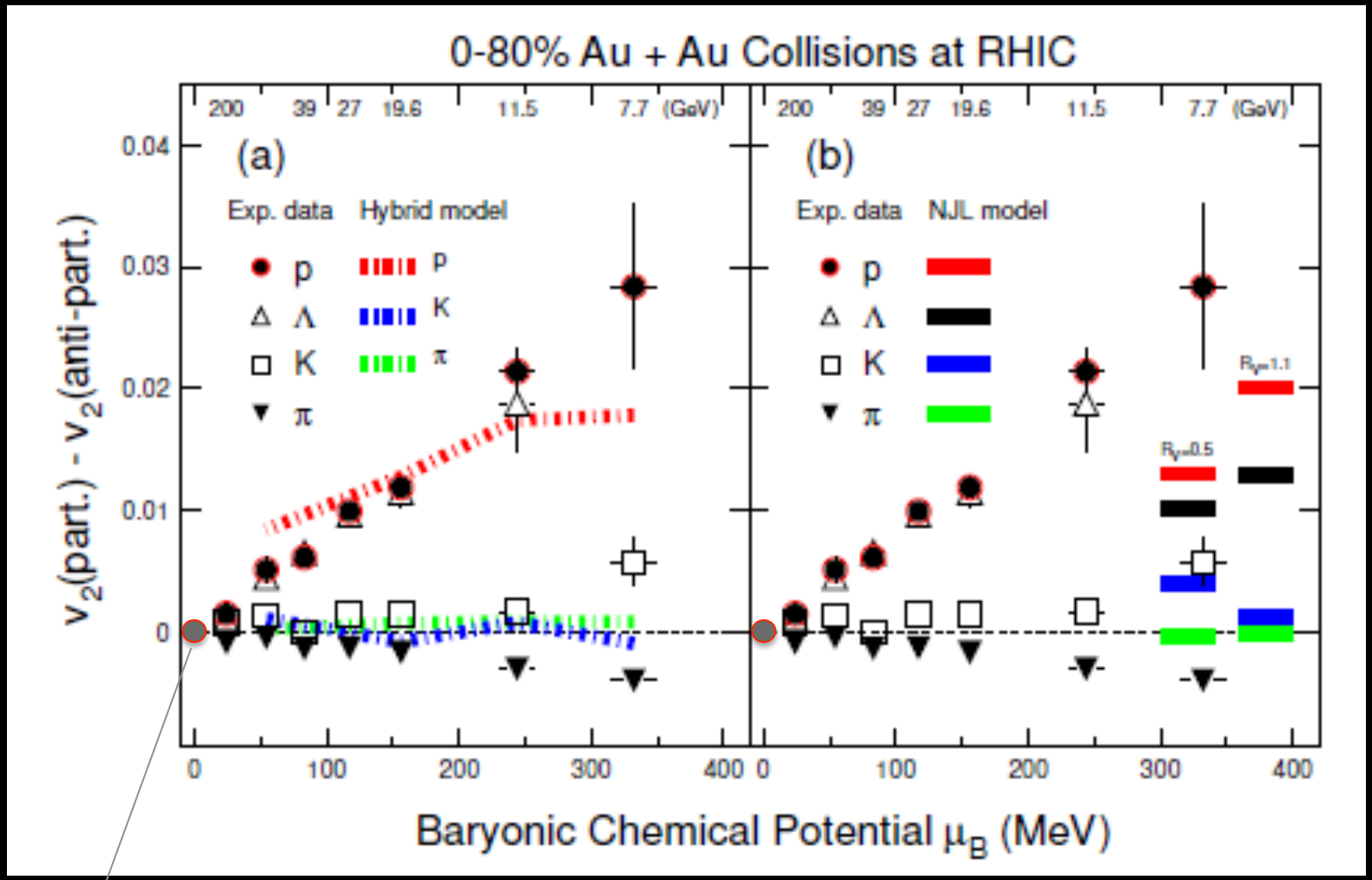
v_2 at intermediate p_T

- need more statistics at low energy

NCQ scaling holds at the ~10% level (~20% at LHC) for *particles,* but...

1a – particle/antiparticle v_2

... strong particle-antiparticle deviation, depending on chemical potential



fully consistent at LHC
http://arxiv.org/pdf/1405.4632v1

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

statistical errors shown only

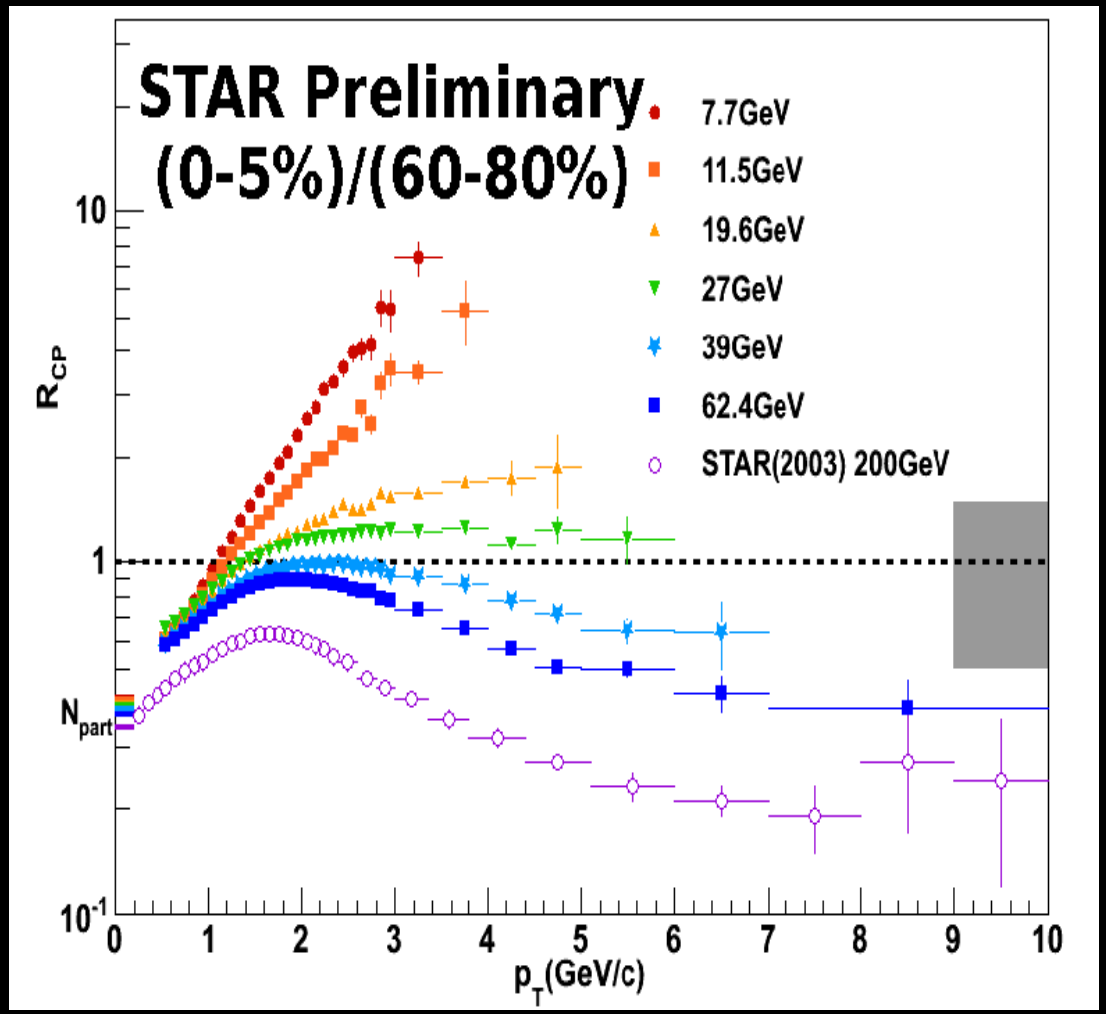
Data: Phys. Rev. Lett. 110, 142301 (2013)
Hybrid: Phys. Rev. C 86, 044903 (2012)
NJL: Acta Phys.Polon.Supp. 7 (2014) 1, 183

1b - R_{CP}

"Turn off?" hmmm...

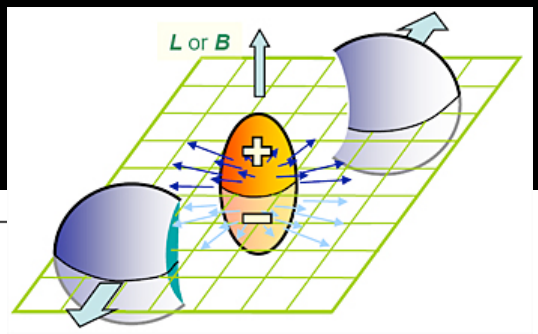
... but clearly less suppression as energy is reduced

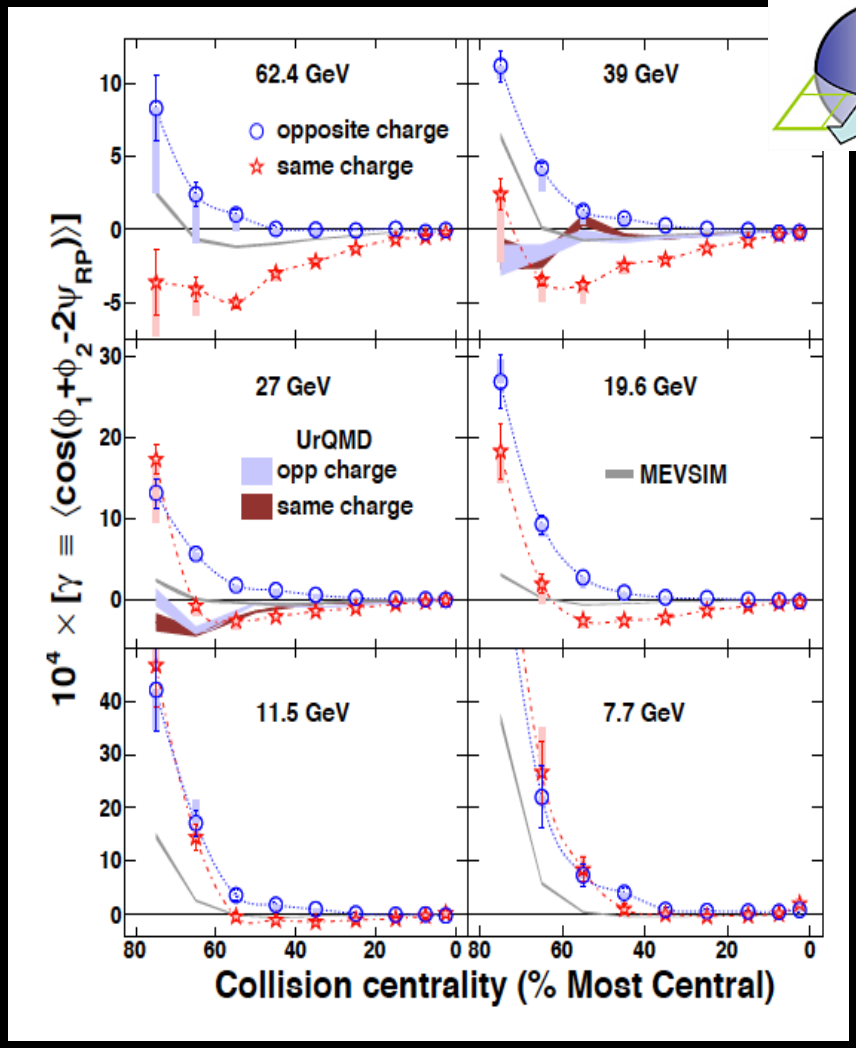
PID-differential and
greater reach possible at low energy with more statistics.



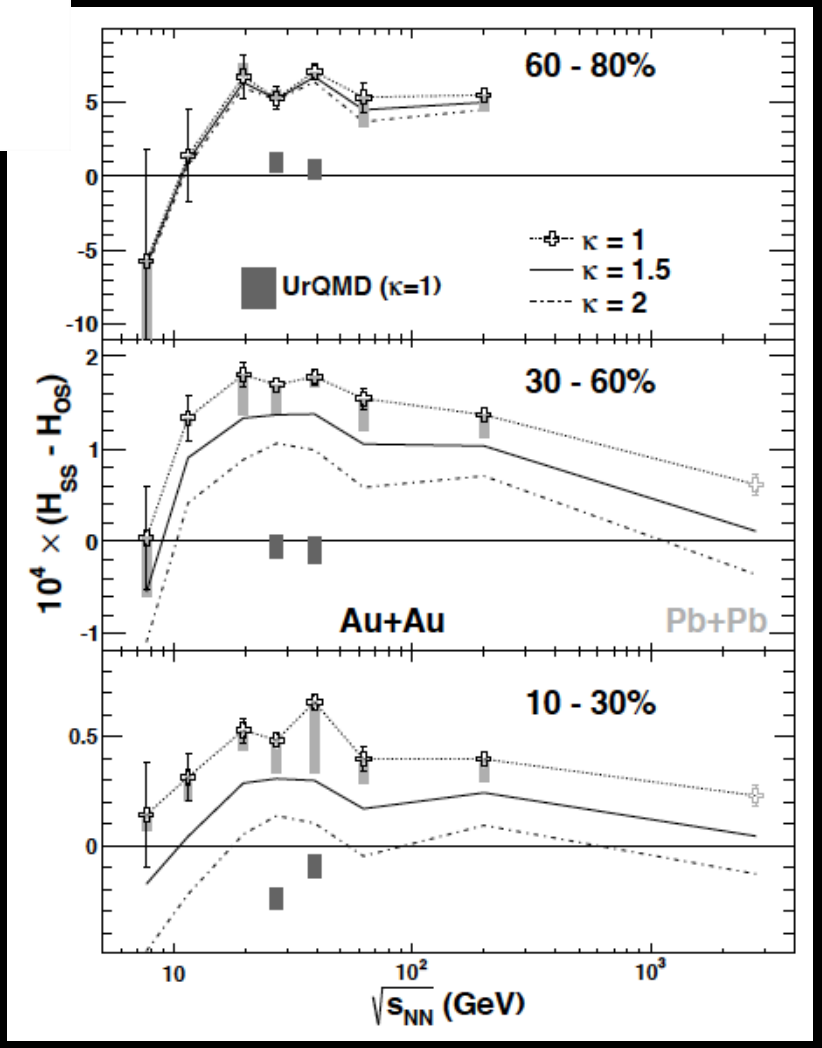
1c – Chiral Magnetic Effect

PRL 113, 052303 (2014)





"Signal-background"



