System Size and Beam Energy Dependence of Hadronic Production and Freeze-out

Orpheus I Mall
University of California, Davis
for the STAR Collaboration

Strangeness in Quark Matter
Polish Academy of Arts and Sciences
18th – 24th Sep Kraków, Polska

QGP Phase: Lattice

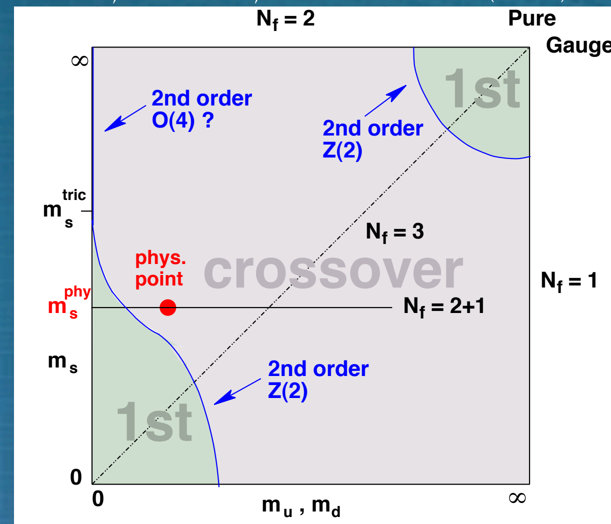
Quark Matter Phase Diagram

- Lattice QCD calculations:

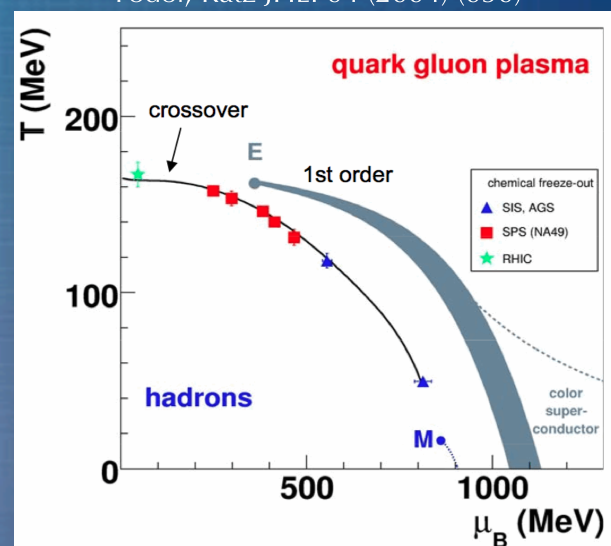
  $m_{u,d} \neq 0, \quad m_s \approx \text{physical}$

  Expect an analytic crossover at low μ_B
- Locations of critical point and first order phase transition vary greatly by model as calculations advance to finite μ_B

Karsch, Laermann, Schmidt PLB520 (2001) 41



Fodor, Katz JHEP04 (2004) (050)

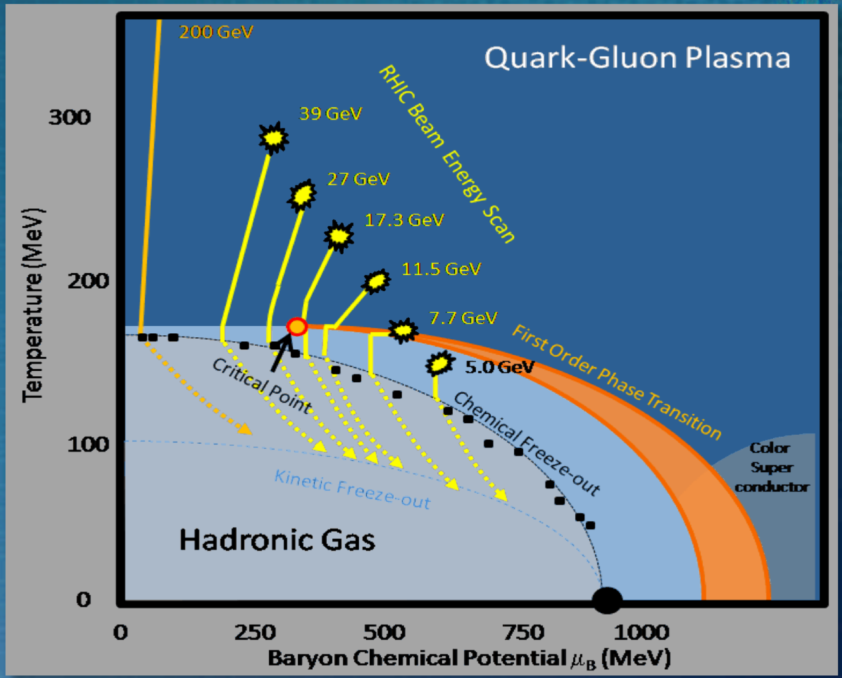


M. Stephanov: arXiv:hep-ph/0402115

Source	(T, μ_B), MeV	Comments	Label
MIT Bag/QGP	none	*only 1st order*	—
Asakawa,Yazaki '89	(40, 1050)	NJL, CASE I	NJL/I
"	(55, 1440)	NJL, CASE II	NJL/II
Barducci, *et al* '89-94	$(75, 273)_{\rm TCP}$	composite operator	CO
Berges, Rajagopal '98	$(101, 633)_{\rm TCP}$	instanton NJL	NJL/inst
Halasz, *et al* '98	$(120, 700)_{\rm TCP}$	random matrix	RM
Scavenius, *et al* '01	(93,645)	linear σ-model	LSM
"	(46,996)	NJL	NJL
Fodor, Katz '01	(160, 725)	lattice reweighting I	
Hatta, Ikeda, '02	(95, 837)	effective potential (CJT)	CJT
Antoniou, Kapoyannis '02	(171, 385)	hadronic bootstrap	HB
Ejiri, *et al* '03	(?,420)	lattice Taylor expansion	
Fodor, Katz '04	(162, 360)	lattice reweighting II	

