Results from JETSCAPE

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For the JETSCAPE Collaboration

Winter Workshop on Nuclear Dynamics, Puerto Vallarta, Mexico Feb 6th - 10th

Outline

- Intro to JETSCAPE
- Review of results from bulk calibration
- Simulation of jets in calibrated media
- Multi-stage jet evolution
- Focus on hard sector of jets
- Coherence in energy loss
- Preliminary results from Bayesian calibration.

What is JETSCAPE

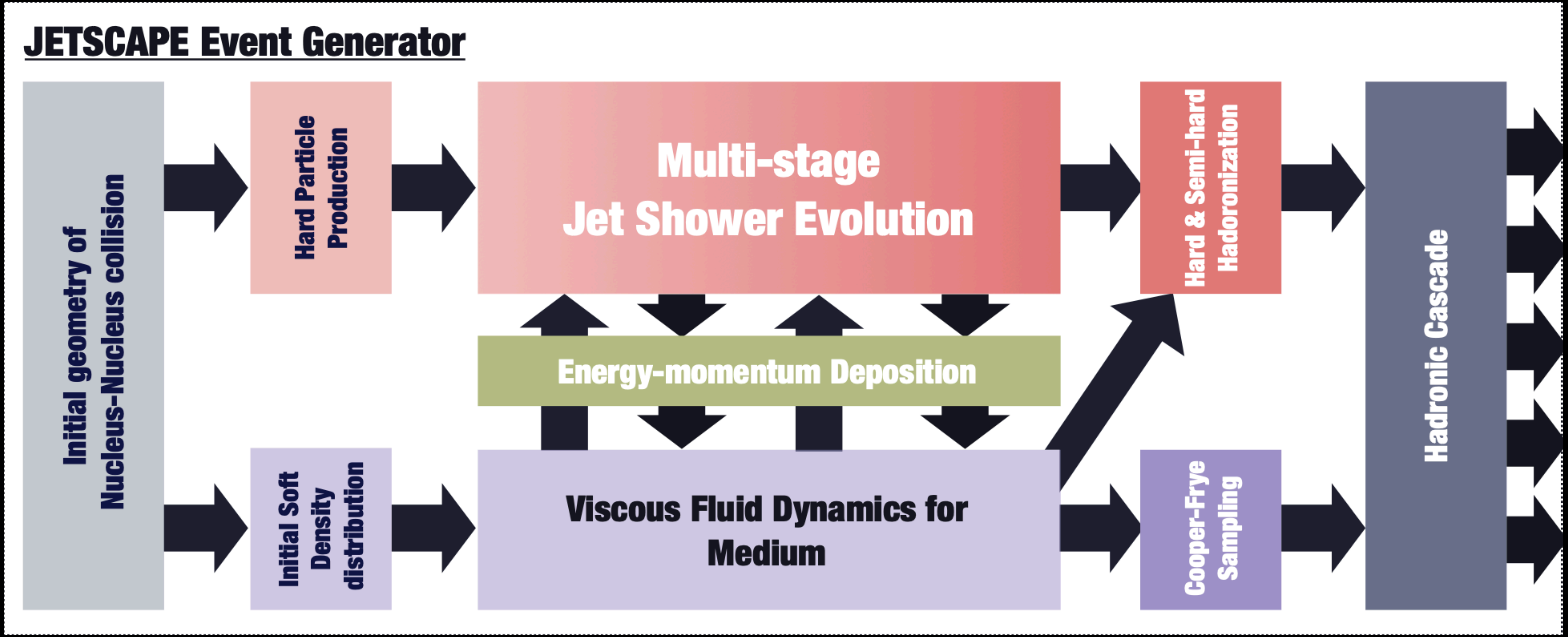
Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope

- NSF funded interdisciplinary collaboration of theorists, experimentalists, computer scientists and statisticians.
- Building an open source framework (https://github.com/JETSCAPE) and modules for event generation of A-A, p-A, p-p, from top LHC to low SPS and eventually e-A.
- Building an open source Bayesian calibration framework to compare modular event generators and data.
- Calibrate event generators and carry out systematic & exhaustive comparisons with experimental data.

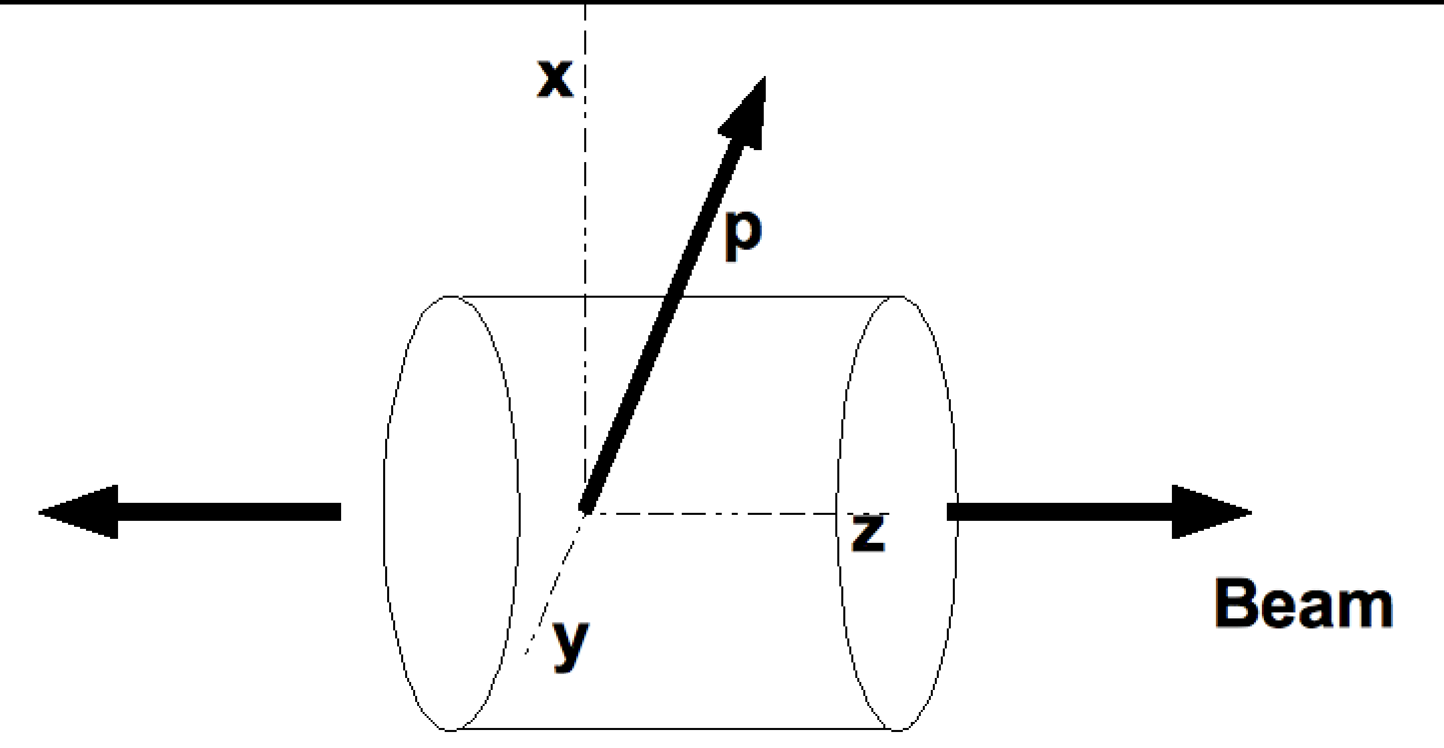
The JETSCAPE event generator

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

Modular, customizable!

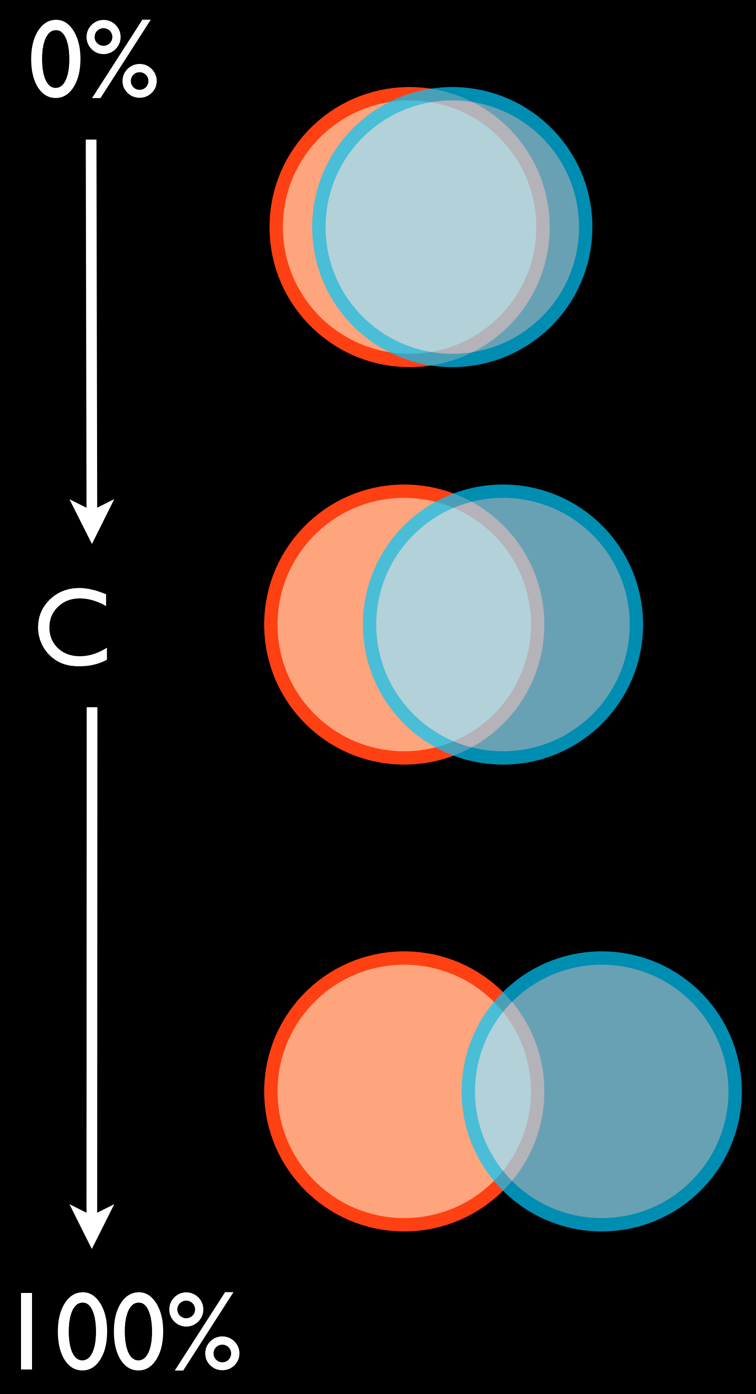


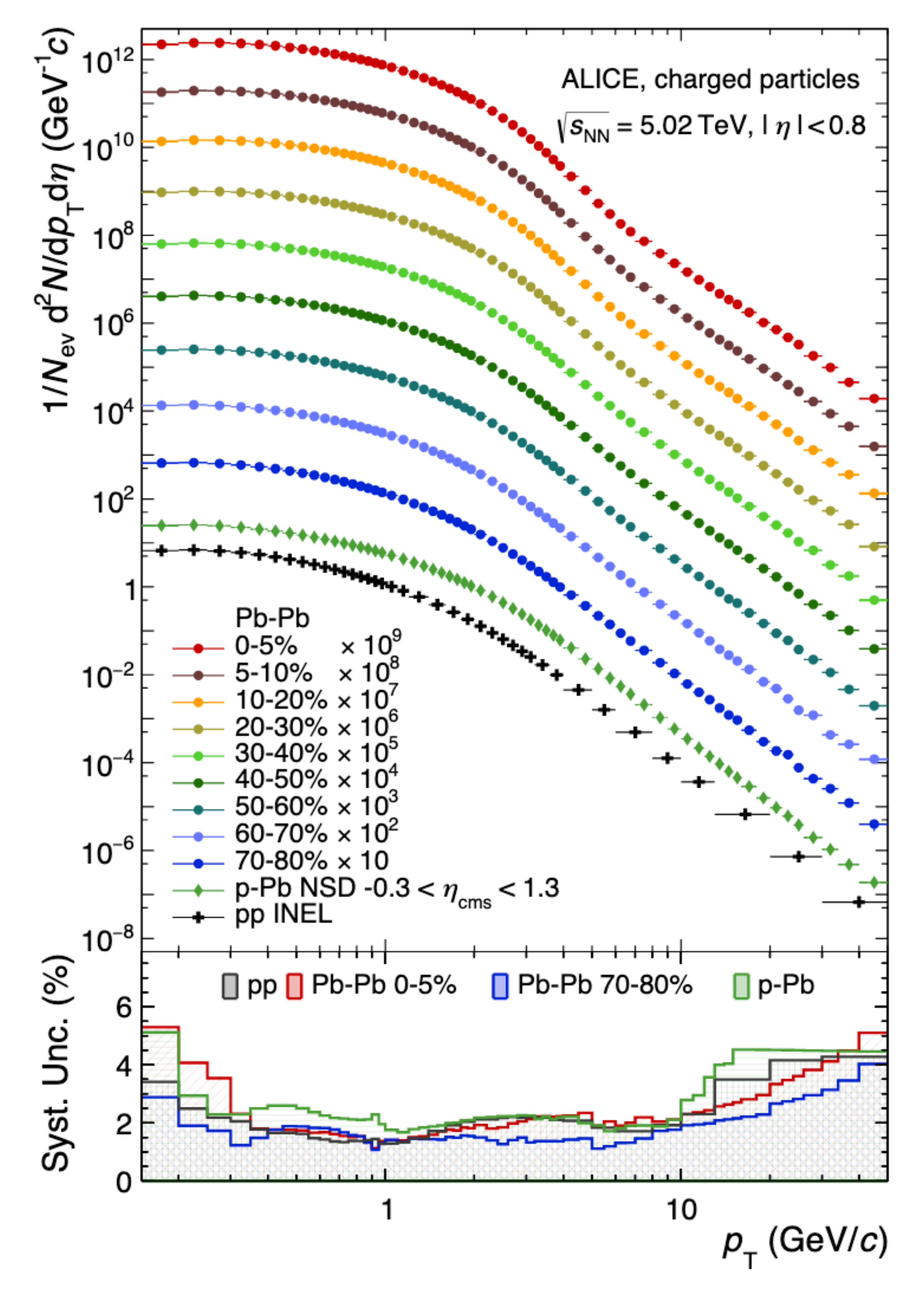
Spectra from a Heavy-Ion collision at LHC



$$p_T^2 = p_x^2 + p_y^2$$

$$y = \frac{1}{2}\log\left|\frac{E + p_z}{E - p_z}\right| \qquad \eta = \frac{1}{2}\log\left|\frac{p + p_z}{p - p_z}\right|$$





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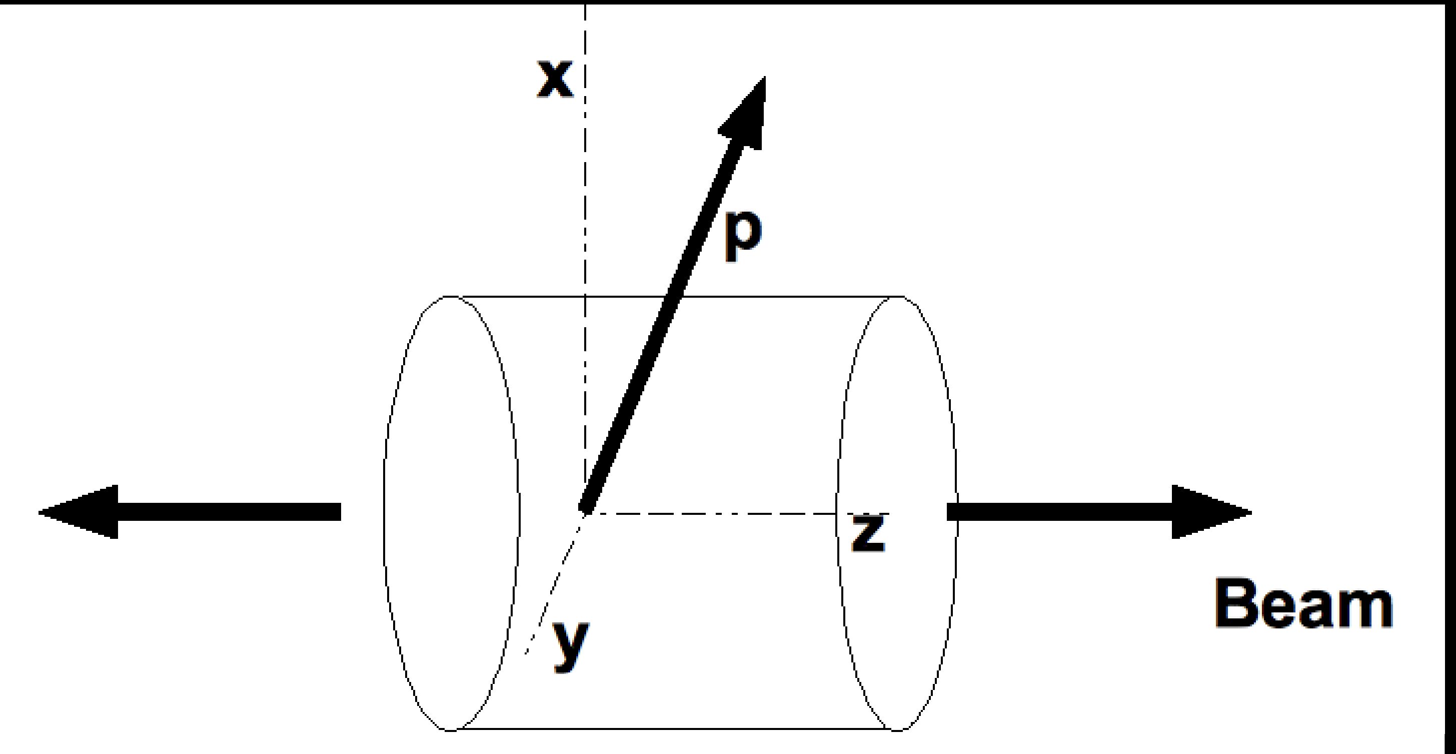

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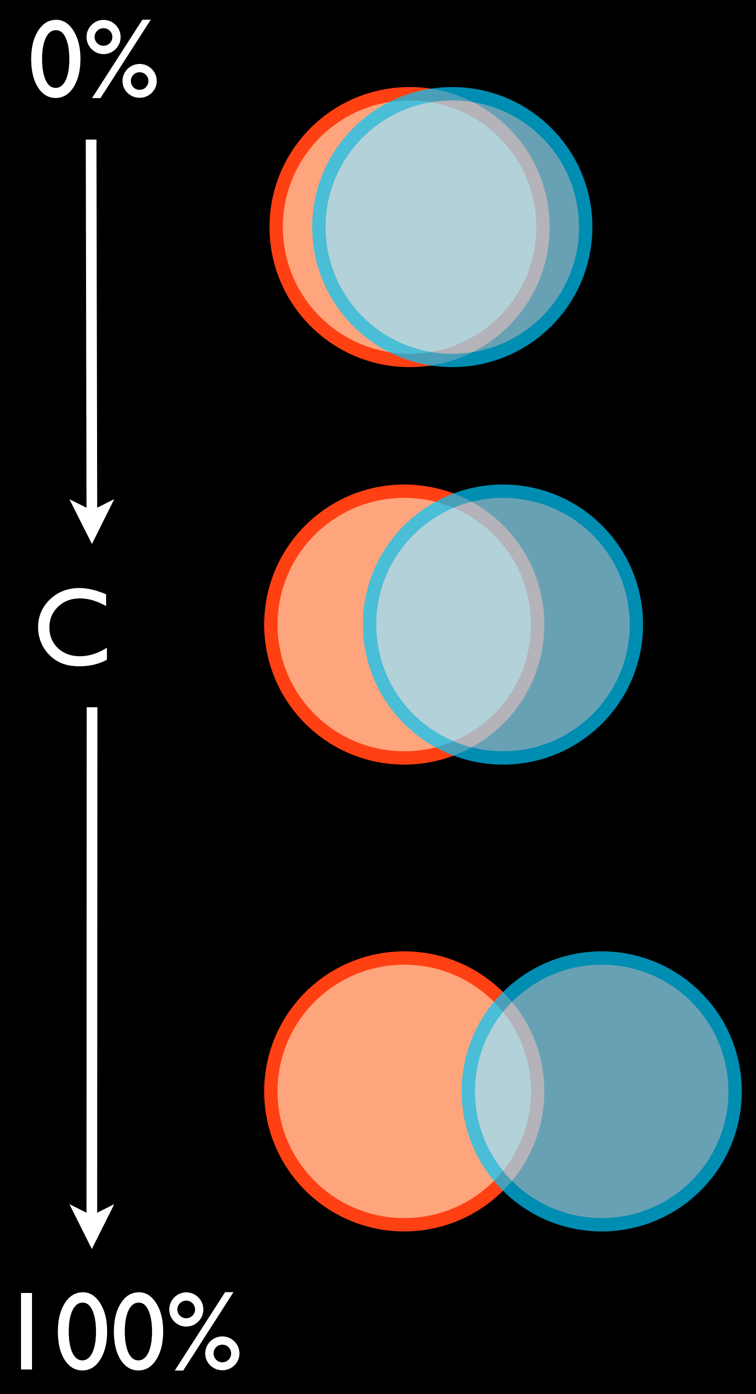

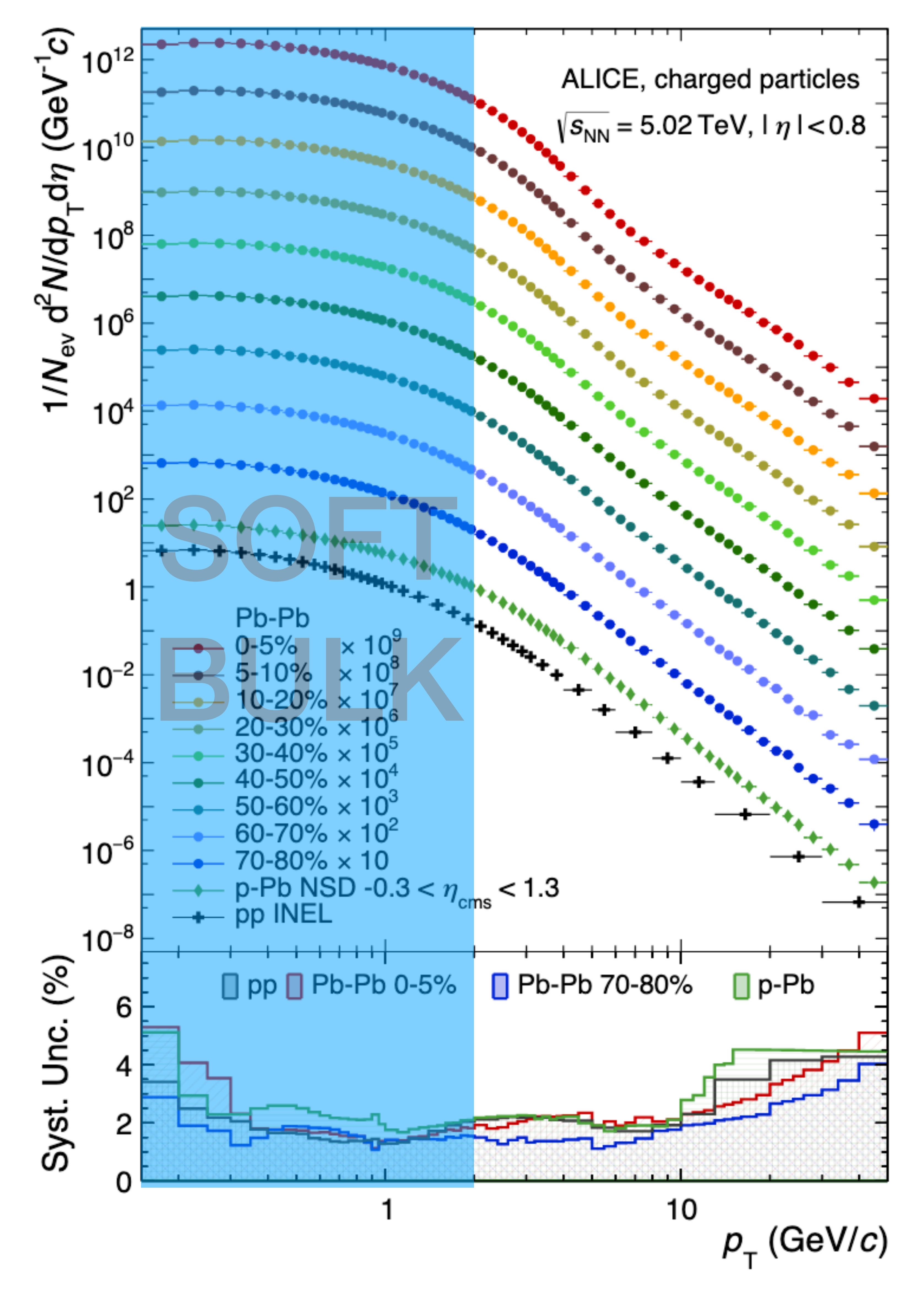

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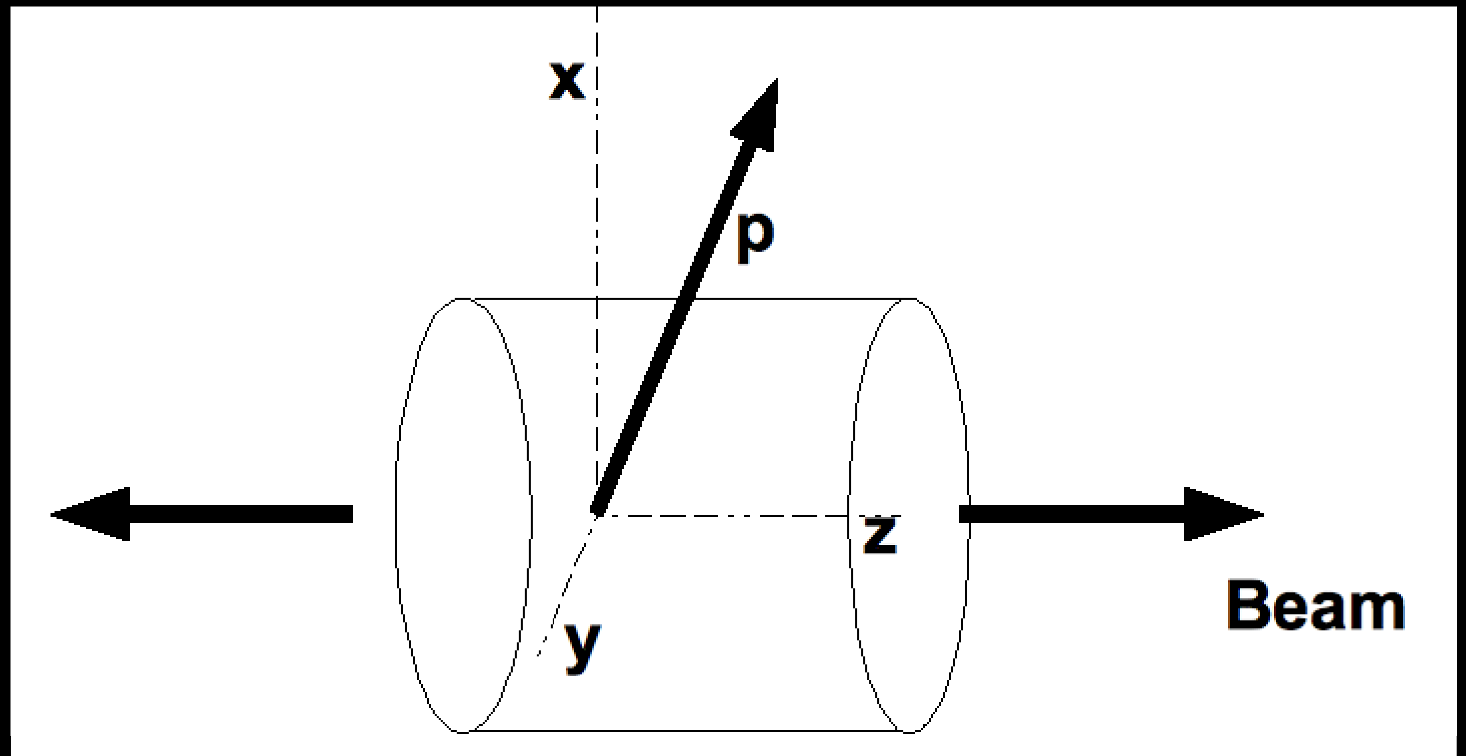

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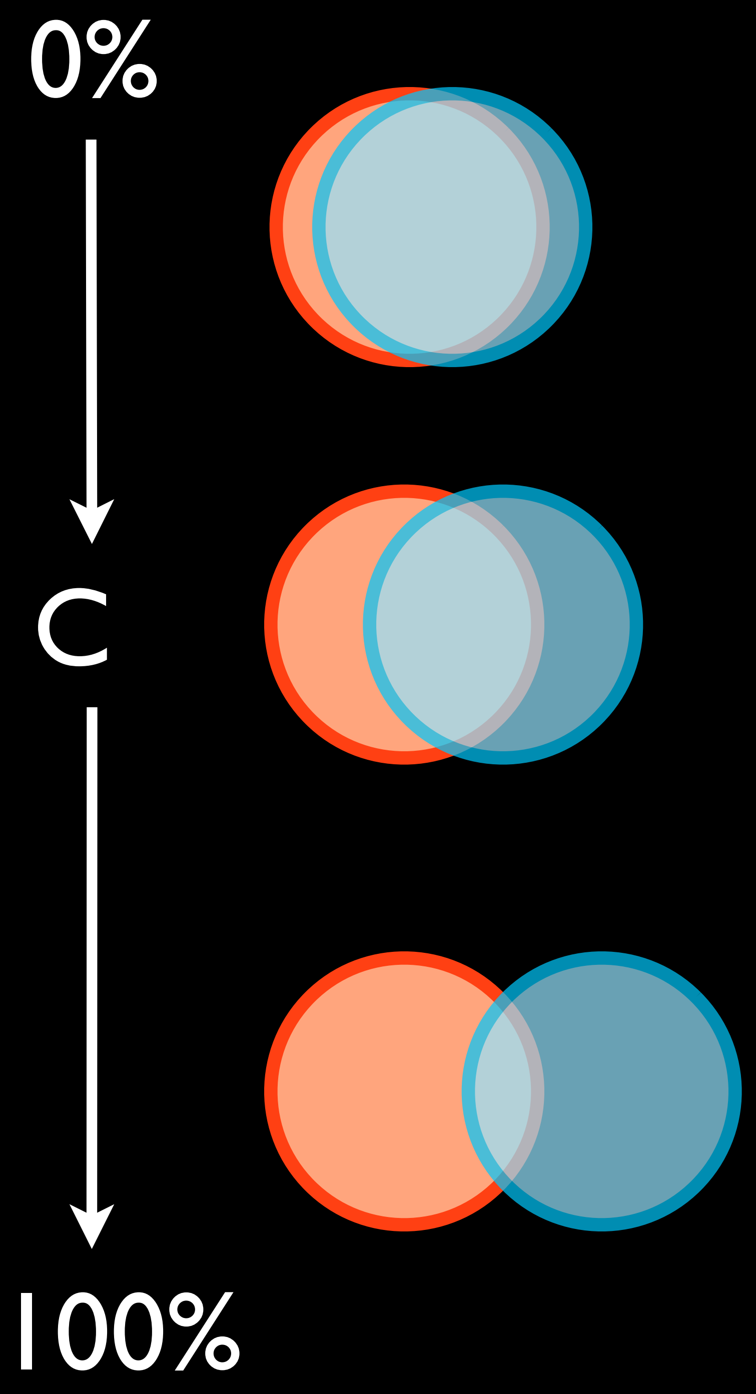
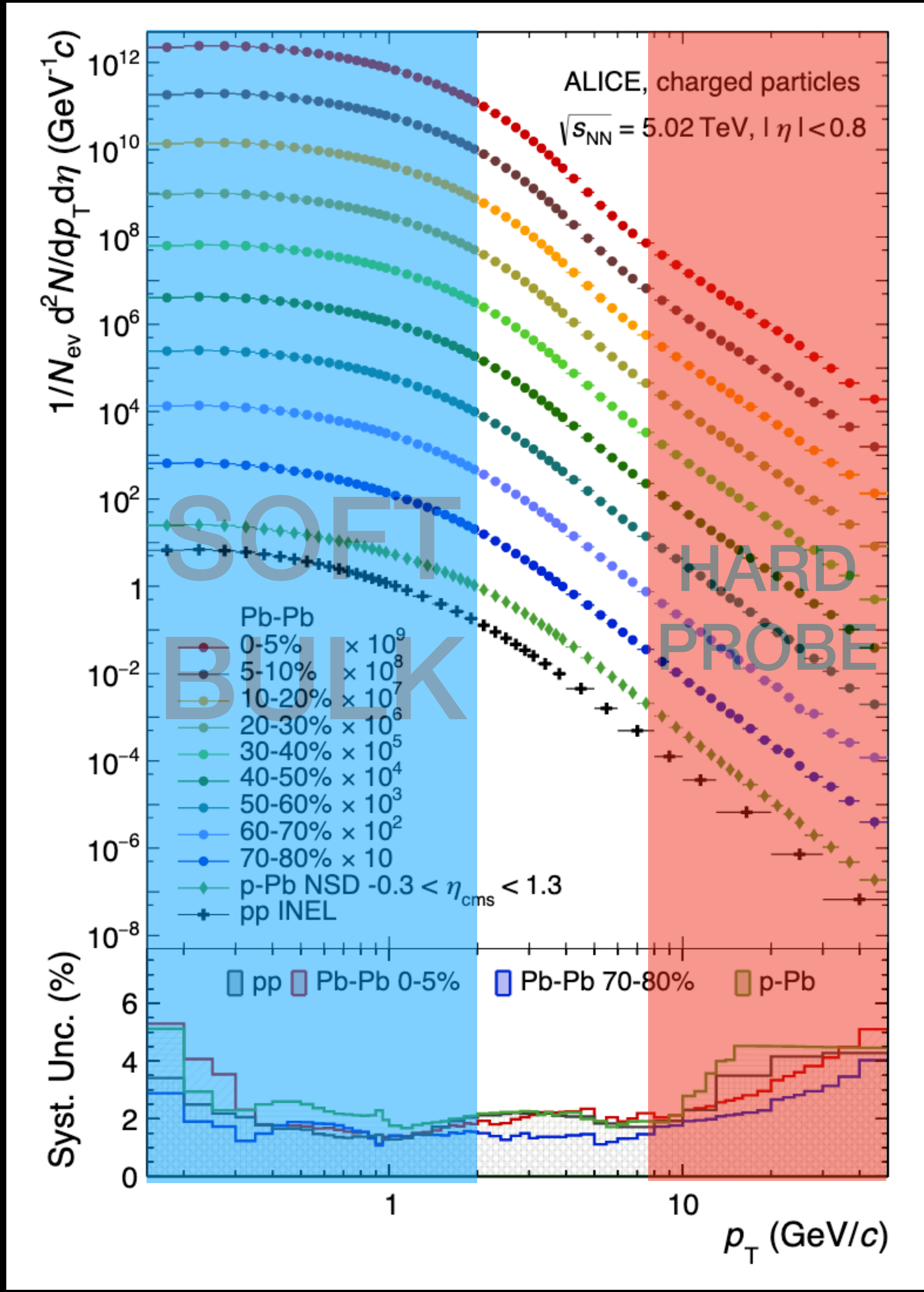