Higher resolution/stats desirable at low energies

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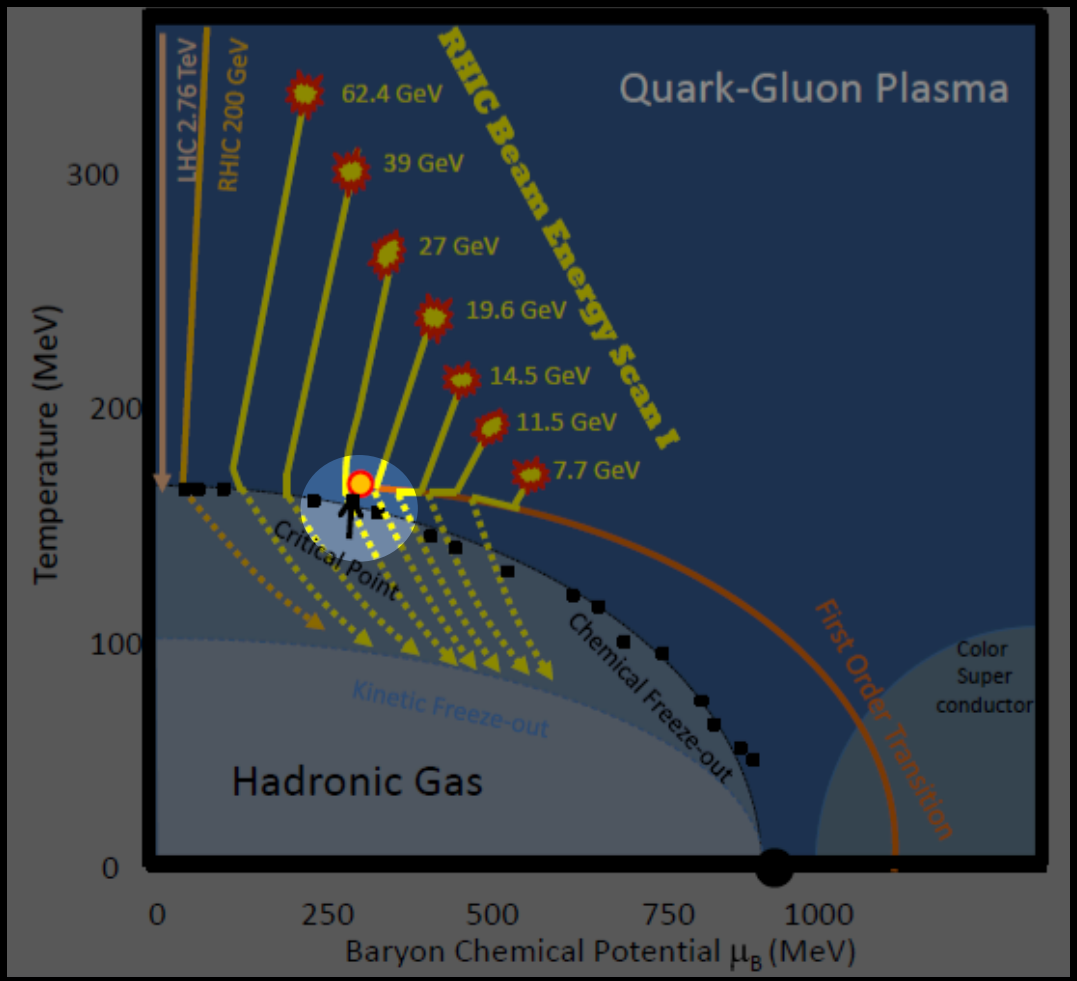

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2a – net-proton multiplicity moments

Susceptibility ratios of conserved quantities (c_{BQS}) are related to the moments of experimentally measurable multiplicity distributions.

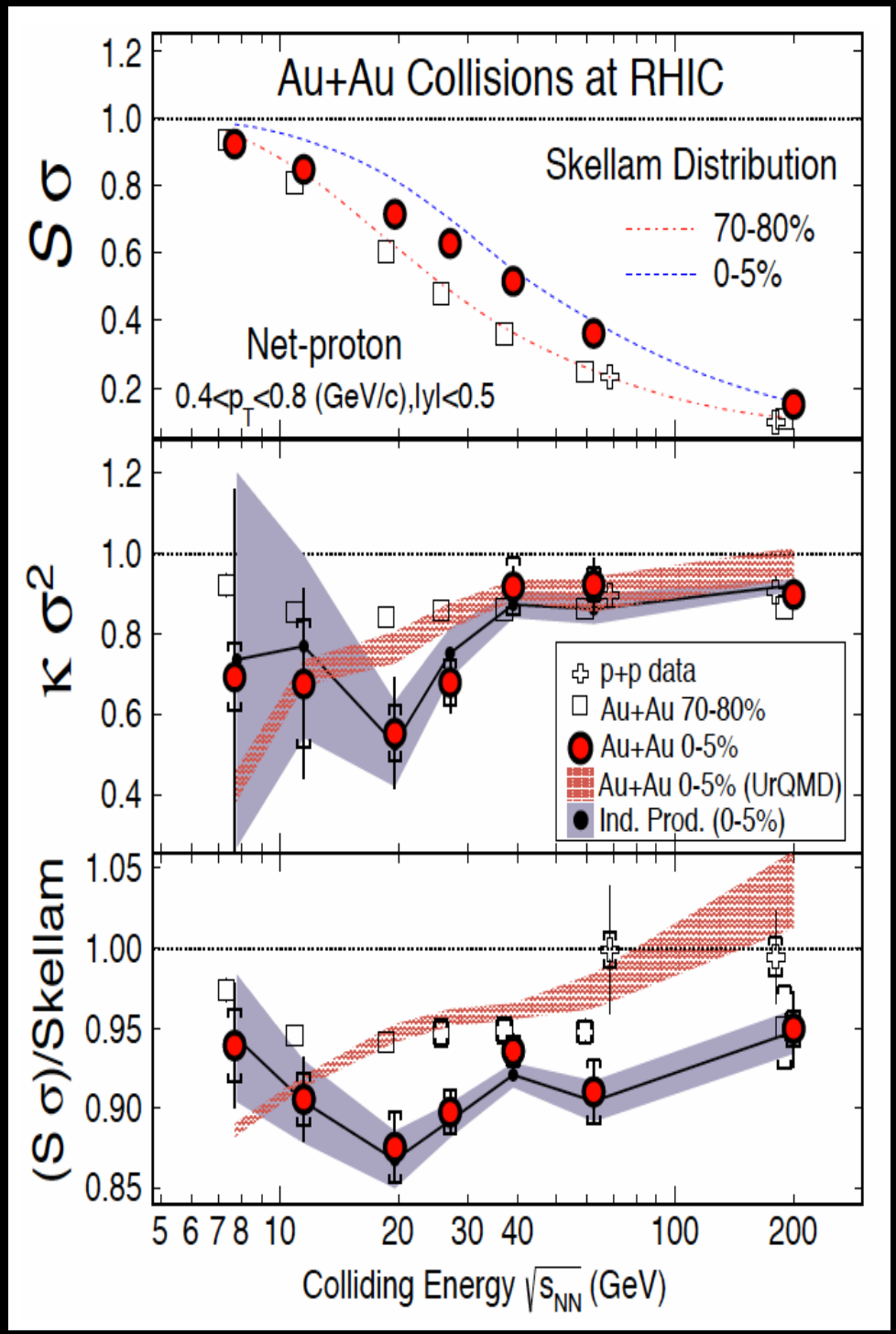
$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial (\mu_B/T)^n}\right|_T$$

$$\chi_B^4 / \chi_B^2 = (\kappa\sigma^2)_B$$
$$\chi_B^3 / \chi_B^2 = (S\sigma)_B$$

F. Karsch, PoS (CPOD07) 026, PoS (Lattice 2007) 015

Higher statistics is necessary to further clarify net-proton results.

PRL 112, 032302 (2014)

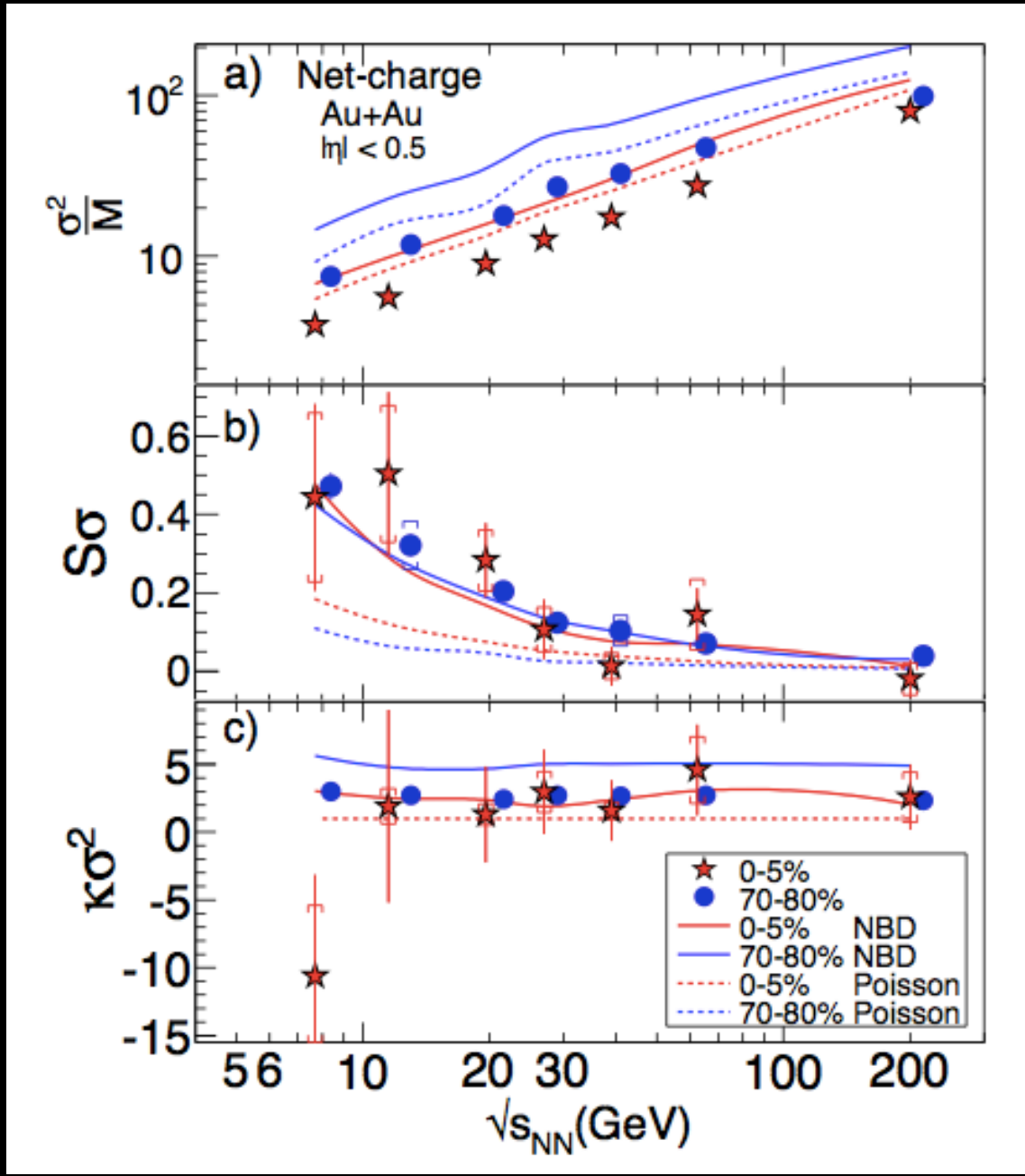


2b – net-charge multiplicity moments

No evidence of non-monotonic behavior of net-charge moment products.

HRG- and lQCD-based analysis of net-proton and net-charge higher moments indicate freezeout conditions ~consistent with those from yields

- Alba et al, arxiv:1403.4903
- Borsanyi et al, arxiv:1403.4576



arXiv:1402.1558, accepted by PRL

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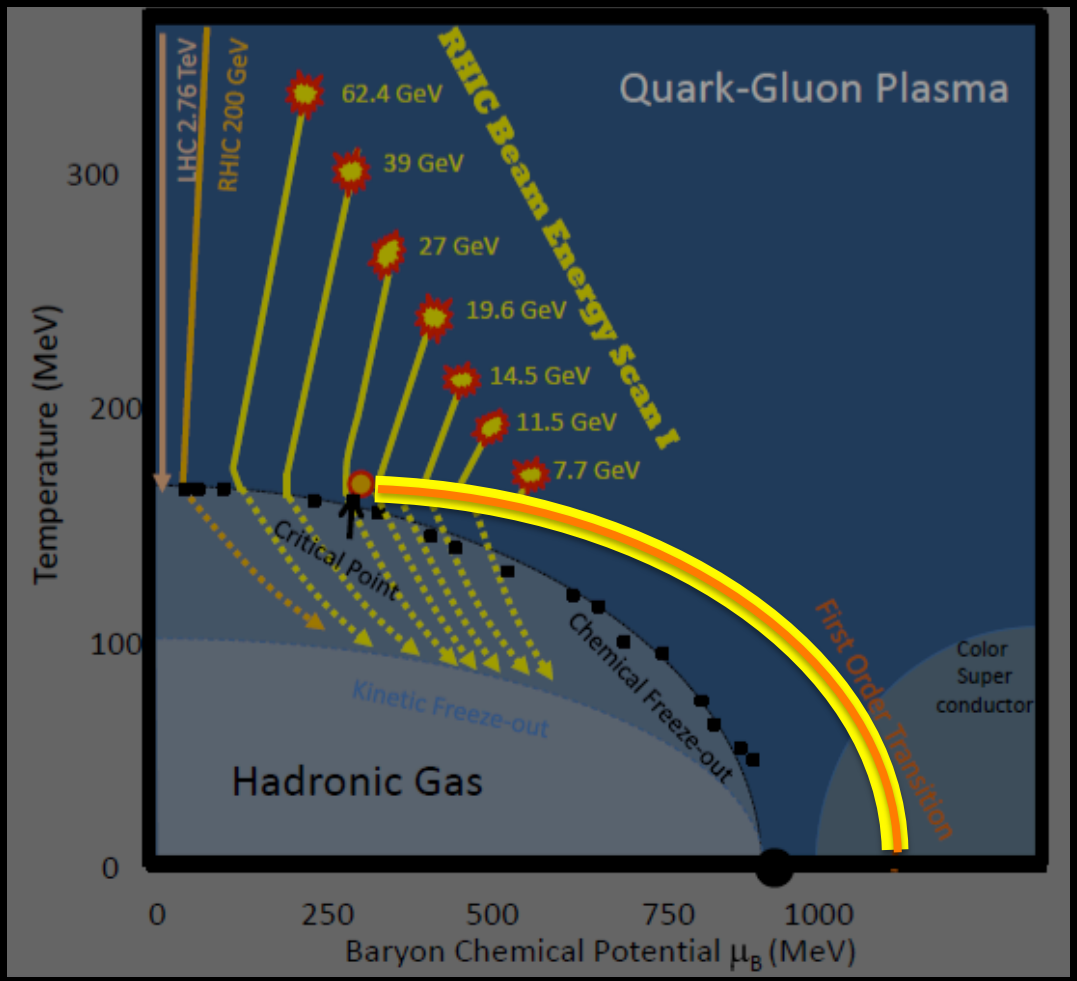

