Exploring the QCD phase structure with A +A collisions (RHIC BES Program)

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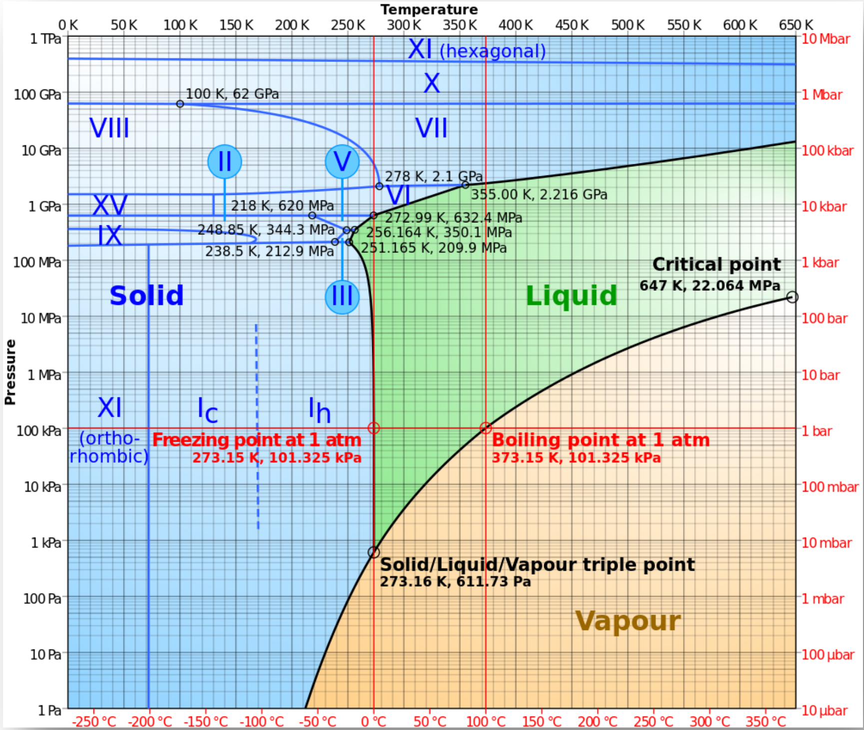
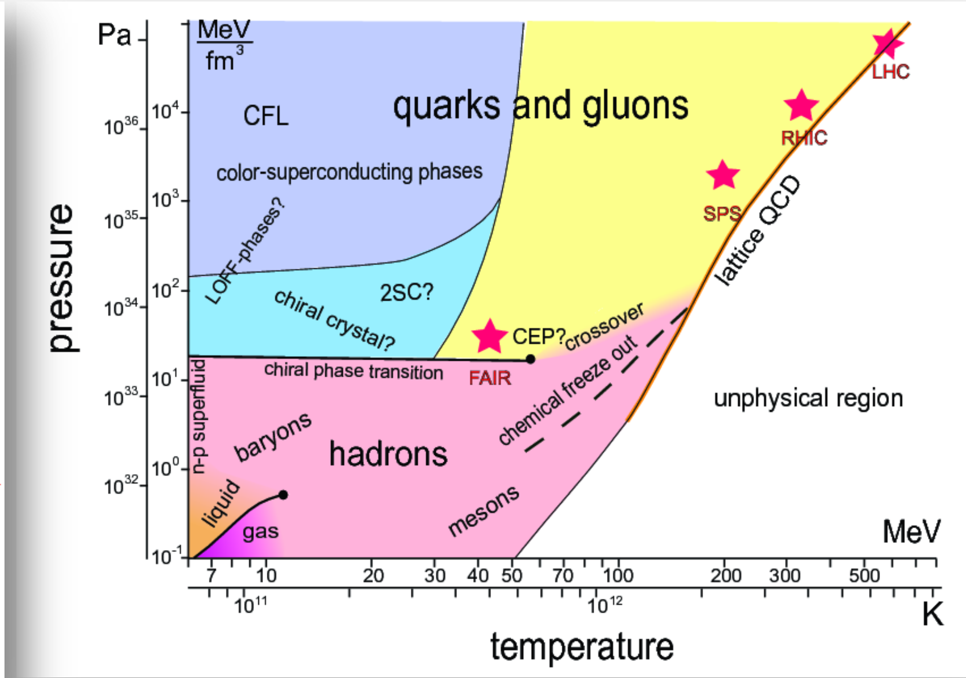
Outline:

- ✧ Phase diagram of QCD
- ✧ Theoretical (brief) and Experimental status (BES-I)
- ✧ Freeze-out Dynamics
- ✧ Summary

Study of QCD Phase diagram – excellent test of QCD in the non-perturbative regime

Phase Diagram and Basic Interactions





Phase diagram of Water
Electromagnetic interaction
Precisely known

Phase diagram of strong interactions. Largely still a conjecture

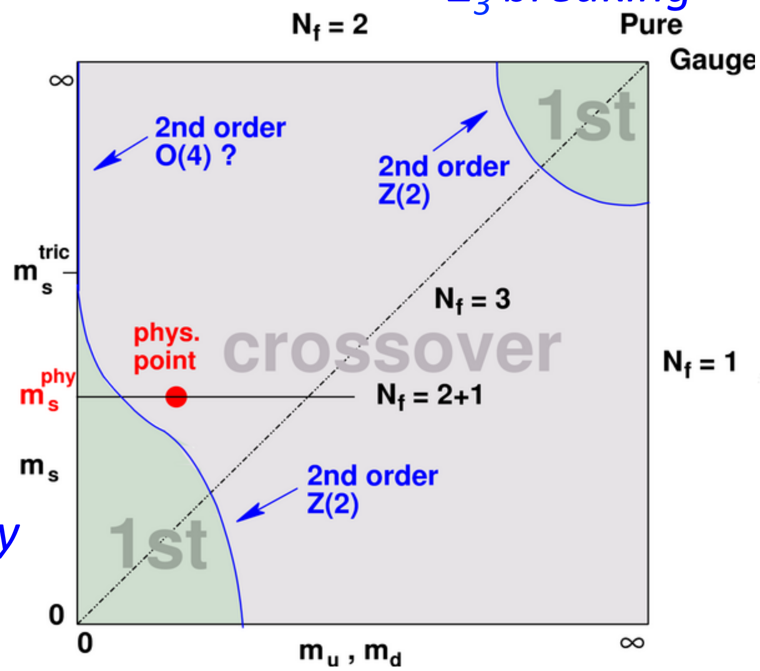
arXiv:1111.5475 [hep-ph]

Phase Diagram of QCD - Theoretically

$\boxed{\mu_B = 0}$

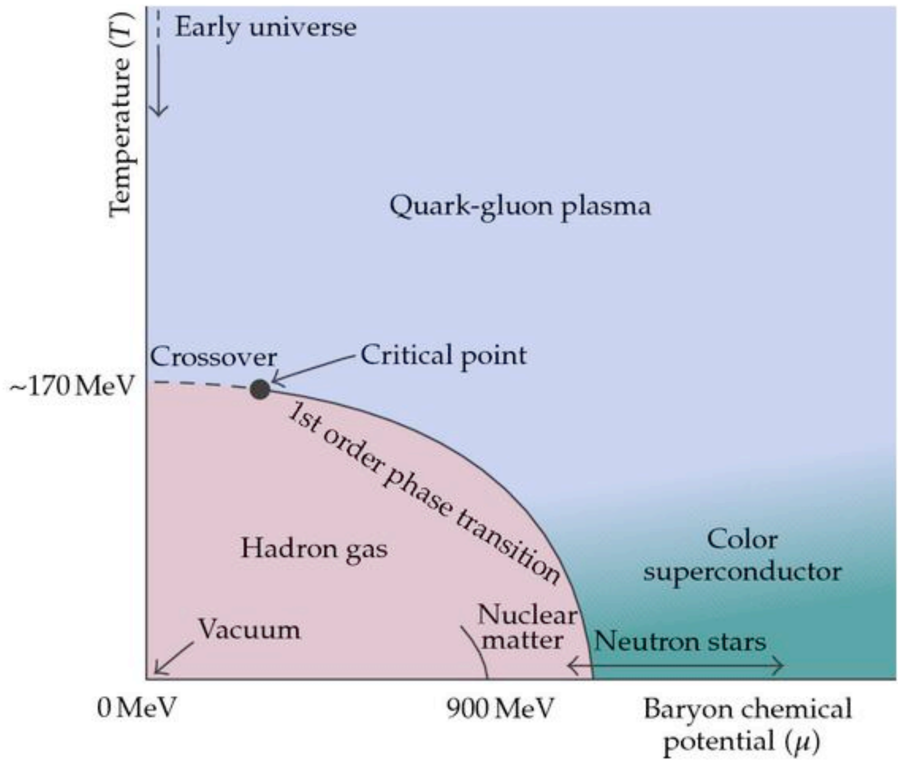
Spontaneous
Z_3 breaking

Chiral symmetry restored



Ann. Rev. Nucl. Part. Sci. 53, 163, 2003

$\boxed{\mu_B > 0}$



K. Rajagopal and F. Wilczek, Handbook of QCD

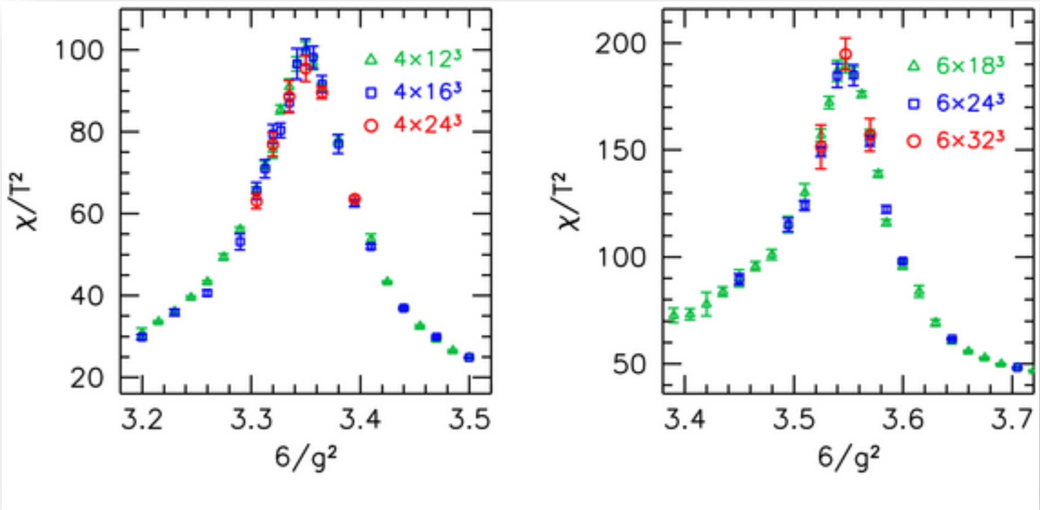
Interplay of the chiral symmetry and the center symmetry. These symmetries are exact for zero and infinite quark masses, respectively.

Very rich phase structure unfolds in the phase diagram.

Cross-over and Temperature

$\chi(N_s, N_t) = \partial^2/(\partial m_{ud}^2)(T/V) \cdot \log Z$

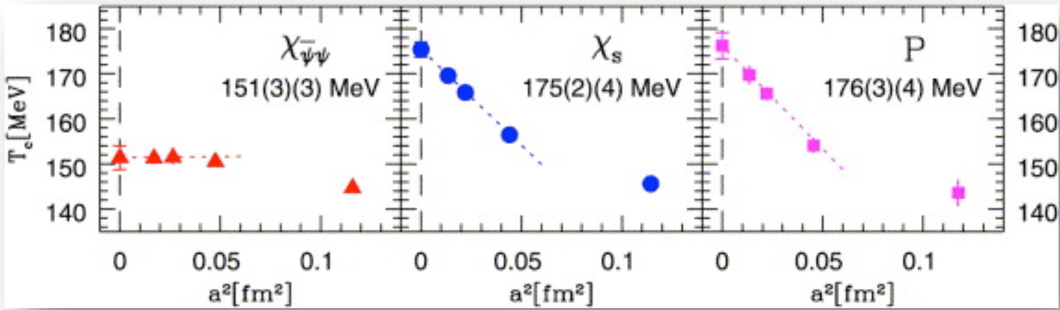
Physical quark masses
Continuum limit
Simulations along Lines of
Constant Physics
m_K/m_π = 3.689; f_K/m_π = 1.185
Staggered fermionic action

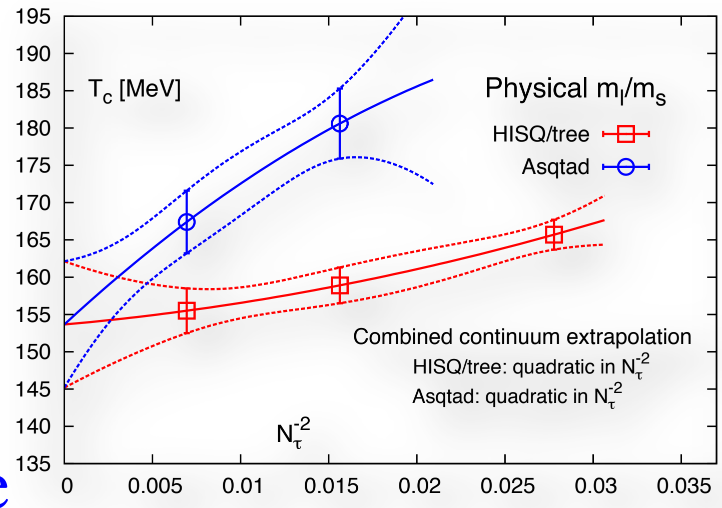


Nature443:675-678,2006

No significant volume dependence

Nucl. Phys. A 830 (2009) 805c

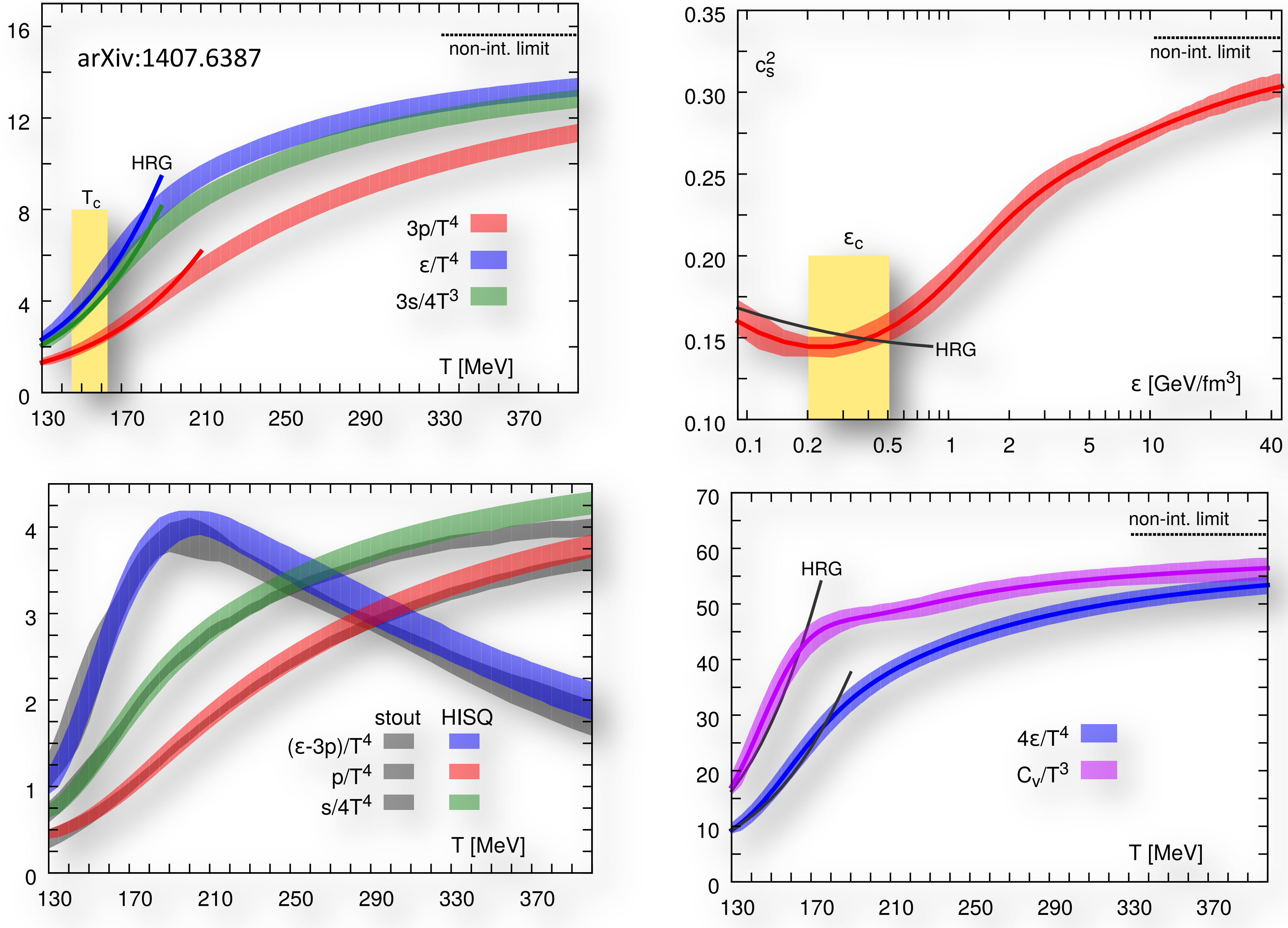




At high T and μ_B = 0 is a cross over.
Agreement on cross over temperature
using chiral condensates.

