X-SCAPE

Calibrated (3+1)D hydrodynamic medium for ultrarelativistic collision physics

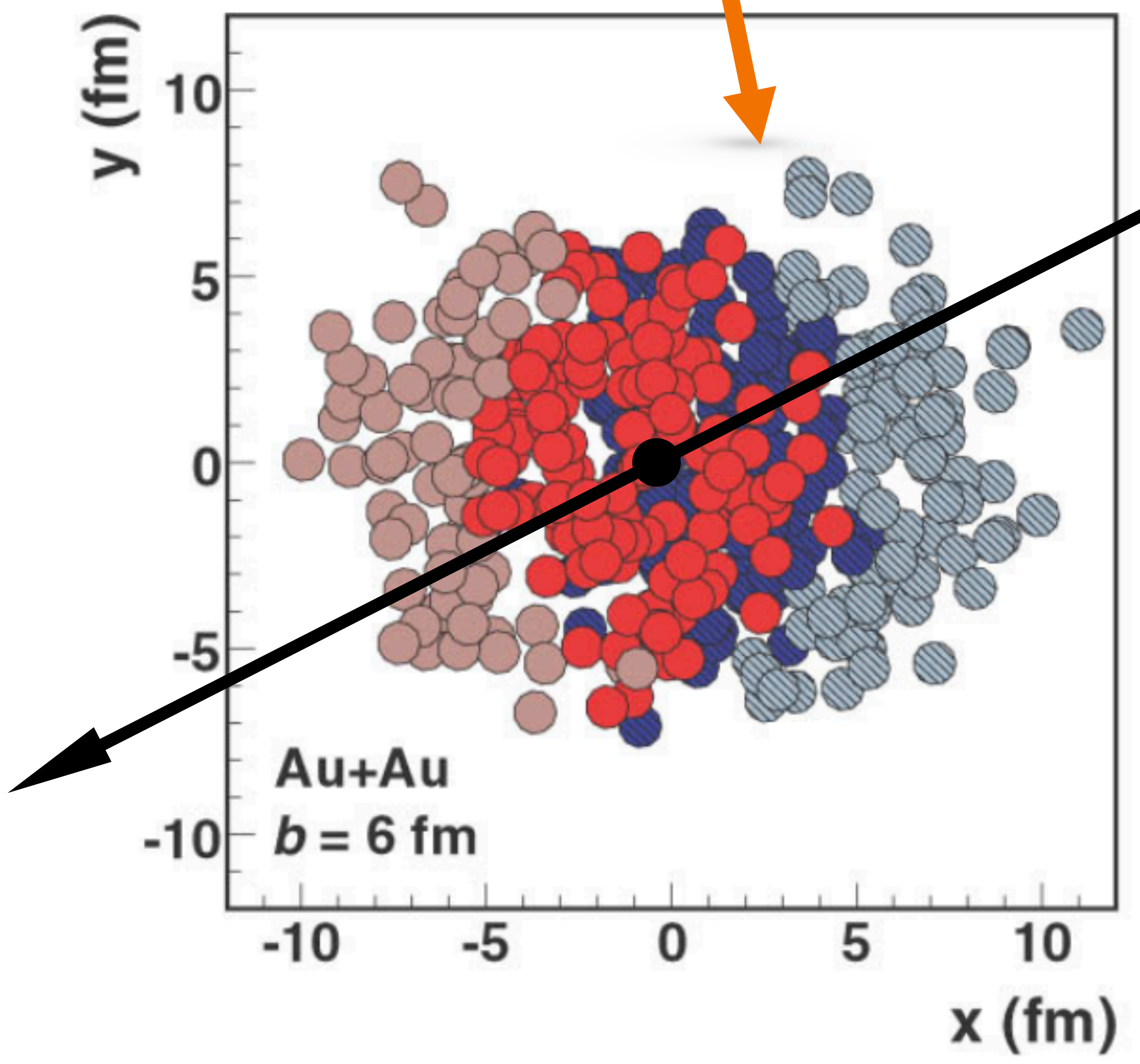
HotJets 2025

Andi Mankolli ***on behalf of the JETSCAPE SIMS working group***

Advancing the Understanding of High Temperature QCD with Jets
University of Illinois Urbana-Champaign, 8-10 Jan 2025

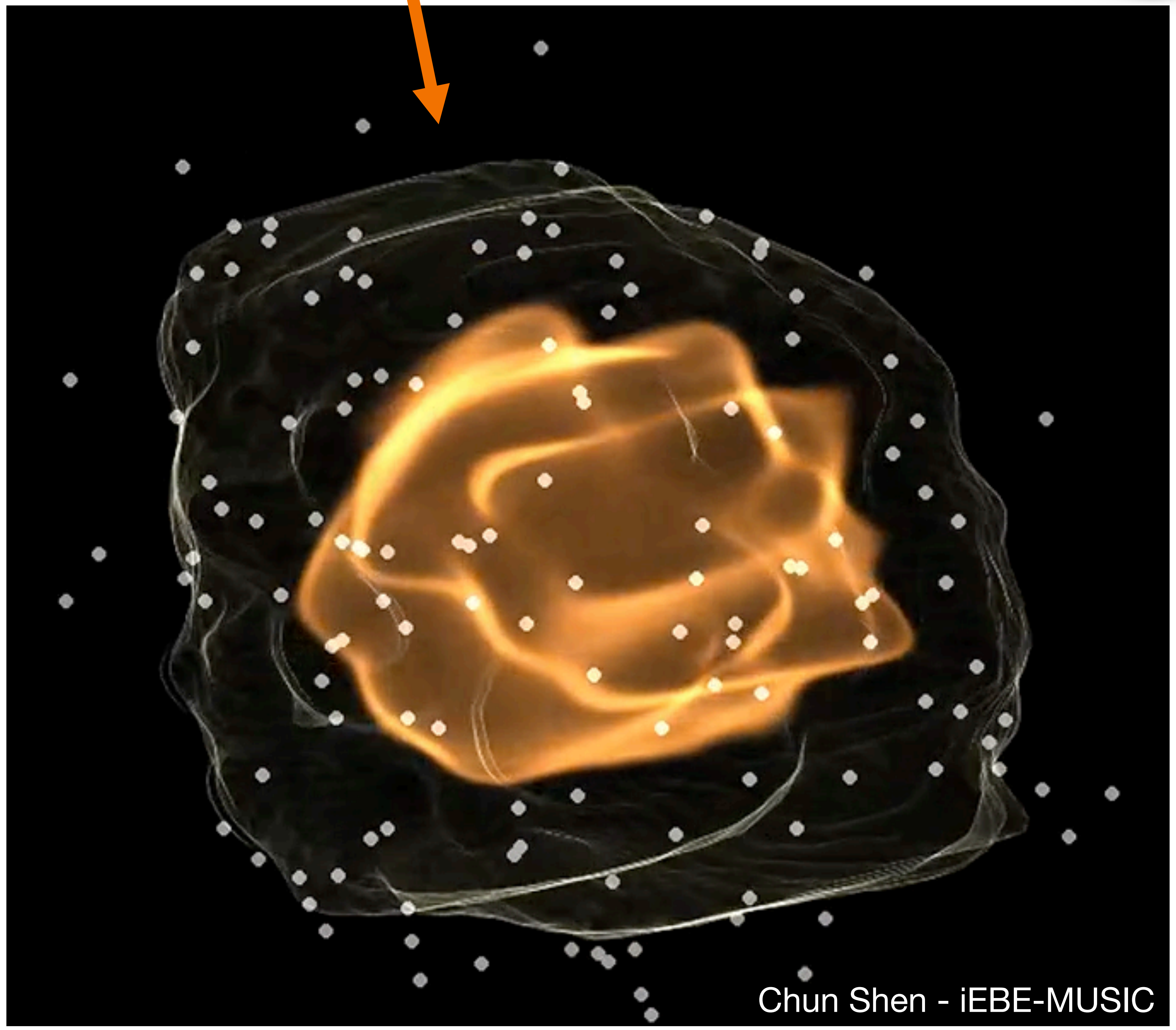
Bulk modeling of QGP

y_{loss}



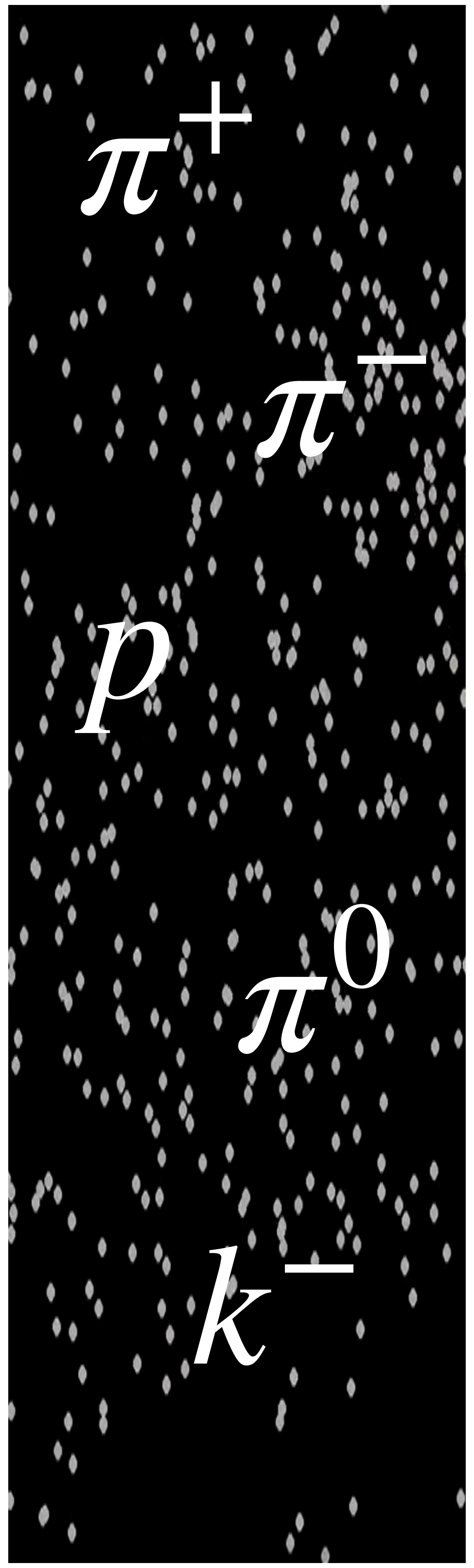
Hydrodynamization

η/s



ϵ_{switch}

Particlization



Observables

$\frac{dN}{d\eta}$

v_2

v_3

Calibrating bulk models with many observables

- Targeted fit

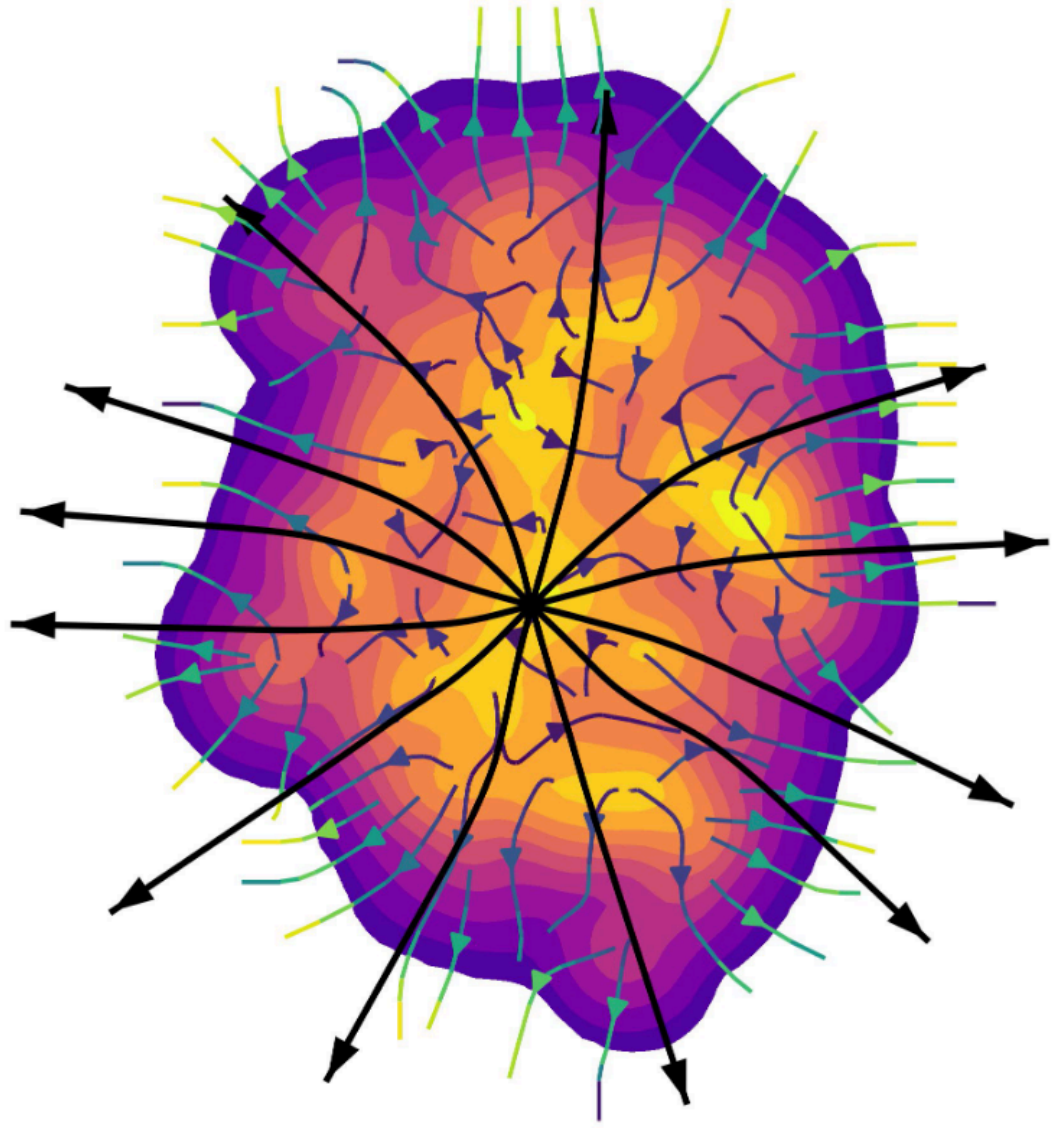
Calibrating bulk models with many observables

