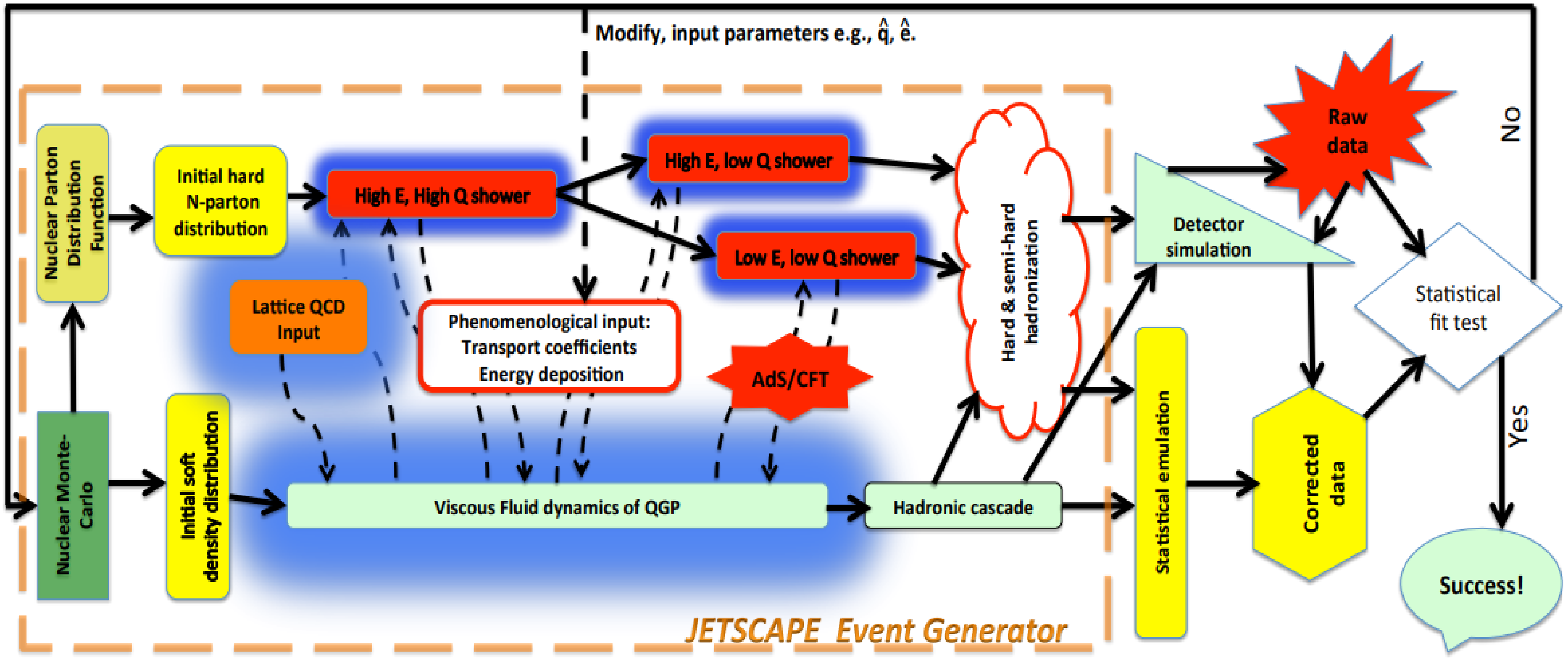
Hybrid Hadronization of Jet Showers from e^+e^- to AA with JETSCAPE

CAMERON PARKER, TEXAS A&M UNIVERSITY, ON BEHALF OF THE JETSCAPE COLLABORATION: 30/3/2023

JETSCAPE Framework[1,2,3]

Many modules for soft and hard physics. We use 3 modules that deal with jets in quark-gluon plasma (QGP):

1. MATTER – propagates and splits an initial jet parton rapidly dropping its virtuality until it falls below a threshold Q_0
2. LBT – propagates low-virtuality and real partons through the medium (QGP)
3. Hybrid Hadronization – hadronizes partons through recombination and string fragmentation



"A modular, task-based framework for simulating all aspects of heavy-ion collisions"

[1] J.H. Putschke et. al., arXiv:1903.07706

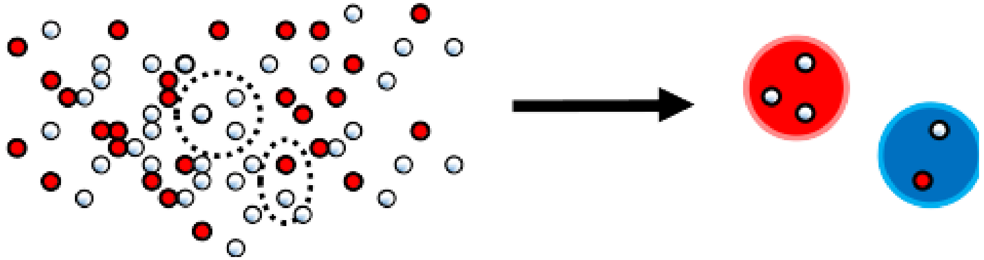
[2] A. Kumar et. al., Phys. Rev. C 102, 054906 (2020)

[3] A. Kumar et. al., arXiv:2204.01163

Hybrid Hadronization[4]

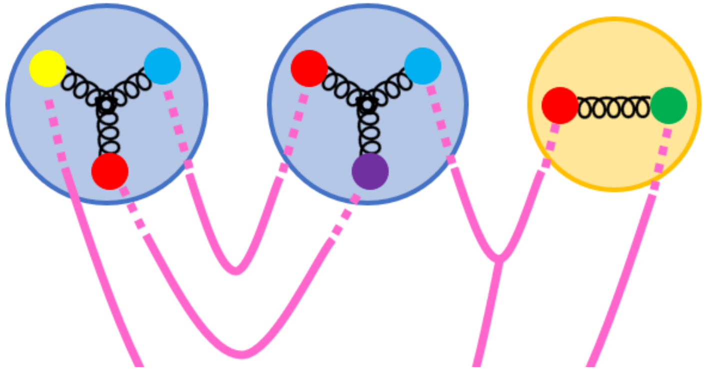
Hadronization of partons cannot be described from first principles.

Phenomenological models can be tuned to fit experimental data.



Hybrid Hadronization (HH) combines two of these models:

1. **Quark recombination** (high-density systems)
   - Quarks can directly recombine into hadrons
2. **Lund string fragmentation** (low-density systems)
   - Color flux tubes in QCD vacuum at large distances → string-like behavior.
   - Quarks connected with strings; gluons are part of these strings – these strings are then broken to form hadrons.



[4] K.C. Han et. al., Phys. Rev. C **93** (2016) 4, 045207

Rationale

JETSCAPE is the ideal framework to test Hybrid Hadronization with and without a medium

Want to see how Hybrid Hadronization does in vacuum when fragmentation alone does a good job

QGP as the medium of interest, probed with jets

Vacuum Systems

Tuning Parameters

MATTER

Virtuality factor (0.1-1): determines starting virtuality for every shower initiating parton as a portion of its initial momentum

Q_0 (0.9-3 GeV): Virtuality threshold for when perturbative QCD stops

λ_{QCD} (0.1-0.4 GeV): strength of QCD interactions in MATTER

Hybrid Hadronization

Hadron scales (0.5-2): factor multiplying the measured wavefunction widths

Strange to up-down ratio (0.2-0.5): rate strange quarks are produced compared to 1^{st} generation quarks in string fragmentation