QGP Phase: Experiment

STAR arXiv:1007.2613



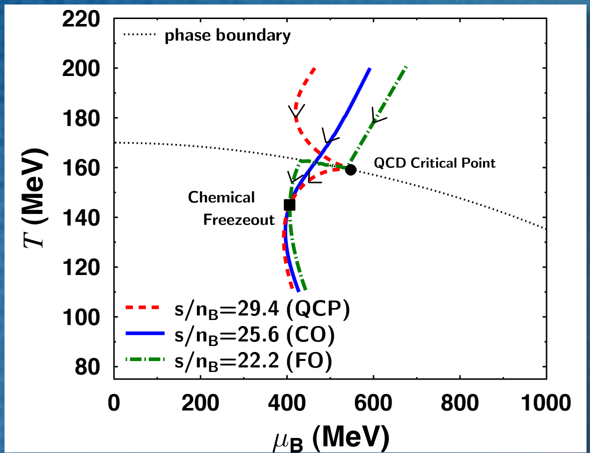
Experimental Search

- Onset of Deconfinement
- First Order Phase Transition
- Critical Point

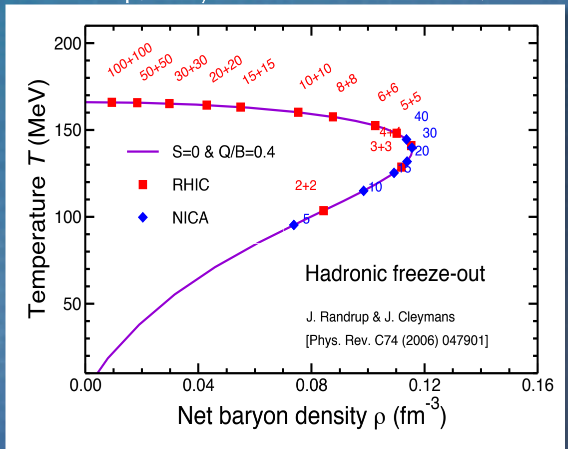
Considerations

- Matter Evolution – Phase Change
- Energy Dependence
- System Size Dependence

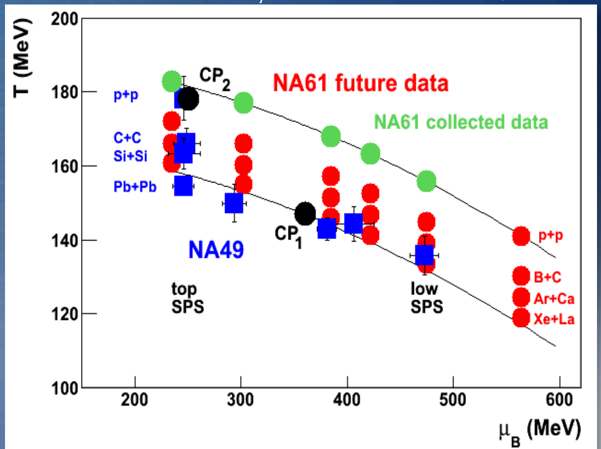
Asakawa et. al. PRL101:122302,2008



Randrup, Cleymans PRC74:047901,2006



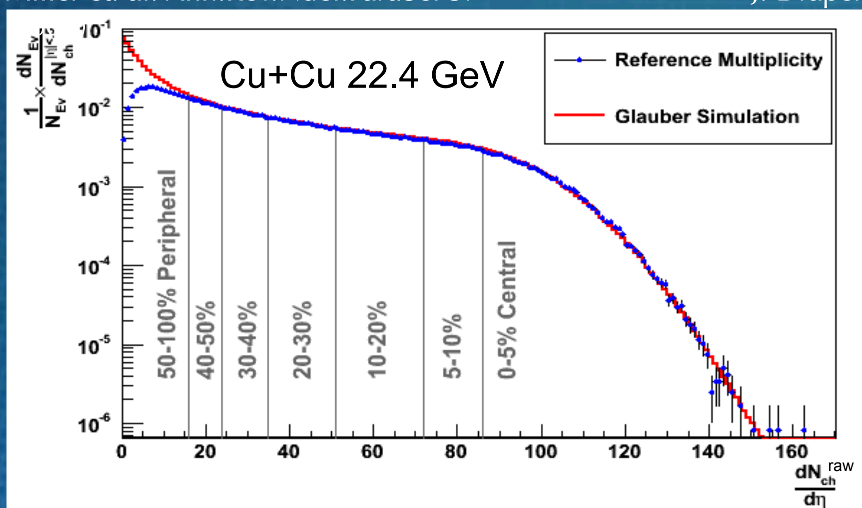
Becattini et. al. Phys.Rev.C73:044905,2006

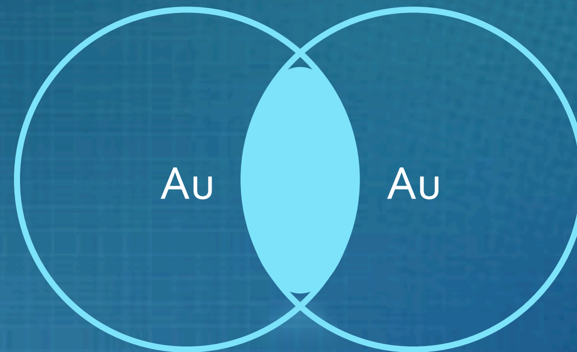


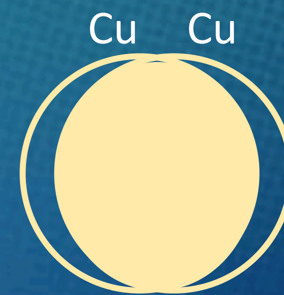
Initial System Size Comparison

System size, impact parameter, and collision centrality are studied via Glauber model fit to the raw multiplicity

