

Bayesian Inference of QGP Properties and 3D Dynamics from Beam Energy Scan Data

Chun Shen (Wayne State University)

In collaboration with Björn Schenke and Wenbin Zhao

C. Shen, B. Schenke and W. Zhao, arXiv:2310.10787 [nucl-th]



Oct. 24, 2023

PROBING THE NUCLEAR MATTER PHASE DIAGRAM



Chun Shen (WSU/RBRC)

RHIC BES Seminar

 Search for a critical point & 1st order phase transition

• How do the QGP transport properties change with baryon

 $(\eta/s)(T, \{\mu_q\}), (\zeta/s)(T, \{\mu_q\})$

doping?

 Access to new transport phenomena

Charge diffusion



2/33

THE MULTI-STAGE THEORETICAL FRAMEWORK



a minertige States

Chun Shen (WSU/RBRC)

RHIC BES Seminar

and the second s





THE MULTI-STAGE THEORETICAL FRAMEWORK



RHIC BES energies



RHIC BES Seminar

Chun Shen (WSU/RBRC)

Hadronic Transport







0-5% Au+Au @ 19.6 GeV



AN OPEN SOURCE HYBRID FRAMEWORK-IEBE-MUSIC <u>https://github.com/chunshen1987/iEBE-MUSIC</u>





3D-MCGlauber model Dynamical initialization

MUSIC ╋ Lattice QCD EoS

EM radiation

Spectators/Electromagnetic fields



Chun Shen (WSU/RBRC)

RHIC BES Seminar

The iEBE-MUSIC Framework



State-of-the-art event-by-event simulations for relativistic heavy-ion collisions







AN OPEN SOURCE FRAMEWORK FOR THE COMMUNITY The iEBE-MUSIC framework takes advantage of free computing resources powered by the Open Science Grid (OSG)

1.20 Mil 1 Mil 800 H Walltime (h) 600 K 400 K 200 K 09/01 09/16 10/01 08/01 08/16

Chun Shen (WSU/RBRC)

RHIC BES Seminar

OSG Flocking WallTime By Project ~

Last 90 days



		total
	SBU_JIa	10 Mi
_	TG-CHE200122	9 Mi
	WSU_3DHydro	7 Mi
	TelescopeArray	7 Mi
_	PixleyLab	5 Mi
_	КОТО	3 Mi
_	UNL_Fuchs	3 Mi
_	PSI_Kaib	2 Mi
_	UConn_Le	2 Mi
-	NCSU_Hall	1 Mi
_	SSGAforCSP	1 Mi
_	EvolSims	1 Mi
_	BiomedInfo	1 Mi
_	REDTOP	937 k
_	xenon1t	924 k
_	NorthwesternMed_Yadav	896 k
_	eht	632 k





7/33

3D MC-GLAUBER MODEL WITH STRING DECELERATION

- Transverse collision geometry is determined by MC-Glauber model
- 3 valence quarks are sampled from PDF with



 Incoming quarks are decelerated with a string tension σ ,

$$dp^z/dt = -\sigma$$



Chun Shen (WSU/RBRC)



3D MC-GLAUBER MODEL WITH STRING DECELERATION

- Transverse collision geometry is determined by MC-Glauber model
- 3 valence quarks are sampled from PDF with



Incoming quarks are decelerated with a string tension σ ,

$$dp^z/dt = -\sigma$$



QCD EQUATION OF STATE AT FINITE DENSITIES

Enabled hydrodynamic simulations at finite µ

Chun Shen (WSU/RBRC)

M. Albright, J. Kapusta and C. Young, Phys. Rev. C90, 024915 (2014) A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019) J. Noronha-Hostler, P. Parotto, C. Ratti and J. M. Stafford, Phys. Rev. C100, 064910 (2019) J. M. Stafford *et. al*, arXiv:2103.08146 [hep-ph]

Lattice QCD: Taylor expansion up to the 4th order

$$\frac{P_0}{T^4} + \sum_{l,m,n} \frac{\chi_{l,m,n}^{B,Q,S}}{l!m!n!} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^l$$

Match to Hadron Resonance Gas model at low T

$$-f(T,\mu_J)]\frac{P_{\text{had}}(T,\mu_J)}{T^4} + \frac{1}{2}[1+f(T,\mu_J)]\frac{P_{\text{lat}}(T,\mu_J)}{T^4}$$