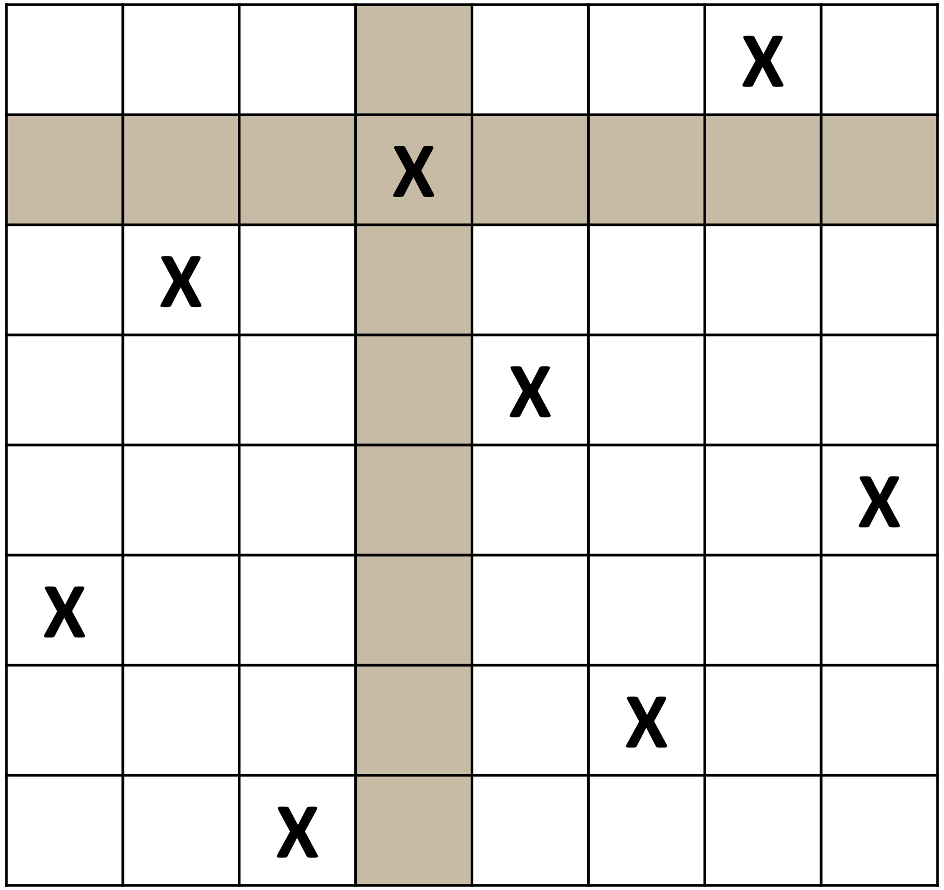
Diquark to quark ratio (0.07-0.2): rate diquarks are produced compared to single quarks in string fragmentation

Collision Systems

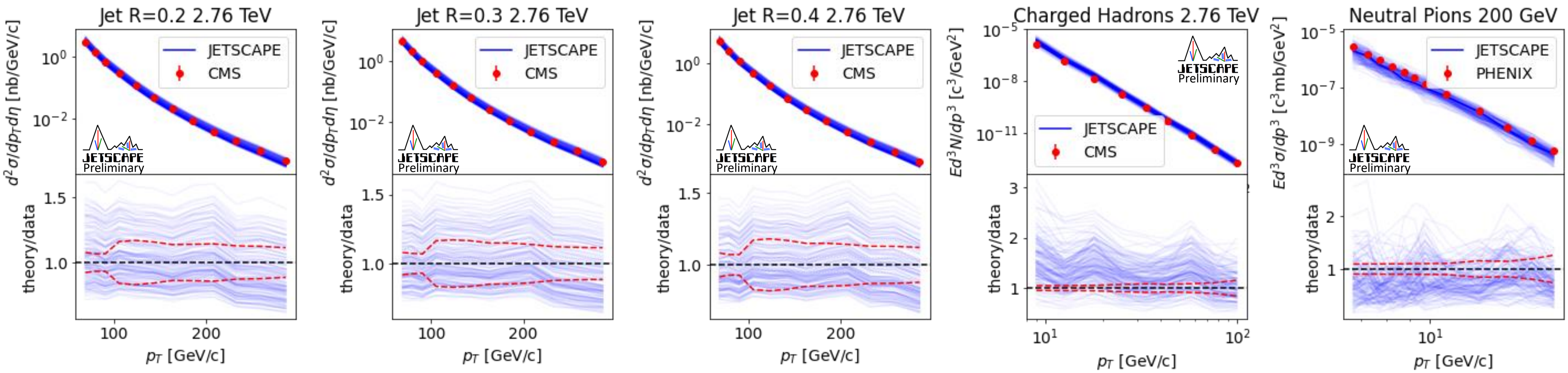
Data sets:

- CMS charged hadron spectra and jets at 2.76 TeV (pp)
- PHENIX neutral pion spectra at 200 GeV (pp)
- ALEPH unidentified and identified hadron spectra at 91.2 GeV (e^+e^-)

Sample parameter space with Latin Hypercube to maximize coverage for Bayesian tuning

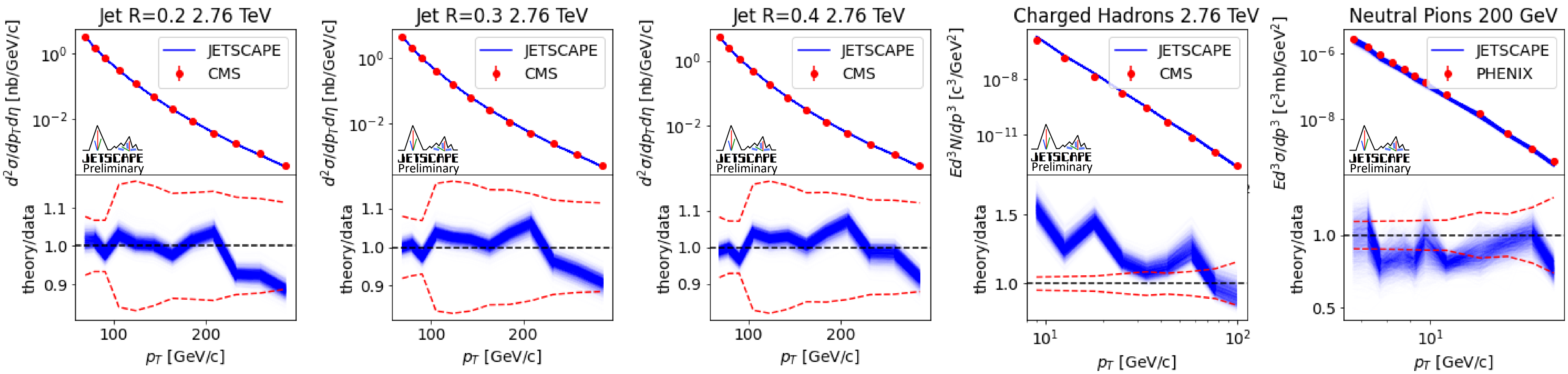


Priors



CMS: https://doi.org/10.17182/hepdata.77601
PHENIX: https://doi.org/10.48550/arXiv.0704.3599

