Summary of CPOD 2017

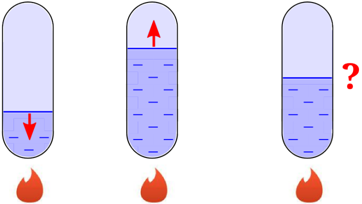
(Critical) comments and personal observations

M. Stephanov

Blanket apology for talks uncovered

History

Cagniard de la Tour (1822): discovered continuos transition from liquid to vapour by heating alcohol, water, etc. in a gun barrel, glass tubes.



Name

Faraday (1844) – liquefying gases:

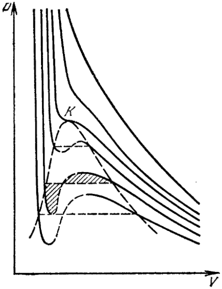
“Cagniard de la Tour made an experiment some years ago which gave me occasion to want a new word.”

Mendeleev (1860) – measured vanishing of liquid-vapour surface tension: “Absolute boiling temperature”.

Andrews (1869) – systematic studies of many substances established continuity of vapour-liquid phases. Coined the name “critical point”.

Theory

van der Waals (1879) –
in “On the continuity of the gas and liquid state”
(PhD thesis) wrote e.o.s. with a critical point.



Smoluchowski, Einstein (1908,1910) – explained critical opalescence.

Landau – classical theory of critical phenomena

Fisher, Kadanoff, Wilson – scaling, full fluctuation theory based on RG.

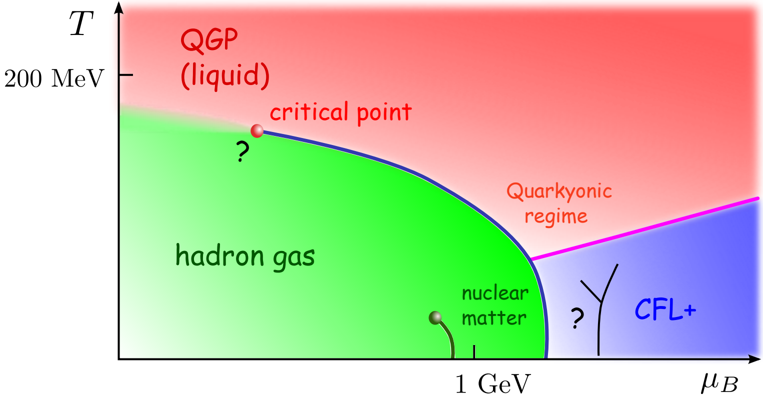
Substance[13][14]	Critical temperature	Critical pressure (absolute)
Argon	−122.4 °C (150.8 K)	48.1 atm (4,870 kPa)
Ammonia[15]	132.4 °C (405.5 K)	111.3 atm (11,280 kPa)
Bromine	310.8 °C (584.0 K)	102 atm (10,300 kPa)
Caesium	1,664.85 °C (1,938.00 K)	94 atm (9,500 kPa)
Chlorine	143.8 °C (416.9 K)	76.0 atm (7,700 kPa)
Ethanol	241 °C (514 K)	62.18 atm (6,300 kPa)
Fluorine	−128.85 °C (144.30 K)	51.5 atm (5,220 kPa)
Helium	−267.96 °C (5.19 K)	2.24 atm (227 kPa)
Hydrogen	−239.95 °C (33.20 K)	12.8 atm (1,300 kPa)
Krypton	−63.8 °C (209.3 K)	54.3 atm (5,500 kPa)
CH_4 (methane)	−82.3 °C (190.8 K)	45.79 atm (4,640 kPa)
Neon	−228.75 °C (44.40 K)	27.2 atm (2,760 kPa)
Nitrogen	−146.9 °C (126.2 K)	33.5 atm (3,390 kPa)
Oxygen	−118.6 °C (154.6 K)	49.8 atm (5,050 kPa)
CO_2	31.04 °C (304.19 K)	72.8 atm (7,380 kPa)
N_2O	36.4 °C (309.5 K)	71.5 atm (7,240 kPa)
H_2SO_4	654 °C (927 K)	45.4 atm (4,600 kPa)
Xenon	16.6 °C (289.8 K)	57.6 atm (5,840 kPa)
Lithium	2,950 °C (3,220 K)	652 atm (66,100 kPa)
Mercury	1,476.9 °C (1,750.1 K)	1,720 atm (174,000 kPa)
Sulfur	1,040.85 °C (1,314.00 K)	207 atm (21,000 kPa)
Iron	8,227 °C (8,500 K)	
Gold	6,977 °C (7,250 K)	5,000 atm (510,000 kPa)
Water[2][16]	373.946 °C (647.096 K)	217.7 atm (22.06 MPa)

Critical point is a ubiquitous phenomenon

Critical point between the QGP and hadron gas phases?

QCD is a relativistic theory of a fundamental force.

CP is a singularity of EOS, anchors the 1st order transition.



