Determining quark-gluon plasma initial condition and transport properties with quantitative uncertainty

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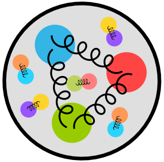
Funding provided by DOE NNSA Stewardship Science Graduate Fellowship

Melting point of the proton

Protons and neutrons have *substructure*:
constituent quarks, sea quarks, gluons, etc.
When are degrees of freedom liberated?



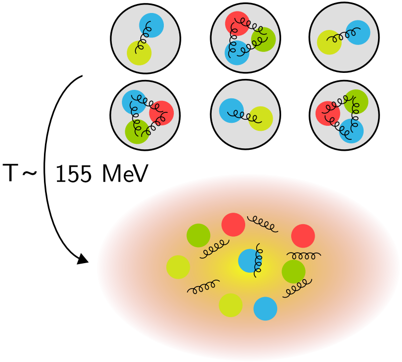
Back of the envelope estimate

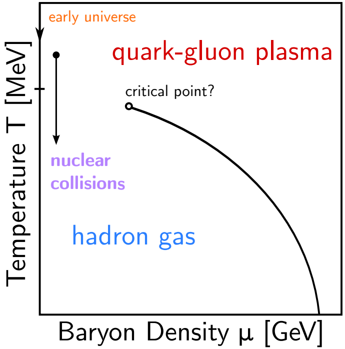
Thermal energy exceeds rest mass when...
proton mass $\sim$ 1 GeV
proton size $\sim$ (0.5 fm)^3
energy density gluon gas: $\epsilon = \frac{64}{15}\frac{\pi^2}{(\hbar c)^3}T^4$
$\epsilon_{\text{proton}} = 8$ GeV/fm^3 $\leftrightarrow T_c \sim 200$ MeV

Proton should melt at ~2,000,000,000,000 K!

QCD predicts new phase of matter

QCD calculations on the lattice find the phase transition at $T \approx 155$ MeV, where nucleons 'melt' to form a plasma of deconfined quarks and gluons dubbed a *quark-gluon plasma*

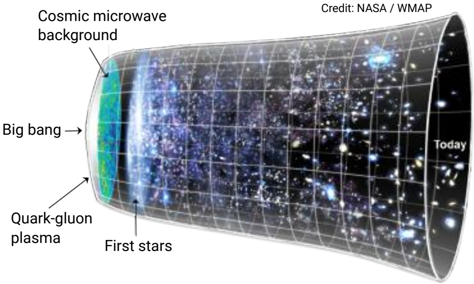


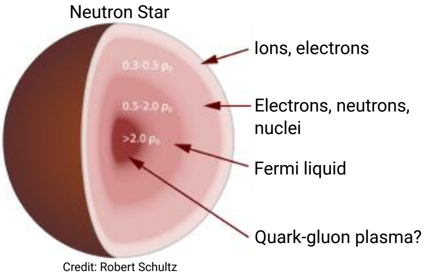


Quark-gluon plasma in nature

Conditions to produce QGP occur(ed) naturally in two places

- Early universe, mere microseconds after big bang where $T > 200$ MeV
- Center of neutron stars at extreme baryon density





Creating quark-gluon plasma in the laboratory

General strategy... collide nuclei at ultrarelativistic energies

- Relativistic Heavy-ion Collider (RHIC):
  Beam energy 7.7–200 GeV per nucleon pair
- Large Hadron Collider (LHC):
  Beam energy 2760–13000 GeV per nucleon pair

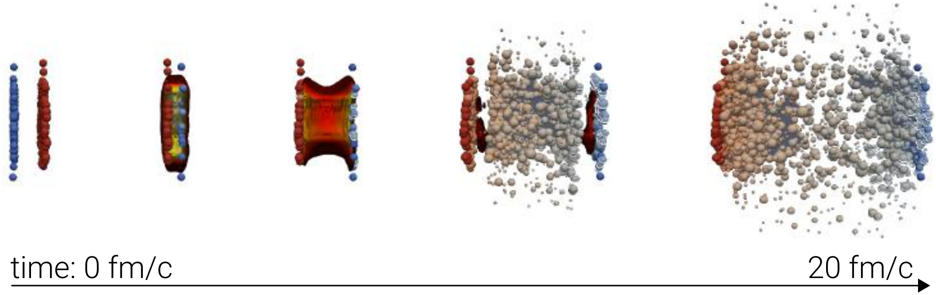


Fig. MADAI collaboration

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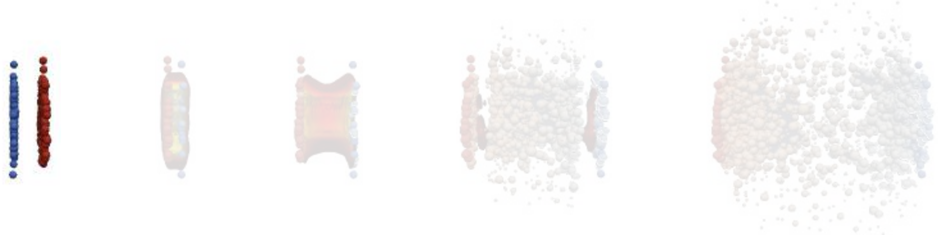

