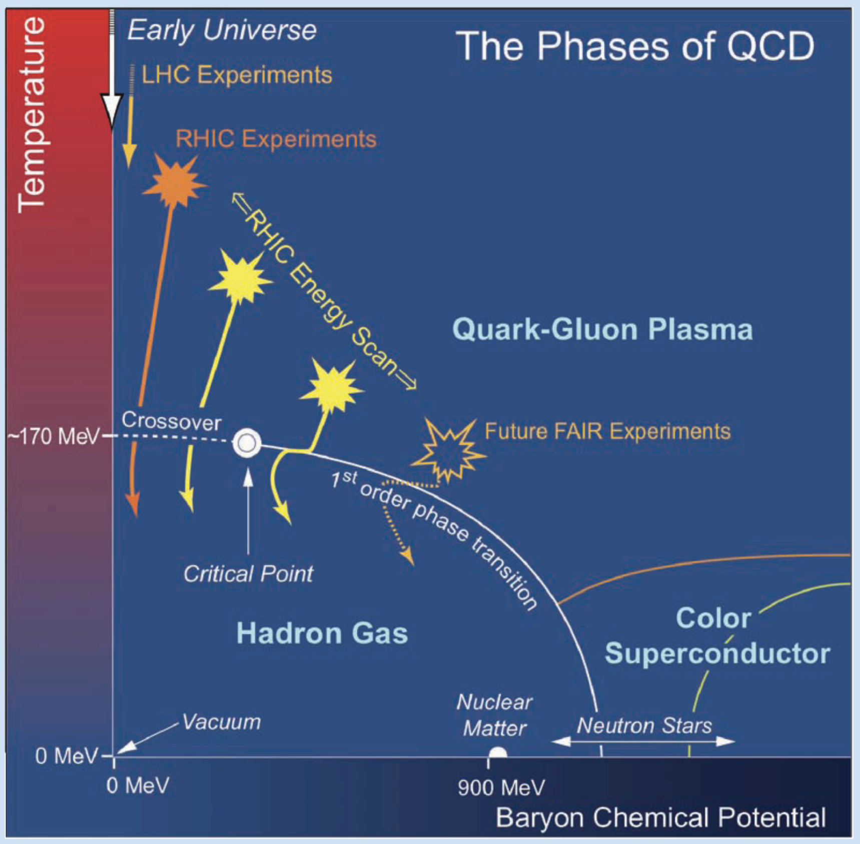
Freeze-out Dynamics In Relativistic Heavy-Ion Collisions



<u>Outline:</u>

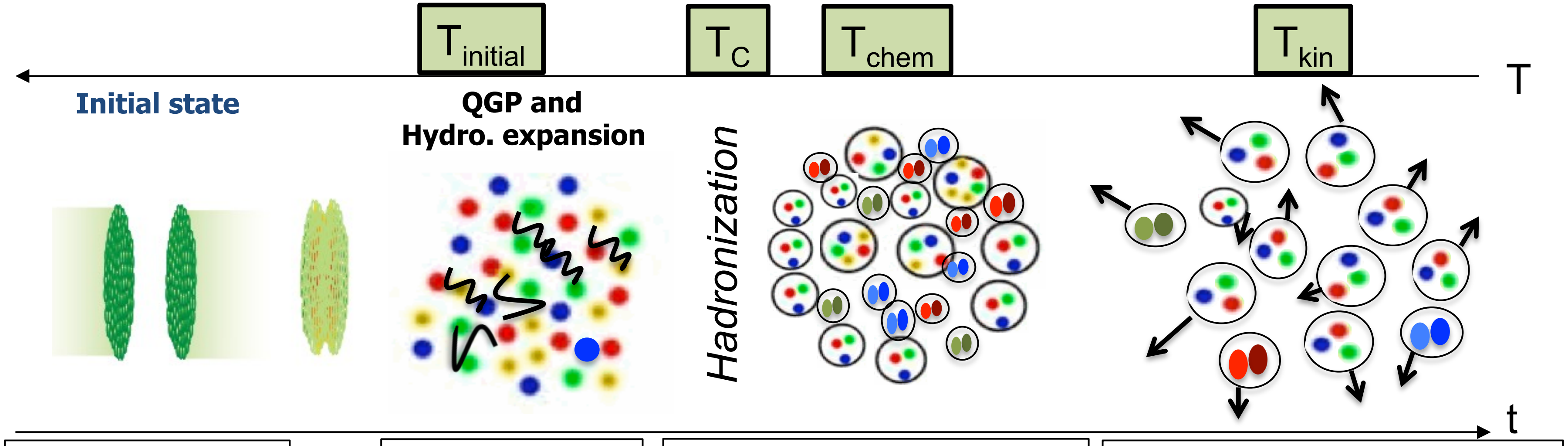
❑Chemical Freeze-out
❑Kinetic Freeze-out
❑Summary

See also talks at -
Chemical FO – 28th June 2016 – Parallel sessions
Freeze-out – 29th June 2016 – Plenary sessions
Particle production – 30th June 2016 – Parallel session

Bedanga Mohanty
National Institute of Science Education and Research
(NISER)

Dynamics of Relativistic Heavy Ion Collisions

Time Evolution of Heavy-ion Collisions:



$T_{initial}$

T_C

T_{chem}

T_{kin}

T

Initial state

QGP and Hydro. expansion

Hadronization

t

Colliding ions

De-confined state

Chemical freeze-out

✧ Inelastic collision cease

Kinetic freeze-out

✧ Elastic collision cease

Information of QCD phase diagram and particle production

Chemical Freeze-out

Inelastic Collisions Ceases

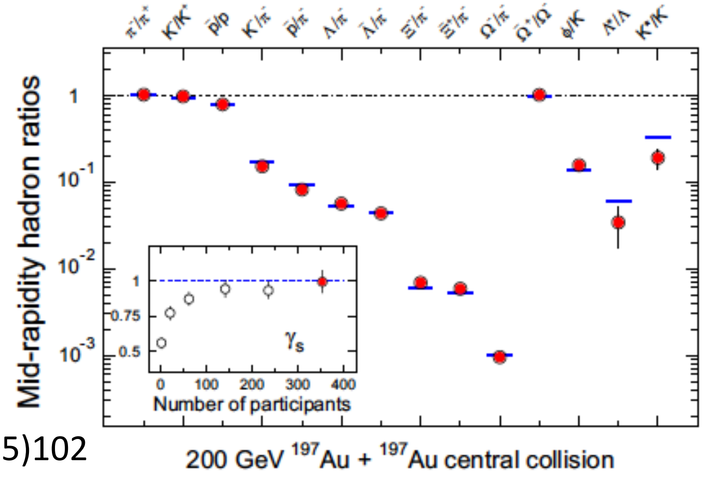
Statistical Model

$$n = \frac{1}{V}\frac{\partial (T \ln Z)}{\partial \mu} = \frac{V T m_i^2 g_i}{2\pi^2} \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k} \left(e^{\beta k \mu_i}\right) K_2\left(\frac{k m_i}{T}\right)$$

THERMUS: S. Wheaton, J. Cleymans Comp. Phys. Comm. 180, 84 (2009)

J. Cleymans and K. Redlich, PRC 60 (1999)054908
F. Becattini, J. Manninen, M. Gazdzicki, PRC 73 (2006) 044905
A. Andronic, P. Brau-Munzinger and J. Stachel, NPA 772 (2006) 167

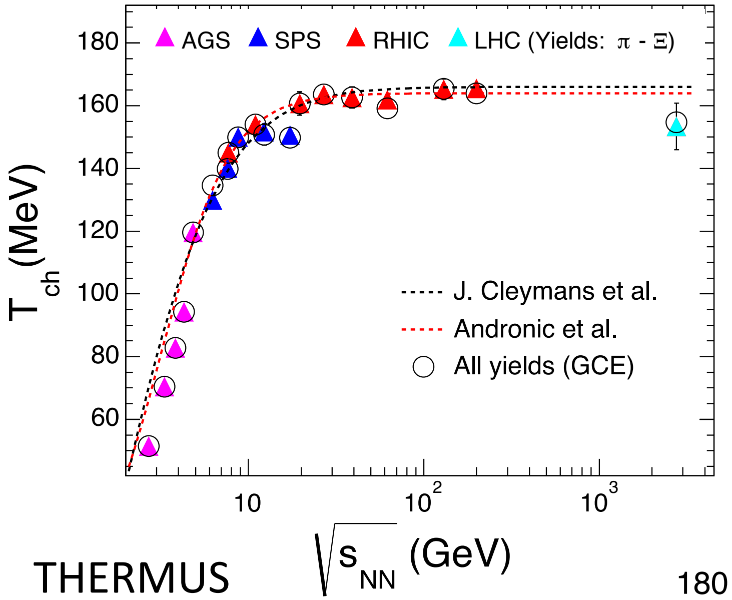
Parameters:
- ❑ Temperature (T_{ch}), Chemical Potentials (μ_B,μ_S,μ_Q), γ_S and Volume
- ❑ Obtained by fitting the particle yields



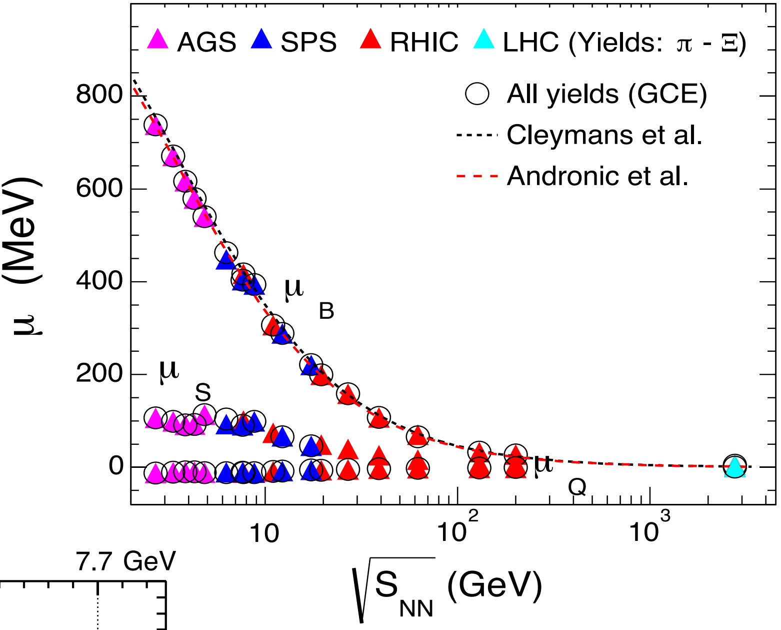
STAR: NPA 757 (2005)102

Model Features:
- ❑ Assumes non-interacting hadrons and resonances
- ❑ Assumes thermodynamically equilibrium system
- ❑ Ensembles : Grand Canonical - average conservation of B, S, and Q
  Strangeness Canonical - exact conservation of S
  Canonical - exact conservation of B, S, and Q

