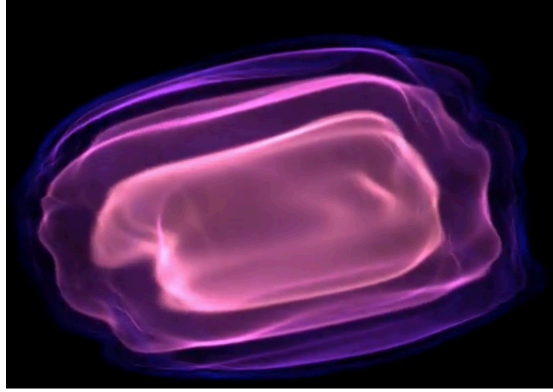
Topical Group on Hadronic Physics
GHP



Studying the Properties of the Quark-Gluon Plasma with Small and Large Systems in a Bayesian Analysis Framework

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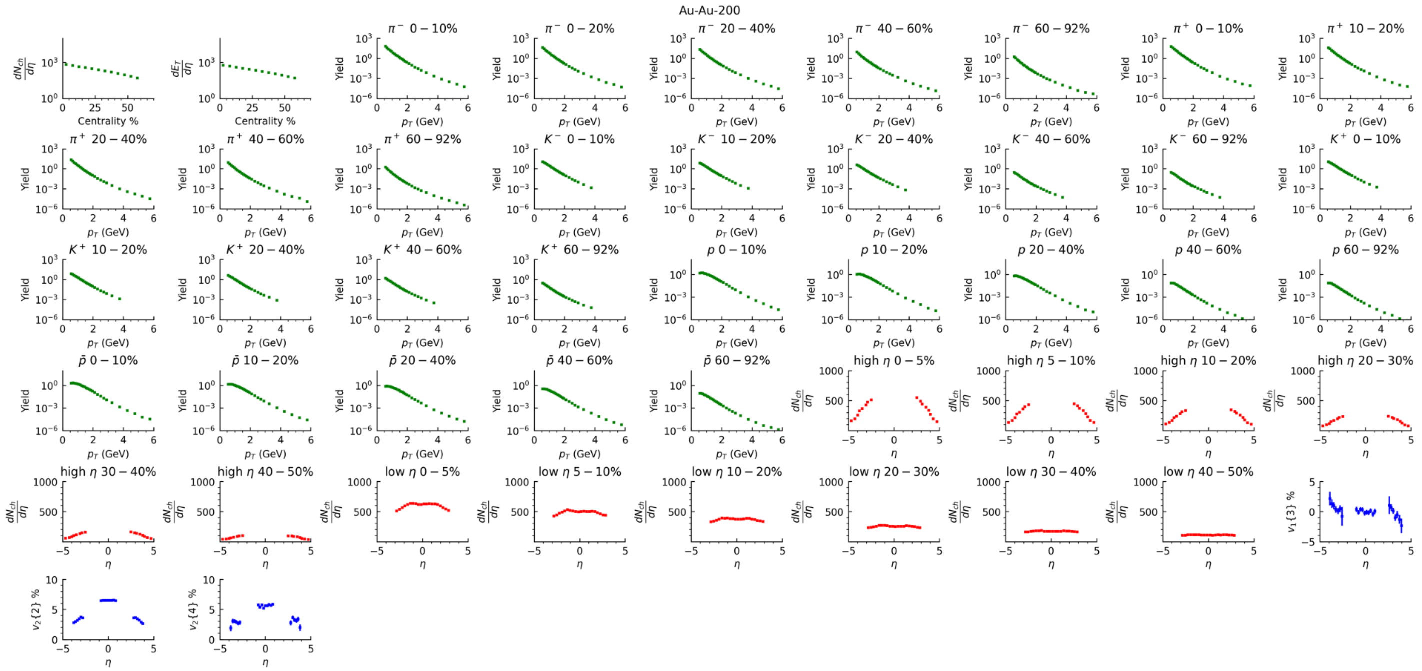
GORDON AND BETTY MOORE FOUNDATION

Quark-Gluon Plasma in Theory and Experiment

- The quark-gluon plasma (QGP) is a strongly-coupled relativistic fluid of deconfined quarks and gluons

- Bulk measurements in colliders: particle average momenta, multiplicities, azimuthal anisotropies, etc



- QGP in “small systems”

- Modeling paradigm: Pre-Hydro → Hydrodynamic Evolution → Post-Hydro

  - Hydro is the central theme of the theoretical modeling of the QGP medium

Constraining QGP Models: Bayesian Analyses

- Using wealth of collider data to learn about physics of QGP evolution
- Fluid properties and properties of the "initial state"
  - Viscosities, nucleon width, sub nucleonic-structure, etc
- Bayes' Theorem

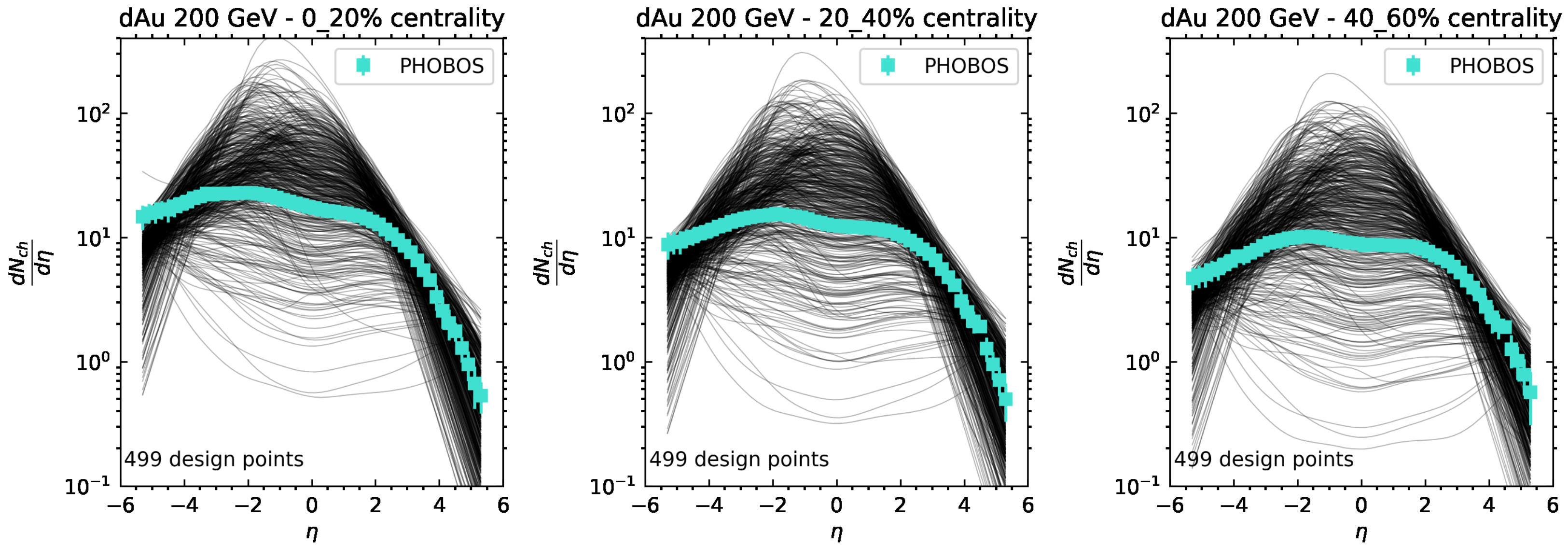
Likelihood function for the parameters given the data

$$P(\vec{\theta}\,|\,\vec{x}) \propto P(\vec{x}\,|\,\vec{\theta})P(\vec{\theta})$$