The JETSCAPE event generator

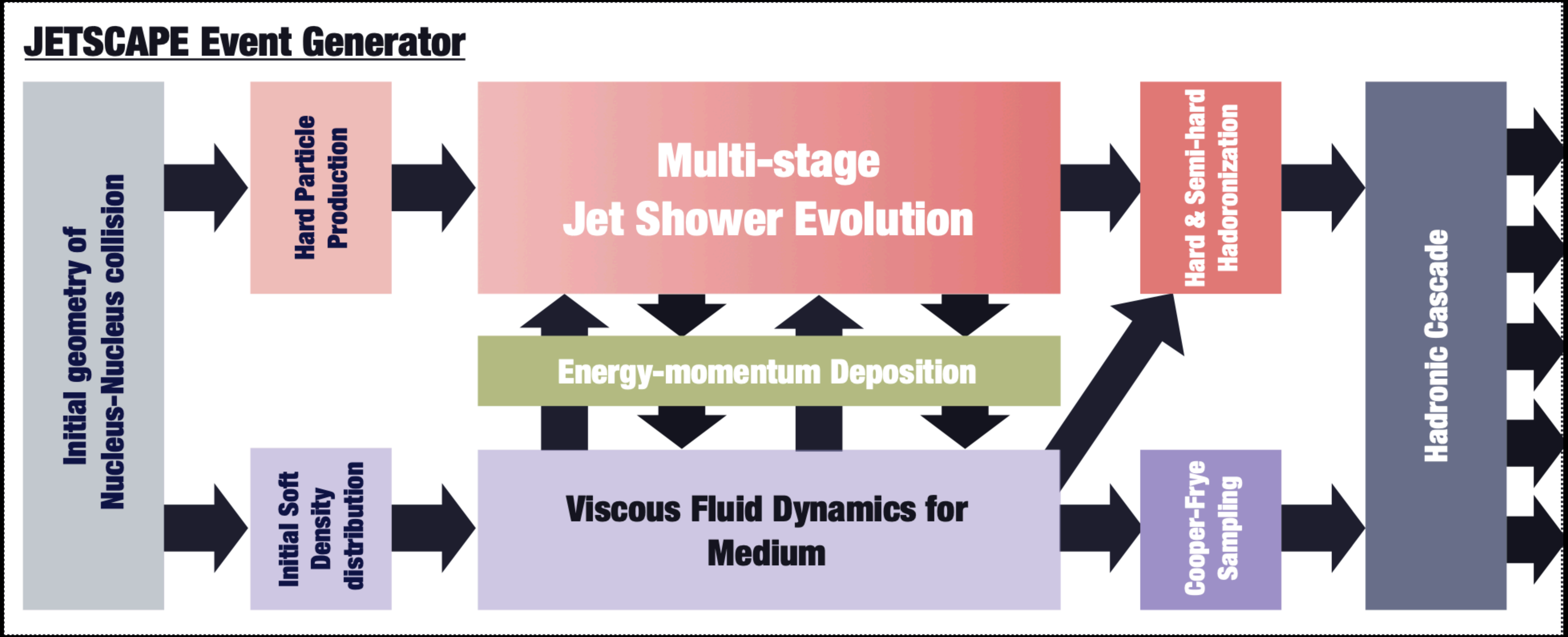
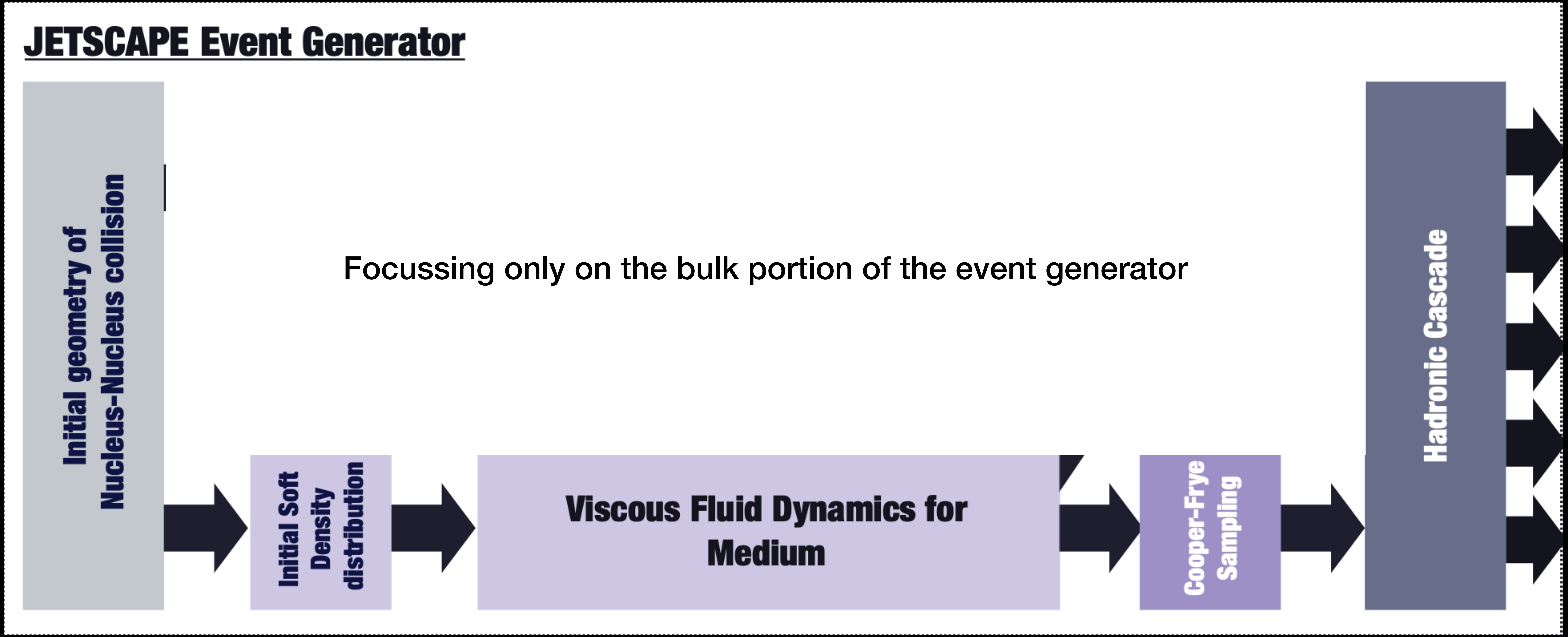


Diagram by Y. Tachibana

The JETSCAPE event generator



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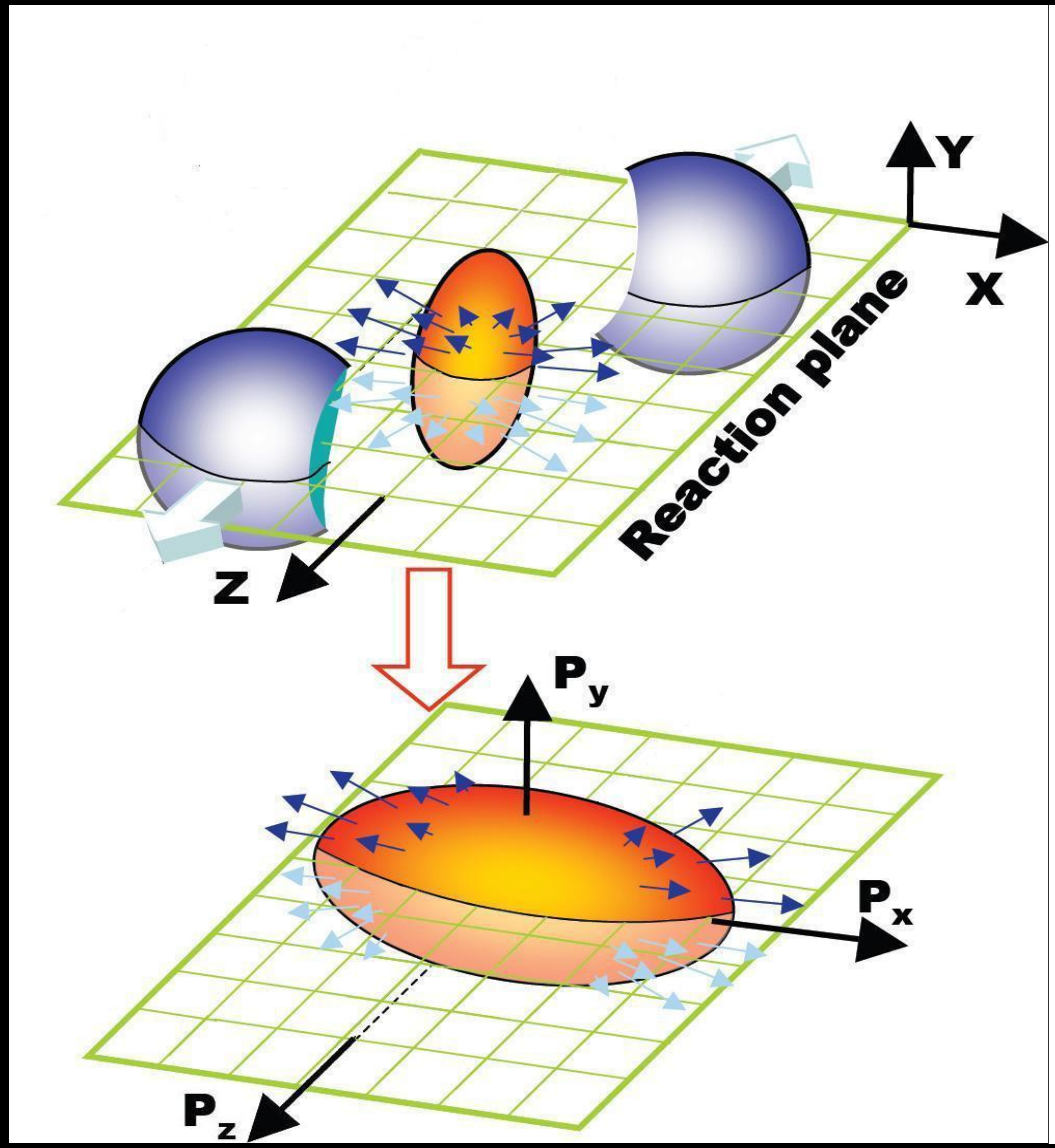
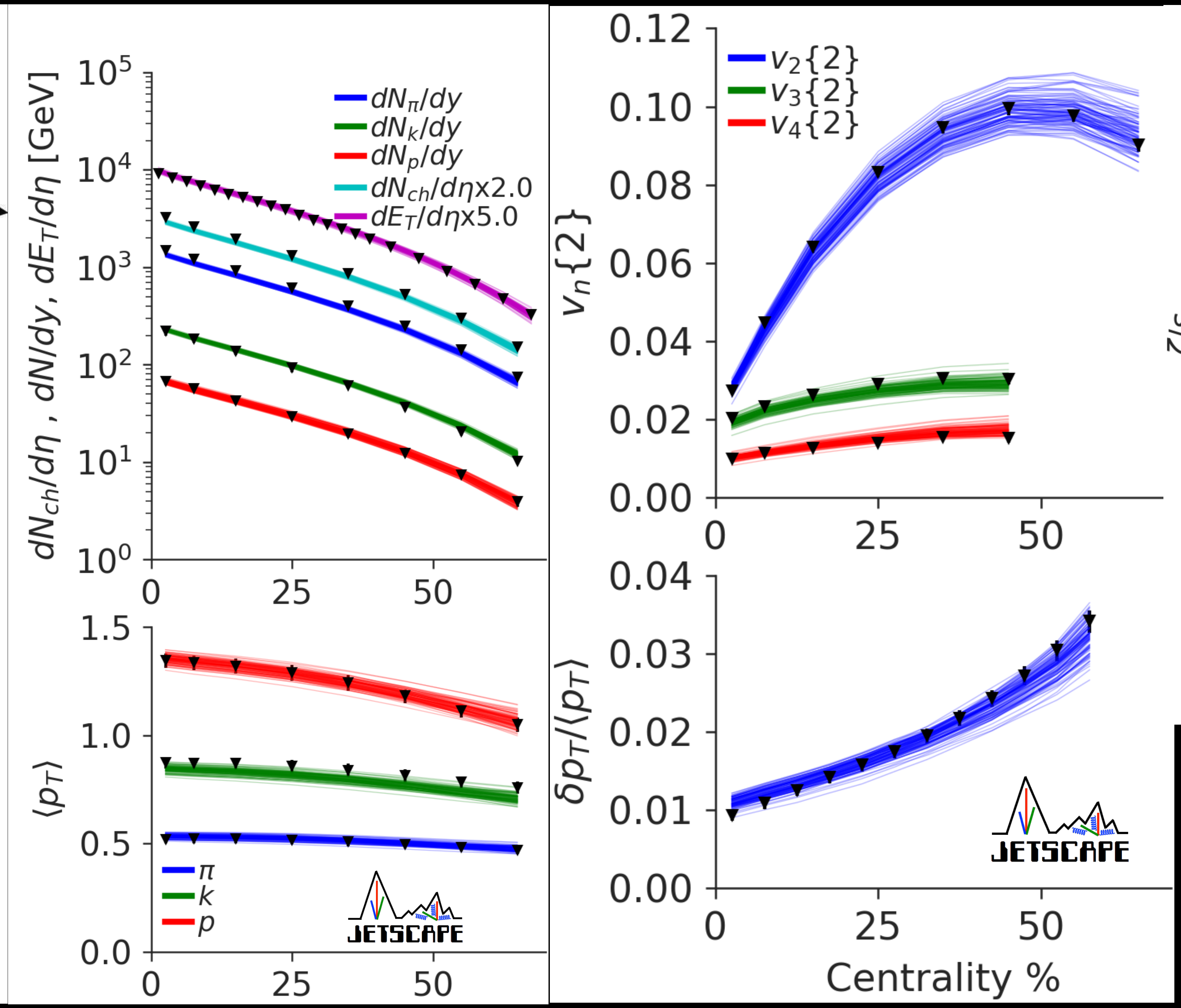
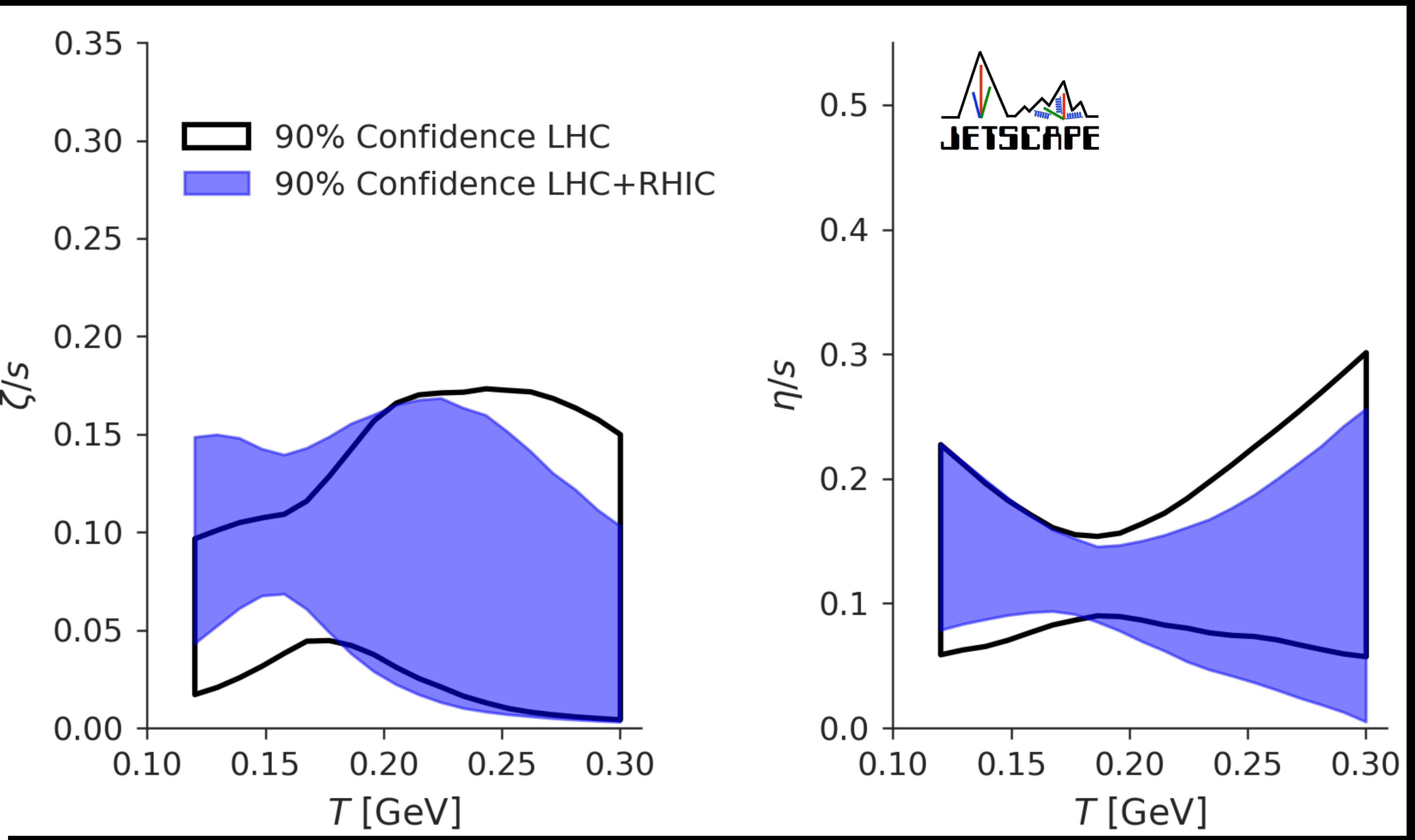
Low viscosity matter produced at RHIC & LHC

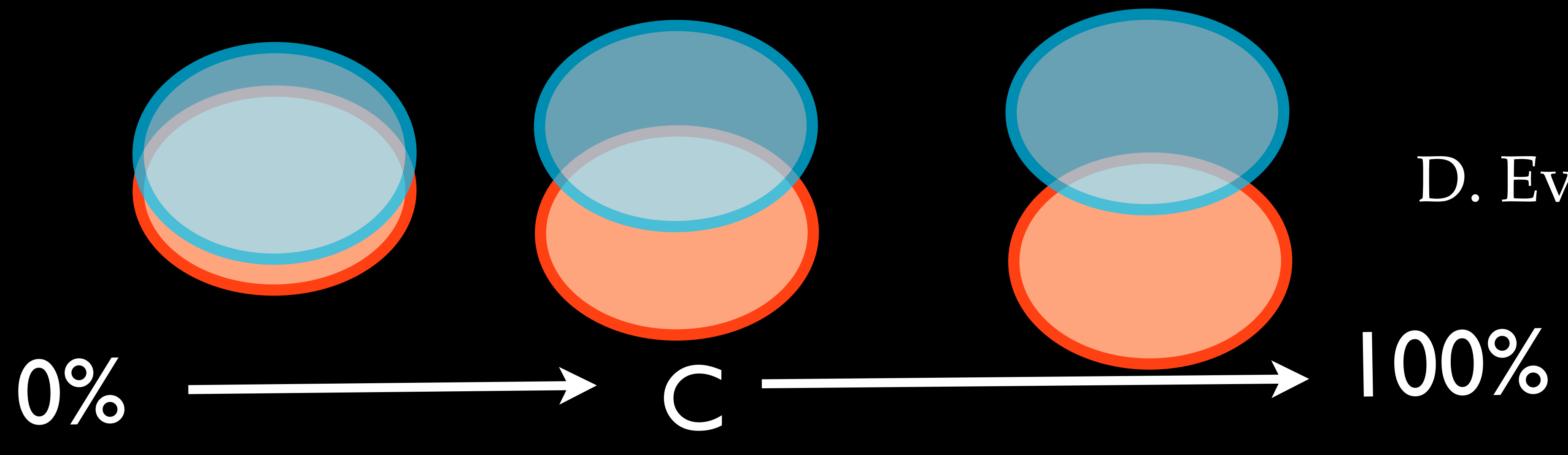






$$\eta \propto \frac{1}{\sigma}$$

$$\frac{dN}{dp_T d\phi} = \frac{dN}{dp_T}\left(1 + 2v_2\cos(2\phi) + \ldots\right)$$



D. Everett et al., Phys. Rev. C 103 (2021) 5, 054904

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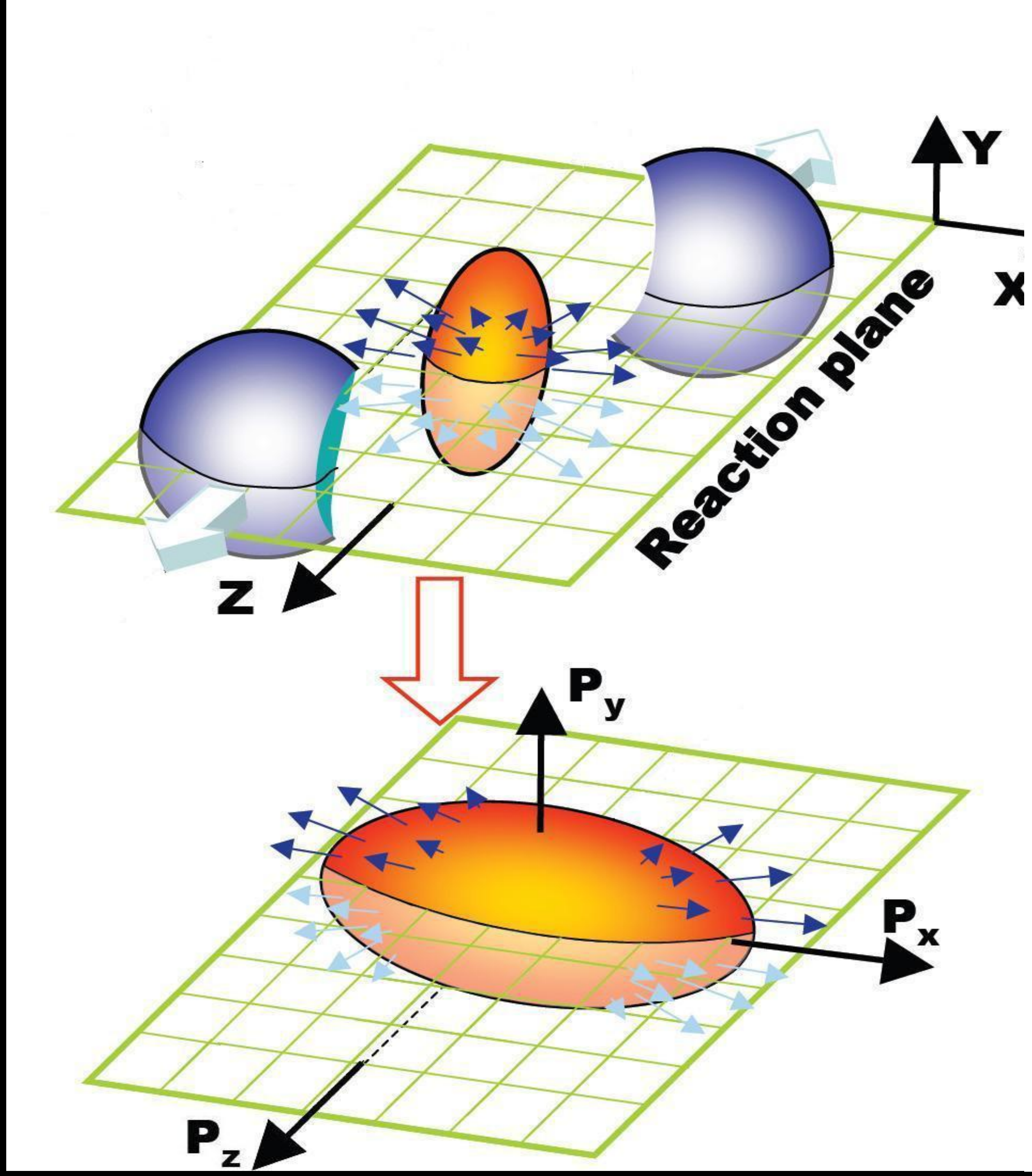

