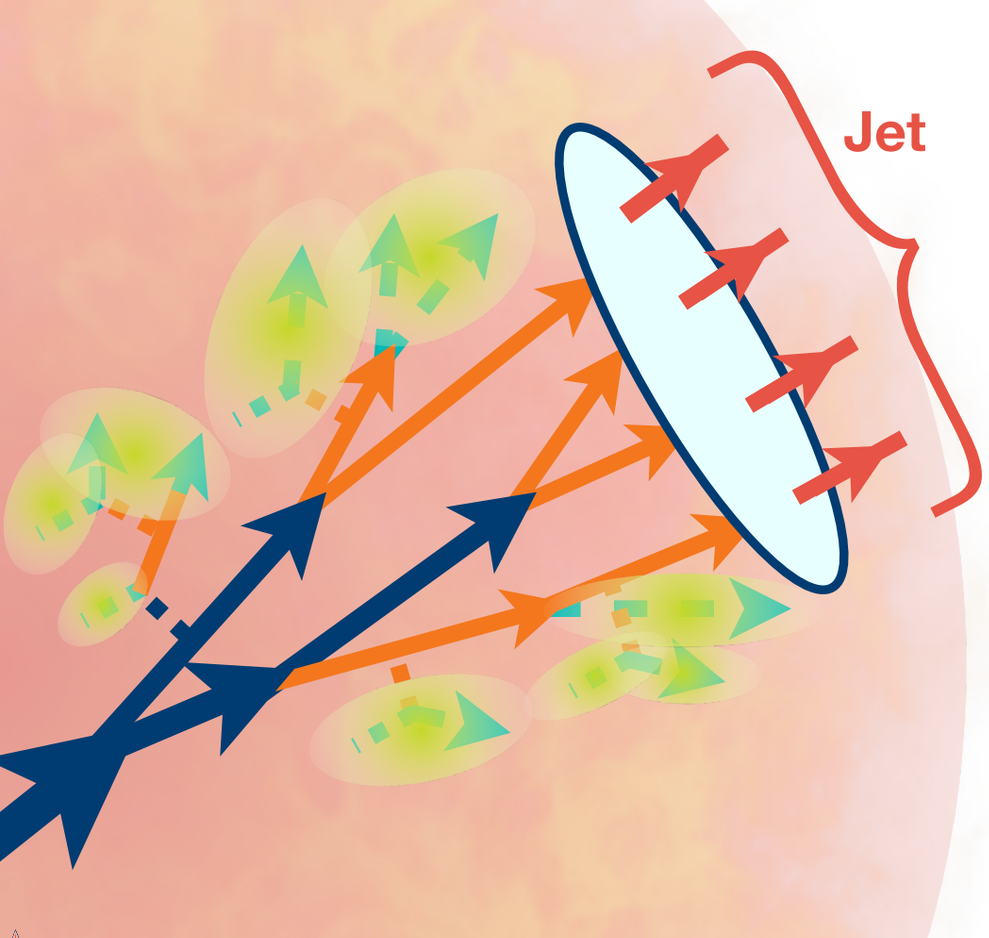
The JETSCAPE Framework



James Mulligan
(UC Berkeley / LBNL)

ALICE Week
July 7 2020

JETSCAPE

Event generator

- A ***framework*** for general-purpose MC event generators in heavy-ion collisions

https://github.com/JETSCAPE/JETSCAPE

Statistical toolkit

- Extract model parameters via Bayesian analysis with Gaussian Process Emulators

https://github.com/JETSCAPE/STAT

A general-purpose MC framework

JETSCAPE is not just for jets!
It is a framework for *general-purpose* event generators

1 **The JETSCAPE framework is modular**

The core framework decides how physics modules can interact with each other — but the modules themselves can be user-contributed

2 **Physics modules are open-source**

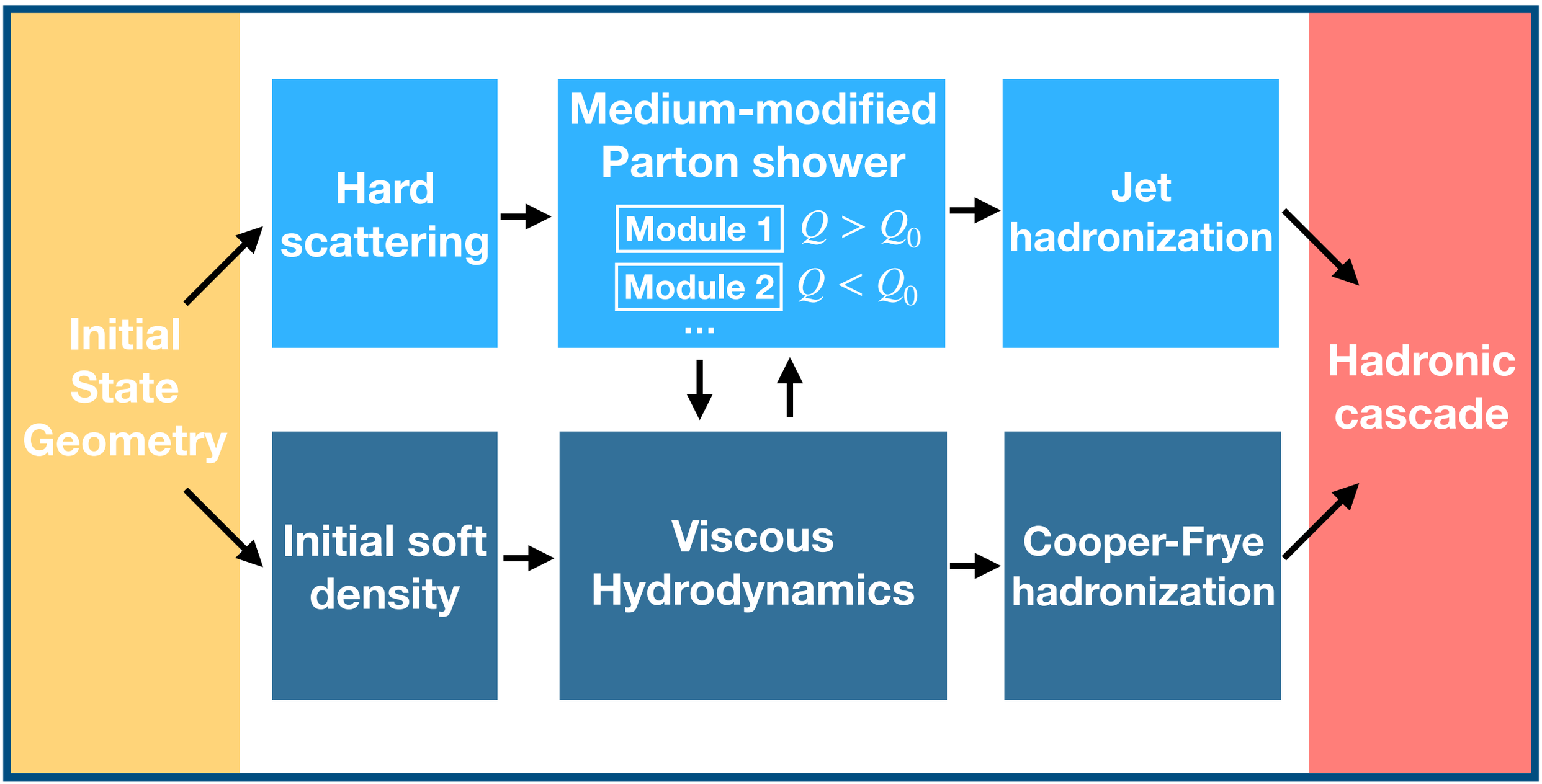
Key improvement in heavy-ion physics — predictions can be checked against many observables simultaneously

A unified framework has clear benefits when we want to compare models of one particular part of a multi-stage event evolution

JETSCAPE Event Generator

JETSCAPE Manual: 1903.07706

https://github.com/JETSCAPE/JETSCAPE



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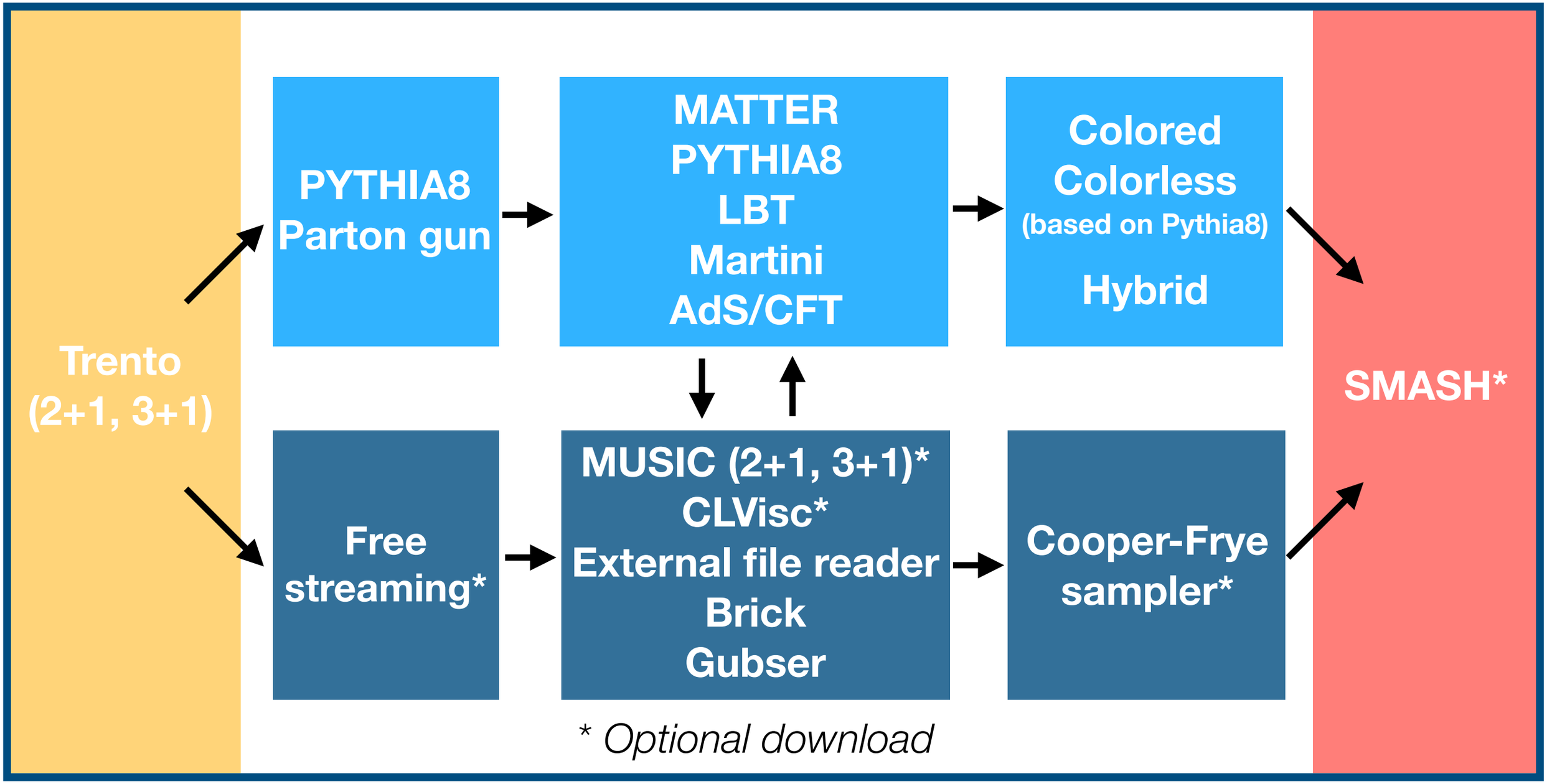

The current status

The framework is available and ready for public use

Many recent improvements to user experience

Work ongoing to incorporate JETSCAPE into the ALICE framework

Thanks to R. Preghenella, A. Maire, M. Fasel

JETSCAPE 3.0

The JETSCAPE simulation framework is an overarching computational envelope for developing complete event generators for heavy-ion collisions. It allows for modular incorporation of a wide variety of existing and future software that simulates different aspects of a heavy-ion collision. For a full introduction to JETSCAPE, please see The JETSCAPE framework.

Please cite The JETSCAPE framework if you use this package for scientific work.

Installation

Please see the Installation Instructions.

