Studying the QGP with JETSCAPE

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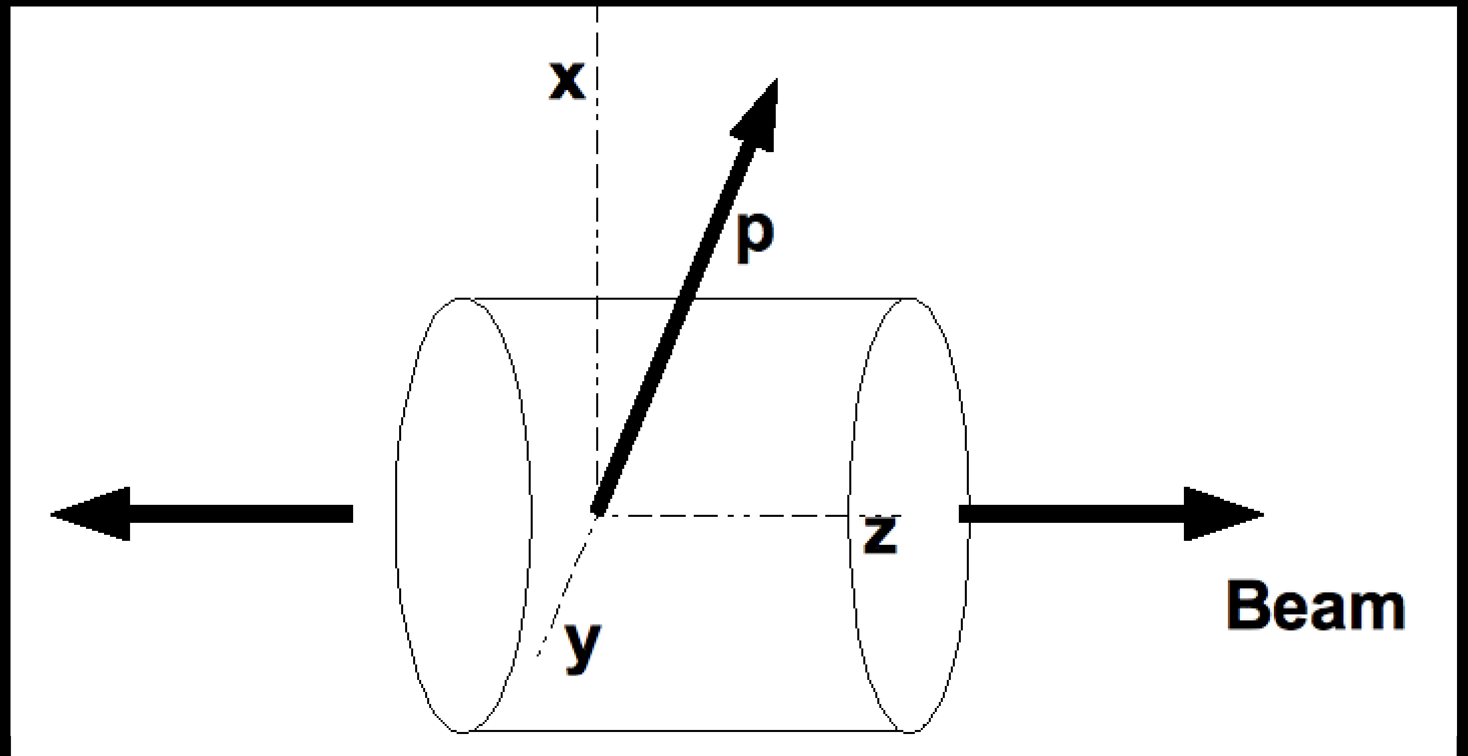
For the JETSCAPE Collaboration

CIPANP 2022, Lake Buena Vista, Florida: Aug 31st 2022

The whole talk in one slide

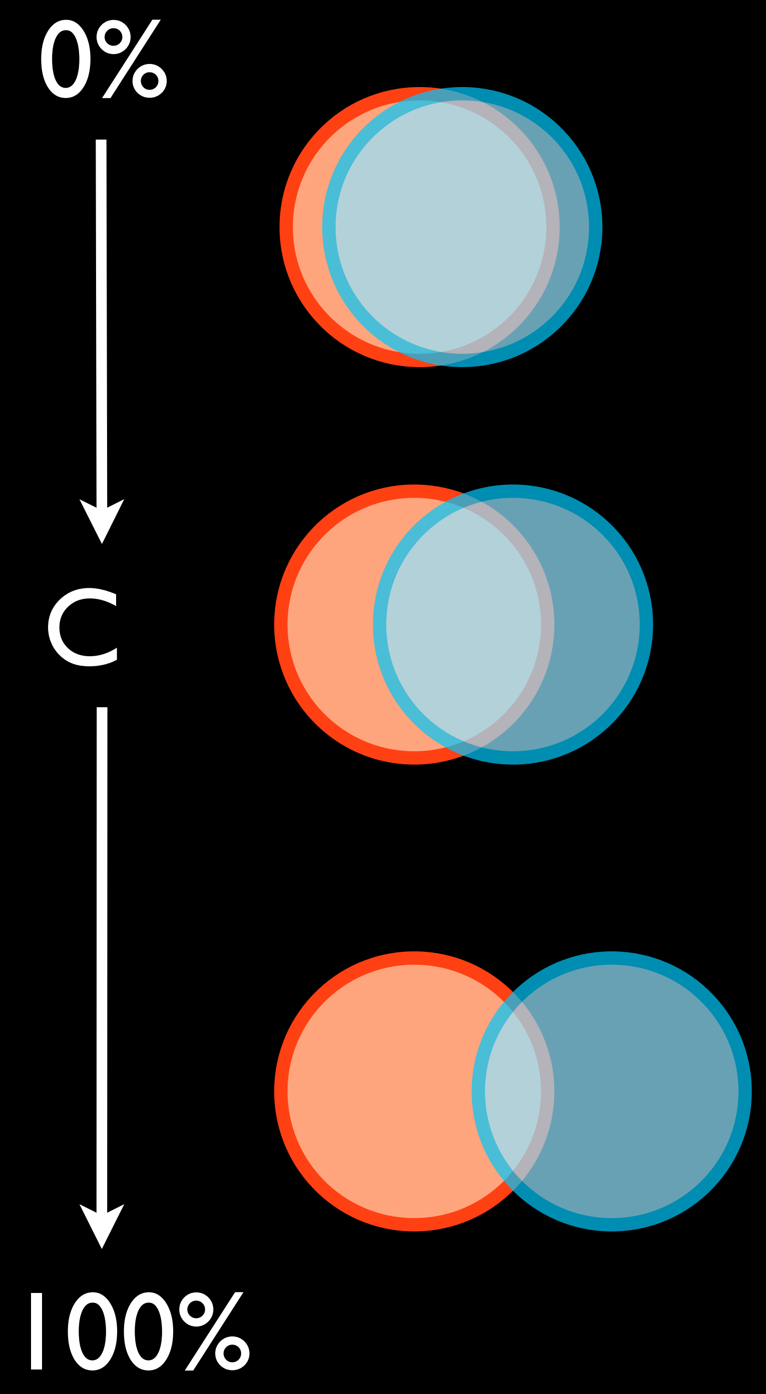
- Comparison with a large amount of data requires some modeling
- A simulator is essential !
- Need a framework to separate pure theory input from modeling
- May require advanced statistical techniques (Bayesian), to extract parameters
- Certain extracted quantities can be compared with theoretical calculations

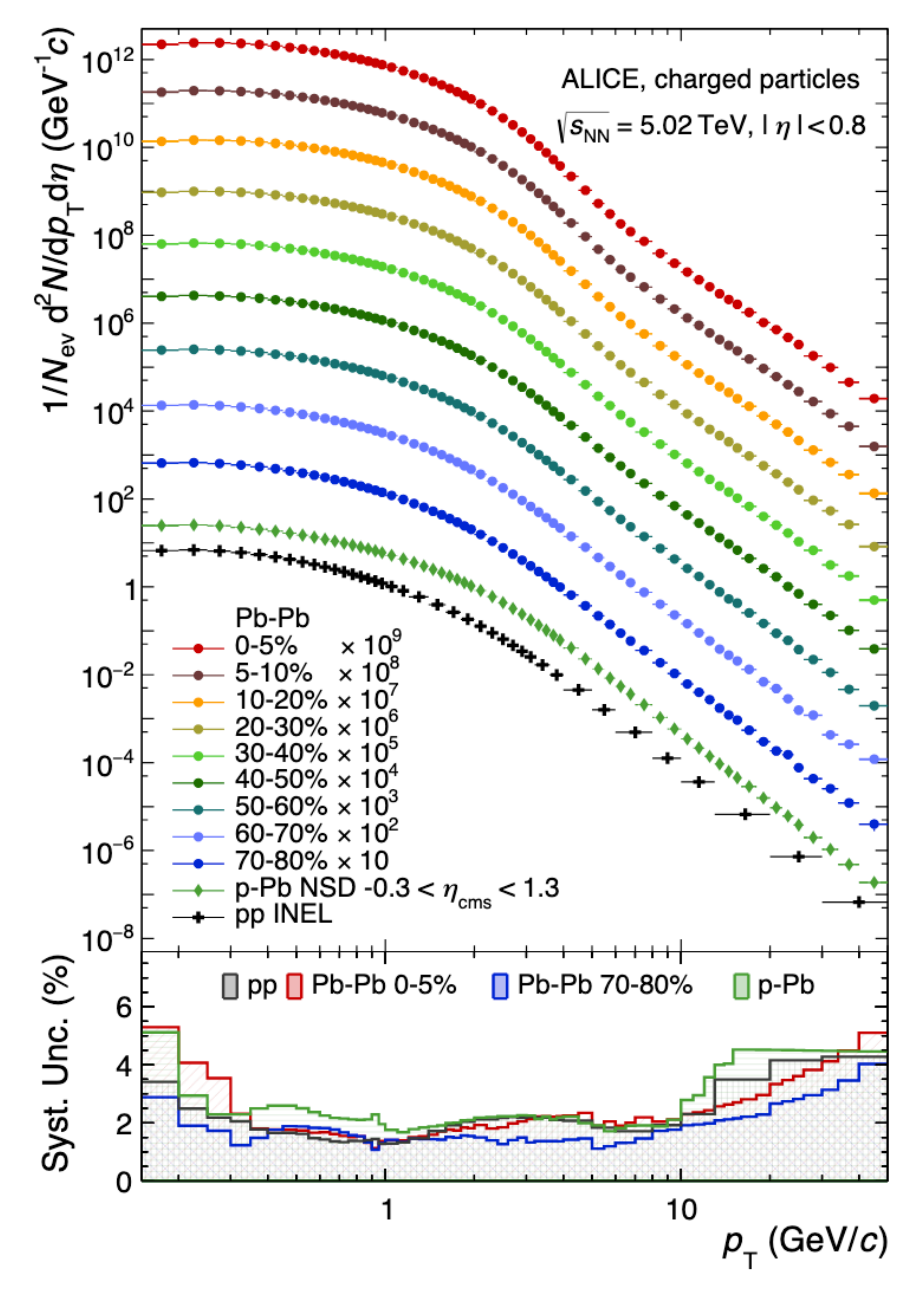
Spectra from a Heavy-Ion collision at LHC



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

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





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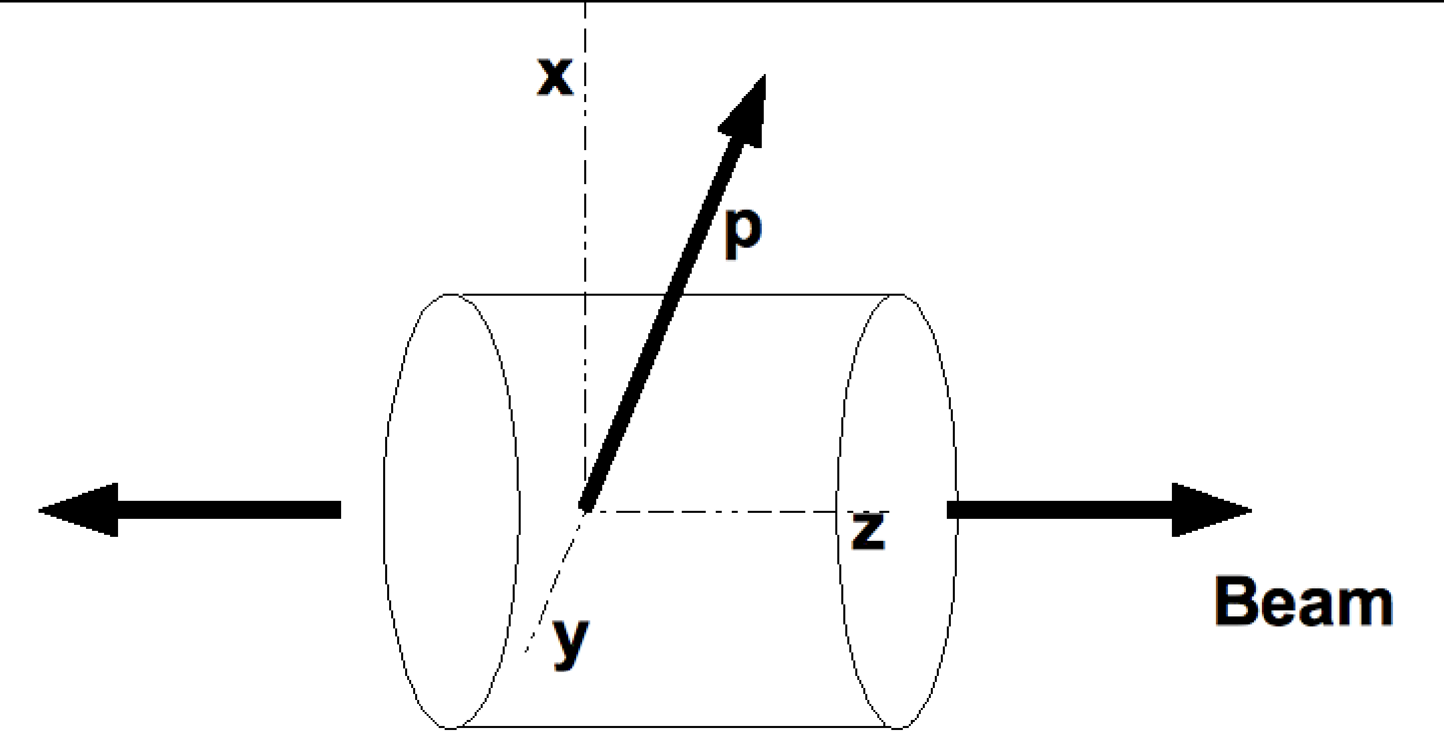

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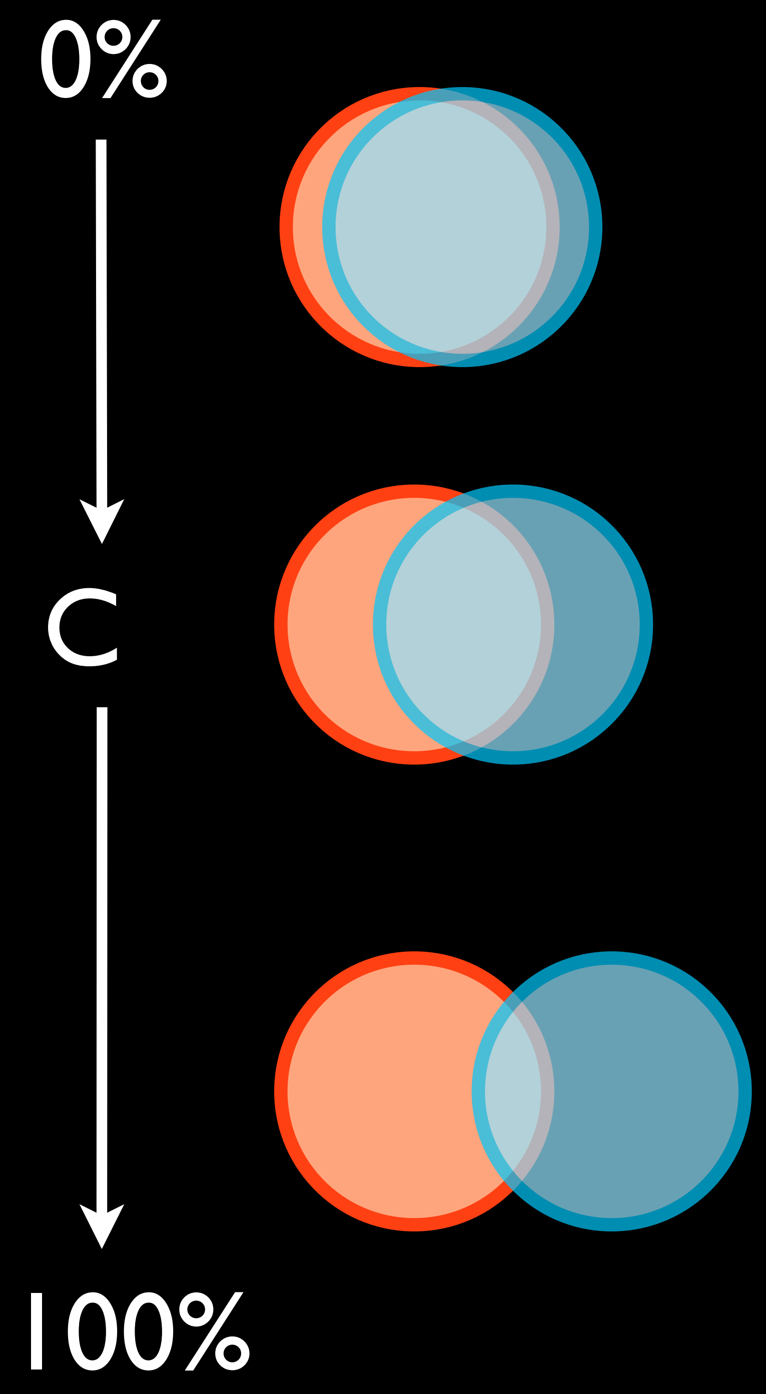

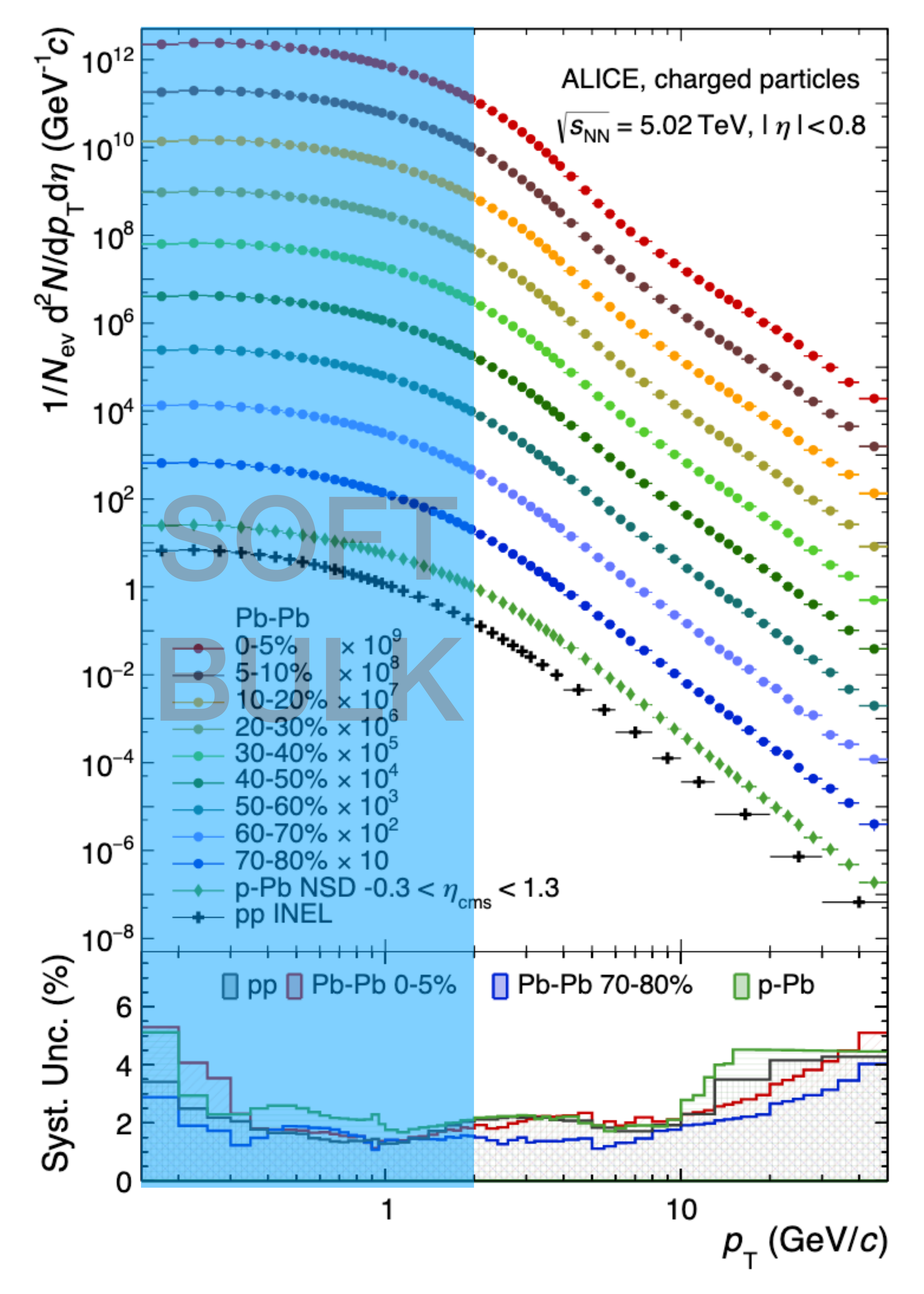

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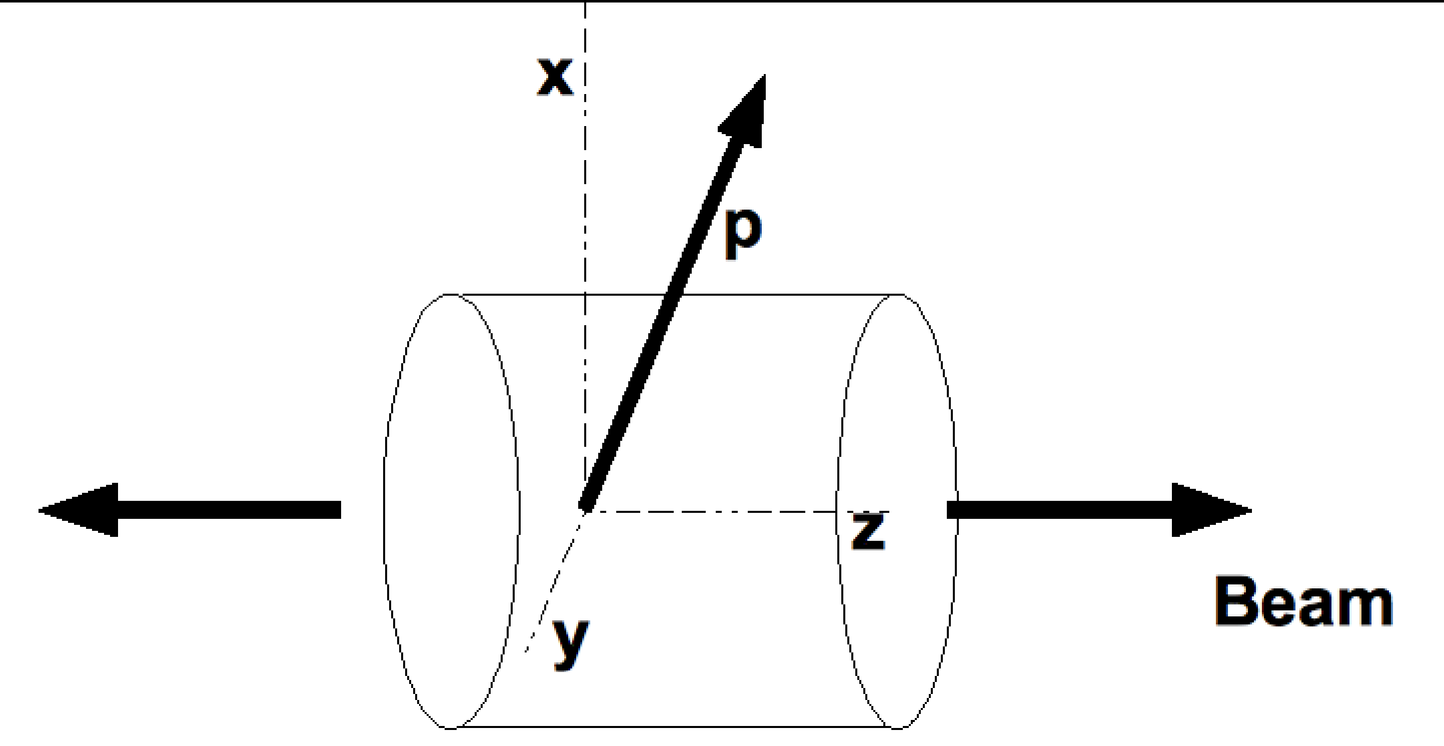

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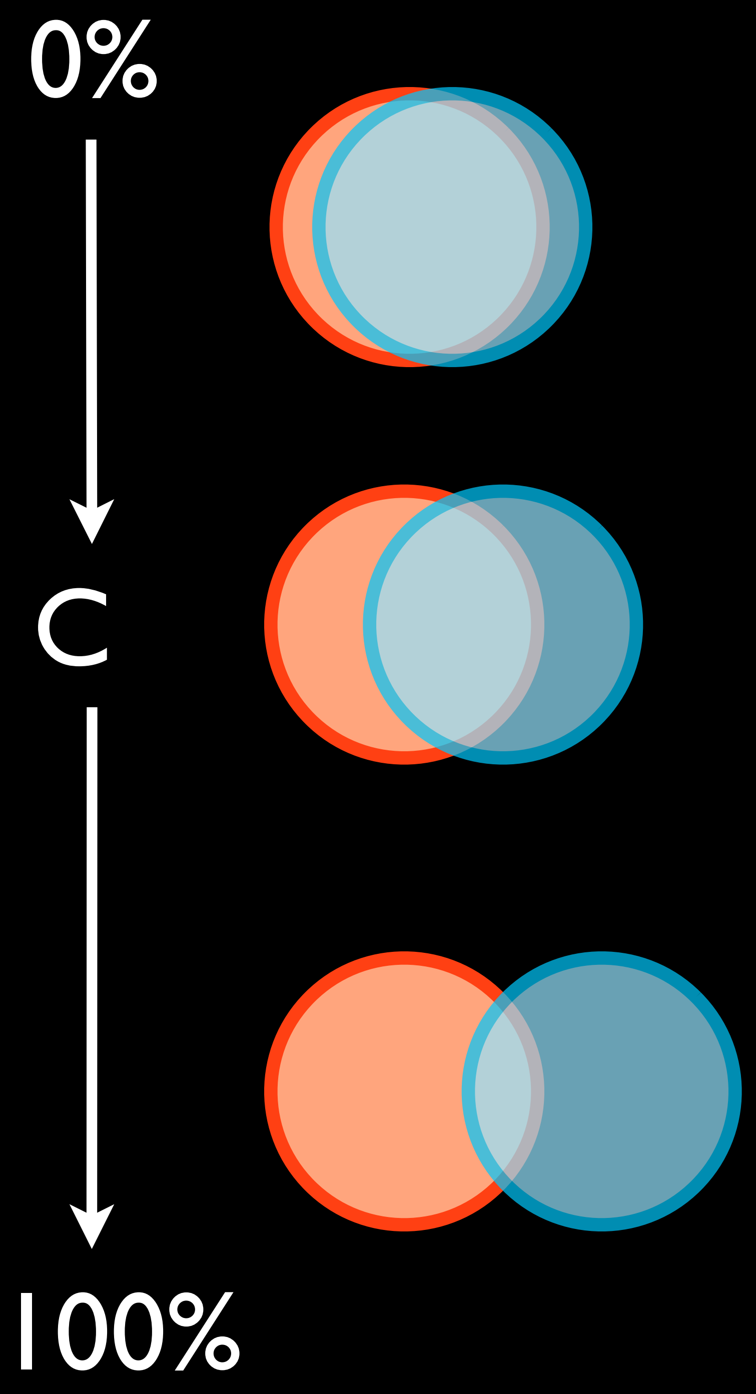

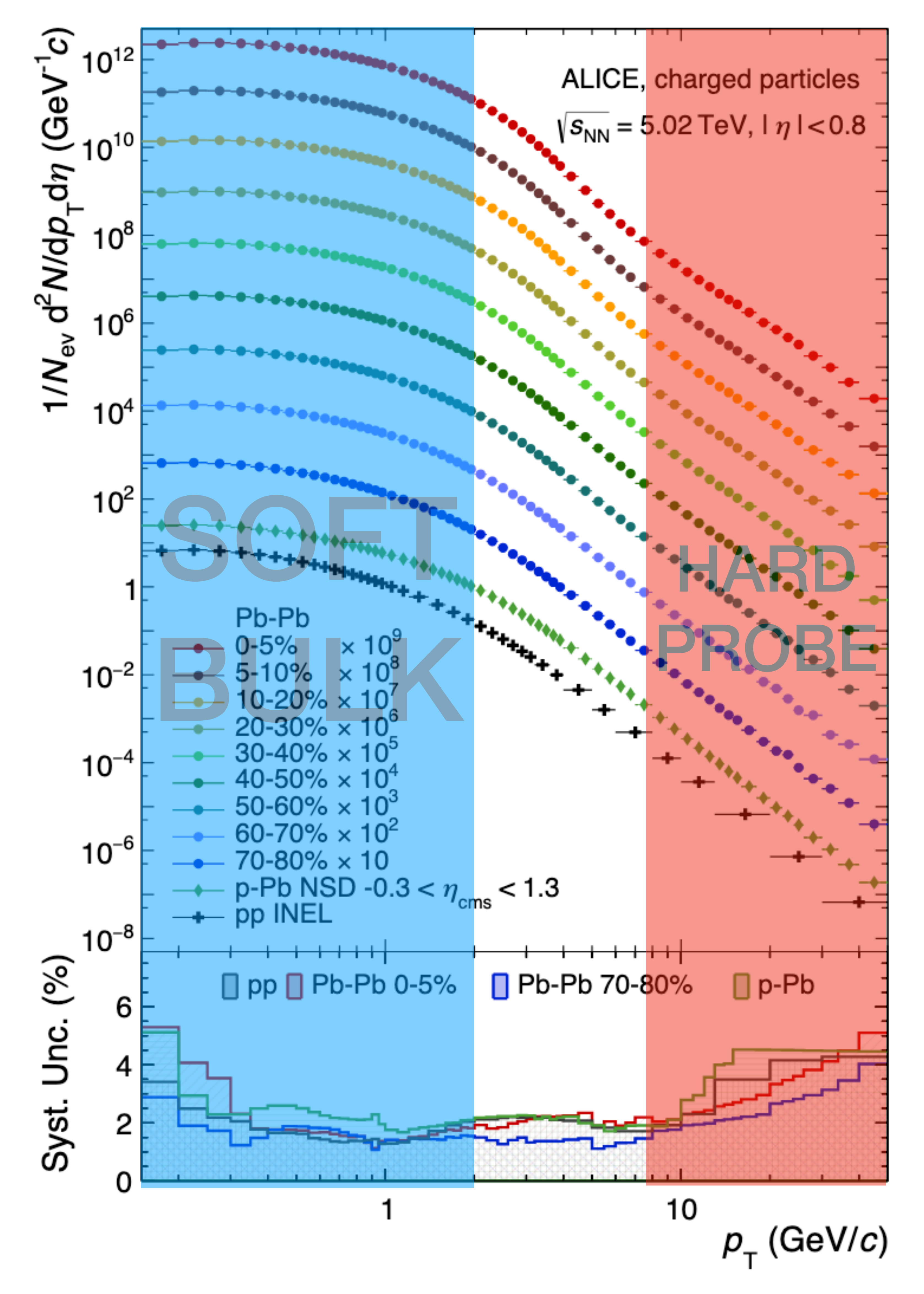

The JETSCAPE event generator

A multi-stage generator for p-p and A-A collsions
Modular, customizable!

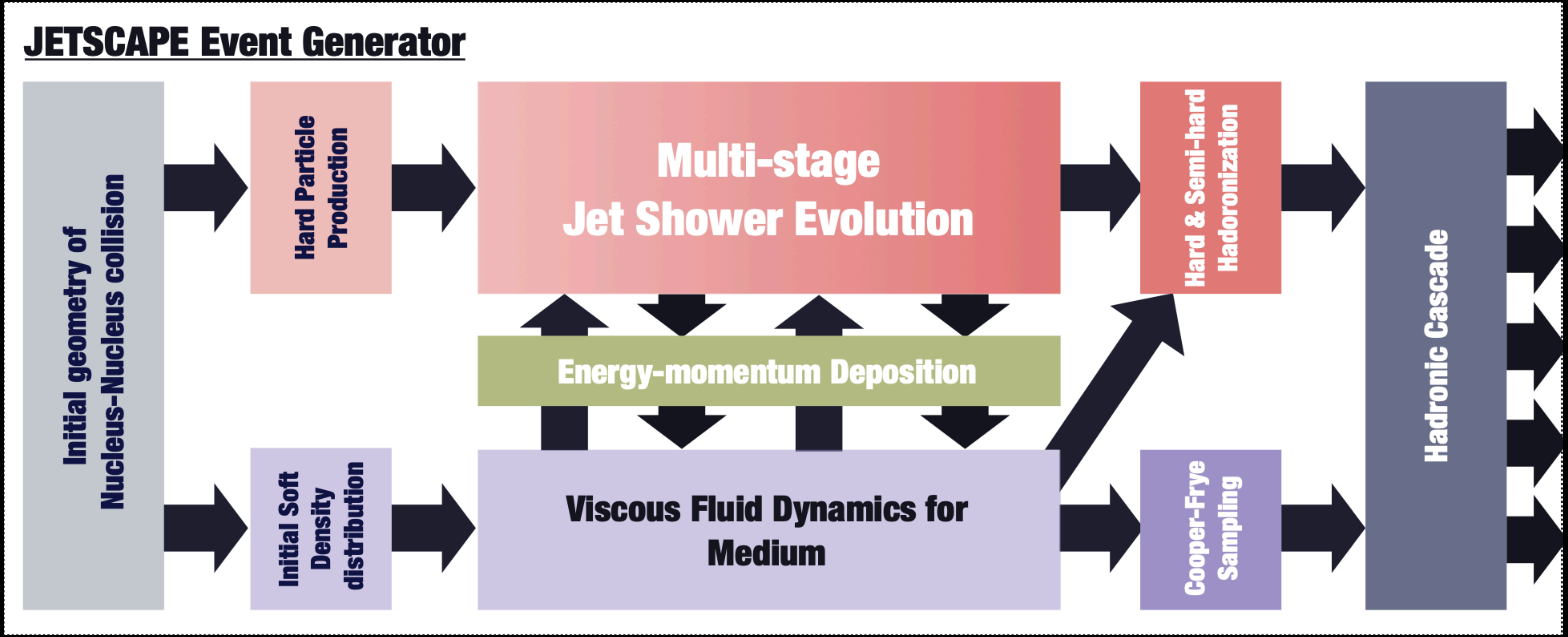

Diagram by Y. Tachibana

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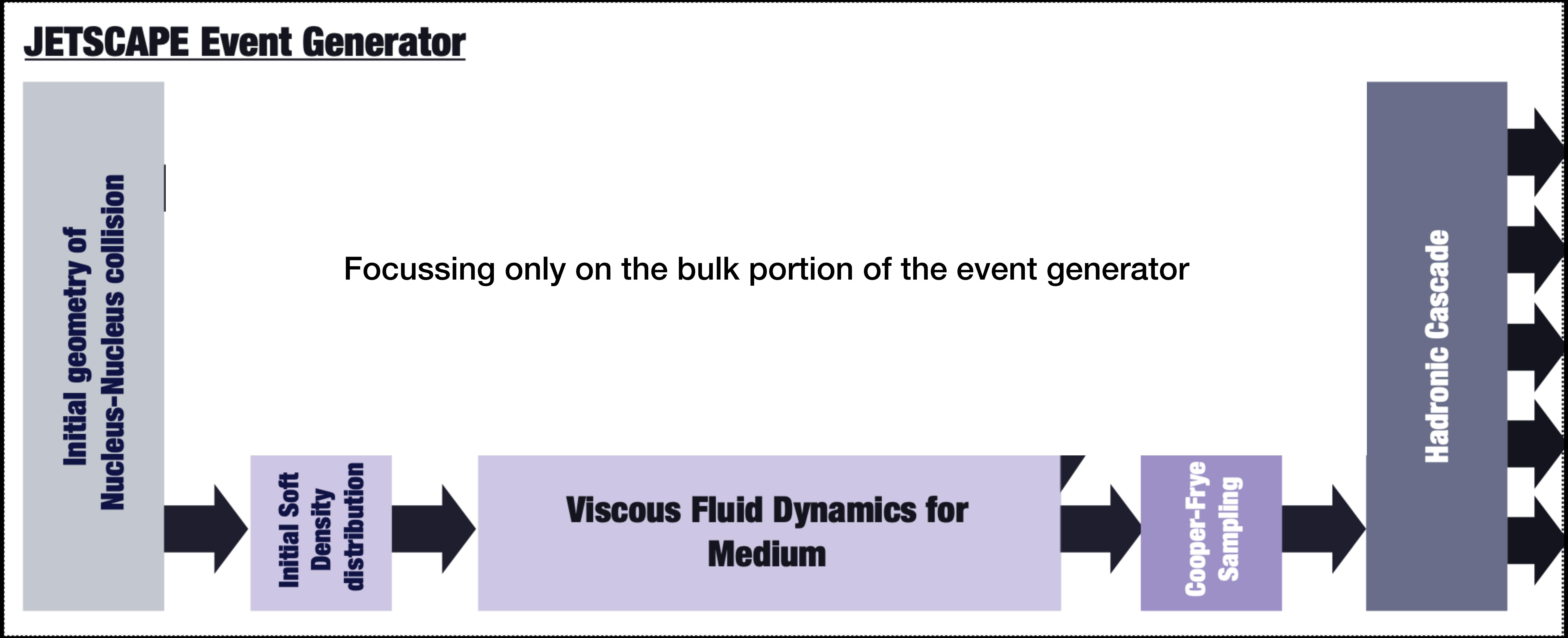
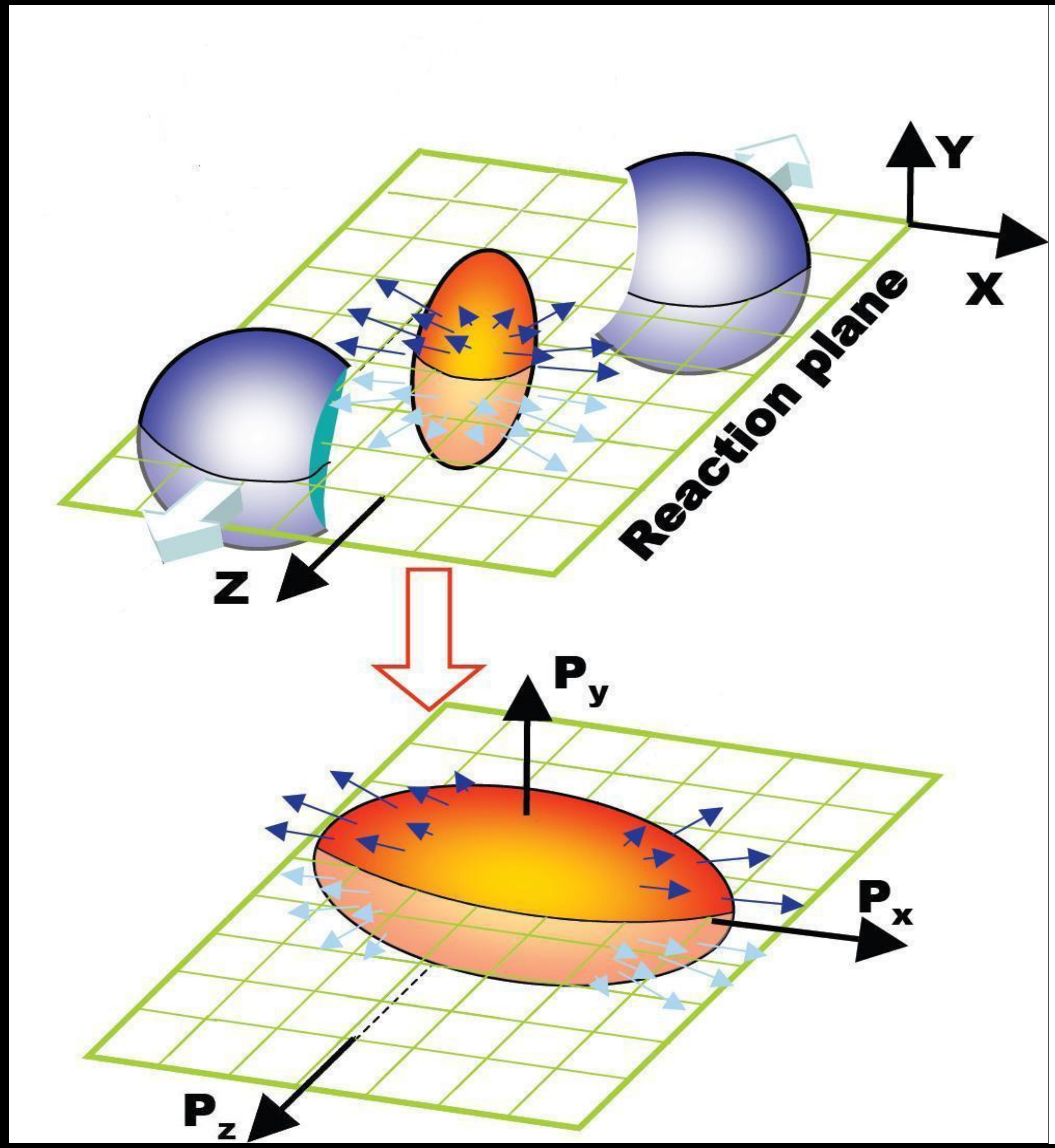
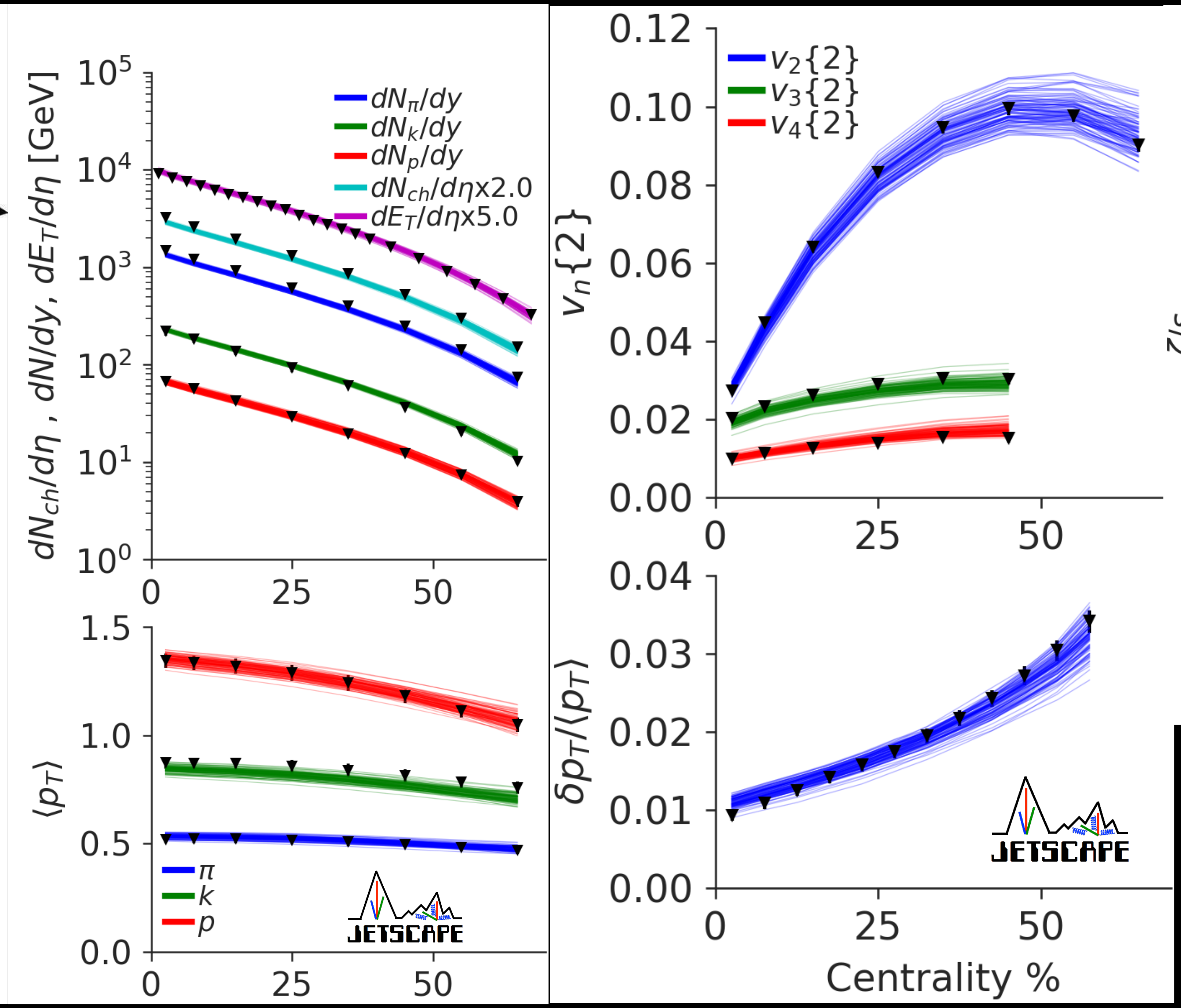
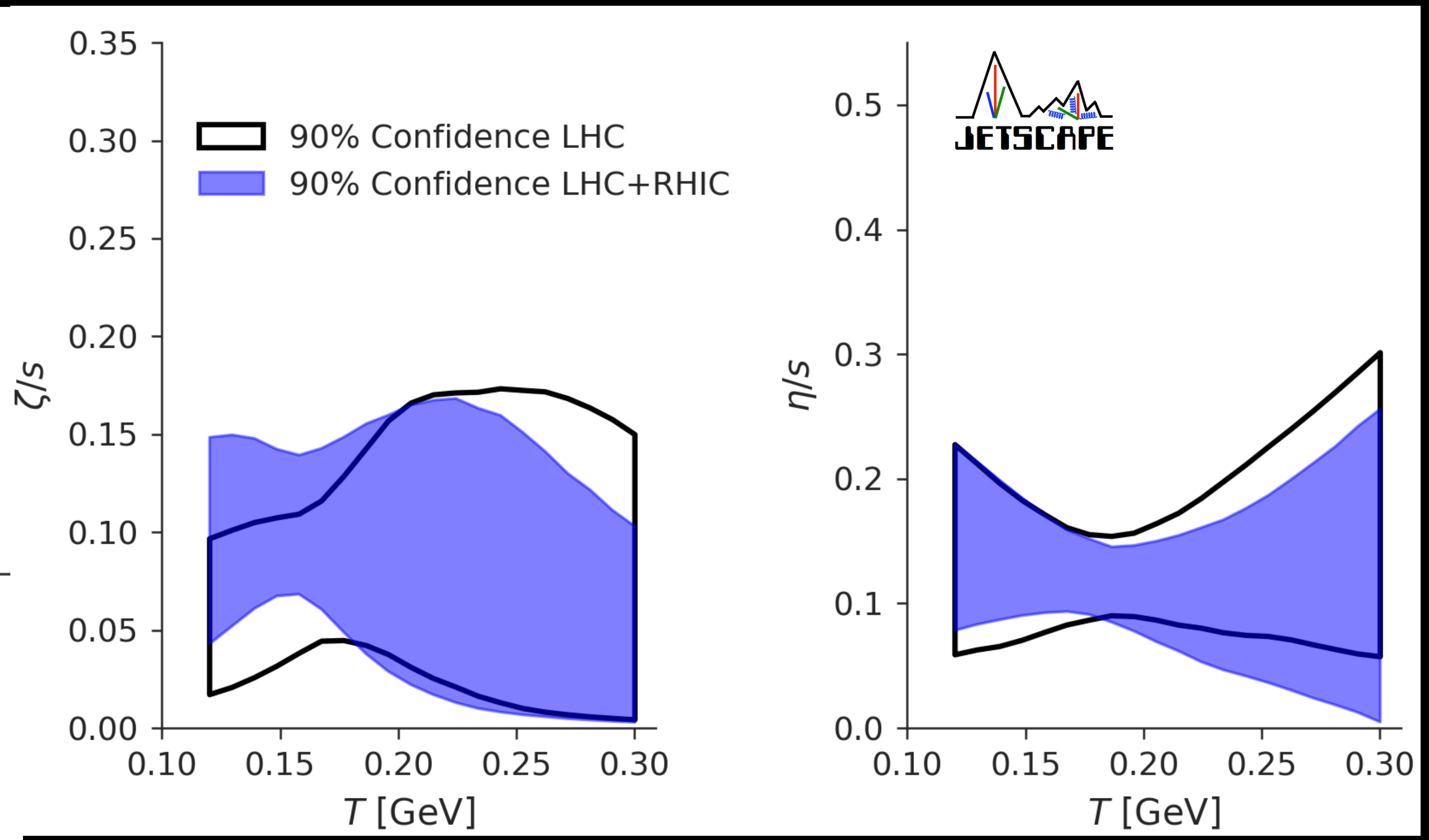


Diagram by Y. Tachibana

Low viscosity matter produced at RHIC & LHC

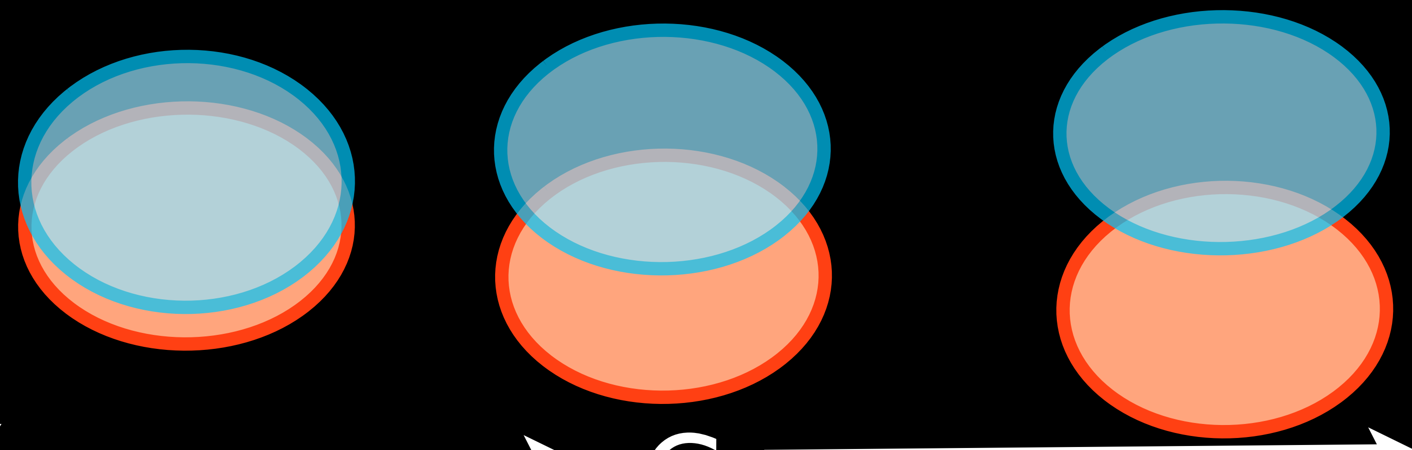






$$\eta \propto \frac{1}{\sigma}$$

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



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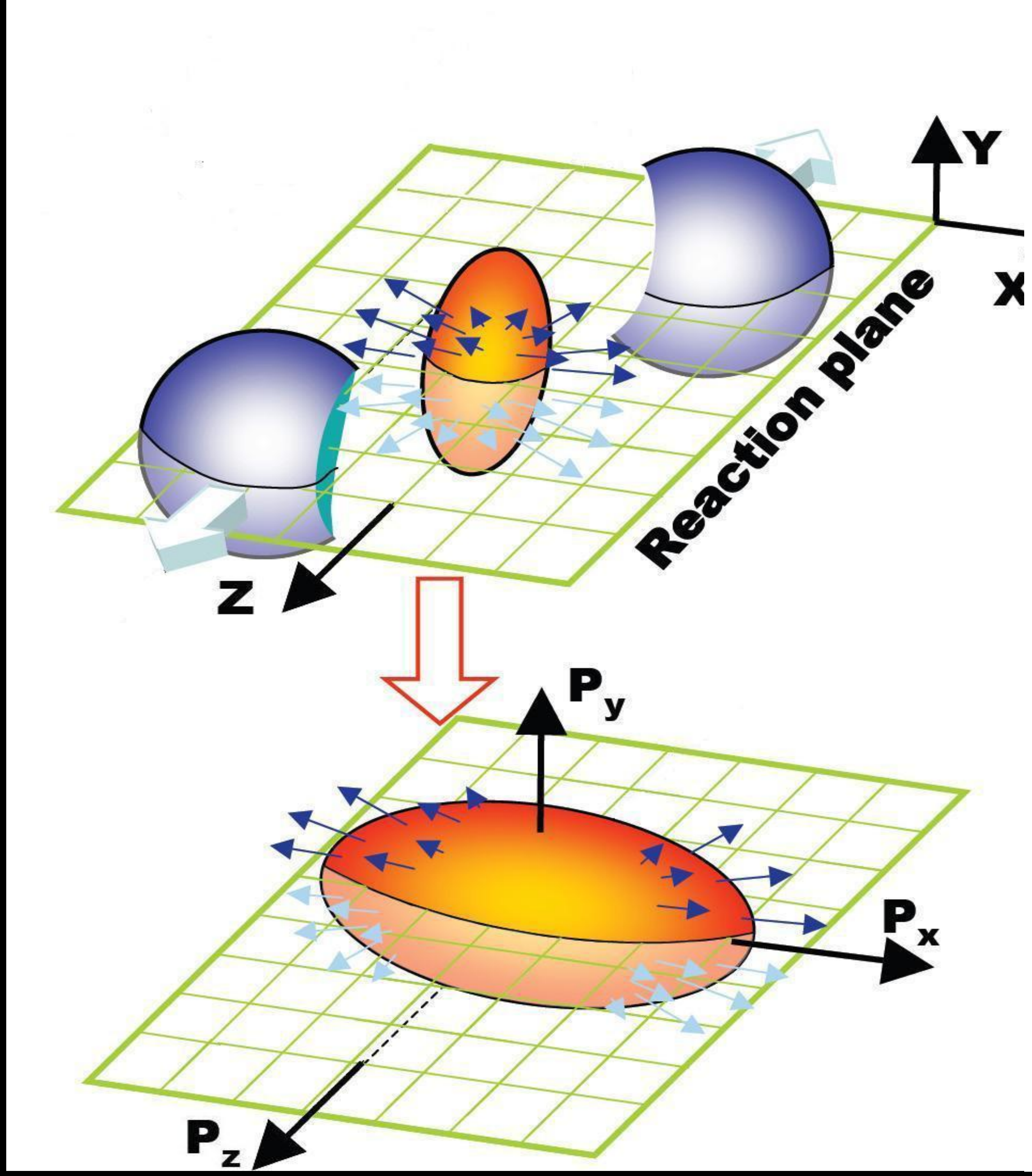
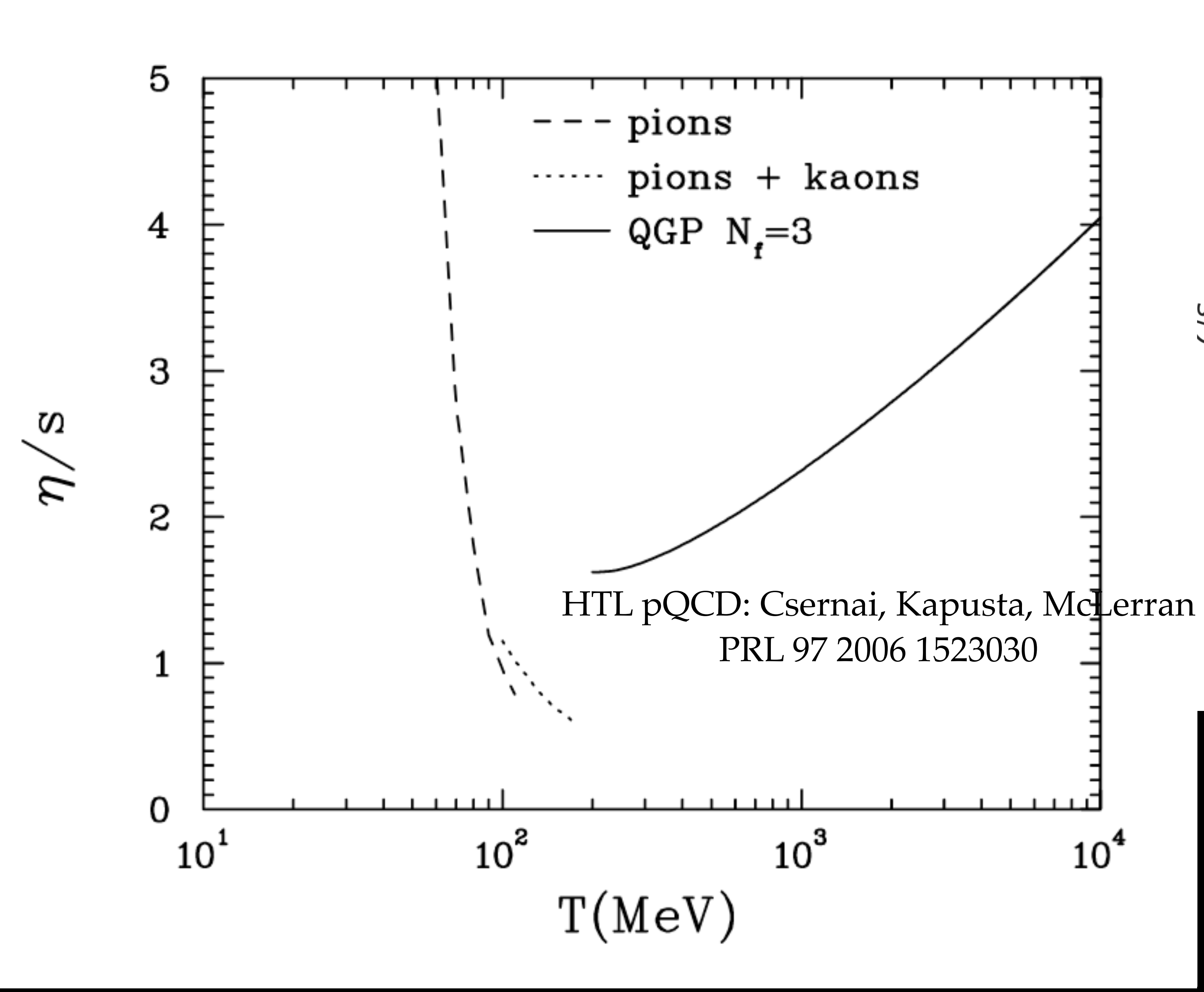
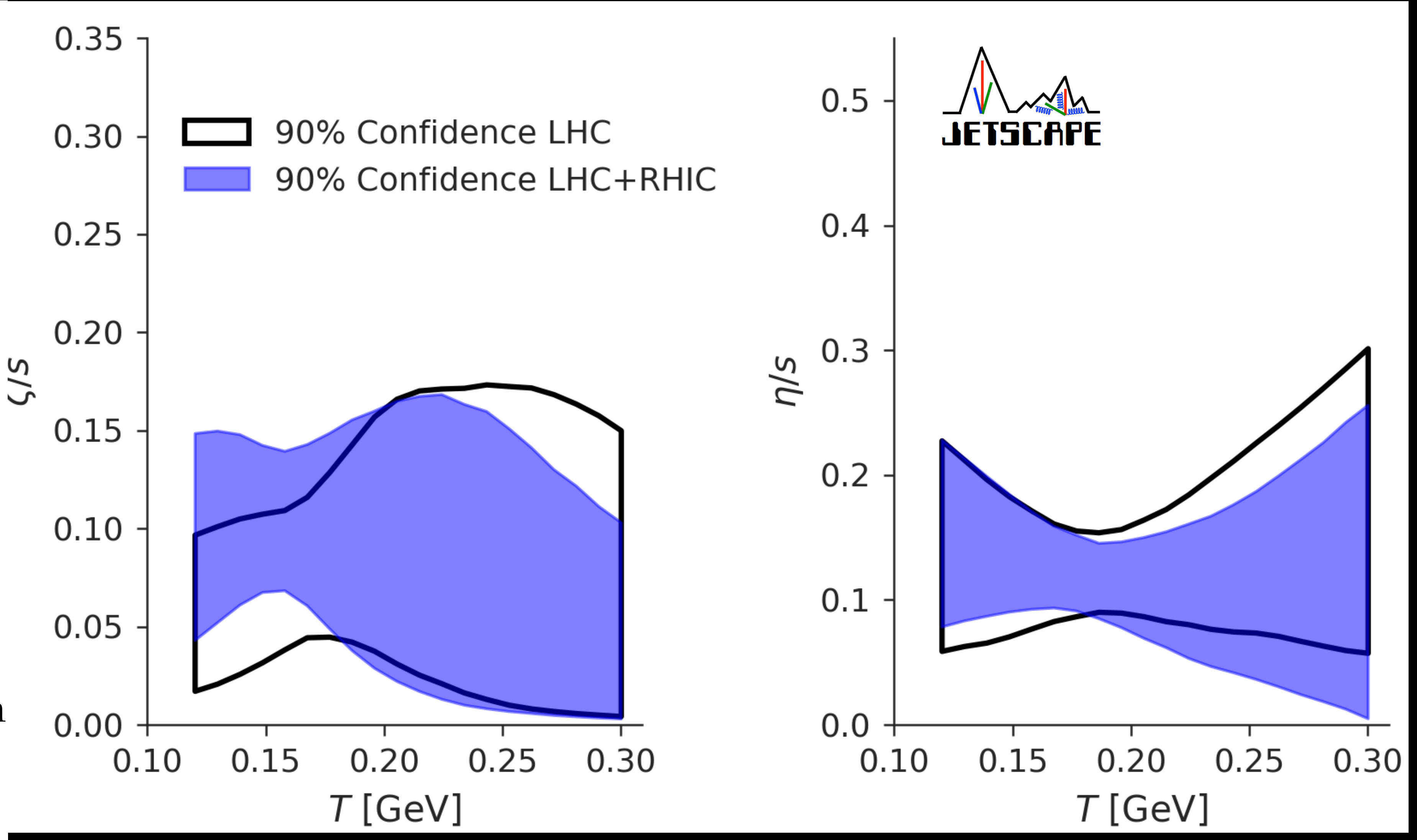
D. Everett et al., Phys. Rev. C 103 (2021) 5, 054904

