The x and scale dependence of $\hat{q}$

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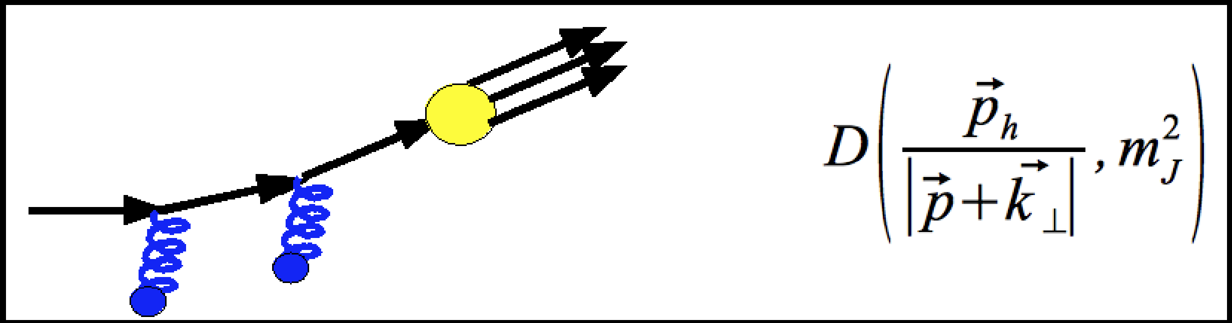
Hard Probes 2016, Wuhan, China Sept 23-28

Validity at high resolution,
transport coefficients for near on-shell partons

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



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

Transverse momentum diffusion rate

Notion of transport coefficient valid in the regime of

$\mu >> \Lambda_{QCD}$

A hierarchy of scales: $Q >> \mu >> \Lambda_{QCD}$

Full jets depend on many things

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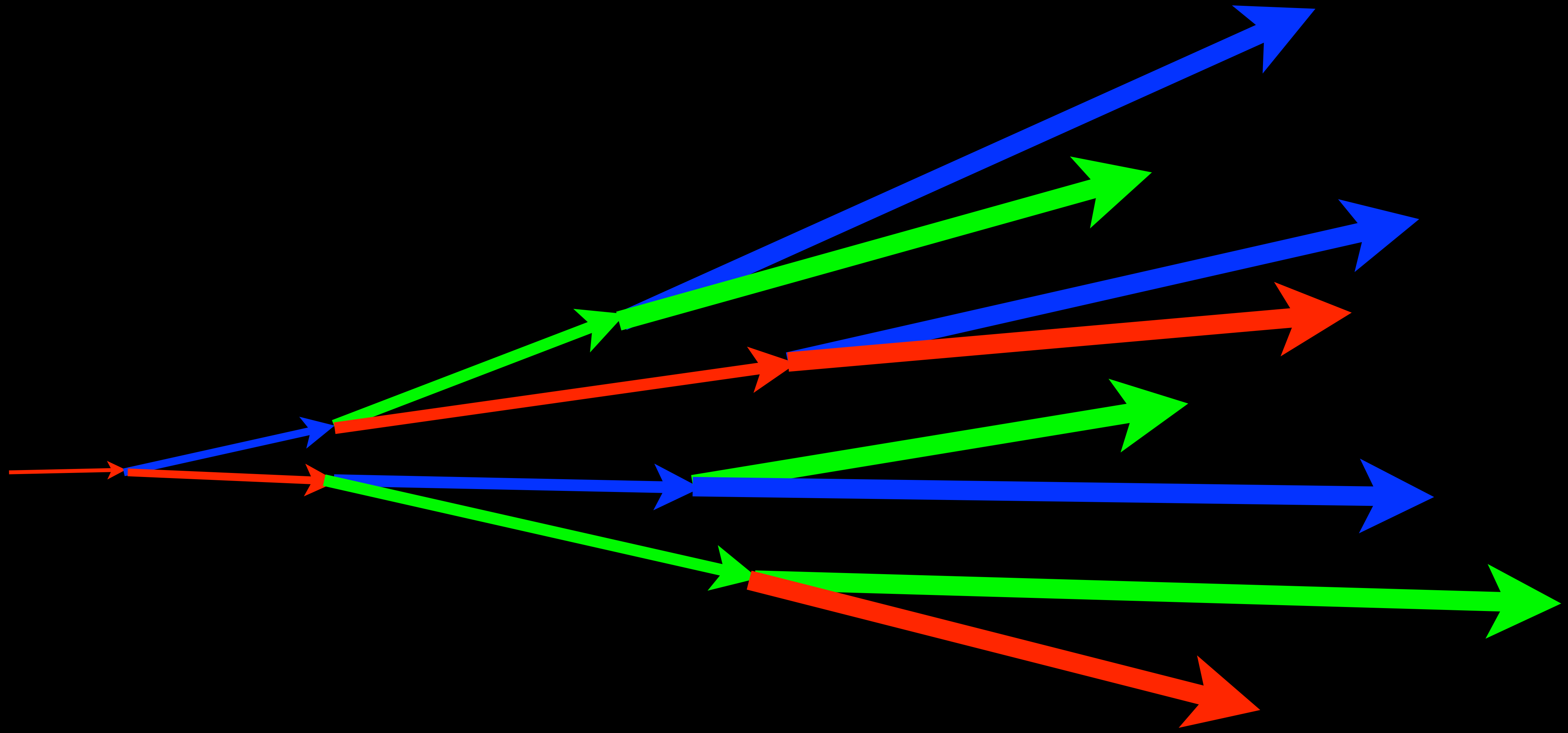
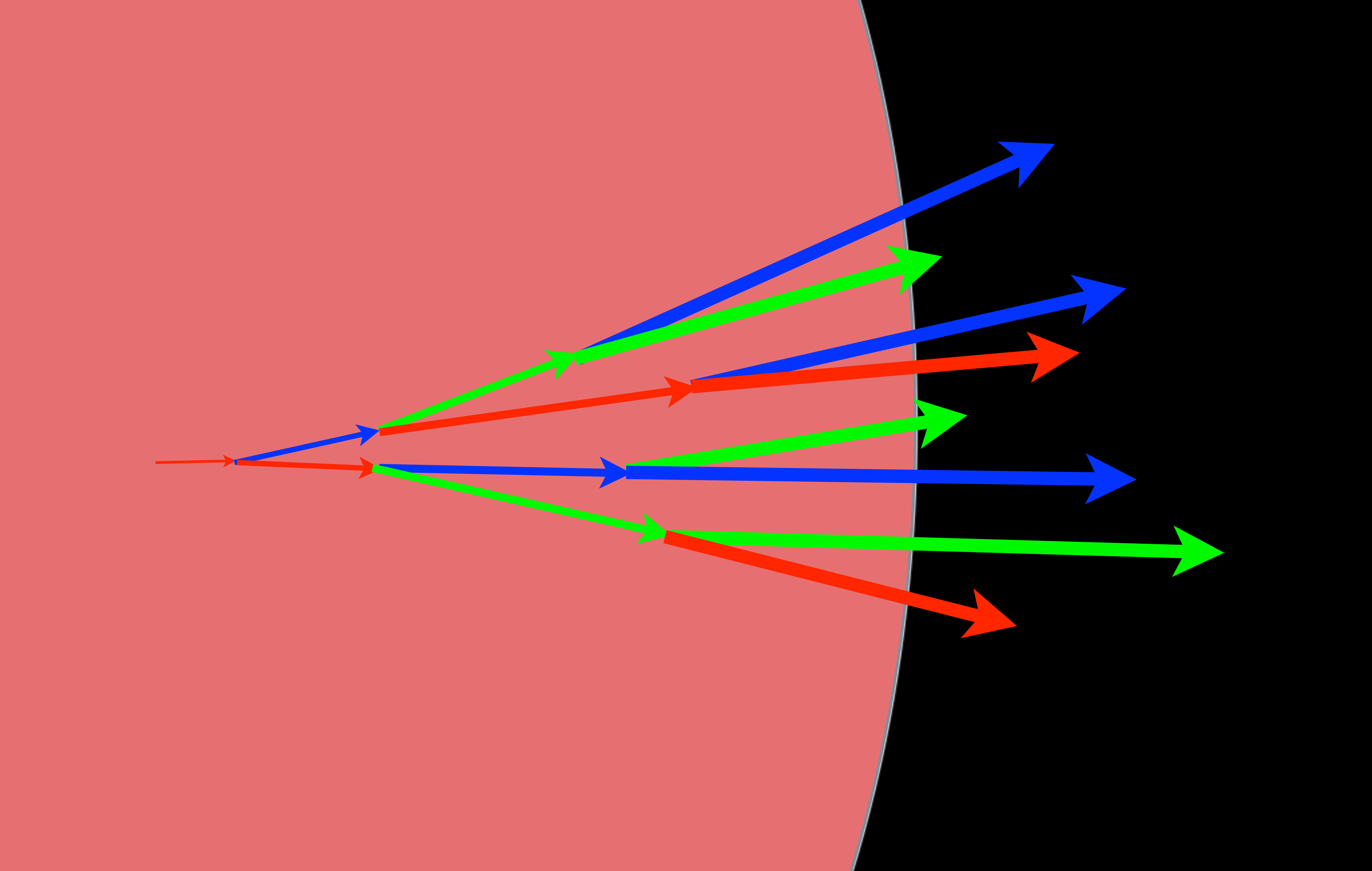


Full jets depend on many things



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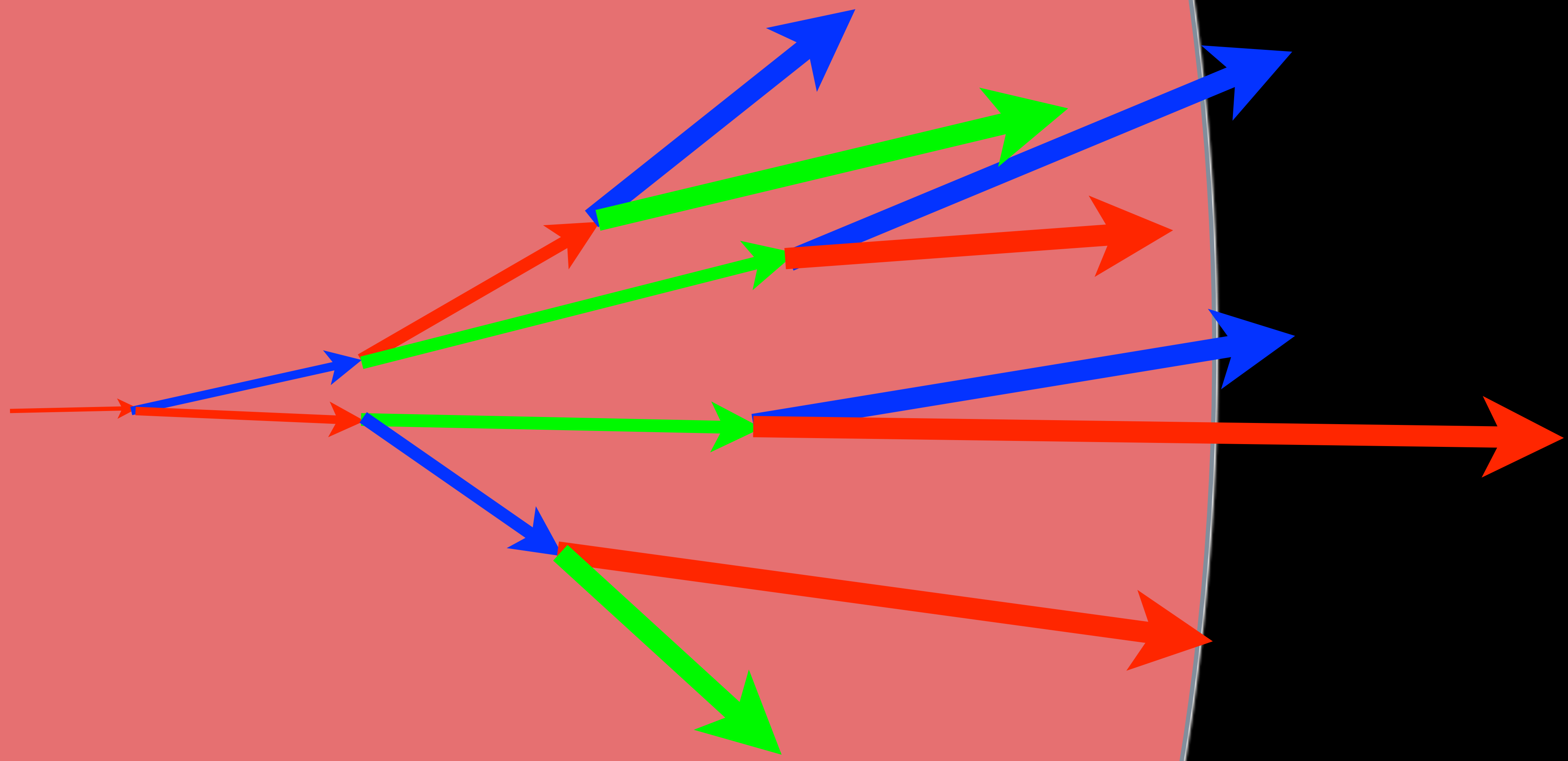

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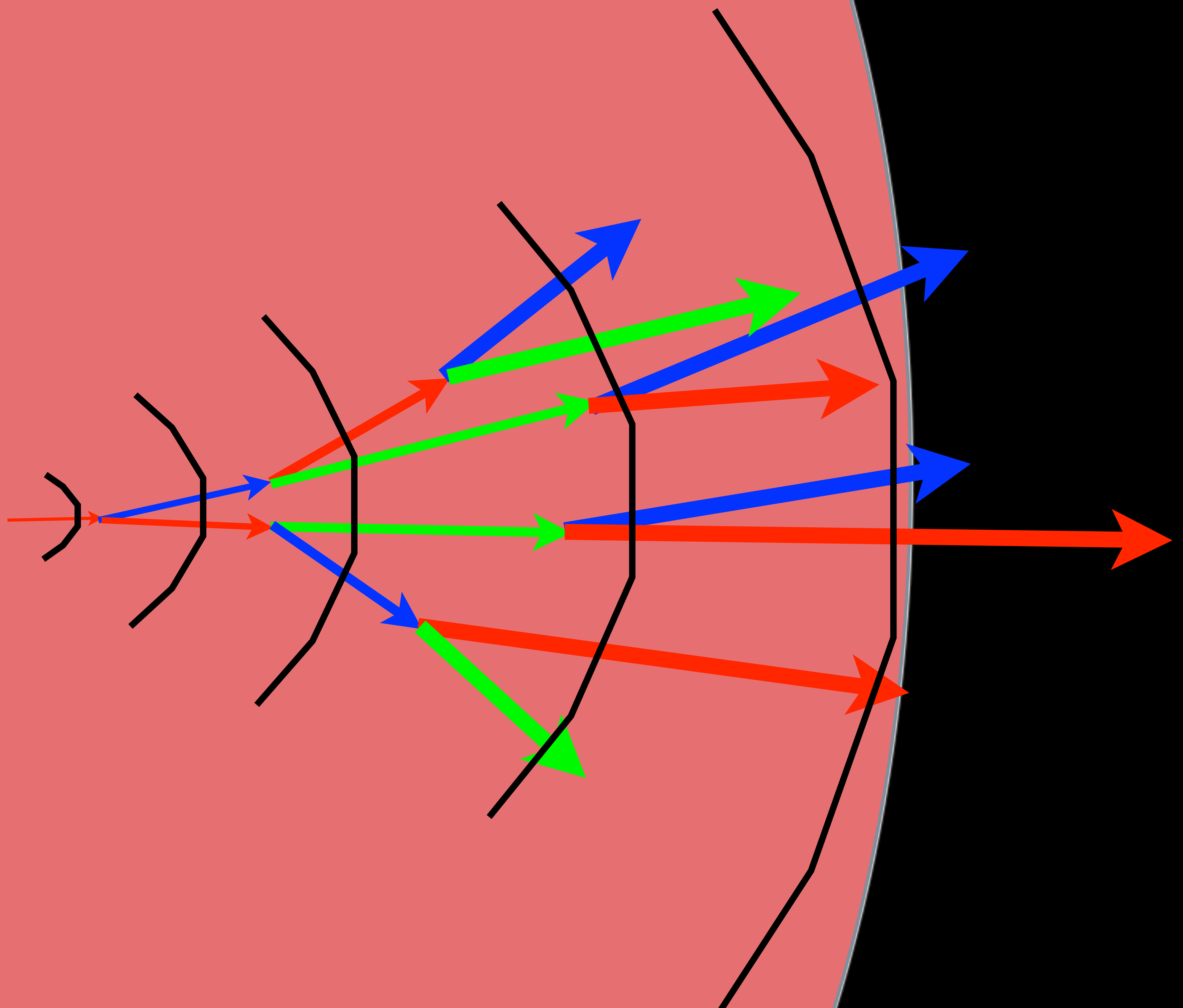

