A multi-messenger Bayesian Inference analysis of QGP jet transport using inclusive hadron and reconstructed jet data by JETSCAPE

Yi Chen (MIT) for the JETSCAPE collaboration

Mar 28, 2023. Hard Probes 2023

Manuscript in preparation 23XX.XXXXX

The MITHIG's work is supported by DOE-NP

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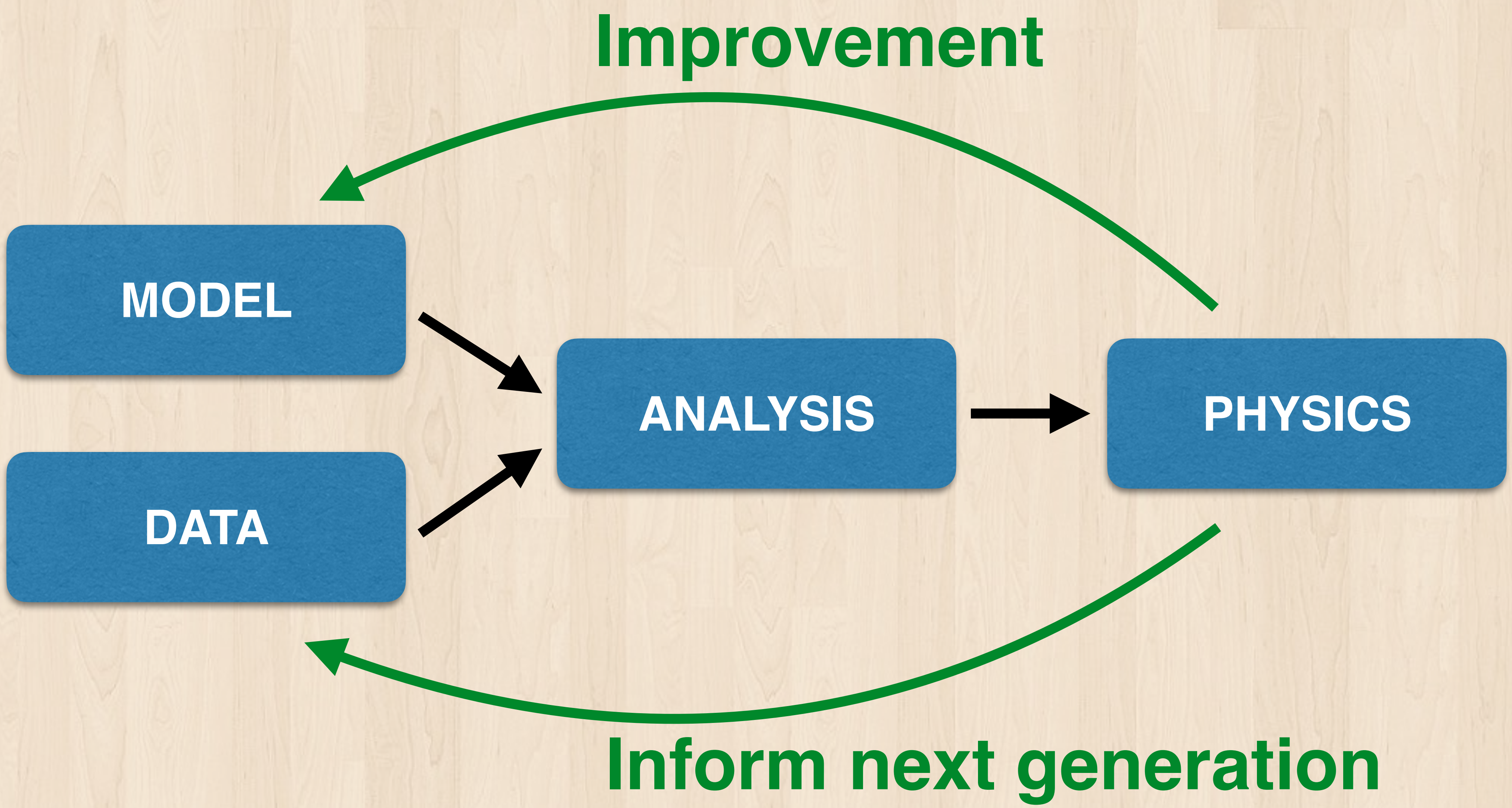
Global Analysis

Gain physics insight by rigorous comparison

Global Analysis



…and also feedback to improve things!

Bayesian analysis

ANALYSIS

Bayes' theorem: $P(\vec{\theta}\,|\,\vec{x}) = \dfrac{P(\vec{x}\,|\,\vec{\theta})P(\vec{\theta})}{P(\vec{x})}$

Posterior encodes all we want to learn

Allows a computationally tractable way to extract parameters (though still CPU intensive)

Generally not dissimilar to previous analyses (backup)

First analysis (2021)

DATA

Hadron R_{AA}

3 energies
2 centralities each

Recreate experimental uncertainty correlation the best we can

MODEL

Extract $\hat{q}(T, E, Q)$

Goal: one step forward from the JET result unified $\hat{q}$ across energy

Multistage: MATTER+LBT

PRC 104, 024905 (2021)

Current iteration

DATA

Hadron & **jet** R_{AA}

3 energies
ALL eligible data

Recreate experimental uncertainty correlation the best we can

MODEL

Extract $\hat{q}(T, E, Q)$

Re-parametrize $\hat{q}$

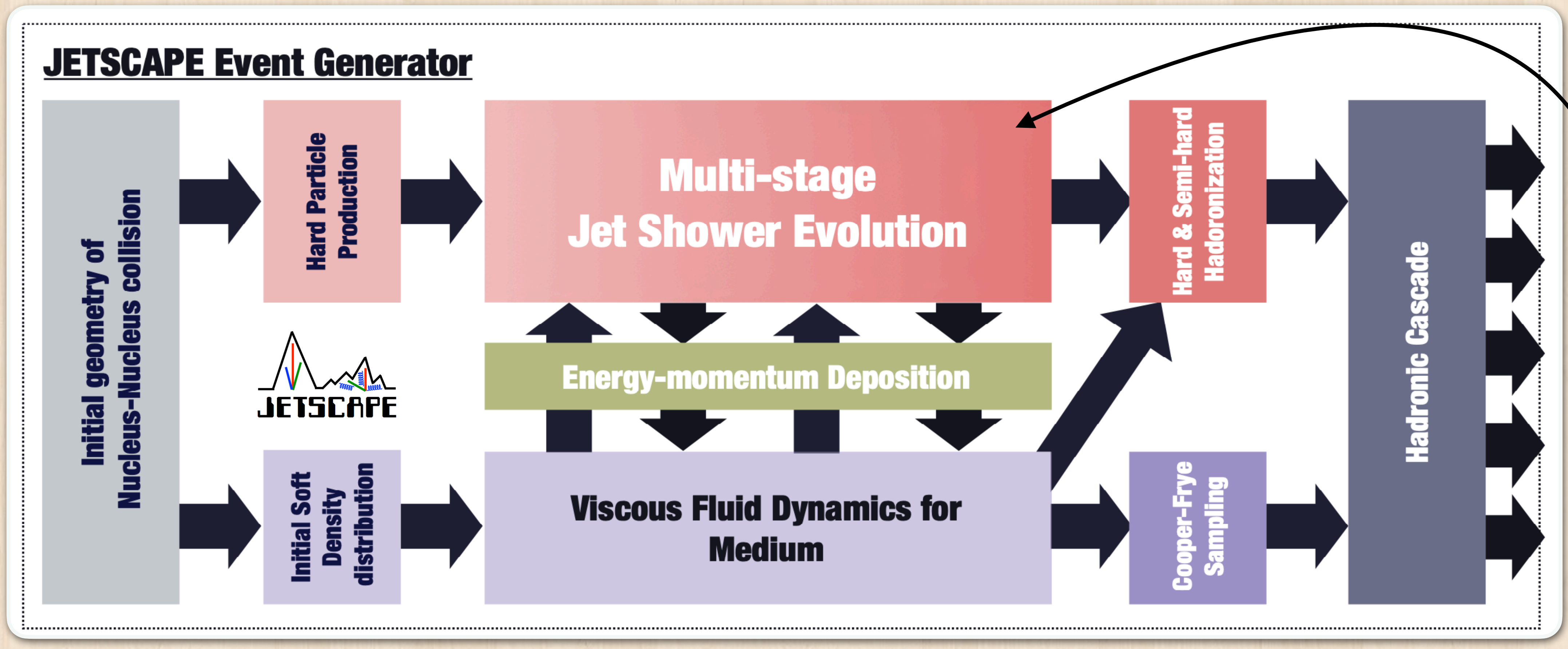
Sample full posterior from JETSCAPE soft sector result

MATTER+LBT

Goal: Explore what jets bring to the table

JETSCAPE framework

Diagram courtesy Y. Tachibana



We welcome new models!

Modular framework:

- Easily extendible
- Testing out different modules while holding everything else identical
- Unified framework for complete heavy-ion events

Parametrization of $\hat{q}$

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

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

Inspired from exponential "PDF": $f_{QGP}(x) \sim e^{-c_3 x}$

$$f(Q^2) \equiv N_0 \frac{\exp\left(c_3\left(1-\frac{Q^2}{2EM}\right)\right)-1}{1+c_1 \ln(Q^2/\Lambda^2_{QCD})+c_2 \ln(Q^2/\Lambda^2_{QCD})}\Bigg|_{Q^2 \geq Q_0^2}$$

Set by $f(Q_0^2) = 1$

Other parameters

Q_0: virtuality switch to LBT

τ_0: start time

2204.01163, see also previous talk

Parametrization of $\hat{q}$

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Set by $f(Q_0^2) = 1$

: parameters (6 in total)

Other parameters

Q_0: virtuality switch to LBT

τ_0: start time

2204.01163, see also previous talk

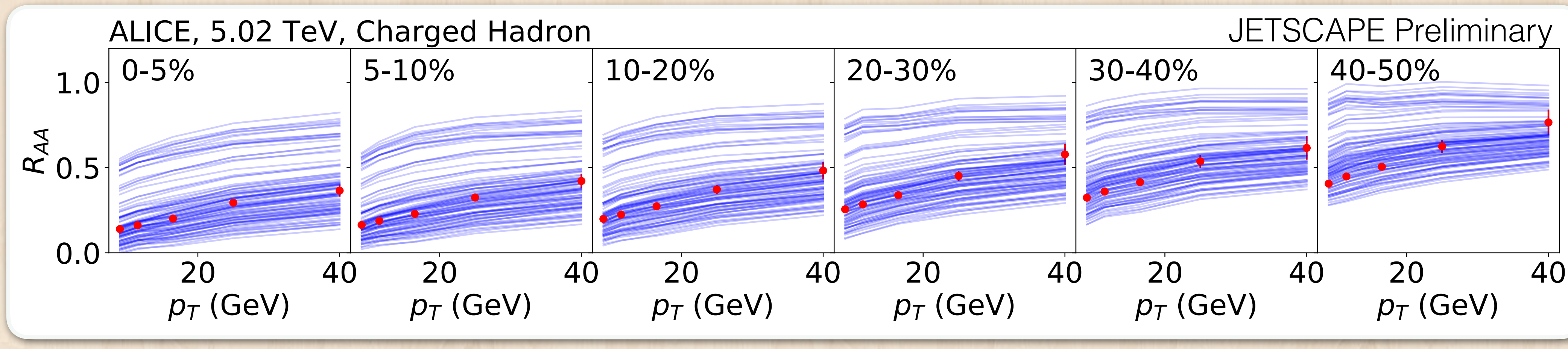
Few words on the analysis

- Huge effort in computing during 2022
  - O(10M) CPU hours, unified submission interface across multiple HPC systems, data curation including all systematic uncertainties, iteration on design points, etc
  - Calculated many more observables than are used in this iteration $\rightarrow$ fast turnaround for next analyses
- Choose dimension of subspace based on statistical uncertainty on the computations

Nominal Results

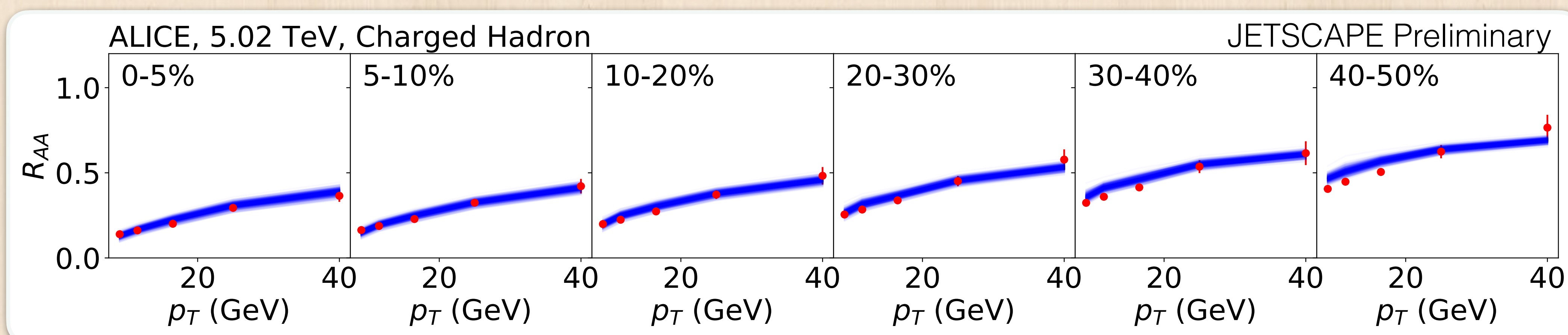
Example: design vs posterior

Data
Calculation



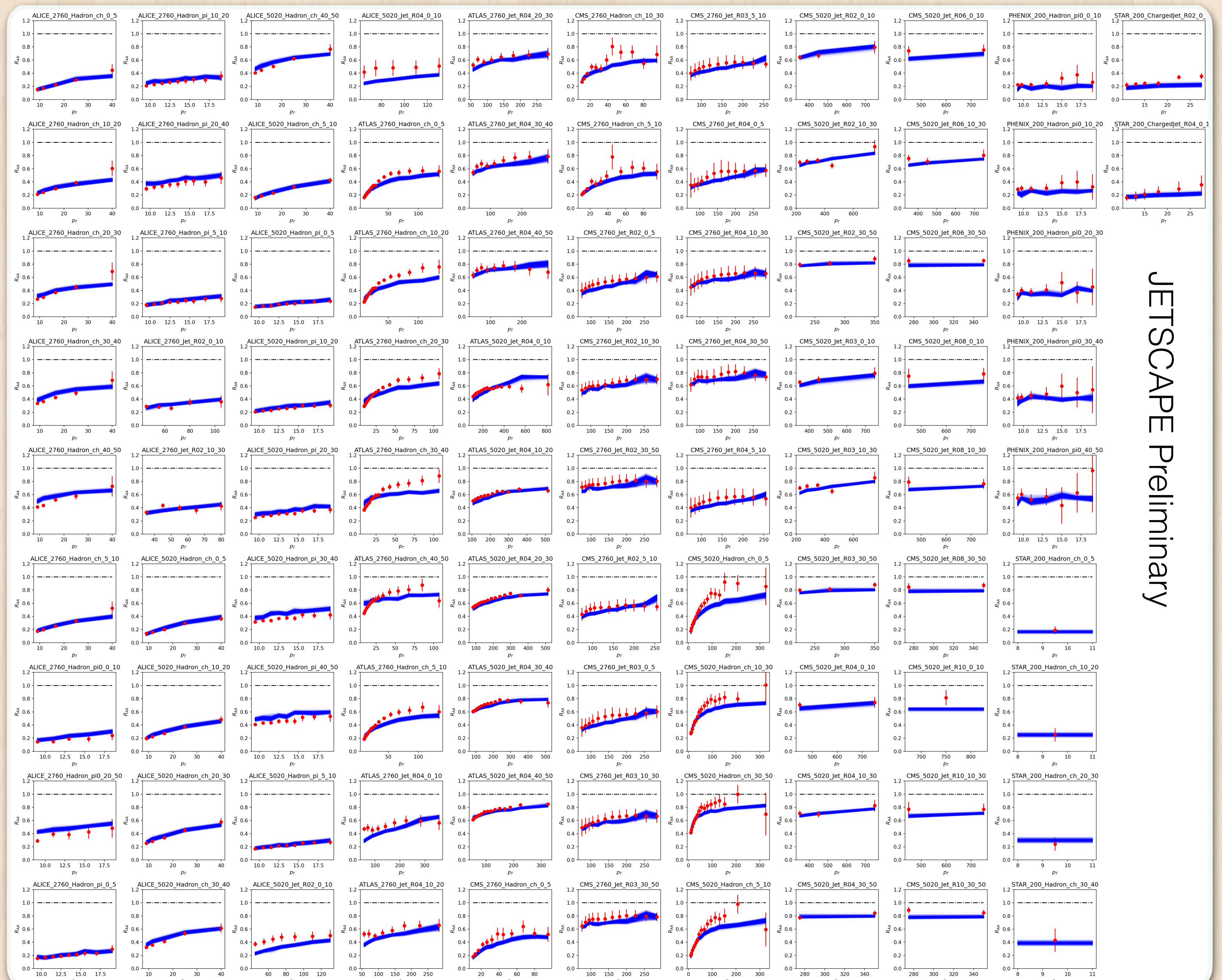
Analysis

Data
Best Fit



Posterior observables

(Don't stare too closely, we have zoomed in version in the next pages)



Data

Best fit

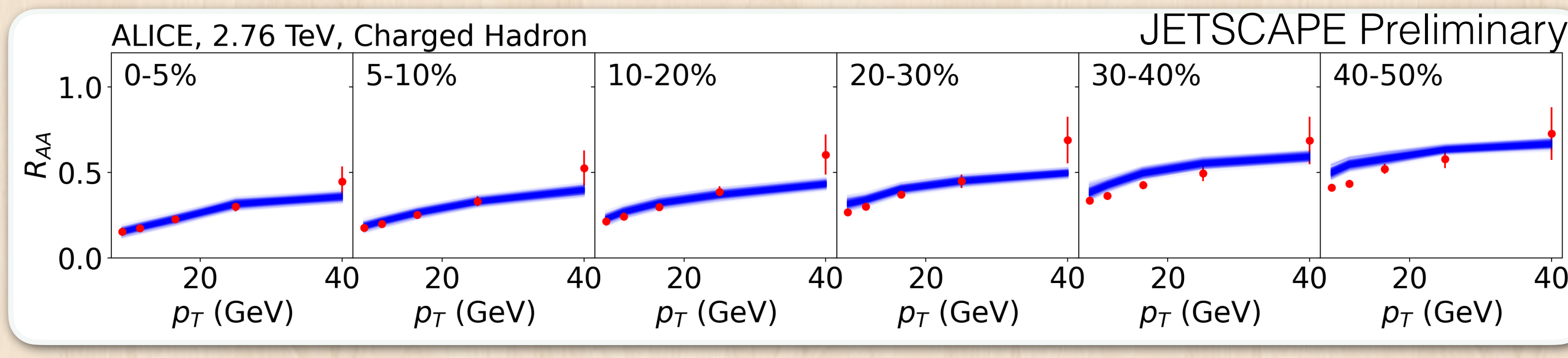
Overall reasonable agreement is observed

