STAT-WG Status & Activities Report

Statistics & Data Working Group

The task of the STAT-WG is to (as set in the collaboration bylaws):

- work with the PHYS and COMP working groups to define multiple formats to compare with experimental data
- set up emulation routines for extensive data sets, and work with the COMP-WG to design generic emulation routines
- design new observables, in collaboration with the PHYS-WG
- design comprehensive statistical tests to distinguish between different physics model assumptions
- work with experimental representatives and the DOCS-WG to obtain data for comparison

New: SIMS-WG - will develop infrastructure and execute large scale simulations that are required for calibration of physics simulations to data. SIMS and STATS work hand in hand to execute the full statistical analysis

Membership

Duke Physics:
- Steffen A. Bass (co-convener)
- Jean-Francois Paquet (SIMS convener)
- Jonah Bernhard (graduated 4/18)
- Weiyao Ke
- Tianyu Dai

Duke Statistics:
- Robert L. Wolpert
- Jake Coleman

Wayne State:
- Abhijit Majumder
- Shanshan Cao

Texas A&M:
- Reiner J. Fries
- Zhidong Yang

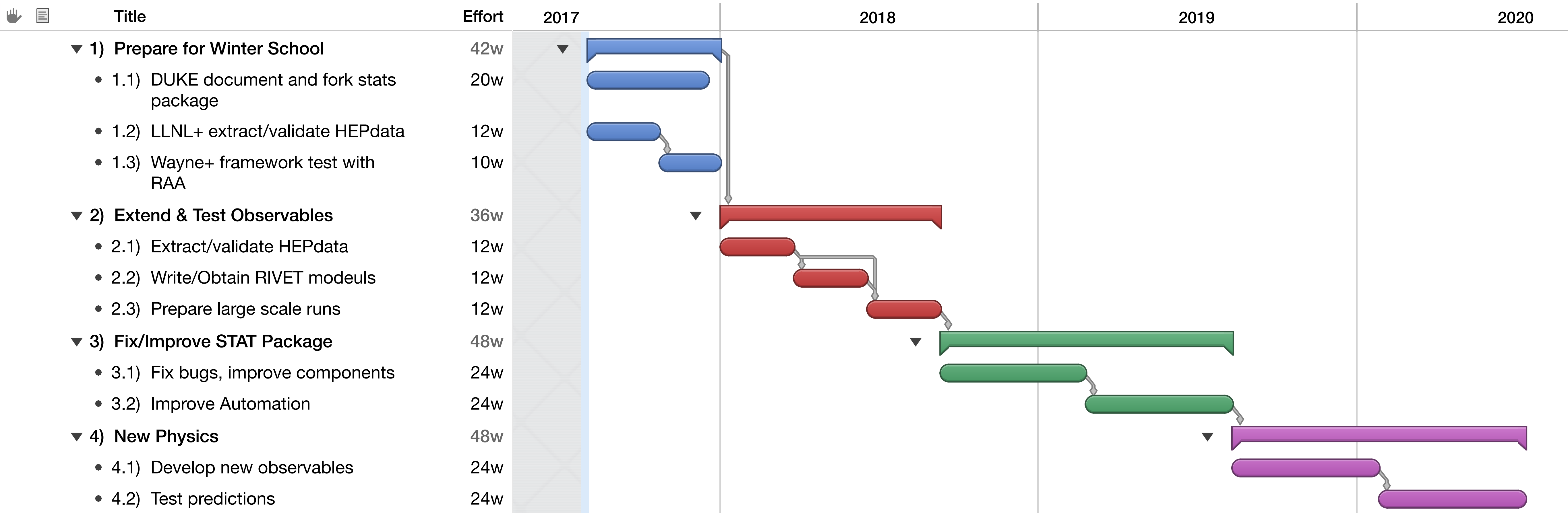
MIT:
- Gunther Roland (co-convener)

LLNL:
- Ron Soltz

UT Knoxville (Jetscape affiliate):
- Christine Nattrass
- Redmer A. Bertens
- James Neuhaus

need more experimental members!!

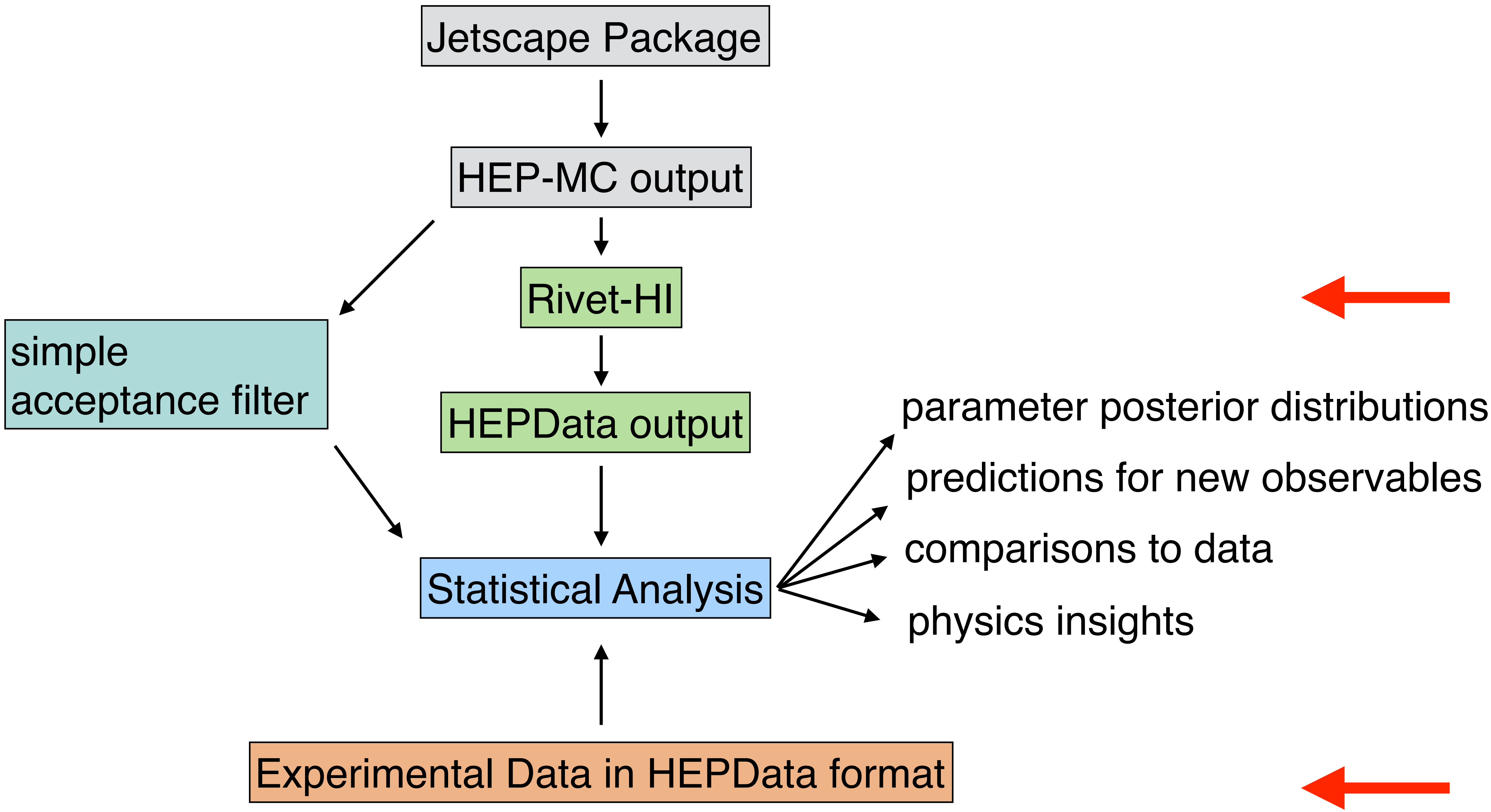
Year 2 plans revisited



- developed statistics tutorial and taught it at Jetscape winter school
- developed first version of statistics tools package (utilized at winter school)
- started development of RIVET-HI modules (via UT Knoxville affiliate)
- integrate HEP-data format into statistics package
- temperature- and momentum dependence of q-hat analysis in LBT (continued from Y1) and MATTER as well as (MATTER+LBT) (new for Y2)
- worked on the development of statistical tools for the comparison of different physics models applied to the same data (Model Discrepancy, Bayes Factor)

