Measuring jet quenching with a Bayesian Inference analysis of hadron and jet data by JETSCAPE

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05 September 2023 Quark Matter 2023

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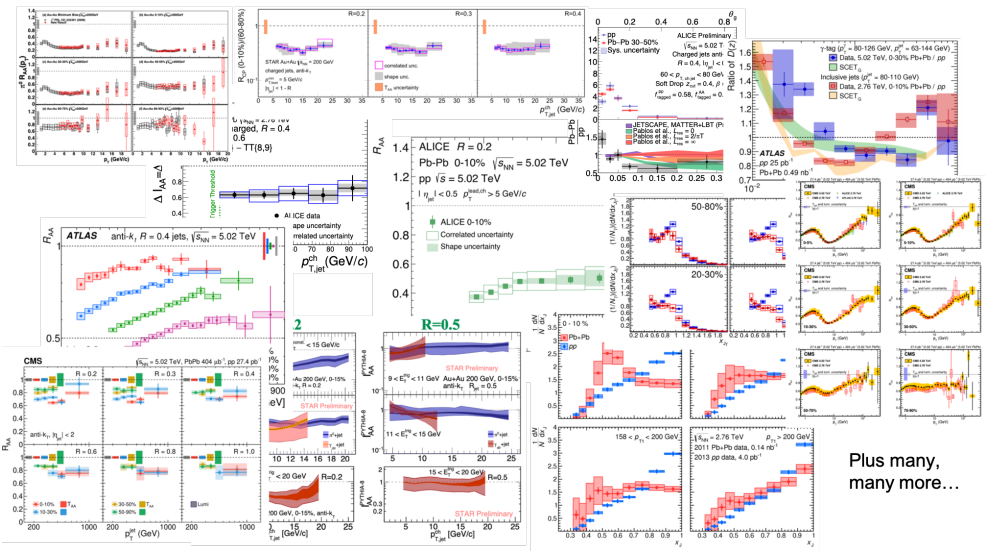
Jet quenching measurements



How can we make a consistent picture?

What physics can we extract?

What information is contained in each observable?

Bayesian inference

Given data $\vec{x}$ and parameters $\vec{\theta}$, we can apply **Bayes' theorem**:

$$P(\theta|x) = \frac{P(x|\theta)P(\theta)}{P(x)}$$

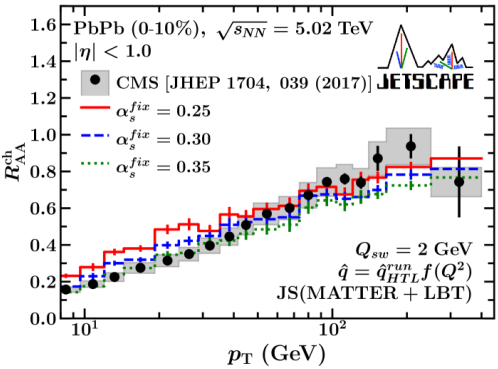
- $P(\theta|x)$: **posterior dist.**: prob. of θ given x
  - Most prob. value $\rightarrow$ **best description** of data
- $P(x|\theta)$: **likelihood** x is described by θ
  - Depends on covariance, **data + theory uncert.**
- $P(\theta)$: **prior** distribution for θ
  - Choice makes assumptions explicit

$\rightarrow$ **Posterior encodes everything we want to learn**

- Approach enables **computationally tractable approach** to extract parameters
  - Although still CPU intensive!

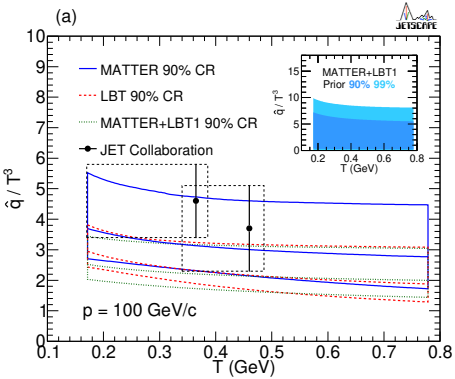
Bayesian inference: high level summary

Qualitative



Bayes →

Quantitative



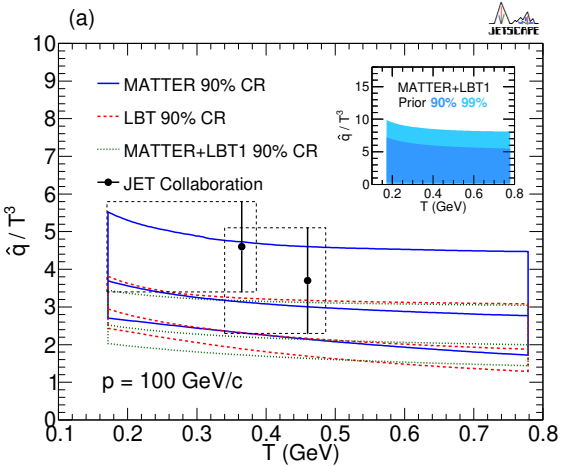
First analysis (2021)

Data

- **Hadron R_{AA}**
- 3 $\sqrt{s_{NN}}$, 2 centralities per energy
- Treat experimental uncert. correlations where possible

