Jets and event generation in AA and at an EIC

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INT program on Probing Nucleons and Nuclei in High Energy Collisions, Oct-Nov 2018

Outline

- Some theory background
- Phenomenology
- Results from JETSCAPE for A-A
- What is needed for an eA generator.

Basic Setup (Vacuum)

- Factorization, Single log resummation:

$$D(z) = \delta(1-z) + \frac{\alpha_S}{2\pi} P(y) \left[\frac{1}{\epsilon} + \gamma - \log(4\pi) + \log\left(\frac{Q^2}{\mu^2}\right) \right]$$

- Evolution equation for fragmentation function

$$\frac{dD(z,Q^2)}{dQ^2} = \frac{\alpha_S}{2\pi Q^2} \int_z^1 \frac{dy}{y} P(y) D\left(\frac{z}{y}, Q^2\right)$$

- Or simulate shower by deriving a Sudakov form factor.

$$S(Q^2, \mu_0^2) = e^{-\int_{\mu_0^2}^{Q^2} \frac{d\mu^2}{\mu^2} \frac{\alpha_S(\mu^2)}{2\pi} \int_{\mu_0^2/\mu^2}^{1-\mu_0^2/\mu^2} dy \hat{P}(y)}$$

Basic setup: concept of distance

- In a pure vacuum calculation, knowing the location of a split is not important
- Becomes very important in a medium
- Need a mechanism of generating locations of splits even in a vacuum simulation.
- Simulated: MATTER simulator

Uncertainty analysis

In light-cone components, the wavefunction is

$$\psi(q)e^{iq^- y^+} e^{iq^+ y^-} e^{-iq_\perp y_\perp}$$

one needs to keep track of y^-

in probability of parton, phase from amplitude and c.c.

$$[e^{iq^- y^+} e^{iq^+ y^-} e^{-iq_\perp y_\perp}][e^{-iq'^- y'^+} e^{-iq'^+ y'^-} e^{ik'_\perp y'_\perp}]$$

focussing only on q+

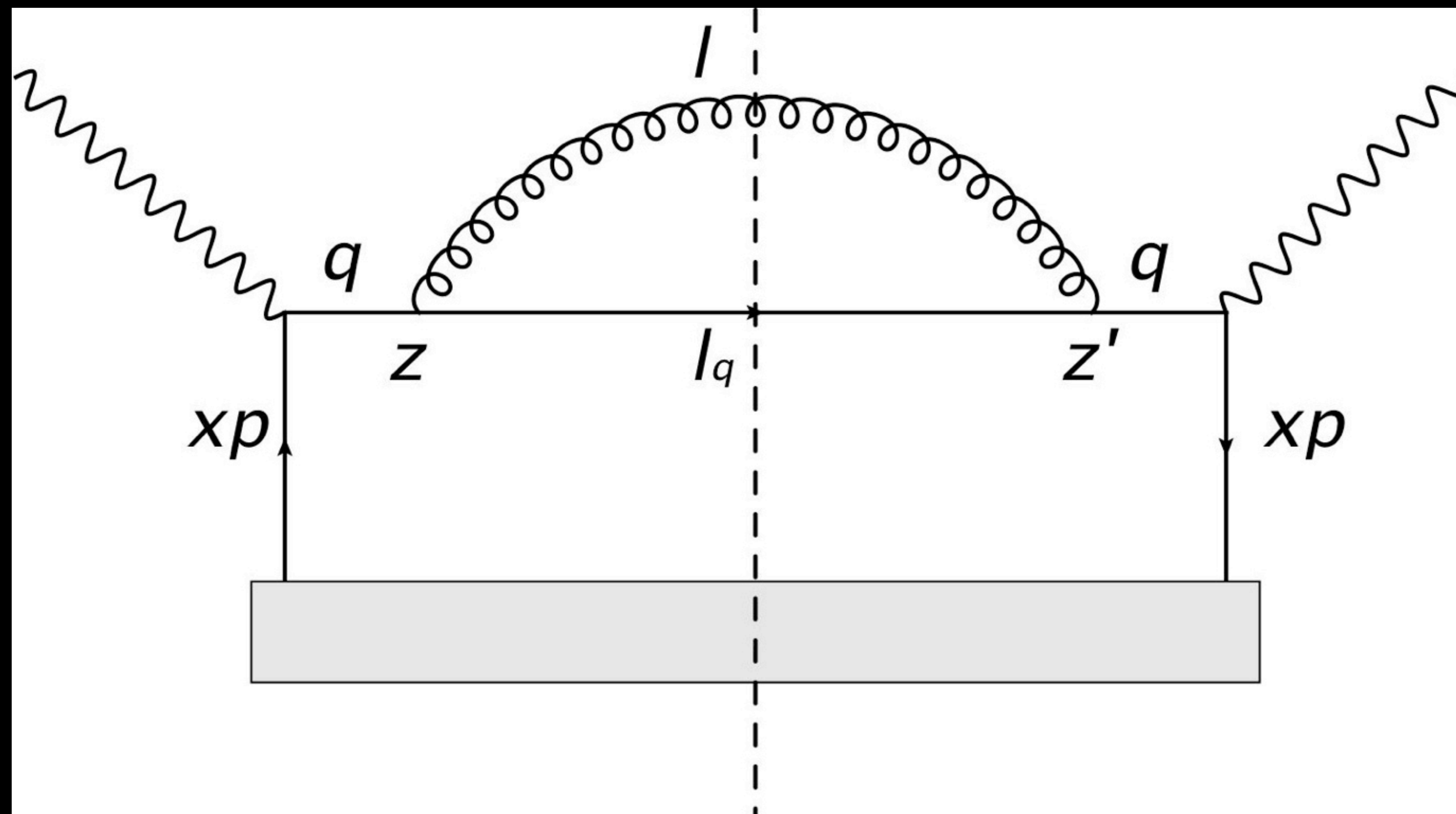
$$e^{i\bar{q}^+ \delta y^-} e^{i\delta q^+ \bar{y}^-}$$

(-)direction

Use hard emissions to denote the parton's length travelled

Consider one emission and q⁺

$$\bar{z} = \frac{z + z'}{2}$$



$$\delta z = z - z'$$

what is the role of z and z′ ?

$$\int_0^{\infty} d^4\bar{z}\,\exp\left[i(\delta q)\bar{z}\right]$$

$$\int d^4\delta z\,\exp\left[i\delta z(l + l_q - q)\right]$$

δq is the uncertainty in q,

How much uncertainty can there be ?

To be sensible: $\delta q \ll q$

we assume a Gaussian distribution around q^+

And try different functional forms of the width

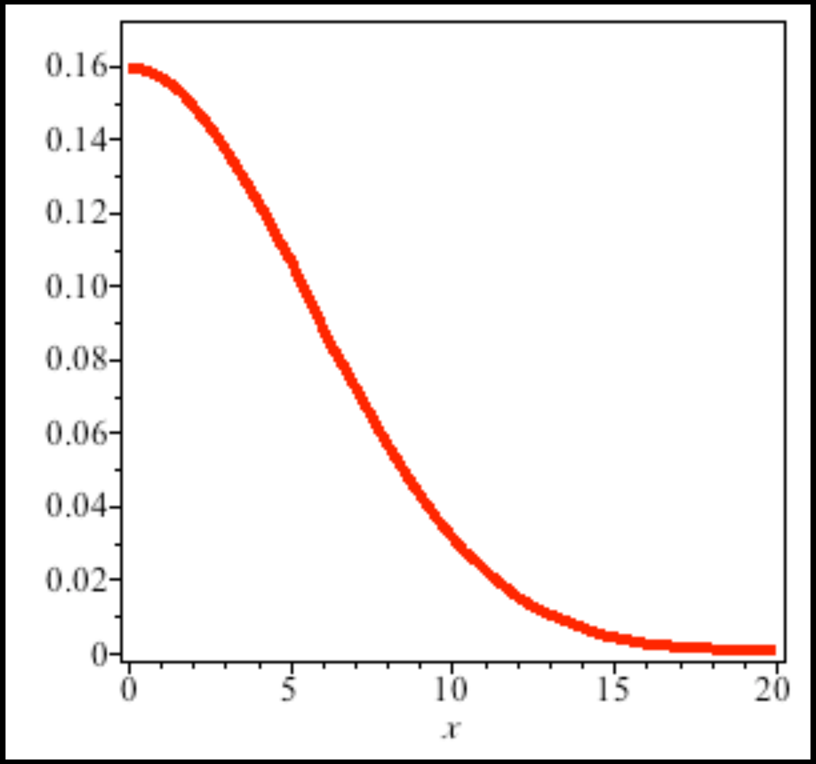
We set the form by insisting $\langle \tau \rangle = 2q^- / (Q^2)$

to obtain the z^- distribution only need to assume a δq^+ distribution

$$\rho(\delta q^+) = \frac{e^{-\frac{(\delta q^+)^2}{2[2(q^+)^2/\pi]}}}{\sqrt{2\pi[2(q^+)^2/\pi]}}$$

A normalized Gaussian with a variance $2q^+/\pi$

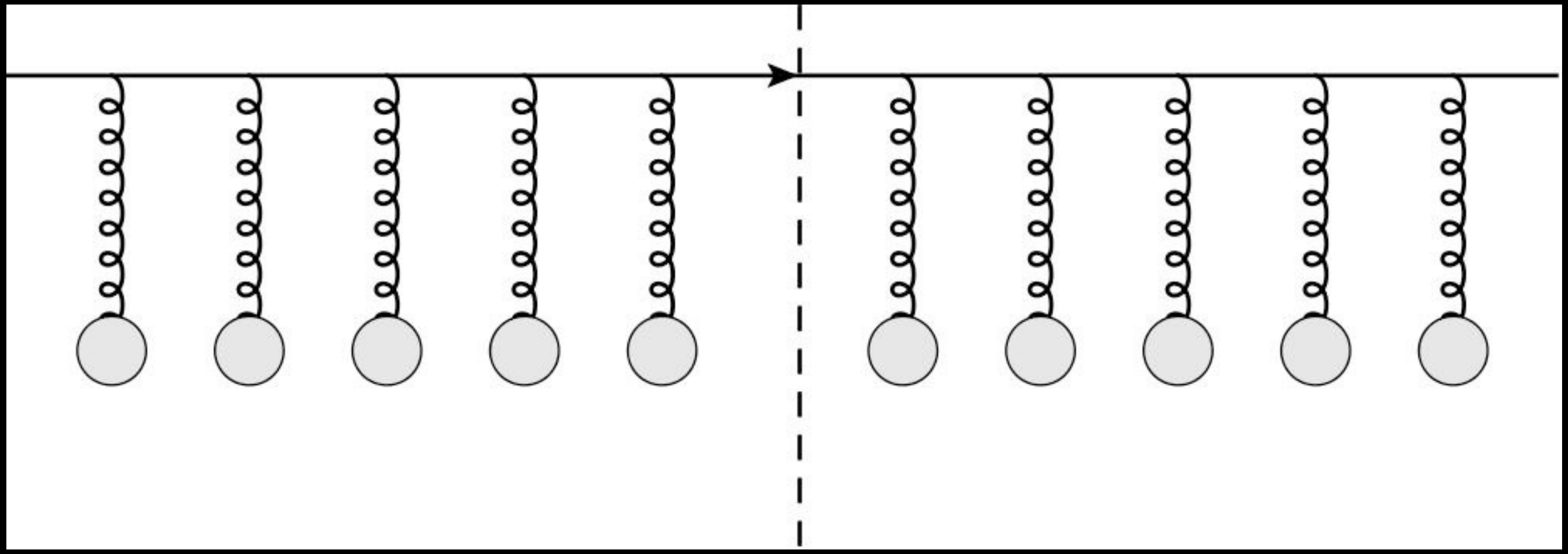
FT gives the following distribution in distance



Scales of a hard parton in a medium

A parton in a jet shower, has momentum components

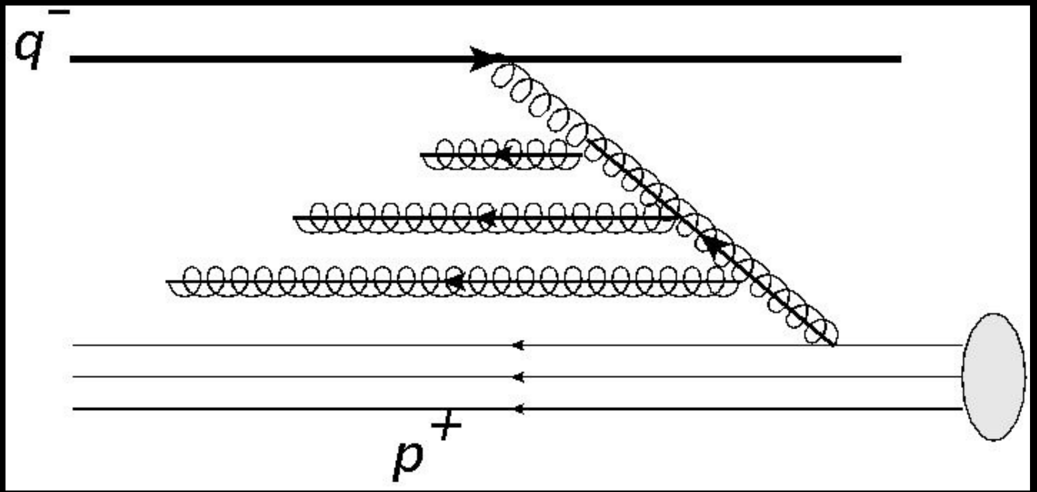
$q = (q^-, q^+, q_T) = (1, \lambda^2, \lambda)Q$, Q: Hard scale, $\lambda \ll 1$, $\lambda Q \gg \Lambda_{QCD}$



hence, gluons have

$$k_\perp \sim \lambda Q, \qquad k^+ \sim \lambda^2 Q$$

Called Glauber gluons

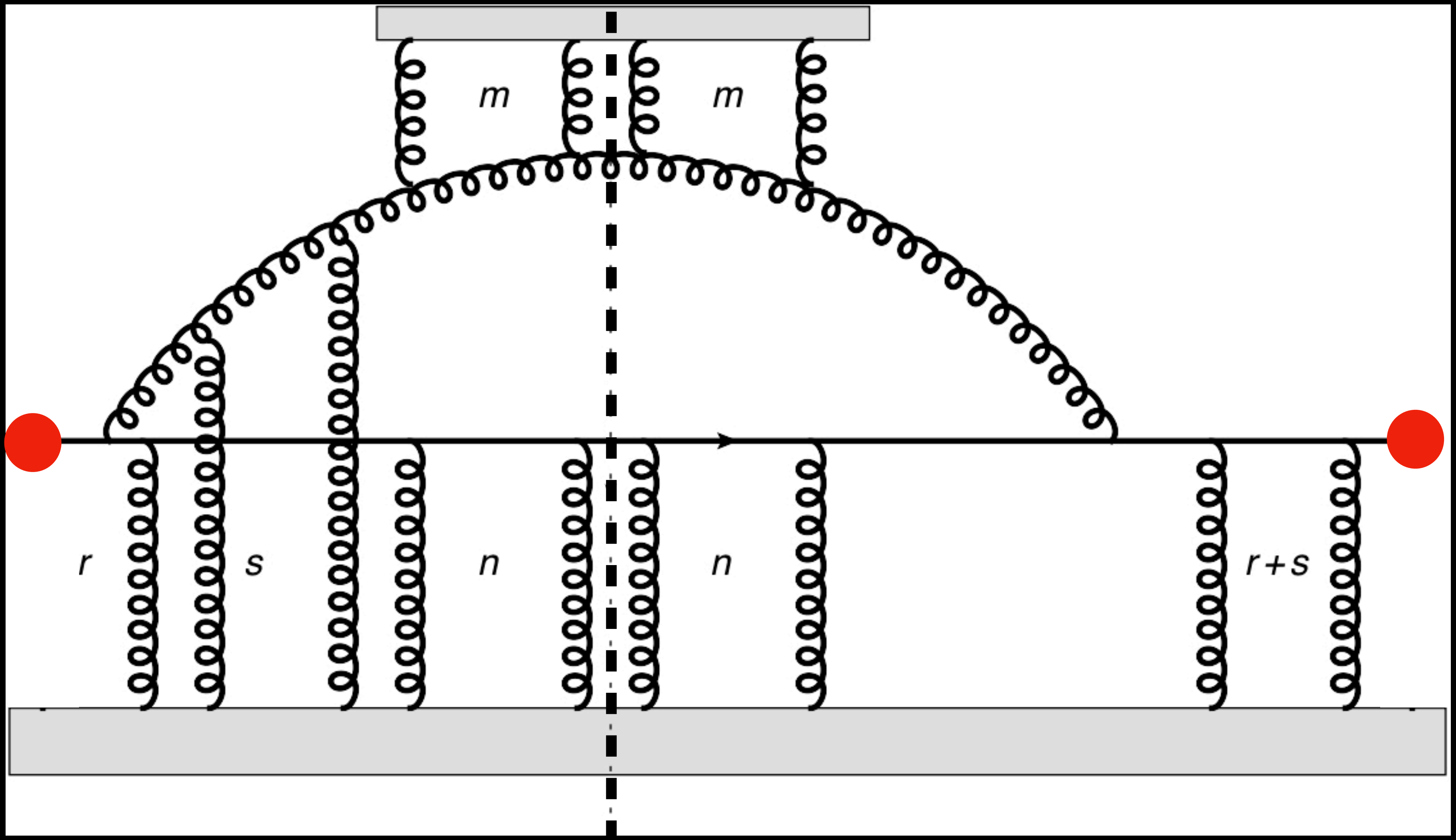


At large virtuality

The transverse momentum is resolved at the scale $Q^2 >> \hat{q}\ \tau$
Rare hard scatterings.

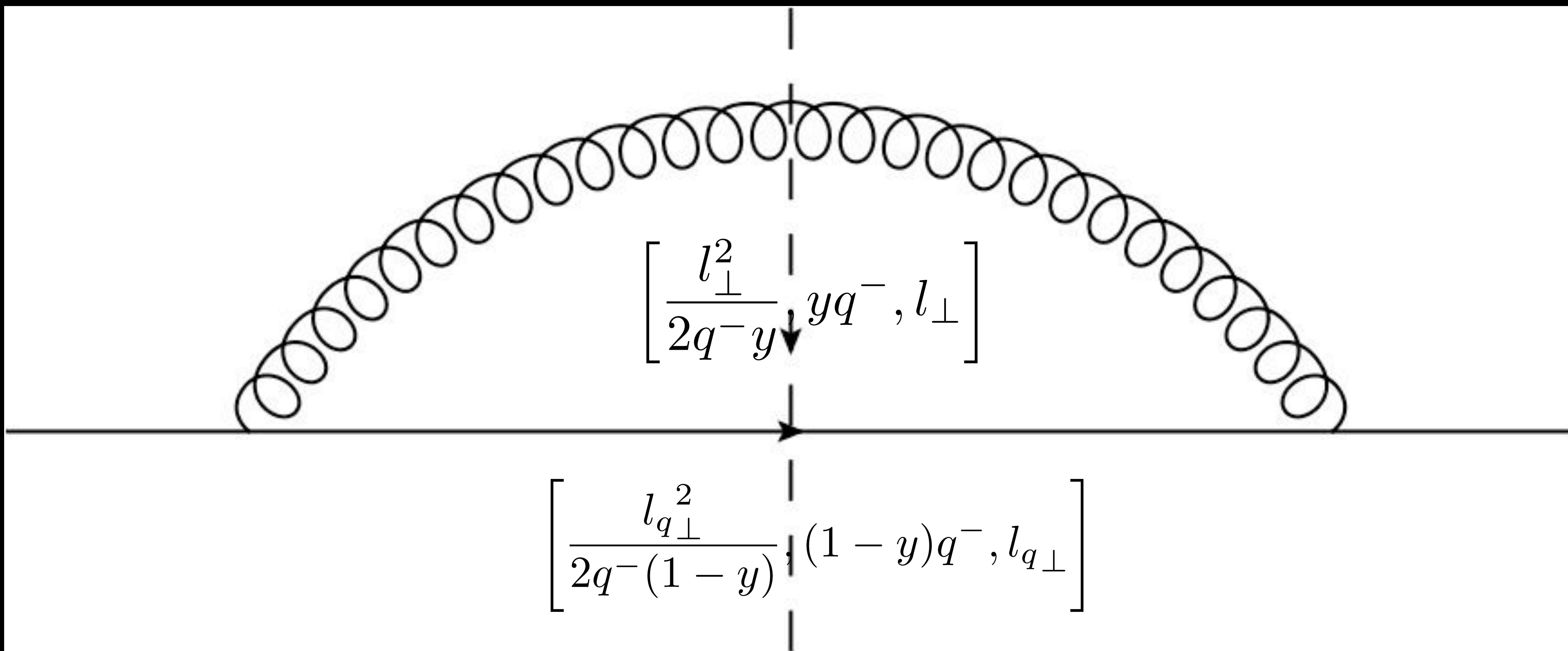
$$Q^2 \sim l_\perp^2 \sim k_\perp^2$$

$$l_\perp^2 \gg \langle k_\perp^2 \rangle \sim \hat{q}\tau$$



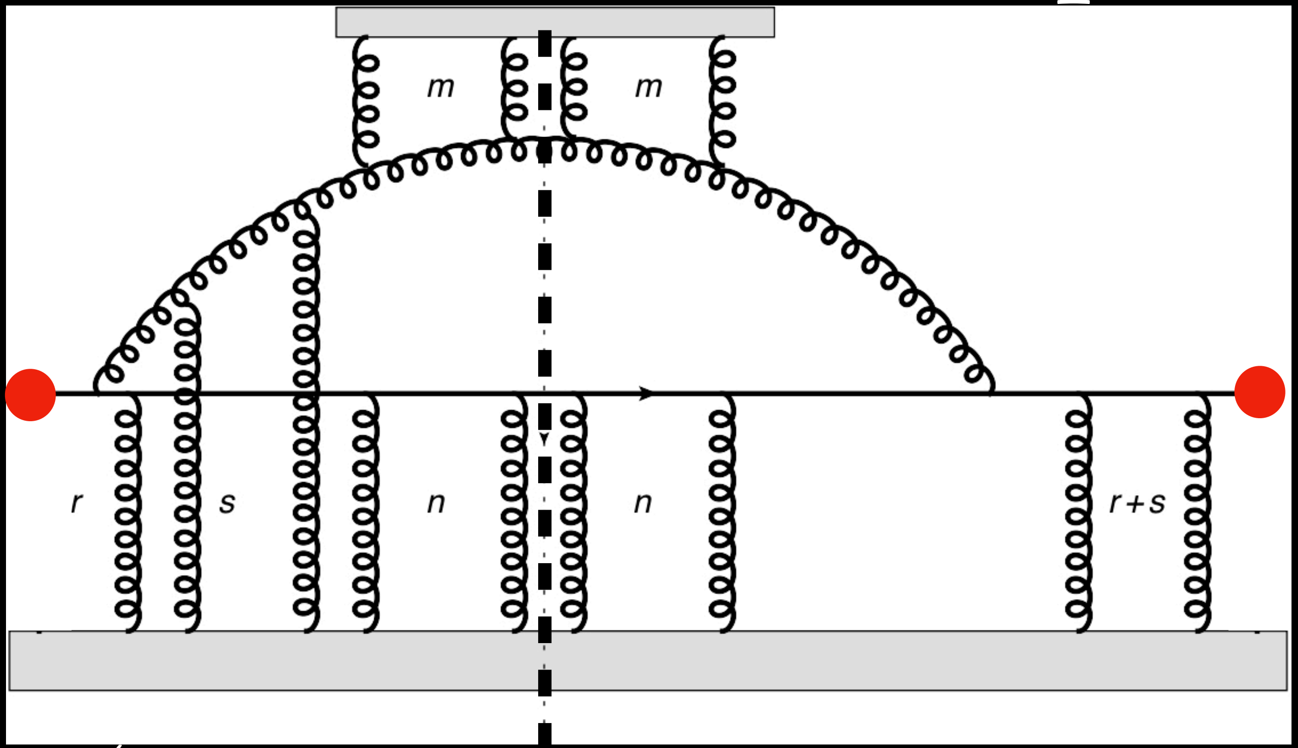
A.M. Phys.Rev. D85 (2012) 014023

Case of no scattering



$$\sim \frac{\alpha_s C_F}{2\pi} \int dy d^2 l_\perp d^2 l_{q_\perp} P(y) \frac{l_\perp \cdot l_\perp}{l_\perp^2 l_\perp^2} \delta^2(l_\perp + l_{q_\perp})$$