See talk by Wenbin Zhao on Sat. 3:30pm

Low viscosity matter produced at RHIC & LHC







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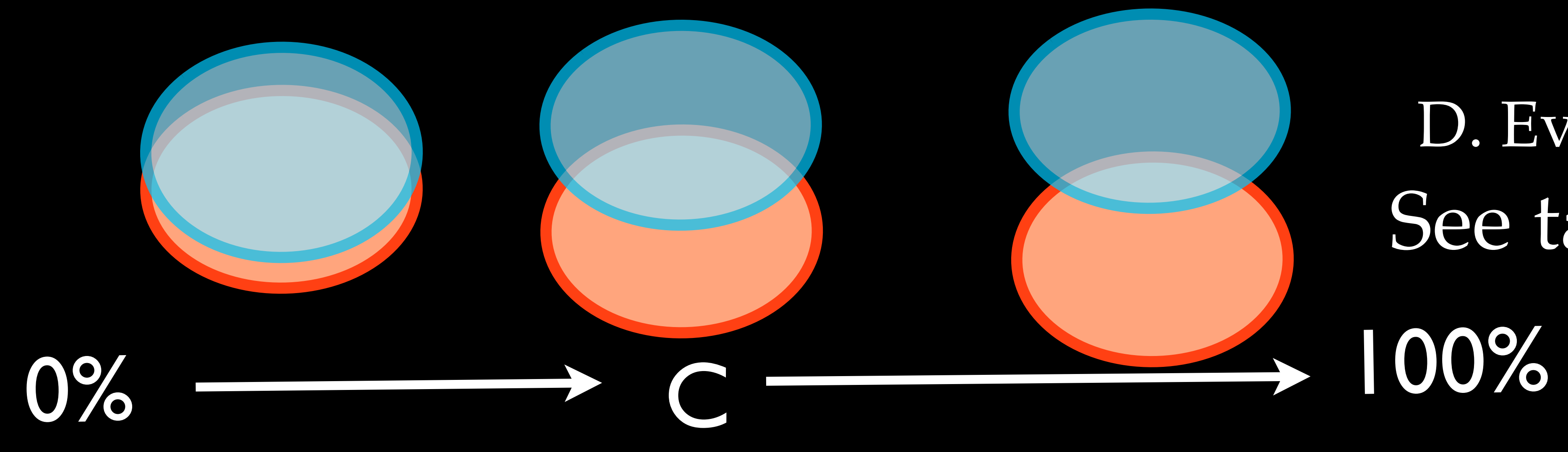

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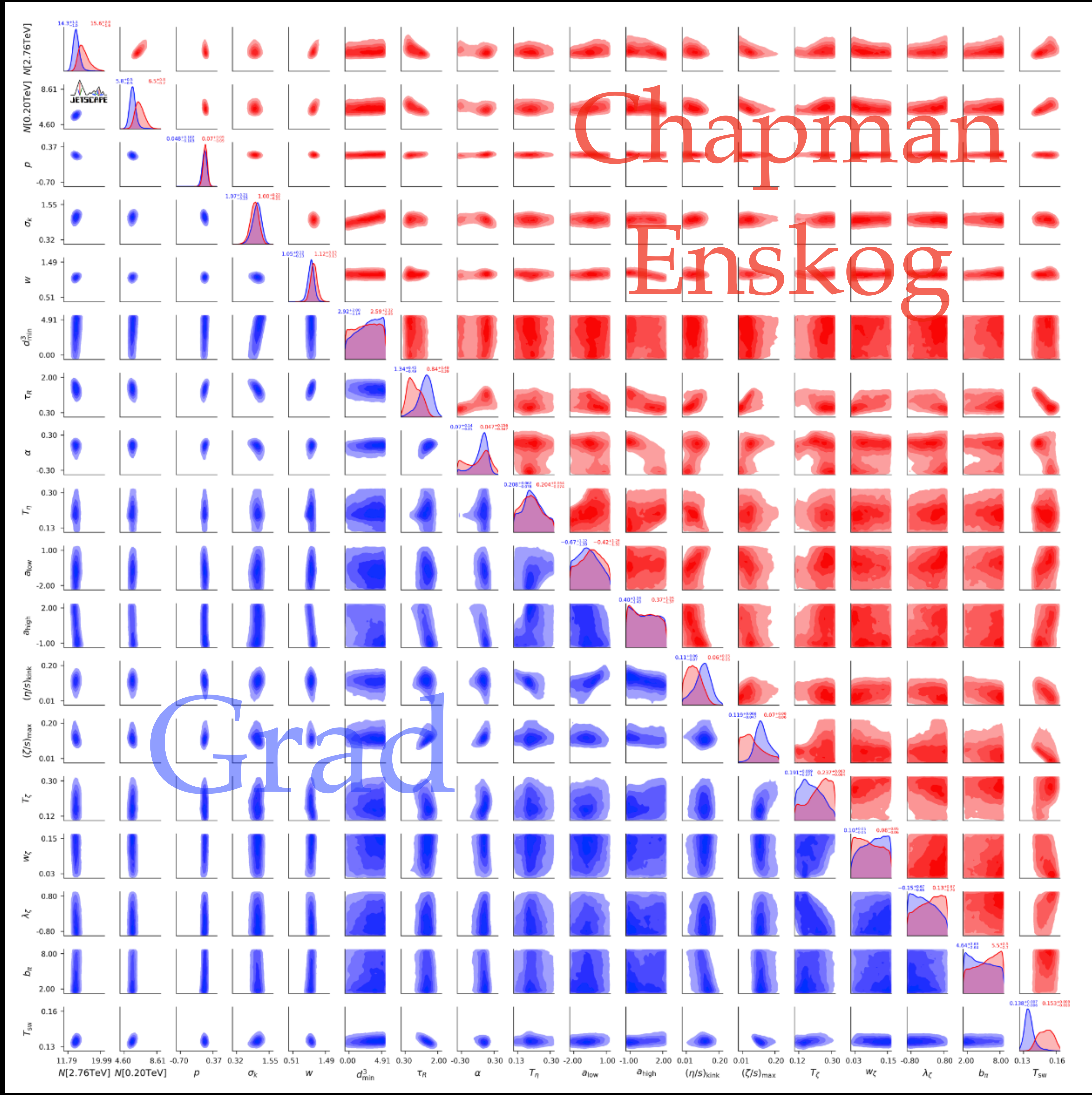
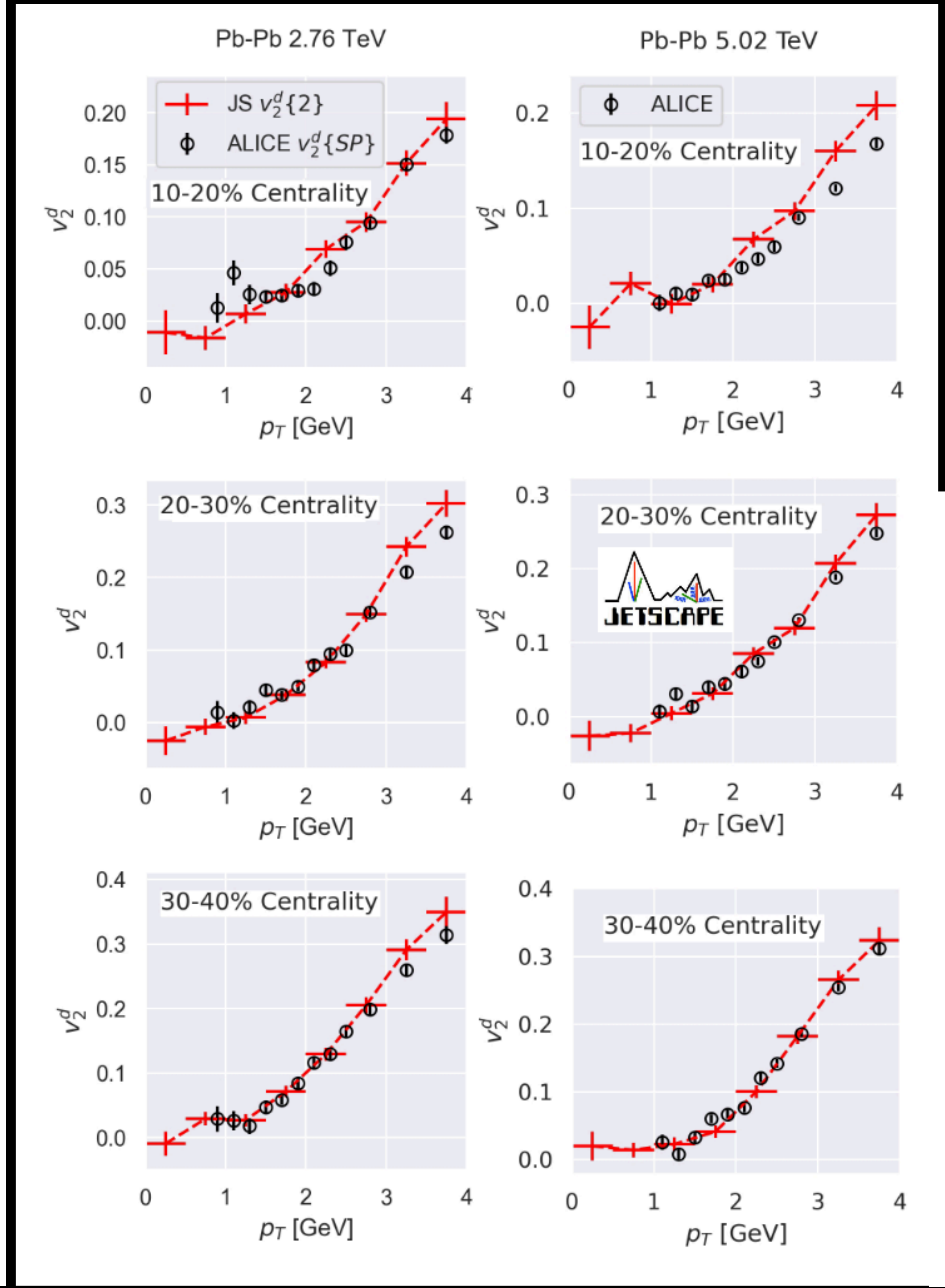
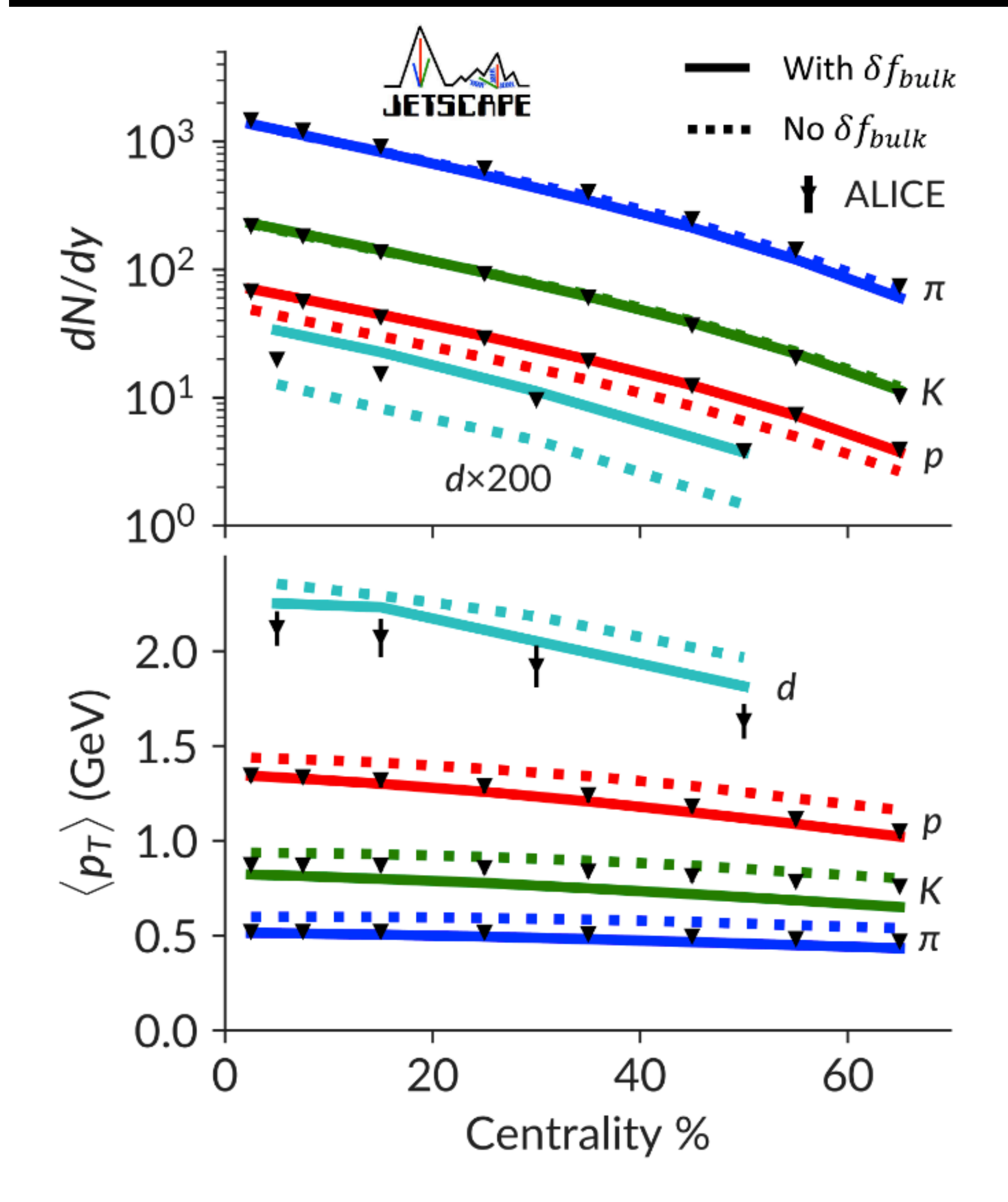
A 17 dimensional calibration





- Predictions for deuteron yield and v_2



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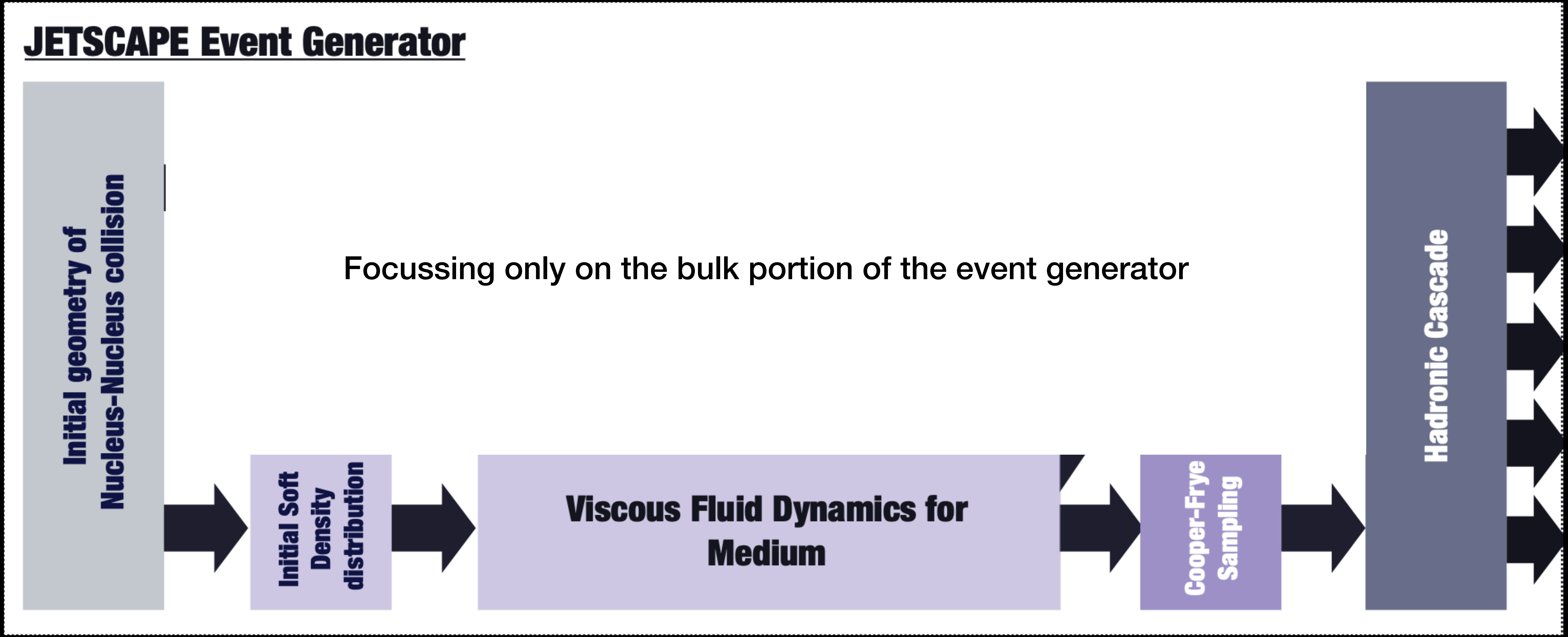
D. Everett et al., e-Print: 2203.08286 [hep-ph]

The JETSCAPE event generator

Incorporating the hard sector back in.



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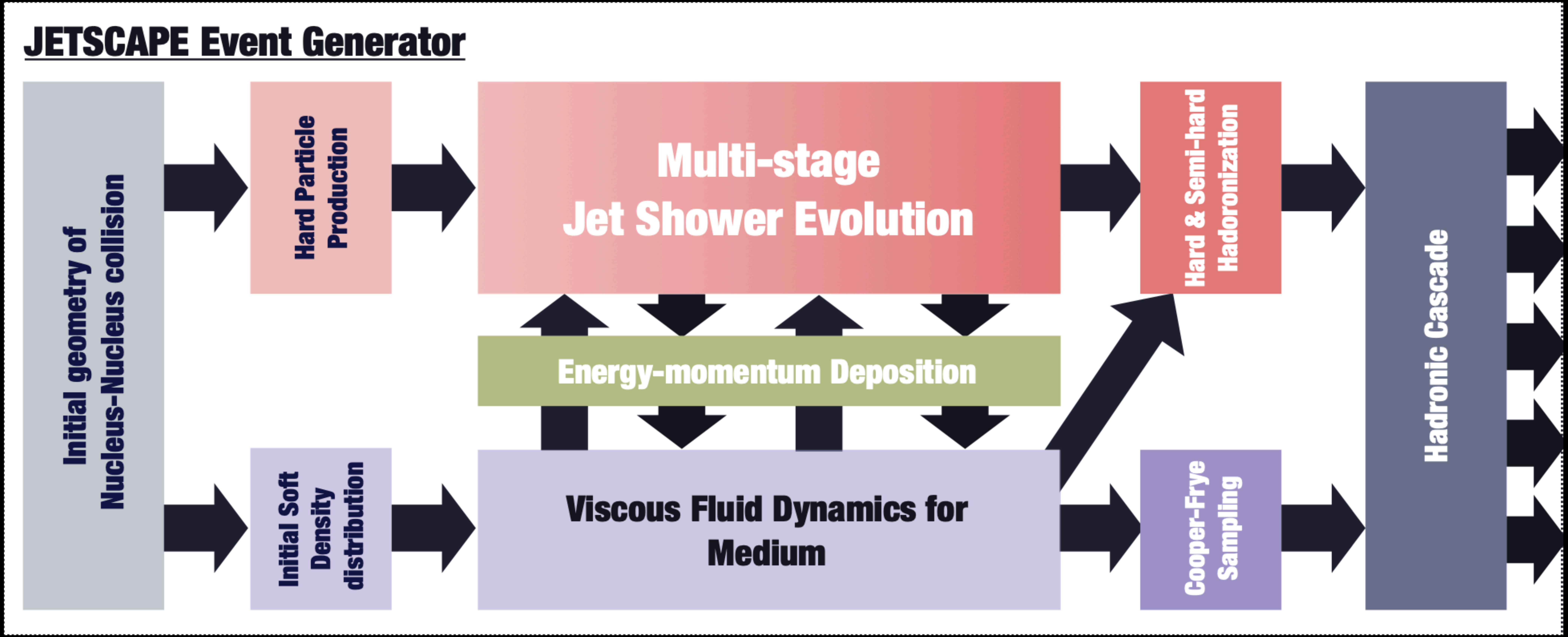
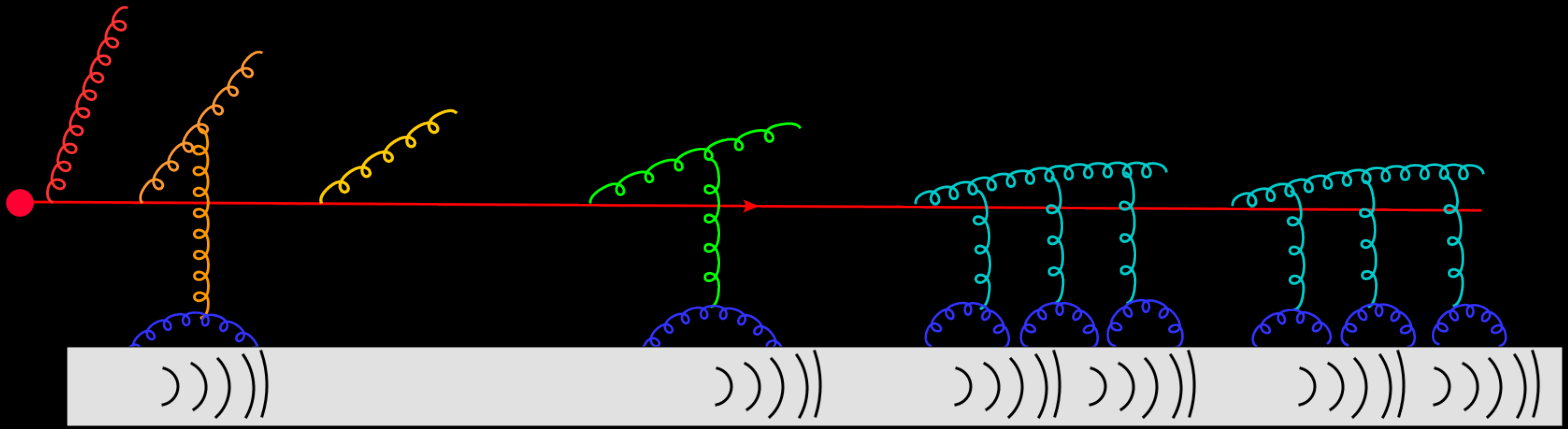


Diagram by Y. Tachibana

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

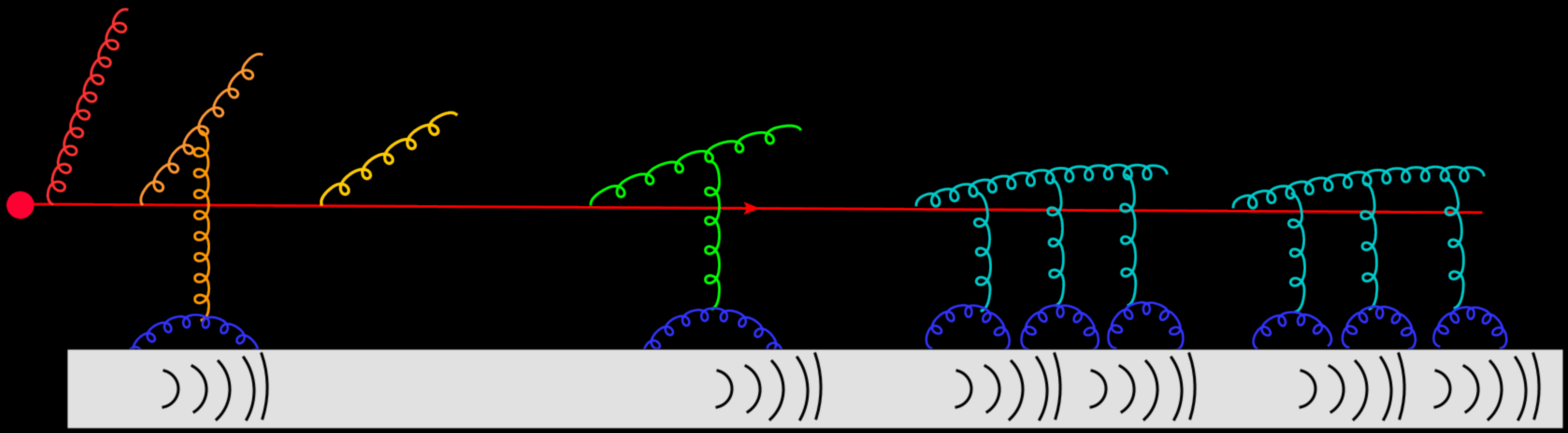


- Exchanges with medium lead to excitations/medium response

Basic Picture: extra scales in energy loss

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

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



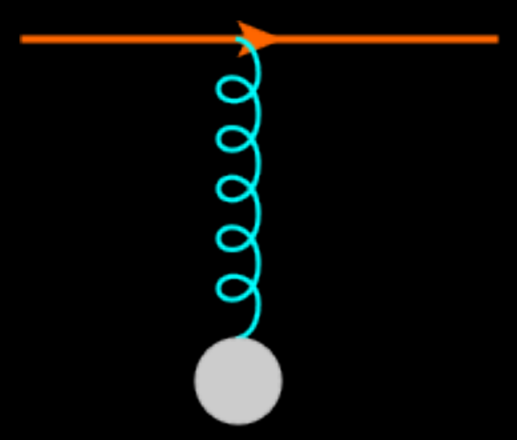
Physics: DGLAP like
Simulator: MATTER

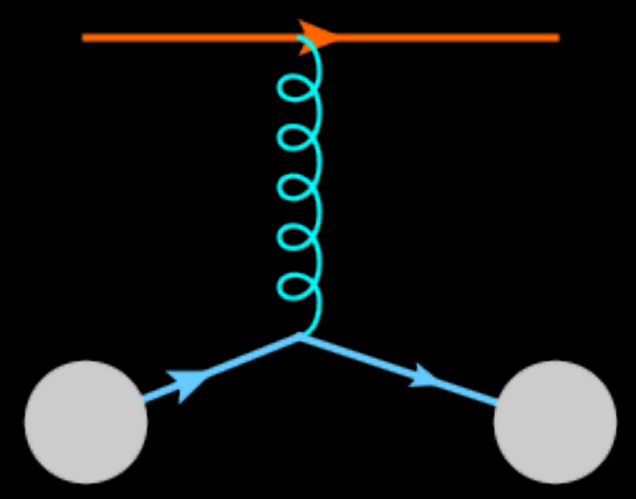
Physics: BDMPS/AMY like
Simulator: MARTINI, LBT

Multi-scale structure in the medium

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

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



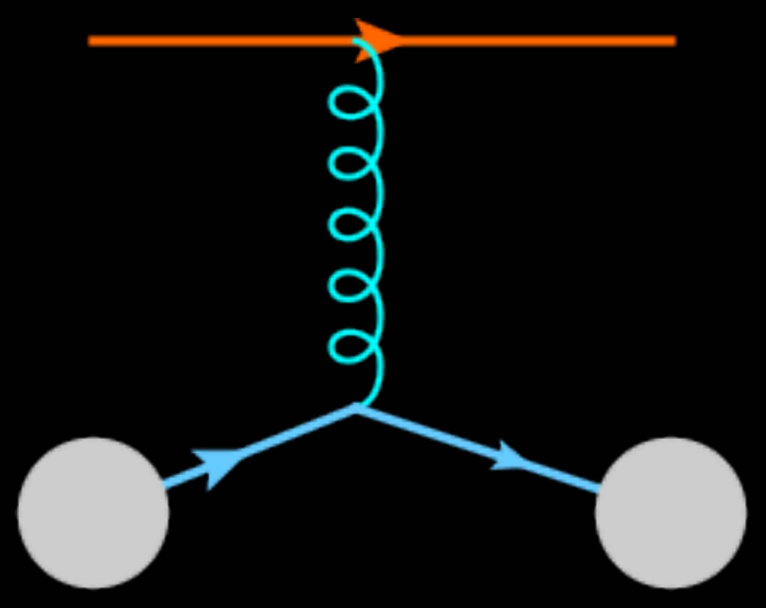


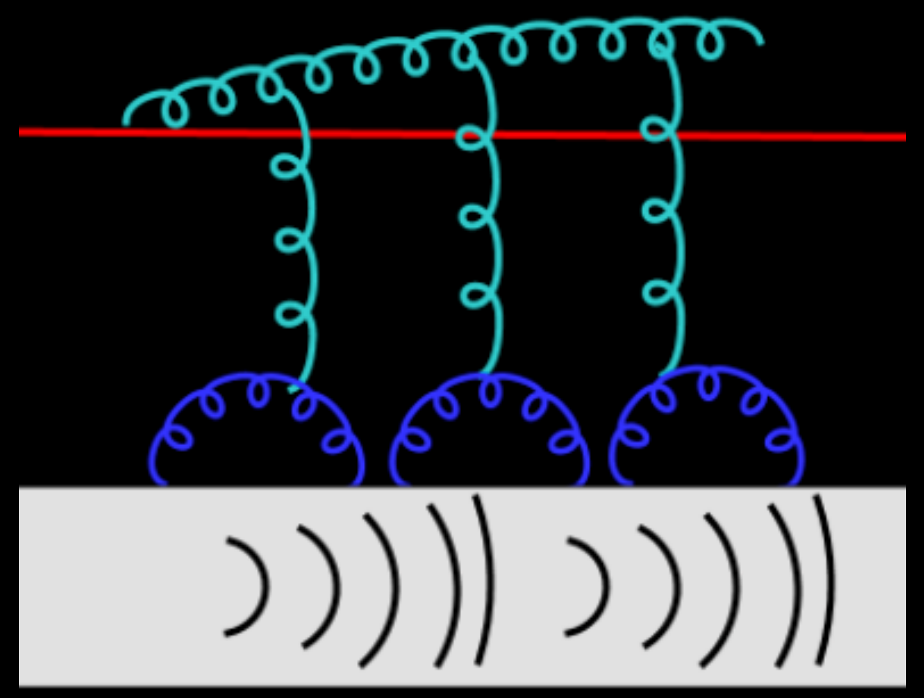
- Incoming "resolved partons" can be modeled with
  - HTL perturbation theory
  - or using QGP PDF (A. Kumar et al., PRC 101 (2020) 034908)
  - Or Both (MATTER + LBT)

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

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

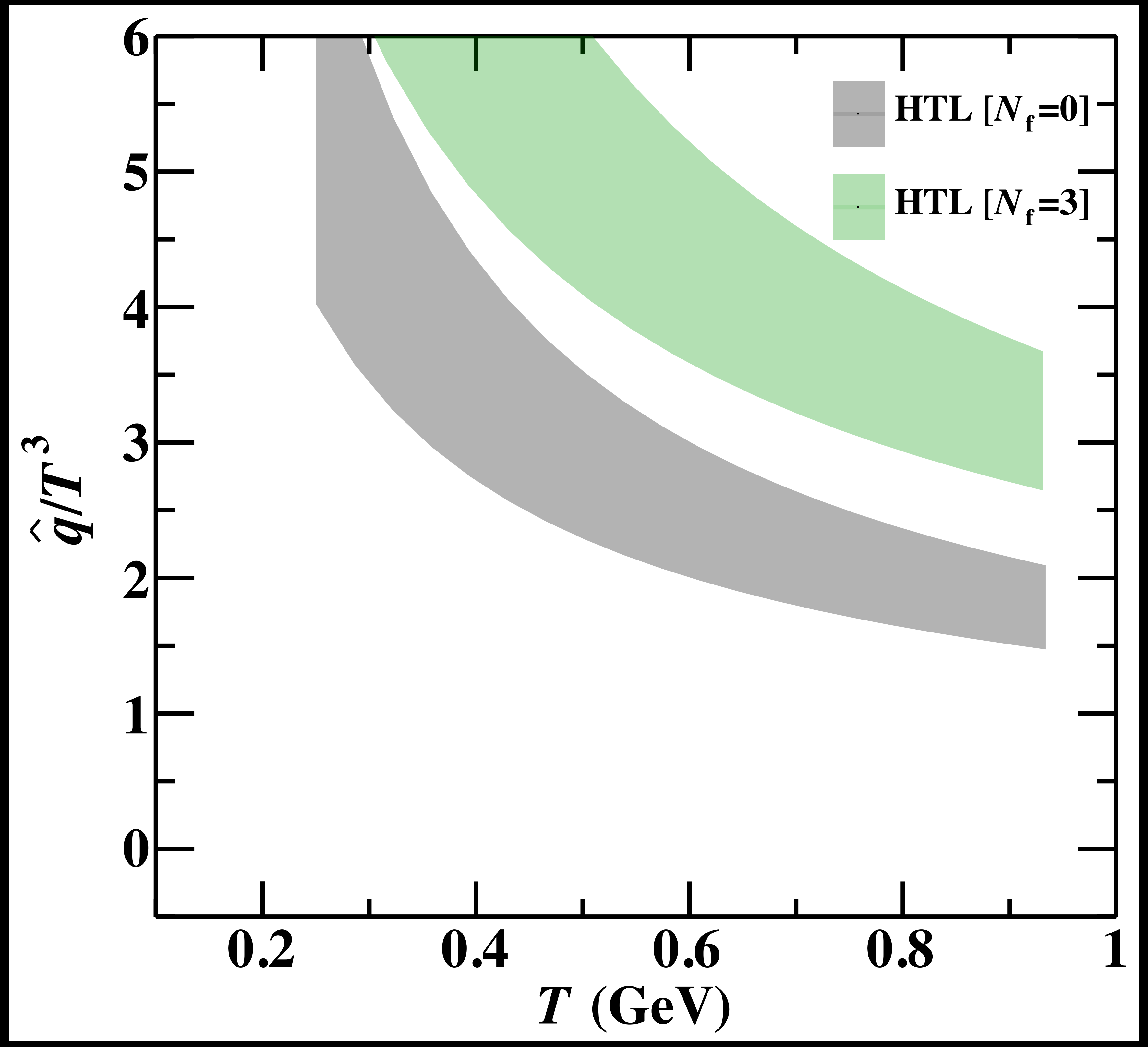
- Use Debye screened potential

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

- 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

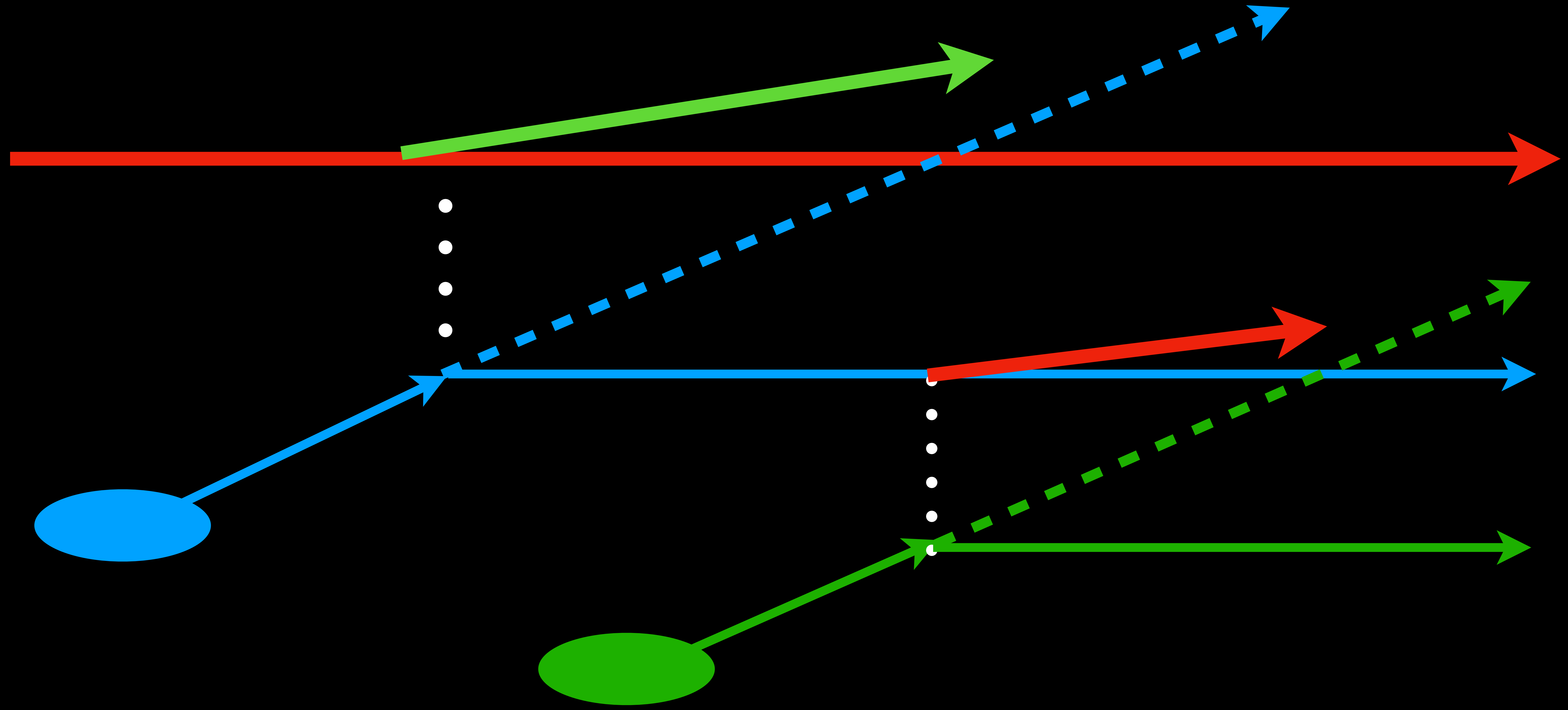


Arnold and Xiao: arXiv: 0810.1026 [hep-ph]

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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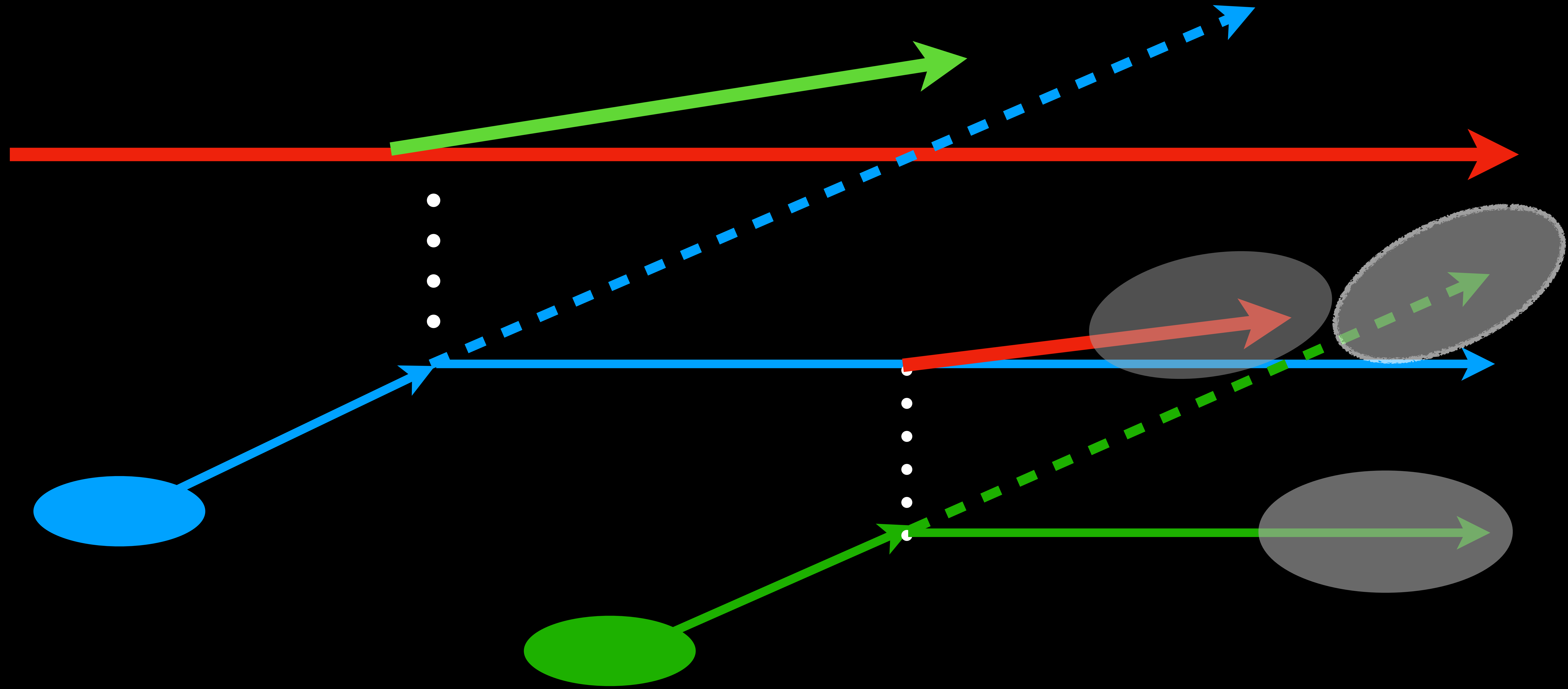
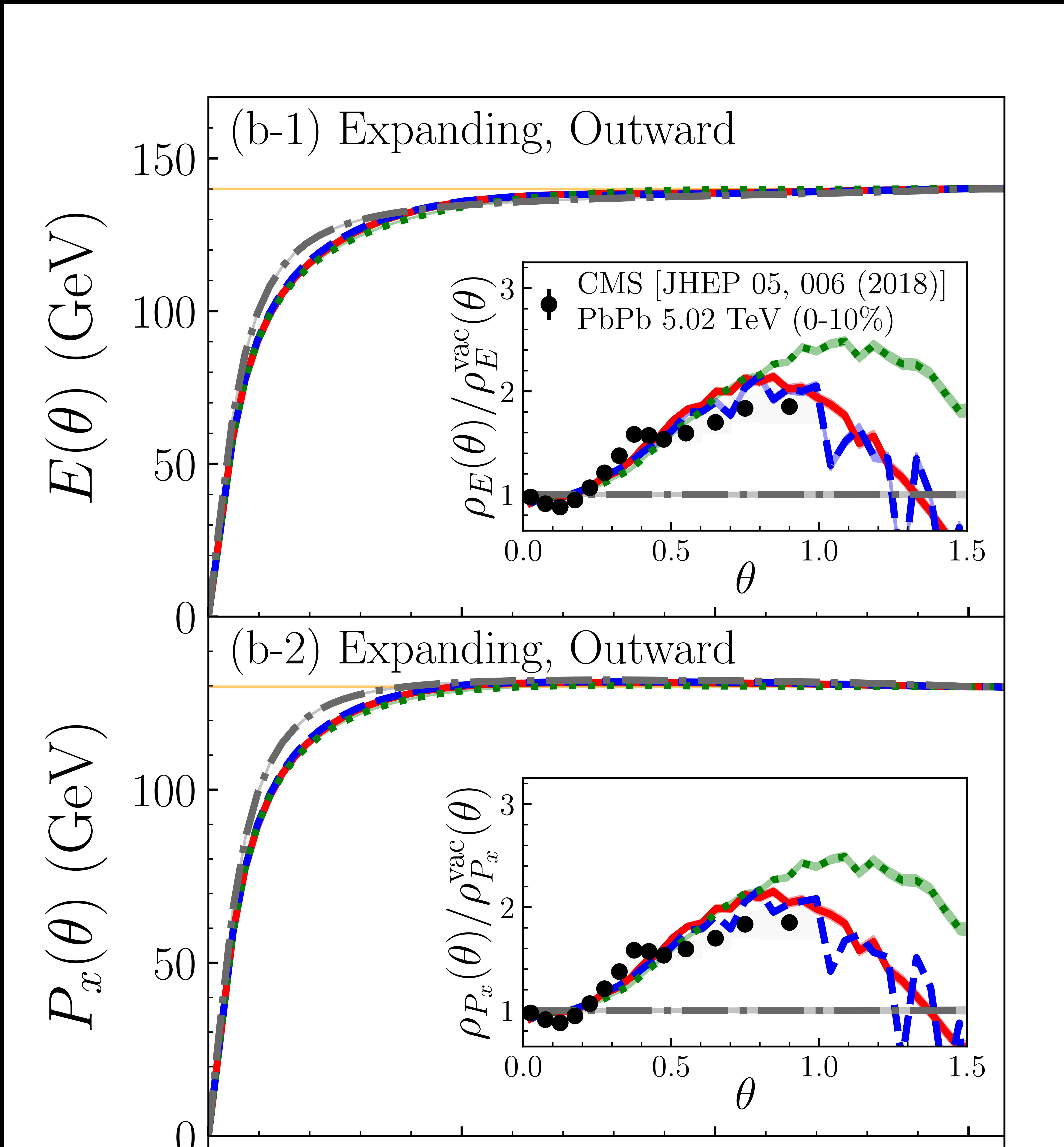


Additionally: Soft partons can be "liquified" into source terms for a subsequent hydro simulation

Does not seem to make much difference inside jet cone

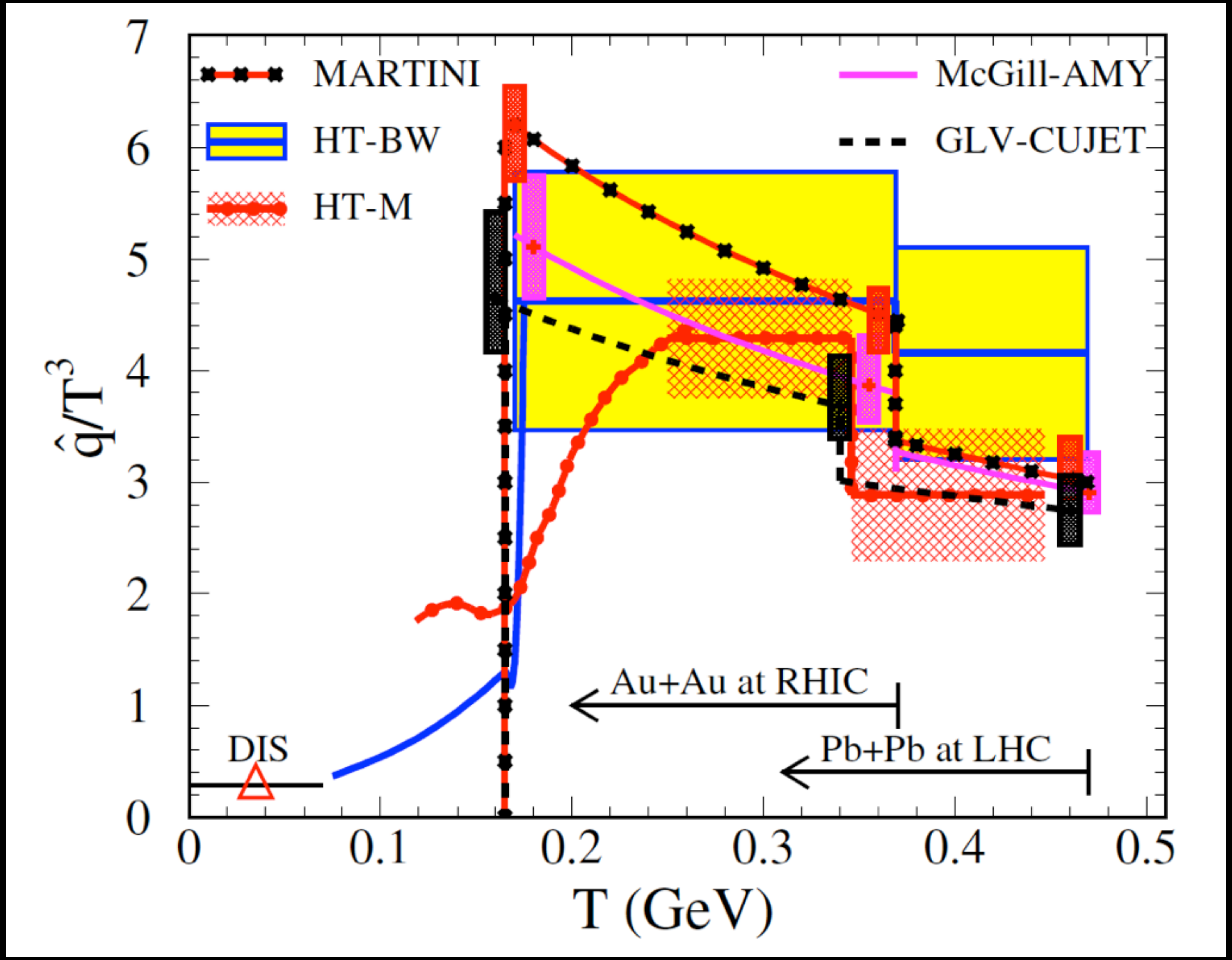
- Simulation (JETSCAPE 0.x) includes:
  - One run of smooth hydro
  - One jet from center outward (left)
  - One jet from out inward (right)
  - Jet simulated for ~10fm/c: MATTER+LBT
  - Jet constructed with partons (weak)
  - Soft partons liquified
  - Source terms developed
  - Hydro re-run
  - Jet 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]

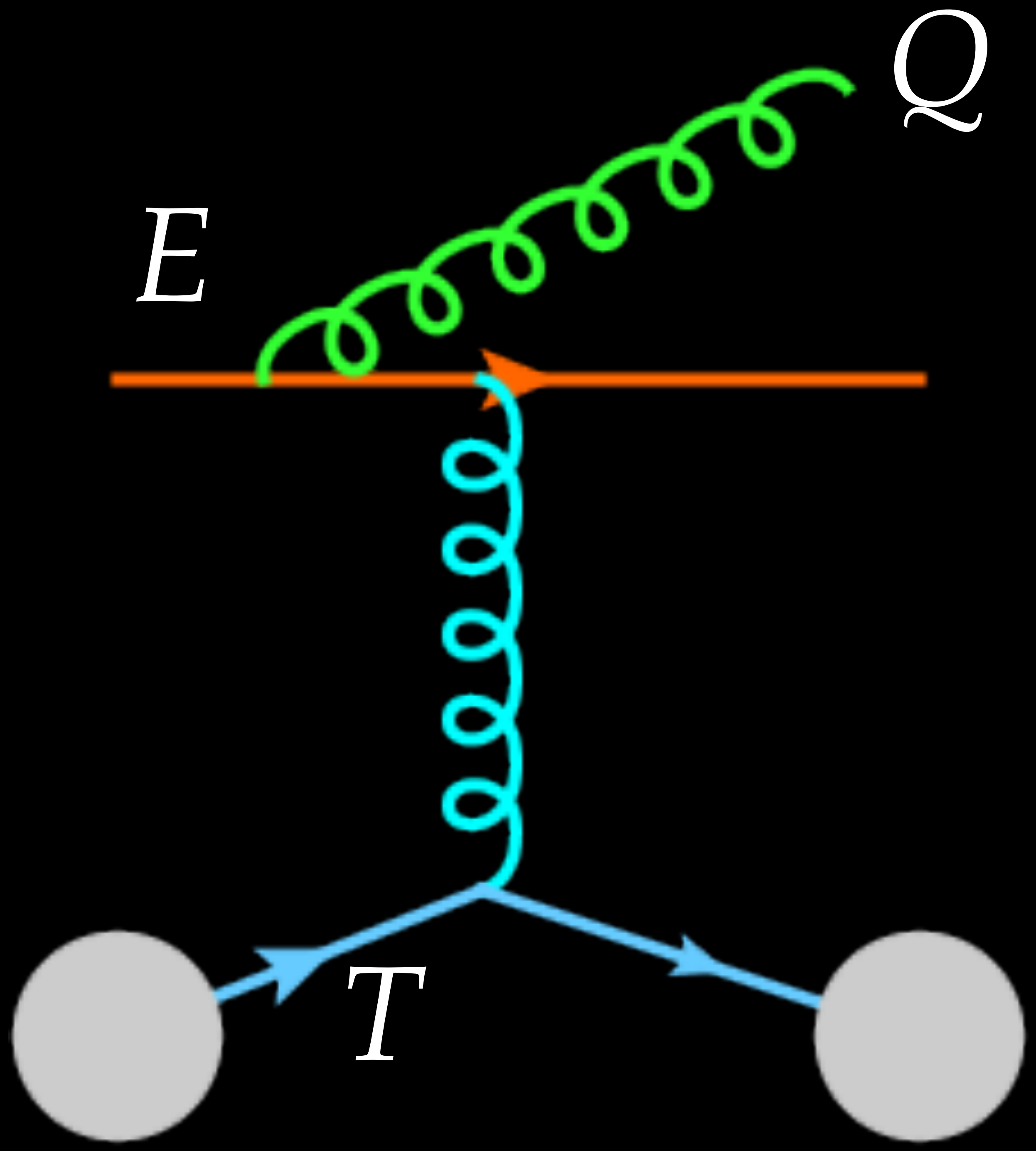


Fluid dynamical simulations and jets

- 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.



