Bayesian Inference with JETSCAPE, and what it takes to carry out a truly multi-messenger Bayesian Analysis for jet quenching

or: Why should sPHENIX care about Bayesian Analysis?

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22 July 2022

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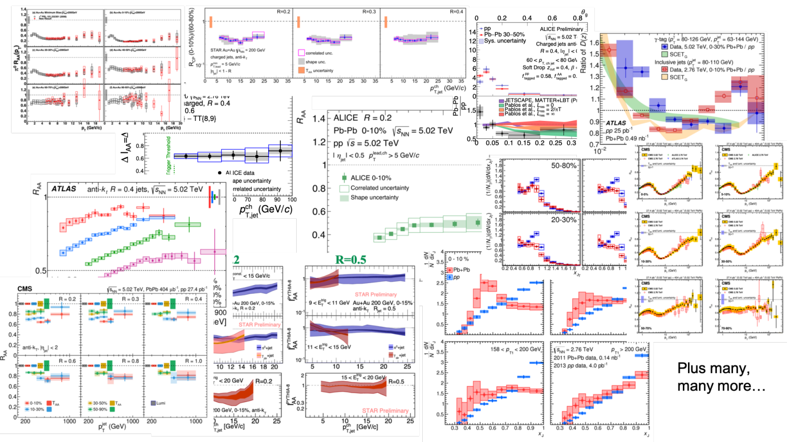
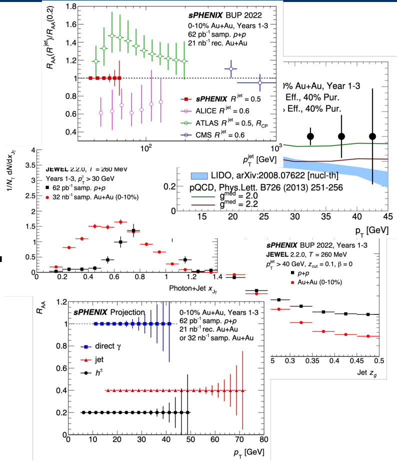
Jet quenching measurements in the 2020s



Plus many, many more…



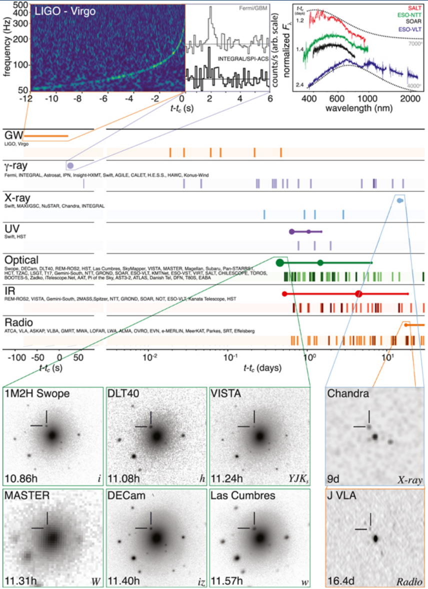
$\xrightarrow{?}$ Extract physics

Multi-messenger astronomy

- Take some inspiration from astrophysics
- First Gravitational Wave confirmed by EM
  B. P. Abbott et al 2017 ApJL 848 L12
    - Binary neutron star merger
- Many different observations of the same phenomena

→ Can we emulate this approach?

- We have many measurements, but can we build the physics picture?



How can we make a consistent picture?

What physics can we extract?

How can sPHENIX maximize its impact?

How can we extract physics from these measurements?

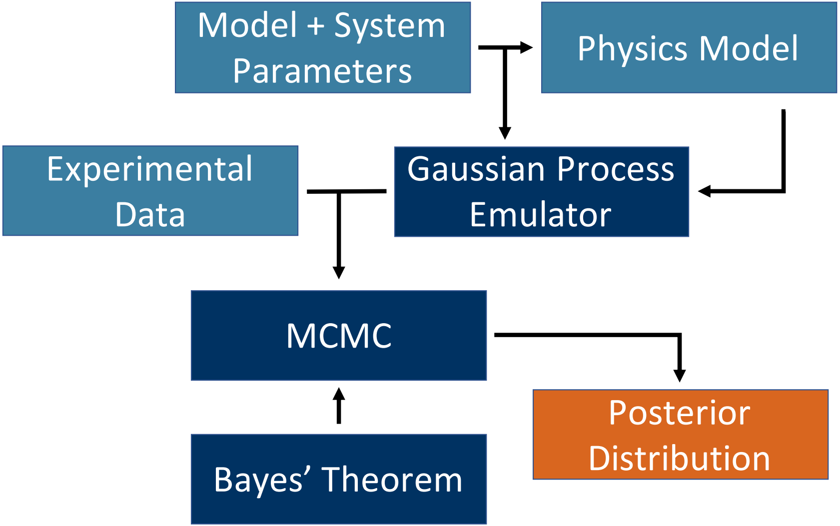
- For a given model, what parameters are **most compatible** with experimental measurements?
- Utilize Bayesian inference to extract parameters, **combining knowledge of theory and exp.**
- Given data x and parameters θ:
- $P(x|\theta)$: likelihood x is described by θ
  - Depends on covariance of data, theory uncertainties
- $P(\theta)$: prior distribution for θ
  - Choice makes assumptions explicit
- $\boldsymbol{P(\theta|x)}$: **posterior distribution**, probability of θ given x
  - Most probable value provides the **best description** of the data