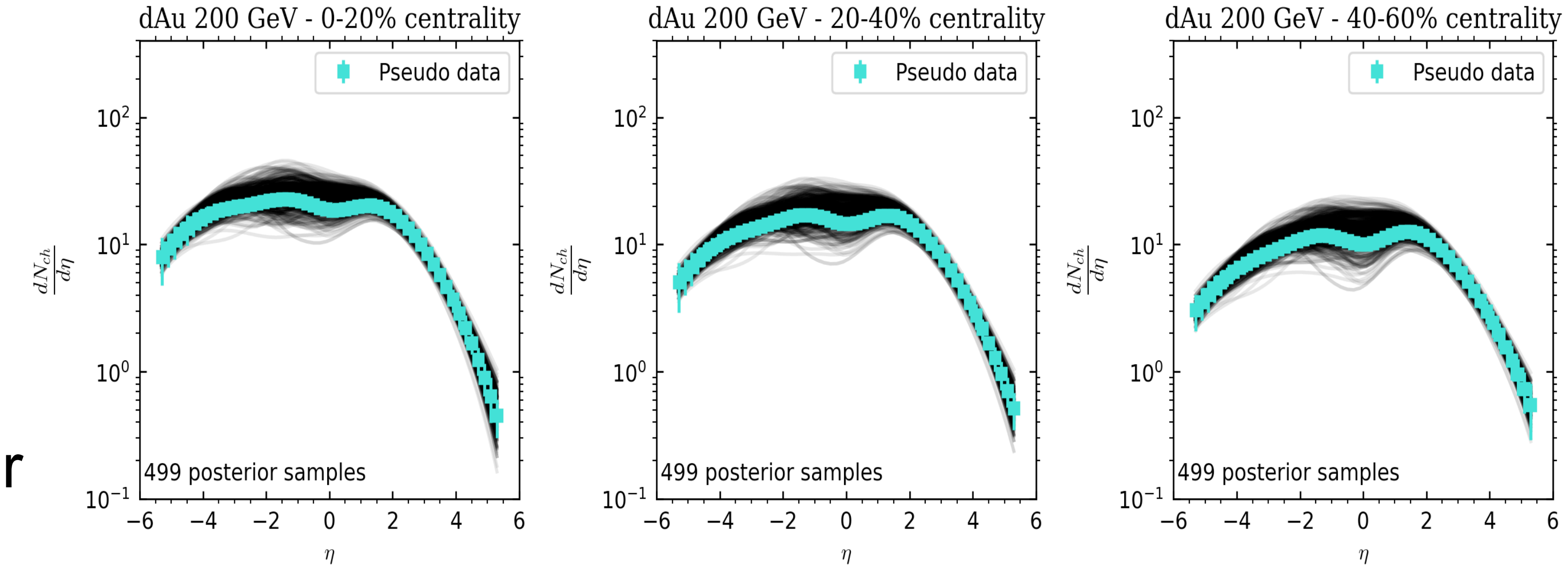
Posterior

Parameter prior

Observable Prior



Observable Posterior



The Status of Bayesian Analyses of Bulk Medium

- Successive Bayesian Analyses in 2D with boost invariant hydrodynamics

PHYSICAL REVIEW C **103**, 054904 (2021)

Multisystem Bayesian constraints on the transport coefficients of QCD matter

D. Everett,[1] W. Ke,[2,3] J.-F. Paquet,[4] G. Vujanovic,[5] S. A. Bass,[4] L. Du,[1] C. Gale,[6] M. Heffernan,[6] U. Heinz,[1] D. Liyanage,[1]

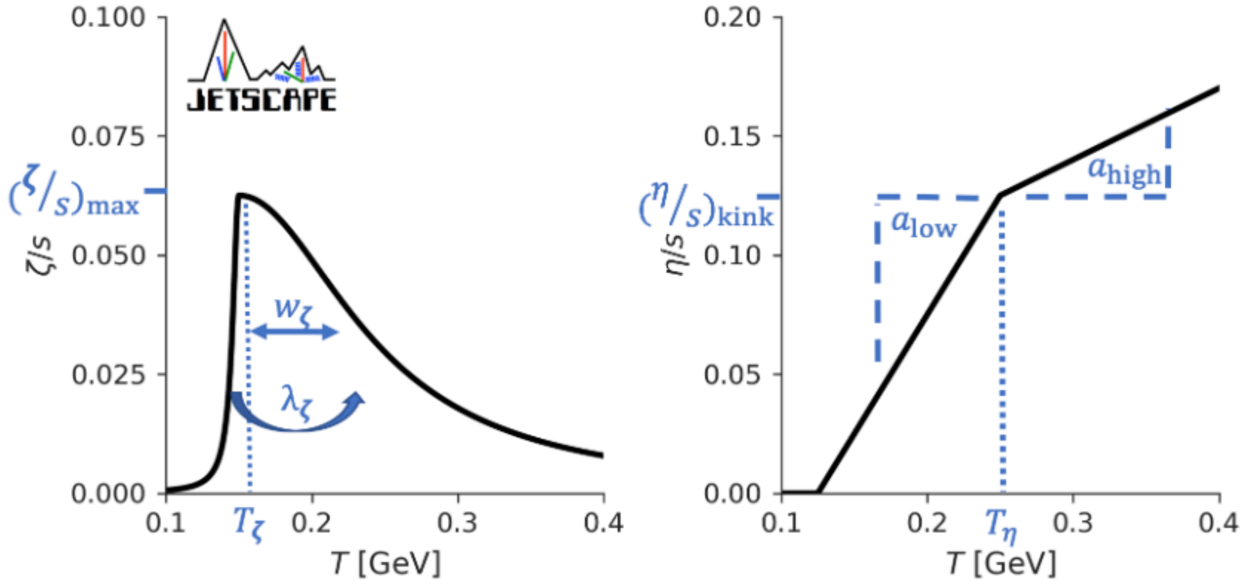
PHYSICAL REVIEW LETTERS **126**, 202301 (2021)

Transverse Momentum Differential Global Analysis of Heavy-Ion Collisions

Govert Nijs,[1,2,*] Wilke van der Schee,[3,†] Umut Gürsoy,[2,‡] and Raimond Snellings[4,5,§]

- Boost invariance:
  - Assume uniform hydro profile along the longitudinal direction
  - Not valid in small systems, RHIC energies

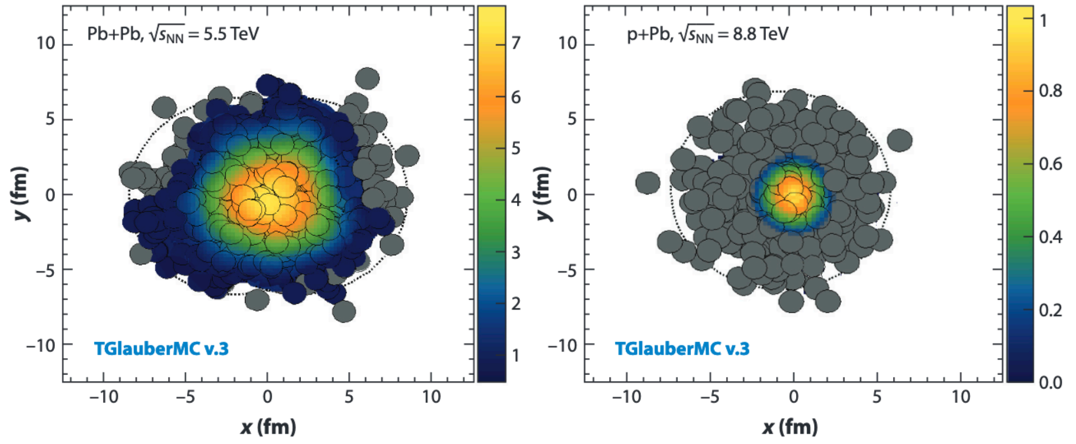
Viscosity parametrization:



The Model: 3D Initial State and Hydrodynamics

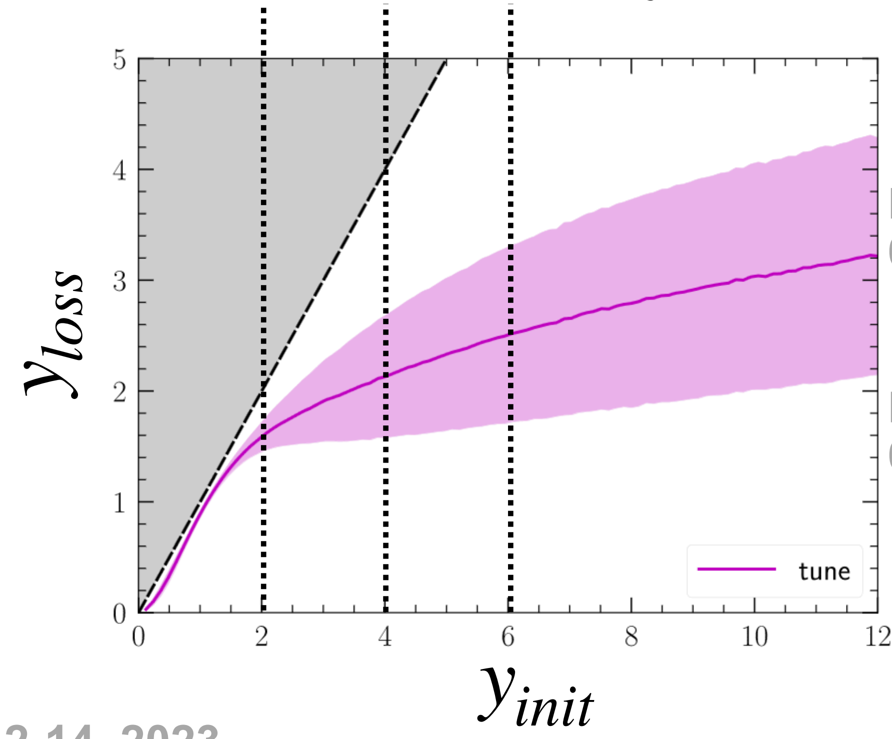
- 3D Monte Carlo Glauber Model
  - Valence quark hot spots
  - Energy deposited along the deceleration string connecting two colliding participants
  - Collision-by-collision fluctuating rapidity loss
- (3+1)D Viscous Hydrodynamics
  - Shear and bulk viscosities parametrized as in previous analyses
- Hadronic scatterings and decays after particlization

2D Glauber density profiles



Ann. Rev. Nucl. Part. Sci. 57 (2007)

Parametrization of rapidity loss function



Phys. Rev. C 105, 064905 (2022)

Phys. Rev. C 97, 024907 (2018)

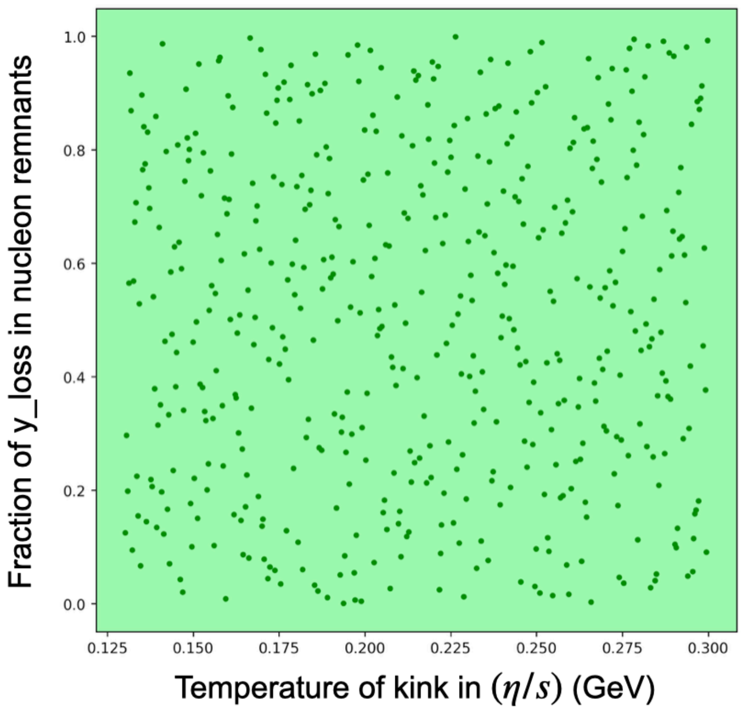
Model Calculations and the Analysis

- Ran simulations across multiple HPC centers

- Trained a Gaussian process emulator on 375 design points in parameter space using two types of observables
  - $dN_{ch}/d\eta$ and v_2 as a function of η
  - Each design point observable averaged over ~2k minimum bias events
  - 20 total parameters
- Data from both Au+Au and d+Au measurements at $\sqrt{s_{NN}}$= 200 GeV

- Markov chain Monte Carlo (MCMC) to guide the emulator through sampling the posterior and calculate the likelihood

Sample 2D parameter space (500 design points)



Multivariate-normal distribution used as likelihood function

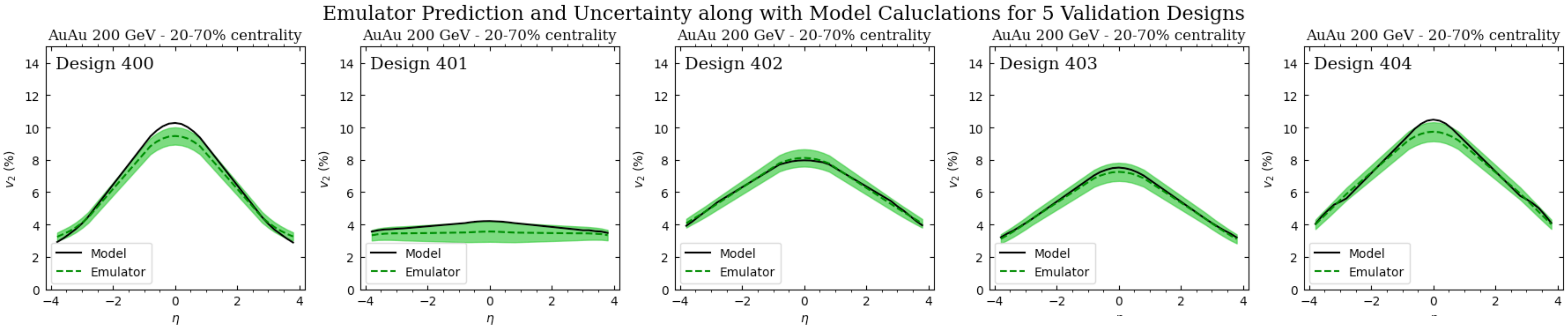
Covariance matrix of uncertainties

$$P(Y_{exp}|\theta) = \frac{1}{\sqrt{2\pi|[\Sigma_{exp}+\Sigma_{sim}(\theta)]|}} \exp\left(-[Y_{exp}-Y_{sim}(\theta)]^T[\Sigma_{exp}+\Sigma_{sim}(\theta)]^{-1}[Y_{exp}-Y_{sim}(\theta)]\right)$$