One emission from multiple scattering



$$\int dl_\perp dl_{q\perp} dy \text{ C.F. } \delta^2 \left(q_\perp + l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{j=1}^{r} p_\perp^j - \sum_{l=1}^{m} k_\perp^l - \sum_{k=1}^{n} p_\perp^k \right)$$

$$\frac{l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l}{\left(l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l\right)^2} \cdot \frac{l_\perp - y\sum_{i=1}^{r+s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l}{\left(l_\perp - y\sum_{i=1}^{s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l\right)^2}$$

$$\prod_{i=1}^{N} \int dy_i^- \frac{\int d^3\delta y_i \rho \langle p| A^+(y_i^- + \delta y_i^-, 0) A^+(y_i^-, -\delta y_\perp^i)|p\rangle}{2p^+(N_c^2-1)} e^{ik_\perp^i \delta y_\perp^i}$$

$$\left[\theta(\zeta_I^- - y_E^-)\left\{e^{-ip^+x_L y_E^-} - e^{-ip^+x_L\zeta_I^-}\right\} - \theta(\zeta_I^- - y_I^-)e^{-ip^+x_L y_I^-} - \theta(y_I^- - \zeta_I^-)e^{-ip^+x_L\zeta_I^-}\right]$$

$$\left[\theta(\zeta_C^- - y_0^-)\left\{e^{ip^+x_L y_0^-} - e^{ip^+x_L\zeta_C^-}\right\} - \theta(\zeta_C^- - y_C^-)e^{ip^+x_L y_C^-} - \theta(y_C^- - \zeta_C^-)e^{ip^+x_L\zeta_C^-}\right] \quad \ldots$$

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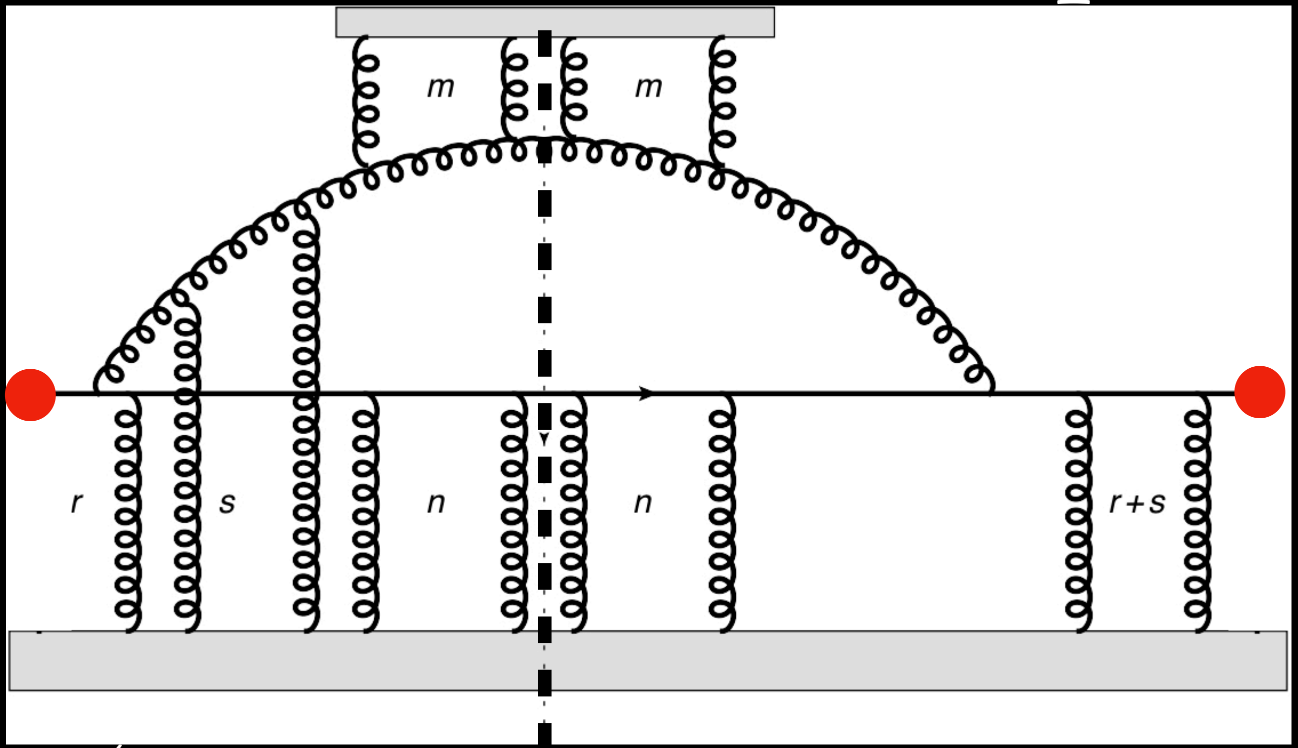

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$$\frac{l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l}{\left(l_\perp - \sum_{i=1}^{s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l\right)^2} \cdot \frac{l_\perp - y\sum_{i=1}^{r+s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l}{\left(l_\perp - y\sum_{i=1}^{s} k_\perp^i - \sum_{l=1}^{m} k_\perp^l\right)^2}$$

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if $l_T \gg \langle k_T \rangle$, can expand in ratio

$$\frac{1}{l_\perp^2} - \frac{(1-y+y^2)\left(\sum_{i=1}^{s} k_\perp^i\right)^2}{l_\perp^4} - \frac{\left(\sum_{i=1}^{m} k_\perp^i\right)^2}{l_\perp^4} + 2(1+y^2)\frac{\left(l_\perp\cdot\sum_{i=1}^{s} k_\perp^i\right)^2}{l_\perp^6} + 4\frac{\left(l_\perp\cdot\sum_{i=1}^{m} k_\perp^i\right)^2}{l_\perp^6}.$$

$$\left[\theta(\zeta_I^- - y_E^-)\left\{e^{-ip^+x_L y_E^-} - e^{-ip^+x_L\zeta_I^-}\right\} - \theta(\zeta_I^- - y_I^-)e^{-ip^+x_L y_I^-} - \theta(y_I^- - \zeta_I^-)e^{-ip^+x_L\zeta_I^-}\right]$$
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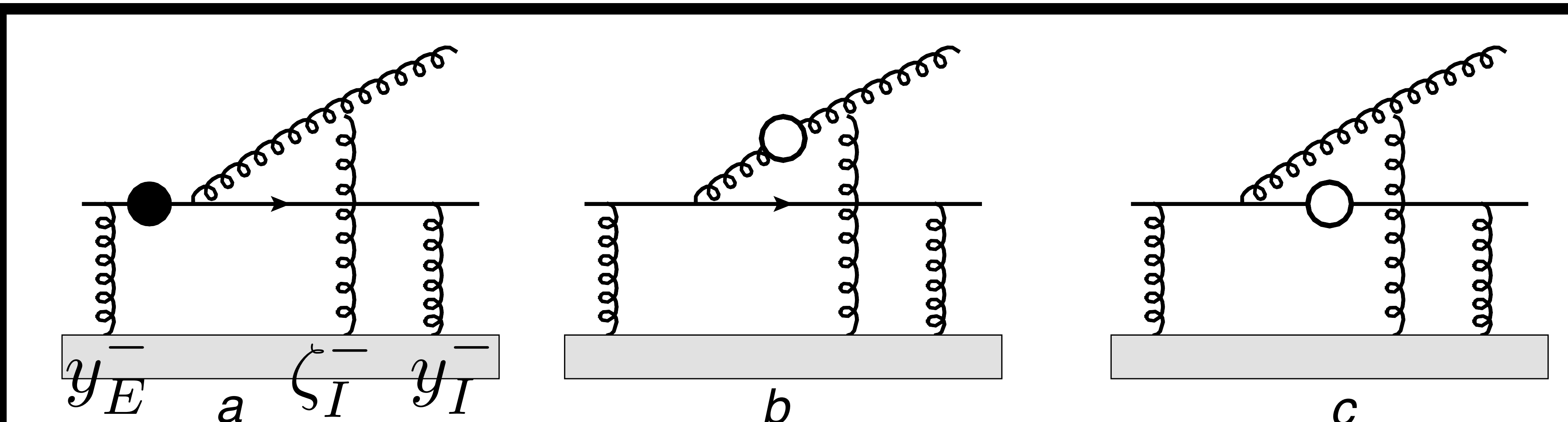
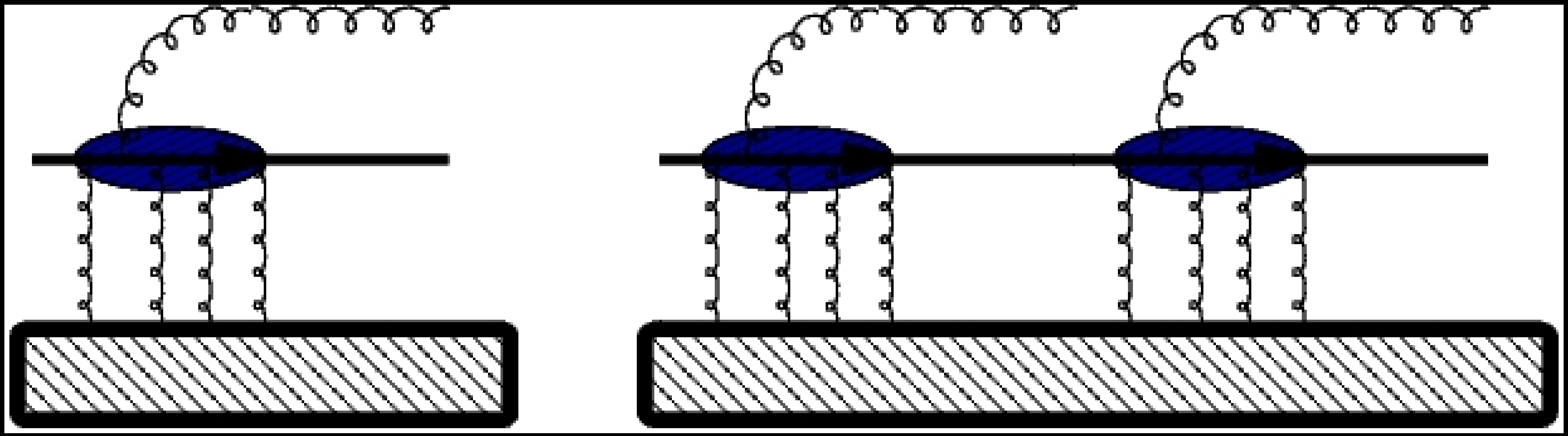


This is what we mean by vacuum medium interference

Can show that this reduces to the case of single scattering induced single emission as in Wang and Guo Nucl.Phys. A696 (2001) 788-832.

This needs to be repeated as long as $Q >> \hat{q}L$



- Usual assumption, multiple emissions are independent!
- The reason for this depends on your approximation scheme
- At next to leading twist, vacuum ordering prevails.

Resum with DGLAP

Per radiation, with or without scattering

$$\frac{\alpha_S}{2\pi}\int\frac{dl_\perp^2}{l_\perp^2}\int dyP(y)\left[1+\int_0^{\tau_f}d\zeta\frac{\hat{q}}{l_\perp^2}\left(PhaseFactors\right)\right]$$

No divergence, yields finite term

$$\tau_f = \frac{2Ey(1-y)}{l_\perp^2}$$

Resum into Fragmentation function

$$\frac{\alpha_S}{2\pi}\int dyP(y)\left[\frac{1}{\epsilon}+\gamma-\log(4\pi)+\log\left(\frac{Q^2}{\mu^2}\right)+\hat{q}\#\right]$$

Or, simulate with Sudakov.

As virtuality comes down

- High energy partons with virtuality $Q = \hat{q}\,\tau$
- Partons with virtuality $\mu^2 = \lambda^2 Q^2$ have lifetime $1/(\lambda^2 Q)$
- Over this long lifetime, the parton "can" endure several scatterings
- BDMPS regime
- need a rate equation
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- Modeled: LBT, MARTINI

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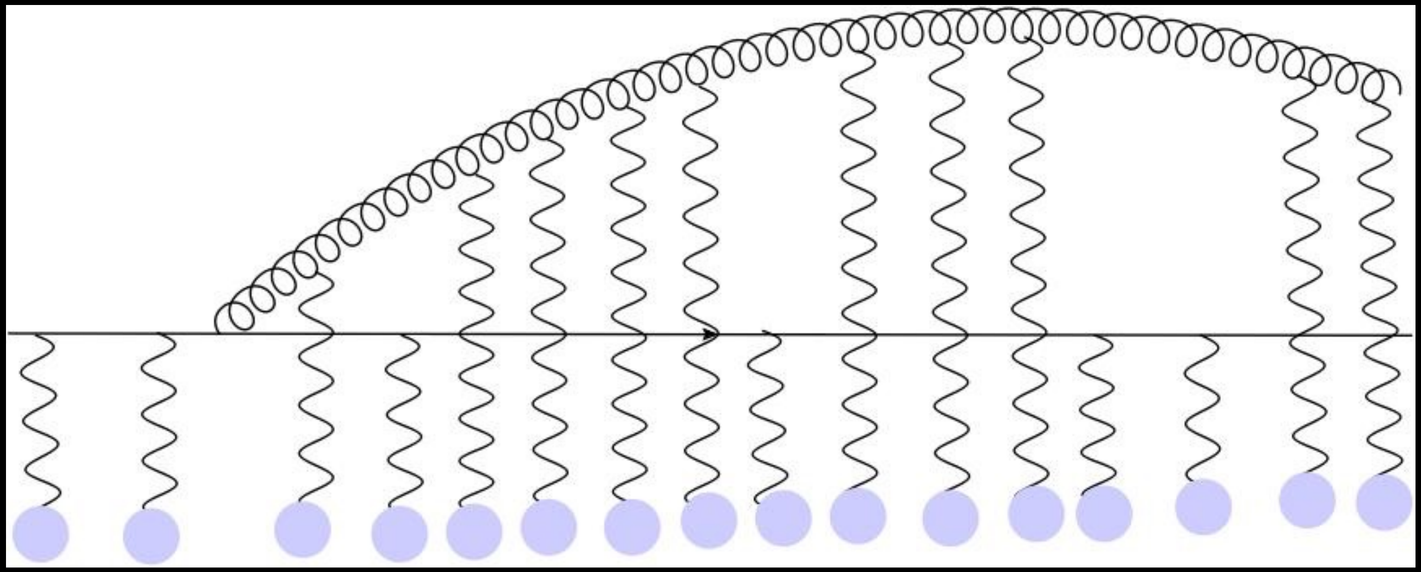

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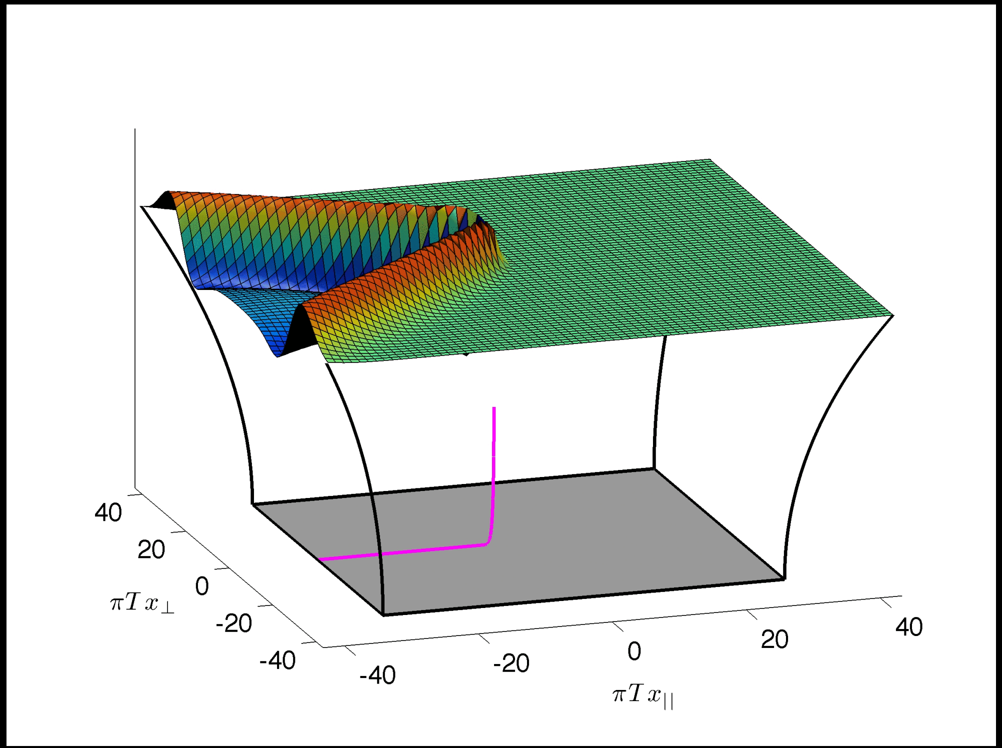