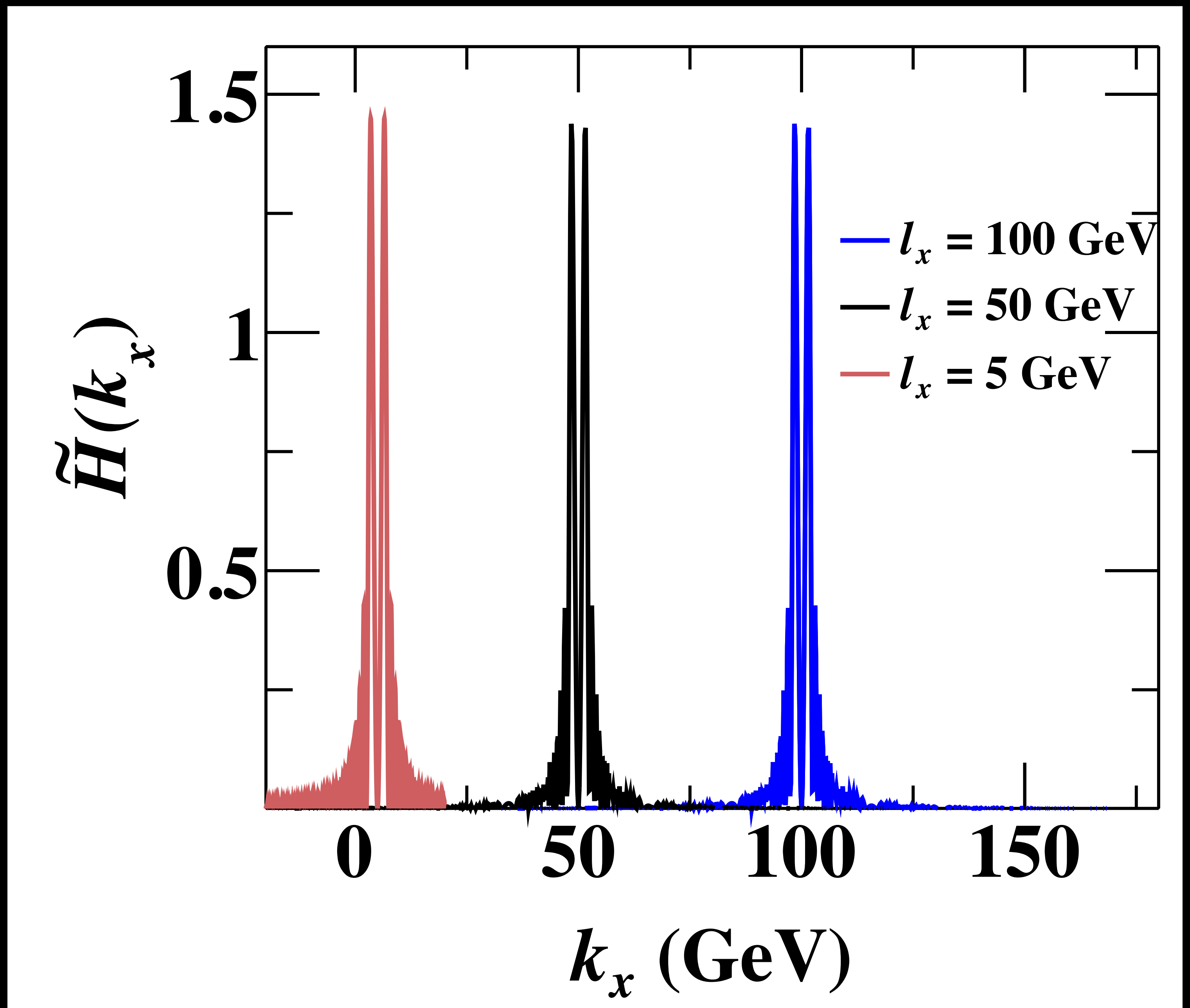
What else can $\hat{q}$ or $\Gamma = \int d^3k C(k)$ depend upon?



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

Virtuality dependence/Coherence

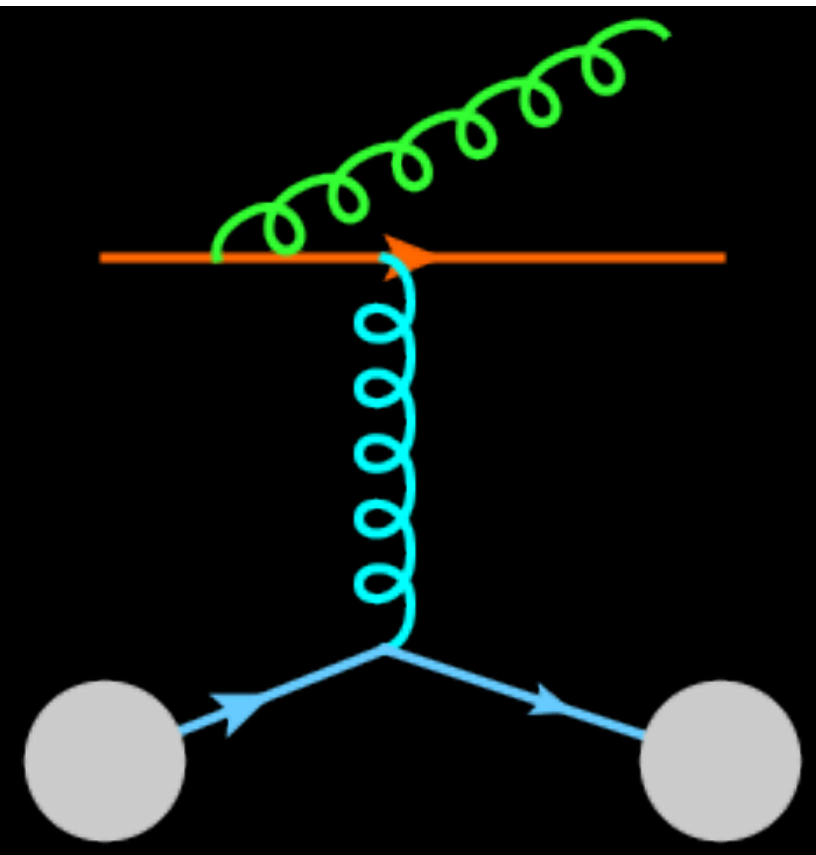
- Coherence arguments: $\hat{q}(Q^2 > \sqrt{2\hat{q}E}) \to 0$
- Can be calculated directly in the Higher Twist formalism.



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

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

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

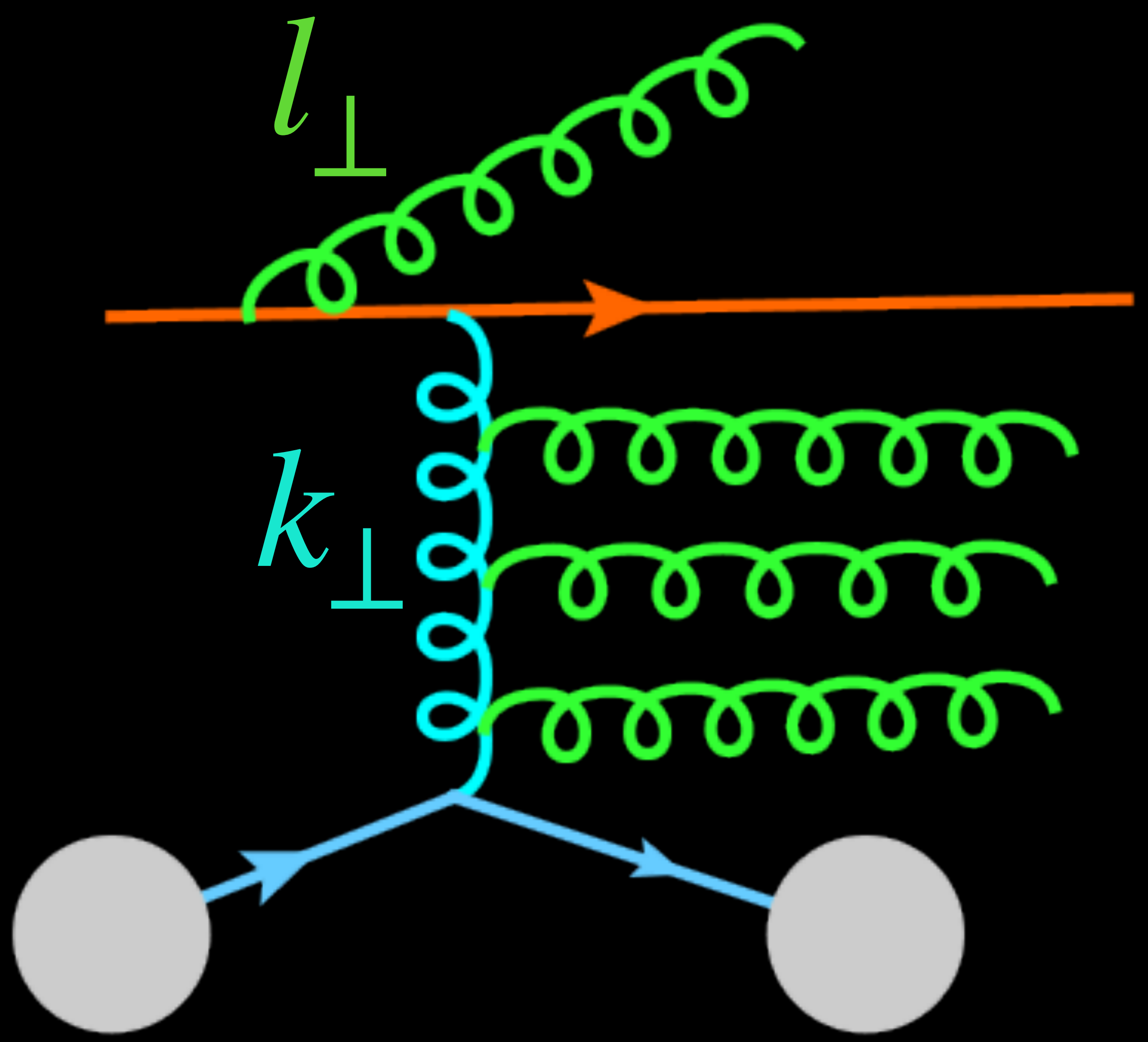


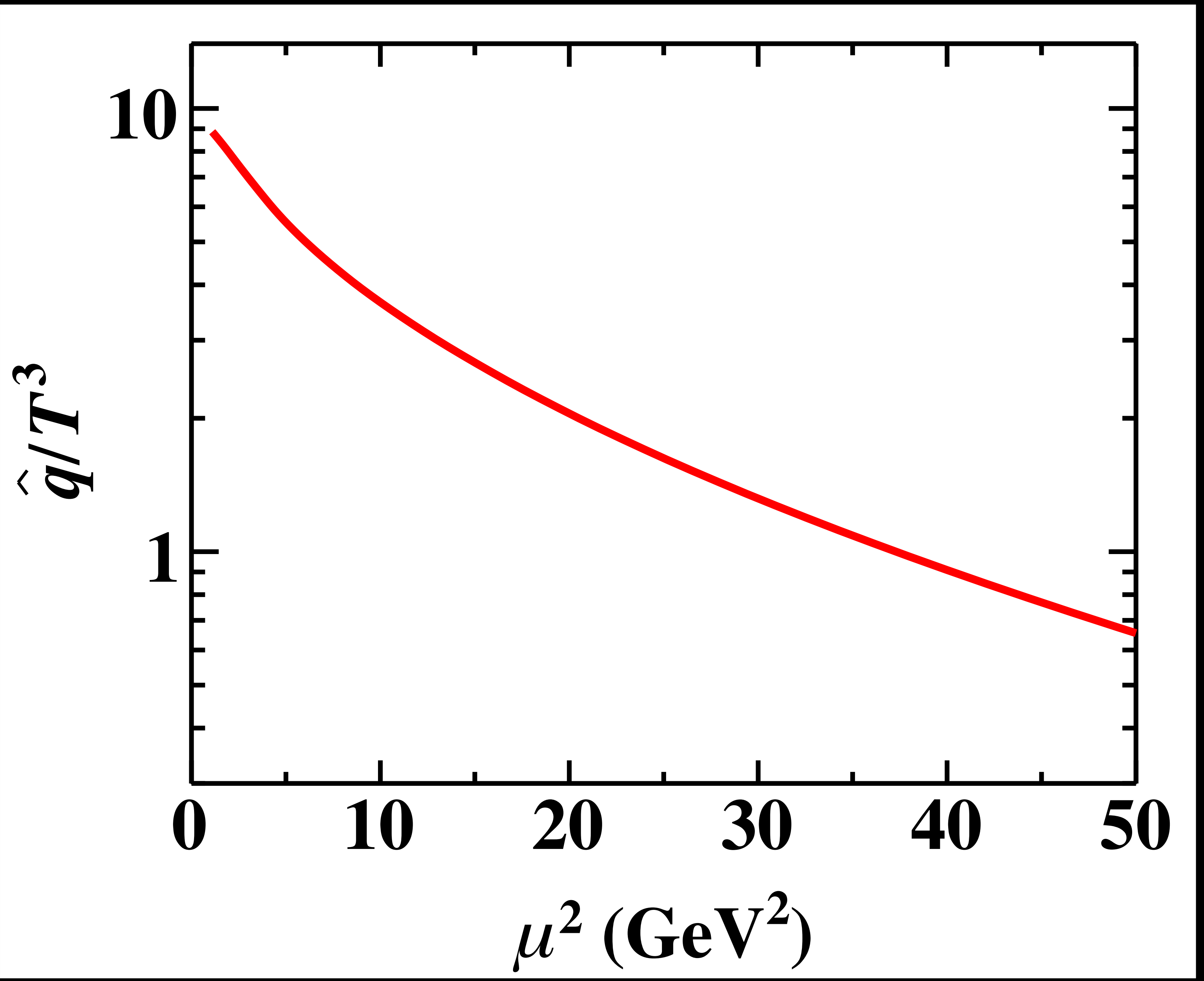
- **The matrix element prefers $k_\perp \sim T$, there is tension between 1st and 3rd line.**

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

Virtuality dependence/Coherence

- 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 $k_\perp \sim l_\perp$





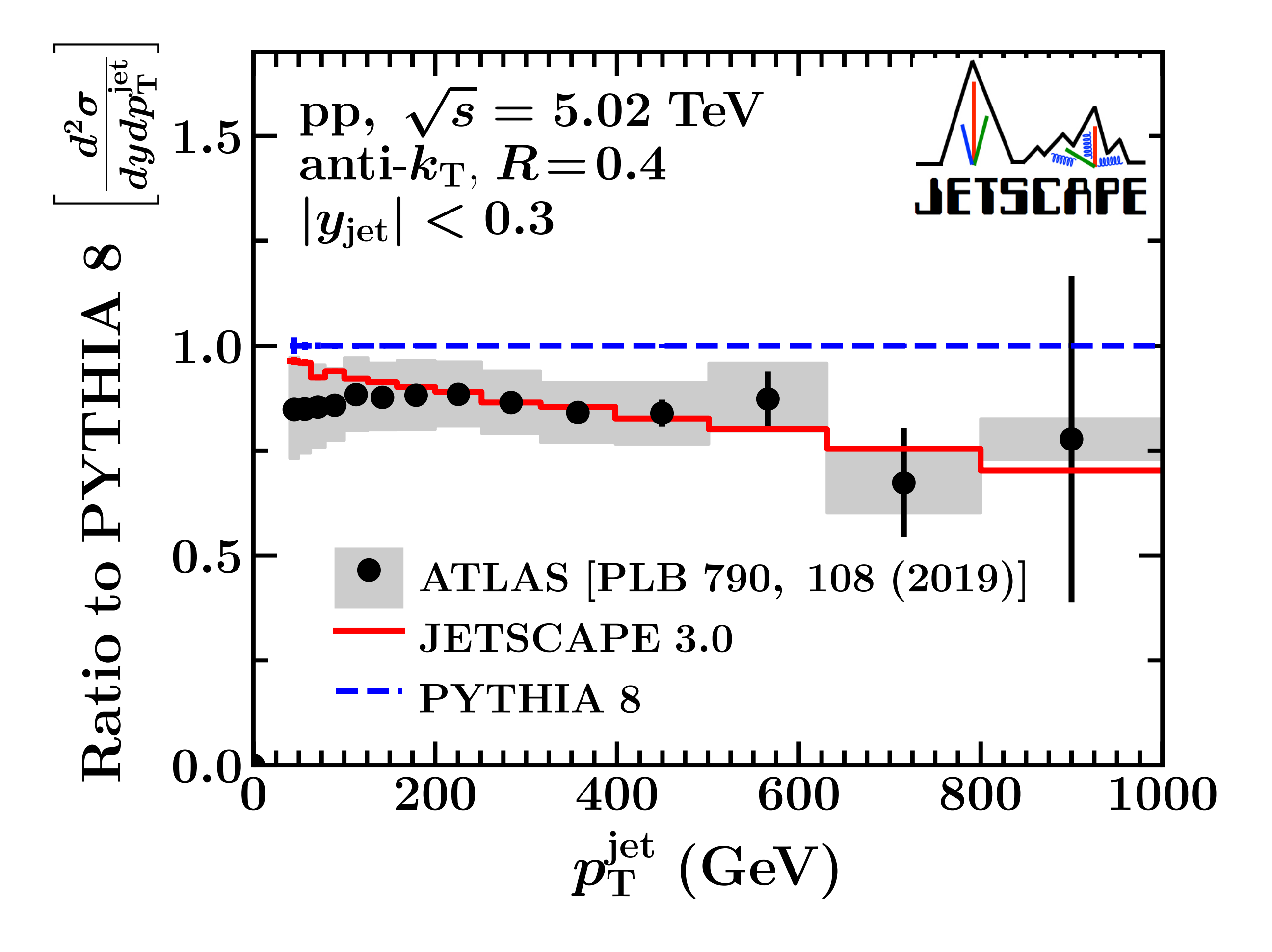
A. Kumar, A.M., C. Shen, PRC 101 (2020) 034908

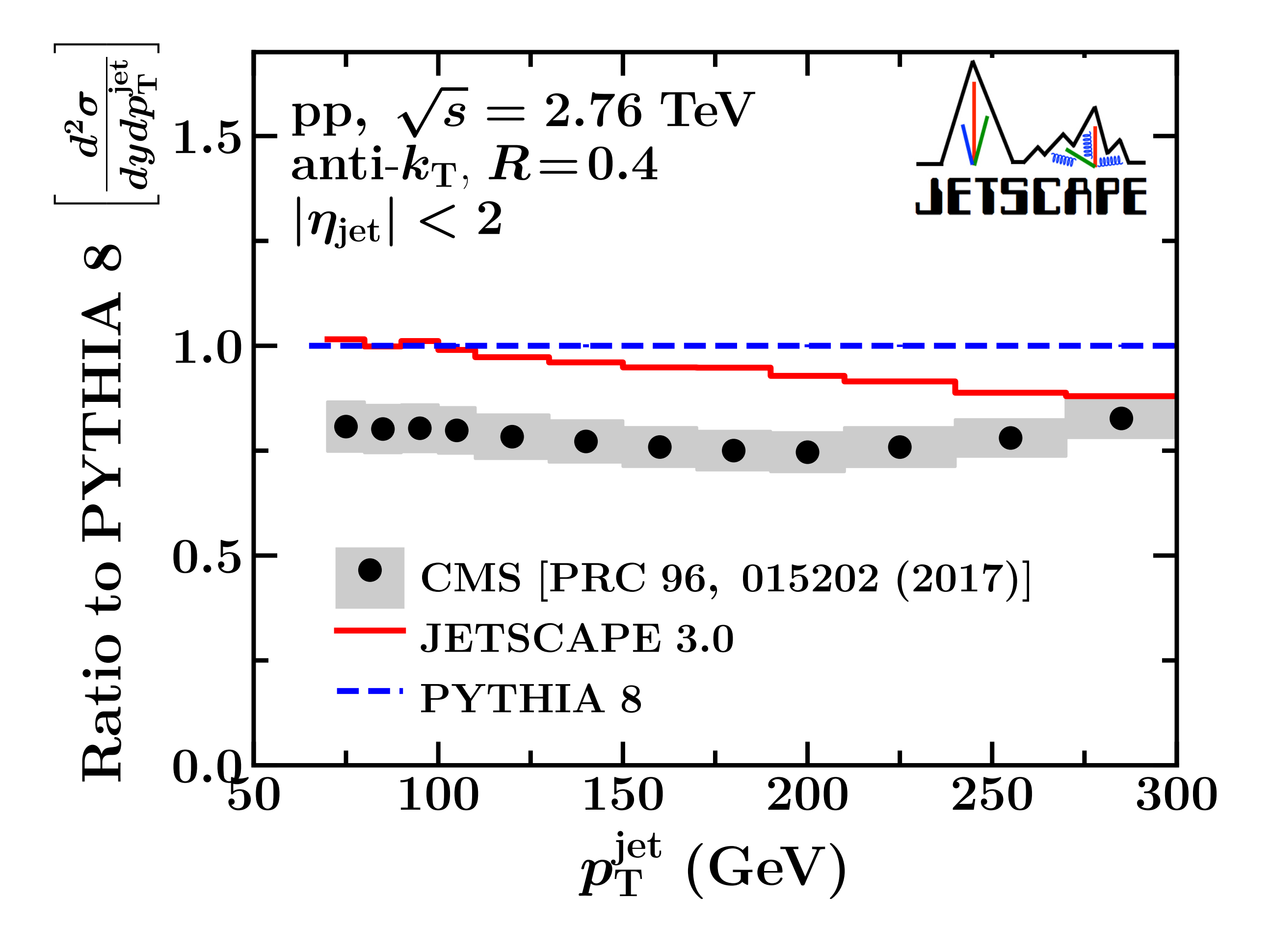
Transition from MATTER to LBT at $Q_0 = Q_{sw}$

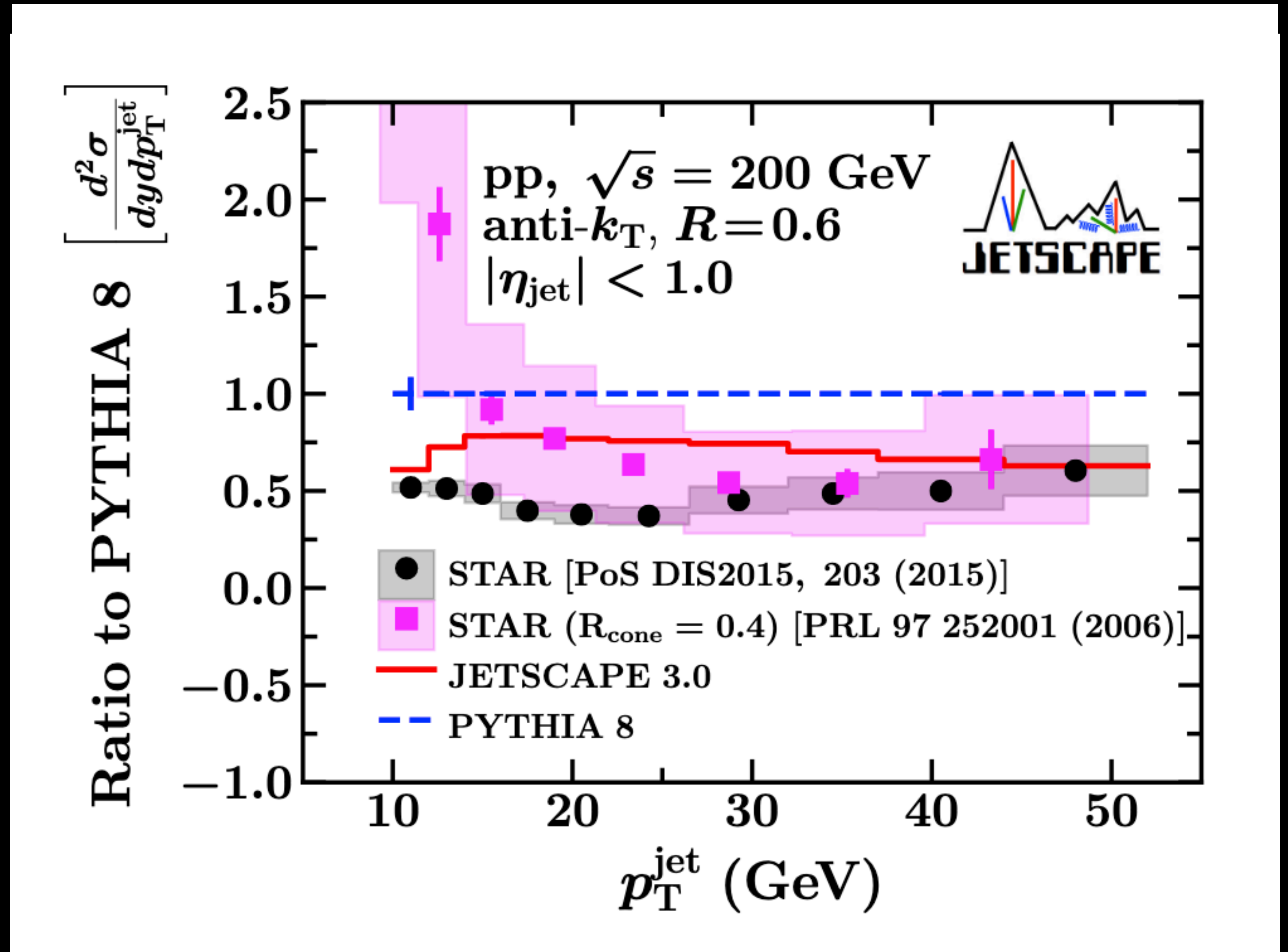
- TRENTO initial state
- Pre Calibrated 2+1D MUSIC gives background
- PYTHIA hard scattering
- High virtuality phase using MATTER
- Lower virtuality phase using LBT
- Both have the same recoil setup
- Evolution starts at Q ~ E and goes down to 1 GeV
- Hadronization applied in vacuum
- Holes subtracted

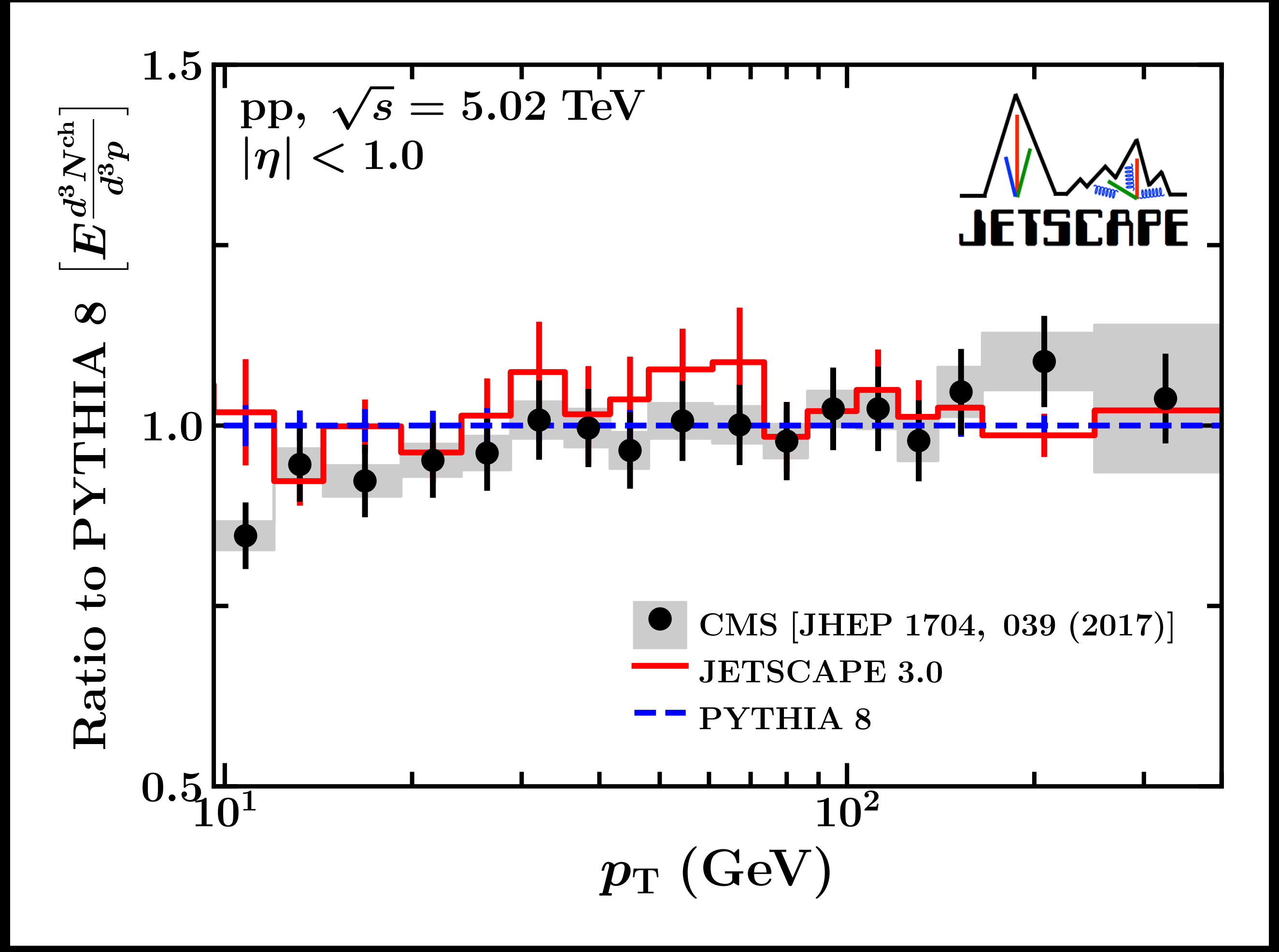
One more constraint before we start

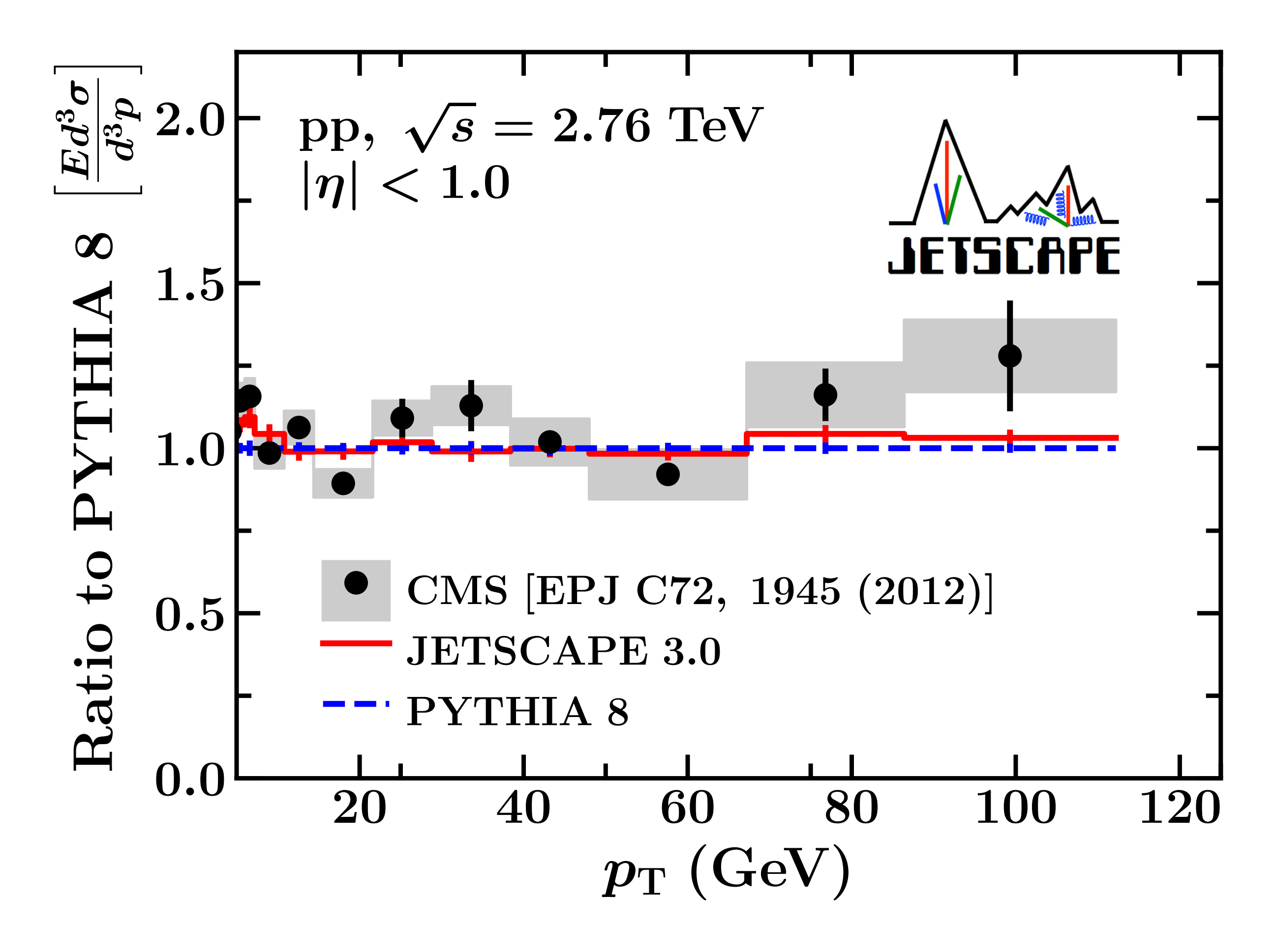
Any decent event generator should reproduce p-p collisions

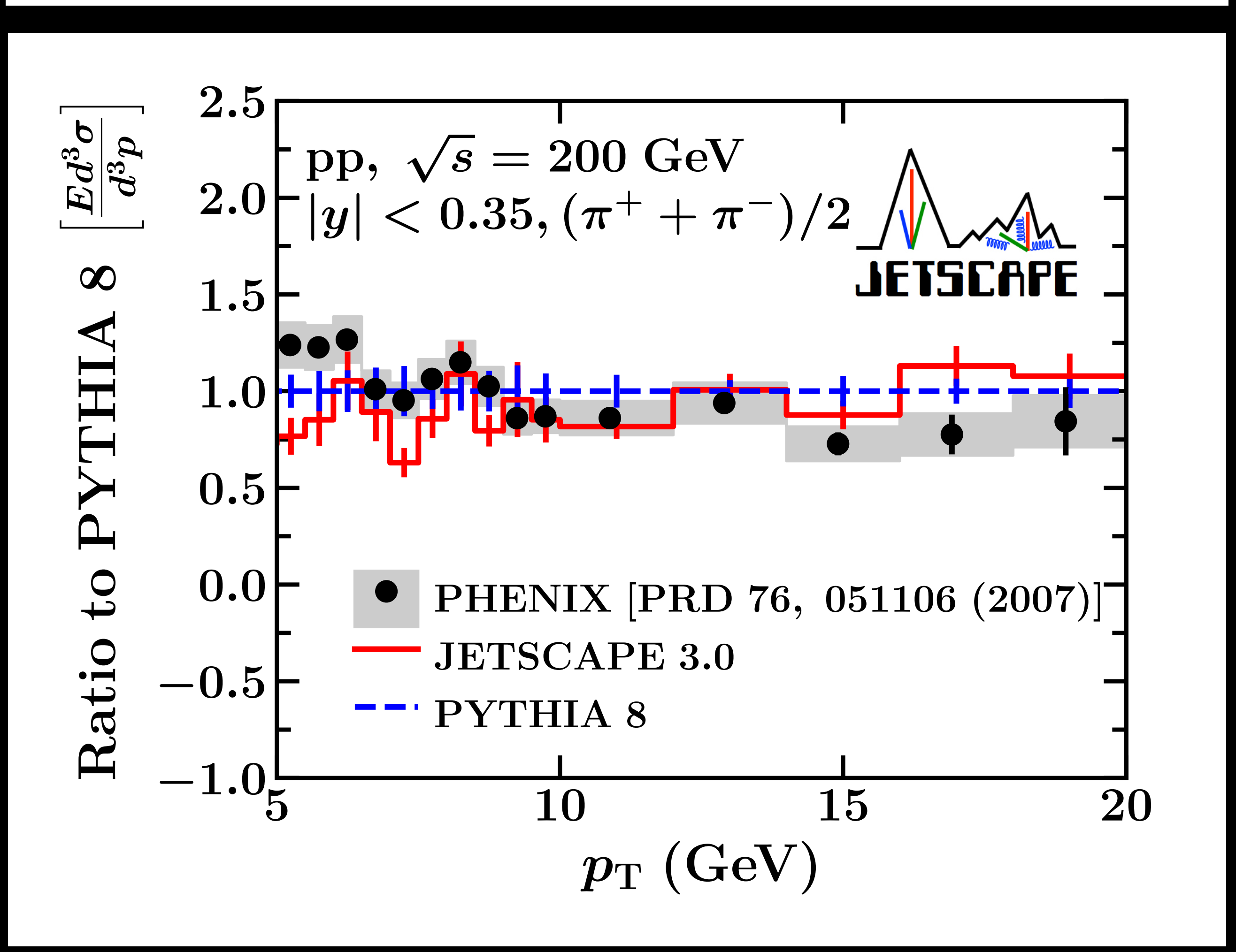










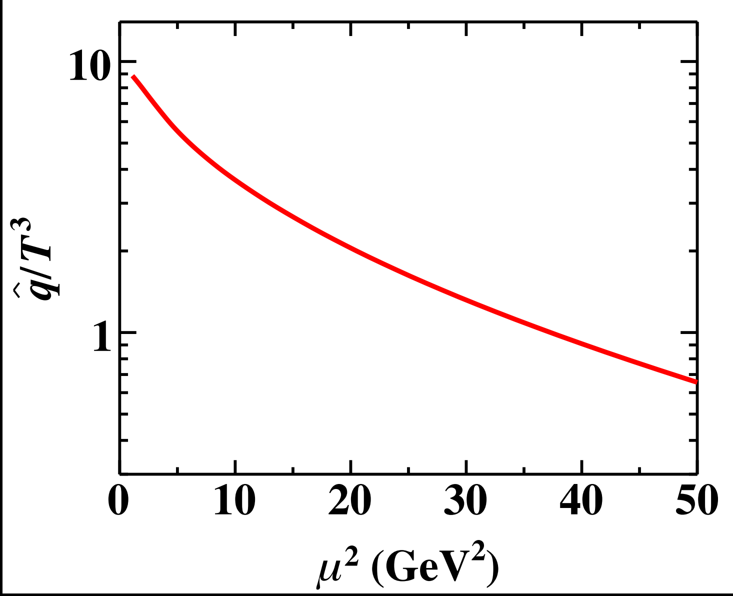


A. Kumar et al., 2204.01163 [hep-ph]

Leading hadrons and jets

At all energies and centralities

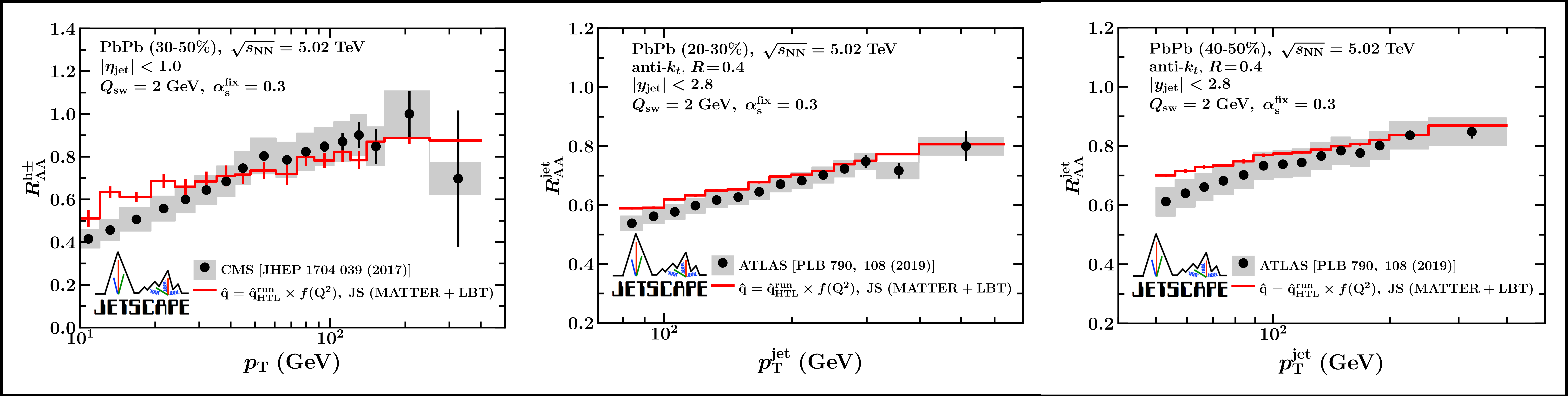
- $\hat{q} = C\alpha_s(2ET)\alpha_s(m_D)T^3 \log\left(\frac{2ET}{m_D^2}\right) \times f(Q^2)$



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

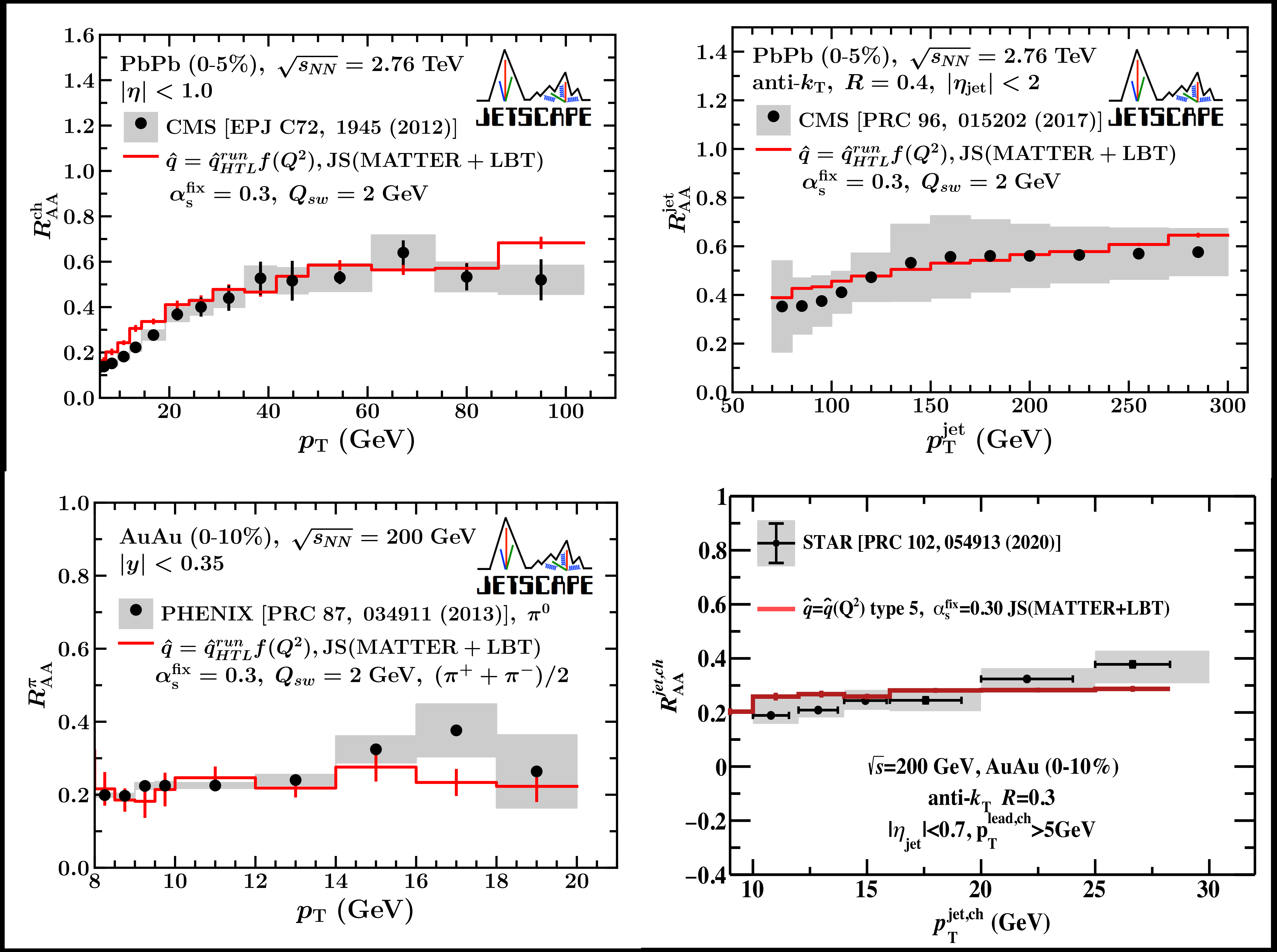
A. Kumar et al., 2204.01163 [hep-ph]

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



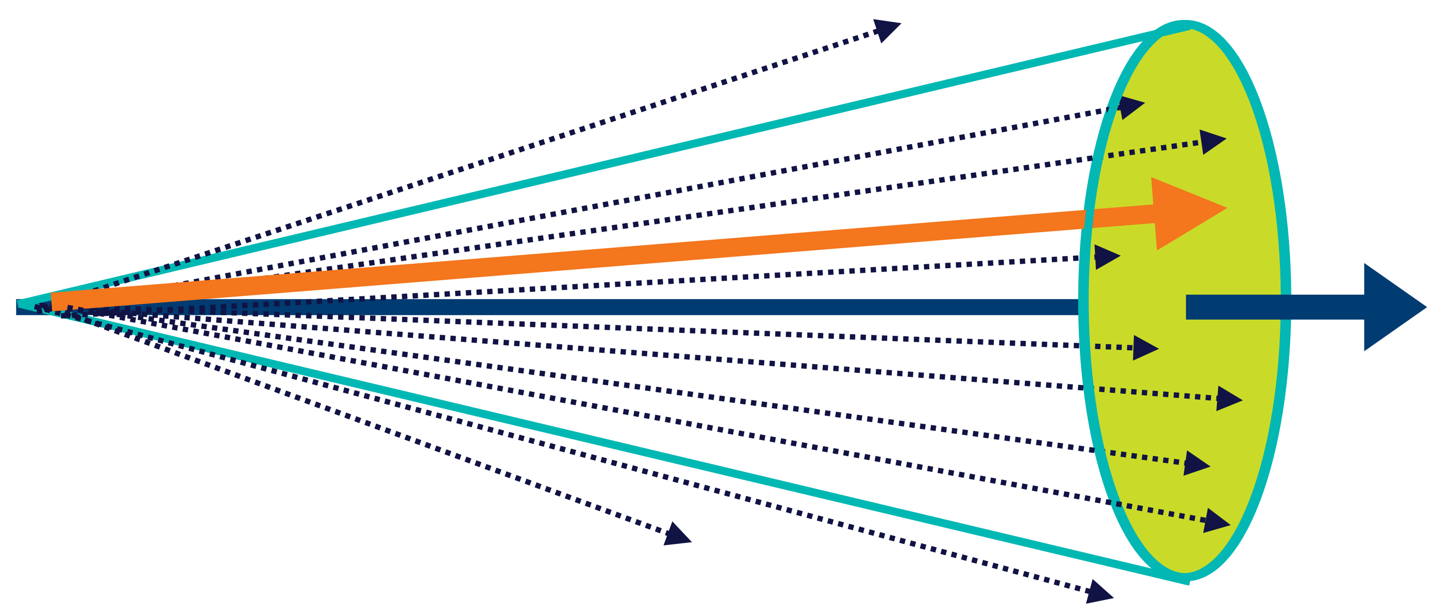
A. Kumar et al., 2204.01163 [hep-ph]

Intrajet

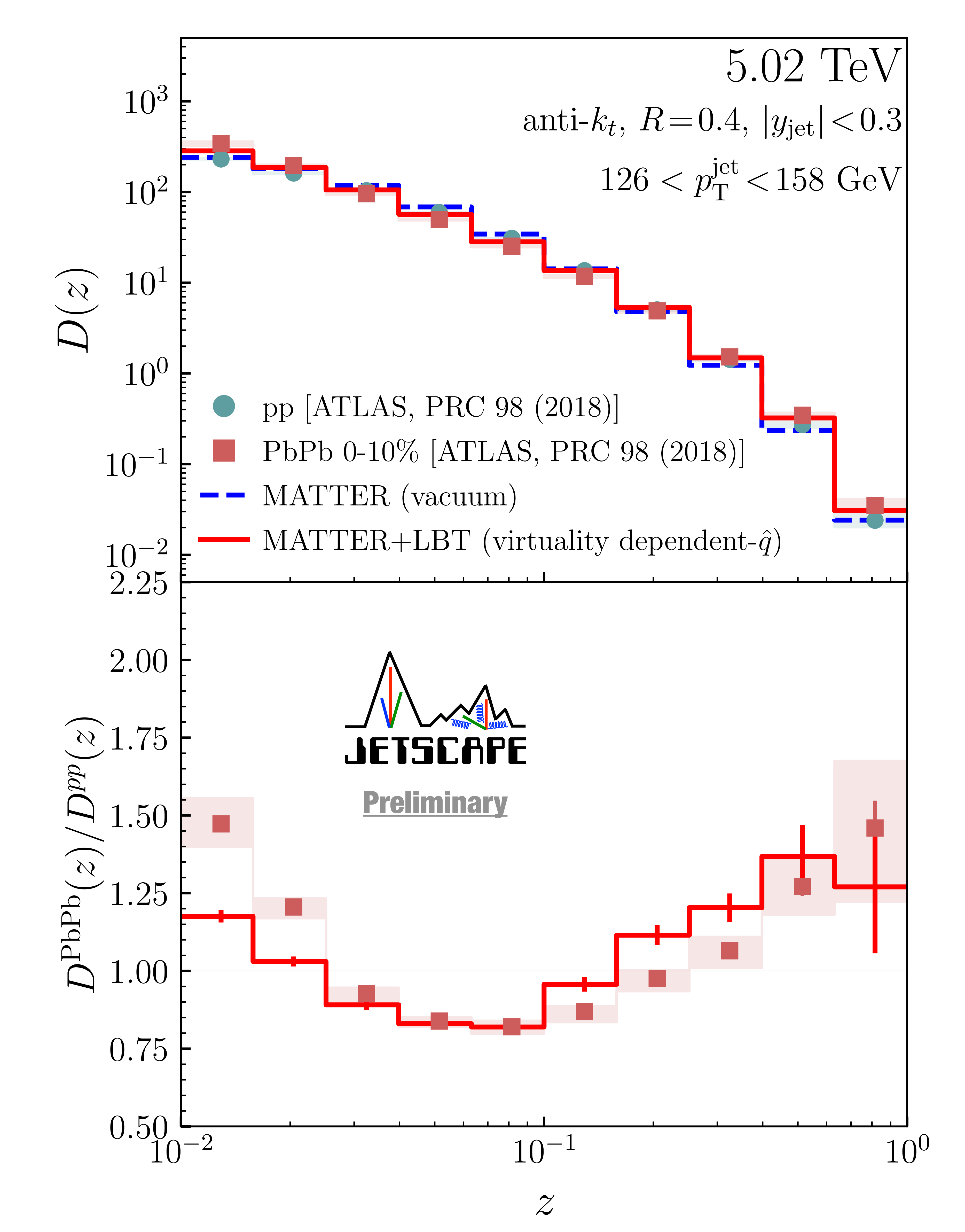
The dependence on E and μ not completely settled

This will probably get done in an upcoming Bayesian analysis

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

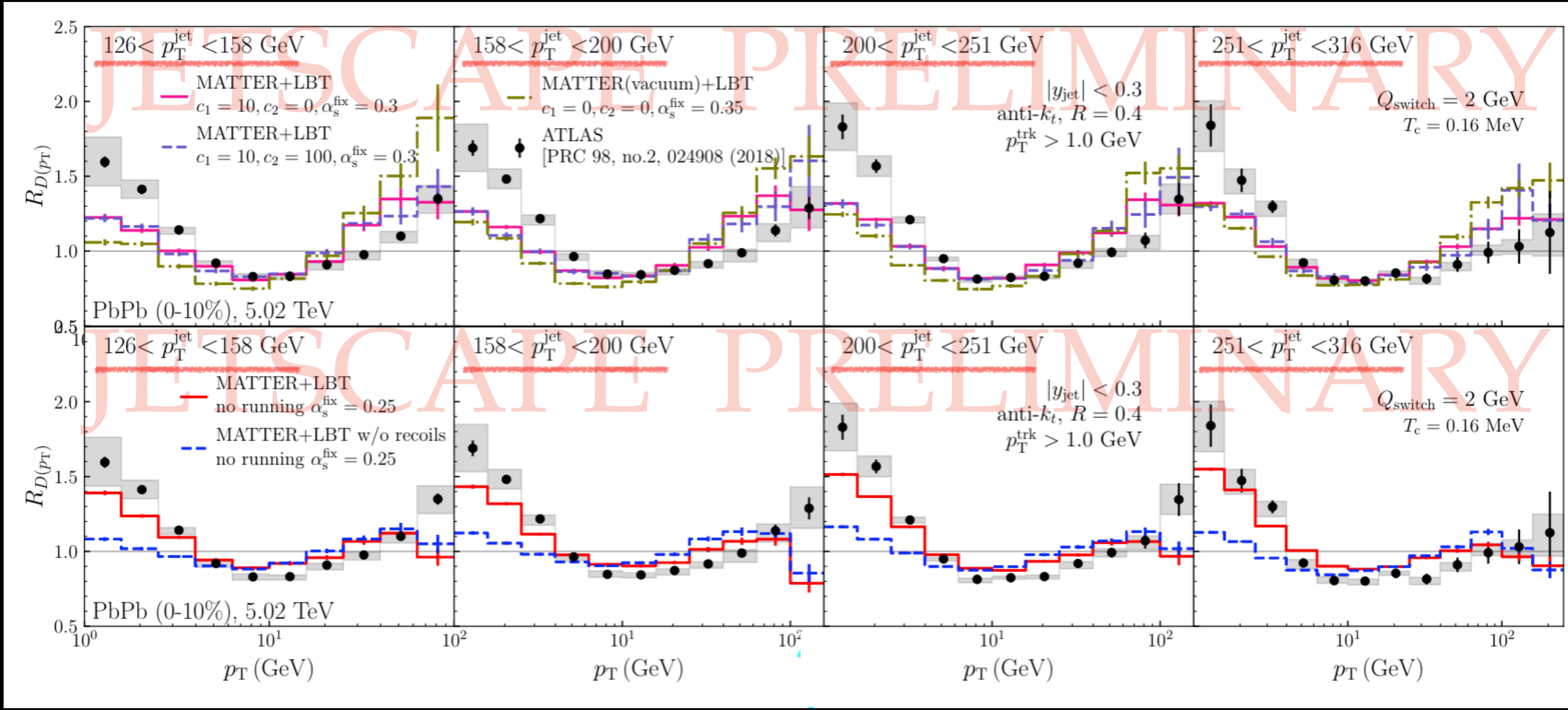


$$z = \frac{p_T^{\text{trk}}}{p_T^{\text{jet}}}$$



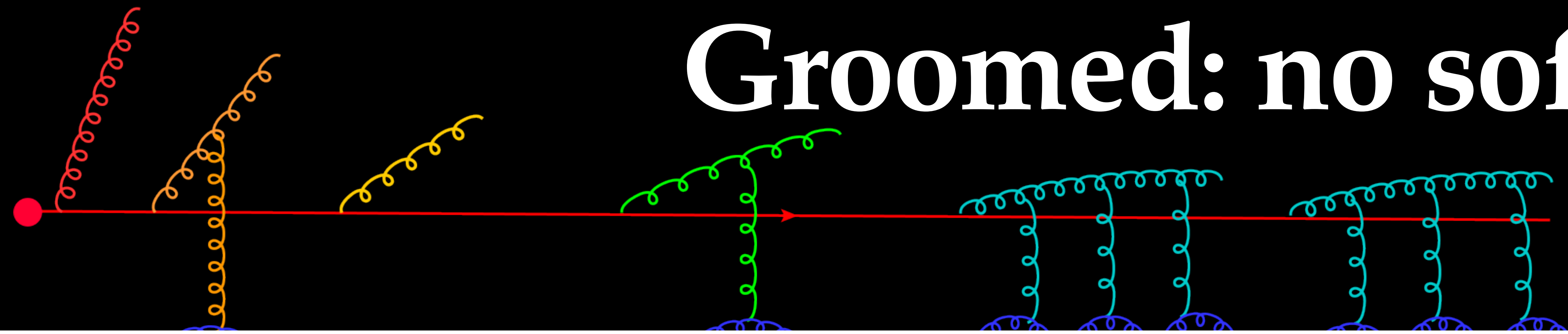
Y. Tachibana et al., *to appear*

Need for quenching in high Q stage



Y. Tachibana et al., *to appear*

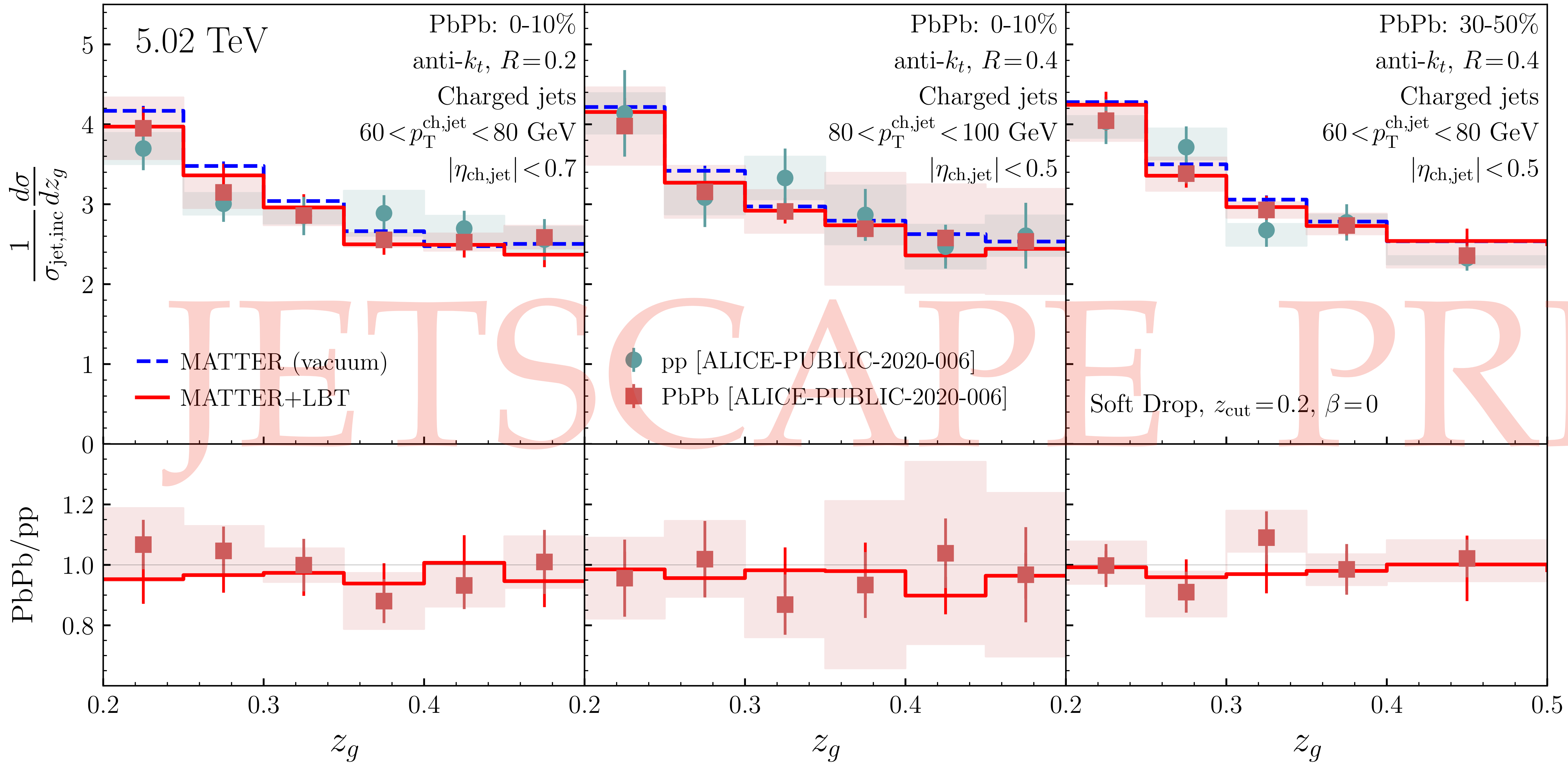
Groomed: no soft modes!

