Scale, Energy, Temperature, and the Emerging Precision of Jet Quenching

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in collaboration with
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G.-Y. Qin, C. Shen,

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Outline

Intro, pQCD and scale dependence

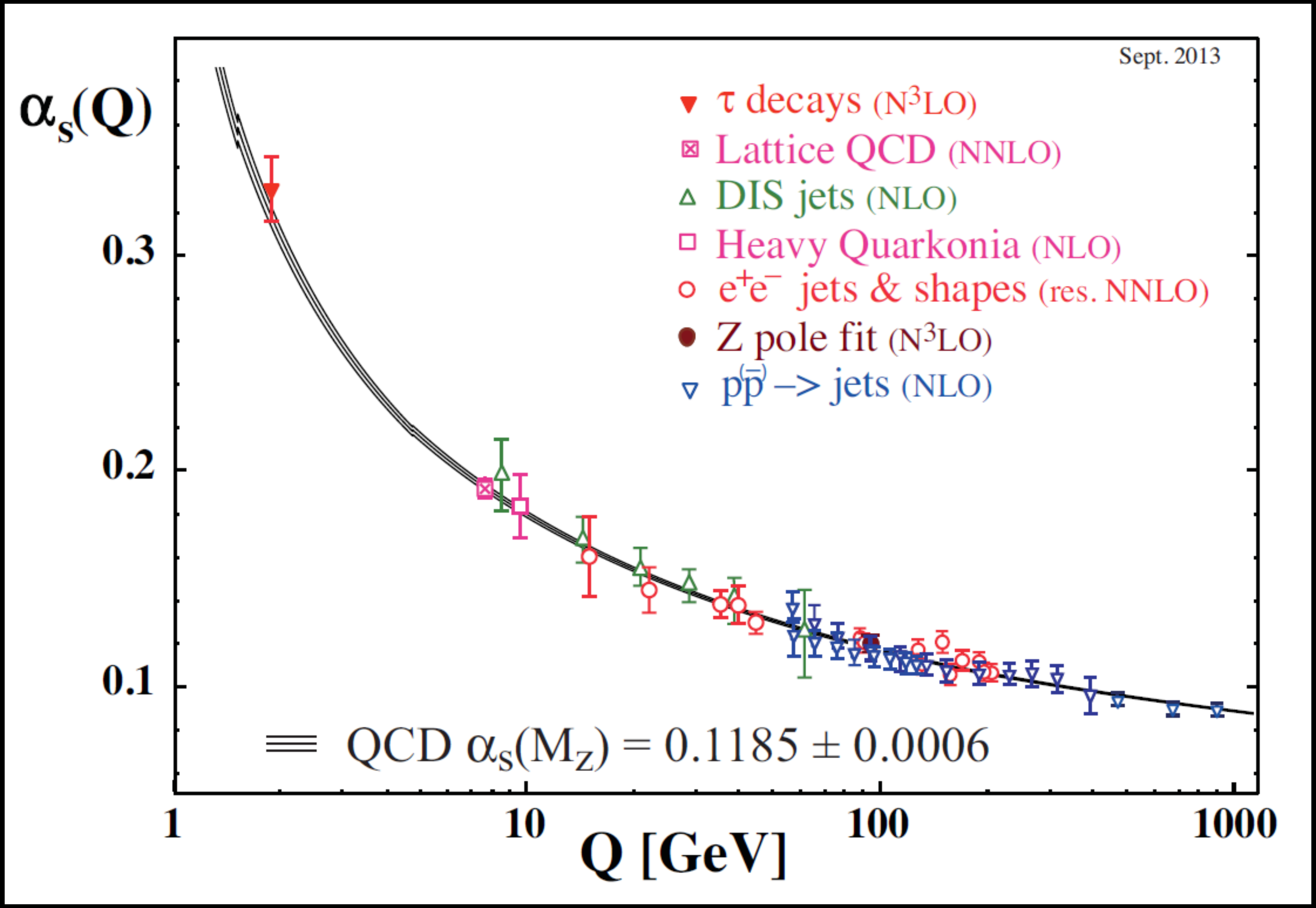
Role of scale in jet evolution,

Role of scale in jet observables,

The scale dependence of transport coefficients,

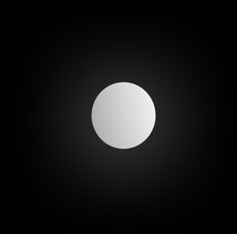
What needs to be done…

QCD is all about scale!



Well known from DIS

What the electron sees, depends on E, Q^2



Increasing energy Q^2 = getting closer to proton

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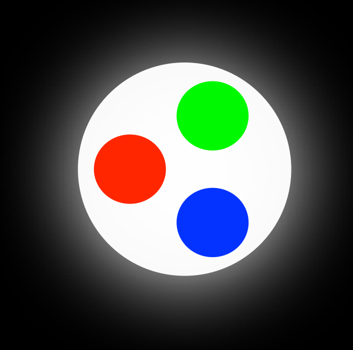

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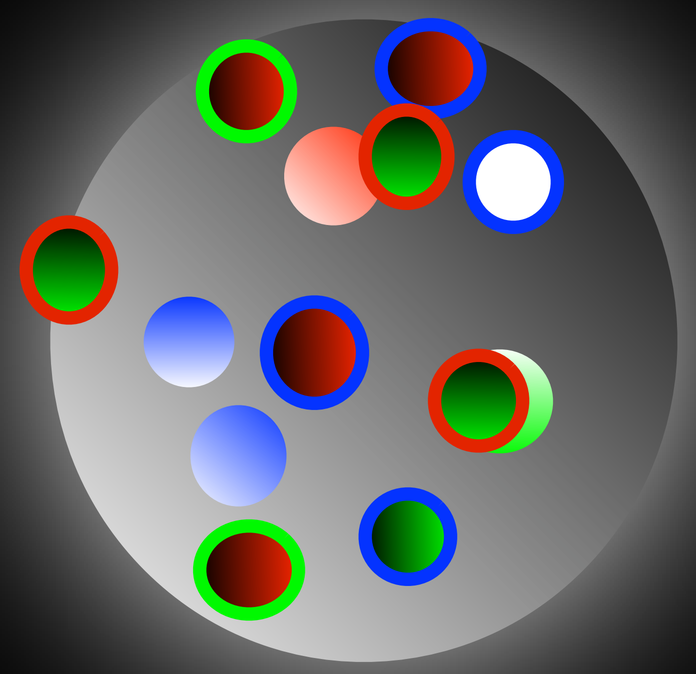

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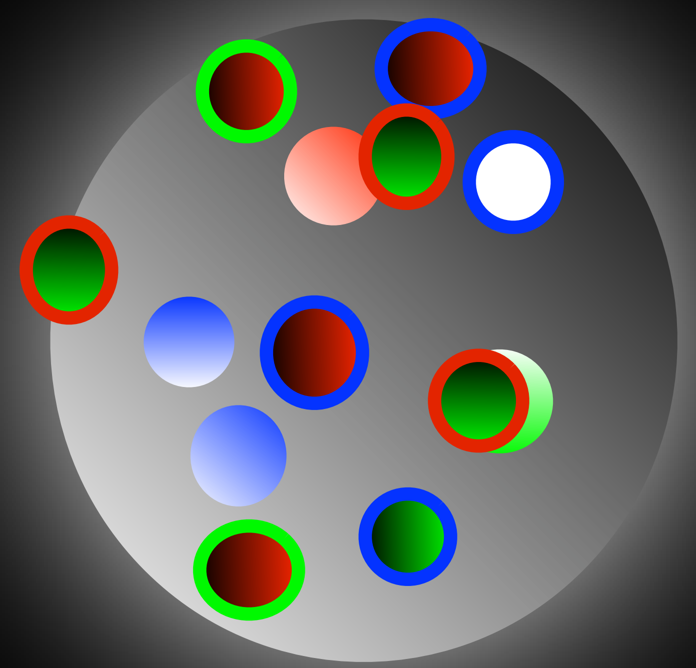

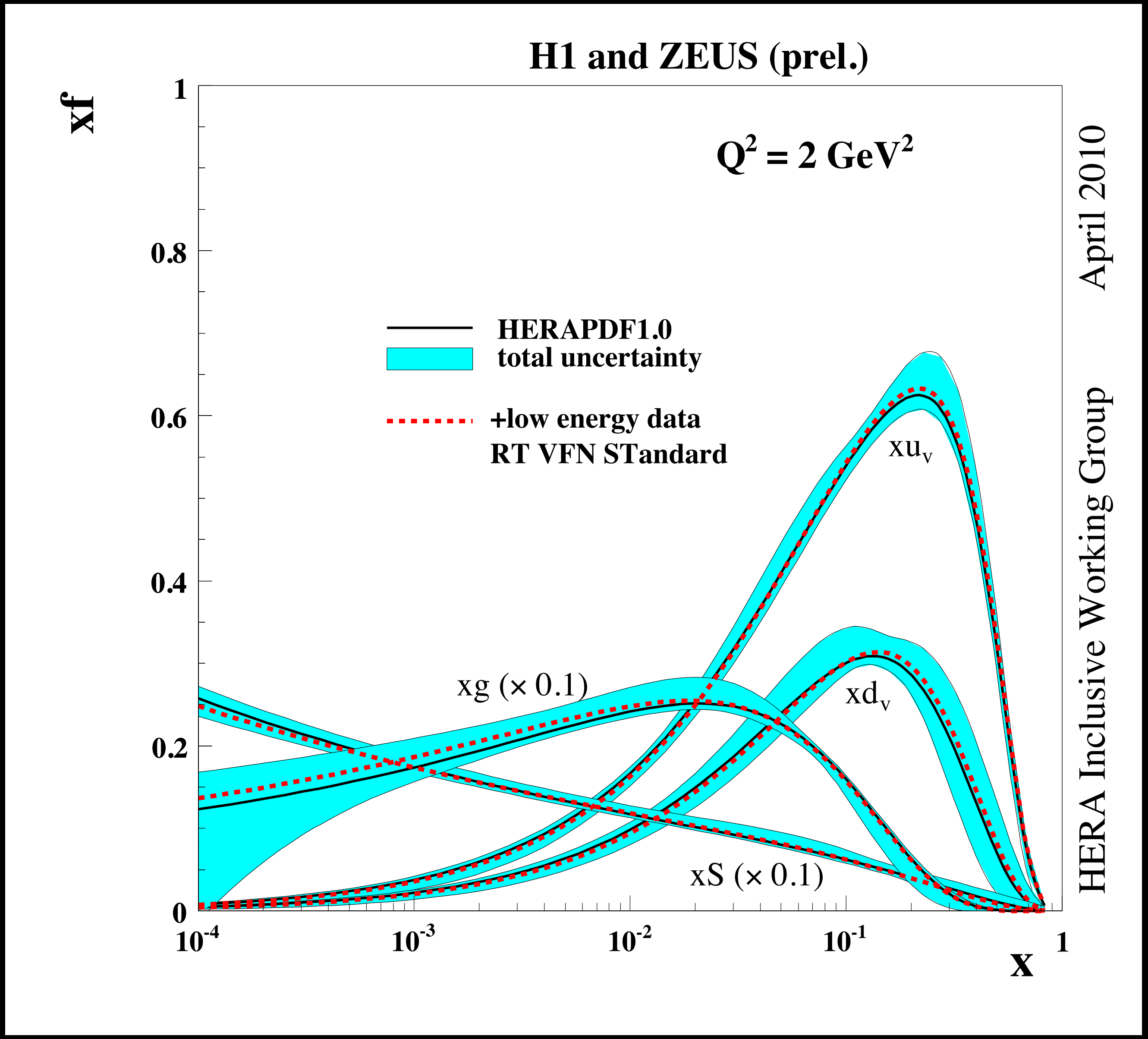

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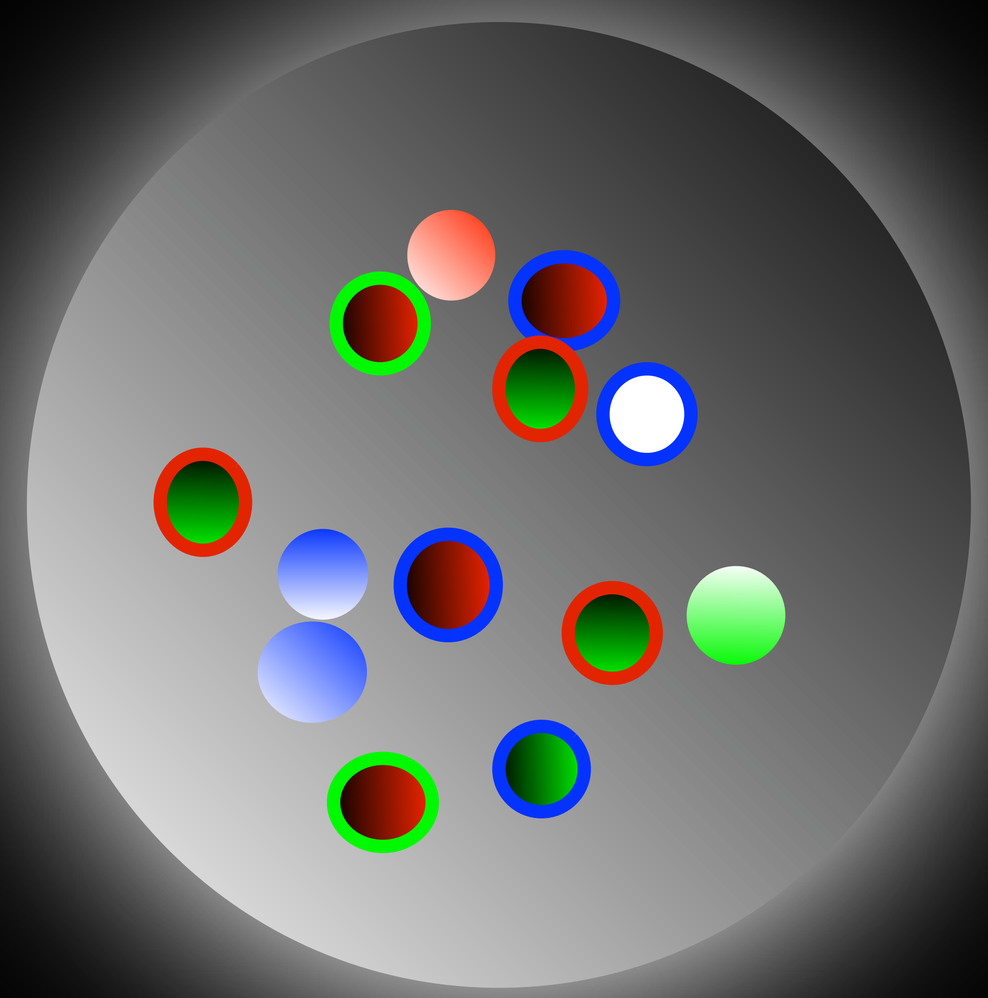

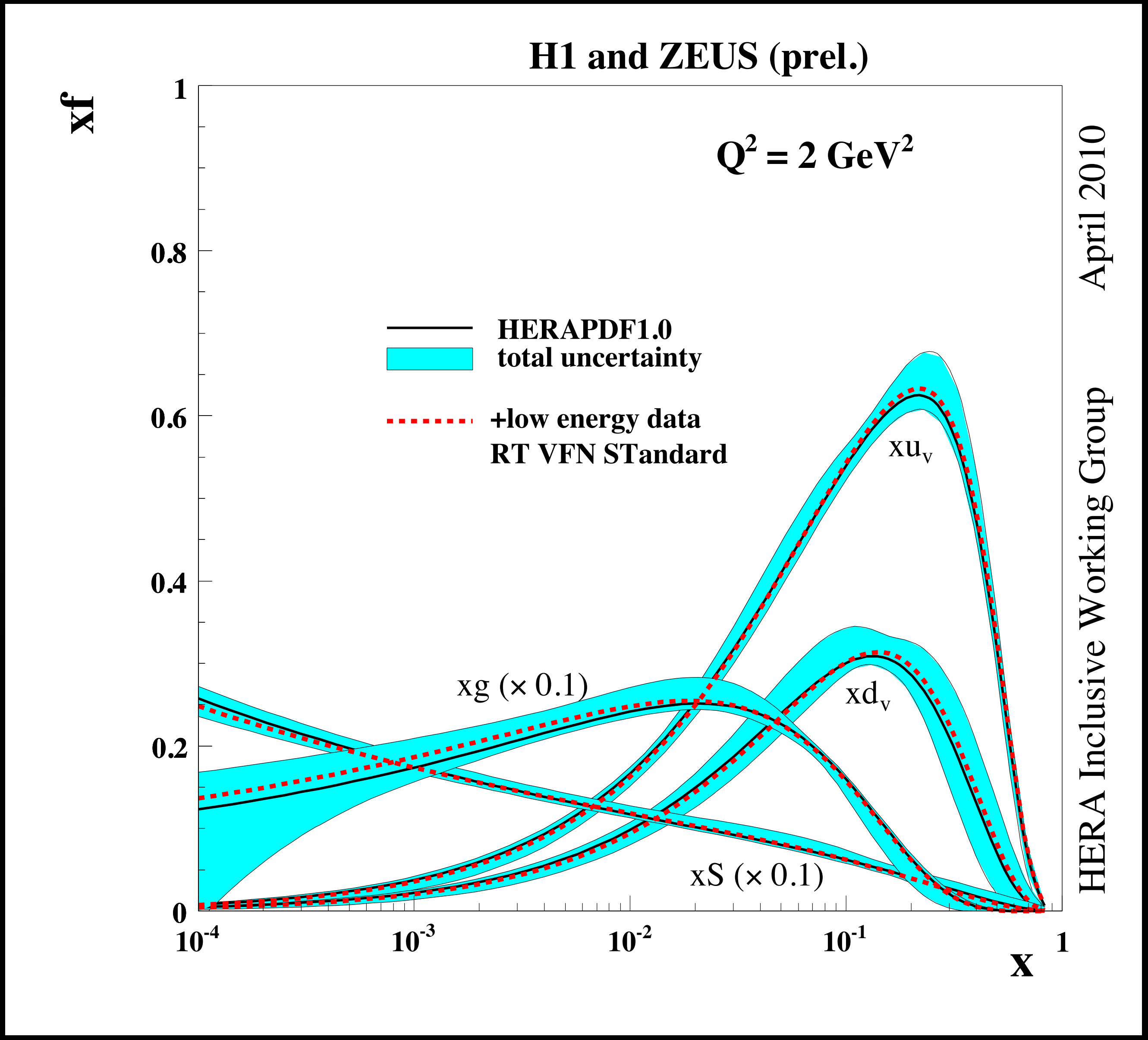

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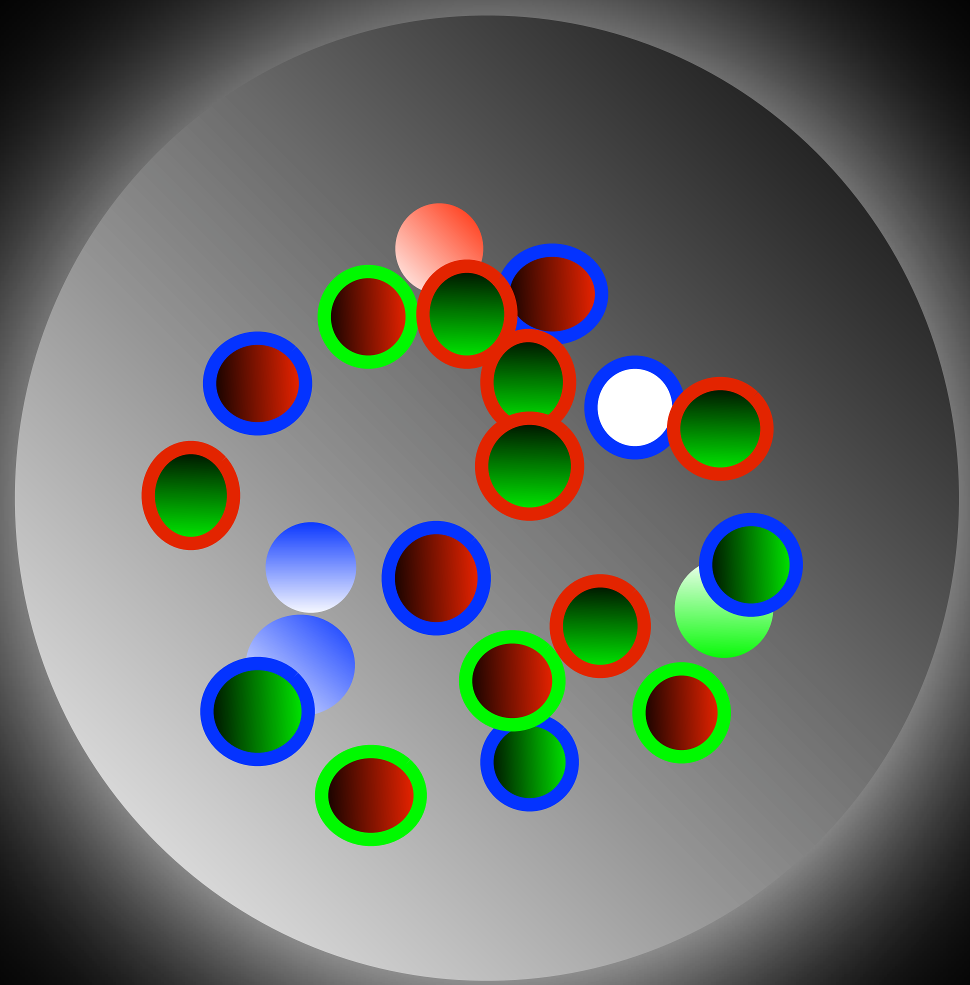

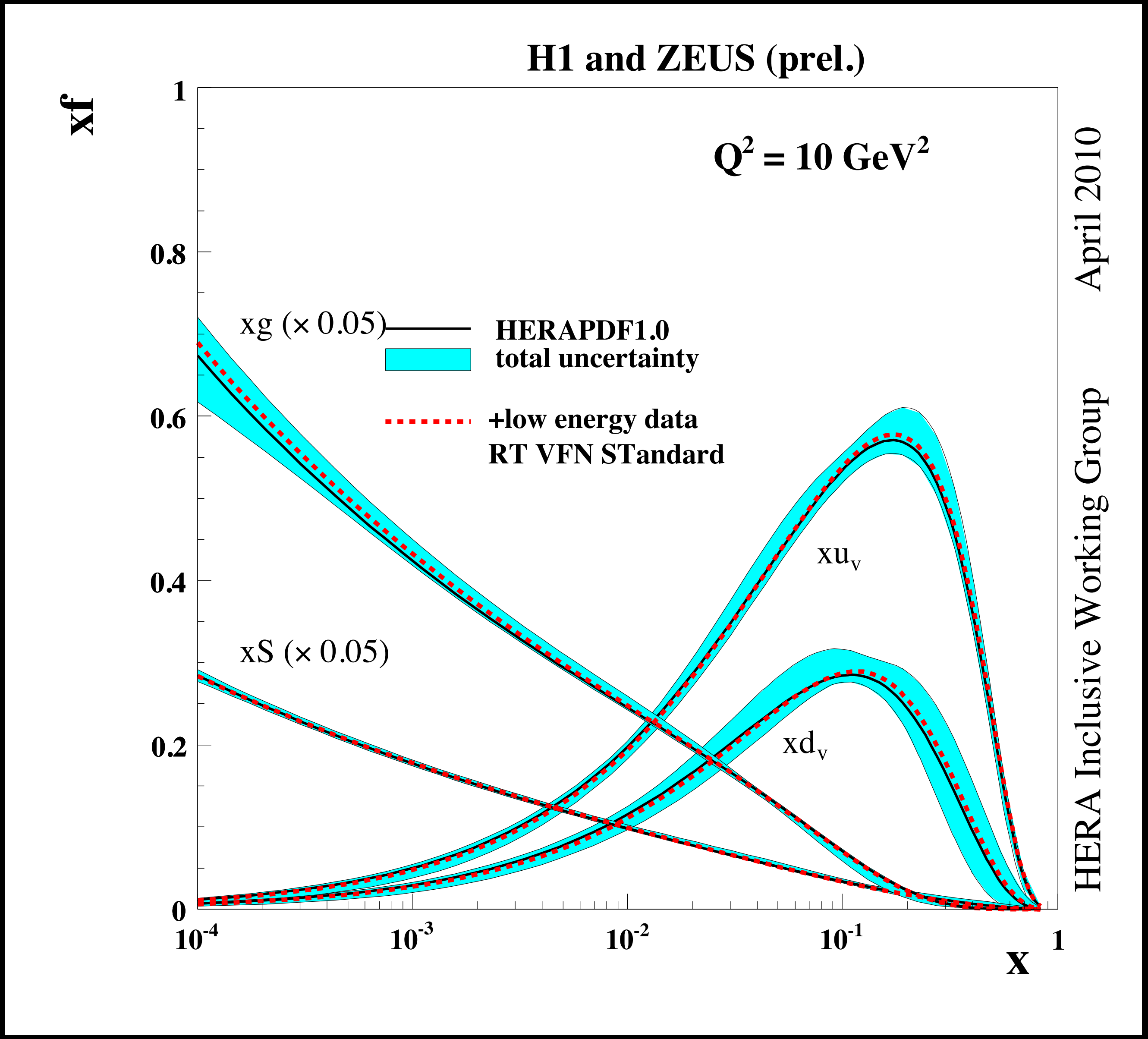

Increasing energy Q^2 = getting closer to proton

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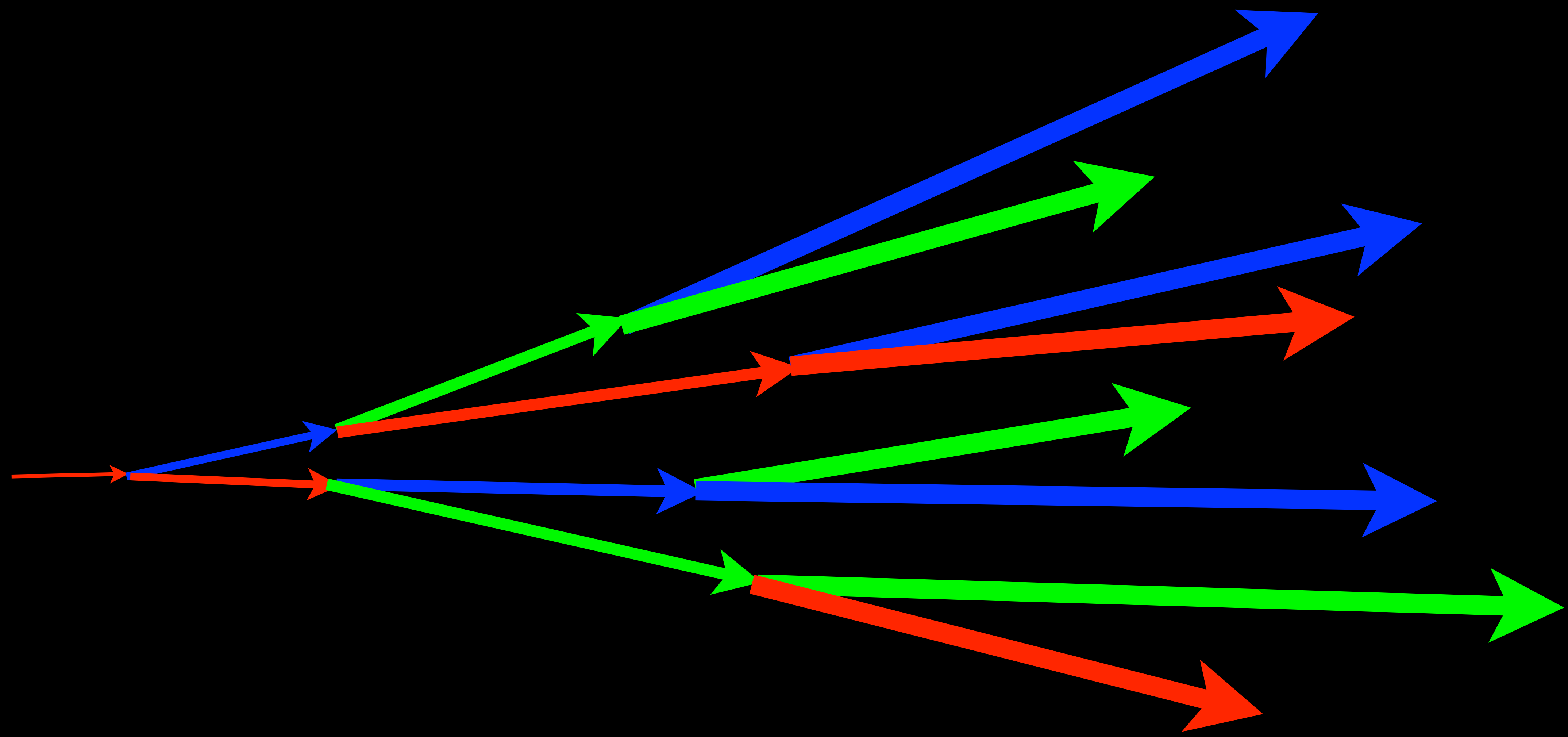

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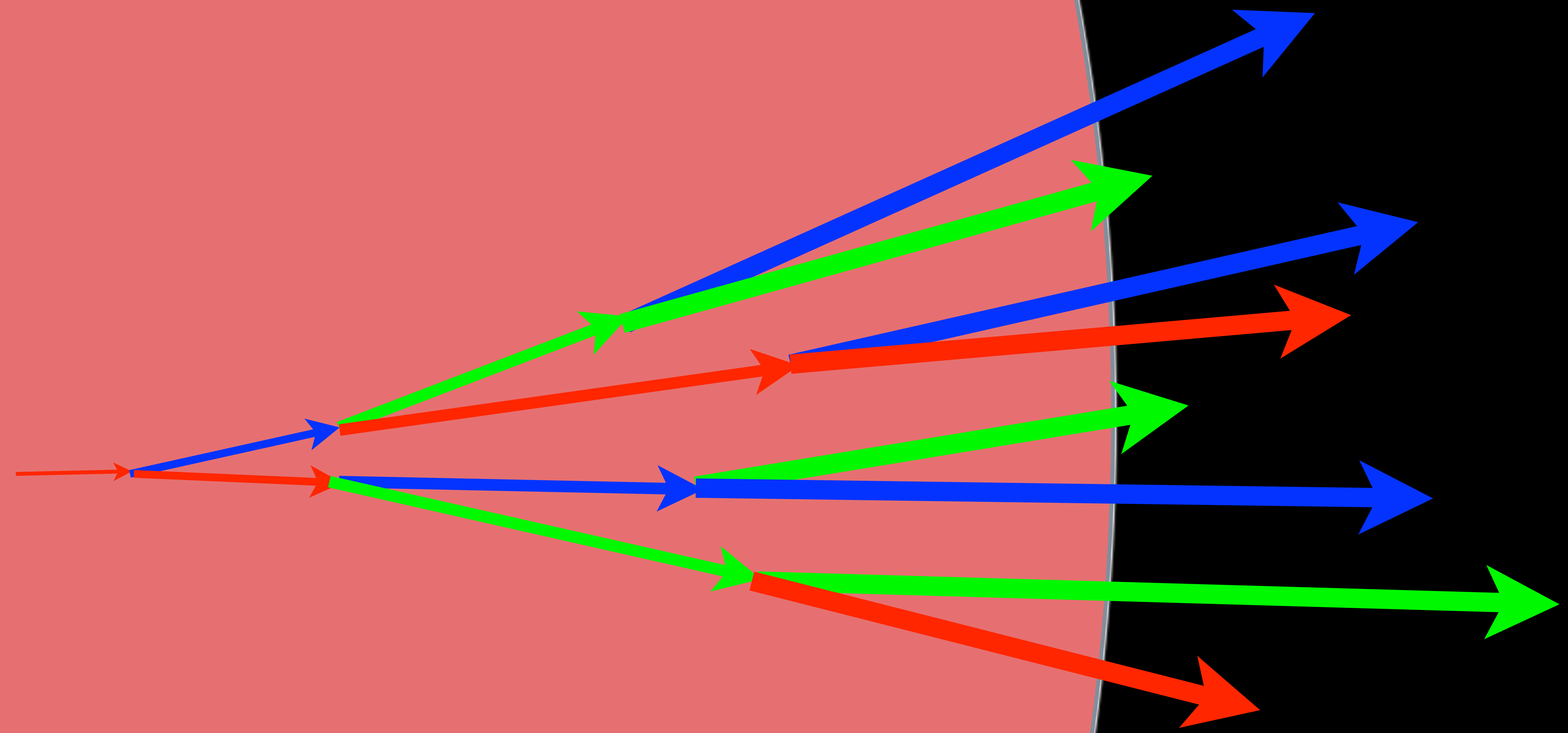

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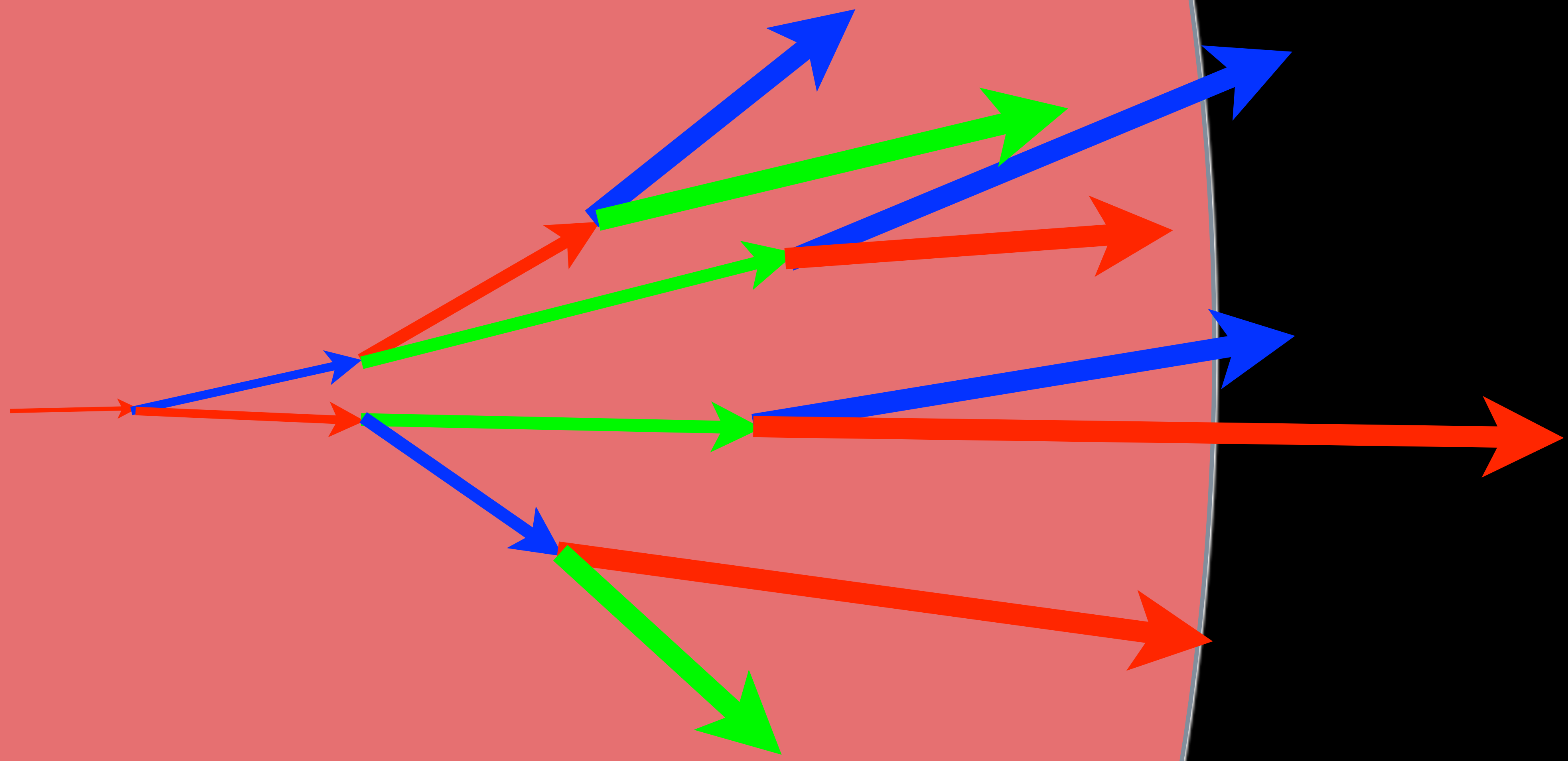