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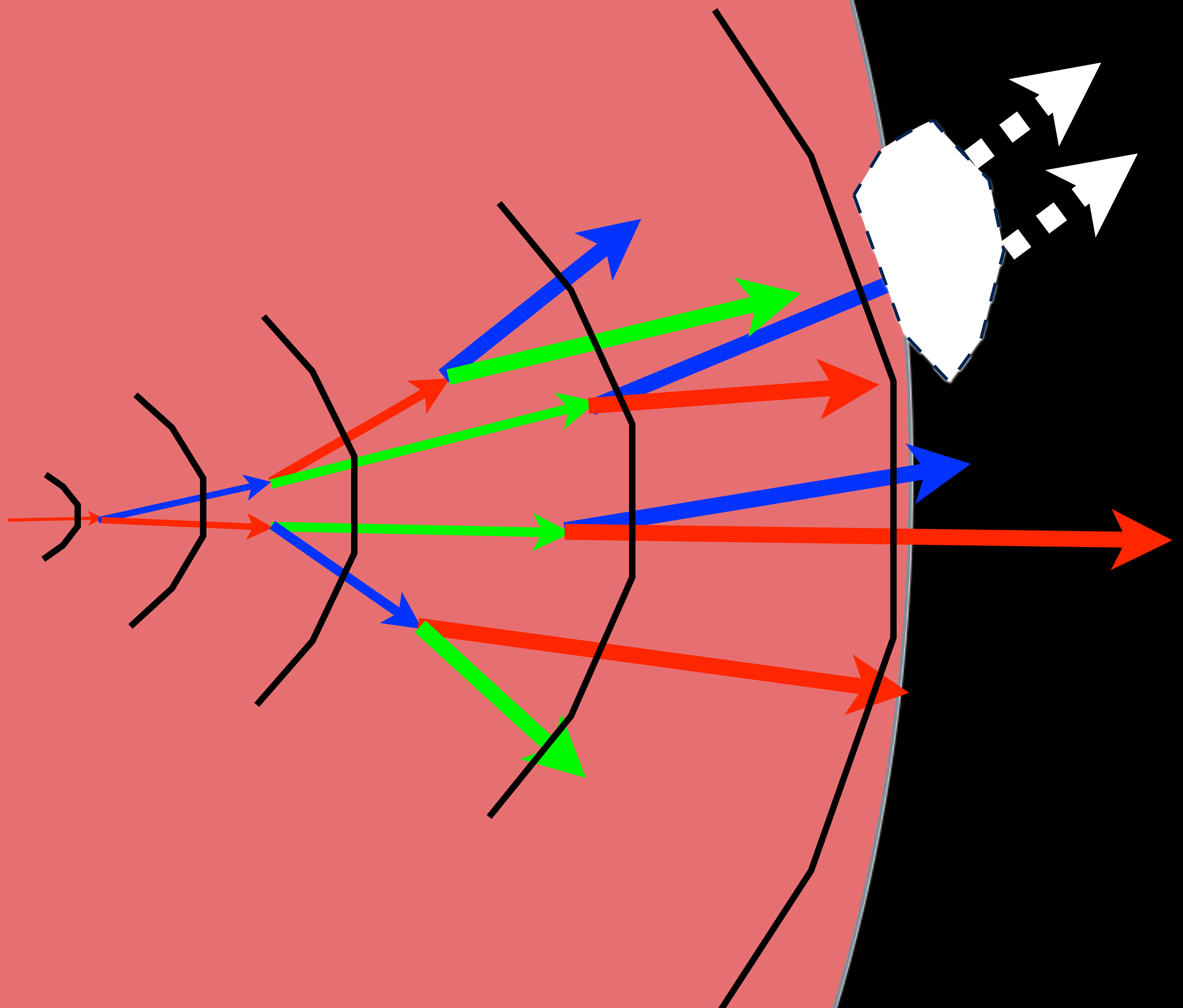

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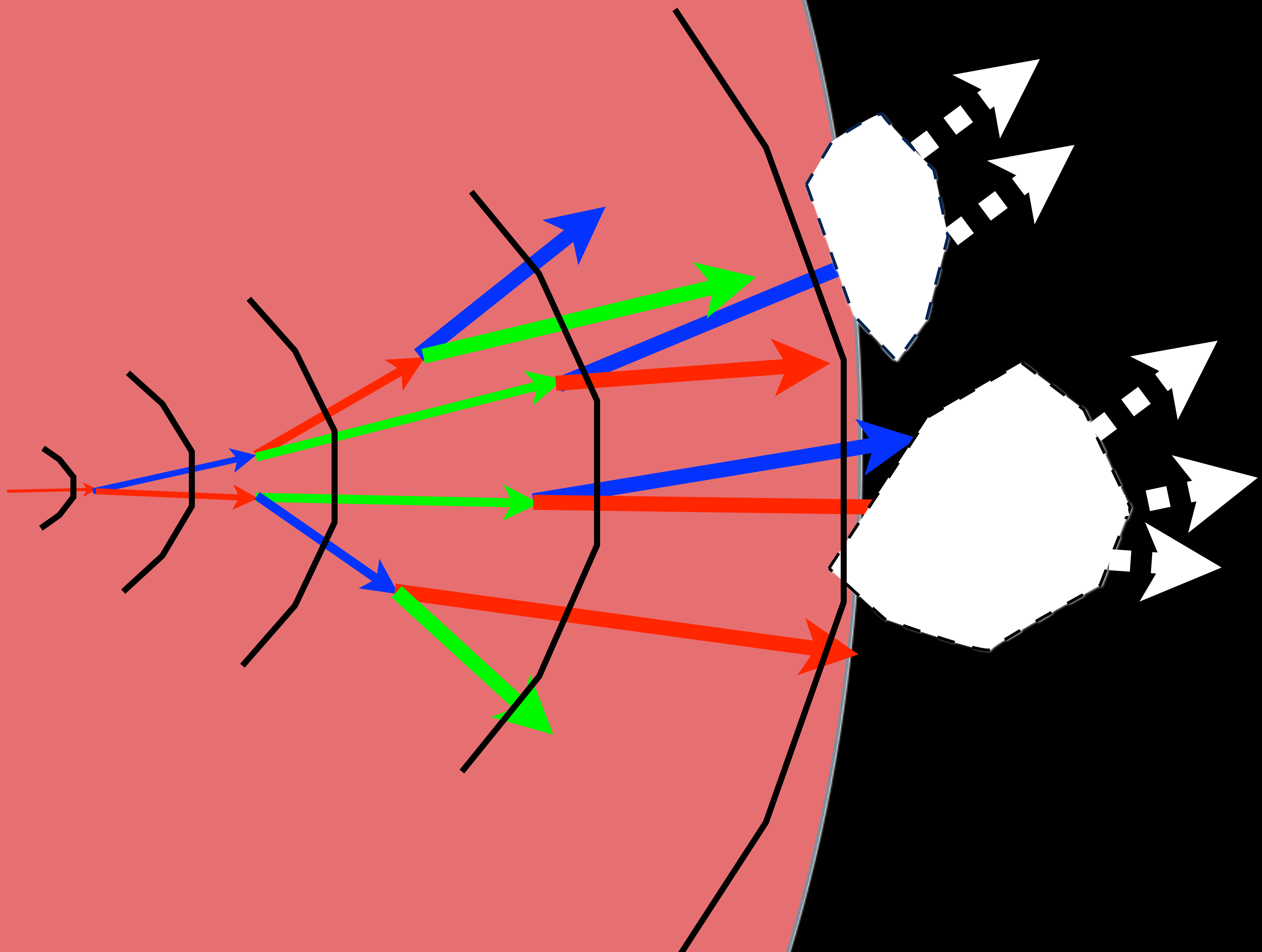
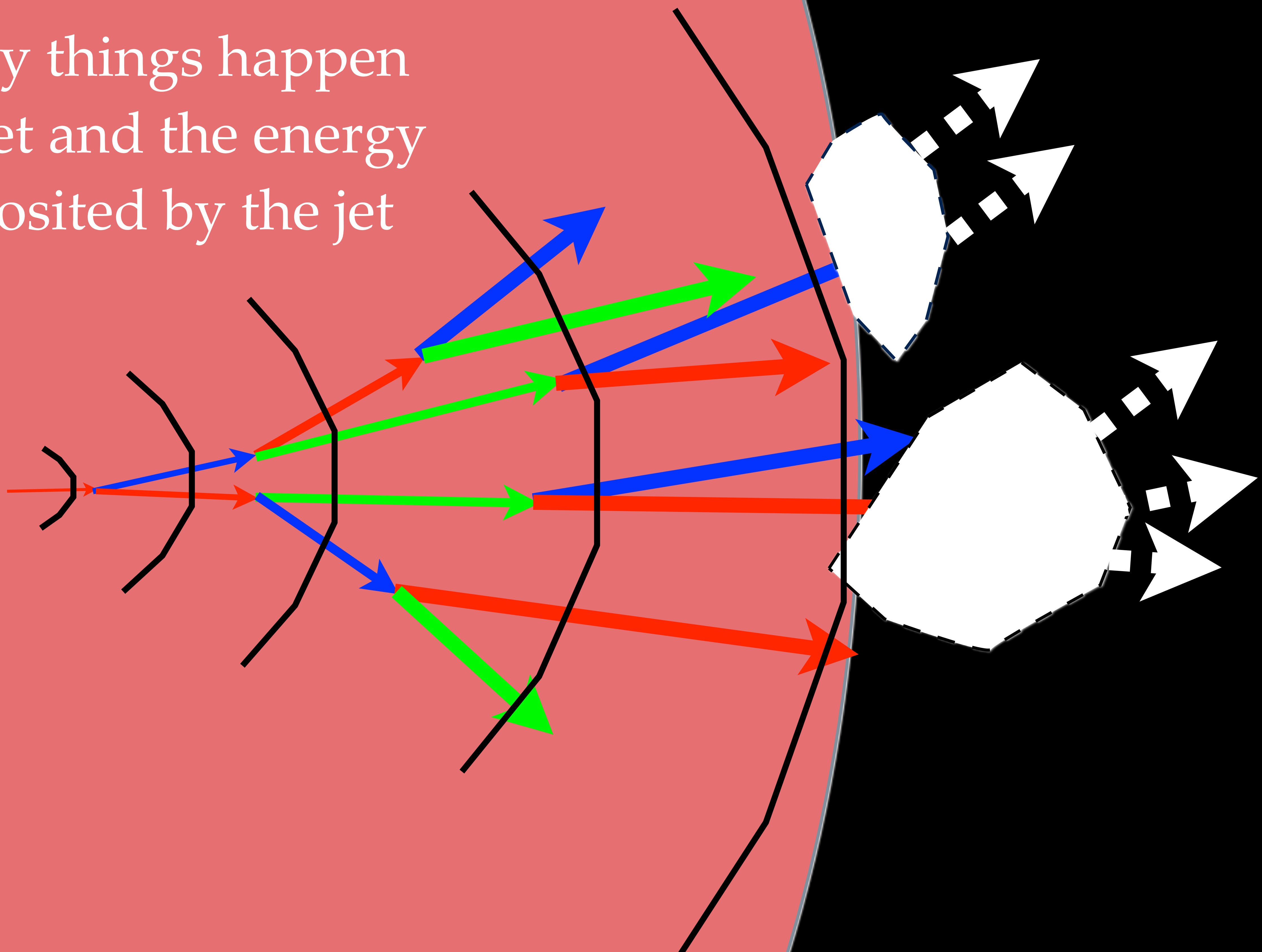


Full jets depend on many things

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



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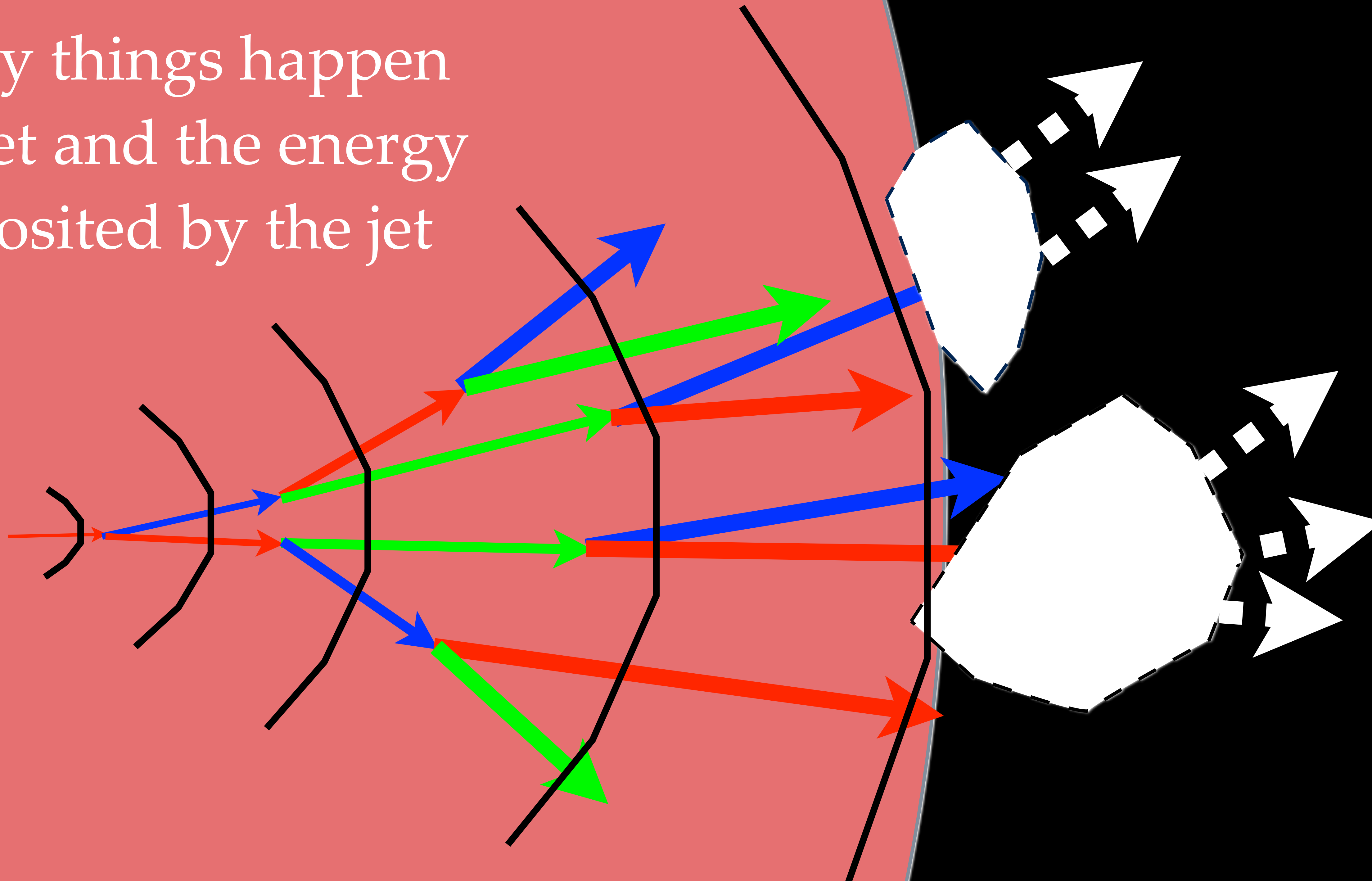

