Jet Quenching Theory

Abhijit Majumder

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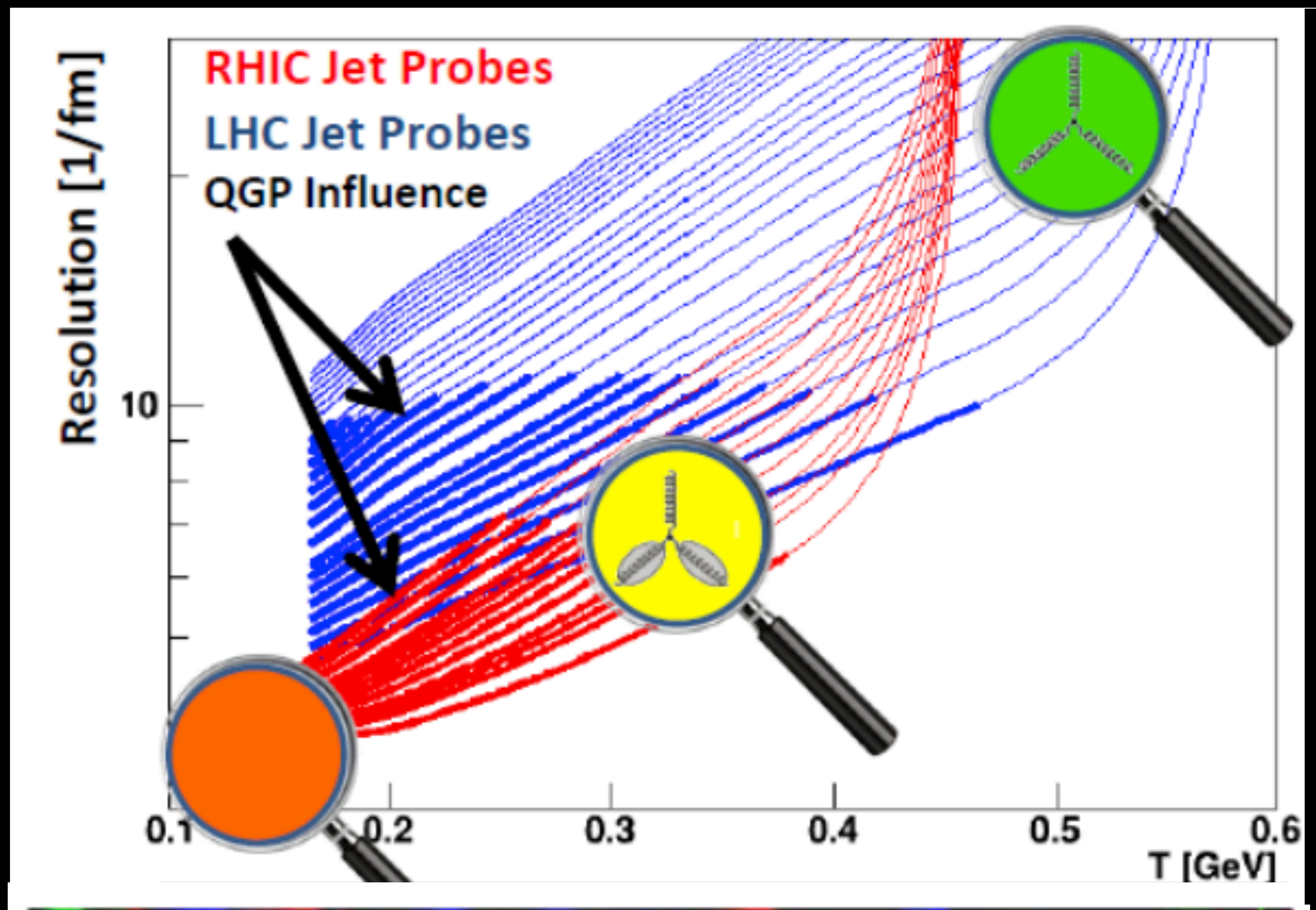
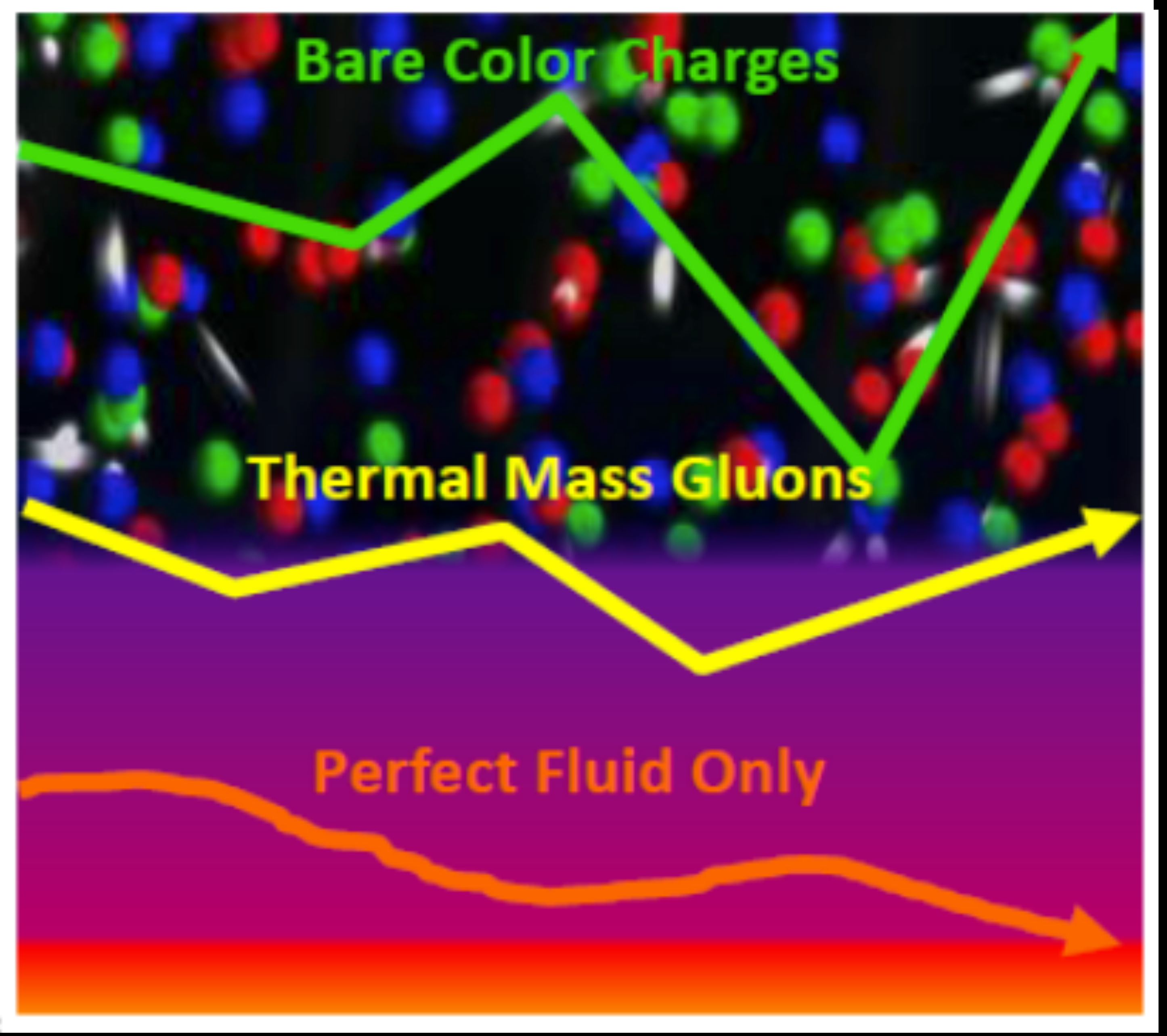


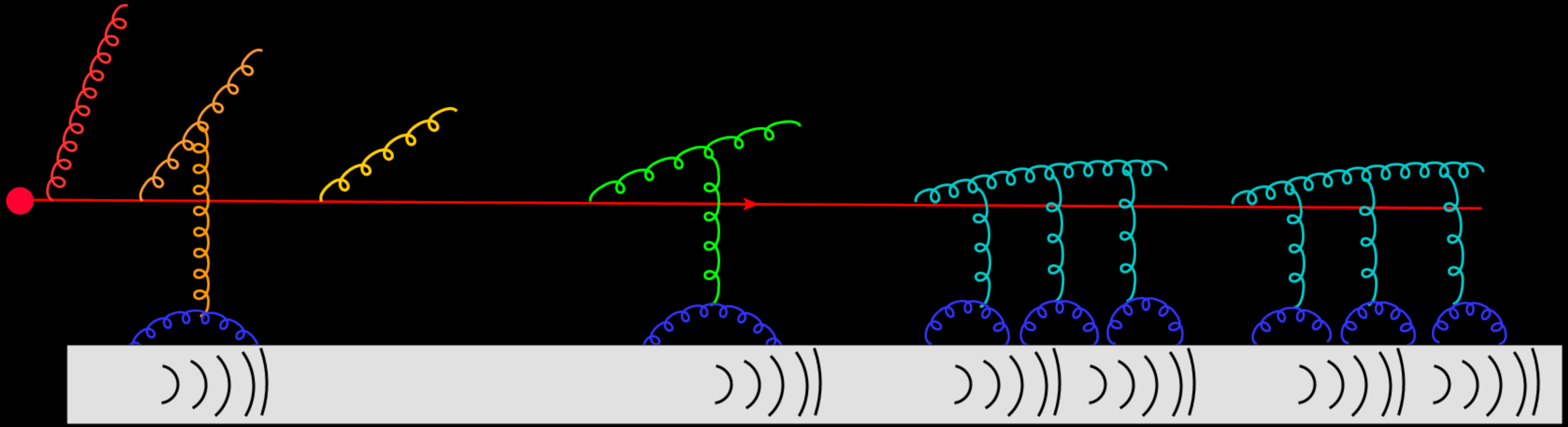


Where are we now with the big picture?

- In the last decade a consensus on basic picture
    - P. Caucal, E. Iancu, A. H. Mueller, Soyez, Phys. Rev. Lett. 120 (2018) 232001.
    - N. Armesto, H. Ma, Y. Mehtar-Tani, C. A. Salgado, JHEP 01, 109.
    - J. Casalderrey-Solana and E. Iancu, JHEP 08, 015.
    - A. Kumar, A. Majumder, and C. Shen, Phys. Rev. C101, 034908 (2020)
    - J. Casalderrey-Solana, D. Can Gulhan, J. Guilherme Milhano, D. Pablos, K. Rajagopal, JHEP 10 (2014) 019.
- A rise of elaborate MC-generators:
    - LBT, MARTINI, MATTER, CUJET, Hybrid, JEWEL
    - Most have a considerable amount of medium response.

Basic Picture: extra scales in energy loss

- Jet starts in a hard scattering with a virtuality $Q^2 \lesssim E^2$
- First few emissions are vacuum like with rare scattering/emission
- Virtuality comes down to $Q^2_{med} \simeq \sqrt{2E\hat{q}}$ transition to many scattering/emission

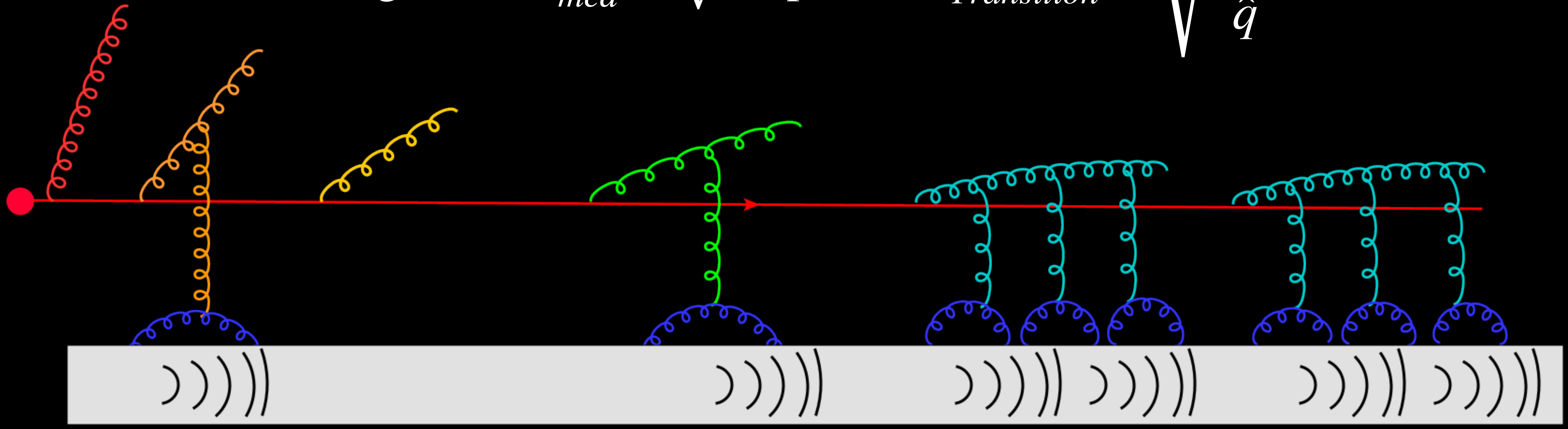


- Exchanges with medium lead to excitations/medium response

Basic Picture: extra scales in energy loss

$$Q^2_{\rm med} \simeq \hat{q}\tau \text{ and } \tau = \frac{2E}{Q^2}. \text{ Substitute } Q = Q_{\rm med}$$

$$\text{This gives } Q^2_{med} \simeq \sqrt{2E\hat{q}} \text{ and } \tau_{Transition} \simeq \sqrt{\frac{2E}{\hat{q}}}$$



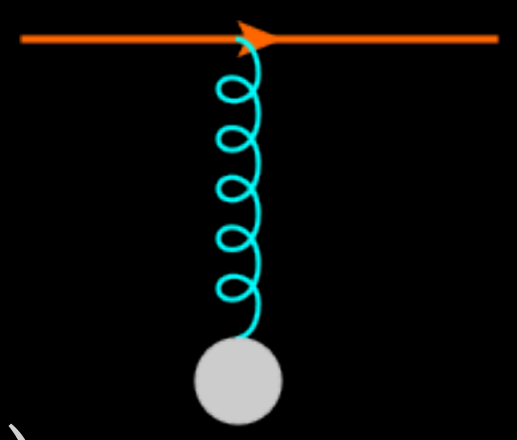
Physics: DGLAP like
Simulator: MATTER

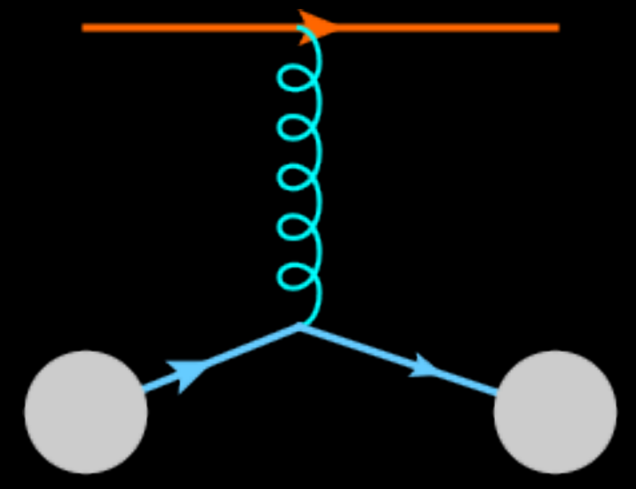
Physics: BDMPS/AMY like
Simulator: MARTINI, LBT

Multi-scale structure in the medium

- Hard exchanges $k_\perp \gg \Lambda_{QCD}$ will resolve partons in the QGP

$$\int_0^\infty d^3k = \int_0^\mu d^3k + \int_\mu^\infty d^3k$$



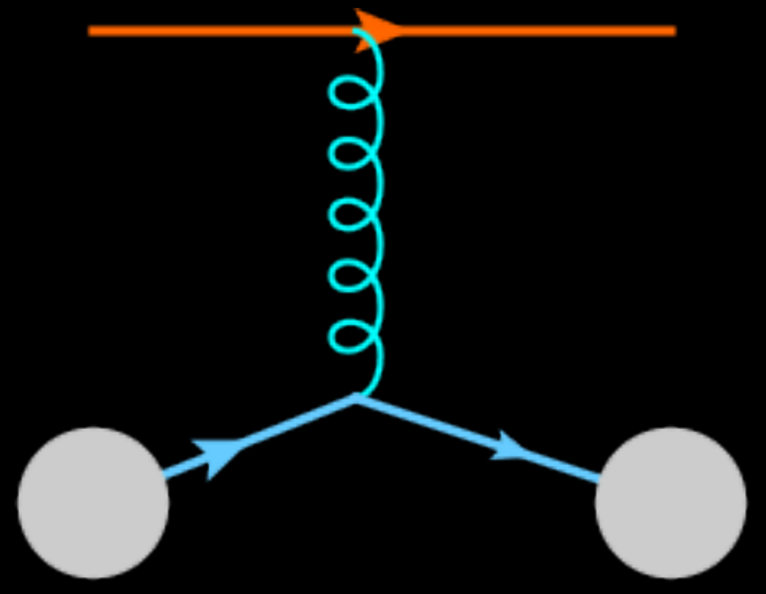


- Incoming "resolved partons" can be modeled with
  - HTL perturbation theory
  - or using QGP PDF (A. Kumar et al., PRC 101 (2020) 034908)
  - Or Both (MATTER + LBT)

- Soft exchanges by generic **broadening** (Lido, Tequila, also do hard exchanges with HTL)
- Or use strong coupling (AdS/CFT) e.g., Hybrid model

- Outgoing "resolved partons" can be modeled with
  - HTL perturbation theory
  - Or turned into energy momentum source term (liquify)

Structure of the interaction



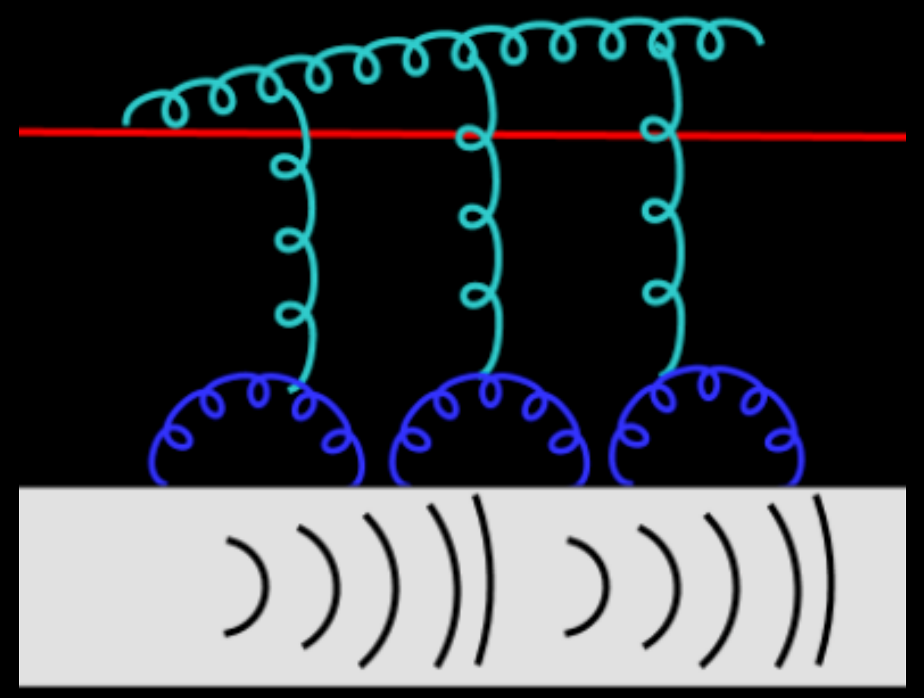
- Start with low virtuality part: $\mu^2 = \sqrt{2\hat{q}E}$

- Use Debye screened potential

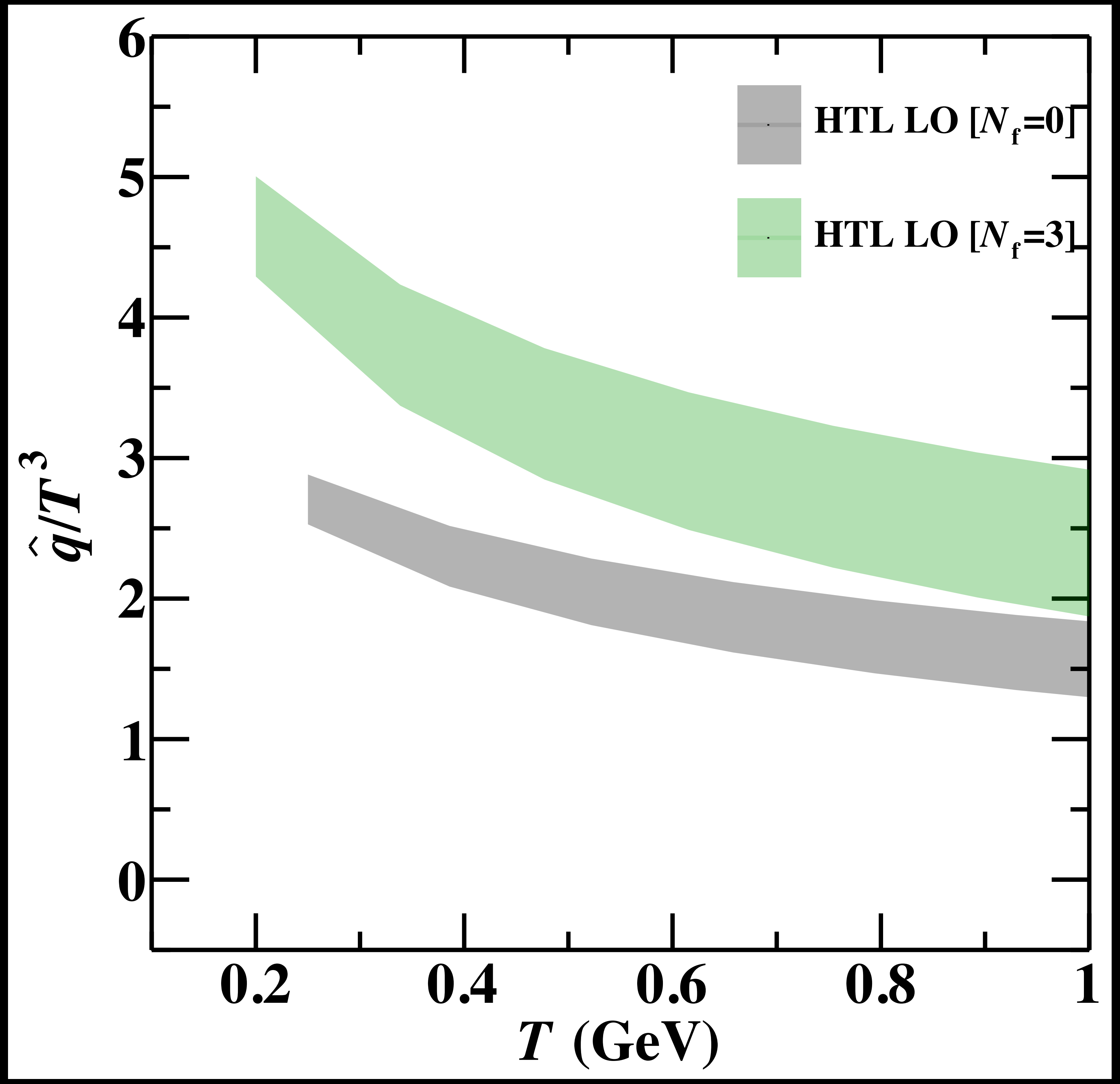
$$C(k_\perp) = \frac{C_R}{(2\pi)^2} \frac{g^2 T m_D^2}{k_\perp^2 (k_\perp^2 + m_D^2)}$$

- Running coupling gives,

$$\hat{q} = C\alpha_s(\{1..6\}ET)\alpha_s(m_D)T^3 \log\left(\frac{6ET}{m_D^2}\right)$$



- Struck partons go into medium, and excite medium. Some get clustered into jets, need to keep track of deposited energy