- Global fit

Calibrating bulk models with many observables

- Global Bayesian fit

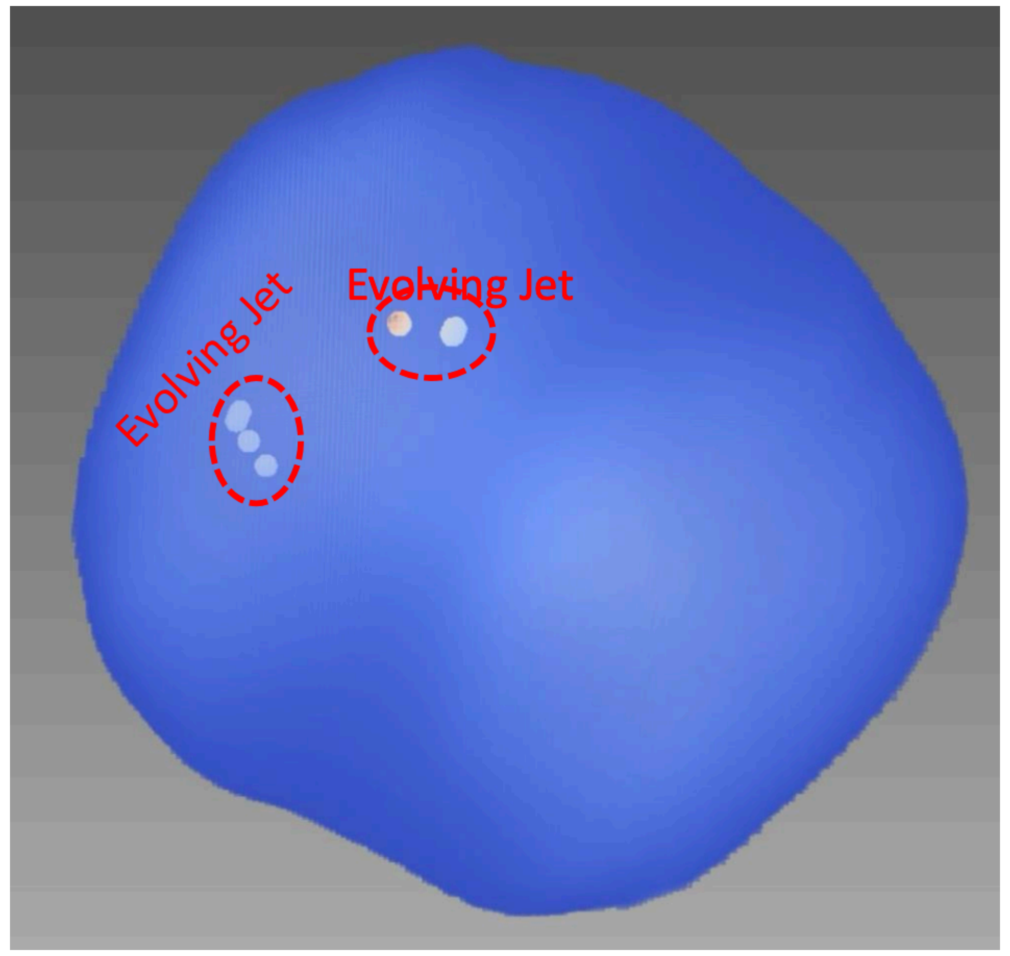
Calibrated medium as a background for hard processes



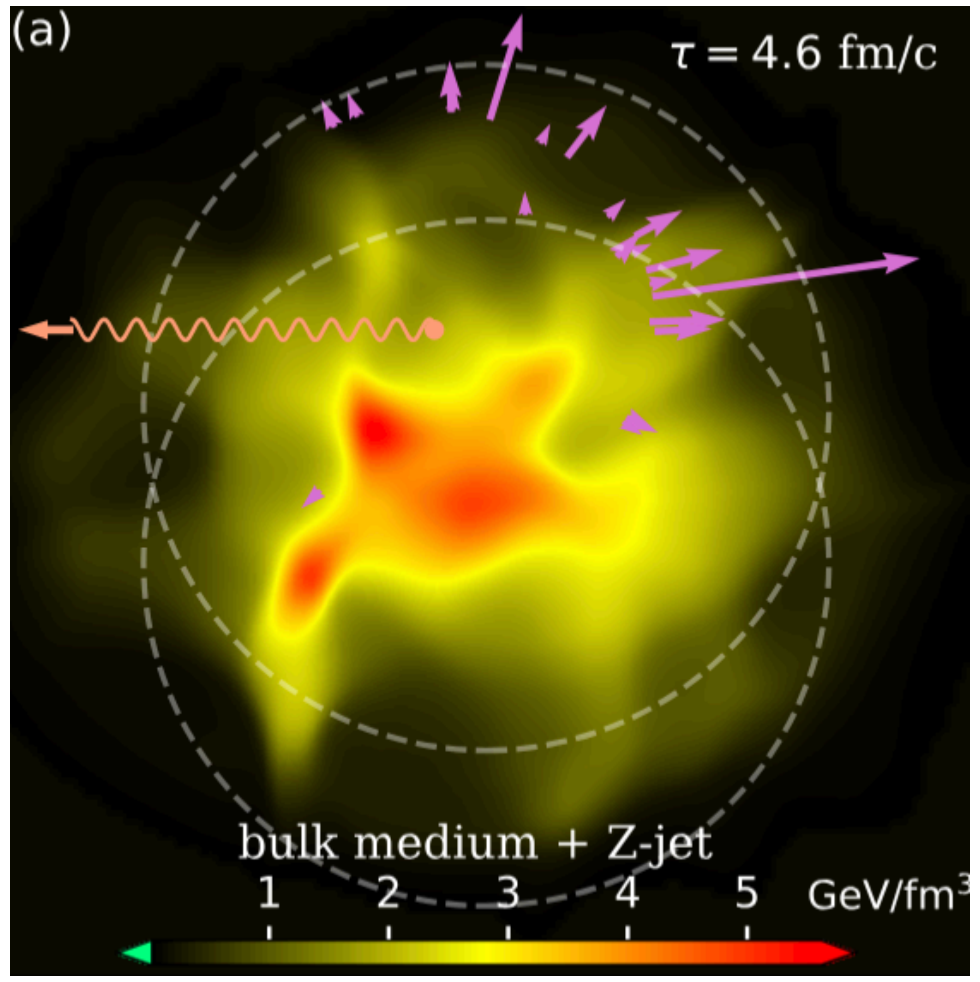
Sievert talk, Wed.

Bahder, Rahman, Sievert, Vitev. (2024)

arxiv:2412.05474



Stewart talk, Wed.



Wang talk, Wed.

Chen, Cao, Luo, Pang, Wang. (2018)

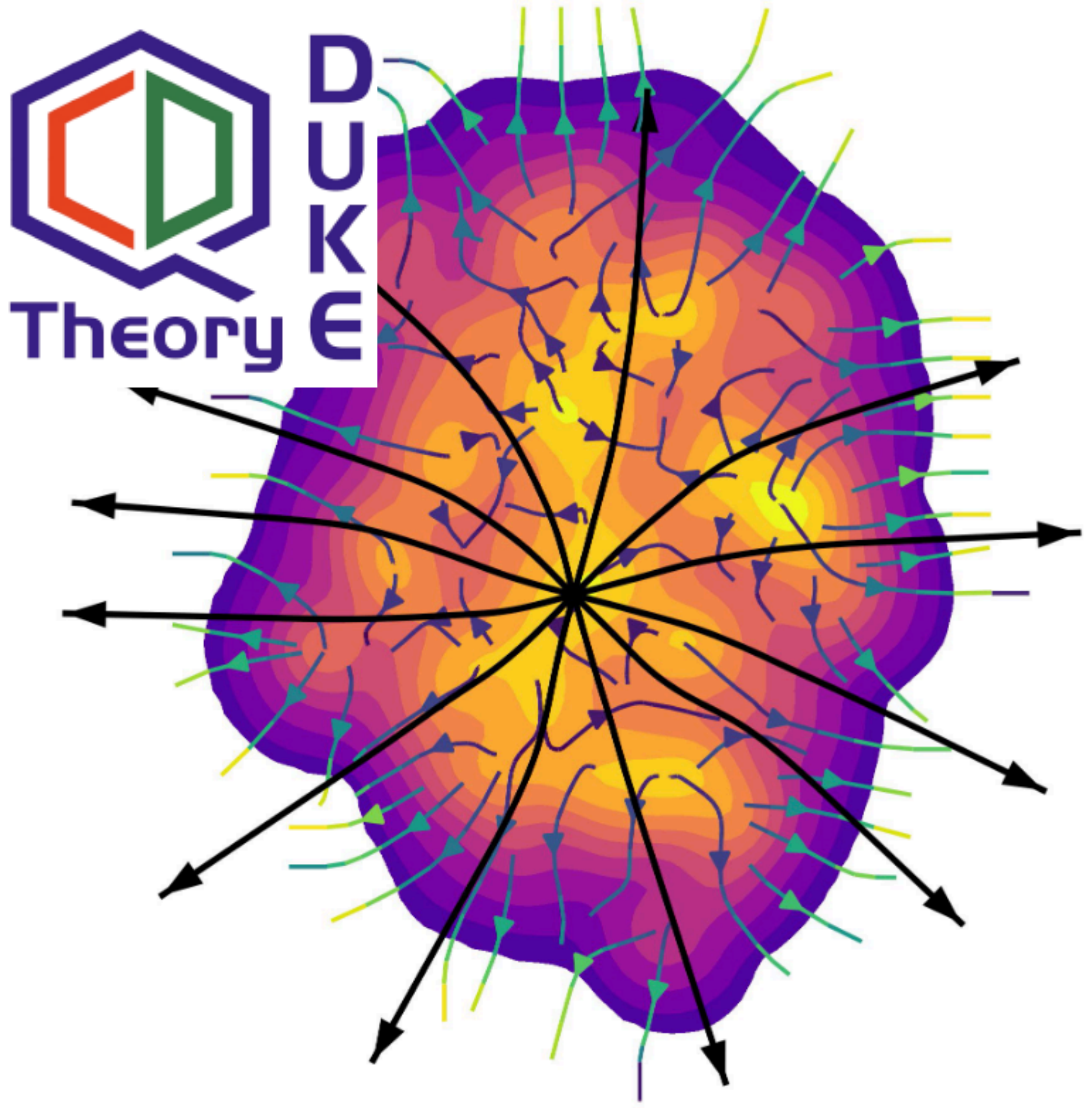
PLB777(2018)86

Yang, Cao, Luo, Pang, Wang. (2023)

PRL. 130, 052301

Calibrated medium as a background for hard processes

Phys. Rev. C. 94, 024907



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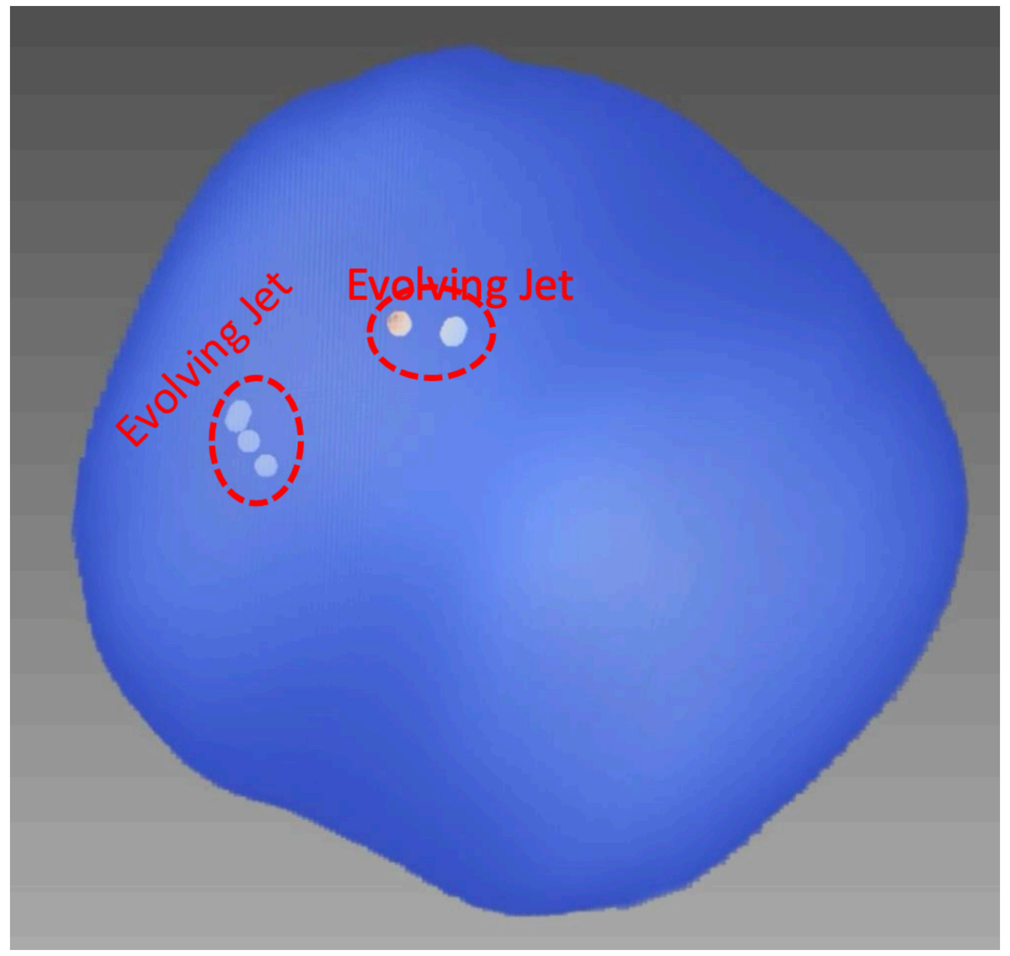

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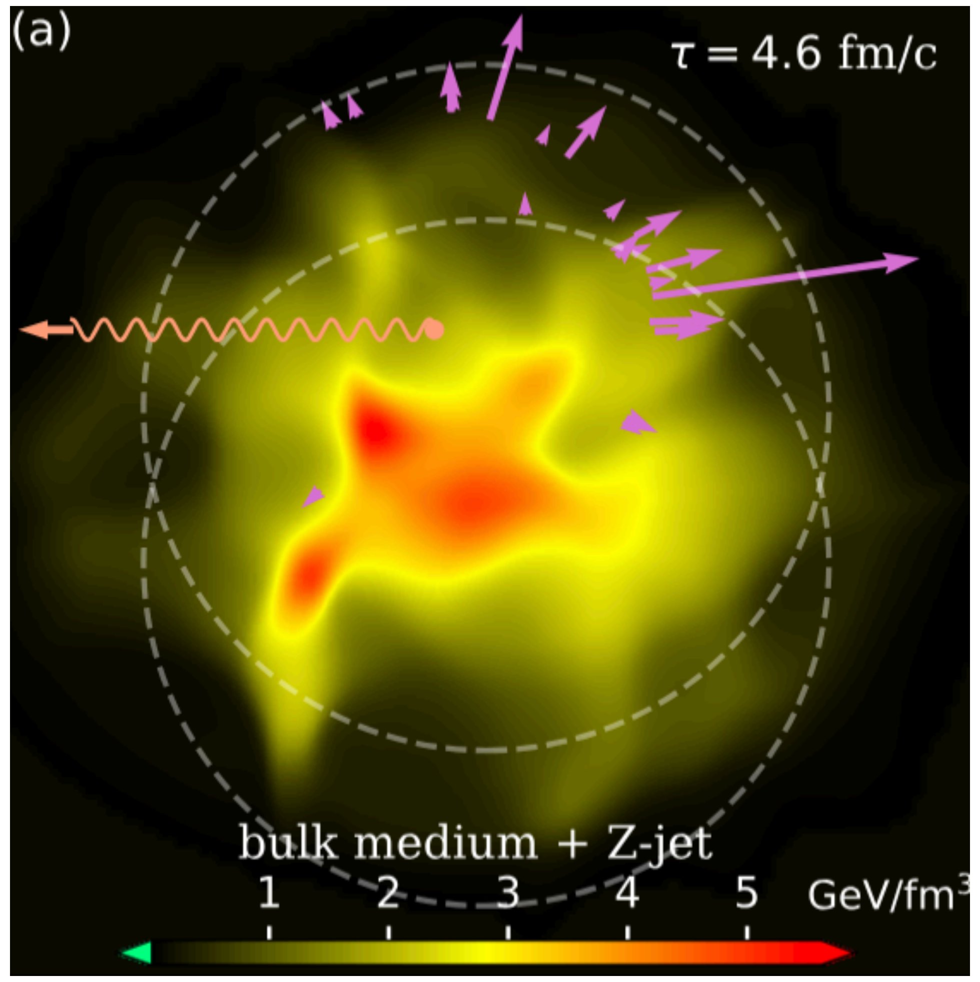