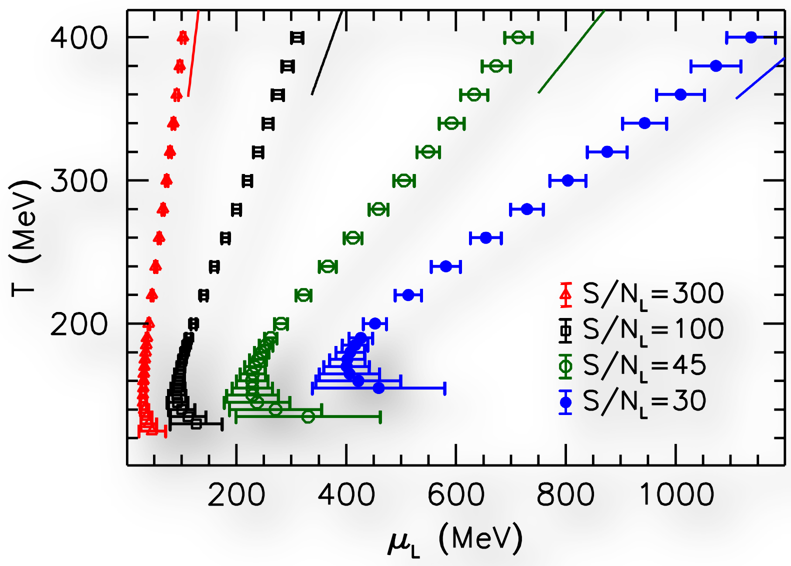
Phys.Rev. D85 (2012) 054503

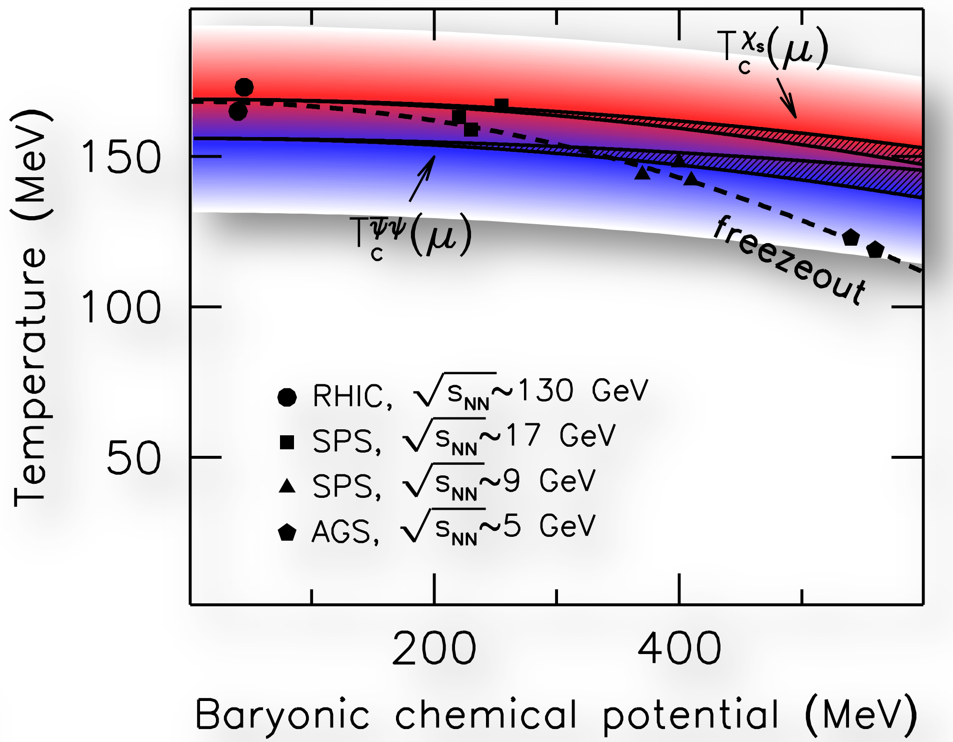
Thermodynamics at μ_B = 0 MeV

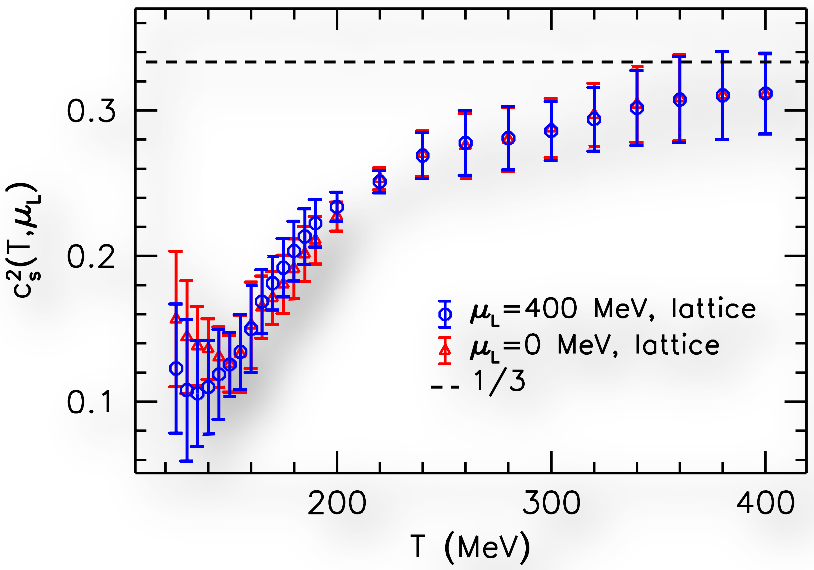


Trajectories, EOS at non-Zero μ_B

JHEP 1208 (2012) 053 JHEP 1104 (2011) 001





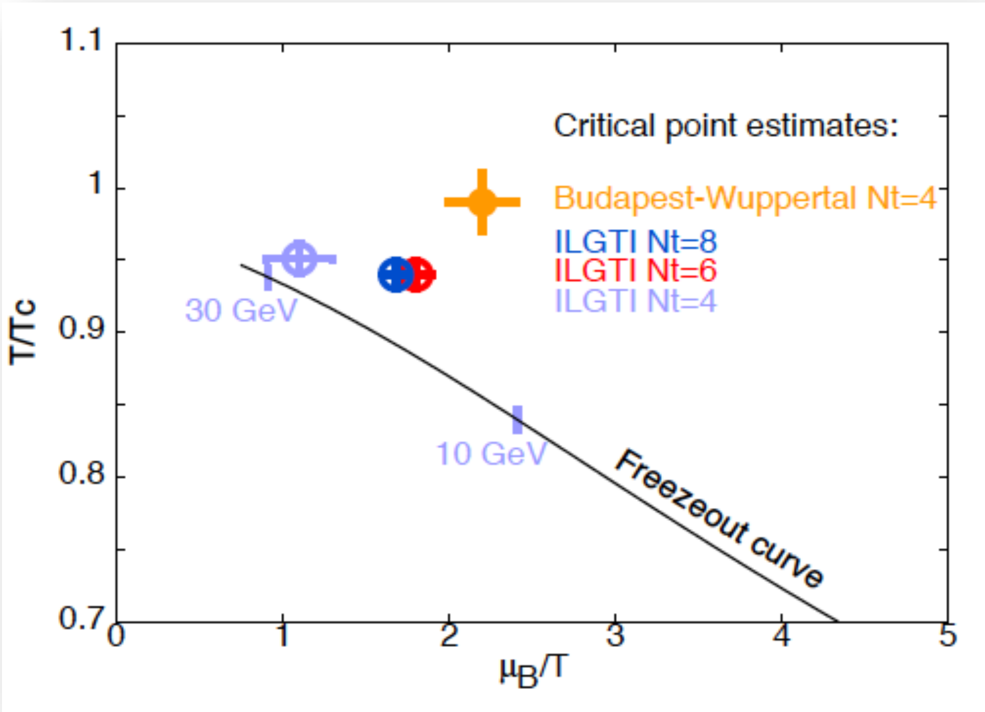


Lattice QCD provides Temperature and Baryon density evolution of the system in the QCD phase diagram.

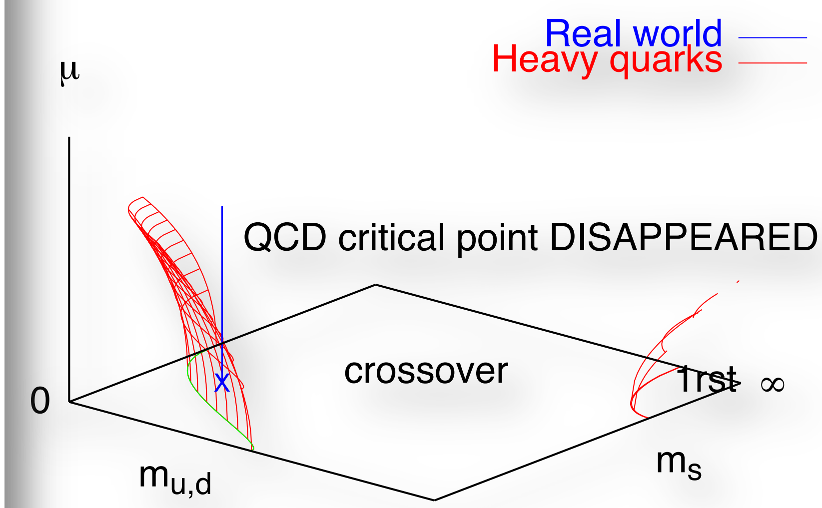
Search for Critical Point - Theory

Numerical QCD calculations at large μ_B – sign problem

Techniques: Reweighting, Taylor expansion & Im. potential



Phys. Rev. D 78, 14503 (2008)
Phys.Rev.D 71, 114014 (2005)
PoS LATTICE2013 (2013) 202



Acta Phys.Polon.Supp. 5 (2012) 825-835
JHEP 0404, 50 (2004)

Issues (not common to all) : lattice spacing, physical quark mass, continuum limit, Volume

Theory: still some more work to be done …… need more CPU

QCD Phase Diagram - Theory

At $\mu_B = 0$

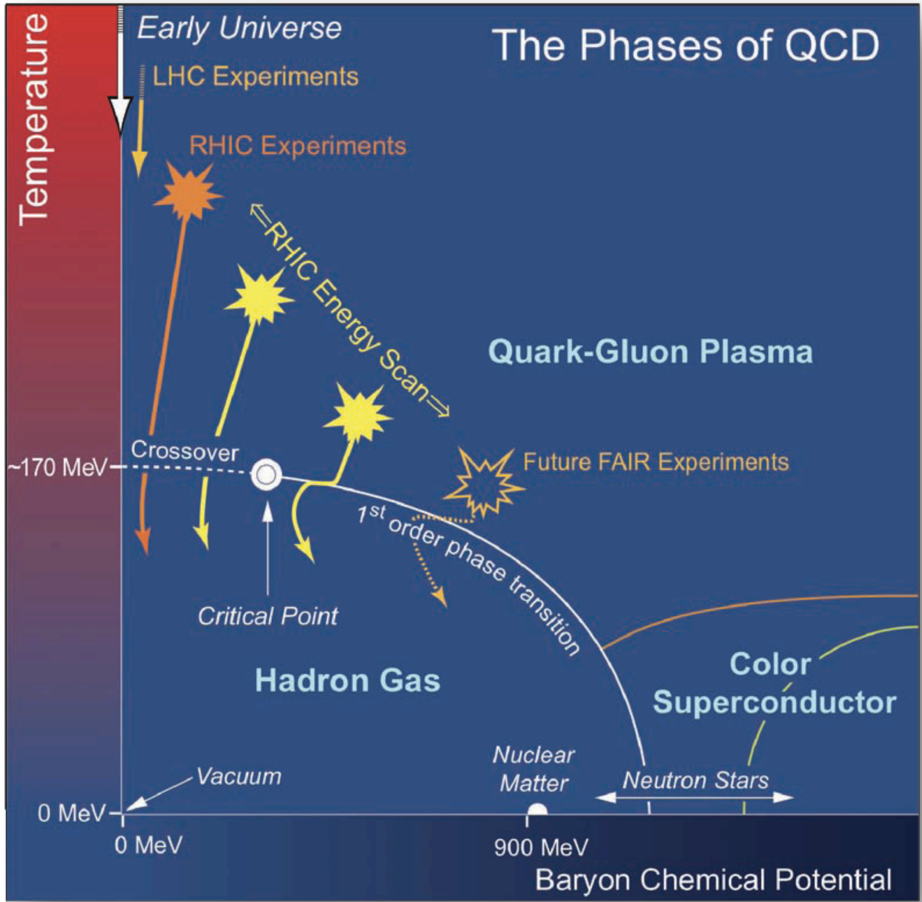
Lattice QCD

- Quark – hadron Transition – Cross-over
- Transition temperature ~ 150 MeV (Observable dependent)
- Robust continuum limit results: EOS and Thermodynamics

At μ_B non-zero

- Efforts on to draw the transition line – large uncertainties
- Efforts on to get EOS and thermodynamics
- Critical point search progressing – positive results indicate CP region below Beam energy 30 GeV

QCD Phase Diagram - Experimental

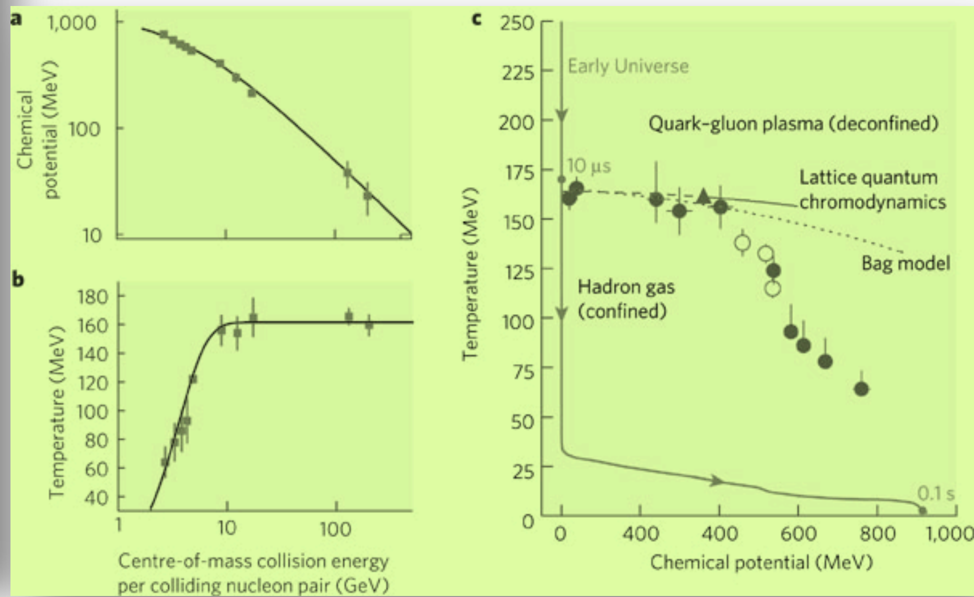


Conservation in strong interactions

-- Charge

-- Baryon number

-- Strangeness



Vary: T, μ_B, μ_S, μ_Q

Nature 448 (2007) 302

Vary beam energy to change Temperature & Baryon Chemical Potential

RHIC Beam Energy Scan−Phase I

$\sqrt{s}$ (GeV)	Statistics(Millions) (0-80%)	Year	μ_B (MeV)	T (MeV)	μ_B /T
7.7	~4	2010	420	140	3.020
11.5	~12	2010	315	152	2.084
19.6	~36	2011	205	160	1.287
27	~70	2011	155	163	0.961
39	~130	2010	115	164	0.684
62.4	~67	2010	70	165	0.439
200	~350	2010	20	166	0.142