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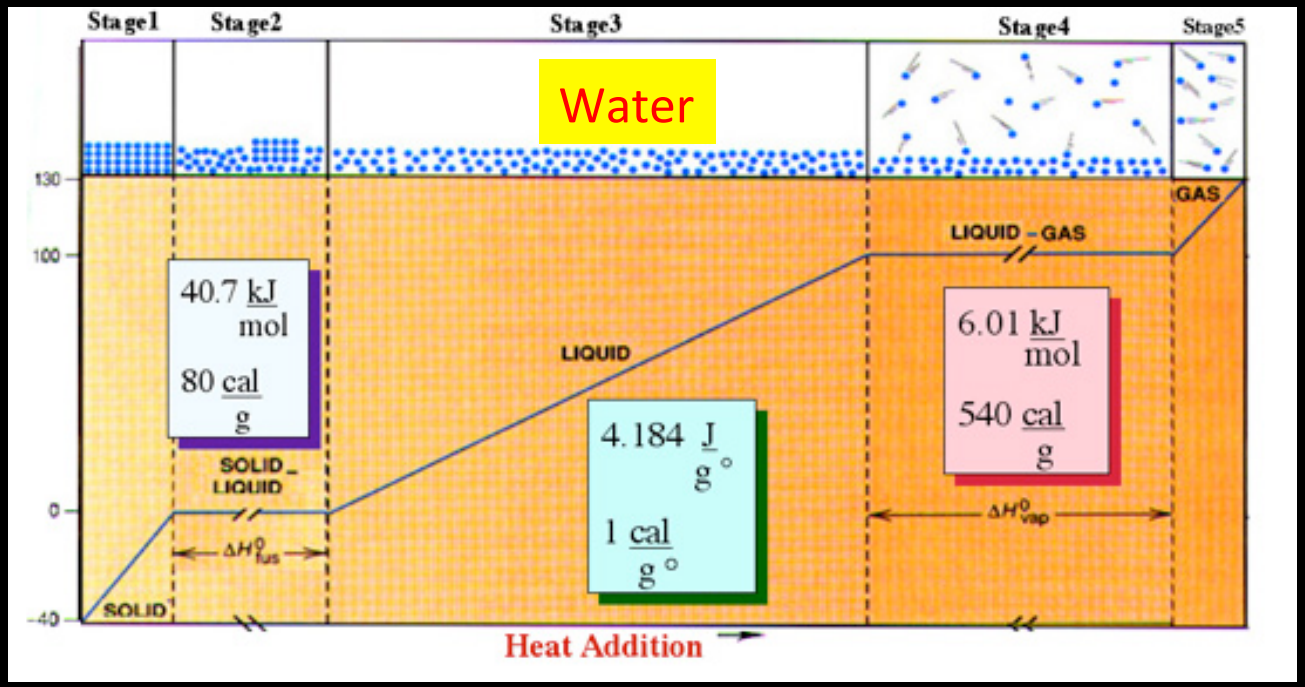
3a – Hints of a caloric curve?



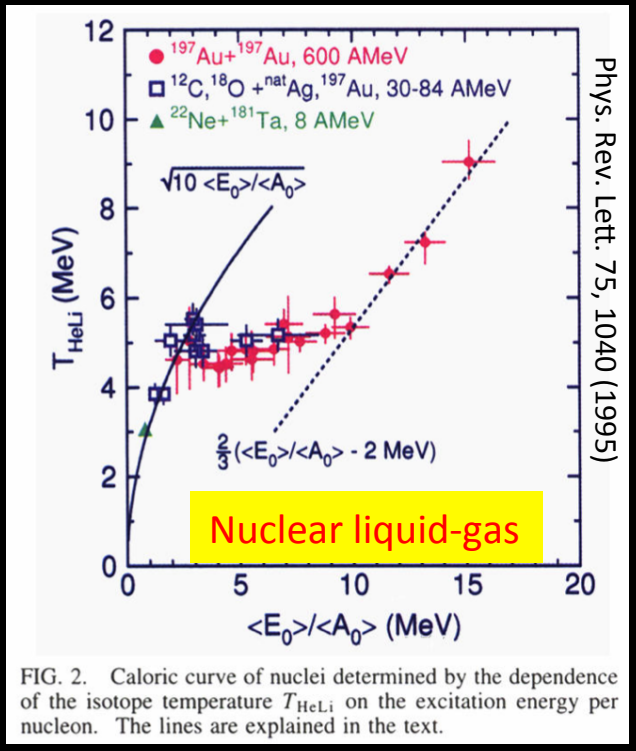
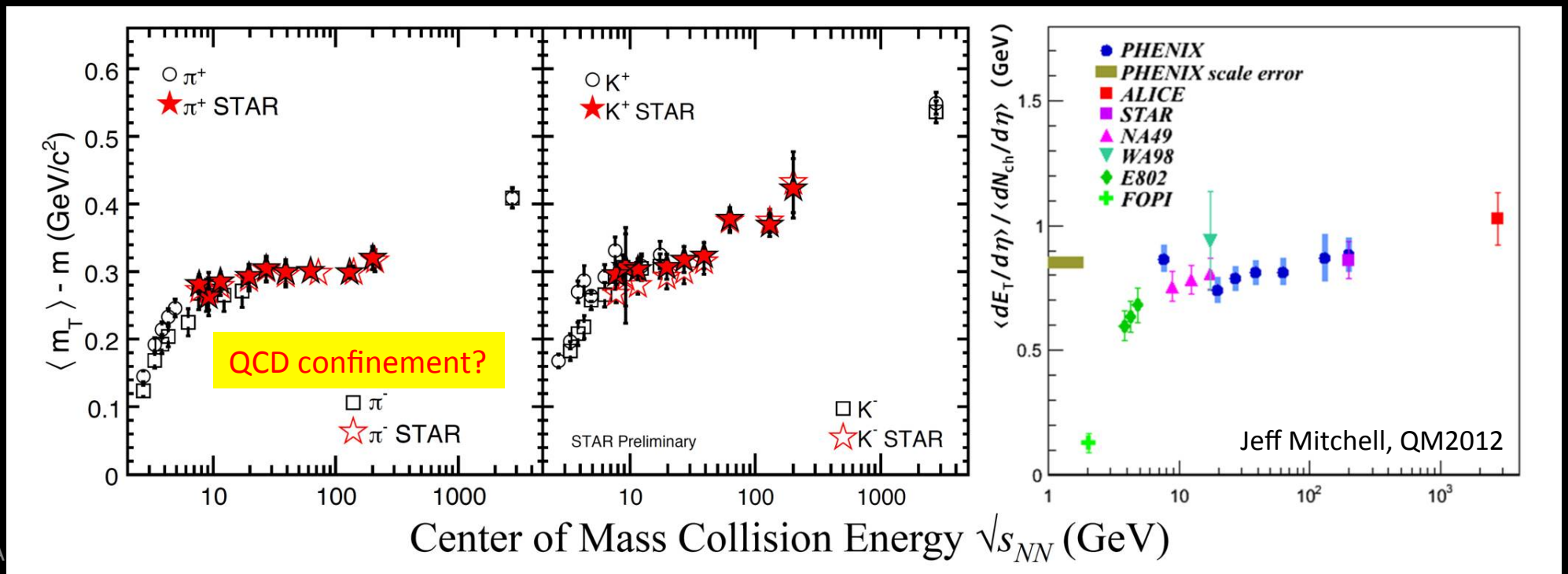
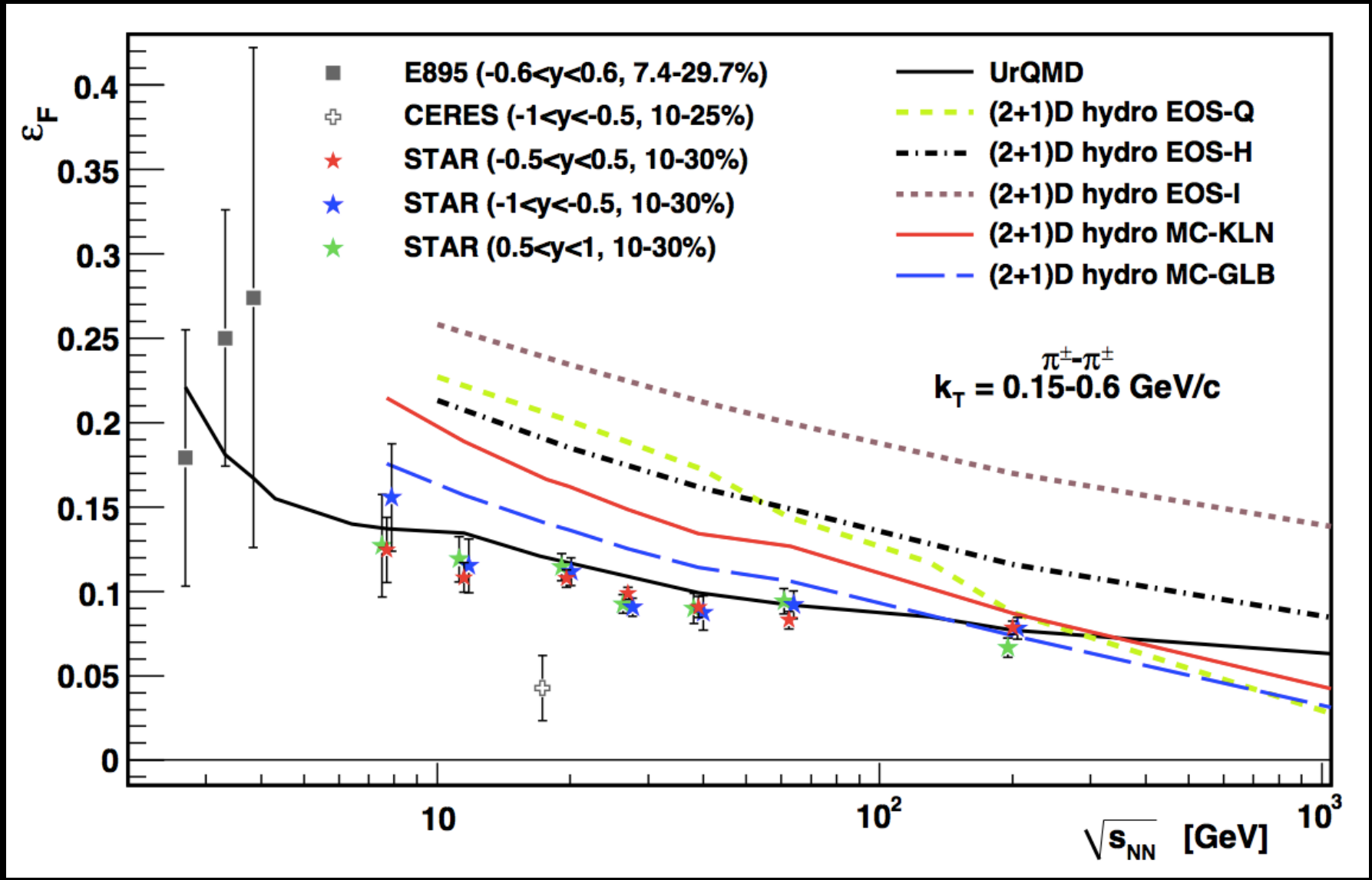


FIG. 2. Caloric curve of nuclei determined by the dependence of the isotope temperature T_{HeLi} on the excitation energy per nucleon. The lines are explained in the text.



