Bayesian parameter estimation in ultra-relativistic heavy-ion collisions

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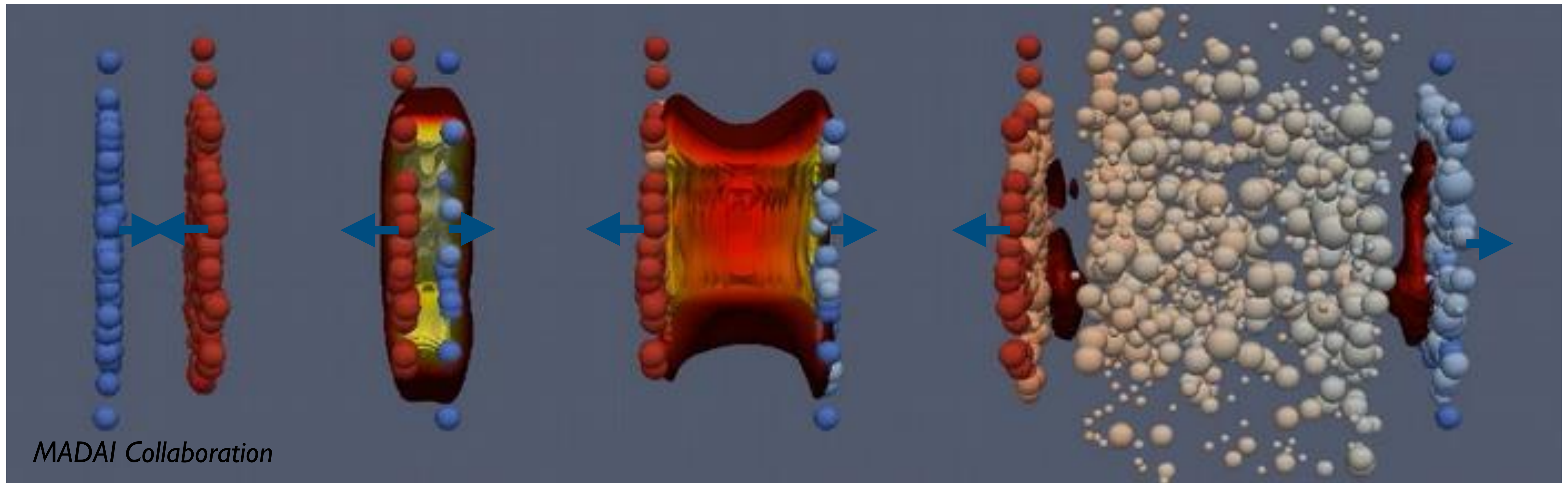
Overview

Heavy-ion collisions involve multiple stages of physics: initial state, hydrodynamic evolution, jet quenching, hadronic rescattering, hadronization, …



Global analysis is needed to:

- Extract physical properties of QGP
- Fit models of the physics that are not known from first-principles

Two different regimes of Bayesian analysis so far

Soft sector

Extract η/s, ζ/s

Novak, Novak, Pratt, Vredevoogd, Coleman-Smith, Wolpert (2014)
Pratt, Sangaline, Sorensen, Wang (2015)
Bernhard, Moreland, Bass, Liu, Heinz (2016)
…

Hard sector

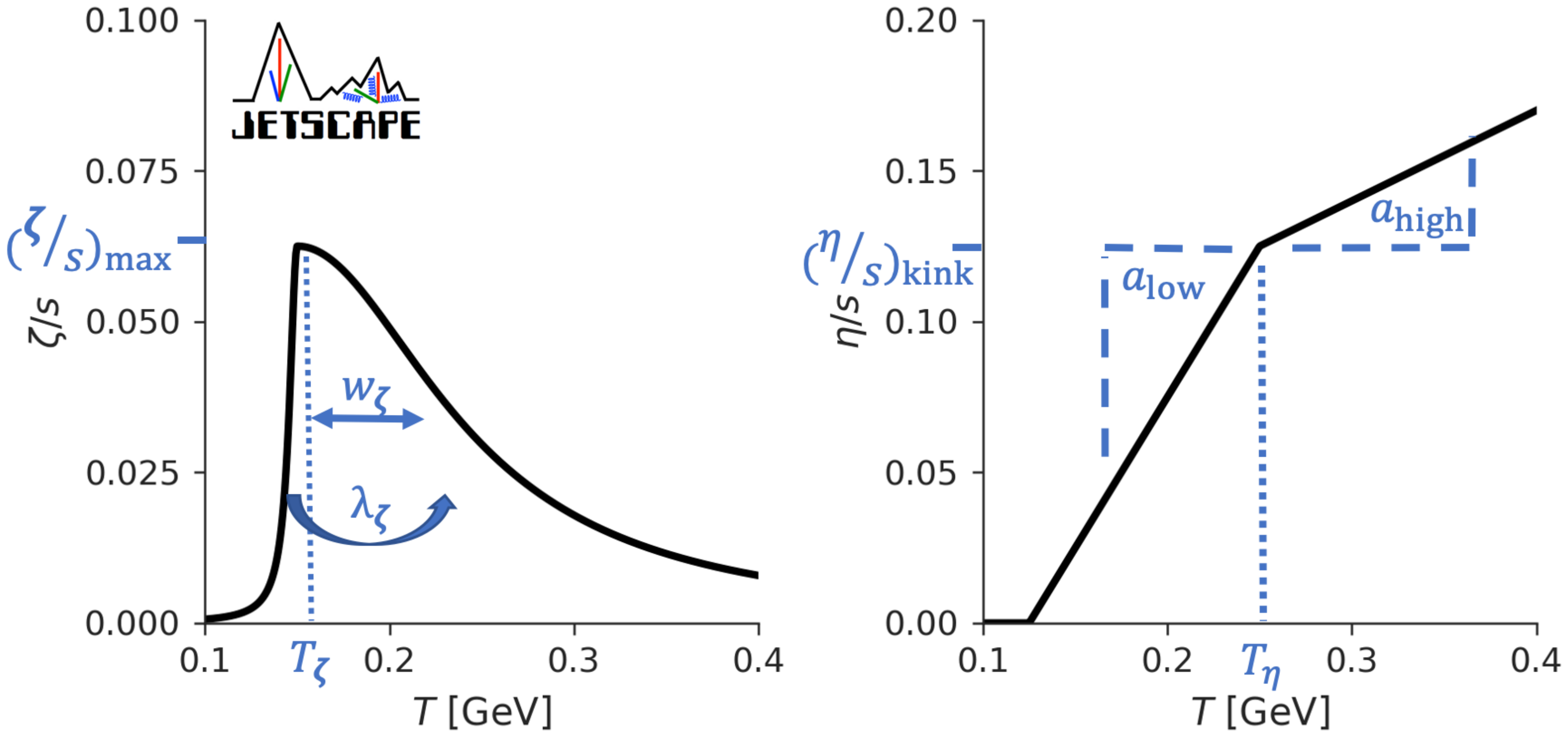
Extract $\hat{q}$, D_s

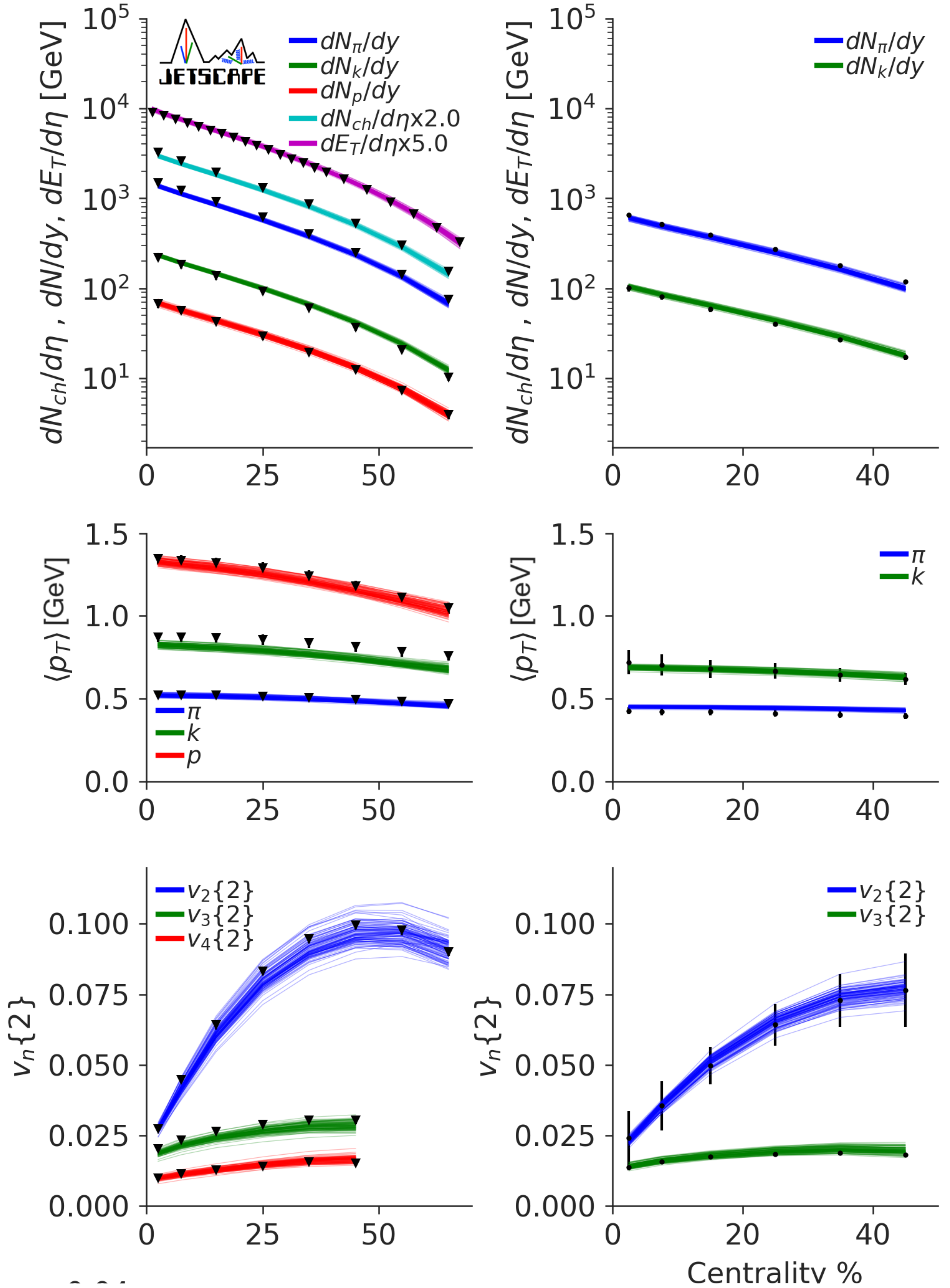
Xu, Bernhard, Bass, Nahrgang, Cao (2018)
JETSCAPE 2102.11337
Ke, Wang (2020)

