Theory of jets in dense matter

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Wayne State University

CIPANP 2018, Indian Wells CA, May 29 - Jun 3, 2018

Outline

Intro, pQCD and scale dependence

From one theory to multiple theories,

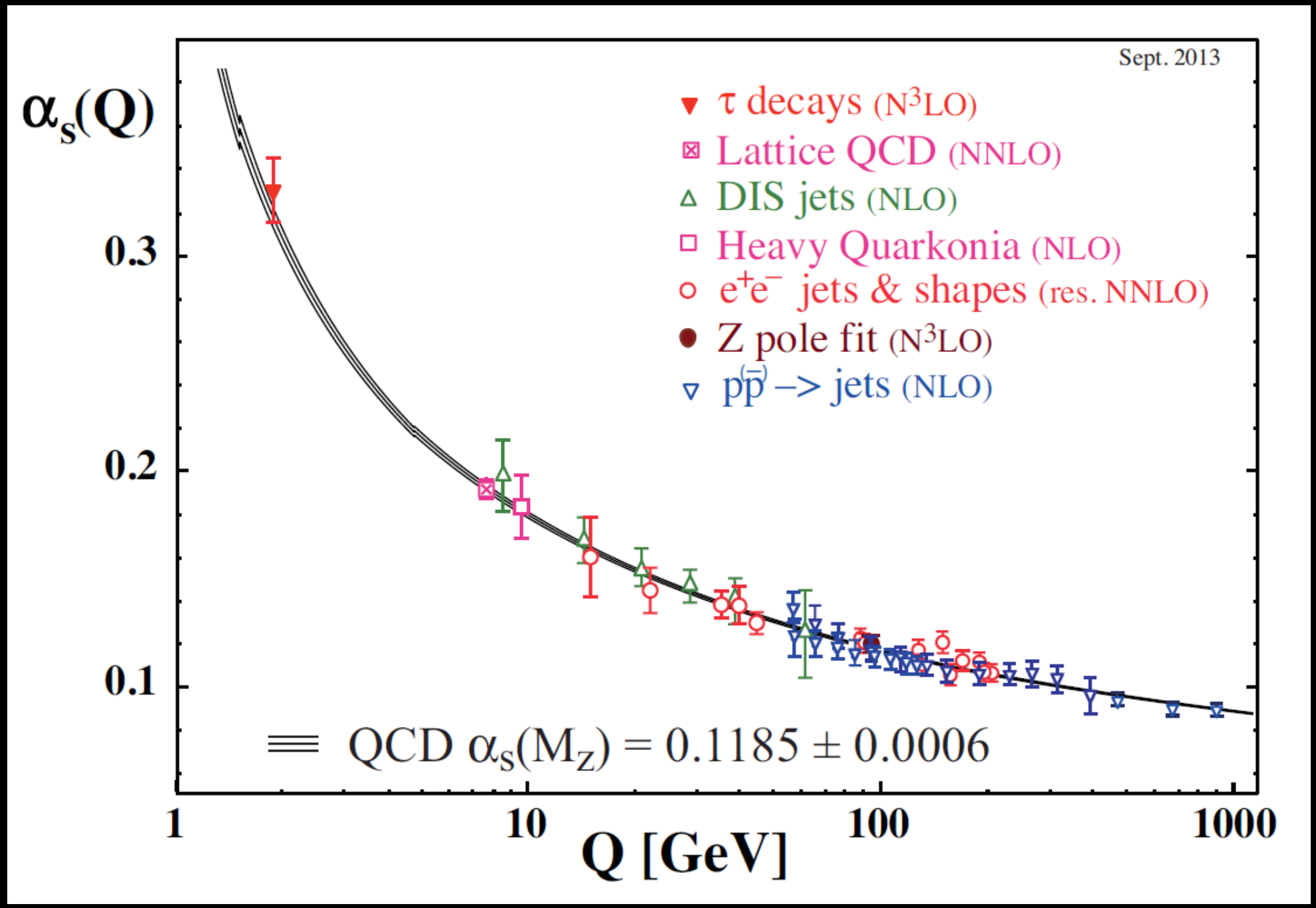
Role of scale in jets and jet observables,

Analytic calculations and Monte Carlo simulations

Results of simulations, and extracted information

Outlook!

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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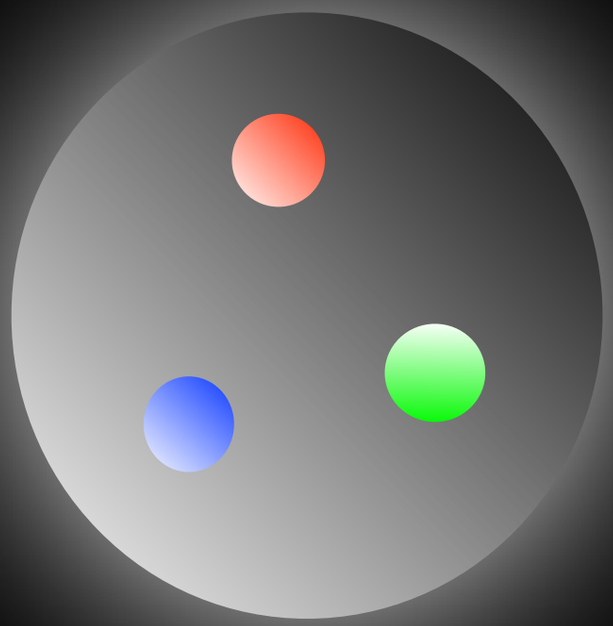

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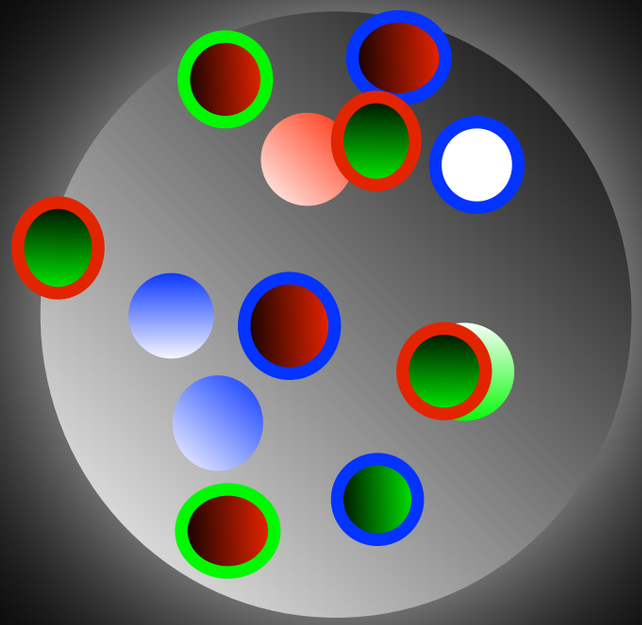

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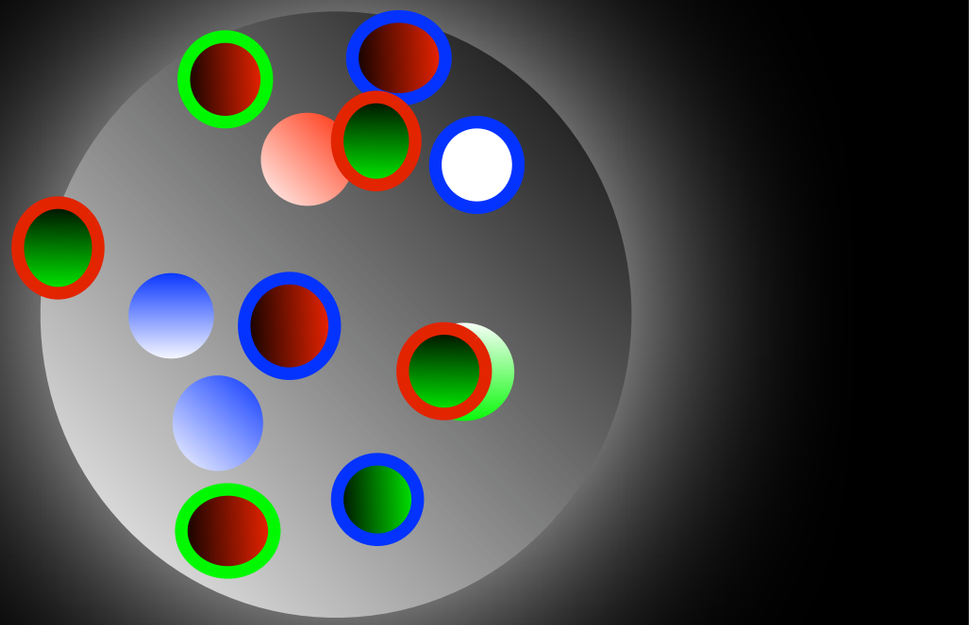

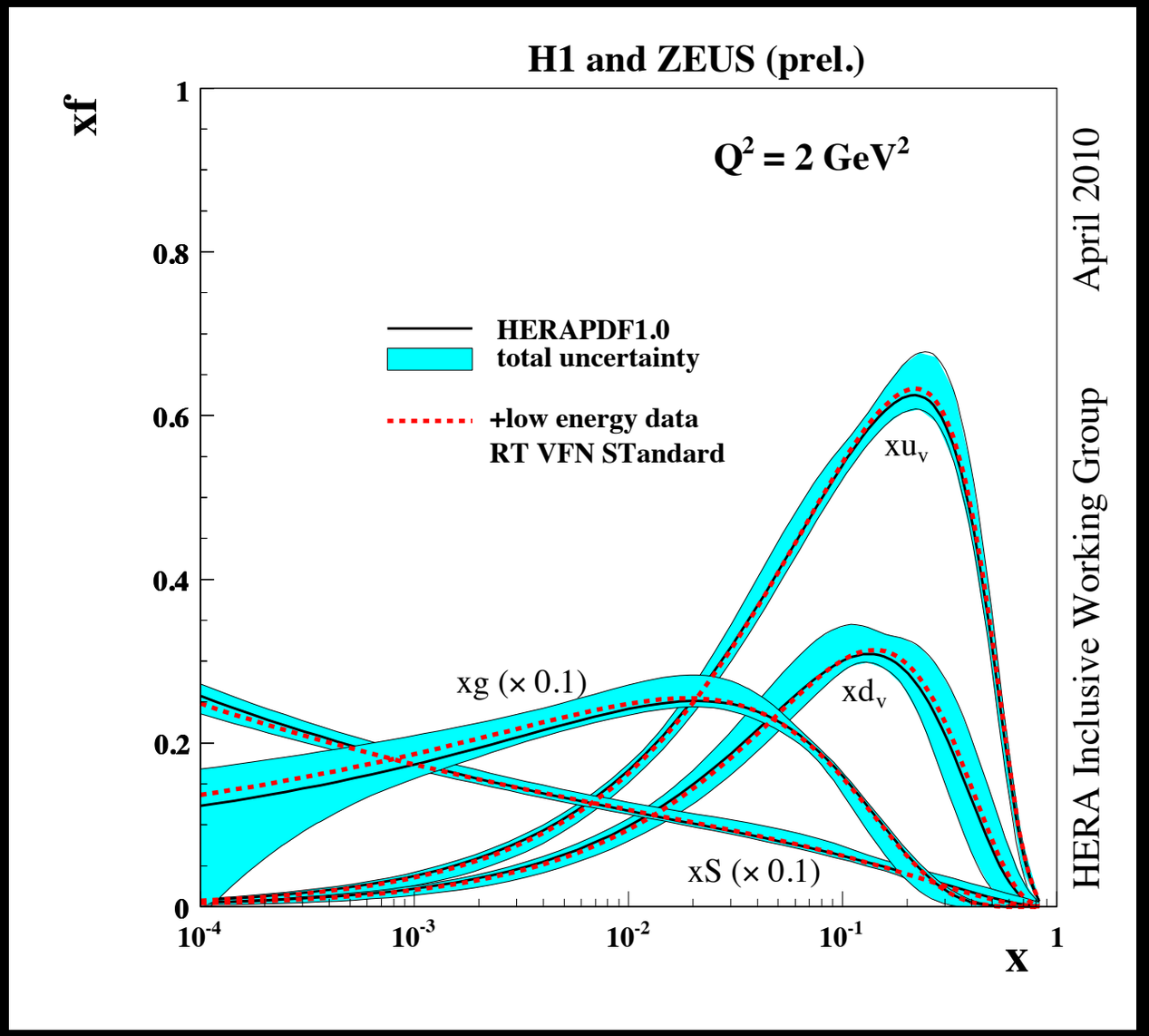

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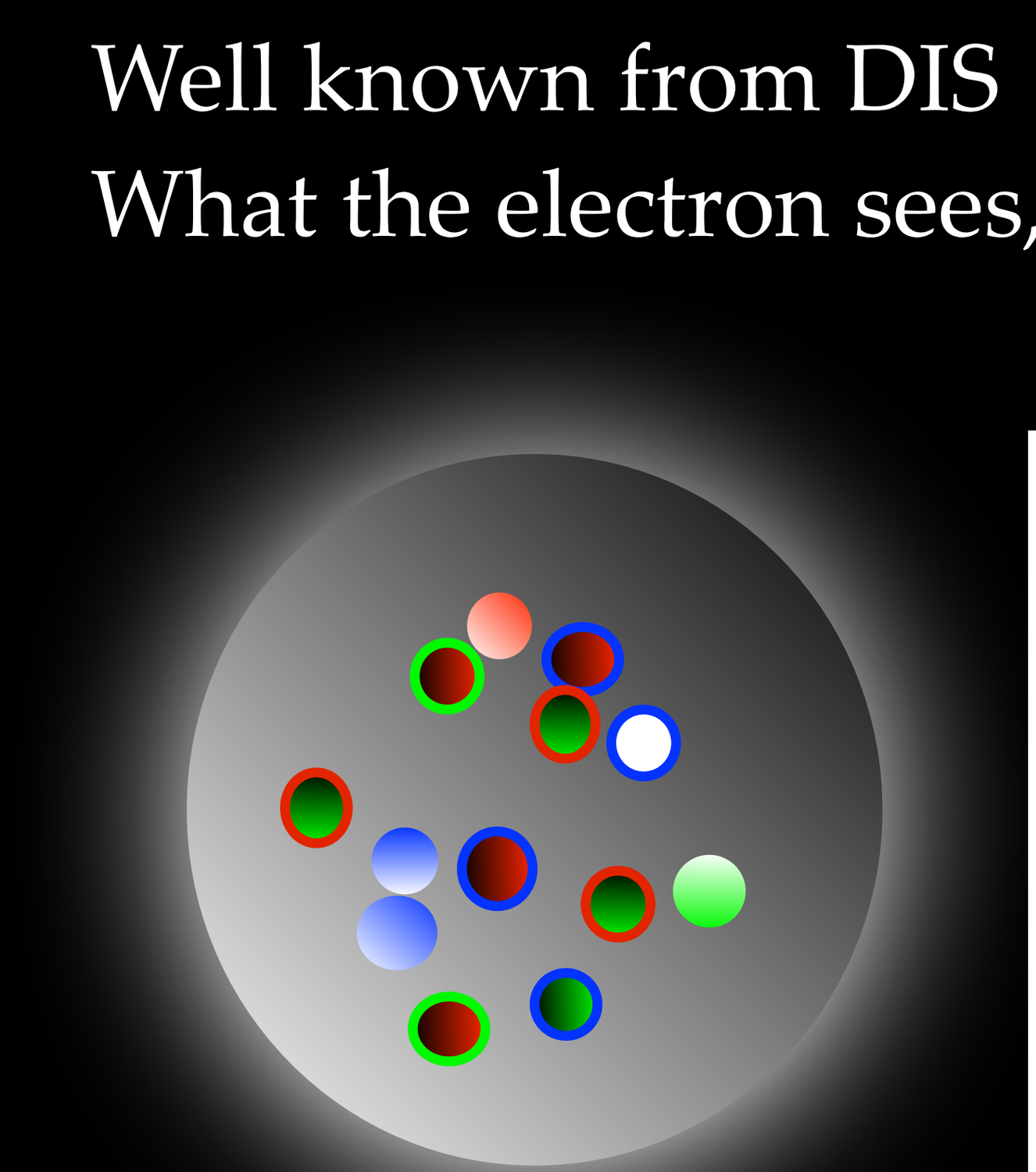

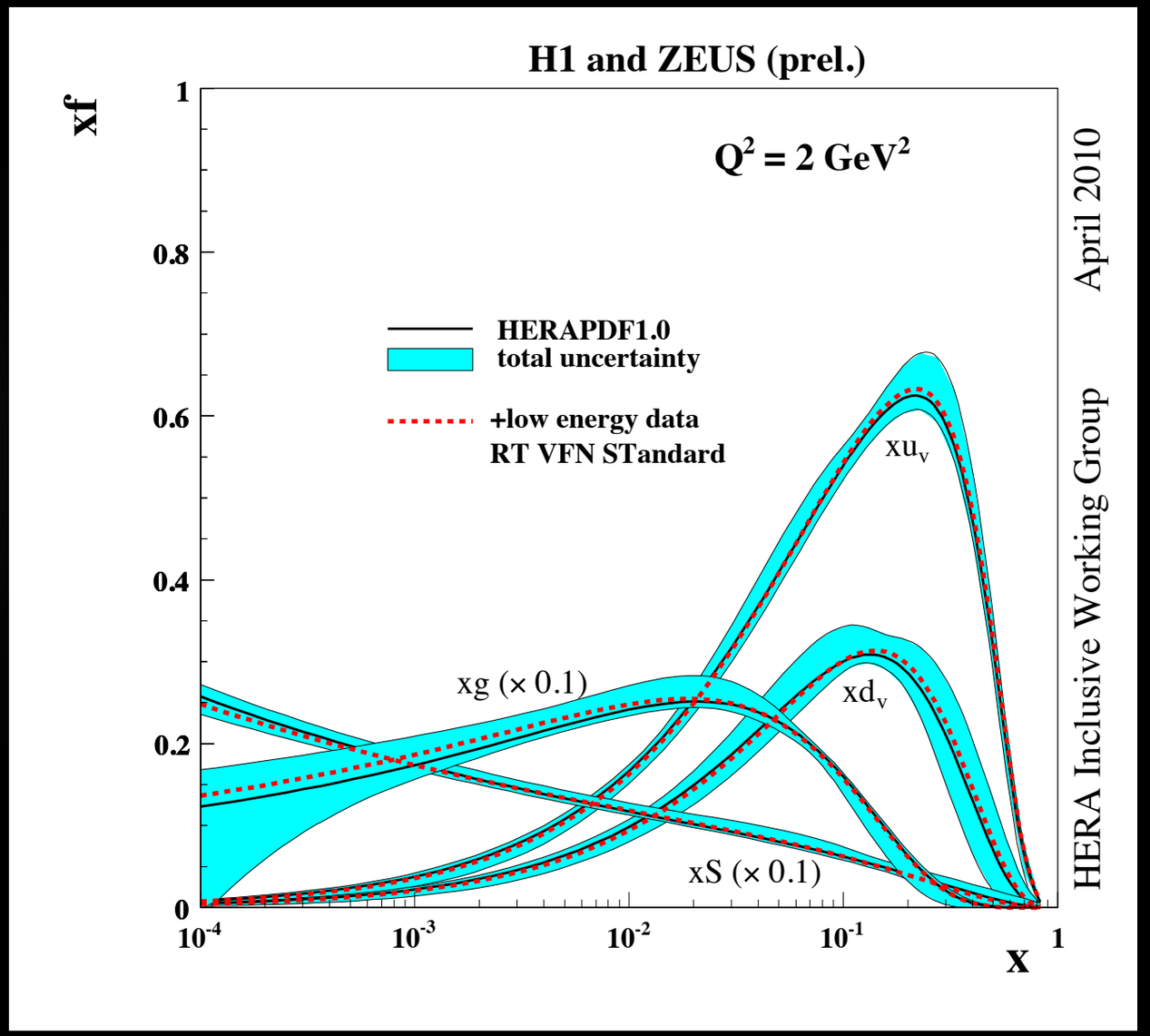

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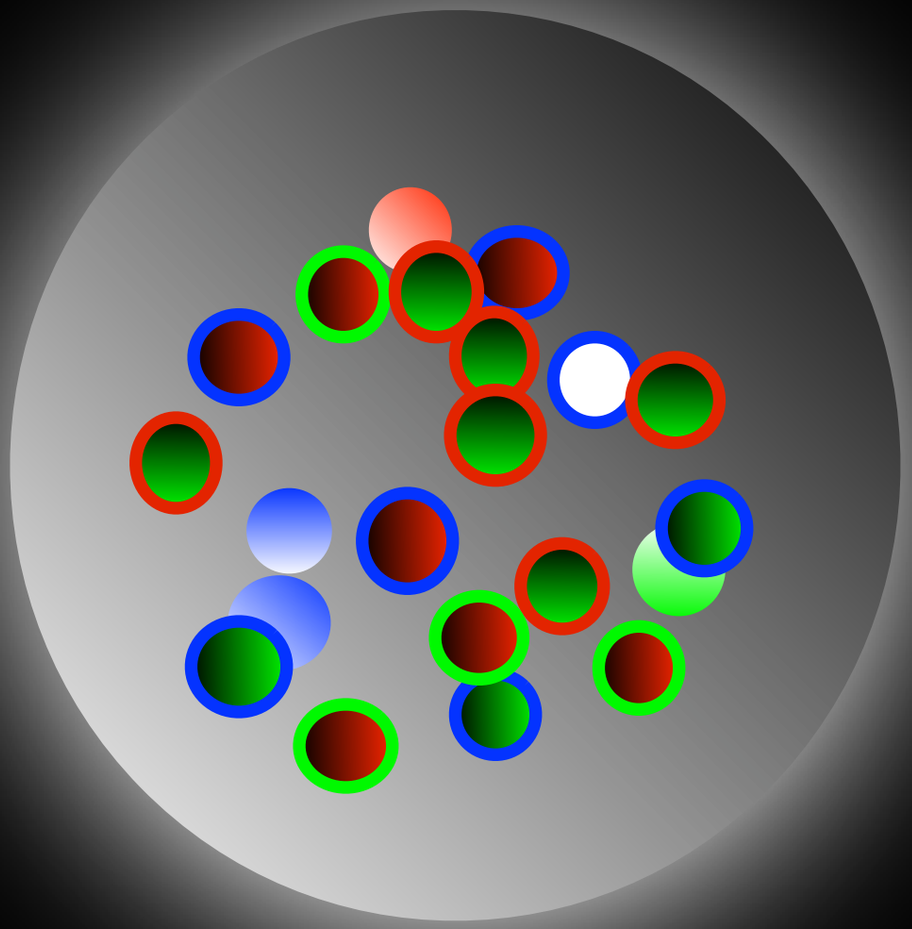

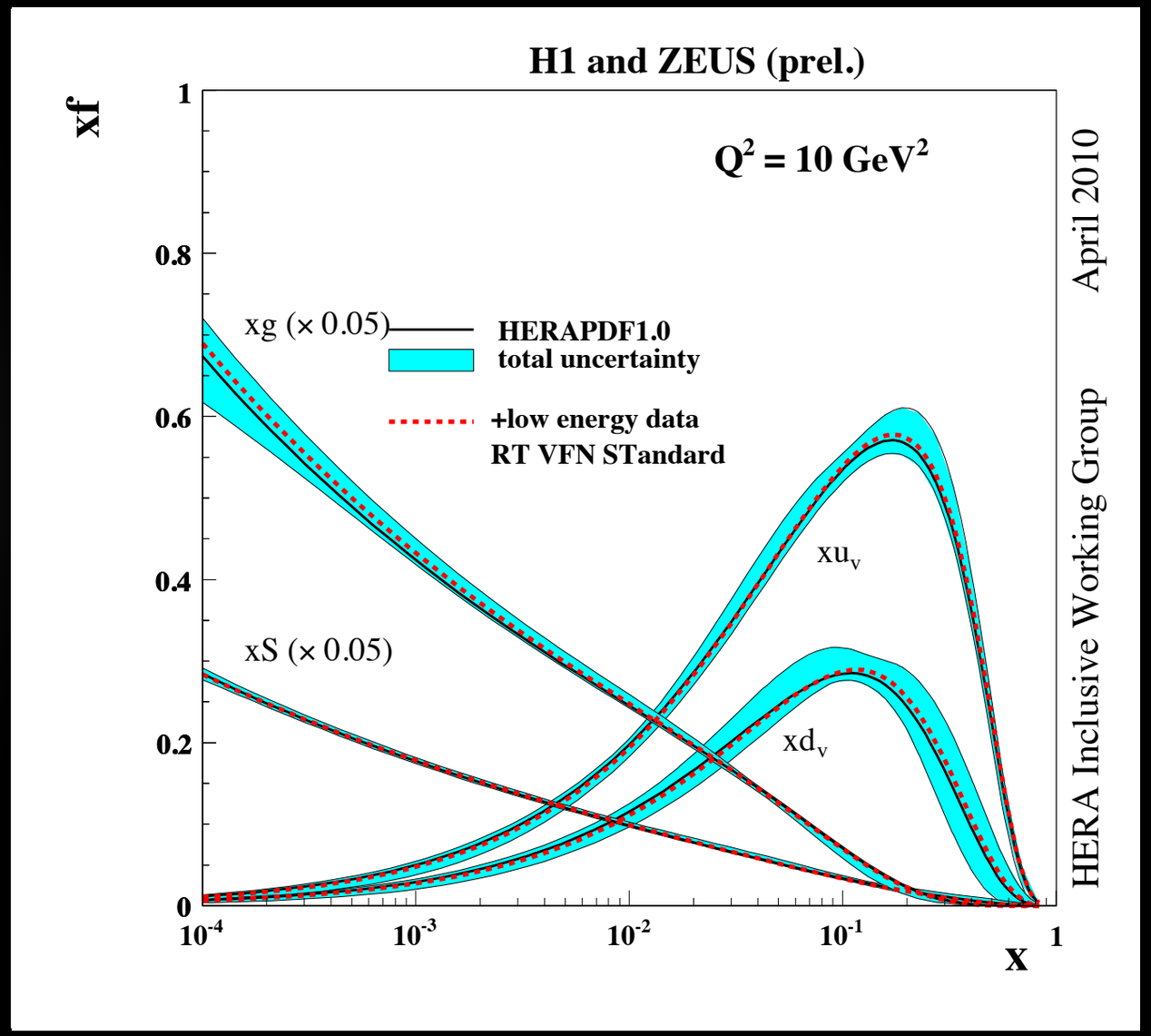

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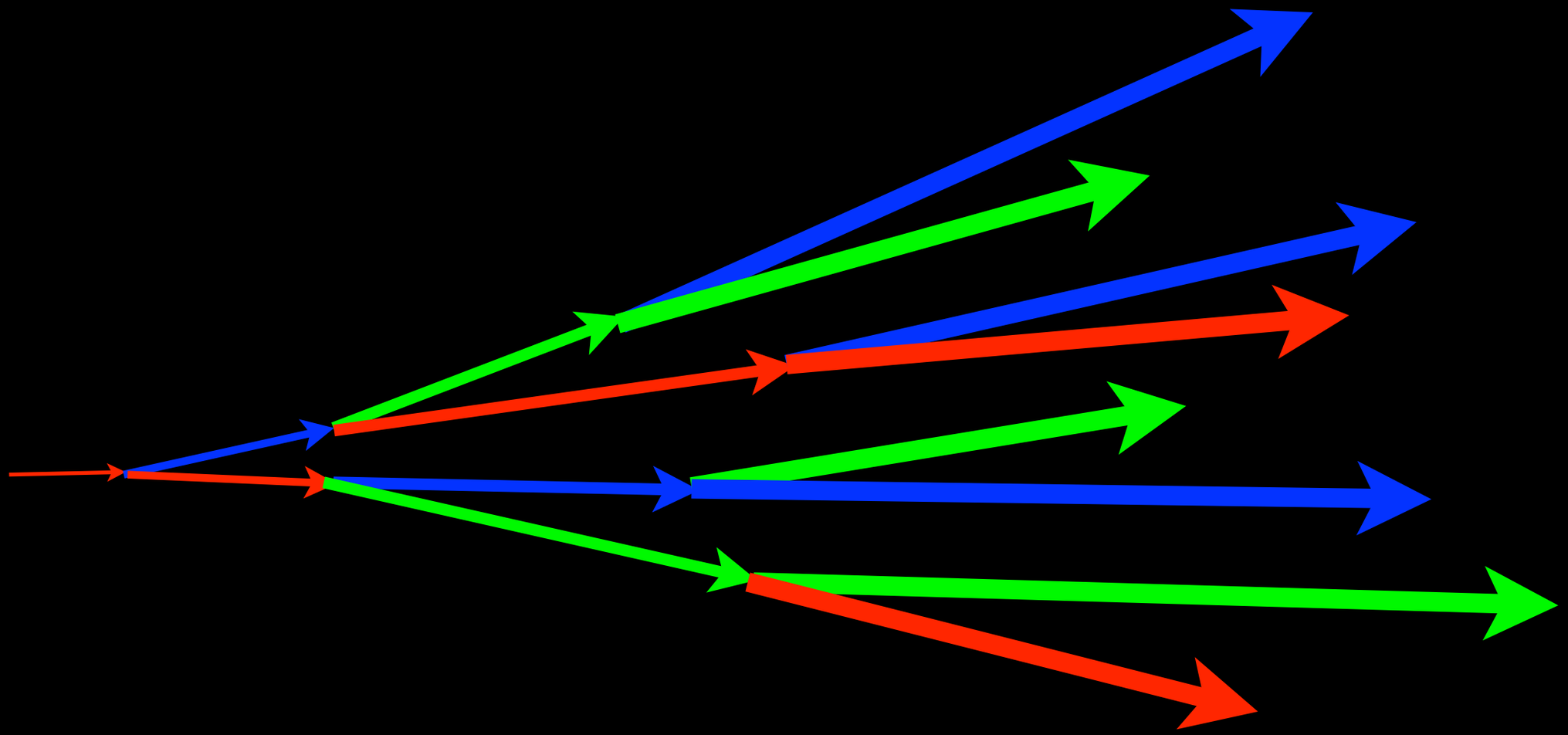

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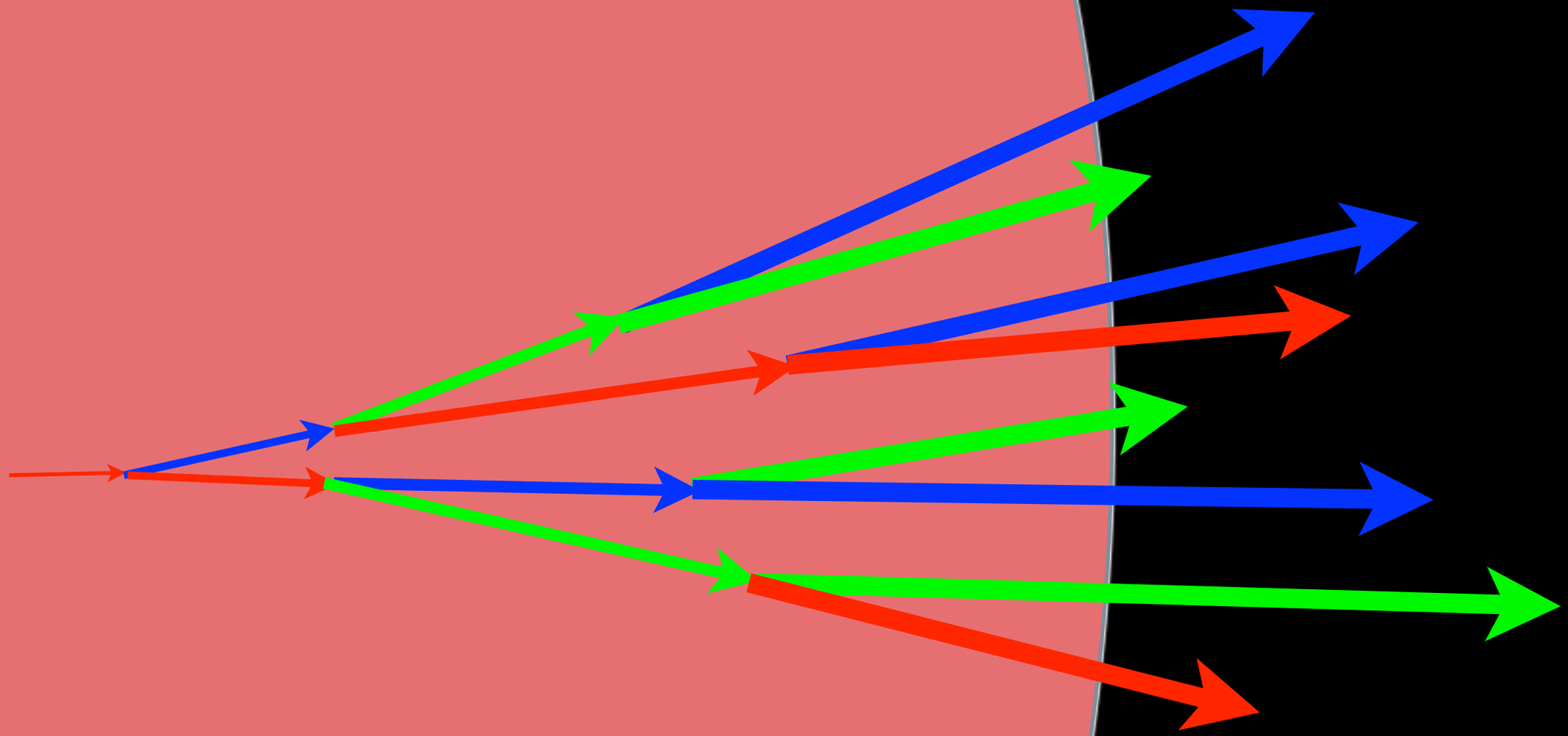

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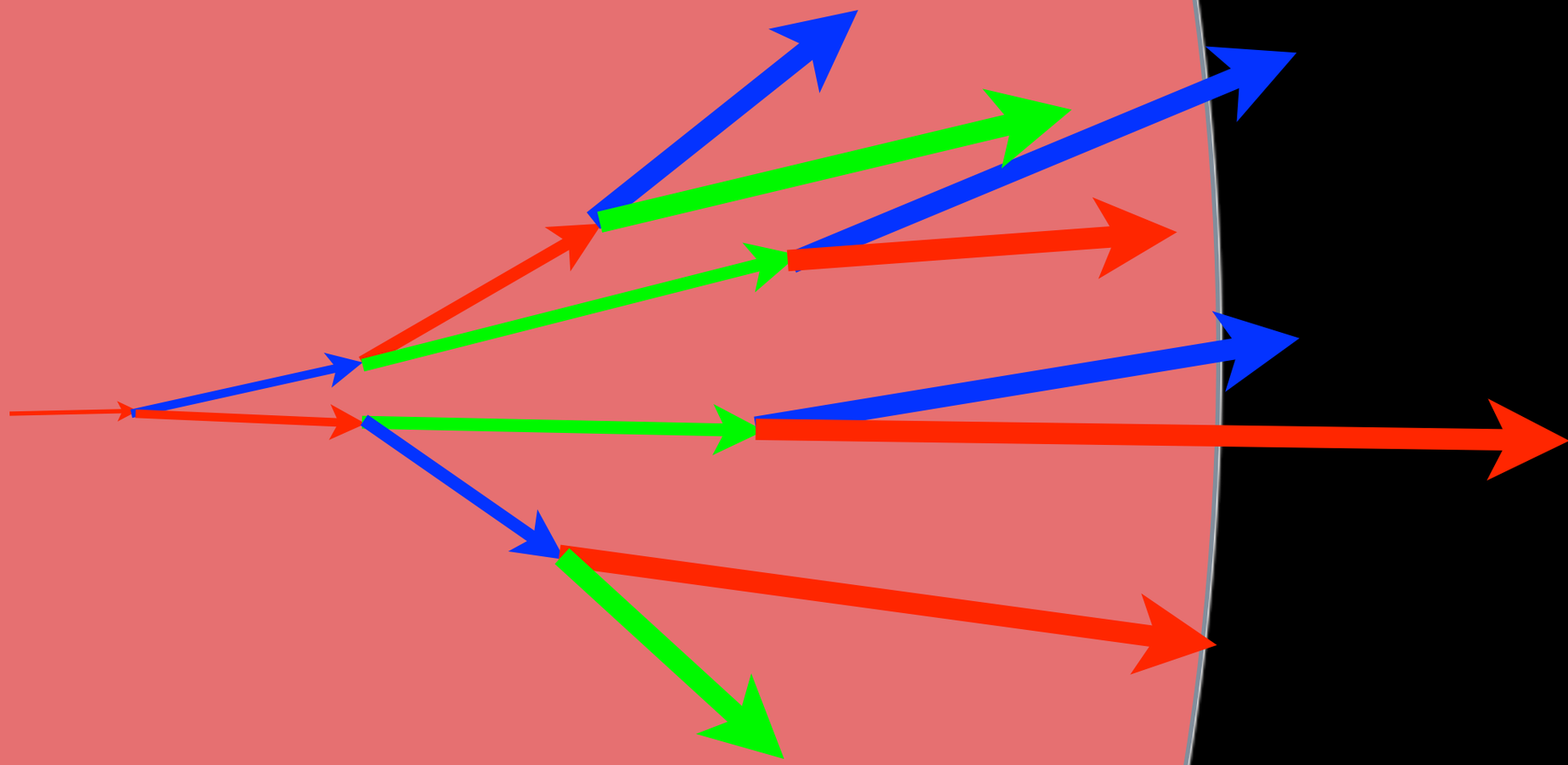

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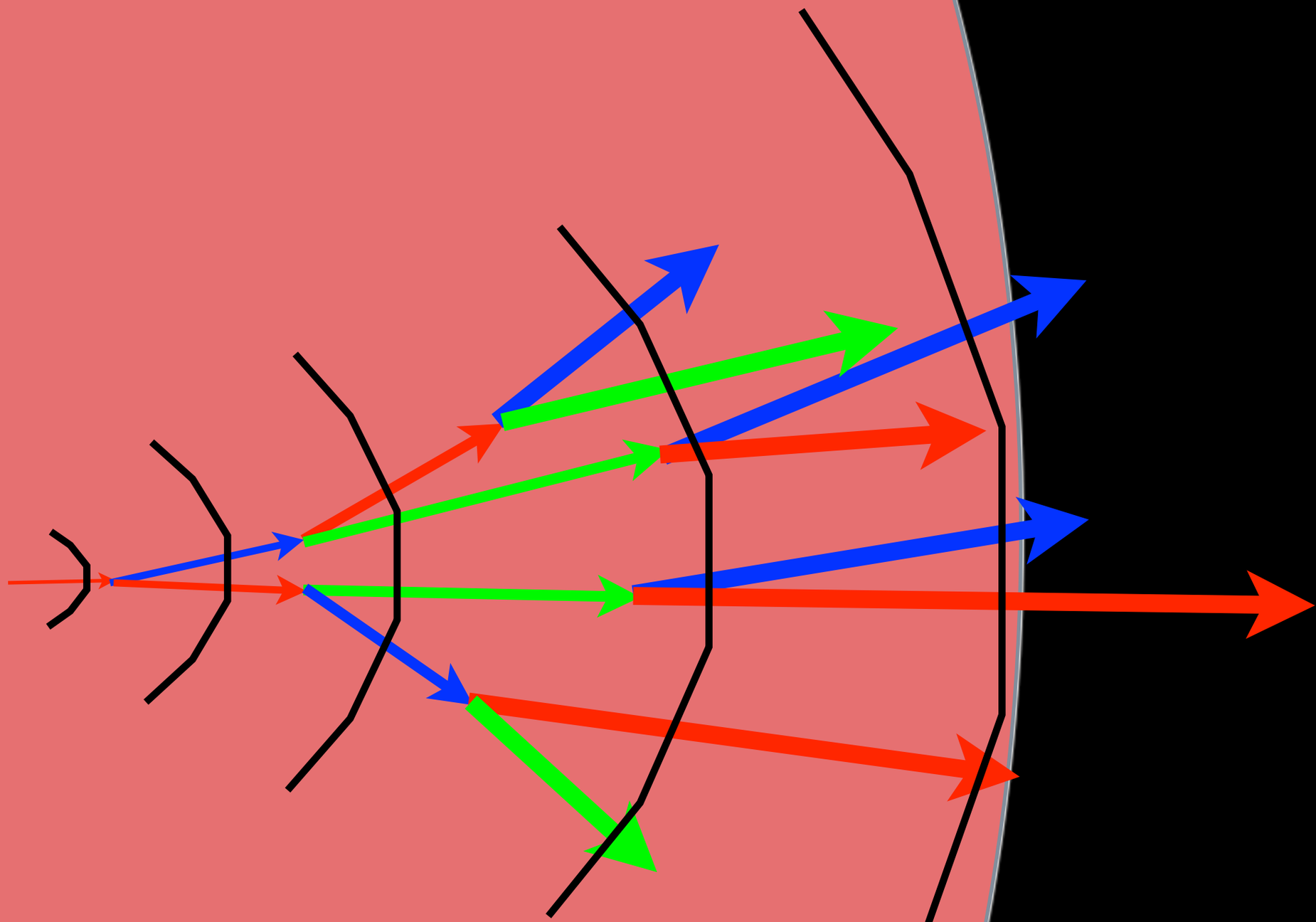