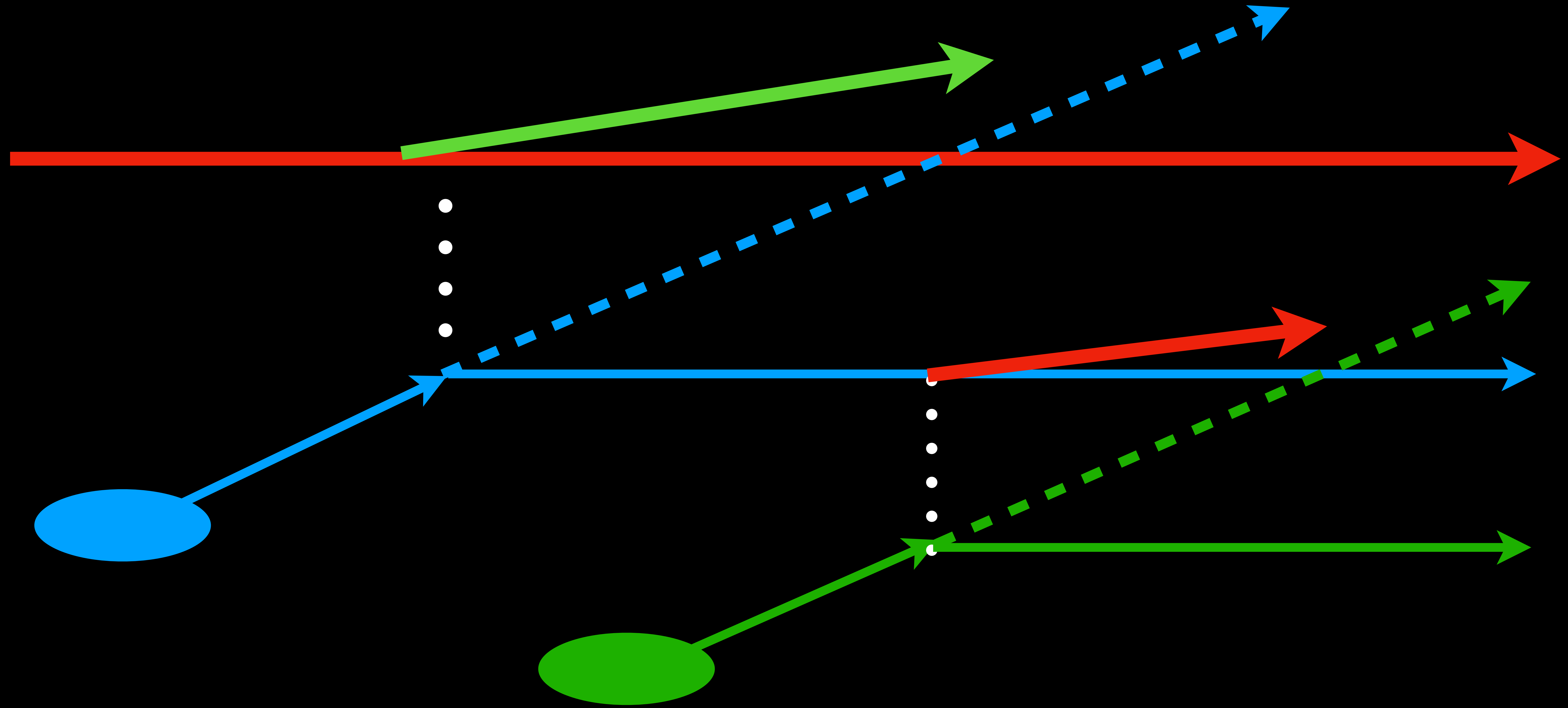


Arnold and Xiao: arXiv: 0810.1026 [hep-ph]

How this is done currently

In LBT, MARTINI, JEWEL, MATTER

Full jet carries recoil particles sampled from a Boltzmann distribution. as regular jet partons, and negative partons or holes



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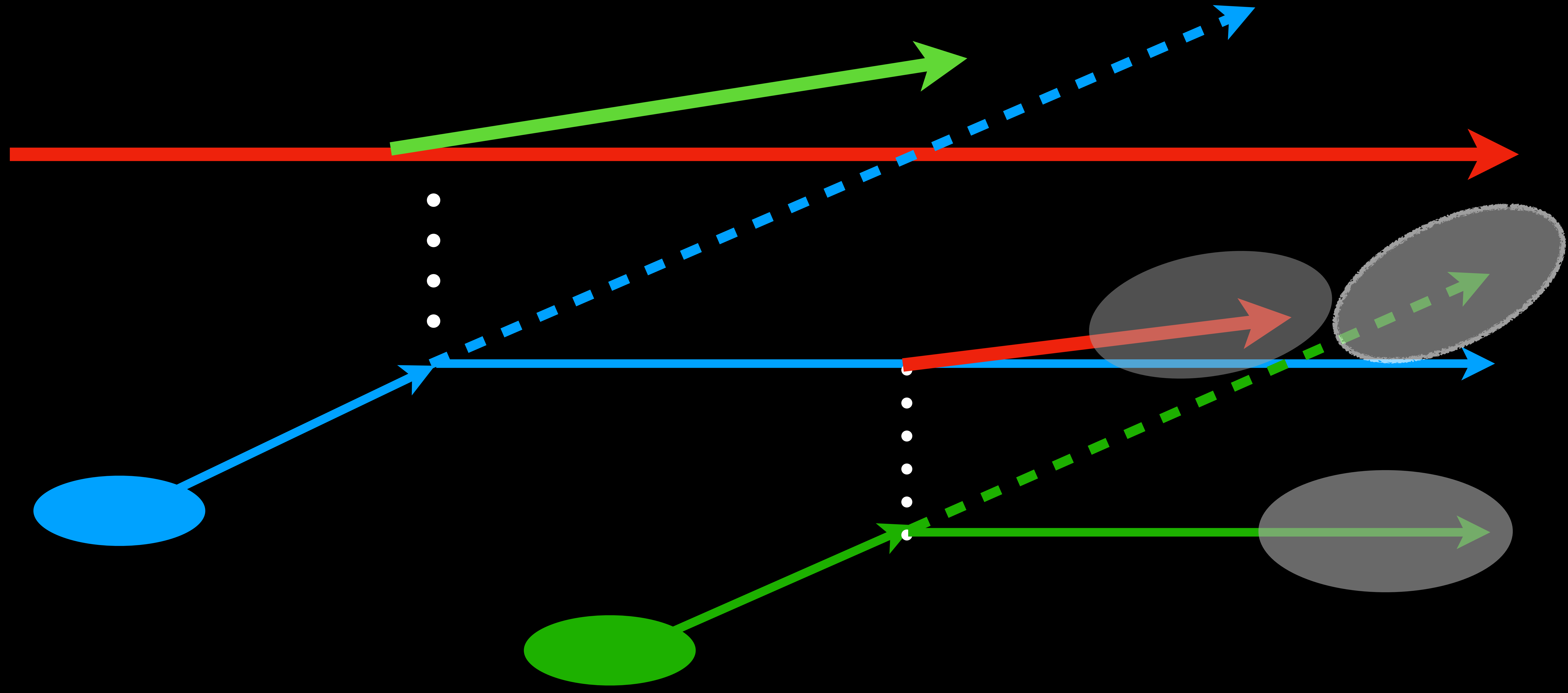
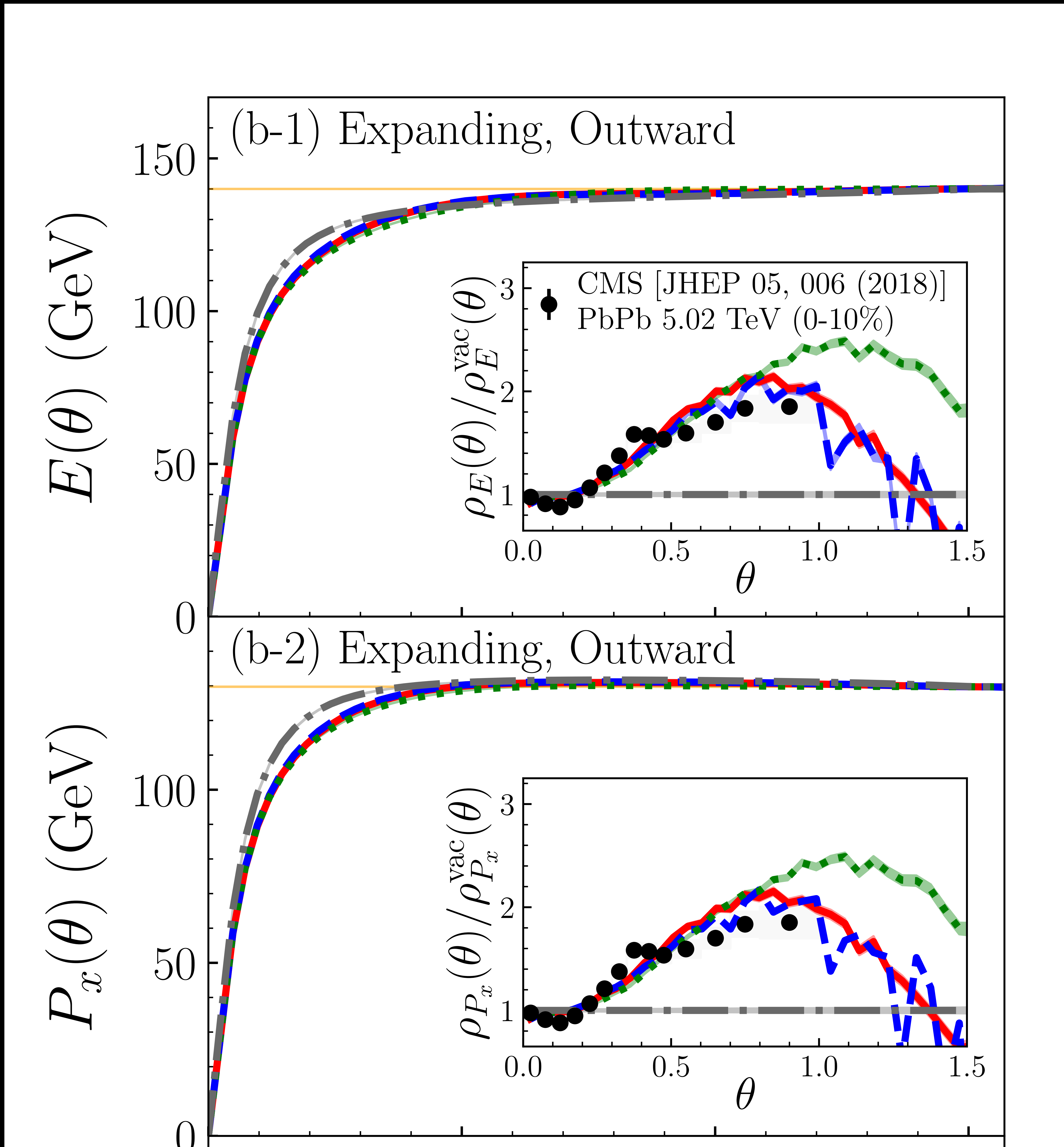


Additionally: Soft partons can be "liquified" into source terms for a subsequent hydro simulation

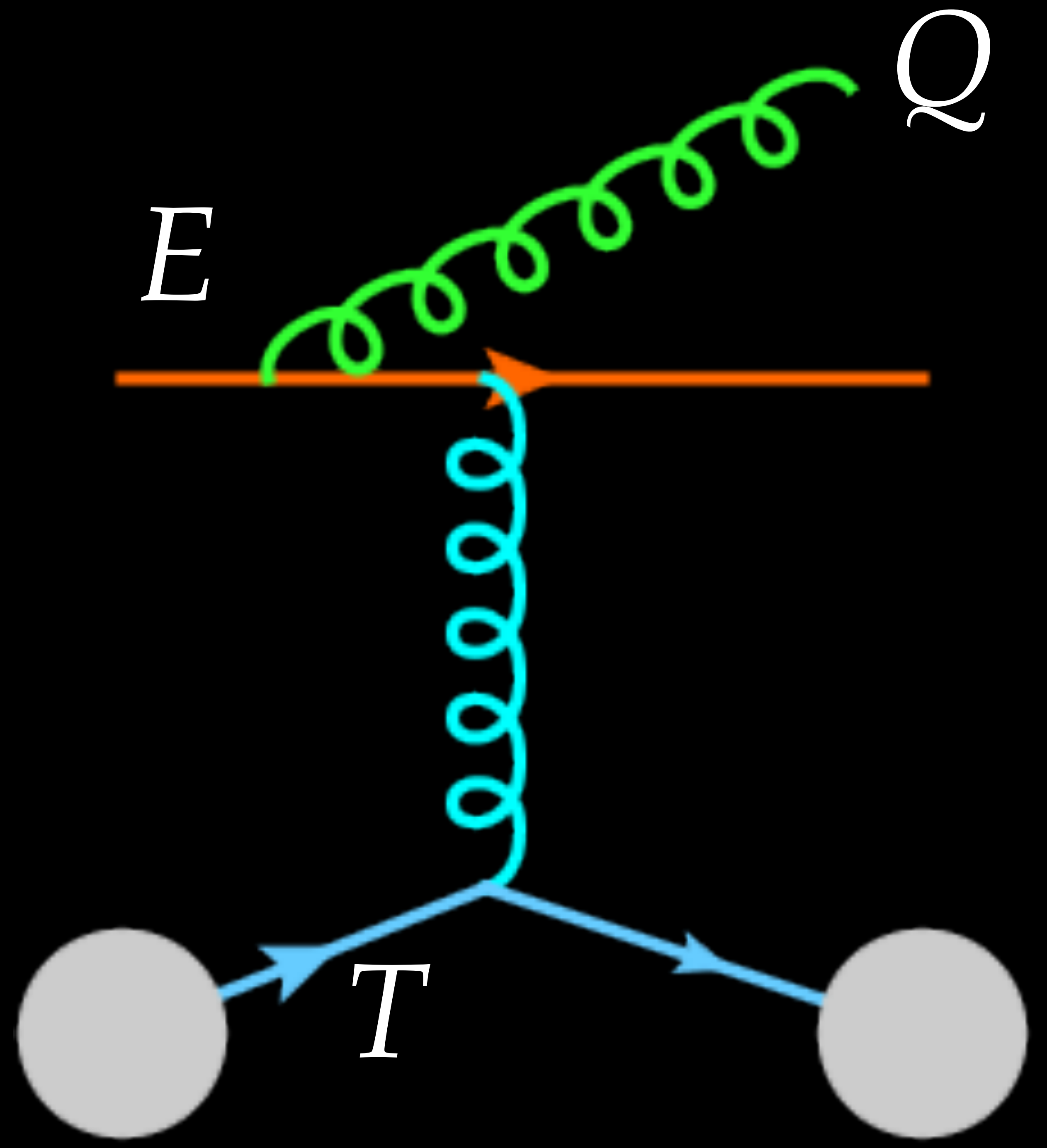
Does not seem to make much difference inside jet cone

- Simulation (JETSCAPE 0.x) includes:
  - One run of smooth hydro
  - One jet from center outward (left)
  - One jet from out inward (right)
  - Jet simulated for ~10fm/c: MATTER+LBT
  - Jet constructed with partons (weak)
  - Soft partons liquified
  - Source terms developed
  - Hydro re-run
  - Jet reconstructed with hard partons and unit cell momenta (strong)
  - Unit cell particlized (Cooper-Frye), jet reclustered (Strong particlized)

Y. Tachibana, A. M., C. Shen Phys.Rev.C 106 (2022) L021902



What else can $\hat{q}$ or $\Gamma = \int d^3k C(k)$ depend upon?



- 2 - 2 scattering depends on *s, t, u*
- In general, will depend on *T, E, Q*
- Thermal recoil requires: $\hat{q} = C\alpha_s(2ET)\alpha_s(m_D)T^3 \log\left(\frac{2ET}{m_D^2}\right)$
- $T_{LHC} \sim 1.25\, T_{RHIC}$
- $E_{LHC} \gtrsim 10 E_{RHIC}$
- $Q_{LHC} \gtrsim 10 Q_{RHIC}$

Virtuality dependence/Coherence

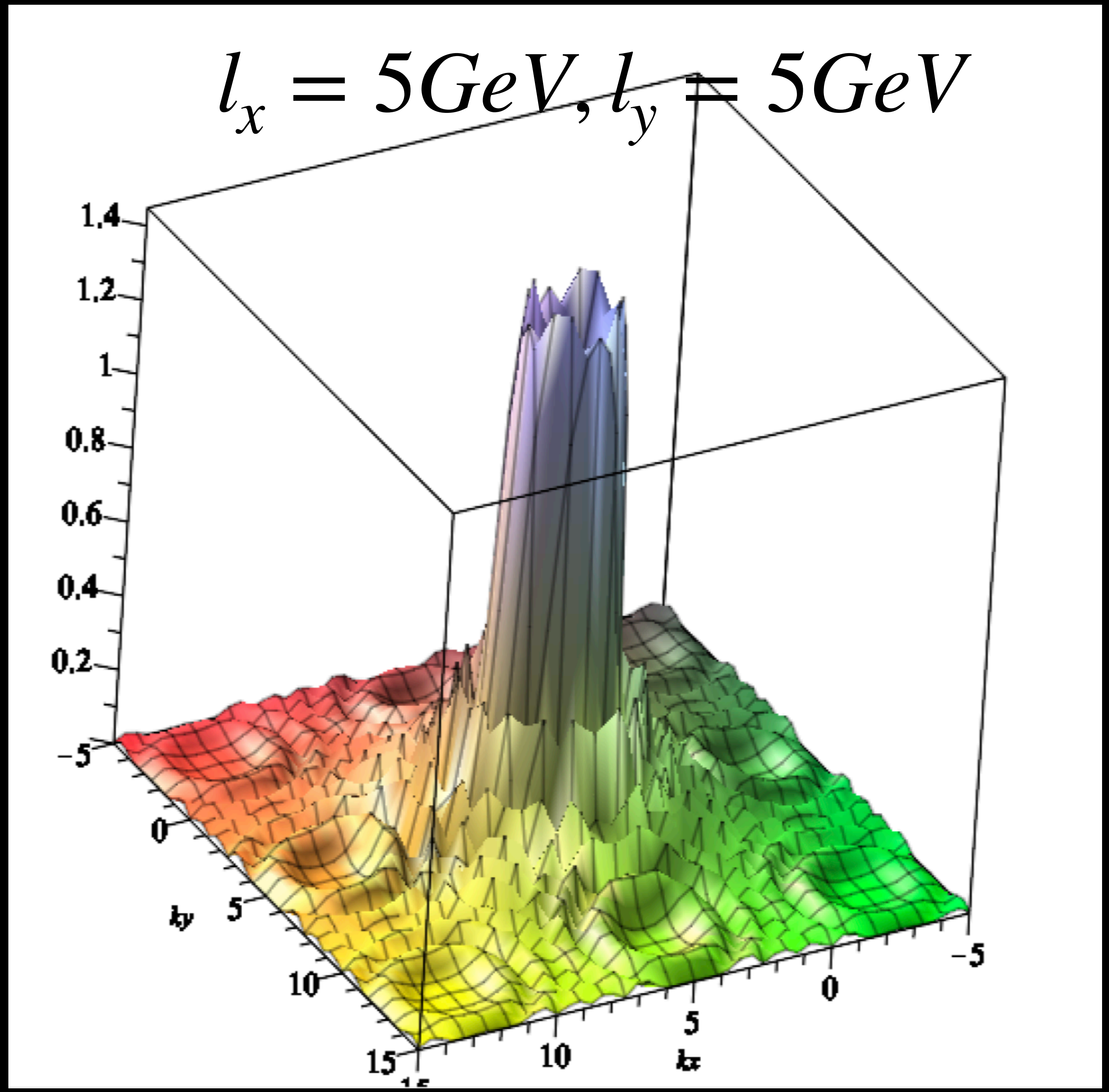
- Coherence arguments: $\hat{q}(Q^2 > \sqrt{2\hat{q}E}) \to 0$

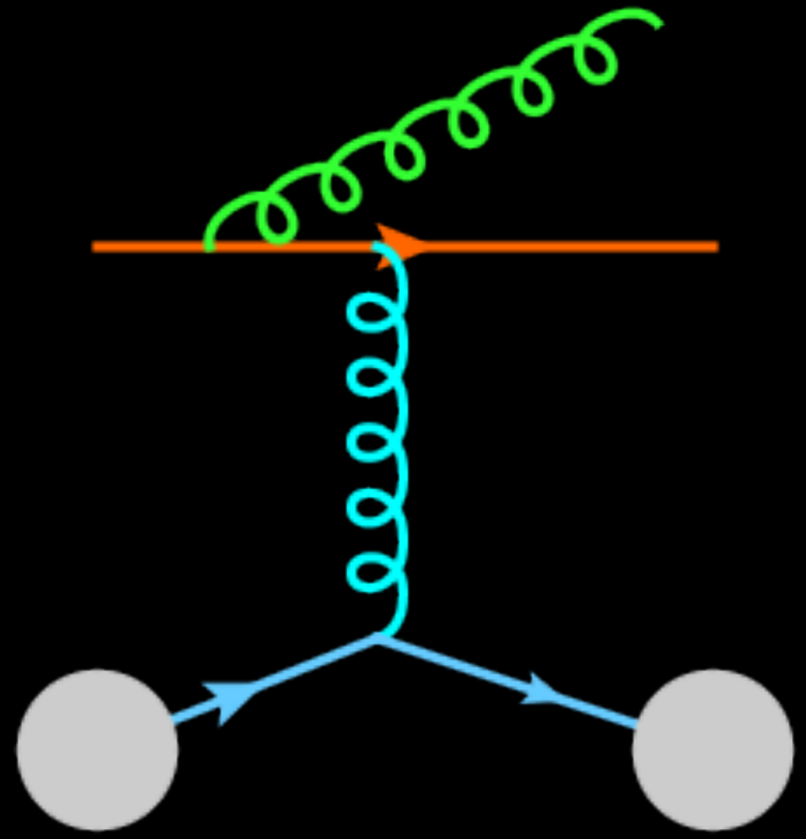
- Can be calculated directly in the Higher Twist formalism.

$$\frac{dN_g}{dyd^2l_\perp} = \frac{\alpha_s}{2\pi}P(y)\int\frac{d^2k_\perp}{(2\pi)^2}\int d\zeta^-\left[\frac{2-2\cos\left(\frac{(l_\perp-k_\perp)^2\zeta^-}{2q^-y(1-y)}\right)}{(l_\perp-k_\perp)^2}\right]$$

- $$\times\int d(\delta\zeta^-)d^2\zeta_\perp e^{-i\frac{\vec{k}_\perp^2}{2q^-}\delta\zeta^- + i\vec{k}_\perp.\vec{\zeta}_\perp}$$

$$\times\langle P|A^{a+}\left(\zeta^-+\frac{\delta\zeta^-}{2}\right)A^{a+}\left(\zeta^--\frac{\delta\zeta^-}{2}\right)|P\rangle$$