Soft sector

JETSCAPE 2011.01430

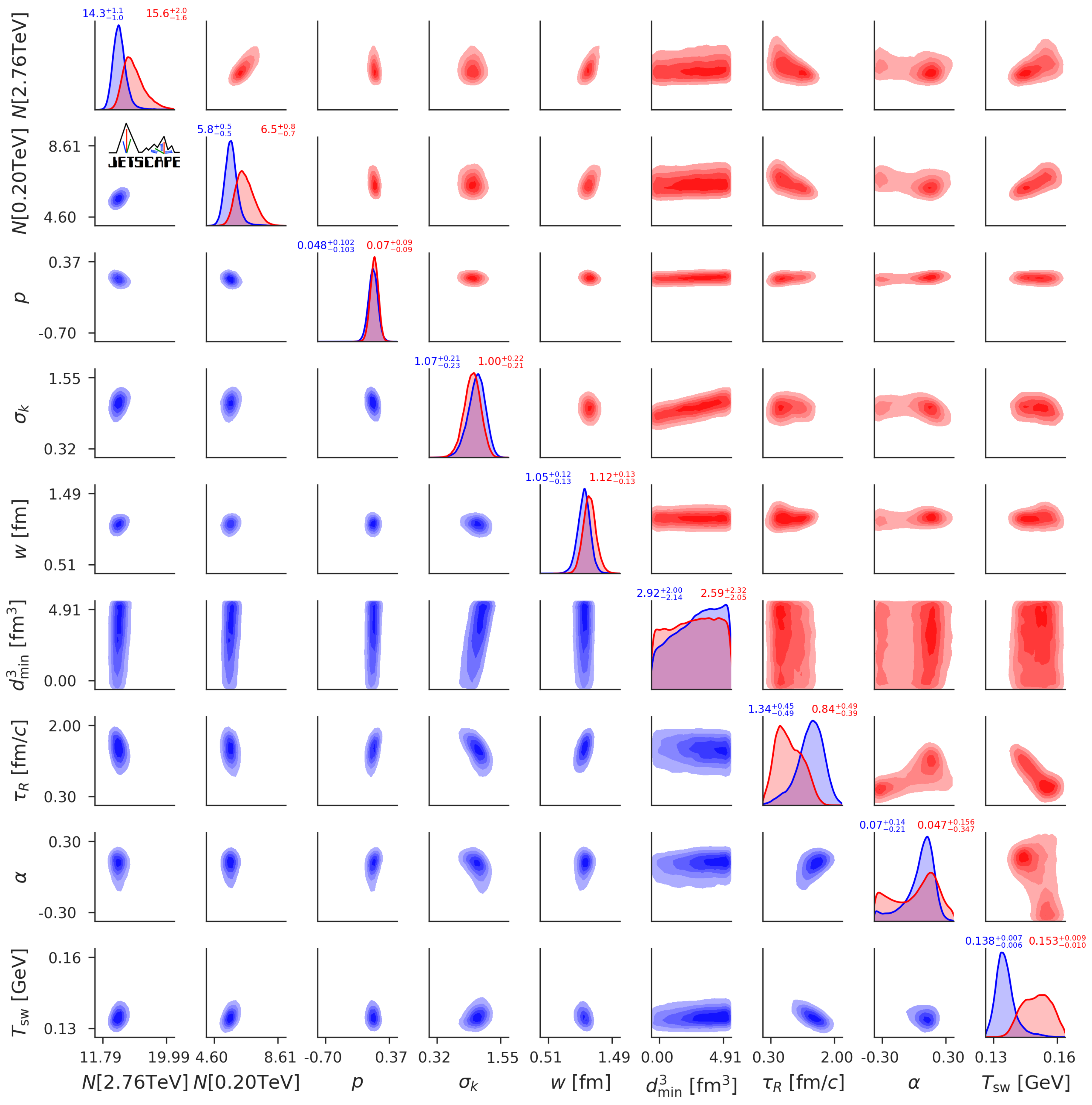
- 17-dimensional fit
  - Flexible parameterizations of η/s, ζ/s
- Data: RHIC+LHC soft observables