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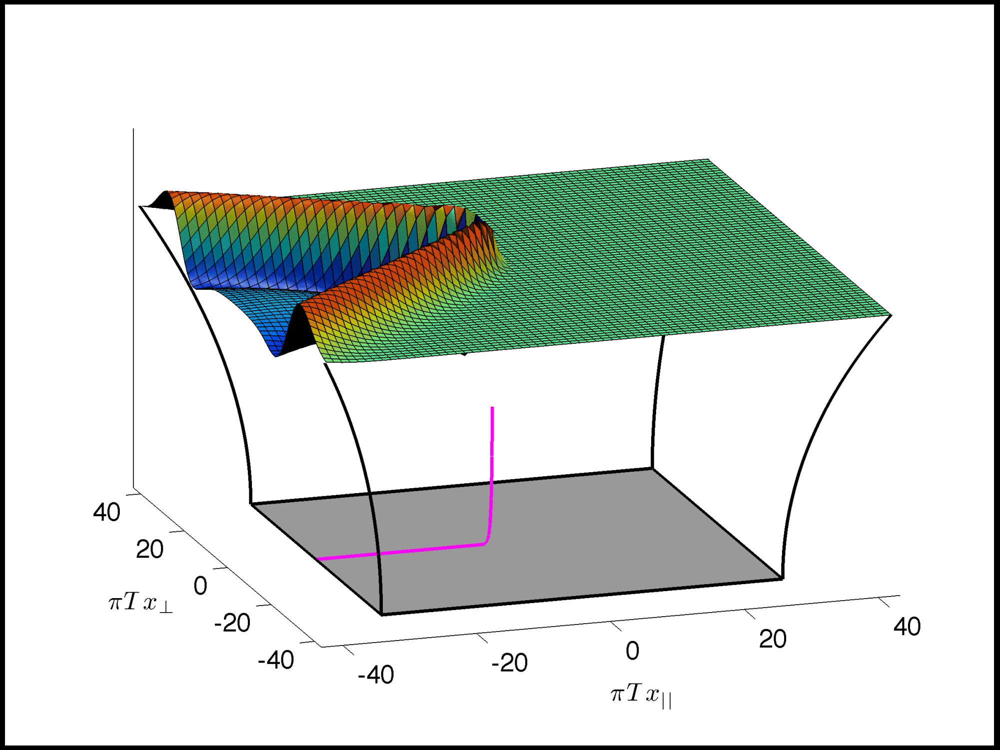
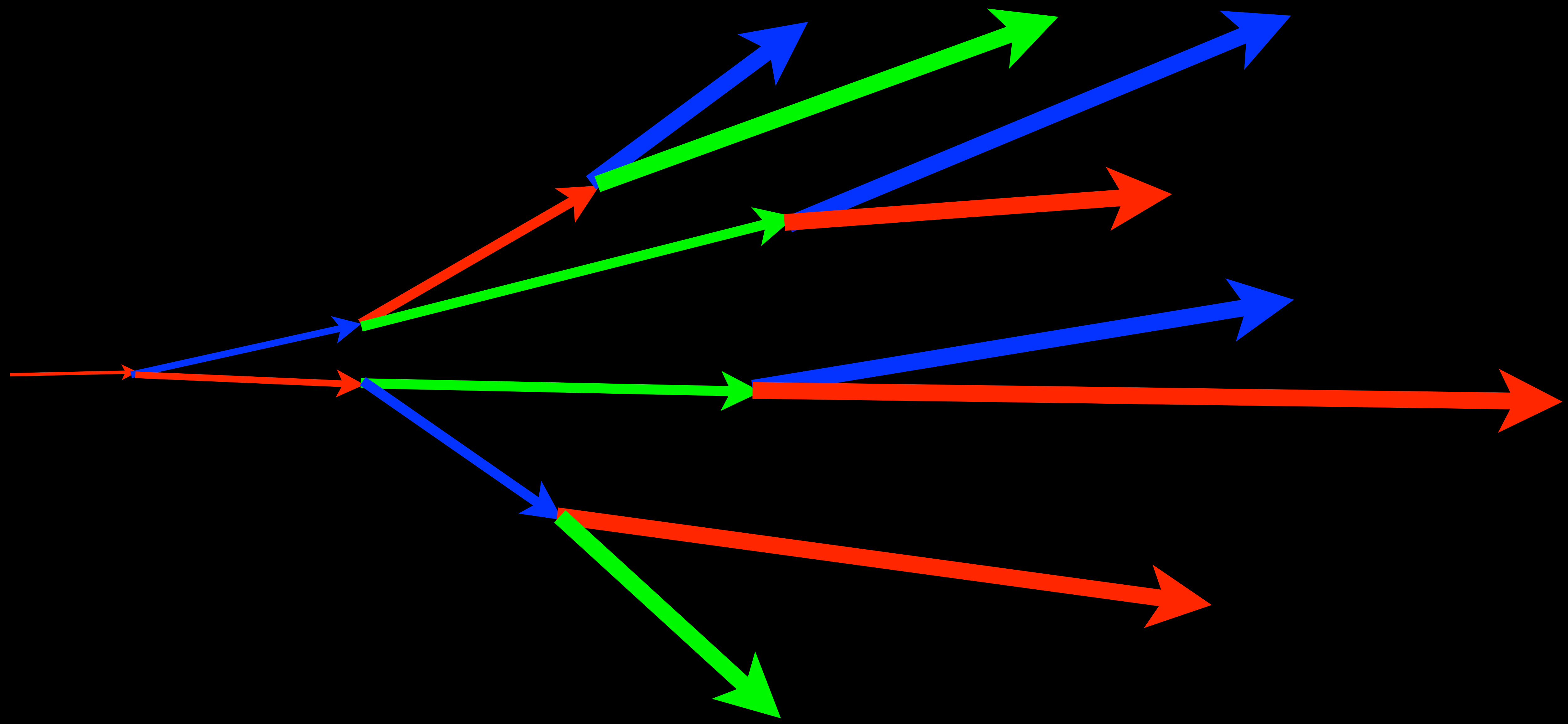


P. Chesler, L. Yaffe, W. Horowitz, A. Mueller, E. Iancu, J. Casalderrey-Solana, G. Milhano, D. Pablos, K. Rajagopal

Grand picture (leading hadrons)



In a static brick

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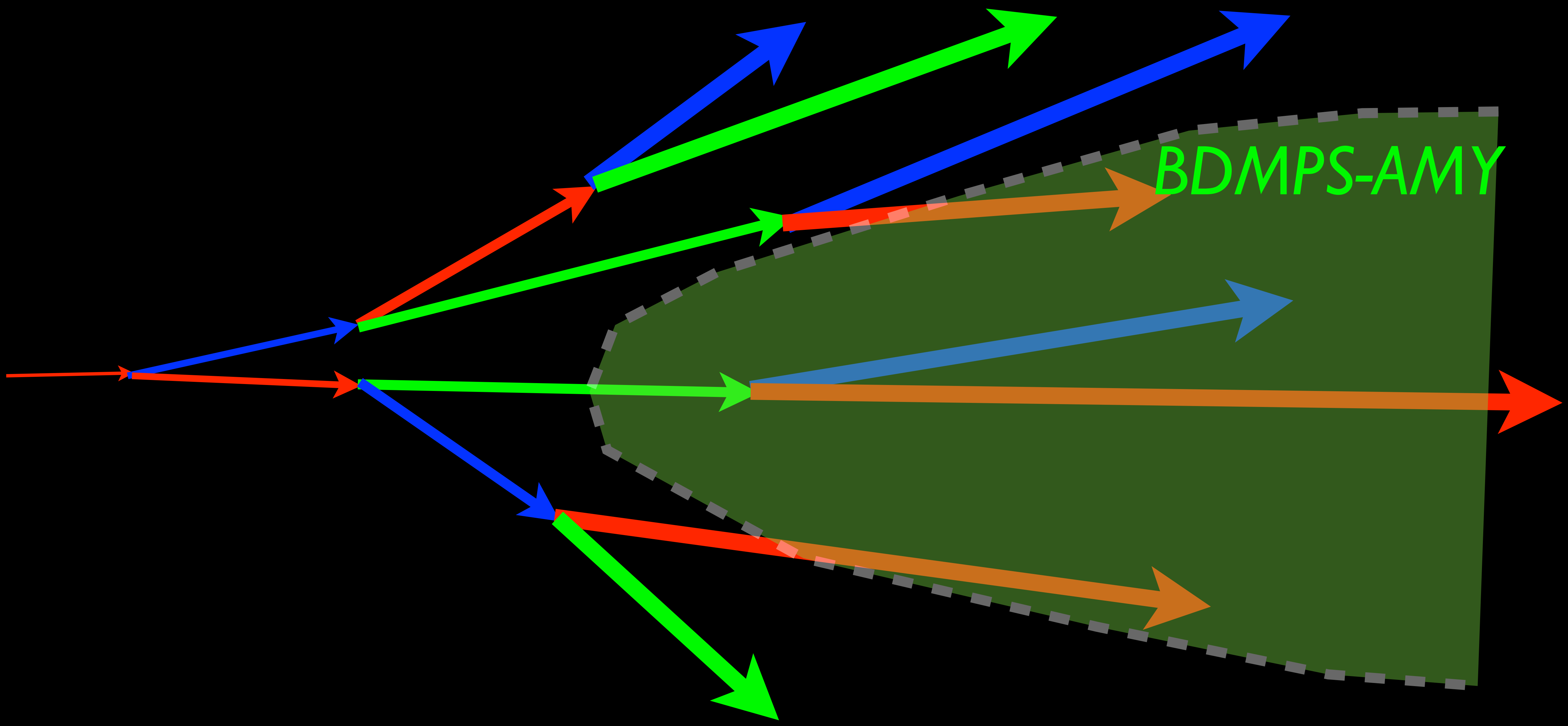

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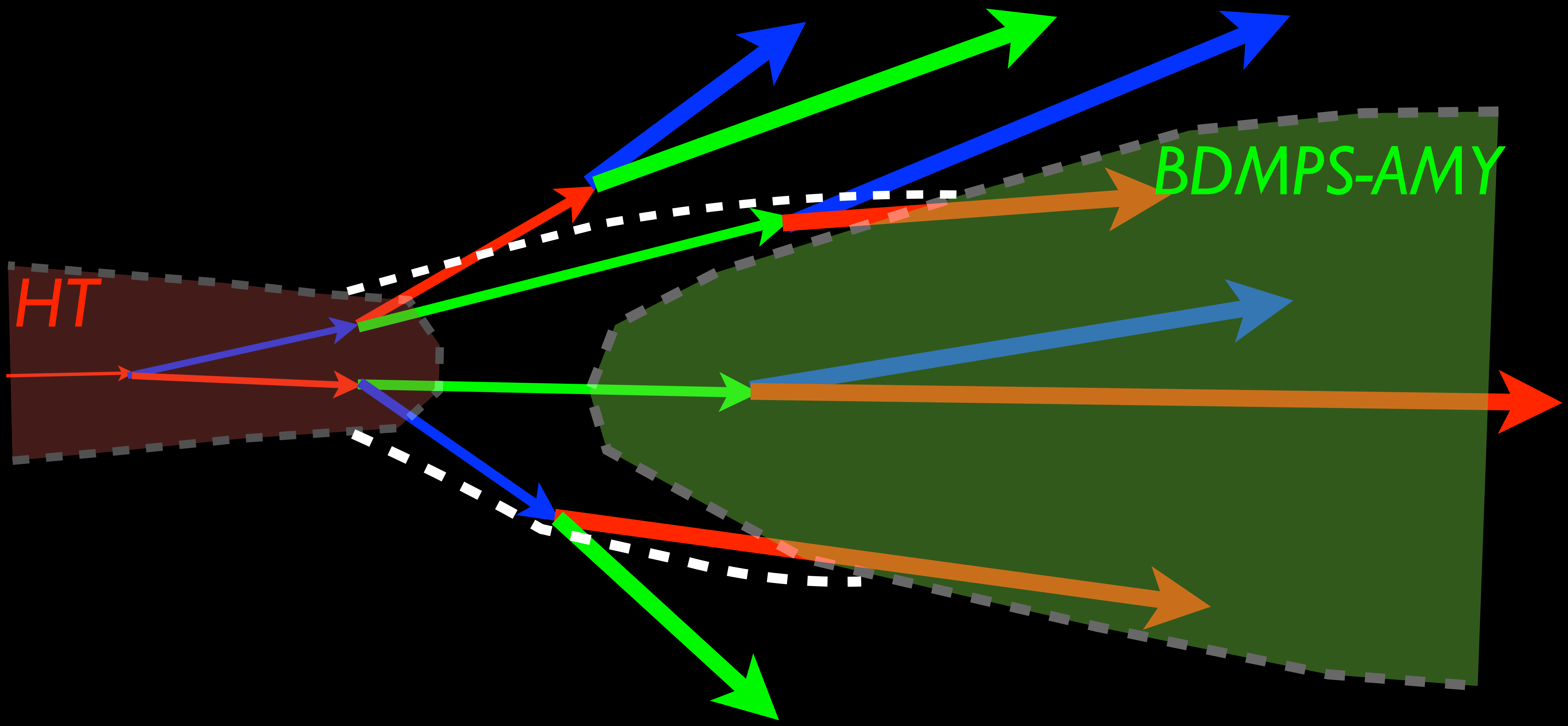

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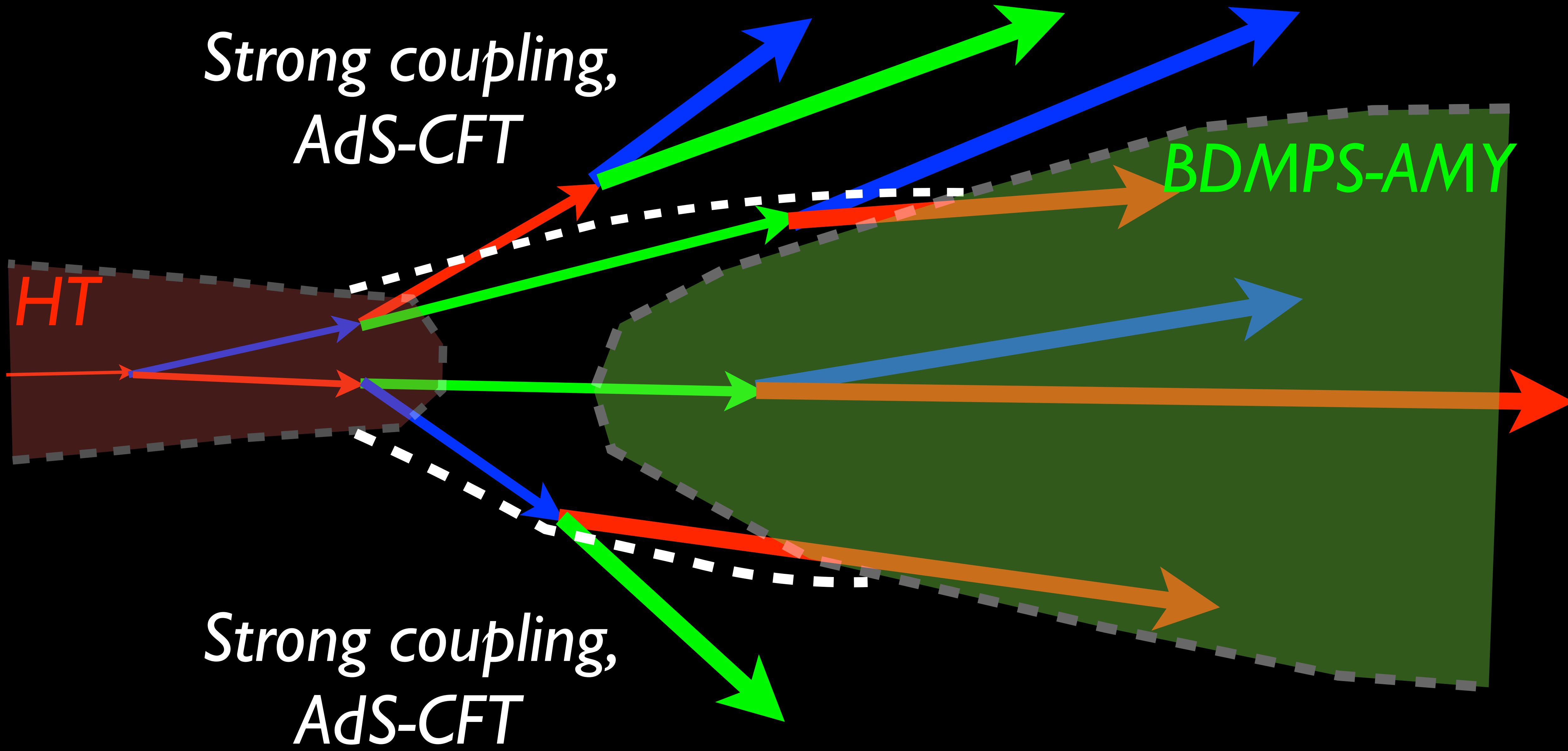

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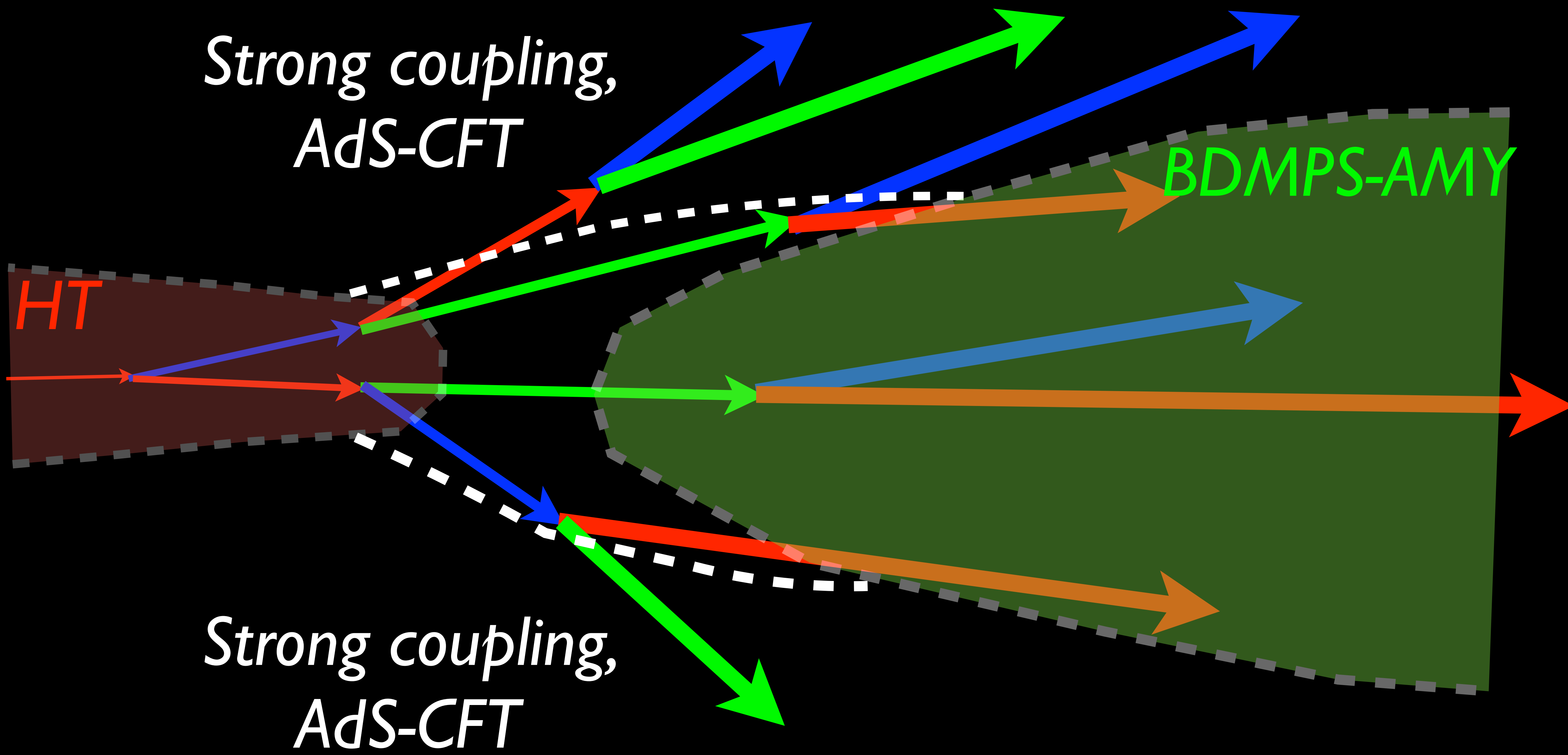
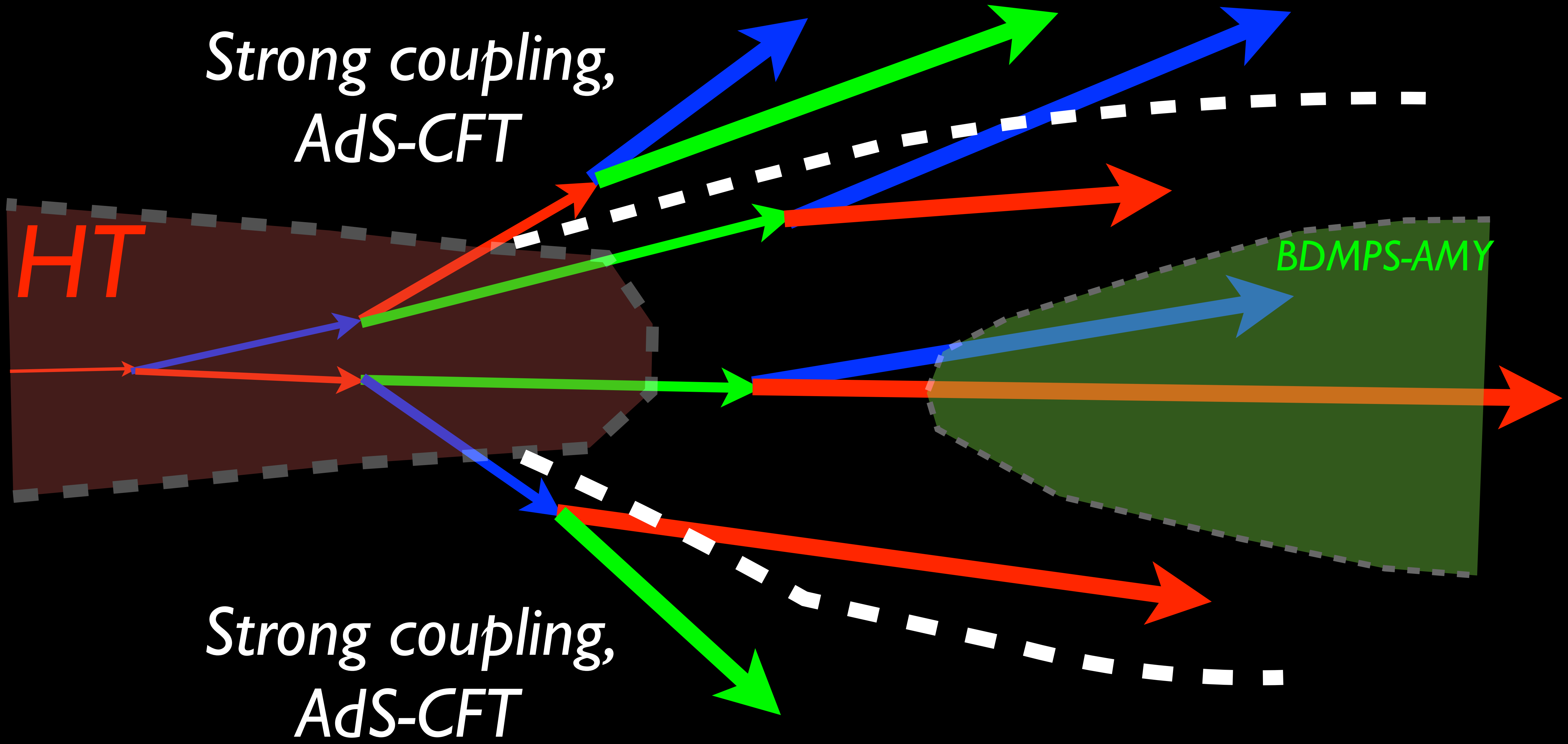