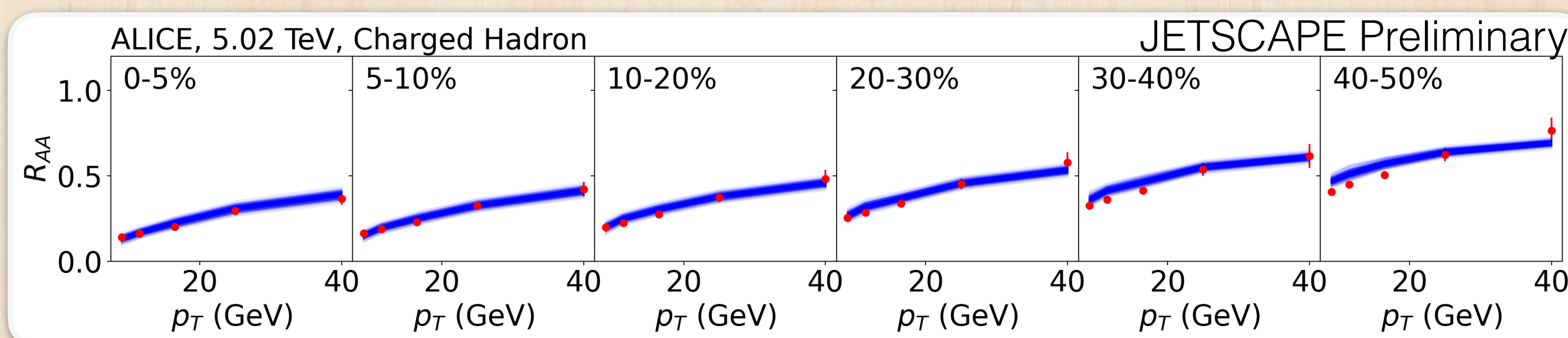
Tension for some measurements

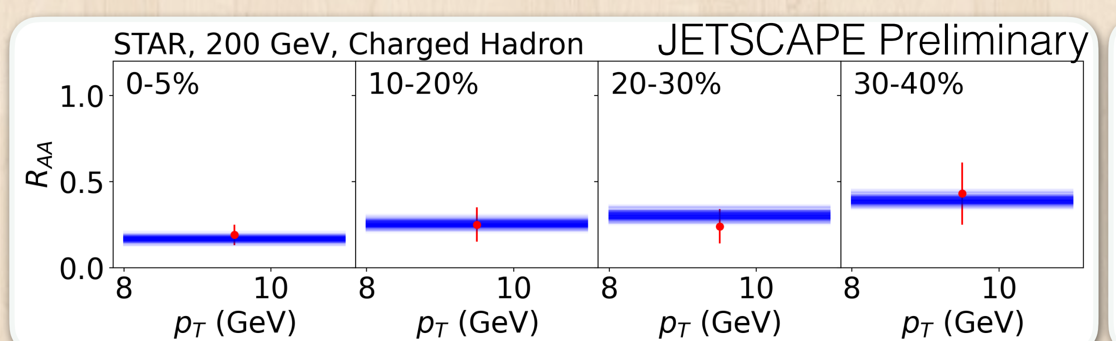
Looking closer — hadrons

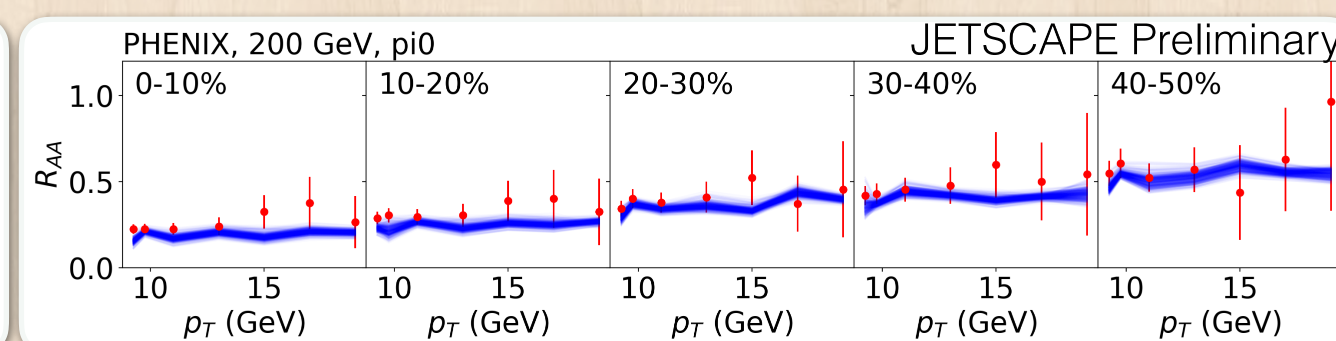
Generally great agreement at lower p_T

No large difference across experiments





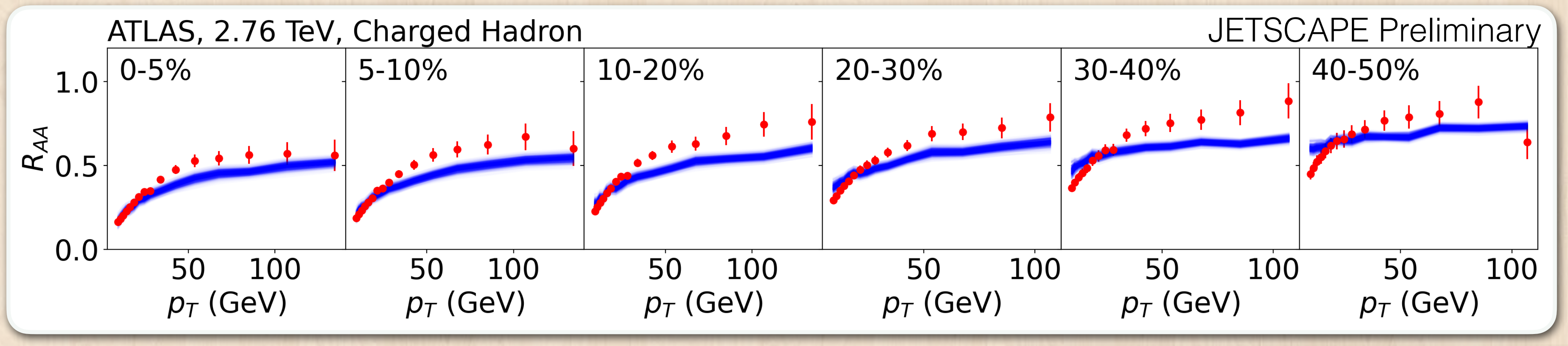


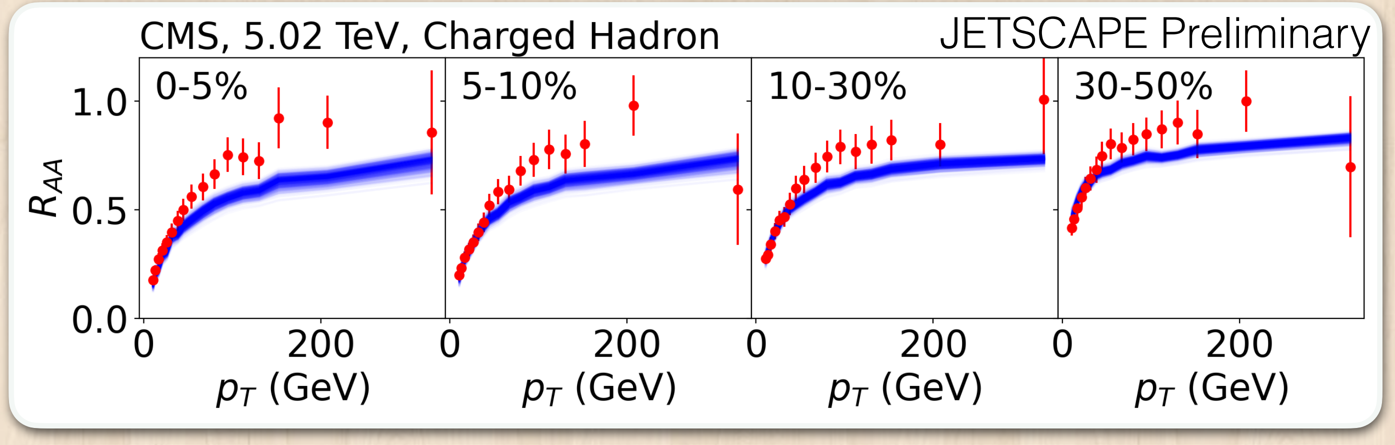


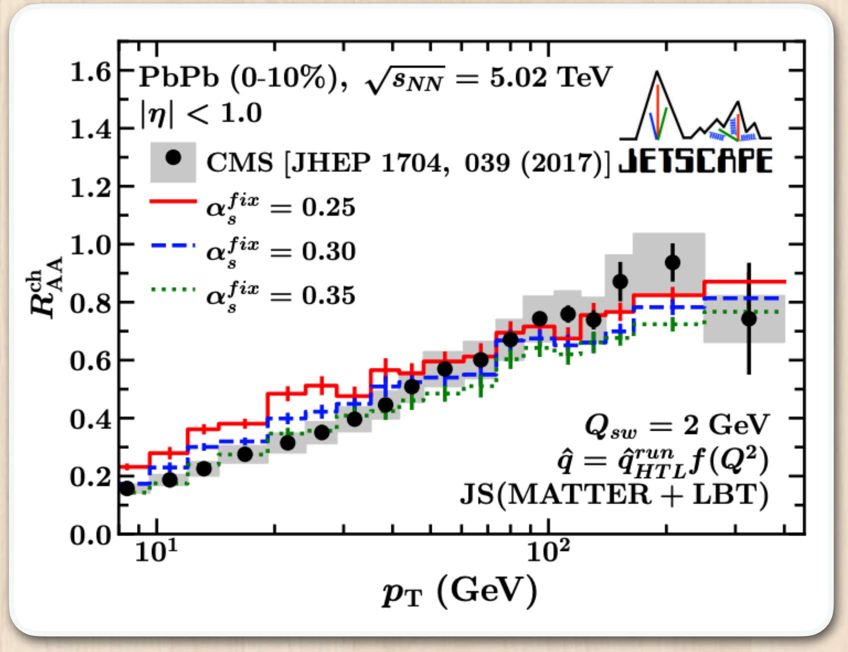
Looking closer — hadrons

Things deviate a bit going to higher p_T

Uncertainty smallest at lower $p_T \rightarrow$ drives result

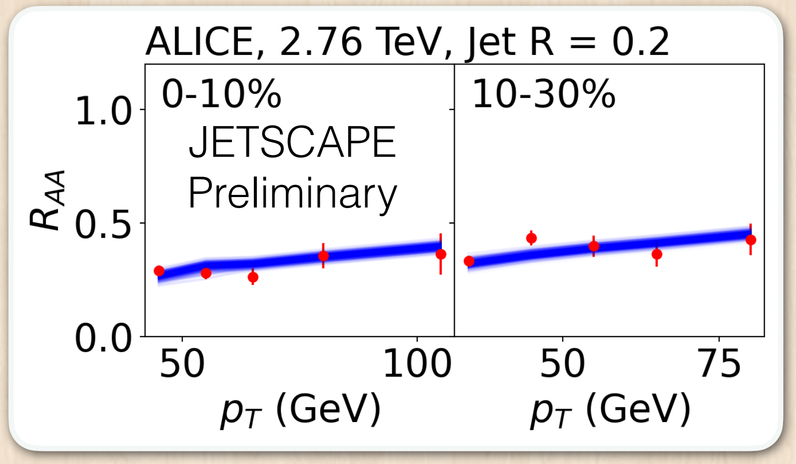




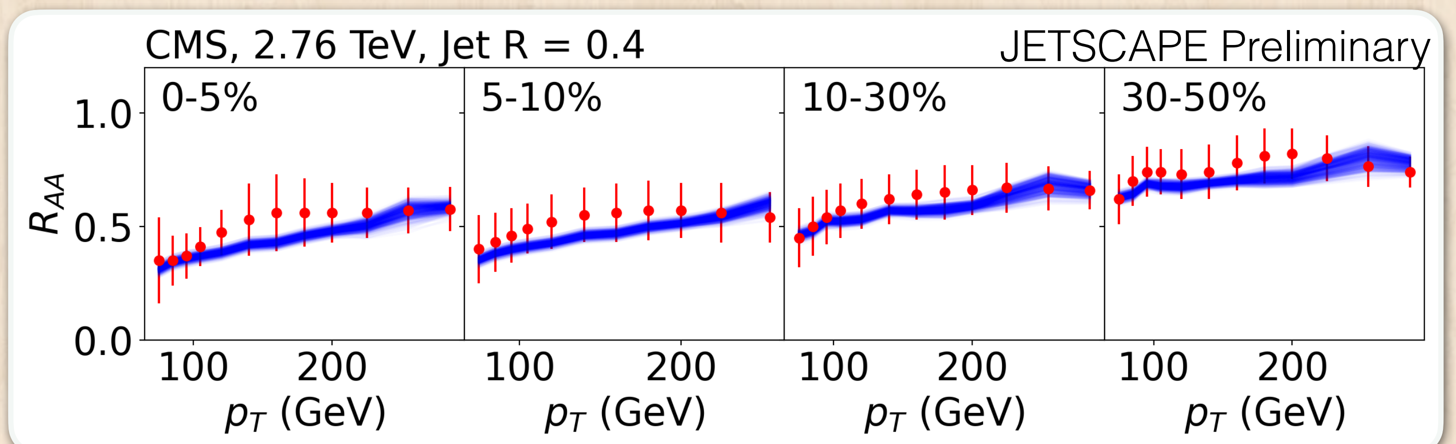


2204.01163

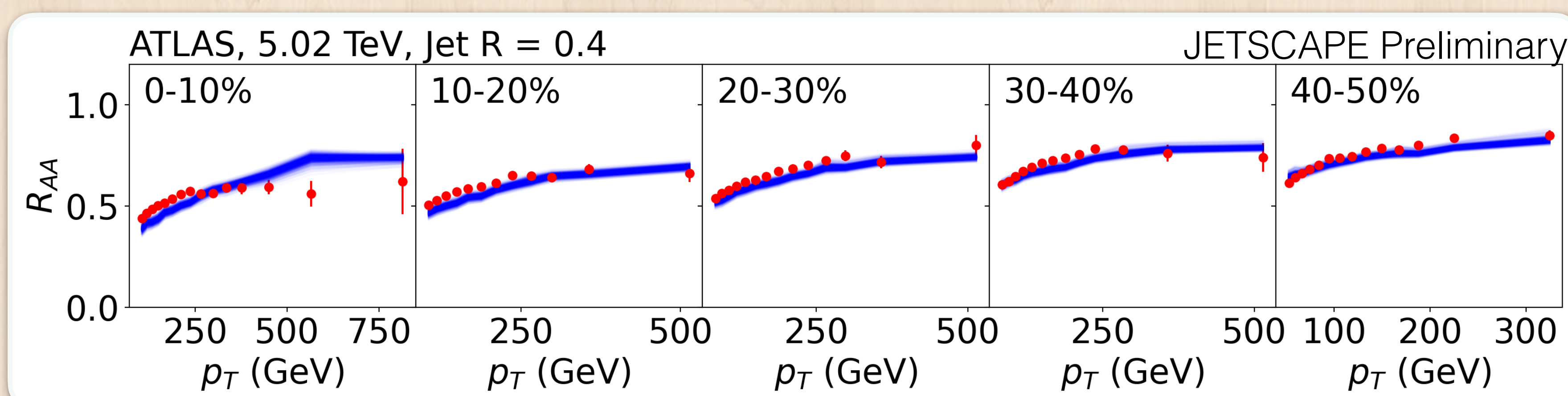