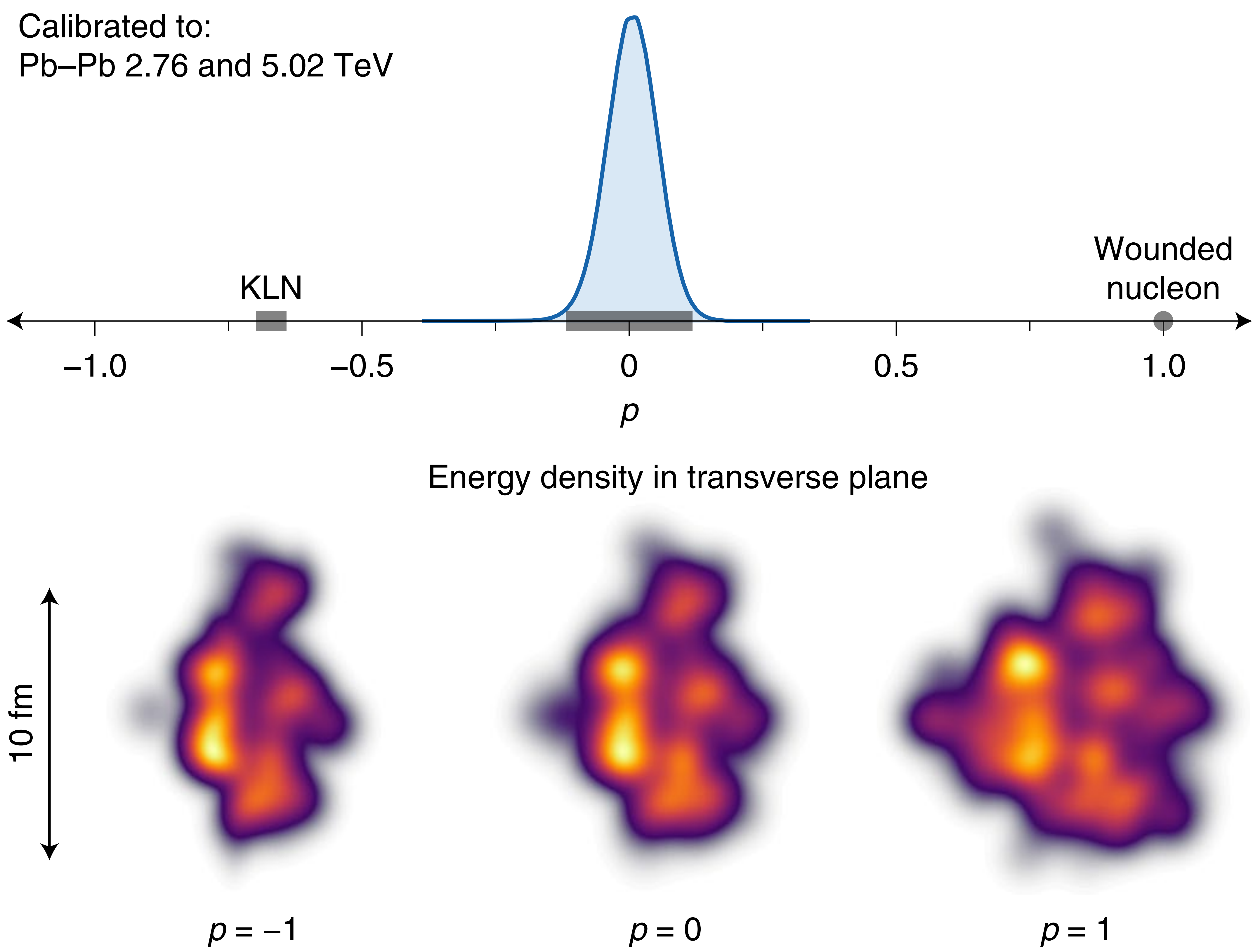
Soft sector

Extracted posteriors



JETSCAPE 2011.01430

Initial energy density

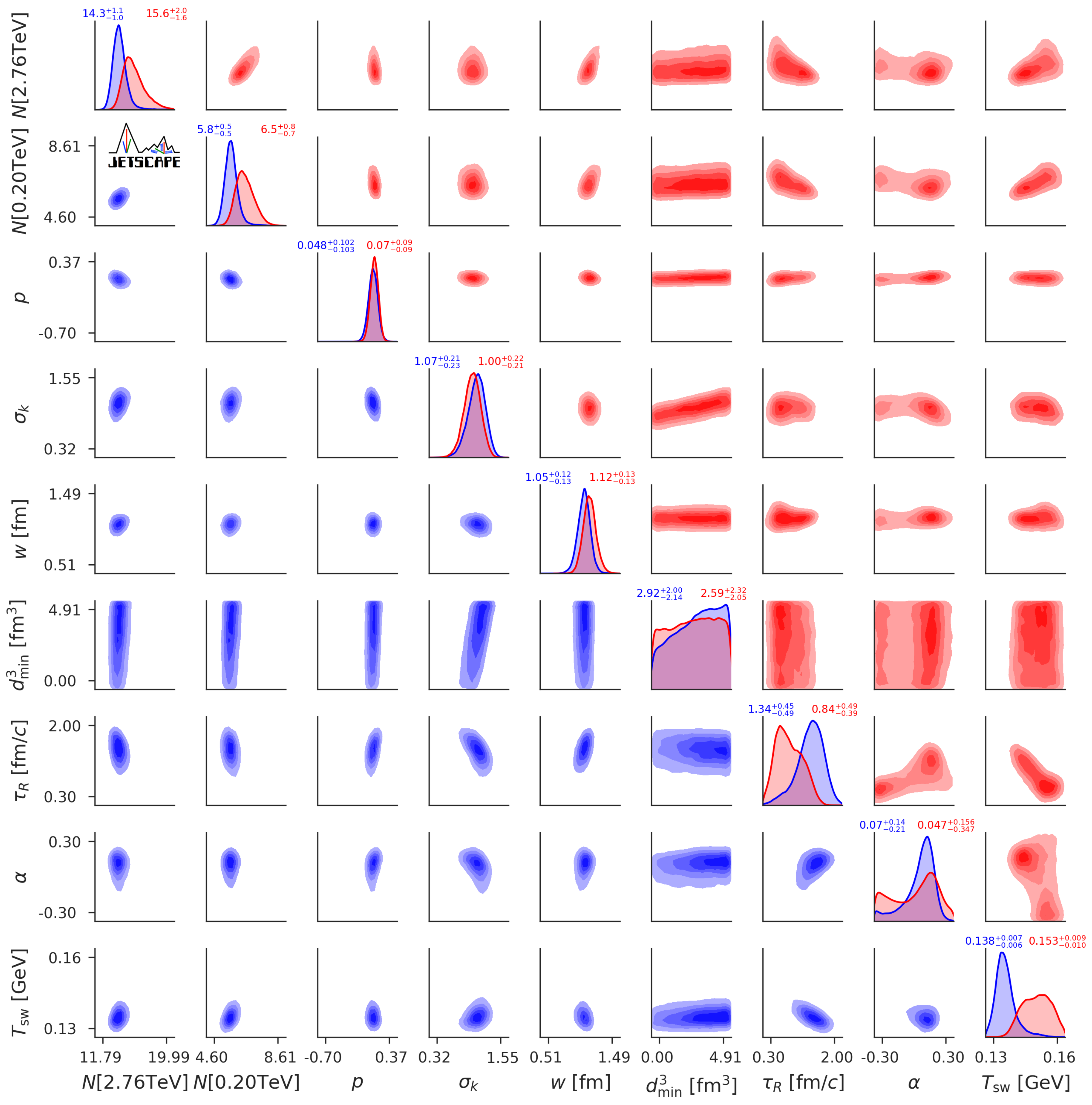


Bernhard, Moreland, Bass Nature Phys. (2019)