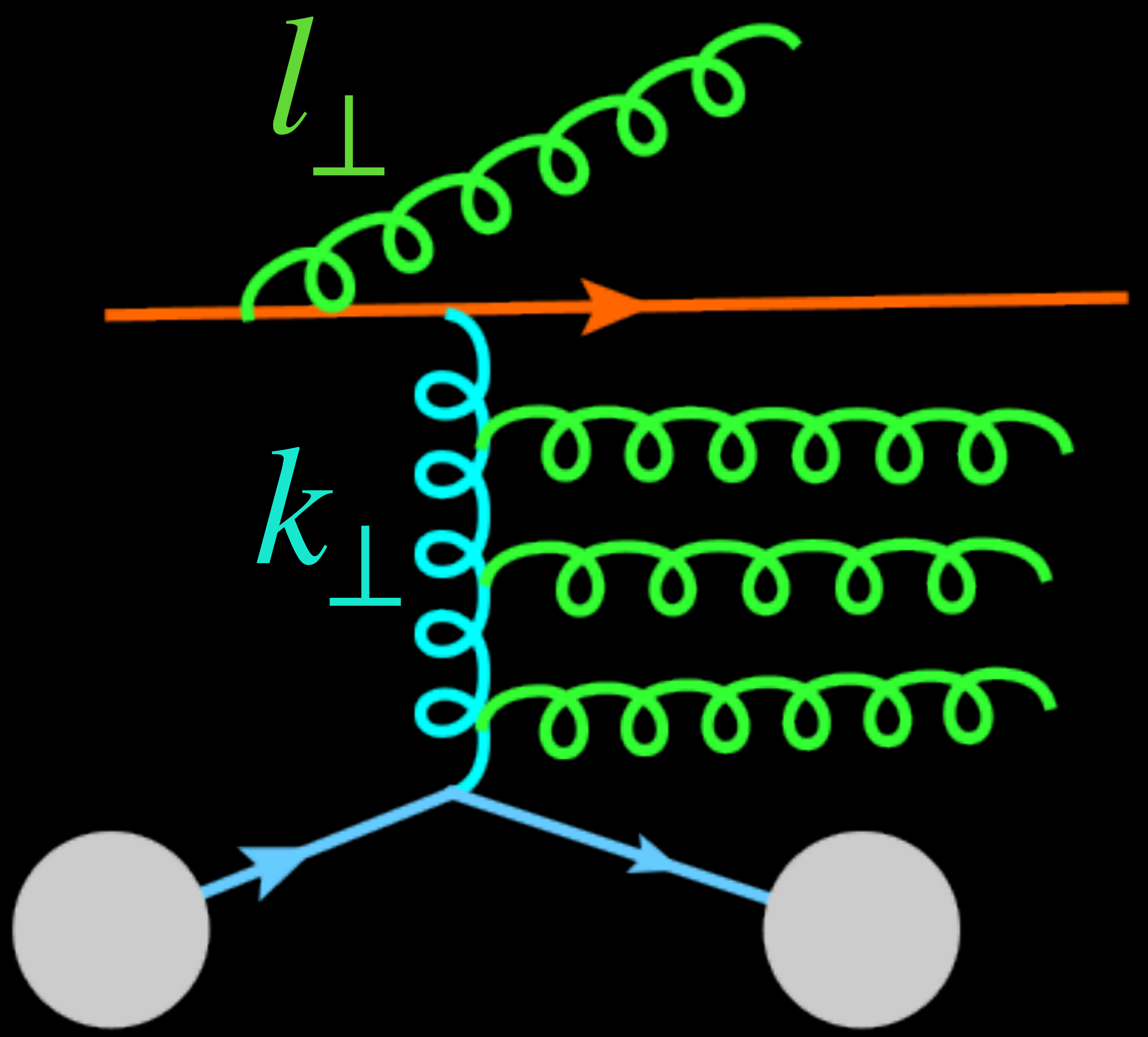
- **The matrix element prefers $k_\perp \sim T$, there is tension between 1st and 3rd line.**

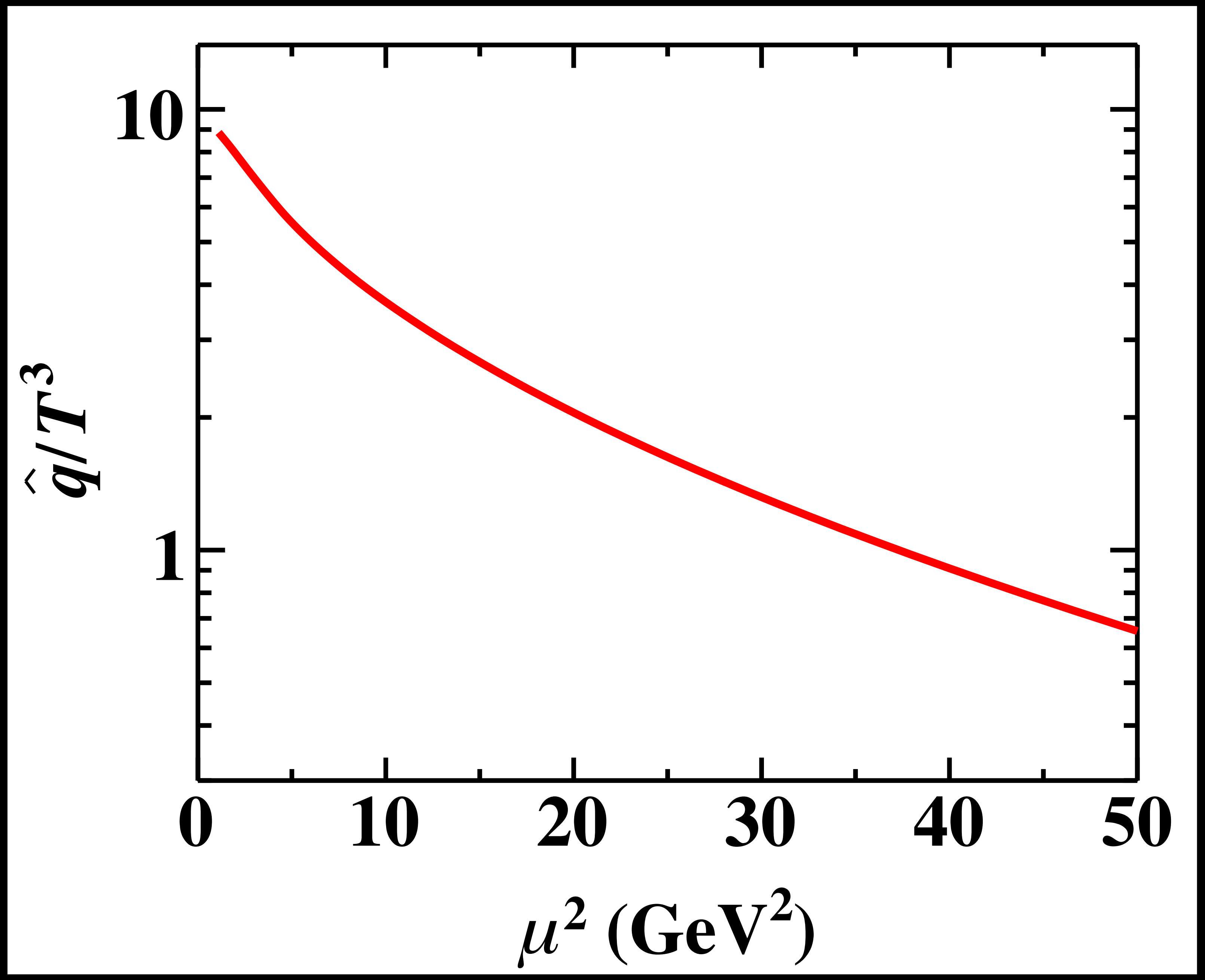
A. Kumar, A.M., C. Shen, PRC 101 (2020) 034908

Virtuality dependence/Coherence

P. Caucal, E. Iancu, A. H. Mueller, Soyez, Phys. Rev. Lett. 120 (2018) 232001. N. Armesto, H. Ma, Y. Mehtar-Tani, C. A. Salgado, JHEP 01, 109. J. Casalderrey-Solana and E. Iancu, JHEP 08, 015.

- How does the thermal distribution produce a hard gluon with $k_\perp \gg T$,
- By fluctuation (evolution)
- Reduces the effective $\hat{q}$, as only sensitive to $k_\perp \sim l_\perp$





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How to put all of this together in one simulation?

A multi-stage generator for p-p and A-A collsions

Modular, customizable!

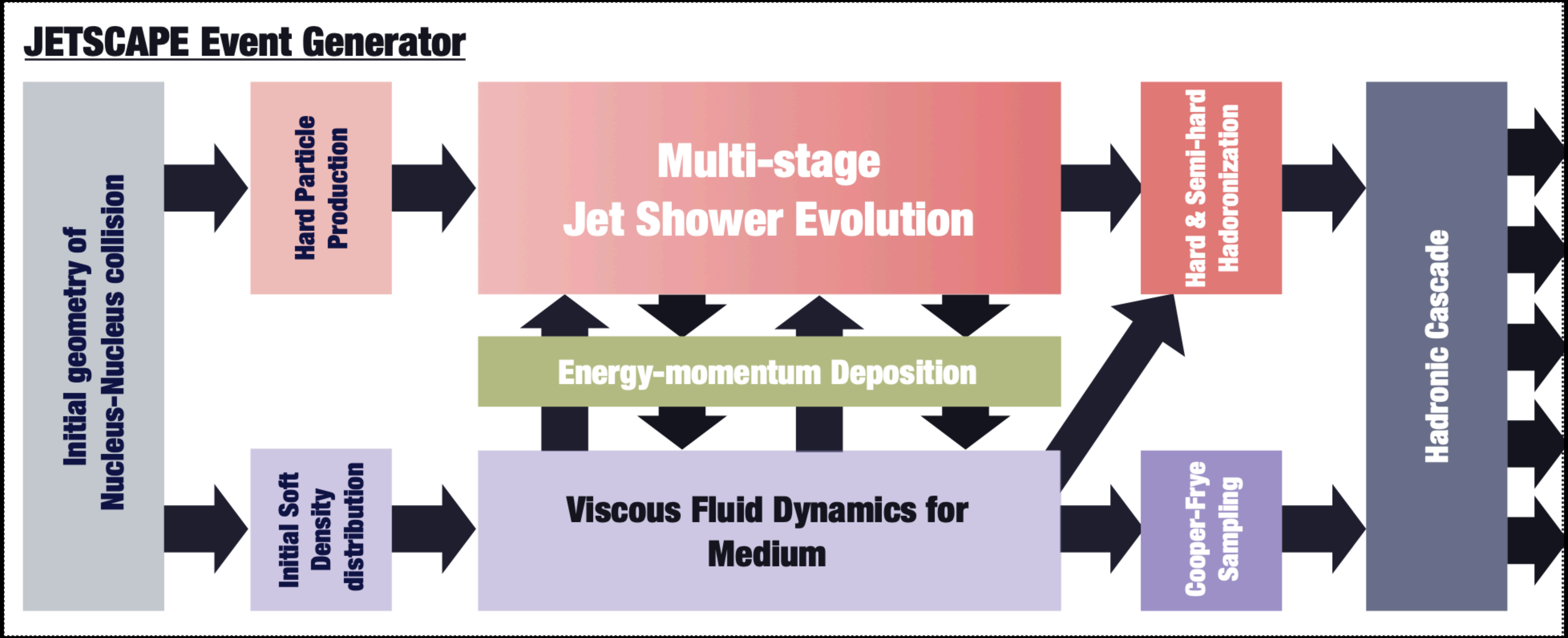


Diagram by Y. Tachibana

A change in how theory and experiment are compared

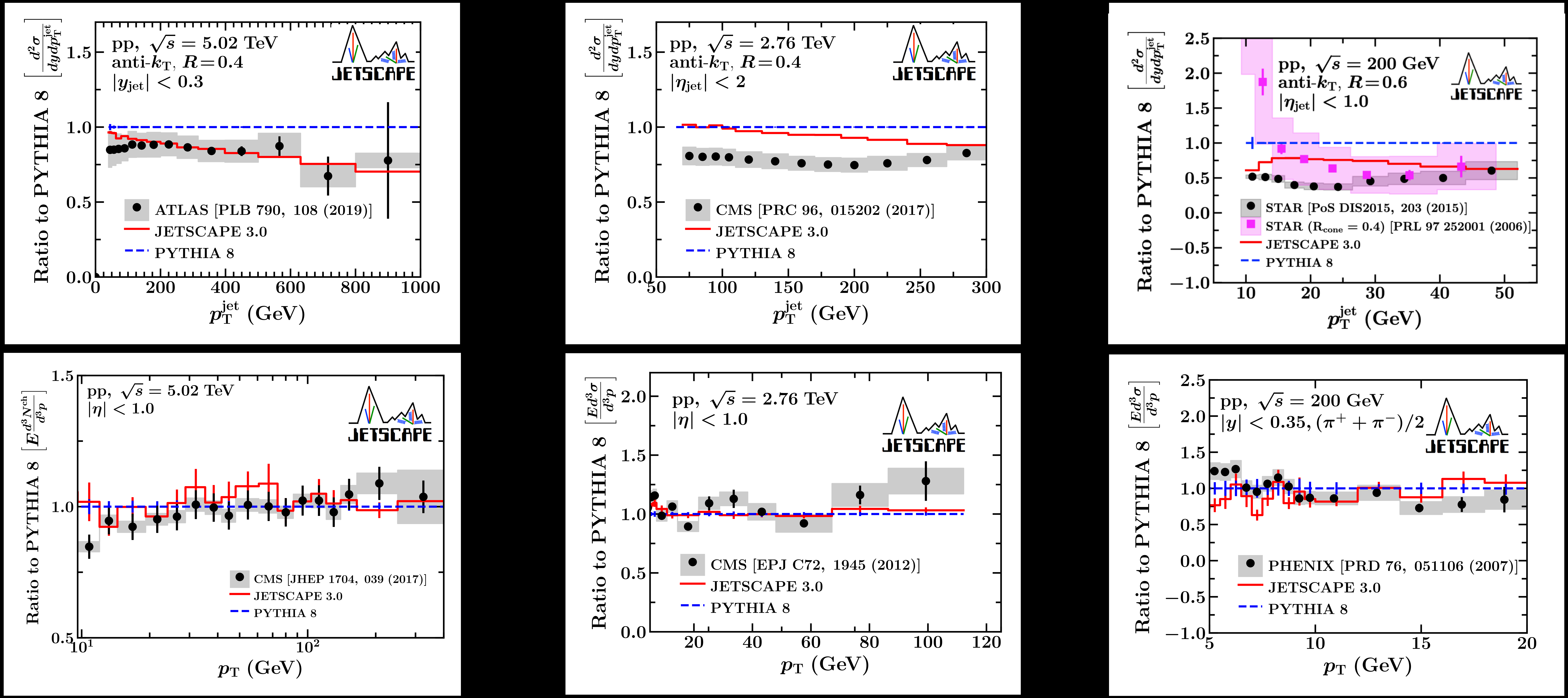
- Need full Monte-Carlo simulations that generate full events
- Observables should be built out of these (as in experiment)
- All jet calculations should be run on a calibrated hydro simulation
- Simulations should reduce to p-p without medium

Transition from MATTER to LBT at $Q_0 = Q_{sw}$

- TRENTO initial state
- Pre Calibrated 2+1D MUSIC gives background —> See talk by J. F. Paquet
- PYTHIA hard scattering
- High virtuality phase using MATTER
- Lower virtuality phase using LBT (we will replace with MARTINI, CUJET, AdS/CFT)
- Both have the same recoil setup
- Evolution starts at Q ~ E and goes down to 1 GeV
- Hadronization applied in vacuum
- Holes subtracted

One more constraint before we start

Any decent event generator should reproduce p-p collisions

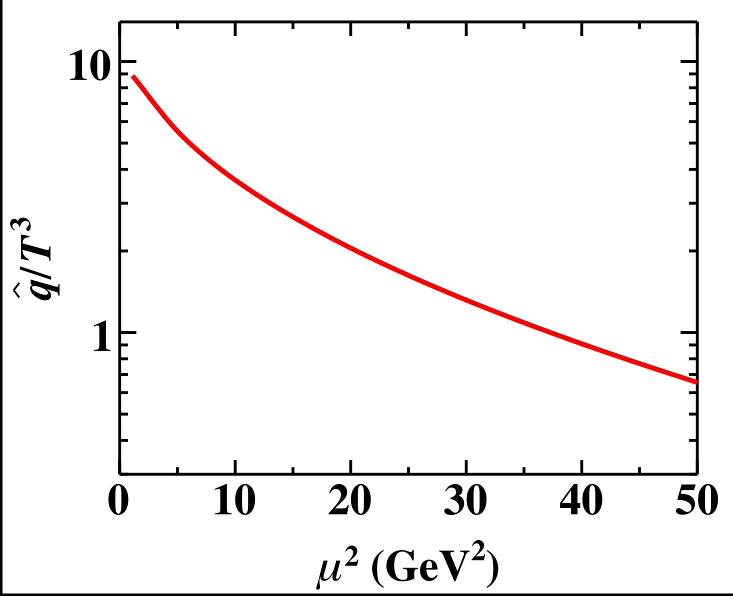


A. Kumar et al., 2204.01163 [hep-ph]

Leading hadrons and jets

At all energies and centralities

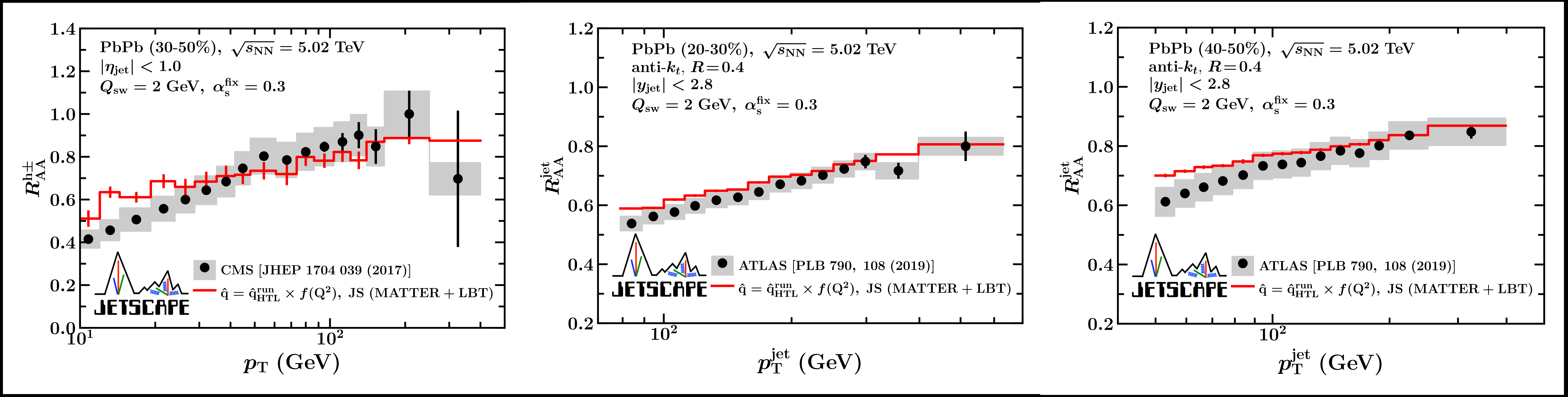
- $\hat{q} = C\alpha_s(2ET)\alpha_s(m_D)T^3 \log\left(\frac{2ET}{m_D^2}\right) \times f(Q^2)$



A. Kumar et al., 2204.01163 [hep-ph]

Centrality

Parameters set in central Pb-Pb at 5 TeV



Note: Quenching stops at 160MeV, no quenching in the hadronic phase,
Expect: low p_T to be less quenched in both jets and leading hadrons

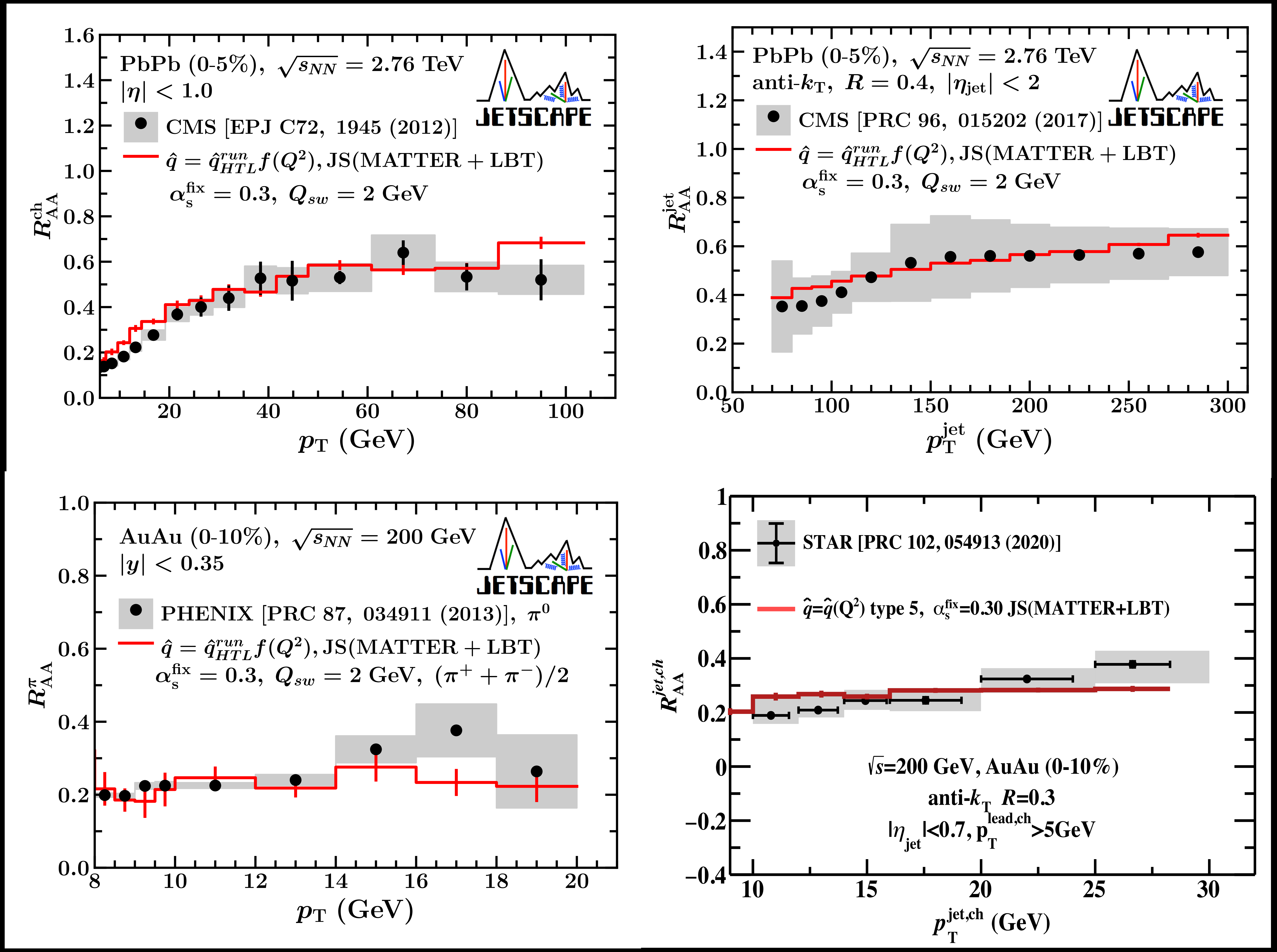
A. Kumar et al., 2204.01163 [hep-ph]