Model

- Extract parametrized $\hat{q}(T, E, Q)$
- Multistage: MATTER + LBT
- Goal: One step forward from JET results, **proof of concept for one unified $\hat{q}$ across $\sqrt{s_{NN}}$**



JETSCAPE, Phys.Rev.C 104 (2021) 2, 024905

Current iteration (2022-present)

Data

- Hadron + **jet R_{AA}**
- **Additional jet observables**
- 3 $\sqrt{s_{NN}}$, **all eligible data**
- Treat experimental uncert. correlations where possible

Model

- Extract **reparametrized $\hat{q}(T, E, Q)$**
- Use **calibrated 2+1D hydro**
- Multistage: MATTER + LBT

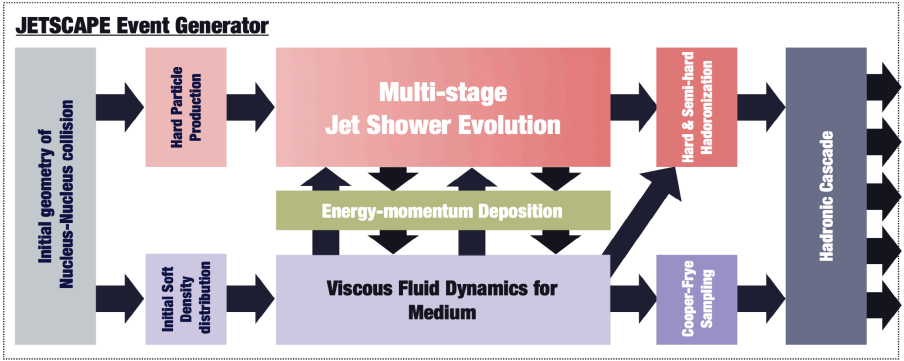
- Goal: what do **jets bring to the analysis**?

Strategy

- **Significant computing effort** - O(10M) CPU hours
- Calculated many **more observables for differential studies**

JETSCAPE Framework

- **MC event generator package for heavy ion collisions**
  - General, modular and extensible
  - Communication between modules
  - Available on GitHub github.com/JETSCAPE



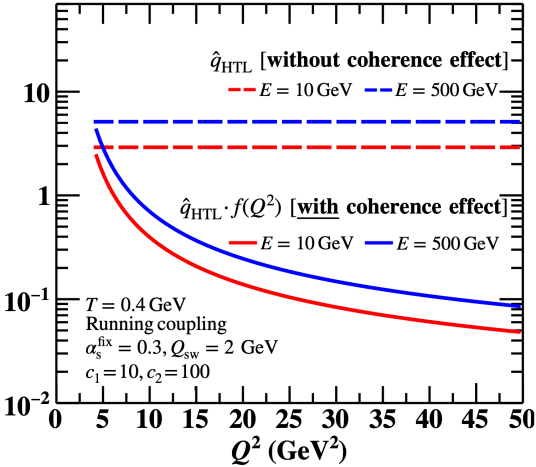
$\hat{q}$ parametrization

$$\hat{q}(E,T,Q) = \hat{q}^{\text{run}}_{\text{HTL}} \times f(Q^2)$$

$$\hat{q}^{\text{run}}_{\text{HTL}} = \alpha_{s,\text{fix}} \times \alpha_s(\mu^2) C_a \frac{42\zeta(3)}{\pi} T^3 \log\left(\frac{\mu^2}{6\pi T^2 \alpha_{s,\text{fix}}}\right)$$

$$f(Q^2) = \left.\frac{N(\exp(c_3(1-x_B))}{1 + c_1 \ln(Q^2/\Lambda^2_{\text{QCD}}) + c_2 \ln^2(Q^2/\Lambda^2_{\text{QCD}})}\right|_{Q \geq Q_0}$$

- 6 total parameters:
  - α_s
  - c_1, c_2, c_3
  - Q_0 (switching virtuality)
  - τ_0 (start time)

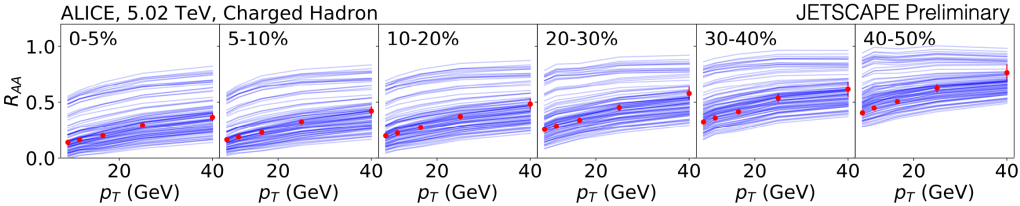


- Taken as one possible **candidate** model
  - Want to take full advantage of JETSCAPE as a modular framework