 $f(T, \mu_B) = \tanh[(T - T_c(\mu_B) / \Delta T_c]]$

3D HYDRODYNAMICS WITH FINITE BARYON CURRENT

 $\mu\nu = J_{\rm source}^{\nu}$ $\partial_{\mu}J^{\mu} = \rho_{\text{source}}$

 $\eta/s(\mu_B)$ has a piece-wise parameteriz ation

A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)

 $\zeta/s(T)$ is parameteriz ed with an two-piece asymmetric Gaussian

RHIC BES Seminar

11/33

THE MODEL PARAMETERS

TA]	TABLE I. The 20 model parameters and their prior ran									
	Parameter	Prior	Parameter	Prior						
	$B_G \; ({\rm GeV}^{-2})$	[1, 25]	$lpha_{ m stringtilt}$	[0, 1]						
	$lpha_{ m shadowing}$	[0, 1]	$lpha_{ m preFlow}$	[0, 2]						
	$y_{ m loss,2}$	[0, 2]	η_0	[0.001, 0.3]						
	$y_{ m loss,4}$	[1, 3]	η_2	[0.001, 0.3]						
	$y_{ m loss,6}$	[1, 4]	η_4	[0.001, 0.3]						
	$\sigma_{y_{ m loss}}$	[0.1, 0.8]	$\zeta_{ m max}$	[0, 0.2]						
	$lpha_{ m Rem}$	[0, 1]	$T_{\zeta,0}$ (GeV)	[0.15, 0.25]						
	λ_B	[0, 1]	$\sigma_{\zeta,+}~({ m GeV})$	[0.01, 0.15]						
	$\sigma_x^{ m string}~({ m fm})$	[0.1, 0.8]	$\sigma_{\zeta,-}$ (GeV)	[0.005, 0.1]						
	$\sigma_\eta^{ m string}$	[0.1, 1]	$e_{\rm sw}~({ m GeV}/{ m fm}^3)$	[0.15, 0.5]						

iges.

MODEL TRAINING & OBSERVABLE SELECTION

A 20-dimensional model parameter space with 1,000 training points

Au+Au	Hydro events per design	Avg. hadronic events per hydro
200 GeV	1,000	1,000
19.6 GeV	2,000	4,000
7.7 GeV	2,000	8,000

Open Science Grid delivered 5 million CPU hours for the data generation

604 experimental data points

Au+Au	STAR midrapdity data vs. centrality	PHOBOS rapidity distribtion
200 GeV	$dN/dy(\pi^{+}, K^{+}, p, \bar{p}) \langle p_{T} \rangle(\pi^{+}, K^{+}, p, \bar{p}) v_{2}^{ch}\{2\}, v_{3}^{ch}\{2\}$	$dN^{ch}/d\eta$ $v_2(\eta)$
19.6 GeV	$dN/dy(\pi^{+}, K^{+}, p) \langle p_{T} \rangle(\pi^{+}, K^{+}, p, \bar{p}) v_{2}^{ch}\{2\}, v_{3}^{ch}\{2\}$	dN ^{ch} /dη
7.7 GeV	$dN/dy(\pi^{+}, K^{+}, p) \langle p_{T} \rangle(\pi^{+}, K^{+}, p, \bar{p}) v_{2}^{ch}\{2\}, v_{3}^{ch}\{2\}$	

Phys. Rev. C79, 034909 (2009) Phys. Rev. C98, 034918 (2018) Phys. Rev. C96, 044904 (2017) Phys. Rev. C74, 021901 (2006) 13/33 **RHIC BES Seminar**

OBSERVABLE RESPONSES TO MODEL PARAMETERS

PHOBOS 200 GeV

Red: Positive correlation; Blue: Negative correlation **RHIC BES Seminar**

Chun Shen (WSU/RBRC)