Posteriors

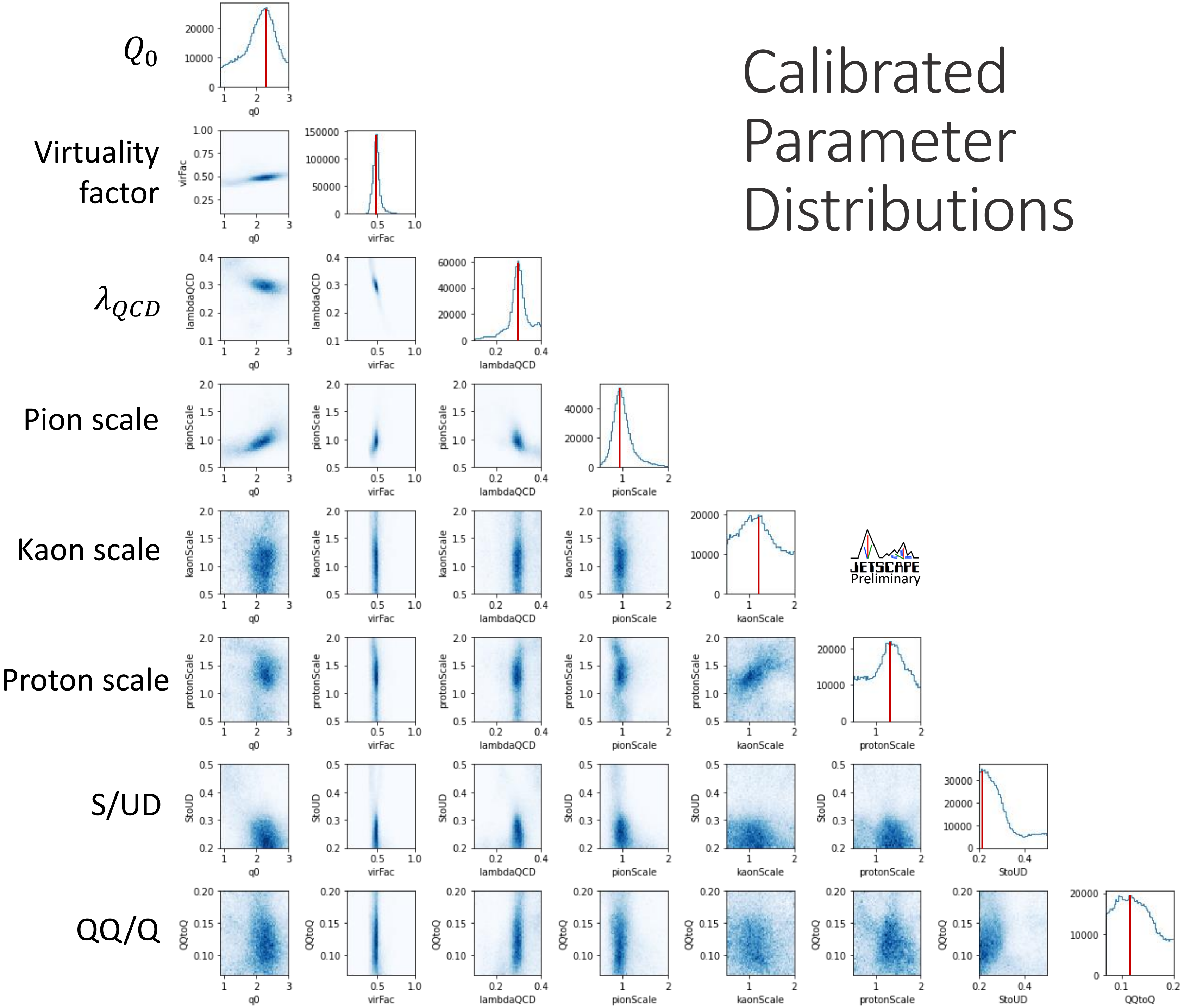


CMS: https://doi.org/10.17182/hepdata.77601
PHENIX: https://doi.org/10.48550/arXiv.0704.3599

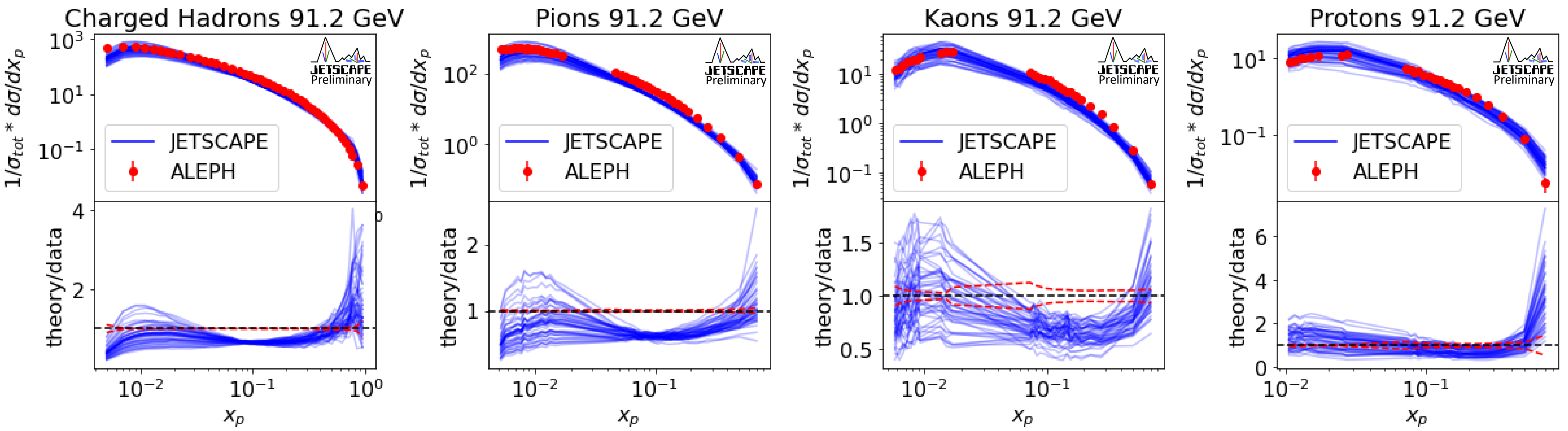
Calibrated Parameter Maximums

- Q_0: 2.29
- Virtuality factor: 0.478
- λ_{QCD}: 0.292
- Pion scale: 0.92
- Kaon scale: 1.19
- Proton scale: 1.31
- Strange to up-down: 0.206
- Diquark to quark: 0.114

Calibrated Parameter Distributions



e^+e^- at 91.2 GeV Hadron Observables



ALEPH: https://doi.org/10.17182/hepdata.47582

Medium Effects

In-Medium Setup

Simulate jets of set energy E in QGP medium of size L

X direction in direction of jet (longitudinal)

Y-Z in plane perpendicular to jet (transverse)

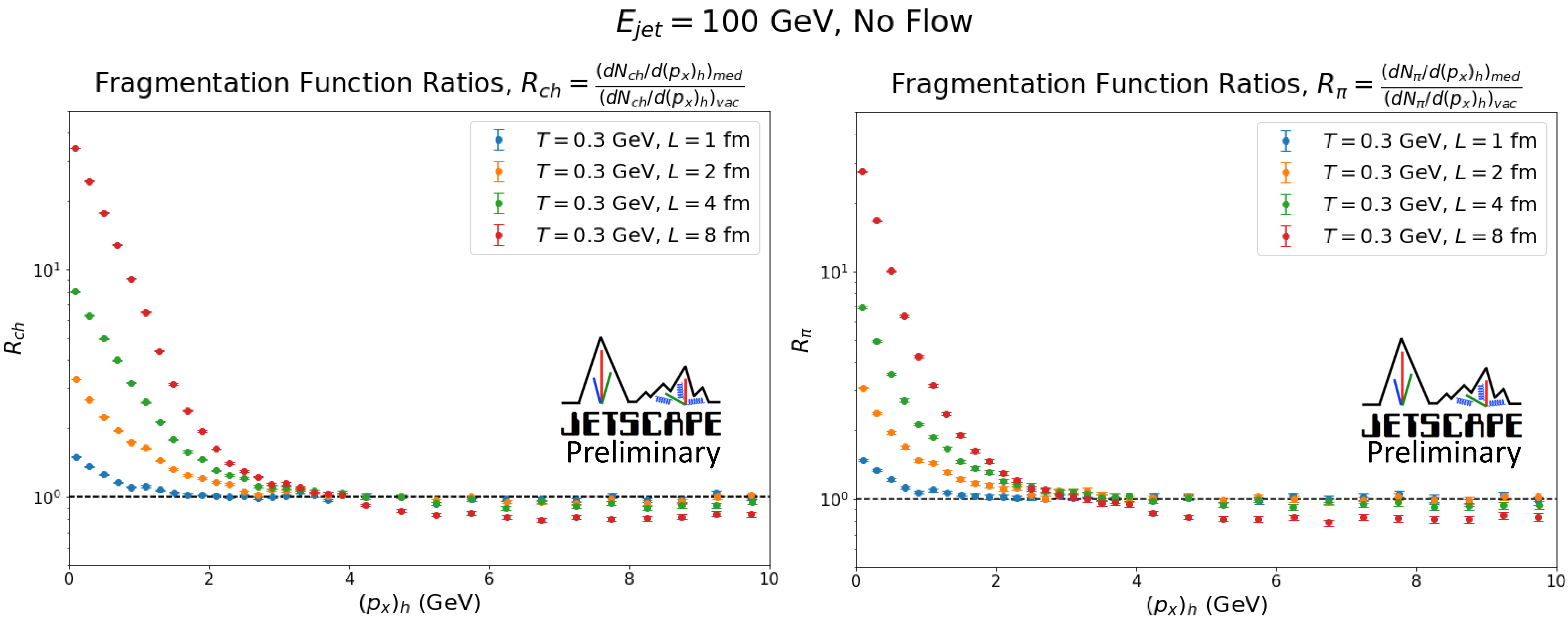
Parton flow can be switched on and off independently during propagation and hadronization