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

Practical Bayesian workflow

- Need to **populate N-dim parameter space** ($N \sim 5$)
- **High computational cost** for simulations

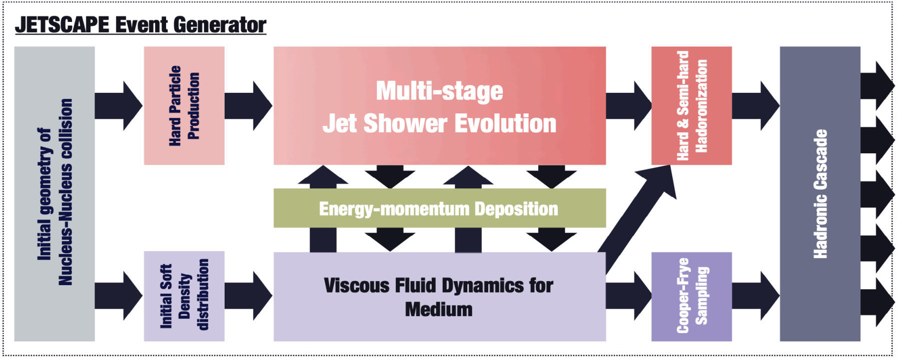
$\rightarrow$ **Millions** of core hours required for simulations
  - Provided by XSEDE (NSF)
- Interpolate between simulations using **Gaussian Process Emulator**



JETSCAPE Framework

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

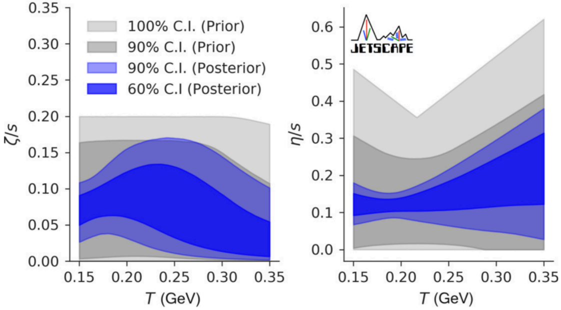
See **Amit Kumar's talk** (Wed, 10:05)



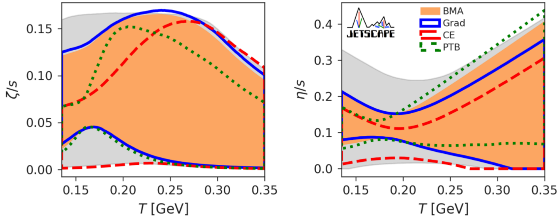
Bayesian analysis in JETSCAPE

Much more from JETSCAPE: A few soft sector results are shown here

Temperature-dependence of specific shear and bulk viscosities



Comparison of particlization models



→ Today I will focus on the **hard sector**!

First result: Inclusive charged hadron R_{AA}

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

First result: Exploring system and centrality dependence

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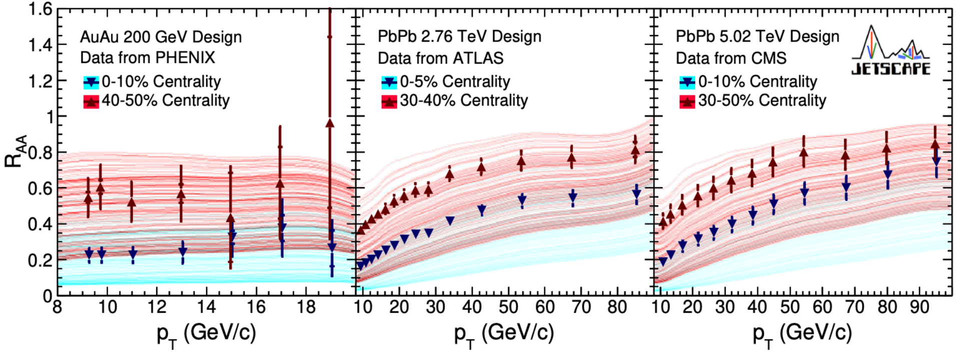
- **Focus in on a single observable**: inclusive charged hadron R_{AA}
- **Subset of measurements** in 200 GeV Au–Au, 2.76 TeV Pb–Pb, 5.02 TeV Pb–Pb
  - Include central and semi-central measurements
- Compare LBT (Linearized Boltzmann Transport), MATTER, and early version of multi-stage approach with MATTER+LBT
  - Partons propagate through 2+1D hydro
- For parameter estimation, need to explore **entire phase space**
- Parametrize physics model according to external parameters