Miller et. al. Ann.Rev.Nucl.Part.Sci 57 J. Draper

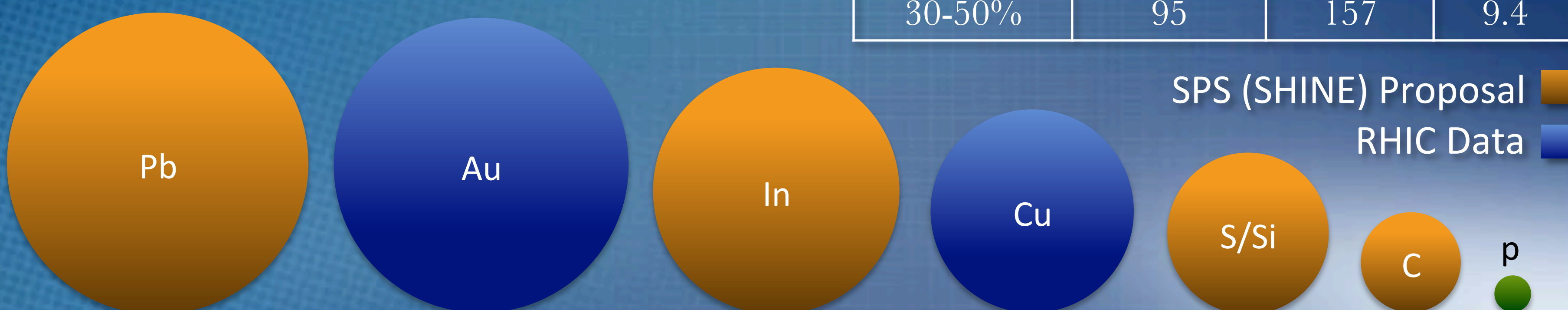




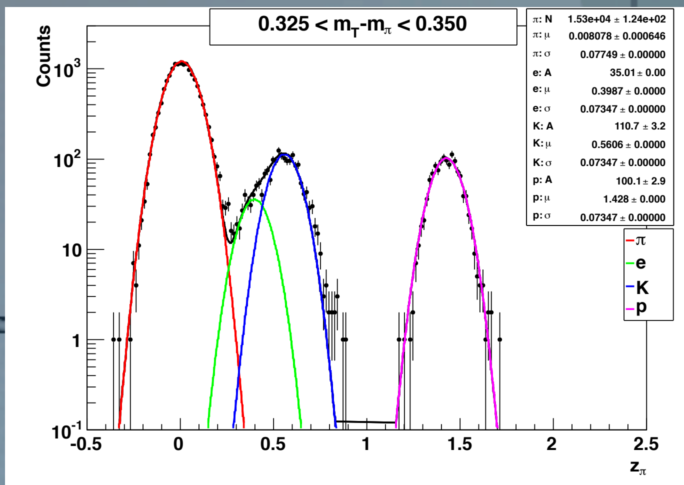


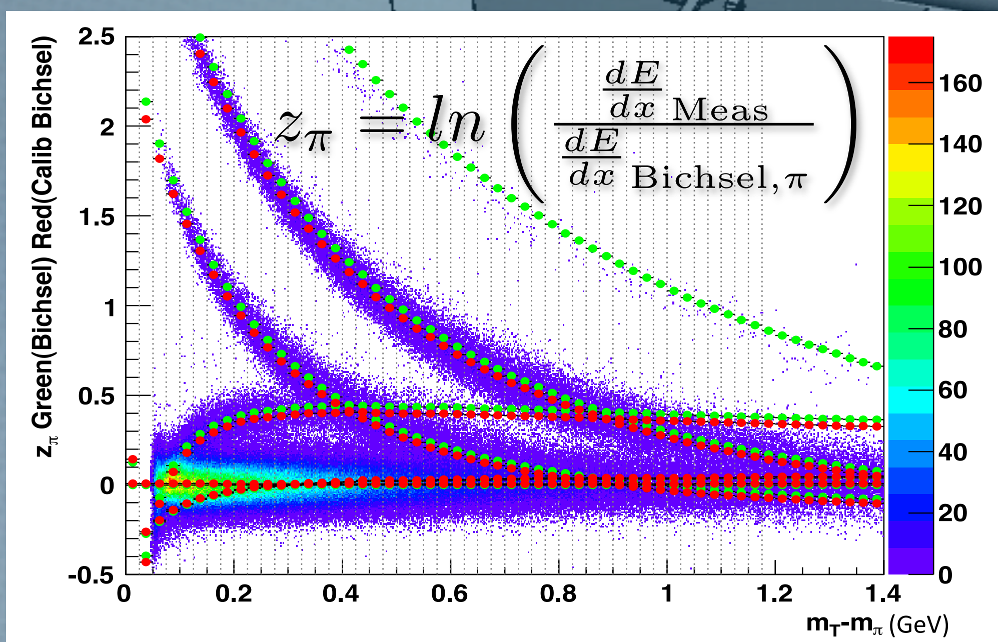
Cu+Cu 22.4 GeV (r~4.8fm)			
Centrality	<N_{part}>	<N_{coll}>	<b>
0-5%	108	185	1.4