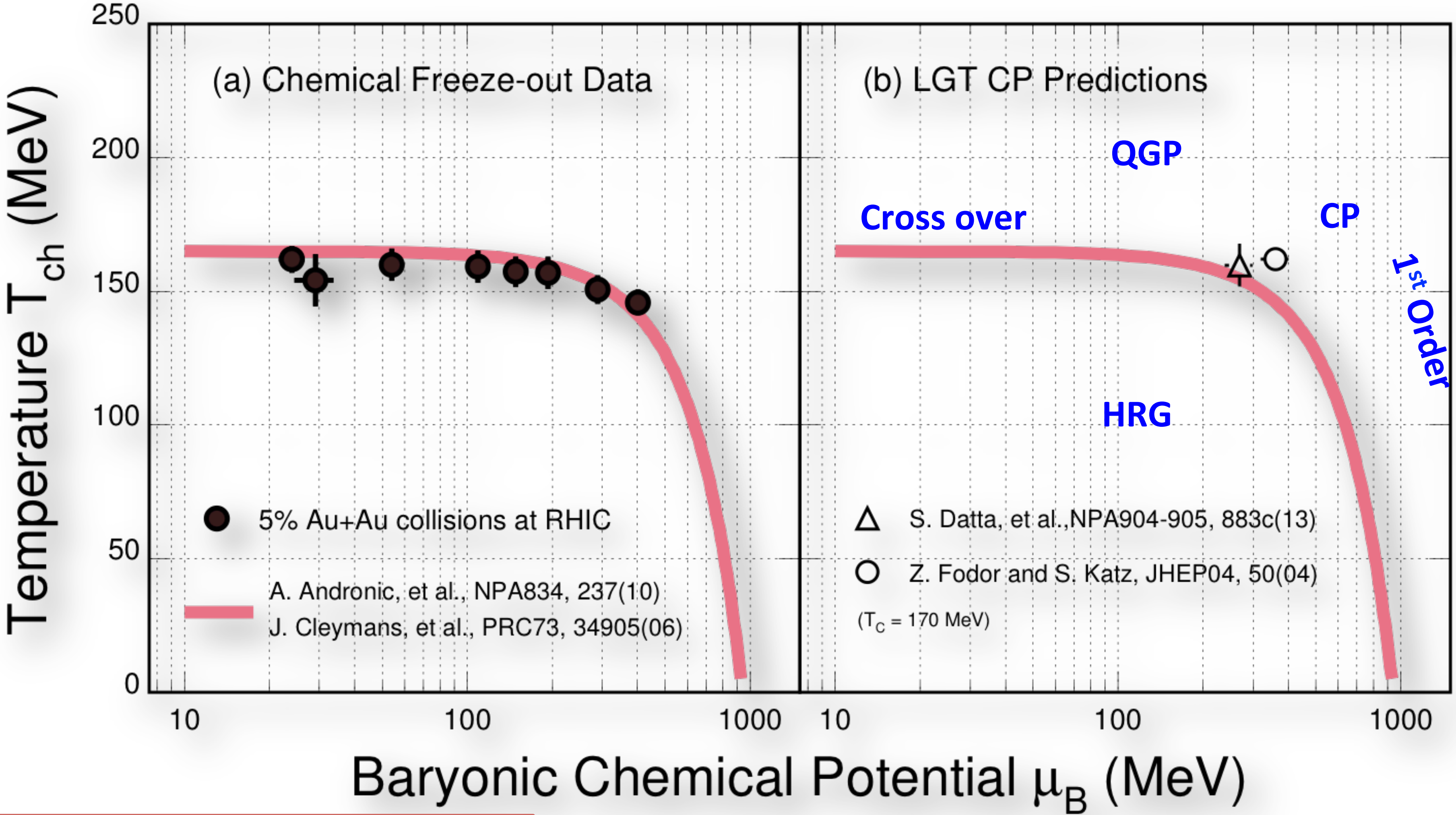
μ_B, T : J. Cleymans et al., Phys. Rev. C 73, 034905 (2006).

Run14(Year 2014):
14.5 GeV
μ_B ~ 266 MeV
Events: 20 Million

The main goals of BES program:

- Freeze-out dynamics
- Search for Onset of De-confinement
- Search for QCD critical point
- Search for signals of first order phase transition

QCD Phase Structure: Theory-Experiment



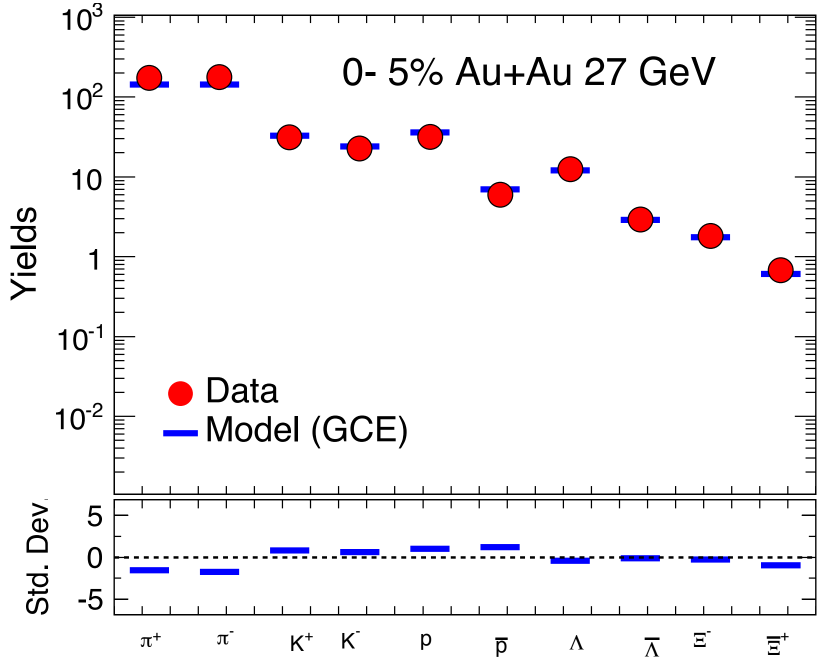
Partonic Phase
Hadronic Phase
Freeze-out dynamics*

Cross Over
First Order*

Critical region*

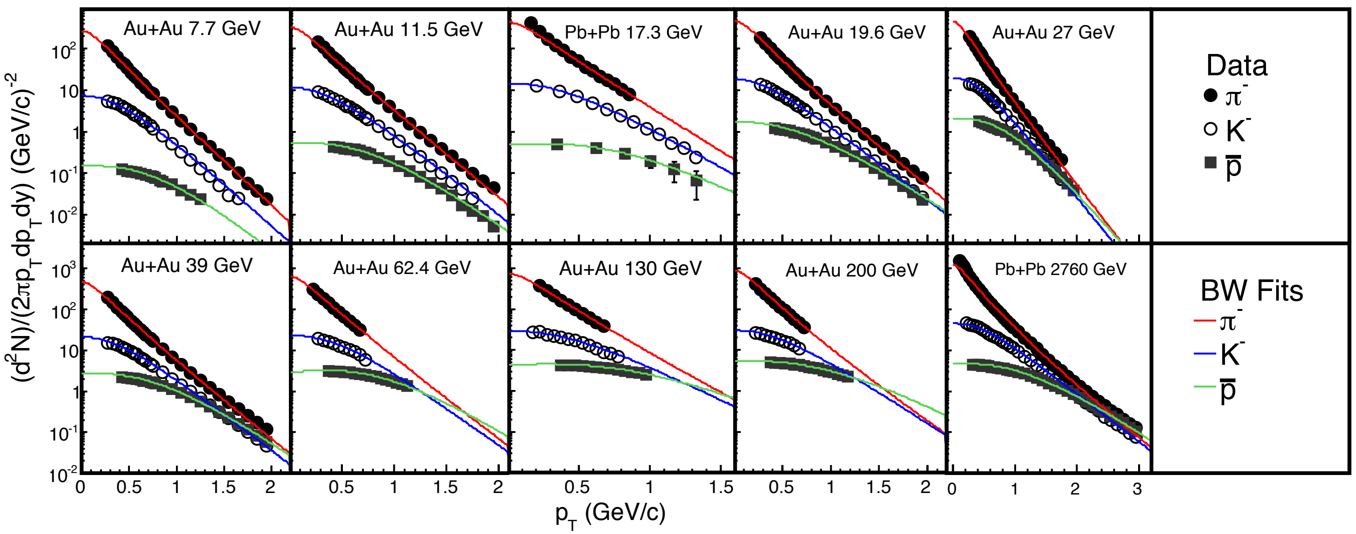
Freeze-out Dynamics

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



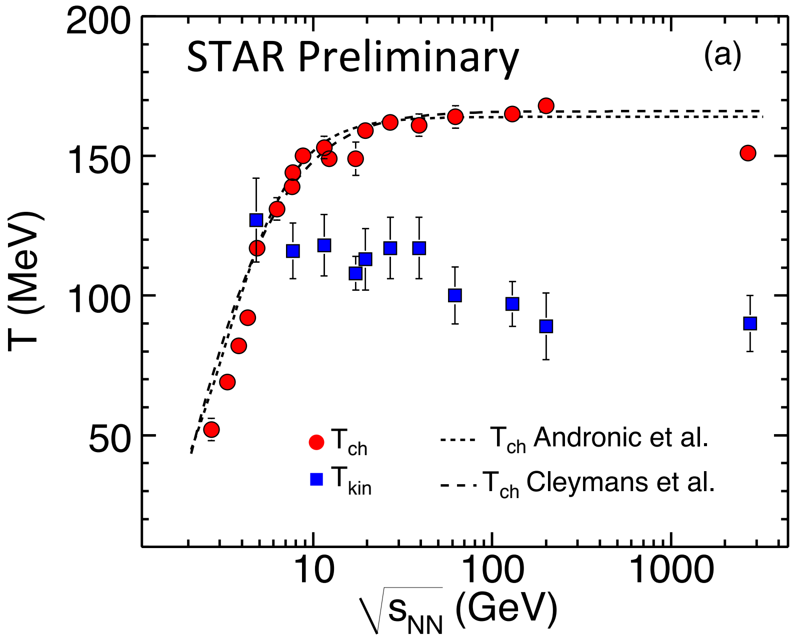
Particle yields : Chemical Freeze-out thermodynamic parameters

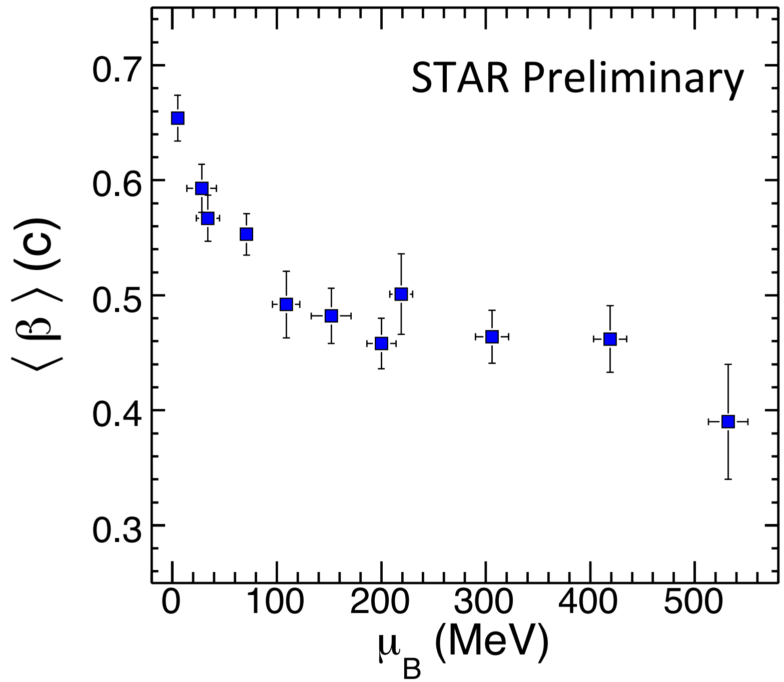
$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

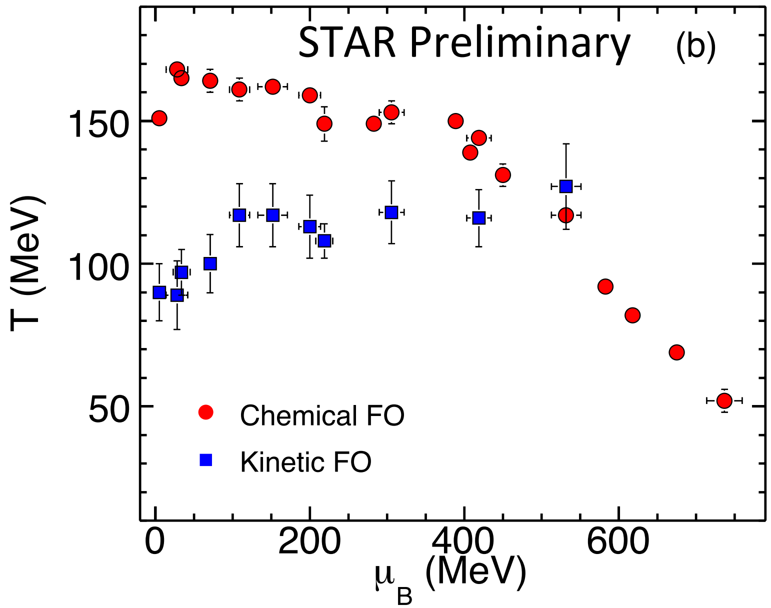


Shape of particle momentum Spectra: Kinetic Freeze-out thermodynamic parameters

Freeze-out Dynamics







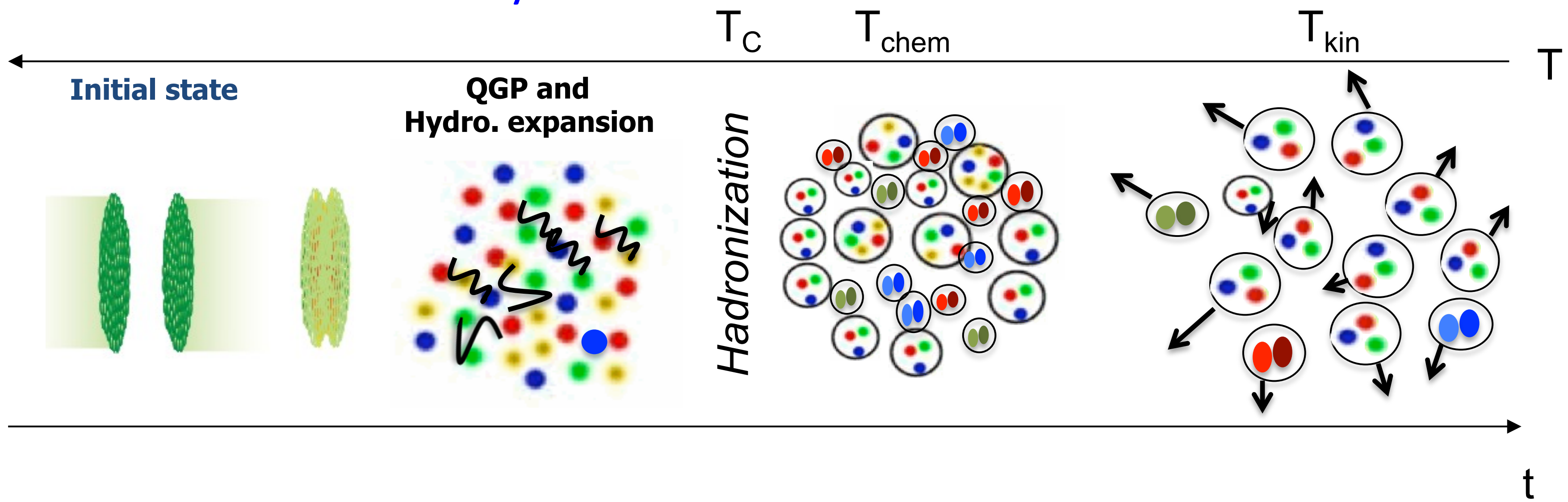
Difference between T_{kin} and T_{ch} increases with increasing energy or decreasing μ_B