JETSCAPE, Phys.Rev.C 107 (2023) 3, 034911
JETSCAPE, arXiv:2301.02485

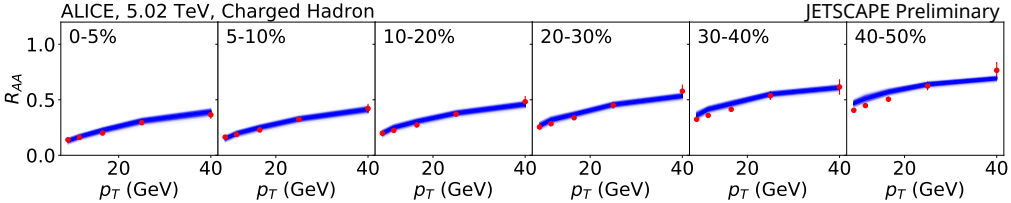
From prior to posterior

Prior:
Data
Calculations



analysis

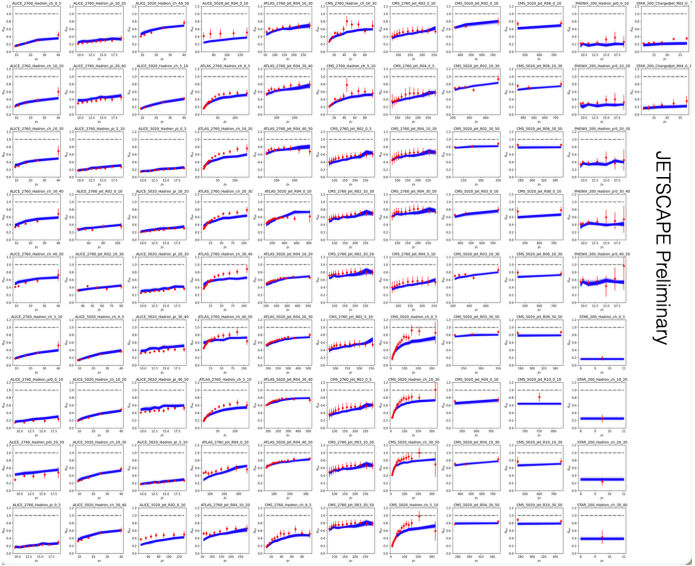
Posterior:
Data
Best fit



Observables posterior

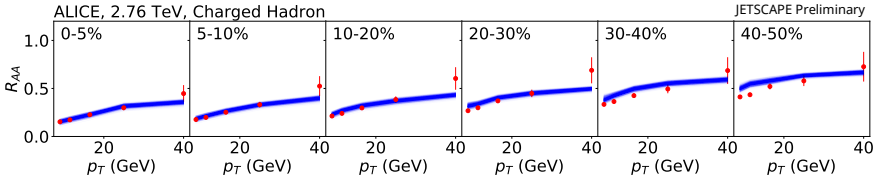
- **Reasonable overall agreement**
- **Some tension** for particular measurements