Data Formats and Curation

Data Formats and Workflow



Working with HEPData

Data Curation Philosophy

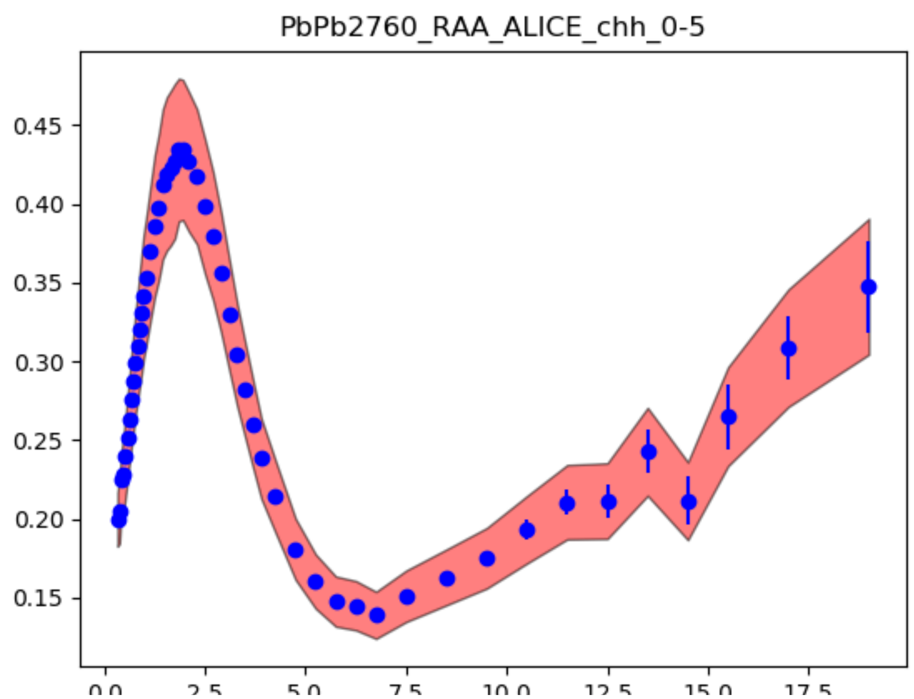
- Work with published results, uploaded to HEPData
- Automate download procedure, cache data locally
- Ensure appropriate treatment correlated errors
- Insert "experimentalist-in-the-loop" for (visual) inspection of all data & errors

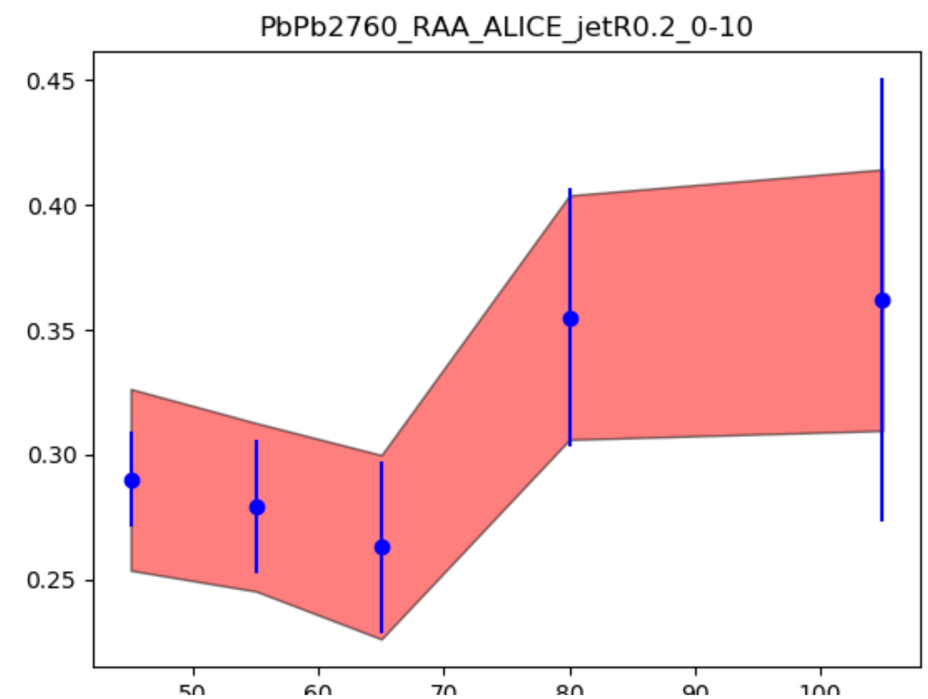
Data Curation Accomplishments

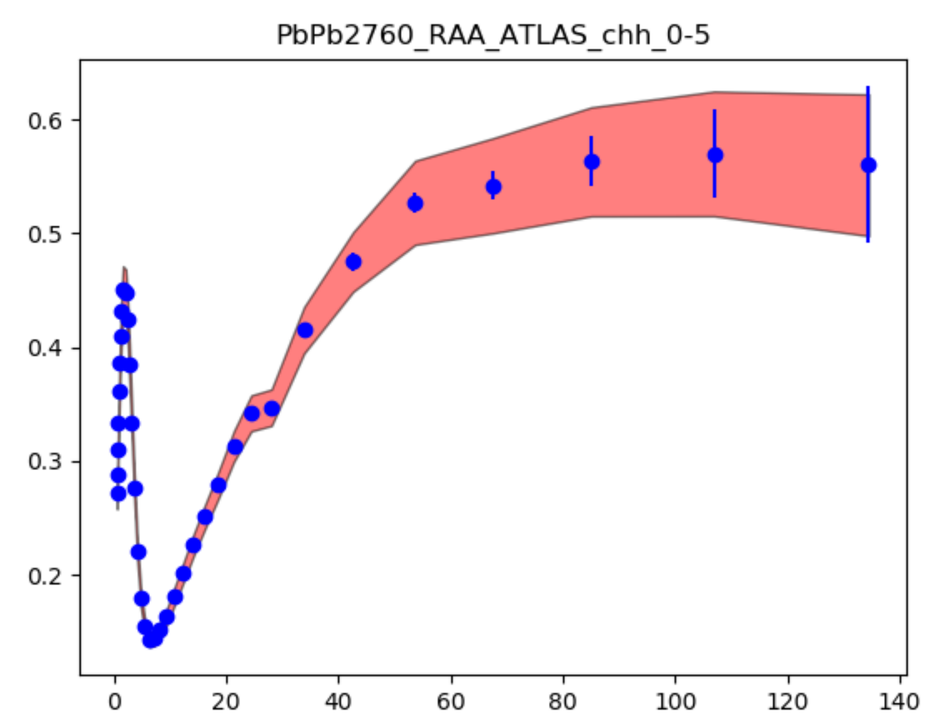
- hic-param-est-2017 python module developed by J. Bernard meets above criteria, has been forked into JETSCAPE githup repository
  - Automated download of .yaml files from hepdata.net
  - Data cached locally in .pkl format
  - Data values, stat & sys errors loaded into numpy arrays
  - Internal data structures allow for correlation length (not yet used)
- Demonstration data sets: LHC central hadron, jet R_{AA}
  - ALICE https://www.hepdata.net/record/ins1377750, https://www.hepdata.net/record/ins1343112
  - ATLAS https://www.hepdata.net/record/ins1360290, https://hepdata.net/record/ins1326911
  - CMS https://www.hepdata.net/record/ins1496050

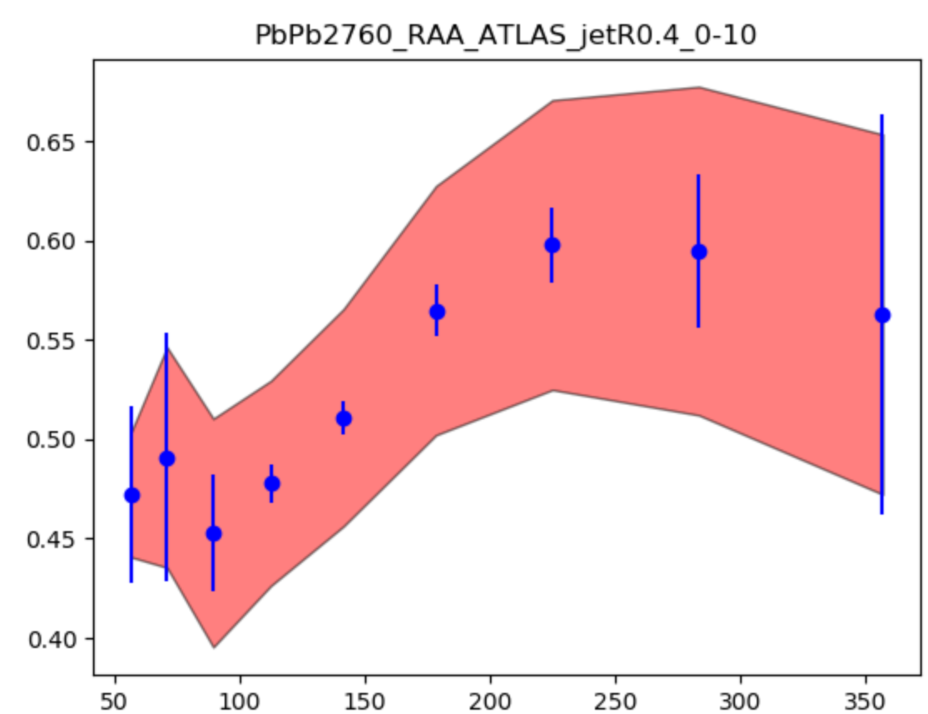
HEPData examples

All plots from hic-param-est-2017/src/expt.py, data/stat/sys parsed appropriately









Experimental Acceptances: Rivet

RIVET(**R**obust **I**ndependent **V**alidation of **E**xperiment and **T**heory):

- a system for validation of Monte Carlo event generators
- published & documented on arXiv:1003.0694 [hep-ph]
- contains a large catalog of experimental analyses (data, cuts, uncertainties)
- takes output from MC generator and calculates observables of a given analysis (i.e. calculates observables using experimental cuts and acceptance corrections)