In an expanding QGP

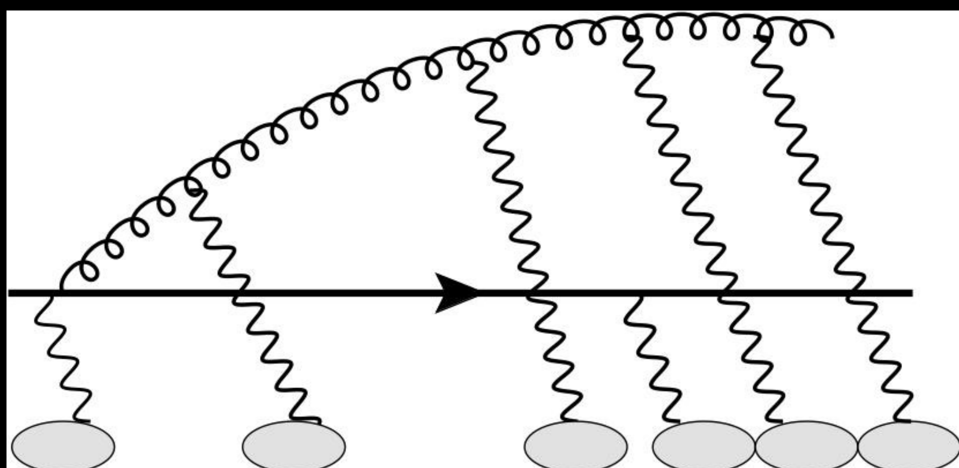
Grand picture (leading hadrons)



In an expanding QGP

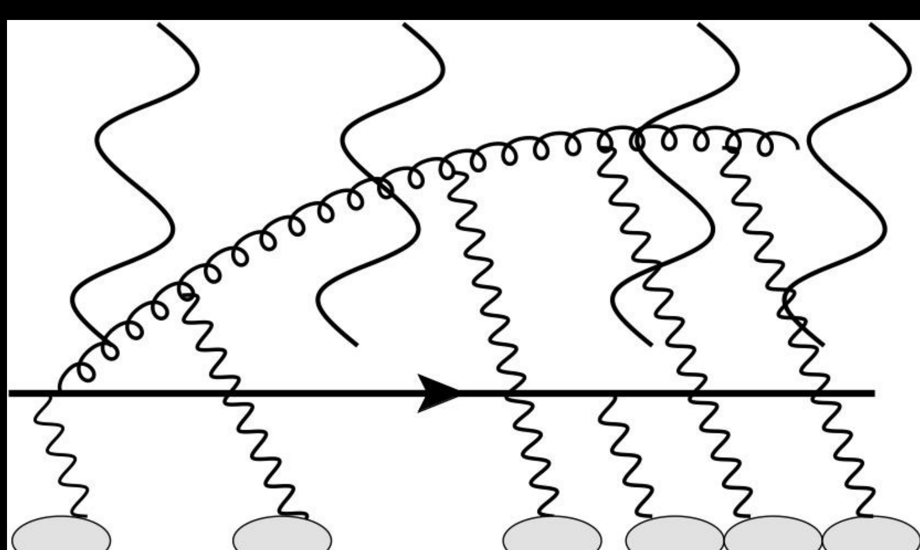
Energy deposition-thermalization

Drag on a jet is energy dump in a medium $\hat{e} = \frac{dE}{dx}$



space-like gluons

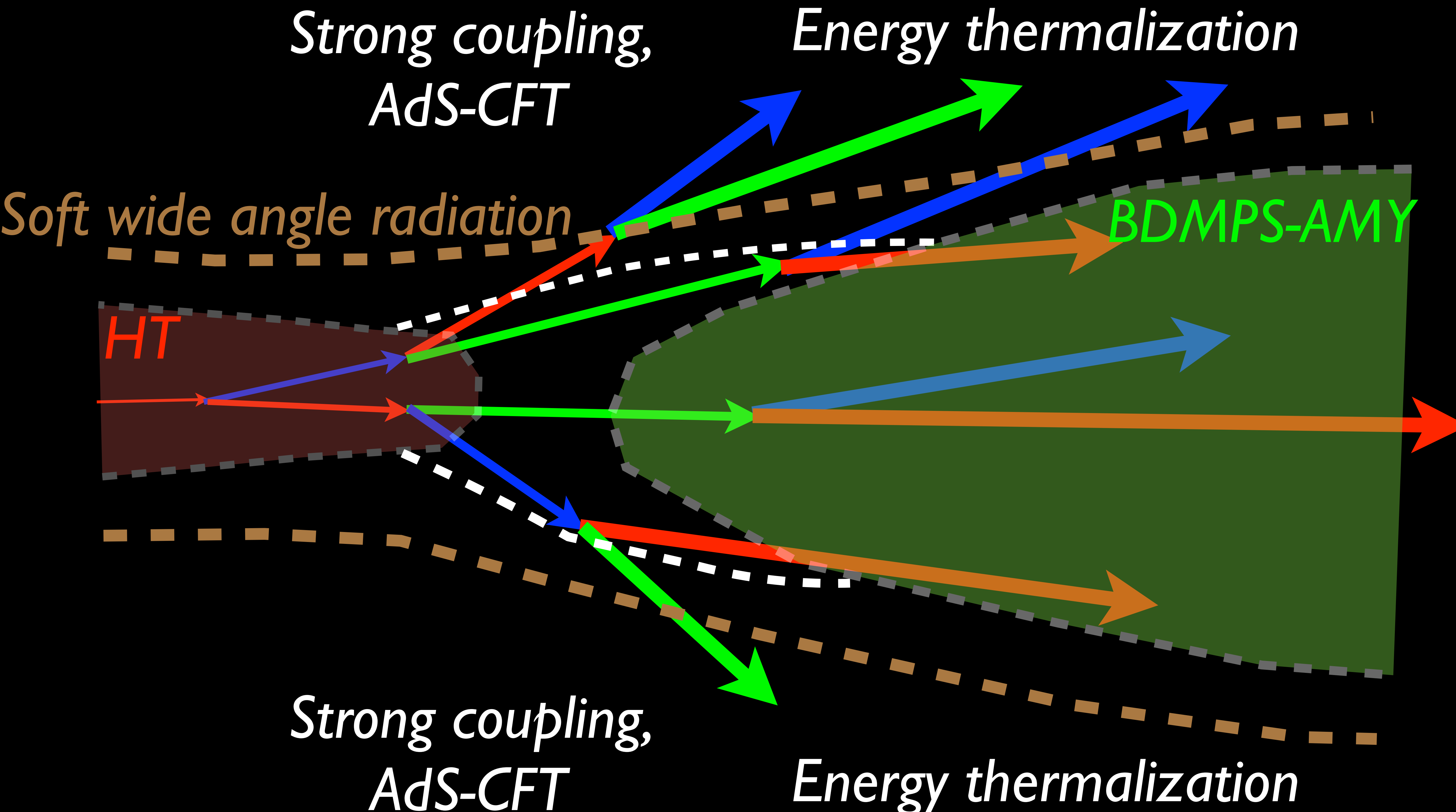
Could also have another component from very soft large angle radiation



time-like gluons

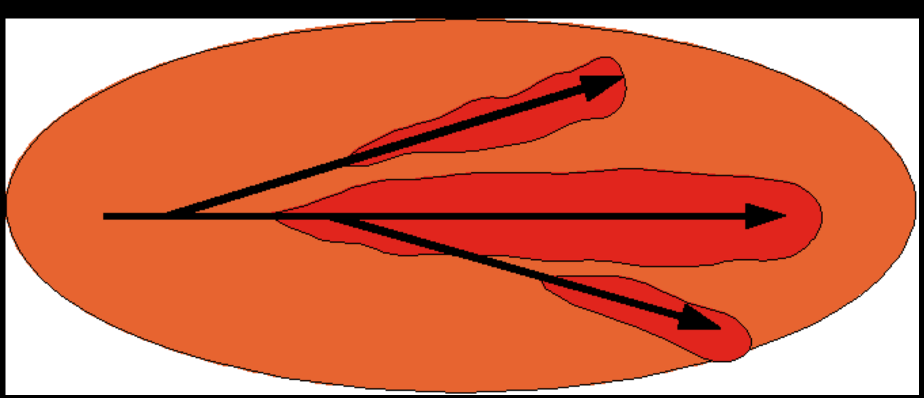
Blaizot, Iancu, Mehtar-Tani

Energy deposition-thermalization

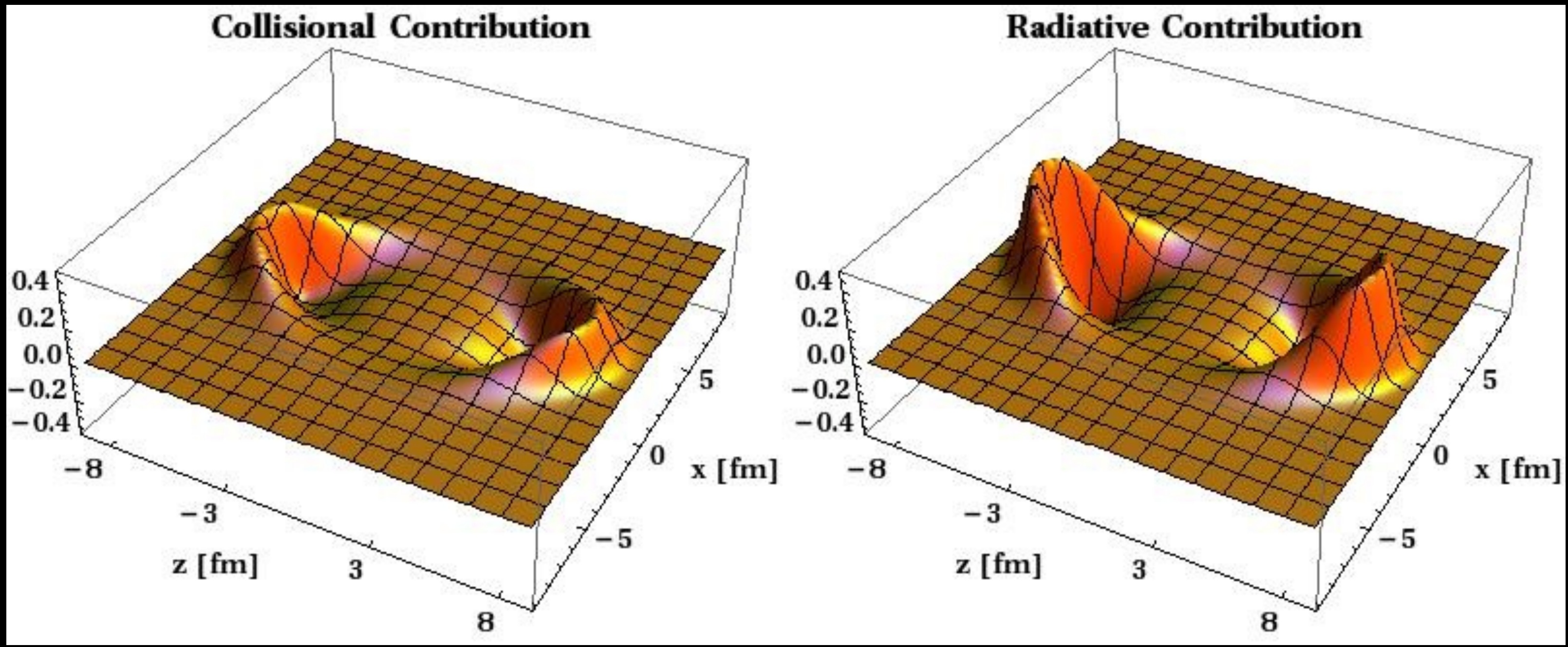


Type II transport coefficients

- Should be calculable directly in AdS/CFT.
- or any phenomenological model of the medium e.g., MARTINI, CCNU-LBNL, JEWEL
- Will be greatly enhanced by perturbative splits
- Need a way to formalize these for any model



B. Neufeld & B. Muller,
G-Y.Qin, AM, H. Song and U. Heinz



In general, 2 kinds of transport coefficients

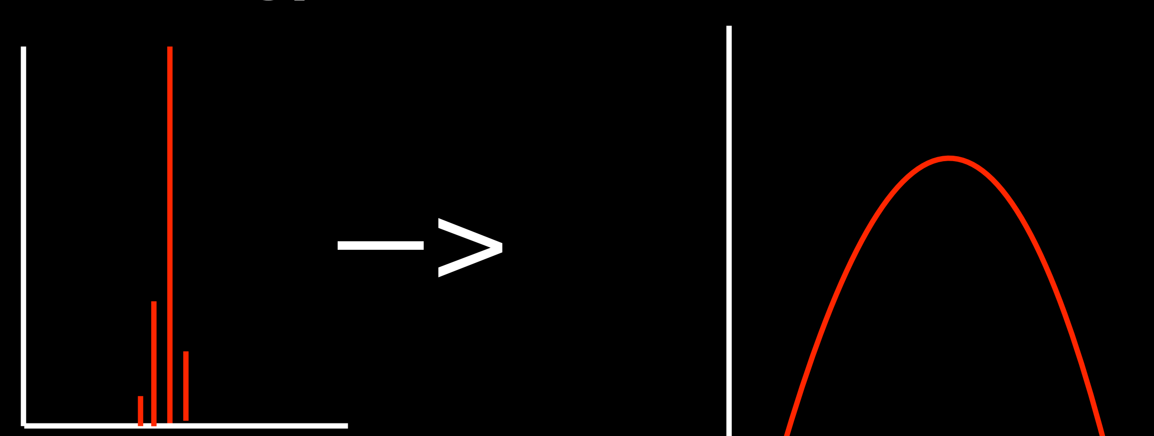
Type 1: which quantify how the medium changes the jet

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

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

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

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



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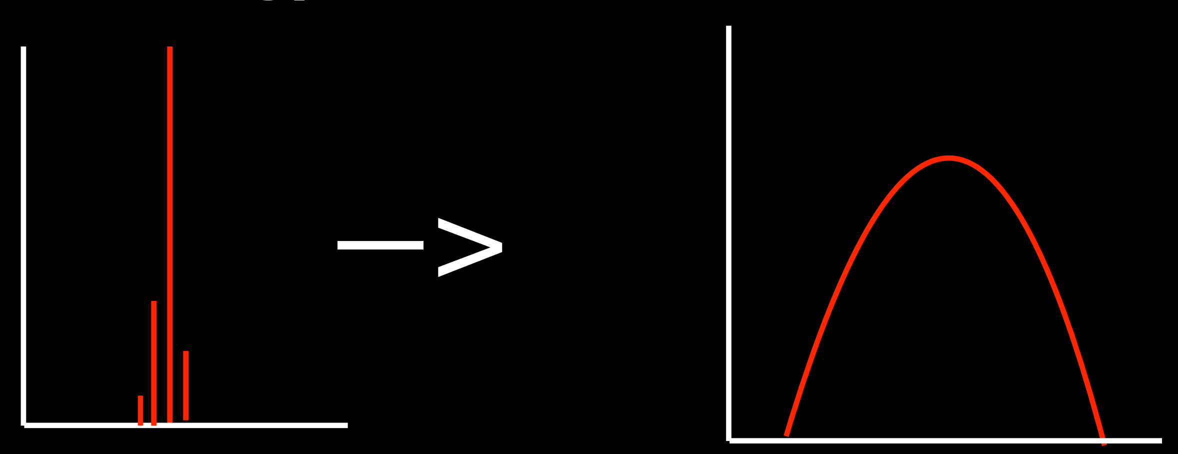

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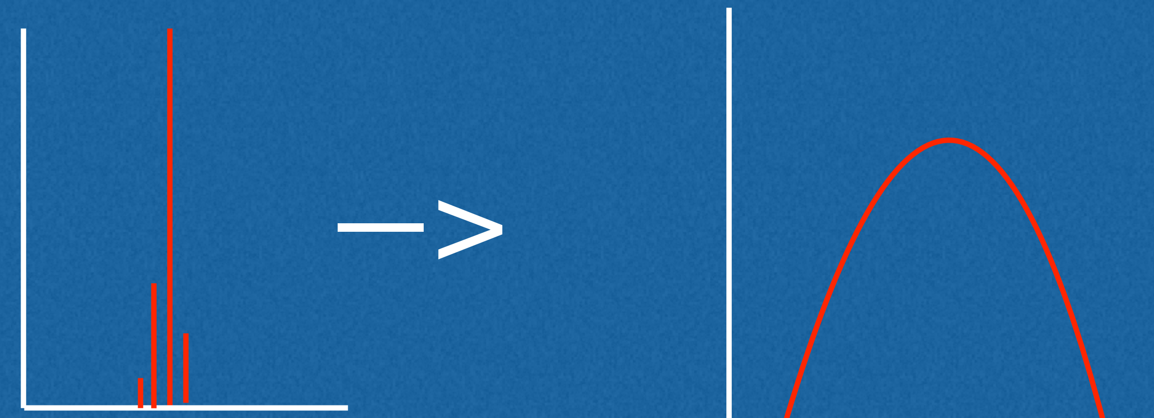
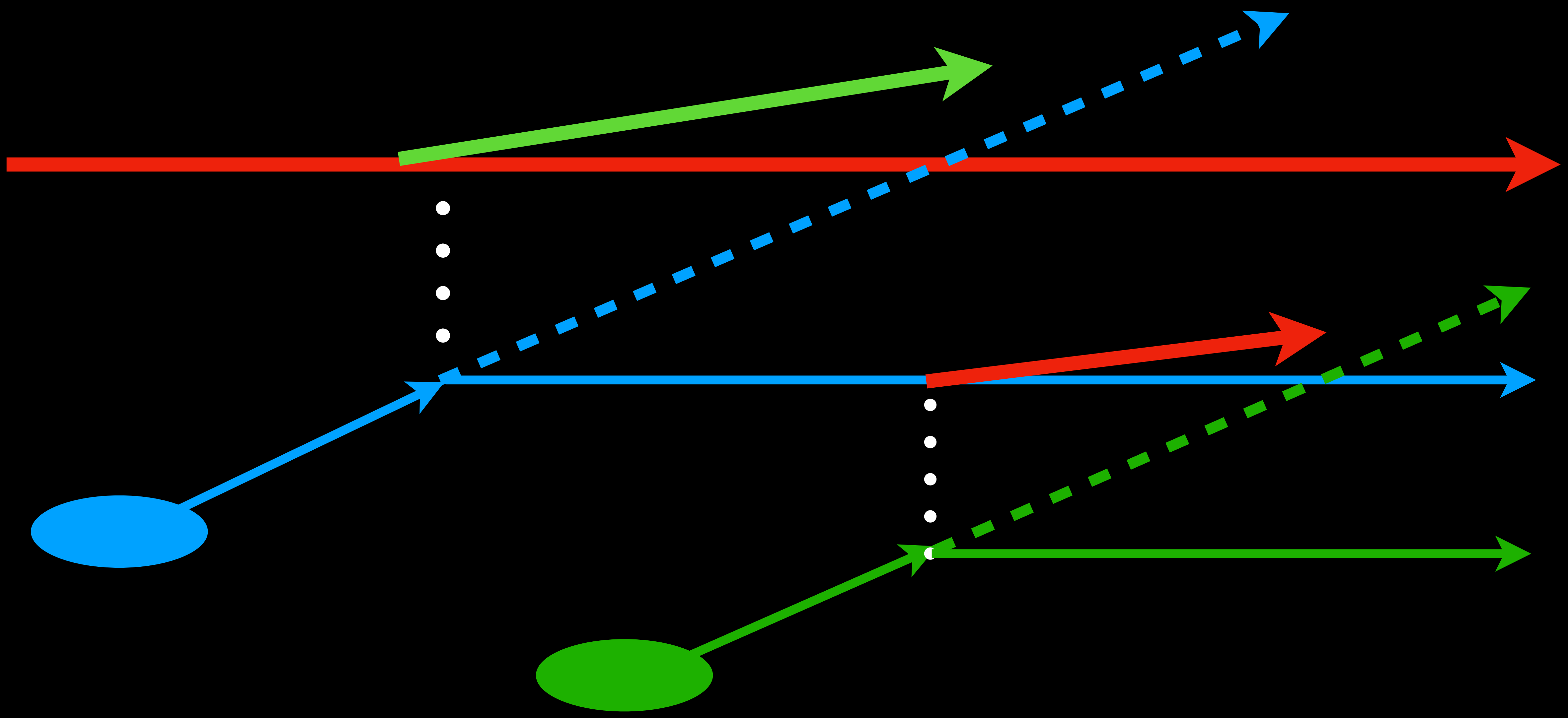