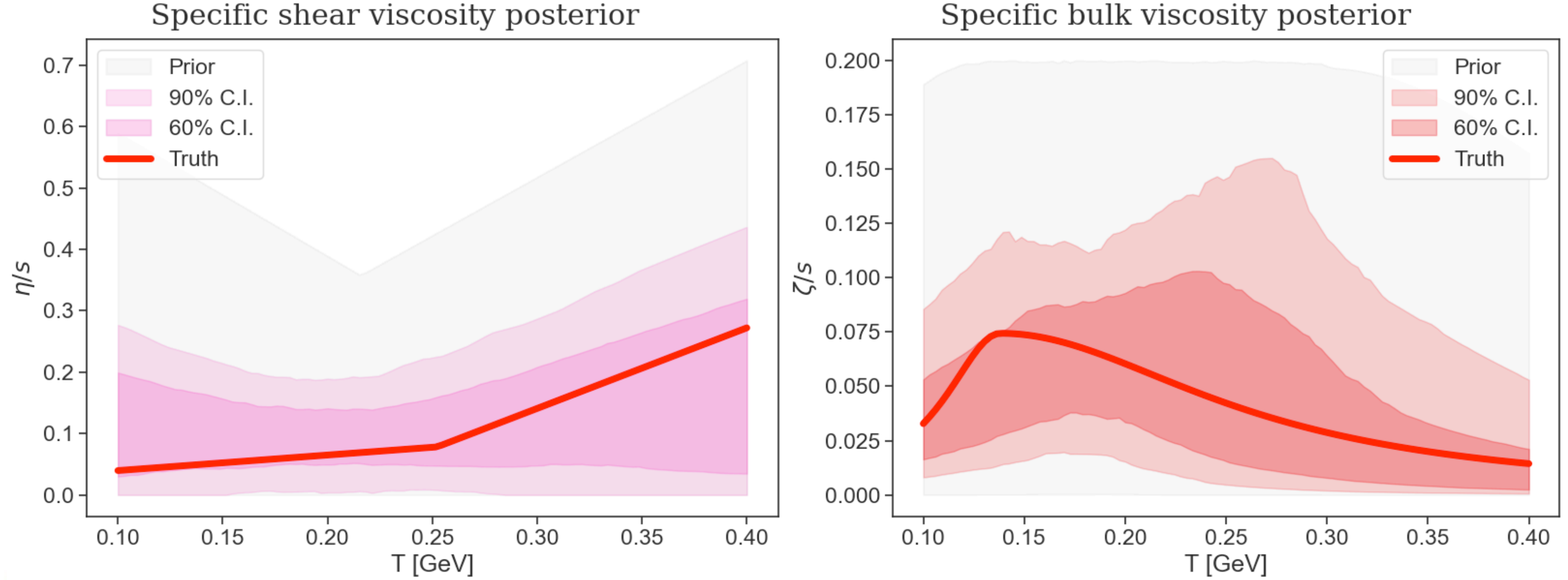
Difference between prediction and data

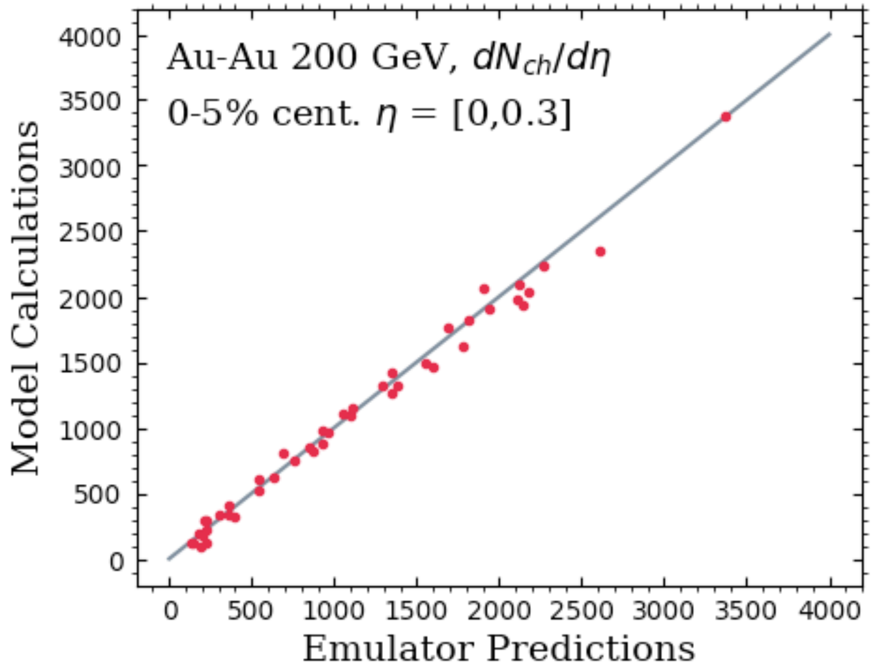
Emulating the Model and Validating the Analysis

- Gaussian Process Emulator: Fast surrogate for slow model



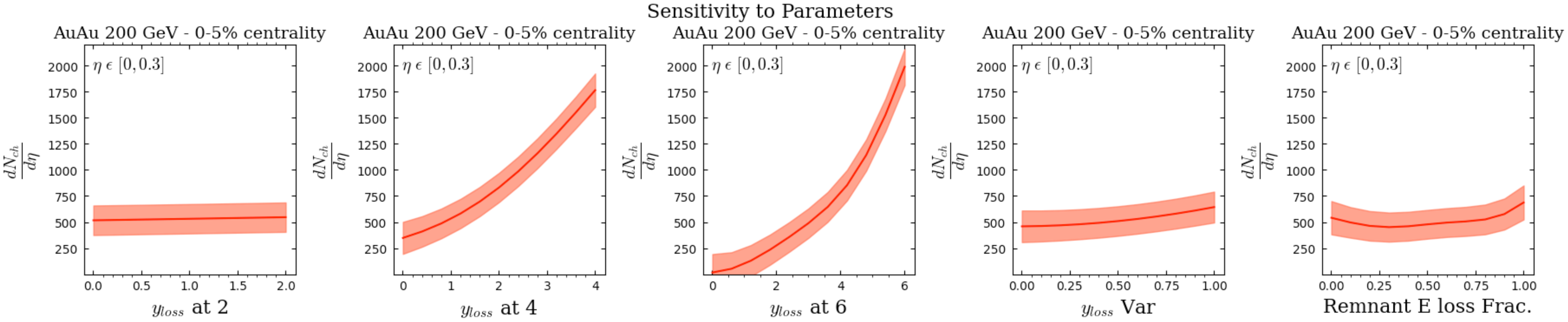
Closure test with the viscosity parameters