STAR

- dN ^{ch} /dŋ(34 — 44%)	- ν ₂ (η)(0 – 40%) - dN/dy(π ⁺)	$\begin{array}{c} dN/dy(K^{+}) \\ dN/dy(p) \\ (p_{T})(\pi^{+}) \\ (p_{T})(\pi^{+}) \\ (p_{T})(p) \\ (p_$	- dN ^{ch} /dη(0 – 5%)	- <i>dN^{ch}/dŋ</i> (5 – 12%)	- dN ^{ch} /dŋ(12 - 24%)	- dN ^{ch} /dŋ(24 – 34%)	- dN ^{ch} /dŋ(34 - 44%)	ST - dN/dλ(K +) - dN/dλ(b) - (p_1)(μ +) - (p_1)(μ +)) - (p_1)(μ +)) - (p_1)(\mu +))) - (p_1)(\mu +))) - (p_1)(\mu +))) - (p_1)(\mu +))) - (p_1)(\mu +)))) - (p_1)(\mu +))))))))))))))))))))))))))))))))))

OBSERVABLE RESPONSI

 Particle yields provide strong constraints on initial-state energy (rapidity) loss parameters

 The opposite correlations between mid-rapidity and forward in PHOBOS pseudo-rapidity distributions can provide complement constraints to those from STAR mid-rapidity measurements at the multiple collision energies

Red: Positive correlation; Blue: Negative correlation **RHIC BES Seminar**

Chun Shen (WSU/RBRC)

ES	T		DE	L P/	AR/		ETE	RS
		STAR	PF	HOBC)S 1	9.6 (GeV	ST
- 44%)	(%(19.6	- 5%)	- 12%)	- 24%)	- 34%)	- 44%)	7.7
- dN ^{ch} /dη(34	- ν ₂ (η)(0 – 4($- dN/dy(\pi^{+}) - dN/dy(K^{+}) - dN/dy(p) - (p_{T})(\pi^{+}) - (p_{T})(K^{+}) - (p_{T})(p) - v_{2} {2} (ch) - v_{3} {2} (ch) - v_{3$	- dN ^{ch} /dŋ(0 –	- dN ^{ch} /dη(5 –	- dN ^{ch} /dη(12	- dN ^{ch} /dη(24	- dN ^{ch} /dη(34	- dN/dy(π ⁺) - dN/dy(K ⁺) - dN/dy(p) - {p _T }(π ⁺)

OBSER	VAE	BLE F	RESF	PONS	SES	T		DEI	L P/	AR/		ETE	ERS
STAR		PHOE	BOS 20	00 GeV			STAR	PH	IOB(DS 19	9.60	зеV	ST
200 GeV	- 5%)	- 12%)	- 24%)	- 34%)	- 44%)	(%(19.6	- 5%)	- 12%)	- 24%)	- 34%)	- 44%)	7.7
$dN/dy(\pi^+)$ $dN/dy(K^+)$ dN/dy(p) $dN/dy(\bar{p})$ $\langle p_{T}\rangle(\pi^+)$ $\langle p_{T}\rangle(p)$ $\langle p_{T}\rangle(p)$ $\langle p_{T}\rangle(\bar{p})$ $v_{2}\{2\}(ch)$ $v_{3}\{2\}(ch)$	dN ^{ch} /dŋ(0 –	dN ^{ch} /dŋ(5 –	dN ^{ch} /dŋ(12	dN ^{ch} /dŋ(24	dN ^{ch} /dŋ(34	$v_{2}(\eta)(0-40)$	$dN/dy(\pi^{+}) dN/dy(K^{+}) dN/dy(p) (p_{T})(\pi^{+}) (p_{T})(K^{+}) (p_{T})(p) (p_{T})(\bar{p}) v_{2} {2} (ch) v_{3} {2} (ch) v_{3} {ch} $	dN ^{ch} /dη(0 –	dN ^{ch} /dη(5 –	dN ^{ch} /dŋ(12	dN ^{ch} /dŋ(24	dN ^{ch} /dŋ(34	$dN/dy(\pi^+)$ $dN/dy(K^+)$ $dN/dy(p)$ $\langle p_T \rangle (\pi^+)$

 Shear viscosity shows positive correlation with particle yields — entropy production; negative correlation with anisotropic flow — viscous damping PHOBOS pseudo-rapidity distributions at 200 GeV offers additional constrains on $\eta/s(\mu_R)$

