Influence of the QCD Equation of State by System Size

Jacquelyn Noronha-Hostler
Collaborators: Paolo Parotto, Valentina Mantovani, Paolo Alba, Israel Portillo, Claudia Ratti, Jorge Noronha,

CIPANP
May 31st, 2018

RUTGERS UNIVERSITY

What is the smallest droplet of liquid?

Collectivity with few participants

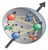
+

R~10 protons

~10^3-10^4 particle

QGP ✓

proton



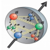
+

R~1-3 protons

~10^2 particles

QGP probably

proton



+

proton

R~1 protons

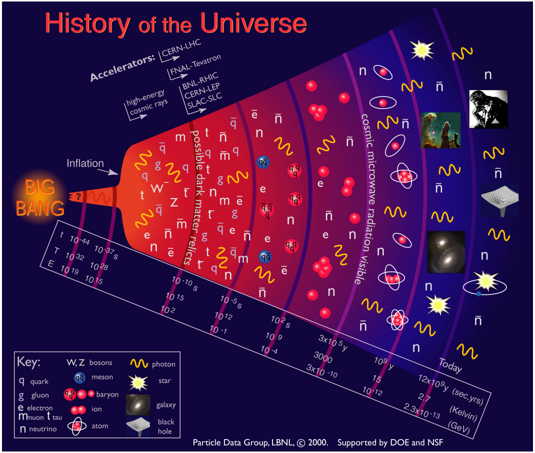
~50 particles

QGP ????

How can we exploit the shrinking system size?

Deconfined Quarks and Gluons in the Early Universe

Quark Gluon Plasma: After the Big Bang a plasma of deconfined Quarks and Gluons was formed (1975 Collins and Perry)



This QGP was "slower" and charm quarks were likely thermalized

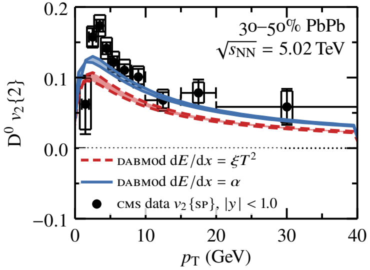
Equilibration times of charm quarks

- Light quarks relaxation time $\tau \sim \frac{\eta}{e+p}$
- Heavy quarks relaxation time $\tau_c \sim \frac{M_c}{T}\frac{\eta}{e+p}$ where the charm quark $M_c \sim 1.3$ GeV
- Then $\frac{\tau_c}{\tau} \sim \frac{M}{T}$. Circa 2005, $T_{RHIC} \sim 250$ MeV $\rightarrow \frac{\tau_c}{\tau} \sim 6$.
- Now, with improvements of Equation of State, freeze-out, η/s, ζ/s...
- $T^{max}_{RHIC} \sim 400 MeV$, $\frac{\tau_c}{\tau} \sim 3.25$
- $T^{max}_{LHC} \sim 600 MeV$, $\frac{\tau_c}{\tau} \sim 2$
- Thermalized charm quarks possible at higher temperatures!

G. D. Moore and D. Teaney, Phys. Rev. C71, 064904 (2005)

Large elliptical flow (and now triangular flow)

See Zhenyu Chen's talk in pPb



Caio Prado, JNH, Katz, Suaide, Noronha, Munhoz , Constentino, Phys.Rev. C96 (2017) no.6, 064903

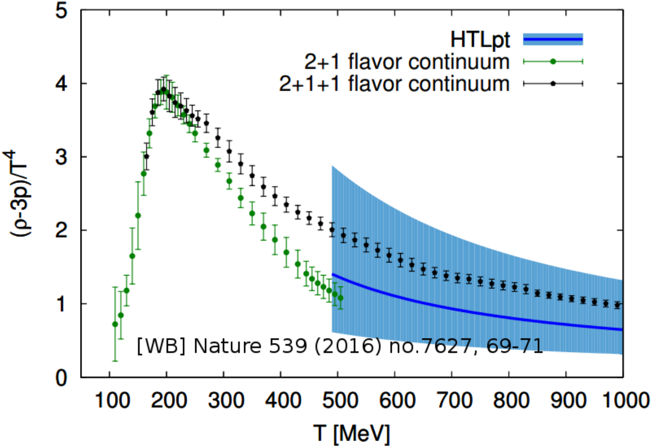
Many other works by TAMU, SUBATECH, USP, DUKE, CCNU/LBNL, BNL, Catania, and Belgrade...

Other approaches

- From Lattice QCD
  S. Mukherjee, P. Petreczky, and S. Sharma, Phys. Rev. D93, 014502 (2016)
- Close in phase space, hard to thermalize
  M. Martinez, M. D. Sievert, and D. E. Wertepny, (2018), arXiv:1801.08986 [hep-ph]
- Experimental Efforts (see X. Dong's Plenary)

Thermalized charm quarks?

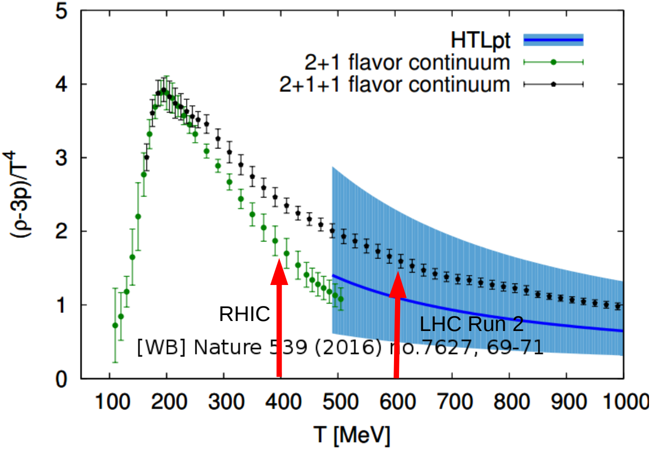
Still questions at $\mu_B = 0$. Sensitive Observables?