Fragmentation Function Ratios (no flow)

Up quark jet, E = 100 GeV in medium vs. in vacuum

Soft shower debris + thermal pickup, growing with medium size

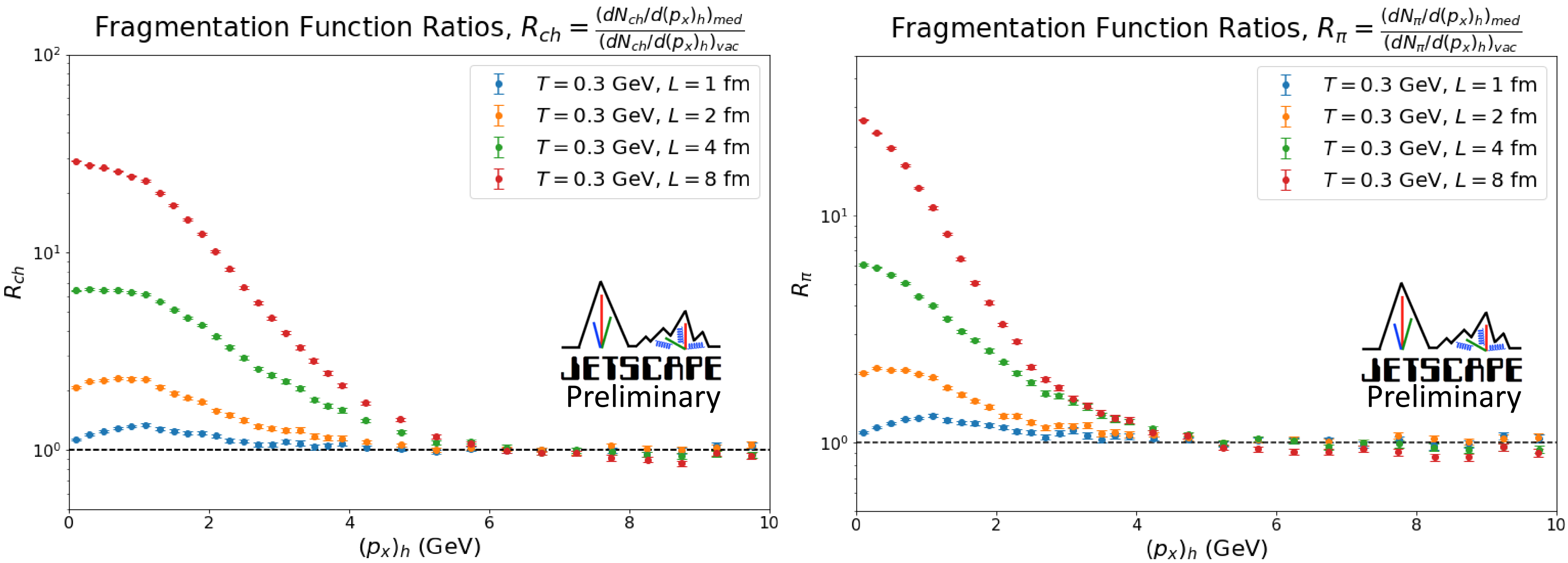
$$R_{AA} = \frac{[dN_{[\ ]}/dp_x]_{medium}}{[dN_{[\ ]}/dp_x]_{vacuum}}$$



Fragmentation Function Ratios (with flow)

Longitudinal flow at hadronization ($v_x^{HH} = 0.8c$) shifts the enhancement of soft partons to larger momenta, raises peak

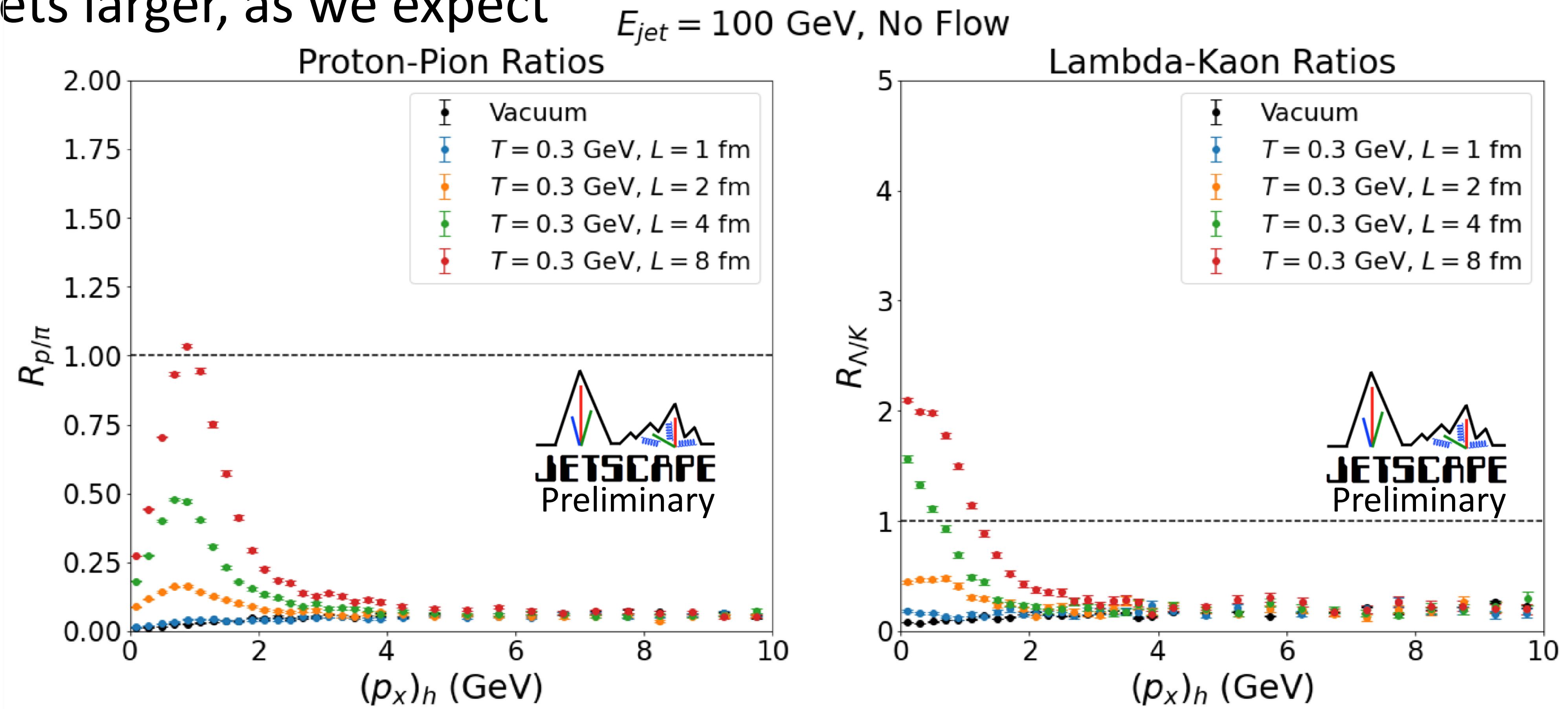
$E_{jet} = 100$ GeV, Flow = (0.8, 0, 0)