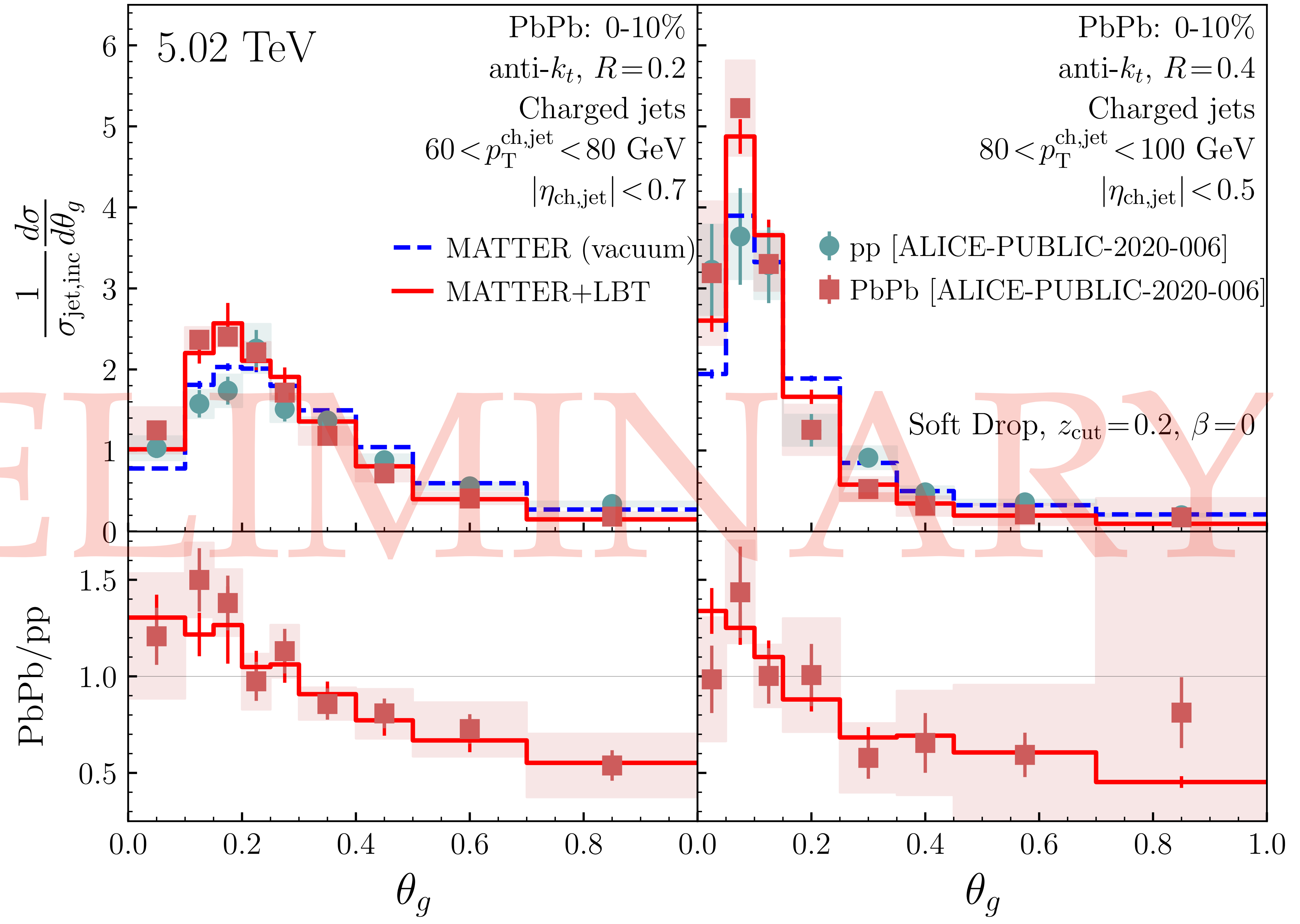


pp: MATTER (vacuum)

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

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

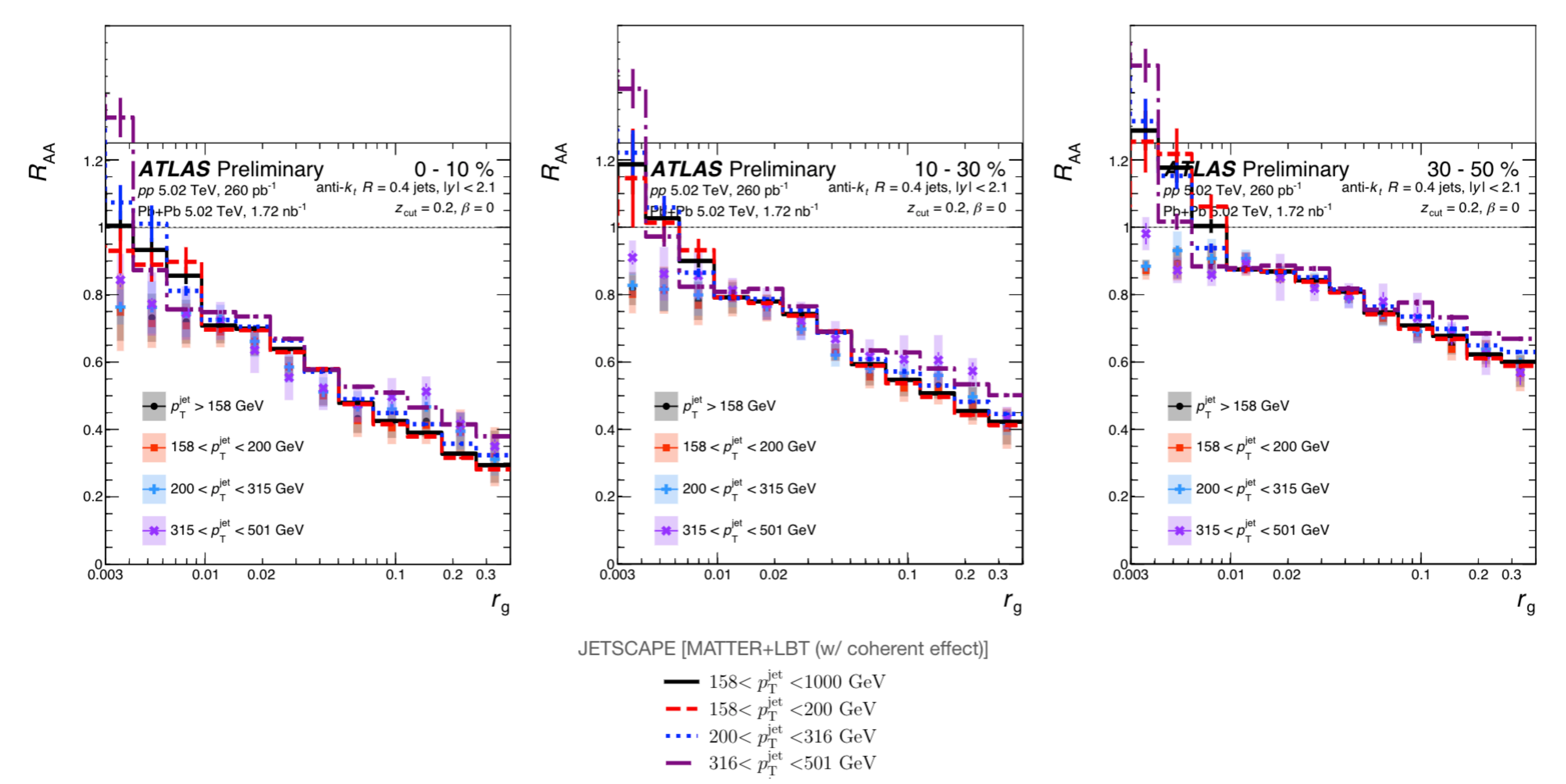




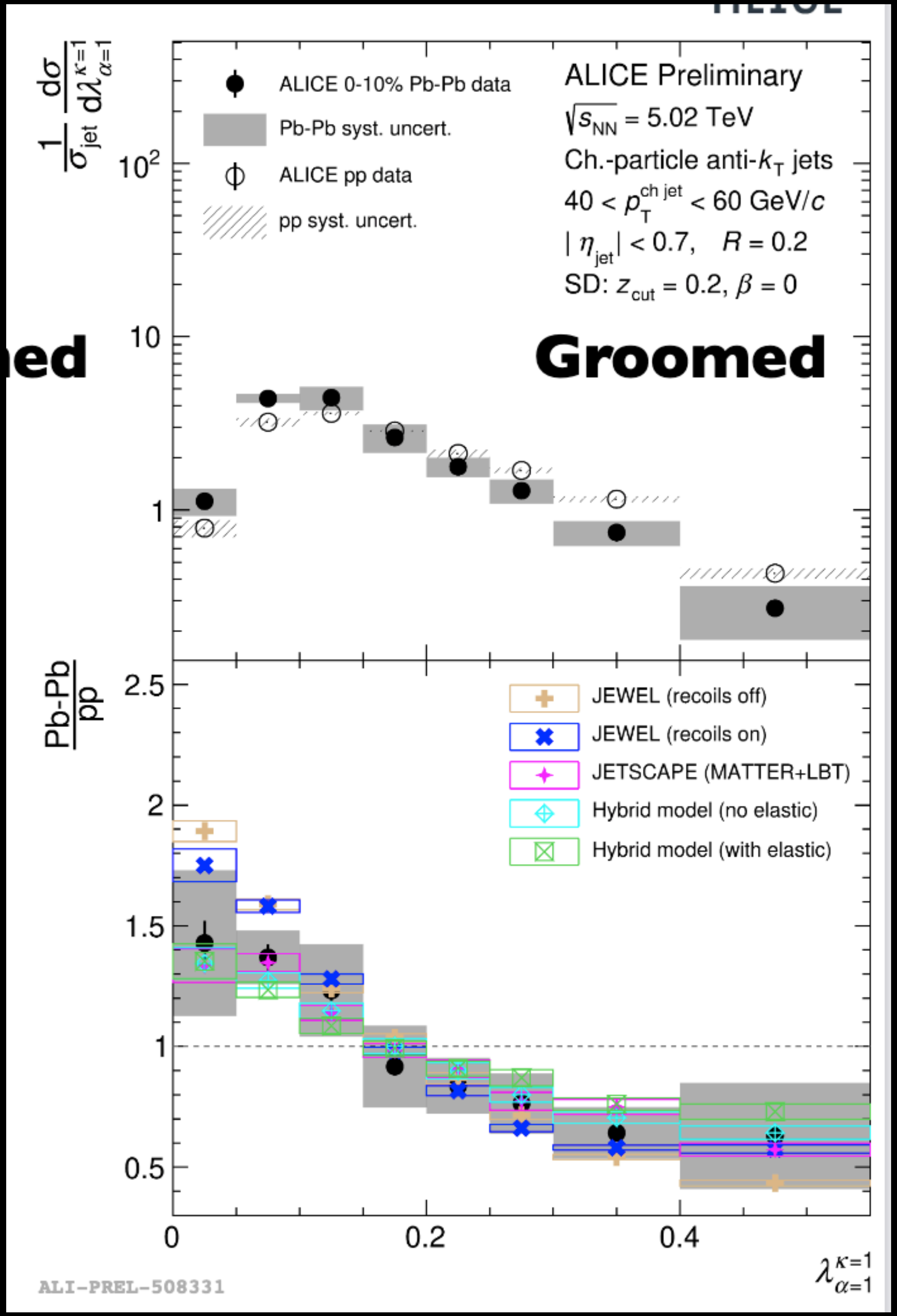
- Soft drop: getting rid of the soft response and looking at the prong structure

Y. Tachibana et al., *to appear*

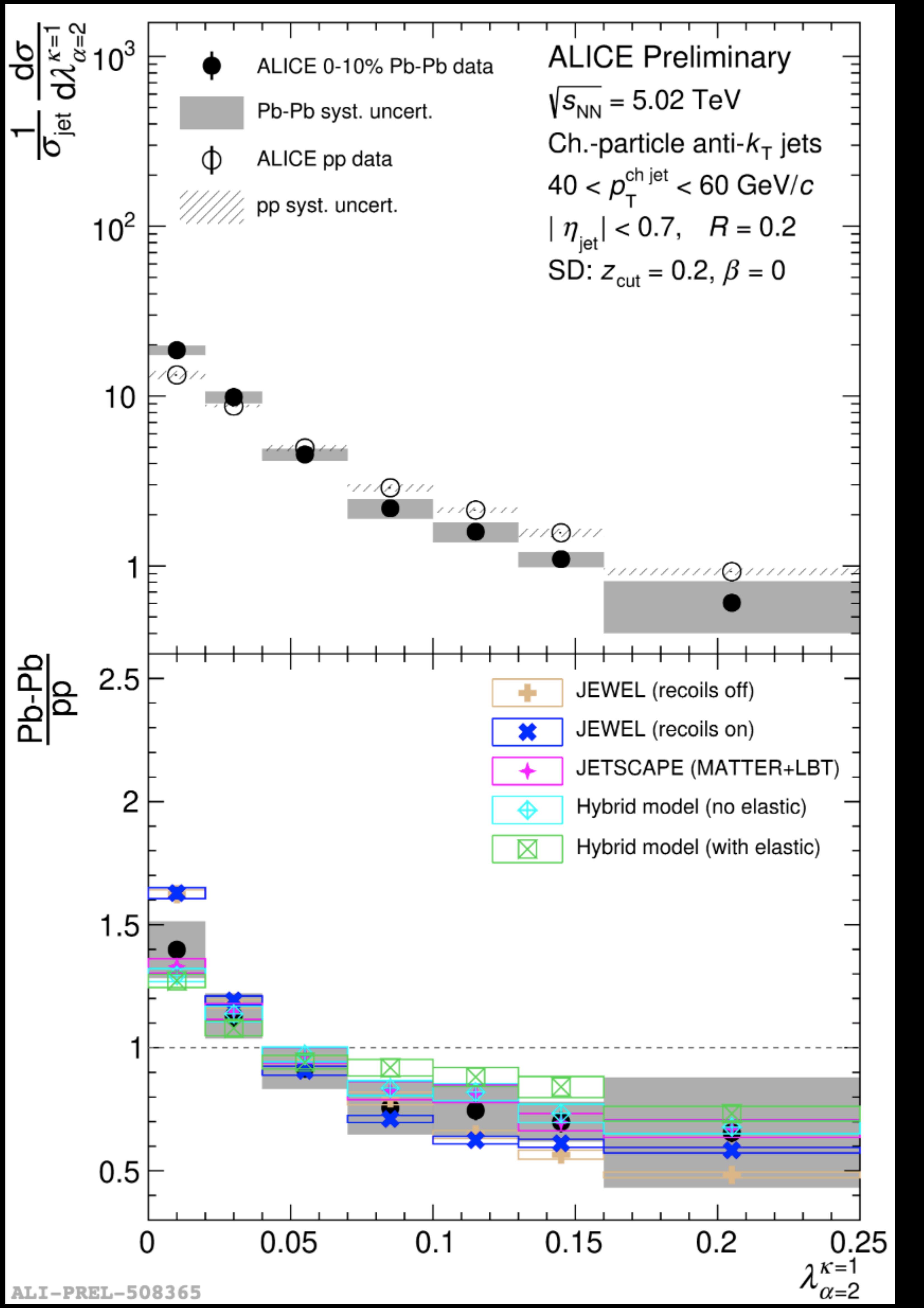
R_{AA} as a function of r_g



Groomed Jet angularities

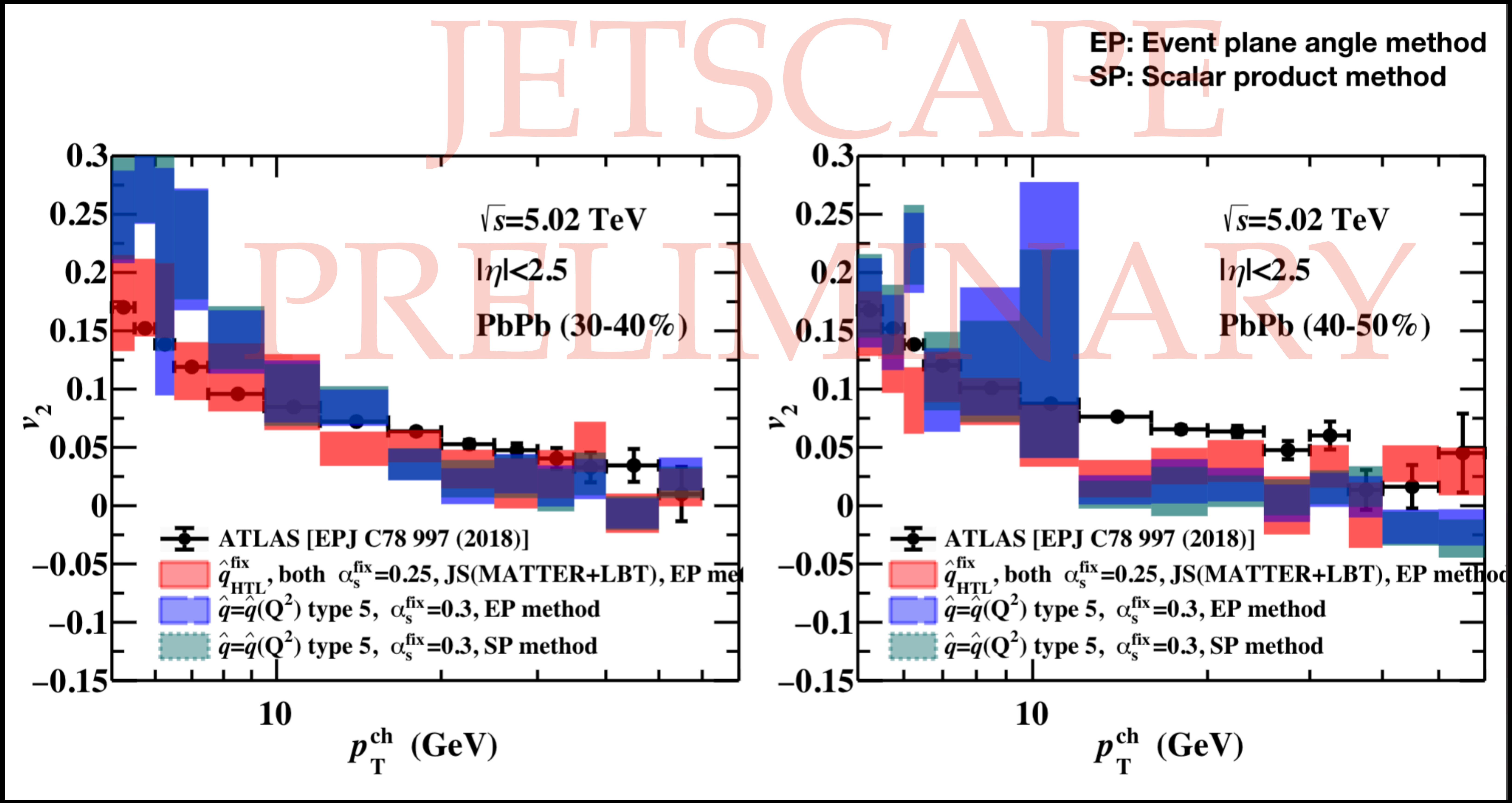


- $$\lambda = \sum_{i \in Groomed} z_i \theta_i^\alpha$$
- Strong constraints on the perturbative part of jet
- Several other similar groomed observables
- JETSCAPE (MATTER +LBT) does very well.

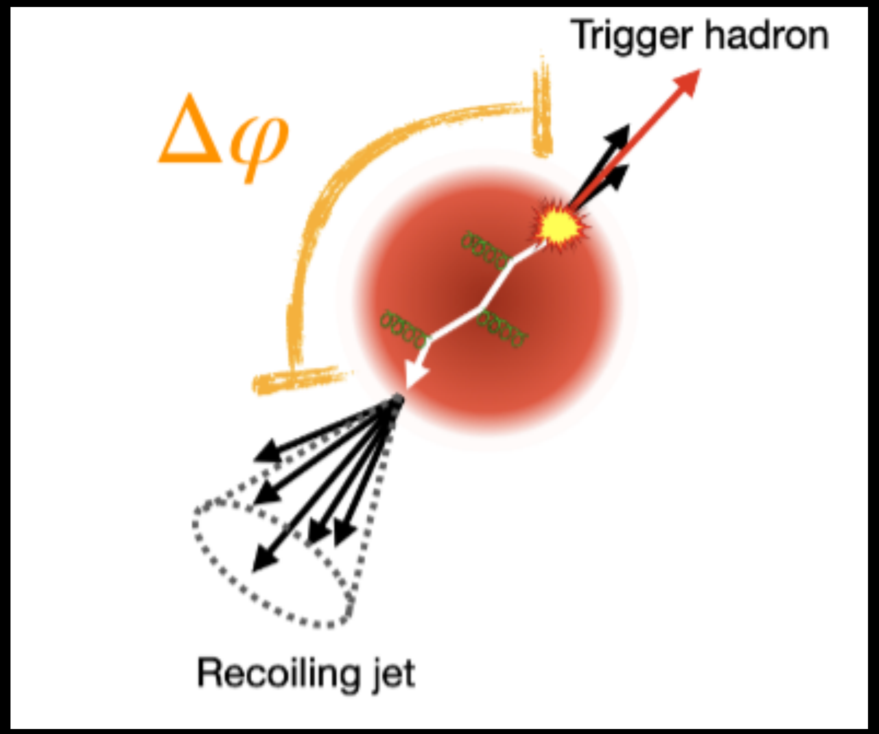


Azimuthal anisotropy

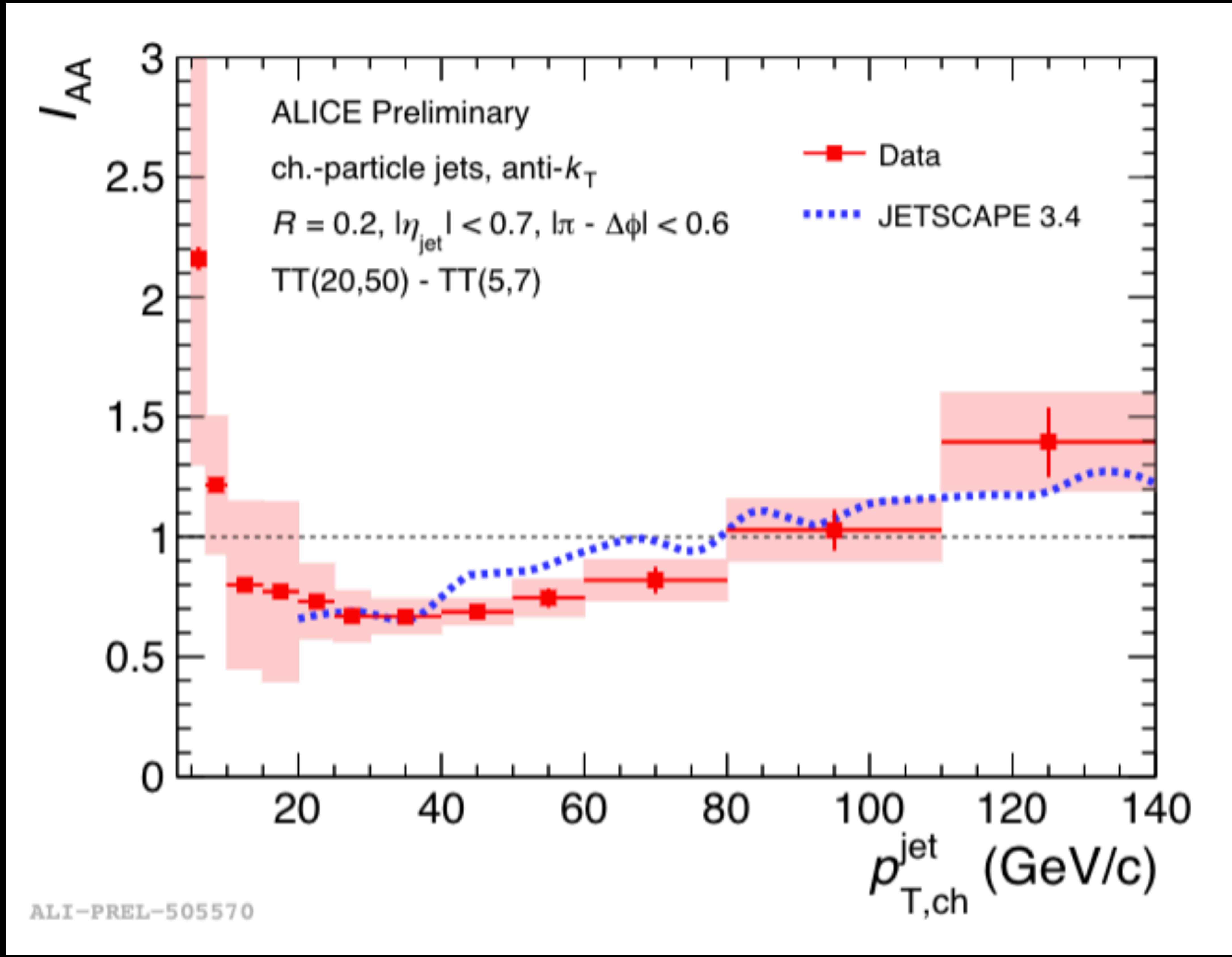
- Note: we haven't played with start and stop times (observation by C. Andres et al, start time important for v_2)
- In the JETSCAPE simulations, hydrodynamics starts around 1fm/c. (Free streaming prior)
- Also with new IP-Glasma, medium has primordial v_2
- Jet modification in the hadronic medium still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

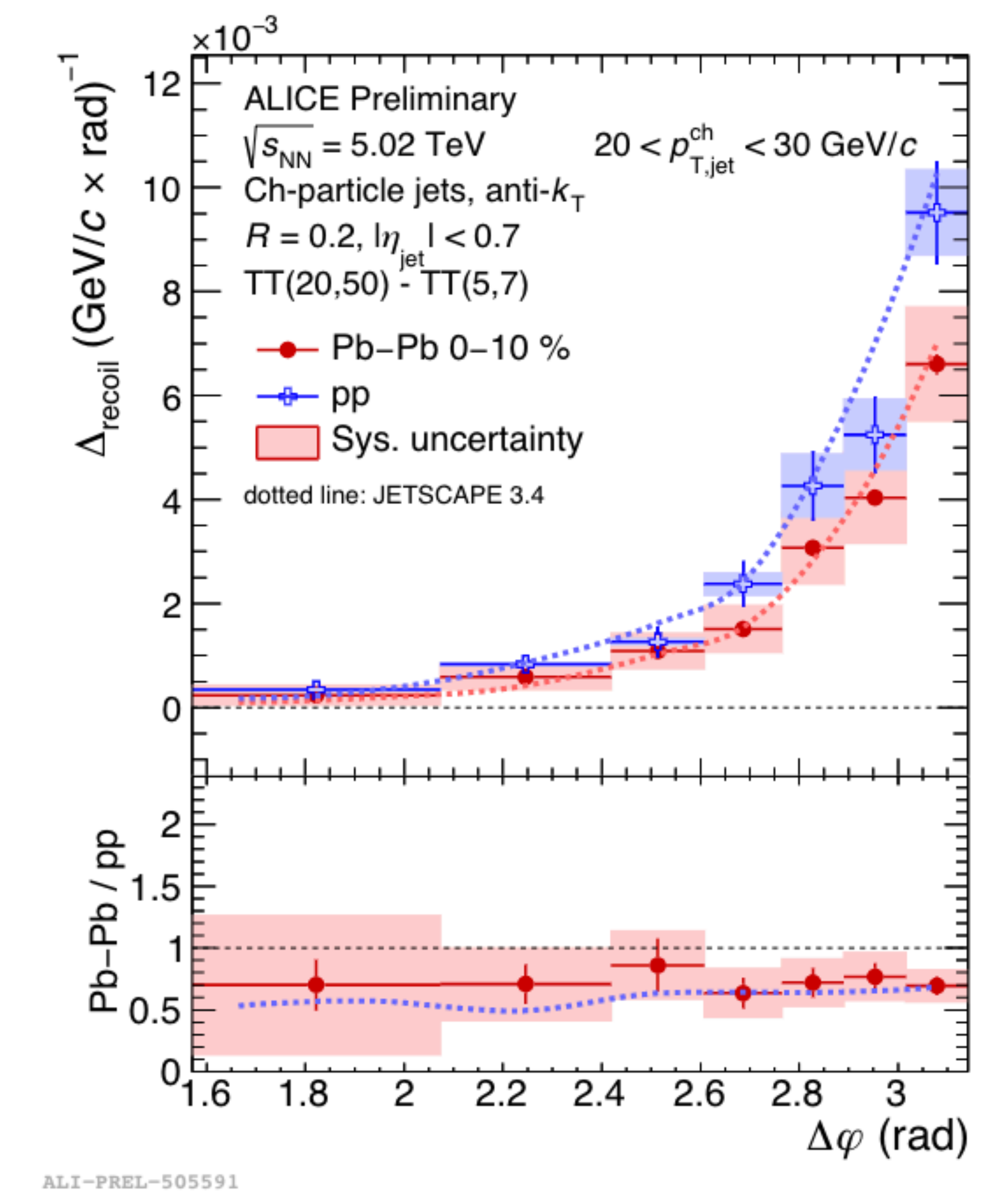


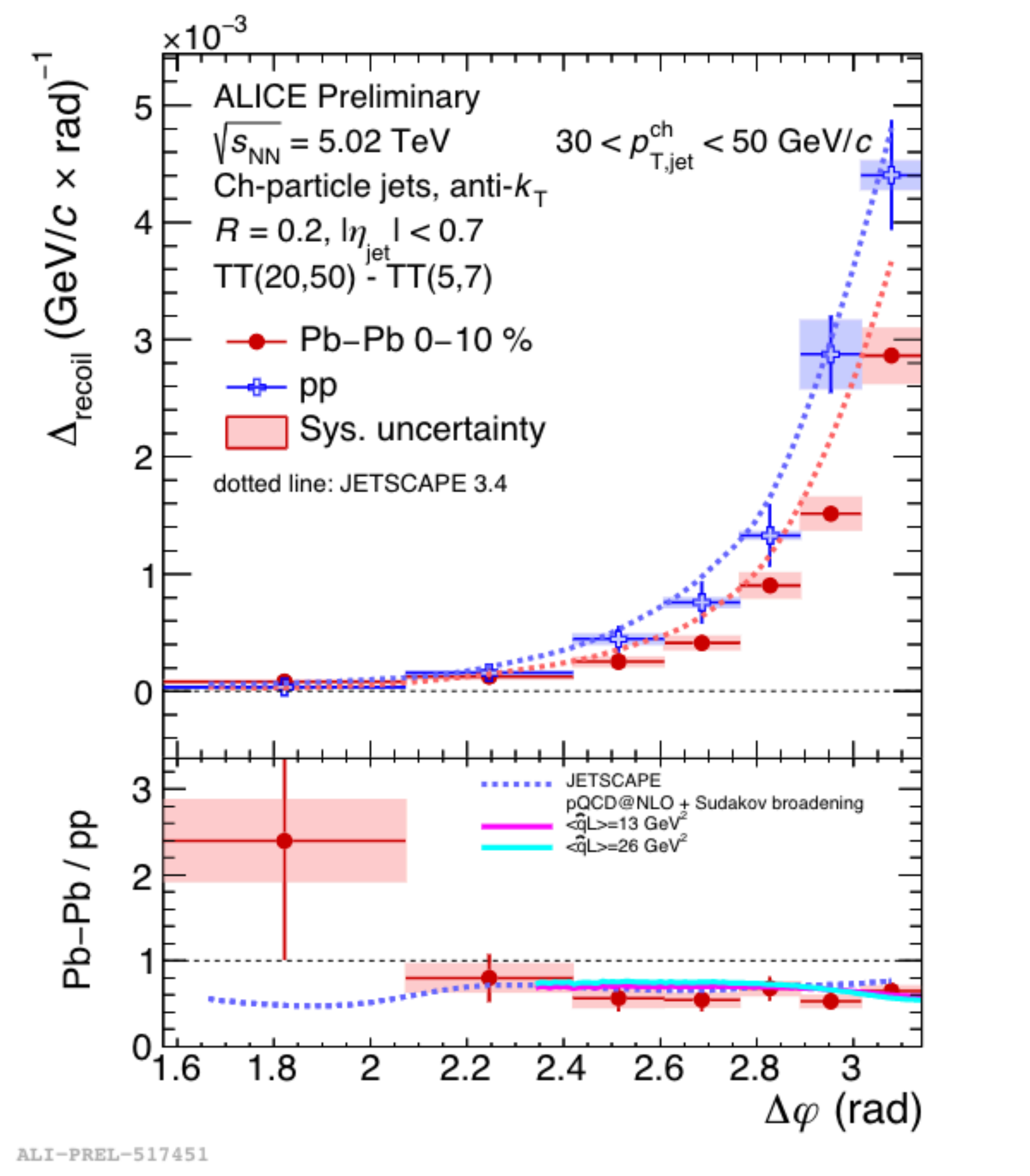
Coincidence with hadrons



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

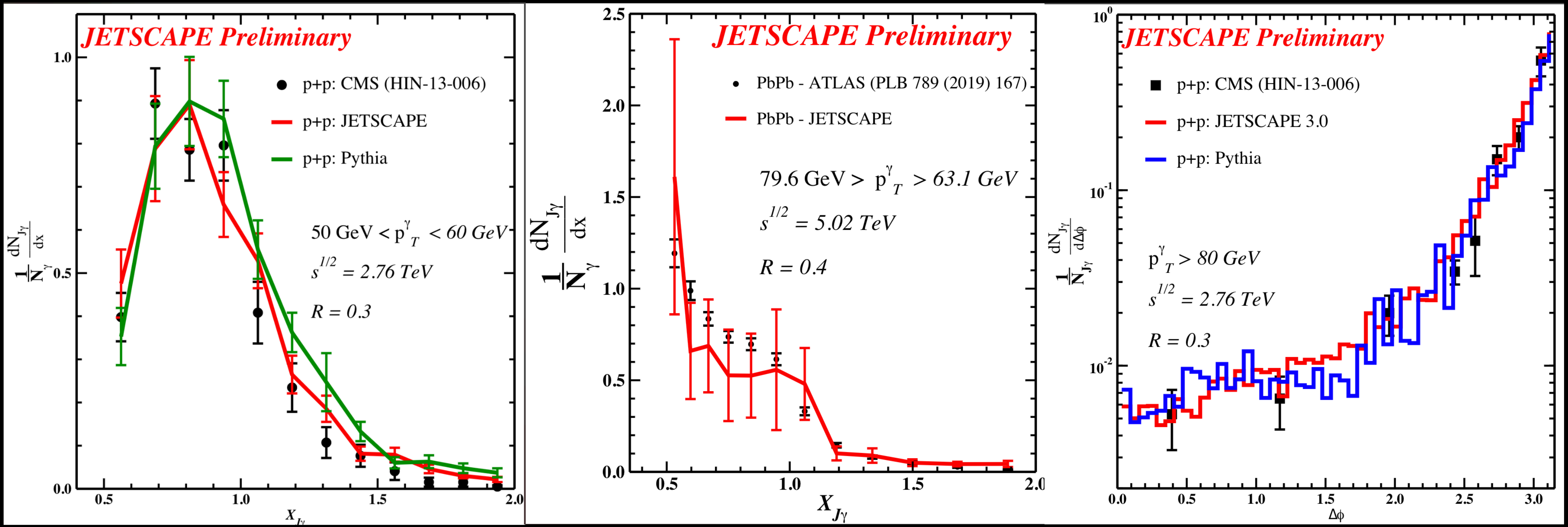






Photon Trigger

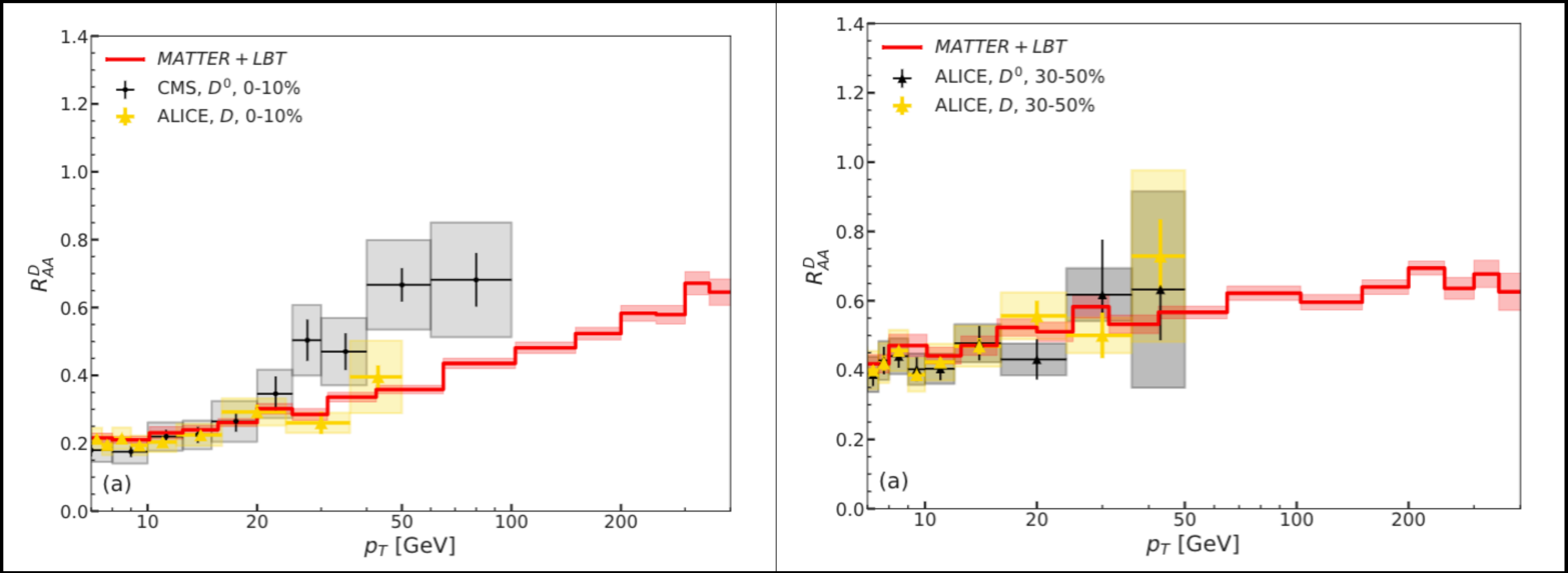
- Higher statistics runs with the exact same parameters as for jets.



C. Sirimanna, *to appear*.

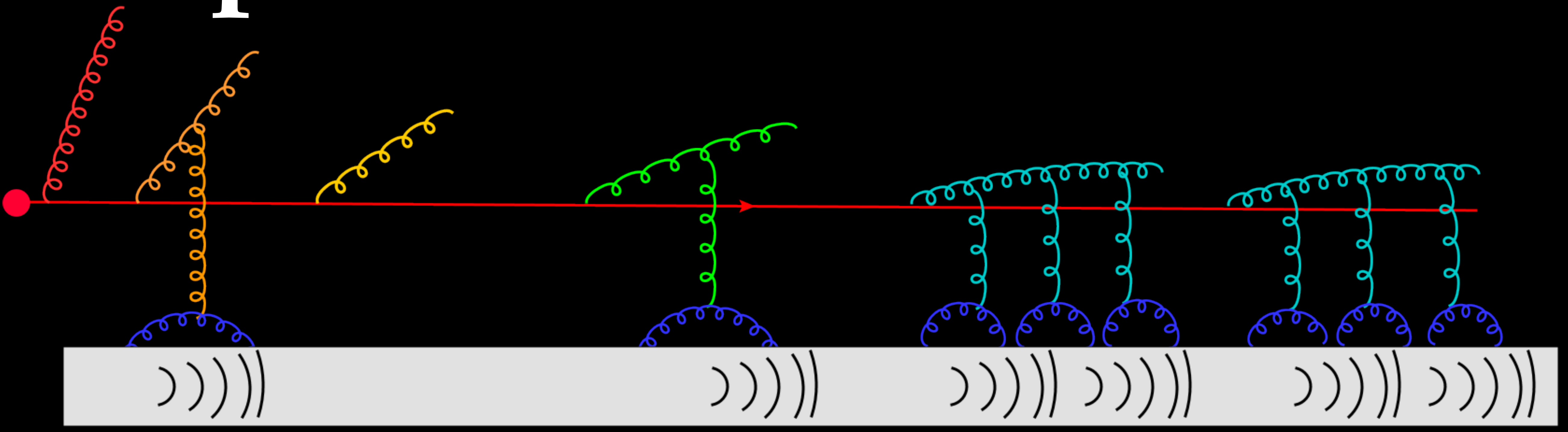
Heavy-quarks

- D meson R_{AA} with identical parameters



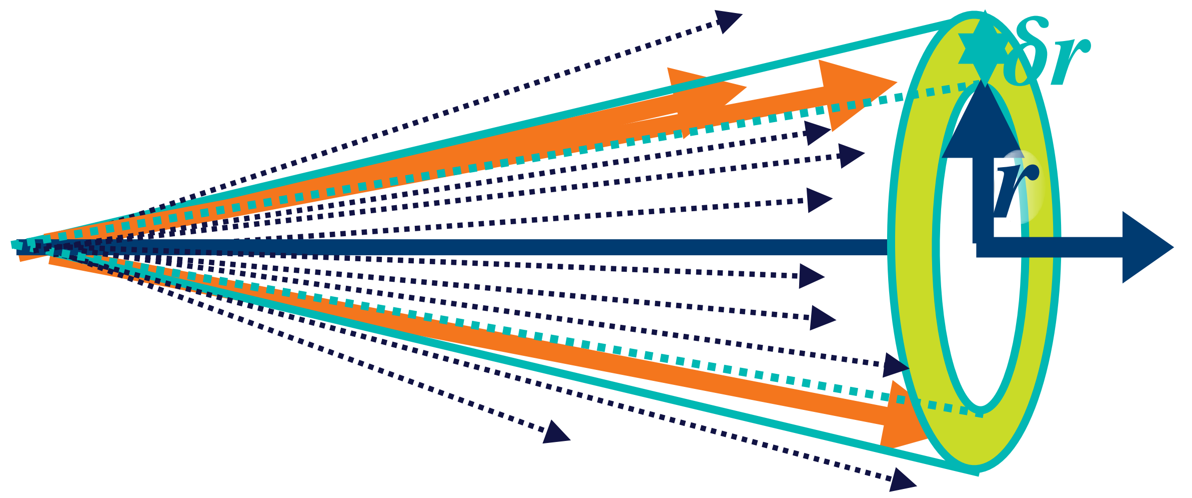
W. Fan, *et al*. e-Print: 2208.00983 [nucl-th]

Jet Shape: more dependence on soft modes

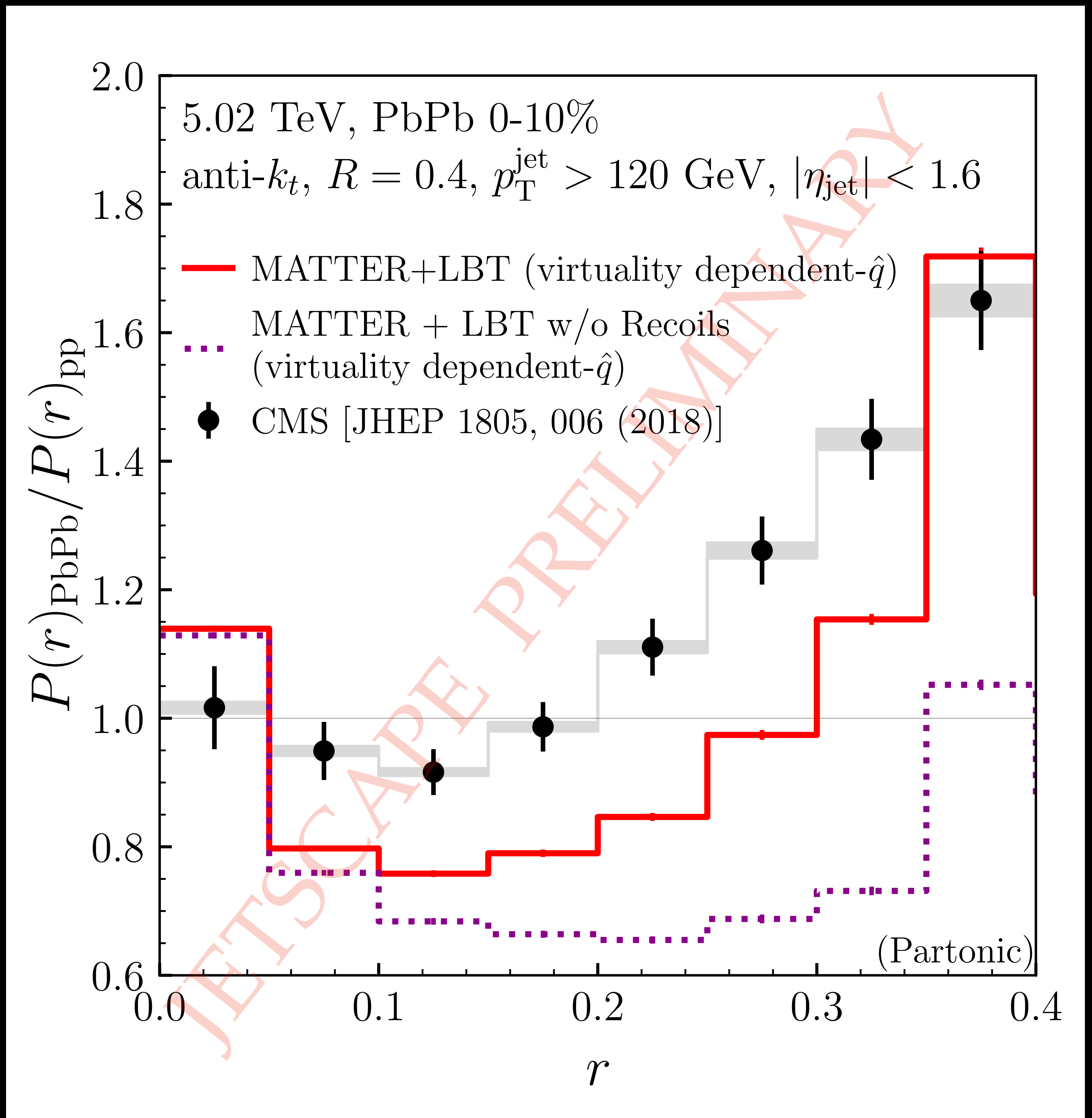


- Jet shape function:
- This depends more on soft non-perturbative modes, especially at larger angles
- Requires 2-stage hydro simulations (hydro+jet+hydro) for response outside jet.