Energy dependence at LHC 2.76 and RHIC 0.2

- Jet and leading hadron RAA show remarkable agreement with experimental data

- Across most centralities and all energies

- No re-tuning or refitting of $\hat{q}$, $C(k)$ or recoil systematics

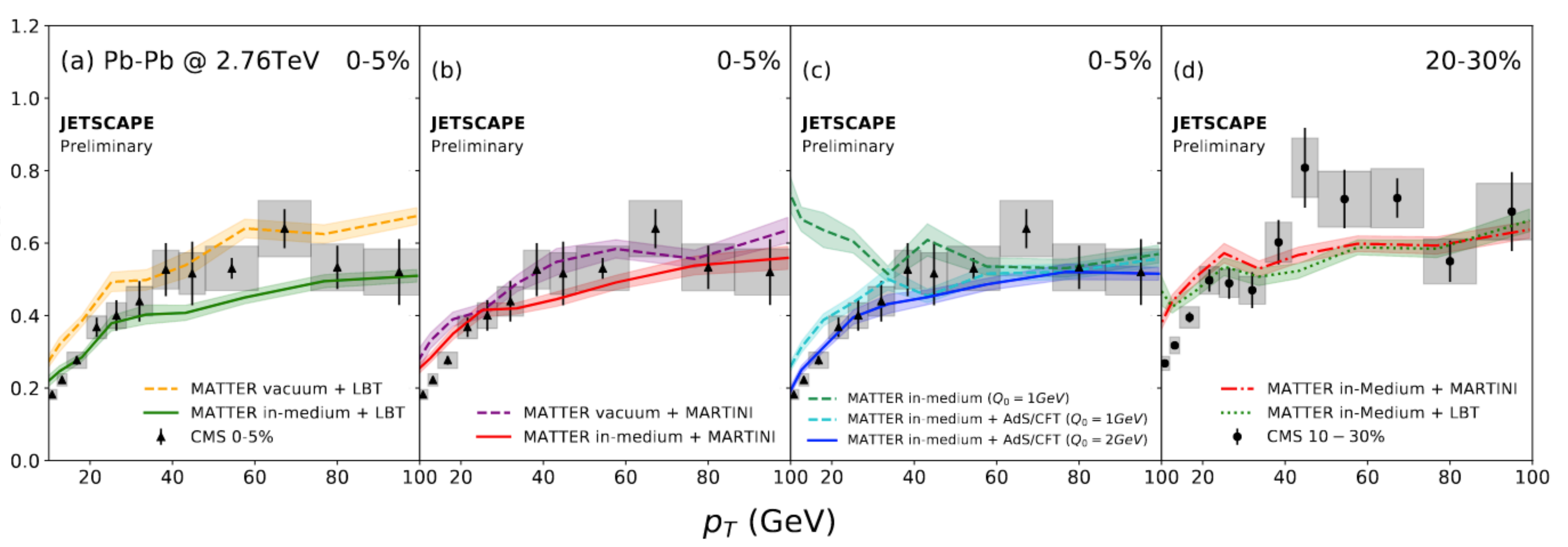


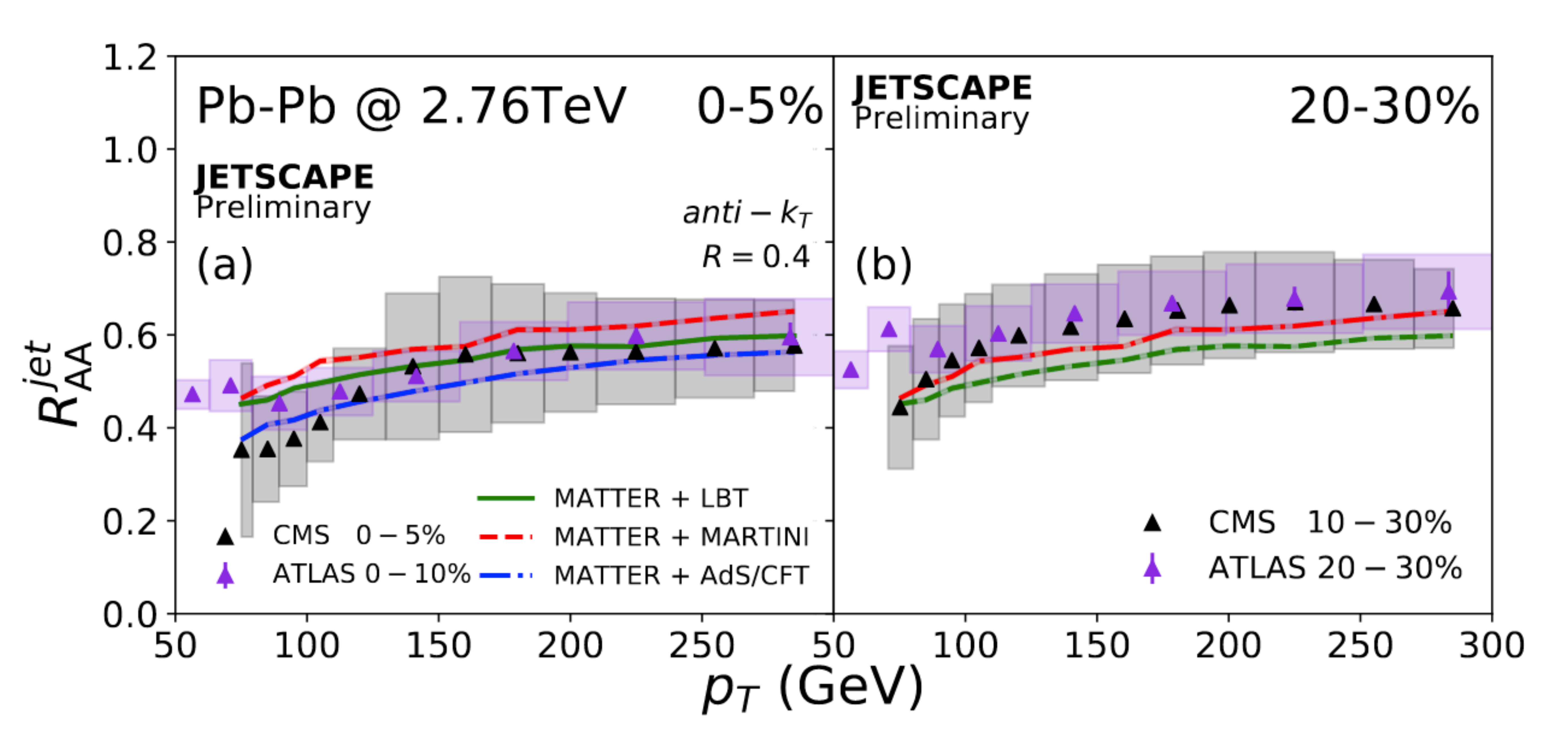
A. Kumar et al., 2204.01163 [hep-ph]

Systematic model uncertainty

[MATTER+LBT] vs. [MATTER+MARTINI] shows almost no change (<5%)

[MATTER+AdS/CFT] also shows <5% change.





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[MATTER+LBT] vs. [MATTER+MARTINI] shows almost no change (<5%)

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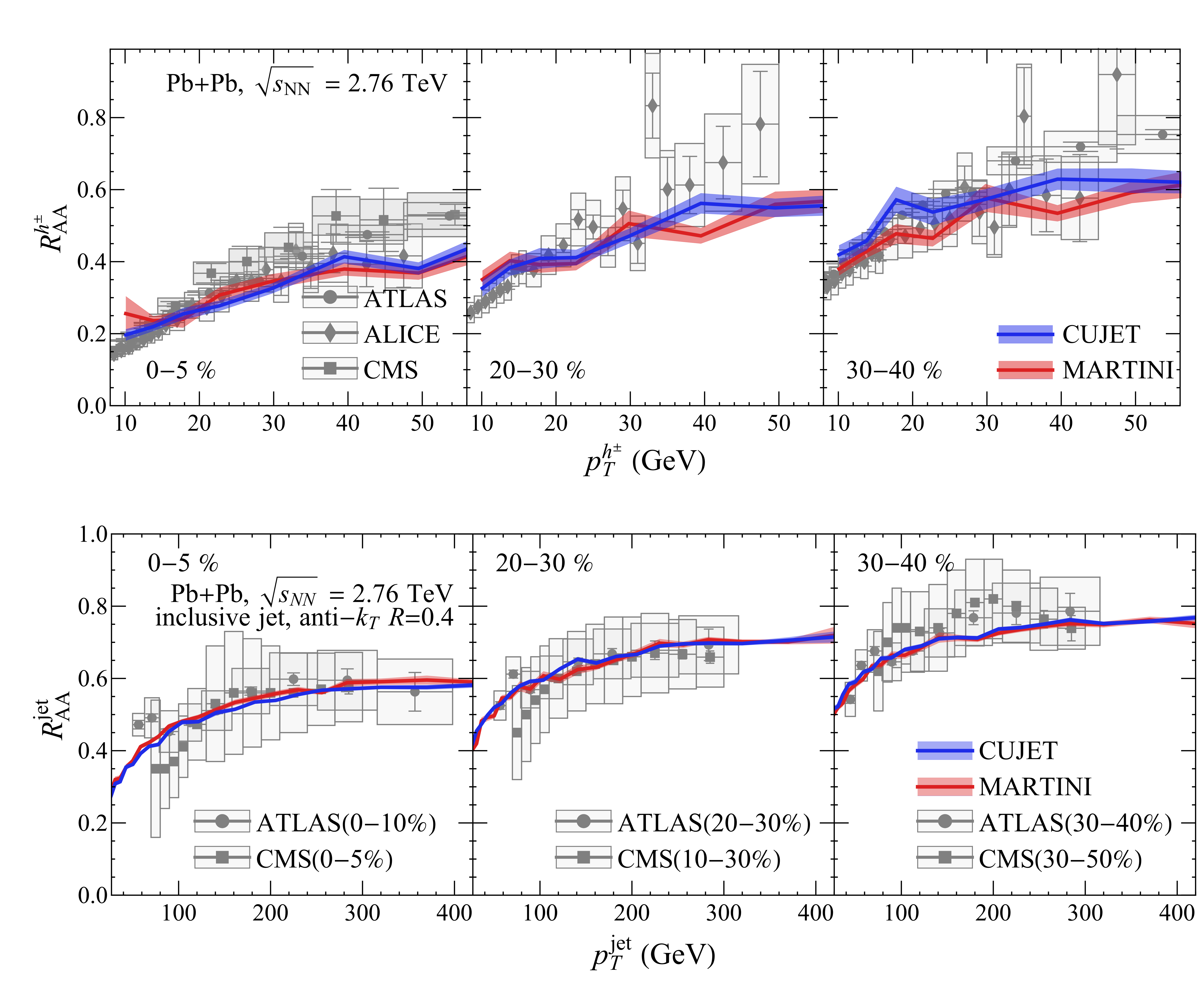
[MATTER+CUJET] vs. [MATTER+MARTINI] < 5%

MATTER+ CUJET-MARTINI comparison by R. Modarresi-Yazdi & S. Shi

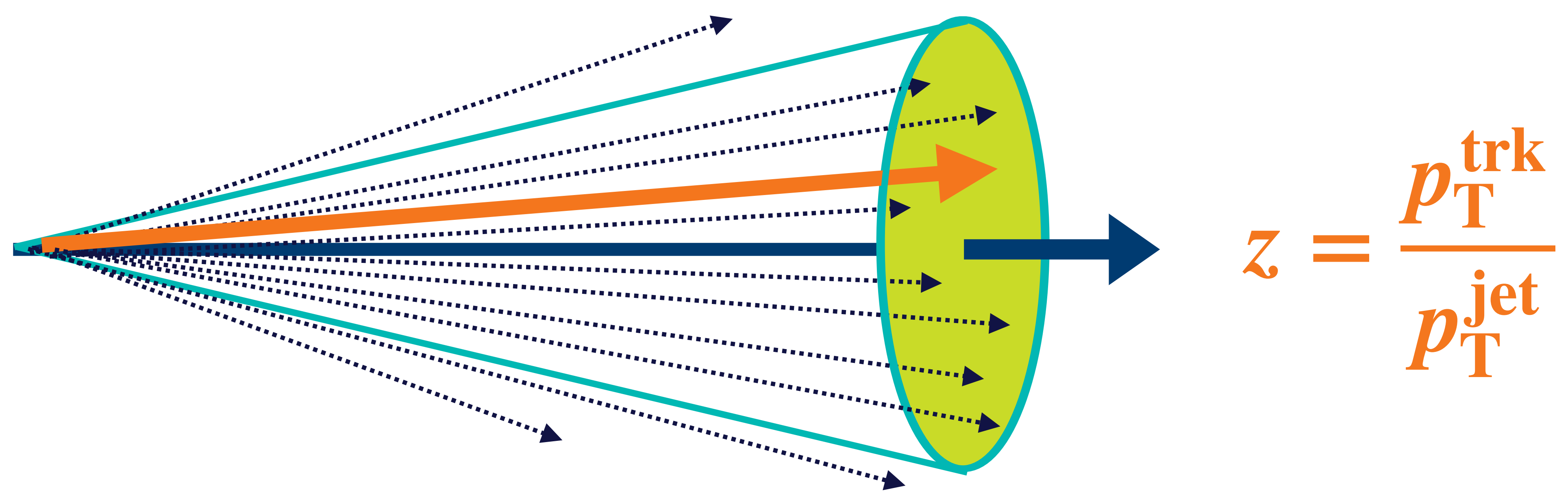


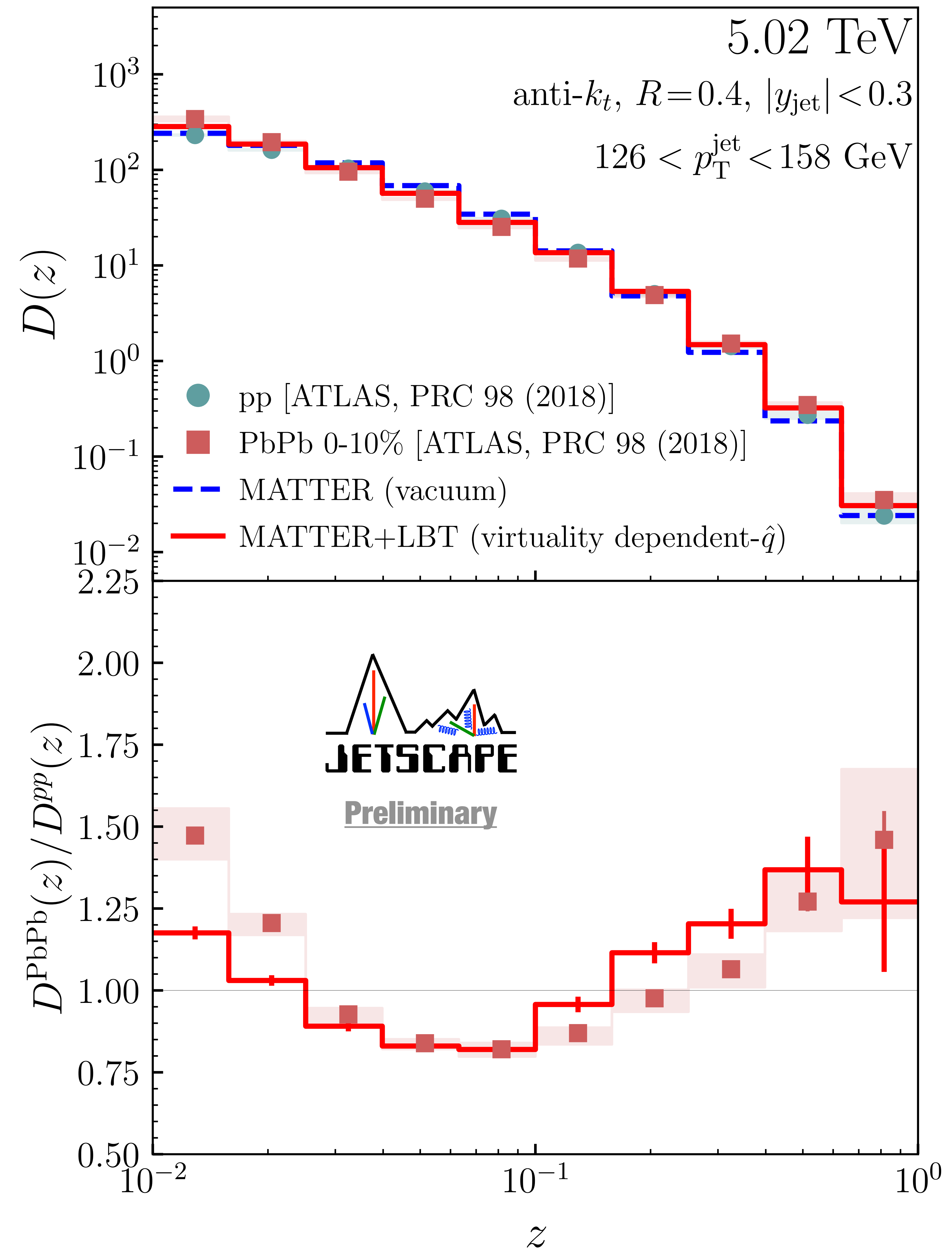
Intrajet

The dependence on E and μ not completely settled

This will probably get done in an upcoming Bayesian analysis

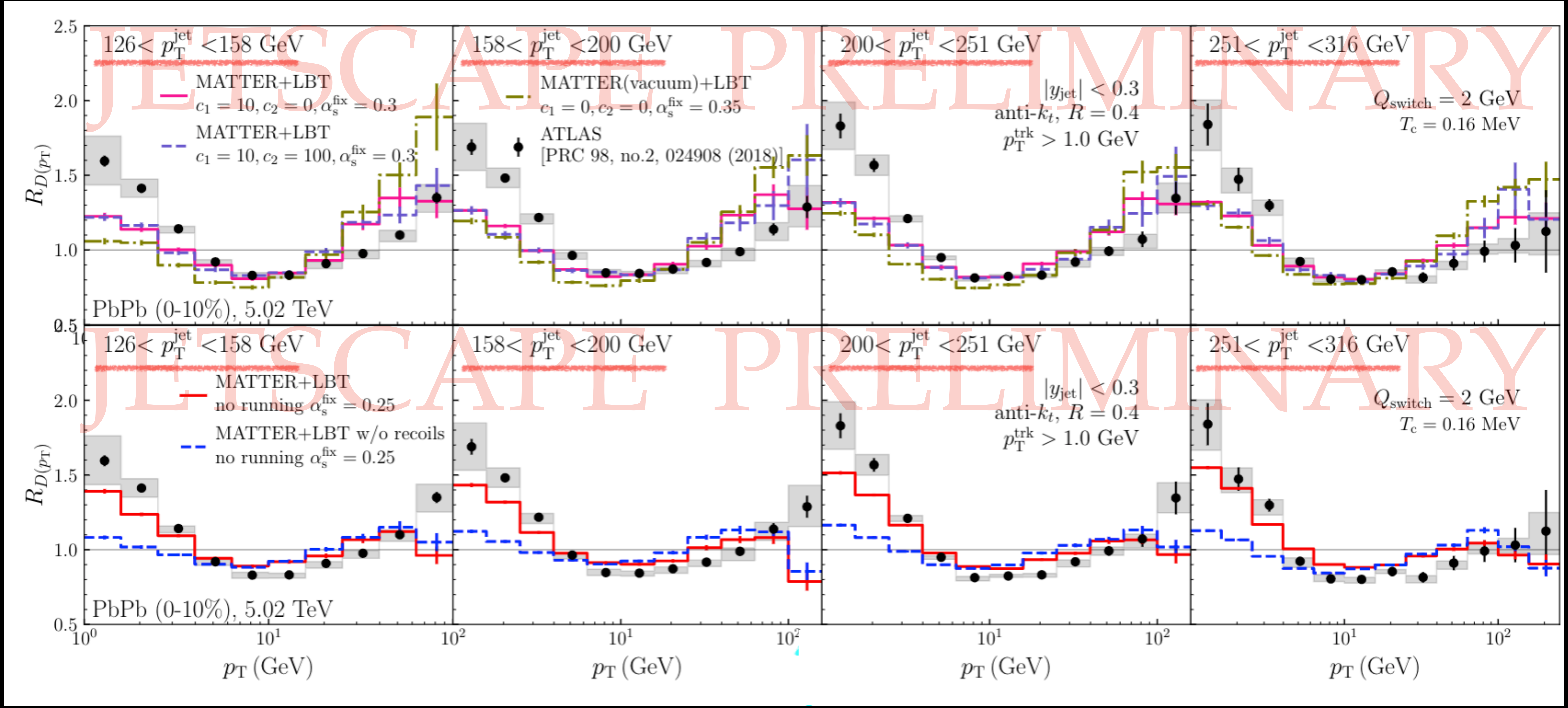
$$D(z) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{dN_{\text{trk}}}{dz}\Bigg|_{\text{in jet}}$$





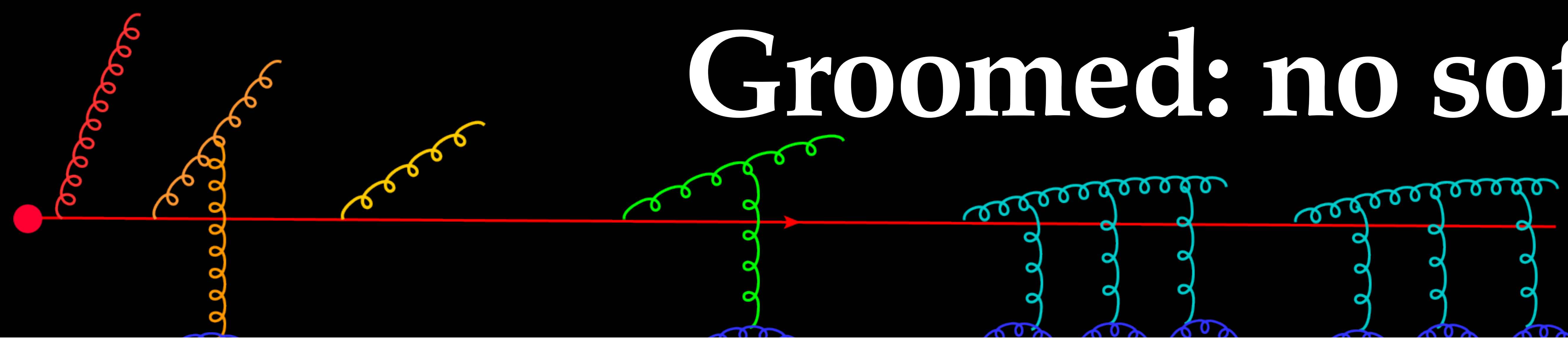
Y. Tachibana et al., *to appear*

Need for quenching in high Q stage



Y. Tachibana et al., *to appear*

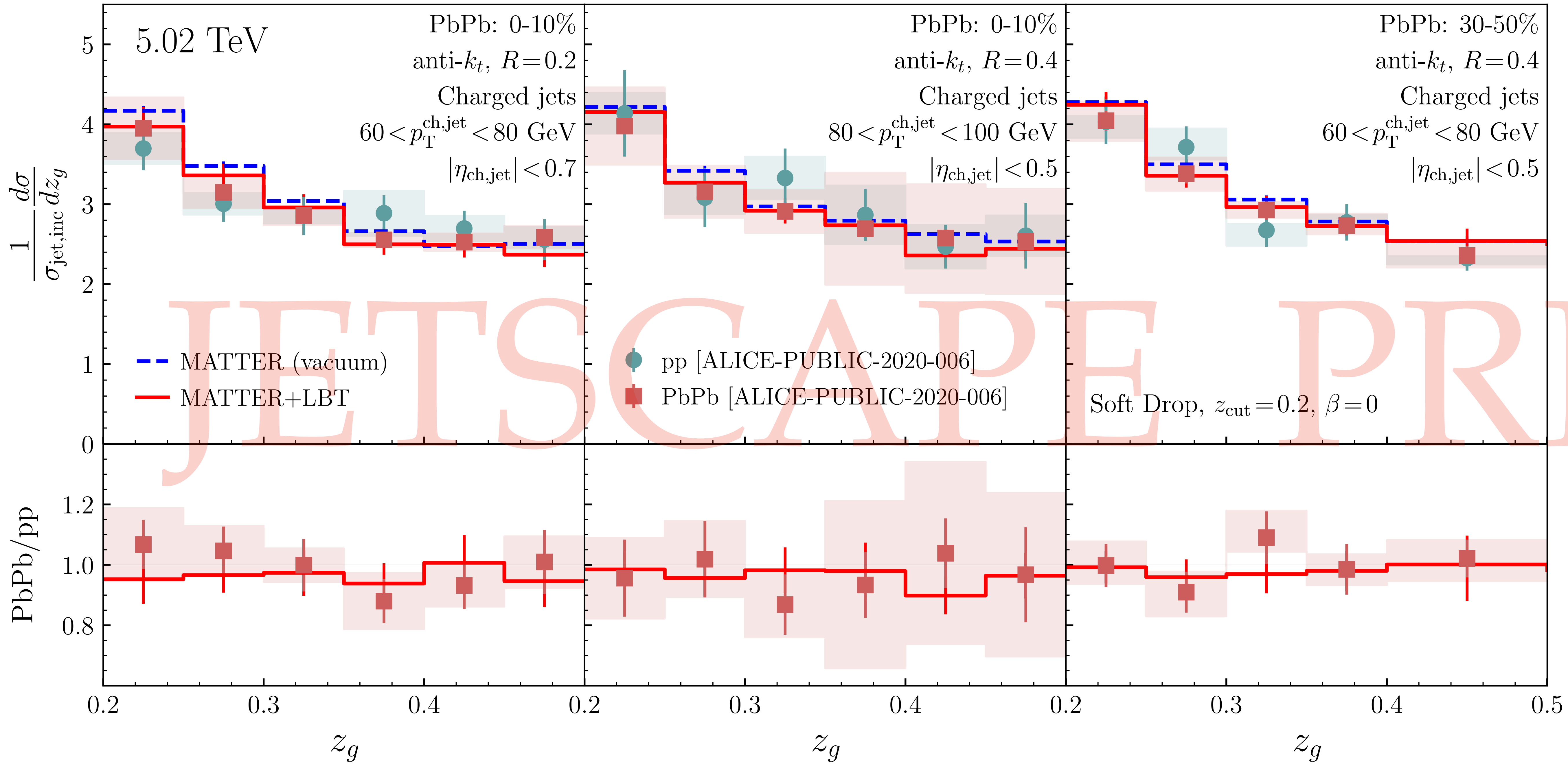
Groomed: no soft modes!

