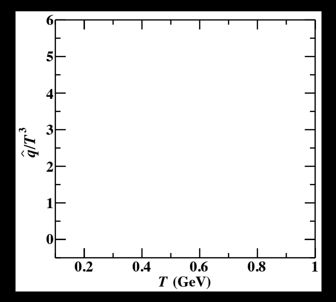
Simulating jet quenching in detail

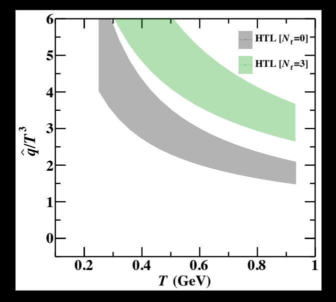
Abhijit Majumder

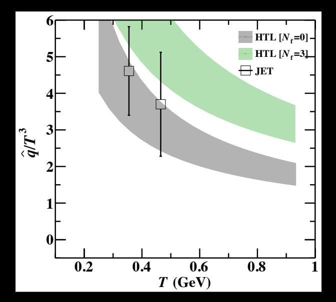
S@INT Feb 16th 2023

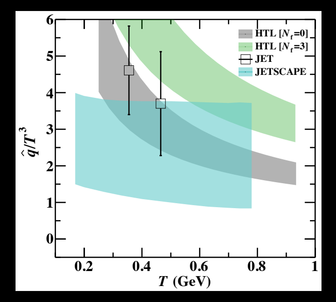
Overview

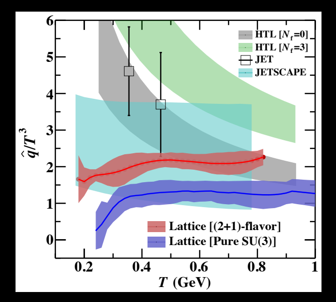
- Scale dependence and Factorization
- Jets and substructure
- $\hat{q}$ and other jet transport coefficients
- The JET collaboration and the JETSCAPE Collaboration
- Scale dependence in the evolution of jets
- Scale dependence in transport coefficients
- Data driven extractions of $\hat{q}$
- Lattice calculations of $\hat{q}$
- The need for a theory beyond HTL







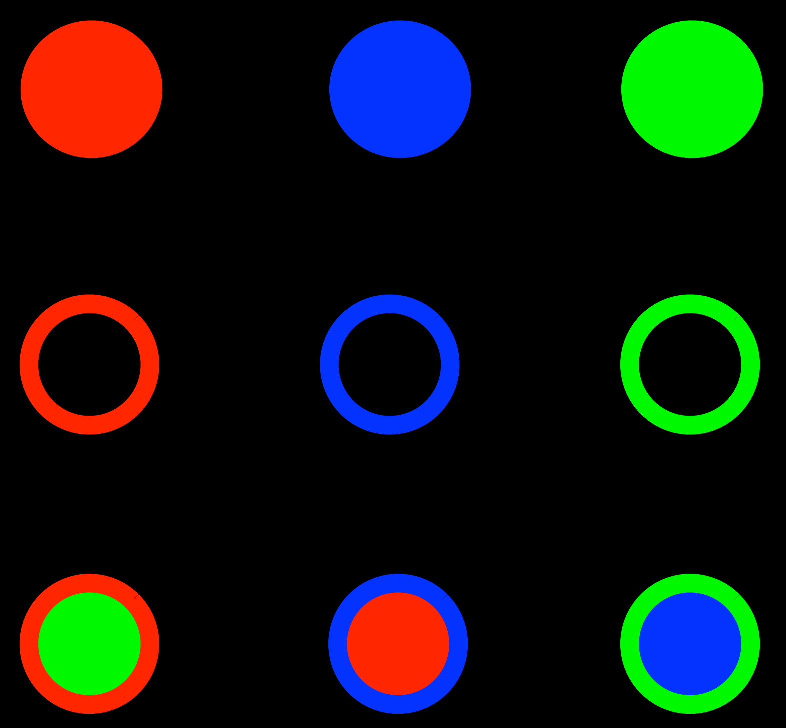




The whole talk in one slide

- 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

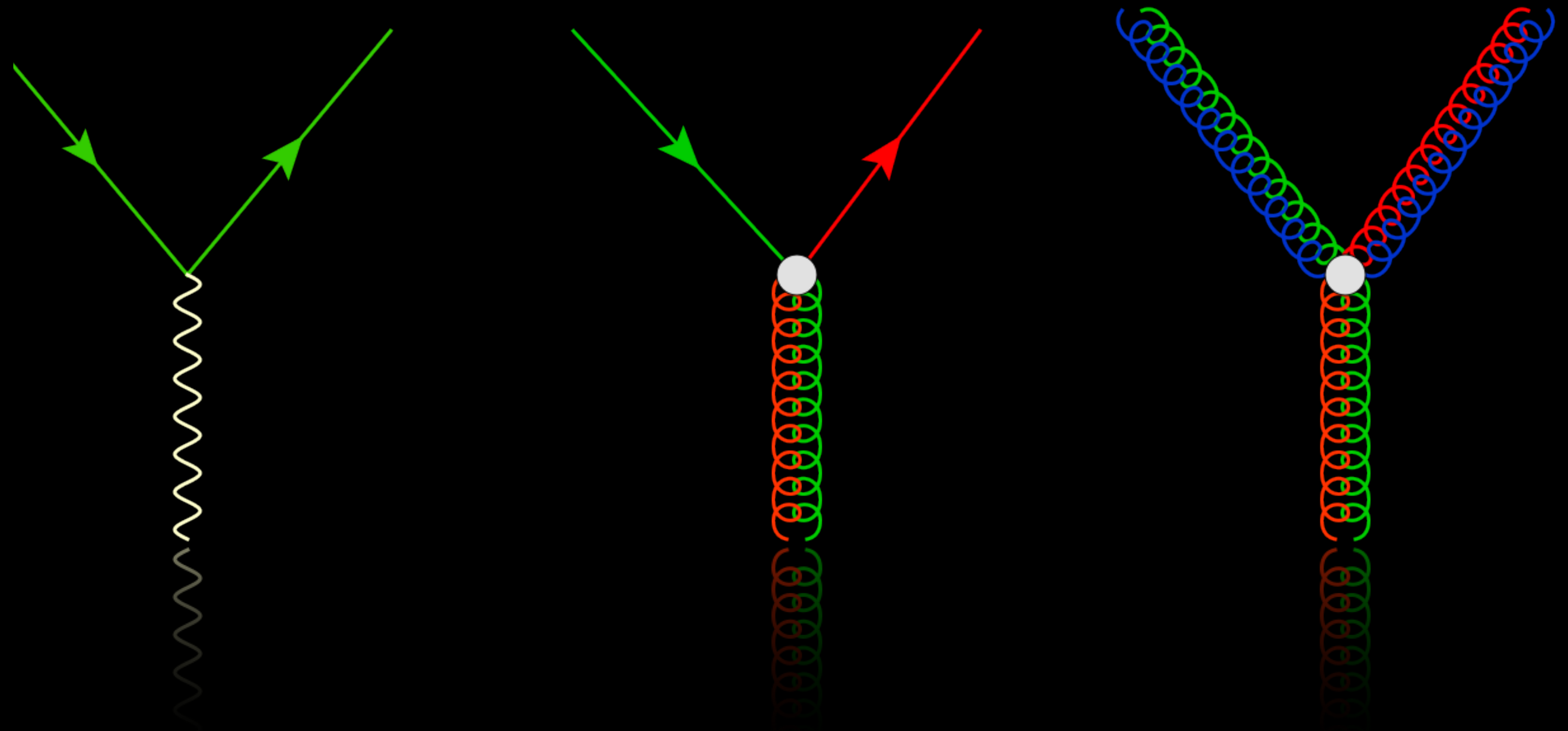
QCD: Quarks Gluons and scale (Q)!

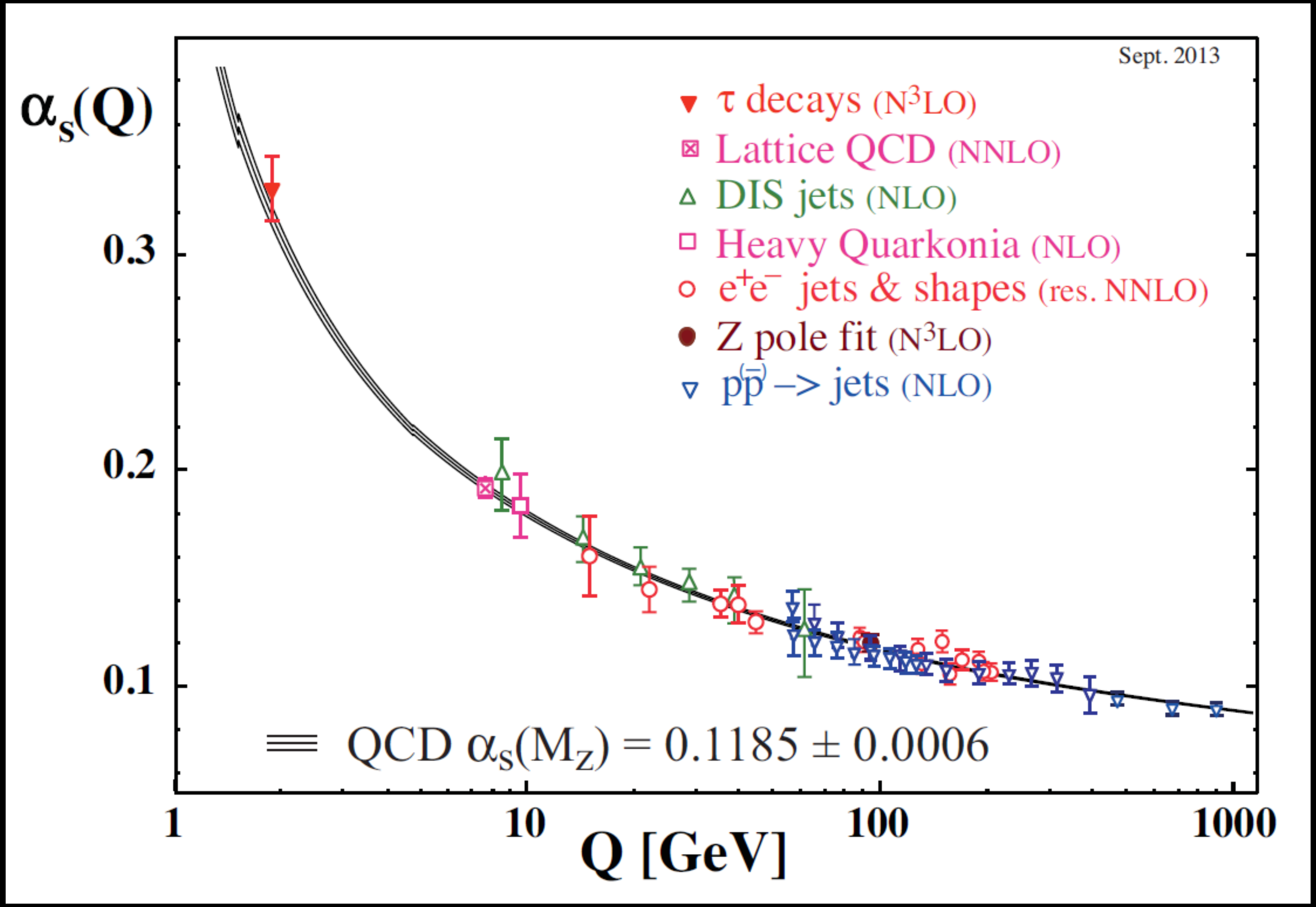


Quarks carry color

Anti-quarks carry anti-color

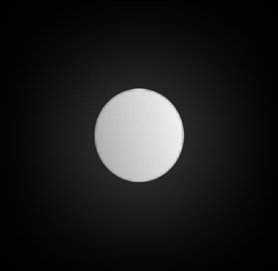
Gluons carry adjoint color





Asymptotic Freedom: weakening of coupling with scale

Well known from Deep Inelastic Scattering
What the electron sees, depends on E, Q^2



Increasing energy Q^2 = getting closer to proton

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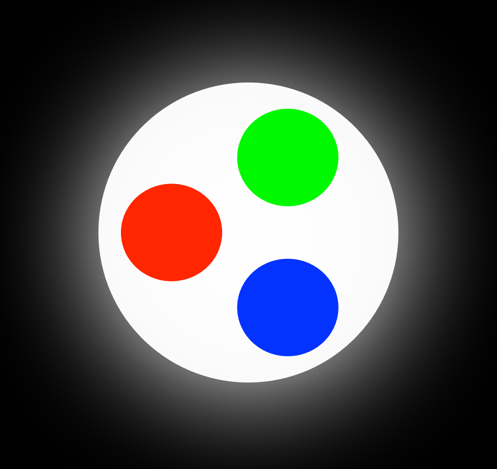

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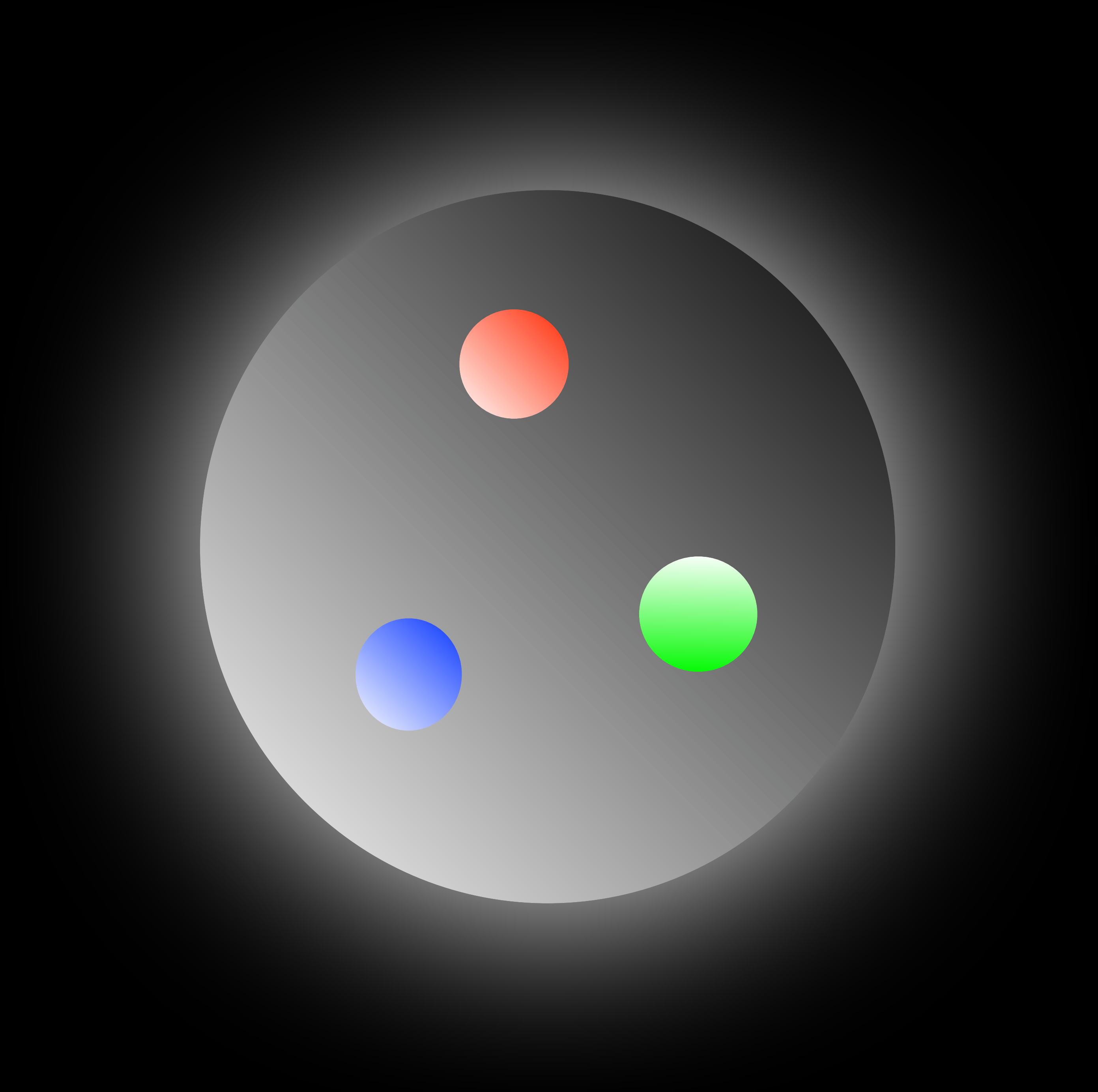

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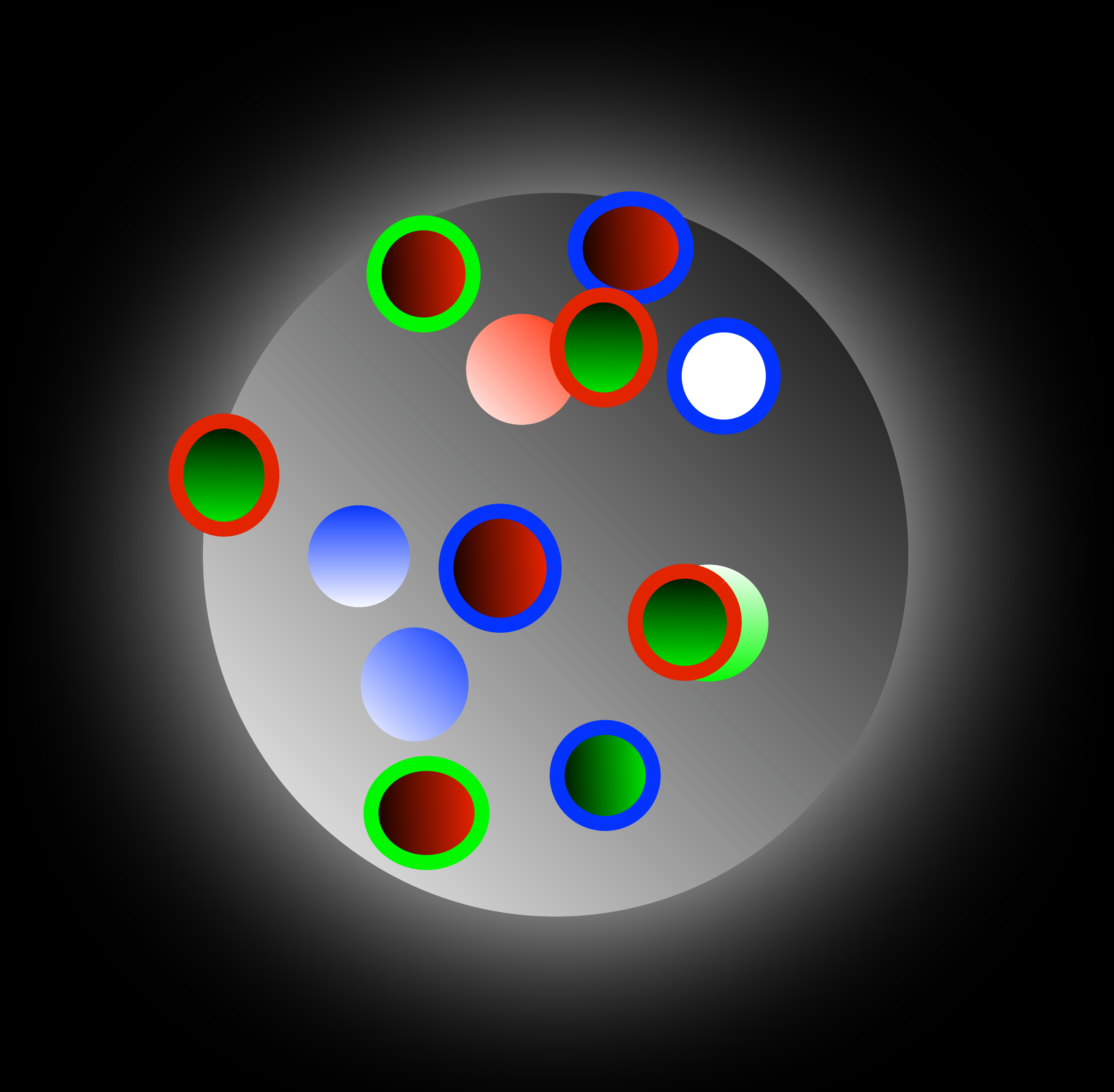

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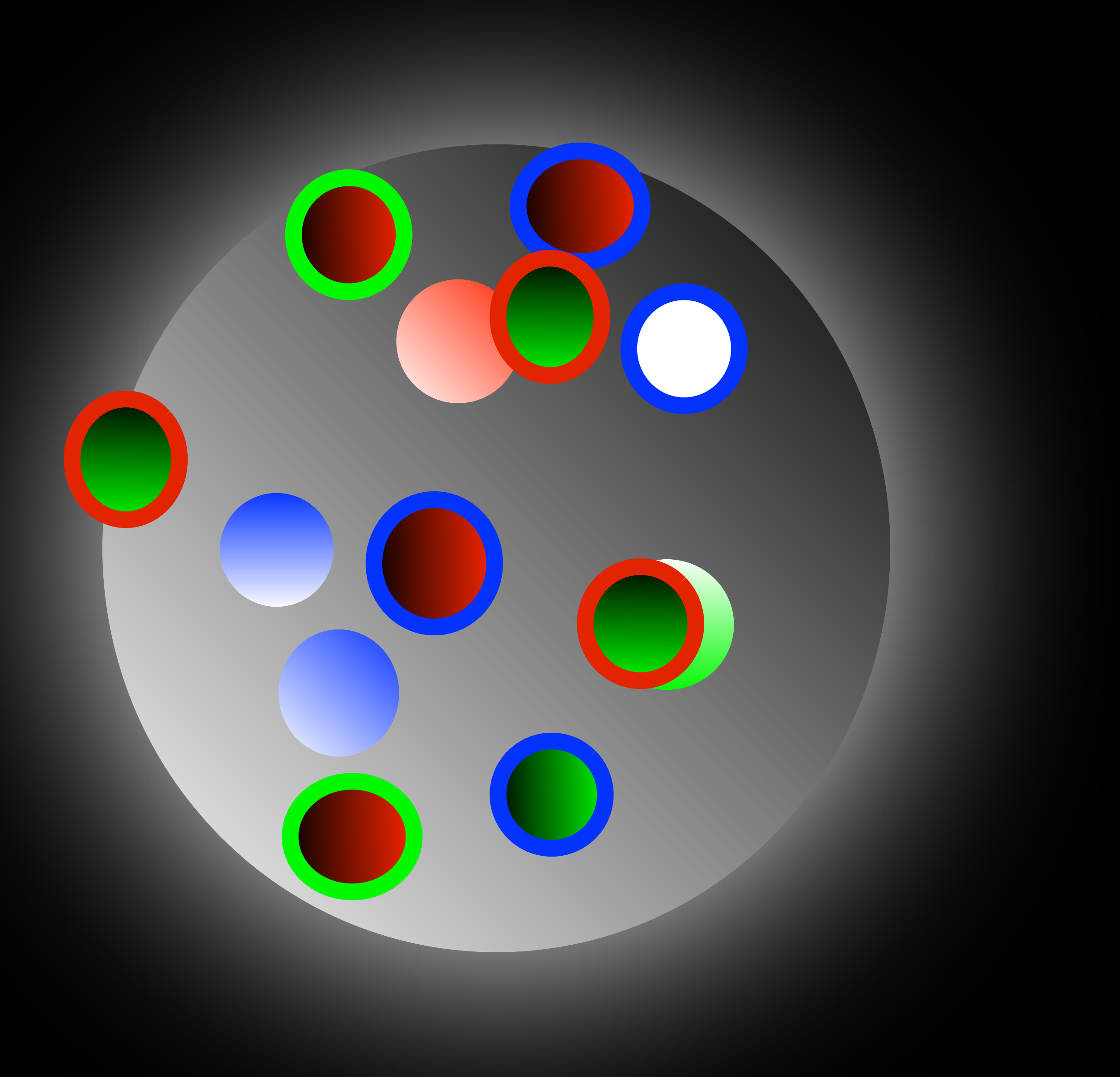

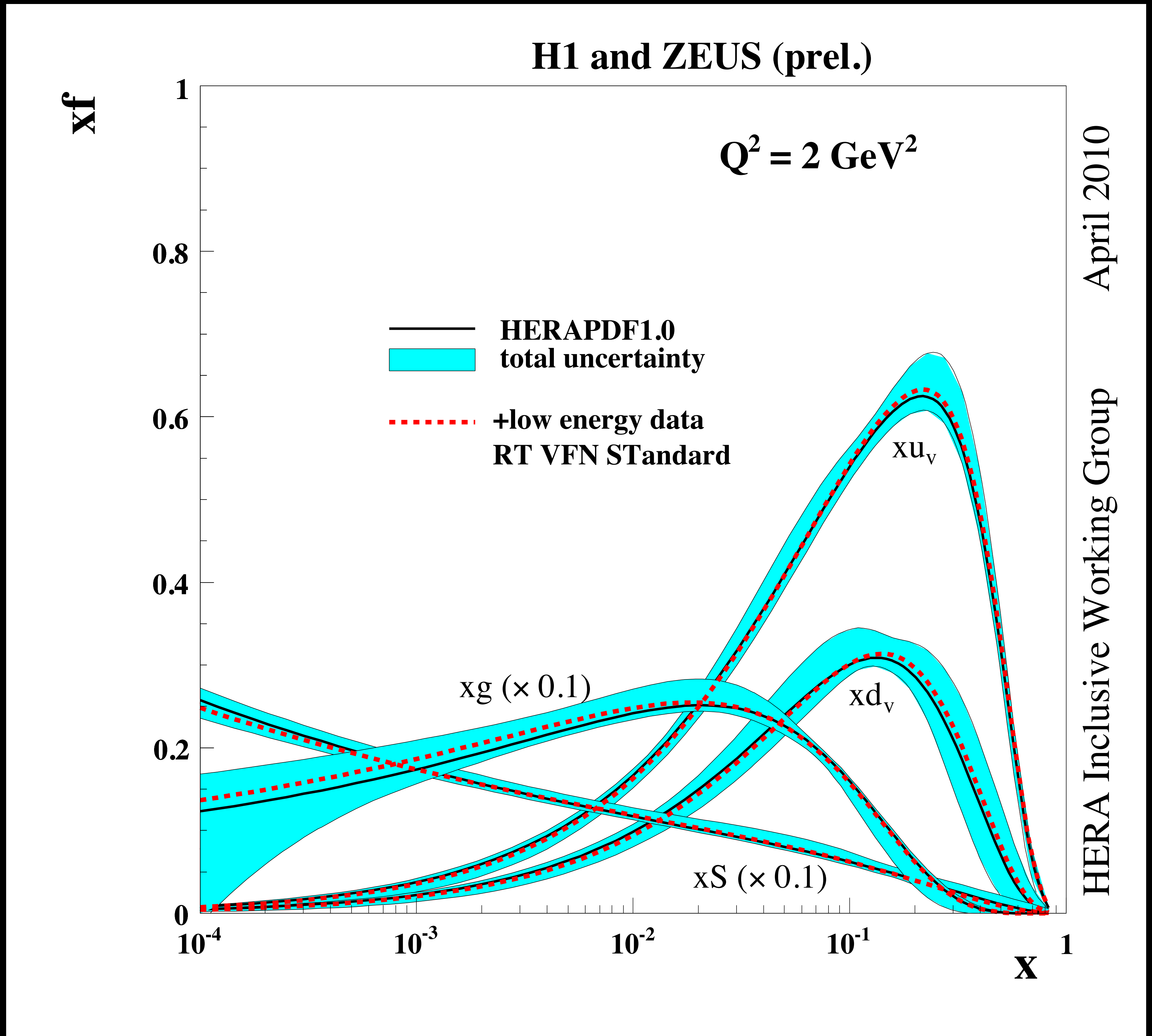

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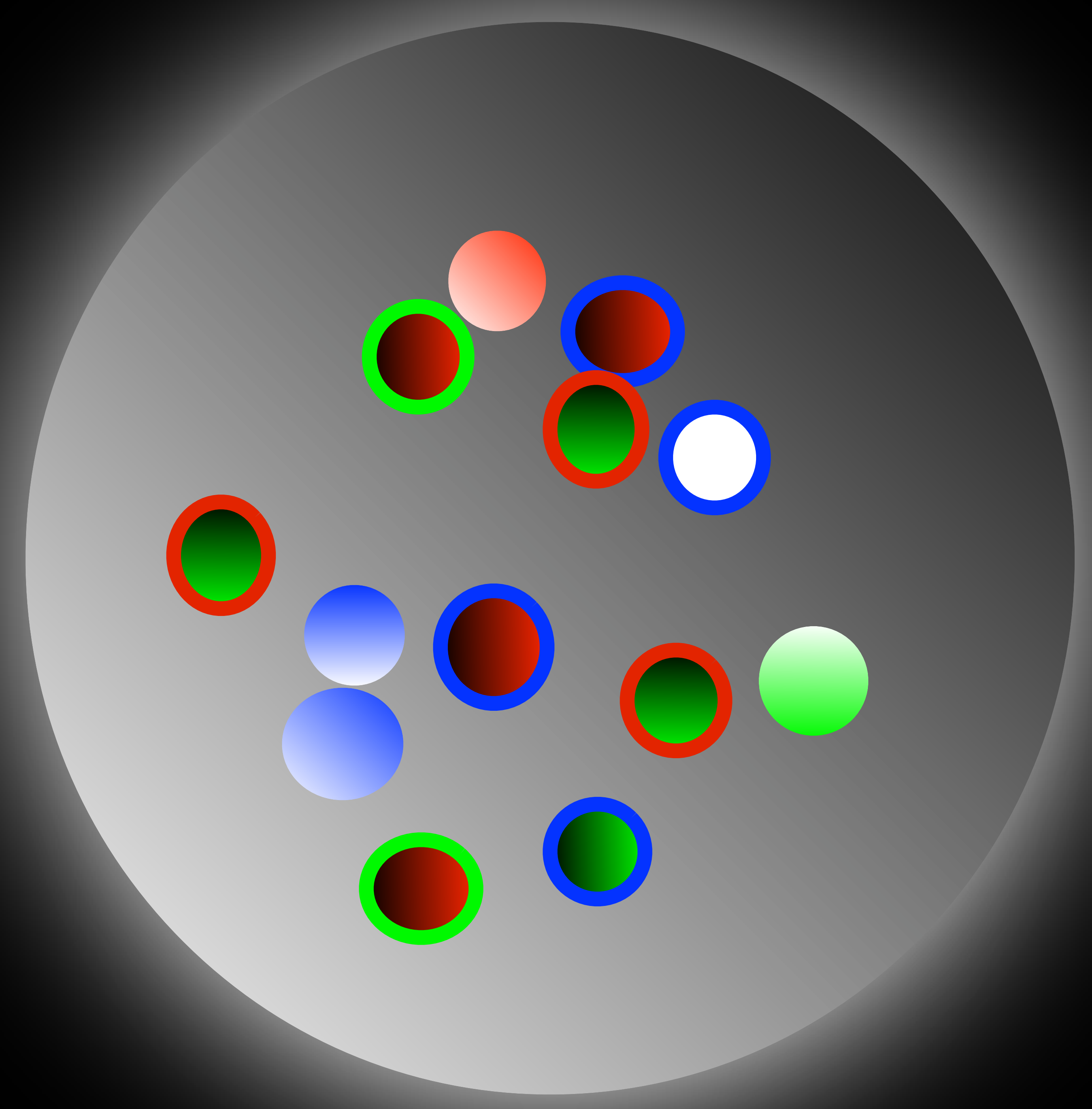

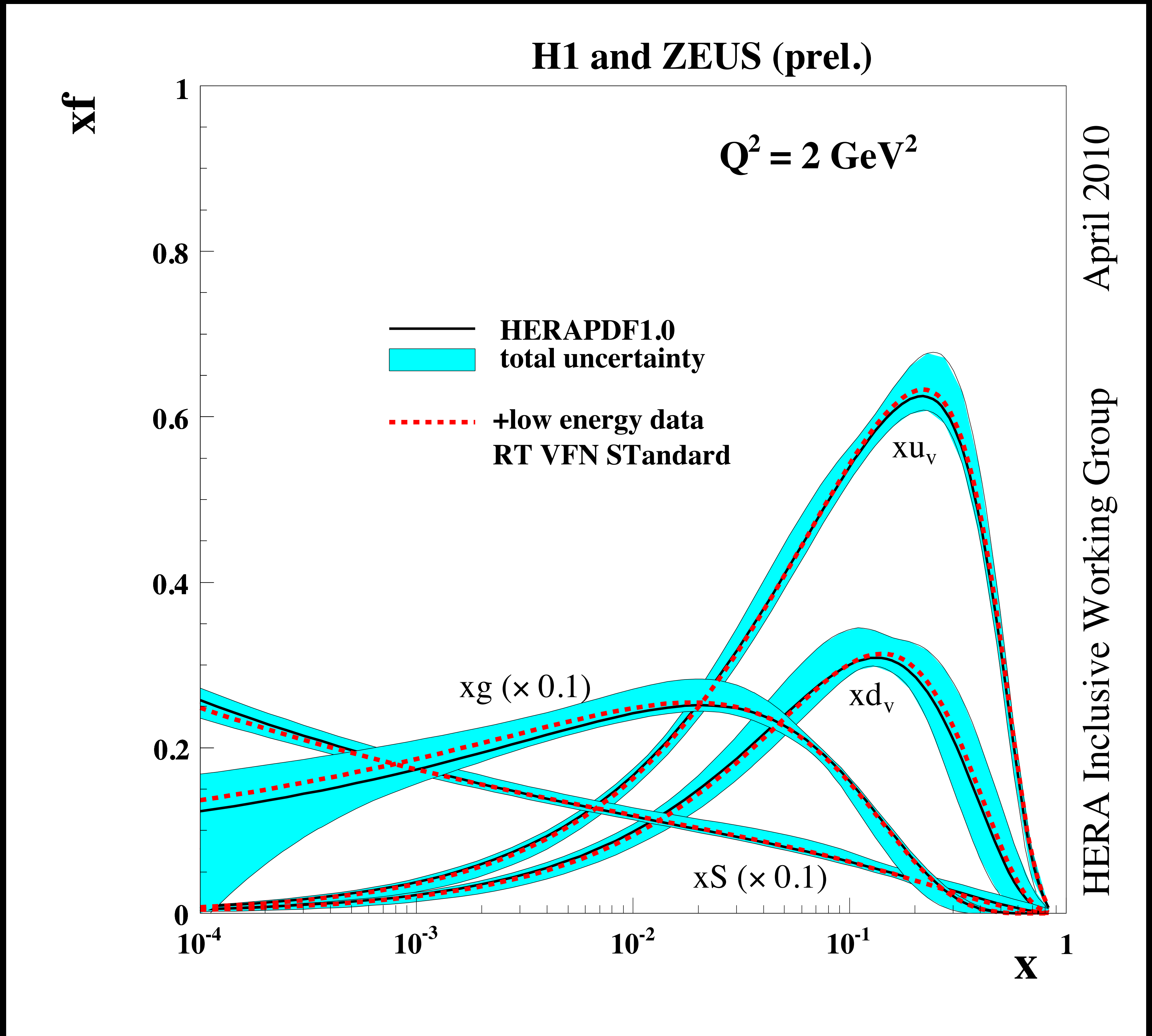

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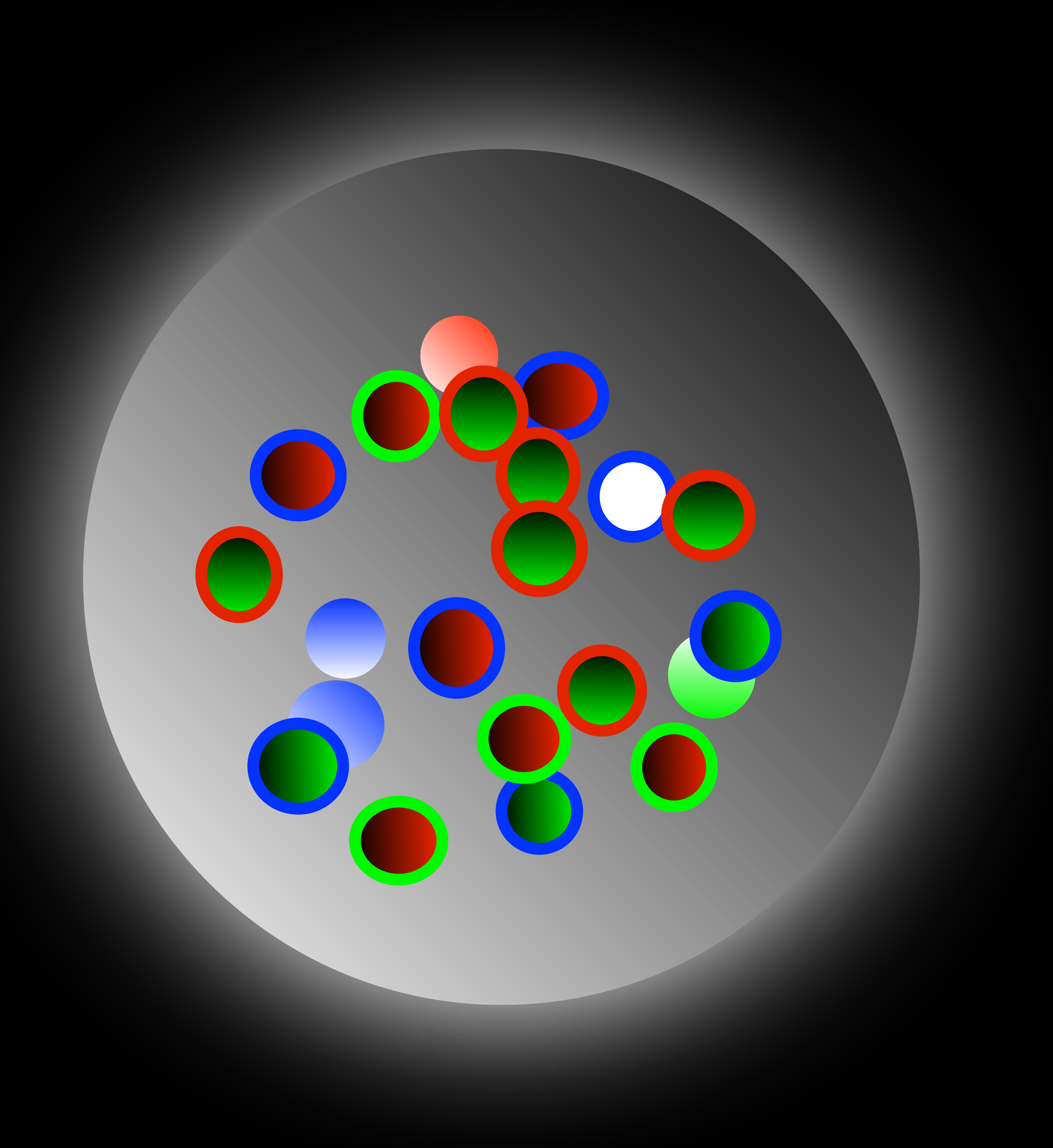
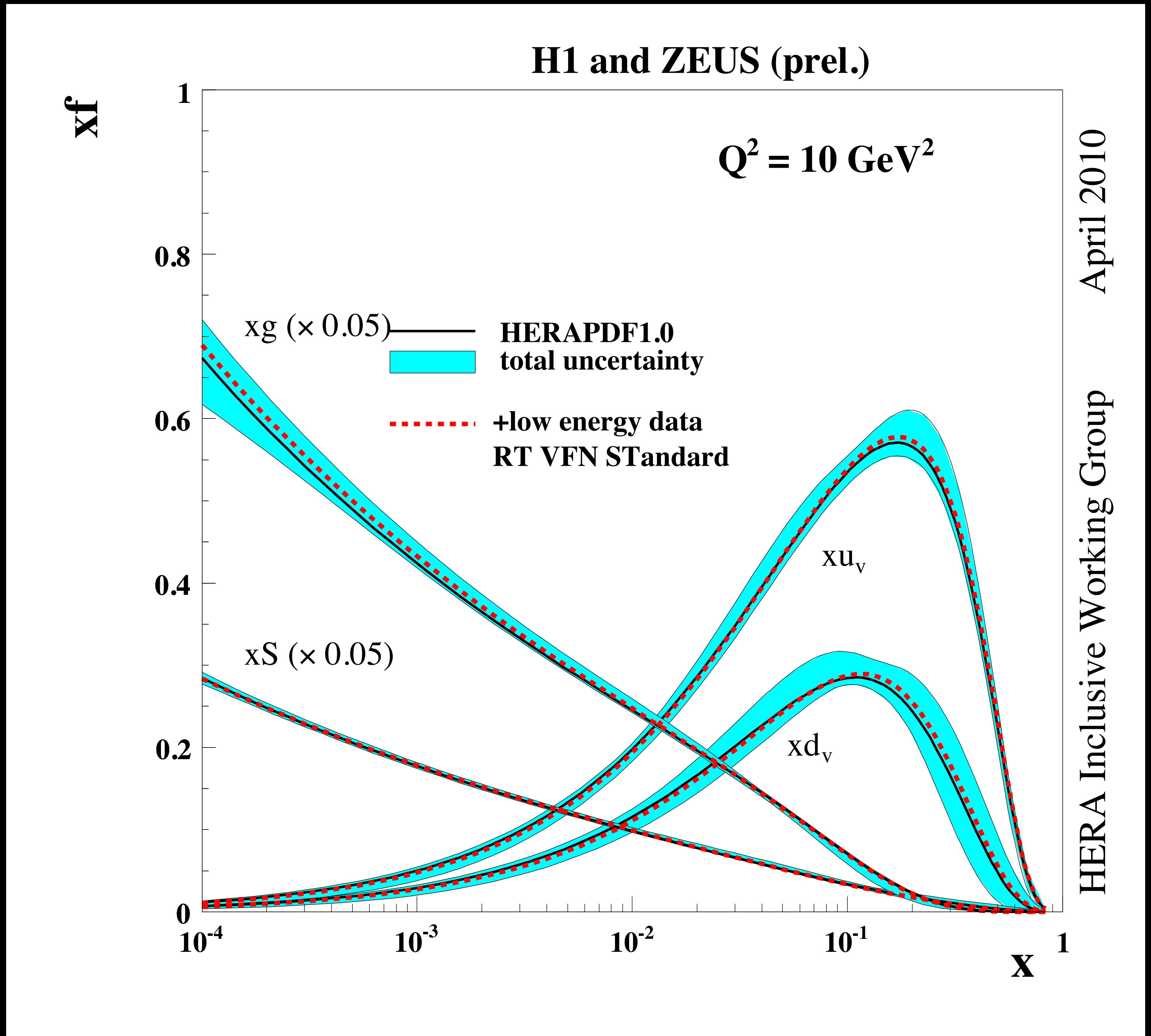
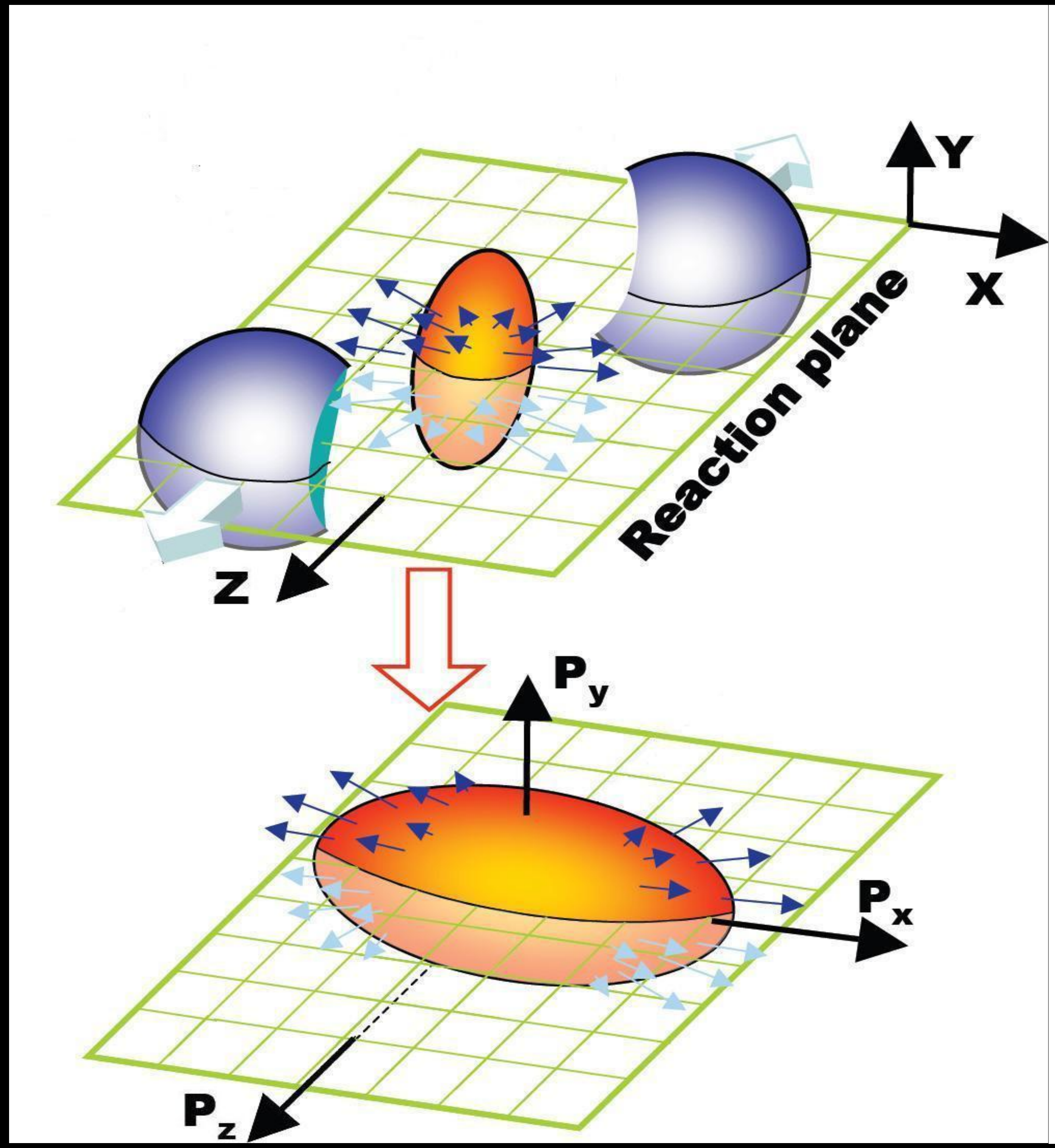
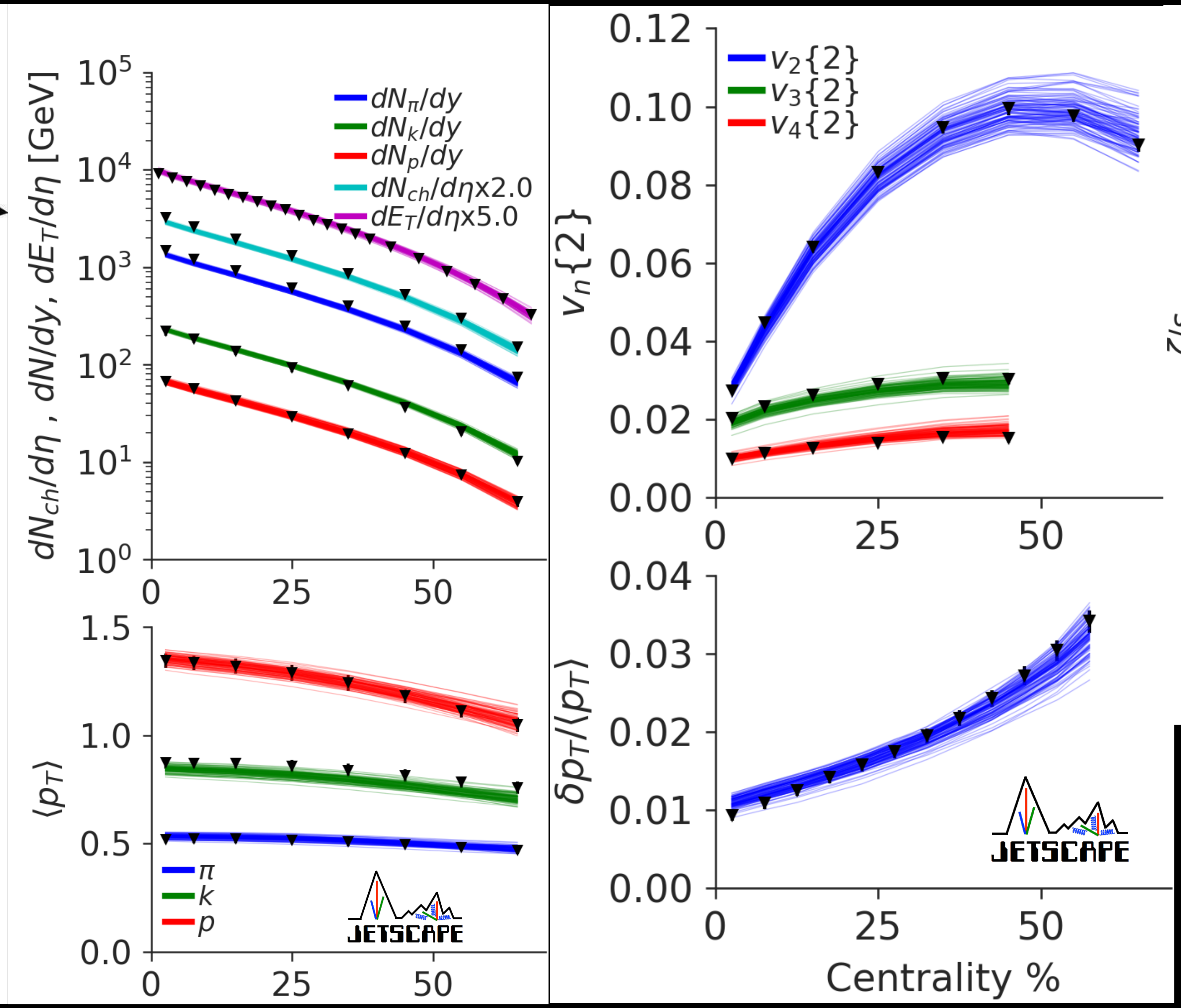


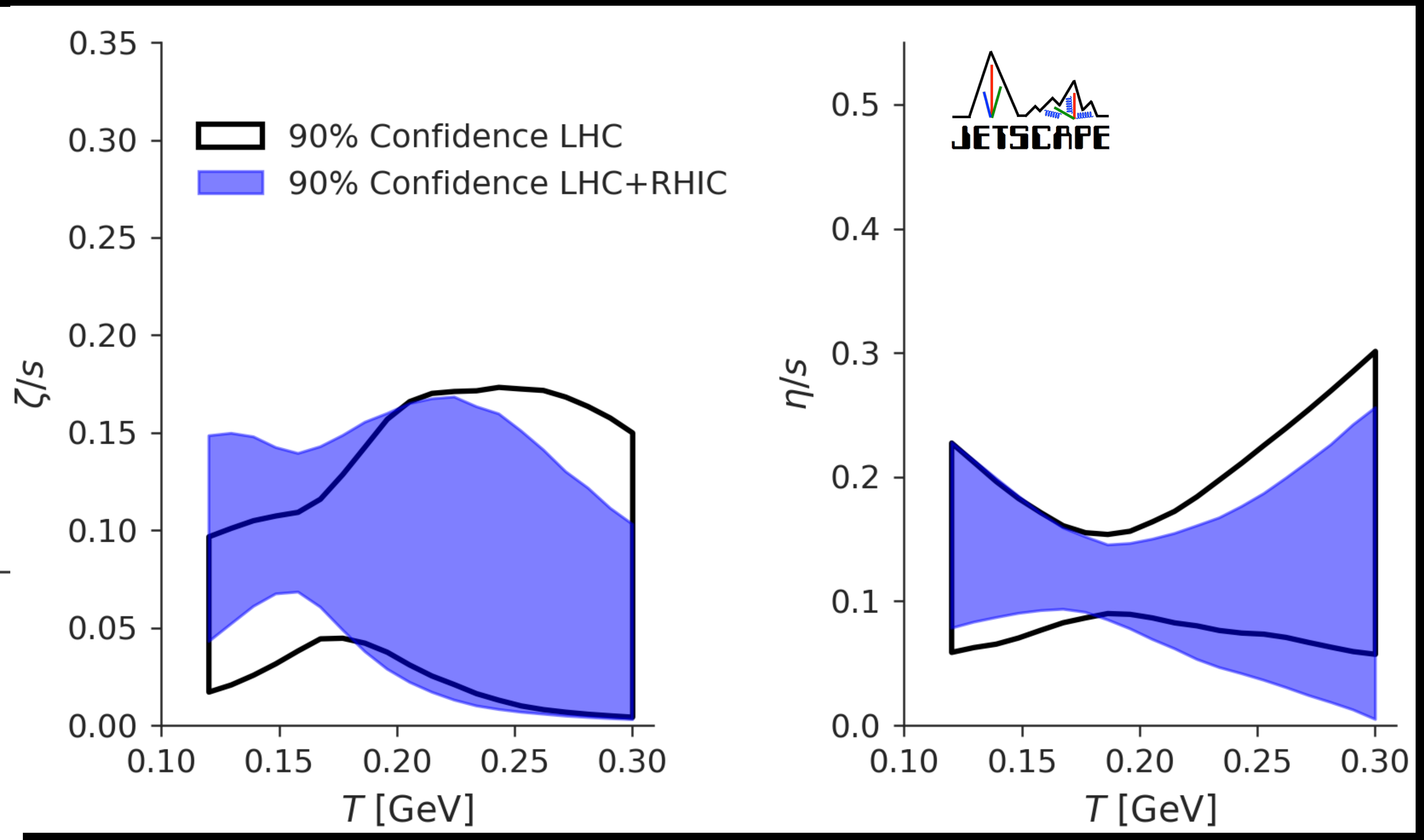


Increasing energy Q^2 = getting closer to proton

Low viscosity matter produced at RHIC & LHC

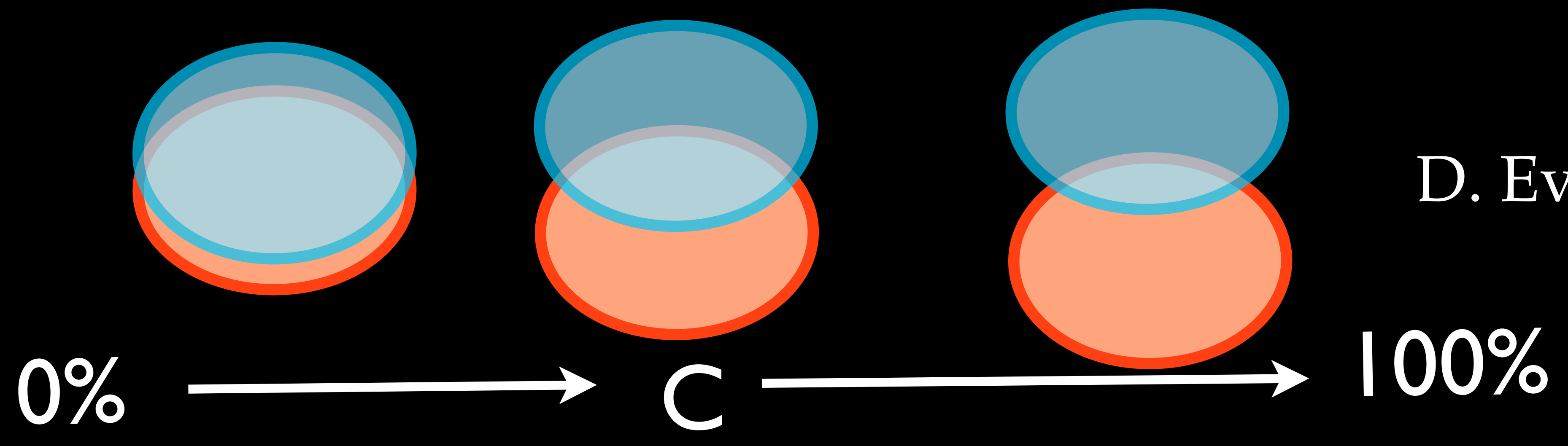






$$\eta \propto \frac{1}{\sigma}$$

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



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

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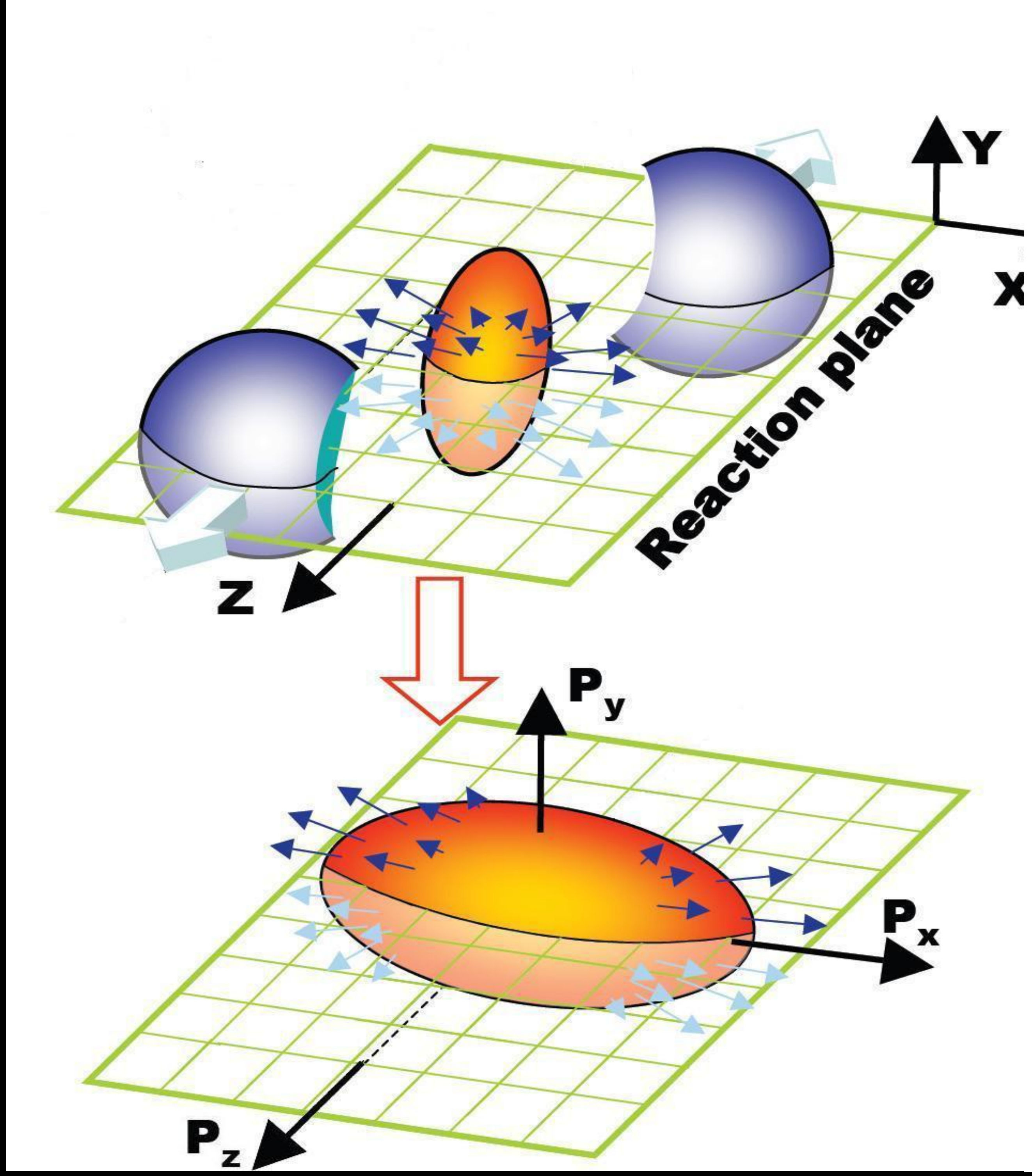