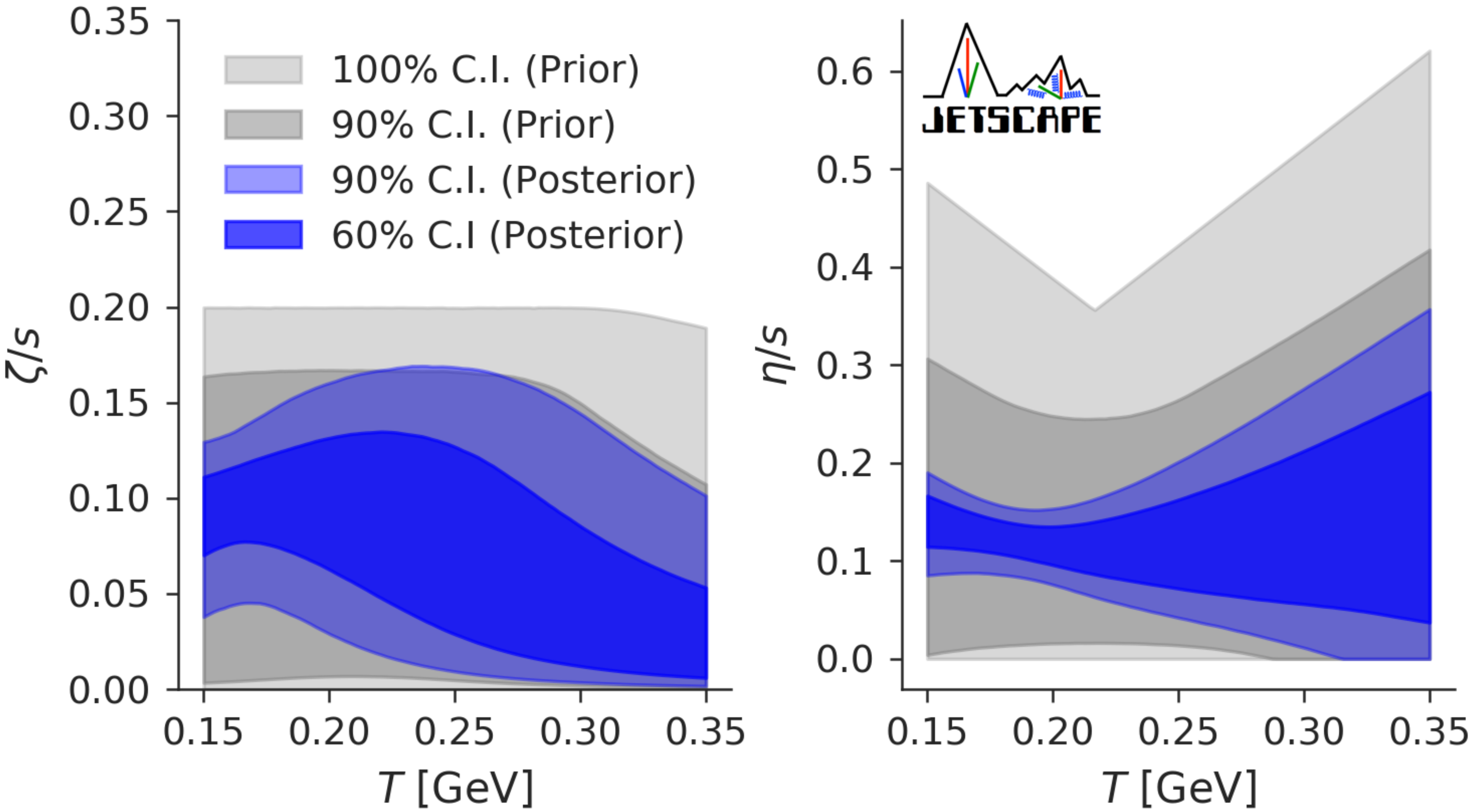
Soft sector

JETSCAPE 2011.01430

Extracted posteriors



Temperature-dependence of specific shear and bulk viscosities



Bayesian Model Selection

JETSCAPE 2011.01430

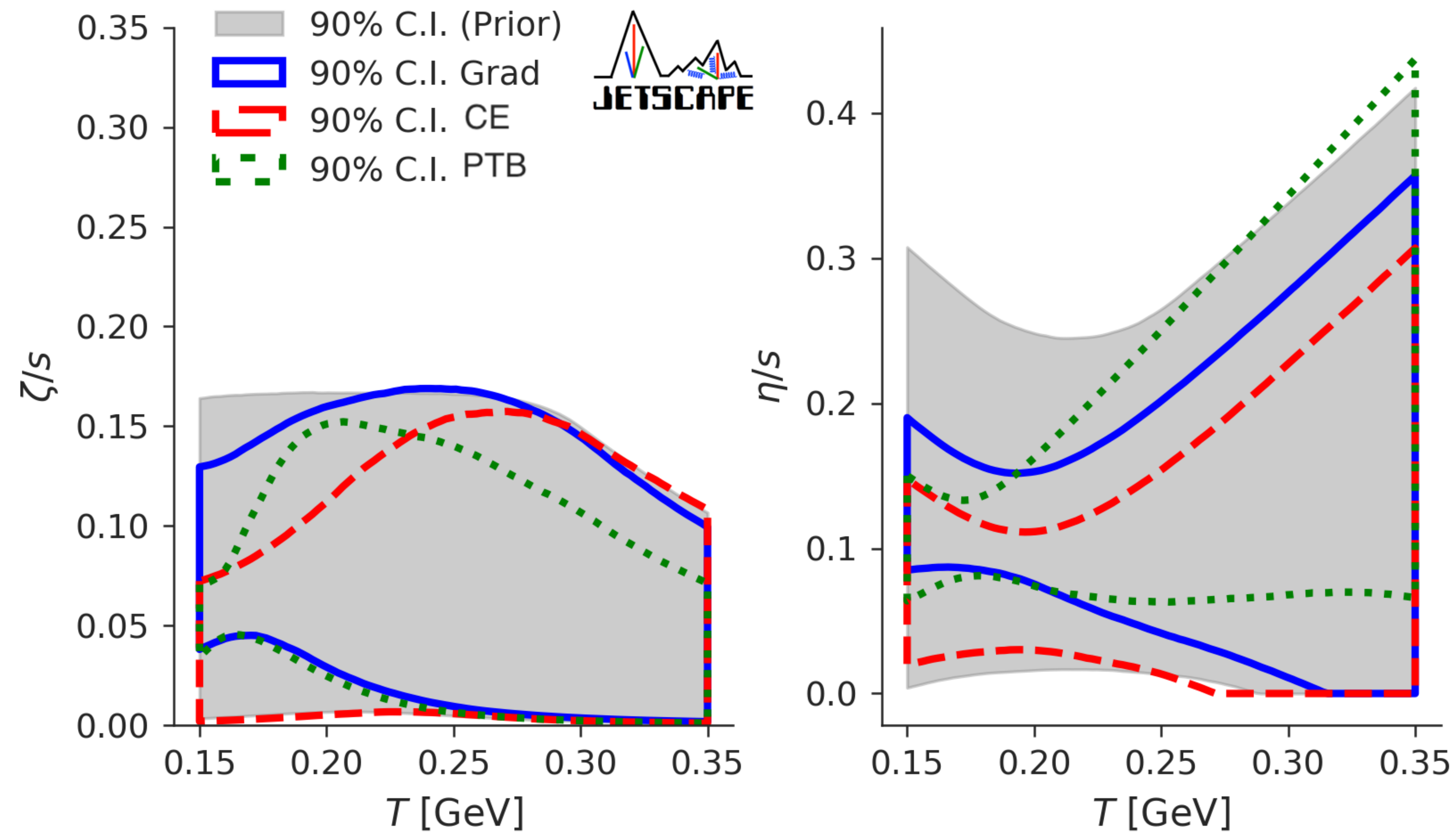
Bayes factor:

$$B_{A/B} = \frac{\mathcal{P}(\mathbf{y}_{\rm exp}|A)}{\mathcal{P}(\mathbf{y}_{\rm exp}|B)}$$

$$\mathcal{P}(\mathbf{y}_{\rm exp}|A) = \frac{1}{\mathcal{V}_A}\int_{\mathcal{D}_A} d\mathbf{x}_A \mathcal{P}(\mathbf{y}_{\rm exp}|\mathbf{x}_A, A)$$

Model A	Model B	$\ln B_{A/B}$
Grad	CE	8.2 ± 2.3
Grad	PTB	1.4 ± 2.5
PTB	CE	6.8 ± 2.4

Provide relative comparison of 3 particlization models



Sensitivity

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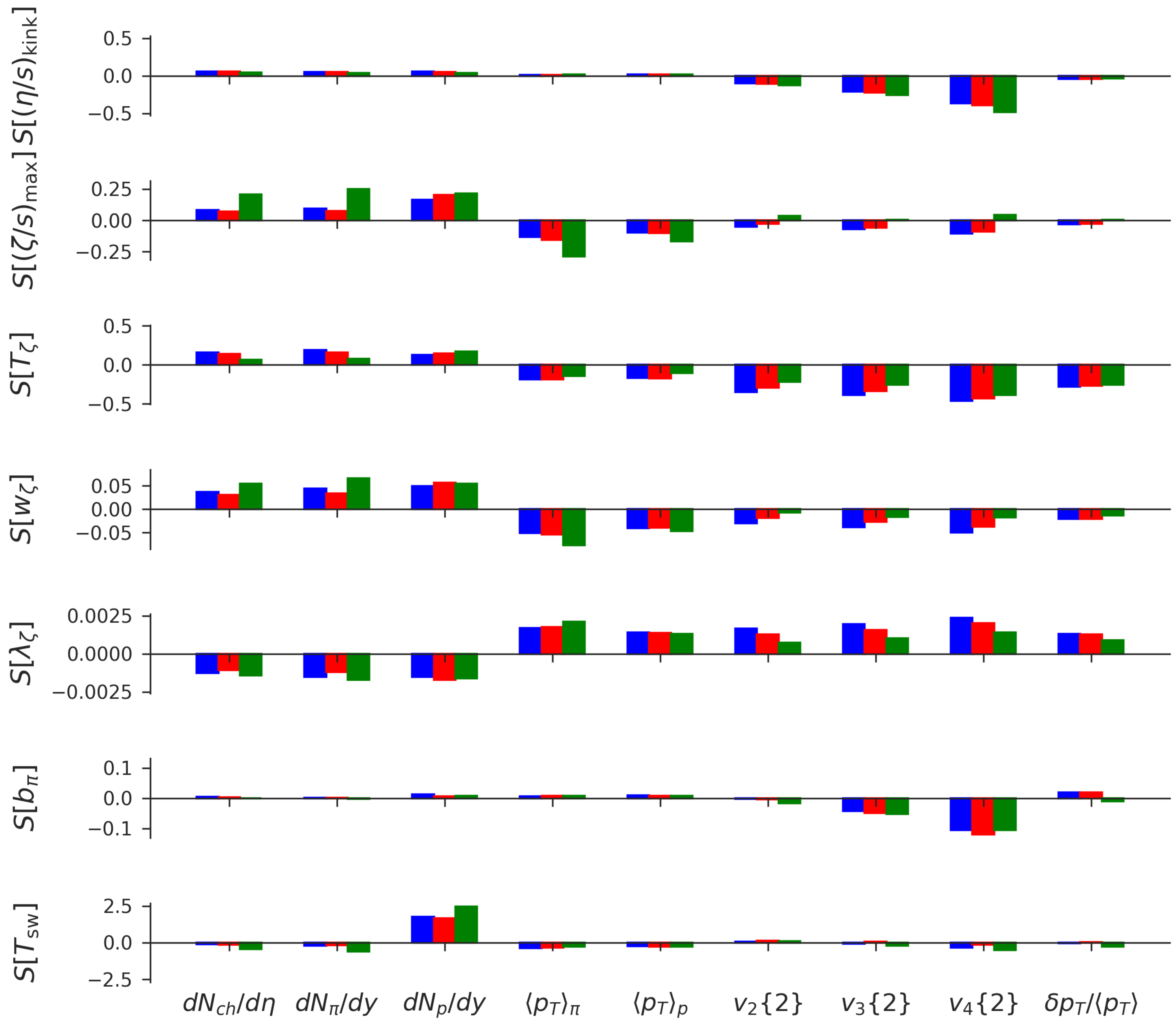
Sensitivity index quantifies the (local) impact of a model parameter on the measured observables