- Pro's:
  - standardized system to compare to data from multiple experiments
  - interfaces to HEP-MC and HEPData already exist

- Bugs/Features:
  - we depend on experiments to incorporate published "analyses", into Rivet
  - extensions needed to handle observables that combine several different measurements, such as R_{AA}

RIVET-HI under development by HI community to develop needed extensions

RIVET-HI Initial Steps

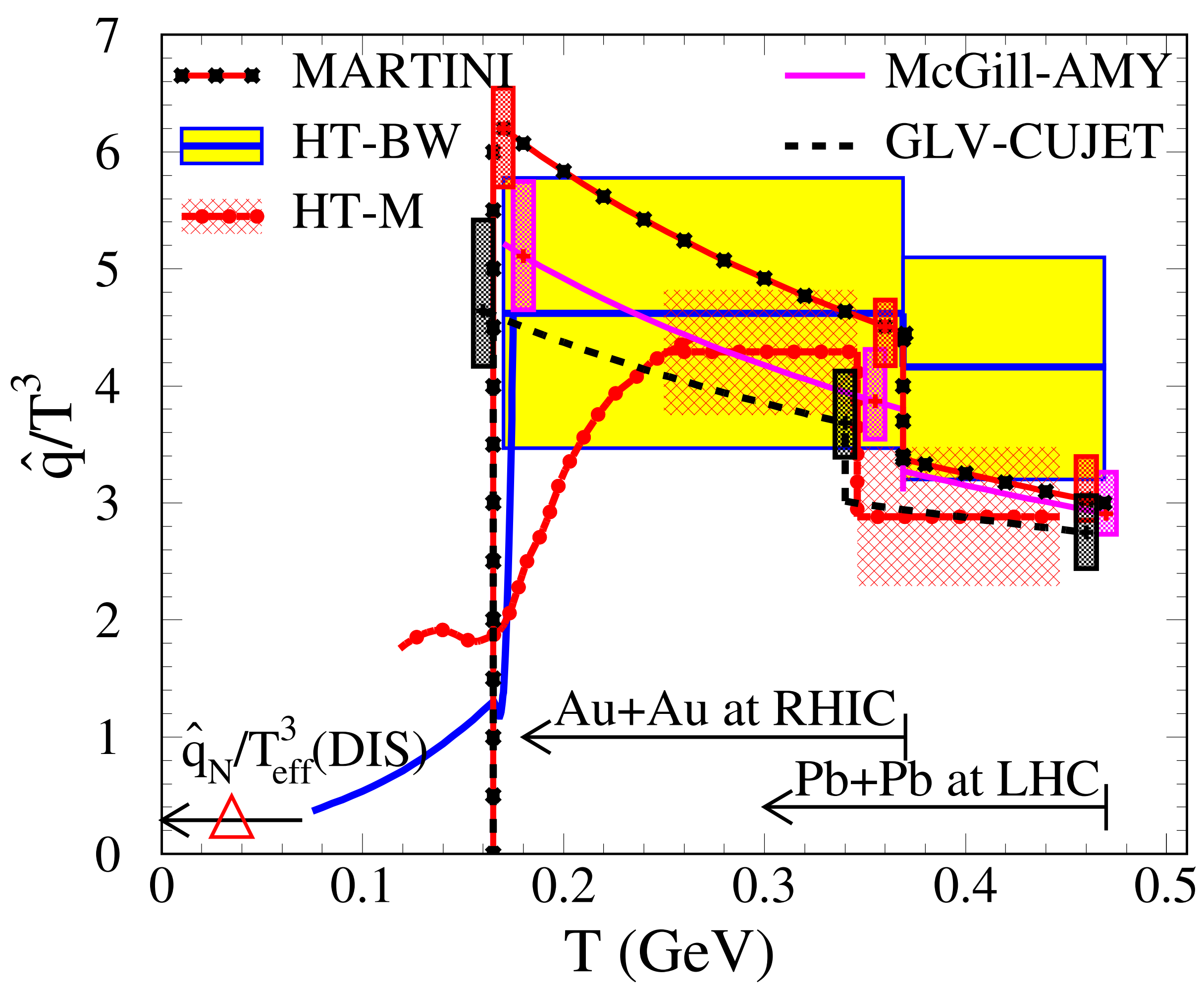
- UT Knoxville Jetscape affiliates actively working on putting Jetscape relevant analyses into RIVET-HI
  - pilot project developed by C. Nattrass to harness undergraduate effort to *rivetize* STAR data for use in JETSCAPE
  - initial progress this summer to develop into classroom project this fall
  - student outreach coupled to demonstration project for other experiments

- Current work in progress:
  - for R_{AA} measurements: how to handle the pp reference
  - centrality determination within analysis
  - event plane reconstruction
  - jet fluctuations due to underlying event background

Statistical Analysis

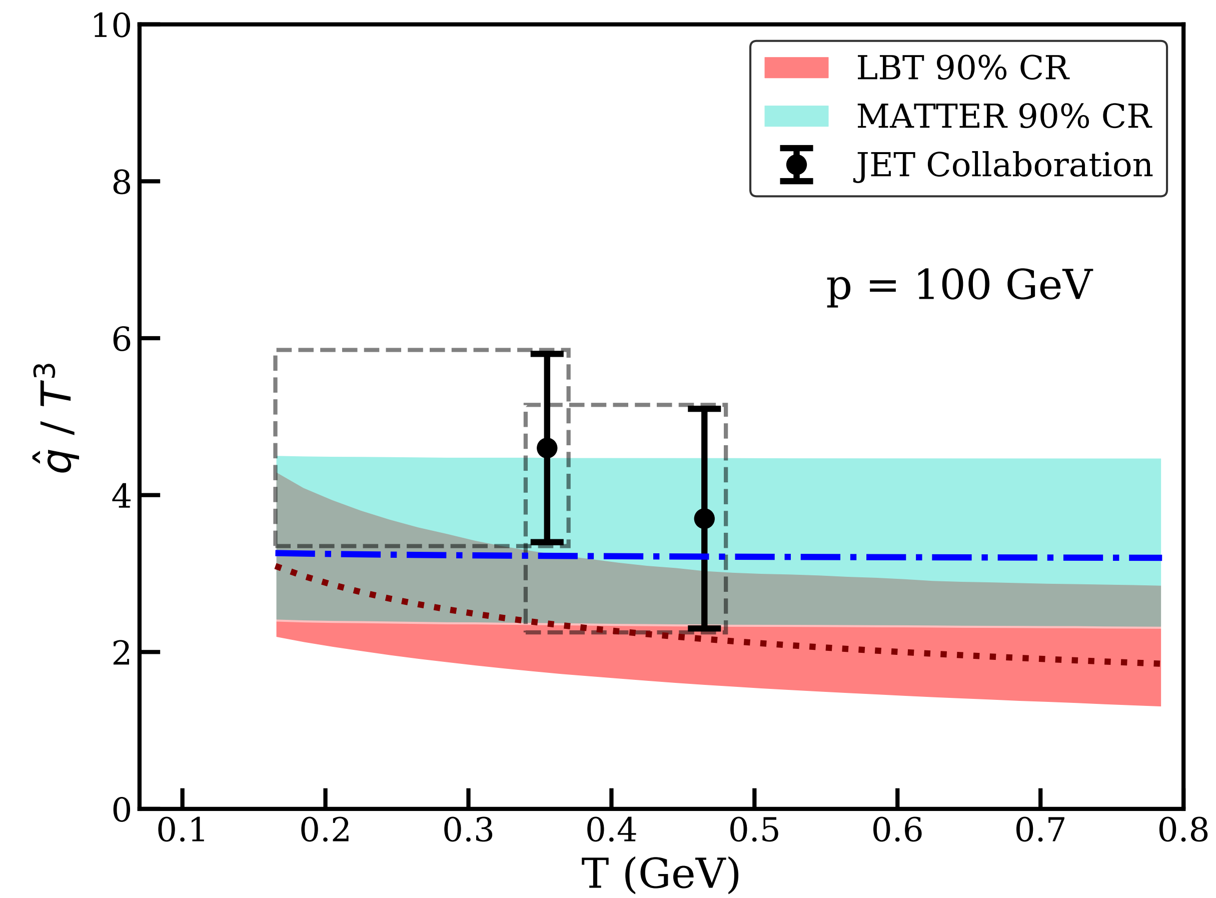
q-hat in LBT and MATTER

JET Collaboration results on the temperature dependence of q-hat with 5 different physics models for energy-loss and 2 different physics models for the bulk evolution:



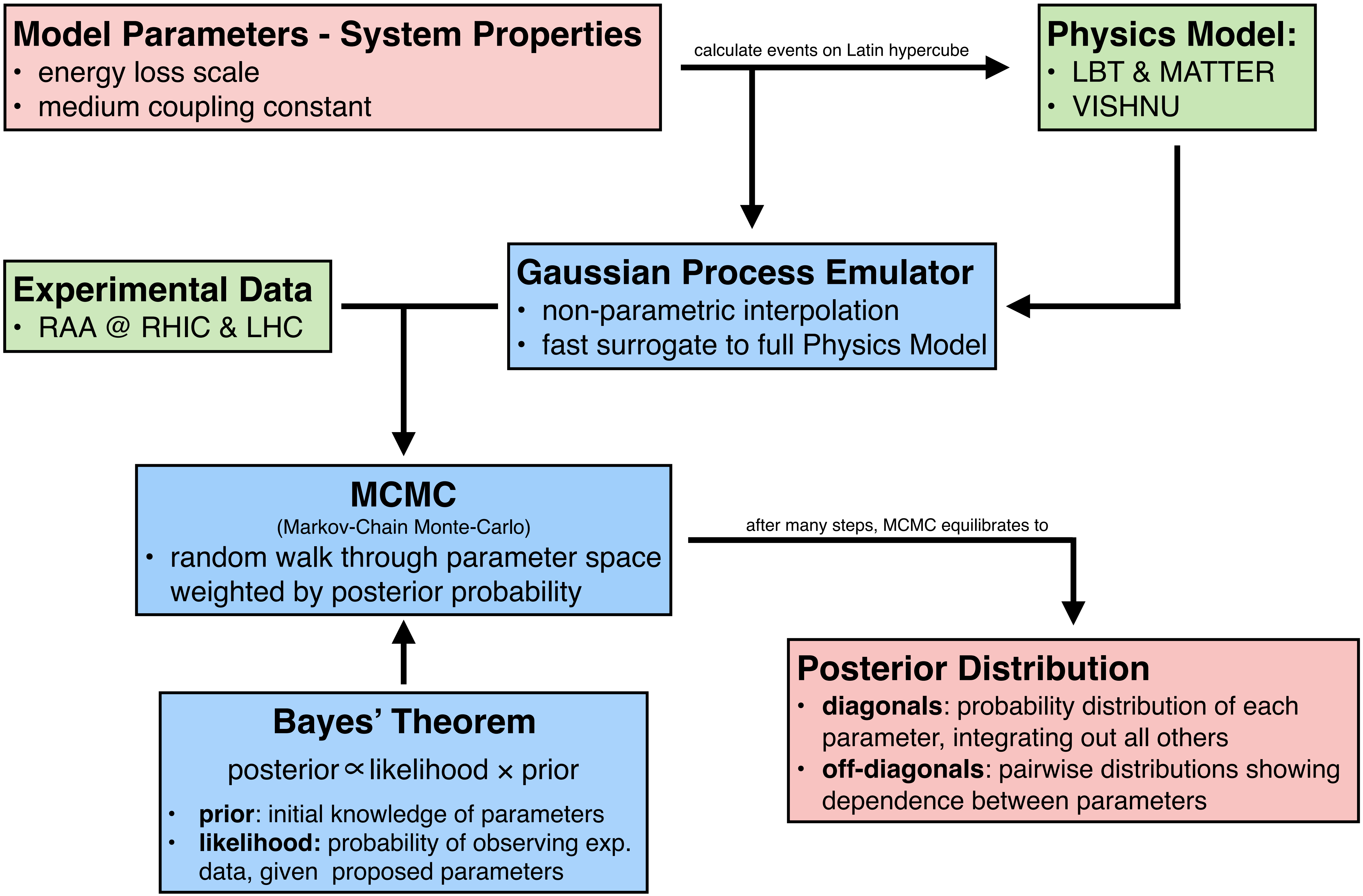
- single parameter q-hat optimization, significant uncertainties remain
- lack of modularity in energy loss and bulk evolution physics models

- preliminary results on calibrating LBT and/or MATTER to RHIC and LHC R_{AA} data at three different energies:



- simultaneous calibration of multiple parameters on multiple data sets, performed on two different energy-loss models
- q-hat as a smooth function of temperature and momentum

Bayesian Analysis Methodology



Parameter Space Design & Physics Model

- Choice of physics model:
  - MATTER
  - LBT
  - MATTER+LBT hybrid (with additional Q_0)
- Data:
  - single inclusive hadron R_{AA} at RHIC and LHC (2 energies)

- formulate jet energy-loss coefficient in terms of its temperature- and energy-dependence:

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

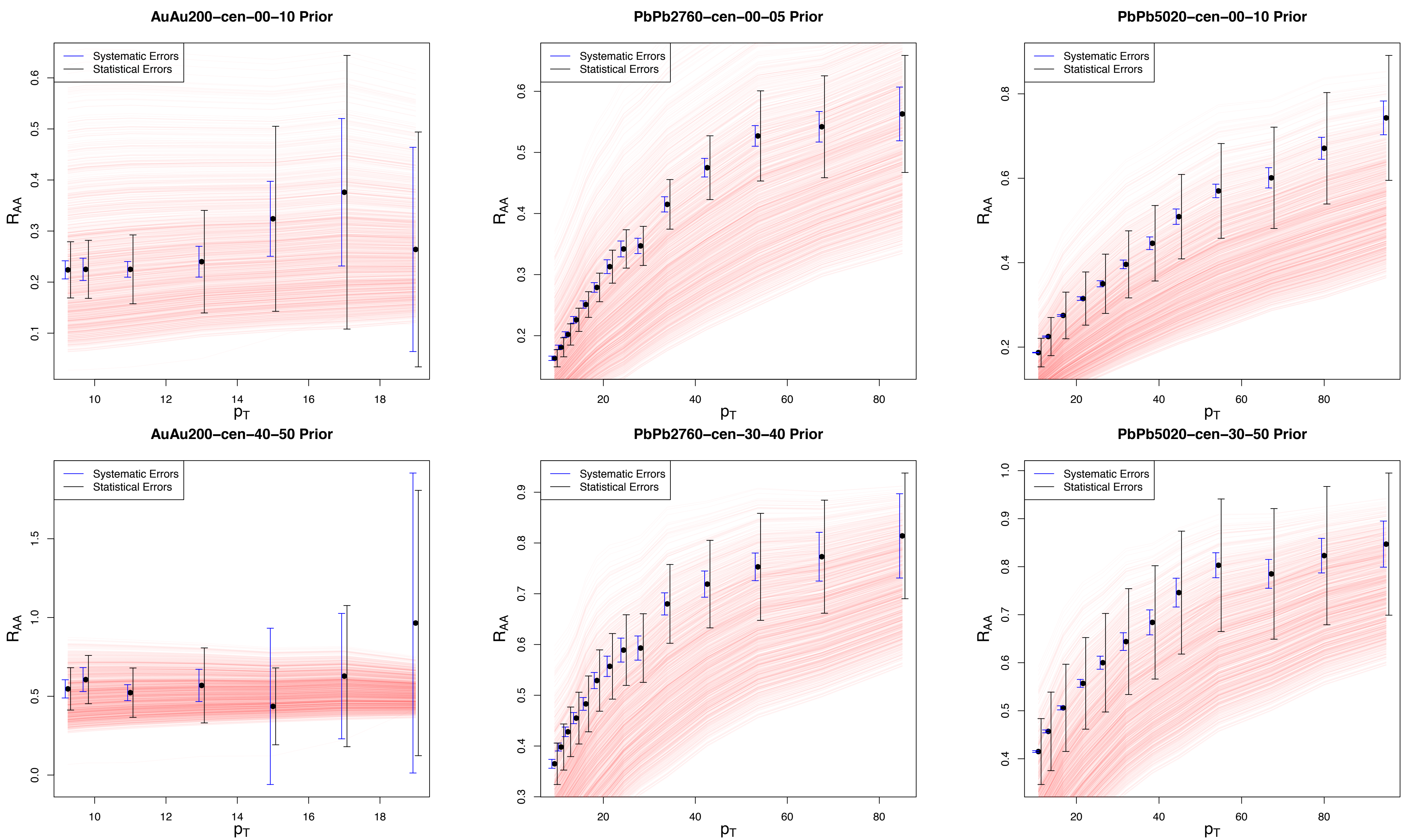
pure dependence on the scale of jet when Q >> T

(reflects physics in MATTER)