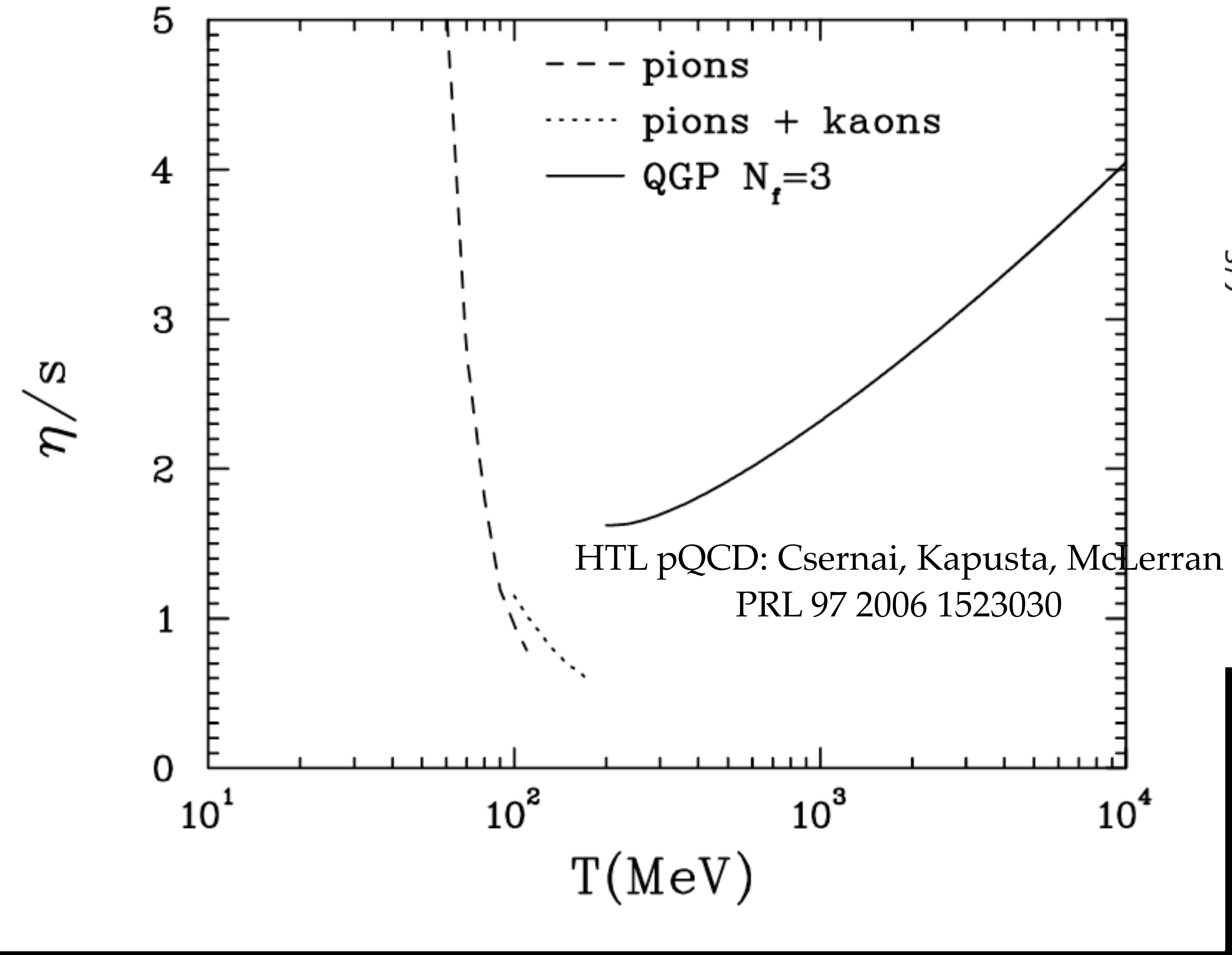

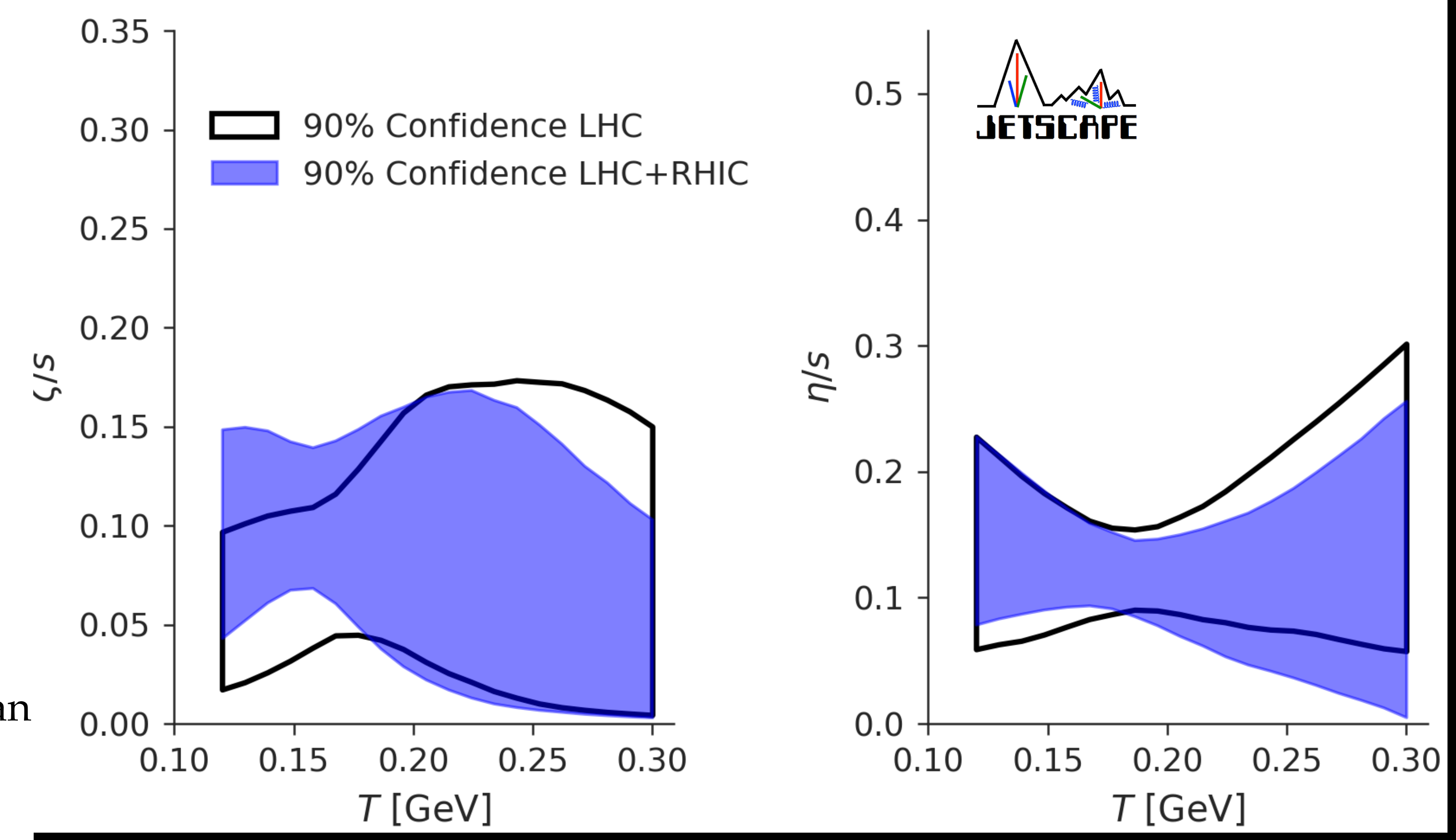

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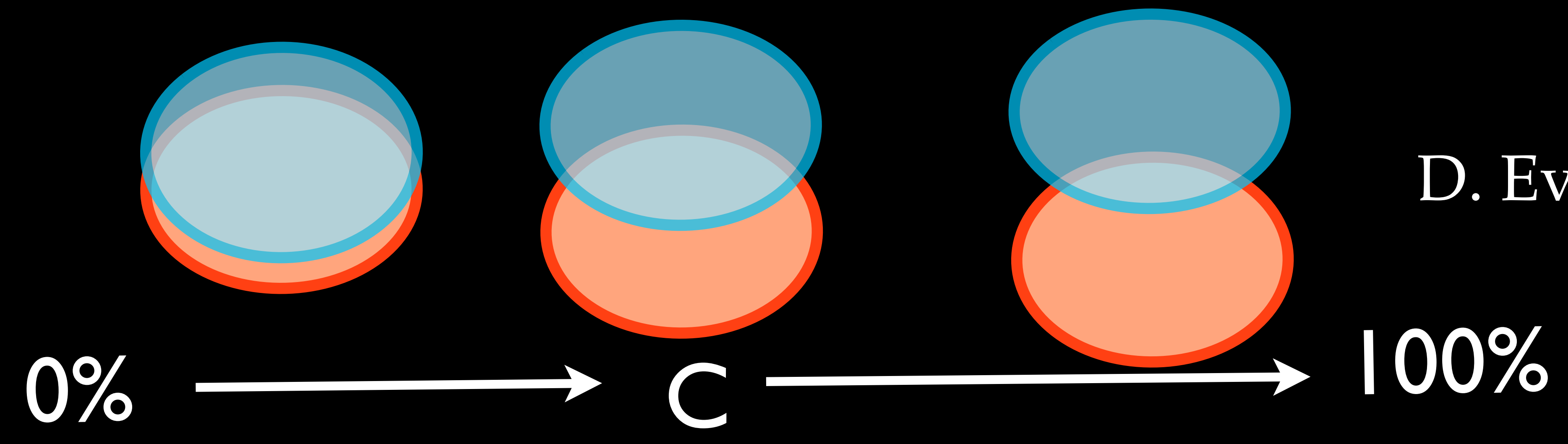

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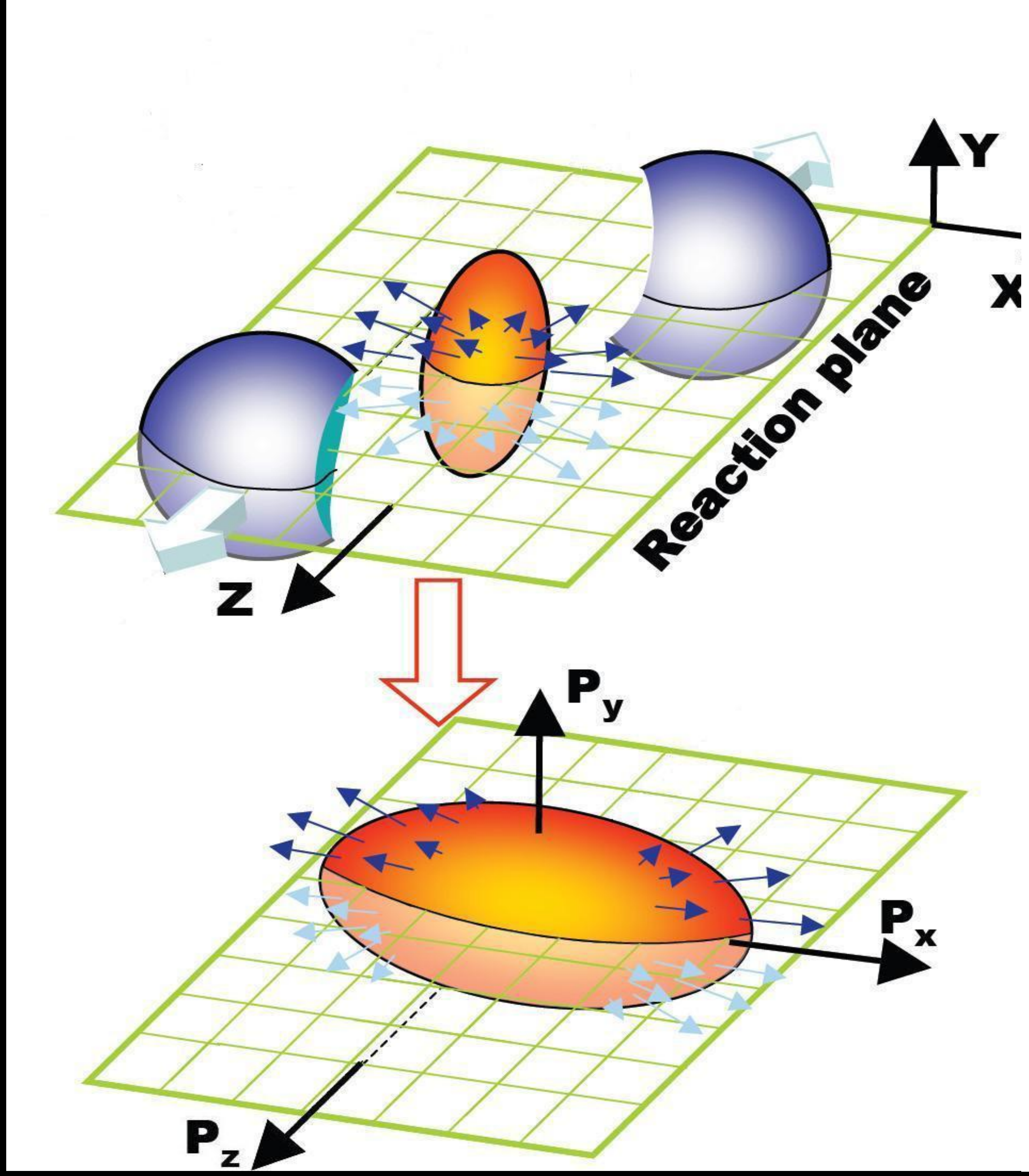

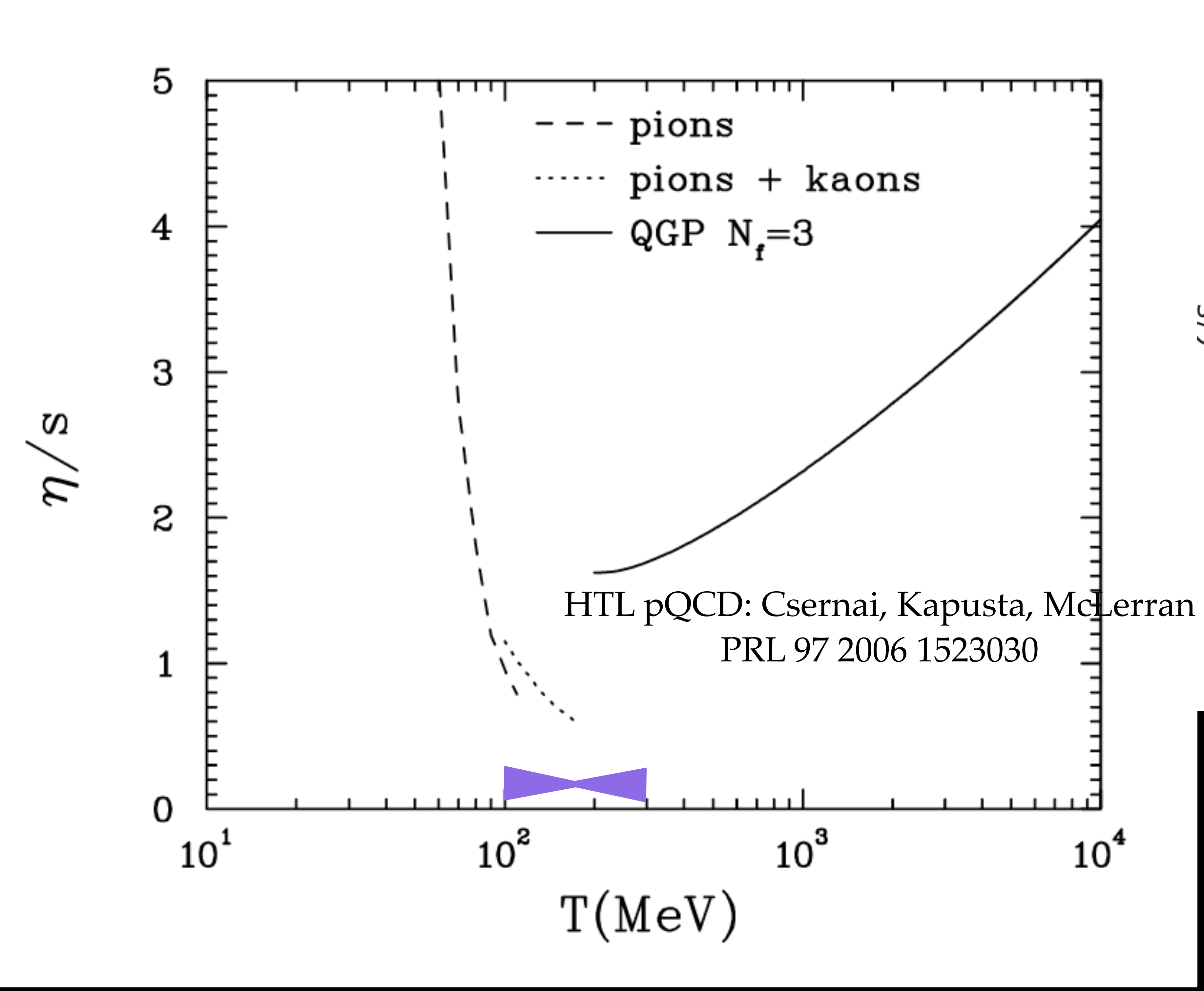

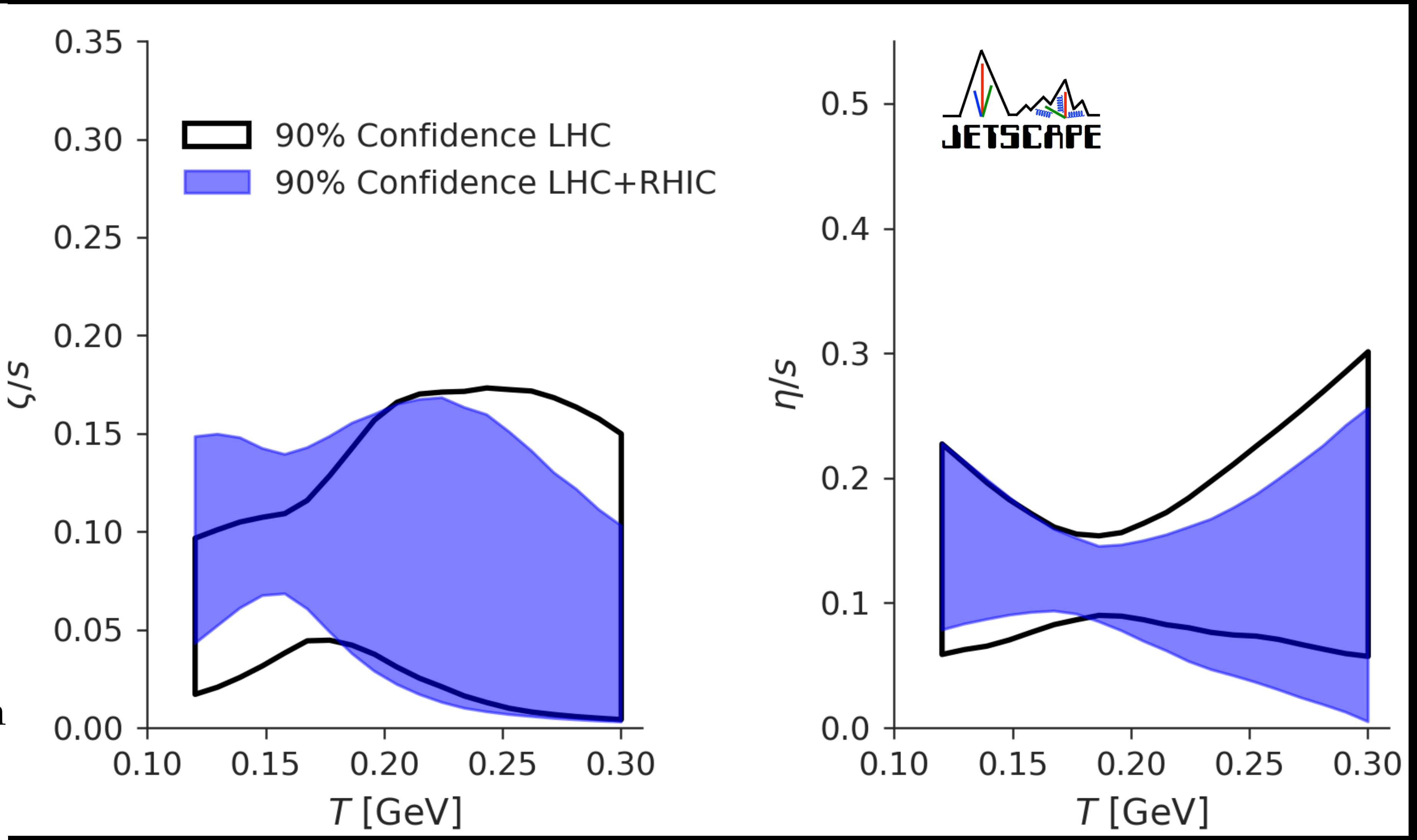

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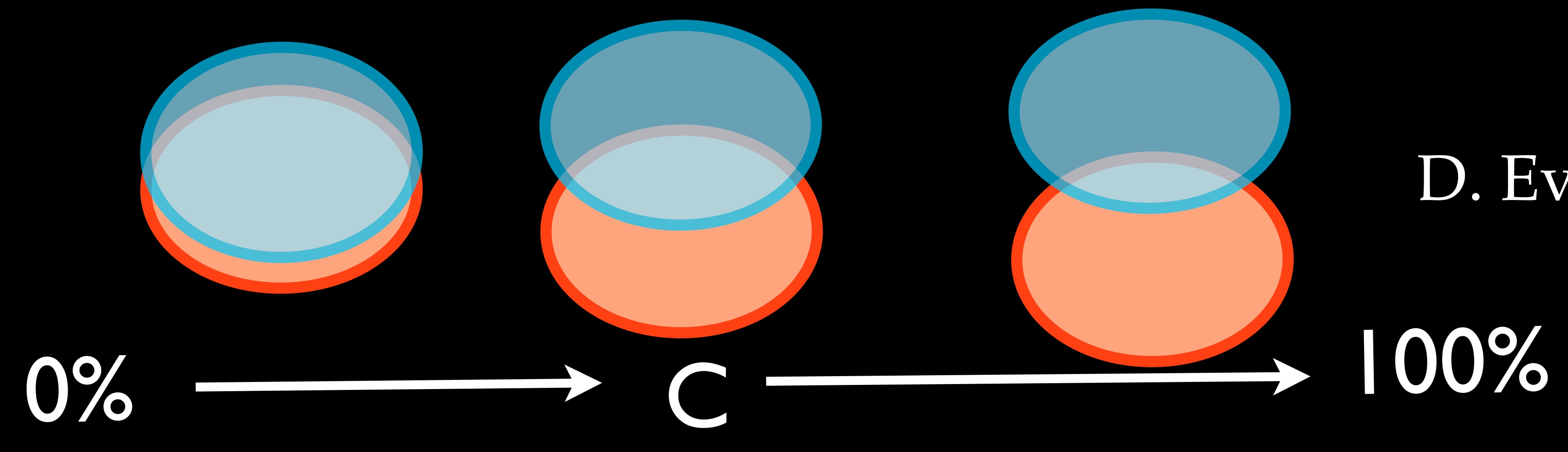

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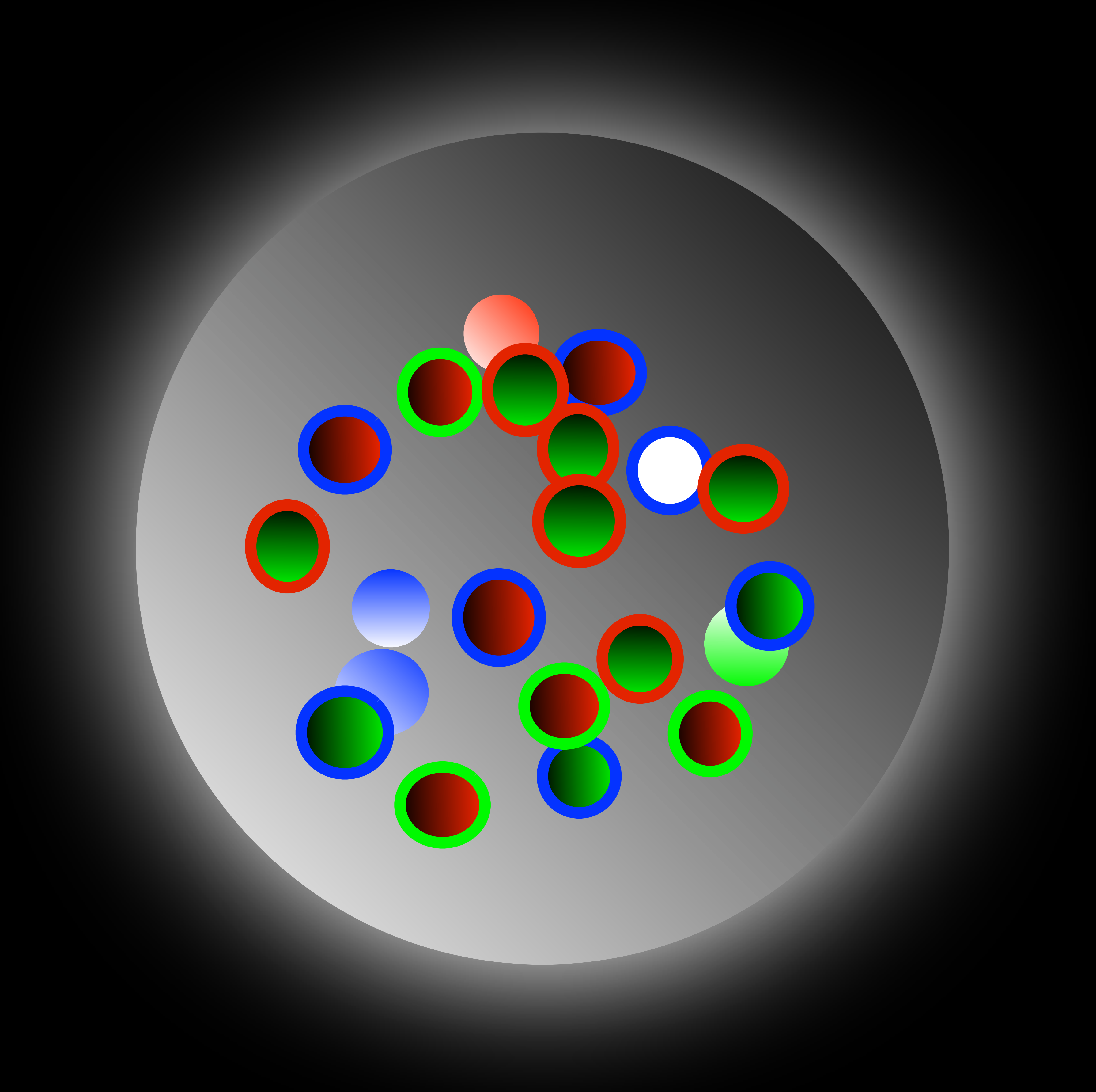

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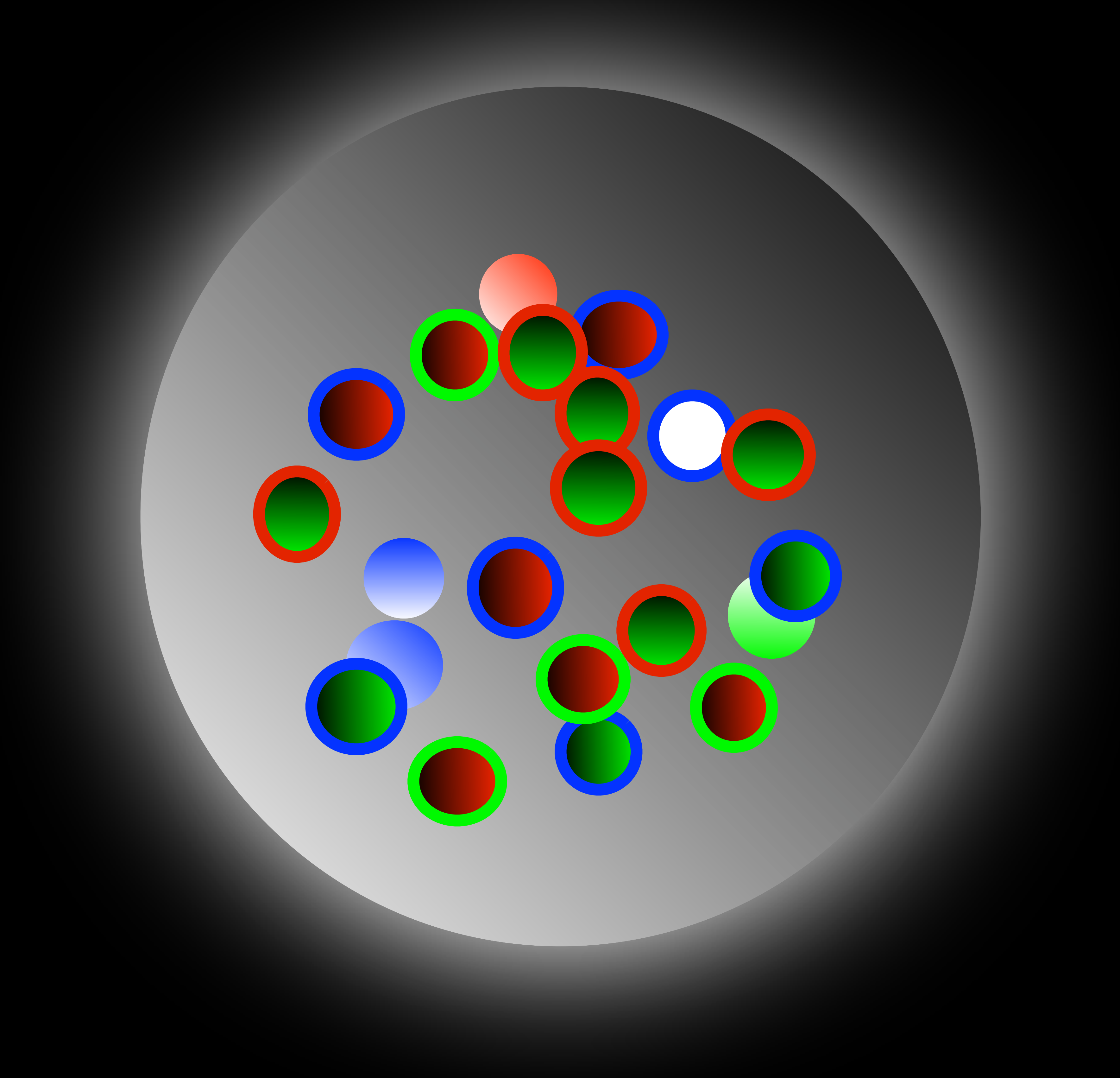

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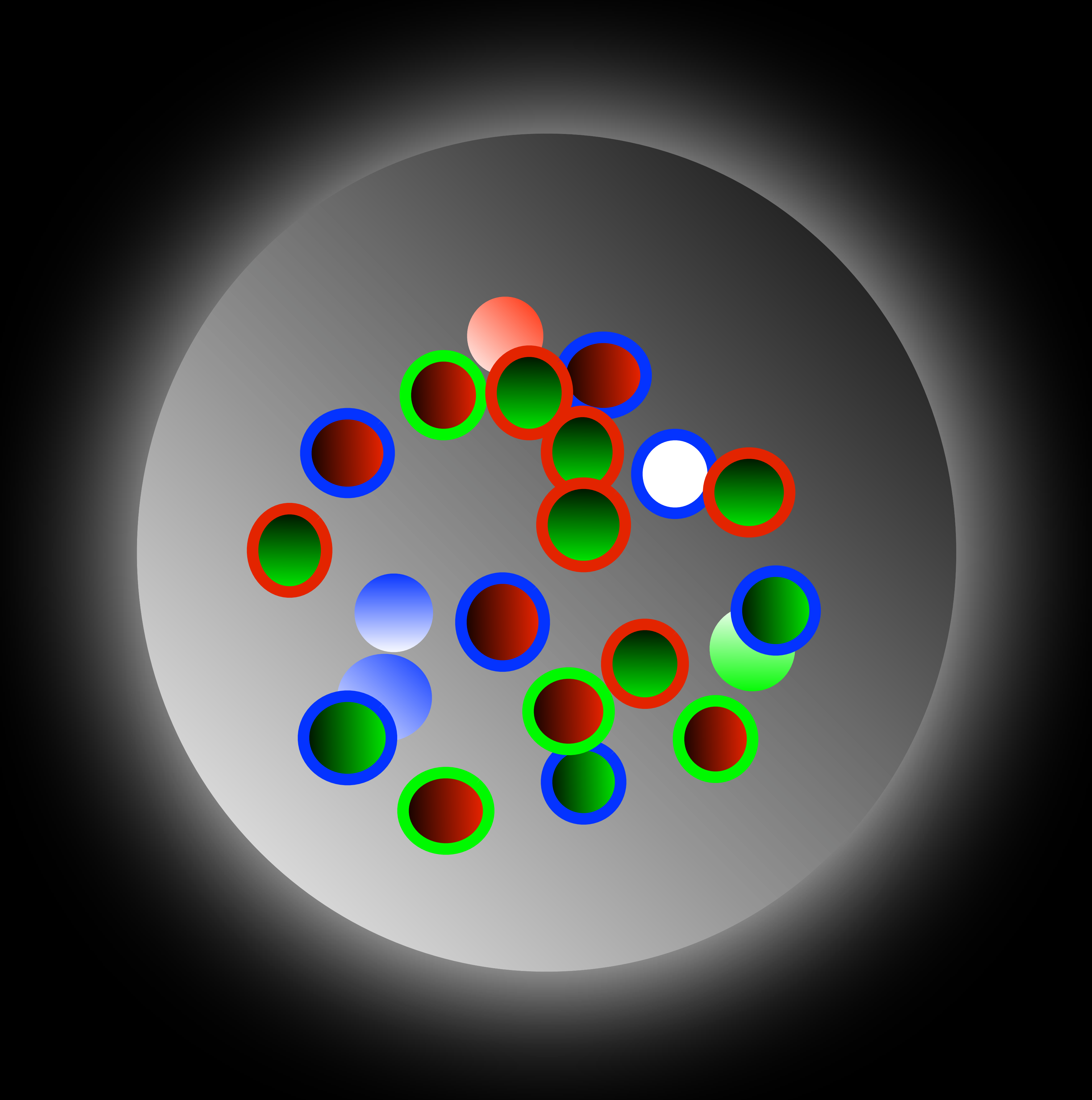

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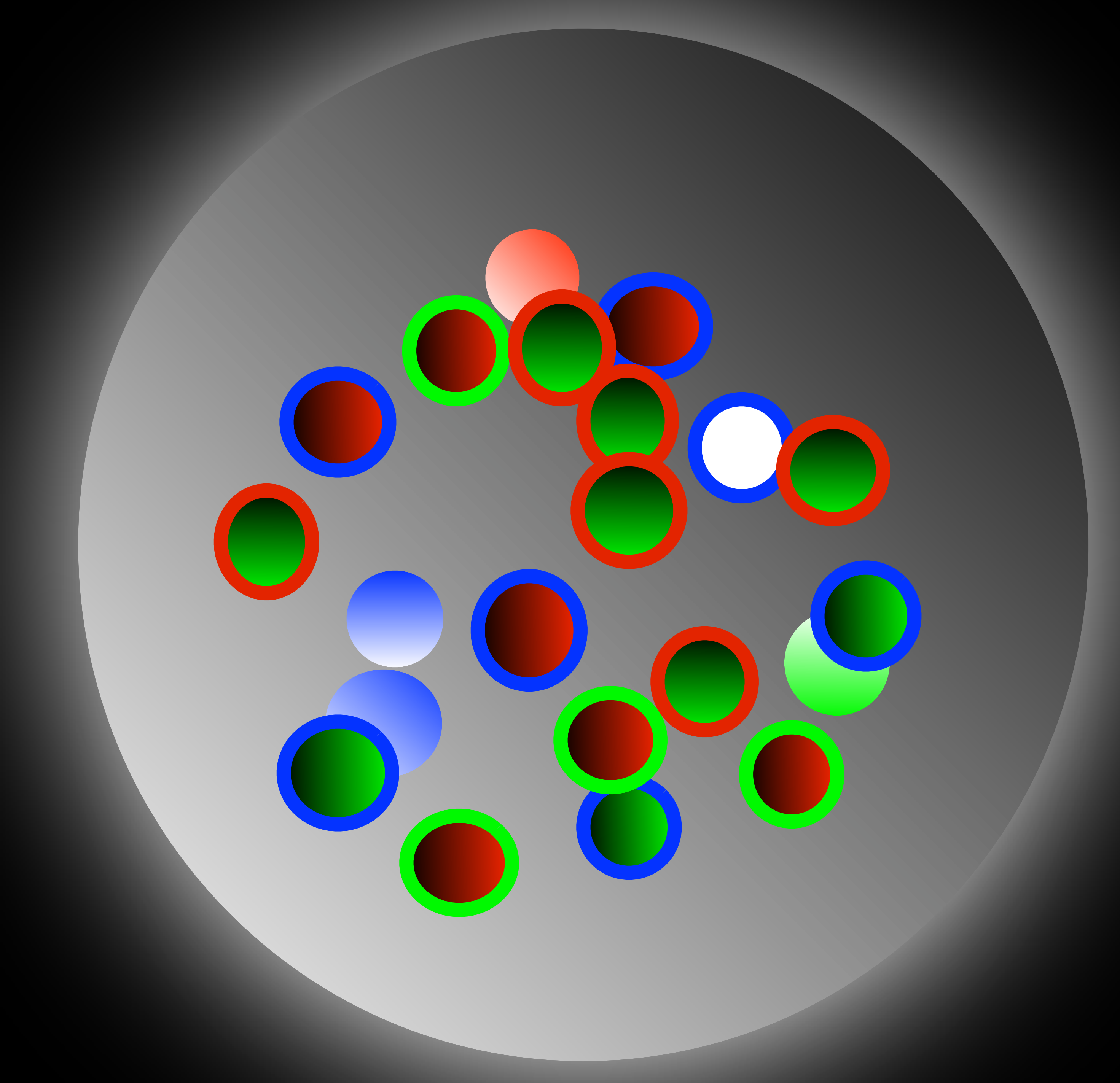
- Use high resolution probes: Jets



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- High resolution, short distance
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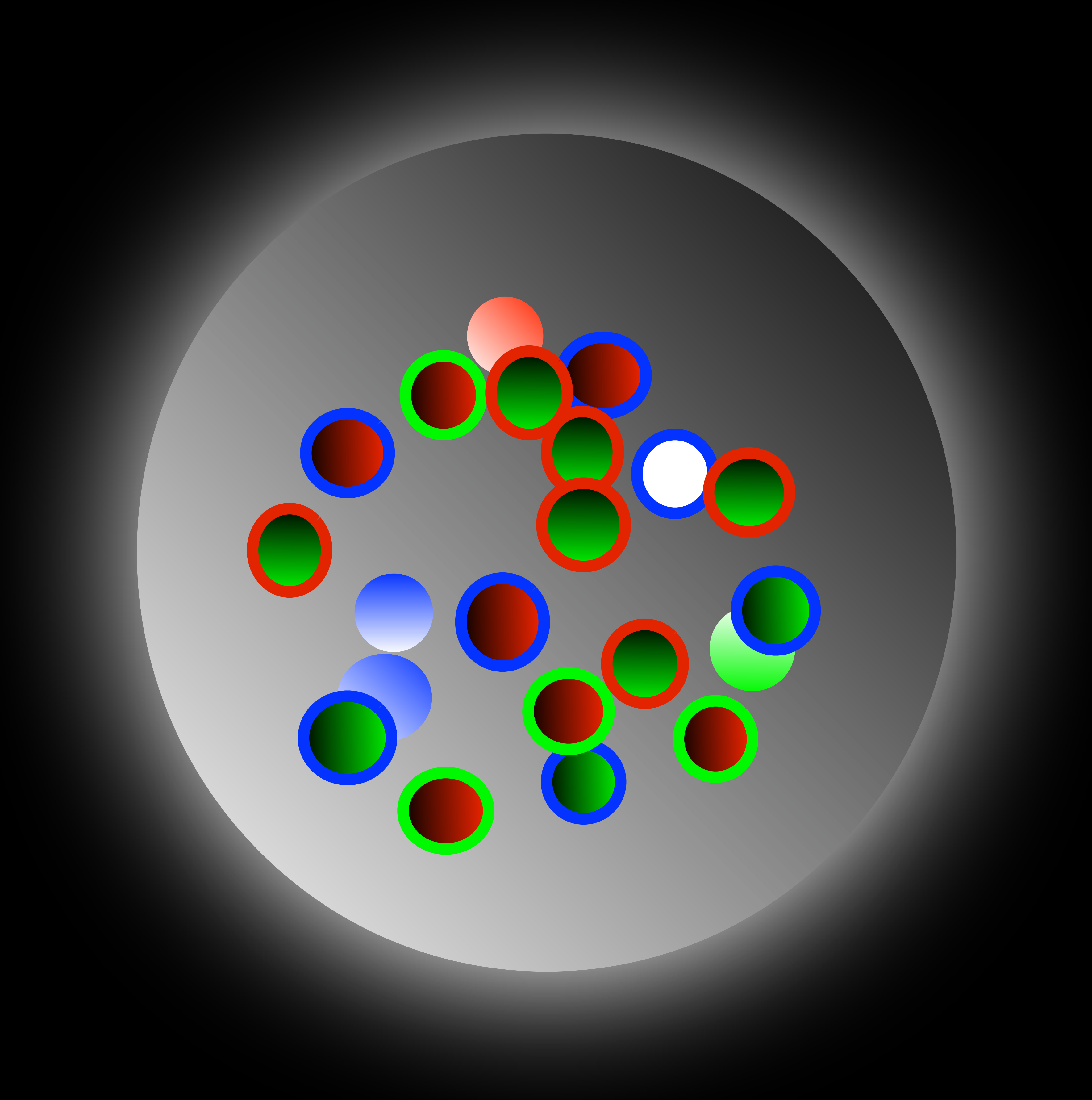
- Use high resolution probes: Jets
- But with several caveats…



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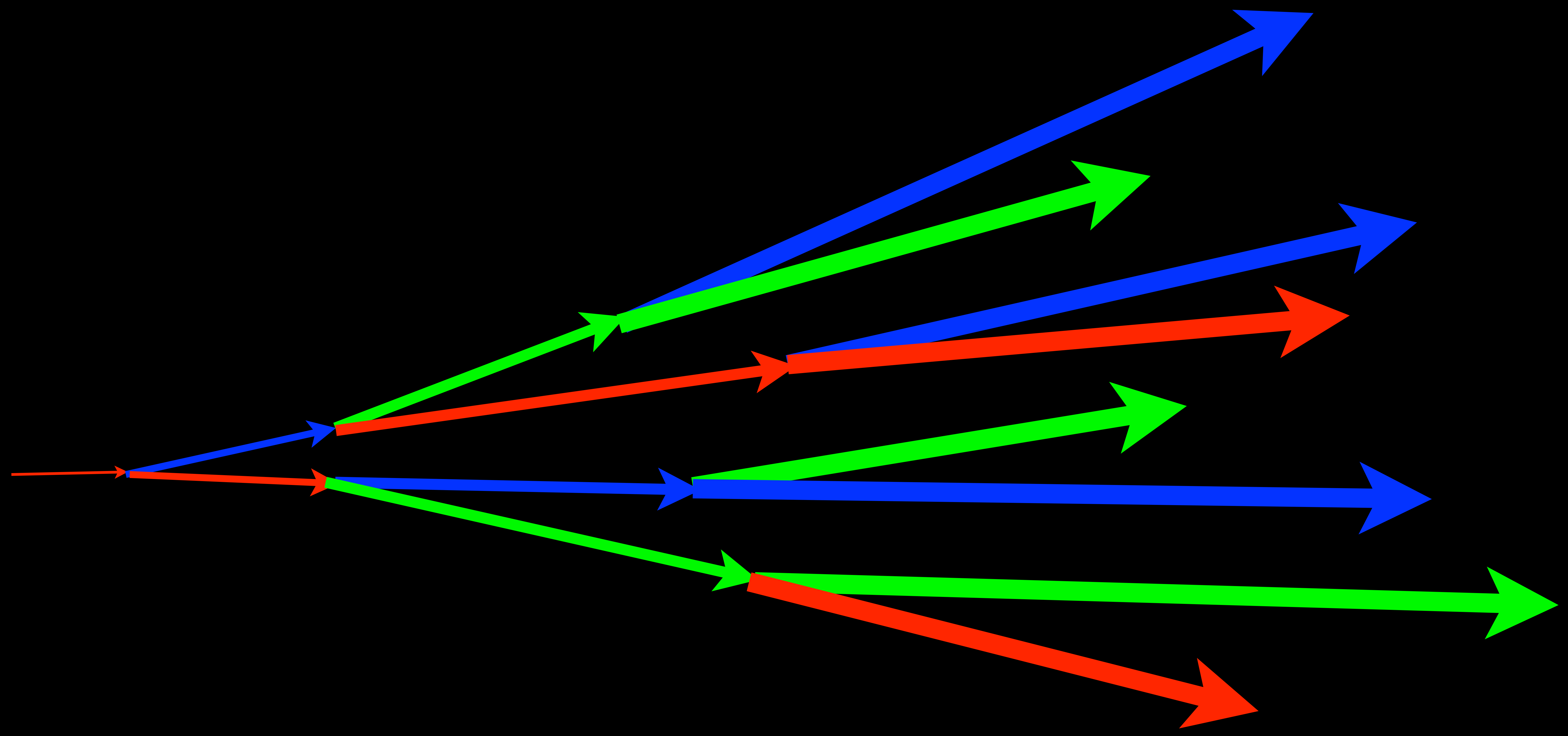

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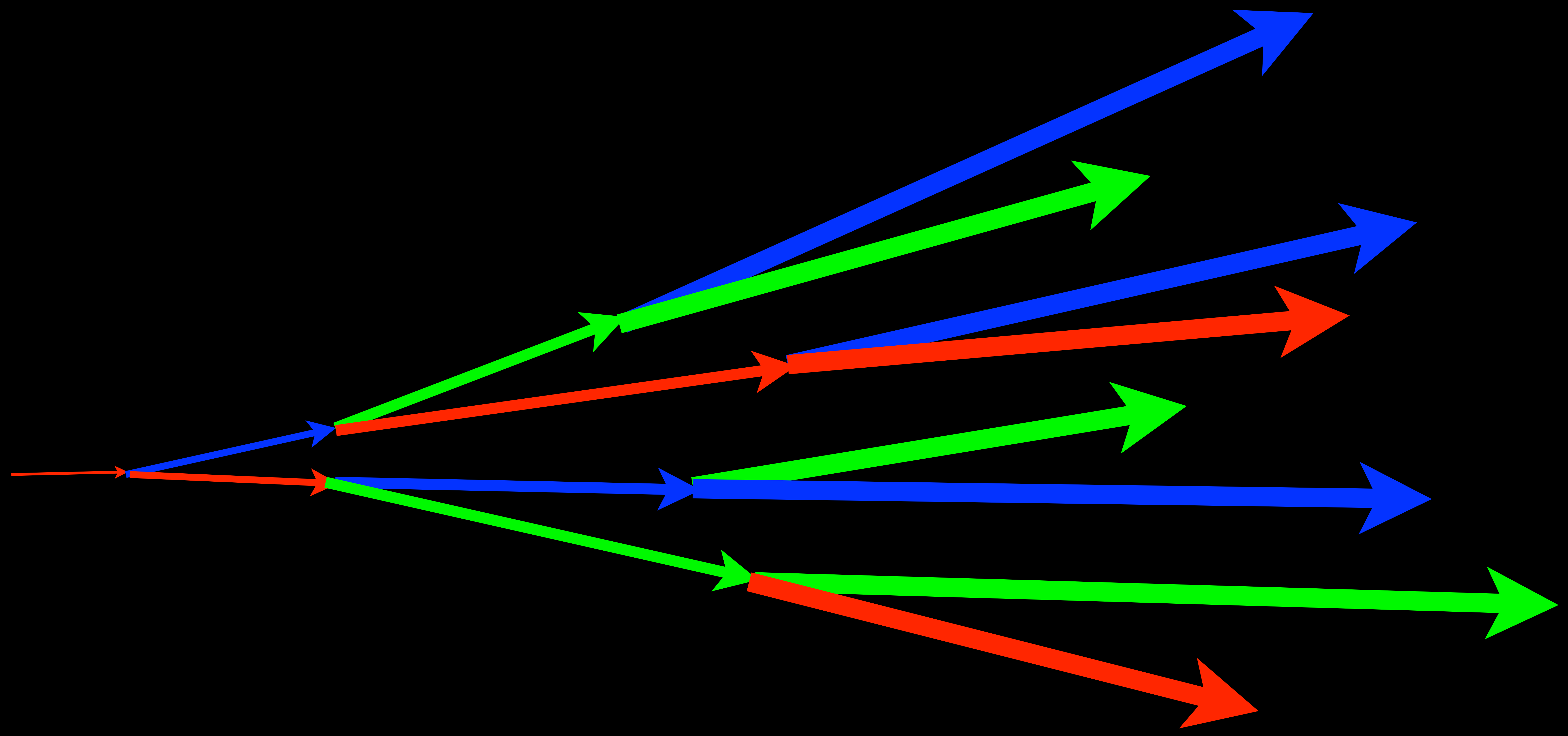

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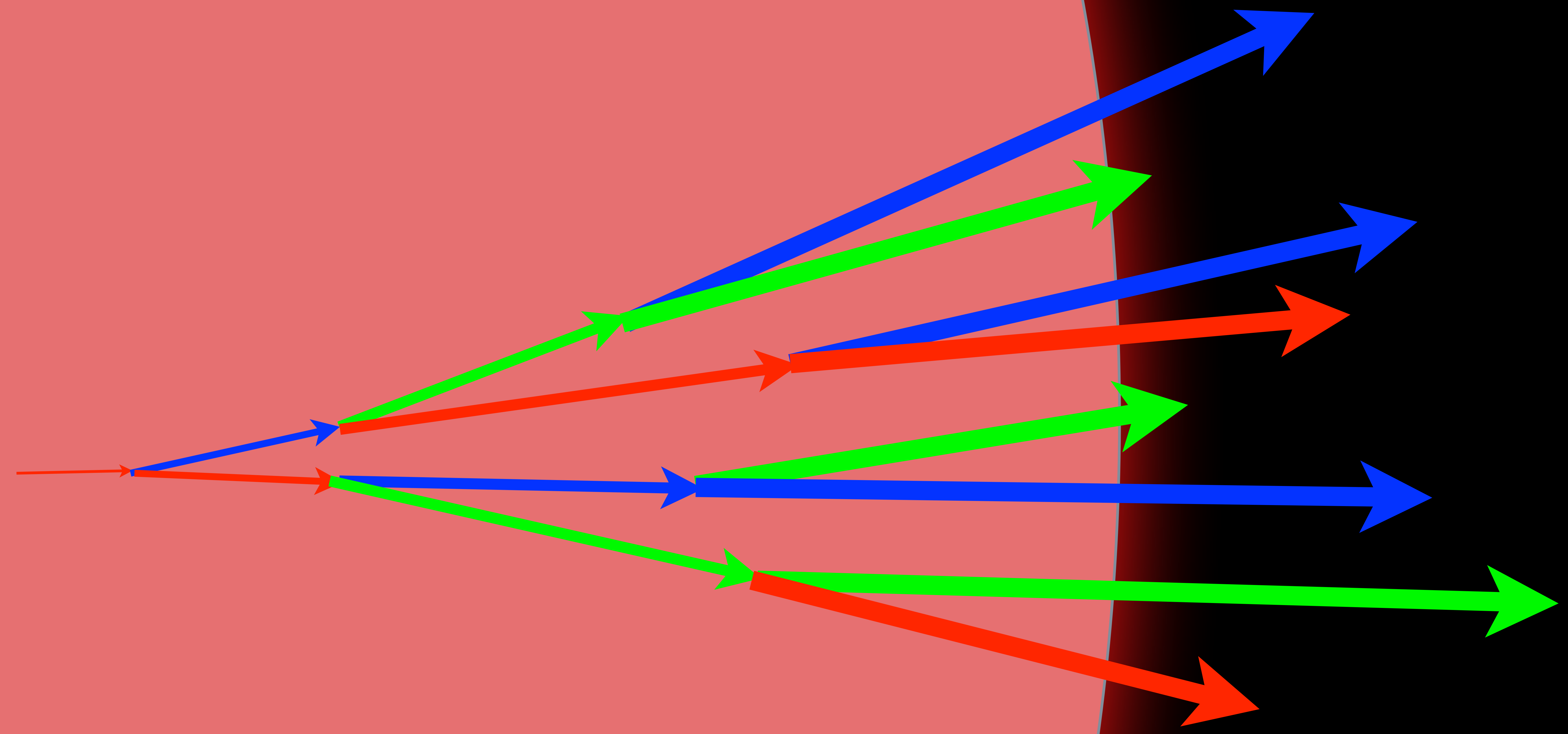

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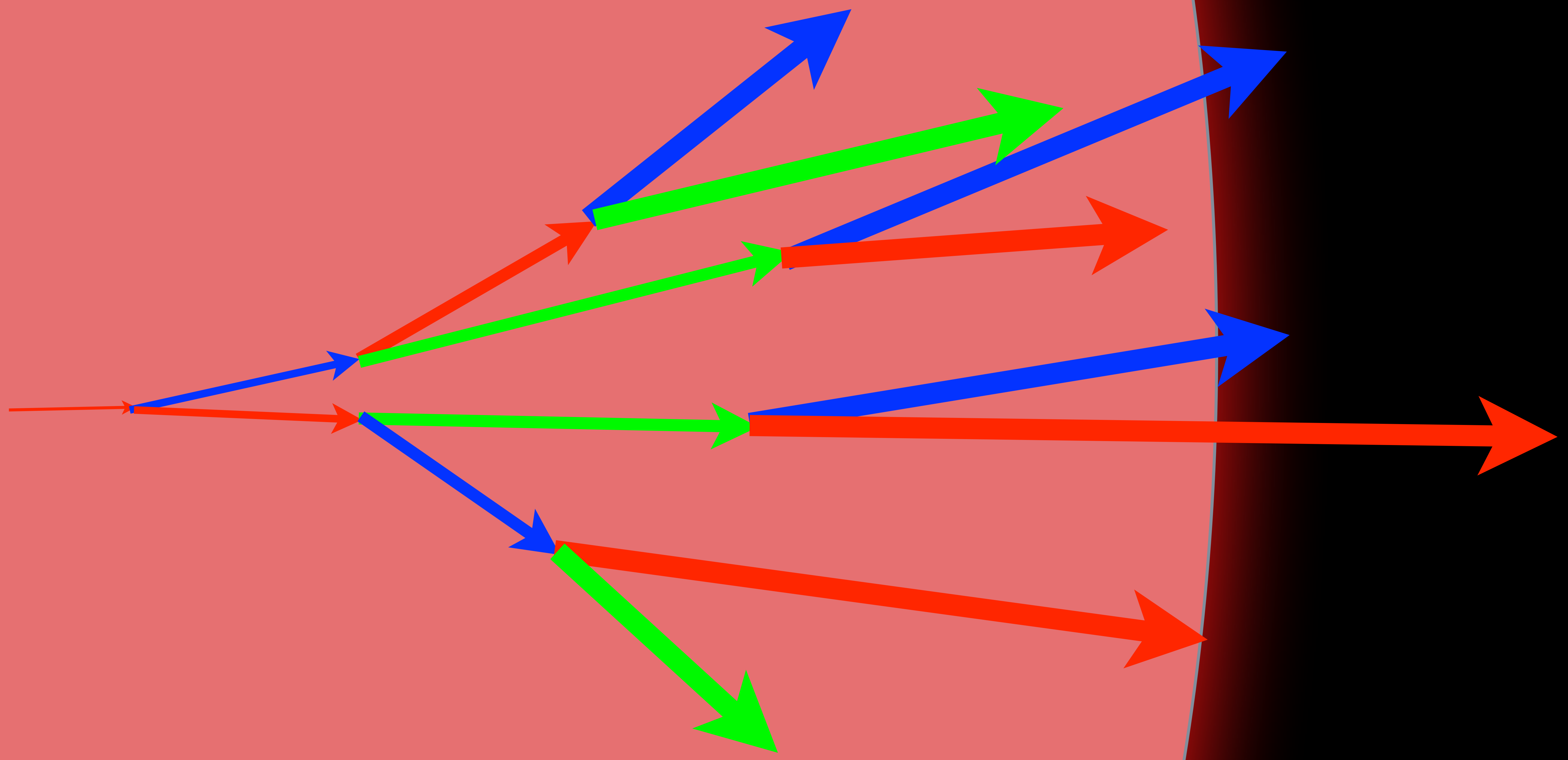

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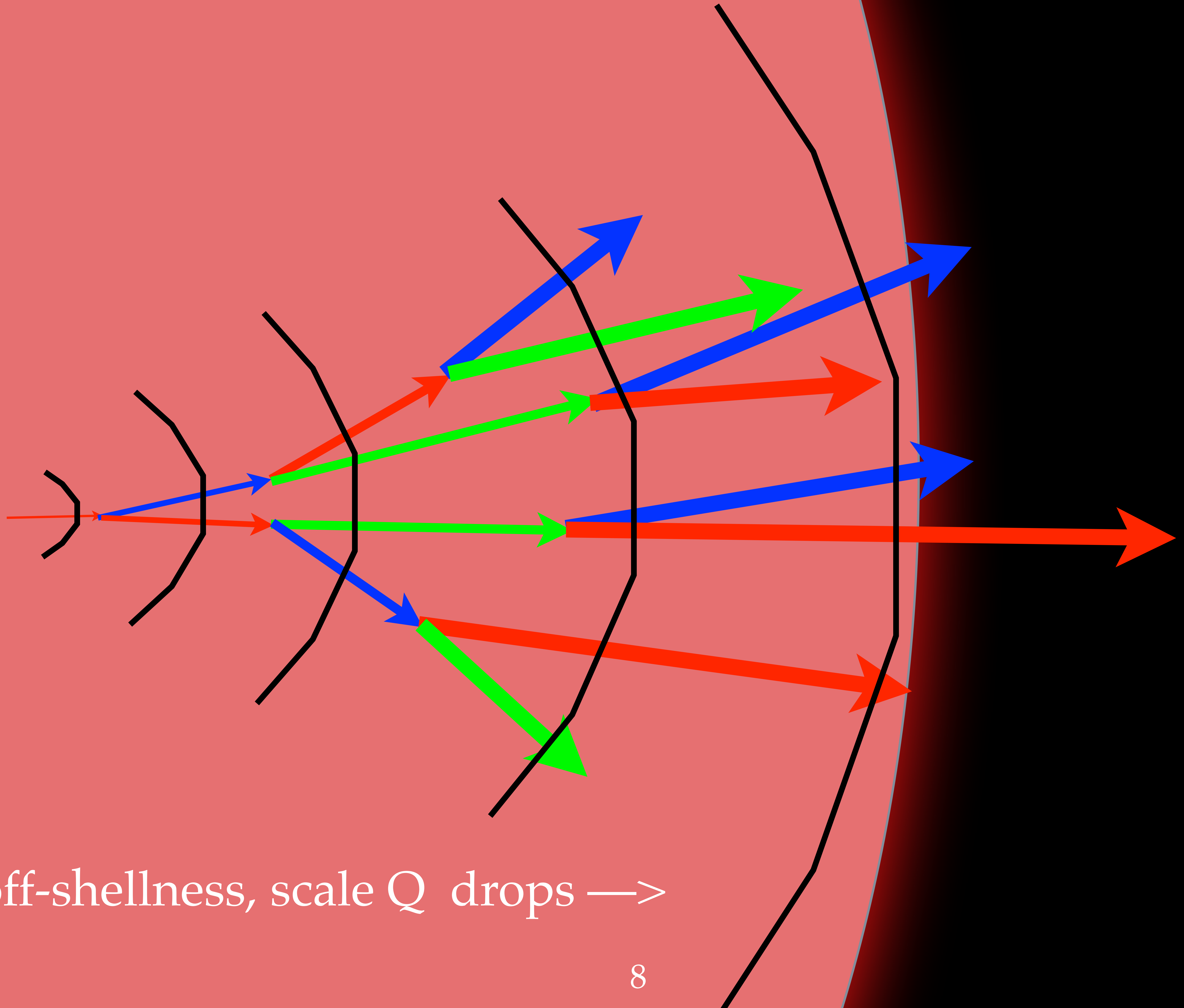