Freeze-out Conditions – Particle Yields

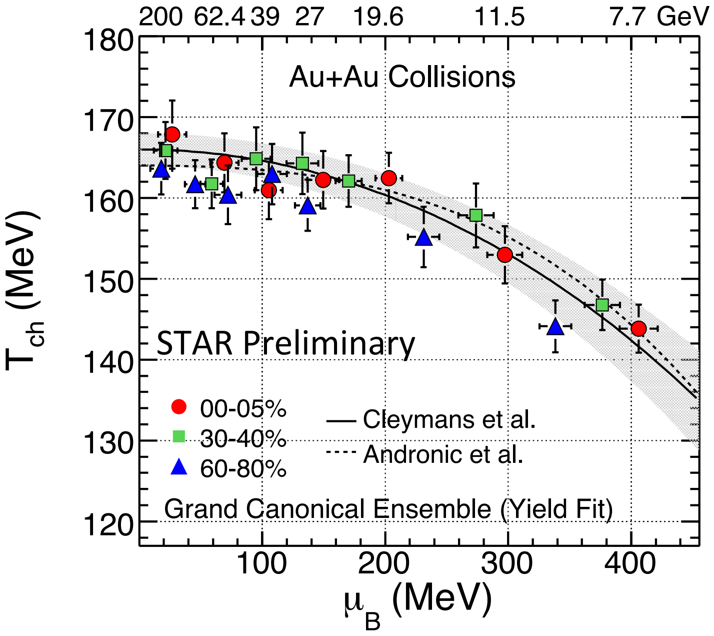


SIS: JPG 25, 281 (1999); PRC 57, 3319 (1998);
AGS: PLB 344, 43 (1995); PLB 365, 1 (1996); PRC 67, 015205 (2003);
SPS: PLB 365, 1 (1996); PLB 465, 15 (1999); PRC 67, 015205 (2003); JPG 28, 1861 (2002); PRC 64, 024901 (2001); PRC 73, 034905 (2006); NPA 772, 167 (2006)
STAR: L. Kumar QM2011 & QM2014
ALICE: A. Andronic, NPA 904 (2013)535c



THERMUS

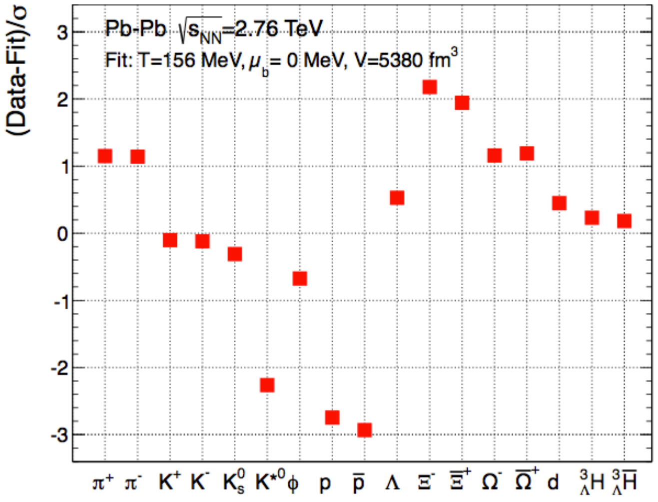
For study on dependence of parameters to choice of ensemble, initial conditions, and particle set see: Adv.High Energy Phys. 2015 (2015) 349013

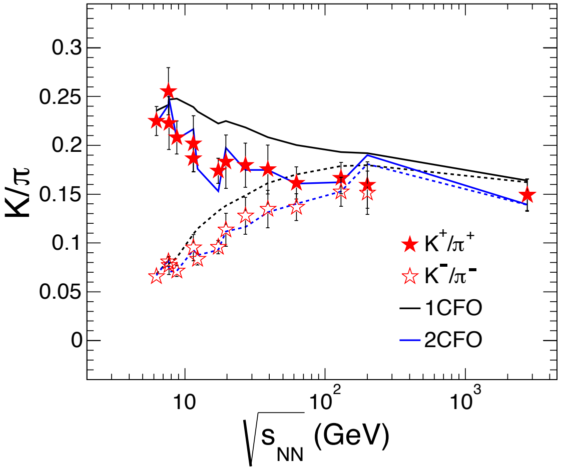


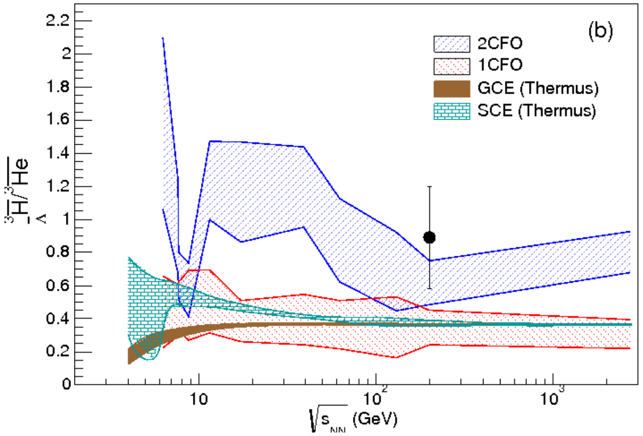
New aspect from BES RHIC Centrality dependence of T_{ch} vs. μ_B

AGS results: Does not include
Multi-strange hadrons

Multiple Freeze-out Scenarios







J Stachel, A Andronic, P Braun-Munziger,
K. Redlich: J. Phys. Conf.Ser 509 (2014) 012019;
Nucl. Phys. A904 (2013) 535c

☐ Advent of LHC data
☐ Difficulty in explaining Strange-to-non-Strange Particle/nuclei ratios

– Led to new developments

Departure from equilibrium physics:

☐ Hadronization followed by hadronic afterburner within the hybrid UrQMD model.
☐ FO with nonequilibrium quark phase space factors for light and strange quarks were used.

Within ambit of equilibrium physics:

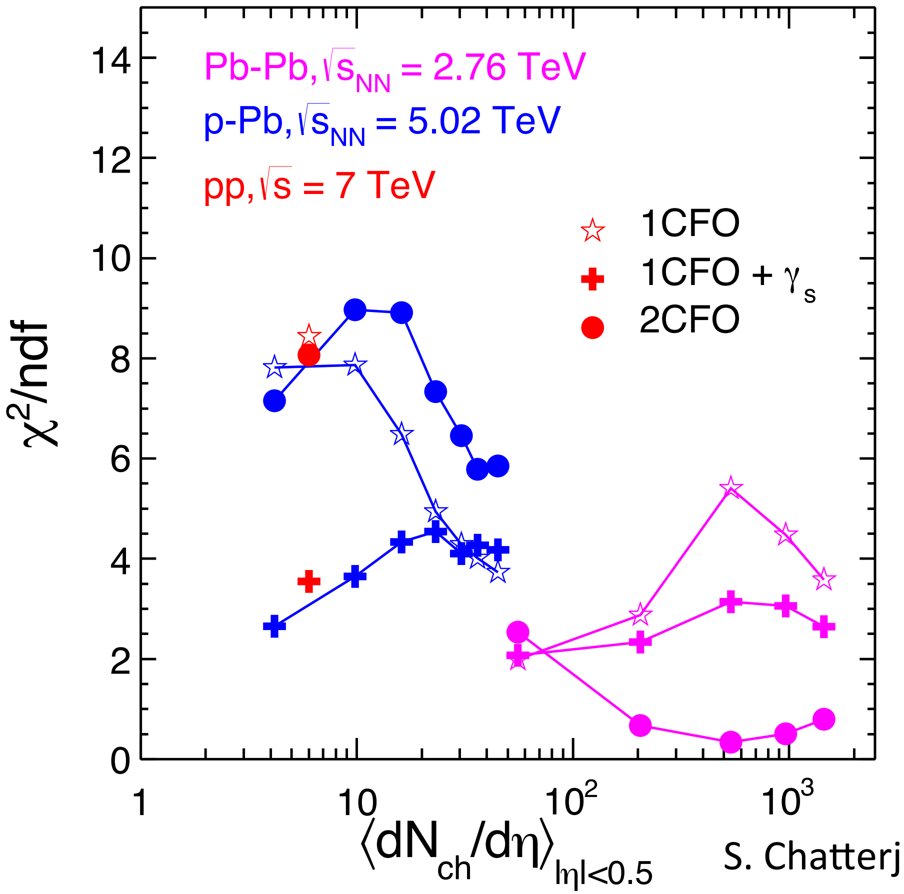
☐ Flavor dependent freeze-out surfaces

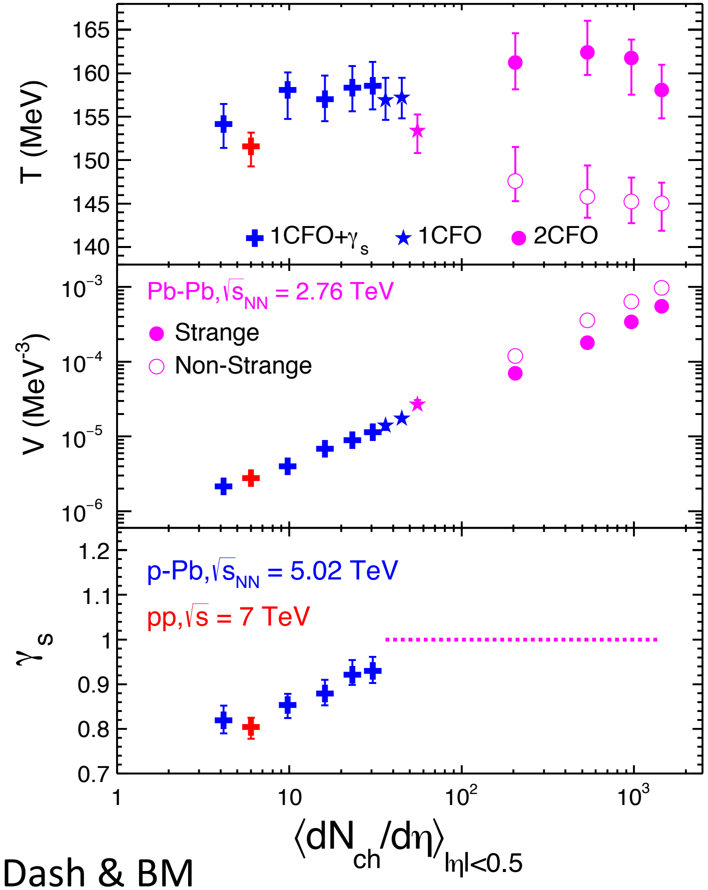
J. Steinheimer, et al., PRL 110 (2013) 042501
F. Becattini, et al., PRC 90 (2014) 054907
M. Petran, et al., PRC 88 (2013) 034907