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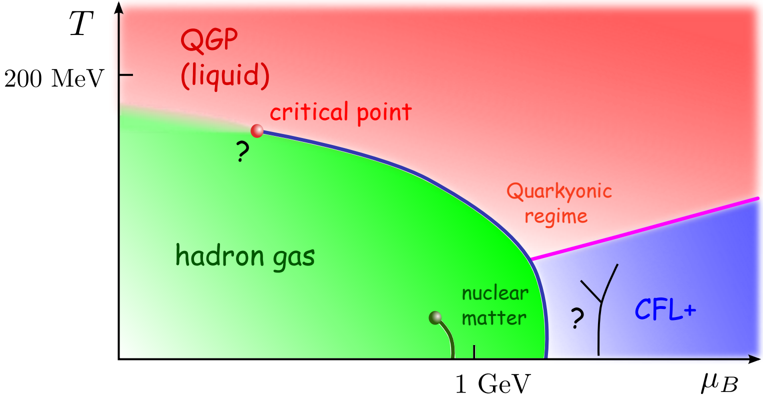


Lattice QCD at $\mu_B \lesssim 2T$ – a crossover.

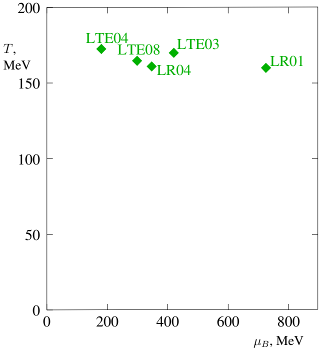
C.P. is ubiquitous in models (NJL, RM, Holog., Strong coupl. LQCD, . . .)

Essentially two approaches to discovering the QCD critical point. Each with its own challenges.

- Lattice simulations.

  The *sign problem* restricts reliable lattice calculations to $\mu_B = 0$.

  Under different assumptions one can estimate the position of the critical point, assuming it exists, by extrapolation from $\mu = 0$.



- Heavy-ion collisions.

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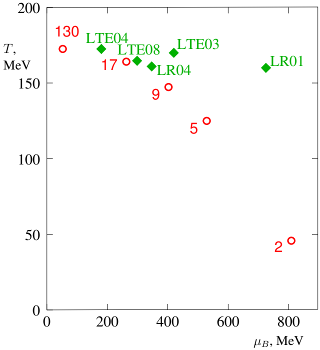

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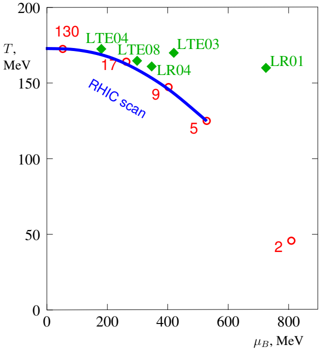

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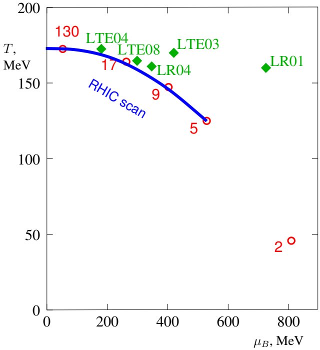


- Heavy-ion collisions. *Non-equilibrium.*

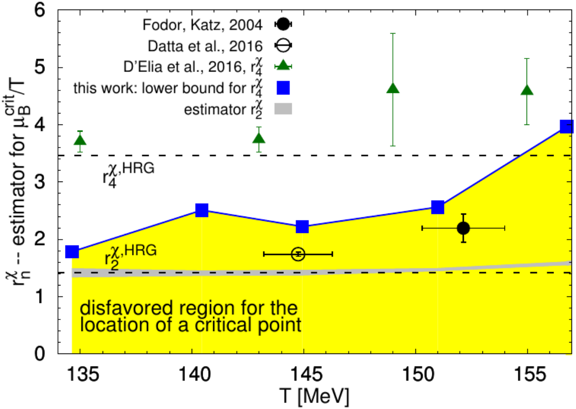
Connecting theory and experiment

BEST
COLLABORATION

- Develop EOS with critical point which also matches available lattice data Parotto
- Implement it into a realistic hydro simulation Shen, Yin, Song, Pratt, . . .
- Compare with experiments to constrain parameters of the critical point: position, non-universal amplitudes, angles, etc. Auvinen
- Develop theory of the CME in heavy-ion collisions and embed in MHD Schlichting, Hirono, Shi . . .
- Compare with experiments. Isobaric run in 2018! Wen
- Vorticity and polarization. Upsal, Wang

Lattice

Schmidt

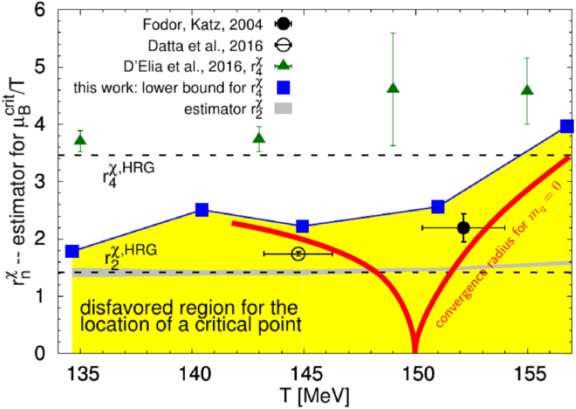


[BNL-Bi-CCNU, PRD 95 (2017), 054504]

- Ratios of Taylor coeffs. are *estimators* of the radius of convergence. Cannot predict, or *exclude*, C.P. without assumptions about *asymptotics*.