WB Collaboration Nature 539 (2016) no.7627, 69-71

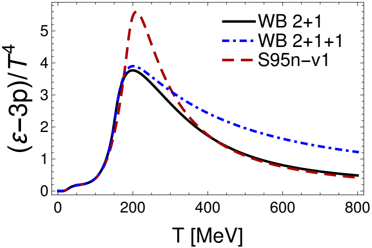
LHC Run 2 good probe of thermalized charm quarks

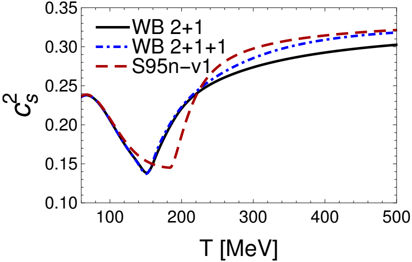
Still questions at $\mu_B = 0$. Sensitive Observables?



WB Collaboration Nature 539 (2016) no.7627, 69-71

State-of-the-art Equation of State at $\mu_B = 0$



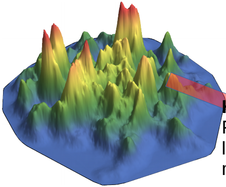


- 2+1 vs. 2+1+1 Lattice QCD based fits combined with PDG 2016+
- PDG16+ needed according to Lattice QCD
  [WB] PRD 96, no. 3, 034517 (2017)
- tanh used for smooth fit at T=150 MeV
- Resonances decays from PDG or extrapolated in the same family (Paolo Parotto)
- Radiation important!
- S95n-v1 with PDG 2005
  Huovinen, Petreczky NPA837 (2010) 26-53

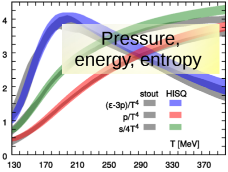
See backup for other recent EOS studies

EOS a key ingredient of relativistic hydrodynamics

Initial Conditions
Quantum fluctuations in the position of nucleons/QCD fields



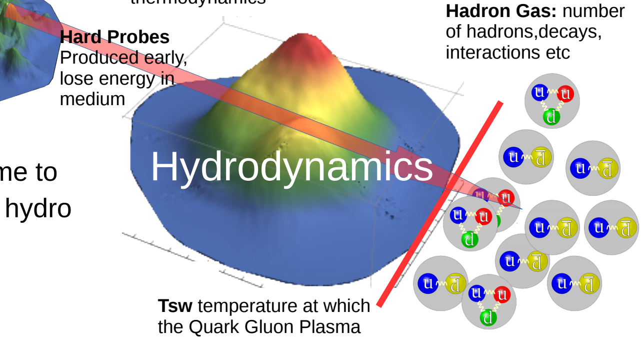
Hydrodynamics (for heavy-ions collisions) in a nutshell



Hydrodynamics viscosity and thermodynamics

Hadron Gas: number of hadrons,decays, interactions etc

Hard Probes
Produced early, lose energy in medium

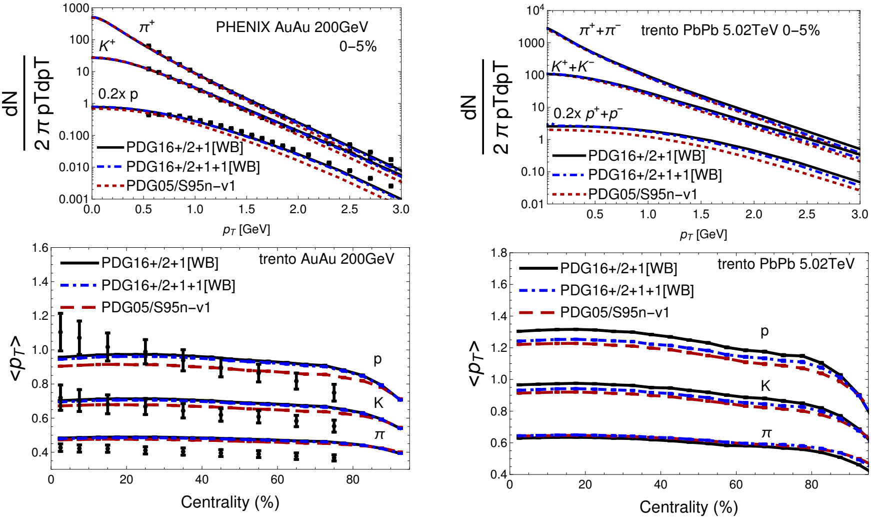


τ_0 initial time to switch on hydro

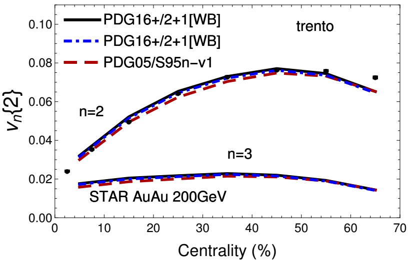
Tsw temperature at which the Quark Gluon Plasma switches to hadrons