S. Chatterjee, et al., PLB 727 (2013) 554
K. Bugaev, EPL 104 (2013) 22002
S. Chatterjee & B. Mohanty, PRC 90 (2014) 034908

S. Gupta, R. Sharma,
PRC 89 (2014) 057904
$\Upsilon - T \sim 250$ MeV

Strange vs. Non-Strange Freeze-out





S. Chatterjee, A. Dash & BM

π, K, p, Λ, Ξ, ϕ, Ω and antiparticles

- ❑ Strange hadrons Freeze-out at different time compared to non-strange hadrons ?
- ❑ Preferred for AA collisions (medium) and NOT preferred for pA or pp

Freeze-out Conditions from Higher Moments of Multiplicity Distributions

PHENIX
Phys.Rev. C93 (2016) 011901
STAR
Phys.Rev.Lett. 113 (2014) 092301
Phys.Rev.Lett. 112 (2014) 032302
Phys.Rev.Lett. 105 (2010) 022302

Ratios of Susceptibilities of conserved quantities (B, Q, S) calculated in QCD/ Models are related to products of moments of corresponding distributions measured in experiments – ***Use this to extract Freeze-out conditions***

Theory (Susceptibilities)	**Experiment** (moments/ Cumulants)
χ_3/χ_2	$S\sigma$
χ_4/χ_2	$\kappa\sigma^2$
χ_1/χ_2	M/σ^2
χ_3/χ_1	$S\sigma^3/M$

One strategy : χ_3/χ_1 is independent of μ_B – estimate temperature
LO in χ_2/χ_1 is linear in μ - estimate chemical potential

Theory: Lattice QCD
HRG

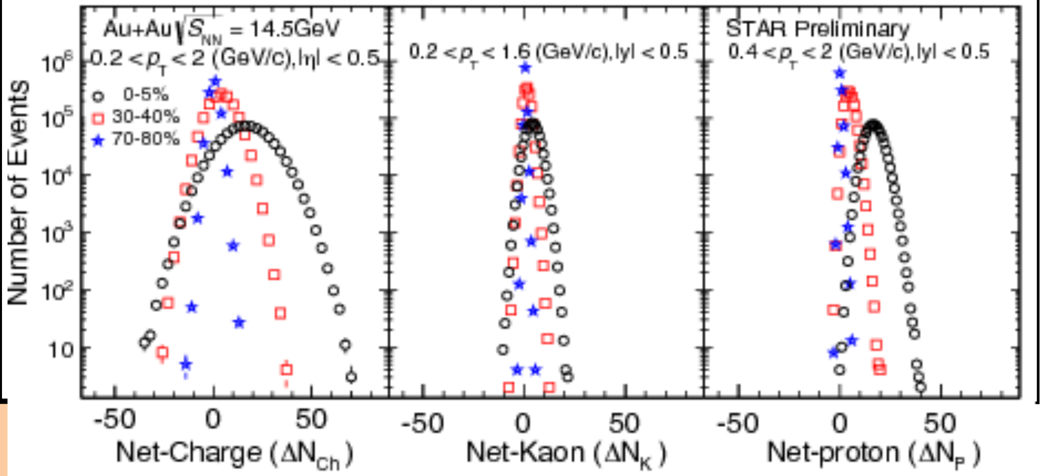
Phys.Rev.Lett. 113 (2014) 052301
Phys.Rev.Lett. 113 (2014) 072001
Phys.Lett. B738 (2014) 305-310
Phys.Rev.Lett. 111 (2013) 062005
Phys.Rev.Lett. 109 (2012) 192302
Phys.Lett. B 696 (2011) 459-463

Experimental data on Higher Moments

PHENIX
Phys.Rev. C93 (2016) 011901

STAR
Phys.Rev.Lett. 113 (2014) 092301
Phys.Rev.Lett. 112 (2014) 032302
Phys.Rev.Lett. 105 (2010) 022302
arXiv:1601.00951

Experiment	Net-Charge	Net-Proton	Net-Kaon
STAR	Obs: M, σ, S, κ Beam Energy (evts): 7.7 (1.4M), 11.5(2.4M), 19.6(15.5), 27(24M), 39(56M), 62.4(32M), 200(75M) η: +/- 0.5; Φ: 2π p_T : 0.2 – 2 GeV/c	Obs: M, σ, S, κ Beam Energy (evts): 7.7 (3M), 11.5(6.6M), 19.6(15M), 27(30M), 39(86M), 62.4(47M), 200(238M) y: +/- 0.5; Φ: 2π p_T : 0.4 – 0.8 (2) GeV/c	Obs: M, σ, S, κ Beam Energy (evts): 7.7 (3M), 11.5(6.6M),14.5 19.6(15), 27(30), 39(86M), 62.4(47M), 200(238M) y: +/- 0.5; Φ: 2π p_T : 0.2 – 1.6 GeV/c
PHENIX	Obs: M, σ, S, κ Beam Energy (evts): 7.7 (2M), 19.6(6M), 27(21M), 39(154M), 62.4(474M), 200(1681M) η: +/- 0.35 Φ: π/2 p_T : 0.3 – 2 GeV/c		



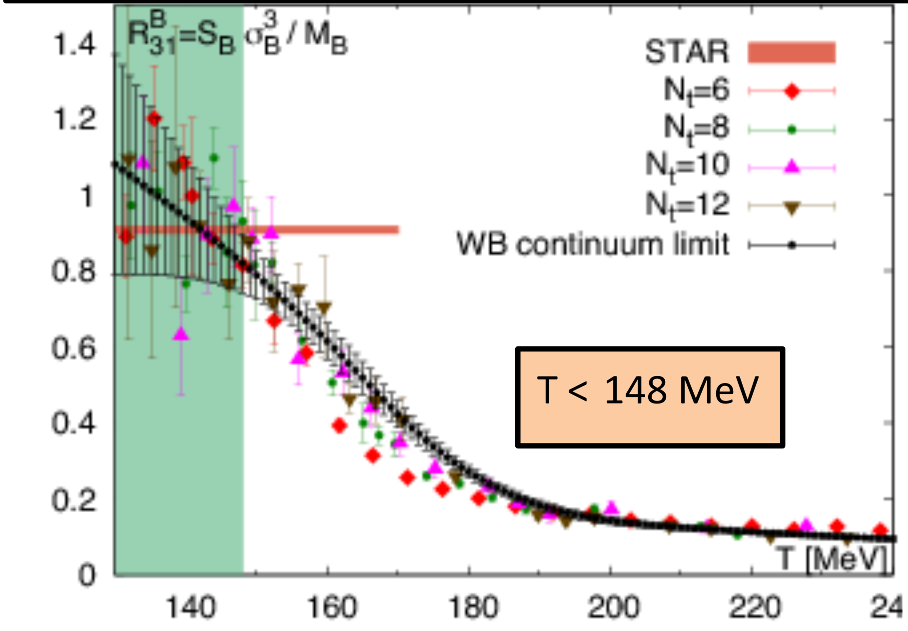
STAR:QM2015

Data: Finite Acceptance (y, φ, p_T)
Efficiency Corrected
net-proton – proxy for net-baryon
net-kaon – proxy for net-strangeness