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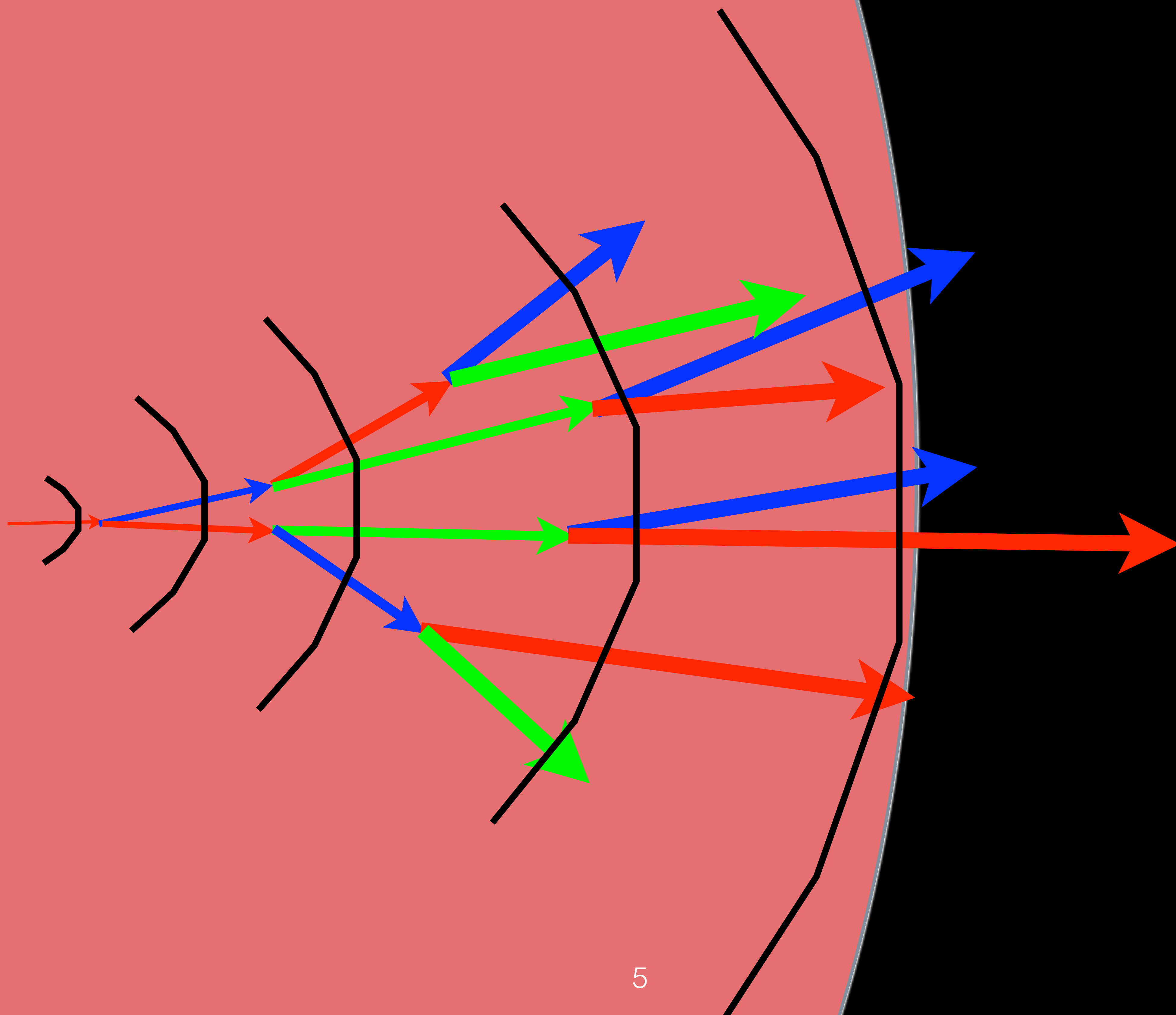

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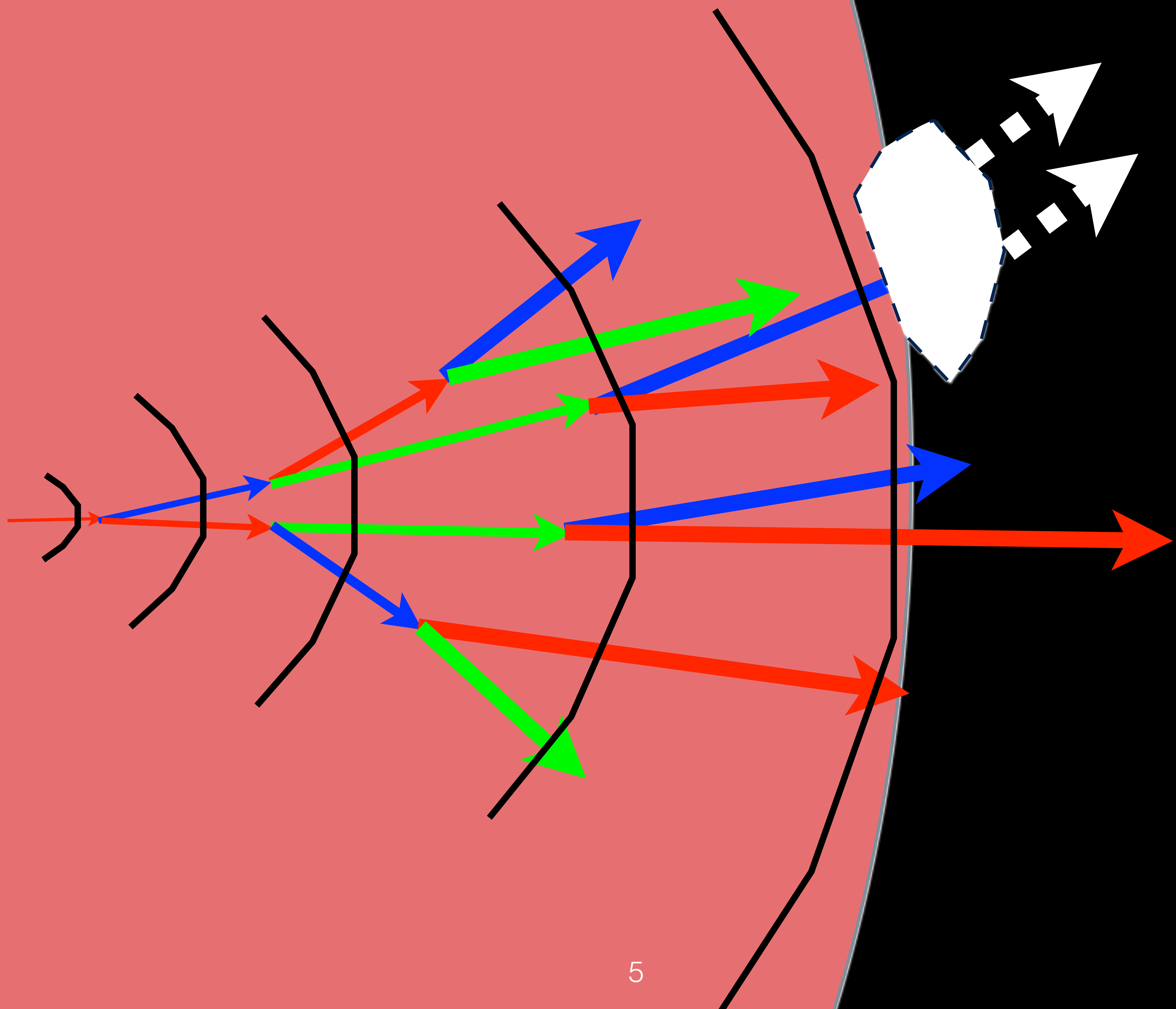

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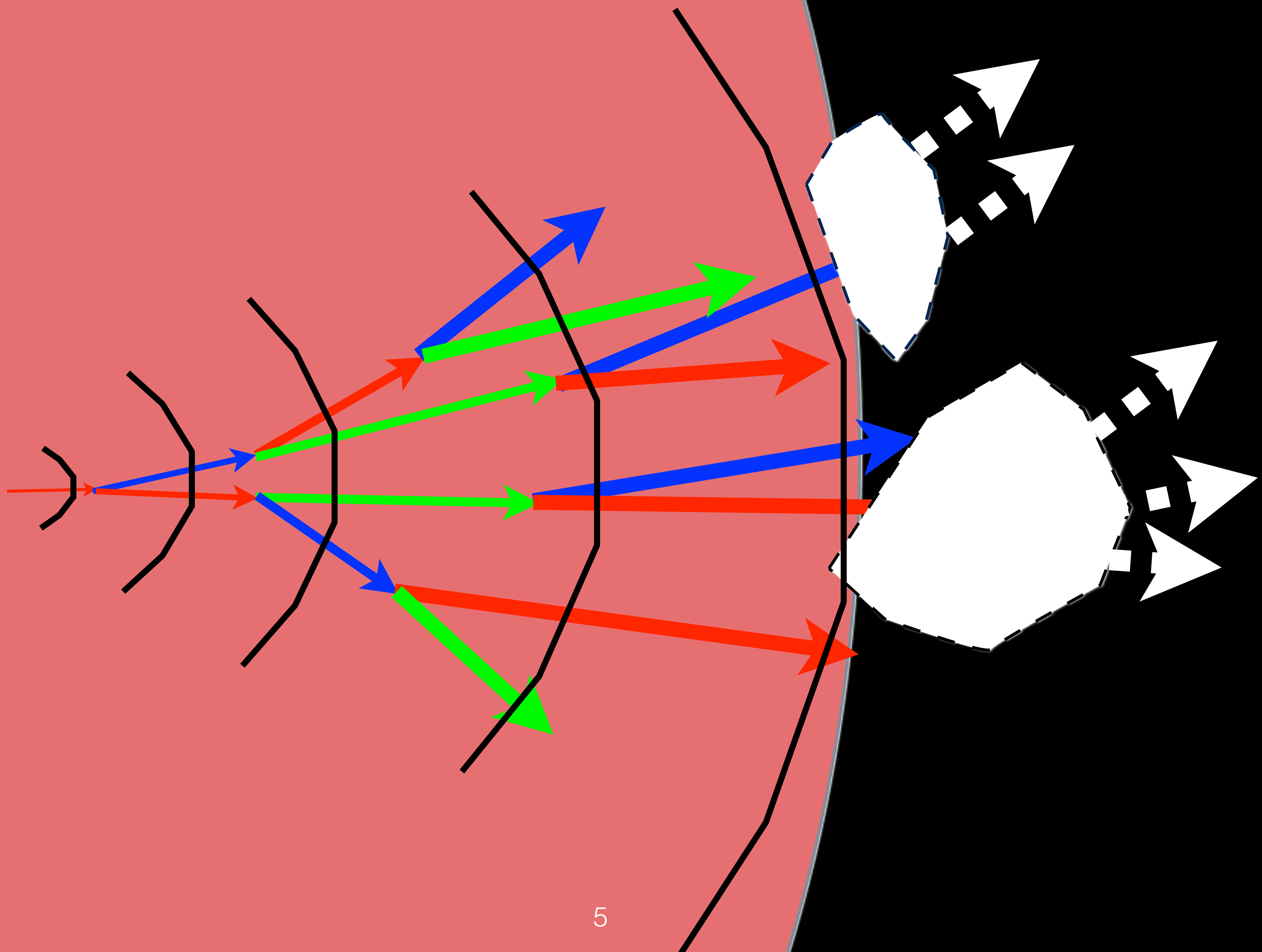

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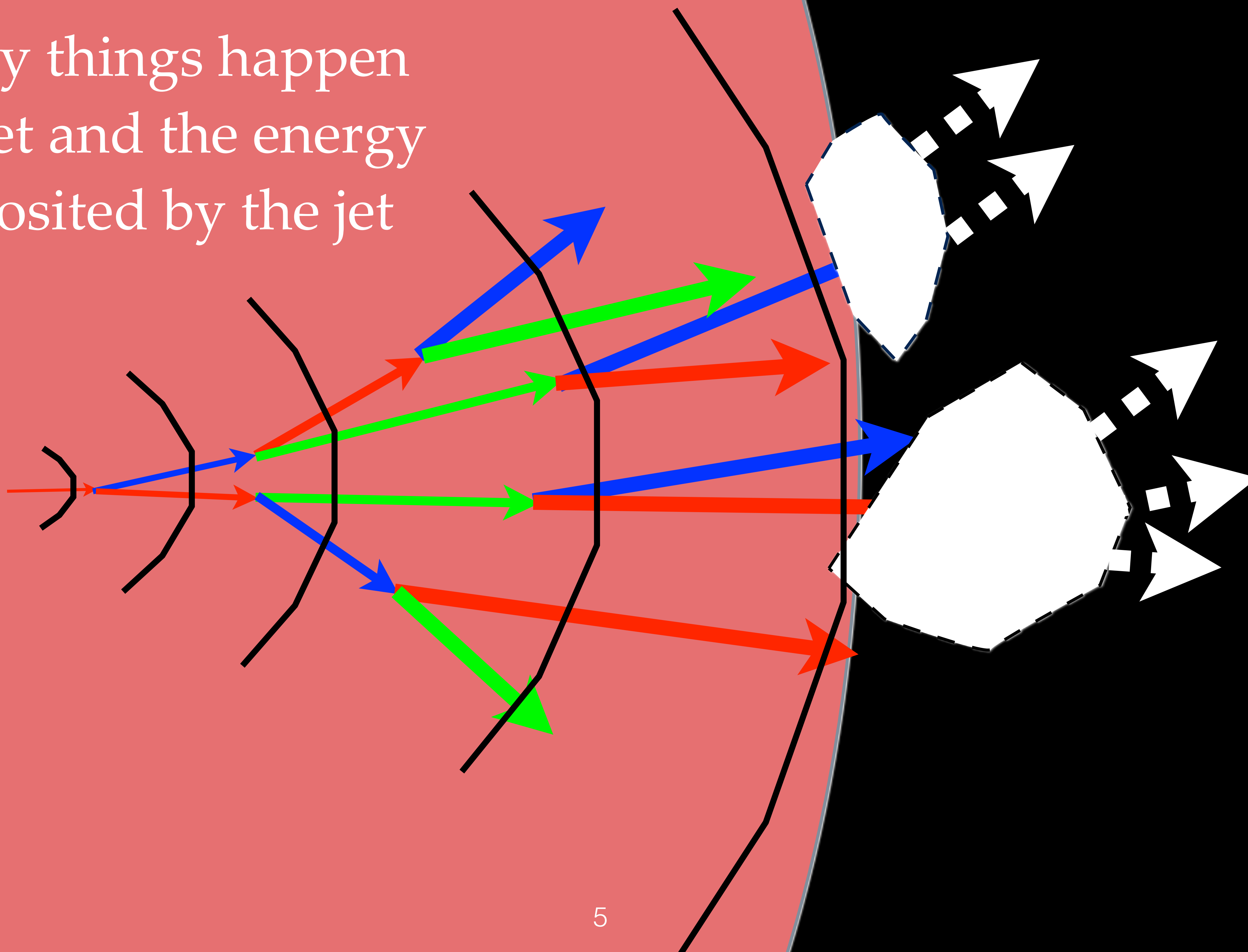
Many things happen to a jet and the energy deposited by the jet



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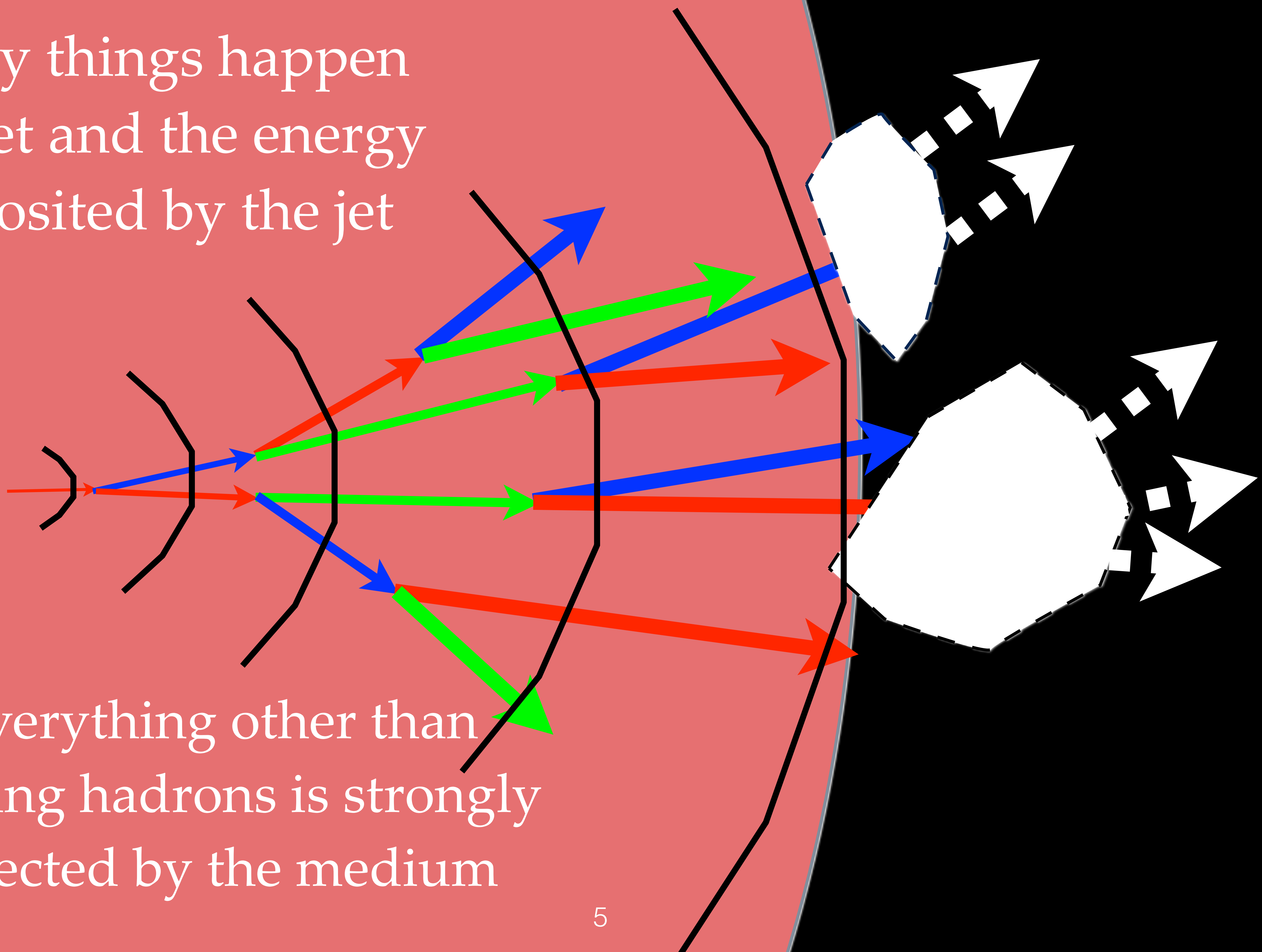
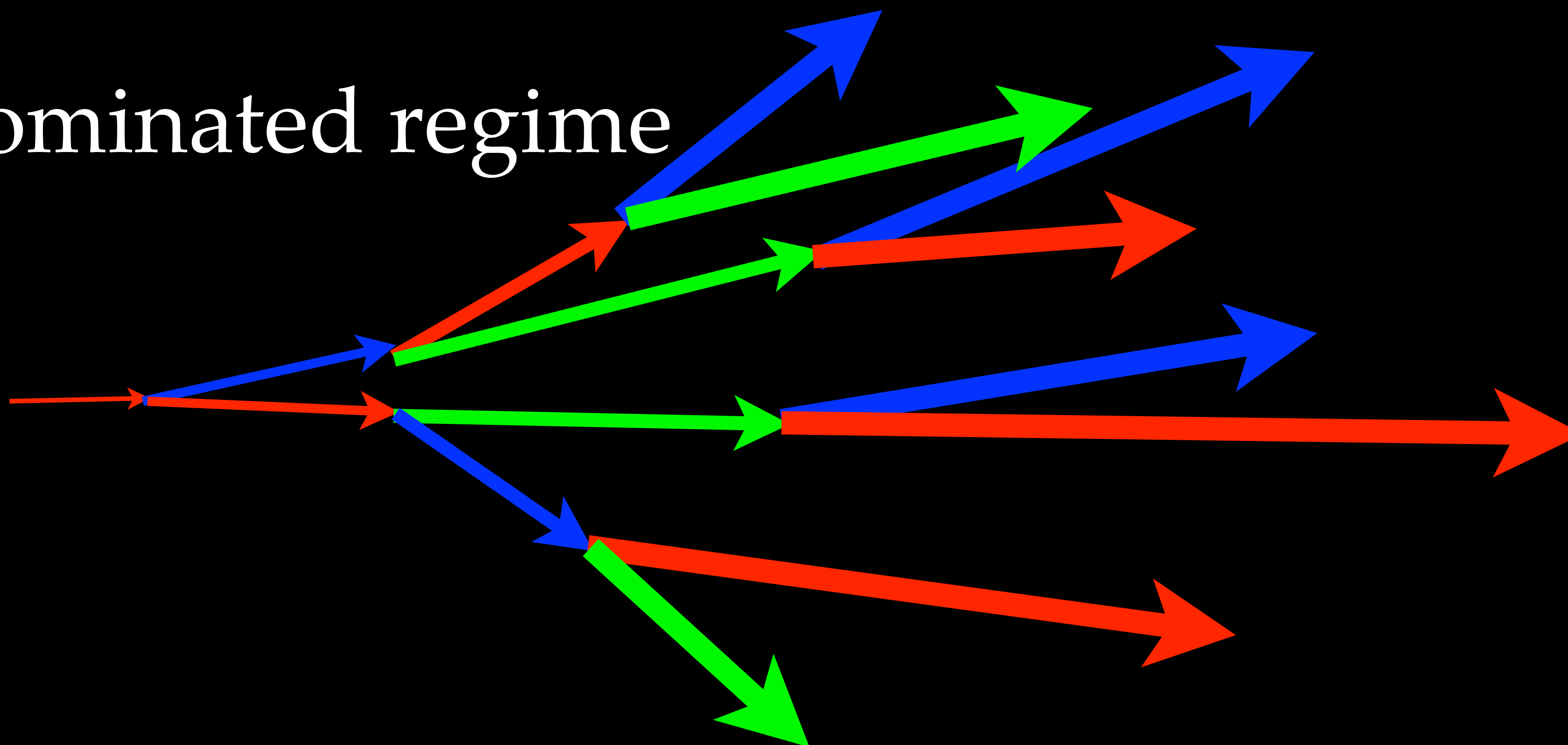


Everything other than leading hadrons is strongly affected by the medium

High energy and high virtuality part of shower

- Radiation dominated regime



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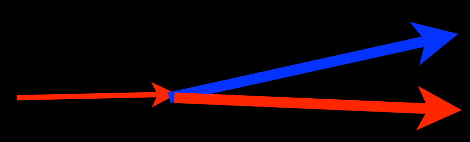

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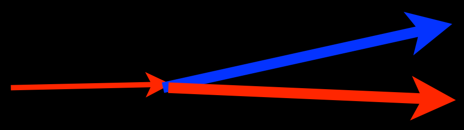

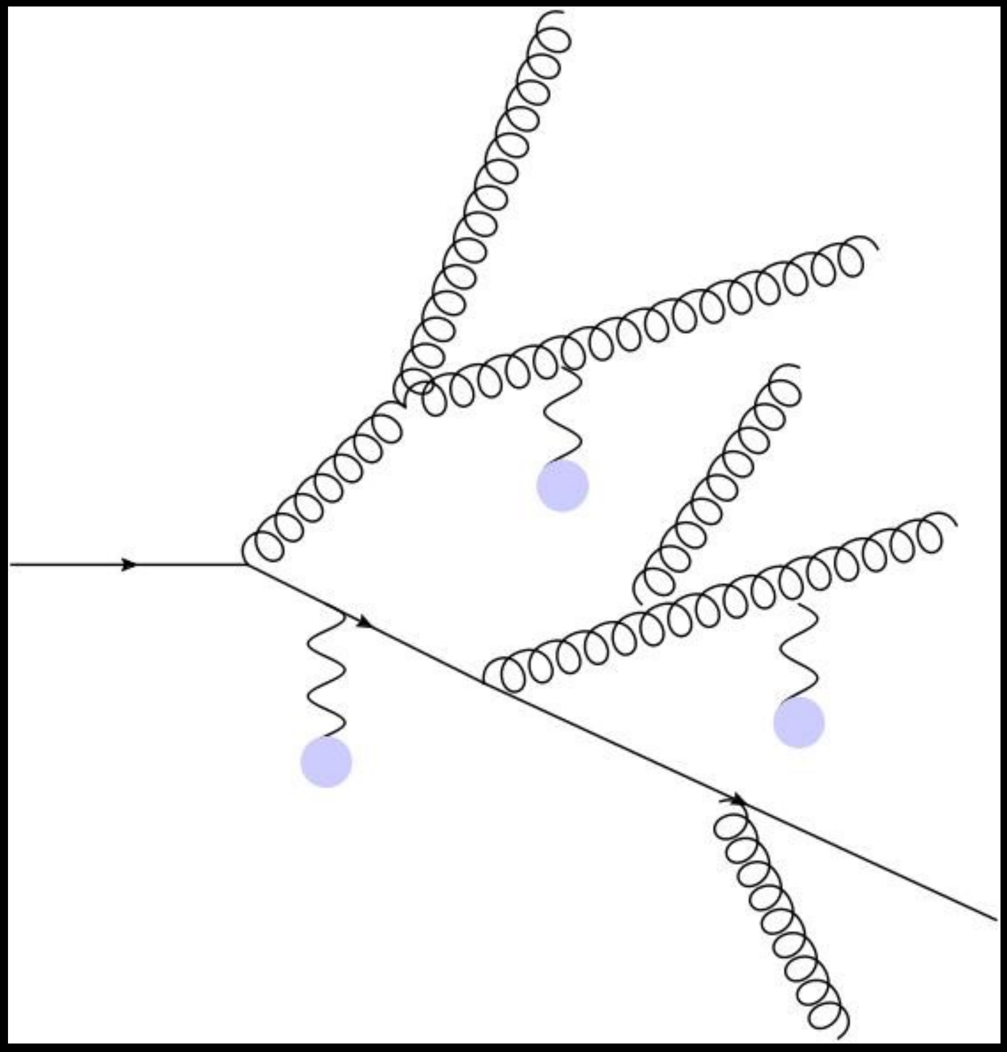

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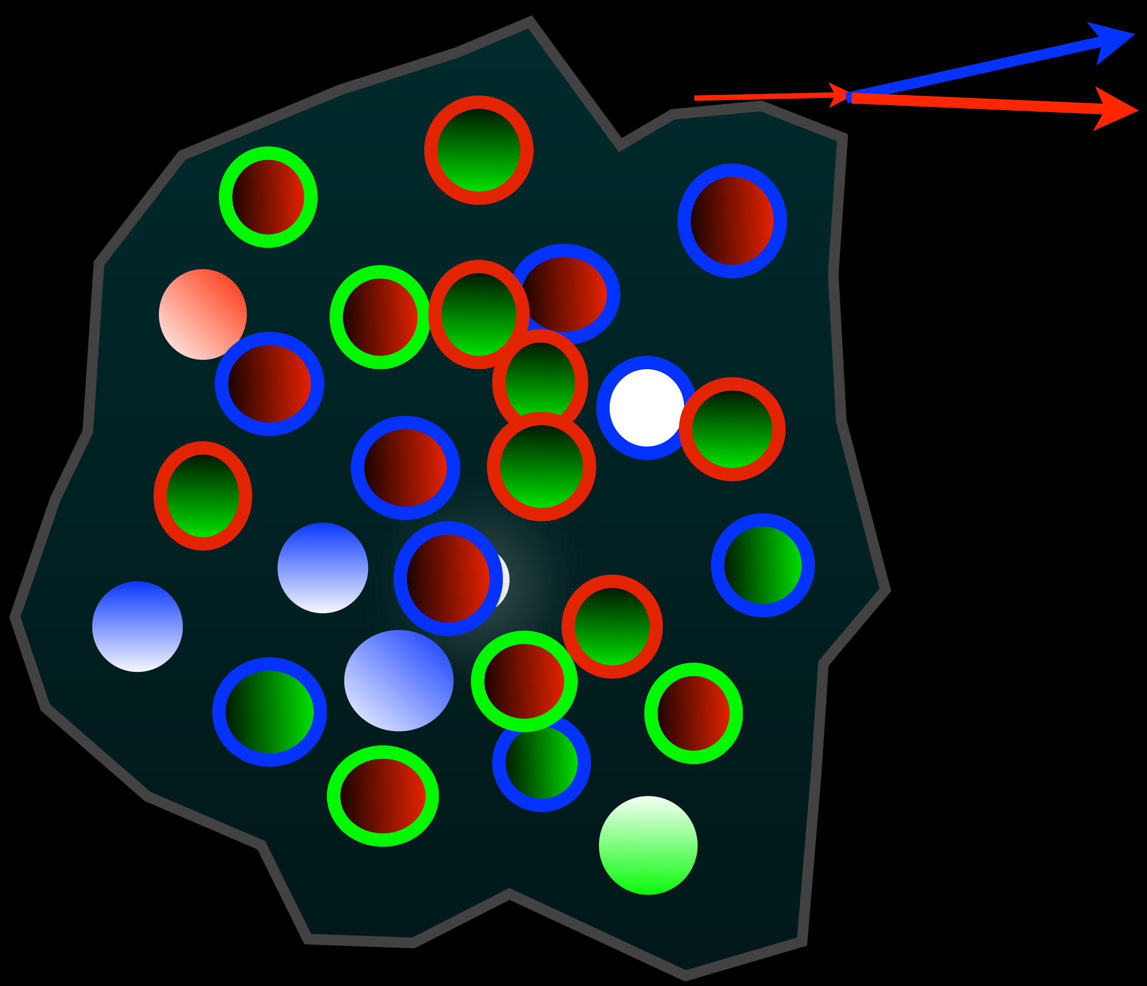

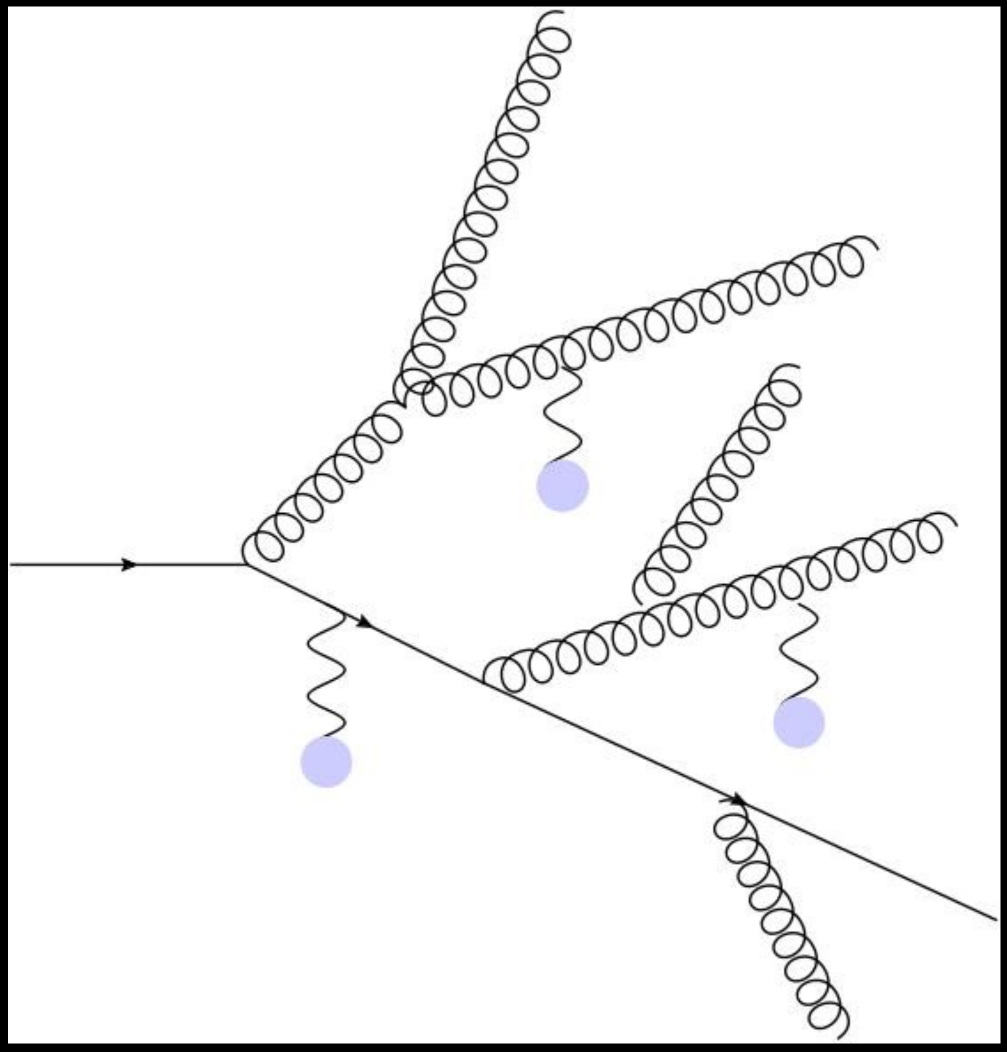

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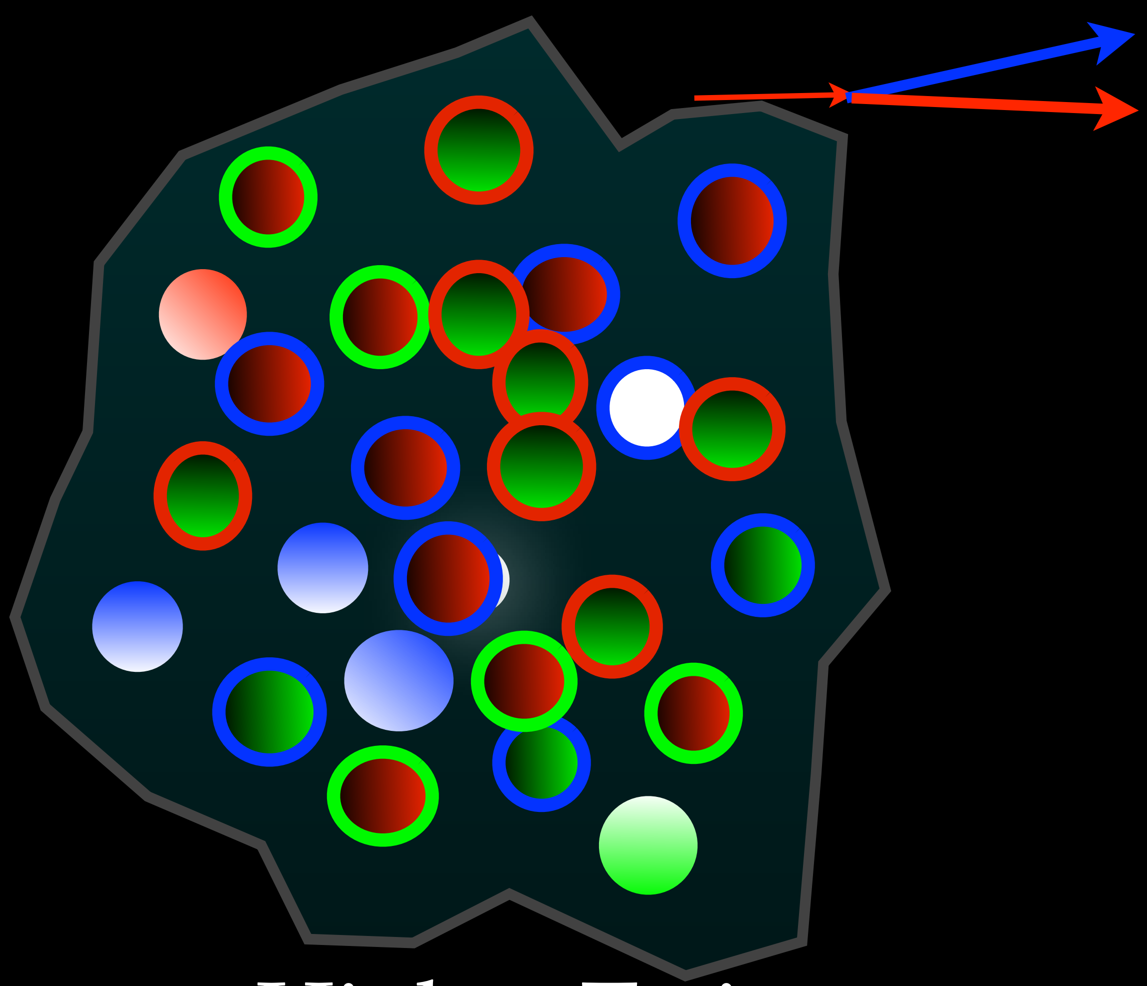
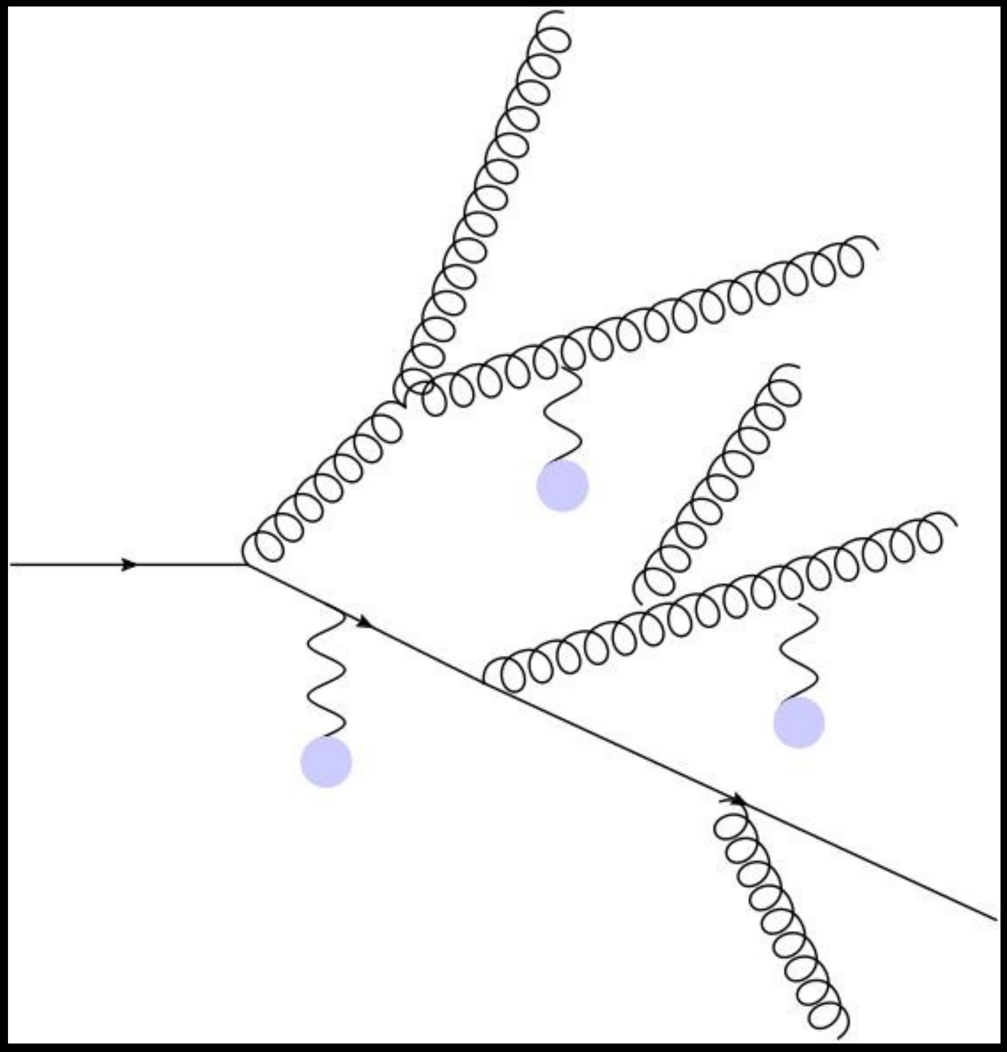