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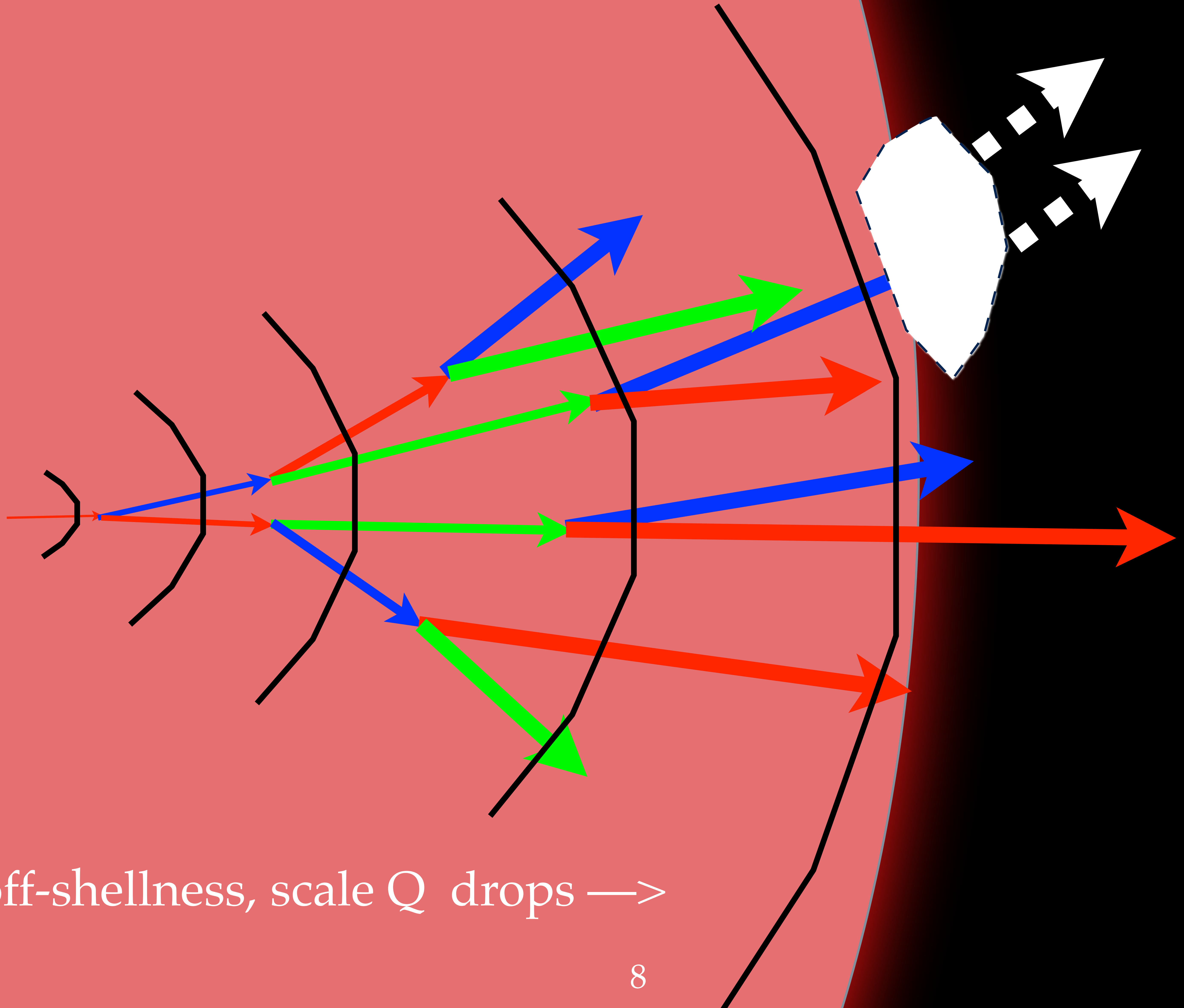

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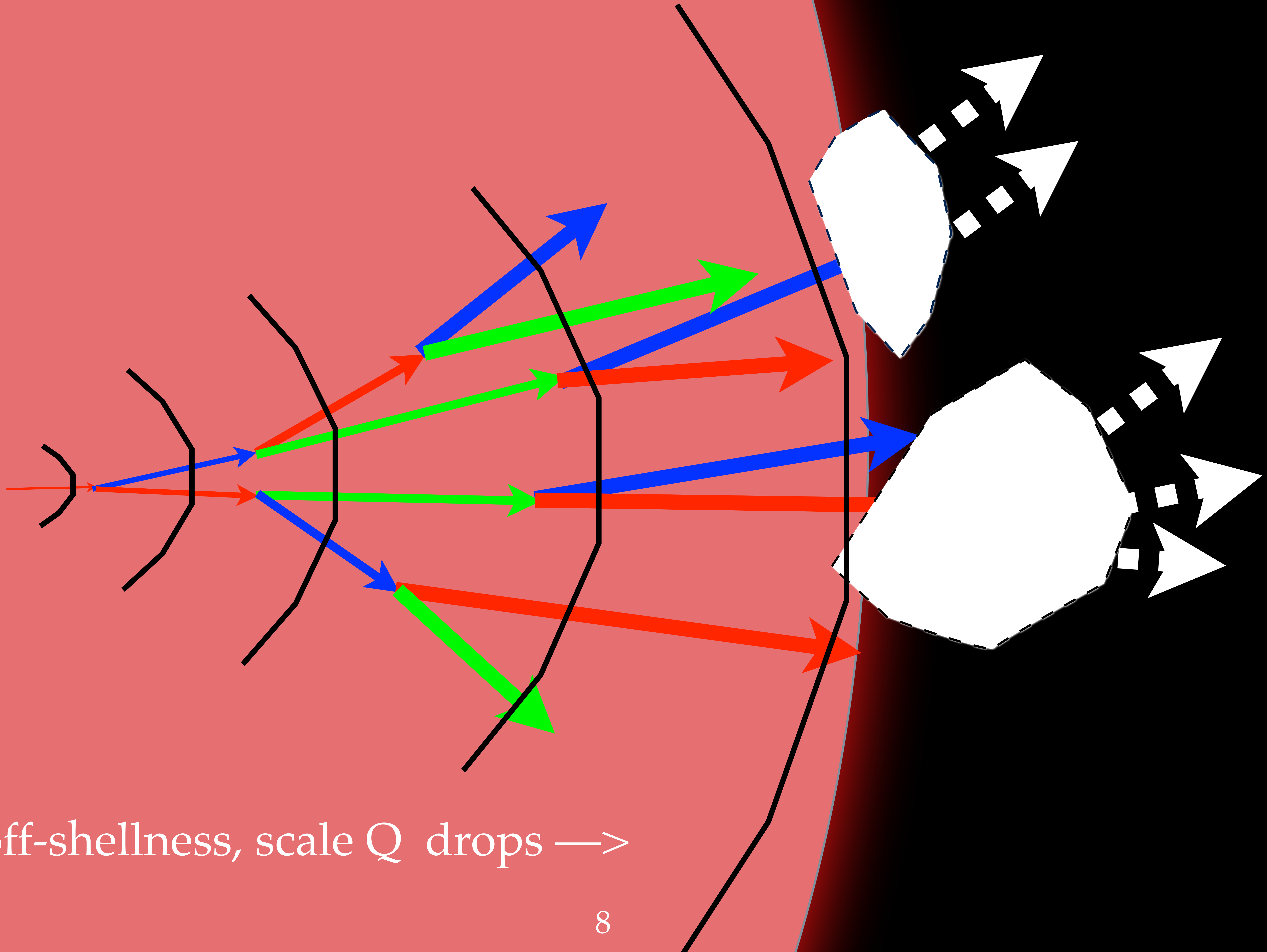

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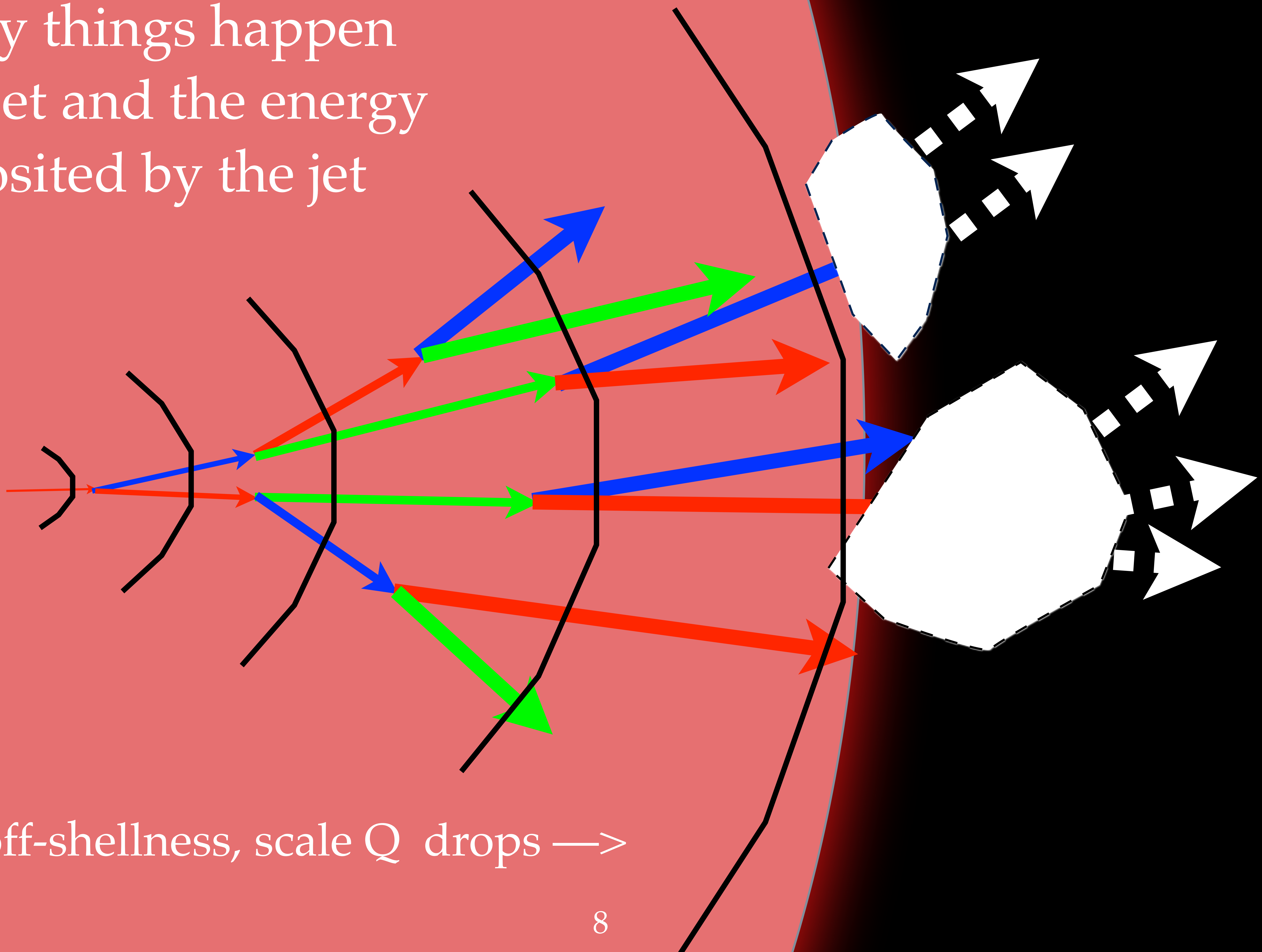

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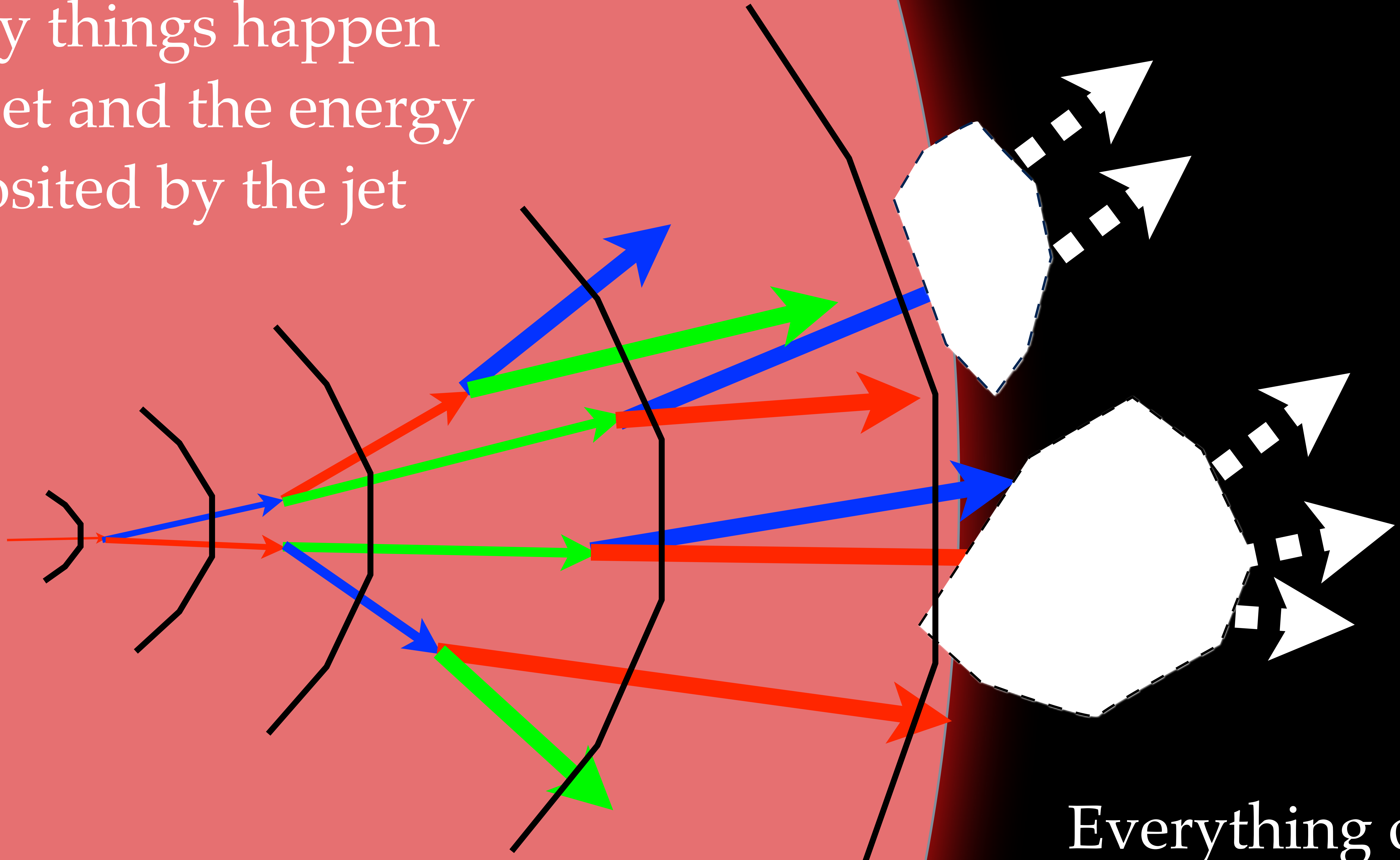
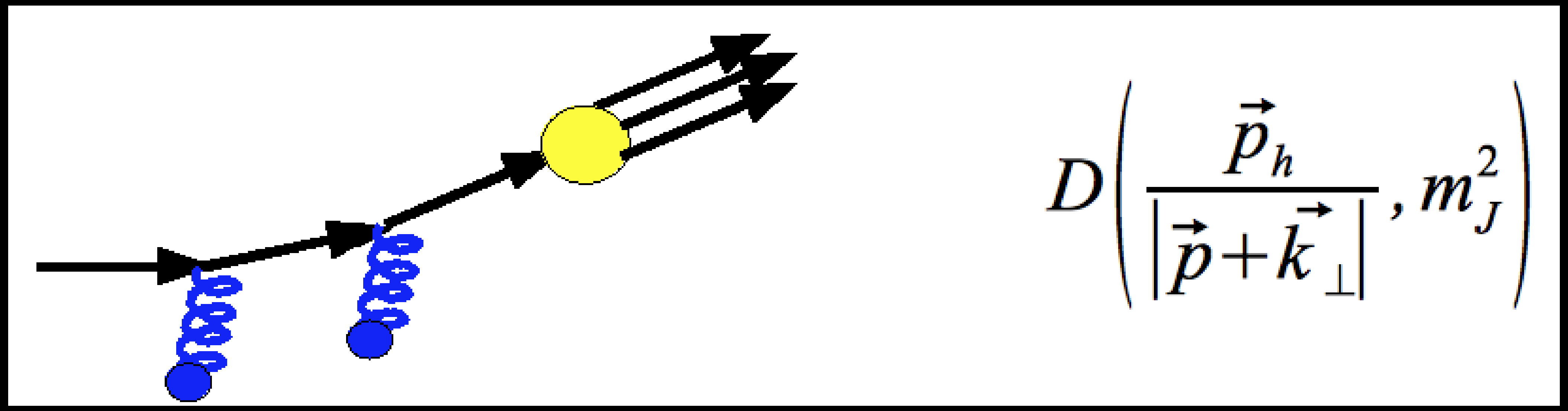


Virtuality, off-shellness, scale Q drops —>

Everything other than leading hadrons includes medium response.

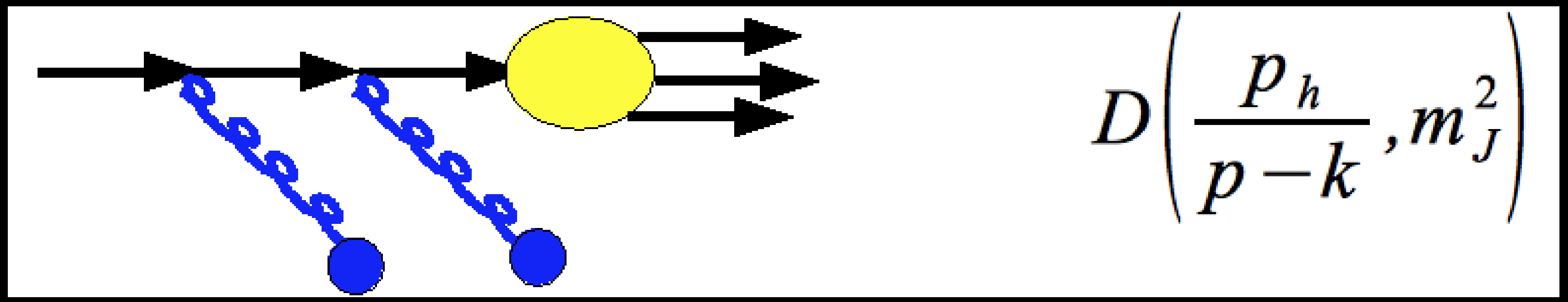
Transport coefficients for partons in a dense medium

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



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

Transverse momentum diffusion rate



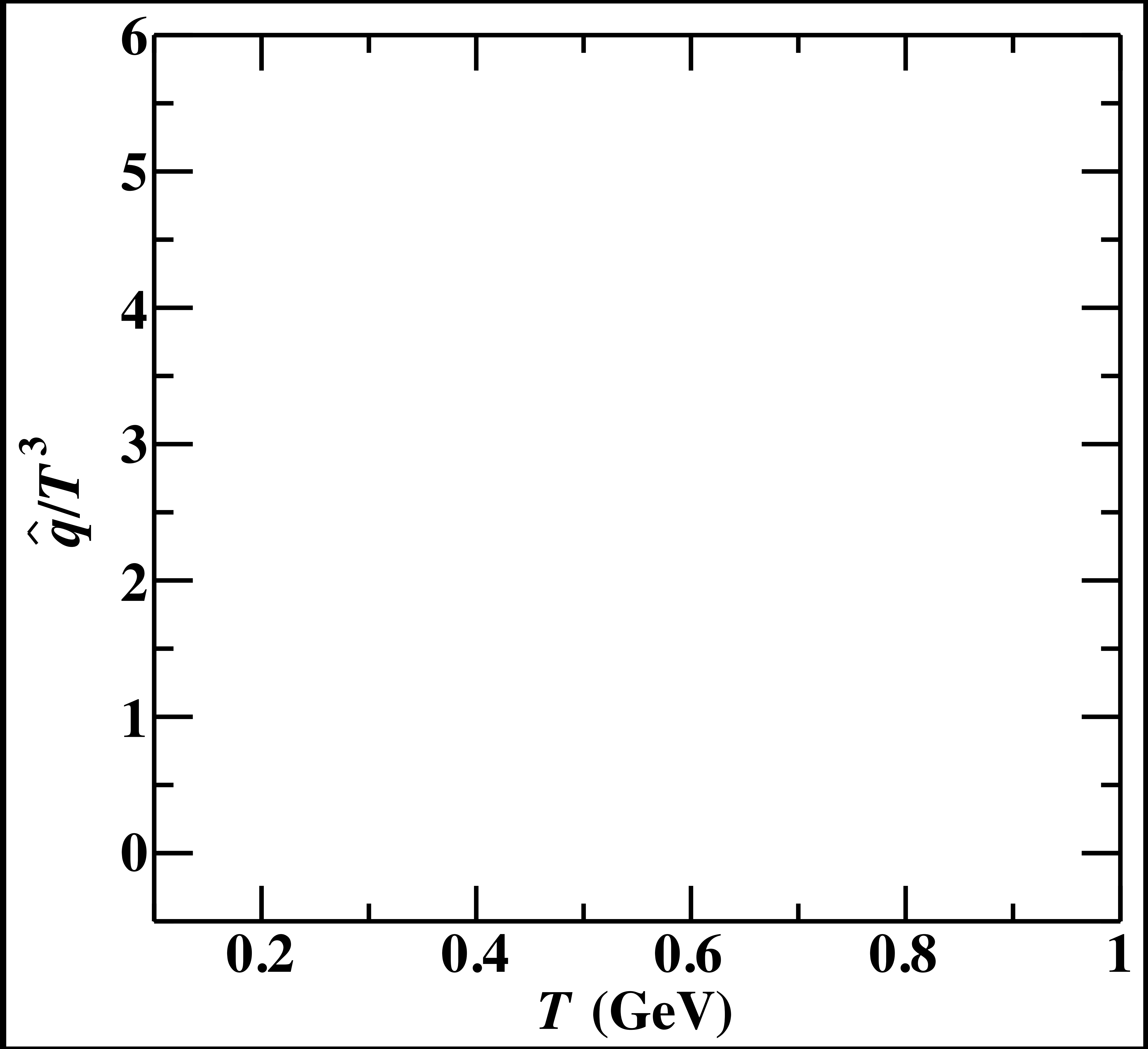
$$\hat{e} = \frac{\langle \Delta E \rangle_L}{L}$$

Elastic energy loss rate
also diffusion rate e_2

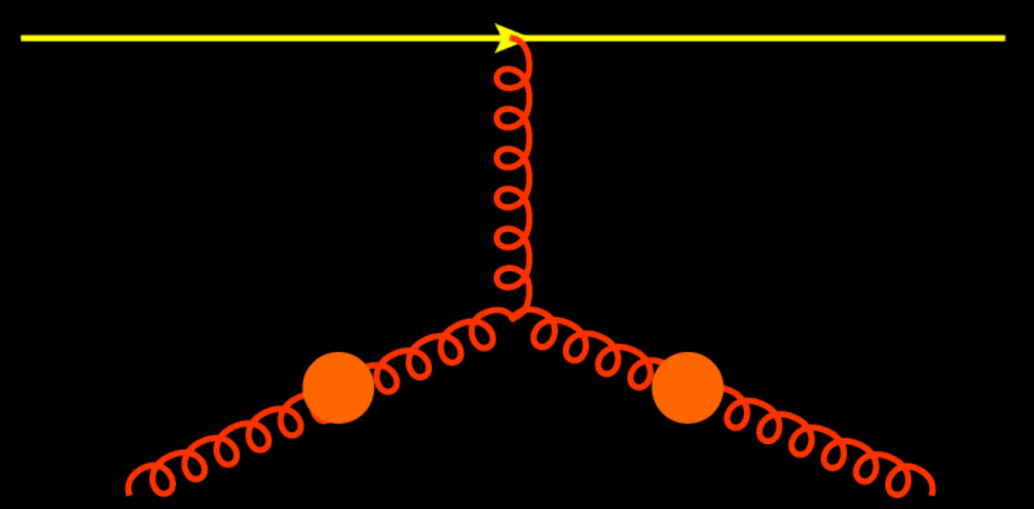
By definition, describe how the medium modifies the jet parton!

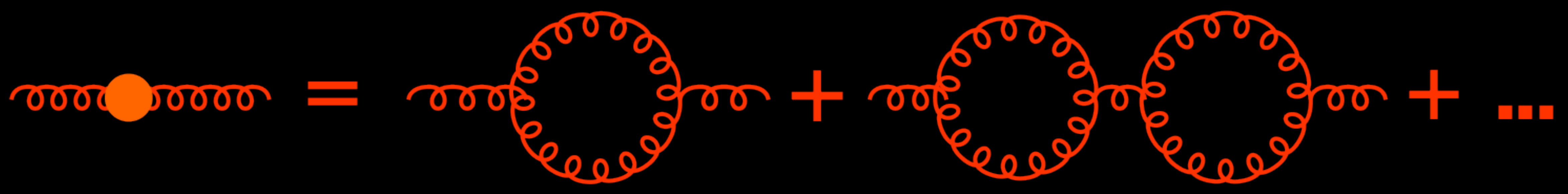
What do we know about $\hat{q}$ (circa 2010)?

- 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



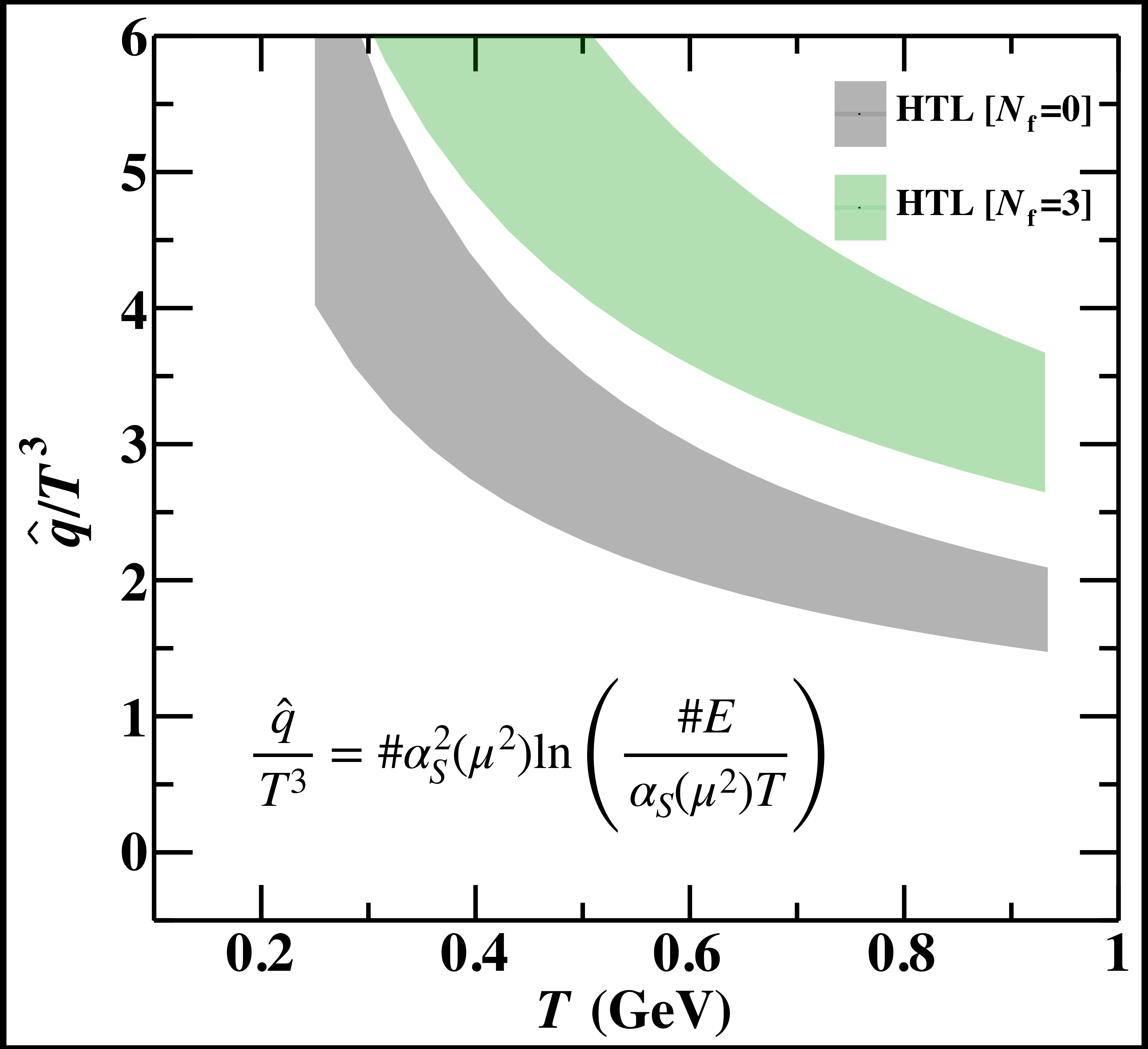


Hard Thermal Loop (HTL) theory

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

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

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



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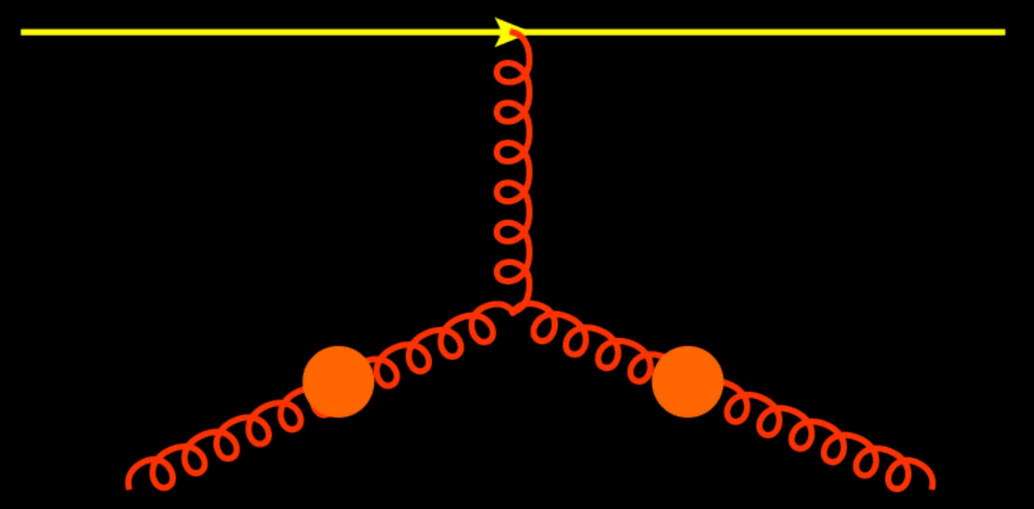

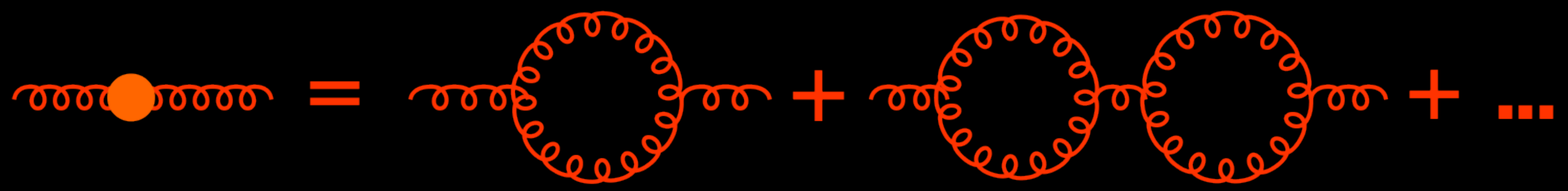

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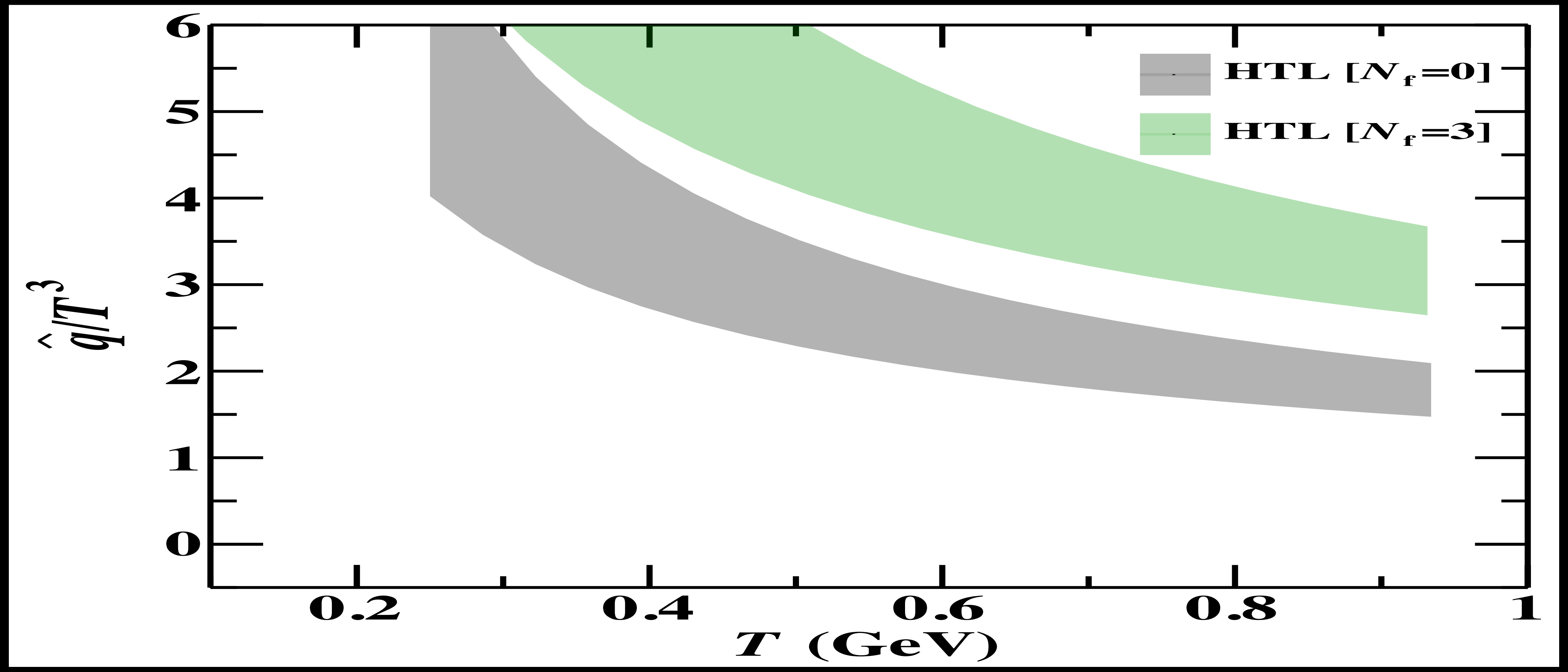

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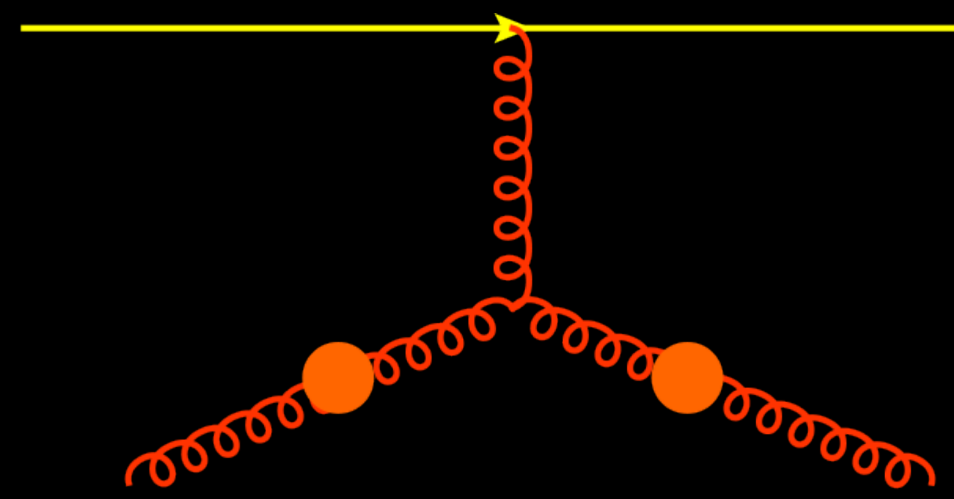
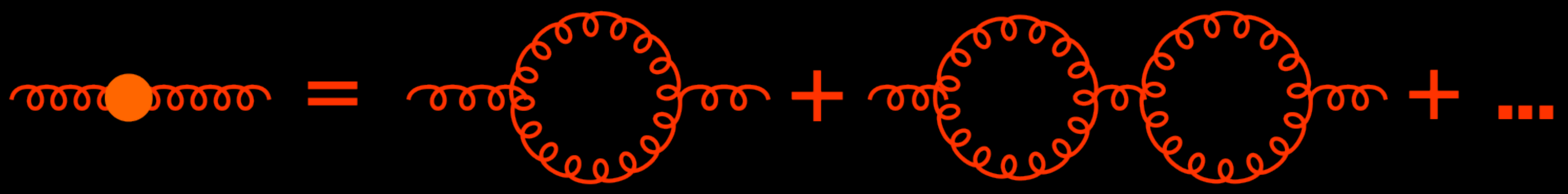
NLO S. Caron-Huot PRD 79. 2009 065039





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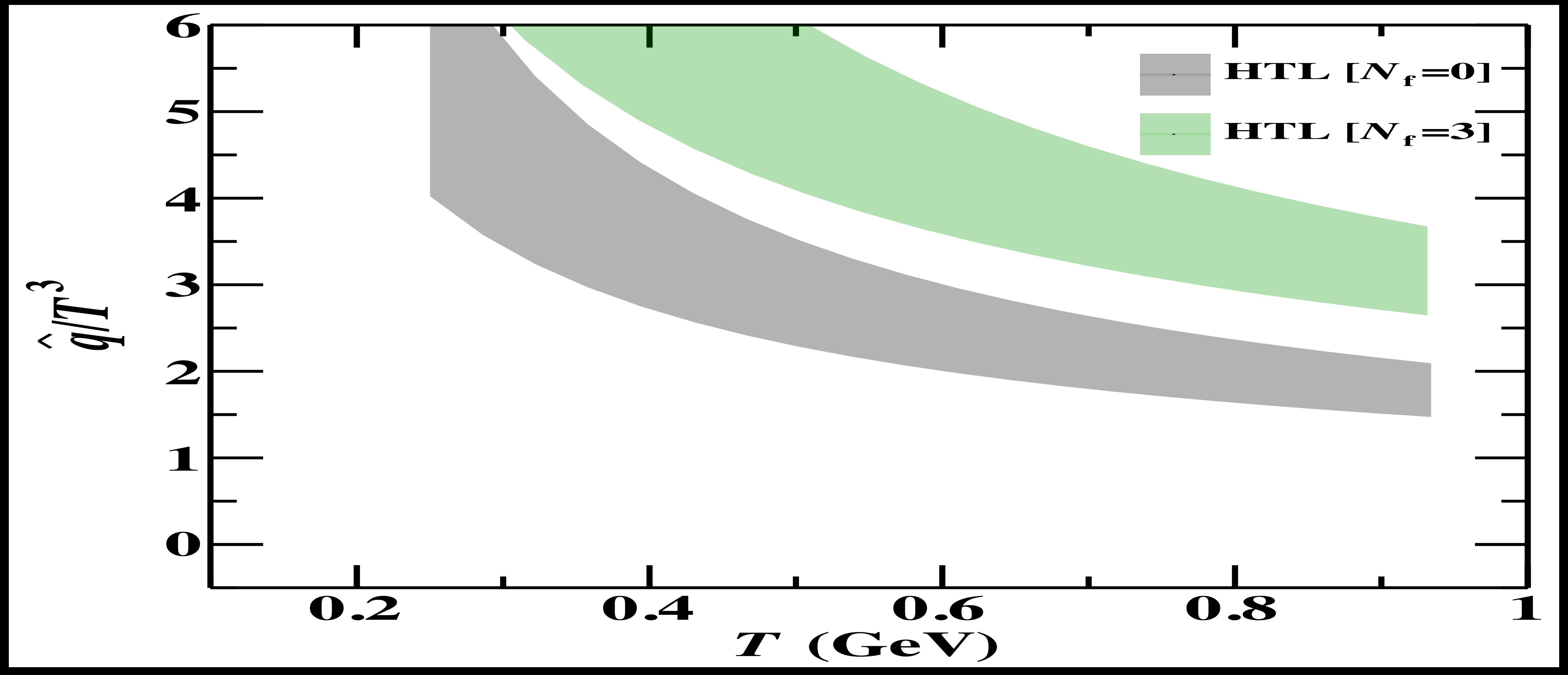
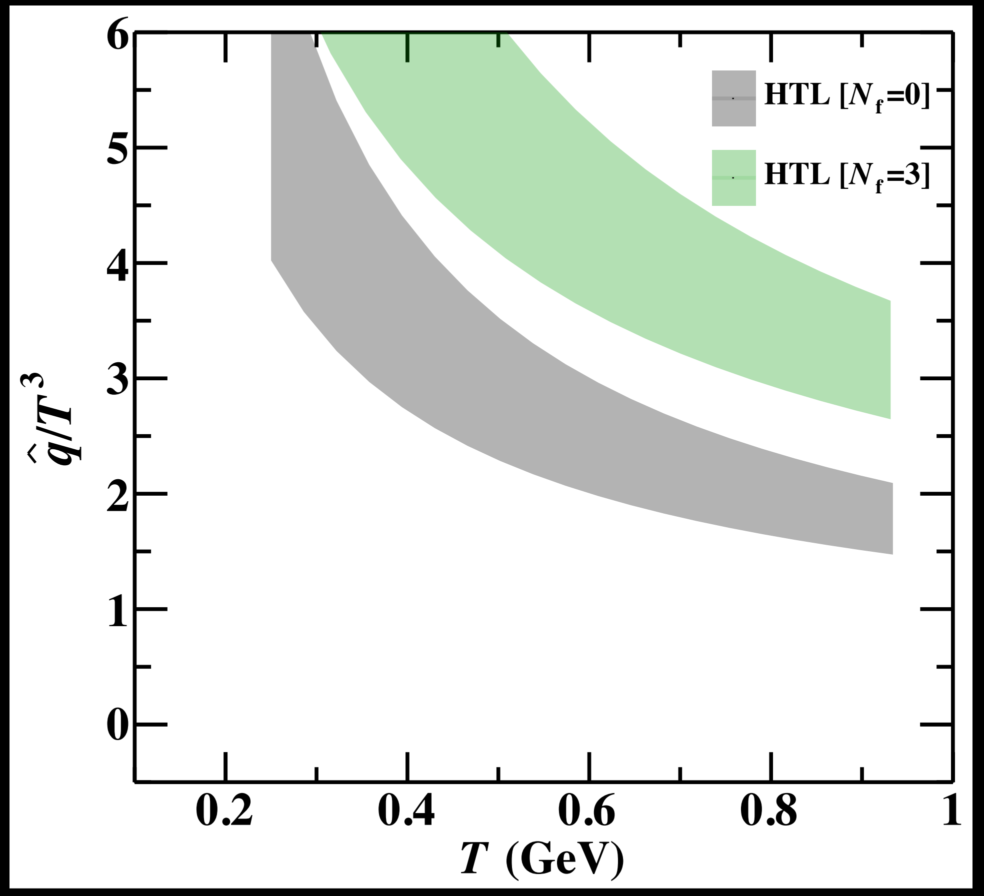
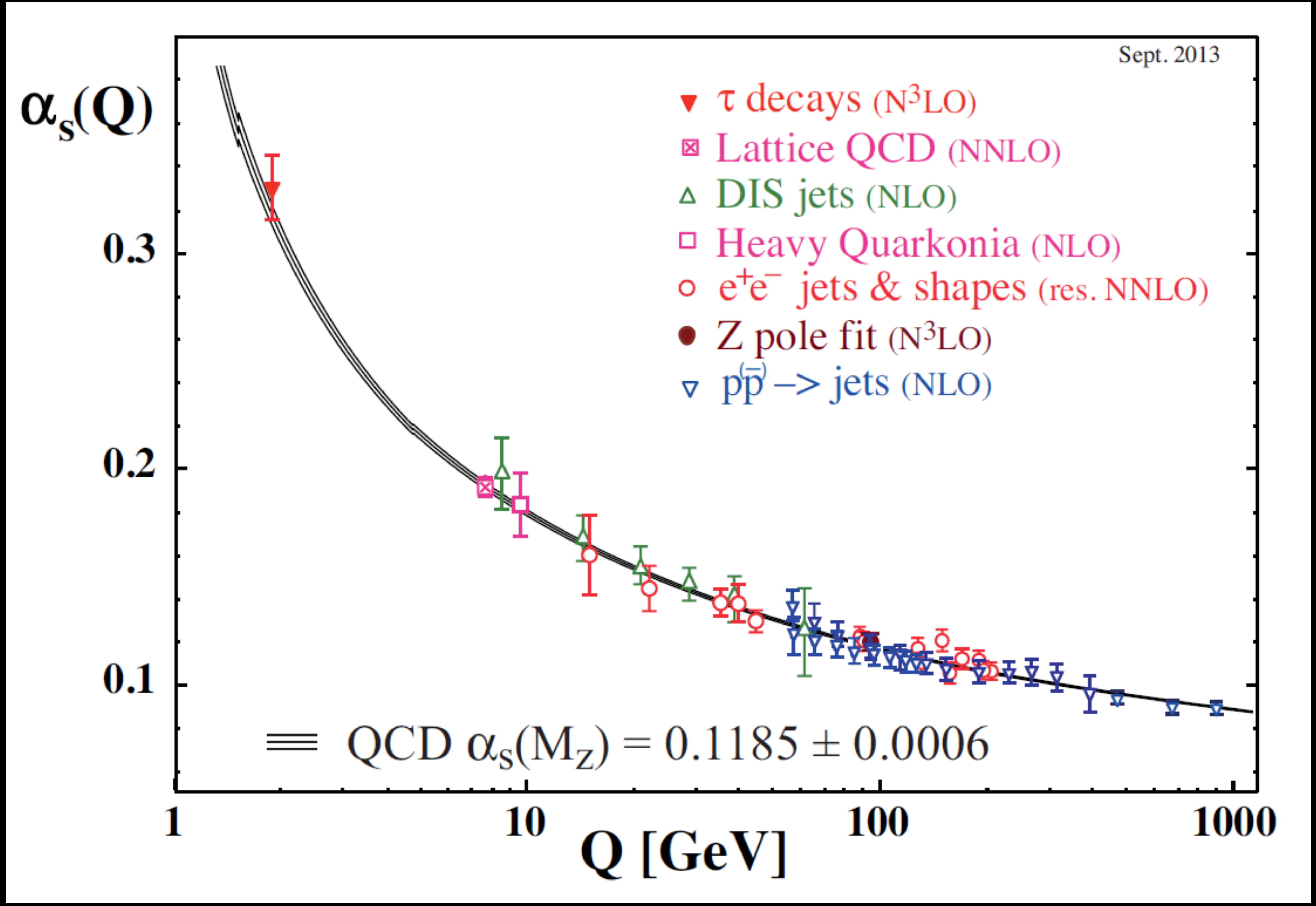


Is Perturbation theory valid at these temperatures?





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}

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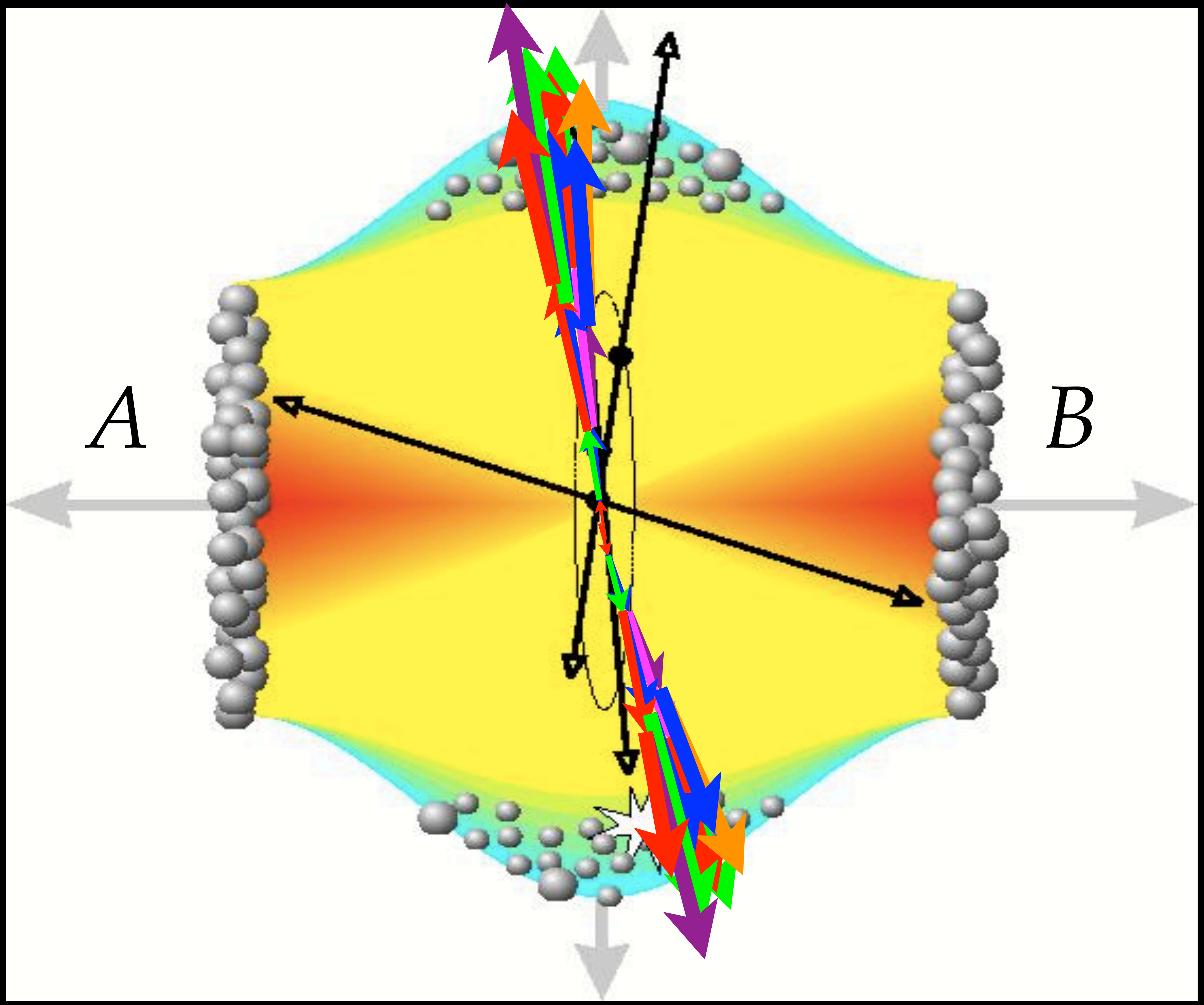

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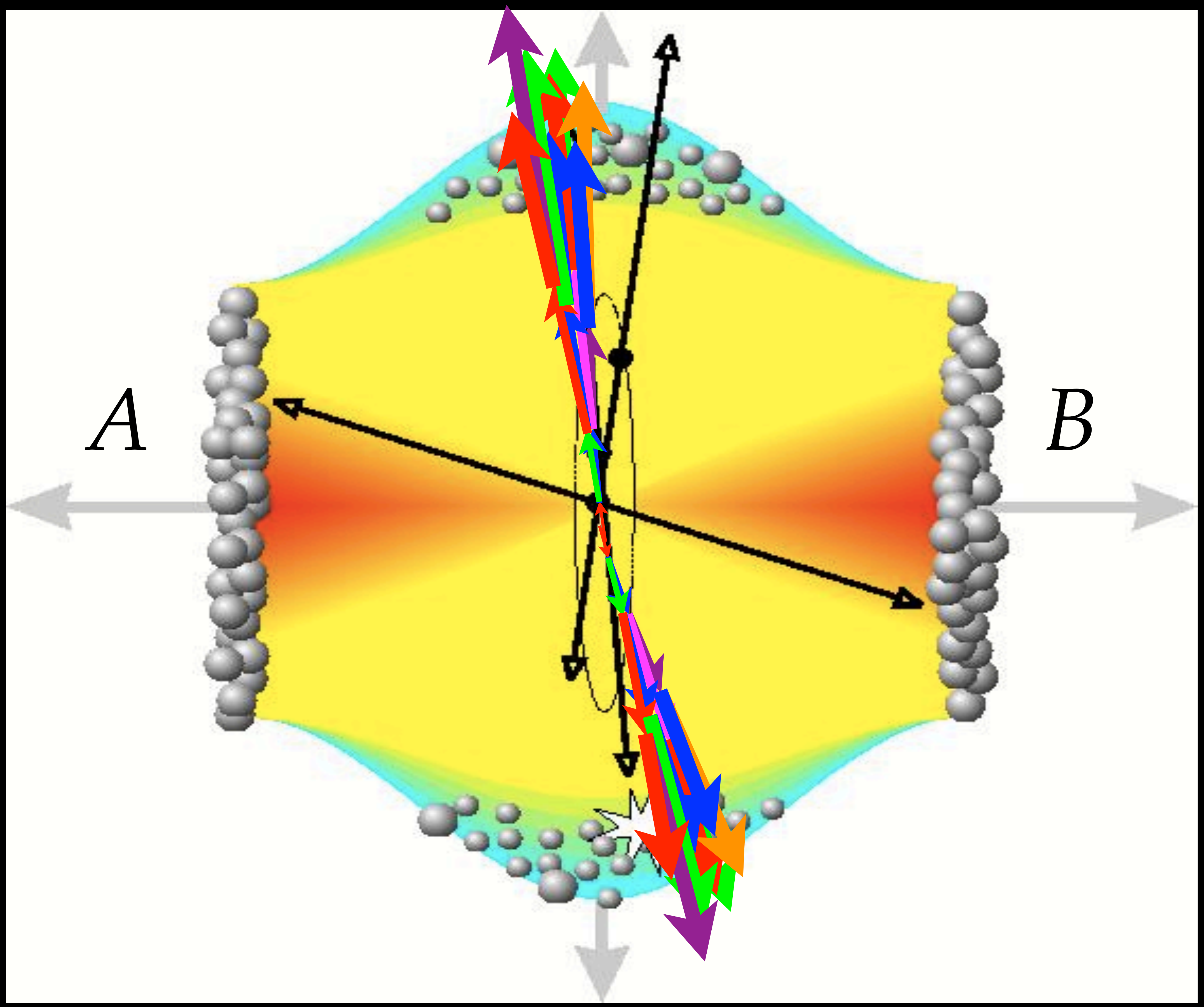

$$R_{AA} = \frac{d\mathcal{N}_{AA}(b_L, b_H)}{\mathrm{N}_{binary}(b_L, b_H)\ d\mathcal{N}_{pp}}$$

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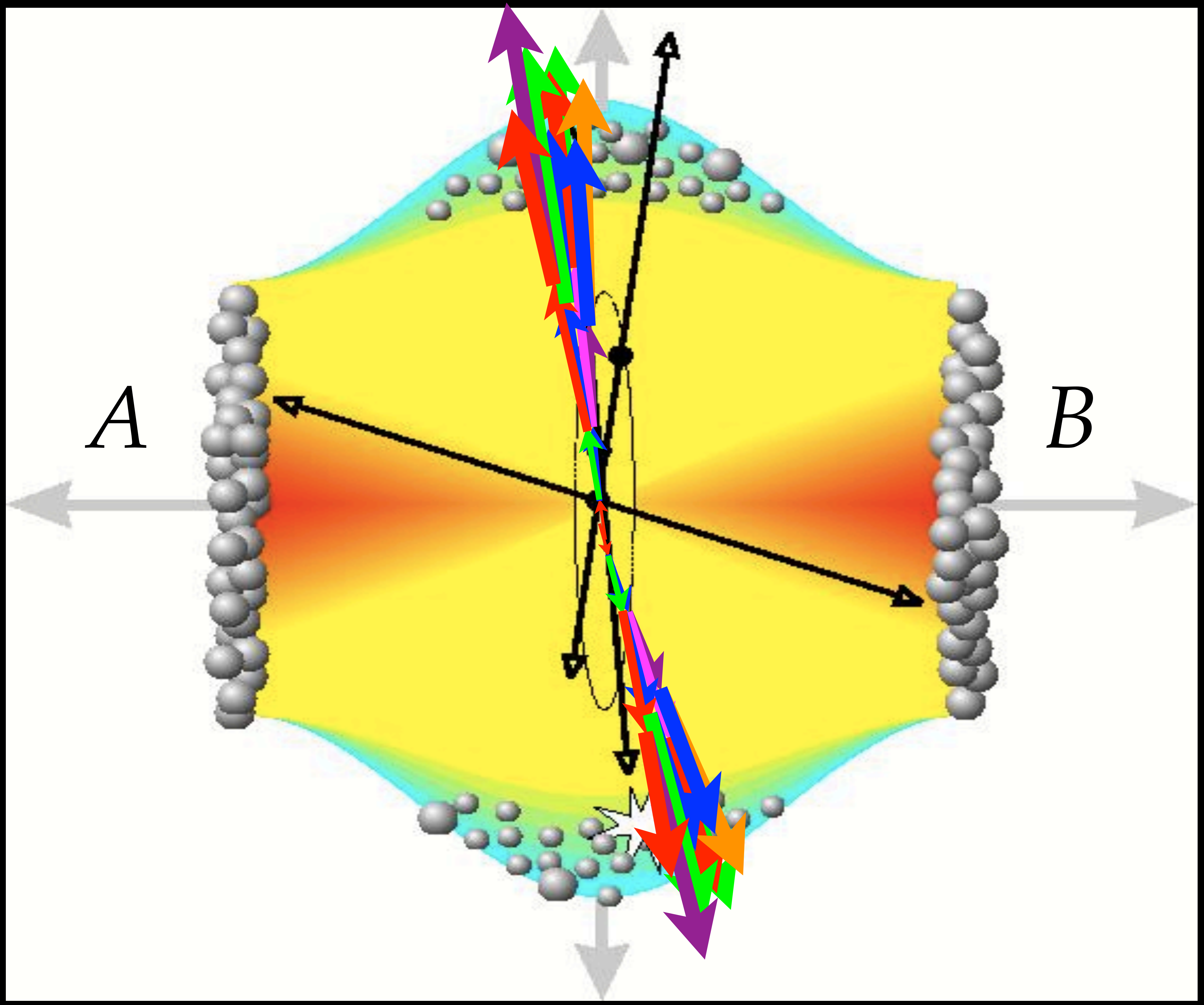

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$$d\mathcal{N}^h_{AB} = \int_{b_L}^{b_h} d^2b \int d^2r \int dp_1 dp_2$$
$$\times\, dP_A(p_1, r) dP_B(p_2, r)$$
$$\times\, \sigma_{1+2\to 3+4}$$
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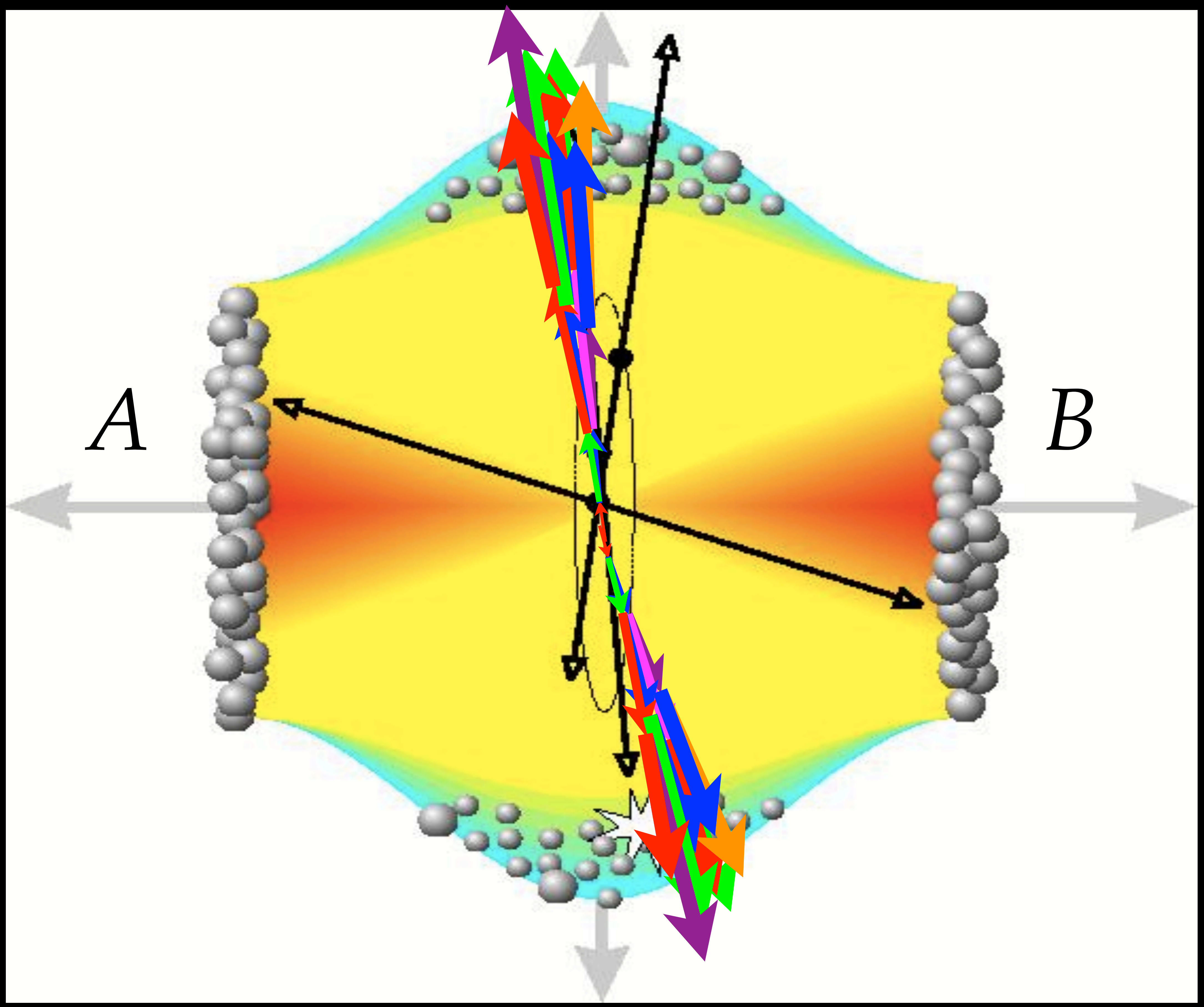