$\rightarrow$ Utilize $\hat{q}$ formulation with **4-5 parameters**:

$$\frac{\hat{q}\left(E,T\right)\big|_{A,B,C,D,Q_{\mathrm{sw}}}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2 \left\{ \underbrace{\frac{A\left[\ln\left(\frac{E}{\Lambda}\right)-\ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2}}_{\text{High virtuality, no T dep}} \underbrace{\theta(Q-Q_{\mathrm{sw}})}_{\text{Switch models}} + \underbrace{\frac{C\left[\ln\left(\frac{E}{T}\right)-\ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2}}_{\text{HTL-like, scatter off T}} \right\}$$

From prior to posterior distributions

- Compare model predictions for hadron R_{AA} to data to see performance
- Using prior distribution and likelihood, sample the phase space using MCMC to determine the posterior distribution



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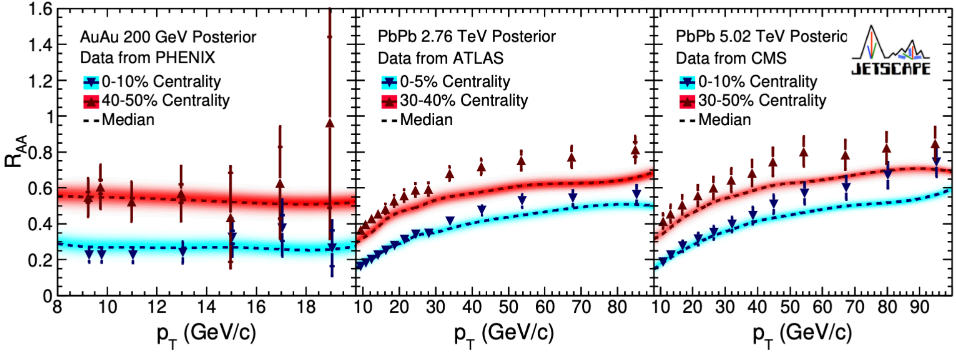

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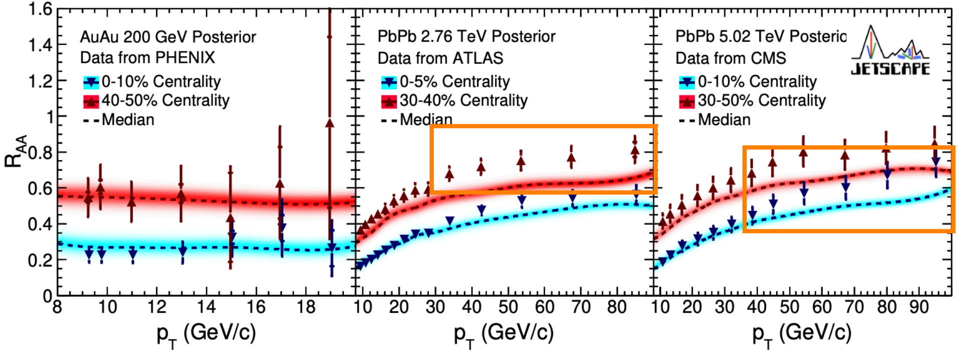
From prior to posterior distributions

- Compare model predictions for hadron R_{AA} to data to see performance
- Using prior distribution and likelihood, sample the phase space using MCMC to determine the posterior distribution
- Posterior describes data **reasonably well**, but **some tension**



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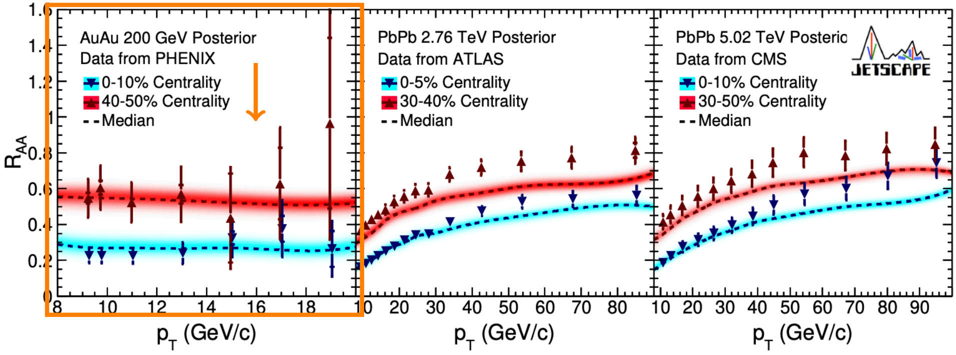
From prior to posterior distributions

- Compare model predictions for hadron R_{AA} to data to see performance
- Using prior distribution and likelihood, sample the phase space using MCMC to determine the posterior distribution
- **Significant uncertainties** from PHENIX at high p_T limits constraining power