3b - asHBT

arxiv:1403.4972

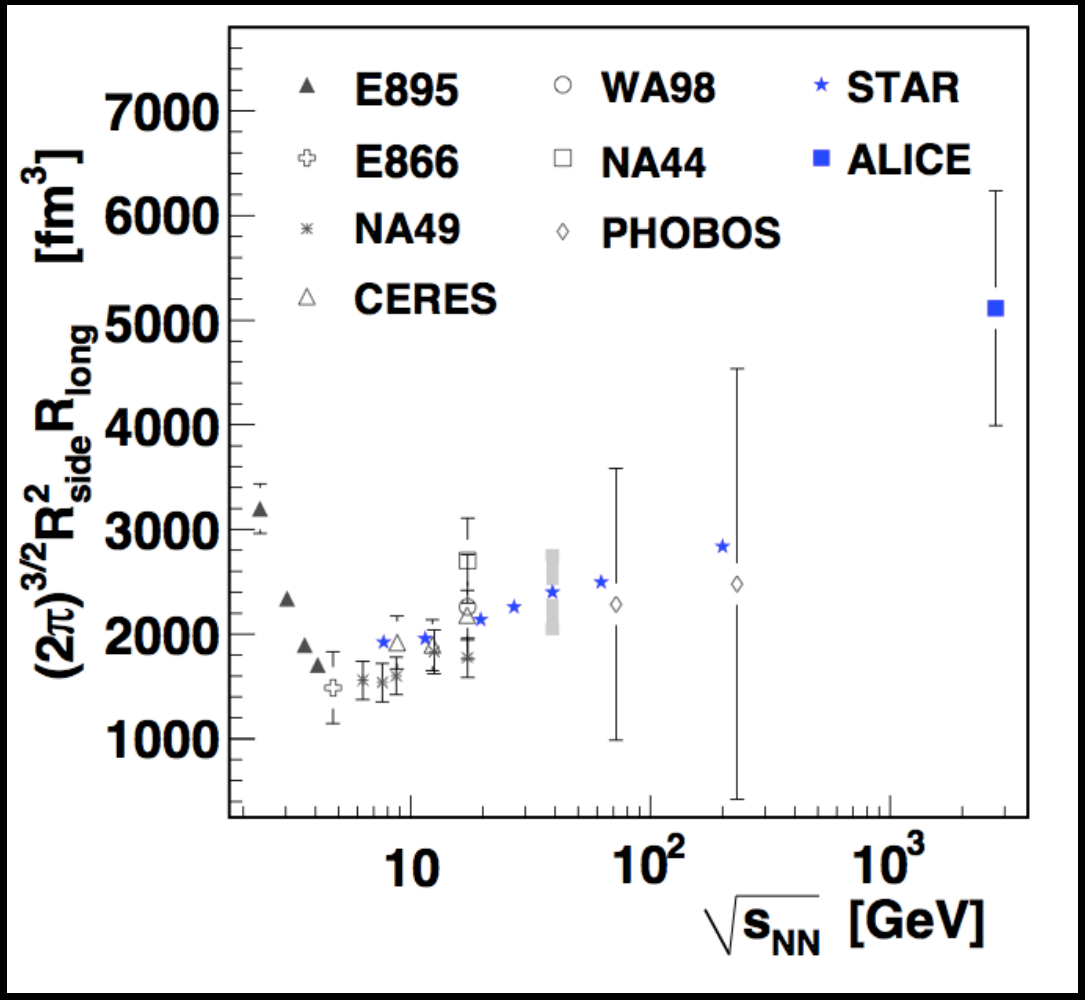


Sensitive to EoS within models, but no “special” behaviour observed

3c - “regular” HBT

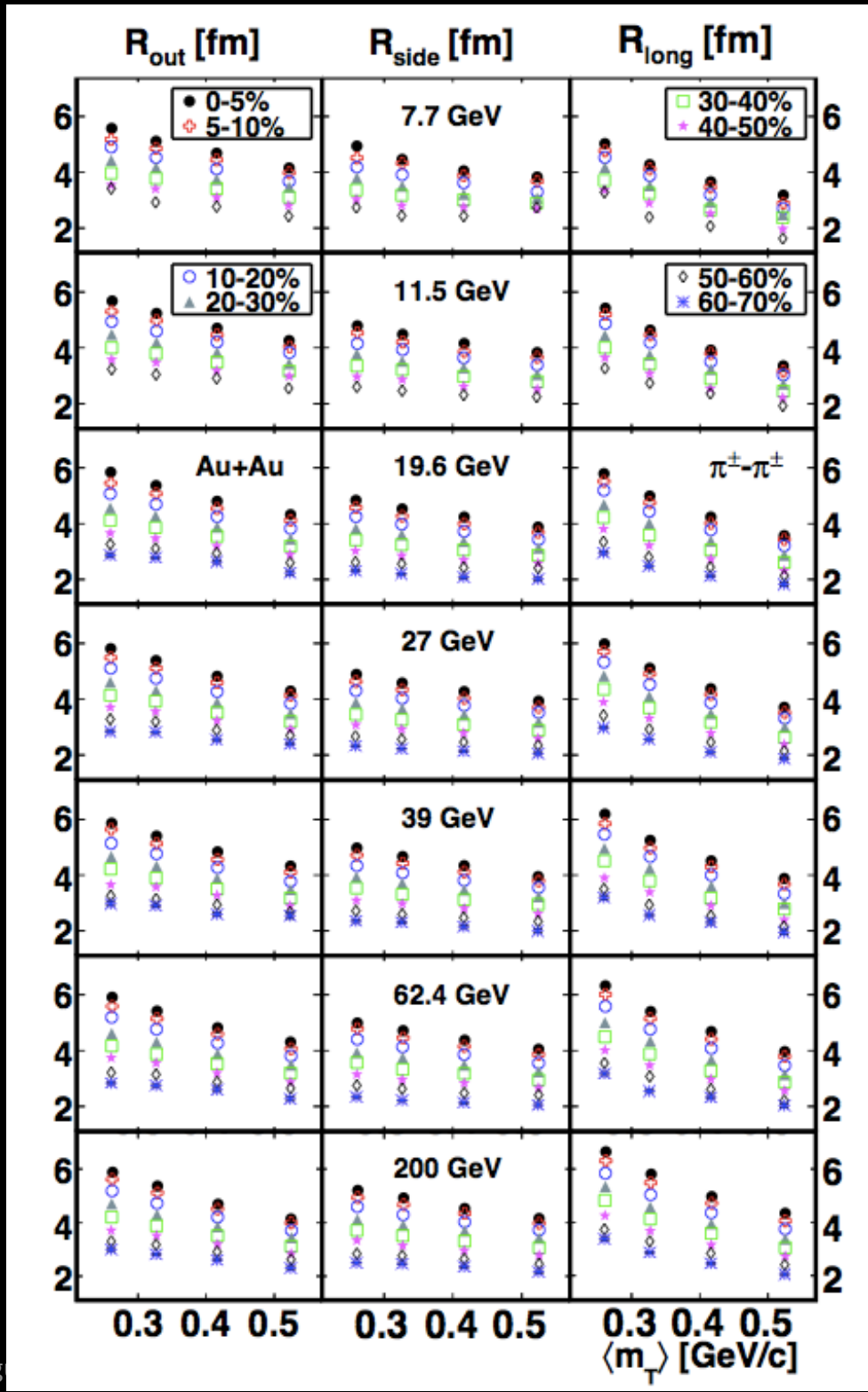
arxiv:1403.4972 -

HBT radii versus: N_{part}, k_T, ϕ, $\sqrt{s_{NN}}$



CERES explanation: constant mfp at F.O..

Minimum as system evolves from baryon- to meson-dominance



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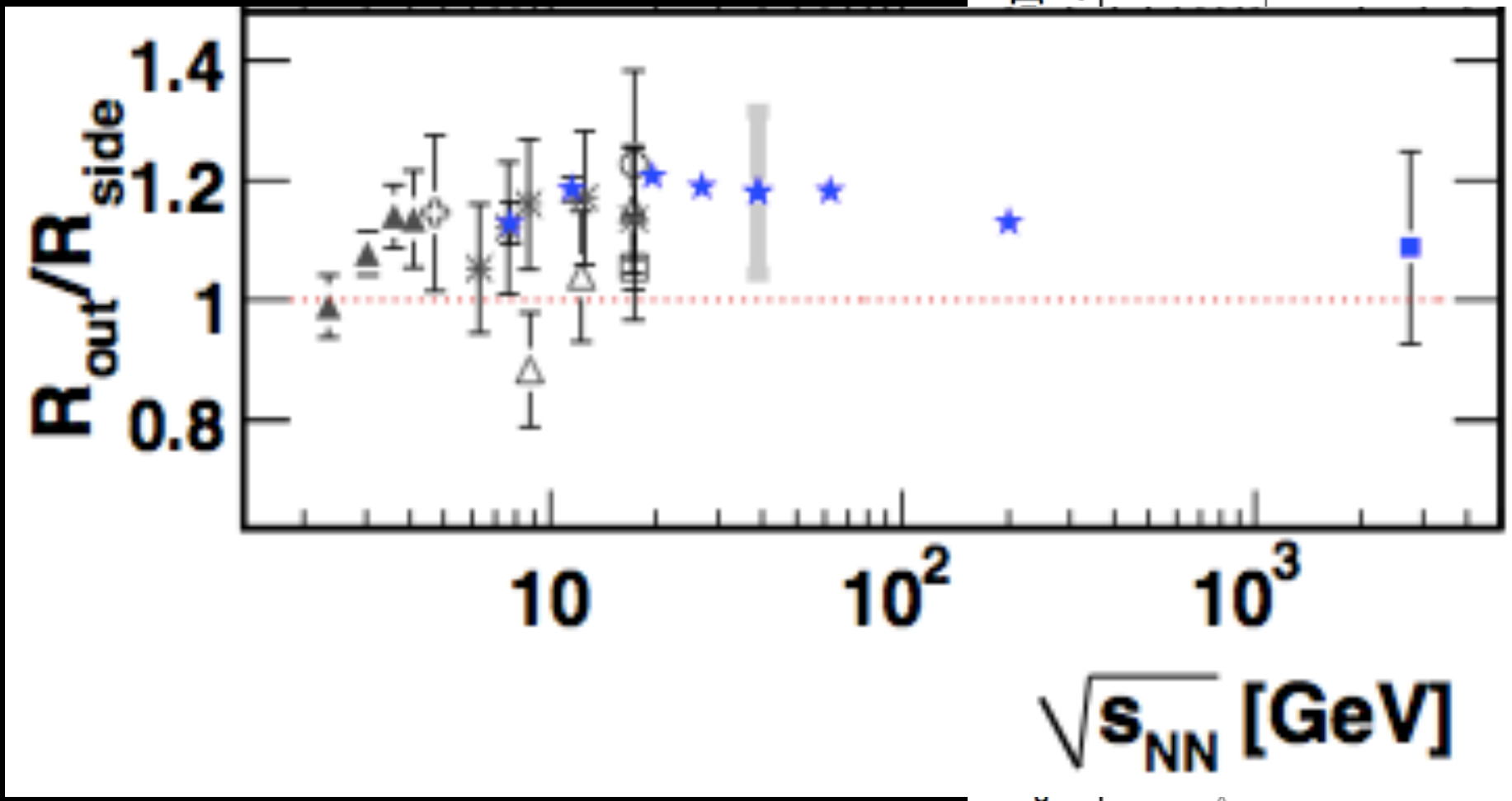
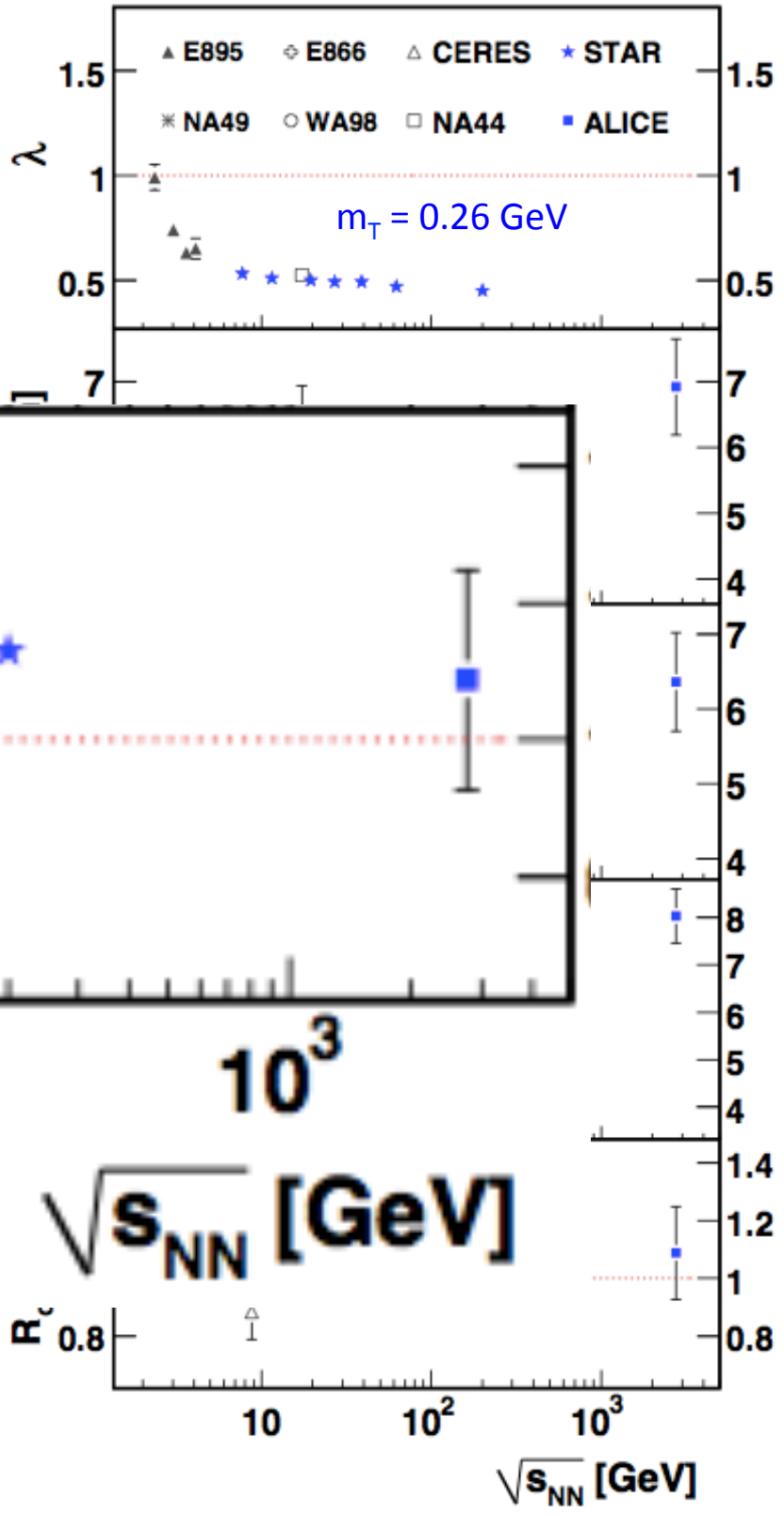
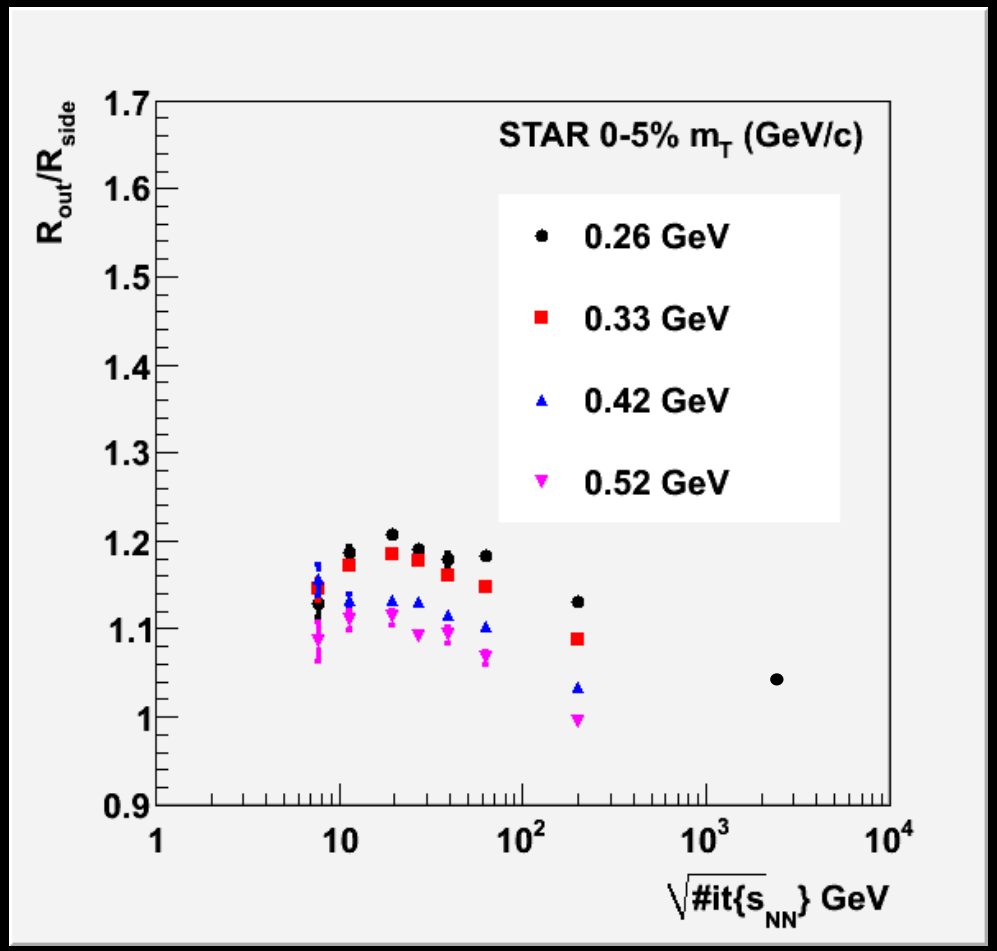
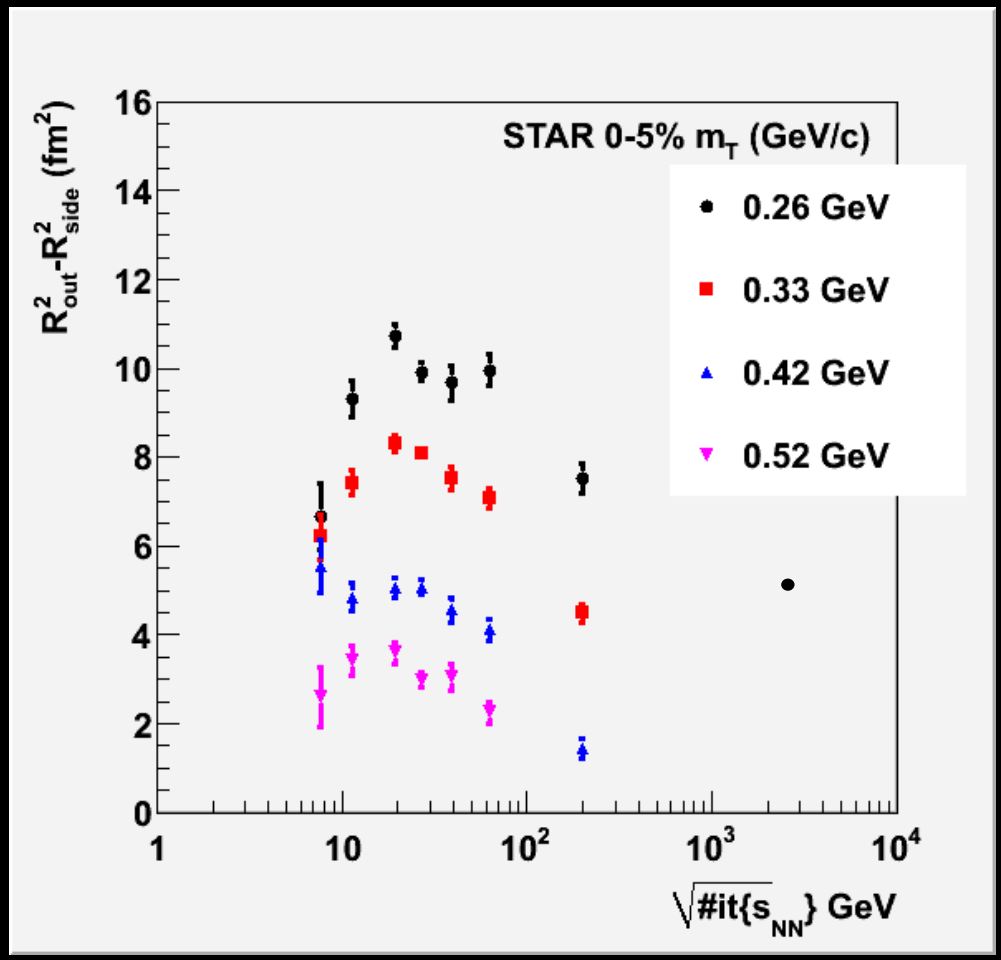