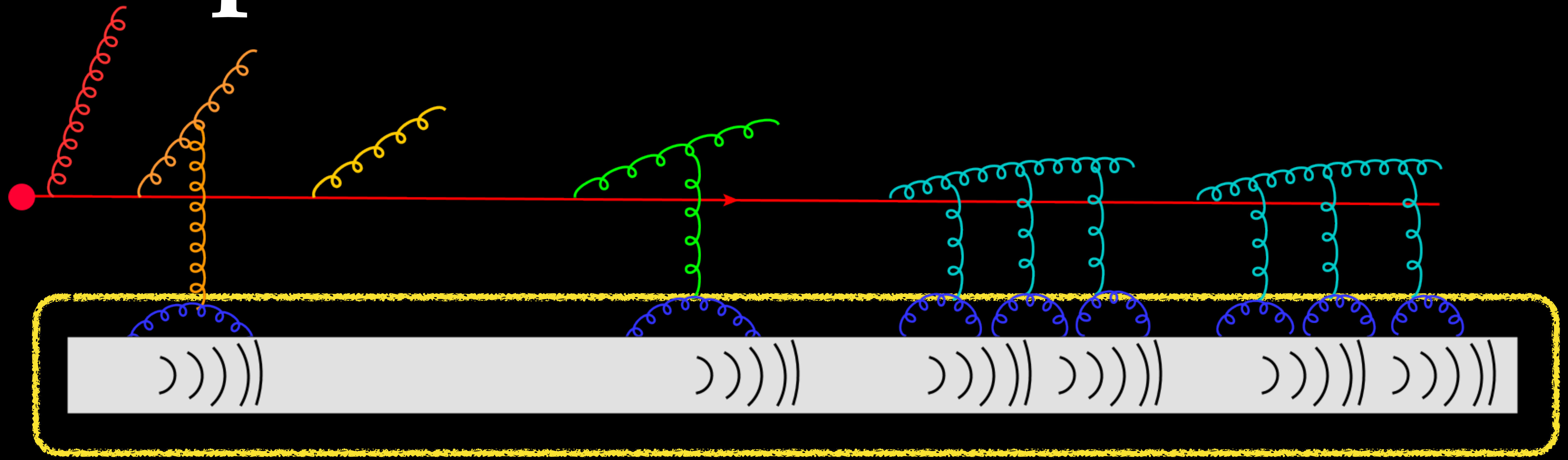
$$P(r) = \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jet}} \frac{\sum_{\mathrm{trk} \in (r \pm \delta r/2)} p_{\mathrm{T}}^{\mathrm{trk}}}{\delta r}$$



Y. Tachibana et al., *to appear*



Jet Shape: more dependence on soft modes



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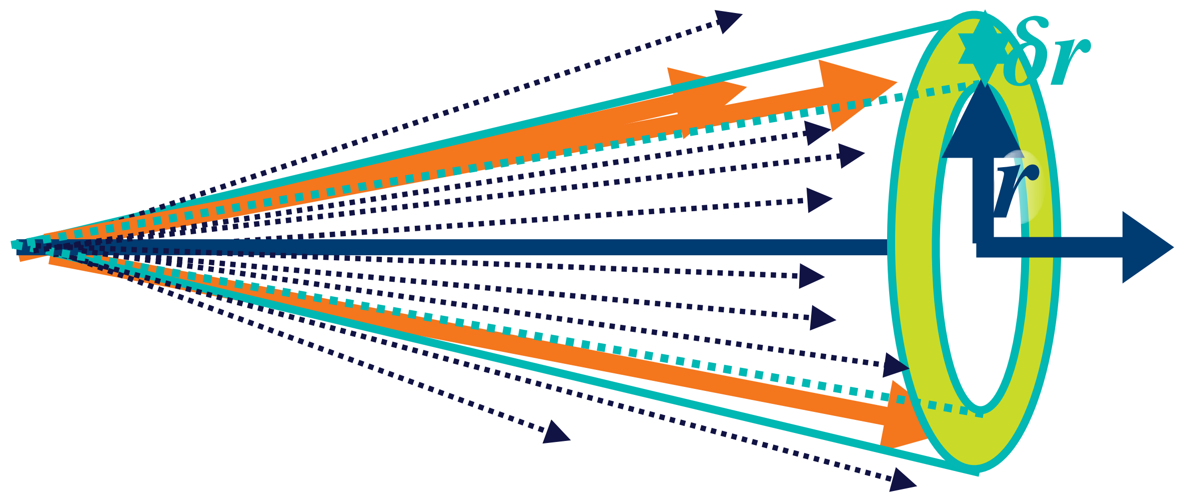
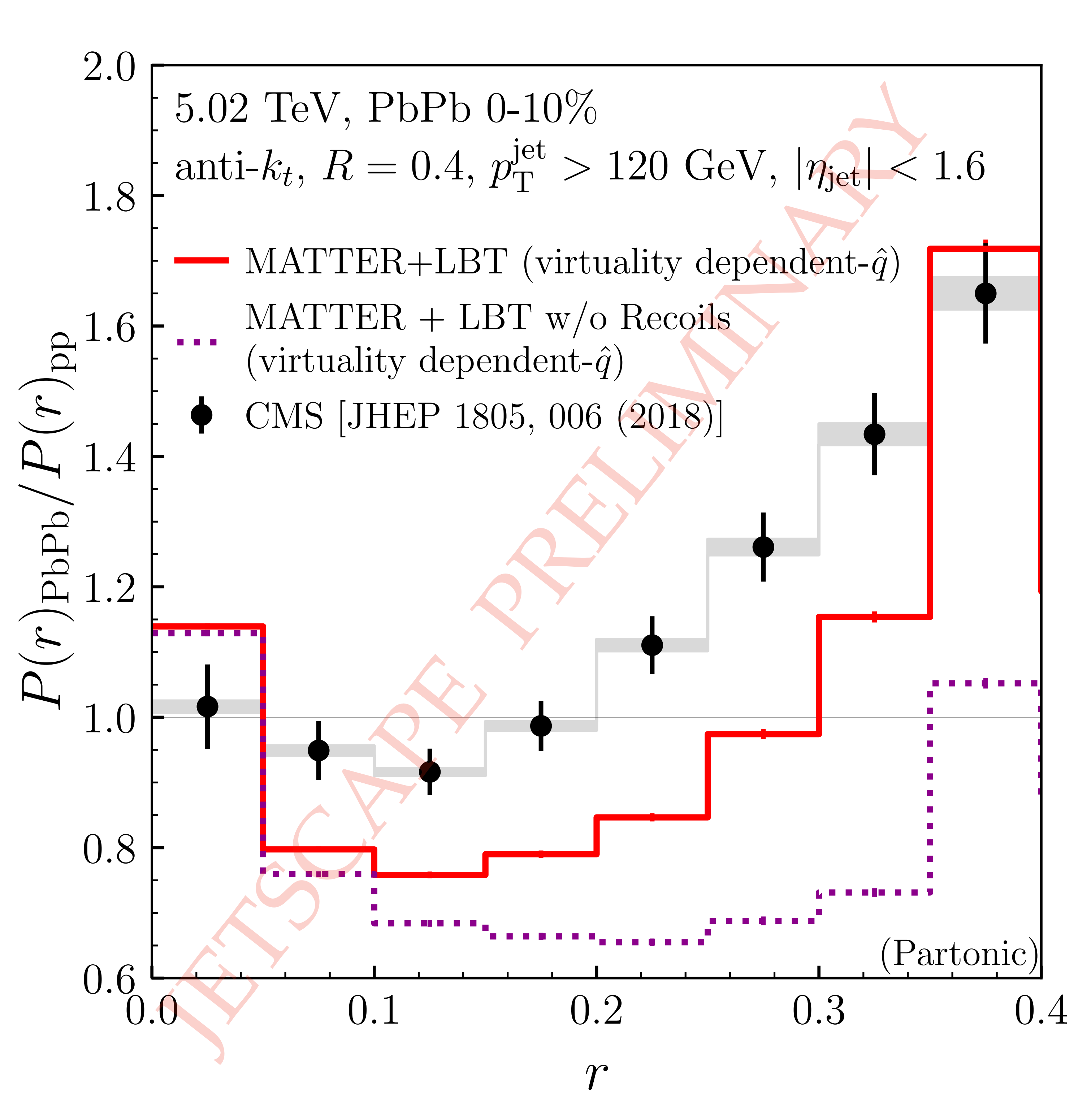




Y. Tachibana et al., *to appear*

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

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

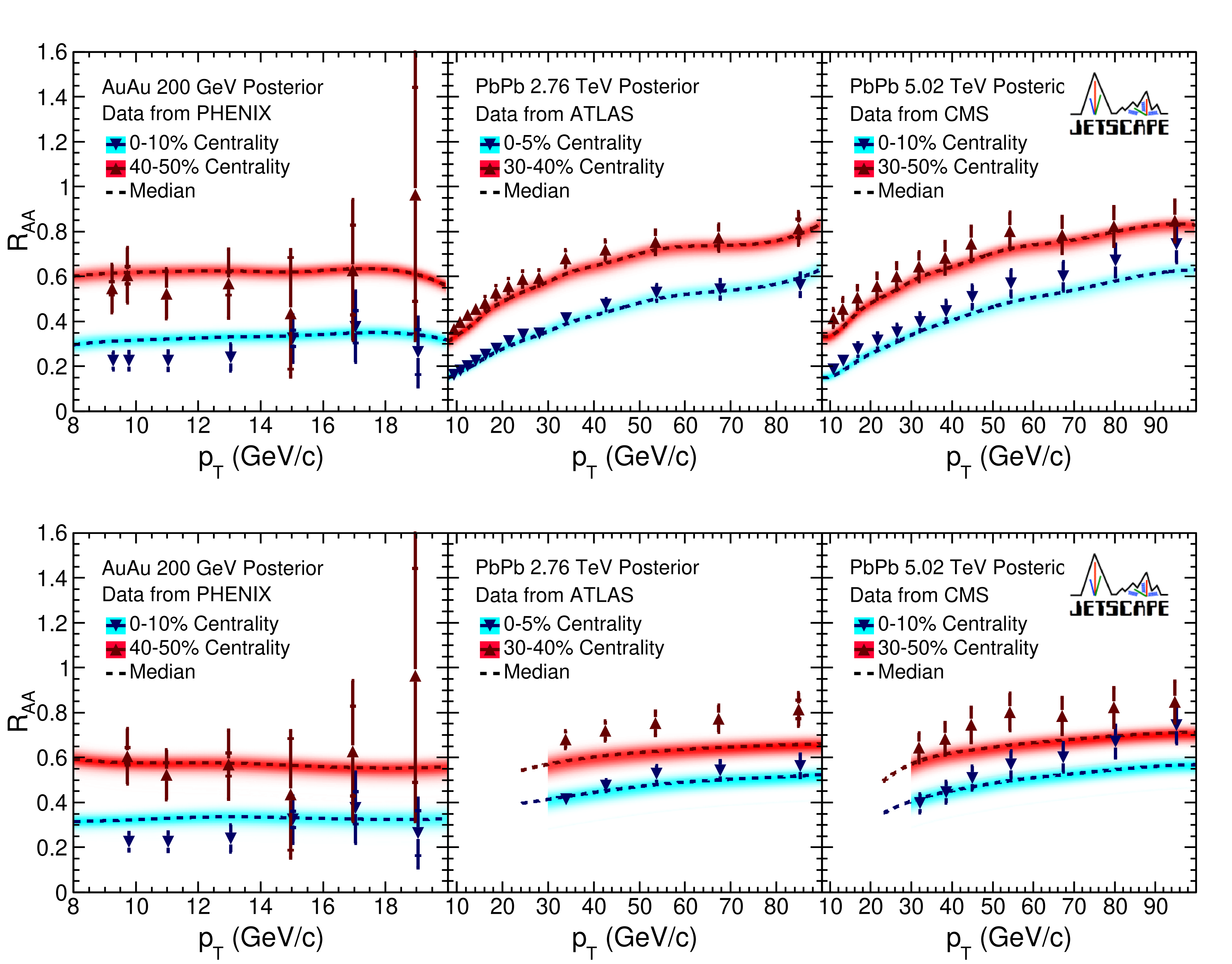
- We parametrize with

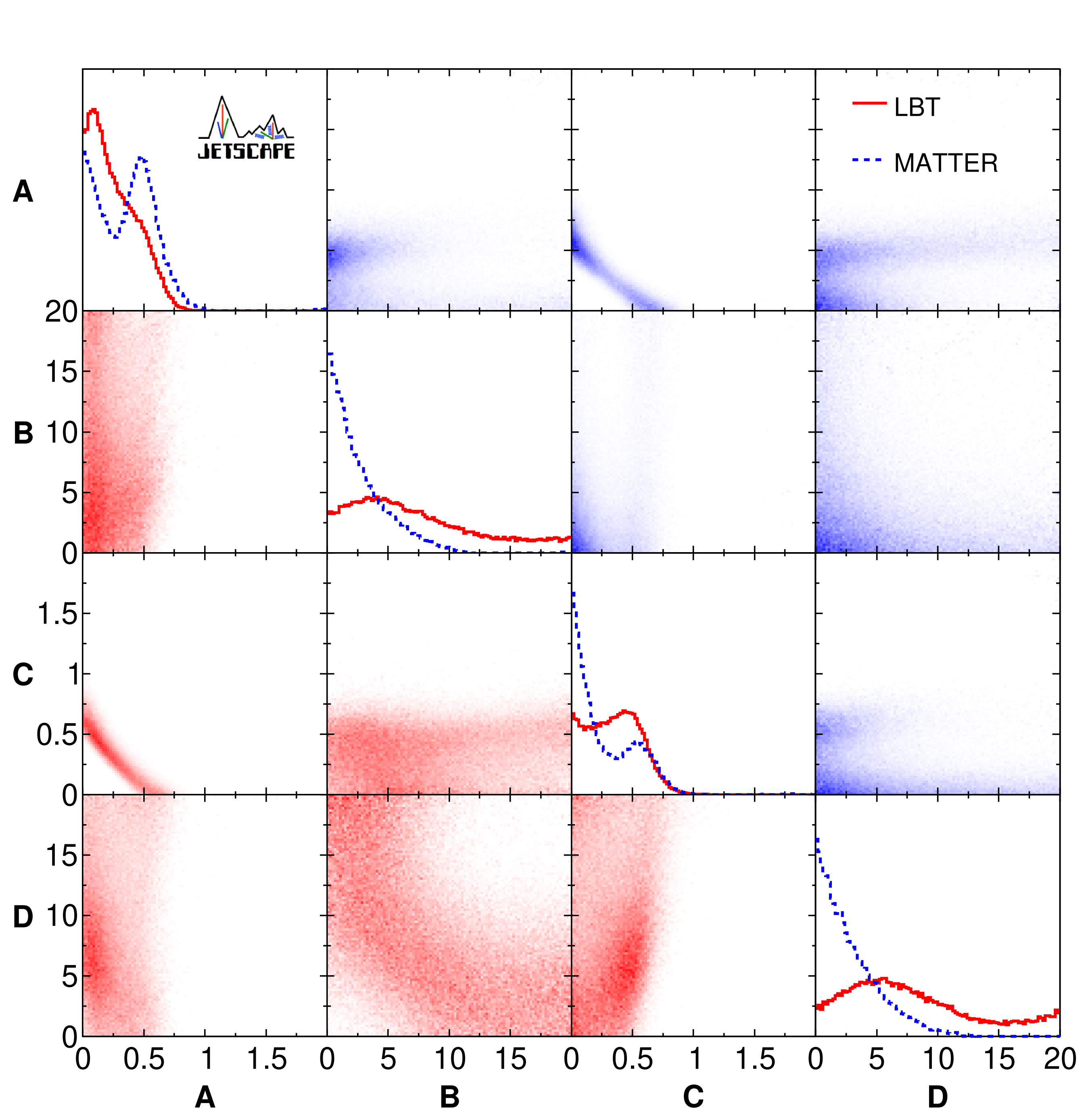
$$\frac{\hat{q}\,(E,T)\,|_{A,B,C,D}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2 \left\{ \frac{A\left[\ln\left(\frac{E}{\Lambda}\right) - \ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2} + \frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2}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

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





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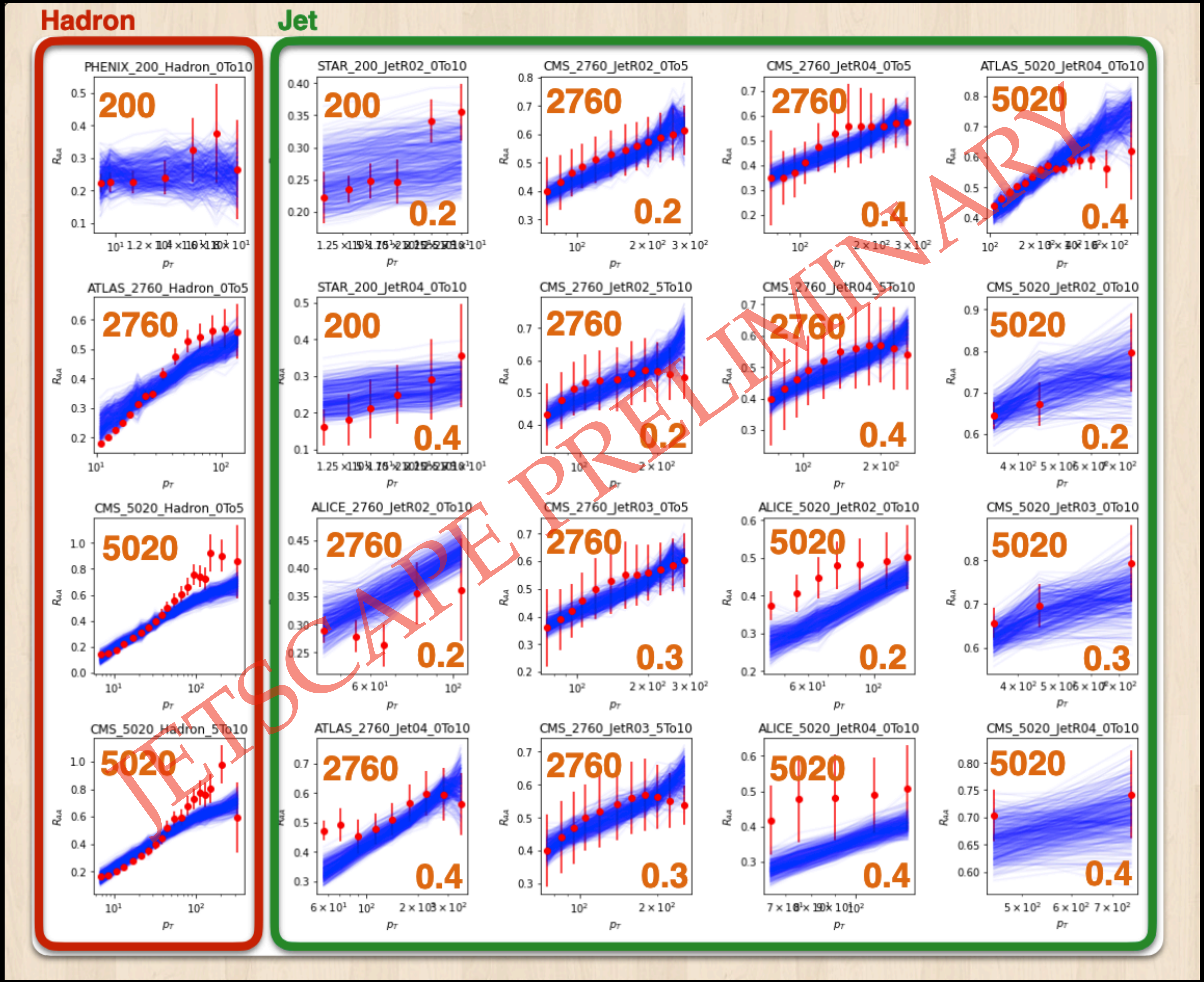
Preliminary Bayesian analysis with JETSCAPE 3.4



Posterior distributions from STAT WG in JETSCAPE

Remarkable improvement from JETSCAPE 0.x

Coherence + Qswitch as described before

Calculations do not contain nuclear shadowing

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 $\mu > Q_0$

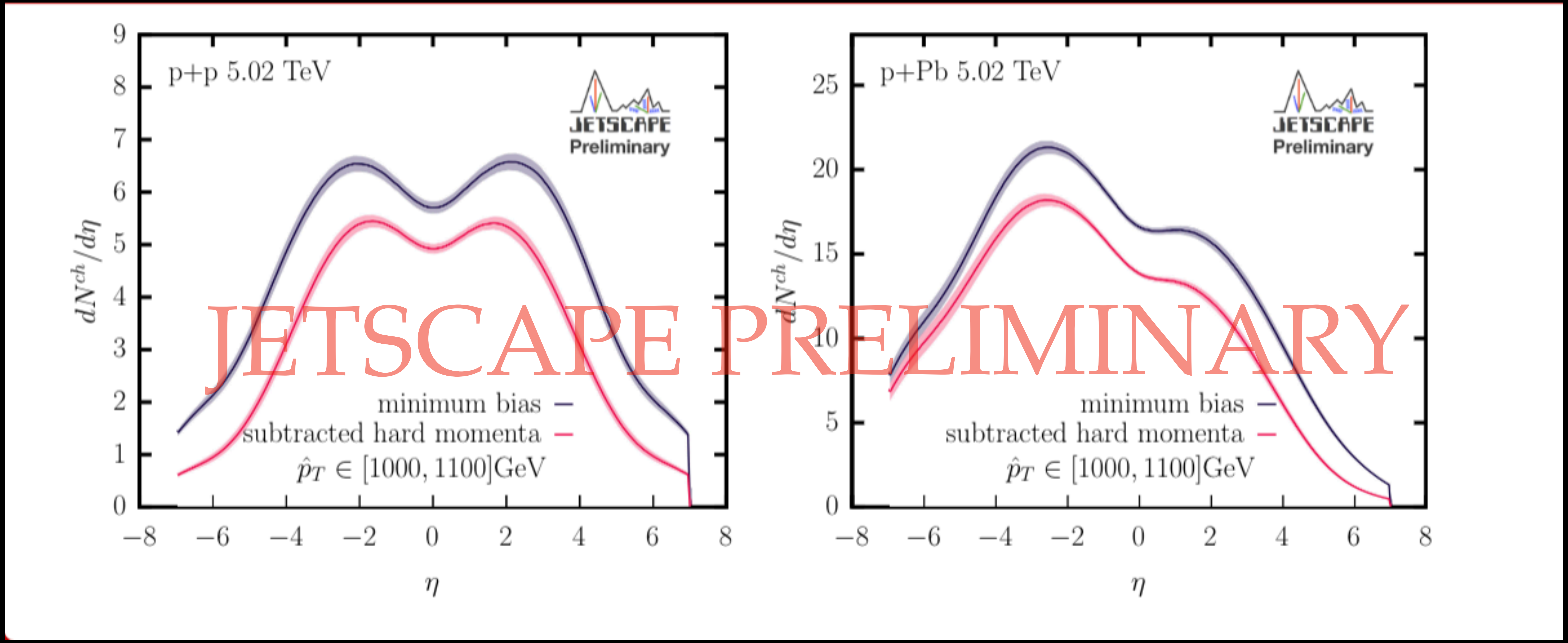
- A portion of the quenching will always be non-perturbative and subject to modeling!

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

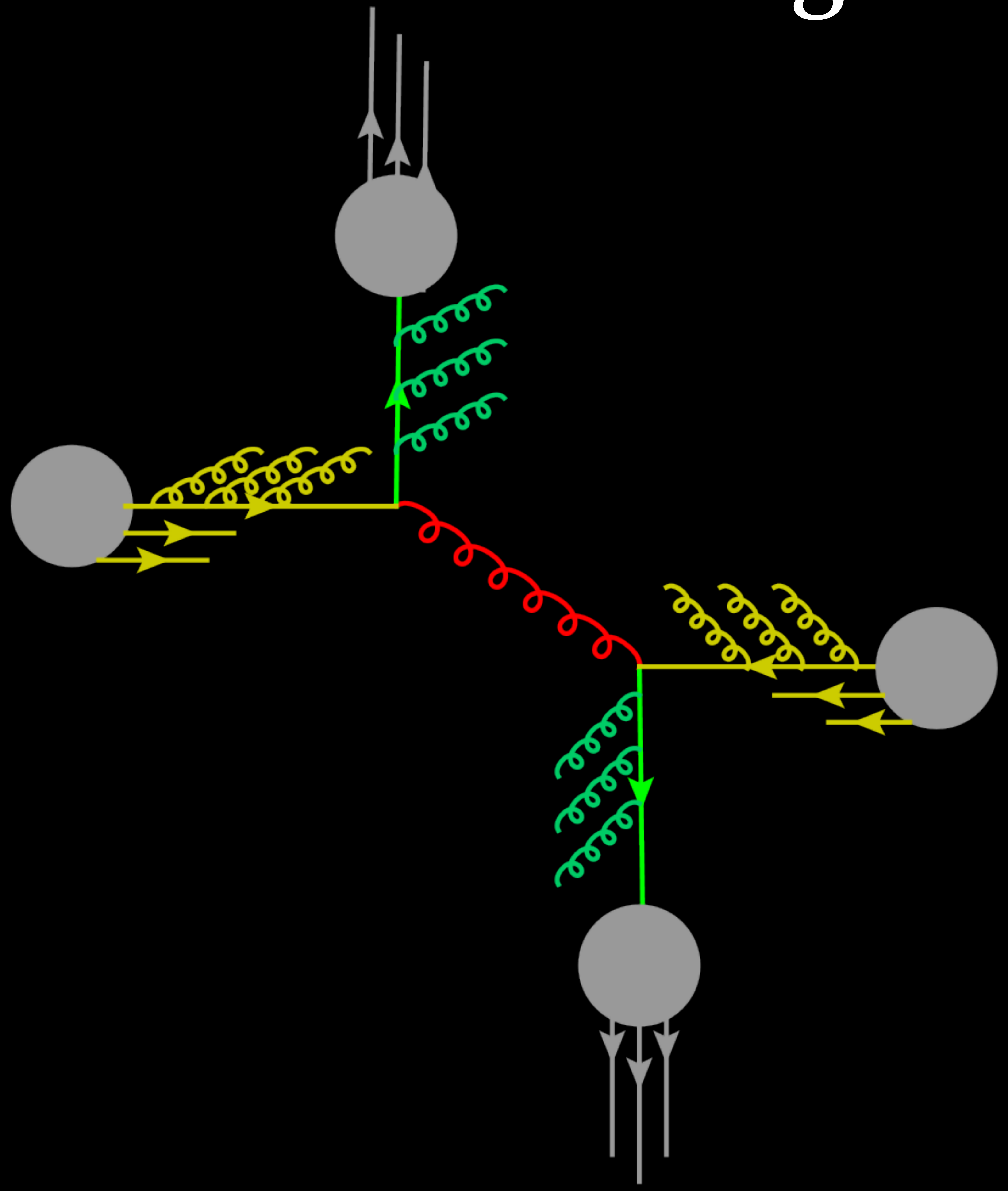
- JETSCAPE is moving towards p-A, low energy A-A and e-A
- See talk by I. Soudi (Sat. 3:50pm)



Thanks to my collaborators

THANK YOU FOR YOUR ATTENTION

Multi-stage is based on factorization



- Processes at hard scales do not interfere with processes at softer scales
- PYTHIA (parton shower + hadronization), a multi-stage process
- In vacuum the only scale is Λ_{QCD}
- In FS/IS there are two stages
- Factorize hard scattering from ISR/FSR using the $\hat{p}_T$ scale.

Other dependencies

- Corrections due to radiation (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 $\hat{q}(T, E, \mu)$

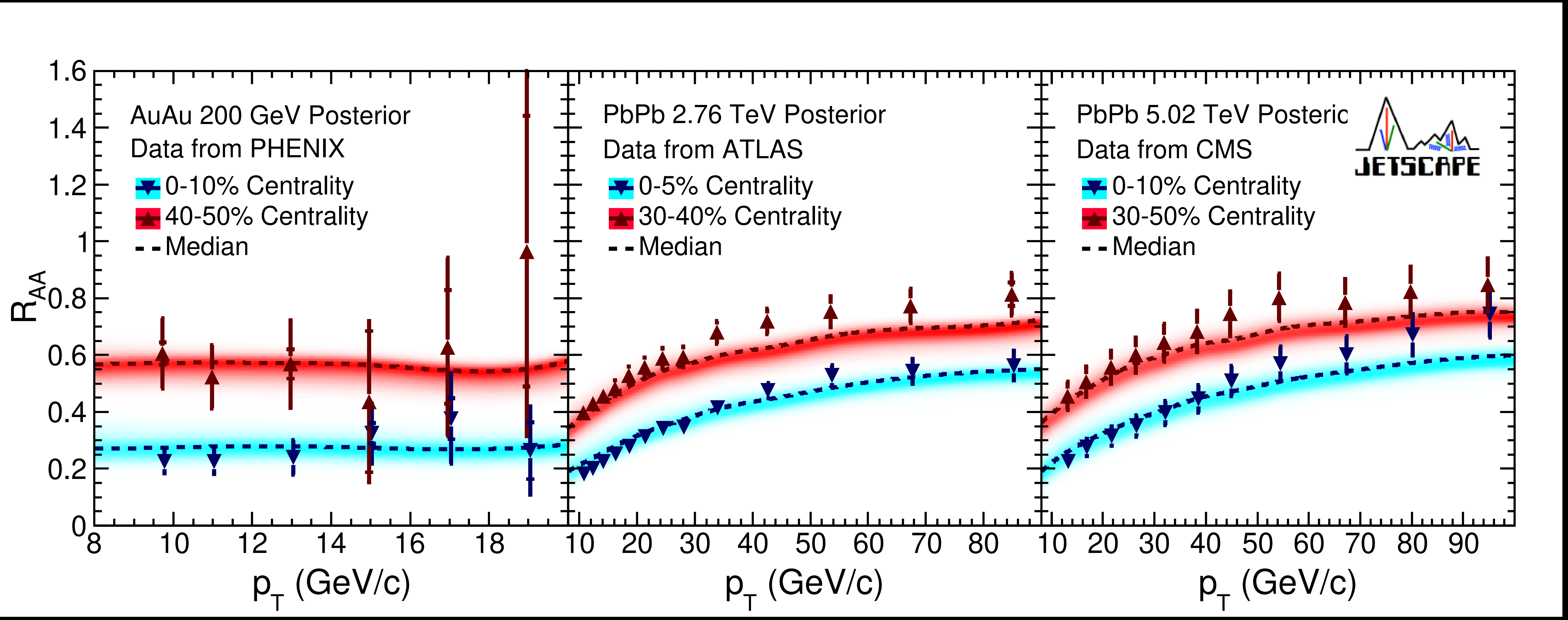
- No real improvement in using the models together, and forcing them to use an additive $\hat{q}$ formula

- Tried a formula with virtuality directly (where $\hat{q}$ increases with Q):

$$\frac{\hat{q}\left(Q,E,T\right)|_{Q_0,A,C,D}}{T^3} = 42C_R\frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2\left\{\frac{A\left[\ln\left(\frac{Q}{\Lambda}\right)-\ln\left(\frac{Q_0}{\Lambda}\right)\right]}{\left[\ln\left(\frac{Q}{\Lambda}\right)\right]^2}\theta(Q-Q_0)+\frac{C\left[\ln\left(\frac{E}{T}\right)-\ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2}\right\}$$

- Need a reduction at large E or Q

- Try the multiplicative approximation



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If you would like to learn how to use JETSCAPE

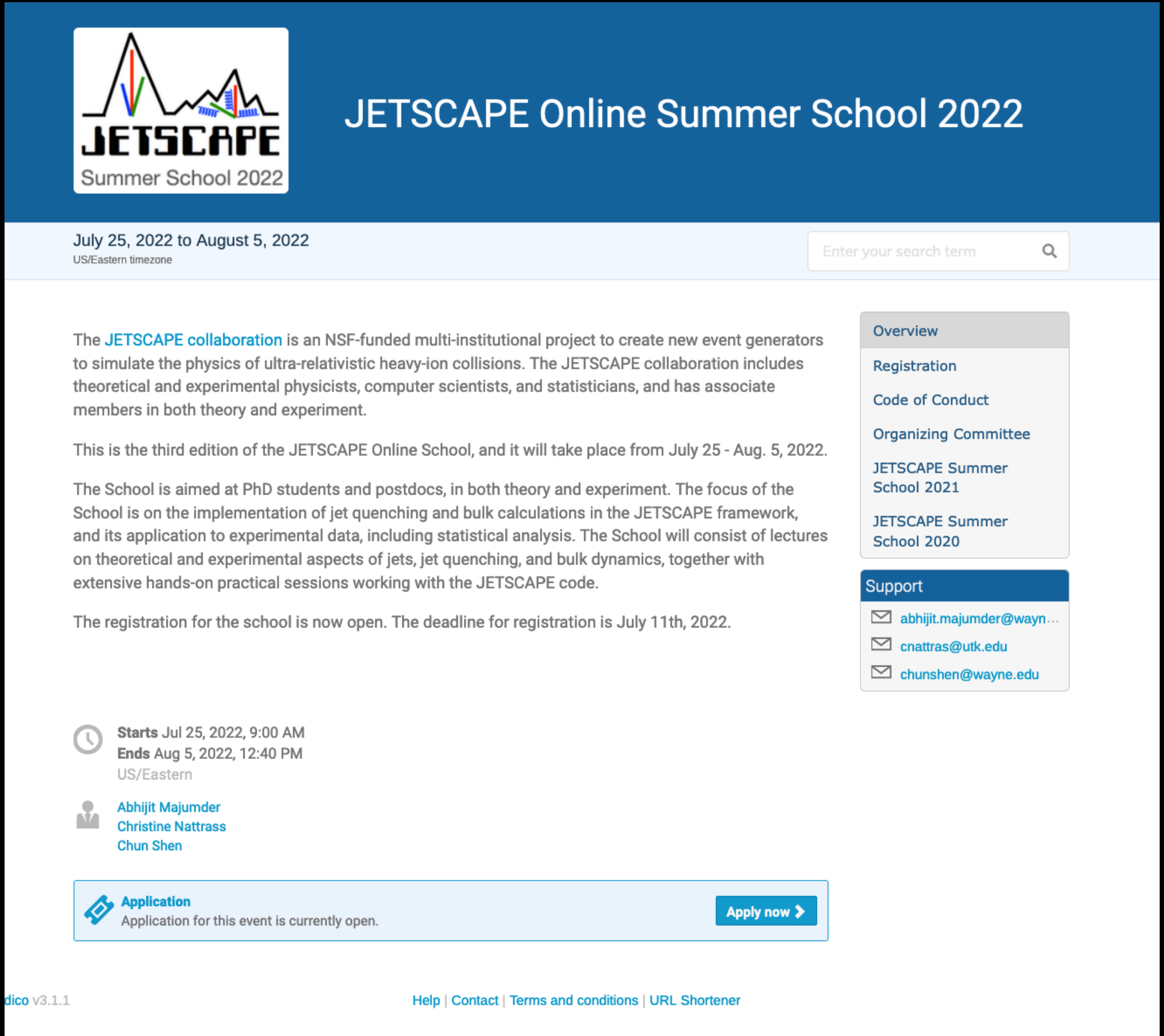
Please attend our online School July 25th to Aug 5th

https://indico.cern.ch/event/1162218/

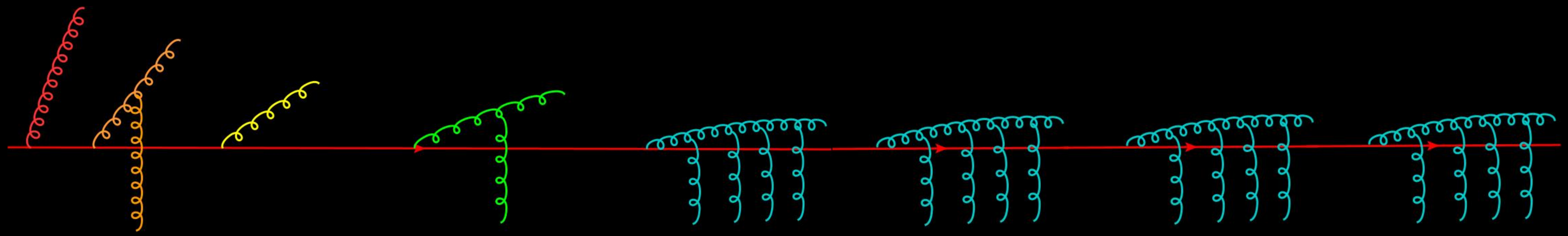
3 hours a day for 2 weeks

Grad student, postdoc, faculty, even senior faculty!

The next generation of JETSCAPE will do pA and BES, and eA physics



Jet radiation structure: when does it transition?



- Estimate from formation time arguments: $\tau = \dfrac{2E}{Q^2} \implies Q^2(t) = \dfrac{2E}{t}$

  (Modulo energy loss effects from emitting gluons).

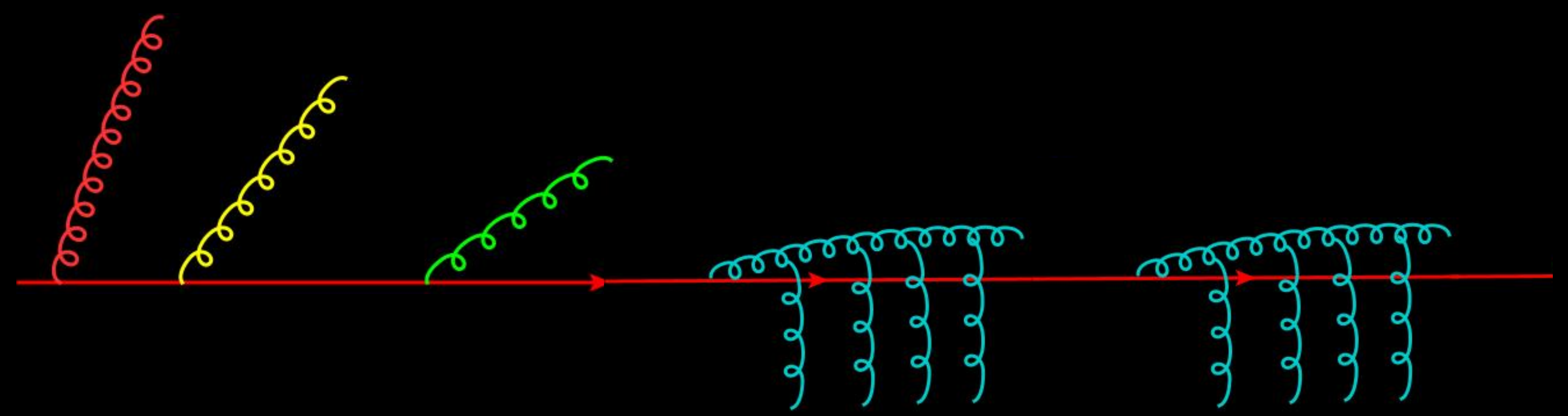
- The maximum virtuality built up from scattering

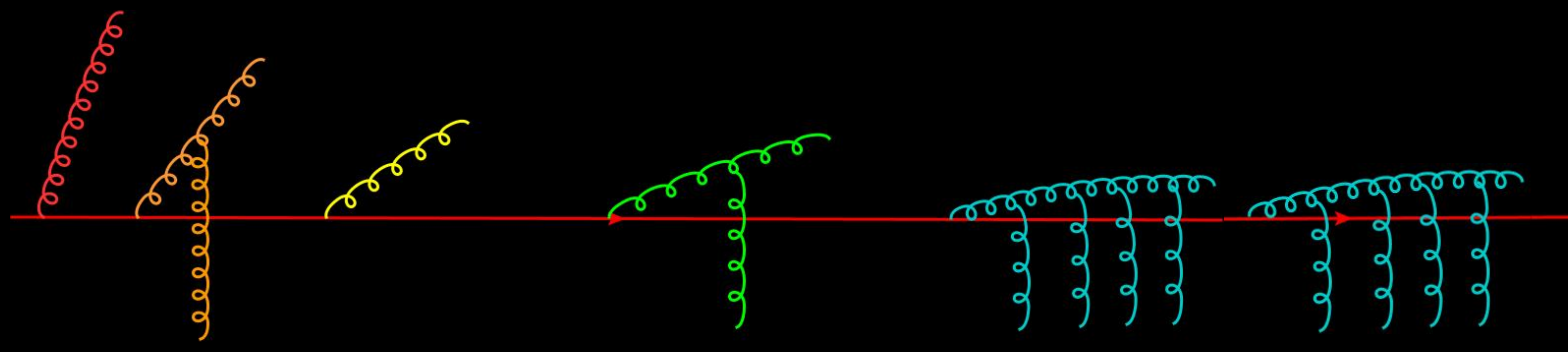
  at time t is $Q^2_{\text{med}} = \hat{q}t \simeq \dfrac{2E}{t} \implies t \simeq \sqrt{\dfrac{2E}{\hat{q}}}$

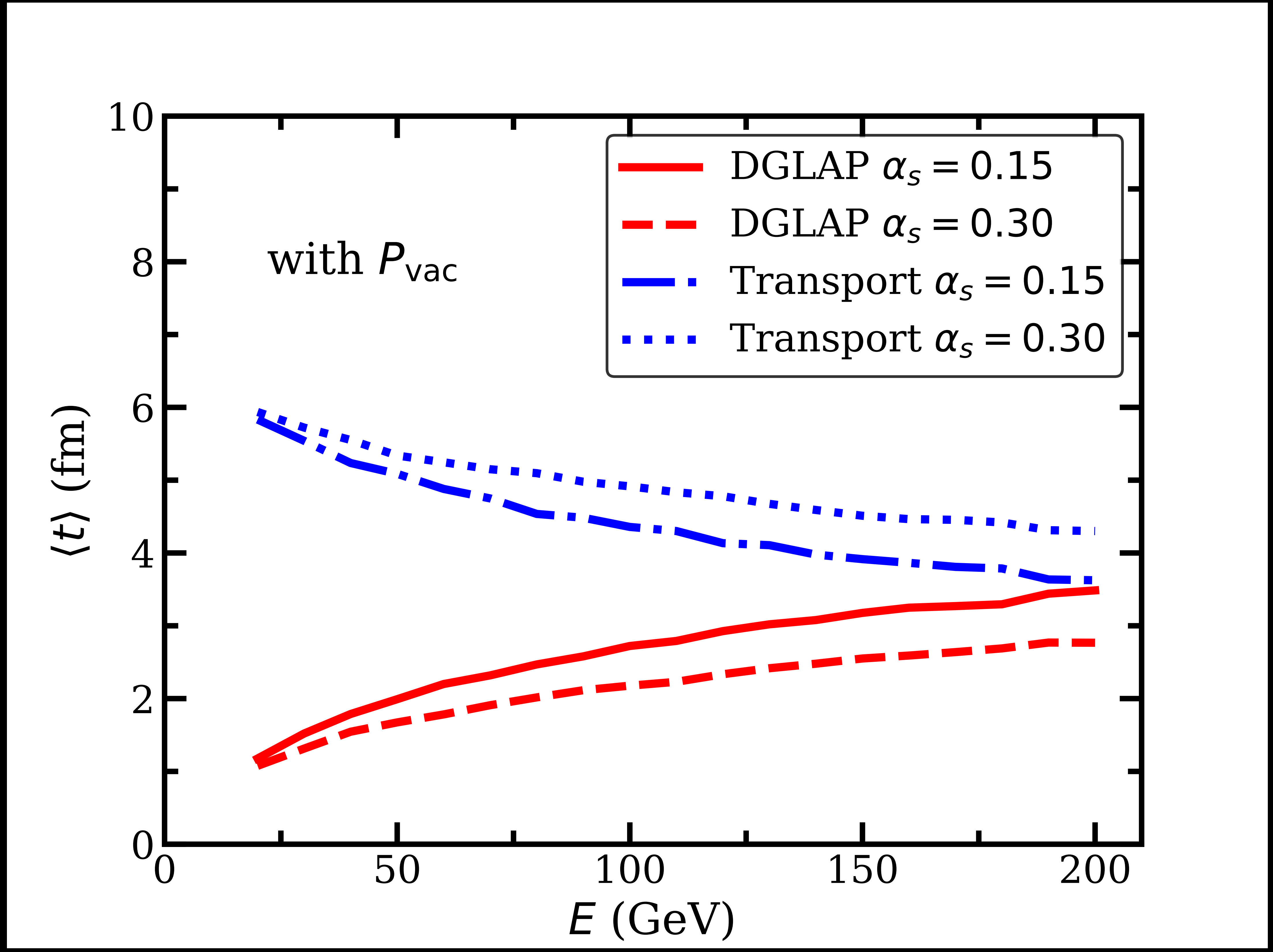
- Highest energy partons (jet core) reach the BDMPS/AMY stage last,

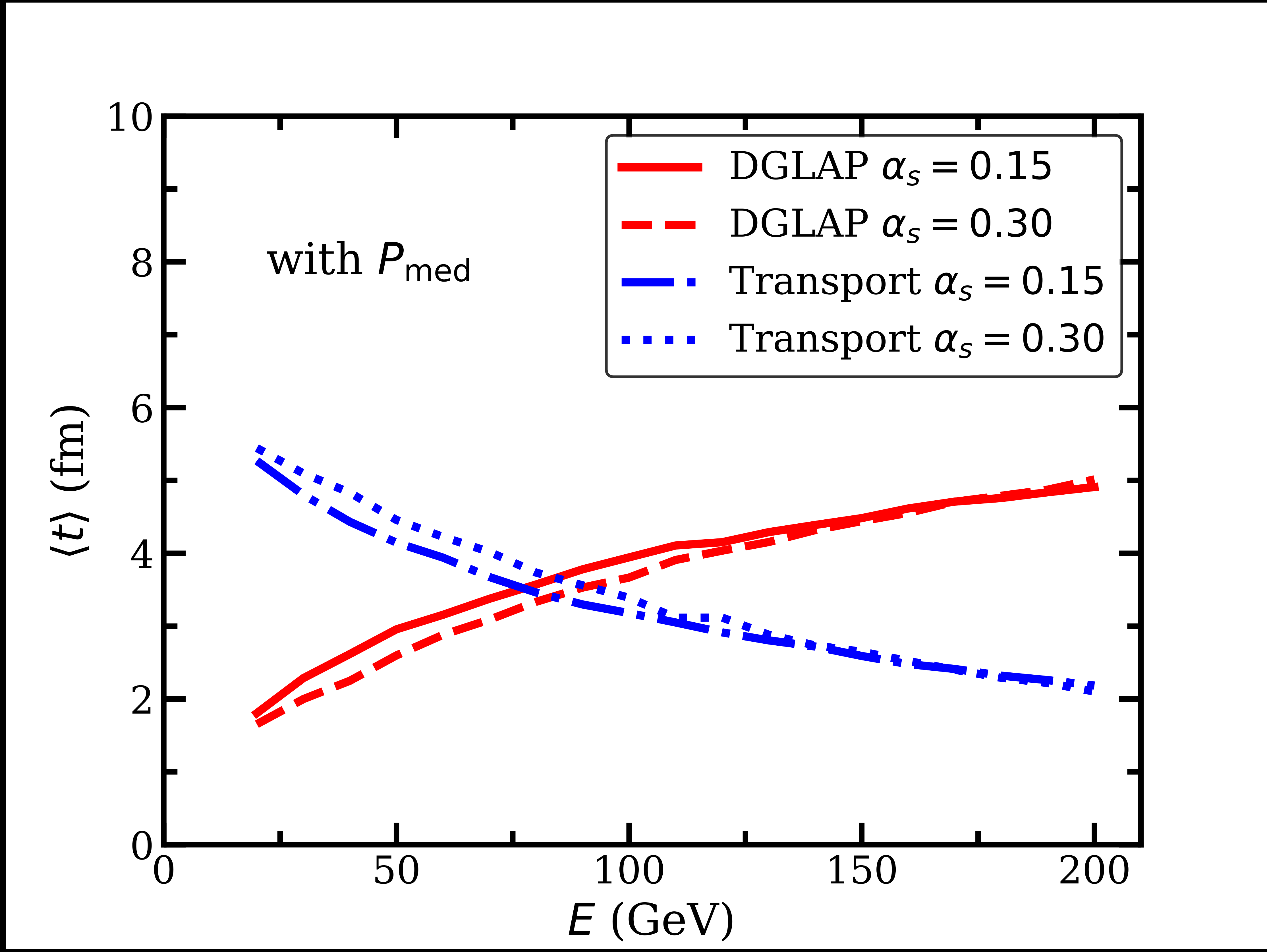
- Smaller the $\hat{q}$, longer it takes to reach the BDMPS/AMY stage: longer DGLAP stage

Time spent by leading parton and scattering in each phase





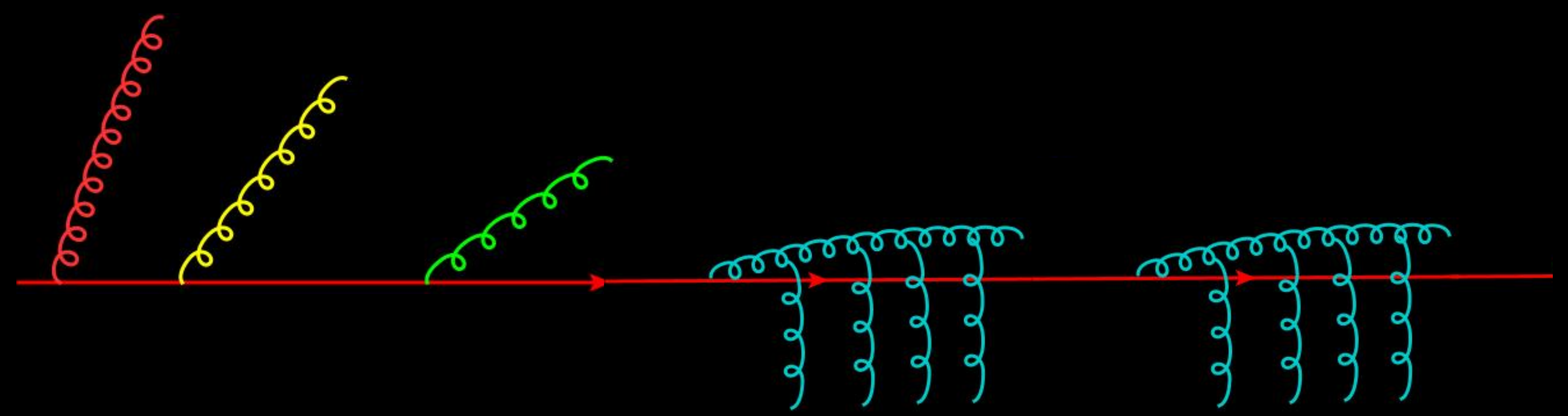


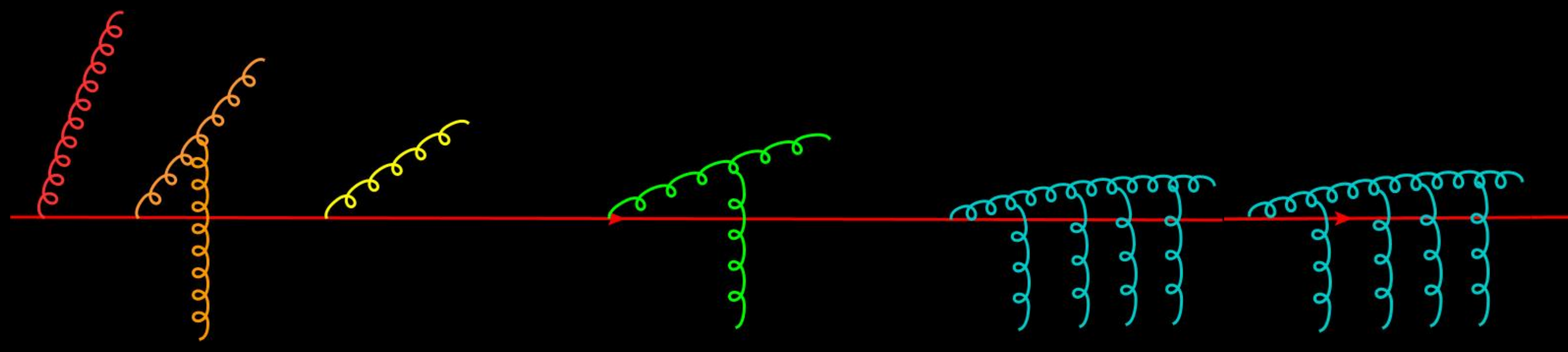


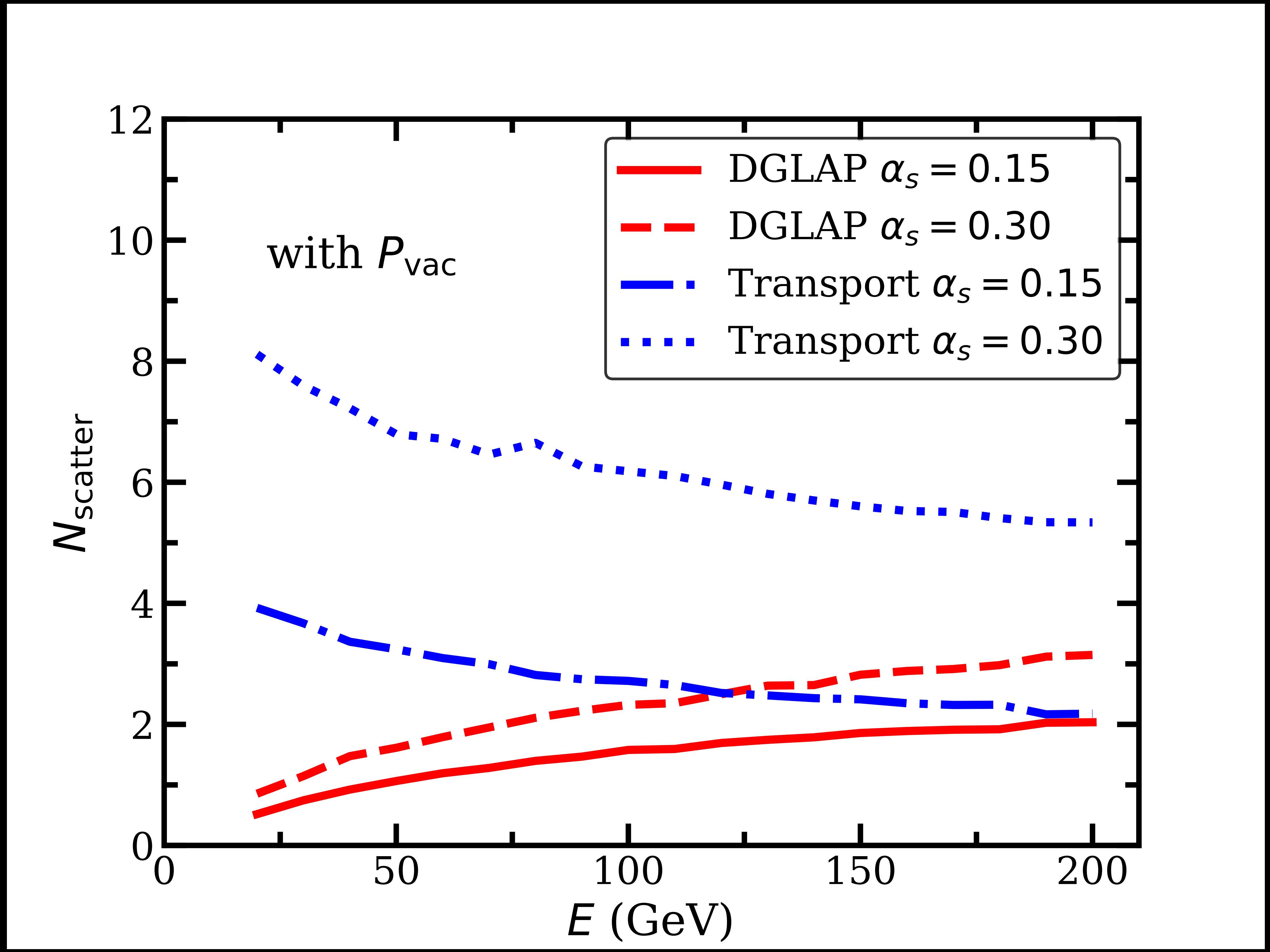
JETSCAPE 0.x

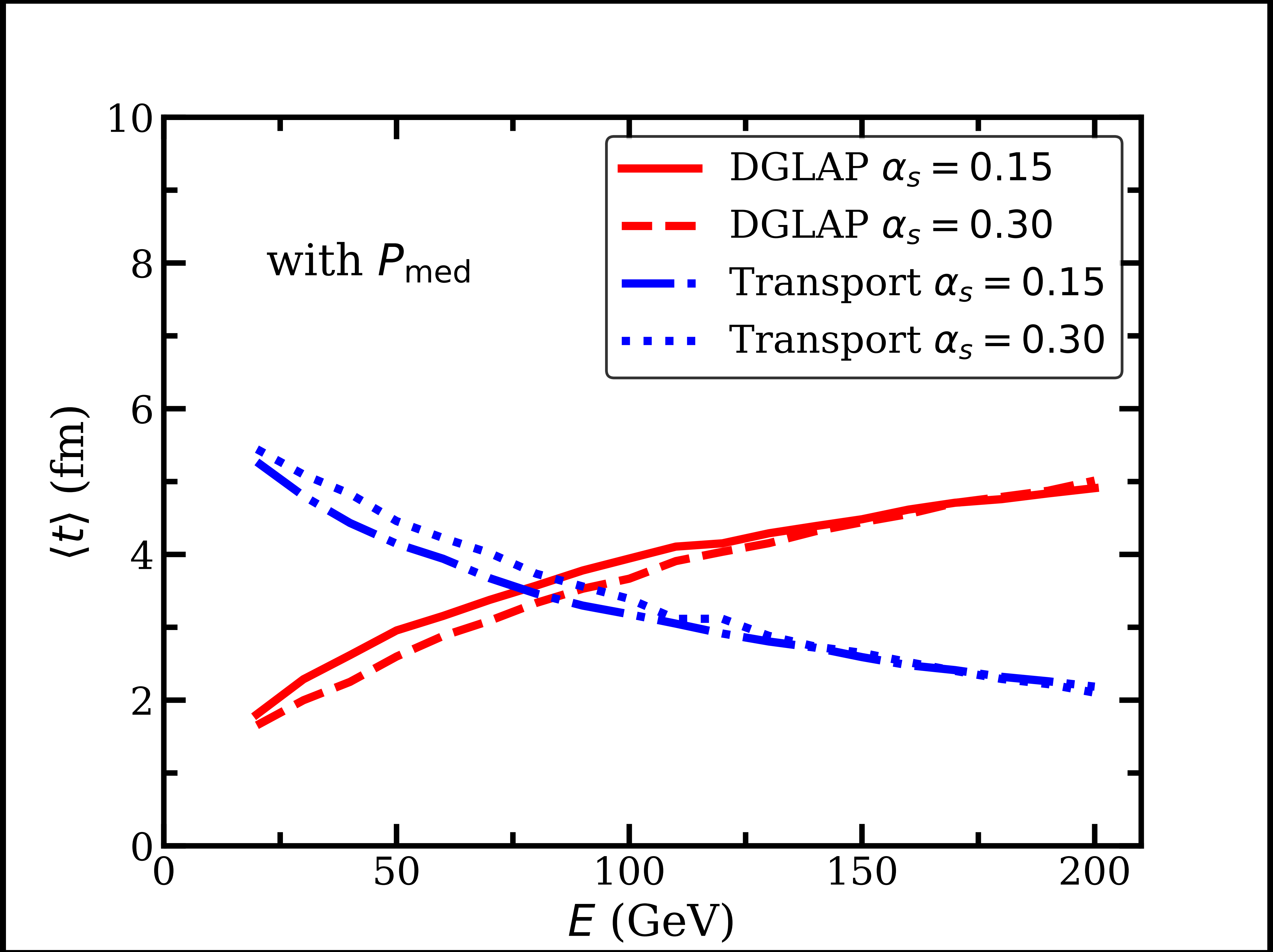
S. Cao, C. Sirimanna, A.M. 2101.03681 [hep-ph]