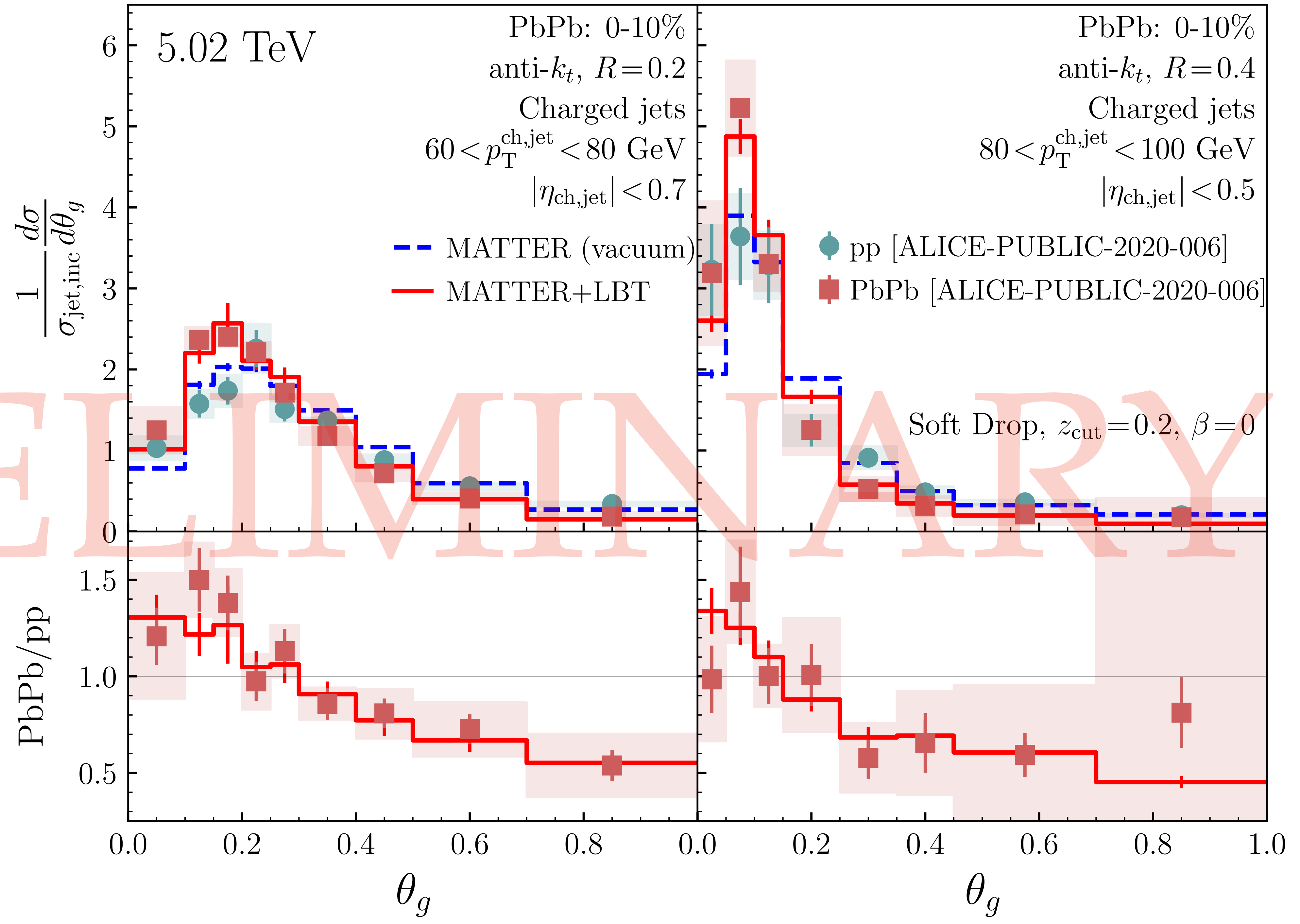


pp: MATTER (vacuum)

PbPb: MATTER+LBT running-α_S, Q^2dependent

$\alpha_S^{\mathrm{fix}} = 0.3, Q_0 = 2\,\mathrm{GeV}, \hat{q}$-paramerization: 5

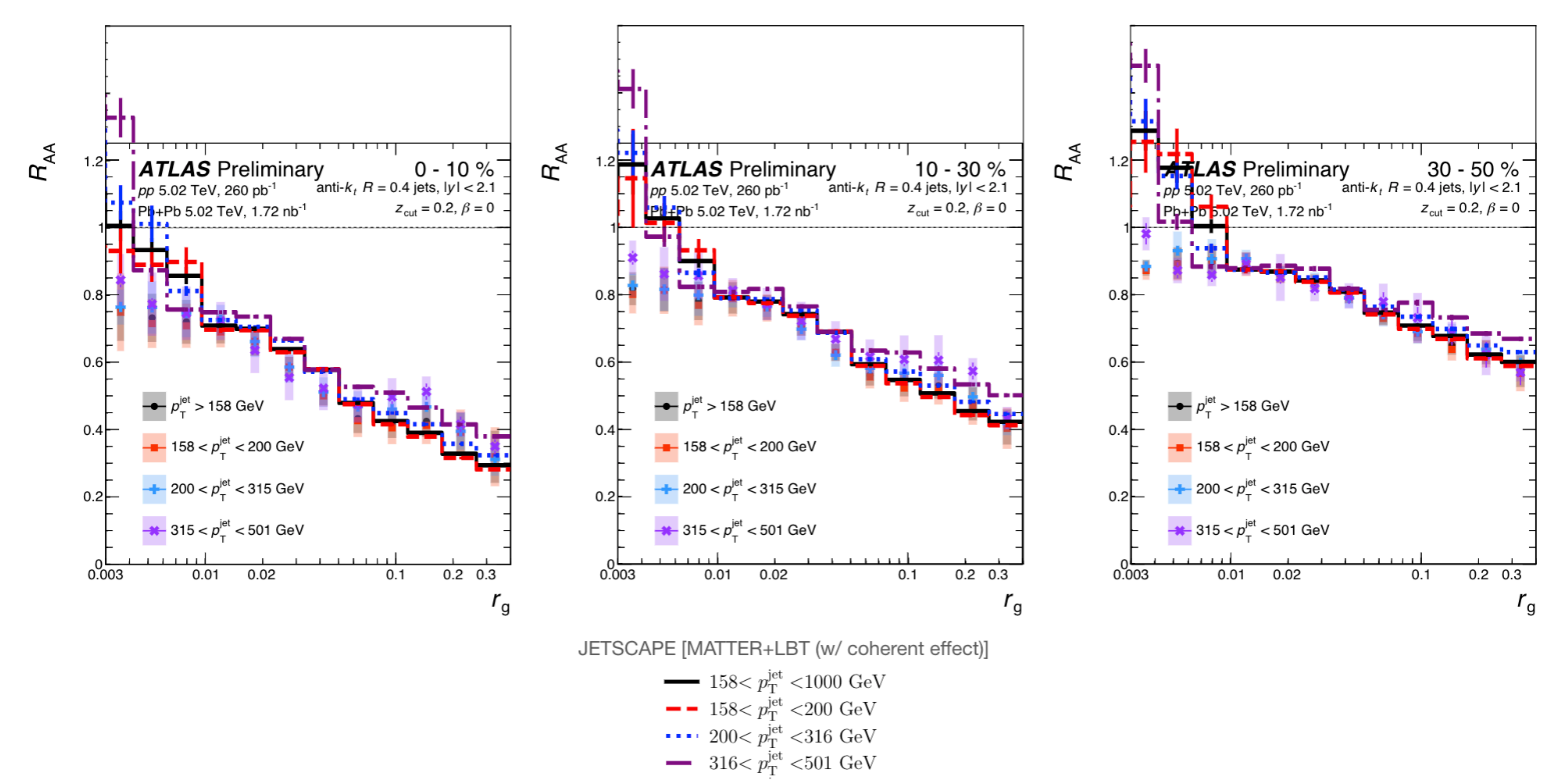




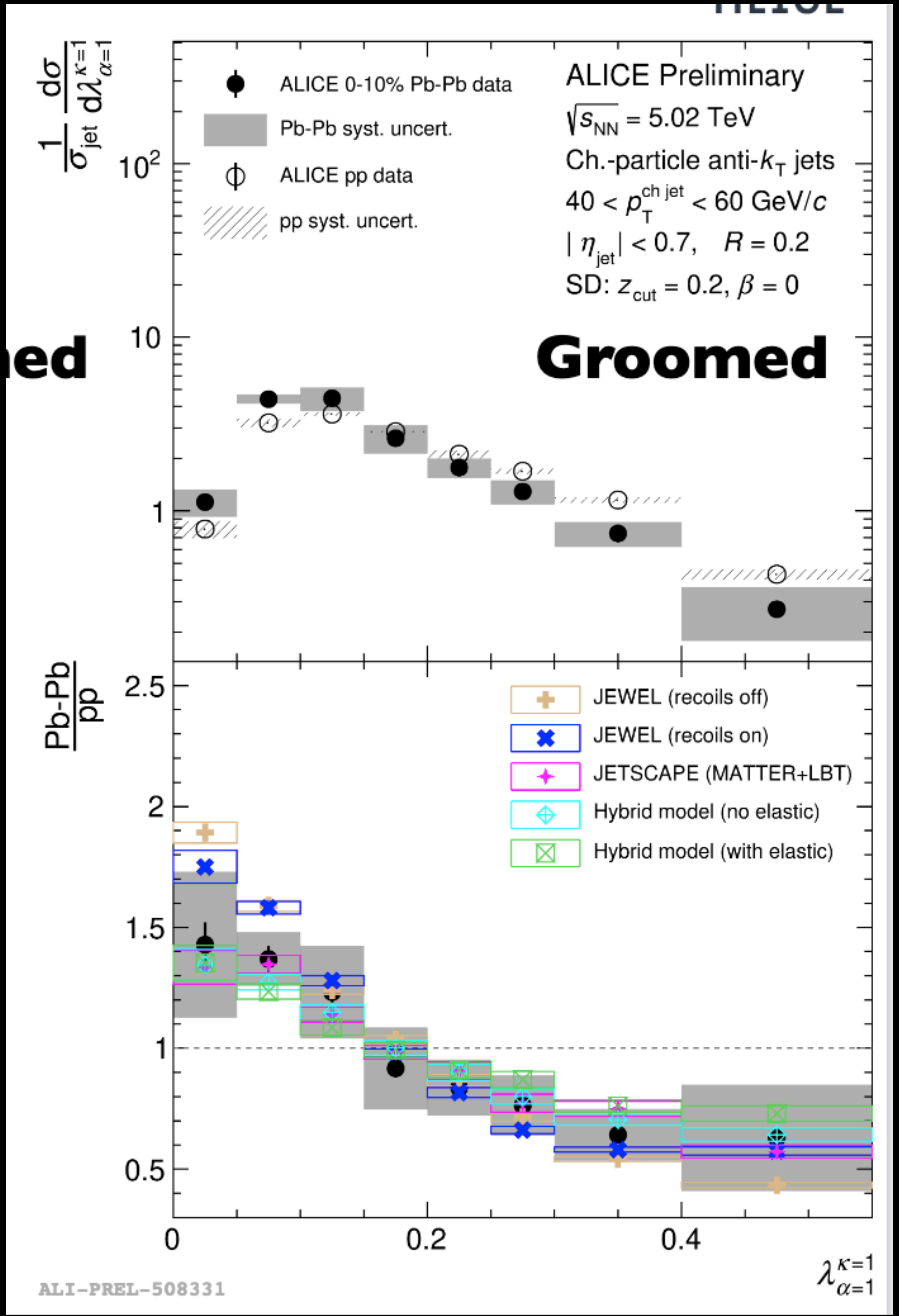
- Soft drop: getting rid of the soft response and looking at the prong structure

Y. Tachibana et al., *to appear*

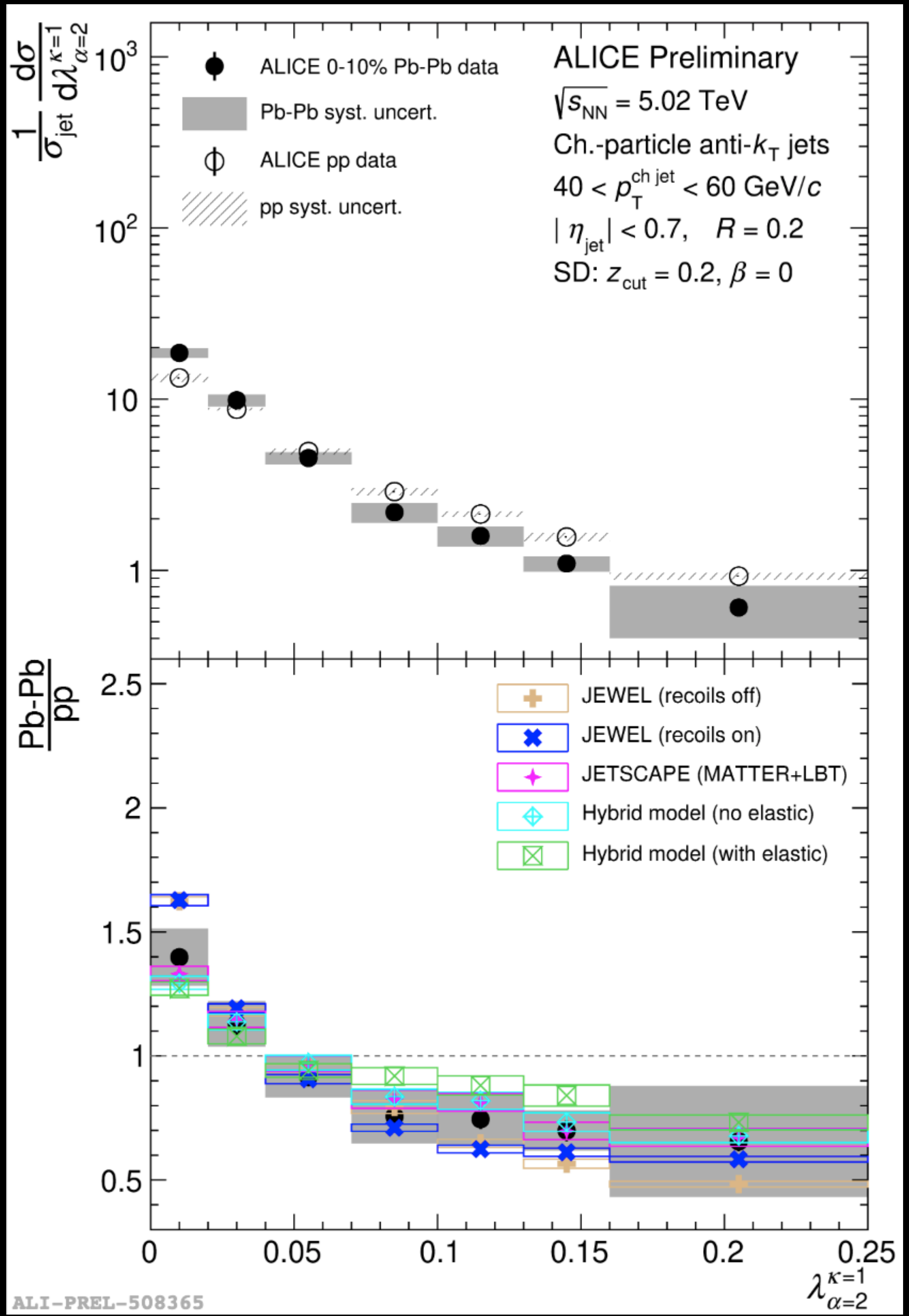
R_{AA} as a function of r_g



Groomed Jet angularities

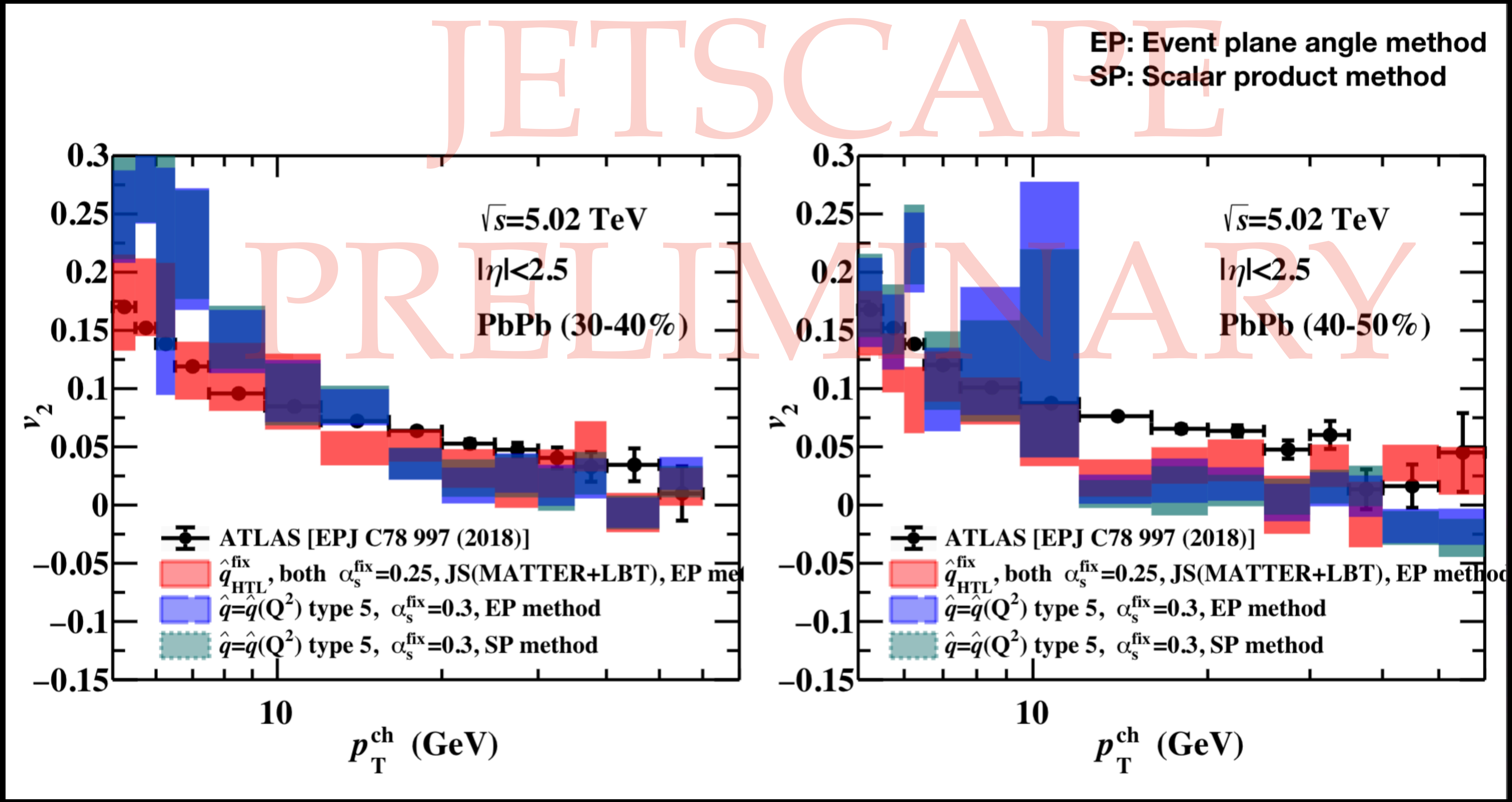


- $\lambda = \sum_{i \in Groomed} z_i \theta_i^{\alpha}$
- Strong constraints on the perturbative part of jet
- Several other similar groomed observables
- JETSCAPE (MATTER +LBT) does very well.

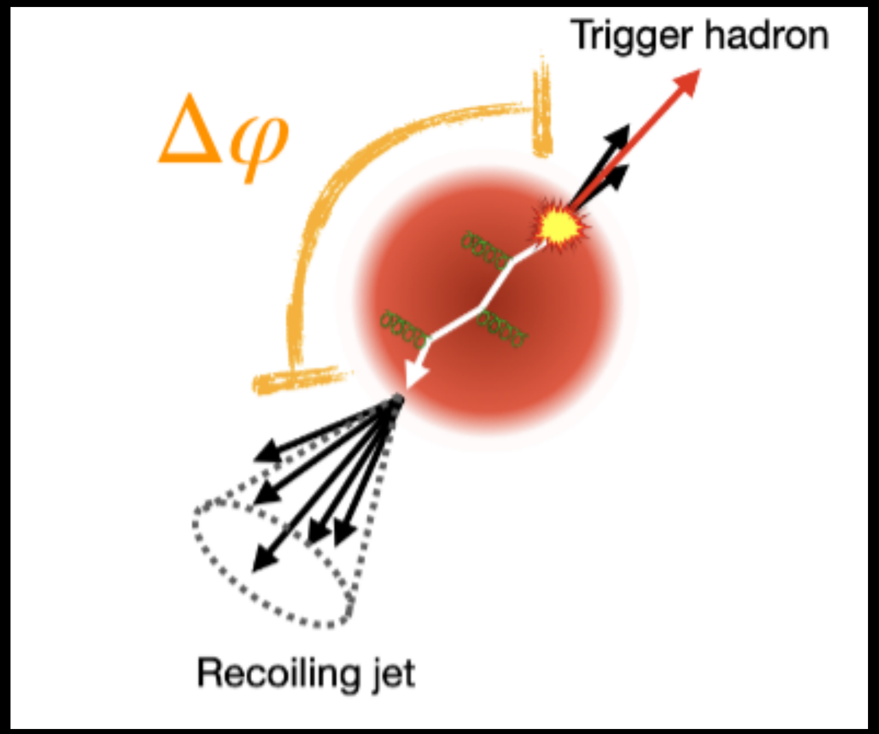


Azimuthal anisotropy

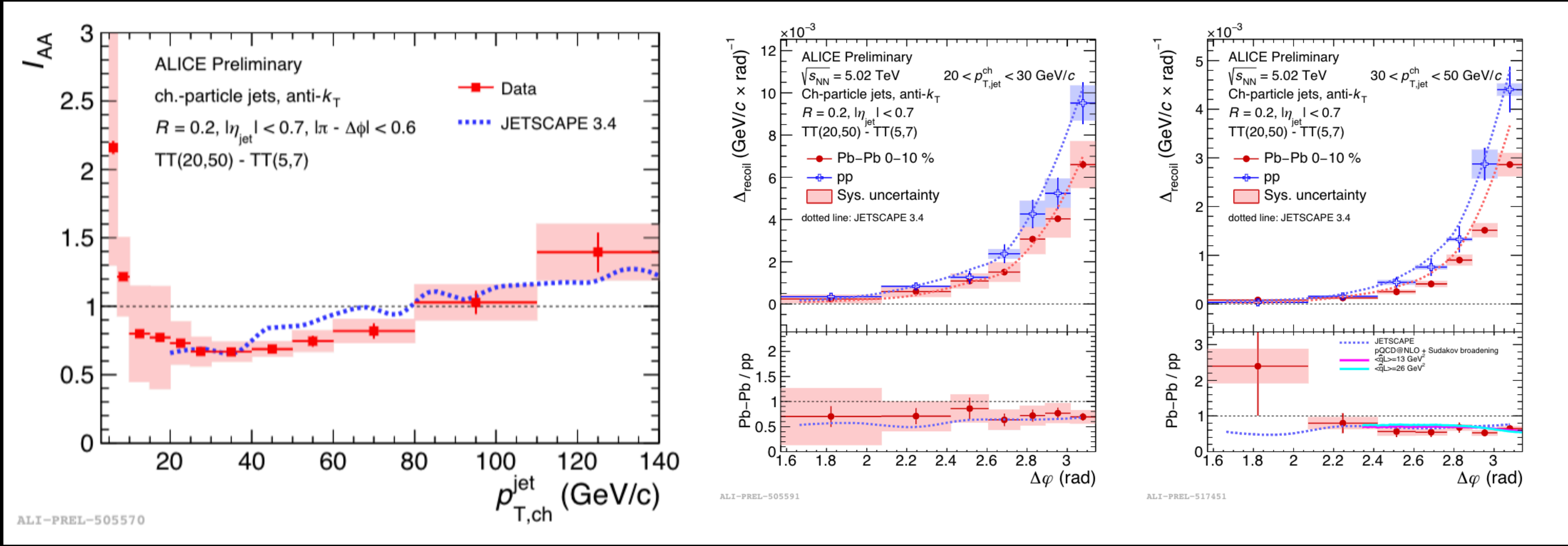
- Note: we haven't played with start and stop times (observation by C. Andres et al, start time important for v_2)
- In the JETSCAPE simulations, hydrodynamics starts around 1fm/c. (Free streaming prior)
- Also with new IP-Glasma, medium has primordial v_2
- Jet modification in the hadronic medium still not known