R_{out} and R_{side}





Gyulassy/Rischke: $\frac{R_o}{R_s}$

Naive, no-flow: $(c\beta\tau)^2 = R_o^2 - R_s^2$

The "grail" after all? – *If so, then it is STAR data, but thanks to Roy for pushing*

side note – "m_T scaling"

HBT radii do not scale as $\frac{1}{\sqrt{m_T}}$

longitudinal radius falls faster; transverse slower.

In all measurements (see Ann.Rev.Nucl.Part.Sci 55 357 (2005))

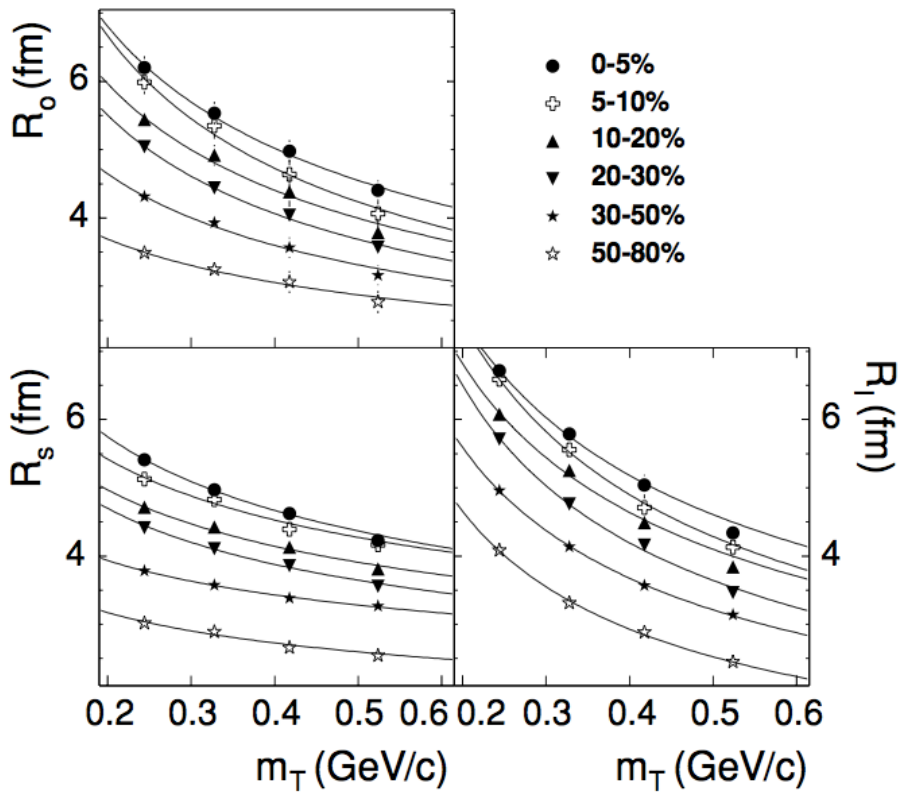
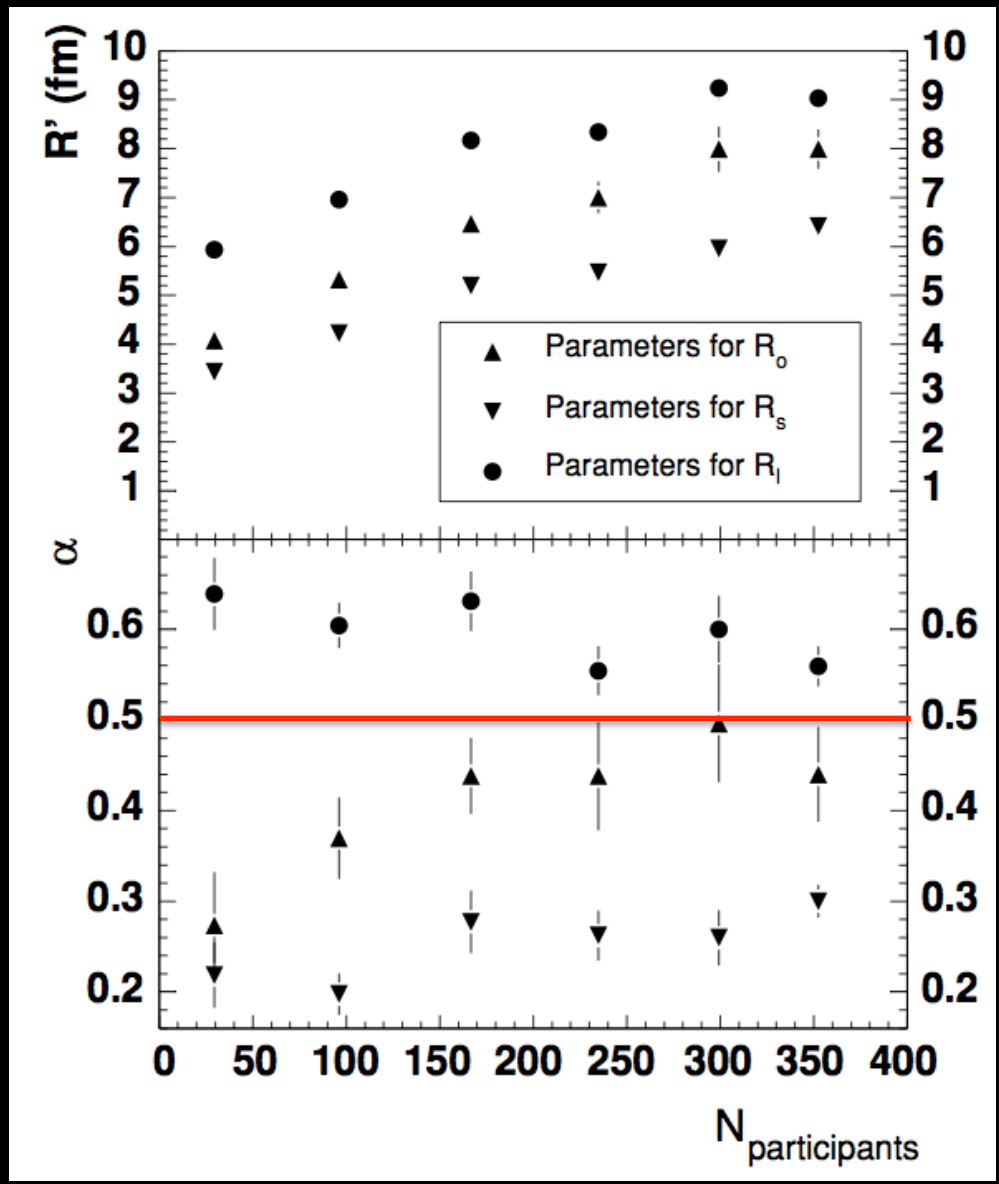


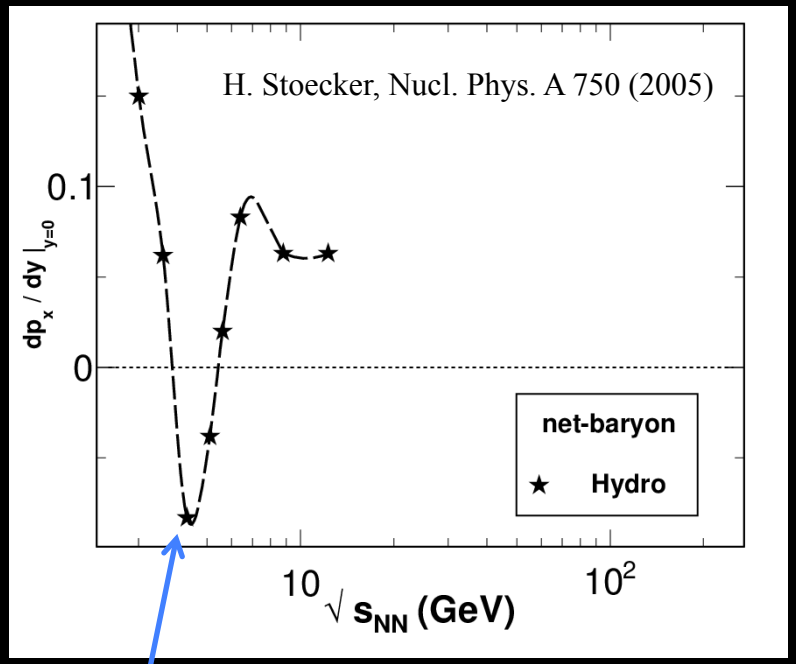
FIG. 20. HBT radius parameters for six different centralities. The lines indicate power-law fits $[R_i(m_T) = R'_i \cdot (m_T/m_\pi)^{-\alpha_i}]$ to each parameter for each centrality.

STAR, 200 GeV Au+Au
PRC **71**, 044906 (2005)



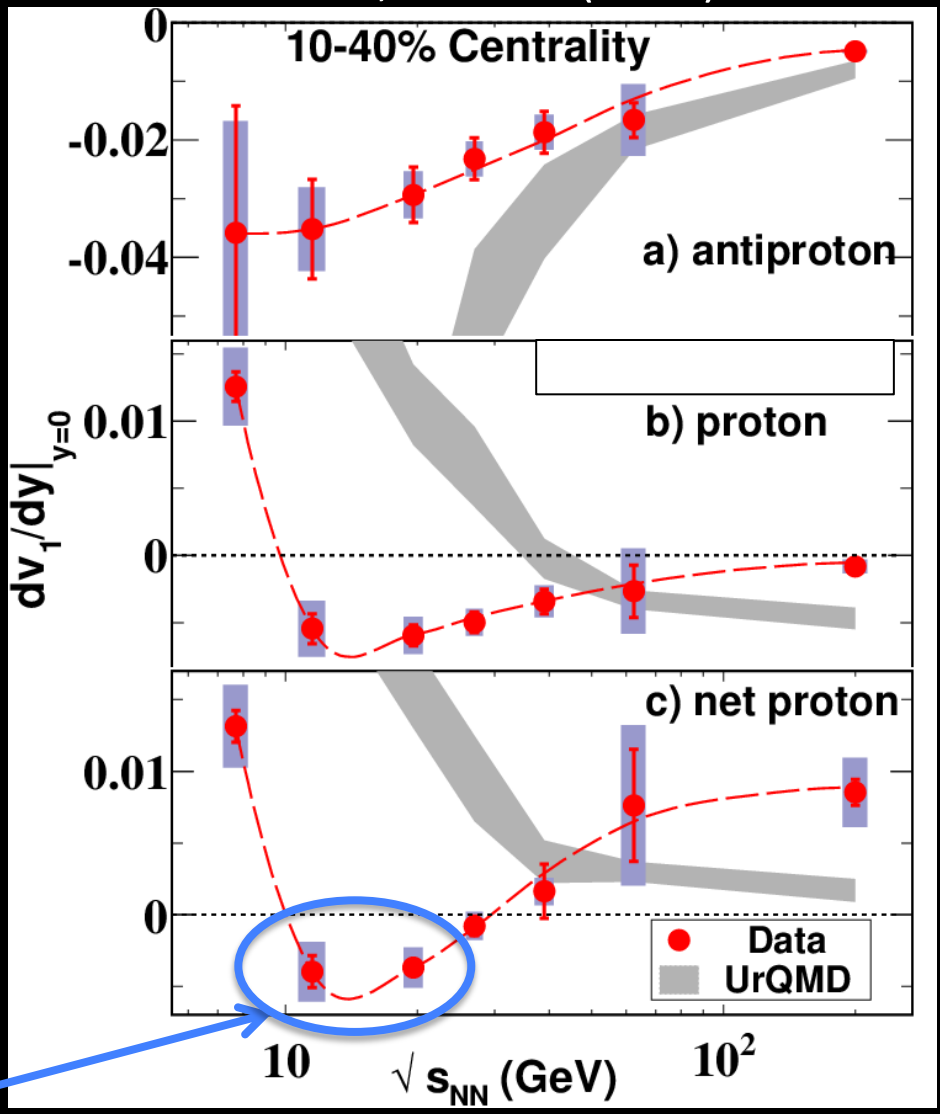
3d – net proton v_1

PRL 112, 162301 (2014)



A 1st order phase transition would be characterized by a region with the lowest compressibility.