Au+Au 19.6 GeV (r~7fm)			
Centrality	<N_{part}>	<N_{coll}>	<b>
30-50%	95	157	9.4



STAR Detector and Particle ID

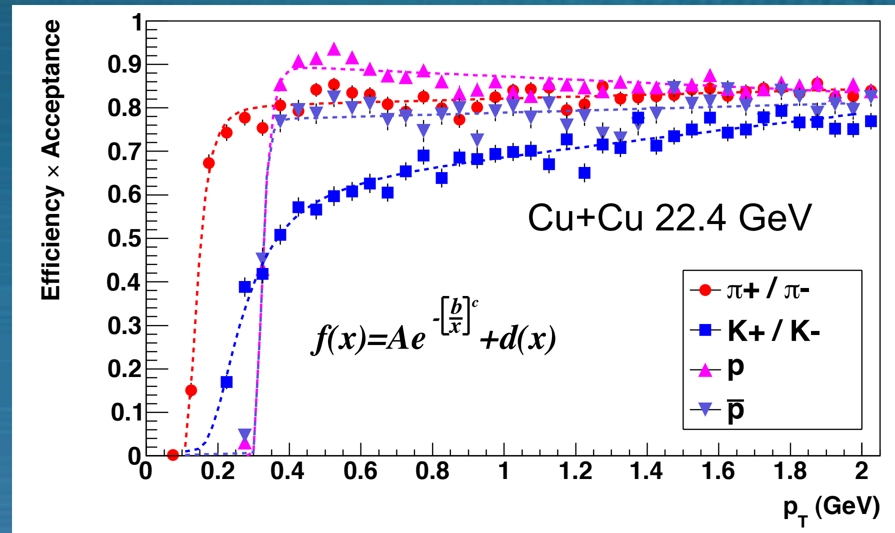


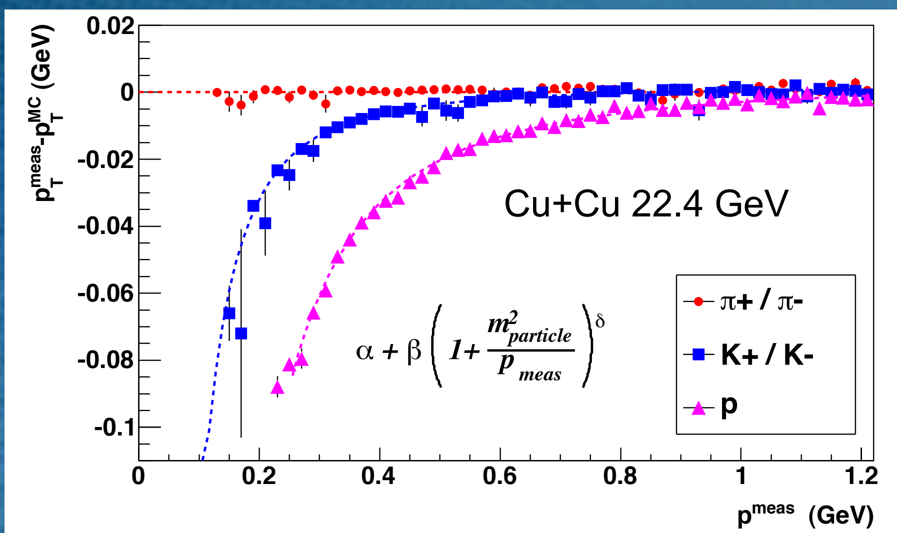


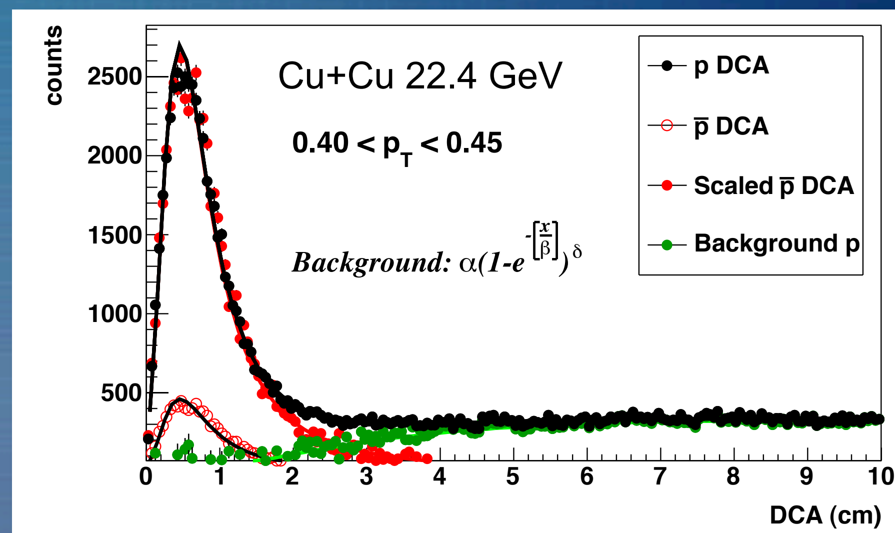
- Event and Centrality Cuts
  - Vertex found
  - $|V_z| < 30$cm, $|V_r| < 1$cm @ RMS
  - Min-bias Trigger
  - Centrality cuts from MC Glauber model simulation
- Track Cuts (Primary)
  - Global DCA < 3.0 cm
  - Number of Fit Points > 24
  - $|y_{particle}| < 0.1$
  - (particle = π±, K±, p, p)
- Particle Identification
  - Energy loss in STAR TPC
  - Bichsel expectation Calibrated for detector effects
  - Multi-Gaussian fits and fix parameters $\mu_{dE/dx}$ and $\sigma_{dE/dx}$ in regions of overlap

Efficiency and Corrections

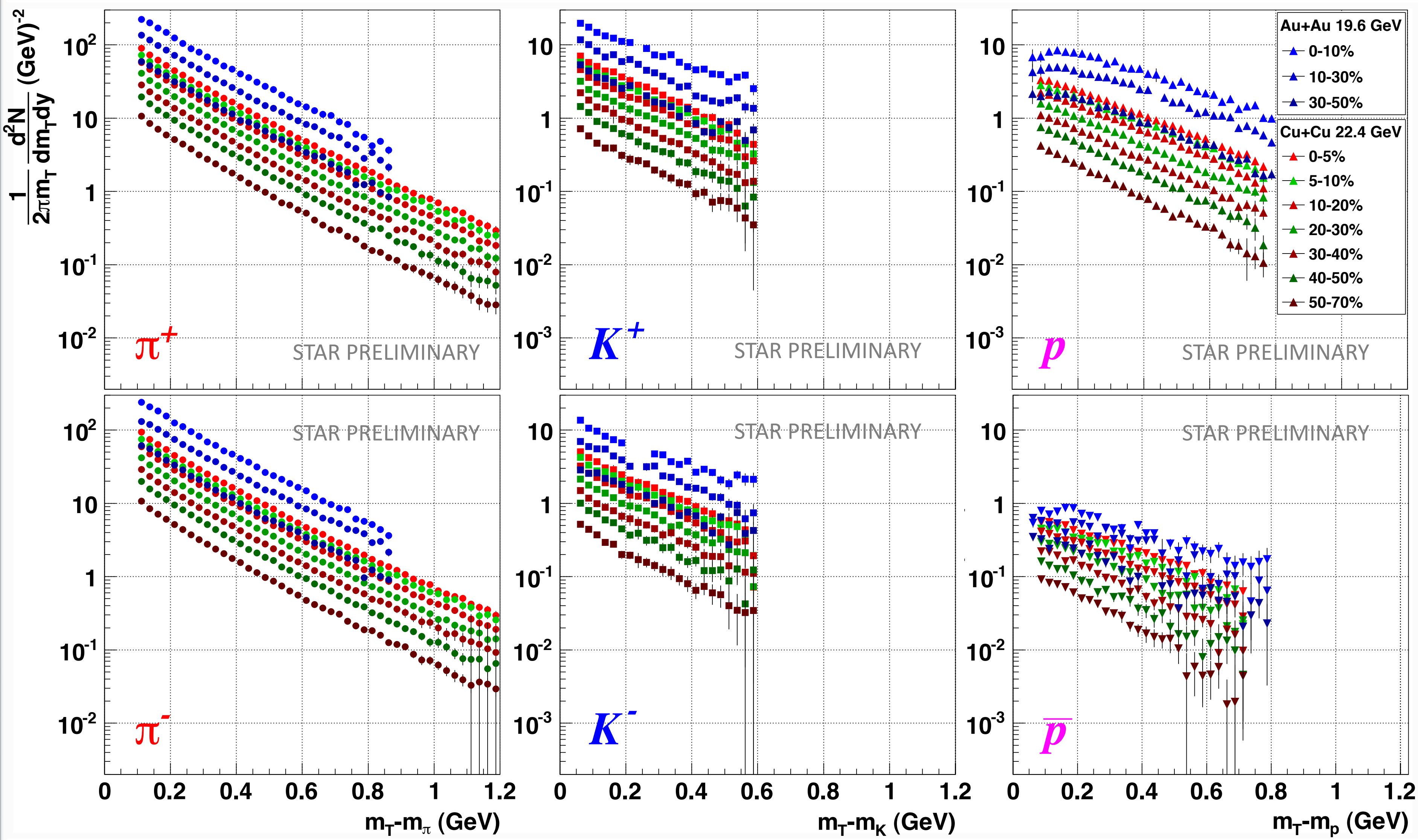
- Detector acceptance and particle reconstruction efficiency
- Energy loss corrections using MC embedding
- Proton background correction using DCA distributions
- π spectra have not been corrected for weak decays, muon contamination, or background pions. This is estimated to be a 15% effect at the lowest m_T-m_O bin and decreases sharply.