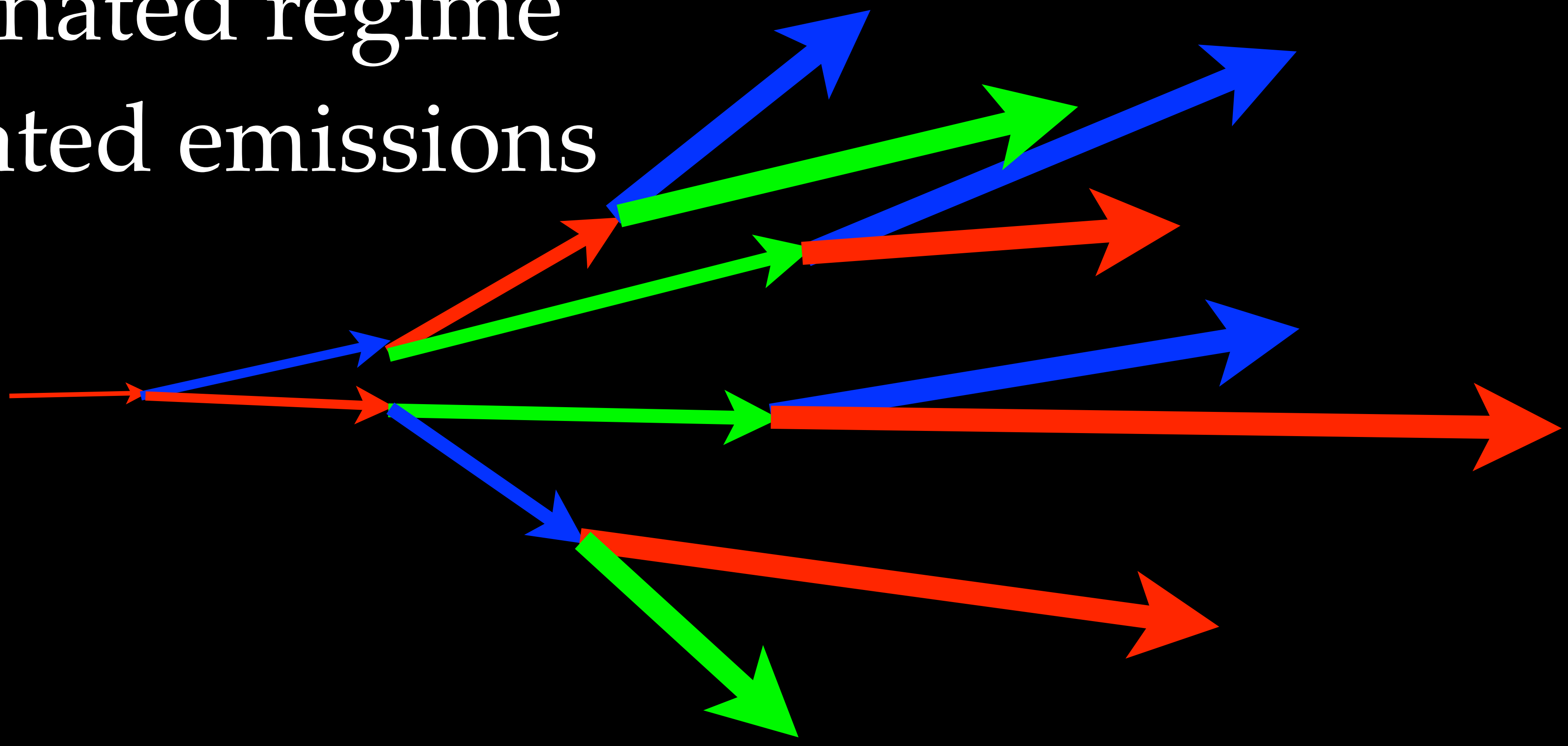
Theory: Higher Twist

MC: MATTER, LBNL-CCNU*, YaJEM

Low virtuality, high energy part

Scattering dominated regime

Few, time separated emissions



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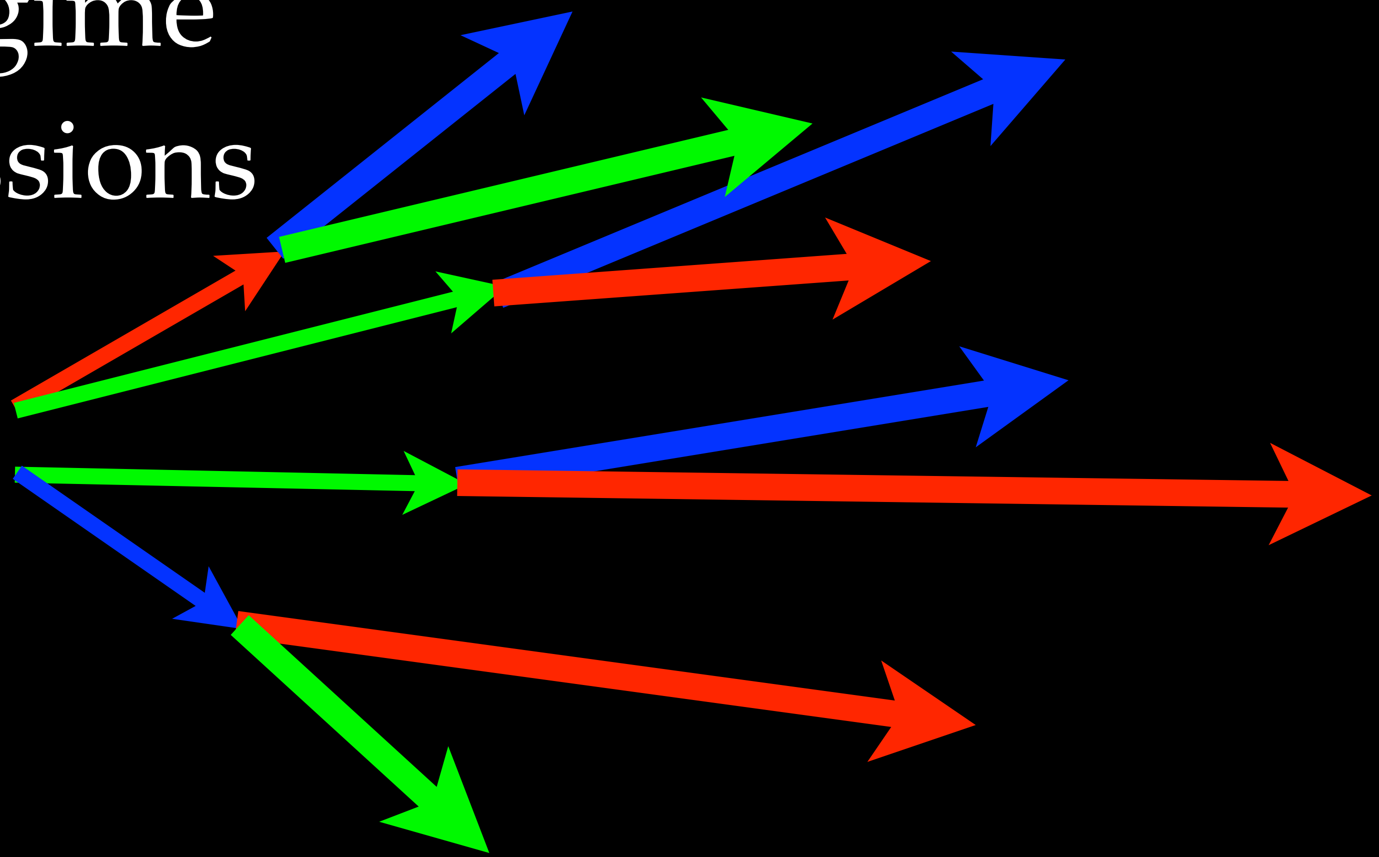

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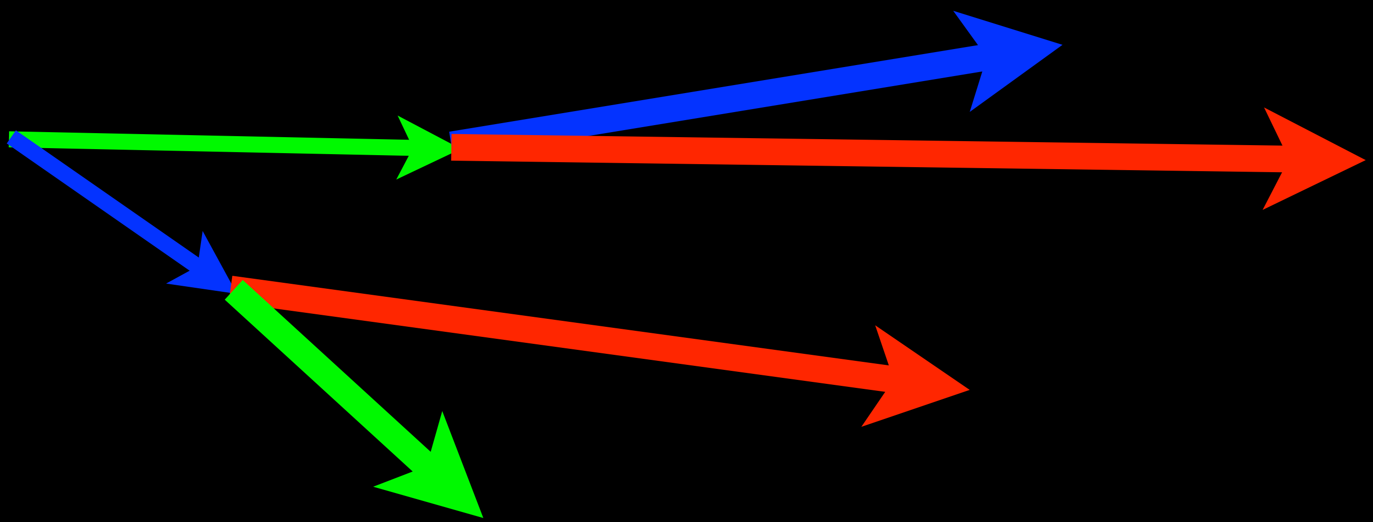

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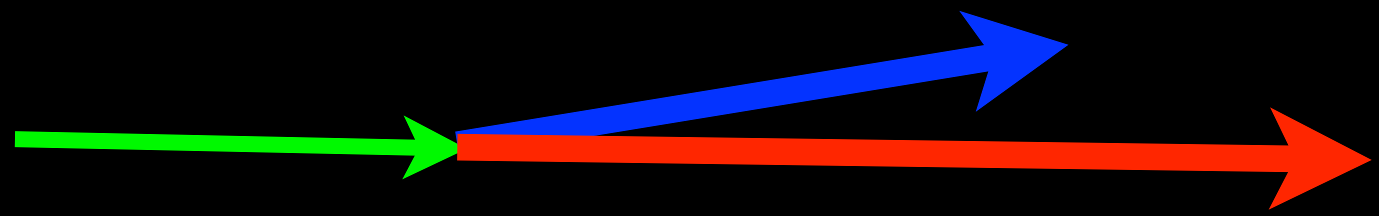

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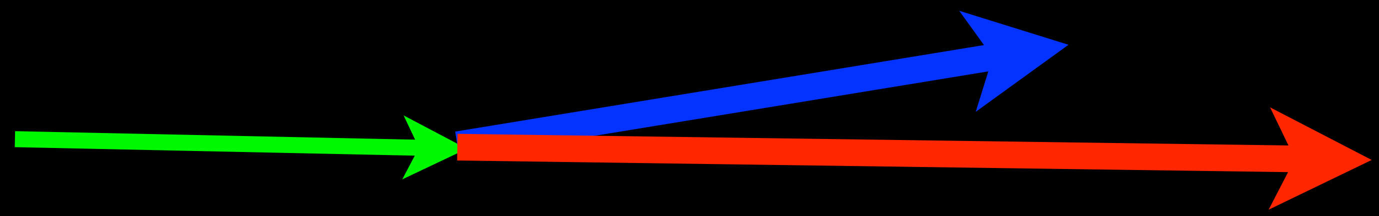

Theory: BDMPS, AMY
MC: MARTINI*, JEWEL*

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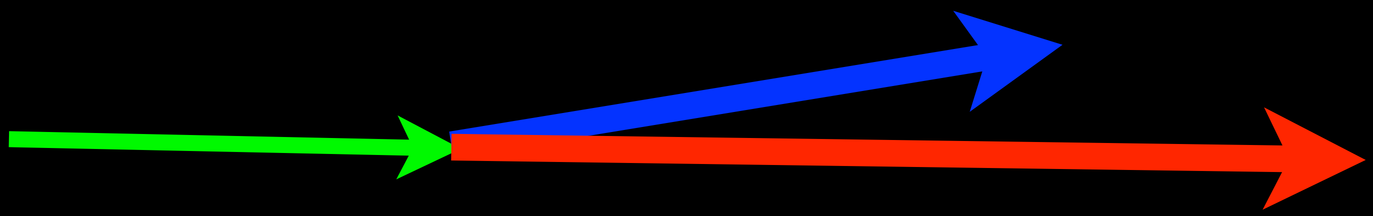
τ: *lifetime of a parton*



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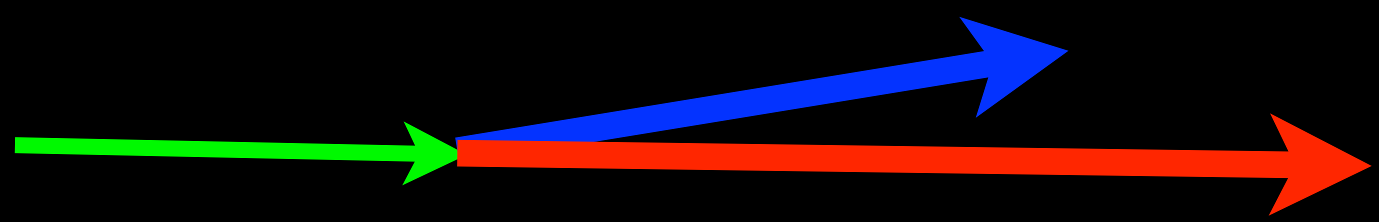

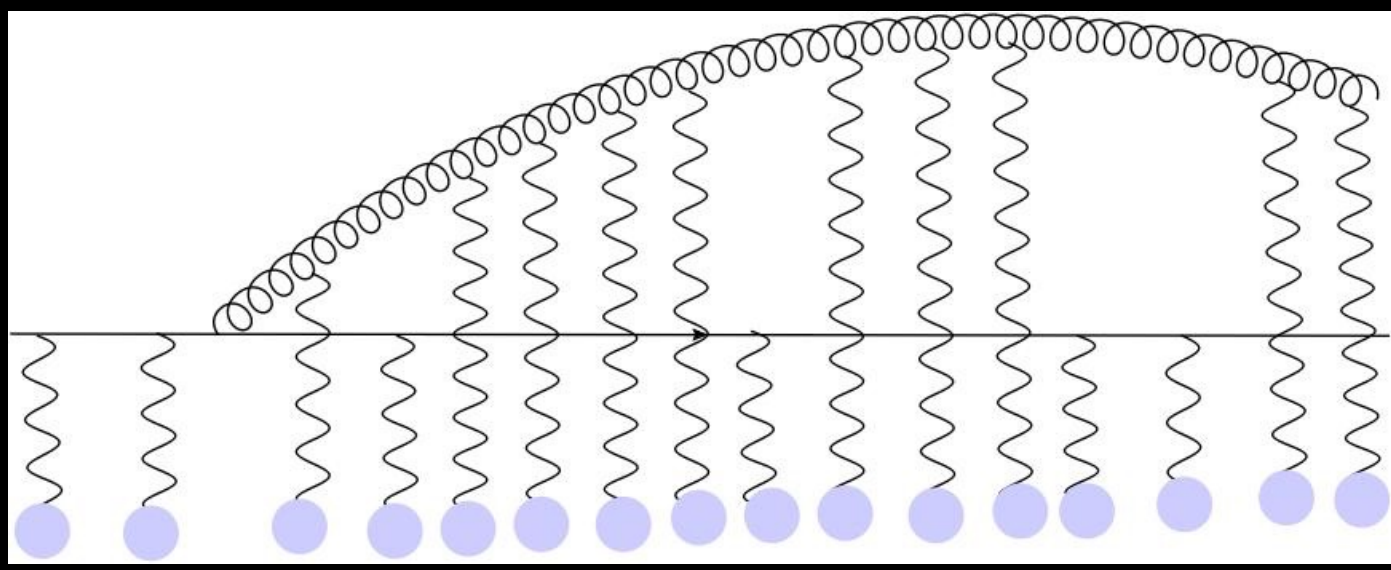

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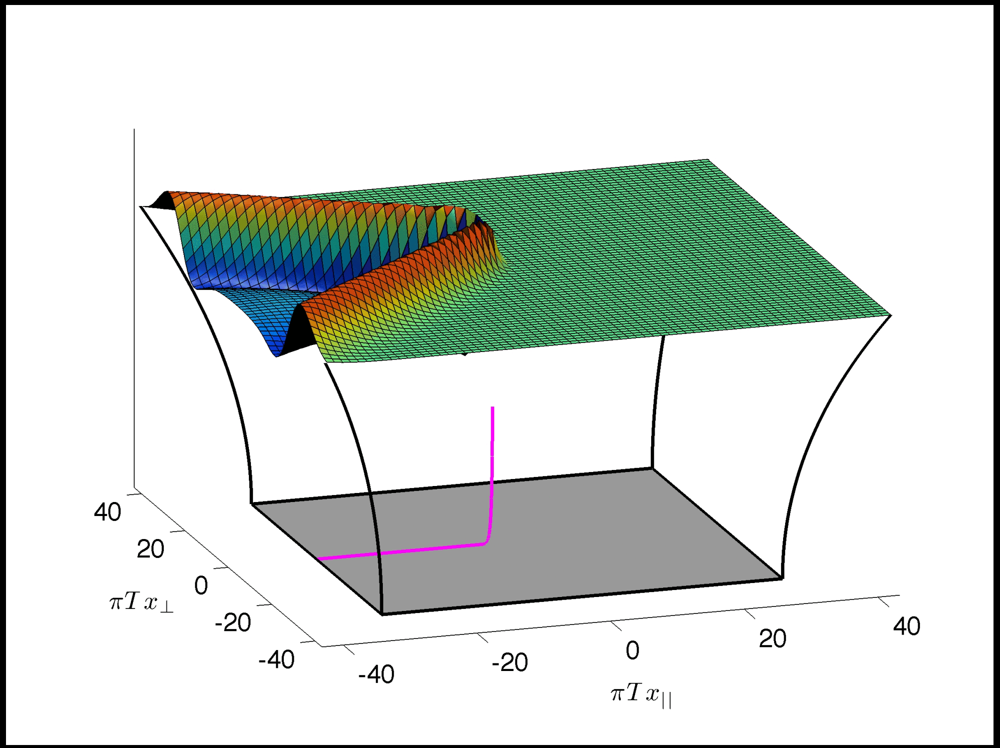

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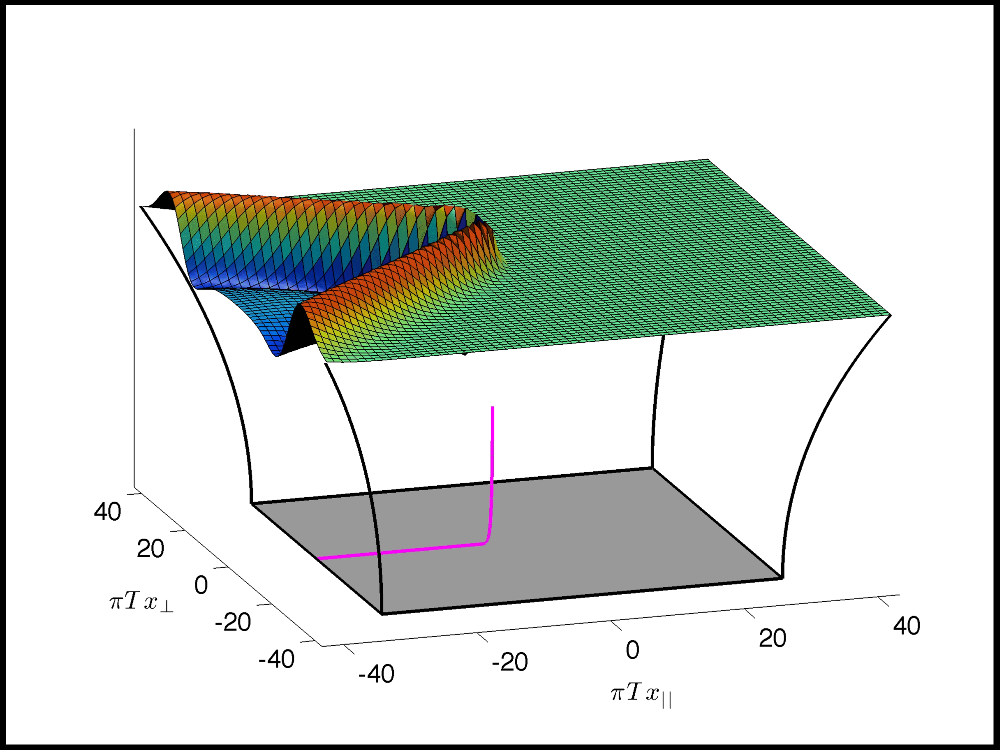
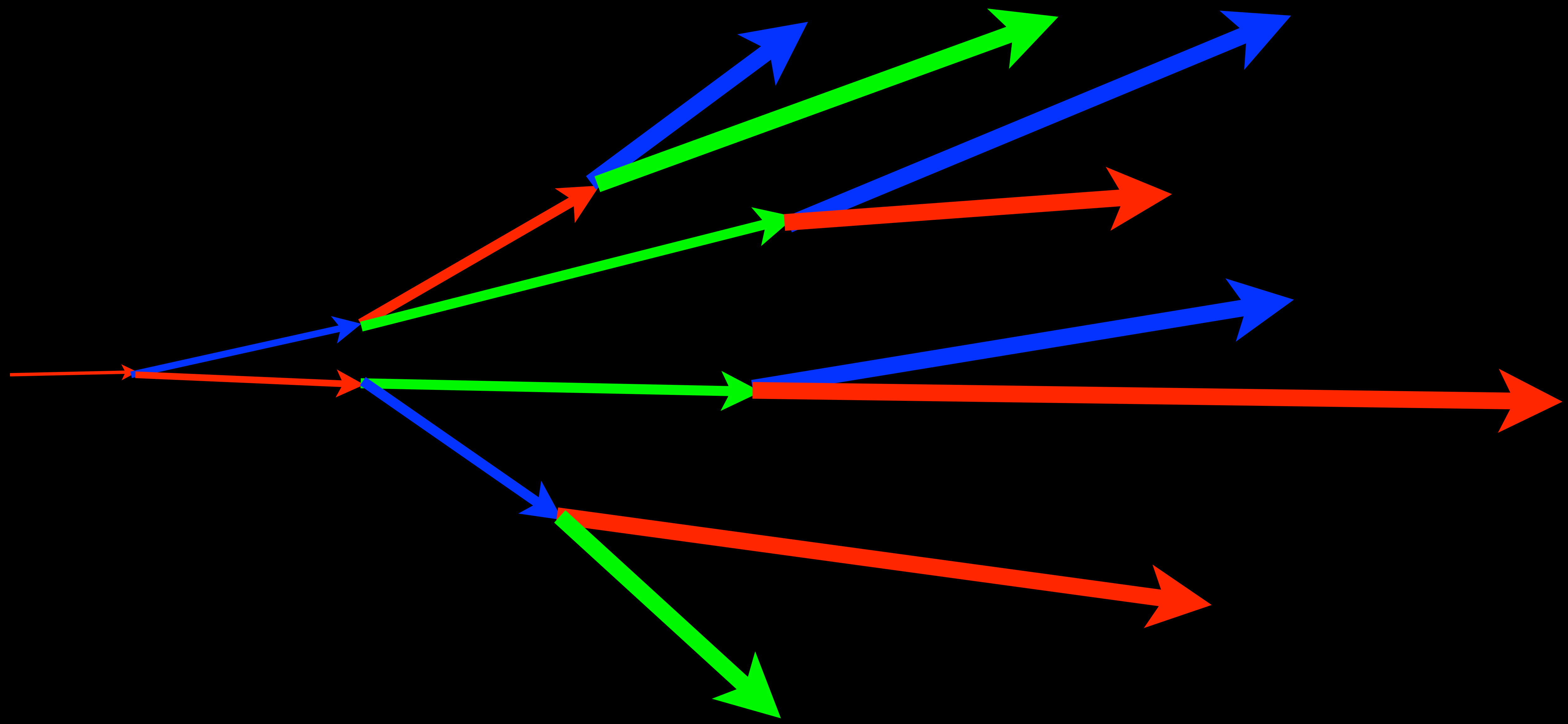


P. Chesler, W. Horowitz J. Casalderrey-Solana, G. Milhano, D. Pablos, K. Rajagopal

Grand picture (leading hadrons)



In a static brick

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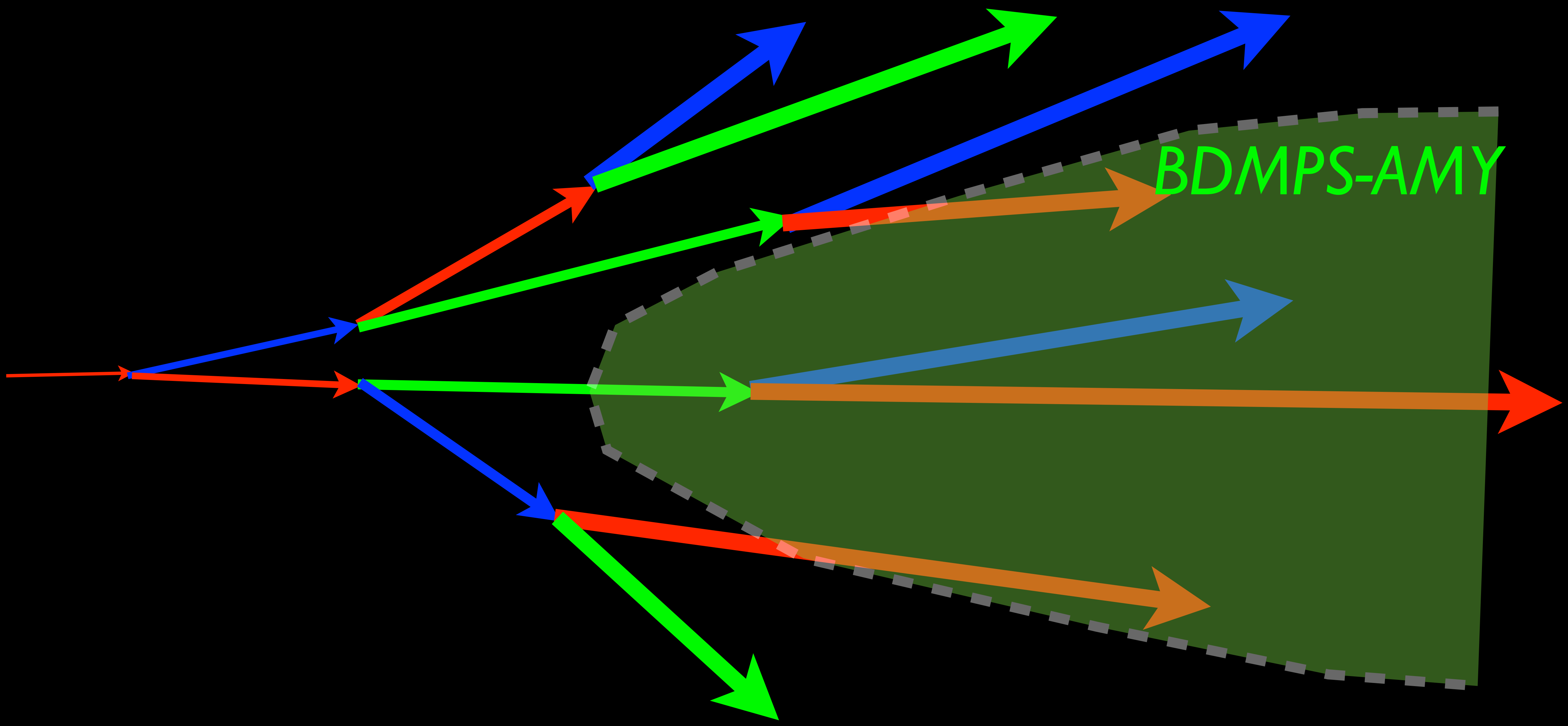

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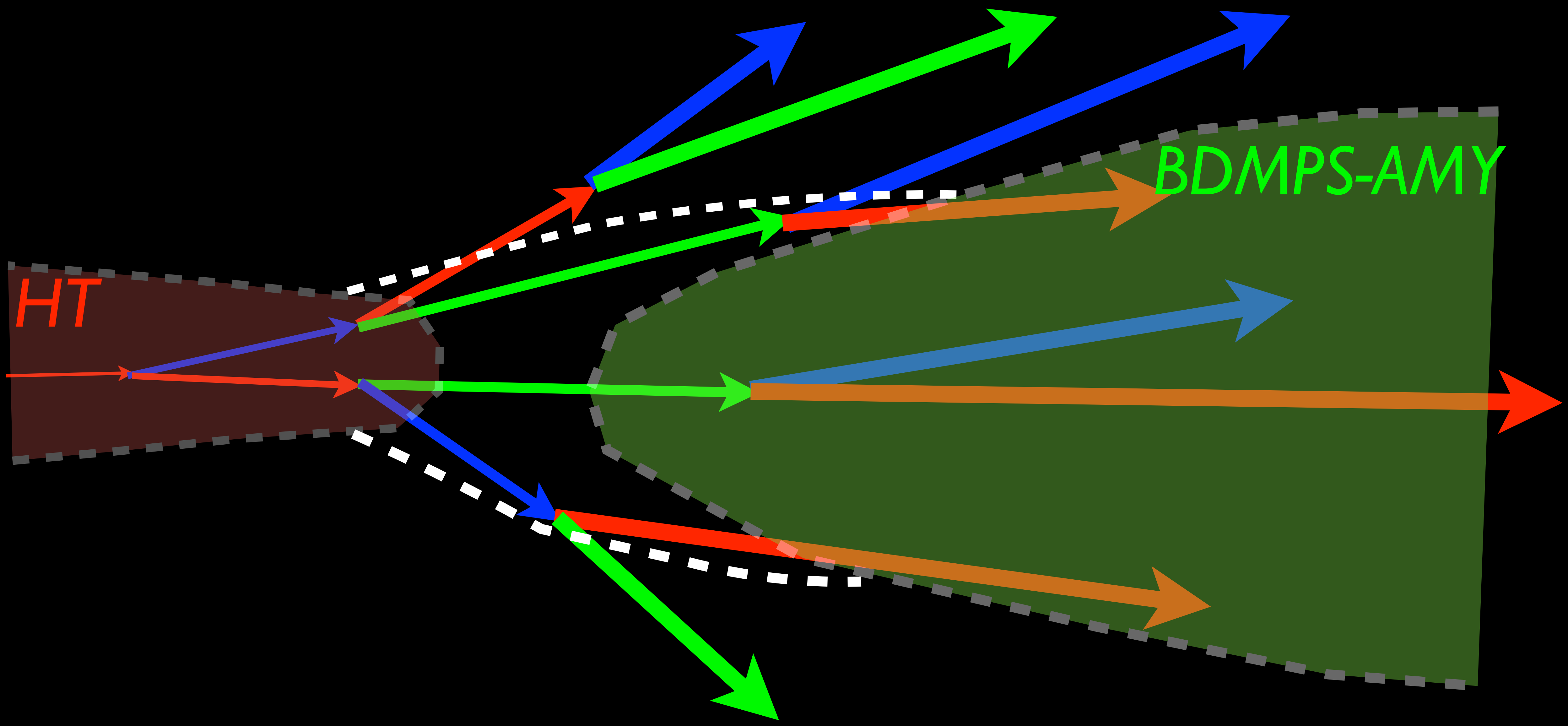

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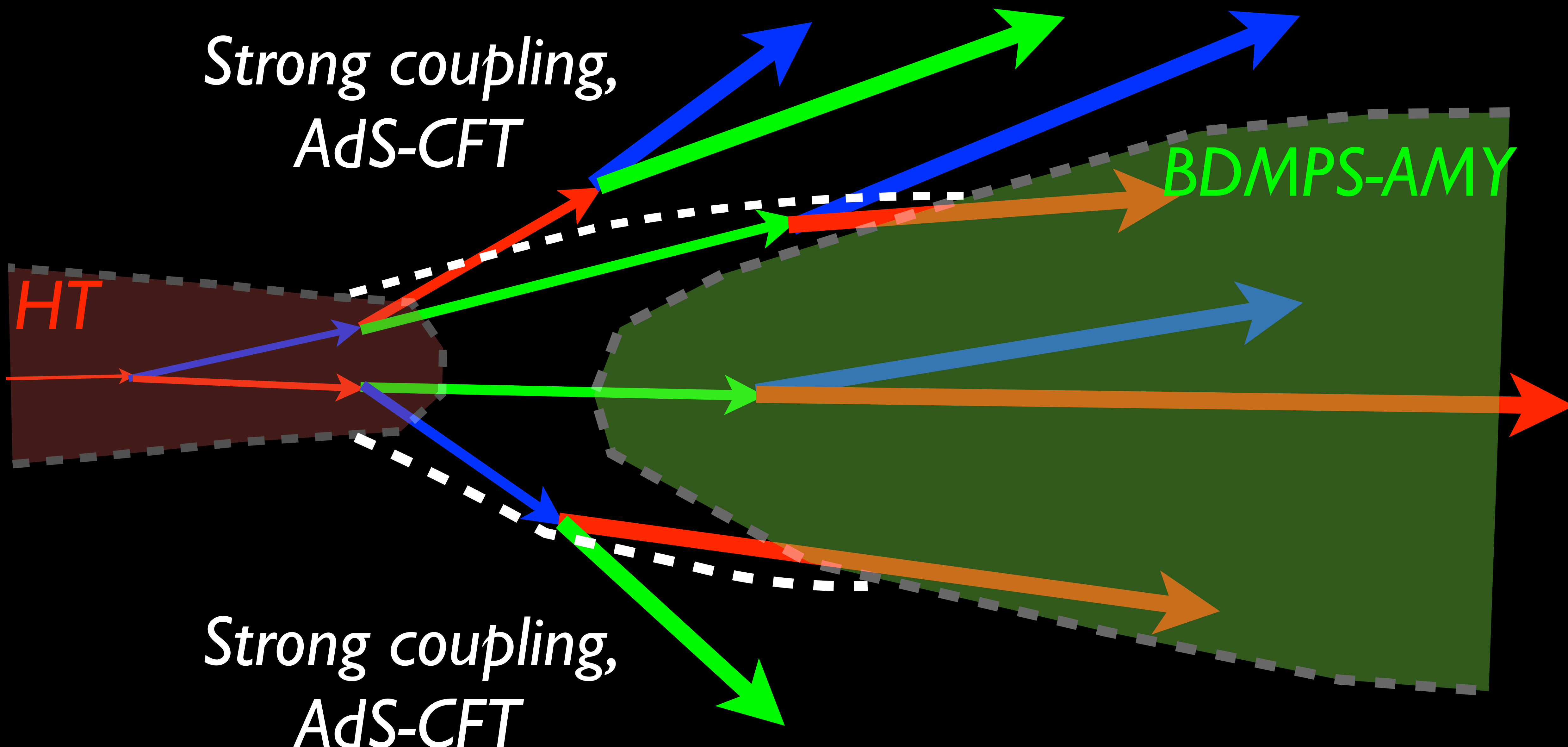

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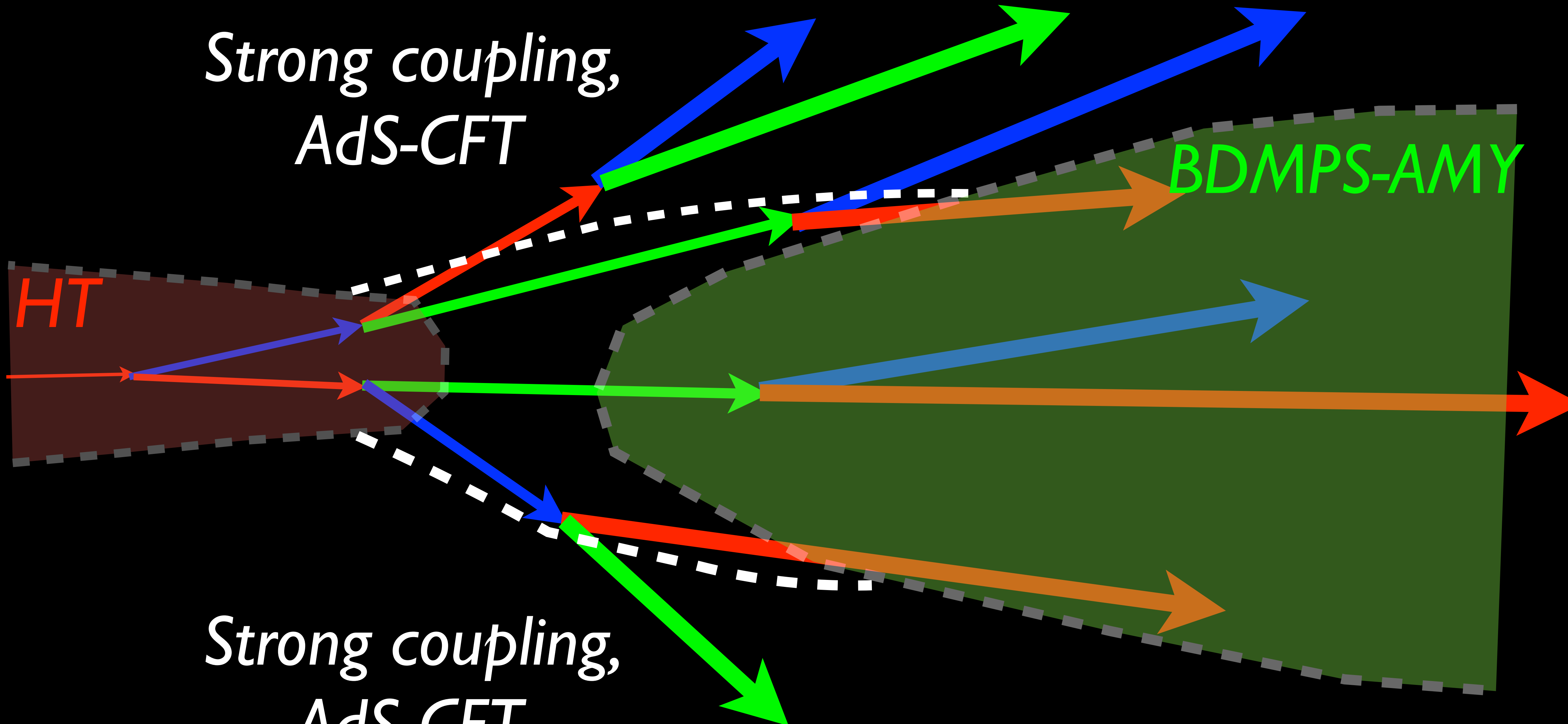