Looking closer — jets



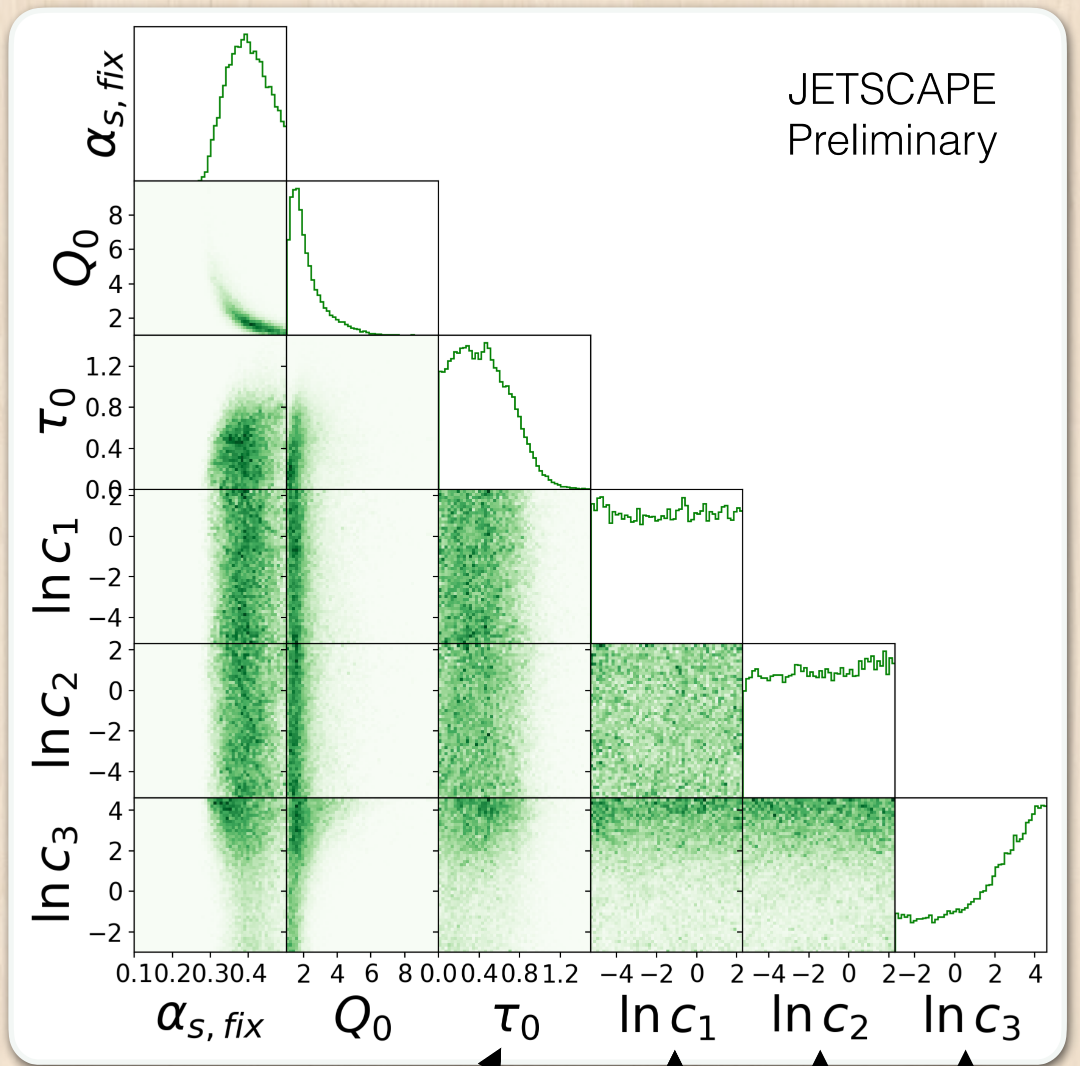
Also generally good agreement

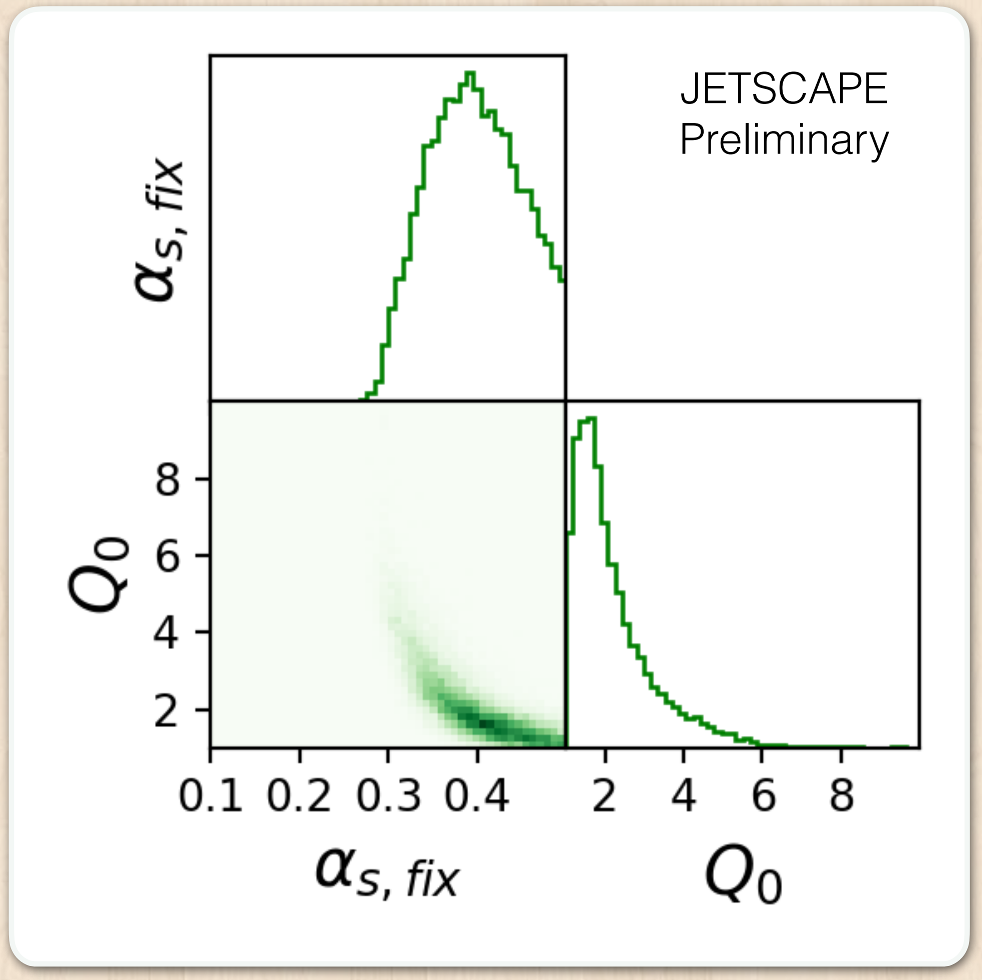


Systematically slightly lower R_{AA}



Posterior distribution





Start time

Virtuality dependent terms

Anti-correlation between $\alpha_{s,fix}$ and Q switch

$\propto \hat{q}$

Between MATTER and LBT

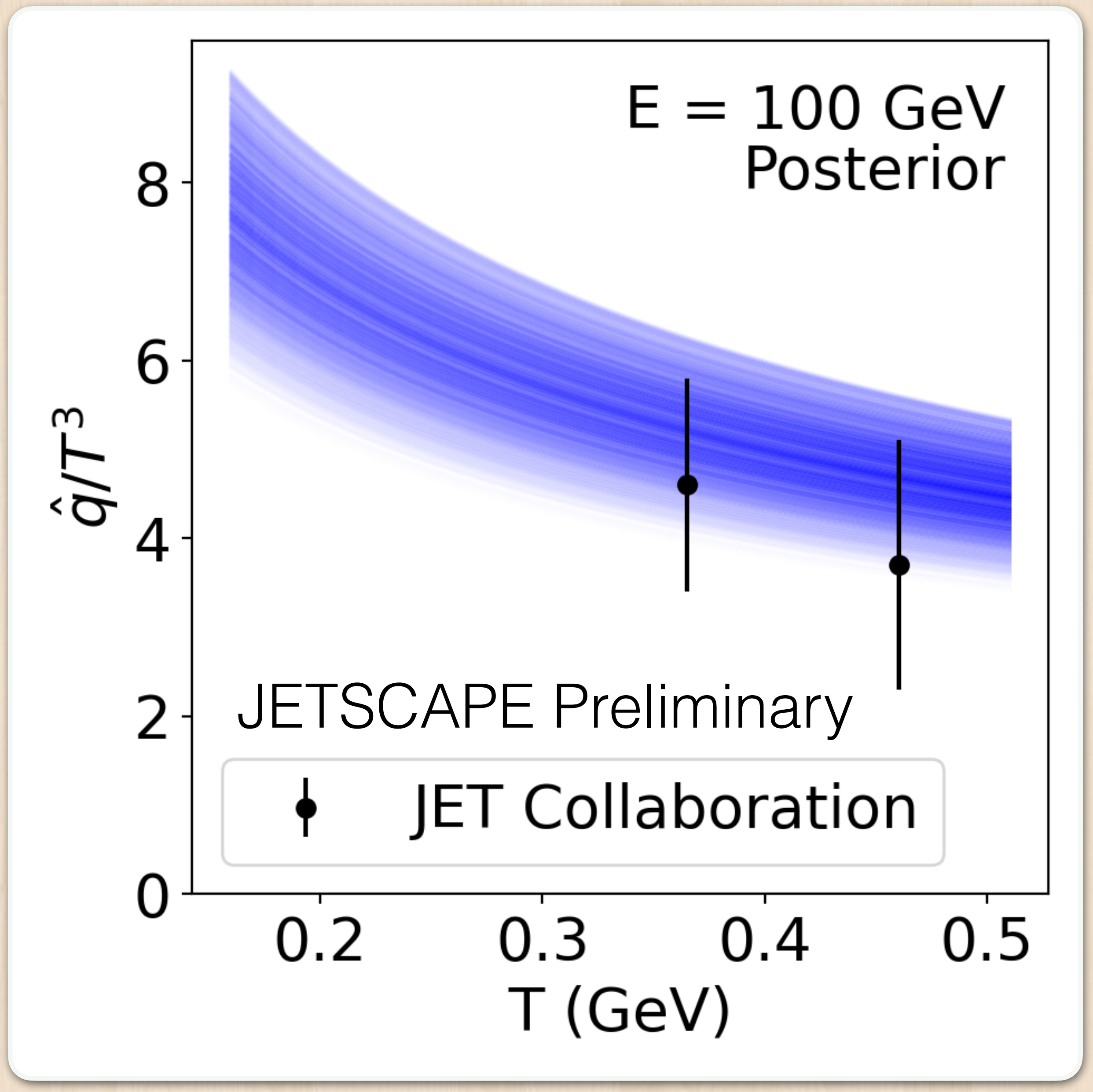
Extracted $\hat{q}$

Compatible with previous extractions

Here we plot the $\hat{q}$ when virtuality is low

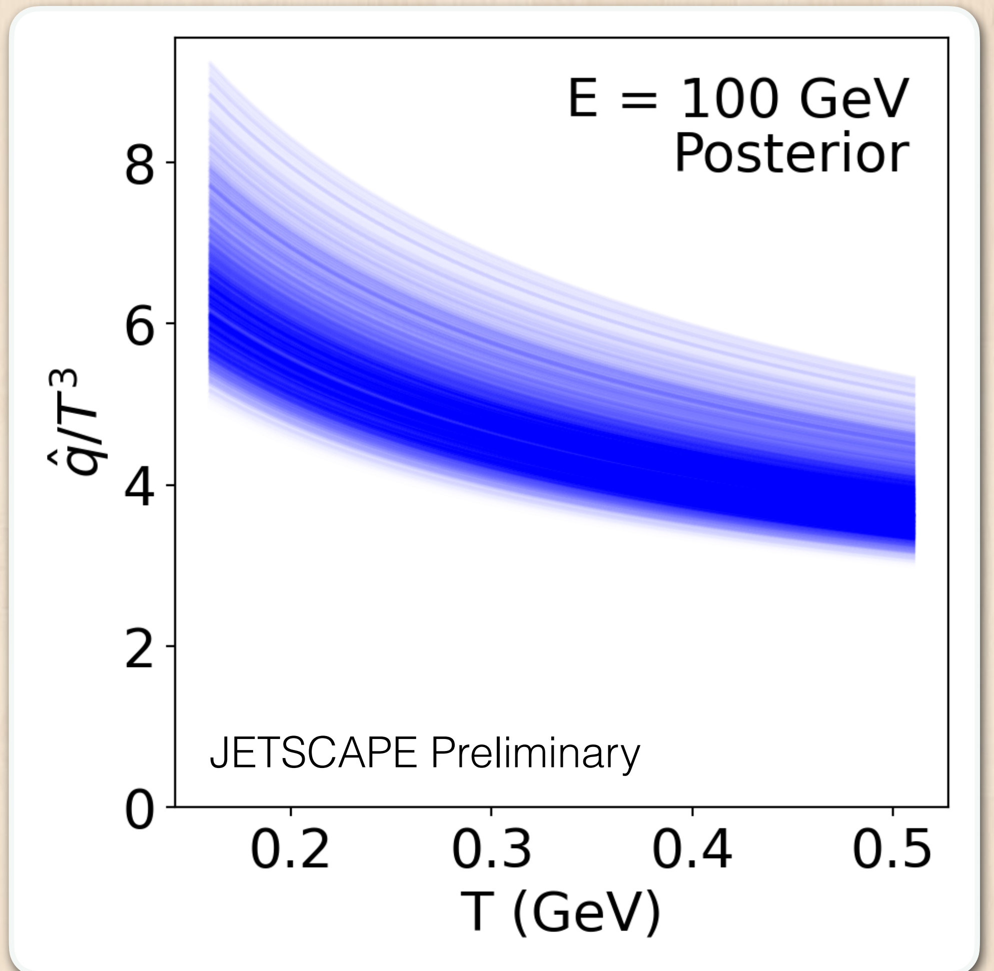
i.e., $\hat{q} = \boxed{\hat{q}^{run}_{HTL}} \times f(Q^2)$

↑ **this**

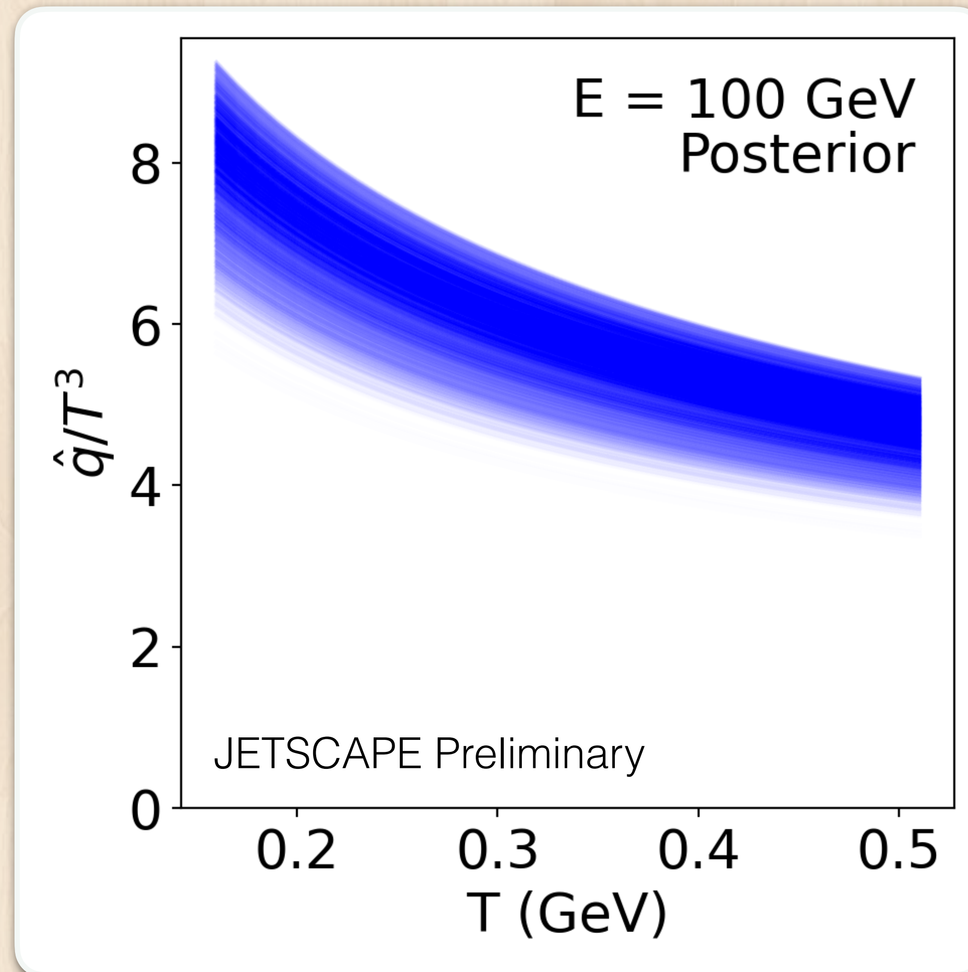


How can we gain more insight?