See talk by M. Kordell
other talks in MC session

Full jets depend on many things

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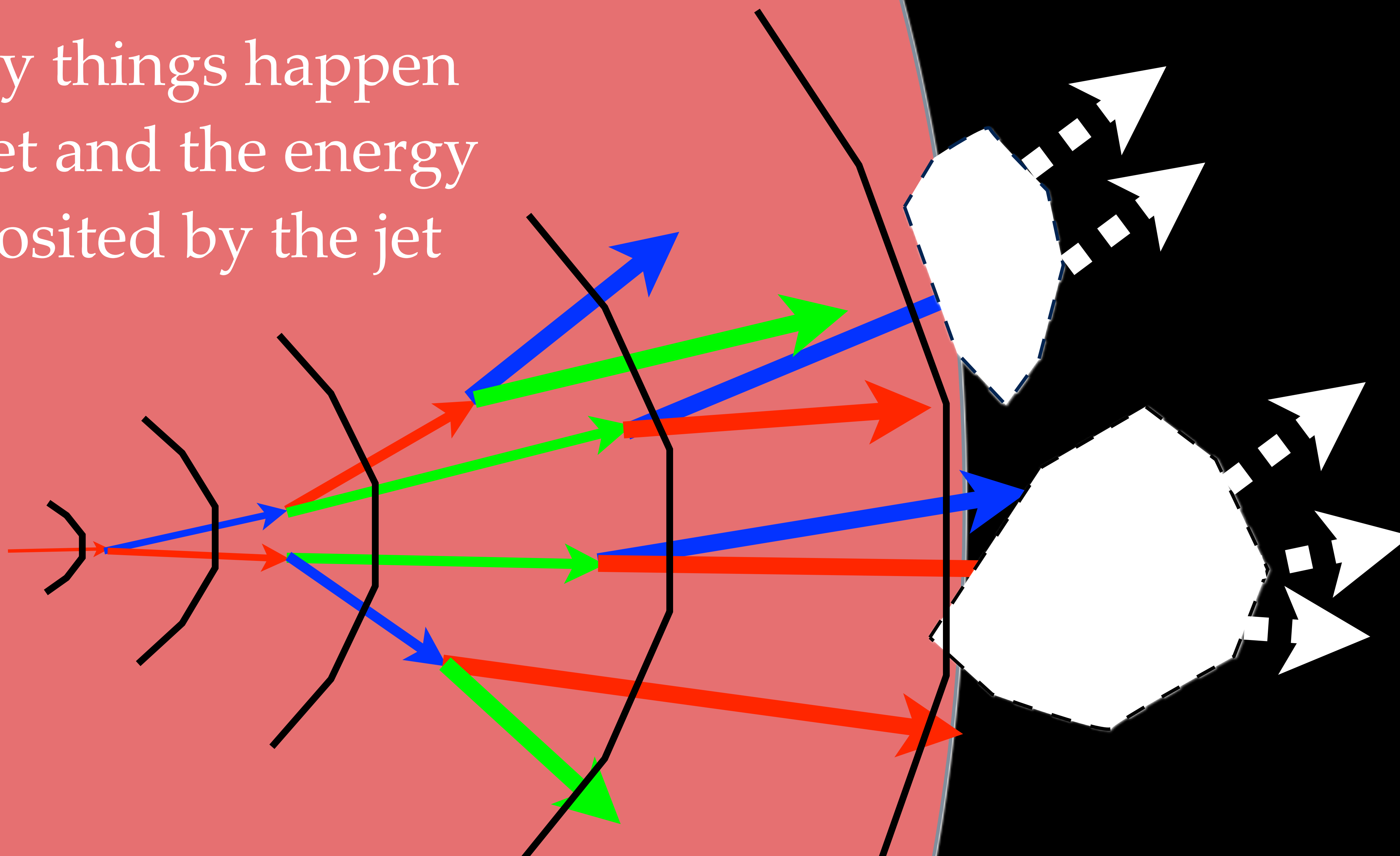
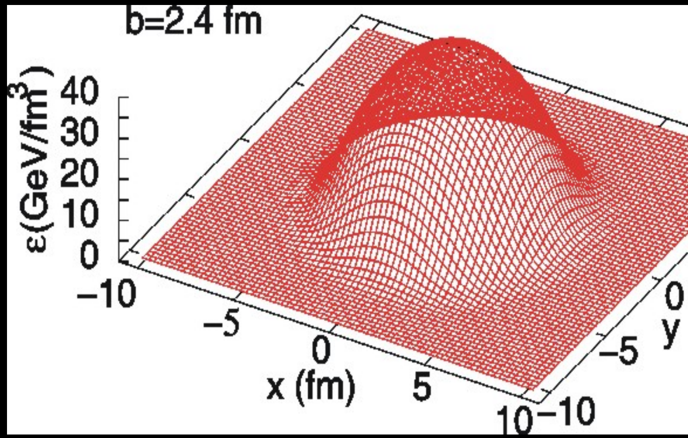


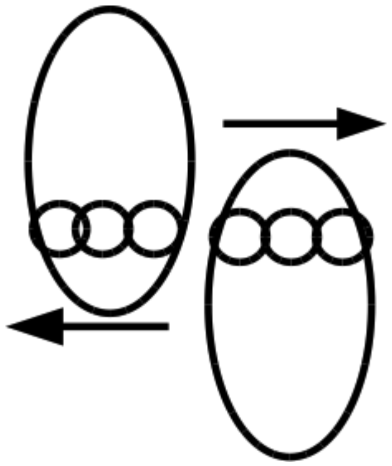
This talk will only focus on leading hadrons

See talk by M. Kordell other talks in MC session

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.

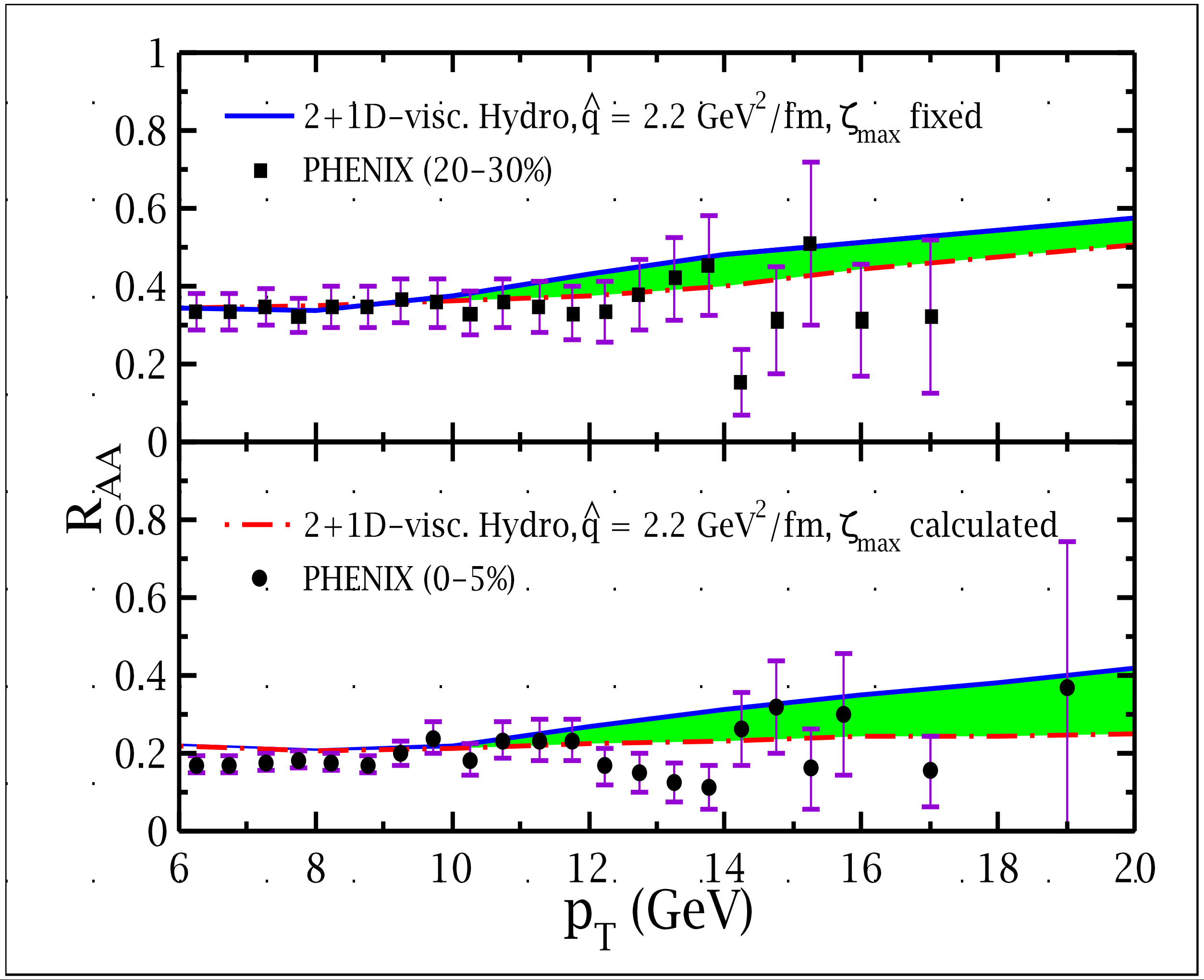




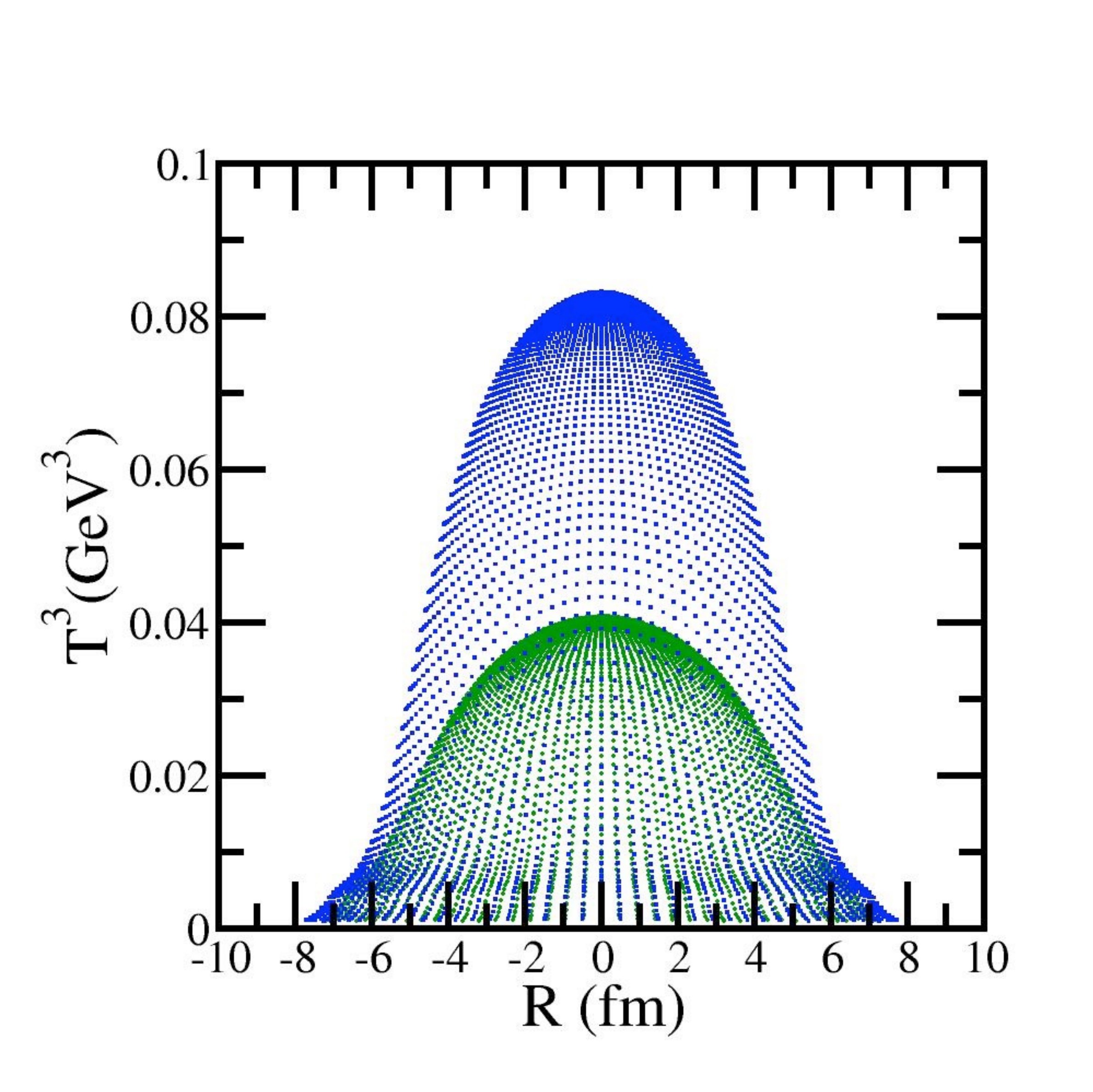
$$\hat{q}(\vec{r},t) = \hat{q}_0 \frac{s(\vec{r},t)}{s_0}$$

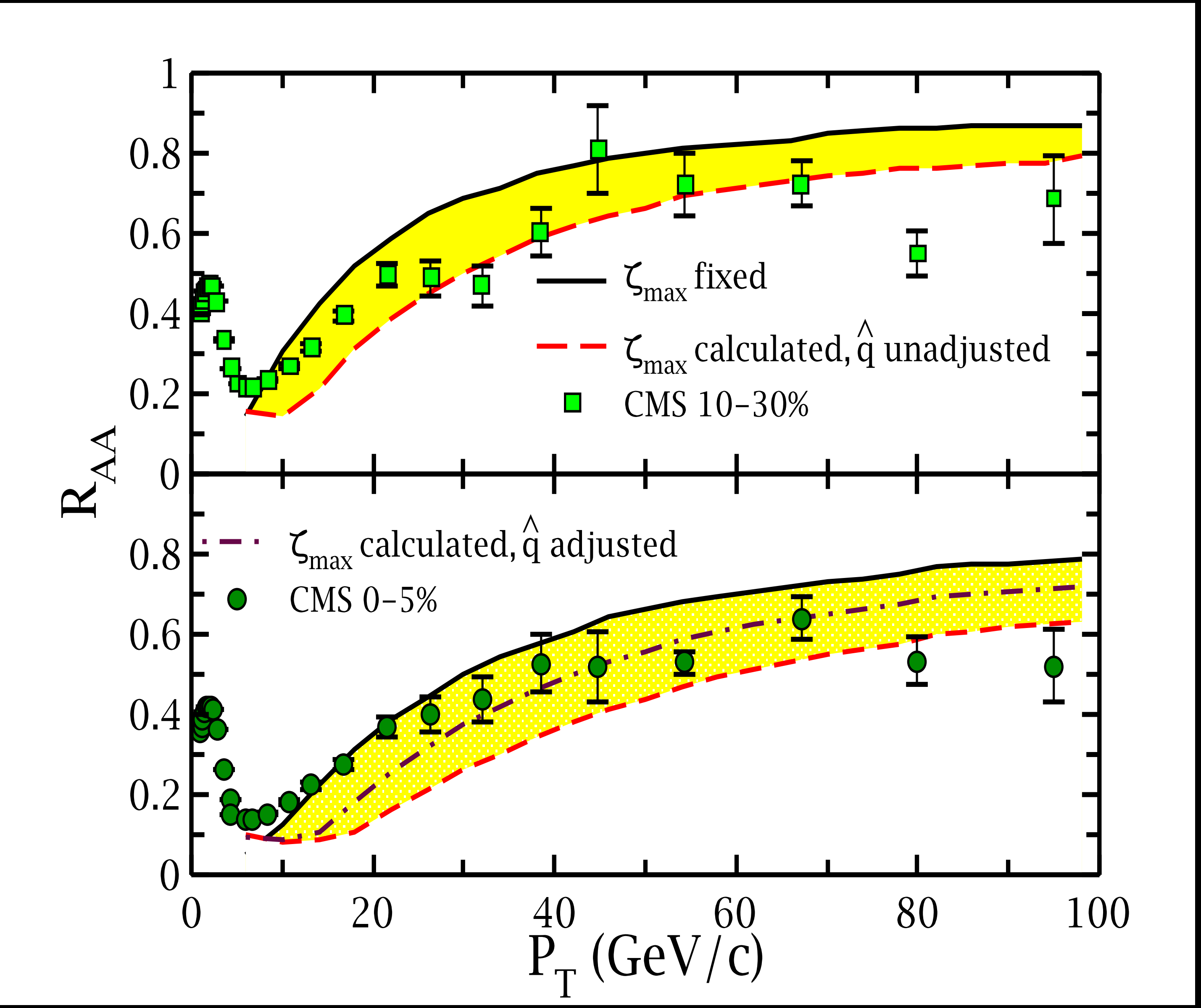
$$s_0 = s(T_0)$$

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



From RHIC to LHC circa 2012



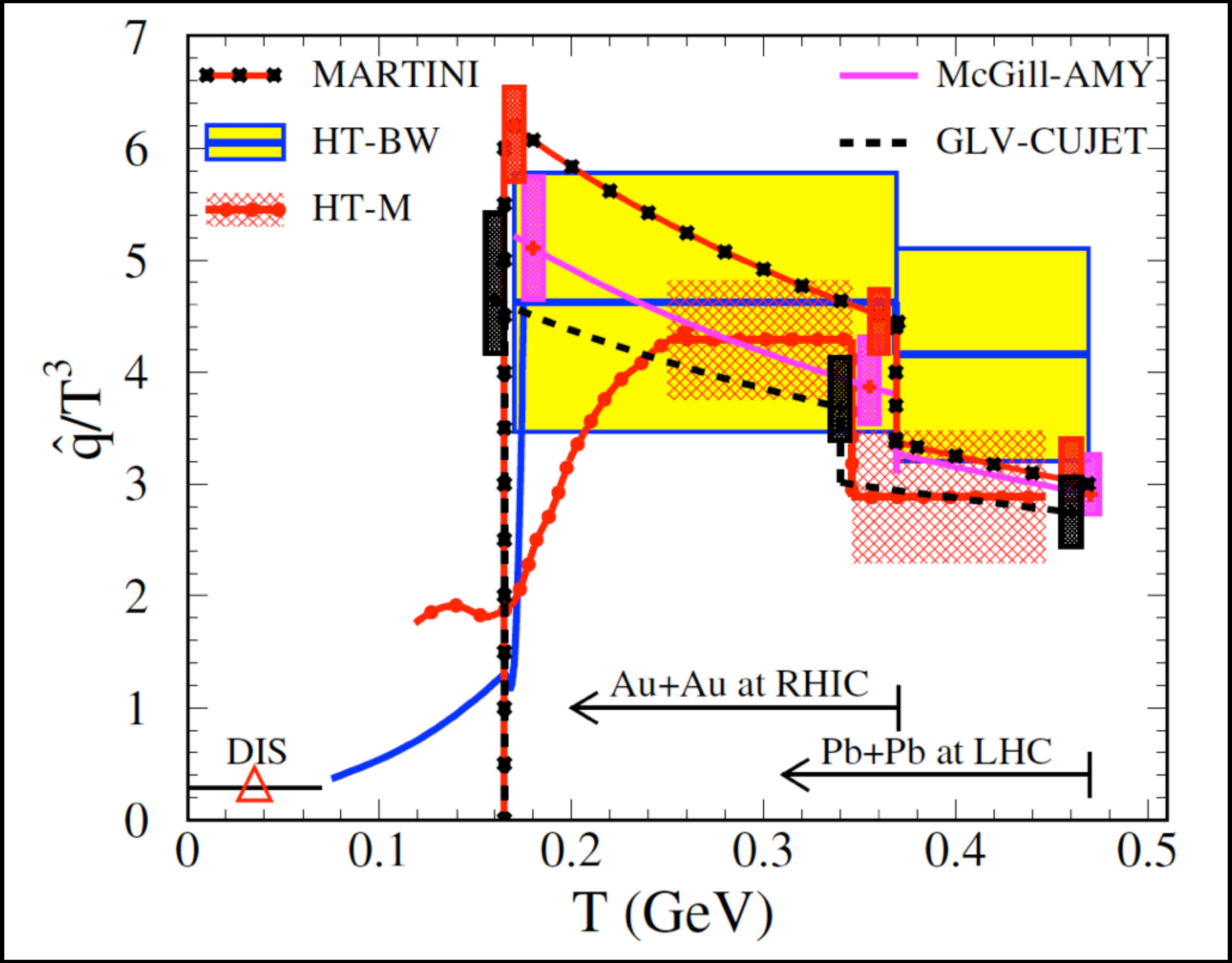


Reasonable agreement with data,
no separate normalization at LHC

Without any non-trivial x-dependence (E dependence)