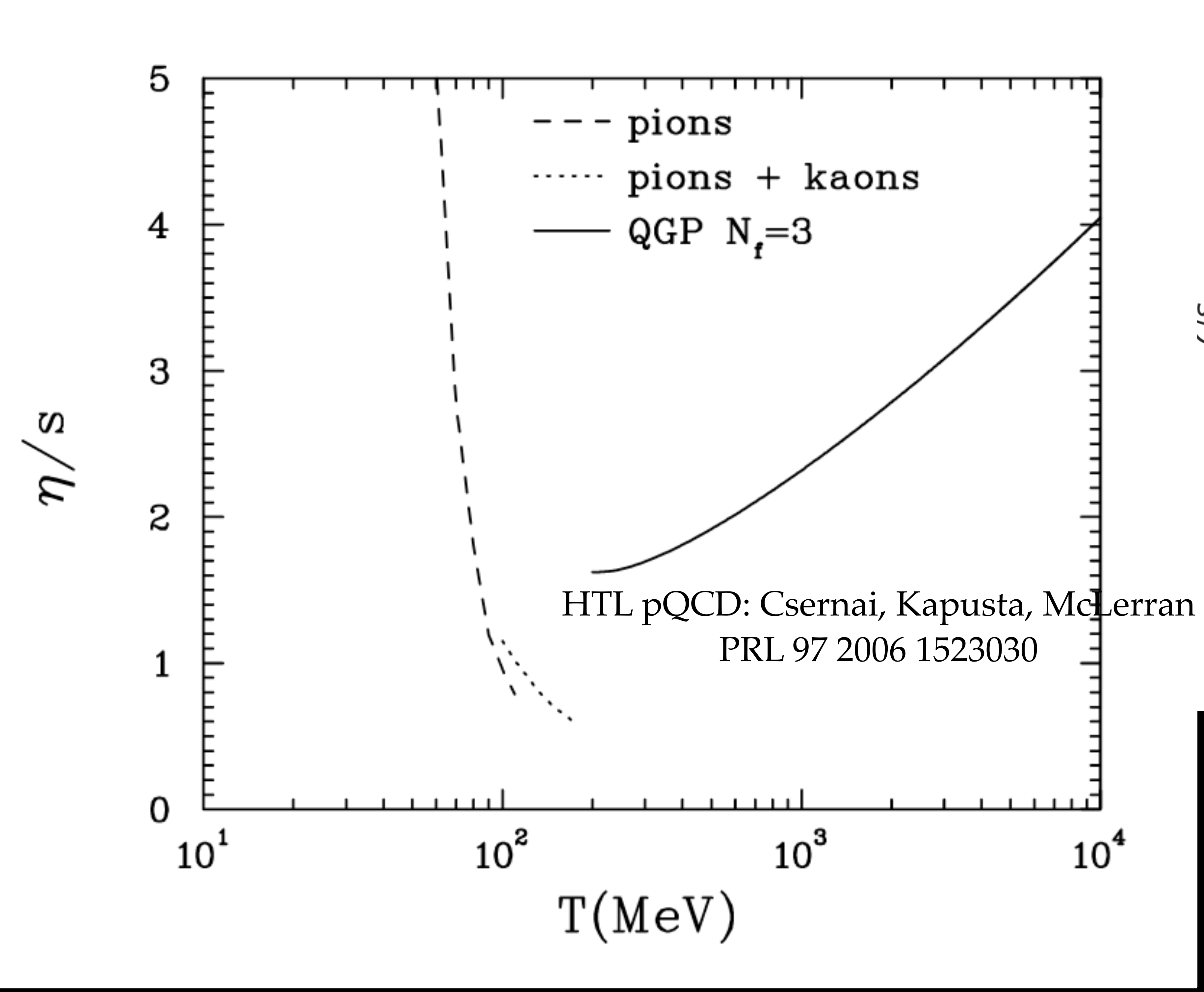

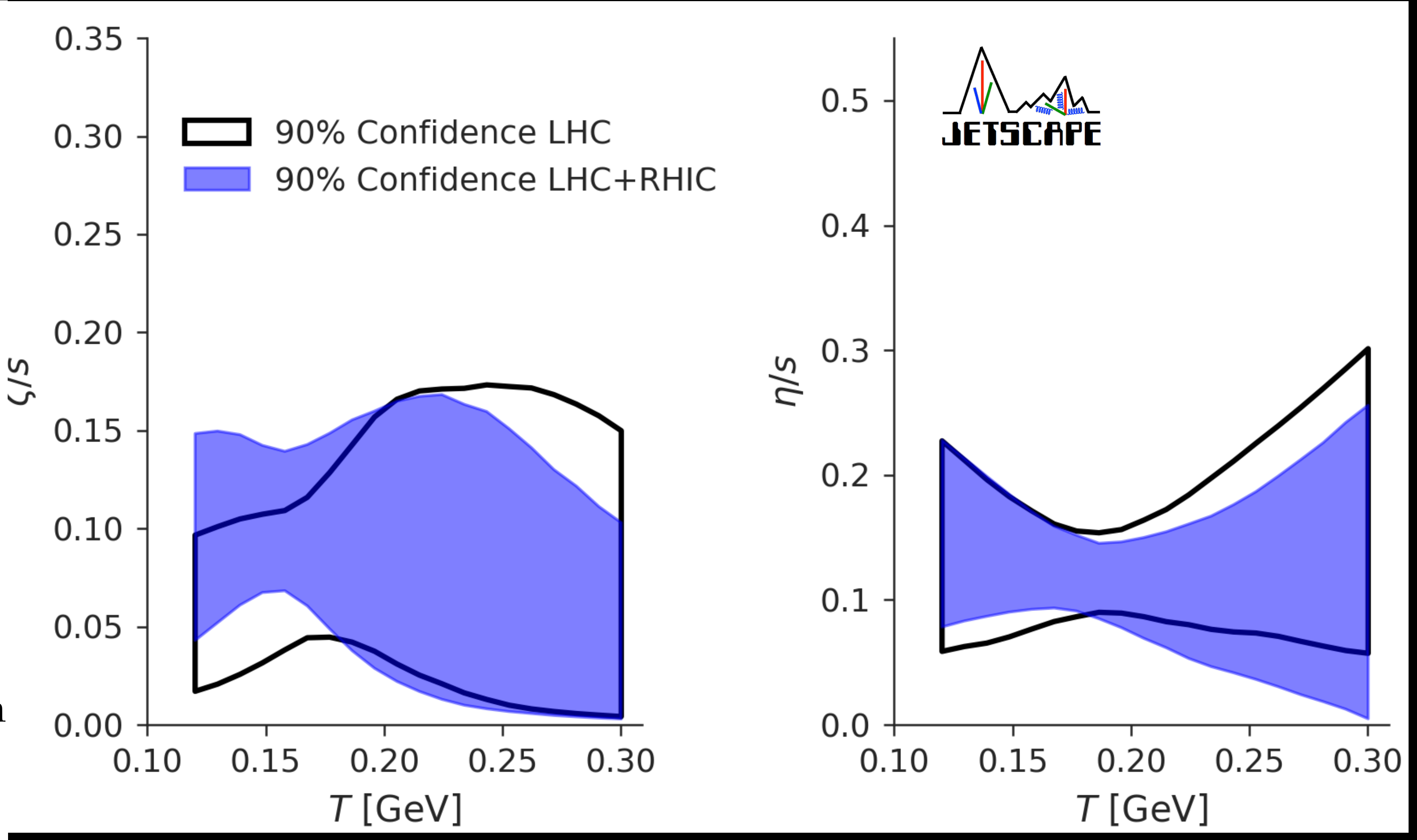

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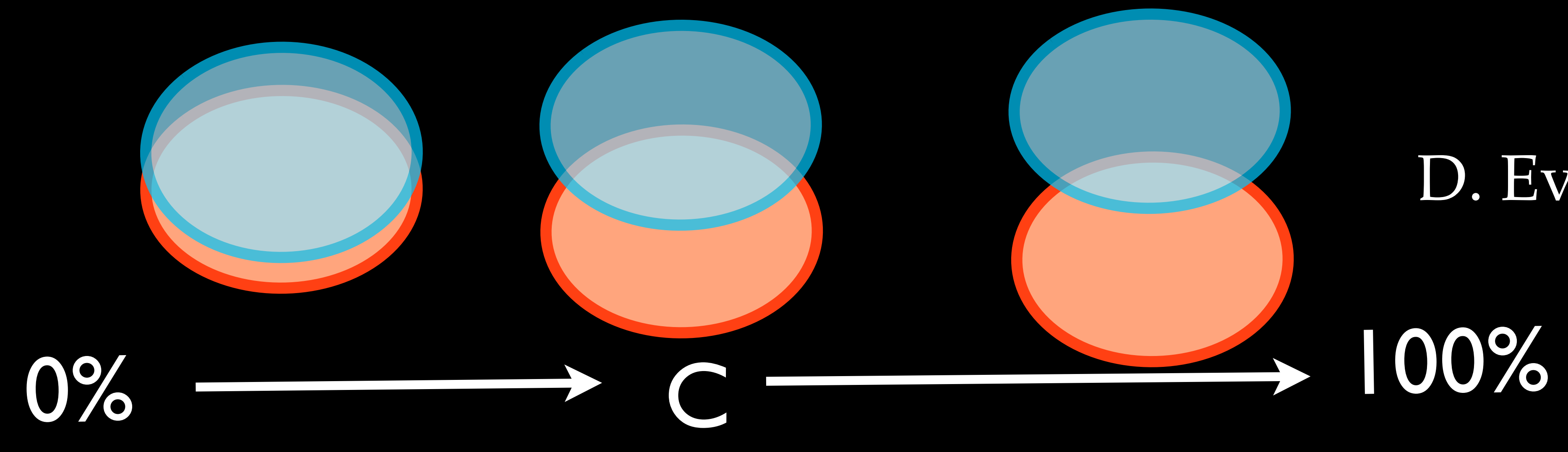
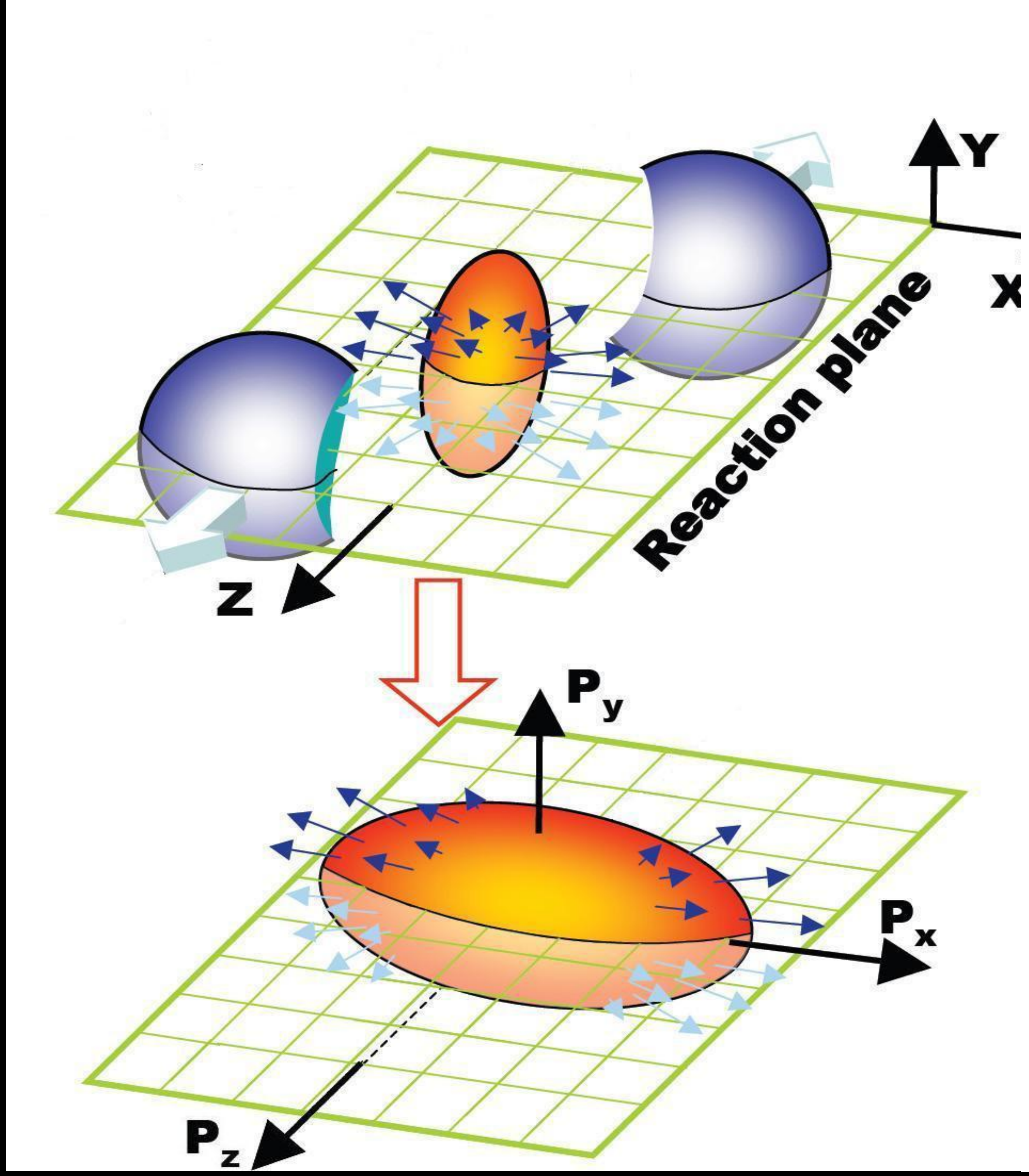
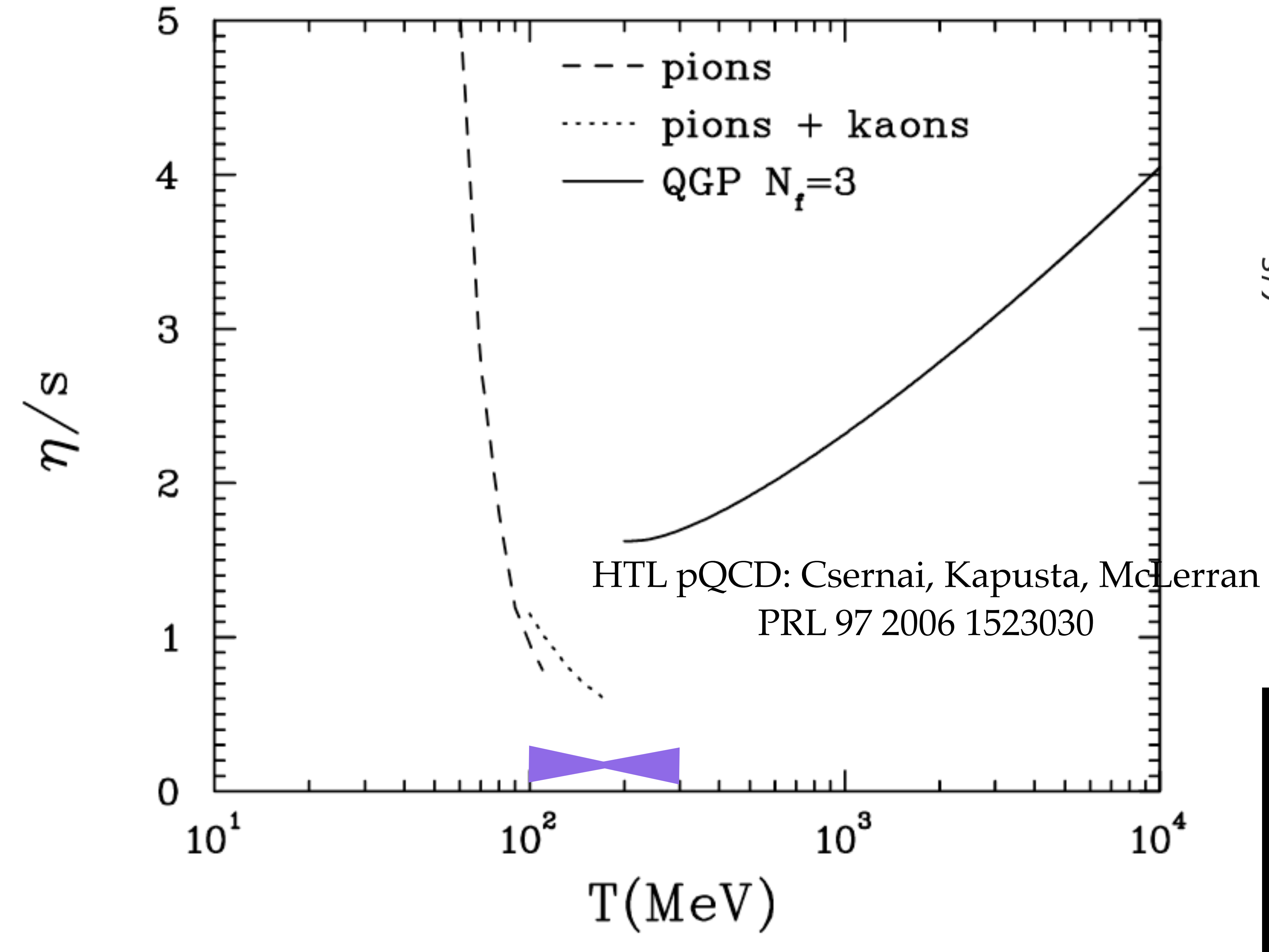
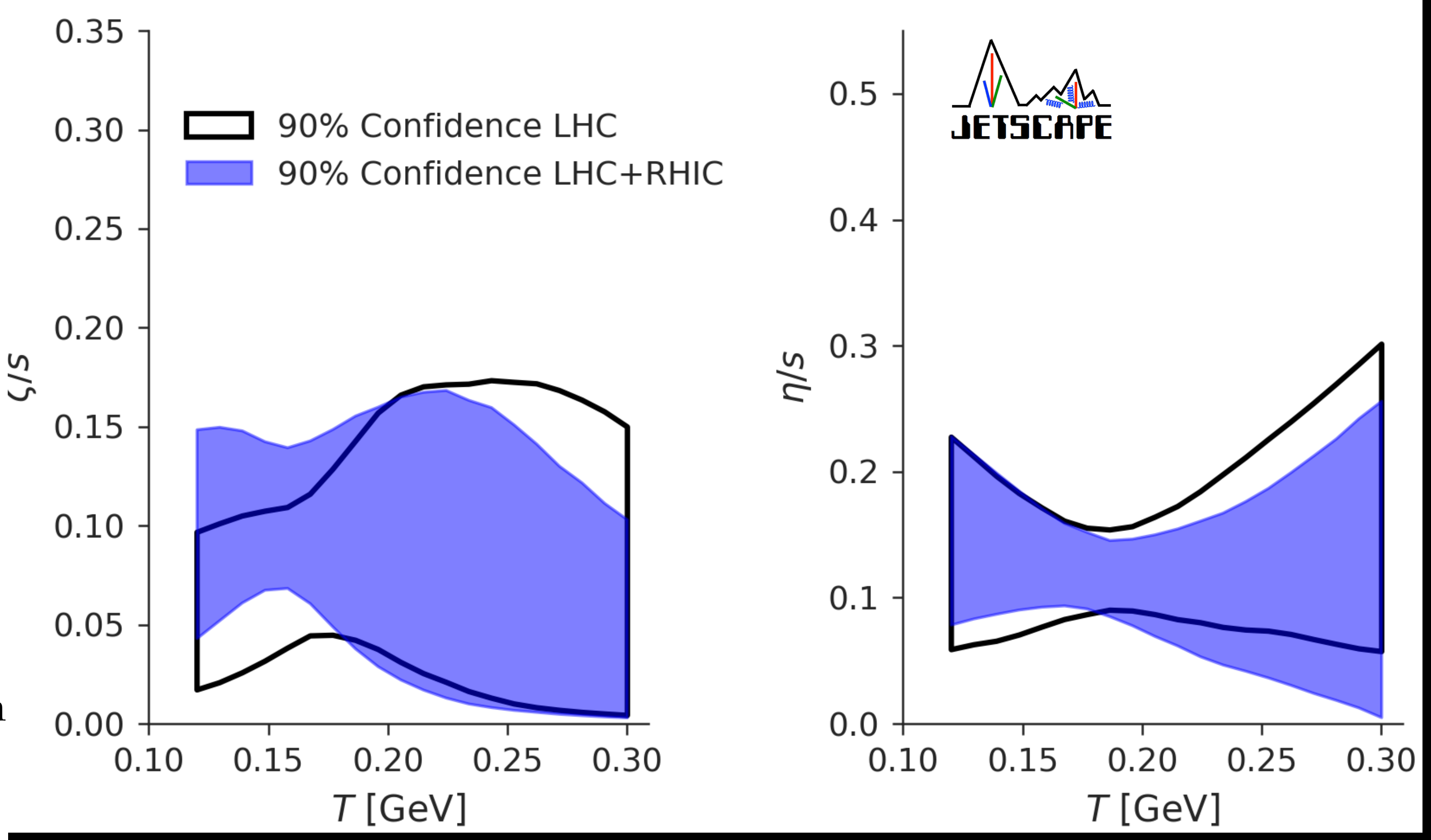


Low viscosity matter produced at RHIC & LHC







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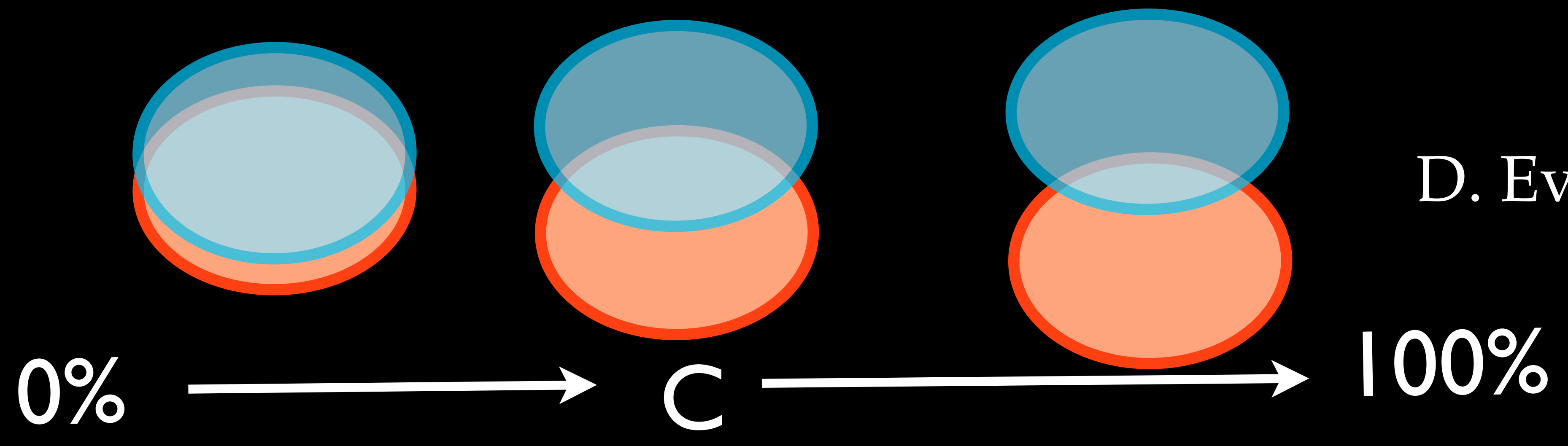
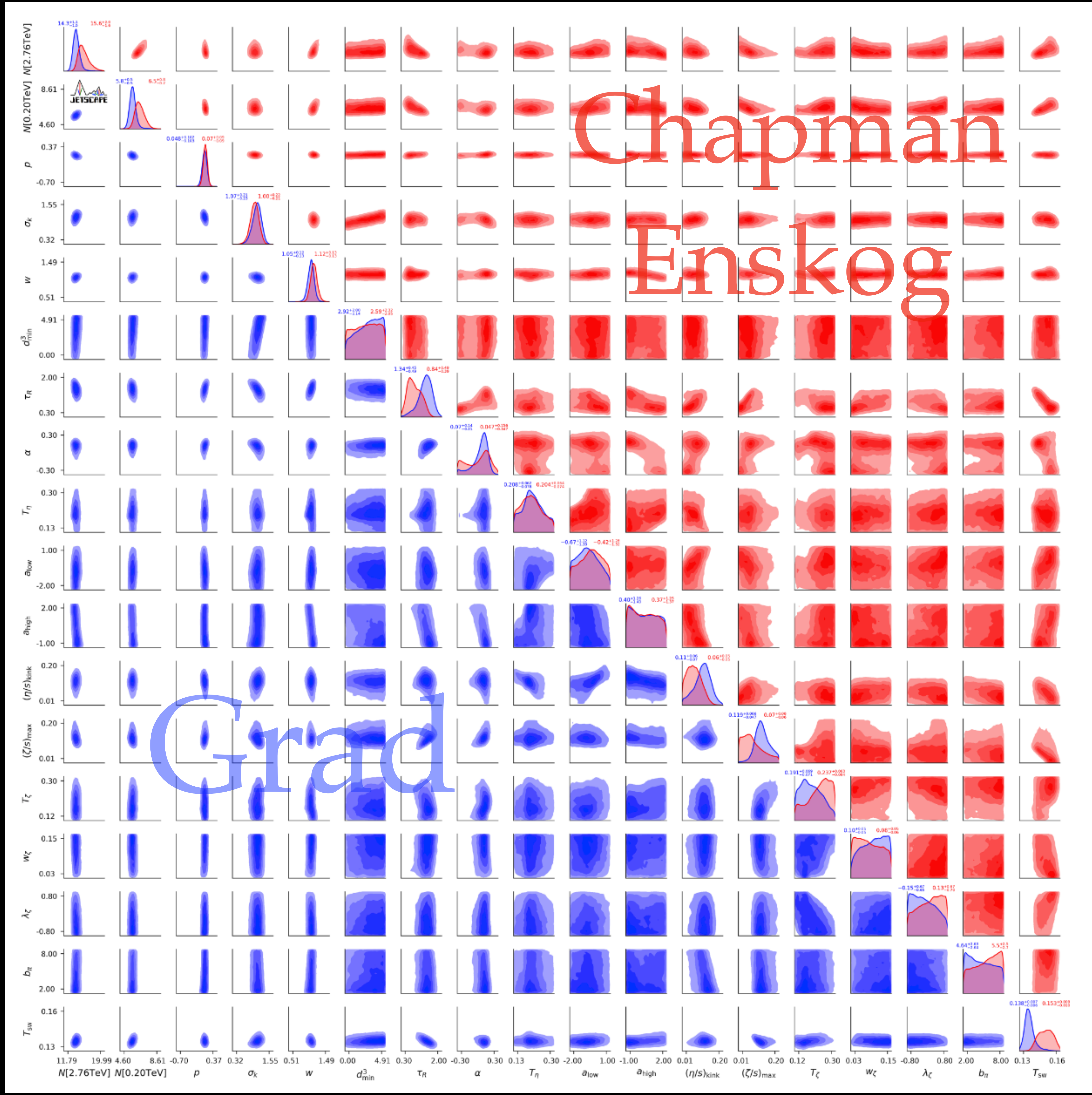
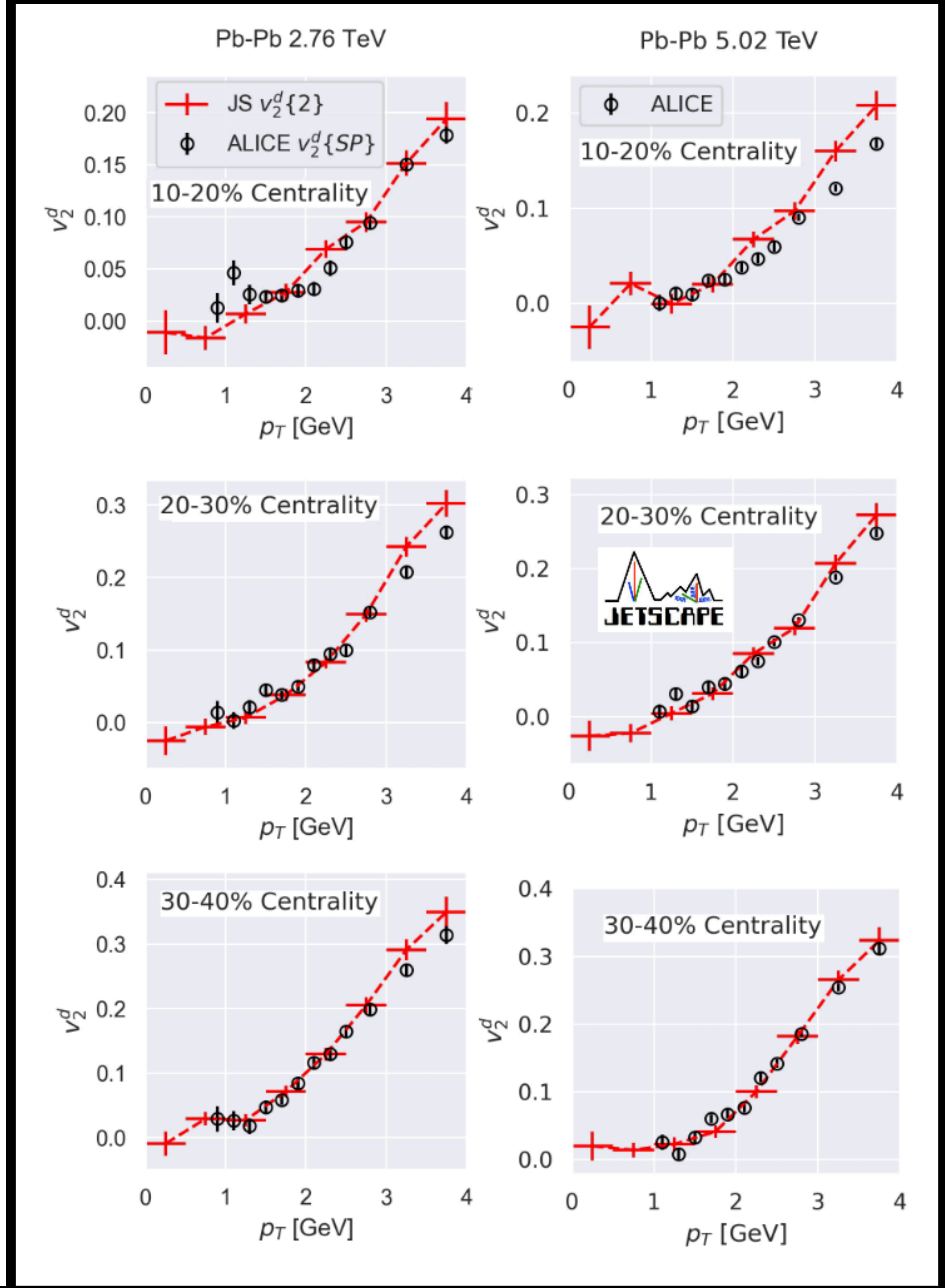
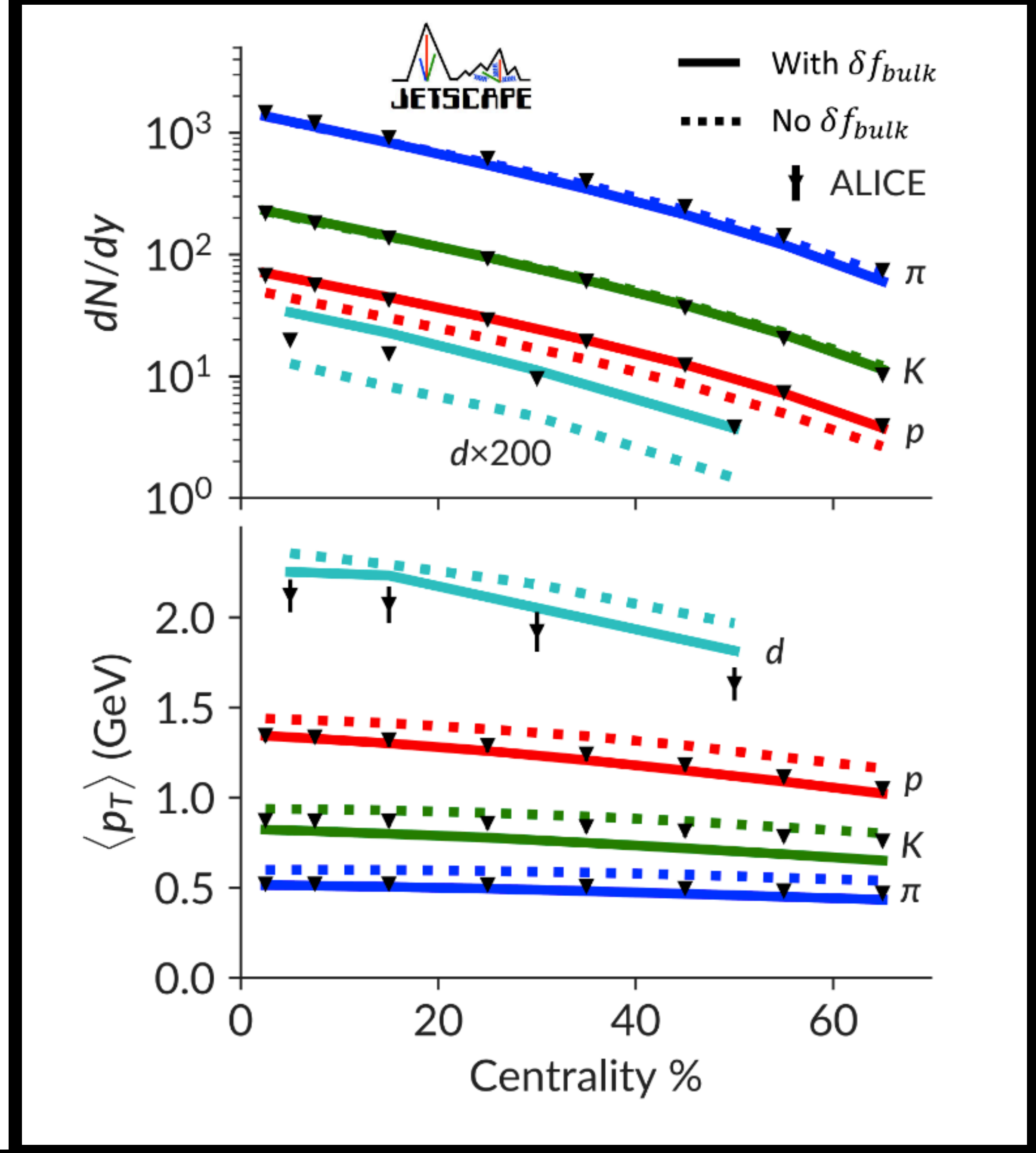


D. Everett et al., Phys. Rev. C 103 (2021) 5, 054904

A 17 dimensional calibration







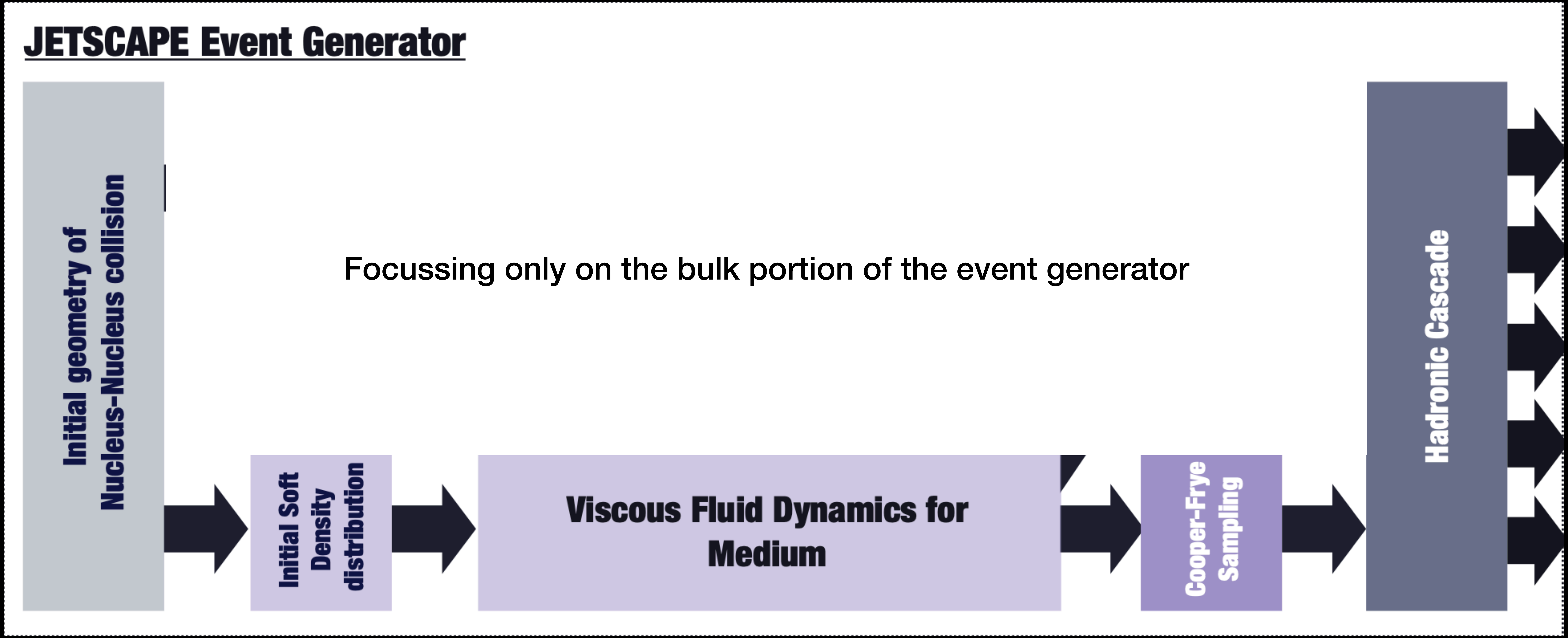
- Predictions for deuteron yield and v_2

D. Everett et al., Phys. Rev. C 103 (2021) 5, 054904

D. Everett et al., Phys.Rev.C 106 (2022) 6, 064901

The JETSCAPE event generator

Incorporating the hard sector back in.