In an expanding QGP

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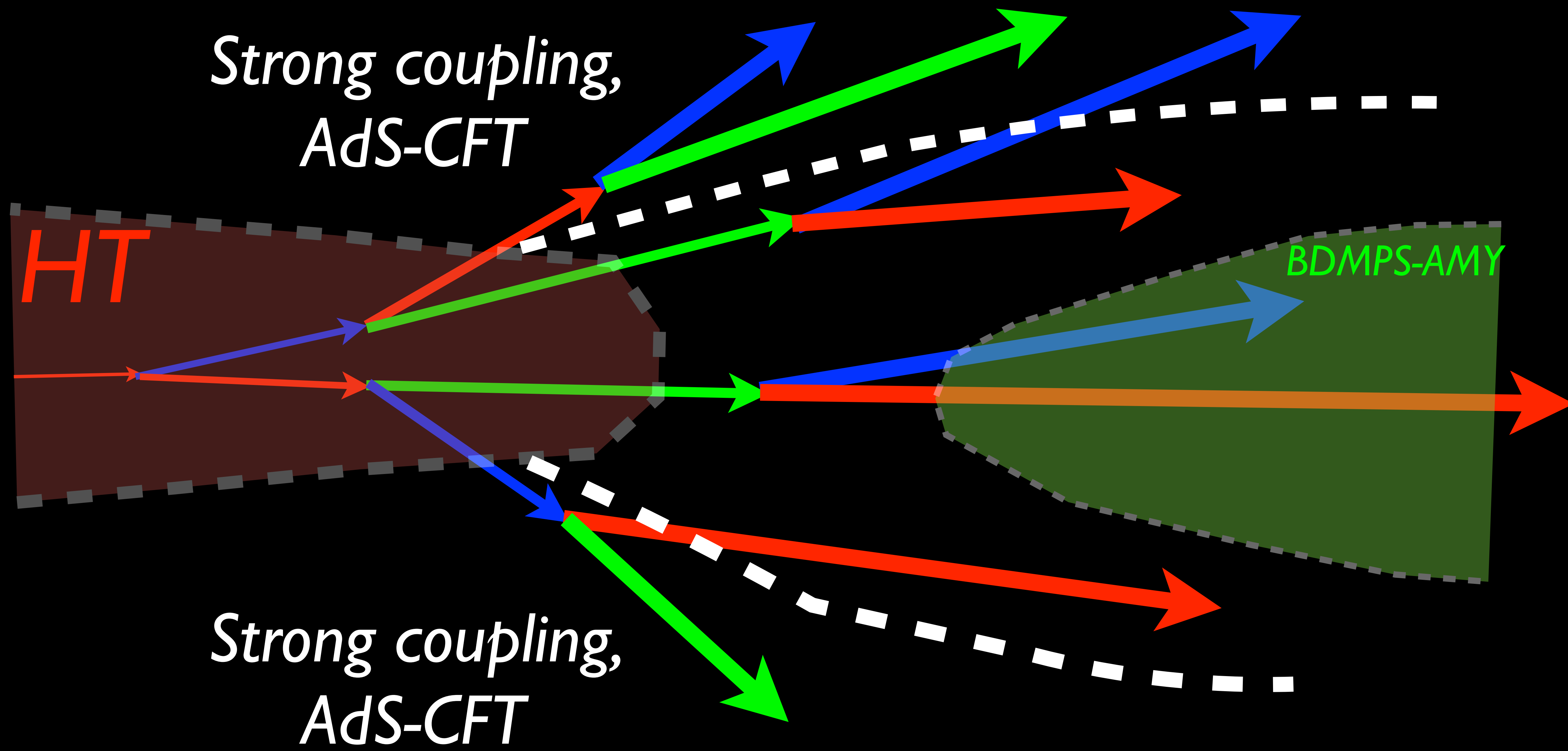
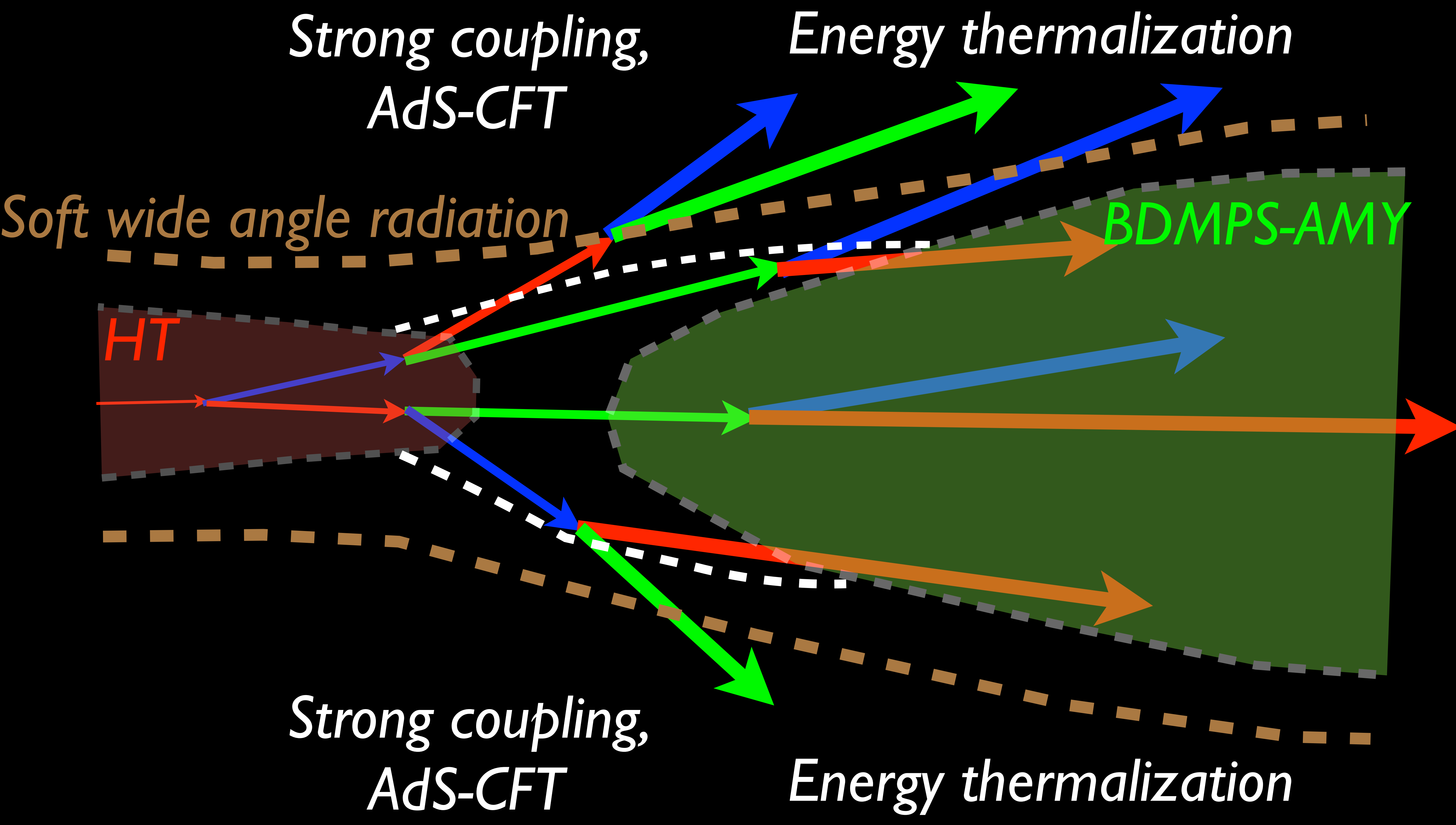


In an expanding QGP

Energy deposition-thermalization



Everything changes with scale in jet quenching

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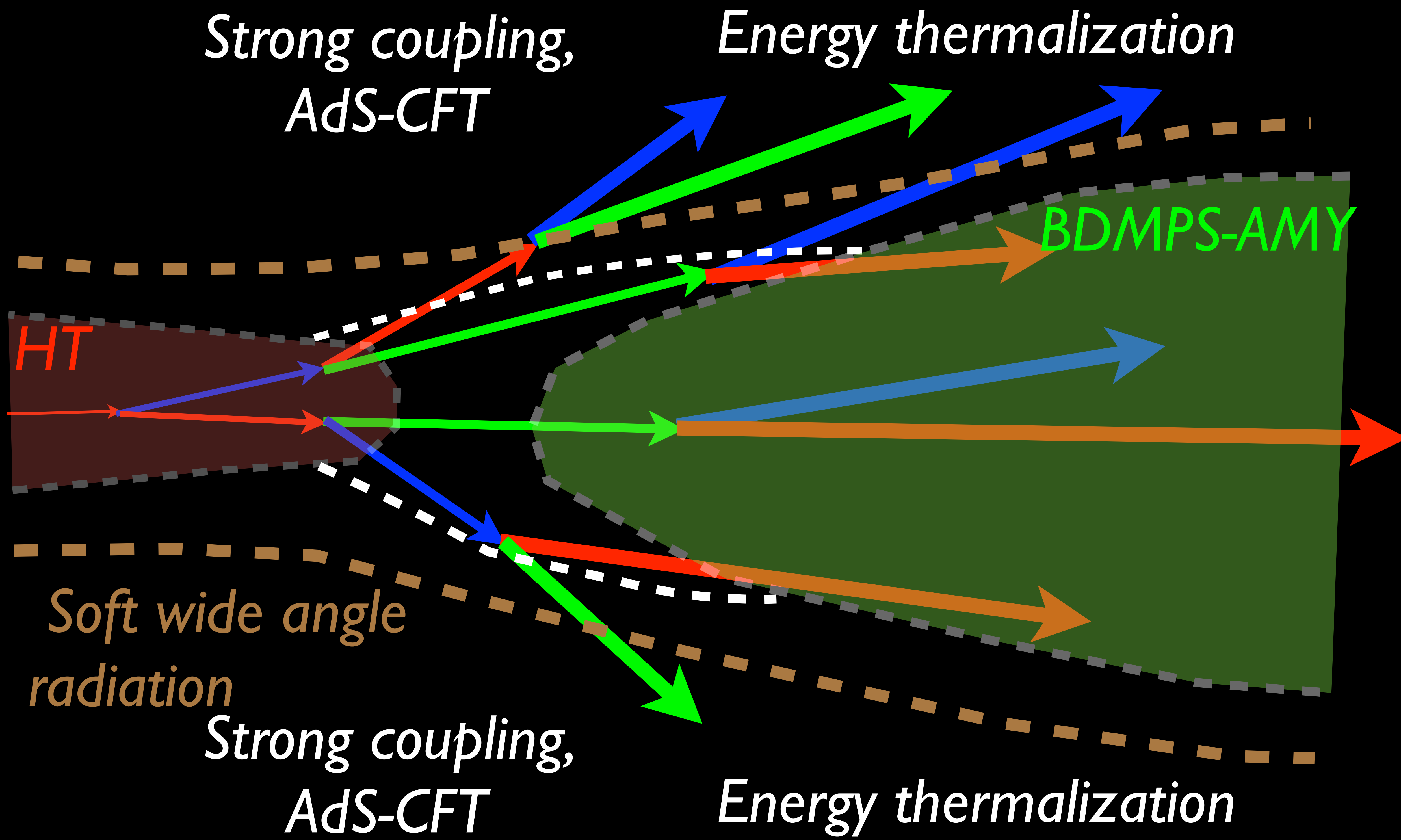

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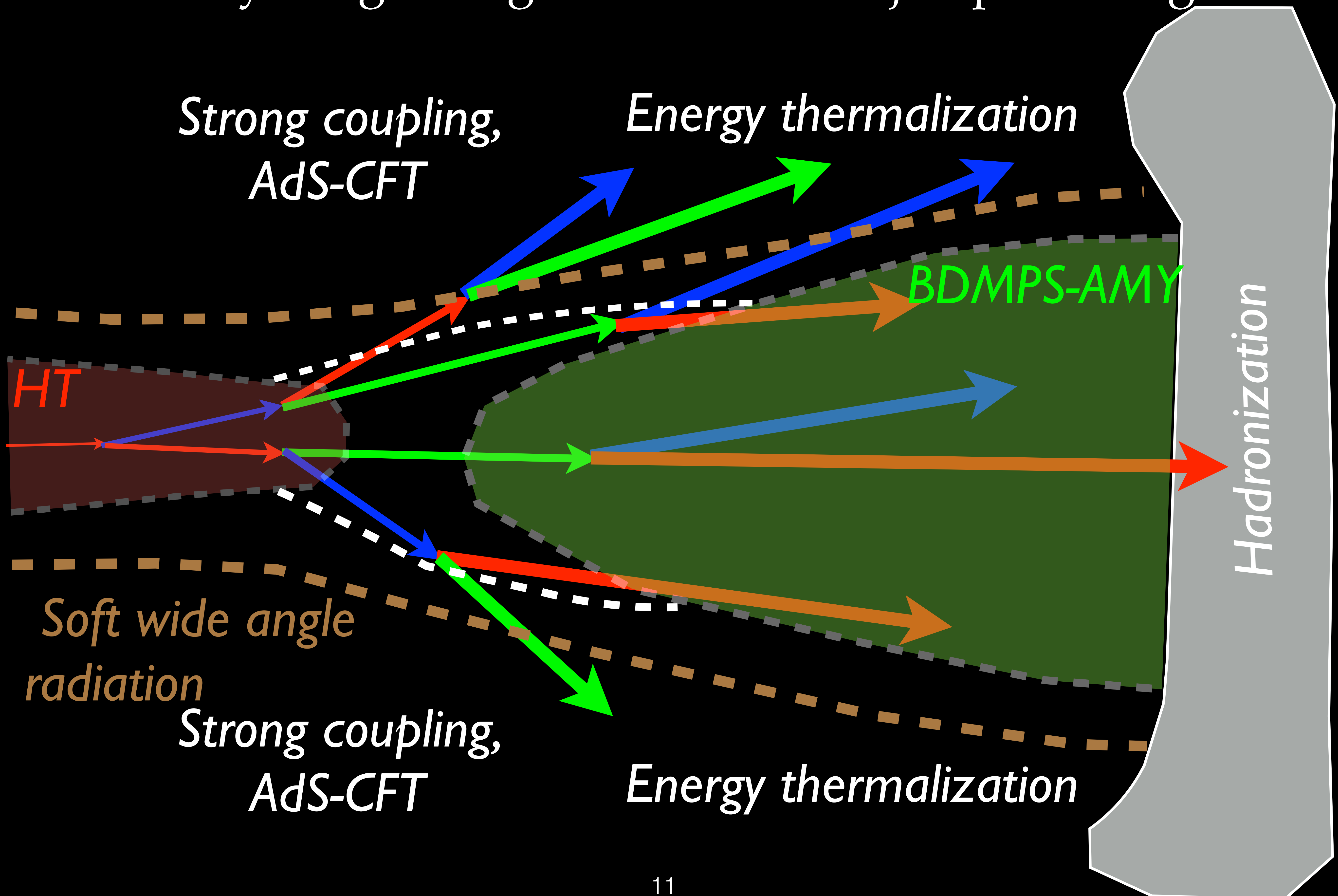
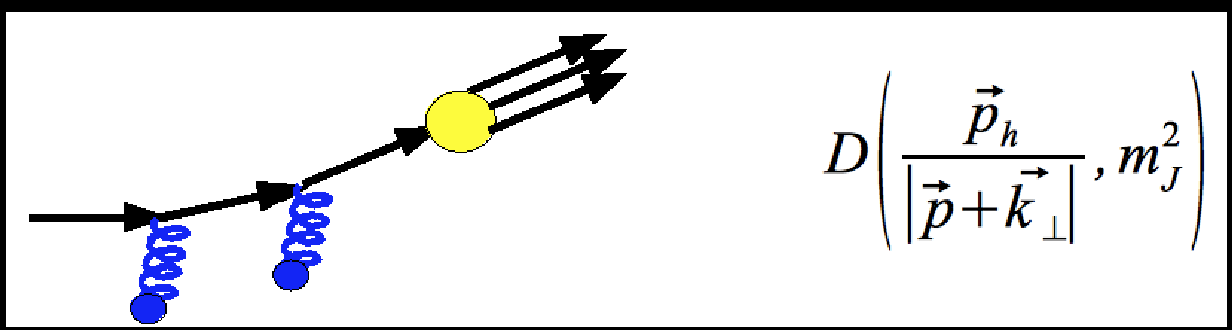


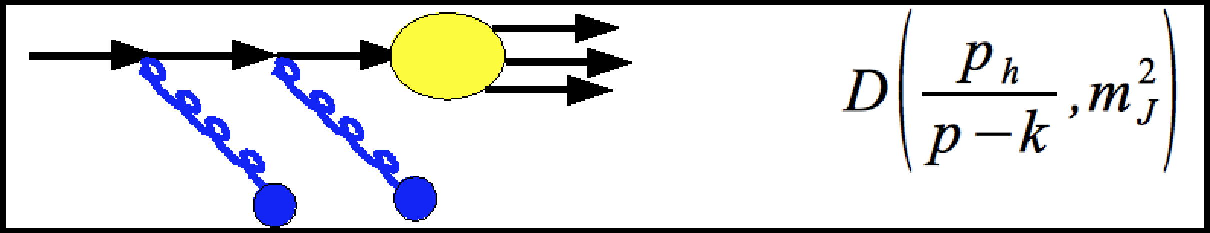
Transport coefficients partons in a dense medium

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



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

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!

In general, 2 kinds of transport coefficients

Type 1: which quantify how the medium changes the jet

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

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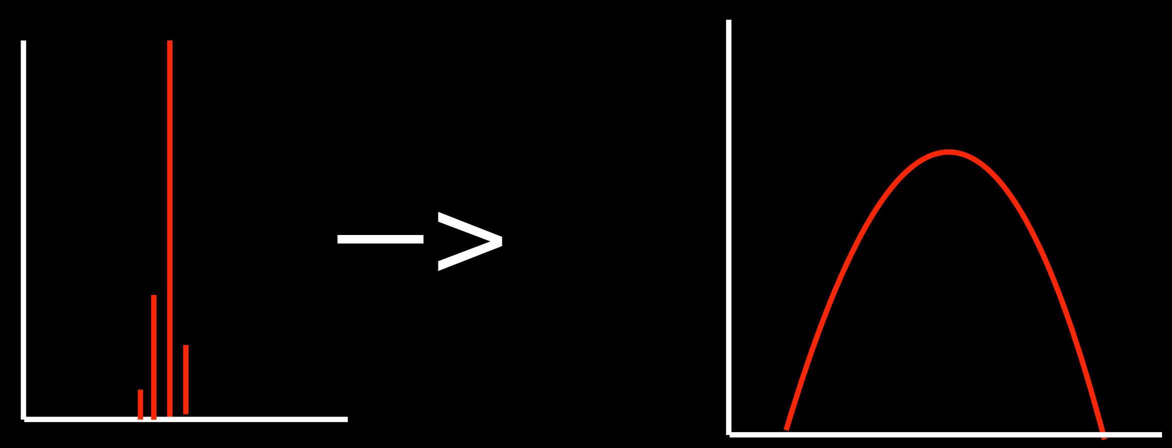
Type 2: which quantify the space-time structure of the deposited energy momentum at the hydro scale

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



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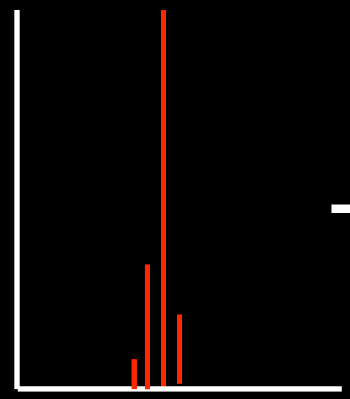

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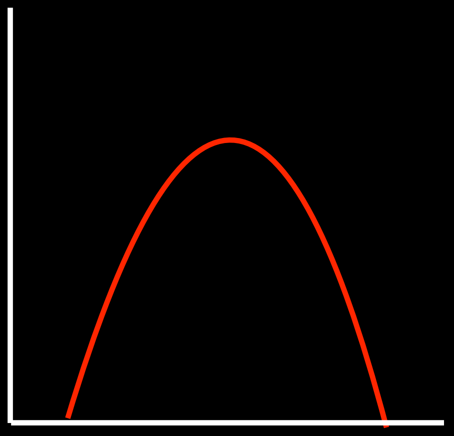

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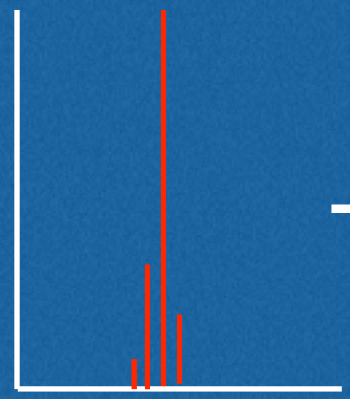

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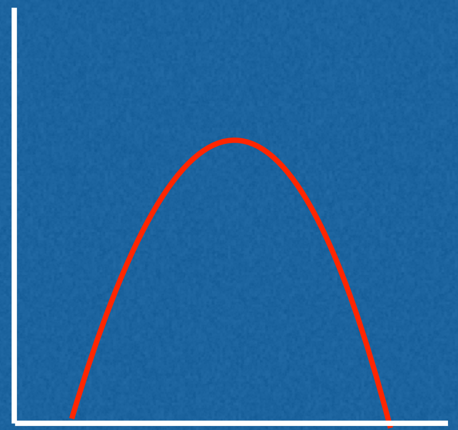
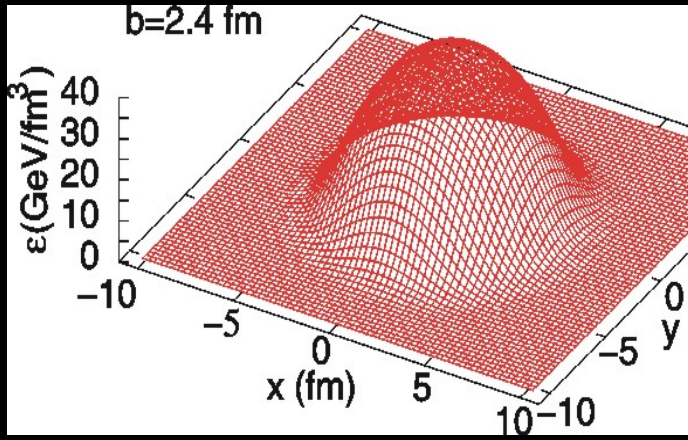


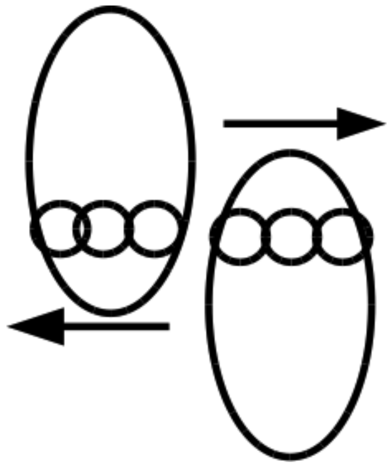
In all calculations presented bulk medium described by viscous fluid dynamics

Medium evolves hydro-dynamically as the jet moves through it
Fit the $\hat{q}$ for the initial T in the hydro in central coll.

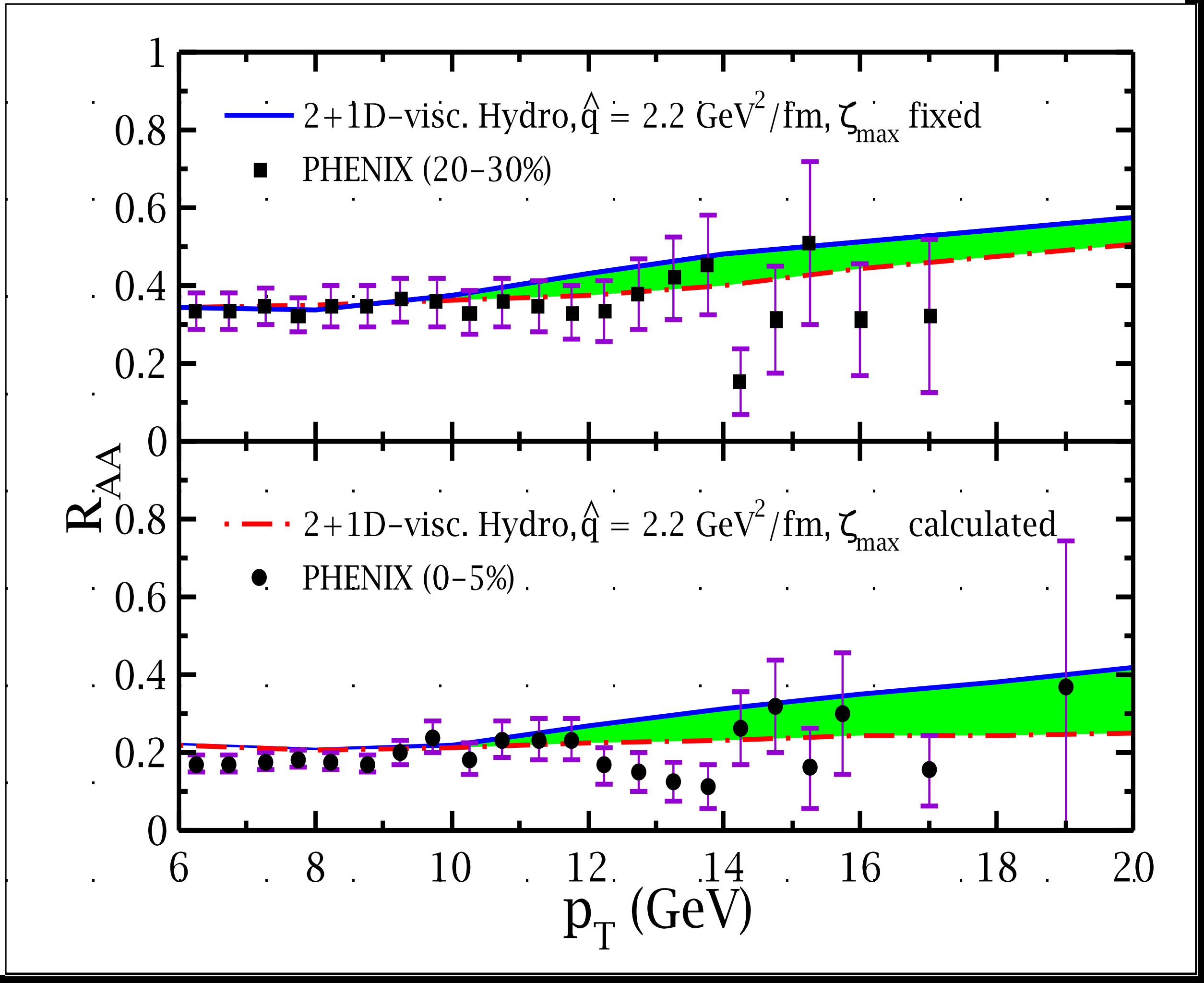


$$\hat{q}(\vec{r},t) = \hat{q}_0 \frac{s(\vec{r},t)}{s_0}$$

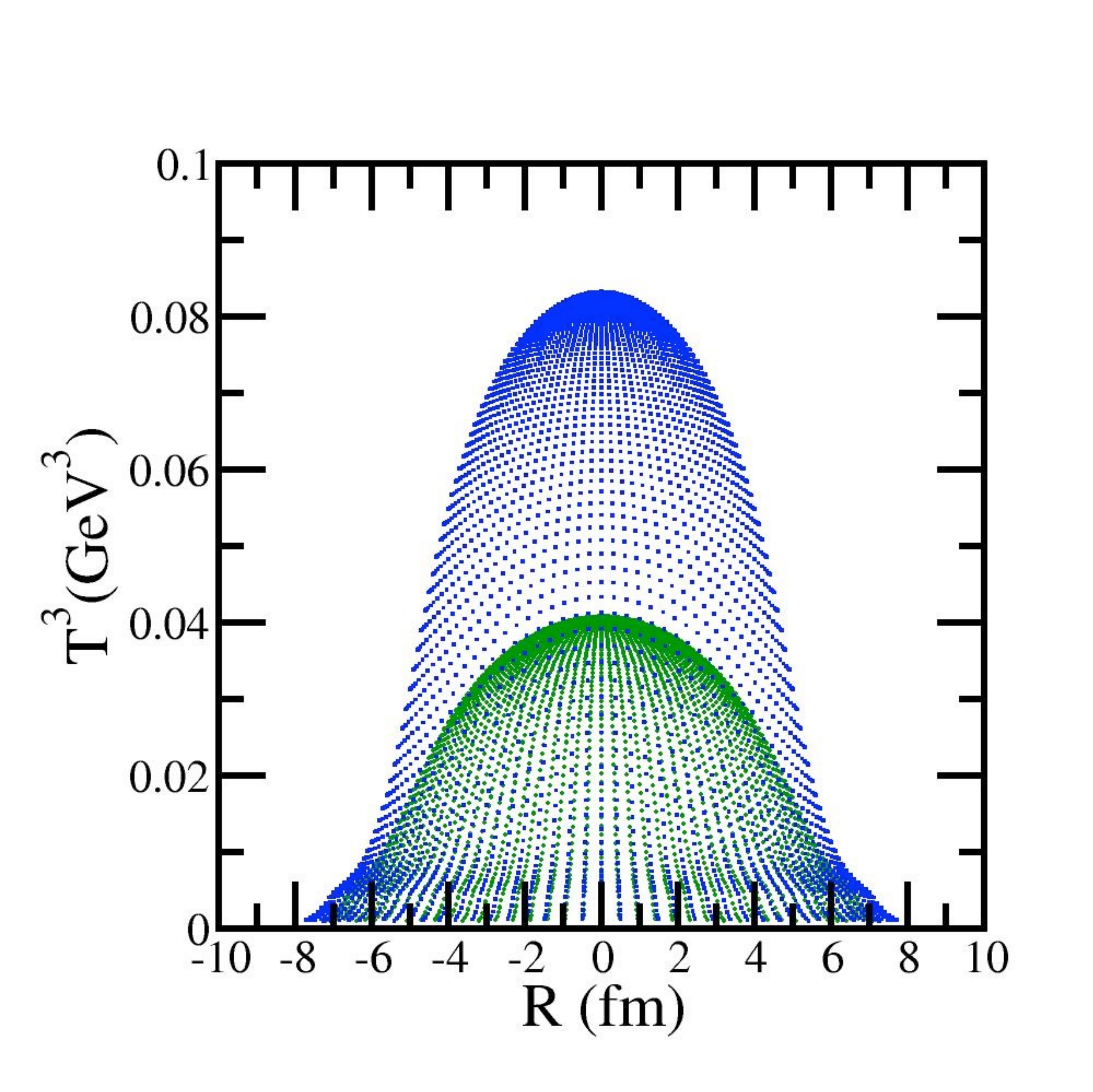
$$s_0 = s(T_0)$$

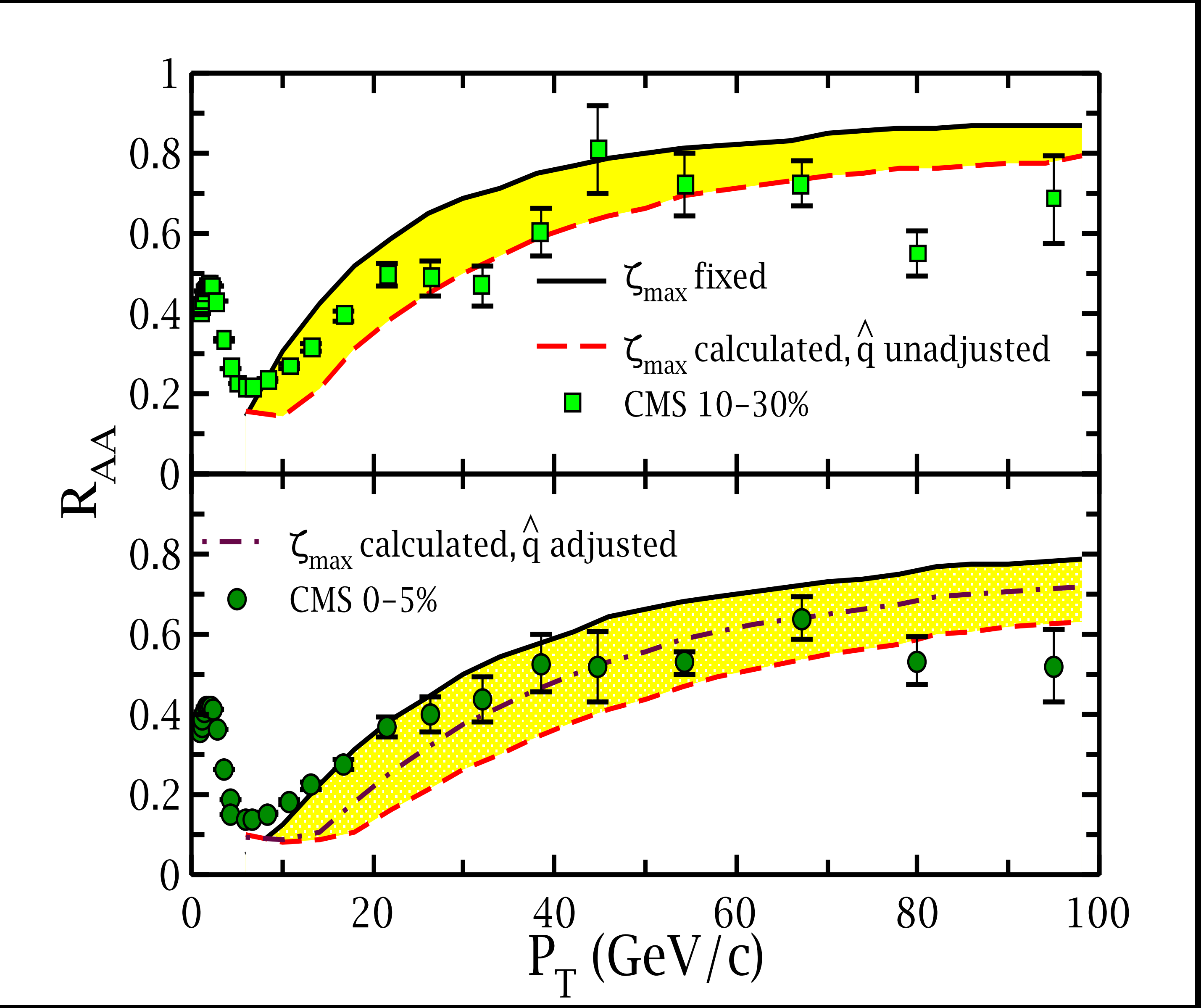


$$R_{AA} \sim \frac{\frac{dN_{AA}}{dp_T dy}}{N_{bin}\frac{dN_{pp}}{dp_T dy}}$$



From RHIC to LHC circa 2012

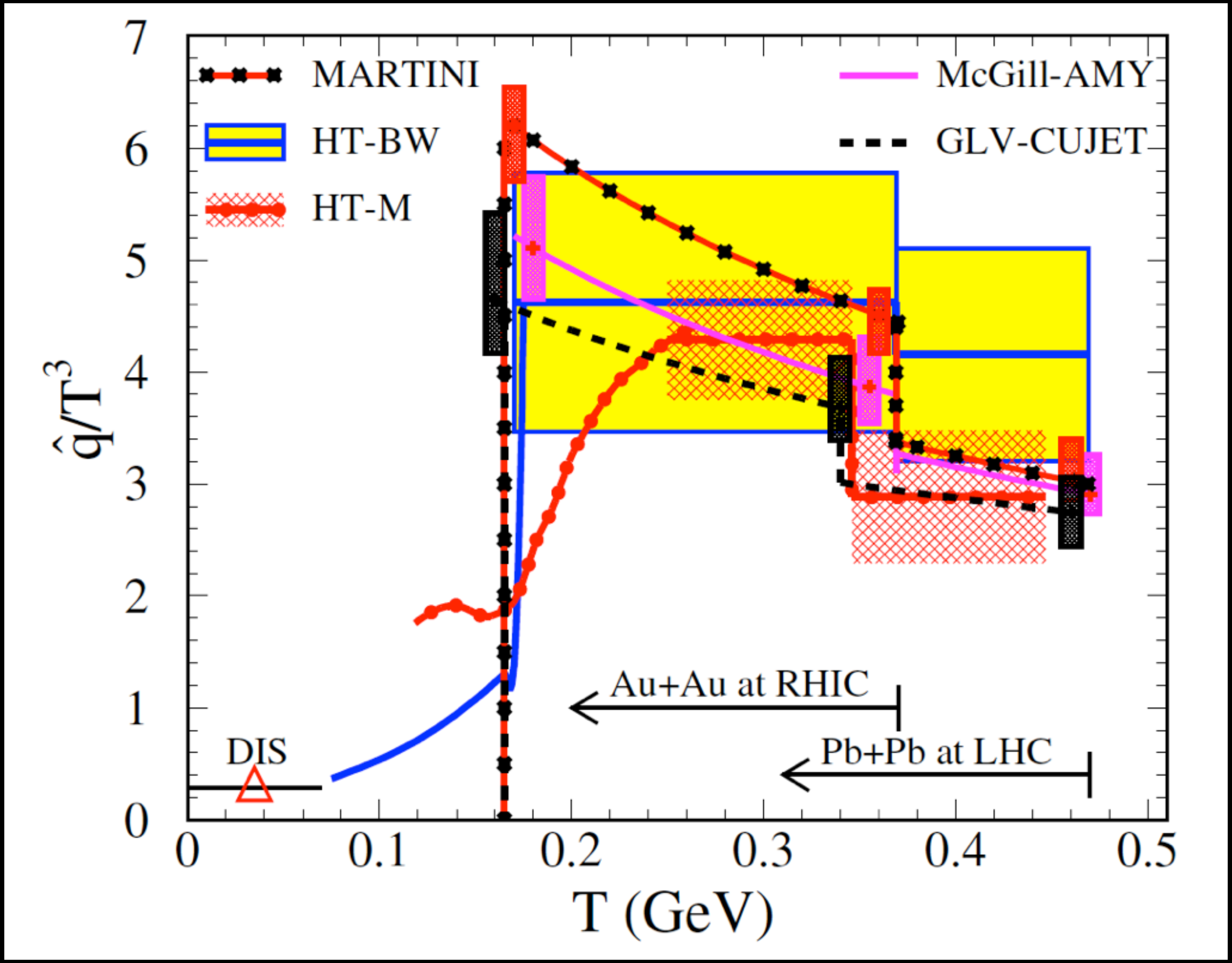




Reasonable agreement with data,
no separate normalization at LHC
W/O any non-trivial x-dependence (E dependence)