Red: Positive correlation; Blue: Negative correlation **RHIC BES Seminar**

Chun Shen (WSU/RBRC)

dvidy(t*) dvidy(p) dv^{ch}/dn(12 - 12%) dv^{ch}/dn(12 - 24%) dv^{ch}/dn(12 - 24%) dv^{ch}/dn(12 - 34%) dv^{ch}/dn(24 - 34%)

Bulk viscosity shows positive correlation with particle yields — entropy production; negative correlation with mean p_T — resistance to expansion
 Particle yields at forward and backward pseudo-rapidity shows stronger correlation with (ζ/s)_{max} than those with the mid-rapidity particle yields

Red: Positive correlation; Blue: Negative correlation

Chun Shen (WSU/RBRC)

ES		DE	L P/	AR/			RS
	STAR	Pł	HOBC)S 1	9.6 (GeV	ST
- 44%)	₃₈ 19.6	- 5%)	- 12%)	- 24%)	- 34%)	- 44%)	7.7
dN ^{ch} /dη(34	$v_{2}(\eta)(0 - 4(dN/dy(\pi^{+})))$ $dN/dy(\pi^{+}))$ dN/dy(p) $\langle p_{T}\rangle(\pi^{+}))$ $\langle p_{T}\rangle(\pi^{+}))$ $\langle p_{T}\rangle(p)$ $\langle p_{T}\rangle(p))$ $v_{2}\{2\}(ch))$ $v_{3}\{2\}(ch))$	dN ^{ch} /dη(0 –	dN ^{ch} /dη(5 –	dN ^{ch} /dη(12	dN ^{ch} /dŋ(24	dN ^{ch} /dη(34	$dN/dy(\pi^{+})$ $dN/dy(K^{+})$ $dN/dy(p)$ $\langle p_{T}\rangle(\pi^{+})$

PUBLIC INTERACTIVE MODEL EMULATOR

Model Parameters:

3D-Glauber + MUSIC + UrQMD Model for RHIC BES energies

This is an interactive web page that emulates particle production and their anisotropic flow as functions of rapidity using the 3D-Glauber+MUSIC+UrQMD model.

This work is based on link

One can adjust the model parameters on the left sidebar.

The colored bands in the figure show the emulator estimations with their uncertainties. The compared experimental data are from the STAR and PHOBOS Collaborations

Au+Au @ 200 GeV vs. STAR

Au+Au @ 19.6 GeV vs. STAR

Au+Au @ 7.7 GeV vs. STAR

Comparisons to the PHOBOS data

Chun Shen (WSU

<u>link</u>

 An interactive webpage for emulating the full (3+1)D simulations for RHIC BES energies at real time

 Build your own intuition for heavy-ion phenomenology!

BAYESIAN VALIDATION: CLOSURE TEST Bayes' Theorem: $P(\theta | y_{exp}) \propto P(y_{exp} | \theta) P(\theta)$ $\eta/S(\mu_R)$

Initial-state stopping

- closure test for initial-state stopping $y_{loss}(y_{init})$, $\eta/s(\mu_B)$, and $\zeta/s(T)$
- The selected observables can give strong constraints on the QGP properties at RHIC BES energies

Chun Shen (WSU/RBRC)

$\zeta/s(1)$

Model emulation with Markov Chain Monte Carlo (MCMC) is verified with a

Chun Shen (WSU/RBRC)

RHIC BES Seminar

20/33

Chun Shen (WSU/RBRC)

BAYESIAN INFERENCE AT RHIC BES ENERGIES

RHIC BES Seminar

21/33

Chun Shen (WSU/RBRC)

RHIC BES Seminar

 Mid-rapidity particle productions at 200 GeV yields $y_{\text{loss}} \sim 2$ for $y_{\text{init}} \sim 5$

color bands indicate 90% credible interval in the posterior

Chun Shen (WSU/RBRC)

- Mid-rapidity particle productions at 200 GeV yields $y_{loss} \sim 2$ for $y_{init} \sim 5$
- The rapidity distributions from PHOBOS give small improvements to the constraint

color bands indicate 90% credible interval in the posterior

Chun Shen (WSU/RBRC)