$\hat{q}$: jets vs hadrons

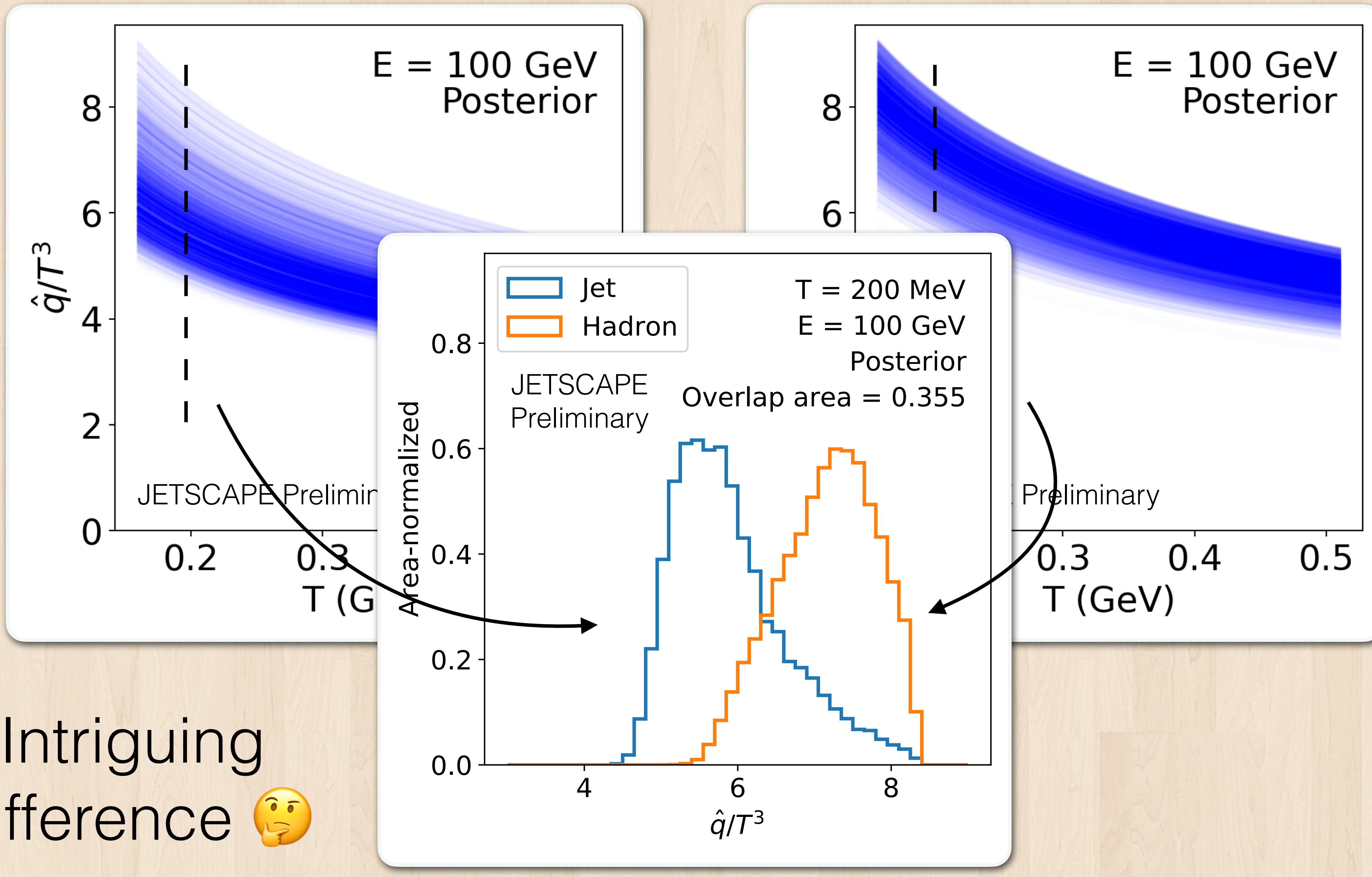


If we do analysis with only jet data



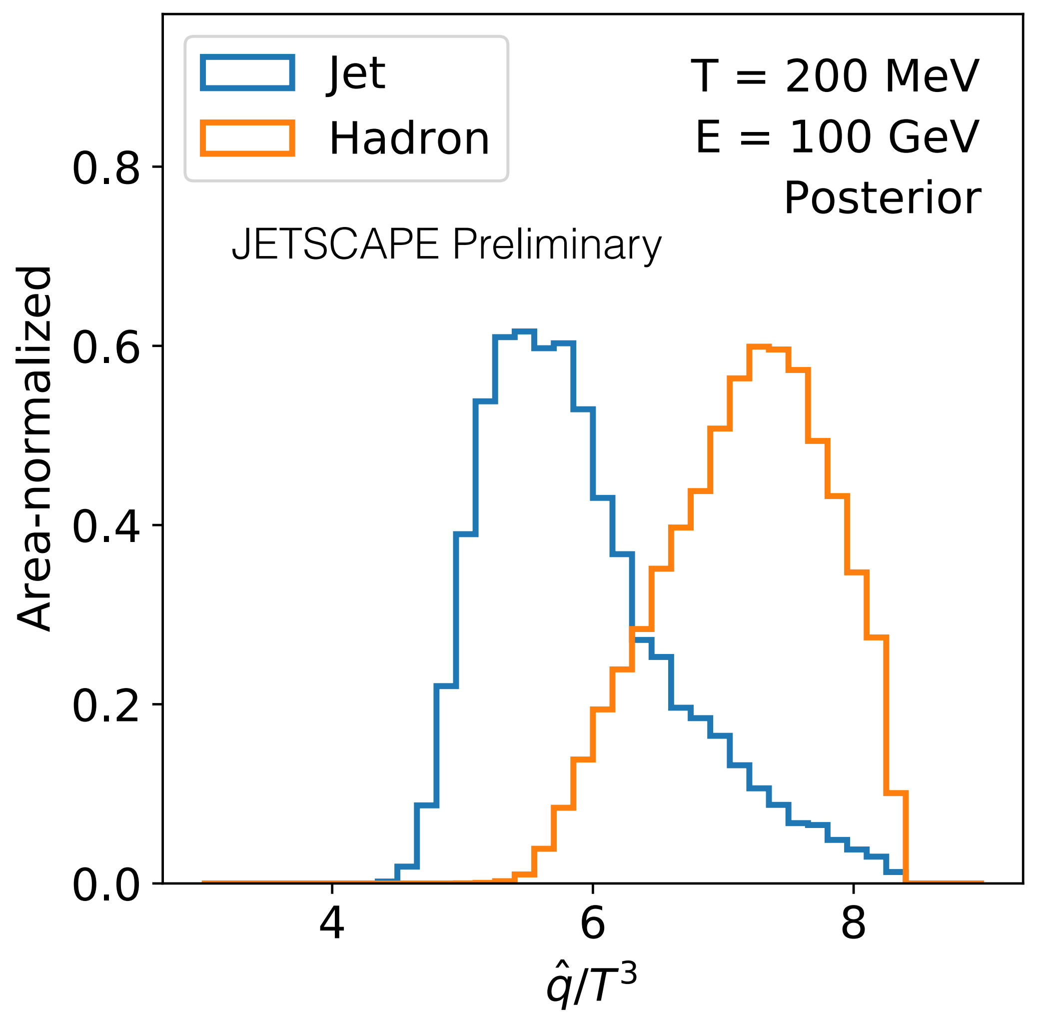
If we do analysis with only hadron data

$\hat{q}$: jets vs hadrons

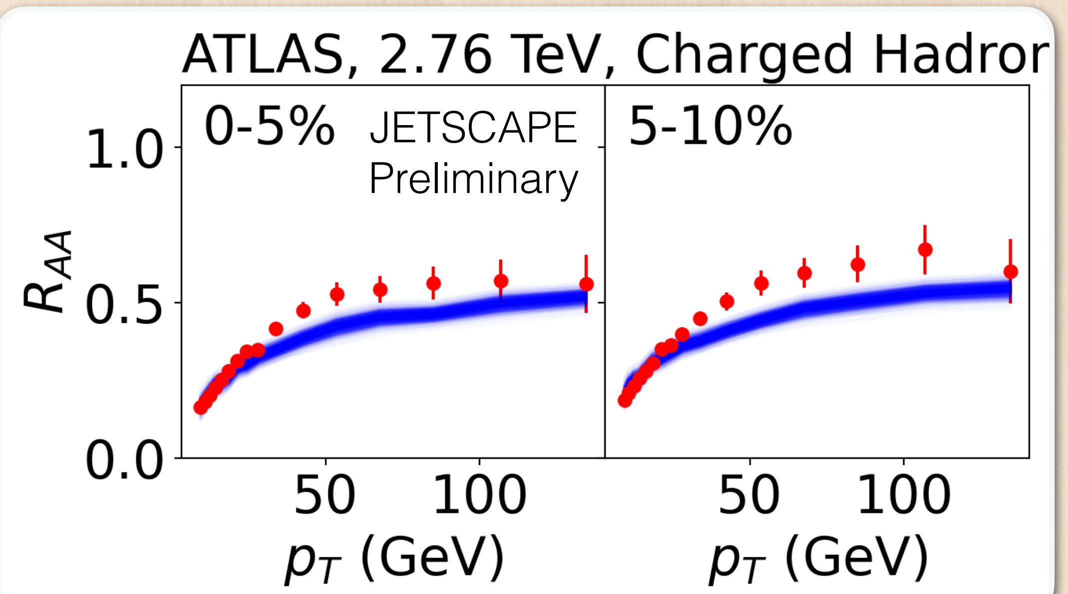


Intriguing difference 🤔

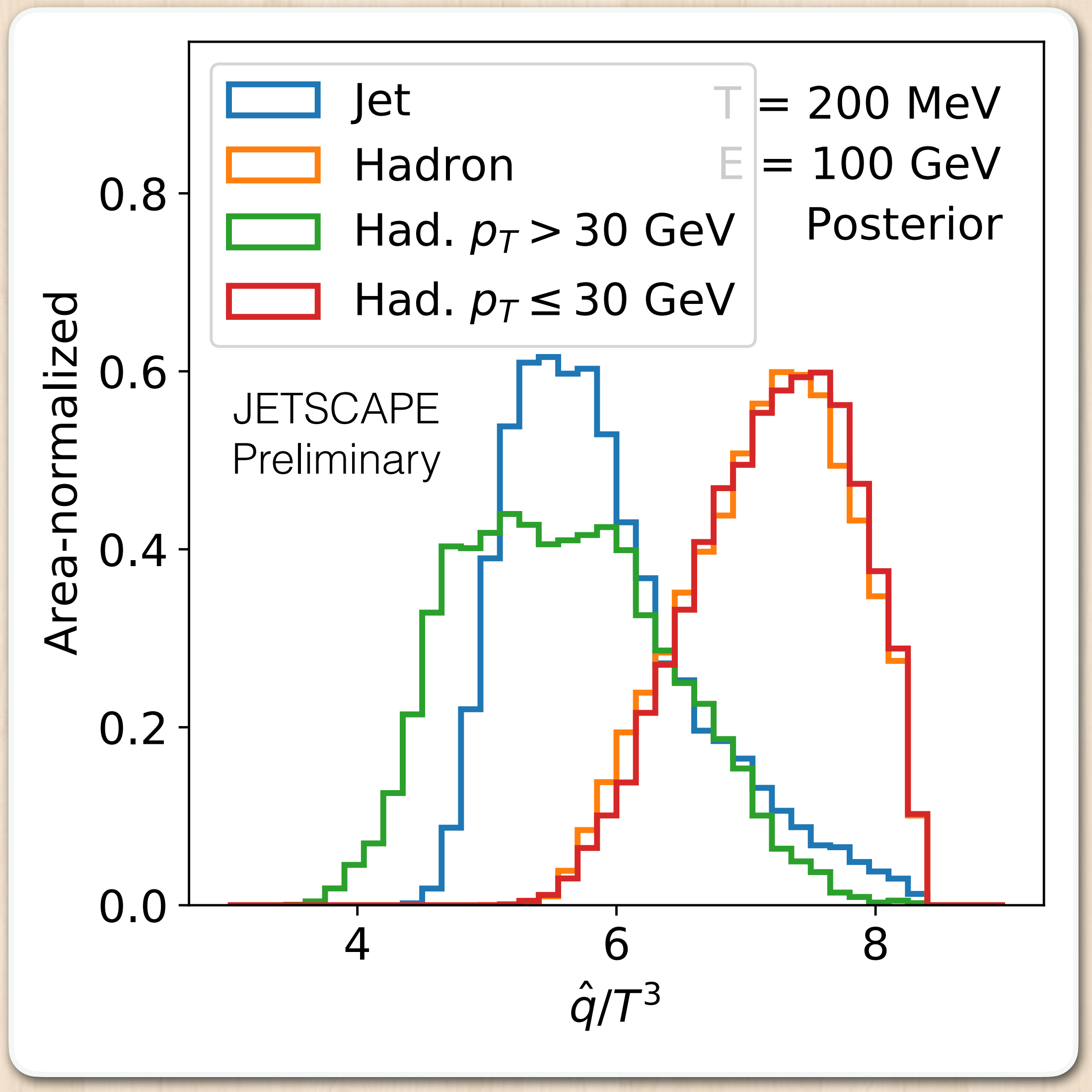
Hadrons, high vs low



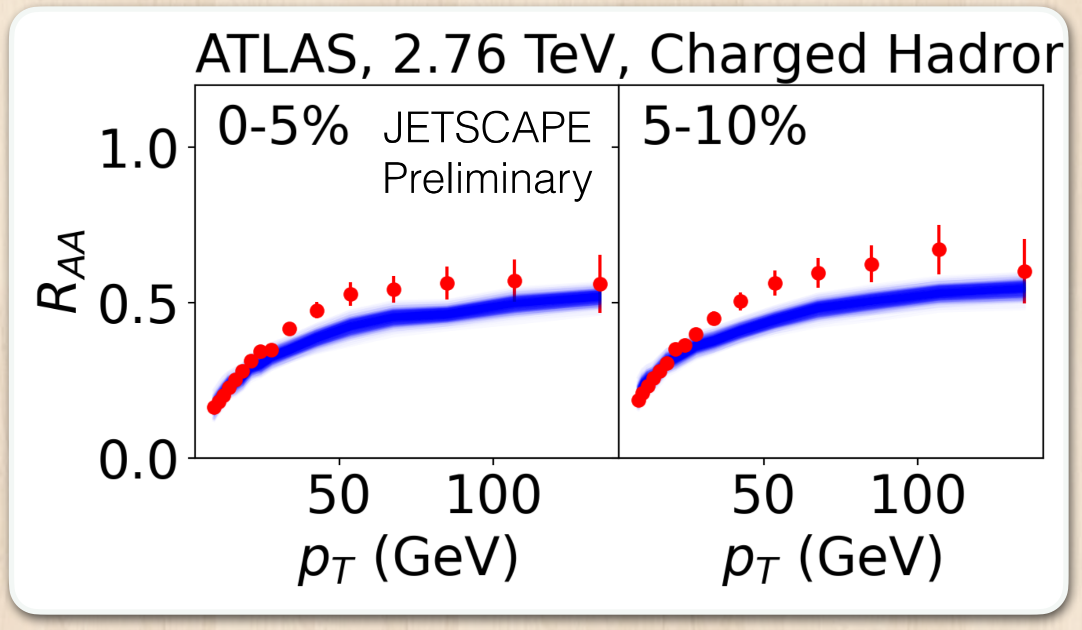
Full p_T range



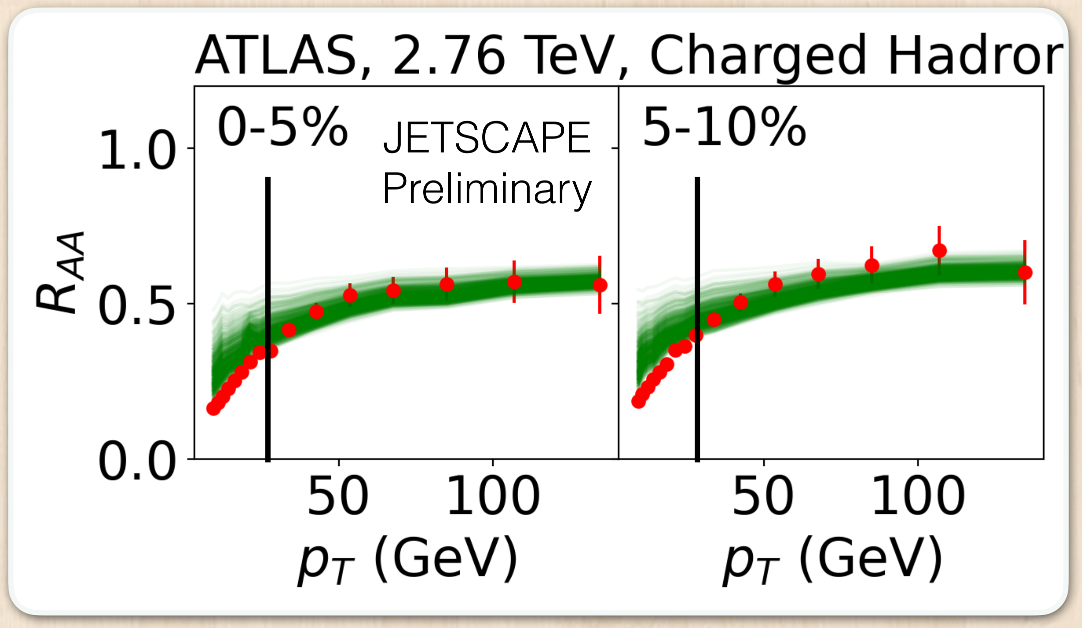
Hadrons, high vs low



Full p_T range

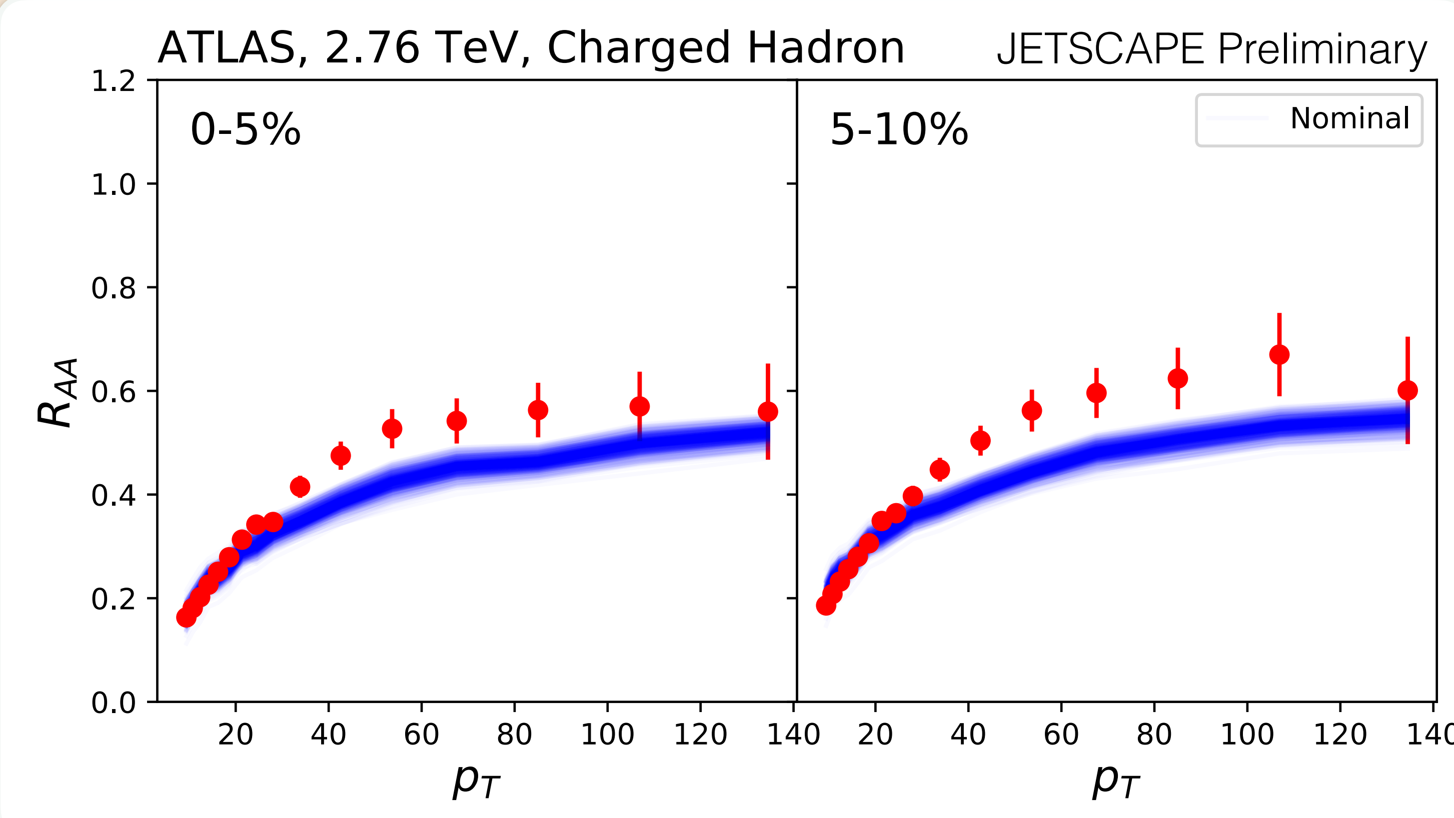


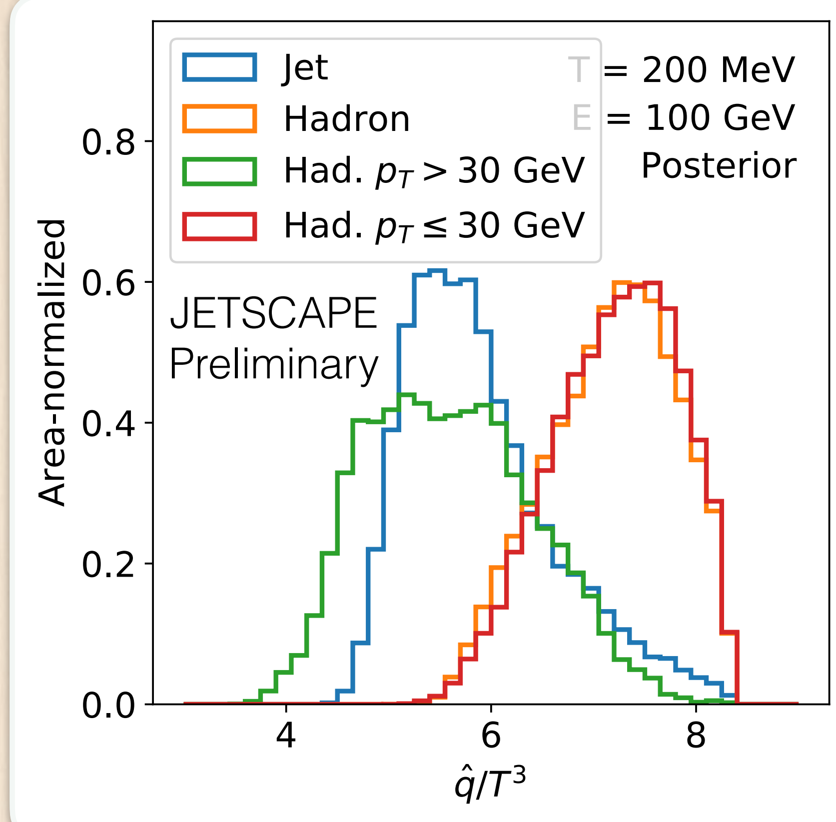
Only hadrons $p_T > 30$ GeV



By eye green seems “better”!

What's happening?





Low p_T part dominates: small experimental uncertainty

High p_T part in line with jet data

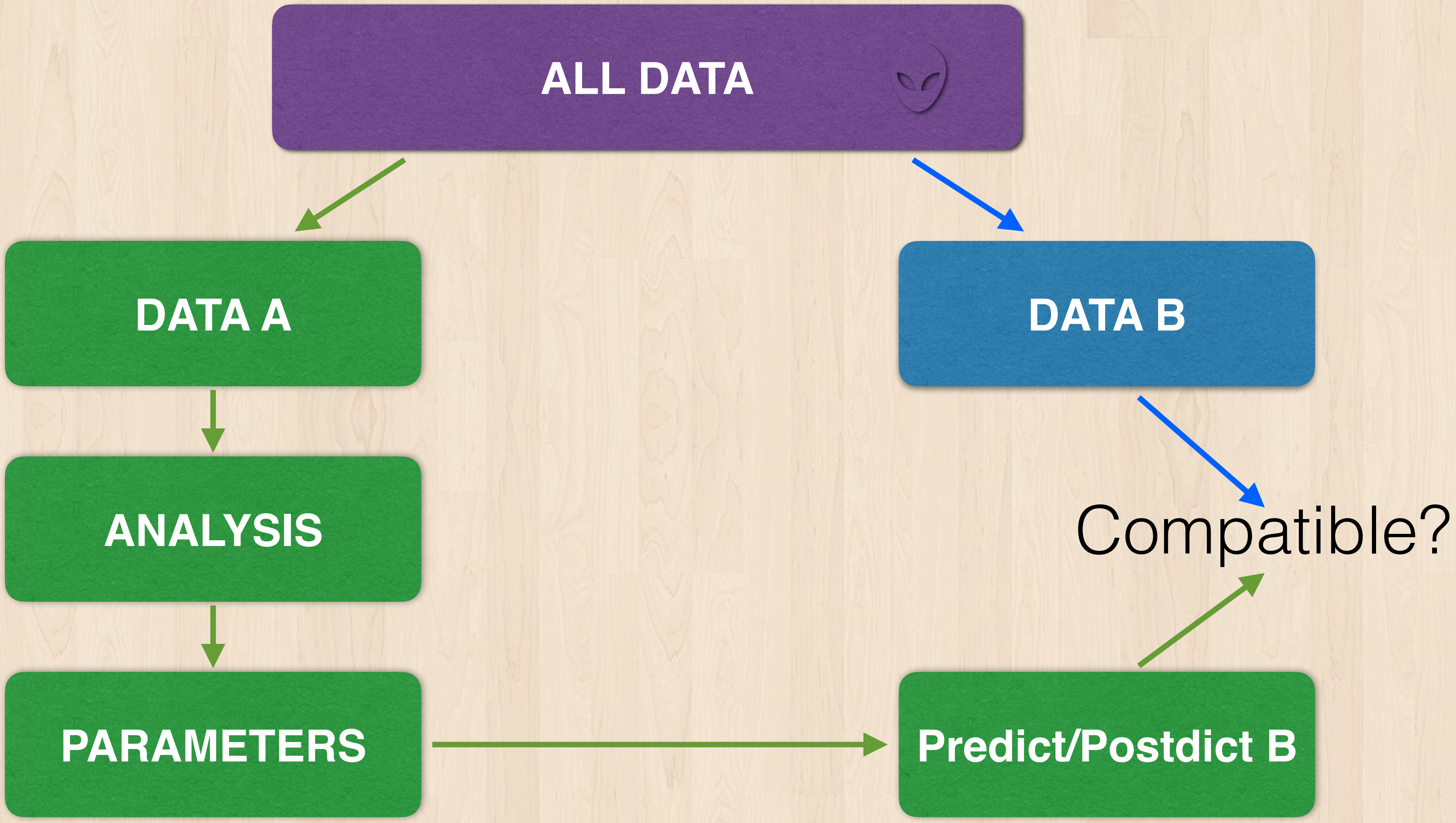
Points clearly to phase space for model improvement

Theory uncertainty is important

Implications

- We can **scrutinize** the specific **model** used in this round of simulations in great detail
    - Low vs high p_T, central vs peripheral, jet vs hadron, different radii jet, and so on
    - Future: **more models needed**!
- Isolate regions of interest
- Important feedback to models
- Points to interesting question: **theory uncertainties**?