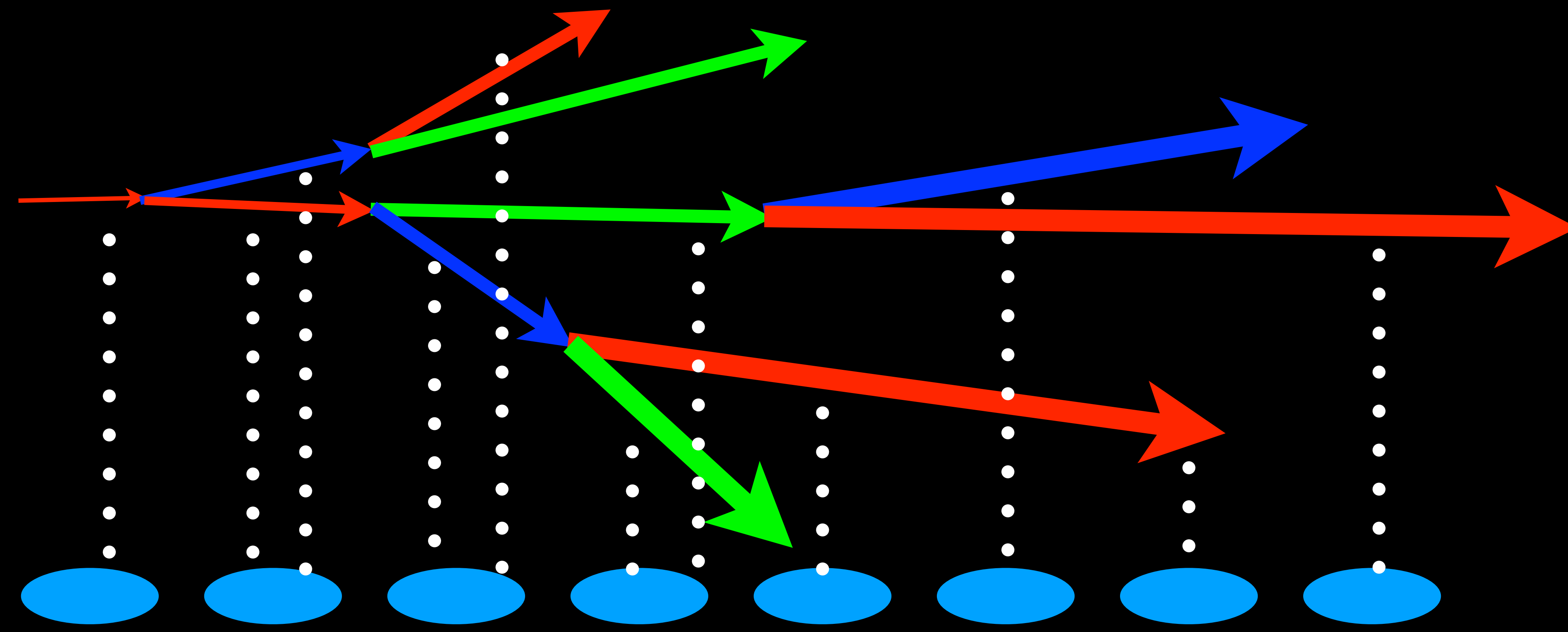
How this done currently



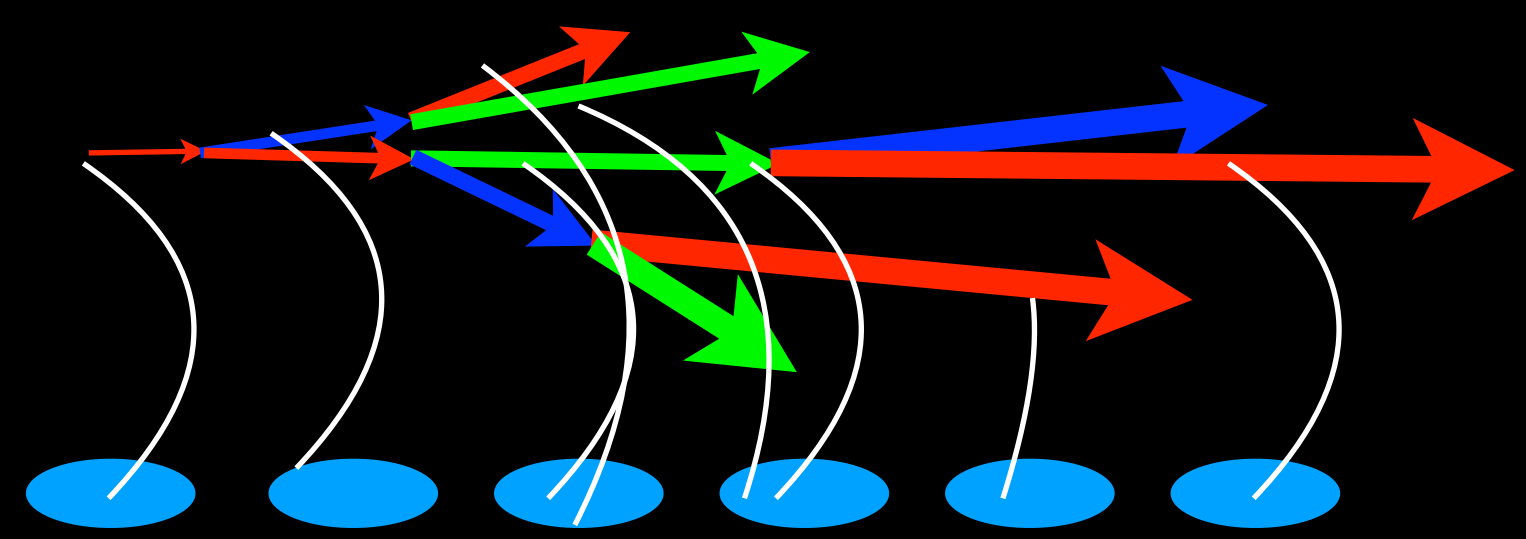
Full jet carries recoil particles
sampled from a Boltzmann distribution.
as regular jet partons, and negative parsons or holes

Other methods

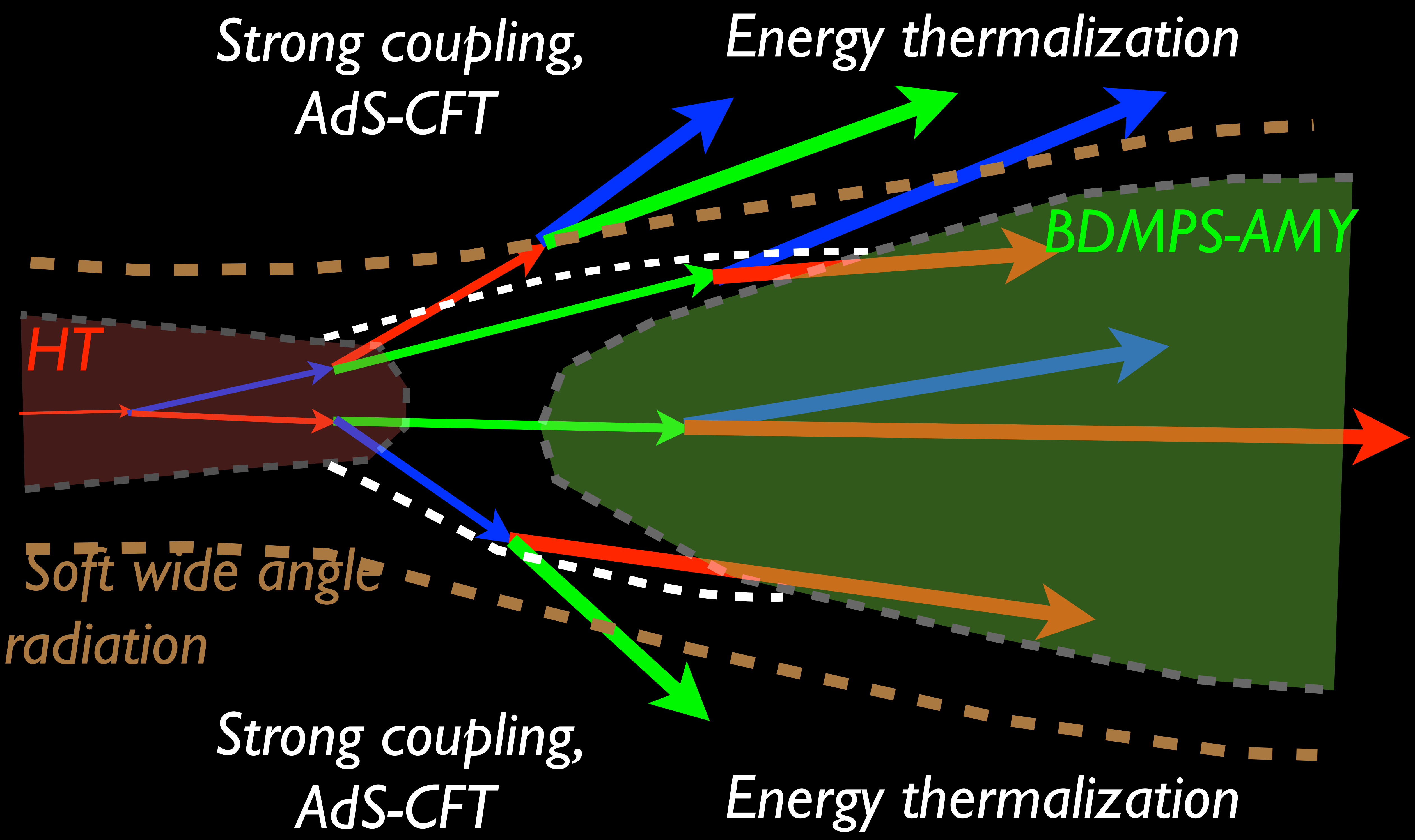
Constant Broadening



AdS/CFT drag



Hadronization: hard, soft and hard -soft



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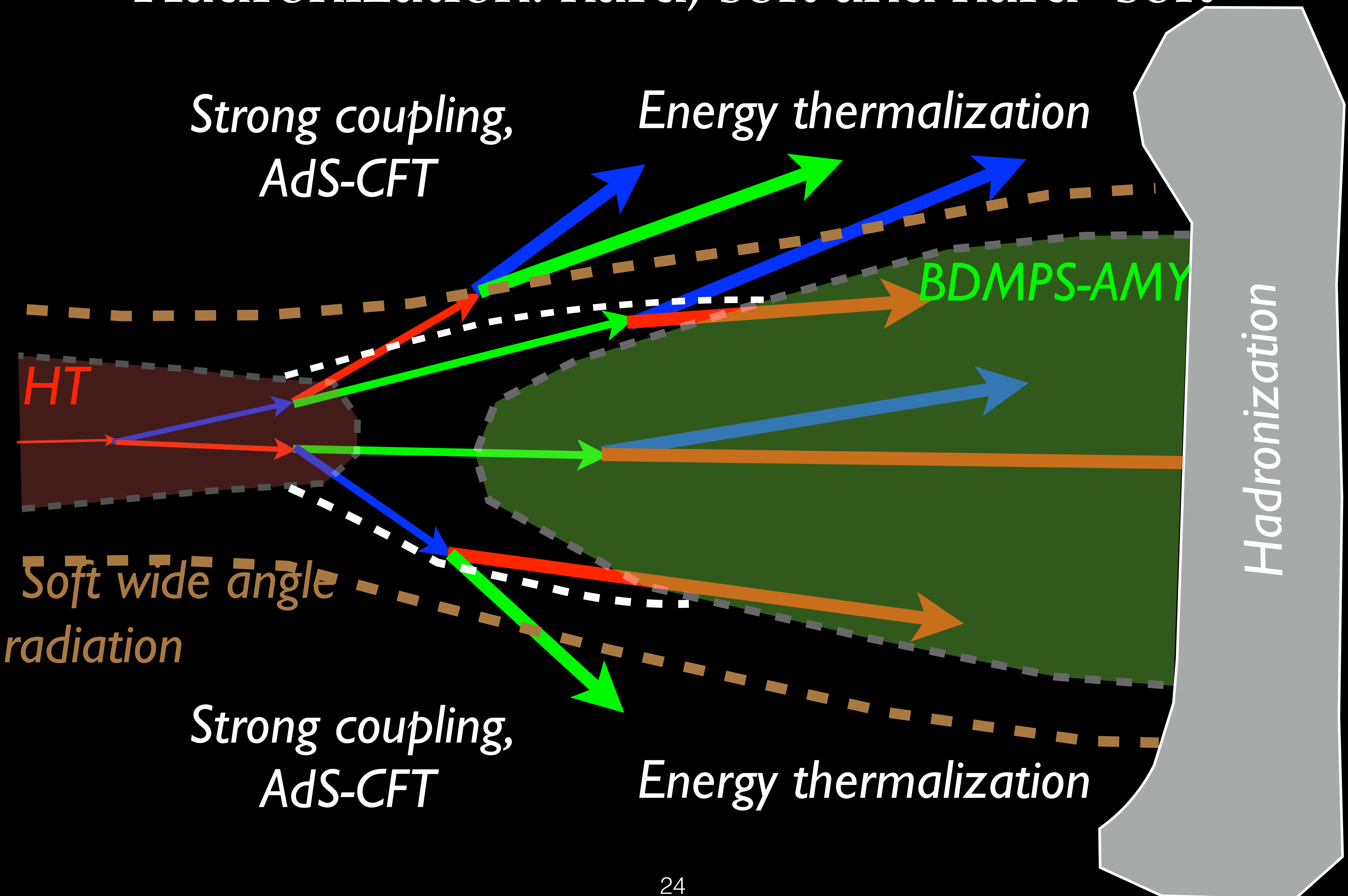
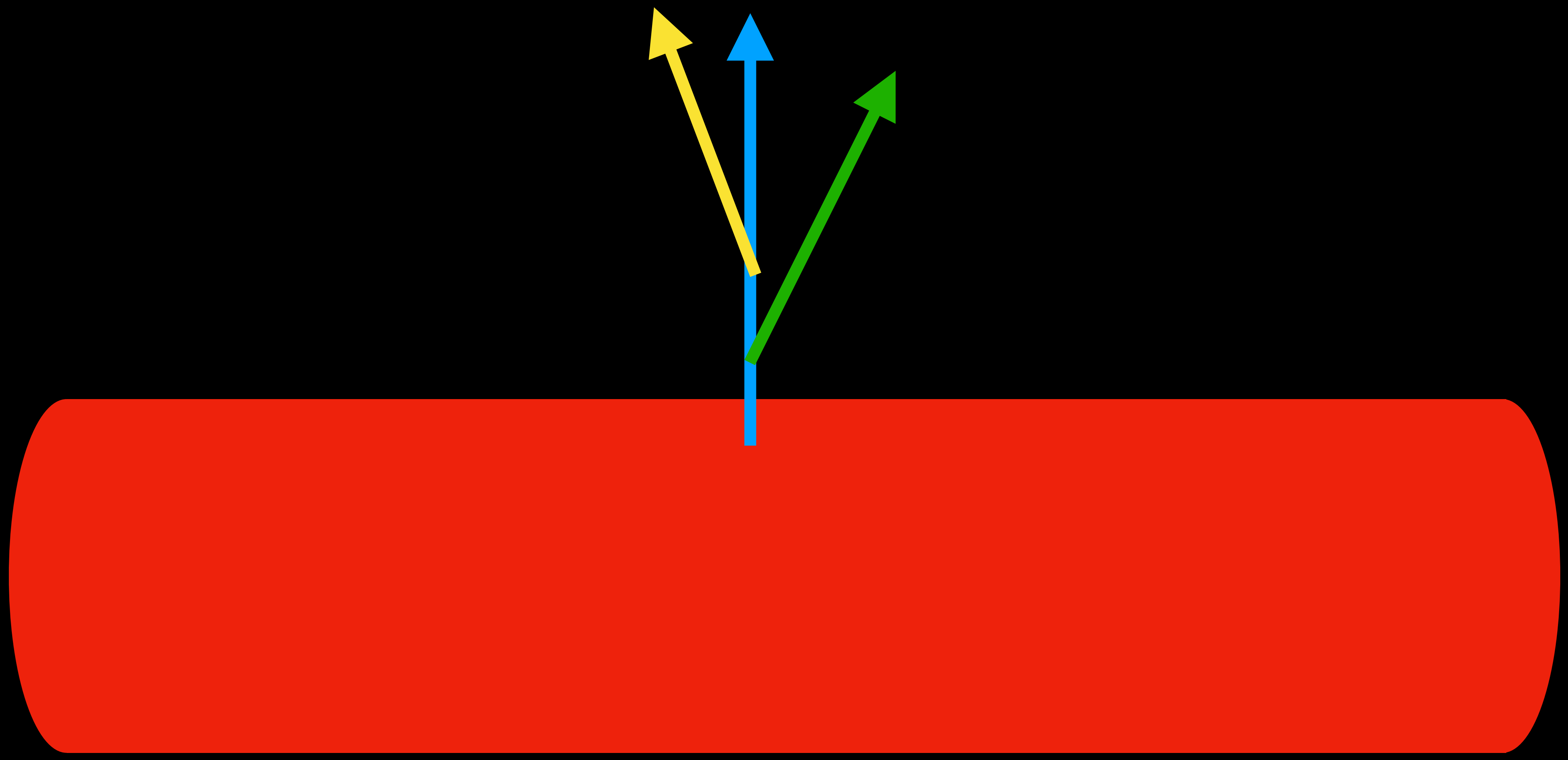
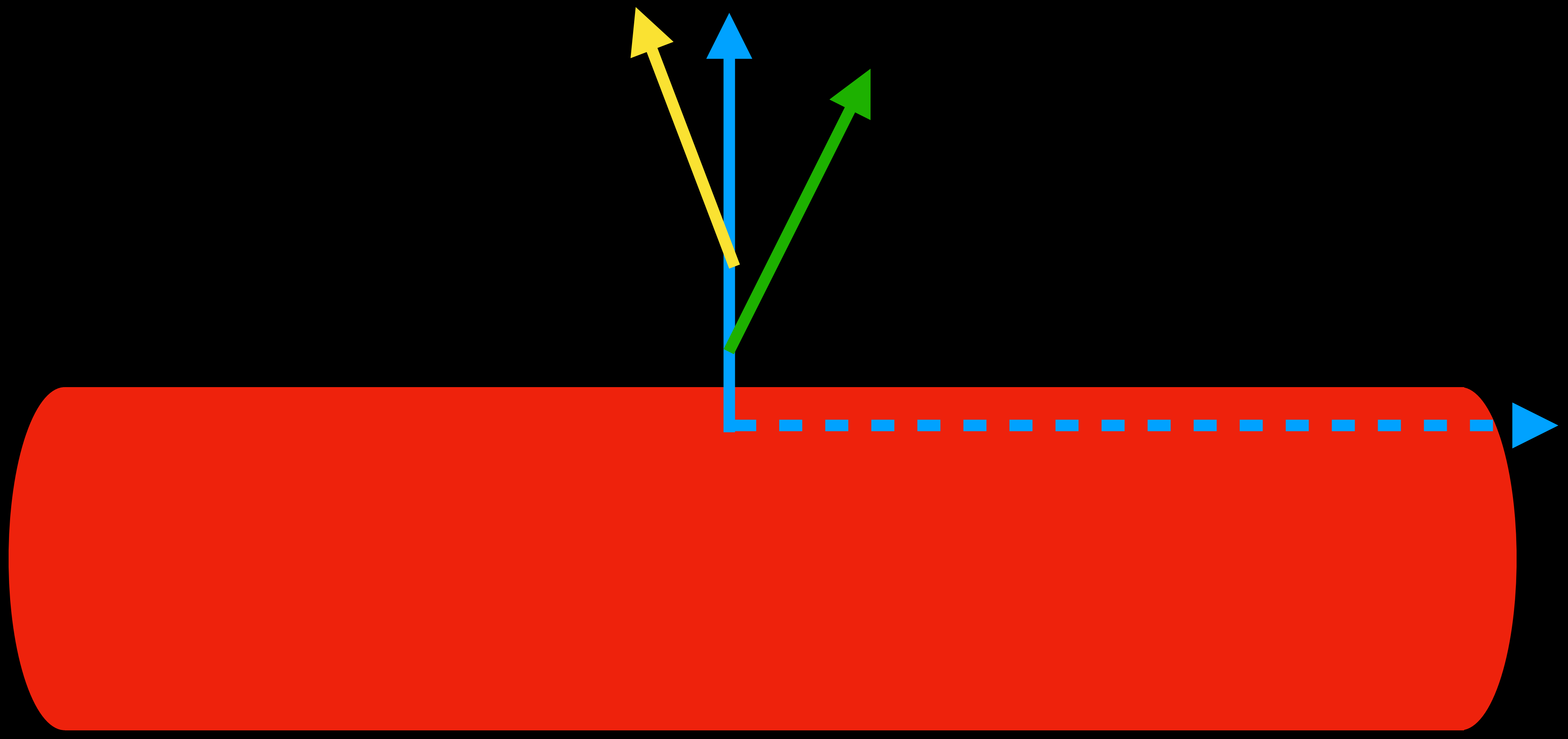