Lattice

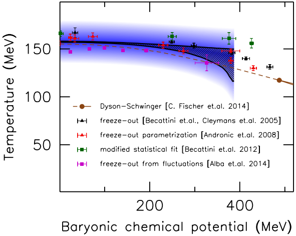
Schmidt

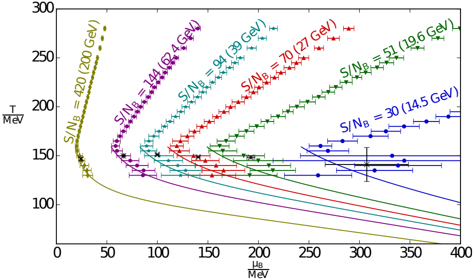


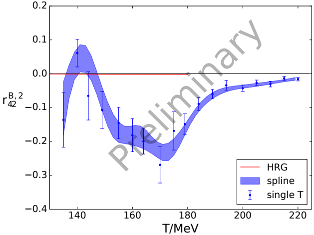
[BNL-Bi-CCNU, PRD 95 (2017), 054504]

- Critical point is not always the nearest singularity. E.g.: The convergence radius at T_c for $m_q = 0$ is zero (hep-lat/0603014).

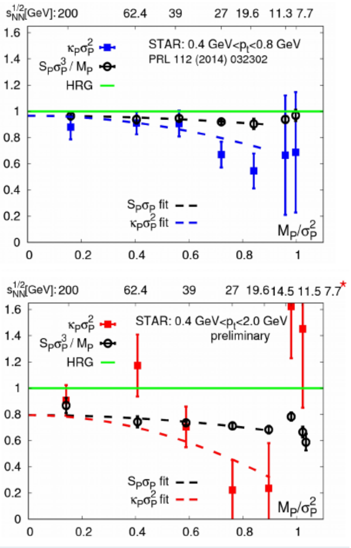
Guenther
(WB collaboration)





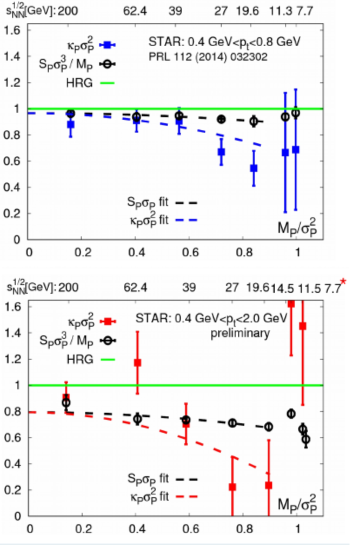


Lattice susceptibilities vs STAR data



- Two caveats:

Lattice susceptibilities vs STAR data

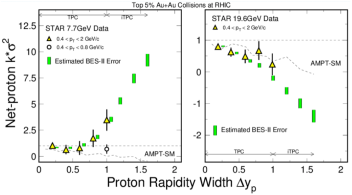


- Two caveats:
  - Isospin blind correlations:

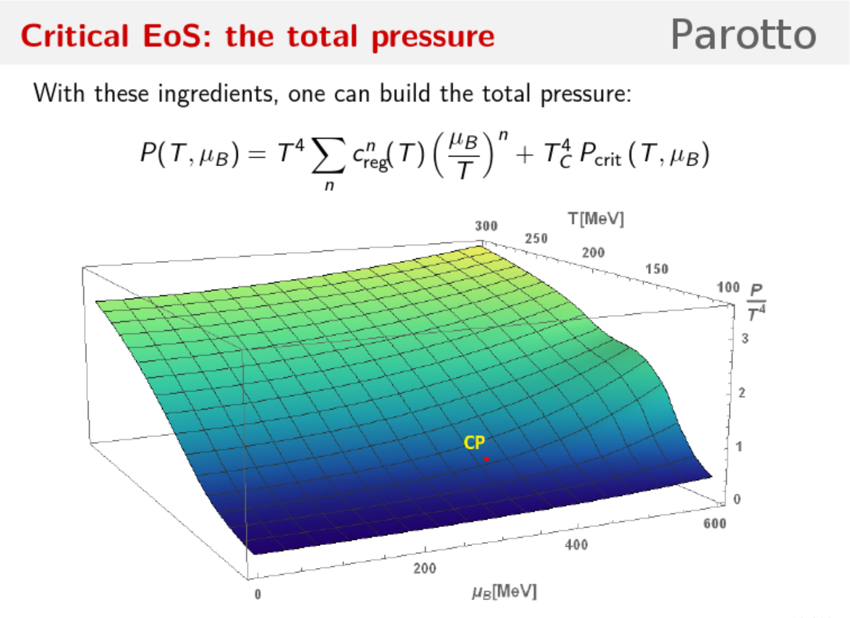
    $$R^B_{n2} - 1 \approx (R^P_{n2} - 1) \times 2^{n-1}$$