A way to quantify compatibility



Explore how well model performs with new data

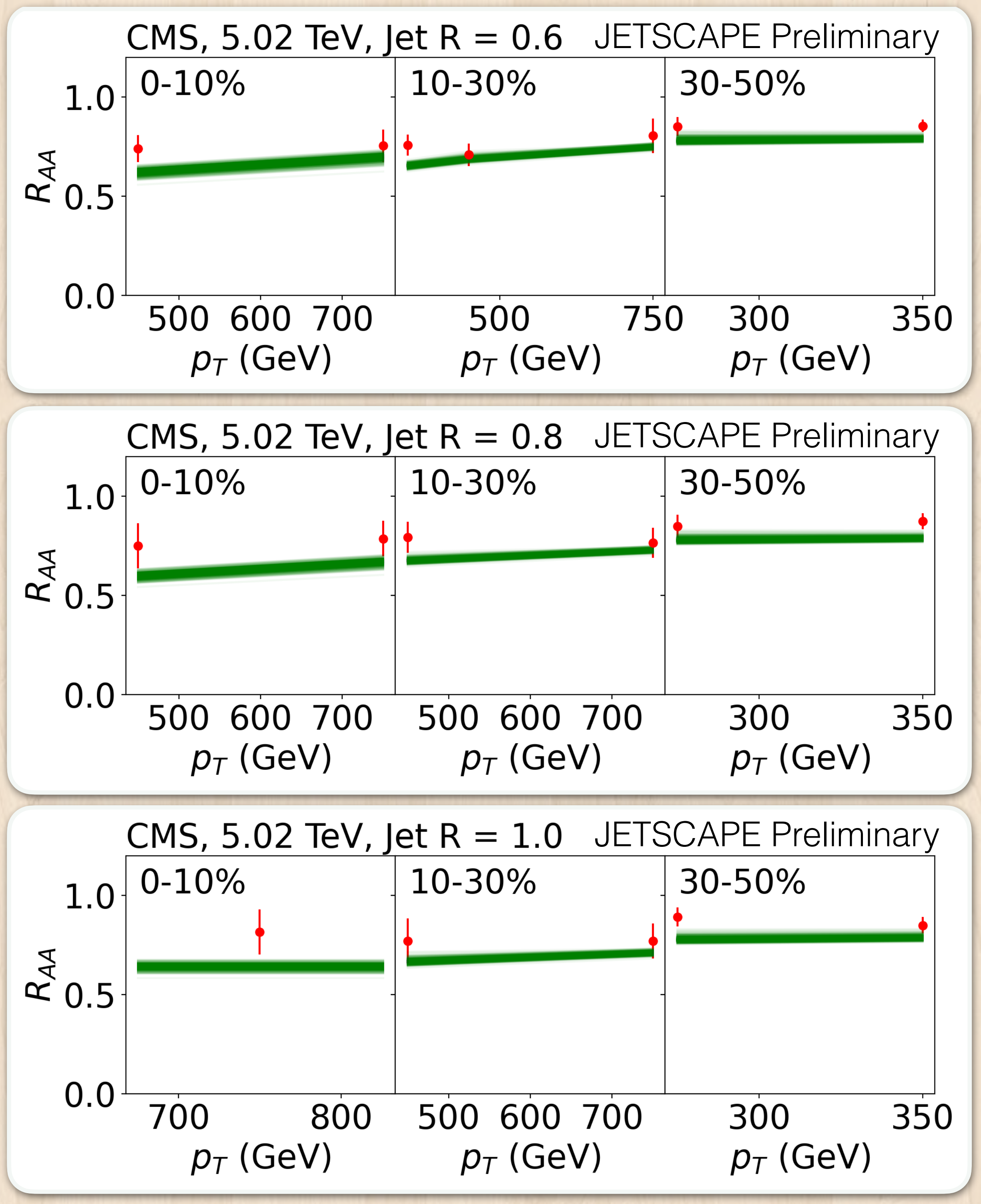
Example: small vs large radii

A: hadron & small jet data

B: large jet data

Reasonable agreement

Uncertainty correlation

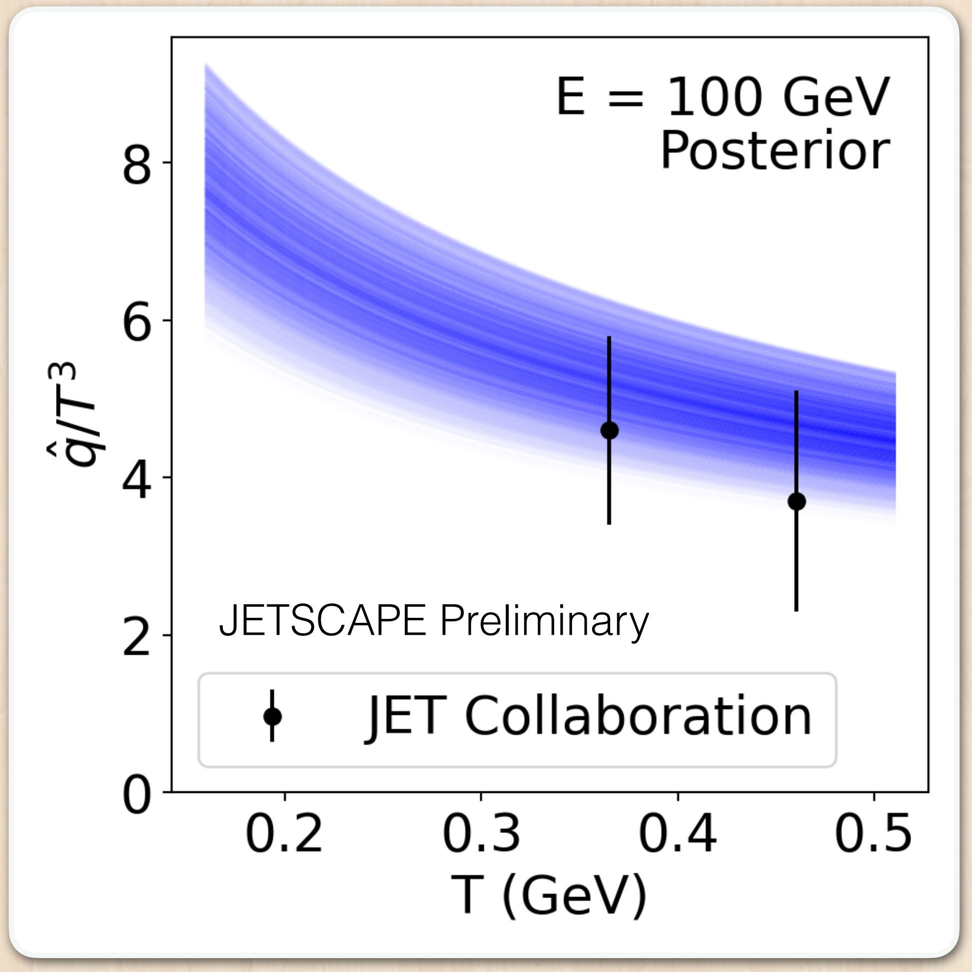


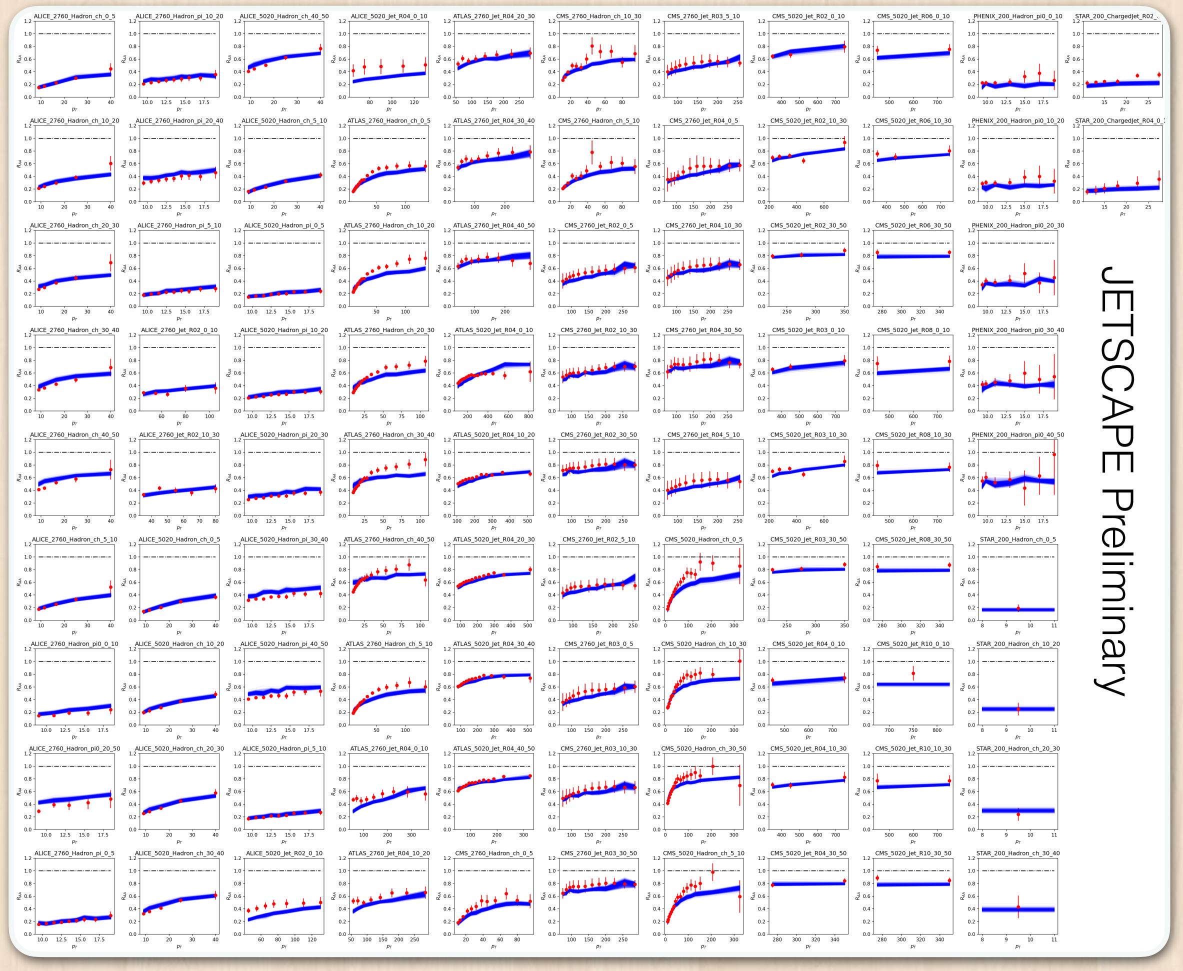
Concluding remarks

New analysis of $\hat{q}$

Included jet R_{AA} into the mix!

General reasonable description of data

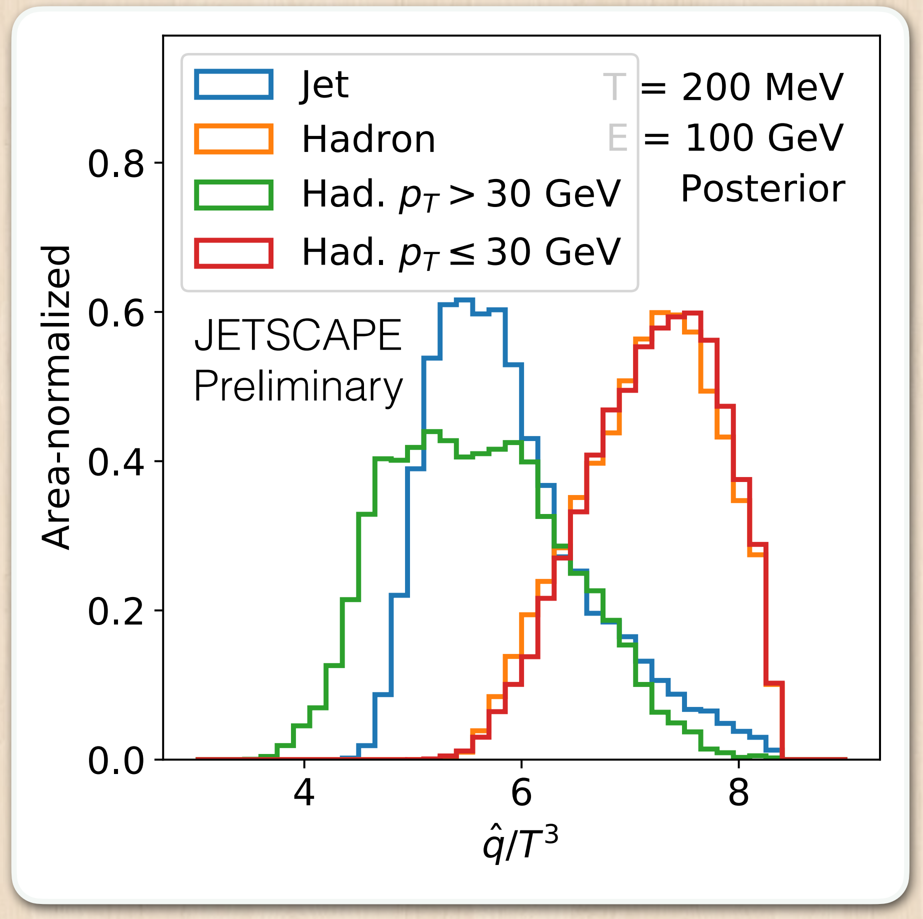


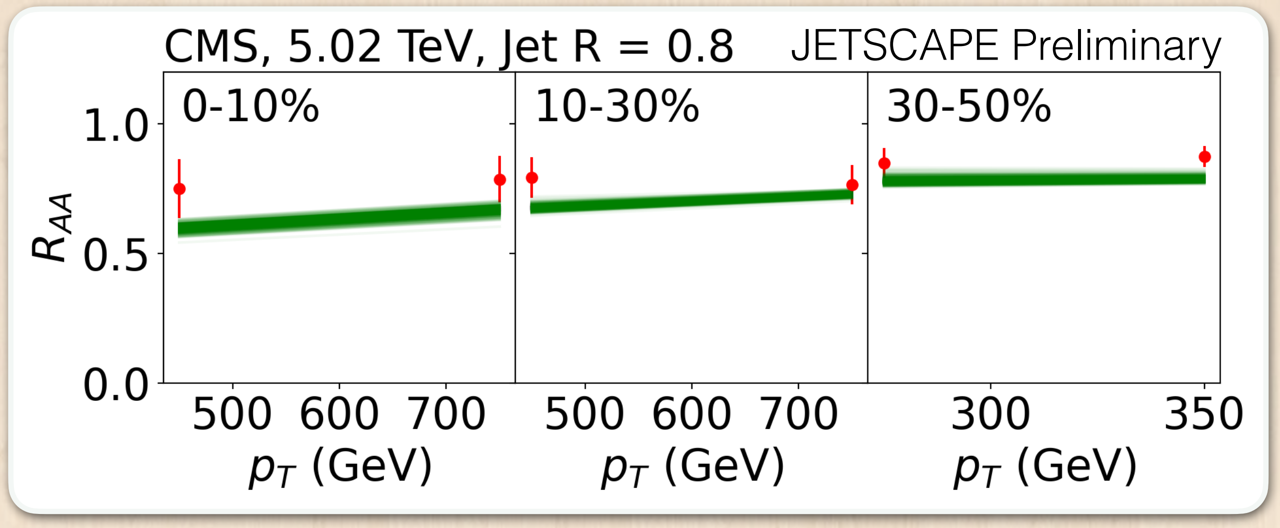


All these impossible without a framework

Endless possibilities

Bayesian analysis: powerful tool for not only **parameter extraction** but also **model studies**





Evaluate how well model does in new observables

Pinpoint interesting phase space in model

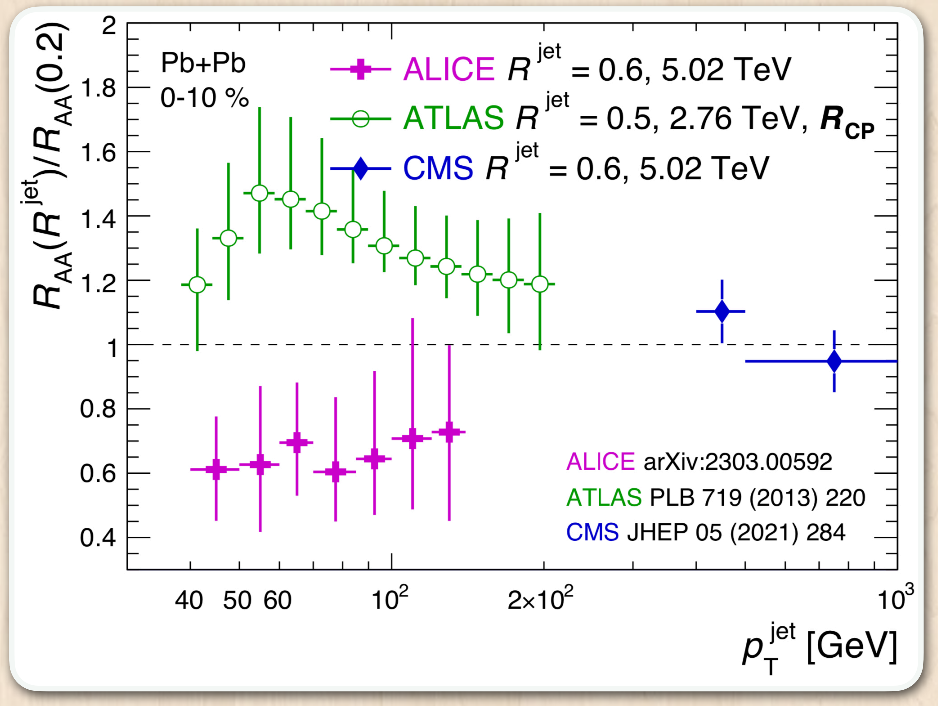
Theory uncertainties?