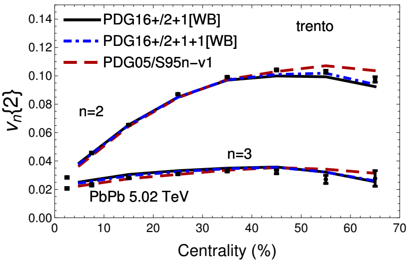
Spectra and $\langle p_T \rangle$

Alba, Mantovani, Noronha, JNH, Parotto, Portillo, Ratti, arXiv:1711.05207



Equation of State connection to η/s





$\eta/s = 0.05$

Consistent with Moreland and Soltz

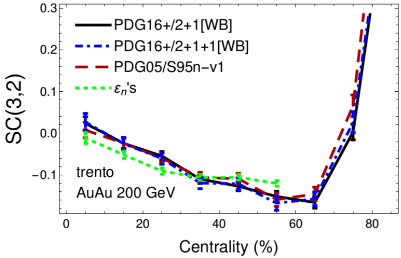
Phys.Rev. C93 (2016) no.4, 044913

- EOS2+1 roughly 2x η/s compared to S95n-v1
- Thermalized charm quarks $\sim$ 15% lower than 2+1

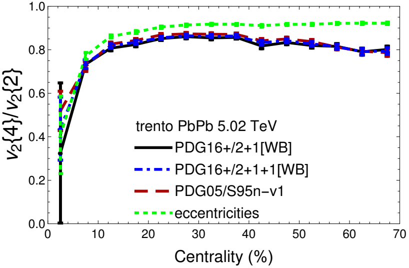
Alba, Mantovani, Noronha, JNH, Parotto, Portillo, Ratti, arXiv:1711.05207

Multiparticle cumulants not dependent on EOS

Symmetric Cumulants



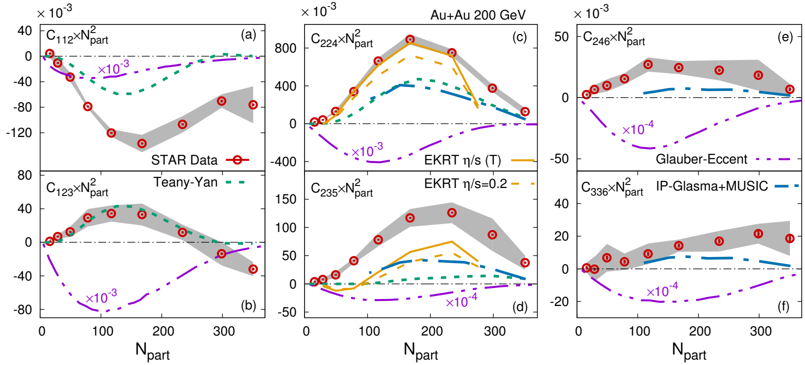
Multiparticle cumulants Driven by IC, see G. Giacalone



Alba, Mantovani, Noronha, JNH, Parotto, Portillo, Ratti, arXiv:1711.05207

Event Plane Correlations- a solution?

$$C_{m,n,m+n} = \langle v_n v_m v_{m+n} \cos(m\phi_m + n\phi_n - (m+n)\phi_{m+n}) \rangle$$

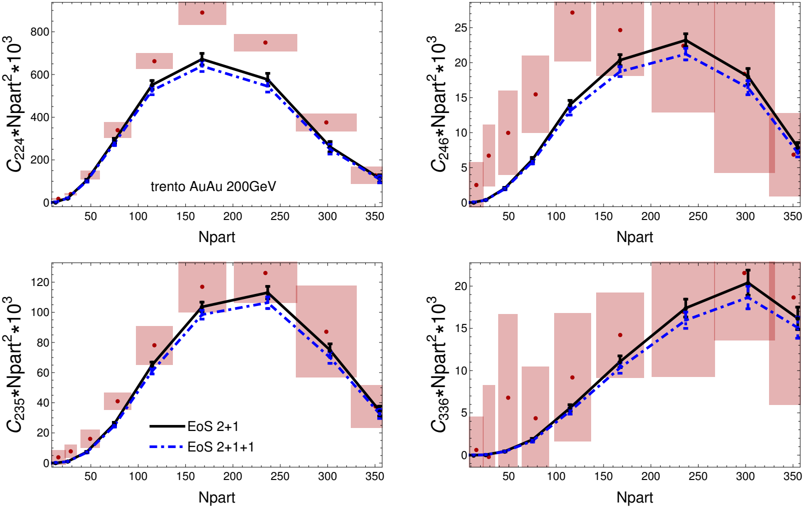


[*STAR*] arXiv:1701.06497

Need to understand $v_1, v_5, v_6 \rightarrow \varepsilon_n$'s or $\eta/s(T)$, $\zeta/s(T)$?

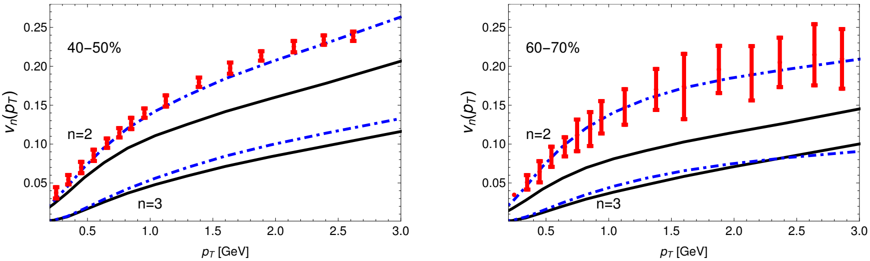
Event Plane Correlations- EOS effects

$$C_{m,n,m+n} = \langle v_n v_m v_{m+n} \cos(m\phi_m + n\phi_n - (m+n)\phi_{m+n}) \rangle$$