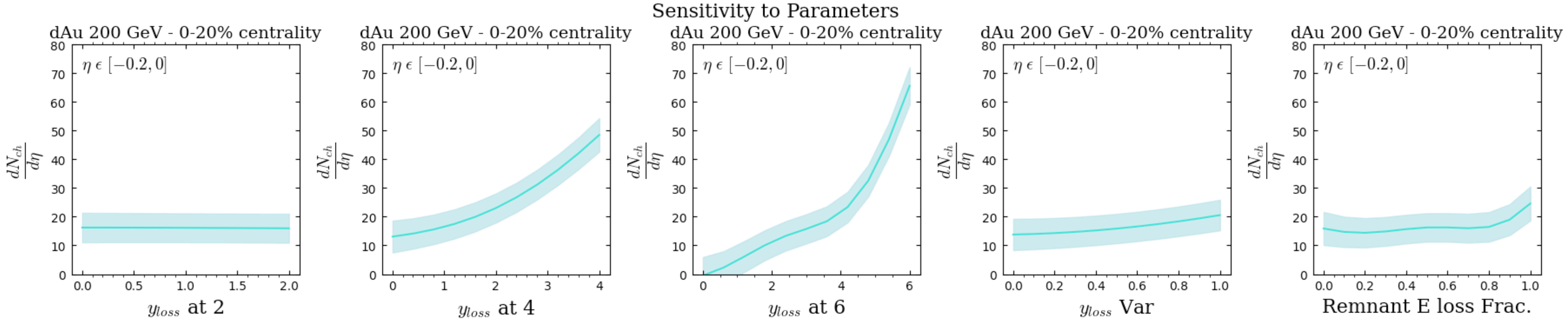


Sensitivity of Multiplicity to Model Parameters

Sensitivity of $dN_{ch}/d\eta$ to the initial state parameters in AuAu

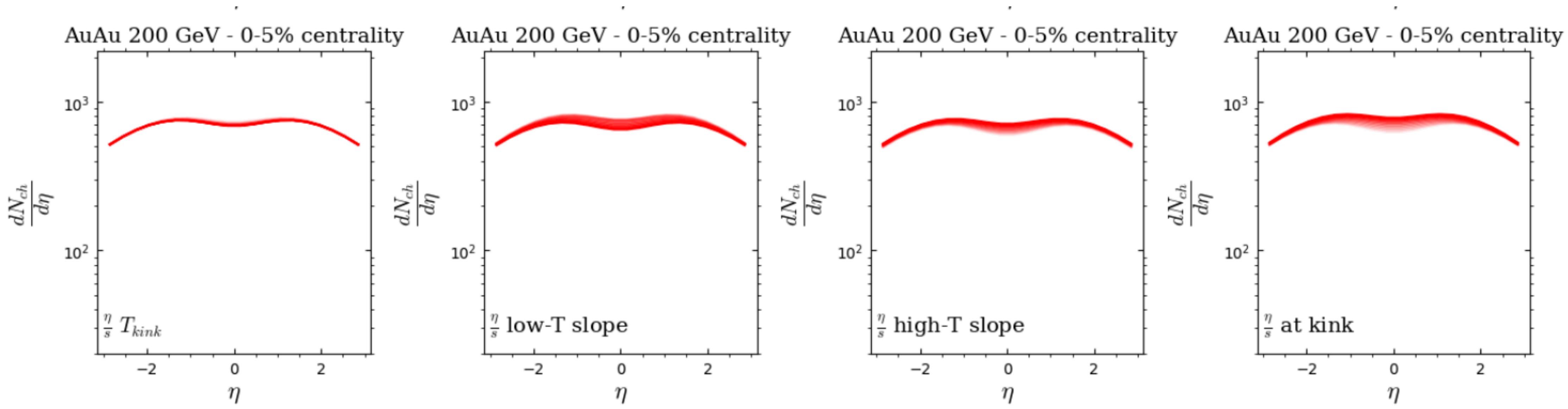


Sensitivity of $dN_{ch}/d\eta$ to the initial state parameters in dAu

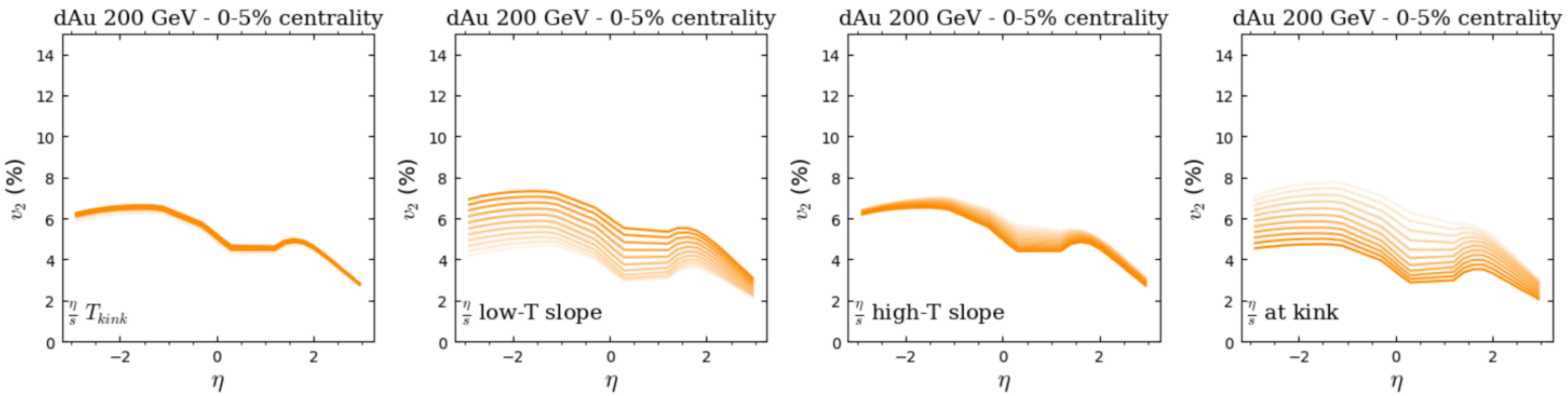


Sensitivity of Observables to Shear Viscosity Parameters

Sensitivity of $dN_{ch}/d\eta$ to shear viscosity parameters in AuAu

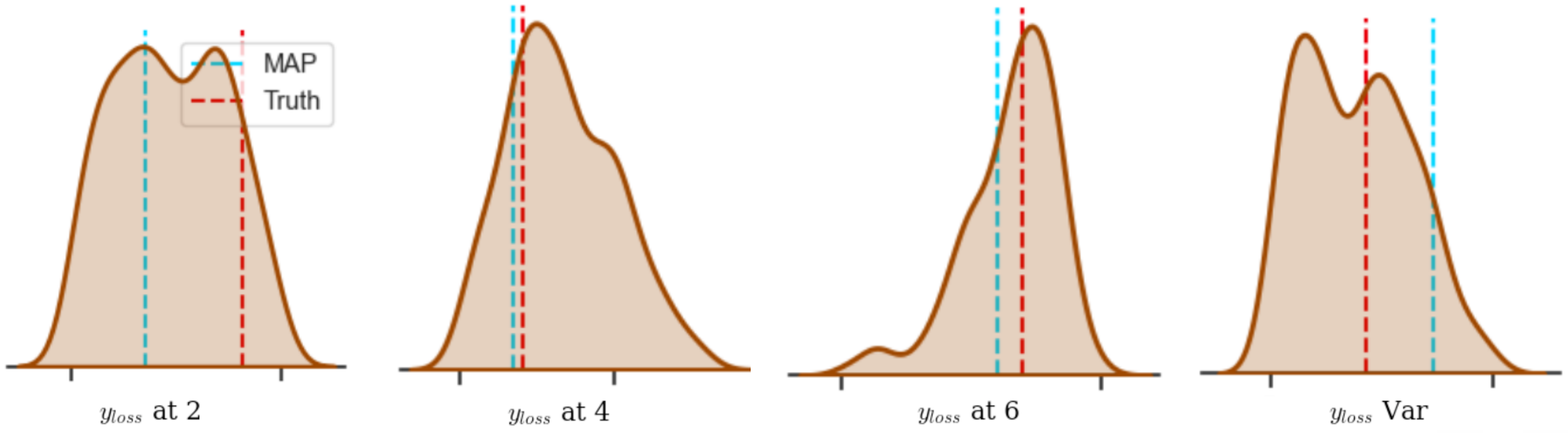


Sensitivity of v_2 to shear viscosity parameters in dAu

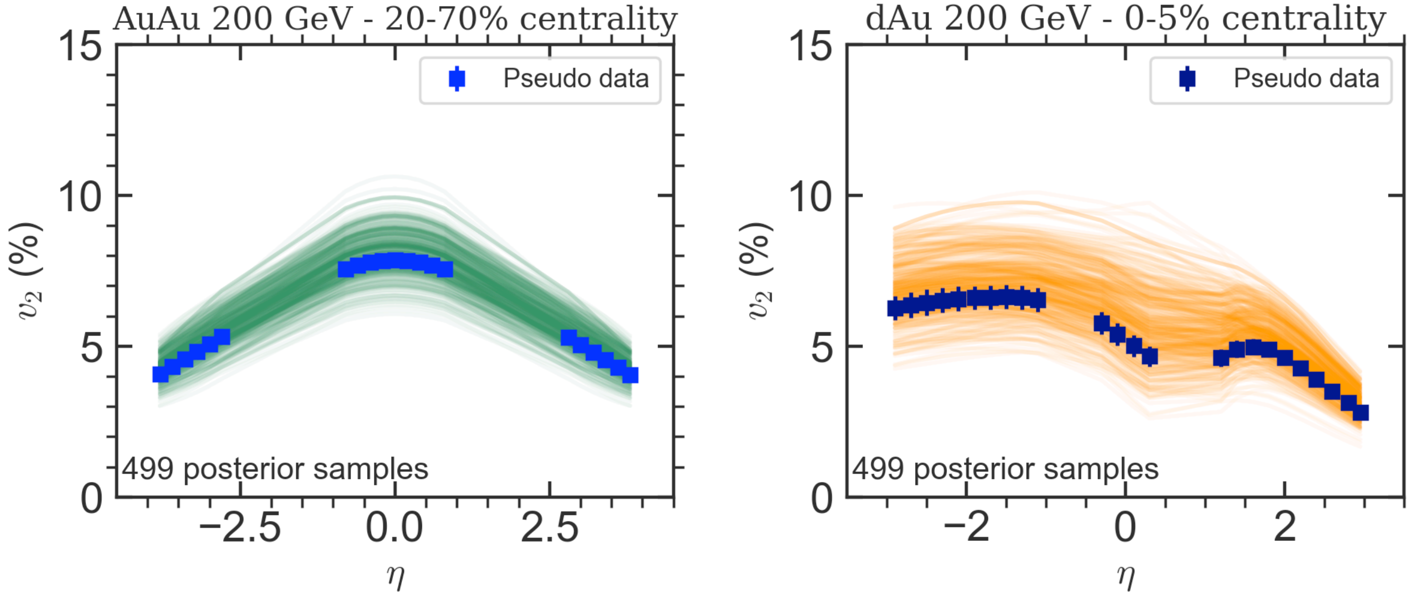


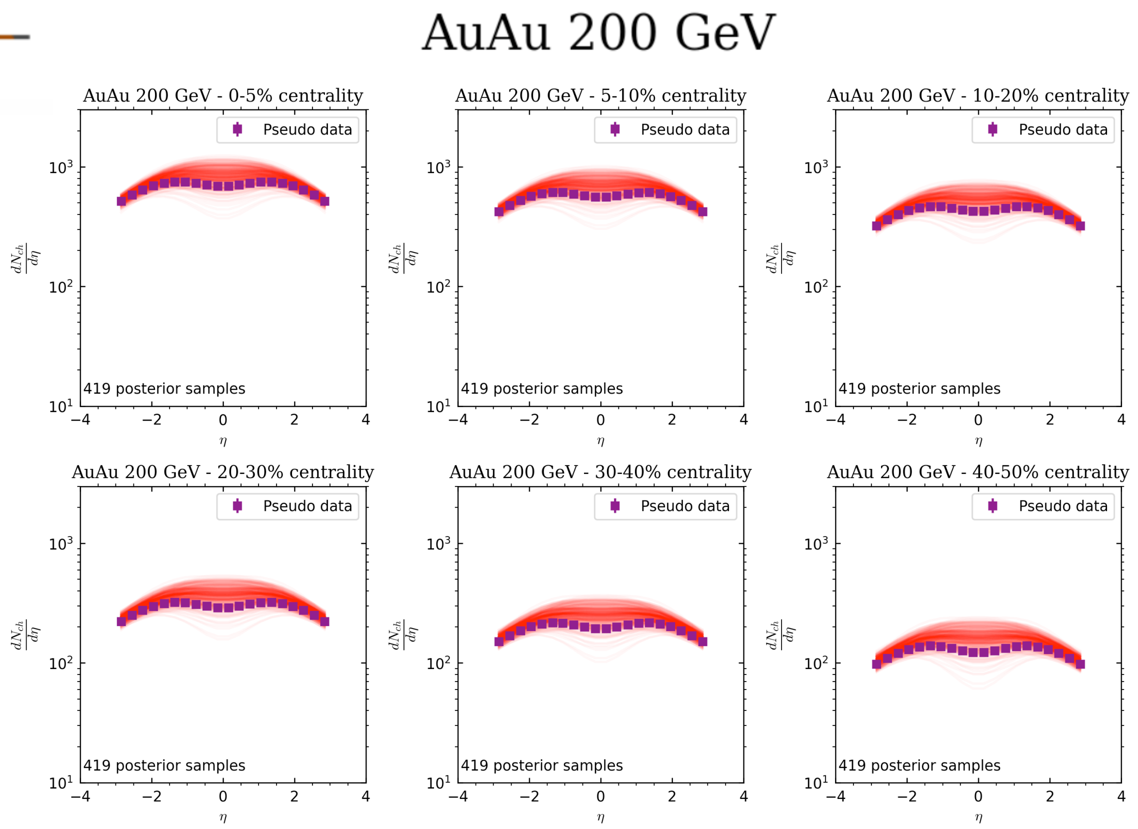
Posterior Distributions

- Updated parameter distributions for MCGlauber



- Observable posterior sampling





Conclusions and More to Come

- Multiplicity and v_2 pseudo-rapidity distributions can successfully constrain a 3D initial state model and hydrodynamics simultaneously

- Better constraints by including more observables in the calibration (extend to higher flow harmonics, mean p_T, identified particle data)

- Explore longitudinal dynamics using the posteriors
  - Pre- and post-dictions of observables using high statistics samples of the posterior distribution

THANK YOU!

Acknowledgements

I would like to thank Chun Shen for providing the event generation framework and Derek Soeder for helping run model simulations. I also thank Dan Liyanage, Weiyao Ke, and Derek Everett for making available well documented bayesian analysis codes as well as J.-F. Paquet and Julia Velkovska for helpful discussions.

Computational resources of the JETSCAPE collaboration were used for the simulations and were provided by the Anvil and Stampede2 clusters through XSEDE.

I also acknowledge generous support from The Gordon and Betty Moore Foundation and the American Physical Society to present this work at the GHP 2023 workshop.