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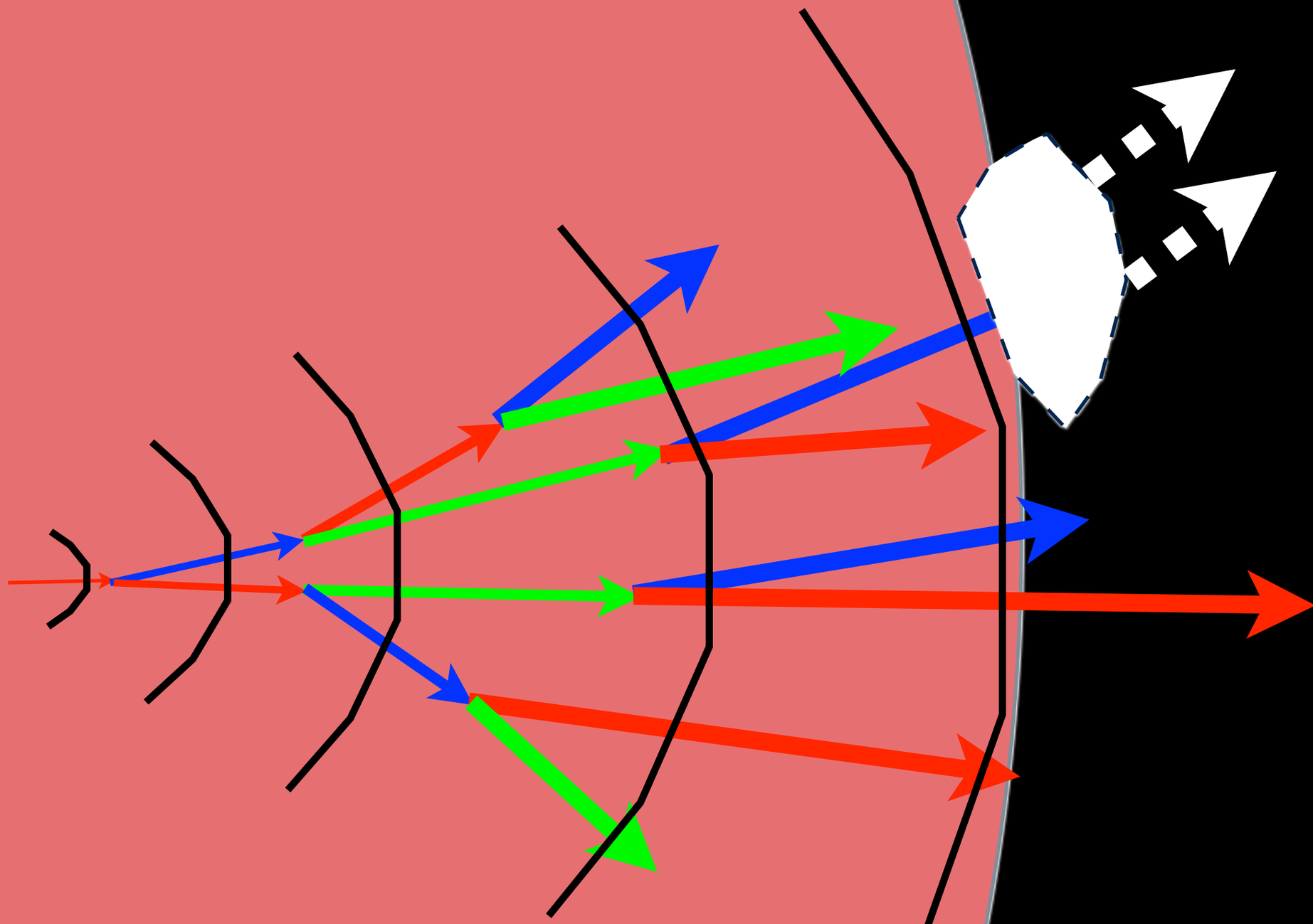

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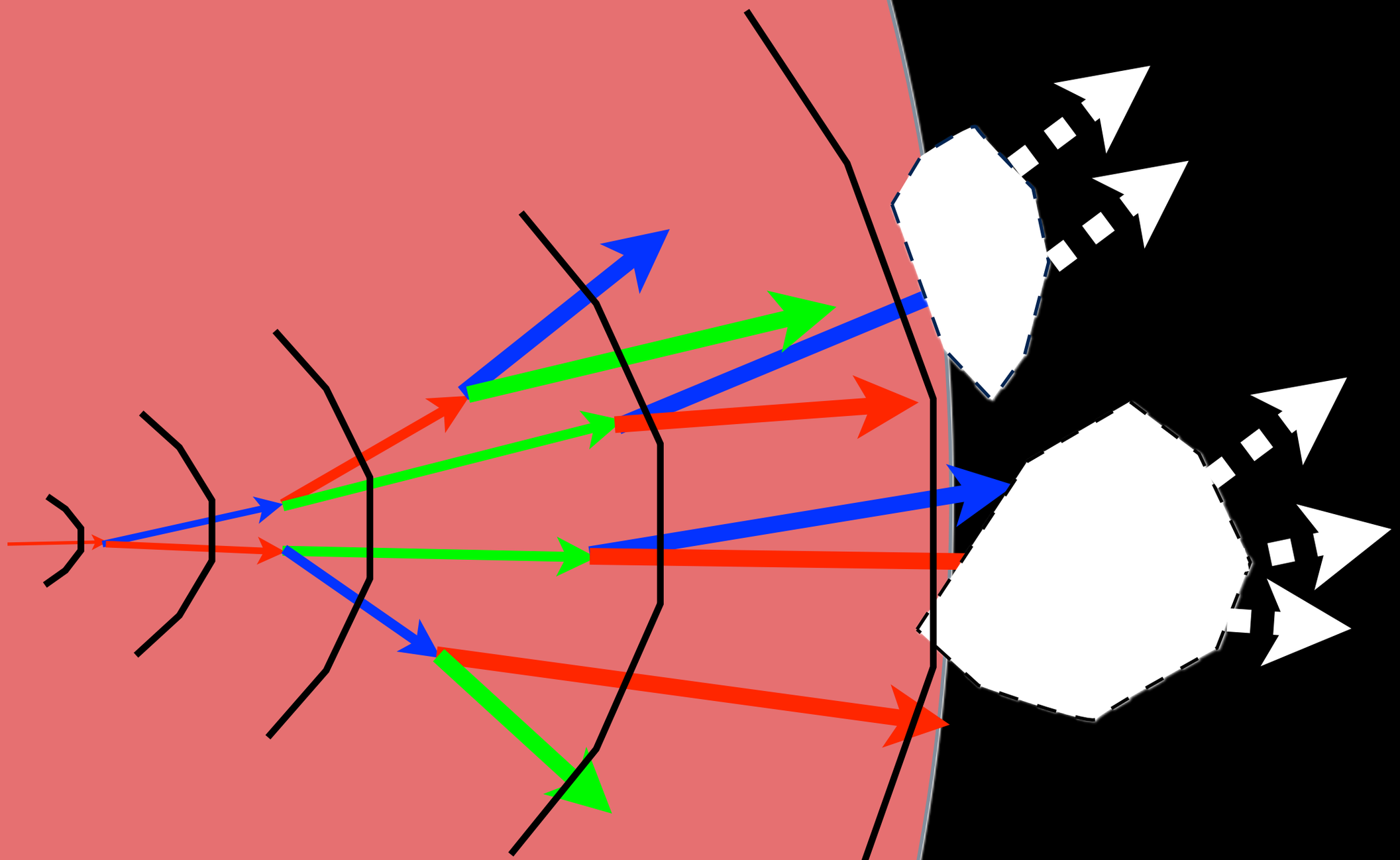

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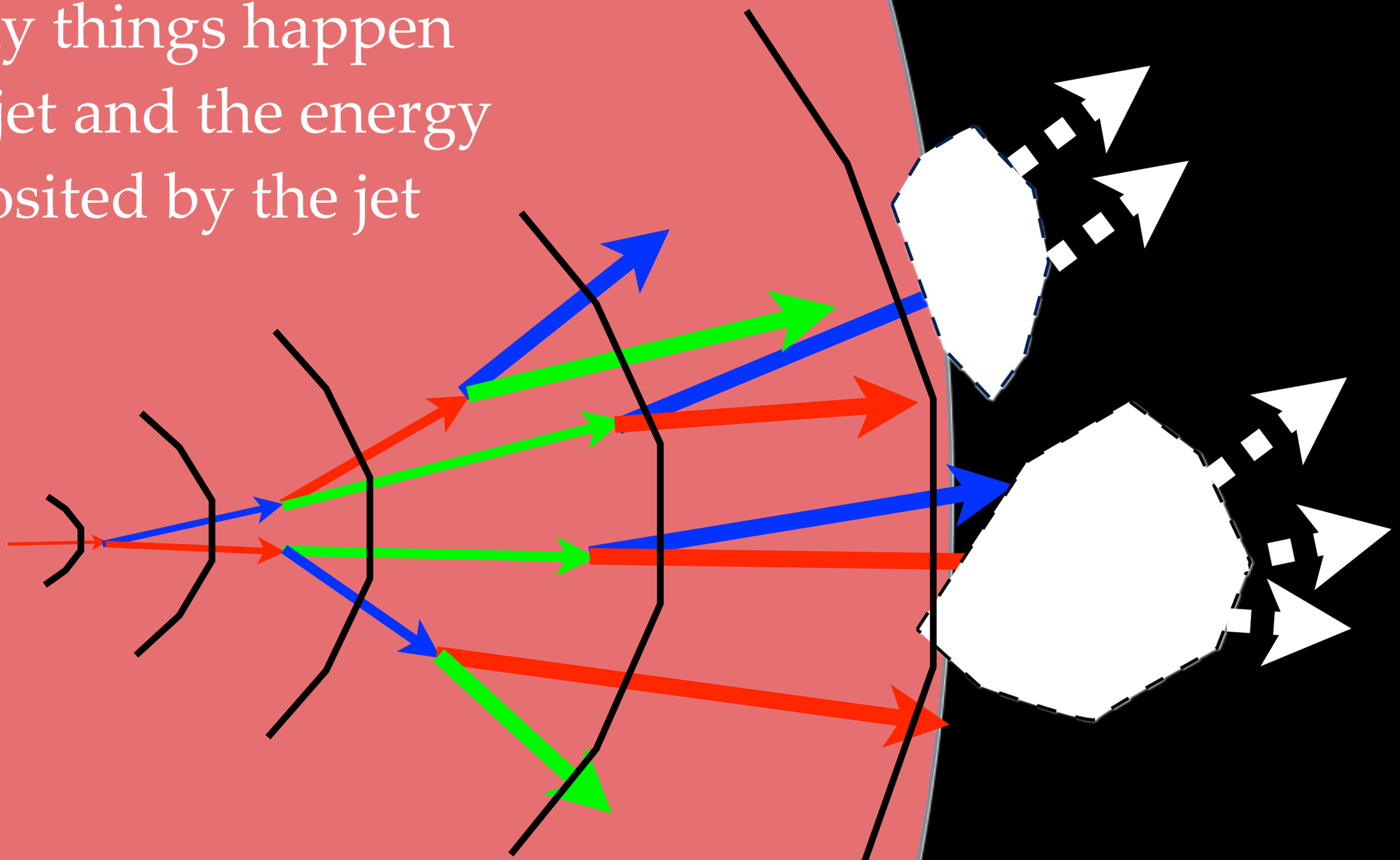

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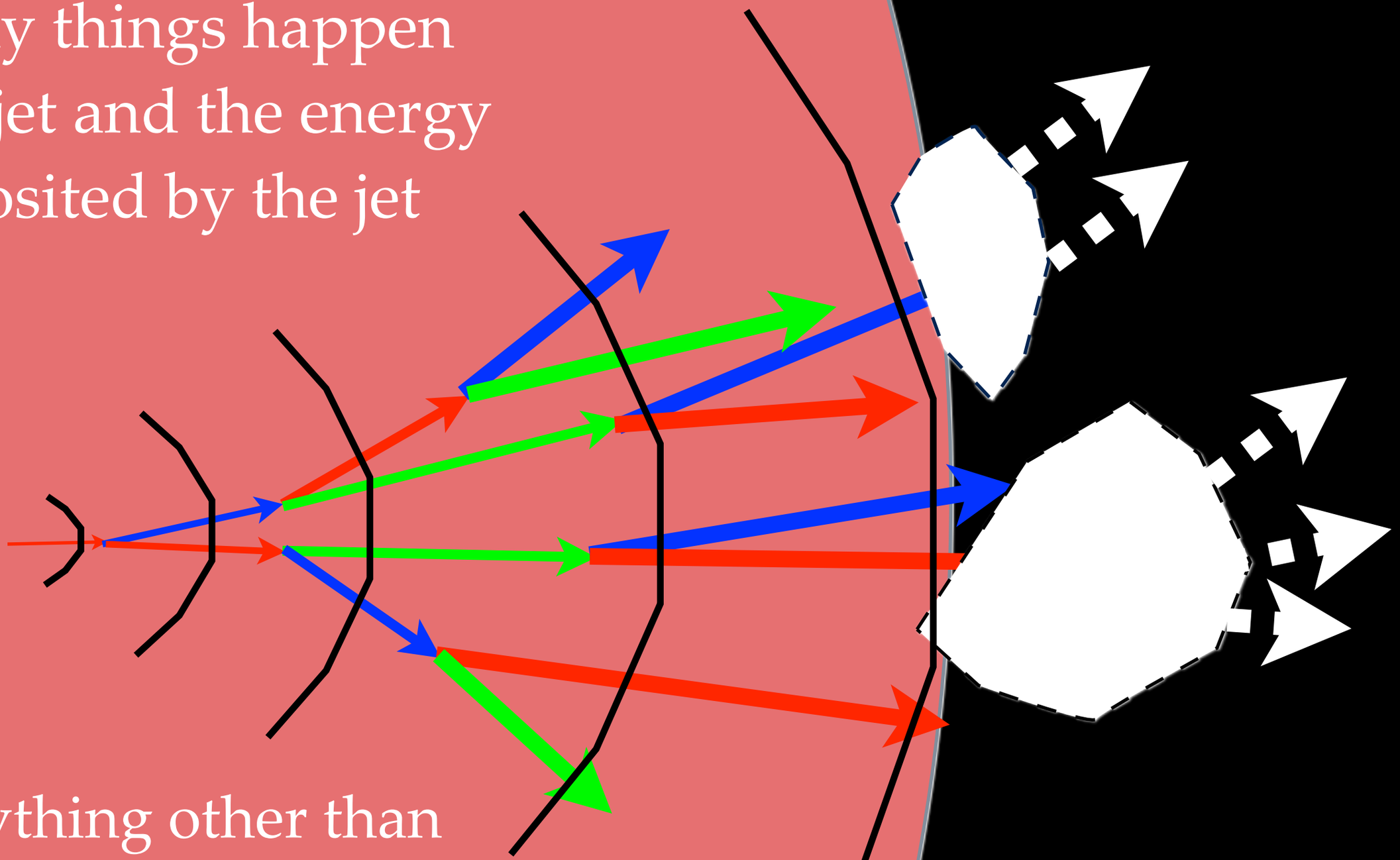

Everything other than
leading hadrons is strongly
affected by the medium

From the talk I gave at CIPANP 2009

The different types of Jet modification

Jet weakly coupled to weakly coupled medium	Jet weakly coupled to arbitrary medium	Jet weakly coupled to strongly coupled medium	Jet strongly coupled to strongly coupled medium
A.M.Y	Higher Twist	L.R.W, C-S.T	Trailing String
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$$\frac{d\sigma^h}{dydp_T} \sim \int dx_a dx_b G(x_a) G(x_b) \frac{d\hat{\sigma}}{d\hat{t}} \tilde{D}_q^h(z_1)$$

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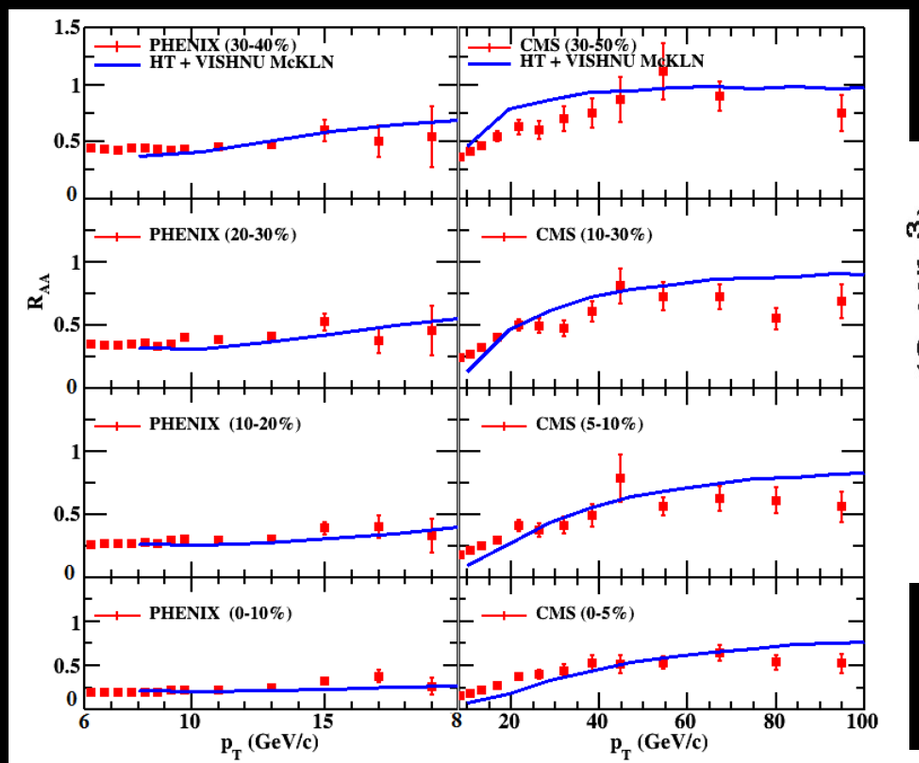
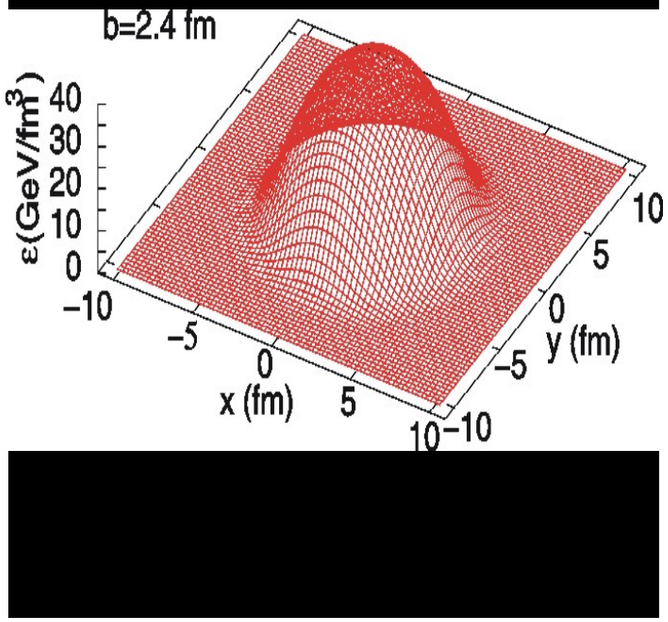
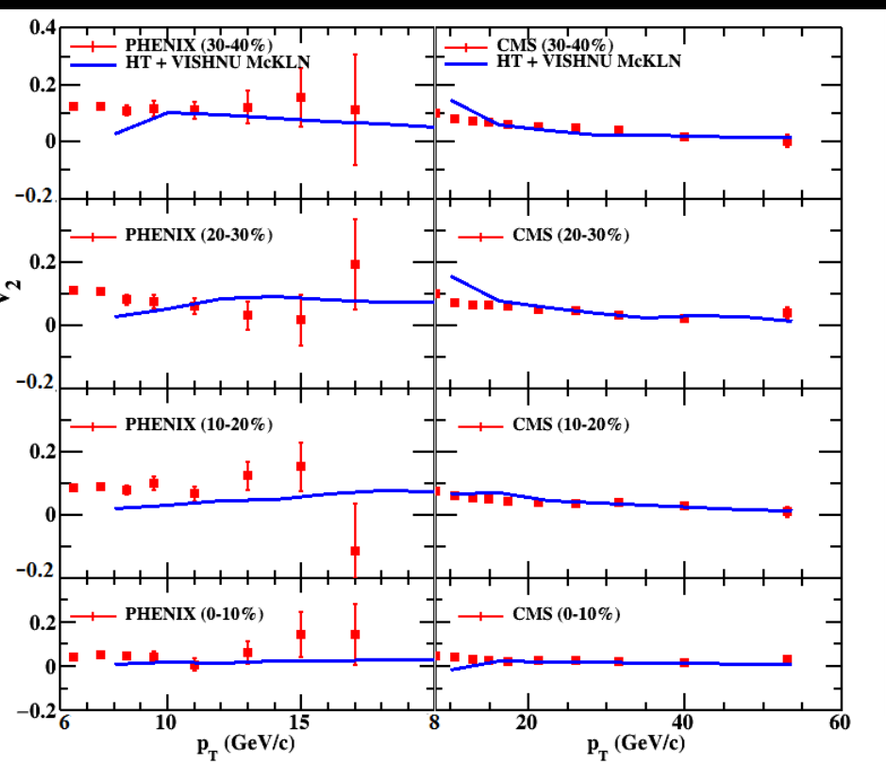
→ N-hadron data

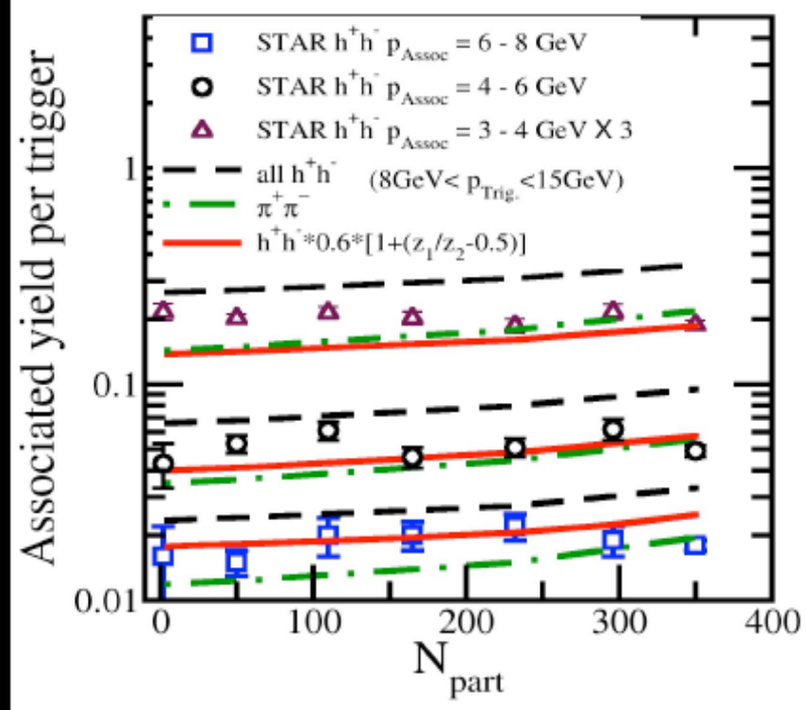
Life was good!
if you only work on a few observables





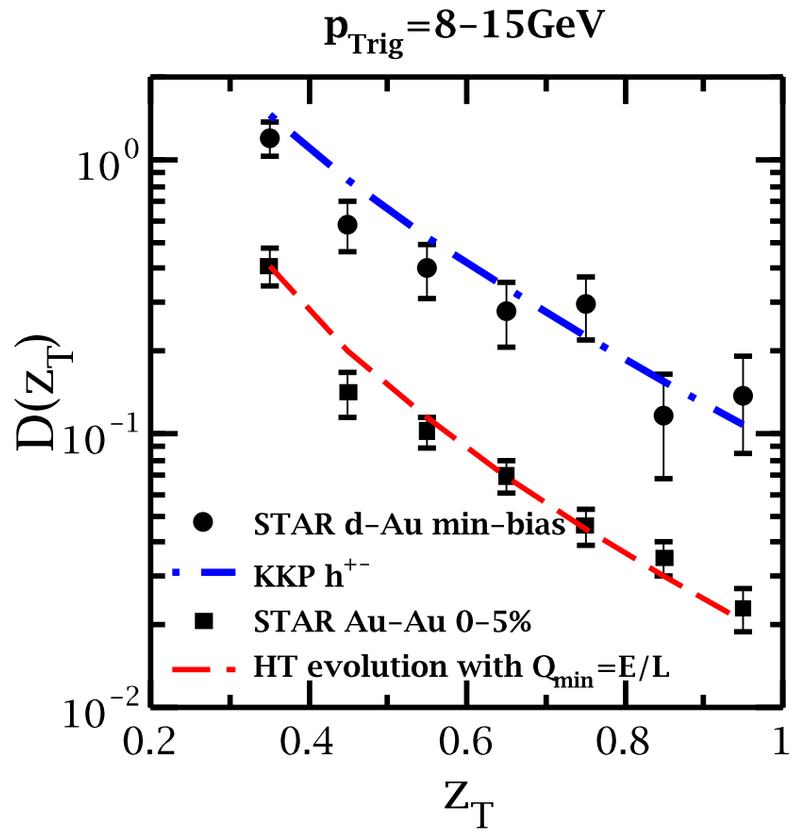


A. Majumder, et. al., nucl-th/0412061



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

$$s_0 = s(T_0)$$



A complete change of paradigm!

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 ($q\ \tau$)

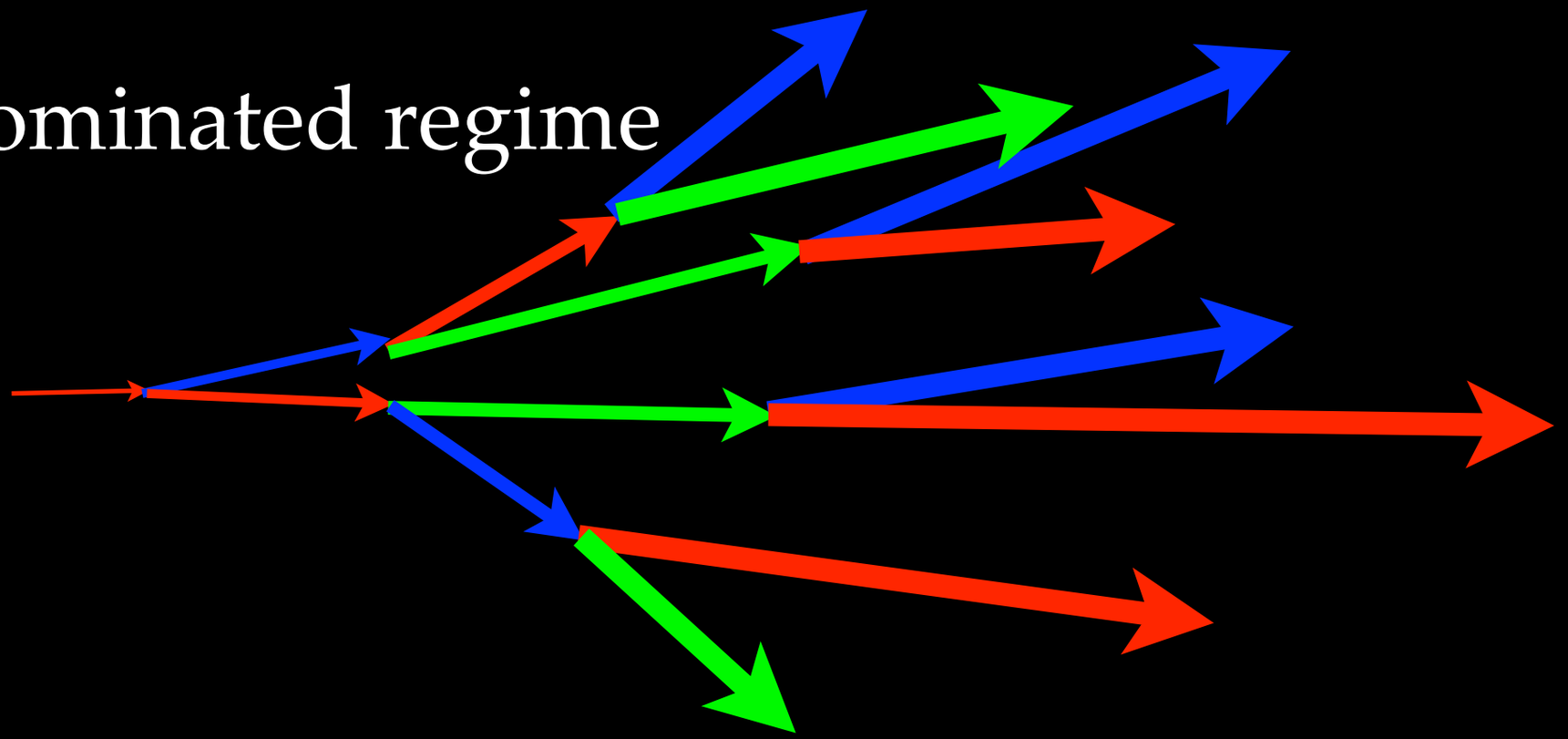
Different approaches to E-loss are valid in different epochs of the jet

A complete description requires all of these approaches

Discussion moves to boundaries between approaches

High energy and high virtuality part of shower

- Radiation dominated regime



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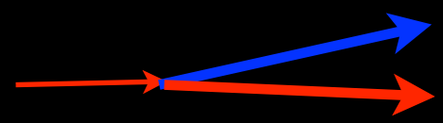

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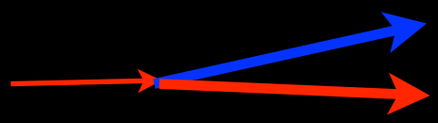

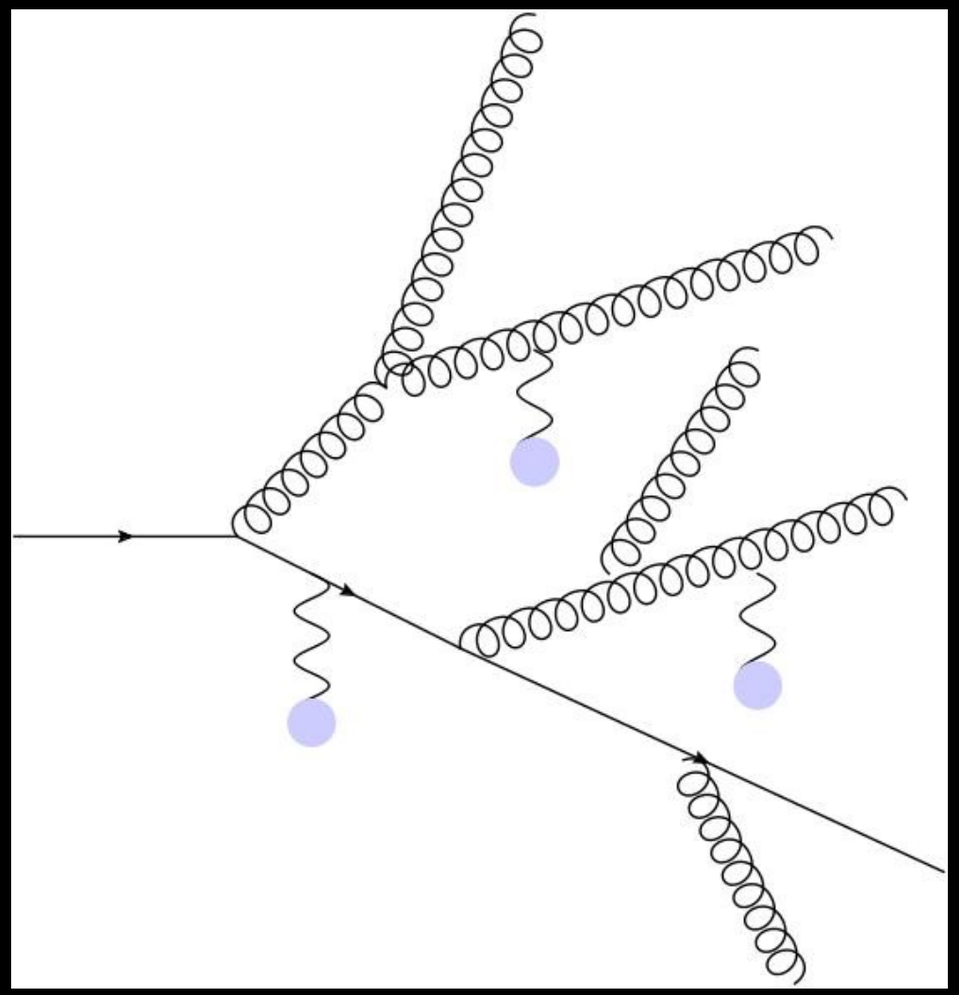

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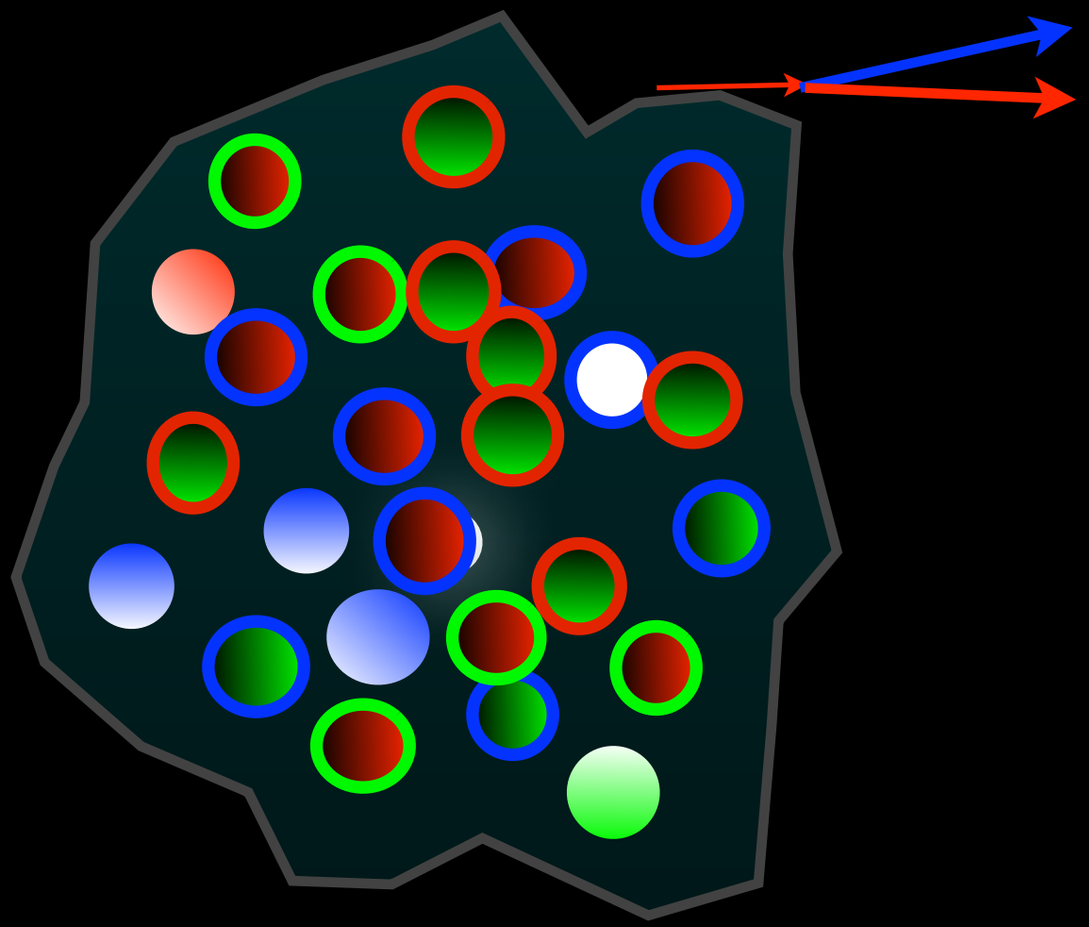