Running JETSCAPE

The main executable to generate JETSCAPE events is `runJetscape`, located in the `build/` directory. To generate JETSCAPE events, you should pass an XML file specifying the settings with which you would like to run:

```
./runJetscape ../config/jetscape_user.xml
```

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```

What this means for physics comparisons

First physics results of "out-of-the-box" models from the JETSCAPE Collaboration

Use responsibly — it is a framework — you get out the physics you put in

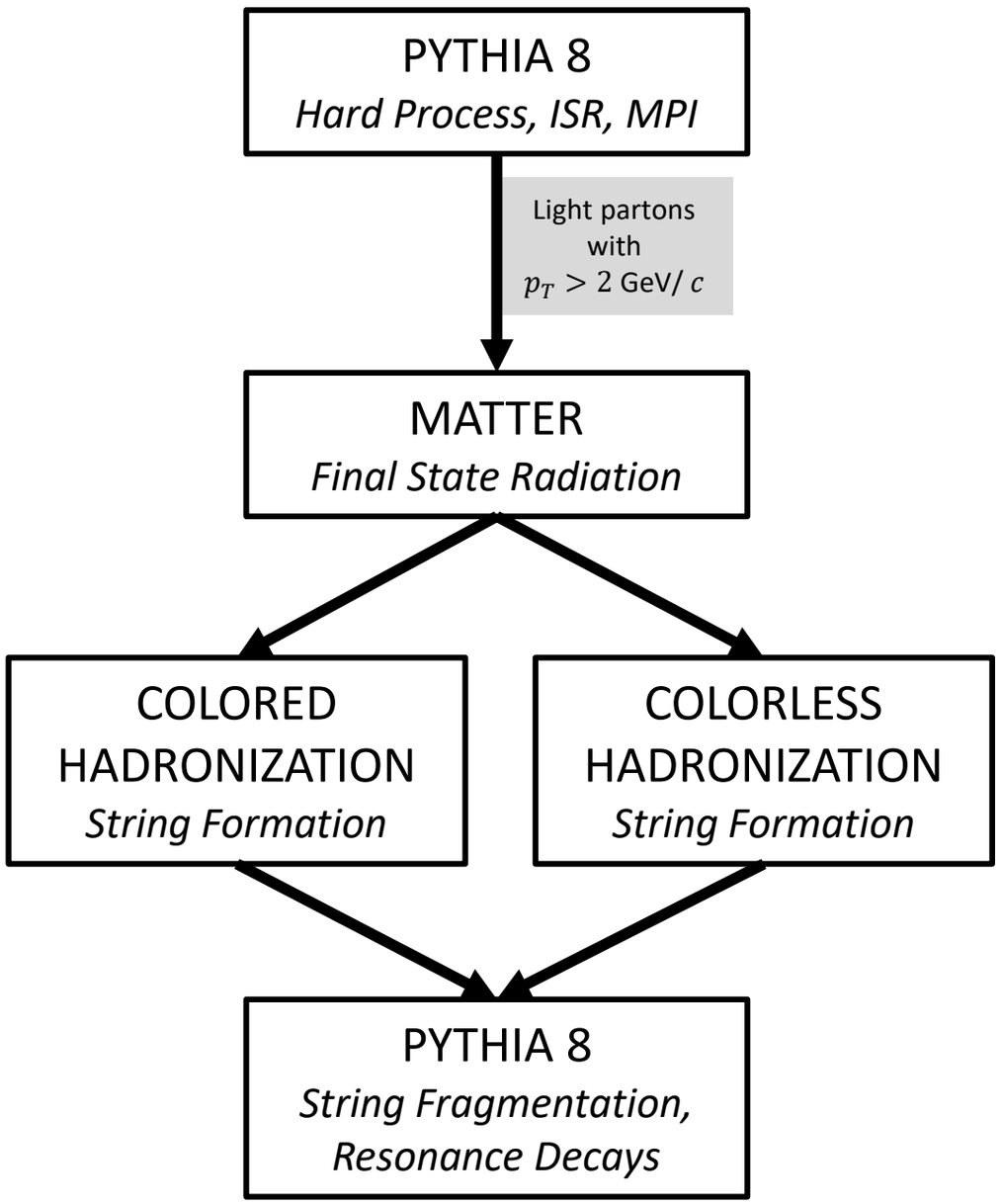
There is a lot of theoretical work inside — but it is only a slice of the theory landscape

→ **We are at the start of the exciting phase — well-controlled theory comparisons**

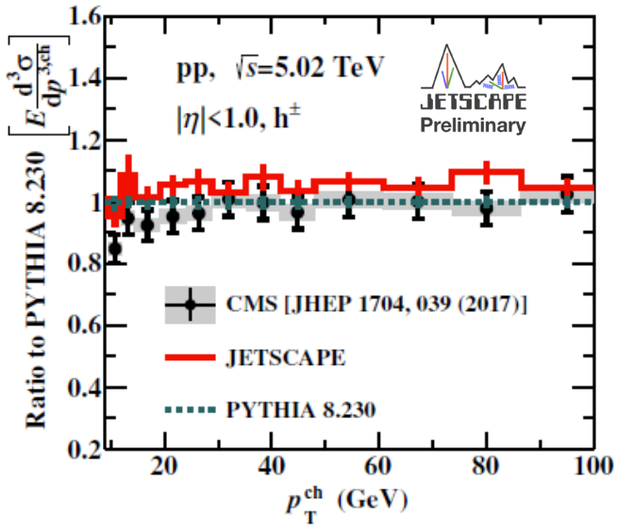
JETSCAPE — pp collisions

1910.05481

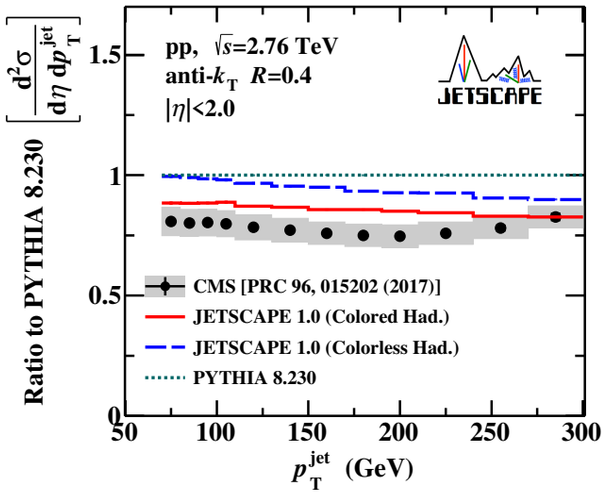
PP19 Tune



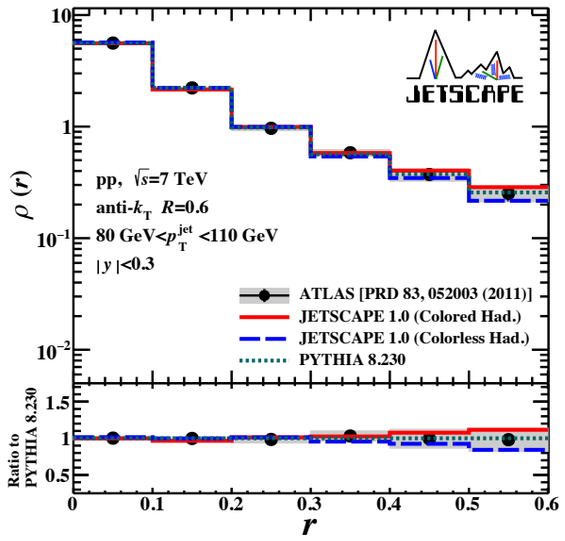
Charged hadron cross-section



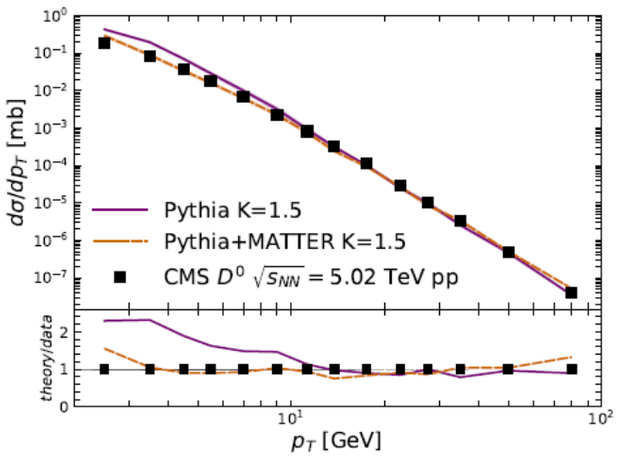
Inclusive jet cross-section



Jet shape



D^0 cross-section



...

Comparable performance to Pythia8

JETSCAPE — heavy-ion collisions

Multi-stage energy loss

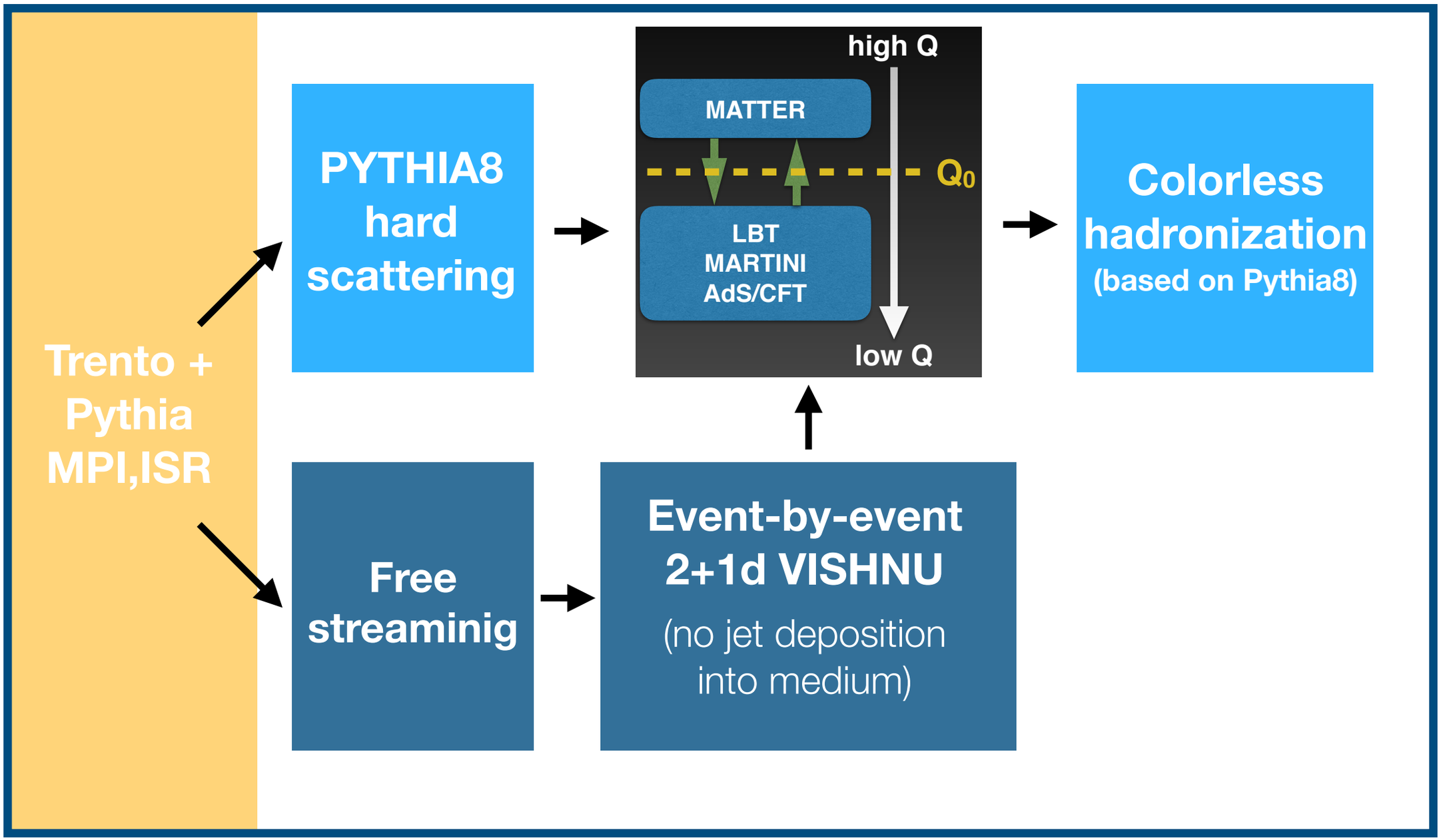
The virtuality of each parton in the shower determines which energy loss module it will undergo

Yasuki Tachibana, HP2018

Large-Q ($> Q_0$)	Small-Q ($< Q_0$)	
	Large-E	Small-E
MATTER	**LBT**	**MARTINI**	**AdS/CFT**
Majumder(13), Kordell, Majumder(17), Cao, Majumder(17)	Wang, Zhu(13), Luo, et al.(15,18) Cao, et al.(16,17), He, et al.(18)	Schenke, Gale, Jeon(09), Park, Jeon, Gale(17, 18)	Chesler, Rajagopal(14, 15) Pablos, et al.(15, 16, 17)
Radiation dominated Virtuality ordered splitting	Scattering dominated On-shell parton transport		Diffusion into medium
Higher Twist Formalism	Higher Twist Formalism	AMY Formalism	$\mathcal{N}$ = 4 super Yang-Mills

PRC 96, 024909 (2017)