Results from the JET collaboration

K. Burke et al.



Do separate fits to the RHIC and LHC data for maximal $\hat{q}$ without assuming any kink in the $\hat{q}$ vs T^3 curve

Results from the JET collaboration

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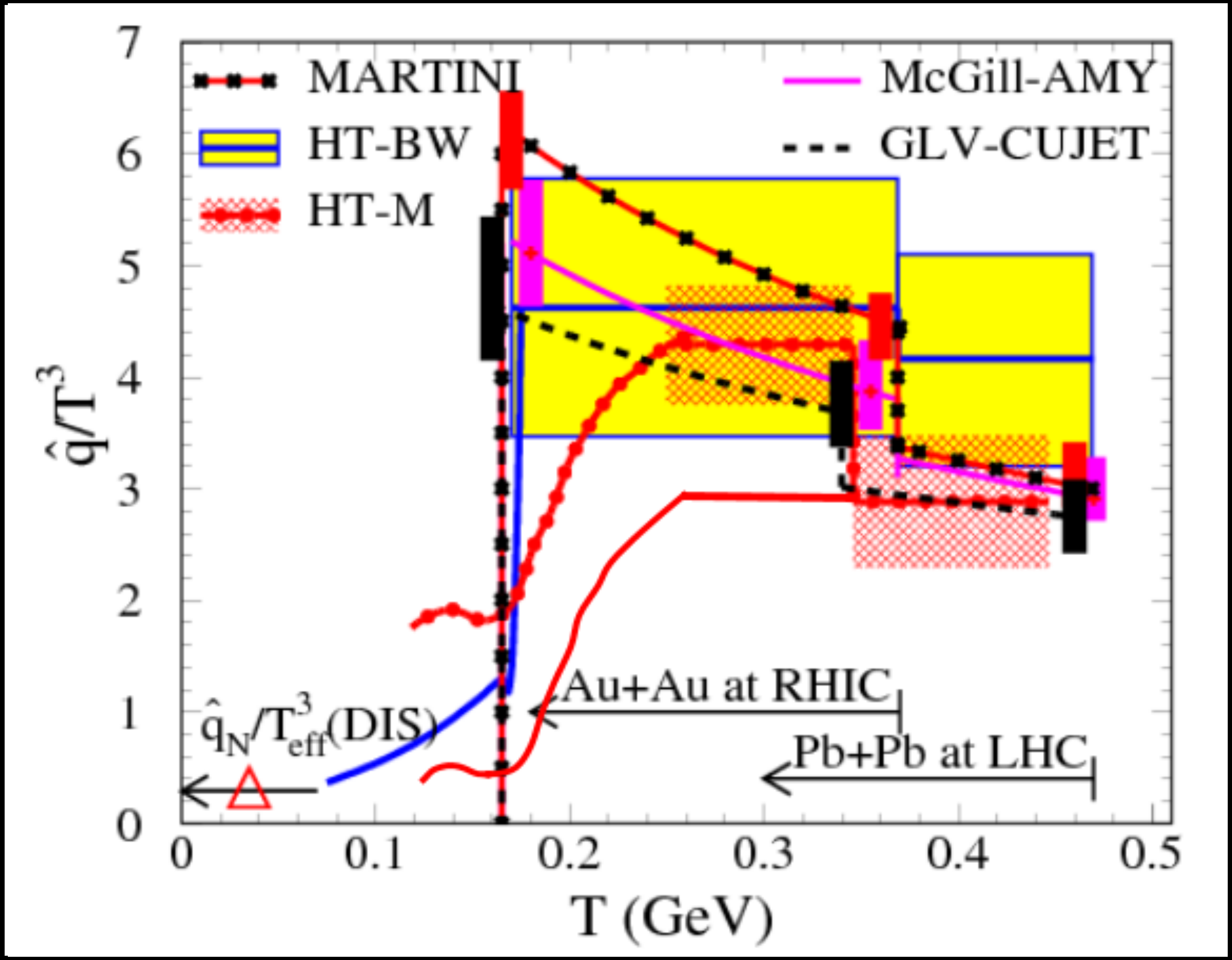
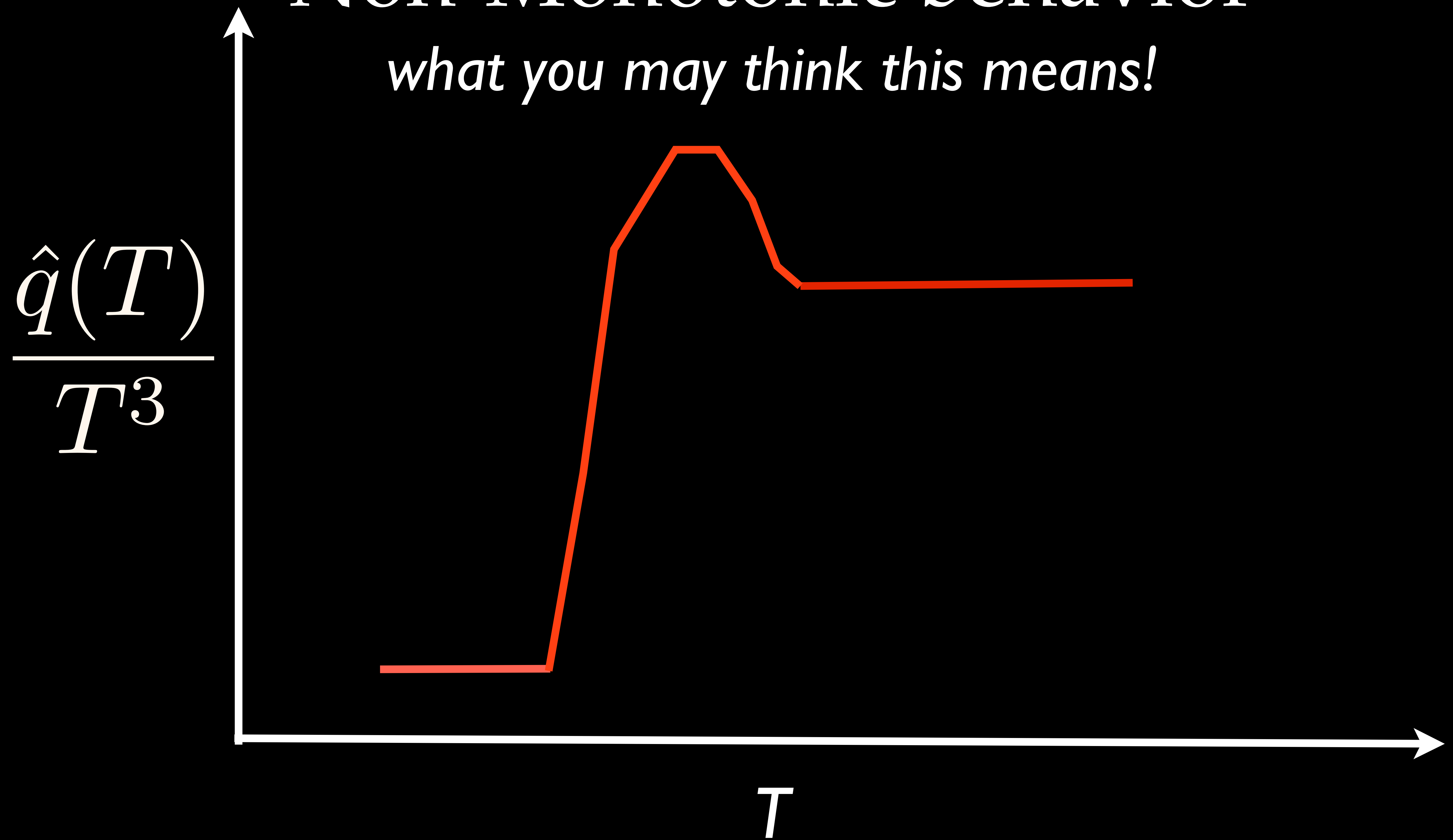


Do separate fits to the RHIC and LHC data for maximal $\hat{q}$ without assuming any kink in the $\hat{q}$ vs T^3 curve

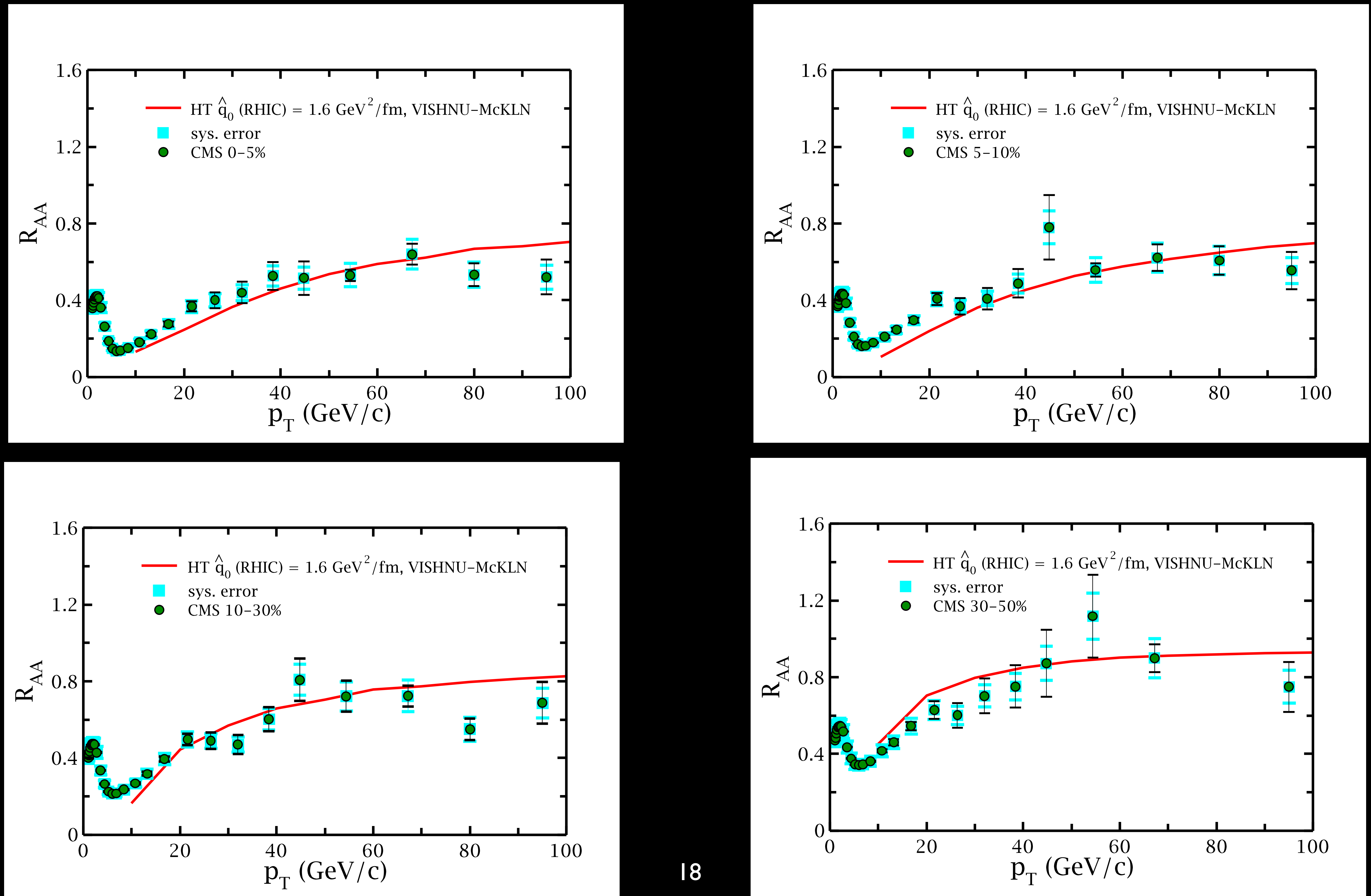
Non-Monotonic behavior

what you may think this means!

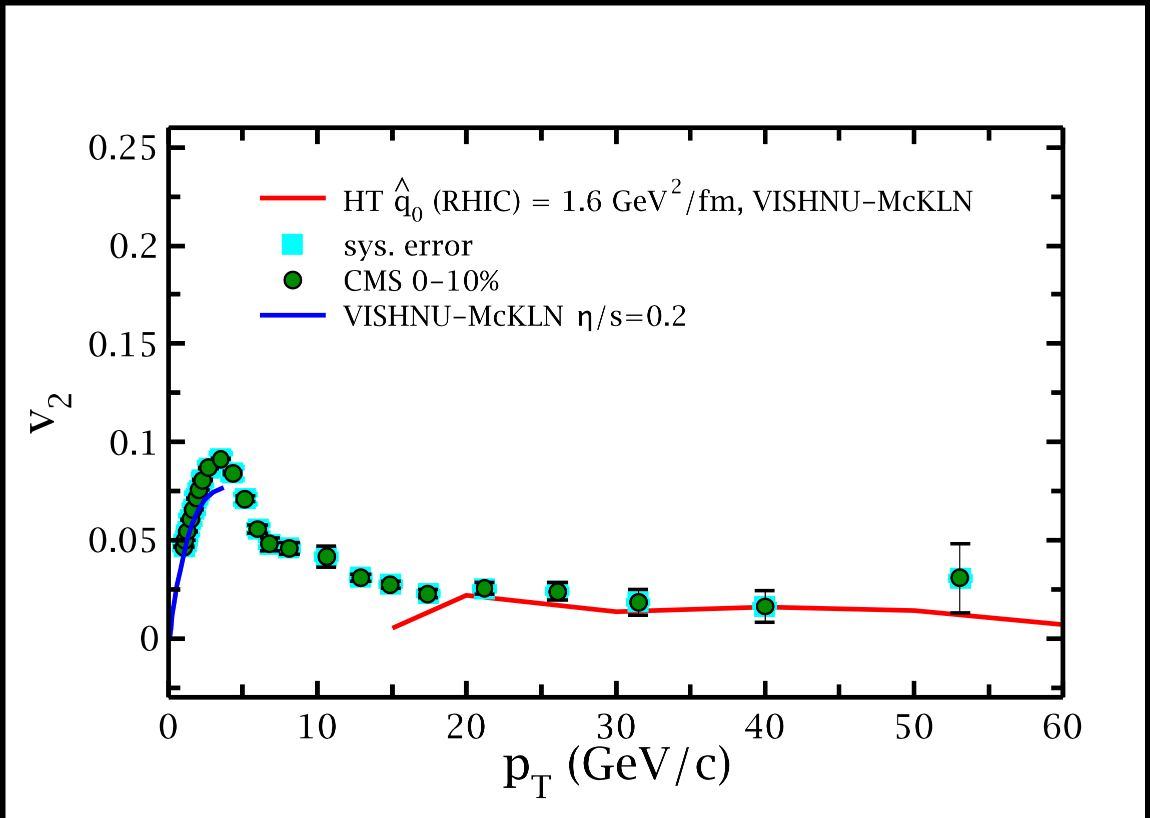


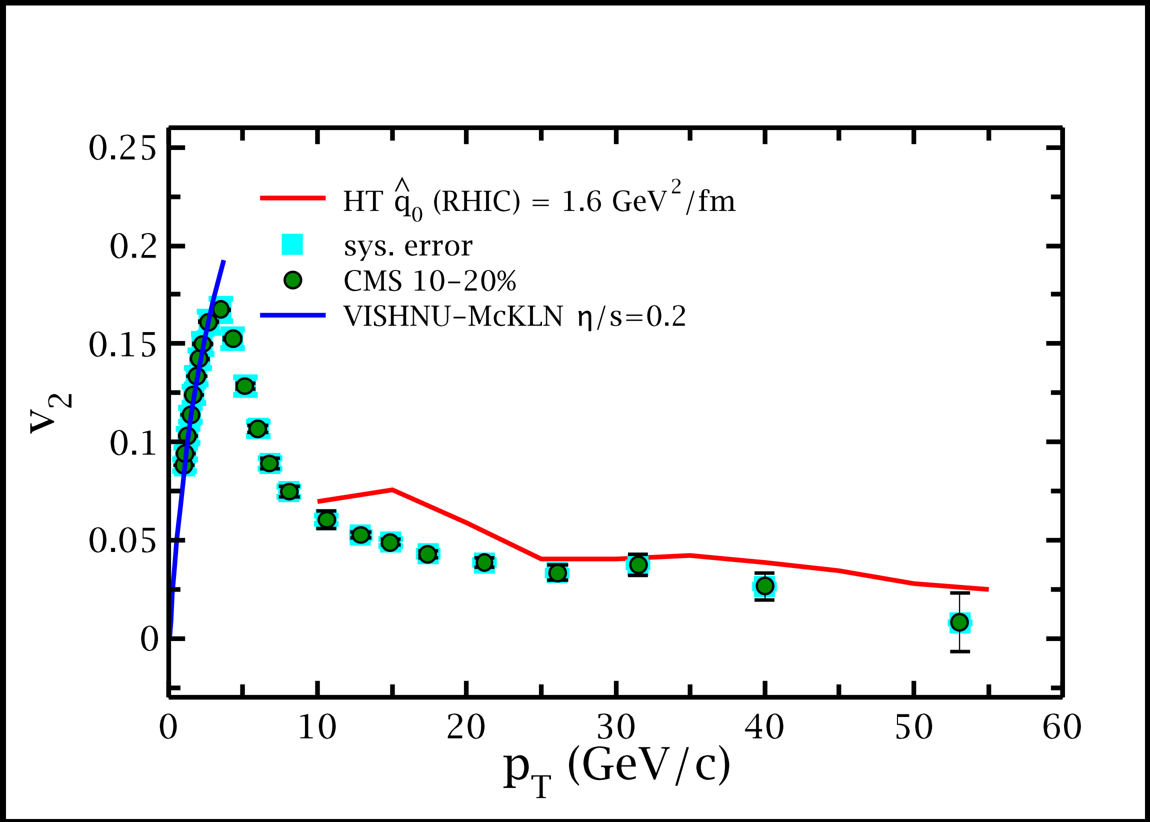
If this is true, must effect the centrality dependence of R_{AA}, v_2, and its centrality dependence at a given collision energy

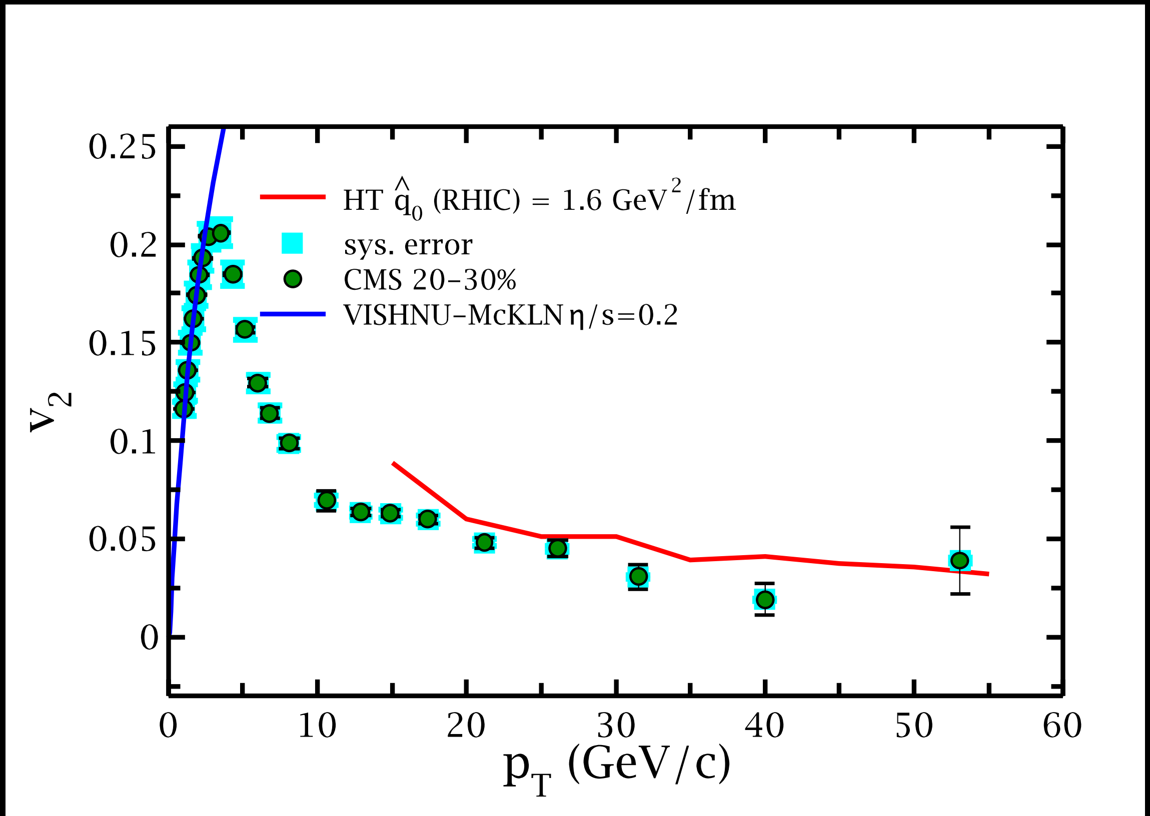
LHC R_{AA} without a bump in $\hat{q}/T^3$

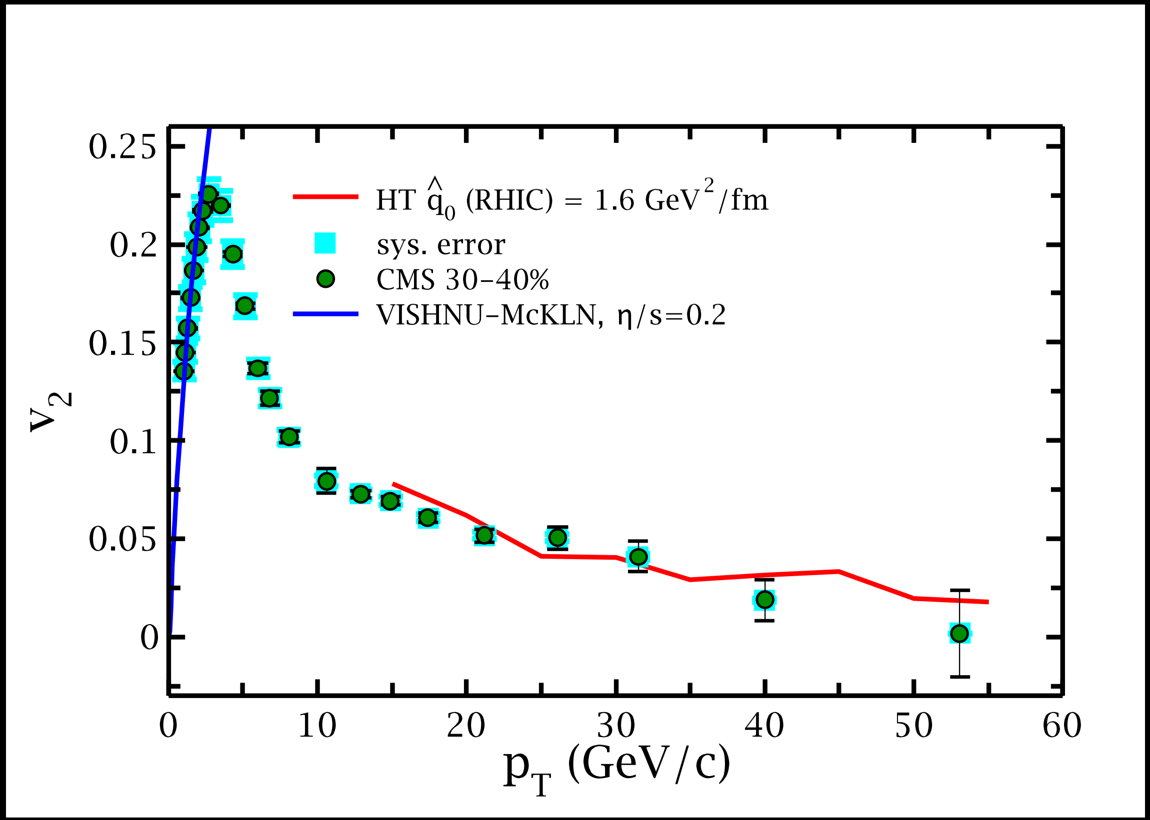


v_2 at LHC without a bump in $\hat{q}/T^3$

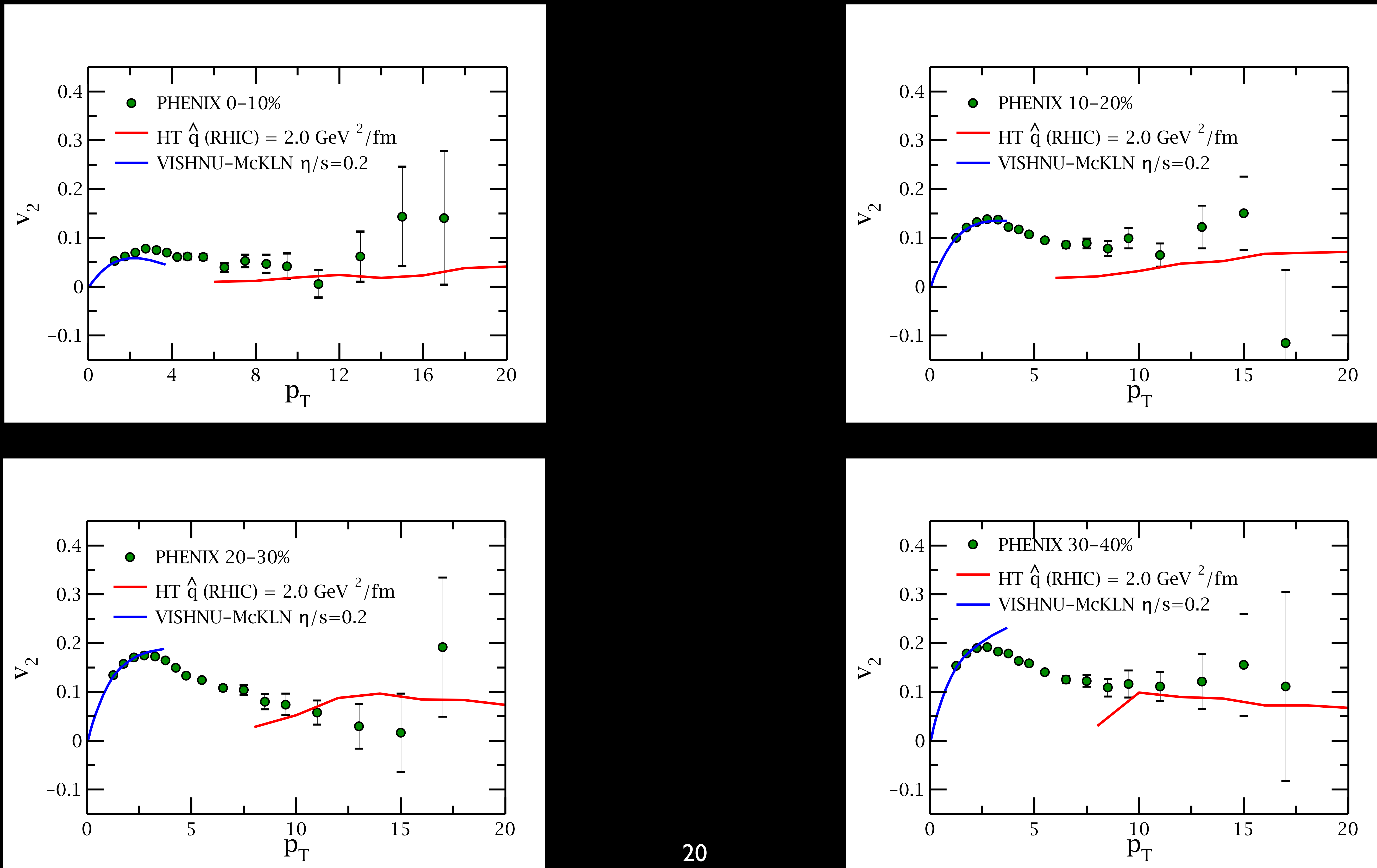




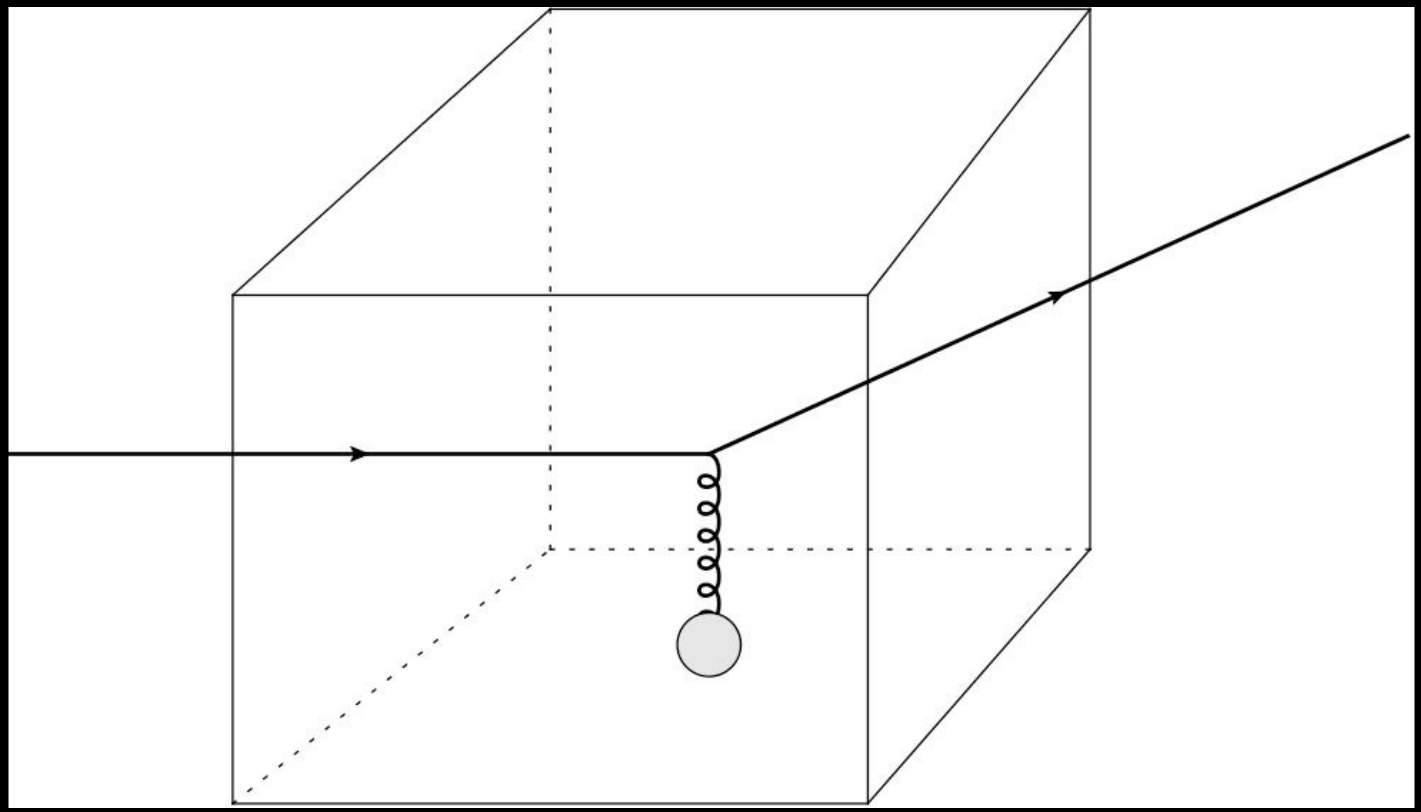




v_2 at RHIC without a bump in $\hat{q}/T^3$



Calculating $\hat{q}$ with more care



$$W(k) = \frac{g^2}{2N_c}\langle q^-;M| \int d^4x d^4y \bar{\psi}(y) \not{A}(y)\psi(y)$$
$$\times \quad |q^- + k_\perp; X\rangle\langle q^- + k_\perp; X|$$
$$\times \quad \bar{\psi}(x) \not{A}(x)\psi(x)|q^-;M\rangle$$

in terms of W, we get $\quad \hat{q} = \sum_k k_\perp^2 \frac{W(k)}{t},$

Final state is close to ``on-shell''

$$\delta[(q+k)^2] \simeq \frac{1}{2q^-}\delta\left(k^+ - \frac{k_\perp^2}{2q^-}\right).$$

Also we are calculating in a finite temperature heat bath

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

$$\langle n|F^{+,}{}_{\perp}(y^-, \vec{y}_\perp)F_\perp^+(0)|n\rangle$$

$$\hat{q}(q^+, q^-) \qquad 2q^-q^+ = Q^2, \;\; \frac{k_\perp^2}{2q^-} = xP^+$$

Can evaluate on Lattice!

What one usually does at this point

- Take the q^- to be infinity

$$\hat{q} \sim \int \frac{dy^- d^2 y_\perp}{(2\pi)^3} d^2 k_\perp e^{i\vec{k}_\perp \cdot \vec{y}_\perp} \langle n | F^{+,}{}_\perp (y^-, \vec{y}_\perp) F^+_\perp (0) | n \rangle$$

$$= \int \frac{dy^-}{2\pi} \langle n | F^{+,}{}_\perp (y^-) F^+_\perp (0) | n \rangle$$

This makes $\hat{q}$ into a one dimensional quantity
an assumption of small x or high E.

$\hat{q}$ at vanishing x has been taken to NLO

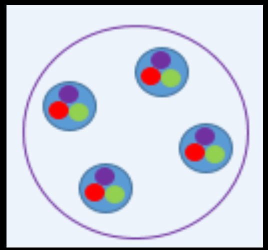
Z. Kang, E. Wang, X.-N. Wang, H. Xing, PRL 112 (2014) 102001

T. Liou, A. Mueller, B. Wu, Nucl.Phys. A916 (2013) 102-125

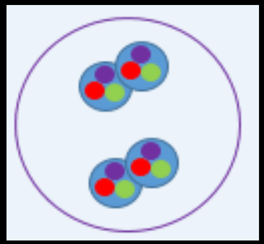
J. Blaizot, Y. Mehtar-tani, arXiv:1403.2323 [hep-ph]

E. Iancu, arXiv:1403.1996 [hep-ph]

None of these NLO corrections have been tested in phenomenology.