Time spent by leading parton and scattering in each phase









JETSCAPE 0.x

S. Cao, C. Sirimanna, A.M. 2101.03681 [hep-ph]

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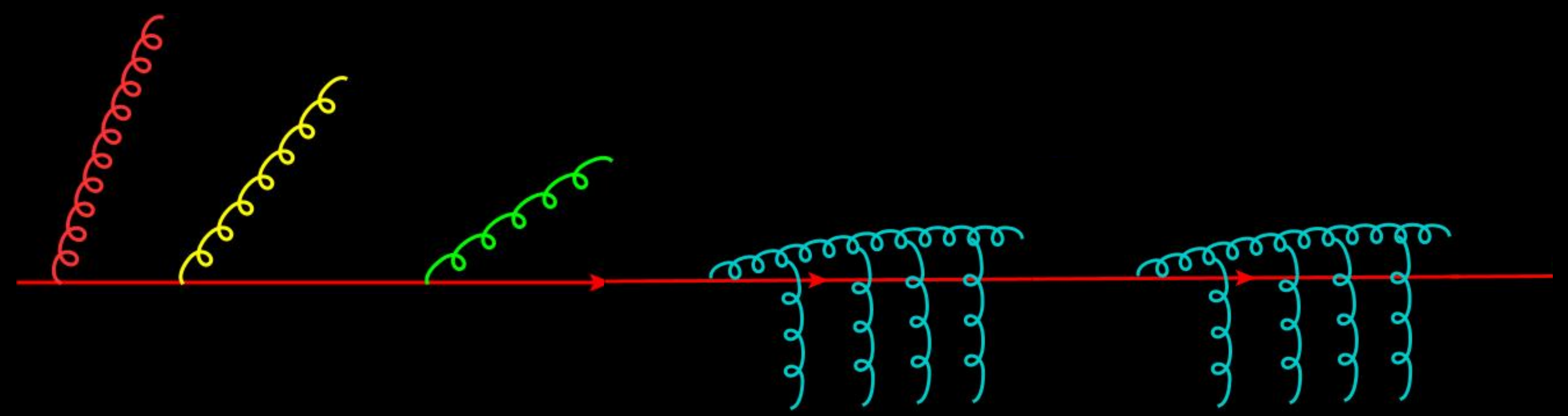
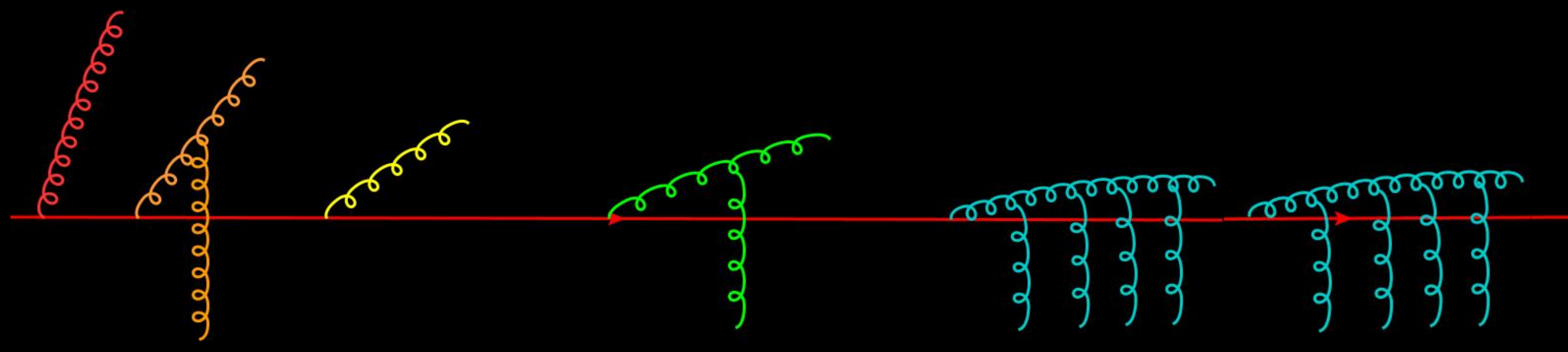
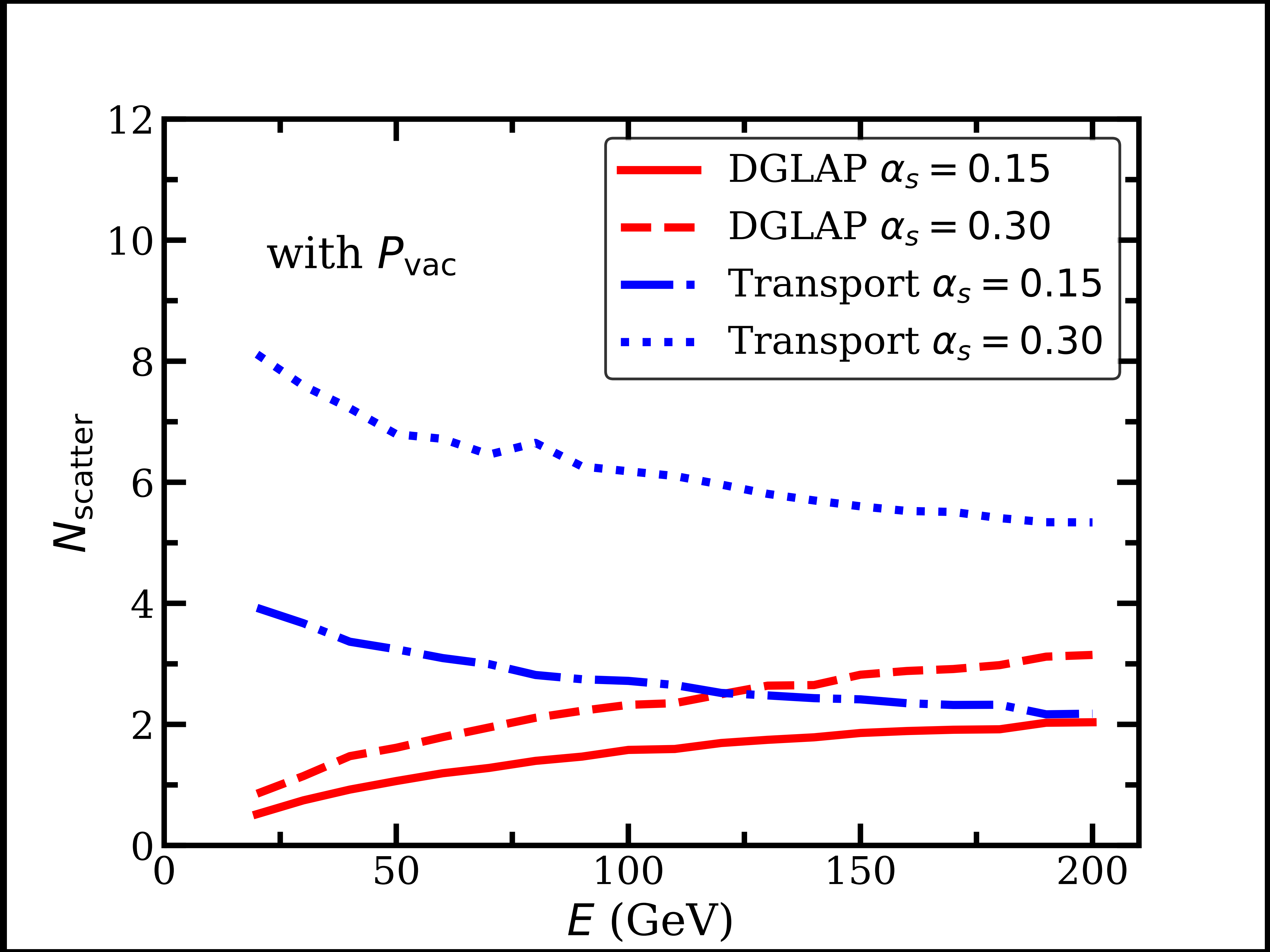
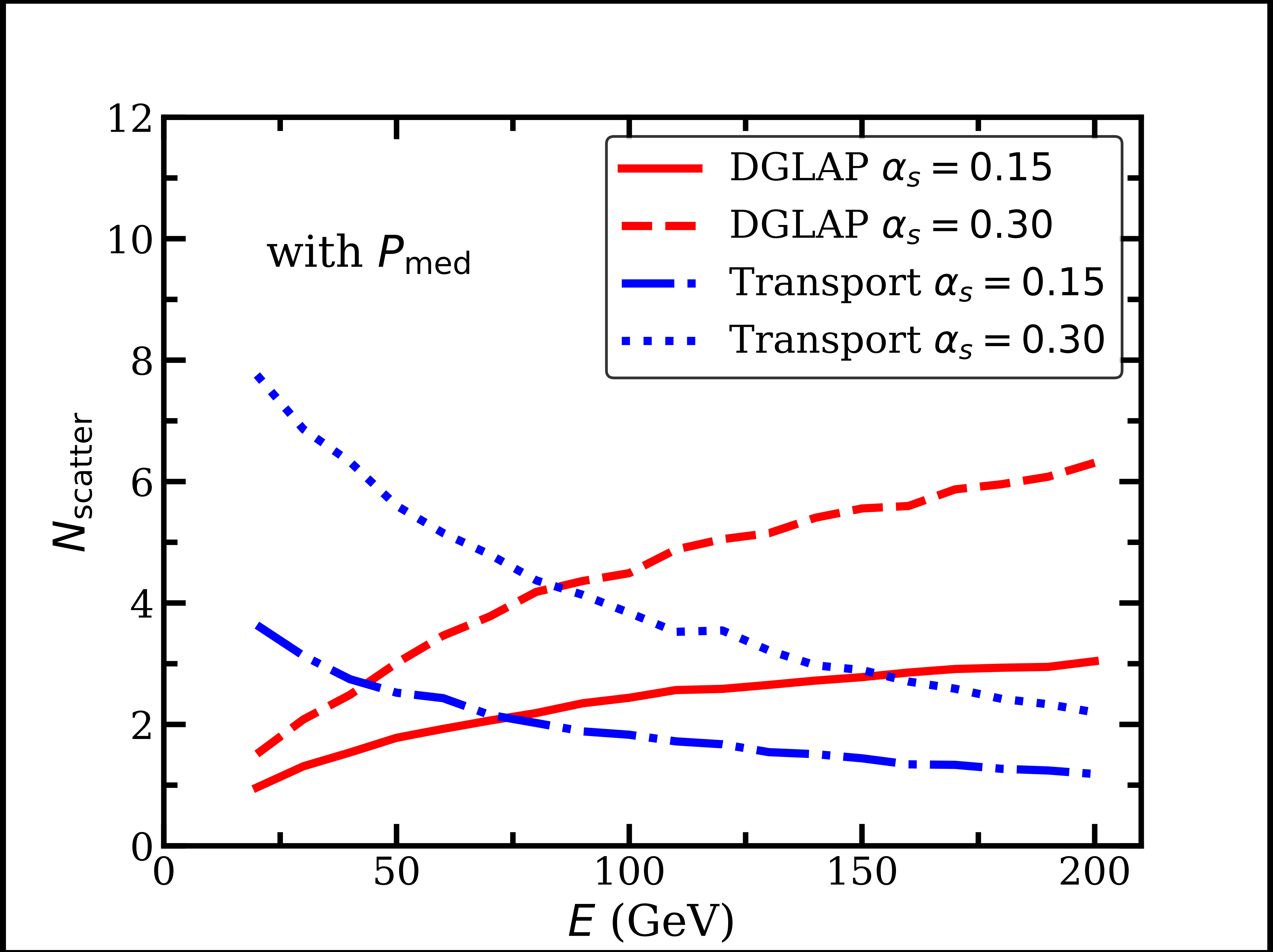






JETSCAPE 0.x



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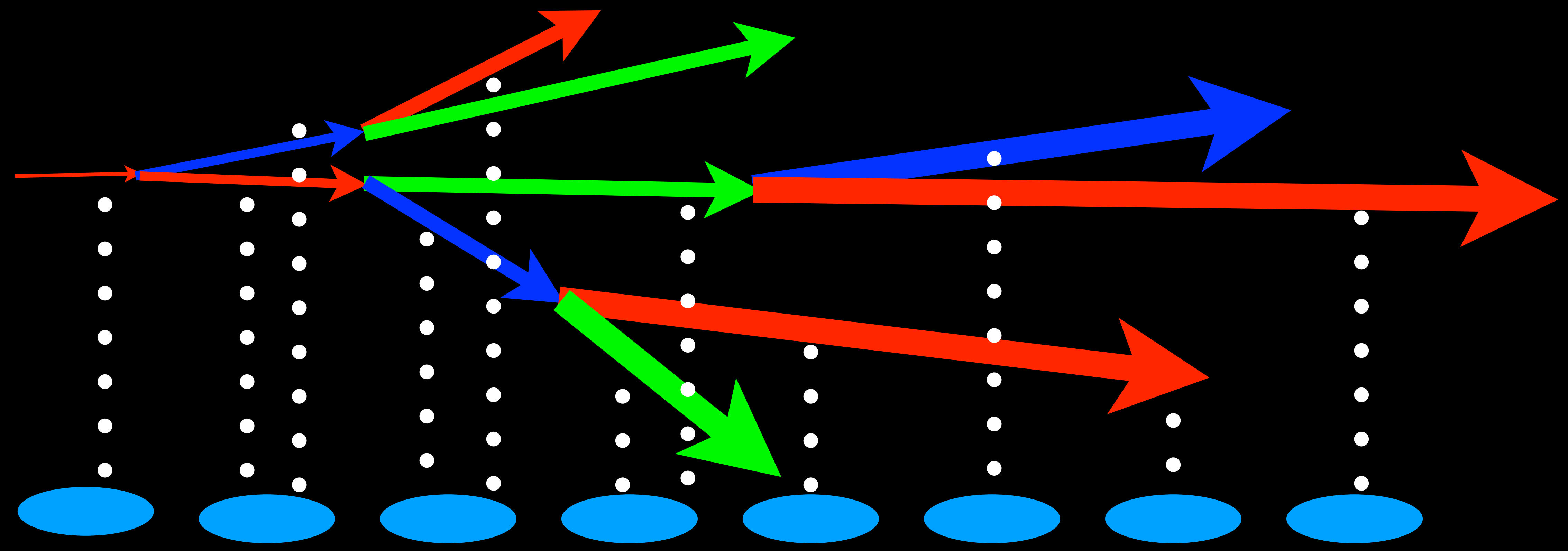
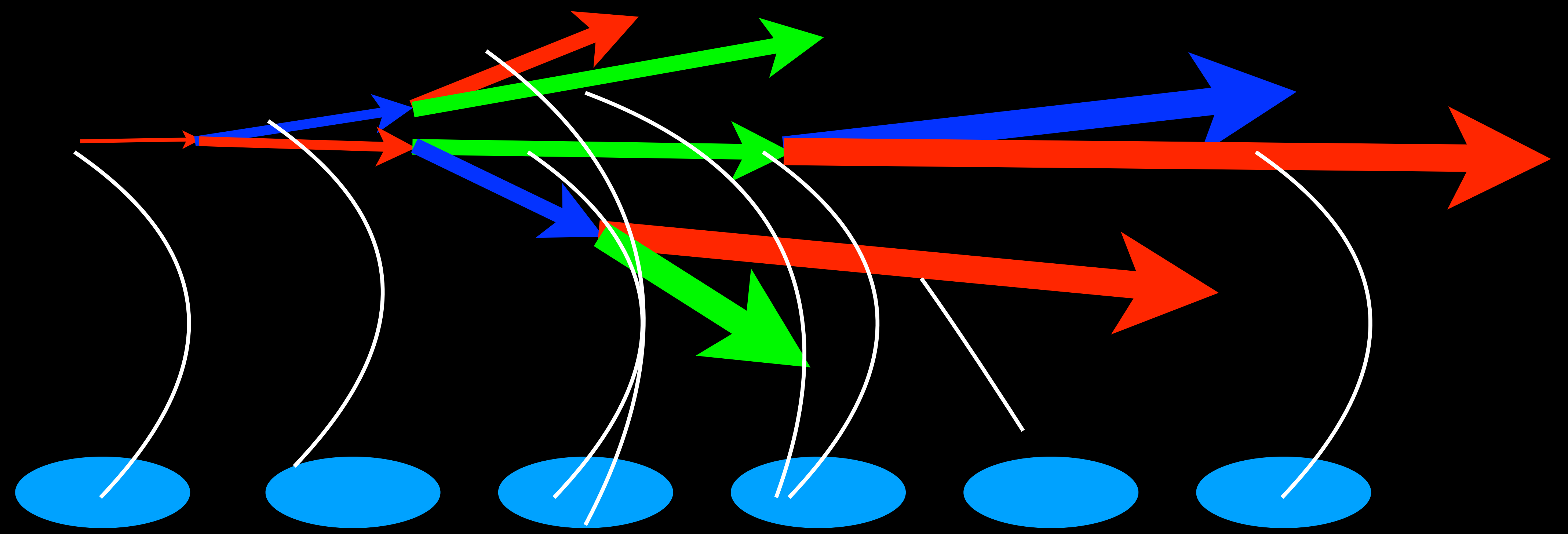
Other methods

Constant Broadening: LIDO, Tequila, MATTER



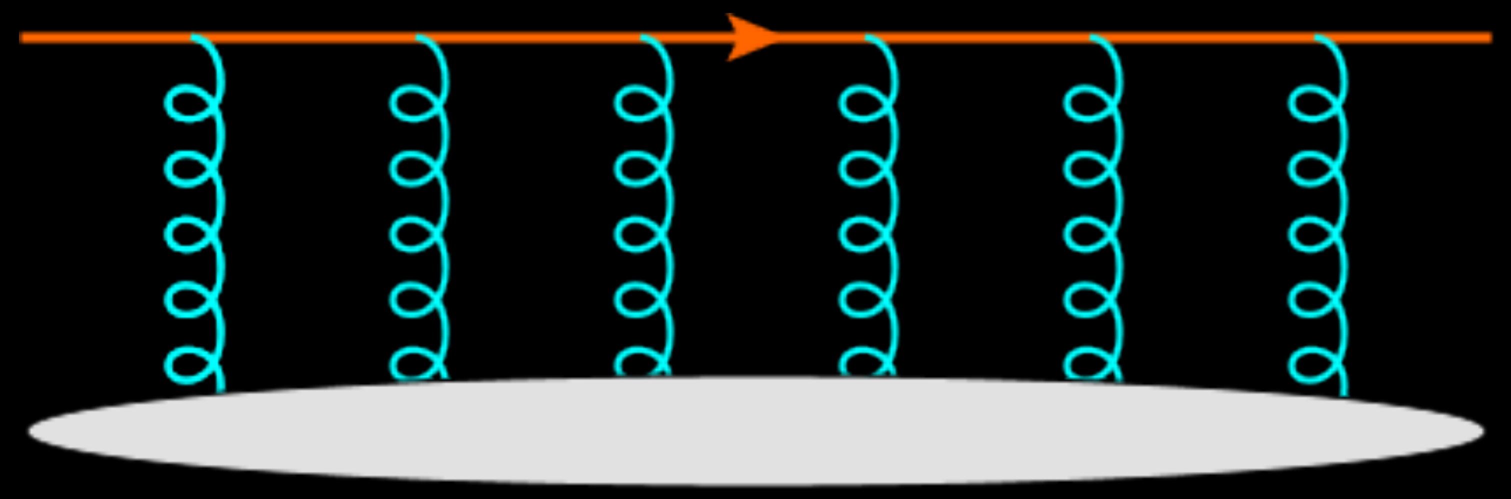
AdS/CFT drag: Hybrid

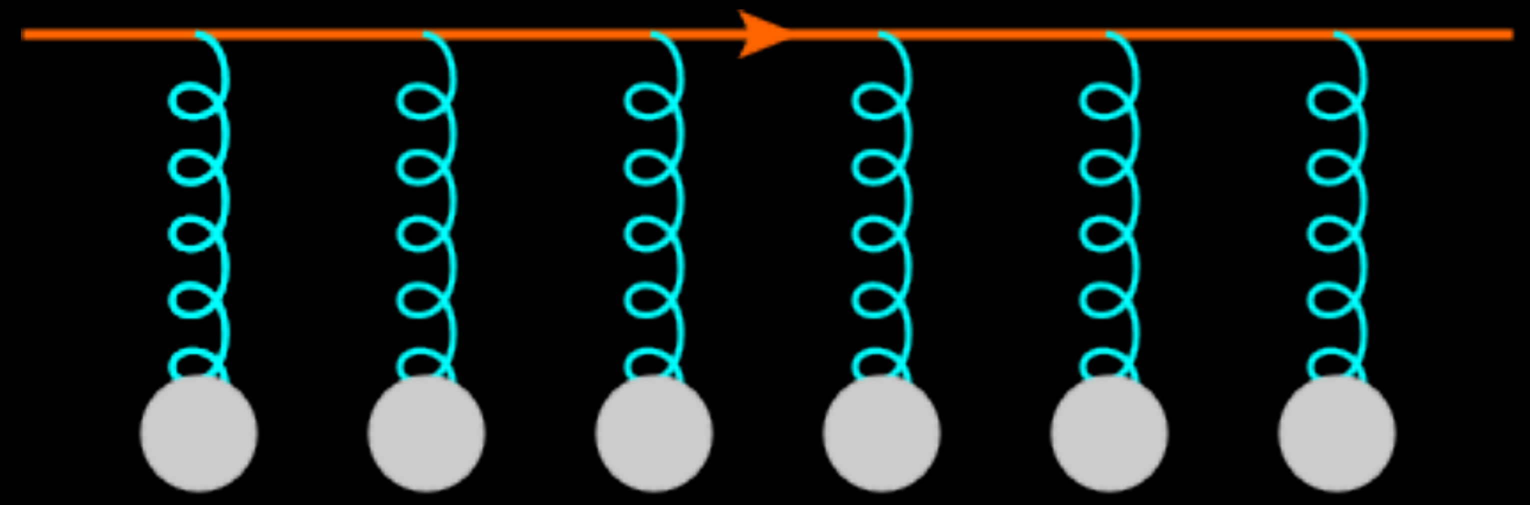


All of these depend on the underlying medium

Independent scattering

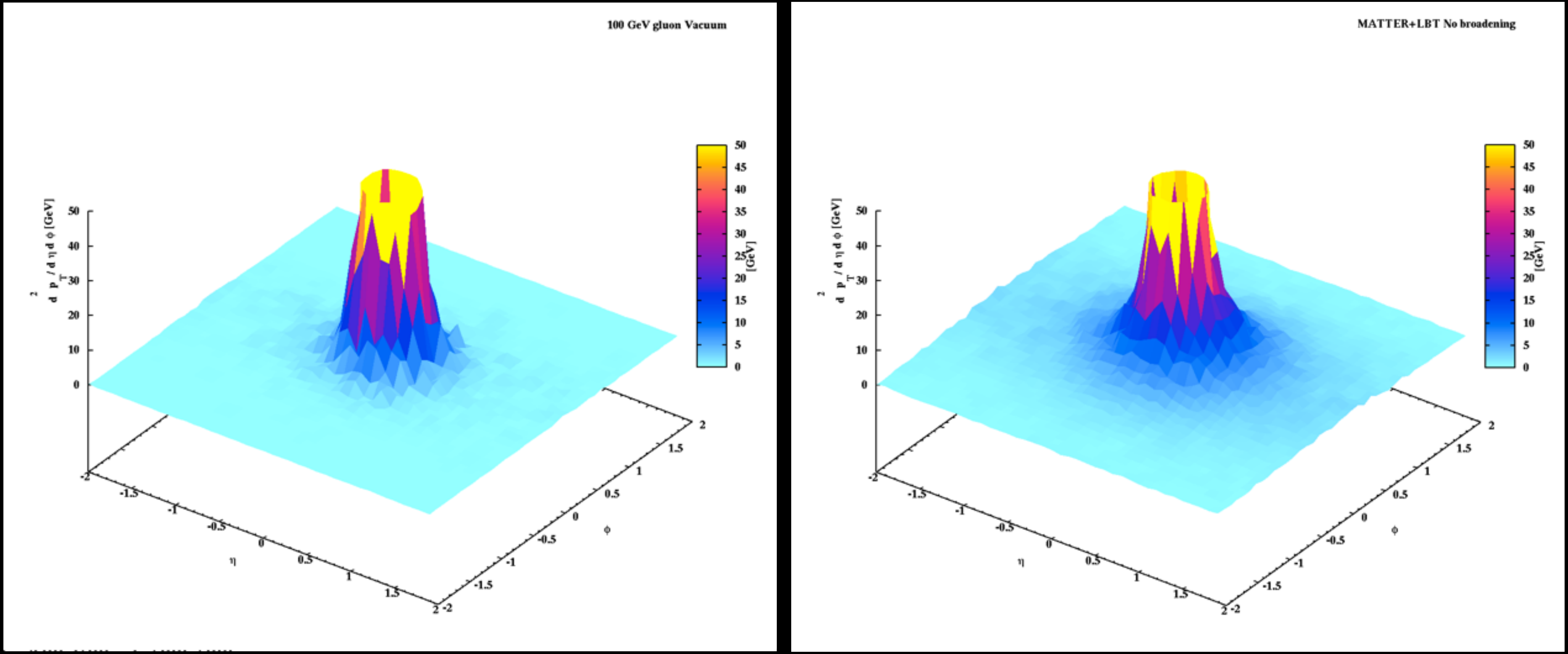
- We assume: Multiple scatterings are not correlated.



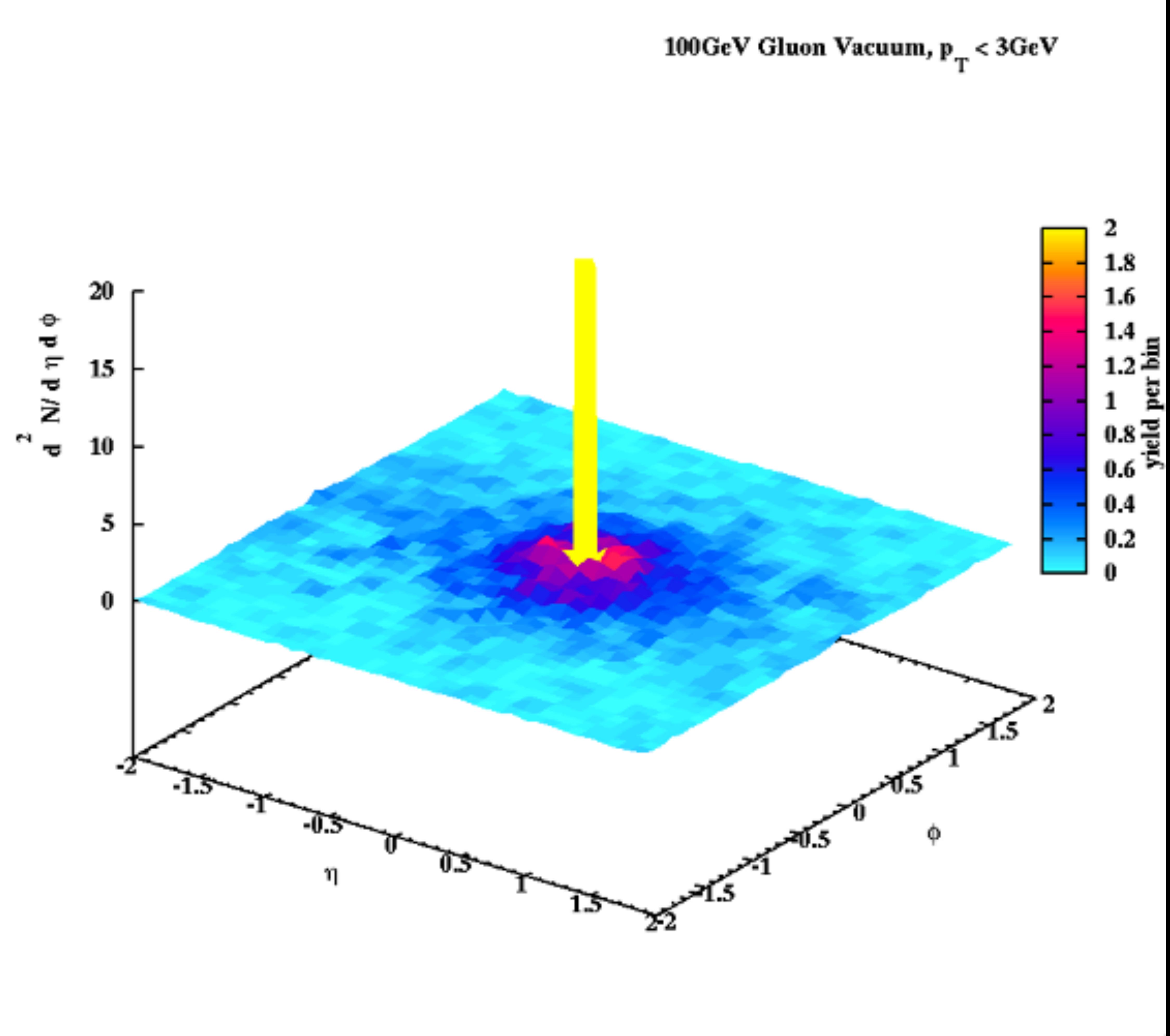


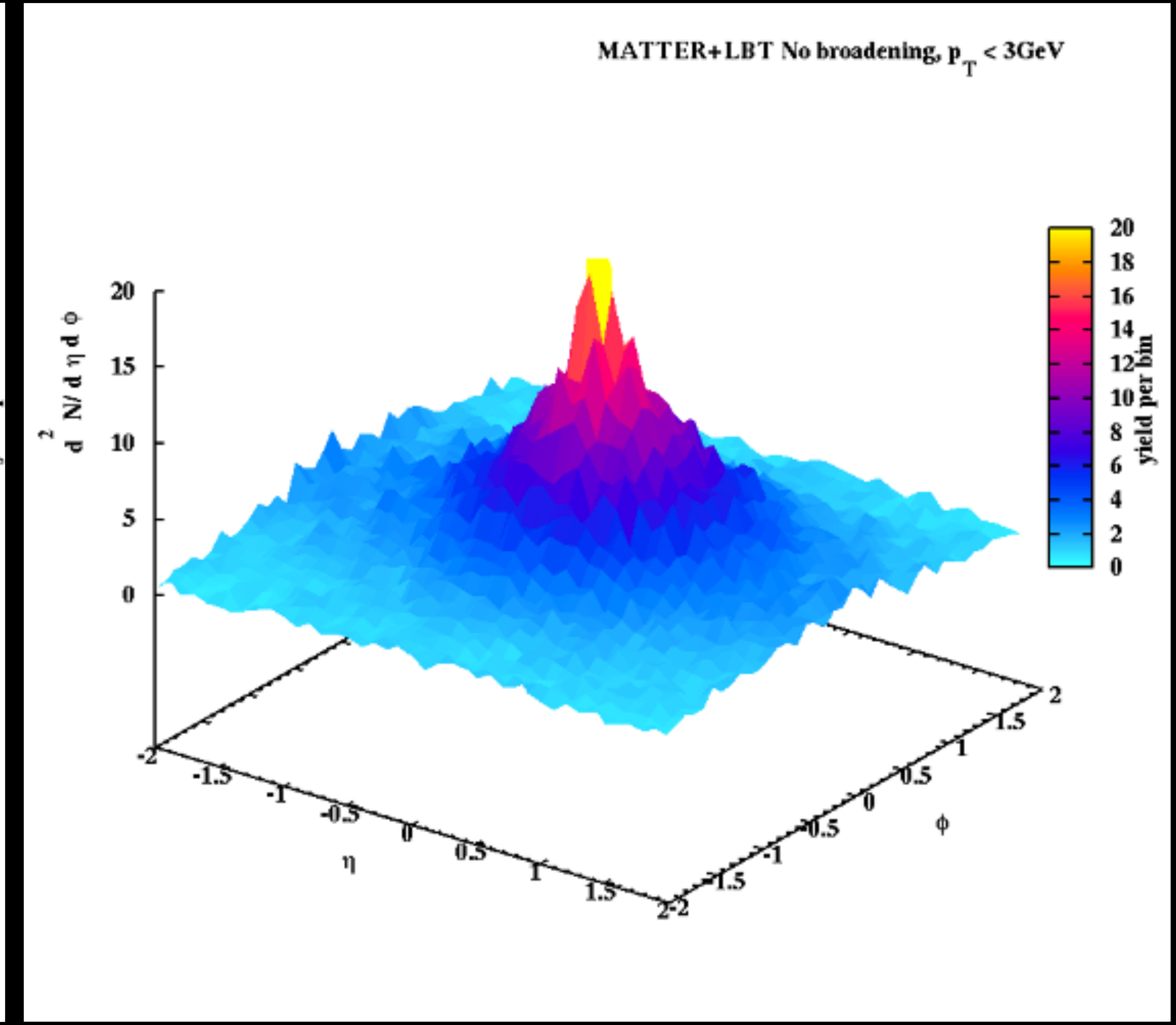
- Grey blob: scattering off field, for $k \gtrsim 1 GeV$, parton distribution.
- Jet parton coupling is always assumed perturbative (except in AdS/CFT)
- Scattering measures the single collision kernel of the system $C(k) = \frac{d\Gamma}{d^3k}$
- Can take moments $\hat{q} = \int d^3k \; k_\perp^2 \; C(k) \quad \hat{e} = \int d^3k \; |\vec{k}| \; C(k)$
- My personal experience: leading hadrons sensitive to mostly $\hat{q}, \hat{e}$. Jets require full $C(k)$

What does it look like in p_T?



What does it look like in soft yield?





In general, 2 kinds of transport coefficients

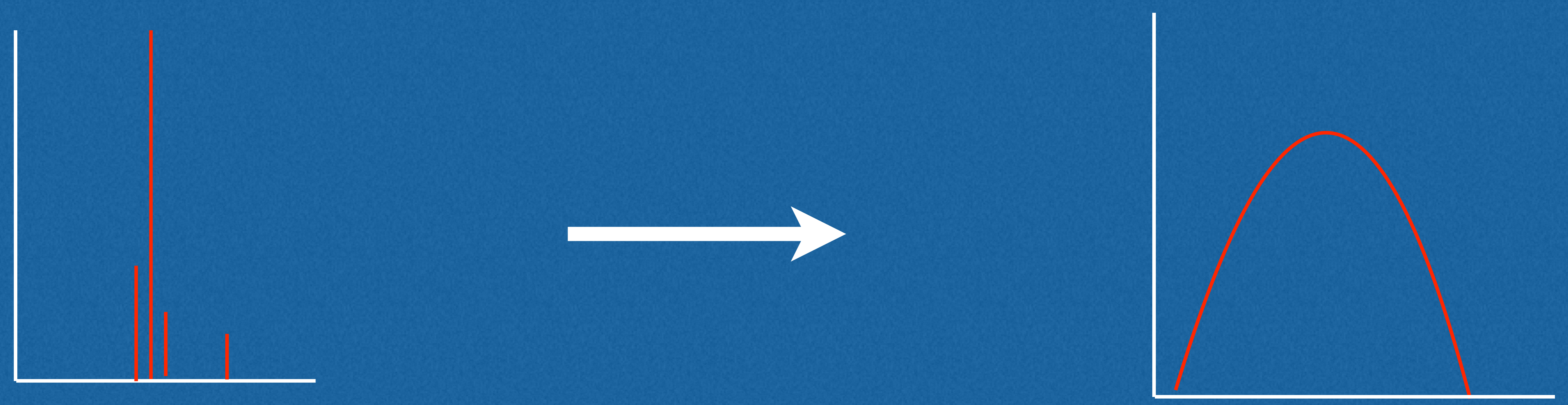
Type 1: which quantify how the medium changes the jet

$$\hat{q}(E,Q^2) = \frac{\langle p_T^2\rangle}{L} \qquad \hat{q}_4(E,Q^2) = \frac{\langle p_T^4\rangle - \langle p_T^2\rangle^2}{L} \ldots$$

$$\hat{e}(E,Q^2) = \frac{\langle \delta E\rangle}{L} \qquad \hat{e}_2(E,Q^2) = \frac{\langle \delta E^2\rangle}{L} \qquad \hat{e}_4(E,Q^2) = \frac{\langle \delta E^4\rangle - \langle \delta E^2\rangle^2}{L} \ldots$$

Type 2: which quantify the space-time structure of the deposited energy momentum at the hydro scale

$$\delta T^{\mu\nu}$$



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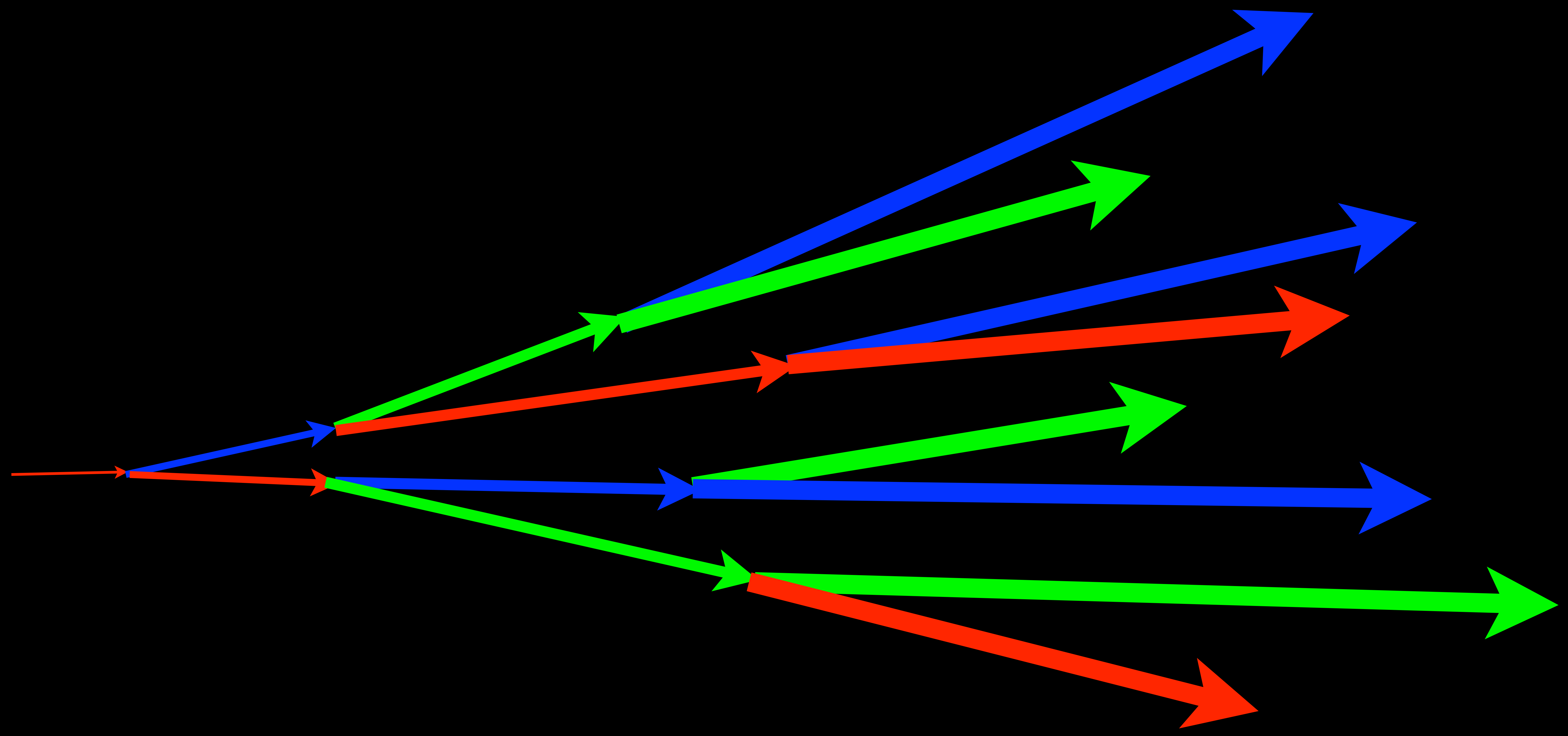

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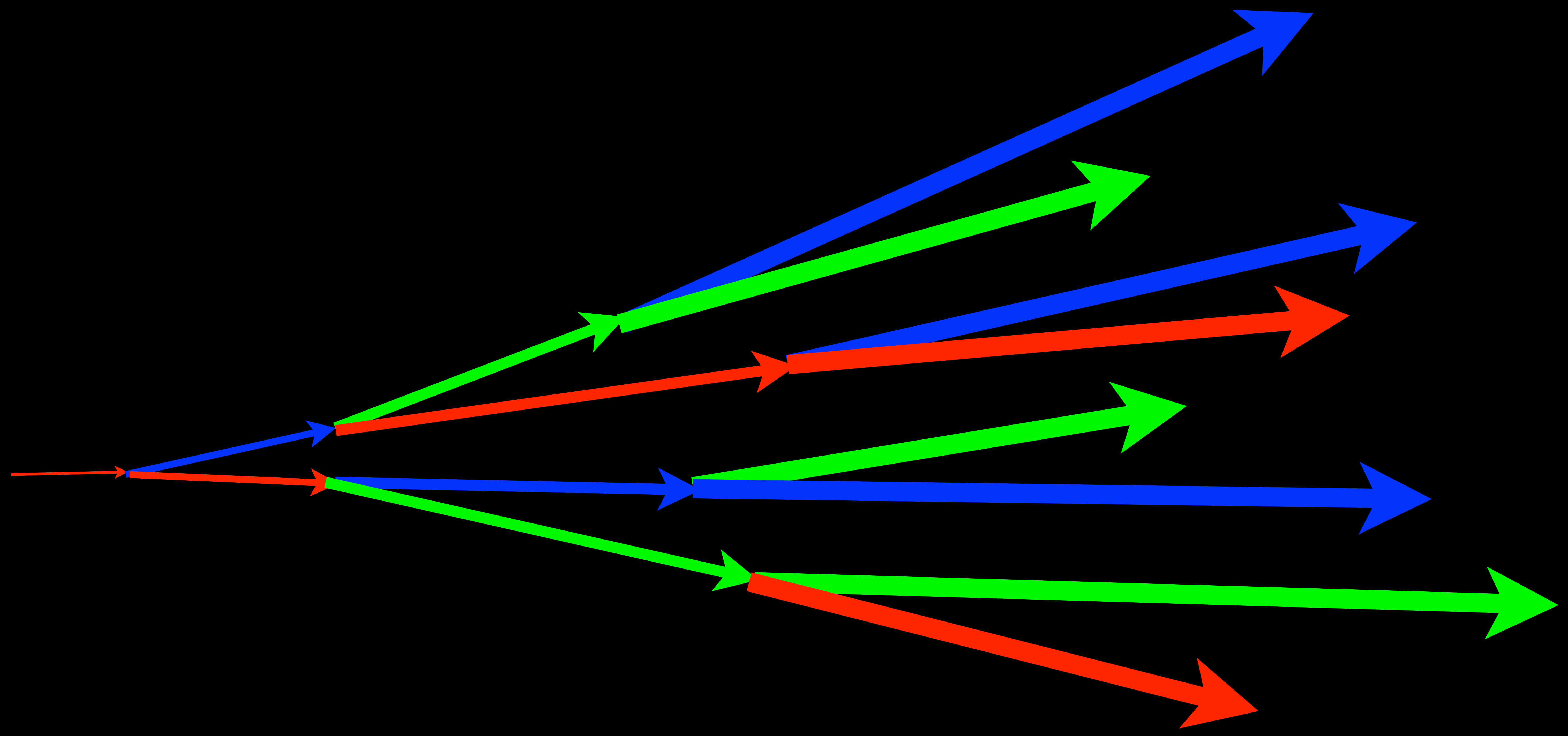

Virtuality, off-shellness, scale Q drops —>

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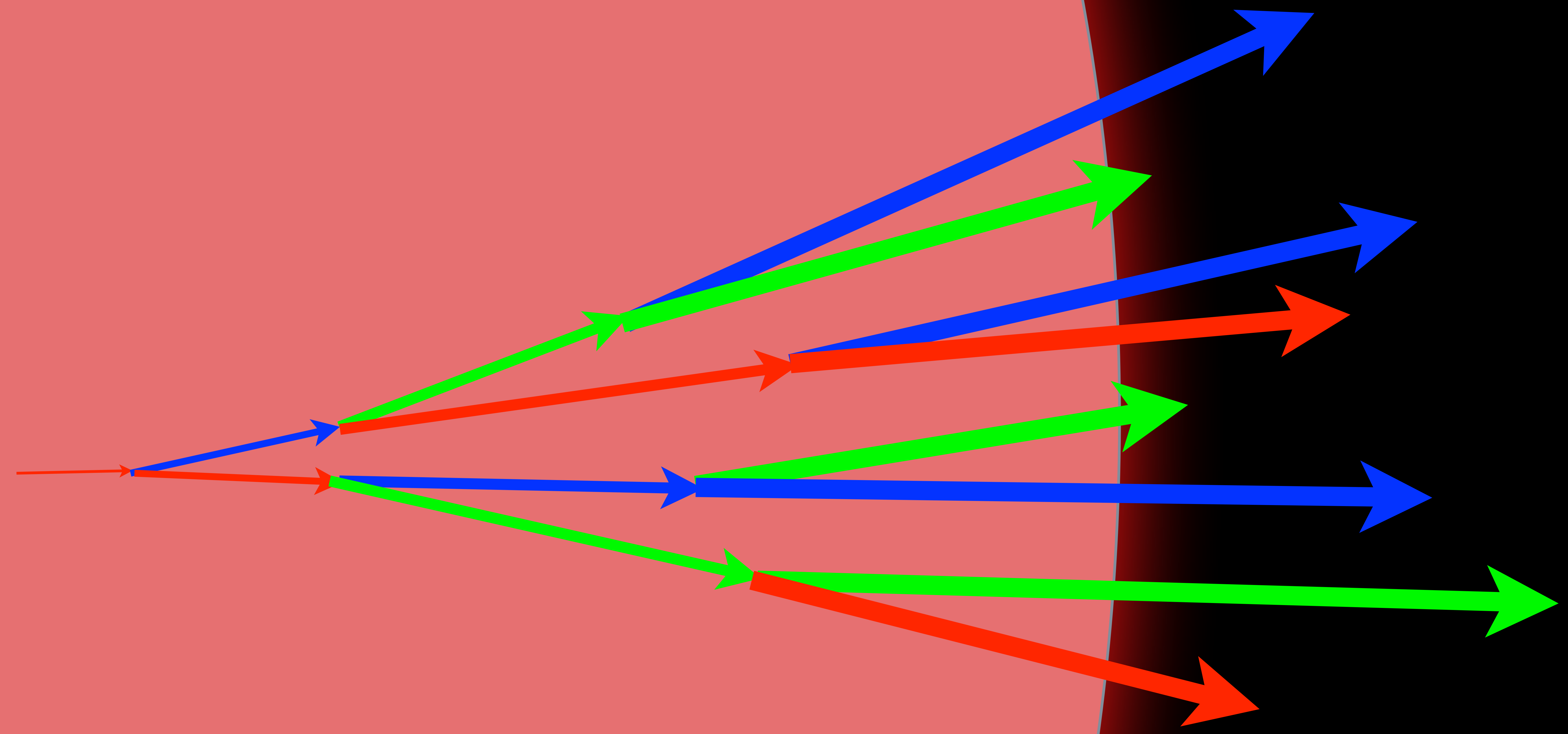

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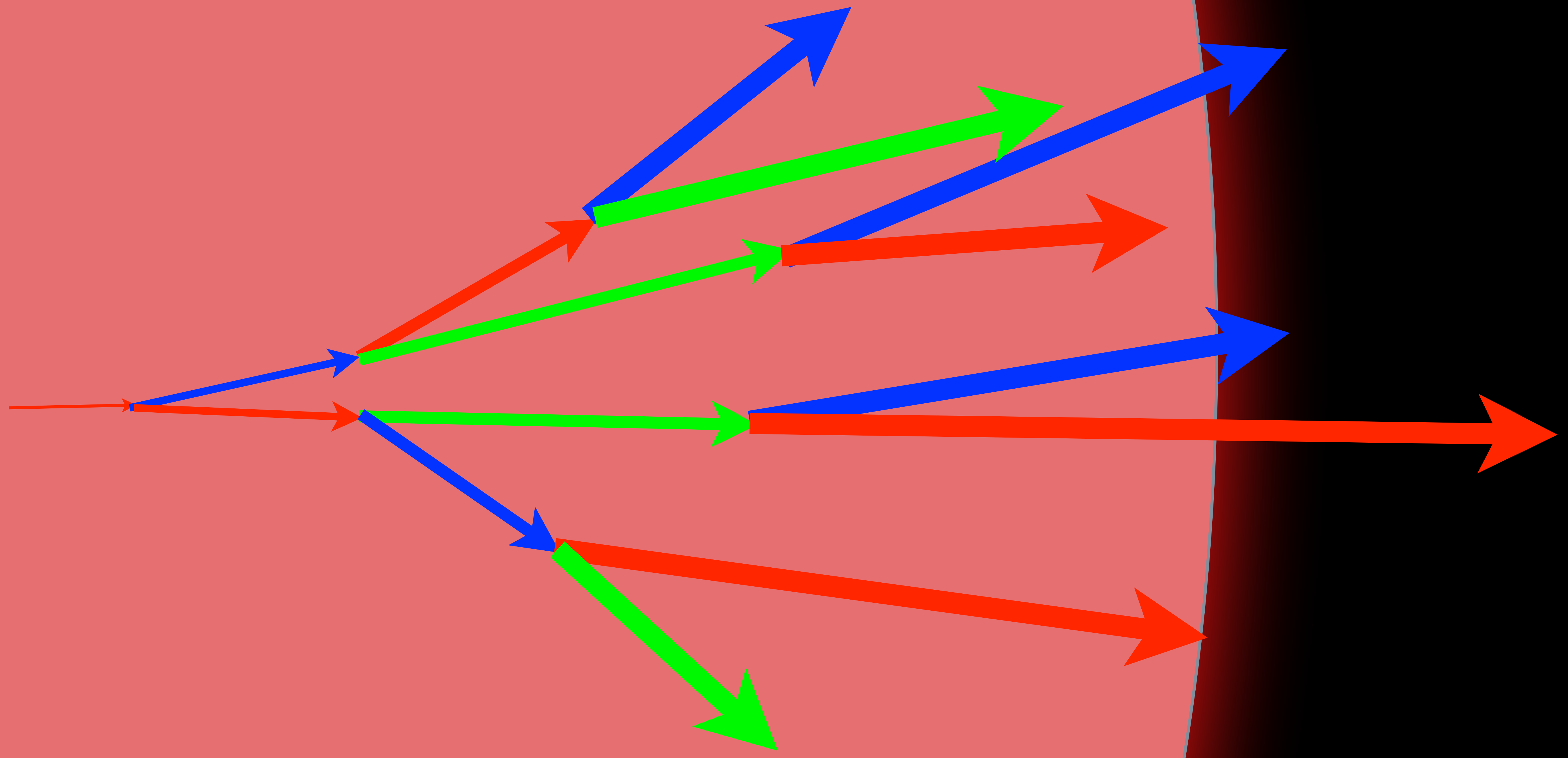

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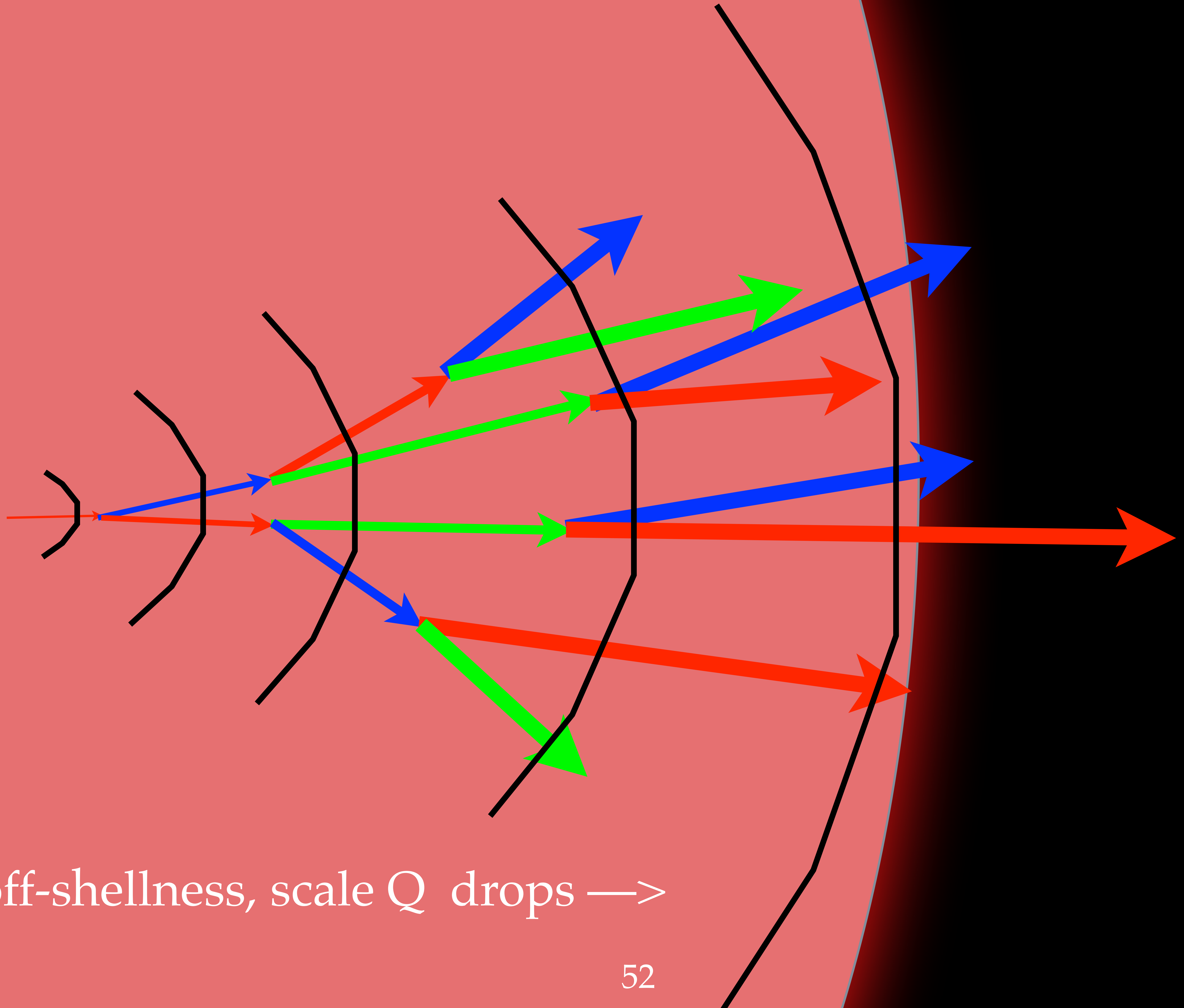

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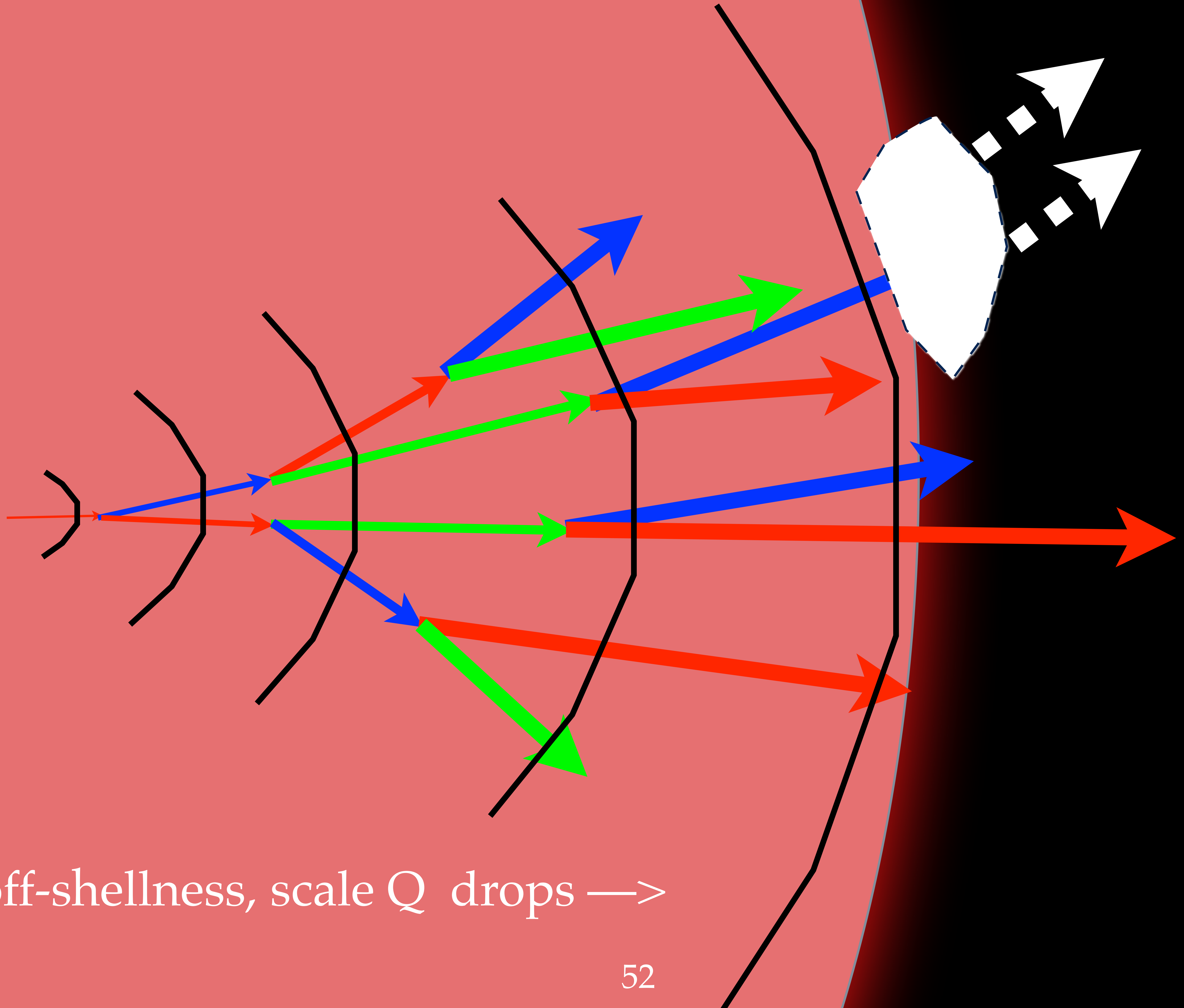

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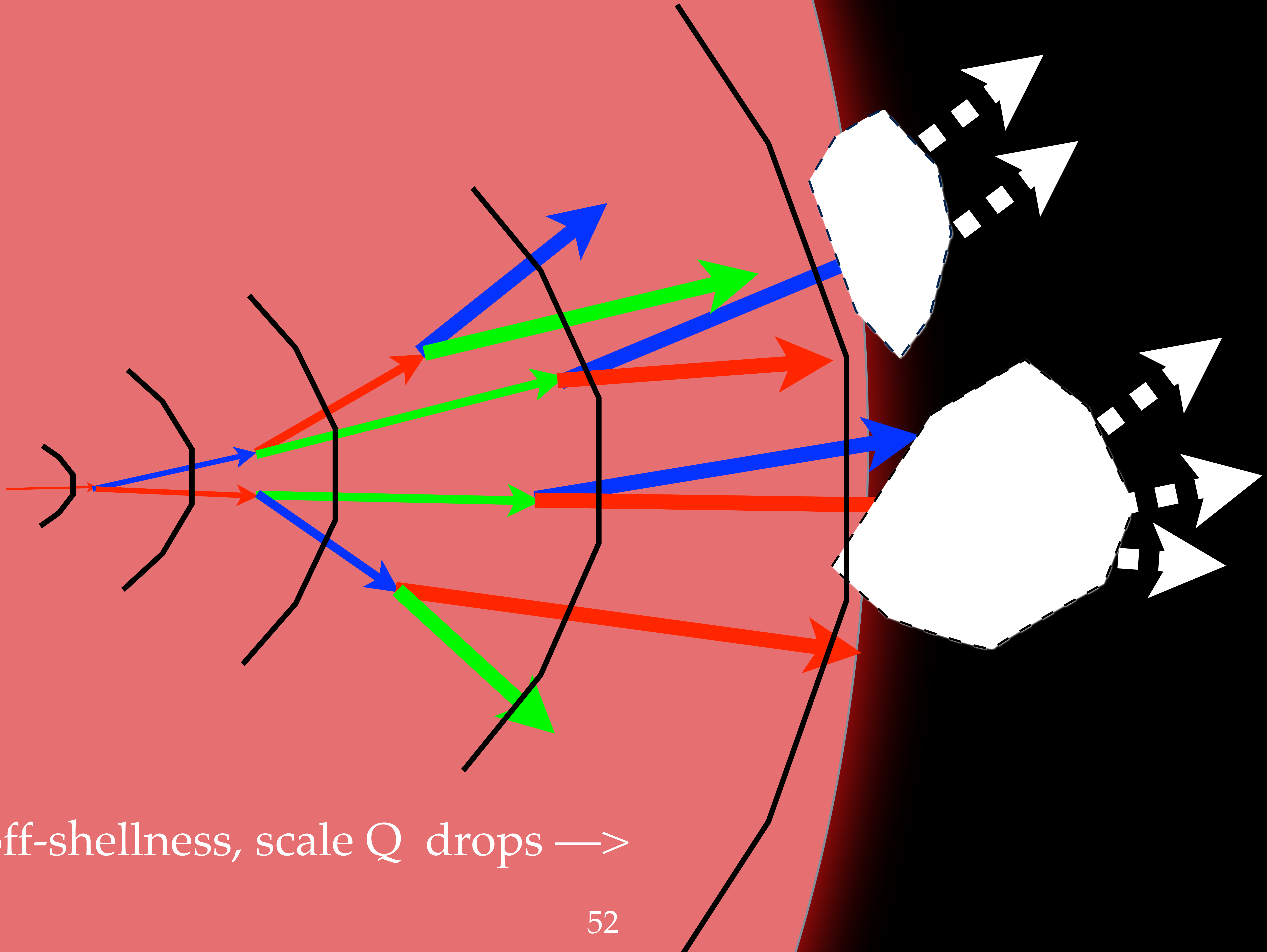