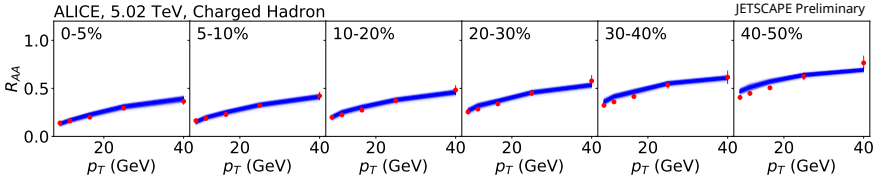
→ Let's explore

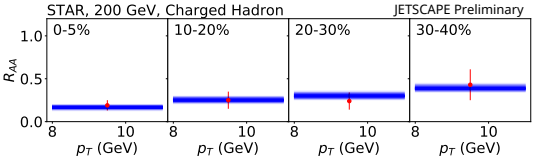


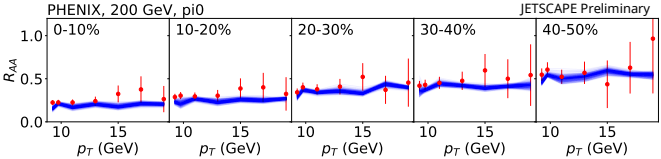
Posterior: hadron R_{AA} at low p_T

- **Good agreement at lower p_T**
- Fairly **consistent across experiments**



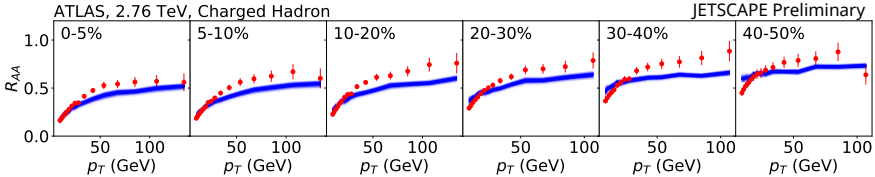


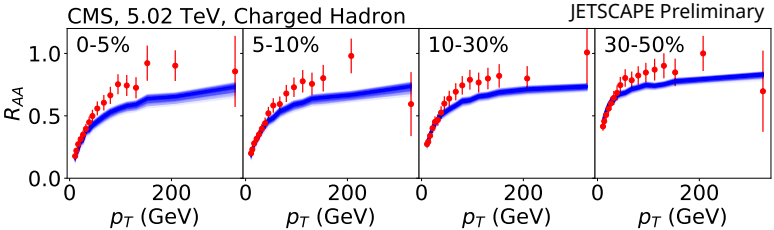


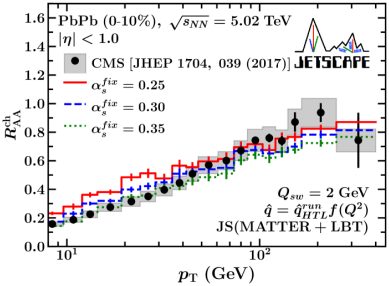


Posterior: hadron R_{AA} at high p_T

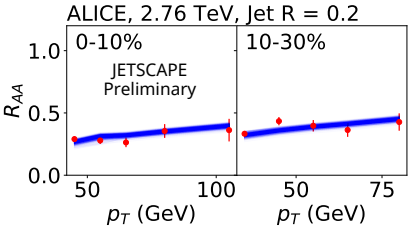
- Some **tension at high p_T**
- **Uncertainty smallest at low p_T**
  $\rightarrow$ drives result

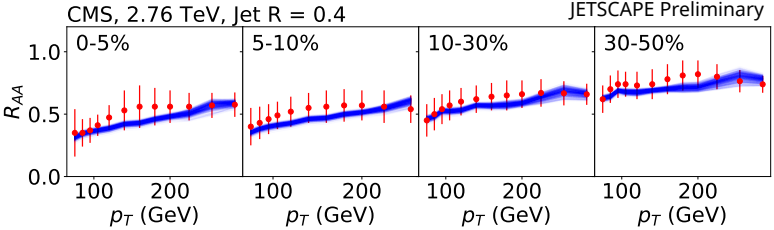




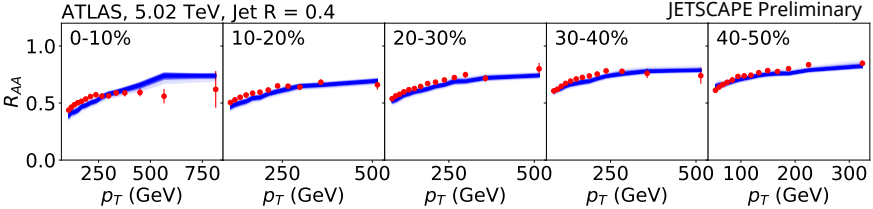


Posterior: jets

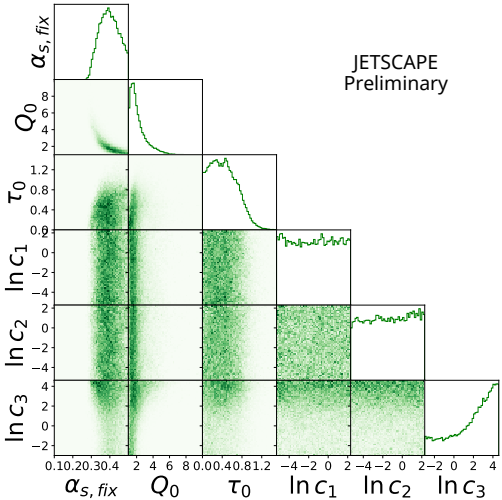




- Generally **reasonable agreement**
- **Systematically slightly lower R_{AA}**



Parameter posterior distributions



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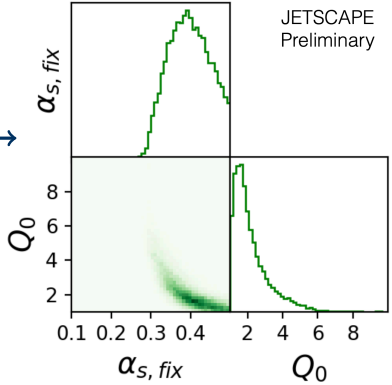
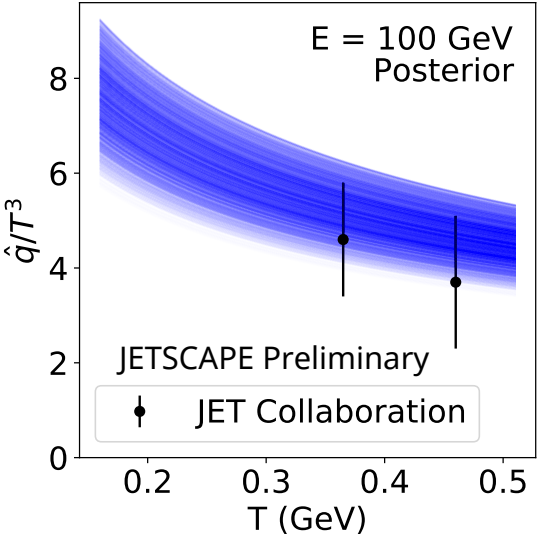
selection



Extracting $\hat{q}$

- **Sample parameter posterior** to extract $\hat{q}$
- Integrate over Q dependence when reporting:
- i.e., $\hat{q} = \hat{q}^{\text{run}}_{\text{HTL}} \times f(Q^2)$

- **Consistent description** using hadron + jet R_{AA}
- **Compatible with previous extractions**



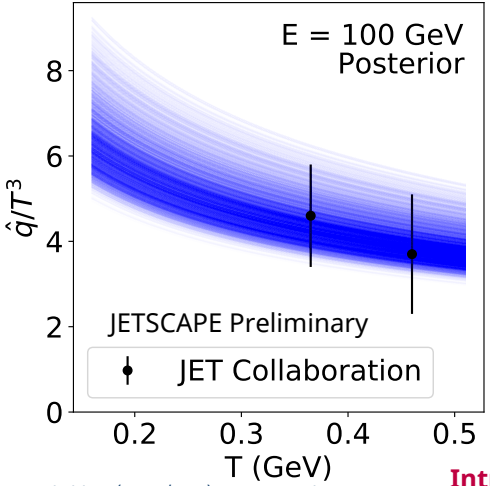
What's next? $\rightarrow$ many possible investigations!