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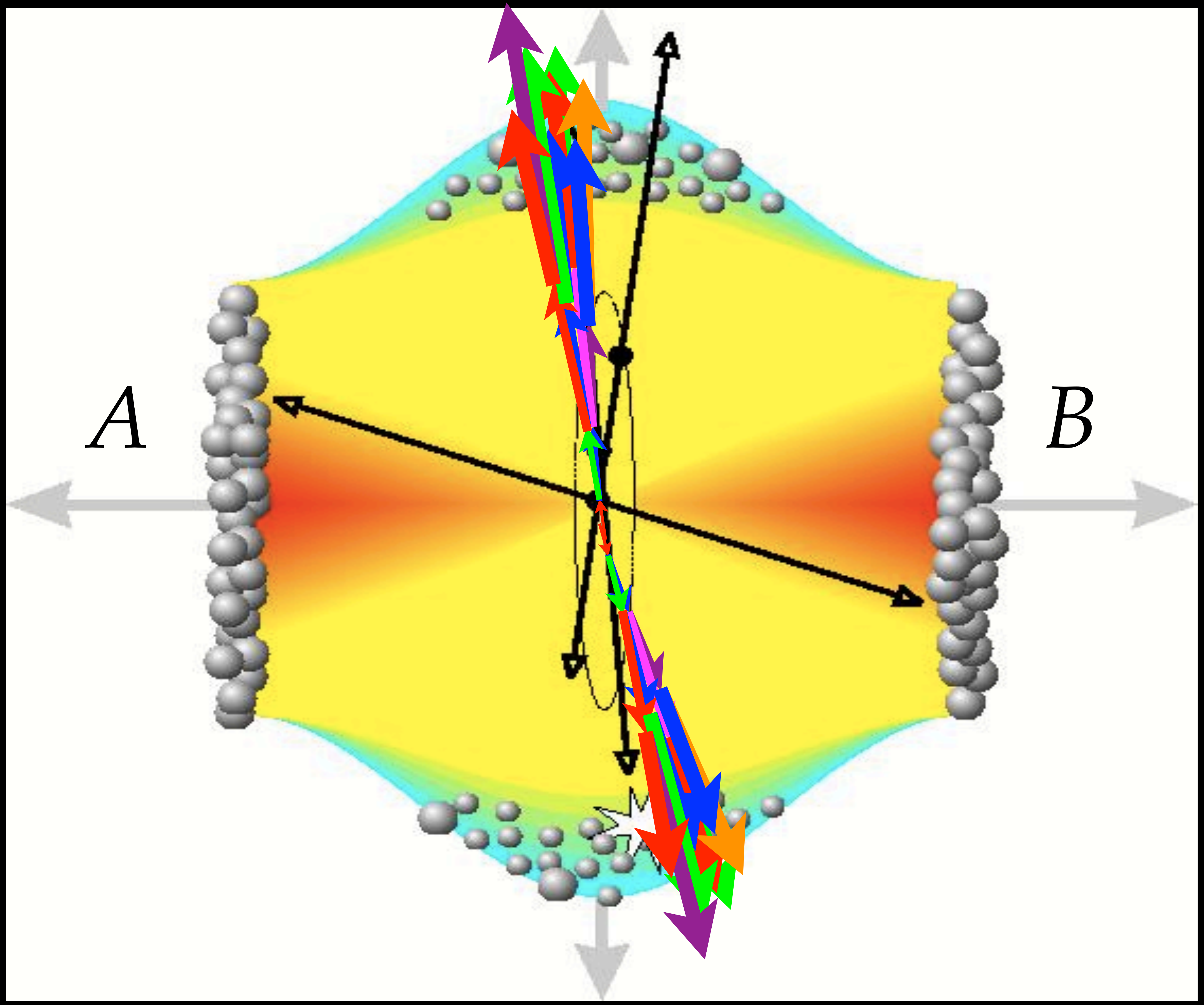

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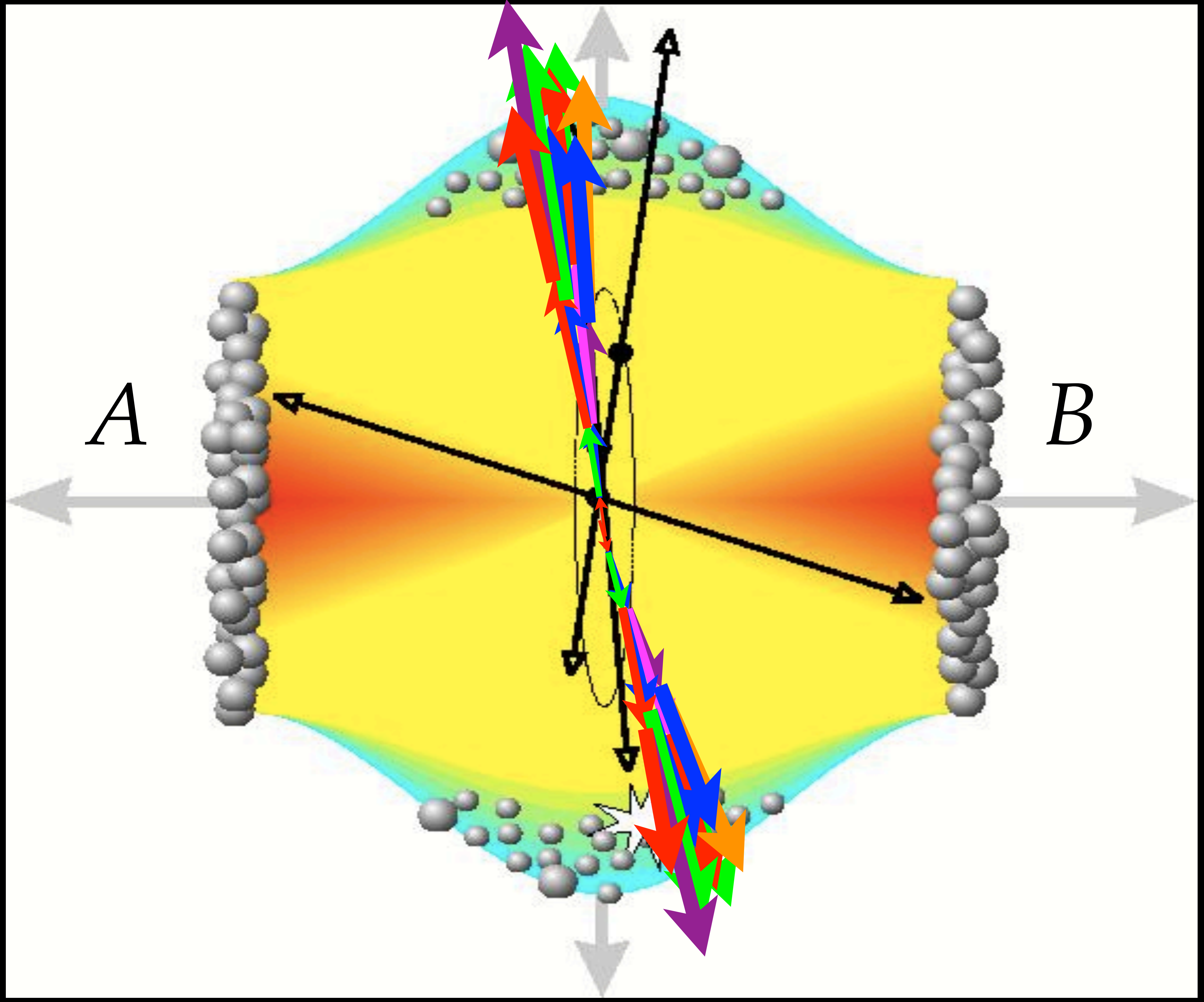

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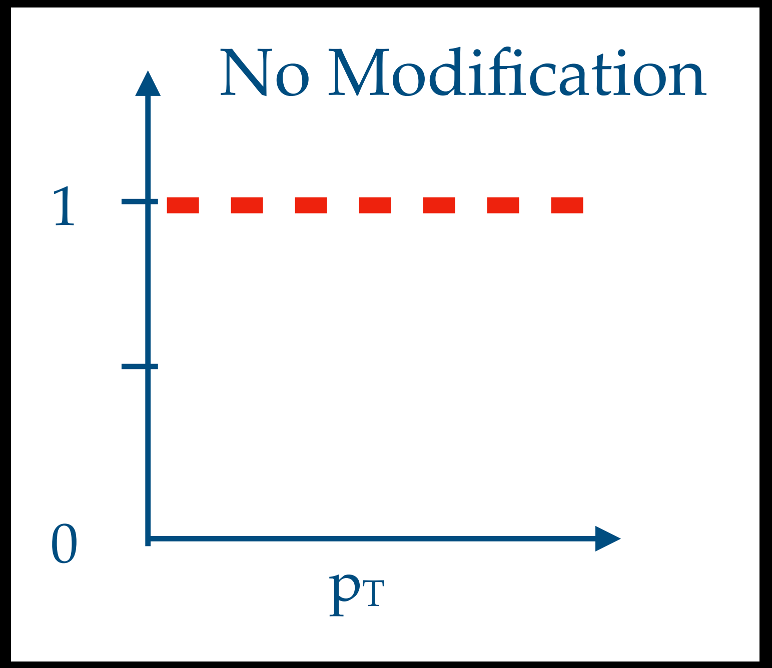

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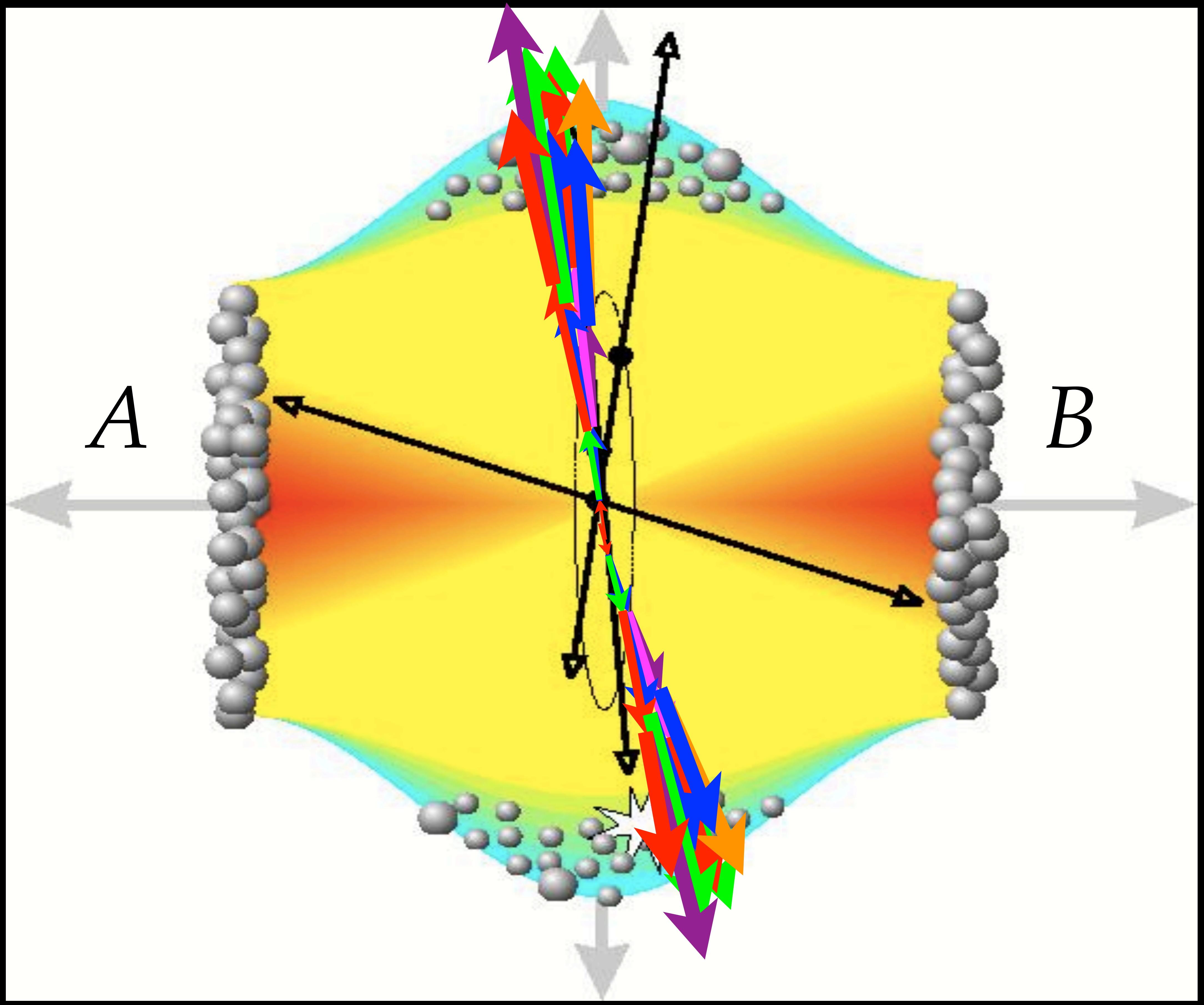

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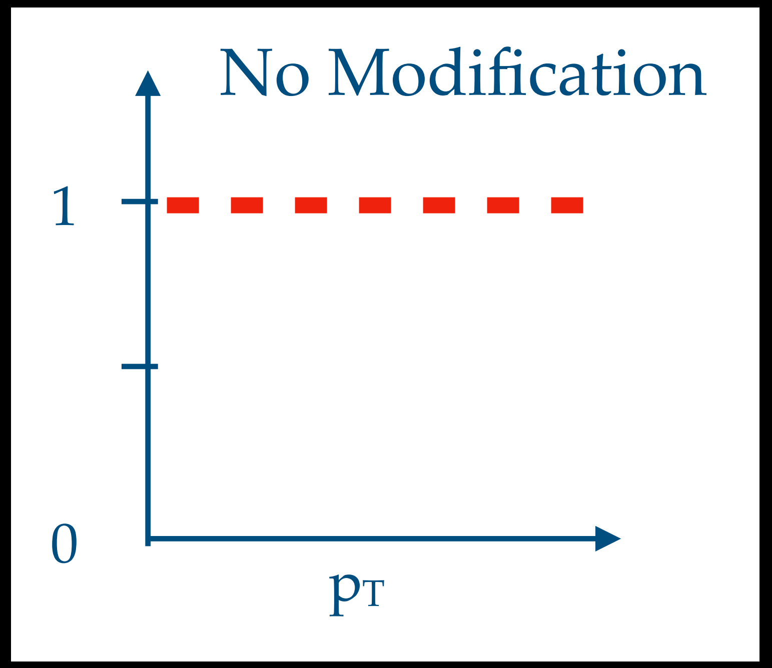

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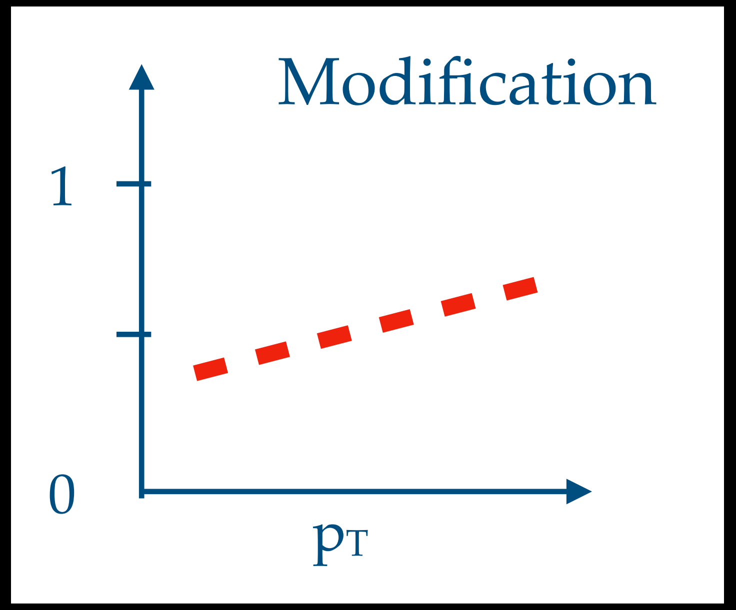

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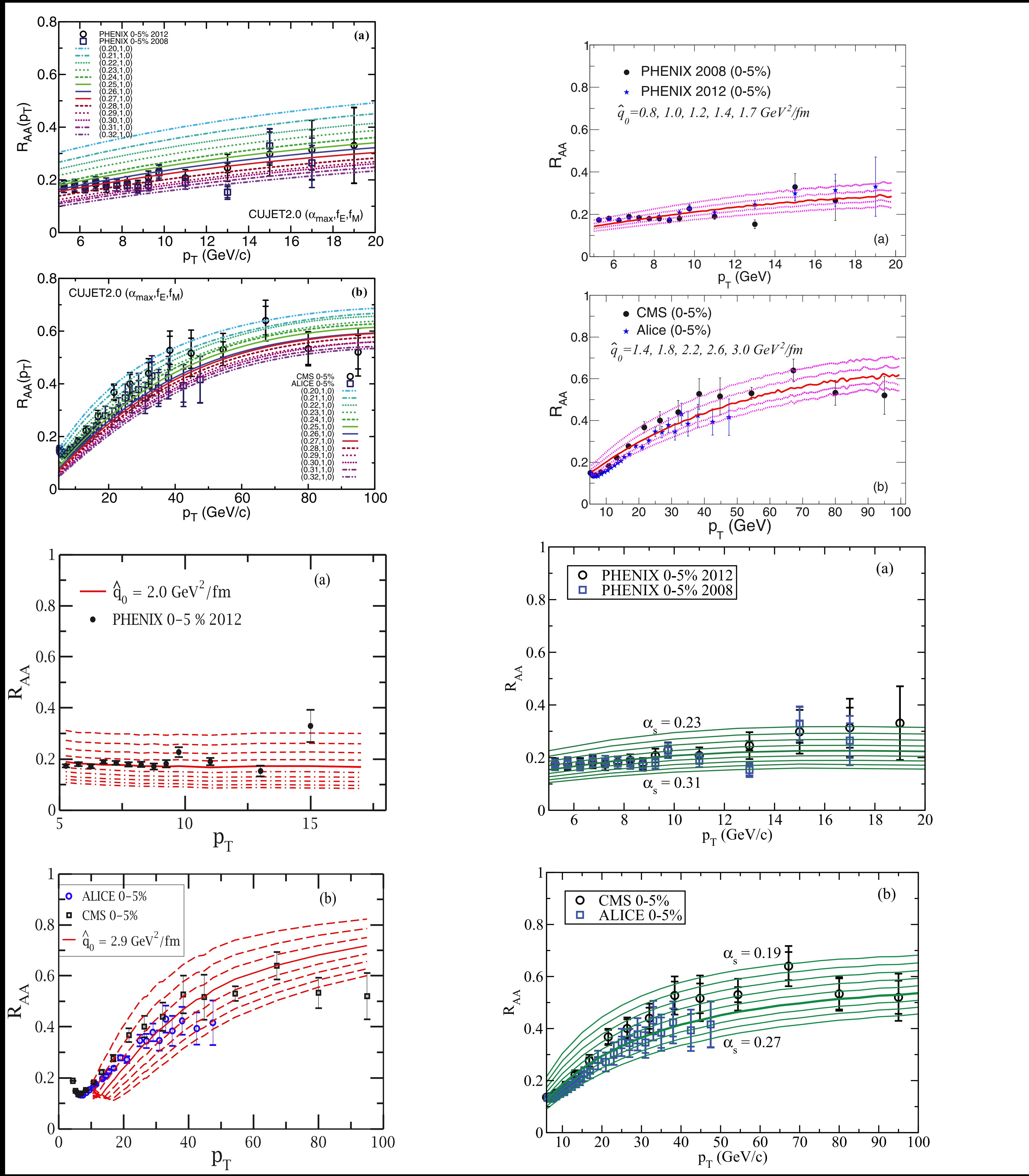
A first serious attempt to extract $\hat{q}$



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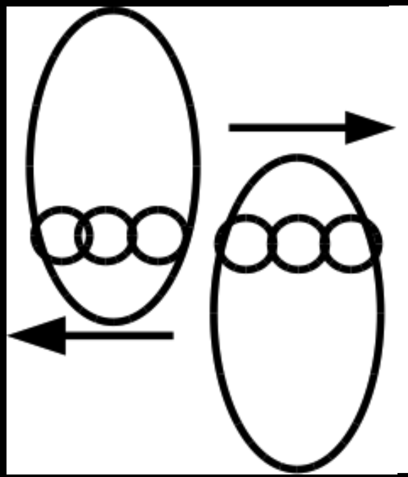
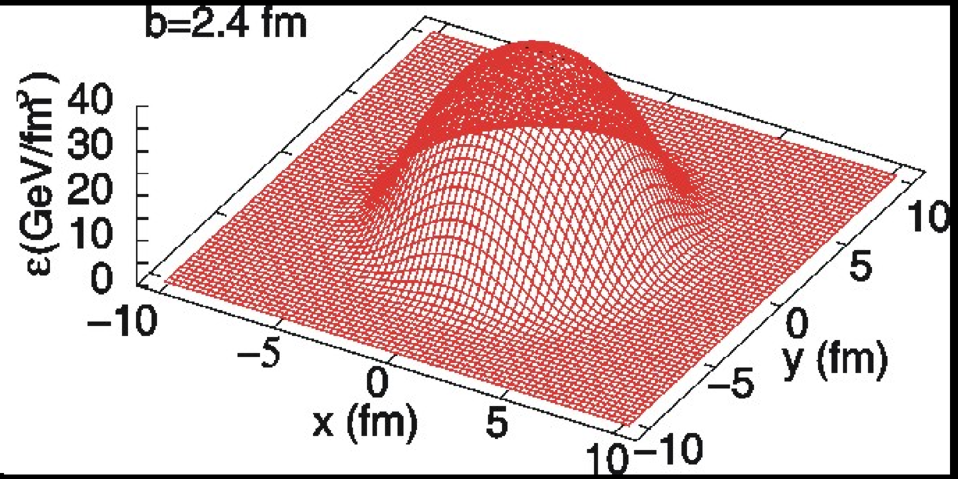
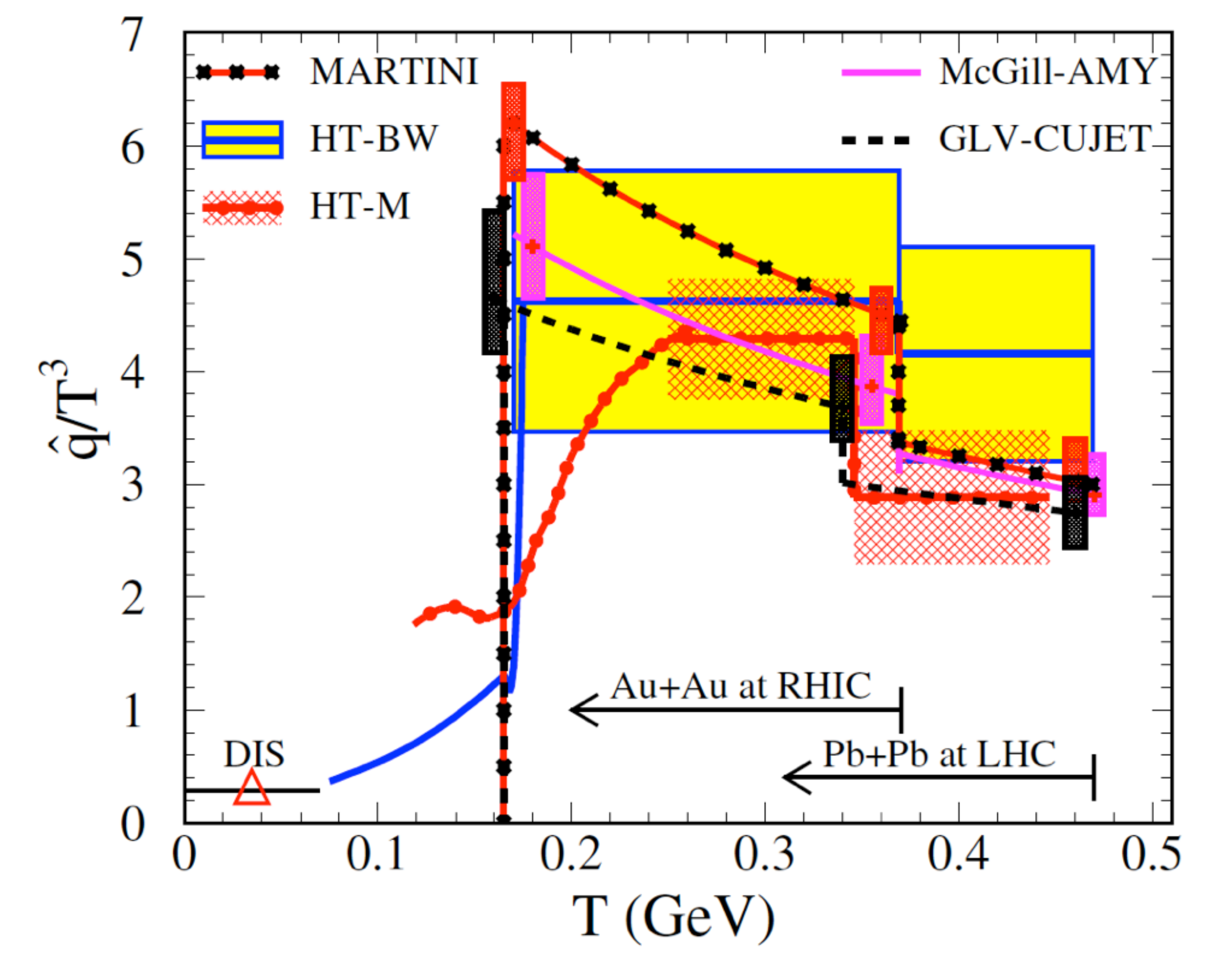


$$R_{AA} \sim \frac{\frac{dN_{AA}}{dp_T dy}}{N_{bin}\frac{dN_{pp}}{dp_T dy}}$$



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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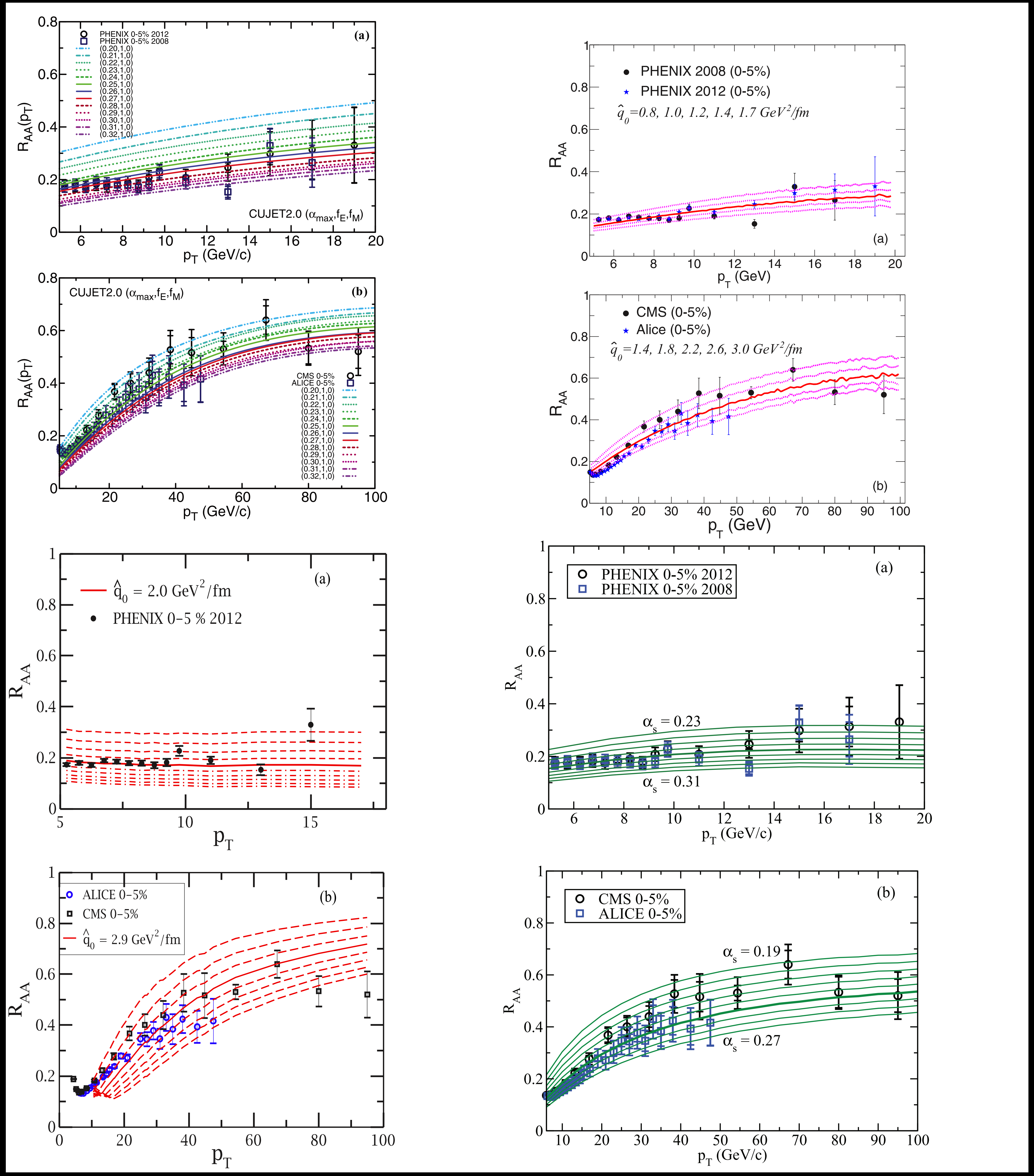

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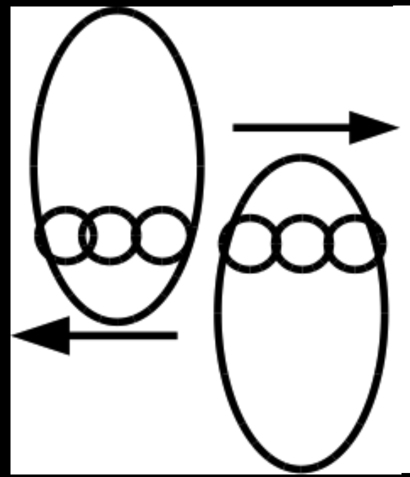

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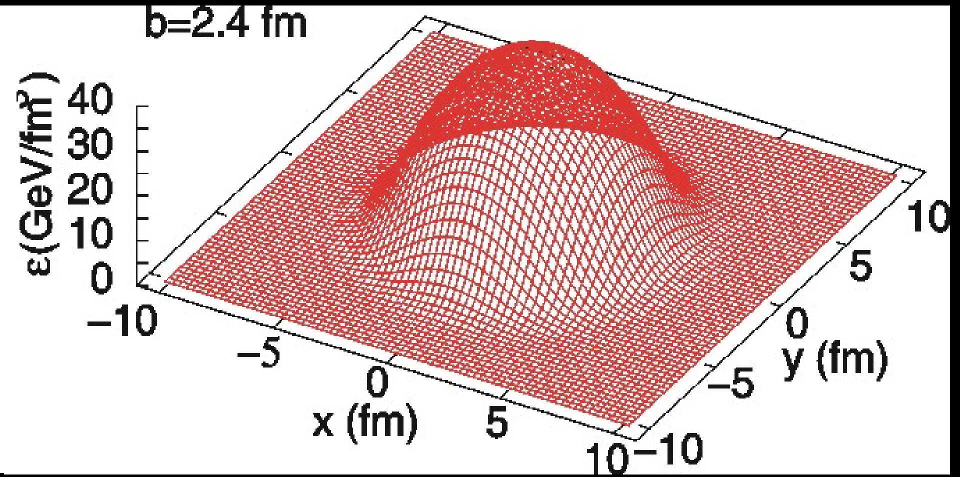

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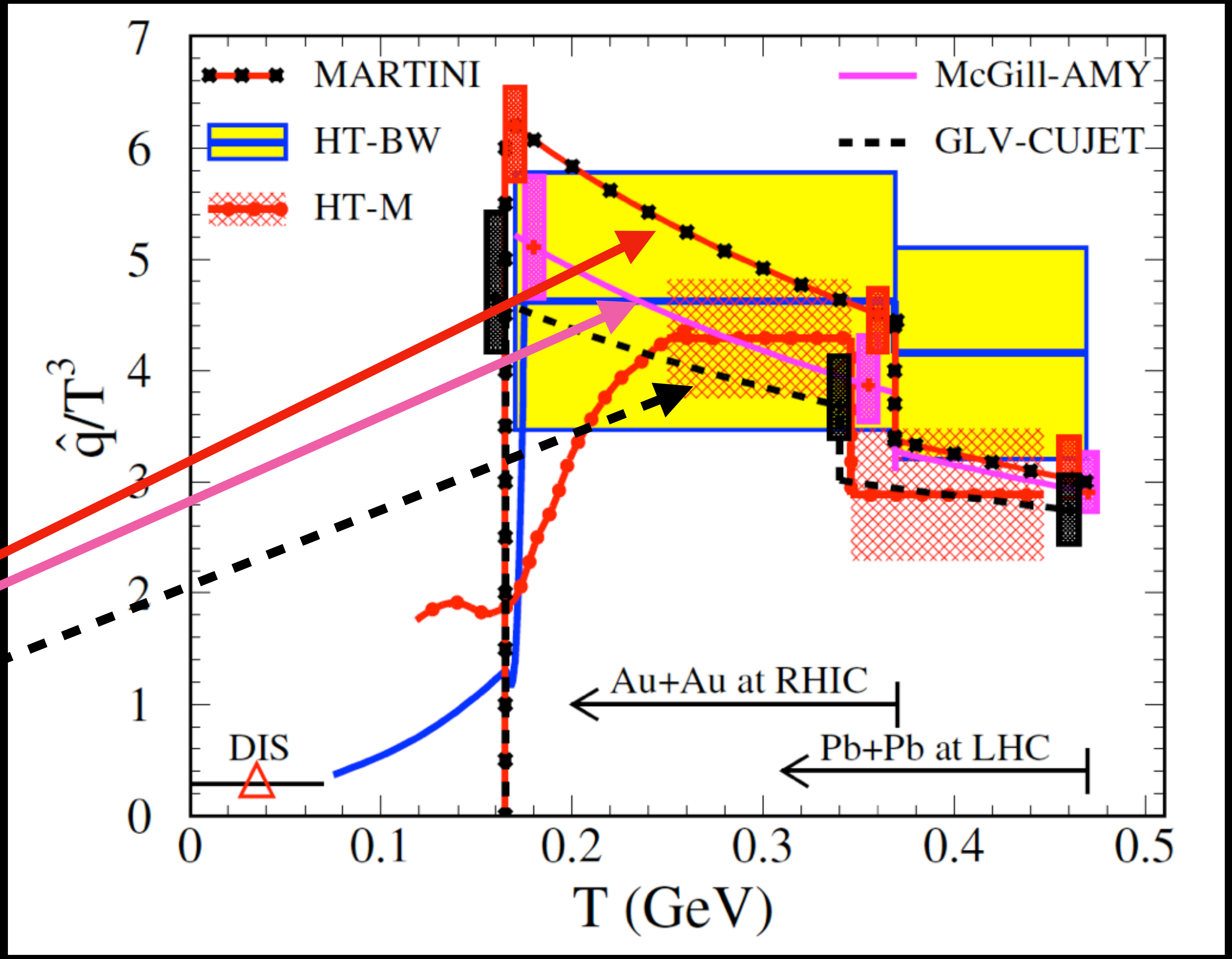
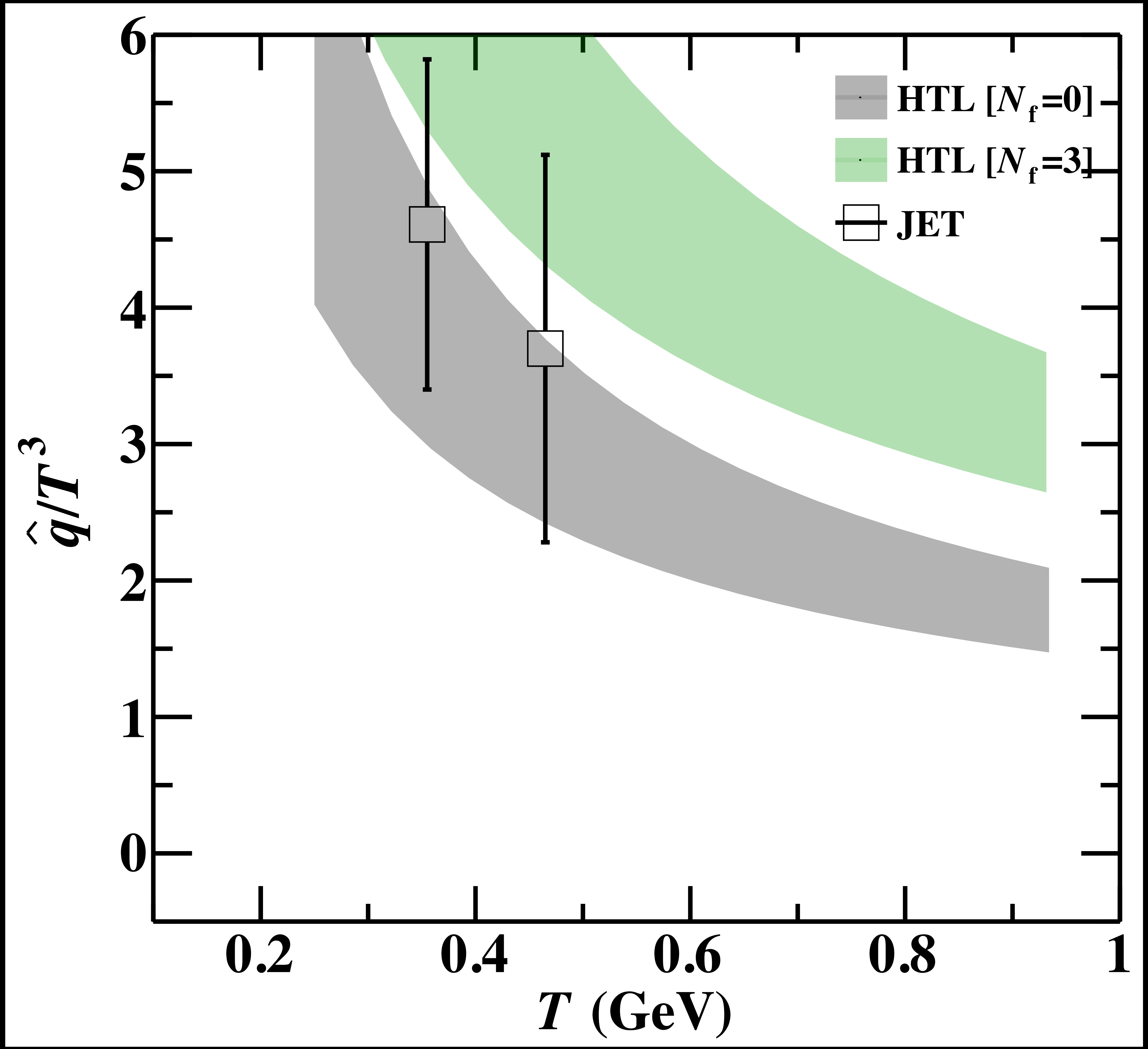
Some use the HTL
Formula for $\hat{q}$ truncated



Adding to our plot! Circa (2014)



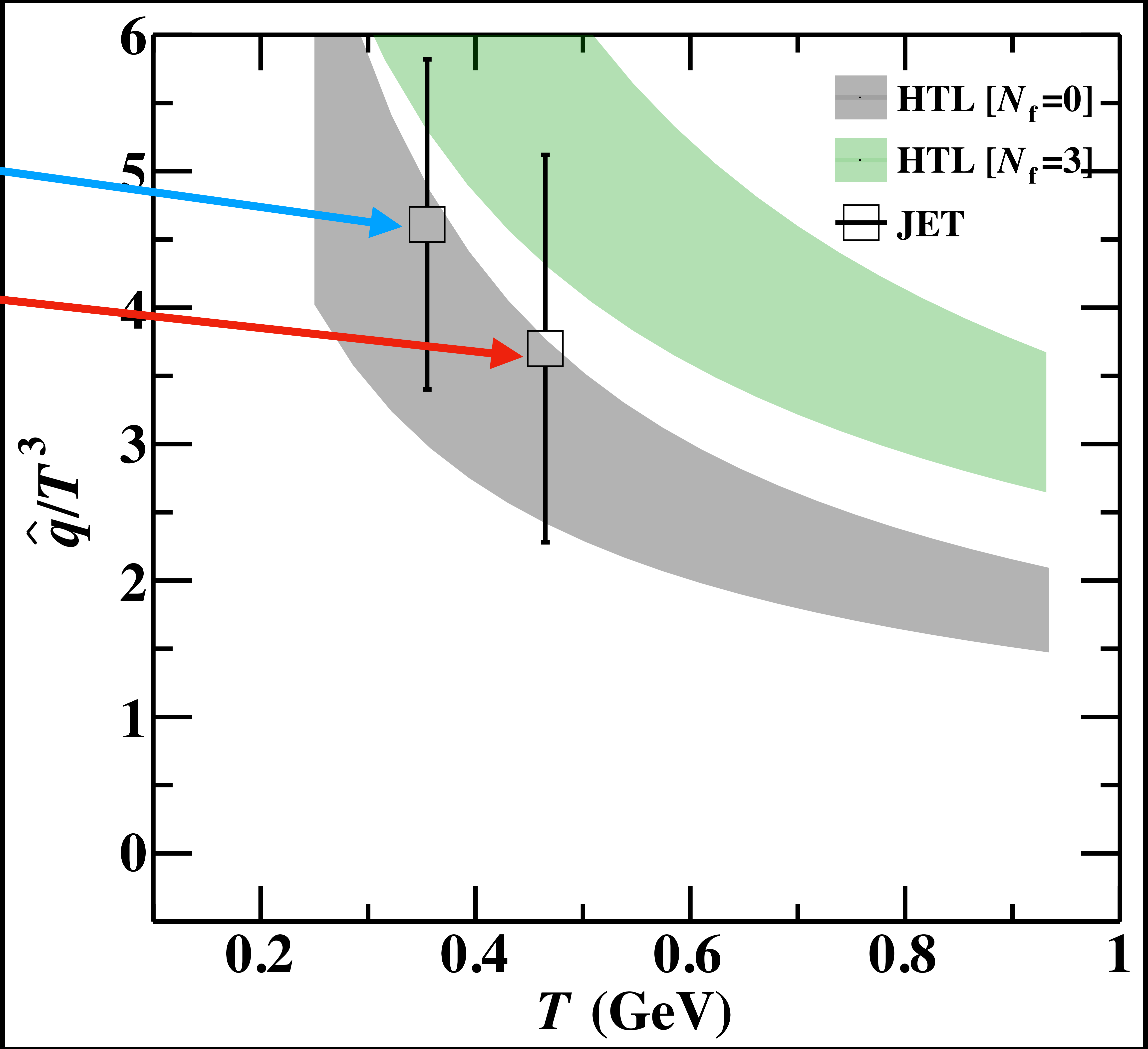
Adding to our plot! Circa (2014)

This point is the normalization at RHIC energies

This point is the normalization at LHC energies

$$T_{LHC}^{max} \simeq 1.2\, T_{RHIC}^{max}$$

$$p_{LHC}^{max} = 5\, p_{RHIC}^{max}$$



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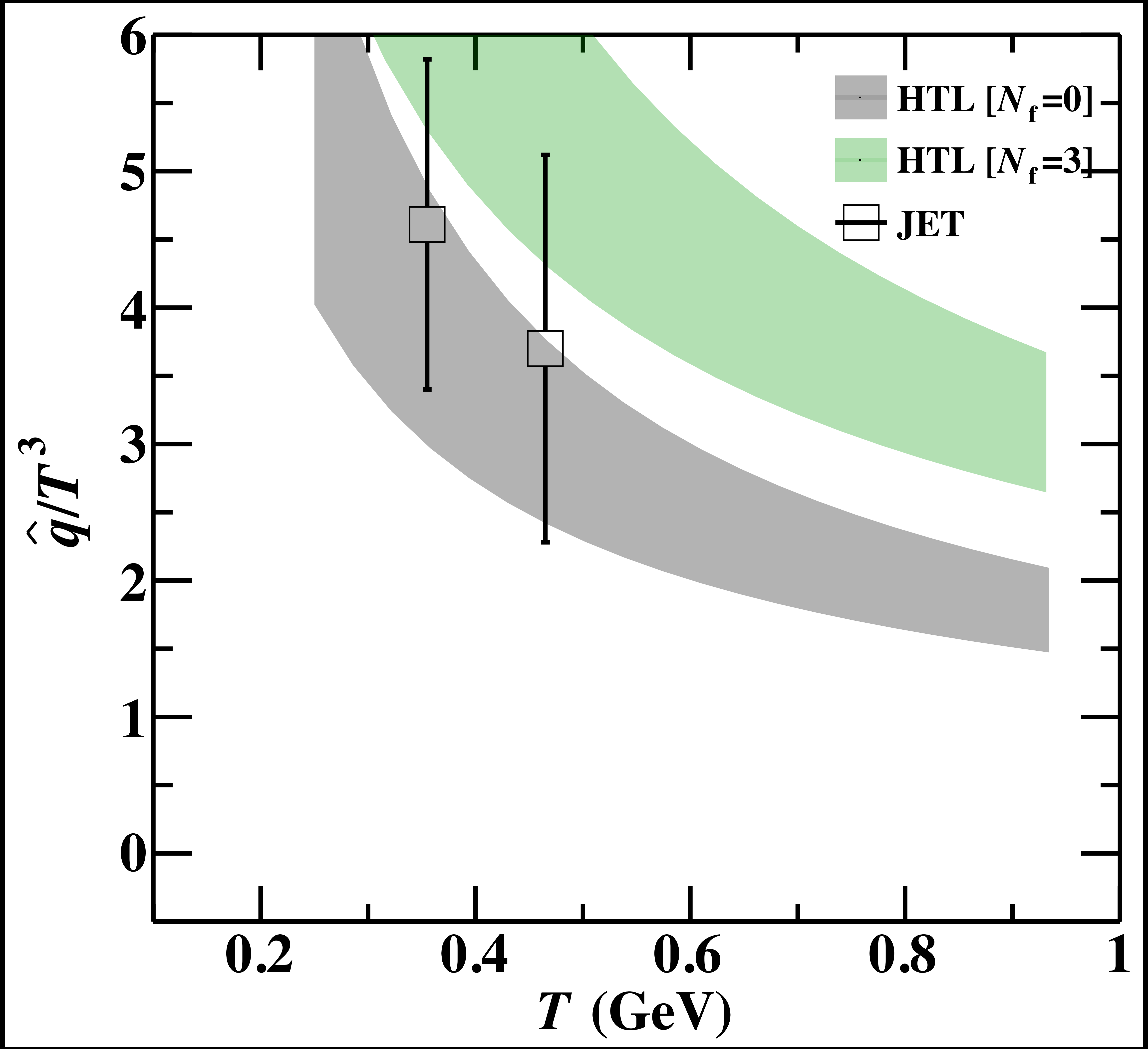

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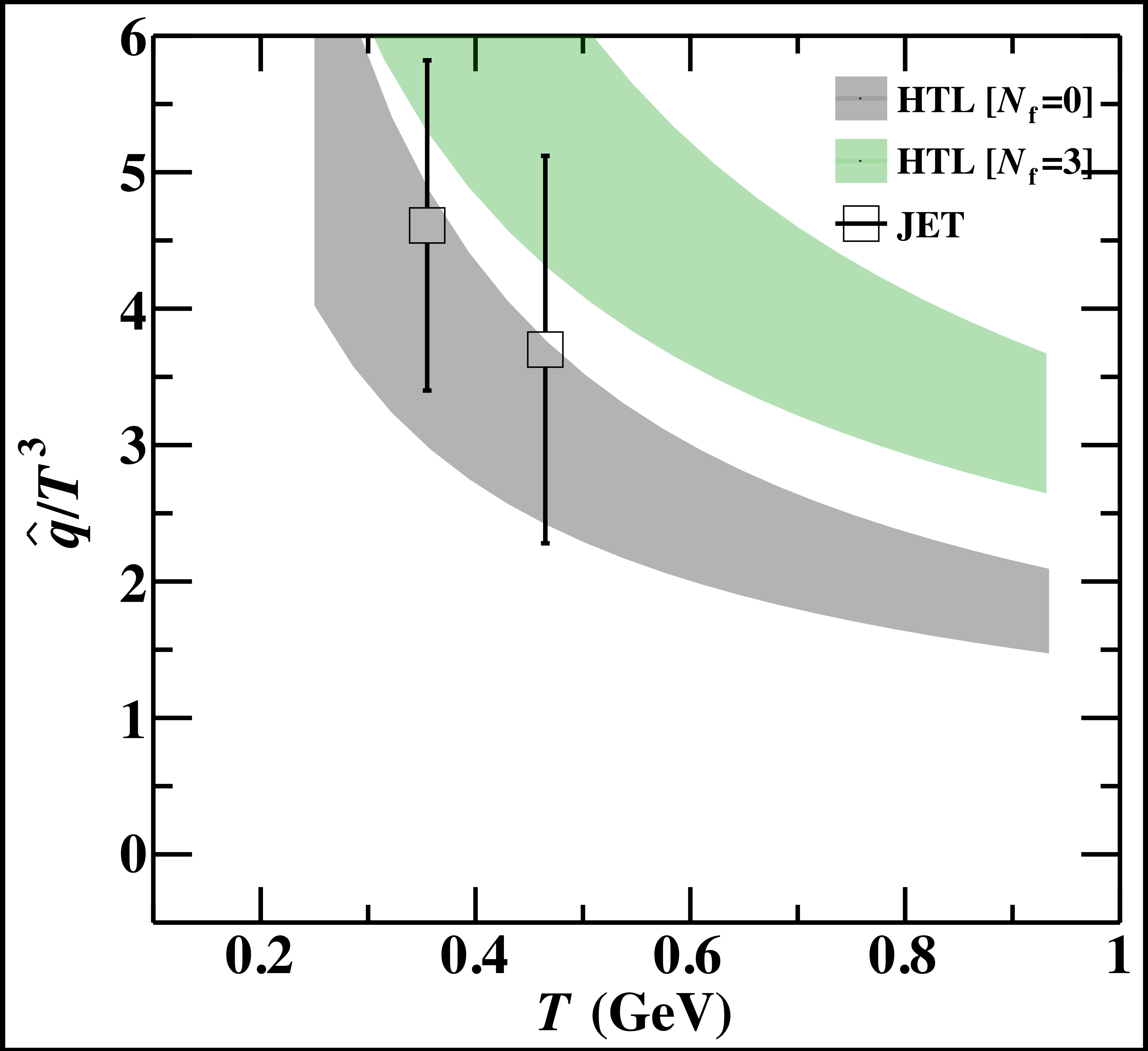


If this is true, must effect the centrality dependence of $R_{AA,}$ $v_{2,}$ and its centrality dependence at a given collision energy but no such evidence is seen

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 $(\hat{q}\tau)$

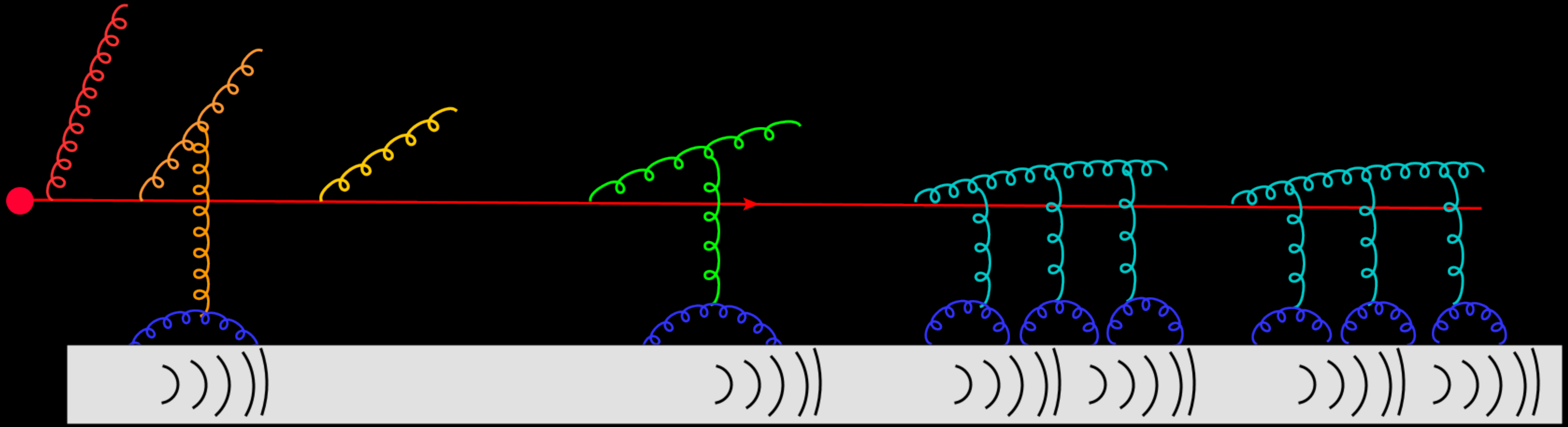
Different approaches to E-loss are valid in different epochs of the jet

A complete description requires multiple approaches in sequence

Discussion moves to boundaries between approaches

Basic Picture

- 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

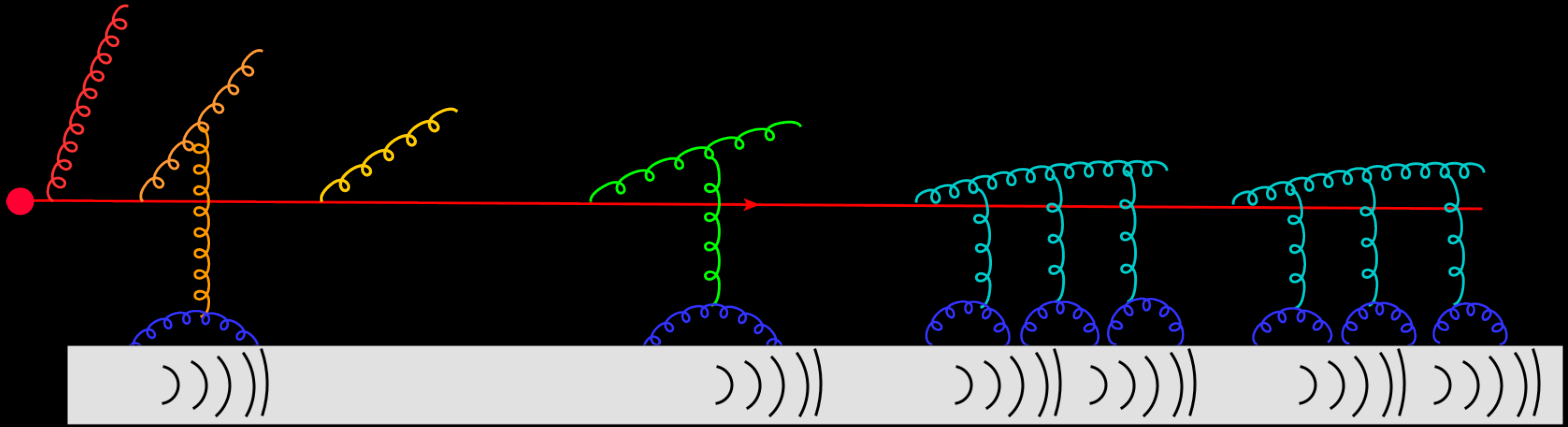


- Exchanges with medium lead to excitations/medium response

Basic Picture

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

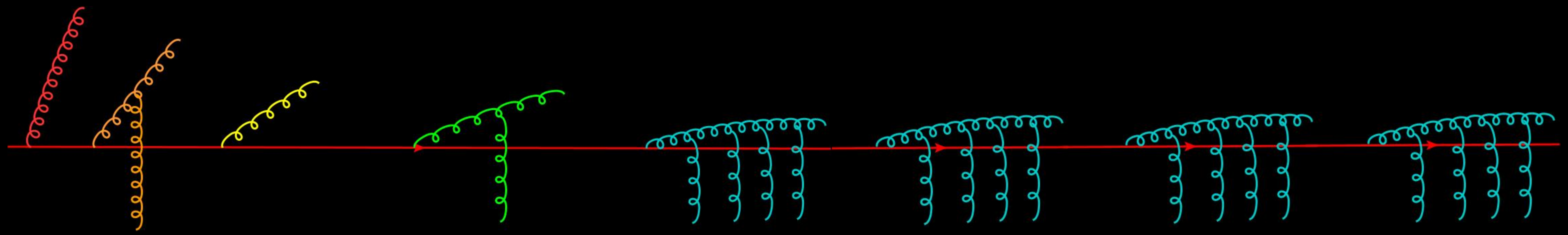
This gives $$Q^2_{med} \simeq \sqrt{2E\hat{q}}$$



Physics: DGLAP like
Simulator: MATTER

Physics: BDMPS/ AMY like
Simulator: MARTINI, LBT

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).