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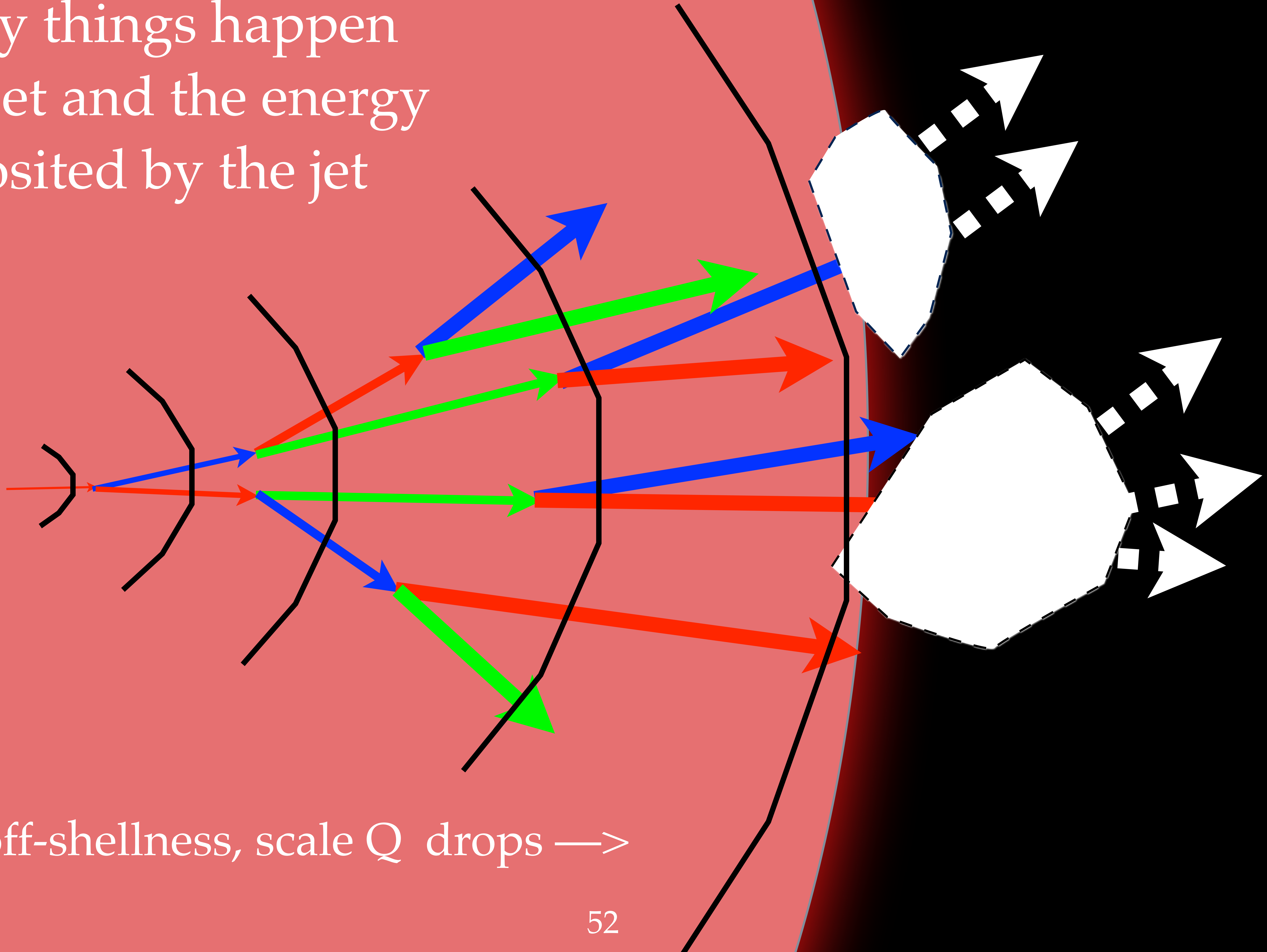
Jets are complicated,

Many things happen to a jet and the energy deposited by the jet



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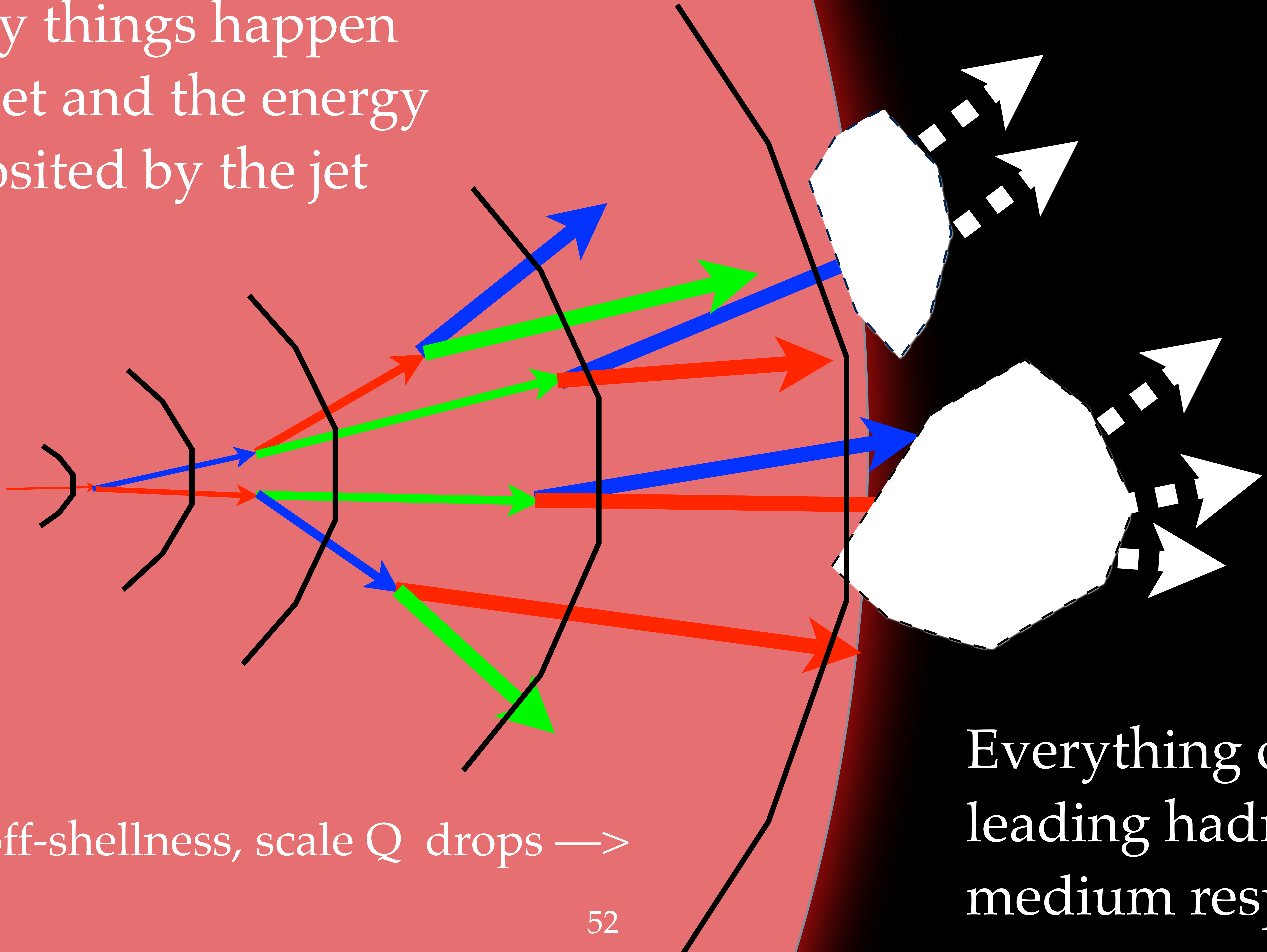
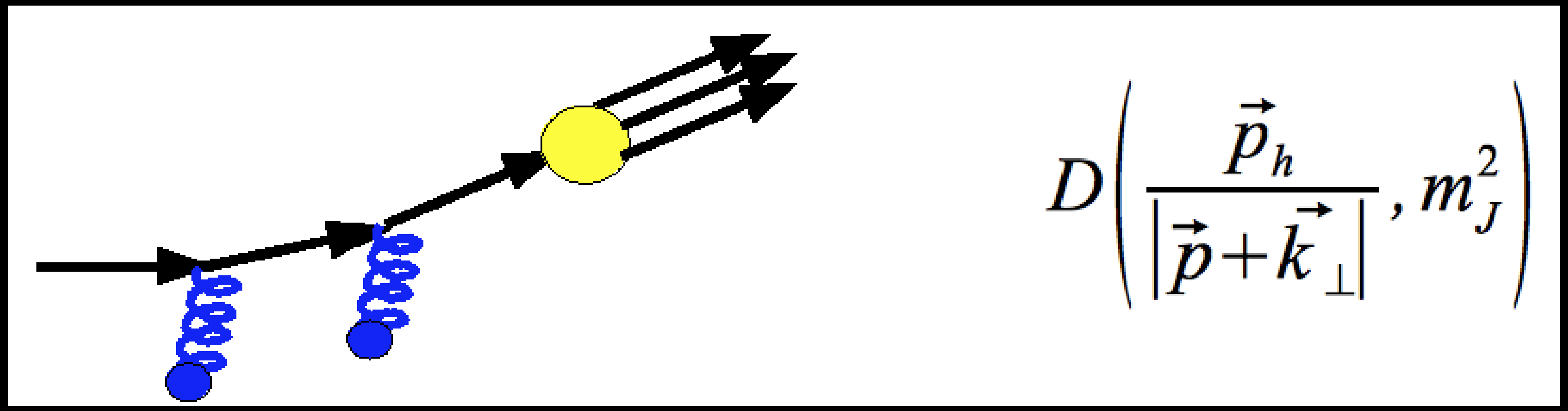


Virtuality, off-shellness, scale Q drops —>

Everything other than leading hadrons includes medium response.

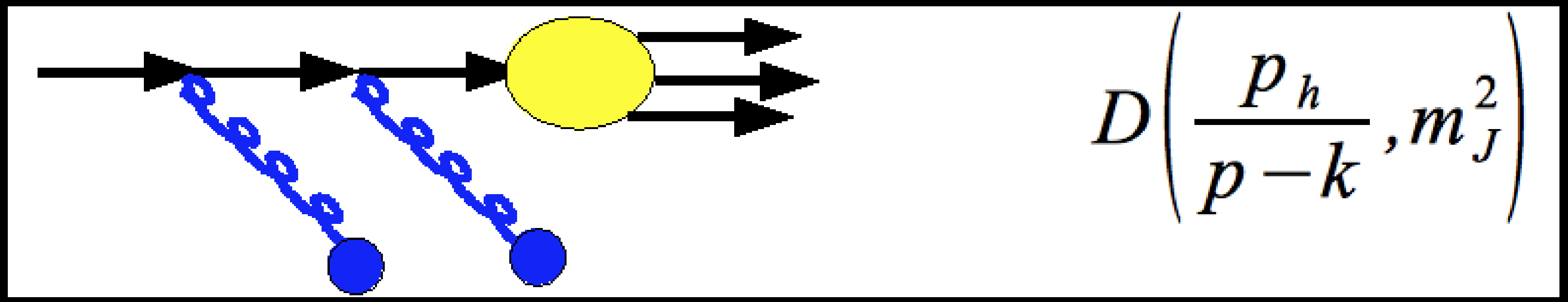
Transport coefficients for partons in a dense medium

$$p_z^2 \simeq E^2 - p_\perp^2 \qquad\qquad p^+ \simeq p_\perp^2/2p^-$$



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

Transverse momentum diffusion rate



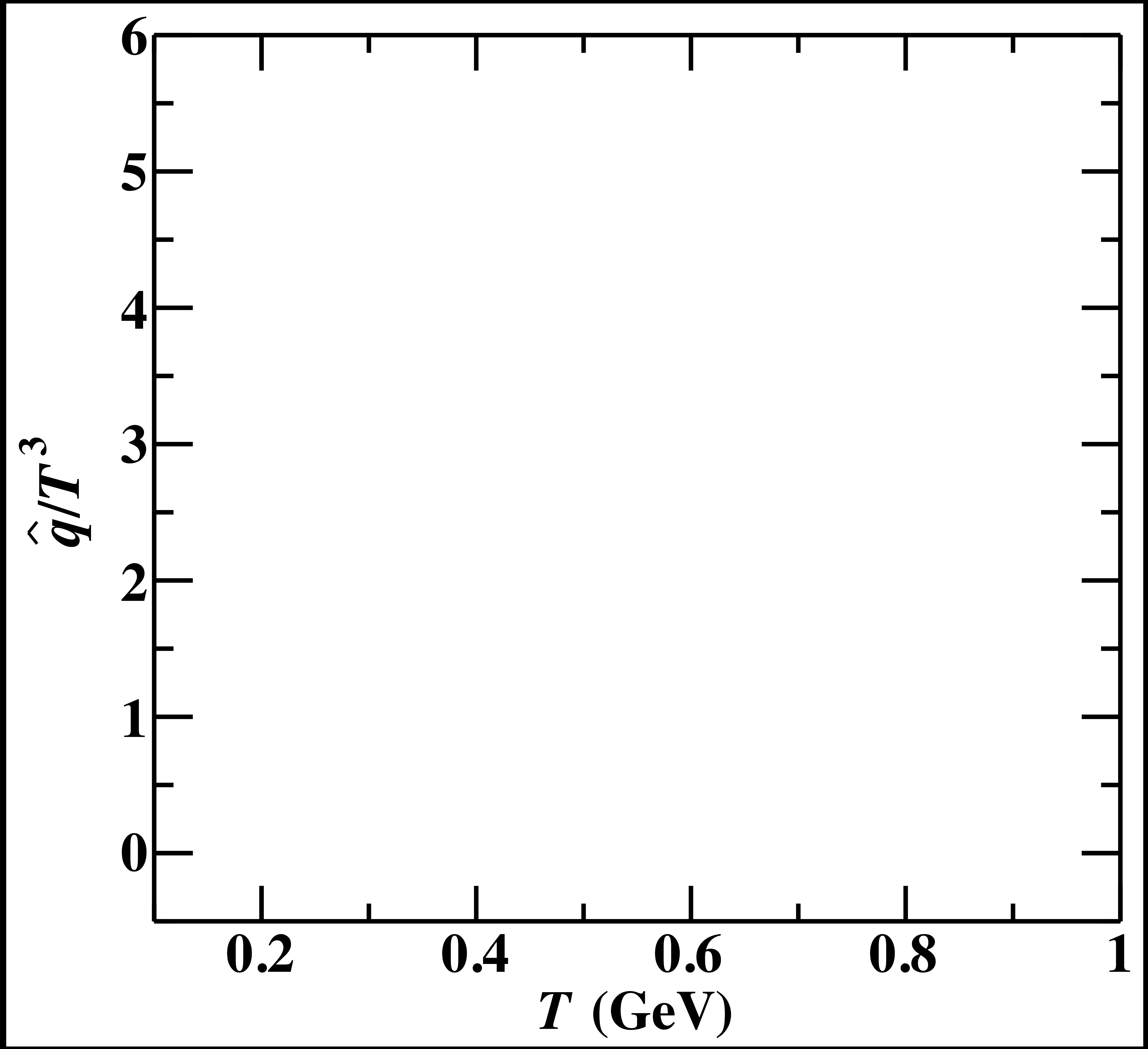
$$\hat{e} = \frac{\langle \Delta E \rangle_L}{L}$$

Elastic energy loss rate
also diffusion rate e_2

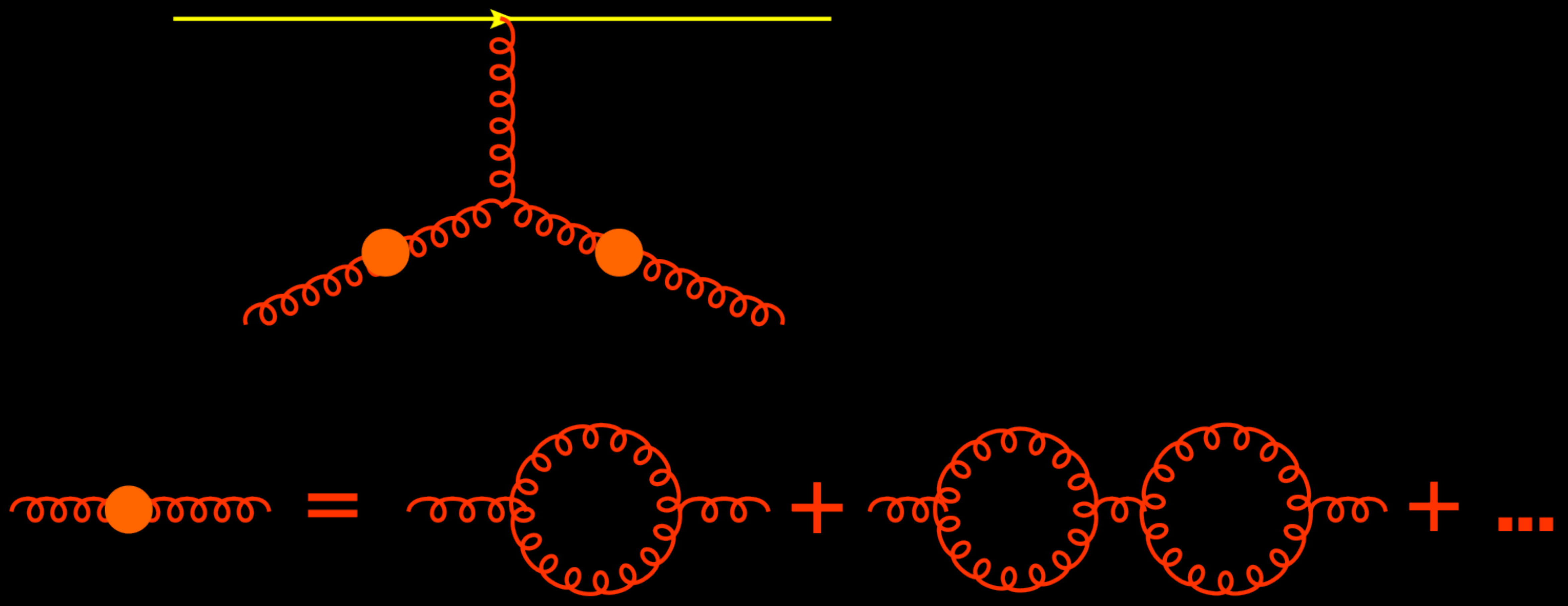
By definition, describe how the medium modifies the jet parton!

What do we know about $\hat{q}$ (circa 2010)?

- An intrinsic property of the medium
- Dimensionally Scales as E^3 or T^3
- Should have a transition between confined and deconfined phase
- Will need to be scaled with some intrinsic quantity in a realistic simulation.



Calculating in Perturbation Theory

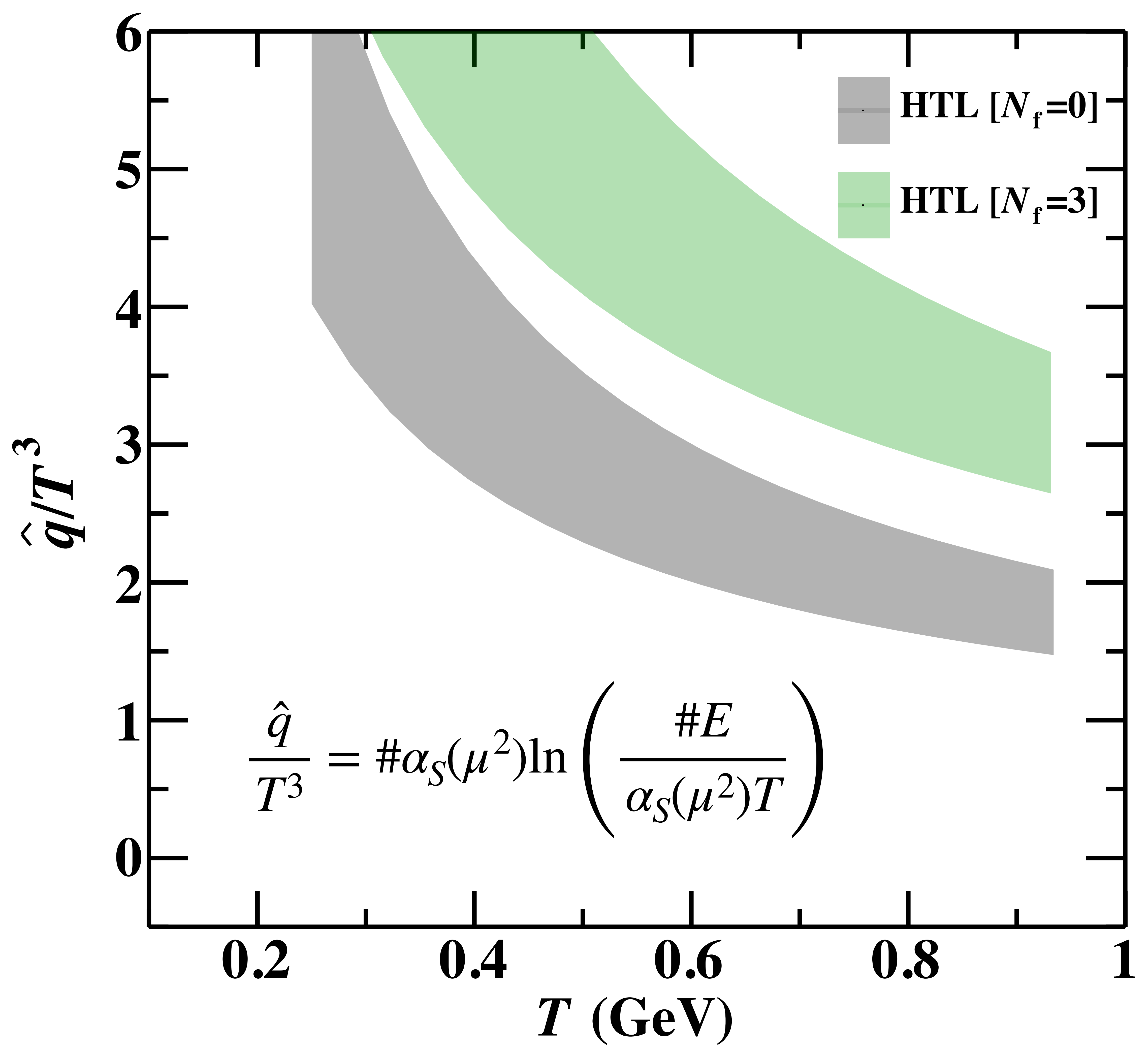


Hard Thermal Loop (HTL) theory

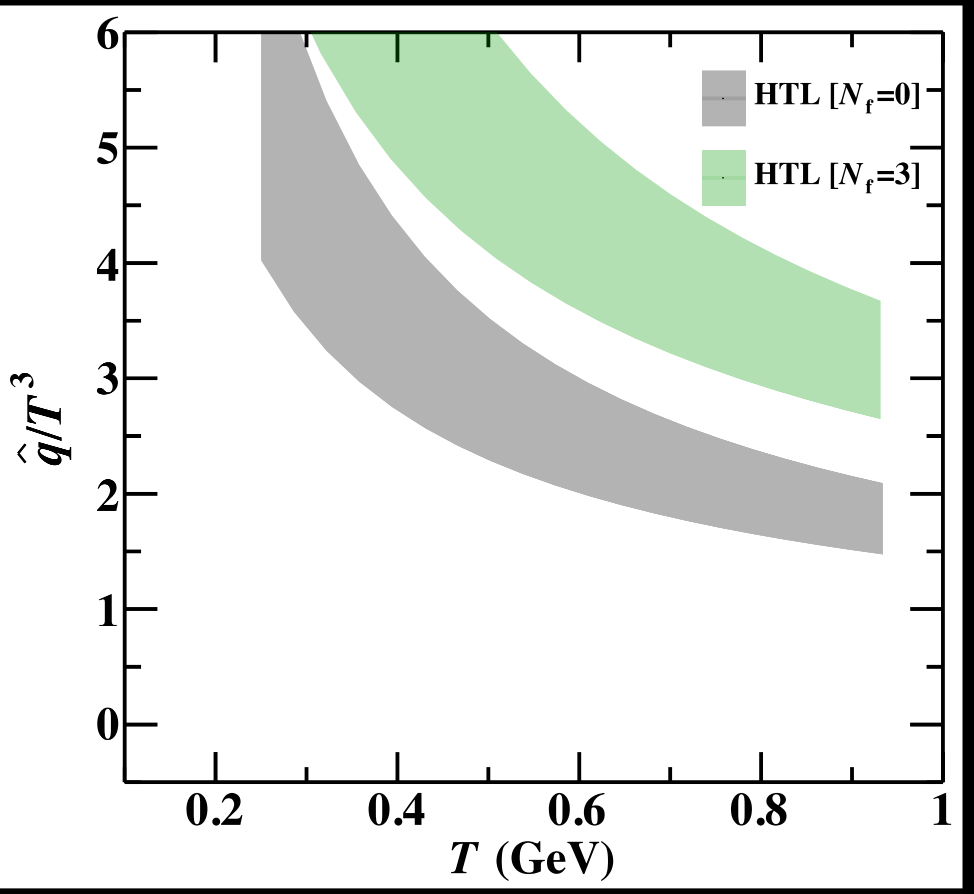
$$\hat{q} = \frac{42 C_F \xi(3)}{\pi} \alpha^2(\mu^2) T^3 \ln\left(\frac{6ET}{m_D^2}\right)$$

$$m_D^2 = \frac{4\pi\alpha_s(\mu^2)}{3} T^2 \left(N_C + \frac{N_f}{2}\right)$$

$$E = 100\,\mathrm{GeV} \quad : \quad 2\pi T < \mu < 4\pi T$$



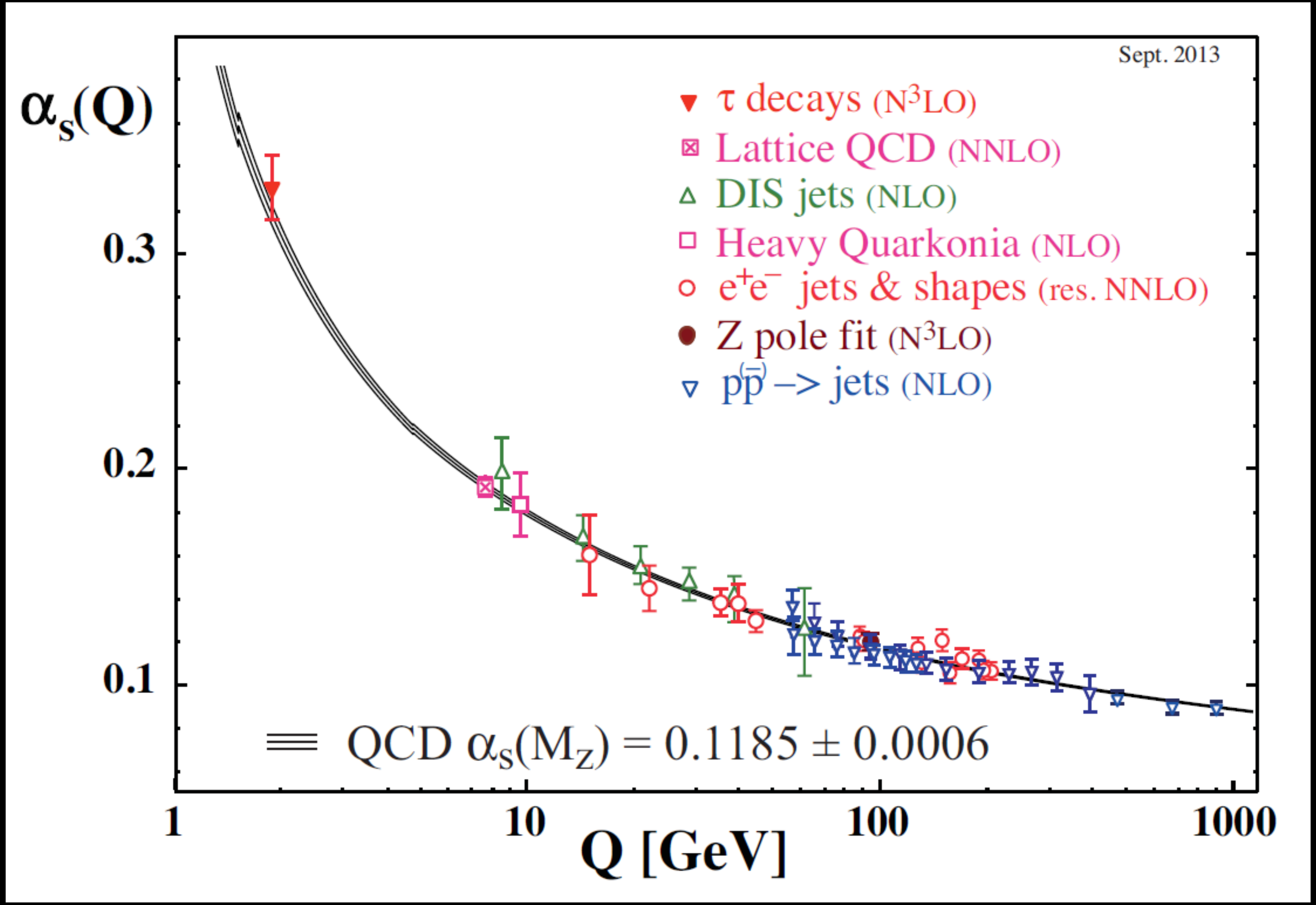
Is Perturbation theory valid at these temperatures?



Plot is $2\pi T \lesssim \mu \lesssim 4\pi T$

At T = 250 MeV, $2\pi T = 1.5$ GeV

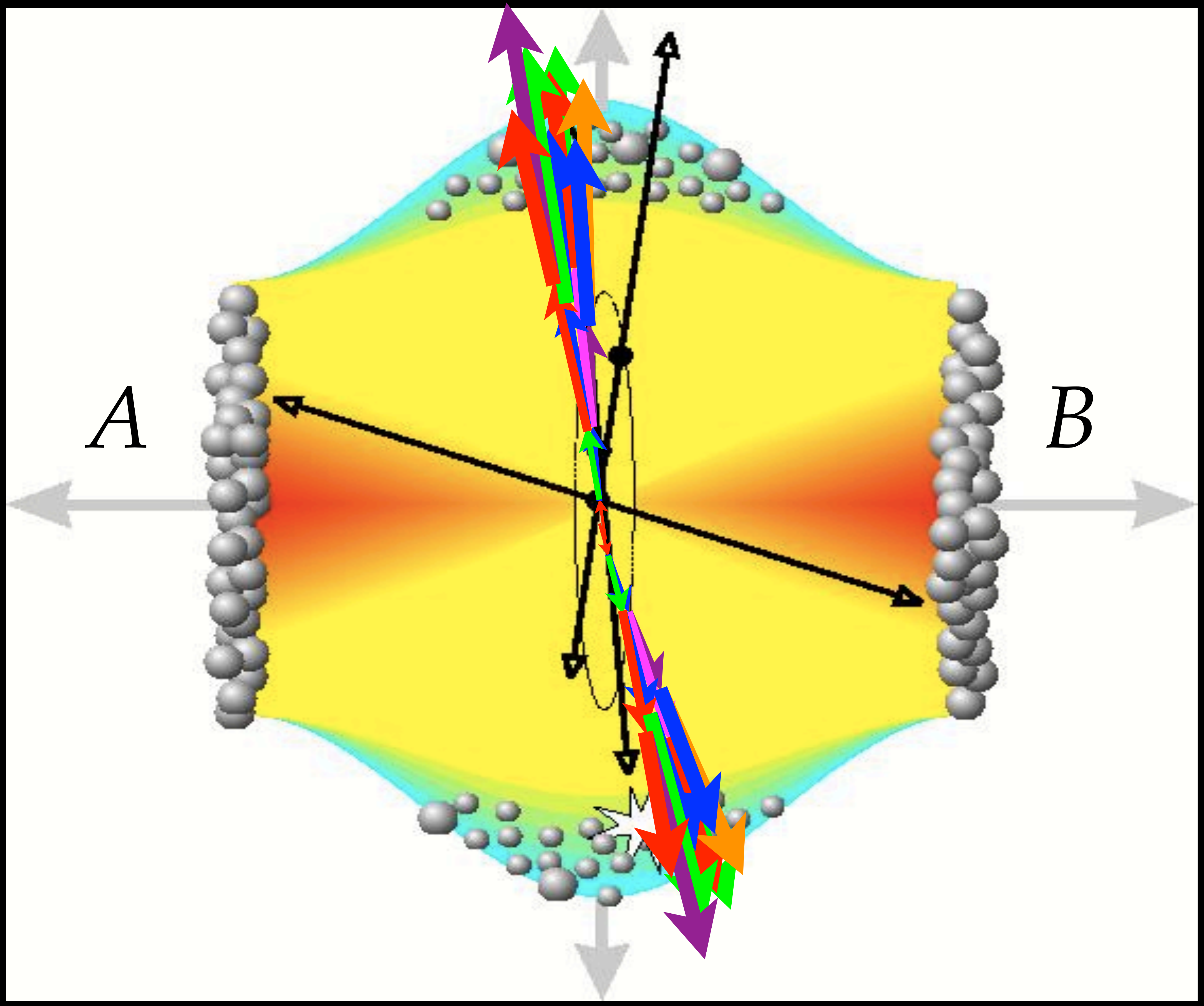
$\alpha_s = 0.4 - 0.5$



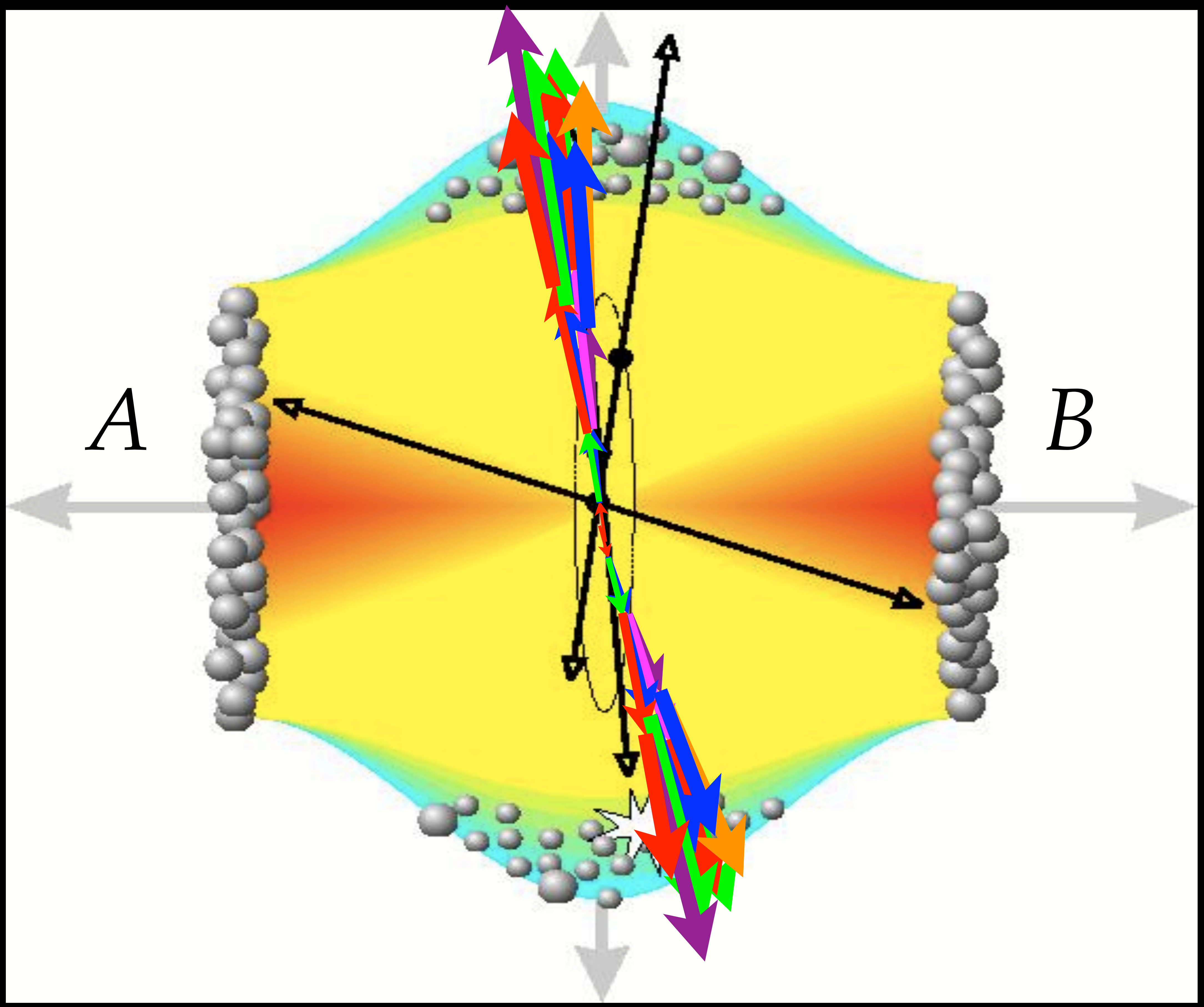
Can try to get $\hat{q}$ using jet/leading hadron phenomenology

Leading hadron nuclear modification factor R_{AA}

Leading hadron nuclear modification factor R_{AA}

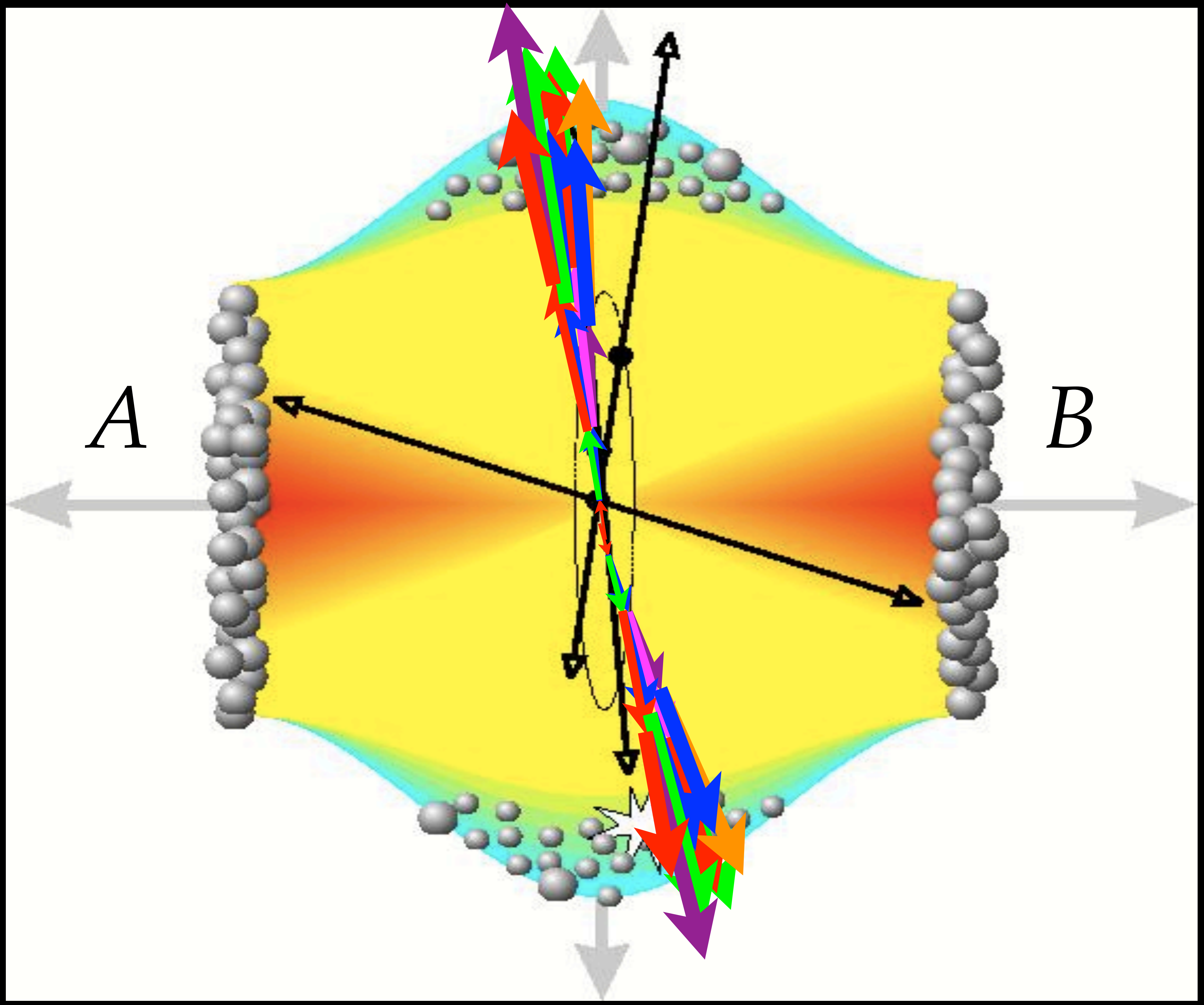


Leading hadron nuclear modification factor R_{AA}



$$R_{AA} = \frac{d\mathcal{N}_{AA}(b_L, b_H)}{\mathrm{N}_{binary}(b_L, b_H)\ d\mathcal{N}_{pp}}$$

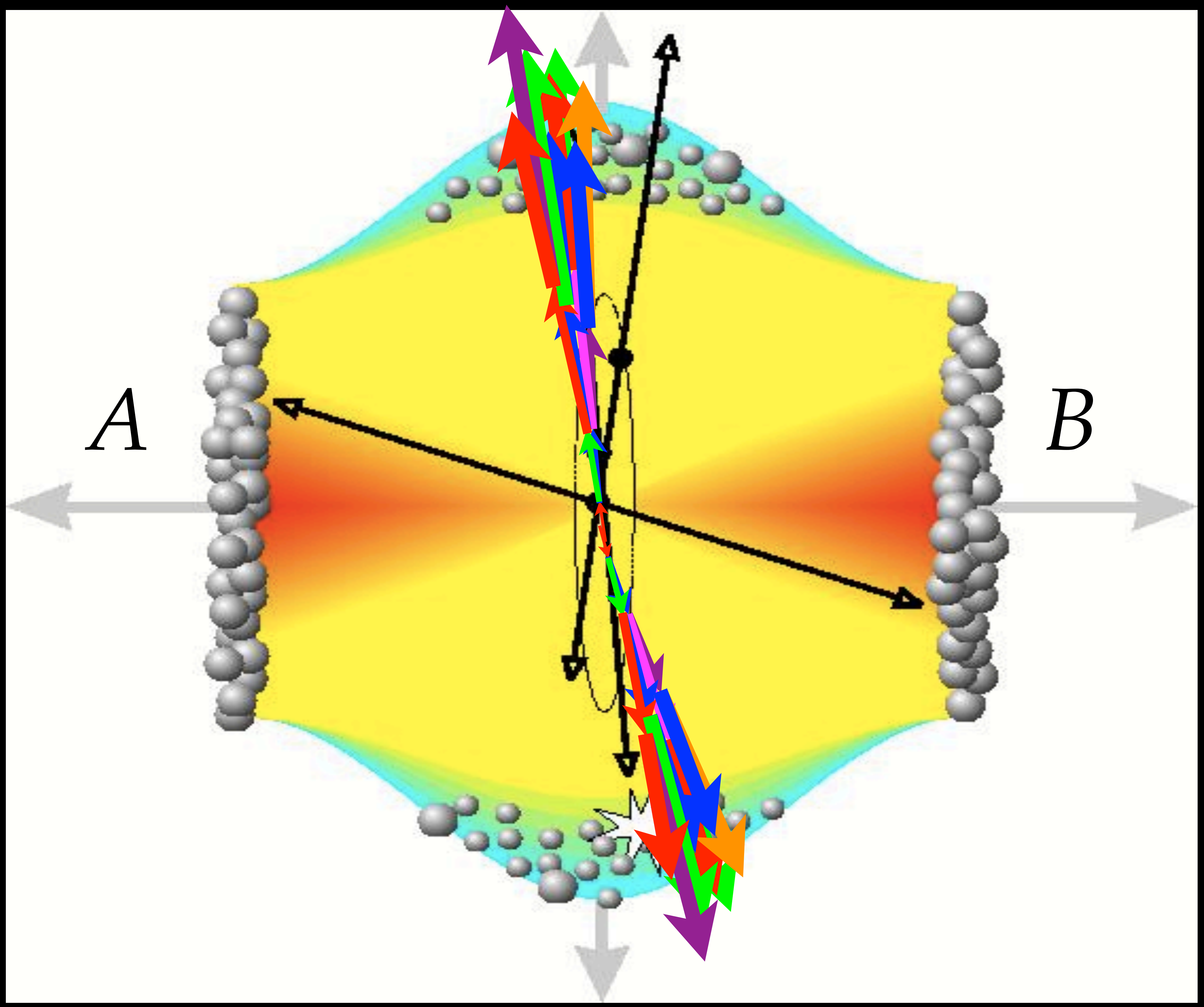
Leading hadron nuclear modification factor R_{AA}



$$R_{AA} = \frac{d\mathcal{N}_{AA}(b_L, b_H)}{\mathrm{N}_{binary}(b_L, b_H)\ d\mathcal{N}_{pp}}$$

$$d\mathcal{N}^h_{AB} = \int_{b_L}^{b_h} d^2b \int d^2r \int dp_1 dp_2$$
$$\times\, dP_A(p_1, r) dP_B(p_2, r)$$
$$\times\, \sigma_{1+2\to 3+4}$$
$$\times\, d\mathscr{P}_3(\Delta E) D_{3\to h}$$

Leading hadron nuclear modification factor R_{AA}



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$$d\mathcal{P}(\Delta E) \propto \hat{q}(T^3/s)$$

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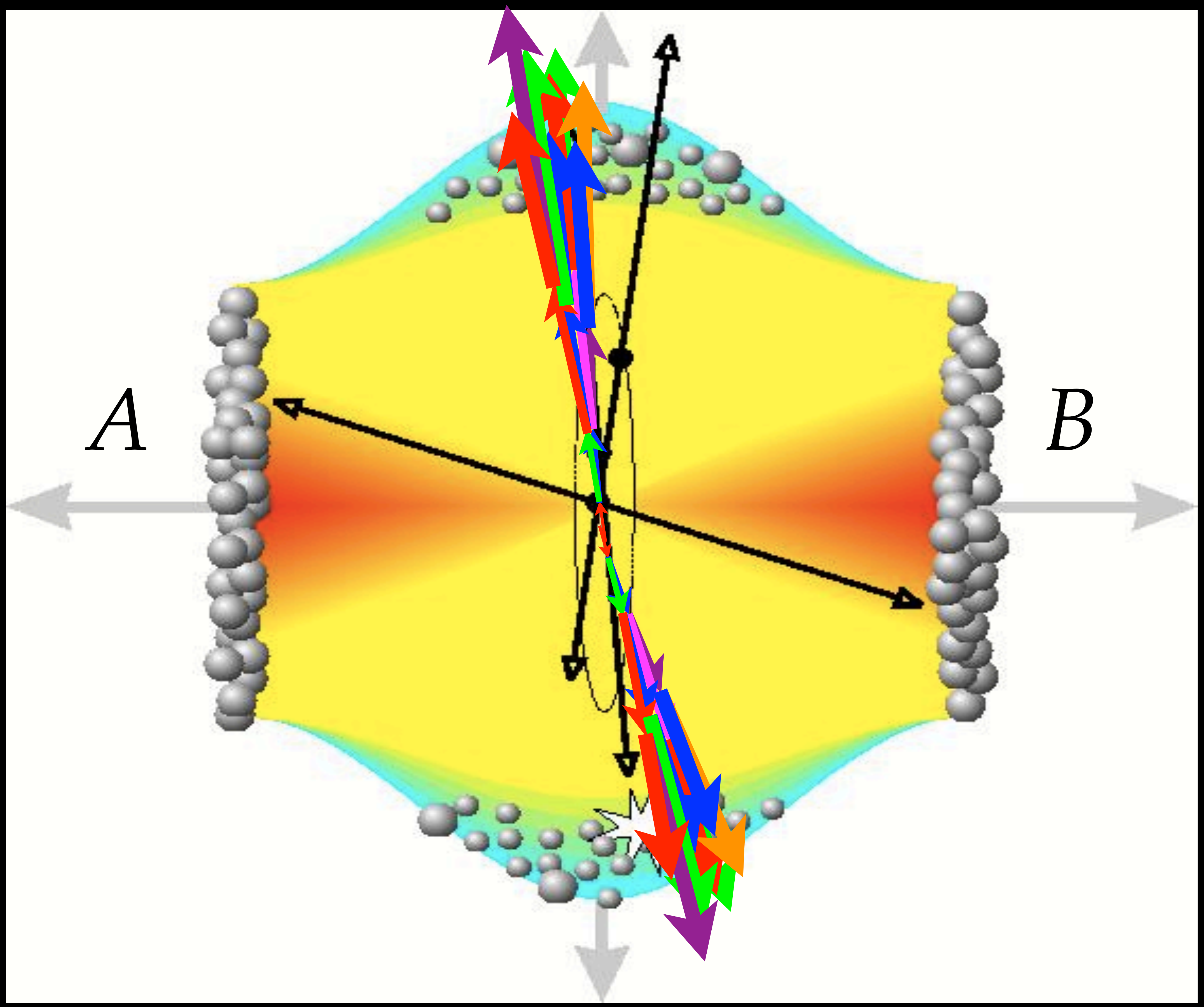

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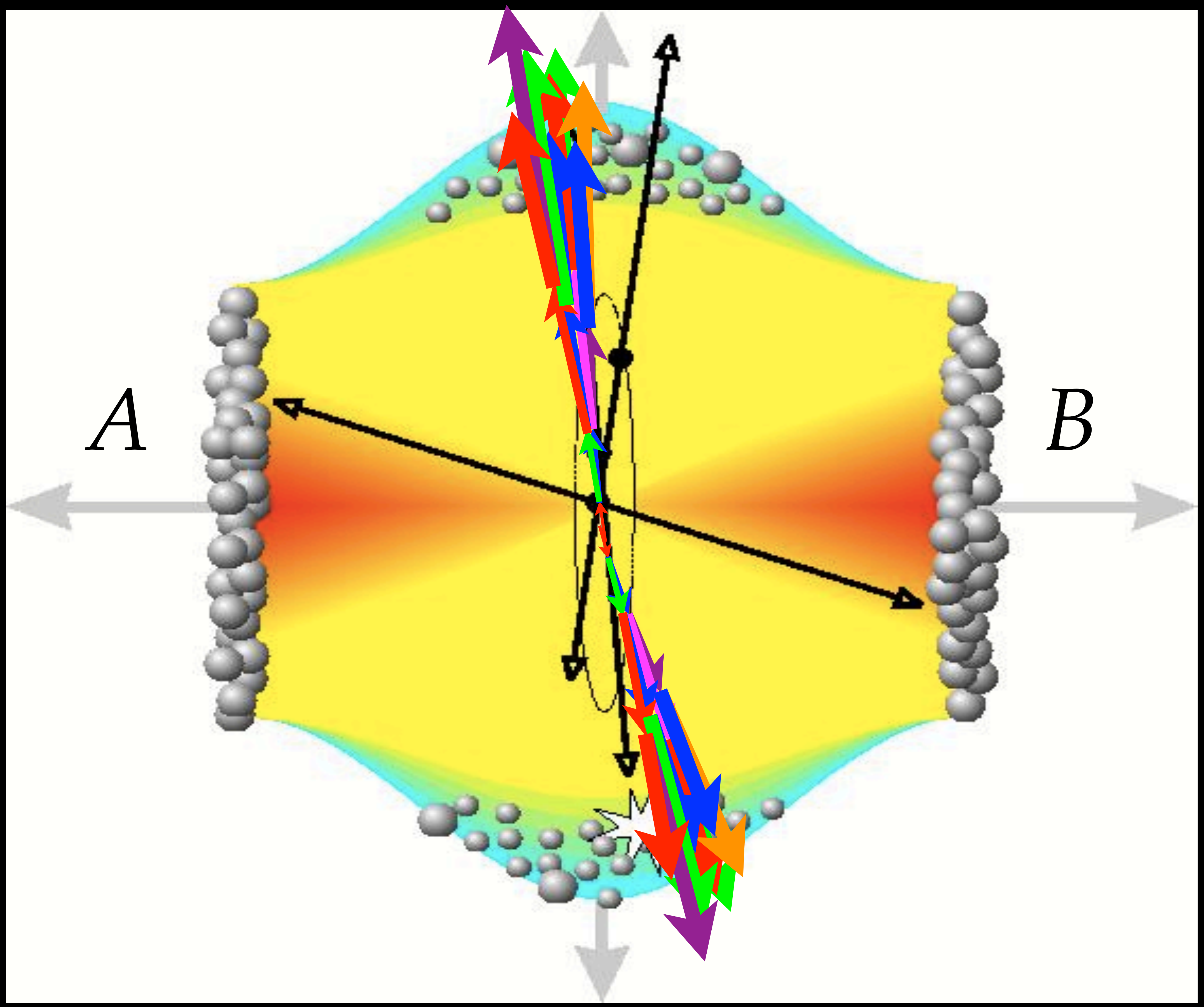
This depends on the space time profile of the Fluid dynamical simulation

Leading hadron nuclear modification factor R_{AA}



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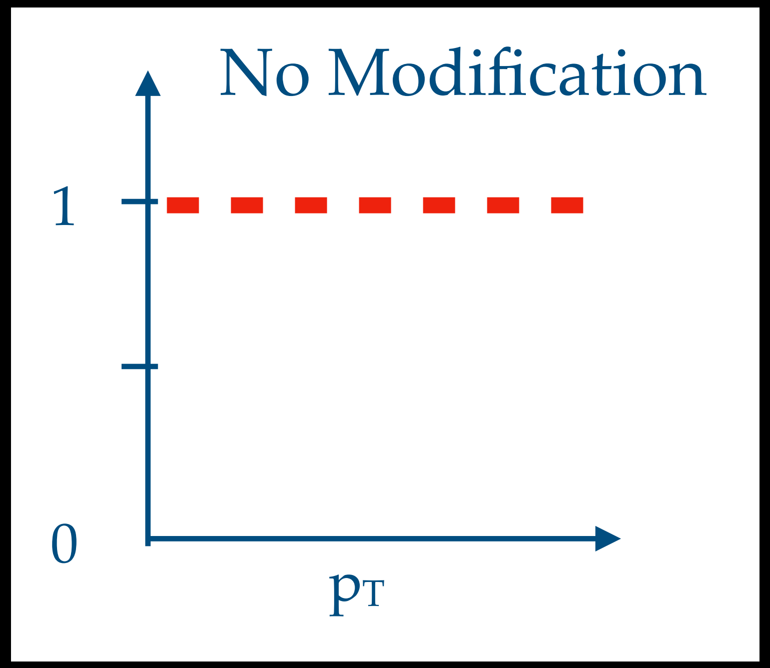