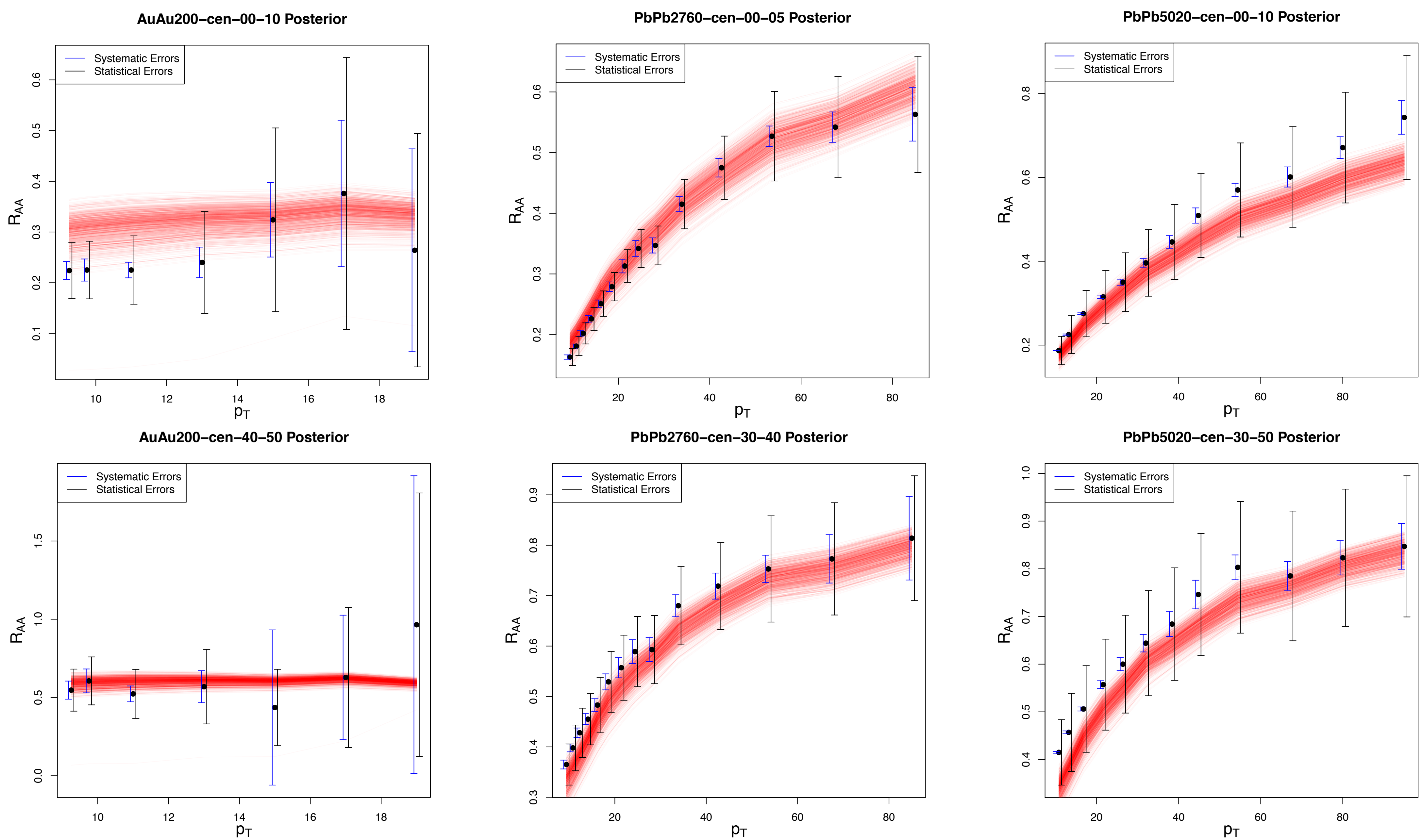
perturbative scattering with quasi-particles from a thermal medium (T)

(reflects physics in LBT)