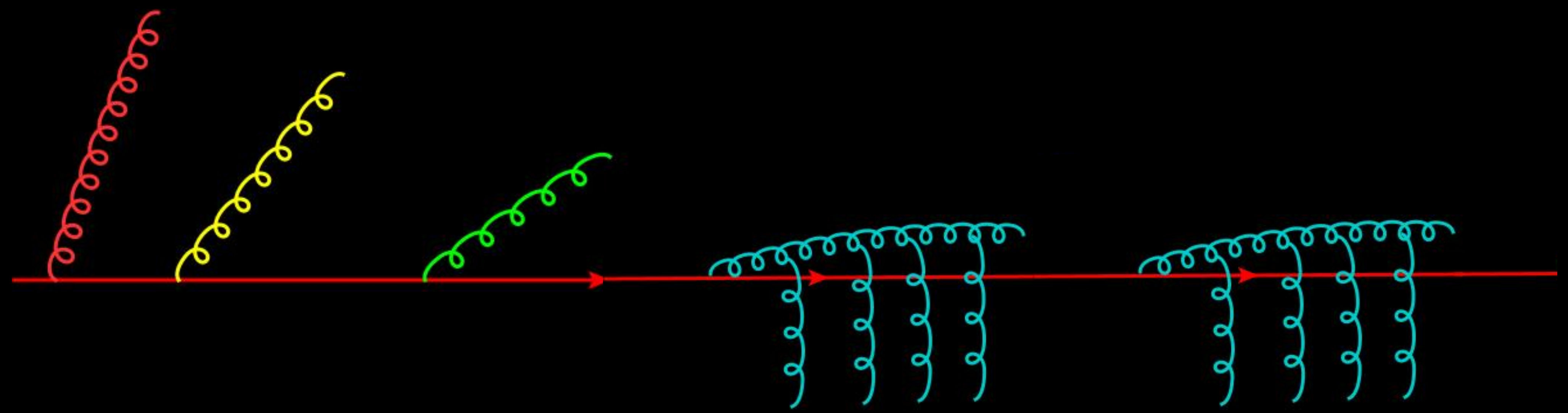
- The maximum virtuality built up from scattering

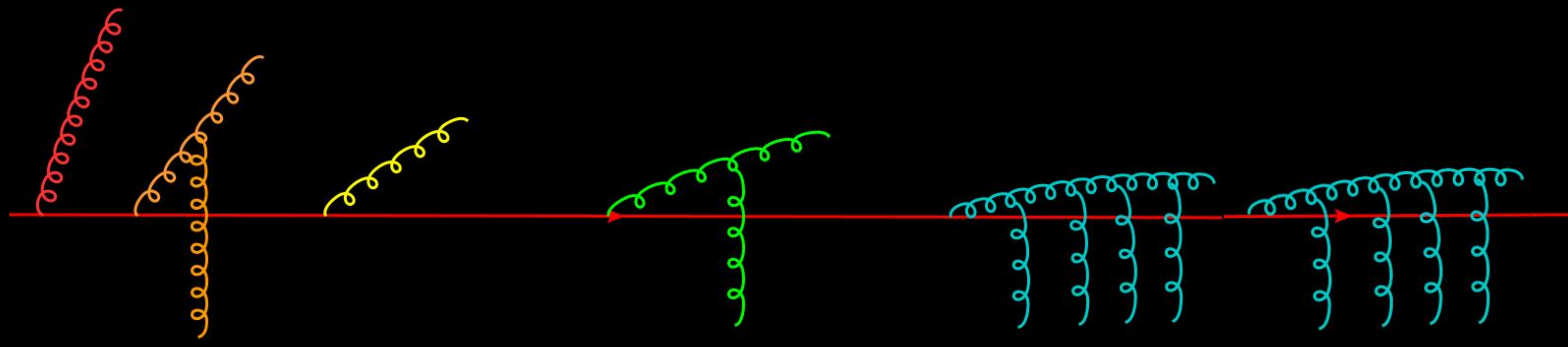
  at time t is $Q^2_{\mathrm{med}} = \hat{q}t \simeq \dfrac{2E}{t} \implies t \simeq \sqrt{\dfrac{2E}{\hat{q}}}$

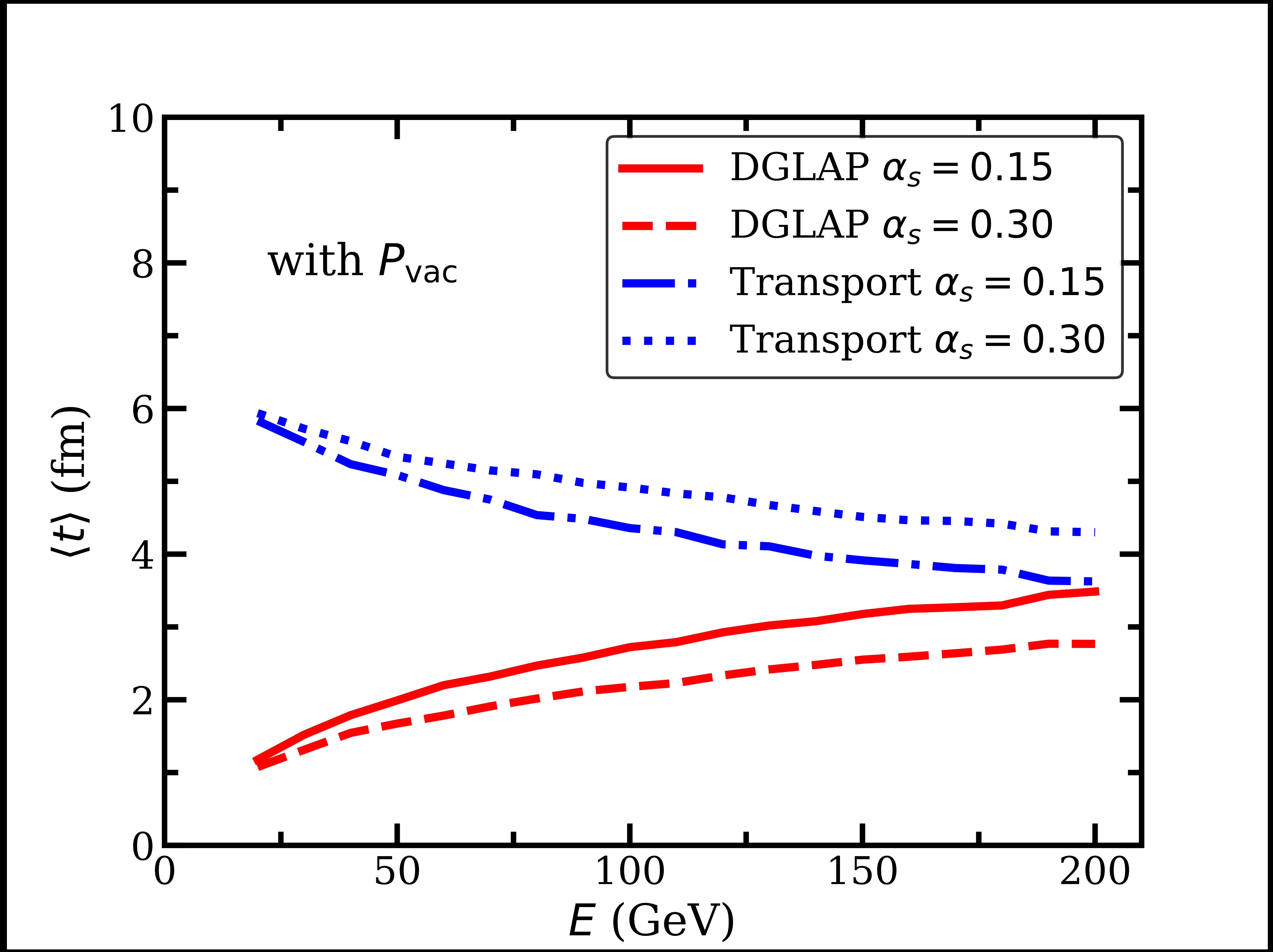
- Highest energy partons (jet core) reach the BDMPS phase last,

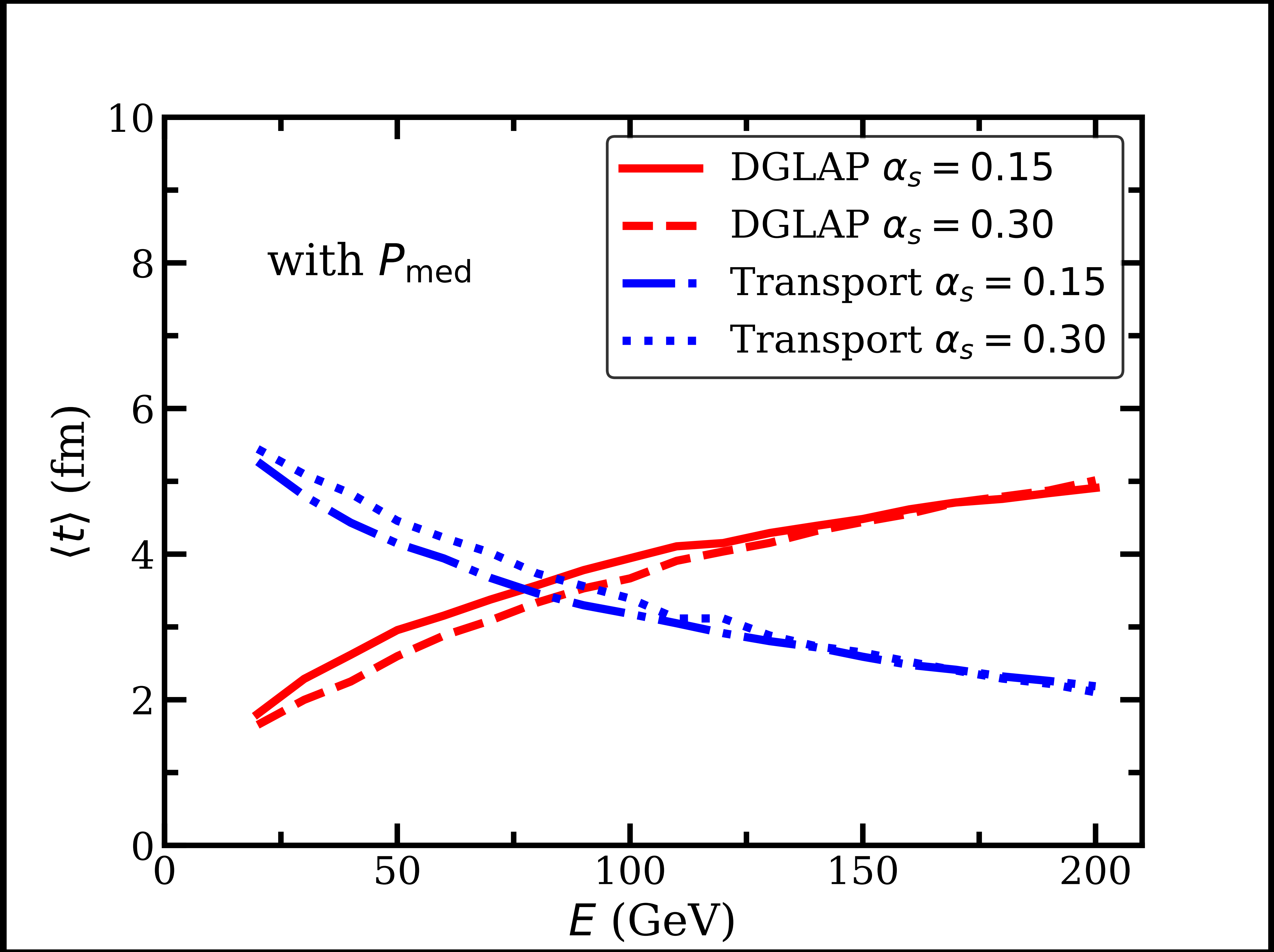
- Smaller the $\hat{q}$, longer it takes to reach the BDMPS phase: longer DGLAP phase

Time spent by leading parton and scattering in each phase









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

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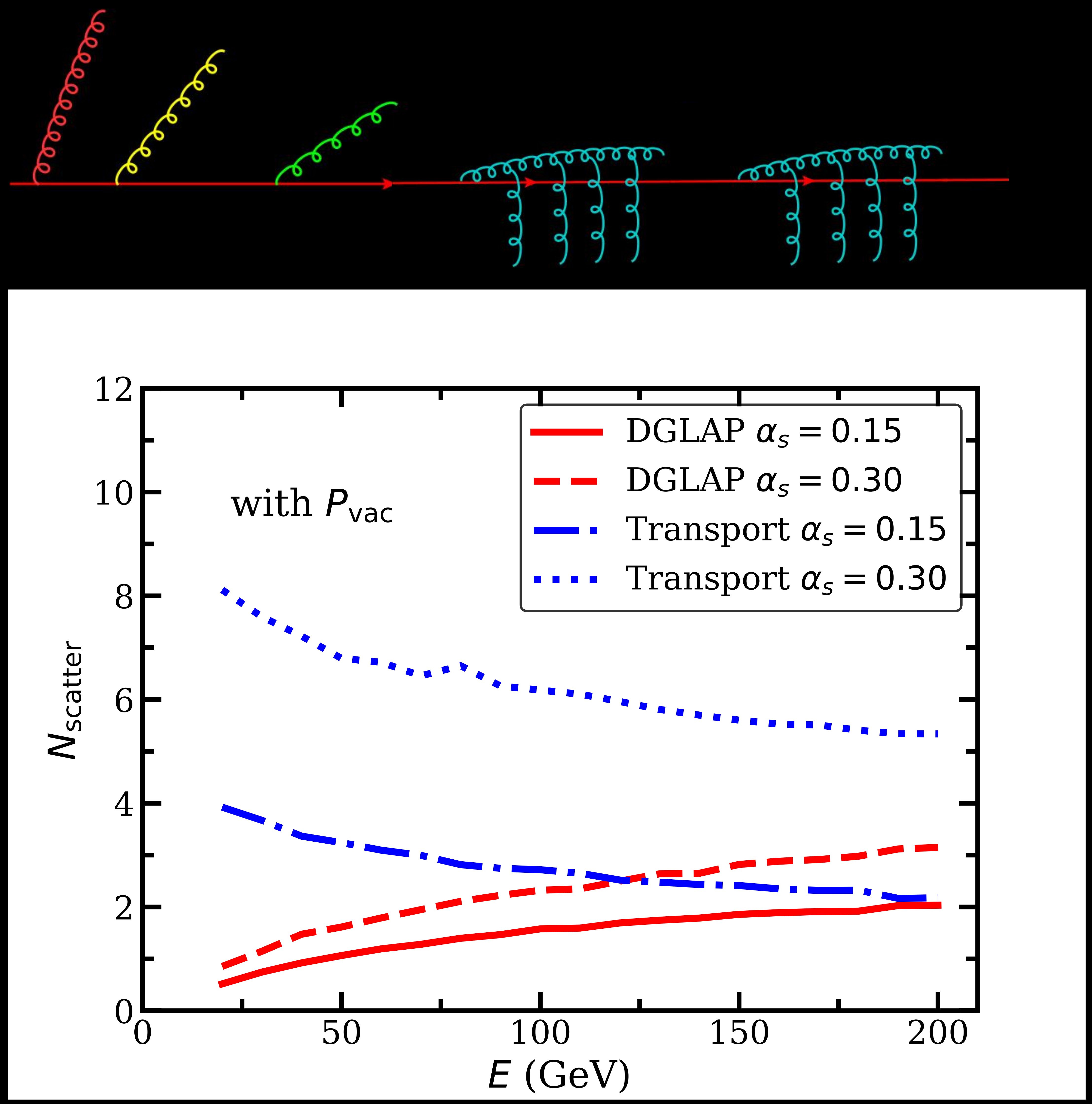

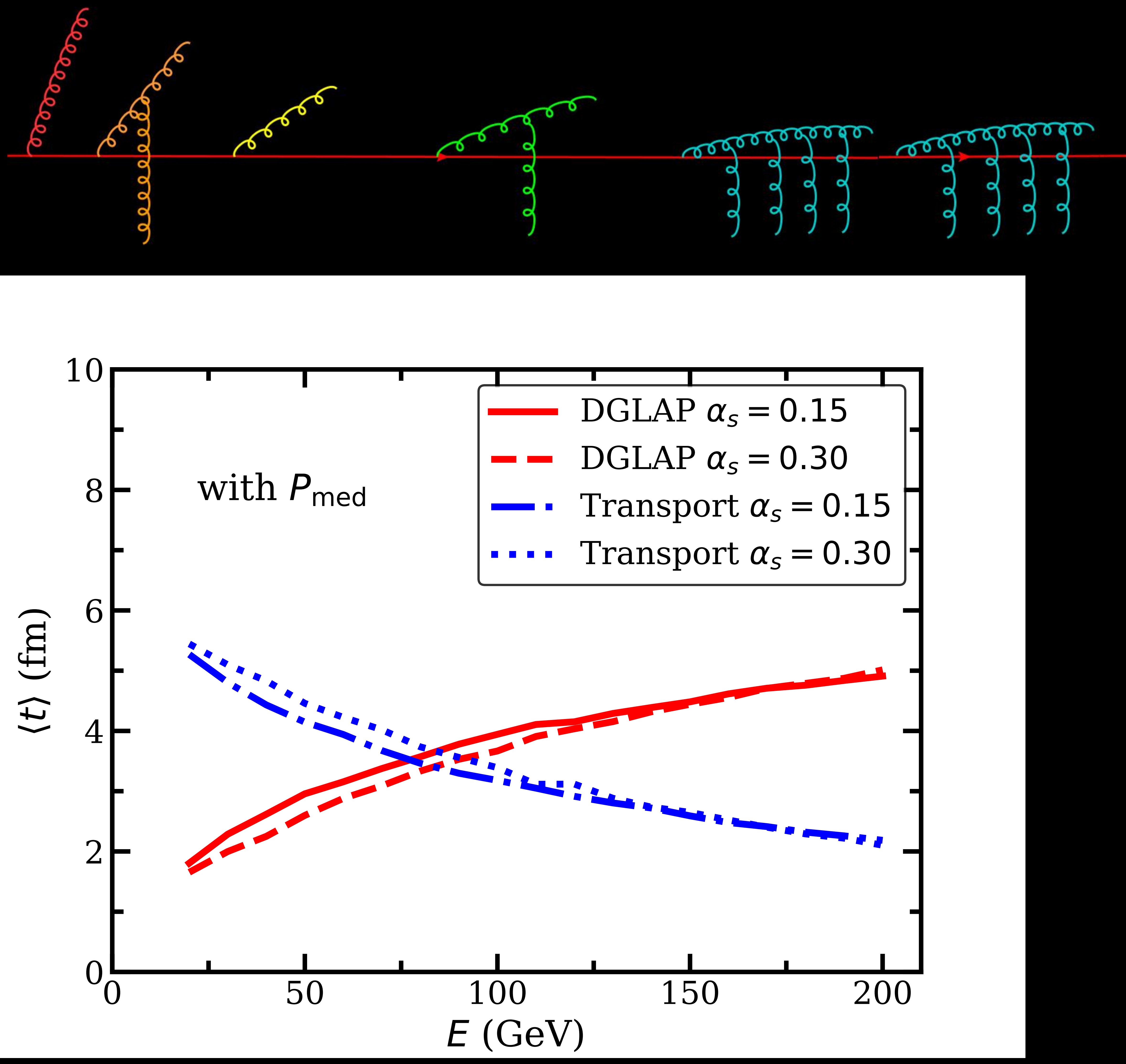

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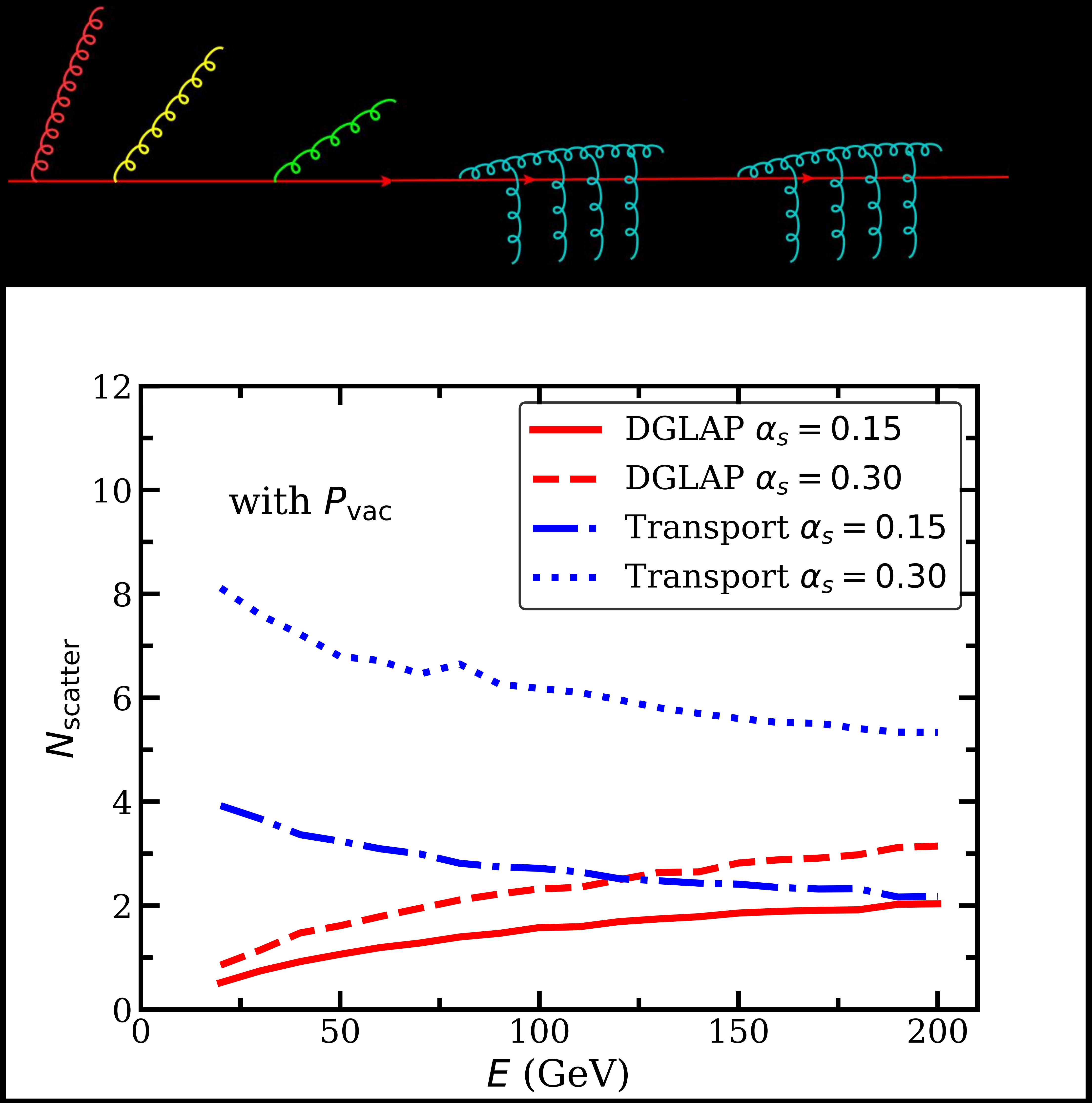

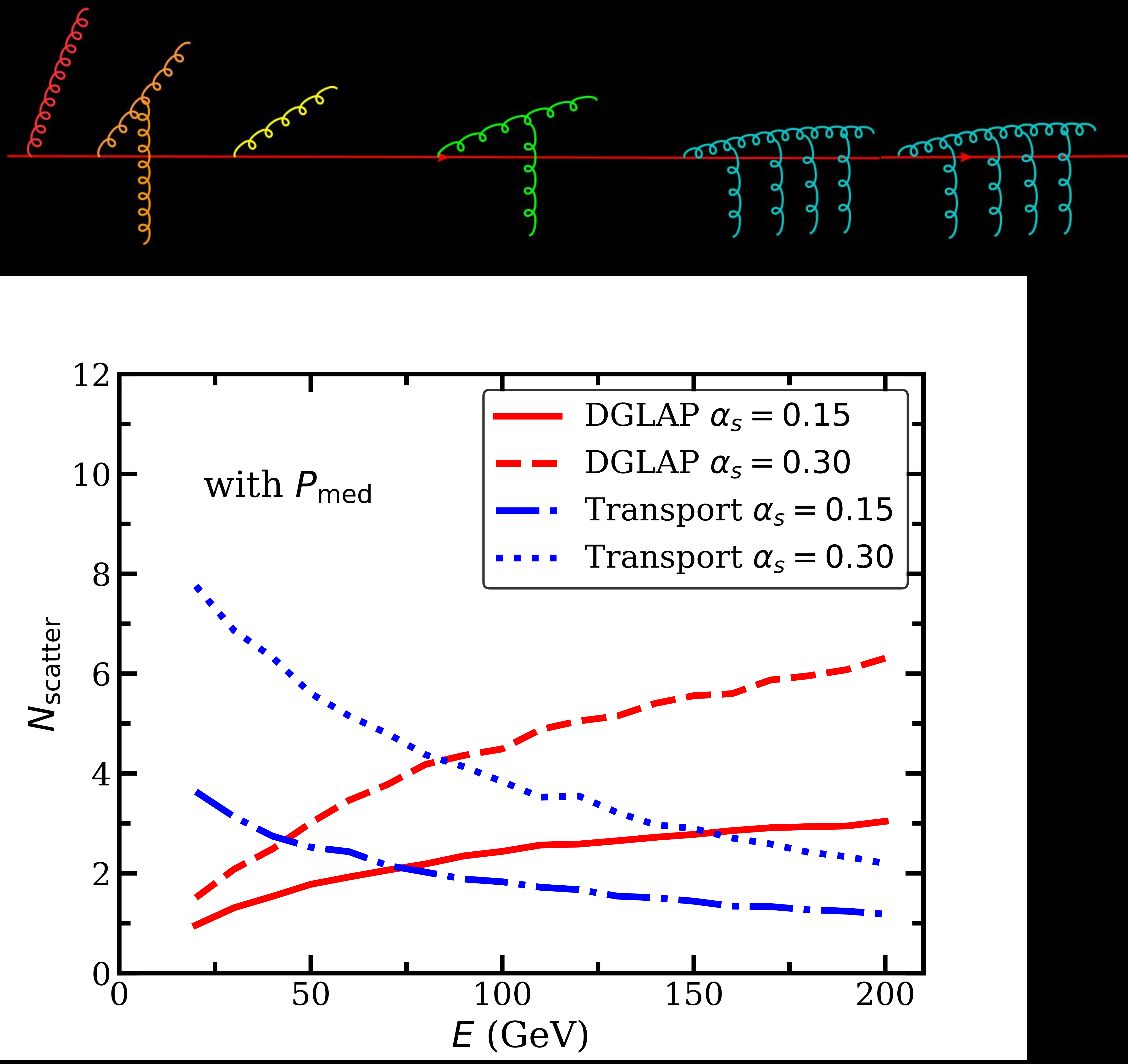

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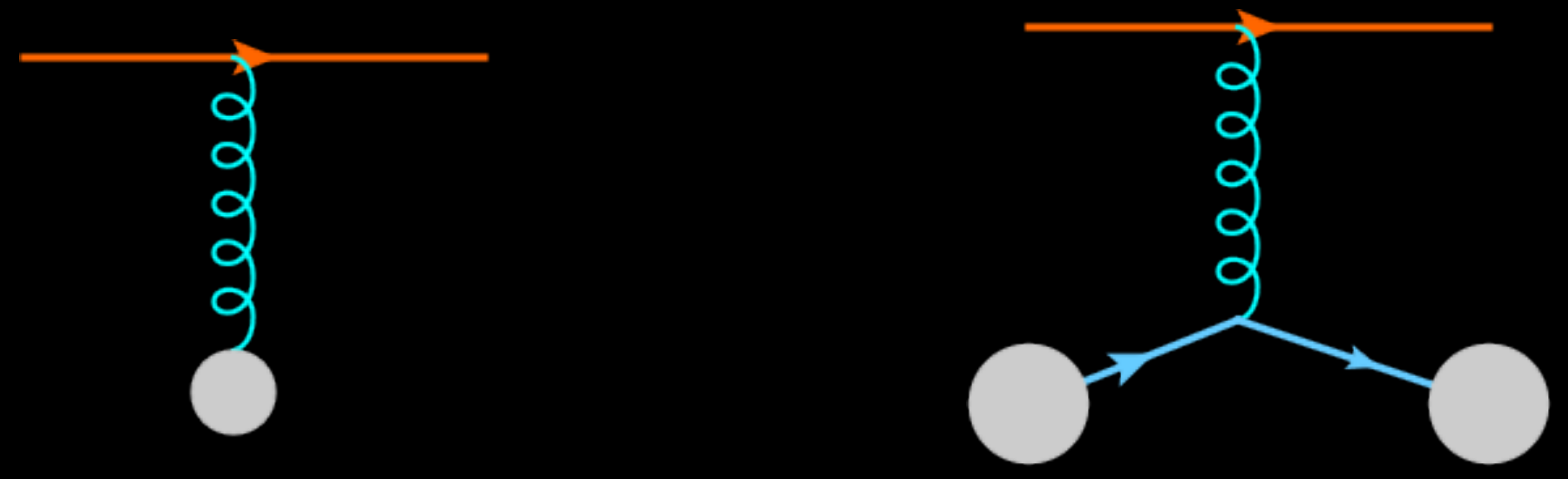
Independent scattering

- 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 $C(k) = \dfrac{d\Gamma}{d^3k}$
- 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)*

Assuming structure in the medium

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



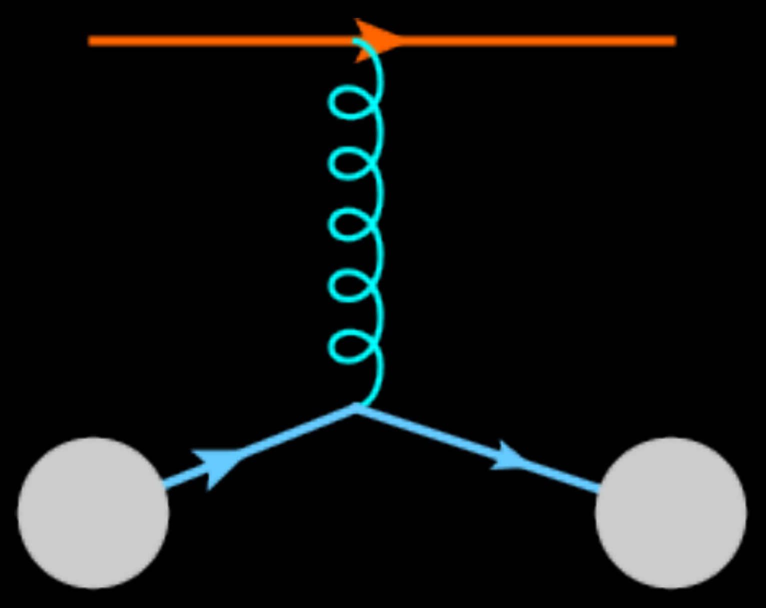
- Hard exchanges will resolve partons in the QGP

- Incoming "resolved partons" can be modeled with
  - HTL perturbation theory
  - or using QGP PDF
  - 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



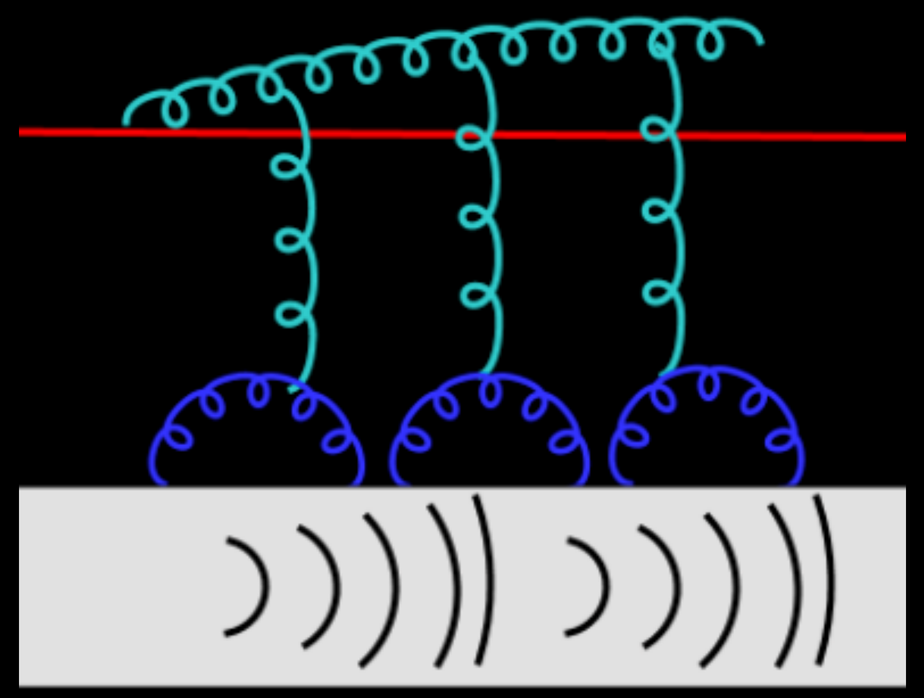
- Start with low virtuality part: $\mu^2 = \sqrt{2\hat{q}E}$

- Use Debye screened potential

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

- Fixed coupling gives,

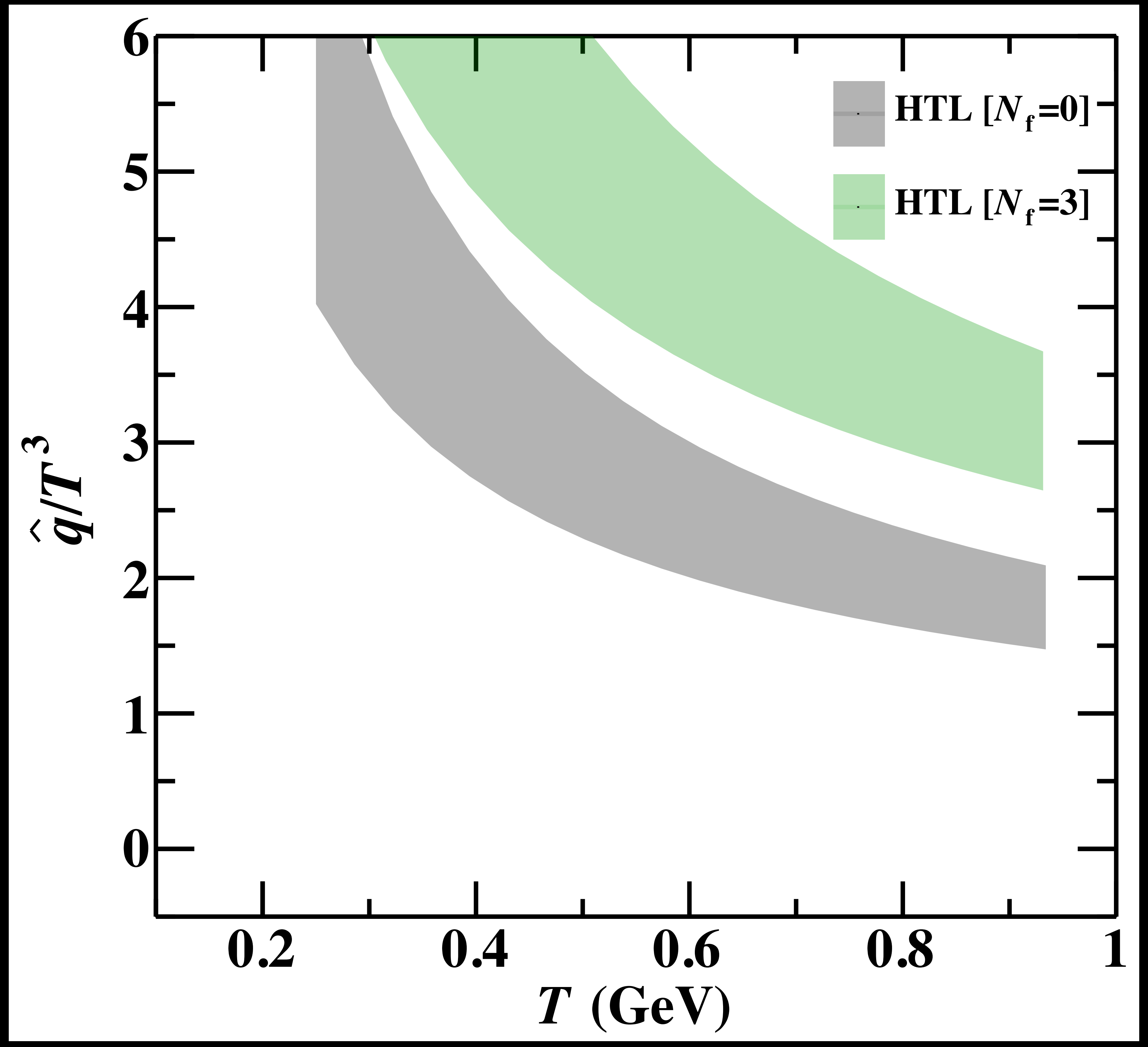
$$\hat{q} = C\alpha_S^2(m_D^2)\log\left(\frac{6ET}{m_D^2}\right)$$



- Running coupling gives,

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

- 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]

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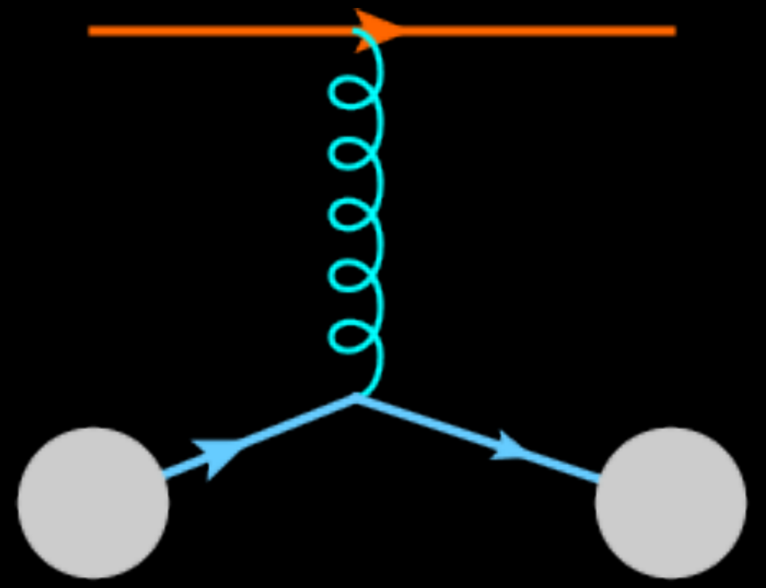

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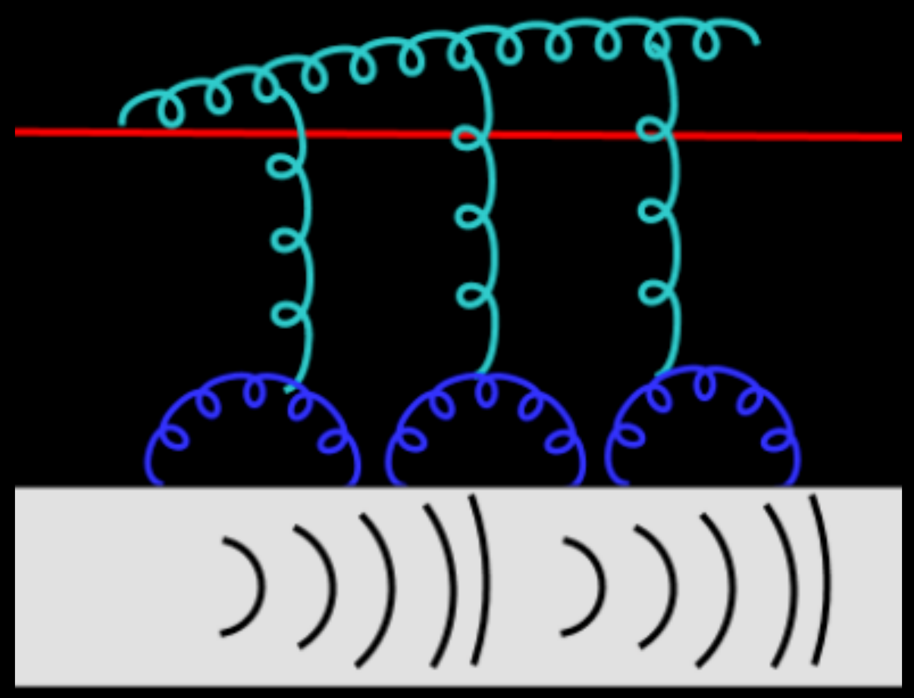

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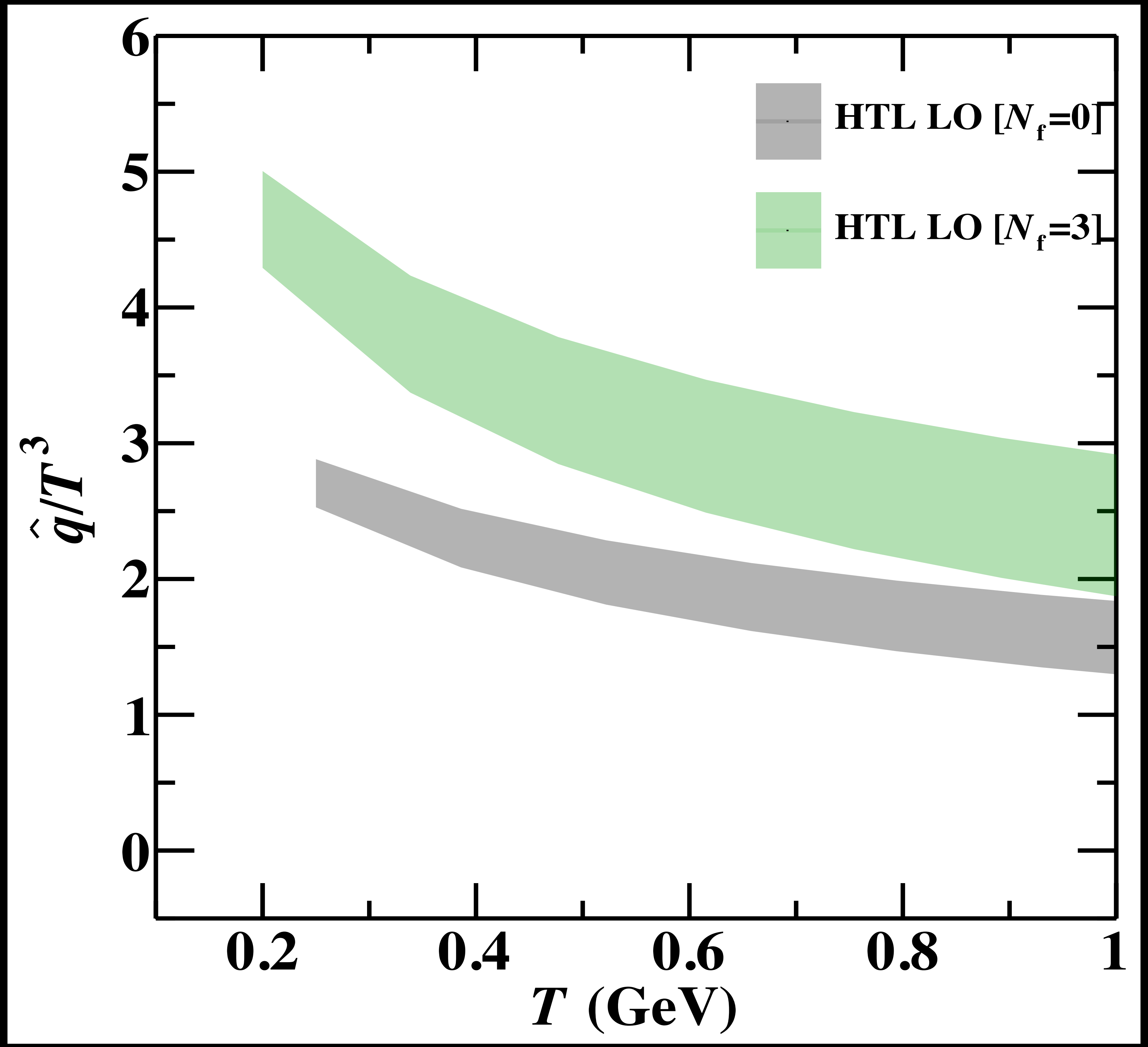

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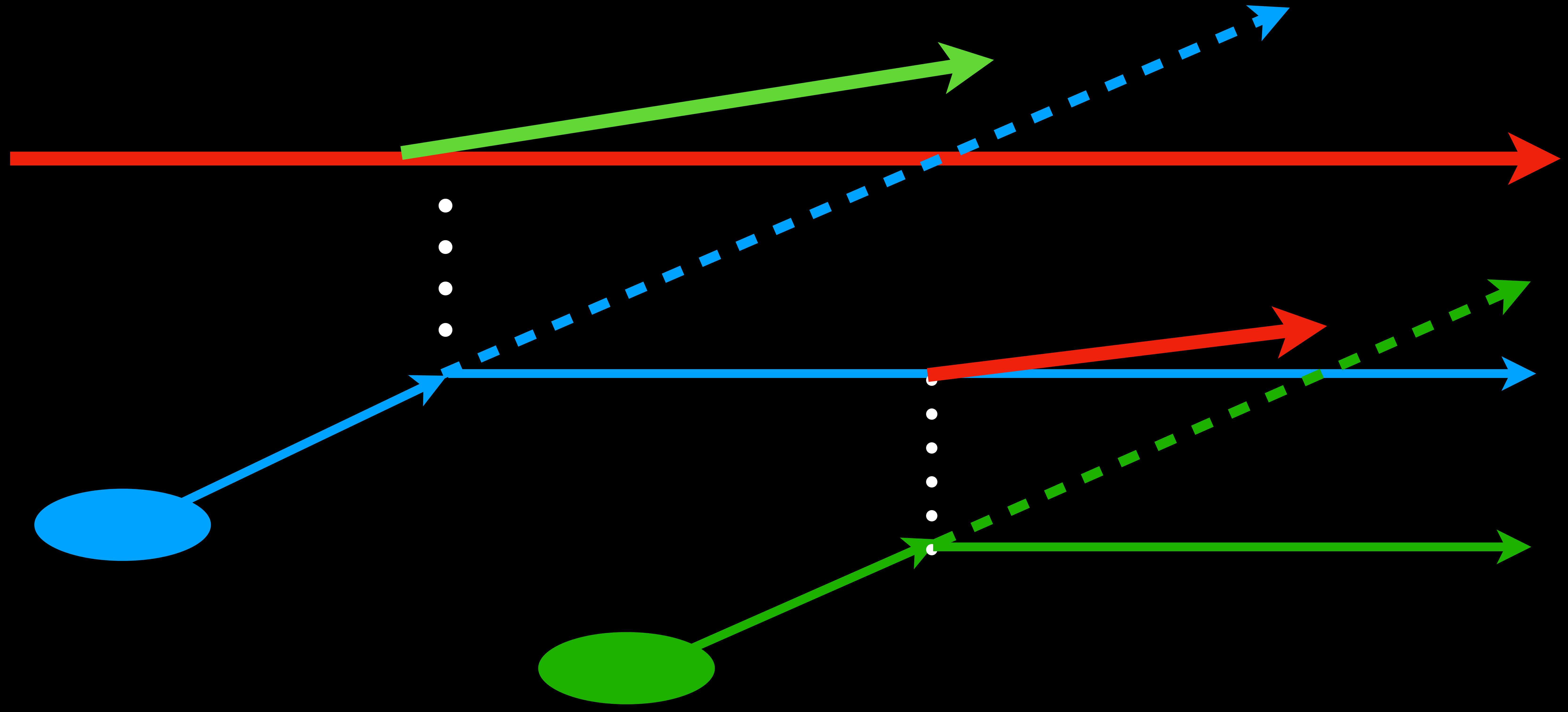
How this is done currently

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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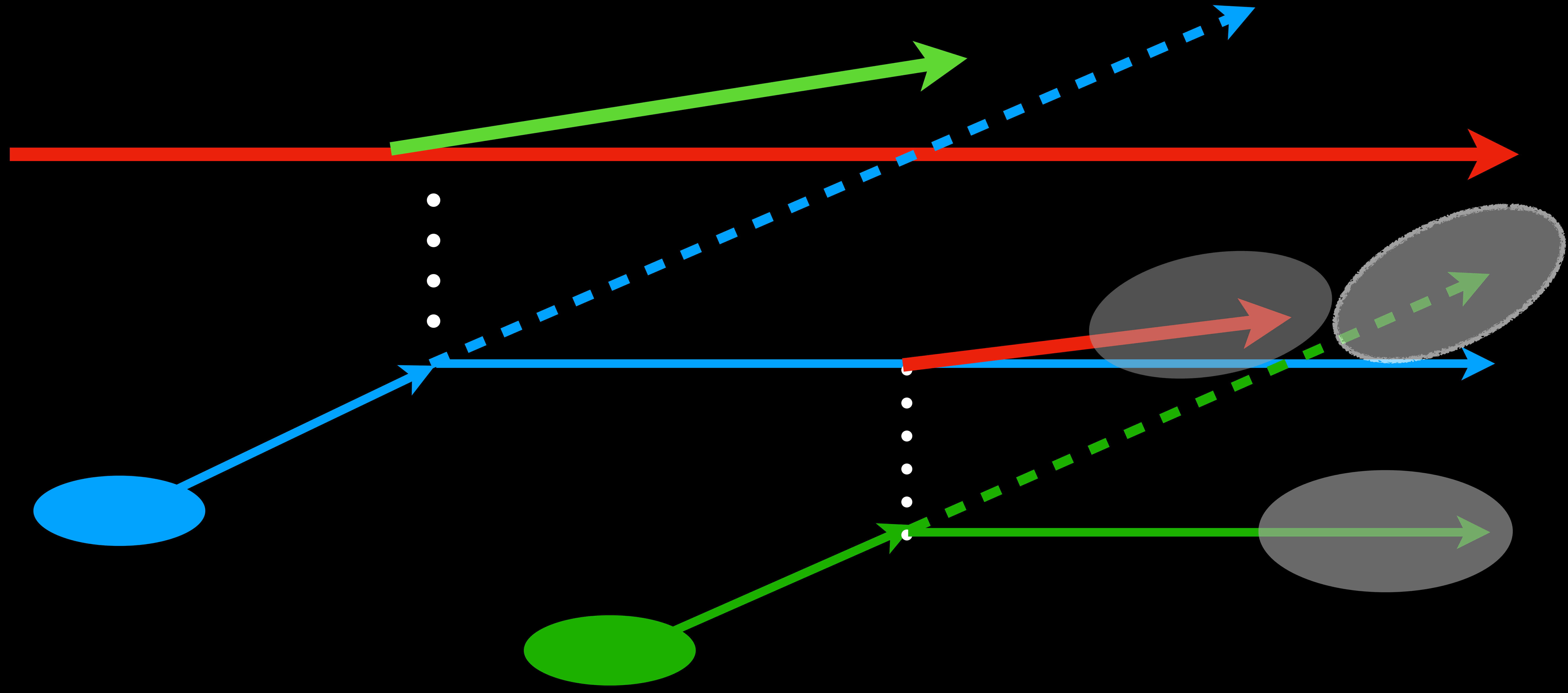
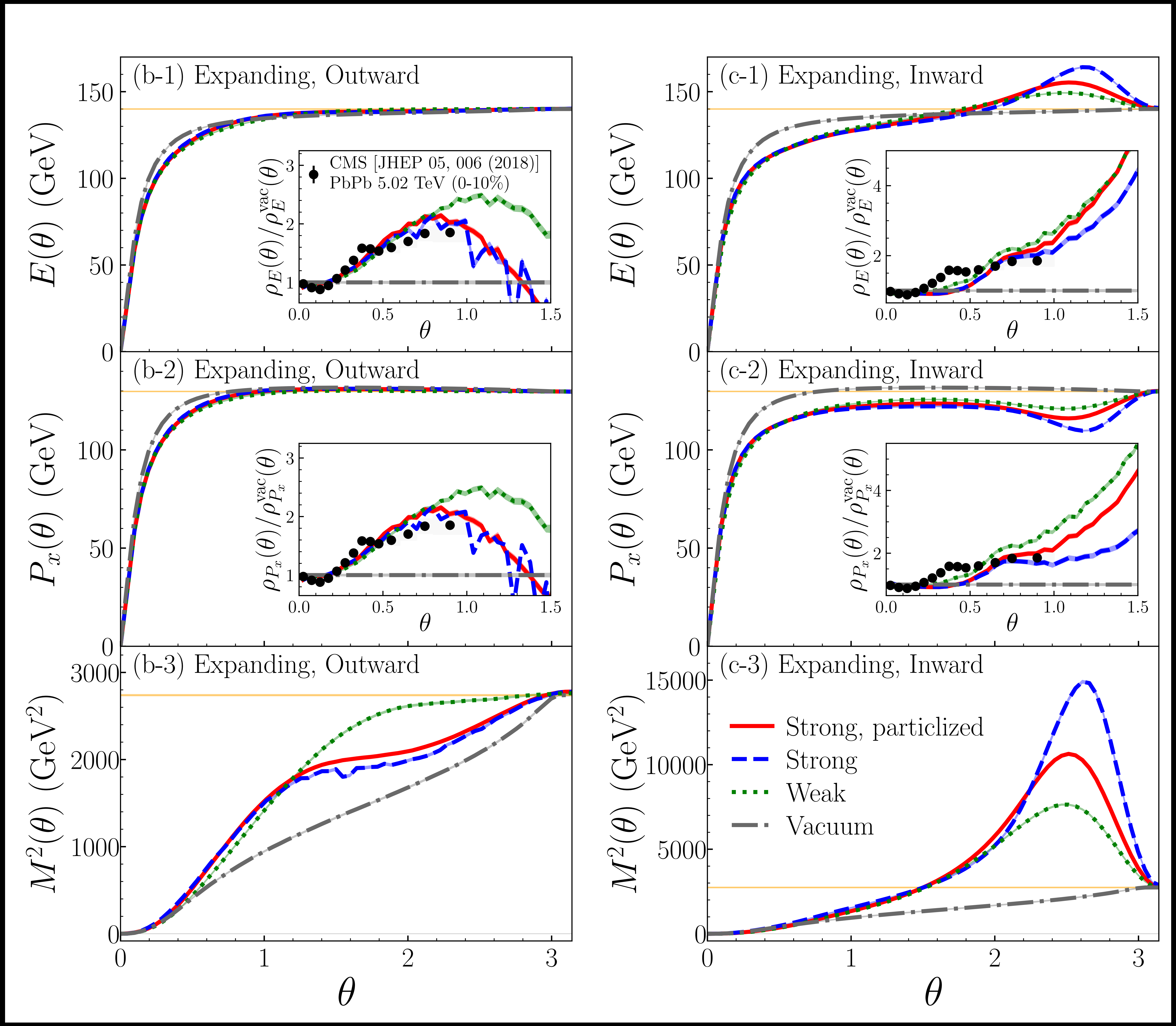


Additionally: Soft partons can be “liquified” into source terms for a subsequent hydro simulation

Does not seem to make much difference inside jet cone

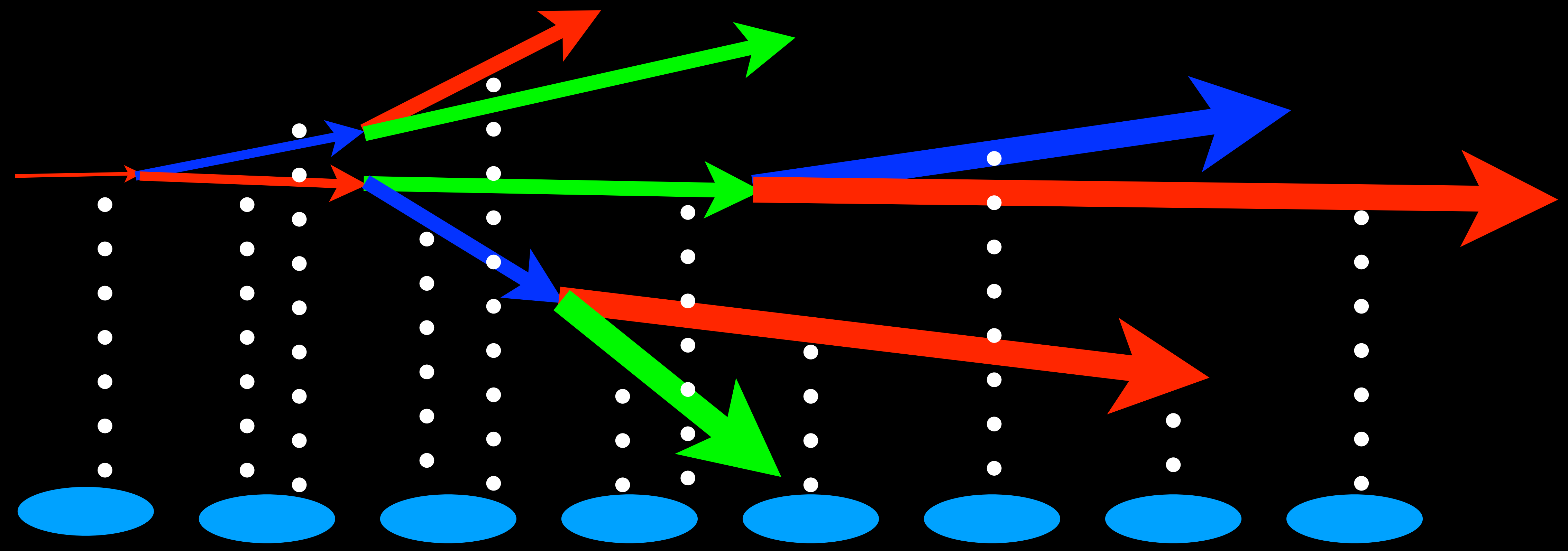
- Simulation (JETSCAPE 0.x) includes:
  - One run of smooth hydro
  - One jet from center outward (left)
  - One jet from out inward (right)
  - Jet simulated for ~10fm/c: MATTER+LBT
  - Jet constructed with partons (weak)
  - Soft partons liquified
  - Source terms developed
  - Hydro re-run
  - Jet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



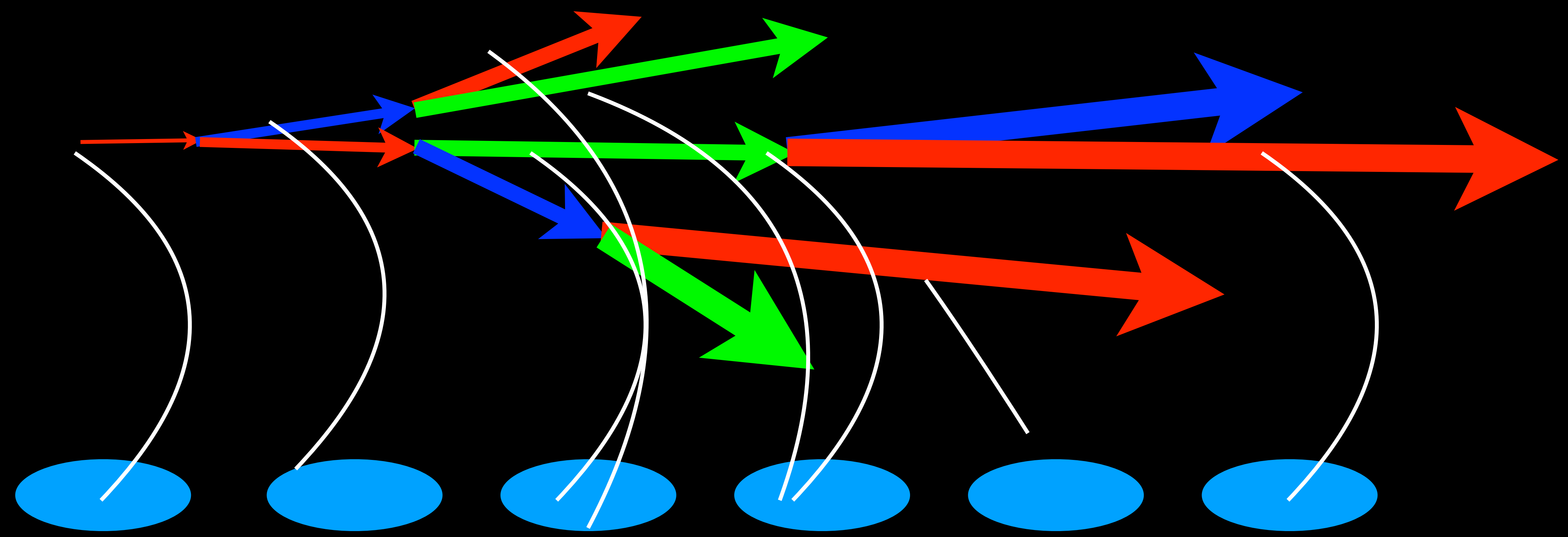
Y. Tachibana, A. M., C. Shen, PRC 106 (2022) 2, L021902

Other methods

Constant Broadening: LIDO, Tequila

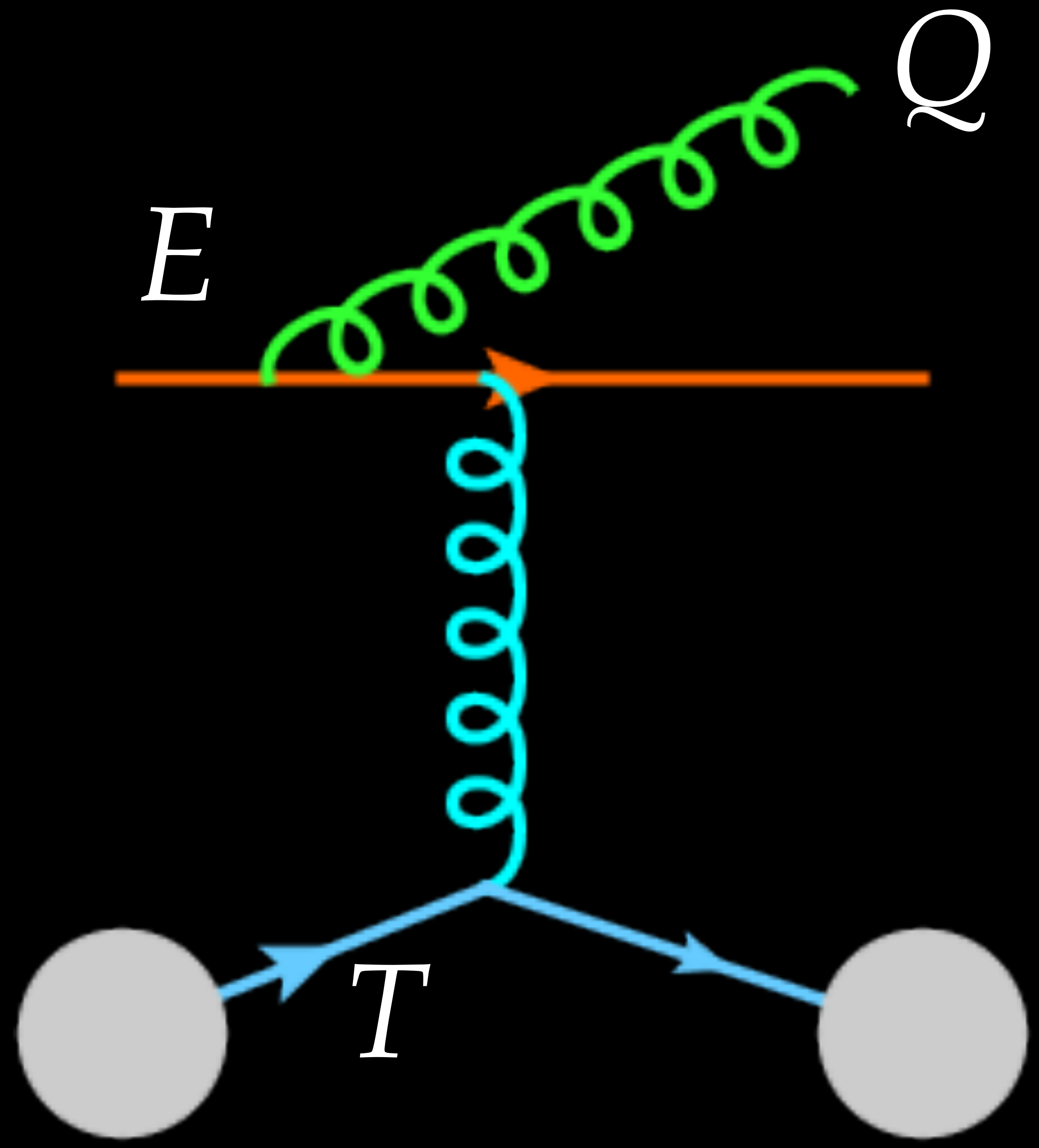


AdS/CFT drag: Hybrid



Won't discuss in this talk, but all of these depend on the underlying medium

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

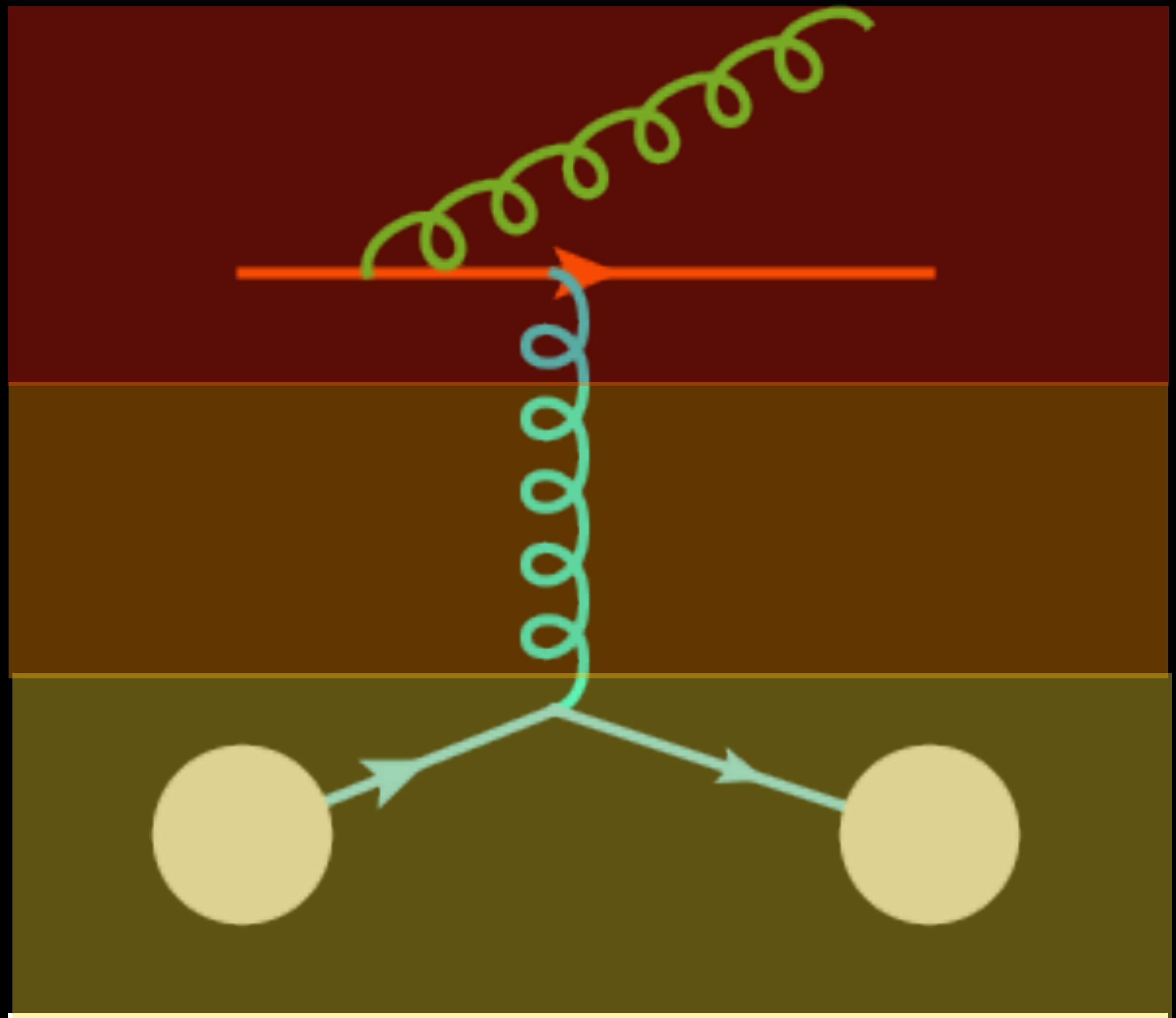
- Coherence arguments: $\hat{q}(Q^2 > \sqrt{2\hat{q}E}) \to 0$
- Can be calculated directly in the Higher Twist formalism.