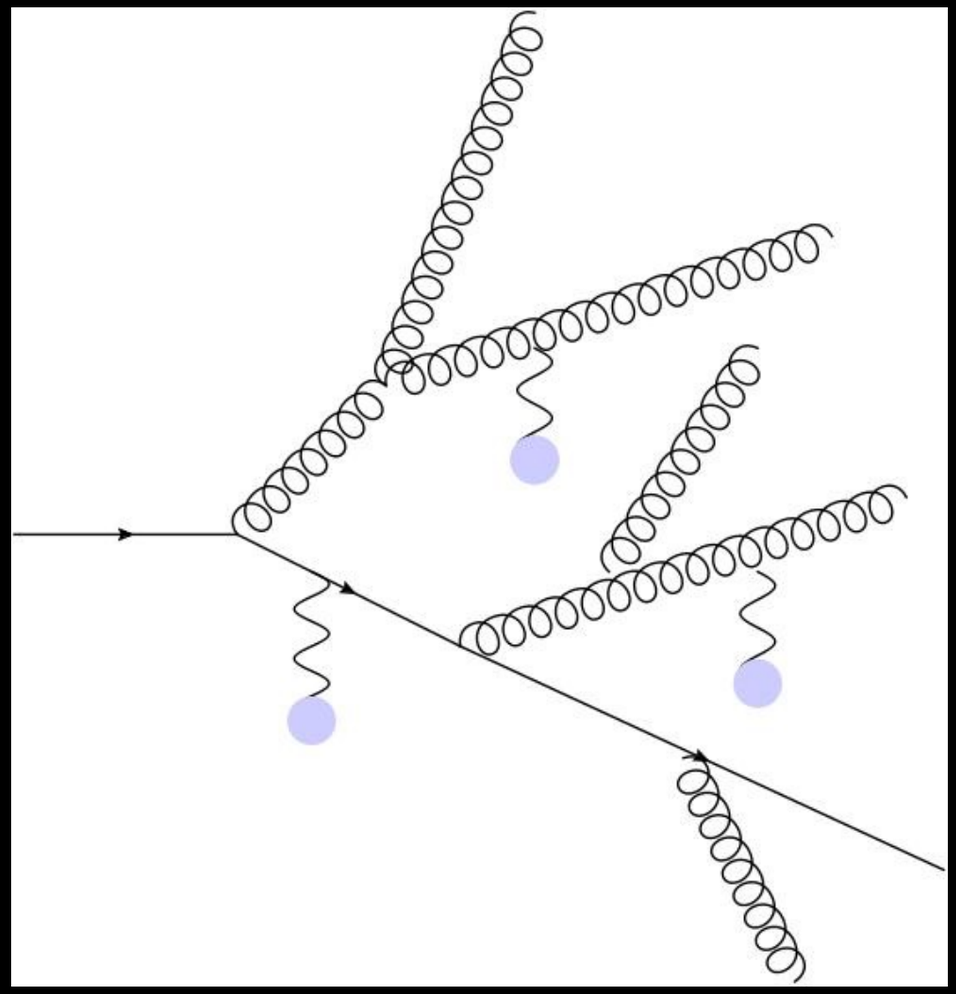

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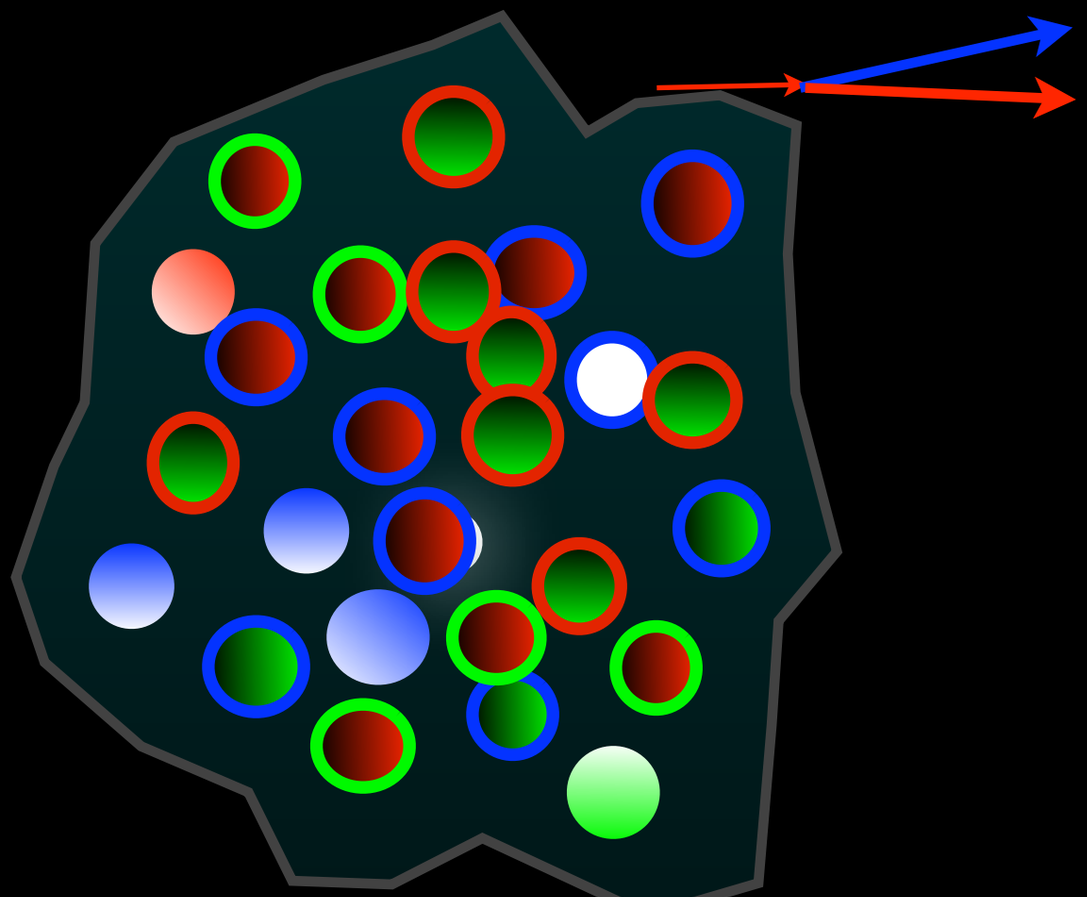
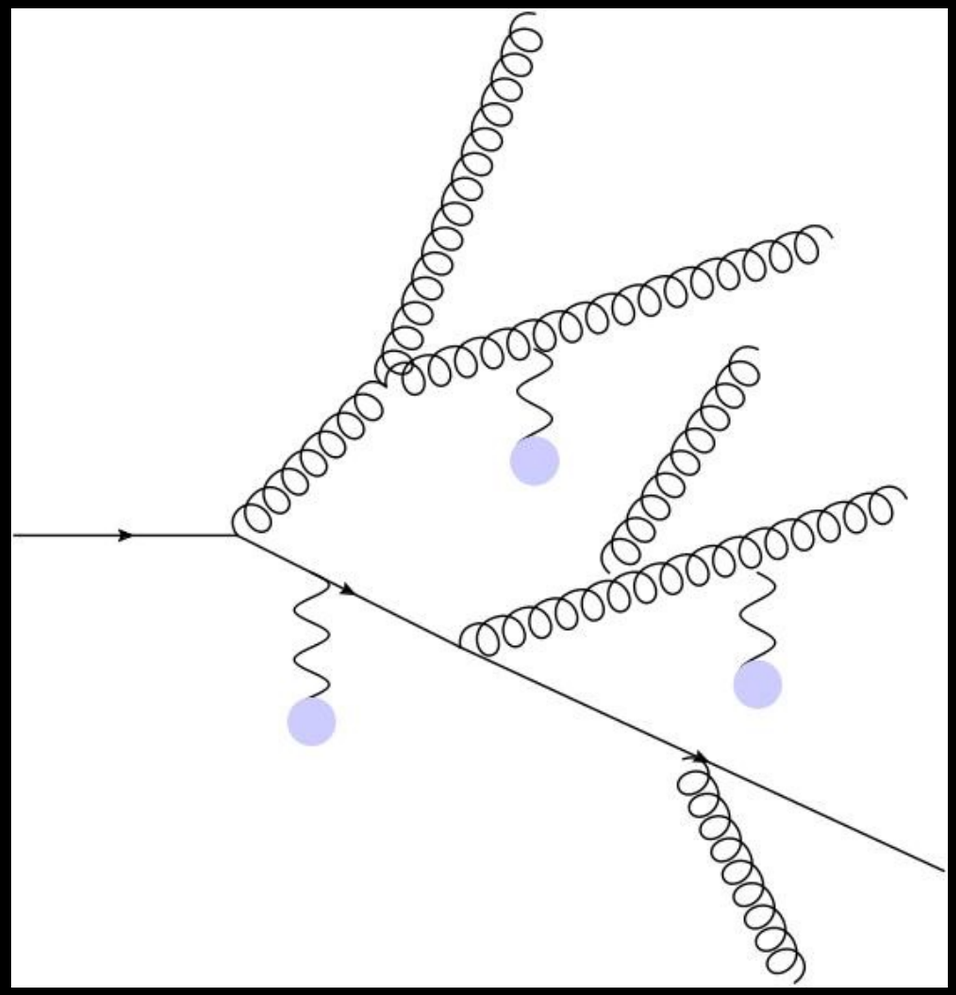




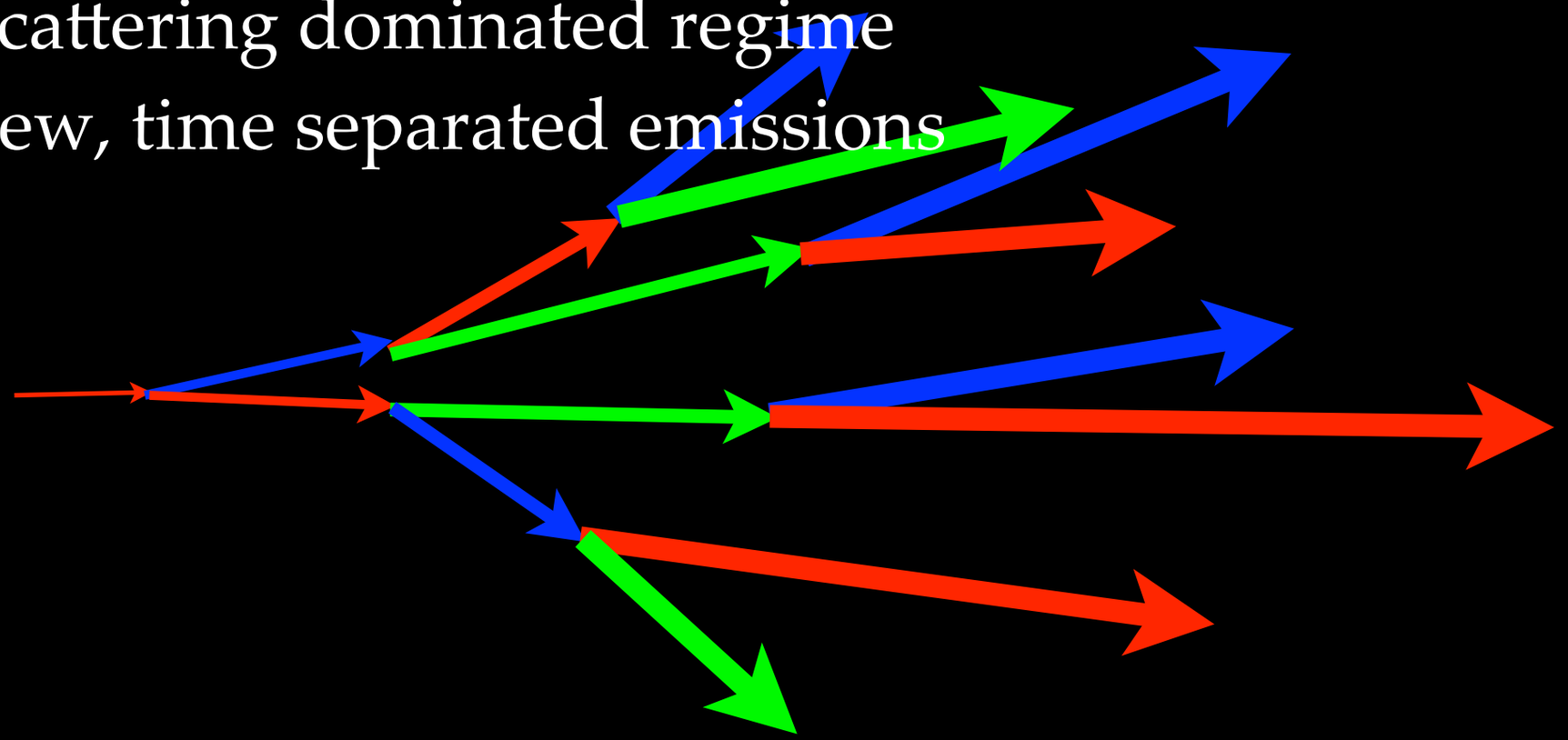
Theory: Higher Twist

MC: MATTER, YaJEM

Low virtuality, high energy part

Scattering dominated regime

Few, time separated emissions



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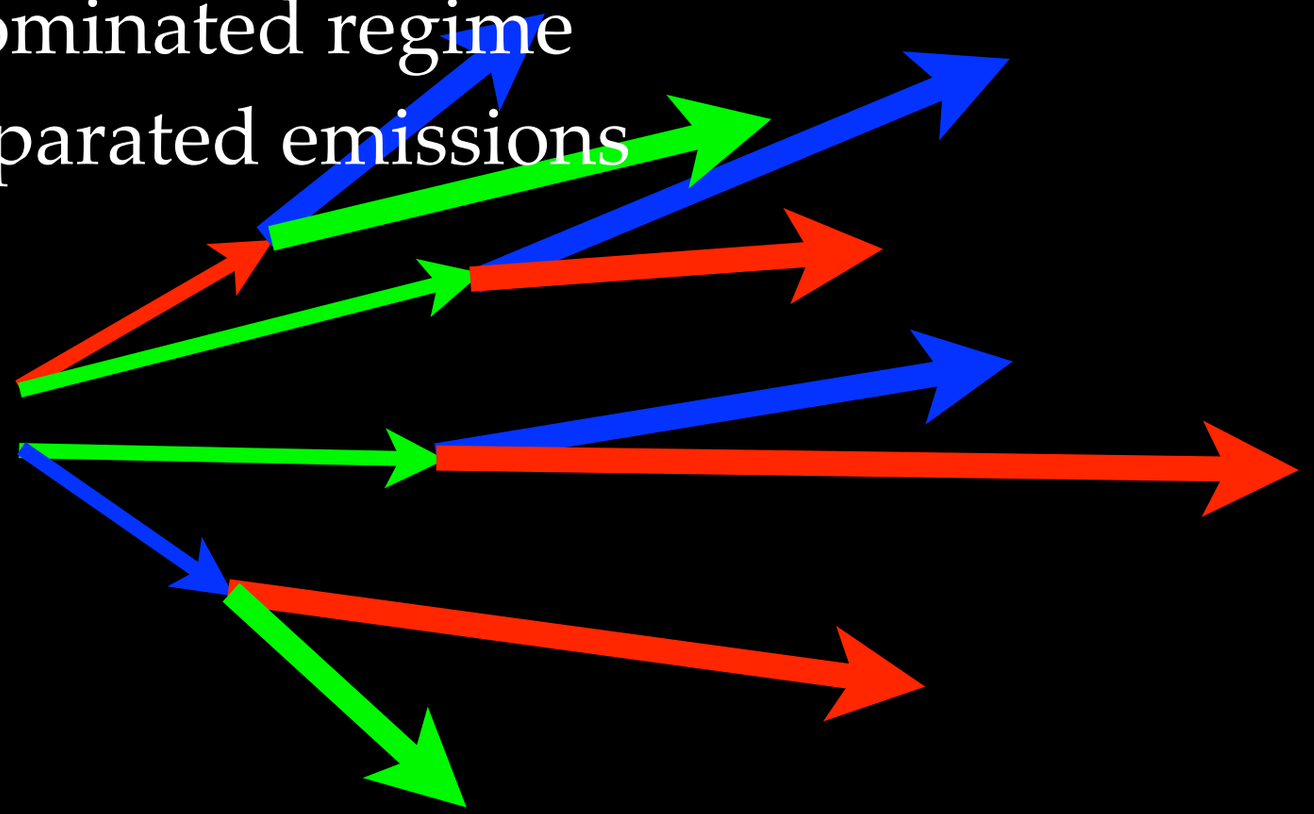

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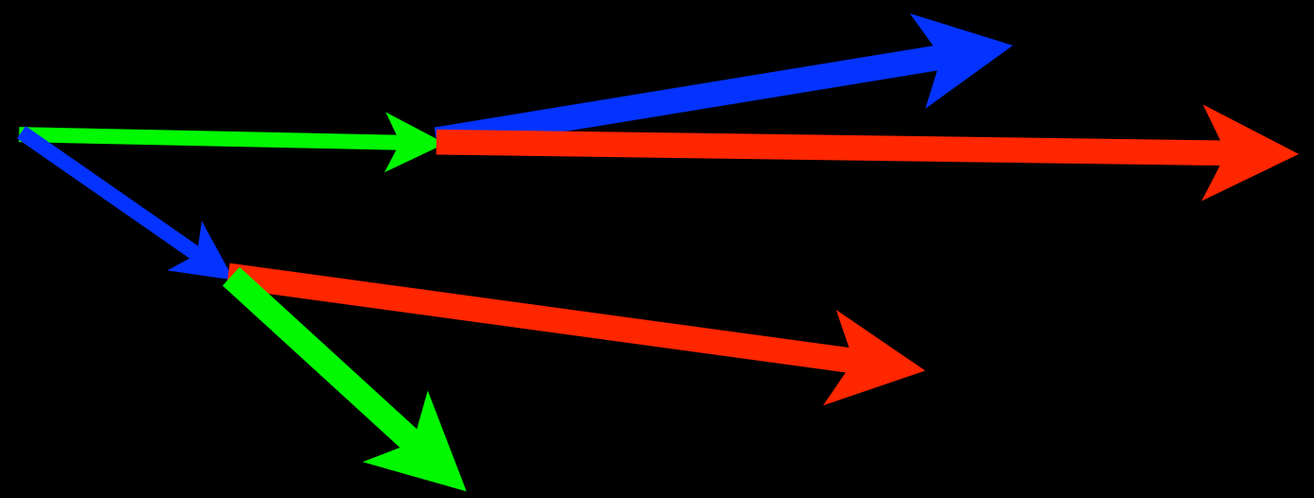

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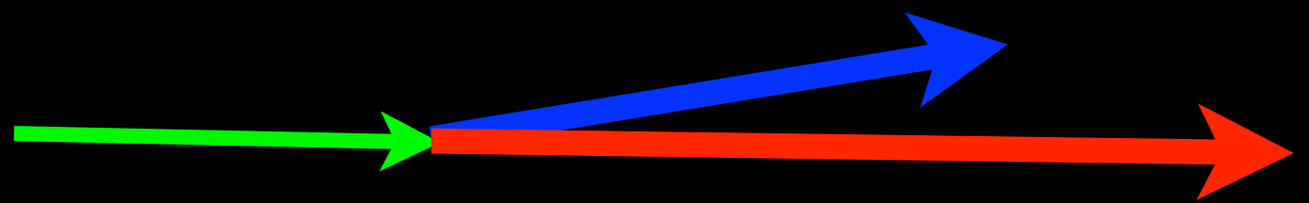

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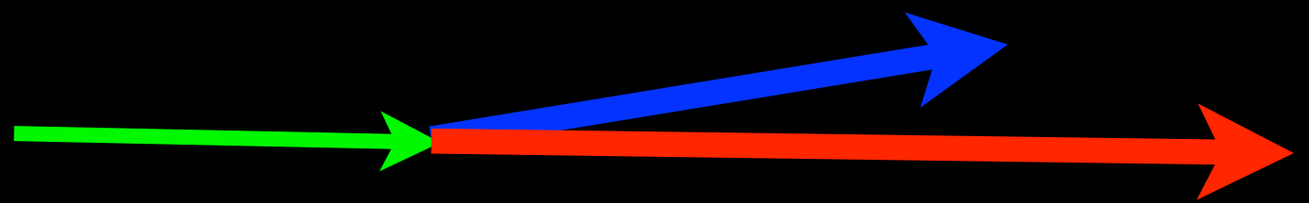

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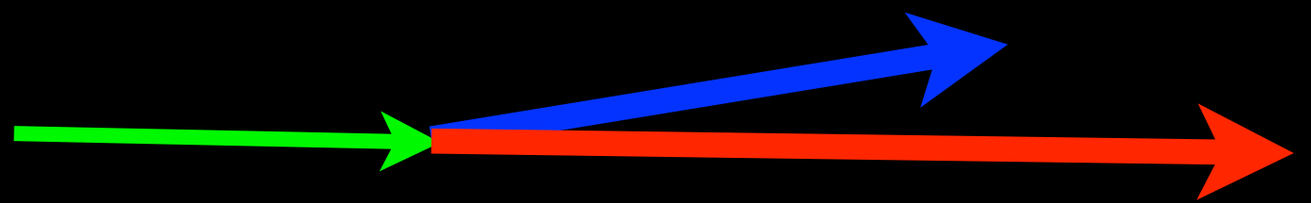

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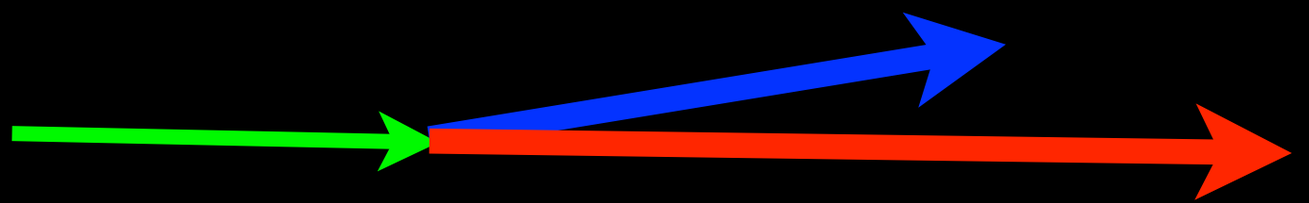

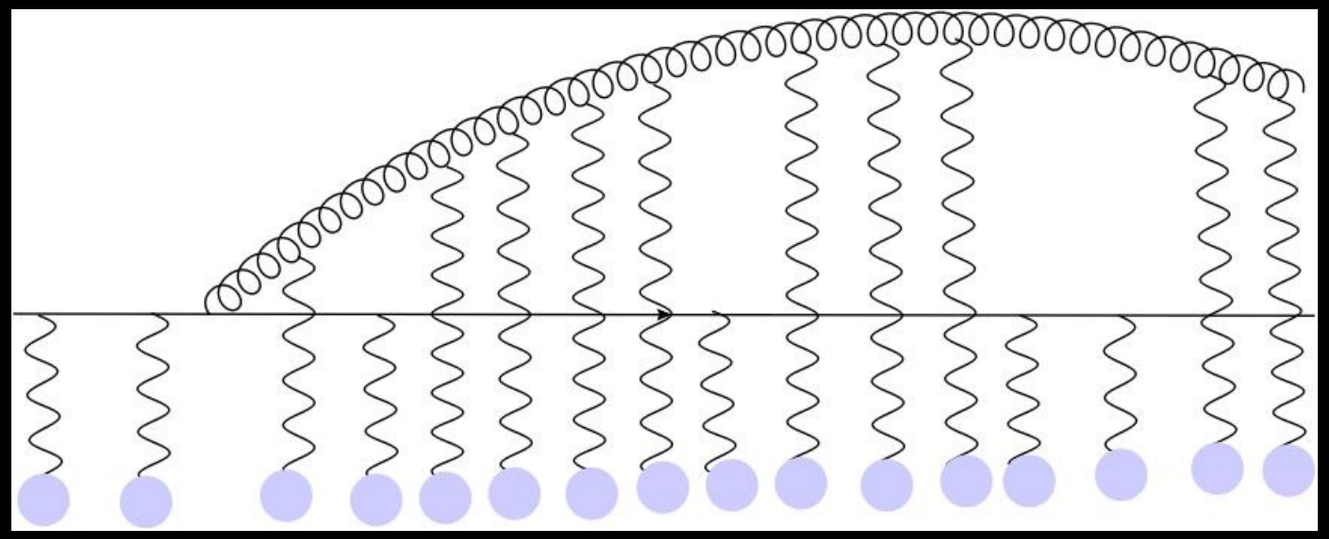

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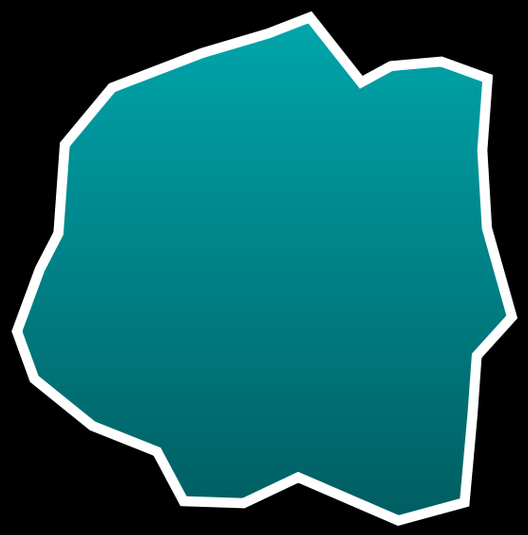

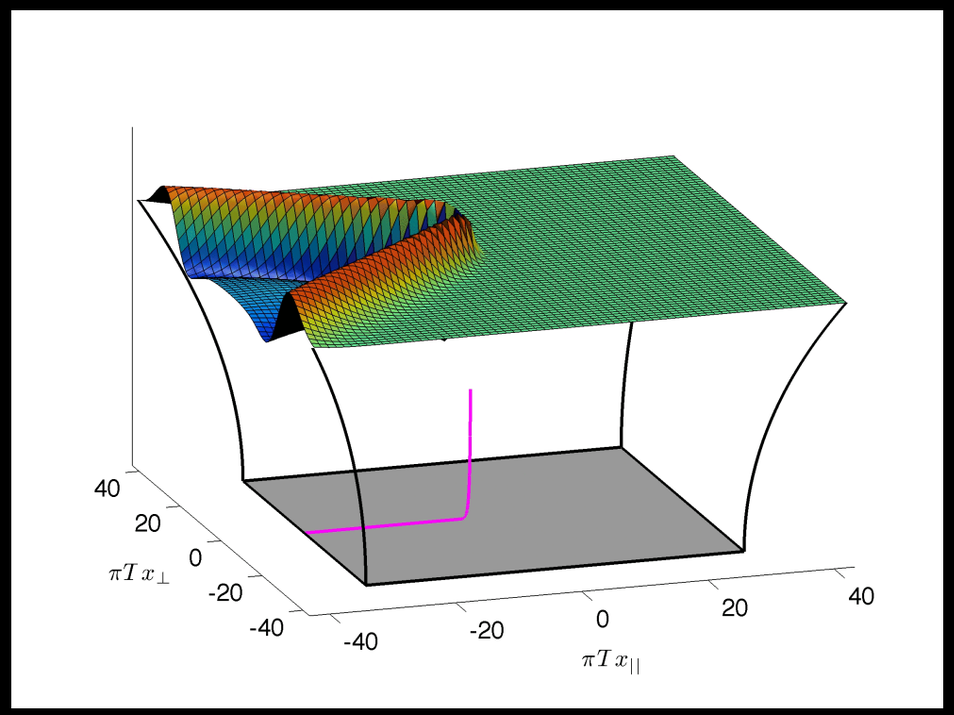

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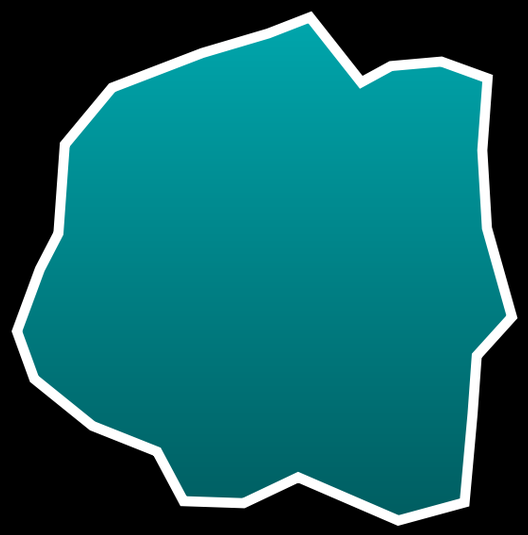
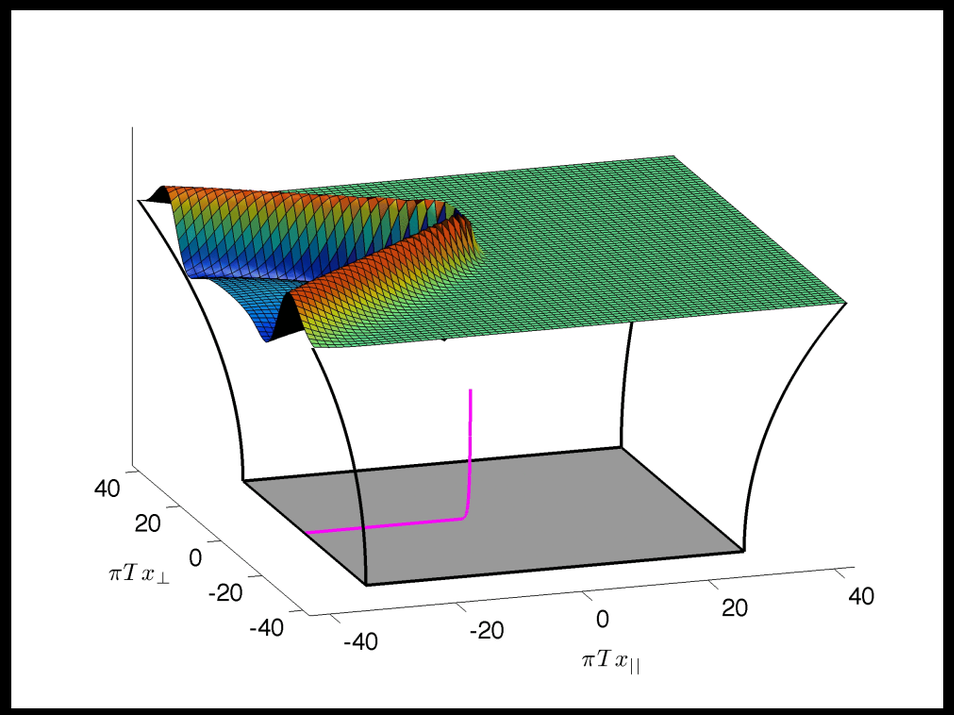
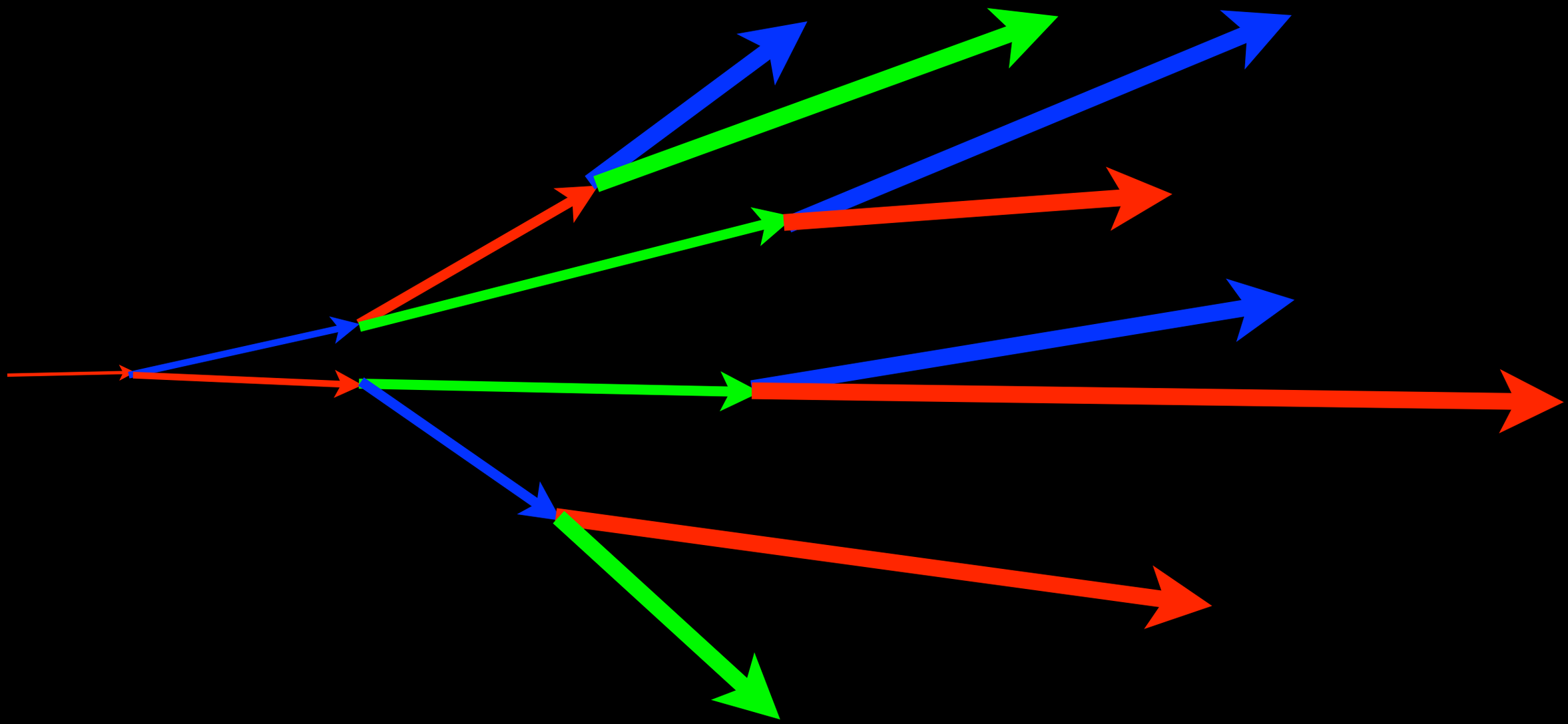




P. Chesler, W. Horowitz J. Casalderrey-Solana,
G. Milhano, D. Pablos, K. Rajagopal

Grand picture (leading hadrons)



In a static brick

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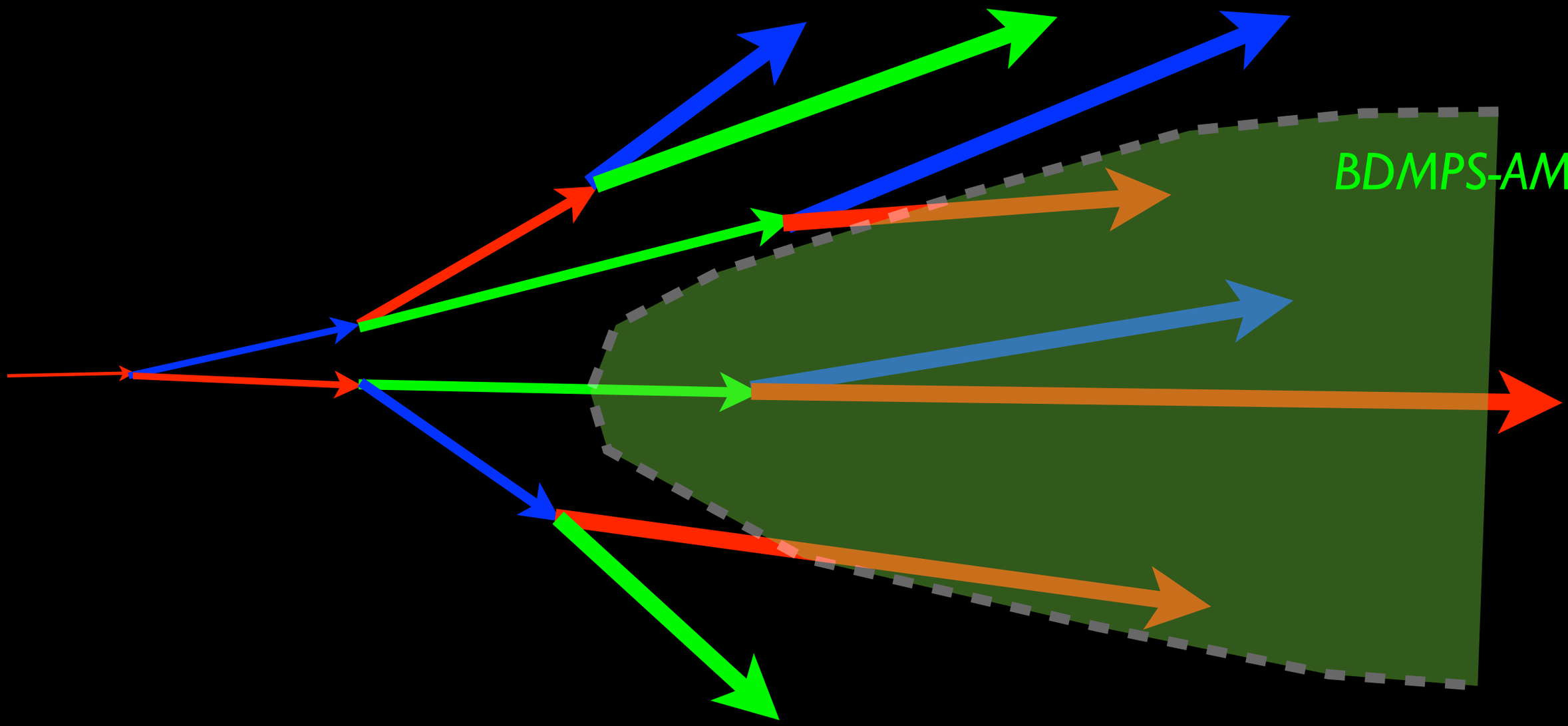

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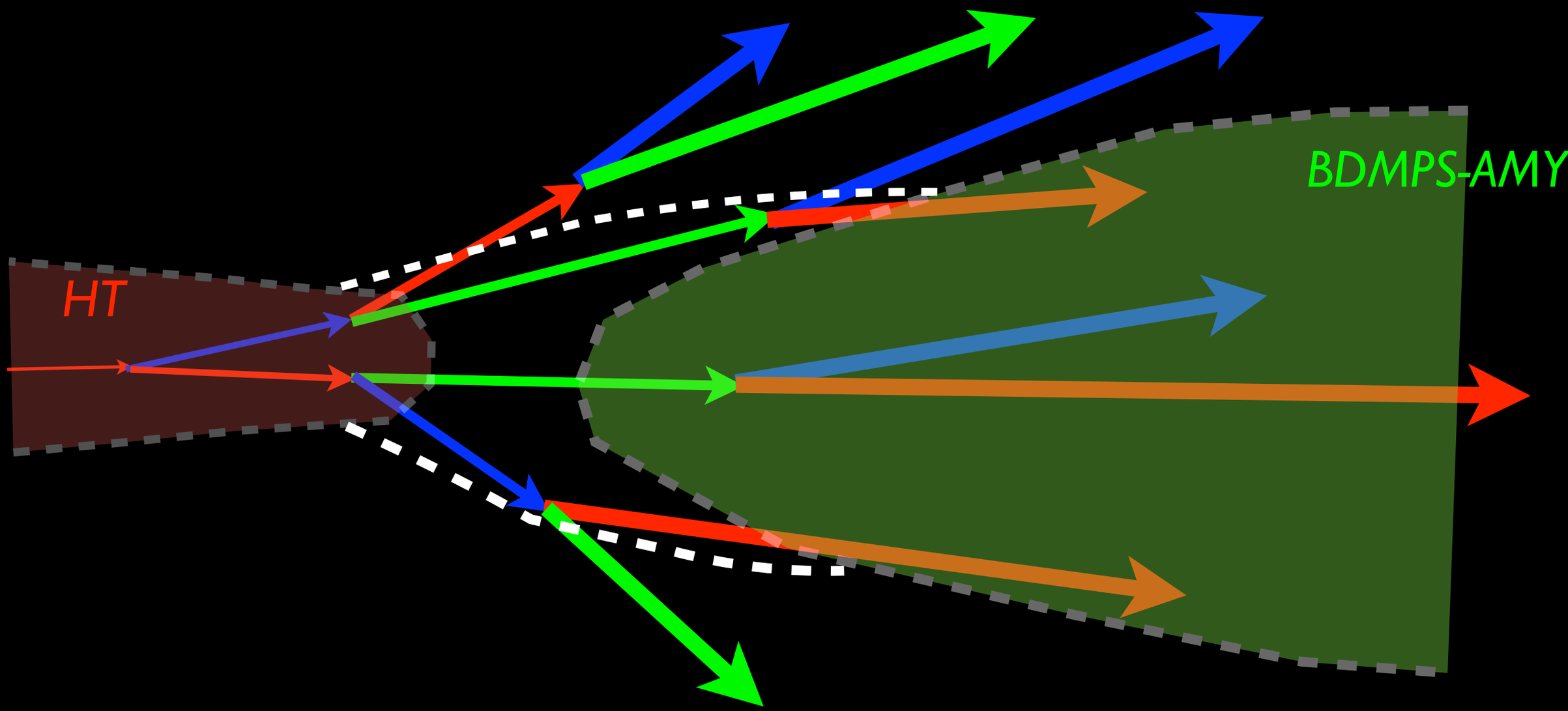