What is x for a QGP



- Bjorken x in DIS on a proton $$x_B = \frac{Q^2}{2p \cdot Q}$$

- In rest frame of proton $$x_B = \frac{Q^2}{2E \cdot M} = \frac{\eta}{M}$$

- In the PDF $$f(x_B) = \int \frac{dy^-}{2\pi} e^{ix_B P^+ y^-} \langle P | \bar{\psi}(y^-) \frac{\gamma^+}{2} \psi | P \rangle$$

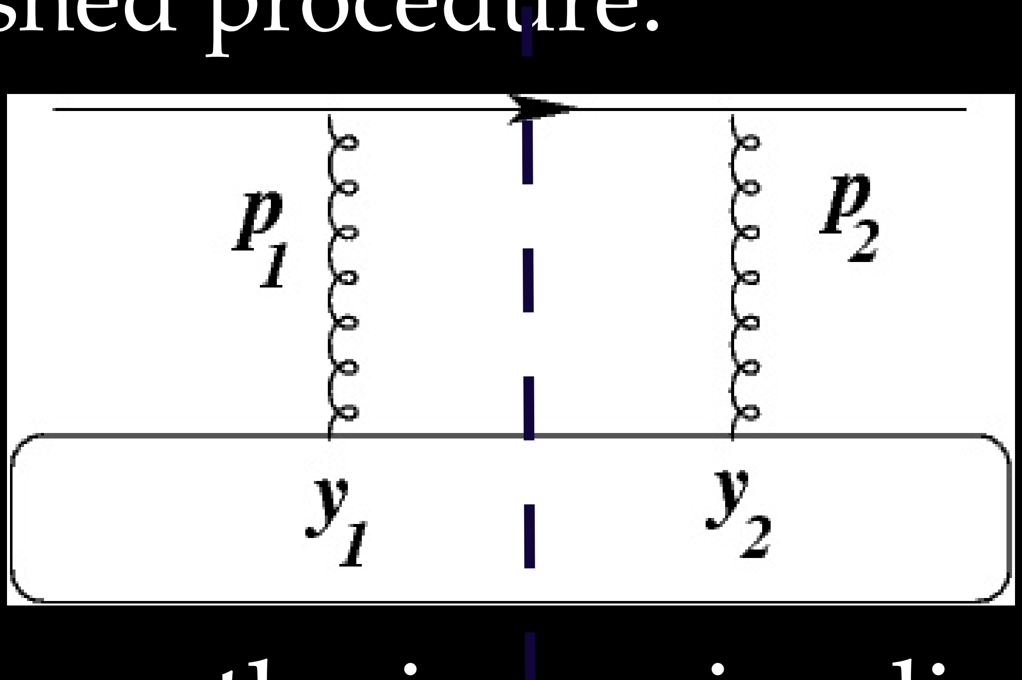
$$g(\eta) = \int \frac{dy^-}{2\pi} e^{i\eta y^-} \langle P | \bar{\psi}(y^-) \frac{\gamma^+}{2} \psi | P \rangle$$

In the rest frame of the proton, x ~ η

We can compare η values between DIS and heavy-ions

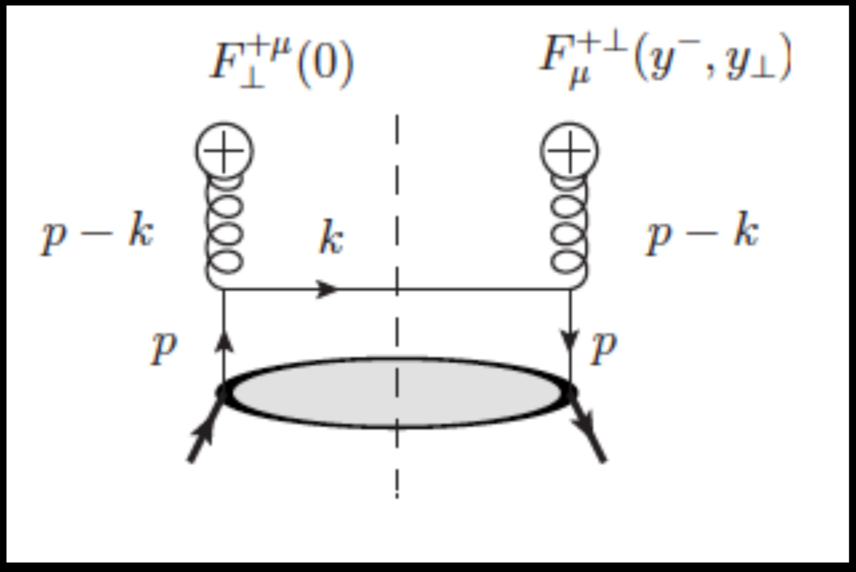
How about x or η dependence of $\hat{q}$

- The Glauber condition prevents a direct application of this established procedure.

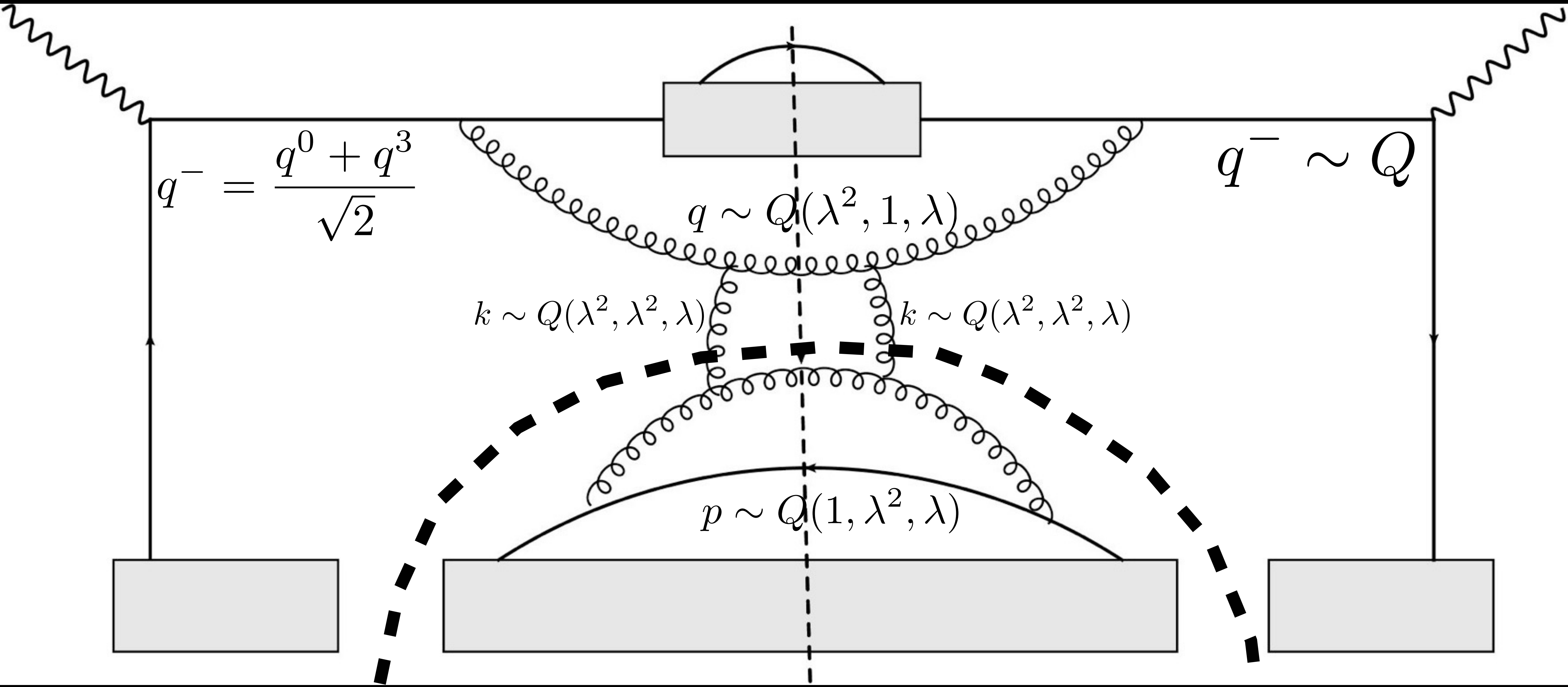


$$\delta\left(k^+ - \frac{k_\perp^2}{2q^-}\right)$$ forces the incoming lines off-shell

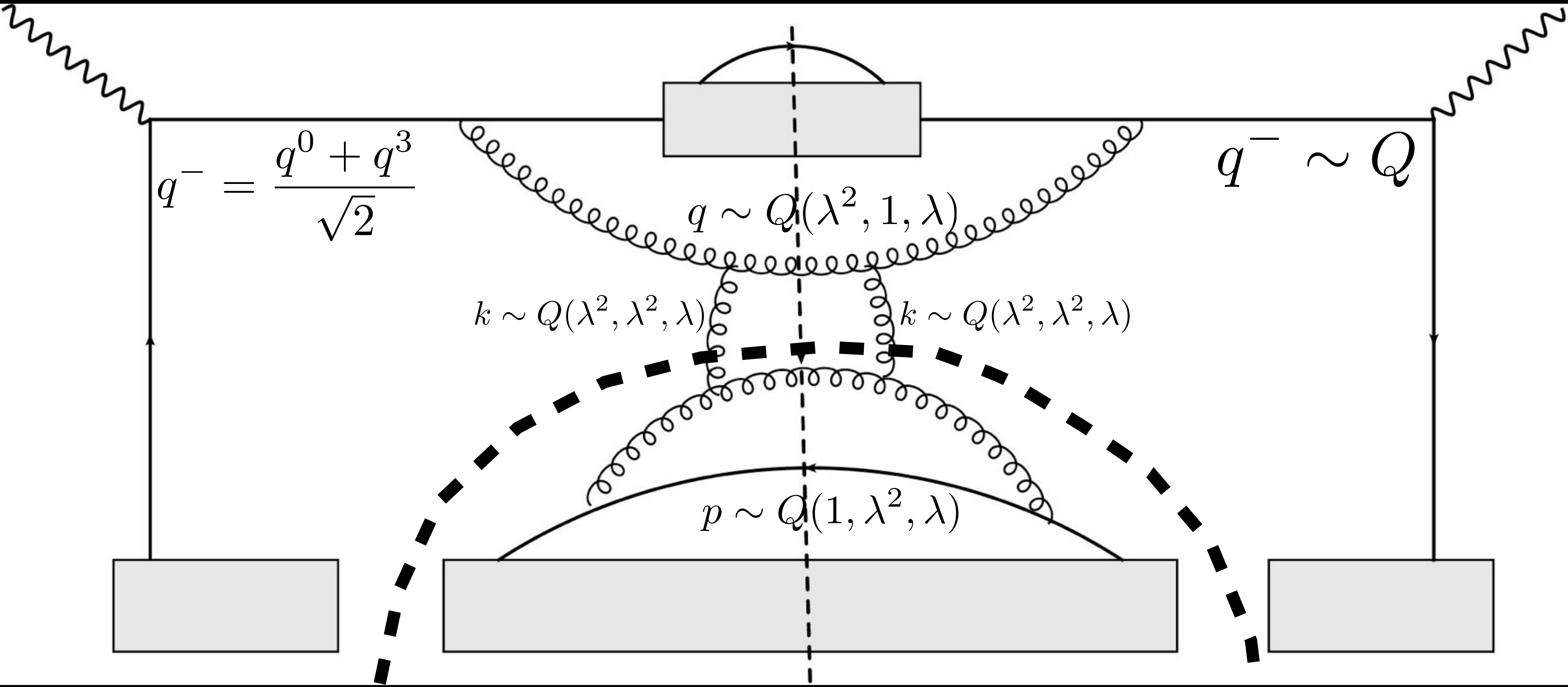
$\hat{q}$ is a 3-D object depending on x, $\underline{k}_T$
Like a TMDPDF,
at large $\underline{k}_T$ can *refactorize* to
regular PDF X radiated gluon
Contributions start at order α_S,



A factorized picture



A factorized picture

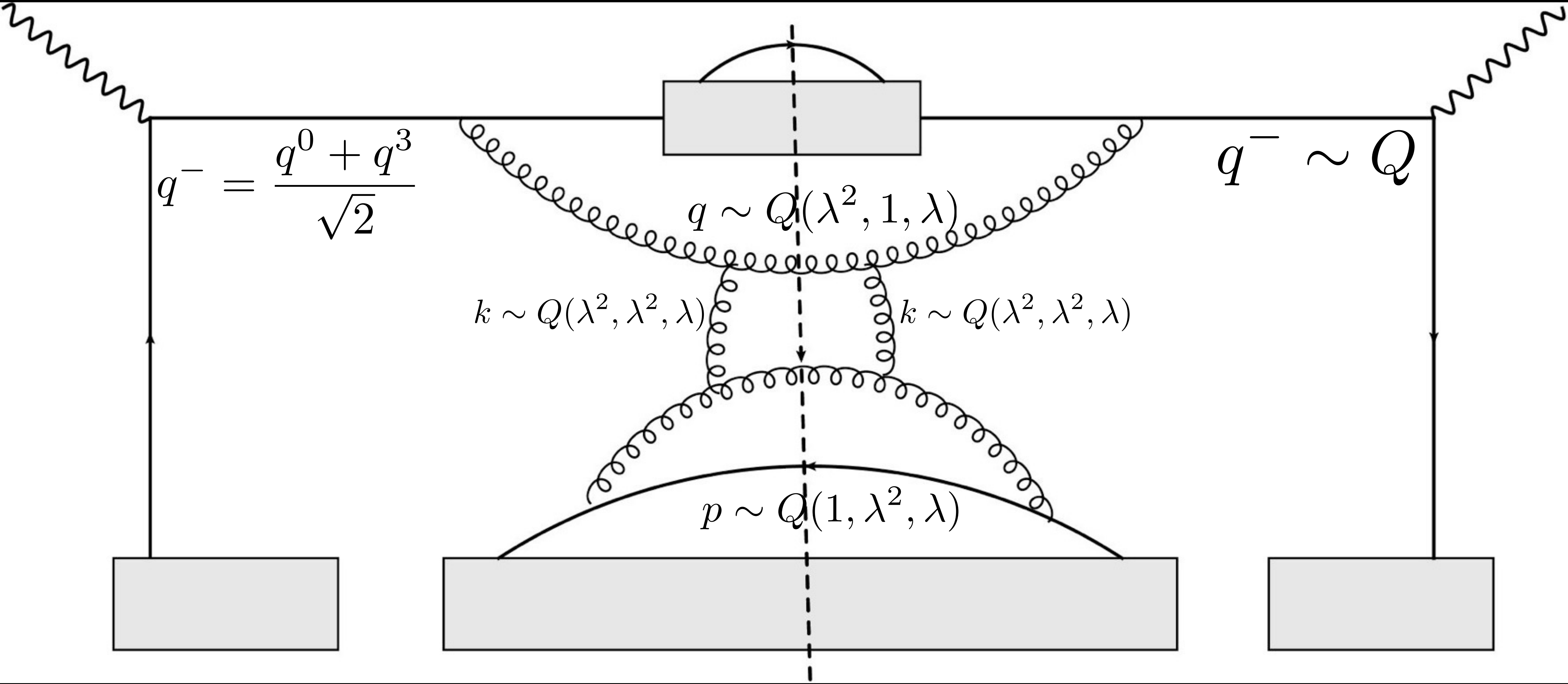


Q is the hard scale of the jet ~ E

$Q\lambda$ is a semi-hard scale ~ $(ET)^{1/2}, \lambda \longrightarrow 0$

$\hat{q}$ contains all dynamics below $Q\lambda$

A factorized picture



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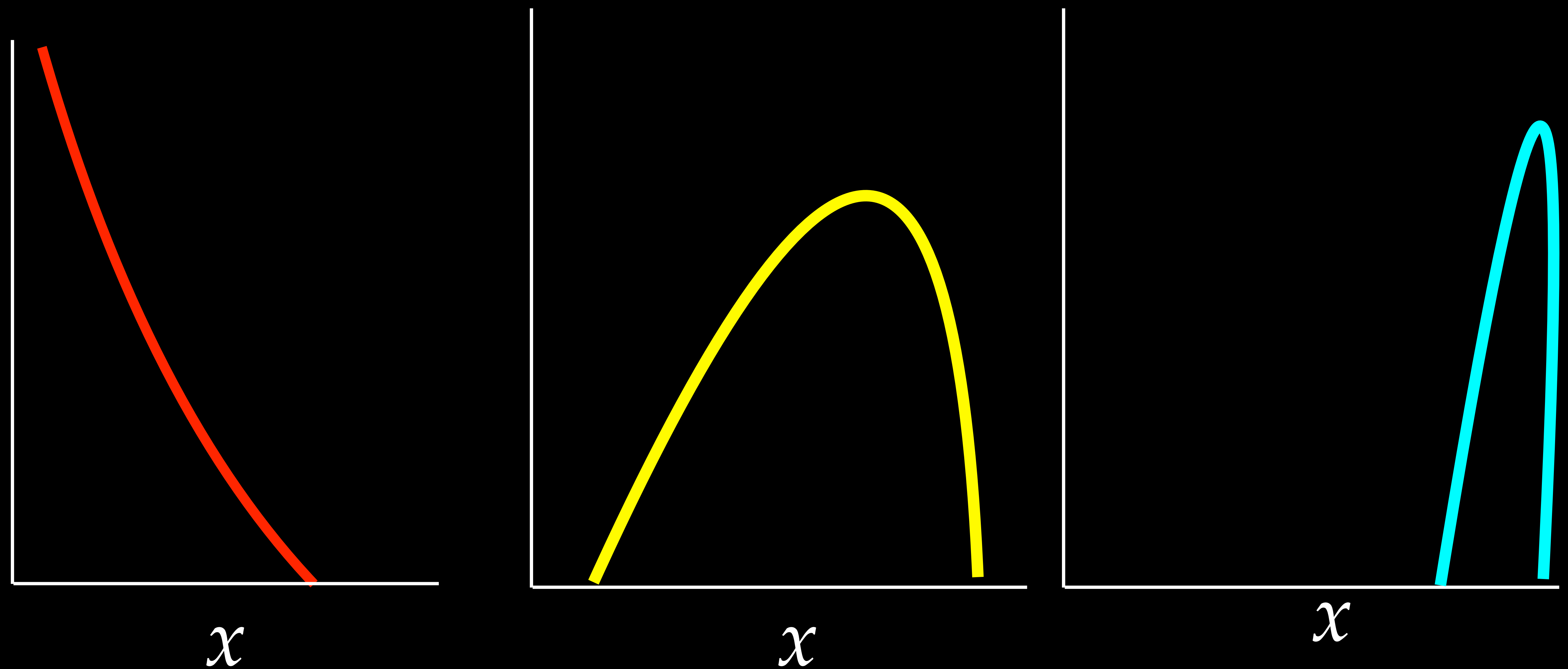
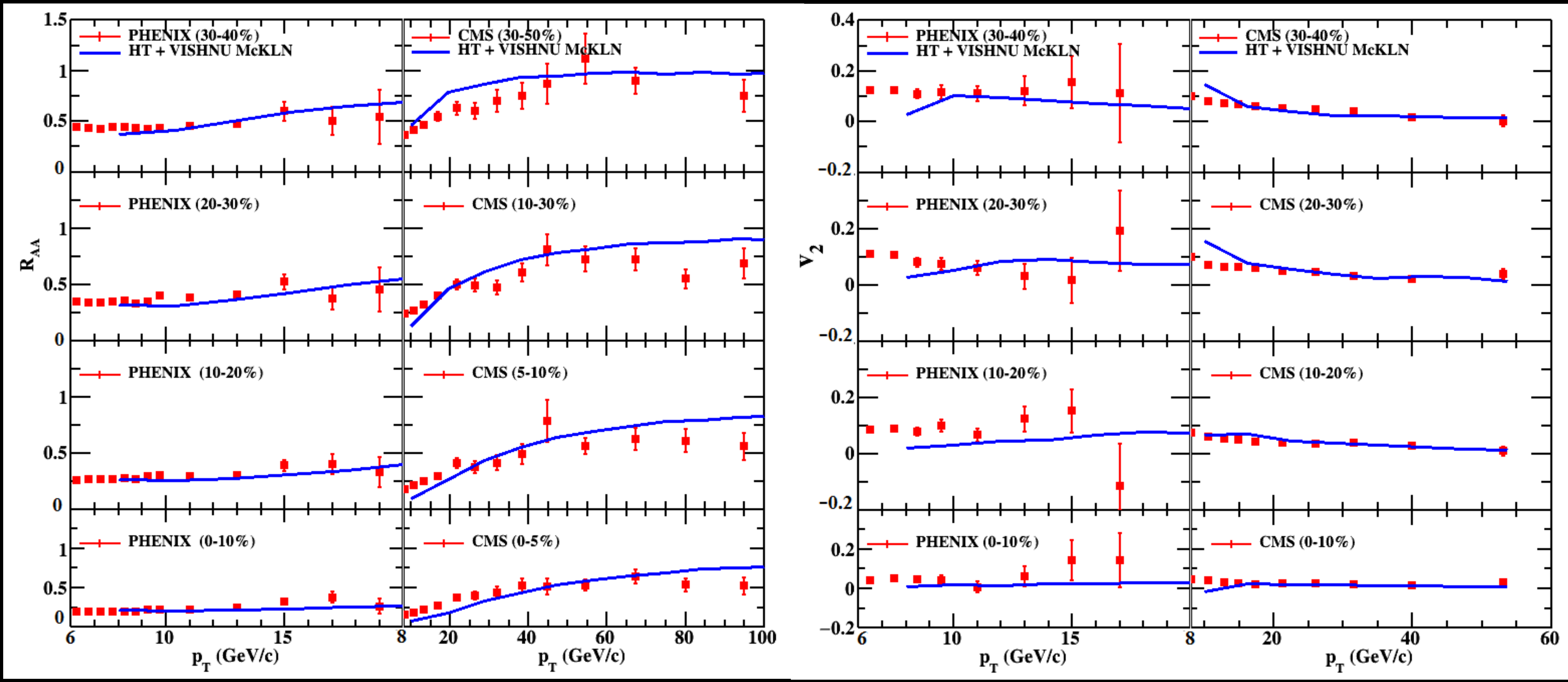
Input PDF at $Q^2 = 1\ \mathrm{GeV}^2$

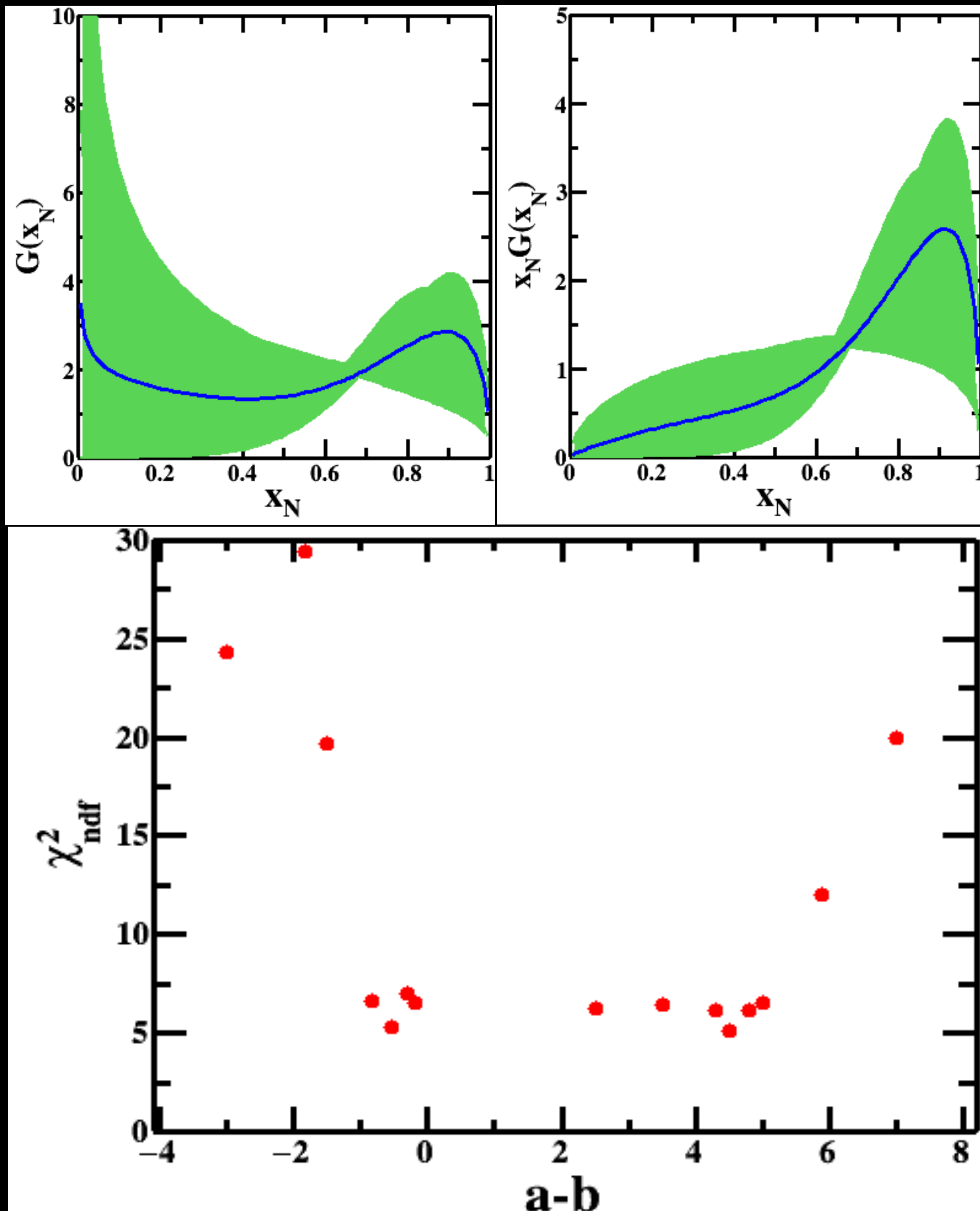


Sea like | Wide Valence | Narrow Valence

Putting it all together



Input PDF



$$G(x) = Cx^a(1-x)^b$$

making *b* negative increases strength at x ~ 1

Seems ruled out by fits..

Mass of d.o.f. less than mass of nucleon.

What does this mean?

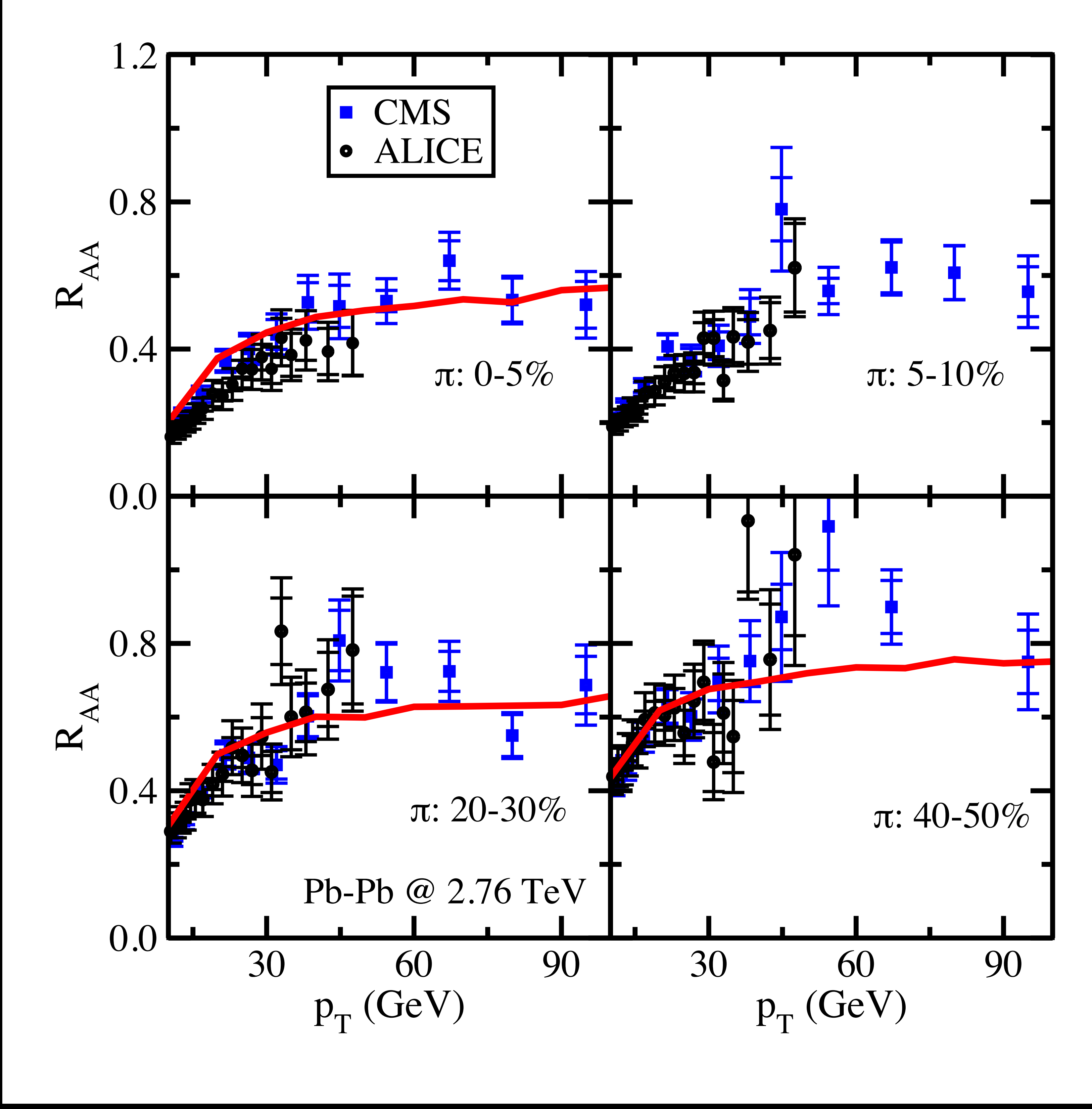
- Possible resolution of the JET puzzle
- Based on consistent Q^2 evolution of $\hat{q}$
- Should have x evolution at high energy
- Applying TMD systematics, may complicate this interpretation.
- $\hat{q}$ may lie at the intersection of DGLAP and BFKL (previously explored by Casalderray-Solana and Wang)

Going from semi-analytic (event-averaged) to MC event generators

Some parts are done with much greater accuracy

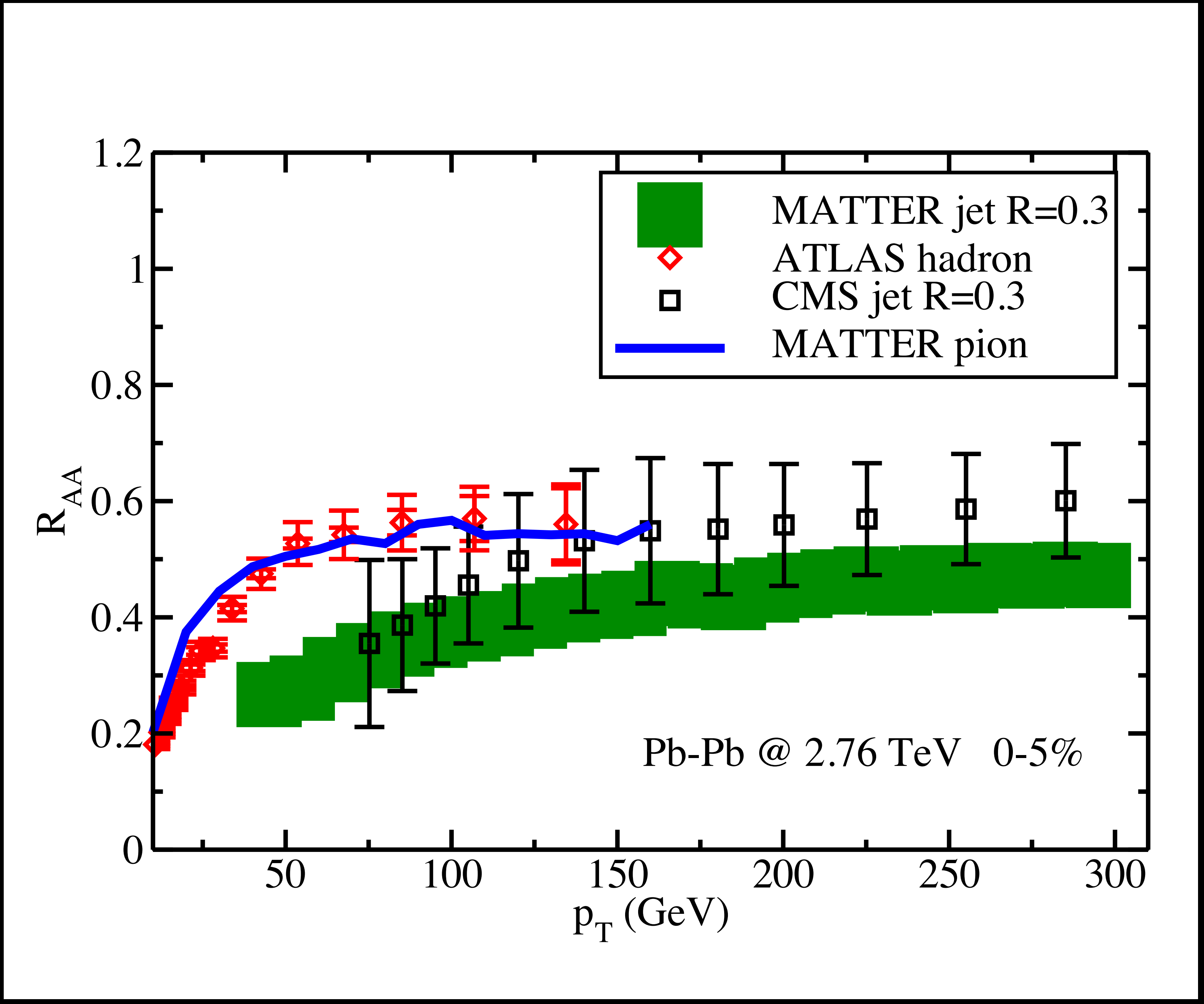
at low p_T sensitive to in-medium frag.

Need a prescription at lower p_T. Used hard cut for partons at Q=1GeV more than a fm inside

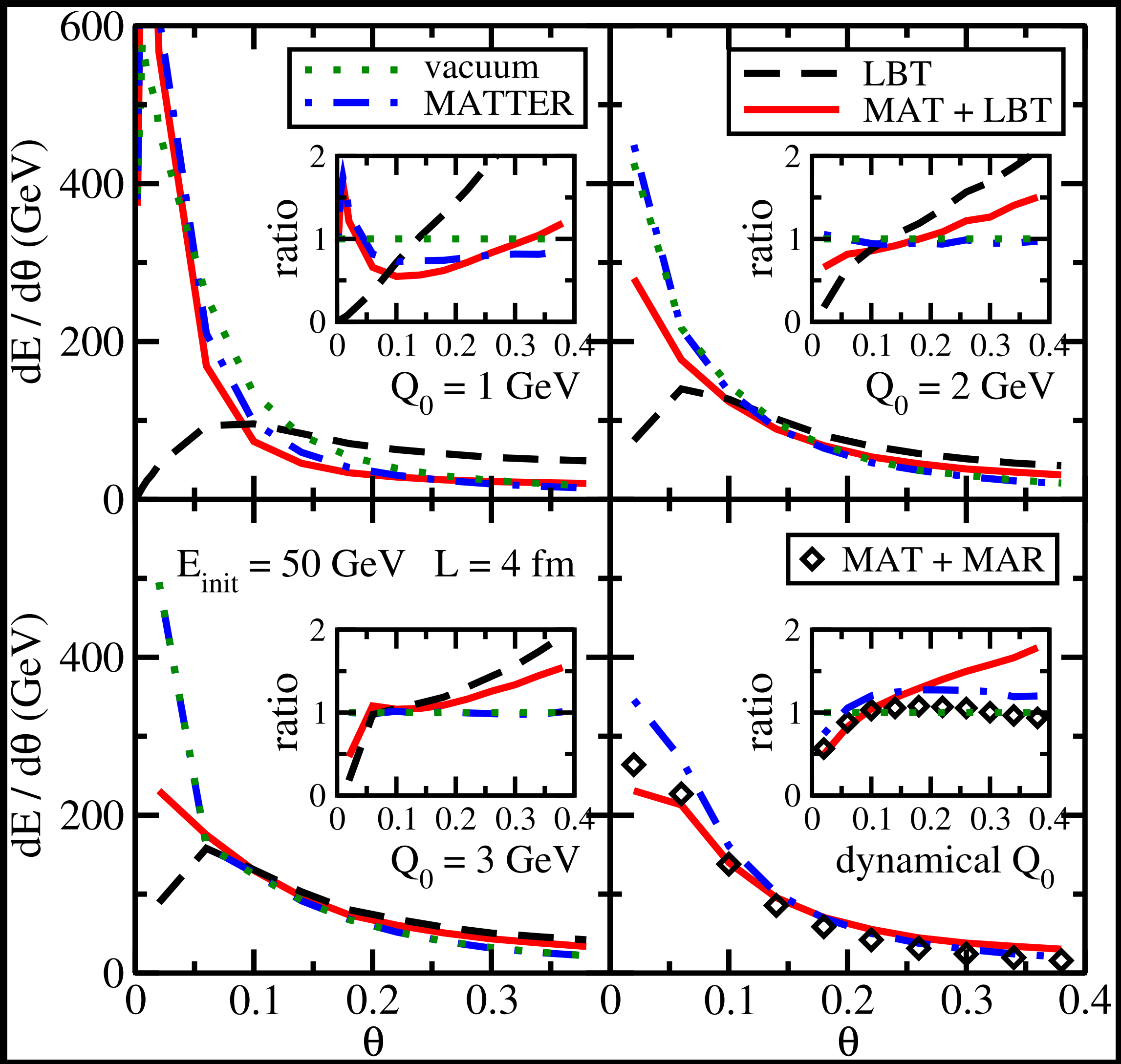


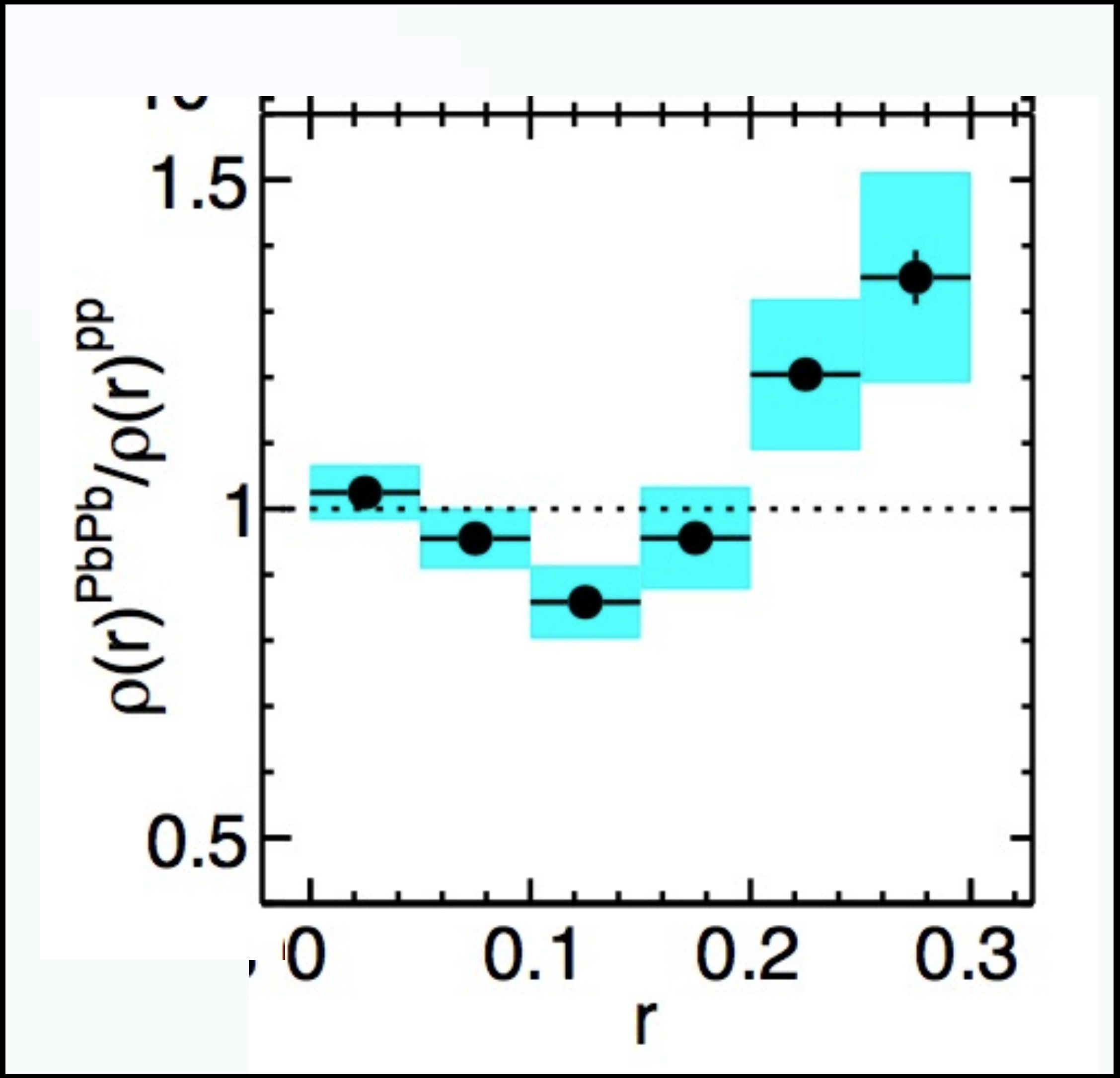
More sensitive to multiple scales for full jet

- jets done partonically
- hard cut for Q<1GeV more than 1fm in
- Should do the Q<1GeV more carefully
- Enter JETSCAPE!