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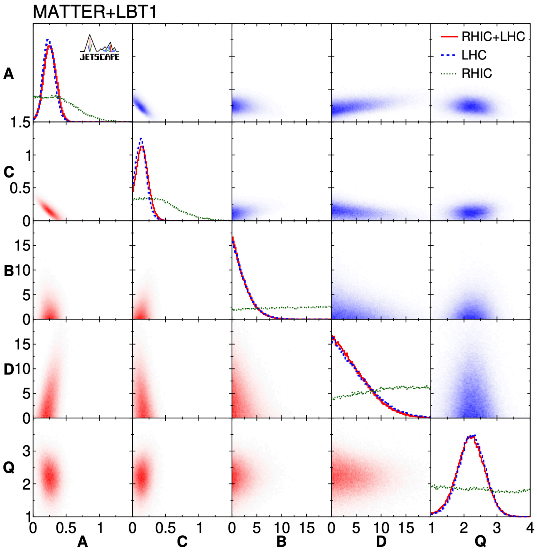
- Individual and joint distributions shown for each parameter
- **Limited constraining power at RHIC** due to limited selection of data

→ Future data will have **big impact**!



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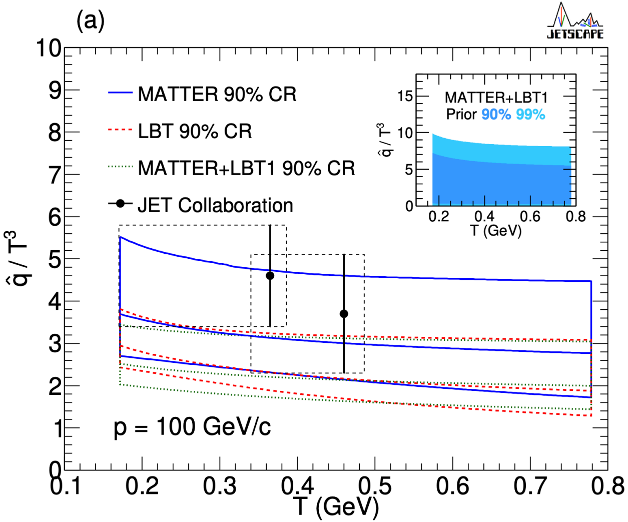
Constraints on $\hat{q}$ from inclusive hadron R_{AA} at RHIC and LHC

- Translate parameters back to $\hat{q}$ to study temperature and momentum dependence
- Significant **constraints on prior** distribution
- Approximately consistent with separate values for RHIC and LHC from JET collaboration
- Multi-stage MATTER+LBT **consistent** with individual models



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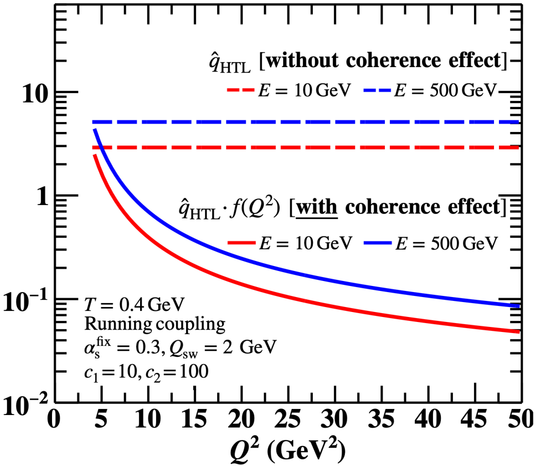
Next step: Inclusive jet and hadron R_{AA}

Model selection

- Using **new 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: $\hat{q}_{\mathrm{HTL}} \cdot f(Q^2)$

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

- Converges to traditional HTL as $Q^2 \to 1$
- See talk by Amit Kumar (link) (Wed, 10:05)
  new JETSCAPE, arXiv:2204.01163 (link)
- Partons propagate through **calibrated 2+1D hydro**
    - Taken as one possible **candidate** model
        - Want to take full advantage of JETSCAPE as a modular framework



Data selection

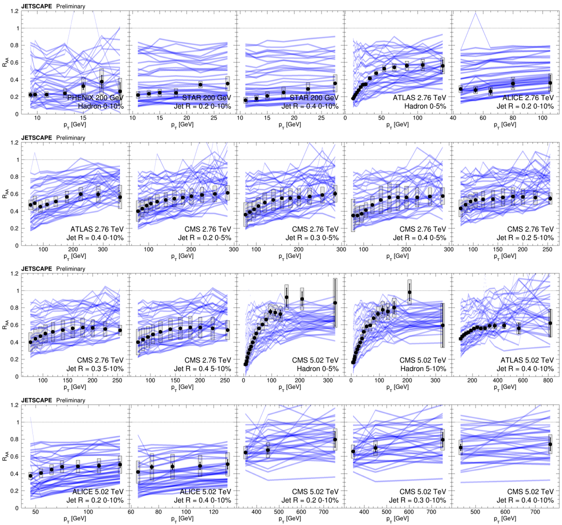
Aim to be as inclusive as possible of **all available measurements**