JNH, Ratti arXiv:1804.10661

Differential Flow in PbPb shows preference for thermalized charm

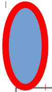


ALICE data arXiv:1804.02944
Hydro JNH, Ratti arXiv:1804.10661

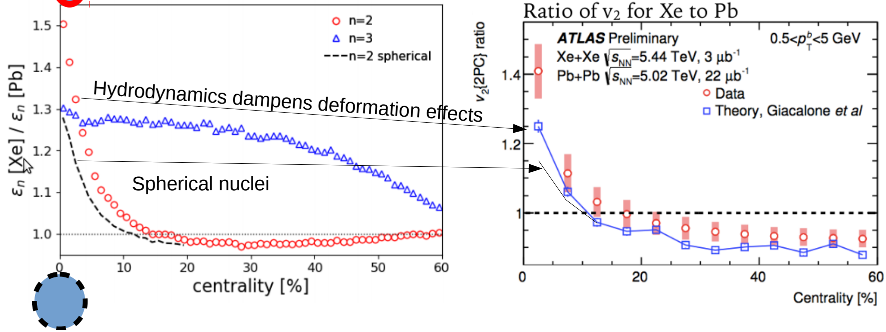
$Xe^{129}Xe^{129}$ collisions at $\sqrt{s_{NN}} = 5.44$ TeV

- Same energy as $Pb^{208}Pb^{208}$ 5.02 TeV collisions but smaller system size
- First noble gas collisions
- $v_2\{2\}$ in central collisions indicates deformed Xe
  Giacalone, JNH, Luzum, Ollitrault, Phys. Rev. C 97, no. 3, 034904 (2018)

Deformed Xe^{129} nucleus



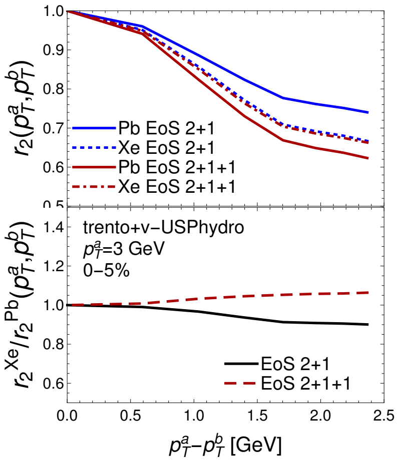
v-USPhydro sensitive to deformed nucleus
Giacalone, JNH et al. Phys. Rev. C 97,034904 (2018)



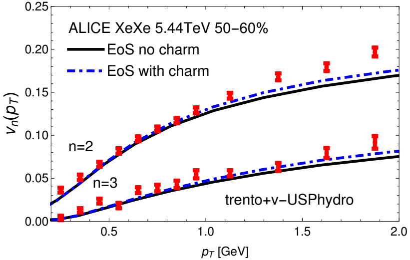
Initial conditions

Questions still remain in central collisions, possible insights into nuclear structure?

Factorization Break Ion Dependence vs. EOS



$v_2(p_T)$ less connected to EOS in XeXe



JNH, Ratti arXiv:1804.10661

Conclusions

- At high energies EoS can affect the extraction of η/s
- Event plane correlation *may* be used to constrain the EoS at RHIC
- Xenon deformation possible to measure in central collisions
- Possibility for thermalized charm quarks in PbPb systems
- Other observables possible to investigate small systems? Effects on hard probes?

BACKUP

Pressure by Baryon Number, Strangeness, Charge

Pressure comes from: $p^{HRG}/T^4 = \frac{1}{VT^3}\sum_i \ln Z_i(T,\mu)$
such that

$$\ln Z_i^{M/B} \simeq \frac{d_i}{2\pi^2}\left(\frac{m_i}{T}\right)^2 \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k^2} K_2\left(\frac{km_i}{T}\right) \cosh\left[k\left(B_i\mu_B + S_i\mu_S + Q_i\mu_Q\right)/T\right]$$

E.g. for strange hadrons (can separate by any BSQ, though)

$$\begin{aligned} P_S(\hat{\mu}_B,\hat{\mu}_S) &= P_{0|1|}\cosh(\hat{\mu}_S) \\ &+ P_{1|1|}\cosh(\hat{\mu}_B-\hat{\mu}_S) \\ &+ P_{1|2|}\cosh(\hat{\mu}_B-2\hat{\mu}_S) \\ &+ P_{1|3|}\cosh(\hat{\mu}_B-3\hat{\mu}_S) \end{aligned}$$

$$\begin{aligned} P_{0|1|} &= \chi_2^S - \chi_{22}^{BS} \\ P_{1|1|} &= \frac{1}{2}\left(\chi_4^S - \chi_2^S + 5\chi_{13}^{BS} + 7\chi_{22}^{BS}\right) \\ P_{1|2|} &= -\frac{1}{4}\left(\chi_4^S - \chi_2^S + 4\chi_{13}^{BS} + 4\chi_{22}^{BS}\right) \\ P_{1|3|} &= \frac{1}{18}\left(\chi_4^S - \chi_2^S + 3\chi_{13}^{BS} + 3\chi_{22}^{BS}\right) \end{aligned}$$