Mid-Rapidity Particle Spectra



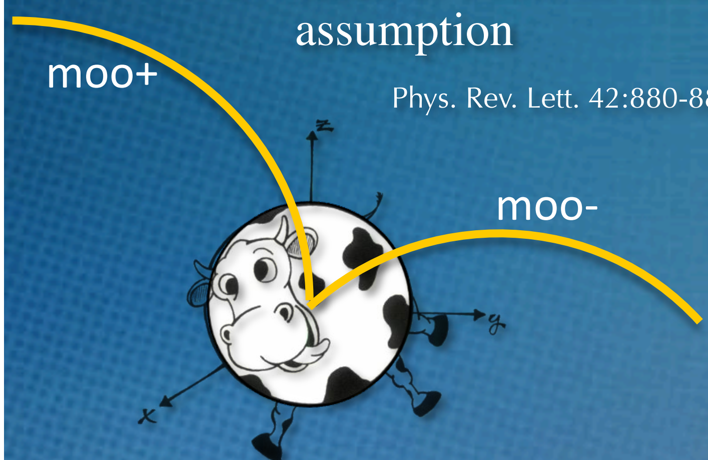
Au+Au 19.6 GeV spectra: Cebra QM08 arXiv:0903.4702v1

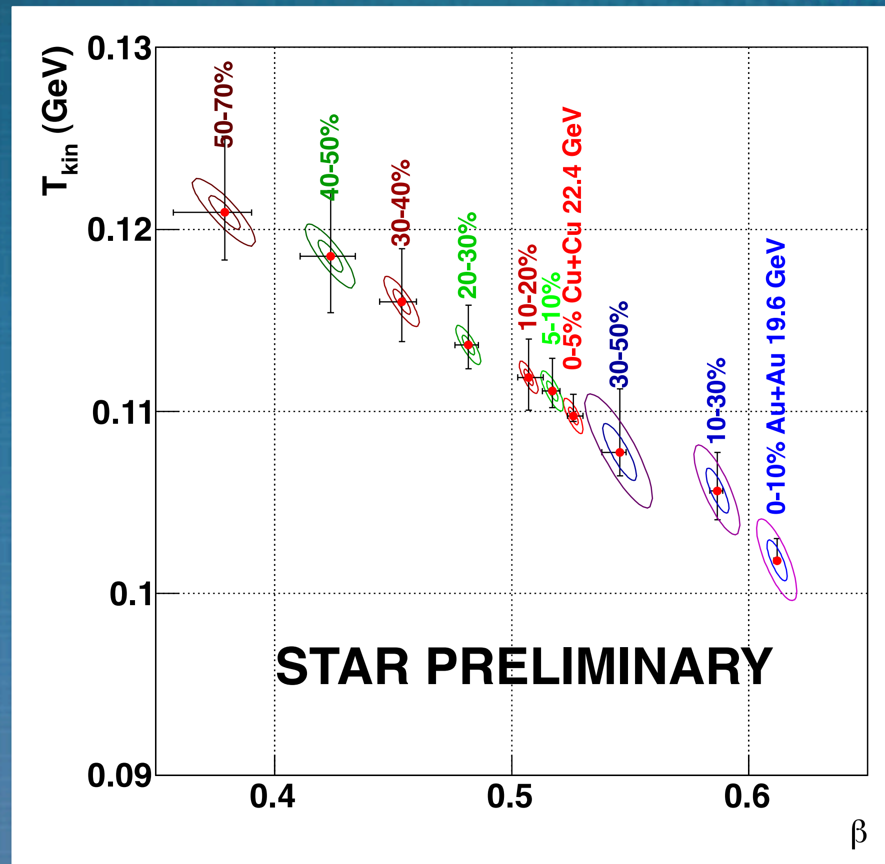
Blast-wave Model:

Siemens and Rasmussen

- Simple model with Spherical symmetry assumed
- T and β are correlated in fitting procedure
- All particles with singular blast velocity (even in center)
- Lack of boost invariance assumption

Phys. Rev. Lett. 42:880-887 1979





$$\frac{d^2N}{m_T dm_T dy} = Ae^{\gamma E/T}\left(\frac{\sinh(\alpha)}{\alpha}(\gamma E + T) - T\cosh(\alpha)\right)$$

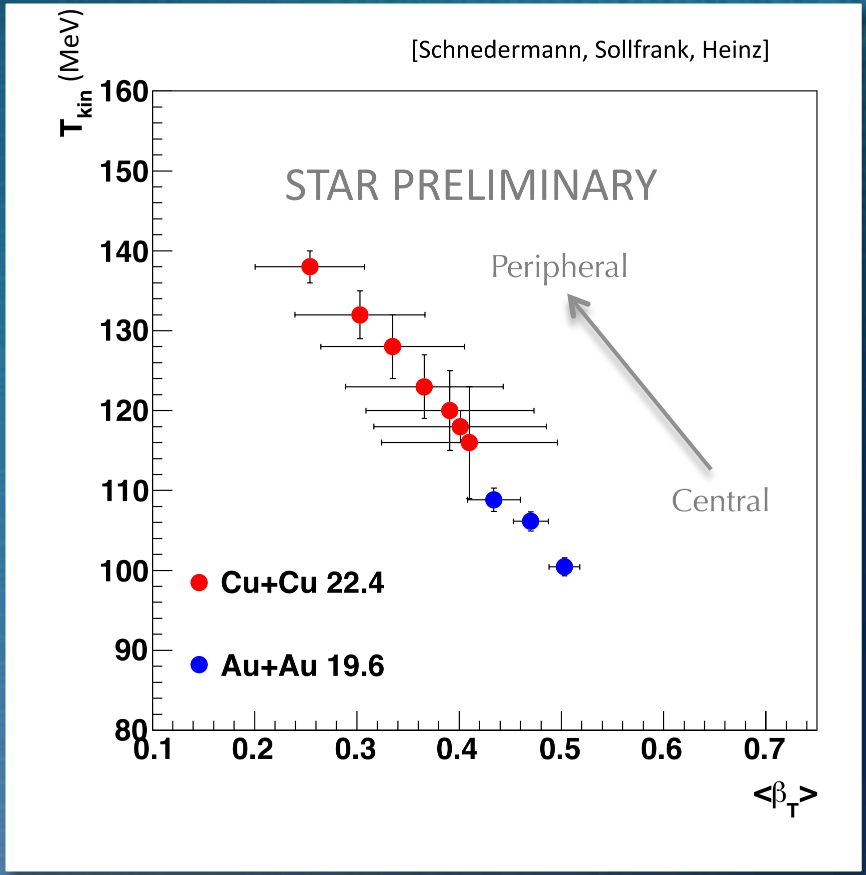
$$\gamma = \left(1-\beta^2\right)^{-1/2}, \quad \alpha = \gamma\beta p/T$$