The v_1 would show early pressure of system. Softest point?



Summary, but not conclusion

- RHIC BES explores QCD phase structure in an interesting region
- Interesting behaviours seen on many fronts...
  - QGP signatures turn off – Rcp, particle/antiparticle v_2, CME
  - non-monotonic dependences of v_1, HBT radii, net-p kurtosis
- ... but a compelling picture requires
  - better statistics, especially at lower energies
  - finer energy scan 7~20 GeV region
  - ideally, reach to lower energies

	1 - turn off		2 – critical pt		3 - softening	
a)	p/pbar v_2	✓	proton moments	??	caloric curve	✓
b)	R_{cp}	✓	charge moments	✗	asHBT	✗
c)	CME	✓			HBT	✓
d)					net-p v_1	✓✓

✓ does not "prove" anything

Summary, but not conclusion

- RHIC BES explores QCD phase structure in an interesting region
- Interesting behaviours seen on many fronts...
  - QGP signatures turn off – Rcp, particle/antiparticle v_2, CME
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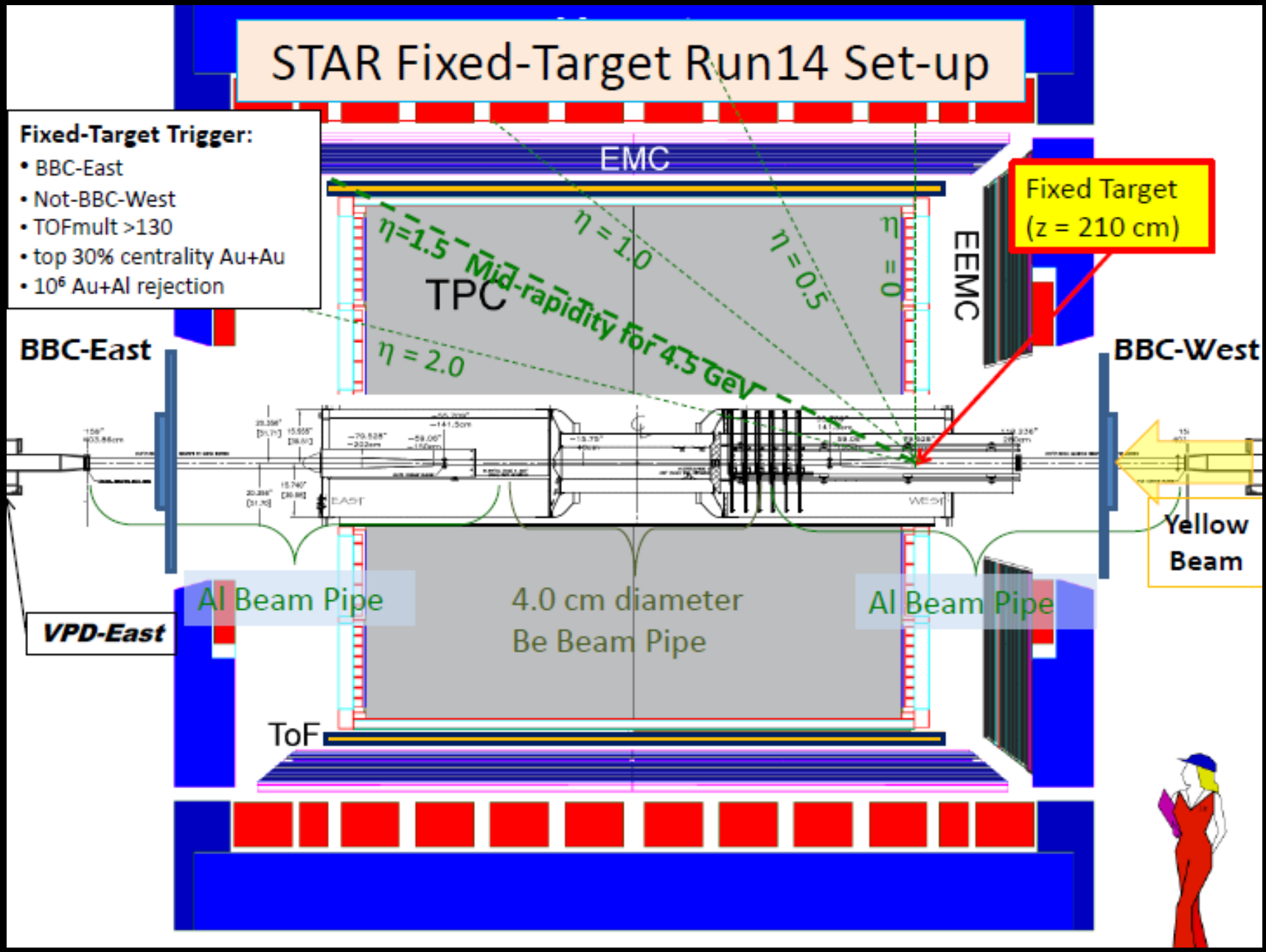
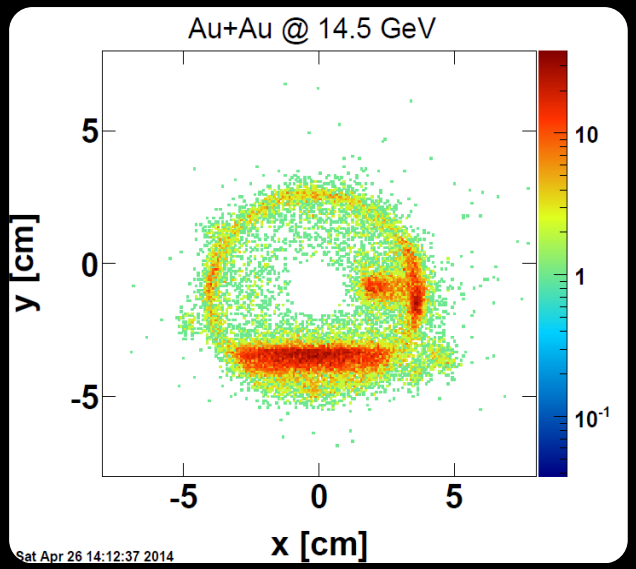
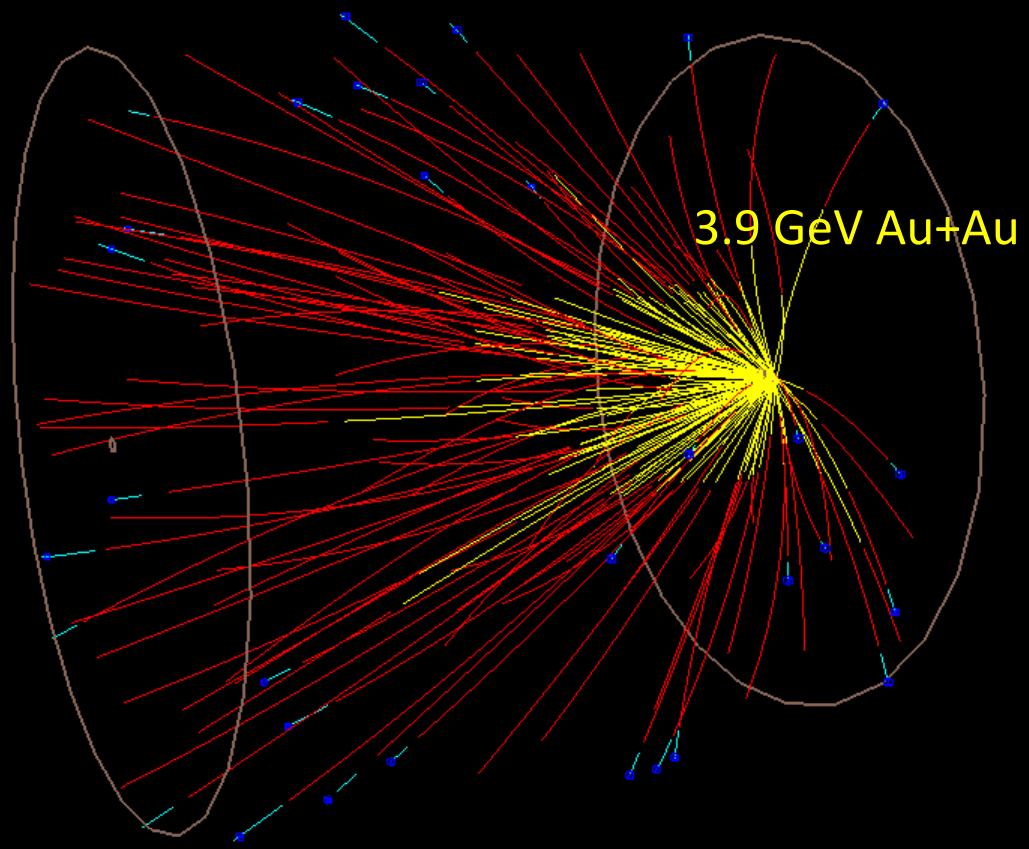
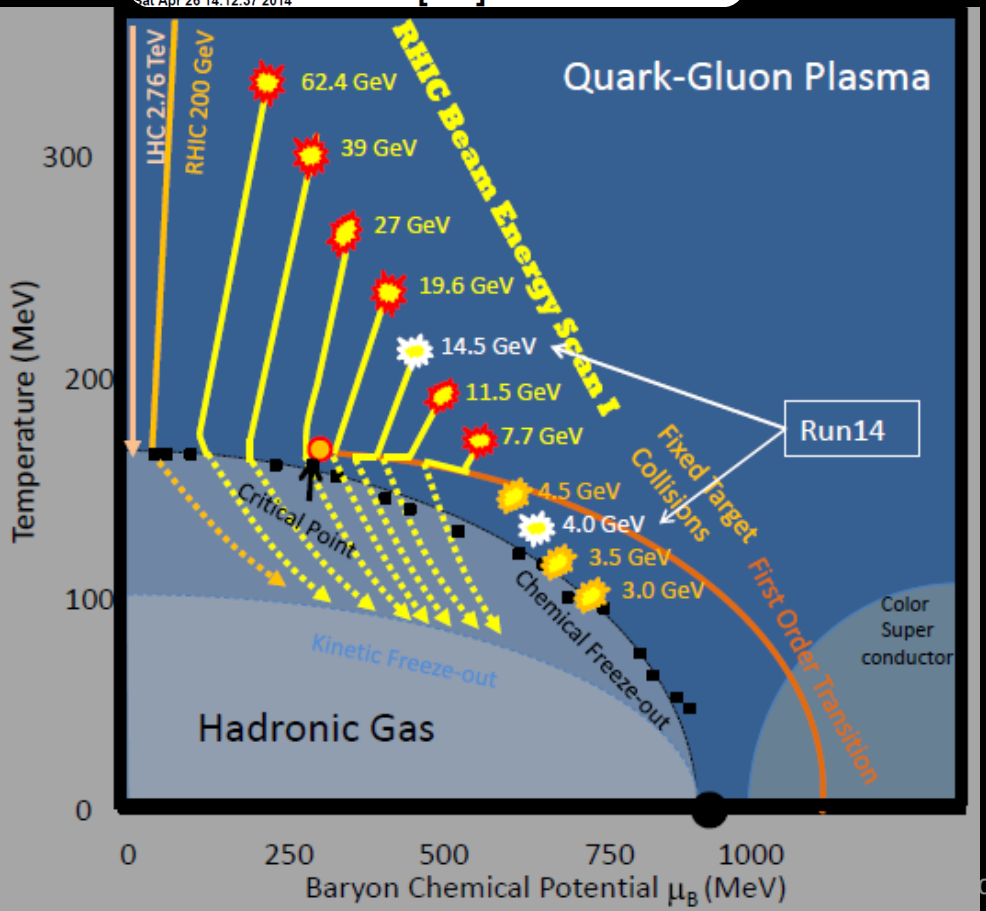

STAR Fixed-Target Run14 Set-up
Fixed-Target Trigger:
• BBC-East
• Not-BBC-West
• TOFmult >130
• top 30% centrality Au+Au
• 10⁶ Au+Al rejection
EMC
η=1.5 Mid-rapidity for 4.5 GeV
η = 1.0
η = 0.5
η = 0
η = 2.0
TPC
EEMC
Fixed Target
(z = 210 cm)
BBC-East
BBC-West
Yellow
Beam
Al Beam Pipe
4.0 cm diameter
Be Beam Pipe
Al Beam Pipe
VPD-East
ToF

3.9 GeV Au+Au event taken during 2014 run







Collider mode Energies (GeV)	7.7	11.5	**14.5**	19.6
Fixed Target $\sqrt{s_{NN}}$ (GeV)	3.0	3.5	**3.9**	4.5
Fixed Target μ_B (MeV)	720	670	**633**	585
Fixed Target y_{CM}	1.05	1.25	**1.37**	1.52