A jet hadronization mechanism that generalizes from p-p to A-A



1) Have separate strings for each shower initiating parton (colored)
2) Connect all the showers with one string to one fake (colorless)

A jet hadronization mechanism that generalizes from p-p to A-A



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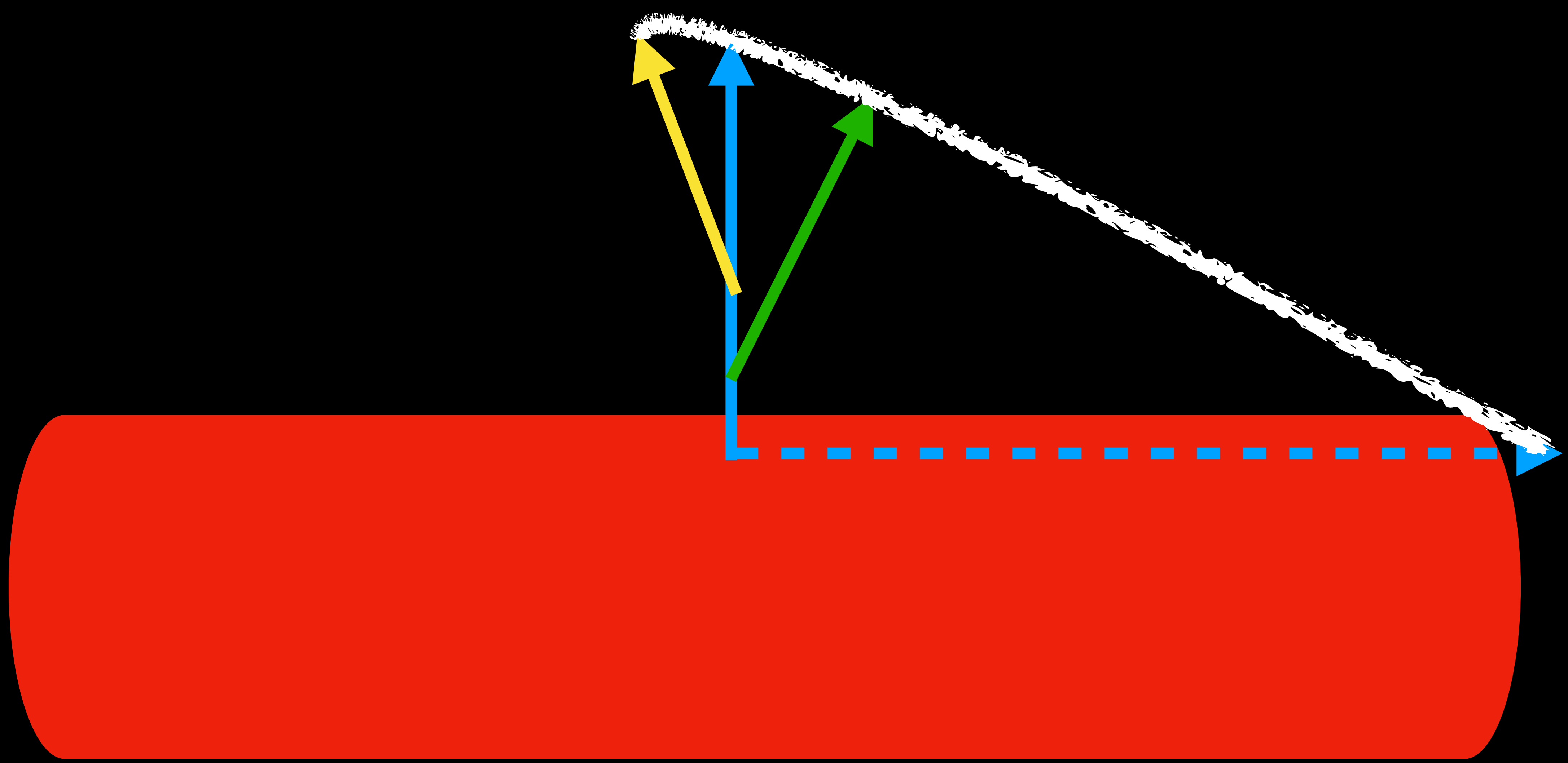

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Need a Monte-Carlo event generator based approach

Need to have a framework

- That can modularly incorporate a variety of theoretical approaches
- Which can allow you to model medium response, and entire range of transport coefficients
- Can address all observables simultaneously

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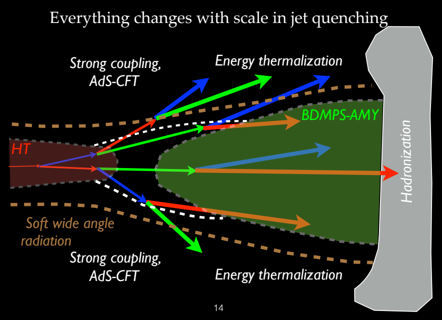

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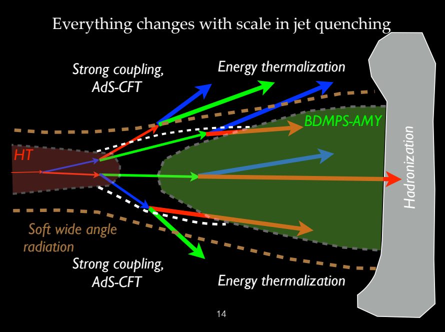

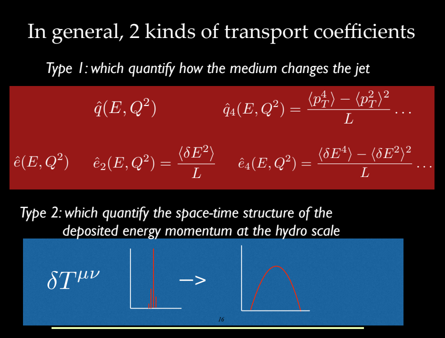

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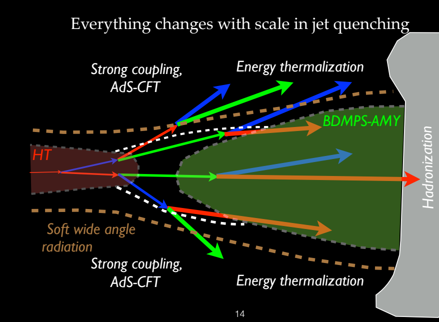

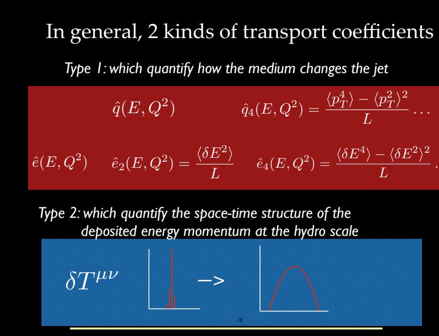

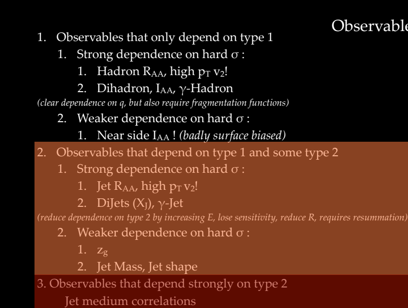

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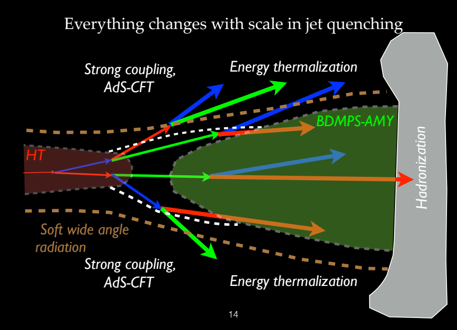
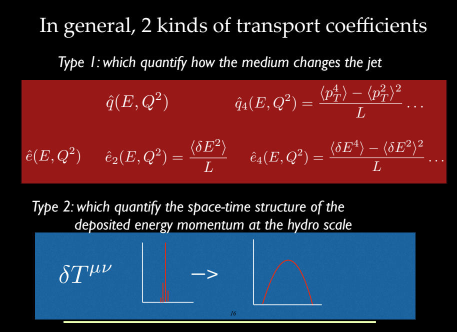
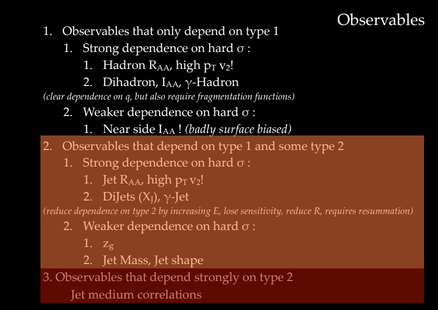




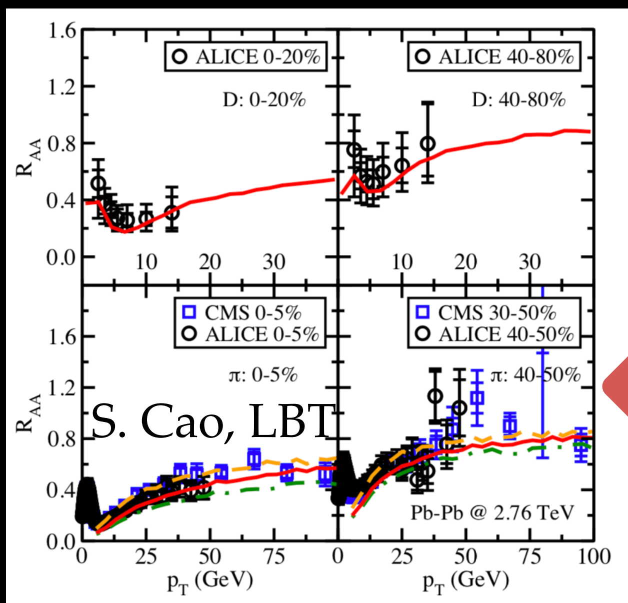


Such a framework now exists: JETSCAPE
https://github.com/JETSCAPE

Applying Multi-scale models

Its the right thing to do.

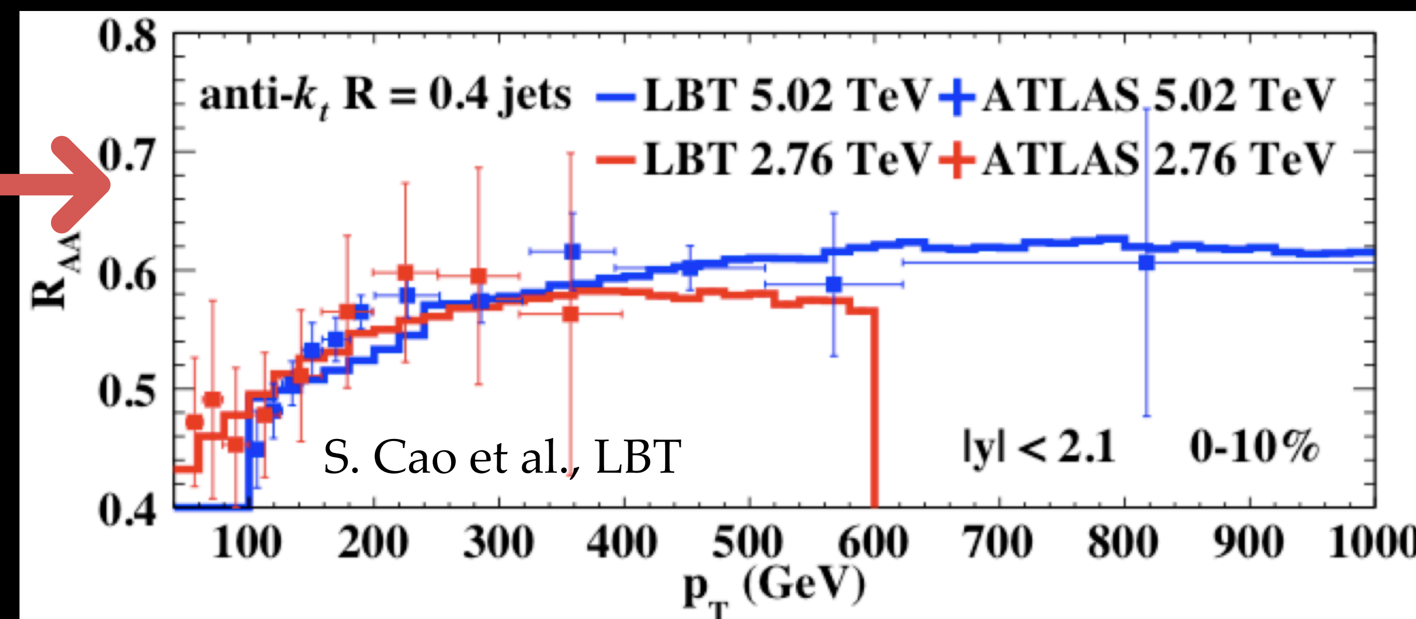
Pushing limited approaches past limits creates tension!

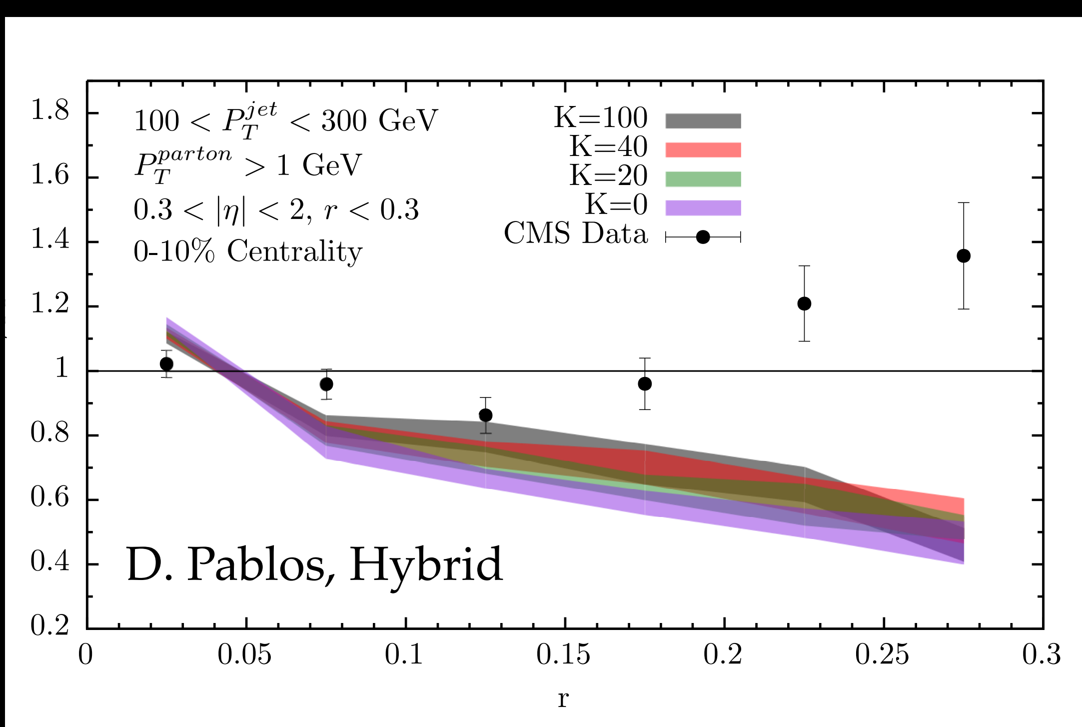


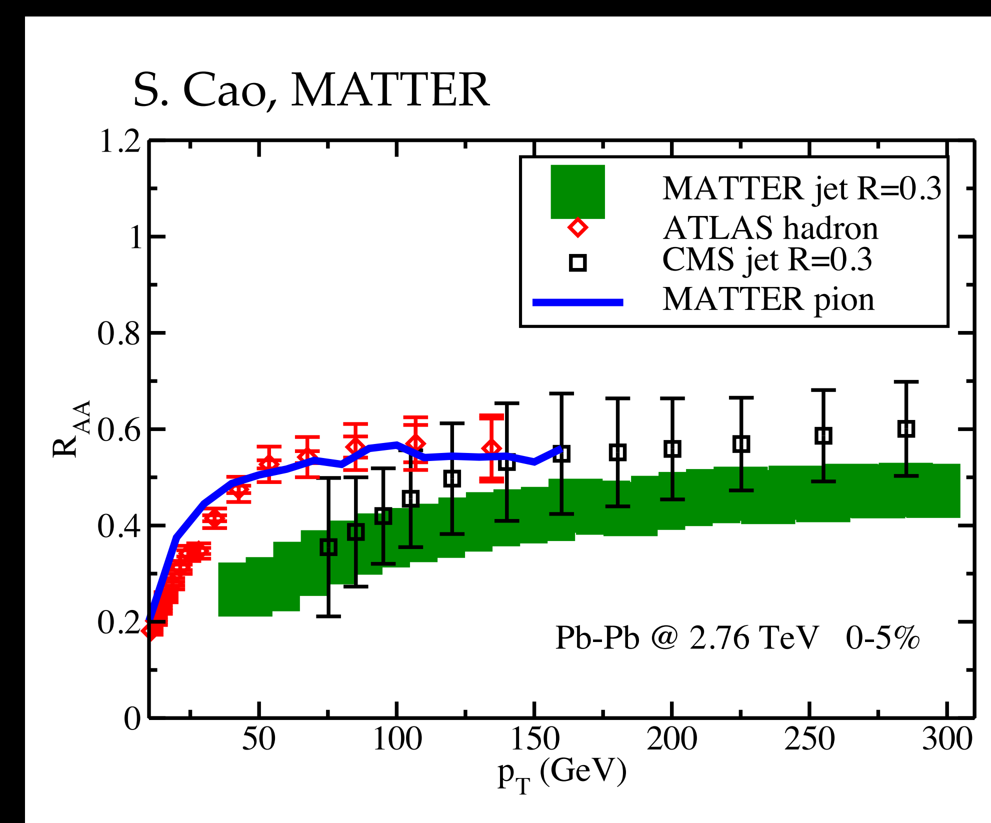
LBT

fixed α_S=0.15

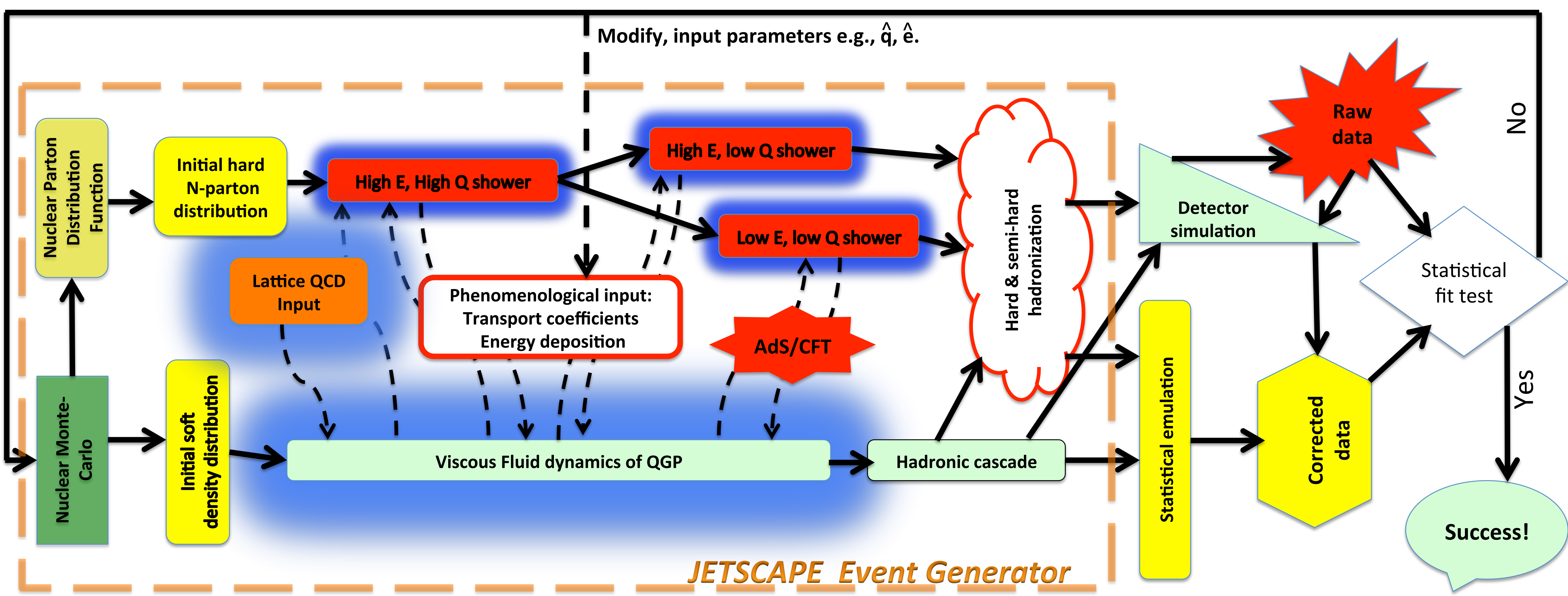
mean α_S=0.2







How would this work?