  - $\Delta y \ll \Delta y_{\rm corr}$:

    $$R_{n2}(\Delta y) - 1 \sim \Delta y^{n-1}$$



Parameterized EOS for hydro simulations



Critical EoS: the total pressure

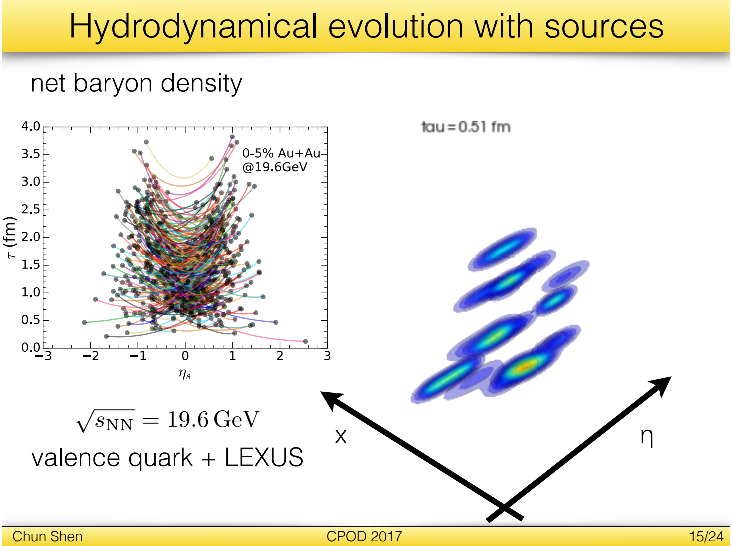
Parotto

With these ingredients, one can build the total pressure:

$$P(T,\mu_B) = T^4 \sum_n c^n_{\text{reg}}(T)\left(\frac{\mu_B}{T}\right)^n + T_C^4\, P_{\text{crit}}(T,\mu_B)$$

Hydrodynamic simulations

Baryon stopping and diffusion: Shen



Hydrodynamical evolution with sources

net baryon density

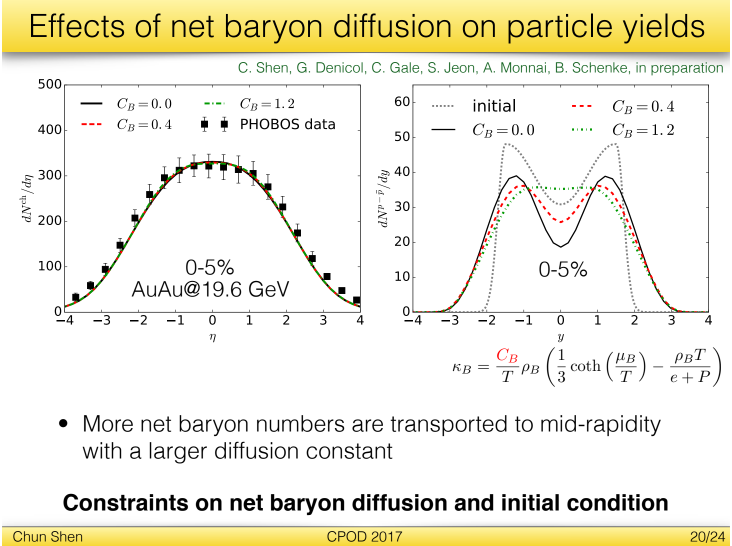
$$\sqrt{s_{\rm NN}} = 19.6\,{\rm GeV}$$

valence quark + LEXUS

Chun Shen CPOD 2017 15/24

Hydrodynamic simulations

Baryon stopping and diffusion: Shen



Effects of net baryon diffusion on particle yields

C. Shen, G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke, in preparation

$$\kappa_B = \frac{C_B}{T}\rho_B\left(\frac{1}{3}\coth\left(\frac{\mu_B}{T}\right) - \frac{\rho_B T}{e+P}\right)$$

- More net baryon numbers are transported to mid-rapidity with a larger diffusion constant

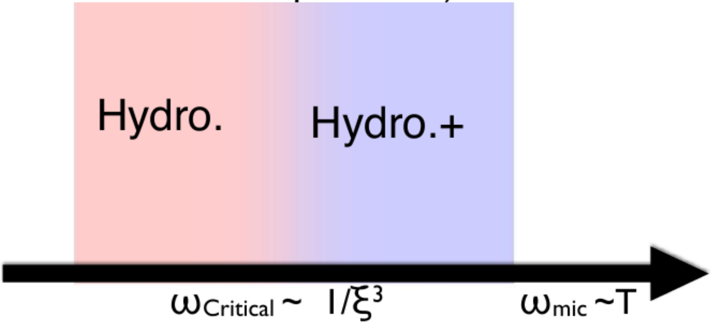
Constraints on net baryon diffusion and initial condition

Chun Shen CPOD 2017 20/24

Critical slowing down and hydrodynamics

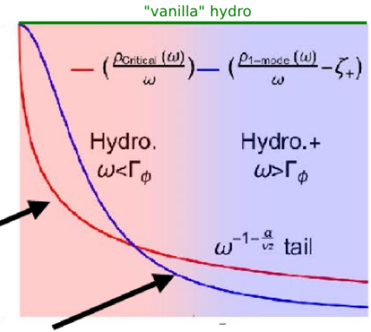
Yin

- "+": adding critical slow modes (parametrically longer life than other microscopic modes).