Results from the JET collaboration

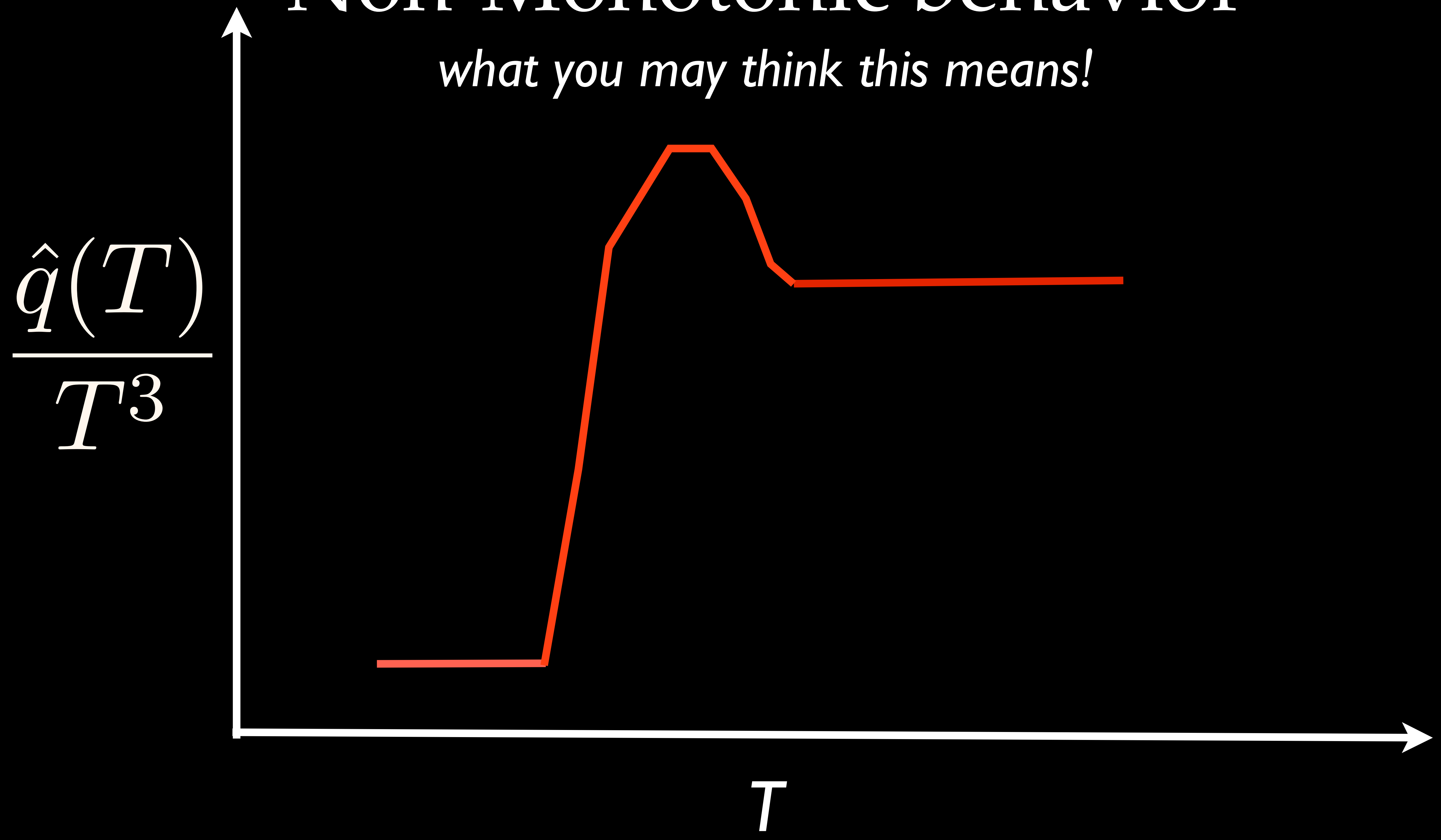
K. Burke et al.



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

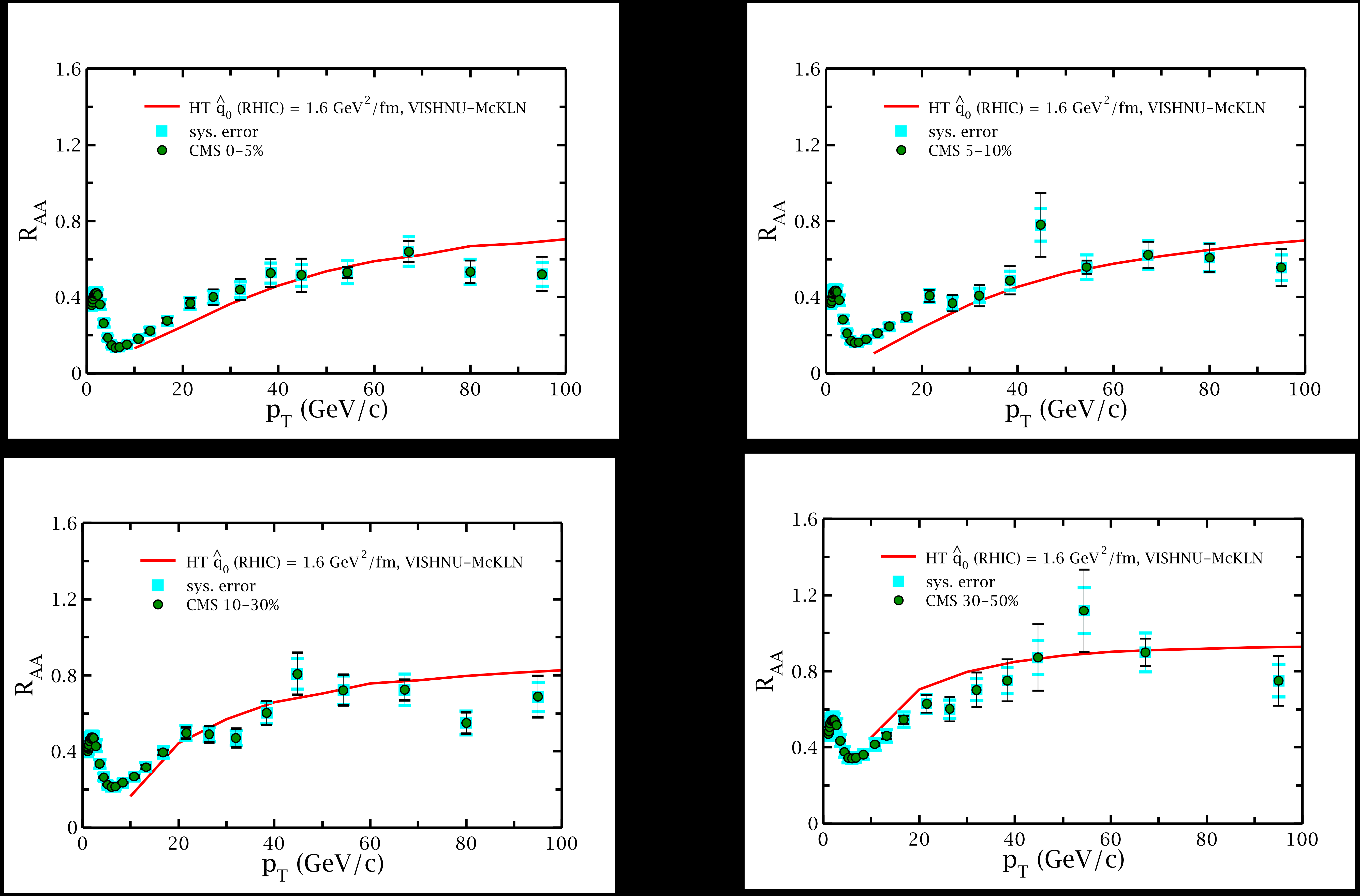
Non-Monotonic behavior

what you may think this means!

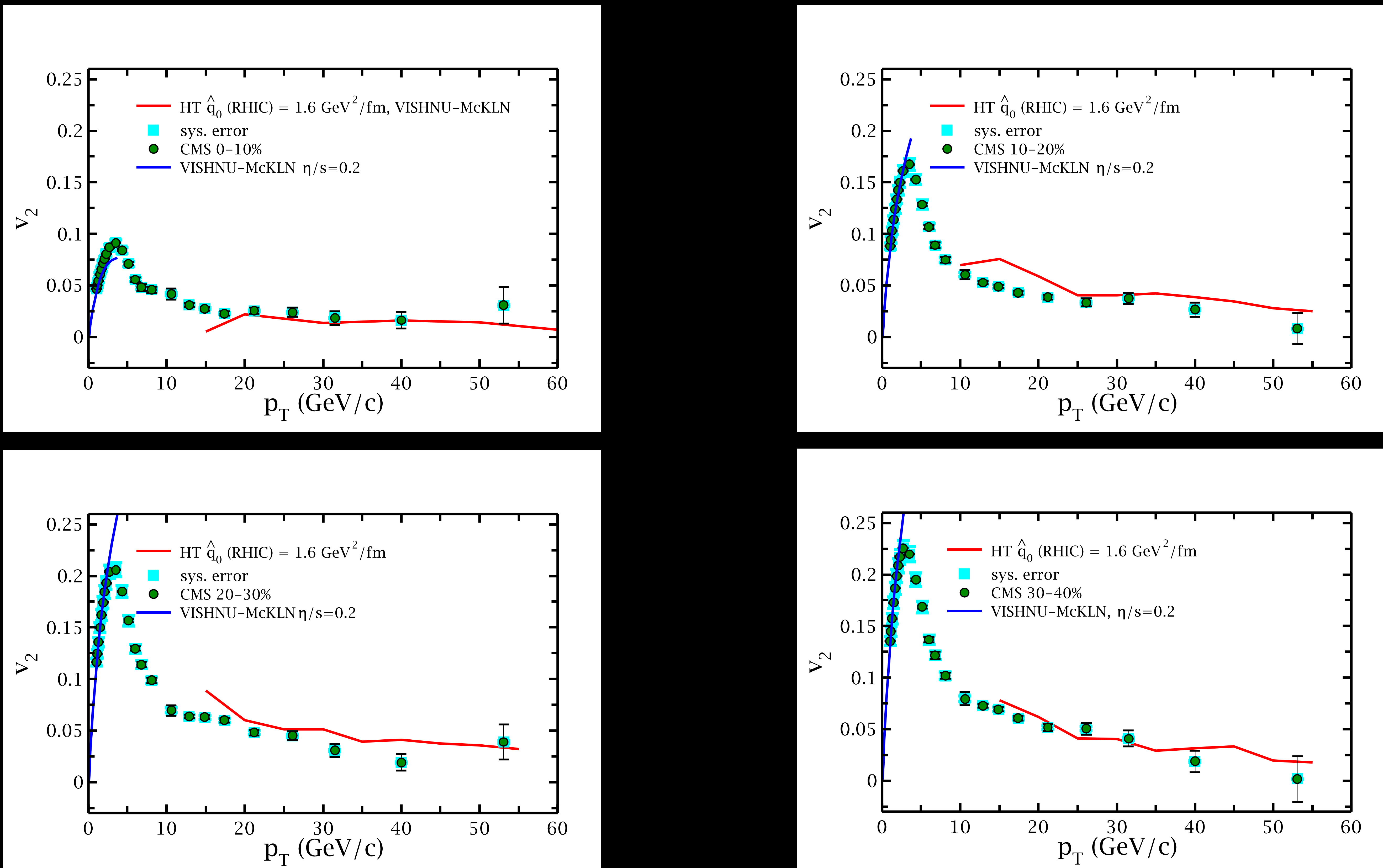


If this is true, must effect the centrality dependence of R_{AA}, v_2, and its centrality dependence at a given collision energy

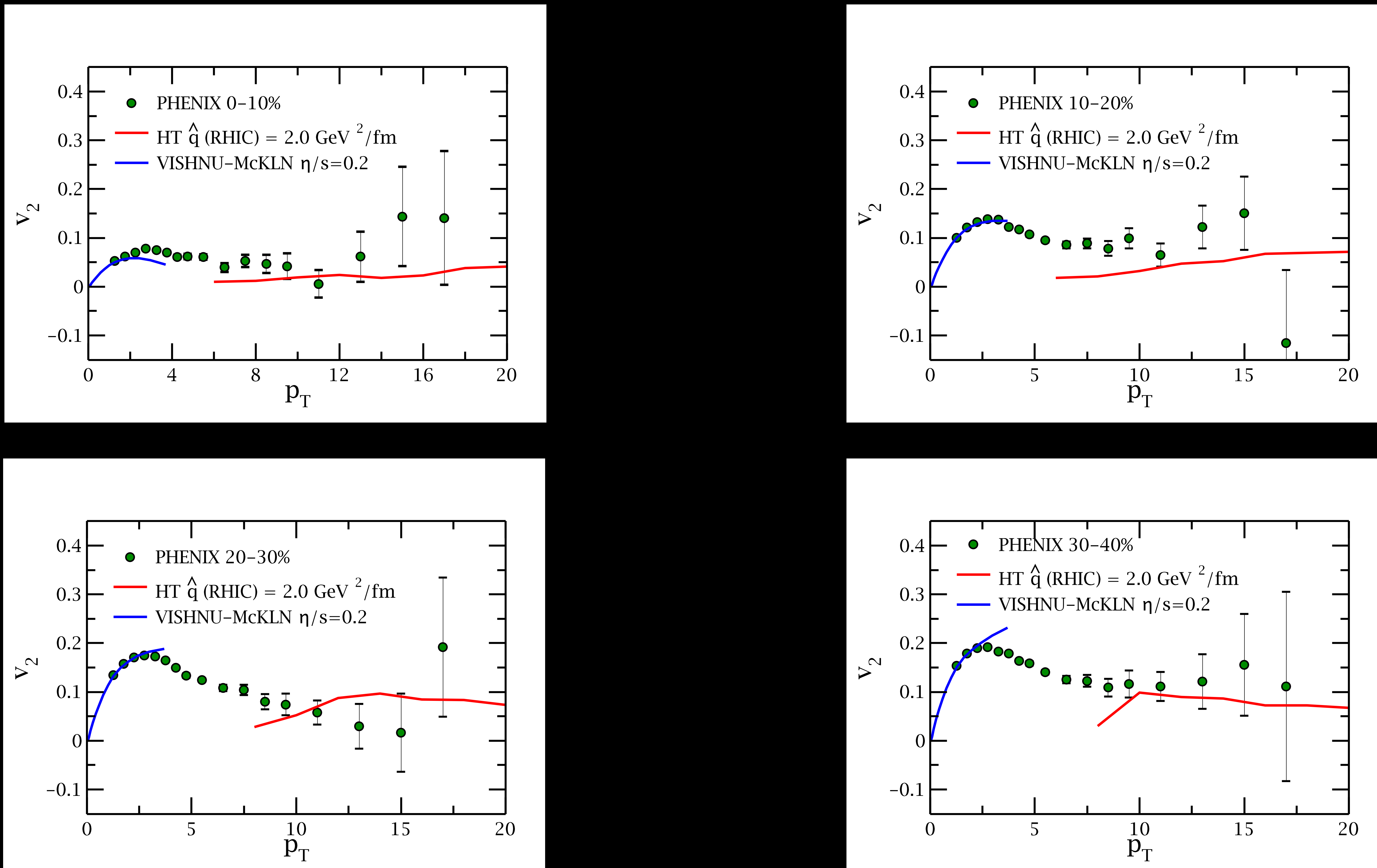
LHC R_{AA} without a bump in $\hat{q}/T^3$