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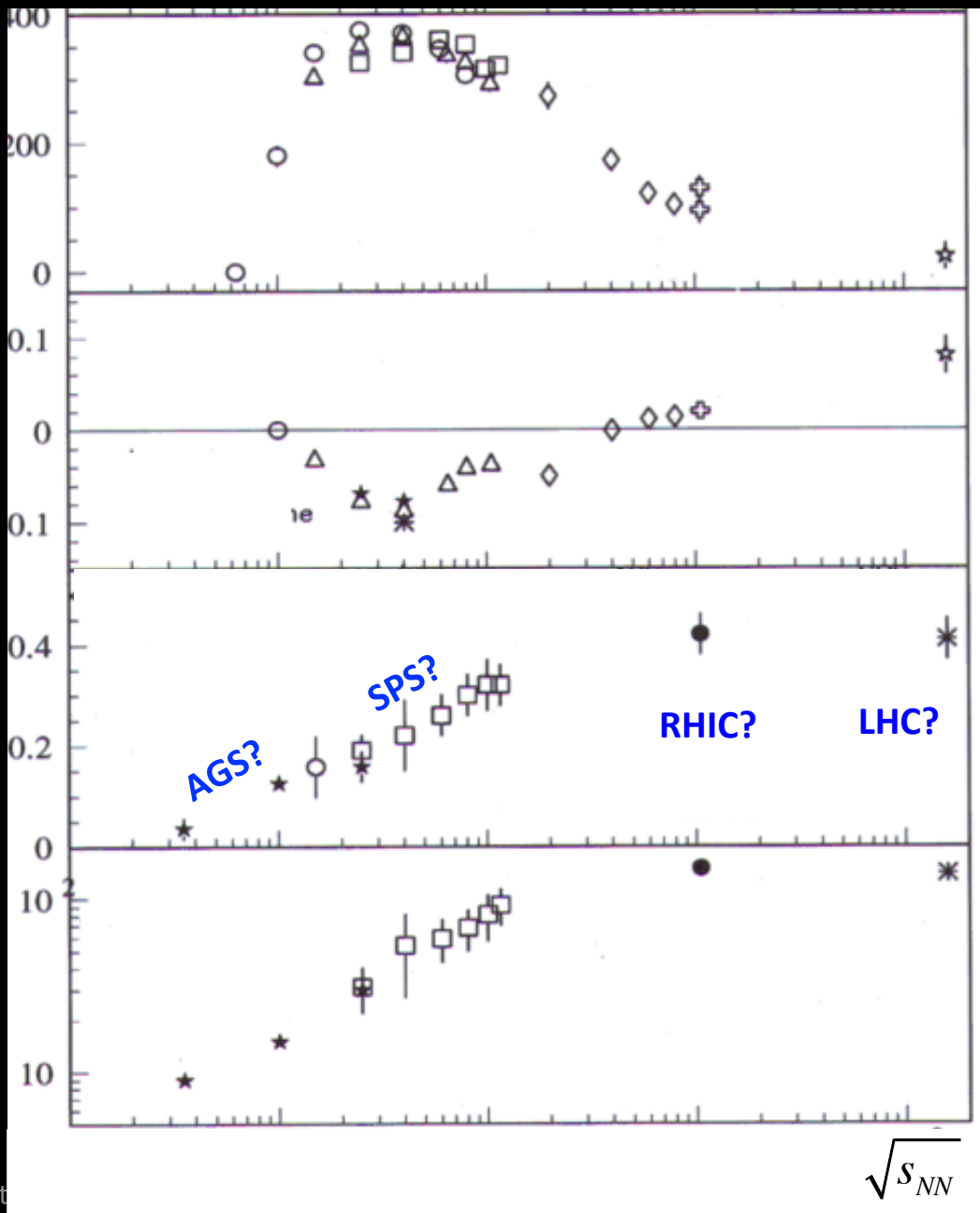
  - serious theory and modeling effort
    - QDC has a scale.
      To understand the strong force, you focus at that scale, even if it's easier somewhere else.

Back to the future?

Scan bulk observables from heavy ion collisions over a large range of energies, looking for “correlated changes”



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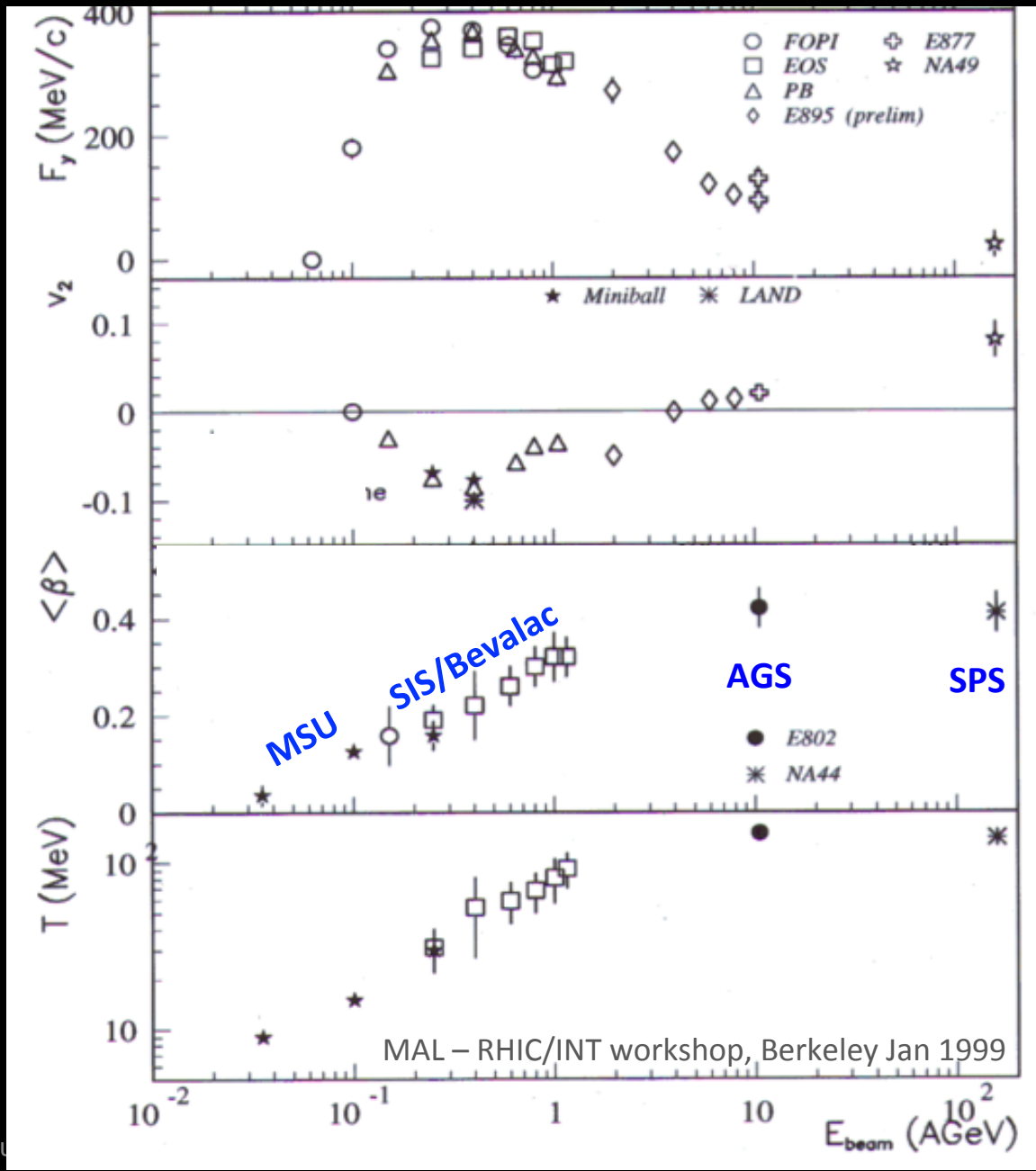

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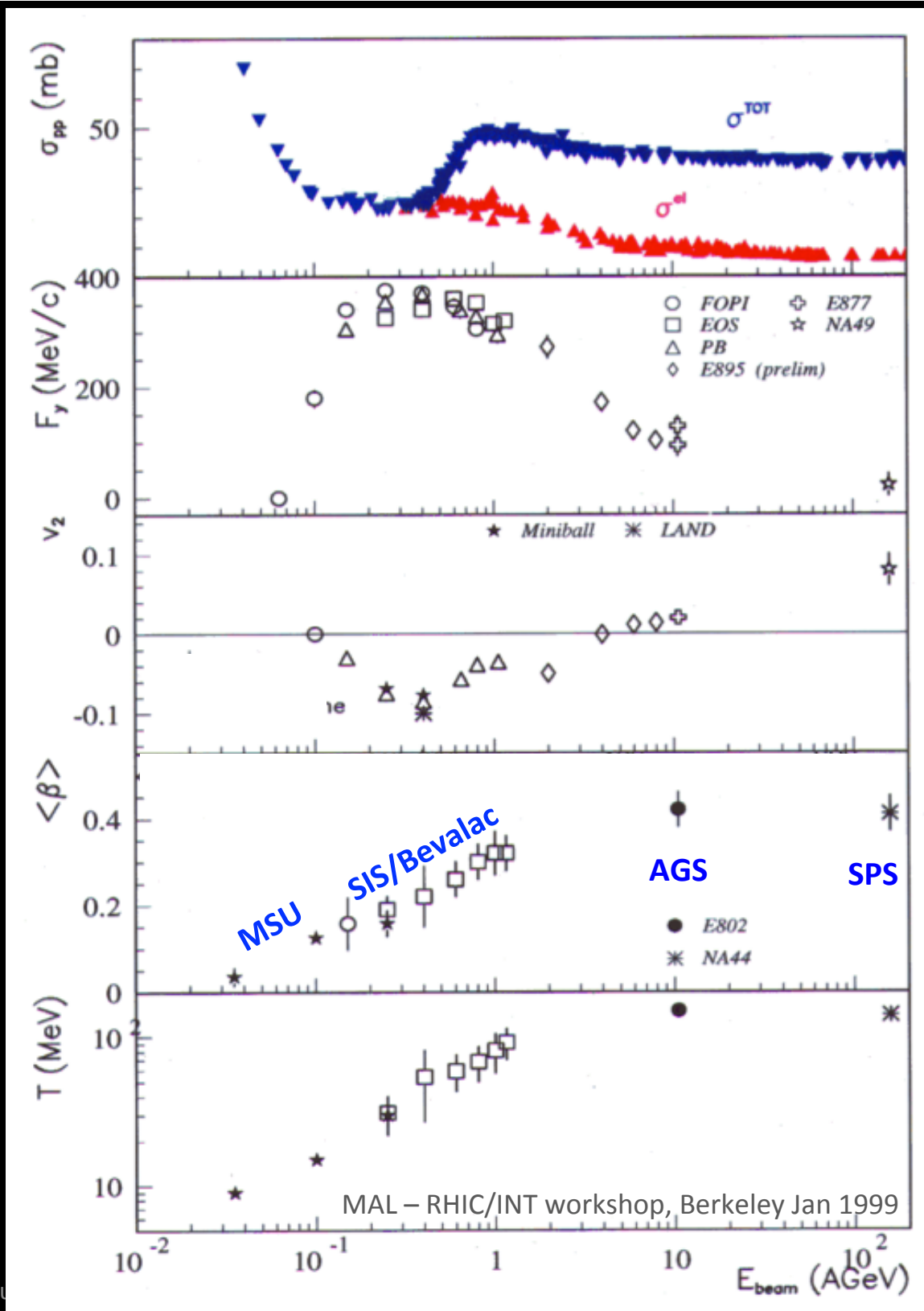