Note all $P_{B|S|}$ taken at the limit of $\mu_B = 0$

Fluctuations of Conserved Charges

Susceptibilities

$$\chi^{BSQ}_{lmn} = \frac{\delta^{l+m+n} p/T^4}{\delta\left(\mu_B/T\right)^l \delta\left(\mu_S/T\right)^m \delta\left(\mu_Q/T\right)^n}$$

where the chemical potentials are related via:

$$\begin{aligned}
\mu_u &= \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q \\
\mu_d &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q \\
\mu_s &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S
\end{aligned}$$

Thermodynamic quantities arXiv:1711.05207

π **gas** $T \leq 33.5$ MeV **HRG** $T \leq 153$ MeV **Lattice QCD**

$$\left(\frac{\varepsilon - 3p}{T^4}\right)_{all} = \left(\frac{\varepsilon - 3p}{T^4}\right)_{\pi} - \frac{1 + \tanh\left[b(T - T_{HRG+Latt/\pi})\right]}{2}\left[\left(\frac{\varepsilon - 3p}{T^4}\right)_{HRG+Latt} - \left(\frac{\varepsilon - 3p}{T^4}\right)_{\pi}\right]$$

$$\left(\frac{\varepsilon - 3p}{T^4}\right)_{HRG+Latt} = \left(\frac{\varepsilon - 3p}{T^4}\right)_{HRG} - \frac{1 + \tanh\left[a(T - T_{HRG/Latt})\right]}{2}\left[\left(\frac{\varepsilon - 3p}{T^4}\right)_{Latt} - \left(\frac{\varepsilon - 3p}{T^4}\right)_{HRG}\right]$$

$$\frac{\varepsilon}{T^4} = \left(\frac{\varepsilon - 3p}{T^4}\right)_{all} + \frac{3p}{T^4}$$

$$\frac{s}{T^3} = \left(\frac{\varepsilon - 3p}{T^4}\right)_{all} + \frac{4p}{T^4}$$

$$c_s^2 = \frac{s}{T}\frac{dT}{ds} = \frac{dp}{d\varepsilon}$$

$$\frac{p}{T^4} = \int_0^T dT\, \frac{1}{T}\left(\frac{\varepsilon - 3p}{T^4}\right)_{all}$$

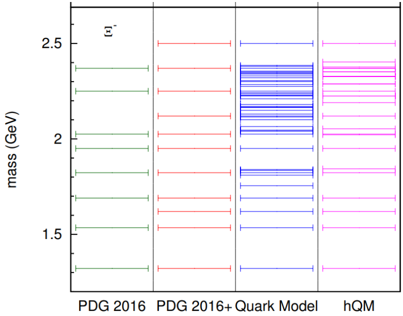
$a = 0.1\ \text{MeV}^{-1}$, $T_{HRG/Latt} = 153$ MeV
$b = 1\ \text{MeV}^{-1}$, $T_{HRG+Latt/\pi} = 33.5$ MeV

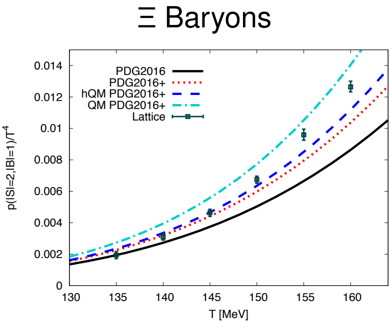
Missing hadron resonances

[WB] Phys.Rev. D96 (2017) no.3, 034517
see also [HotQCD] Phys.Rev.Lett. 113 (2014) no.7, 072001

Partial pressure can find missing strange states.

$$P_{1|2|} = -\frac{1}{4}\left(\chi_4^S - \chi_2^S + 4\chi_{13}^{BS} + 4\chi_{22}^{BS}\right)\cosh(\hat{\mu}_B - 2\hat{\mu}_S)$$





Uncertainty in decays of heavier resonances! Extrapolated from same family.

Alba,Mantovani Sarti, JNH, P. Parotto, Portillo Vazquez, Ratti. To appear soon.

TRENTO

TRENTO Moreland, Bernhard, Bass PRC92(2015)no.1,011901

Total initial entropy profile

$$S(p; S_A, S_B) = \left(\frac{S_A^p + S_B^p}{2} \right)^{\frac{1}{p}}, \quad (1)$$

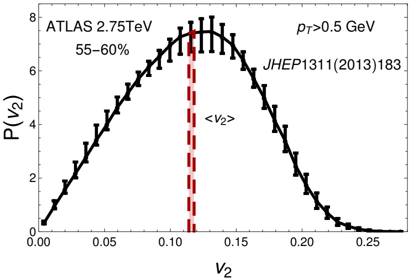
where

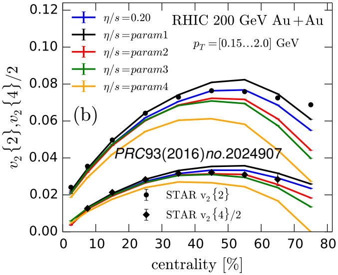
$$S_{A,B} = w_{A,B} \frac{1}{2\pi\sigma^2} \exp\left[\frac{(x - x_{A,B})^2 + (y - y_{A,B})^2}{2\sigma^2} \right]. \quad (2)$$

normalization, w, is a random number which is assigned to each participant nucleon, Γ probability distribution with the width k.

Constraining initial condition models

- Mean shape $\langle \varepsilon_n \rangle \rightarrow \eta/s$, EOS etc..