Relativistic nuclei highly Lorentz contracted ...pancake-shaped in lab frame

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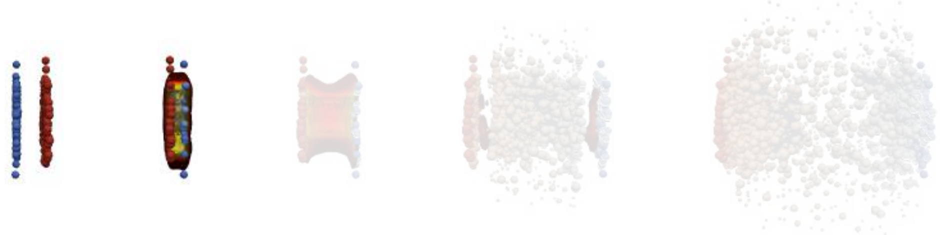

Nuclei collide, compress and heat matter beyond QGP critical point

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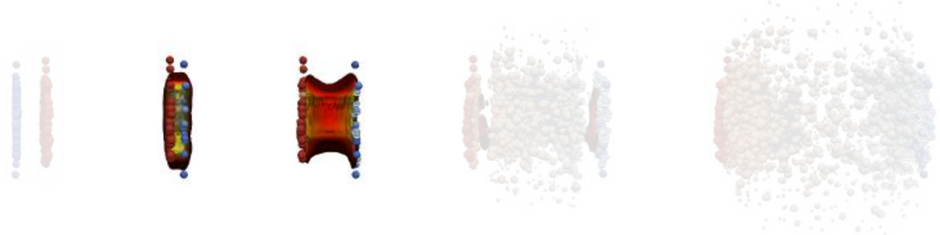

QGP thermalizes, starts to expand hydrodynamically

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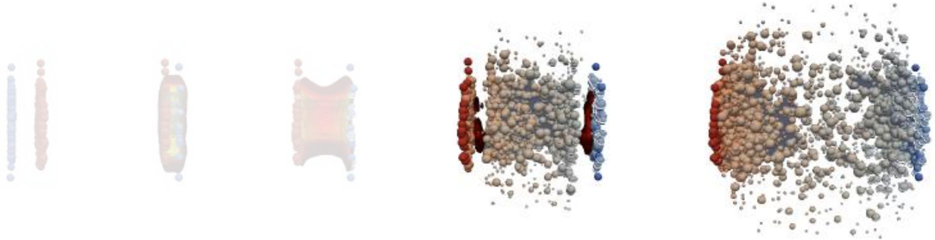
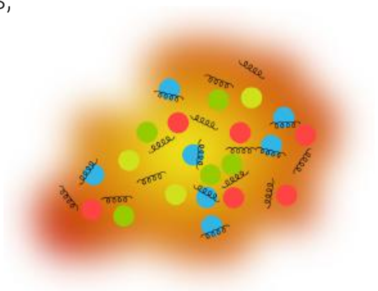


Quarks and gluons recombine into colorless hadrons and hit the detector.

Studying bulk properties of the QGP liquid

Equation of state?
Relations between
thermal quantities,
e.g. $P = P(\epsilon)$

How and under what
conditions is it formed
in a nuclear collision?



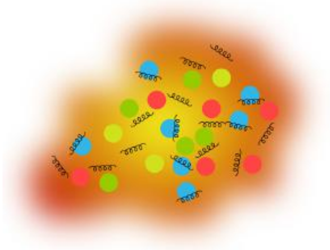
Transport properties?
shear/bulk viscosity,
probe energy loss, etc

How does it recombine
to form colorless hadrons?

Quark-gluon plasma is not directly detectable

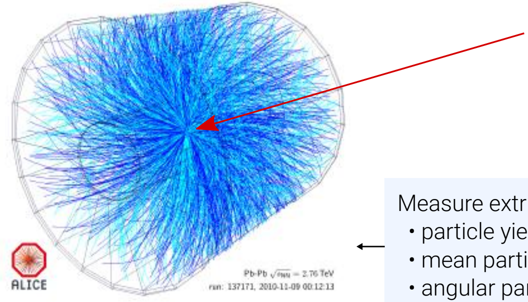
Study intrinsic QGP properties
- equation of state
- transition temperature
- viscosity

Quark-gluon plasma



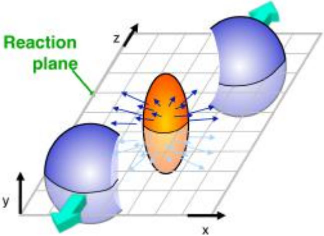
~ 10^{-14} m extent
~ 10^{-23} s lifetime

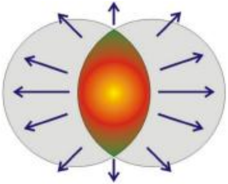
What the experiment sees...



Measure extrinsic final-state properties
- particle yields
- mean particle momenta
- angular particle correlations

Notable example: infer viscosity from flow anisotropy





Overlap region, compressed and heated

Elliptic flow (v_2):

- pressure gradients steeper along short axis of ellipse, drives asymmetric flow
- quantified by 2[nd] Fourier coeff. of angular dist: v_2
- Good agreement for small viscosity η/s