$$S[x_j] \equiv \Delta/\delta$$

Useful for guiding which observables can best constrain models

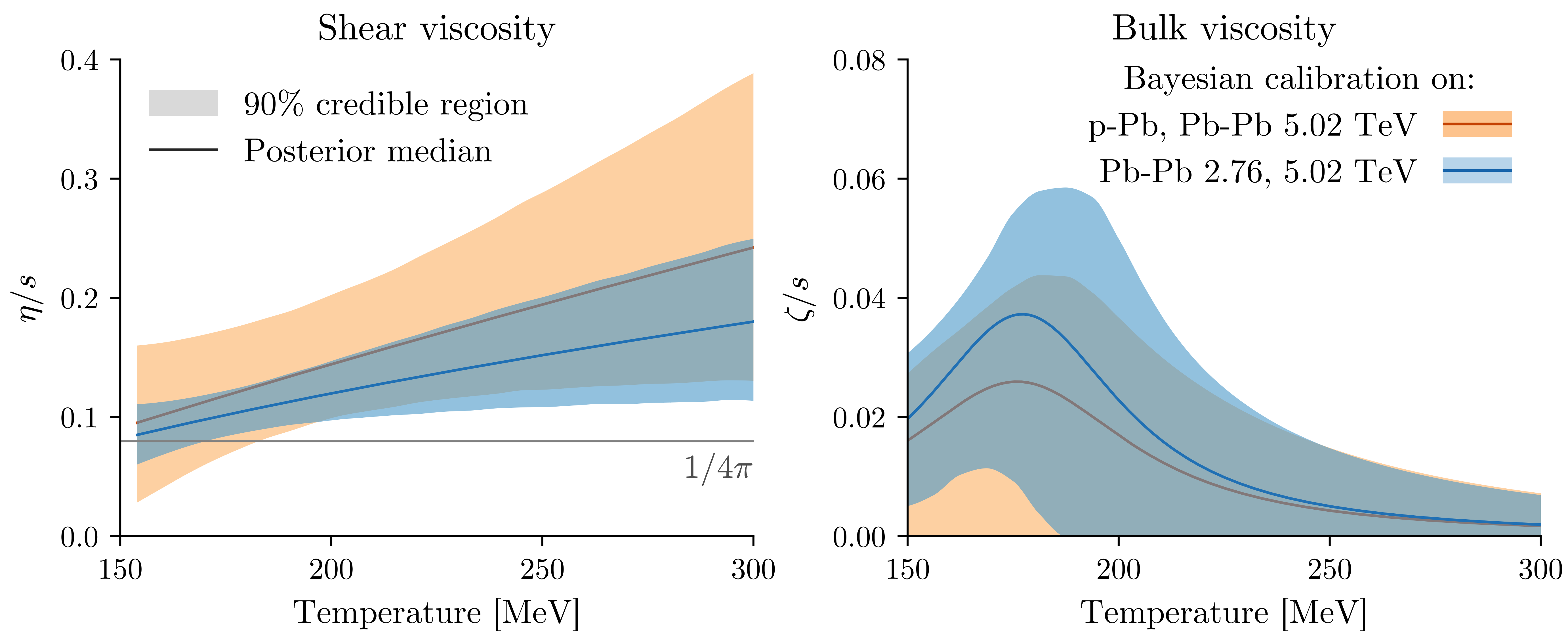
See also:
Sangaline, Pratt (2015)



Small systems

Addition of p-Pb data gives consistent fit — $dN/d\eta$, $\langle p_T \rangle$, v_n

Moreland, Bernhard, Bass (2020)

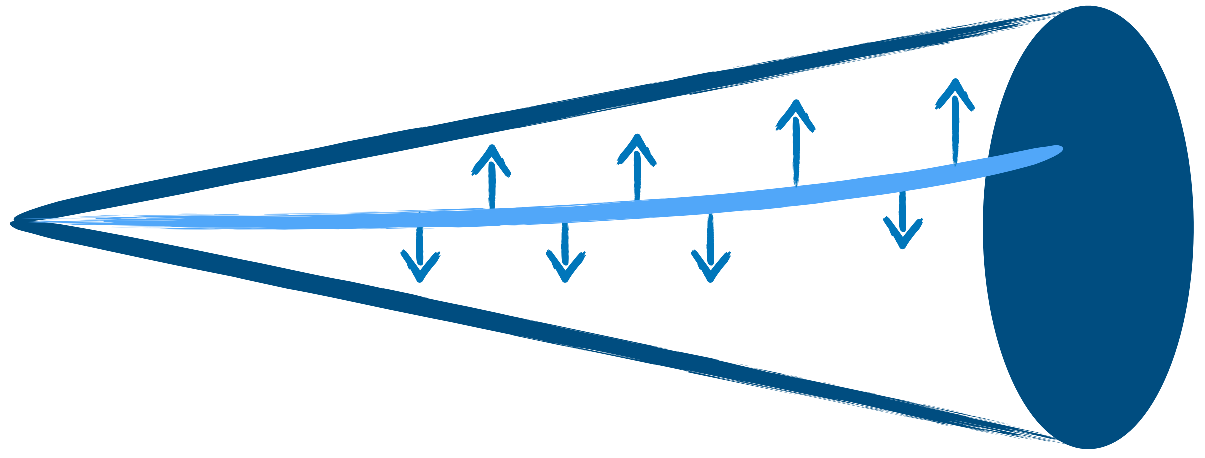


See also:
Nijs, van der Schee, Gursoy, Snellings (2020)
O-O projections

Hard sector

As a parton propagates through the QGP, it will undergo momentum exchanges transverse to its direction of propagation:

$$\hat{q} \equiv \frac{\langle k_\perp^2 \rangle}{L} = \frac{1}{L} \int dk_\perp^2 \frac{dP\left(k_\perp^2\right)}{dk_\perp^2}$$



where $P\left(k_\perp^2\right)$ is a scattering kernel.

We **parameterize** $\hat{q}$ in JETSCAPE with a more general form:

$$\frac{\hat{q}\left(E,T\right)|_{A,B,C,D}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi} \left(\frac{4\pi}{9}\right)^2 \left\{ \frac{A\left[\ln\left(\frac{E}{\Lambda}\right) - \ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2} + \frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2} \right\}$$