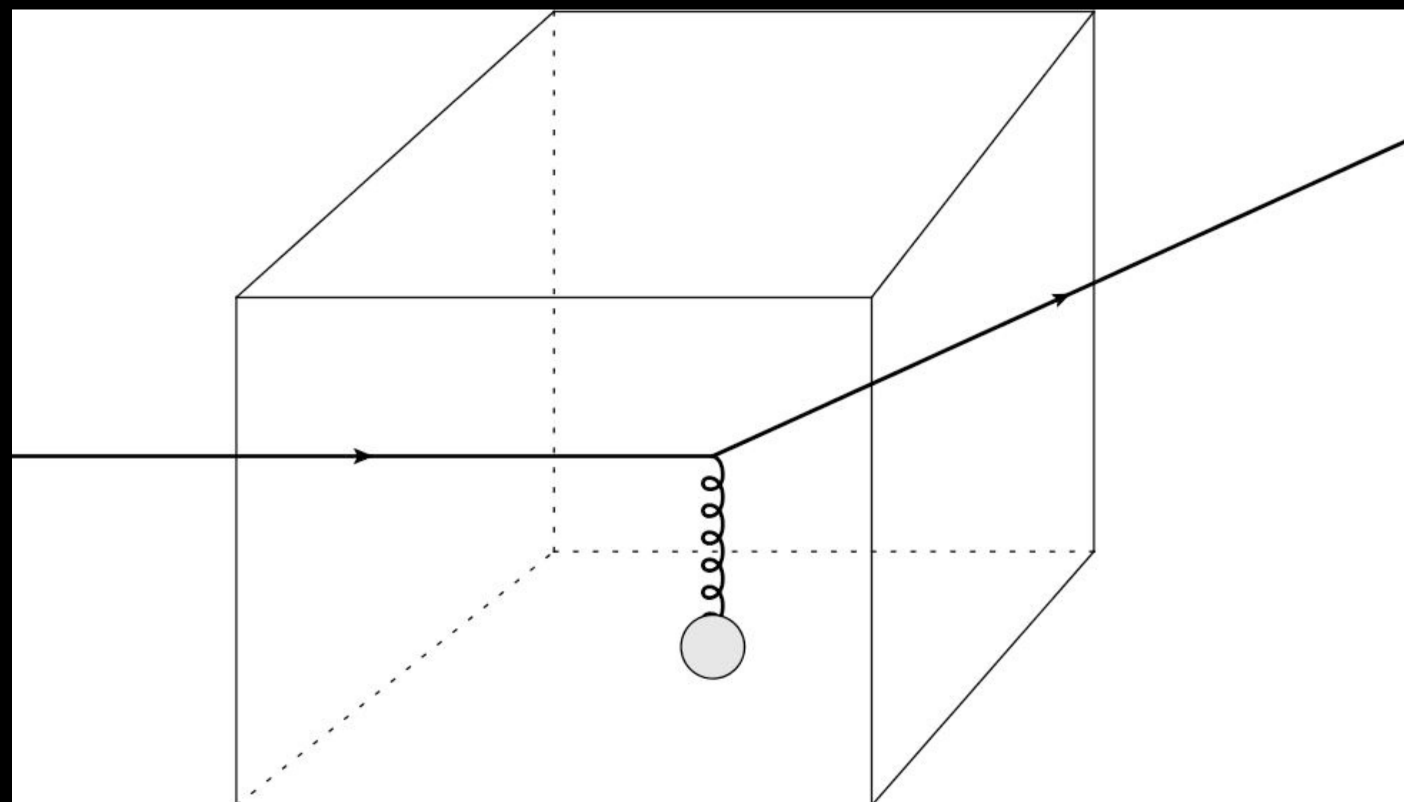
v_2 at LHC without a bump in $\hat{q}/T^3$



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



Calculating $\hat{q}$ with more care



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

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

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

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

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

$$\hat{q}(q^+,q^-)$$

$$2q^-q^+ = Q^2,\ \ \frac{k_\perp^2}{2q^-} = xP^+$$

Can evaluate on Lattice, see talk by C. Nonaka

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

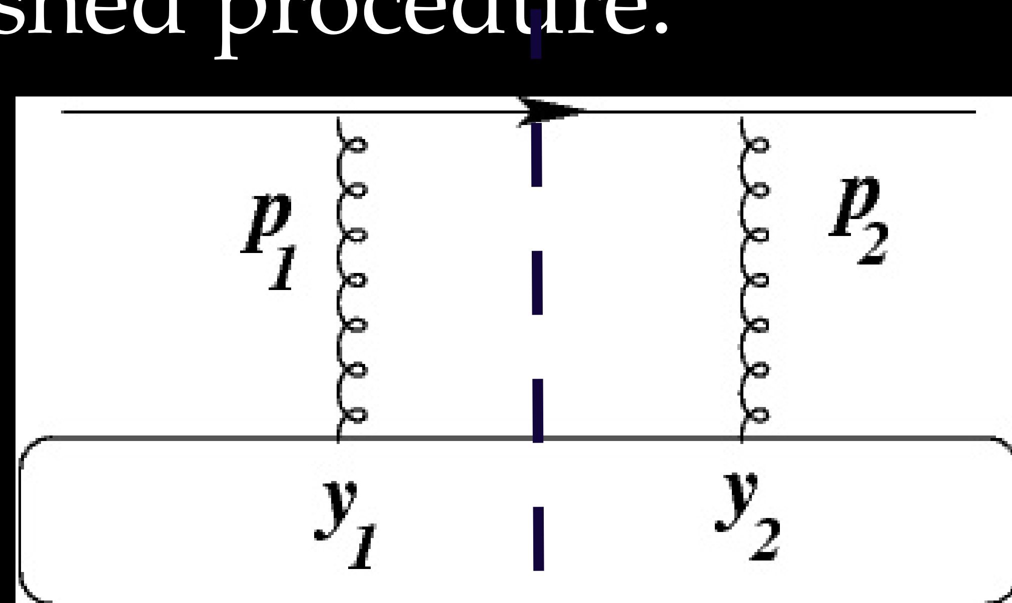
$$g(\eta) = \int \frac{dy^-}{2\pi} e^{i\eta y^-} \langle P|\bar{\psi}(y^-)\frac{\gamma^+}{2}\psi|P\rangle$$

In the rest frame of the proton, x ~ η

We can compare η values between DIS and heavy-ions

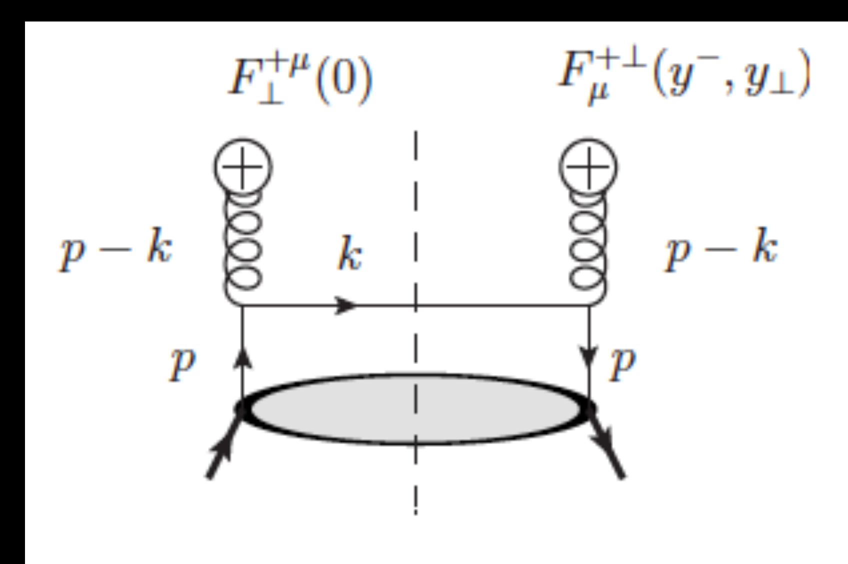
How about x or η dependence of $\hat{q}$

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

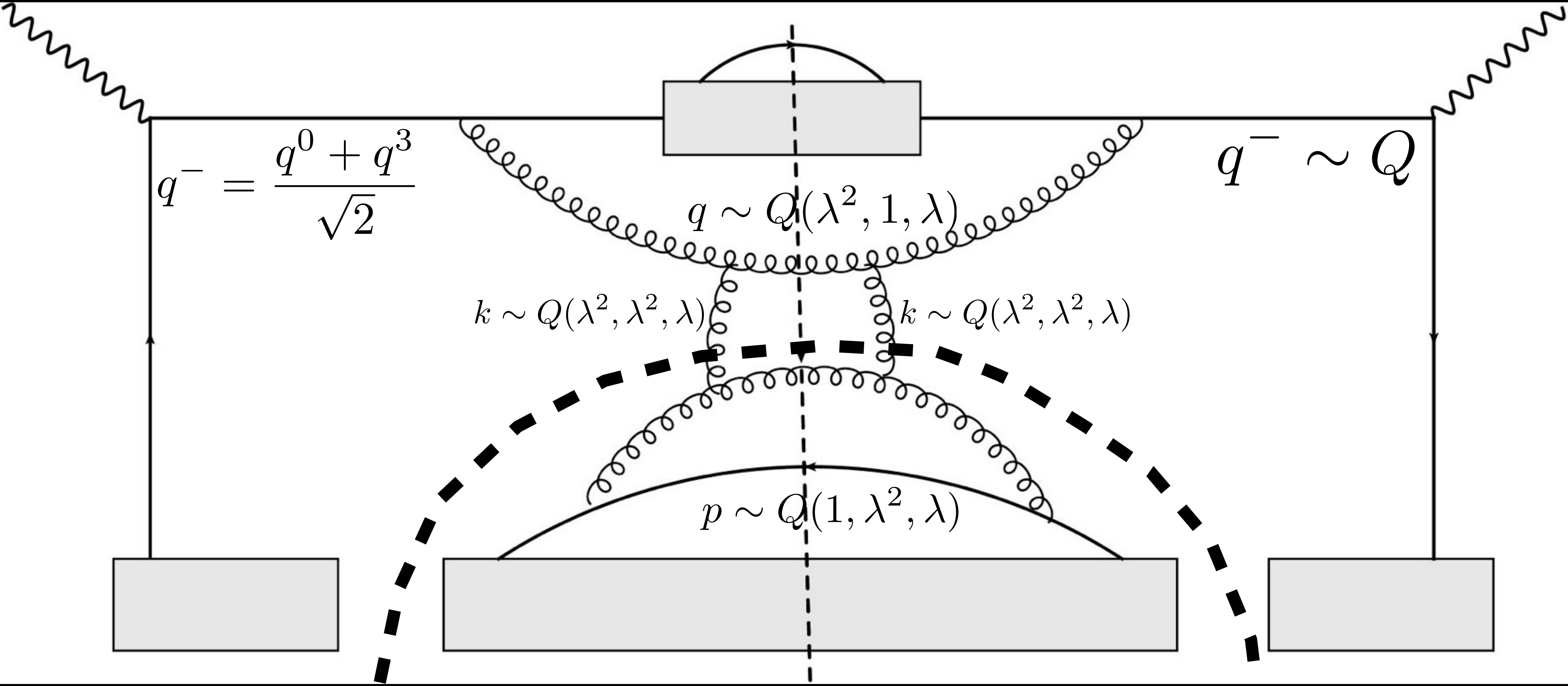


$$\delta\left(k^+ - \frac{k_\perp^2}{2q^-}\right)$$ forces the incoming lines off-shell

q is a 3-D object depending on x, k_T
Like a TMDPDF,
at large k_T can *refactorize* to
regular PDF X radiated gluon
Contributions start at order α_S,



A factorized picture



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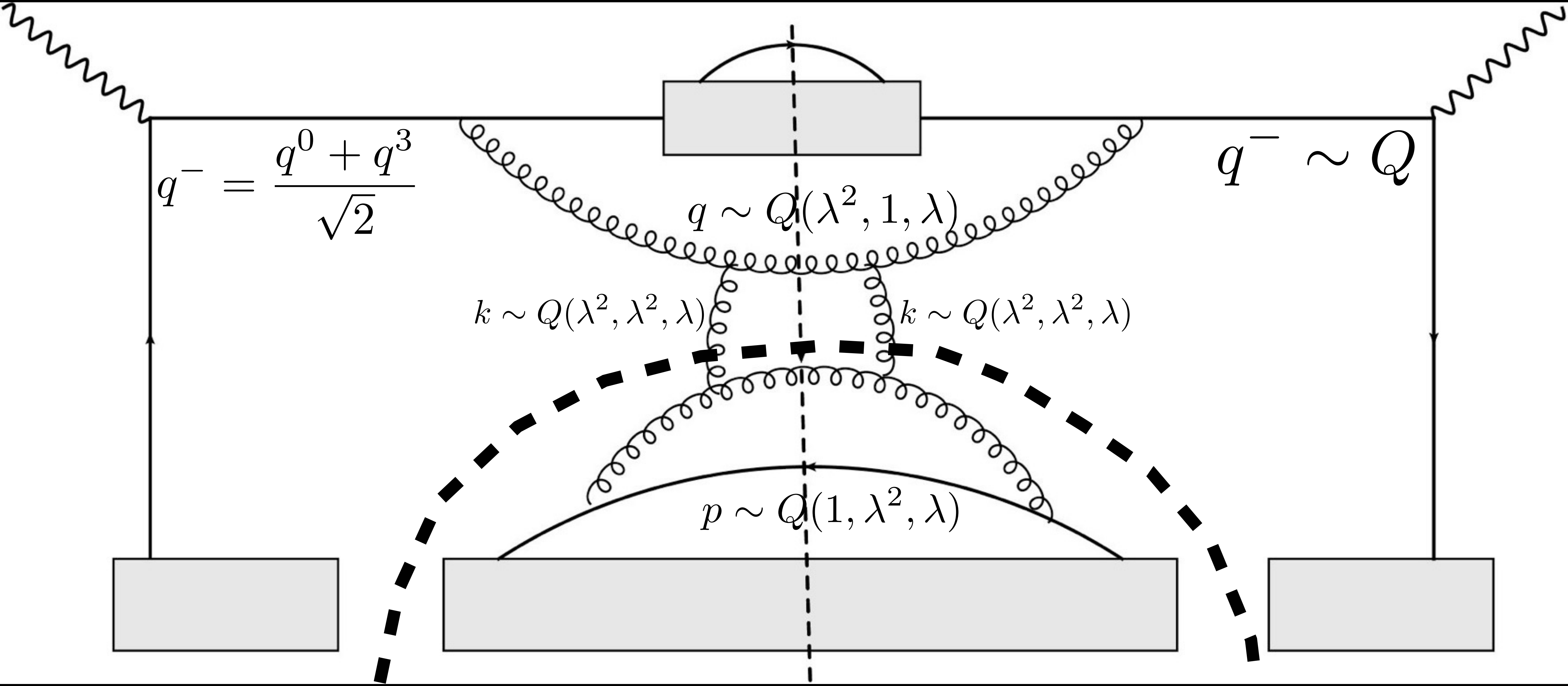
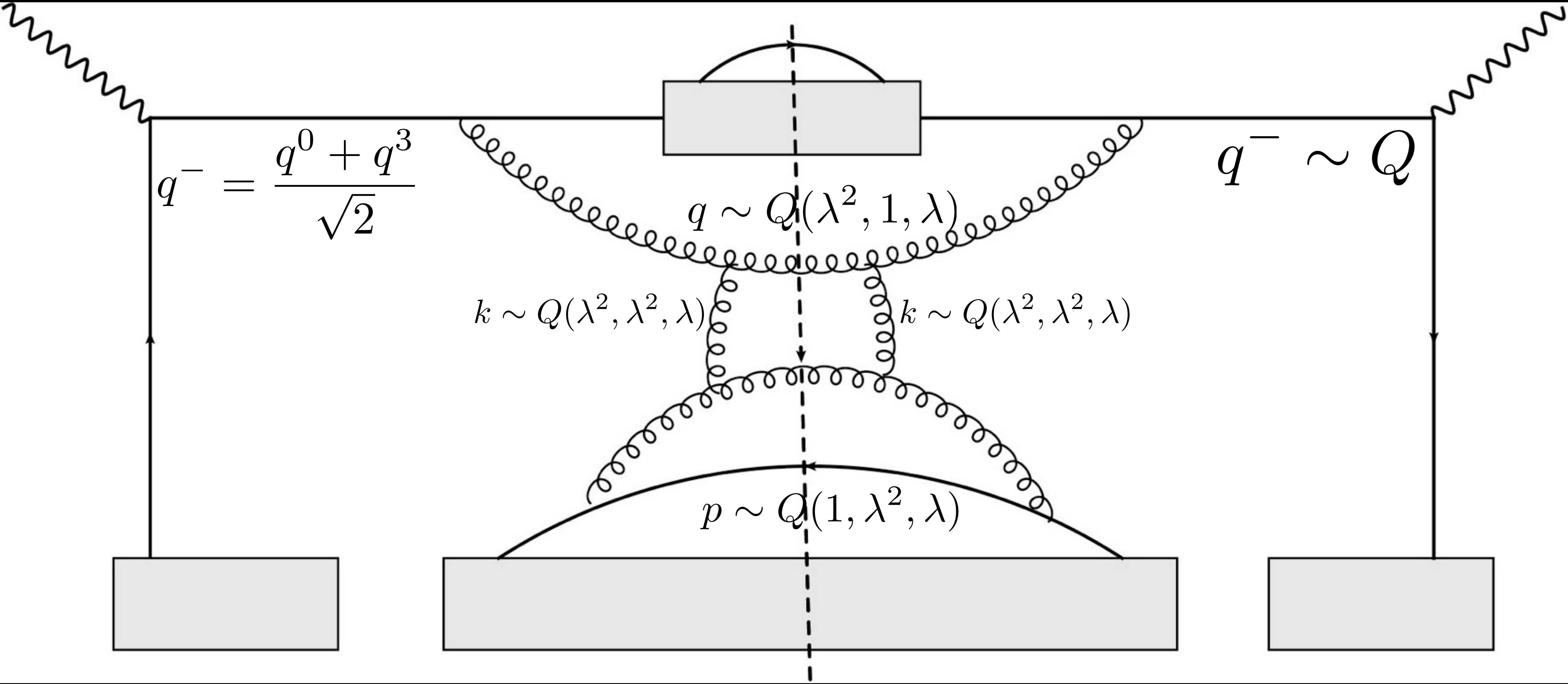