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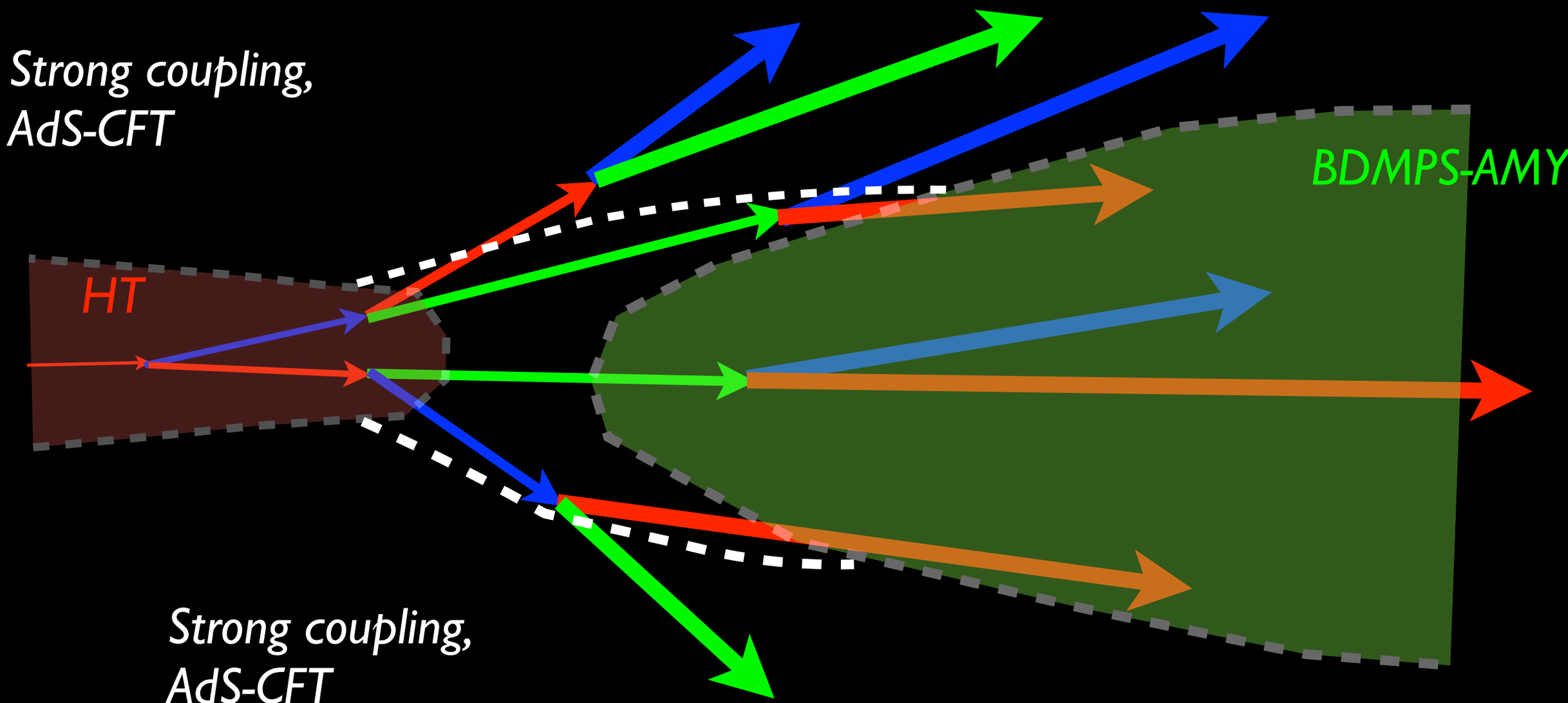

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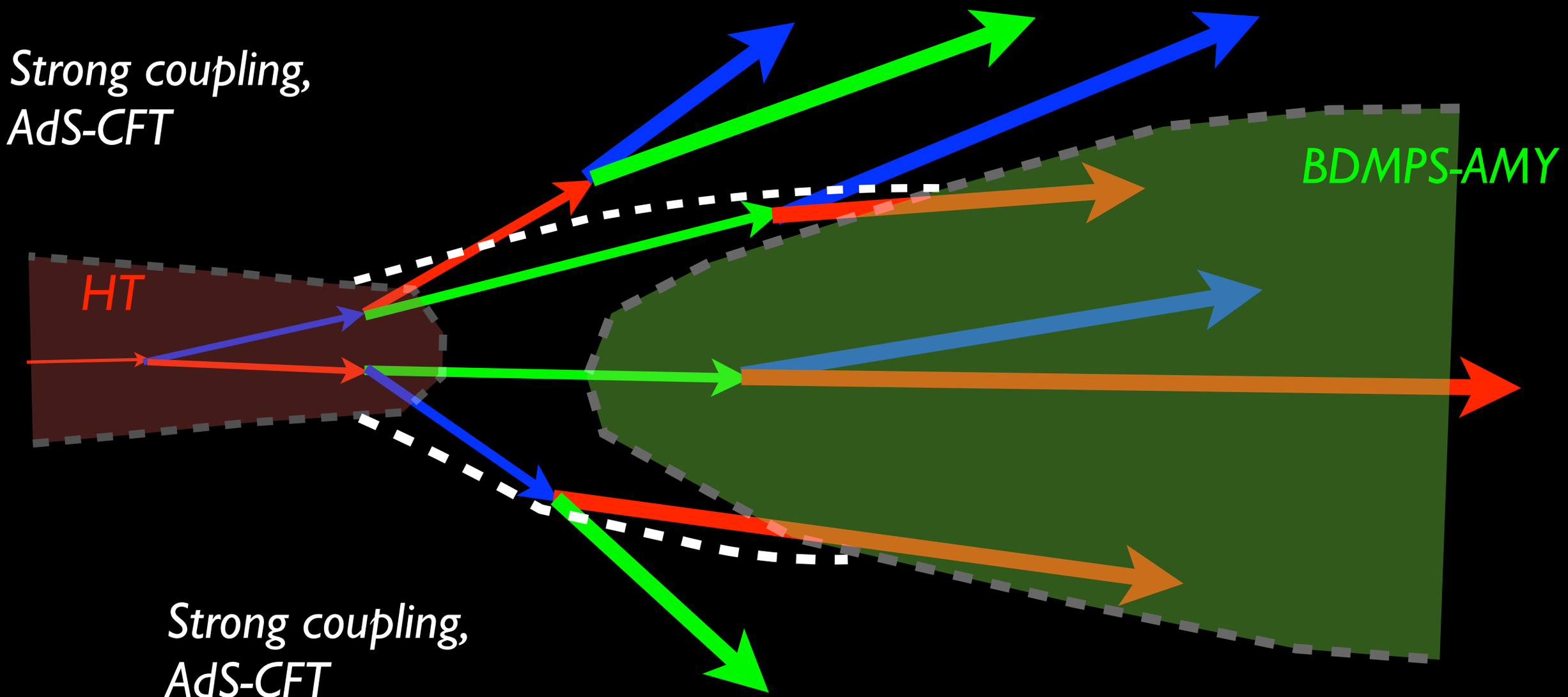

In an expanding QGP

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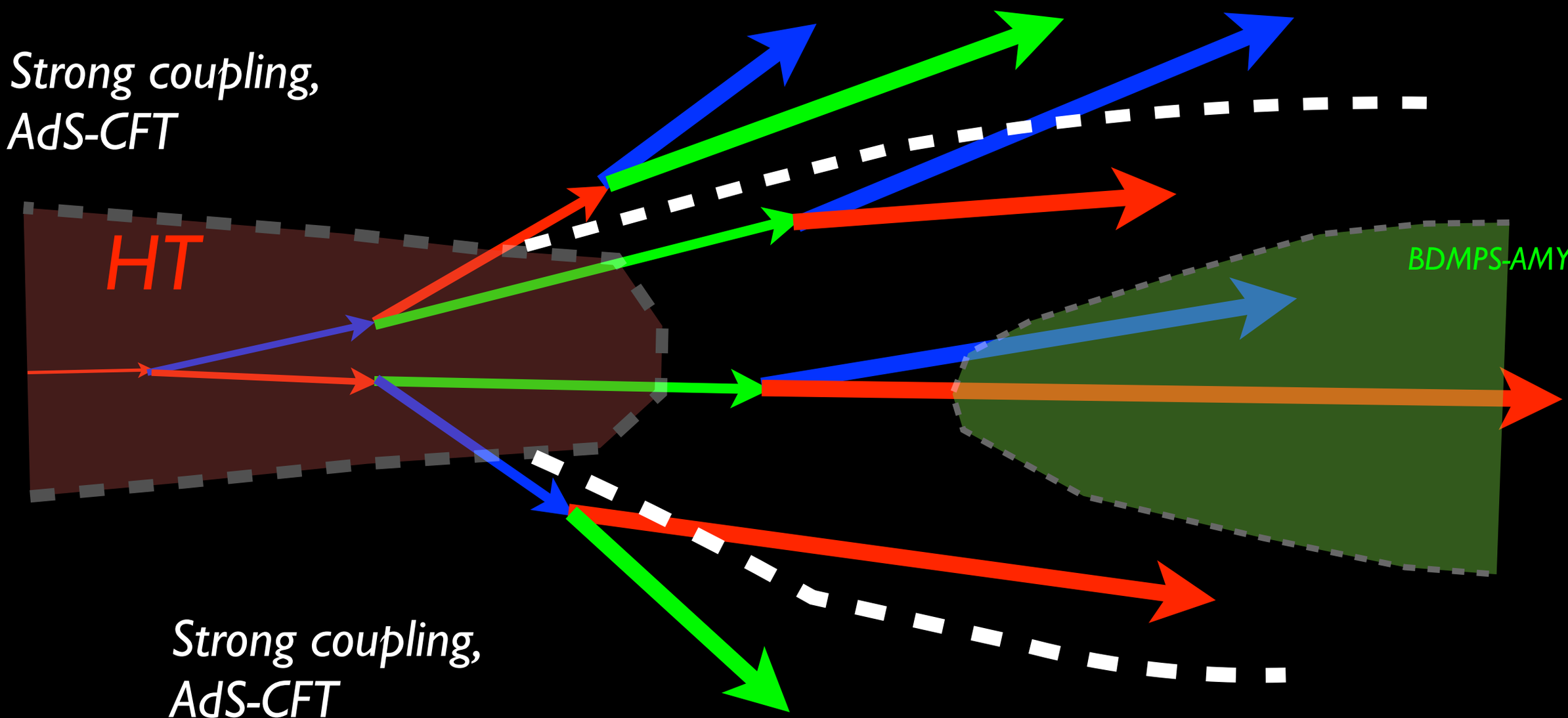
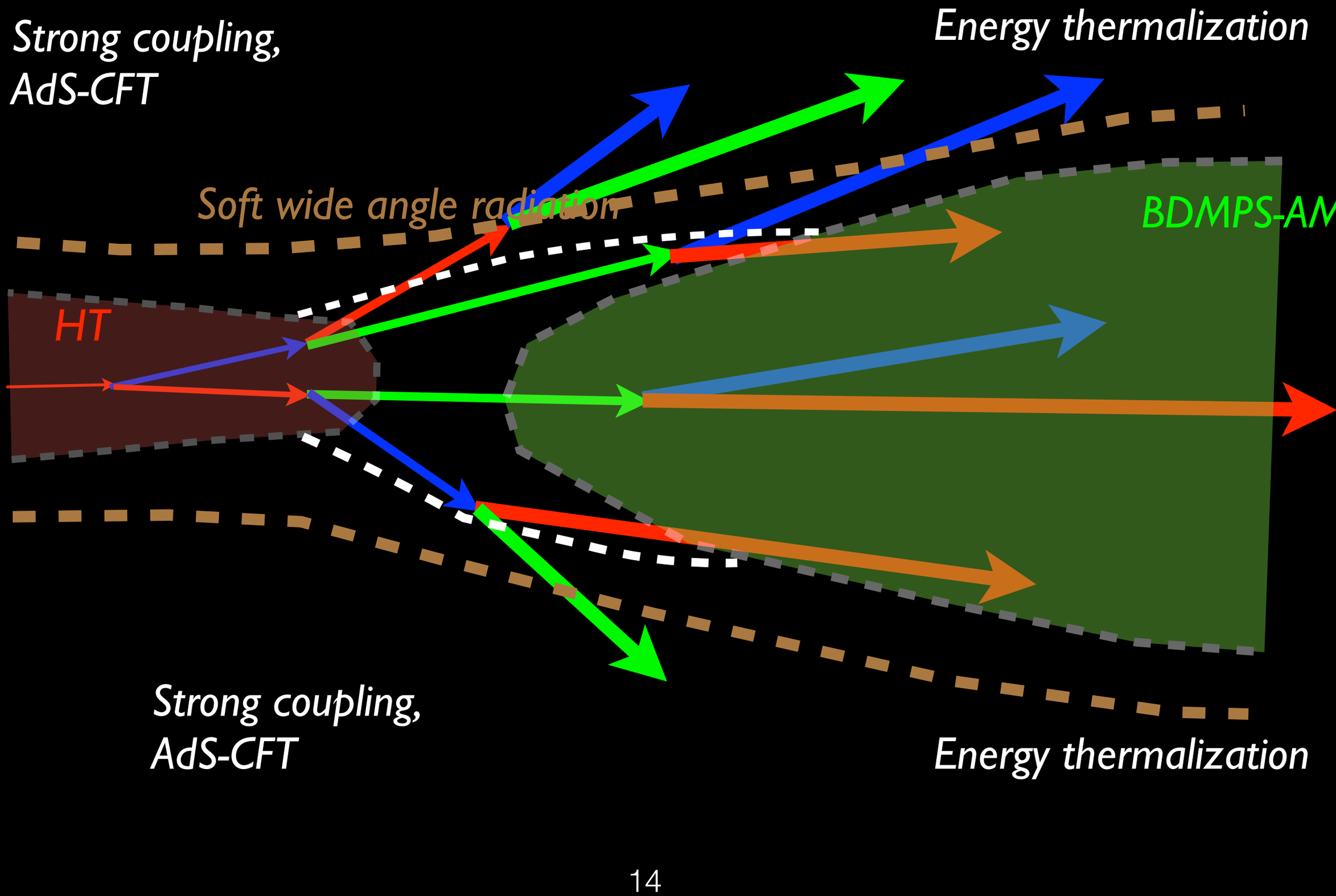


In an expanding QGP

Energy deposition-thermalization



Everything changes with scale in jet quenching

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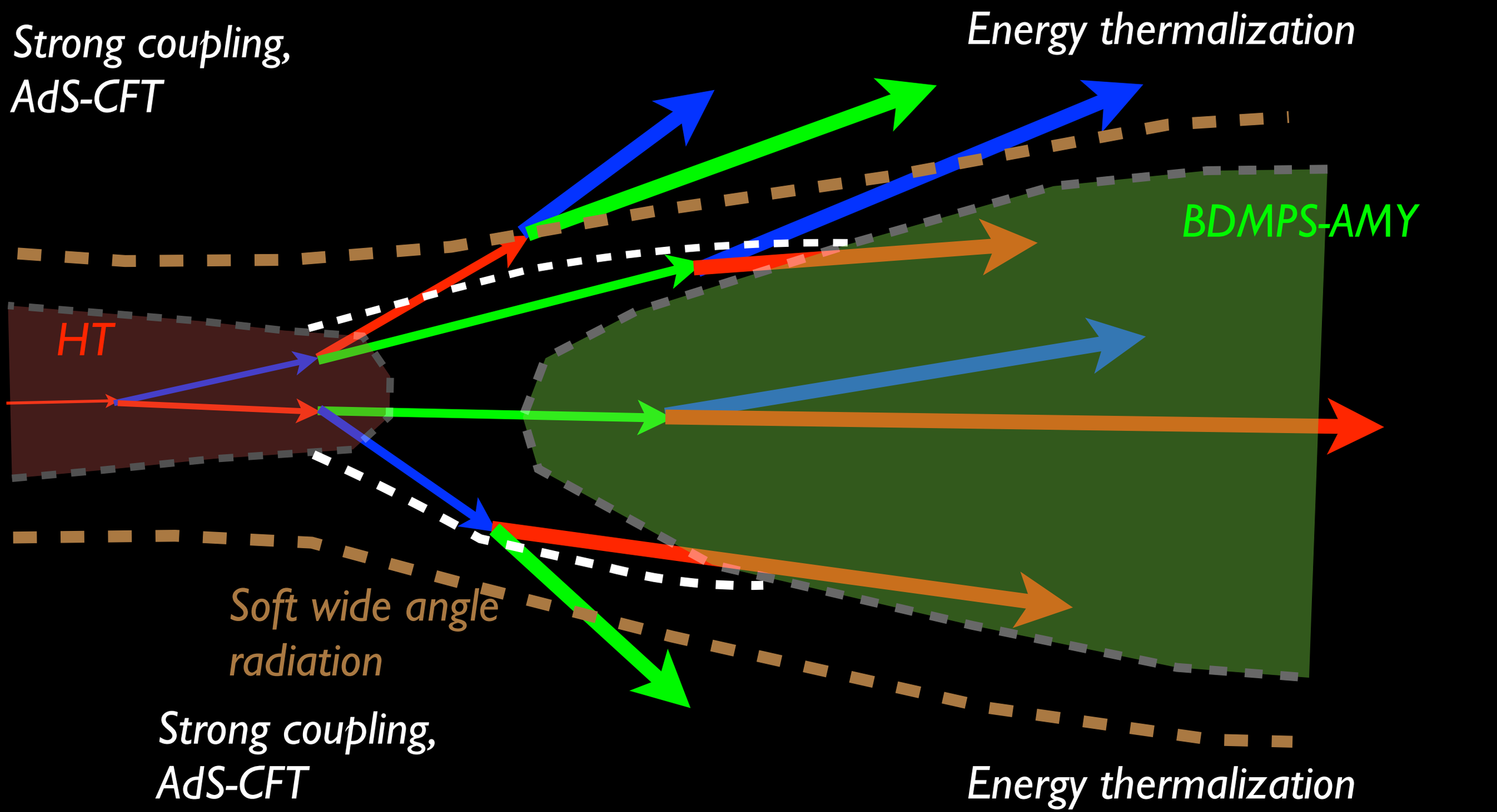

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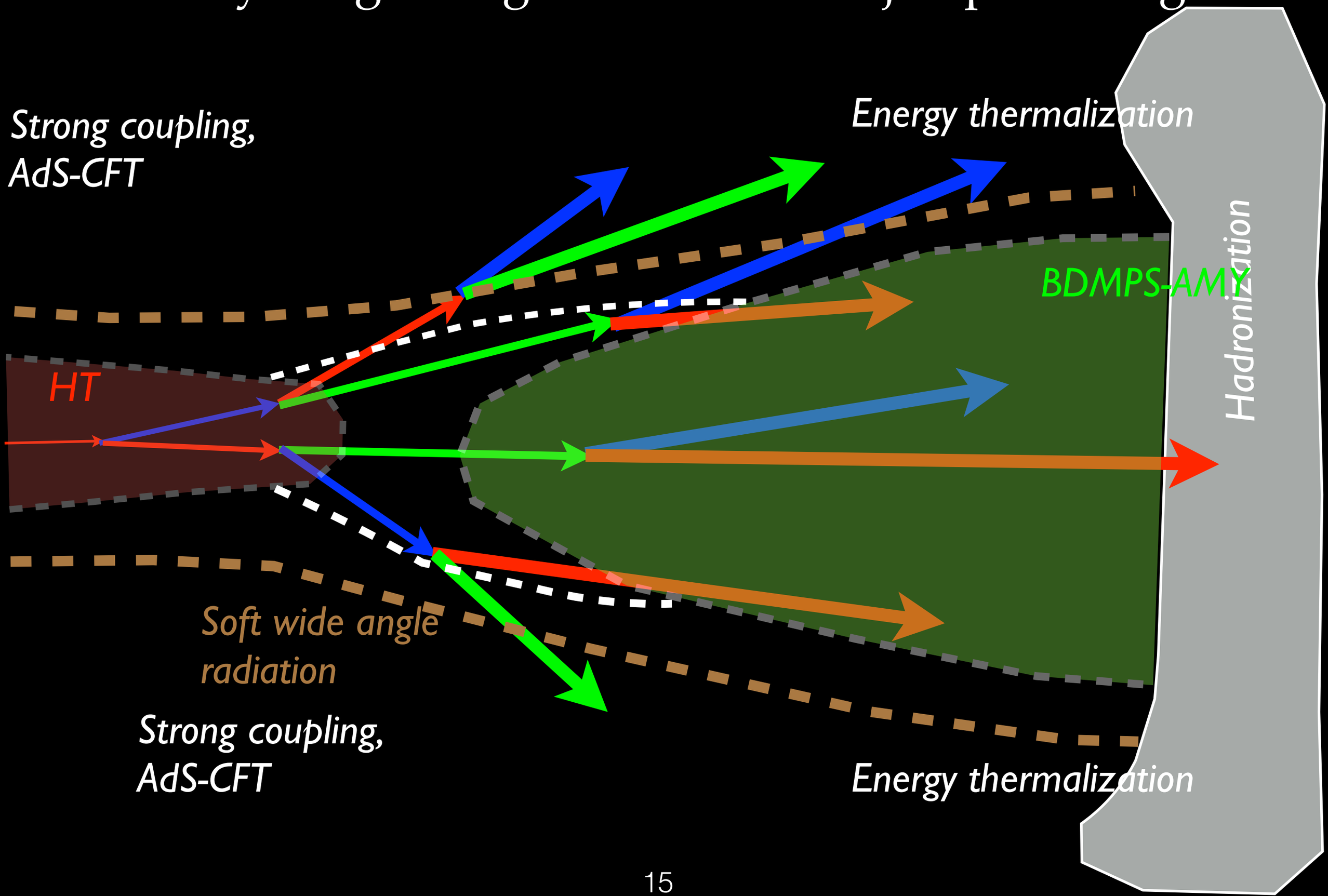
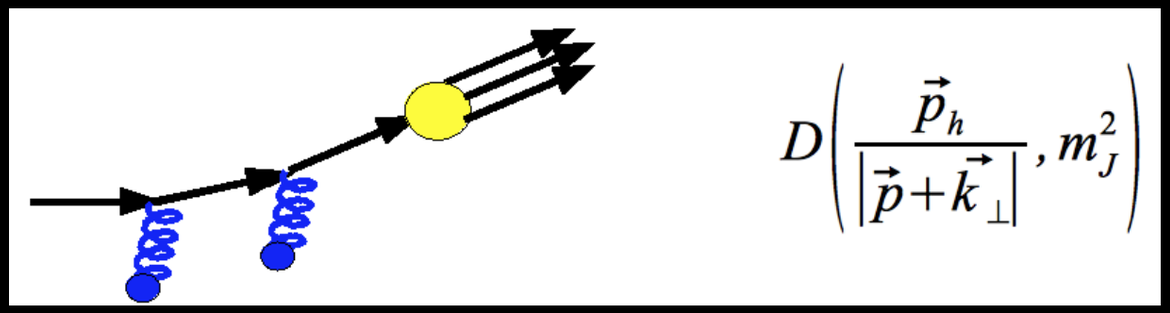


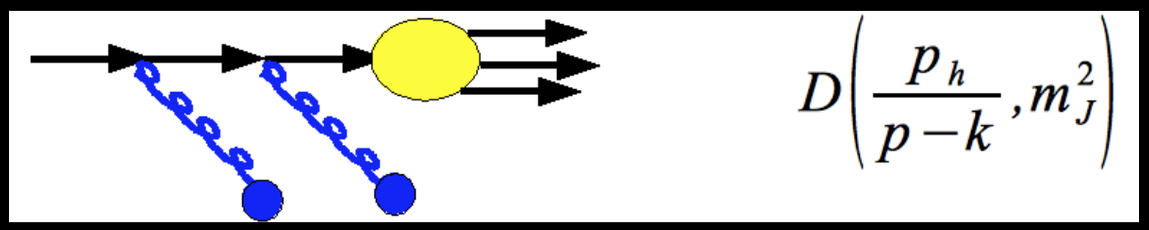
Transport coefficients for partons in a dense medium

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



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

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!

In general, 2 kinds of transport coefficients

Type 1: which quantify how the medium changes the jet

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

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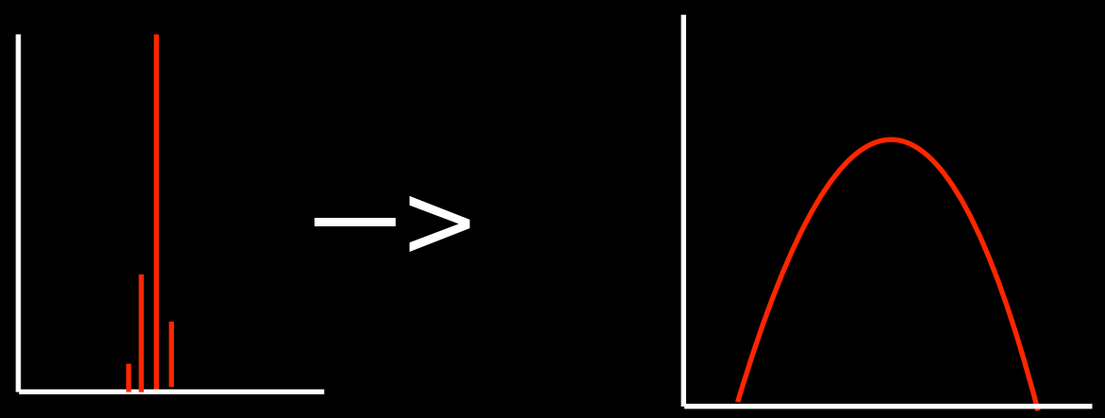
Type 2: which quantify the space-time structure of the deposited energy momentum at the hydro scale

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



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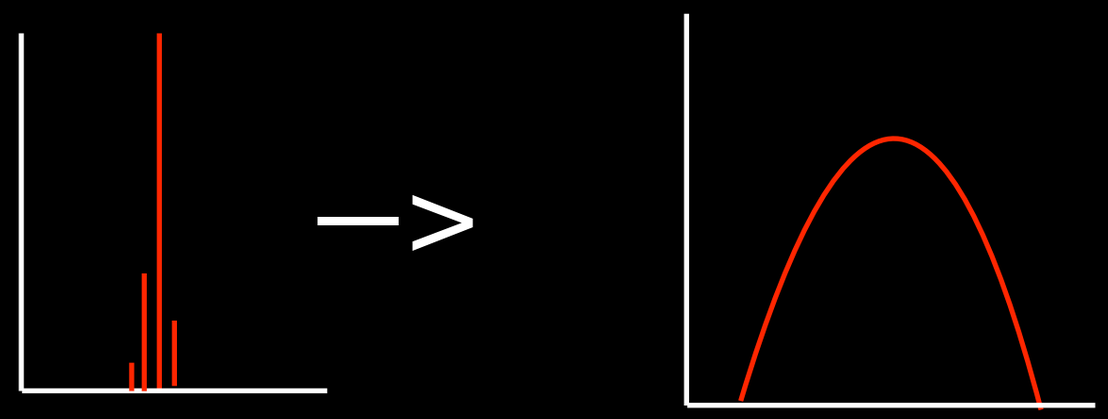

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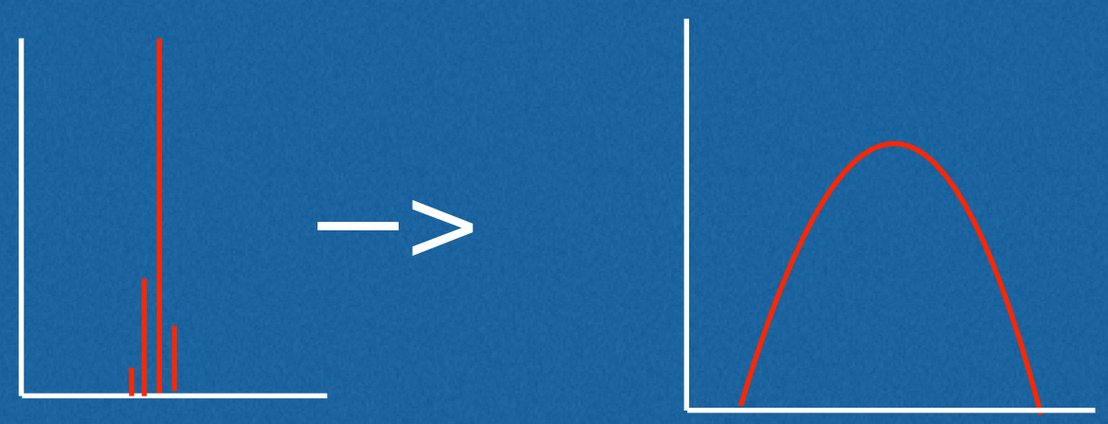

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Need to have a framework

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- Can address all observables simultaneously

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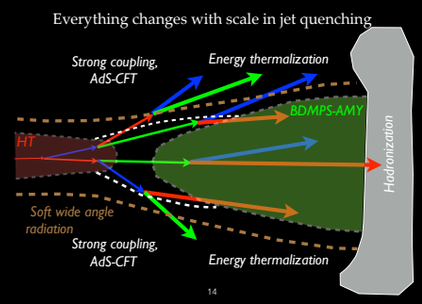

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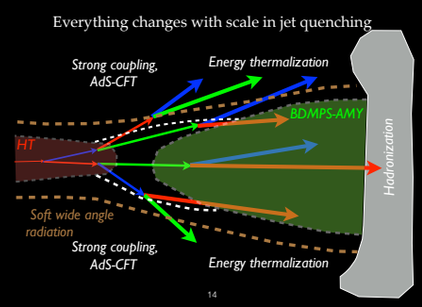

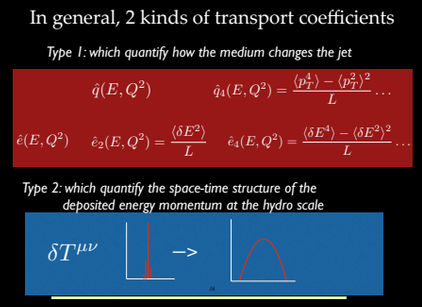

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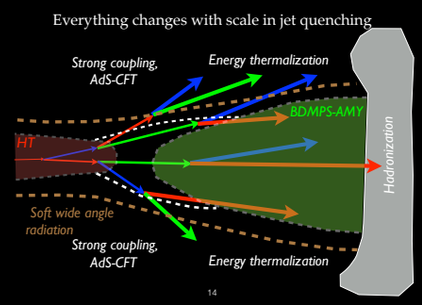

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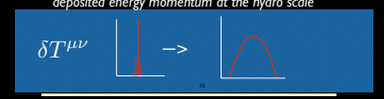

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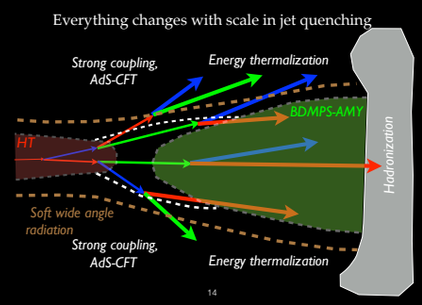
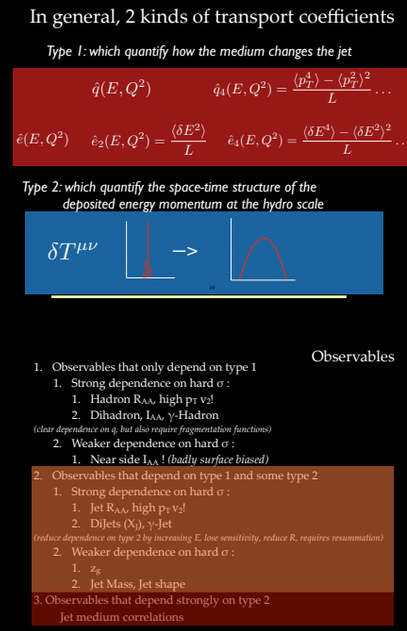
Such a framework now exists: JETSCAPE
https://github.com/JETSCAPE

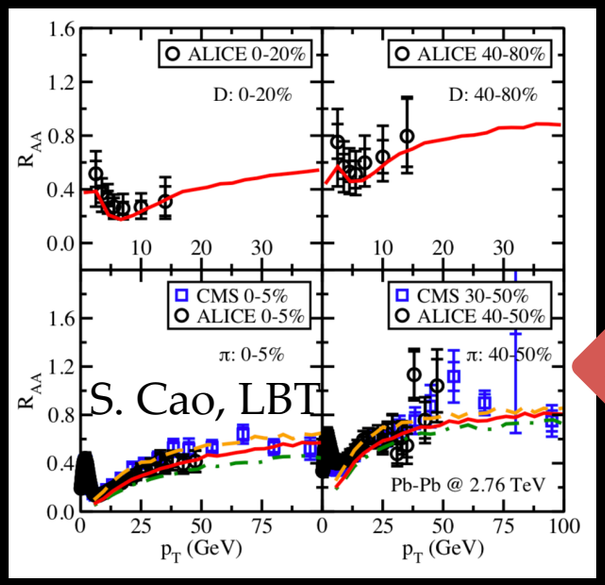




Applying Multi-scale models

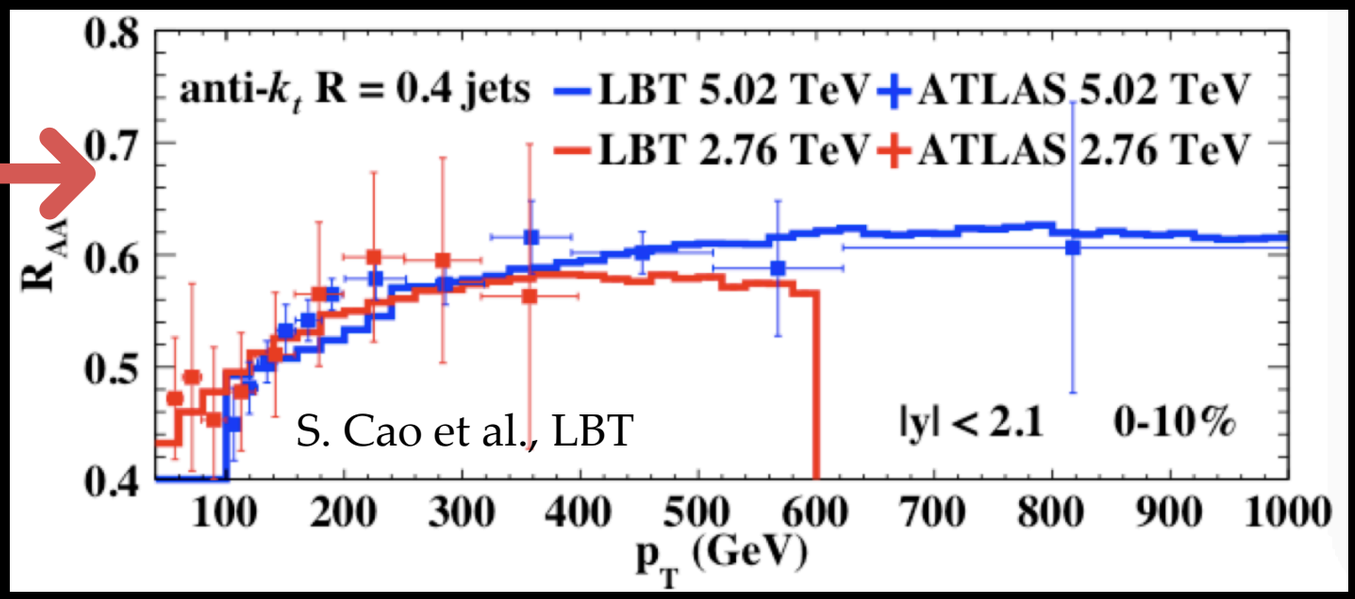
Its the right thing to do.

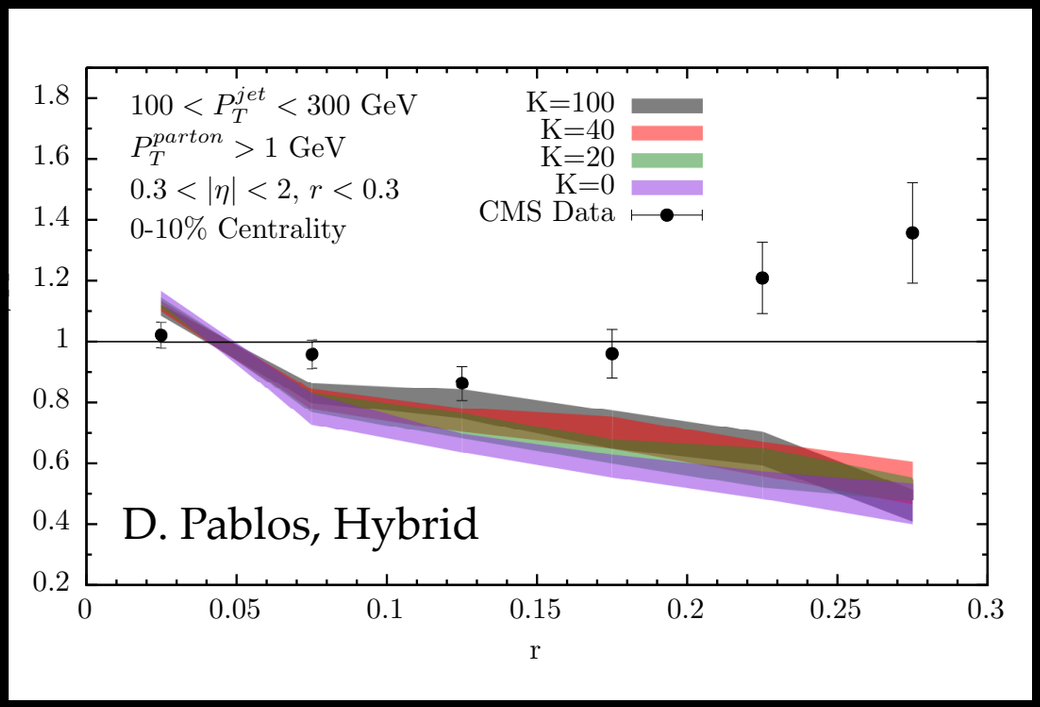
Pushing limited approaches past limits creates tension!