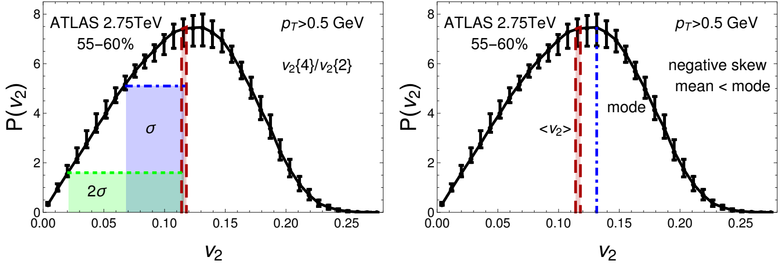


- Size of event-by-event fluctuations $\varepsilon_n\{4\}/\varepsilon_n\{2\}$

- Correlation different harmonics $SC(3,2)$

Constraining initial condition models

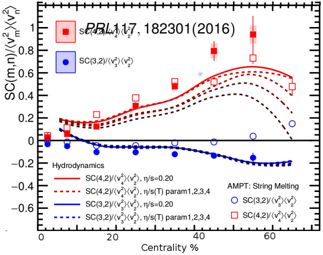
- Mean shape $\langle\varepsilon_n\rangle \rightarrow \eta/s$, EOS etc..
- Size of event-by-event fluctuations $\varepsilon_n\{4\}/\varepsilon_n\{2\}$ 

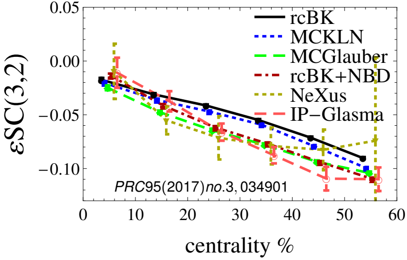


- Correlation different harmonics $SC(3,2)$ 

Constraining initial condition models

- Mean shape $\langle \varepsilon_n \rangle \rightarrow \eta/s$, EOS etc..
- Size of event-by-event fluctuations $\varepsilon_n\{4\}/\varepsilon_n\{2\}$ 
- Correlation different harmonics $SC(3,2)$ 

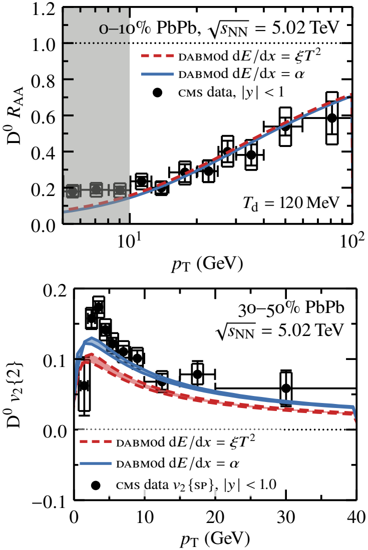




DABMOD- parameterized energy loss model

- Sample charm quarks inside medium with initial momentum distribution from pqcd fonll calculations
- Energy loss motivated by:
  S. K. Das, F. Scardina, S. Plumari, and V. Greco, Phys. Lett. B747, 260 (2015)
- Decoupling temperature $T_d = 120 - 160$ MeV
- Hadronization: Peterson fragmentation function
- Quark Coalescence being implemented (Roland Katz).

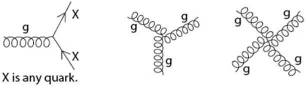
Caio Prado, JNH, Katz, Suaide, Noronha, Munhoz , Constentino, Phys.Rev. C96 (2017) no.6, 064903



Solving Quantum Chromodynamics

$$L_{QCD} = \underbrace{-\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a}_{\text{Gluon Interactions}} + \underbrace{\bar{\psi}^q \left(i\gamma_\mu D^\mu - m_q \right) \psi^q}_{\text{Quark Interactions}} \text{ where } D^\mu = \partial^\mu - ig \underbrace{A^\mu(x)}_{Gluons}$$