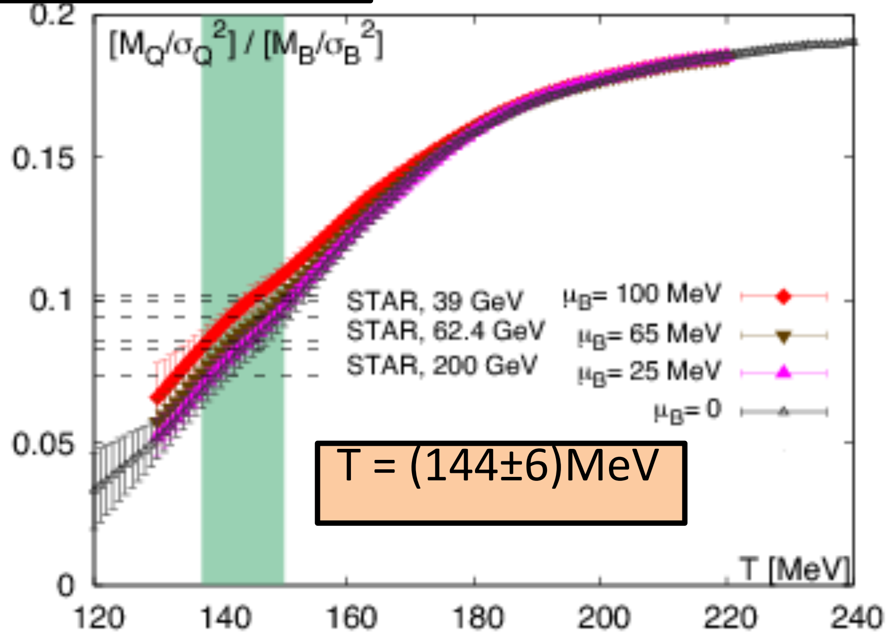
J. Phys. G 40 (2013) 055103
1603.09057

LQCD: Freeze-out Conditions from Higher Moments of Multiplicity Distributions

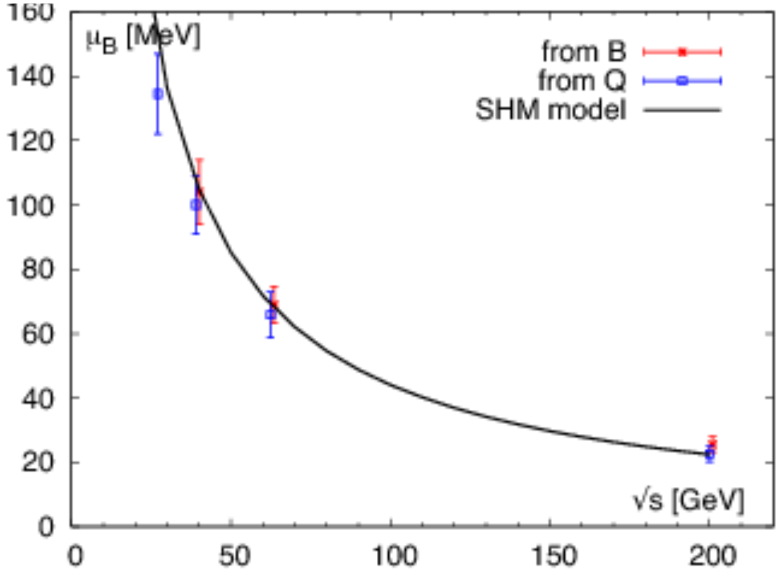
S. Borsanyi, et al.,
Phys.Rev.Lett. 113 (2014) 052301



T < 148 MeV



T = (144±6)MeV

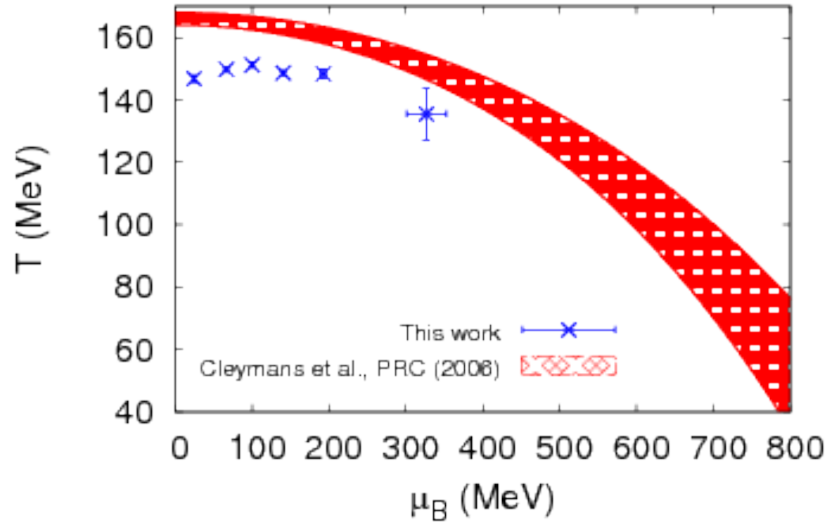


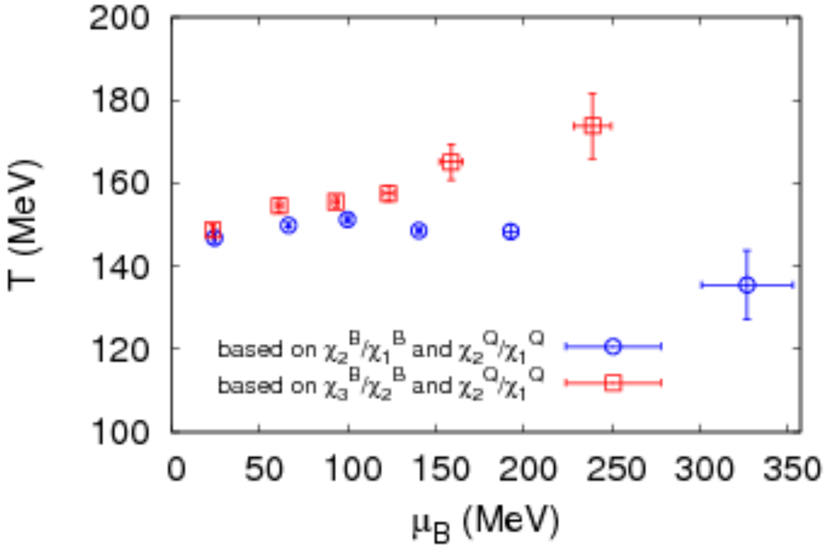
Assumption: If the freeze-out can be described by the same temperature and chemical potentials for charge and protons.

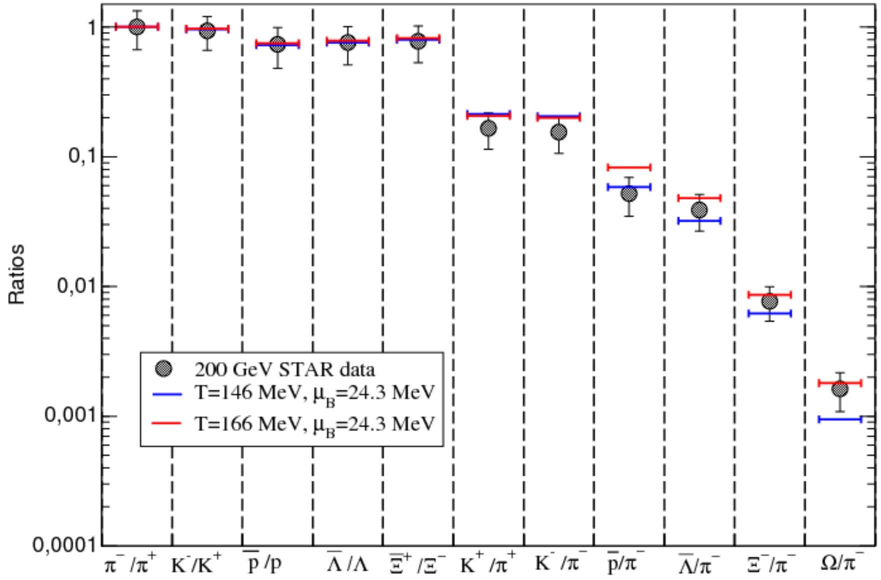
1. Consistency in freeze-out parameters for various observables.
2. Fluctuations Freeze-out at a slightly lower temperature than yields ?

HRG: Freeze-out Conditions from Higher Moments of Multiplicity Distributions

Paolo Alba, et al.
Phys.Lett. B738 (2014) 305-310
(Calculations with experimental acceptances, resonance decay, isospin randomization)

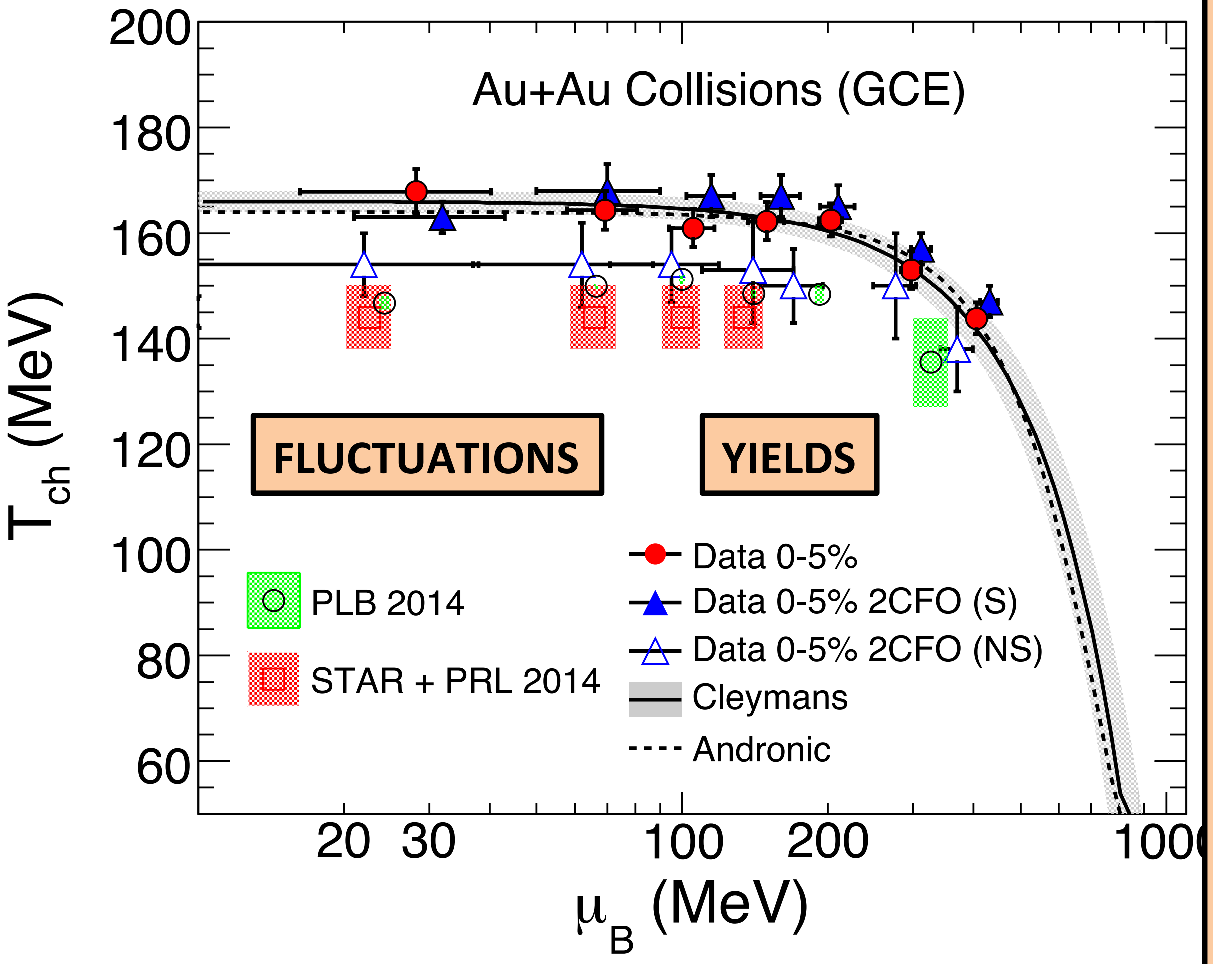






1. Fluctuations Freeze-out at a lower temperature than yields ?
2. Consistency in freeze-out parameters for various observables at higher energies (indication of chiral critical fluctuations at lower energies ?)
3. Freeze-out temperature from fluctuations – explains anti-proton yields better, misses the multi-strange baryons (need for strangeness fluctuations ?)