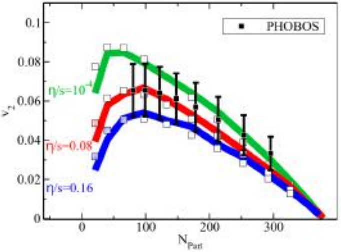


Fig. credit: Luzum, Romatschke

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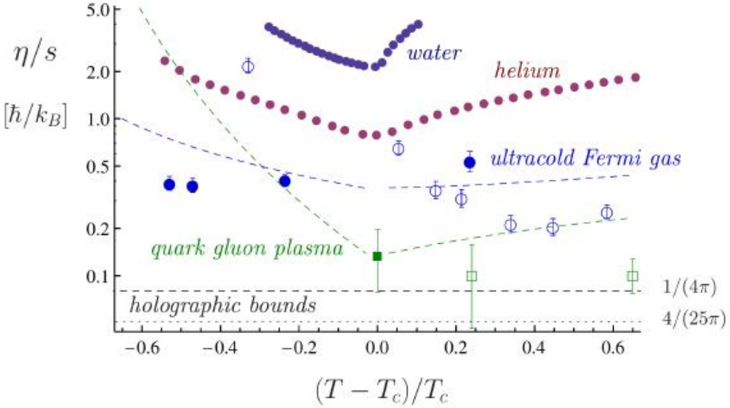


A. Adams, et. al. New Journal of Physics 14 (2012)

QGP believed to be most ideal fluid in nature!

Transport models connect experiment and theory

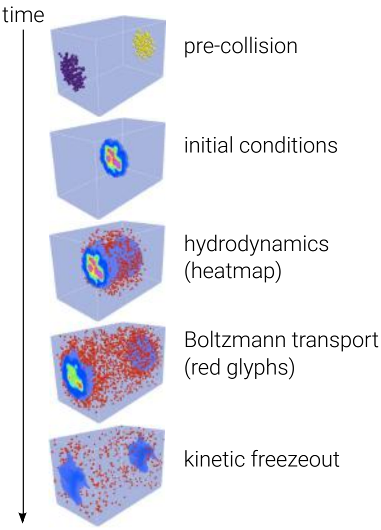


Figure credit Zhi Qiu

Initial conditions

Describe initial $T^{\mu\nu}$ at the QGP thermalization time

Hydrodynamics (QGP)

Hydrodynamics imposes energy and momentum conservation,

$$\partial_\mu T^{\mu\nu} = 0$$

Requires medium viscosity and equation of state from LQCD

Boltzmann Eqn (hadron gas)

Fluid discretized into particles at transition temperature.

Non-equillibrium Boltz. transport,

$$\frac{df_i(x,p)}{dt} = \mathcal{C}_i(x,p)$$

Model-to-data comparison: solving the inverse problem

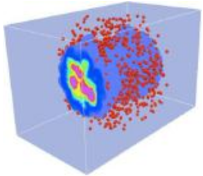
Theory

- QCD equation of state
- relativistic hydrodynamics
- hadronic cross sections

Procedure

given model with some unknown parameters $f(x_1, x_2, \ldots, x_n)$ optimize the parameters $x_1, x_2, \ldots, x_n$ to fit an observed data set $y_1, y_2, \ldots, y_m$

Model



Simulated observables

tune free model parameters

Data

Measured observables

extract new physics insight

Current practicum and thesis work

"What are you doing and why are you doing it."

–sponsors

1. Quantify sensitivity of hydrodynamic simulations to different calculations of the QCD equation of state (LLNL)

   Phys. Rev. C93 (2016) 044913

2. Improve theoretical description of the QGP initial conditions

   Nucl. Phys. A 904-905, 815c (2013)

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3. Rigorously constrain QGP medium properties using Bayesian model-to-data analysis

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Studying the QGP equation of state

Equation of state calculable from QCD Lagrangian $\mathcal{L}[A^a_\mu, \bar{\Psi}, \Psi]$

Vaccuum-to-vaccuum transition amplitude Z

$$Z = \int \mathcal{D}A^a_\mu(x)\mathcal{D}\bar{\Psi}(x)\mathcal{D}\Psi(x)e^{i\int d^4x\mathcal{L}[A^a_\mu,\bar{\Psi},\Psi]}$$

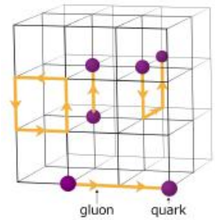
$t \to i\tau$

Partition function $\mathcal{Z} = \mathrm{tr}\,\hat{\rho}$, where $\hat{\rho} = e^{-\beta\hat{H}}$

$$\mathcal{Z} = \int \mathcal{D}A^a_\mu(\mathbf{x},\tau)\mathcal{D}\bar{\Psi}(\mathbf{x},\tau)\mathcal{D}\Psi(\mathbf{x},\tau)e^{-\int_0^\beta d\tau \int d^3x\mathcal{L}_E[A^a_\mu,\bar{\Psi},\Psi]}$$

Path integral is discretized and solved on a lattice $\rightarrow$

Partition function yields the QCD equation of state

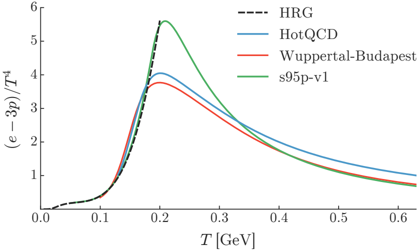


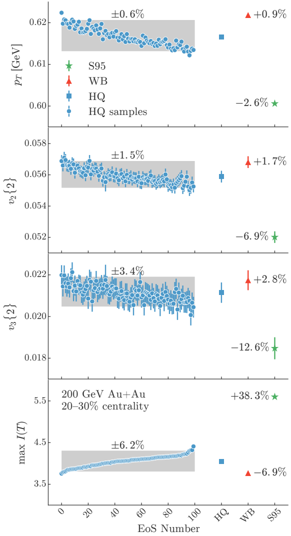
Lattice QCD equation of state error analysis