Q is the hard scale of the jet ~ E

$Q\lambda$ 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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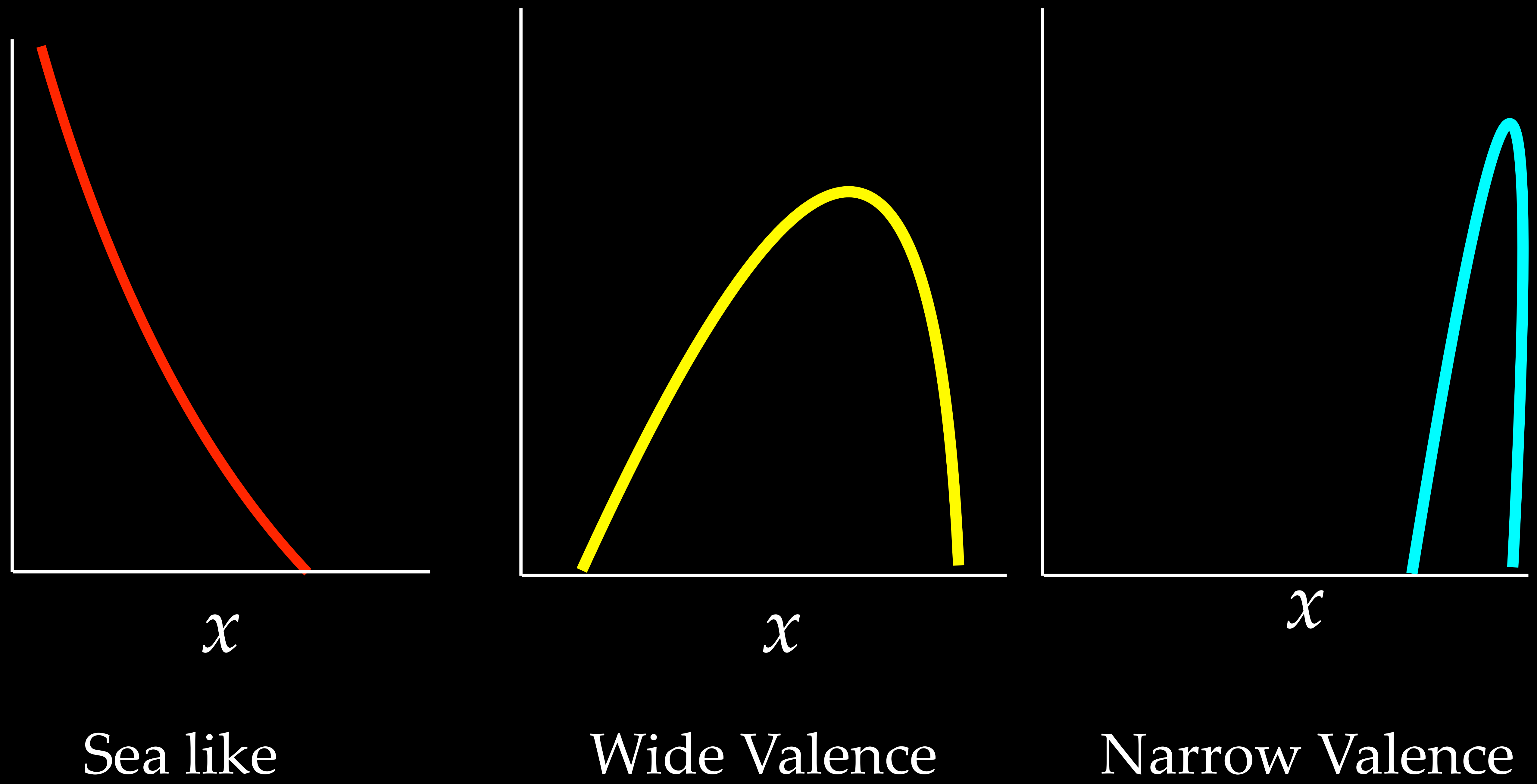
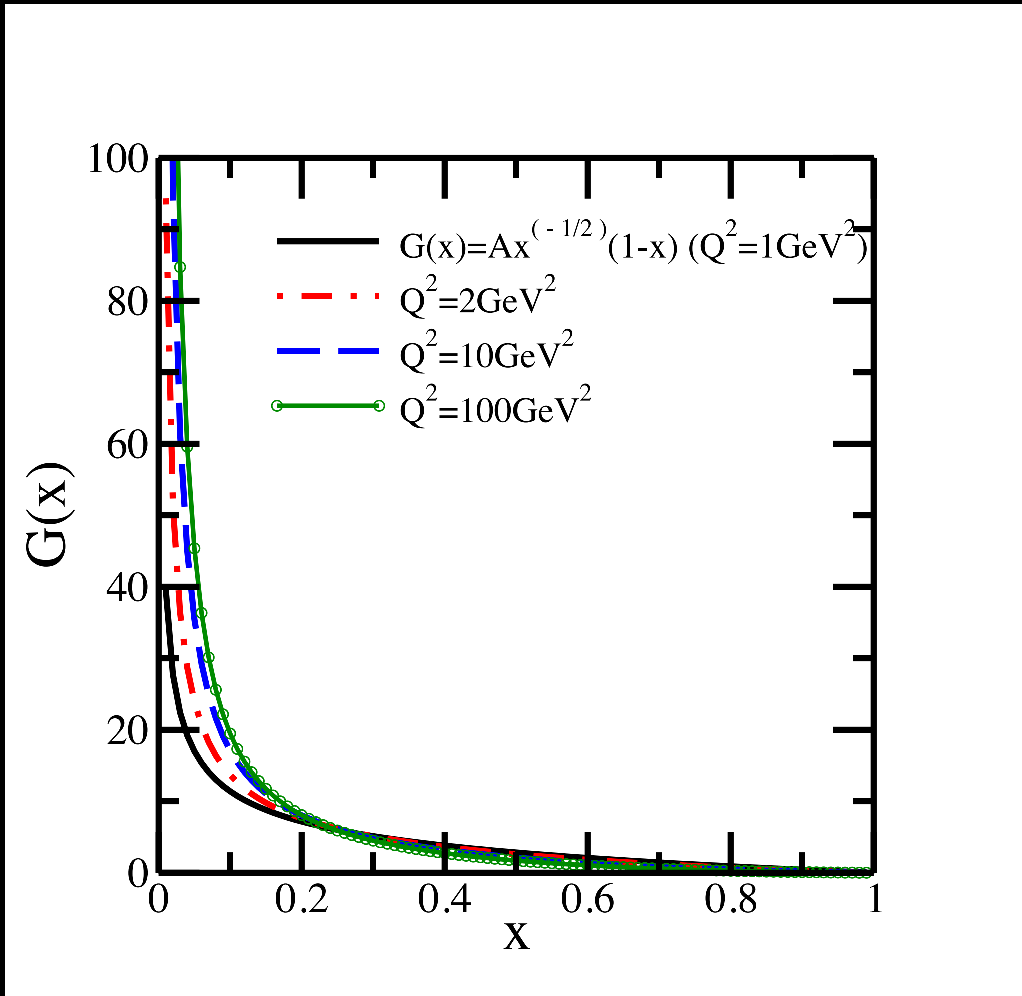
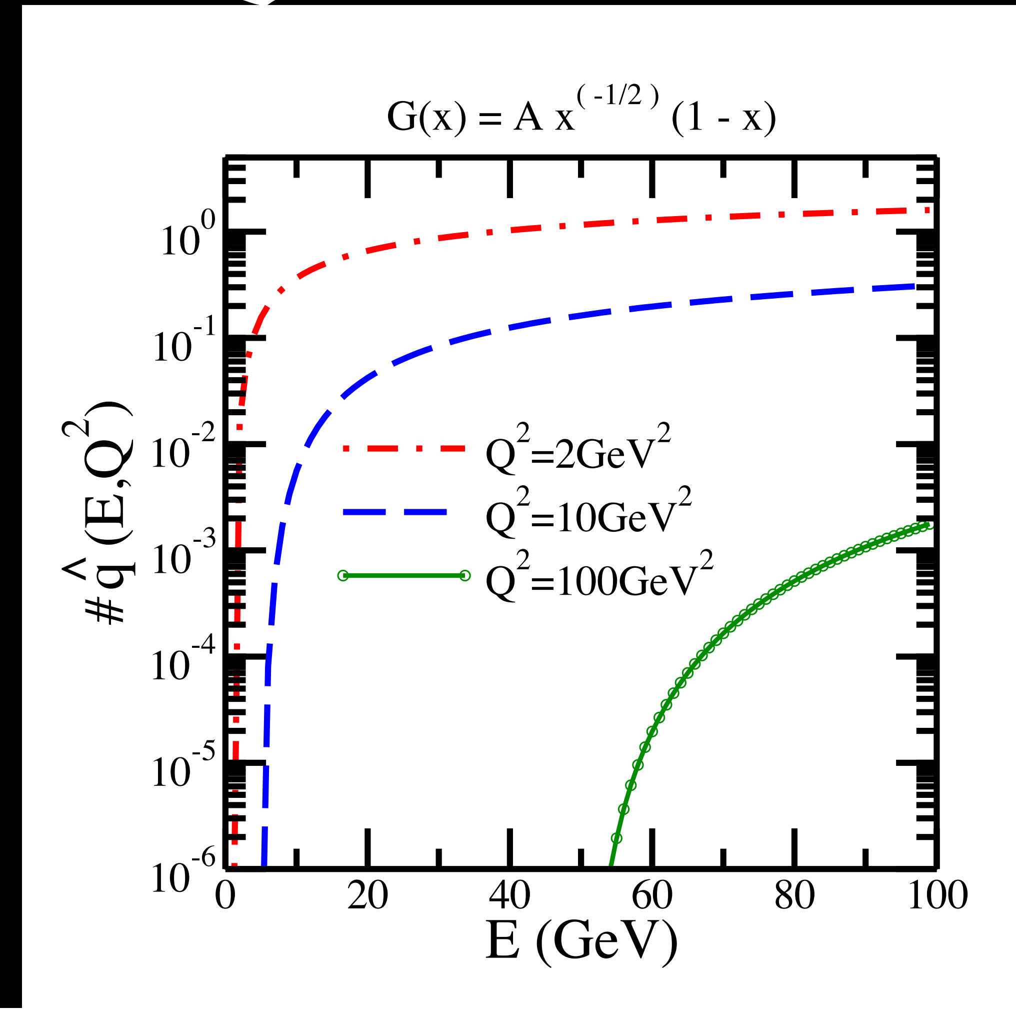
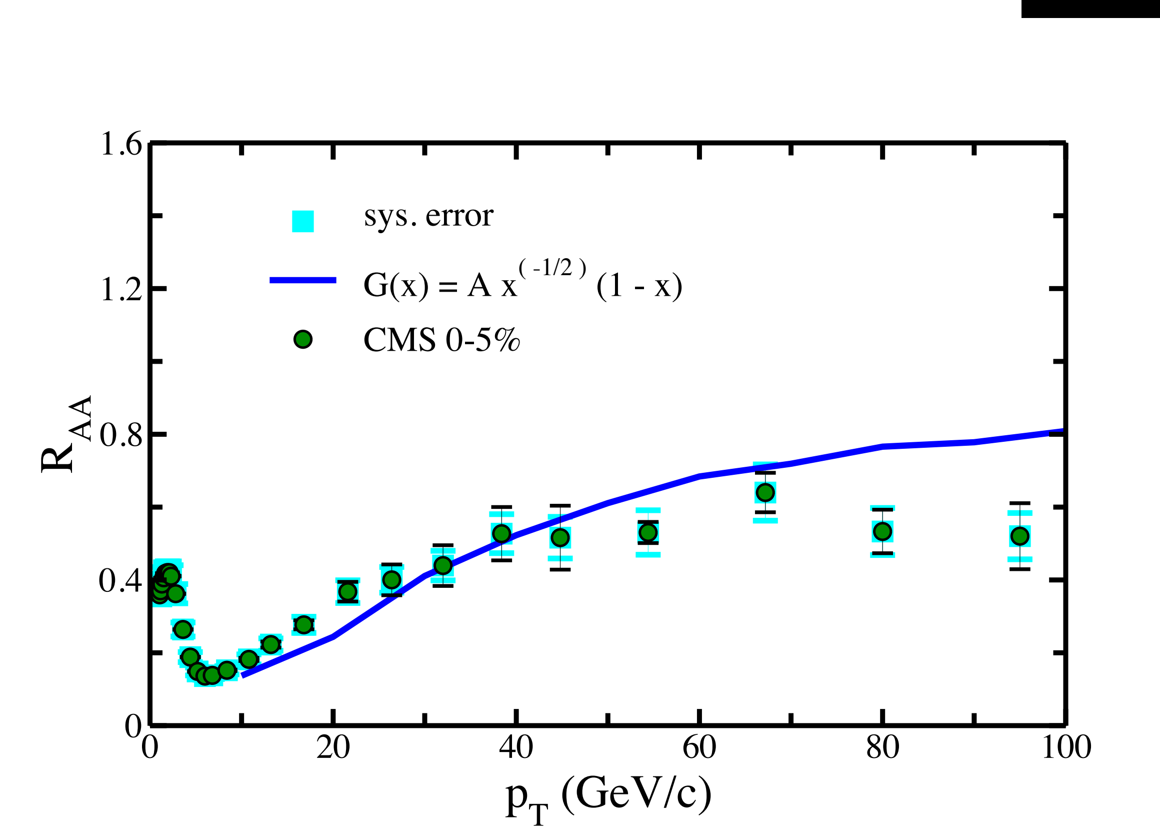
Input PDF at $Q^2 = 1\ GeV^2$