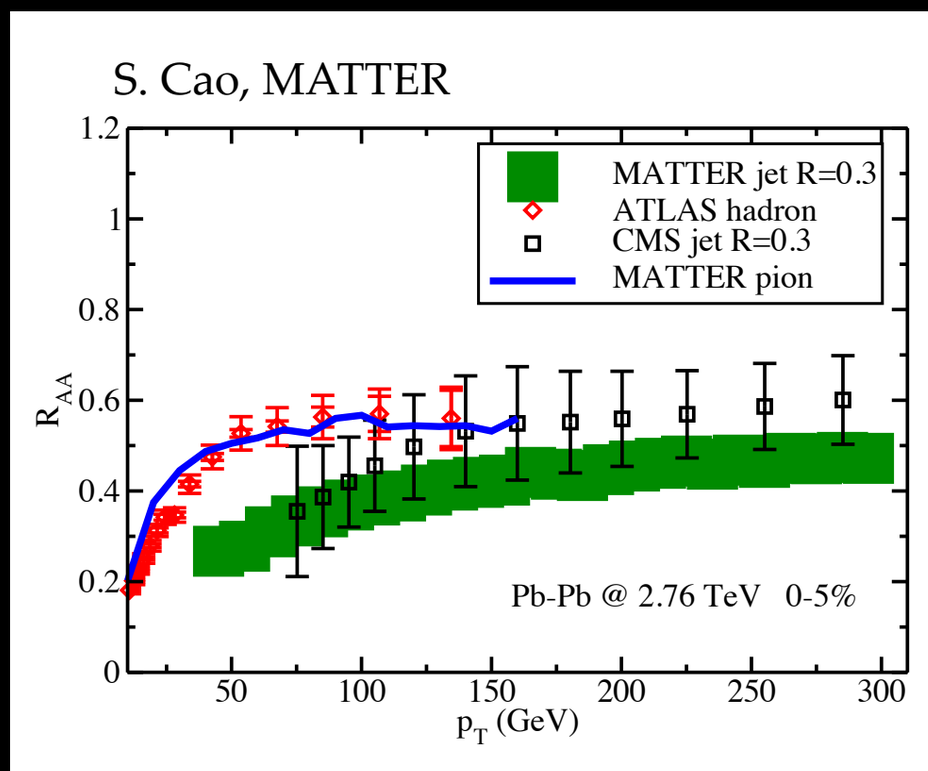


LBT
fixed α_S=0.15

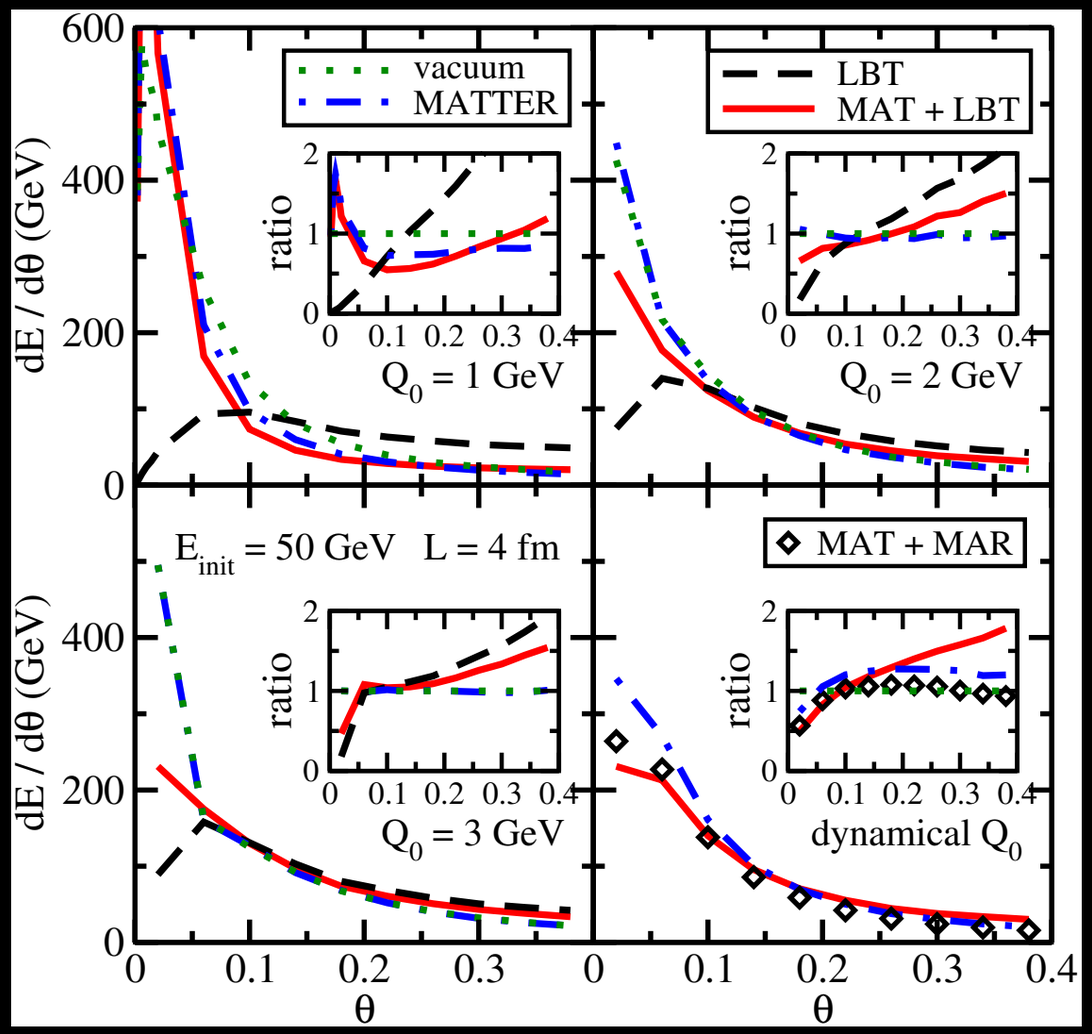
mean α_S=0.2

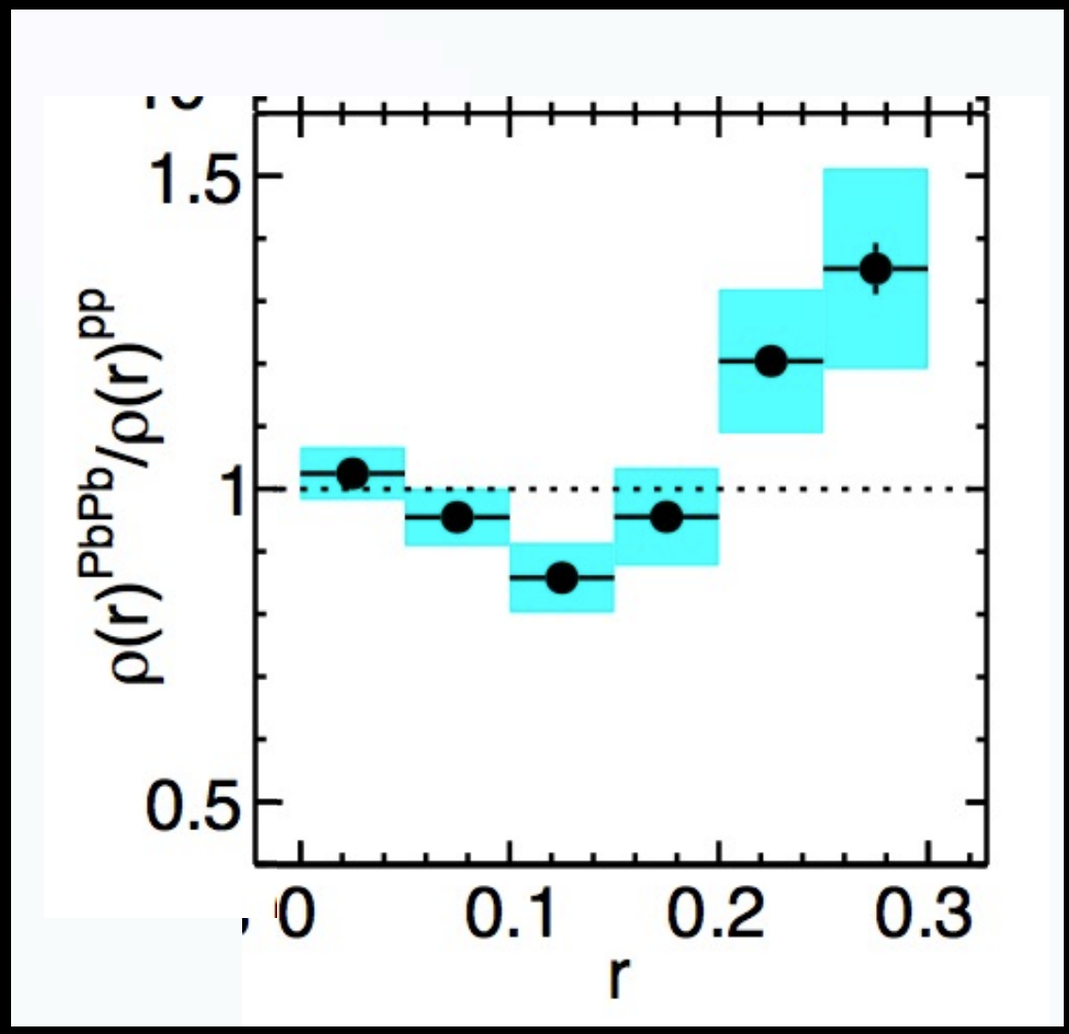






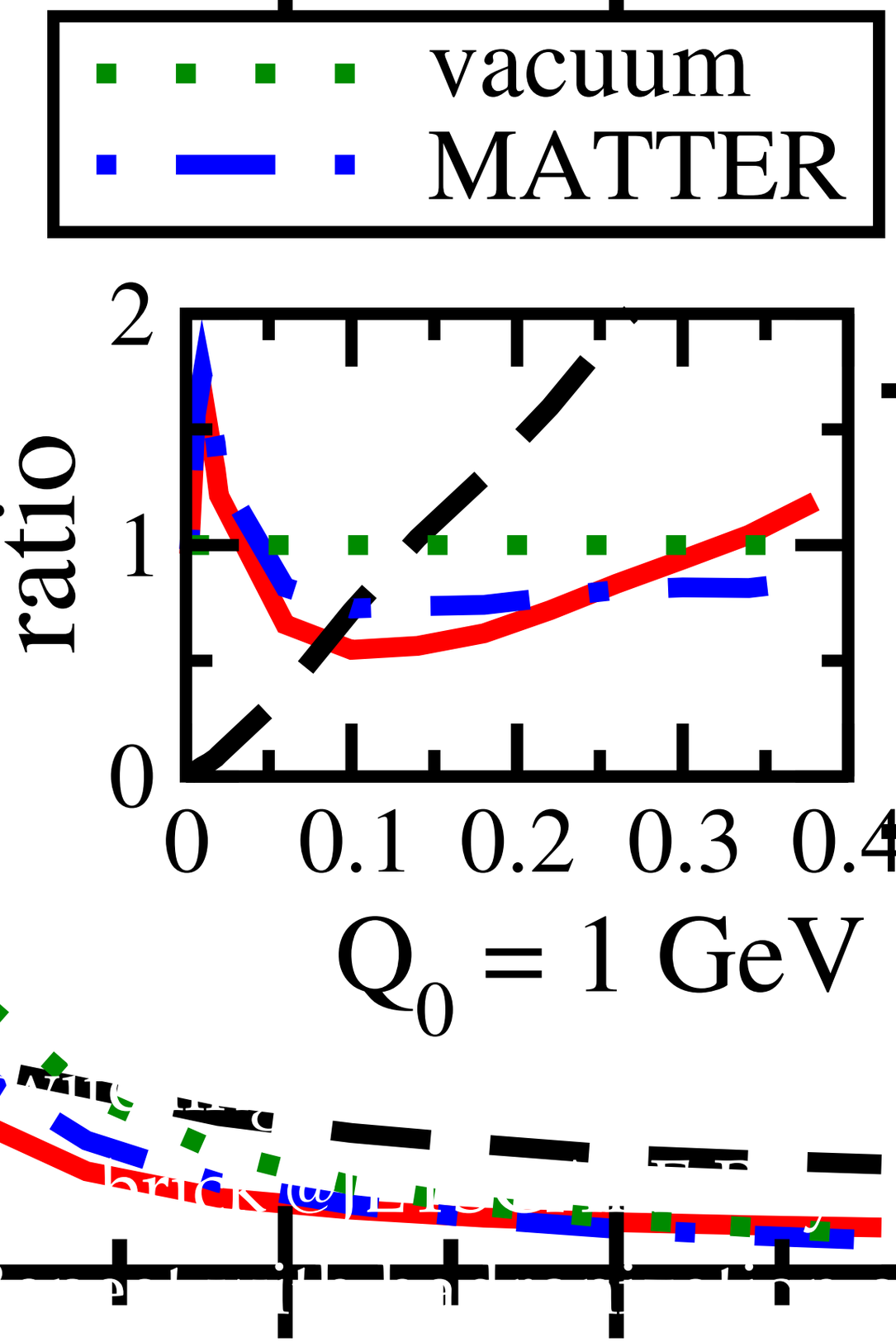
Evidence of multiple scales from multiple-stage Monte Carlos

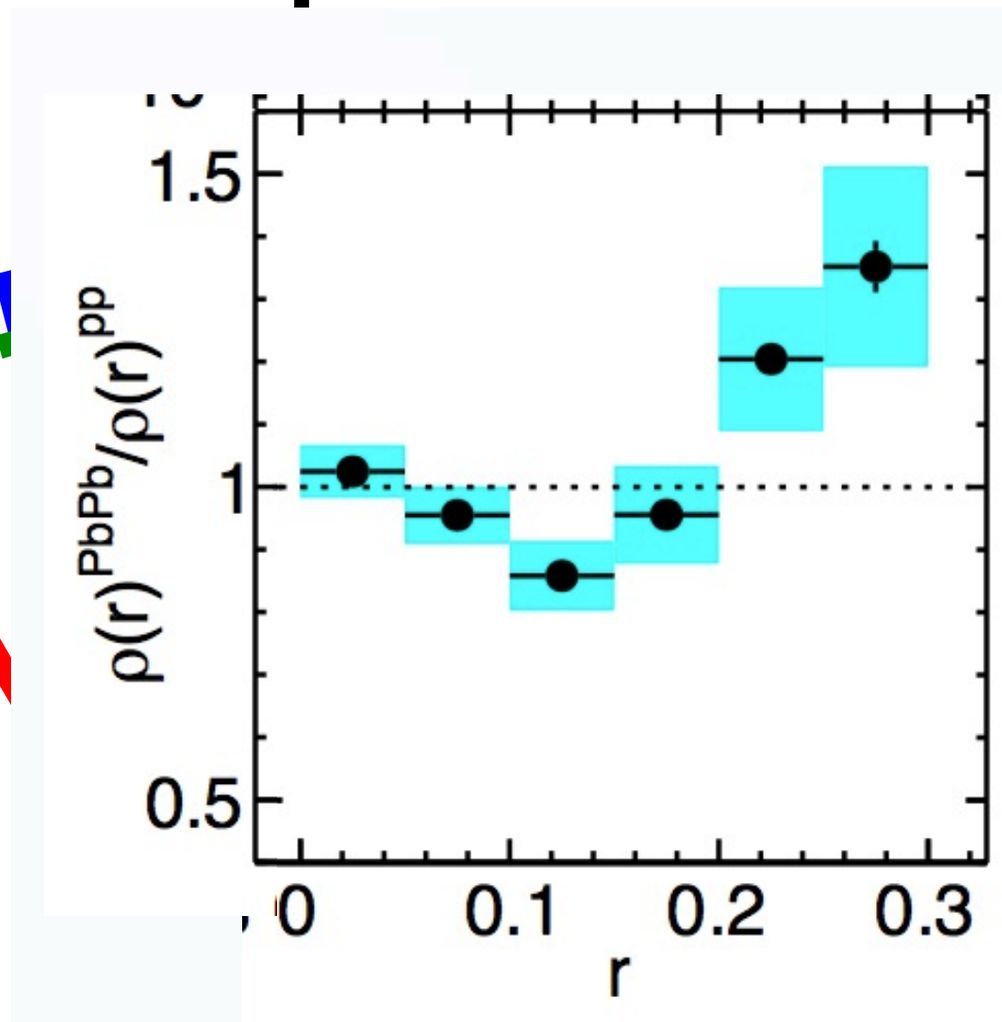


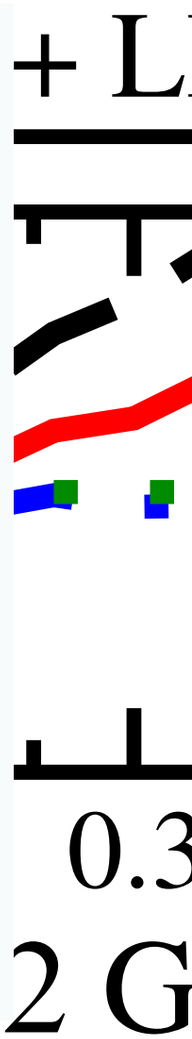


Switching between one event-generator and the next
in a brick @JETSCAPE Phys.Rev. C96 (2017) no.2, 024909
Repeat with hadronization and fluid medium being calculated

Evidence of multiple scales from

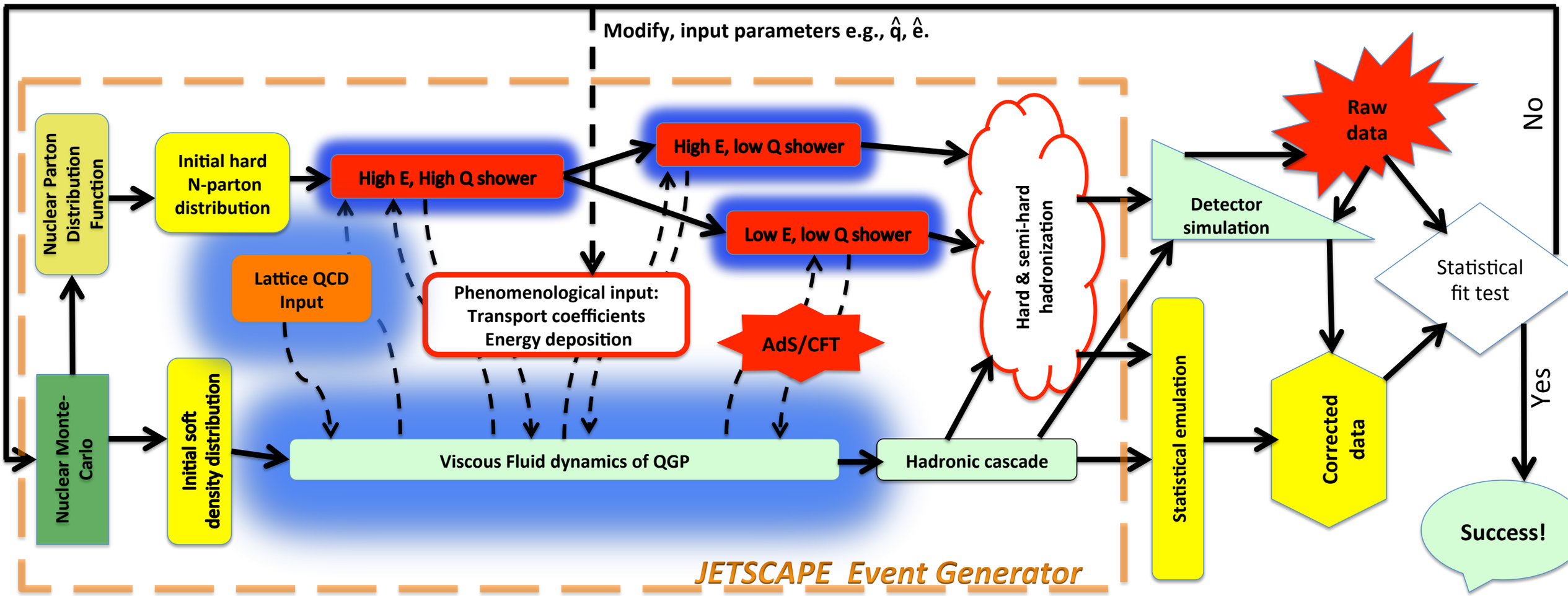






brian@LBL.gov

How would this work?



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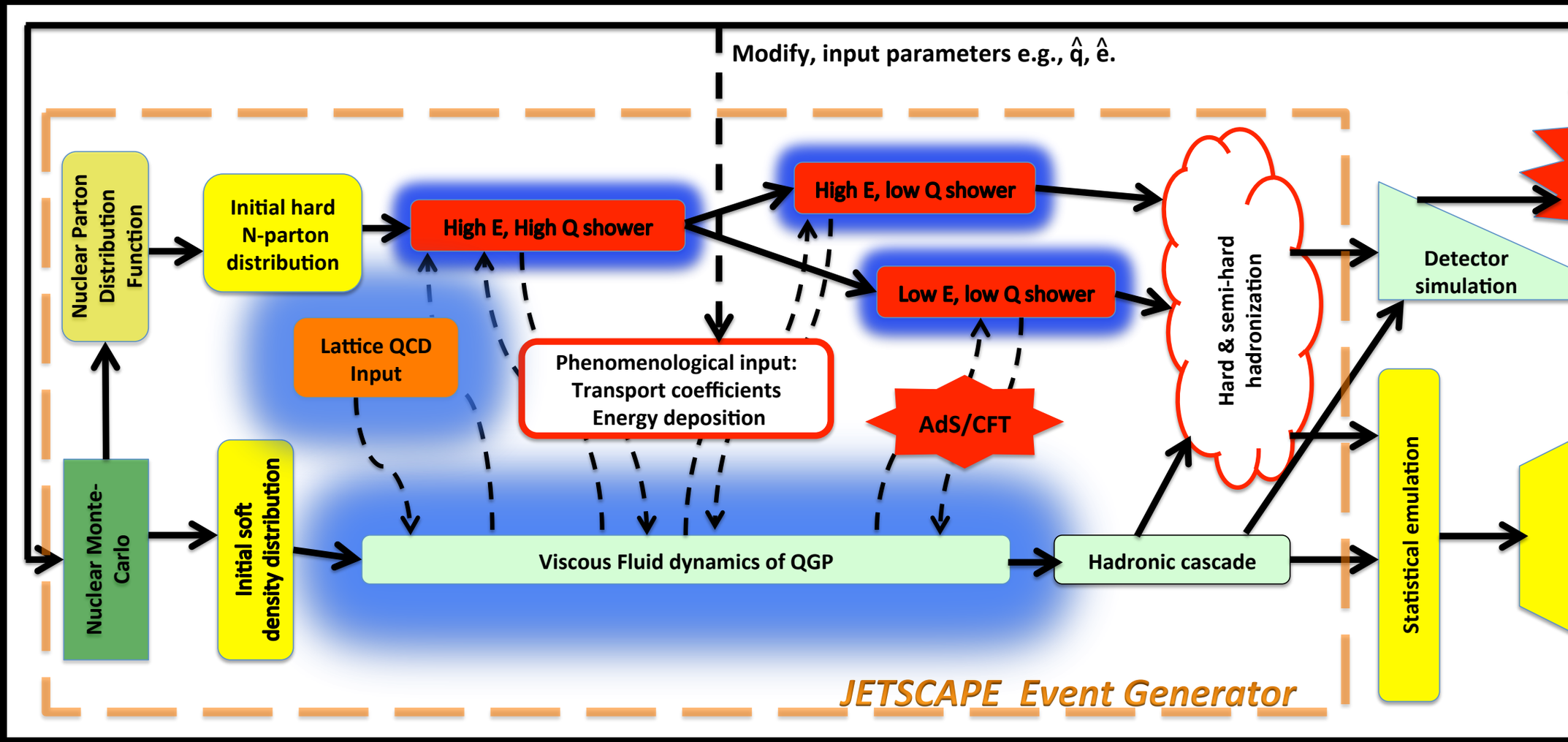

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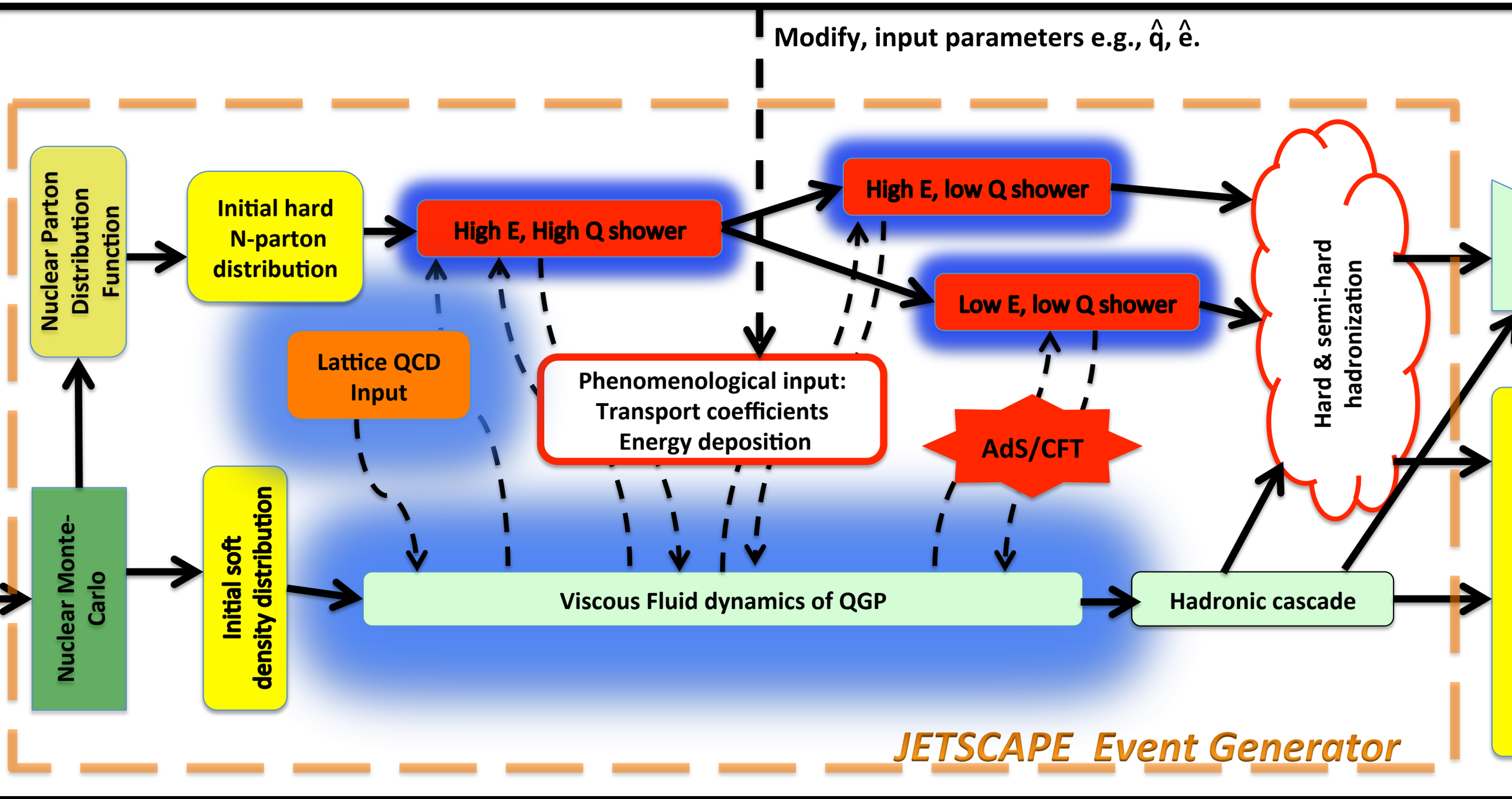
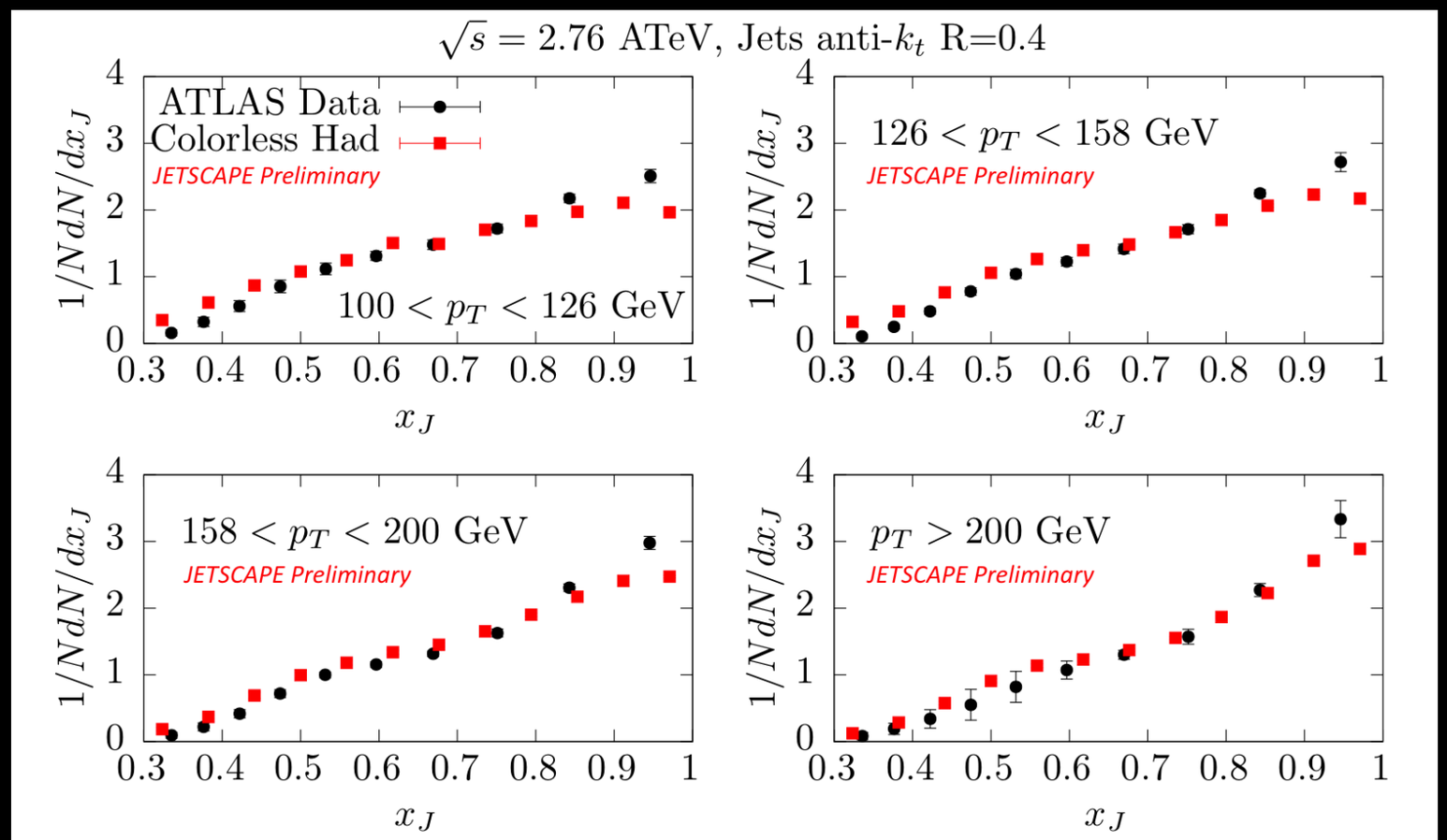
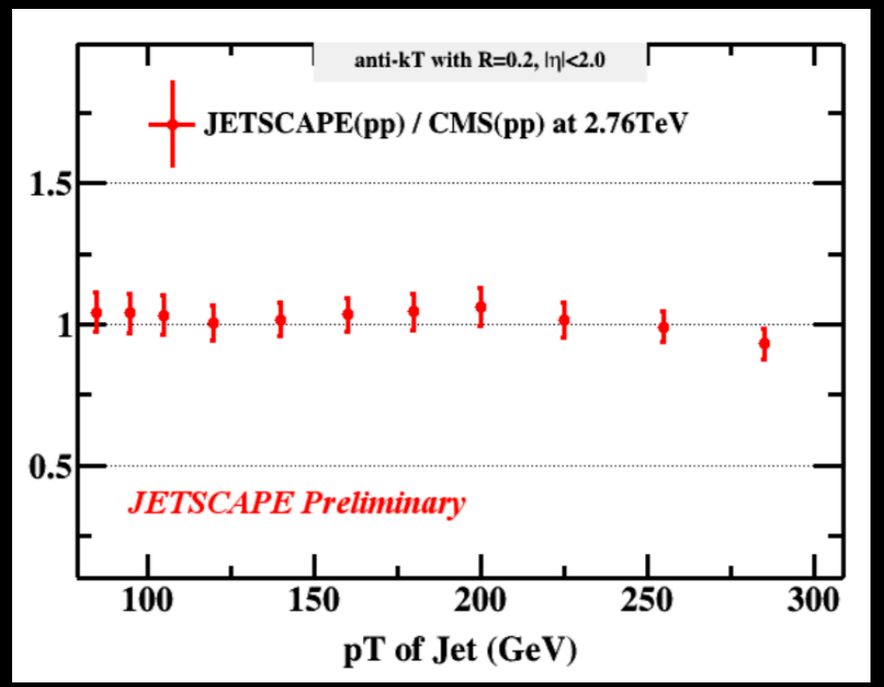


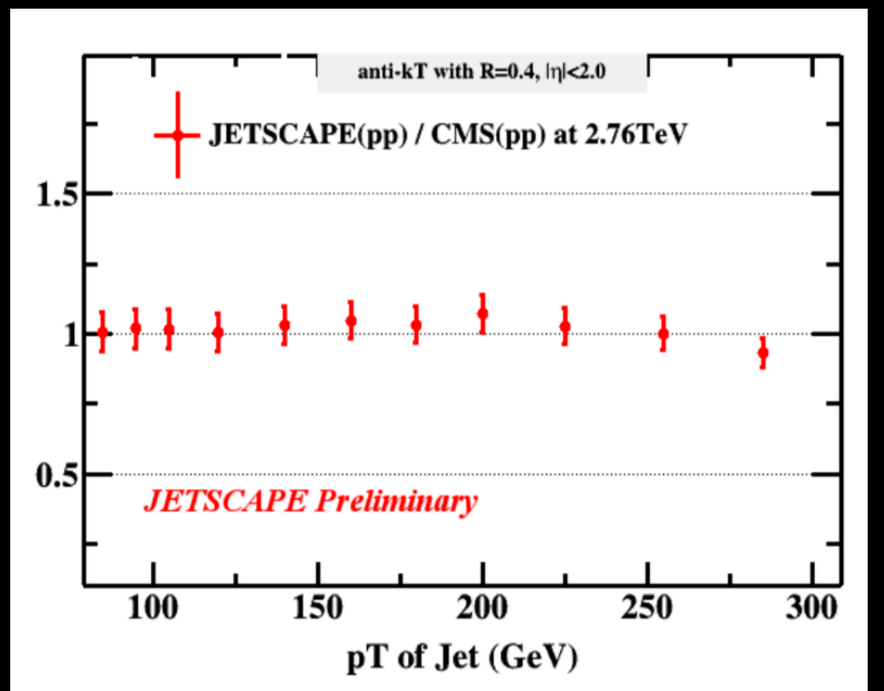
Using the full event generator

- Any good event generator needs a good p-p baseline

PYTHIA for initial state
MATTER for all final state partons > 1GeV
PYTHIA based hadronization of final partons







Preliminary results from JETSCAPE

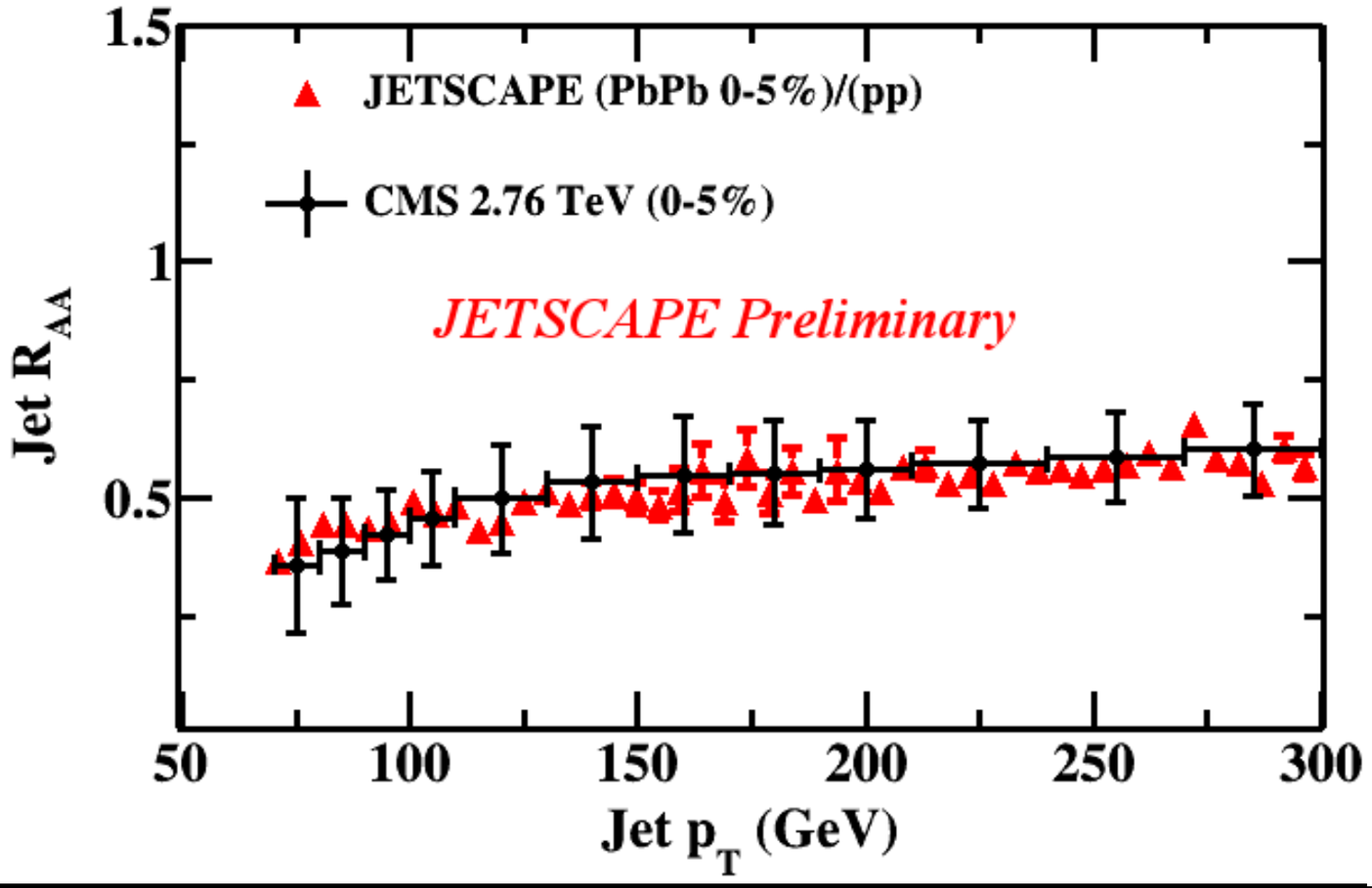
Initial state with TRENTO for both hydro and jets

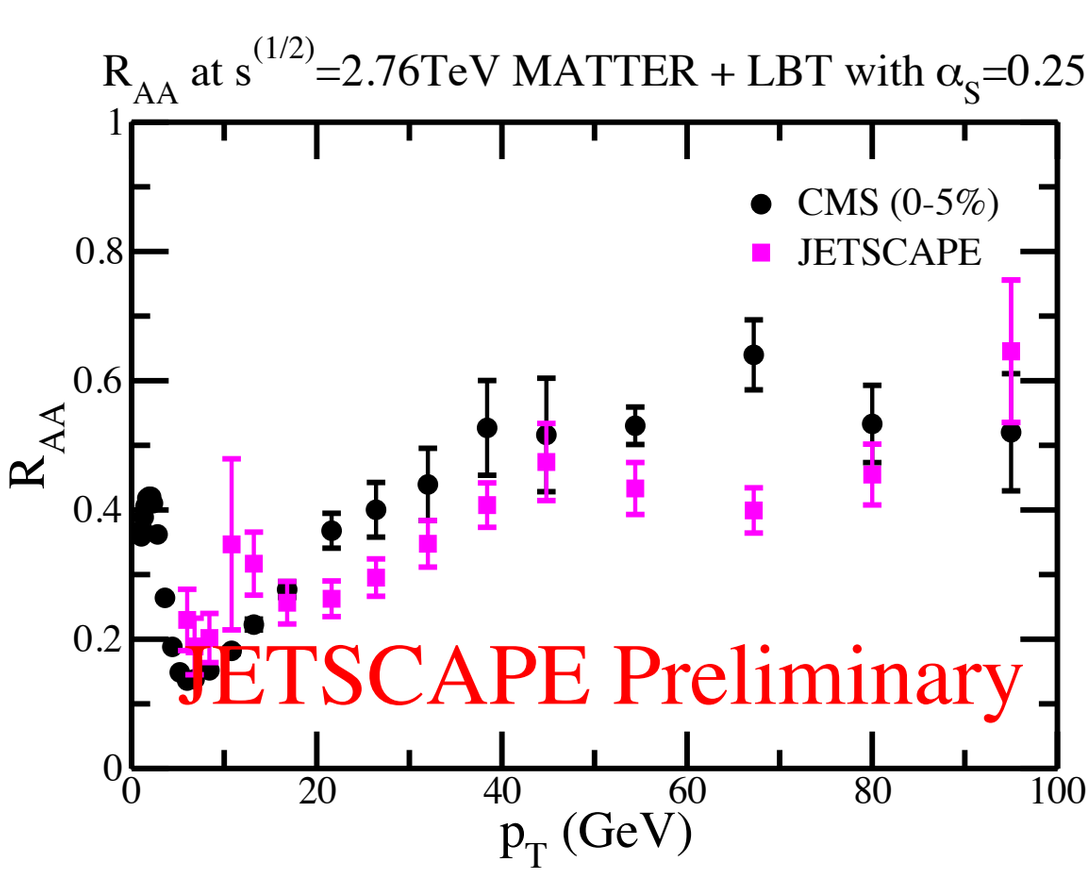
TRENTO —> PreEquib—> MUSIC —> Soft Hadronization