Hydro+

- "Hydro+" one mode qualitatively captures the transition from hydro regime $\omega < 1/\xi^3$ to "hydro+" regime $\omega > 1/\xi^3$.



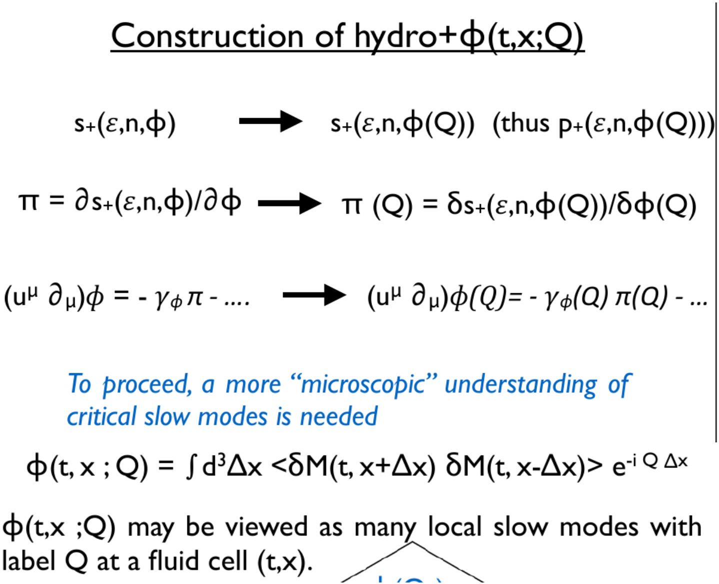
($\rho_{\mathrm{Bulk}}(\omega)$ from mode H)

($\rho_{\mathrm{Bulk}}(\omega)$ from hydro+one mode)

- One mode is not enough to fully capture the critical dynamic behavior.

- Next step: Hydro+ a spectrum of slow modes.

Hydro+



Construction of hydro+$\phi(t,x;Q)$

$$s_+(\varepsilon,n,\phi) \longrightarrow s_+(\varepsilon,n,\phi(Q)) \quad (\text{thus } p_+(\varepsilon,n,\phi(Q)))$$

$$\pi = \partial s_+(\varepsilon,n,\phi)/\partial\phi \longrightarrow \pi\,(Q) = \delta s_+(\varepsilon,n,\phi(Q))/\delta\phi(Q)$$

$$(u^\mu\,\partial_\mu)\phi = -\,\gamma_\phi\,\pi - \ldots. \longrightarrow (u^\mu\,\partial_\mu)\phi(Q) = -\,\gamma_\phi(Q)\,\pi(Q) - \ldots$$

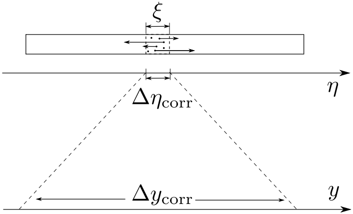
To proceed, a more "microscopic" understanding of critical slow modes is needed

$$\phi(t,x\,;Q) = \int d^3\Delta x <\delta M(t,x+\Delta x)\,\delta M(t,x-\Delta x)>e^{-i\,Q\,\Delta x}$$

$\phi(t,x\,;Q)$ may be viewed as many local slow modes with label Q at a fluid cell (t,x).

Hydrodynamic fluctuations

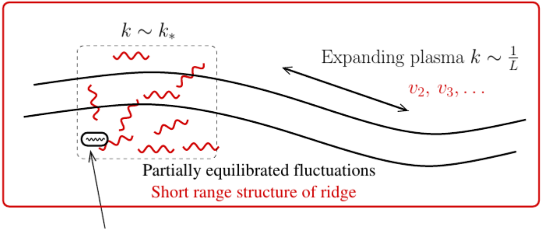
- Initial state fluctuations:
  - Long rapidity correlations
  - v_n's
- Thermo/hydro-dynamic fluctuations.
  - Correlations over rapidity $\Delta y_{\text{corr}} \sim 1$.



- Critical fluctuations. Even for $\xi = 2 - 3$ fm $\Delta\eta = \xi/\tau \ll 1$.

Dynamics of fluctuations

Thermal fluctuations need time to equilibrate.