High-virtuality inspired

T-independent

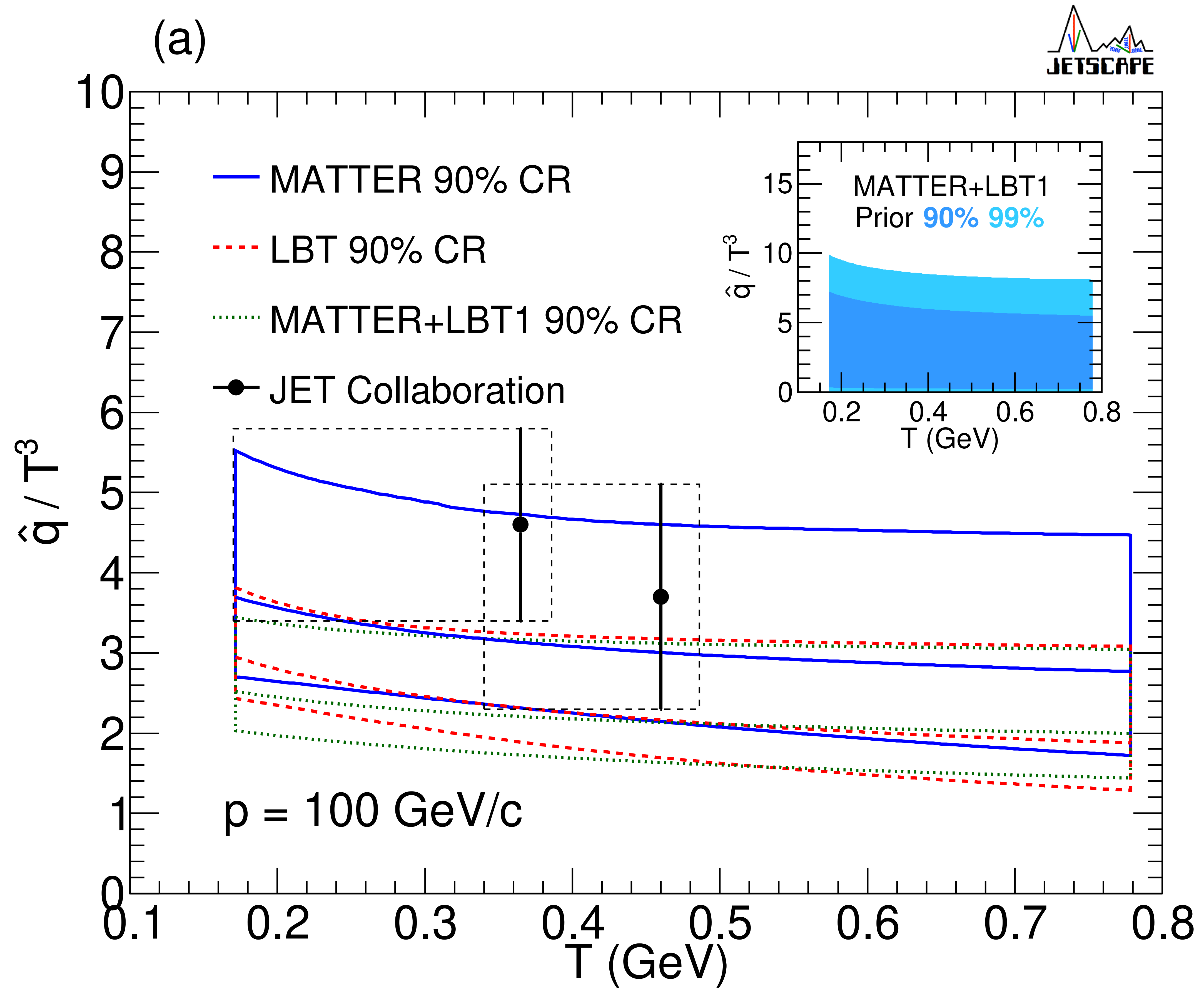
HTL-inspired

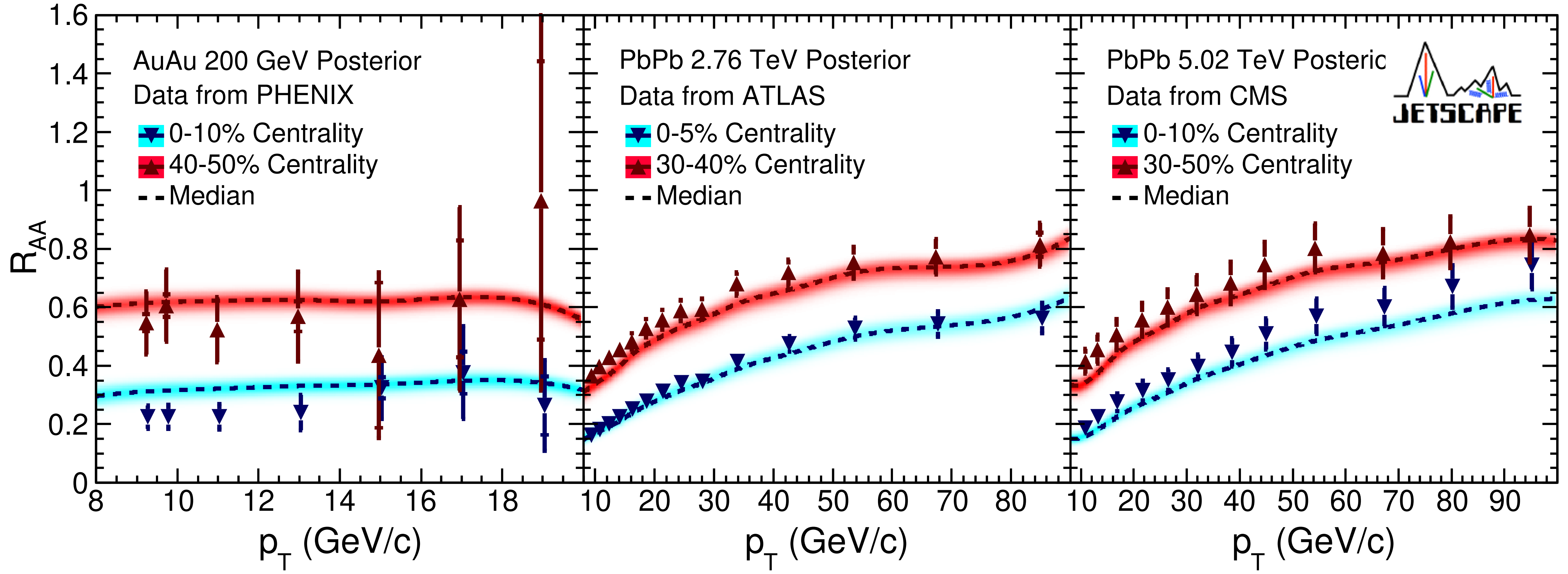
elastic scattering off temperature T

Bayesian estimation of $\hat{q}$

JETSCAPE 2102.11337

Extraction of $\hat{q}$ as a continuous function of T, p using inclusive hadron R_{AA} data from RHIC+LHC





Main conclusions:

- Significant constraints on prior
- No evidence (yet) that multi-stage model improves agreement with data

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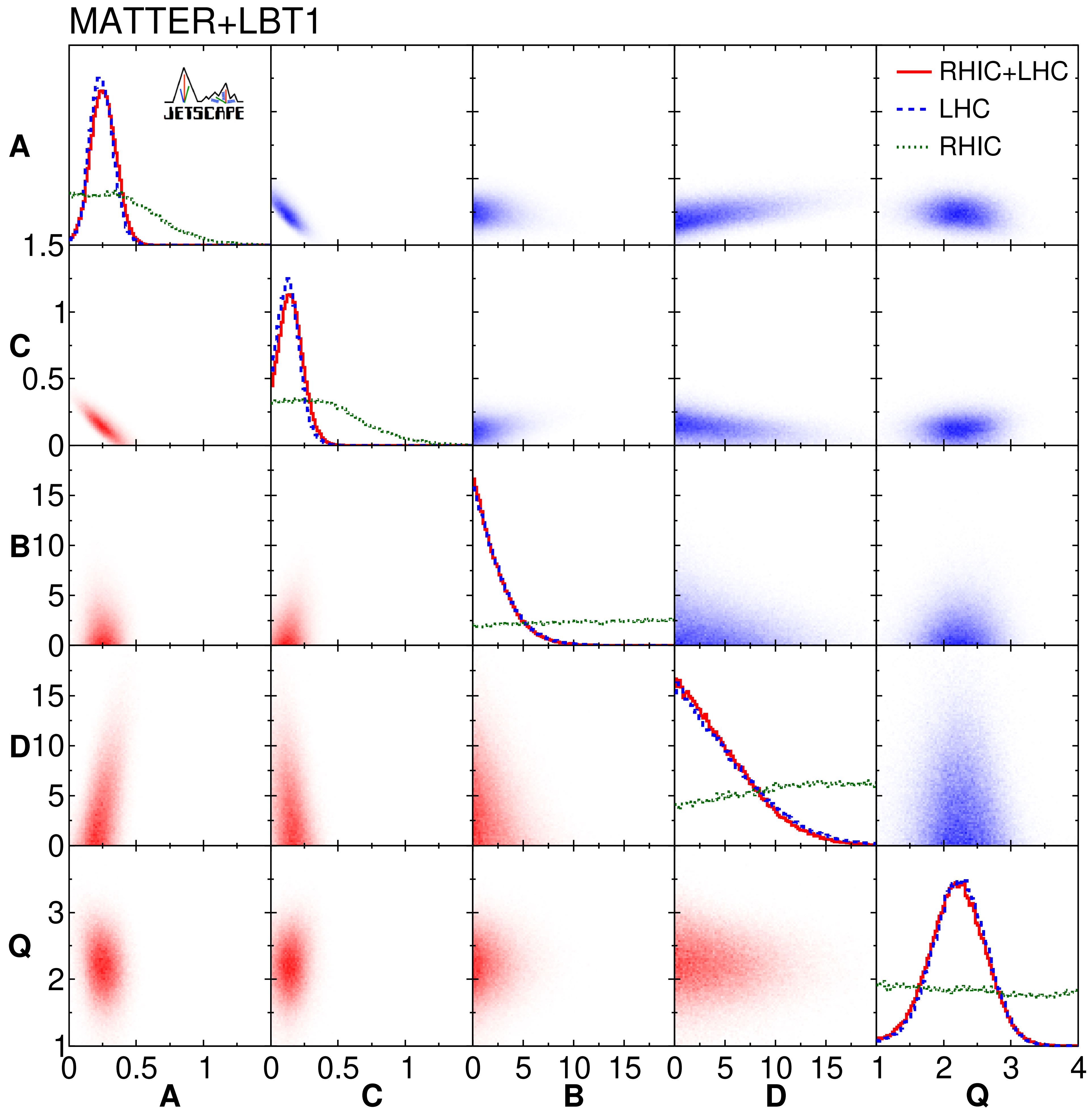
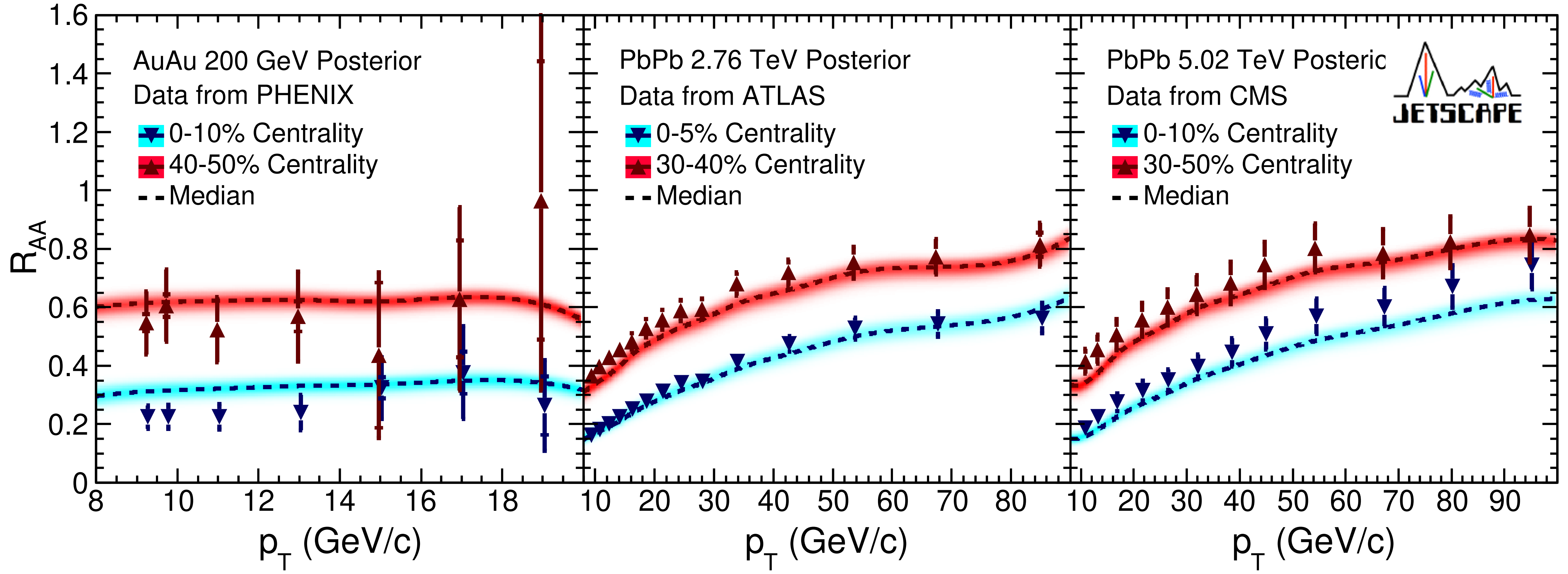