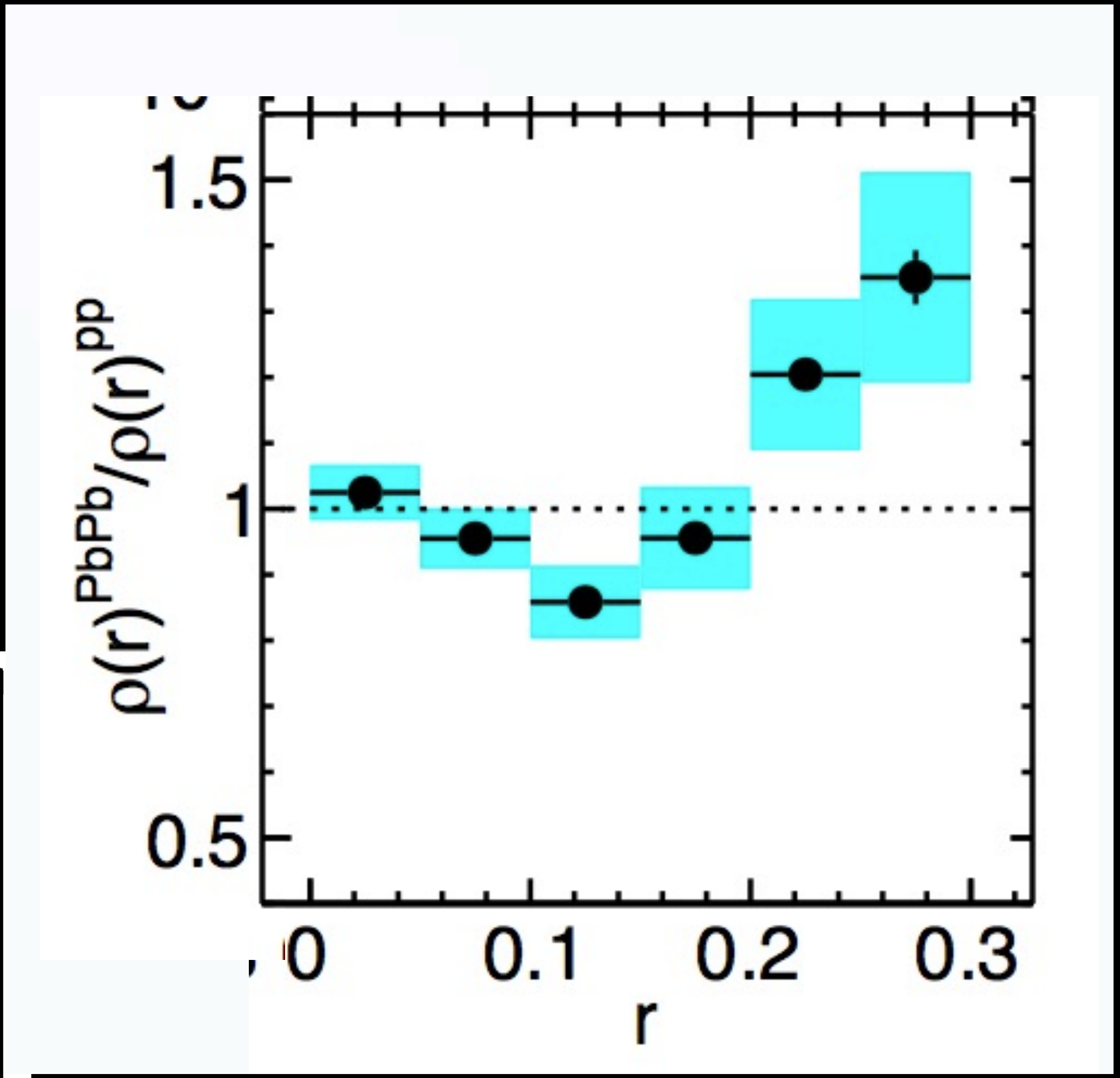
Evidence of multiple scales from multiple-stage Monte Carlos

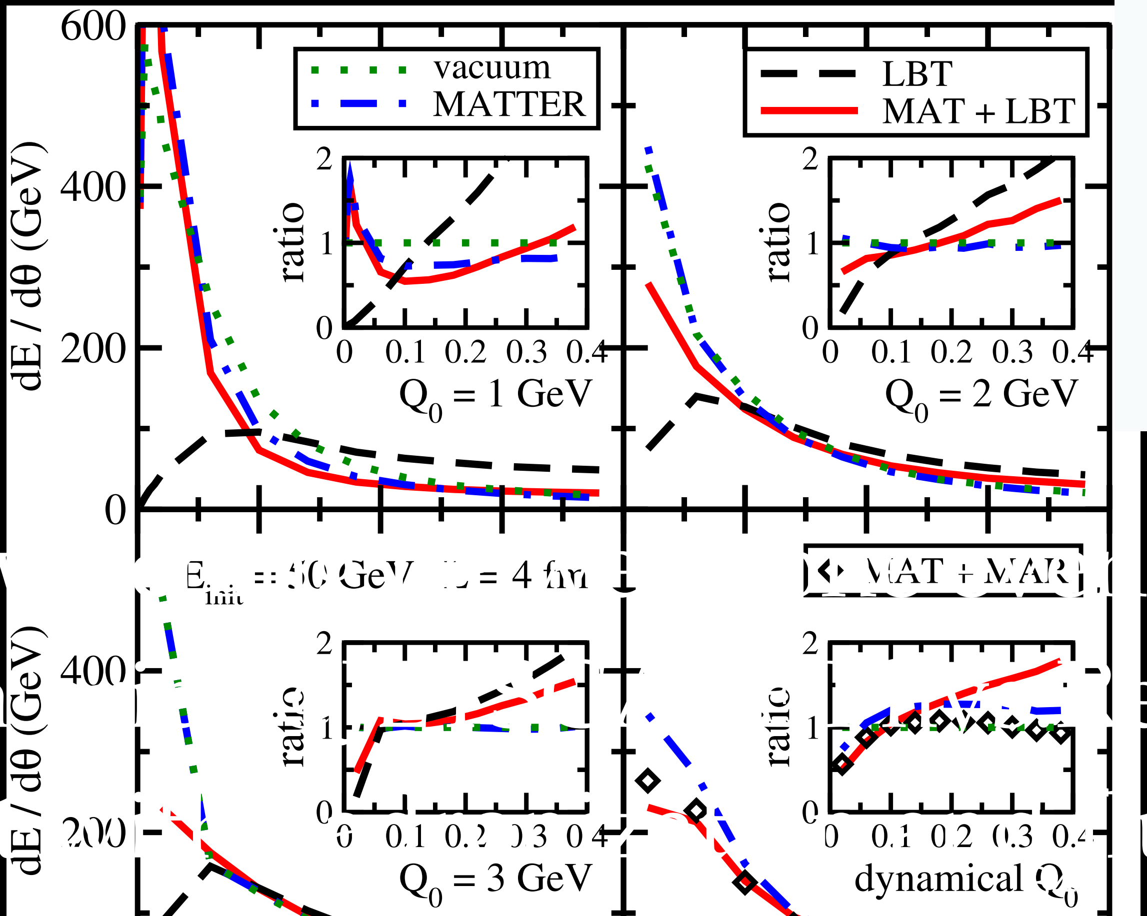




Switching between one event-generator and the next
in a brick @JETSCAPE Phys.Rev. C96 (2017) no.2, 024909
Repeat with hadronization and fluid medium being calculated

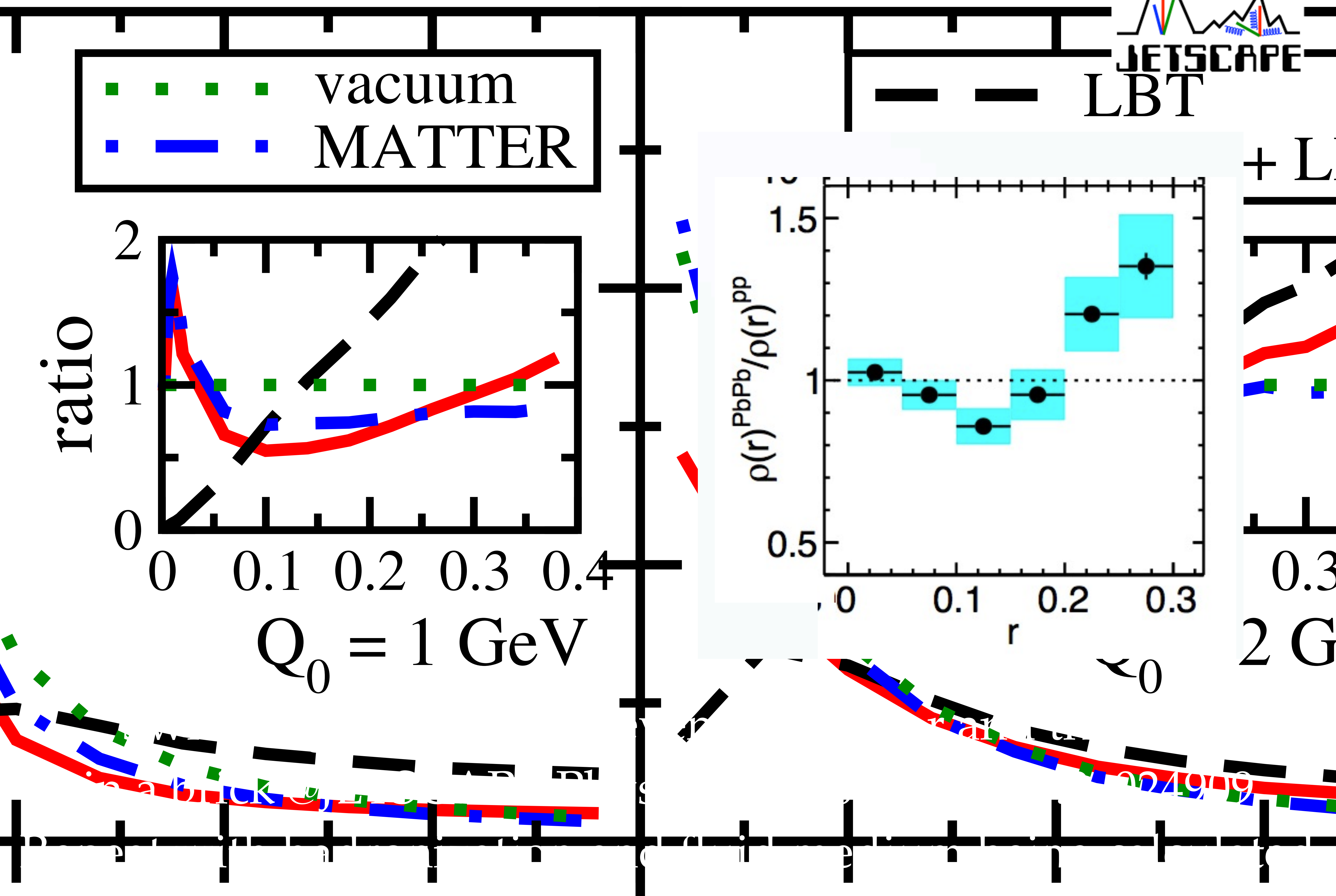
Evidence of multiple scales from multiple-stage Monte Carlos





Sy… t-generator and the next
in a… ev. C96 (2017) no.2, 024909
Repea… uid medium being calculated

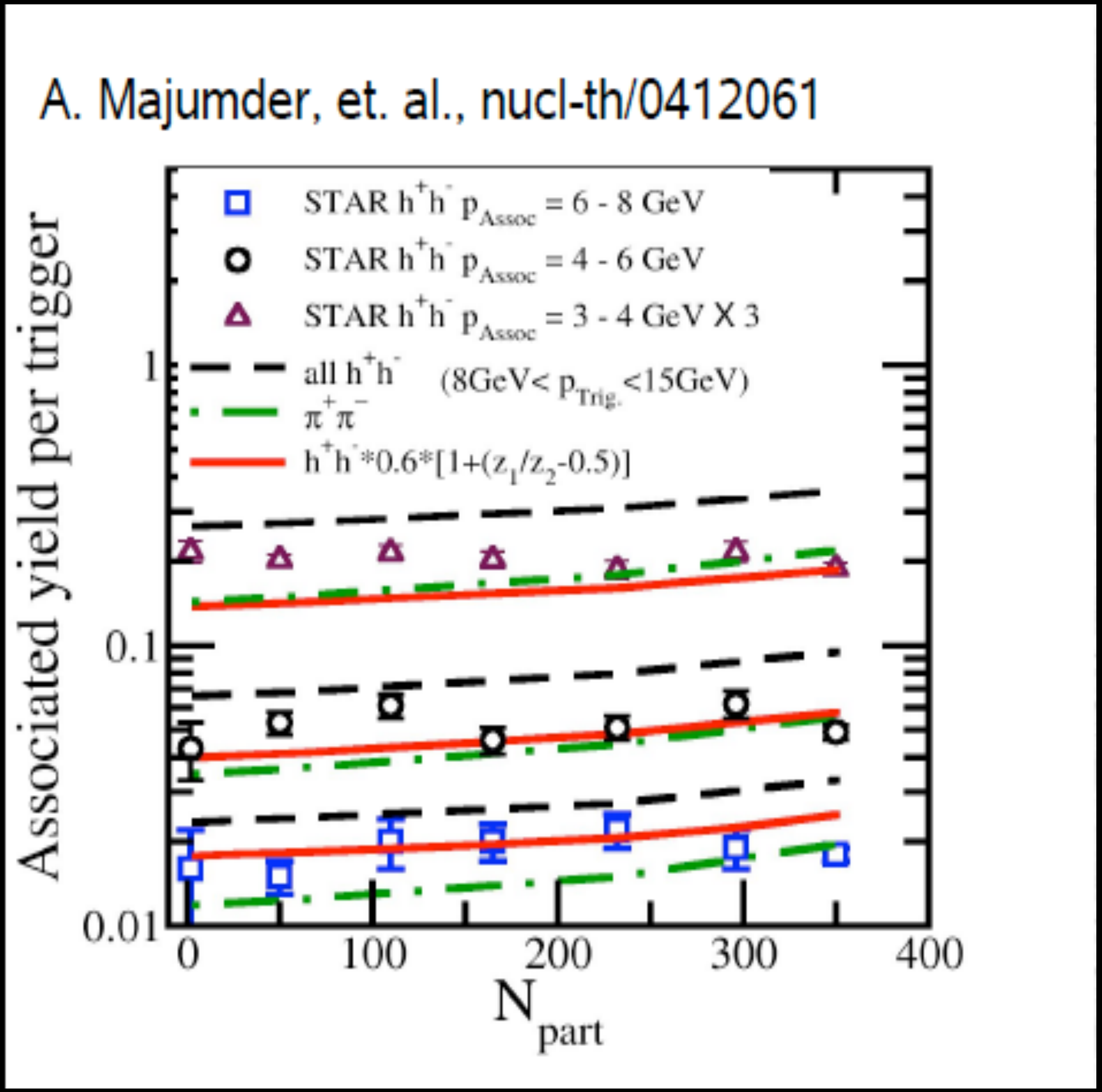
Evidence of multiple scales from

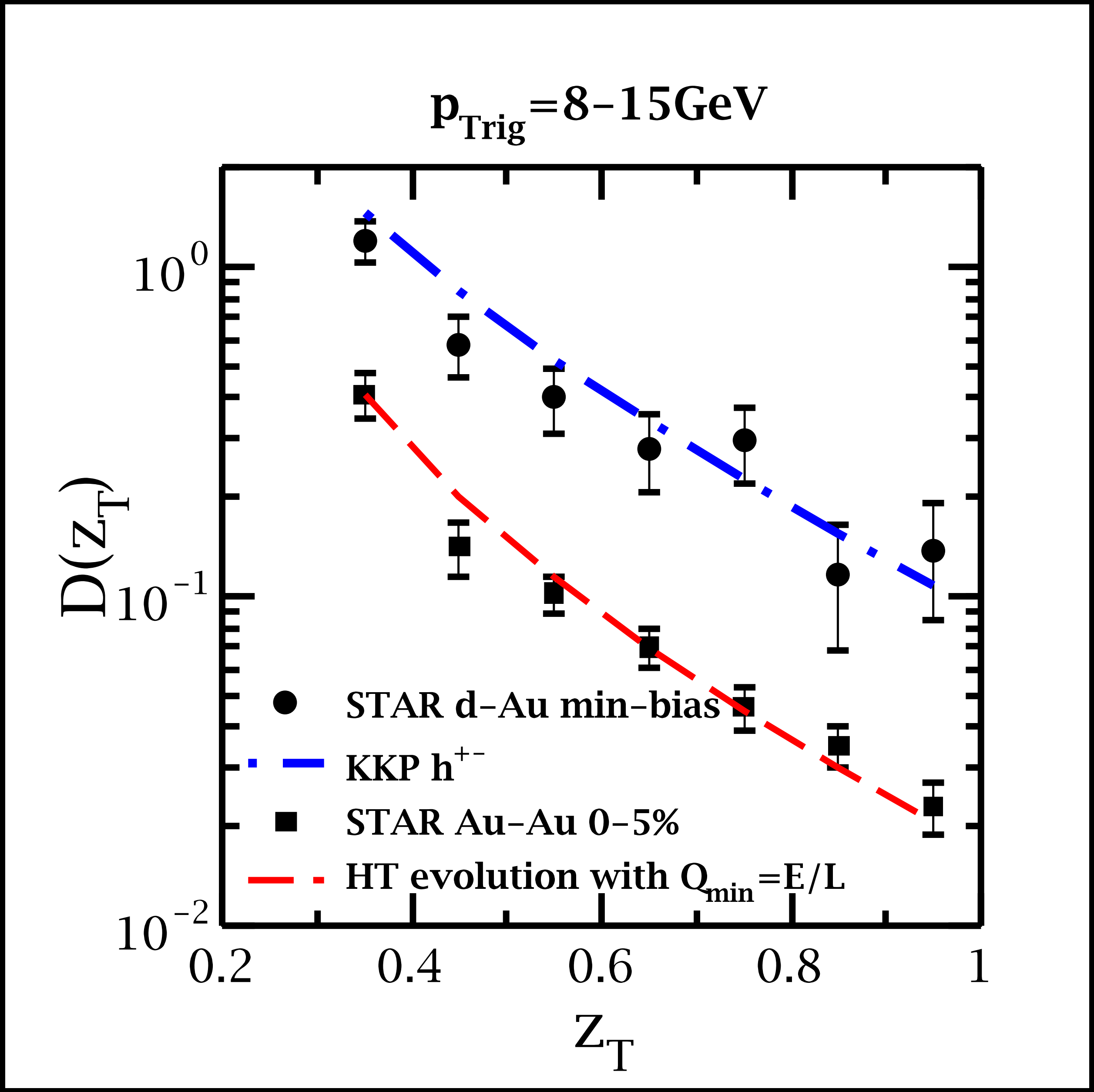


Outlook

- We really need to understand/model sub-leading hadronization
- Jets with R ~ 0.4 involve hadrons from the medium
- Jets involve energy deposited from hard partons to medium and then reconstructed in jet (This process needs to be well understood and modeled)
- There is no vacuum jet formation for RHIC and LHC jets
  $\tau \sim E/(E\,R)^2 = 1/(ER^2) = 1\ \mathrm{GeV}^{-1} \sim 0.2\ \mathrm{fm}$
  (for E =100 GeV, R = 0.1).

Near side and away side correlations

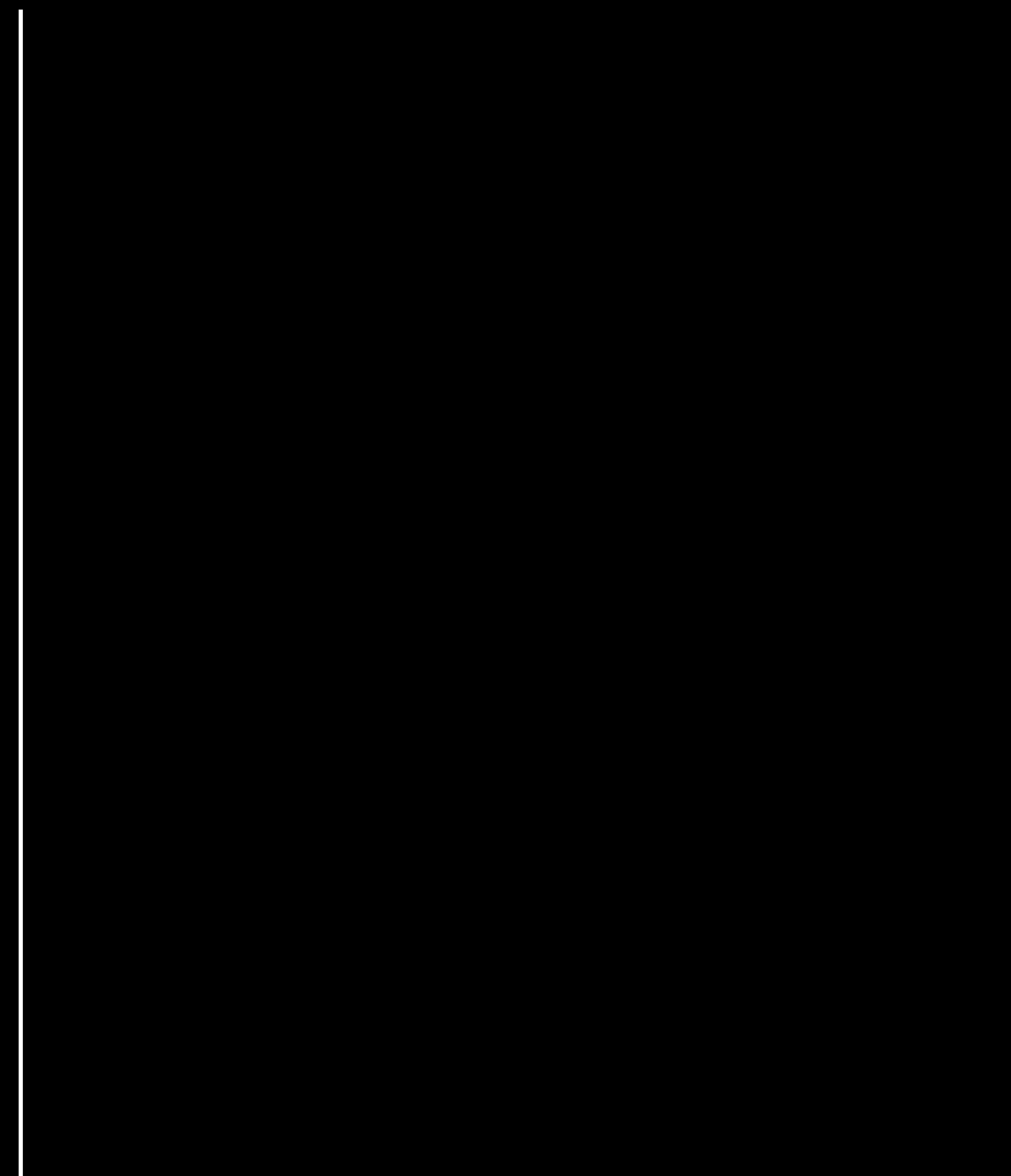




A wide range of single particle observables can be explained by a weak coupling formalism

How the jet sees the medium depends on jet scale

Extracted $\hat{q}$ has a lot or fluctuation included in it. Looks different at different scales



l /E or x

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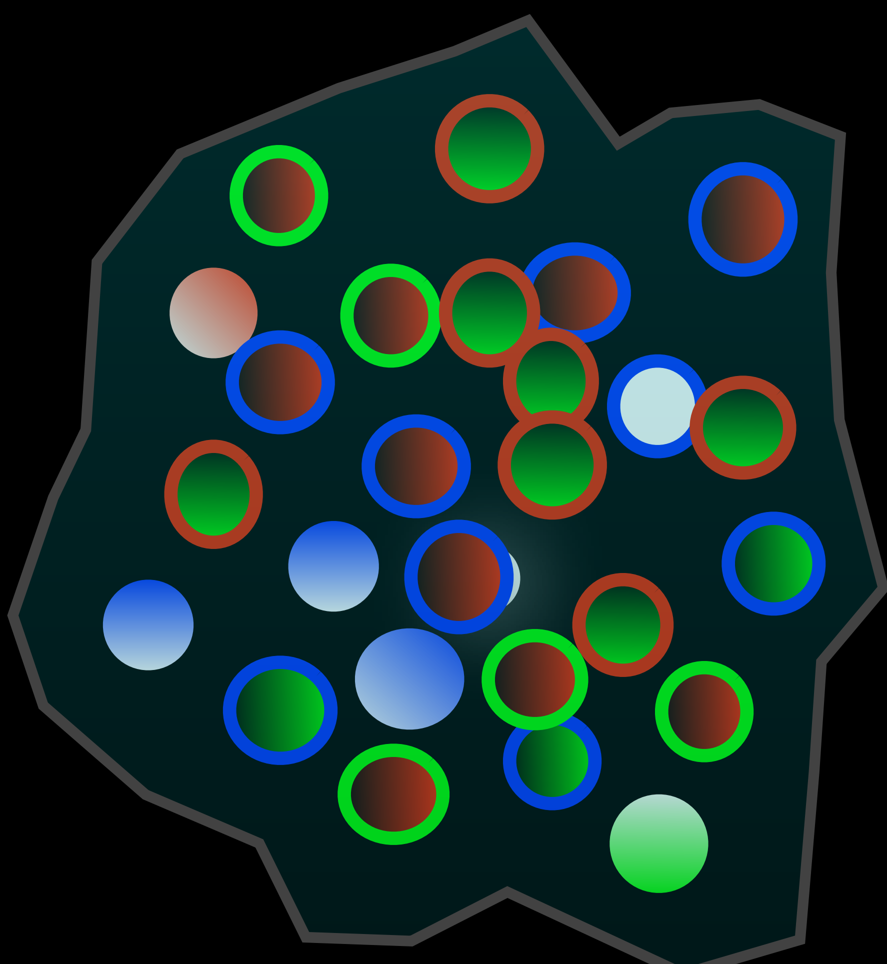

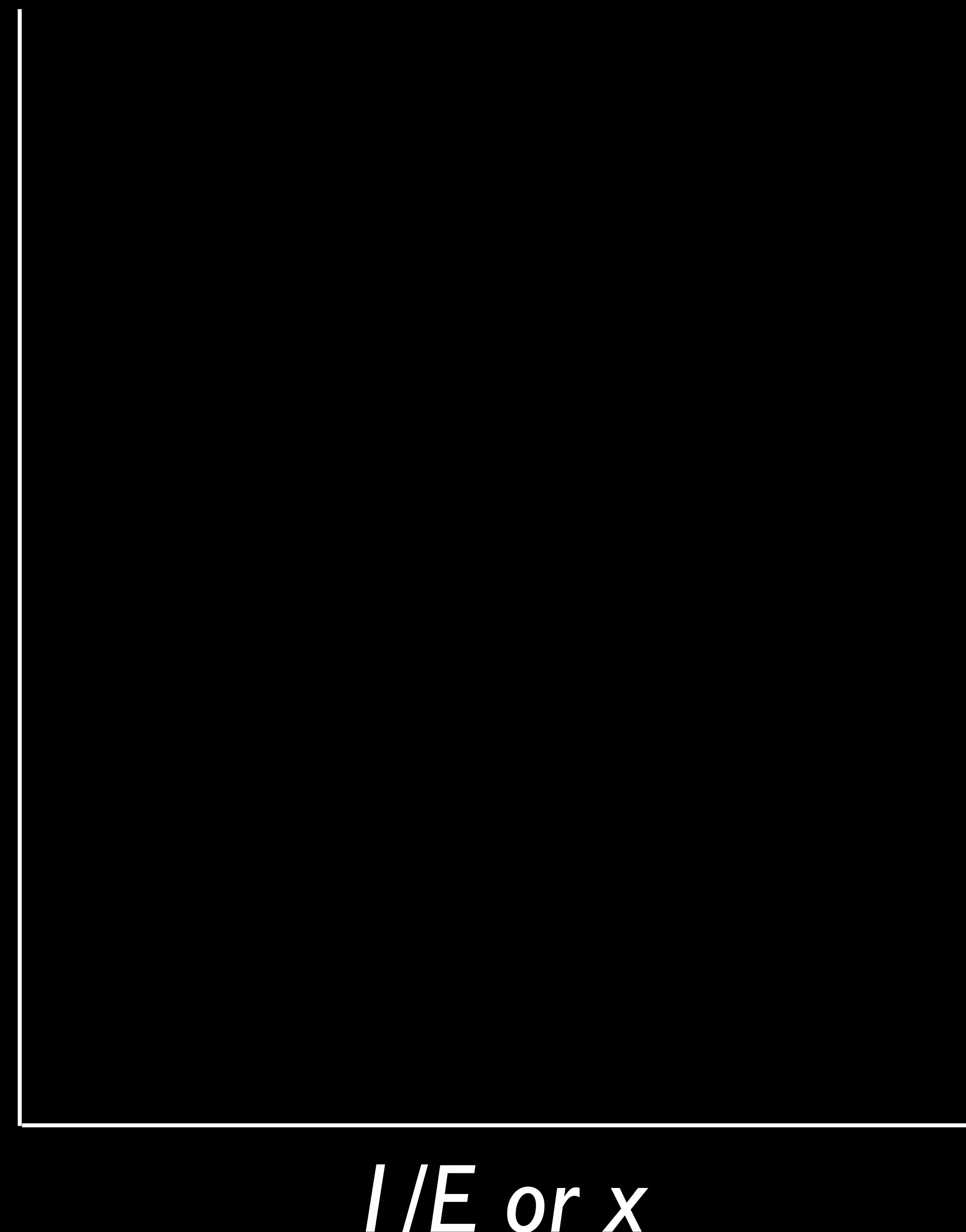

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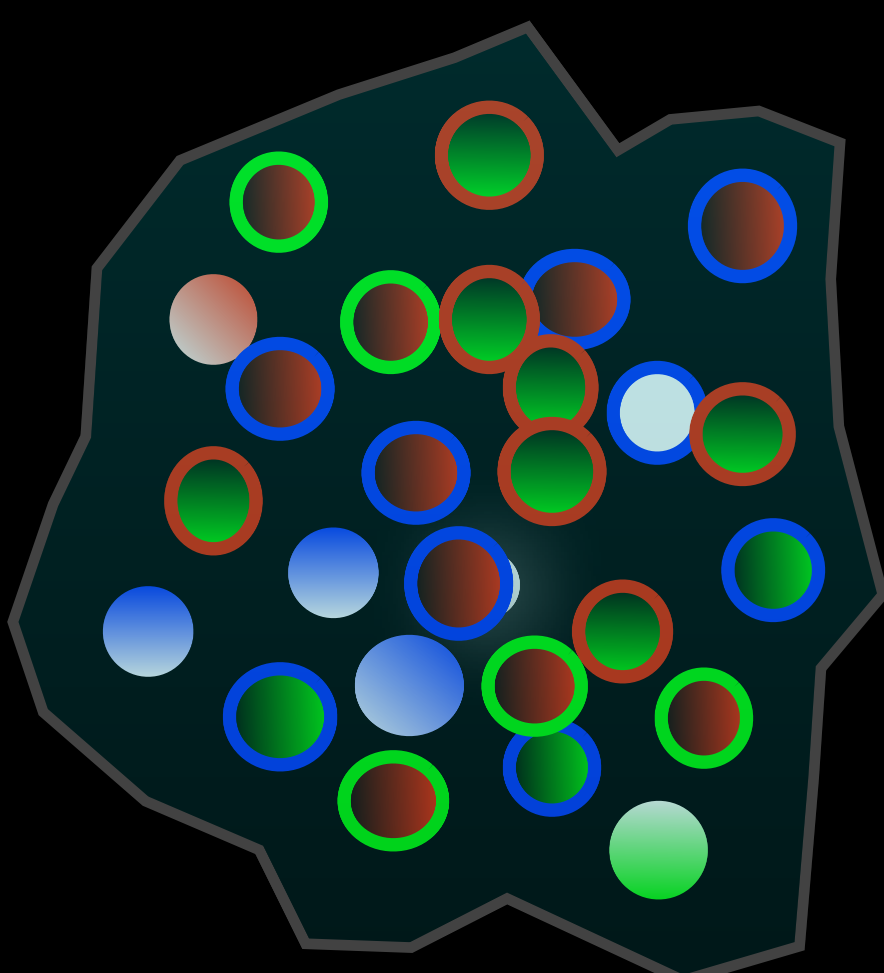

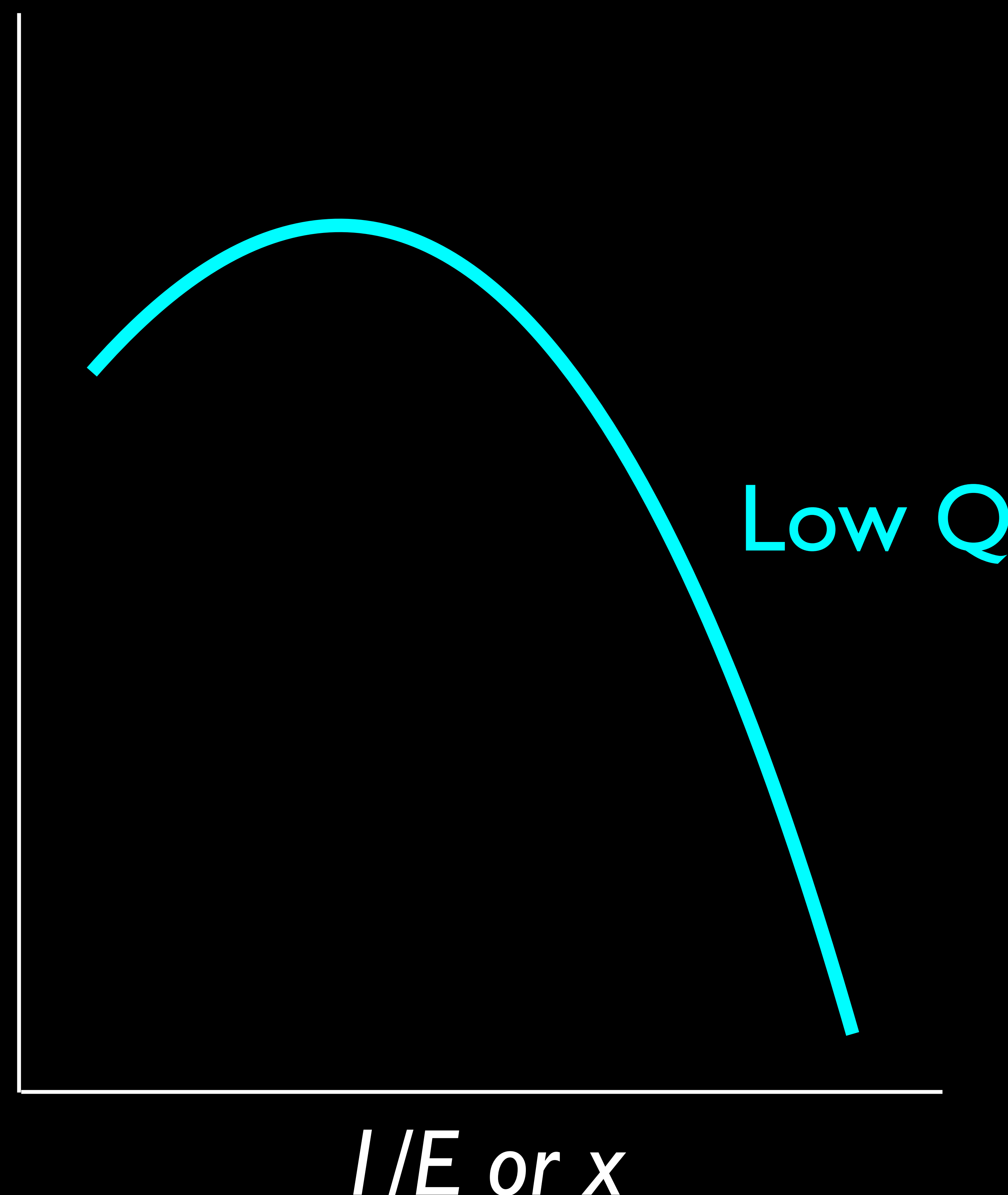

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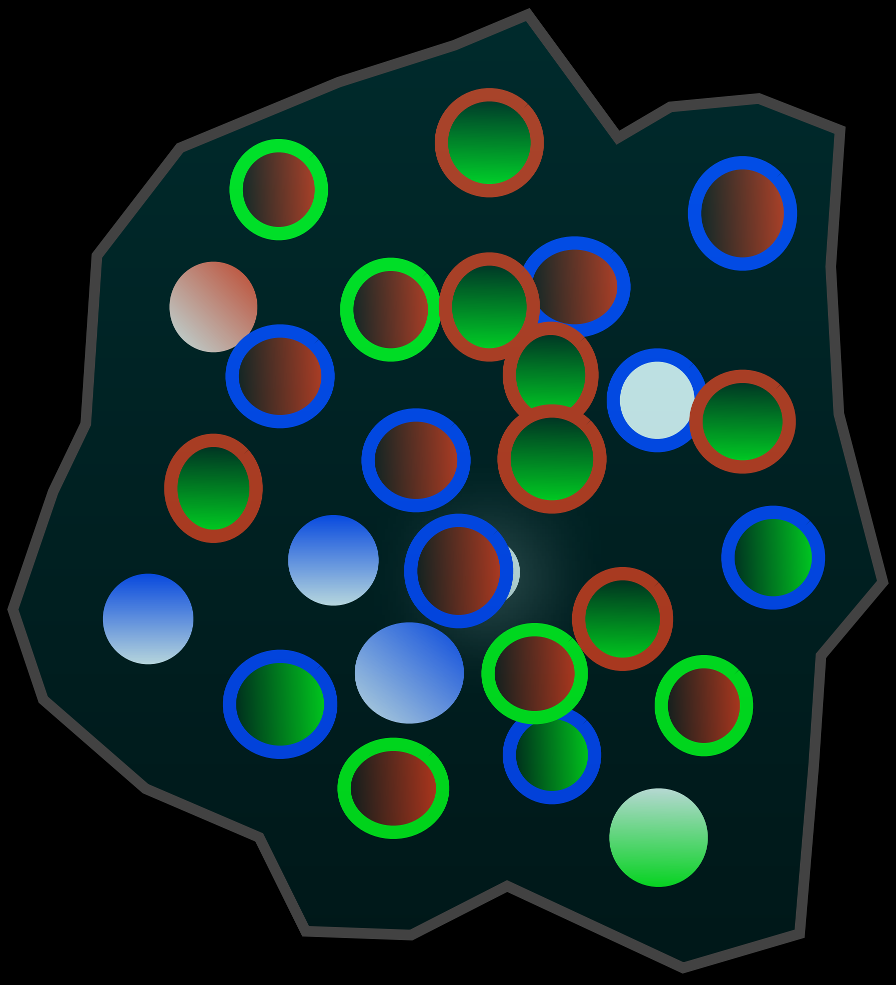