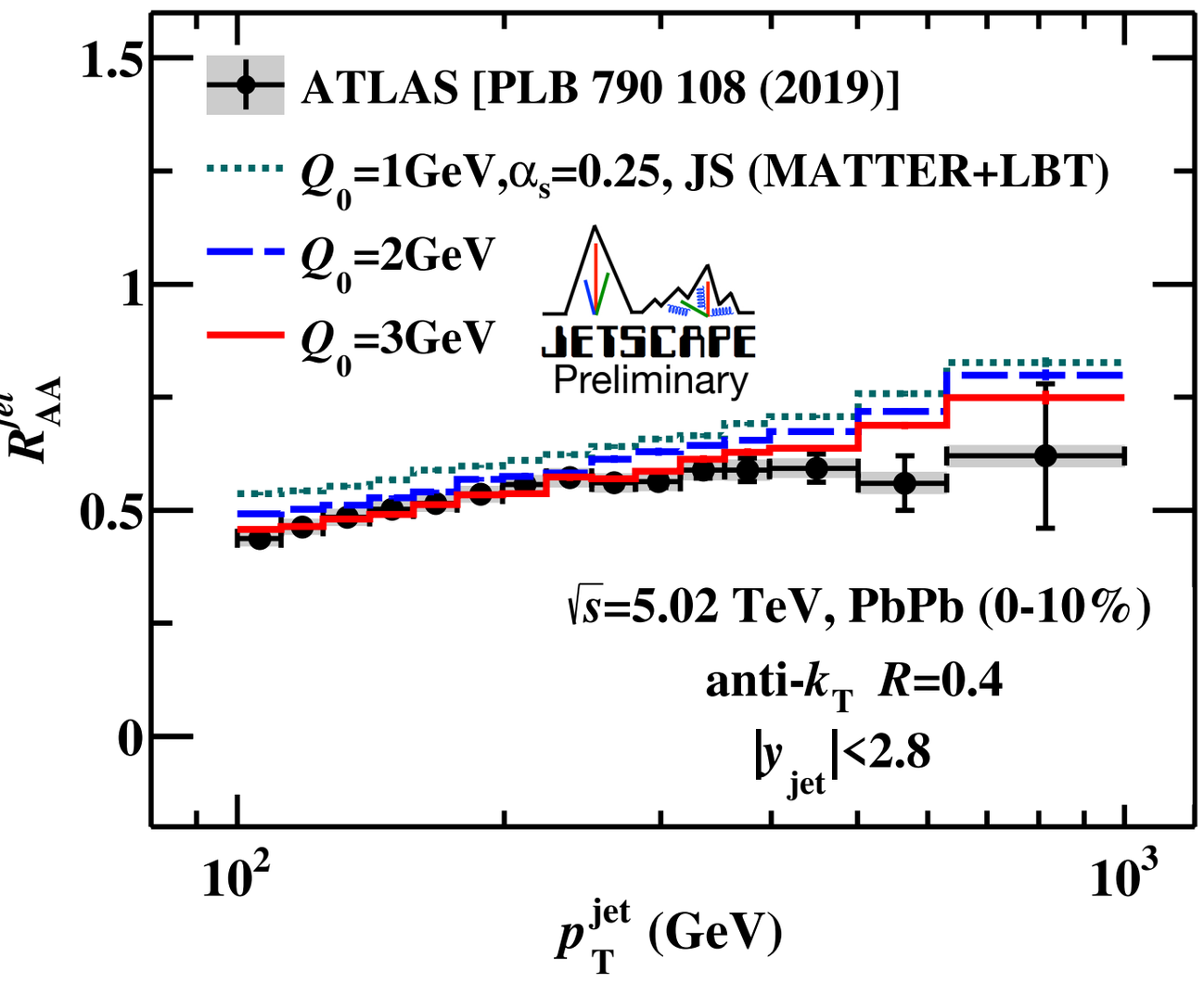
JETSCAPE — heavy-ion collisions



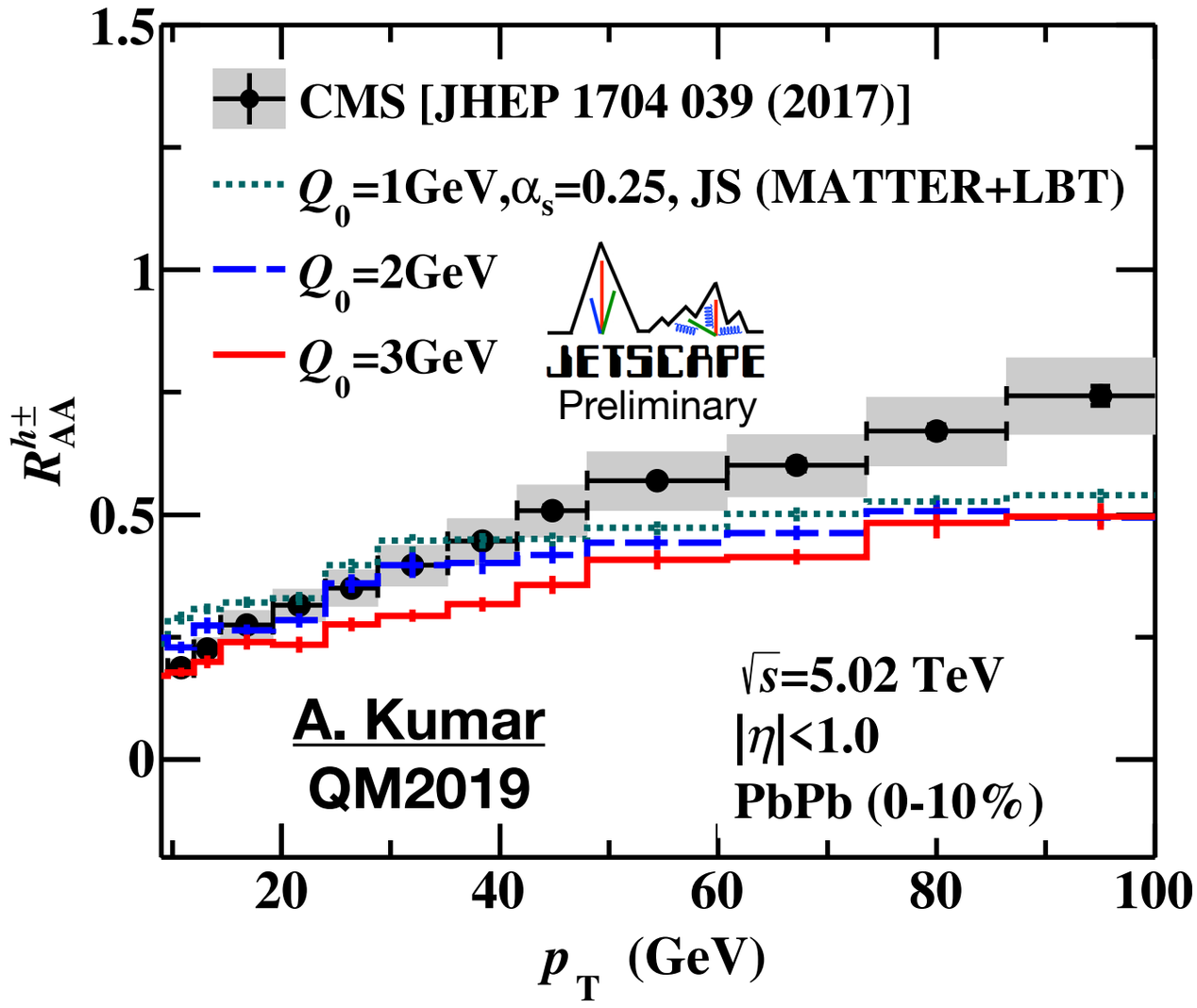
Medium recoil implemented in jet shower, based on weakly-coupled kinetic theory approach

Example: Inclusive cross-sections

Jet R_{AA}



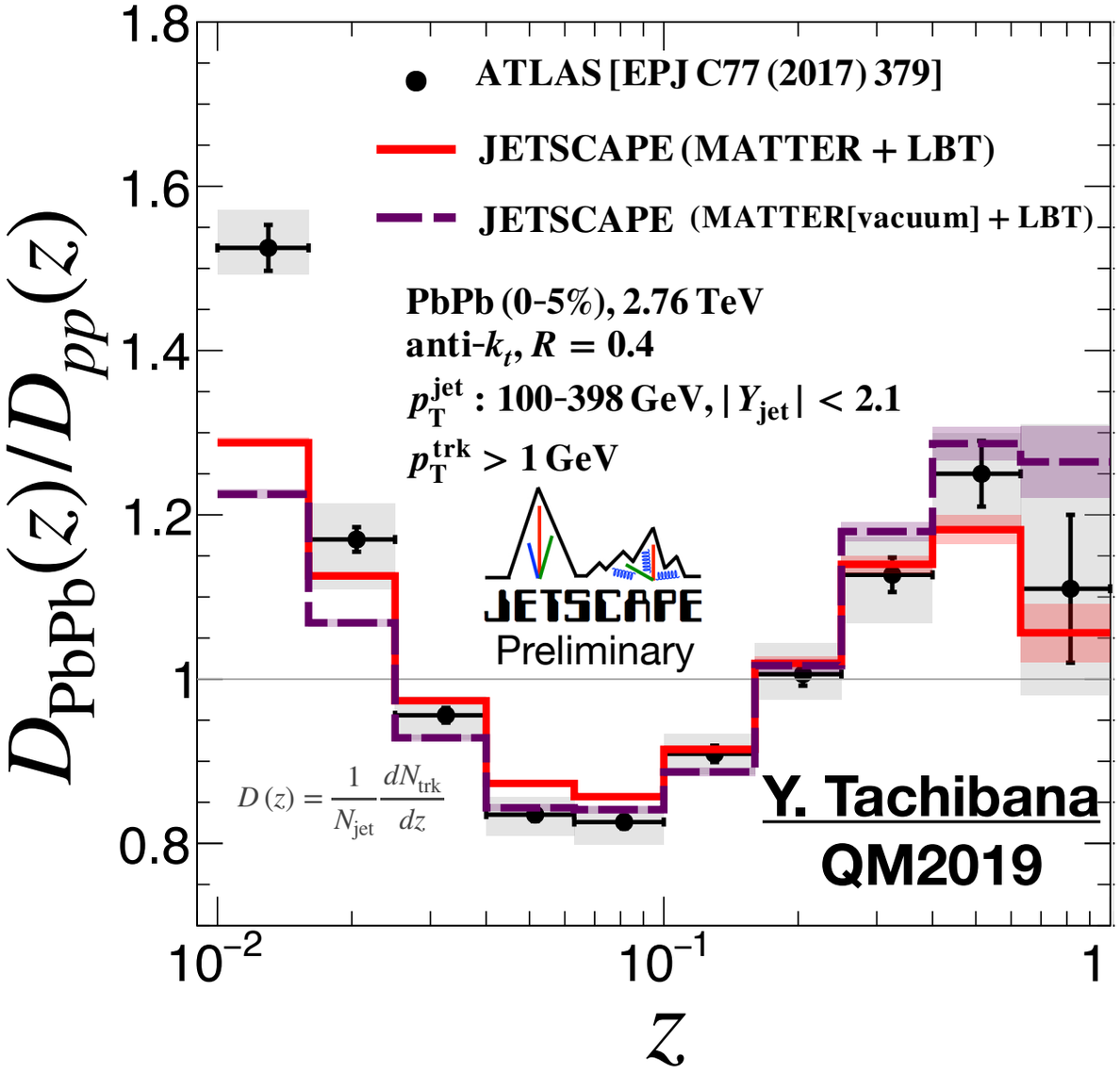
Hadron R_{AA}



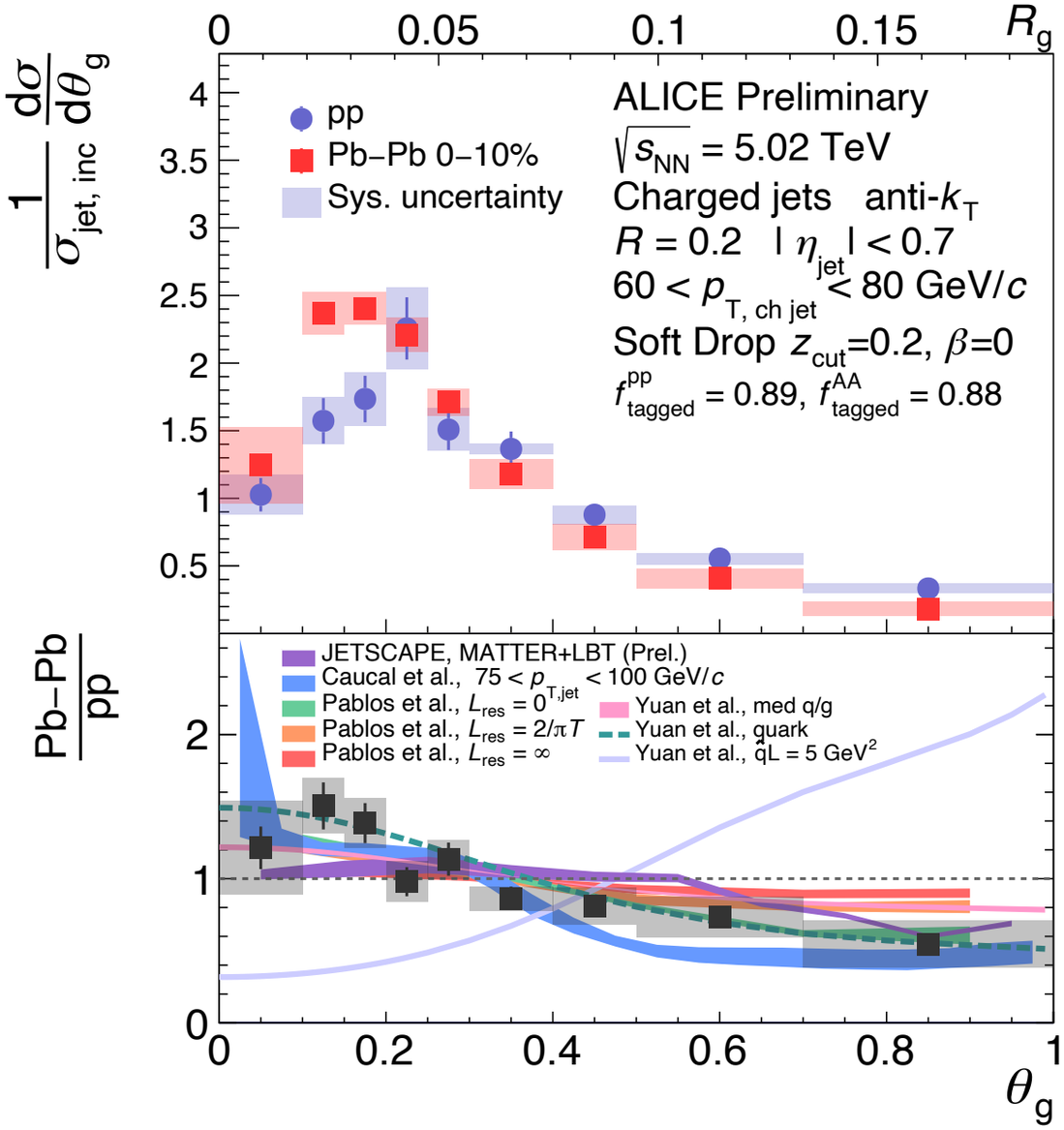
Virtuality switching parameter $Q_0 = 2$ GeV provides reasonably good simultaneous description of the data