Blast-wave Model: Boltzmann

- Invoke boost invariance to assume cylindrical symmetry
- Applies blast profile with radial dependence
- Systematic errors predominantly due to cut at low m_T-m_0 to exclude region of weak decay and muon contamination and variation in n parameter, in this plot n=1

$$m_T - m_\pi > 0.275\ \mathrm{GeV},\ p_T > 0.4\ \mathrm{GeV}$$

- Assumes Boltzmann statistics: Problematic at low m_T-m_0 for π



$$\beta_T(r) = \beta_S \left(\frac{r}{R}\right)^n$$

β_T: Individual shell velocity

β_S: Surface shell velocity

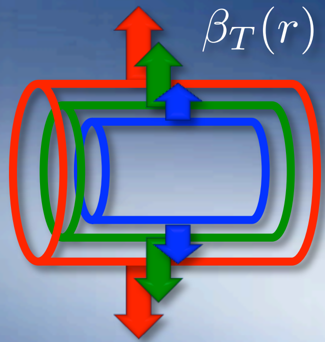
r : Radius of individual shell

R : Radius of surface shell

n : Blast profile parameter

Schnedermann, Sollfrank, Heinz
Phys. Rev. C. 48:2462-2475 1993

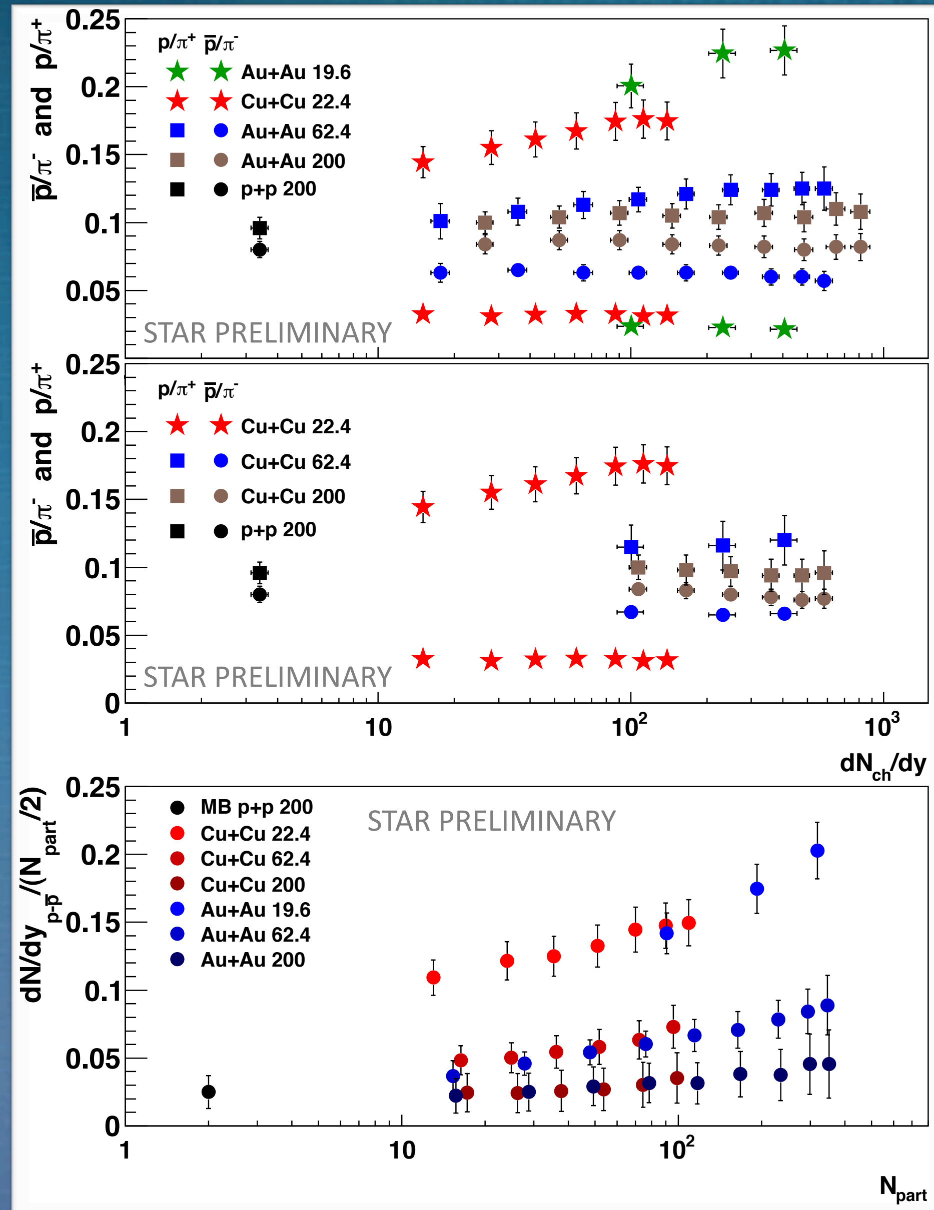
$$\langle \beta_T \rangle = \beta_S \frac{1}{(1+n/2)}$$



Baryon Transport

- Imbalance of p/π^+ vs. $\bar{p}/\pi^-$ ratio increases with lower collision energies
- Increasing p/π^+ ratios with increasing centrality
- No effect on $\bar{p}/\pi^-$ ratio in centrality.
- Net-baryon density increases with centrality. Effect most prominent at lower energies
- Q: How is net baryon number transported over 3 to 5 (10-100 GeV beam) units of rapidity?

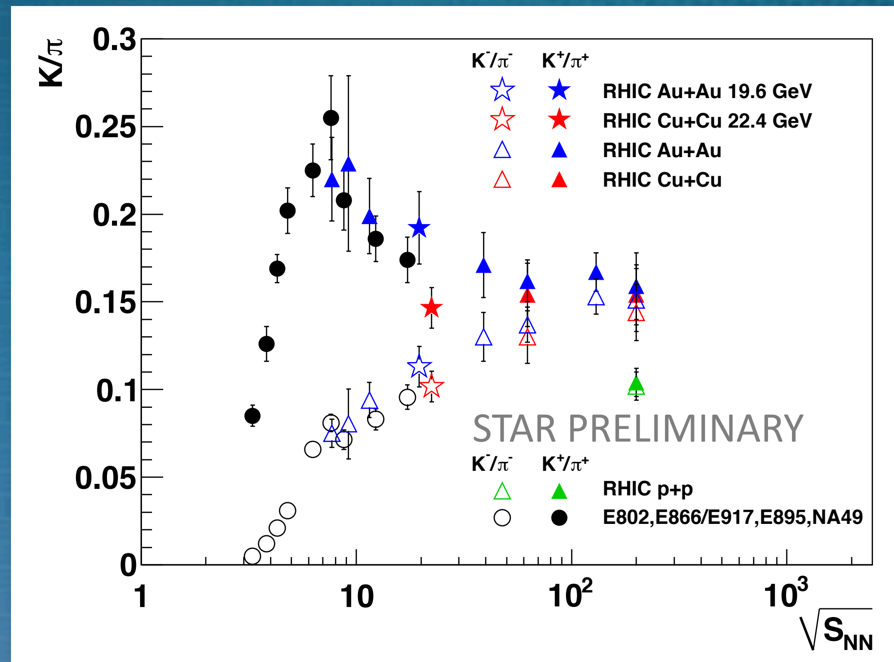
p+p 200, Au+Au 200, 62.4 GeV:
[STAR: PhysRevC.79.034909]
Cu+Cu 62.4, 200 GeV:
[STAR: PhysRevC.83.034910]