Experiment	$\sqrt{s_{NN}}$	Inclusive R_{AA} observables
STAR	200	jets $R = 0.2, 0.4$
PHENIX	200	π_0 R_{AA}
ALICE	2.76, 5.02	jets $R = 0.2, 0.4$
ATLAS	2.76, 5.02	hadron, jets $R = 0.4$
CMS	2.76, 5.02	hadron, jets $R = 0.2$-0.4

Some are **still in the process** of being incorporated

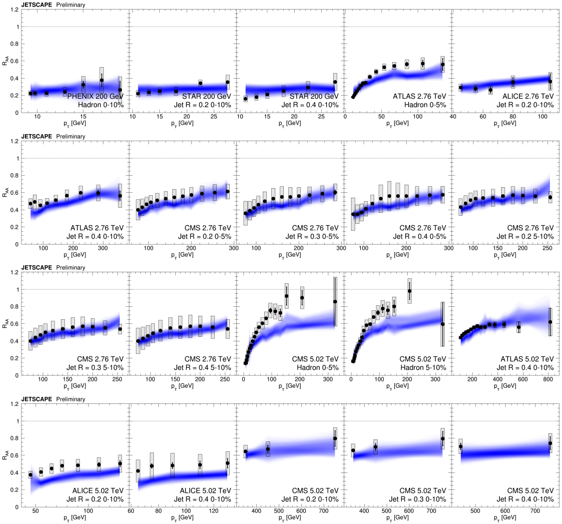
Experimental uncertainties and prior distribution

- Overall analysis procedure is similar to previous analysis
- Additional observables bring additional complications!
- Need **careful treatment** of exp. uncertainties
- New sources of systematic uncertainties, such as **shape uncertainties**
  - Accounted for with anti-correlated covariance
- **Shared exp. uncertainties** across observables
- Apply 10% correlation length to correlated uncertainties
- Encourage experiments to provide **full covariance!**
  - Or simpler: **signed uncertainties**



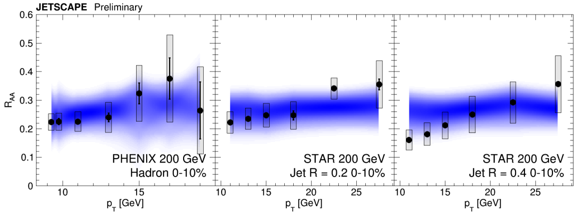
Posterior distribution

- Posterior distribution compared to observables in work-in-progress analysis
- Posterior is **simultaneously constrained** by all included observables
  - Spanning across $\sqrt{s_{NN}}$ and experiment
- Model describes observables **reasonably well**, but there is **tension**
- Focus on particular regions to better understand behavior…



Examining the posterior distribution

- 200 GeV: **Mostly consistent** with data
  - Constraining power **somewhat limited** due to uncertainties in this high p_T range



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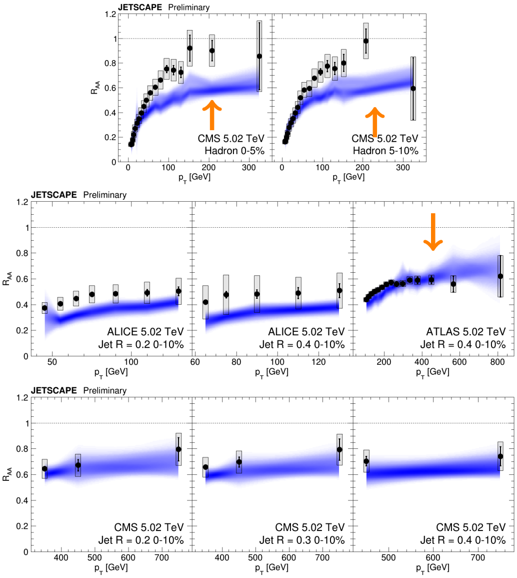
  - Posterior tends to **underpredict**



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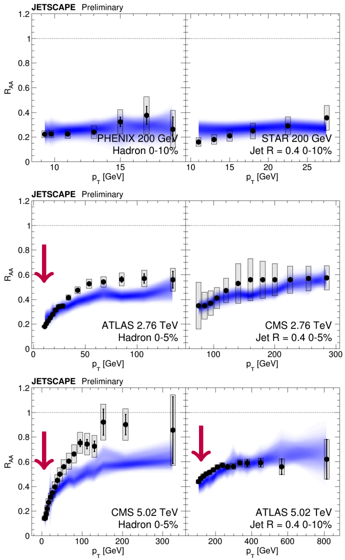

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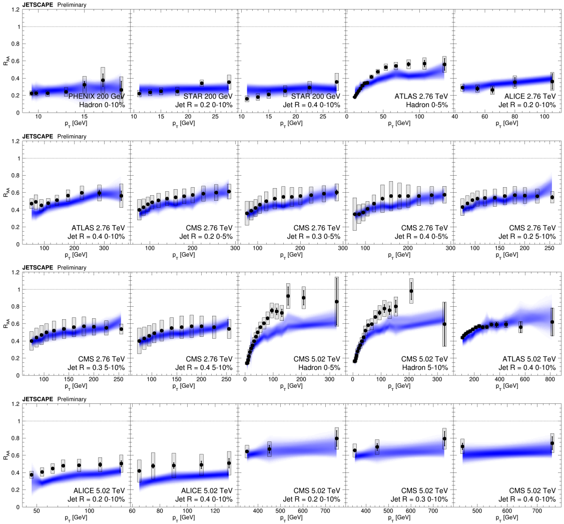