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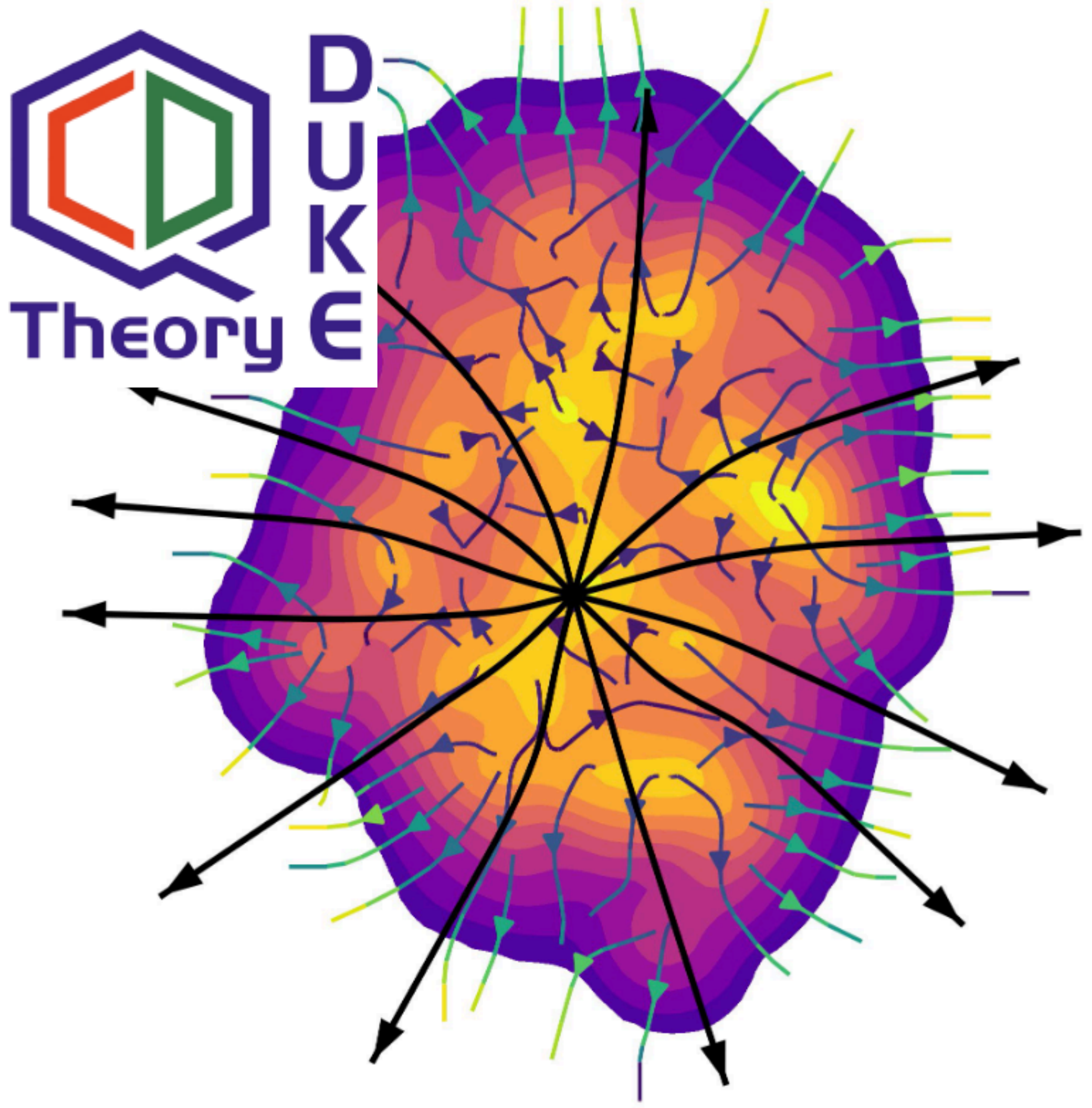

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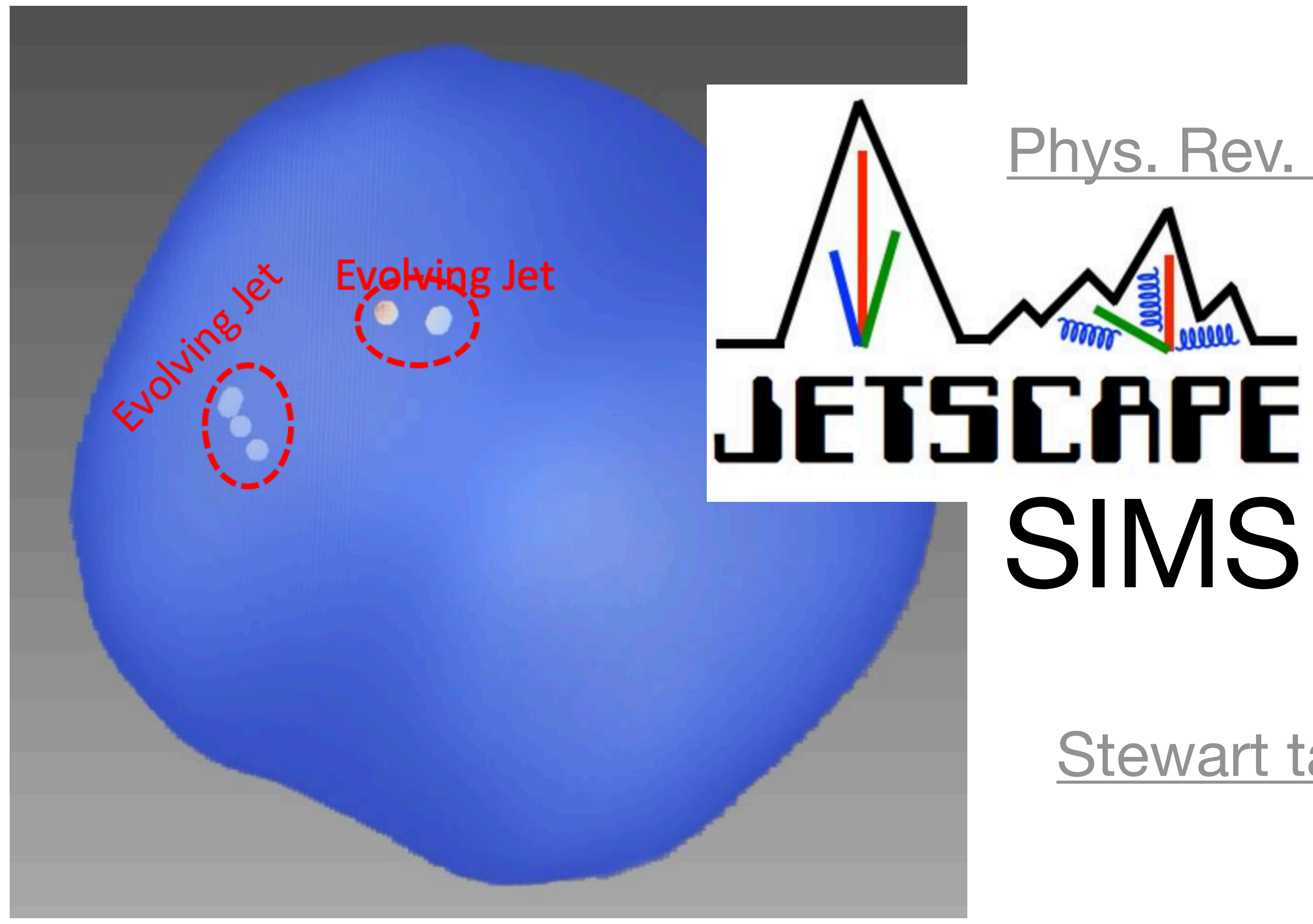
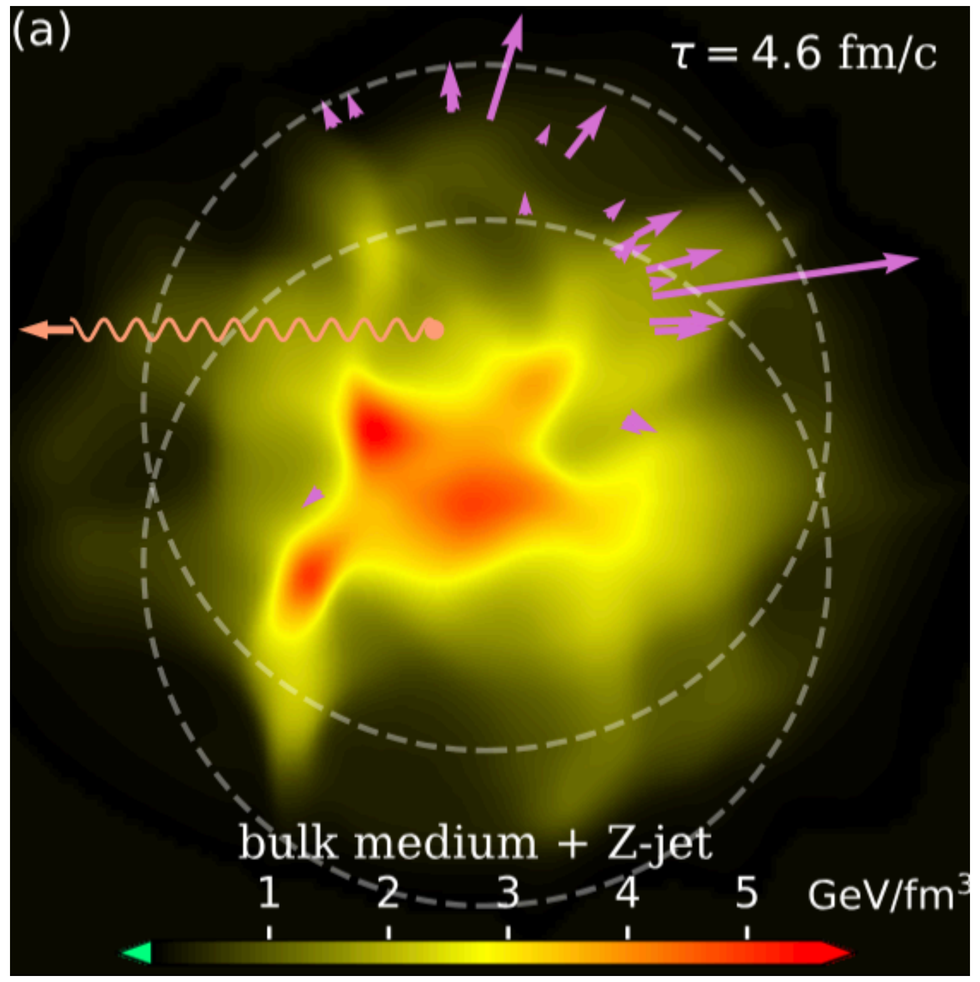


Phys. Rev. C. 103, 054904

SIMS 2D

Stewart talk, Wed.



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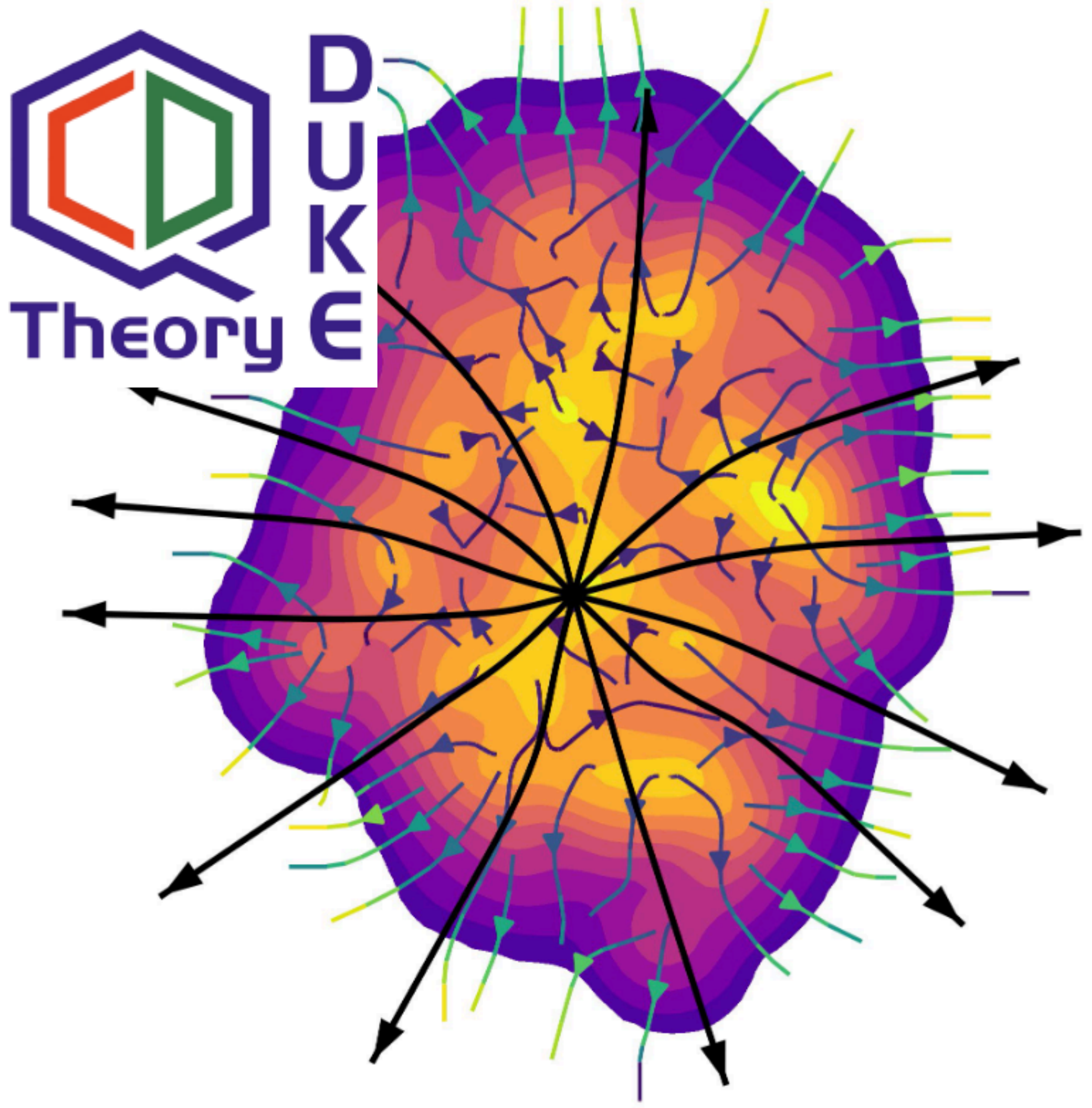