Compilation of Freeze-out Conditions



Does Particle yields and Fluctuations freeze-out differently ?

Or

It is a simple question of Sensitive observable ?

Or

Strange and non-Strange Freeze-out at different Times ?

Freeze-out line and Transition Line

$$\frac{T(\mu_B)}{T_c(0)} = 1 - \kappa \left(\frac{\mu_B}{T(\mu_B)} \right)^2 +$$

$$\Sigma_r^{QB} = \Sigma_r^{QB,0} + \left(\Sigma_r^{QB,2} - \kappa_2^f T_{f,0} \frac{\mathrm{d}\Sigma_r^{QB,0}}{\mathrm{d}T} \bigg|_{T_{f,0}} \right) \hat{\mu}_B^2$$

Assumption:

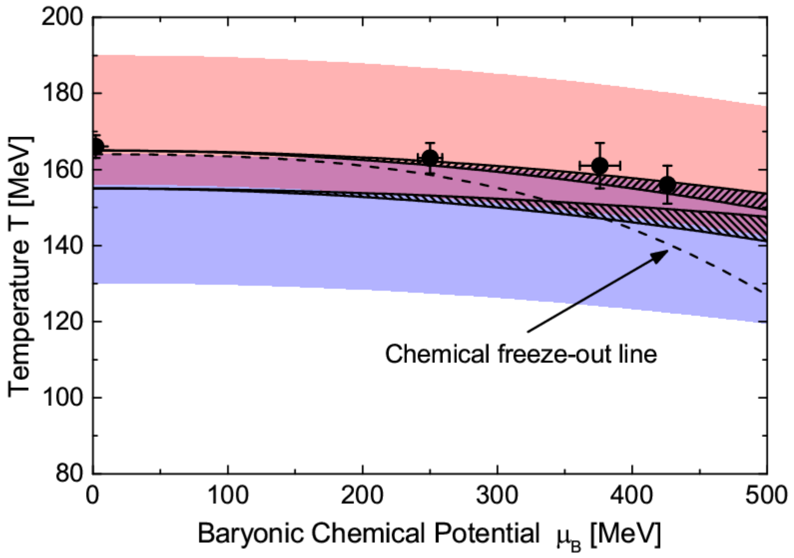
- ☐ Charge-conjugation invariance at $\mu_B=0$
- ☐ Analyticity at the point $\mu_B=0$
- ☐ Low Baryon densities and lowest order expansion

κ > 0 Transition line
κ ~ 0 or < 0 Freeze-out line

κ-values (error)	Calculation	Remarks
0.020(4)	PRD 93, 014507 (2016) : LQCD, im. μ	Transition Line
0.0135(20)	PRD 92, 054503 (2015): LQCD im. μ	Transition line
0.059(2)(4)	PRD 83, 014504 (2011): LQCD T. exp.	Transition line
0.0089(14) (χ_s); 0.0066(20)(ψ_c)	JHEP 1104, 001 (2011): LQCD	Transition line
0.015(6) (I); 0.017(5) (ε) 0.018(7) (c_s); 0.016(4) (s)	JHEP 1208, 053 (2012) LQCD, T. exp..	Transition line
0.023(3)	PRC 73, 034905 (2006): Fit to Yields	Freeze-out line
Weaker than above	PRL 111, 082302 (2013): Fit to yields	Freeze-out line
~ 0	NPA 772, 167 (2006): Fit to Yields	Freeze-out line
-0.073(16)- STAR pub. -0.012(15) STAR-prel. -0.056(67) STAR+PHENIX	Phys.Rev. D93 (2016), 014512: Fit to higher moments	Freeze-out line < 0.011

Freeze-out line and Transition Line

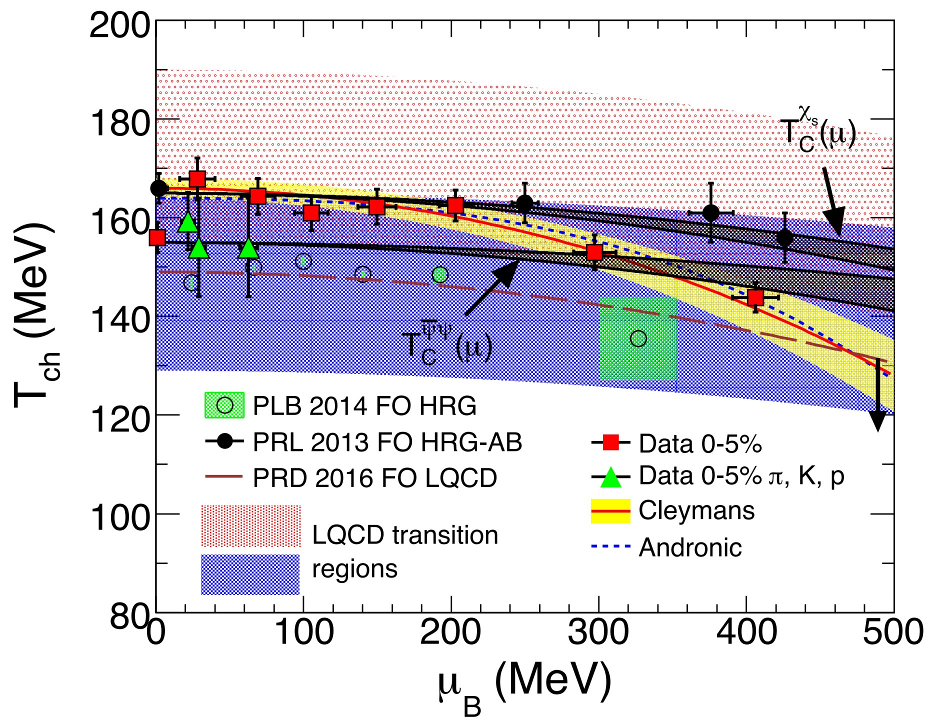
F. Becattini, M. Bleicher, T. Kollegger, T. Schuster, J. Steinheimer, R. Stock, Phys.Rev.Lett. 111 (2013) 082302



LQCD: G. Endrodi, Z. Fodor, S. D. Katz and K. K. Szabo, JHEP 1104, 001 (2011) & O. Kaczmarek et al. , Phys. Rev. D 83, 014504 (2011)

FO: A. Andronic, P. Braun-Munzinger and J. Stachel, Phys.Lett. B 673 , 142 (2009) & J. Cleymans, H. Oeschler, K. Redlich and S. Wheaton, Phys. Rev. C 73 , 034905 (2006)

P. Cea, L. Cosmai, A. Papa, Phys. Rev. D 93, 014507 (2016)



FO-Fluctuations: P. Alba, W. Alberico, R. Bellwied, M. Bluhm, V. Mantovani Sarti, et al., Phys.Lett. B738, 305 (2014)

- FO parameters using thermal model without multi-strange and strange baryons yields closer to FO parameters from net-p and net-Q fluctuation data.
- Freeze-out points closely follow the parton-hadron phase boundary.

Kinetic Freeze-out

Elastic Collisions Ceases

E. Schnedermann, J. Sollfrank, and U. W. Heinz, Phys. Rev. C 48, 2462 (1993).

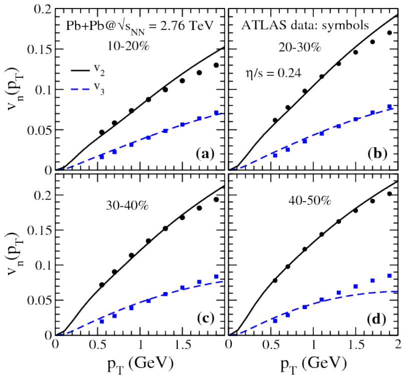
Blast-Wave Model

$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

Parameters: Temperature (T_{kin}) and transverse radial velocity (β)
Obtained by fitting the momentum distribution of particles

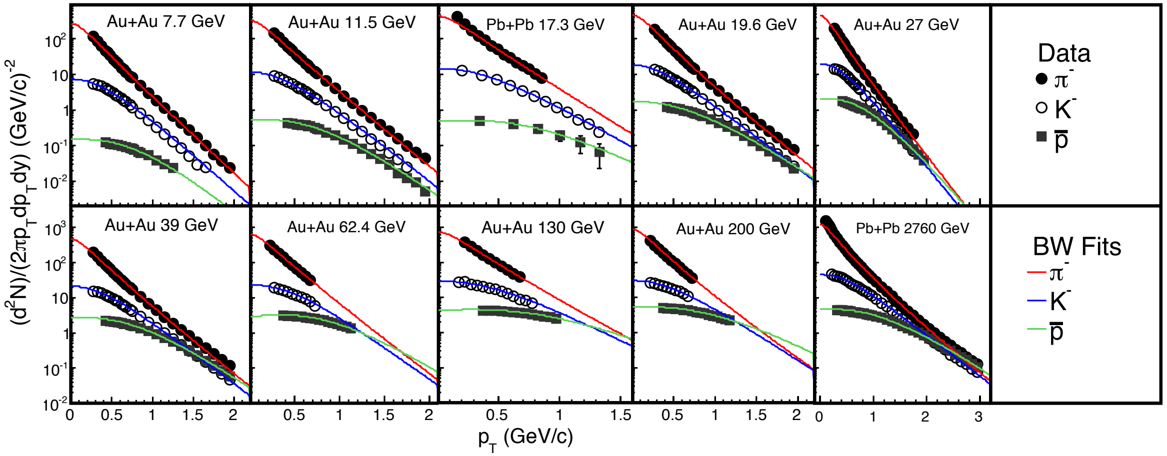
Features:
- Approximates Hydrodynamic based model
- Assumes particles are locally thermal and moving with a common velocity