Maximizing the impact of sPHENIX measurements

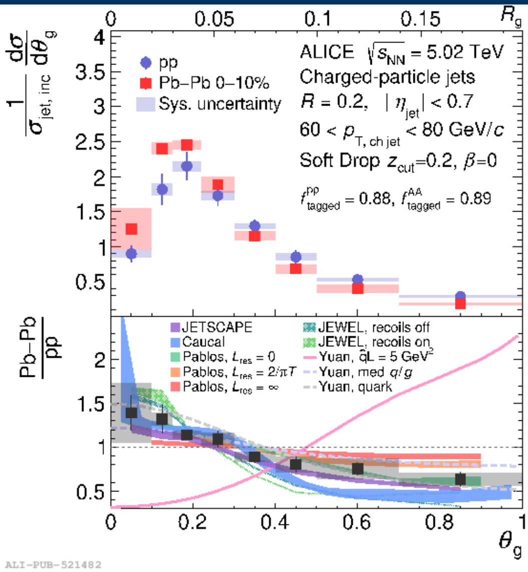
sPHENIX and Bayesian Analysis

- Models are able to describe many observables, yet **contain different physics**
- In order to make qualitative statements, need to constrain in a more comprehensive manner

→ **Global Bayesian analysis**

  - sPHENIX measurements will play a critical role

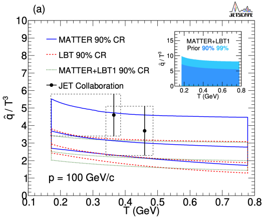
- Can Bayesian analysis be useful even **before sPHENIX starts taking data**?



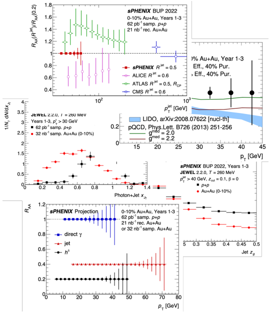
Bayesian sensitivity quantification

- **Quantify impact** of new sPHENIX data (to prioritize measurements?)
    - eg. Neutrino physics: Phys.Rev.C 103 (2021) 6, 065501
    - eg. OO w/ Trajectum: arXiv:2110.13153

1. **Calibrate model** to existing data (ie. Bayesian analysis)
    - eg. JETSCAPE hard sector calibration
2. **Generate pseudo-data** with expected sPHENIX uncertainties
    - Can sample posterior dist. for parameters
3. Re-run Bayesian Inference, and **observe impact on new posterior**
    - Further vary observables included



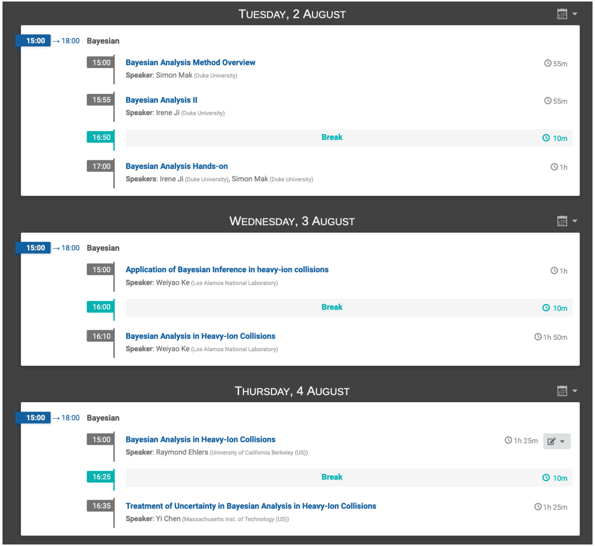
New Bayesian analysis



Further constraints

Where to learn more + get started?

- For sensitivity studies, need posterior distribution
  - In progress, but not yet available
- Our Bayesian Inference code is available on GitHub: **JETSCAPE/STAT**
- The overall process is not turn key, but the tools are there
- Bayesian Inference will be extensively discussed at the online **2022 JETSCAPE Summer School**
- Covers **conceptual underpinning + hands-on sessions**!
- Sessions will be recorded