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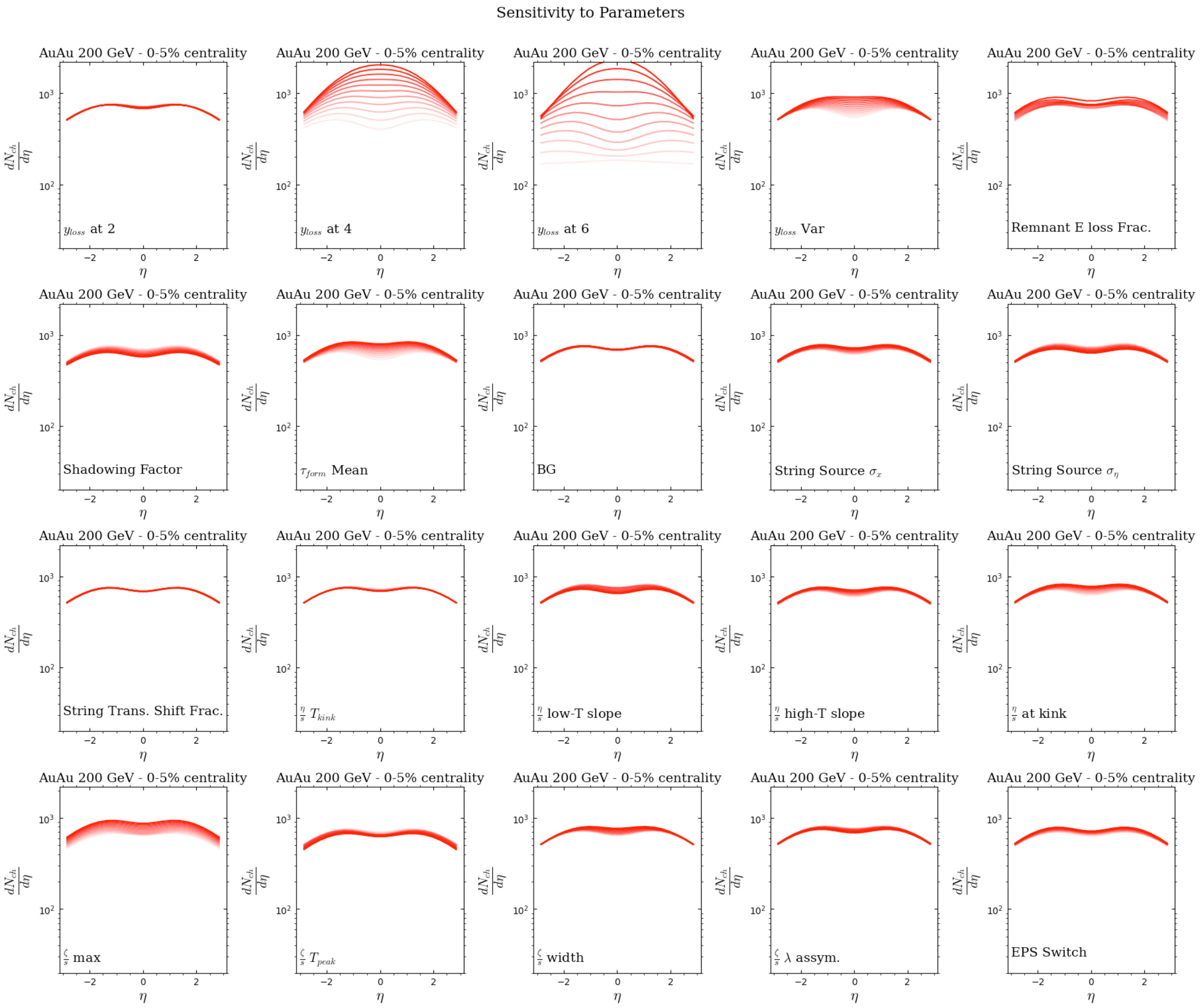
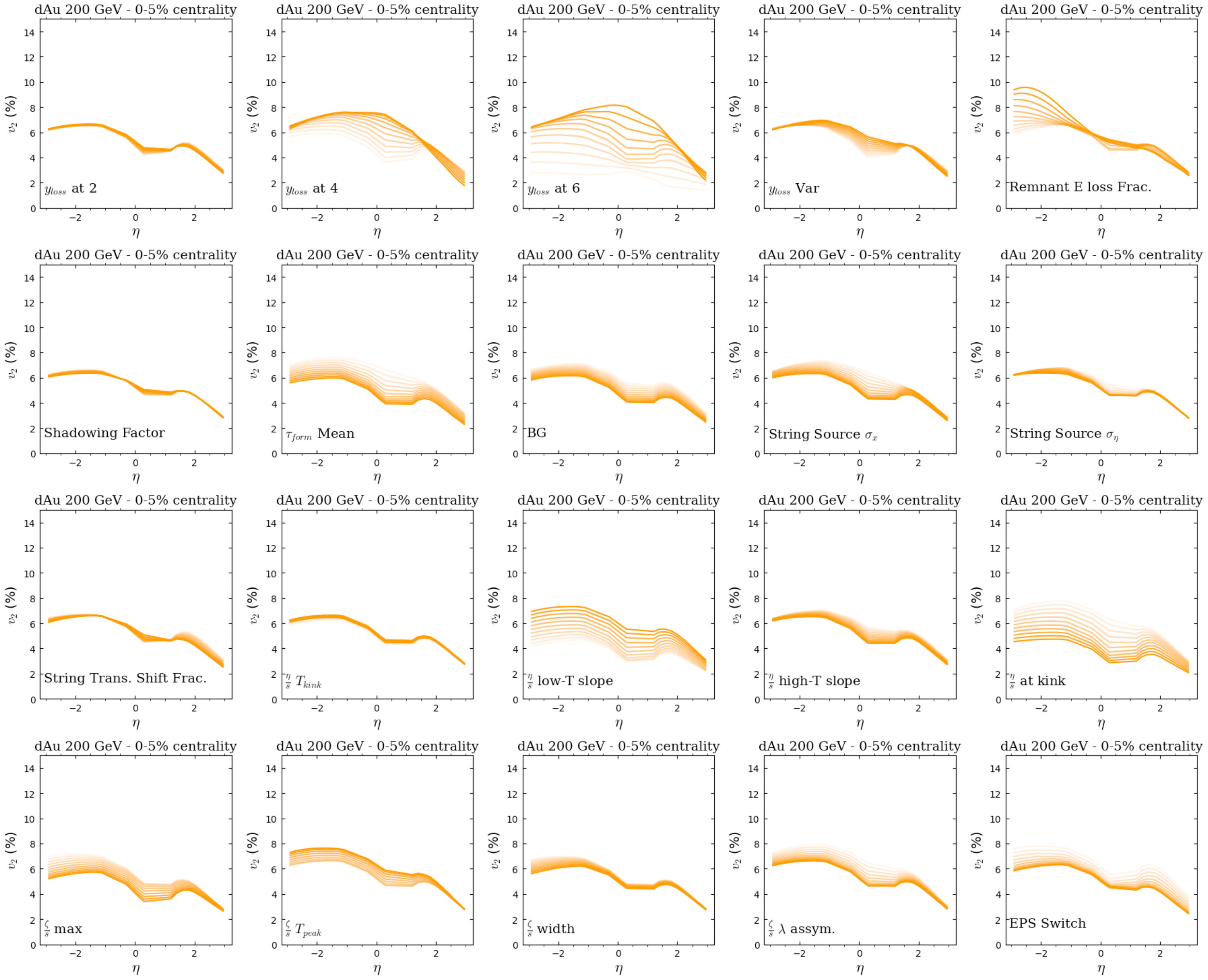
Backup


Sensitivity to Parameters
AuAu 200 GeV - 0-5% centrality
$\frac{dN_{ch}}{d\eta}$
η
y_{loss} at 2
y_{loss} at 4
y_{loss} at 6
y_{loss} Var
Remnant E loss Frac.
Shadowing Factor
τ_{form} Mean
BG
String Source σ_x
String Source σ_η
String Trans. Shift Frac.
$\frac{\eta}{s}$ T_{kink}
$\frac{\eta}{s}$ low-T slope
$\frac{\eta}{s}$ high-T slope
$\frac{\eta}{s}$ at kink
$\frac{\zeta}{s}$ max
$\frac{\zeta}{s}$ T_{peak}
$\frac{\zeta}{s}$ width
$\frac{\zeta}{s}$ λ assym.
EPS Switch