Baryon/Meson Enhancement (no flow)

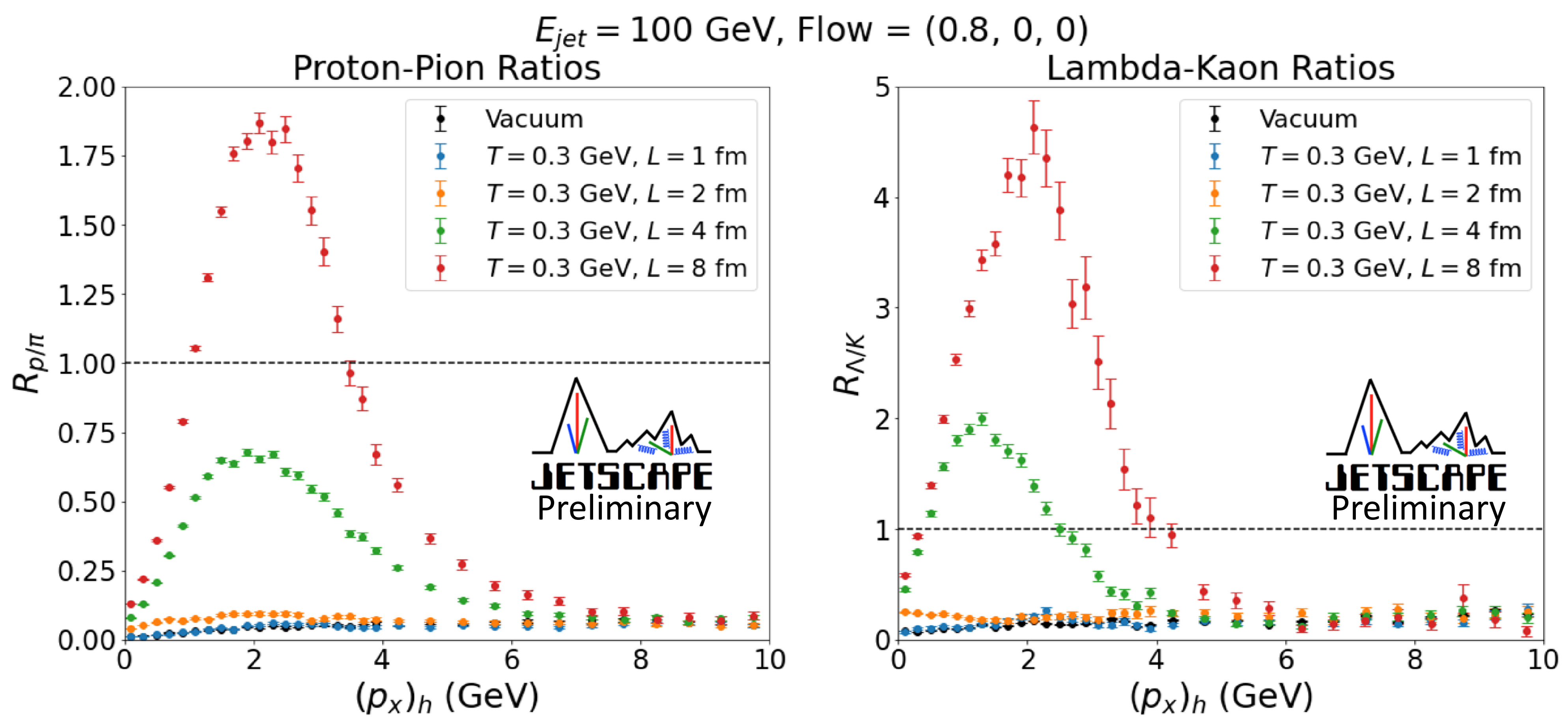
Up quark jet, E = 100 GeV, baryons/mesons for different mediums

Baryon/meson enhancement below 10 GeV increases as the medium gets larger, as we expect



Baryon/Meson Enhancement (with flow)

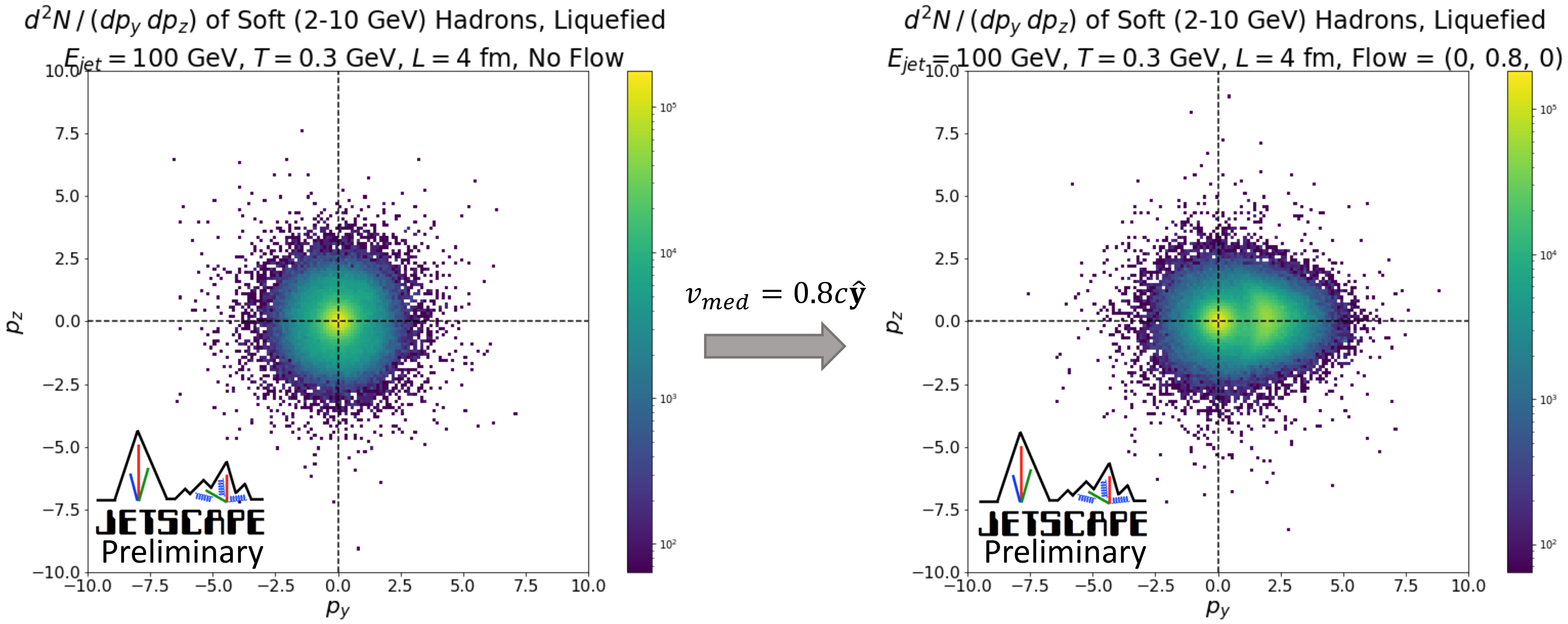
Longitudinal flow at hadronization ($v_x^{HH} = 0.8c$) **enhances** the B/M signal tremendously and **shifts** it to larger momenta.