-- Effect of hadronic interactions

Collective flow decreases and then remains constant with increase in μ_B

Freeze-out Dynamics

Time Evolution of Heavy-ion Collisions:



Colliding ions

De-confined state

Chemical freeze-out
- ✧ Inelastic collision cease
- ✧ Particle yield fixed

Kinetic freeze-out
- ✧ Elastic collision cease
- ✧ Spectral shape fixed

S. Chatterjee et al., PLB 727, 554 (2013)
K. Bugaev et al., EPL 104, 22002 (2013)

T_S : Strange particles
T_{NS}: Non-Strange particles

←

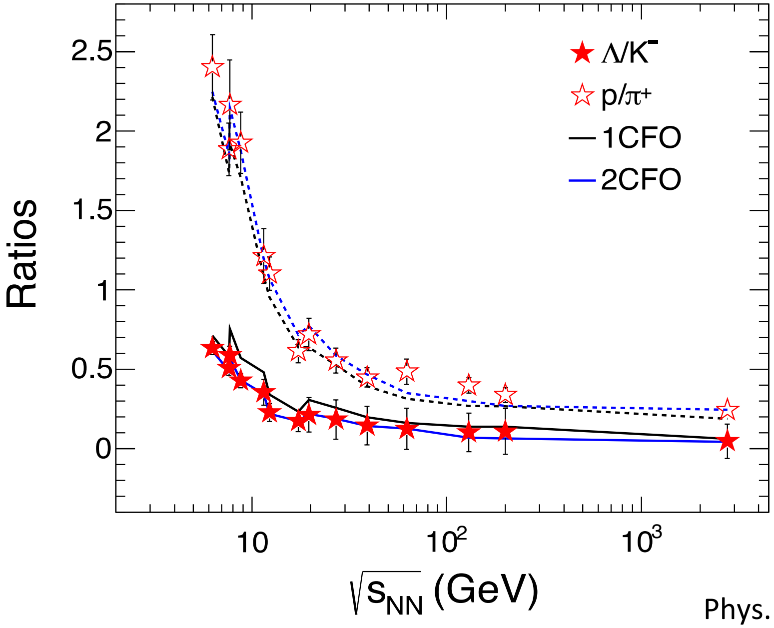
Statistical thermal model: T_{ch} and μ_B

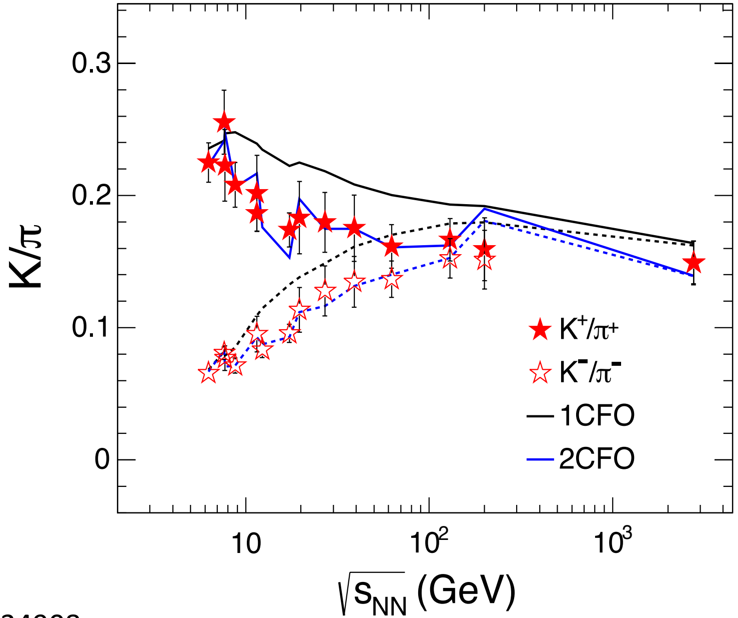
Blast wave model: T_{kin} and $\langle\beta\rangle$

Microscopically – multiple/sequential/Flavor dependent freeze-out expected

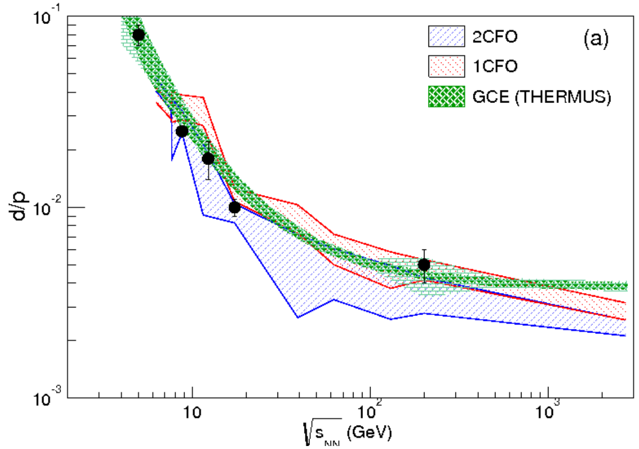
See talks by S. Chatterjee and R. Singh

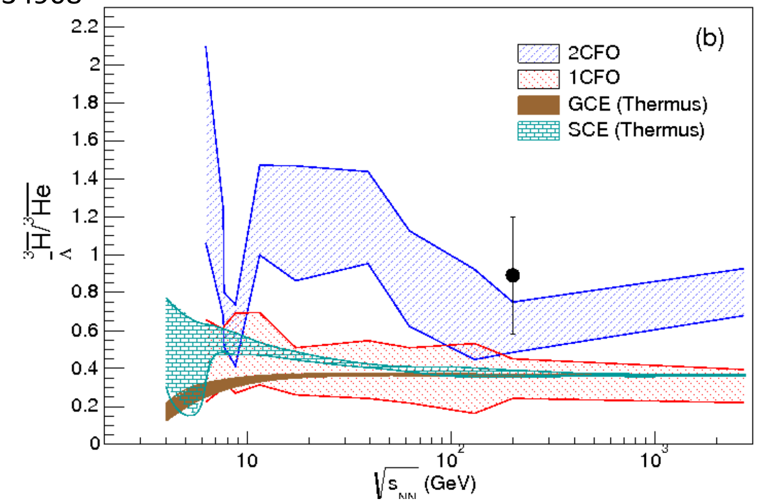
1CFO vs. 2CFO





Phys.Rev. C90 (2014) 034908



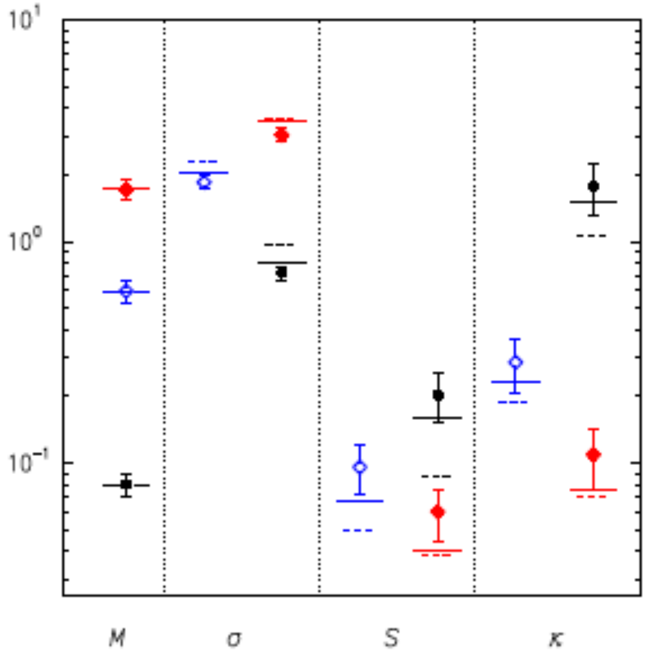


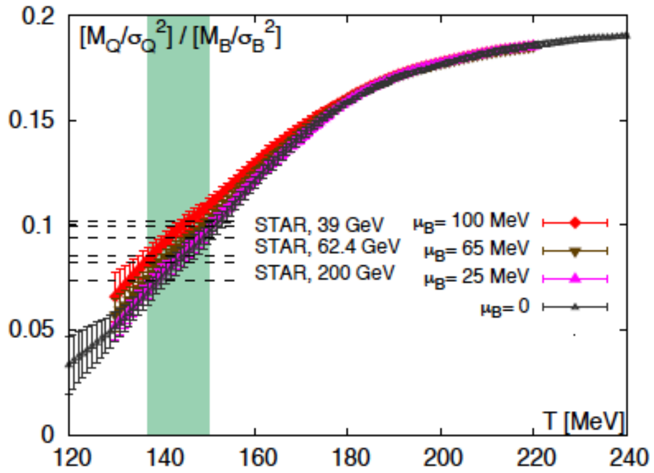
p/π, Λ/K, d/p: Described by both 1CFO and 2CFO

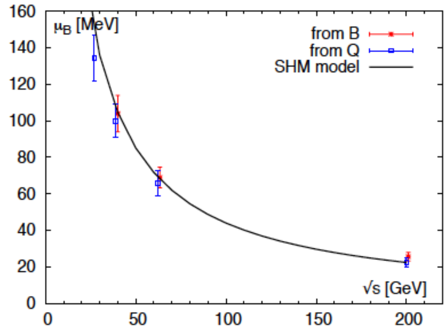
K/π, hypertriton/helium : Better described by the 2CFO

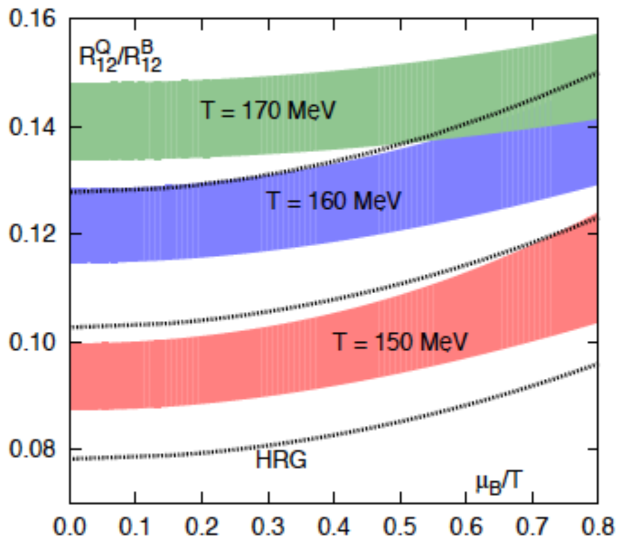
Freeze-out Dynamics

So far 1st moments of multiplicity distributions were used, now higher moments are being considered.









Phys.Rev. C84 (2011) 064911

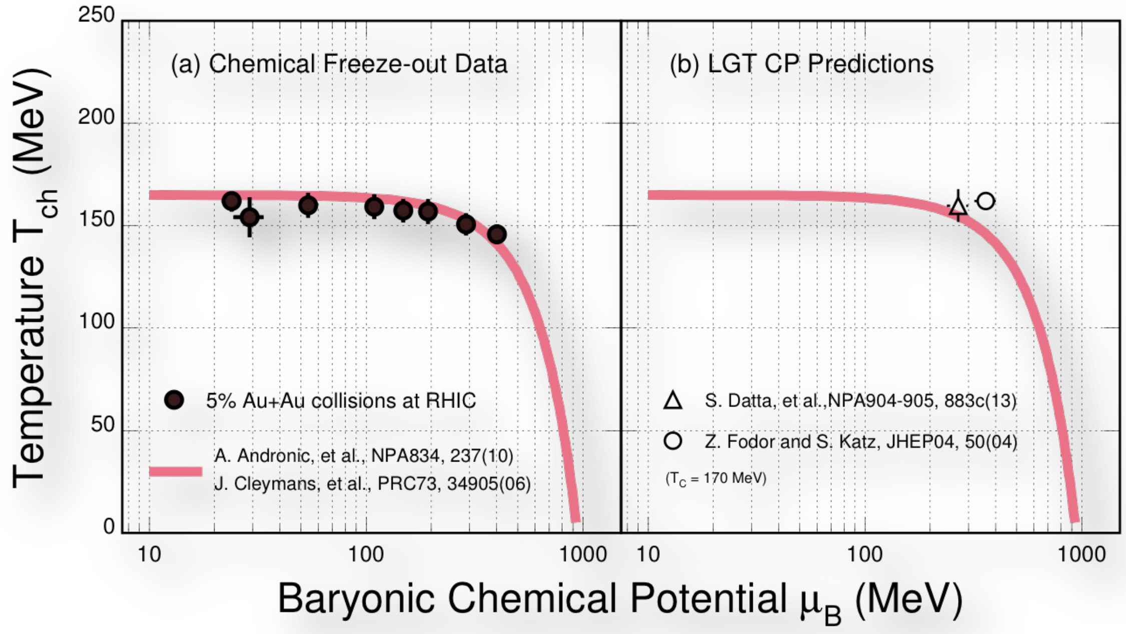
Phys.Rev.Lett. 109 (2012) 192302

Phys.Rev.Lett. 111 (2013) 062005

Phys.Rev.Lett. 113 (2014) 052301

Phys.Rev.Lett. 113 (2014) 072001

QCD Phase Structure: Freeze-out

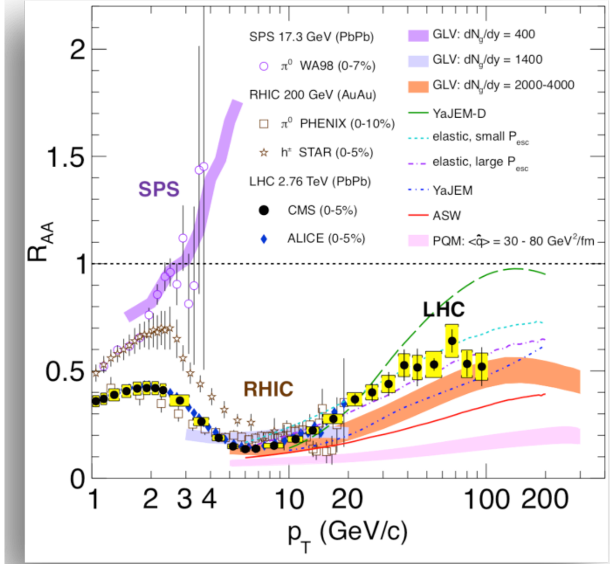


- RHIC experiments cover a μ_B region: 20 – 400 MeV (largest at a single experimental facility)
- Potentially covers the expected CP region
- Recently new directions in freeze-out dynamics has emerged
  - Higher moments of multiplicity distribution
  - Multiple/sequential/flavor freeze-out