Backup

Sensitivity to Parameters



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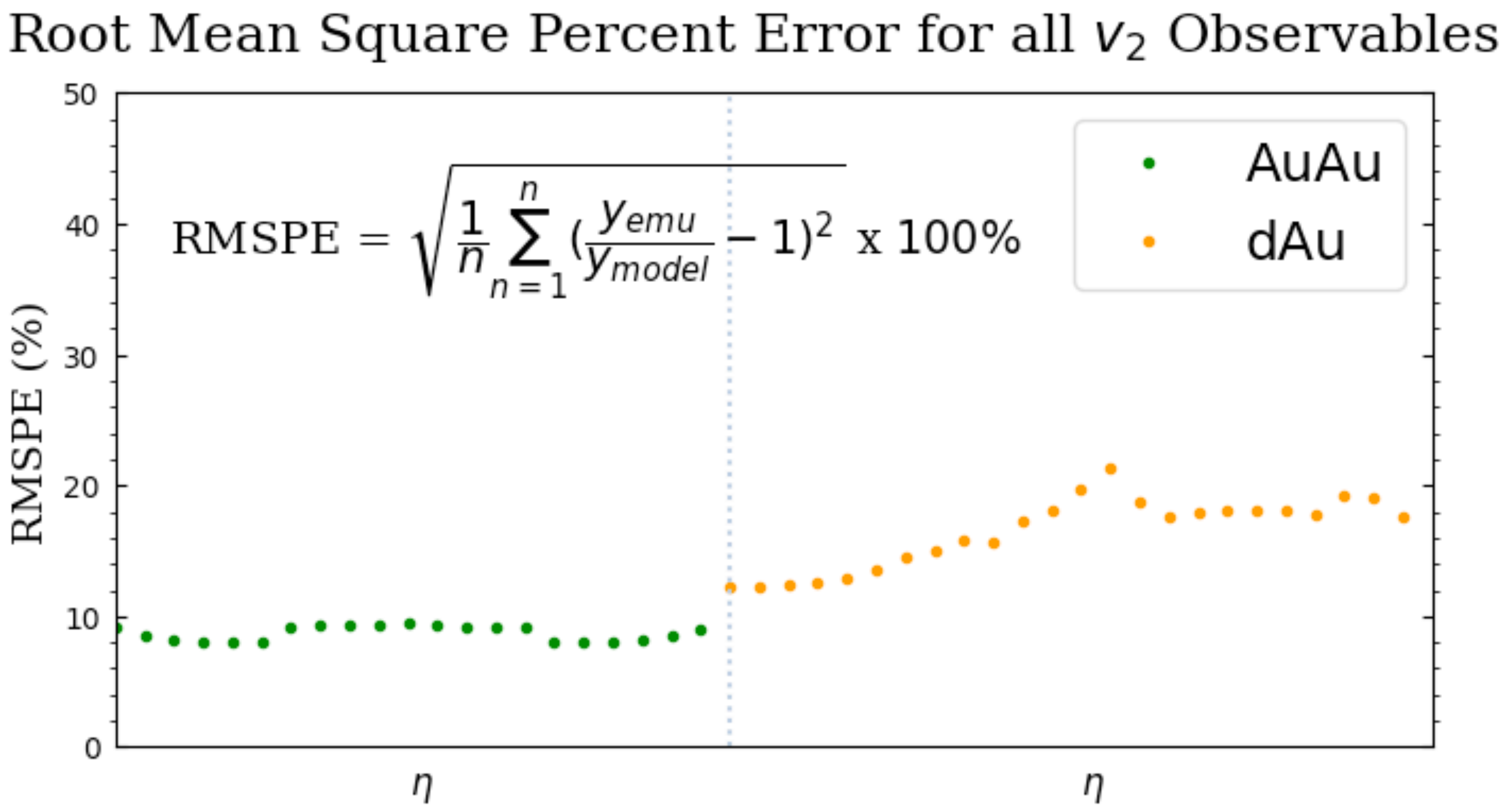
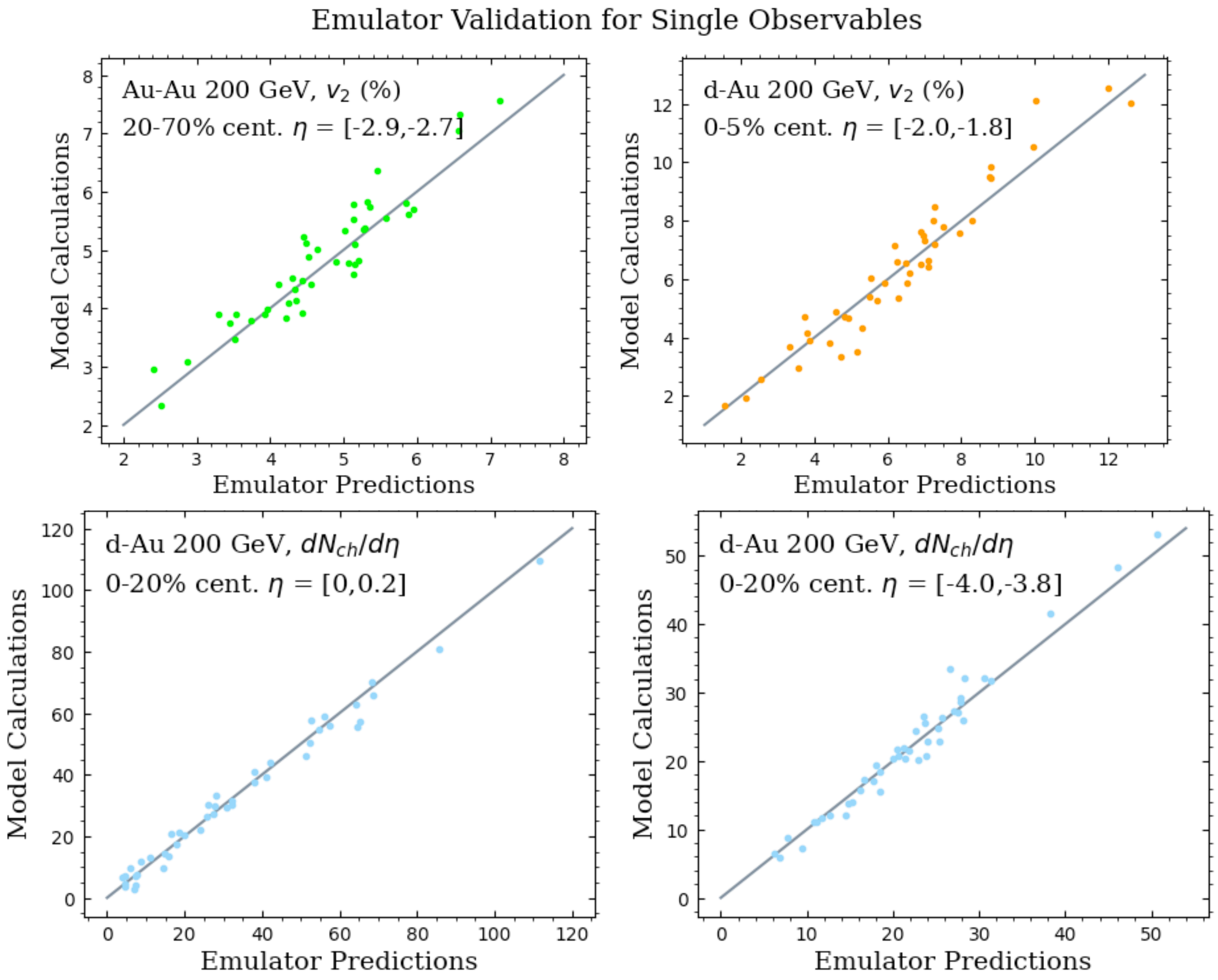

Root Mean Square Percent Error for all v_2 Observables
RMSPE $= \sqrt{\frac{1}{n}\sum_{n=1}^{n}(\frac{y_{emu}}{y_{model}} - 1)^2}$ x 100%
AuAu
dAu
RMSPE (%)
50
40
30
20
10
0
η
η

Backup


Emulator Validation for Single Observables
Au-Au 200 GeV, v_2 (%)
20-70% cent. η = [-2.9,-2.7]
d-Au 200 GeV, v_2 (%)
0-5% cent. η = [-2.0,-1.8]
d-Au 200 GeV, $dN_{ch}/d\eta$
0-20% cent. η = [0,0.2]
d-Au 200 GeV, $dN_{ch}/d\eta$
0-20% cent. η = [-4.0,-3.8]
Model Calculations
Emulator Predictions