Transverse Flow Effects

Up quark jet, E = 100 GeV, L = 4 fm, liquefier on, soft hadrons transverse momentum shown

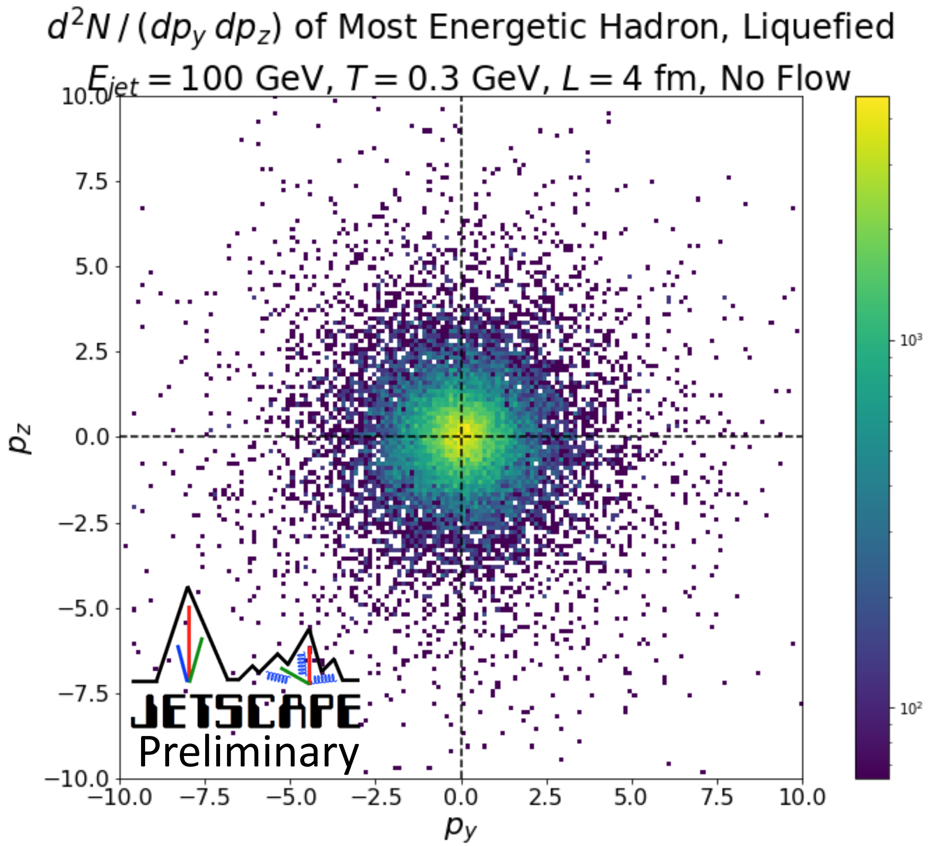
Soft jet partons are likely to recombine with thermal partons during hadronization
→ Transverse flow at hadronization ($v_{\mathbf{y}}^{HH} = 0.8c$) induces flow for soft jet hadrons.



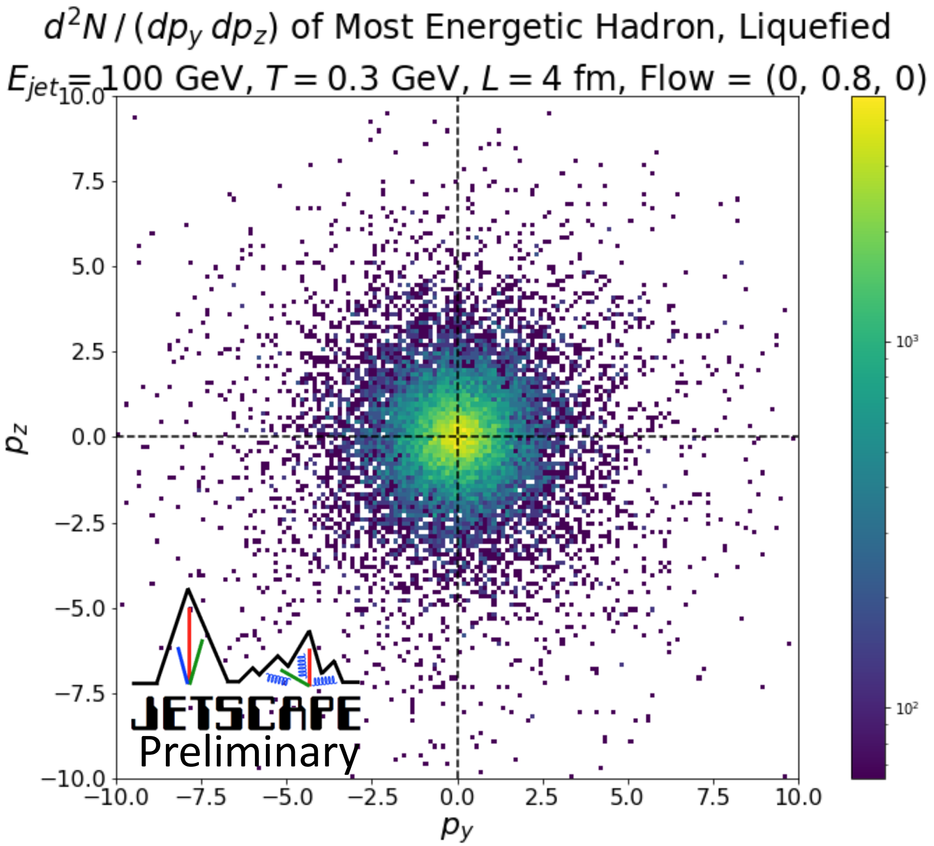
Transverse Flow Effects

Leading hadrons only

Hard jet partons are unlikely to recombine with thermal partons, and don't pick up the flow.



$v_{med} = 0.8c\hat{\mathbf{y}}$



Takeaways

Successfully describe jets and high p_T hadrons

Can reproduce signature recombination effects, like baryon/meson enhancement

Jet hadrons can pick up significant flow from a flowing medium

Outlook

Expansion to identified hadrons electron-positron systems in progress

- Extending analysis to soft hadrons in pp

Challenge in getting enough protons

Comparing different PYTHIA tunes

Heavy quark jet analysis

- Charm jets

Thanks to:

The JETSCAPE collaboration and the NSF for funding this project

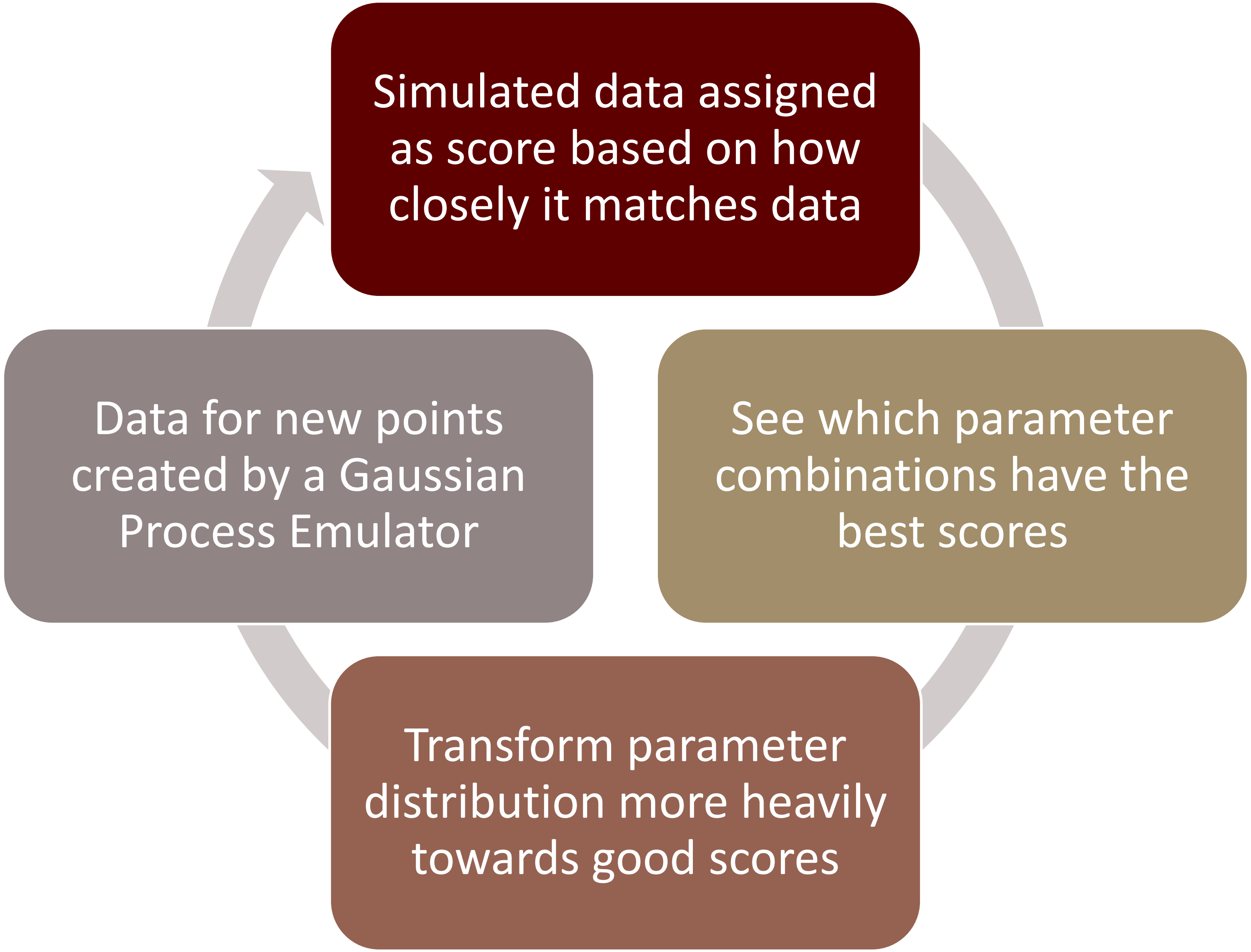
The Texas A&M University HPRC center for providing the computational resources