Coincidence with hadrons

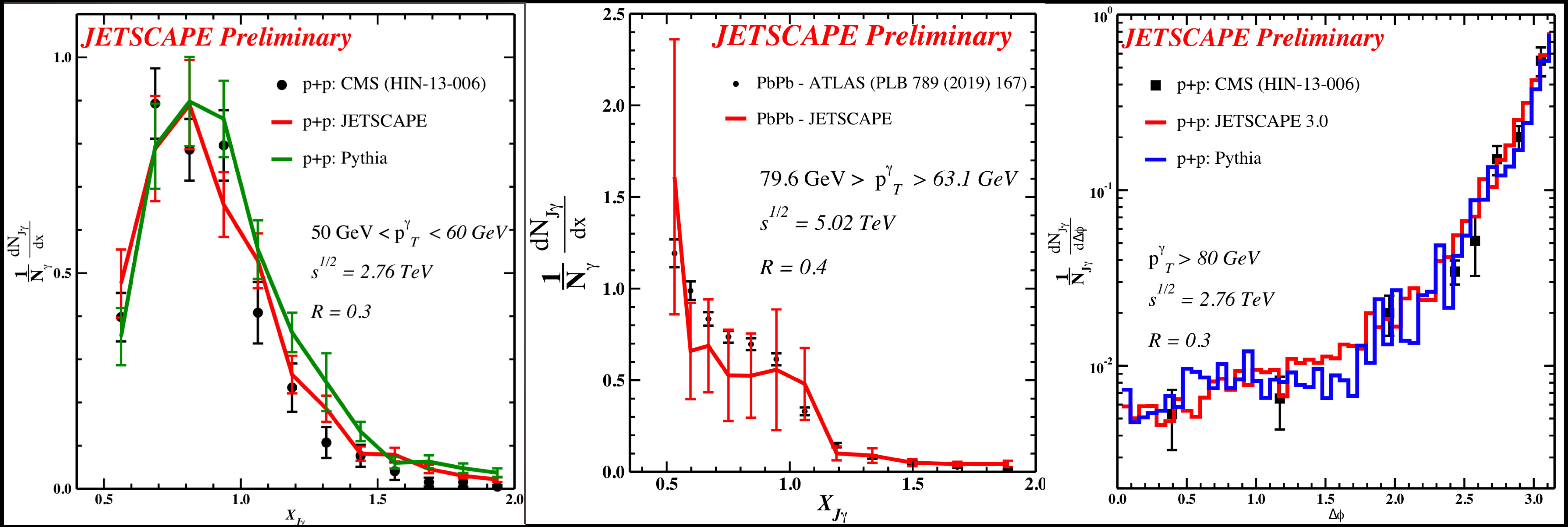


- Results from MATTER+LBT runs use for ratio of difference of triggered jet distribution per trigger.



Photon Trigger

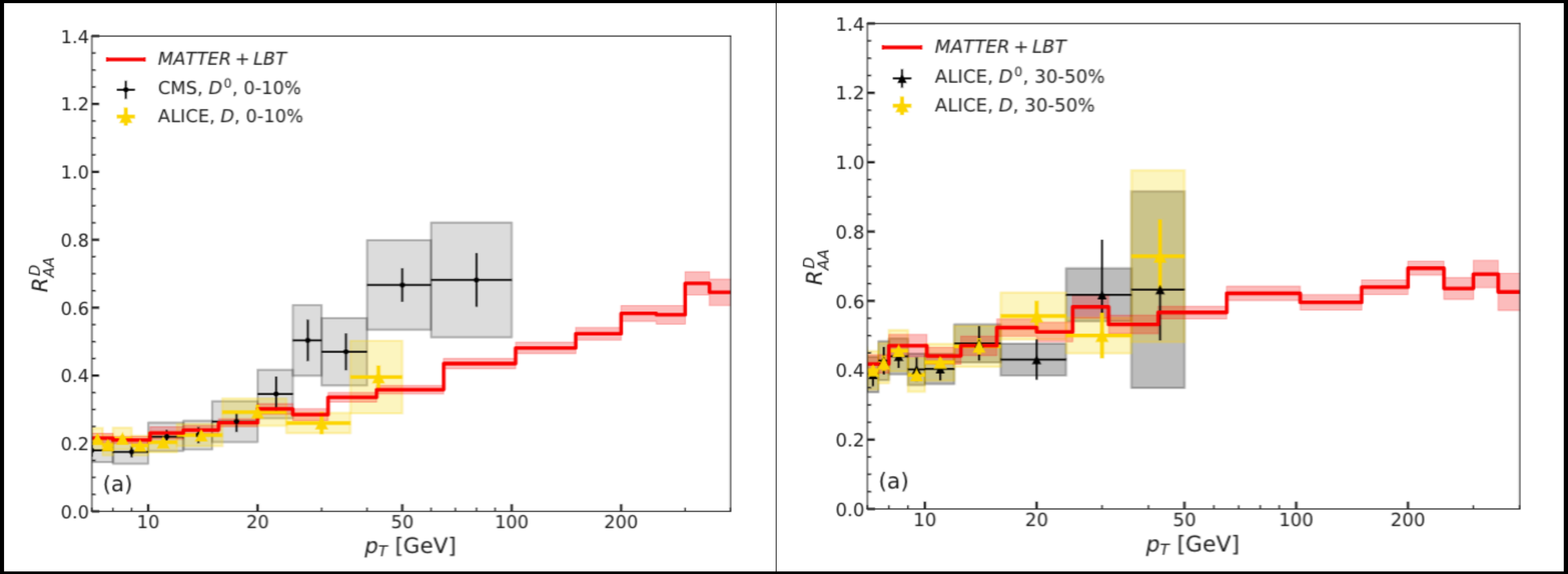
- Higher statistics runs with the exact same parameters as for jets.



C. Sirimanna, *to appear*.

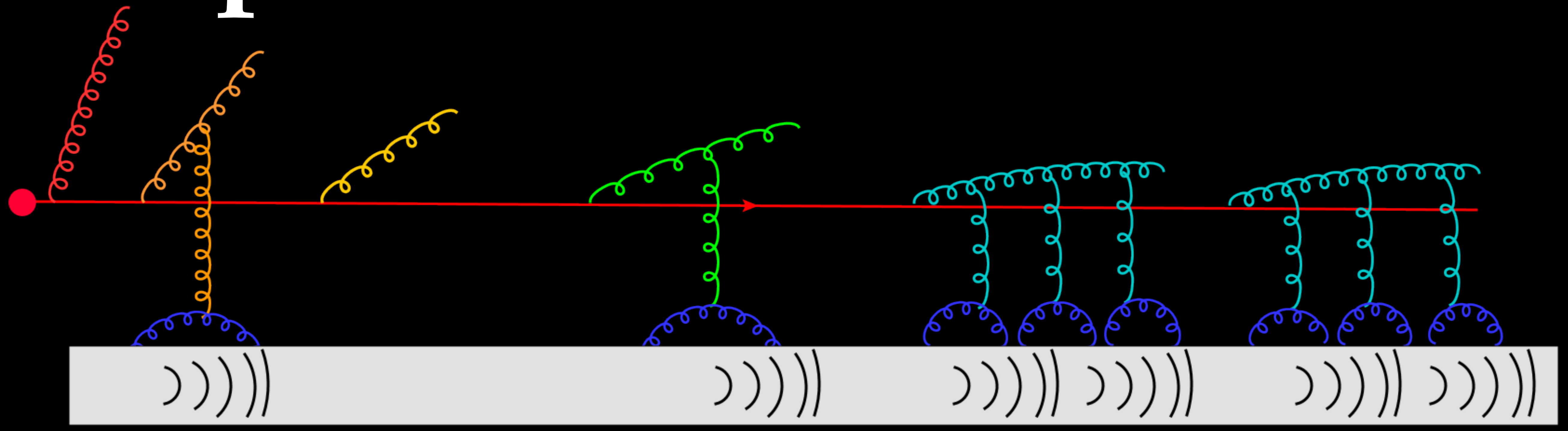
Heavy-quarks

- D meson R_{AA} with identical parameters

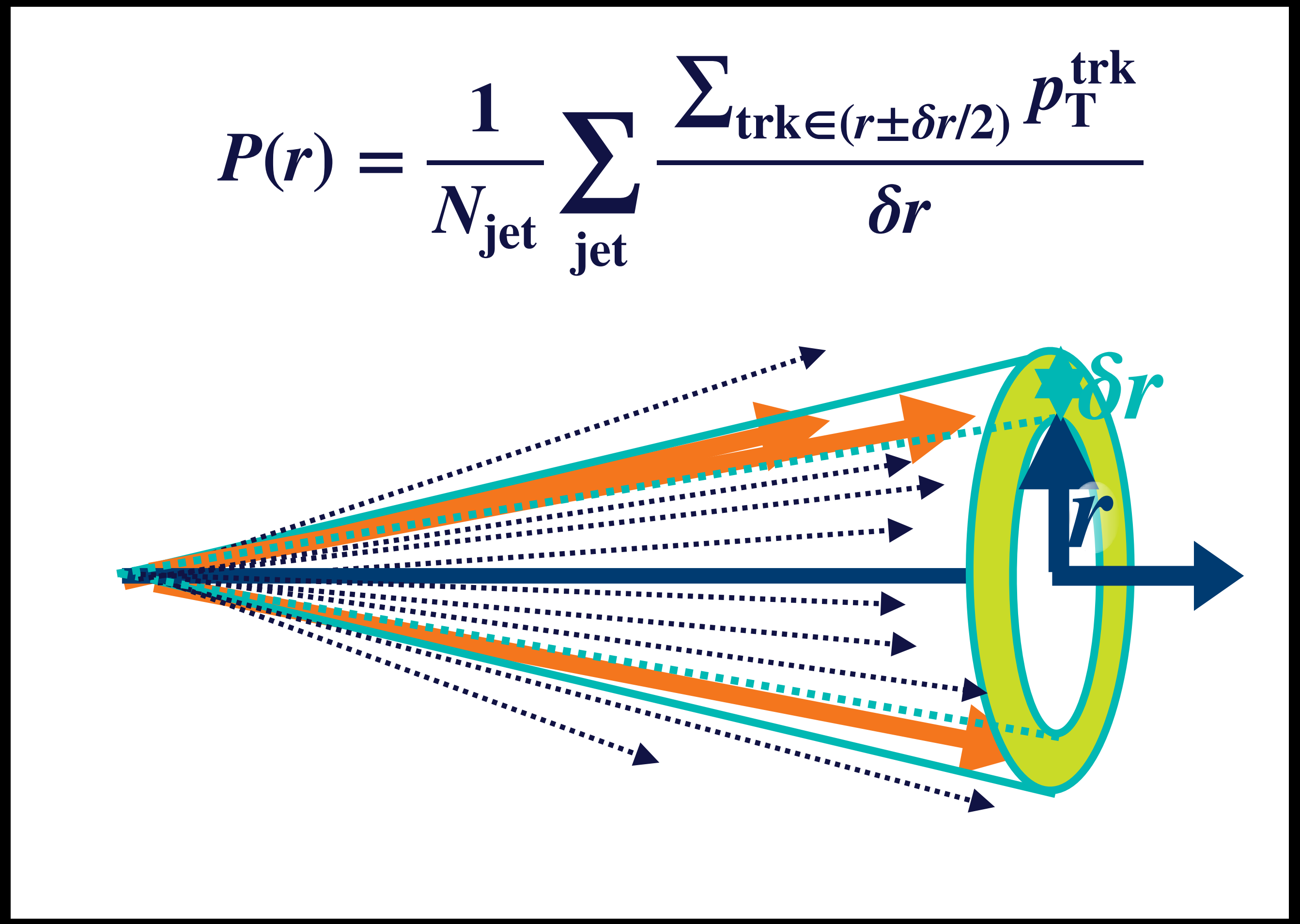


W. Fan, *et al*. e-Print: 2208.00983 [nucl-th]

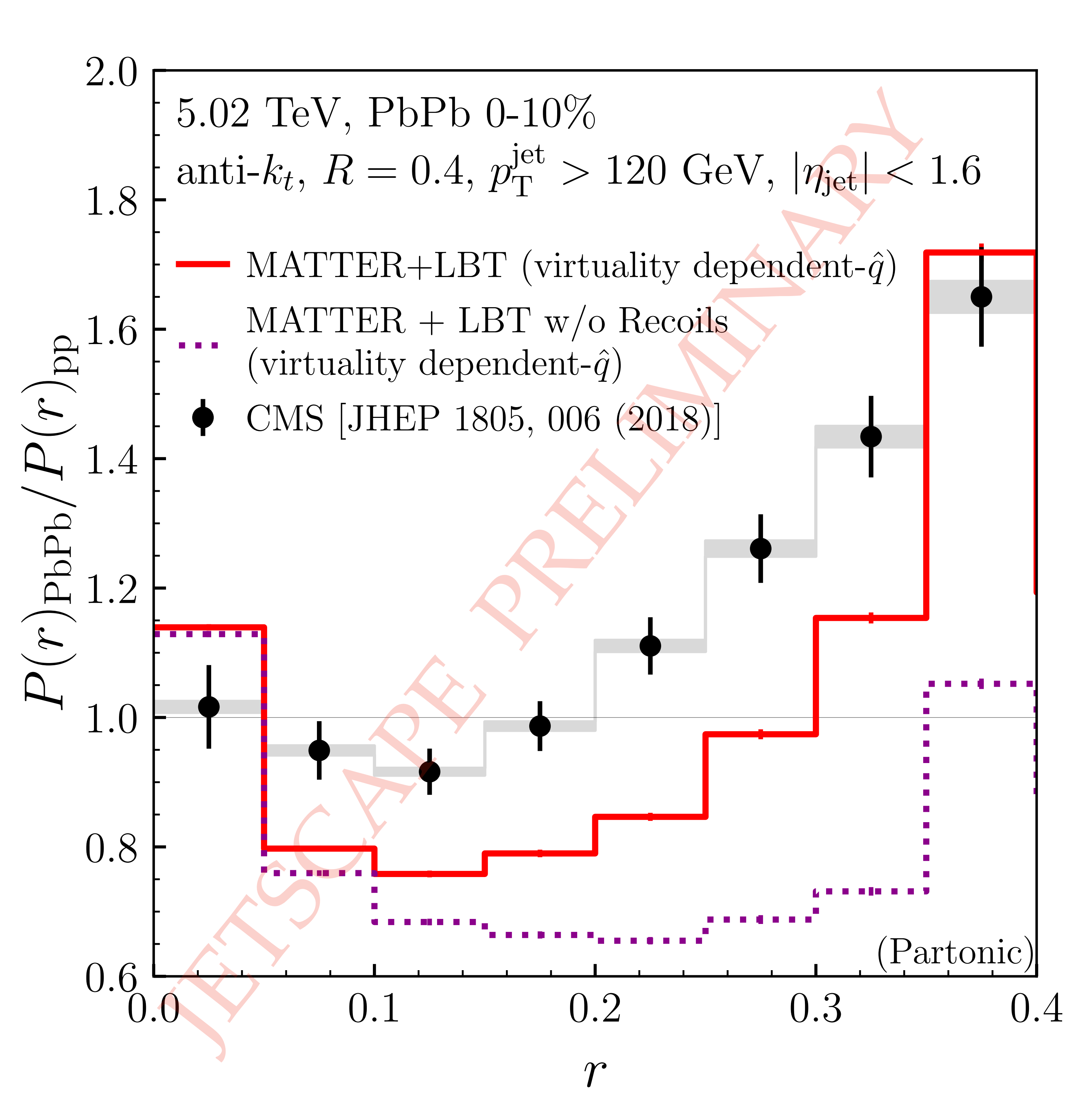
Jet Shape: more dependence on soft modes



- Jet shape function:
- This depends more on soft non-perturbative modes, especially at larger angles
- Requires 2-stage hydro simulations (hydro+jet+hydro) for response outside jet.



Y. Tachibana et al., *to appear*



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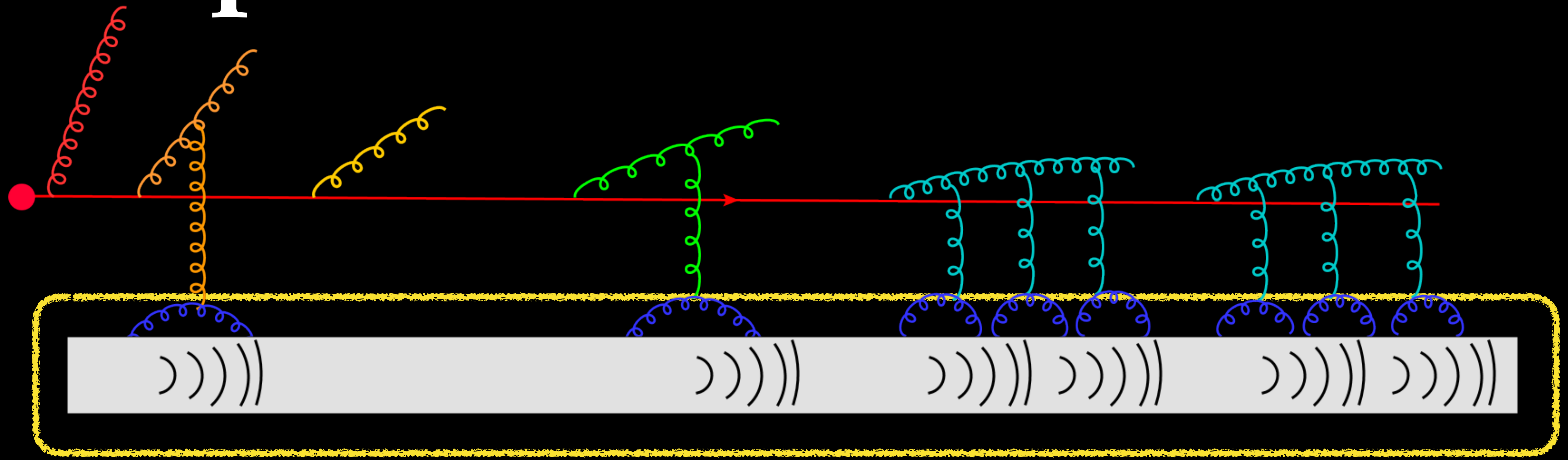

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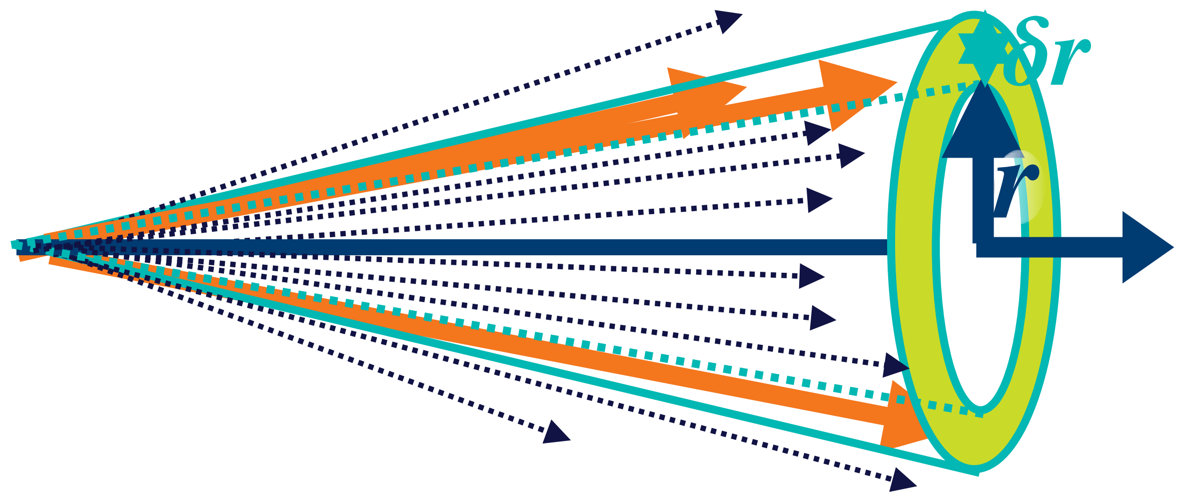
$$P(r) = \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jet}} \frac{\sum_{\mathrm{trk}\in(r\pm\delta r/2)} p_{\mathrm{T}}^{\mathrm{trk}}}{\delta r}$$