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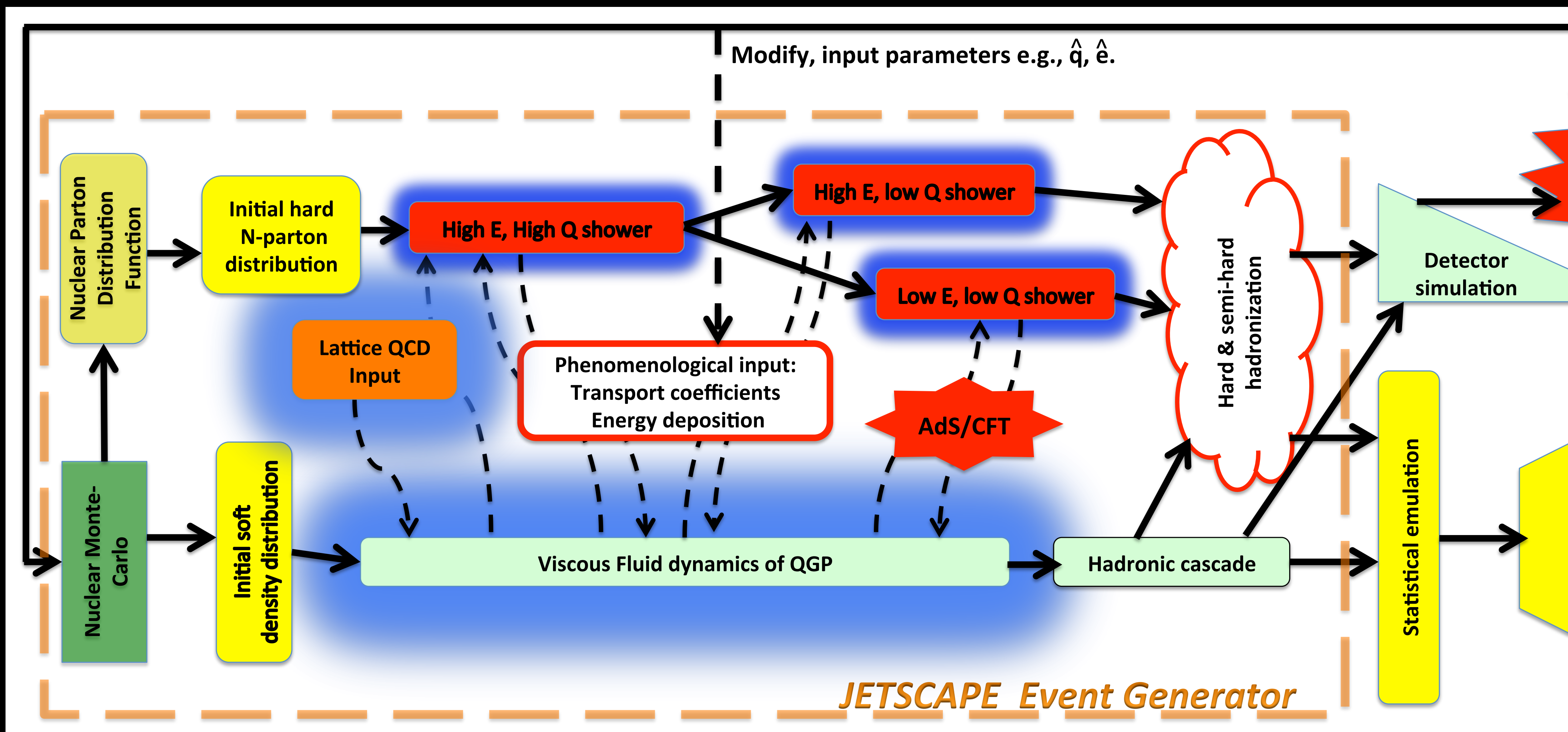

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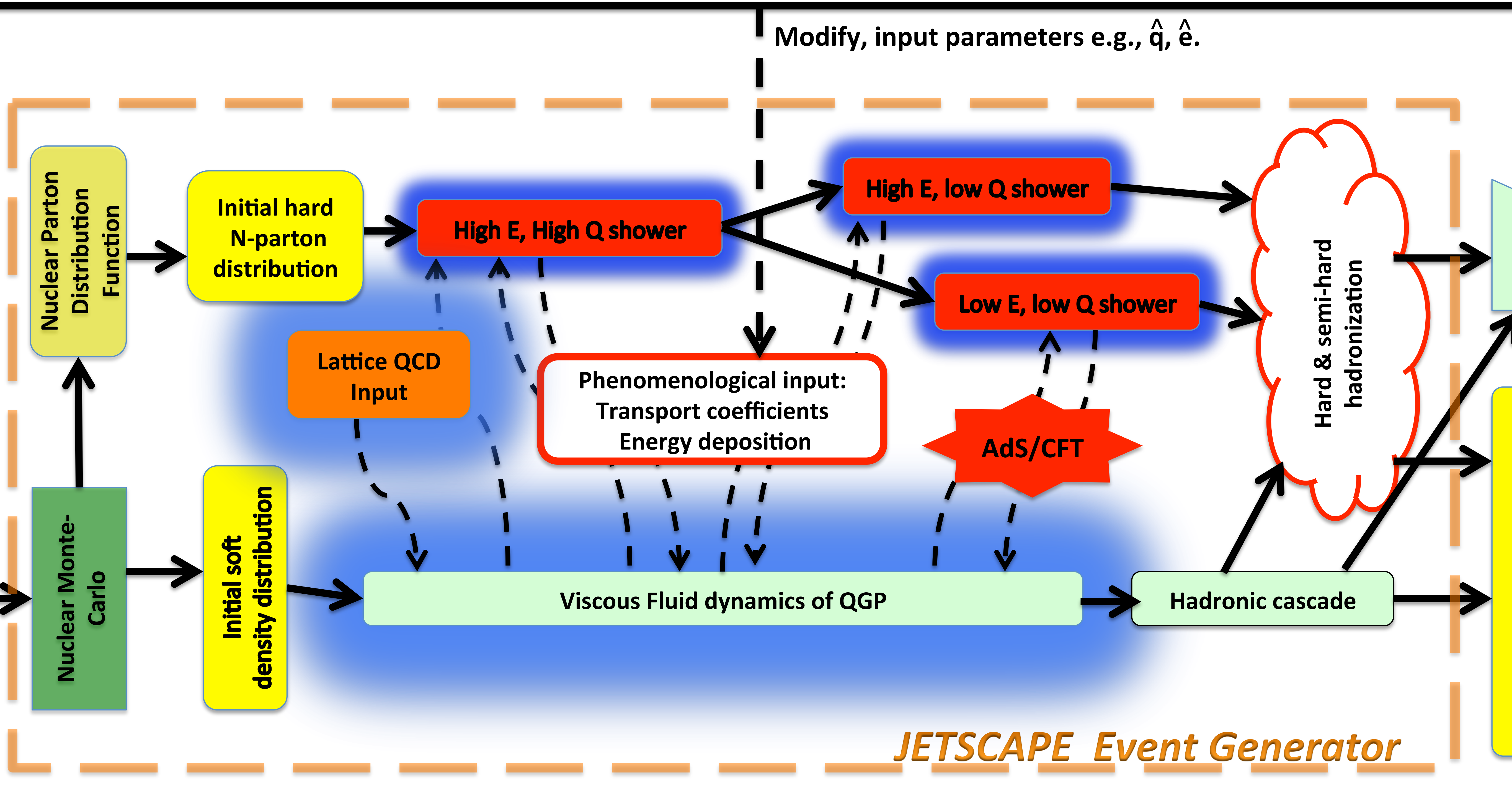
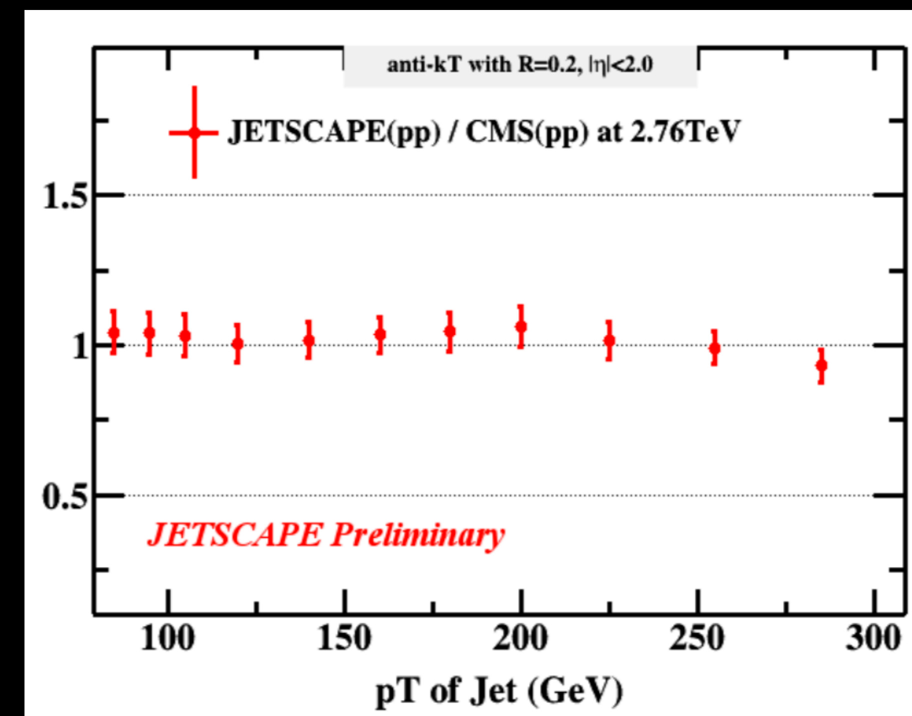
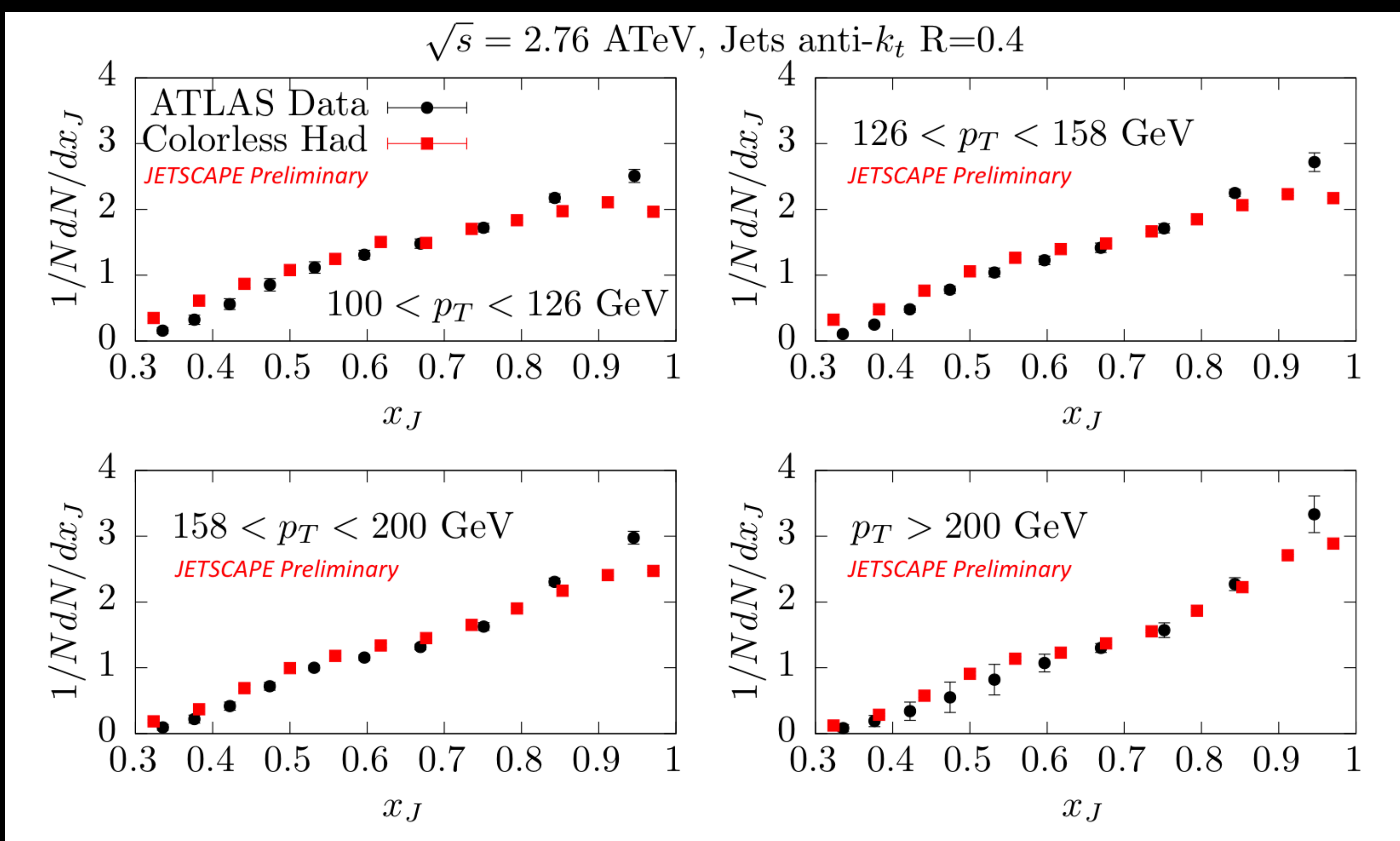


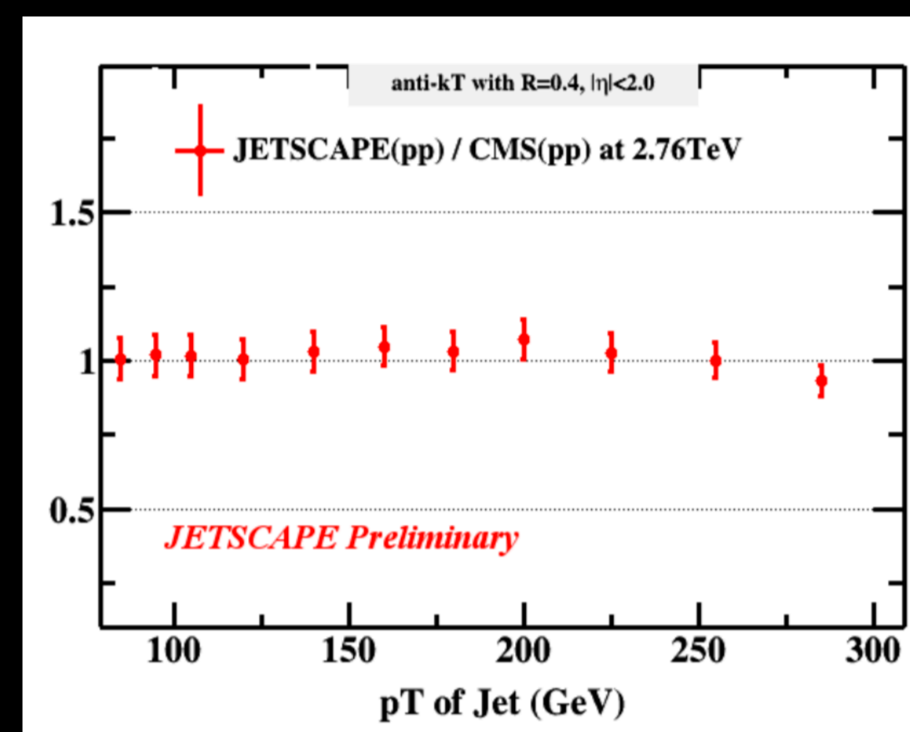
Using the full event generator

- 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

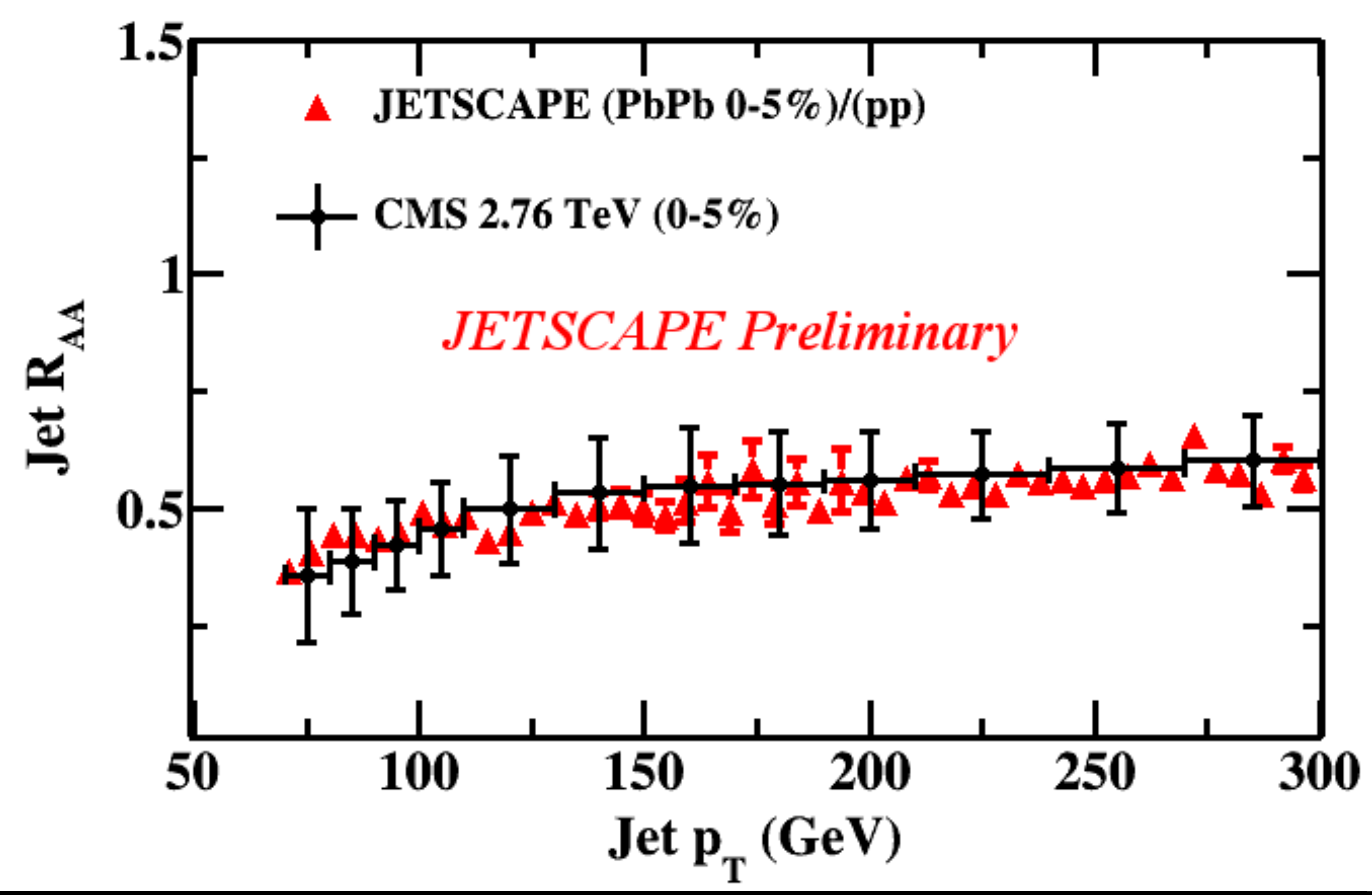
Initial state with TRENTO for both hydro and jets

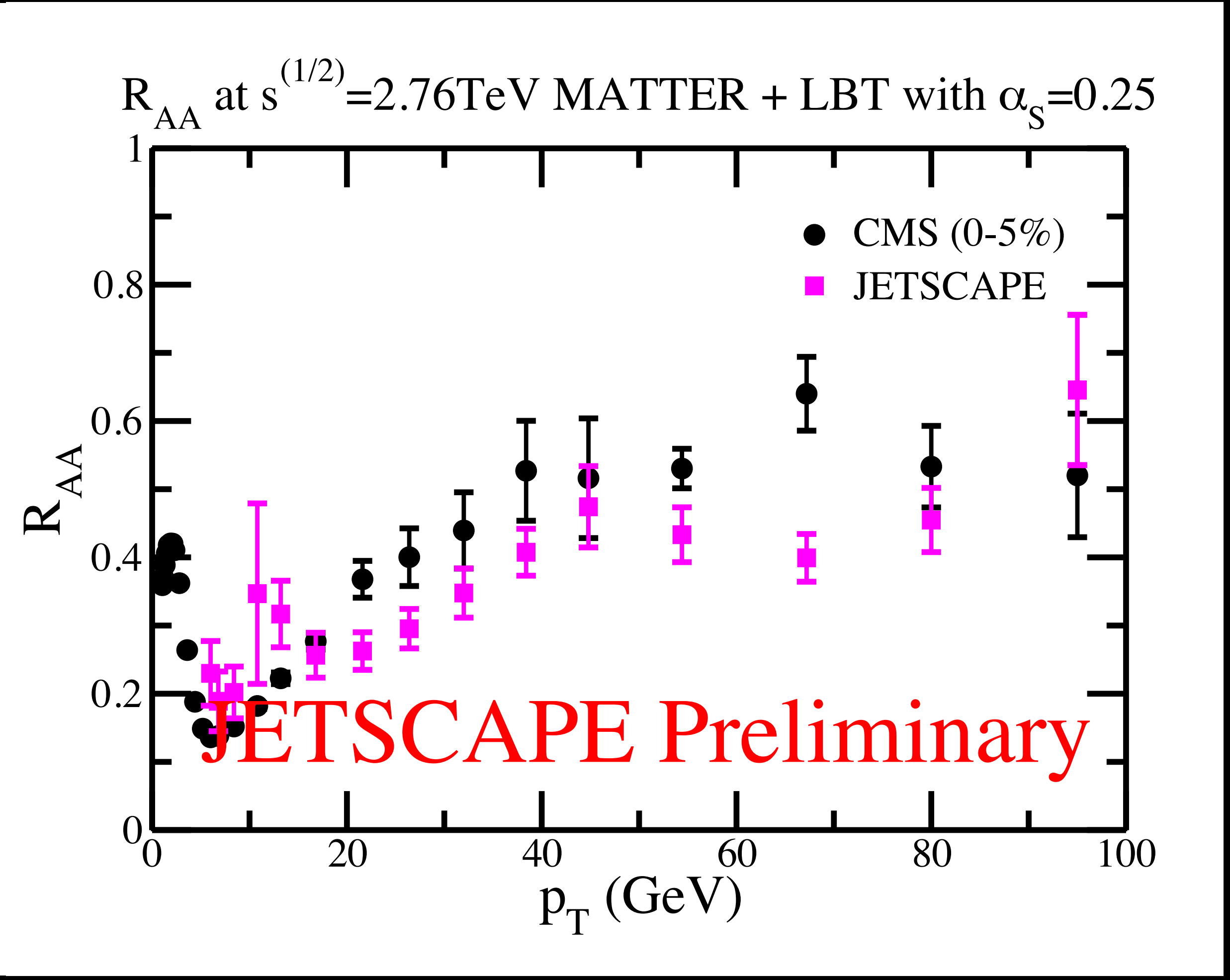
TRENTO —> PreEquib—> MUSIC —> Soft Hadronization