Bayesian Tuning Methods

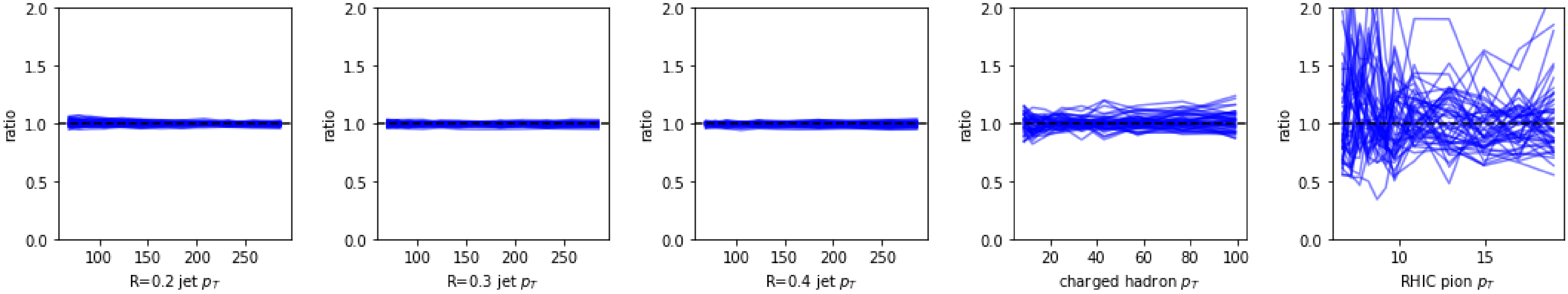
Iterative method of multi-parameter tuning

Scores assigned with Bayesian inference

Each cycle is a step performed for each walker



Emulator Validation



HH Study Parameter Space

	Parameter	Range
Jet Properties	Flavor	Up (light), Charm & Bottom (heavy)
	Energy, E	5 - 100 GeV (x-direction)
QGP Brick Properties	Temperature, T	0.2 - 0.3 GeV (hadronization at 0.165 GeV)
	Size, L	0 - 8 fm
	Hadronization flow velocity, $\mathbf{v}^{HH}$	0 - 0.8c $\hat{\mathbf{x}}$ (longitudinal), 0 - 0.8c $\hat{\mathbf{y}}$ (transverse)
	Medium flow velocity, $\mathbf{v}^{Eloss}$	0 - 0.8c $\hat{\mathbf{x}}$ (longitudinal), 0 - 0.8c $\hat{\mathbf{y}}$ (transverse)
	Liquefier	On/off (cutoff at $E < 3.2\,T$)
Jet Clustering	Jet radius, R	0.1 - 1.2

JETSCAPE[1,2,3] Setup for HH Studies

[1] J.H. Putschke et. al., arXiv:1903.07706, [2] A. Kumar et. al., Phys. Rev. C **102**, 054906 (2020), [3] A. Kumar et. al., arXiv:2204.01163

Run 3 modules in a QGP brick medium:

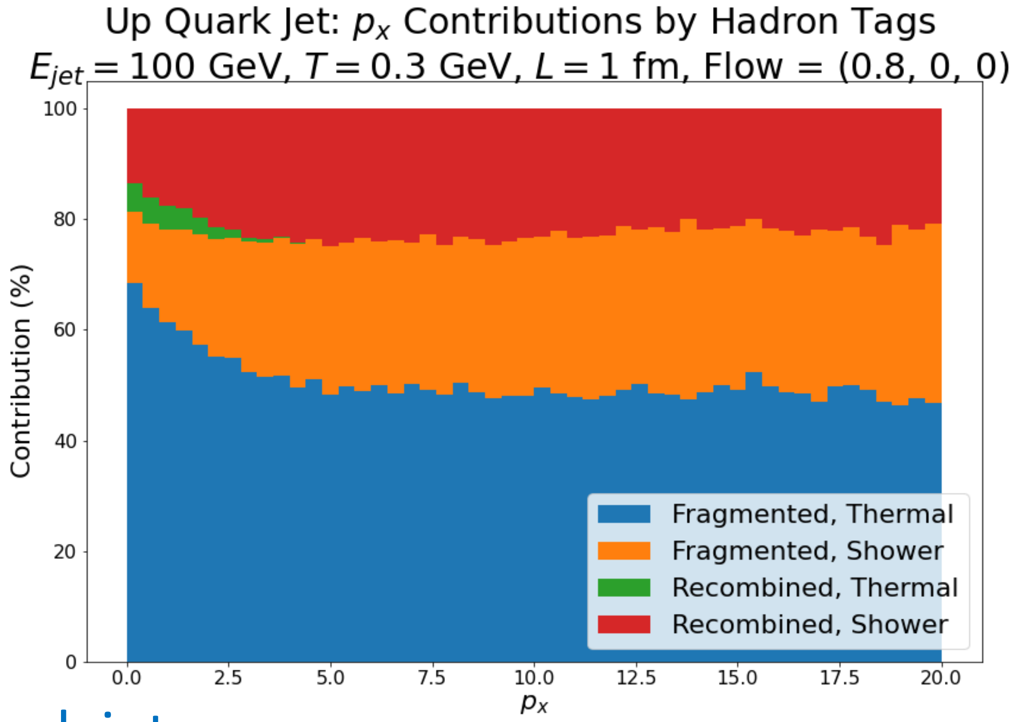
1. **MATTER** – propagates and splits an initial jet parton (in the **x-direction**), rapidly dropping its virtuality until it falls below a threshold Q_0 (= 1.2 GeV)
2. **LBT** – propagates low-virtuality and real partons through the QGP
3. **Hybrid Hadronization** – hadronizes partons through recombination and string fragmentation, respecting all given color tags:

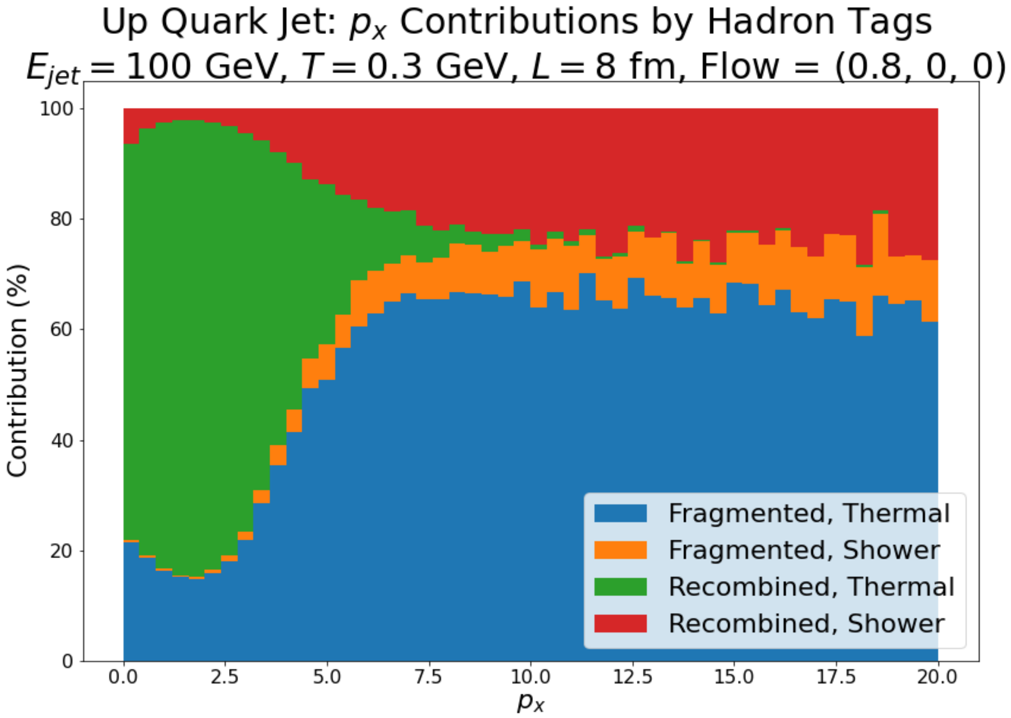
Input	Shower (MATTER, LBT) & thermal partons (sampled QGP brick) – momentum, position, color information
Recombination	Sample probabilities for random quark pairs and triplets to recombine into hadrons, using color flow information from a shower Monte Carlo
String Prep	Prepare remnant partons on a string-by-string basis for PYTHIA – constructing a fake history for junction containing strings
String Fragmentation	Call PYTHIA to perform string fragmentation on remnant strings and handle hadron resonances
Output	Recombined and fragmented hadrons, including space-time information

PYTHIA decays switched ON

$c\tau = 10$ mm

Contribution of Different Channels to Total Hadron Production





Up quark jet

Shower-thermal recombination increases drastically with medium size at low and intermediate momenta

Transverse Jet Profile

Up quark jet, E = 100 GeV, L = 1,4 fm.

Jet axis determined by taking the most energetic pseudojet, using the anti-k_T algorithm with $R = 0.6$.

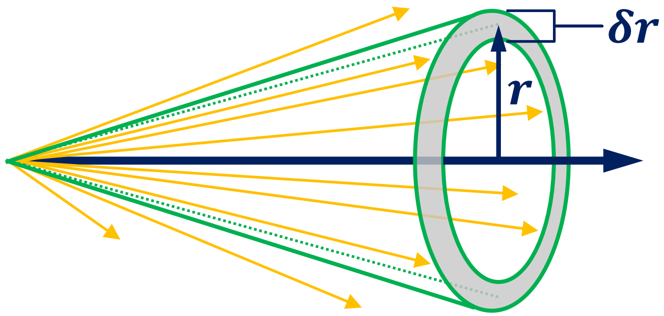
Longitudinal flow **widens** the jet, but transverse flow has little effect.

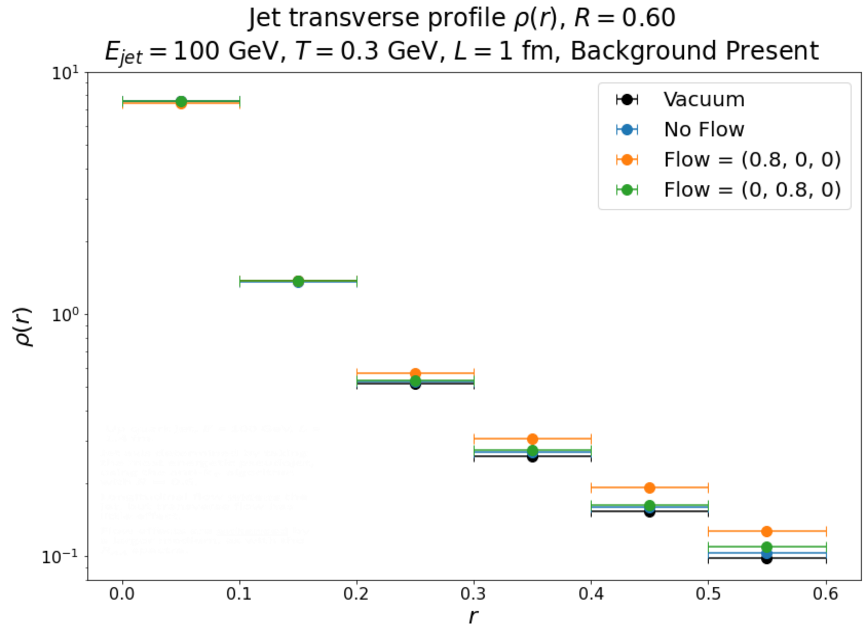
Flow effects are **enhanced** by a larger medium, as with the R_{AA} spectra.

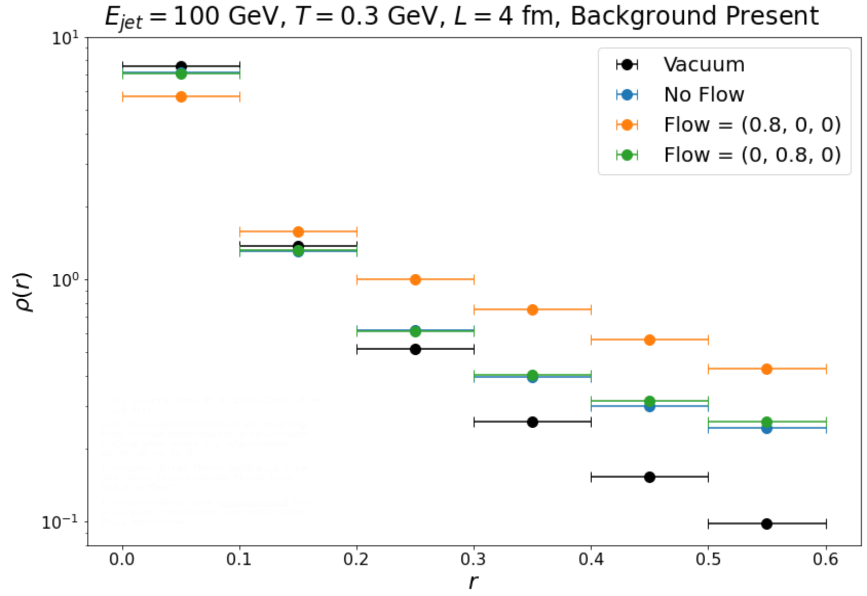
Up quark jet

Jet transverse profile defined as:

$$\rho(r) = \frac{1}{N^{jet}} \sum_{jets} \left[\frac{1}{\delta r} \frac{\sum_{i \in (r \pm \delta r/2)} p_T^i}{\sum_{i \in (0,R)} p_T^i} \right]$$







Collision Systems

PythiaGun > Matter > Hybrid Hadronization > Pythia

- CMS charged hadron spectra at 2.76 TeV (pp)
  - 50 $\hat{p}_T$ bins
- PHENIX neutral pion spectra at 200 GeV (pp)
  - 22 $\hat{p}_T$ bins

epemGun > Matter > Hybrid Hadronization > Pythia

- ALEPH charged hadron spectra at 91.2 GeV (e^+e^-)

Run each for every design point

146 design points, 48 validation points, 48 exploratory runs

Other Parameters

Recombination excited states allowed: 1

Energy loss max time = 200 fm/c

- Set so that MATTER has enough time to step every parton down from its initial virtuality to Q_0

Decay time: how long particles have to decay before being determined a final state hadron

- Changed to match detector specifications (usually in mm)
- Hybrid hadronization

Bayesian analysis code from JETSCAPE