Main conclusions:

- Significant constraints on prior
- No evidence (yet) that multi-stage model improves agreement with data
- Fit dominated by LHC data

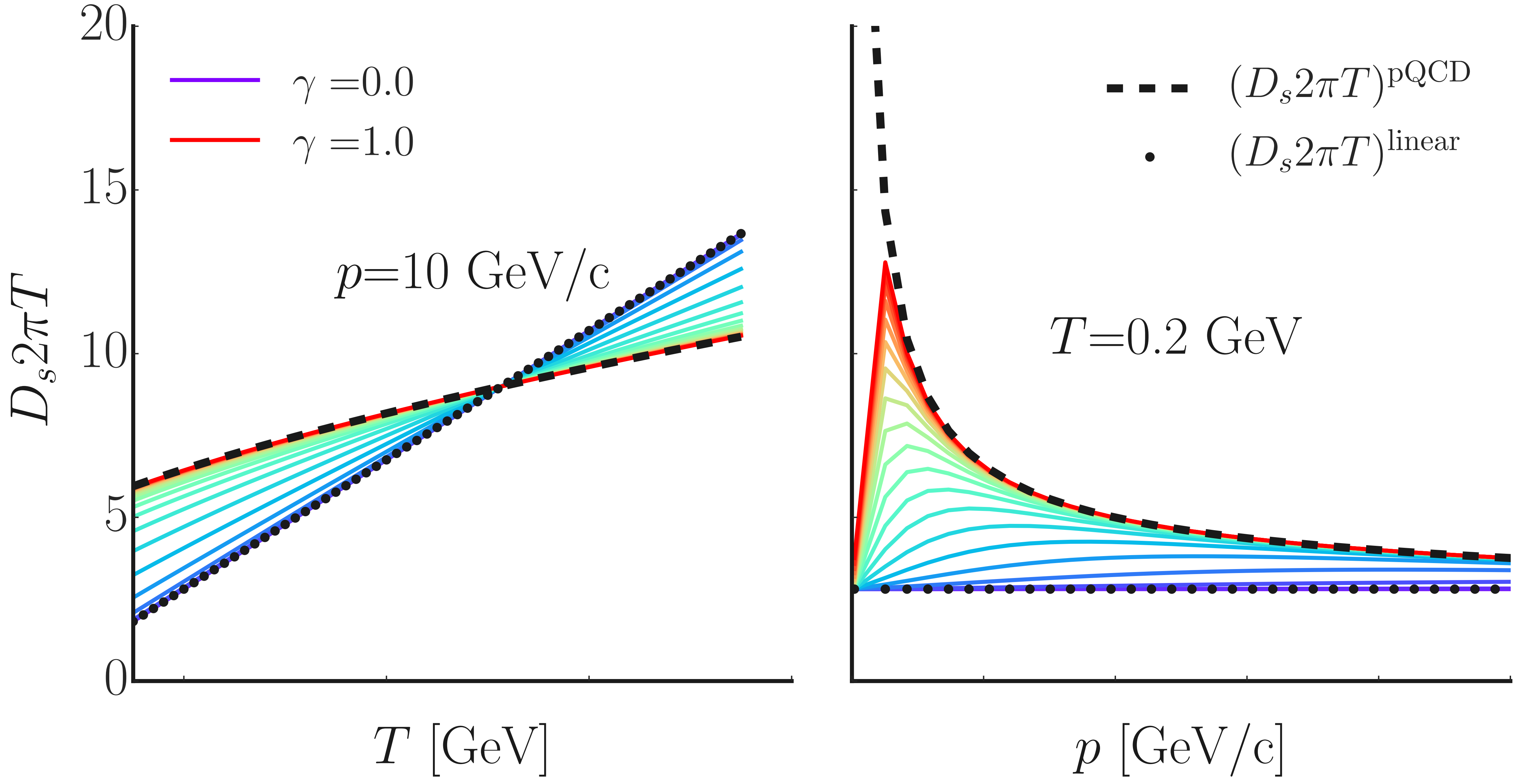
  Due to choice of cutoff: $p_T < 8$ GeV$/c$

Heavy quark diffusion

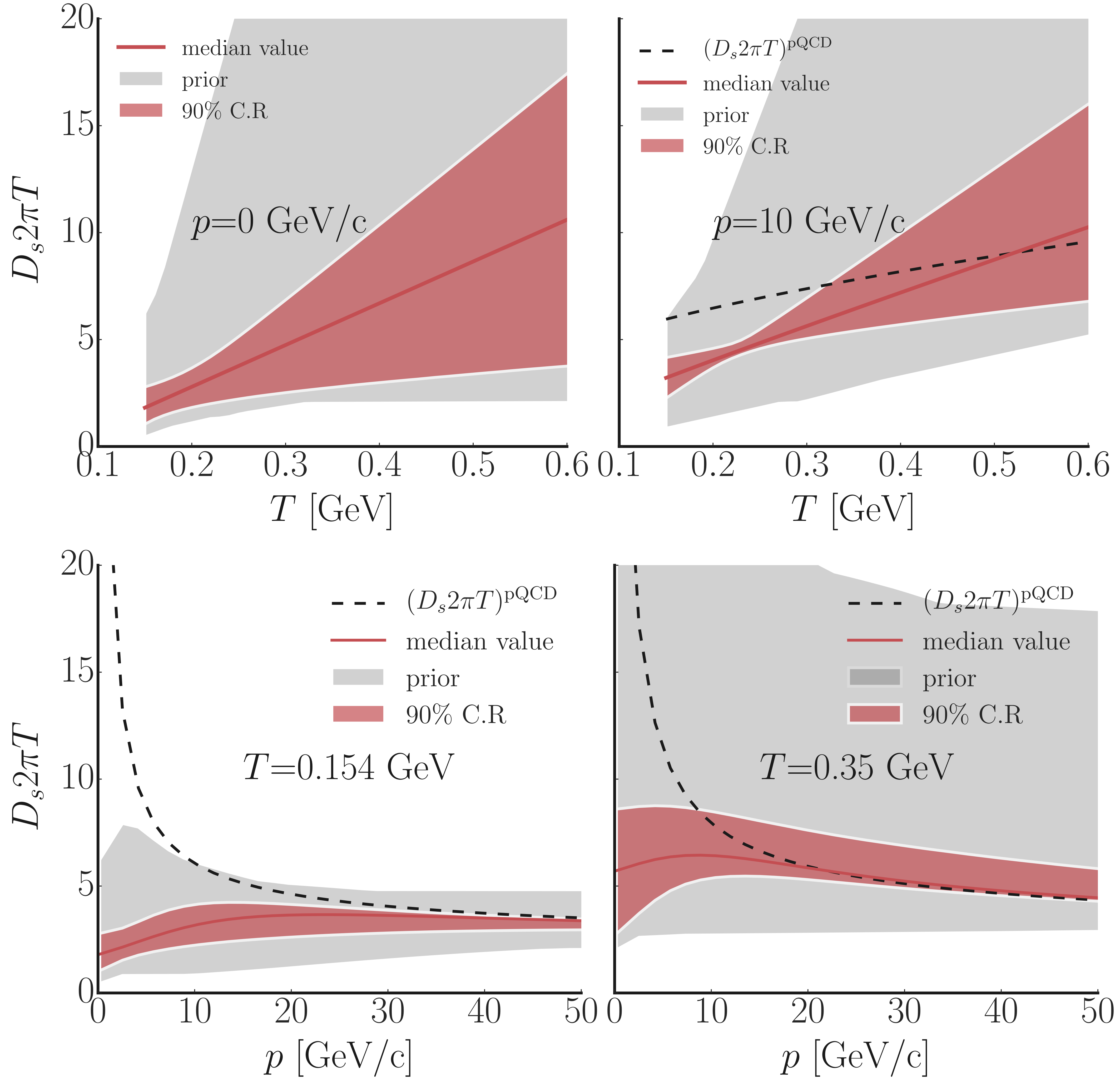
Xu, Bernhard, Bass, Nahrgang, Cao (2018)

Parameterize spatial diffusion coefficient with nonperturbative and pQCD contributions:

$$D_s 2\pi T(T, \boldsymbol{p}) = \frac{1}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\text{linear}} + \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\text{pQCD}}$$



Bayesian estimation using D-meson R_{AA}, v_2



Summary

Bayesian parameter estimation has been actively used in recent years to extract a variety of properties of the quark-gluon plasma

- Soft sector
  - Handful of analyses: Shear and bulk viscosity, initial state, particlization, …
  - Small systems: p-Pb, O-O
- Hard sector
  - Jets: proof-of-principle extraction of $\hat{q}$ using inclusive hadron R_{AA} data
  - Heavy quarks: first Bayesian extraction of D_s using D meson R_{AA}, v_2

Some work done on model sensitivity and model selection — important for future!