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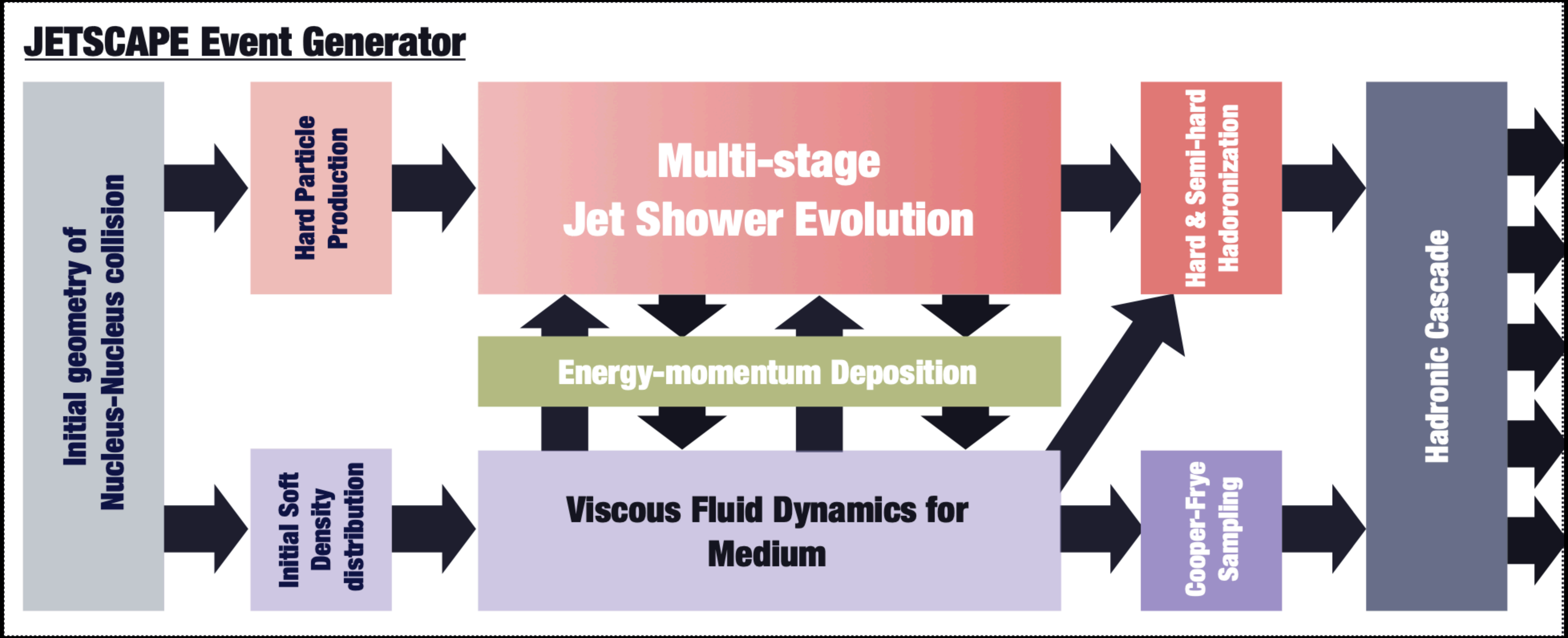
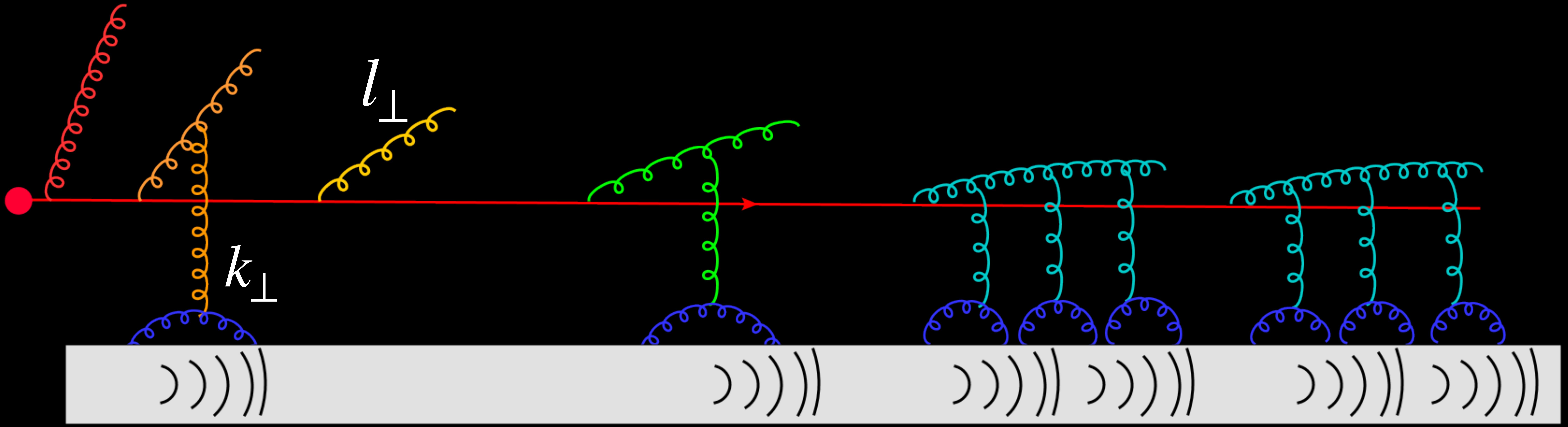


Diagram by Y. Tachibana

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



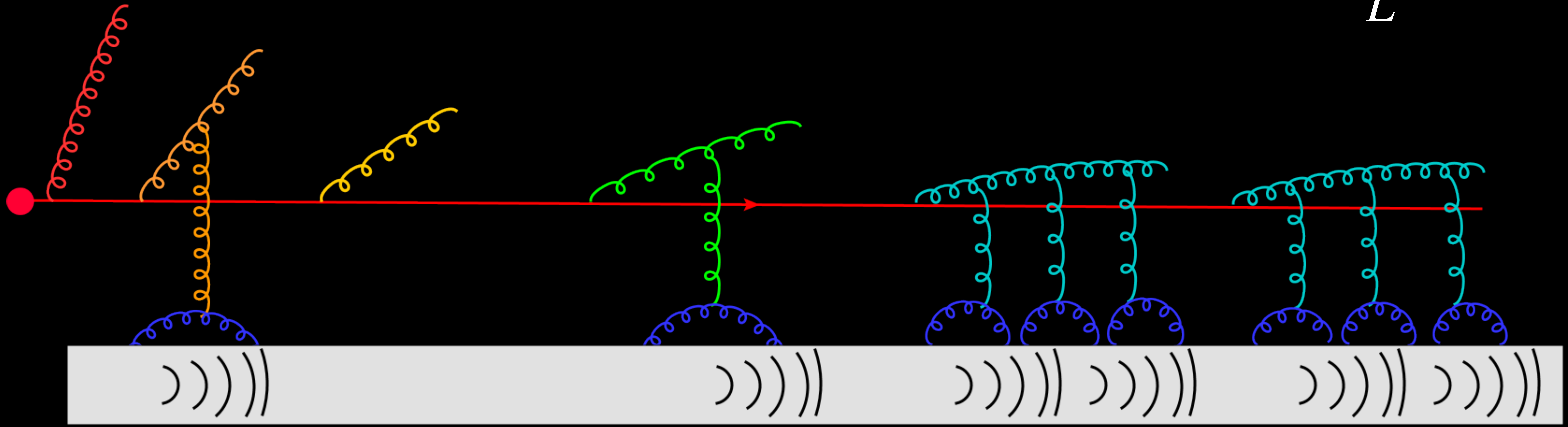
- Exchanges with medium lead to excitations/medium response

Basic Picture: extra scales in energy loss

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

This gives $Q^2_{med} \simeq \sqrt{2E\hat{q}}$

$$\hat{q} = \frac{\langle k_\perp^2 \rangle_L}{L}$$



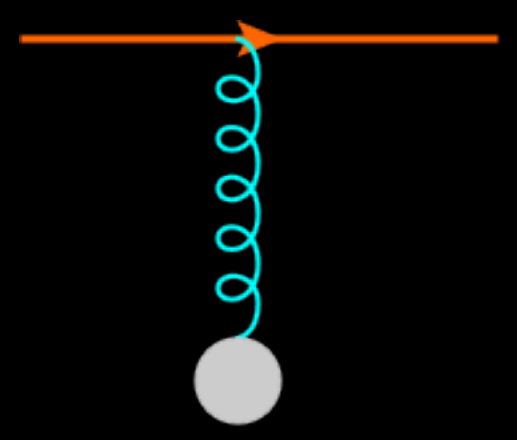
Physics: DGLAP like
Simulator: MATTER

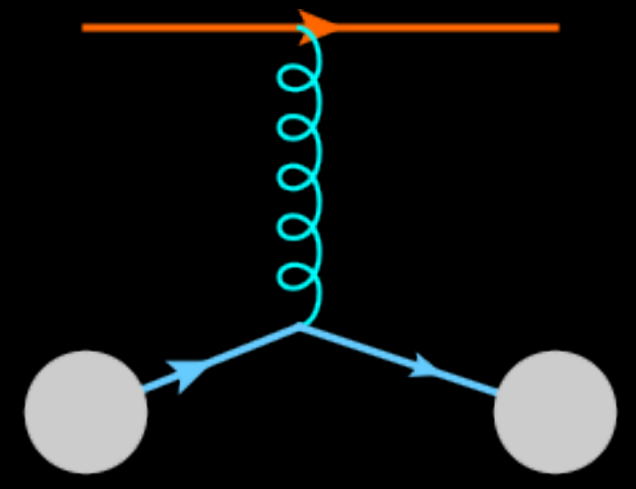
Physics: BDMPS/ AMY like
Simulator: MARTINI, LBT

Multi-scale structure in the medium

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

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



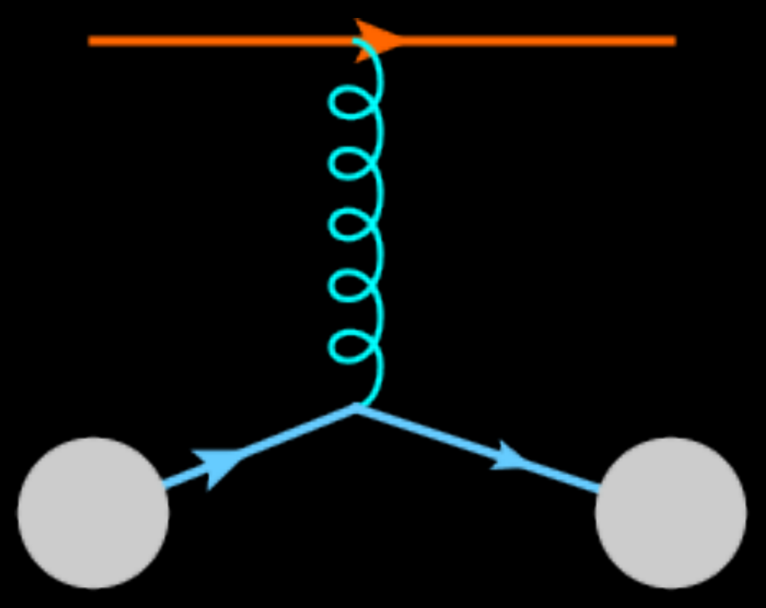


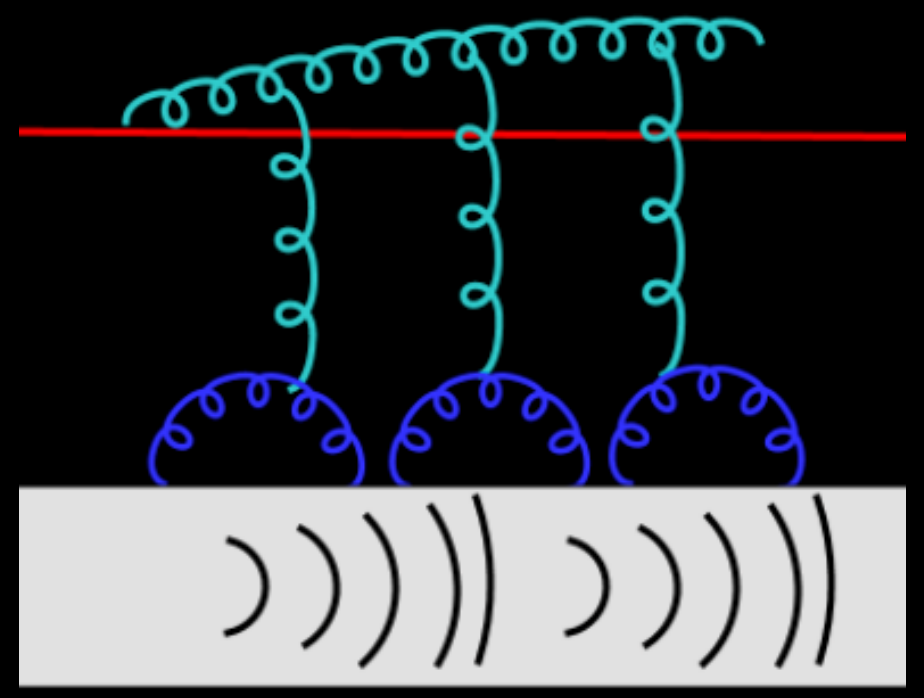
- Incoming "resolved partons" can be modeled with
  - HTL perturbation theory
  - or using QGP PDF (A. Kumar et al., PRC 101 (2020) 034908)
  - Or Both (MATTER + LBT)

- Soft exchanges by generic **broadening** (Lido, Tequila, also do hard exchanges with HTL)

- 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: $\mu^2 = \sqrt{2\hat{q}E}$

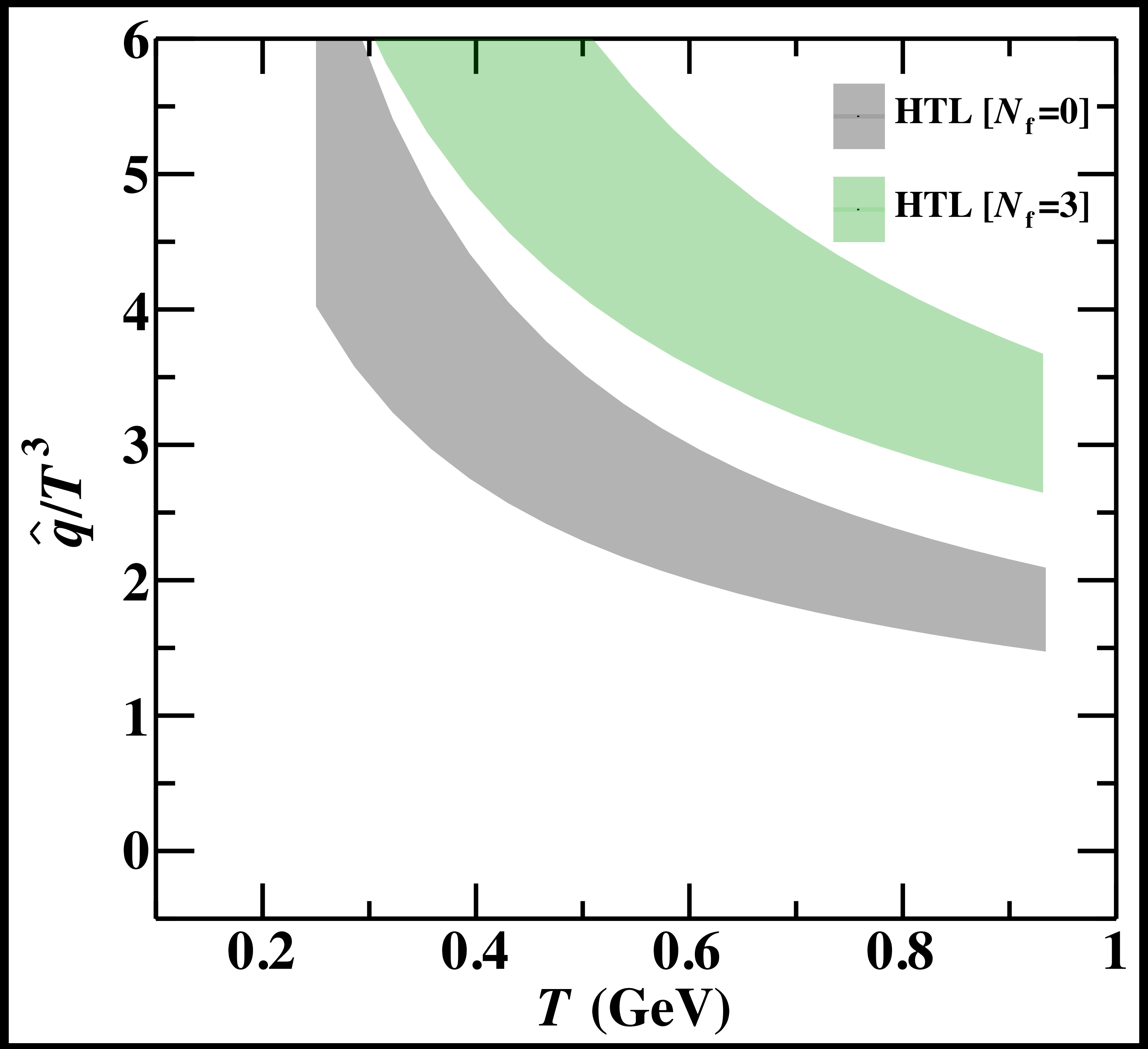
- Use Debye screened potential

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

- Running coupling gives,

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

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

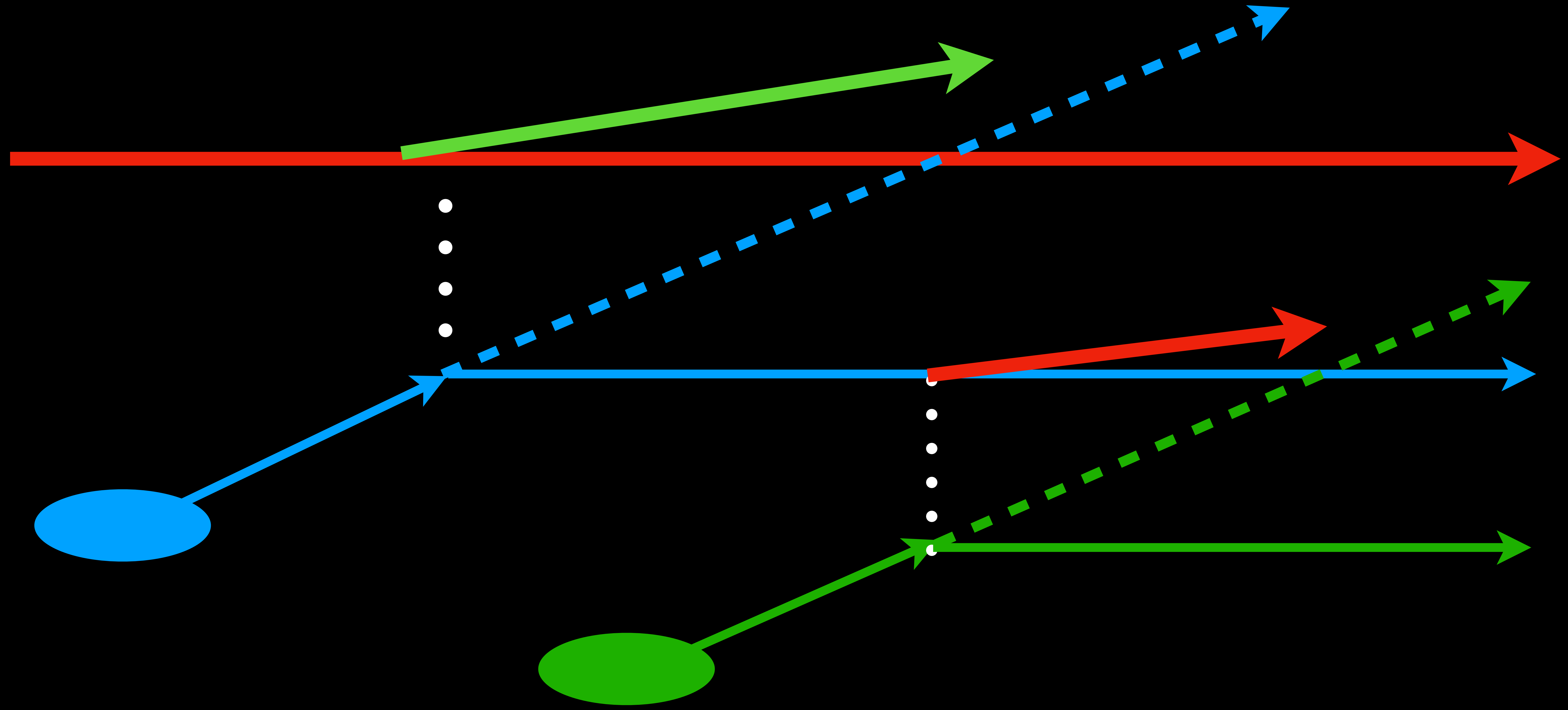


Arnold and Xiao: arXiv: 0810.1026 [hep-ph]

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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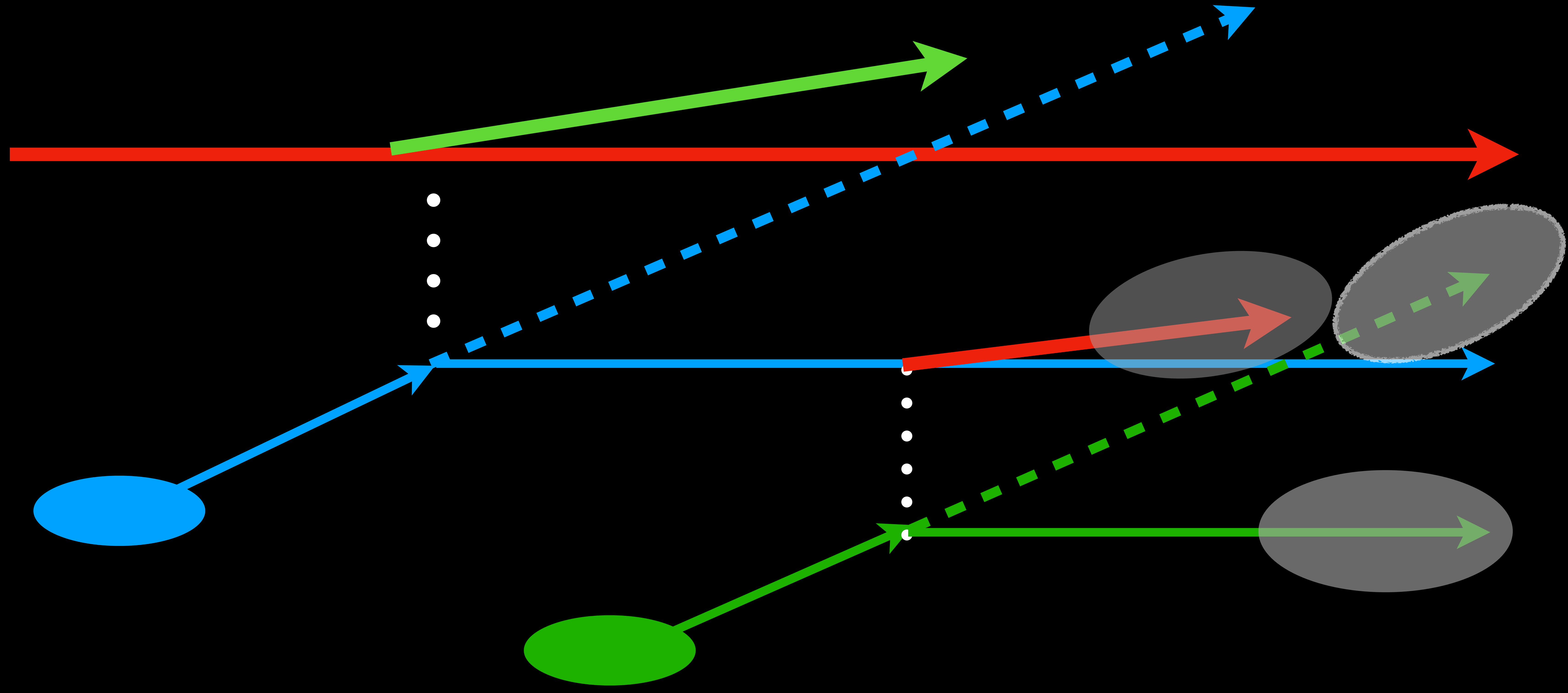
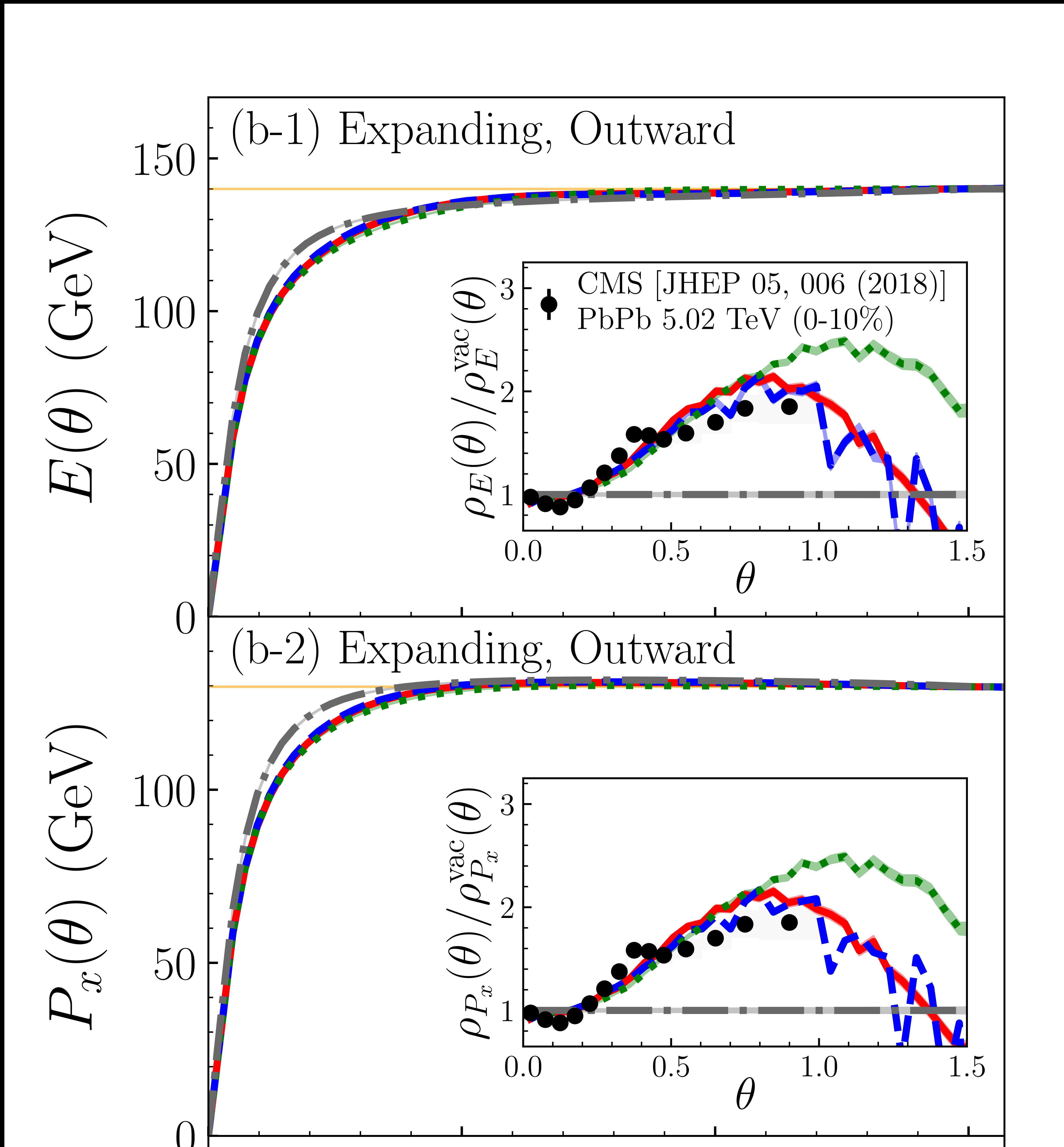


Additionally: Soft partons can be "liquified" into source terms for a subsequent hydro simulation

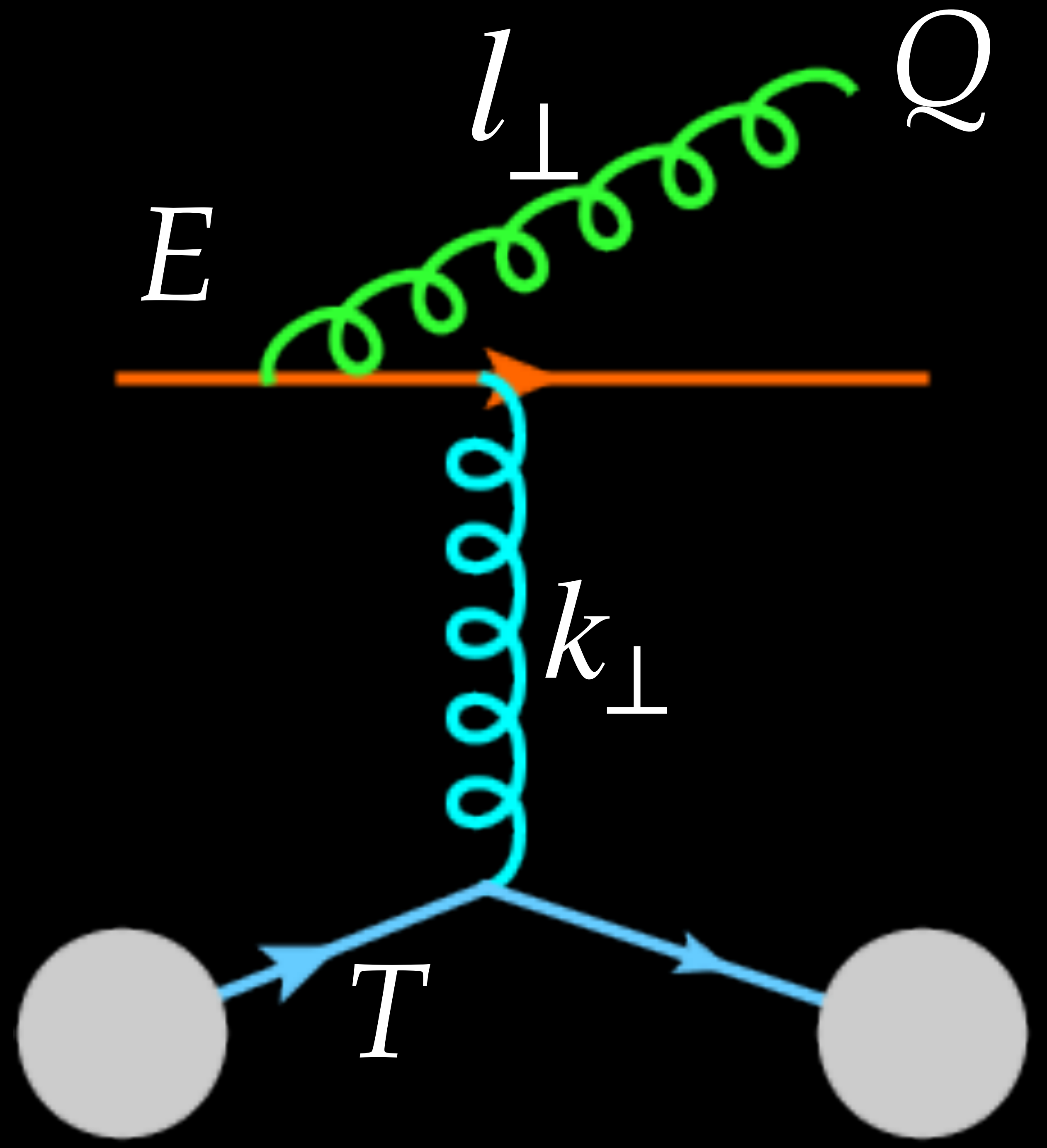
Does not seem to make much difference inside jet cone

- 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 arXiv: 2001.08321 [nucl-th]



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



- In general, could 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.