Example: Jet substructure

Hadron-in-jet distribution



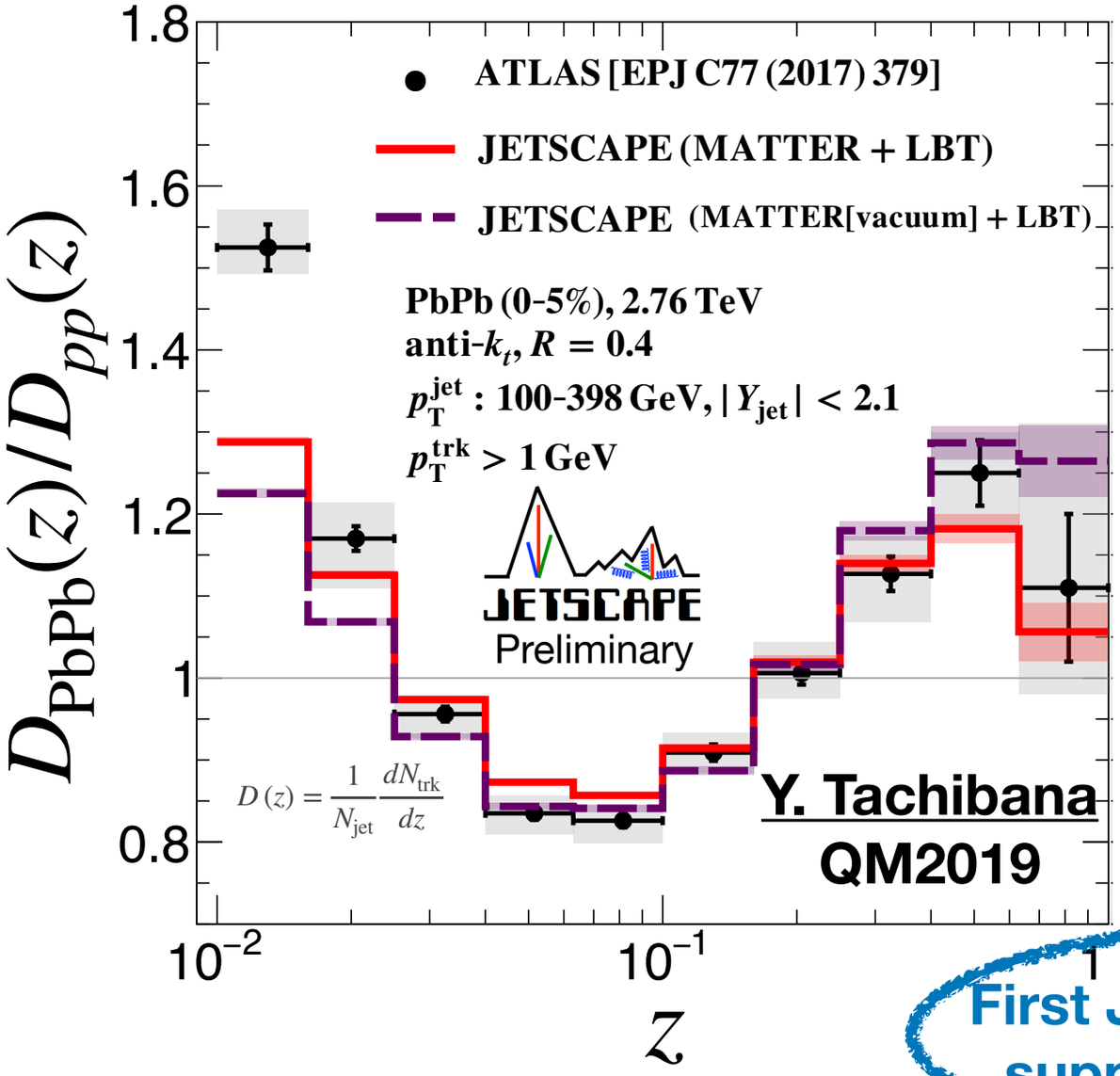
Groomed jet radius



Reasonable (not perfect) description of jet substructure

Example: Jet substructure

Hadron-in-jet distribution



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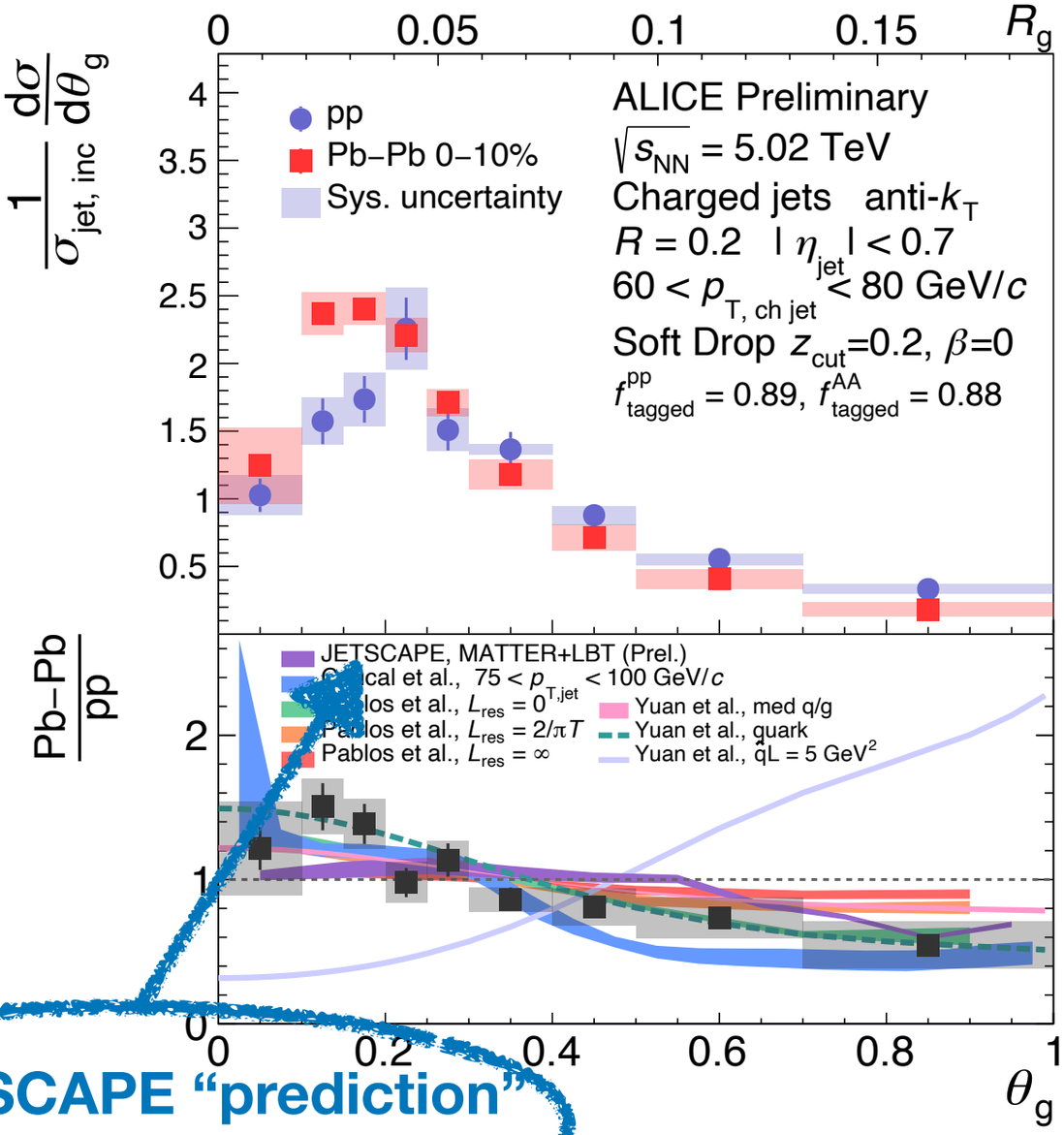


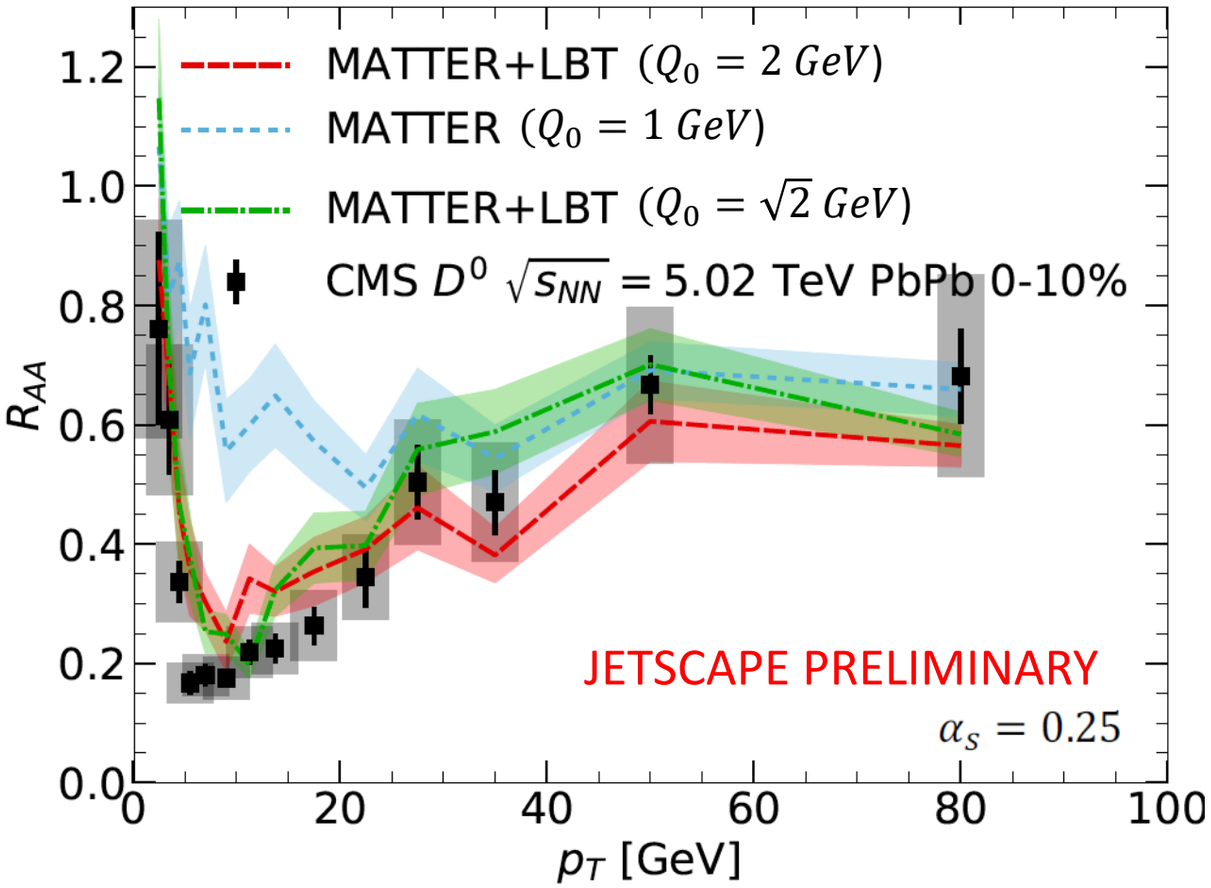
First JETSCAPE "prediction" supplied to an experiment

Reasonable (not perfect) description of jet substructure

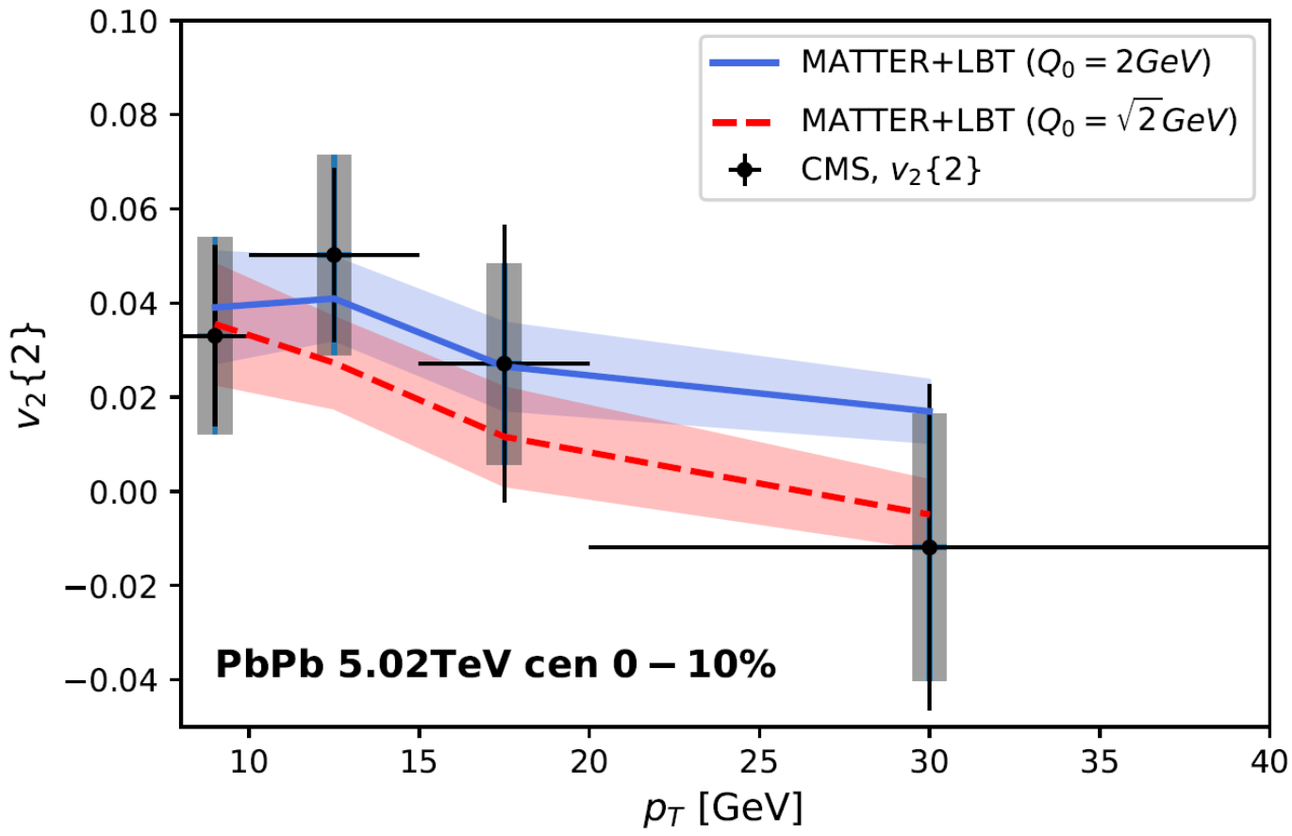
Example: Heavy flavor

W. Fan, HP2020

D_0 meson R_{AA}



D_0 meson v_2



No additional tuning for heavy-flavor

Future studies: Consider recombination and hadronic transport

Reasonably good description of the data with multi-stage approach

Two-stage hydro

Y. Tachibana, QM2019

Run first hydro event without jet deposition — determine jet evolution
Re-run same hydro event — with quenched jet depositions into medium