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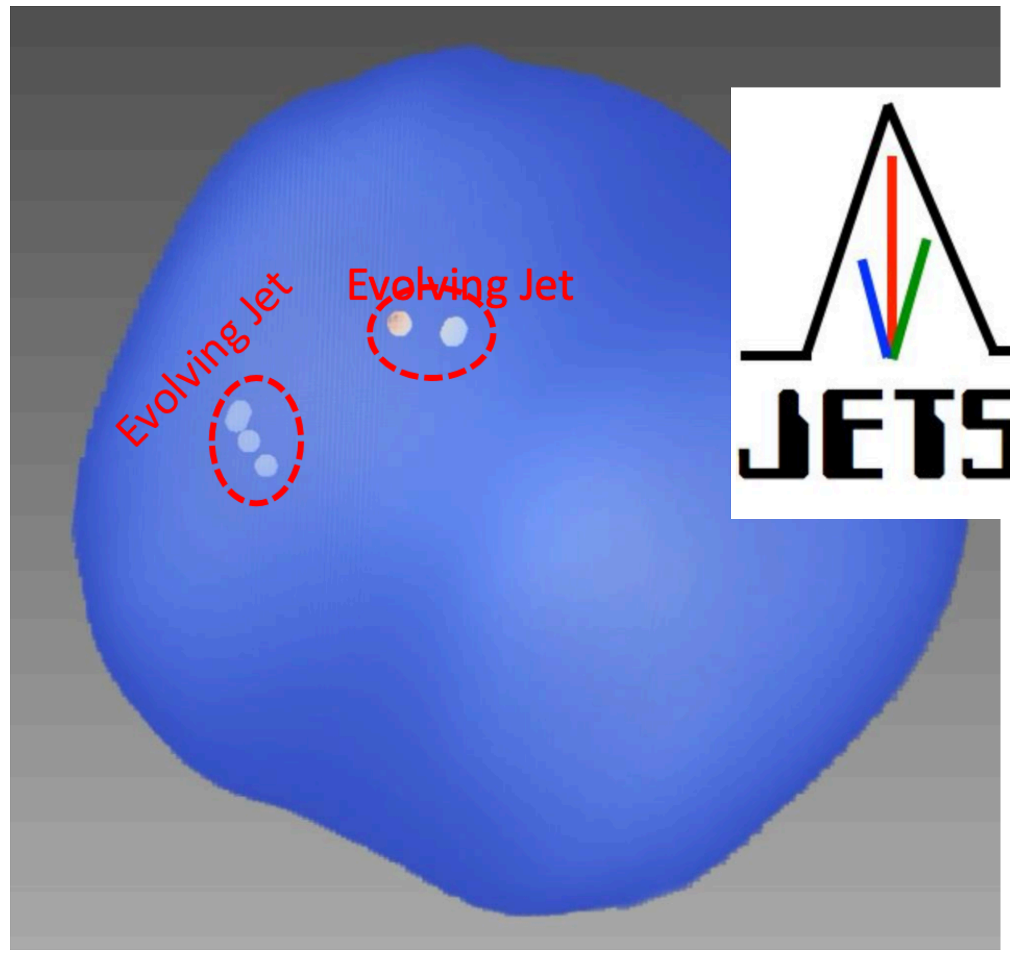

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Phys. Rev. C. 103, 054904

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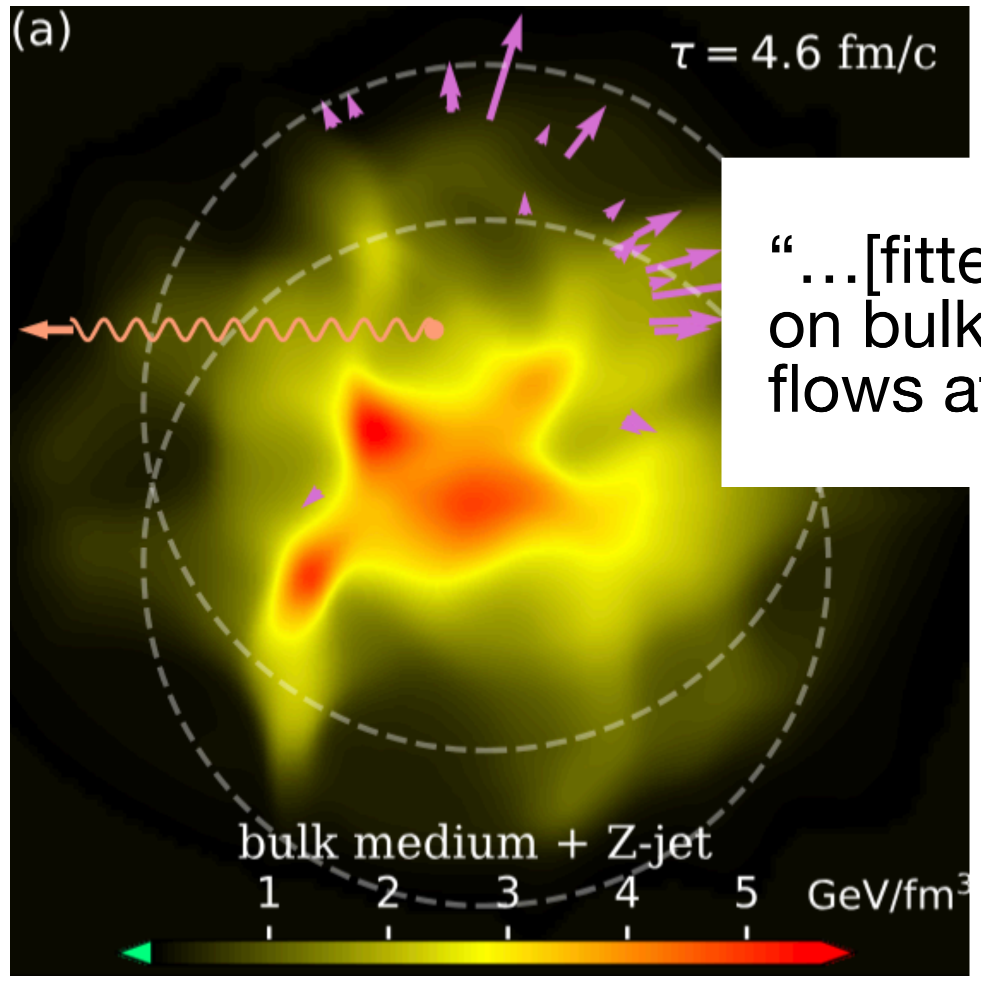


"…[fitted to] reproduce experimental data on bulk hadron spectra and anisotropic flows at the LHC…" within Co-LBT

Wang talk, Wed.

Chen, Cao, Luo, Pang, Wang. (2018)

PLB777(2018)86

Yang, Cao, Luo, Pang, Wang. (2023)

PRL. 130, 052301

The experimental data for calibration

- Large and small system
- All four RHIC experiments

BRAHMS PHOBOS STAR PHENIX

Au-Au 200 GeV

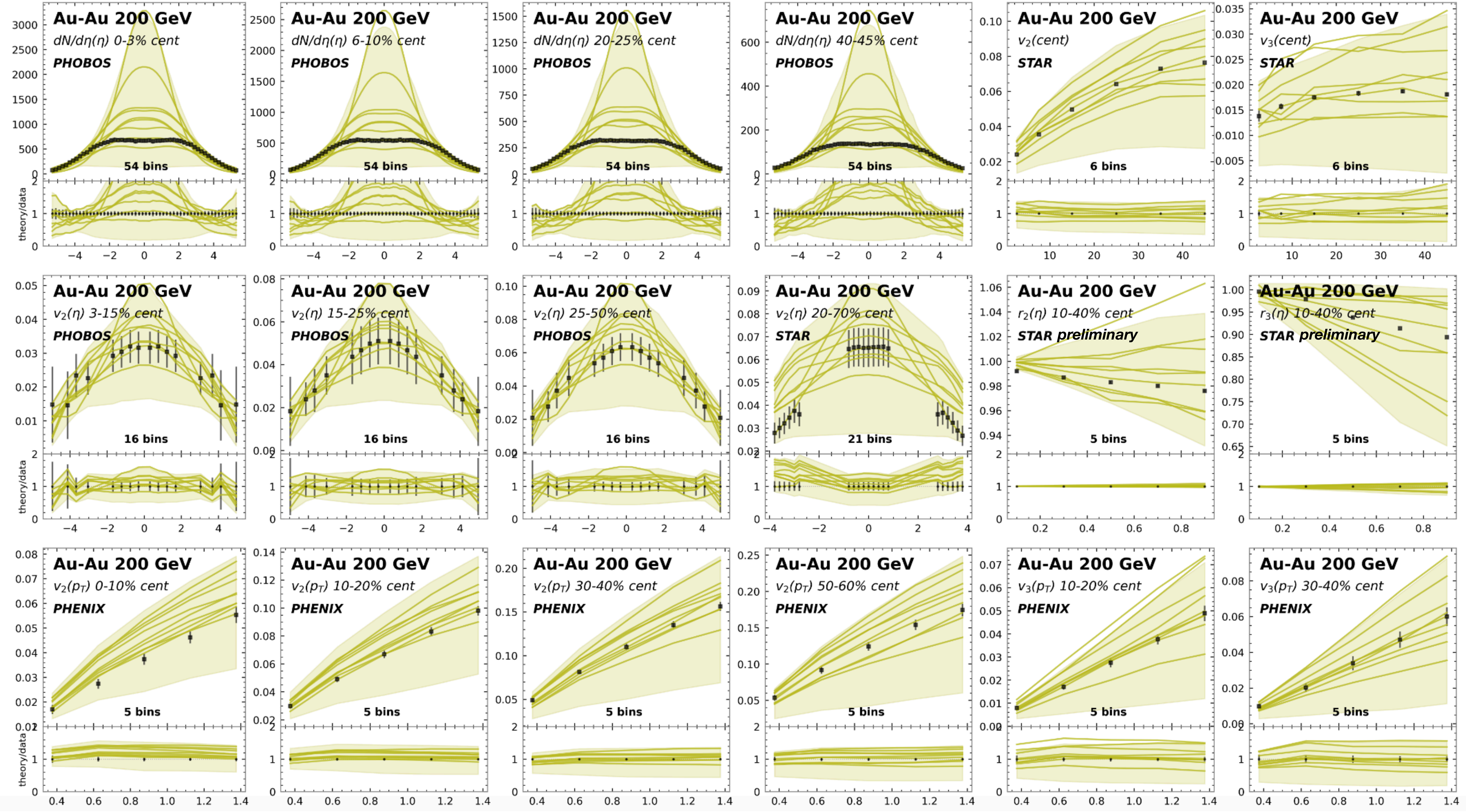
- $dN_{ch}/d\eta(\eta)$ PHOBOS
- v_2(cent) STAR
- v_3(cent) STAR
- $v_2(p_T)$ PHENIX
- $v_2(p_T)$ STAR
- $v_2(\eta)$ STAR
- $v_2(\eta)$ PHOBOS
- $\langle p_T \rangle$ π, k STAR
- $\langle p_T \rangle$ k, p PHENIX

d-Au 200 GeV

- $dN_{ch}/d\eta(\eta)$ PHOBOS
- $dN_{ch}/d\eta(\eta)$ PHENIX
- $v_2(p_T)$ PHENIX
- $v_2(p_T)$ STAR
- $v_2(\eta)$ PHENIX

- Focus on rapidity-dependent observables
- Include p_T-dependent (at low p_T) observables with small uncertainties