TRENTO —> PYTHIA init

—> (MATTER/LBT/MARTINI/AdS) + MUSIC profile

—> PYTHIA based hadronization





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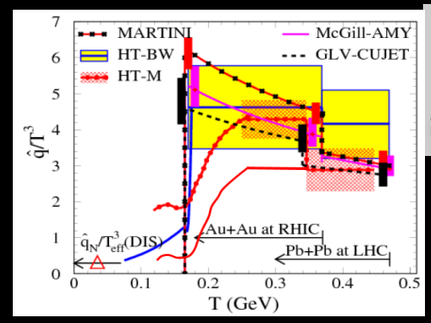

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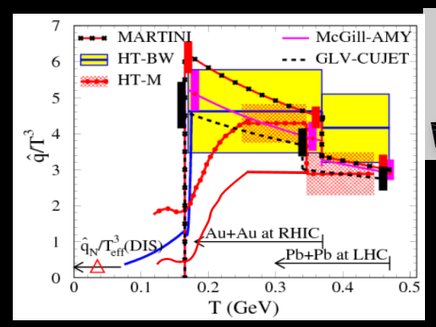
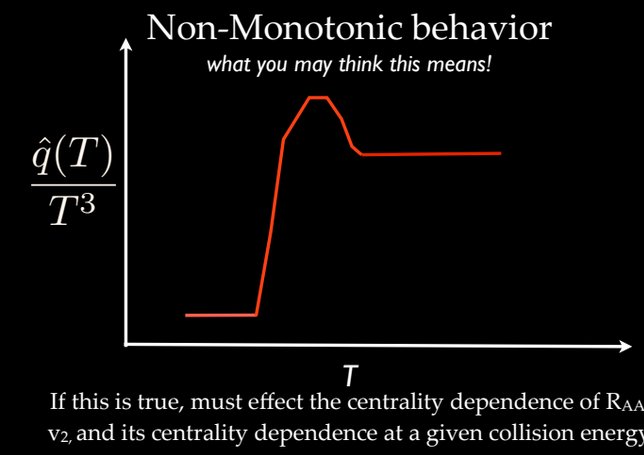


Personal opinion: its not this —> rather an energy or scale dependence in $\hat{q}$



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

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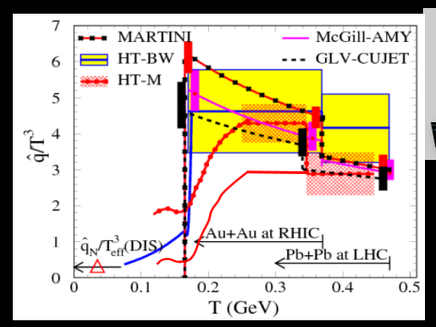

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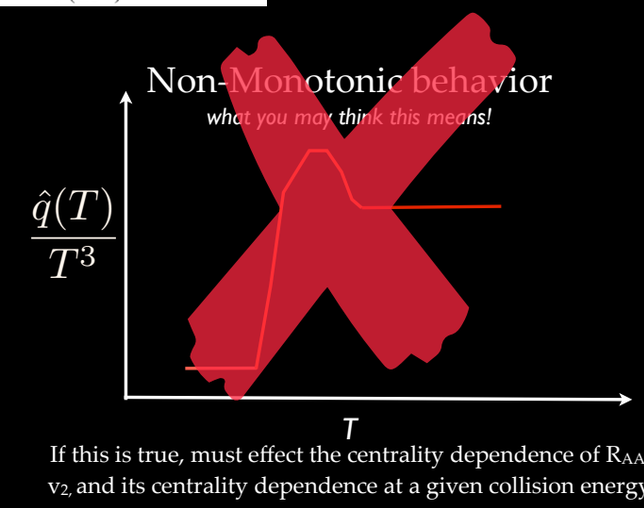

If this is true, must effect the centrality dependence of R_{AA}, v_2, and its centrality dependence at a given collision energy

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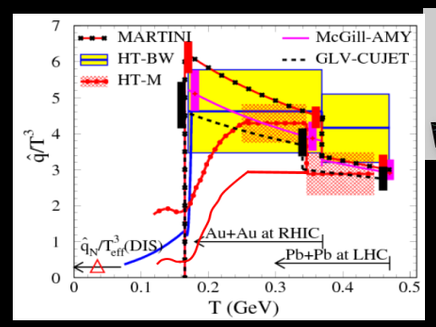

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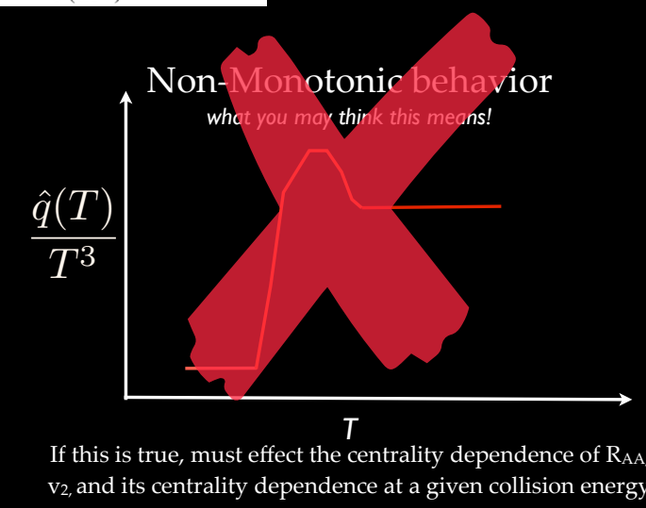

Jets have multiple scales, with different interactions with medium

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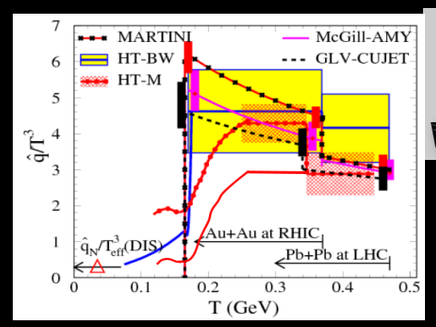

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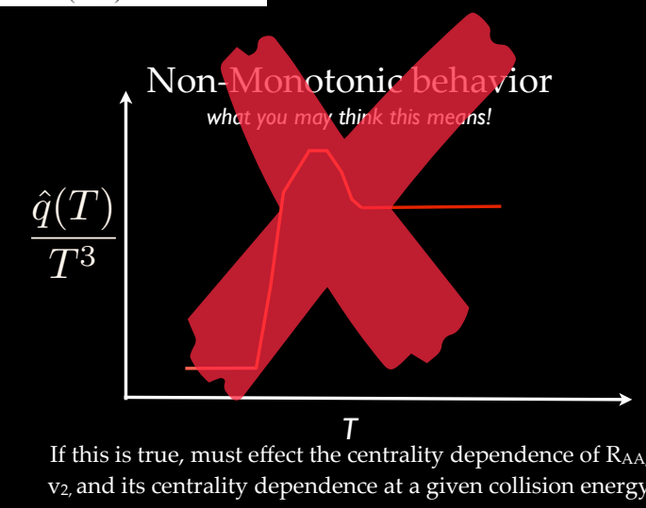

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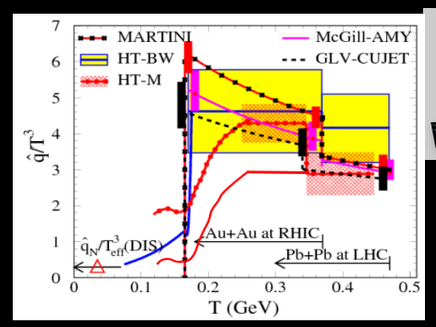

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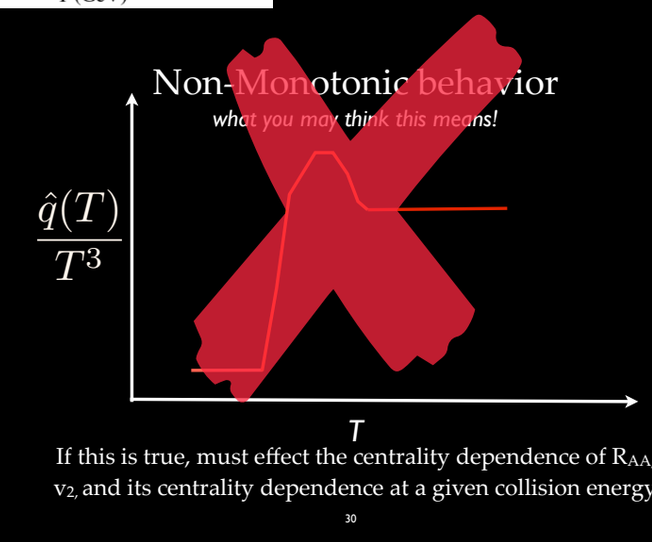

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Qualitatively similar but quantitatively different picture for heavy Q (*see Shanshan's talk*)

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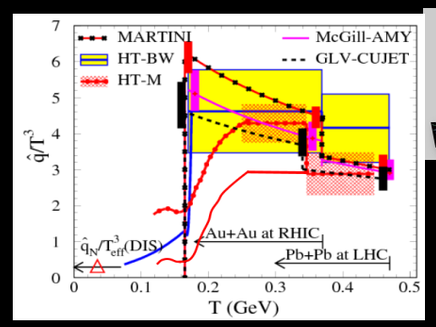

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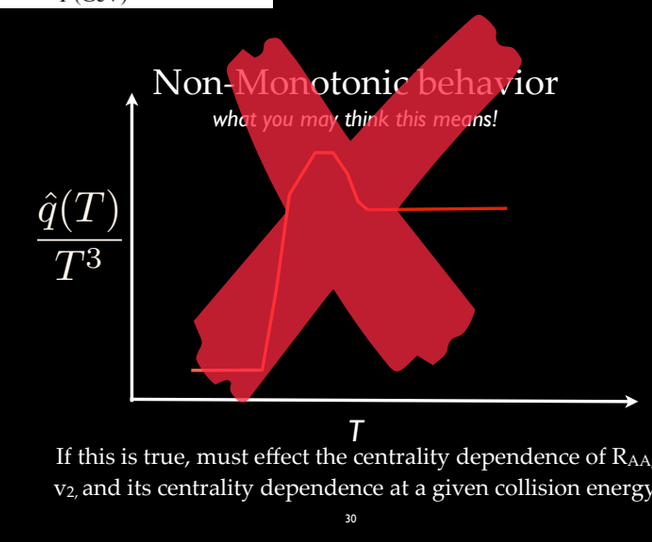

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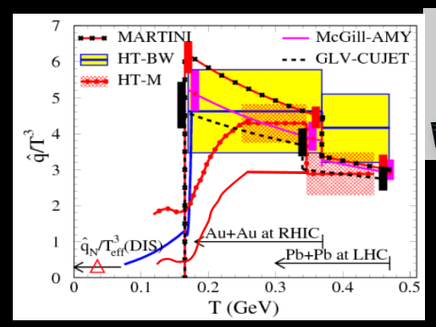

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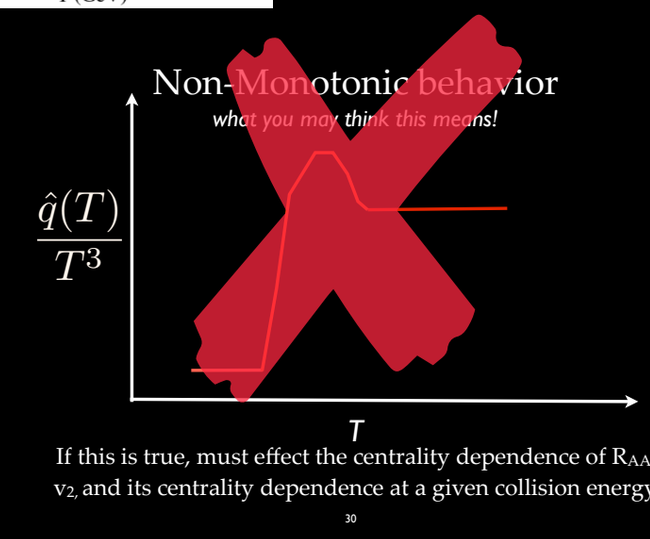

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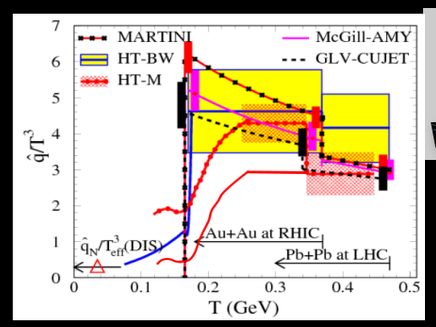

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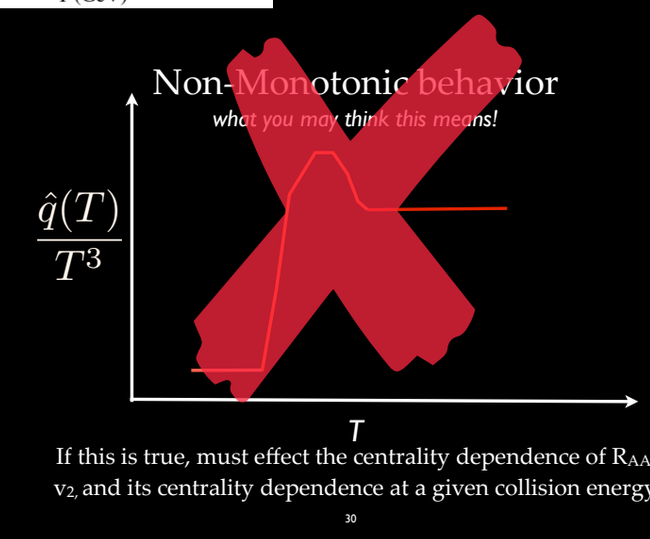

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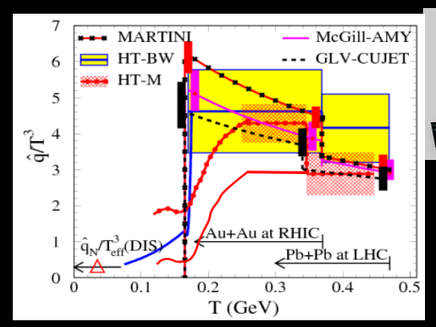

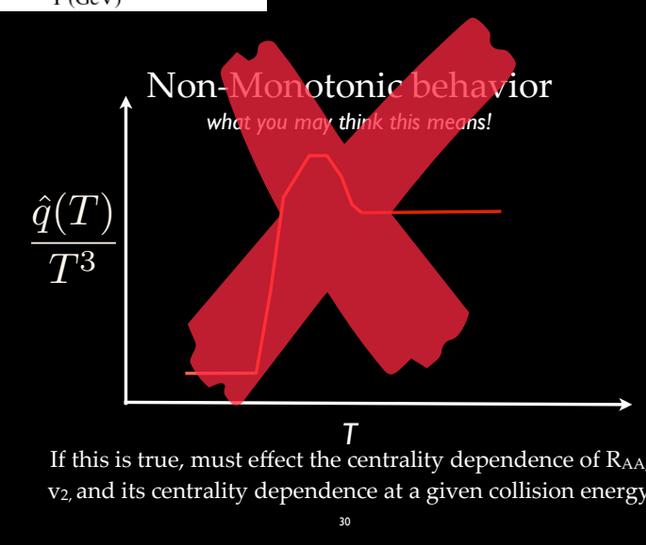

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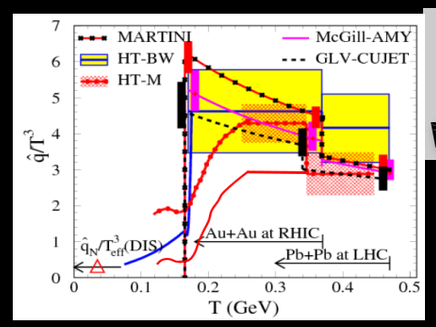

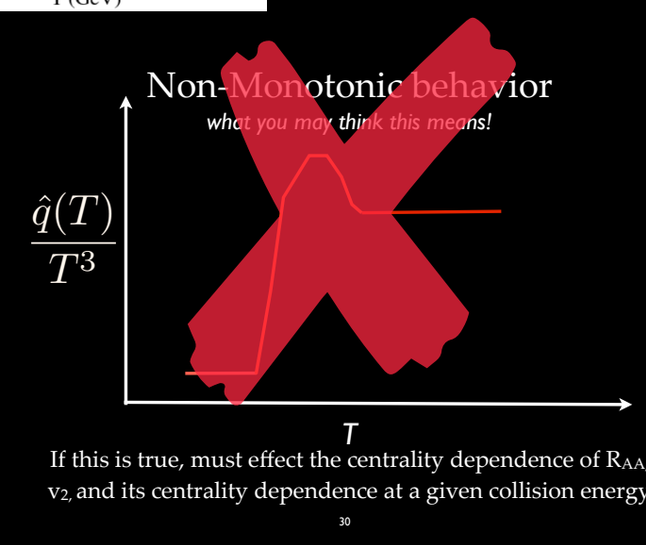

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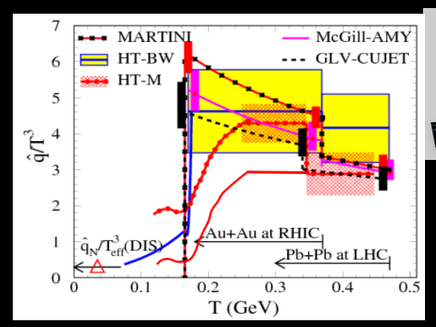

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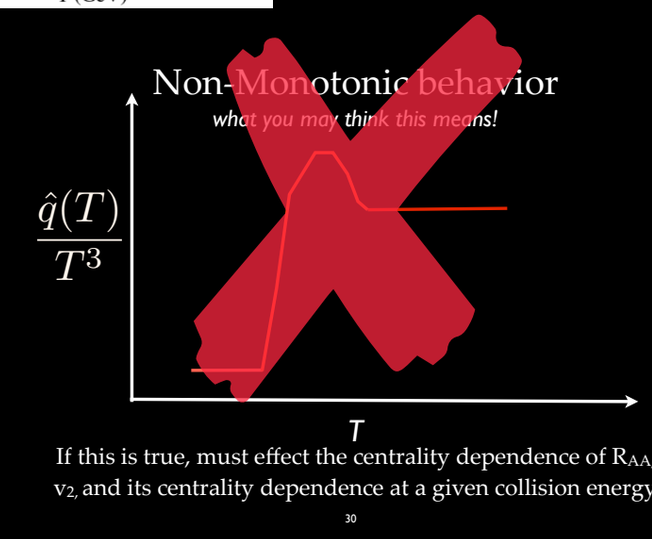

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Limits on $\hat{e}$ from jets and leading hadrons

Medium recoil needed to get jet physics

Deposited energy seems to thermalize very rapidly into fluid

What do you want to learn

What do you want to learn

How does the parton in the jet see the medium?

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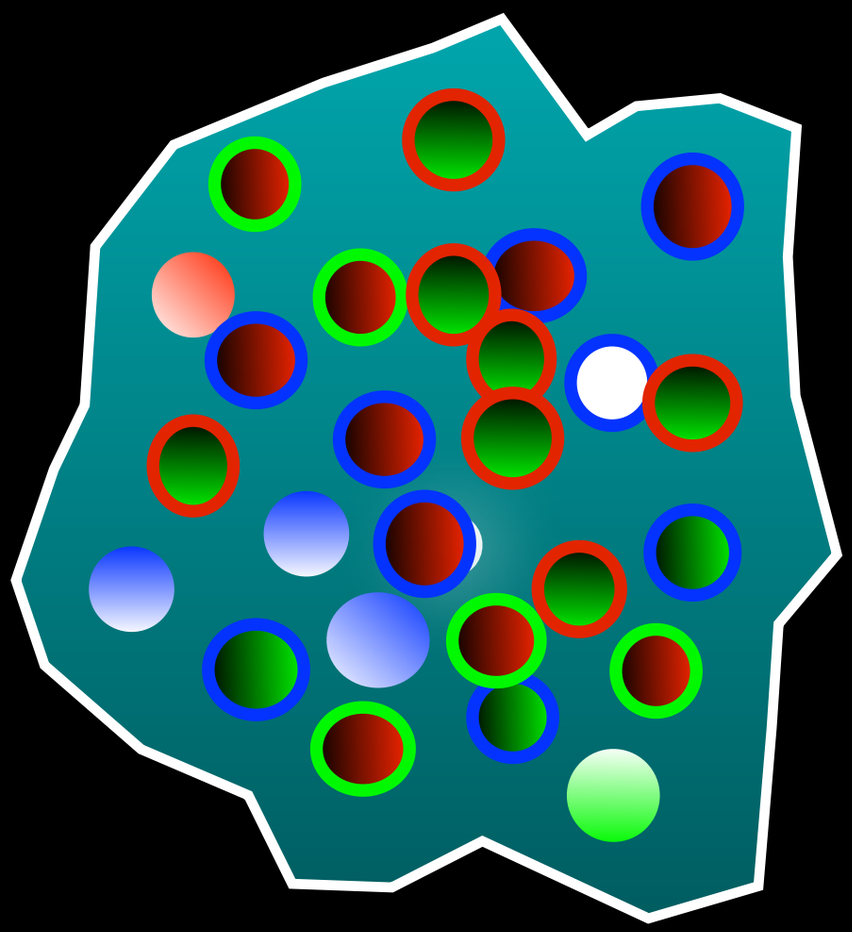

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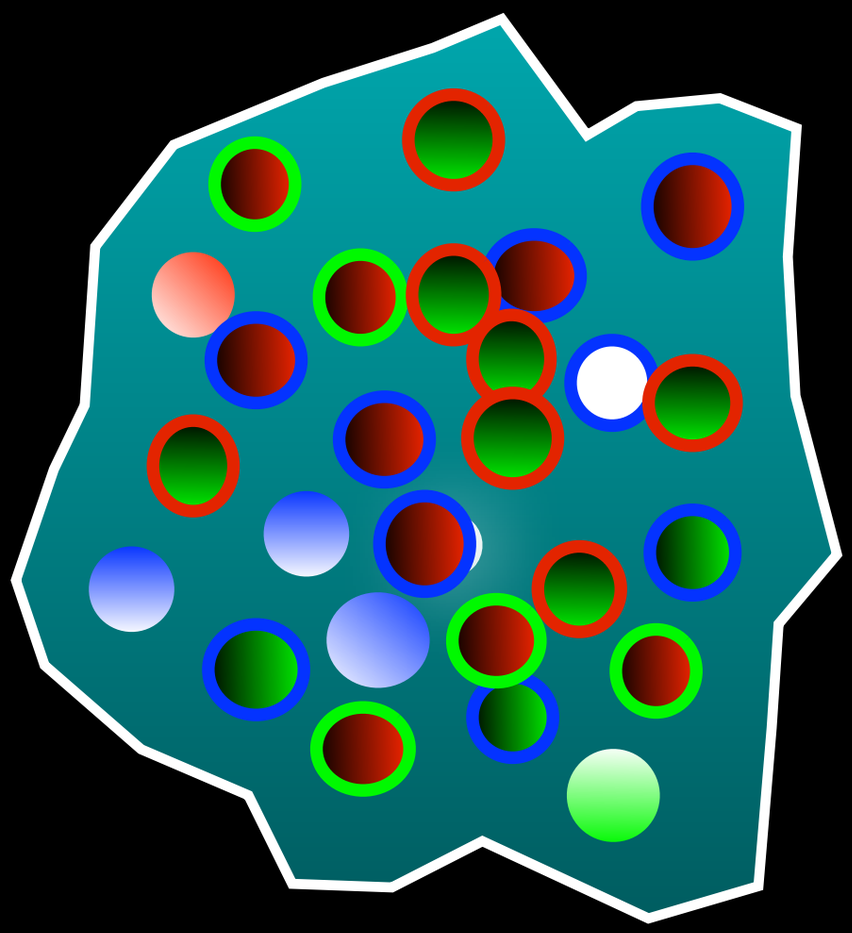
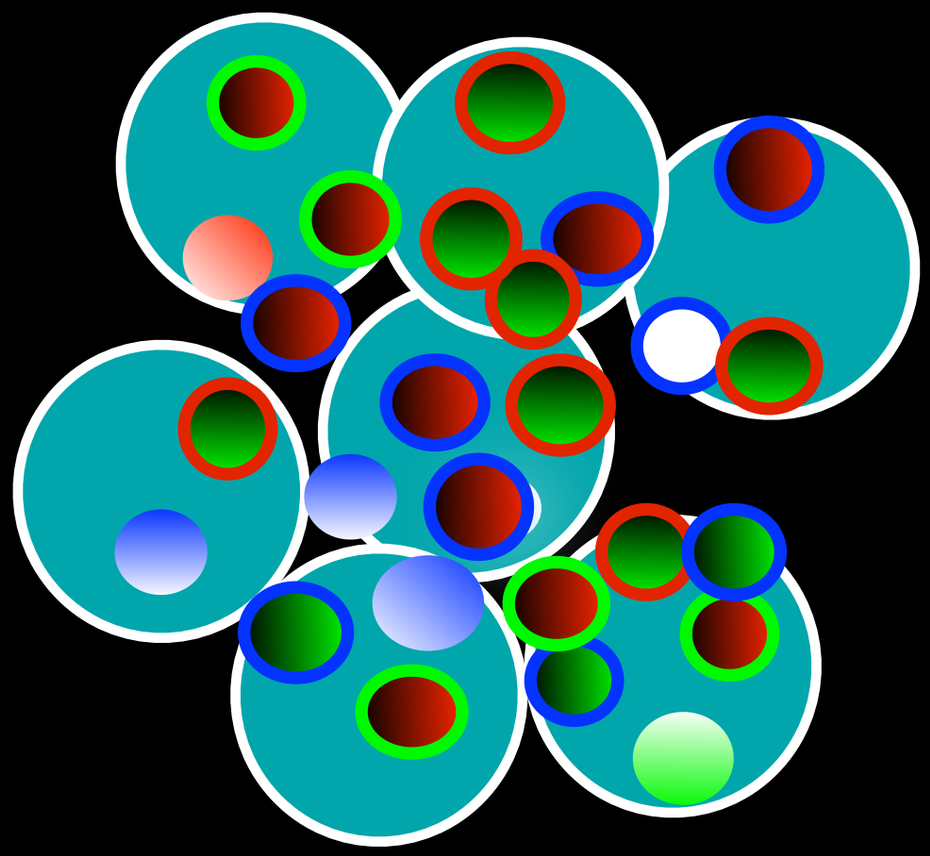




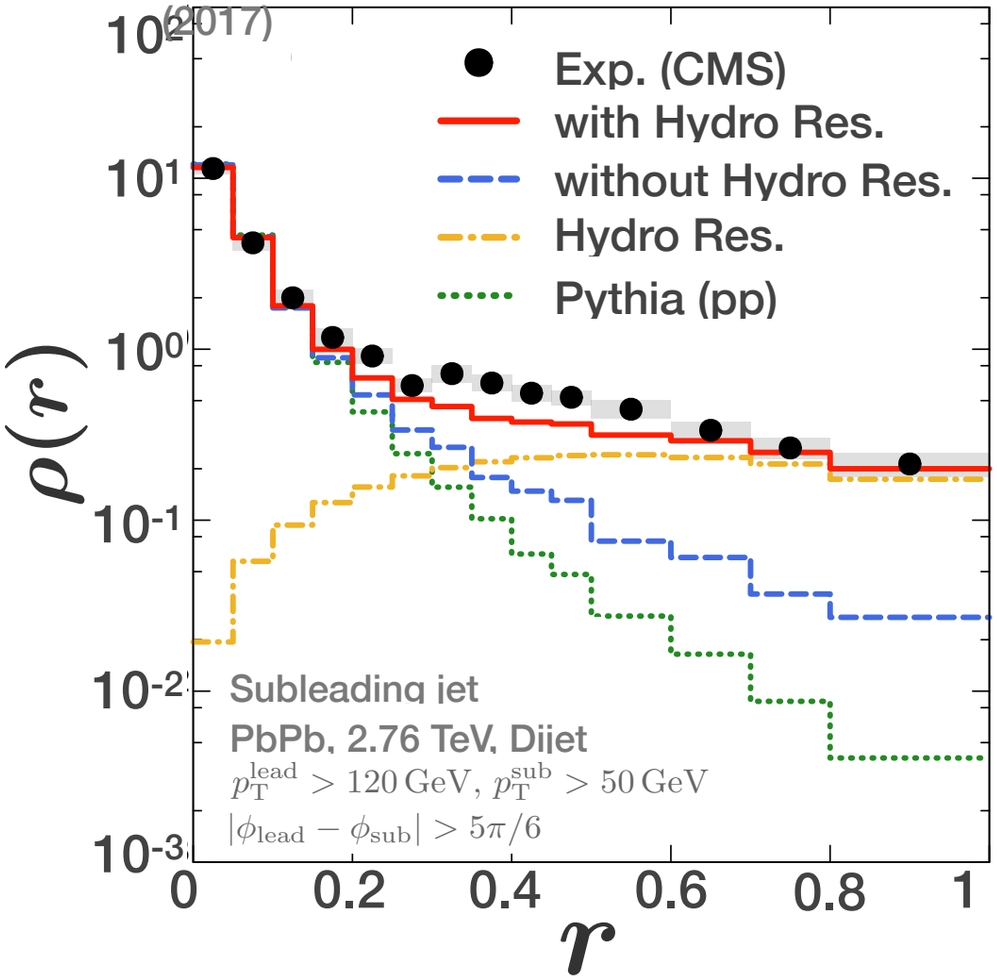
What do you want to learn

Jet medium interactions, allow for a needle like probe of the hydro medium

Allow us to shatter quasi-particles and see them reconstitute, and equilibrate

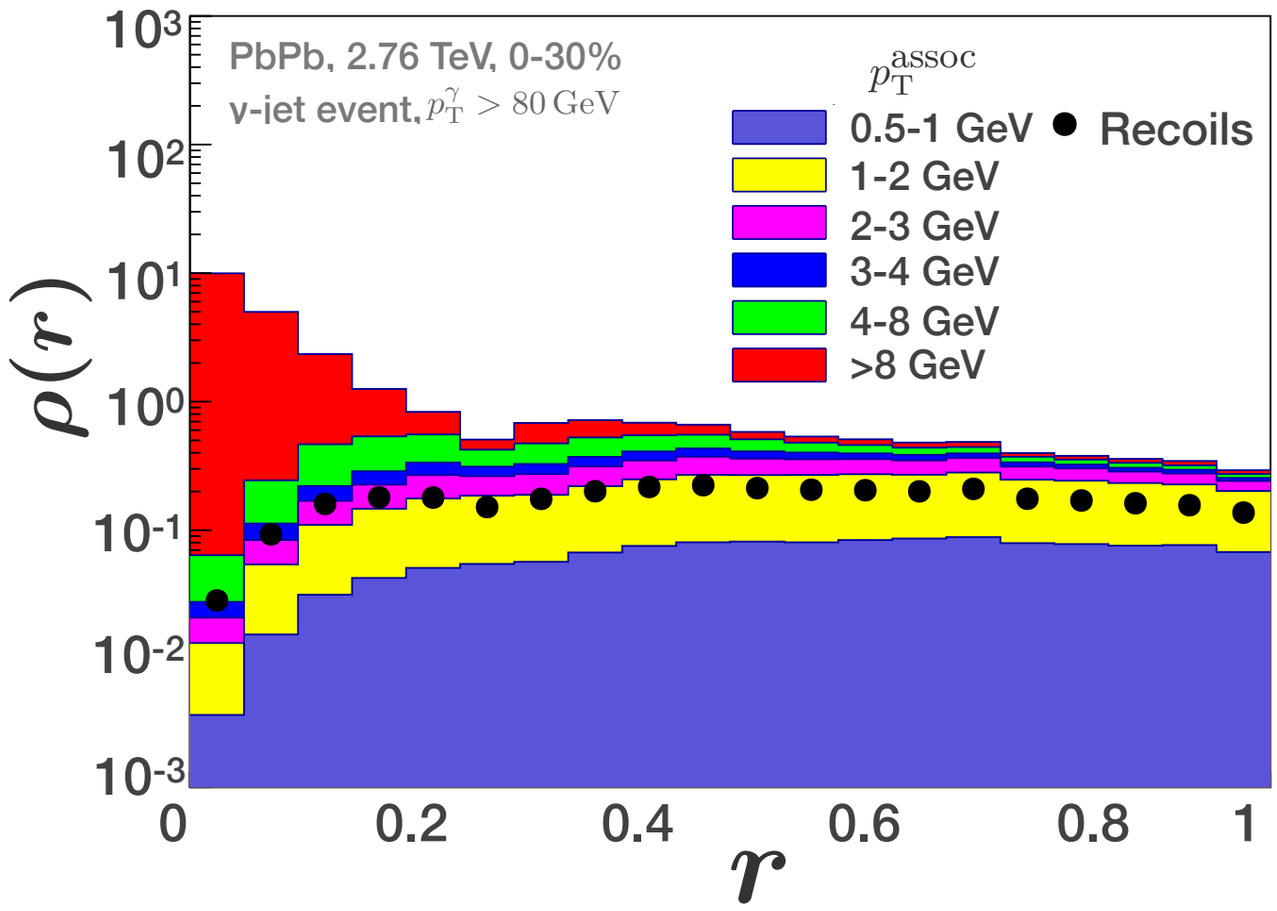
Coupled Jet-Fluid Model Hydro

YT, N.-B. Chang, G.-Y. Qin, PRC 95, 044909 (2017)



LBT model Recoil

T. Luo, S. Cao, Y. He, X.-N. Wang, arXiv:1803.06785



Outlook

Jets provide multi-scale probes of the evolving QGP

Multi-scale dynamics, growing number of T.Cs, and observables require a modular, modifiable, event generator —> JETSCAPE

Established values of q, e,

(Heavy-quarks provide a slightly shifted view of this)

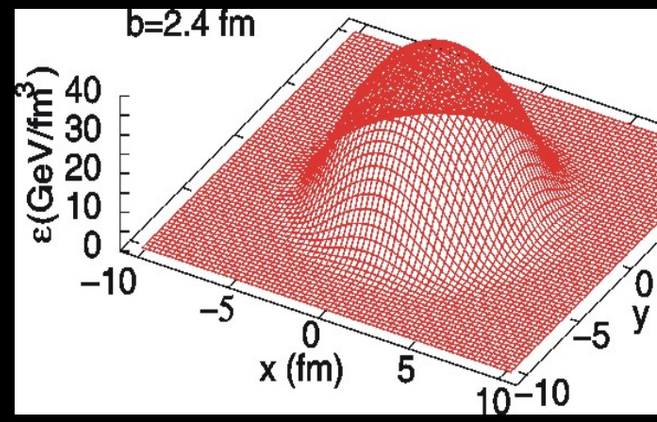
Need for medium response for jets studies.

Jet medium correlations provide a possible window into degrees of freedom of the QGP, next stage of JETSCAPE.