Strongly-coupled Description of Medium Response

Diffusion into the medium

Model: **Causal Diffusion**

➡ **Source Profile for Fluid**

Evolution as part of bulk medium

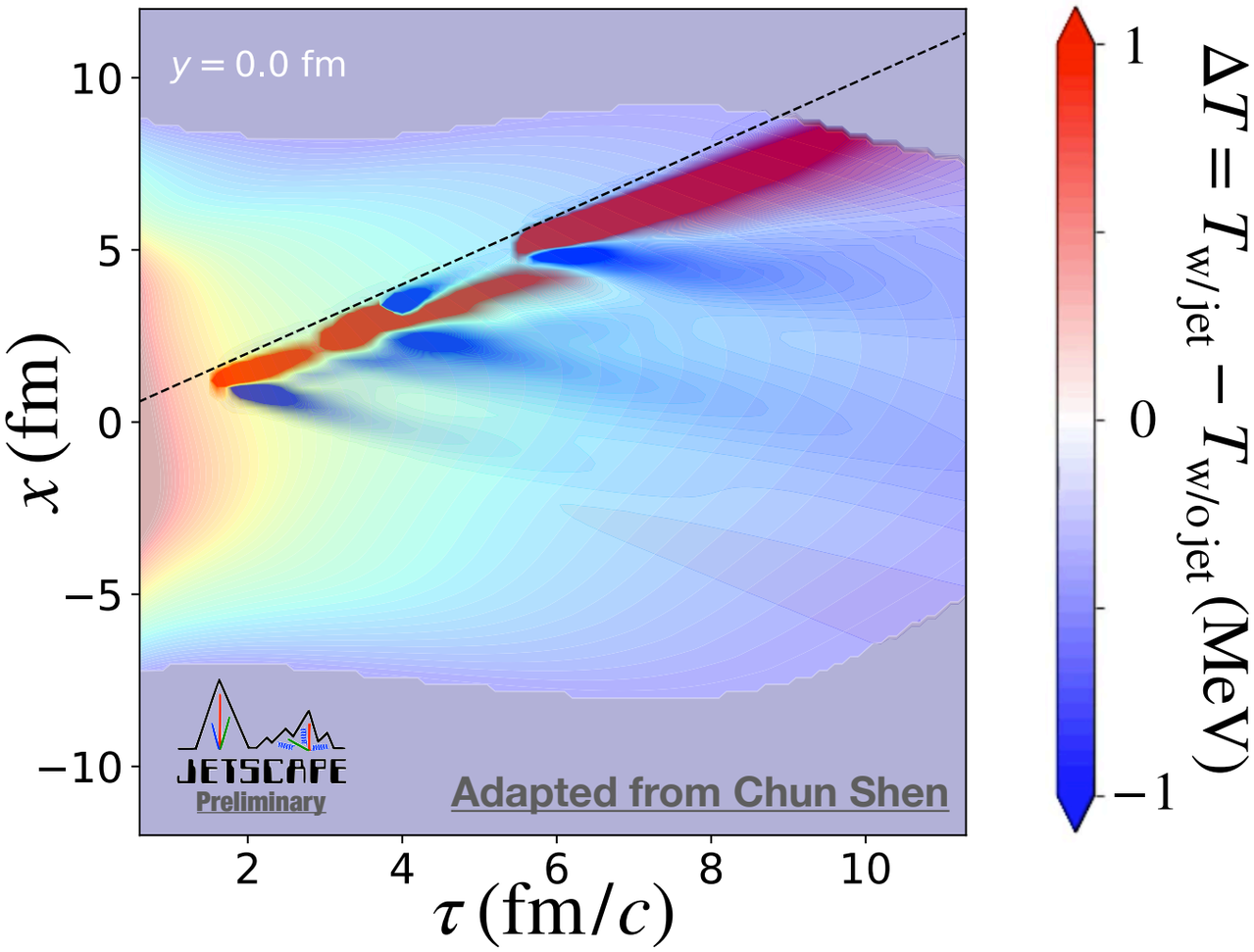
Model: **Hydrodynamics**

➡ **Hydrodynamic Response**

$$\nabla_\mu T^{\mu\nu}_{\text{med}}(x) = J^\nu_{\text{jet}}(x)$$

$$\left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{signal}} = \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\text{shower}} + \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\substack{\text{med.}\\ \text{w/ jet}}} - \left.\frac{dp^\mu}{d\eta d\phi}\right|_{\substack{\text{med.}\\ \text{w/o jet}}}$$

Physics results using "two-stage hydro" in the works…



JETSCAPE

Event generator

- A ***framework*** for general-purpose MC event generators in heavy-ion collisions

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Statistical toolkit

- Extract model parameters via Bayesian analysis with Gaussian Process Emulators

https://github.com/JETSCAPE/STAT

JETSCAPE

Heavy-ion collisions are complicated — but we have measured a large number of complementary observables

Global analysis

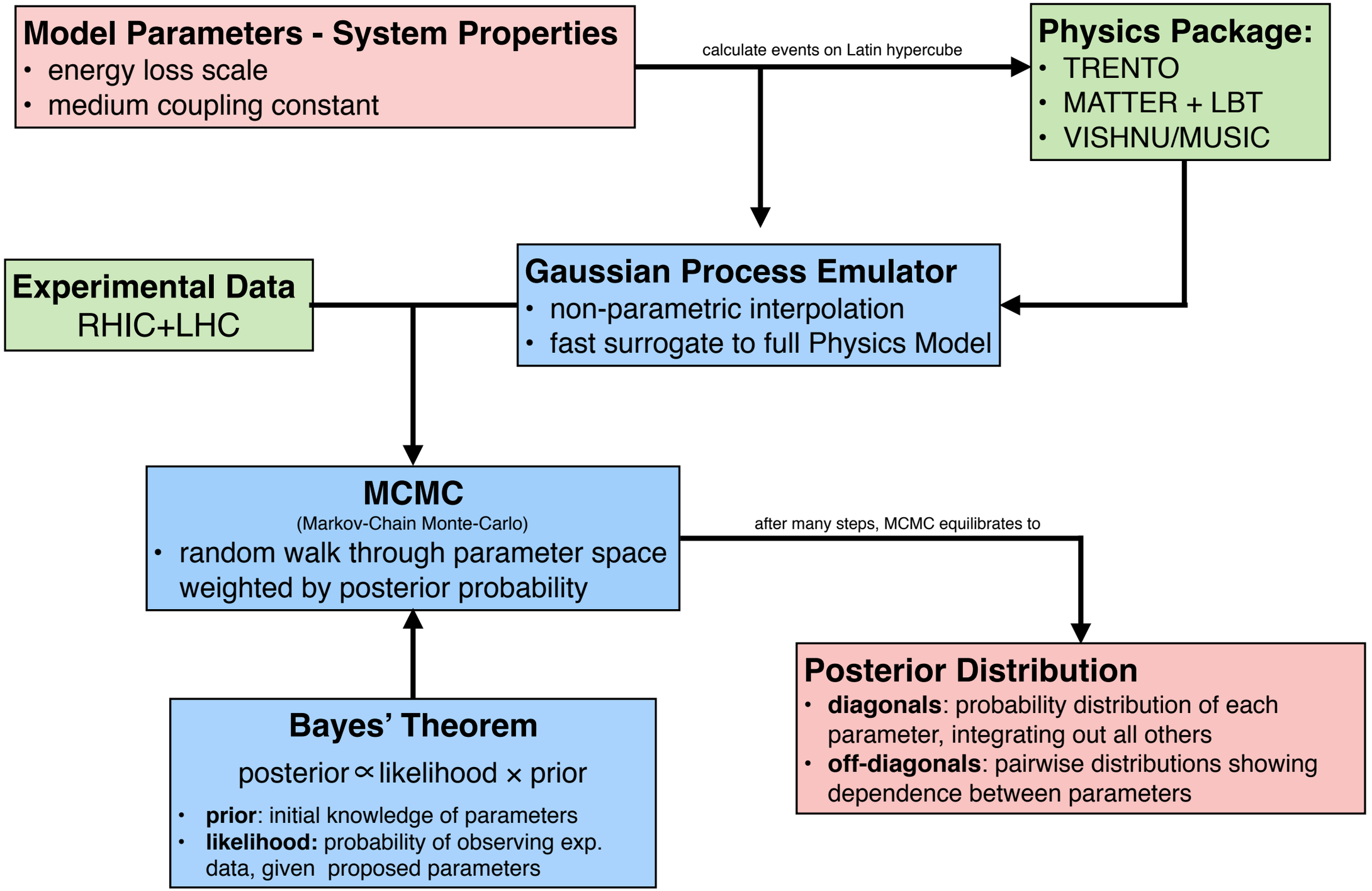
1. Can models simultaneously fit all observables?
2. Extract free parameters

Statistical toolkit

- Extract model parameters via Bayesian analysis with Gaussian Process Emulators

https://github.com/JETSCAPE/STAT

JETSCAPE — Bayesian Analysis



Slide from R. Soltz QM2019 (adapted from Bass, Bernhard, Moreland 1704.0767)

Example: Extraction of bulk properties

Extract $\zeta/s, \eta/s$ as a function of *T* using soft observables at RHIC and LHC

Modelling the soft sector

J-F. Paquet
QM2019

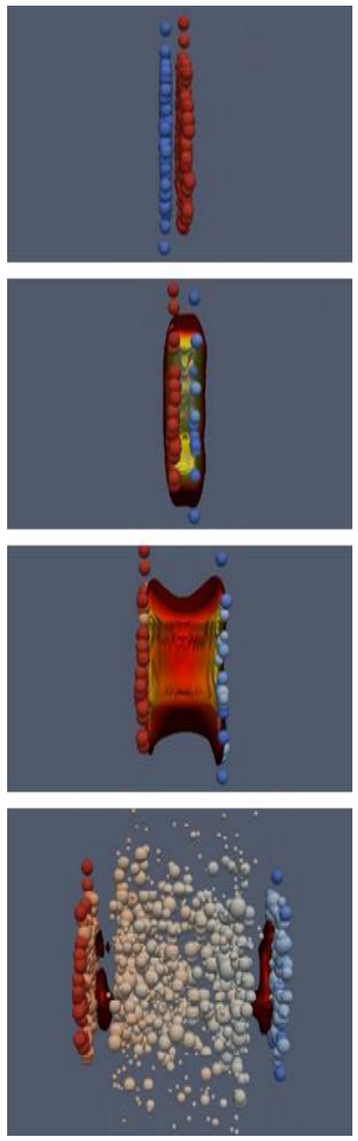


Figure ref.: J. Bernhard, H. Petersen, MADAI Collaboration

$\tau = "0^+"$: Nuclei collide

- Trento ansatz used to parametrize the energy deposition
- 5 parameters: (i-iii) nucleon width, fluctuation & minimum distance, (iv) transparency parameter, (v) normalization

$\tau \sim 0.1$ fm: "Pre-equilibrium phase"

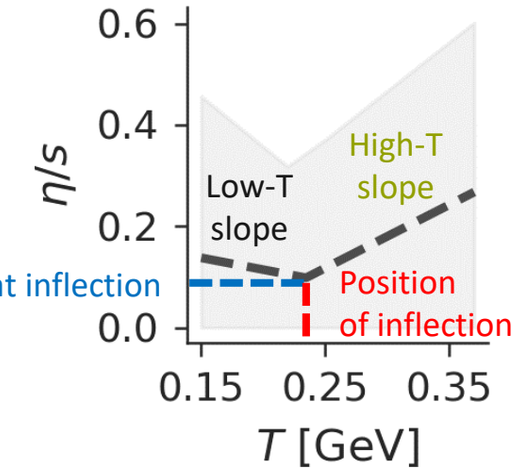
- Free-streaming
- Free-streaming time is a parameter

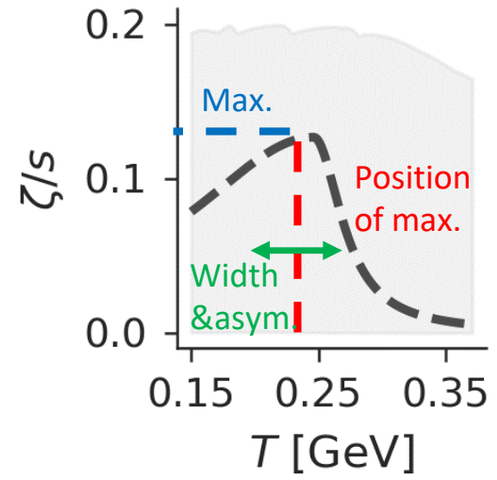
$\tau \sim 1$ fm: Beginning of "hydrodynamic phase"

- 2+1D relativistic viscous hydrodynamics [MUSIC]
- Equation of state: hadron resonance gas + lattice QCD [HotQCD]
- Shear and bulk viscosity: $\frac{\eta}{s}(T)$ and $\frac{\zeta}{s}(T)$ parametrized

$\tau \sim 10$ fm: End of "hydrodynamic phase"

- Fluid converted to hadrons [iS3D]: Cooper-Frye at temperature T_{sw}
- Viscous corrections in Cooper-Frye: 4 different models
- Hadronic interactions with SMASH hadronic transport