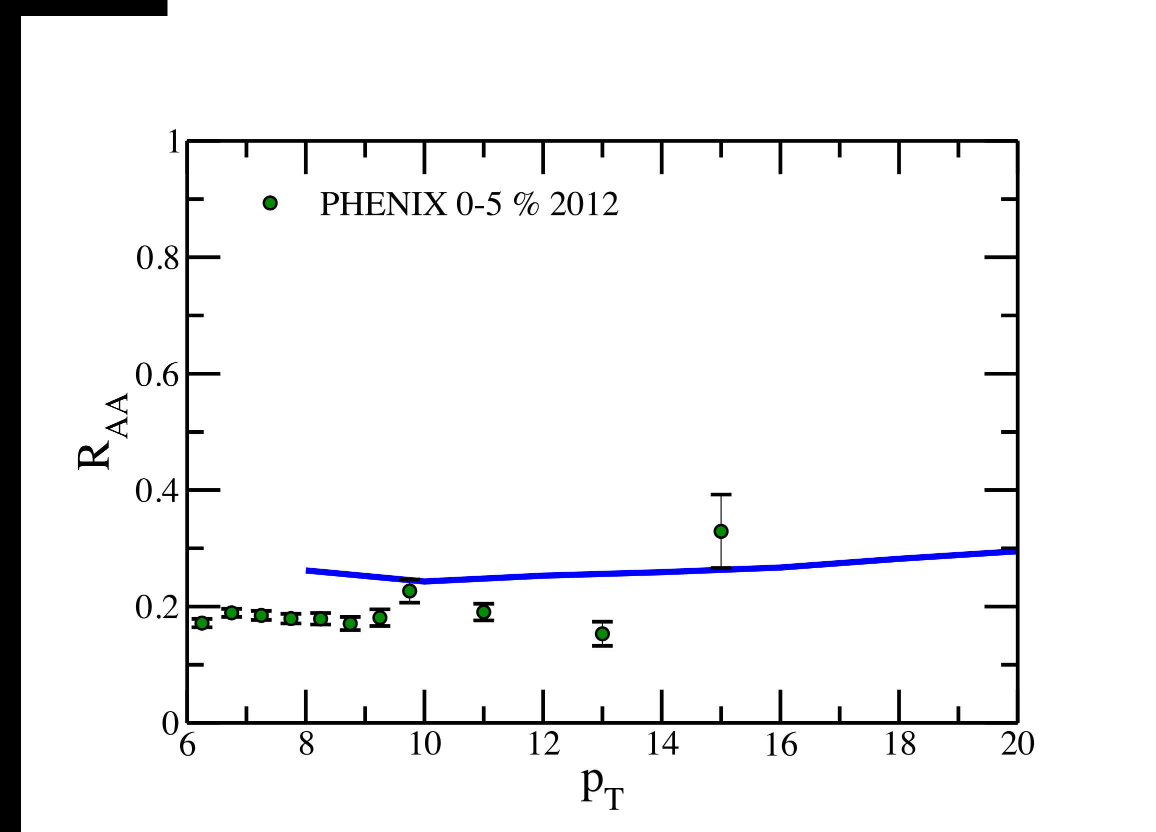


Sea-like PDF of the QGP

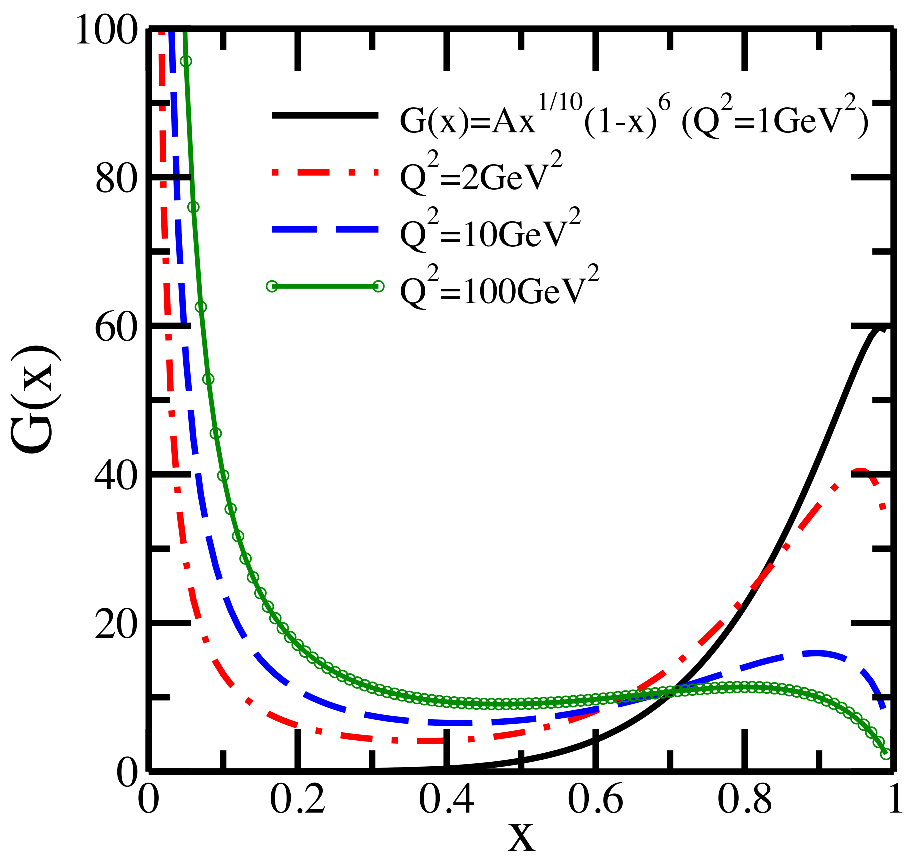


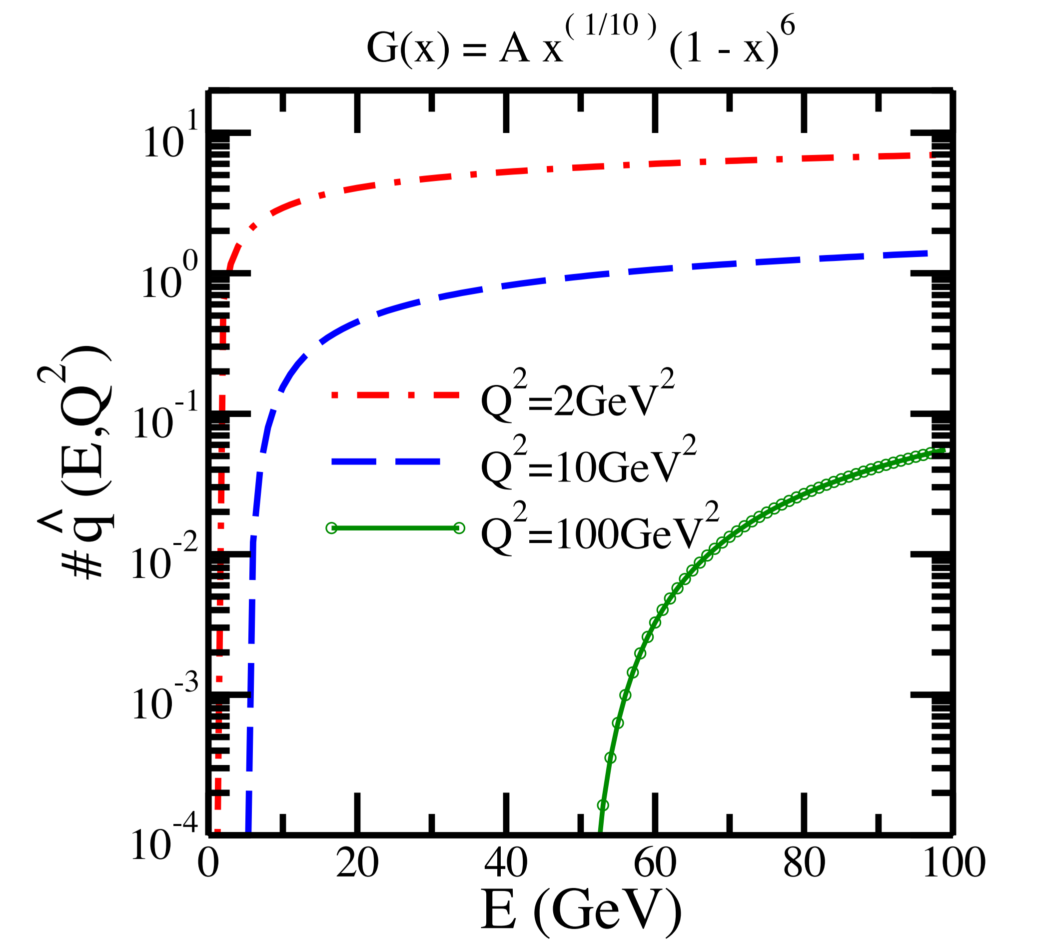


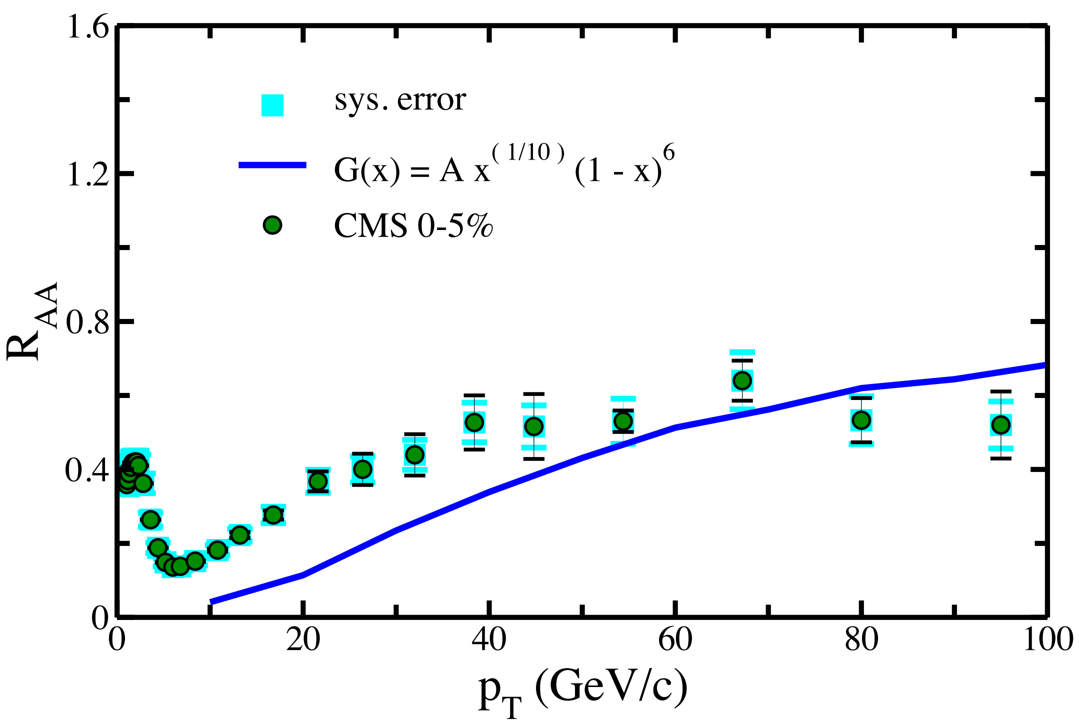


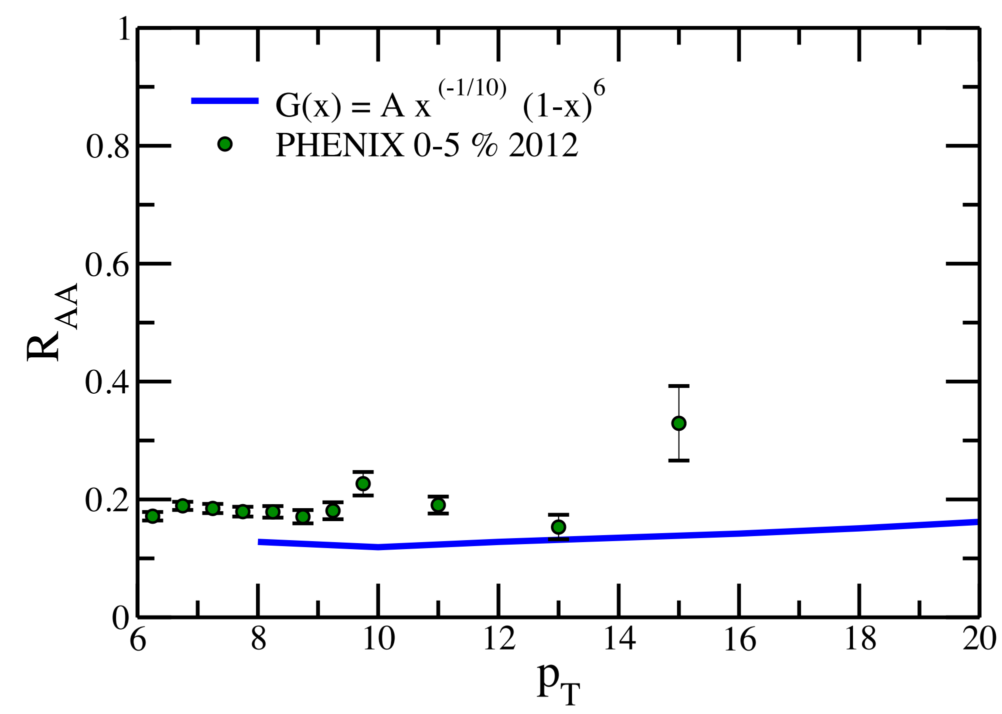


Narrow valence like PDF of QGP

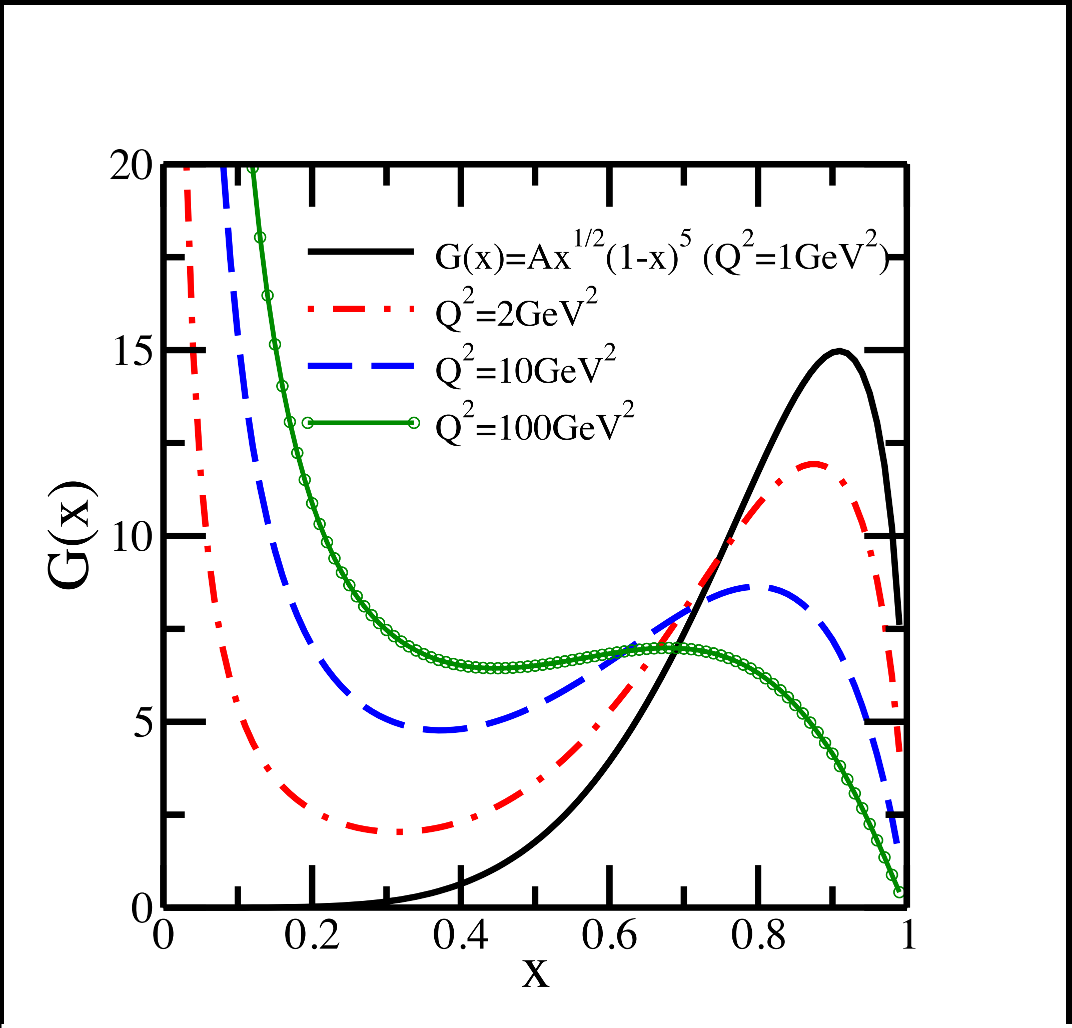


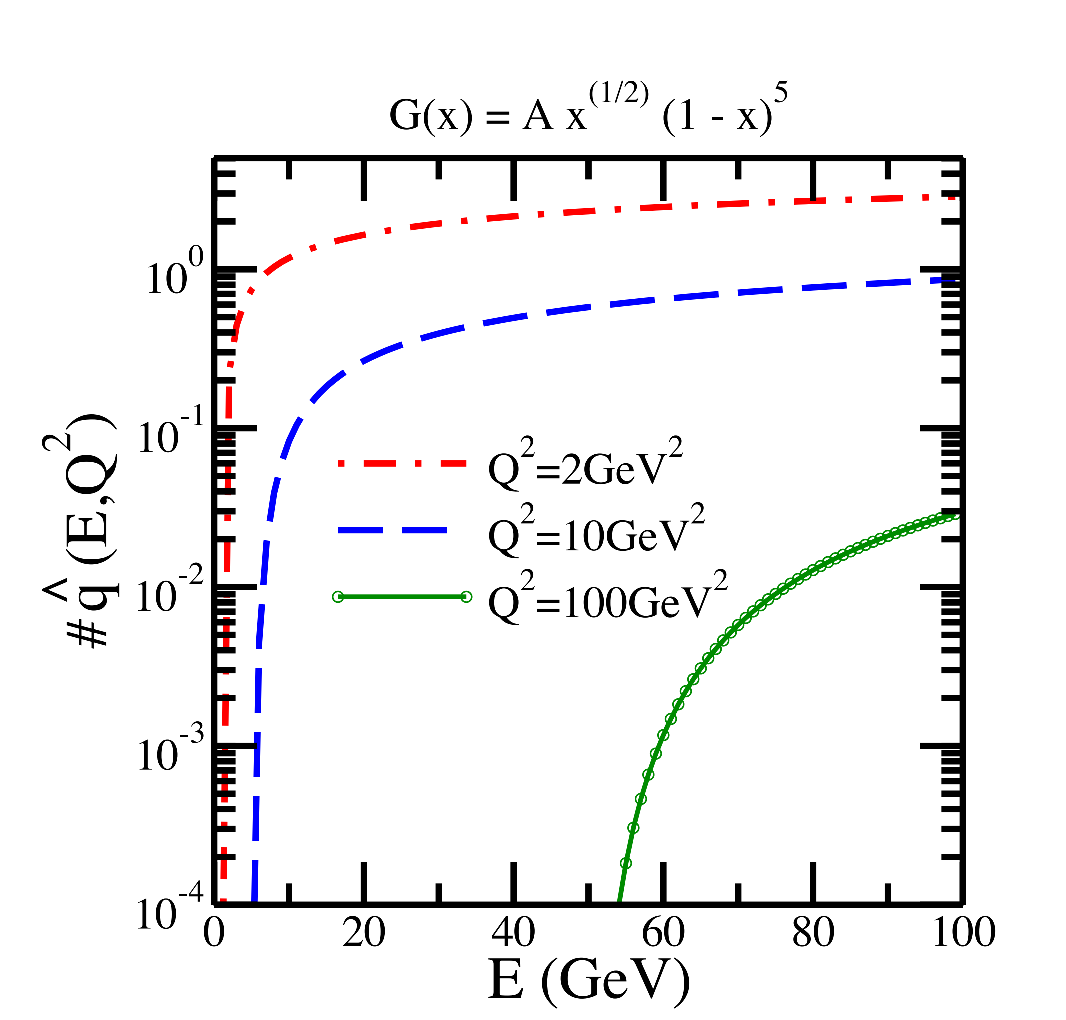


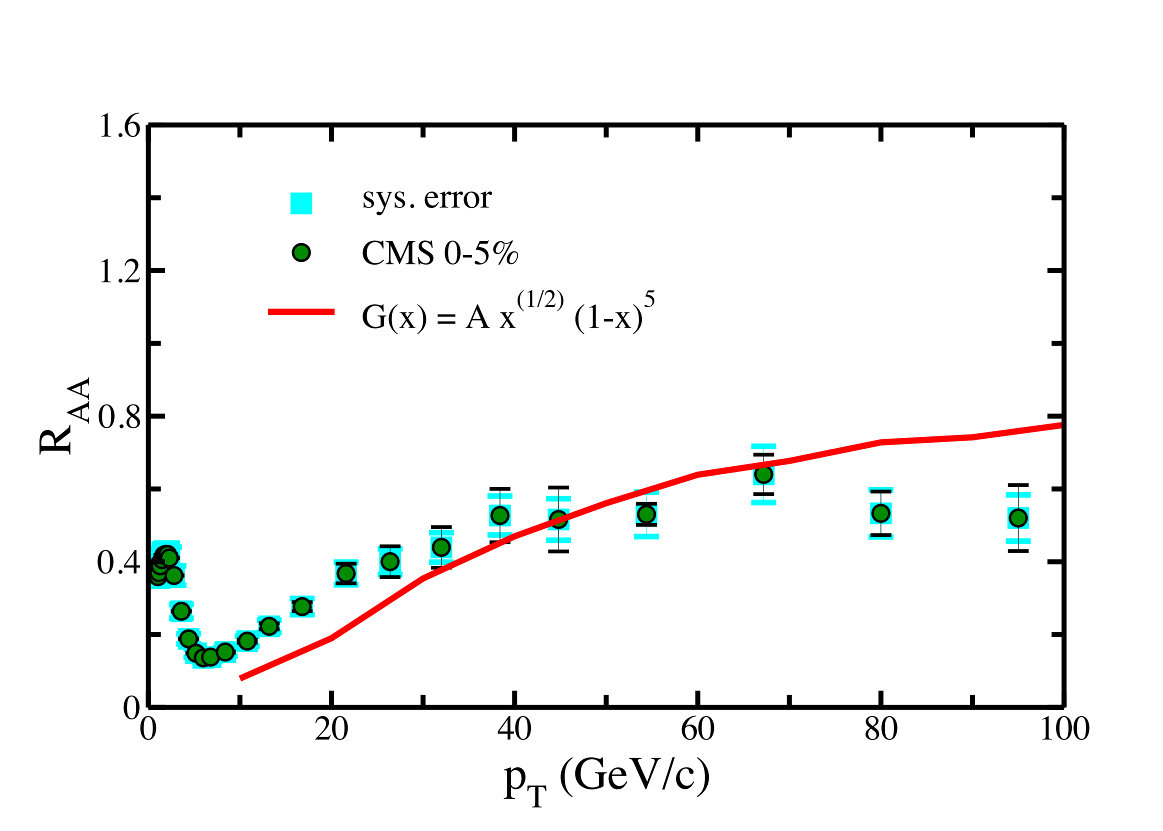


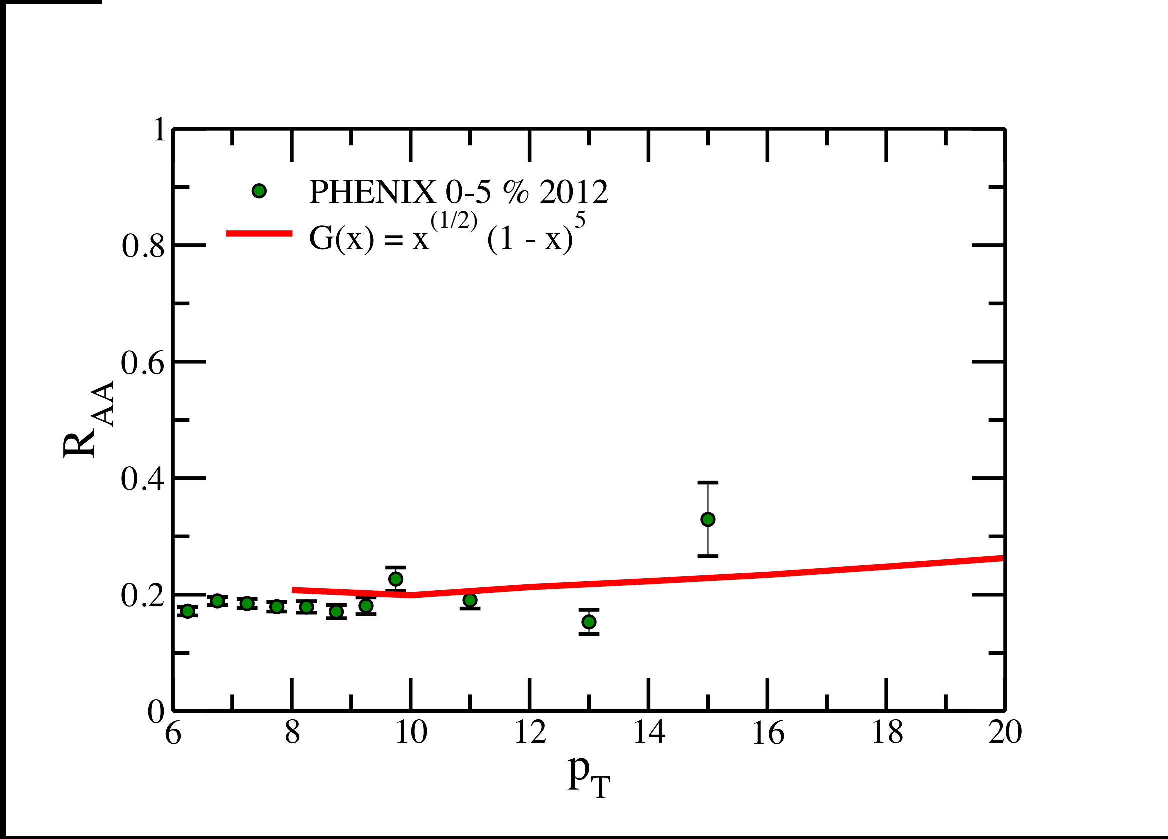


Wide valence like PDF of the QGP