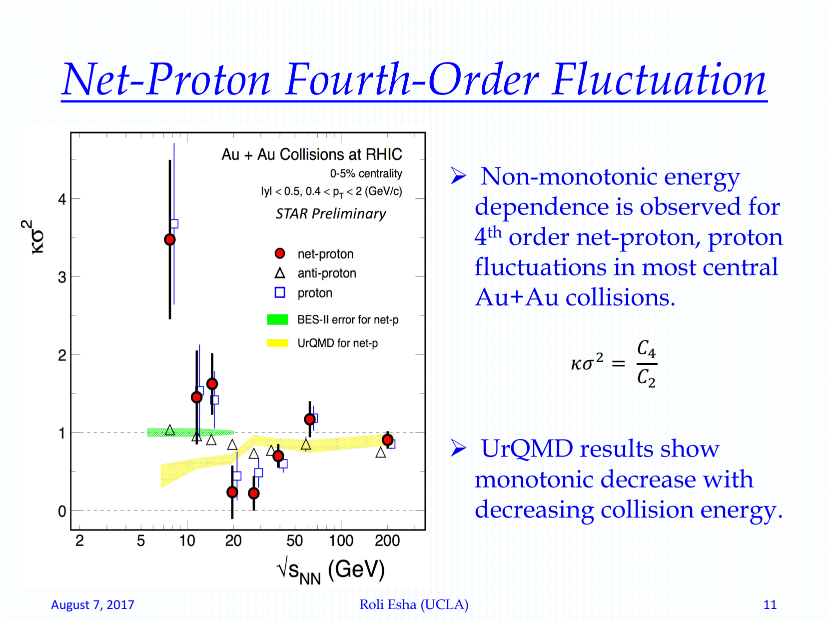
Some modes could remain out of eqlbm.
Dynamics of fluctuations: Mazeliauskas, Teaney, Lau, Song

This is especially true near critical point due to critical slowing down.

This is the origin of the Hydro+ modes.

Experiments

STAR

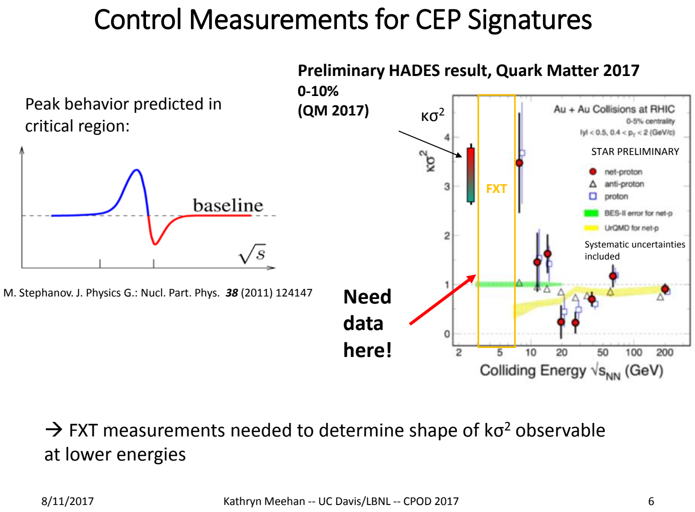


Net-Proton Fourth-Order Fluctuation

- Non-monotonic energy dependence is observed for 4th order net-proton, proton fluctuations in most central Au+Au collisions.

$$\kappa\sigma^2 = \frac{C_4}{C_2}$$

- UrQMD results show monotonic decrease with decreasing collision energy.



Control Measurements for CEP Signatures

Peak behavior predicted in critical region:

M. Stephanov. J. Physics G.: Nucl. Part. Phys. ***38*** (2011) 124147

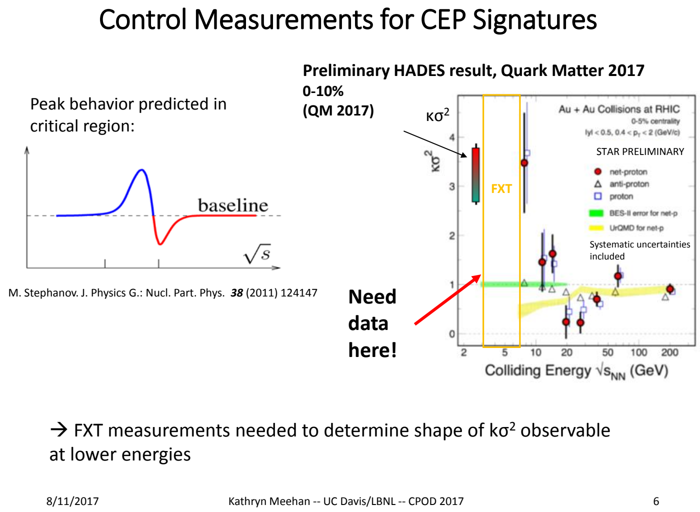
Preliminary HADES result, Quark Matter 2017

0-10%
(QM 2017)

Need data here!

→ FXT measurements needed to determine shape of $\kappa\sigma^2$ observable at lower energies

8/11/2017 Kathryn Meehan -- UC Davis/LBNL -- CPOD 2017 6



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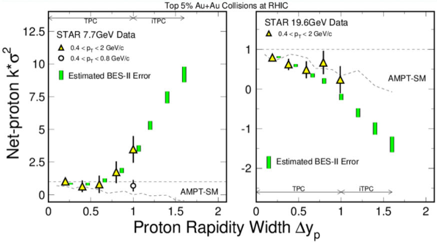
To draw physics conclusions from this comparison, one needs to take into account rapidity acceptance Δy, different in the experiments.