Back Up

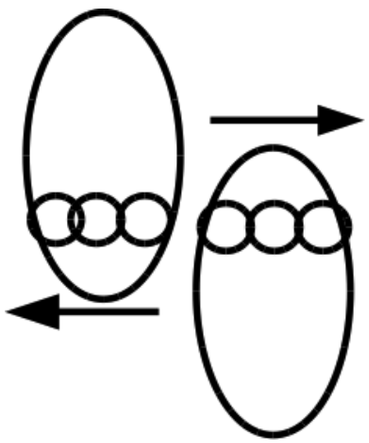
In all calculations presented
bulk medium described by viscous fluid dynamics

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

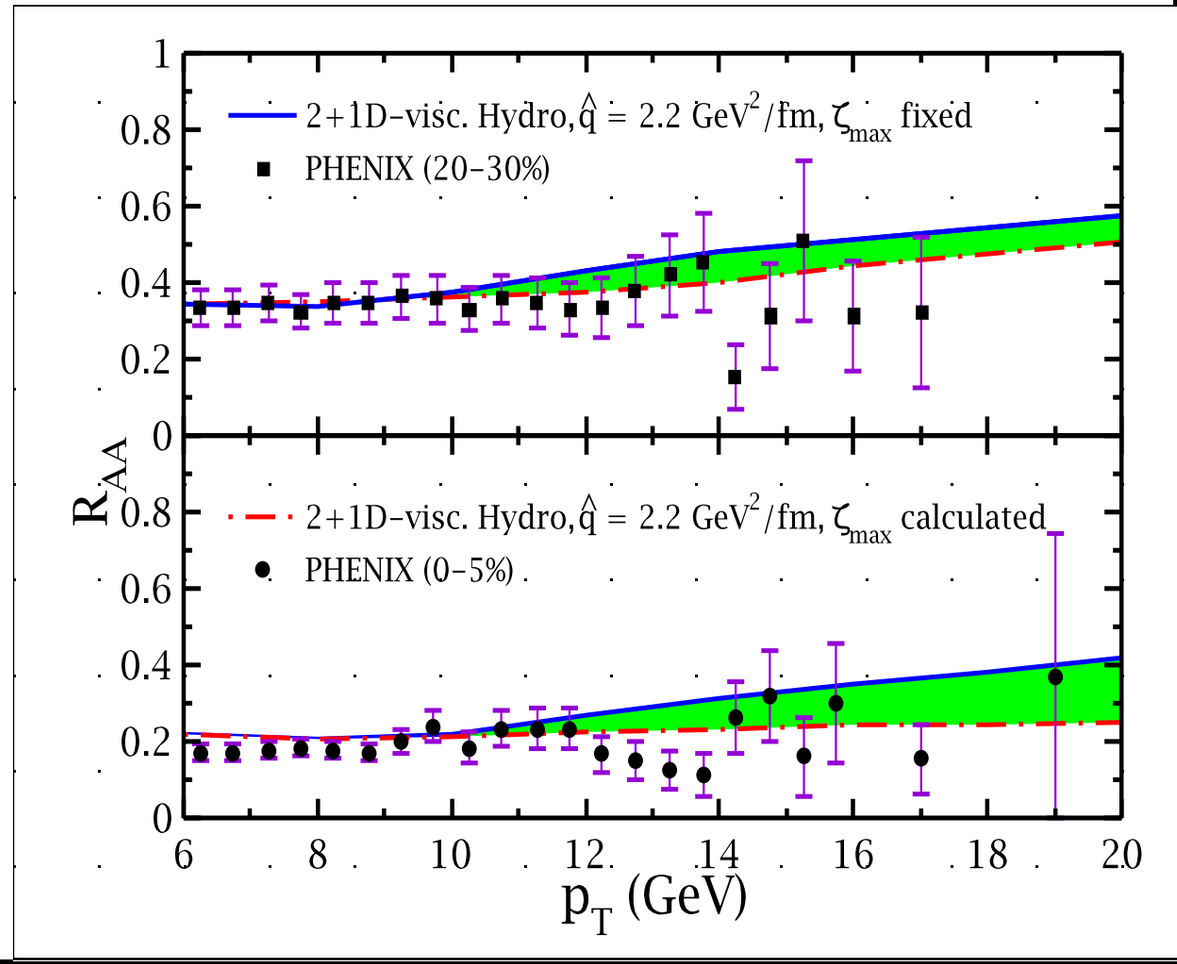


$$\hat{q}(\vec{r},t) = \hat{q}_0 \frac{s(\vec{r},t)}{s_0}$$

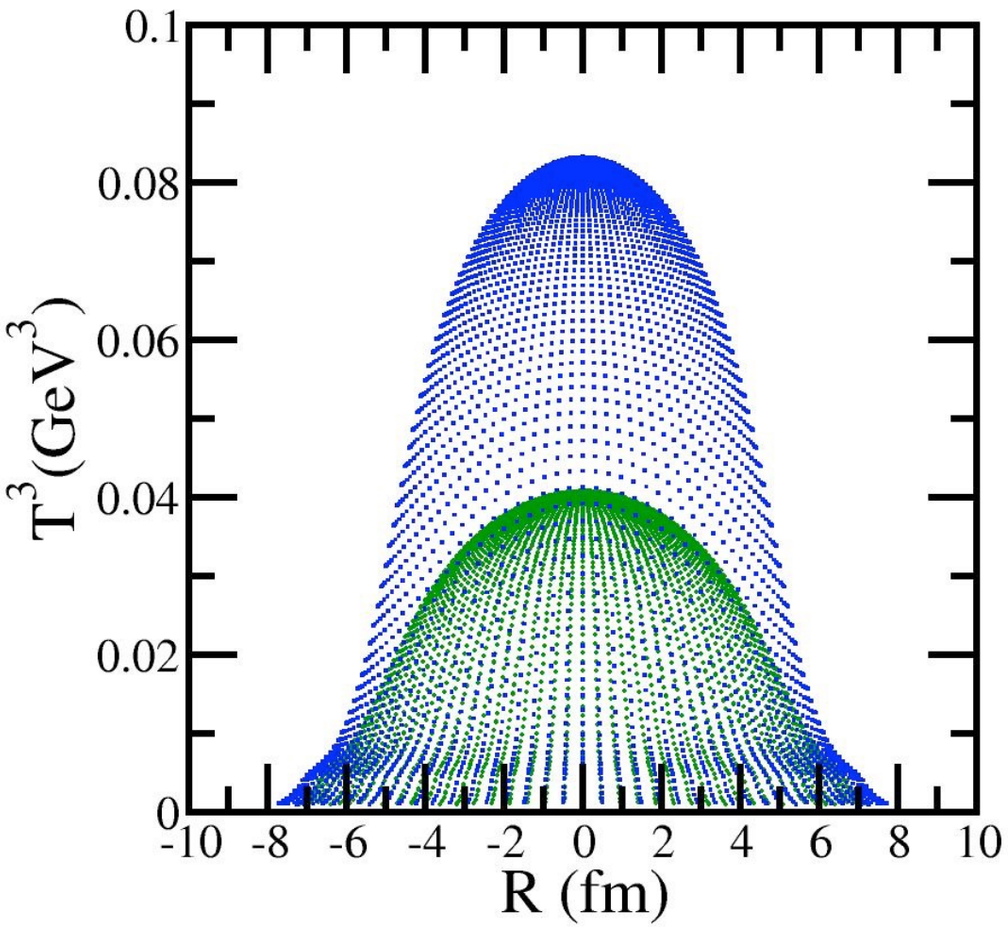
$$s_0 = s(T_0)$$

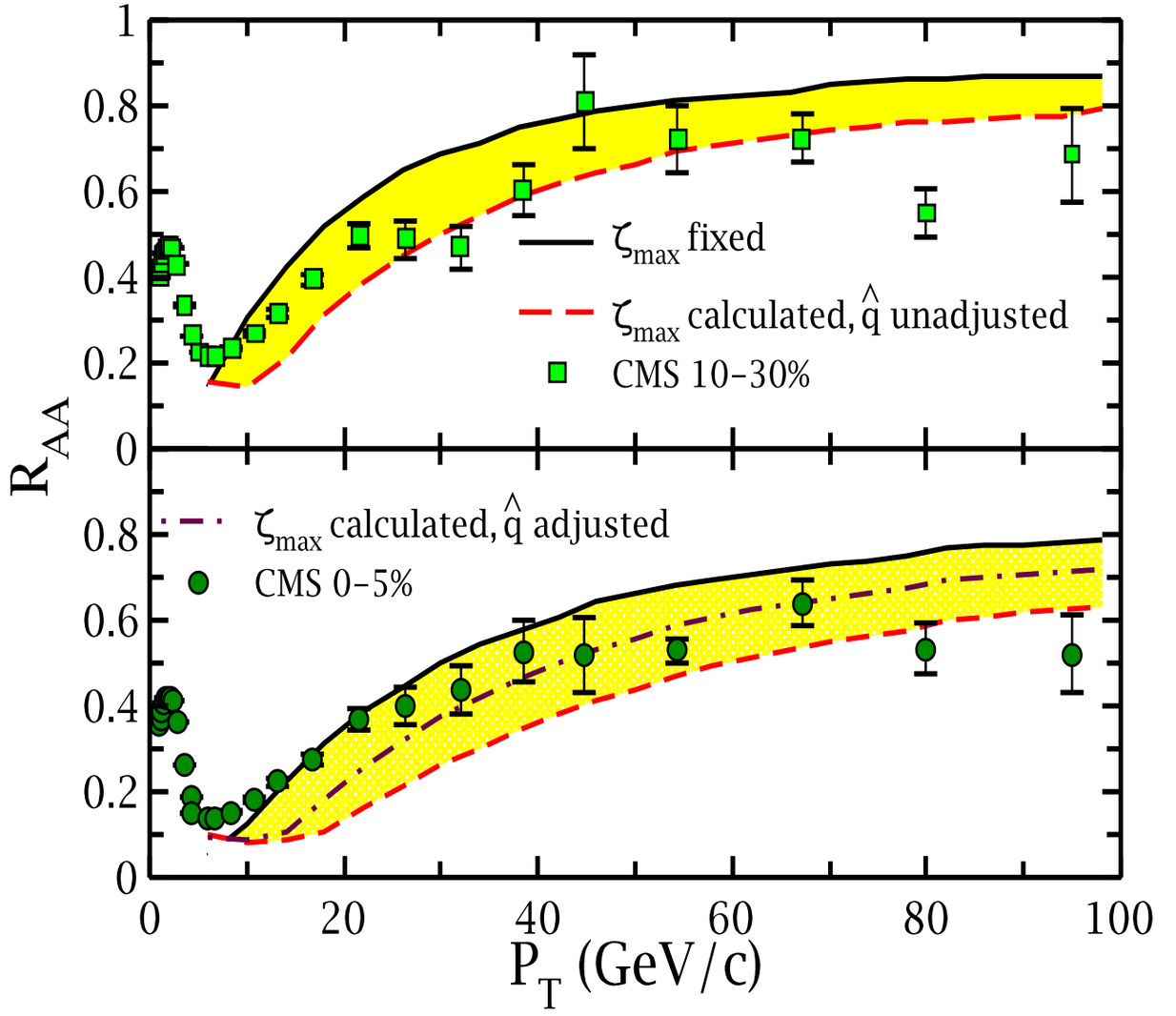


$$R_{AA} \sim \frac{\frac{dN_{AA}}{dp_T dy}}{N_{bin}\frac{dN_{pp}}{dp_T dy}}$$



From RHIC to LHC circa 2012

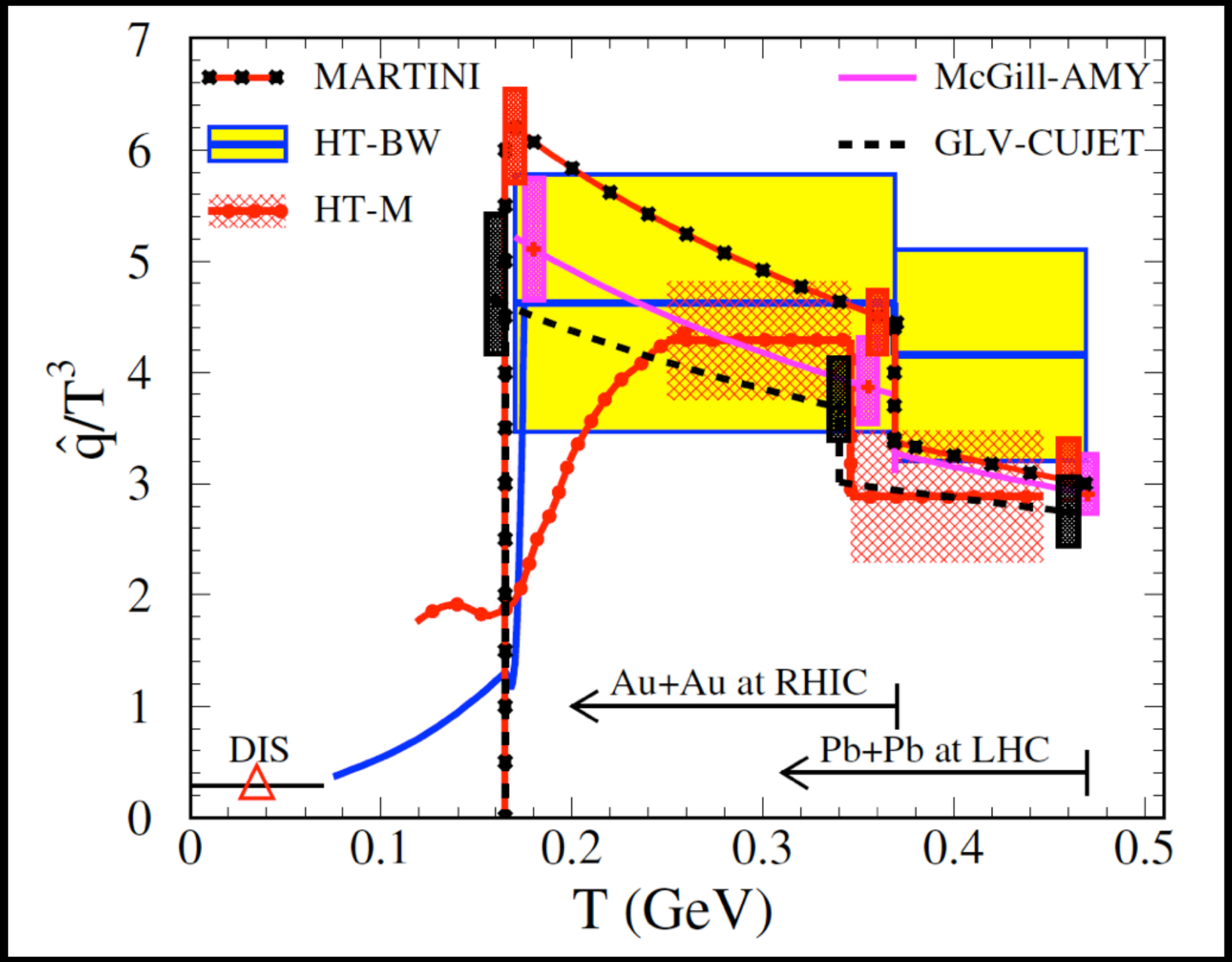




Reasonable agreement with data,
no separate normalization at LHC

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 assûming any kink in the q vs T^3 curve

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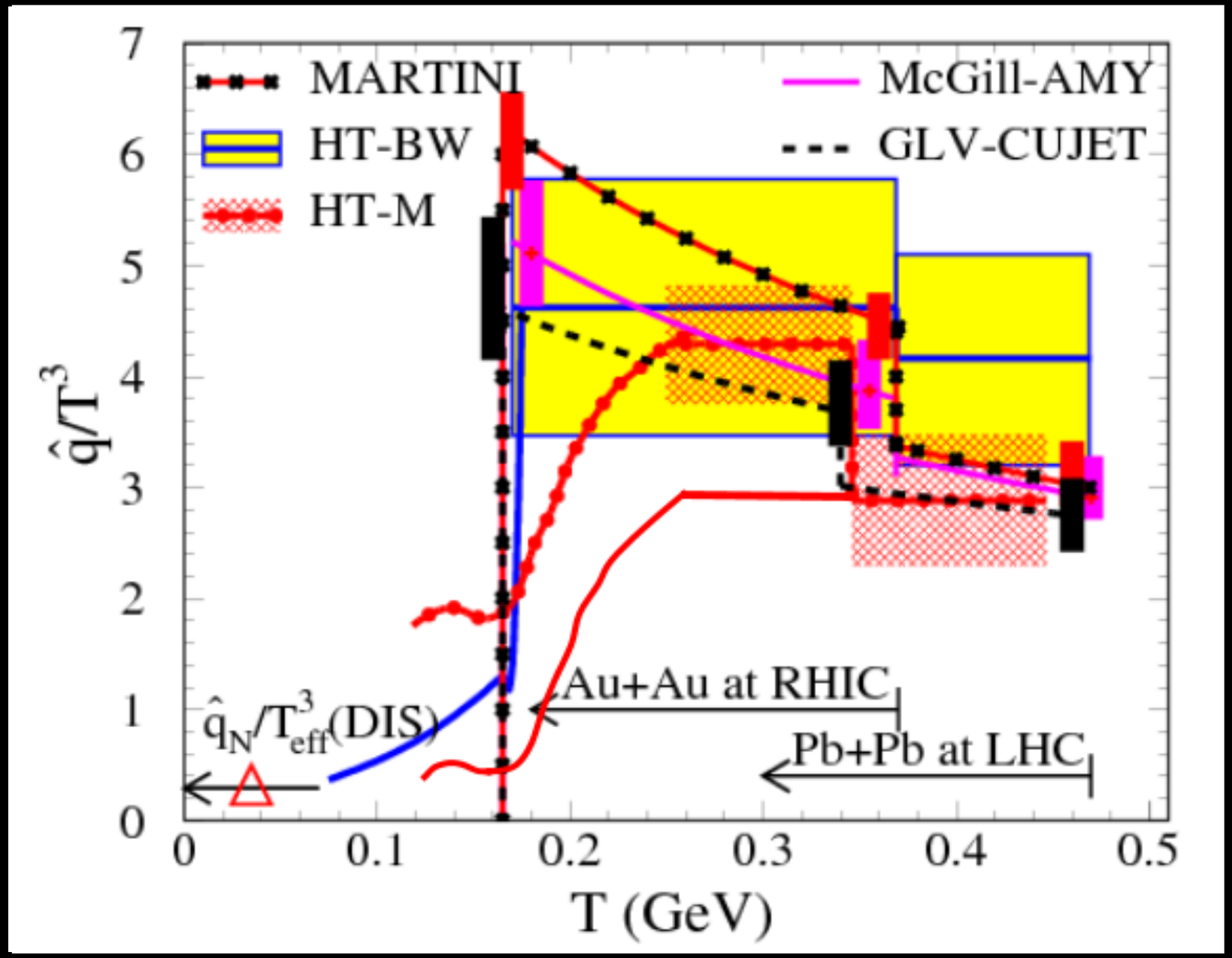

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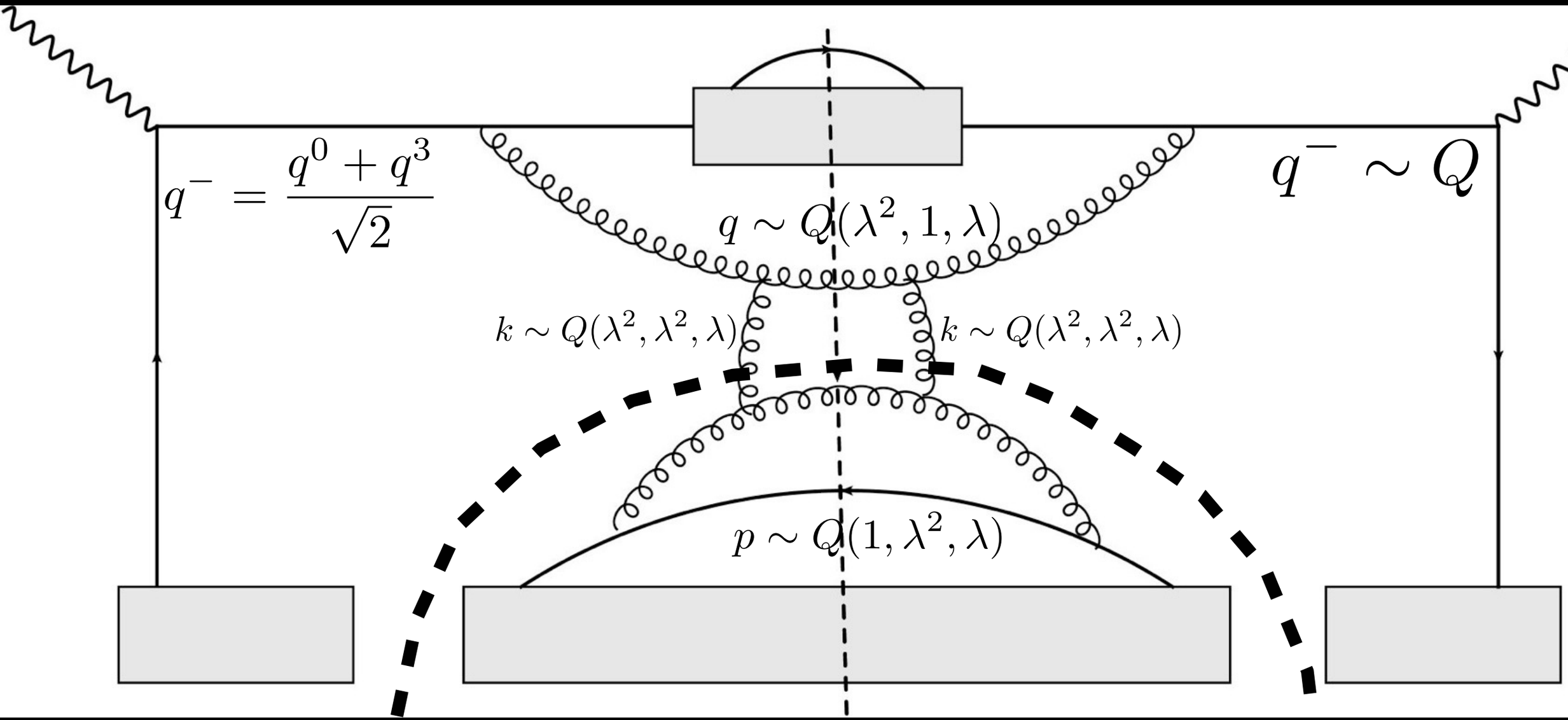
A factorized picture



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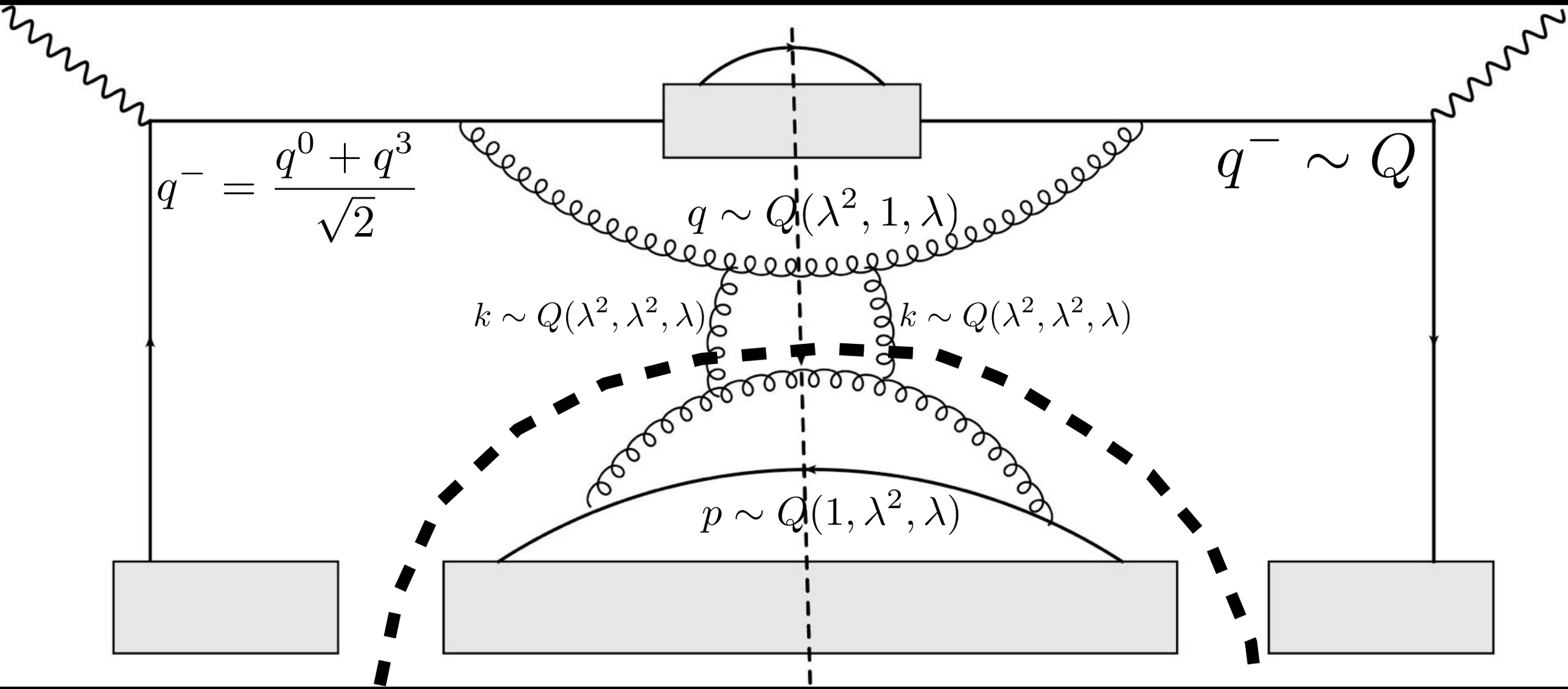


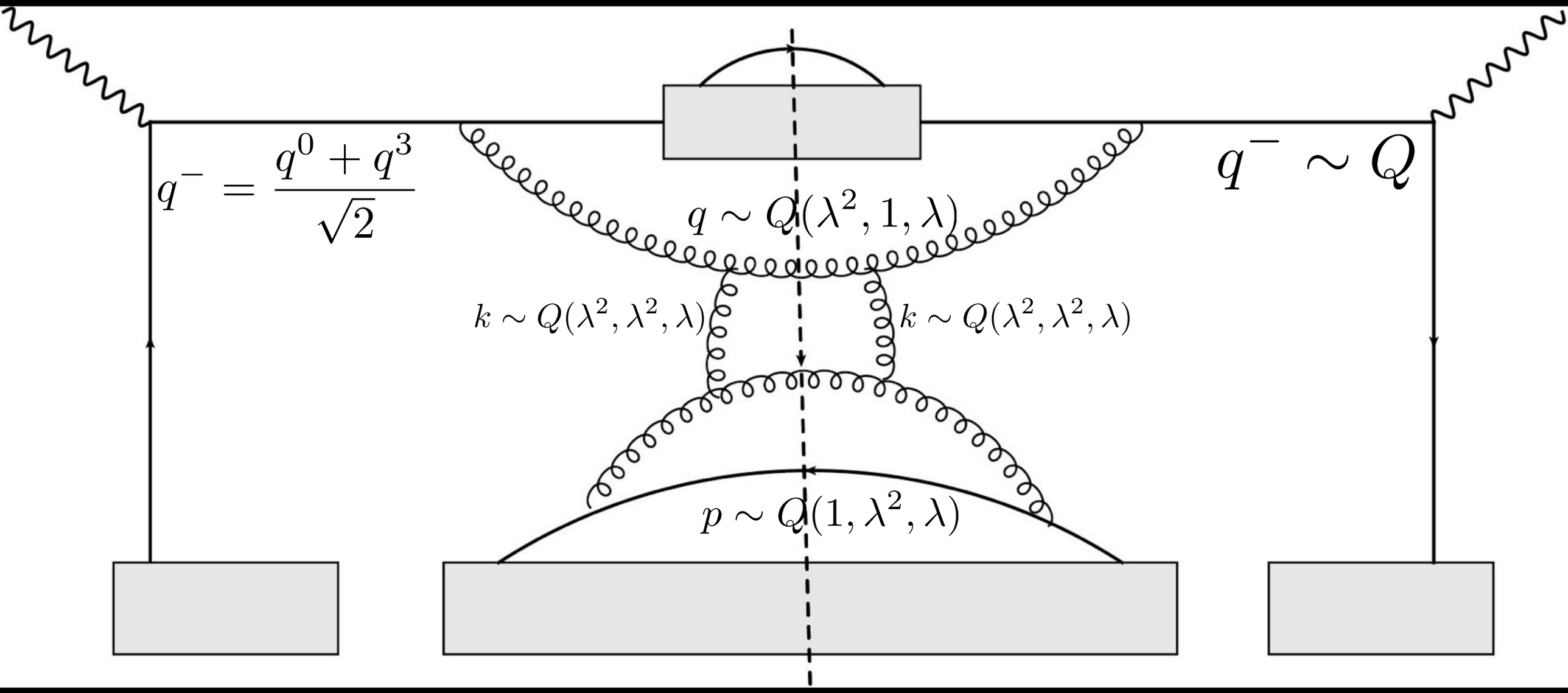
Q is the hard scale of the jet ~ E

Qλ is a semi-hard scale ~ (ET)$^{1/2}$,

q contains all dynamics below Qλ

$$\lambda \longrightarrow 0$$

A factorized picture



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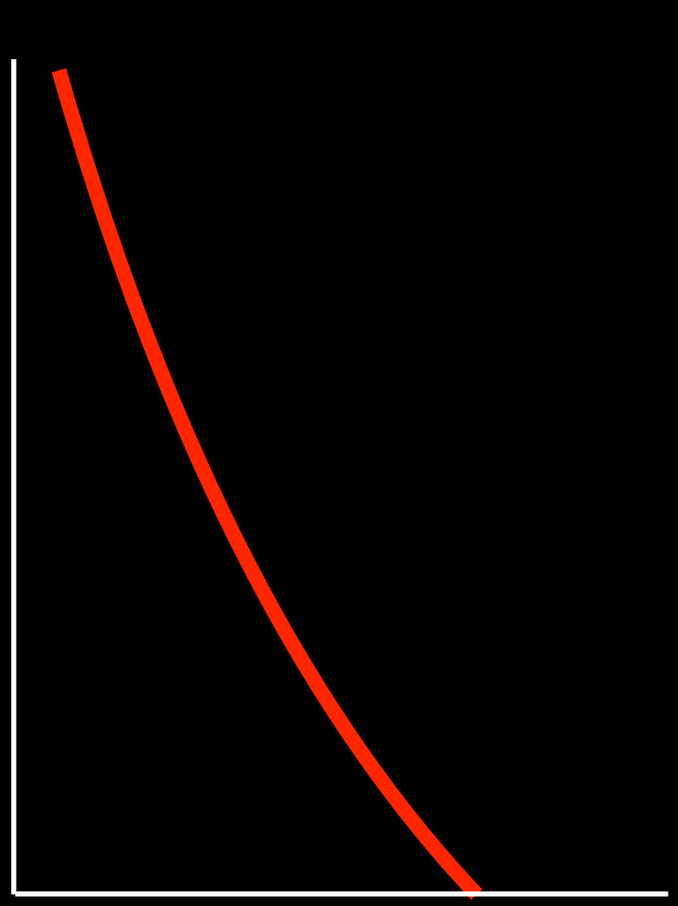
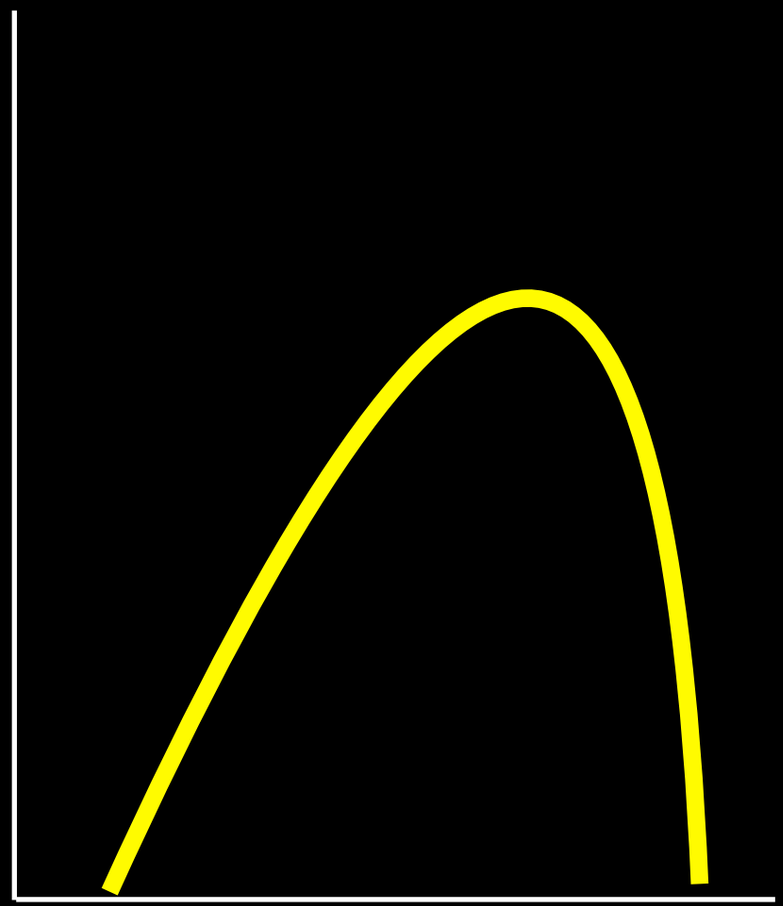
Input PDF at $Q^2 = 1$ GeV^2