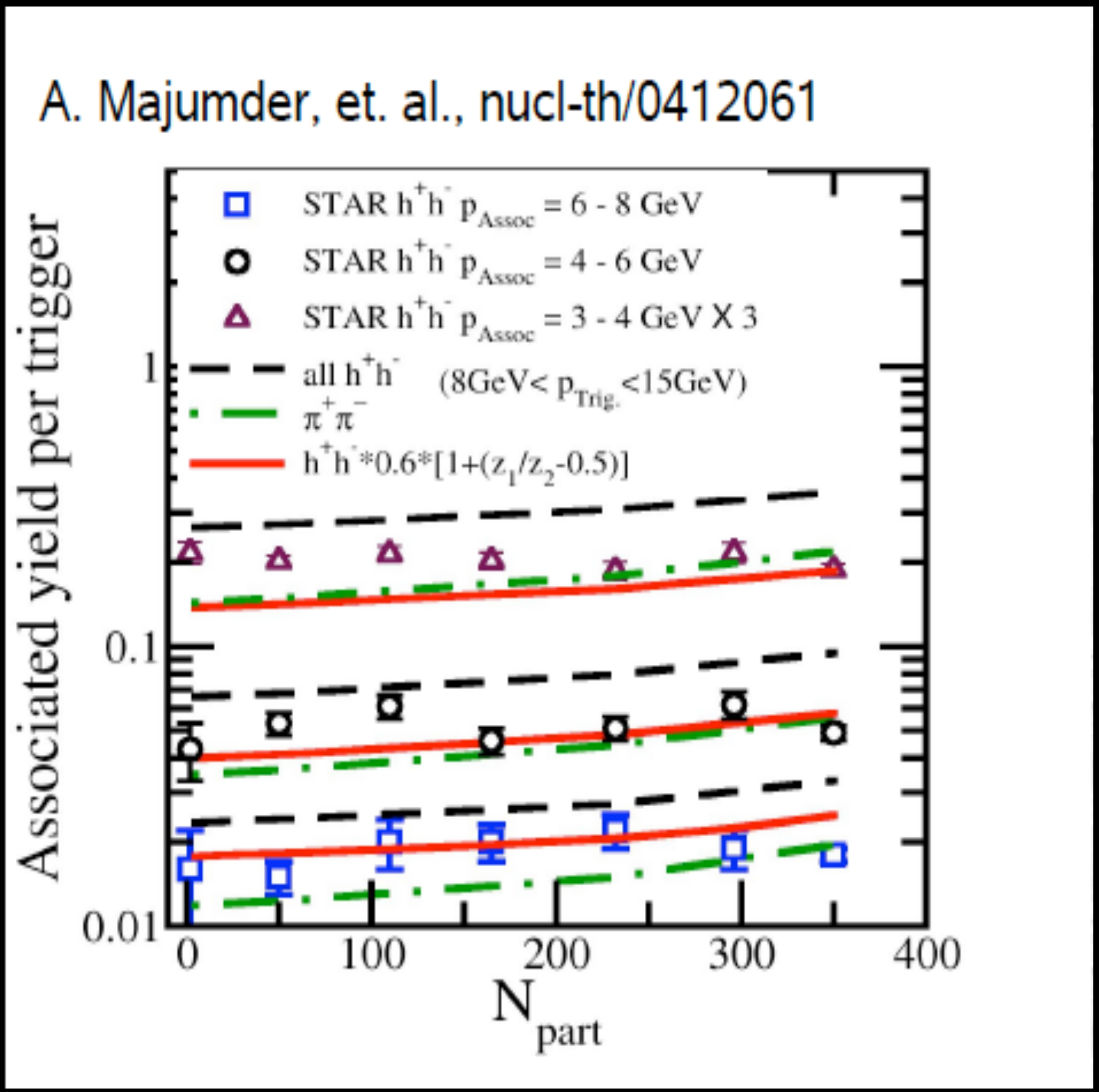


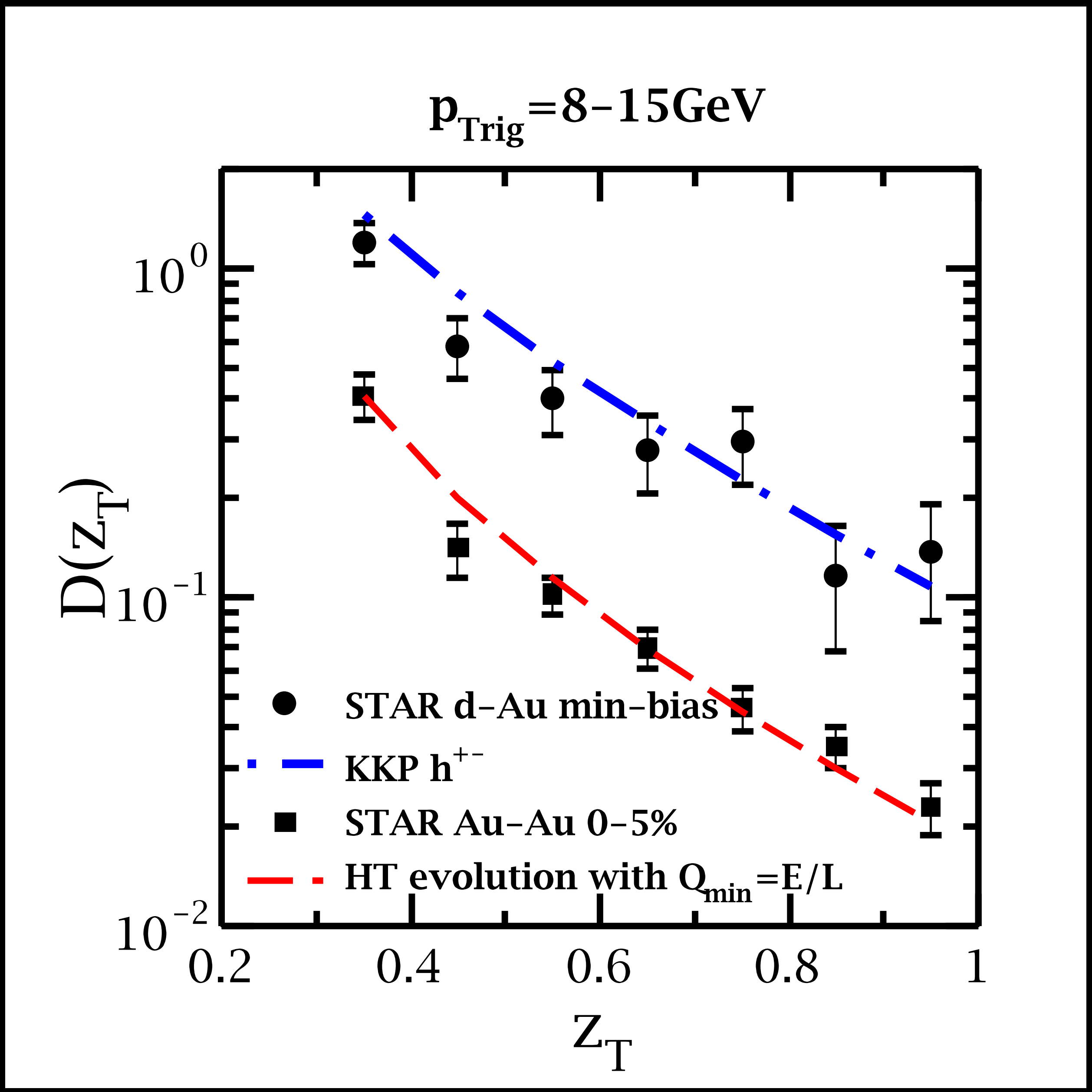


What does this mean?

- Possible resolution of the JET puzzle
- Based on consistent Q^2 evolution of q
- Should have x evolution at high energy
- Will be done in reverse very soon, will get PDF's with bands (by Quark Matter !!!)
- Applying TMD systematics, may complicate this interpretation.

Near side and away side correlations





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