(Near-) future prospects

We also calculated huge number of **other jet-related observables**

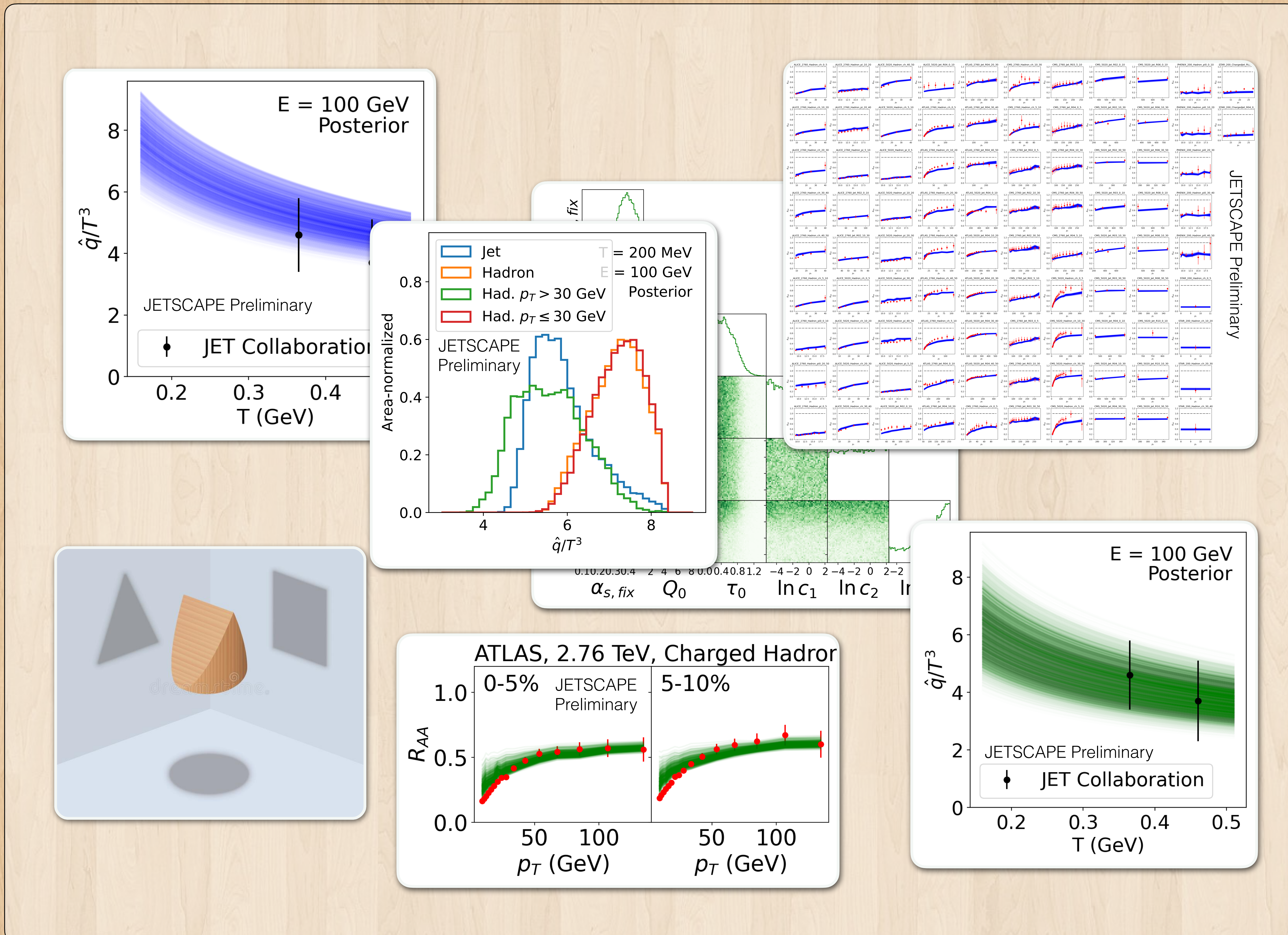
Move one step at a time and **sequentially include more observables** → stay tuned for many new results in the near future!

Plot taken from Y. Go, Mon Mar 27



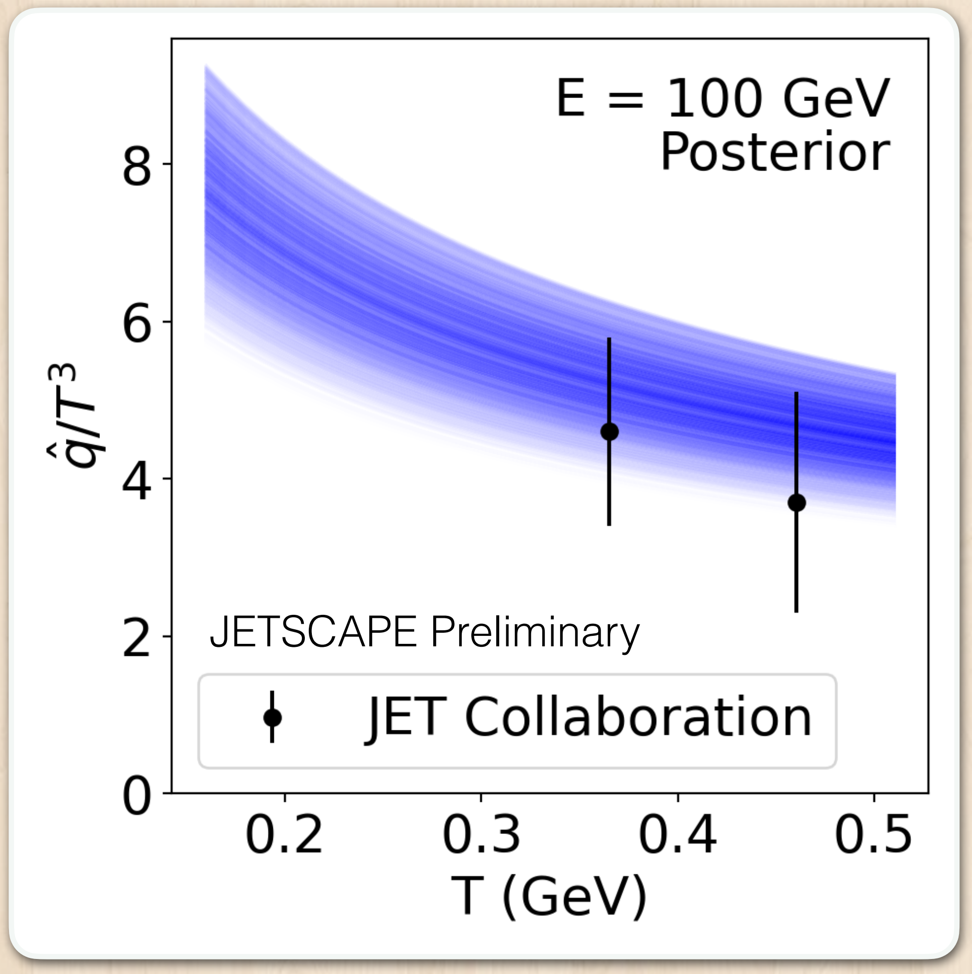
Important to include ALL eligible data

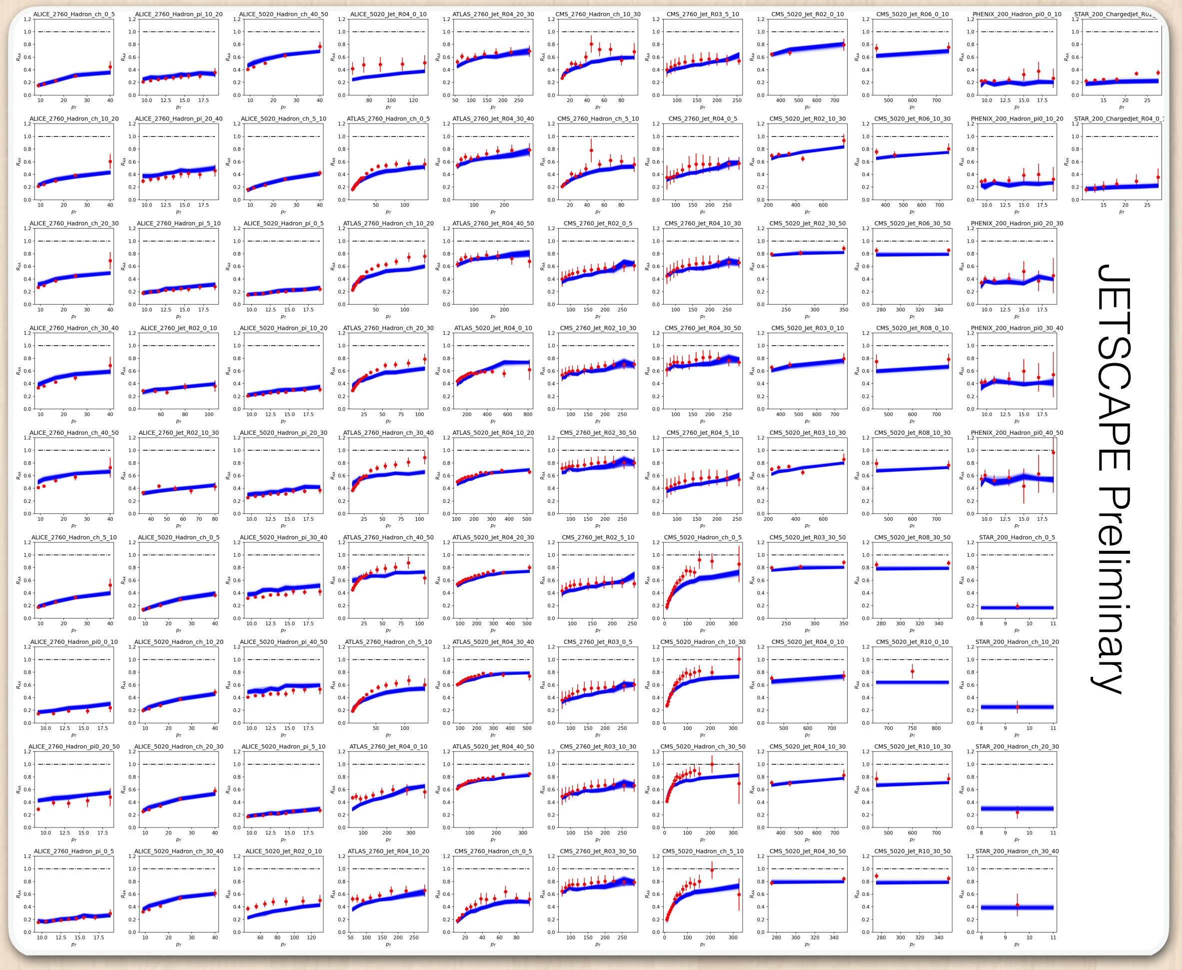
Ready to explore the theory / experimental landscape


E = 100 GeV
Posterior
JETSCAPE Preliminary
JET Collaboration
$\hat{q}/T^3$
T (GeV)
Jet
Hadron
Had. $p_T > 30$ GeV
Had. $p_T \leq 30$ GeV
T = 200 MeV
E = 100 GeV
Posterior
JETSCAPE
Preliminary
Area-normalized
$\alpha_{s,fix}$
Q_0
τ_0
$\ln c_1$
$\ln c_2$
JETSCAPE Preliminary
ATLAS, 2.76 TeV, Charged Hadron
0-5%
5-10%
JETSCAPE
Preliminary
R_{AA}
p_T (GeV)
E = 100 GeV
Posterior
JETSCAPE Preliminary
JET Collaboration
$\hat{q}/T^3$
T (GeV)