Recent work: Viscous Blast-Wave Model:
arXiv:1508.05878 , A. Jaiswal and V. Koch



Kinetic Freeze-out Conditions

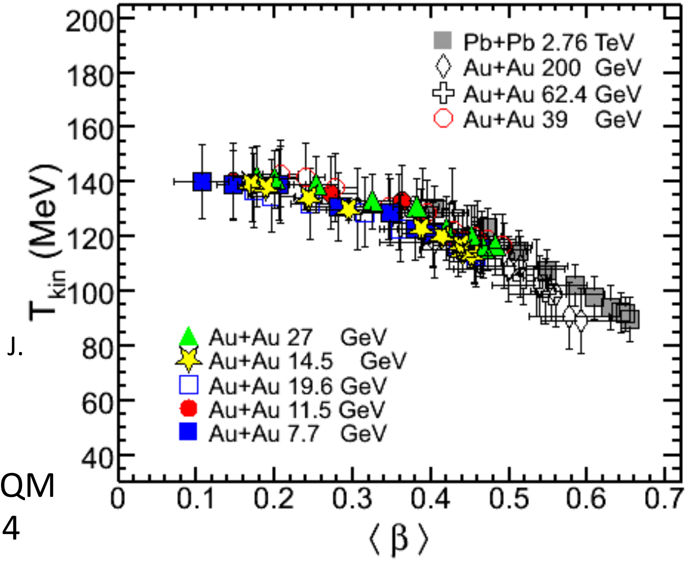
- ☐ Central collisions: lower ***T**$_{kin}$* and larger collectivity β
- ☐ Stronger collectivity at higher energy

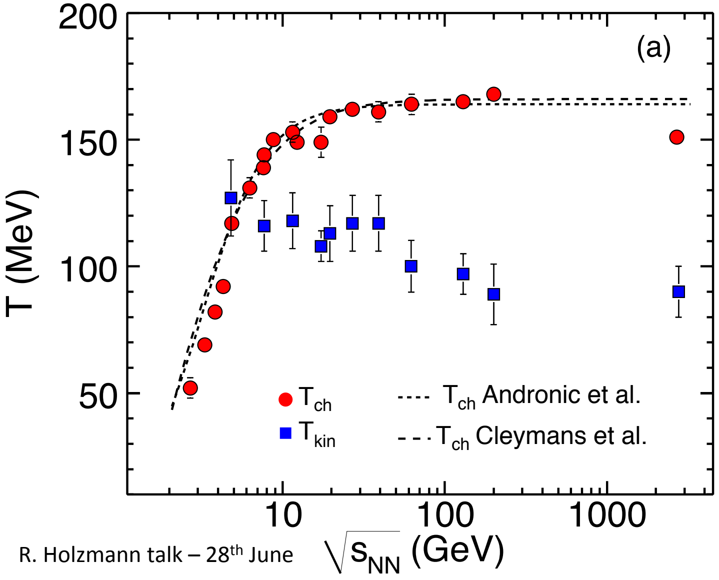


- ☐ Kinetic Freeze-out temperature lower than Chemical Freeze-out temperature
- ☐ Reflects Interactions in hadronic phase

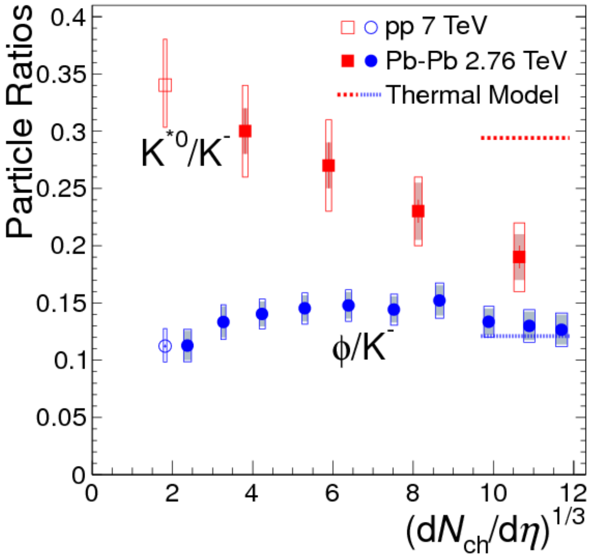
BW: E. Schnedermann, J. et al., PR C 48, 2462 (1993).

STAR: V. Bairathi QM
L. Kumar QM2014





R. Holzmann talk – 28th June



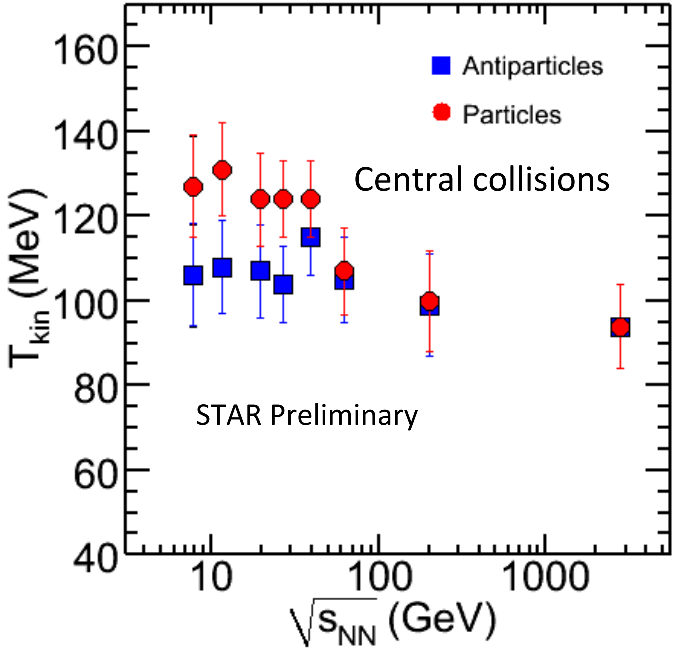
STAR : PRC 79 (2009) 034909;
ALICE: PRC 88, 044910 (2013)

ALICE:
Phys.Rev. C91 (2015) 024609

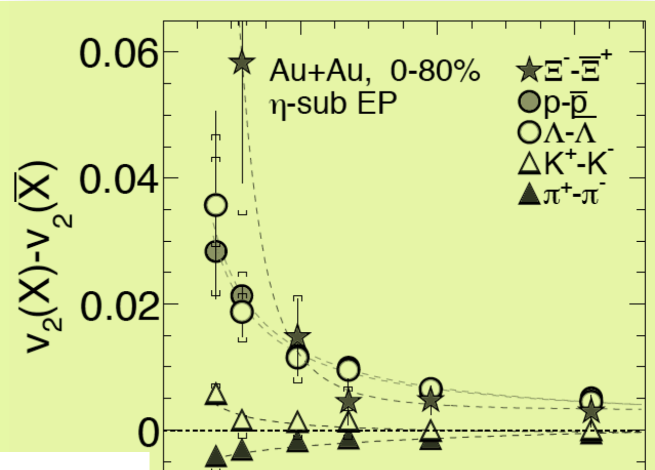
Experimental evidence of re-scattering

Kinetic Freeze-out New Observation: RHIC-BES

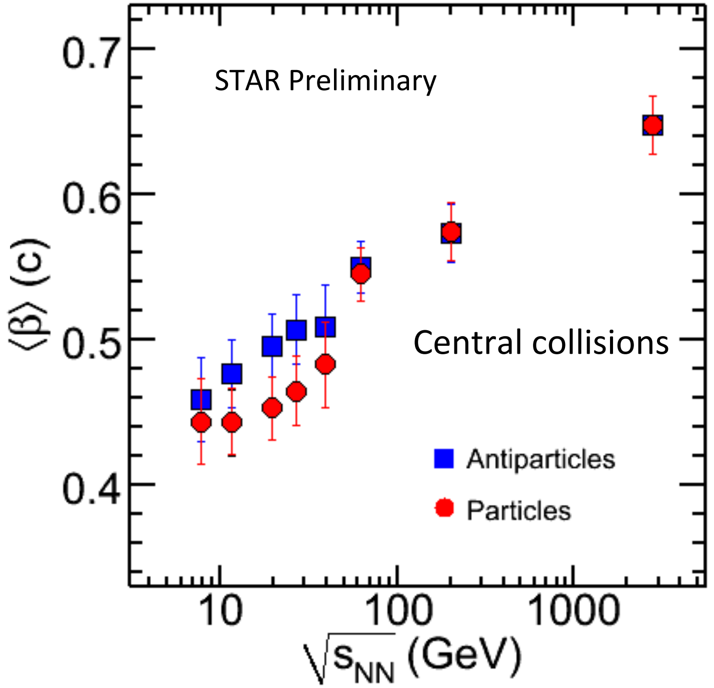
Particles: π^+, K^+, p, Λ, Ξ^- ;
Antiparticles: π^-, K^-, pbar, Λbar, Ξ^+