The experimental data and priors

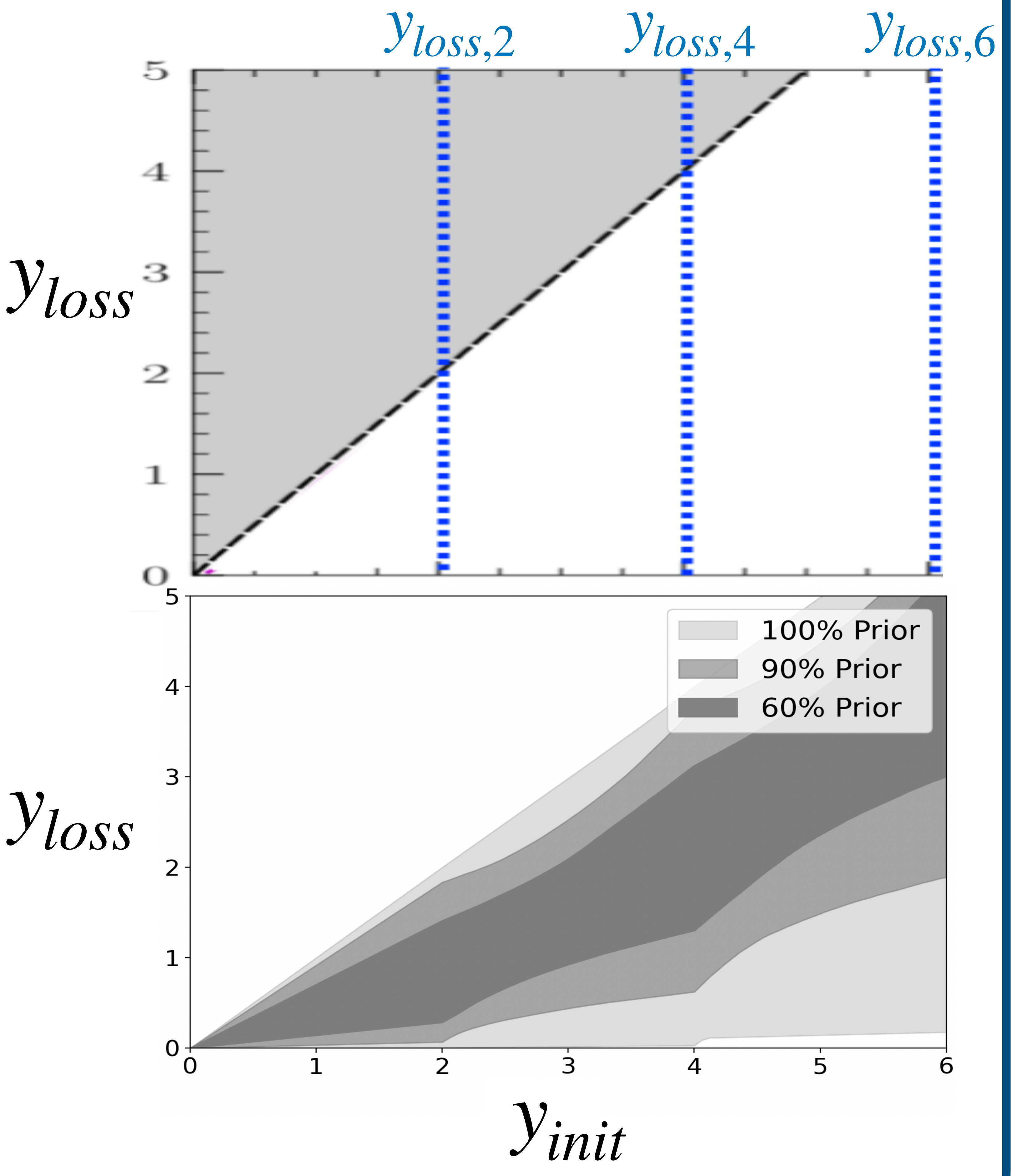


3D model parametrizations

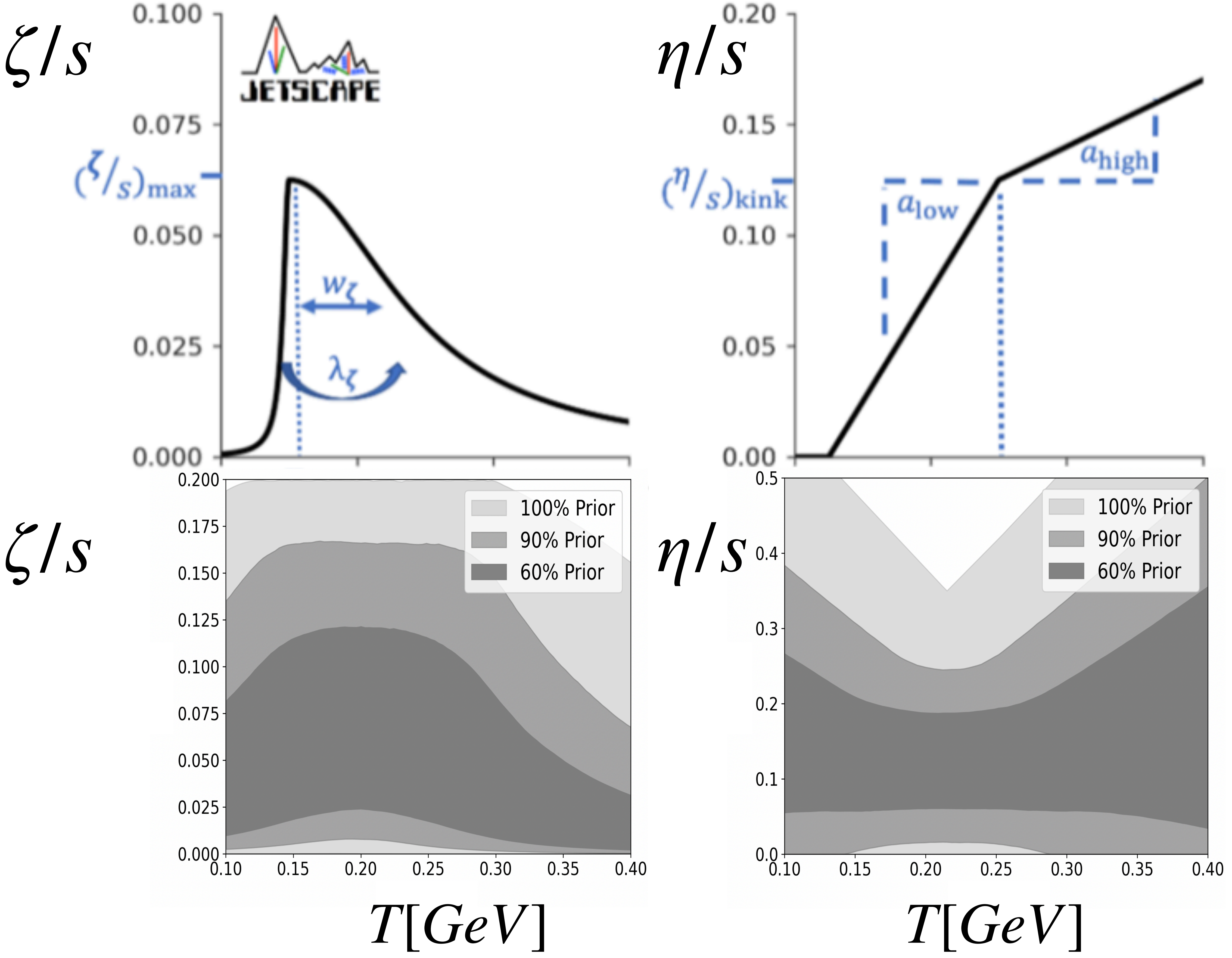
Initial State

Parametrization

Prior



Hydrodynamics



Schenke, Shen, Zhao.

Phys. Rev. C 105, 064905 (2022)

Phys. Rev. C 97, 024907 (2018)

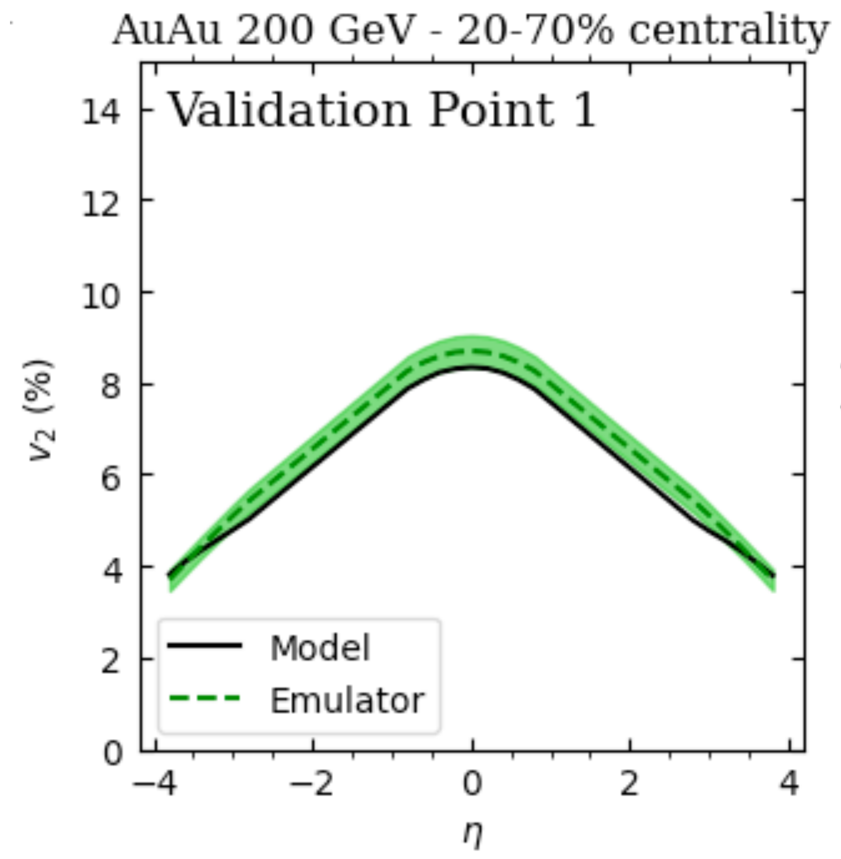
Model emulation and comparison with data

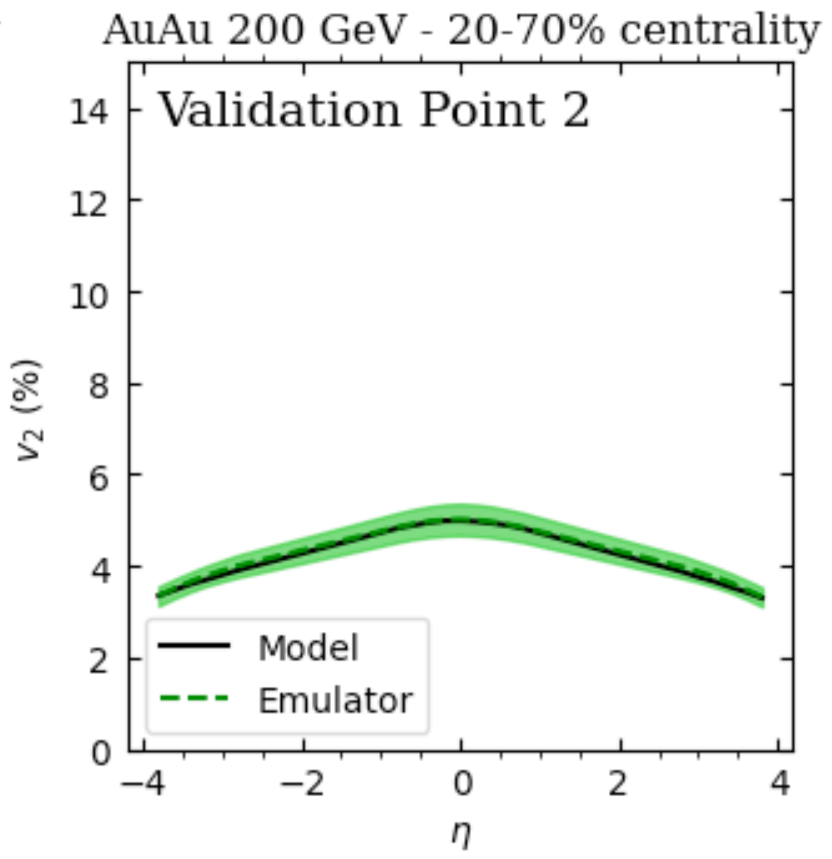
Model simulations

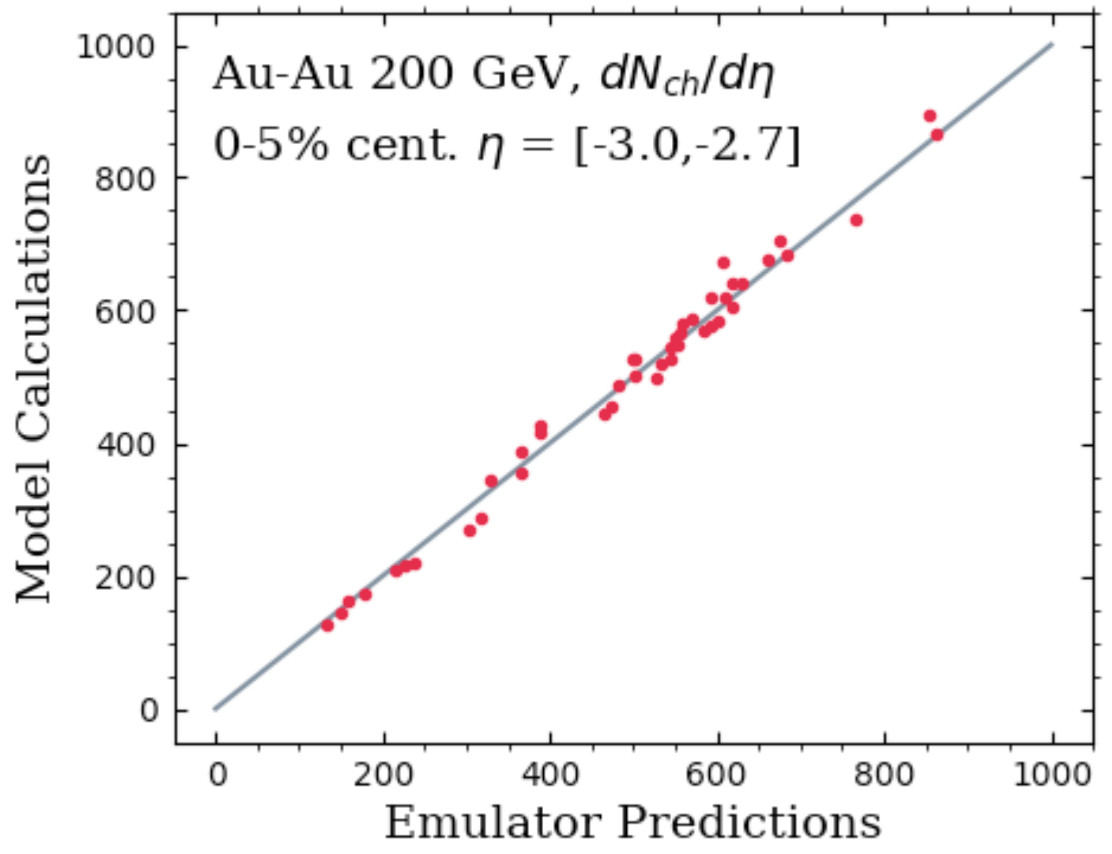
- 20 model parameters
- ~2000 events at 400 parameter points simulated with full model