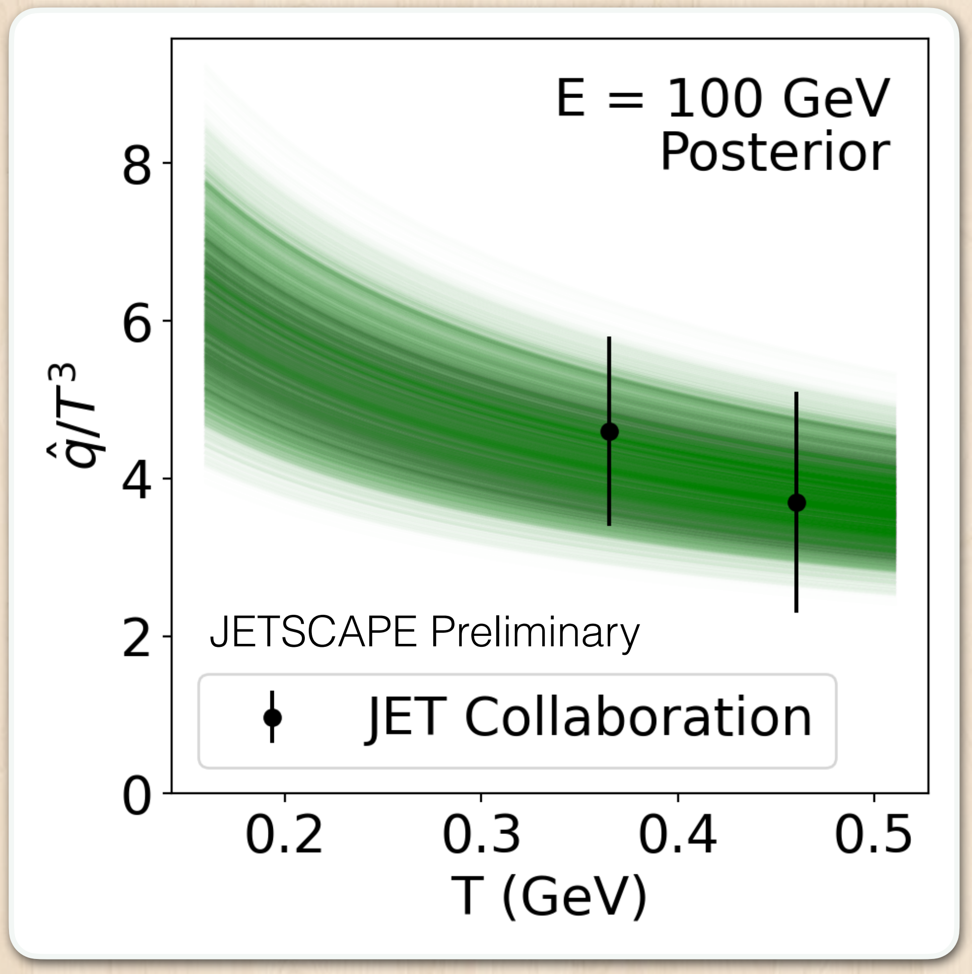
Backup Slides Ahead

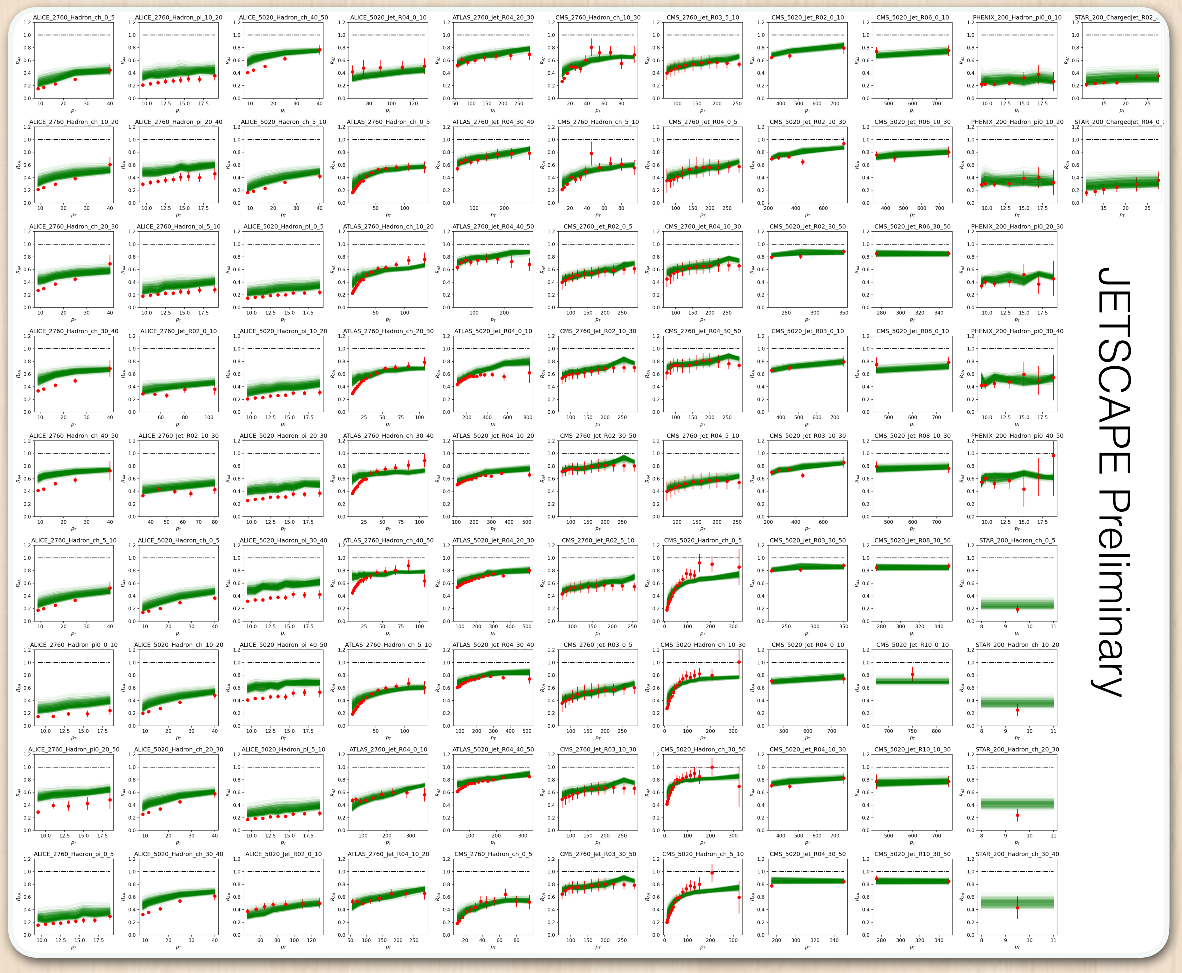
Nominal $\hat{q}$



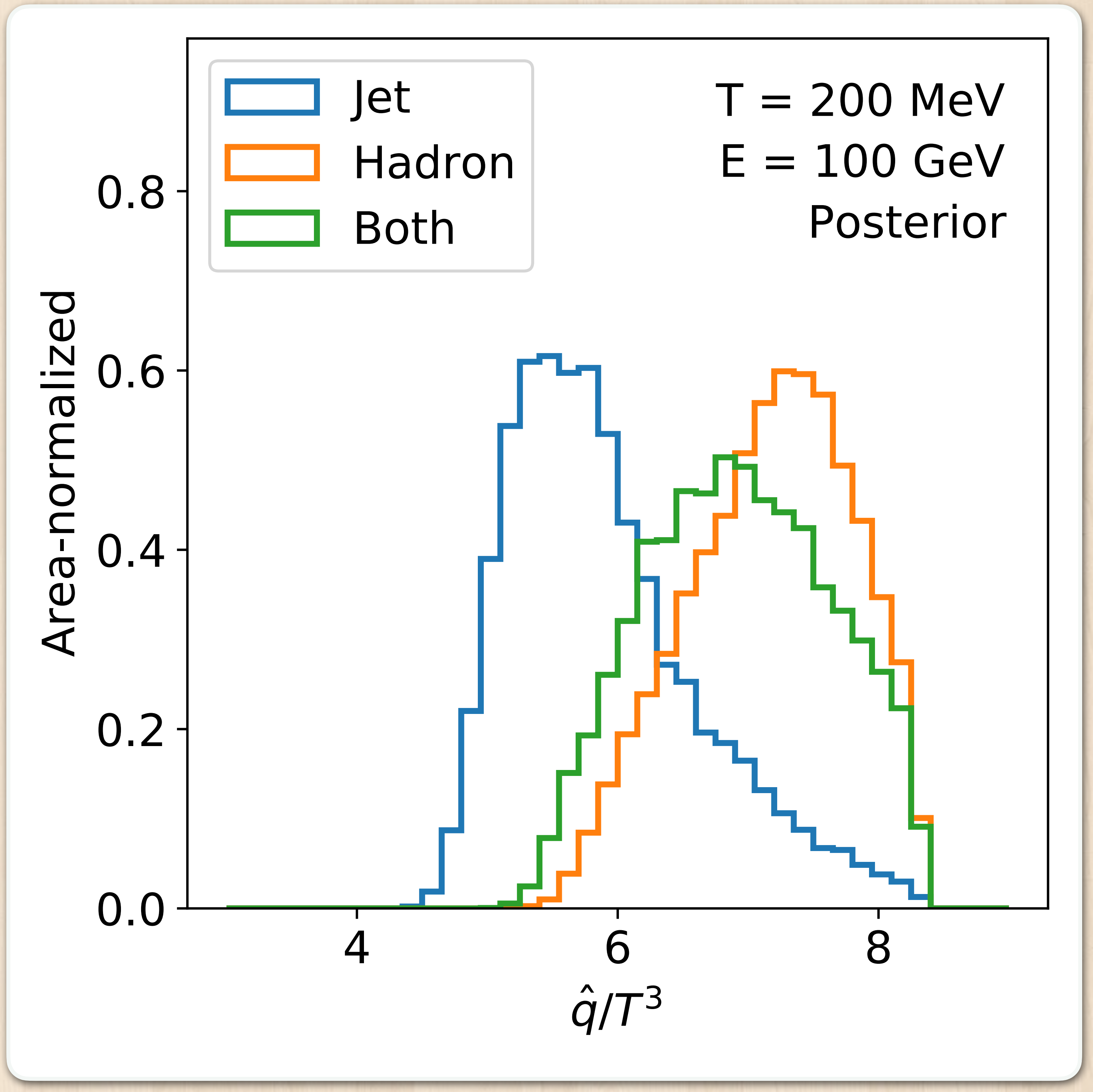


$\hat{q}$ with hadron $p_T > 30$ GeV

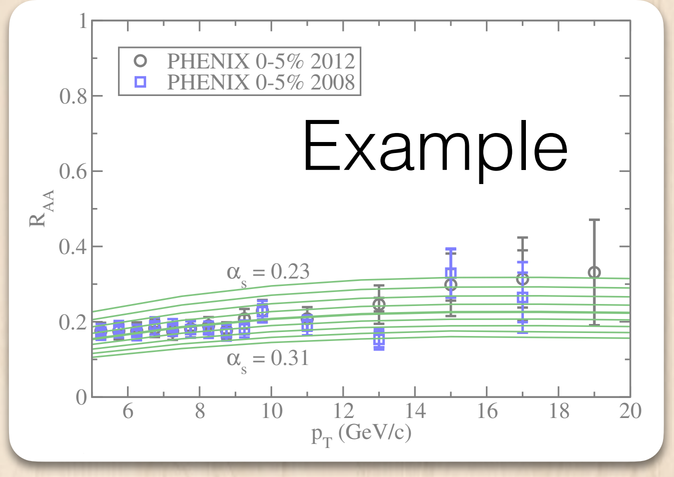




Jet vs hadron vs both

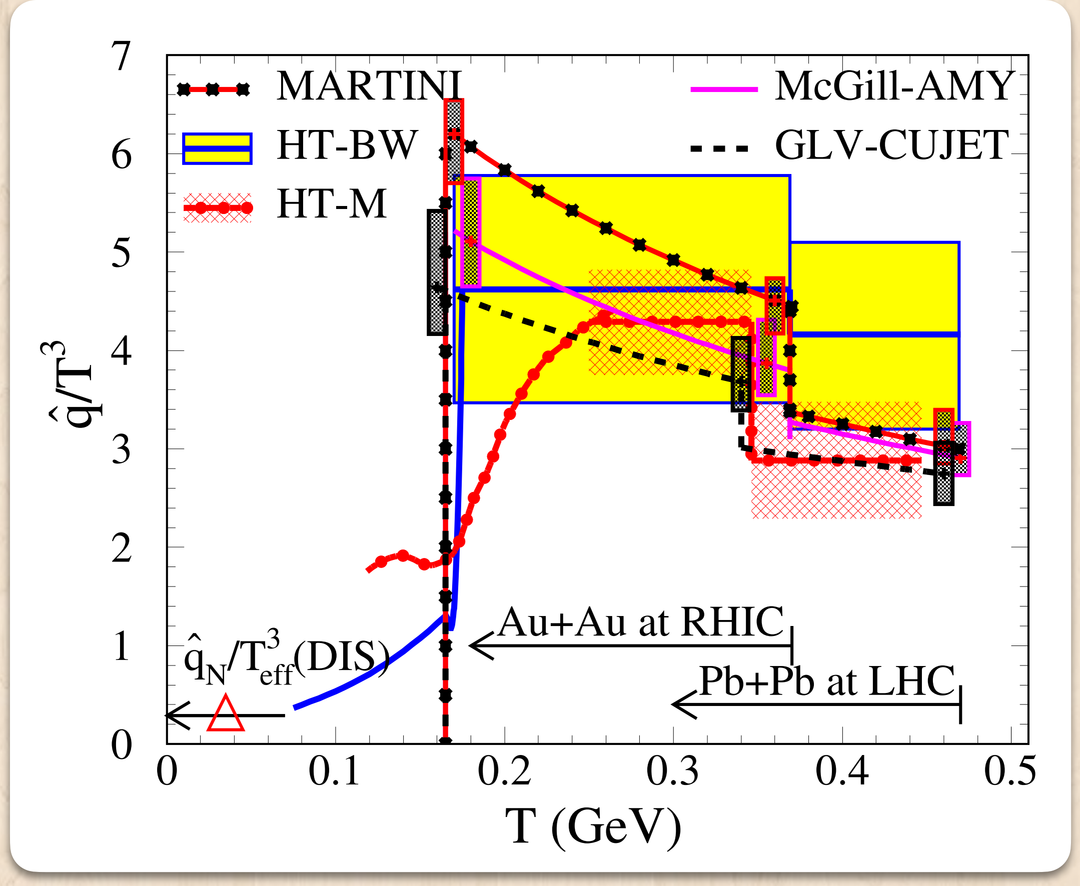


JET collaboration result



R_{AA} Data

Separate analyses to RHIC and LHC data from a variety of models



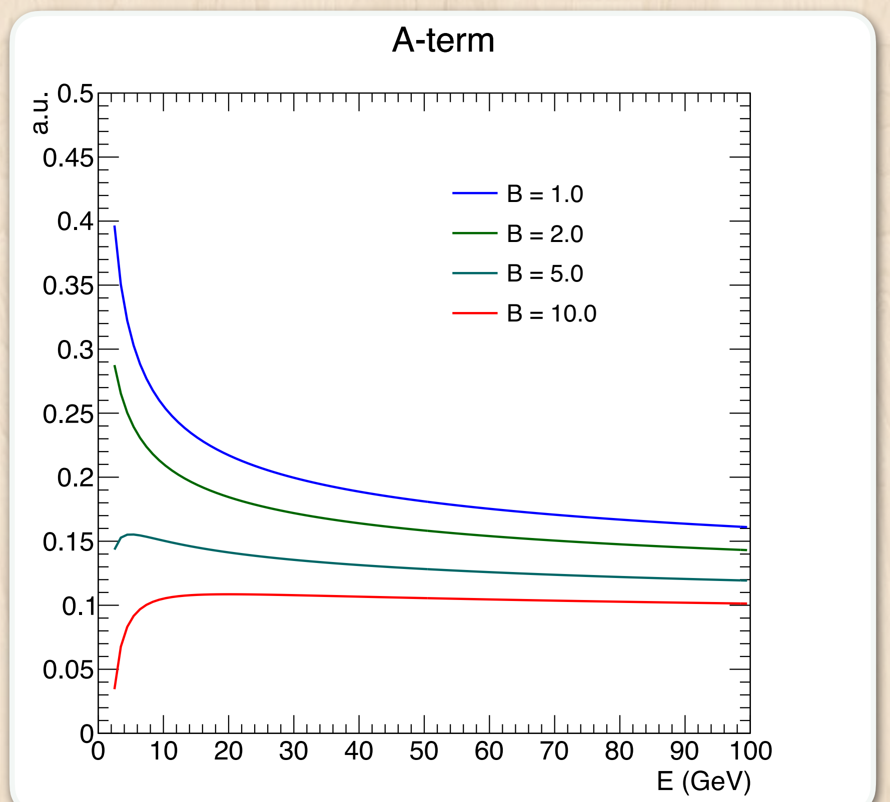
Taking it one step further

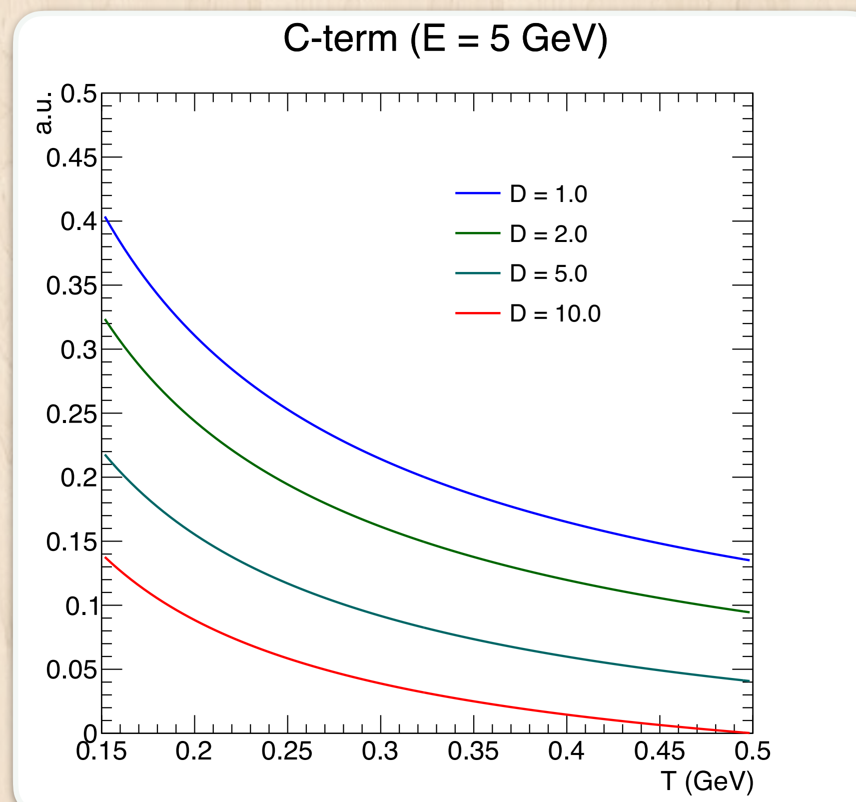
Previous iteration of $\hat{q}$

$$\frac{\hat{q}}{T^3} \propto A\frac{\ln(E/\Lambda) - \ln(B)}{\ln^2(E/\Lambda)} + C\frac{\ln(E/T) - \ln(D)}{\ln^2(ET/\Lambda^2)}$$

MATTER-inspired term

LBT-inspired term





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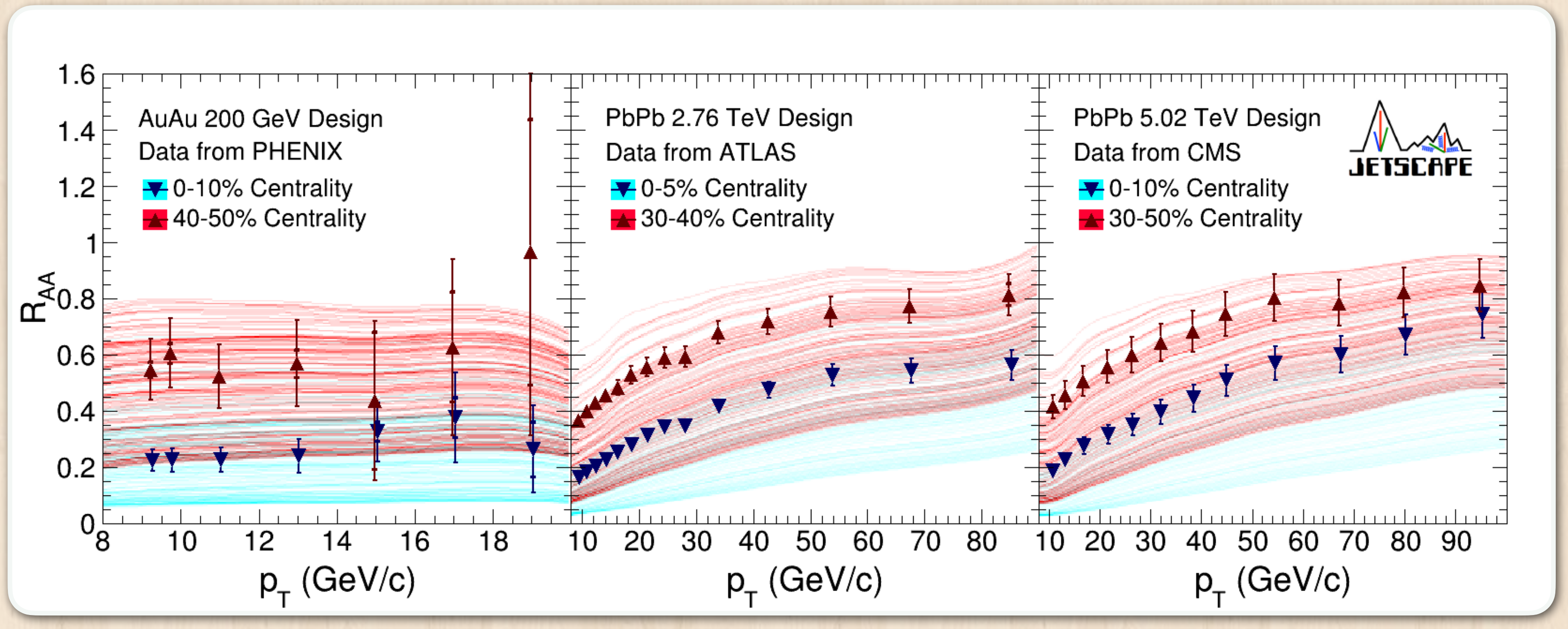
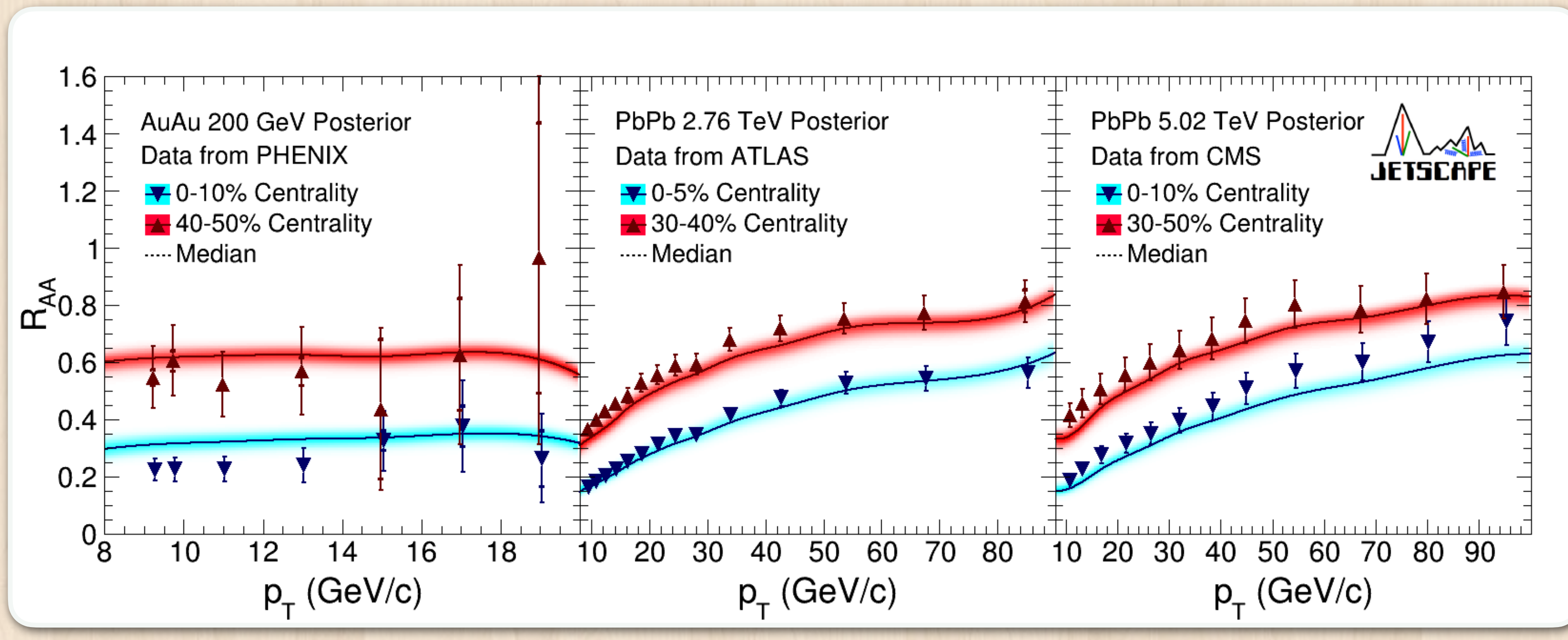
Previous iteration of $\hat{q}$

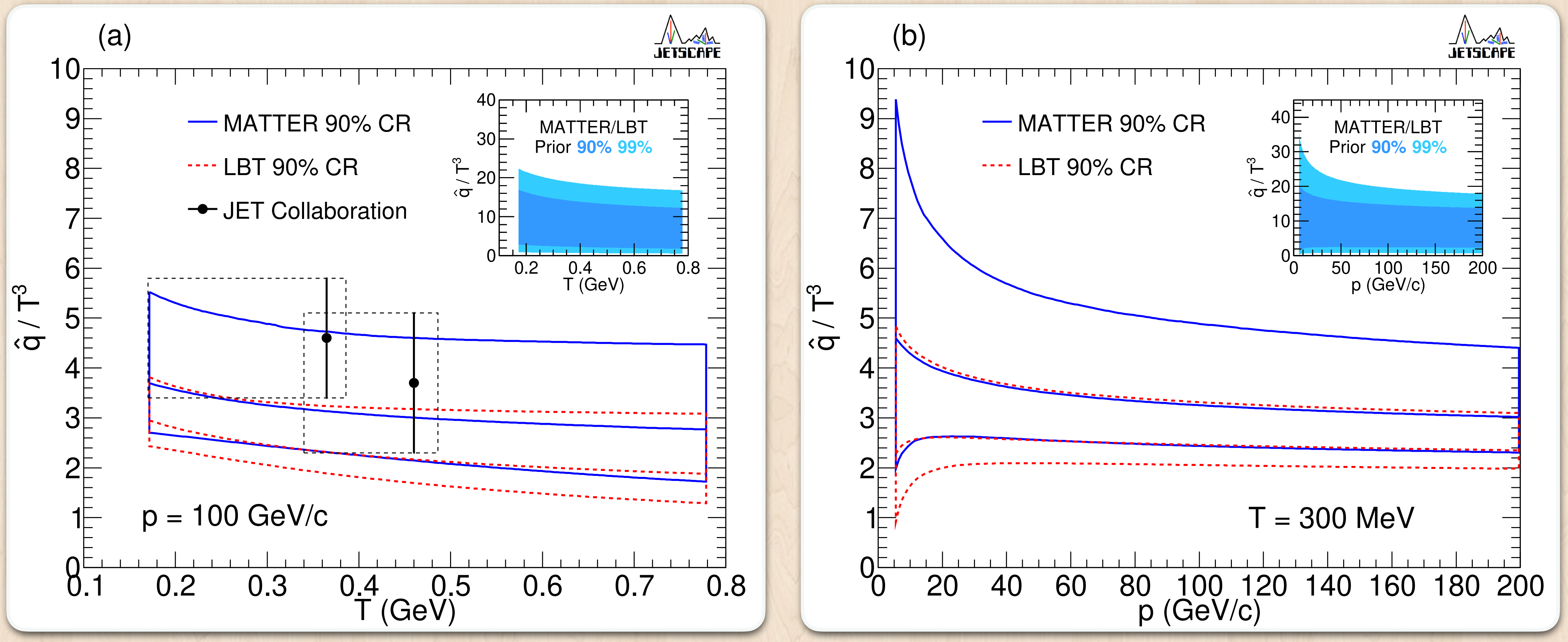


Before data is used

After using data



Previous iteration of $\hat{q}$



Compatible with JET collaboration results

Prior range » posterior range

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Effect of $f(Q^2)$

- Type-1: HTL $\hat{q}$ with fixed coupling (applies for any Q^2),

$$\hat{q} \equiv \hat{q}^{\rm fix}_{\rm HTL} = C_a \frac{50.484}{\pi} \alpha_{\rm s}^{\rm fix} \alpha_{\rm s}^{\rm fix} T^3 \ln\left[\frac{2ET}{m_{\rm D}^2}\right], \quad (24)$$

where $m_{\rm D}^2 = 6\pi T^2 \alpha_{\rm s}^{\rm fix}$ is the Debye mass for $N_f = 3$ flavors.