	Energy (GeV)	Chemical Potential μ_B	Pred. Temp. (MeV)
LHC	2760.0	2	166.0
RHIC	200.0	24	165.9
RHIC	130.0	36	165.8
RHIC	62.4	73	165.3
RHIC	39.0	112	164.2
RHIC	27.0	156	162.6
RHIC	19.6	206	160.0
SPS	17.3	229	158.6
RHIC	14.5	262	156.2
SPS	12.4	299	153.1
RHIC	11.5	316	151.6
SPS	8.8	383	144.4
RHIC	7.7	422	139.6
SPS	7.7	422	139.6
SPS	6.4	476	131.7
AGS	4.7	573	114.6
AGS	4.3	602	108.8
AGS	3.8	638	100.6
AGS	3.3	686	88.9
AGS	2.7	752	70.4
SIS	2.3	799	55.8

Establishing Quark Gluon Phase

Jet Quenching

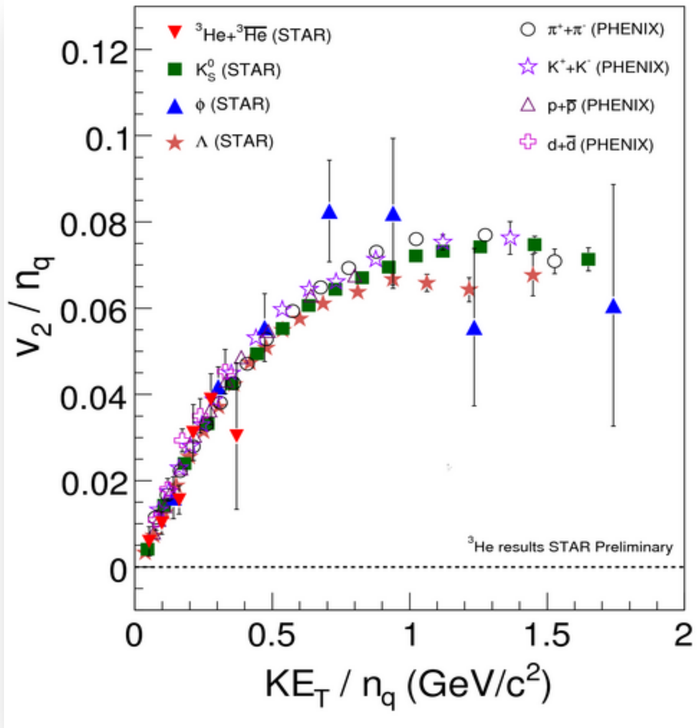


NCQ Scaling

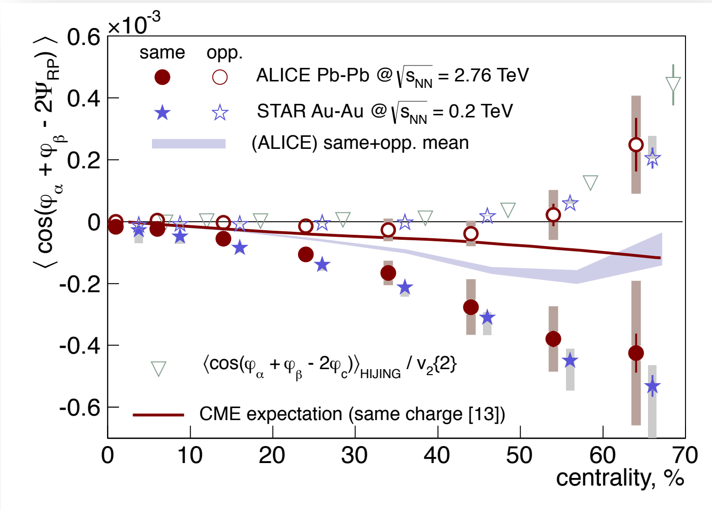
$$v_2 = \langle \cos 2\varphi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

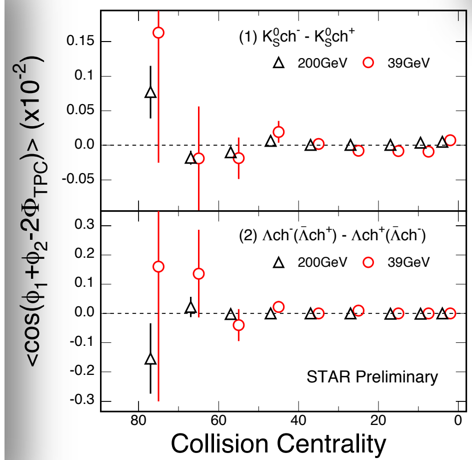
$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

Eur.Phys.J. C72 (2012) 1945



Charge correlations



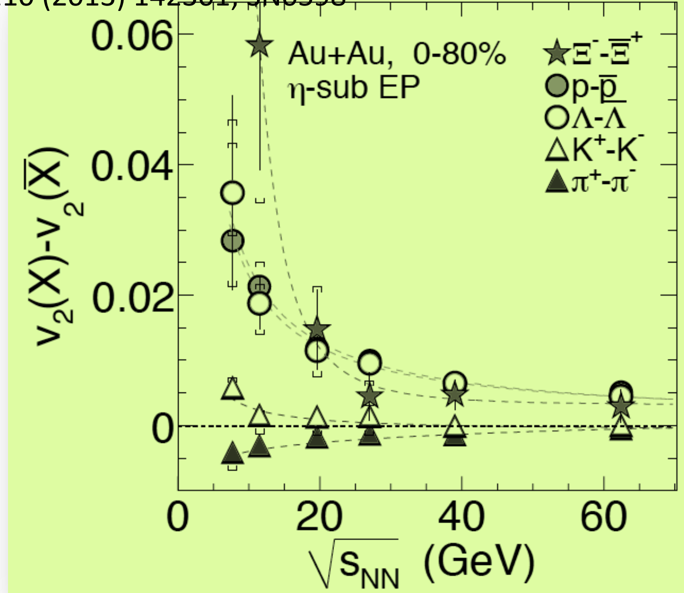


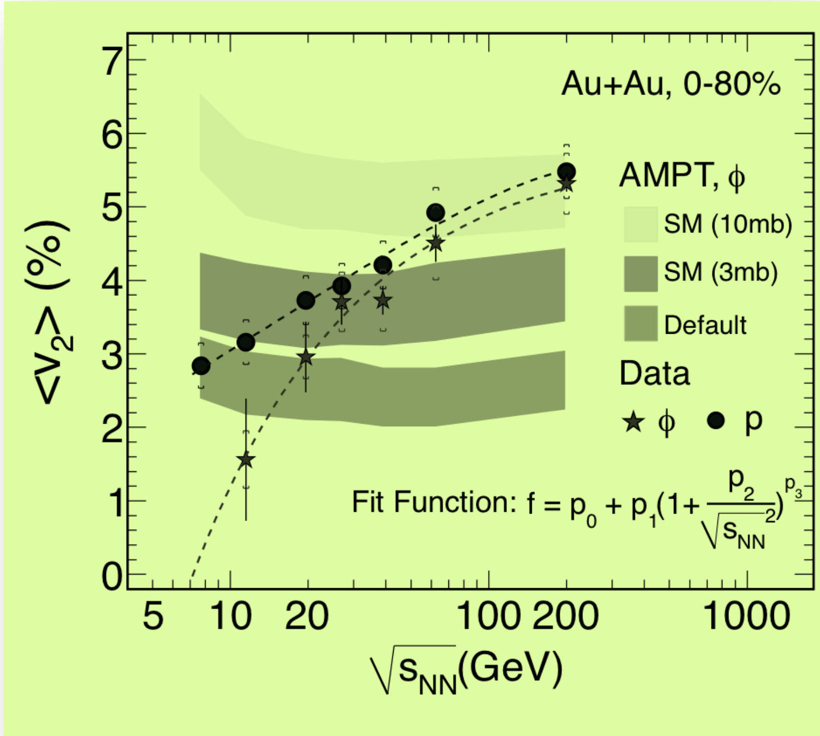
Phys.Rev.Lett. 110 (2013) 012301

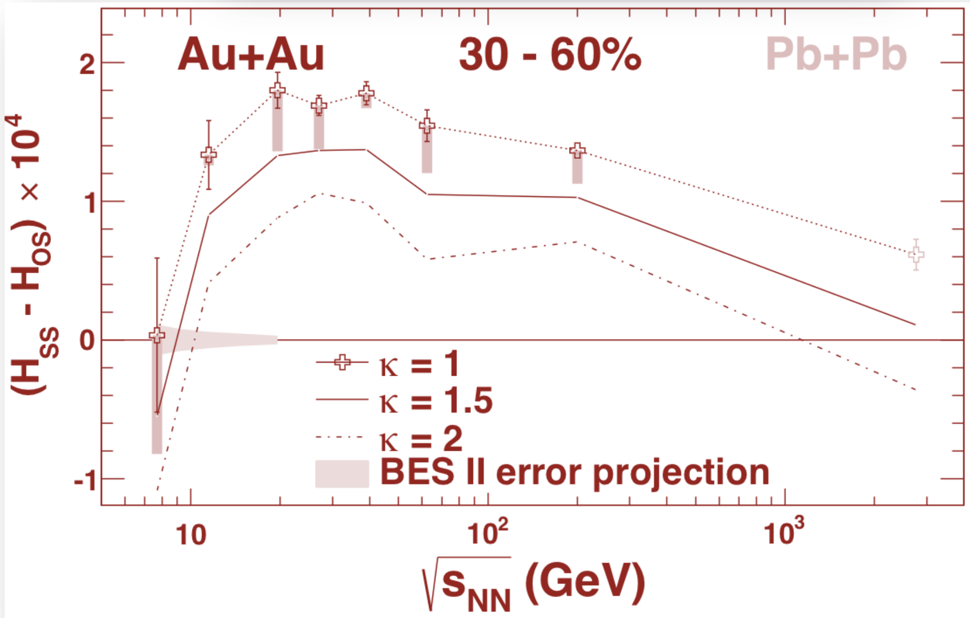
Charge Correlations disappears: with neutral hadrons

QCD Phase Structure: Partonic vs. Hadronic

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







Partonic interactions dominant

NCQ Scaling, Large ϕ v_2 & Charge Correlations

Two Distinct Regions:

$>$ 39 GeV

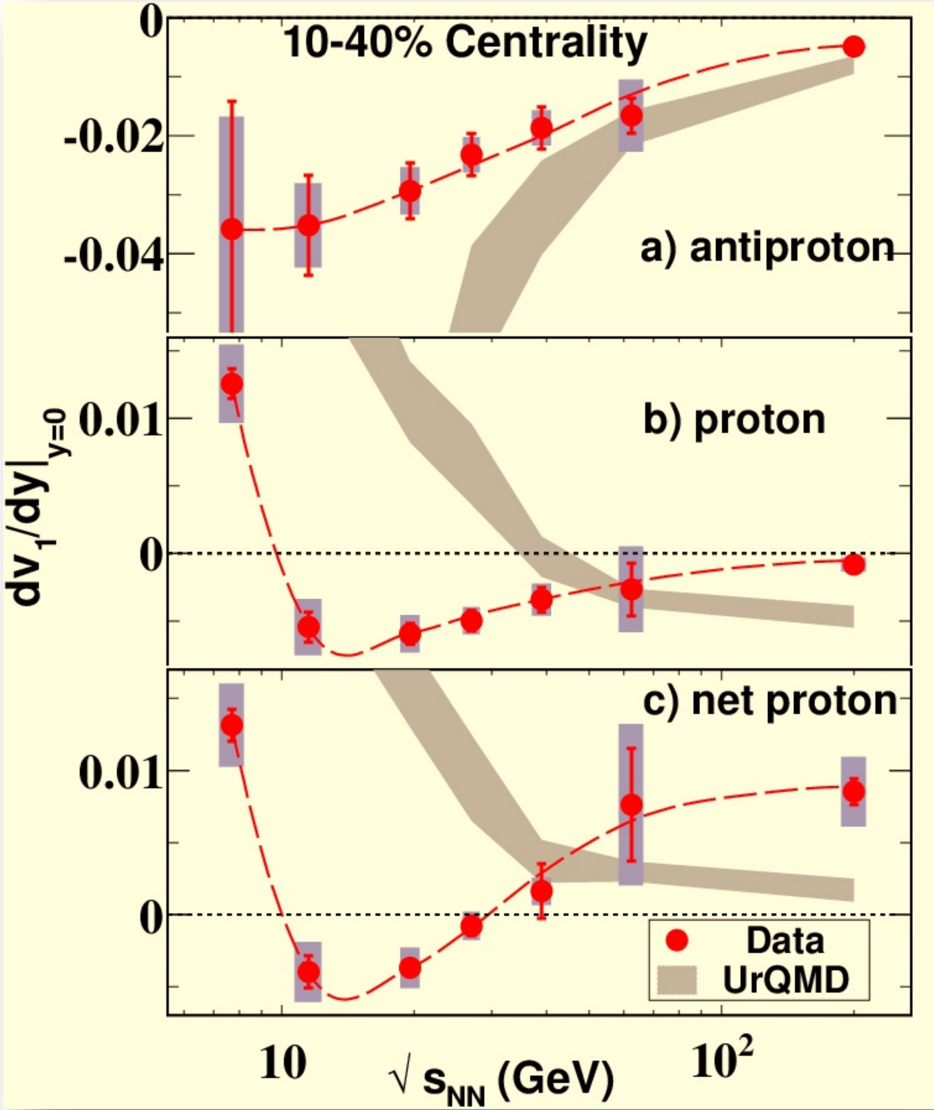
$<$ 11.5 GeV

QCD Phase structure – Quark-Gluon and Hadronic Phases

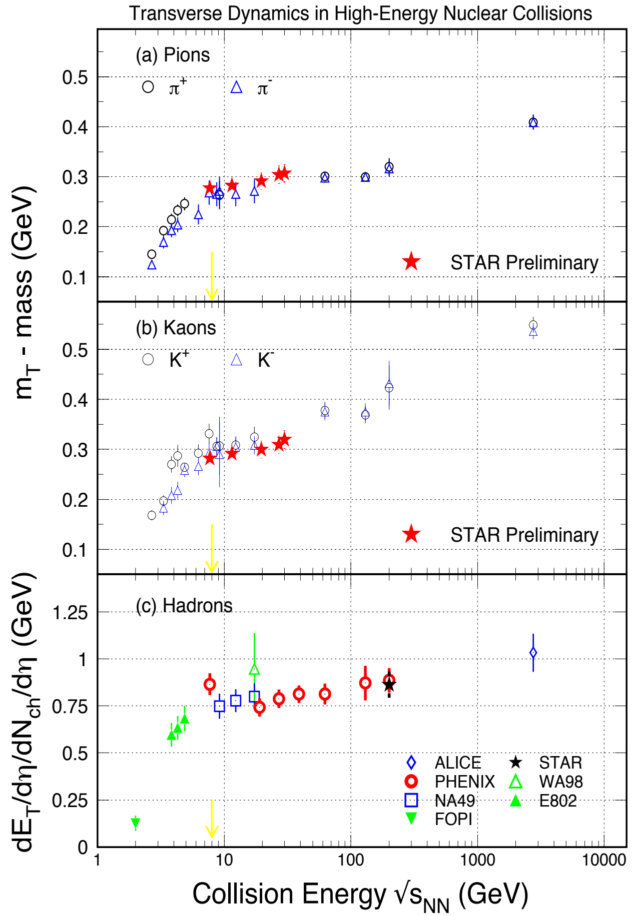
- ✧ At small ***baryonic chemical*** potential the ***QCD transition*** corresponding to a state of de-confined quarks and gluons takes place at high temperature.