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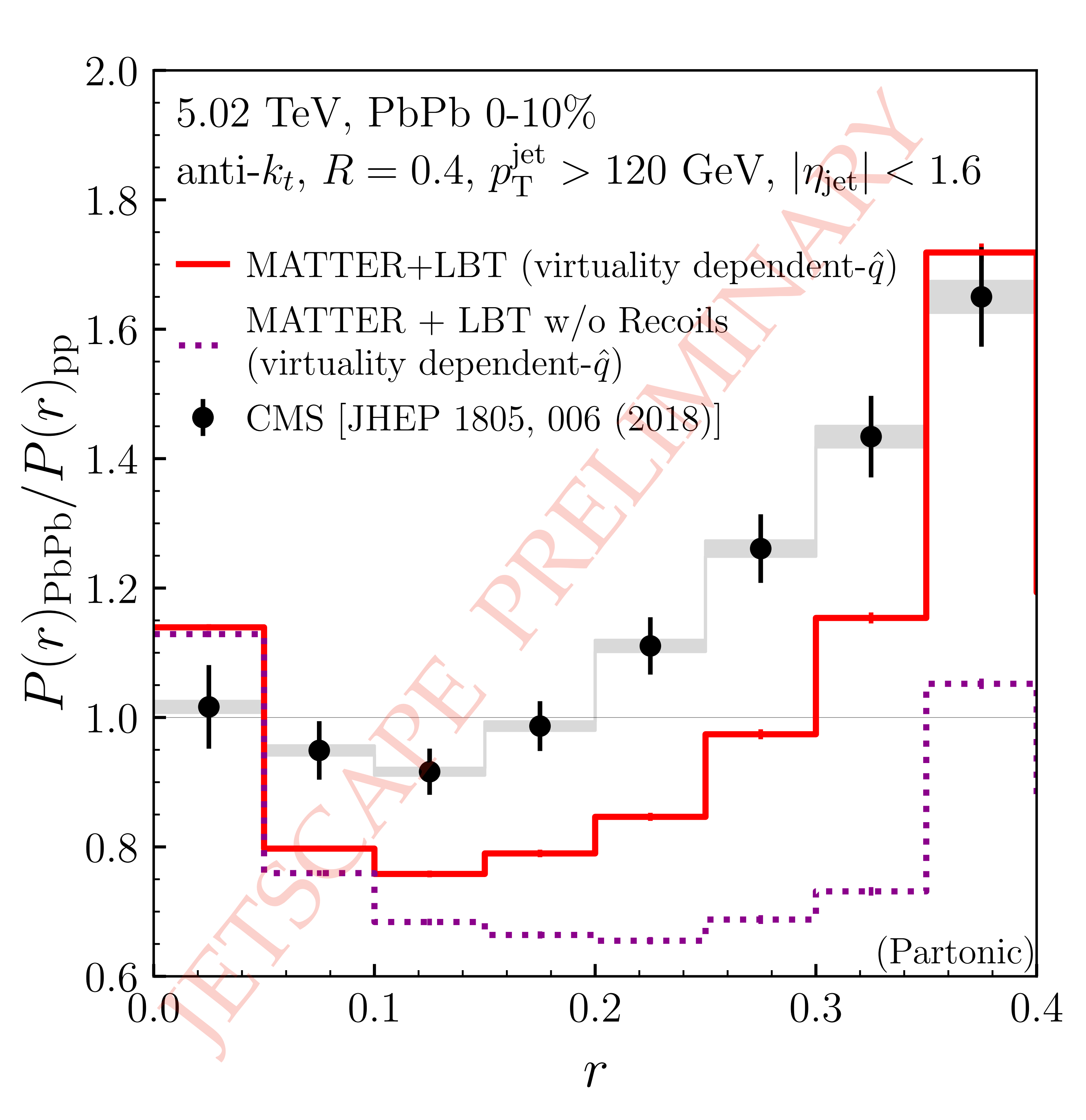
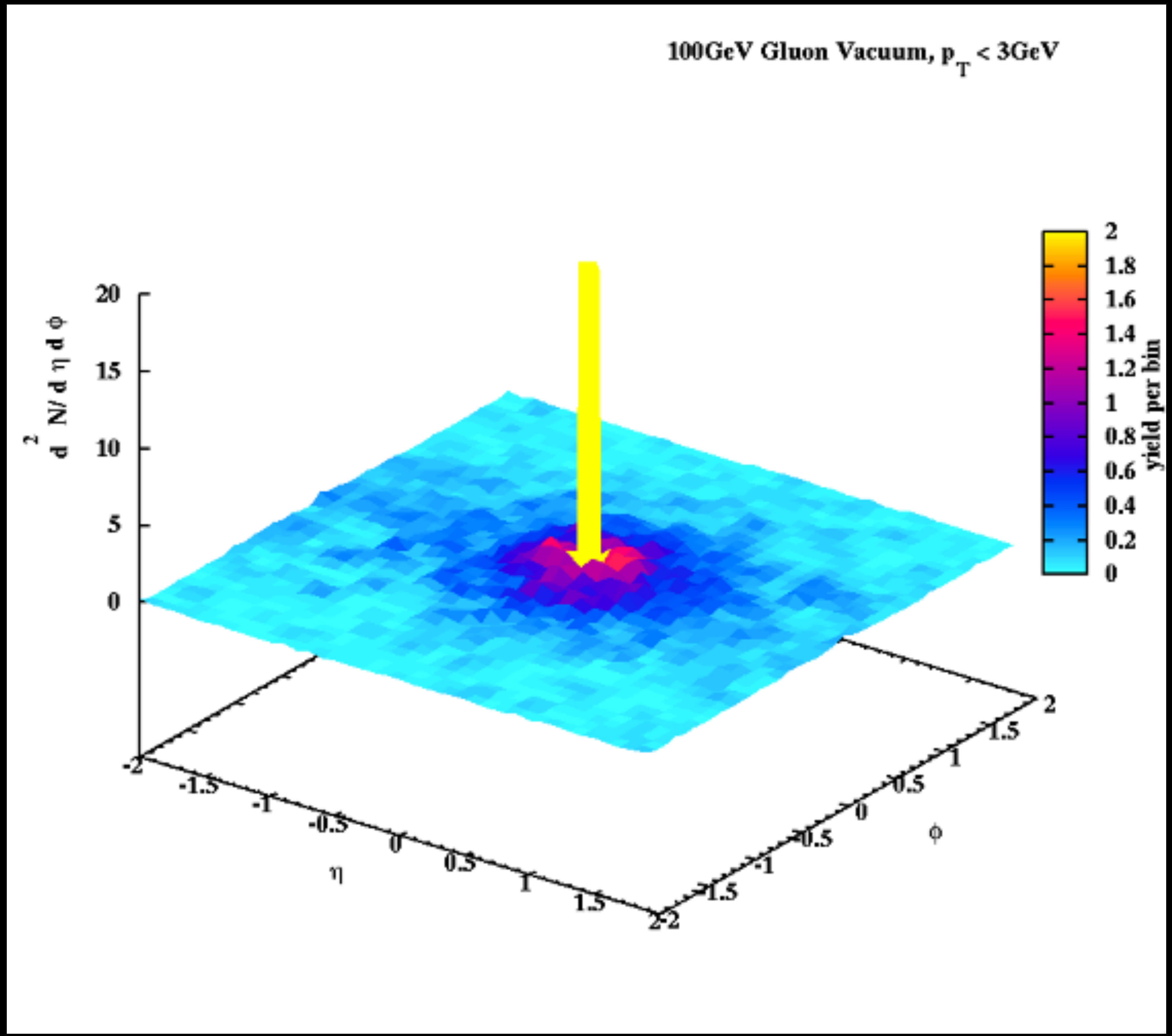
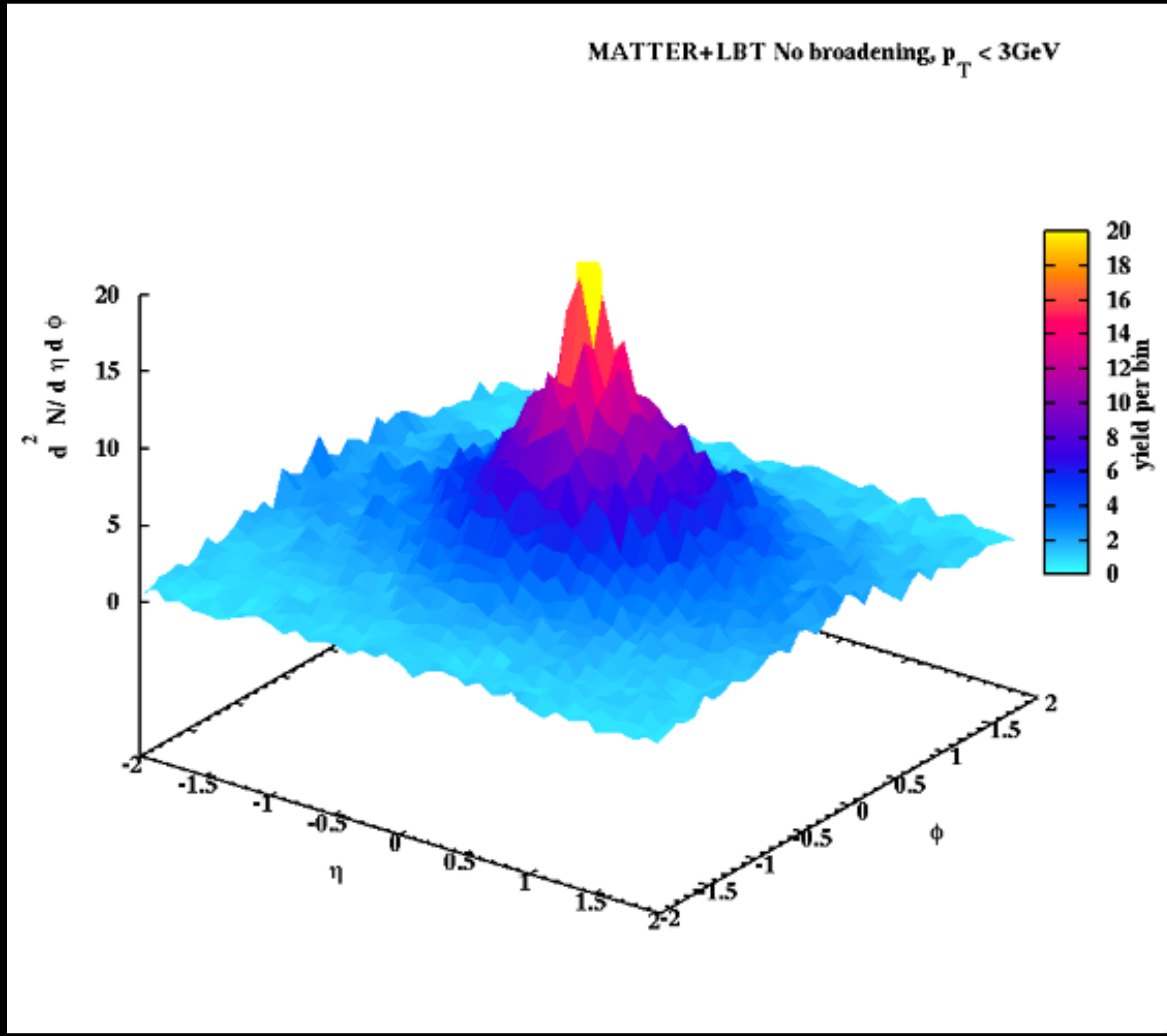


Soft jet partons move far away from the jet

Need to deposit this as an $\delta T^{\mu\nu}$ source in the fluid

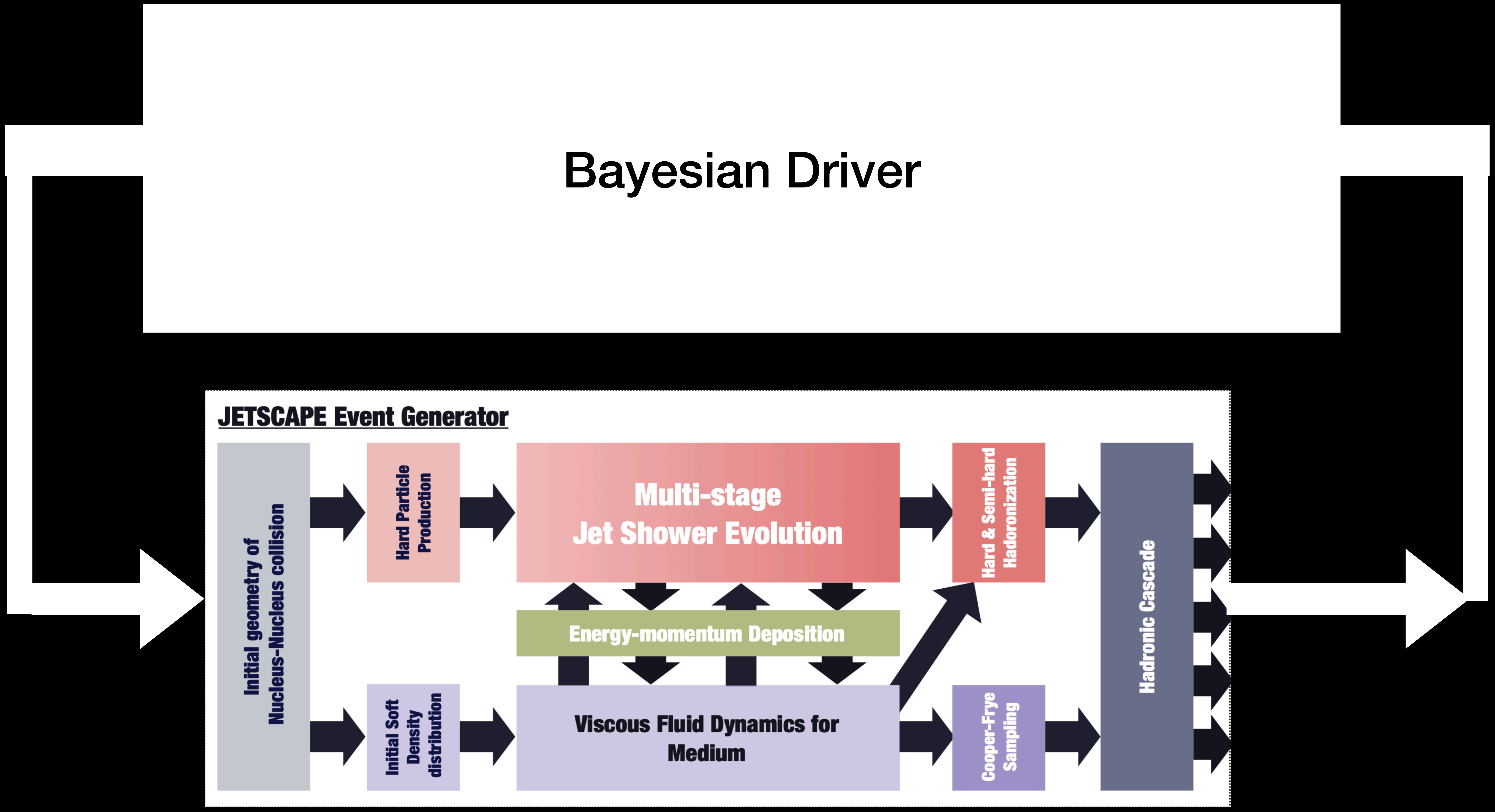




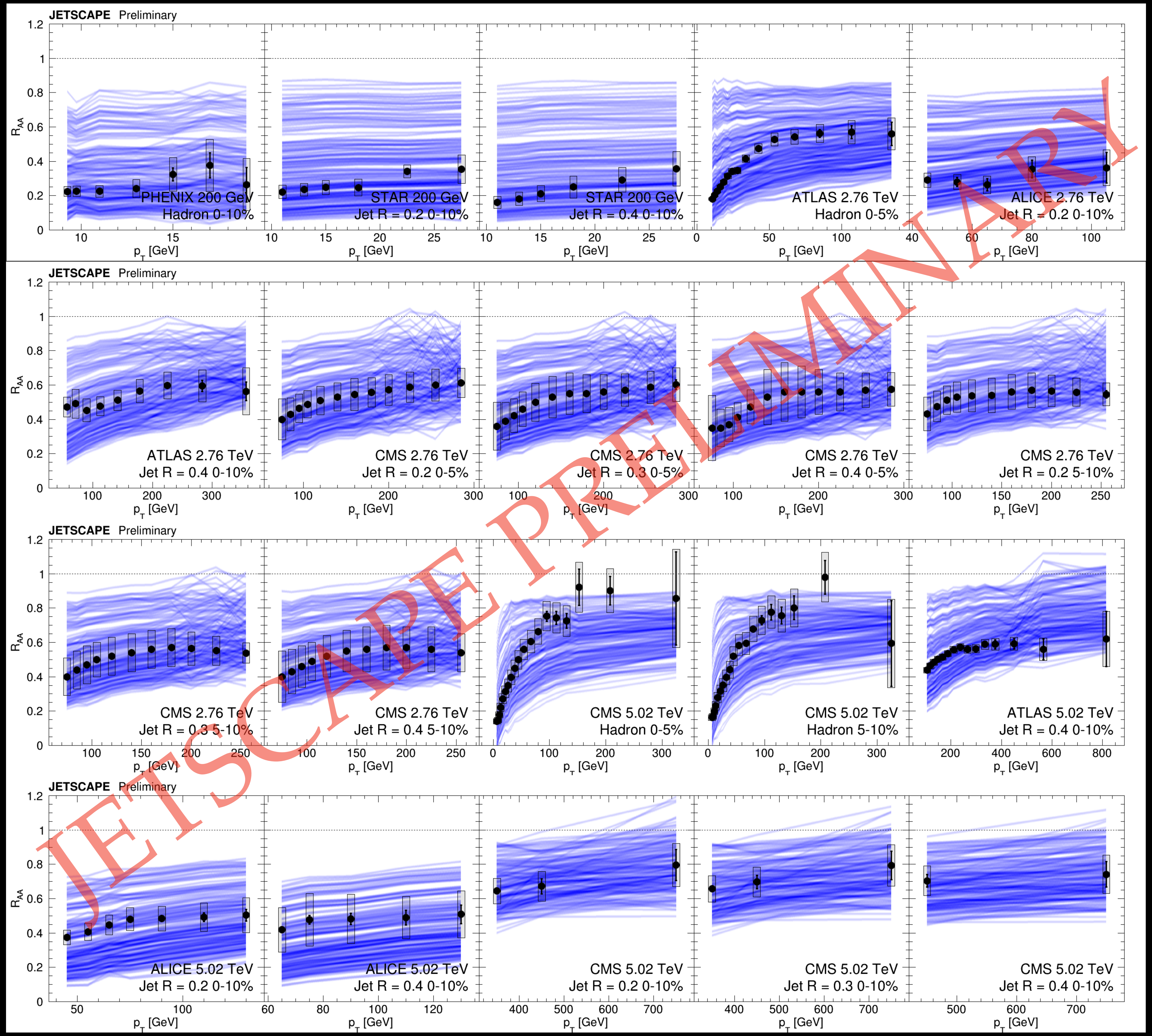
This requires to run one hydro simulation per hard event.

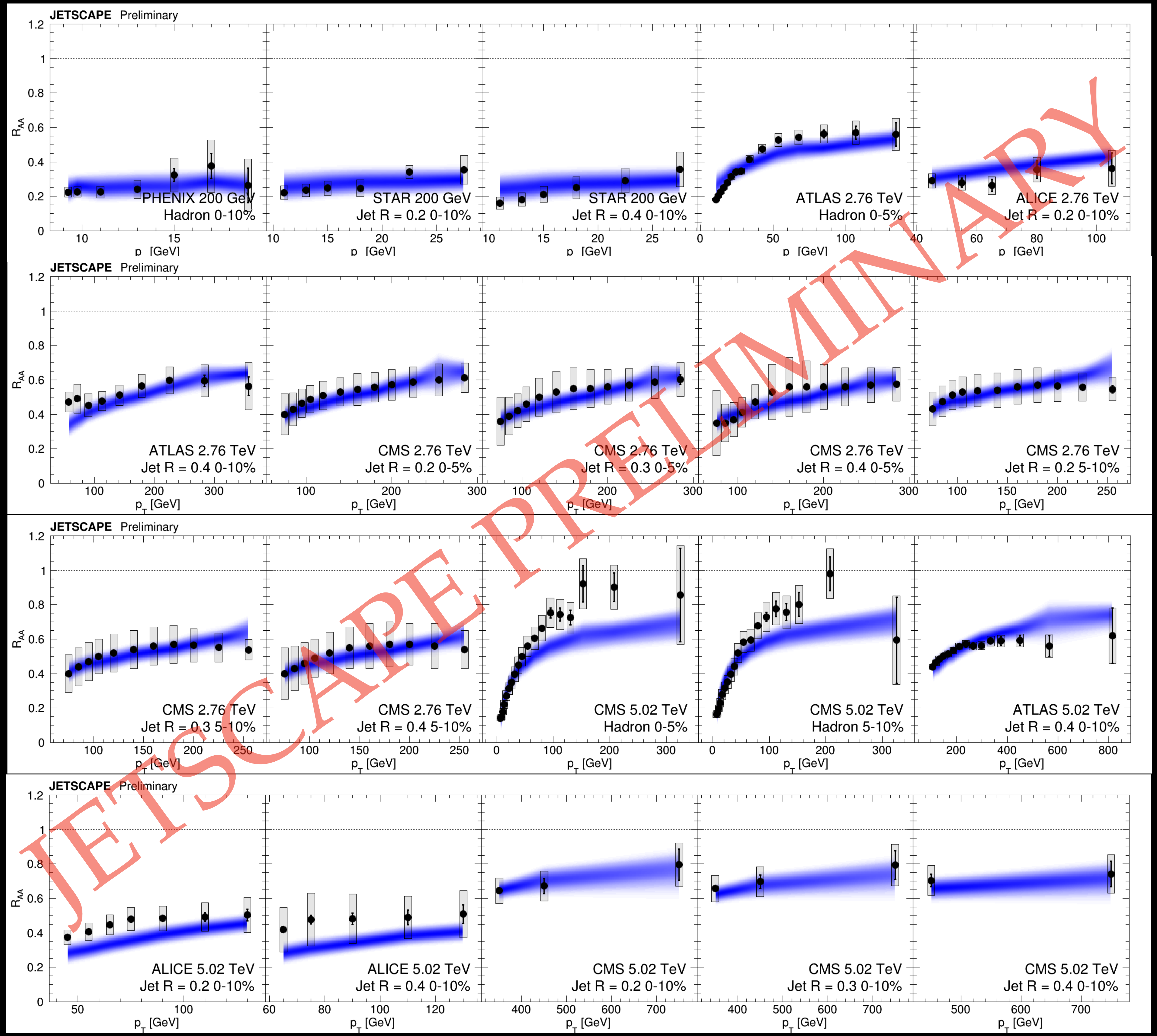
How do you test any change in the theory

Or find the best distribution of parameters, for a given theory



Bayesian with jets and hadrons at 0.2, 2.76 & 5.02TeV



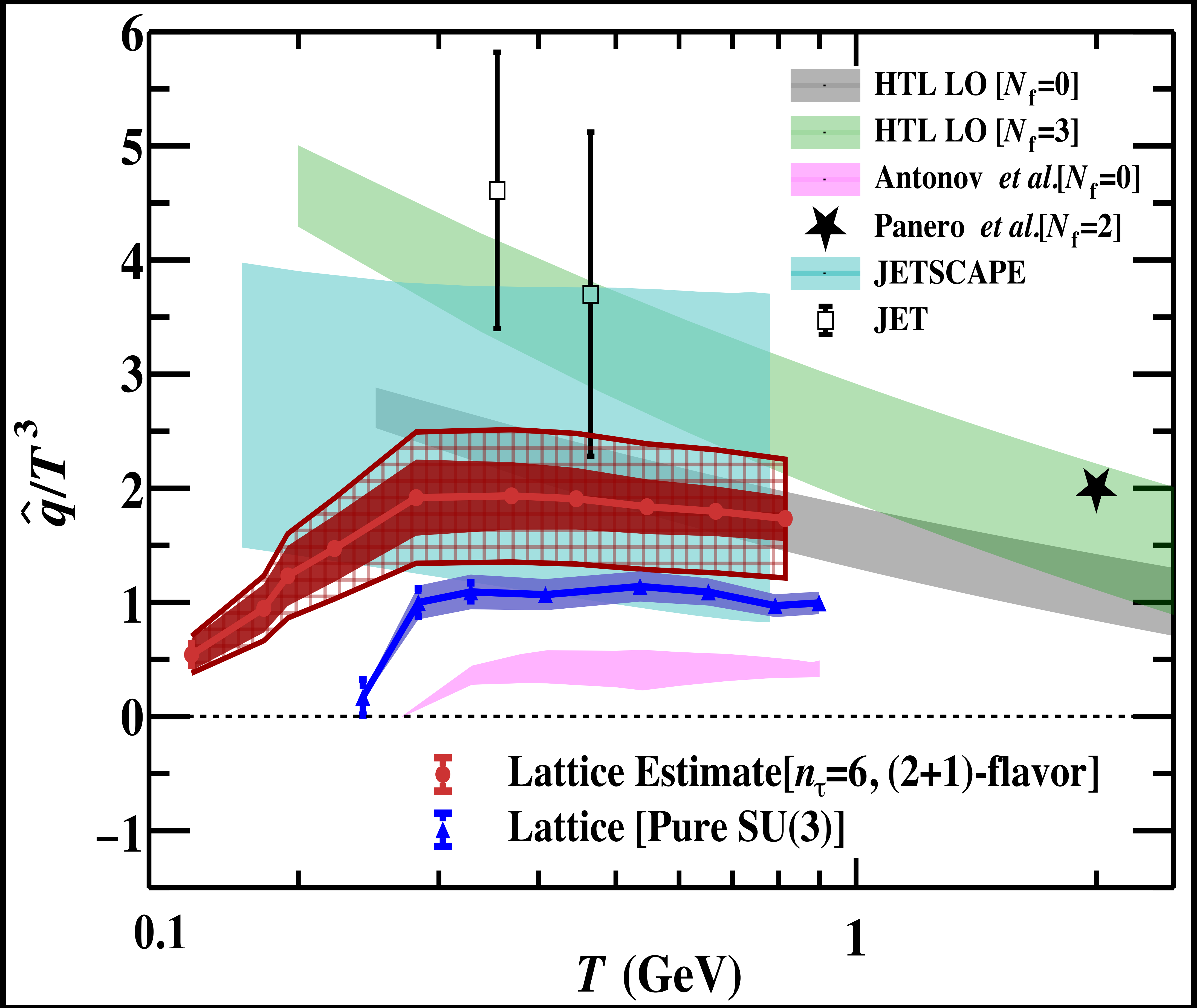


4 parameters used

See talk by Yi Chen

All of this is still a pre-requisite

- Now that a consistent framework exits we can compare extractions from data with Lattice QCD
- With both of these conditions met, we can now explore possibilities for the QGP-DOF.
- And test these in elaborate Bayesian analysis.
- Will require massive improvements on the Bayesian front.