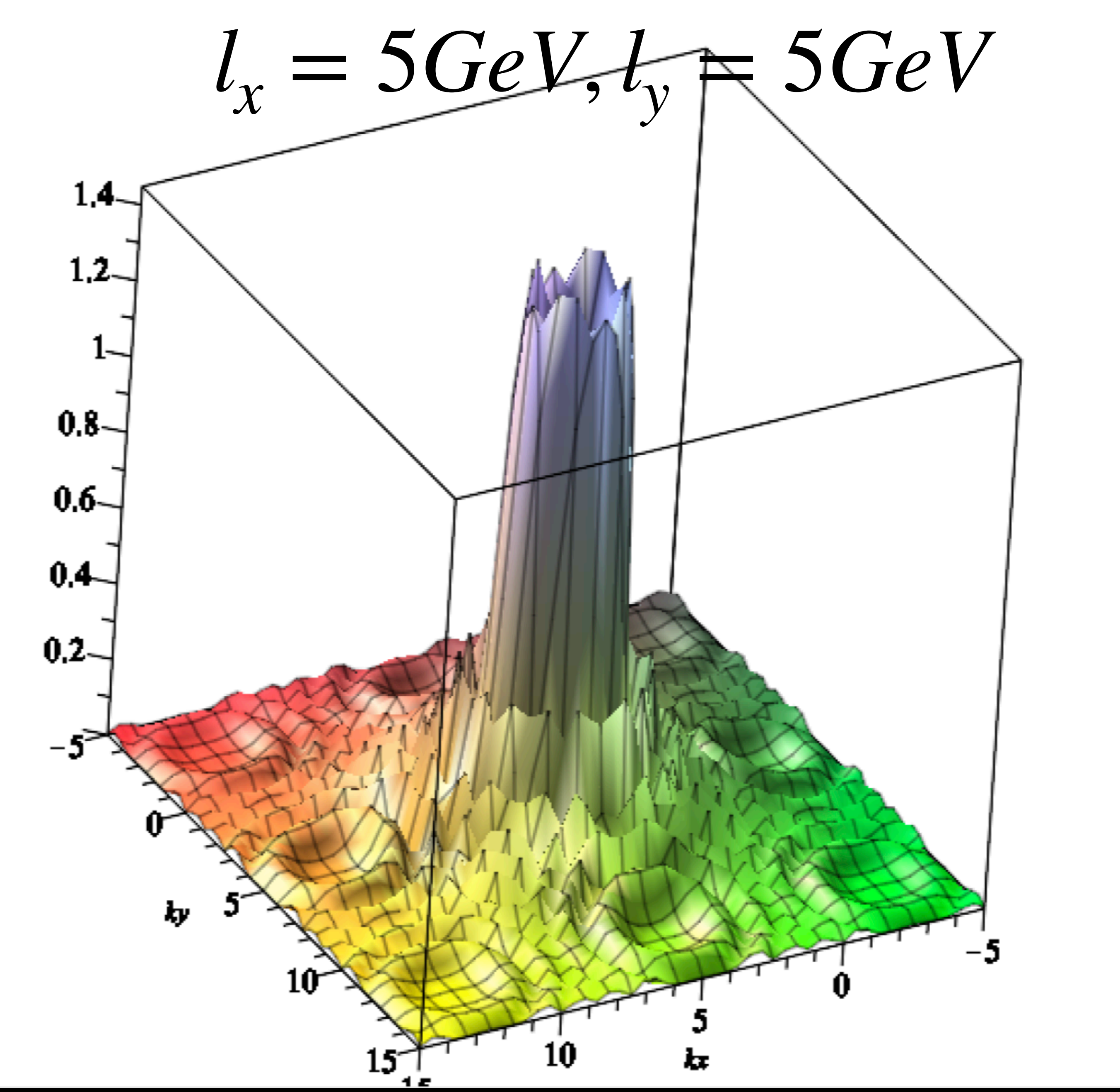
$$\frac{dN_g}{dy\,d^2l_\perp} = \frac{\alpha_s}{2\pi}P(y)\int\frac{d^2k_\perp}{(2\pi)^2}\int d\zeta^-\left[\frac{2-2\cos\left(\frac{(l_\perp-k_\perp)^2\zeta^-}{2q^-y(1-y)}\right)}{(l_\perp-k_\perp)^2}\right]$$

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

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

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



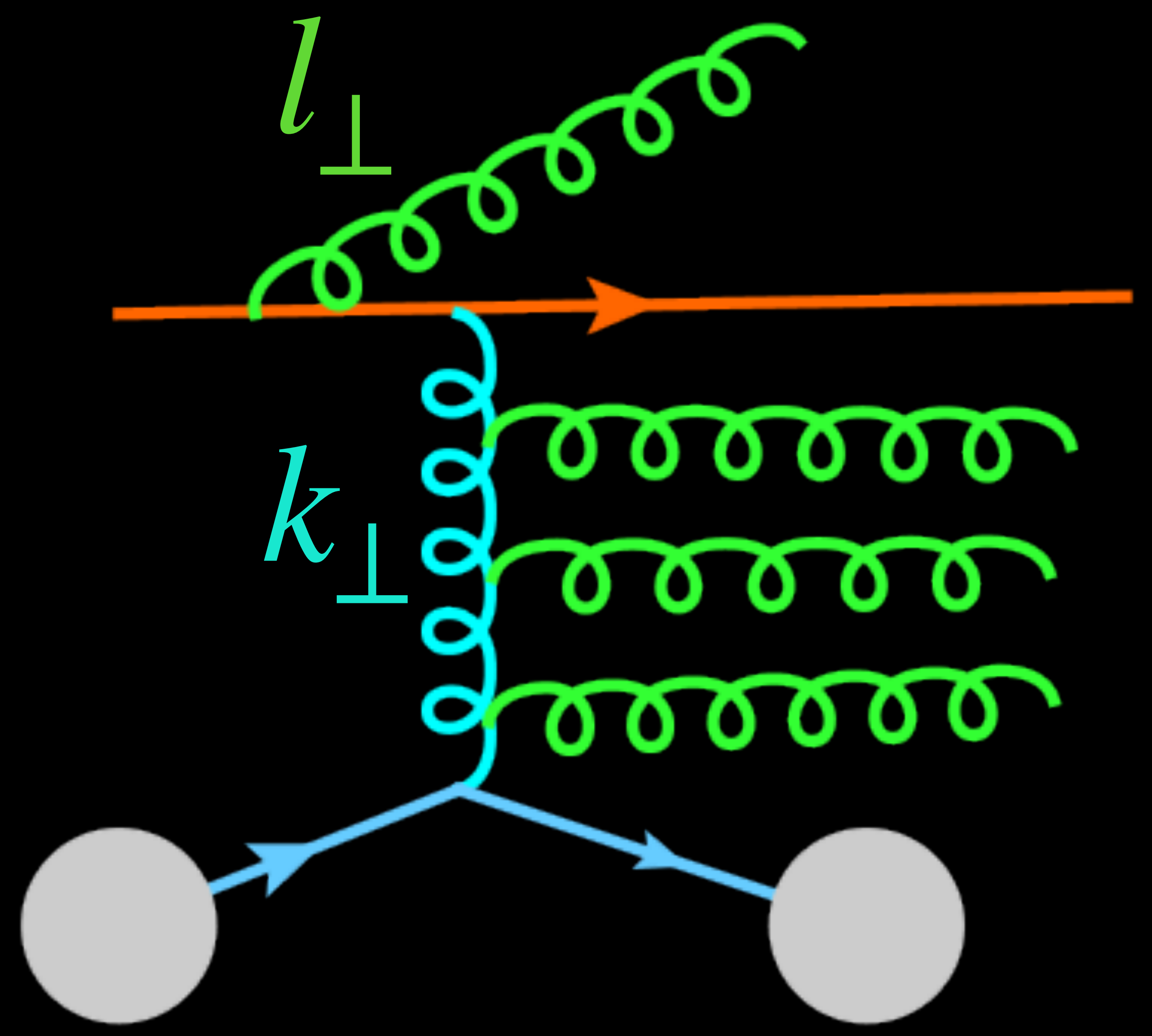


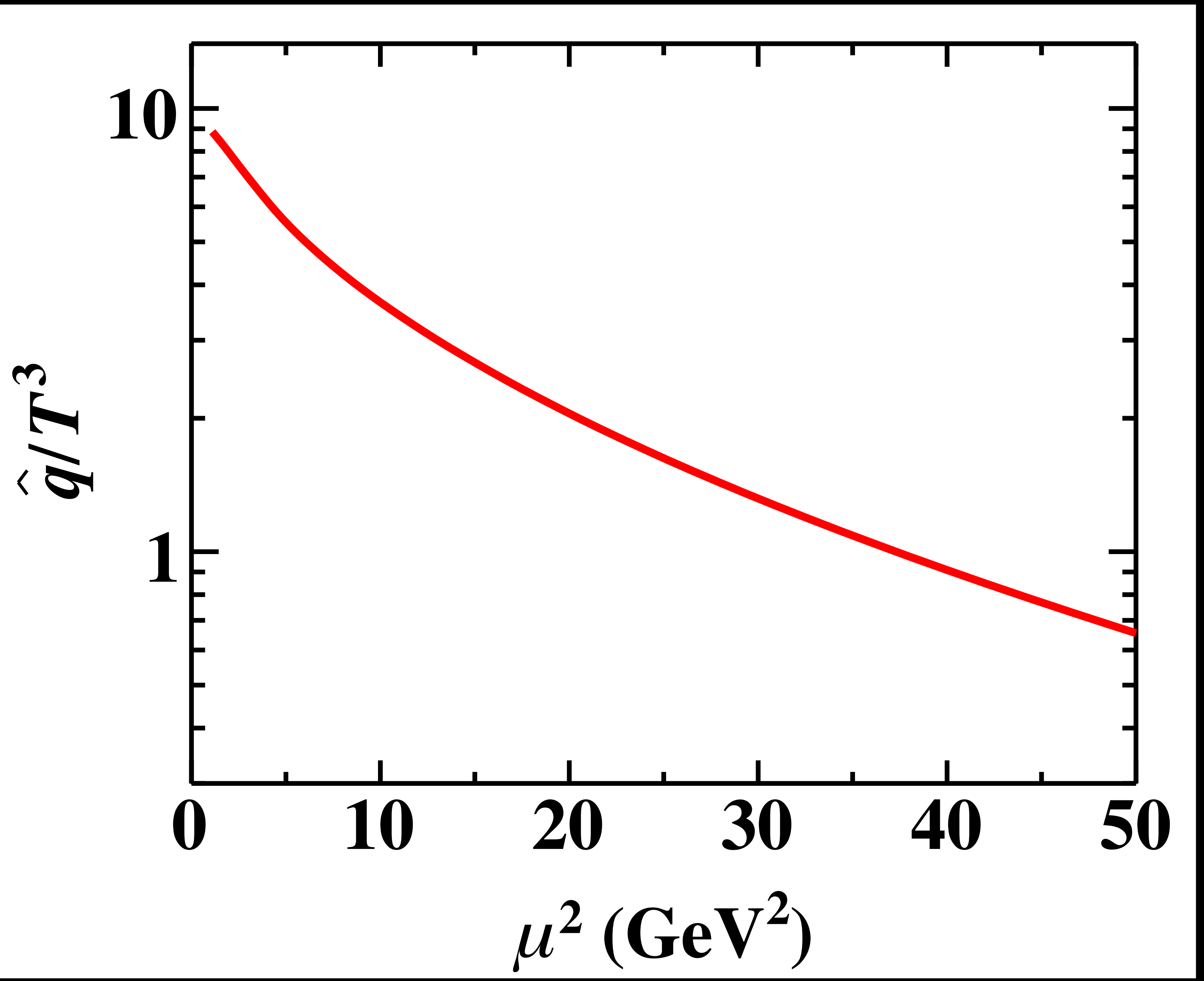
A. Kumar, A.M., C. Shen, PRC 101 (2020) 034908

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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Other dependencies

- It 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?

The need for an event generator framework

The need for an event generator framework

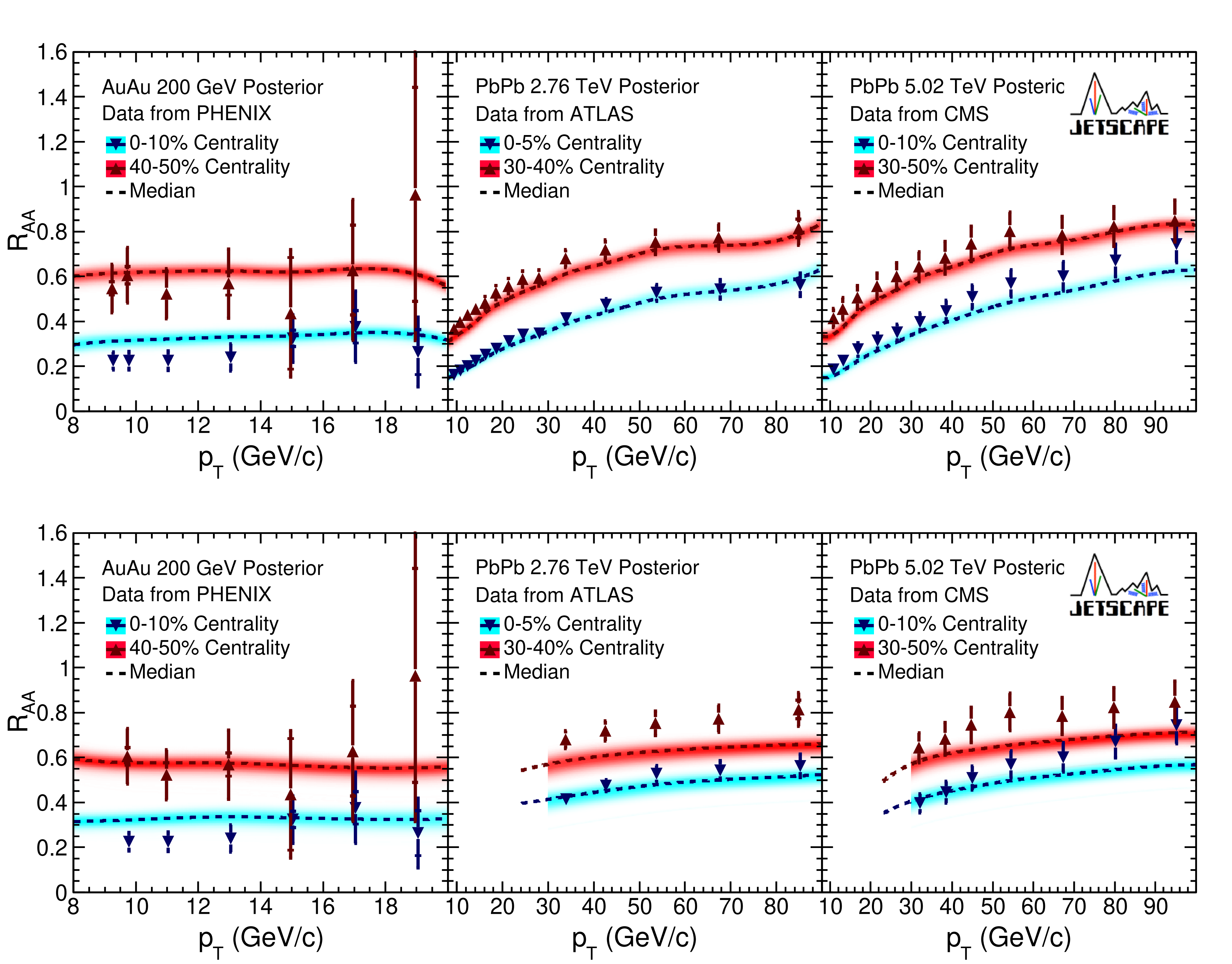
- An event generator is a computer simulation that produces experiment like events
- An E. G. framework allows a user to design/modify modular elements in a simulator.
- Carrying out a systematic analysis requires a systematic framework
- You have to work with several correlated input parameters, in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

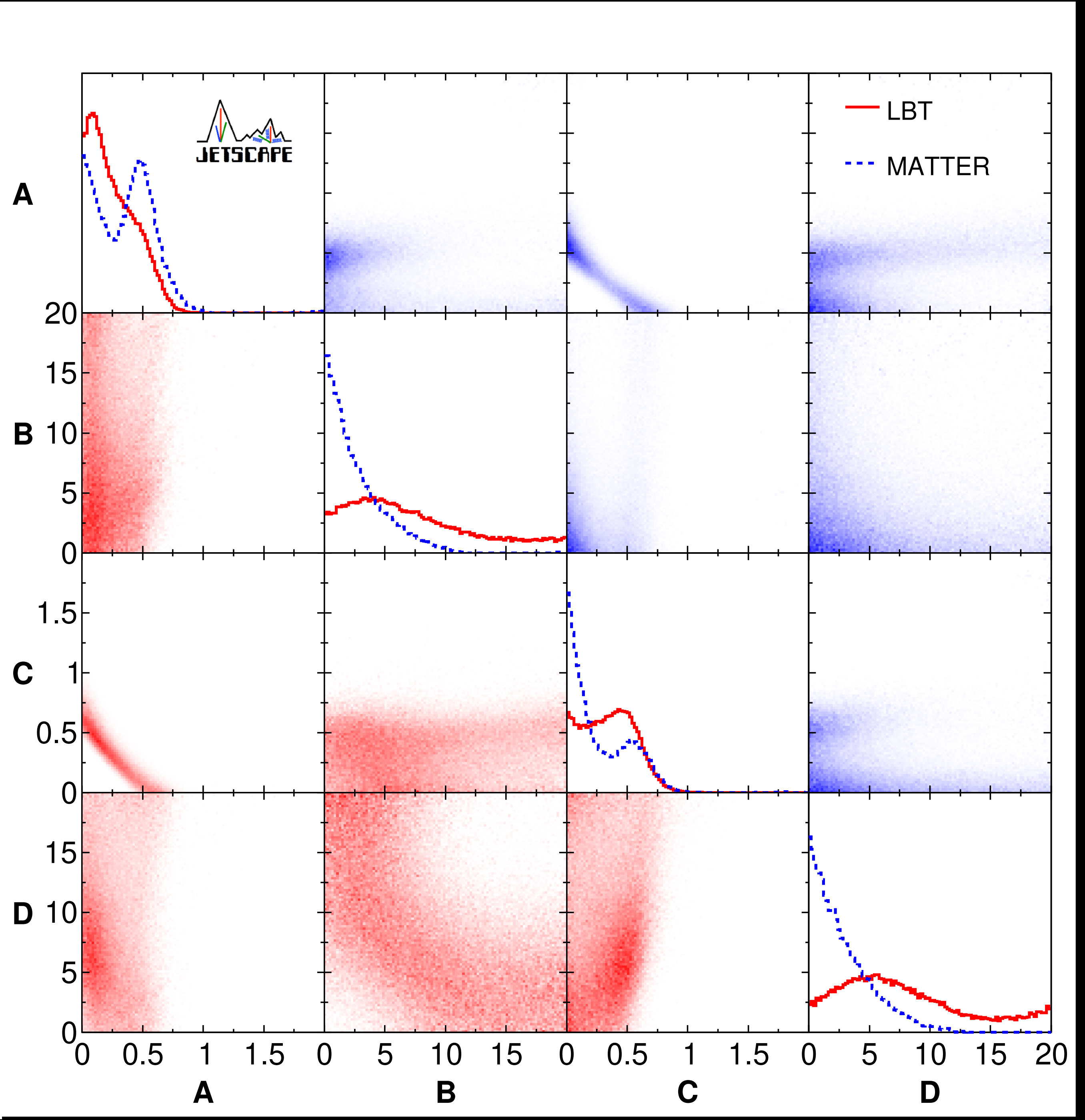
Bayesian analysis with $\hat{q}(T, E, \mu)$

- We parametrize with

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

- 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

But not additive !!

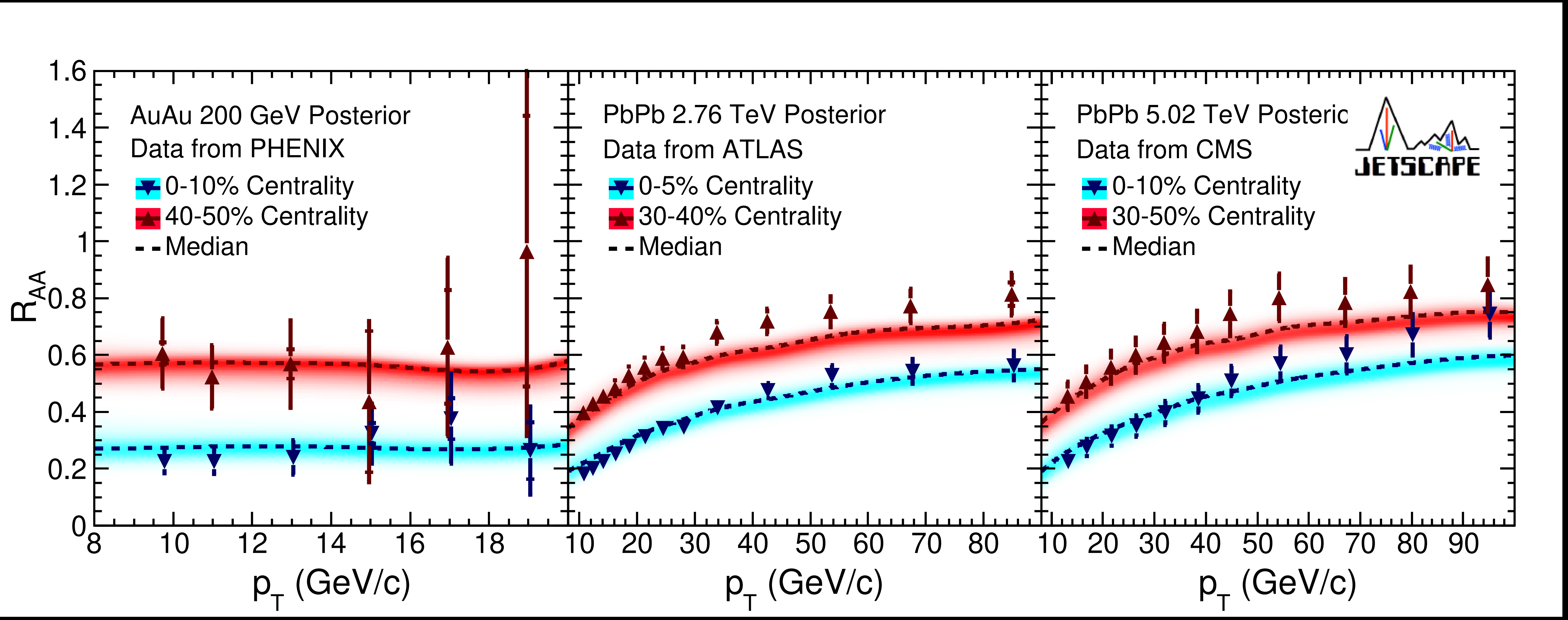
- No real improvement in using the models together, and forcing them to use the same $\hat{q}$ formula

- Also tried a formula with virtuality directly:

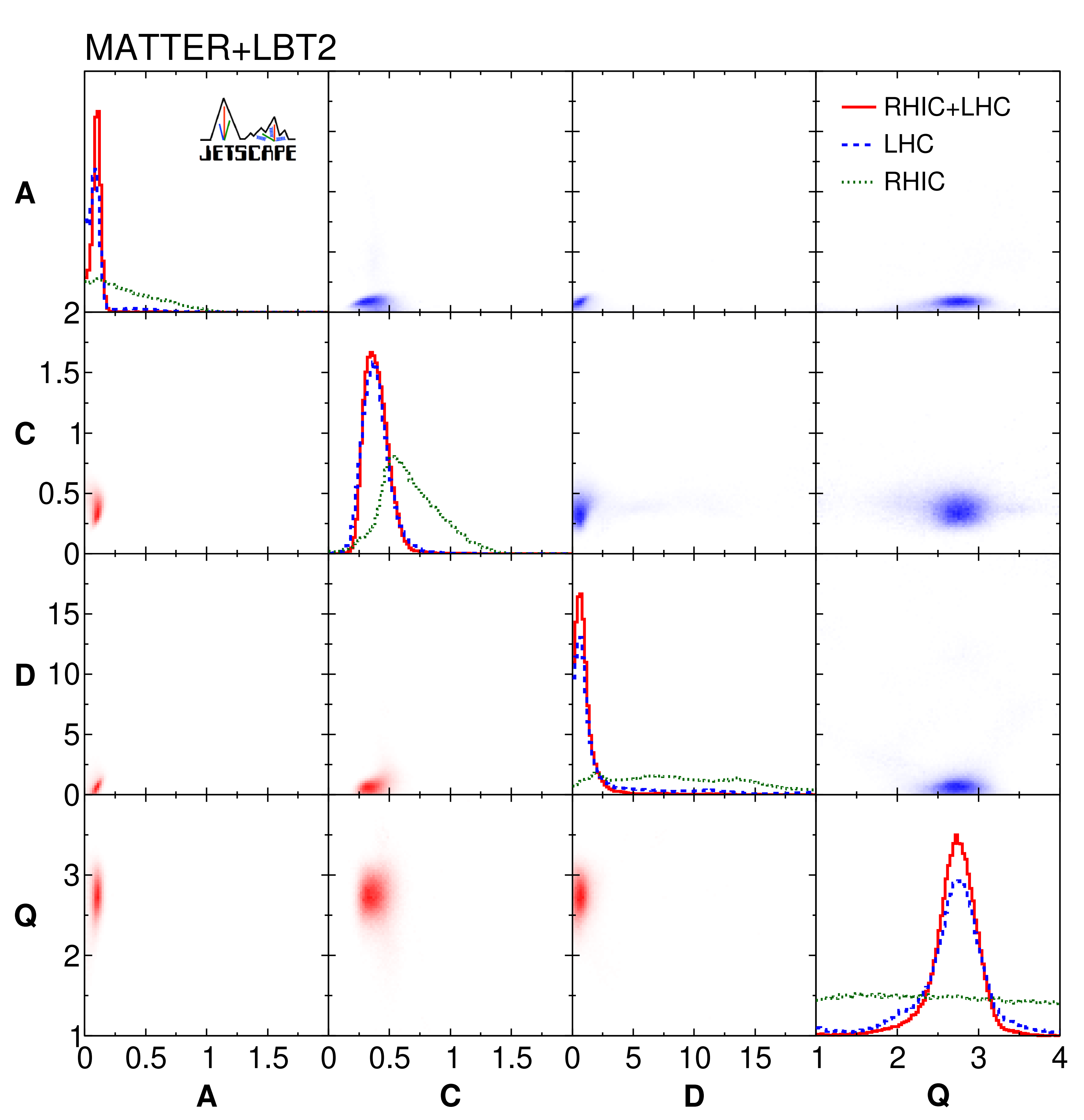
$$\frac{\hat{q}\left(Q,E,T\right)|_{Q_0,A,C,D}}{T^3} = 42C_R\frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2\left\{\frac{A\left[\ln\left(\frac{Q}{\Lambda}\right)-\ln\left(\frac{Q_0}{\Lambda}\right)\right]}{\left[\ln\left(\frac{Q}{\Lambda}\right)\right]^2}\theta(Q-Q_0)+\frac{C\left[\ln\left(\frac{E}{T}\right)-\ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\ri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

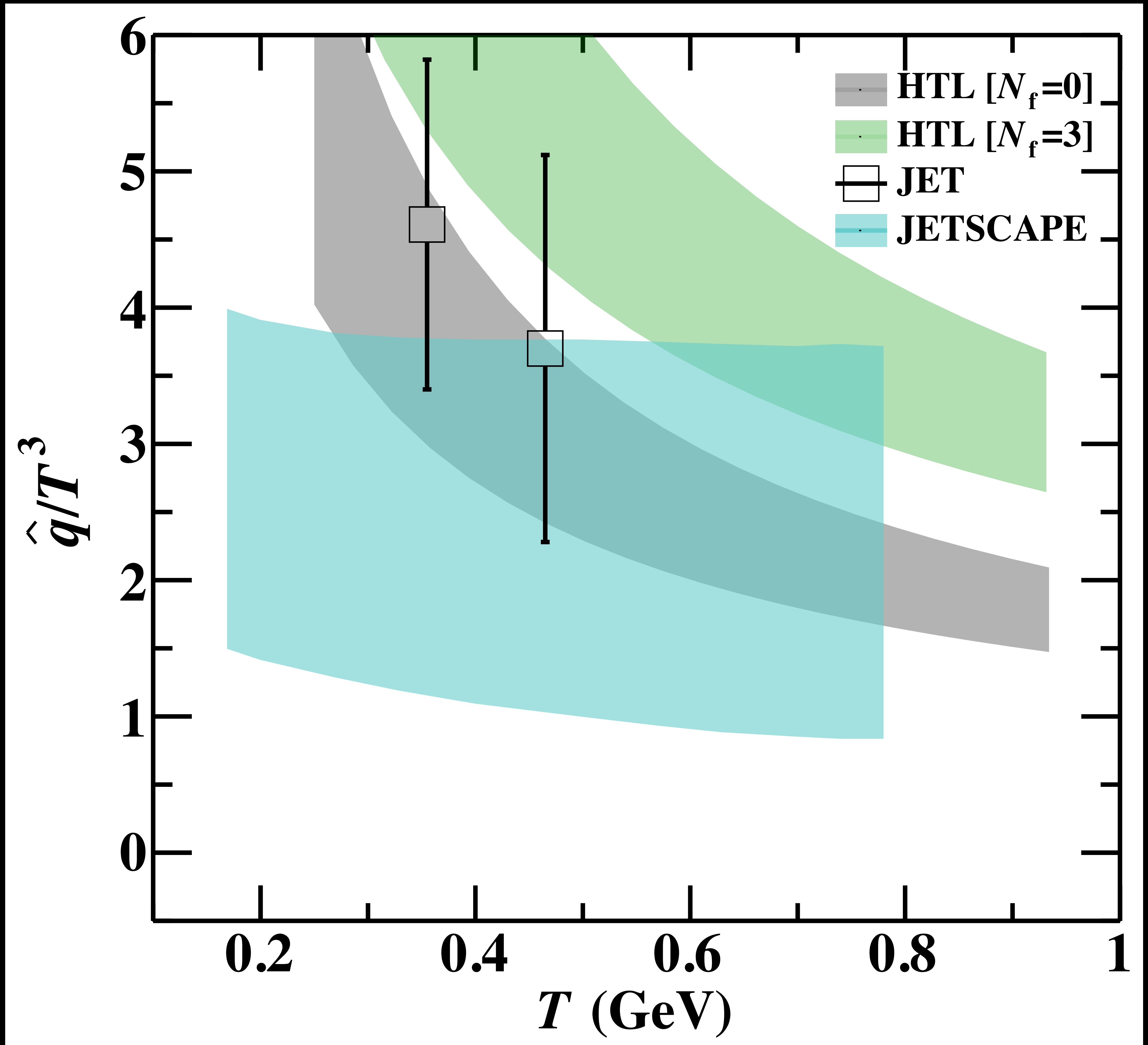
- Need a reduction at large E or Q

- Try the multiplicative approximation



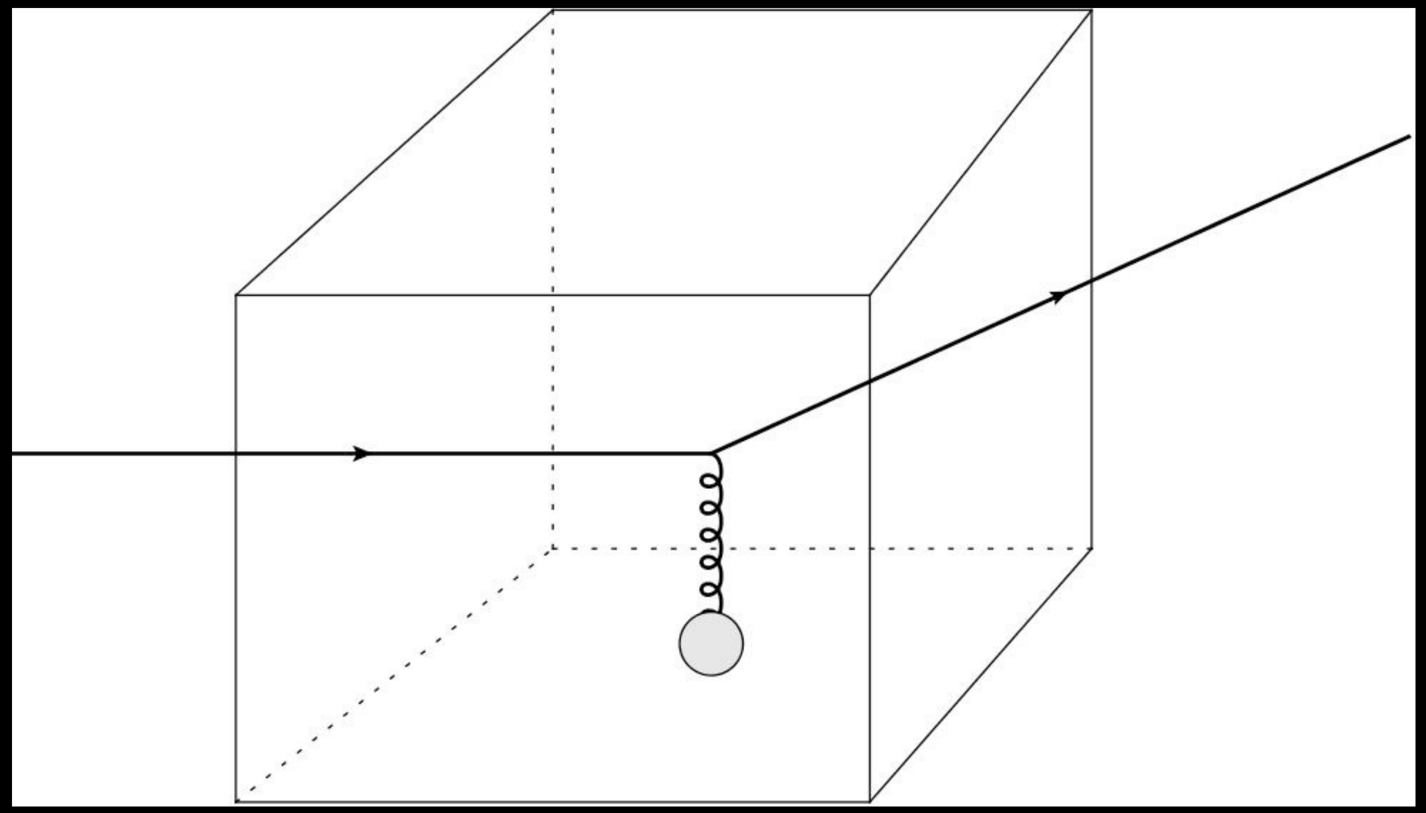
Transition scale and new $\hat{q}/T^3$ range





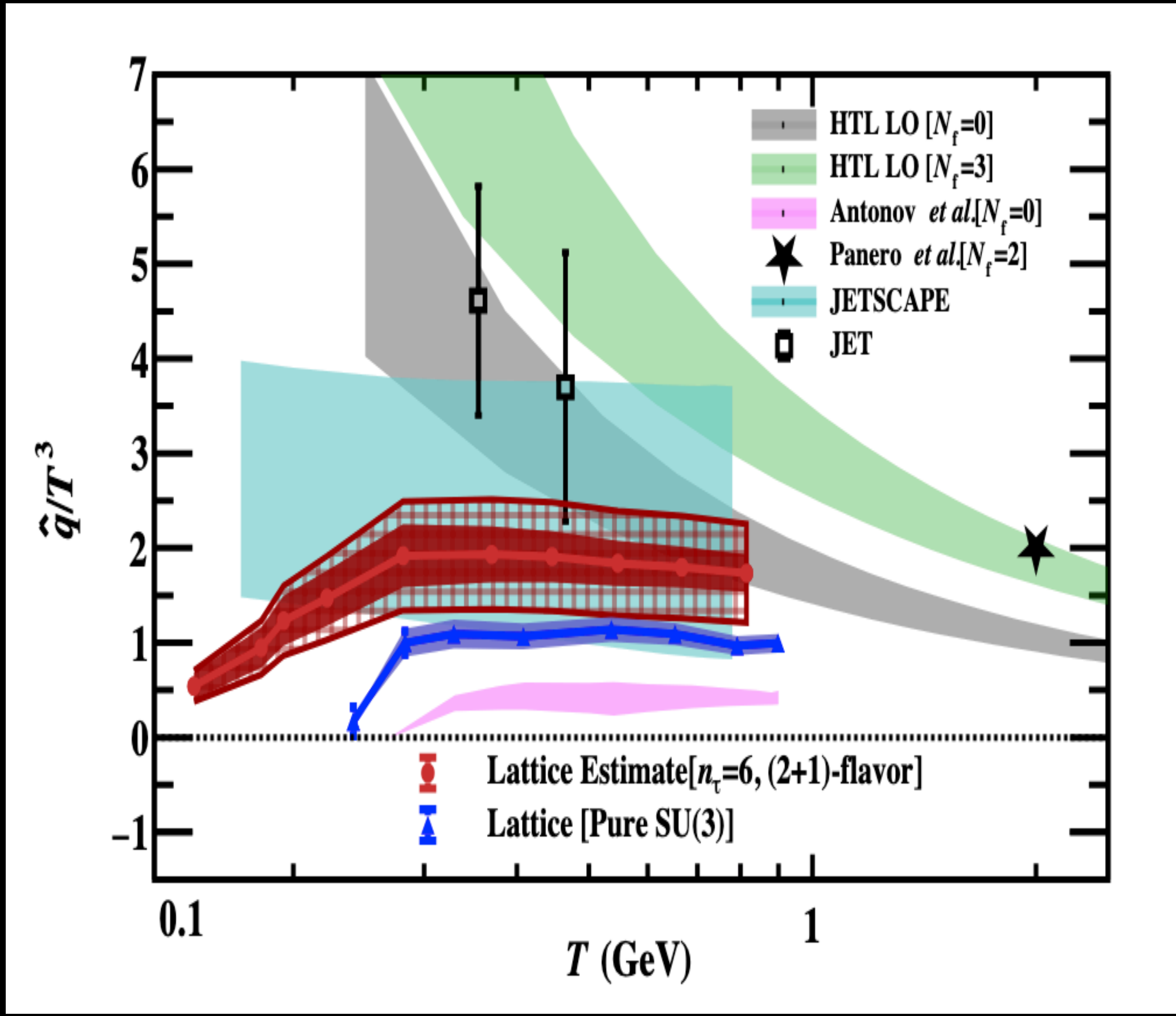
Calculating $\hat{q}$ in Lattice QCD

A. Kumar, A.M., J. Weber, PRD 106 (2022) 3, 034505



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

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



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

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

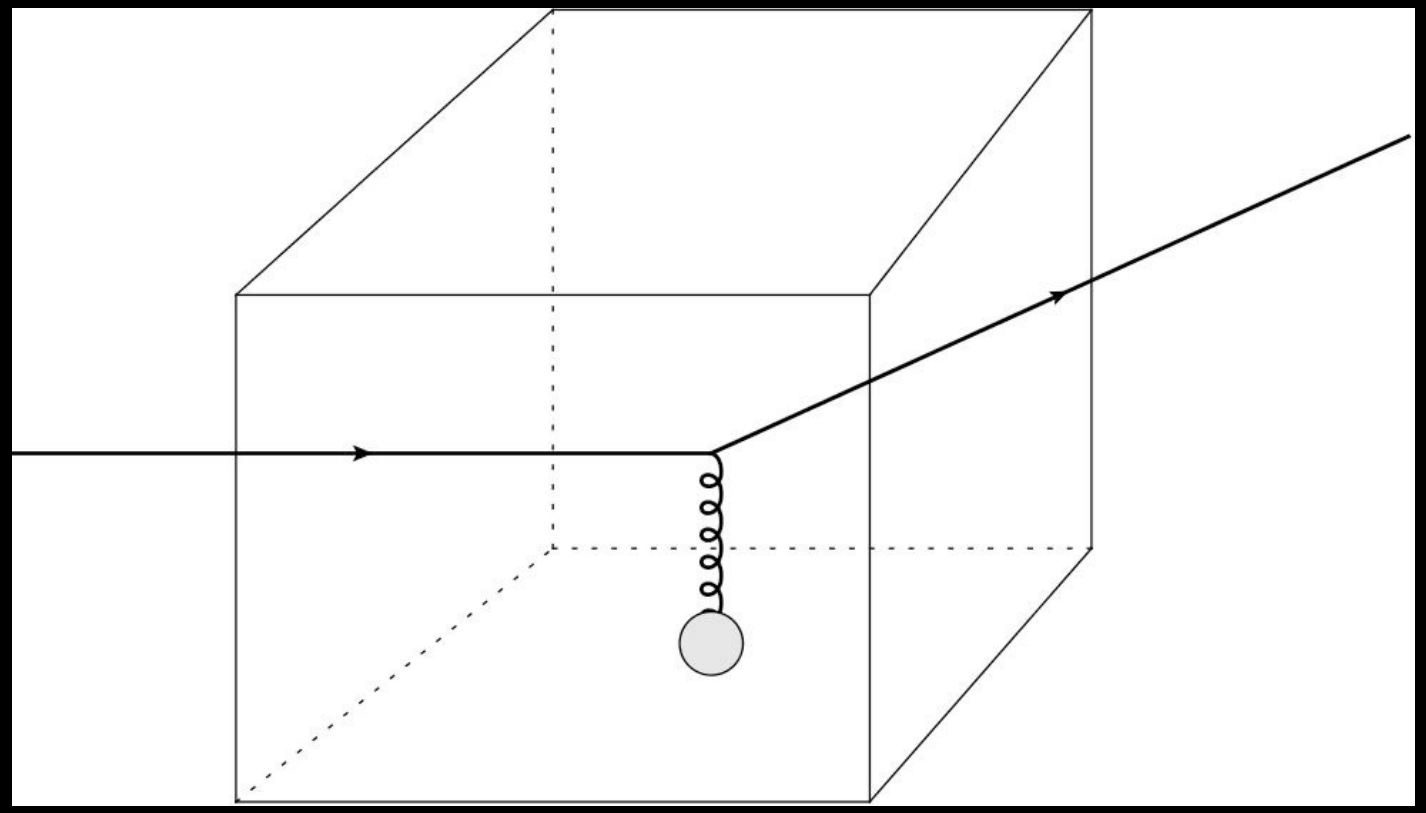
Fully non-perturbative calculation of $\hat{q}$

All calculations for a 100 GeV quark,

Lattice Calculations show weak dependence on E

Calculating $\hat{q}$ in Lattice QCD

A. Kumar, A.M., J. Weber, PRD 106 (2022) 3, 034505



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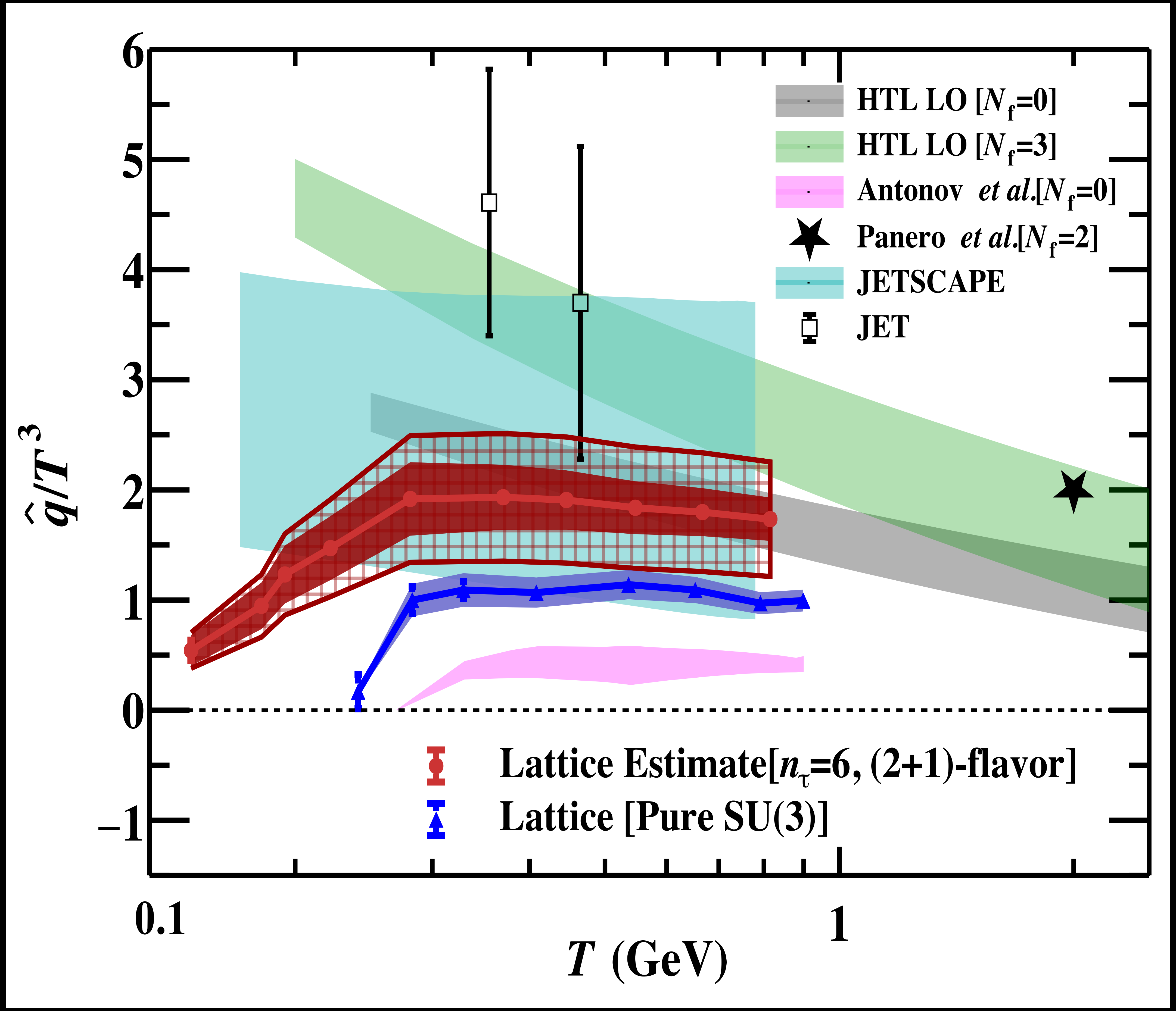

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Fully non-perturbative calculation of $\hat{q}$

All calculations for a 100 GeV quark,

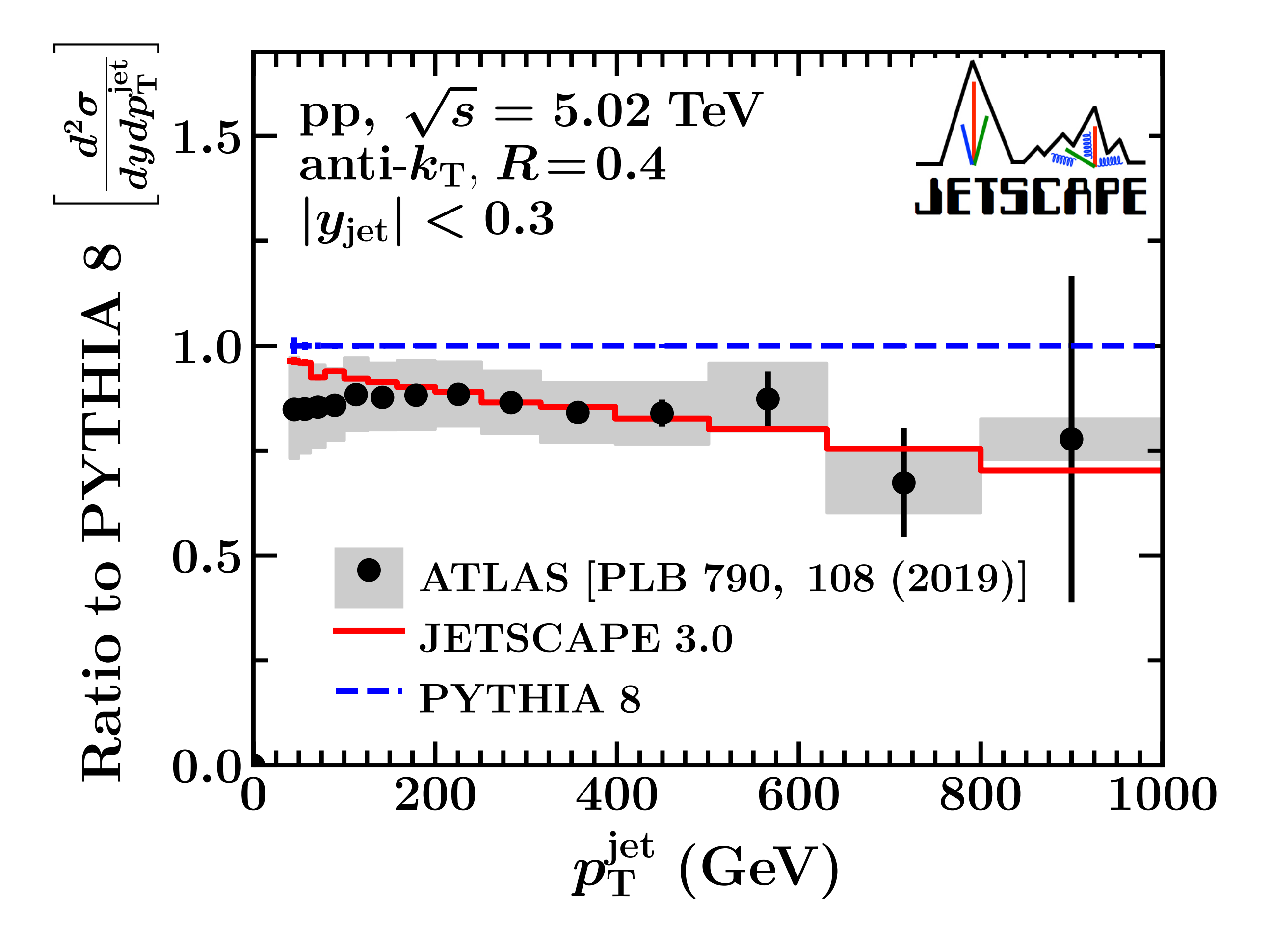
Lattice Calculations show weak dependence on E

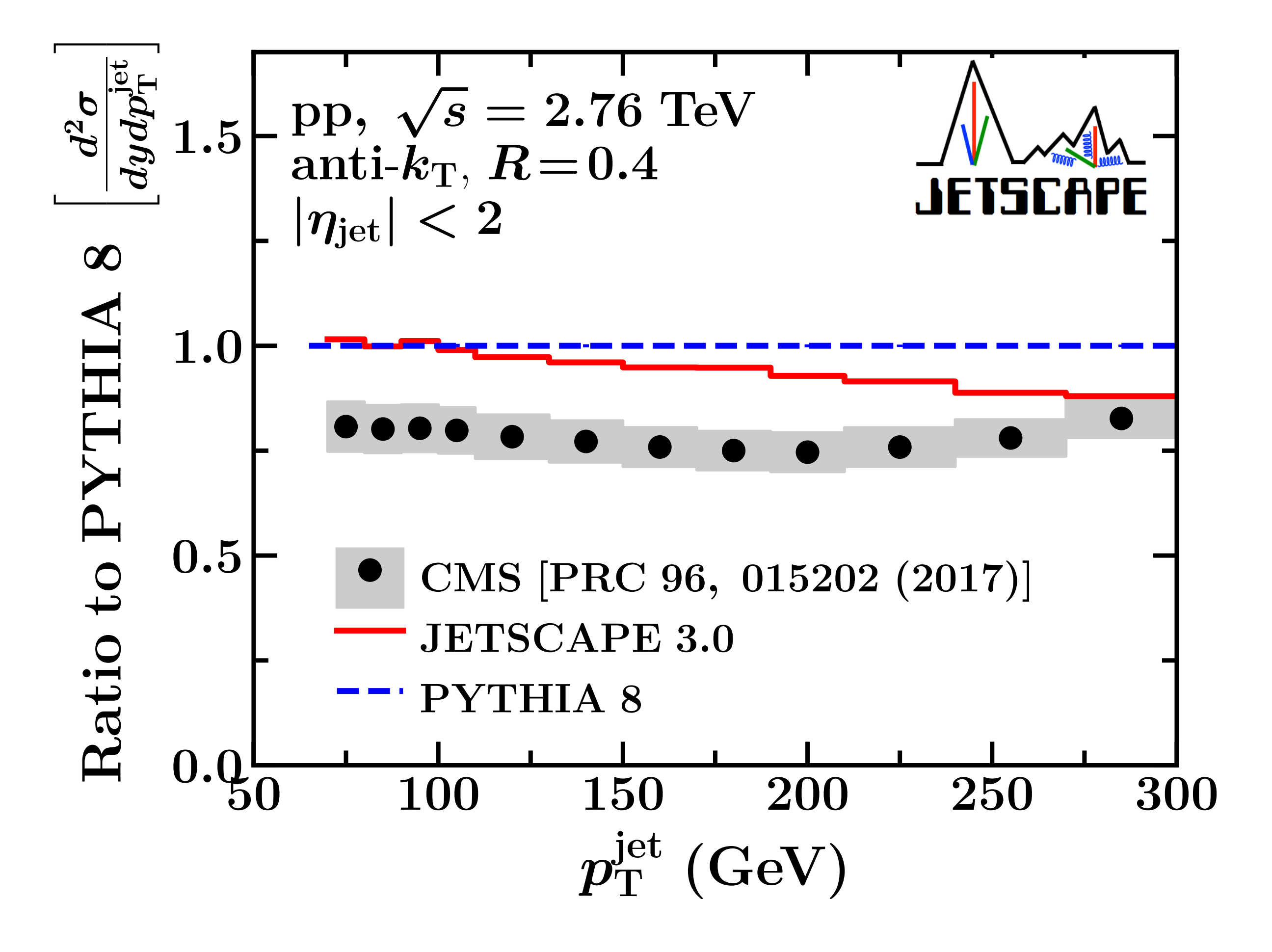
A jump from 1-2 to all observables

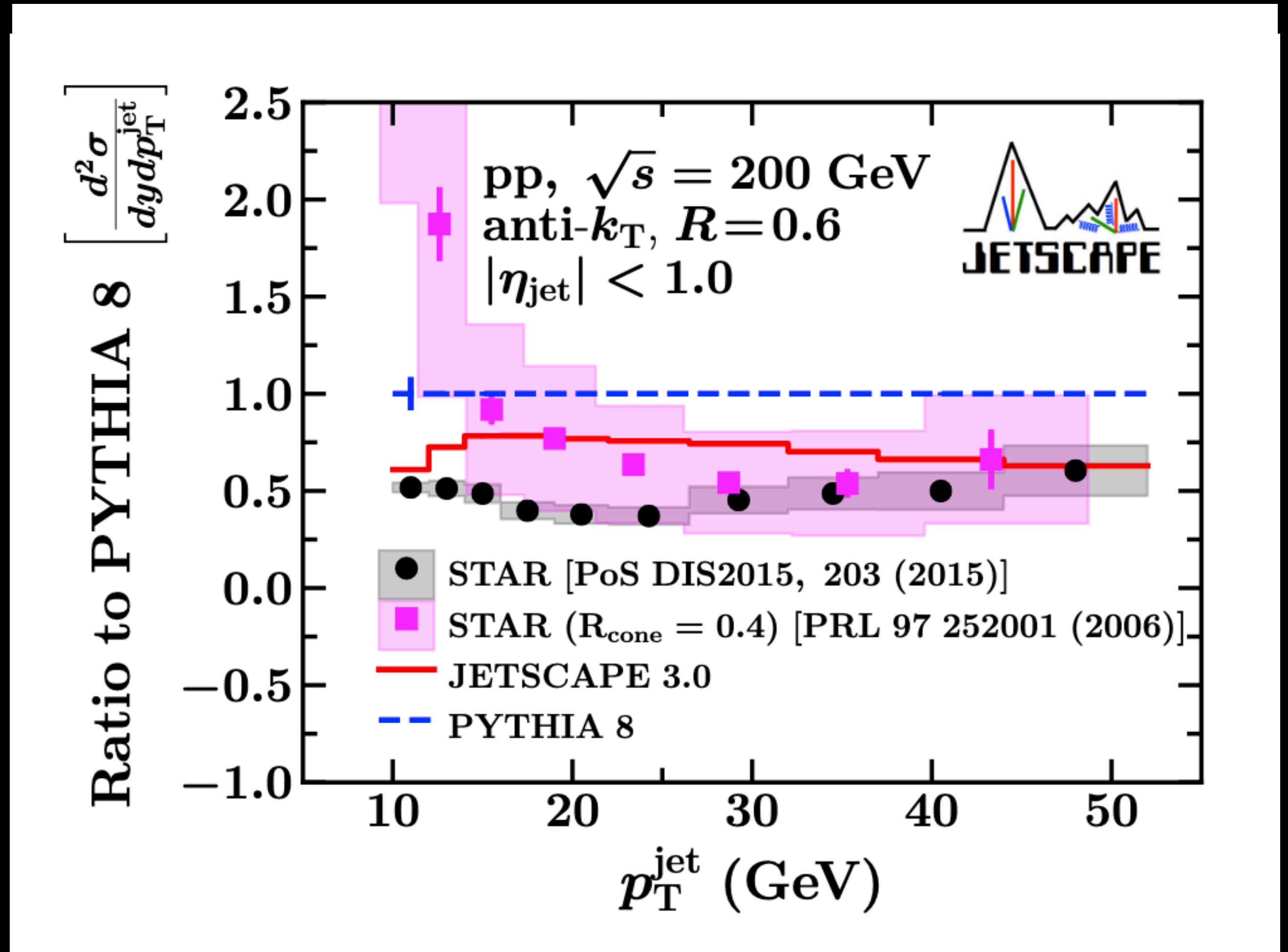
- TRENTO initial state
- Pre Calibrated 2+1D MUSIC gives background
- PYTHIA hard scattering
- High virtuality phase using MATTER
- Lower virtuality phase using LBT
- Transition at scale Q_{SW}
- Both have the same recoil setup
- Evolution starts at Q ~ E and goes down to 1 GeV
- Hadronization applied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