Model emulation

- ~1000 observable bins
- ~10 principal components
- Estimation of uncertainty



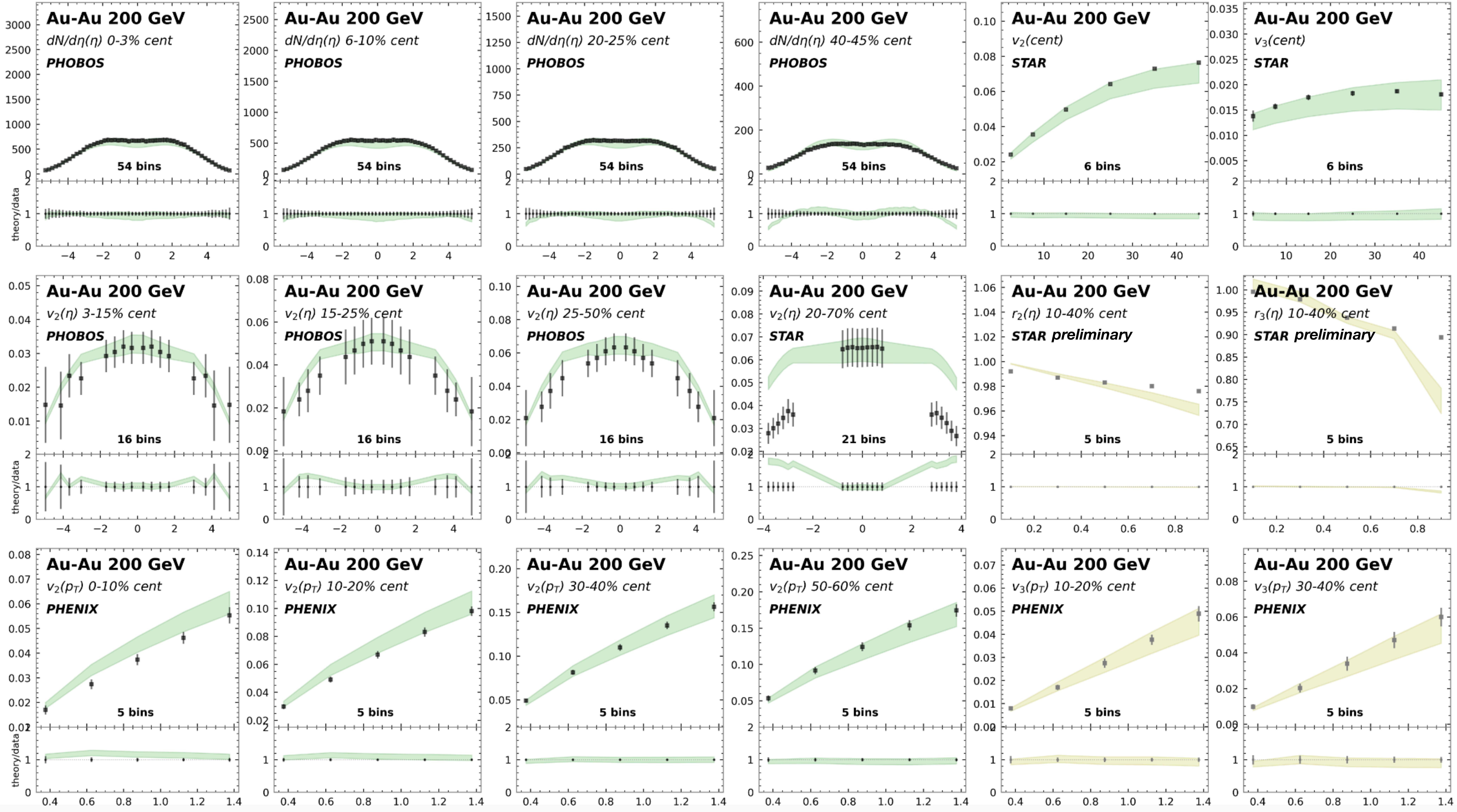




Comparison with data

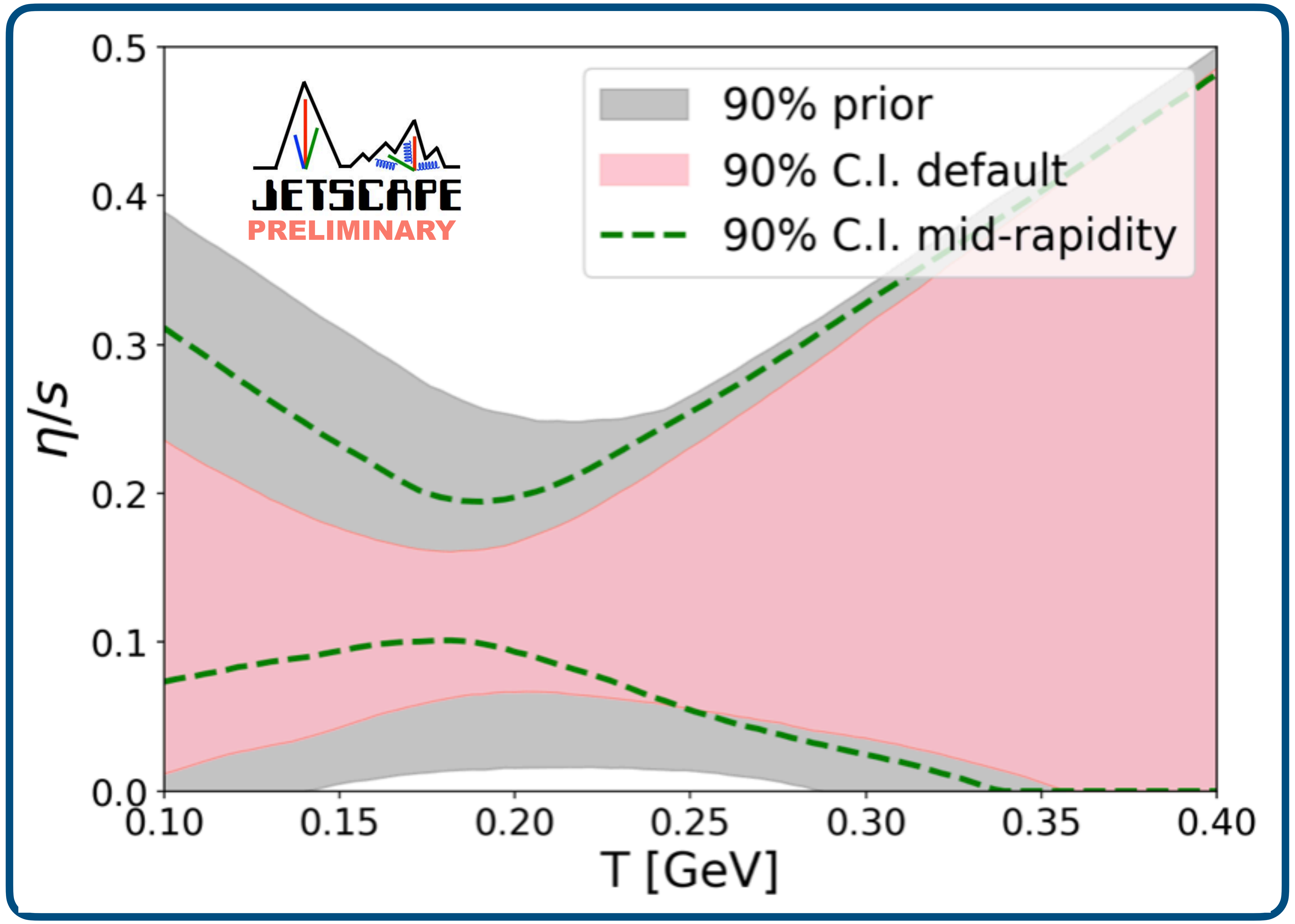
- Likelihood function: $P(Y_{exp}|\theta) \propto \exp\left(-[Y_{exp} - Y_{sim}(\theta)]^T[\Sigma_{exp} + \Sigma_{sim}(\theta)]^{-1}[Y_{exp} - Y_{sim}(\theta)]\right)$

Calibrated description of the data



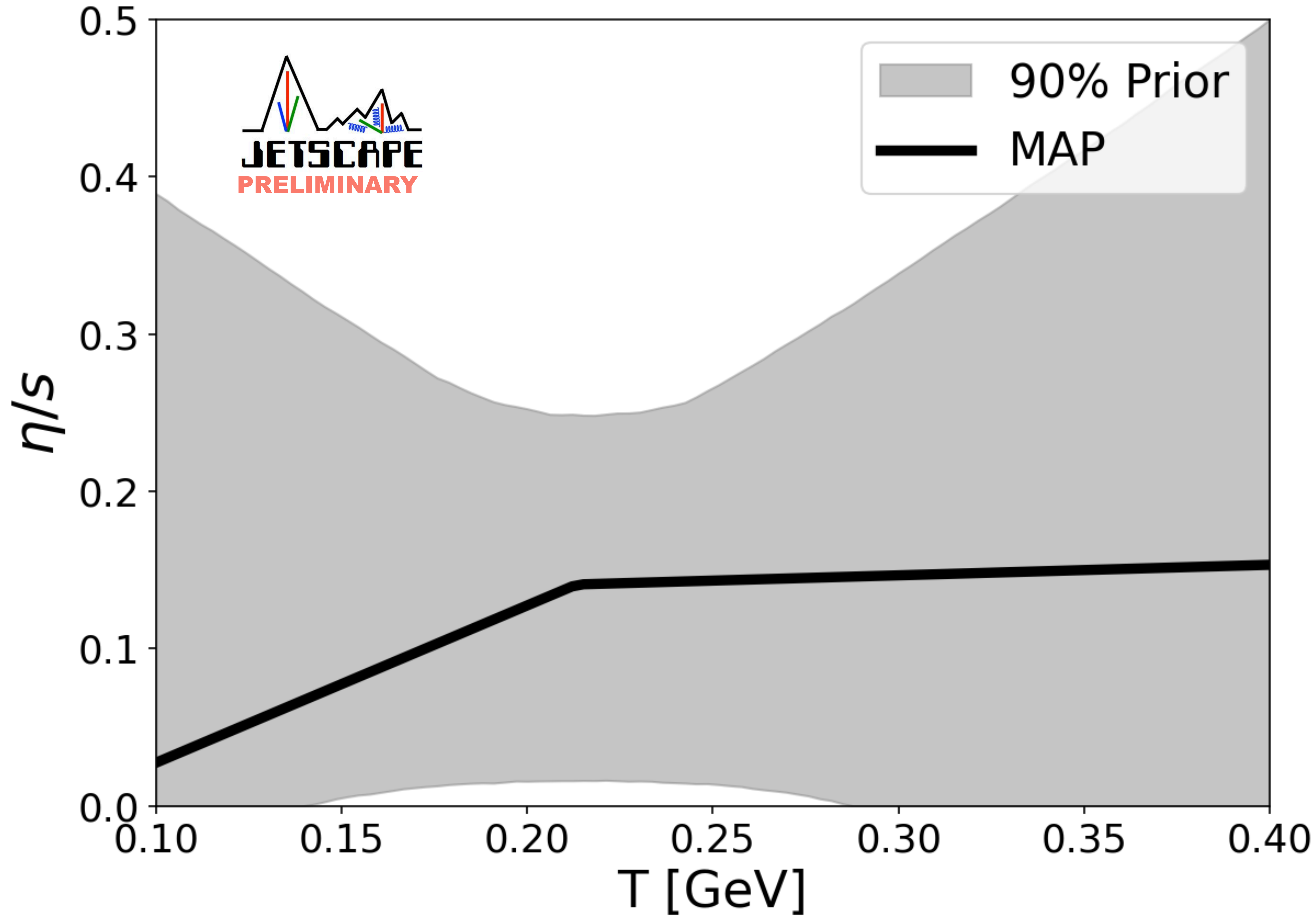
Rapidity-dependent constraints on the shear viscosity

- Mid-rapidity data often includes 3D information
  - Centrality selection
  - Flow measurement reference
- Data with explicit rapidity-dependence reduces the shear viscosity
- Minimal sensitivity at high T



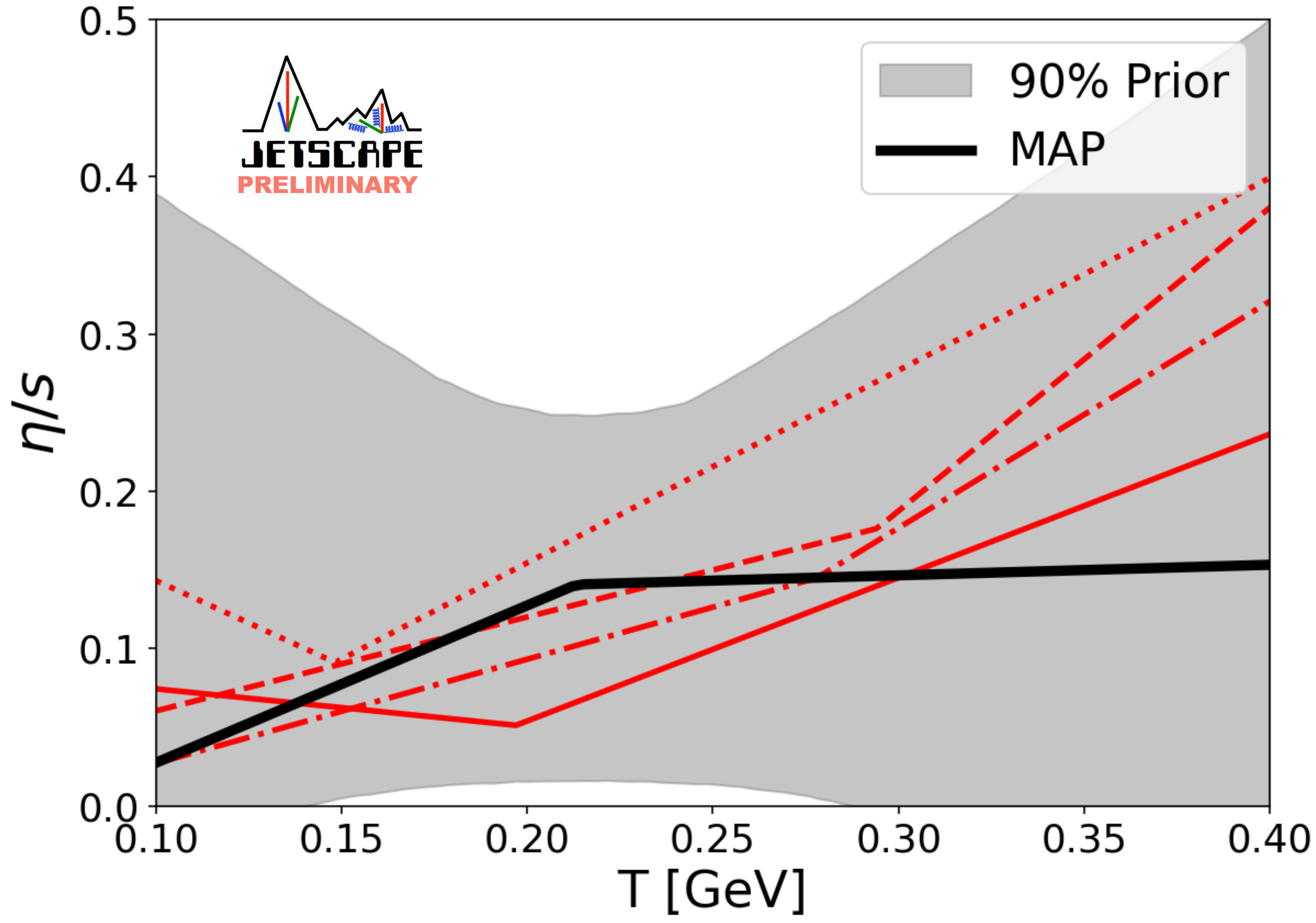
The information content of the MAP vs the full posterior

- The Maximum a Posteriori (MAP) is the highest-likelihood point in parameter space



The information content of the MAP vs the full posterior

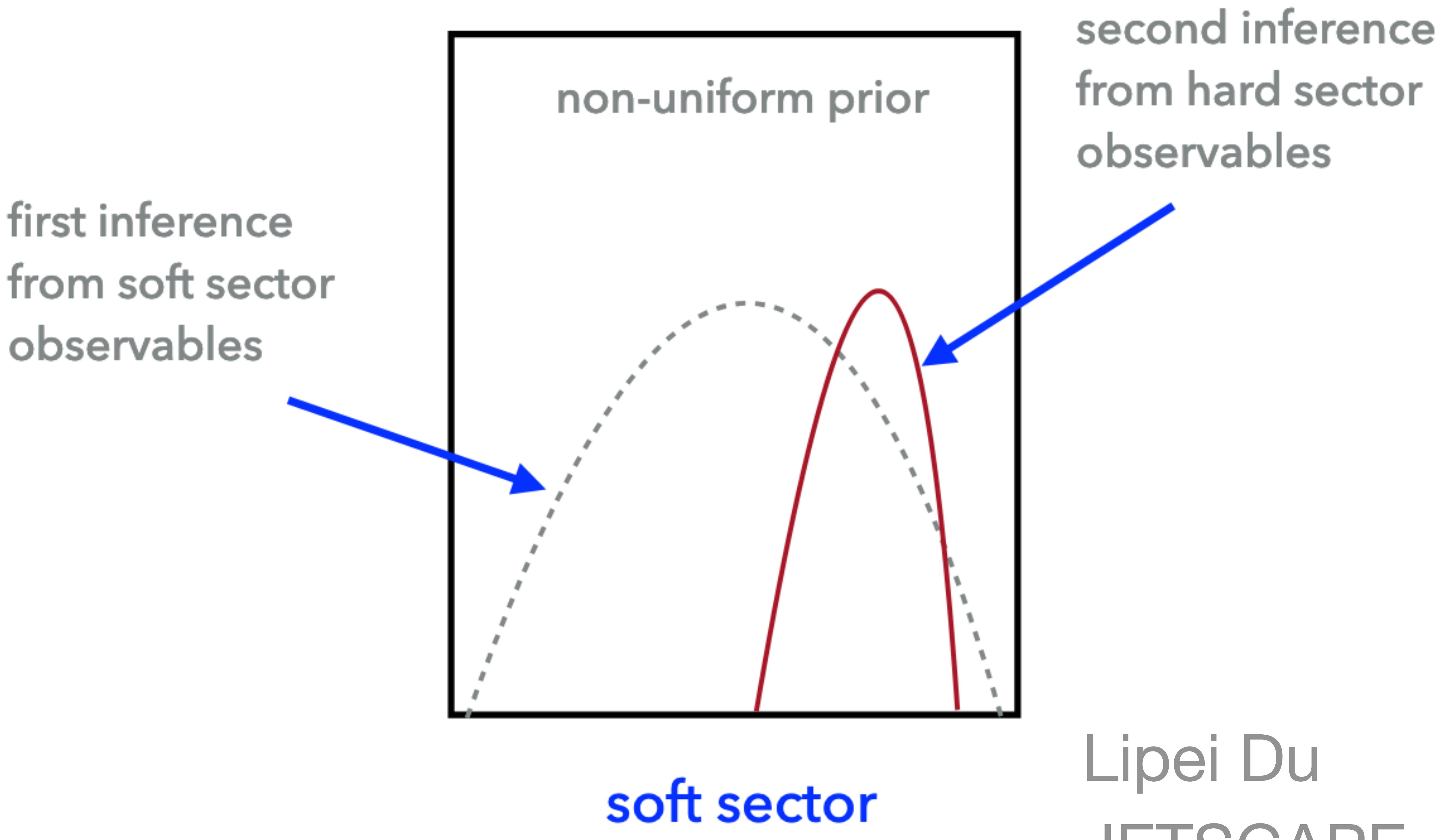
- The Maximum a Posteriori (MAP) is the highest-likelihood point in parameter space
- It does not reflect uncertainties inherent in the full posterior
- A similarly-likely point in parameter space may be physically very different
- To avoid precise but inaccurate predictions, a sampling of the posterior should be used whenever feasible