Focus for today:

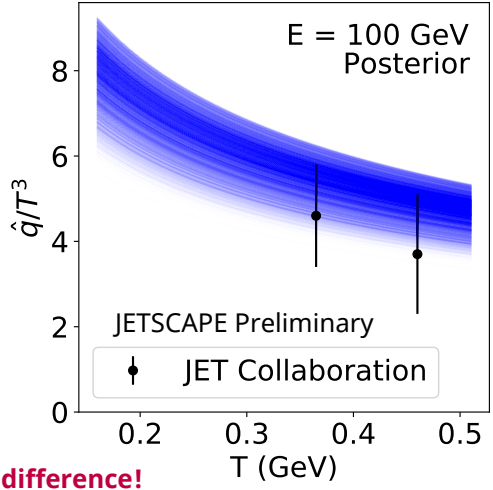
1. **Hadron vs jet R_{AA}**
2. **Adding jet substructure**

Selecting only hadron or jet R_{AA}

Jet R_{AA} only



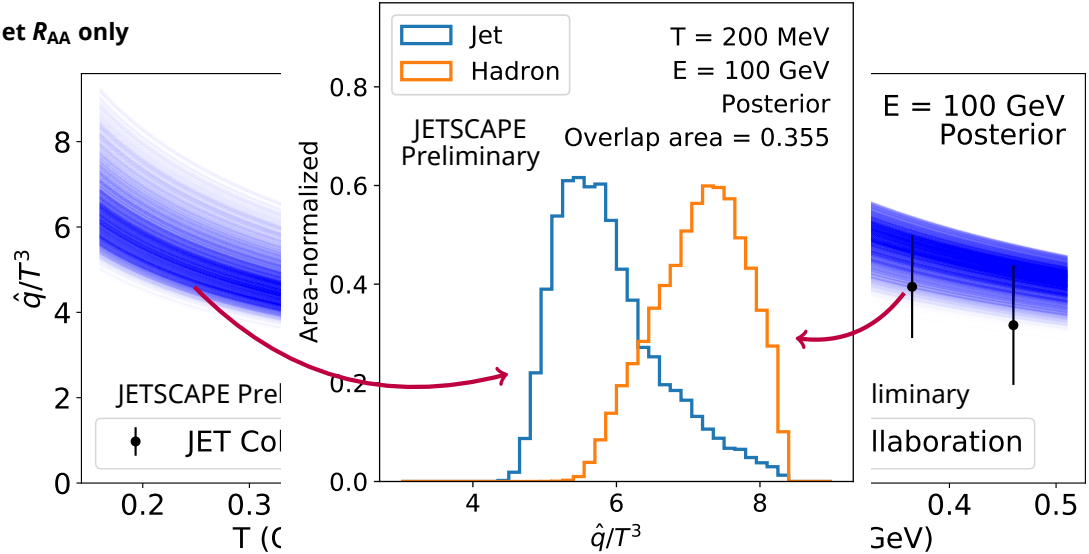
Hadron R_{AA} only



Intriguing difference!

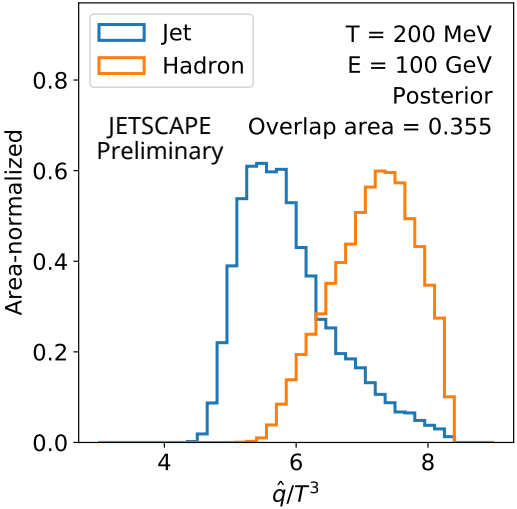
Selecting only hadron or jet R_{AA}

Jet R_{AA} only

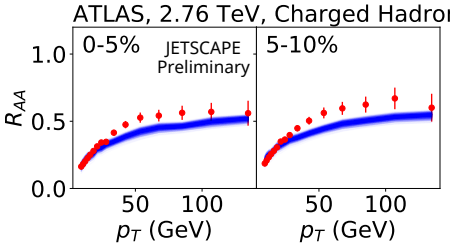


Intriguing difference!