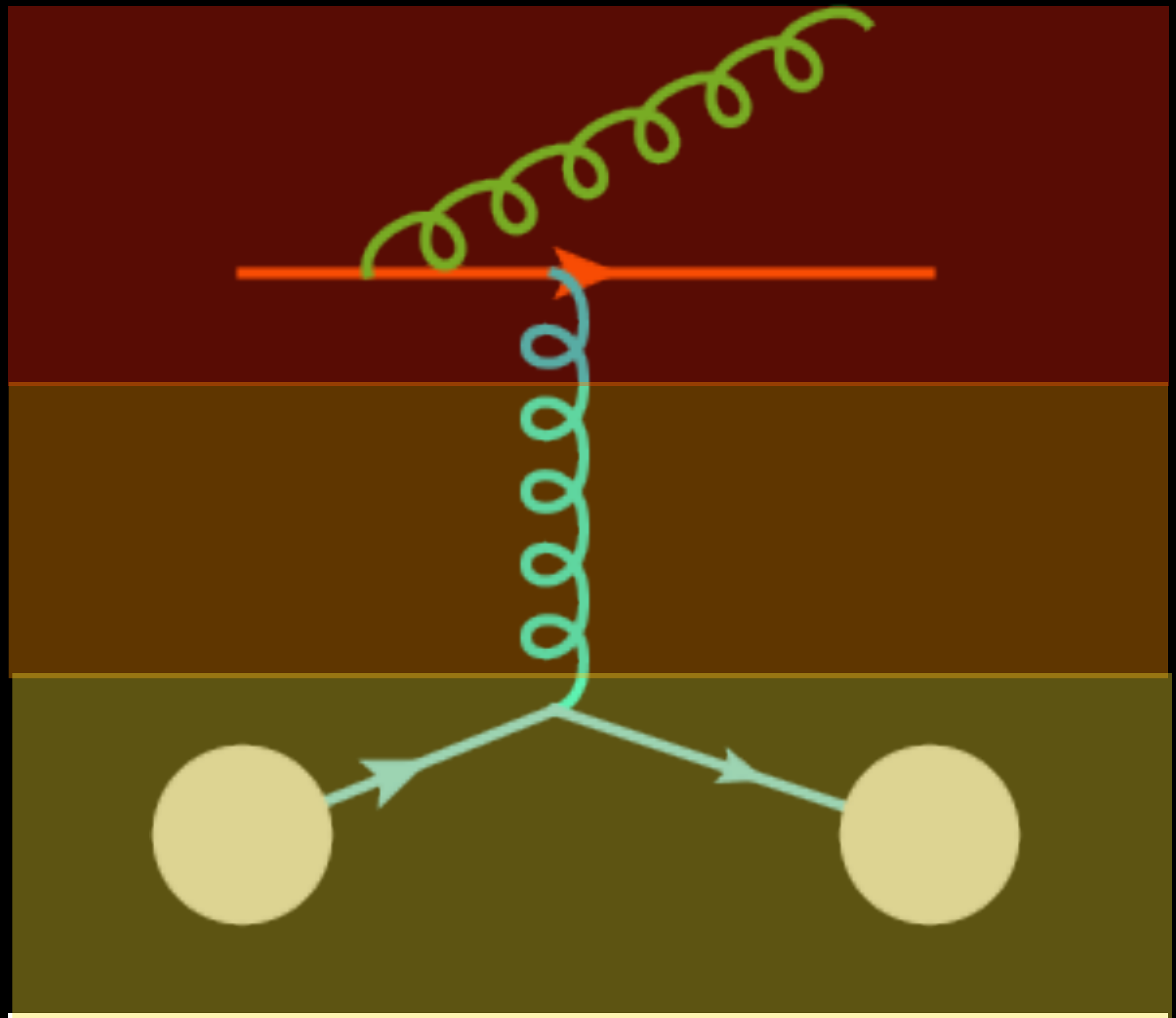
$$\frac{dN_g}{dy d^2 l_\perp} = \frac{\alpha_s}{2\pi} P(y) \int \frac{d^2 k_\perp}{(2\pi)^2} \int d\zeta^- \left[\frac{2 - 2\cos\left(\frac{(l_\perp - k_\perp)^2 \zeta^-}{2q^- y(1-y)}\right)}{(l_\perp - k_\perp)^2} \right]$$

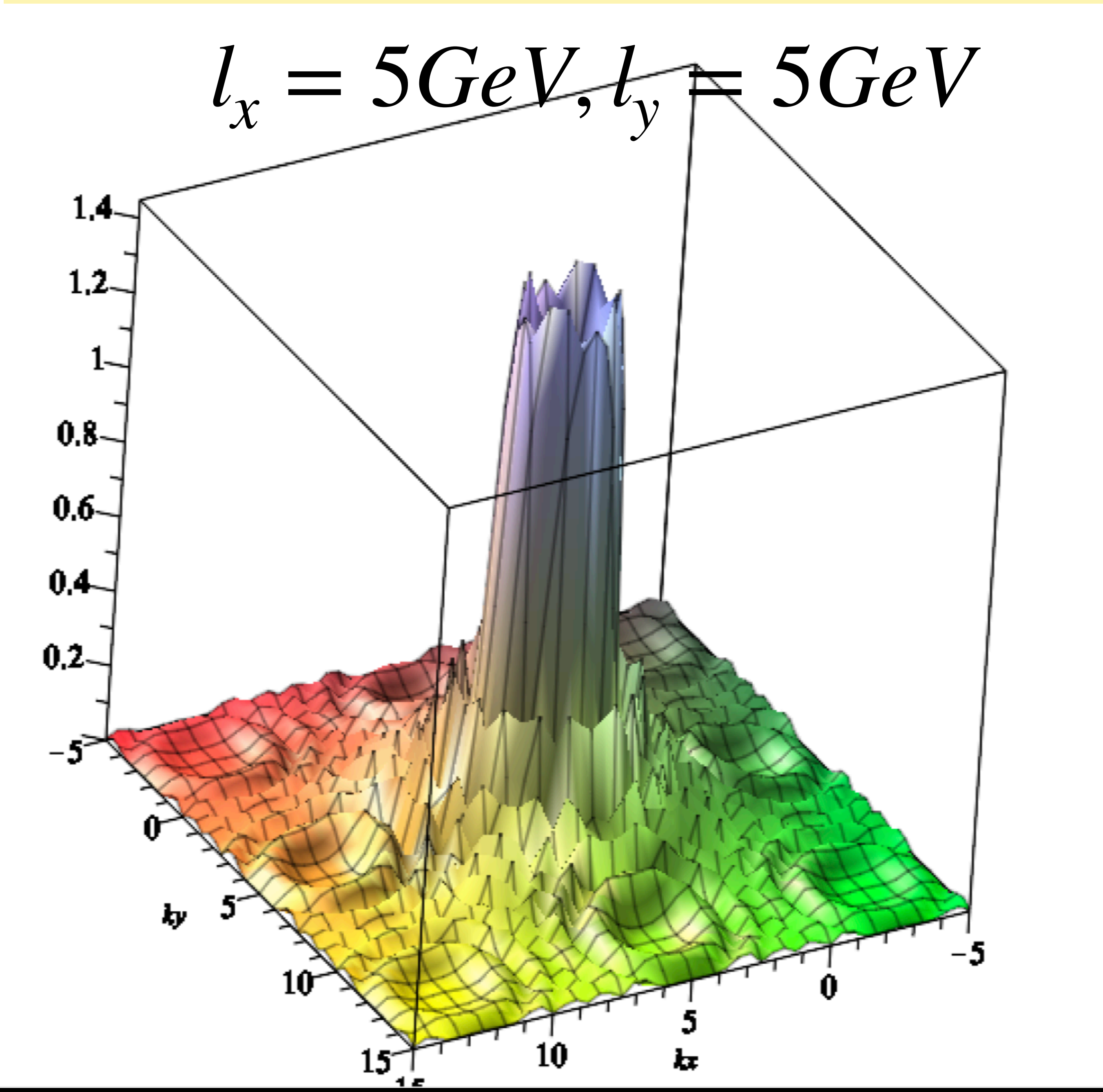
$$\times \int d(\delta\zeta^-) d^2\zeta_\perp e^{-i\frac{\vec{k}_\perp^2}{2q^-}\delta\zeta^- + i\vec{k}_\perp . \vec{\zeta}_\perp}$$

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

-

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



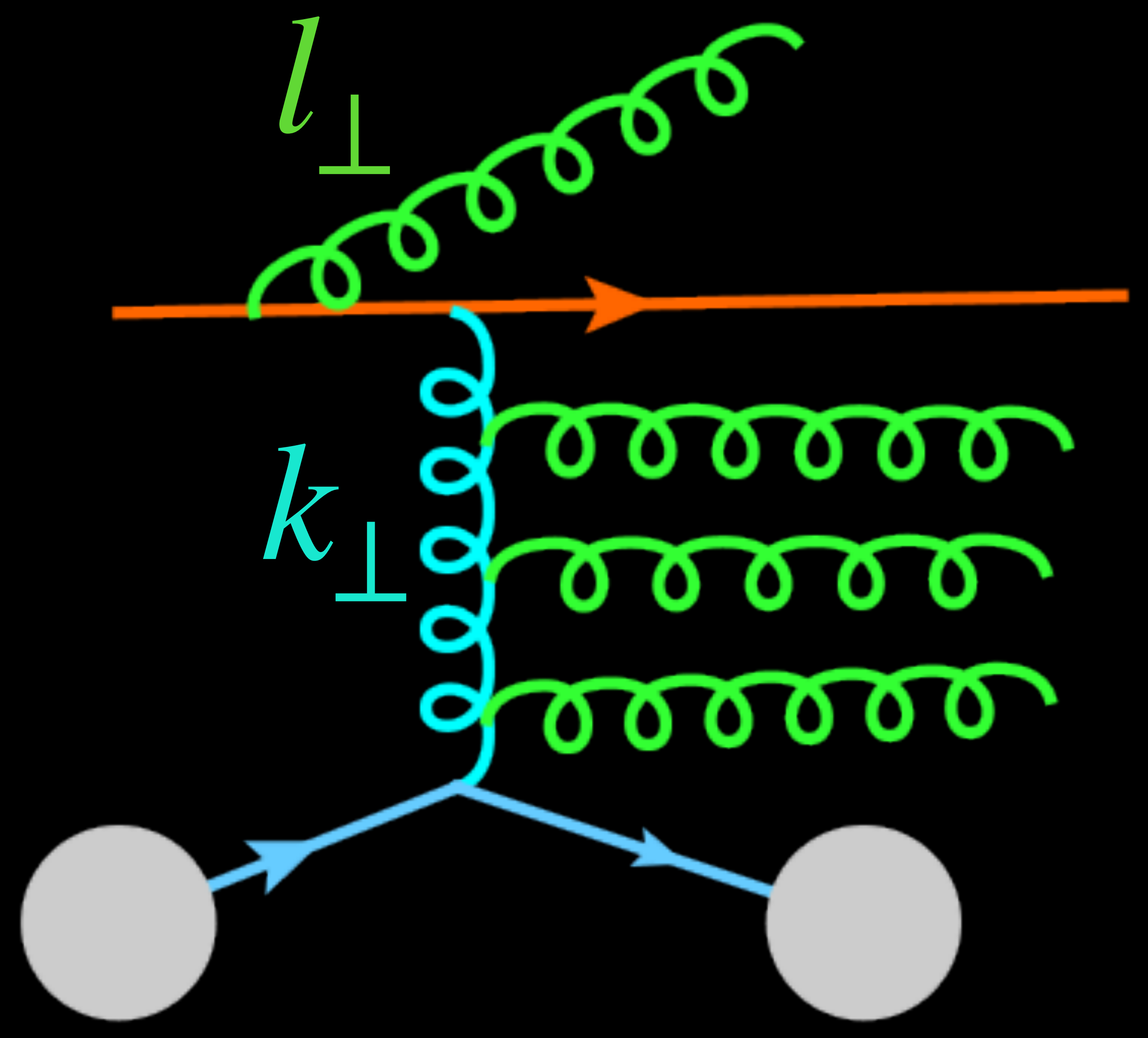


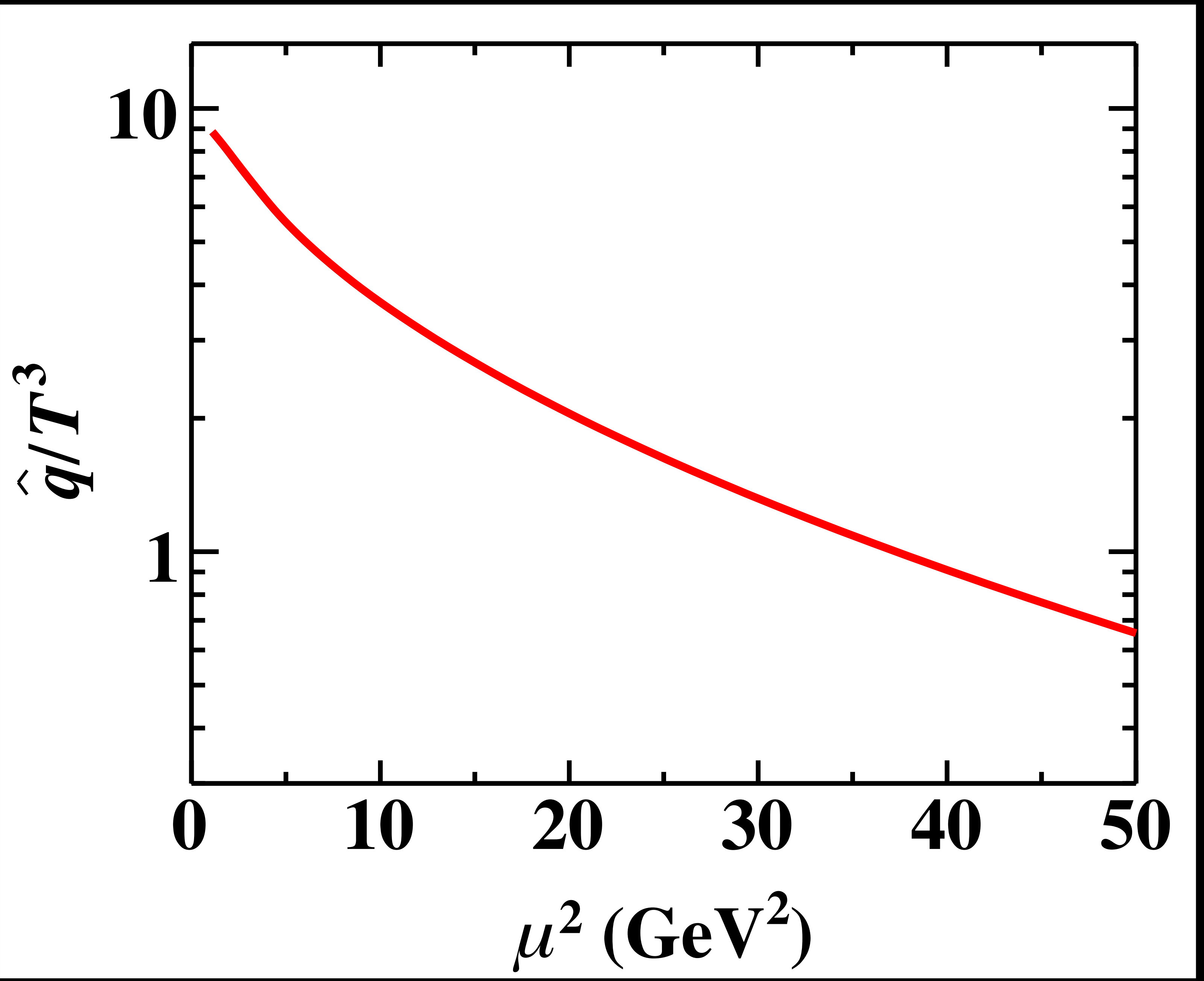
A. Kumar, A.M., C. Shen, PRC 101 (2020) 034908

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 $k_\perp \sim l_\perp$





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

A change in how theory and experiment are compared

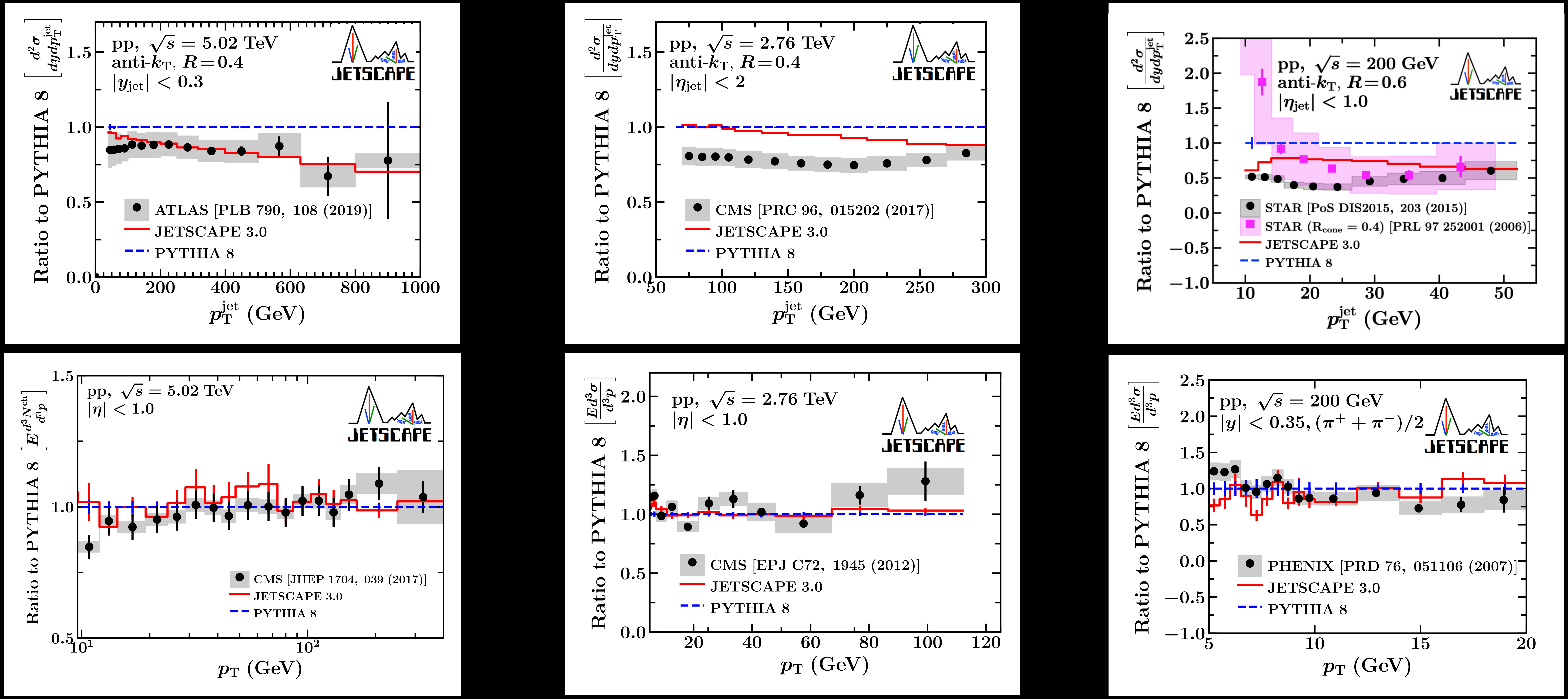
- Need full Monte-Carlo simulations that generate full events
- Observables should be built out of these (as in experiment)
- All jet calculations should be run on a calibrated hydro simulation
- Simulations should reduce to p-p without medium

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

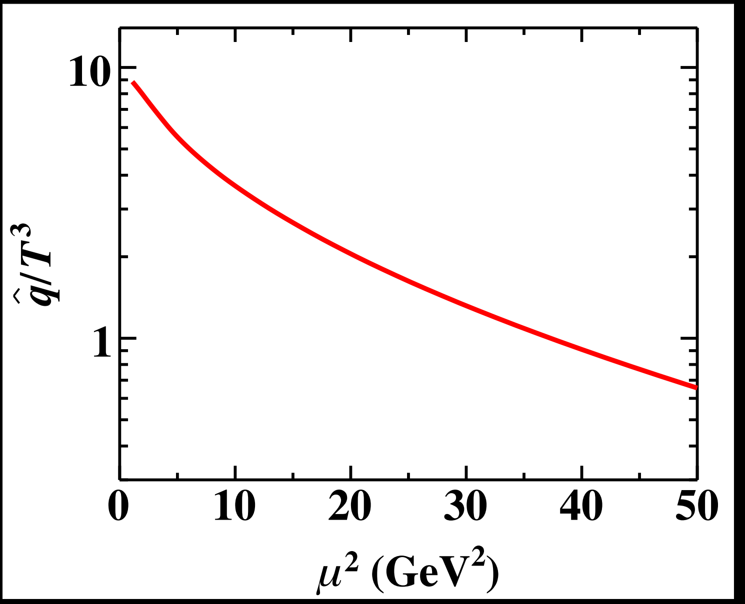


A. Kumar et al., 2204.01163 [hep-ph]

Leading hadrons and jets

At all energies and centralities

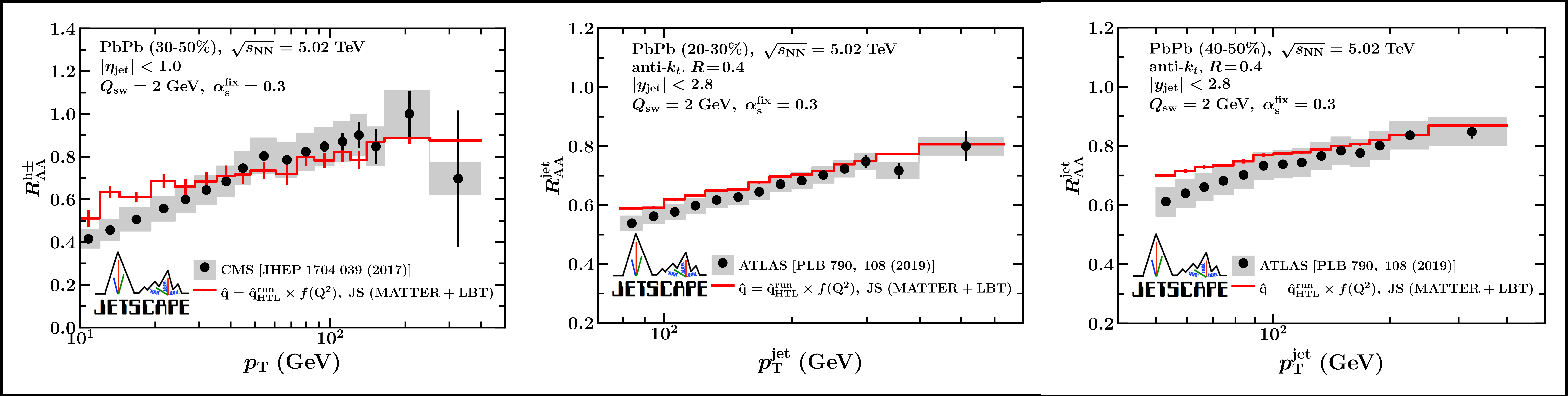
- $\hat{q} = C\alpha_s(2ET)\alpha_s(m_D)T^3 \log\left(\frac{2ET}{m_D^2}\right) \times f(Q^2)$



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

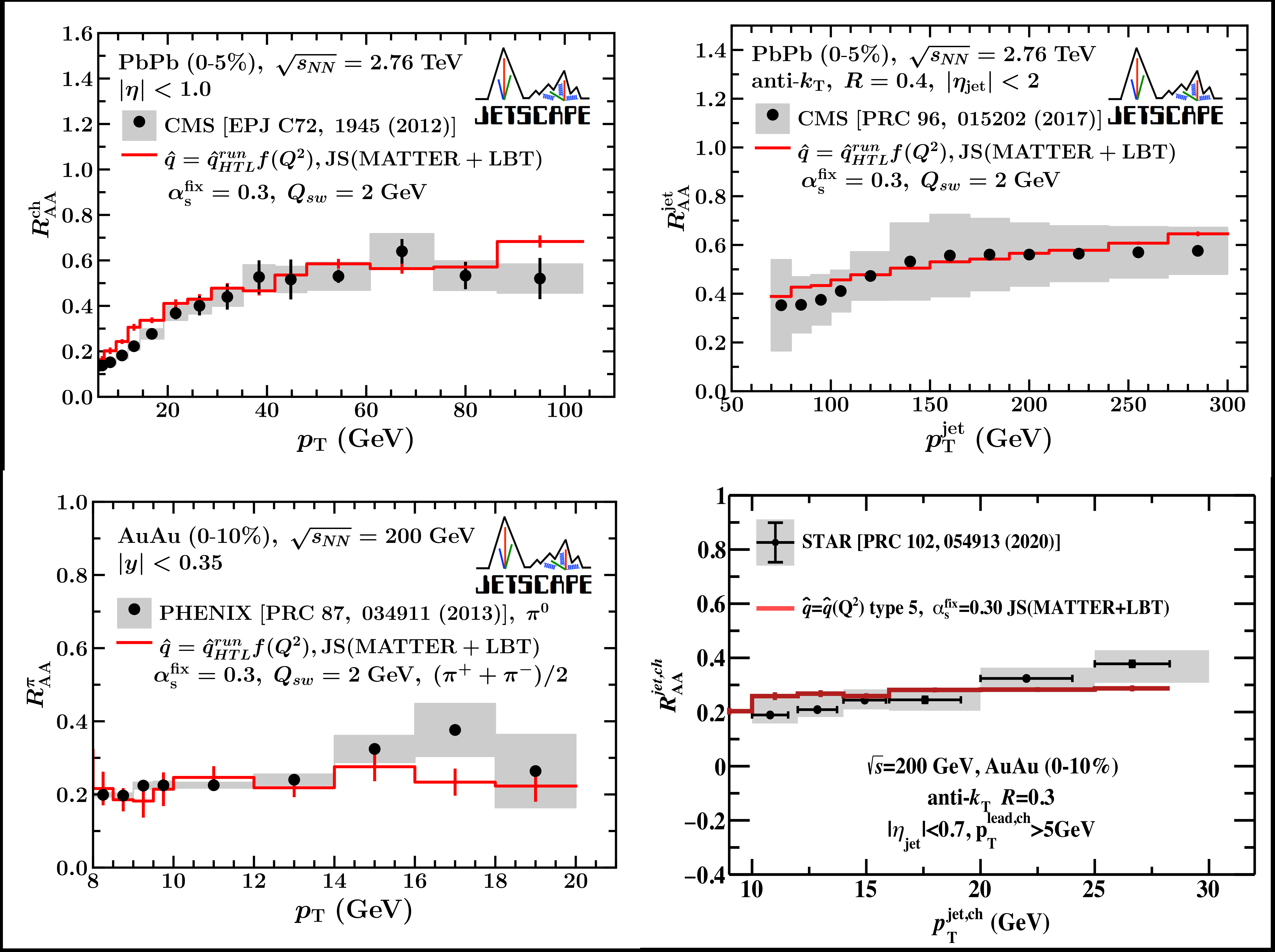
A. Kumar et al., 2204.01163 [hep-ph]

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

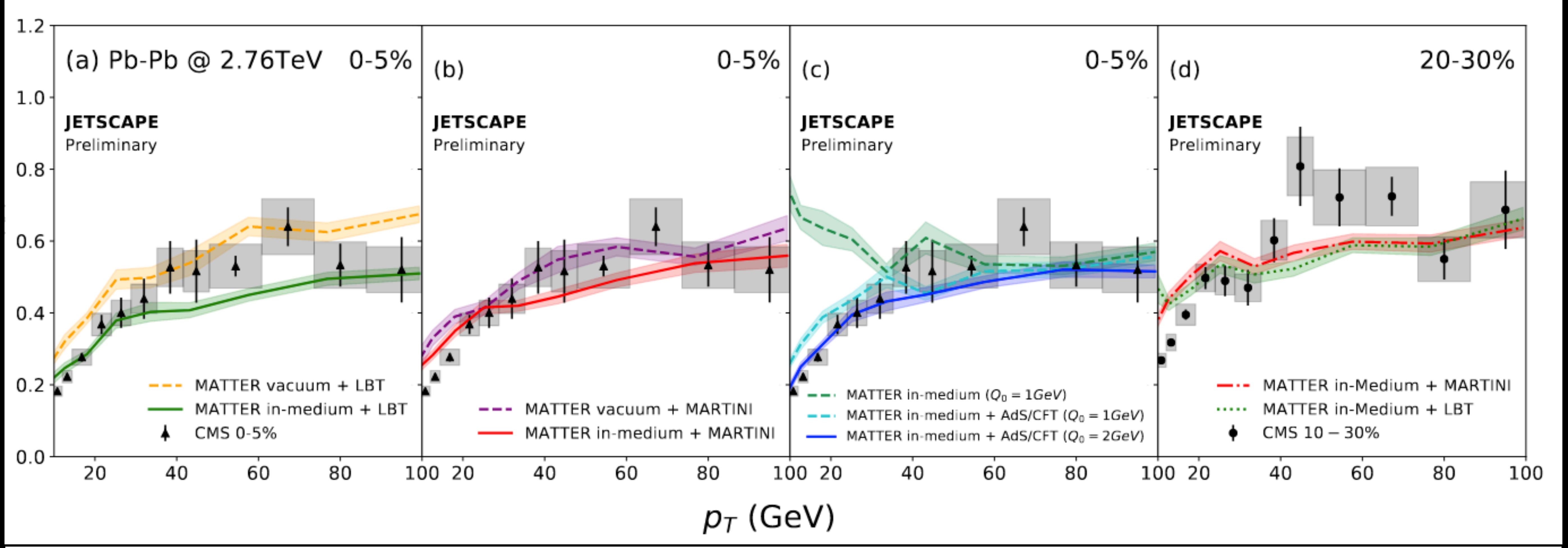


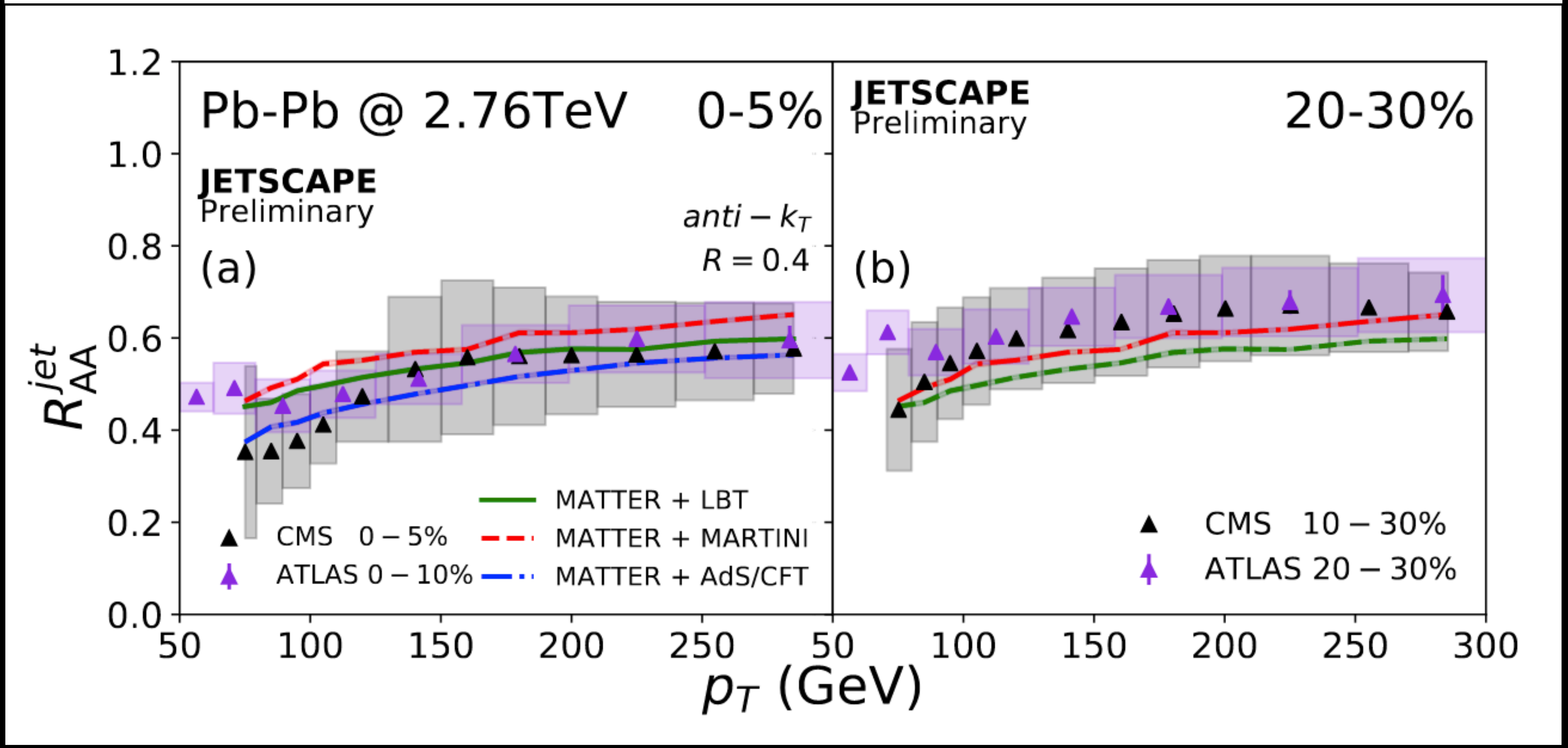
A. Kumar et al., 2204.01163 [hep-ph]