- Type-2: HTL $\hat{q}$ with running coupling (applies for any Q^2),

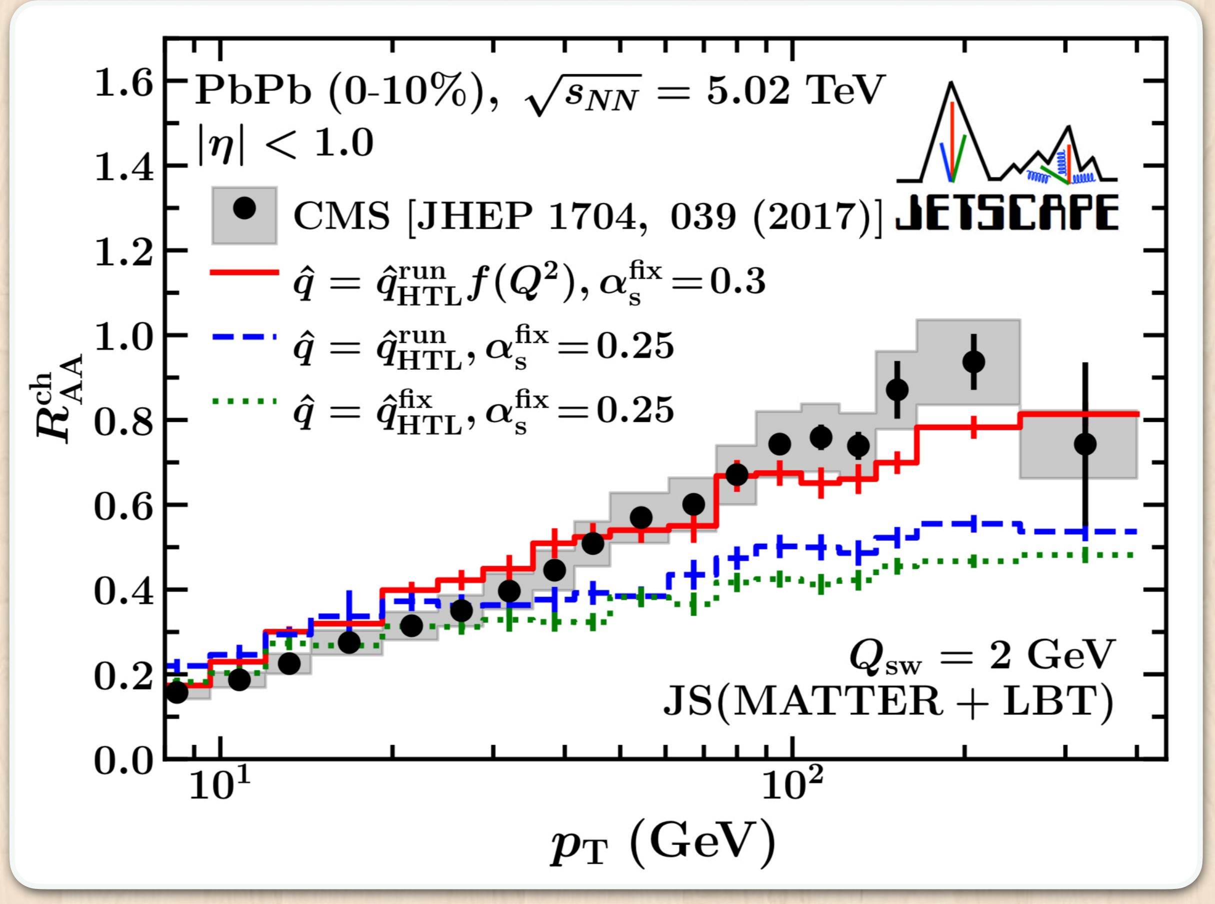
$$\hat{q} \equiv \hat{q}^{\rm run}_{\rm HTL} = C_a \frac{50.484}{\pi} \alpha_{\rm s}^{\rm run}(Q^2_{\rm max}) \alpha_{\rm s}^{\rm fix} T^3 \ln\left[\frac{2ET}{m_{\rm D}^2}\right], \quad (25)$$

where $Q^2_{\rm max} = 2ET$

- Type-3: HTL $\hat{q}$ with a virtuality (Q^2) dependence factor

$$\hat{q} \cdot f \equiv \hat{q}^{\rm run}_{\rm HTL} f(Q^2) \quad (26)$$

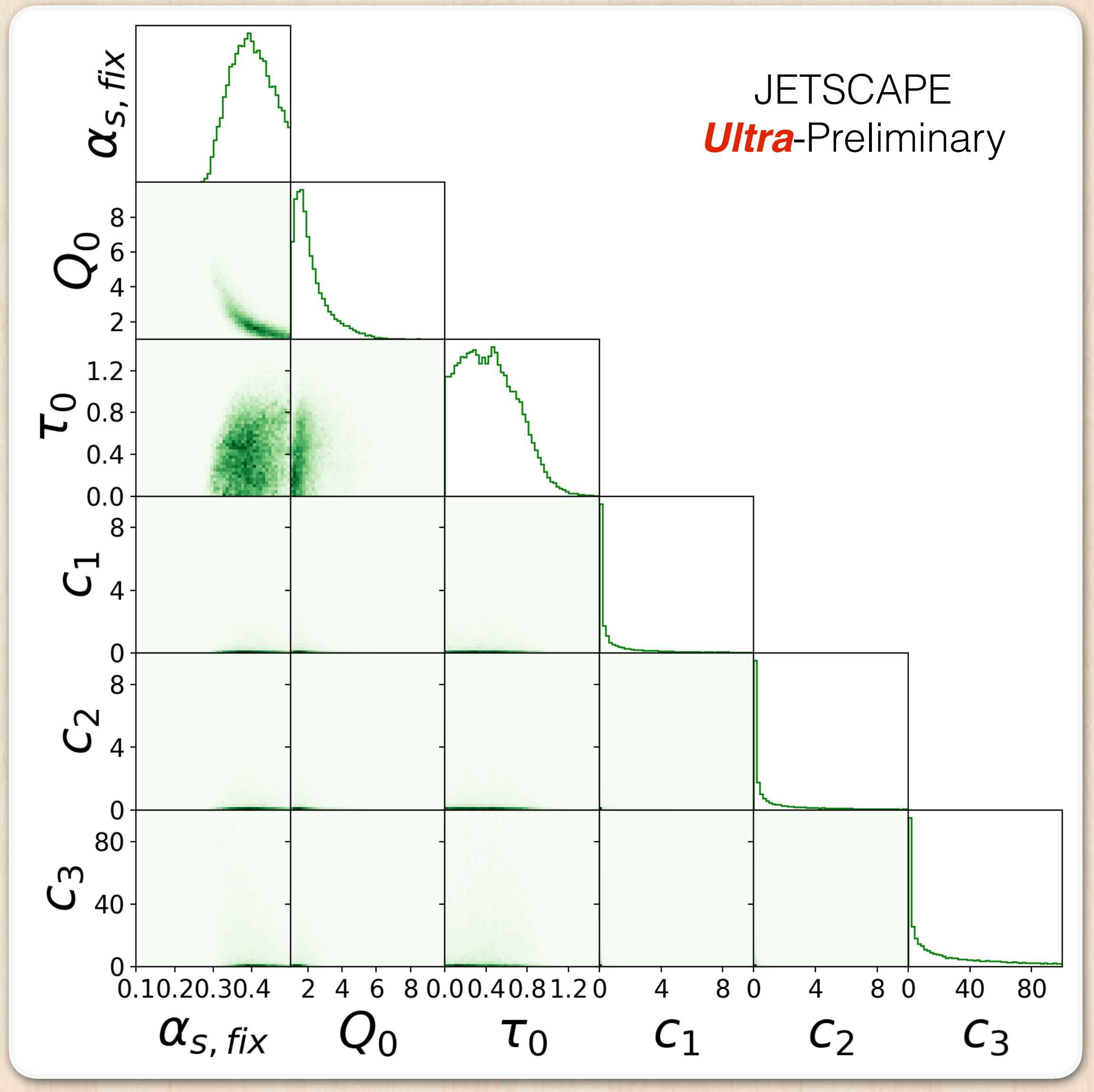
$$f(Q^2) = \begin{cases} \frac{1+10\ln^2(Q^2_{\rm sw})+100\ln^4(Q^2_{\rm sw})}{1+10\ln^2(Q^2)+100\ln^4(Q^2)} & Q^2 > Q^2_{\rm sw} \\ 1 & Q^2 \le Q^2_{\rm sw} \end{cases}, \quad (27)$$

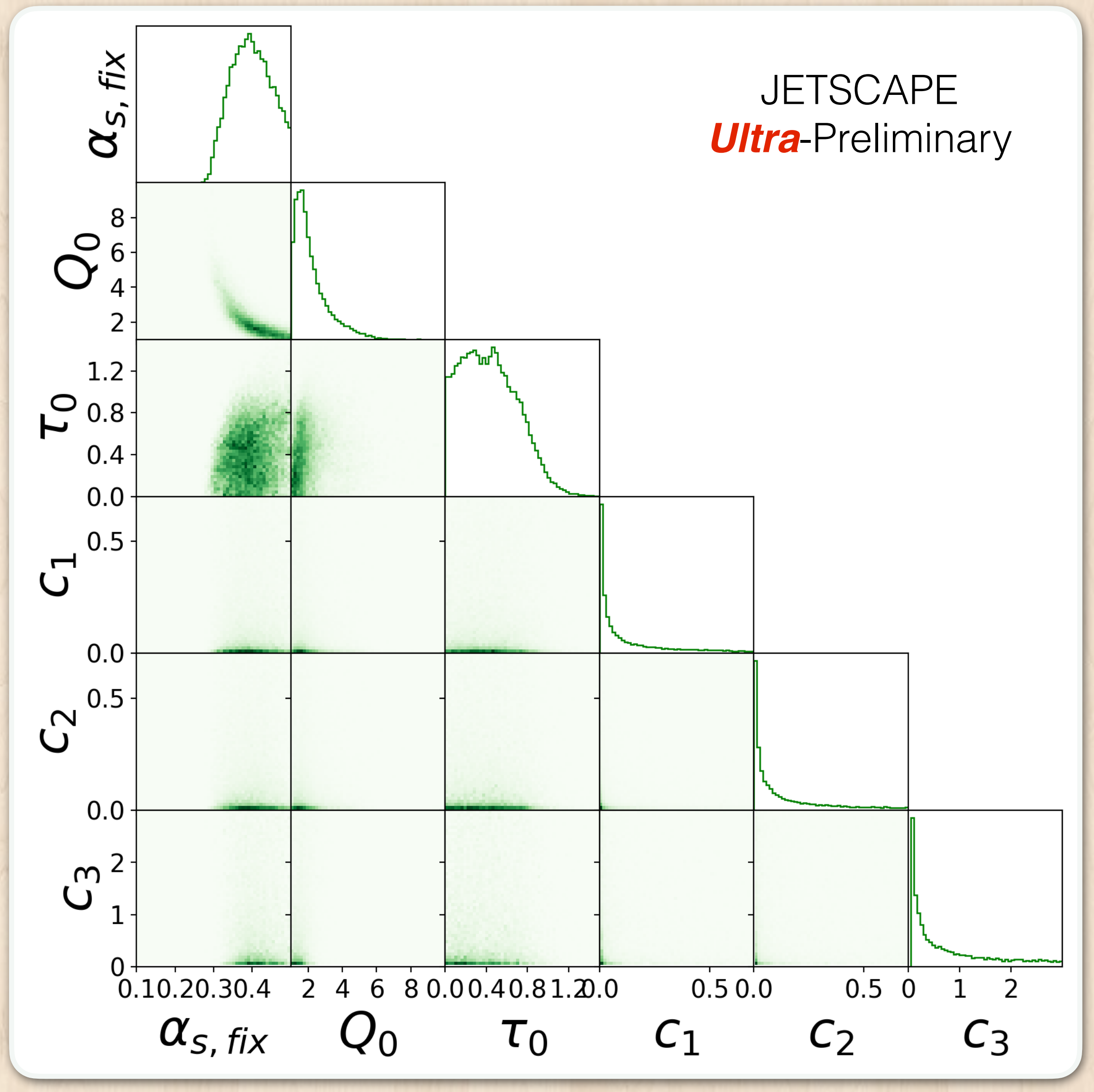


Type-2 → Type-3

Reduction of $\hat{q}_{eff}$ when Q^2 is large

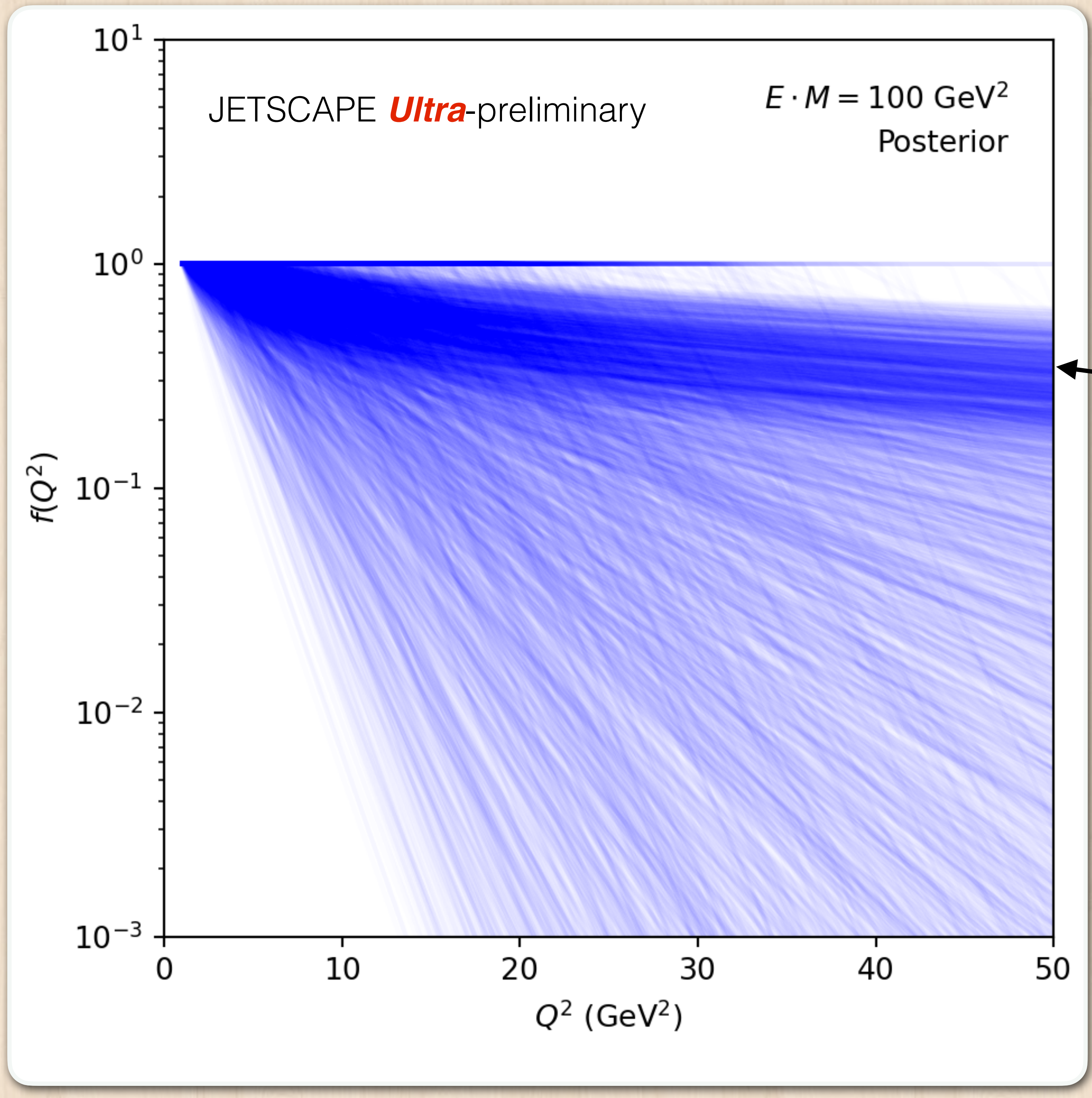
Linear scale





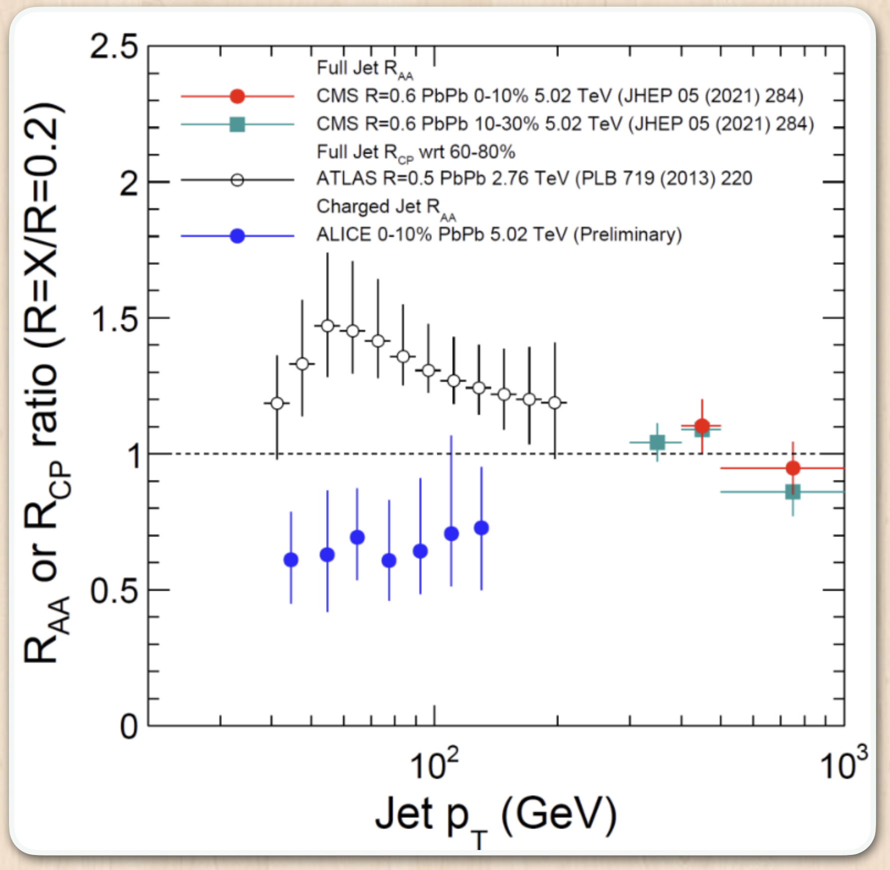
Zoom in $c_{1,2,3}$

$f(Q^2)$



Relatively shallow $f(Q^2)$

Under scrutiny!
still very preliminary


Full Jet R_AA
CMS R=0.6 PbPb 0-10% 5.02 TeV (JHEP 05 (2021) 284)
CMS R=0.6 PbPb 10-30% 5.02 TeV (JHEP 05 (2021) 284)
Full Jet R_CP wrt 60-80%
ATLAS R=0.5 PbPb 2.76 TeV (PLB 719 (2013) 220
Charged Jet R_AA
ALICE 0-10% PbPb 5.02 TeV (Preliminary)
R_AA or R_CP ratio (R=X/R=0.2)
Jet p_T (GeV)
2.5
2
1.5
1
0.5
0
10^2
10^3