Quantify effect of different LQCD equation of state calculations on heavy-ion collision observables

JSM and RAS, Phys. Rev. C93, 044913 (2016)

- Three different LQCD EoS calc.
- Modern Monte Carlo hydro model
- Large scale simulation on open science grid





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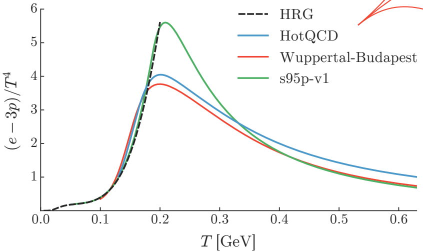

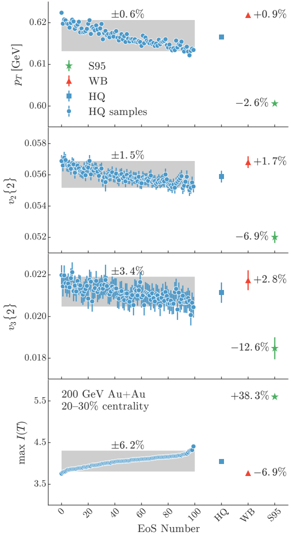

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What are the initial conditions?

Initial conditions: energy density and fluid velocity at $\tau = \tau_0$.

Initial energy density (3D)

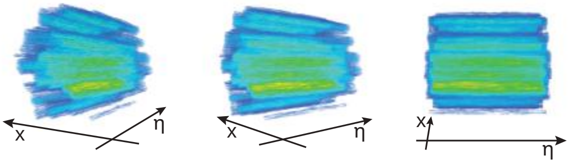
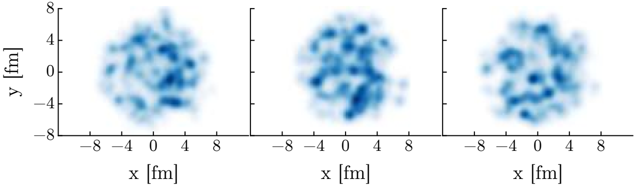


Figure credit: Schenke, Schlichting

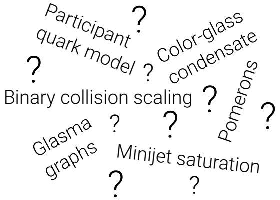
Common to project out beam dimension (η-coordinate)

Initial energy density (2D)



The initial condition problem

The QGP initial conditions are <u>not well understood.</u> Many models/theories proposed in the literature.



- QGP viscosity extracted by tuning simulation viscosity to fit elliptic flow data.
- *Different* initial condition models predict *different* flow behavior and hence prefer *different* QGP viscosity values!

Extracted QGP viscosity depends on theoretical initial conditions!

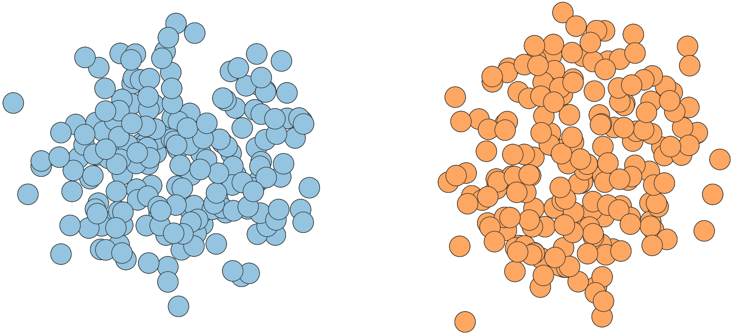
Estimates inherit large theory uncertainty!

Solution—data driven approach

Parametrize QGP initial conditions using flexible 'meta-model'.

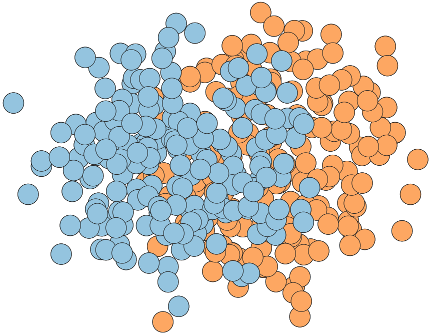
Apply rigorous statistical methods to simultaneously constrain initial condition and QGP medium parameters.

TRENTo: new parametric initial condition model



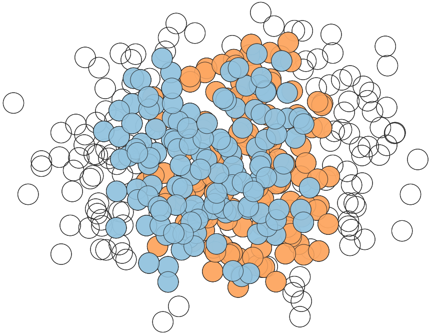
Sample positions of nucleons within colliding nuclei