Systematic model uncertainty

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

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





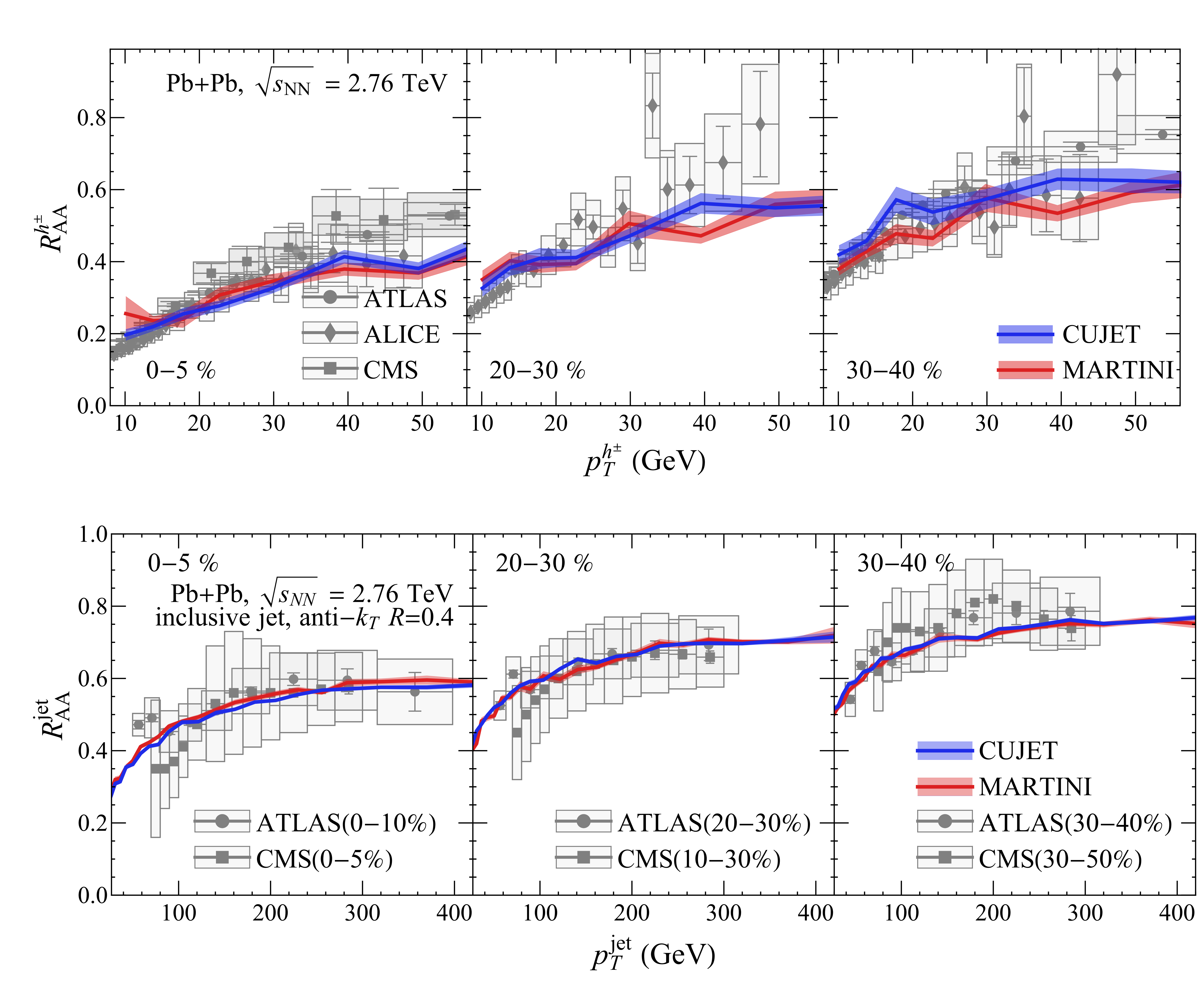
Systematic model uncertainty

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

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

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

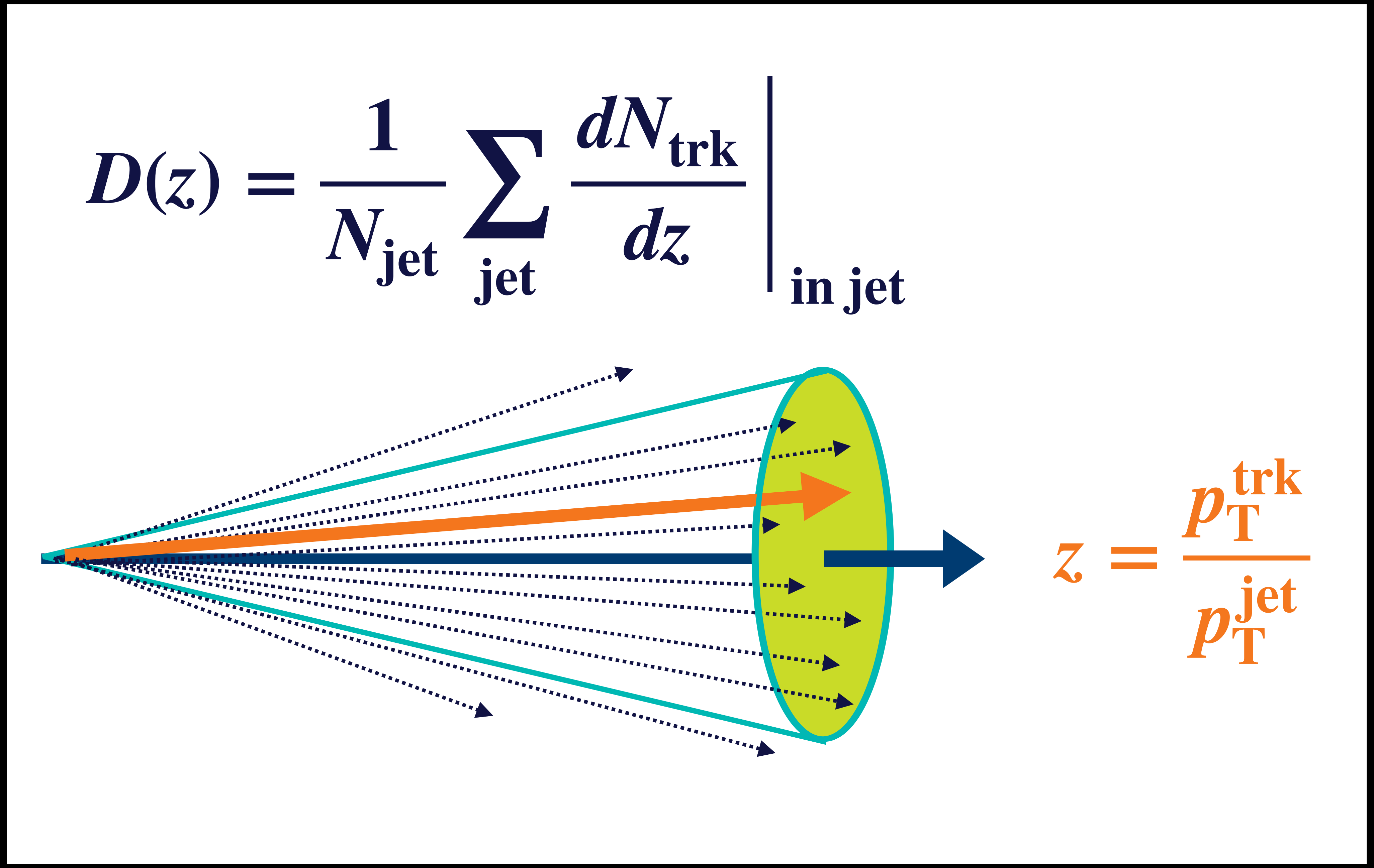
MATTER+ CUJET-MARTINI comparison by R. Modarresi-Yazdi & S. Shi

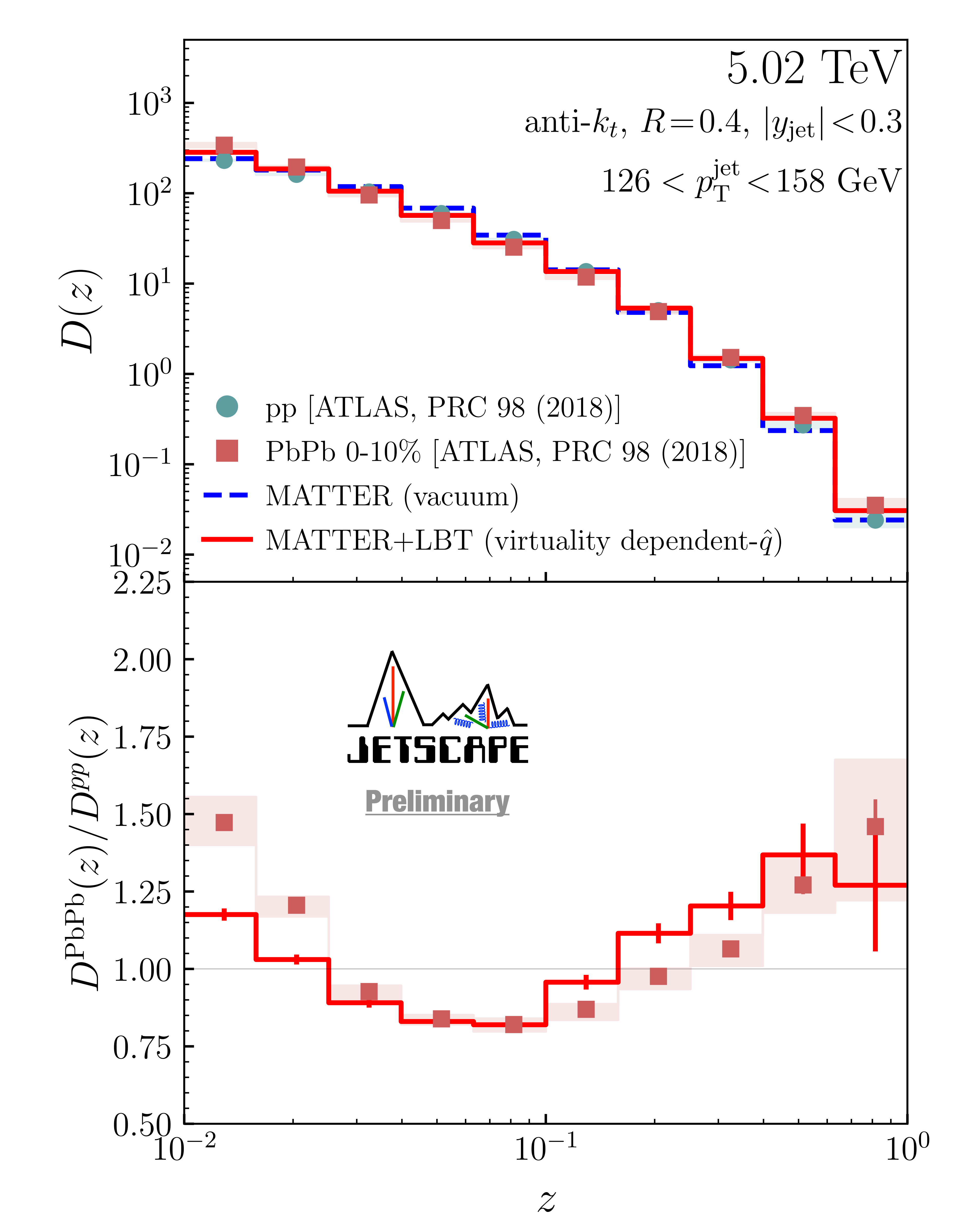


Intrajet

The dependence on E and μ not completely settled

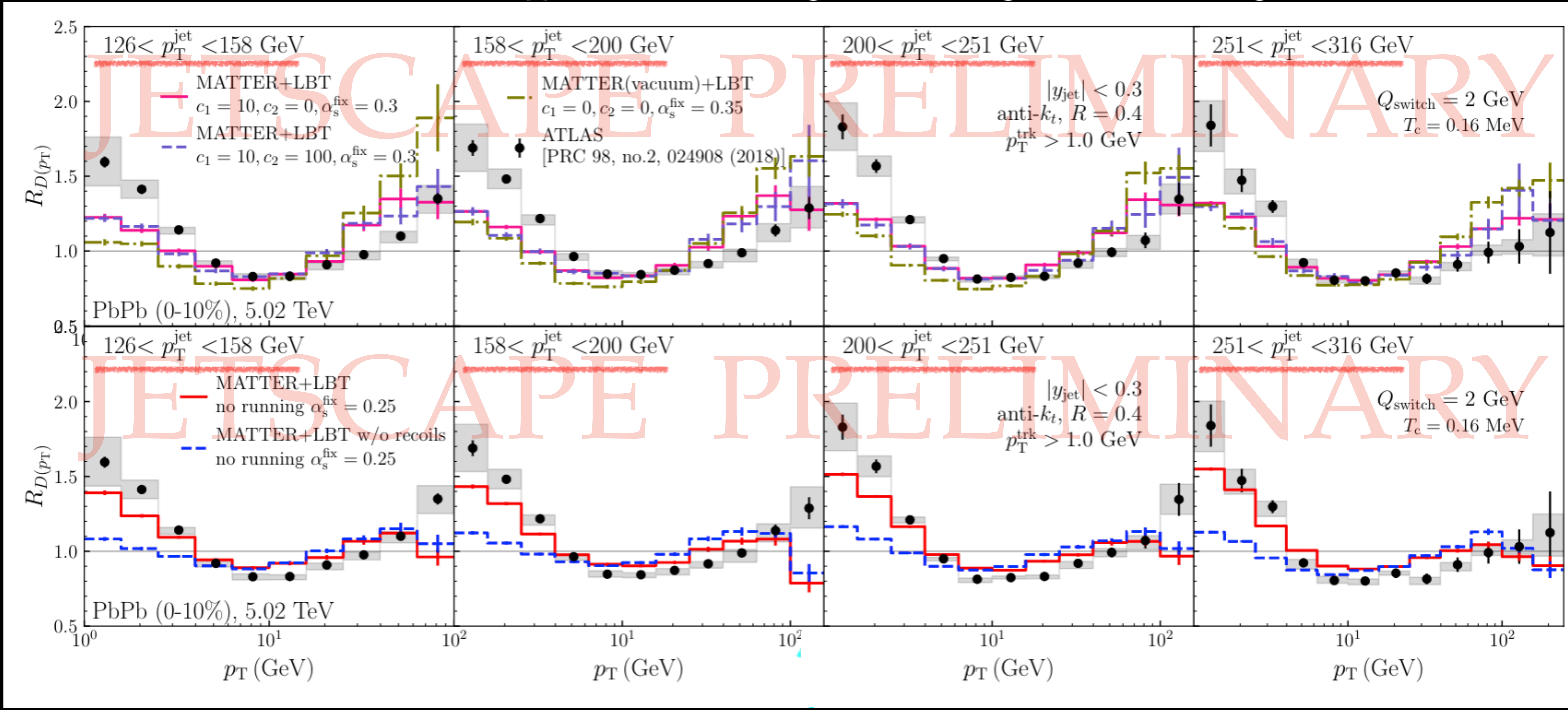
This will probably get done in an upcoming Bayesian analysis





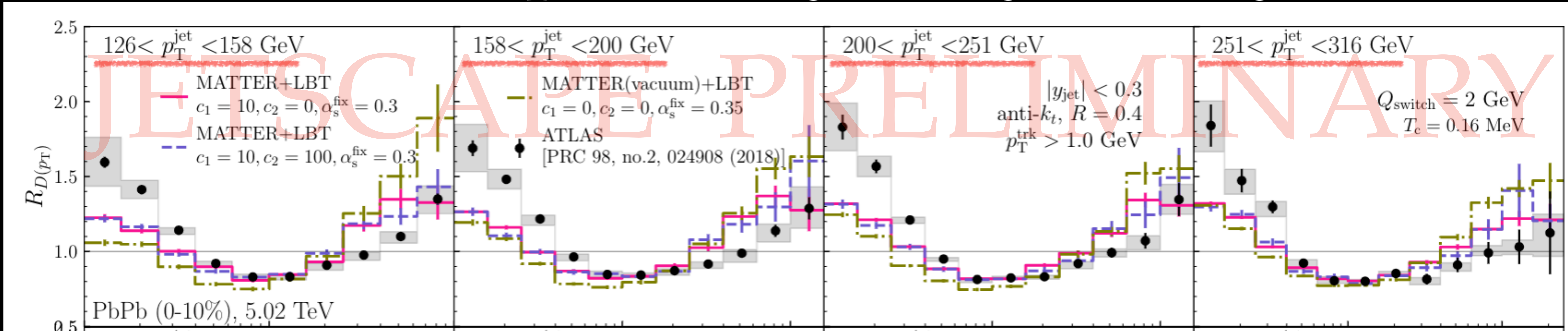
Y. Tachibana et al., *to appear*

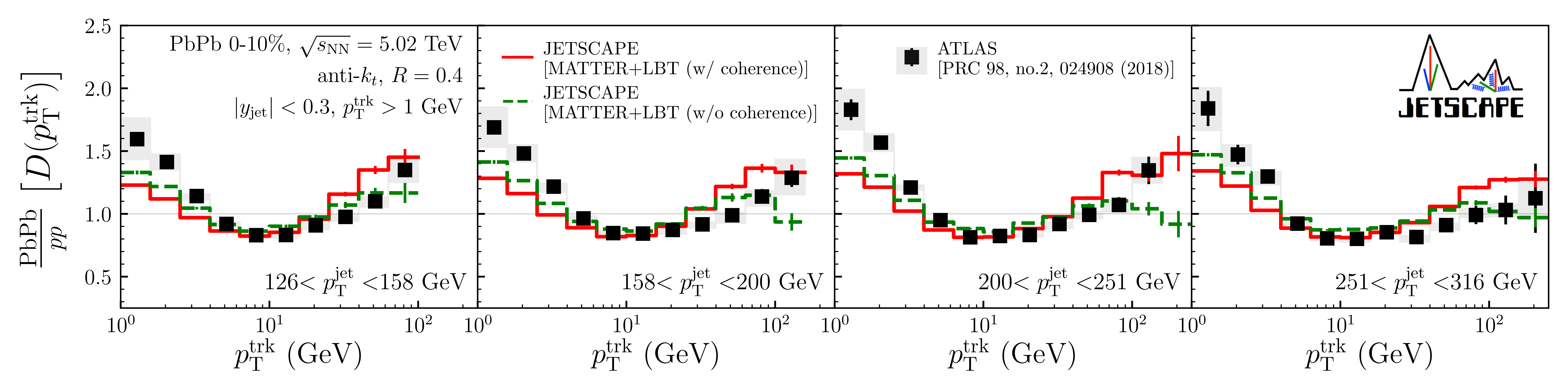
Need for quenching in high Q stage



Y. Tachibana et al., 2301.02485 [hep-ph]

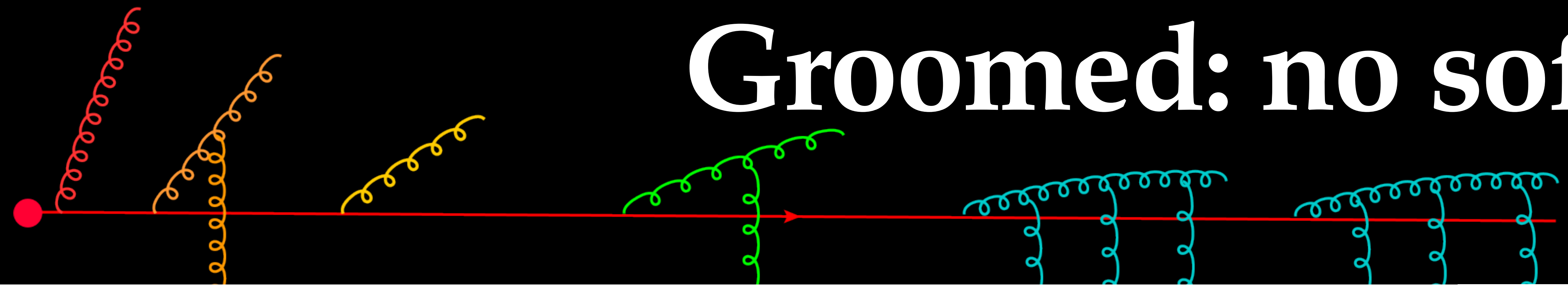
Need for quenching in high Q stage





Y. Tachibana et al., 2301.02485 [hep-ph]

Groomed: no soft modes!



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

Y. Tachibana et al., 2301.02485 [hep-ph]

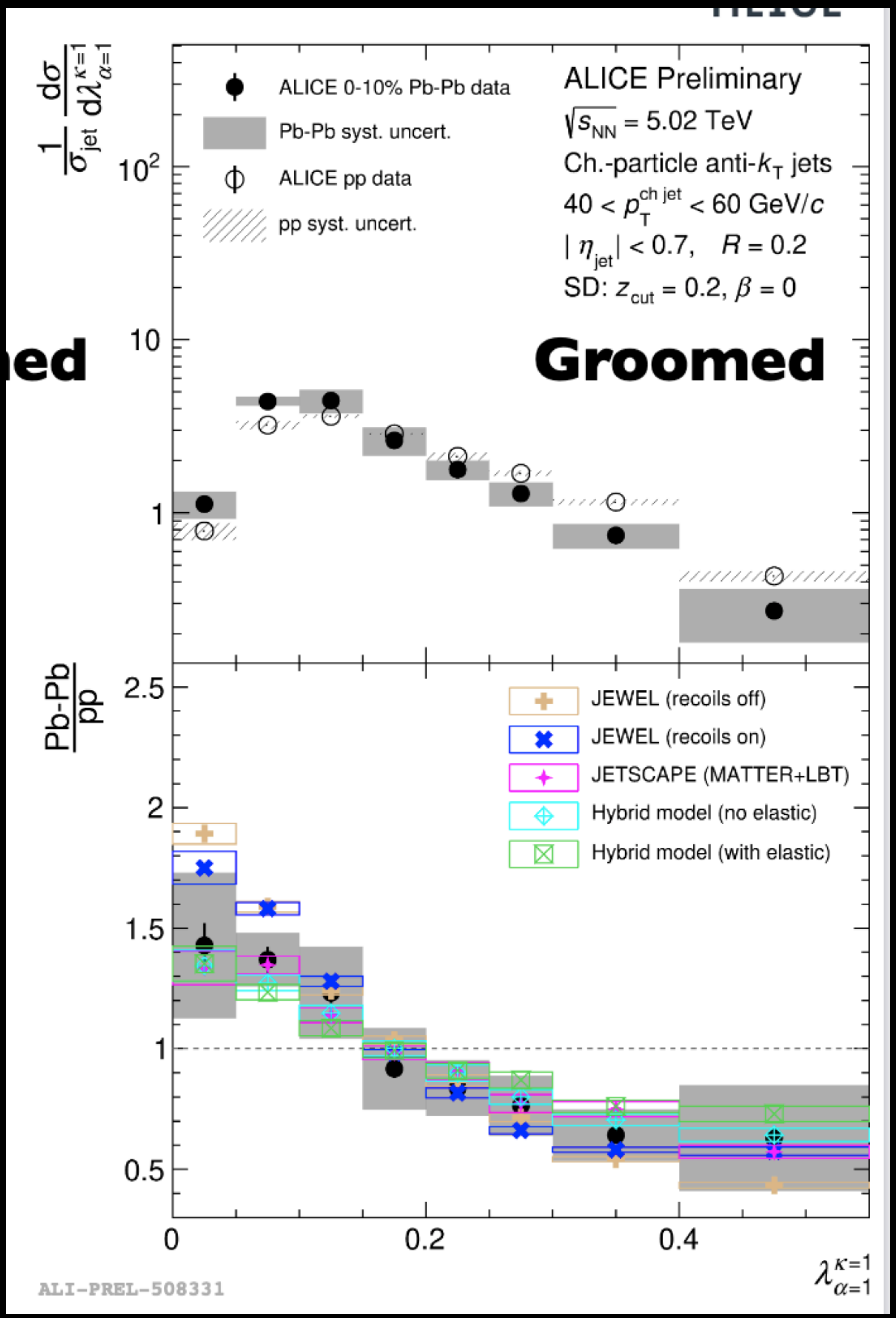
R_{AA} as a function of r_g

Yellow band represents region with $Q \simeq r_g E \lesssim 1 GeV$

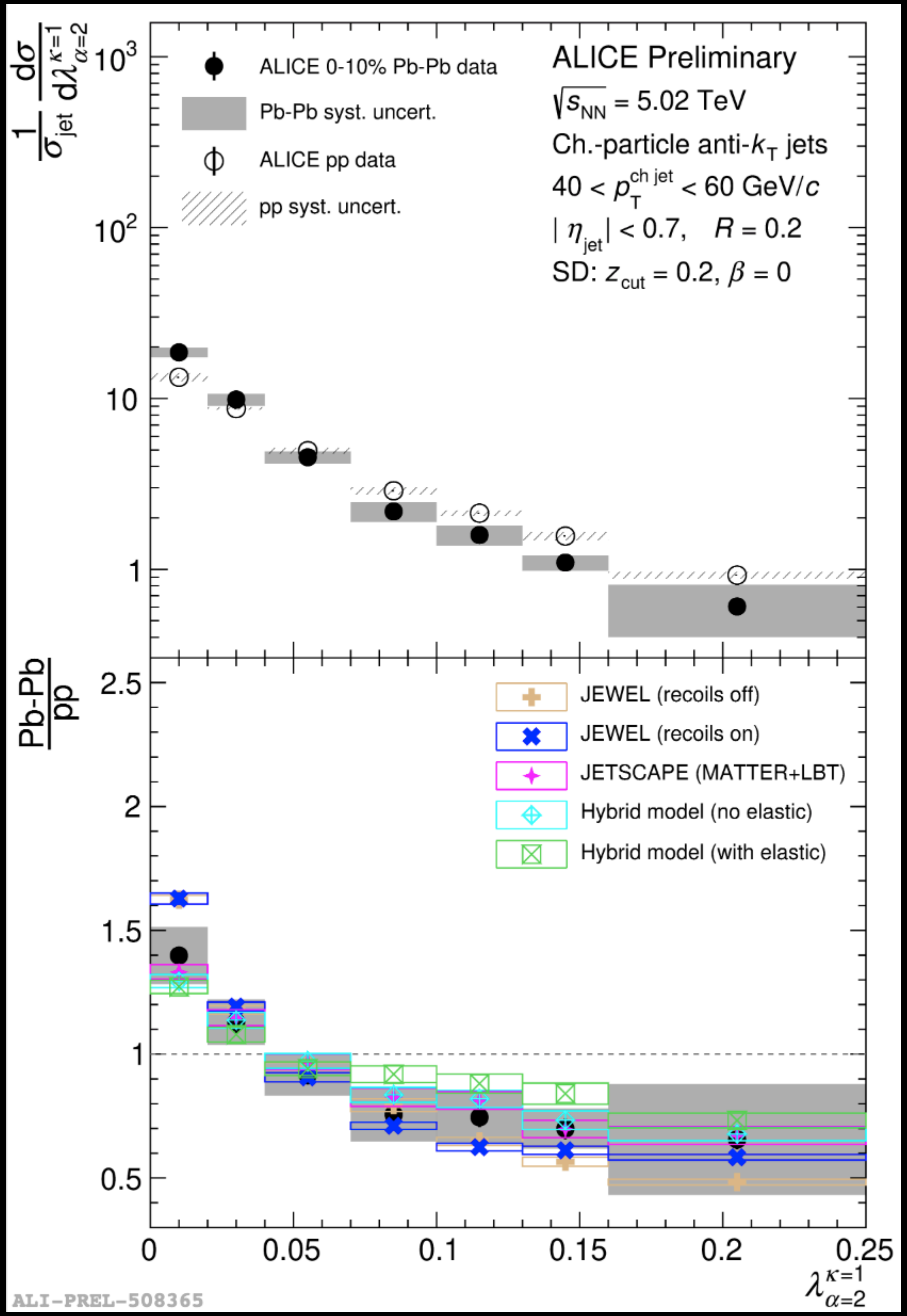
Calculations without Coherence show a bump

$$Q_{med}^2 \simeq \sqrt{2E\hat{q}} \quad or \quad Q_{med} = (2E\hat{q})^{\frac{1}{4}}$$

Groomed Jet angularities

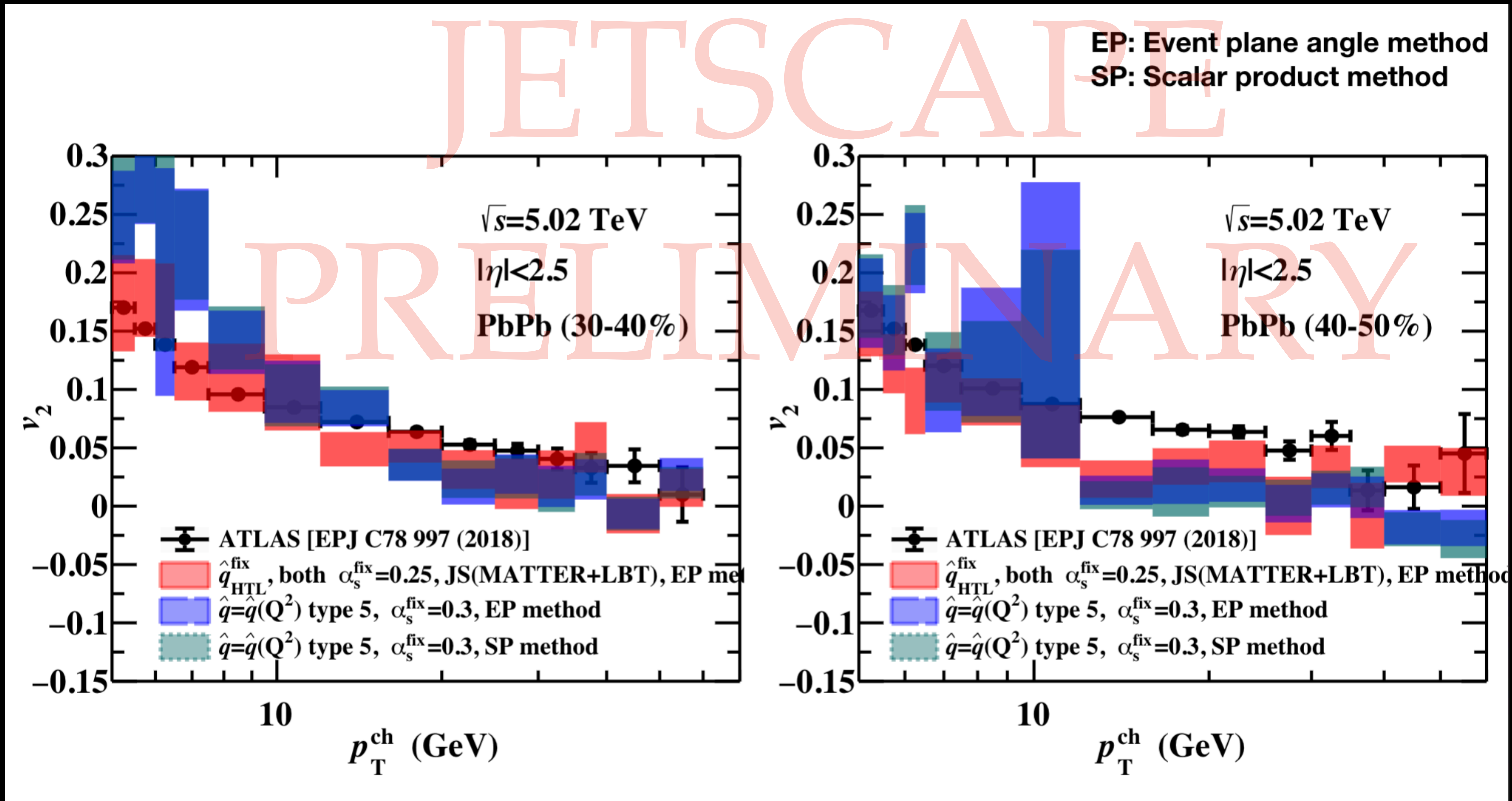


- $\lambda = \sum_{i \in Groomed} z_i \theta_i^{\alpha}$
- Strong constraints on the perturbative part of jet
- Several other similar groomed observables
- JETSCAPE (MATTER +LBT) does very well.