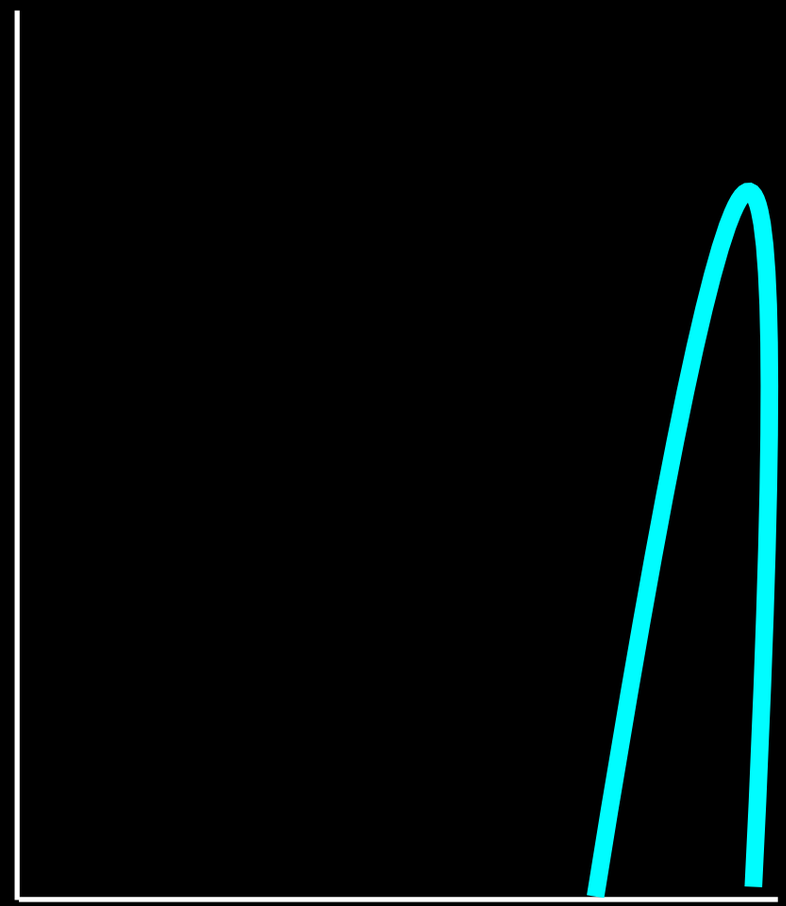
x

Sea like



x

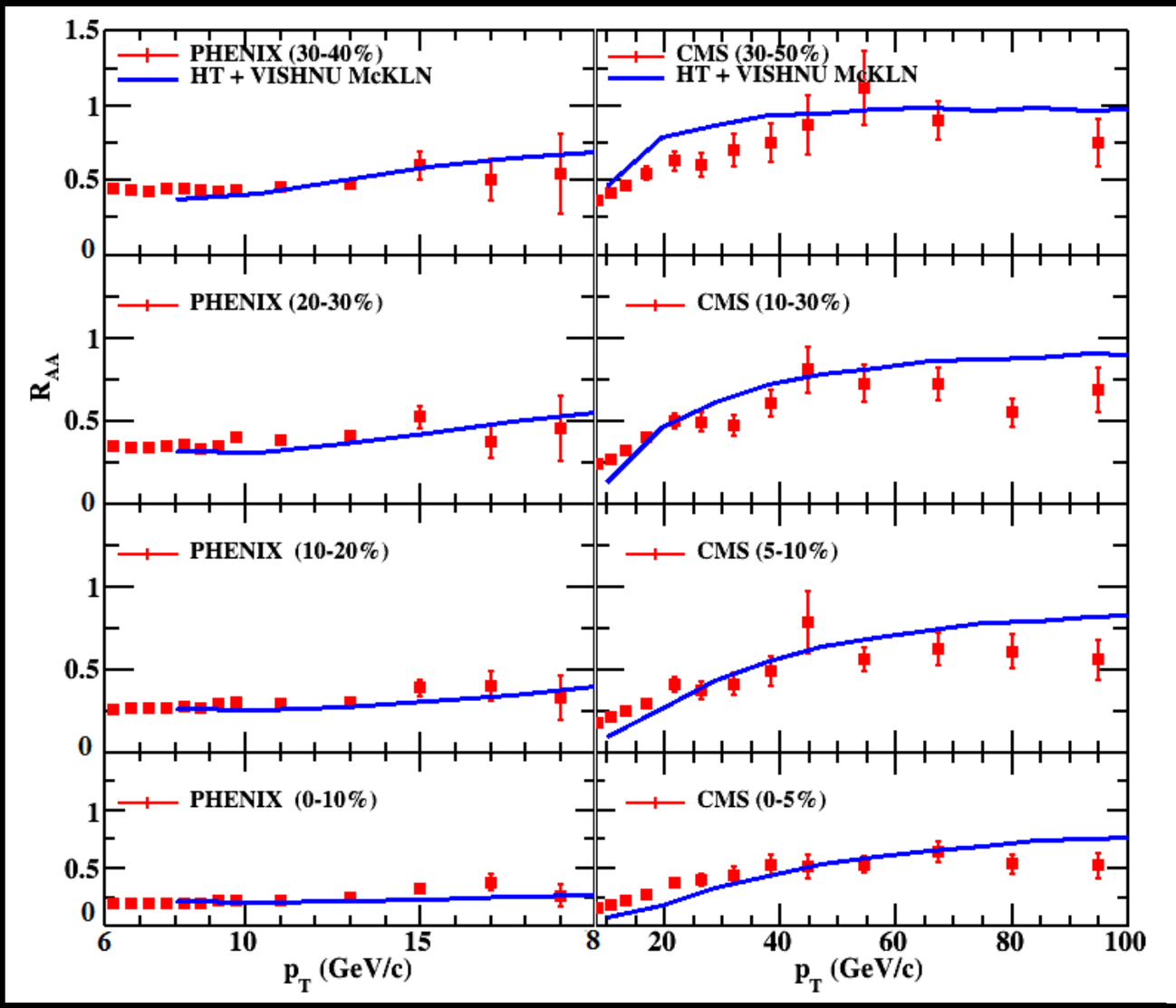
Wide Valence

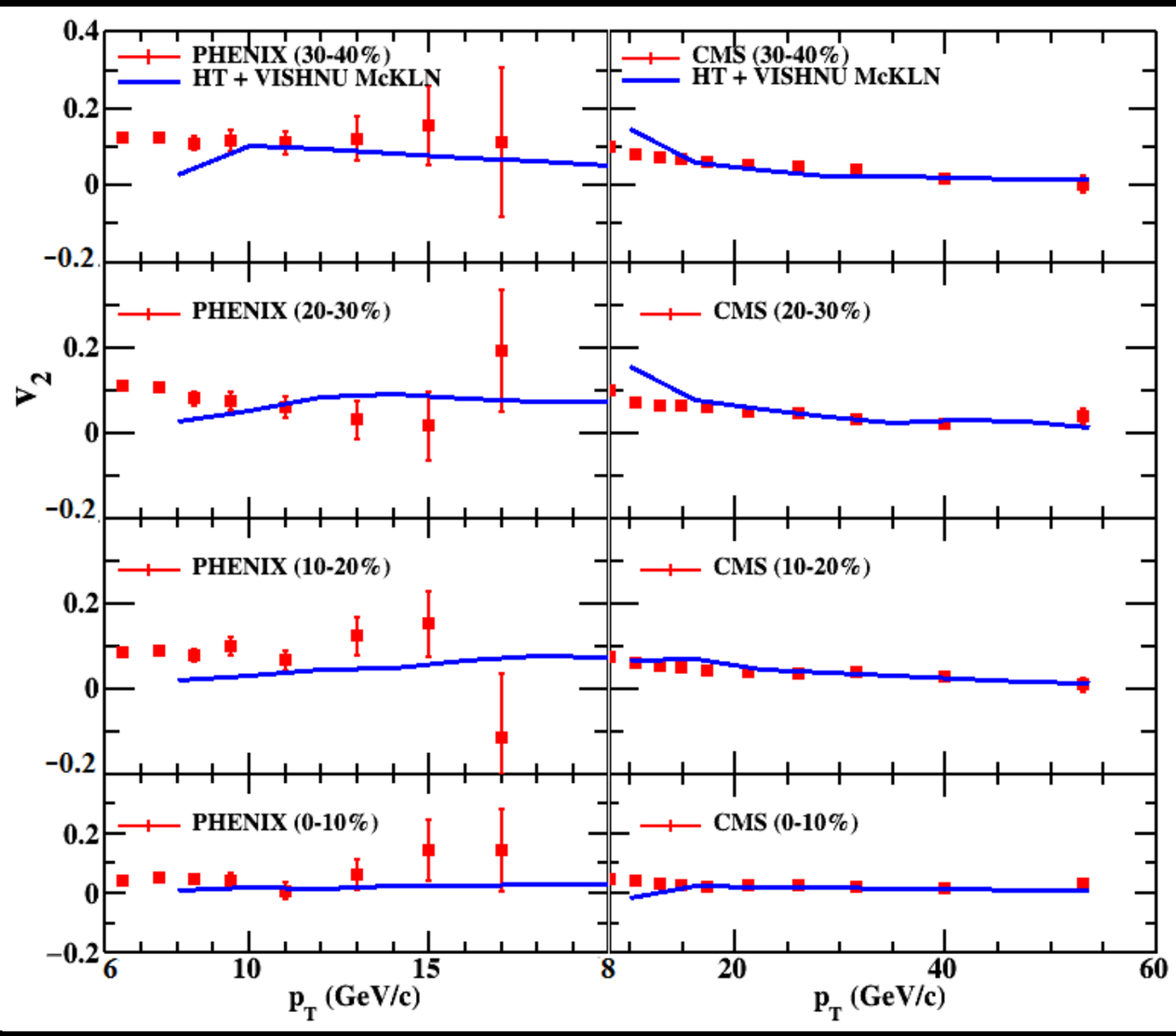


x

Narrow Valence

Putting it all together





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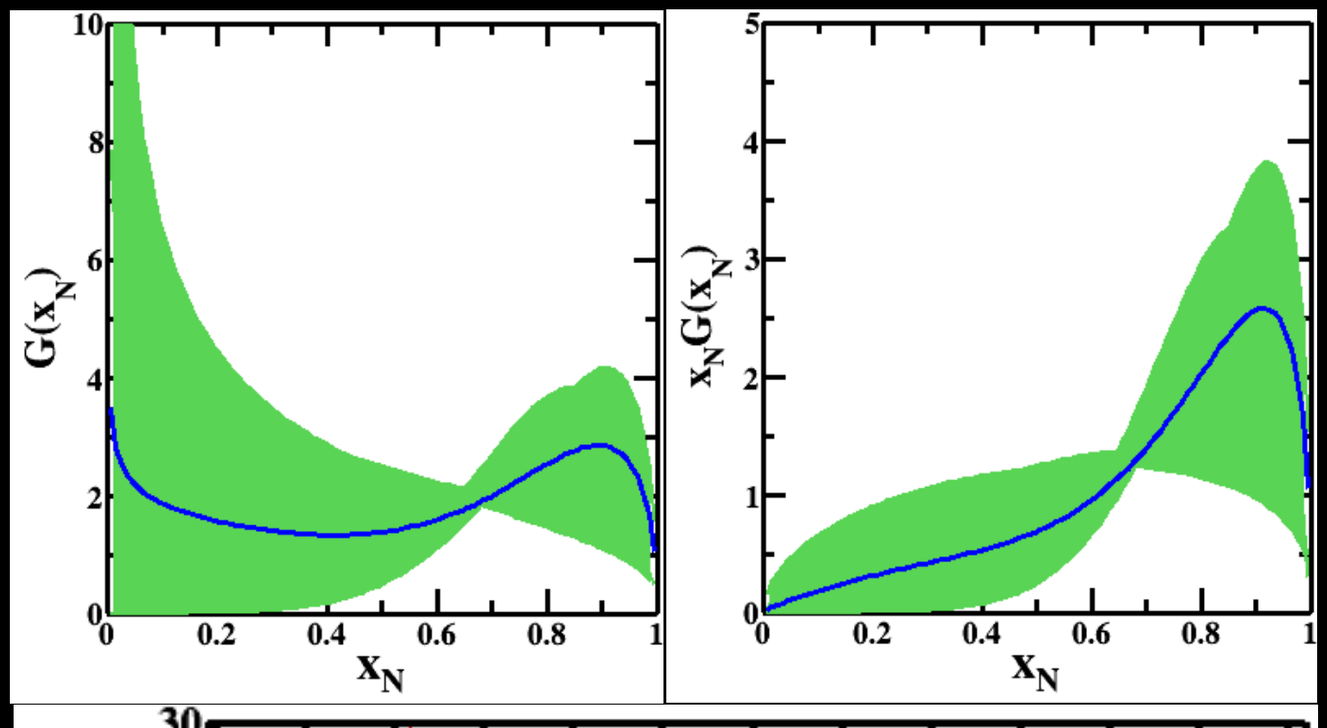
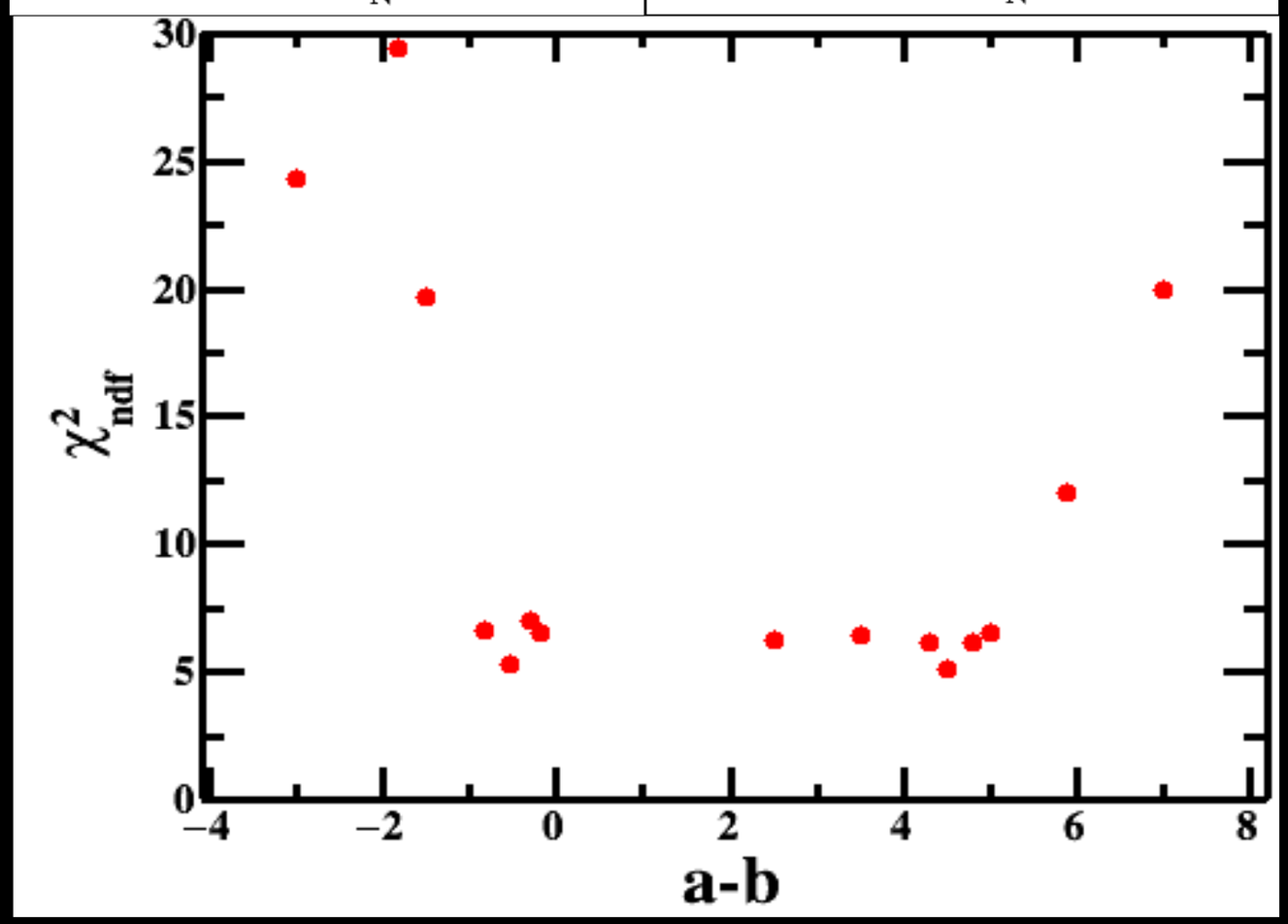




$$G(x) = Cx^a(1-x)^b$$

making b negative increases strength at x ~ 1

Seems ruled out by fits..

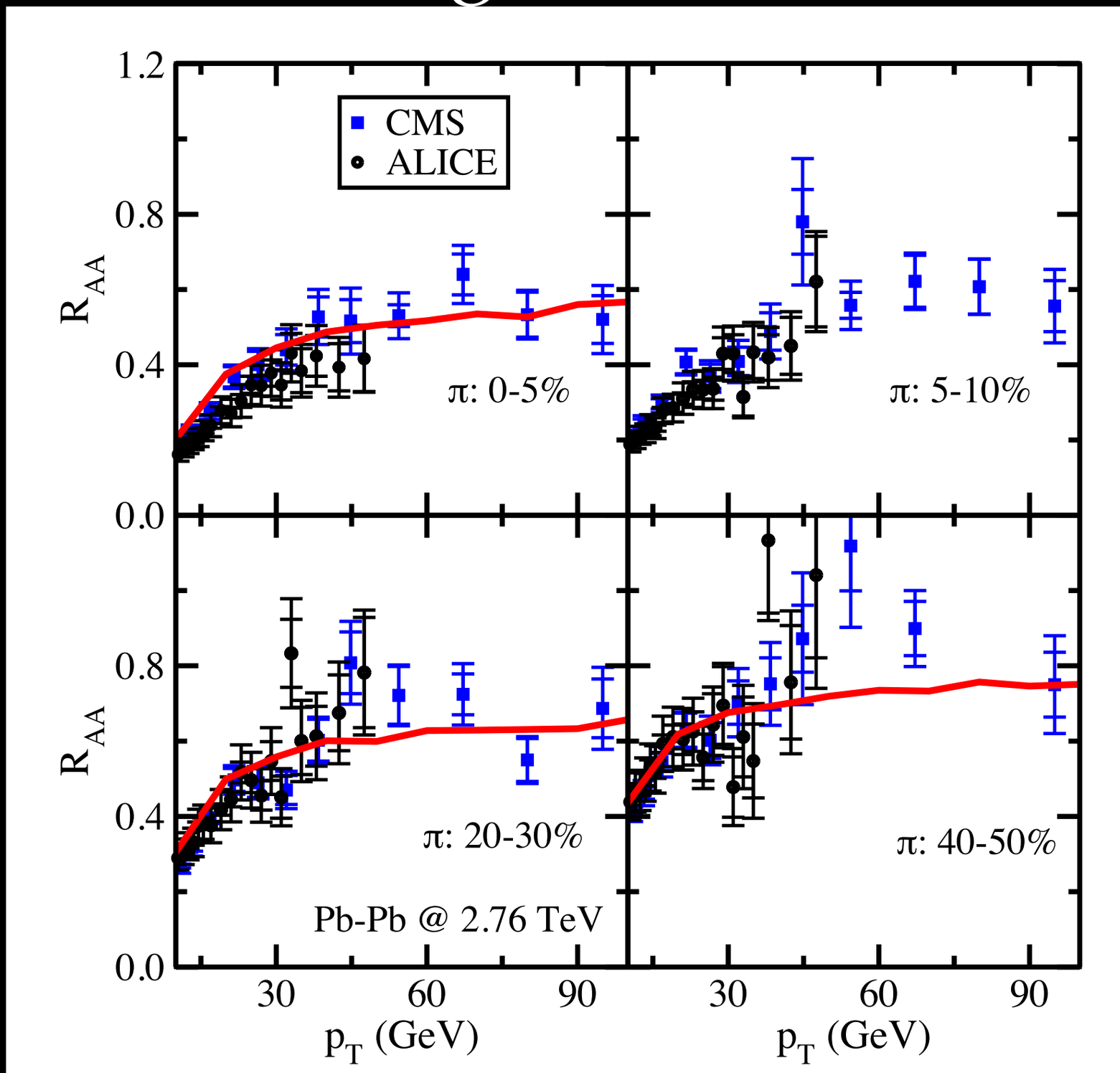
Mass of d.o.f. less than mass of nucleon.

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

Some parts are done with much greater accuracy

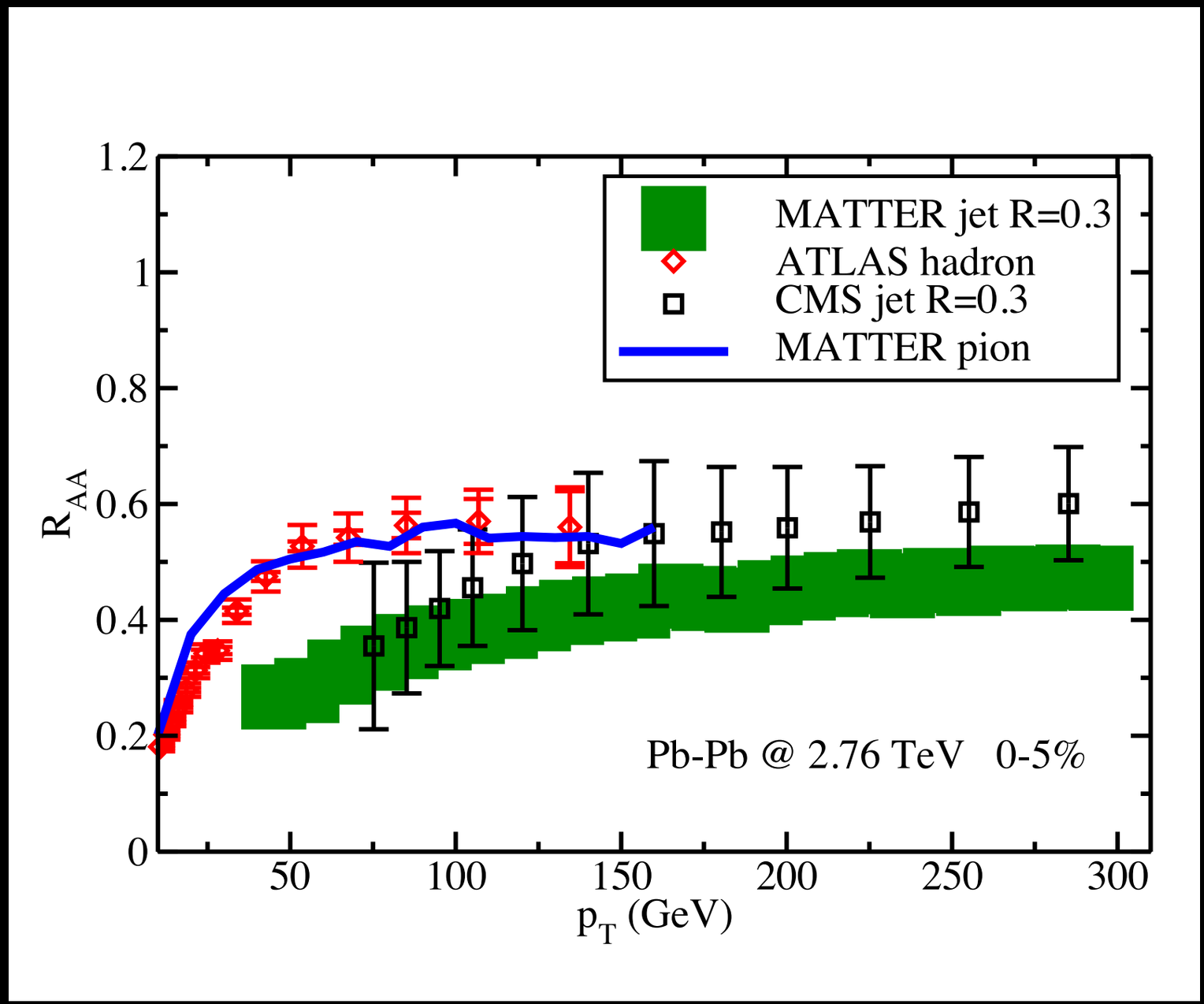
at low p_T sensitive to in-medium frag.

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

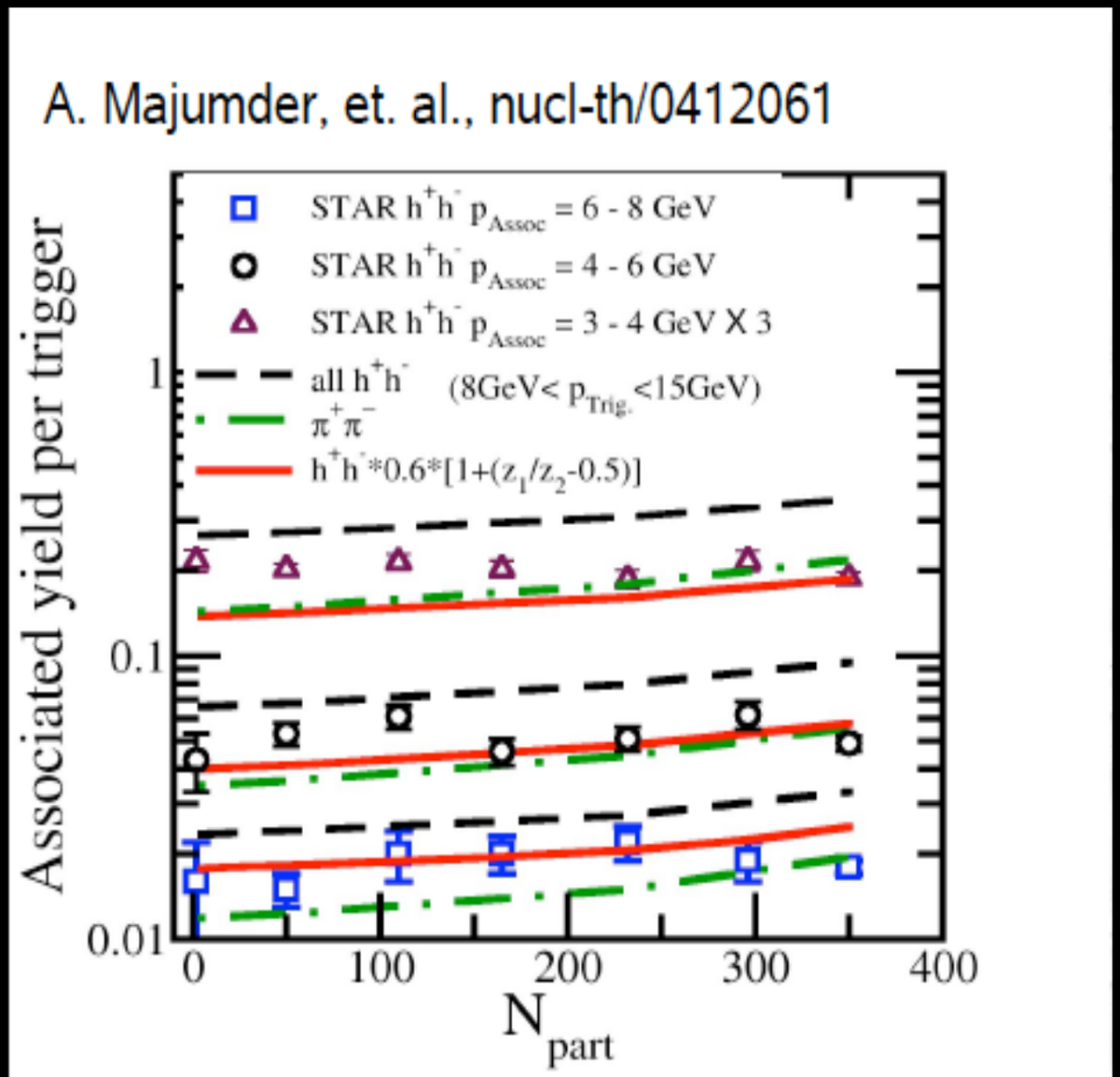


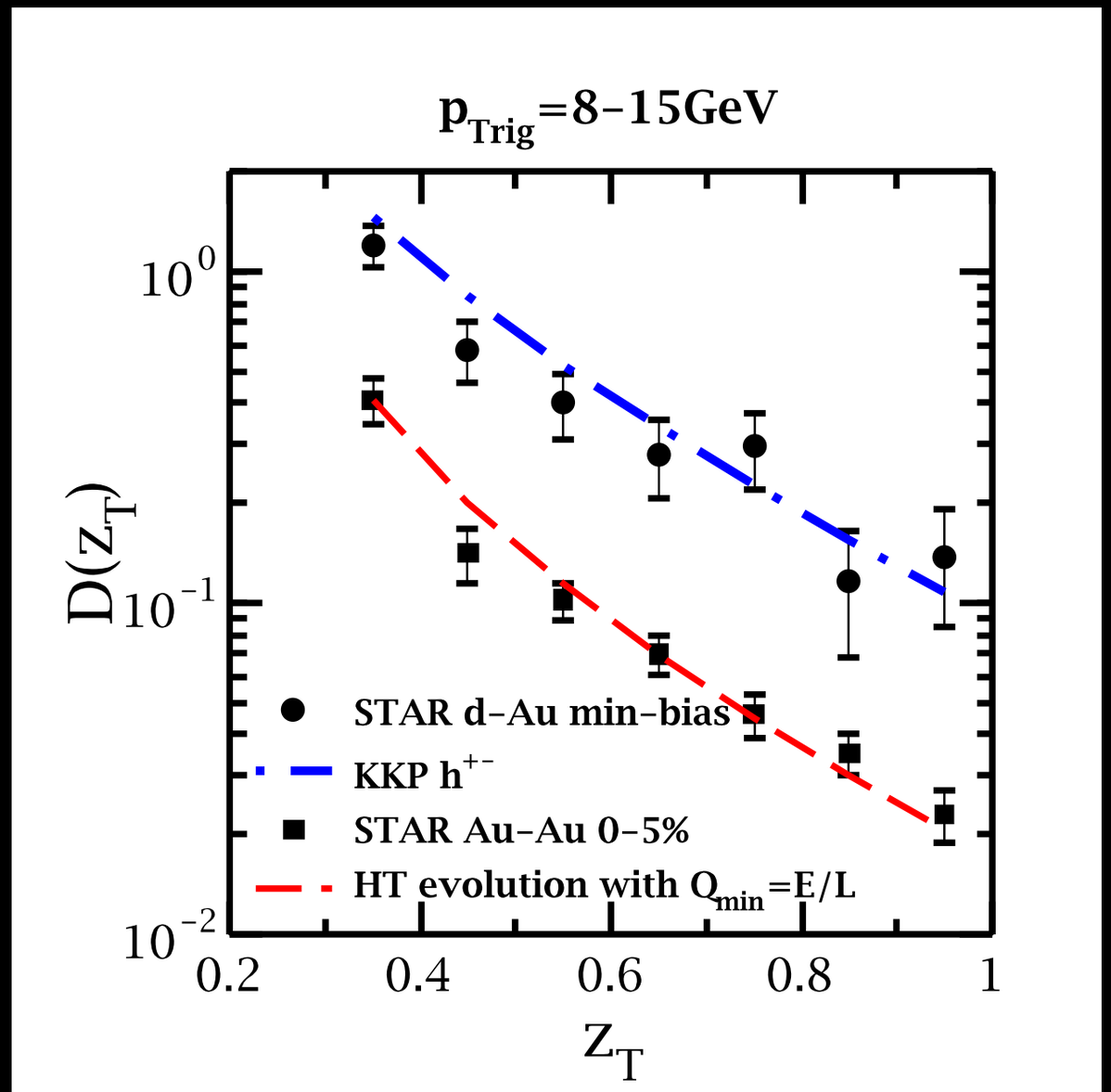
More sensitive to multiple scales for full jet

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



Near side and away side correlations

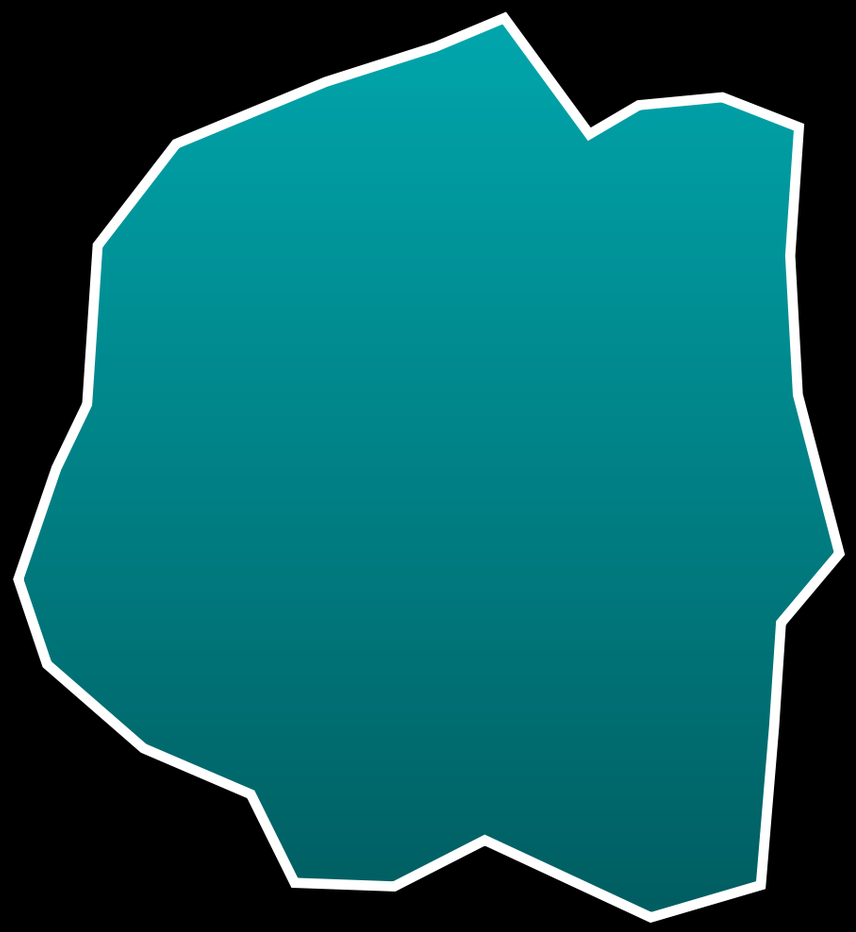




A wide range of single particle observables can be explained by a weak coupling formalism

How the jet sees the medium depends on jet scale

Extracted q^has
a lot or fluctuation
included in it.
Looks different at different
scales



l /E or x

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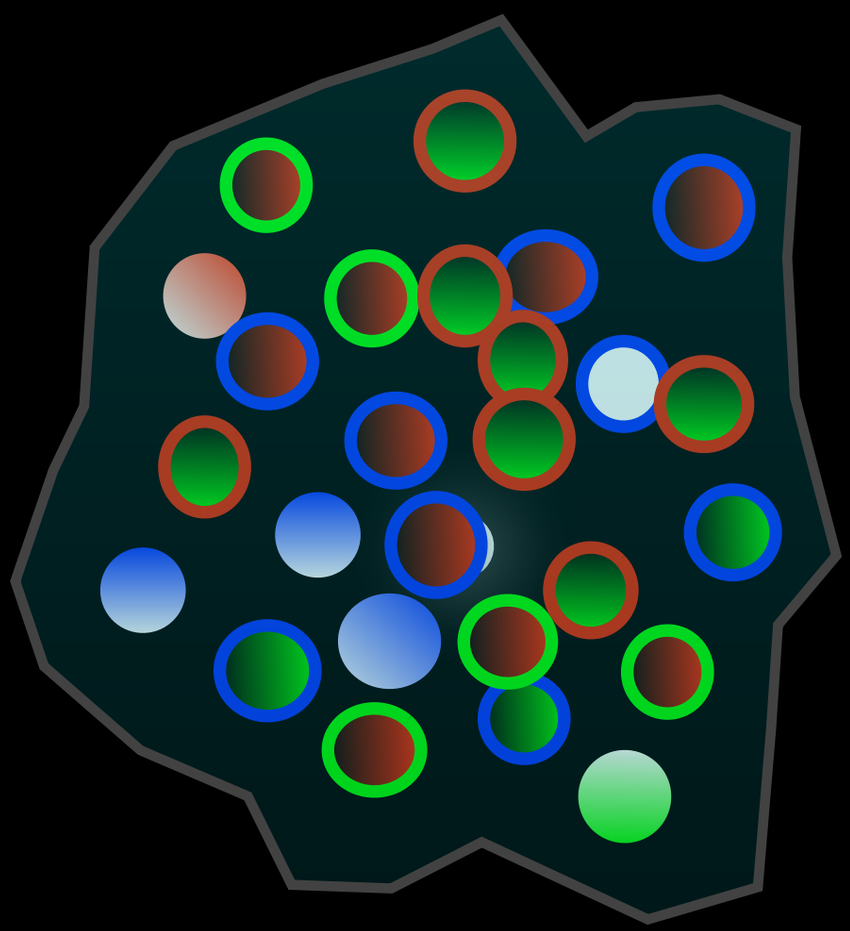
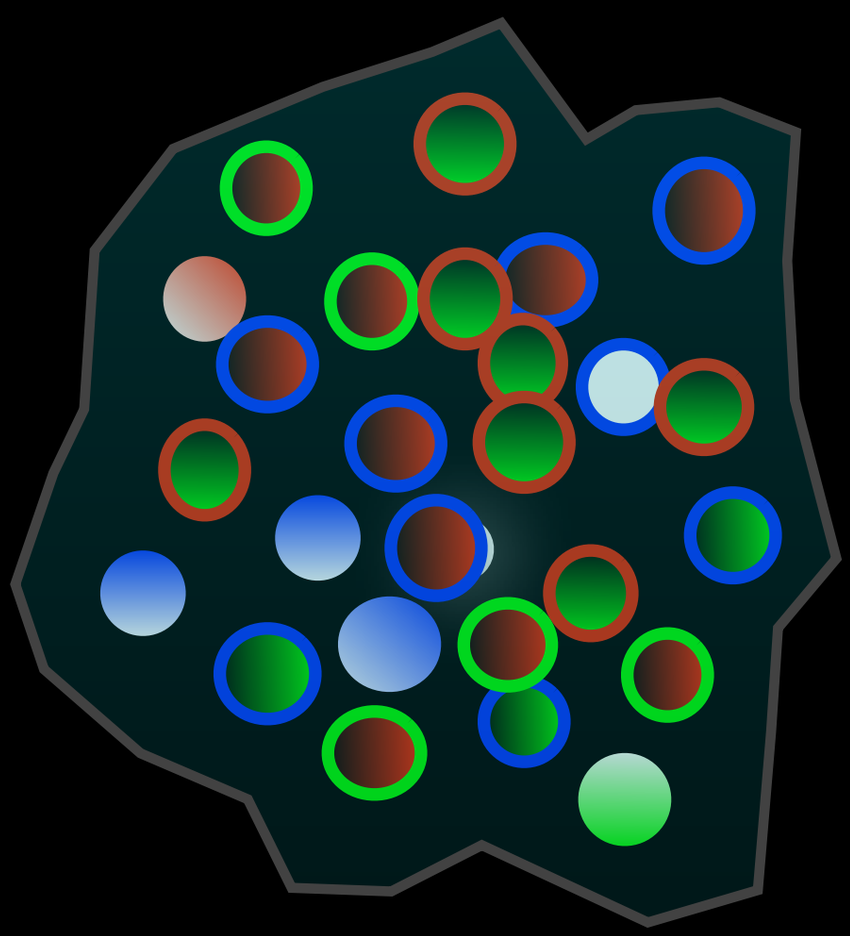
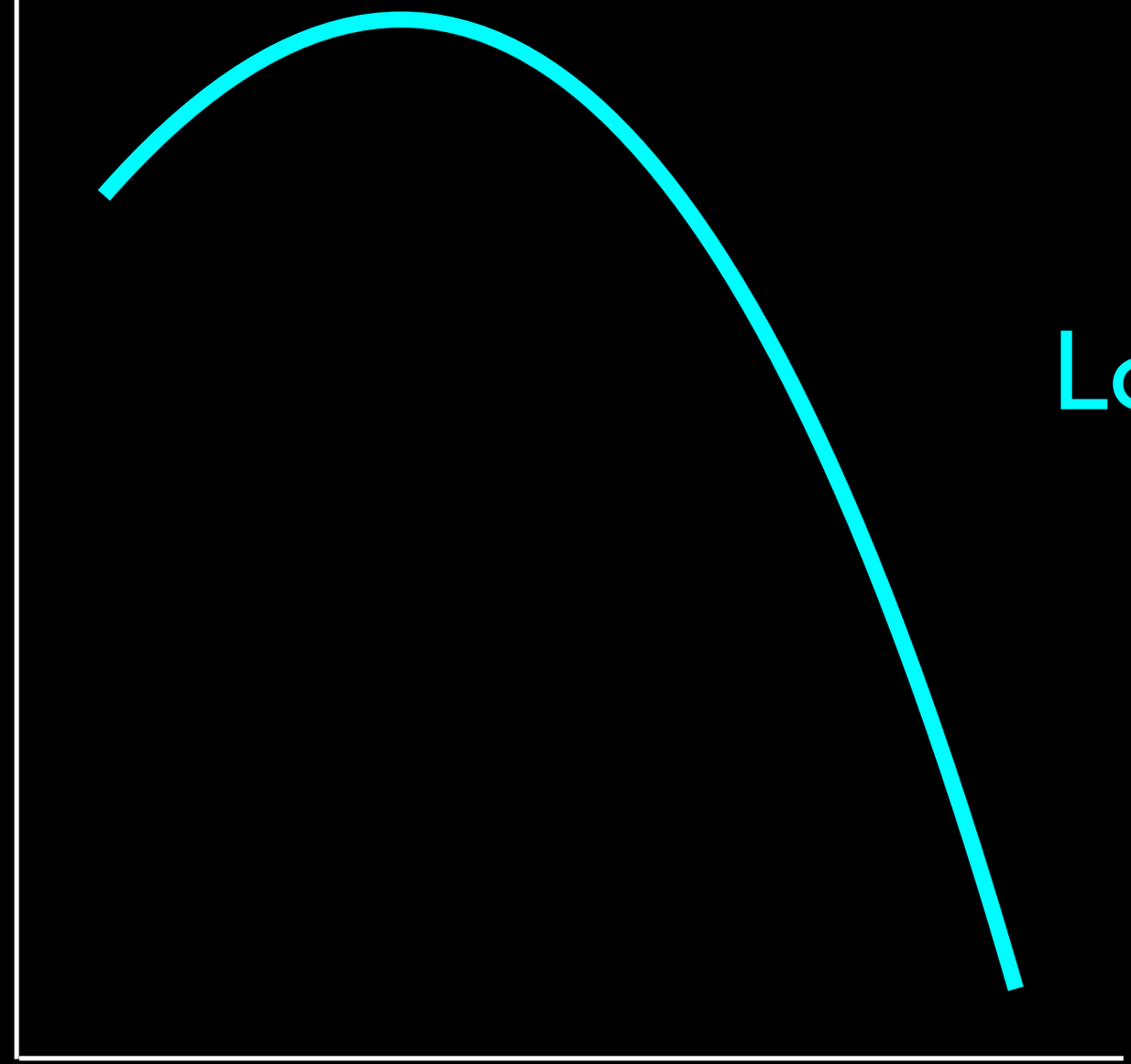


l /E or x

How the jet sees the medium depends on jet scale

Extracted q^has
a lot or fluctuation
included in it.
Looks different at different
scales





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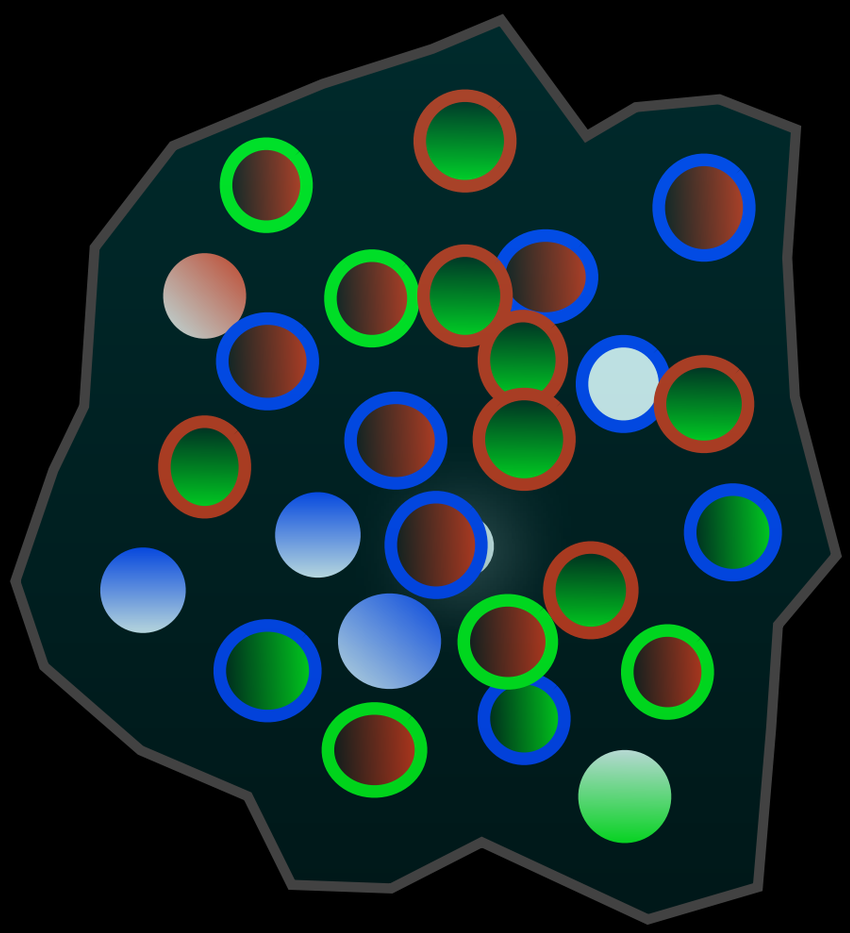

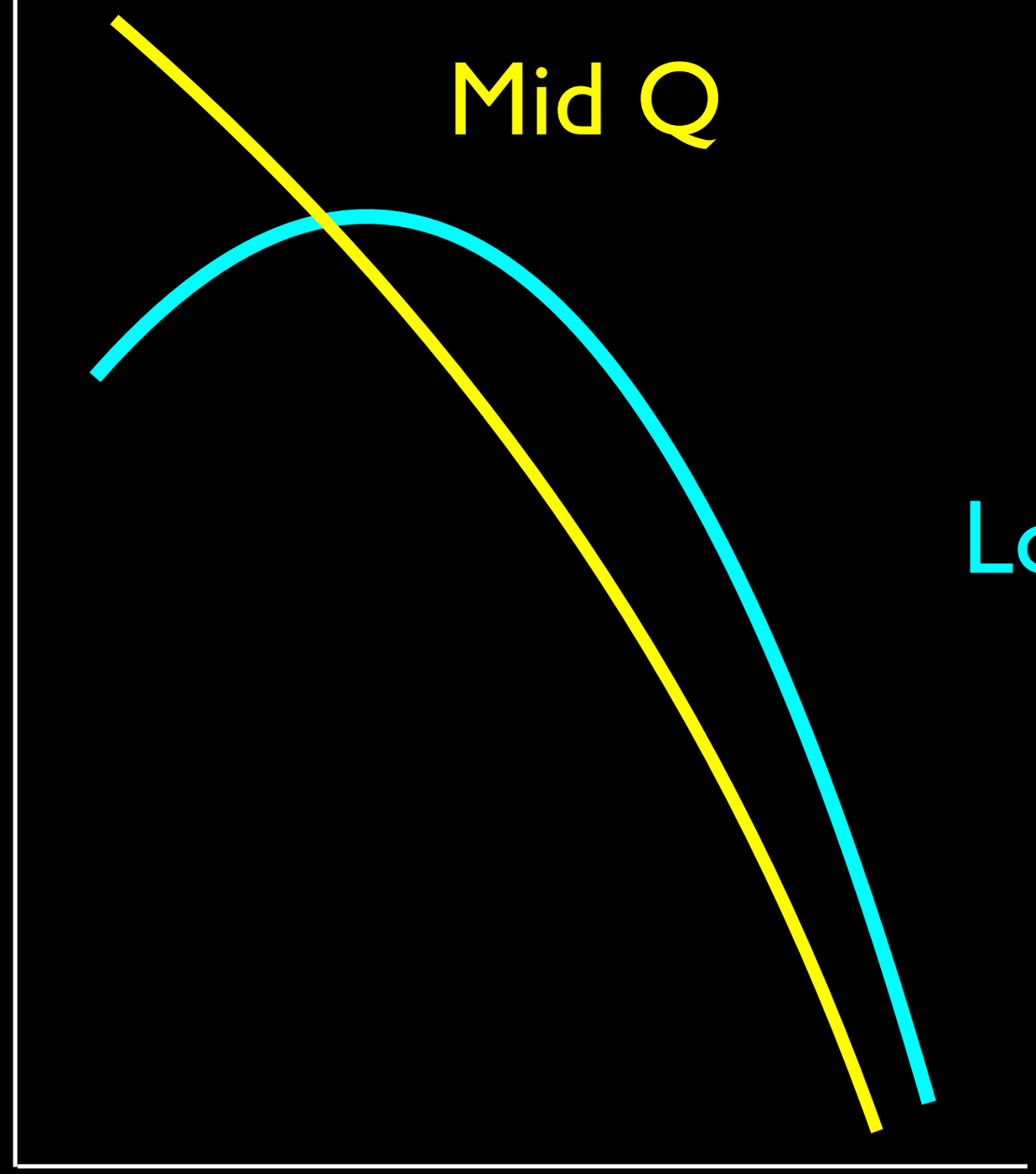

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