Bzdak, Holzmann

Acceptance dependence

The acceptance dependence consistent with Δy^{n-1}

(Ling-MS 1512.09125; Bzdak-Koch 1607.07375)



As long as $\Delta y \ll \Delta y_{\rm corr}$ the correlators $\hat{\kappa}_n$ count the number of n-plets in acceptance.

Factorial cumulants

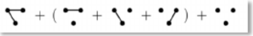
More precisely, the scaling with Δy is for *factorial* cumulants ($\hat{\kappa}_n$ or C_n).

Because they isolate irreducible n-point correlations.

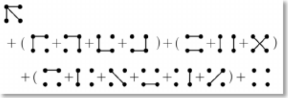
Ling & Stephanov, PRC 93, 034915 (2016)

The cumulants κ_k hold information on multi-particle correlators C_k:

$$\kappa_3 = <N> + 3C_2 + C_3$$



$$\kappa_4 = <N> + 7C_2 + 6C_3 + C_4$$



Bzdak, Koch & Strodthoff, PRC 95, 054906 (2017) ← based on STAR data (X. Luo et al., CPOD2014)

Propose C_k vs. N_{part} (& Δy) as a better approach to isolate critical fluctuations:

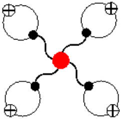
Normal cumulants ($n > 2$) are deviations from normal distribution.

Factorial cumulants – from Poisson distribution.

Physics of correlations

One can describe the correlations in the language of “clusters” (Bzdak).
Or, more physically, repuslive mean-field (Petreczky).

The correlations induced by critical mode have similar effect.



Isospin blind n-particle correlations.
Characteristic *non-monotonous* $\sqrt{s}$ dependence.

The size of the “cluster” of order number of particles within ξ^3 (qualitatively).

Critical fluctuations and experimental observables

Observed fluctuations are related to fluctuations of σ.

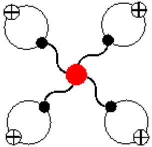
MS-Rajagopal-Shuryak PRD60(1999)114028; MS PRL102(2009)032301)

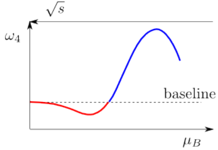
Think of a collective mode described by field σ such that $m = m(\sigma)$:

$$\delta n_{\boldsymbol{p}} = \delta n_{\boldsymbol{p}}^{\text{free}} + \frac{\partial \langle n_{\boldsymbol{p}} \rangle}{\partial \sigma} \times \color{red}{\delta\sigma}$$

The cumulants of multiplicity $M \equiv \int_{\boldsymbol{p}} n_{\boldsymbol{p}}$: $\qquad (M_P \sim n_B \times \Delta y)$

- $$\kappa_4[M] = \underbrace{\langle M \rangle}_{\text{baseline}} + \underbrace{\color{red}{\kappa_4[\sigma]} \times g^4 \underbrace{\left(\qquad \right)^4}_{\sim M^4}}_{\text{this is } \hat{\kappa}_4 (\text{a.k.a.} C_4^{\text{Bzdak-Koch}})} + \ldots,$$

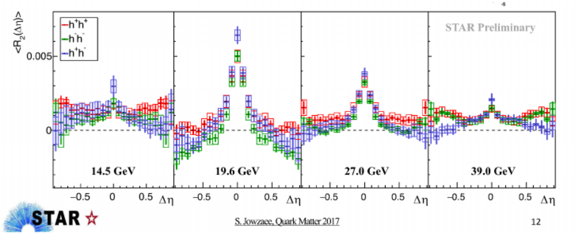




The ratio $\dfrac{\hat{\kappa}_4[M]}{M^4} \sim g^4 \color{red}{\kappa_4[\sigma] \sim \xi^7}$.

Back to the two-point correlations

Preliminary, but very interesting:



S. Jowzaee, Quark Matter 2017

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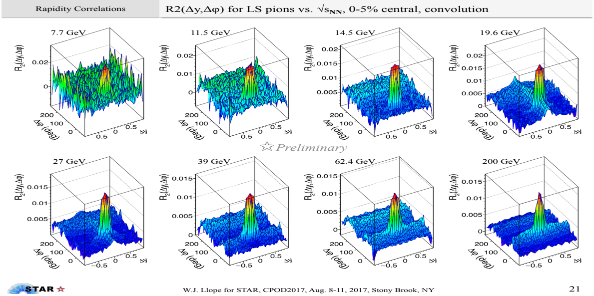
Rapidity Correlations