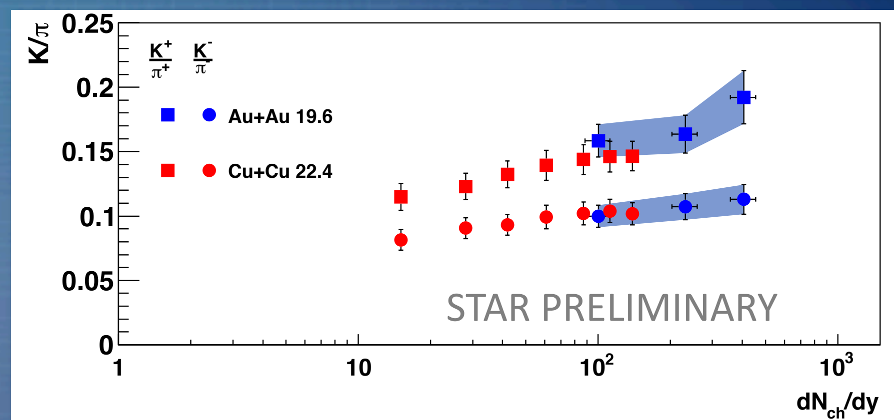


Strangeness Enhancement

- One of the initially predicted signatures of QGP
- Kaon production mechanisms:
  - Pair production
  - Associated production with hyperons (sensitive to baryon density)
- Showing a shift from associated to pair production at higher energies?
- What is the behavior of the Cu+Cu system?

STAR: Central Mid-rapidity Yields
Cu+Cu 22.4 GeV 0-5%, Au+Au 19.6 GeV 0-10%



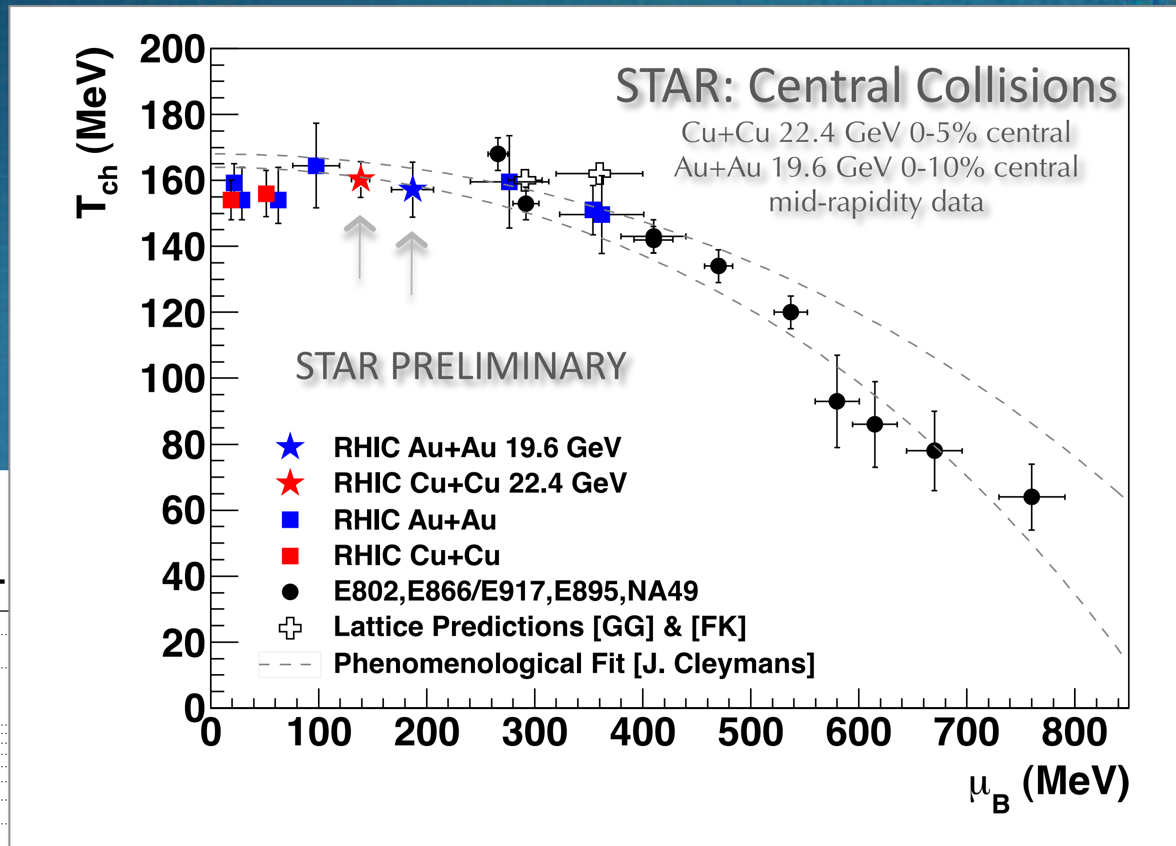


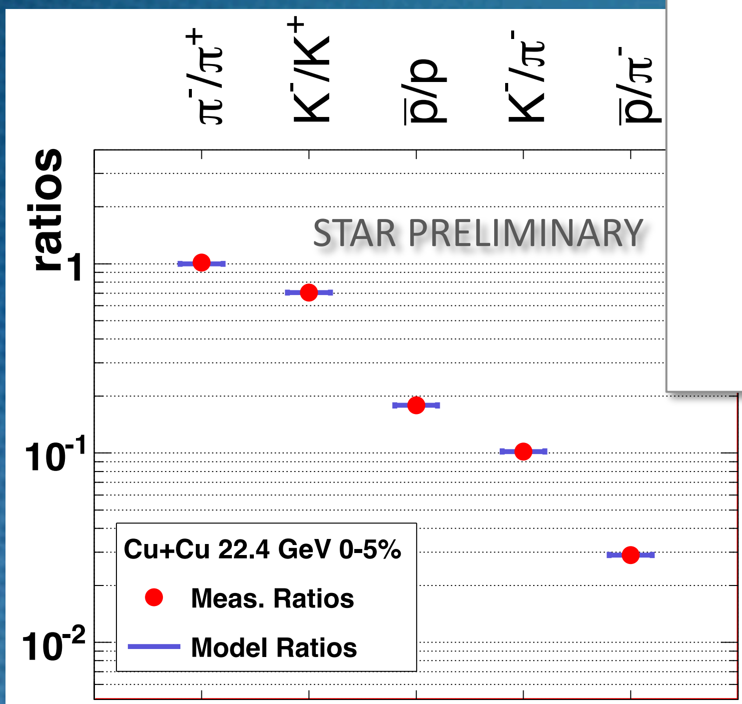
p+p 200, Au+Au 200, 130, 62.4 GeV
[STAR: PhysRevC.79.034909]
Cu+Cu 62.4, 200 GeV
[STAR: PhysRevC.83.034910]
Au+Au 9.2 GeV
[STAR: PhysRevC.81.024911]
7.7, 11, 39 GeV: Kumar QM2011