Conclusions + Open Questions

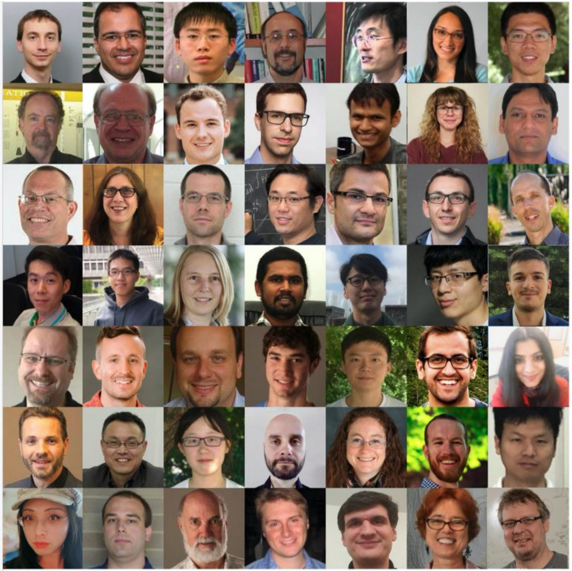
- Bayesian Inference is **essential to fully exploit** the power of **multi-messenger** heavy ion data
- **Broader than just JETSCAPE**: a key issue for the entire community

- What to be done going forward?

1. sPHENIX
   - Report **full covariance** or **signed experimental uncertainties!**
   - Current 200 GeV data provides limited constraints

   → Forthcoming RHIC data **will have big impact**
   - Assess impact with **sensitivity studies**
2. JETSCAPE
   - Complete first **multi-messenger** analysis
   - **Release posterior** in usable form
3. How do we as a field **support robust Bayesian Inference efforts** in the long term?

Thanks!



Backup

Bayesian Experimental Design

- **Optimize experimental utility**, accounting for all available information
- Also includes information and uncertainties from theory
- Inclusion of such uncertainties shown on the right
- Can have a **substantial impact** on most beneficial regions of phase space to explore

> Bayesian experimental design provides a general framework to maximize the success of an experiment based on the best information available on the existing data, experimental conditions (including the amount of beam time available, experimental setup, budgetary constraints), and theoretical models used to process and interpret the data. The goal of BED is to maximize the expected utility of the outcome. Formally this is done by

arXiv:2112.02309

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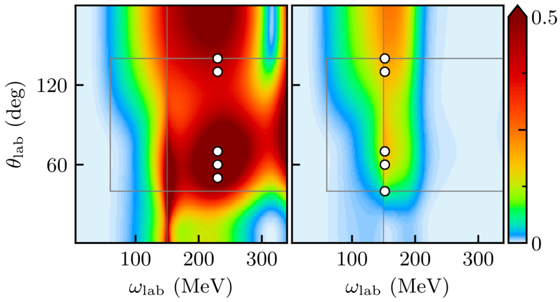

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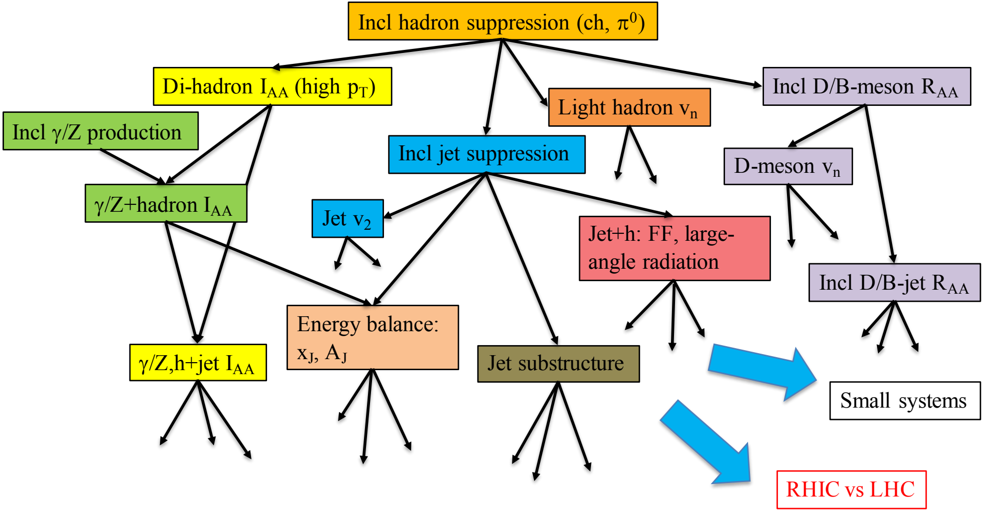
A possible taxonomy of experimental jet quenching measurements



Each line adds **one experimental element**, from simple to complex

Colors relate experimentally similar measurements

Model parameter estimation

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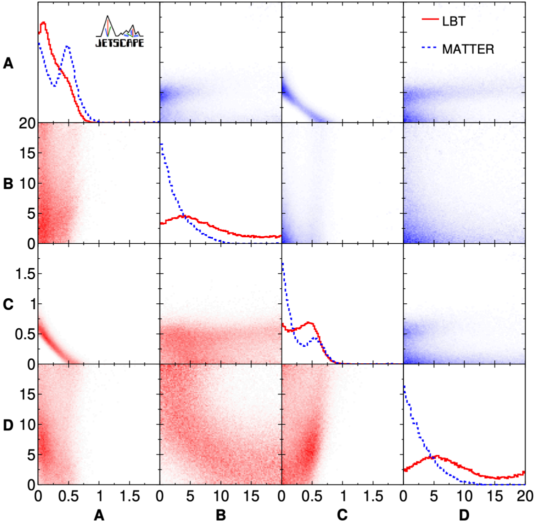
- Individual and joint distributions shown for each parameter
- MATTER prefers A, LBT prefers C
- A and C tend to strongly anti-correlate