- ✧ For large baryonic chemical potential (> 350 MeV) *hadronic interactions dominate.*

QCD Phase Structure: 1st order P.T



Phys.Rev.Lett. 112 (2014) 162301; SN0598



D.H. Rischke et al. HIP1, 309(1995)
H. Stoecker, NPA750, 121(2005)
J. Steinheimer et al., arXiv:1402.7236
P. Konchakovski et al., arXiv:1404.276

Observations consistent with general theoretical expectations from a First Order Phase Transition

Critical Point Observable

Necessity: Observable sensitive to correlation length and susceptibilities

Challenges: Finite system size effects, $\xi < 6$ fm
Finite time effects, $\xi \sim 2 - 3$ fm

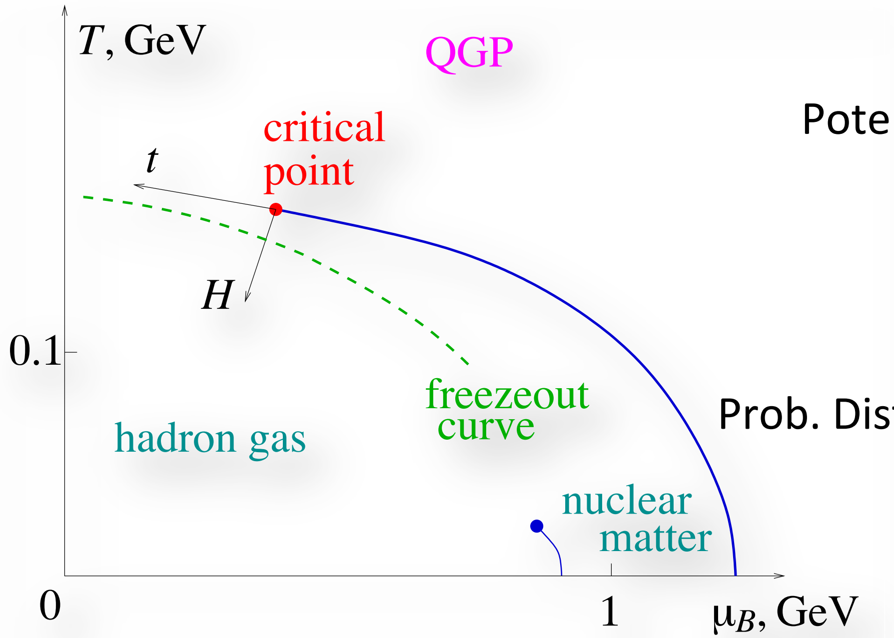
Observable:

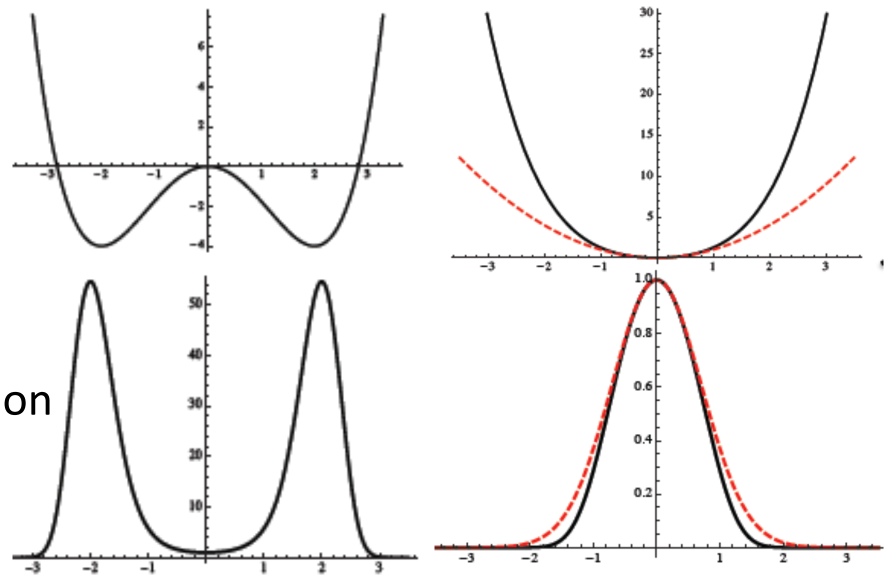
$\boxed{\langle (\delta N)^2 \rangle \sim \xi^2}$ $\boxed{\langle (\delta N)^3 \rangle \sim \xi^{4.5}}$ $\boxed{\langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \sim \xi^7}$

$\boxed{S\sigma \sim \chi_B^{(3)}/\chi_B^{(2)}}$ $\boxed{\kappa\sigma^2 \sim \chi_B^{(4)}/\chi_B^{(2)}}$

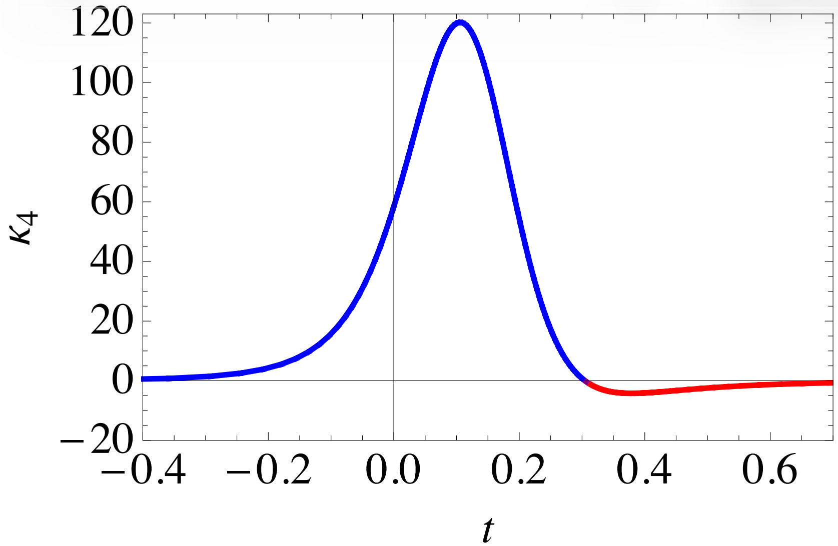
Phys.Rev.Lett. 107 (2011) 052301 Phys. Rev. Lett. 102, 032301 (2009) Phys.Lett. B696 (2011) 459
Phys. Rev. Lett. 91, 102003 (2003) Phys. Rev. D 61, 105017 (2000) Phys.Rev.Lett. 105 (2010) 022302

QCD based Model: CP Region and Kurtosis





J. Deng



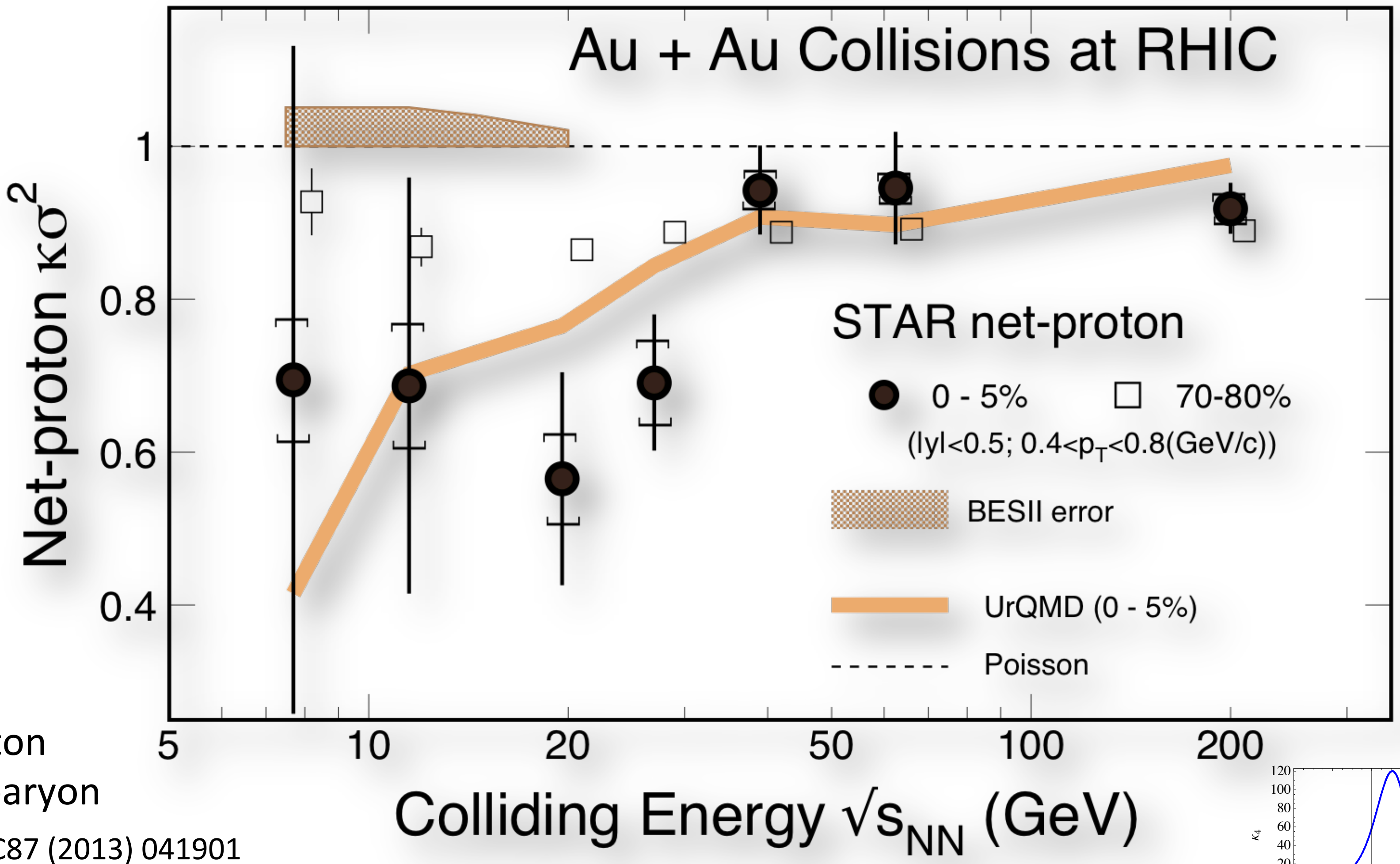
Collisions Energy → increasing

Poisson → Oscillation → Poisson

M. Stephanov: Phys.Rev.Lett. 107 (2011) 052301
M. Asakawa et al., Phys. Rev. Lett. 103 (2009) 262301

QCD Phase Structure: Critical Point Search

Phys.Rev.Lett. 112 (2014) 032302; SN0598

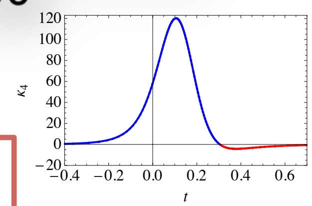


Net-proton

→ Net-baryon

Phys.Rev. C87 (2013) 041901

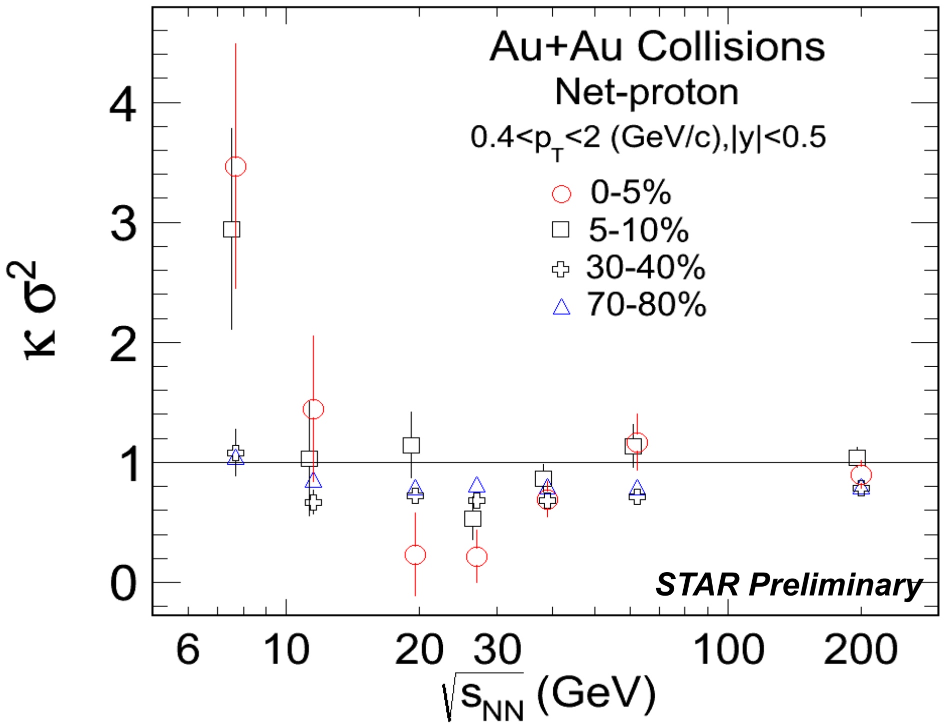
Phys.Rev. C86 (2012) 024904

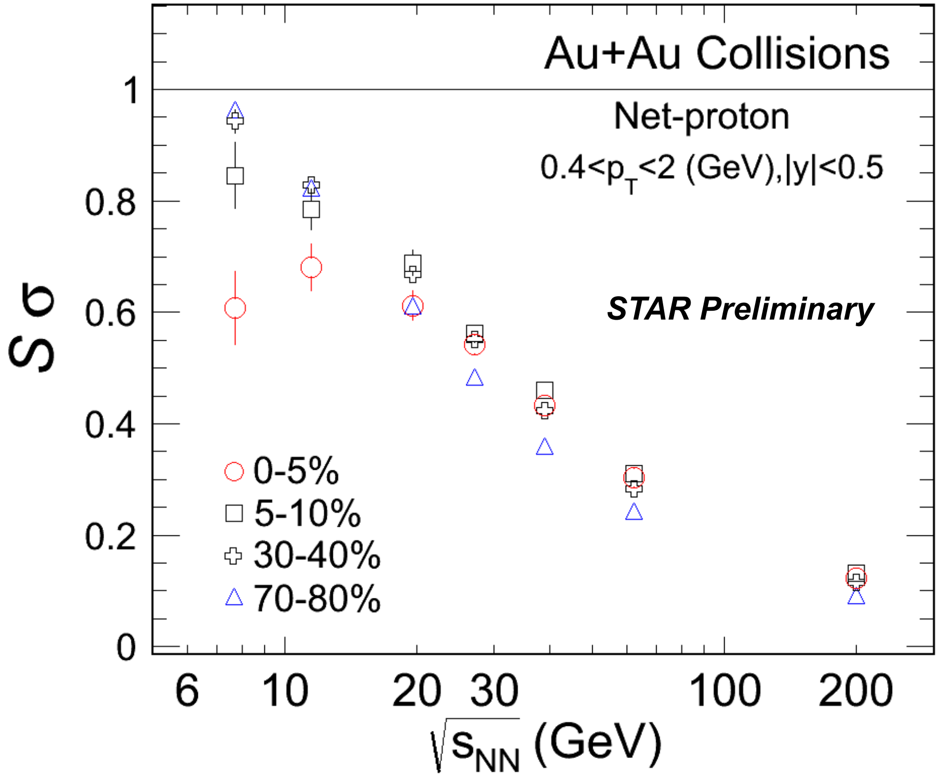


Critical Region: below 27 GeV ?