TRENTo: new parametric initial condition model



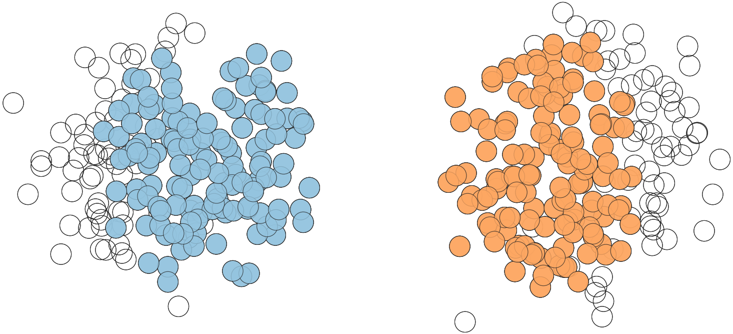
Nuclei collide at some random offset (impact parameter)

TRENTo: new parametric initial condition model



Determine nucleons which are struck in the collision

TRENTo: new parametric initial condition model



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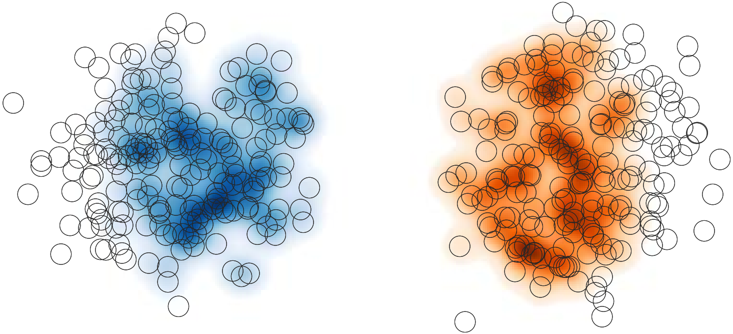
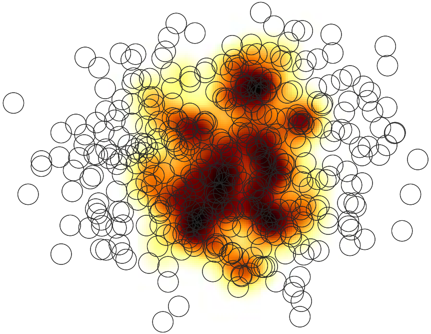


Construct participant density—superposition of struck nucleons

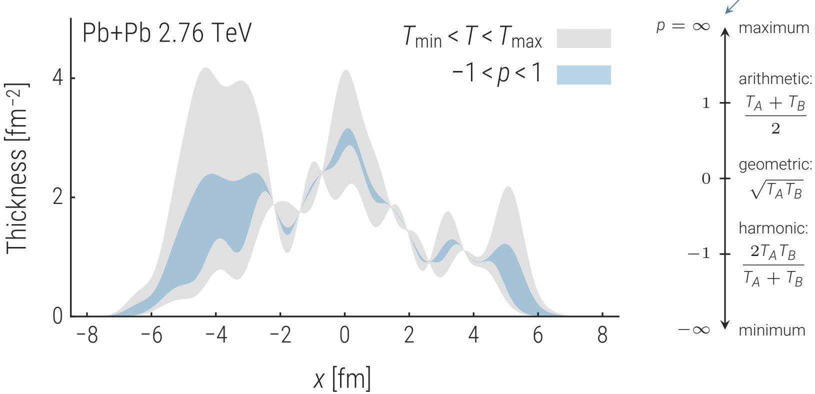
TRENTo: new parametric initial condition model



Convert local overlap density $\rightarrow$ entropy deposition
Mapping represents some scalar function of two arguments

Parametrizing local entropy deposition

Generalized mean ansatz: $$\frac{dS}{d^2r\,dy} \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$



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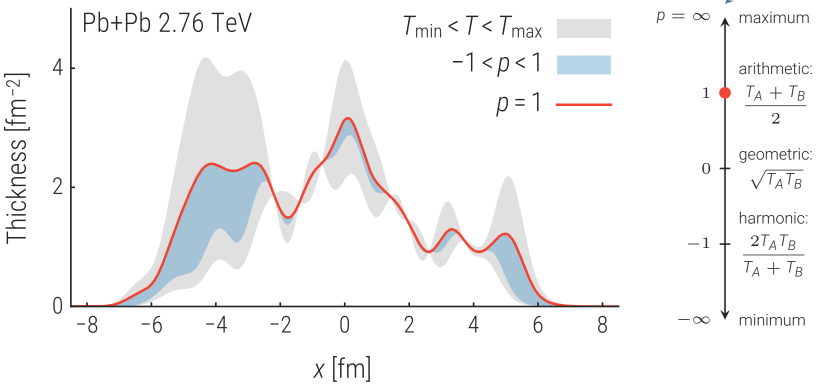

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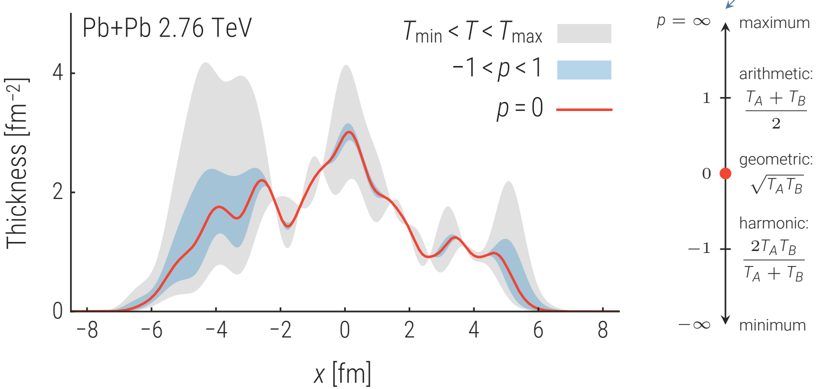