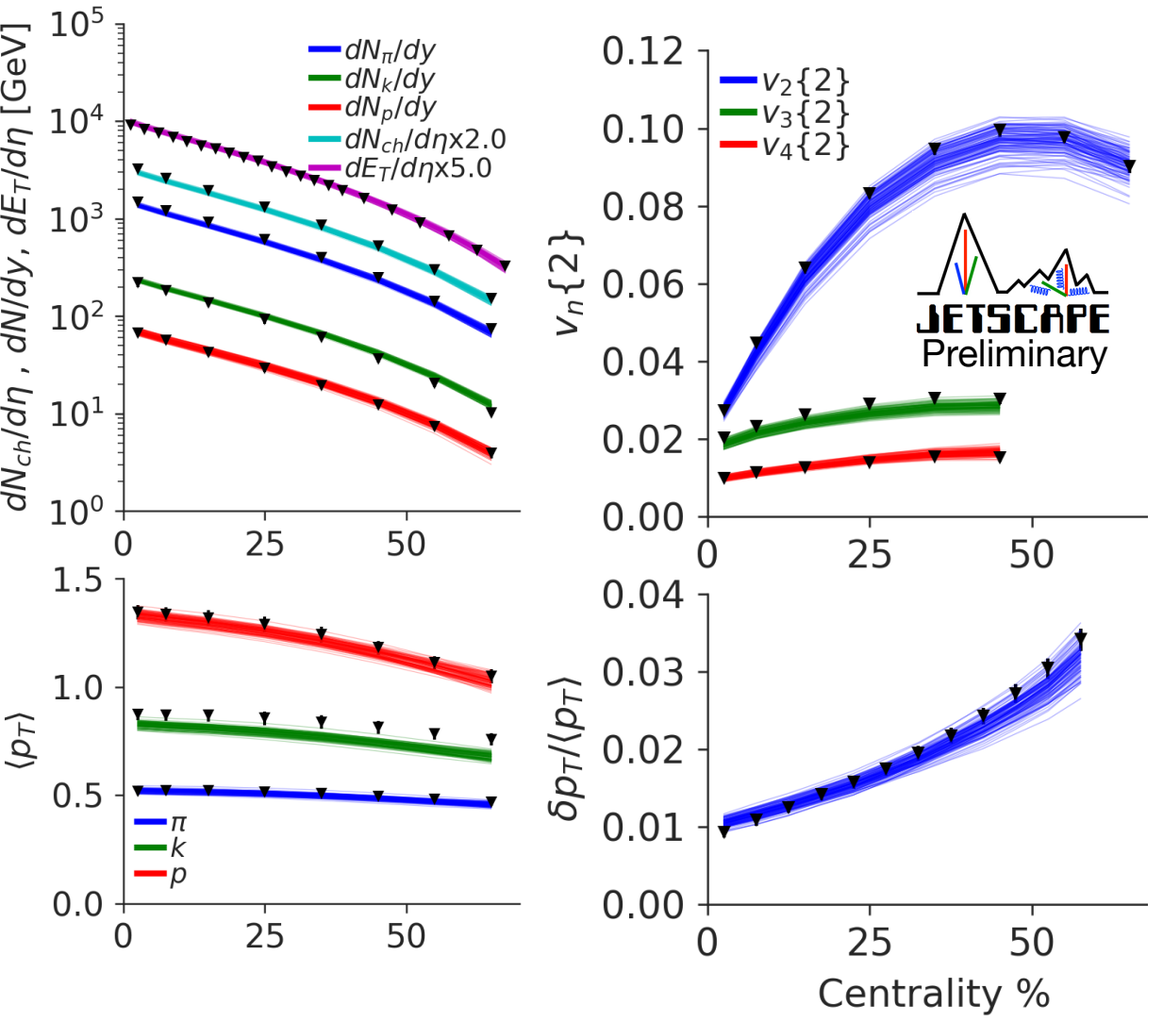




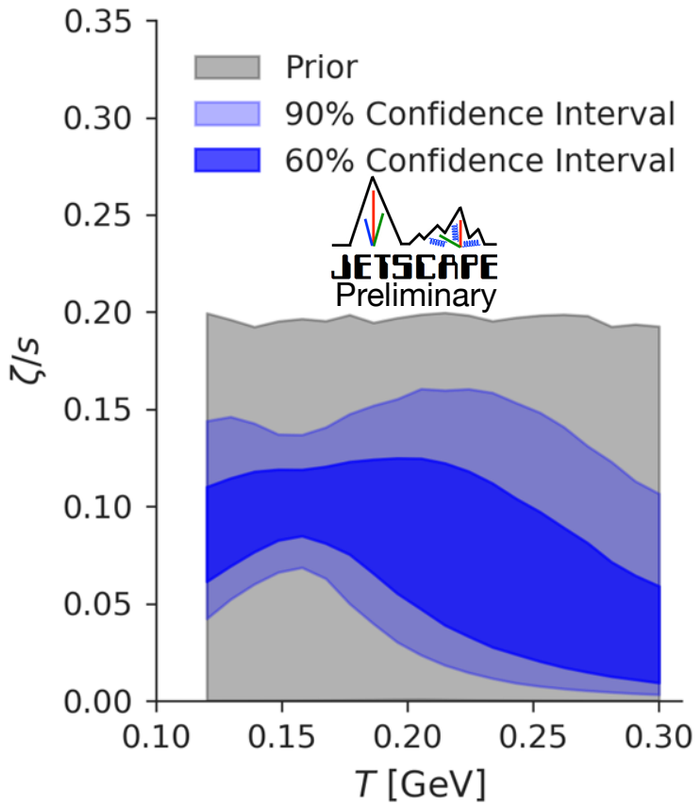
Example: Extraction of bulk properties

Extract $\zeta/s, \eta/s$ as a function of *T* using soft observables at RHIC and LHC

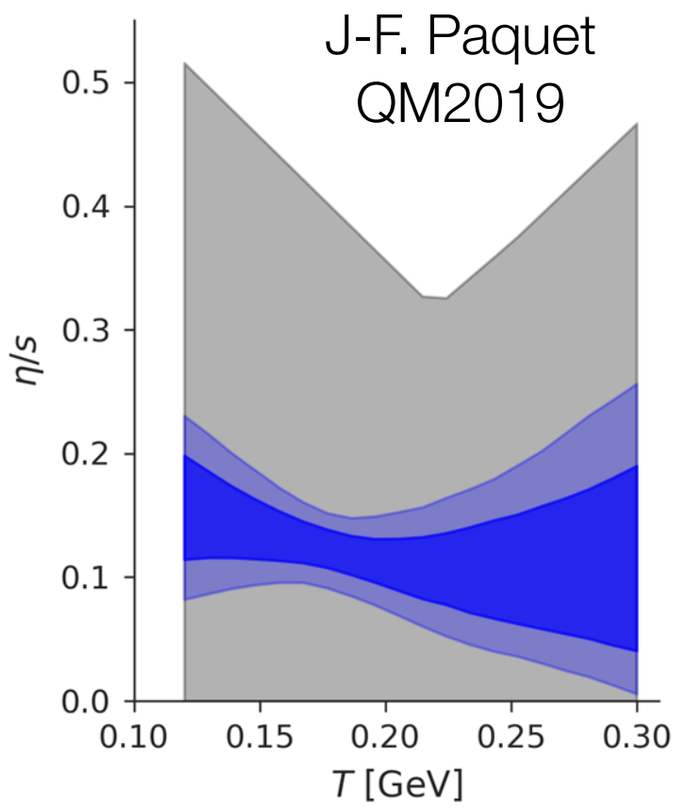
17-parameter extraction to constrain $\eta/s, \zeta/s$ as a function of T using ALICE measurements at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV



Bulk Viscosity

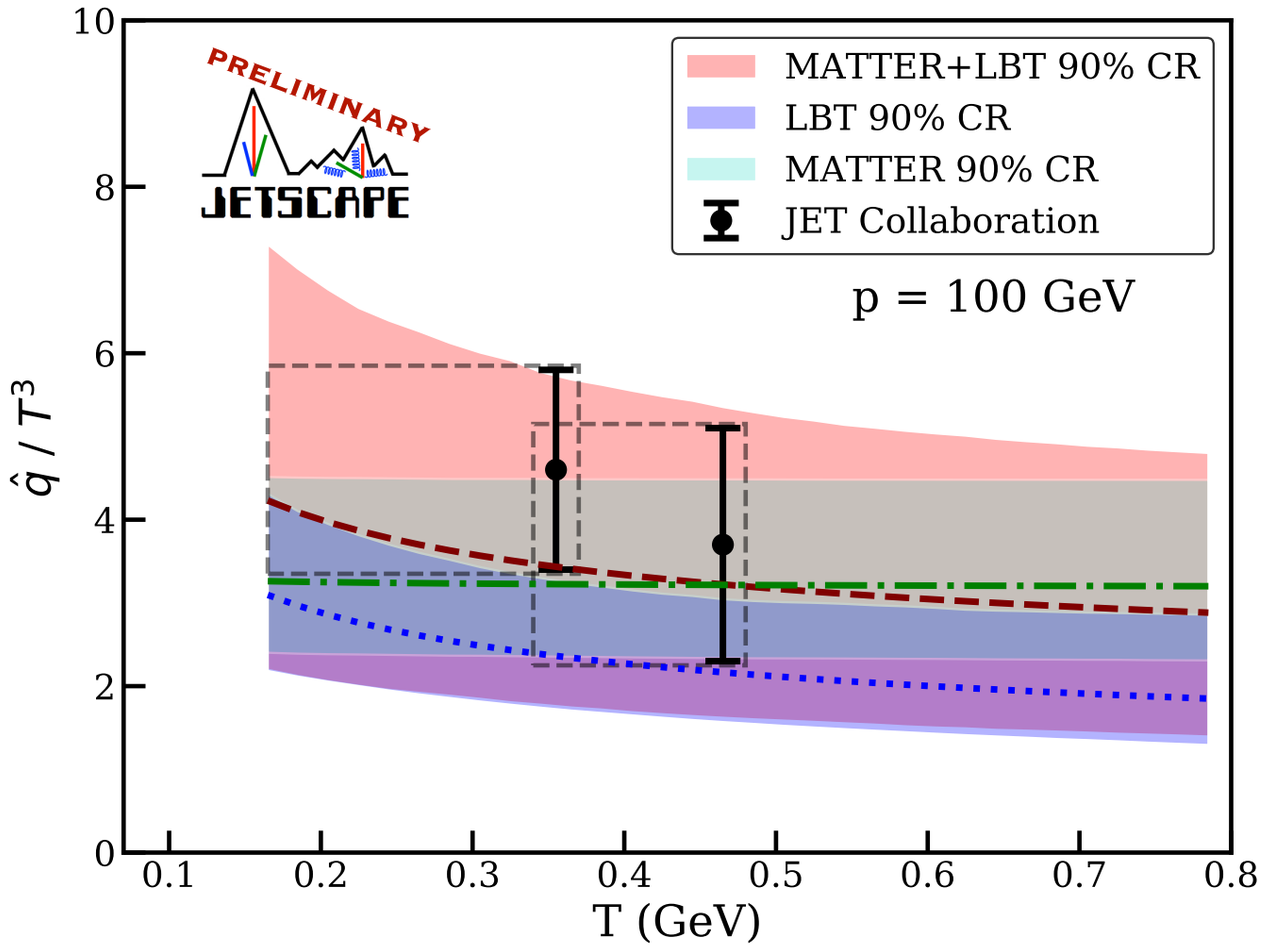


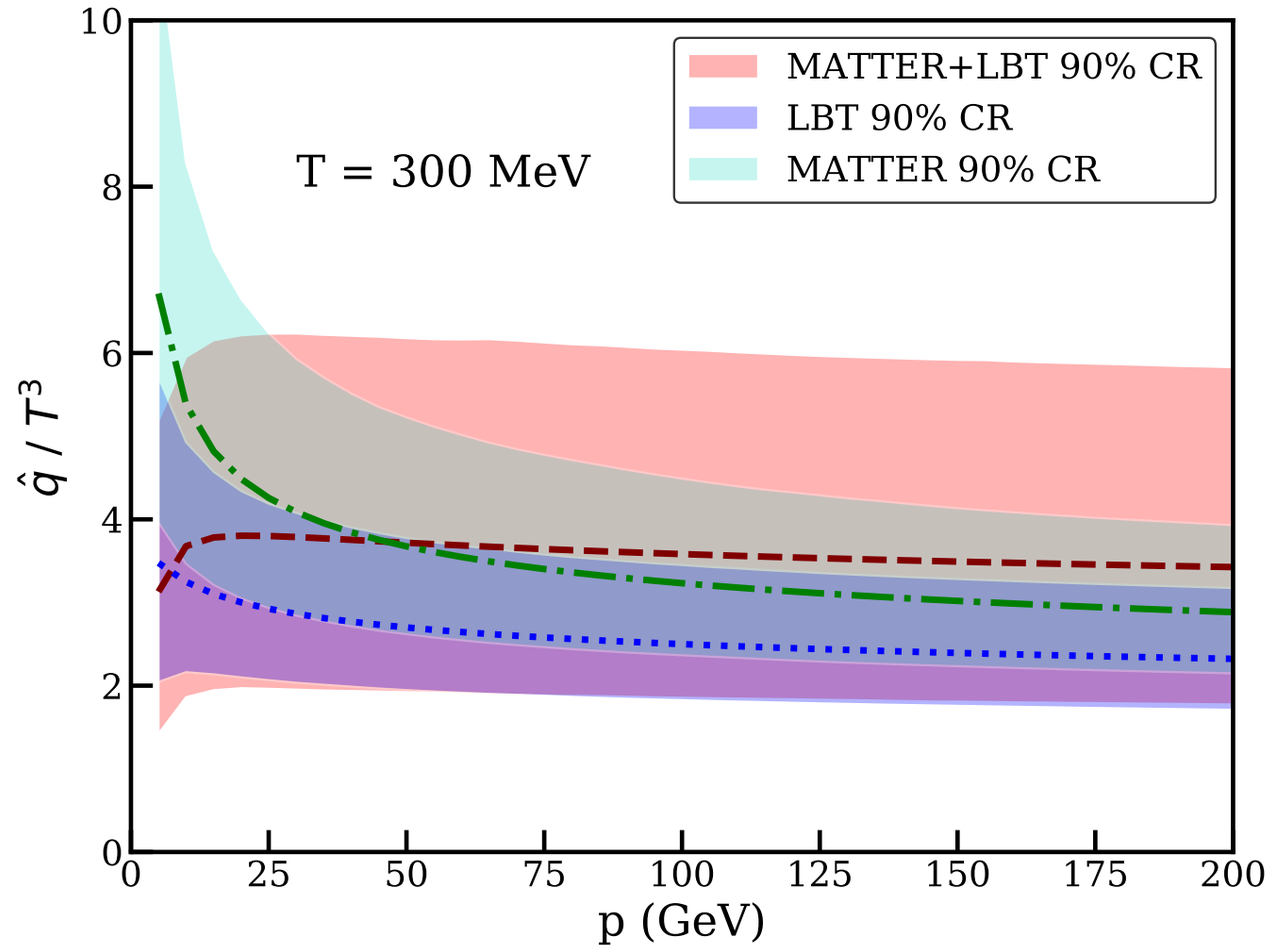
Shear Viscosity



Example: Extraction of $\hat{q}$

Extract $\hat{q}$ as a function of T, E_{jet} using inclusive hadron R_{AA} at RHIC, LHC





Final result pending improved treatment of experimental systematic uncertainties

Successful extraction of q-hat as a smooth function of T, p_{jet} !