R2(Δy,Δφ) for LS pions vs. √sNN, 0-5% central, convolution

W.J. Llope for STAR, CPOD2017, Aug. 8-11, 2017, Stony Brook, NY

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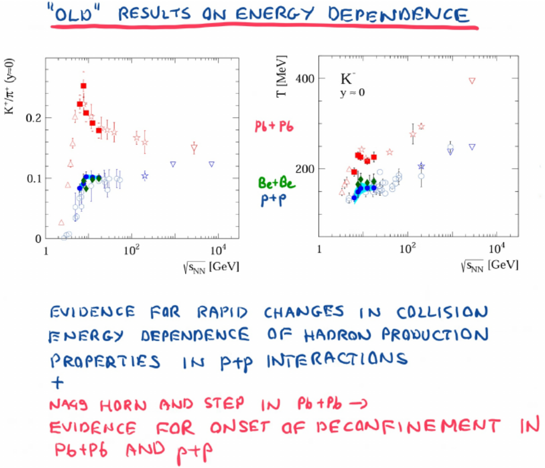
- Non-monotonous $\sqrt{s}$ dependence with max near 19 GeV.
- Charge/isospin blind.
- $\Delta\phi$ (in)dependence is as expected from critical correlations.
- Width $\Delta\eta$ suggests *soft* pions – but p_T dependence need to be checked.
- But: no signal in R_2 for K or p.

Intriguing nontrivial $\sqrt{s}$ dependence in bulk observables



"OLD" RESULTS ON ENERGY DEPENDENCE

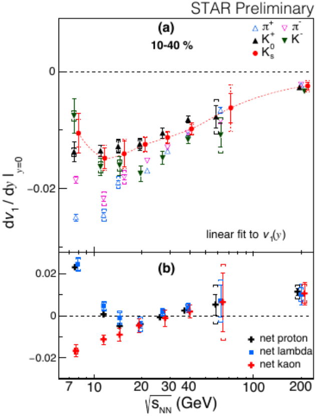
EVIDENCE FOR RAPID CHANGES IN COLLISION ENERGY DEPENDENCE OF HADRON PRODUCTION PROPERTIES IN p+p INTERACTIONS

+

NA49 HORN AND STEP IN Pb+Pb →

EVIDENCE FOR ONSET OF DECONFINEMENT IN Pb+Pb AND p+p

NA61/SHINE: Pulawski, Gazdzicki



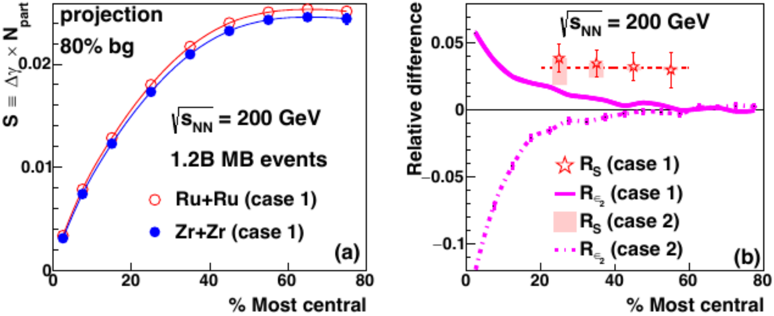
Singha

Critical point, first order transition/onset of deconfinement, . . . ?

CME at RHIC: Isobars

Wen

- If it’s 20% CME-driven, the difference in $\Delta\gamma$ is 5σ above ϵ_2



Other Talks About Chiral Effects @ CPOD 2017

[WEN, Liwen WED 9:00]
Searches for Chiral Effects and Prospects for Isobaric Collisions at STAR/RHIC

[SCHLICHTING, Soeren WED 9:30]
Chiral magnetic effect and anomalous transport in real time

[HIRONO, Yuji WED 10:00]
Properties of chiral magnetohydrodynamics

[UPSAL, Isaac WED 11:00]
Global polarization of Lambda hyperons in Au+Au Collisions at RHIC

[WANG, Qun WED 11:30]
Global Lambda polarization in heavy-ion collisions

[SORIN, Alexander WED 12:00]
Vorticity and polarization in baryon-rich matter

[TU, Zhoudunming WED 14:00]
Studies of charge-dependent azimuthal correlations in search for the chiral magnetic effect in pPb and PbPb collisions at CMS

[YEE, Ho-Ung WED 14:30]
Anatomy of Chiral Magnetic Effect In and Out of Equilibrium

[VENUGOPALAN, Raju WED 15:00]
World-line approach to chiral kinetic theory

Conclusions

- This is the most exciting time for CPOD
- New and groundbreaking results in theory (BEST) and intriguing data from experiment (STAR, HADES, NA61/SHINE). More to think about and to analyse.
- Isobar run in 2018. Fixed target at RHIC.
- RHIC BES-II
- Future facilities: CBM/FAIR, NICA, J-PARK.

"Dangerous to make predictions, especially about the future," but it is reasonable to expect an exciting time ahead.

Local Organizing Committee

- Thomas Hemmick (SBU)
- Jiangyong Jia (SBU)
- Dmitri Kharzeev (SBU, BNL)
- Roy Lacey (Co-chair) (SBU)
- Swagato Mukherjee (Co-chair, BNL)
- Edward Shuryak (SBU)
- Paul Sorensen (BNL)
- Derek Teaney (SBU)
- Zhangbu Xu (BNL)

THANK YOU!