Steps toward including hard observables

- A sequential calibration may be appropriate when:
  - There are no model inconsistencies
  - The datasets do not overlap
- We know the medium properties affect hard observables
- Need to gauge whether sensitivity can overcome experimental and theoretical uncertainties

A sequential calibration



Lipei Du
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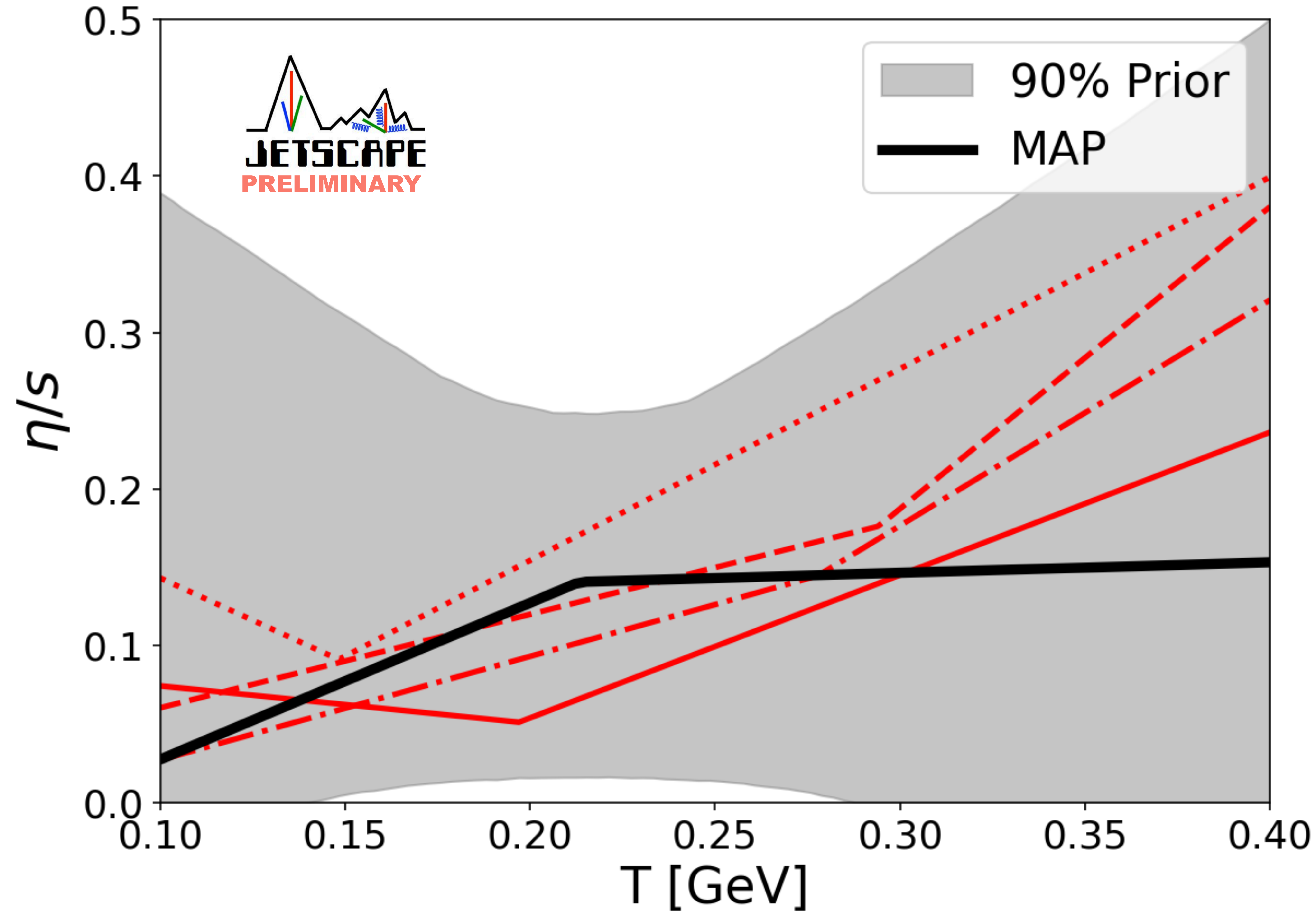
Summary

- 3D Bayesian fit to the widest dataset at RHIC top energy may be used as a calibrated medium for future studies, including for jet-medium interaction
- Rapidity-dependent data provides additional constraints for viscosity
- To fully exploit a Bayesian analysis, a sample of the posterior should be used whenever feasible



Acknowledgements

I would like to thank J-F Paquet, Matt Luzum, Chun Shen, Julia Velkovska, Mayank Singh, Gabriel Soares Rocha, and Dan Liyanage for their help.

Thanks also to the organizers of HotJets 2025 for inviting me!

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NSF

Backup

Large and small system constraints on the shear viscosity

- Au-Au and d-Au constraints largely consistent
- Au-Au dominates the fit due to data volume & uncertainties
  - Including d-Au in the fit does not appreciably affect shear viscosity in Au-Au simulations

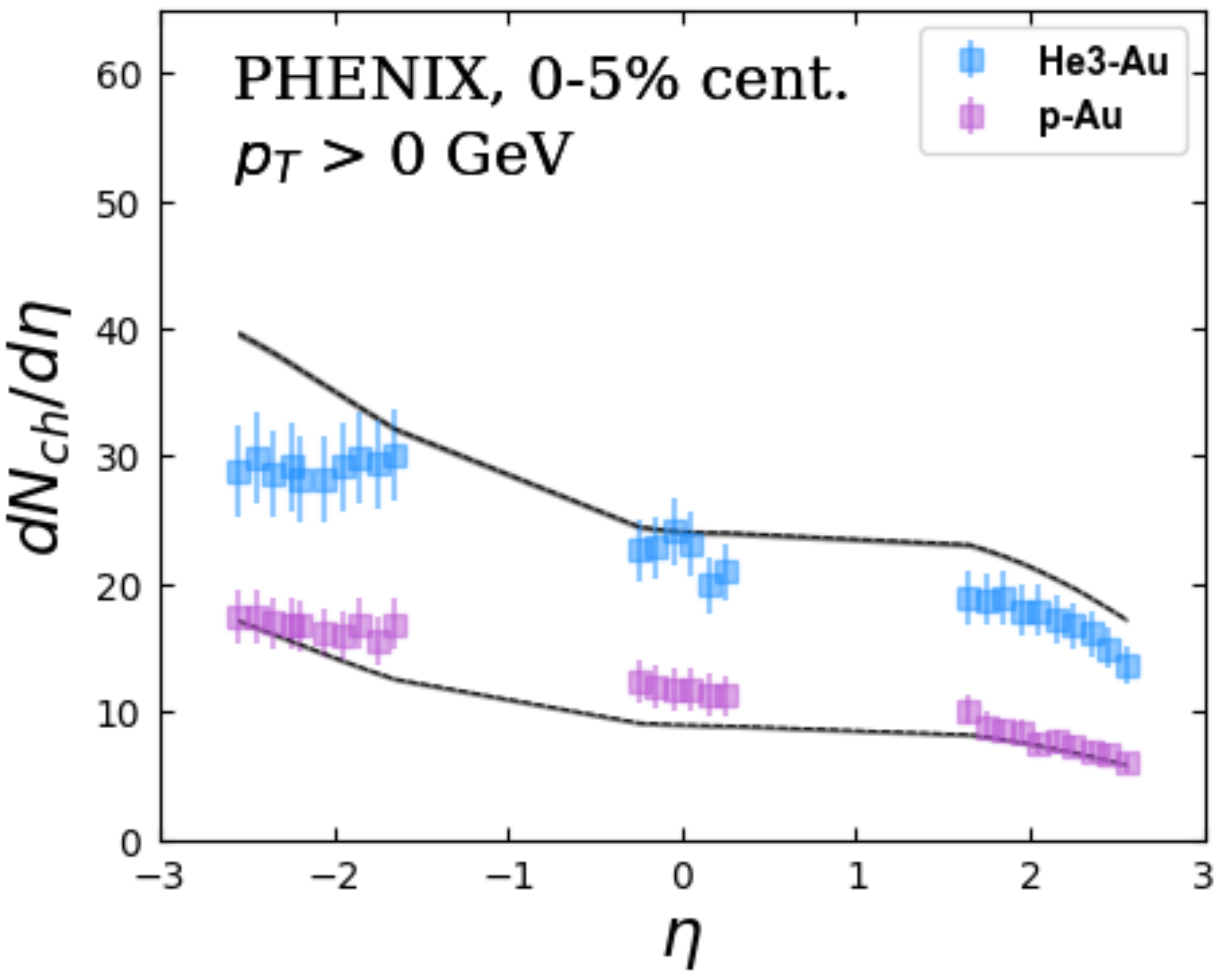
The experimental data

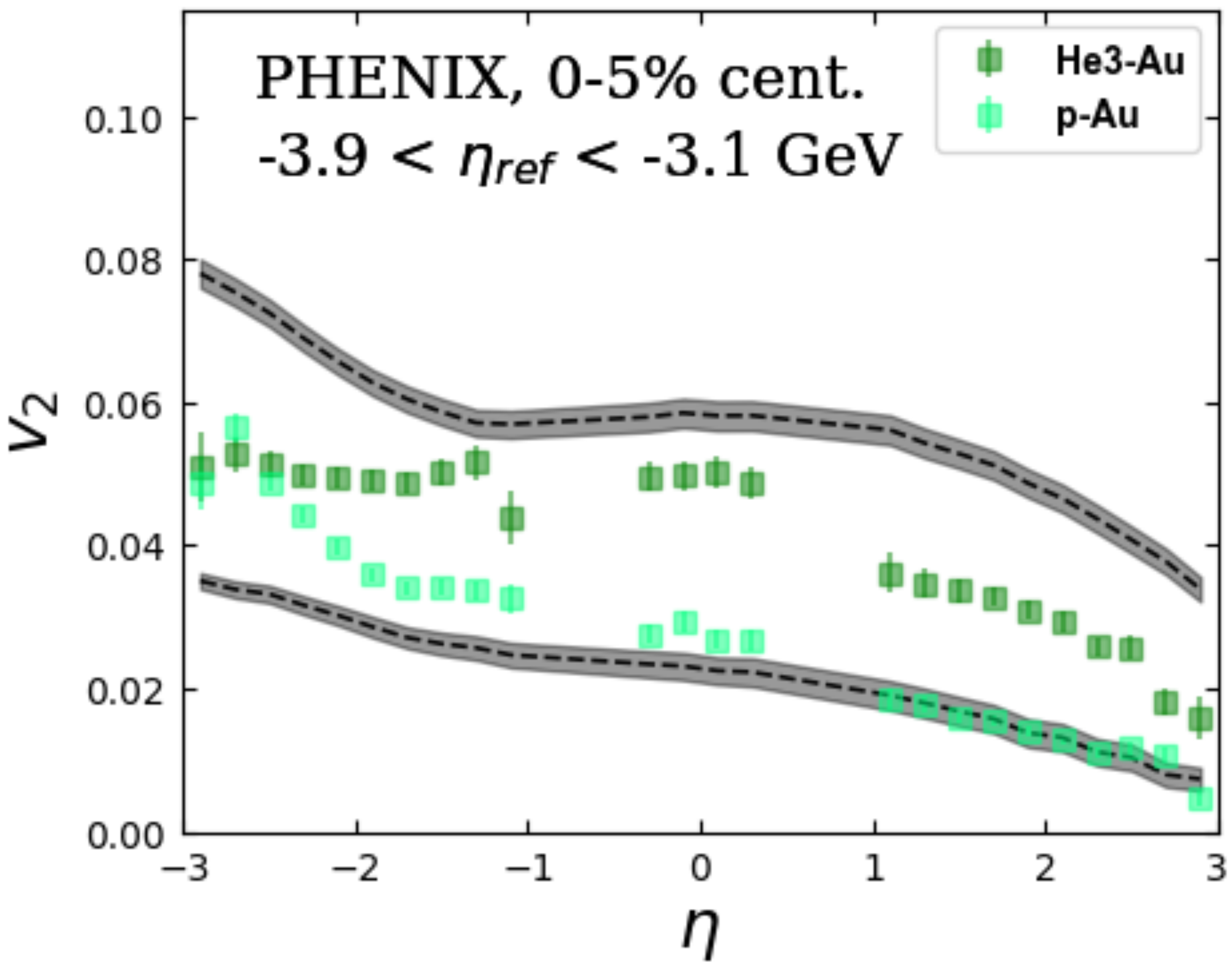
	system	Experiment	cent.bins	data points
$dN_{ch}/\mathrm{d}\eta(\eta)$	Au-Au	PHOBOS	11	594
$v_2(\eta)$	Au-Au	PHOBOS	3	48
$v_2(\eta)$	Au-Au	STAR	1	21
$v_2(p_T)$	Au-Au	PHENIX	6	30
$v_2(p_T)$	Au-Au	STAR	7	63
$v_2(\text{cent.})$	Au-Au	STAR	6	6
$v_3(\text{cent.})$	Au-Au	STAR	6	6
$\pi\ \langle pT\rangle(\text{cent.})$	Au-Au	STAR	7	7
$\text{k}\ \langle pT\rangle(\text{cent.})$	Au-Au	STAR	7	7
$\text{k}\ \langle pT\rangle(\text{cent.})$	Au-Au	PHENIX	8	8
$\text{p}\ \langle pT\rangle(\text{cent.})$	Au-Au	PHENIX	8	8
$dN_{ch}/\mathrm{d}\eta(\eta)$	d-Au	PHOBOS	1	54
$dN_{ch}/\mathrm{d}\eta(\eta)$	d-Au	PHENIX	3	102
$v_2(\eta)$	d-Au	PHENIX	1	14
$v_2(p_T)$	d-Au	PHENIX	1	5
$v_2(p_T)$	d-Au	STAR	1	5
Total				978