Phys.Rev.Lett. 110 (2013) 142301; SN0598

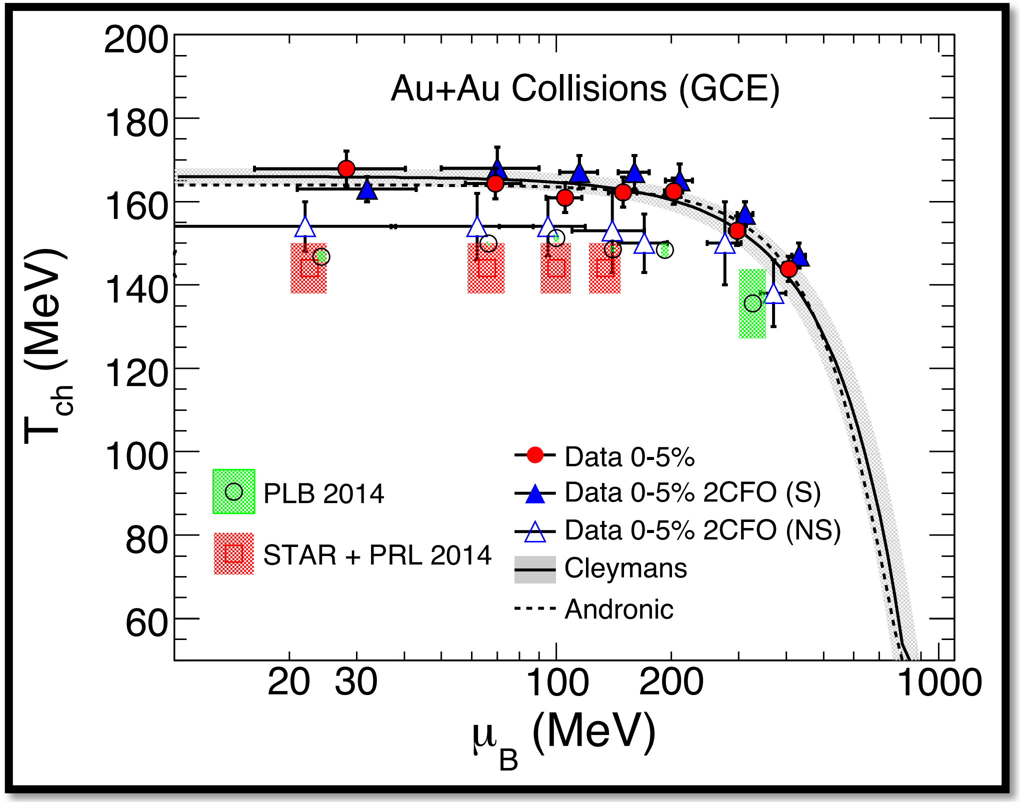


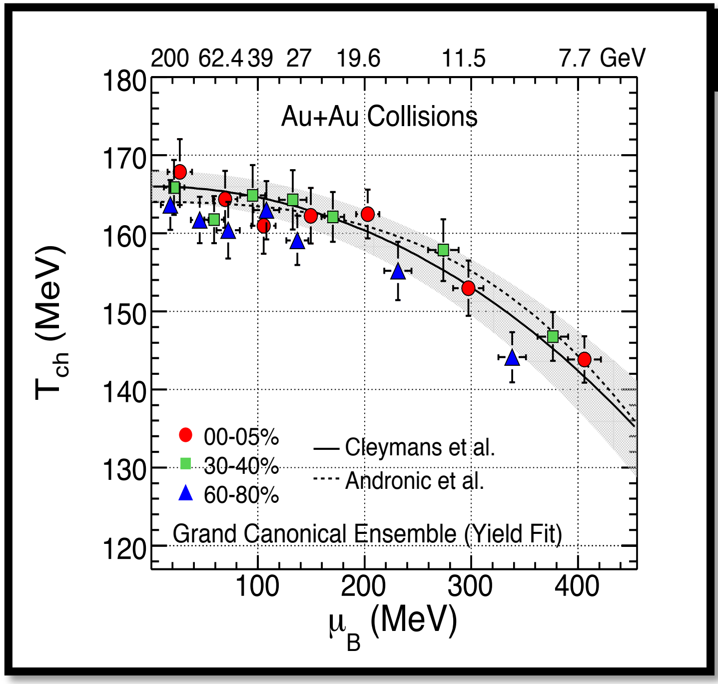
STAR: L. Kumar QM2014

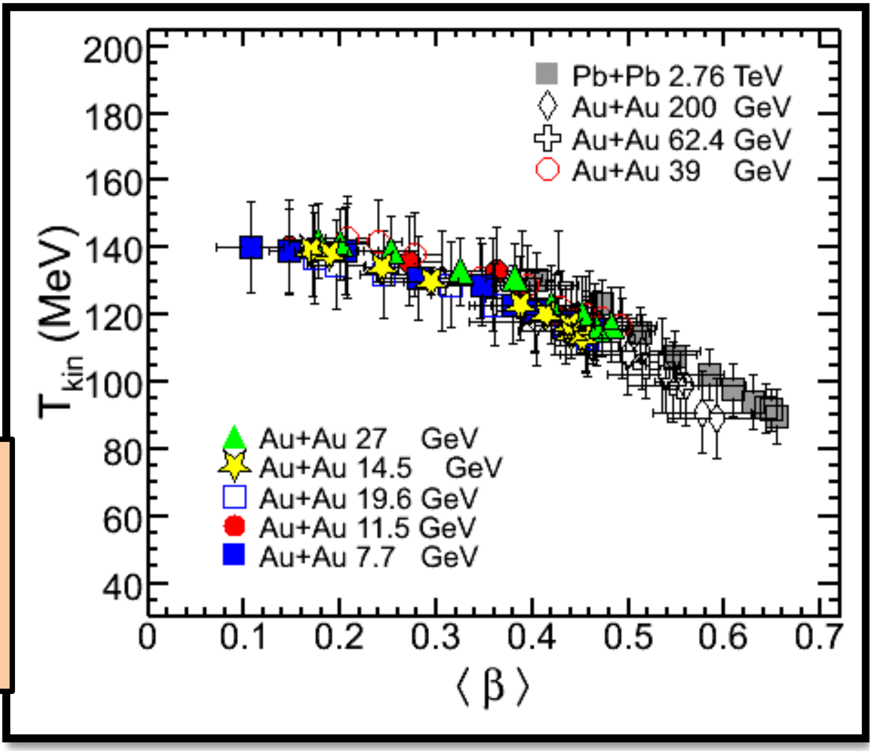


Differences between particle
And anti-particles ?

Summary



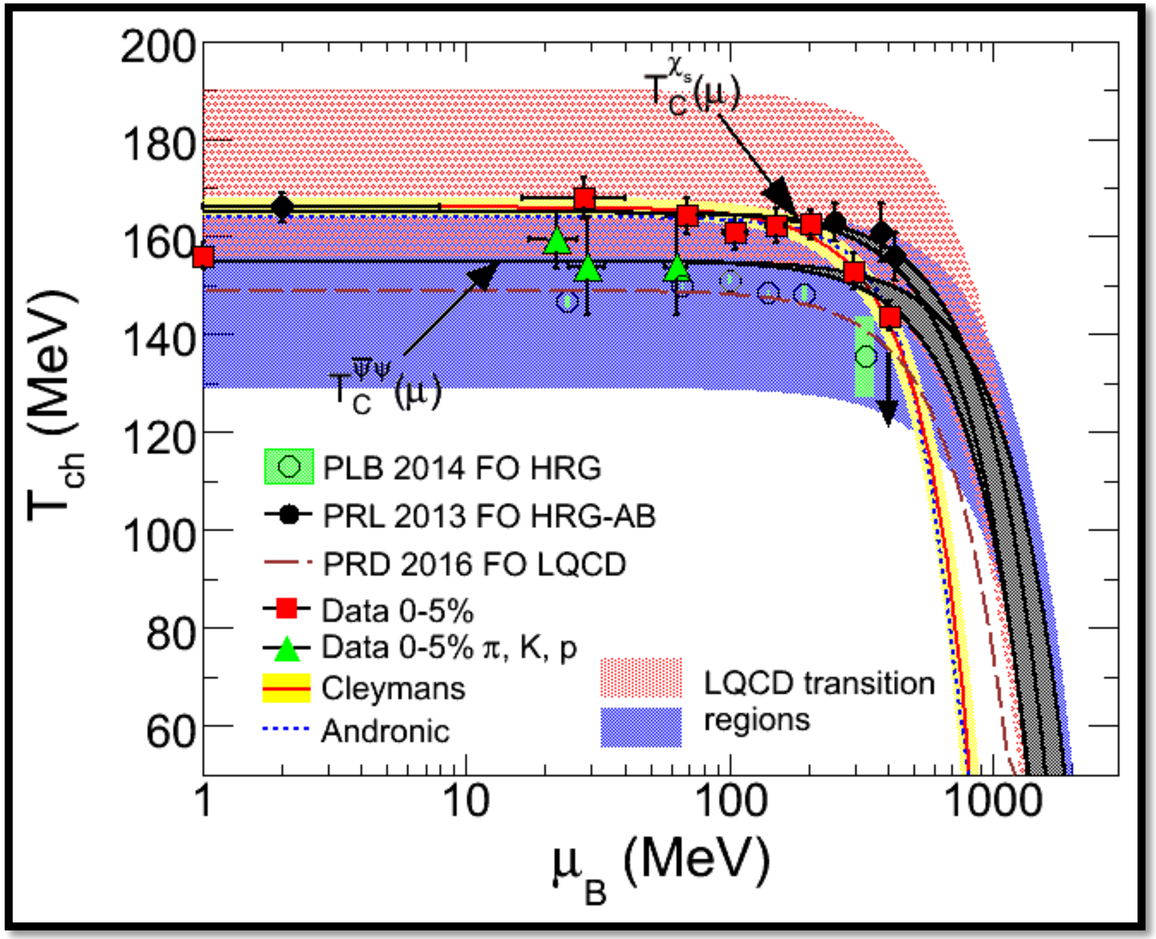




- ❑ New data (LHC, RHIC BES)
- ❑ New Observables (Higher Moments)
- ❑ New Models/Approaches

Discussion

New: Freeze-out parameters using Lattice QCD calculations and HRG vs. experimental data on high moments



Difference in Freeze-out parameters from yields and fluctuations:

☐ Yields and fluctuations freeze-out at different times ?

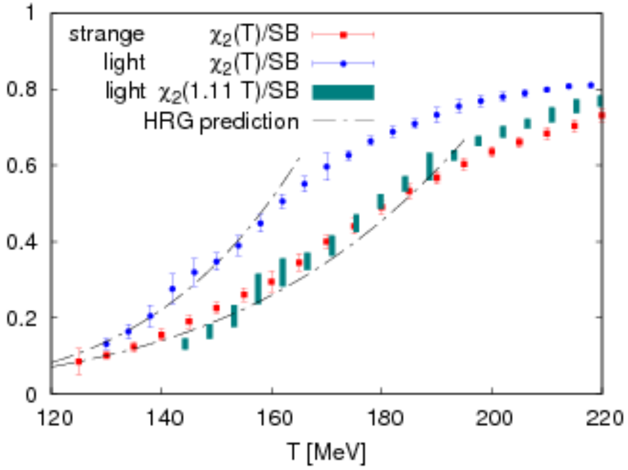
☐ Fluctuations more sensitive to Freeze-out dynamics than yields ?