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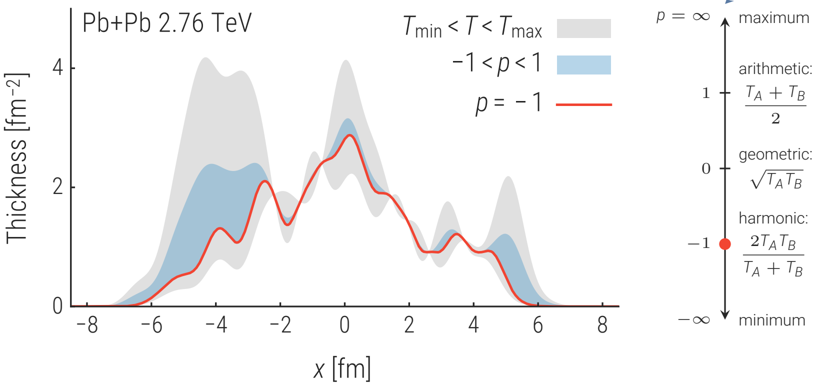
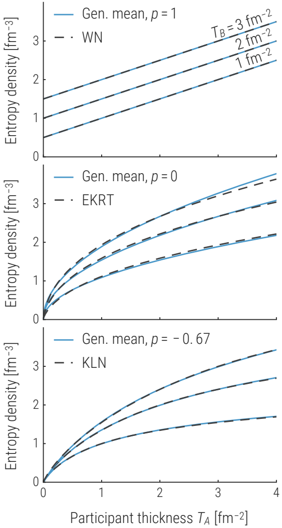


Compare parametrization to existing IC models



- Wounded nucleon model

$$\frac{dS}{dy\, d^2r_\perp} \propto T_A + T_B$$

* T denotes *participant* thickness

- EKRT model PRC 93, 024907 (2016)

after brief free streaming phase

$$\frac{dE_T}{dy\, d^2r_\perp} \sim \frac{K_\text{sat}}{\pi} p^3_\text{sat}(K_\text{sat}, \beta; T_A, T_B)$$

- KLN model PRC 75, 034905 (2007)

$$\frac{dN_g}{dy\, d^2r_\perp} \sim Q^2_{s,\text{min}} \left[2 + \log\left(\frac{Q^2_{s,\text{max}}}{Q^2_{s,\text{min}}}\right)\right]$$

Modern event-by-event hybrid model

- TRENTo initial conditions

  Moreland, Bernhard, Bass, PRC 92, no. 1, 011901 (2015)

norm	entropy normalization
p	entropy deposition parameter
k	proton-proton multiplicity fluctuations
w	Gaussian nucleon width

- HotQCD equation of state

  Bazavov, et. al. PRD 90, 094503 (2014)

- iEBE-VISHNU hydrodynamics

  Shen, Qiu, Song, Bernhard, Bass, Heinz, Comp. Phys. Comm. 199, 61 (2016)

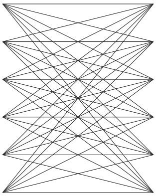
η/s min	shear viscosity minimum
η/s slope	shear viscosity slope
ζ/s norm	bulk viscosity normalization
T_{sw}	hydro-to-urqmd switching temp

- UrQMD hadronic afterburner

  Bass et. al, Prog. Part. Nucl. Phys. 41, 255 (1998)

The challenge of rigorous model-to-data comparison

Parameter	Observable
shear viscosity	identified yields
bulk viscosity	identified mean p_T
pre-equilibrium flow	flow cumulants
nucleon width	mode mixing observables
hadronization temp	event plane decorrelations
p+p fluctuations	HBT interferometry



Testing a single set of parameters requires $\mathcal{O}(10^4)$ hydro events

...and evaluating eight different parameters five times each requires $5^8 \times 10^4 \approx 10^9$ hydro events.

That's roughly 10^5 computer *years*!