Calibrating with low vs high p_T hadrons



Full p_T range



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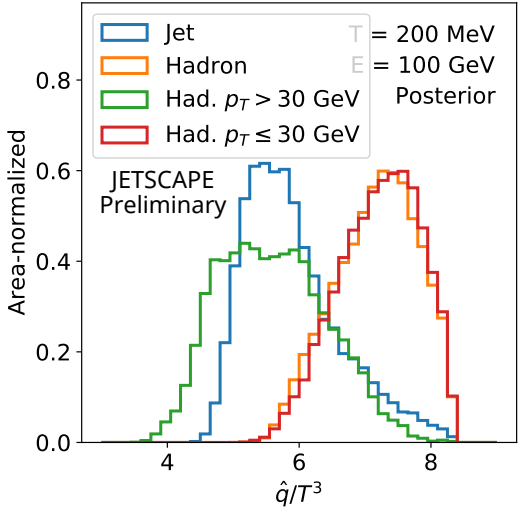
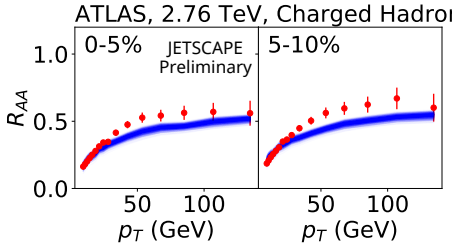
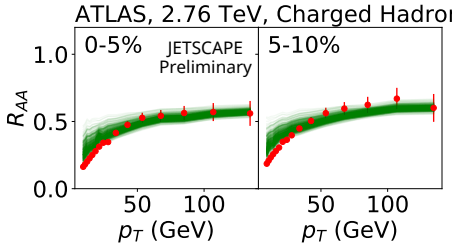


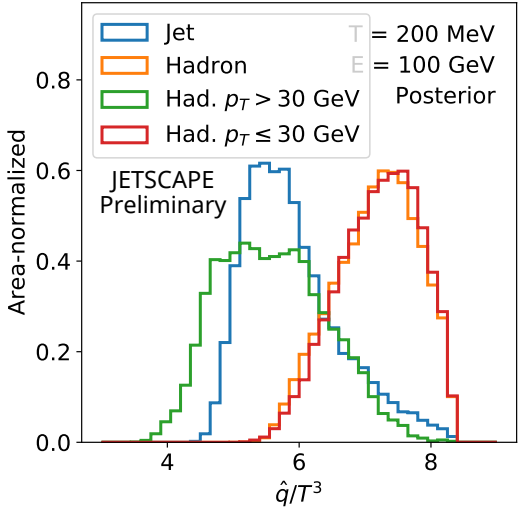
Full p_T range



Only hadron $p_T > 30$ GeV/c



What's driving this behavior?



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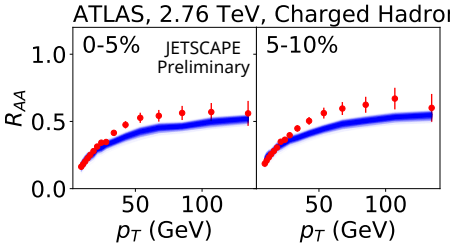


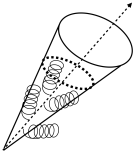
- **Low p_T dominates** due to small exp. uncert.
- **High p_T** in line with jet data
- Points to phase space for model improvement
- **Theory uncertainty is important**!
  - eg. No shadowing included
- **Small exp. uncertainty where theory has largest uncertainty**

Jets and jet substructure

- **What (additional) information do jet substructure observables contain**?
- Further **insight into differences** in $\hat{q}$ from hadron- and jet-only extractions?
- Exploratory investigation with **simplified but consistent** error treatment
  - Focus on 0–10% central data
- **Baseline: Jet R_{AA} only**