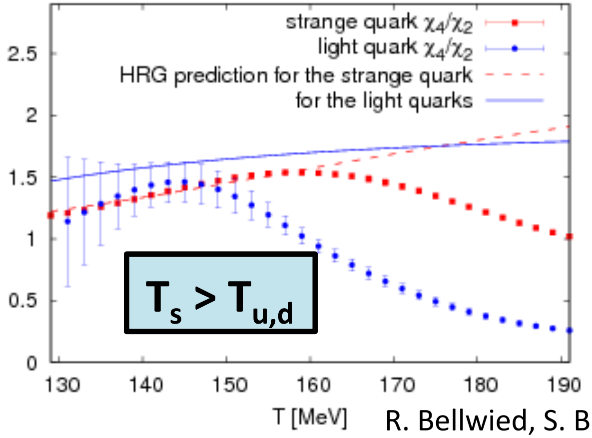
☐ Role of strangeness (Strangeness data on fluctuations important) ?

Discussion

Strange (s) vs. Non-Strange (u,d) FO

Fluctuations: Lattice and HRG

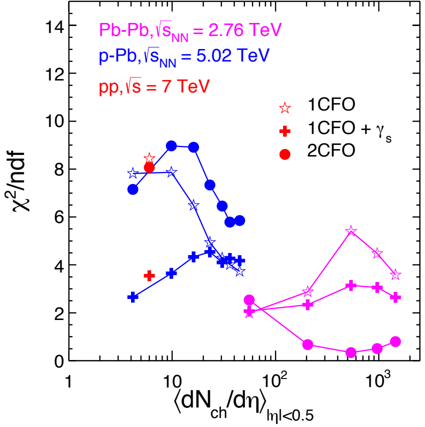




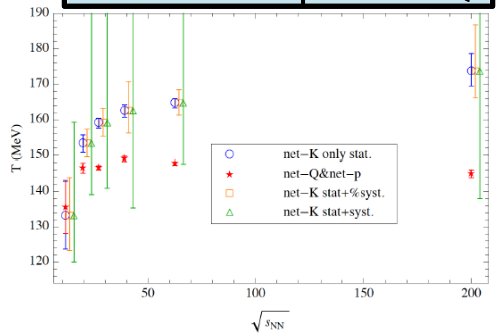
$T_s > T_{u,d}$

R. Bellwied, S. Borsanyi, Z. Fodor, S. D. Katz
Phys.Rev.Lett. 111 (2013) 202302

S. Chatterjee, A. Dash & BM



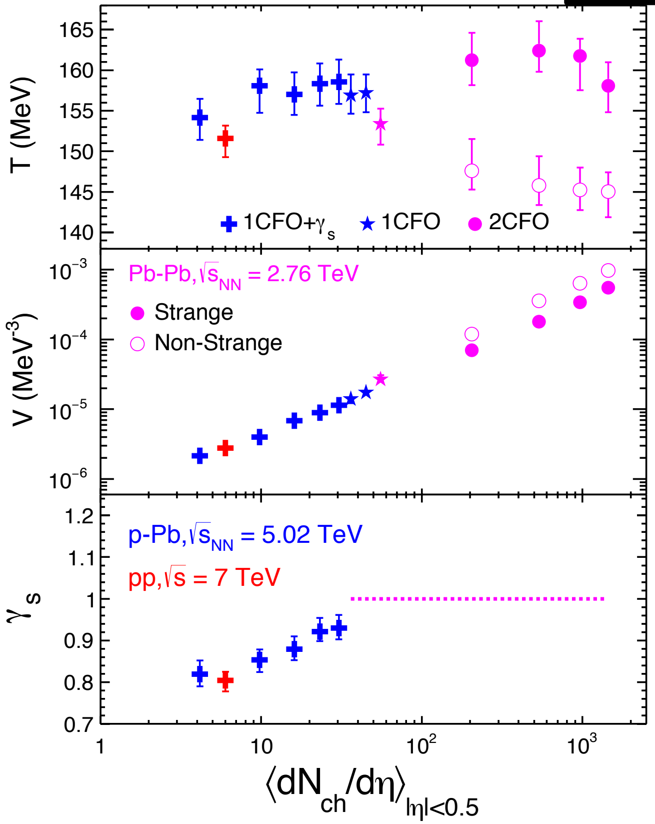
$T_{net\text{-}K} > T_{net\text{-}p} \sim T_{net\text{-}Q}$



R. Bellwied – WWND2016

Yields: Statistical Model

$T_s > T_{u,d}$



Role of additional Strange Hadrons ?
Phys.Rev.Lett. 113 (2014) 072001

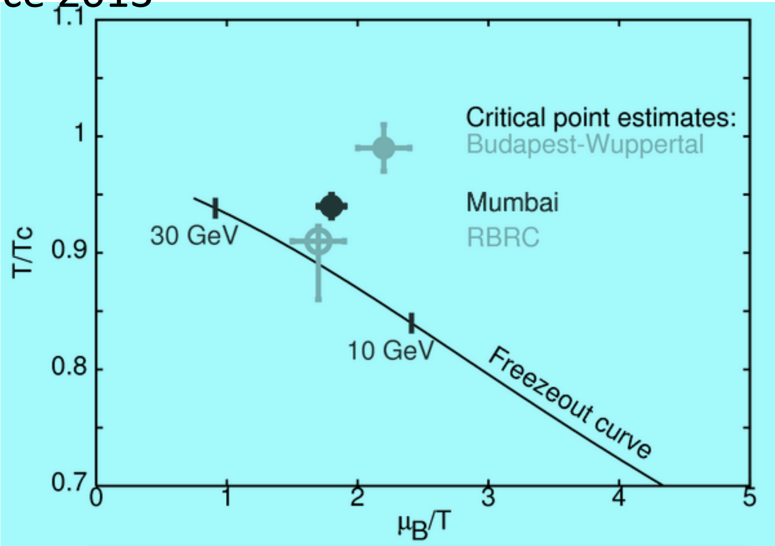
Are there sufficient evidence that non-strange hadrons freeze-out at different time compared to strange hadrons ? – May be ?

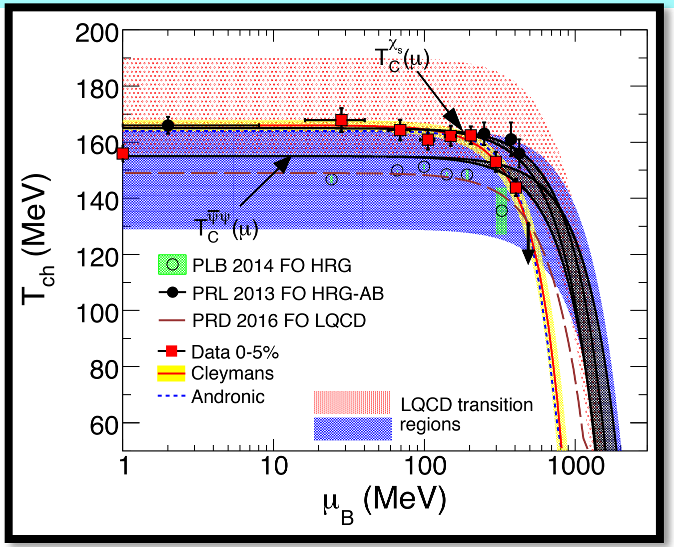
Landmark Point (CP) on Phase Diagram

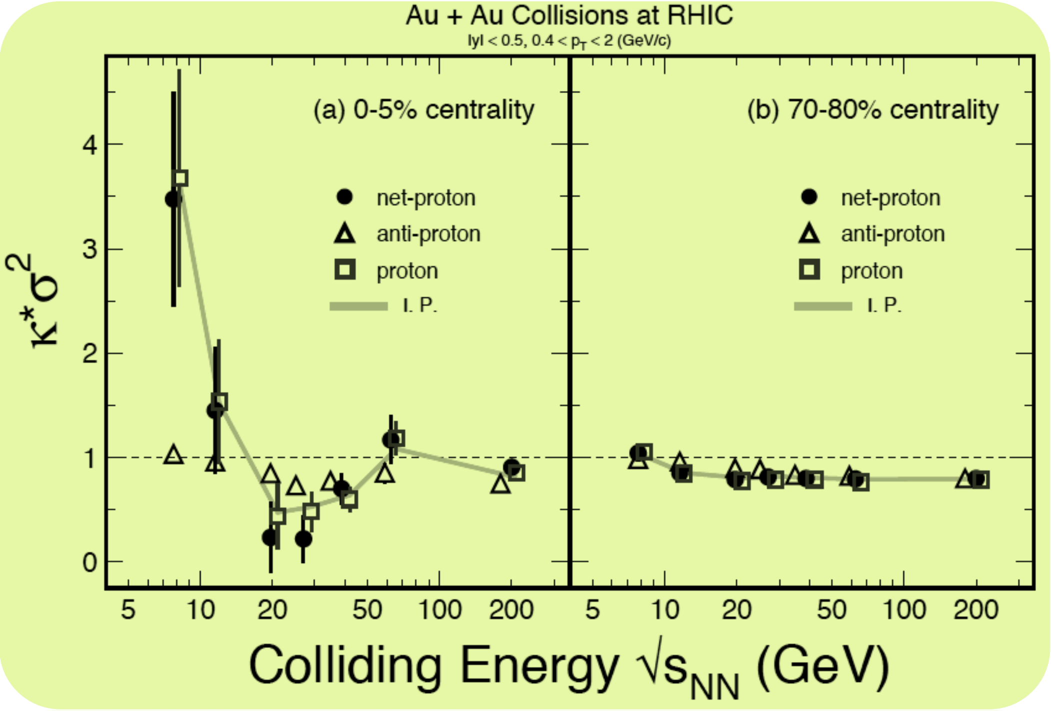
S. Gupta
Lattice 2013

Expectation

Measurement







STAR: CPOD 2015

Exciting times ahead ....

Thanks