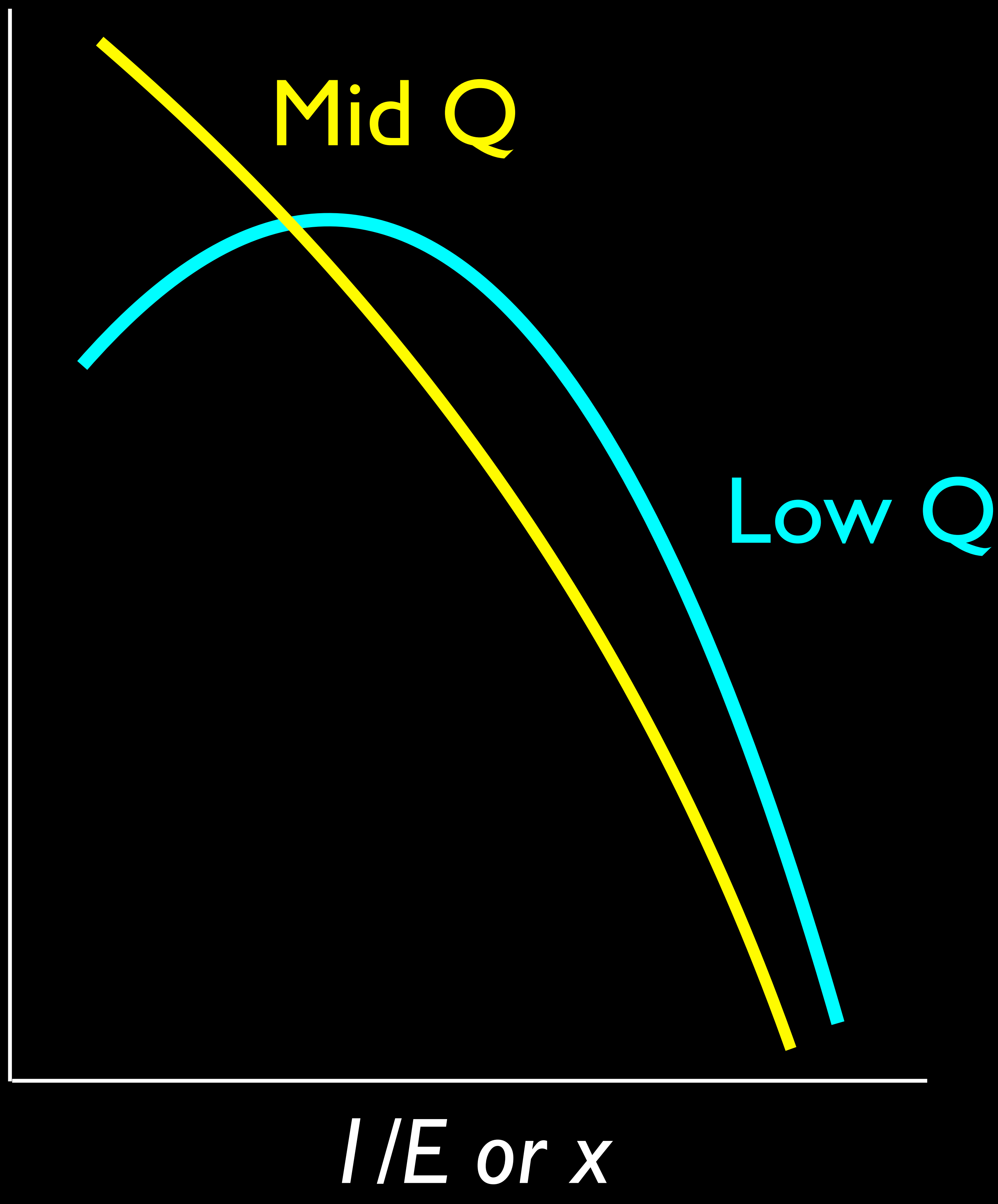

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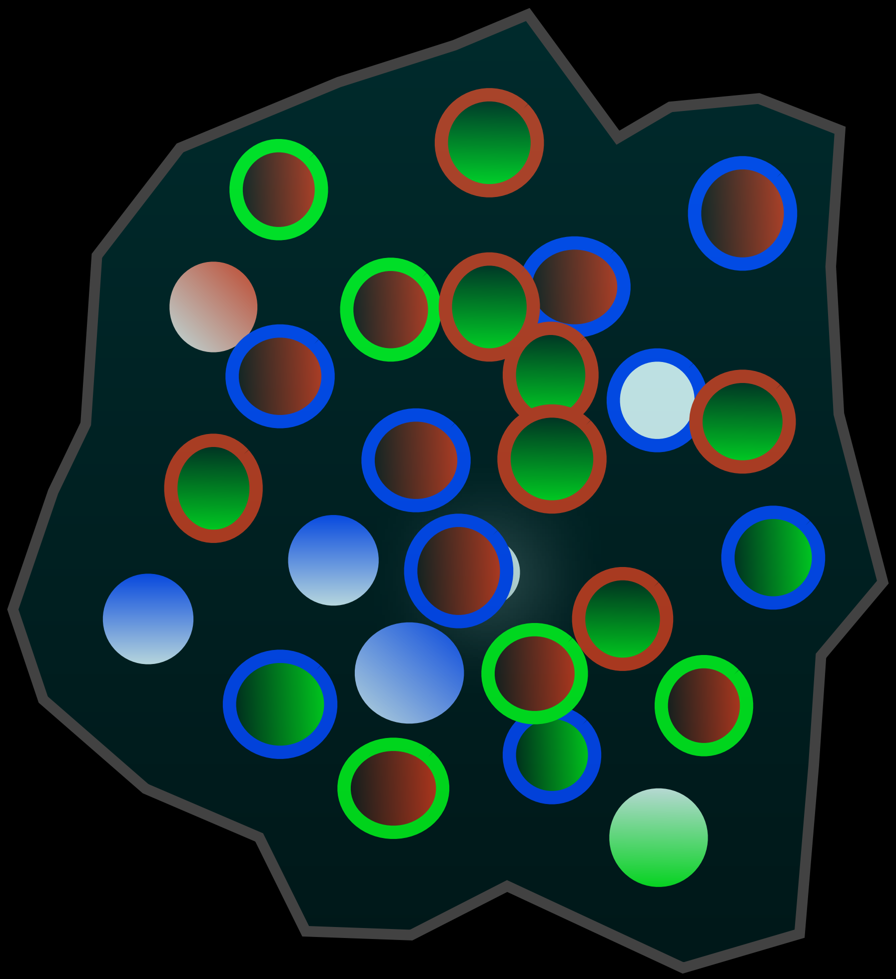
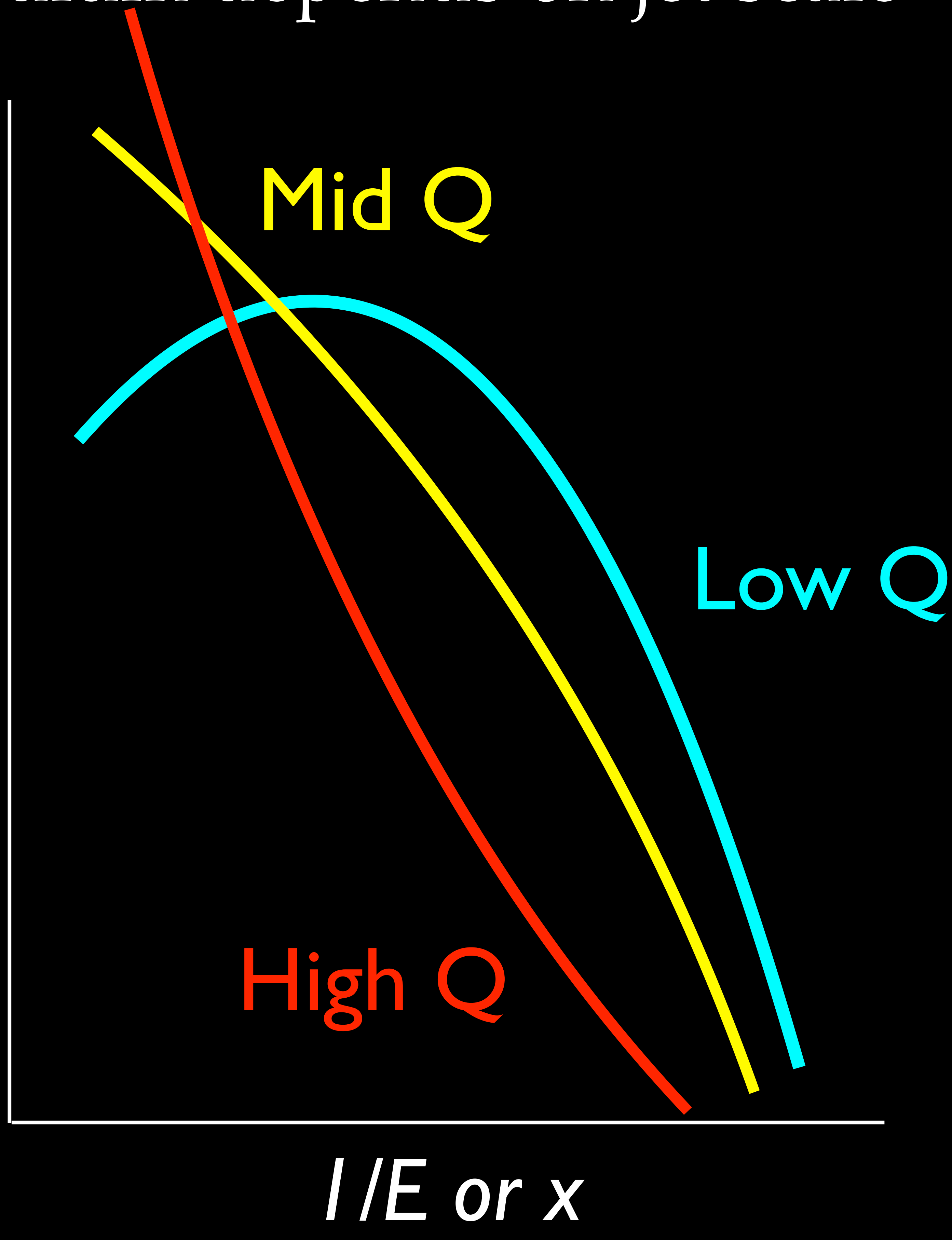
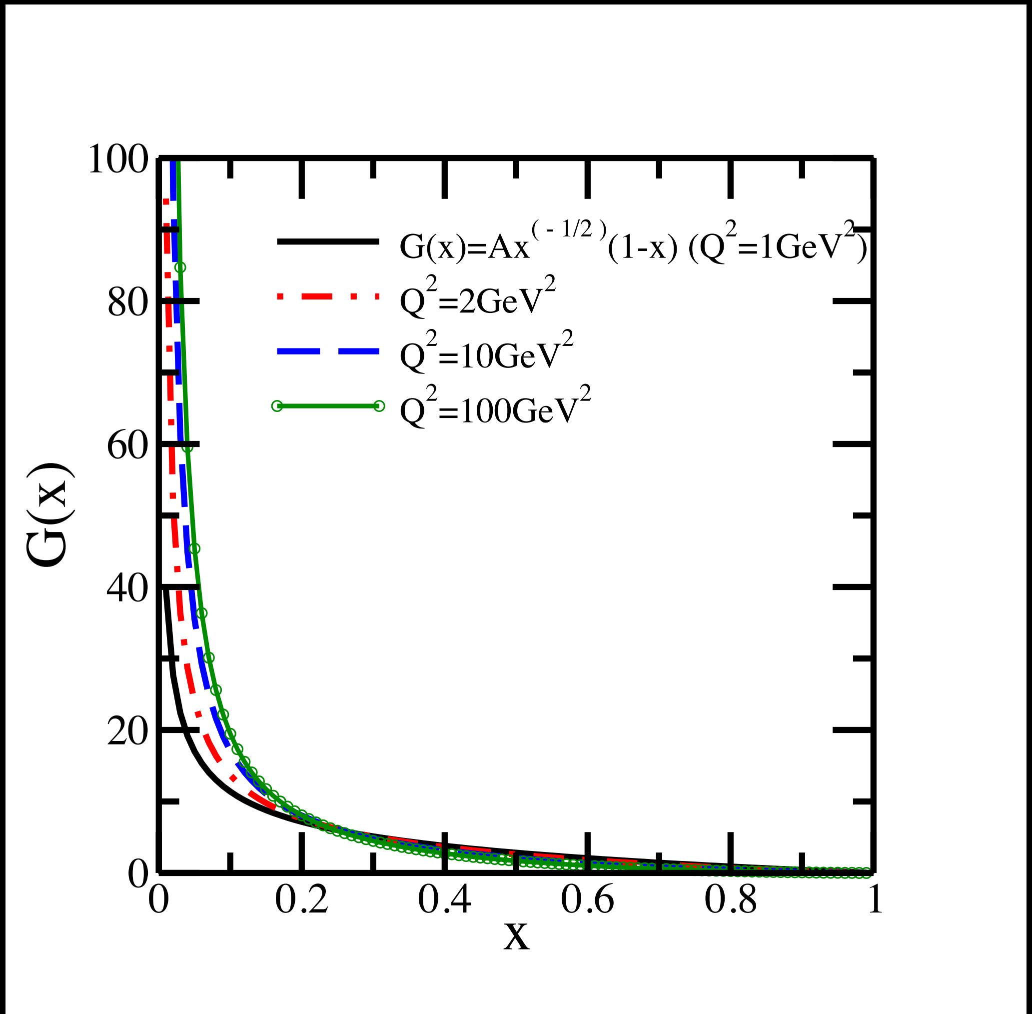
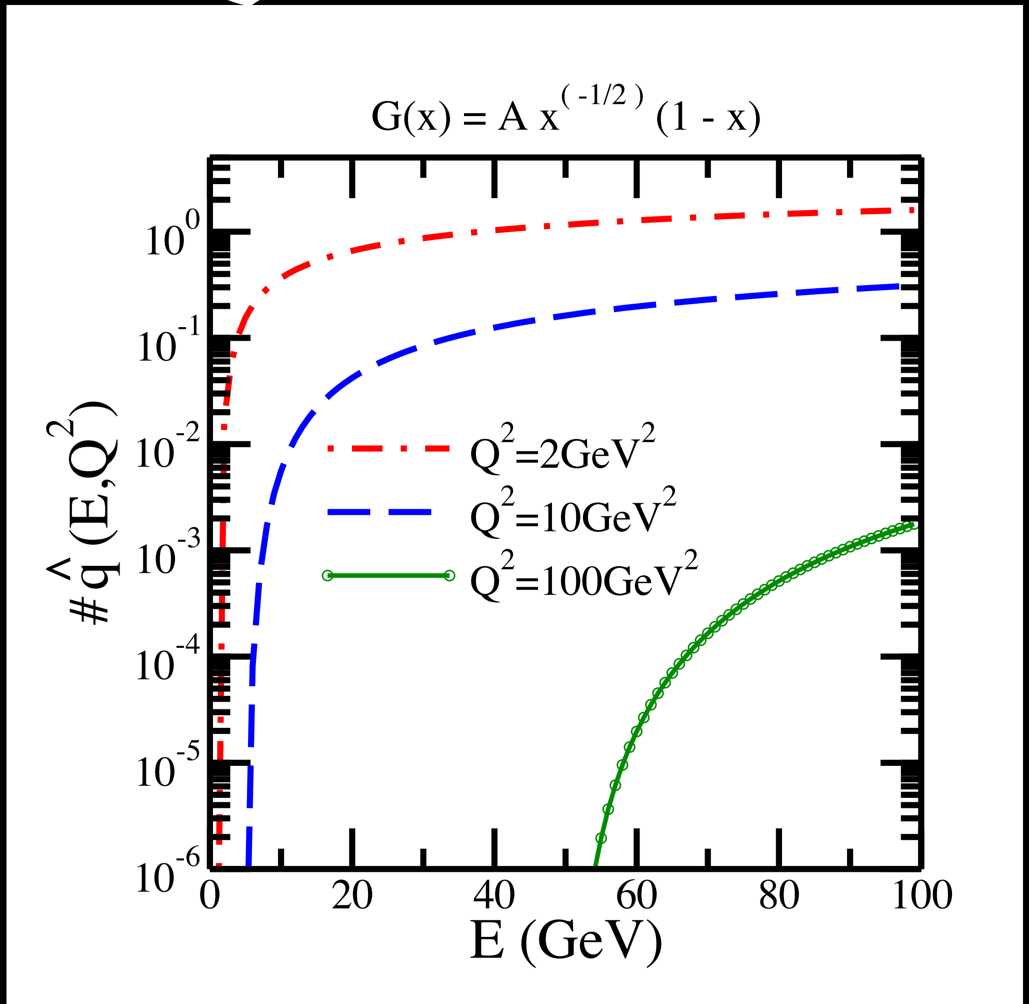
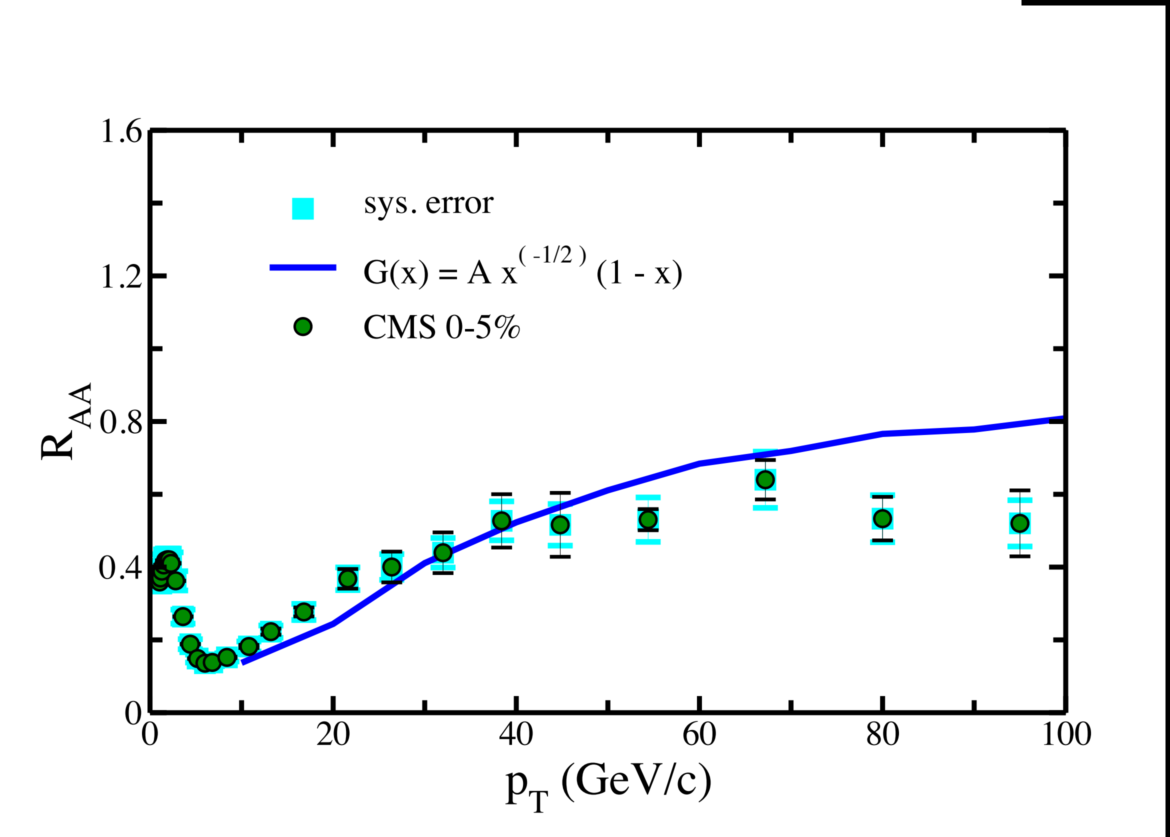


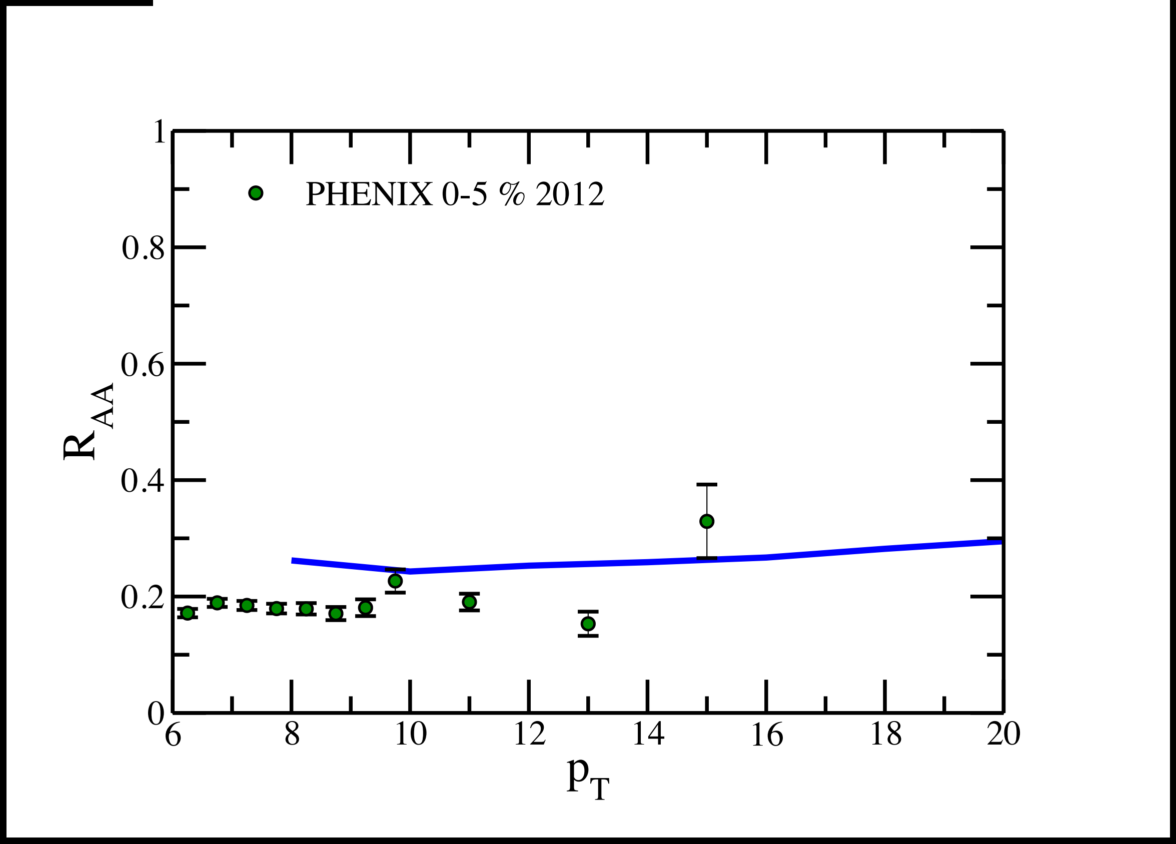


Sea-like PDF of the QGP

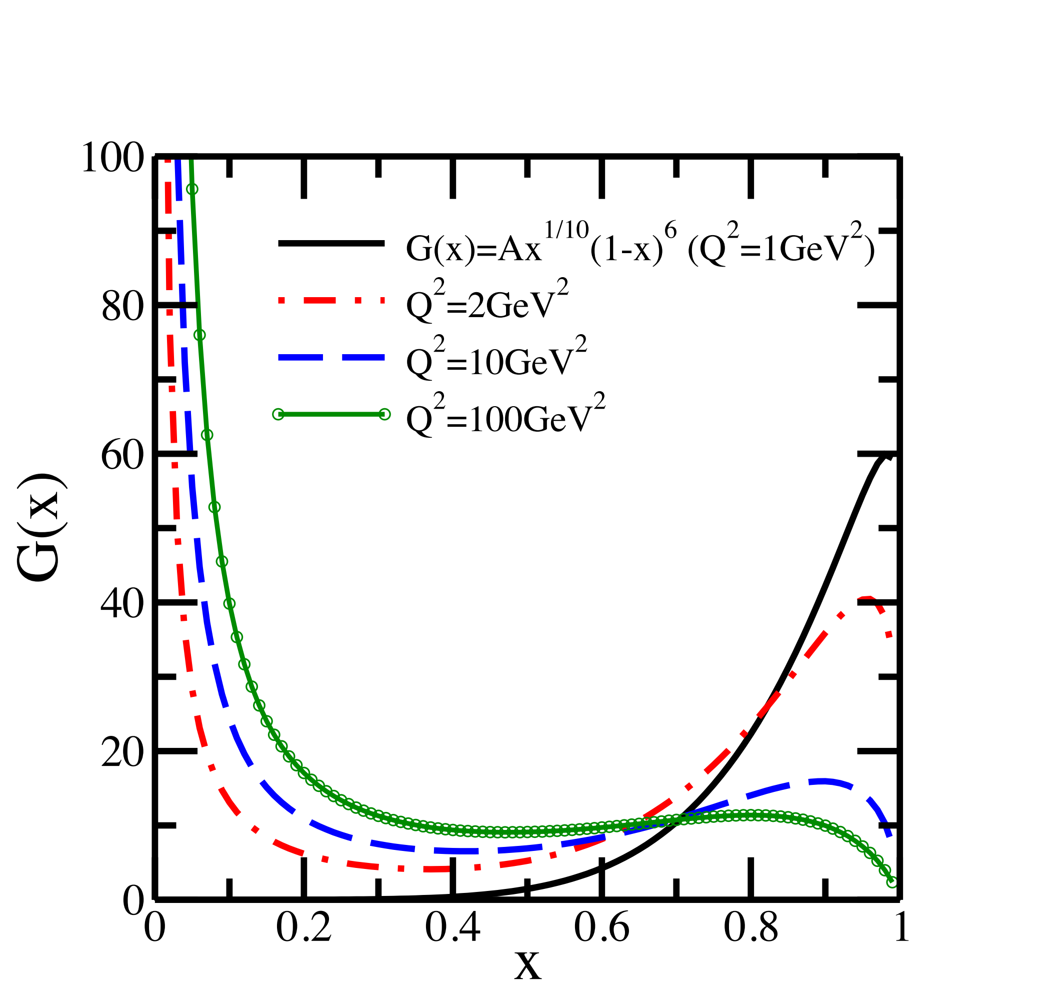


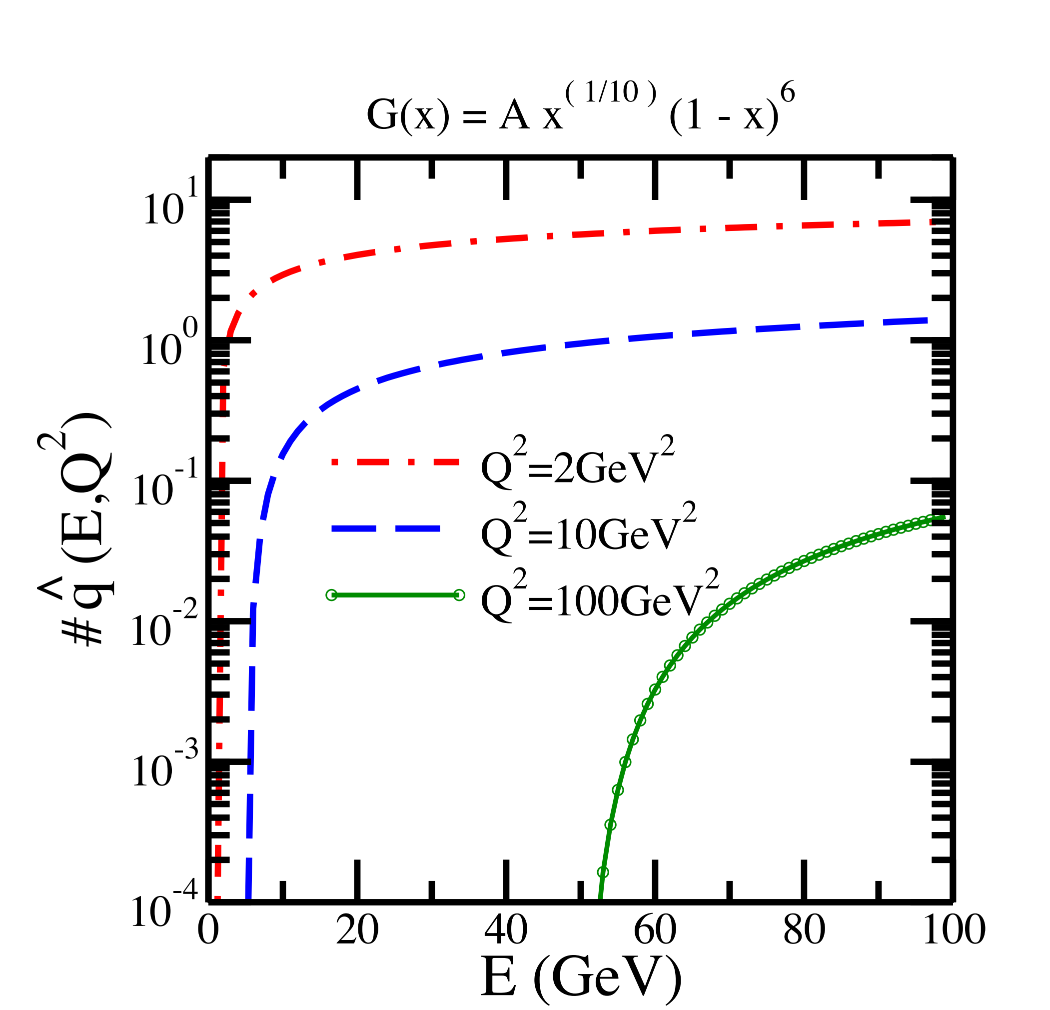


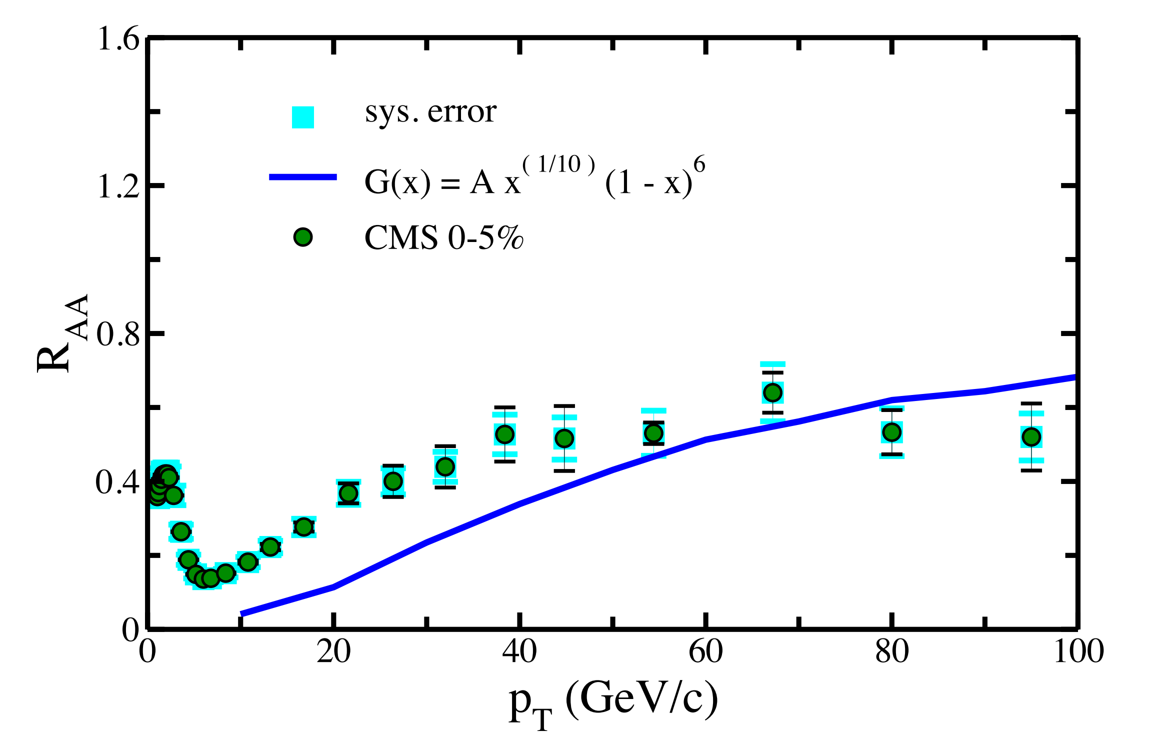


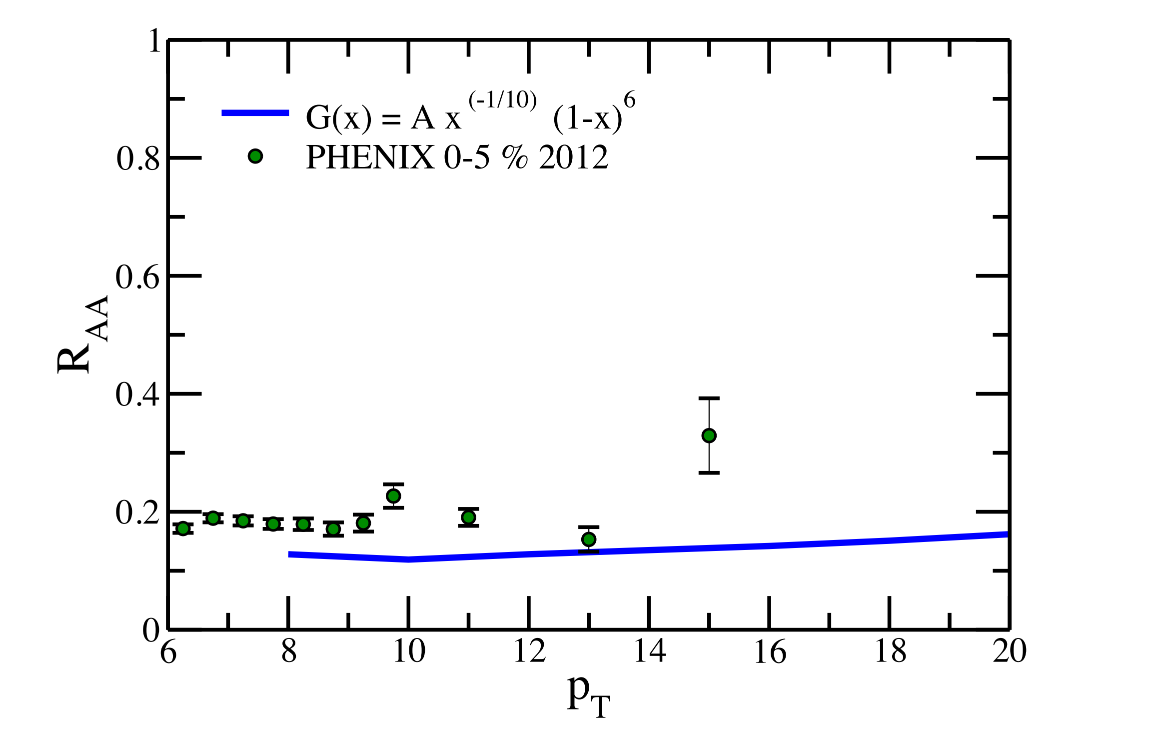


Narrow valence like PDF of QGP









Wide valence like PDF of the QGP