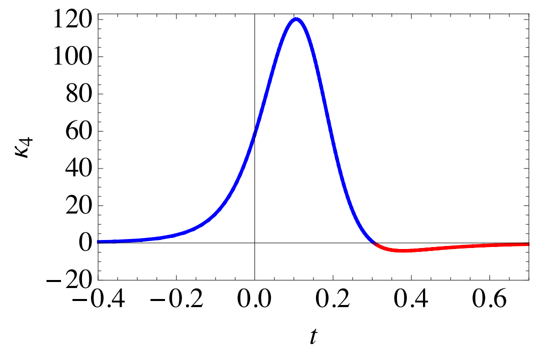
Find the Oscillation …….BES-II

New results: Higher Moments





$$\kappa\sigma^2 = \frac{C_4}{C_2}, \qquad S\sigma = \frac{C_3}{C_2}$$

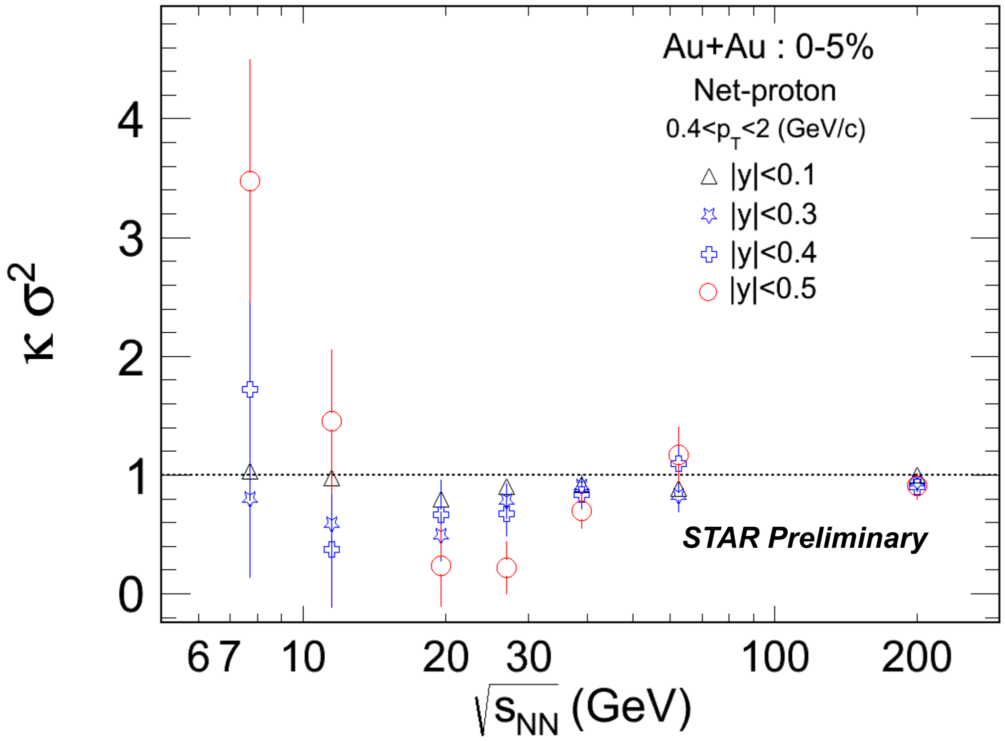


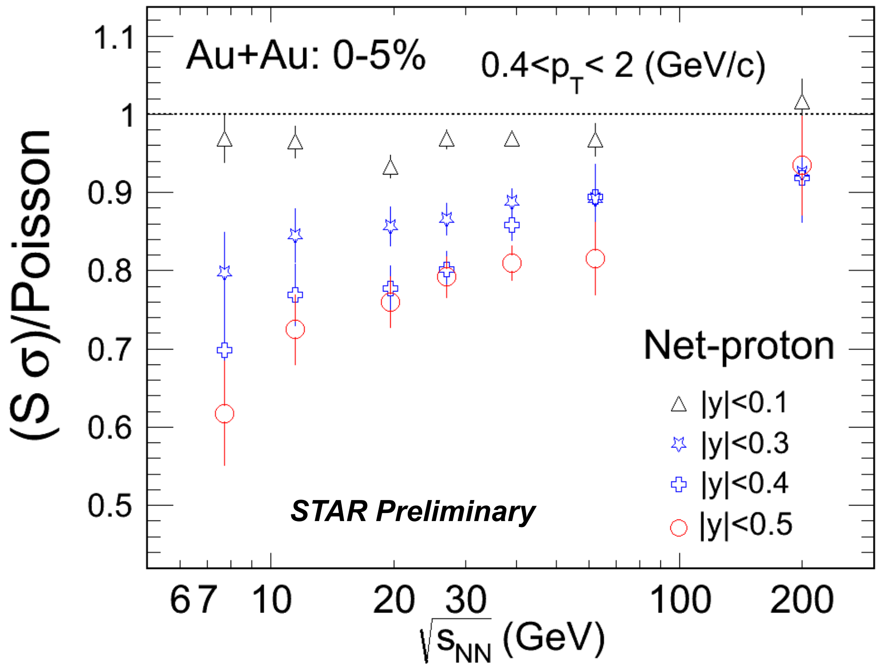
Error bars are statistical only. Systematic errors estimation underway. Dominant contributors: a) efficiency corrections b) PID.

X.F.-Luo:CPOD2014

Non-monotonic variation

Higher Moments: Rapidity Acceptance

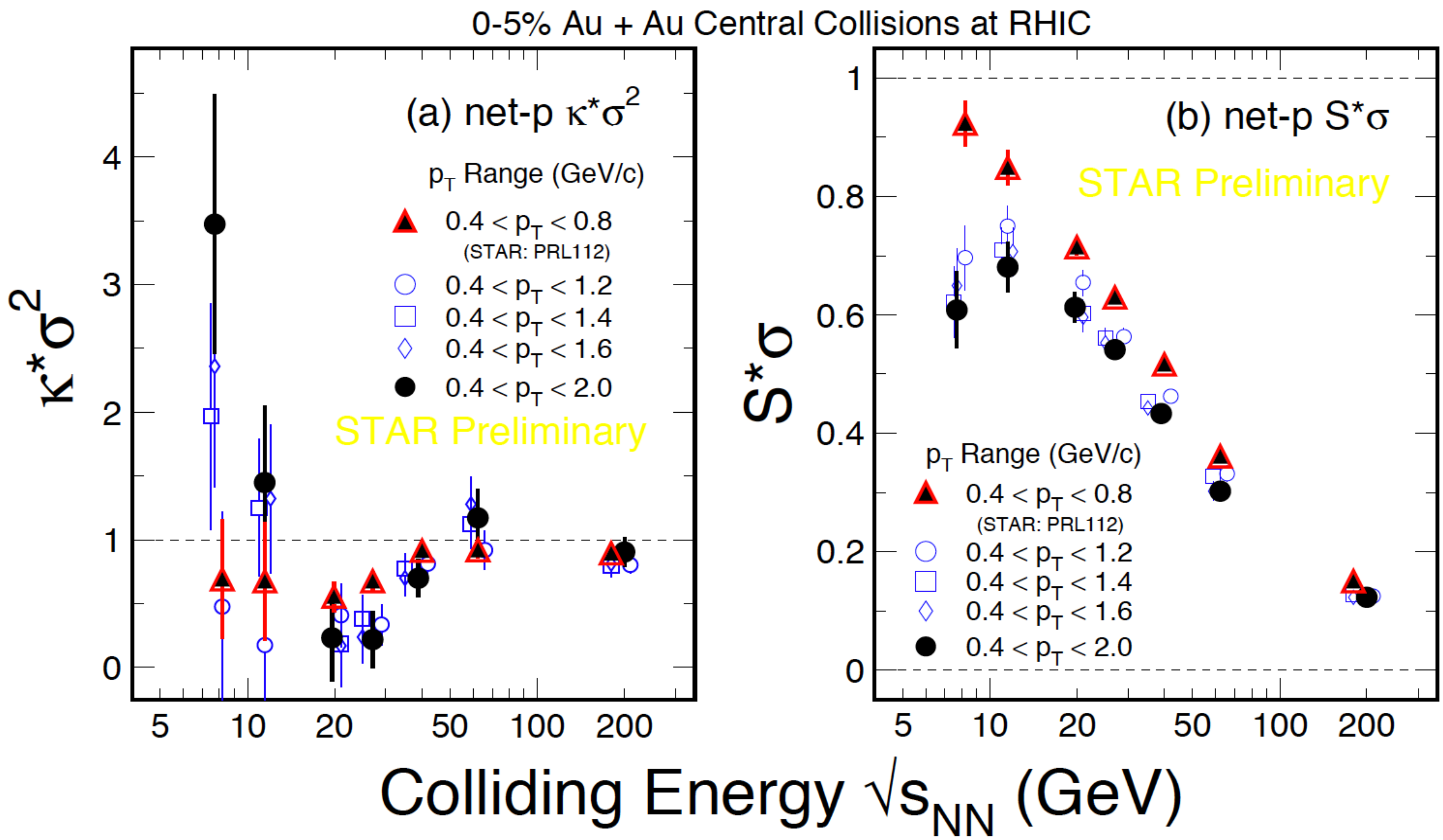




X.F.-Luo:CPOD2014

Approaches Poisson values for smaller rapidity range

Higher Moments : Acceptance in p_T

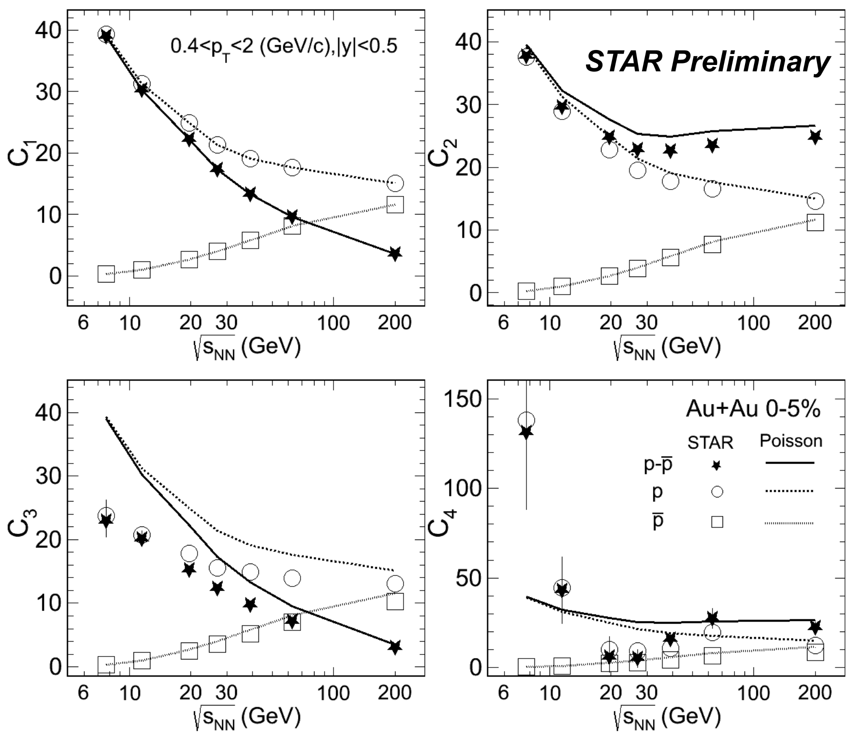


X.F.-Luo:CPOD2014

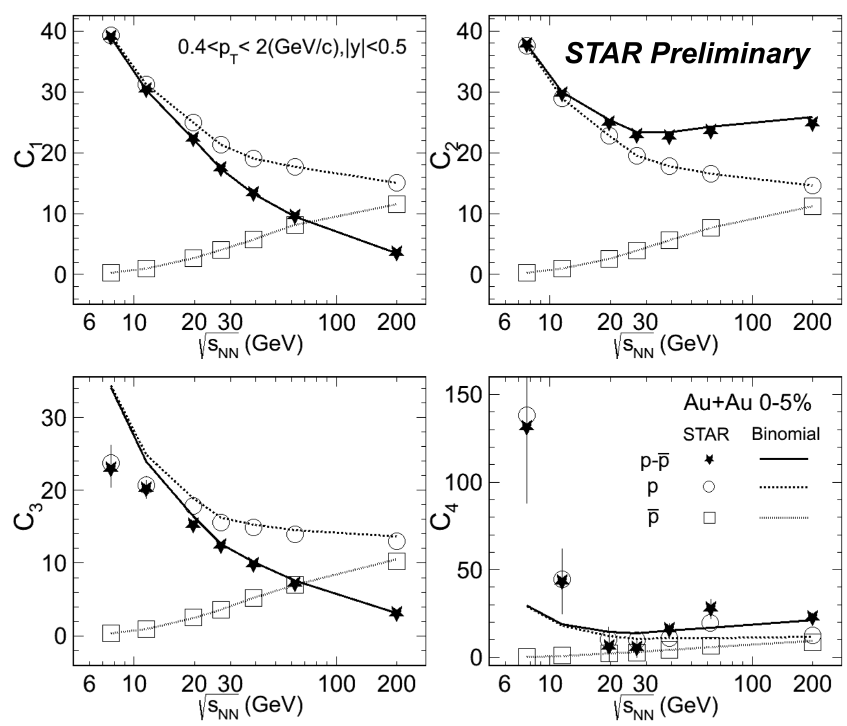
Values depend on p_T acceptance

Cumulants vs. Baselines

Cumulants vs. Poisson



Cumulants vs. Binomial



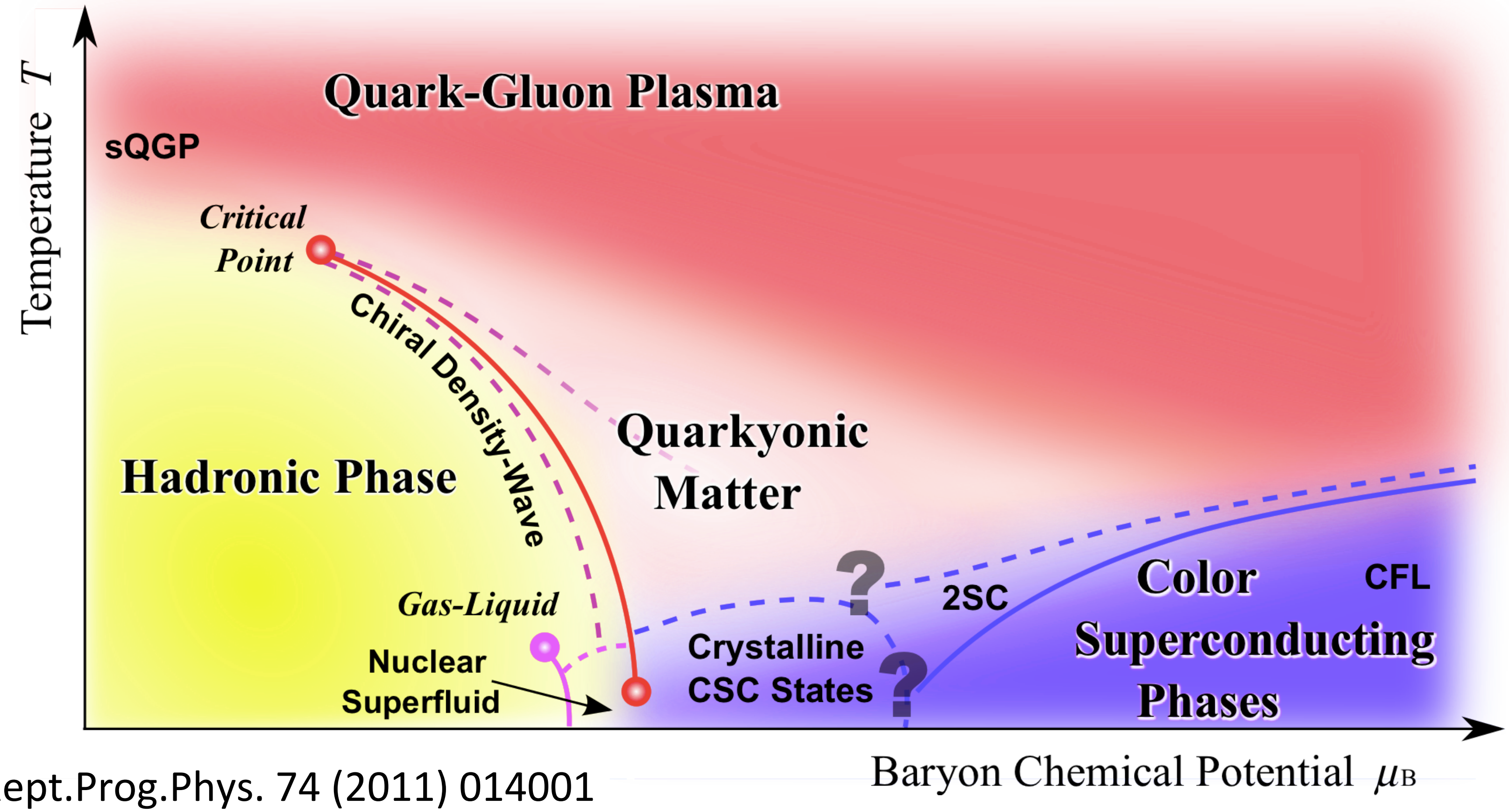
- The higher the order of cumulants the larger deviations from Poisson expectations for net-proton and proton.
- The binomial distribution (BD) better described the data than Poisson. But large deviations seen in C_3 and C_4 in central Au+Au collisions 7.7, 11.5, 19.6, 27 and 62.4 GeV.