The model parameters

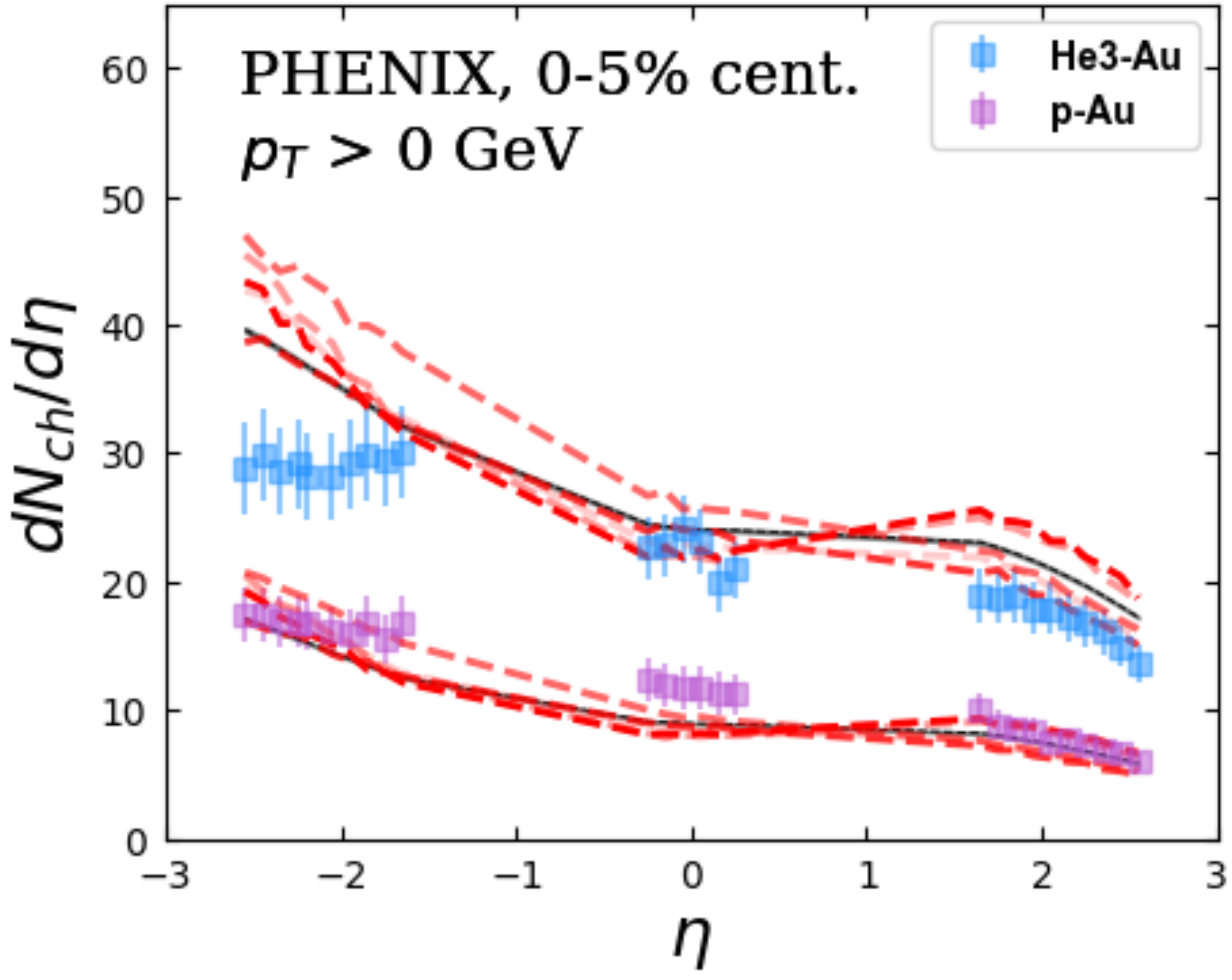
Parameter	Collision Stage	Prior Range
$y_{loss,2}$	Initial State	[0,2]
$y_{loss,4}$	Initial State	[$y_{loss,2}$,4]
$y_{loss,6}$	Initial State	[$y_{loss,4}$,6]
$\sigma_{y_{loss}}$	Initial State	[0,1]
α_{rem}	Initial State	[0,1]
Shadowing Factor	Initial State	[0,1]
τ_{form} Mean	Initial State	[0.2,1]
B_G [1/GeV^2]	Initial State	[2,25]
String Source σ_x [fm]	Initial State	[0.1,0.5]
String Source σ_η	Initial State	[0.1,0.8]
String Trans. Shift Frac.	Initial State	[0,1]
$\frac{\eta}{s}$ T_{kink} [GeV]	Hydro	[0.13,0.3]
$\frac{\eta}{s}$ low-T slope	Hydro	[-2,1]
$\frac{\eta}{s}$ high-T slope	Hydro	[-1,2]
$\frac{\eta}{s}$ at kink	Hydro	[0.01,0.2]
$\frac{\zeta}{s}$ max	Hydro	[0.01,0.2]
$\frac{\zeta}{s}$ T_{peak} [GeV]	Hydro	[0.12,0.3]
$\frac{\zeta}{s}$ width	Hydro	[0.025,0.15]
$\frac{\zeta}{s}$ λ assym.	Hydro	[-0.8,0.6]
EPS Switch [GeV/fm^3]	Particlization	[0.1,0.6]

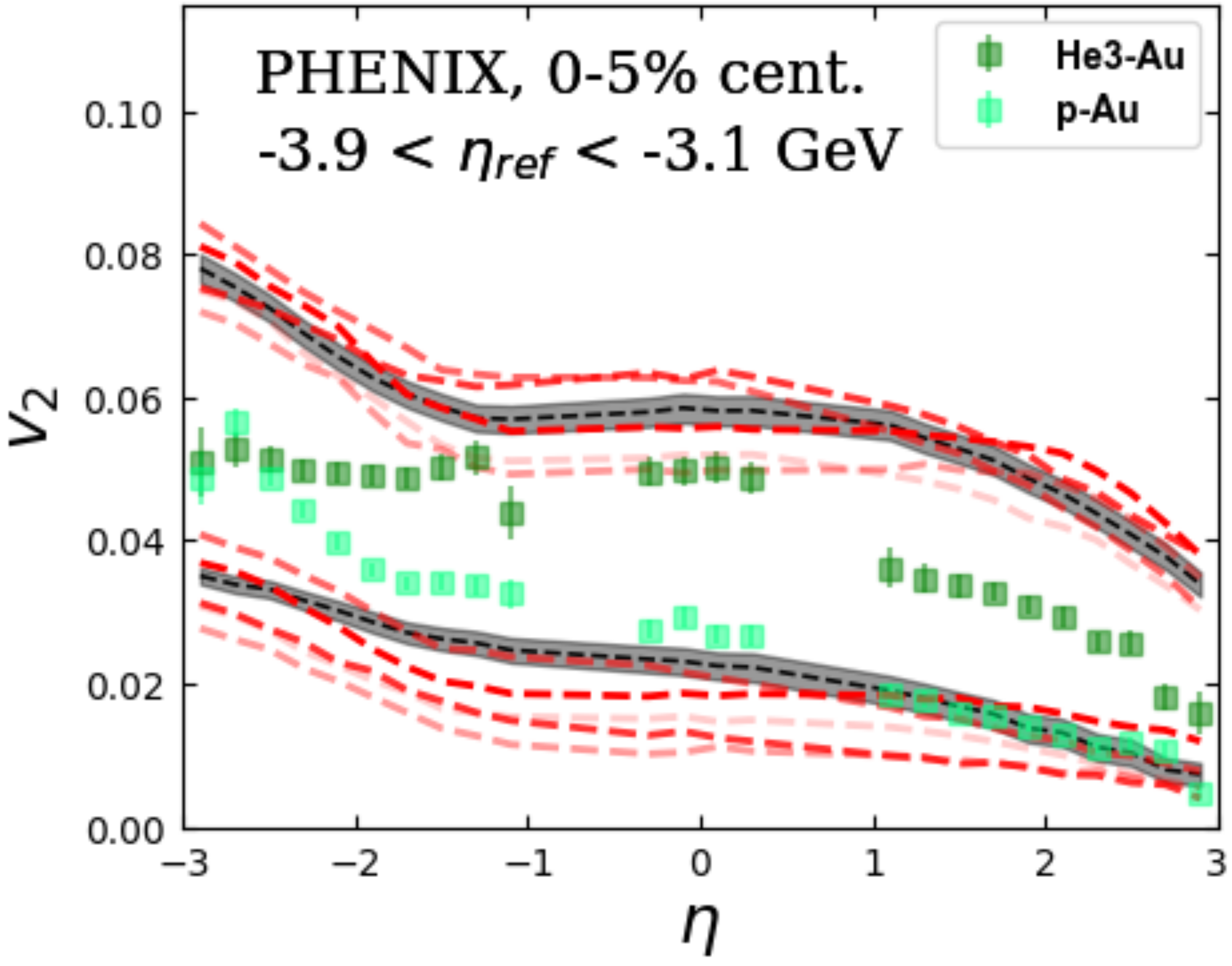
The information content of the MAP vs the full posterior



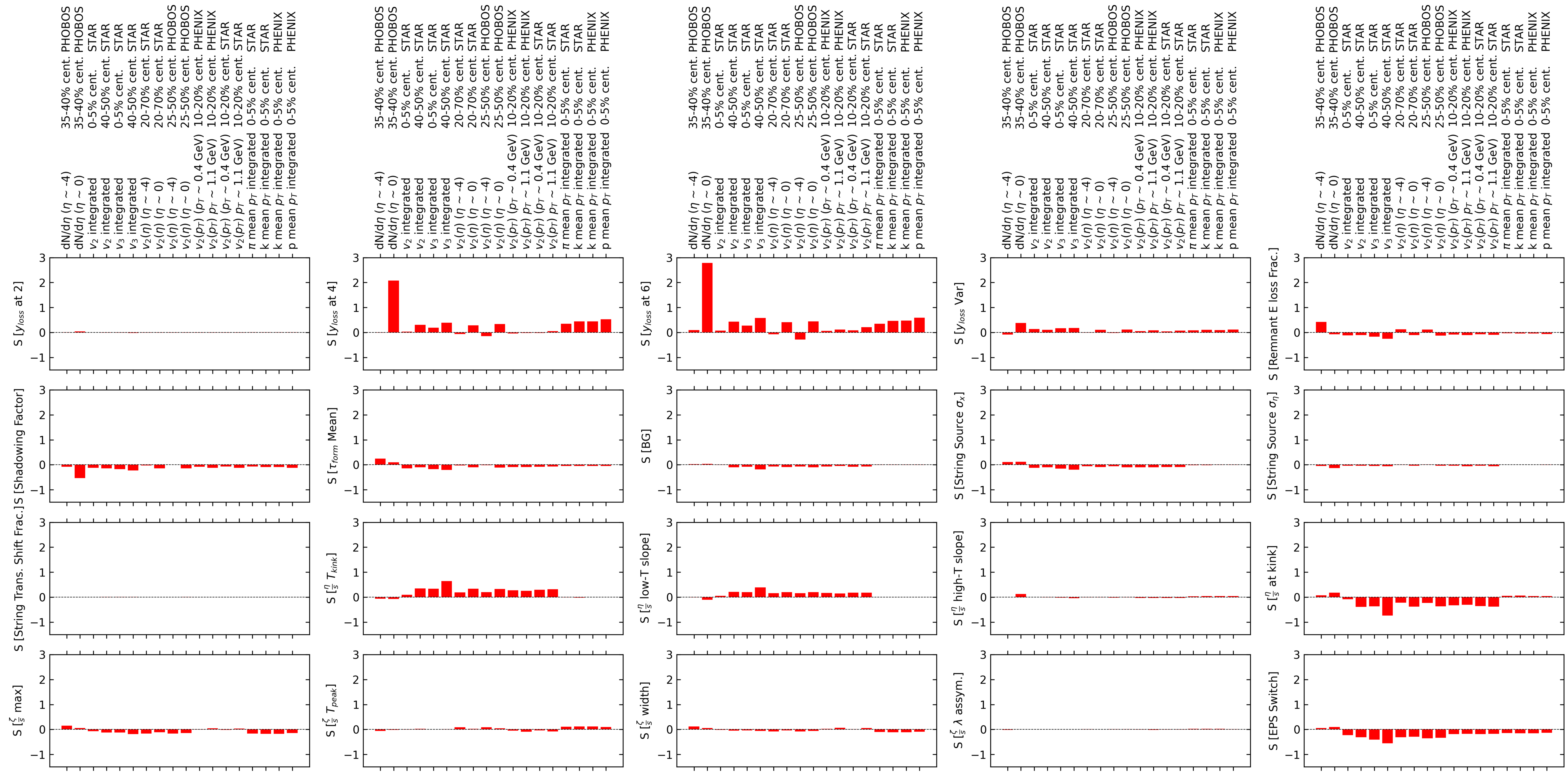


The information content of the MAP vs the full posterior





Model sensitivity to parameters



Sensitivity to key parameters

$$S[x_j] = \Delta_j / \delta$$

x_j - varied parameter

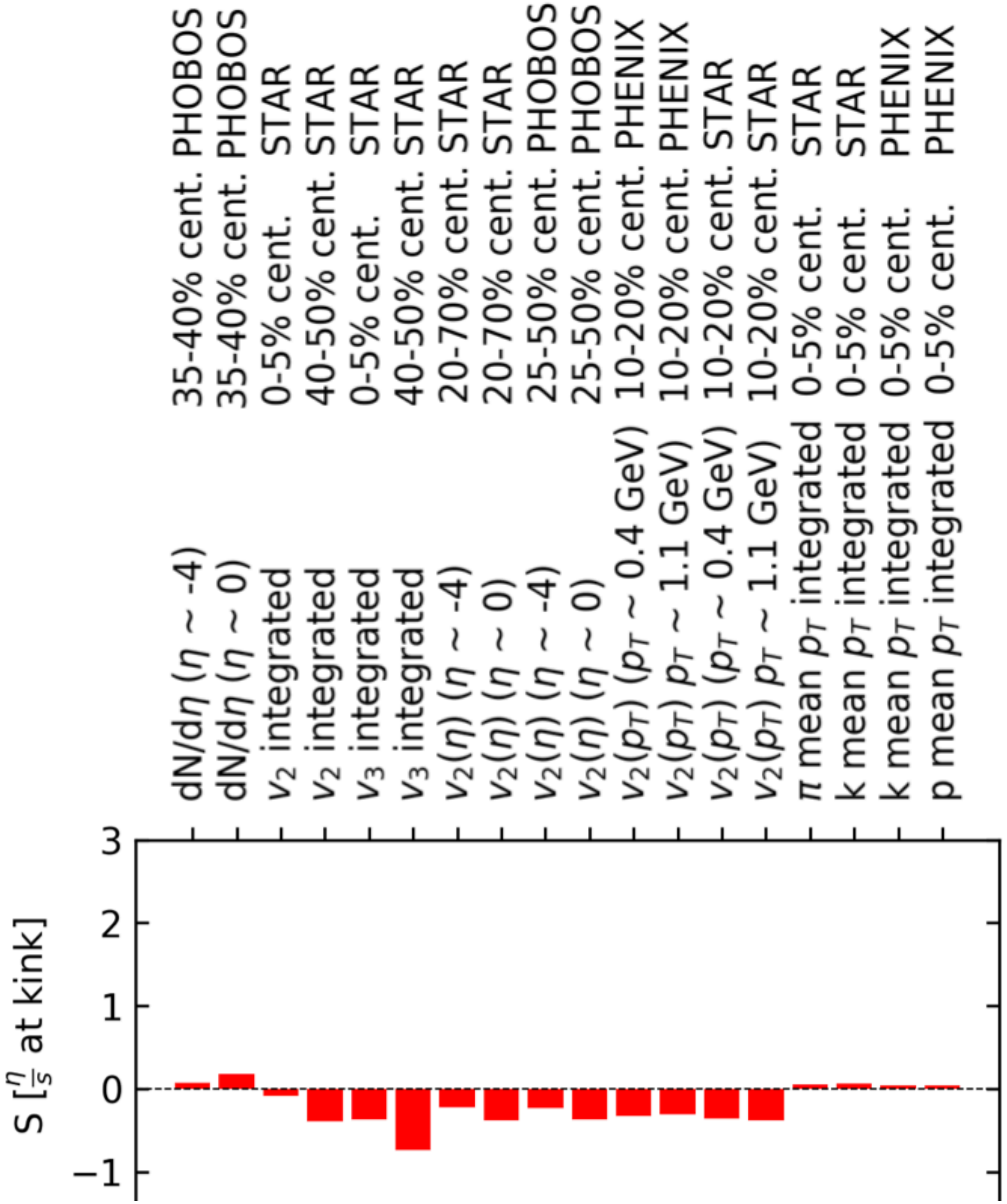
δ - fraction of the latin hypercube training range

$$\Delta_j = \frac{\hat{O}[X_j'] - \hat{O}[X]}{\hat{O}[X]}$$

X - MAP parameters

X_j' - X where x_j is adjusted by an amount proportional to δ

$\hat{O}[\ldots]$ - observables evaluated at a given parameter set



Observable posterior in d-Au