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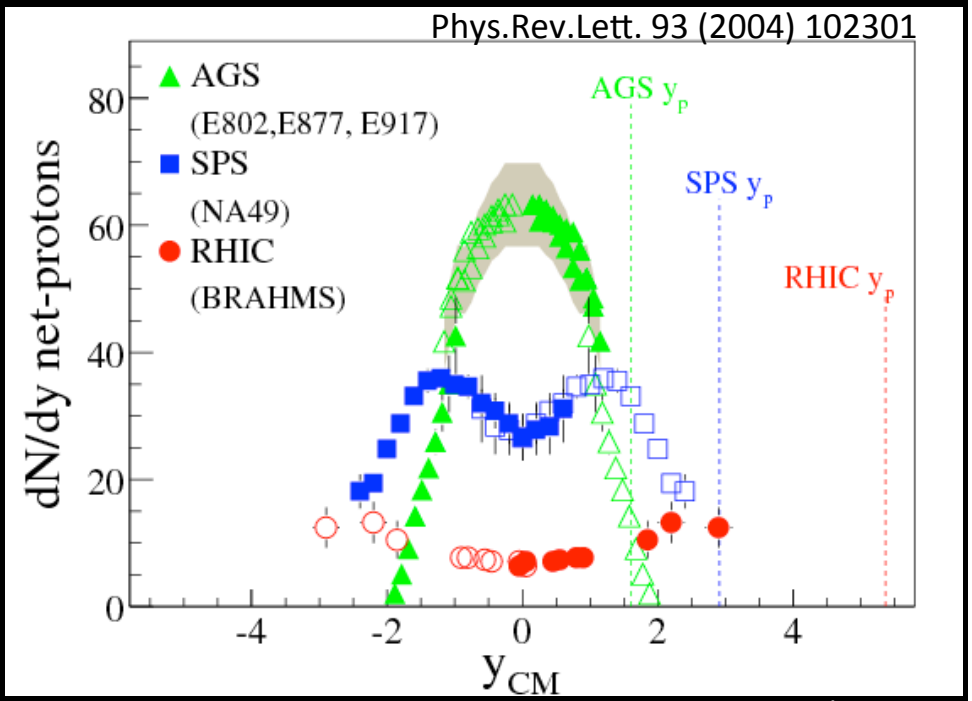
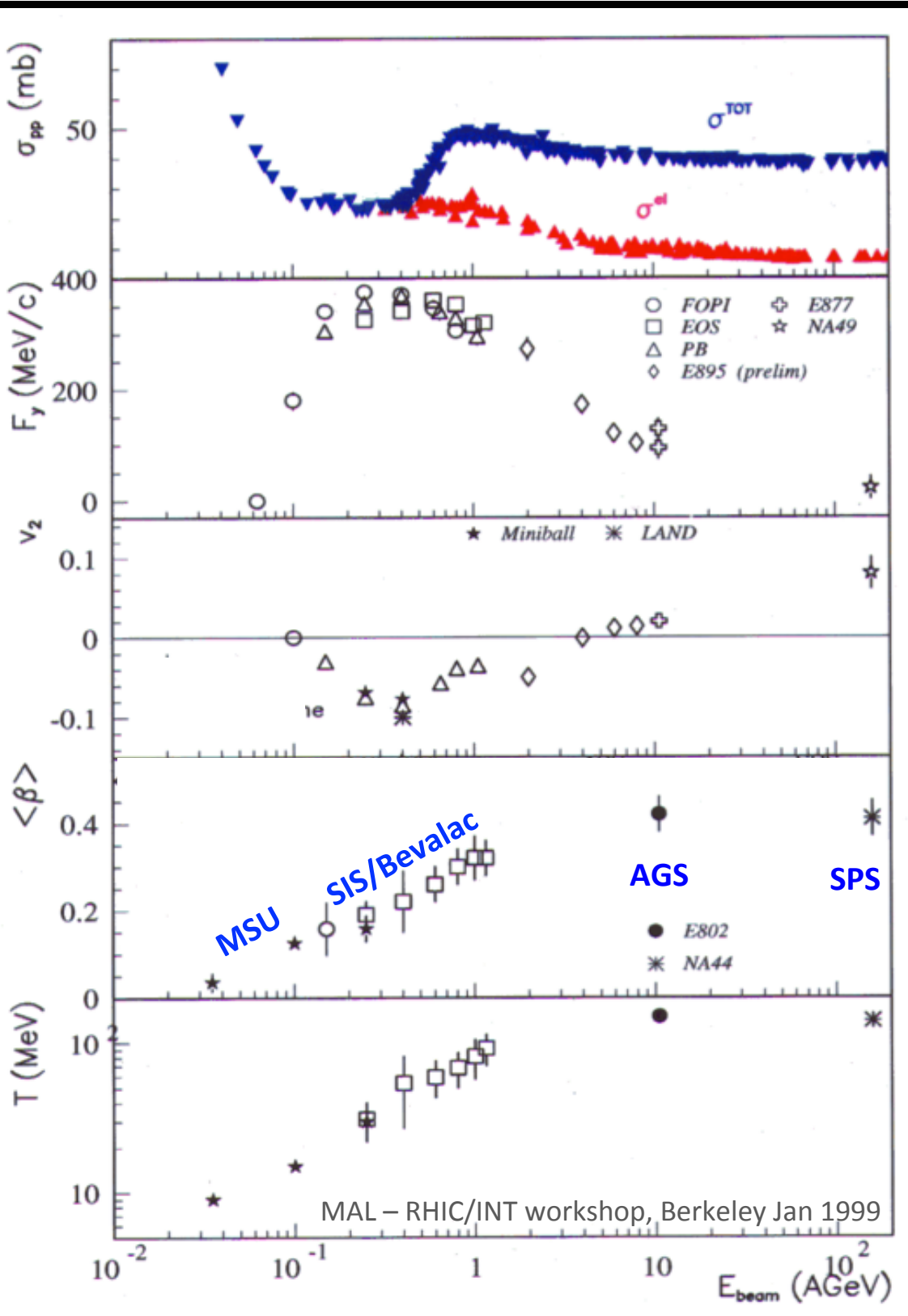
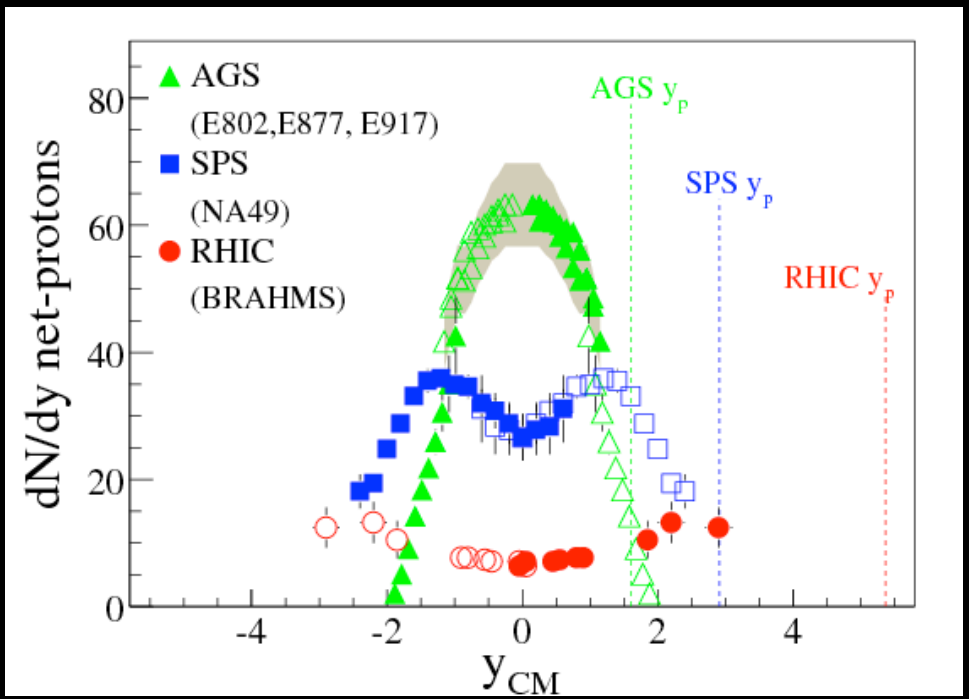


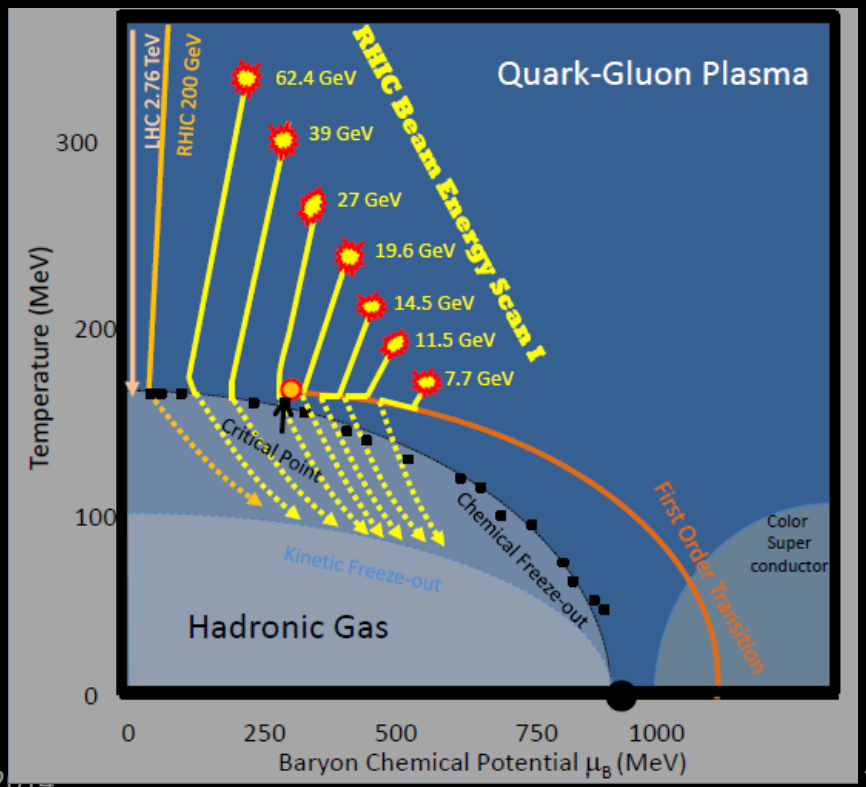


Are the changing signals due to stopping?

Answer – Duh!

The real question is, are they *trivially* due to stopping?





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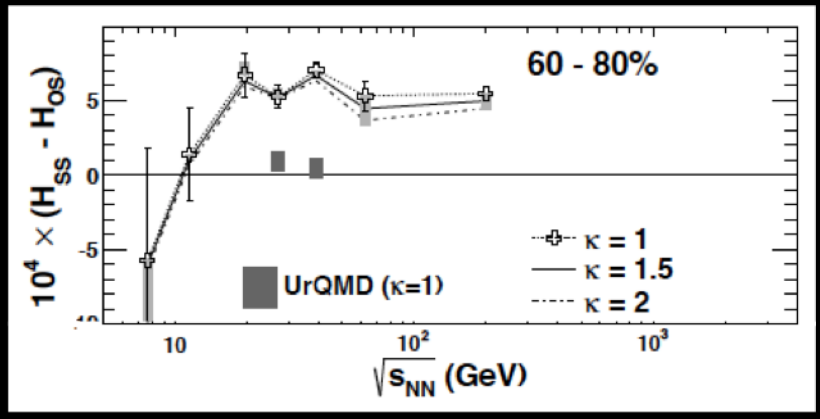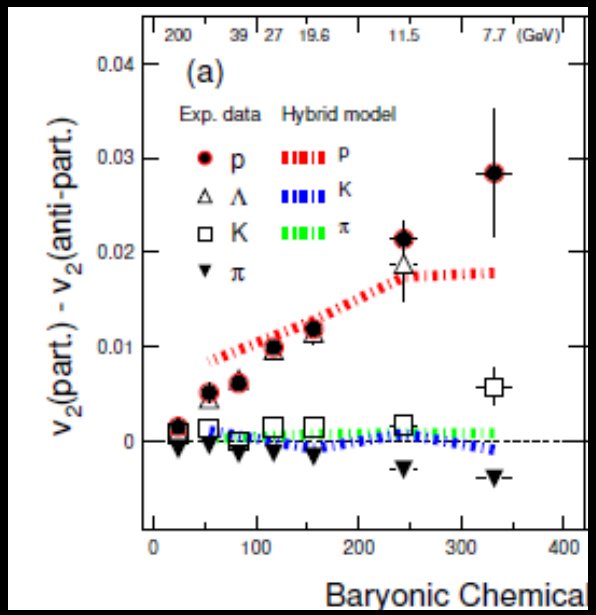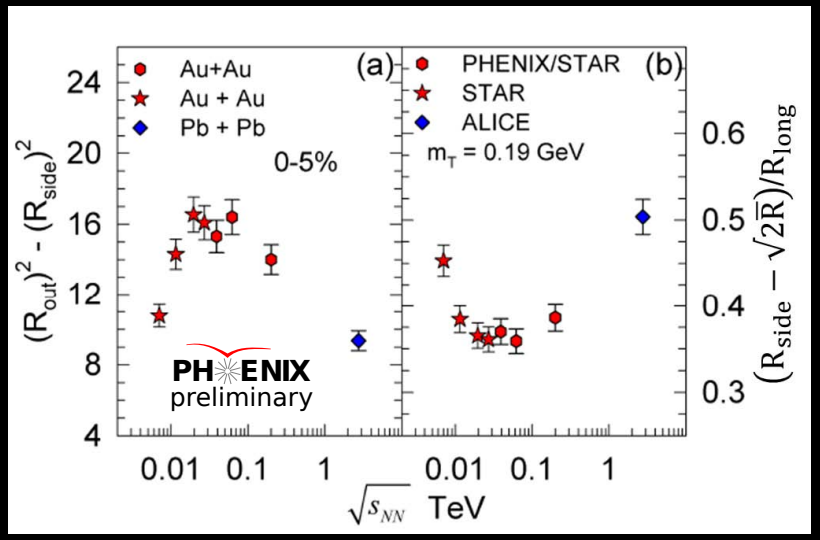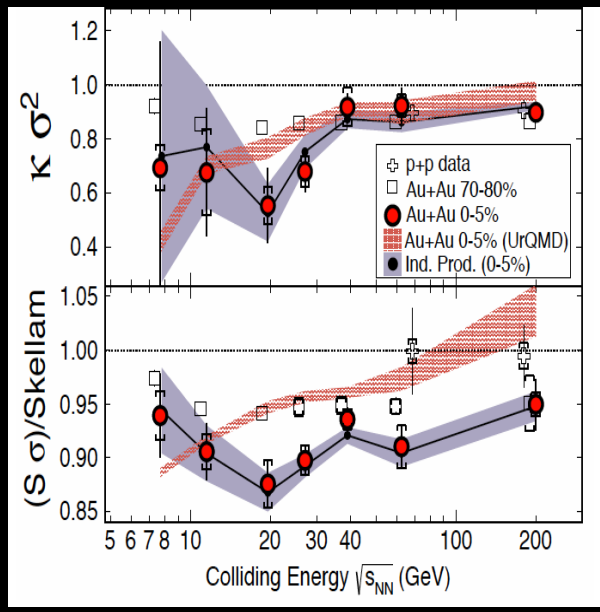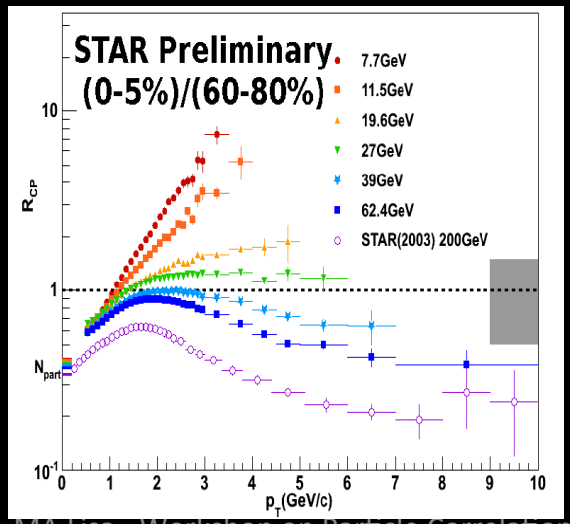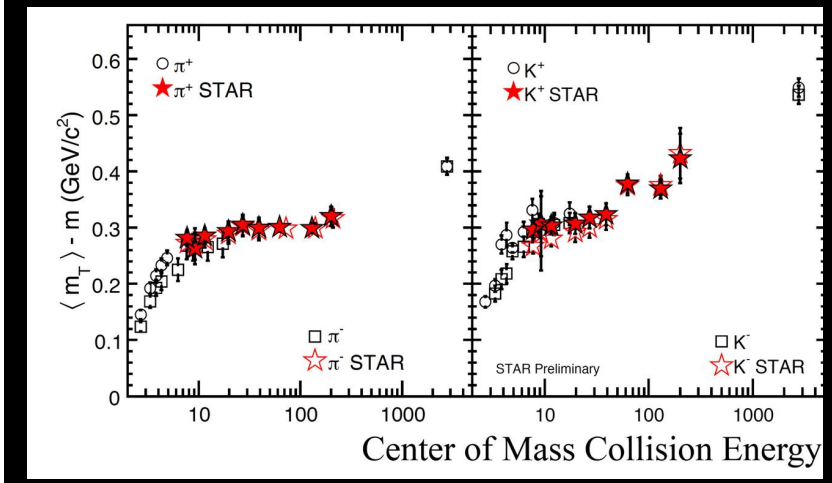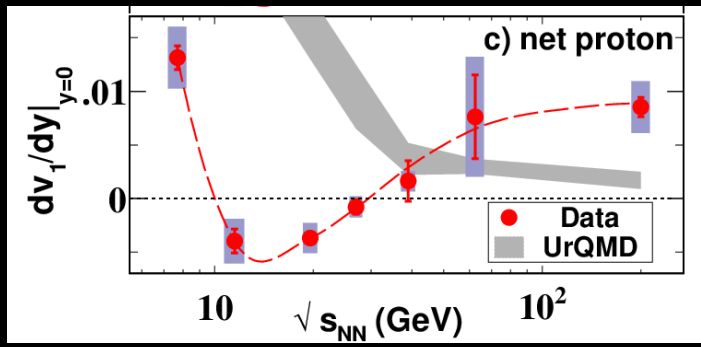
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- more important and harder to answer