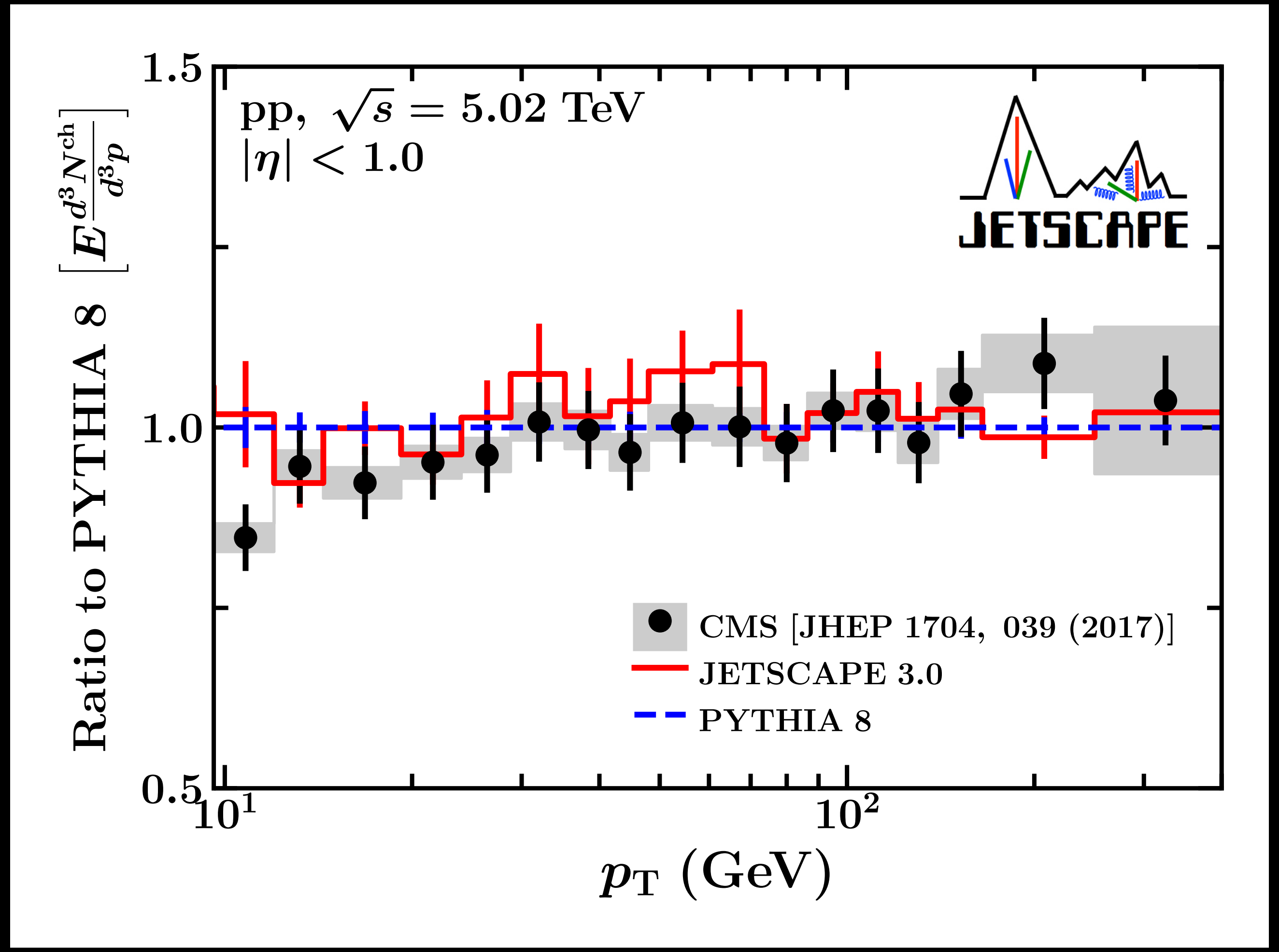
One more constraint before we start

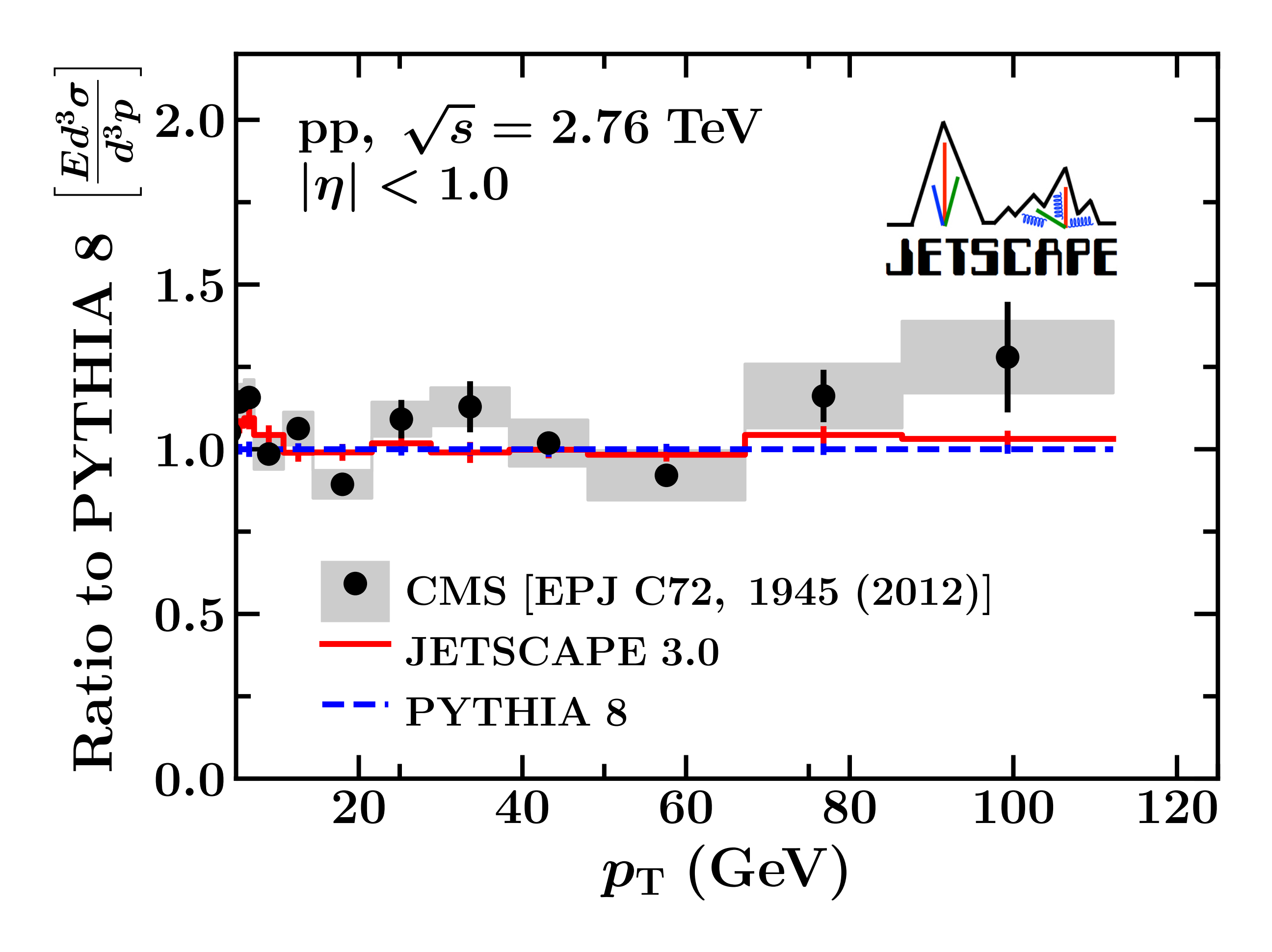
Any decent event generator should reproduce p-p collisions

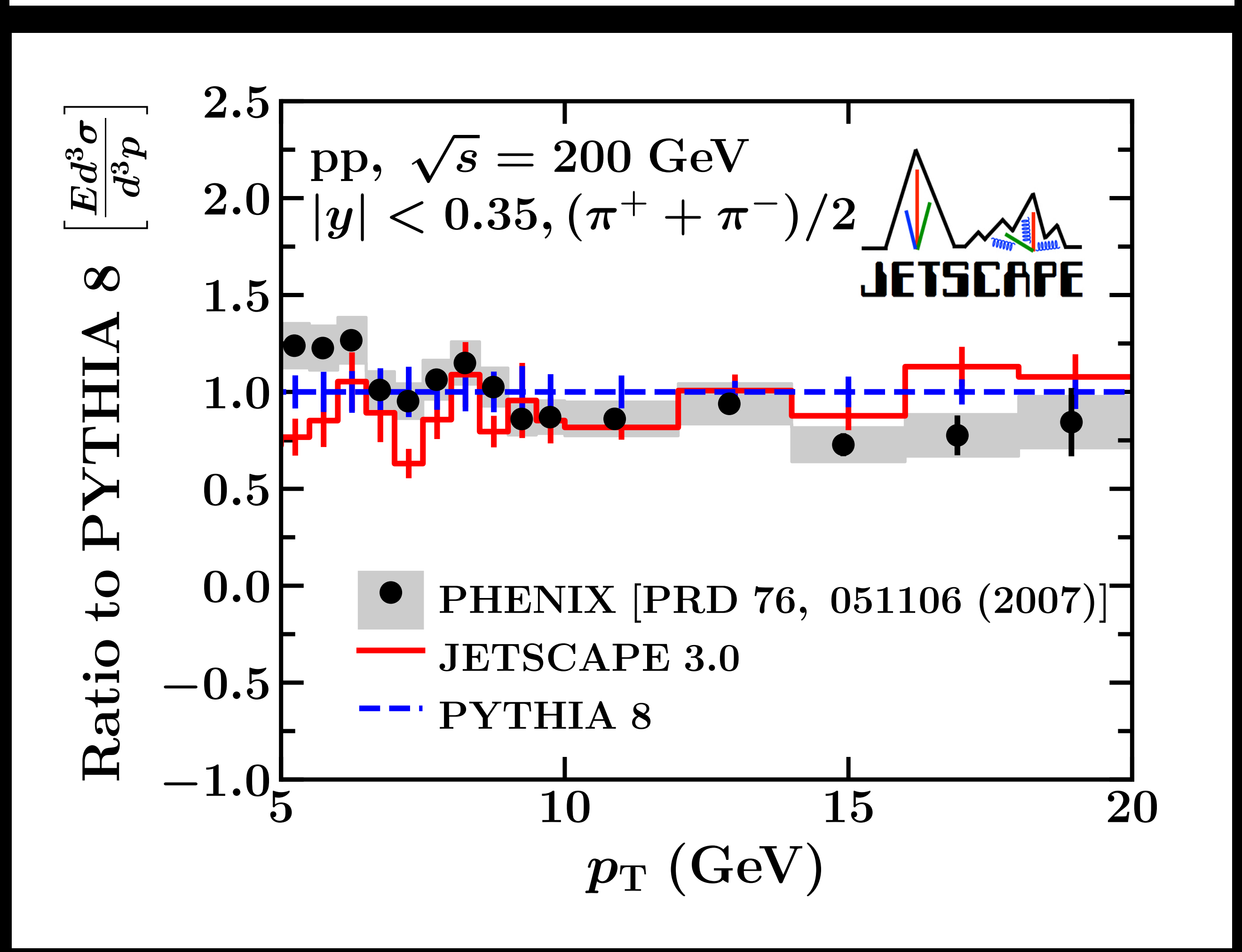










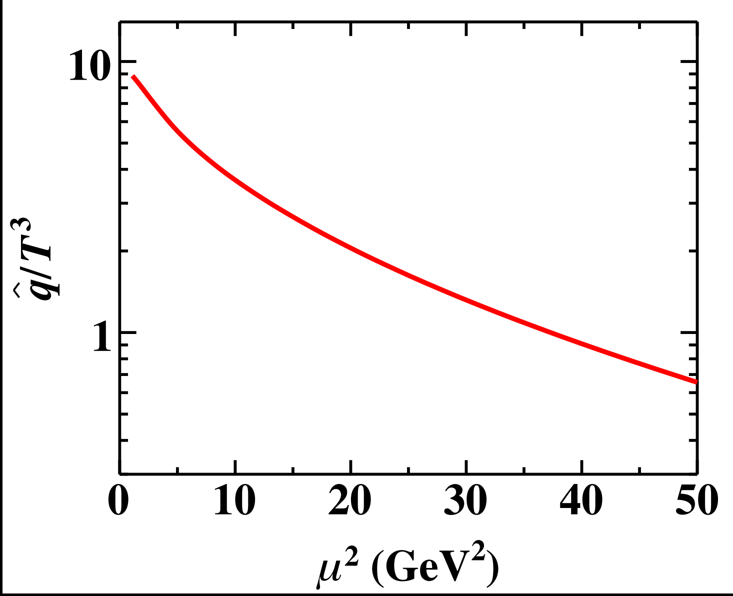


A. Kumar et al., 2204.01163 [hep-ph]

Leading hadrons and jets

At all energies and centralities

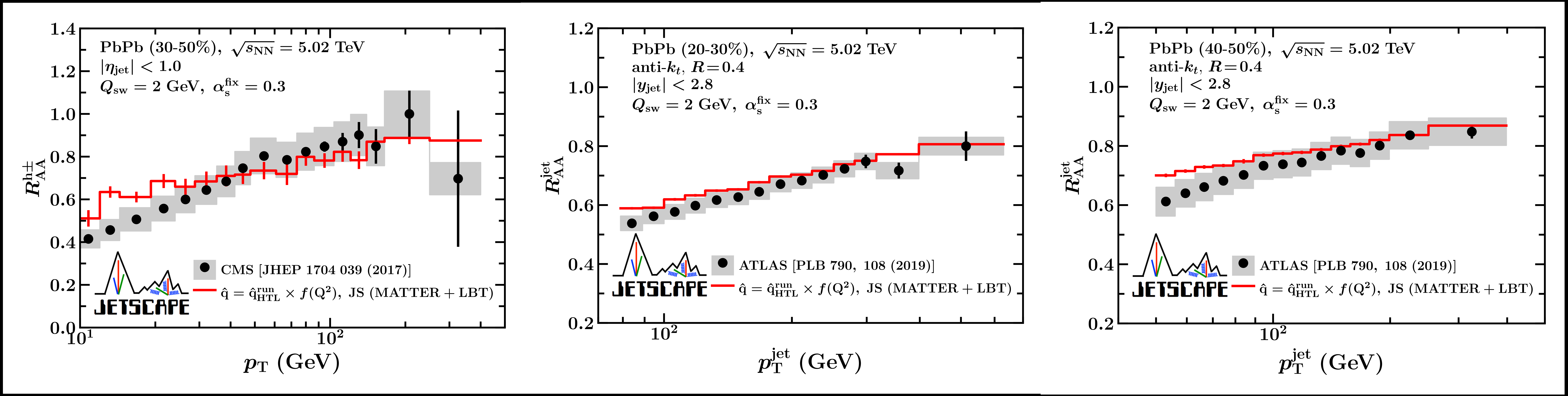
- $\hat{q} = C\alpha_s(2ET)\alpha_s(m_D)T^3 \log\left(\frac{2ET}{m_D^2}\right) \times f(Q^2)$



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

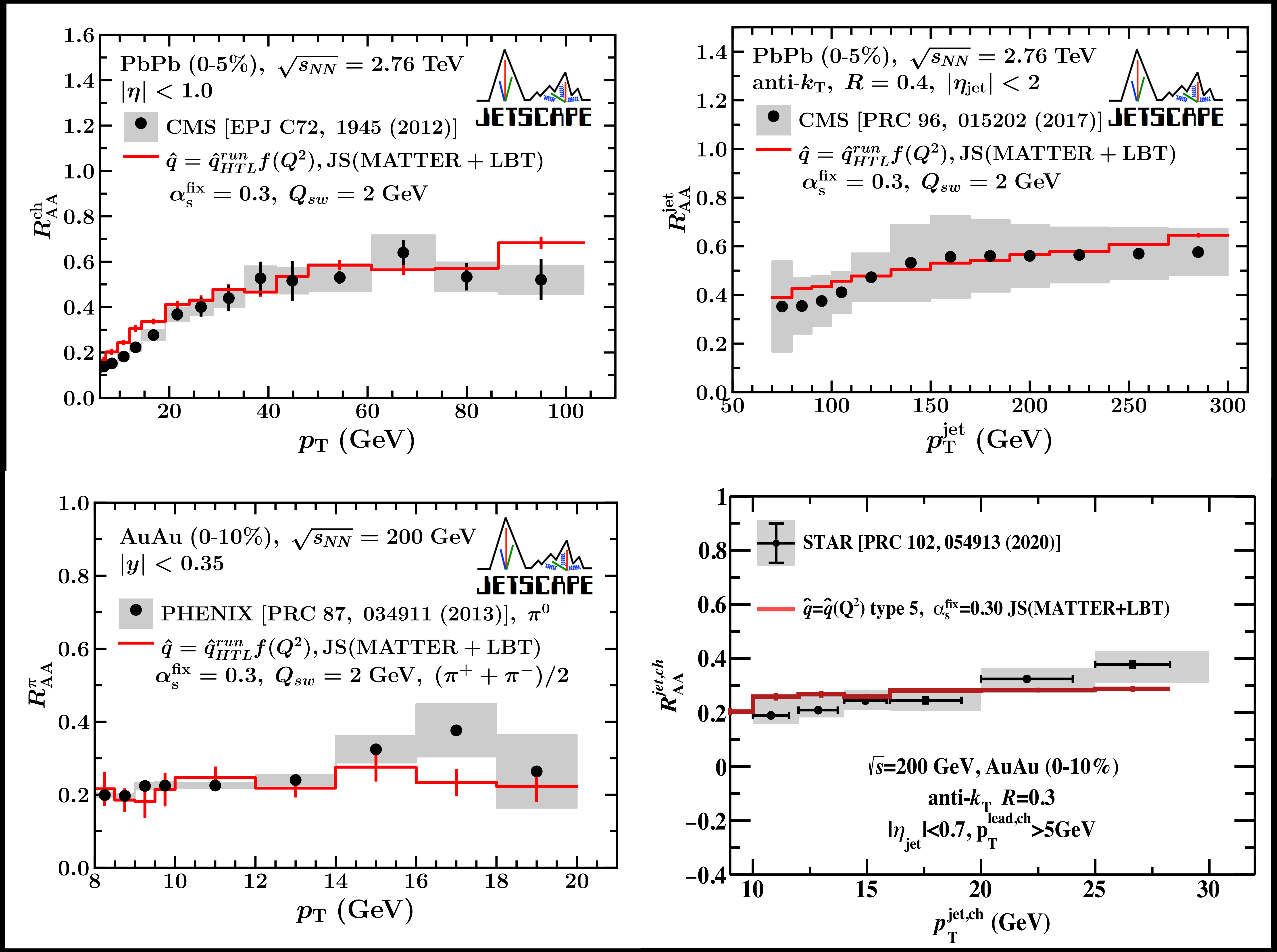
A. Kumar et al., 2204.01163 [hep-ph]

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

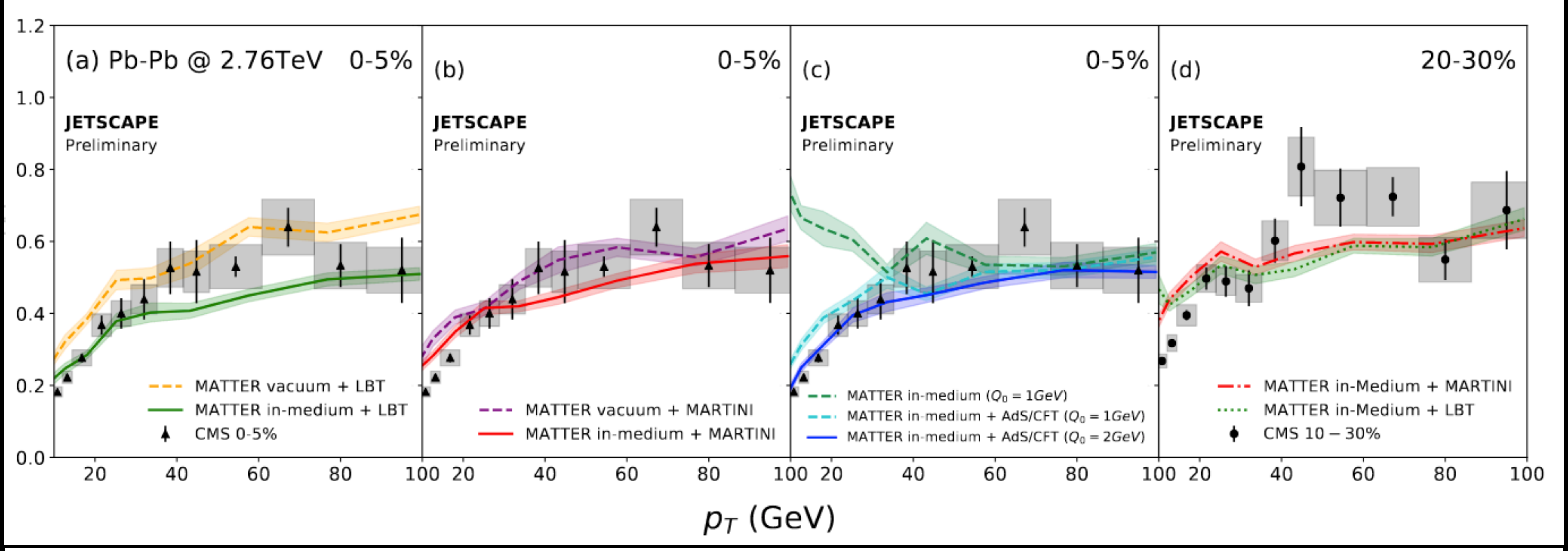


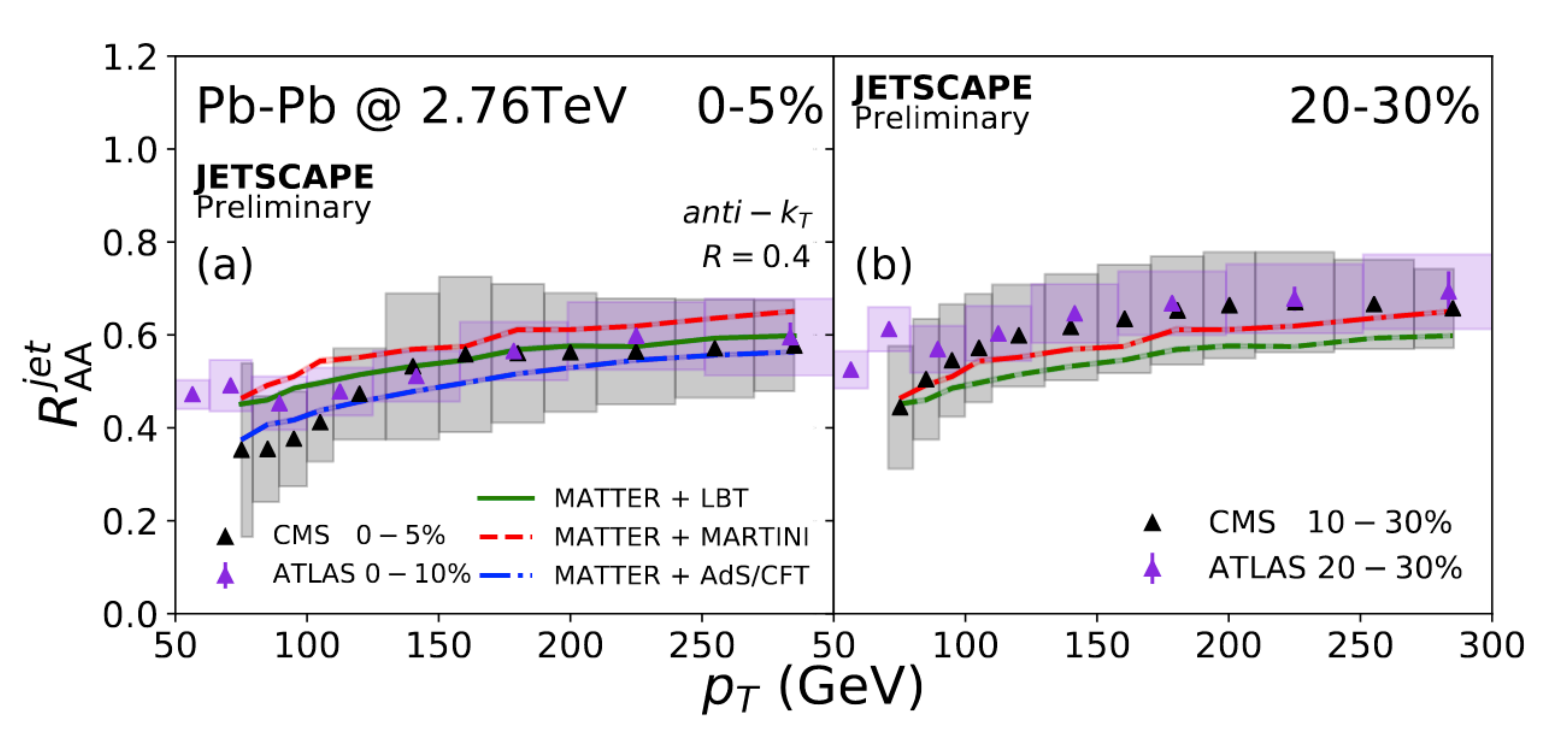
A. Kumar et al., 2204.01163 [hep-ph]

Systematic model uncertainty

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

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





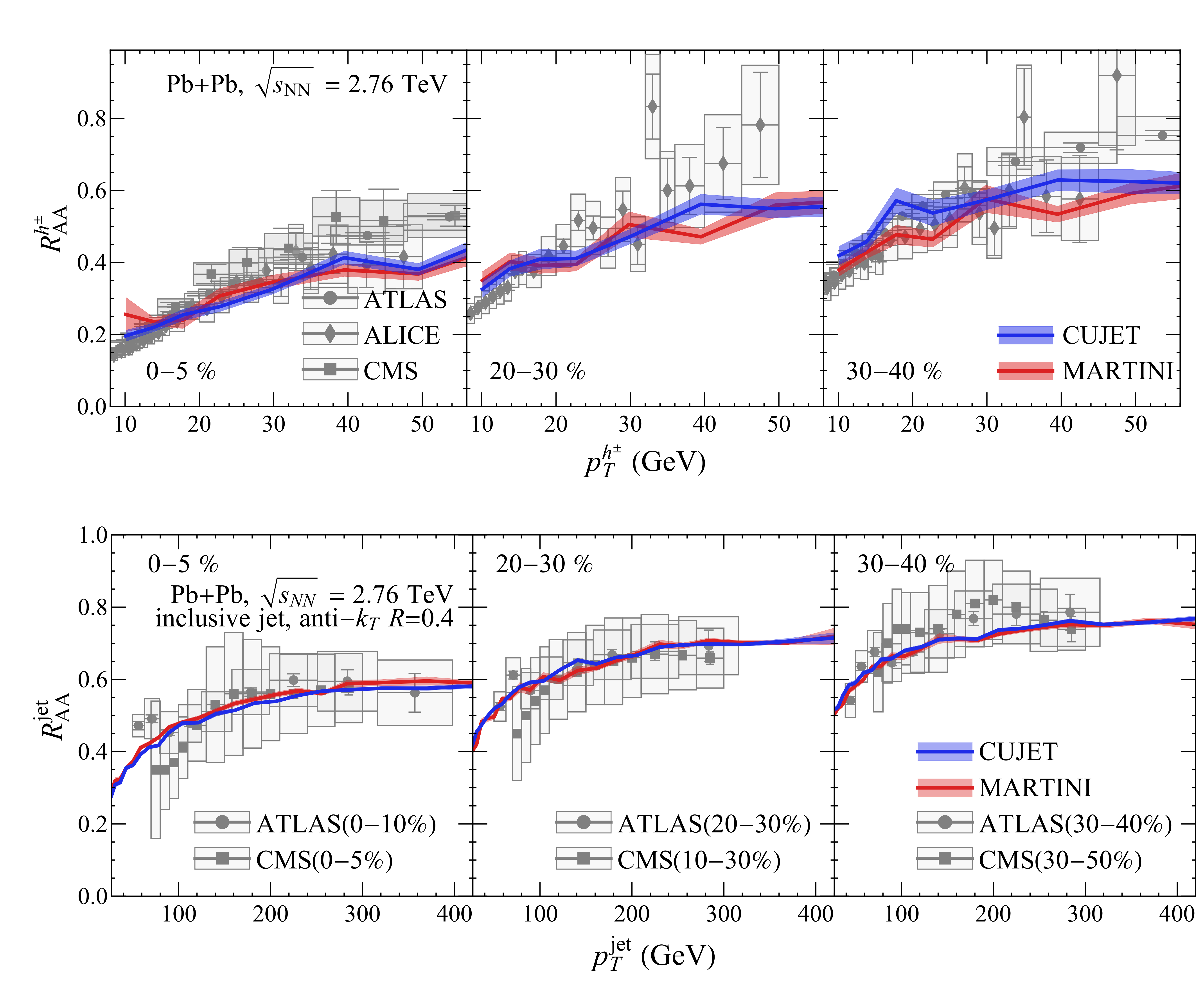
Systematic model uncertainty

[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

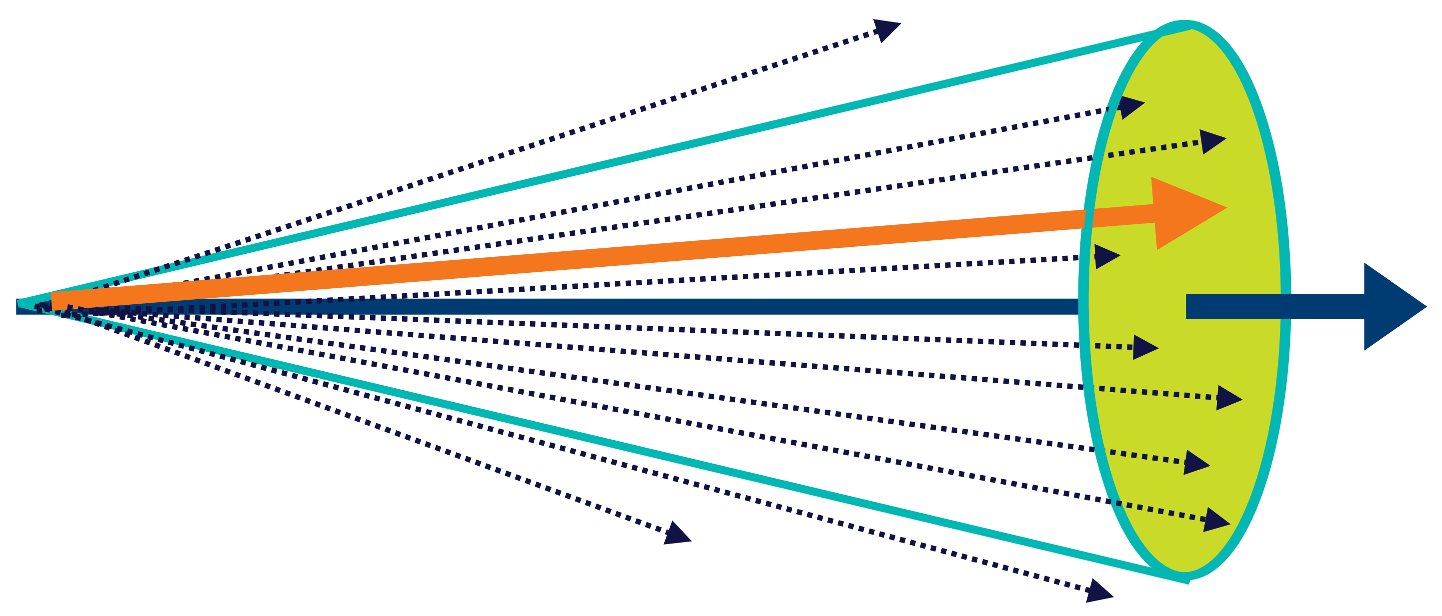


Intrajet

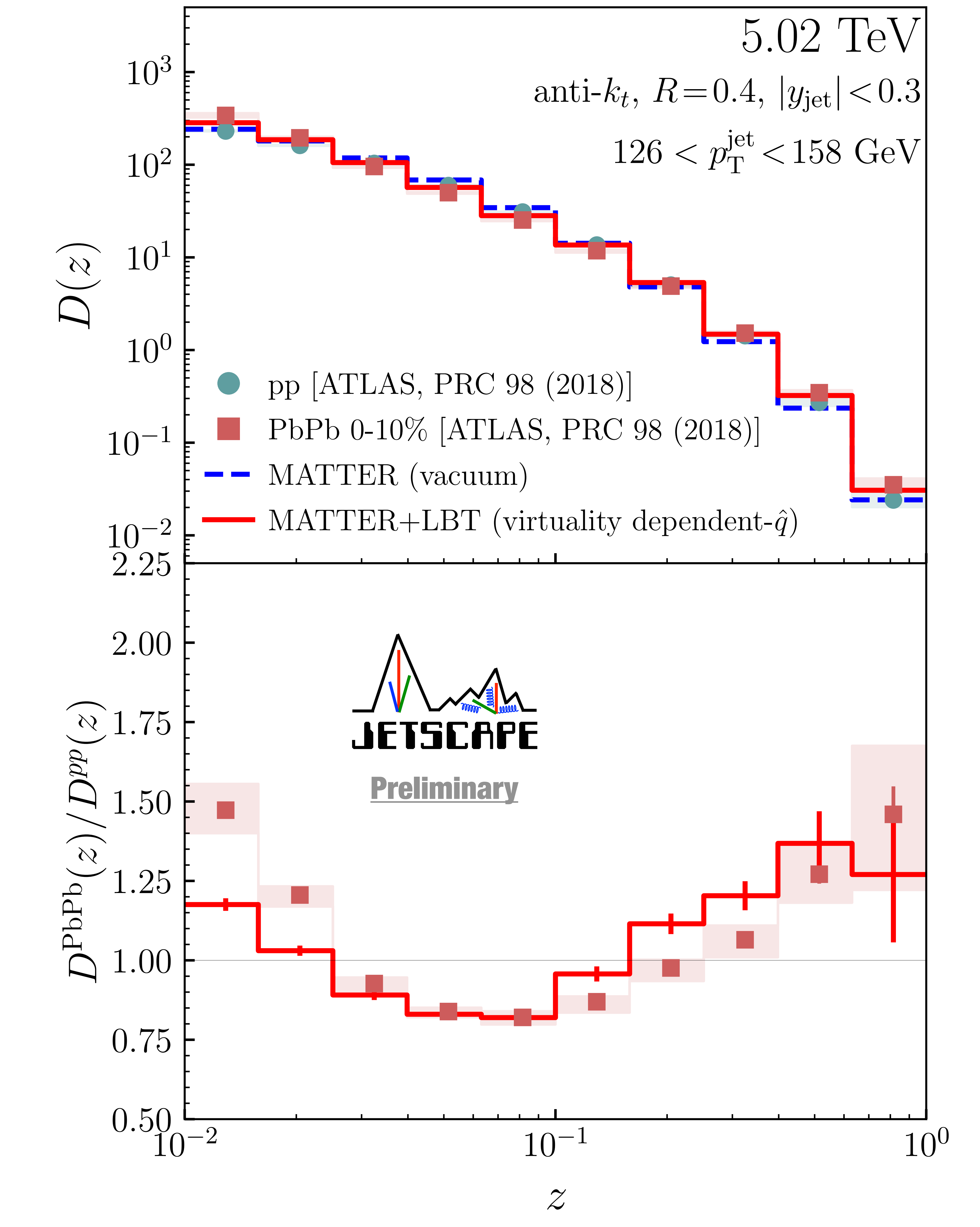
The dependence on E and μ not completely settled

This will probably get done in an upcoming Bayesian analysis

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

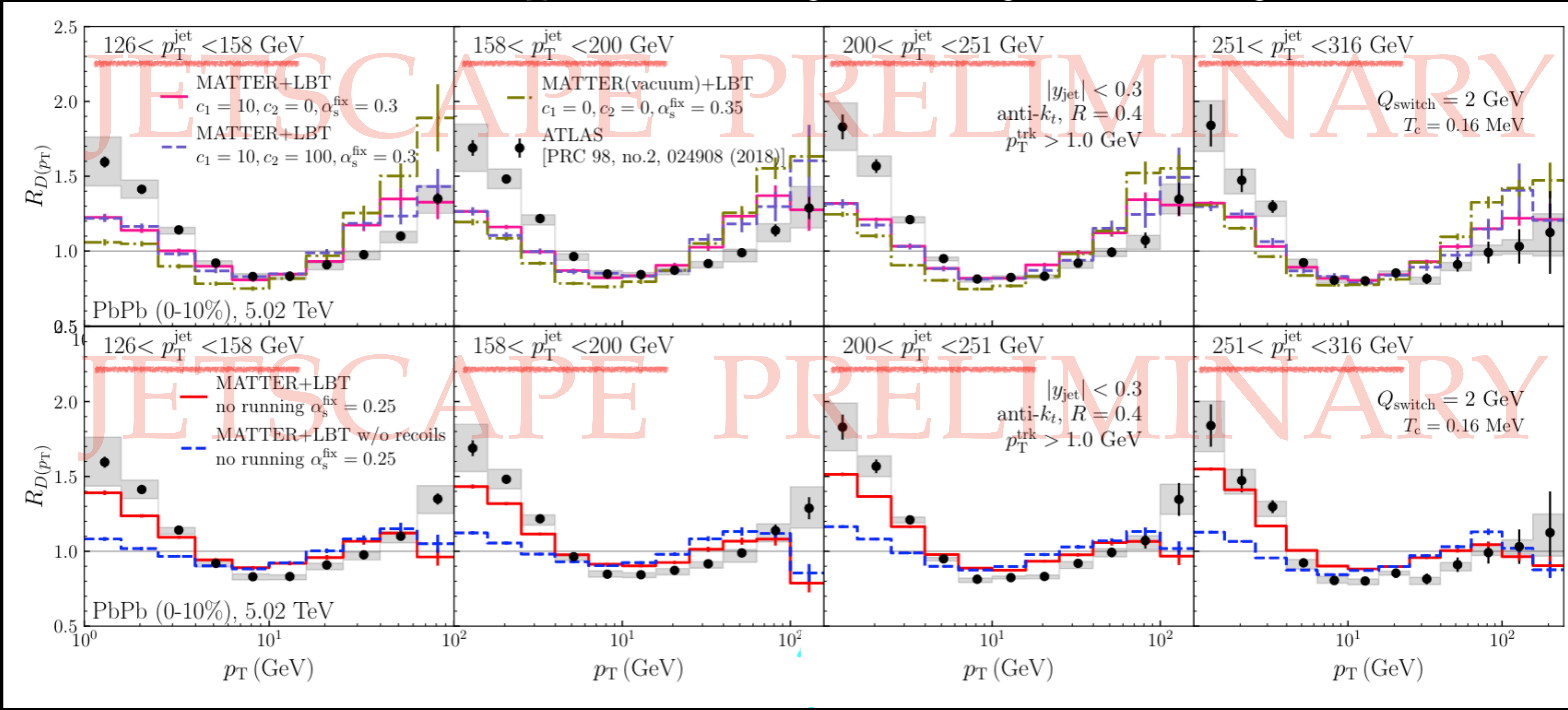


$$z = \frac{p_T^{\text{trk}}}{p_T^{\text{jet}}}$$



Y. Tachibana et al., *to appear*

Need for quenching in high Q stage



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

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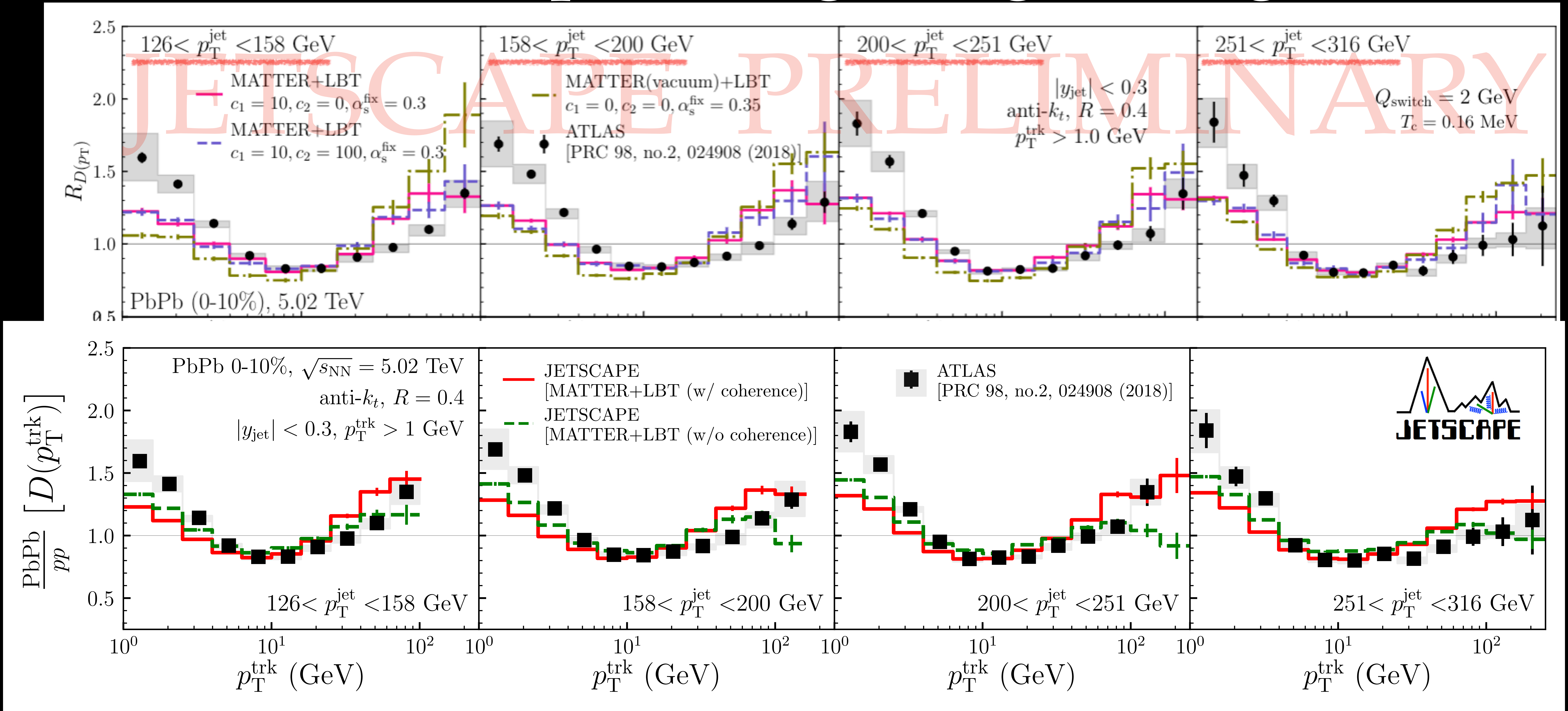
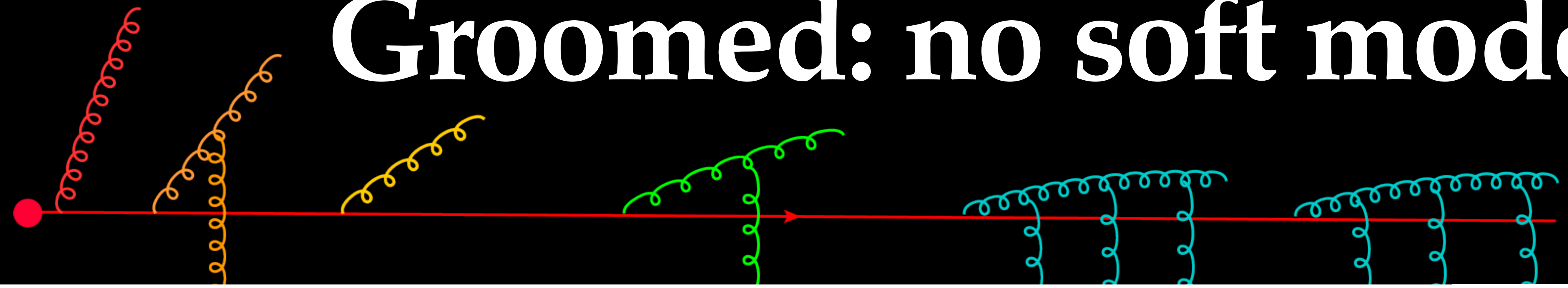
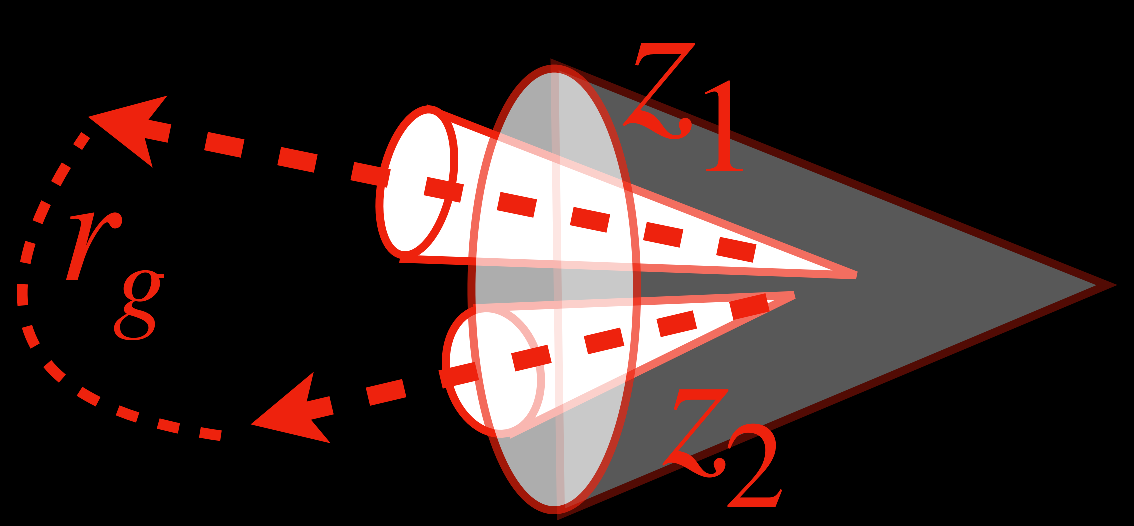


Y. Tachibana et al., 2301.02485 [hep-ph]

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]

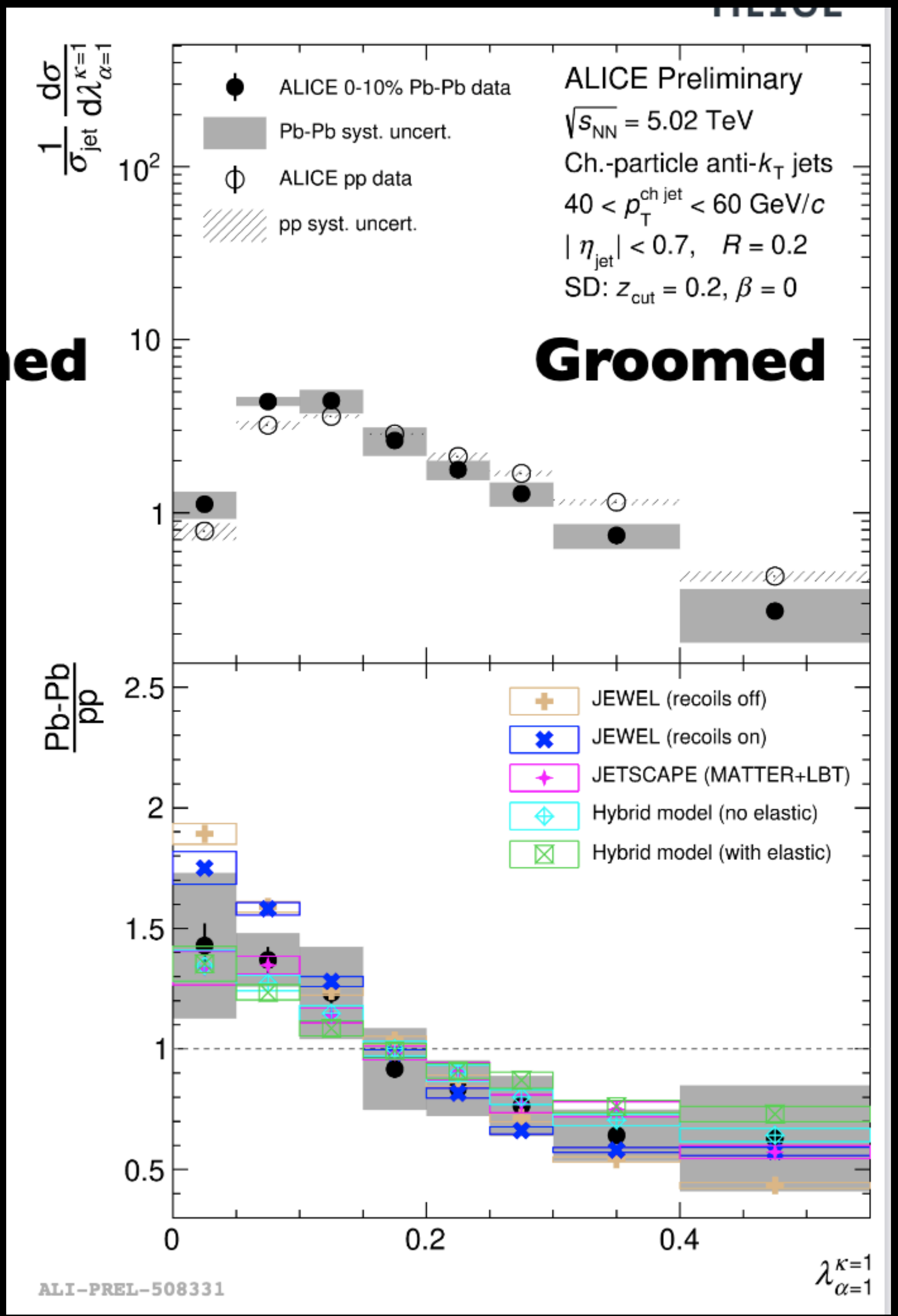
R_{AA} as a function of r_g

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

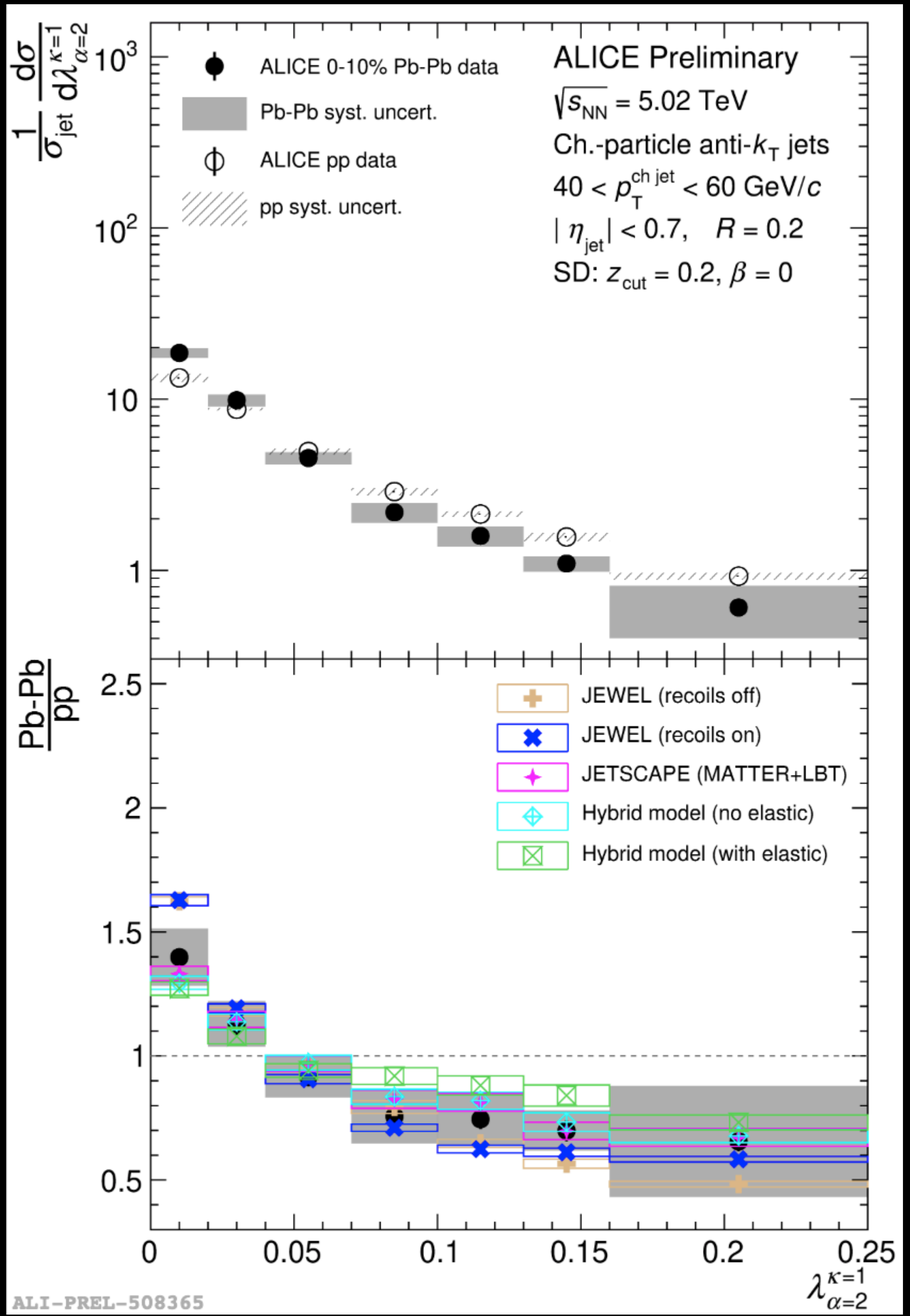
Calculations without Coherence show a bump

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

Groomed Jet angularities

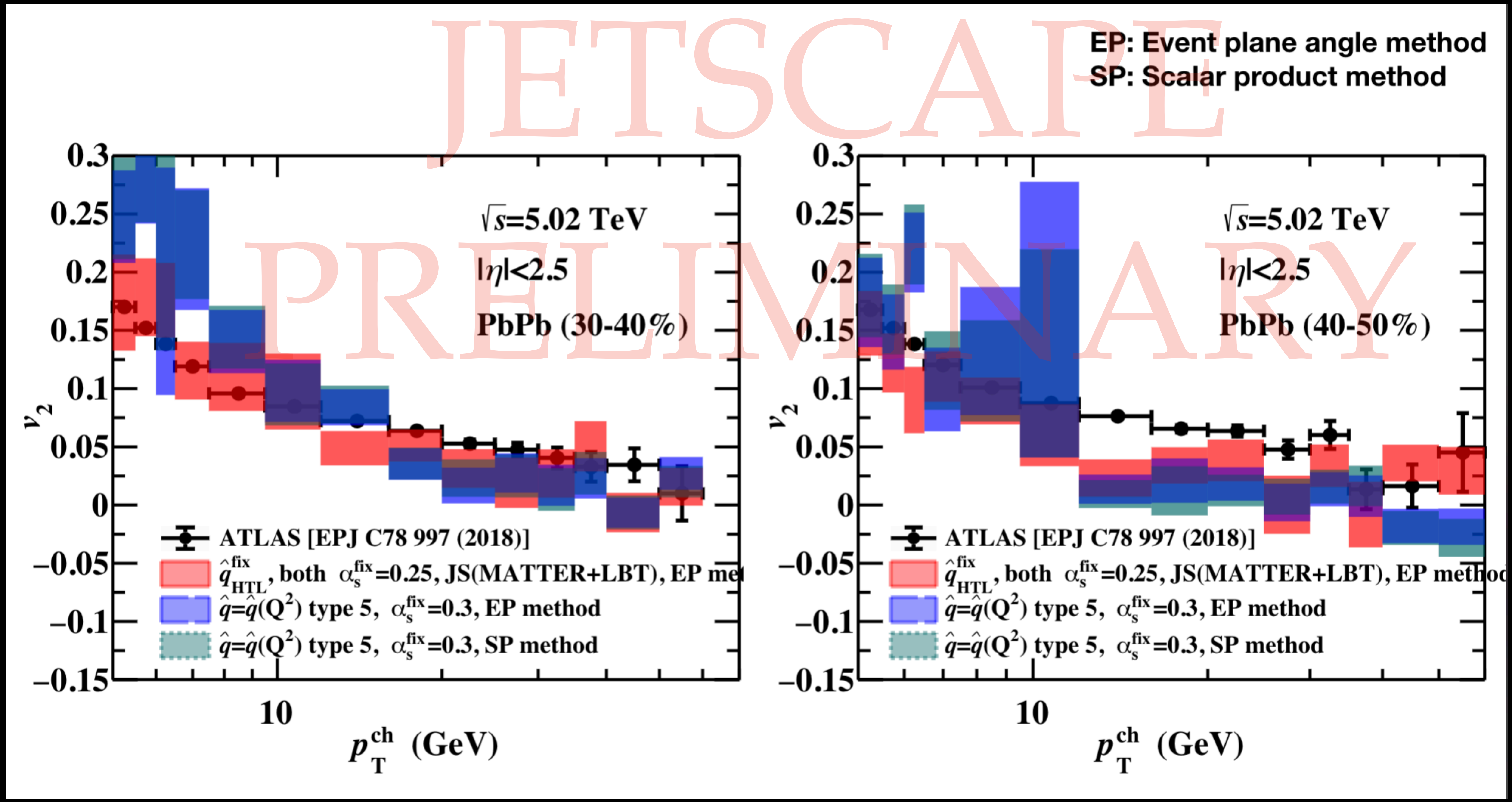


- $$\lambda = \sum_{i \in Groomed} z_i \theta_i^{\alpha}$$
- Strong constraints on the perturbative part of jet
- Several other similar groomed observables
- JETSCAPE (MATTER +LBT) does very well.