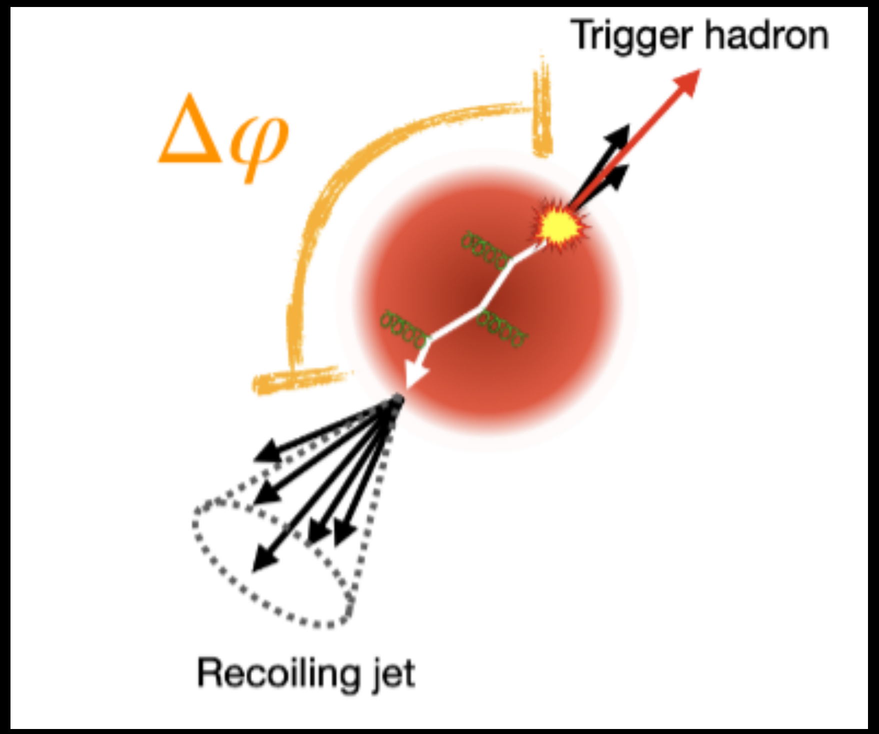


Azimuthal anisotropy

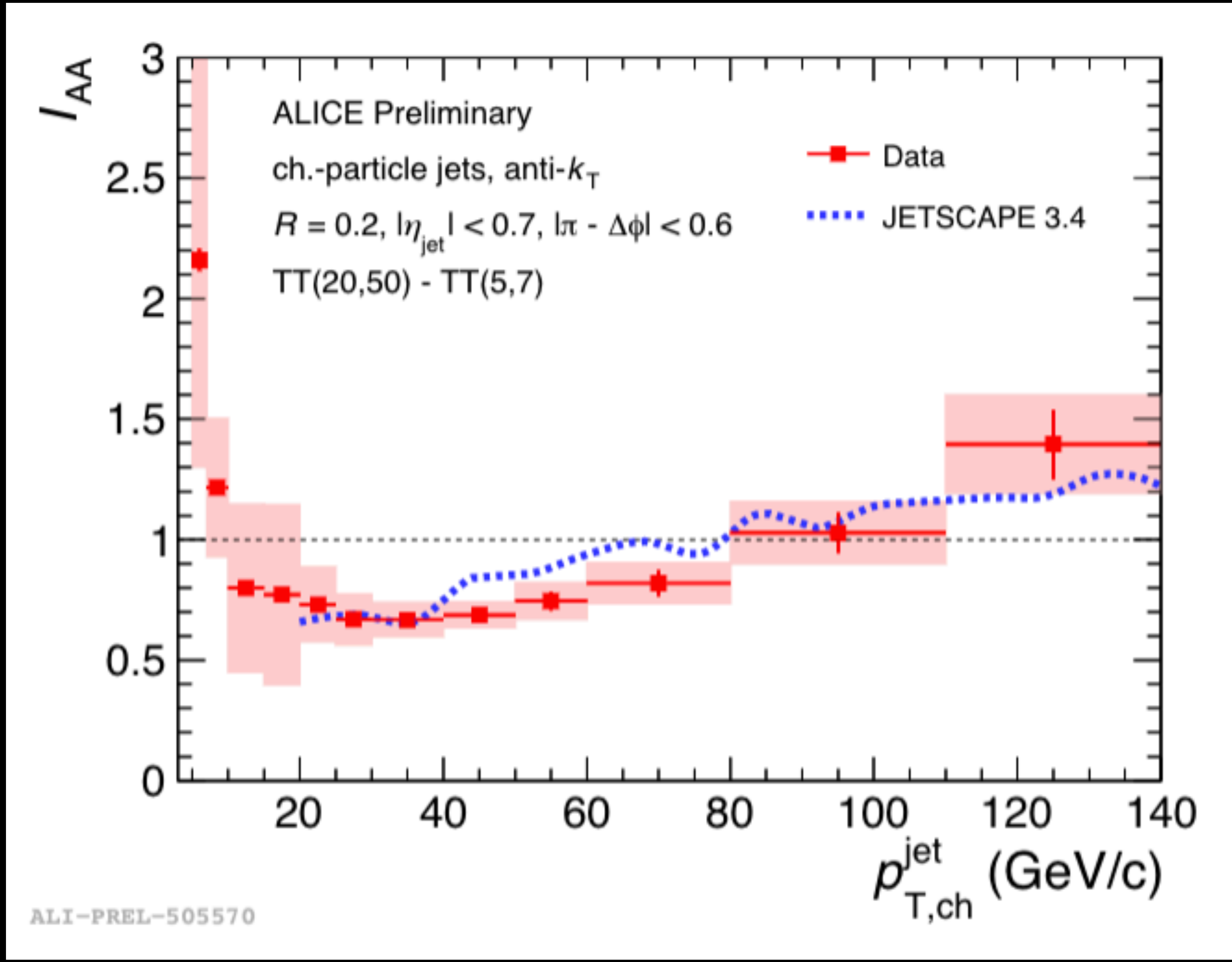
- Note: we haven't played with start and stop times (observation by C. Andres et al, start time important for v_2)
- In the JETSCAPE simulations, hydrodynamics starts around 1fm/c. (Free streaming prior)
- Also with new IP-Glasma, medium has primordial v_2
- Jet modification in the hadronic medium still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

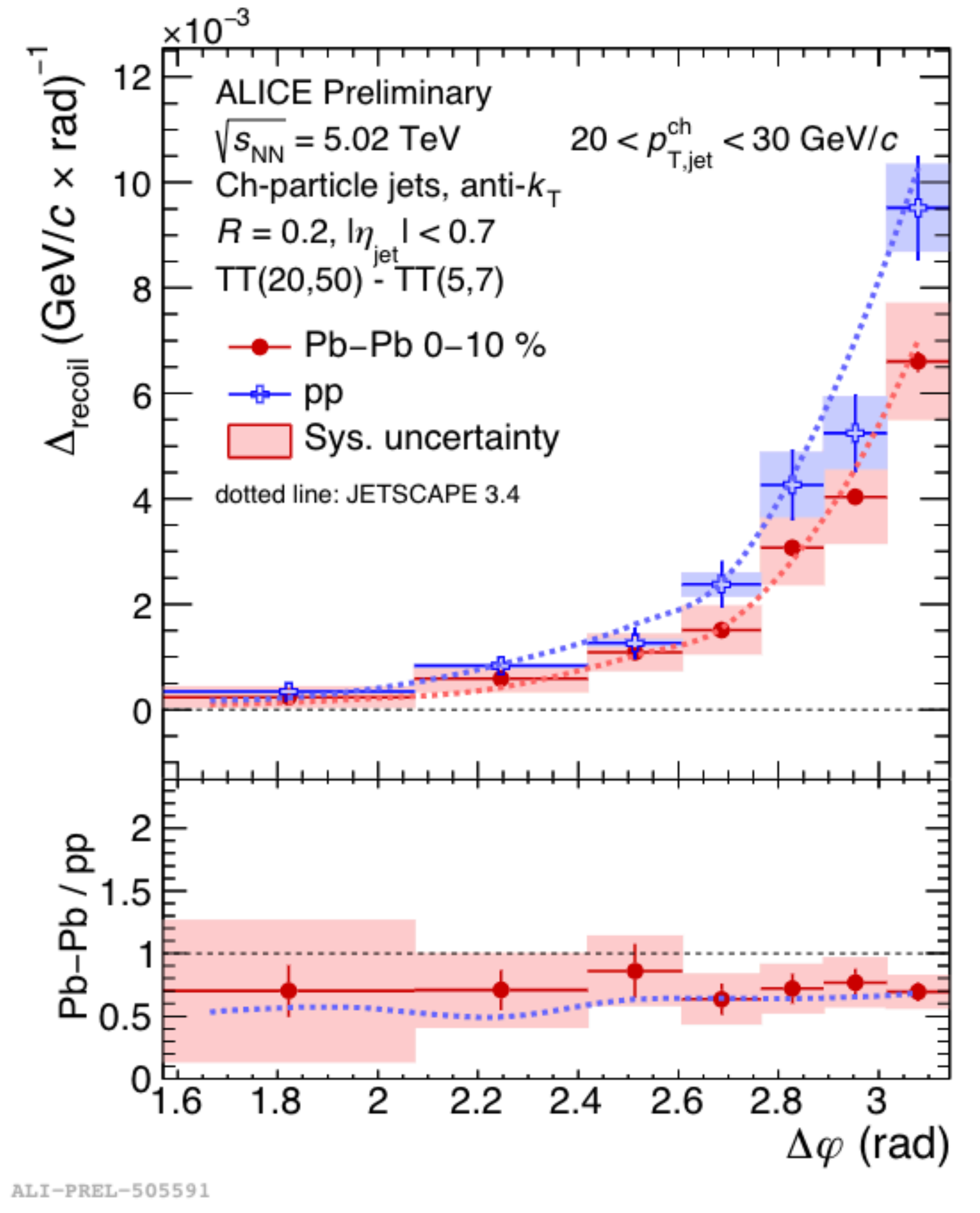


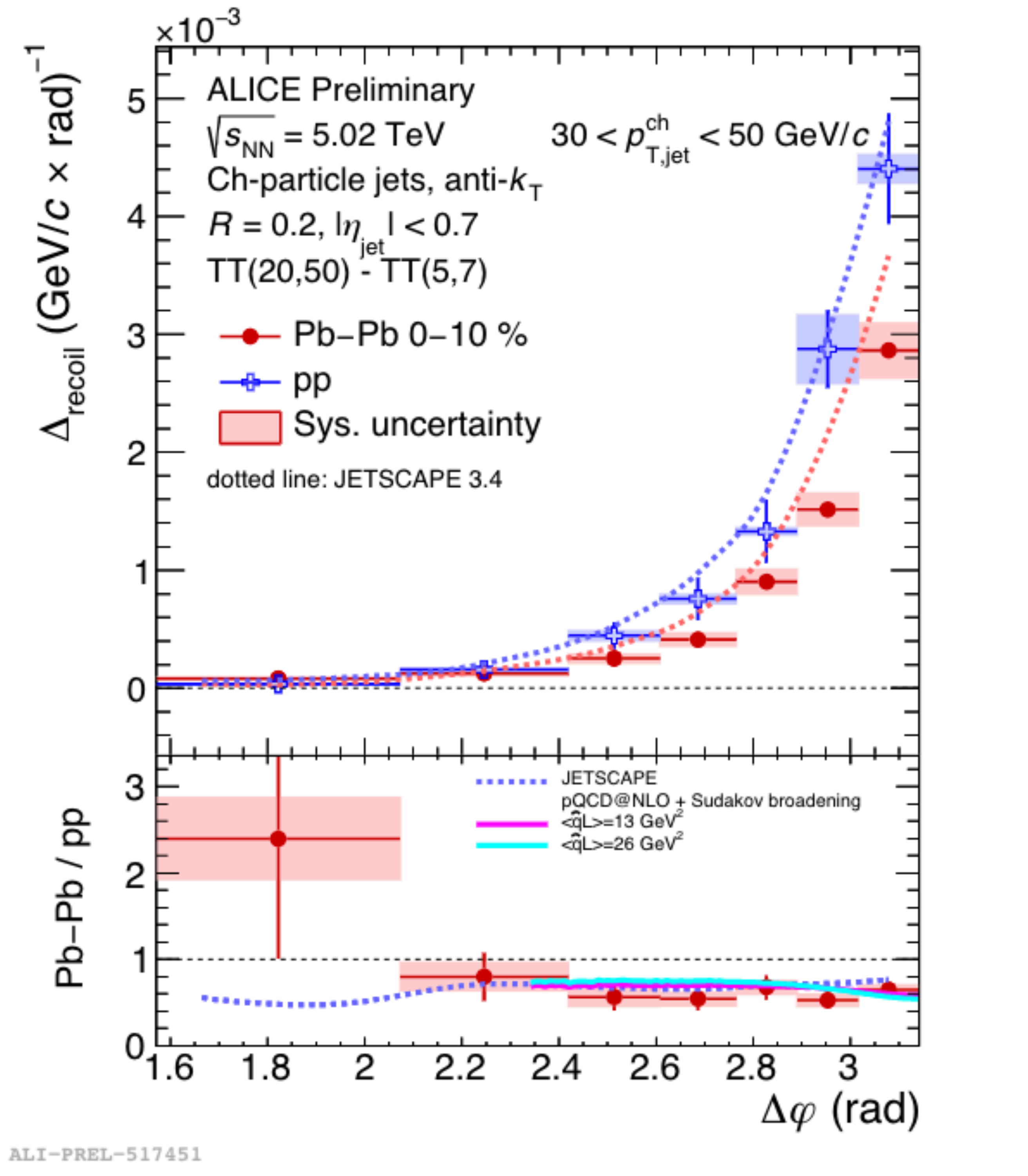
Coincidence with hadrons



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

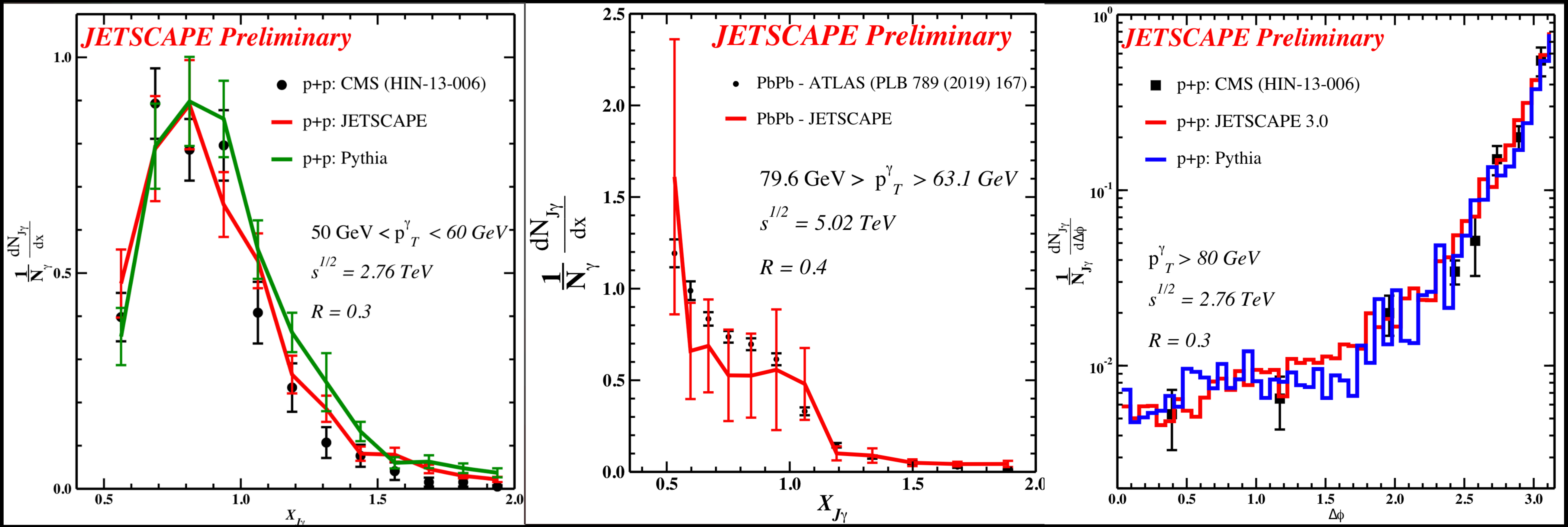






Photon Trigger

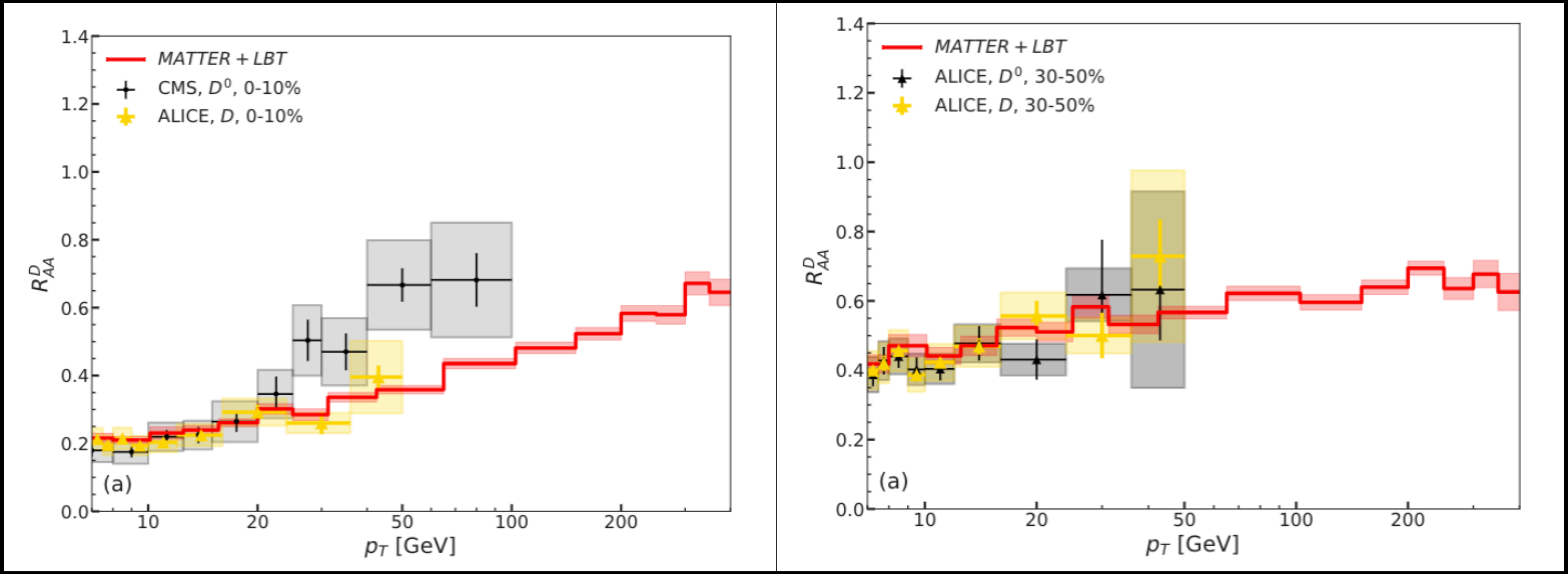
- Higher statistics runs with the exact same parameters as for jets.



C. Sirimanna, *to appear*.

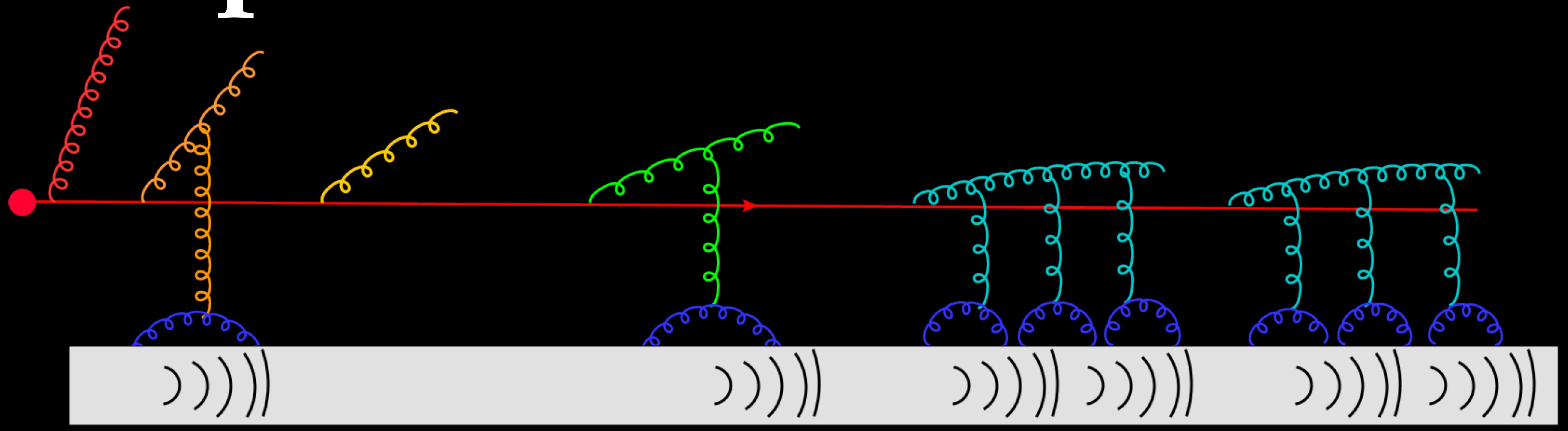
Heavy-quarks

- D meson R_{AA} with identical parameters



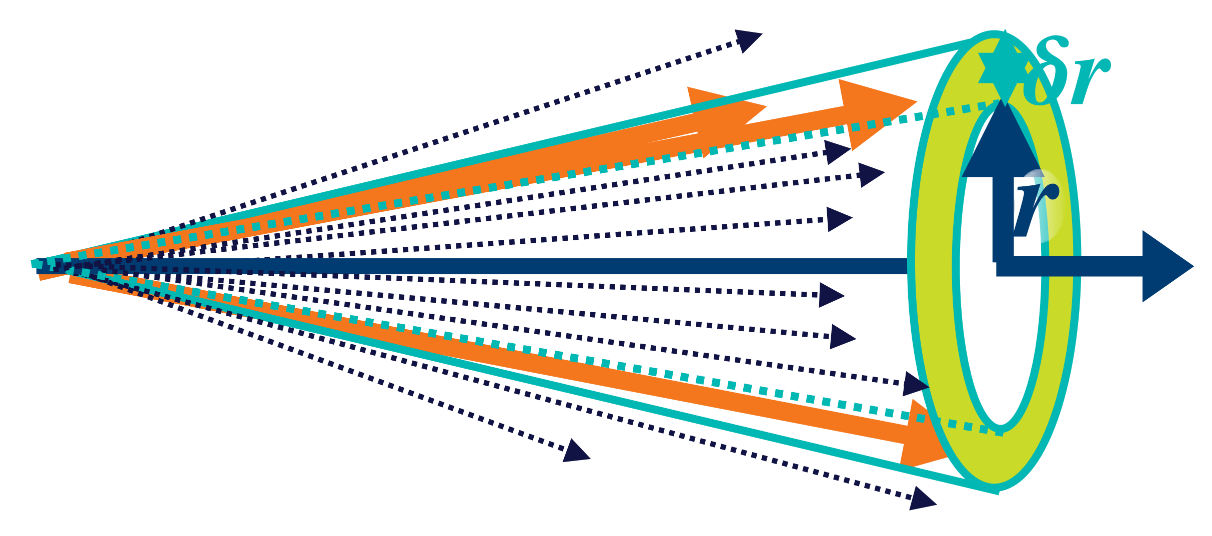
W. Fan, *et al*. e-Print: 2208.00983 [nucl-th]

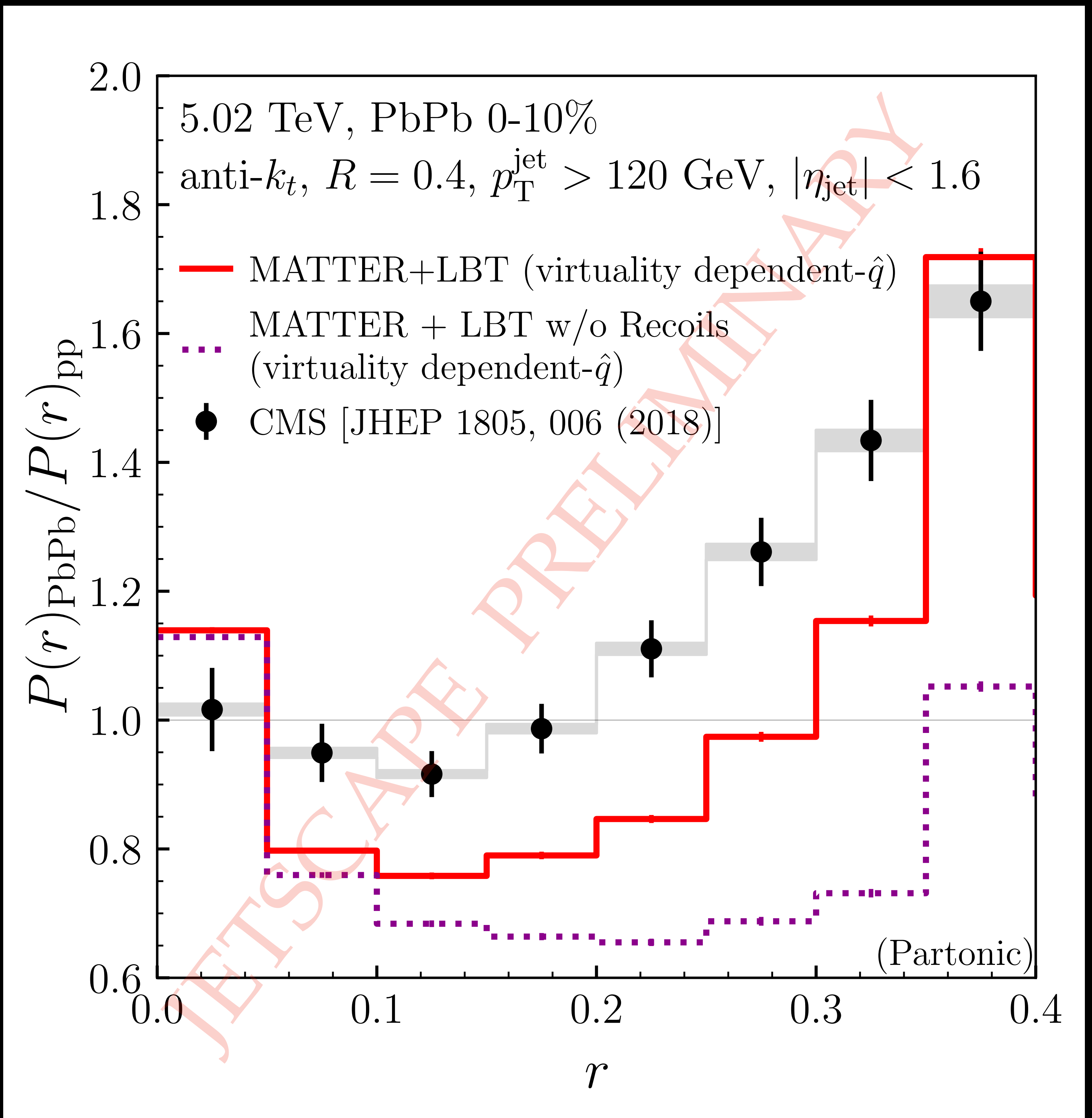
Jet Shape: more dependence on soft modes



- 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.

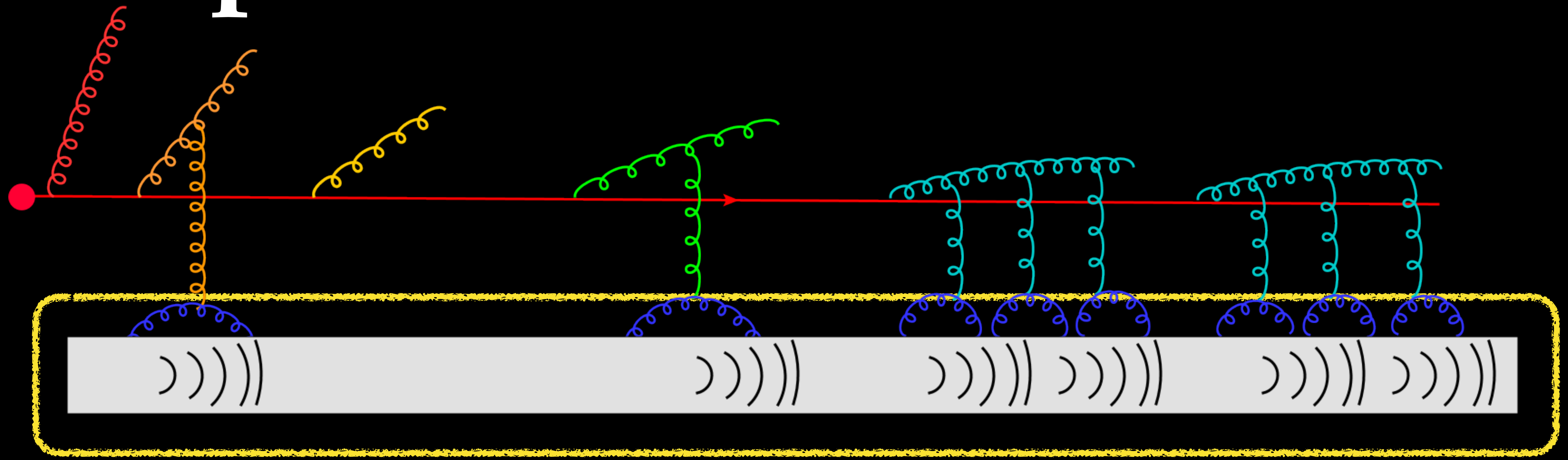
$$P(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{trk}\in(r\pm\delta r/2)} p_{\text{T}}^{\text{trk}}}{\delta r}$$