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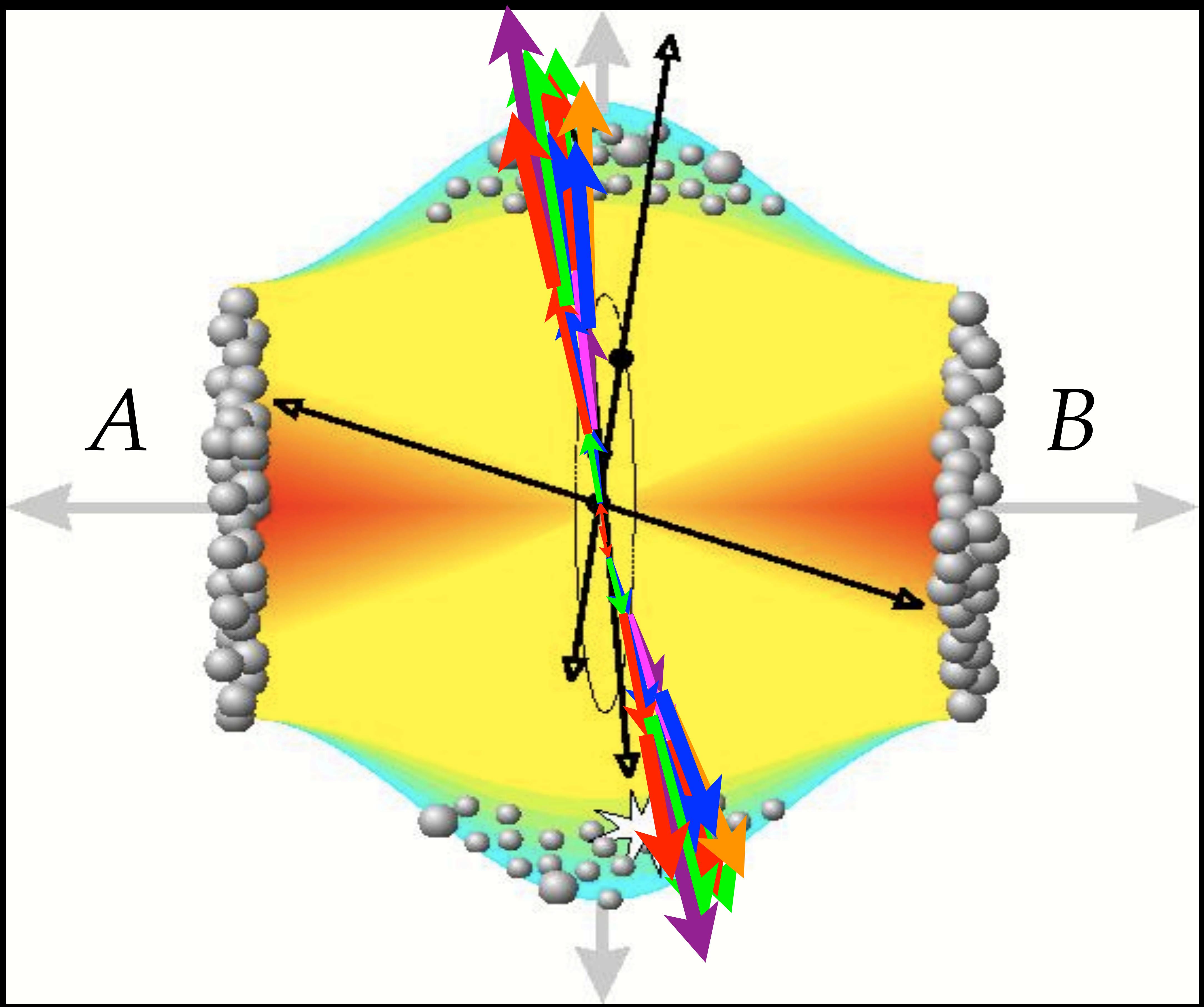

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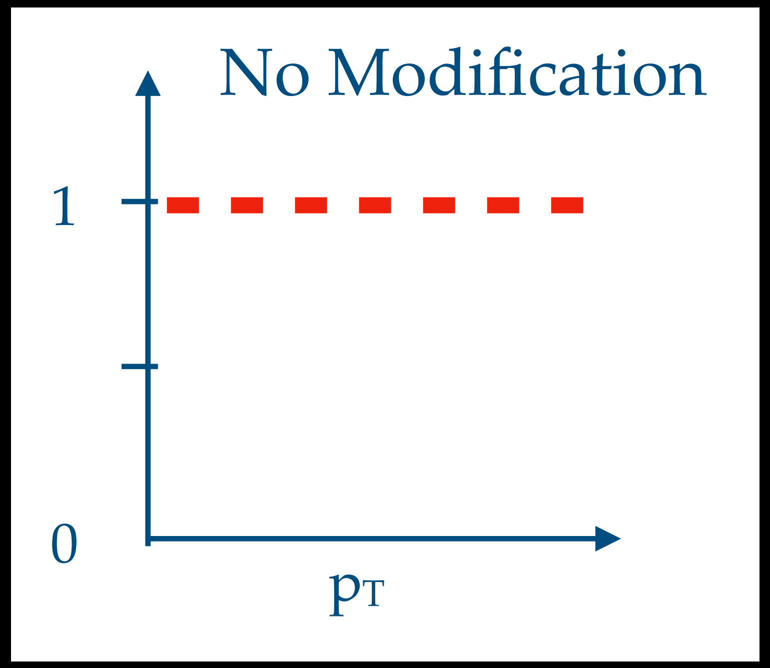
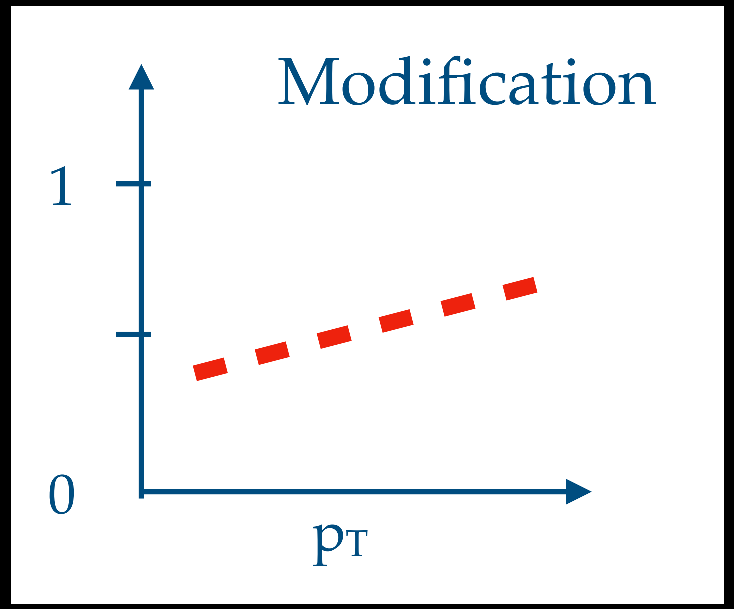
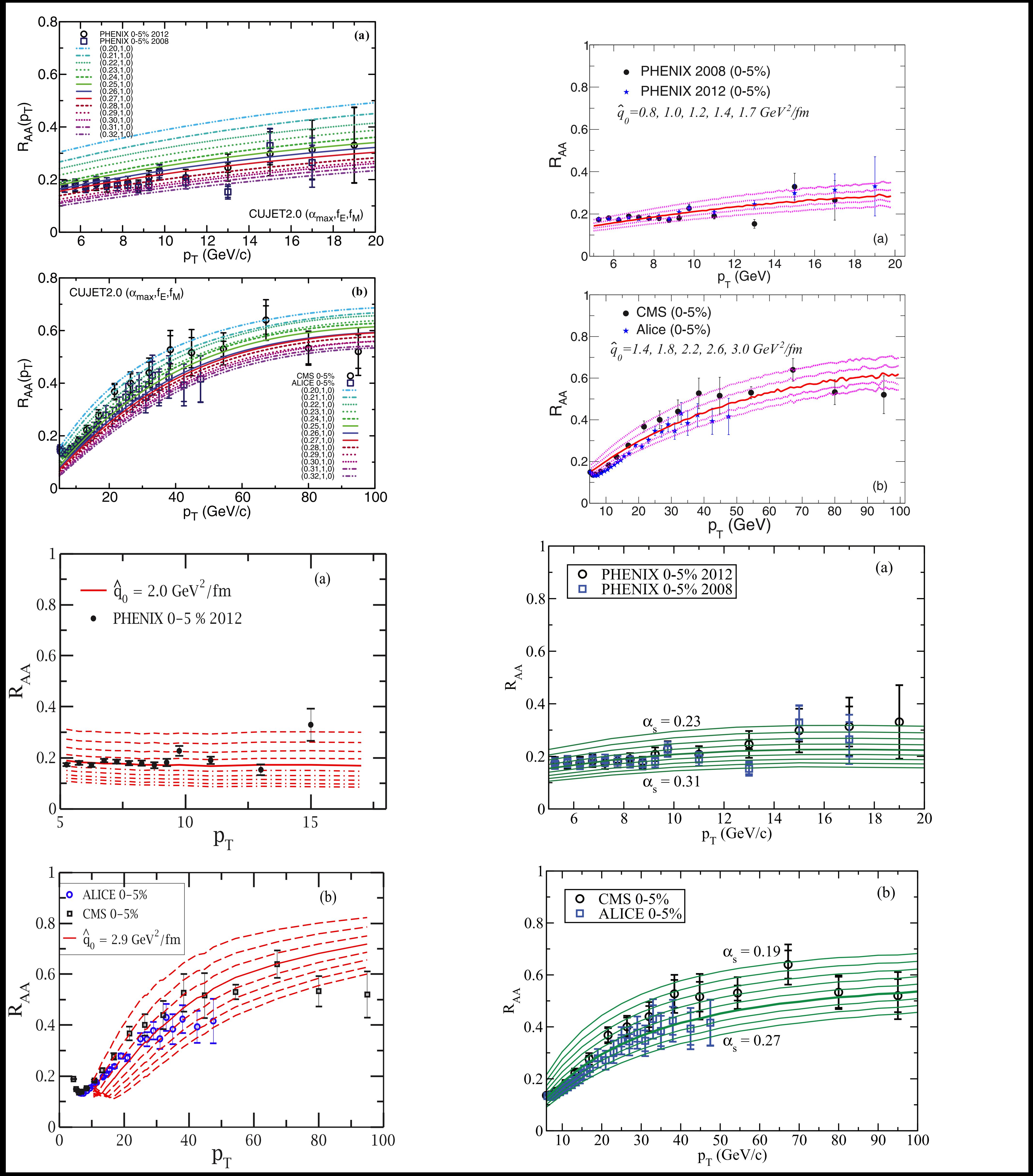


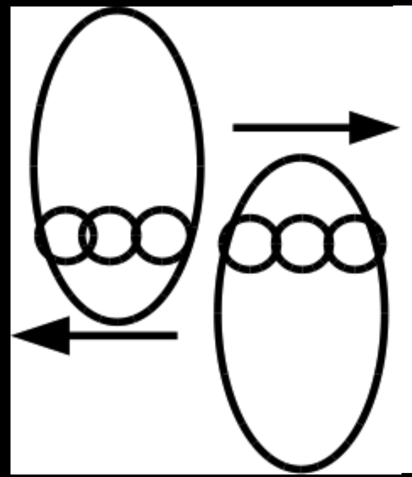


This depends on the space time profile of the Fluid dynamical simulation

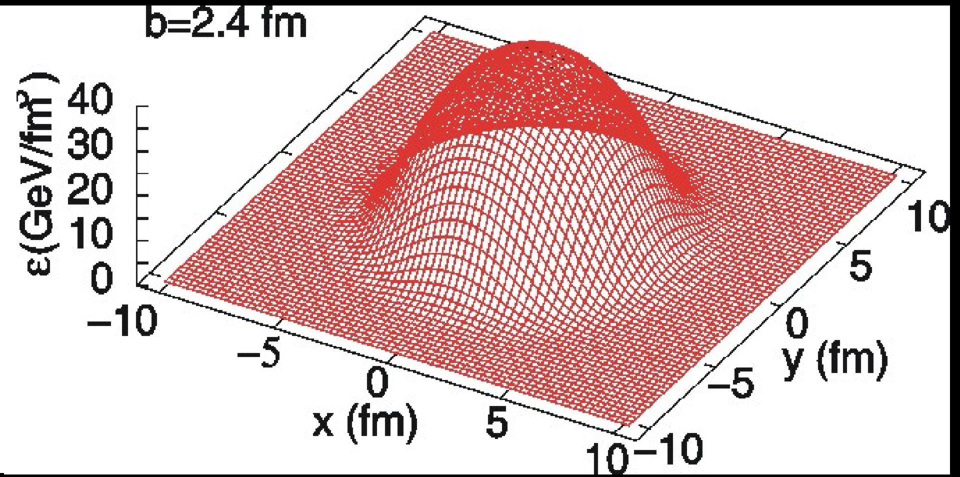
A first serious attempt to extract $\hat{q}$



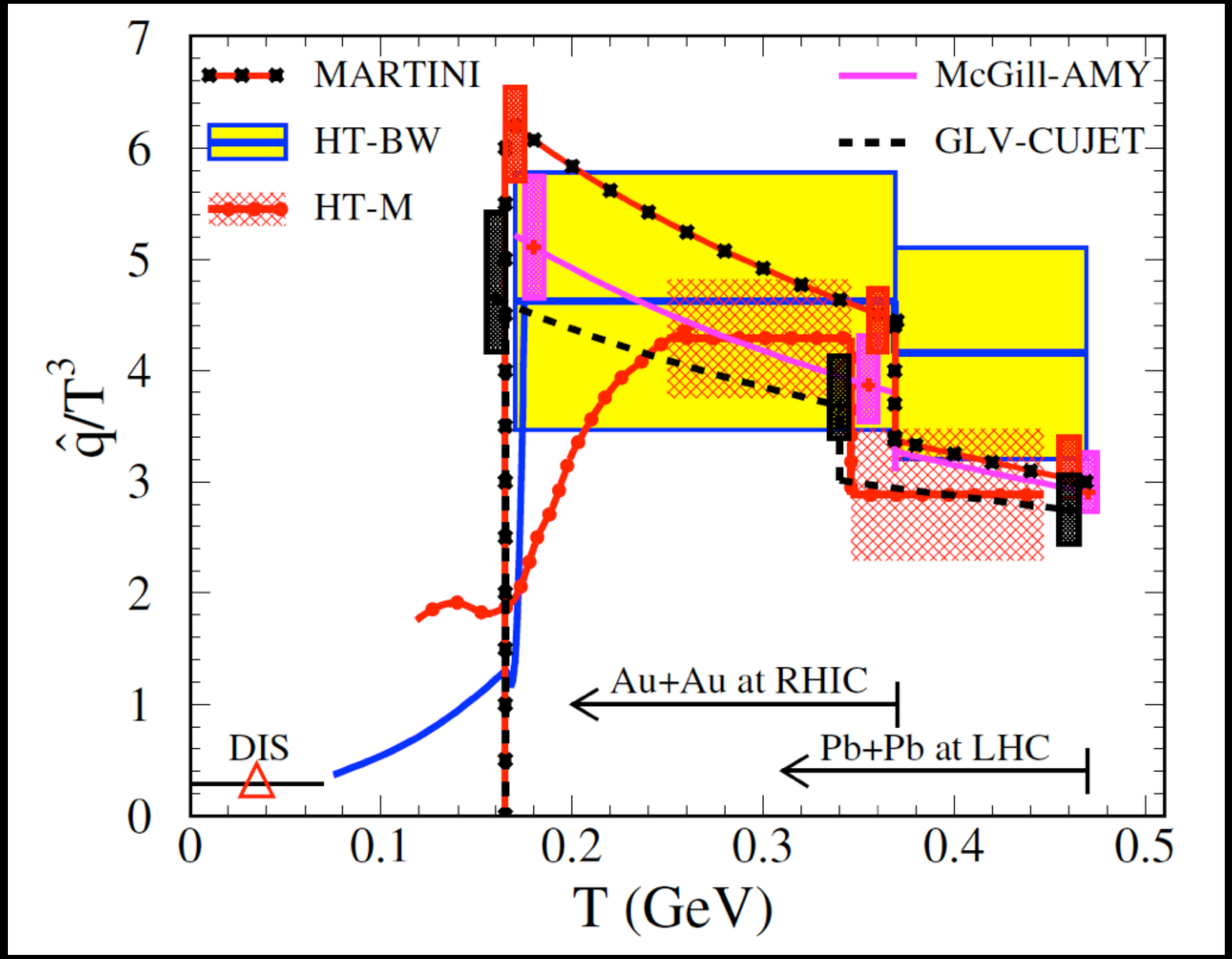
PRC 90 014909 2014



$$R_{AA} \sim \frac{\frac{dN_{AA}}{dp_T dy}}{N_{bin} \frac{dN_{pp}}{dp_T dy}}$$



Same hydro simulation used in all plots,
All other aspects of the calculation different!
All reported the effective range of $\hat{q}$



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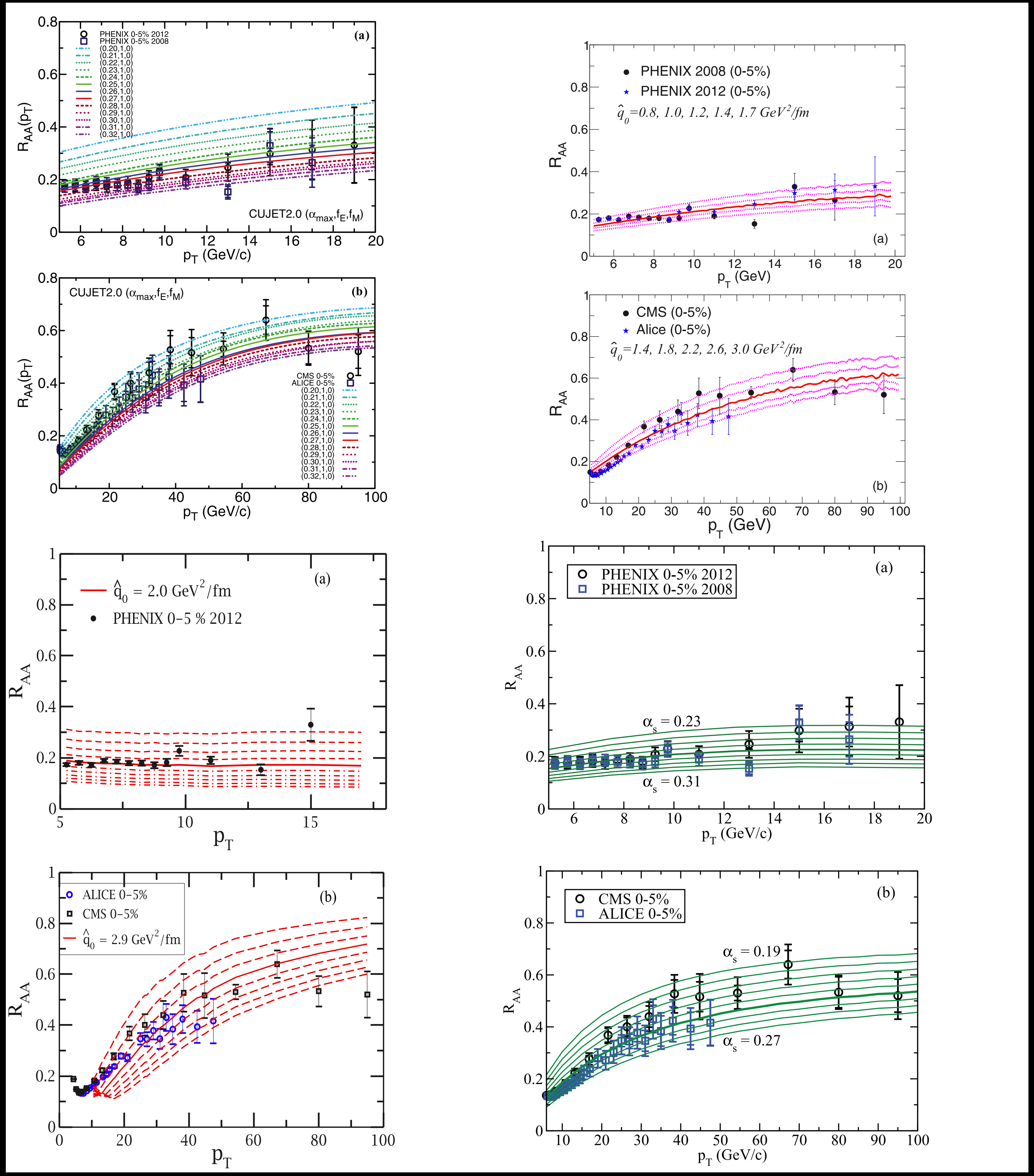

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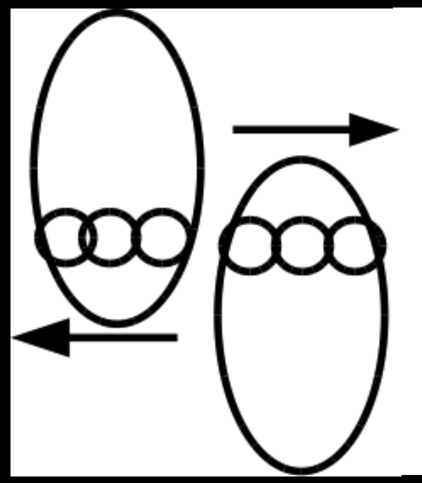

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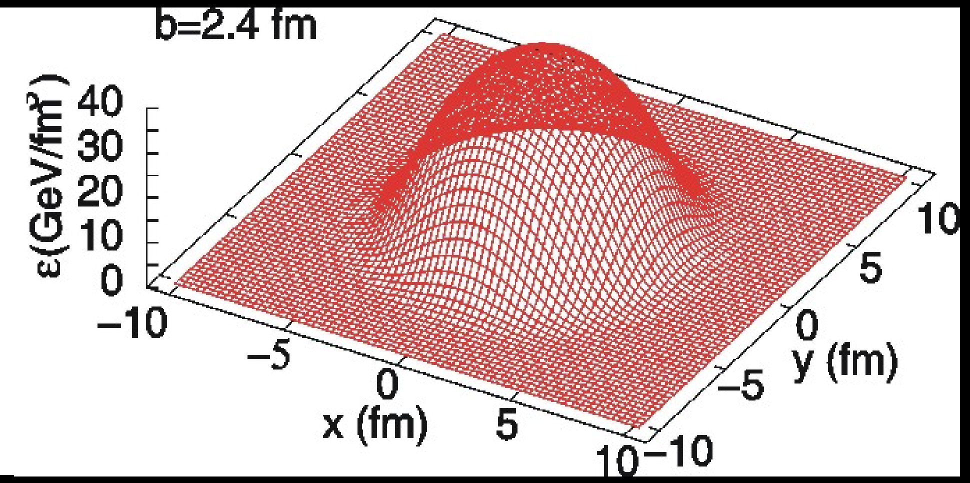

Same hydro simulation used in all plots,
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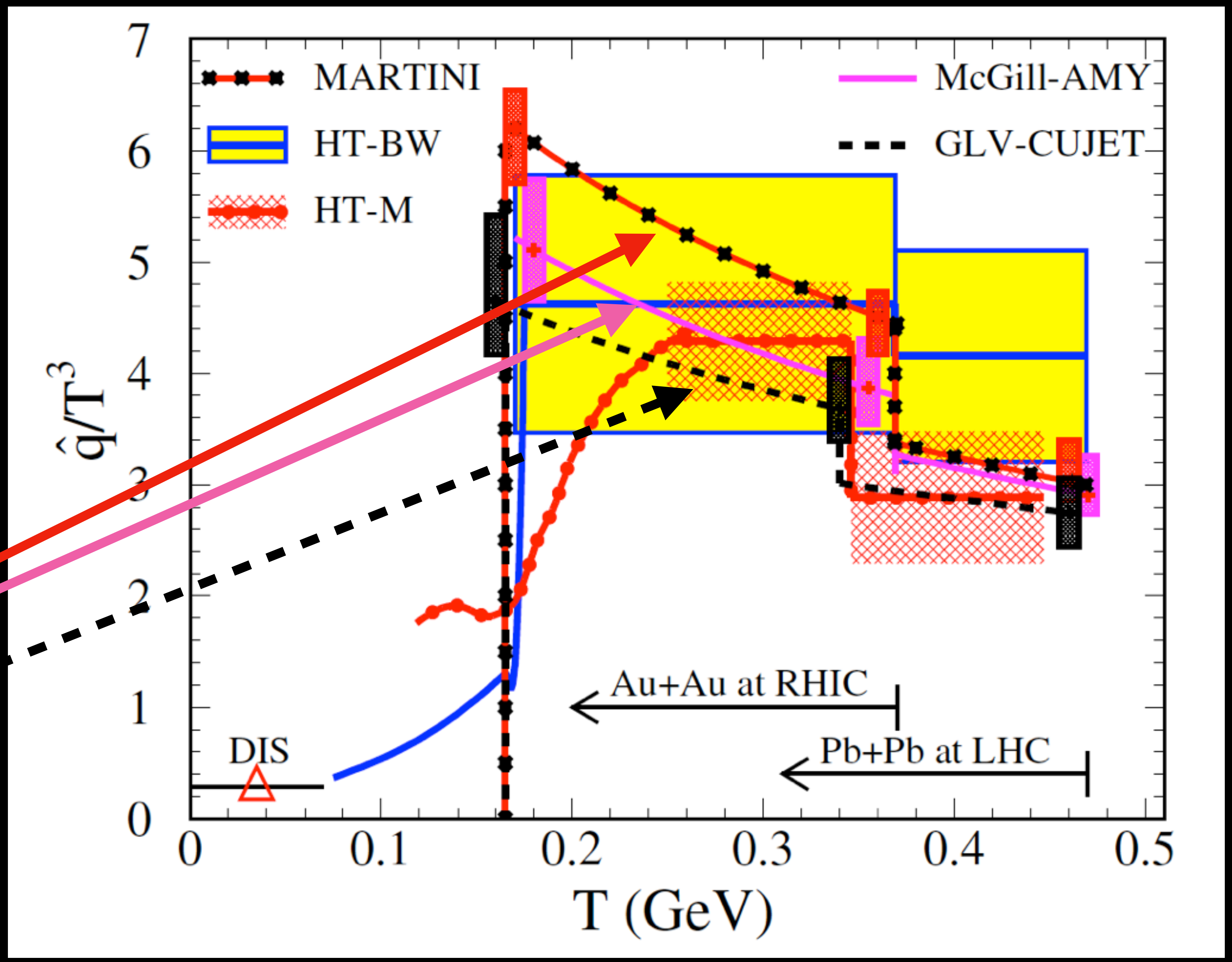
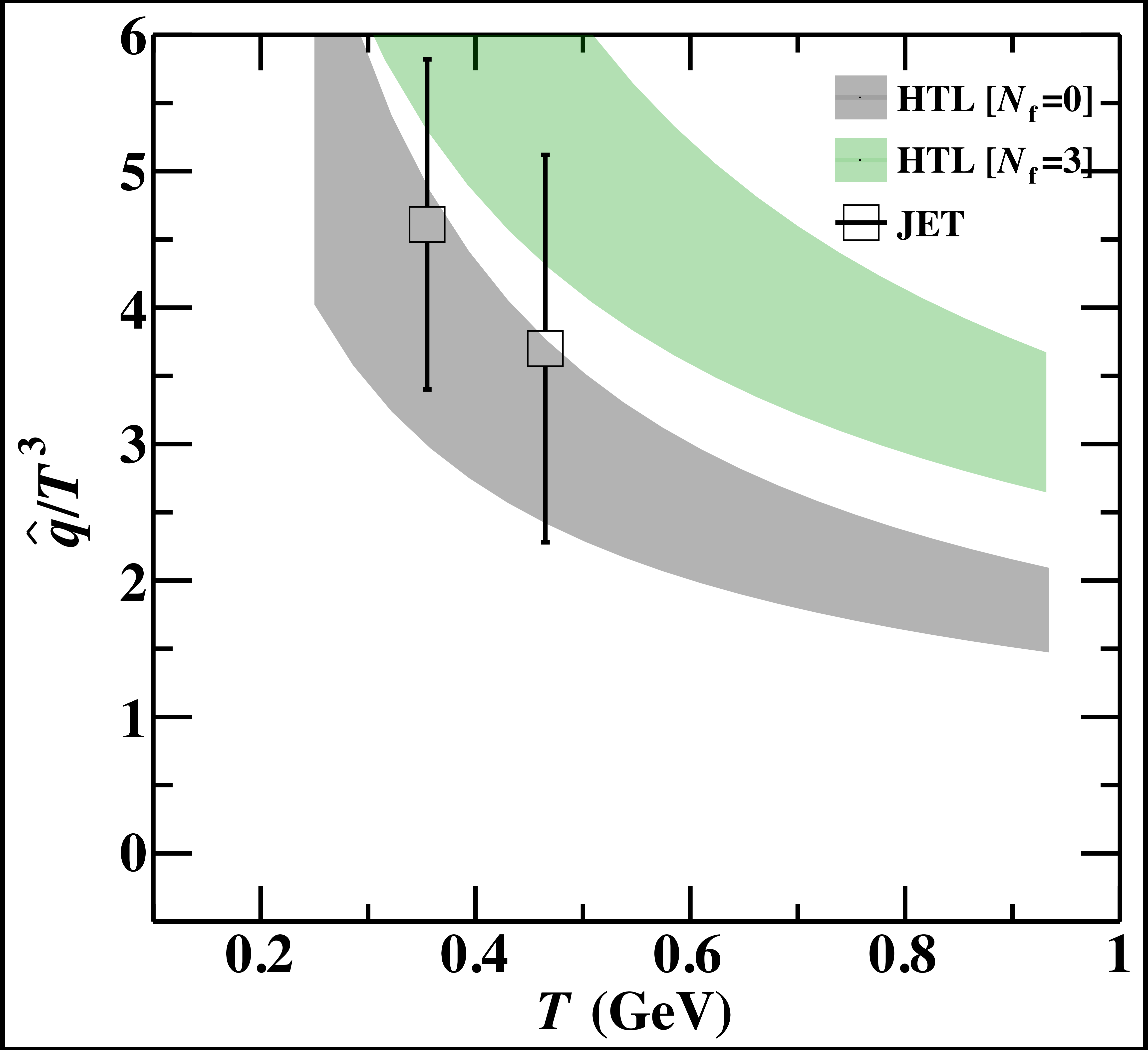
All reported the effective range of $\hat{q}$

Some use the HTL
Formula for $\hat{q}$ truncated



Adding to our plot! Circa (2014)



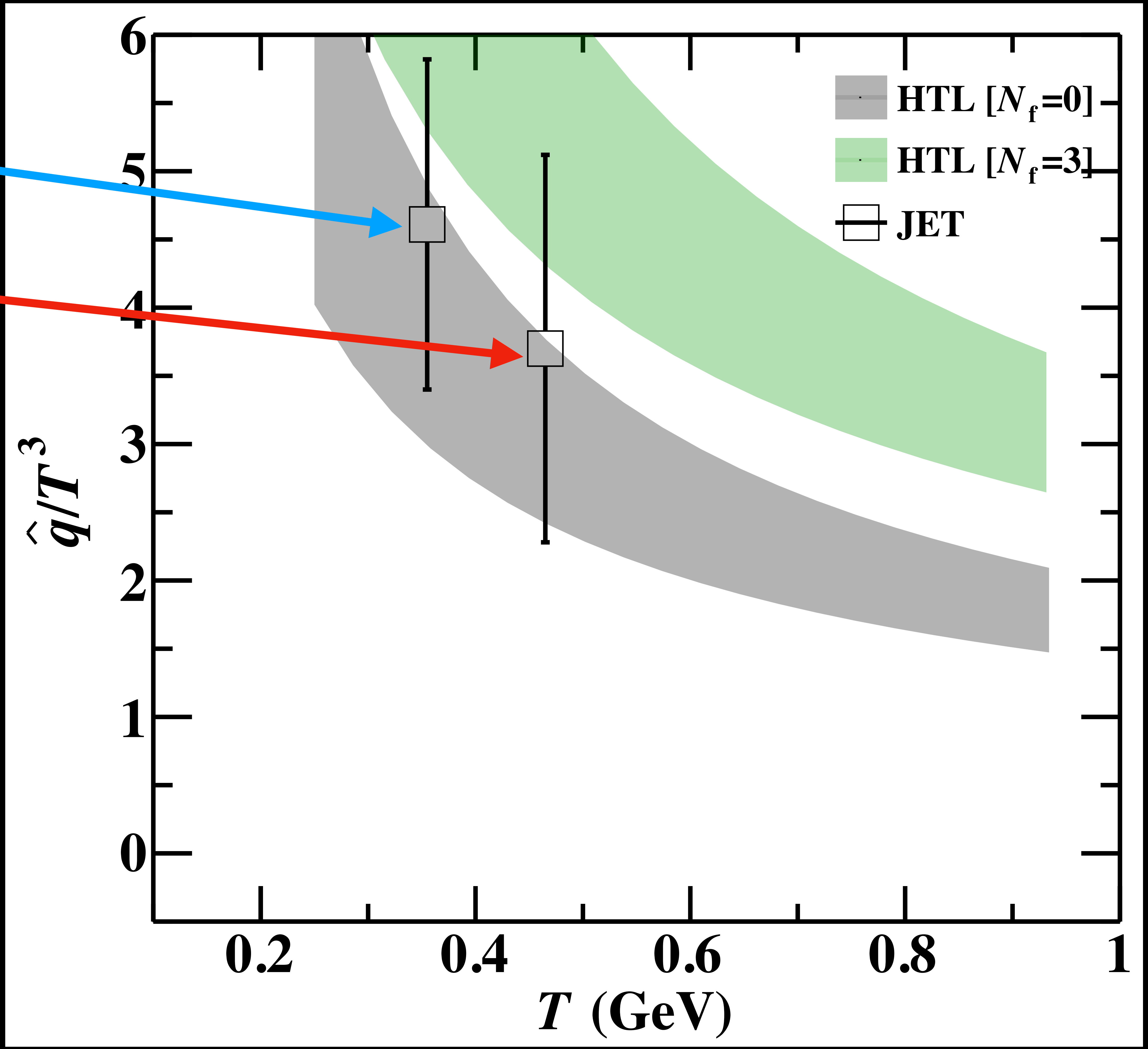
Adding to our plot! Circa (2014)

This point is the normalization at RHIC energies

This point is the normalization at LHC energies

$$T^{max}_{LHC} \simeq 1.2\, T^{max}_{RHIC}$$

$$p^{max}_{LHC} = 5\, p^{max}_{RHIC}$$



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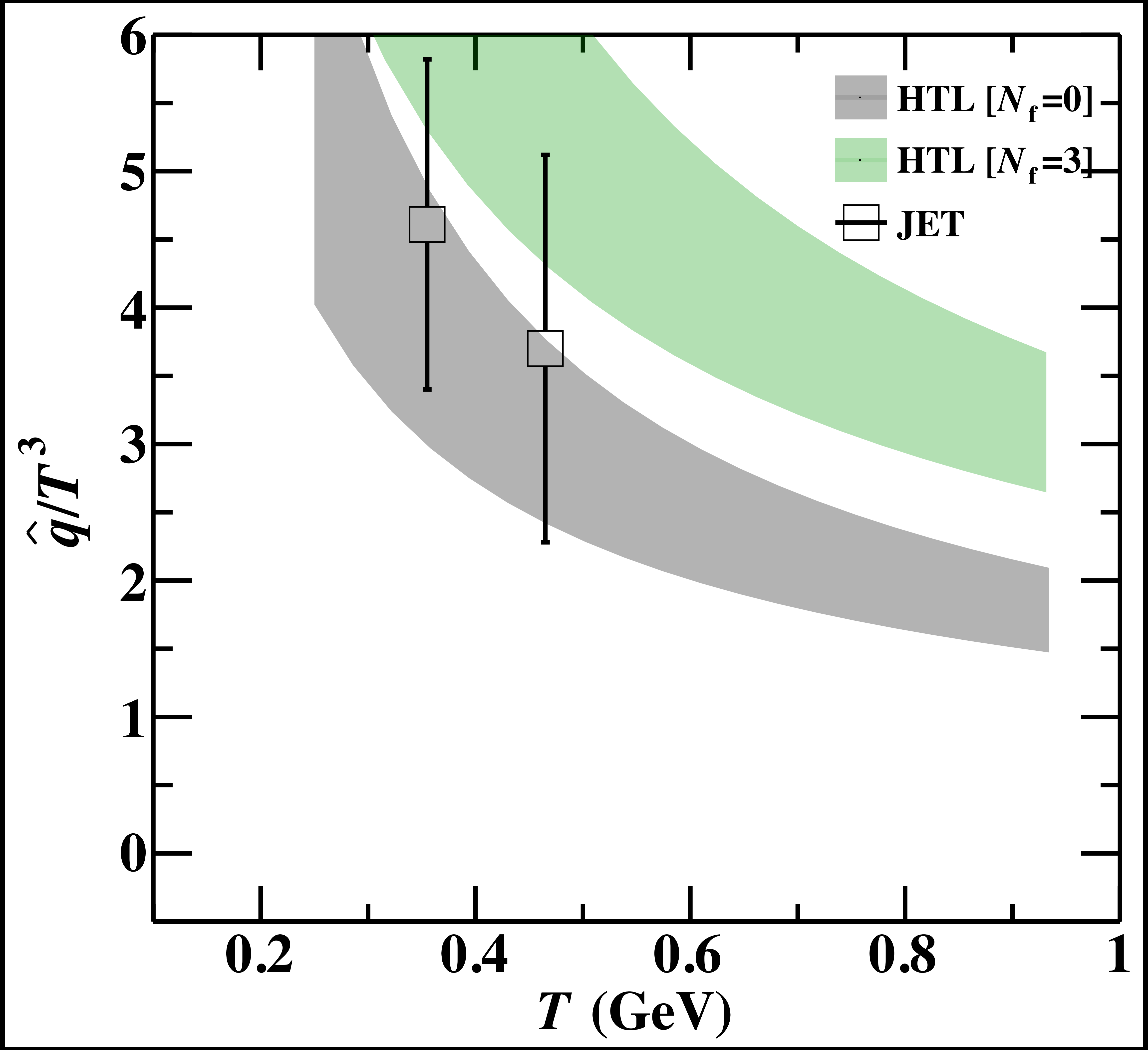
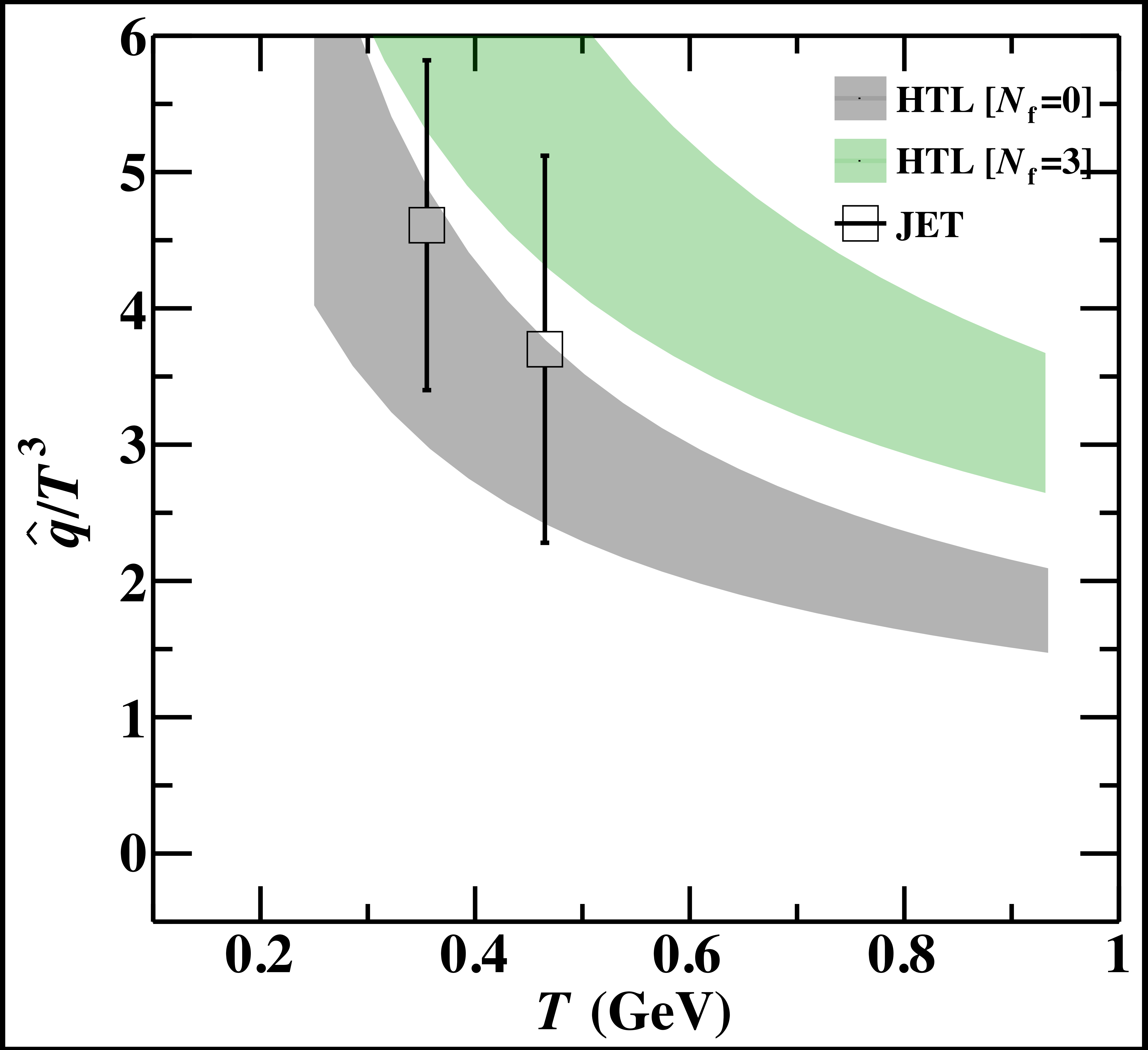


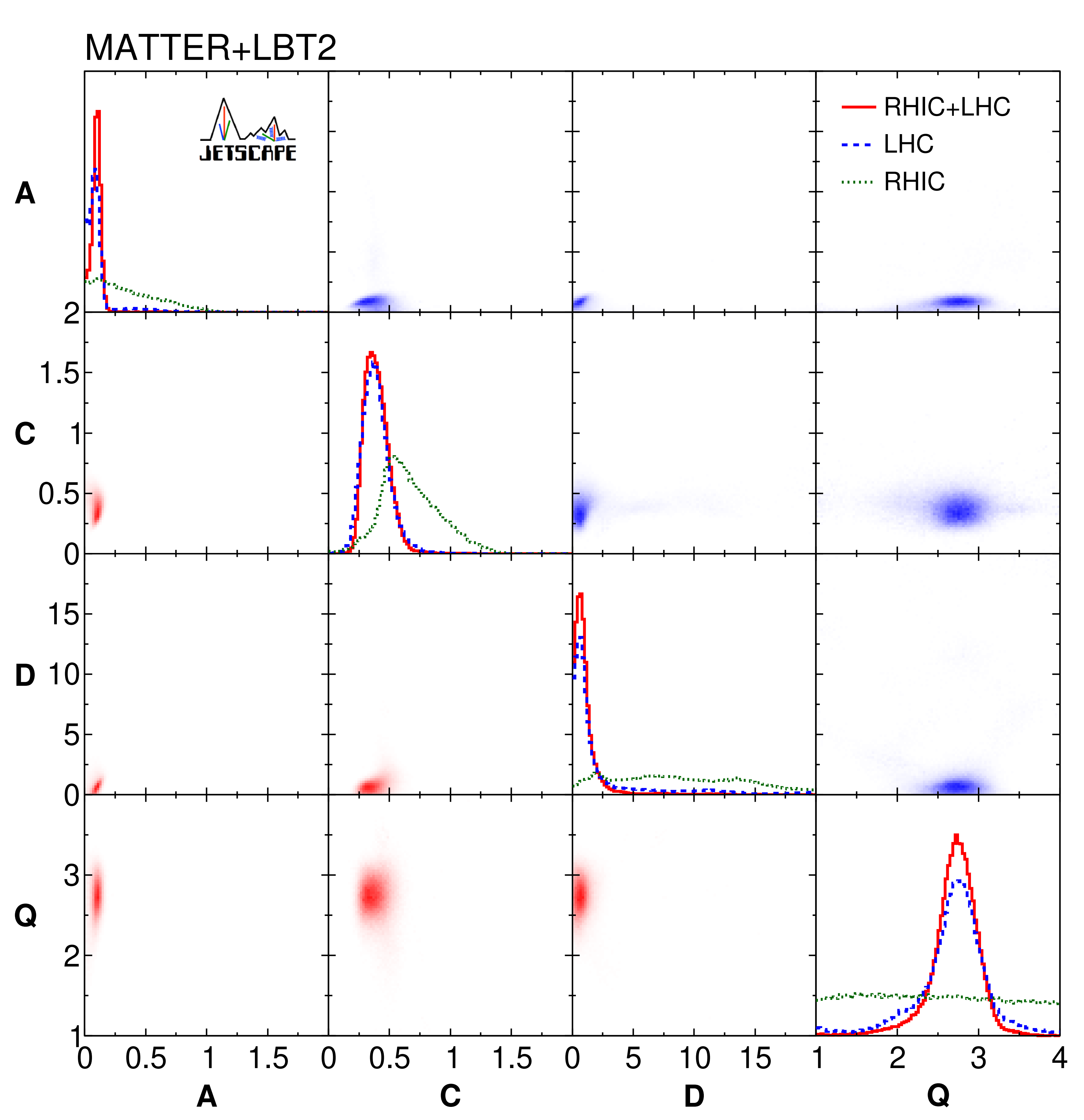
Adding to our plot! Circa (2014)

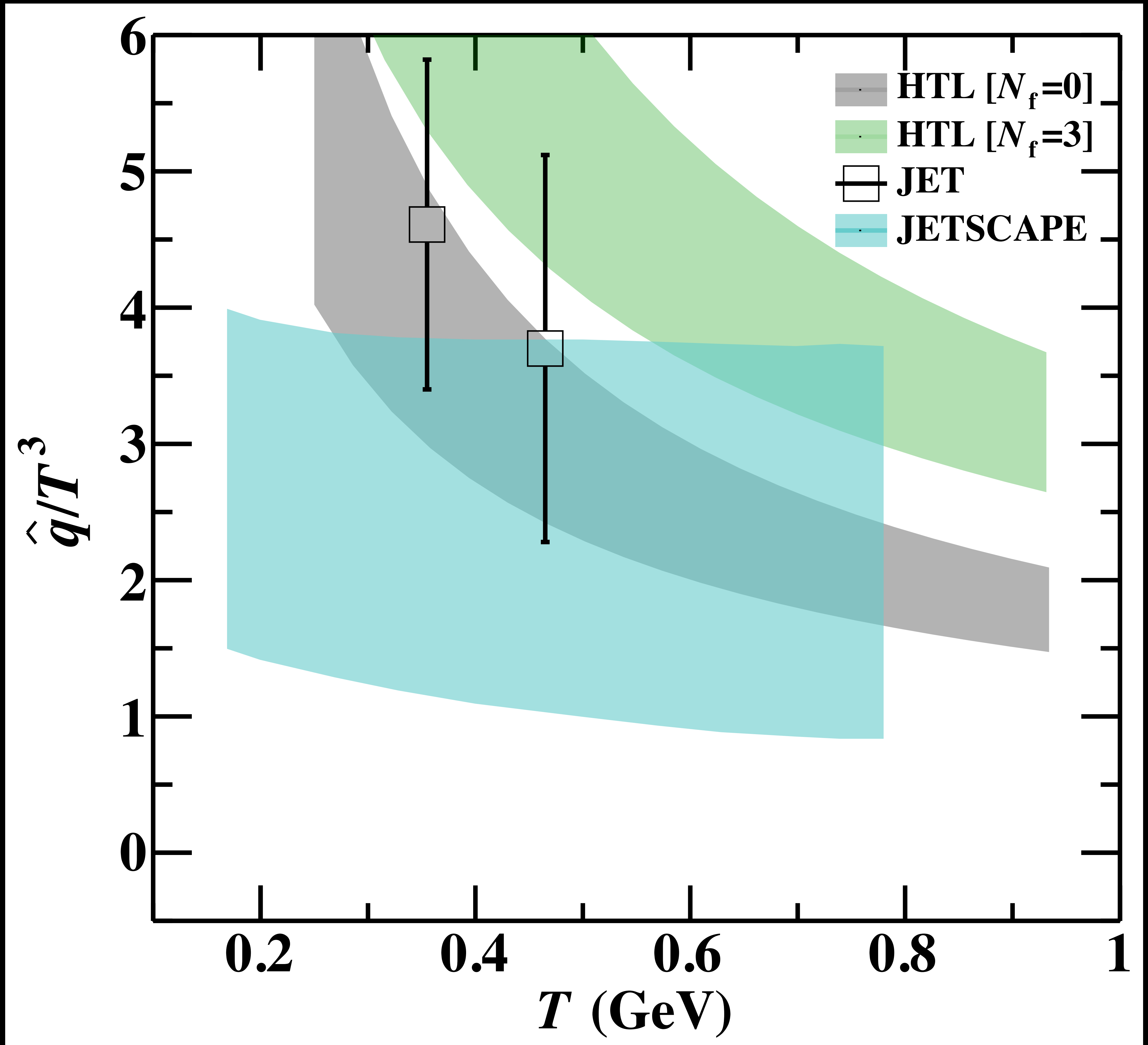
Non-Monotonic behavior
what many thought this meant!



If this is true, must effect the centrality dependence of R_{AA}, v_2, and its centrality dependence at a given collision energy but no such evidence is seen

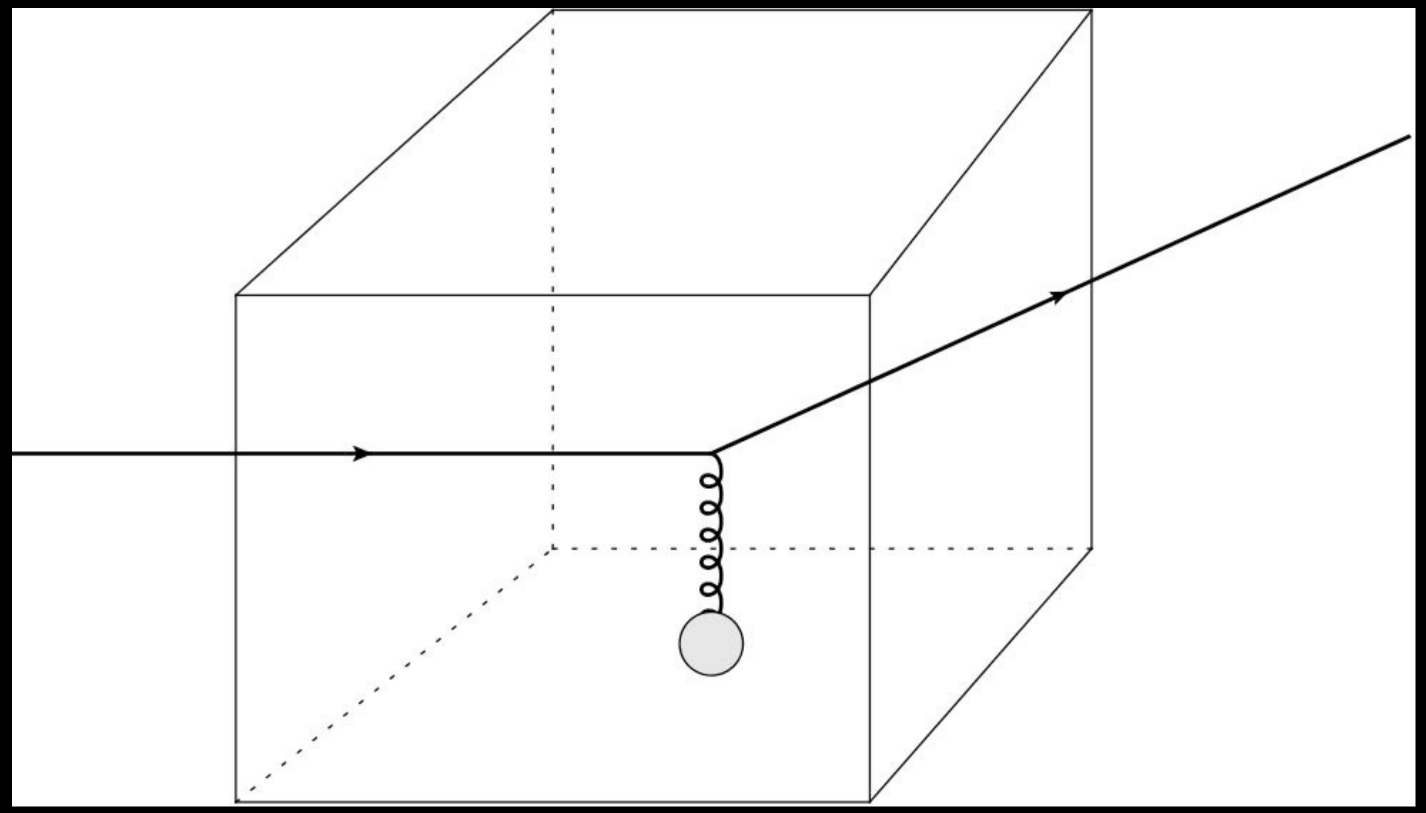
Transition scale and new $\hat{q}/T^3$ range





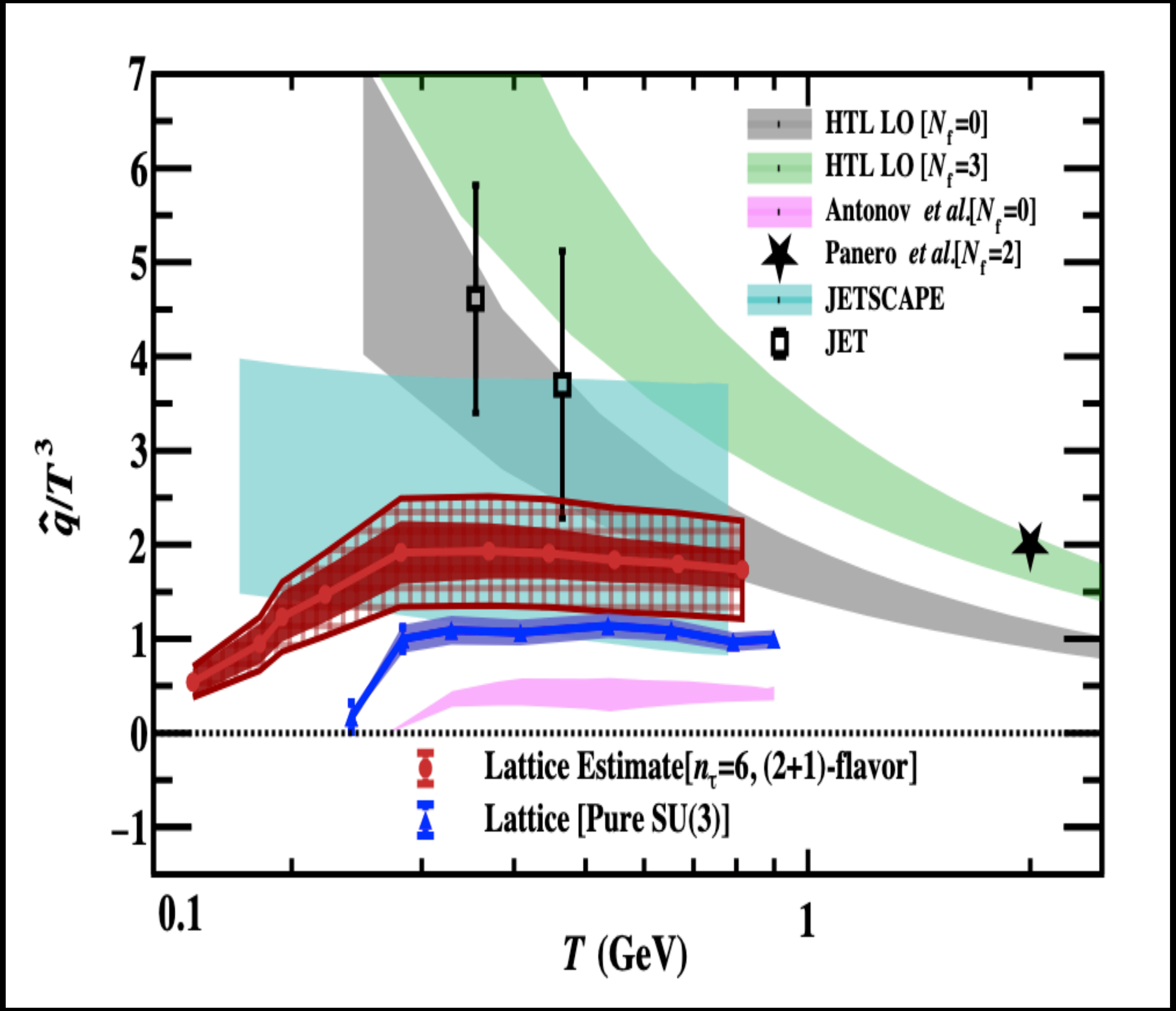
Calculating $\hat{q}$ in Lattice QCD

A. Kumar, A.M., J. Weber, arXiv:2010.14463



$$q^- = \frac{q^0 - q^3}{\sqrt{2}} \to \infty$$

$$q^+ = \frac{q^0 + q^3}{\sqrt{2}} \to 0$$



$$\hat{q} = \frac{4\pi^2\alpha_S}{N_c}\int \frac{dy^- d^2y_\perp}{(2\pi)^3} d^2k_\perp e^{-i\frac{k_\perp^2}{2q^-}y^- + i\vec{k}_\perp\cdot\vec{y}_\perp}$$

$$\times \sum_n \frac{e^{-\beta E_n}}{Z} \langle n | F_\perp^+(y^-, \vec{y}_\perp) F_\perp^+(0) | n \rangle$$

Fully non-perturbative calculation of $\hat{q}$

All calculations for a 100 GeV quark,

Lattice Calculations show weak dependence on E

The need for an event generator framework

The need for an event generator framework

- An event generator is a computer simulation that produces experiment like events
- An E. G. framework allows a user to design/modify modular elements in a simulator.
- Carrying out a systematic analysis requires a systematic framework
- You have to work with several correlated input parameters, in correlated modules.
- Every time you change an input, compare with all the data simultaneously

Overview

- Scale dependence and Asymptotic freedom of QCD
- Factorization and multi-scale approaches in QCD
- Jets and substructure
- Scale dependence in the evolution of jets
- The hard, intermediate and soft regions of a jet
- Observables that depend on all 3 regions
- Observables that depend on 2 regions
- Understanding the soft region of jet quenching

About that Jet Shape

- With correlated broadening up to the Mach angle from viscous hydro.