→ Reflect features of the parametrization

- Multi-stage model does not yet appear to improve description of data
- Model switch occurs around 2 GeV
- **Limited constraining power at RHIC** due to limited selection of data



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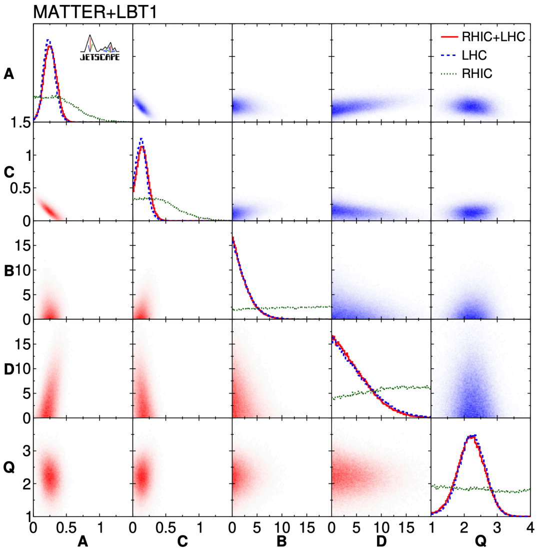

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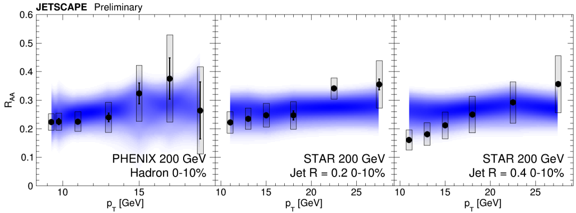

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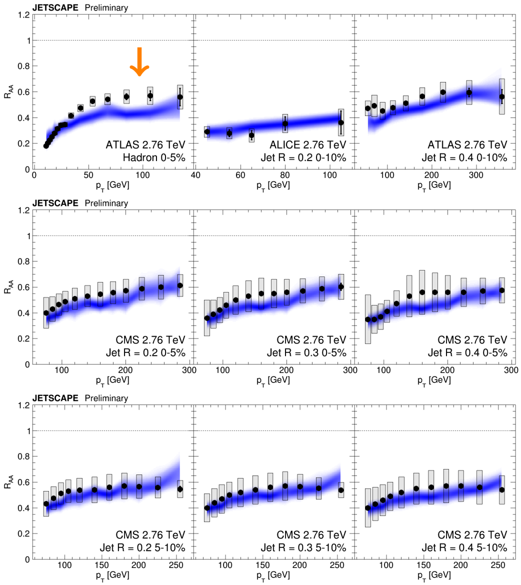

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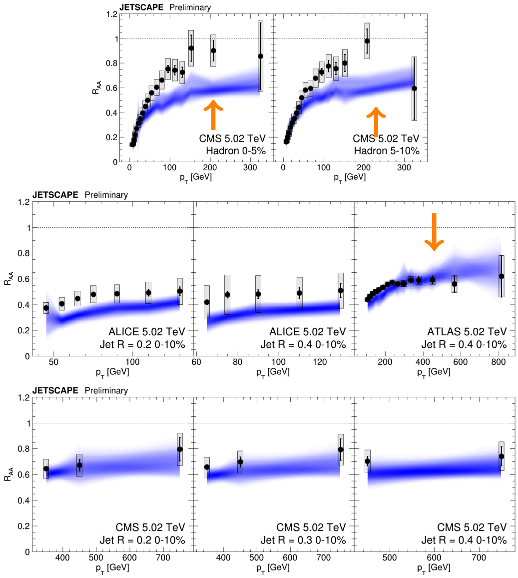

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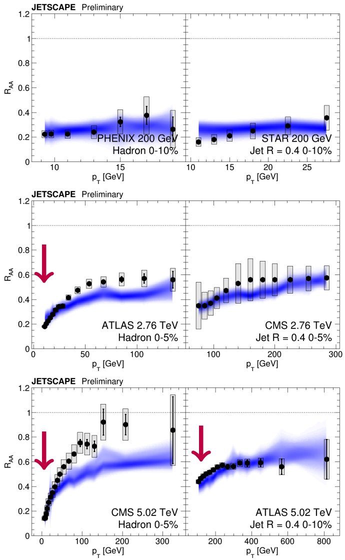

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  - Tension **driven by small uncertainties** at low p_T
- R = 0.4 jets at $\sqrt{s_{NN}} = 5.02$ TeV
  - Posterior prefers the ATLAS jets, **correlating with the small uncertainties**