Calibration Data & Prior

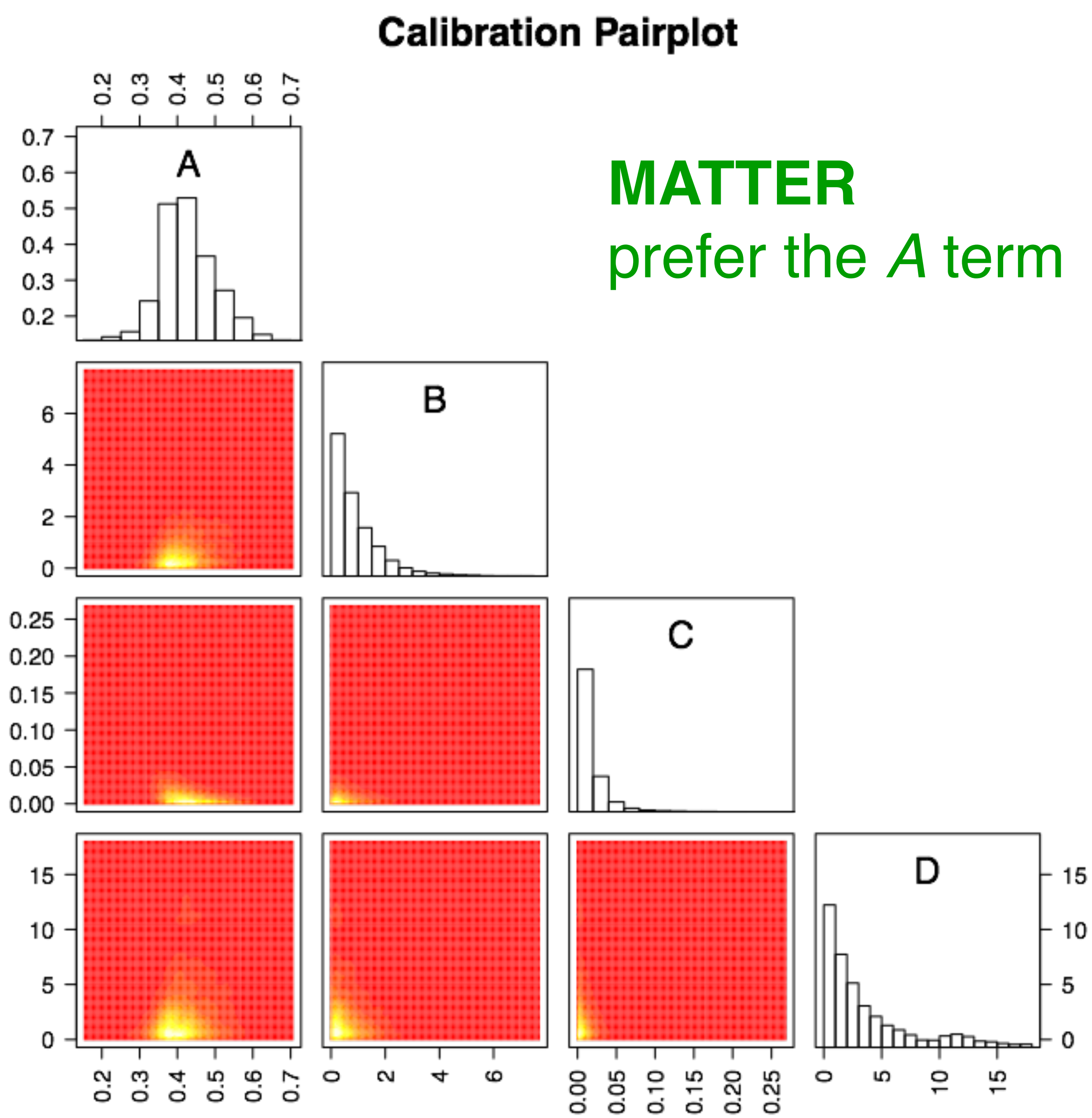


Calibration Data & Posterior

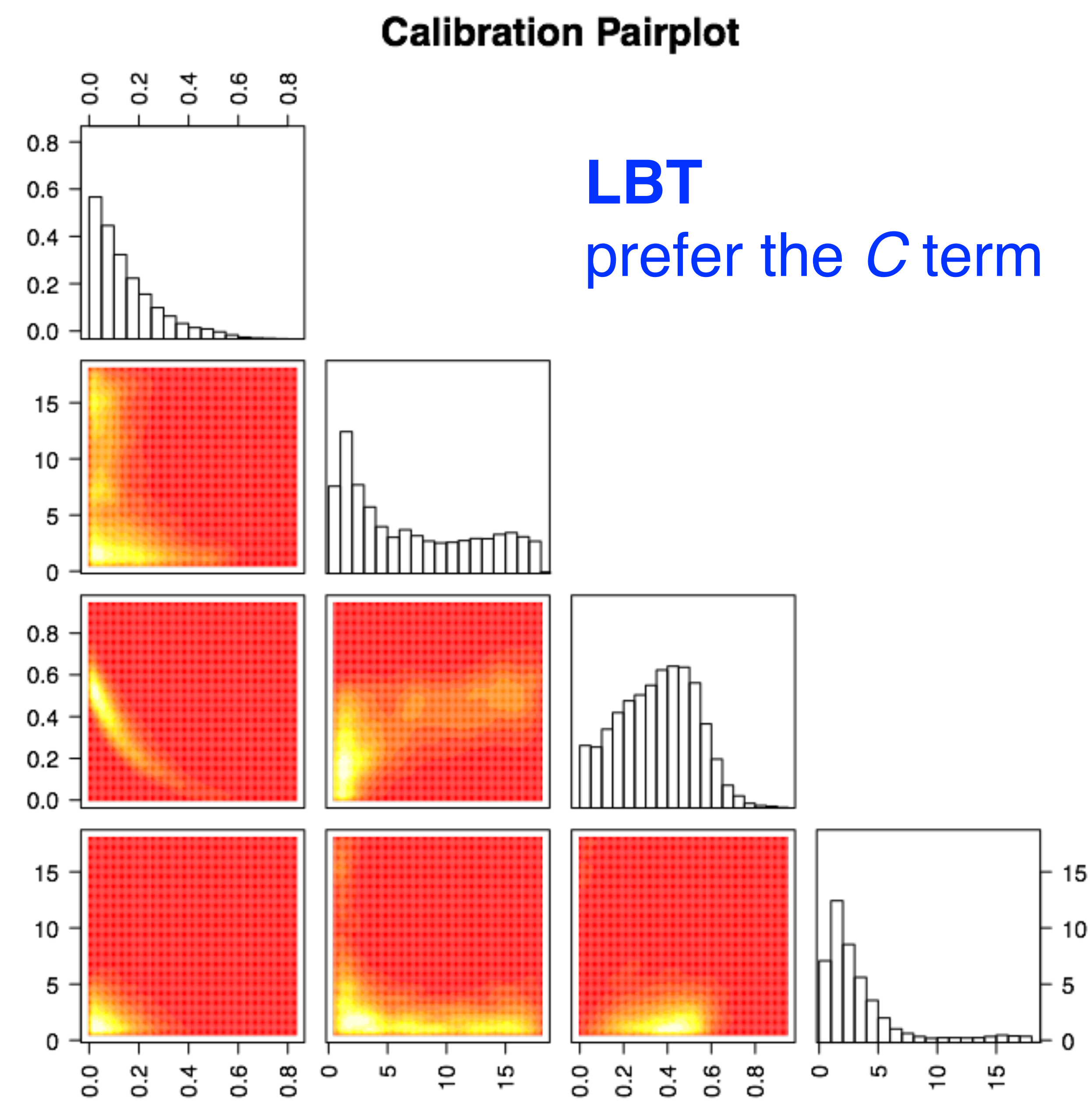


Posterior Distribution

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

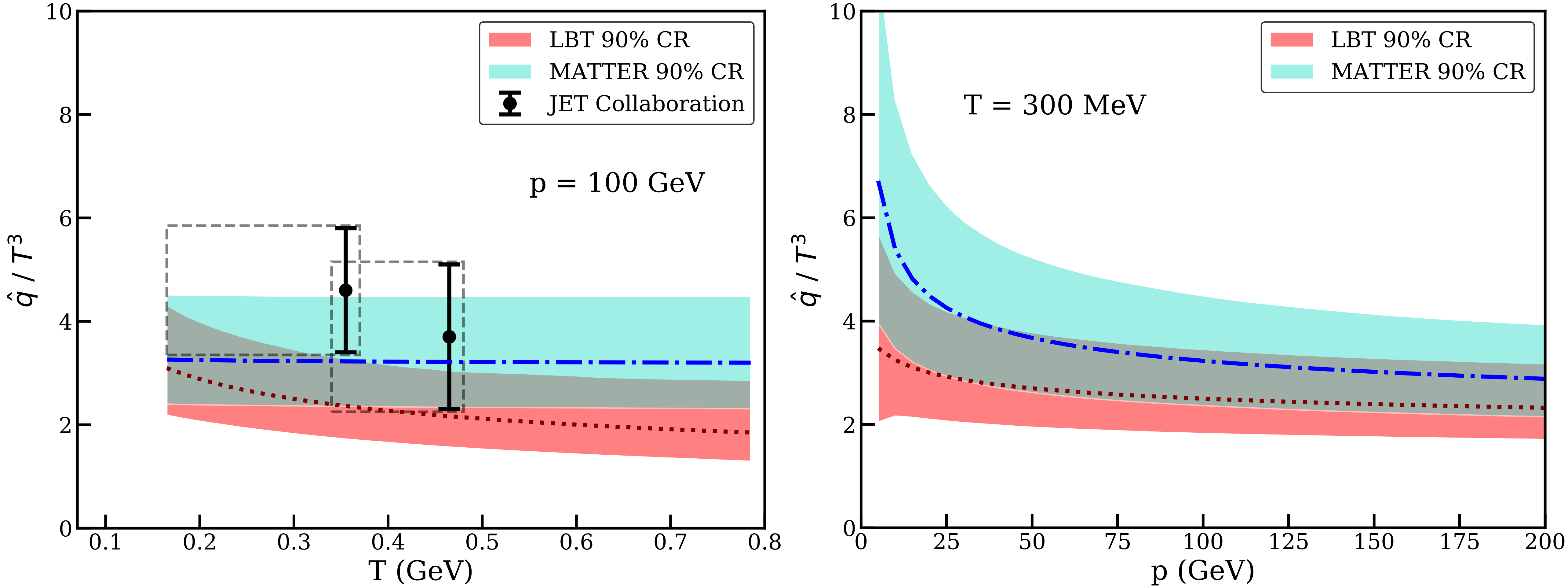


MATTER
prefer the *A* term



LBT
prefer the *C* term

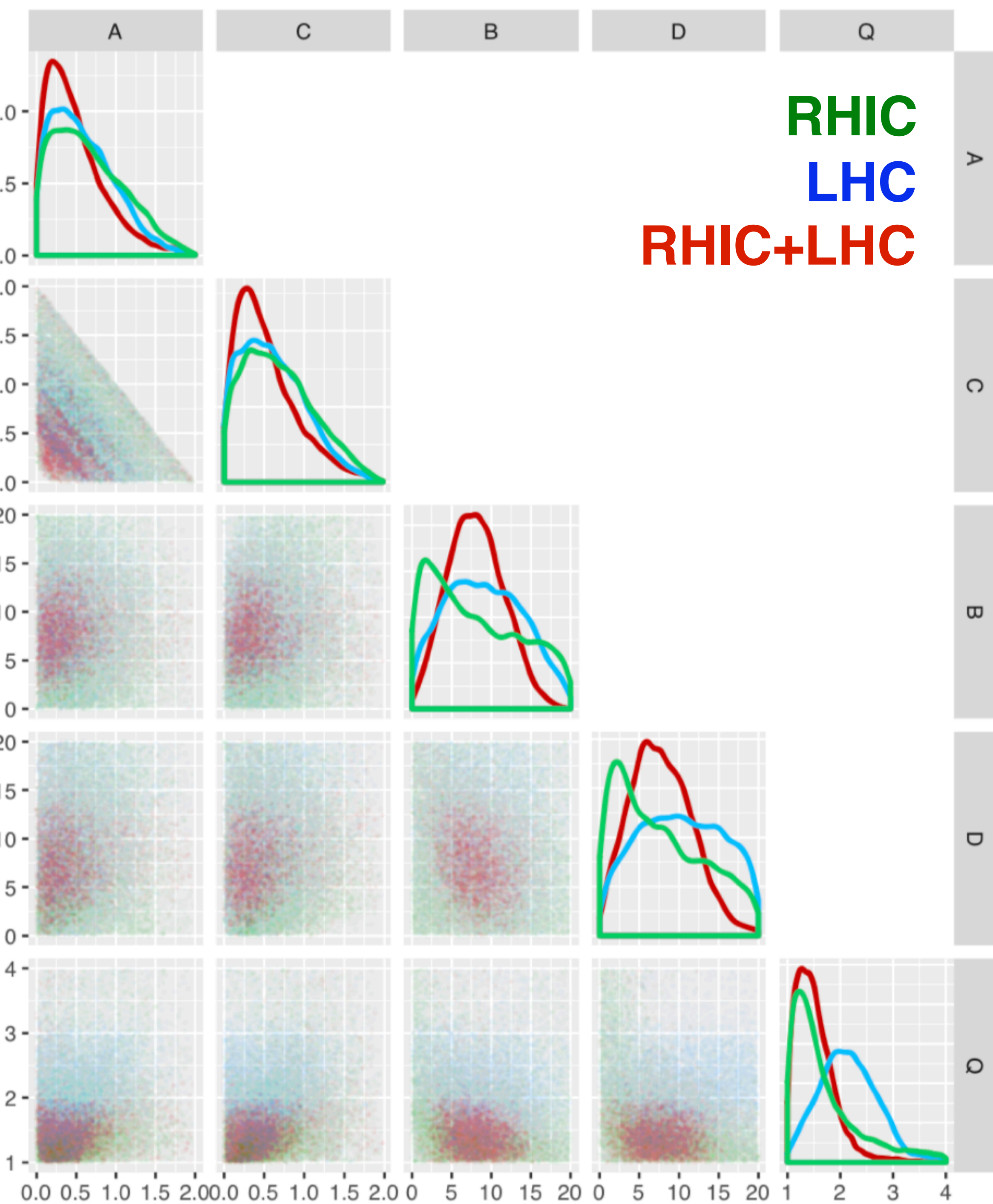
T and p dependence of q-hat



- smooth functions of *q* (mean value together with a 90% C.R.)
- larger value extracted from MATTER than from LBT
- stronger *T* dependence extracted from LBT than from MATTER

CPU expenditure: over 1,000,000 hours on the Open Science Grid

Hybrid Approach: MATTER+LBT



analysis setup:

- use same general parametrization:

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

- introduce scale parameter Q_0 to determine wether probe be evolved in MATTER or LBT respectively
- perform separate calibrations for RHIC and LHC as well as a combined calibration

preliminary results:

- first constraint on Q_0 (around 1.5 GeV)
- individual RHIC and LHC calibrations yield different values of Q_0, suggest possible T & p dependence of $Q_0(T,p)$
- better constraints on parameters possible, if more data are included

STAT-WG plans for Y3

Data Collection & Curation

- Extend HEPData readers to other results
  - hadron/jet v2, di-jet asymmetry, jet-hadron correlations, etc…
  - different centralities, collision systems, beam energies
  - we may extend our local data sets to include preliminary results for internal analyses, but JETSCAPE publications will only compare model outputs to published data