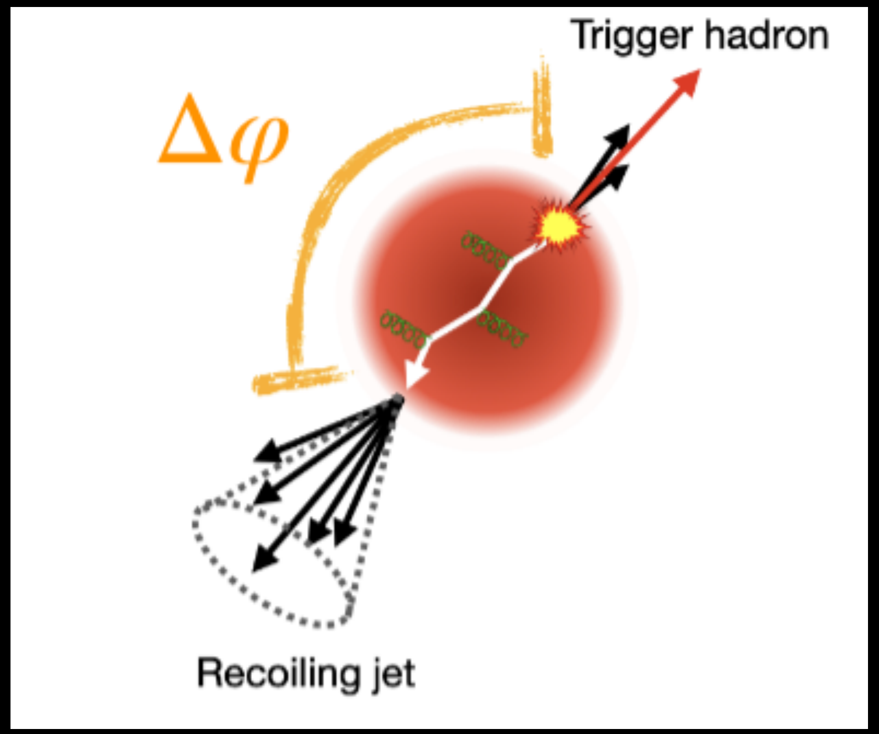


Azimuthal anisotropy

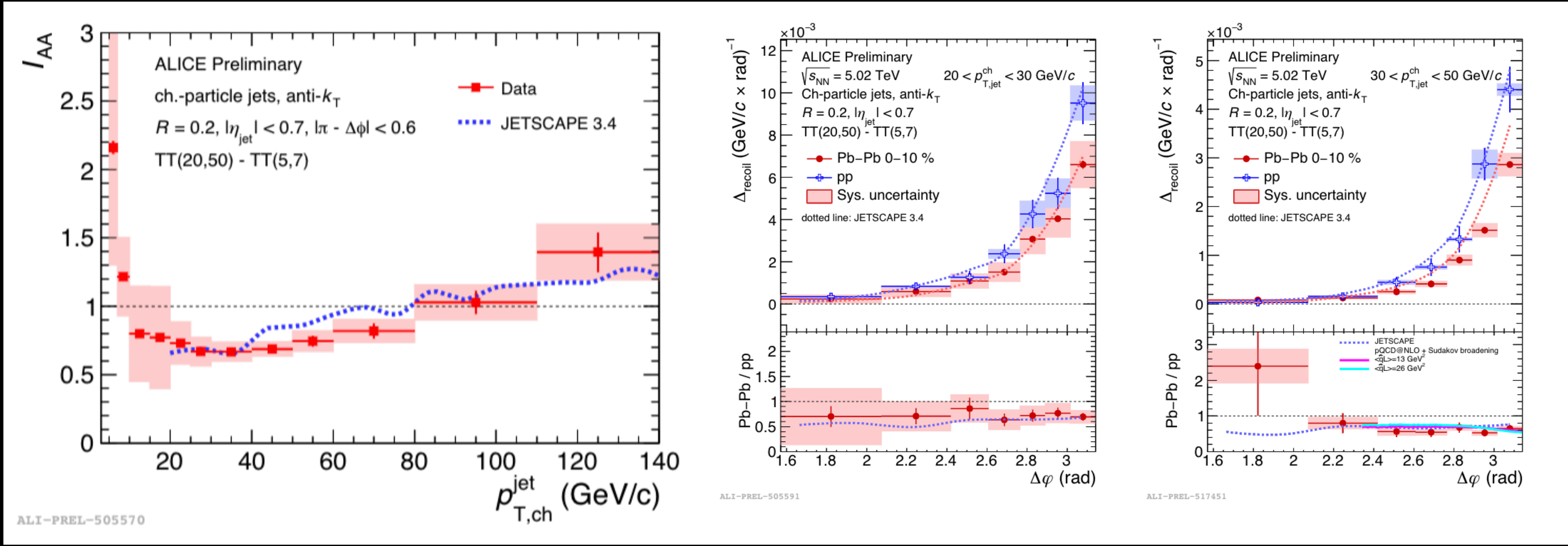
- Note: we haven't played with start and stop times (observation by C. Andres et al, start time important for v_2)
- In the JETSCAPE simulations, hydrodynamics starts around 1fm/c. (Free streaming prior)
- Also with new IP-Glasma, medium has primordial v_2
- Jet modification in the hadronic medium still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



Coincidence with hadrons

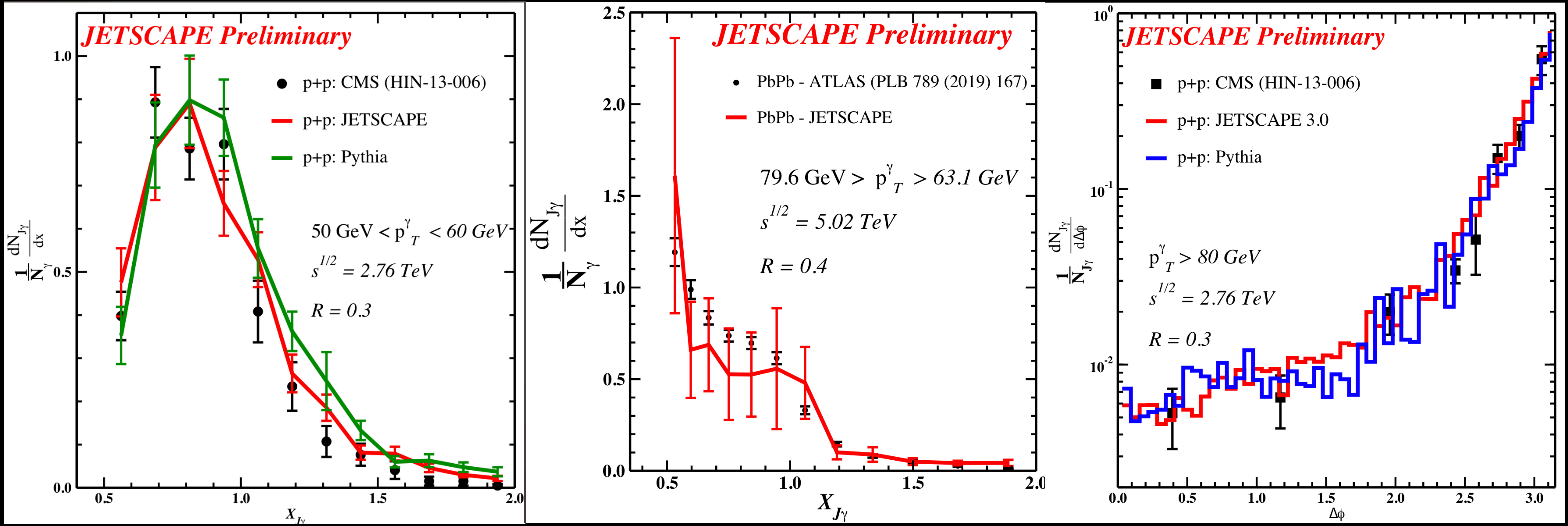


- Results from MATTER+LBT runs use for ratio of difference of triggered jet distribution per trigger.



Photon Trigger

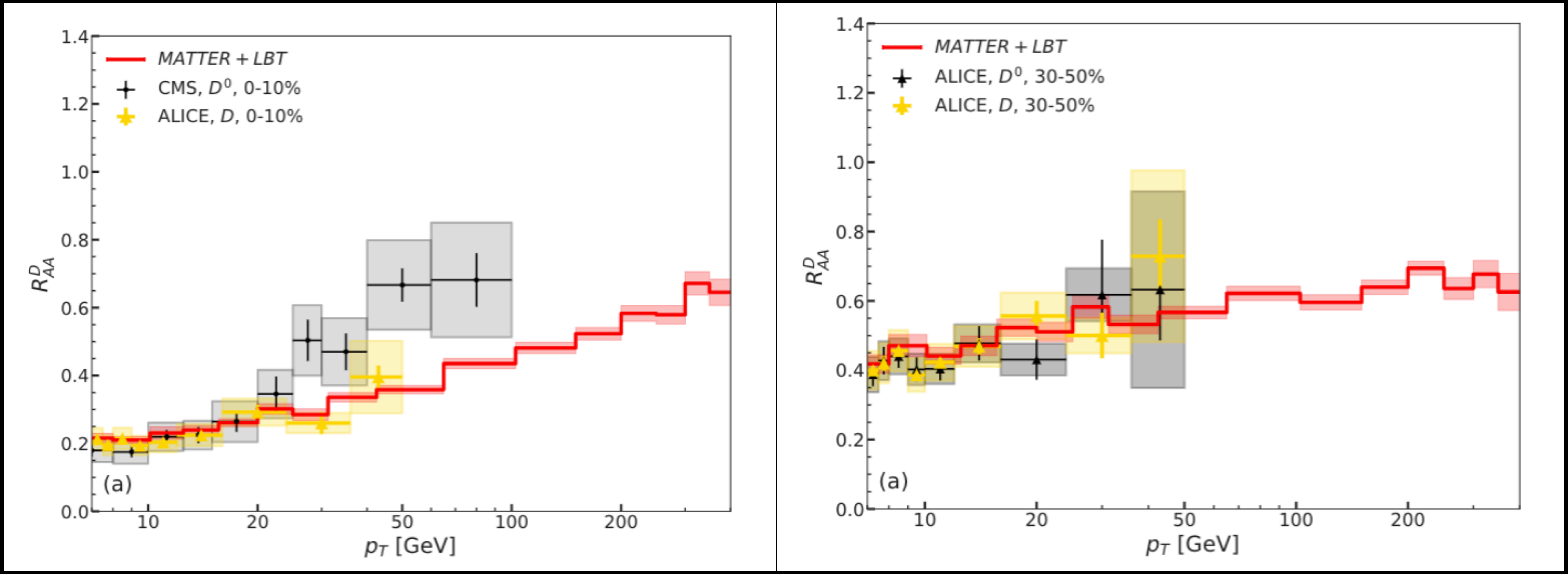
- Higher statistics runs with the exact same parameters as for jets.



C. Sirimanna, *to appear*.

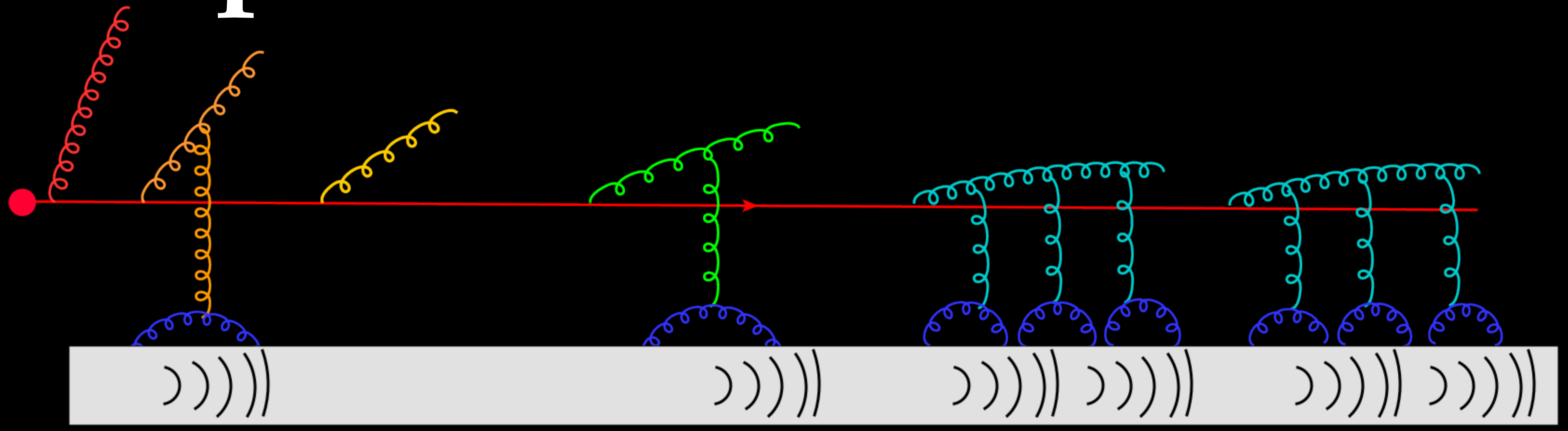
Heavy-quarks

- D meson R_{AA} with identical parameters

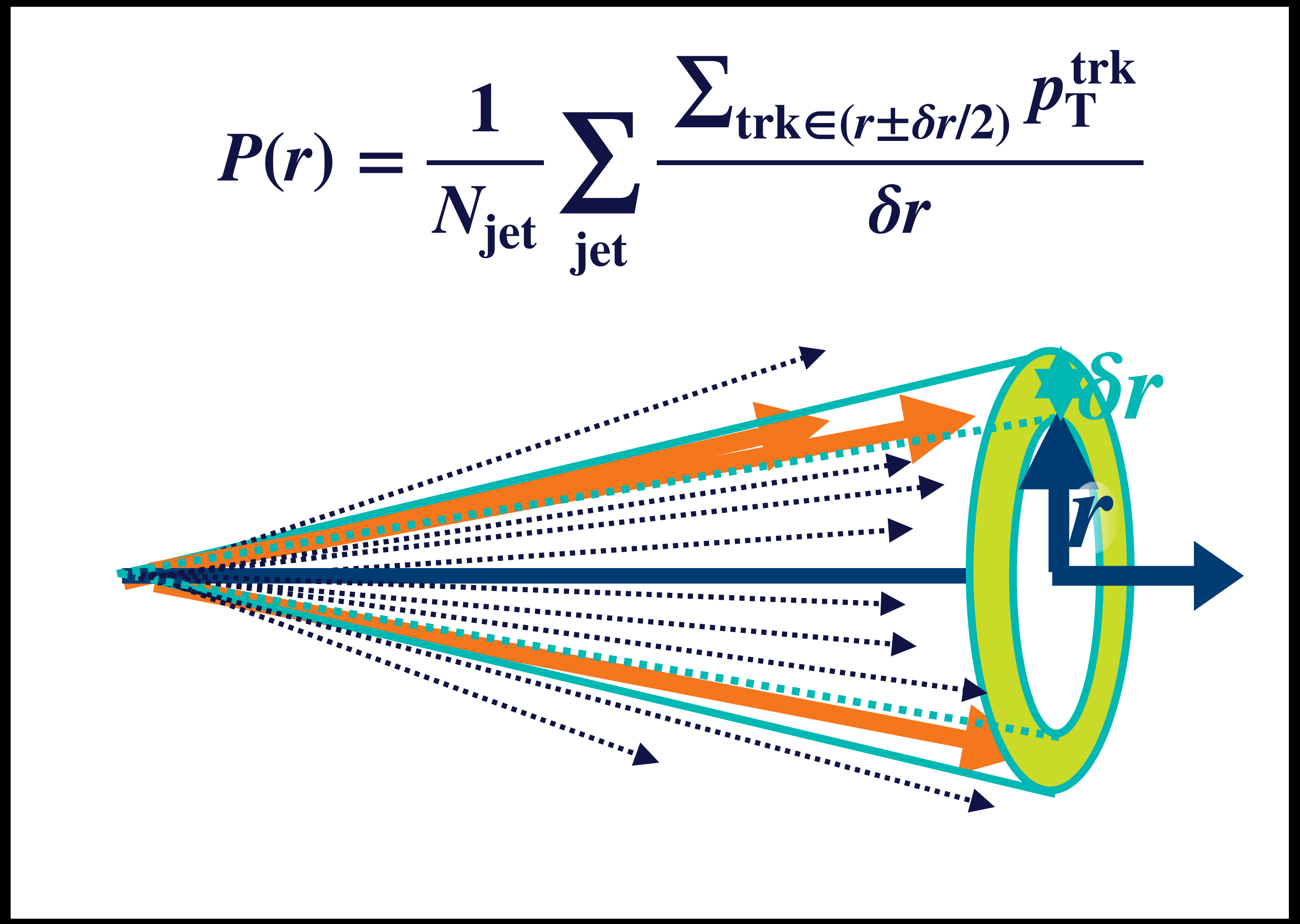


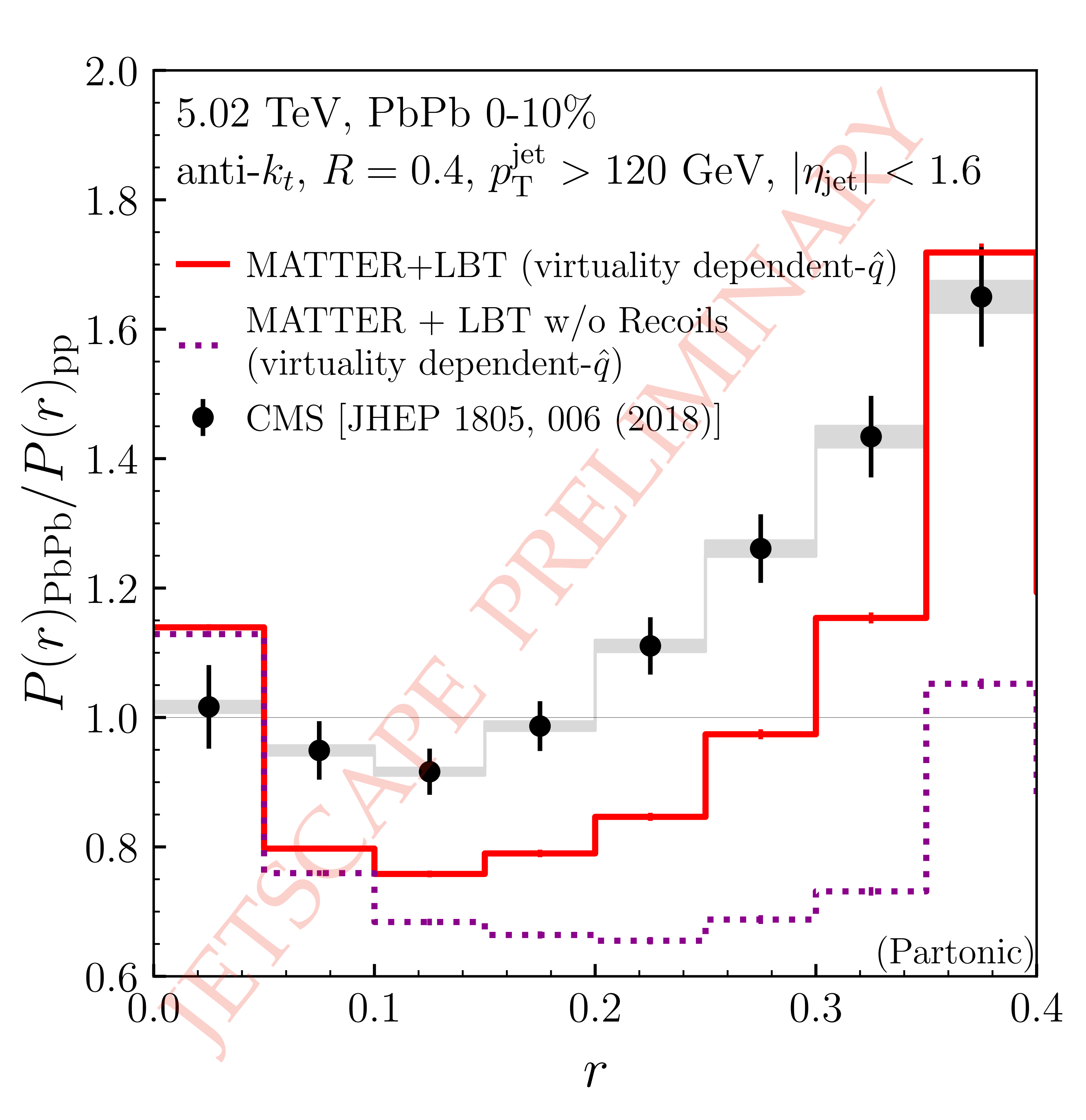
W. Fan, *et al*. e-Print: 2208.00983 [nucl-th]

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.





Y. Tachibana et al., *to appear*

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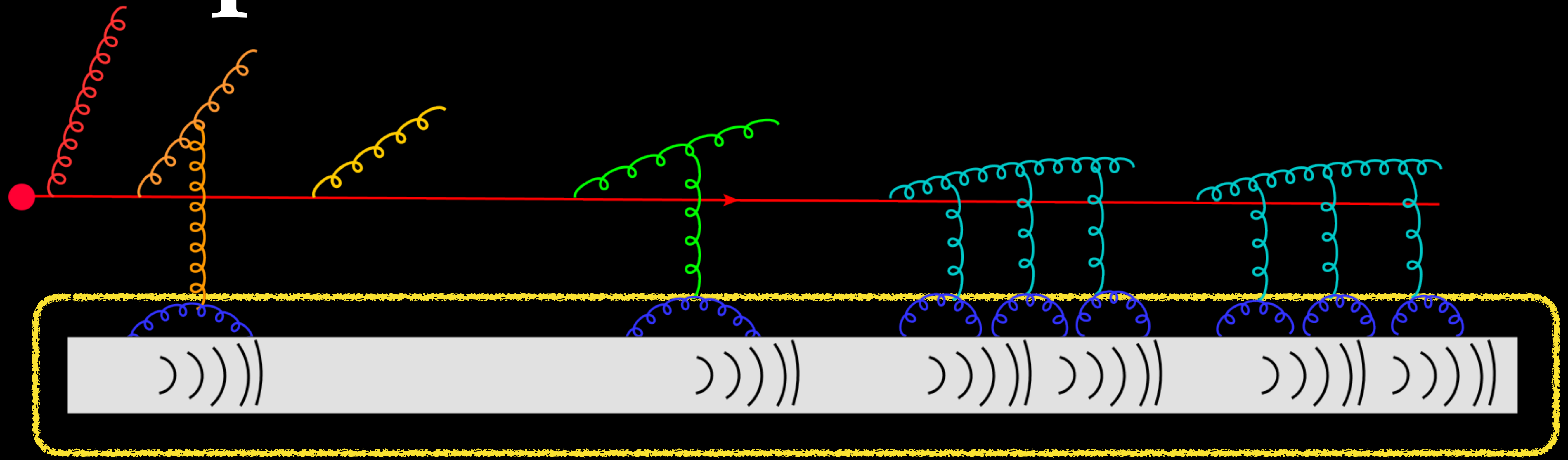

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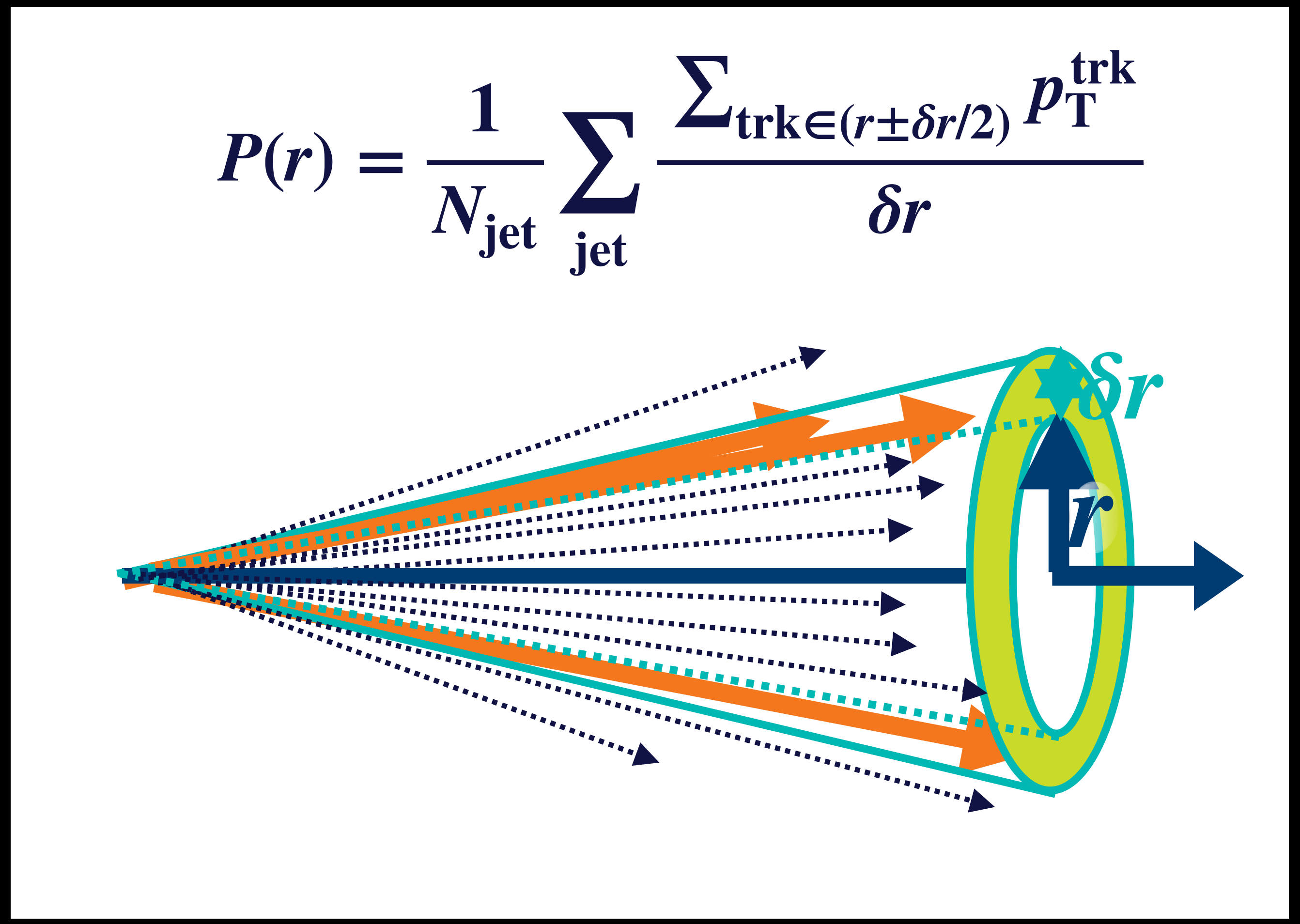

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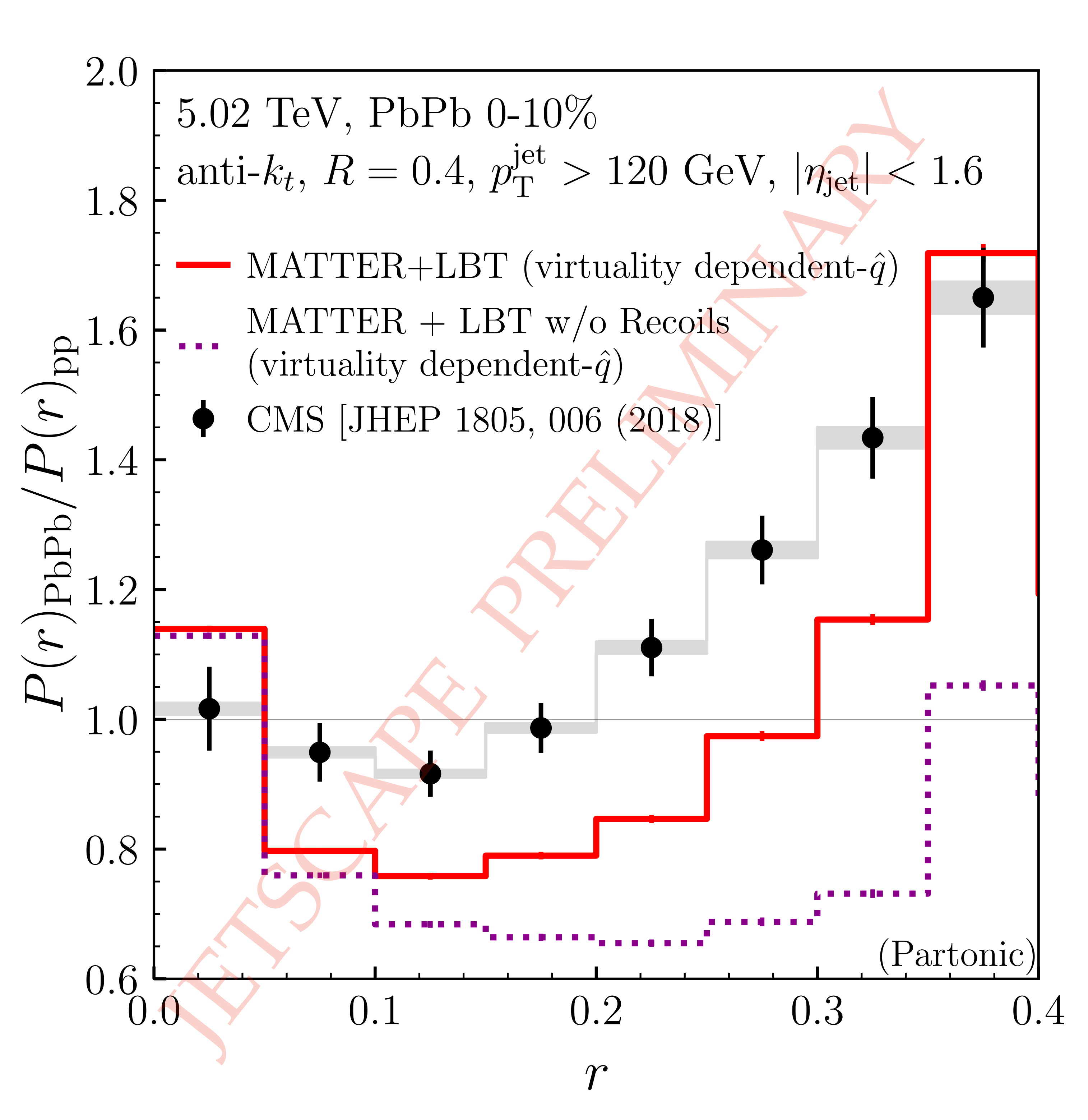
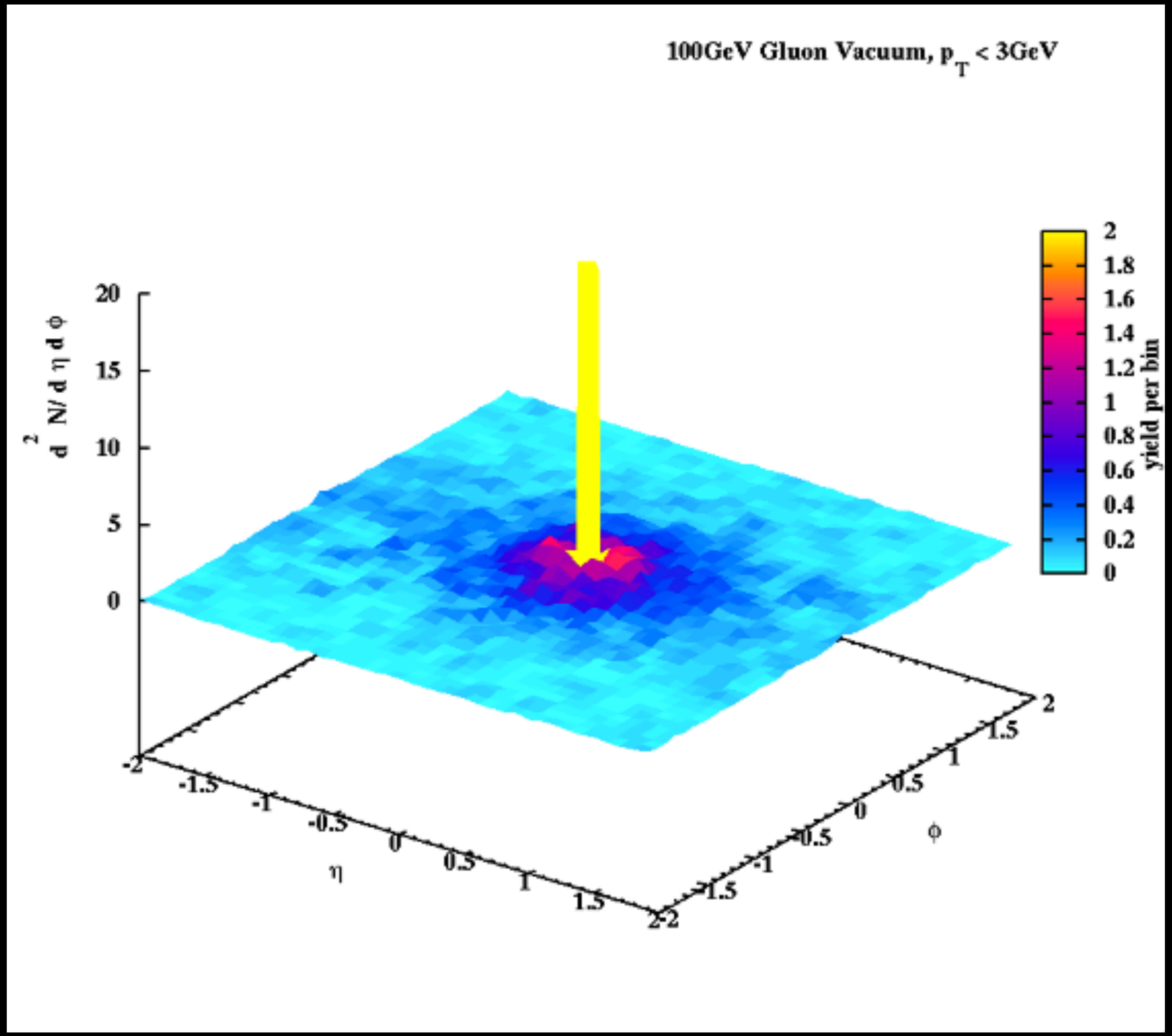
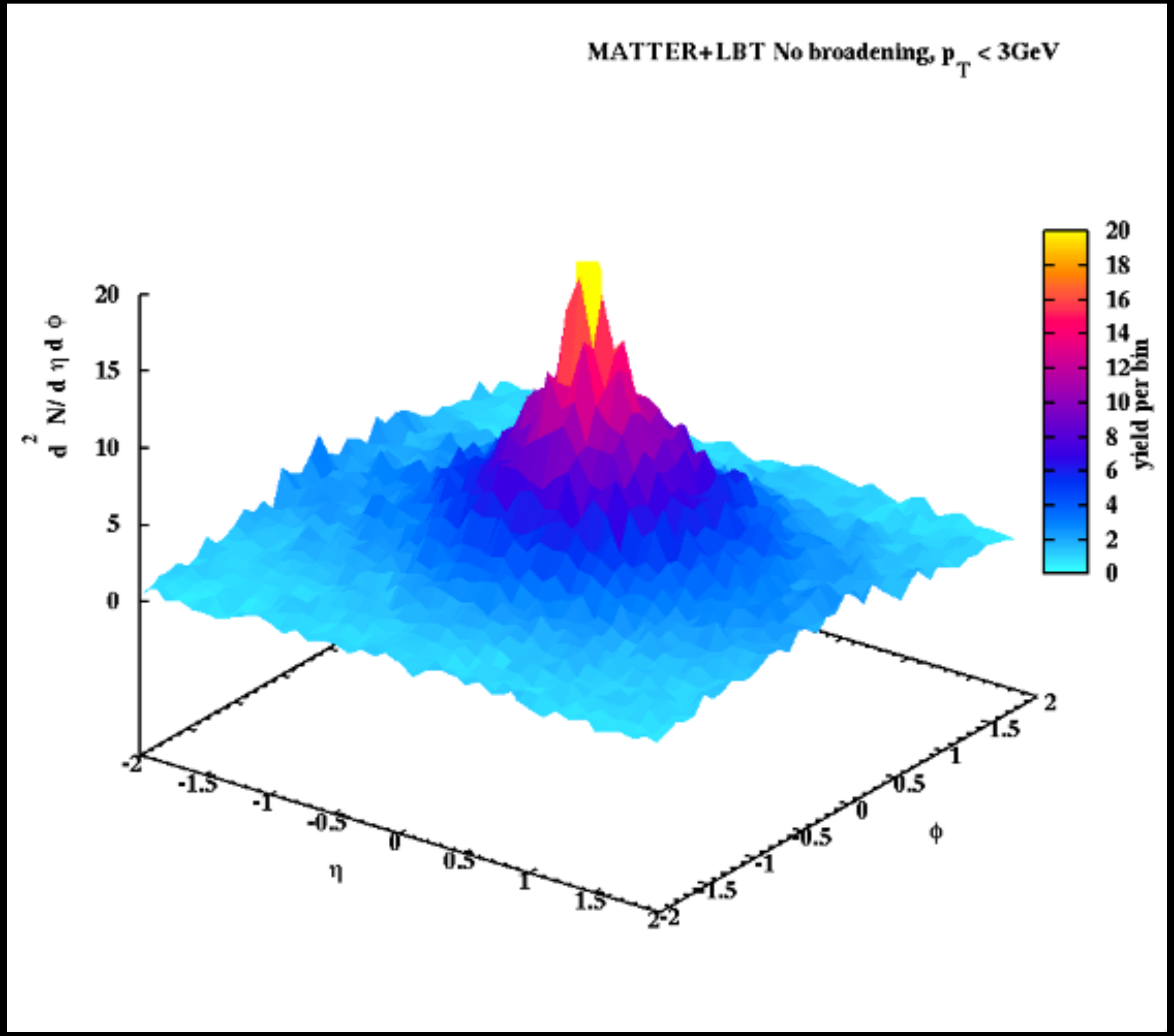


Soft jet partons move far away from the jet

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

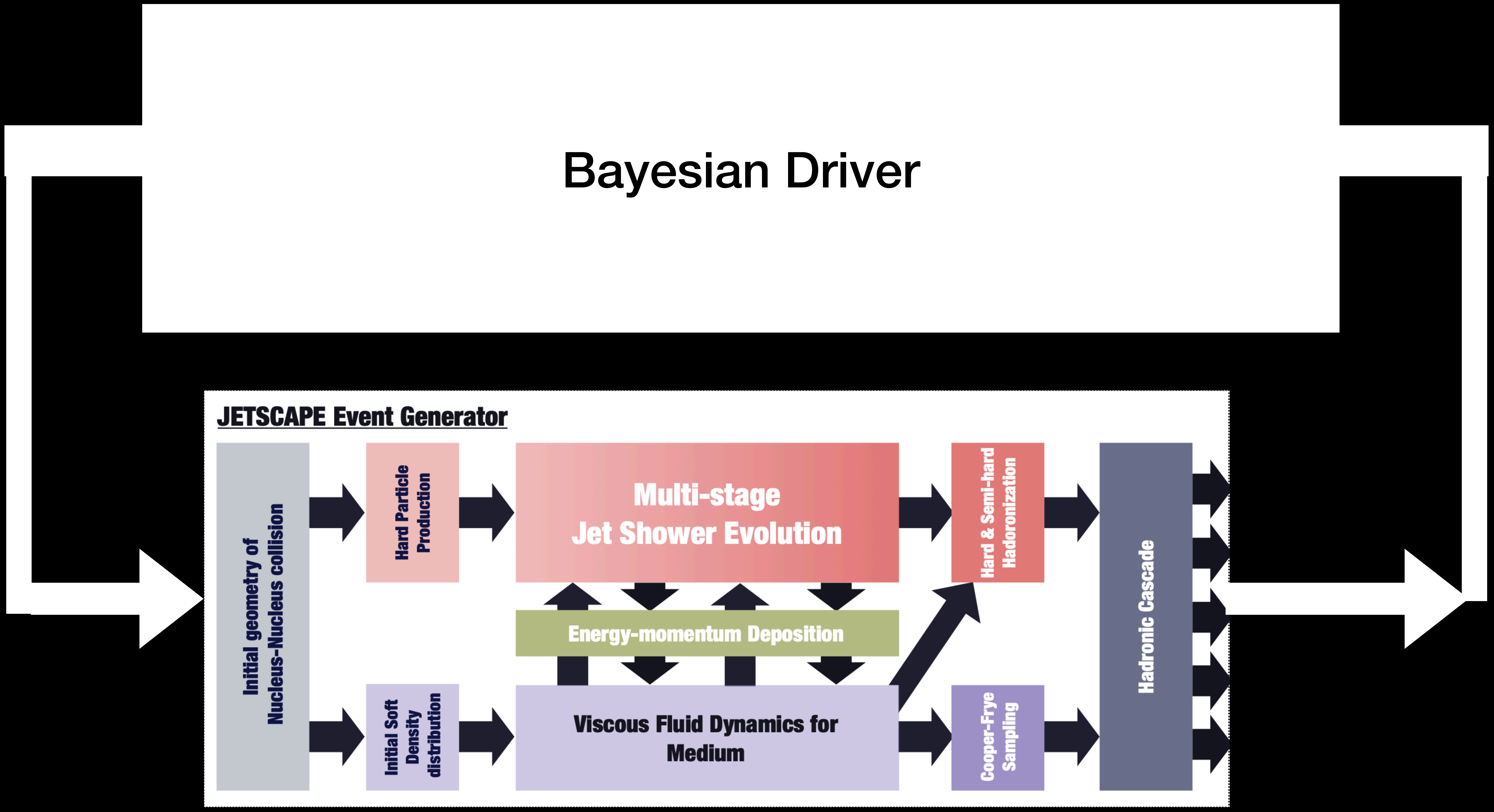




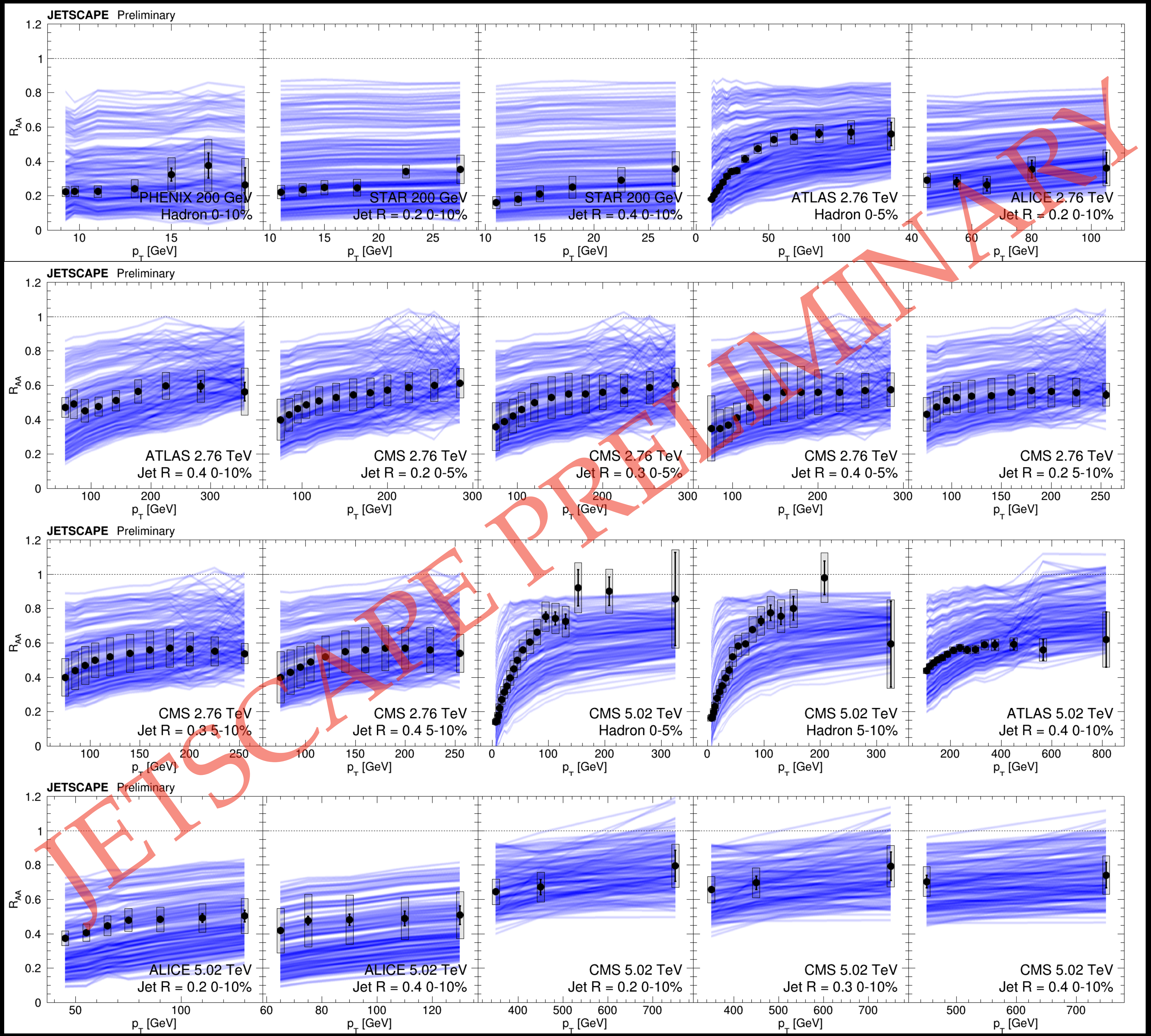
This requires to run one hydro simulation per hard event.

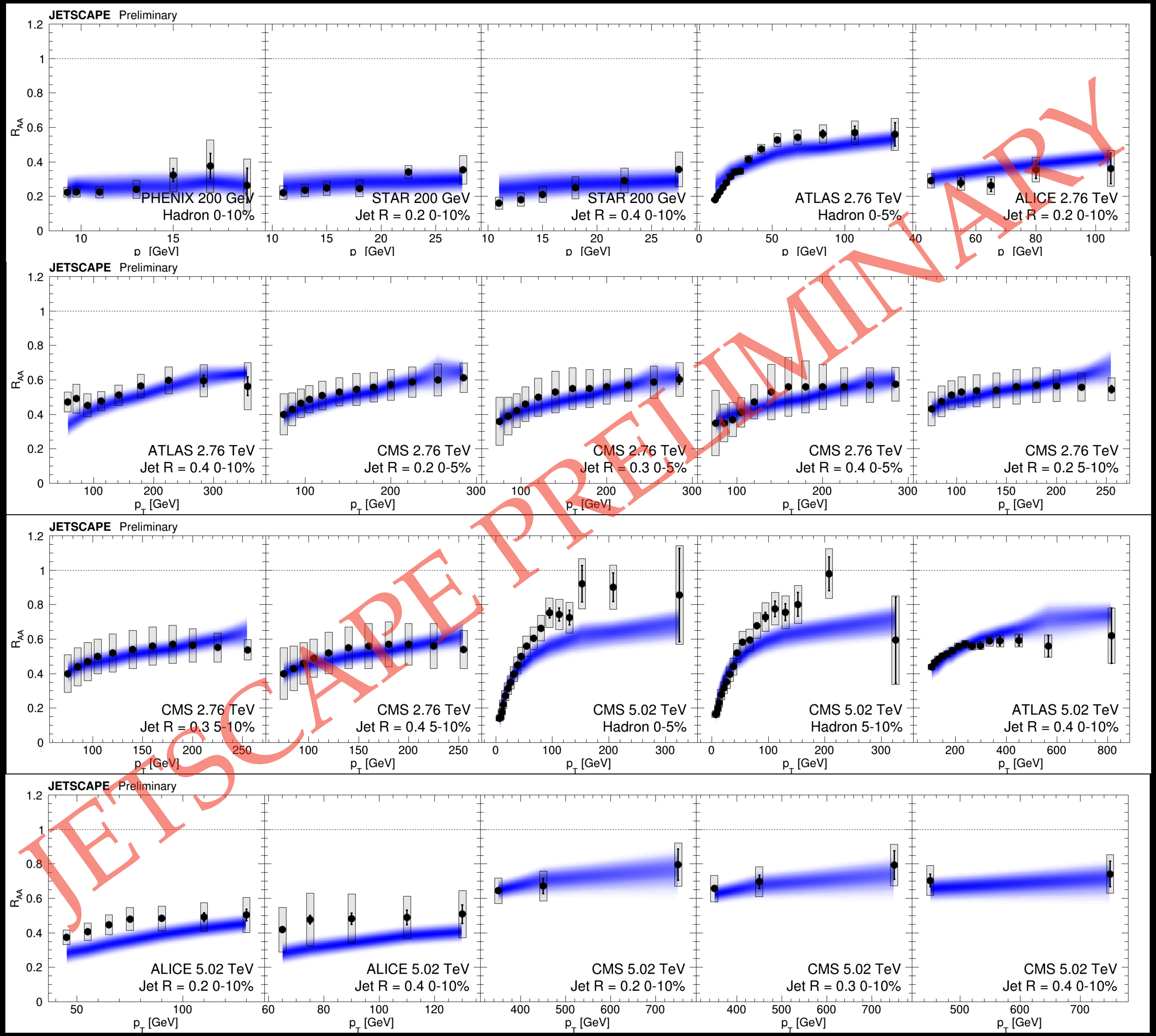
How do you test any change in the theory

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



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

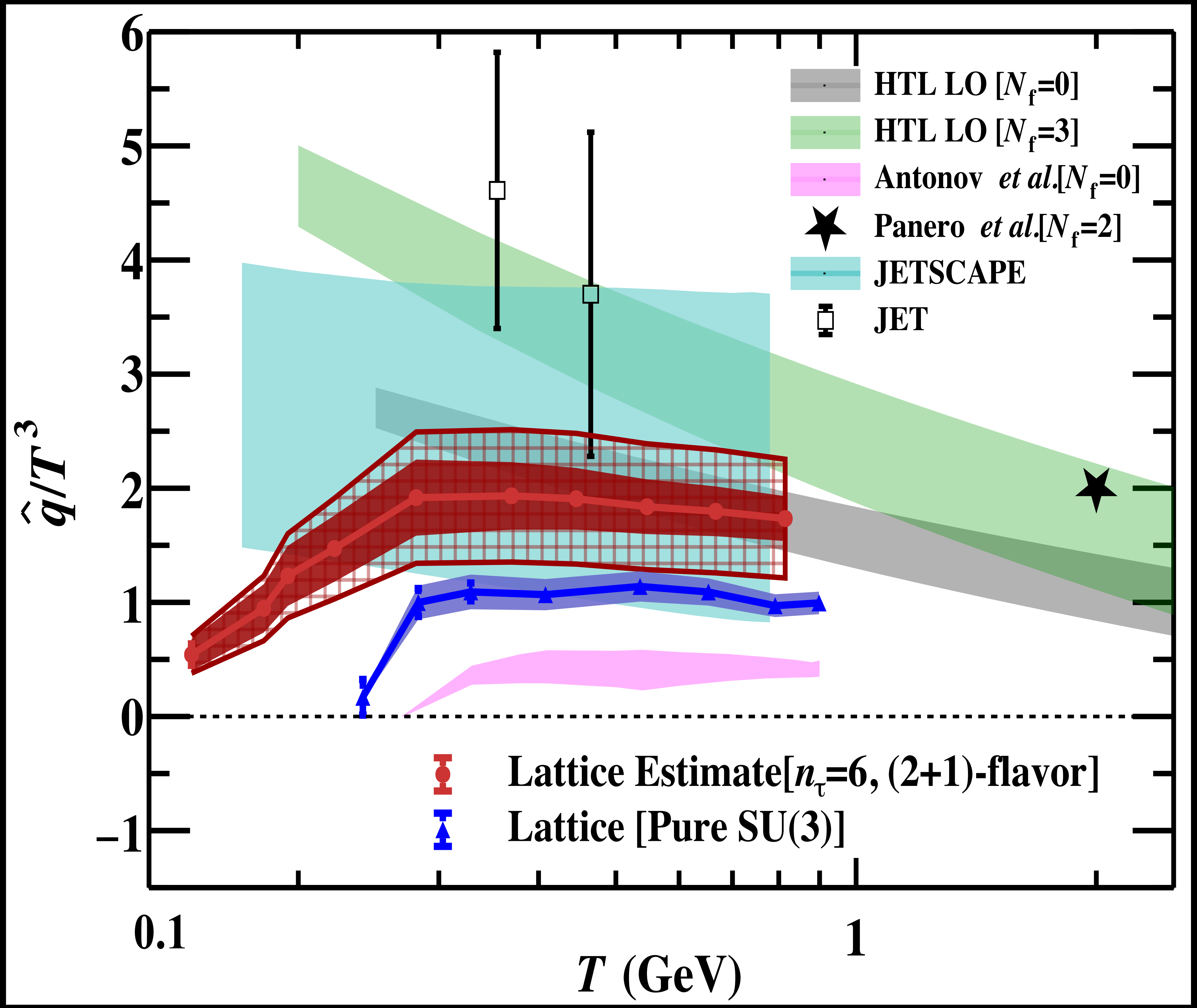




4 parameters used

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.

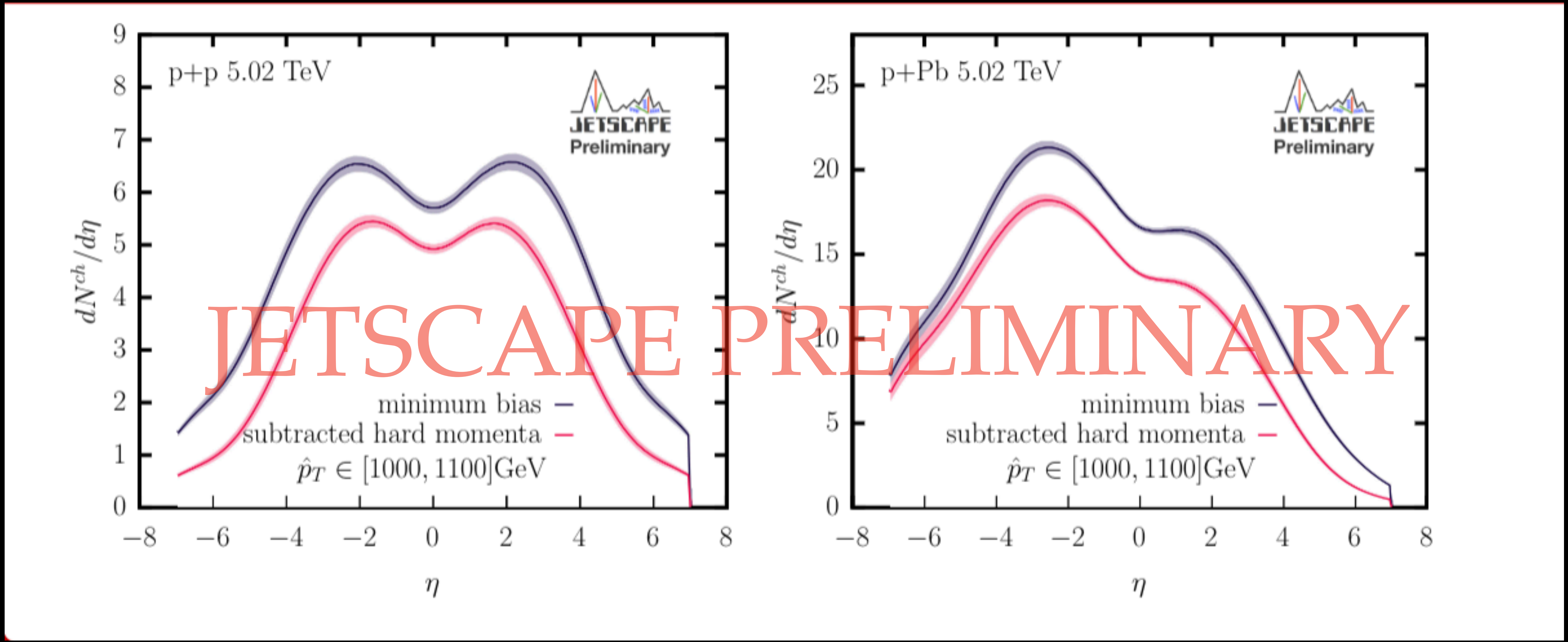


Summary

- 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
- Minor effects still being studied in anisotropy, jet shapes etc.
- Is the medium made of quasi-particles or not? We are getting closer to answering this question.

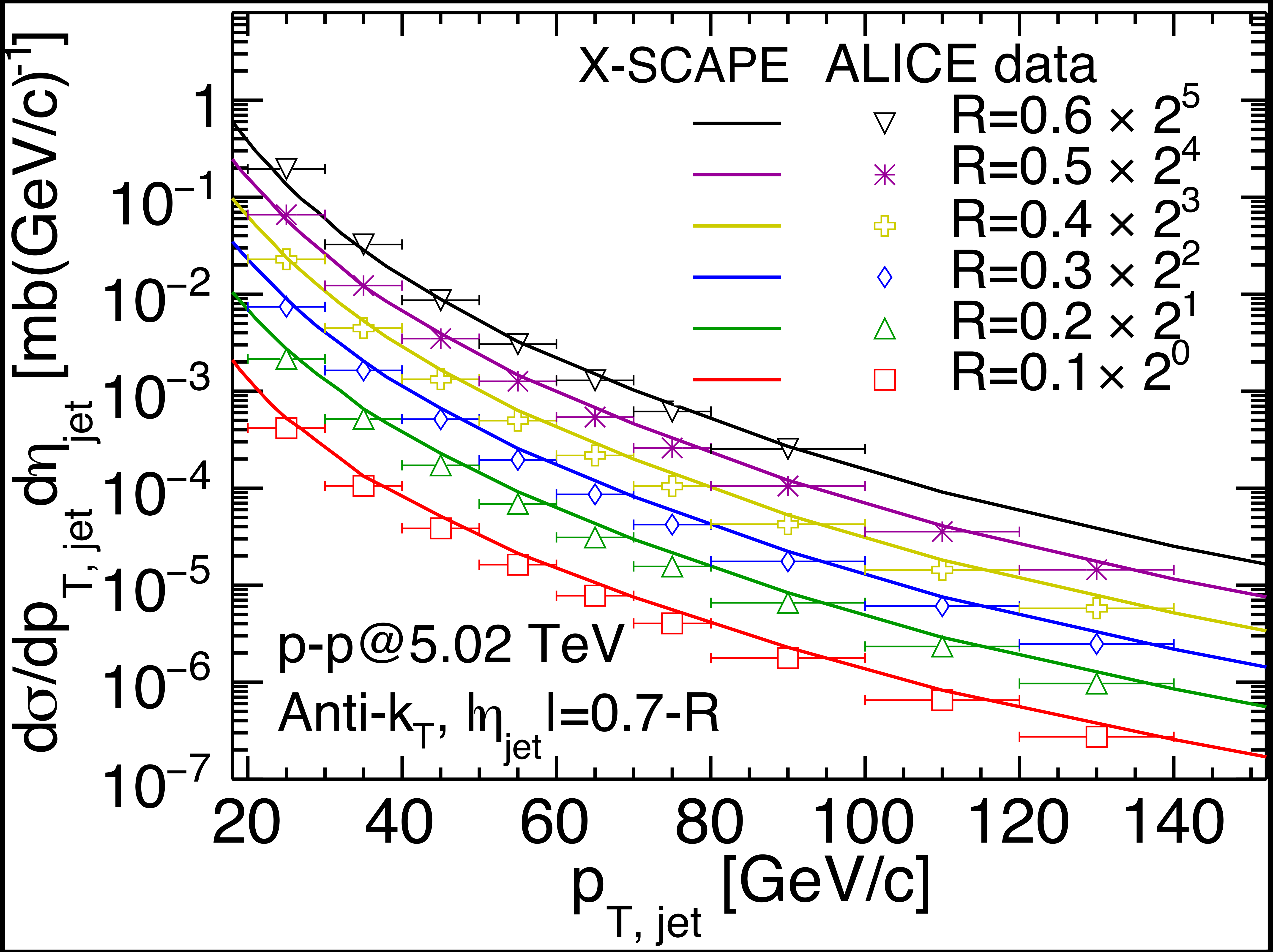
Next Steps

- 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

THANK YOU FOR YOUR ATTENTION