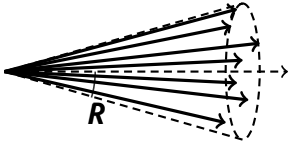
Jet R_{AA}

- ALICE, ATLAS, CMS, STAR



Fragmentation: $D(z)$

- ATLAS: $D(z)$
- CMS: $\xi(z)$

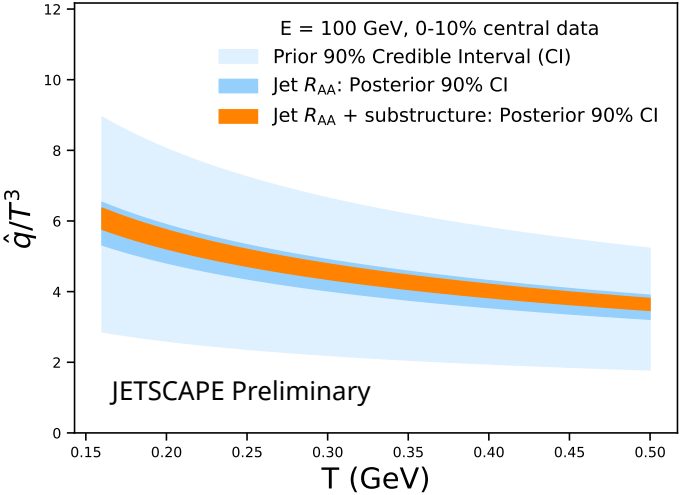


Groomed jet substructure

- ALICE: R_g, z_g

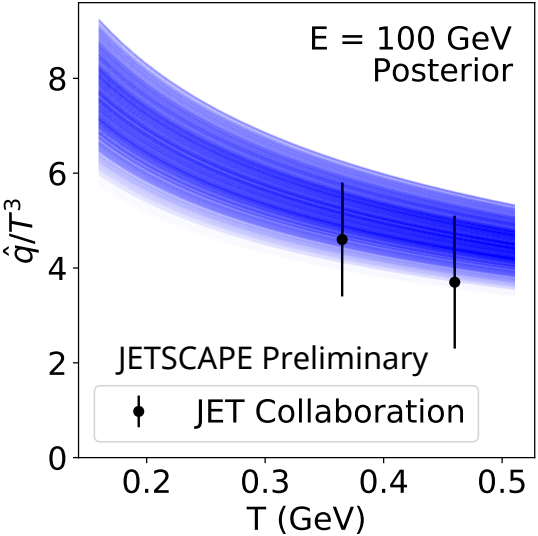
Constraints on $\hat{q}$

- **Consistent description of jet R_{AA} with substructure observables**
- Substructure yield **stronger relative constraint**
- Low p_T inclusive hadrons show tension, low z jet fragmentation consistent…?



Conclusions and Outlook/1

- Bayesian inference is powerful tool for parameter extraction and model studies
- New $\hat{q}$ extraction including **jet R_{AA}**
  - Includes **all applicable experimental data**
  - Overall reasonable description of data
- Studies on **hadron vs jet**, **jet substructure** point to regions of **agreement, tension**
- **Enabled by JETSCAPE framework**



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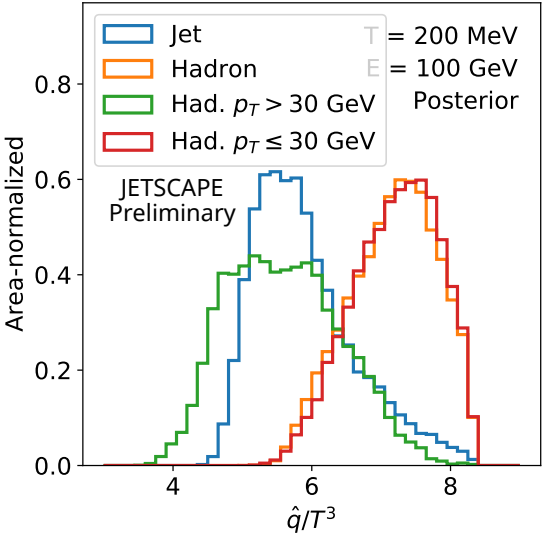


Conclusions and Outlook/2

- **Continue to scrutinize the specific model** used in this round of simulations in detail
  - Low vs high p_T, central vs peripheral, jet vs hadron, different jet radii, etc

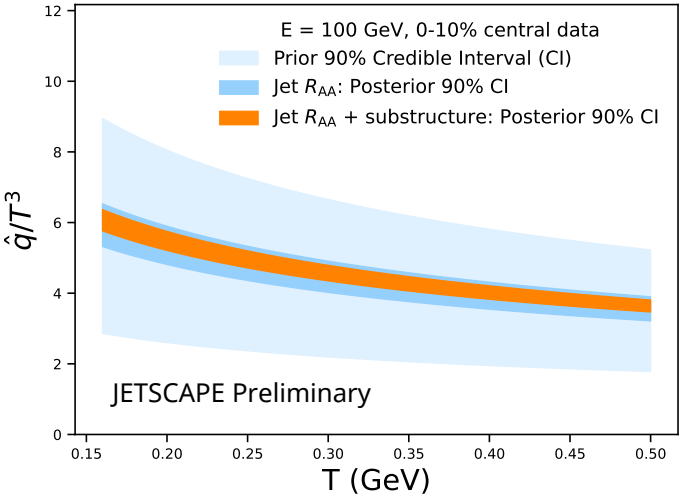
→ Pinpoint regions of interest

- Provide **important feedback for models**

Future:

- **More models needed**
- **Theory uncertainties**

Much more to come - stay tuned!