Let's Imagine a few years into the future

A full jet+soft 3+1D calibration

- For jets need the $\alpha_S(T, \Lambda)$, Q_{sw} , τ_{start} so hard parameters = 3
- Energy loss in hadronic phase, maybe 3 parameters (nonlinear shape) = 3
- Energy deposition in fluid needs: E_{soft} ,D_{diff}, τ_{relax}, τ_{end} = 4
- We will still need like 10 parameters for the initial state (TRENTO). =10
- The equilibrating phase KOMPOST/Free streaming needs 2 = 2
- η has 5 parameters, ζ has 4, and there is a $T_{hadronization}$ = 10
- 2 more if you want to parametrize coherence = 2
- Total for combined jet and 3-D fluid (for one $\sqrt{s}$) = 34

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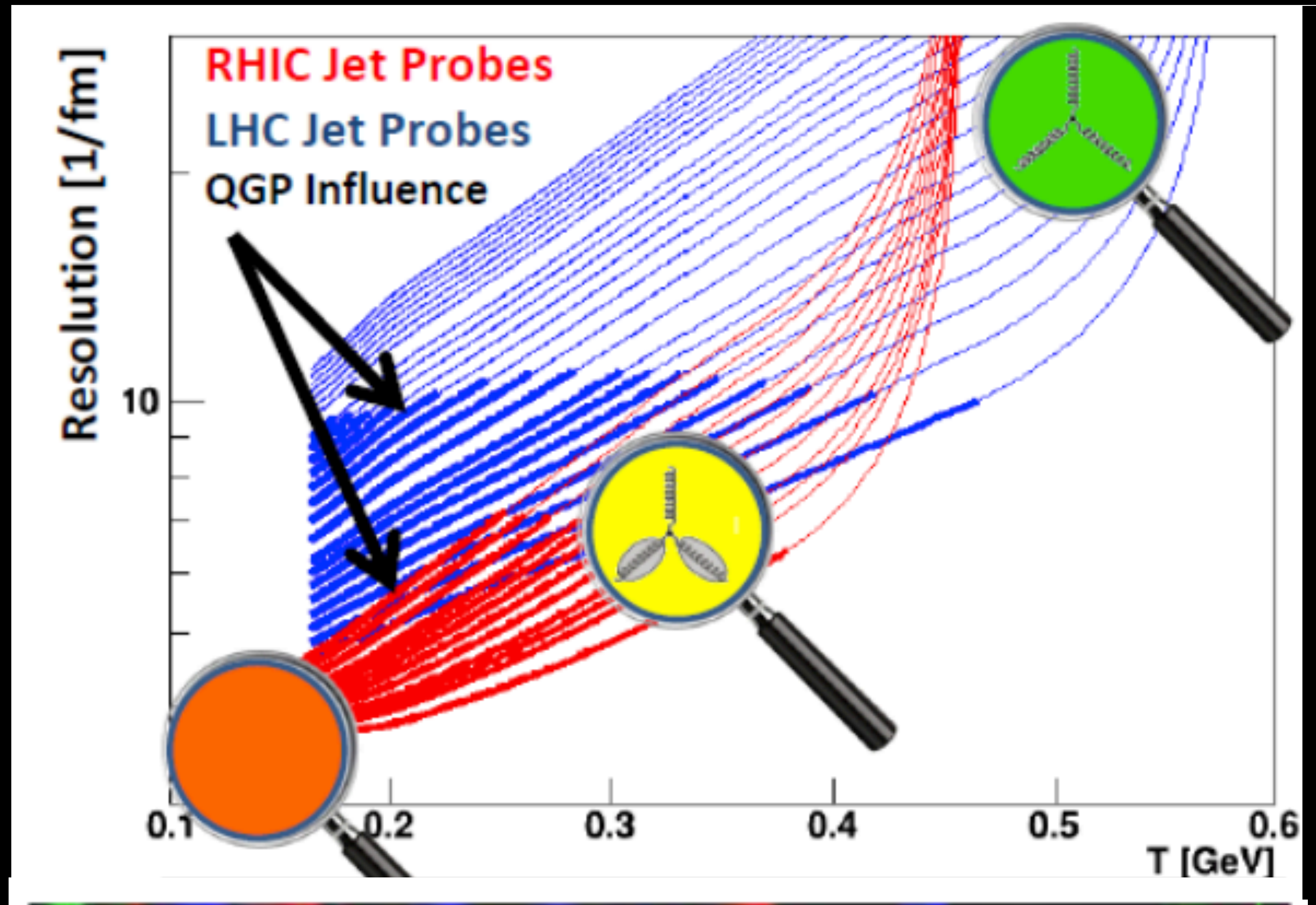
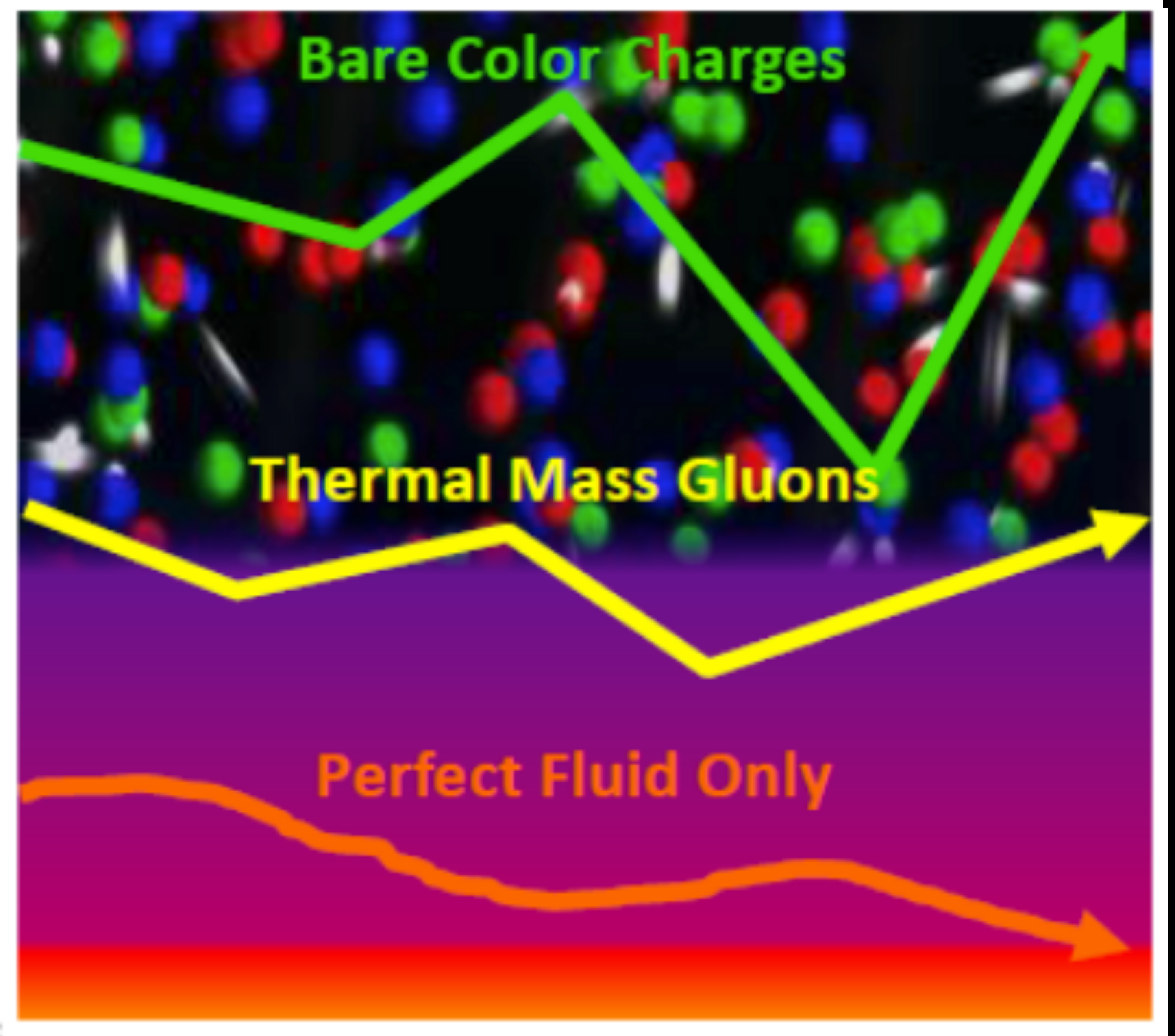
- Since Frontier has 10,000 nodes, we will need Frontier for “just” 46 years!
- Need major improvements in simulation methods and Bayesian analysis

This is where we are now

- Overarching framework to simulate and test new theories established
    - Still need a non-perturbative section for soft energy momentum deposition in the hydro.
- We can now rigorously test existing and new theories with a wide swath of experimental data
- We need enormous improvements in Bayesian methods to handle the computational complexity
- Ready for new data from LHC and sPHENIX and new theoretical improvements.





Thank you for your attention

Workshop Resolution

From the Computational Nuclear Physics Town Hall

High-performance computing is essential to advance nuclear physics on the experimental and theory frontiers. Increased investments in computational nuclear physics will facilitate discoveries and capitalize on previous progress. Thus, we recommend a targeted program to ensure the utilization of ever-evolving HPC hardware via software and algorithmic development, which includes taking advantage of novel capabilities offered by AI/ML.

The key elements of this program are to:

1) Strengthen and expand programs and partnerships to support immediate needs in HPC and AI/ML, and also to target development of emerging technologies, such as quantum computing, and other opportunities.
2) Take full advantage of exciting possibilities offered by new hardware and software and AI/ML within the nuclear physics community through educational and training activities.
3) Establish programs to support cutting-edge developments of a multi-disciplinary workforce and cross-disciplinary collaborations in high-performance computing and AI/ML.
4) Expand access to computational hardware through dedicated and high-performance computing resources.

Is there stuff that we could rule out?

- could be increasing (Mehtar-Tani & Blaizot; Iancu; Liou, Mueller and Wu)

$$\hat{q}_{Ren.}(\mu^2) = \hat{q}\left[1 + \frac{\alpha_S C_A}{2\pi}\log^2\left(\frac{\mu^2}{\hat{q}\tau_0}\right)\right], \quad with \quad \mu \lesssim E$$

- See also similar formula $\hat{q}_{Ren} = \hat{q} + \Delta\hat{q}$ from Arnold, Gorda and Iqbal.
- This is the case in the low virtuality limit.
- Corrections to the basic $\hat{q}$ formula can be additive or multiplicative corrections involving μ and/or E.
- Can a data driven approach help resolve this?

Bayesian analysis with $\hat{q}(T, E, \mu)$

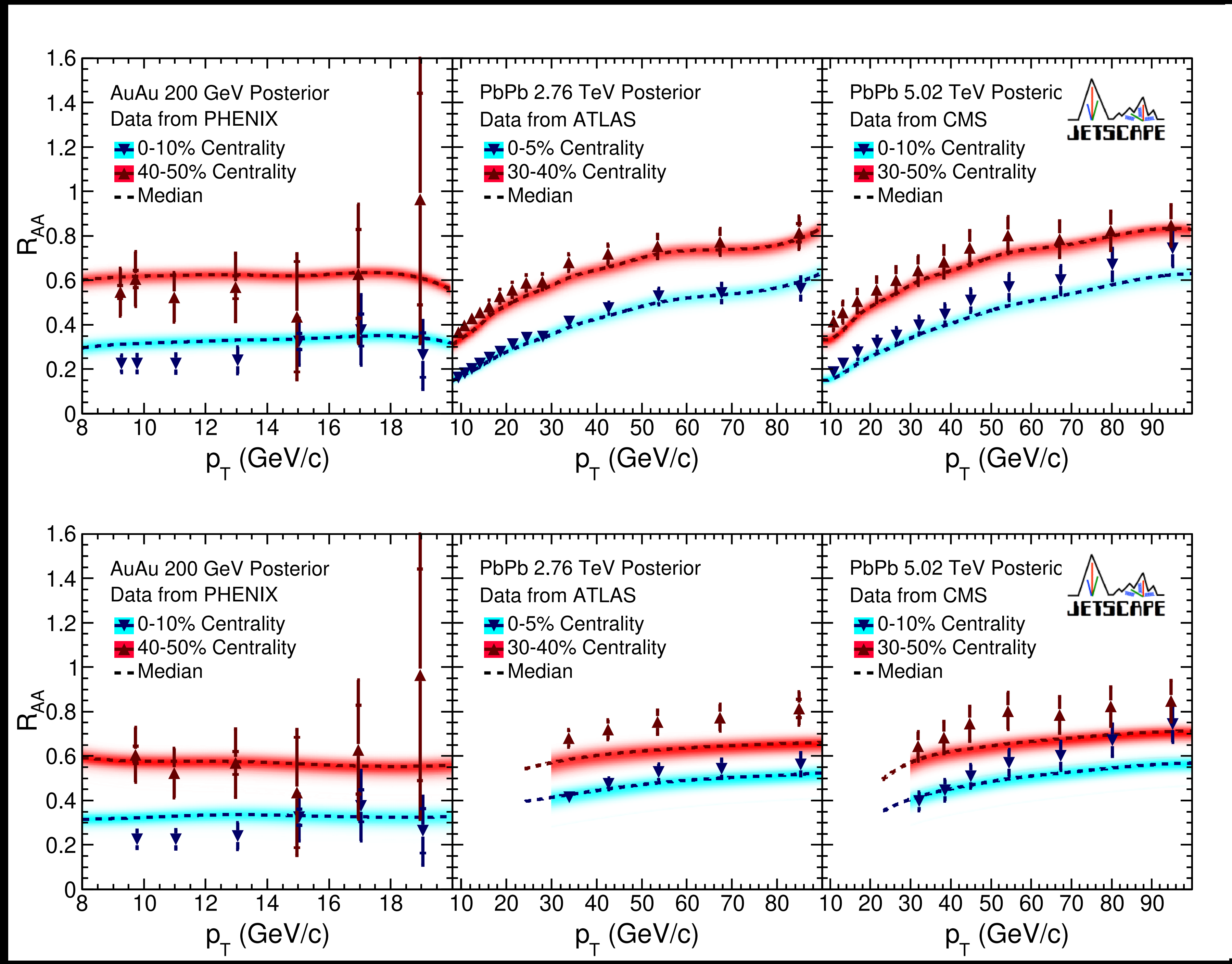
- We parametrize with

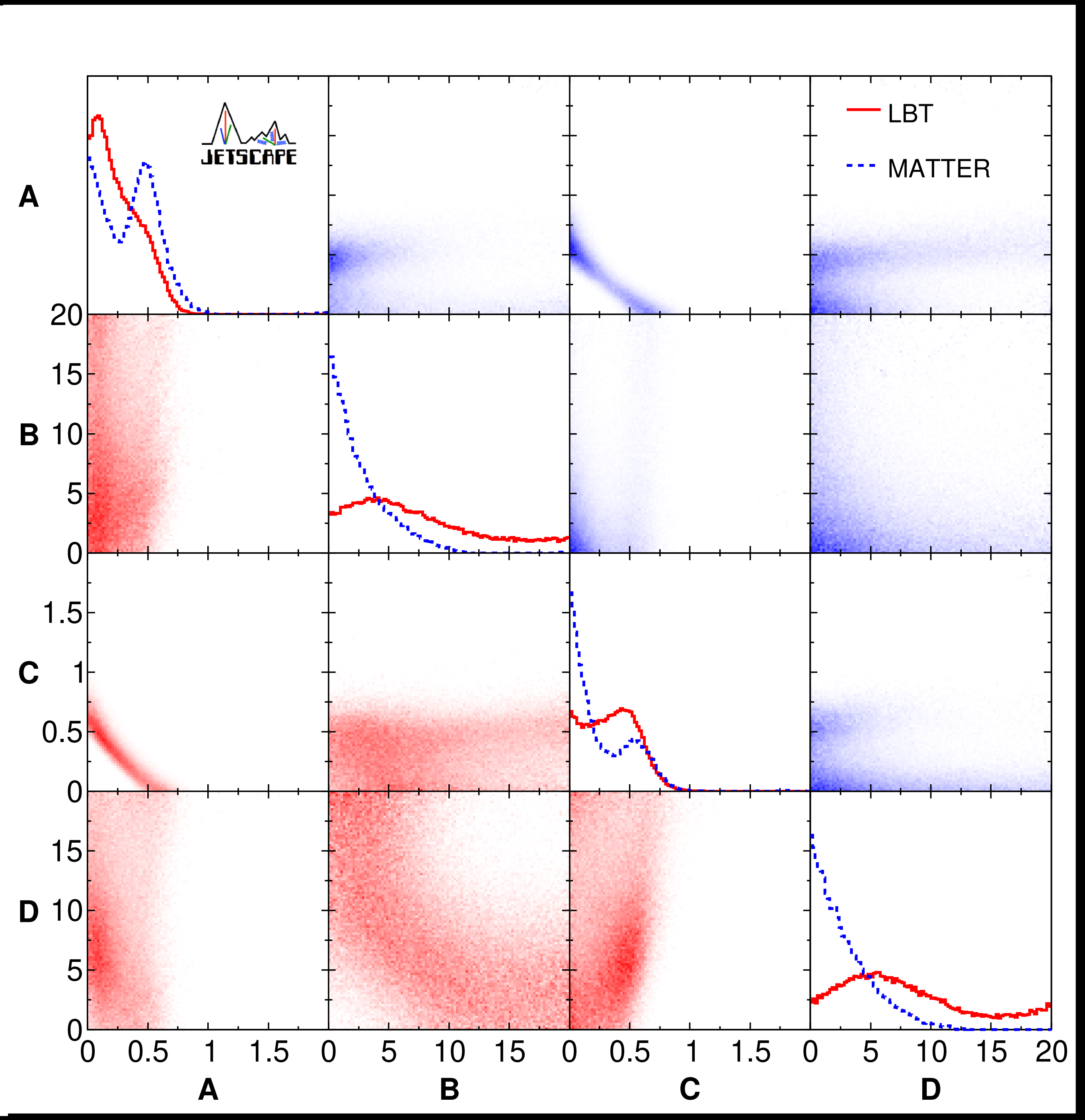
$$\frac{\hat{q}\,(E,T)\,|_{A,B,C,D}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2 \left\{ \frac{A\left[\ln\left(\frac{E}{\Lambda}\right) - \ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2} + \frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2}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

Additive approximation

No coherence

- Compare with single hadrons at RHIC 0.2 + LHC 2.76 + LHC 5
- Central + semi-Central
- MATTER & LBT applied separately
- Fit improves!
- MATTER and LBT select different parts of formula





S. Cao et al. Phys.Rev.C 104 (2021) 2, 024905

This is where we are now

- We added one more parameter Q_0, transition between high and low virtuality.
- Multi-stage set up seems to able to explain almost all the data
- The Bayesian calibration is being conducted as we speak
- Will rigorously test picture of 2-stage energy loss, with HTL based kernel at $\mu < Q_0$, and gradual weakening for $\mu > Q_0$
- A portion of the quenching will always be non-perturbative and subject to modeling!

Summary of presented plots

- All simulations carried out on a calibrated fluid profile
- All simulations reproduce p-p on removal of medium
- All simulations have a consistent recoil and $\hat{q}$ incorporation
- The multi-stage (or scale dependent jet modification) seems to be able to describe
  - Jet and leading hadrons simultaneously
  - Centrality dependence
  - Collision energy dependence
  - Intra jet observables
  - Coincidence with hadrons and photons
  - Heavy quarks
  - Azimuthal anisotropy
  - R dependence of R_{AA} (sort of)
- Minor effects still being studied in jet anisotropy, jet shapes etc.
- Is the medium made of quasi-particles or not? We are getting closer to answering this question.

A complete change of paradigm in the last 6 years!

How jets interact with the medium and evolve depends on

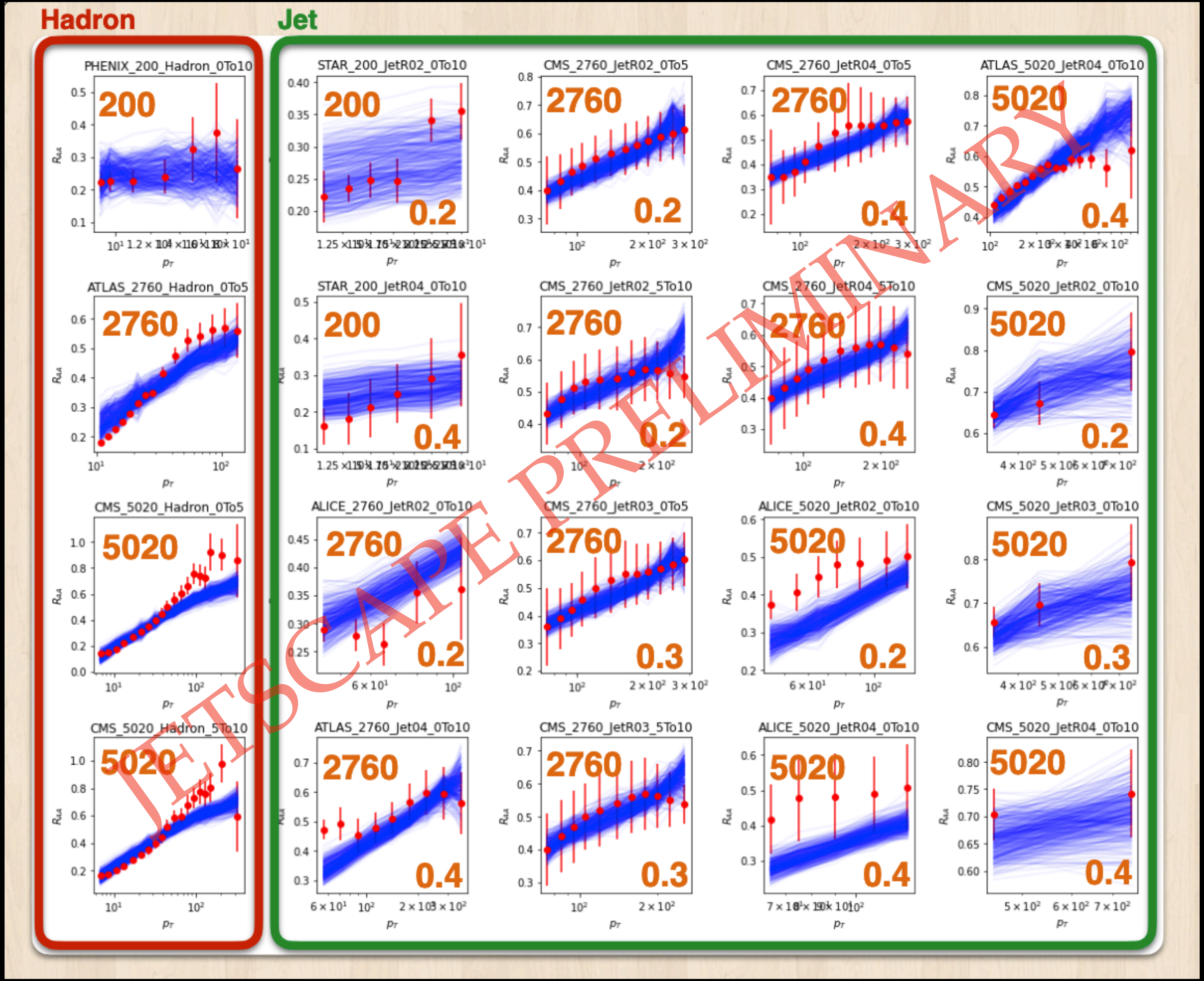
- Temperature of the medium
- Energy of the jet
- scale of the parton in the jet (E, μ^2)
- other scale of the medium $(\hat{q}\tau)$

Different approaches to E-loss are valid in different epochs of the jet

A complete description requires all of these approaches

Discussion moves to boundaries between approaches

Preliminary Bayesian analysis with JETSCAPE 3.4



Posterior distributions from STAT WG in JETSCAPE

Remarkable improvement from JETSCAPE 0.x

Coherence + Qswitch as described before

Calculations do not contain nuclear shadowing

Fluid dynamical simulations and jets

- Fluid simulations are now extremely accurate in determining bulk properties
- Yield well calibrated medium
- Hydrodynamics assumes local thermal equilibrium
- $\hat{q}$ should be constrained by local properties like $T, s, \epsilon, u, \ldots \eta, \zeta \ldots$
- Once the functional form of $\hat{q}$ as a function of T is given, it should not be recalibrated.