- Mid-rapidity particle productions at 200 GeV yields $y_{loss} \sim 2$ for $y_{init} \sim 5$
- The rapidity distributions from PHOBOS give small improvements to the constraint
- Particle production from 7.7, 19.6, and 200 GeV sets strong constrain on $y_{\text{loss}}(y_{\text{init}})$ for $y_{\text{init}} \in [0,6]$

color bands indicate 90% credible interval in the posterior

- Mid-rapidity particle productions at 200 GeV yields $y_{loss} \sim 2$ for $y_{init} \sim 5$
- The rapidity distributions from PHOBOS give small improvements to the constraint
- Particle production from 7.7, 19.6, and 200 GeV sets strong constrain on $y_{\text{loss}}(y_{\text{init}})$ for $y_{\text{init}} \in [0,6]$

color bands indicate 90% credible interval in the posterior

SHEAR VISCOSITY $\eta/s(\mu_R)$

 $\mu_B = 0$

can constrain η/s around

color bands indicate 90% credible interval in the posterior

SHEAR VISCOSITY $\eta/s(\mu_R)$

• The $dN^{ch}/d\eta$ and $v_2(\eta)$ at 200 GeV significantly improve the η/s constraint at $\mu_R \sim 0.2 \text{ GeV}$

color bands indicate 90% credible interval in the posterior

RHIC BES Seminar

0.40

SHEAR VISCOSITY $\eta/s(\mu_R)$

- Mid-rapidity data at 200 GeV can constrain η/s around $\mu_B = 0$
- The $dN^{\rm ch}/d\eta$ and $v_2(\eta)$ at 200 GeV significantly improve the η/s constraint at $\mu_B \sim 0.2 \, {
 m GeV}$
- The full RHIC BES data (STAR+PHOBOS) shows that the QGP η/s is **larger** at finite μ_R than that at $\mu_R = 0$

color bands indicate 90% credible interval in the posterior

INFERENCE WITH ONLY STAR MID-RAPIDITY DATA

Chun Shen (WSU/RBRC)

- The mid-rapidity data from STAR BES energies can set a good constraint on $y_{\rm loss}(y_{\rm init})$
- The rapidity dependent $v_2(\eta)$ measurement imposes strong constraints on $\eta/s(\mu_R)$

RHIC BES Seminar

29/33

BULK VISCOSITY $\zeta/s(T)$

Chun Shen (WSU/RBRC)

RHIC BES Seminar

• Mid-rapidity identified particle yields and their $\langle p_T \rangle$ at 200 GeV set constraints on the temperature dependence of the QGP bulk viscosity

• The additional PHOBOS data shifts the posterior $\zeta/s(T)$ to larger values

color bands indicate 90% credible interval in the posterior

0.30

• Allowing $\zeta/s(T)$ to be an independent function for the three collision energies, our calibration suggests a larger $\zeta/s(T)$ at 19.6 GeV than those at 200 and 7.7 GeV for $T \in [0.15, 0.2]$ GeV Hint for softening(hardening) EoS at $\mu_R = 0.2(0.4)$ GeV? **RHIC BES Seminar**

BULK VISCOSITY $\zeta/s(T, \sqrt{s})$

color bands indicate 90% credible posterior

interval in the

CONCLUSIONS

- We performed a comprehensive Bayesian Inference study at multiple RHIC BES energies with a state-ofthe-art event-by-event (3+1)D hybrid framework
- With the RHIC BES phase I data, robust constraints are obtained for initial state nuclear stopping, QGP $\eta/s(\mu_R)$, and $\zeta/s(T,\sqrt{s})$ for the first time
- The QGP effective η/s is larger at finite μ_R , while $\zeta/s(T)$ shows a hint for non-monotonic energy dependence around $\sqrt{s} = 19.6$ GeV
- Our work marks an important step towards quantitative characterization of the QCD phase structure with the RHIC BES and future FAIR programs

Chun Shen (WSU/RBRC)

RHIC BES Seminar

32/33

bands indicate 90% credible interval in the posterior

OUTLOOK

- Confront with the RHIC BES phase II data \rightarrow Constrain the speed of sound $c_s^2(T, \mu_R)$ \rightarrow Extend to multiple conserved charge currents $P(e, n_B, n_O, n_S)$ Critical fluctuations/first-order phase transition (3+1)D dynamics at the LHC Rapidity (small-x) evolution The role of nuclear structure
- Open data
 - statistical analyses

Engage more collaboration on developing robust and efficient