Temp



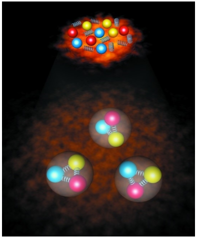
gluon self-interactions

Theoretical Description

Perturbative Quantum Chromodynamics

T_c

T_c~155 MeV
~1.8*10[12] K

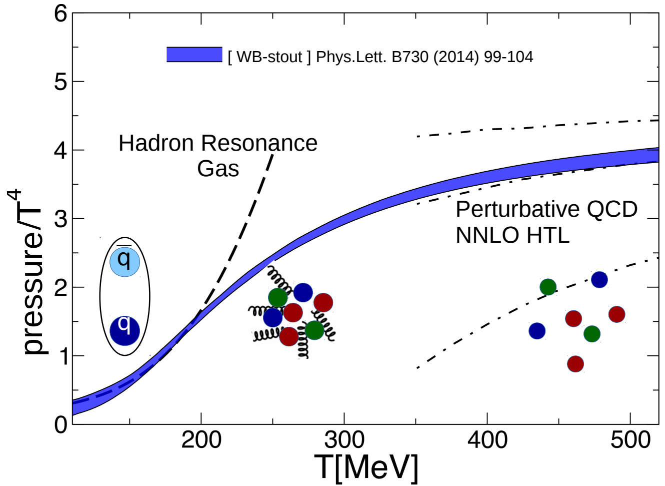


Lattice Quantum Chromodynamics

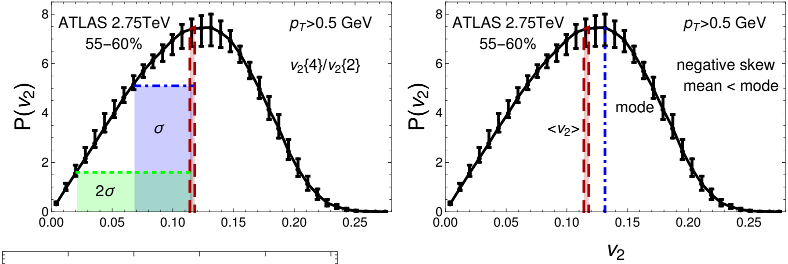
Hadron Resonance Gas
Boltzmann Equation

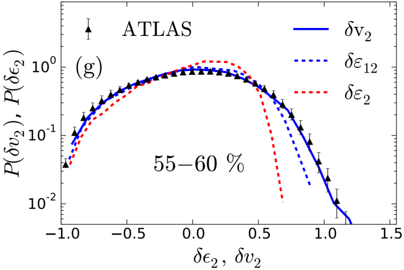
Lattice QCD: Phase Transition

- Cross-over phase transition $T_c \sim 155$ MeV
- Degrees of freedom increase x10!



Elliptical Flow distribution





Niemi, Eskola, Paatelainen PRC93(2016)no.2024907

In peripheral collisions, cubic response affects $P(v_2)$, otherwise $P(\varepsilon_2) \sim P(v_2)$

JNH, Yan, Gardim, Ollitrault Phys.Rev. C93 (2016) no.1, 014909

Multi-particle cumulants

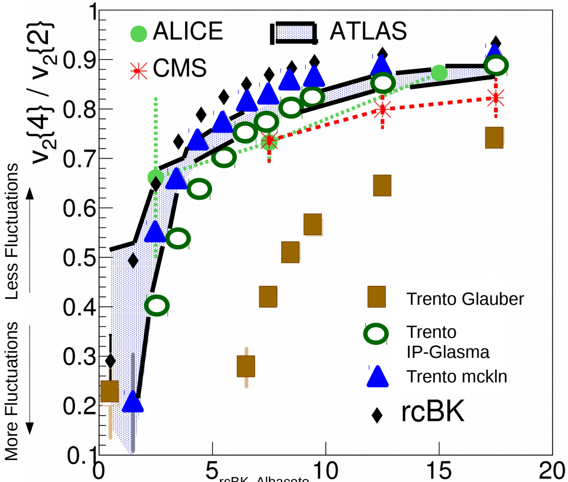
Reconstructing the v_n distribution with cumulants

$$\begin{aligned} v_n\{2\}^2 &= \langle v_n^2 \rangle, \\ v_n\{4\}^4 &= 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle, \\ v_n\{6\}^6 &= \frac{1}{4}\left[\langle v_n^6 \rangle - 9\langle v_n^2 \rangle \langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3 \right], \\ v_n\{8\}^8 &= \frac{1}{33}\left[144\langle v_n^2 \rangle^4 - 144\langle v_n^2 \rangle^2 \langle v_n^4 \rangle + 18\langle v_n^4 \rangle^2 \right. \\ &+ \left. 16\langle v_n^2 \rangle \langle v_n^6 \rangle - \langle v_n^8 \rangle \right], \end{aligned}$$

where collectivity $\rightarrow v_n\{2\} > v_n\{4\} \sim v_n\{6\} \sim v_n\{8\}$ but there are differences between higher order cumulants!

$v_2\{4\}/v_2\{2\}$ vs initial conditions in PbPb

Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.5, 054910

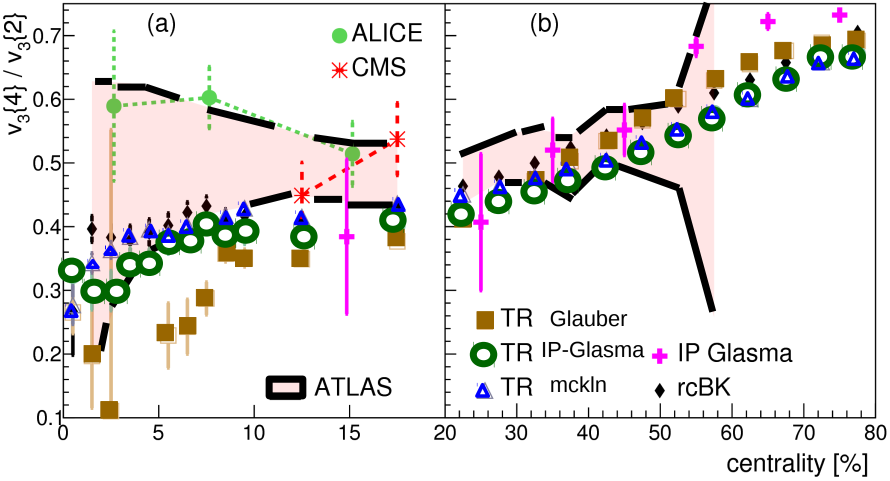


TRENTO Moreland, Bernhard, Bass PRC92(2015)no.1,011901

rcBK Albacete, Dumitriu arXiv:1011.5161

All initial conditions miss $v_3\{4\}/v_3\{2\}$ in PbPb

Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.5, 054910



Azimuthal anisotropies

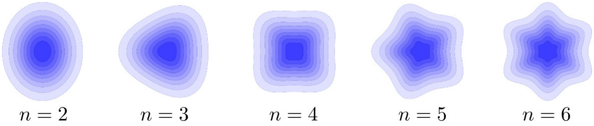
The distribution of particles can be written as a Fourier series

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_n 2v_n \cos\left[n\left(\phi - \psi_n\right)\right]\right]$$