- Study implementation and treatment of correlated errors
  - Note: *this is a challenging and important task*
  - Past/current experience shows that global fits are very sensitive to the magnitude and coherence length for correlated errors
  - Implementation of correlations requires detailed knowledge of analysis methods
    - Calibrations and normalizations induce positive correlations
    - Resolution corrections (unfolding) lead to anti-correlations

- Work closely with experimental colleagues to
  - interpret errors correctly in JETSCAPE
  - build the case for developing standard formats for uploading correlated errors to HEPdata (i.e. covariance matrices)

RIVET-IZATION

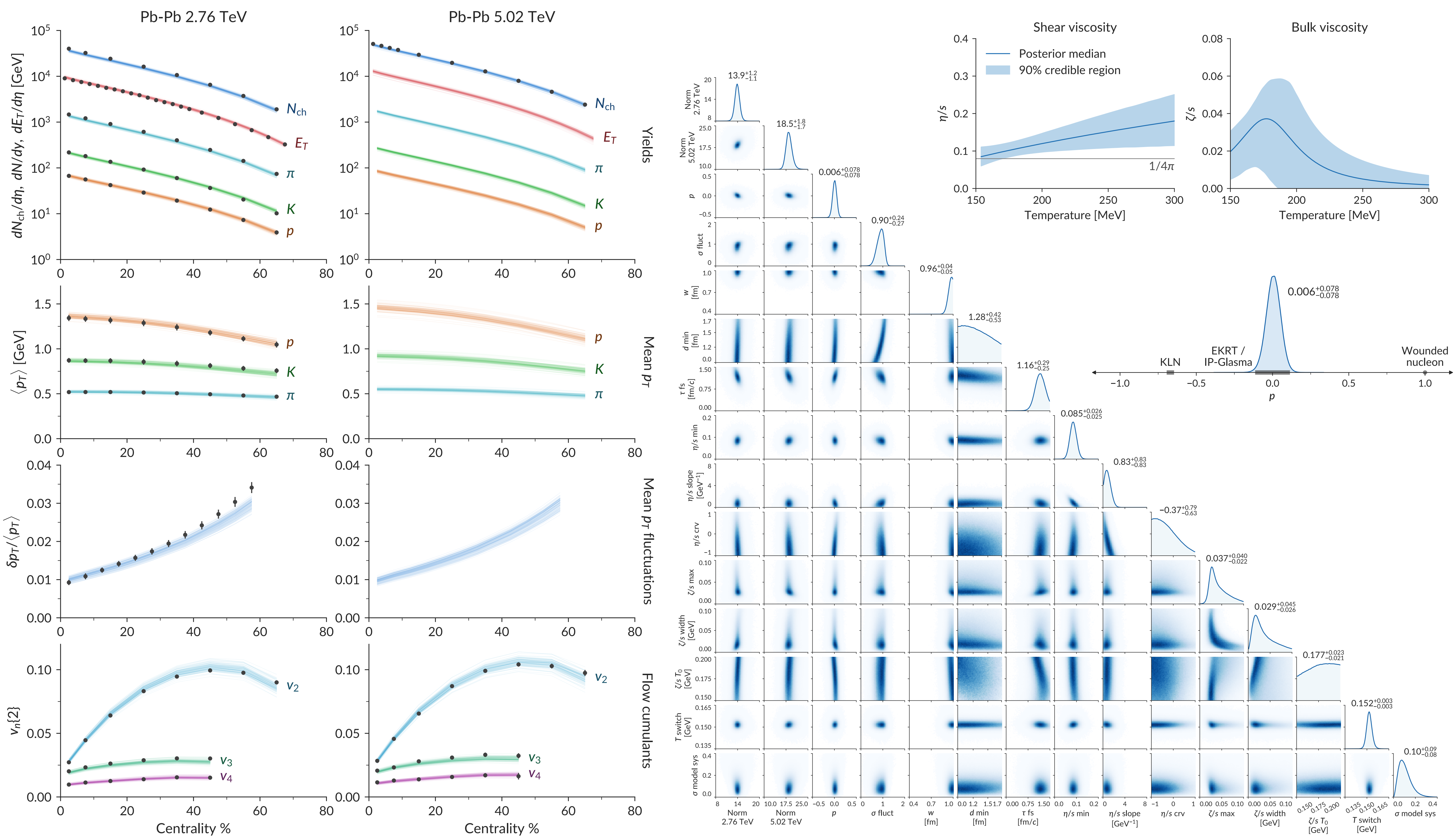
- Work with UTK affiliates on RIVET-HI demonstration project

- Support community-wide efforts to develop and adopt RIVET-HI standard
  - extend RIVET-HI to other experiments through JETSCAPE member affiliations

- Publicize JETSCAPE results using RIVET-HI to build momentum

Soft Medium Calibration

- follow up on latest Duke calibration of QGP medium properties
- physics model: Trento + free streaming + MUSIC + SMASH
- scope: Au+Au (200 GeV); Pb+Pb (2.76 & 5.02 TeV)



Calibration/Statistics Support to Collaboration

The STAT-WG should support all Jetscape analyses that contains tunable parameters and compare to data by designing and executing (in concert with SIMS-WG) a Bayesian calibration for these analyses.

- finalize q-hat analysis in LBT, MATTER and LBT-MATTER hybrid
- revisit proton-proton tune
- conduct analysis for hadronization modules
- calibrate heavy quark energy loss modules
- provide support for any other Jetscape analysis that looks at data

Stats development work:
- develop and release public version of statistical tools by end of Y3
- develop tools for comparison of different physics models and quantifying their “performance”

Duke Group Planned Activities Y3

Personnel & WG Membership

Duke Physics:
- Steffen A. Bass (STAT co-convener)
- Jean-Francois Paquet (SIMS co-convener)
- Weiyao Ke (50% Jetscape funded)
- Tianyu Dai (50% Jetscape funded)
- Wenkai Fan

Duke Statistics:
- Robert L. Wolpert
- Jake Coleman

STAT-WG:
- Steffen A. Bass
- Jean Francois Paquet
- Weiyao Ke
- Tianyu Dai
- Robert L. Wolpert
- Jake Coleman

PHYS-WG:
- Steffen A. Bass
- Jean Francois Paquet
- Weiyao Ke
- Wenkai Fan

SIMS-WG:
- Steffen A. Bass
- Jean Francois Paquet
- Weiyao Ke

COMP-WG:
- Weiyao Ke
- Wenkai Fan

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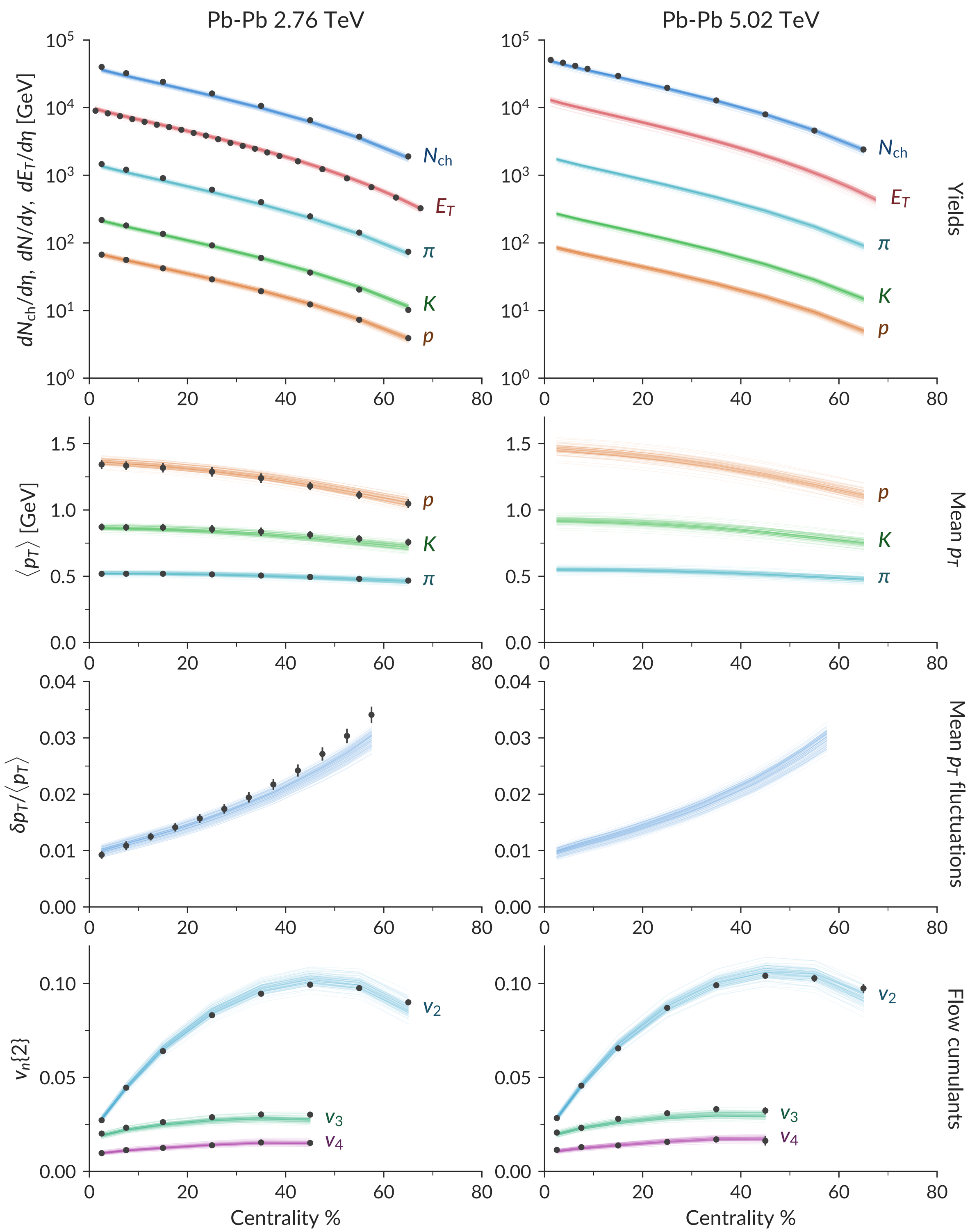