Backup

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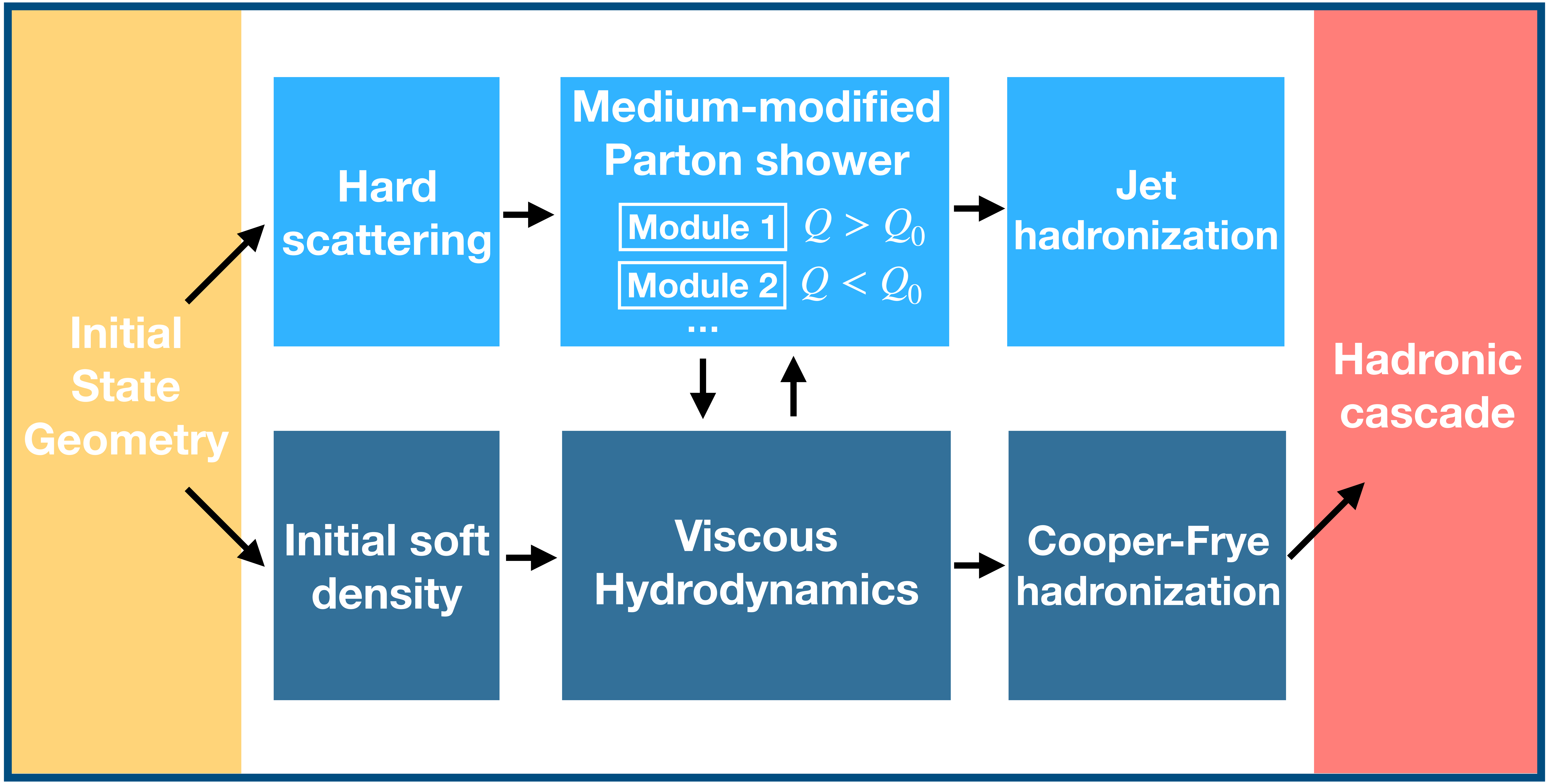
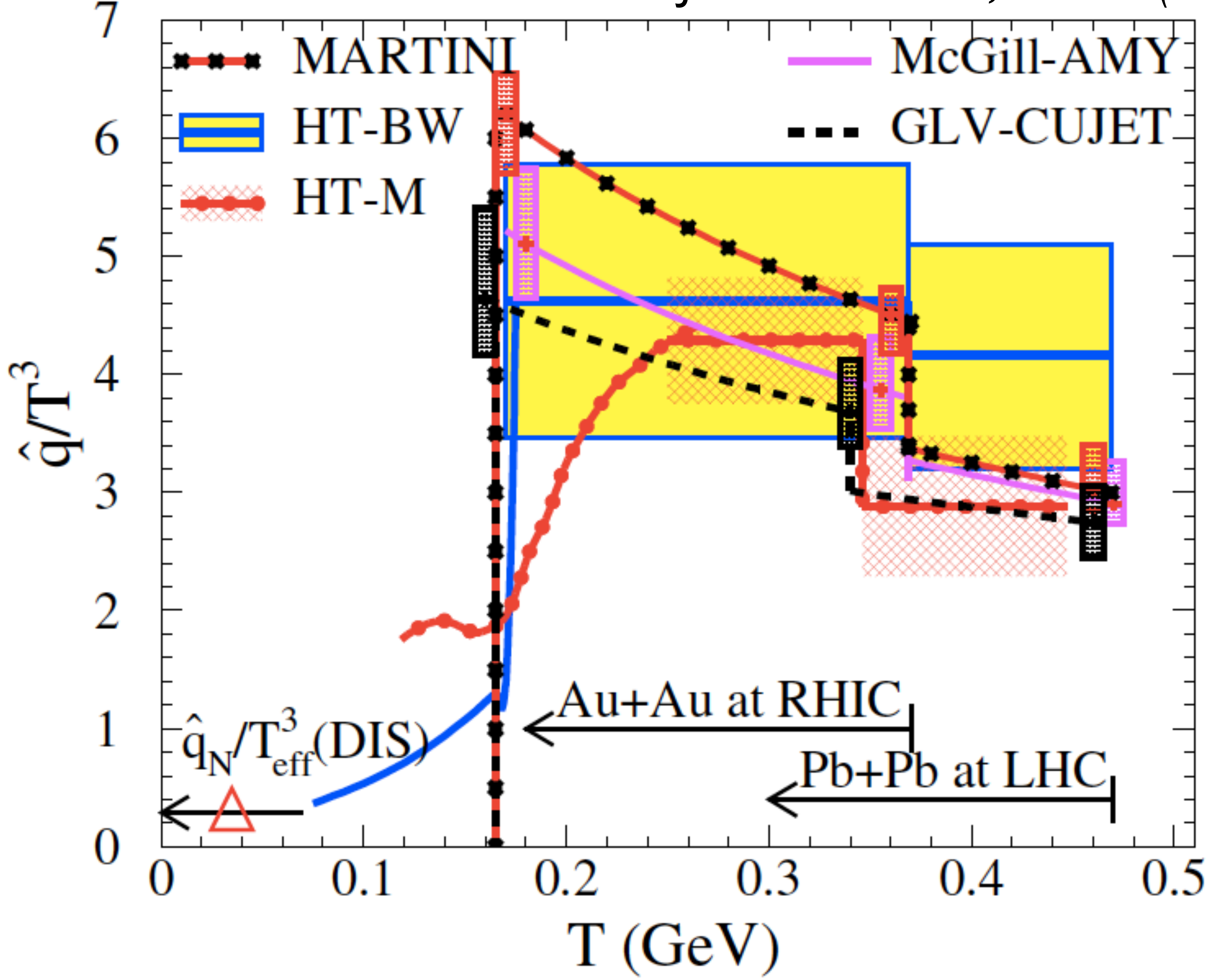


Initial
State
Geometry
Hard
scattering
Medium-modified
Parton shower
Module 1 $Q > Q_0$
Module 2 $Q < Q_0$
...
Jet
hadronization
Initial soft
density
Viscous
Hydrodynamics
Cooper-Frye
hadronization
Hadronic
cascade

From Least Squares to Bayesian

Previous work: Separate fits of $\hat{q}$ at RHIC and LHC for various pQCD models

JET Collaboration, PRC 90 (2014)



JETSCAPE: Extraction of $\hat{q}$ as a continuous function of T, p

JETSCAPE 2102.11337