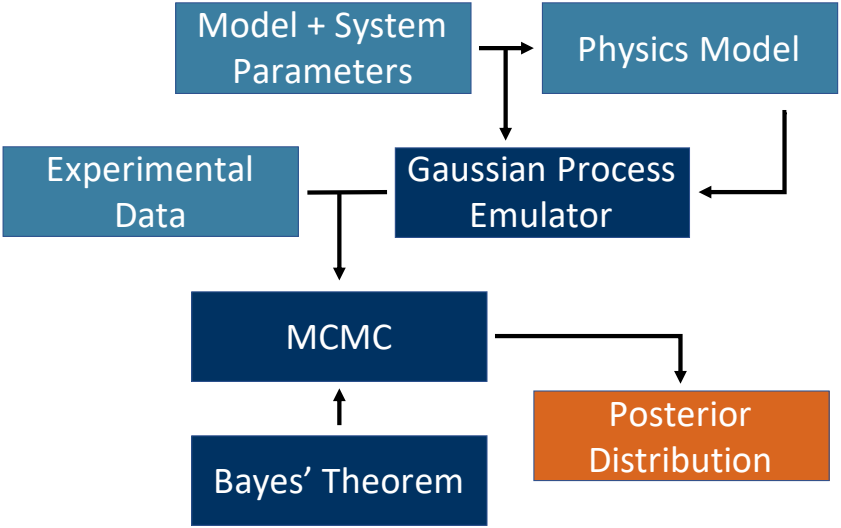


The JETSCAPE Collaboration

Backup

Practical Bayesian workflow

- Need to **populate N-dim parameter space** ($N \sim 5$)
- **High computational cost** for simulations
- **Millions** of cores hours provided by XSEDE (NSF)
- Interpolate between simulations using **Gaussian Process Emulator**

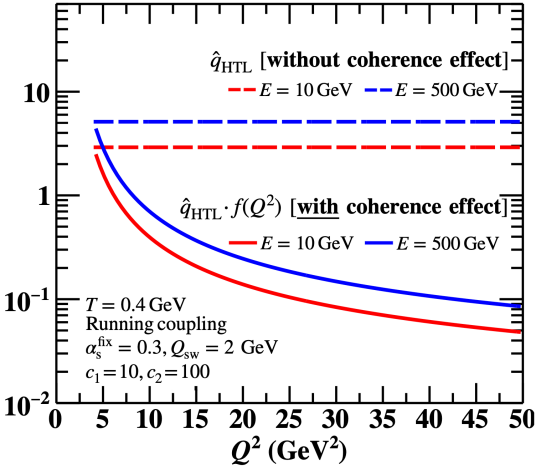


Model selection

- Using **multi-stage** MATTER+LBT model with coherence effects at high virtuality
- Includes scale evolution of QGP constituent dist.
- **Fewer interactions** for large-Q^2 partons
- Effective jet quenching strength: $\hat{q}_{\mathrm{HTL}} \times f(Q^2)$

$$f(Q^2) = \frac{N(\exp(c_3(1-x_B))}{1 + c_1 \ln(Q^2/\Lambda^2_{\mathrm{QCD}}) + c_2 \ln^2(Q^2/\Lambda^2_{\mathrm{QCD}})}$$

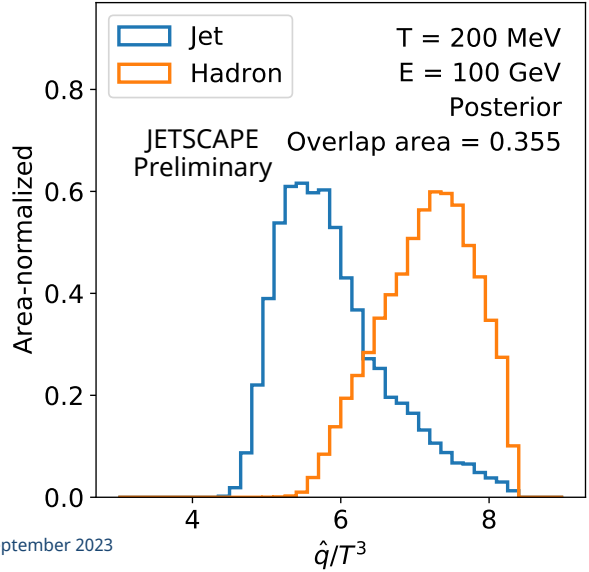
- Converges to traditional HTL as $Q^2 \to 1$
- Partons propagate through **calibrated 2+1D hydro**



- Taken as one possible **candidate model**
  - Want to take full advantage of JETSCAPE as a modular framework

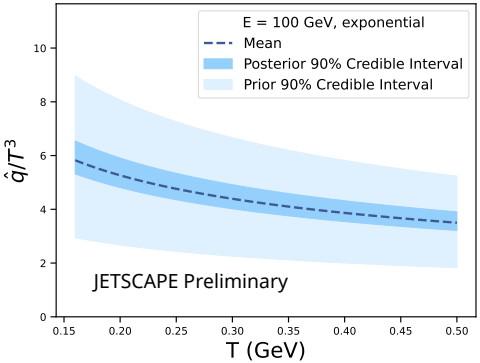
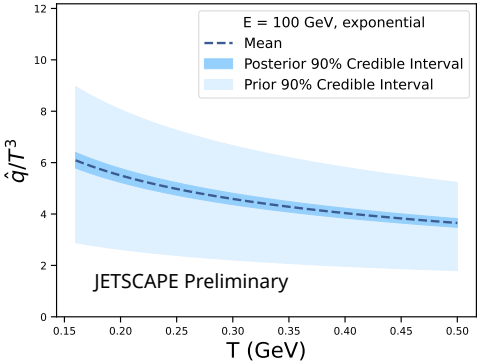
JETSCAPE, Phys.Rev.C 107 (2023) 3, 034911
JETSCAPE, arXiv:2301.02485

Selecting only hadron or jet R_{AA}



Constraints on $\hat{q}$

Jet R_{AA} only



Including substructure