See talk by Xin-Nian Wang

Jet Shape: more dependence on soft modes



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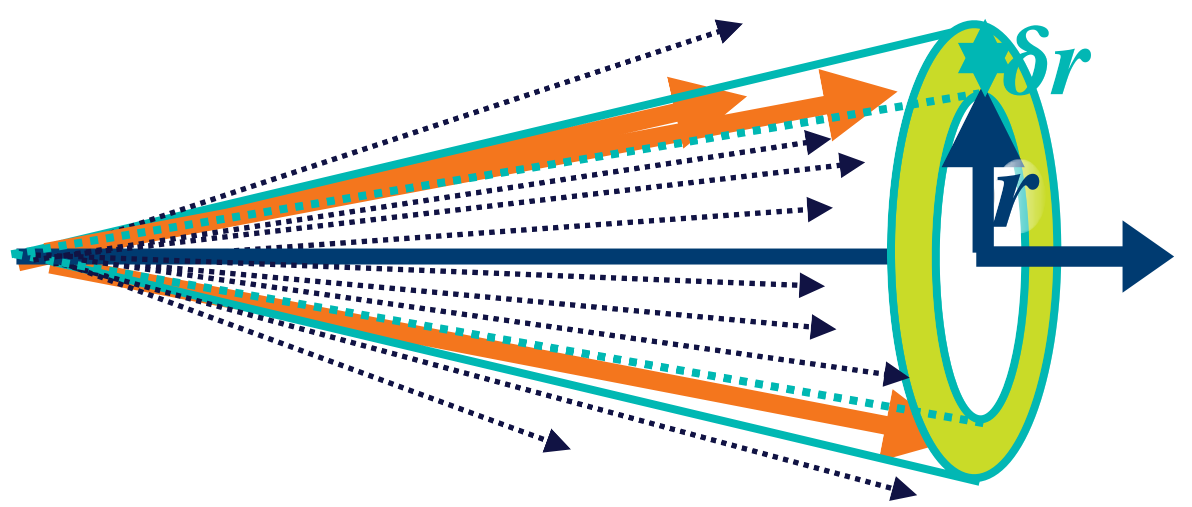
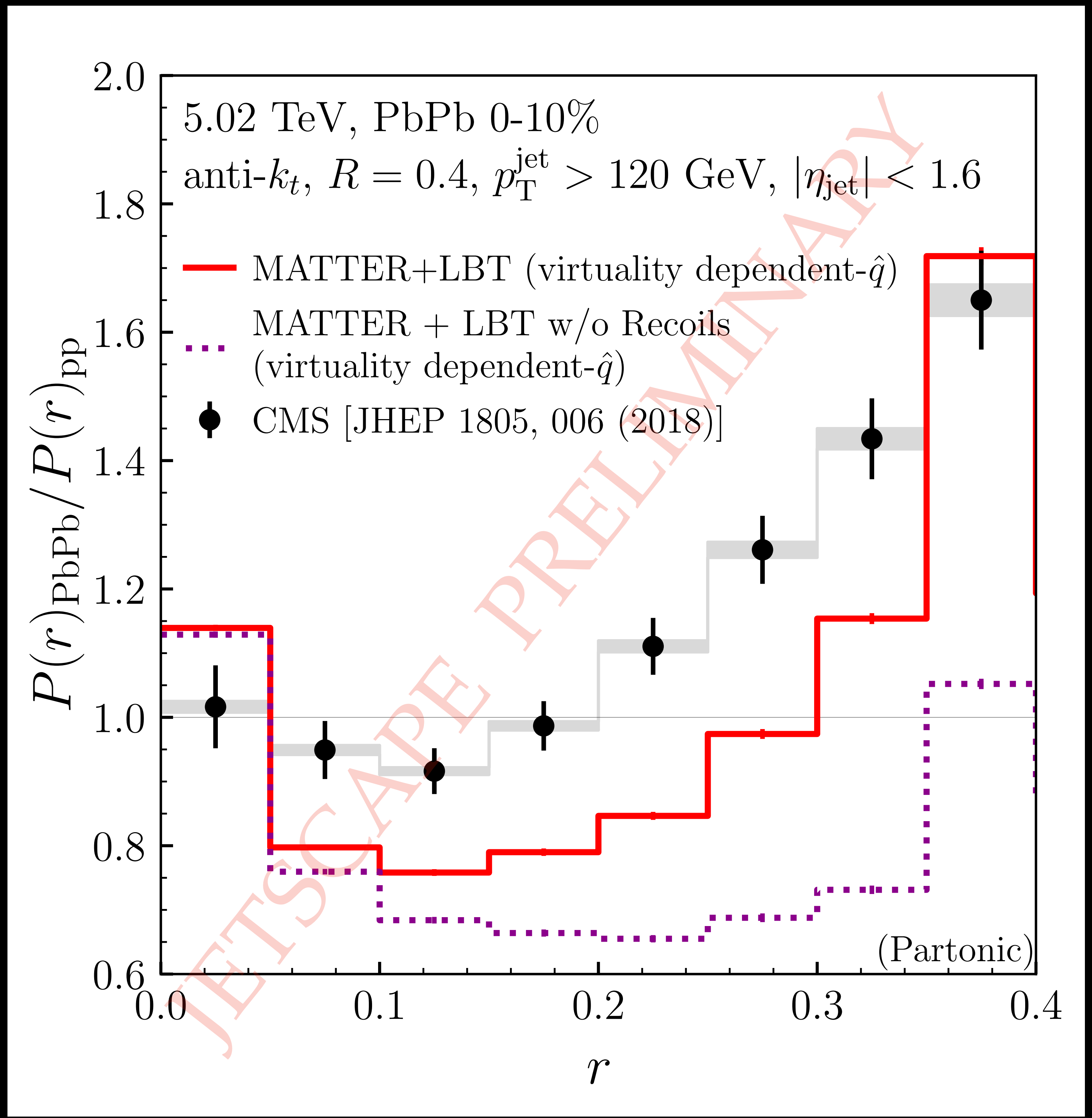
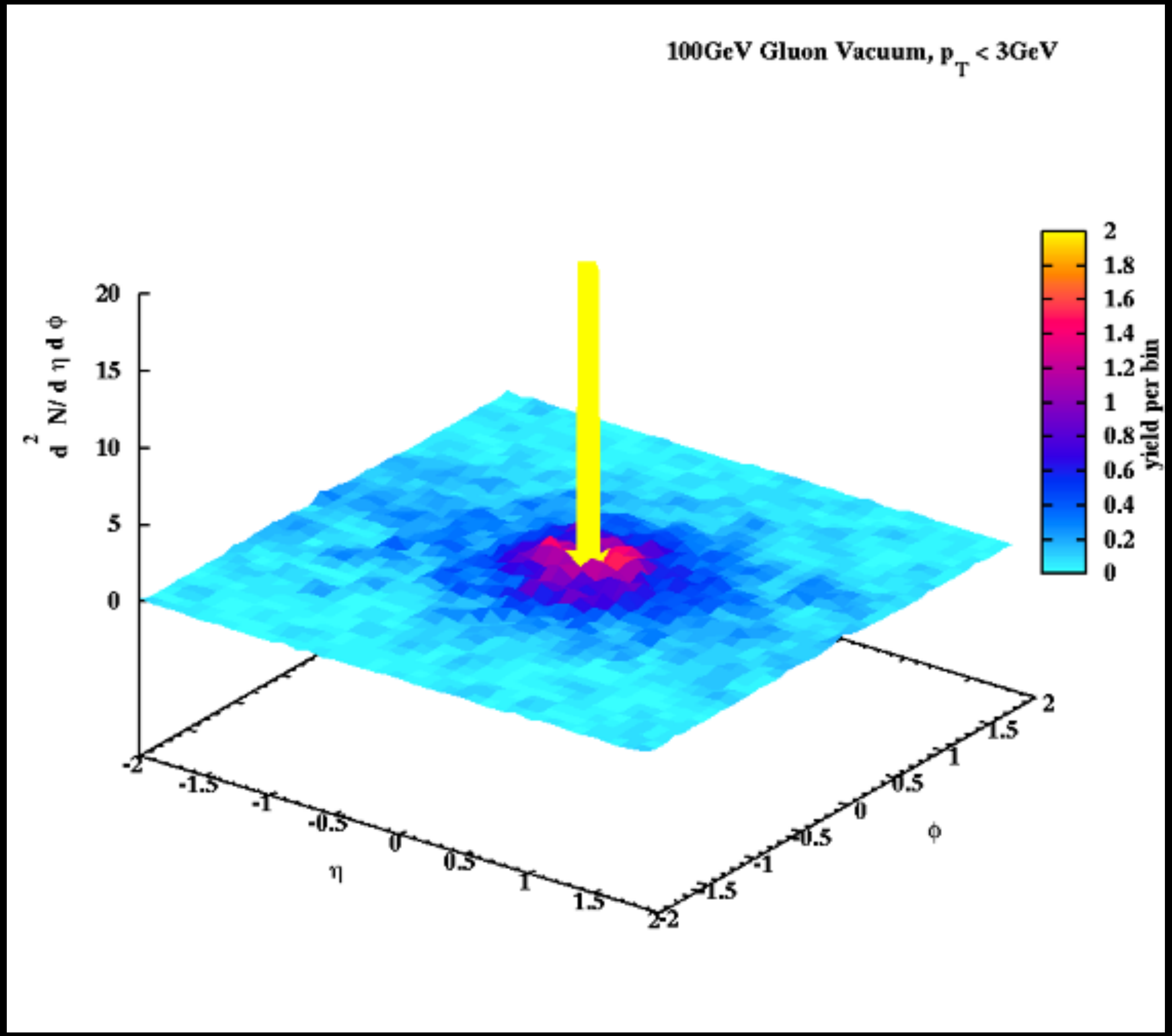


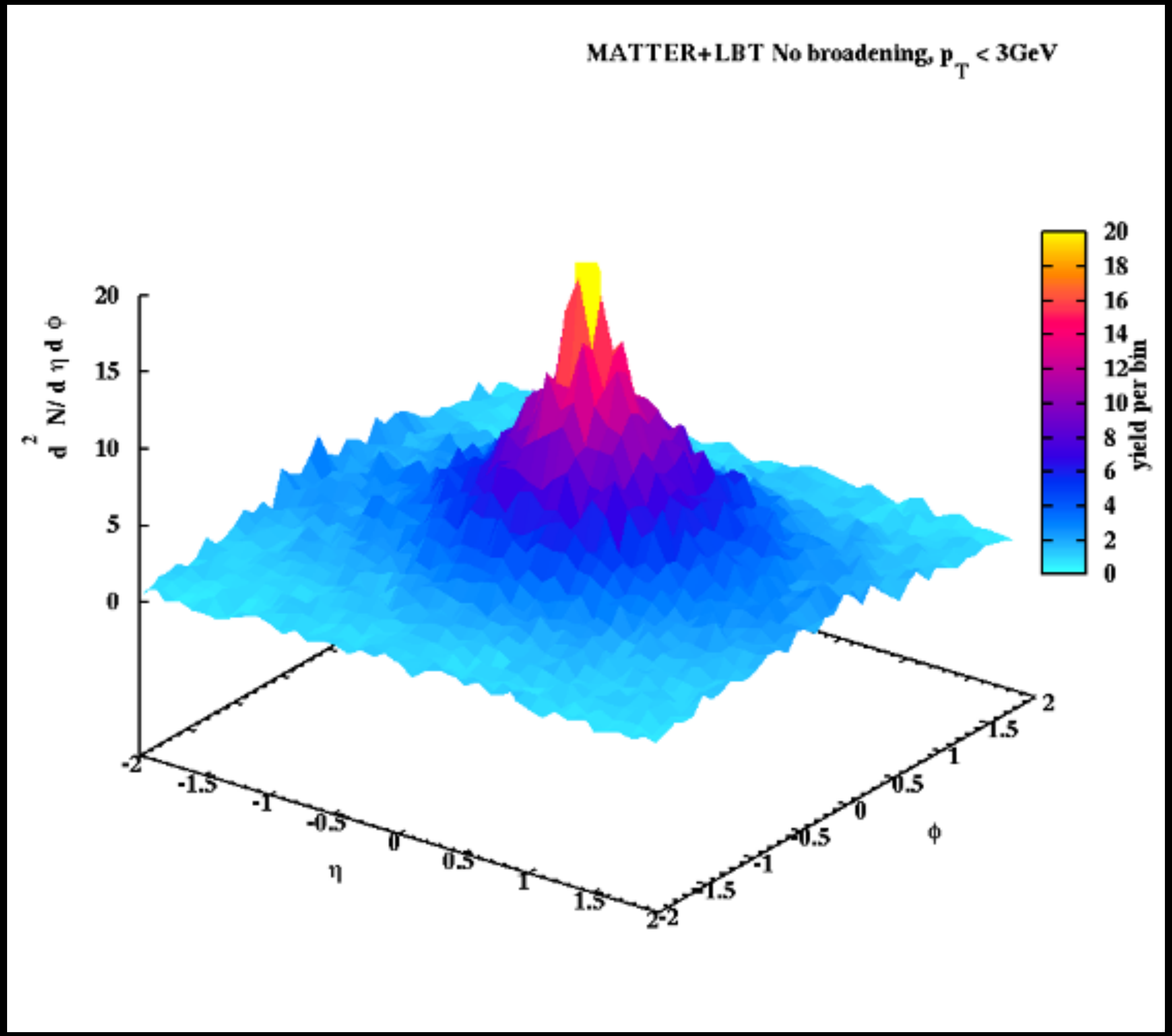


See talk by Xin-Nian Wang

Soft jet partons move far away from the jet

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

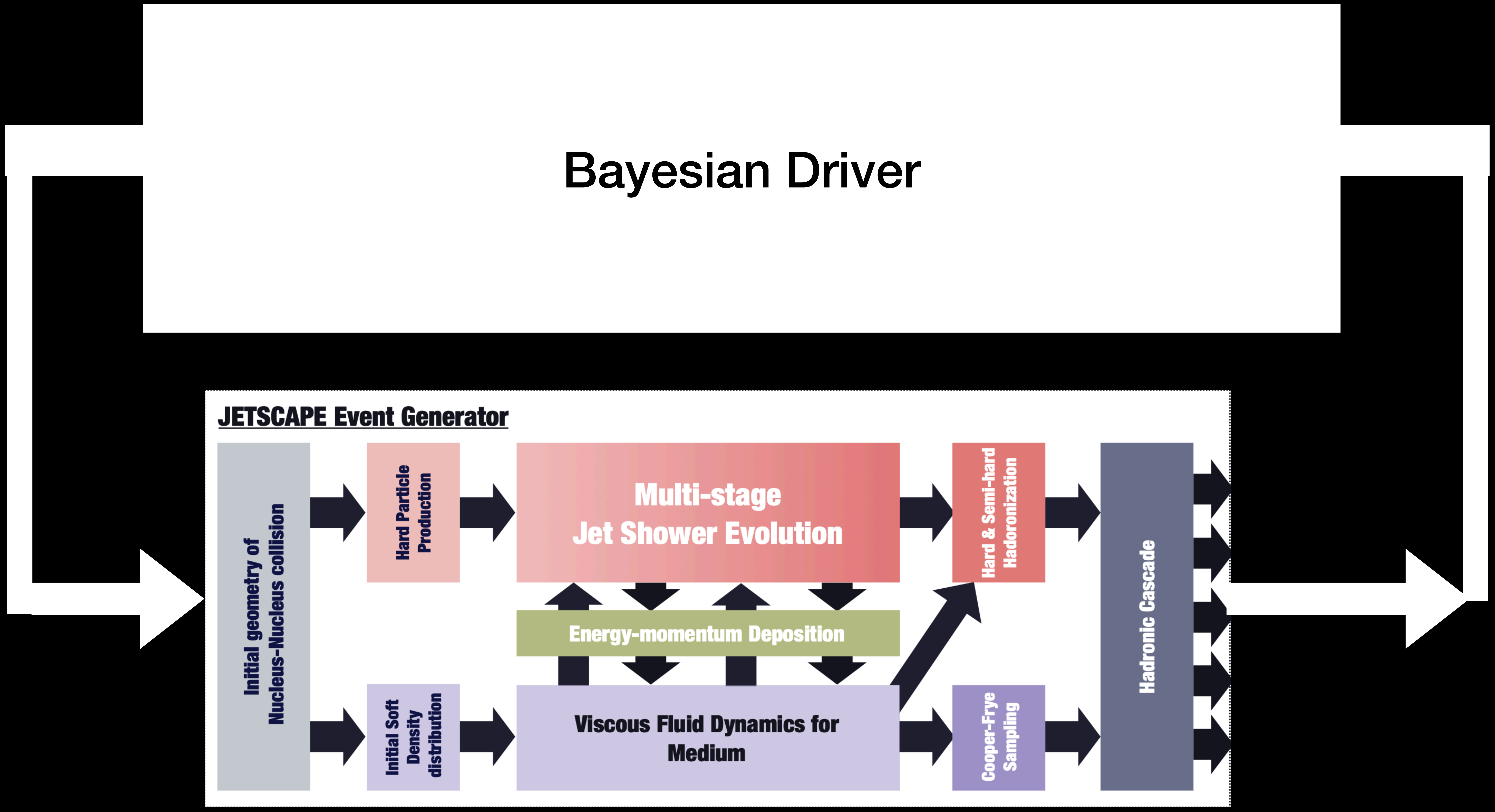




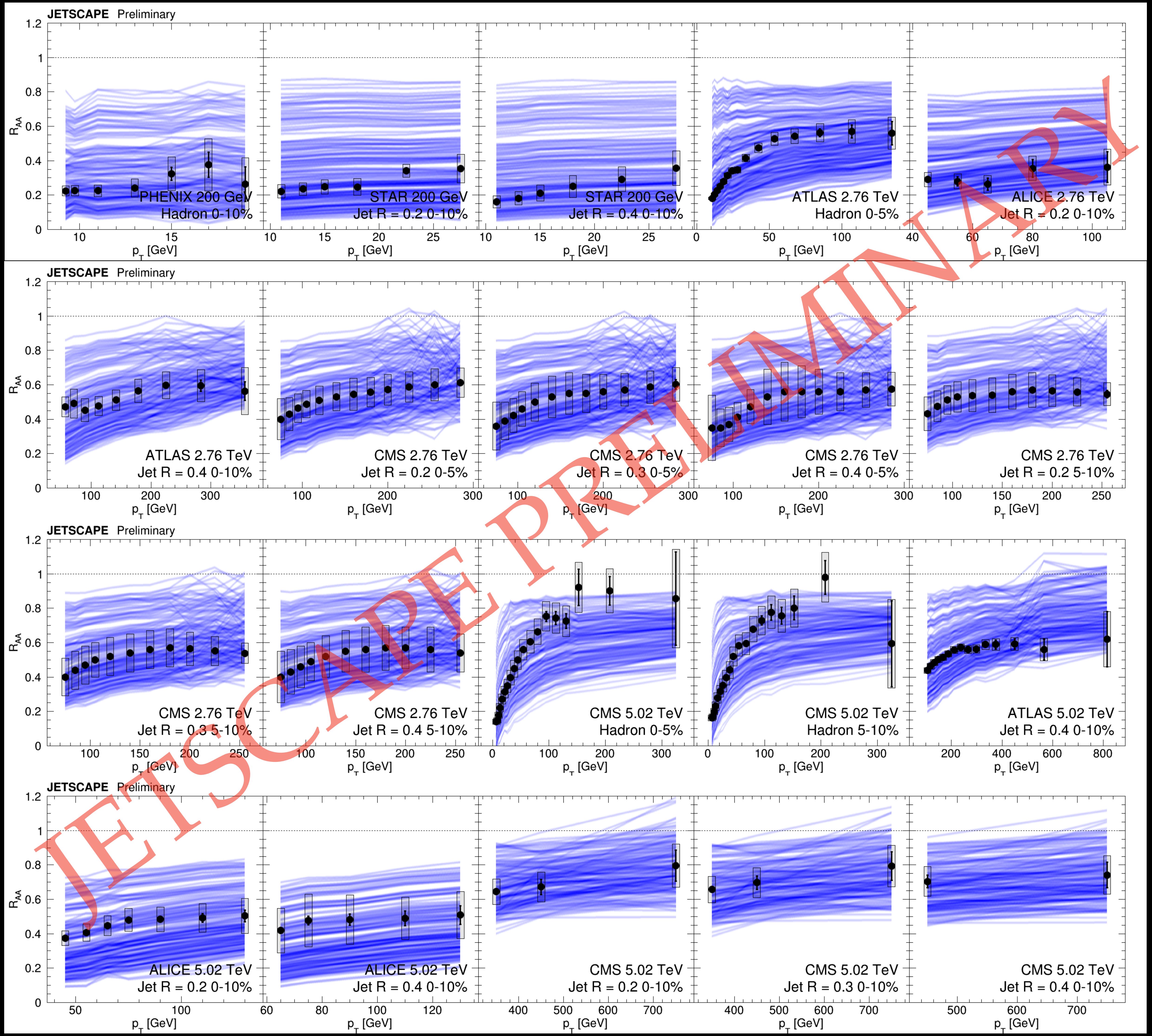
This requires to run one hydro simulation per hard event.

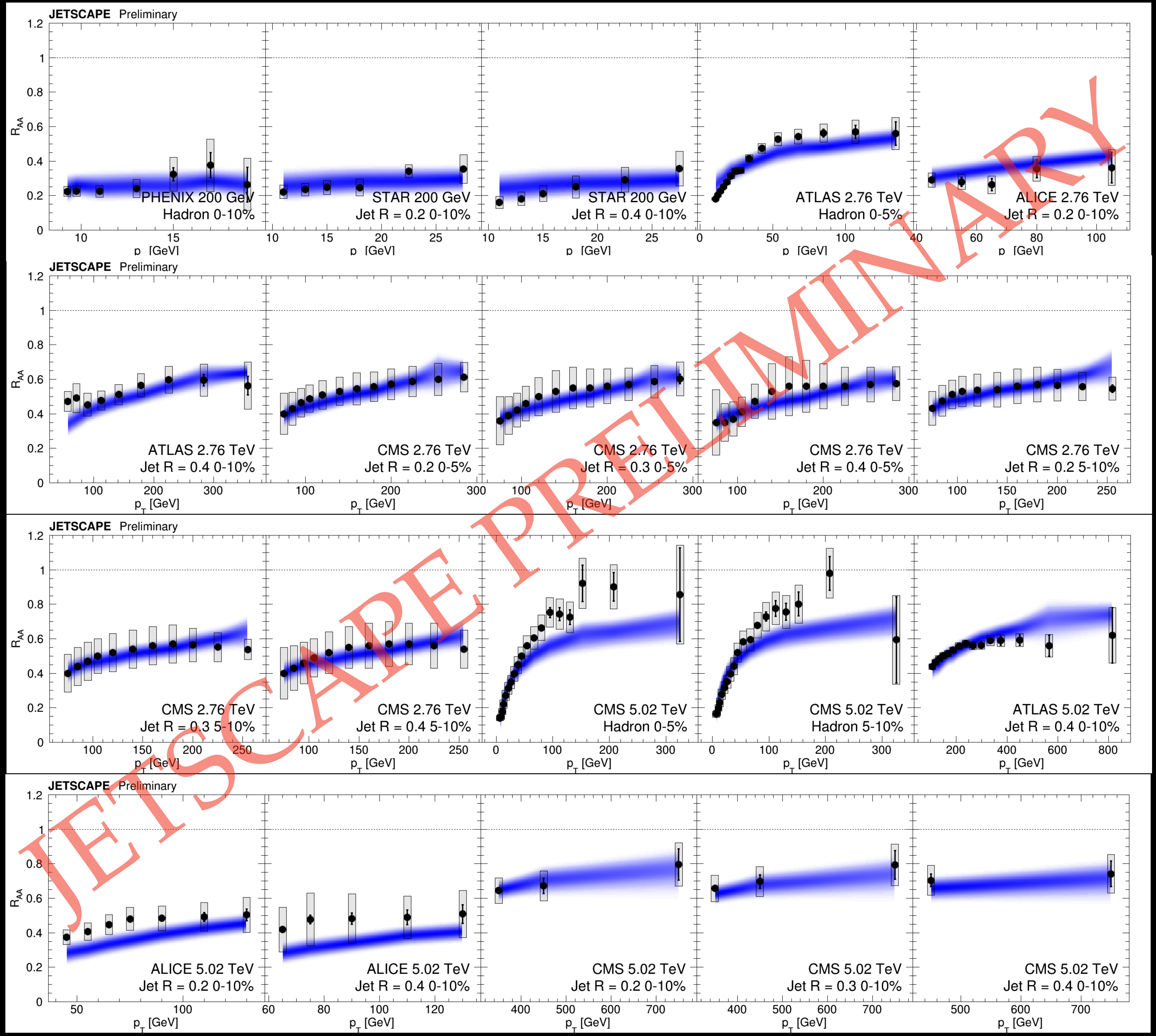
How can we make this even more rigorous?

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



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

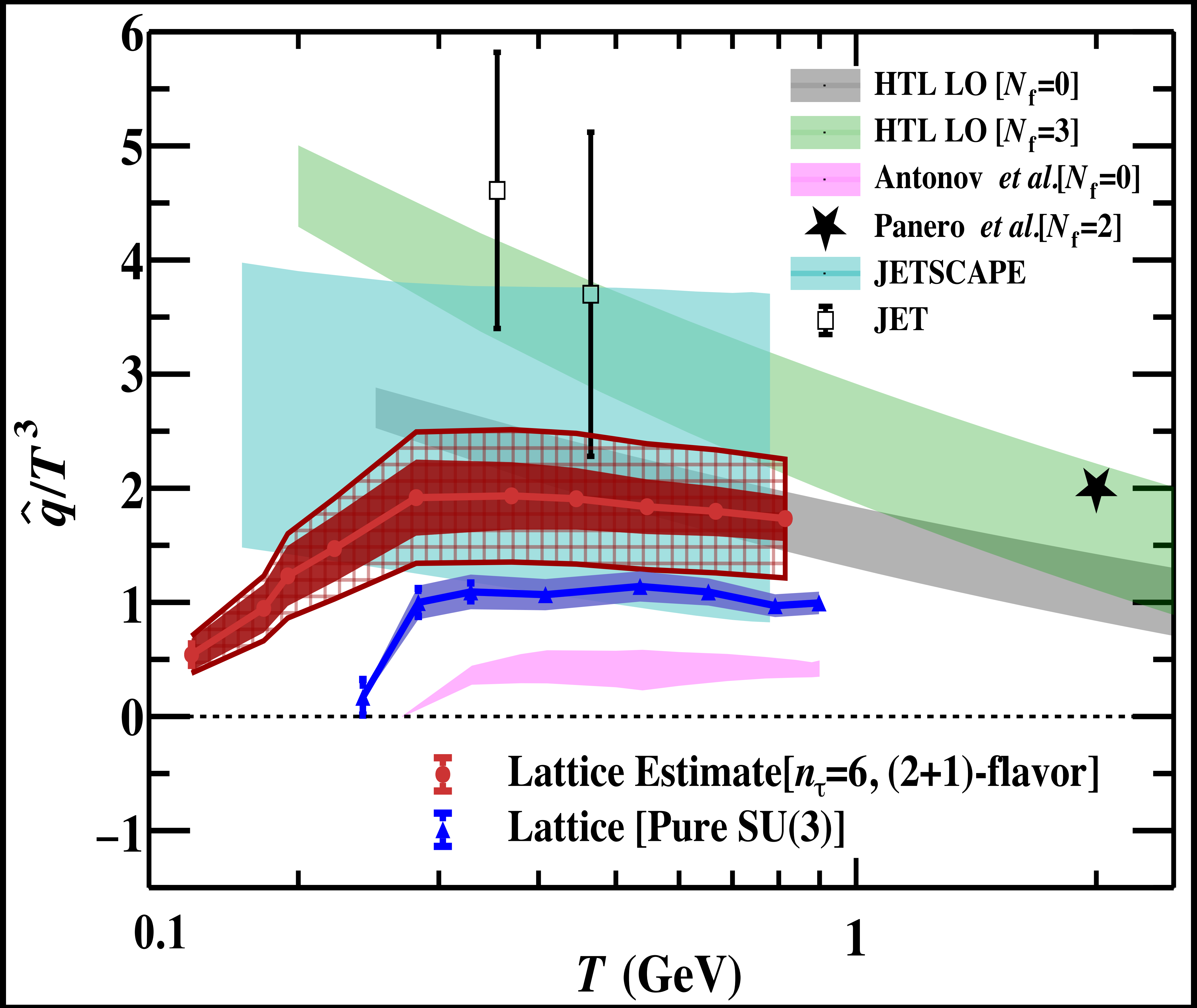




4 parameters used

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.



Kumar et al. PRD 106 (2022) 3, 034505

This is where we are now

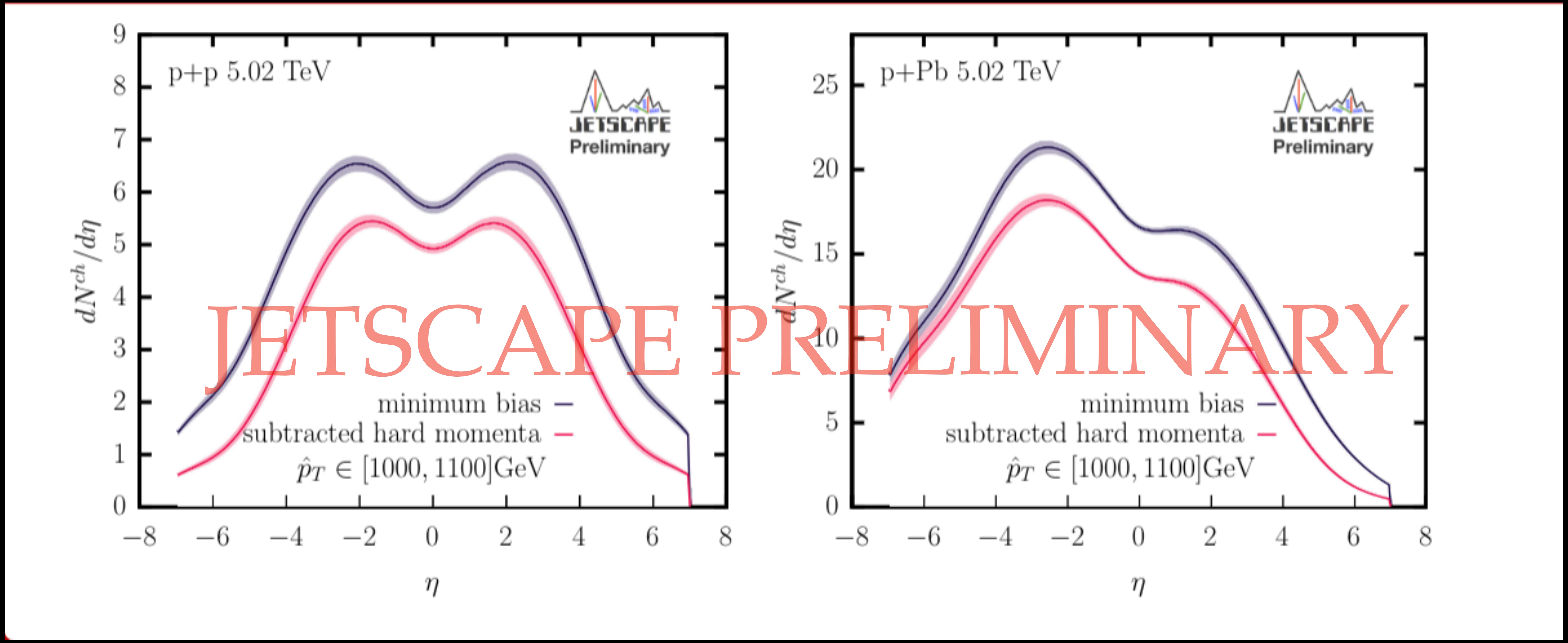
- We added one more parameter Q_0, transition between high and low virtuality.
- Multi-stage set up seems to able to explain almost all the data
- The Bayesian calibration is being conducted as we speak
- Will rigorously test picture of 2-stage energy loss, with HTL based kernel at $\mu < Q_0$, and gradual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

Summary

- 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.

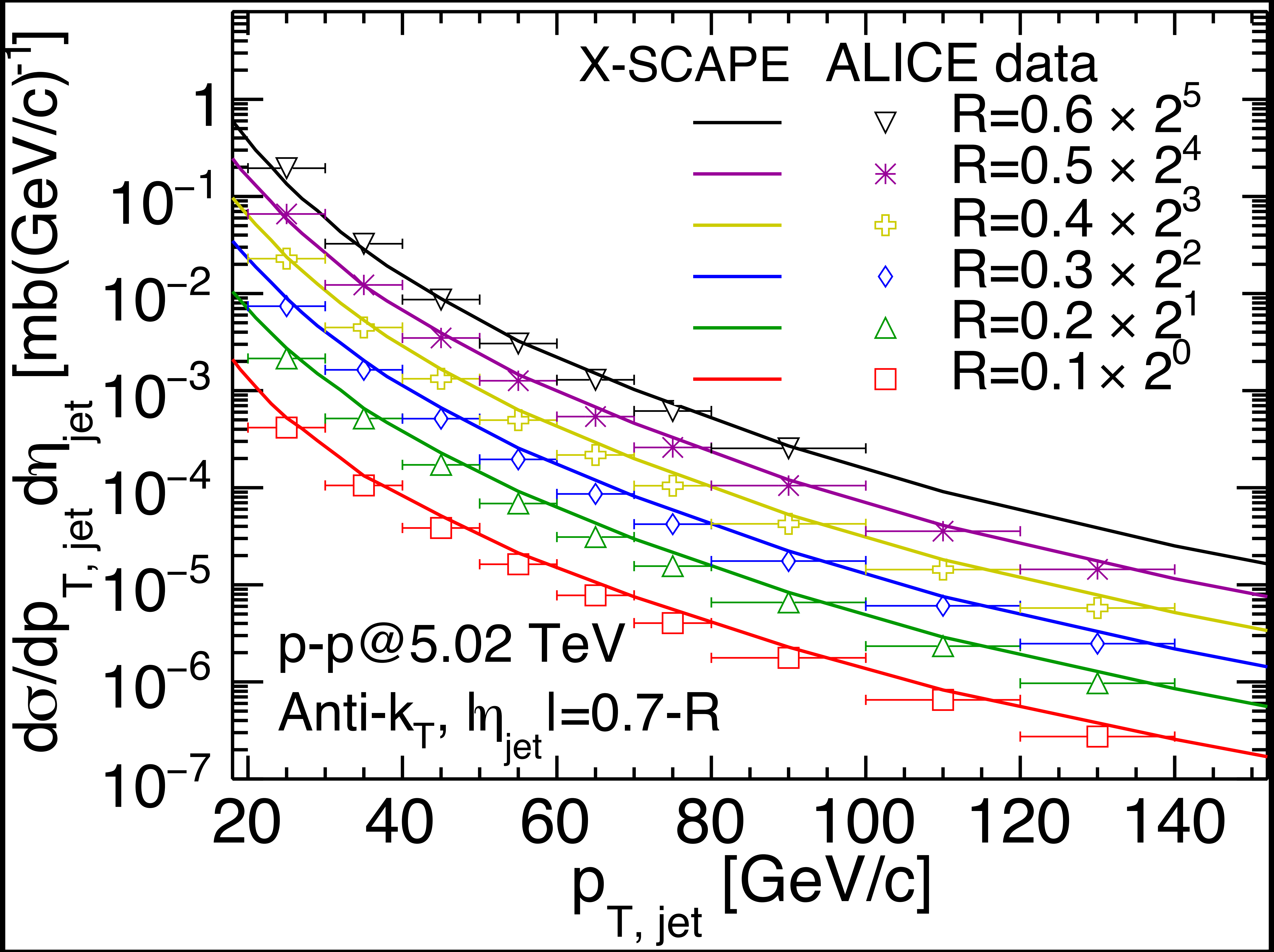
Next Steps

- JETSCAPE is moving towards p-A, low energy A-A and e-A



XSCAPE

Combining ISR with MPI correlated with an initial state and a hydro



Thanks to my collaborators