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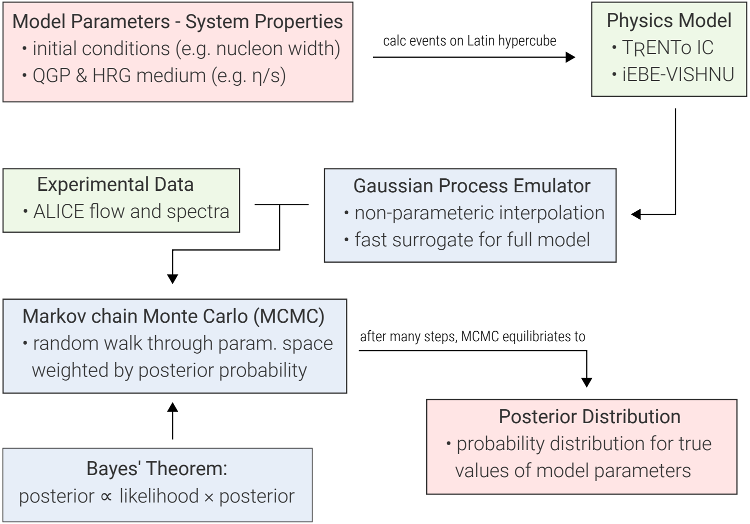
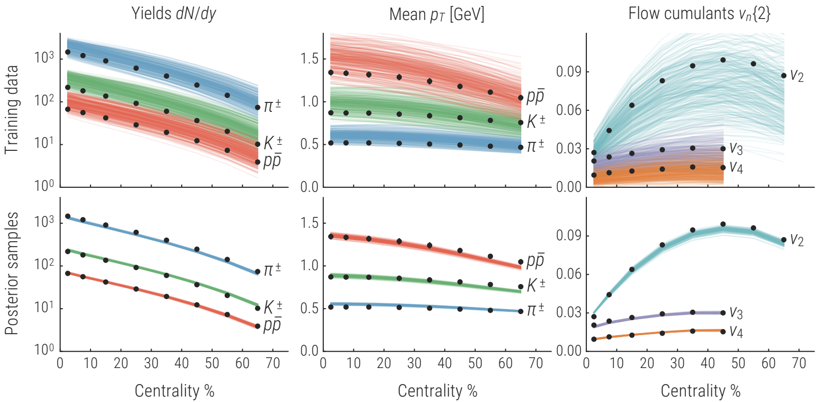
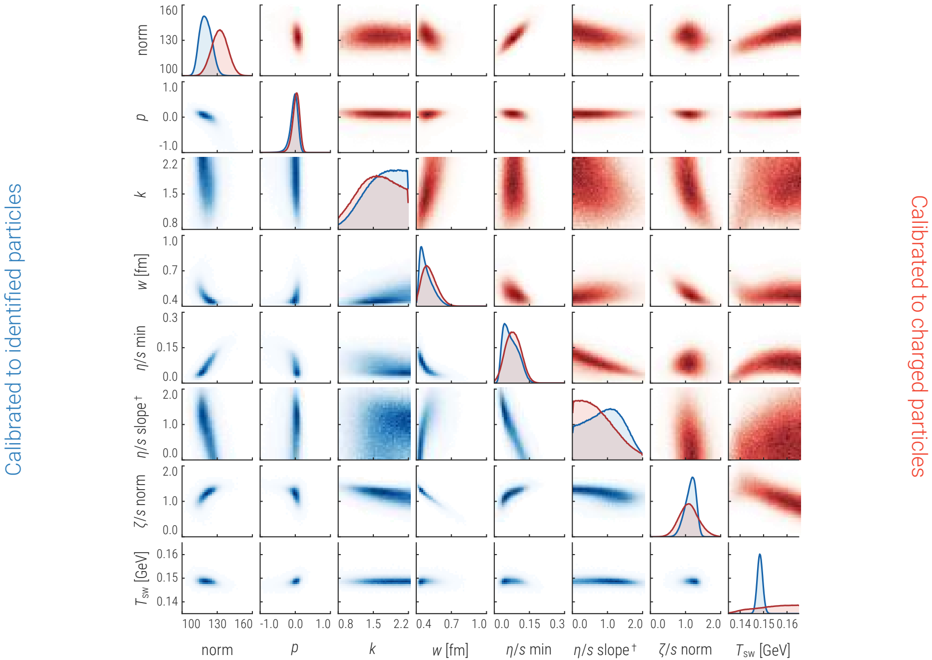
Solution: Bayesian methodology