(Proof of principle — uses only inclusive hadron R_{AA} data)

Summary

JETSCAPE is a framework for general-purpose heavy-ion event generators

Modular — encourage your theory friends to contribute modules

JETSCAPE is producing first physics results

Event generator — jet observables

Bayesian analysis — soft and hard physics

JETSCAPE is a tool for the community

To enable well-controlled event generator comparisons

To perform global analyses and extract free parameters

As a testbed for theoretical and experimental development

2020 JETSCAPE School (online)
July 13-24
https://indico.bnl.gov/event/8660/

JETSCAPE and ALICE

Ideas — How can ALICE maximize benefit to ourselves and to the community?

1. Generate sets of JETSCAPE predictions to compare to our measurements, and constrain specific physics mechanisms

   Central productions to share among each other? Computing effort?

   Note: Bayesian analysis ~ $\mathcal{O}\,(10\mathrm{M})$ CPU-hours

2. Report sufficient measurement information for global analyses

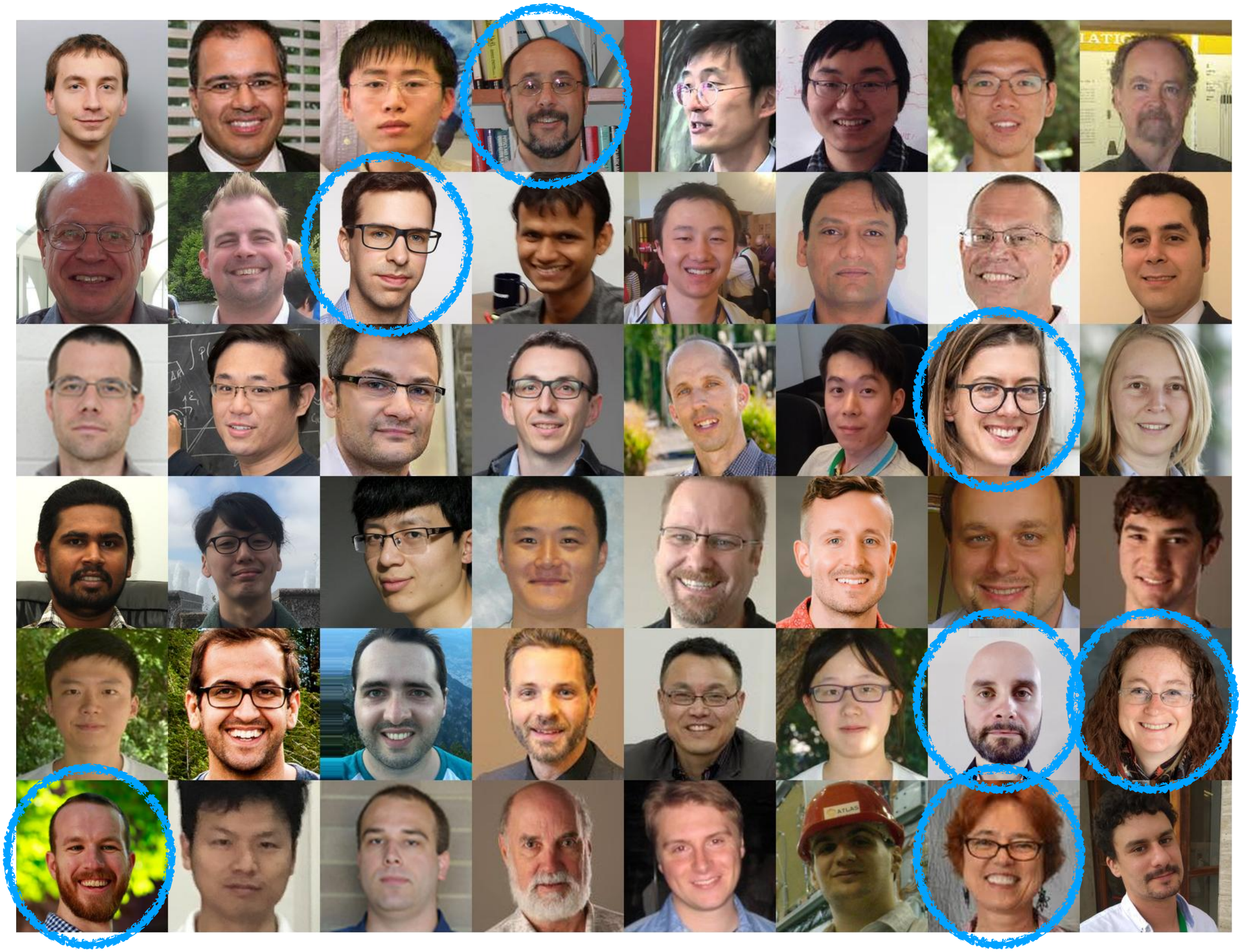
   We **need** to report correlations of systematic uncertainties

   —> Report *signed* uncertainty breakdowns on HEPData

3. Use JETSCAPE as a testbed to decide what observables are sensitive to specific physics mechanisms

Other ideas welcome!

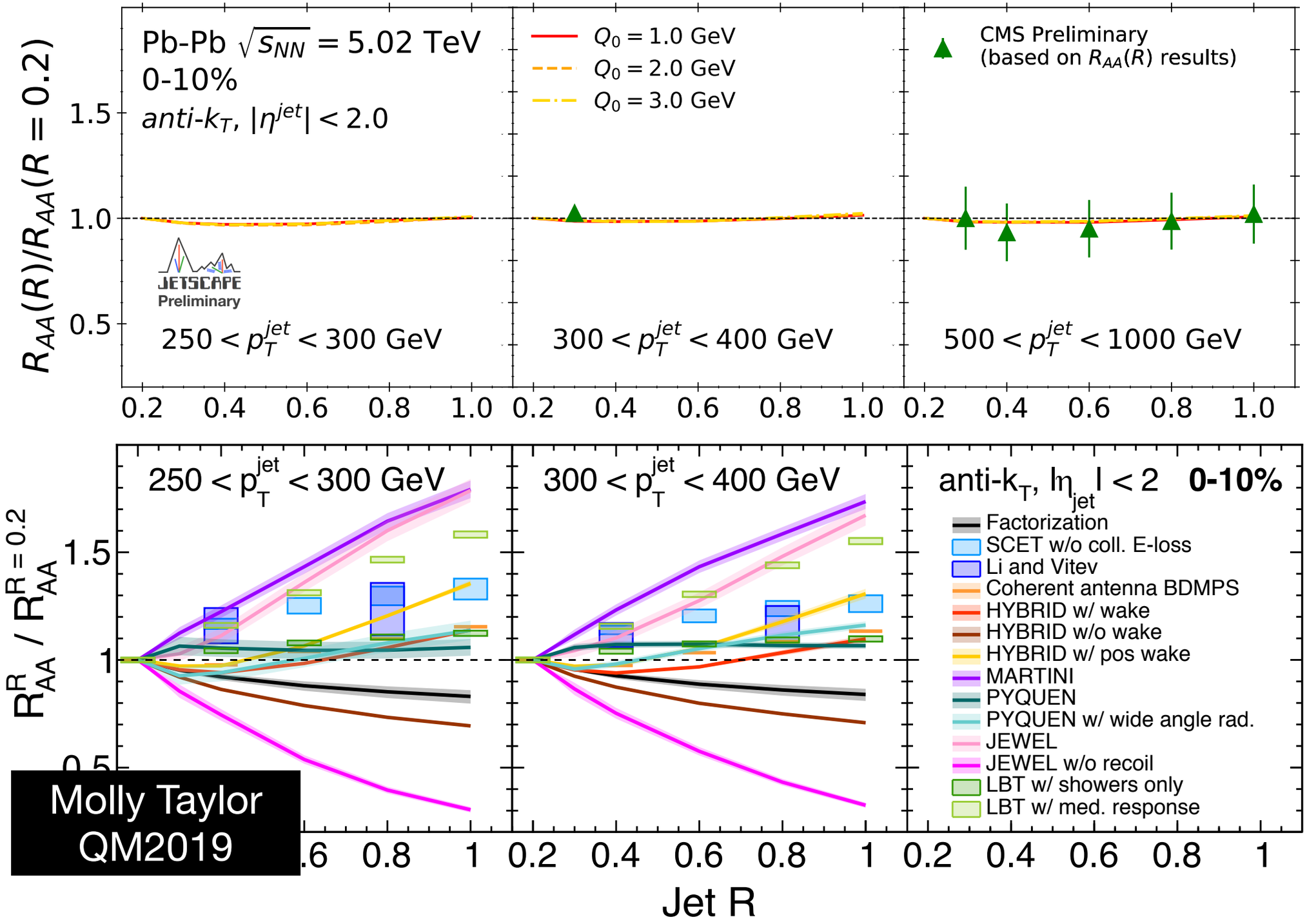
Thank you!