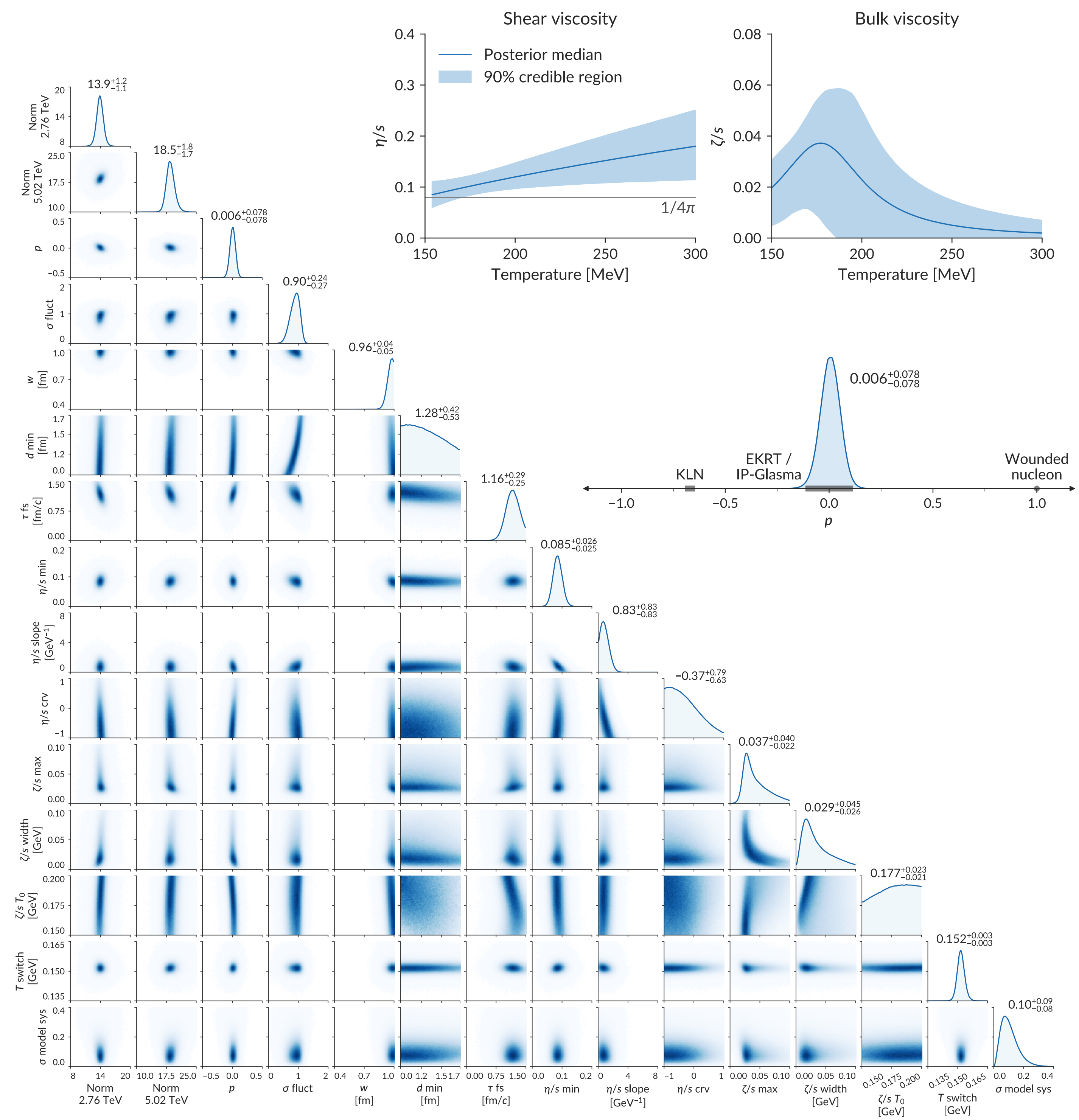

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Implementation of heavy quark energy-loss

- Heavy quarks: good quasi-particles; on-shell approximation in QGP
- interaction with medium treated in a linearized transport equation
- two components: perturbative scattering & non-perturbative diffusion (will be modularized to allow for studies of individual contributions)

$$(\partial_t + \vec{v} \cdot \nabla) f_Q = \left(\hat{\mathcal{C}} + \hat{\mathcal{D}}\right) f_Q$$

- space-time evolution of QGP is obtained from viscous hydrodynamics

Duke contribution:

- personnel: Weiyao Ke (5th year student) and Wenkai Fan (2nd year student)
- experience in heavy quark transport:
  - Yingru Xu, Jonah E. Bernhard, Steffen A. Bass & Marlene Nahrgang:
    Data-driven analysis for the temperature & momentum dependence of the heavy quark diffusion coefficient
    Physical Review **C97** (2018) 014907
  - Weiyao Ke, Yingru Xu & Steffen A. Bass:
    A linearized Boltzmann-Langevin model for heavy quark transport in hot and dense QCD matter
    arXiv:1806.08848

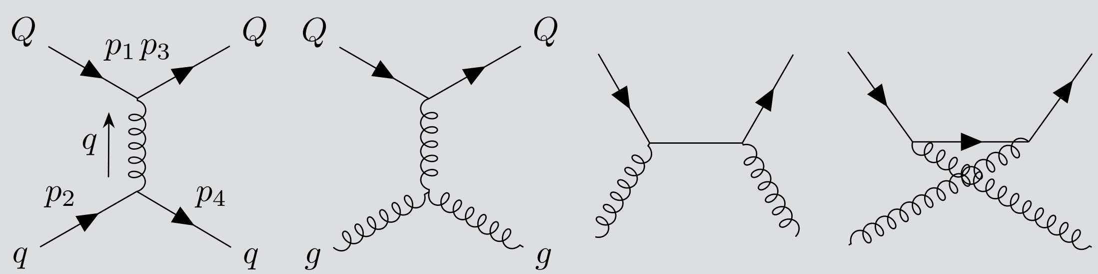
Scattering and Diffusion Dynamics

Combine the strength of the linearized-Boltzmann and Langevin approaches:

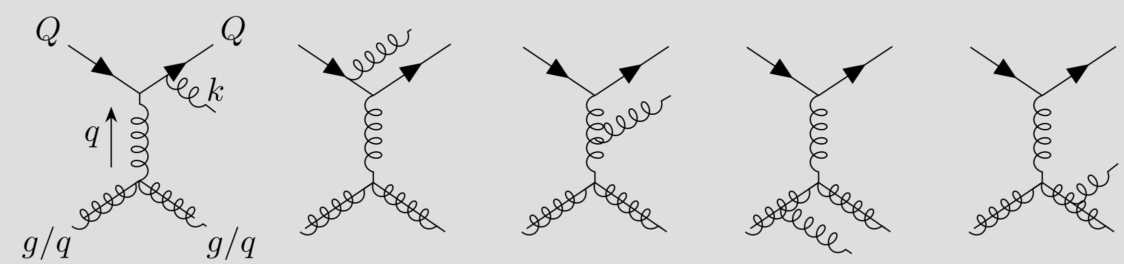
$$\frac{p \cdot \partial f_Q}{E} = \mathcal{C}[f_Q] - \frac{\partial}{\partial p_i}\left(A_i - \frac{1}{2}\frac{\partial}{\partial p_j}B_{ij}\right) f_Q = \left(\hat{\mathcal{C}} + \hat{\mathcal{D}}\right) f_Q$$

perturbative processes:

- elastic scattering:



- inelastic: improved Gunion Bertsch



Fochler et al. PRD88 014018

- gluon radiation **and** absorption implemented to conserve detailed balance

non-perturbative processes:

- treated in a Langevin equation with isotropic random force

$$\Delta\vec{x_i} = \frac{\vec{p_i}}{E}\Delta t \quad \Delta\vec{p_i} = -\eta_D\,\vec{p_i}\,\Delta t + \Delta t\,\vec{\xi}_i(t)$$

- Einstein relation connects random force to drag coefficient to ensure proper equilibrium