- Flow Harmonics at mid-rapidity

$$v_n(p_T) = \frac{\int_0^{2\pi} d\phi \frac{dN}{p_T dp_T d\phi} cos\left[n\left(\phi - \Psi_n\right)\right]}{\int_0^{2\pi} d\phi \frac{dN}{p_T dp_T d\phi}}$$

where $\Psi_n = \frac{1}{n} \arctan \frac{\langle sin[(n\phi)]\rangle}{\langle cos[(n\phi)]\rangle}$



Initial Conditions and Hydrodynamics

TRENTO parameters

Moreland, Bernhard, Bass PRC92(2015)no.1,011901

- $p = 0$ entropy deposition parameter
- $k = 1.6$ nucleon-nucleon fluctuation shape parameter
- $\sigma = 0.51$ nucleon width

Hydro Parameters

- $\tau_0 = 0.6$ fm
- $T_{SW} = T_{CE} = 150$ MeV
- v-USPhydro
  JNH et al, PRC88(2013)no.4,044916; PRC90(2014)no.3,034907
- Hadronic feed-down only

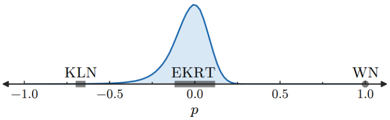


FIG. 9. Posterior distribution of the T$_R$ENTo entropy deposition parameter p introduced in Eq. (14). Approximate p-values are annotated for the KLN ($p \approx 0.67 \pm 0.01$), EKRT ($p \approx 0.0 \pm 0.1$), and wounded nucleon ($p = 1$) models.

J. S. Moreland, J. E. Bernhard, and S. A. Bass, Phys. Rev. C92, 011901 (2015)
J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu, and U. Heinz, Phys. Rev. C94, 024907 (2016),

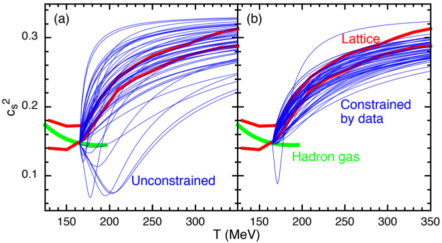
Bulk viscosity

$\zeta/s = 0$ to avoid δf uncertainty.

Constraining the EoS

Bayesian analysis

RHIC/LHC, smoothed IC



Pratt, Sangaline, Sorensen, Wang Phys.Rev.Lett. 114 (2015) 202301; Sangaline and Pratt Phys.Rev. C93 (2016) no.2, 024908

RHIC, event-by-event

$1 - 10\%$ effect

Moreland and Soltz Phys.Rev. C93 (2016) no.4, 044913

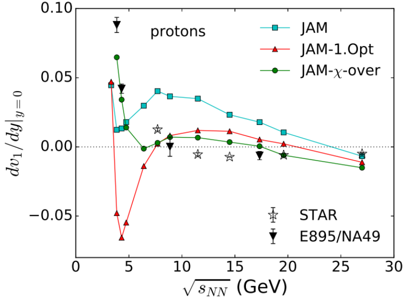
$\langle m_T \rangle$ vs. dN/dy of central collisions

Monnai and Ollitrault Phys.Rev. C96 (2017) no.4, 044902

Deep Learning confirms Lattice QCD EoS

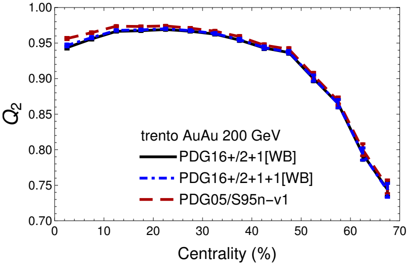
Pang et al, arXiv:1612.04262

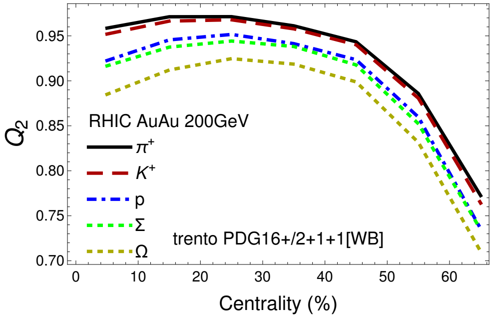
dv_1/dy sensitive to EoS

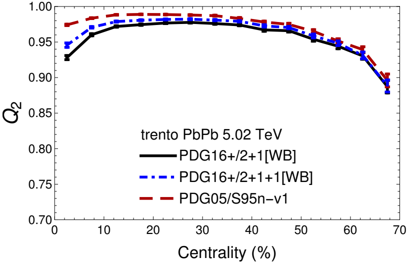


Nara et al Phys.Lett. B769 (2017) 543-548

Correlation between Initial State and Flow Harmonics







Pearson Coefficient ($\varepsilon_n \rightarrow v_n$)

$$Q_n = \frac{\langle v_n \varepsilon_n \cos(n[\psi_n - \phi_n]) \rangle}{\sqrt{\langle |\varepsilon_n|^2 \rangle \langle |v_n|^2 \rangle}}$$

$Q_n = (-)1$ (anti-)correlated

$Q_n = 0$ no correlation

Gardim et al, PRC85 (2012) 024908; PRC91 (2015) no.3, 034902

Normalized Event Plane Correlations

Normalizing $C_{m,n,m+n} = \frac{\langle v_n v_m v_{m+n} \cos(m\phi_m + n\phi_n - (m+n)\phi_{m+n})\rangle}{\sqrt{\langle v_n^2\rangle\langle v_m^2\rangle\langle v_{m+n}^2\rangle}}$