Backup

Example — Inclusive jets

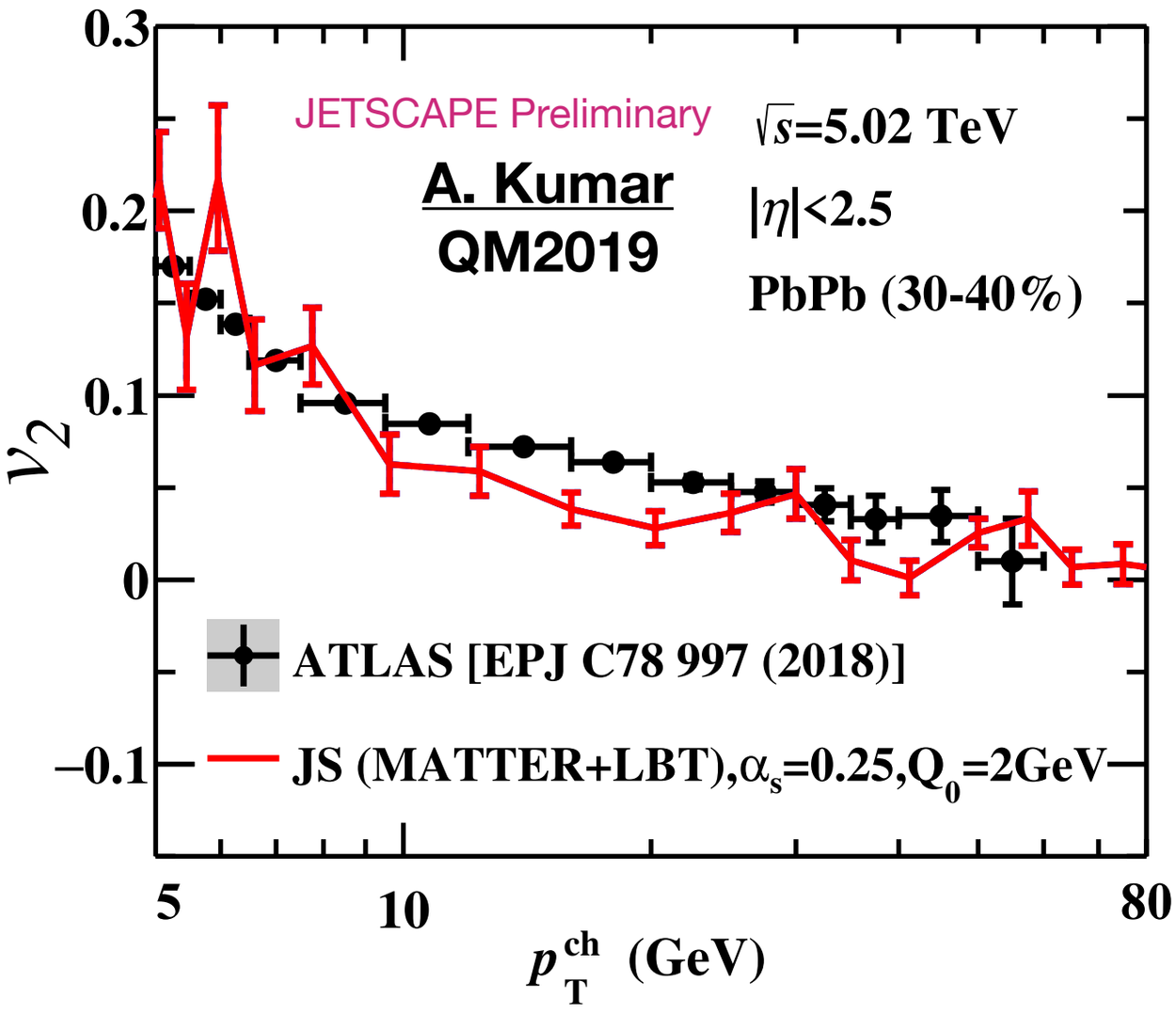
Low p_T → High p_T



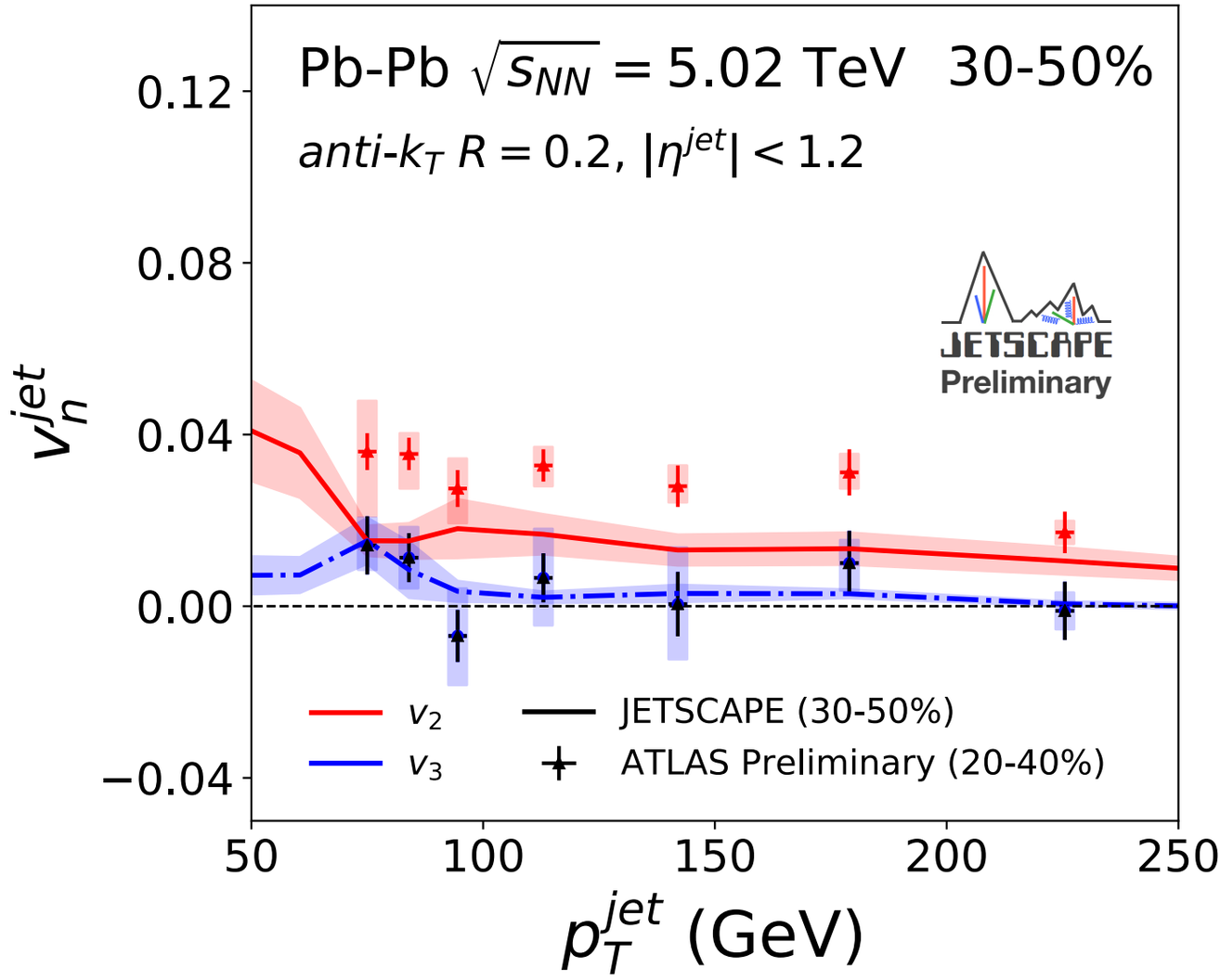
Example — v_n

Hadron v_2

$$v_2(p_T) = \langle \cos\left(2\phi^{trk}(p_T) - 2\psi_2^{\mathrm{EP}}\right)\rangle_{\mathrm{ev}}$$



Jet v_2, v_3



Reasonably good description of the data

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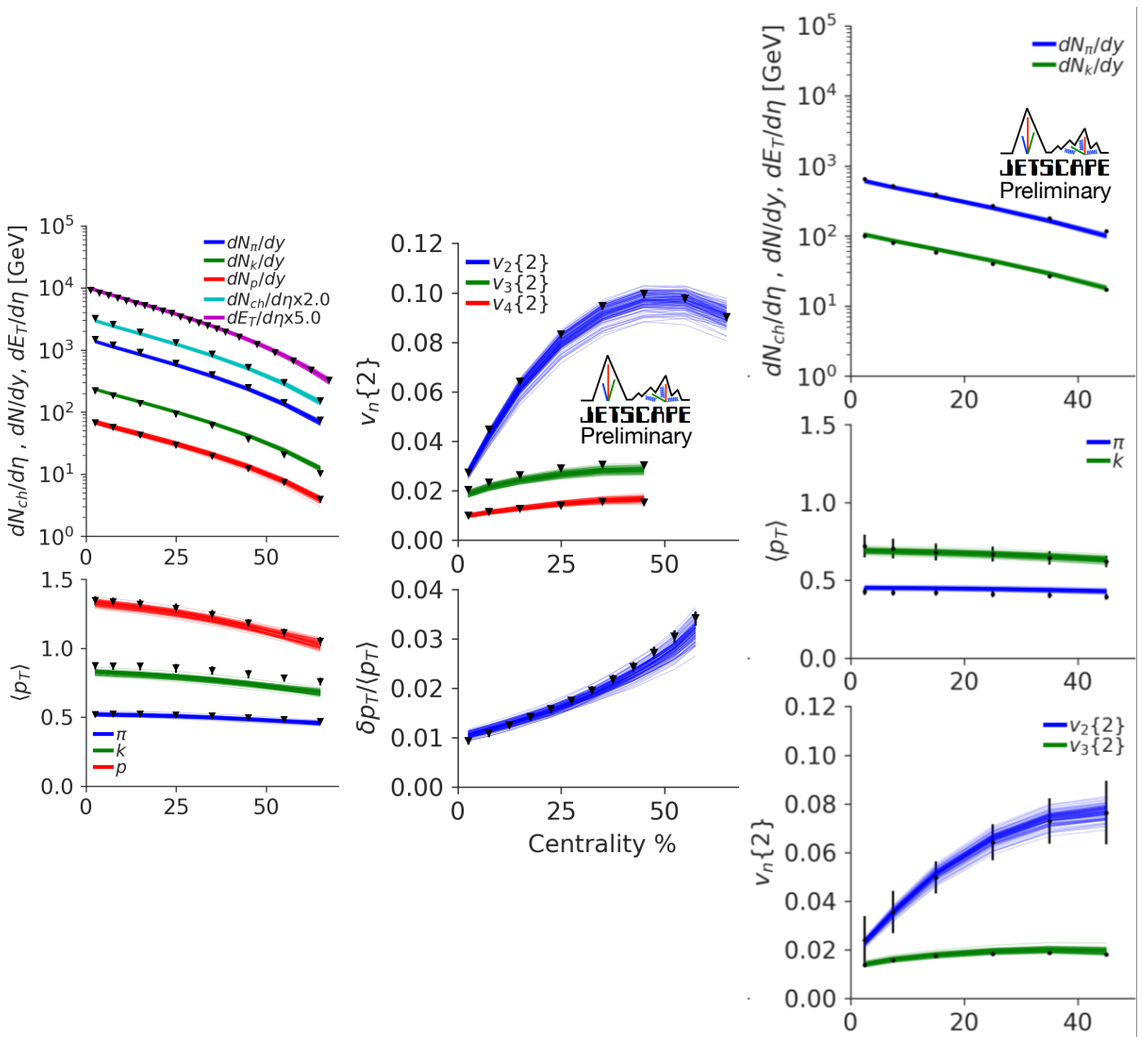
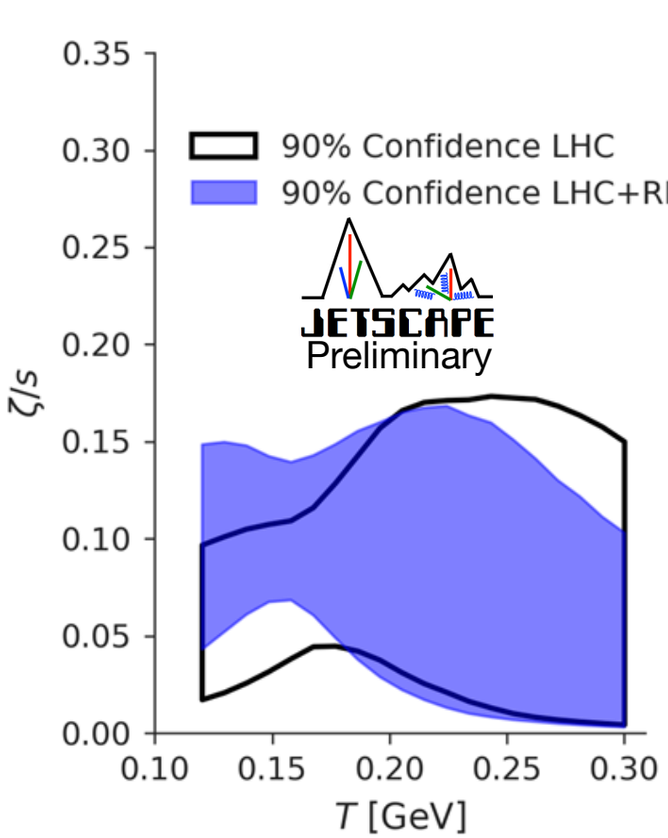
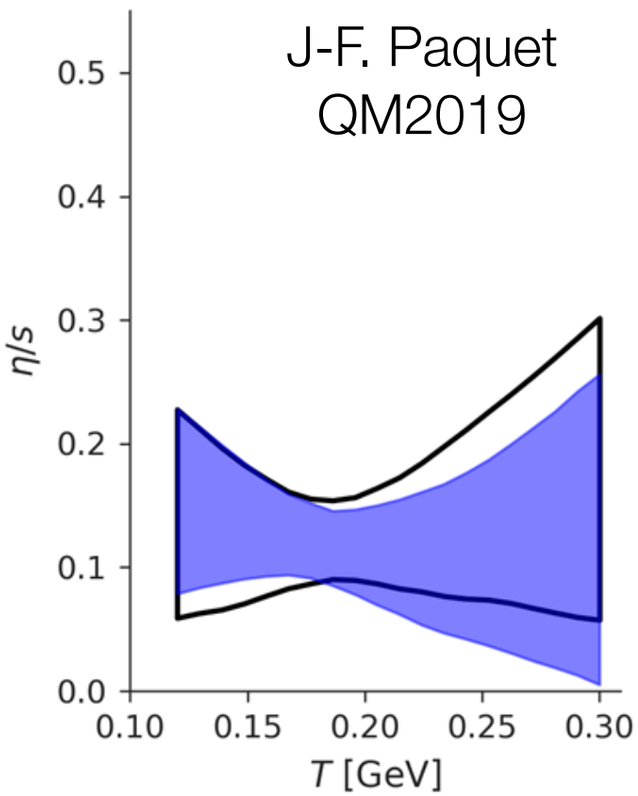
Extract $\zeta/s, \eta/s$ as a function of *T* using soft observables at RHIC and LHC







J-F. Paquet
QM2019

RHIC and LHC data complement each other to some extent

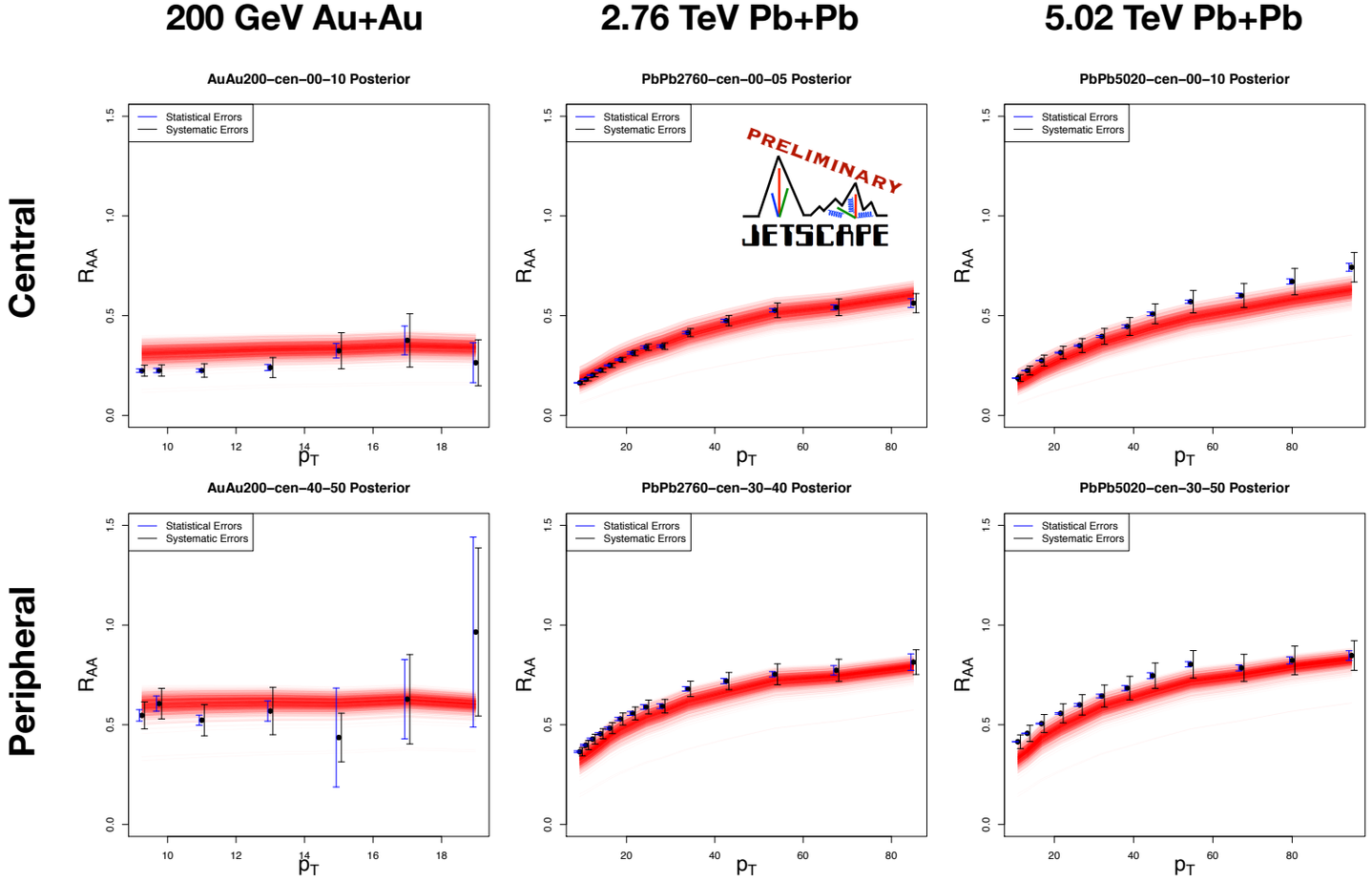
Example: Extraction of $\hat{q}$

R. Soltz
QM2019

Extract $\hat{q}$ as a function of T, E_{jet} using inclusive hadron R_{AA} at RHIC, LHC

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

Depends on jet scale only **Depends on medium scale**



Jet energy loss models considered:

MATTER
LBT
MATTER+LBT