E866/917 PLB476.1.2000
E895 PRC68.054905.2003
E802 PRC58.3523.1998
NA44 PRC66.044907.2002
NA49 PRC66.054902.2002

Chemical Freeze-out

- Statistical Model Fit: Appreciable change in μ_B due to species size for central collisions
- Fit to particle ratios to get T_{ch}, μ_q, μ_s (μ_B, μ_S) and γ_S. Model reproduces ratios with great precision



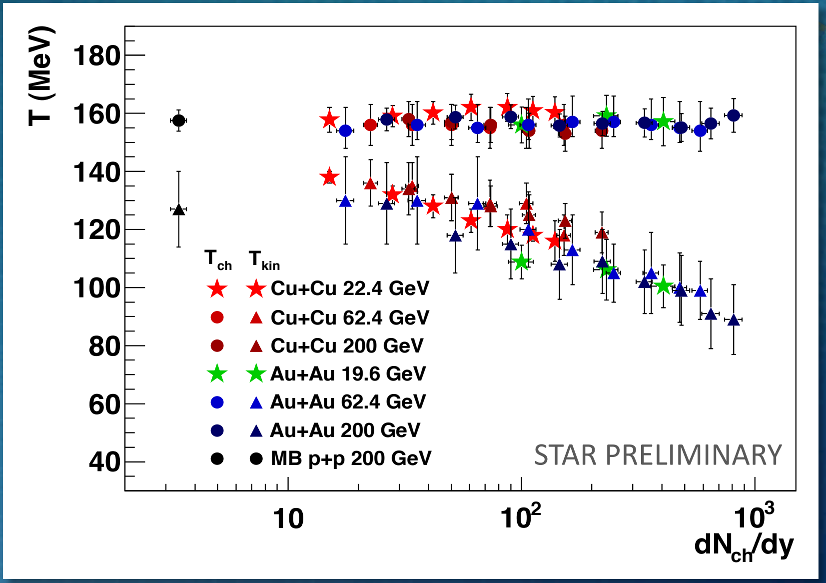


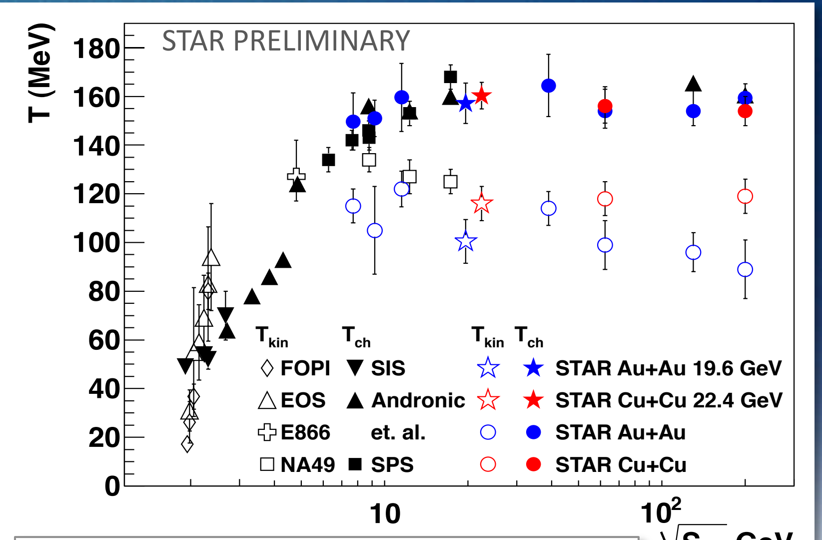
p+p 200, Au+Au 200, 130, 62.4 GeV [STAR: PhysRevC.79.034909]
Cu+Cu 62.4, 200 GeV [STAR: PhysRevC.83.034910]
Au+Au 9.2 GeV [STAR: PhysRevC.81.024911]
7.7, 11, 39 GeV: Kumar QM2011

E866/917 PLB476.1.2000
E895 PRC68.054905.2003
E802 PRC58.3523.1998
NA44 PRC66.044907.2002
NA49 PRC66.054902.2002
Braun-Munzinger, Heppe, Stachel Phys.Lett.B465.15-20. 1999
Kaneta, Xu, QM04 nucl-th/0405068

Collision Evolution

- Chemical freeze-out temperatures show no dependence on centrality or collision ion species.
- Kinetic freeze-out temperatures decrease with increasing centrality
- Cu+Cu systems might have higher kinetic freeze-out temperatures in comparison with Au+Au collisions at similar collision energies
- If so, does this give us hints about initial system energy density? Does it tell us about $\tau_{kin} - \tau_{ch}$?





STAR: Central collisions (mid-rapidity)
Cu+Cu 22.4 GeV 0-5%, Au+Au 19.6 GeV 0-10%

p+p 200, Au+Au 200, 130, 62.4 GeV
[STAR: PhysRevC.79.034909]
Cu+Cu 62.4, 200 GeV
[STAR: PhysRevC.83.034910]
Au+Au 9.2 GeV
[STAR: PhysRevC.81.024911]
7.7, 11, 39 GeV: Kumar QM2011

E866/917 PLB476.1.2000
NA49 PRC66.054902.2002
FOPI Nuc.Phy.A612.493.1997
EOS Phy.Lett.75.2662.1995
Andronic et. al: Nu.Ph.A772.167.2006
Cleymans et. al. J.Phy.G25.281.1999
Cleymans et. al. PRC57.3319.1998
Braun-Munzinger et. al. PLB365.1.1996

Summary

- Spectral shapes differ at low m_T-m_0 for protons in Cu+Cu 22.4 GeV collisions compared to Au+Au 19.6 GeV collisions
- Blast-wave results hint at lower blast velocity β_T and higher temperature T_{kin} for Cu+Cu 22.4 GeV vs. Au+Au 19.6 GeV collisions.
- Less p/π^+ vs. $\bar{p}/\pi^-$ asymmetry observed for central Cu+Cu 22.4 GeV vs. Au+Au 19.6 GeV collisions. Net baryon density increases for lower collision energies and increases with N_{part}
- For central Cu+Cu 22.4 GeV, K^+/π^+ ratio is slightly lower than Au+Au 19.6 GeV central collisions
- Chemical freeze-out temperature seems independent of collision centrality and system size at RHIC energies. The baryon chemical potential appears lower in Cu+Cu 22.4 GeV collisions in comparison with Au+Au 19.6 GeV for central collisions.

Question: How to reach the critical point and the 1st order phase transition?

- If it is possible we have missed the critical point and first order phase transition, how else may we attempt to reach towards it (along with an energy scan)?
- 1: Decrease system size to increase T_{ch}? The NA61 expectation was not a significant effect for our data
- 2: Does increasing system size increase μ_B? Challenge with non spherical ions: While head-on Uranium collisions would be ideal for this there is very low cross-section for such collisions.