QCD Phase Structure: 1st order Phase Transition and CP

✧ *Non-monotonic* variations of v_1 slope for net-protons – *signature of softening of equation of state/1st Order Phase transition ?*

✧ *Non-monotonic* variation of $\kappa\sigma^2$ for net-protons --- *Is there an osscilation* ? – BES- II / larger phase space acceptance needed/CBM/NICA.

Phase structure: Interesting Possibilities



Rept.Prog.Phys. 74 (2011) 014001

CPOD:2013: J. Stroth

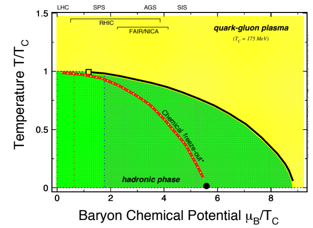
Quarkyonic phase (Theoretical) → Experimental signature (Baryon correlations, Photons) ?

Nucl.Phys. A830 (2009) 709C-712C

Nucl. Phys. A 796, 83 (2007

arXiv:1302.1119

Summary



Theory

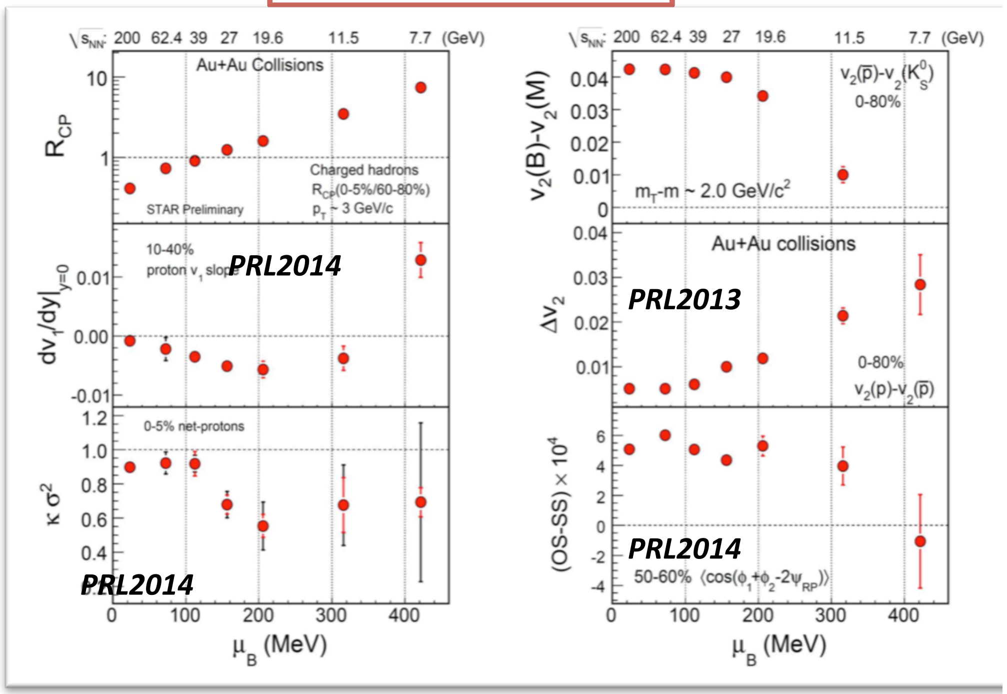
Lattice QCD: Solid results at zero μ_B

- Cross over
- EOS, Transition Temp.
- QCD Thermodynamics

Progress at large μ_B

- CP > μ_B = 300 MeV
- Non Monotonic variation in high moments observed

Experiment



+ Freeze-out Dynamics

Success of BES@RHIC

Future

Measure CP Oscillations

Increased statistics and phase space in RHIC

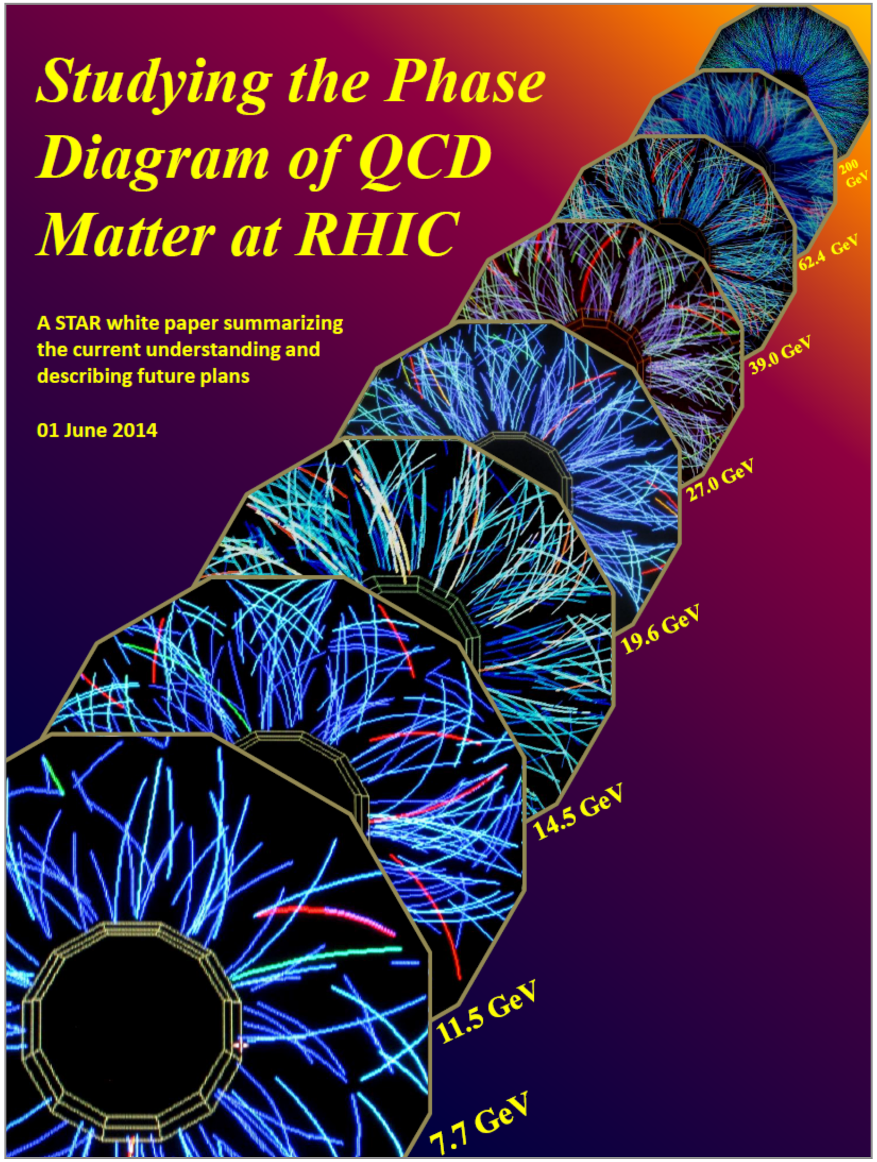
BES-II/CBM, FAIR / NICA/SHINE

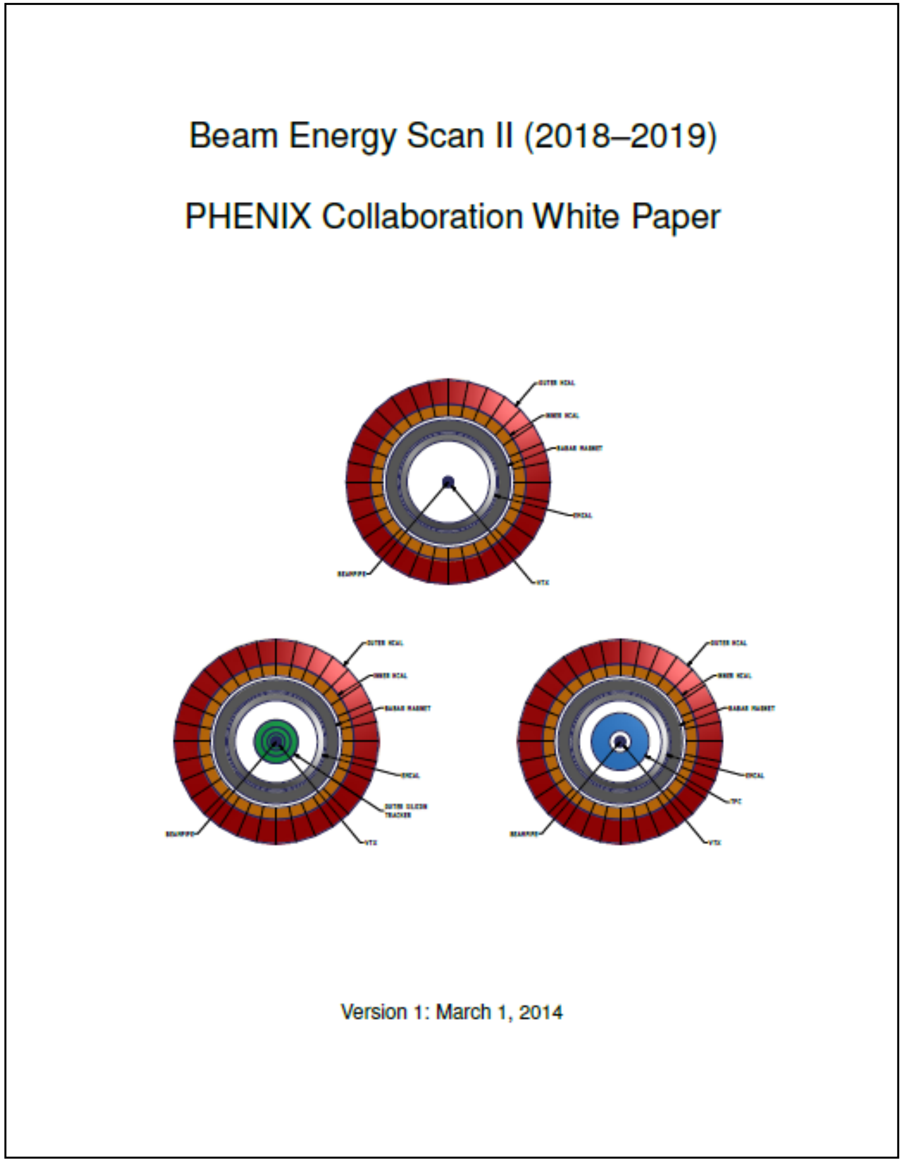
Search for a new state of Matter – Quarkyonic Phase

SHINE/CBM, FAIR/NICA

Beam Energy Scan
Phase II

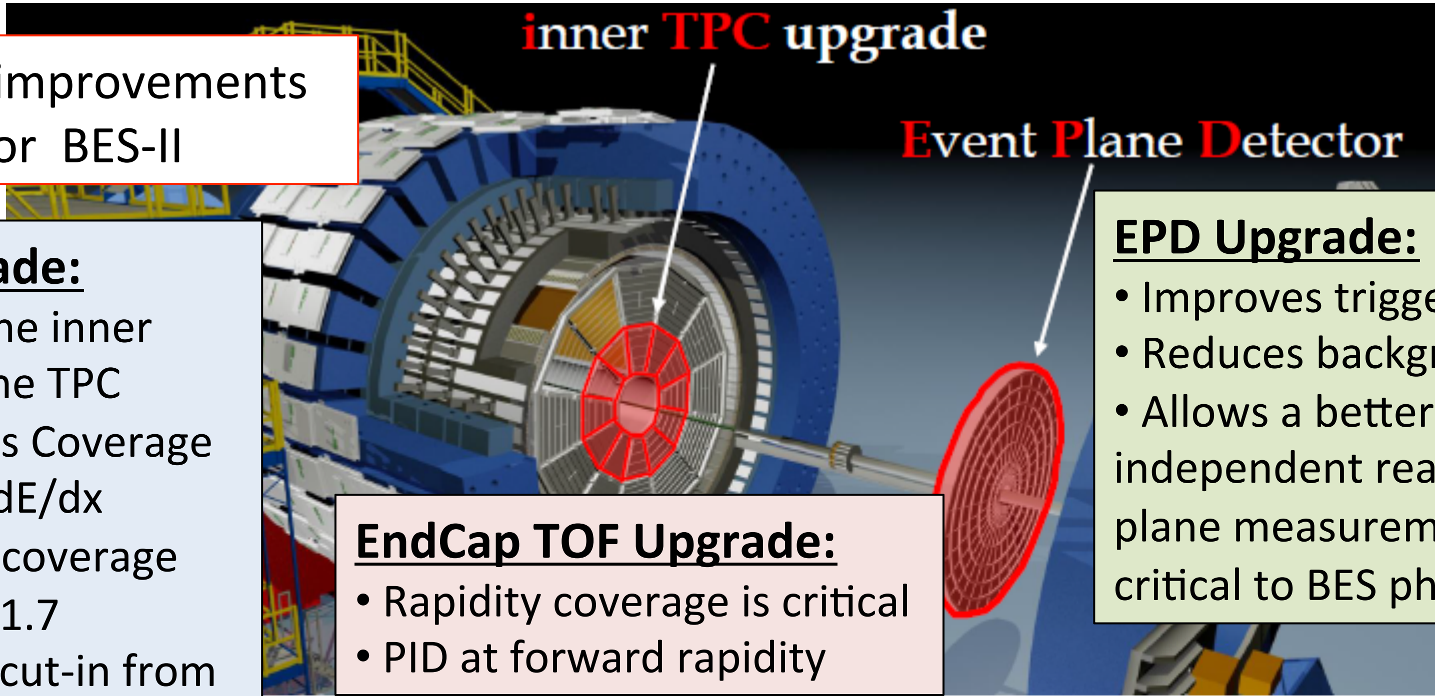
STAR and PHENIX BES-II White Papers





The STAR Upgrades and BES Phase II

Major improvements for BES-II



iTPC Upgrade:

- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.7
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:

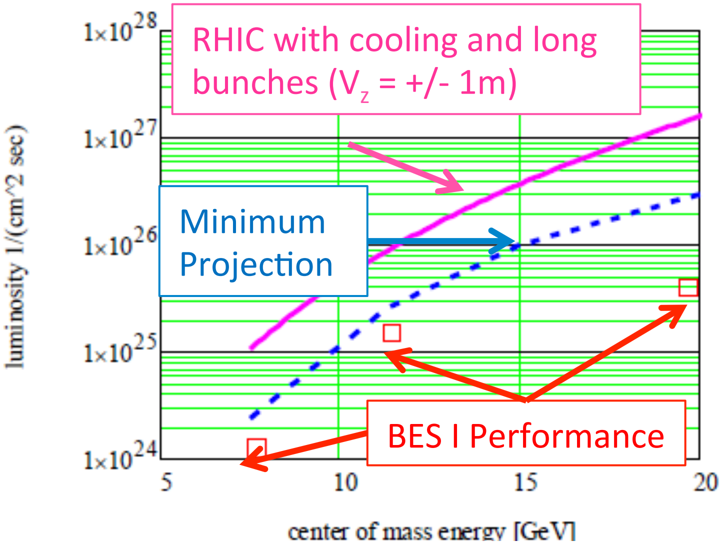
- Rapidity coverage is critical
- PID at forward rapidity

EPD Upgrade:

- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

Electron Cooling can raise the luminosity by a factor of 3-10 in the range from 5 – 20 GeV

Long Bunches increase luminosity by factor of 2-5



Stage I
$\sqrt{s_{NN}}$ = 5-9 GeV

Stage II -- 3 MeV booster cavity
$\sqrt{s_{NN}}$ = 9-20 GeV

BES Phase II Proposal

BES Phase II is planned for two 22 cryo-week runs in 2018 and 2019

$\sqrt{S_{NN}}$ (GeV)	5.0	7.7	9.1	11.5	13.0	14.5	19.6
μ_B (MeV)	550	420	370	315	290	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	250	300	400
eCooling (Factor)	2	3	4	6	8	11	15
Beam Time (weeks)		**14**	**9.5**	**5.0**	**3.0**	**2.5**	**3.0**