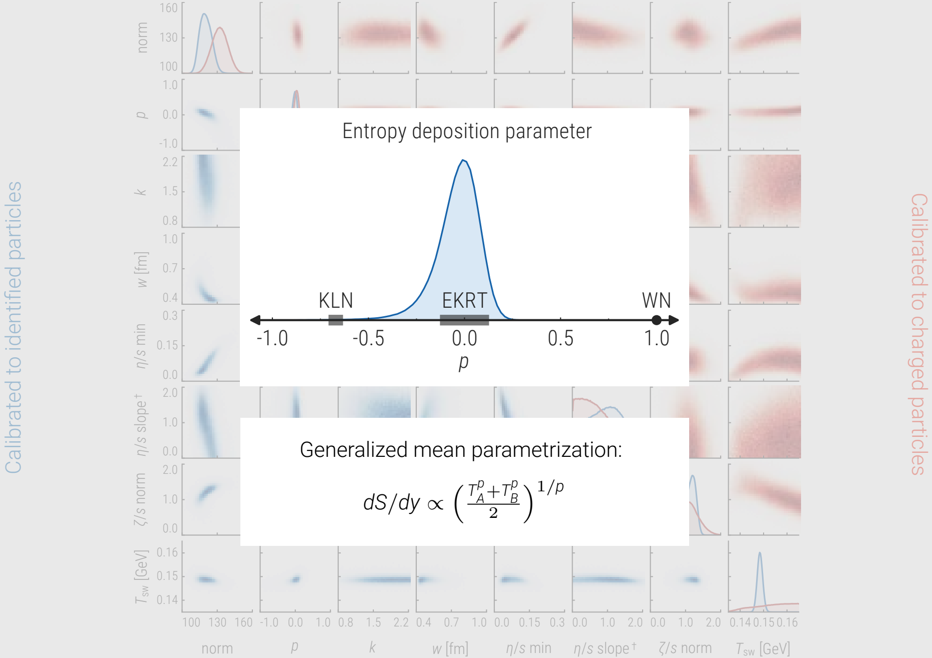
Calibrating the model: before and after



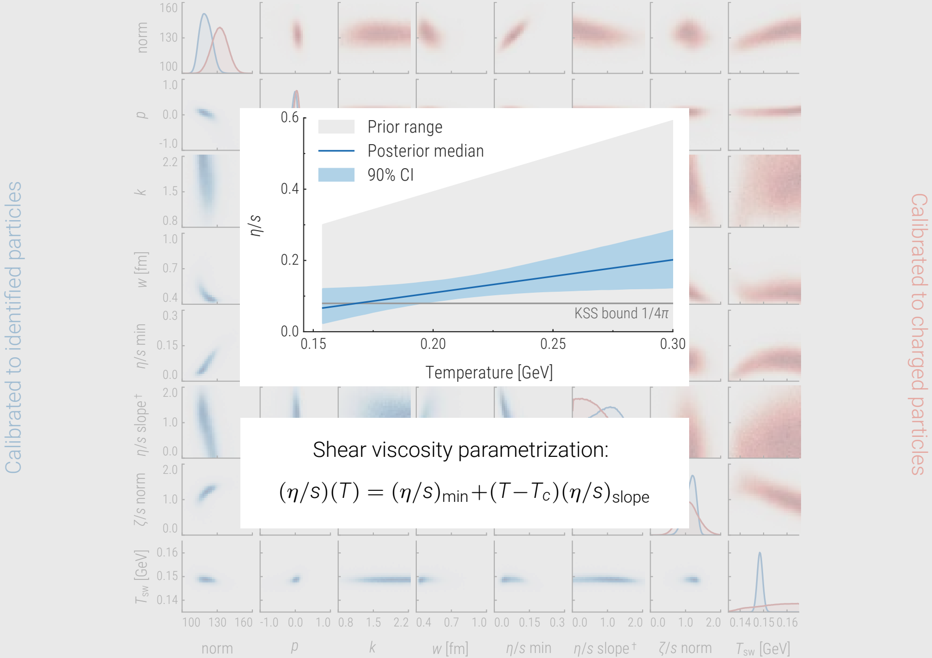
- Top: run model ($\times 10^4$ events) at each design point ($\times 300$ evals)
- Bottom: emulator predictions for 100 samples from the posterior



Calibrated to identified particles
Calibrated to charged particles
norm
p
k
w [fm]
η/s min
η/s slope†
ζ/s norm
T_sw [GeV]
100 130 160
-1.0 0.0 1.0
0.8 1.5 2.2
0.4 0.7 1.0
0.0 0.15 0.3
0.0 1.0 2.0
0.0 1.0 2.0
0.14 0.15 0.16



$$dS/dy \propto \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$



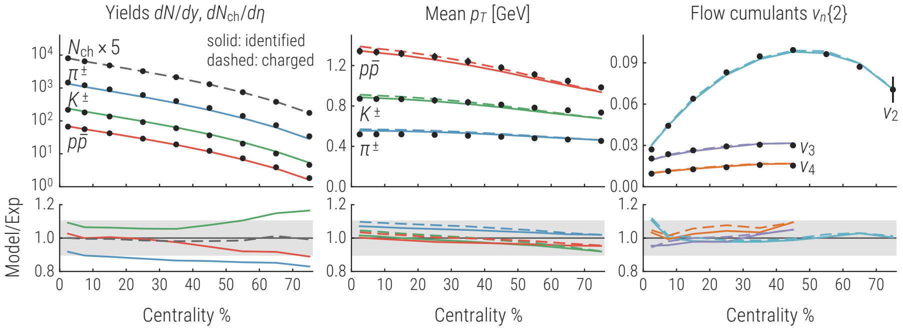
Shear viscosity parametrization:

$$(\eta/s)(T) = (\eta/s)_{\mathrm{min}} + (T - T_c)(\eta/s)_{\mathrm{slope}}$$

Running the model with high probability parameters

- Choose high probability model parameters from Bayesian posterior (right)
- Run full hybrid model using high probability parameters (bottom)

Initial condition		QGP medium	
norm	120.	η/s min	0.08
p	0.0	η/s slope	0.85 GeV^{-1}
k	1.5	ζ/s norm	1.25
w	0.43 fm	T_{sw}	0.148 GeV



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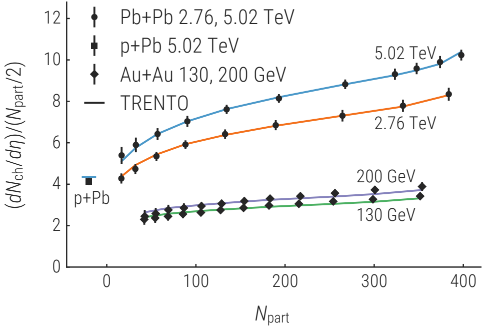

- Also describes particle production for different collision systems at multiple beam energies.

Conclusions

Lattice QCD equation of state (LLNL summer project)

- Modern LQCD equations of state in good agreement.
  Negligible differences for experimental observables.

Initial condition properties

- Yields, mean p_T and flows impose strong constraints on IC.
- Entropy deposition mimicked by $dS/dy \sim \sqrt{T_A T_B}$
- Preferred initial conditions agree with two theory calc.

Hydrodynamic transport properties

- First quantitative credibility interval on $(\eta/s)(T)$!

Special thanks to the Krell institute for the exceptional support!

Backup: computer experiment design

Maximin Latin hypercube

- Random, space-filling points
- *Maximizes* the *minimum* distance between points
  $\rightarrow$ avoids gaps and clusters
- Uniform projections into lower dimensions

This work:

- 300 points across 8 dimensions
- 8 centrality bins
- $\mathcal{O}(10^7)$ events total