TRENTO —> PYTHIA init

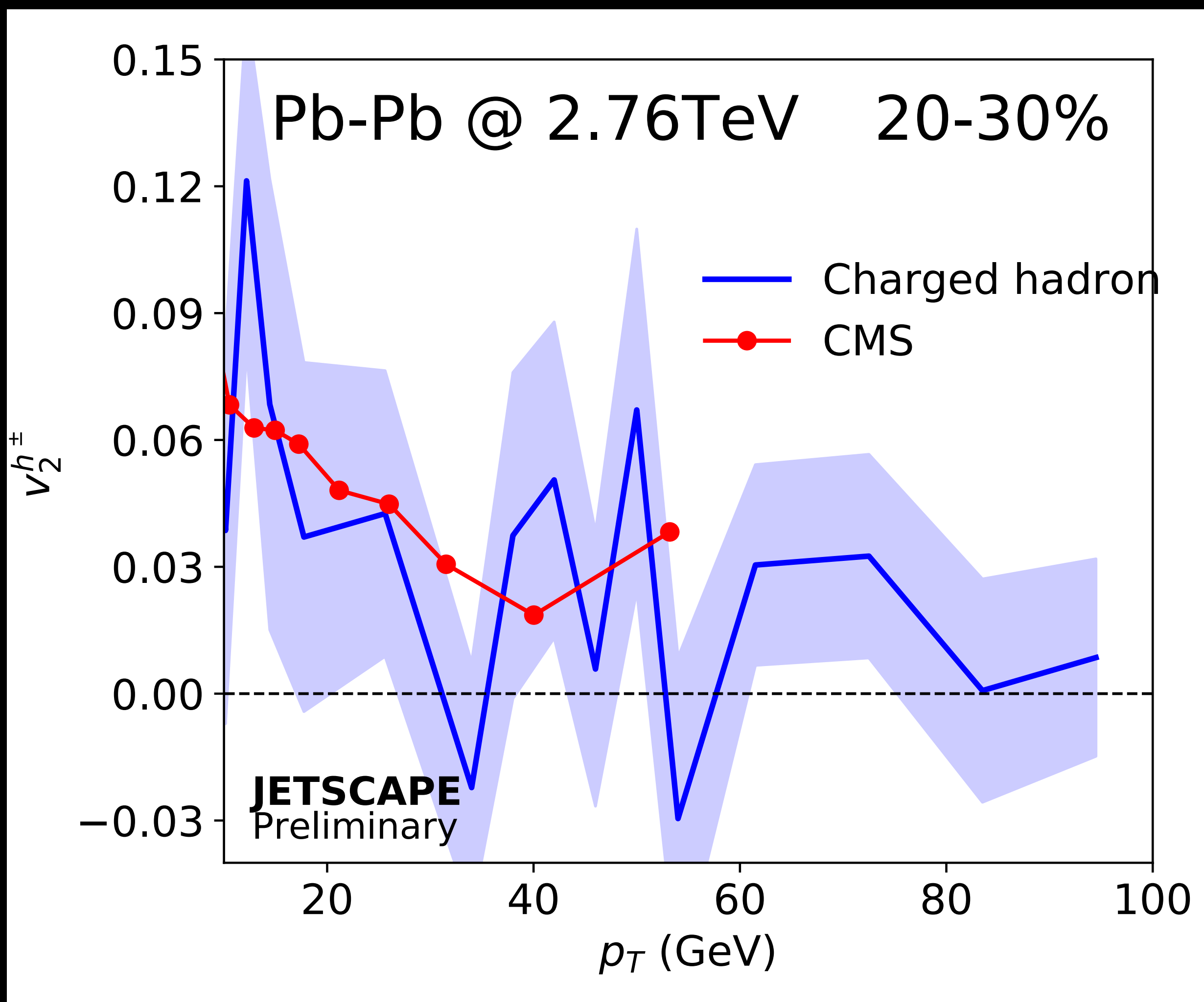
—> (MATTER/LBT/MARTINI/AdS) + MUSIC profile

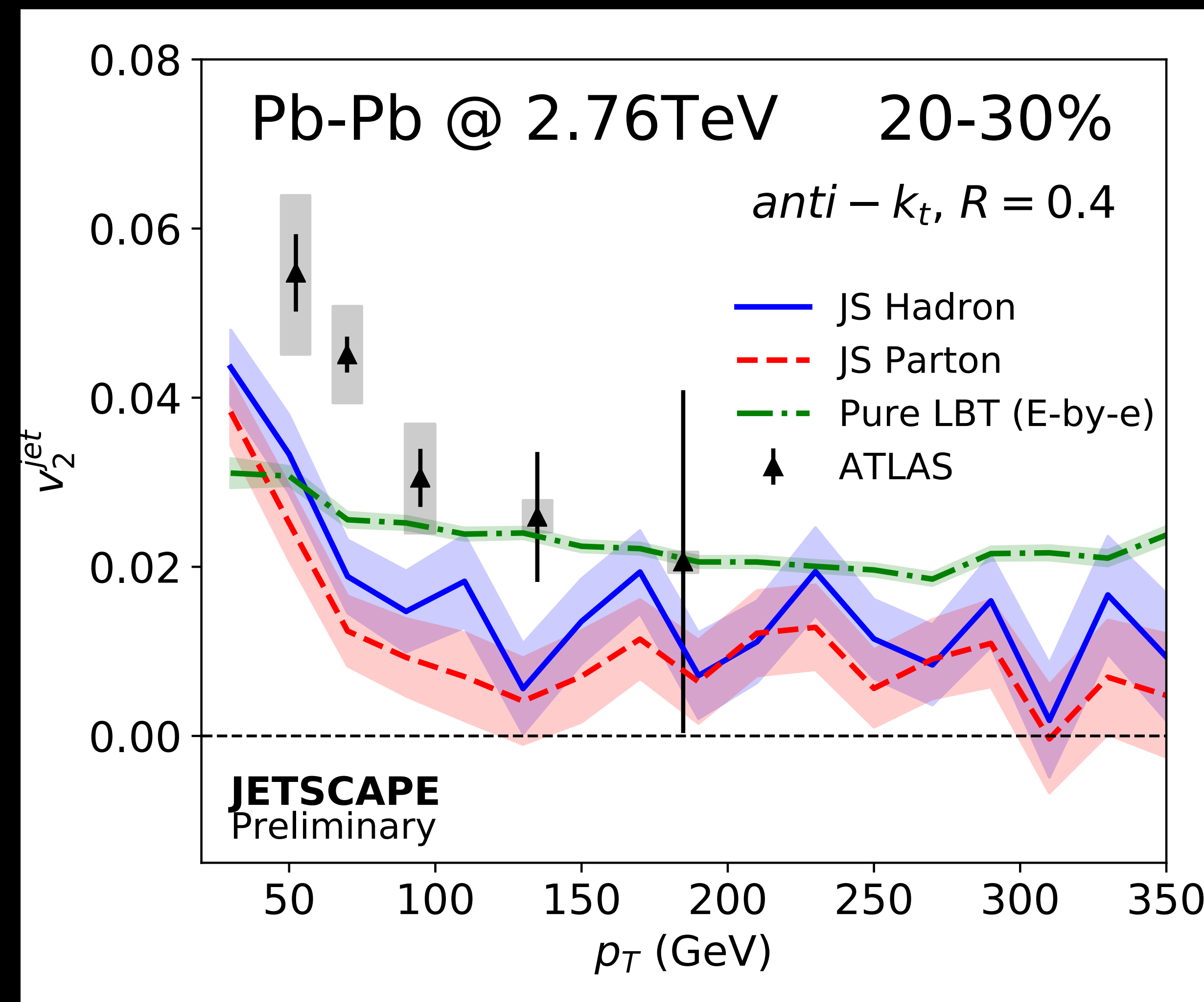
—> PYTHIA based hadronization





Jet and leading hadron v_2

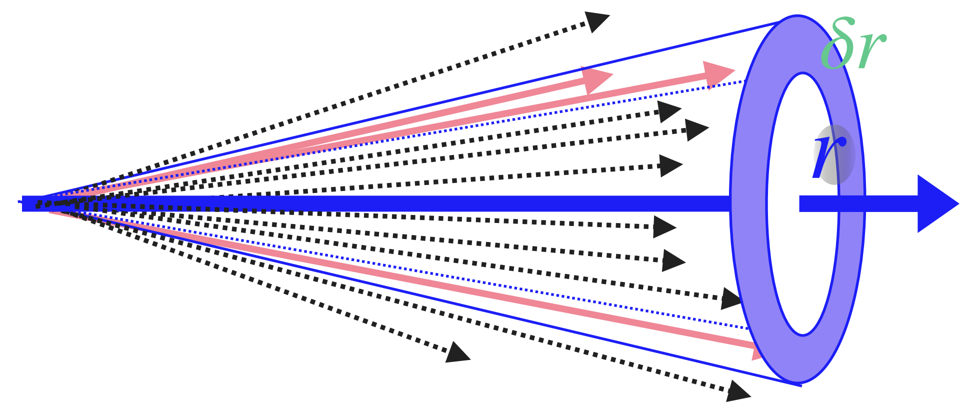




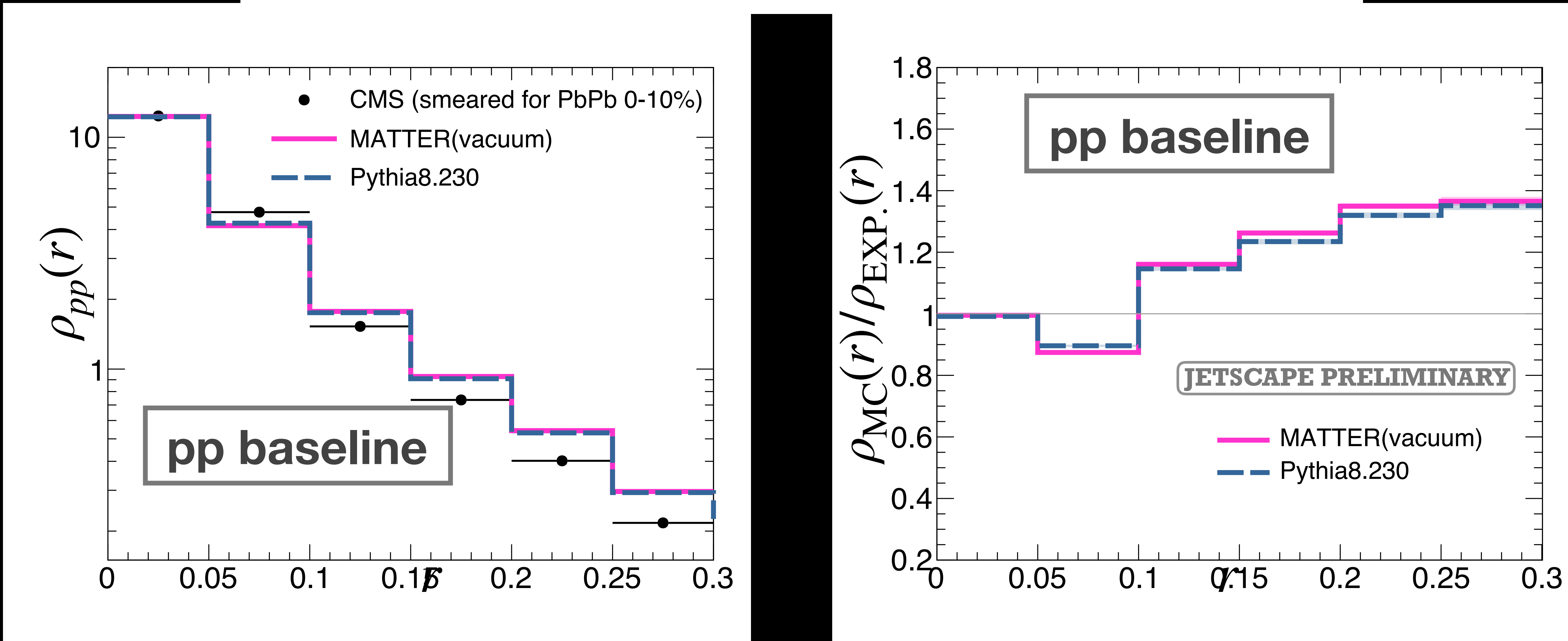
Need event-by-event hydro and initial state to hydro adjustments

Jet shape

$$\rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[\frac{1}{p_{\text{T}}^{\text{jet}}} \frac{\sum_{\text{trk}\in(r-\delta r/2,\, r+\delta r/2)} p_{\text{T}}^{\text{trk}}}{\delta r} \right]$$



JETSCAPE, pp 2.76 TeV, anti-k_{T} $R = 0.3$, $p_{\text{T}}^{\text{jet}} > 100$ GeV, $0.3 < |\eta_{\text{jet}}| < 2.0$, $p_{\text{T}}^{\text{trk}} > 1$ GeV

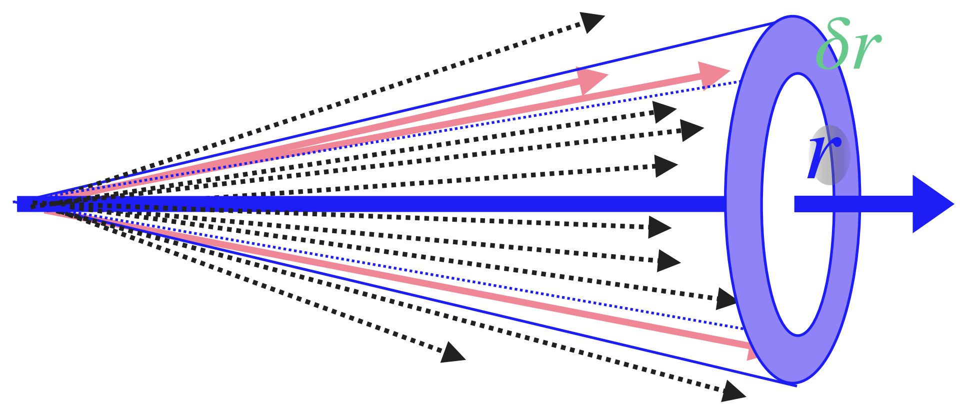


p_{T} in angular bins from jet axis

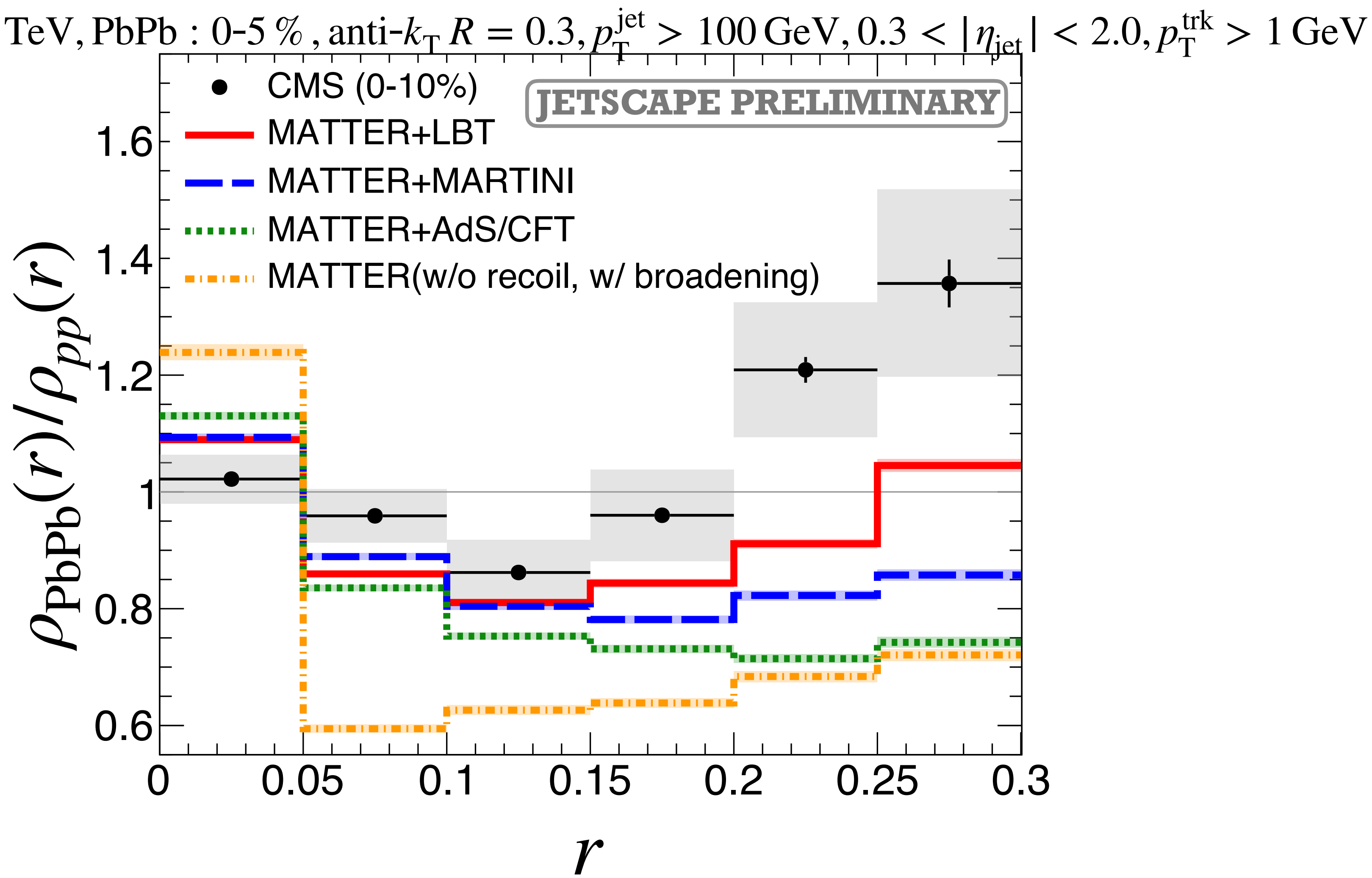
Jet Shape

$$\rho(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[\frac{1}{p_T^{\text{jet}}} \frac{\sum_{\text{trk} \in (r-\delta r/2, r+\delta r/2)} p_T^{\text{trk}}}{\delta r} \right]$$

note: self-normalized observable



PbPb/pp



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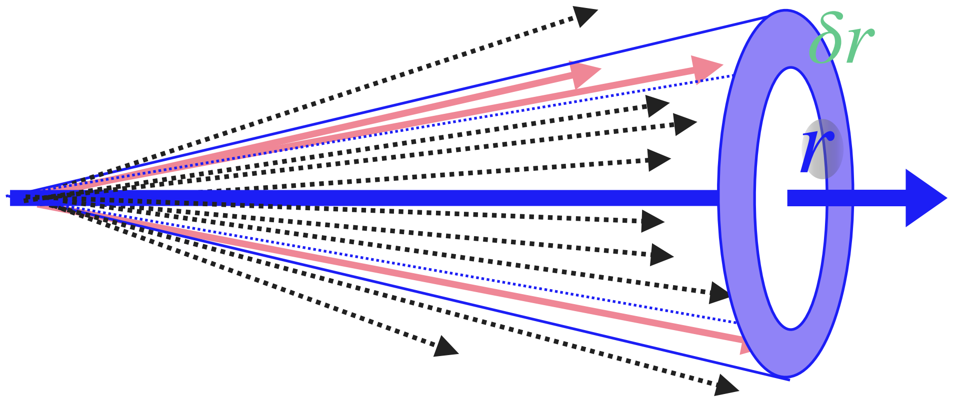

JETSCAPE, 2.76 TeV, PbPb : 0-5 % , anti-k_{T} $R = 0.3$, $p_{\mathrm{T}}^{\mathrm{jet}} > 100$ GeV, $0.3 < |\eta_{\mathrm{jet}}| < 2.0$, $p_{\mathrm{T}}^{\mathrm{trk}} > 1$ GeV

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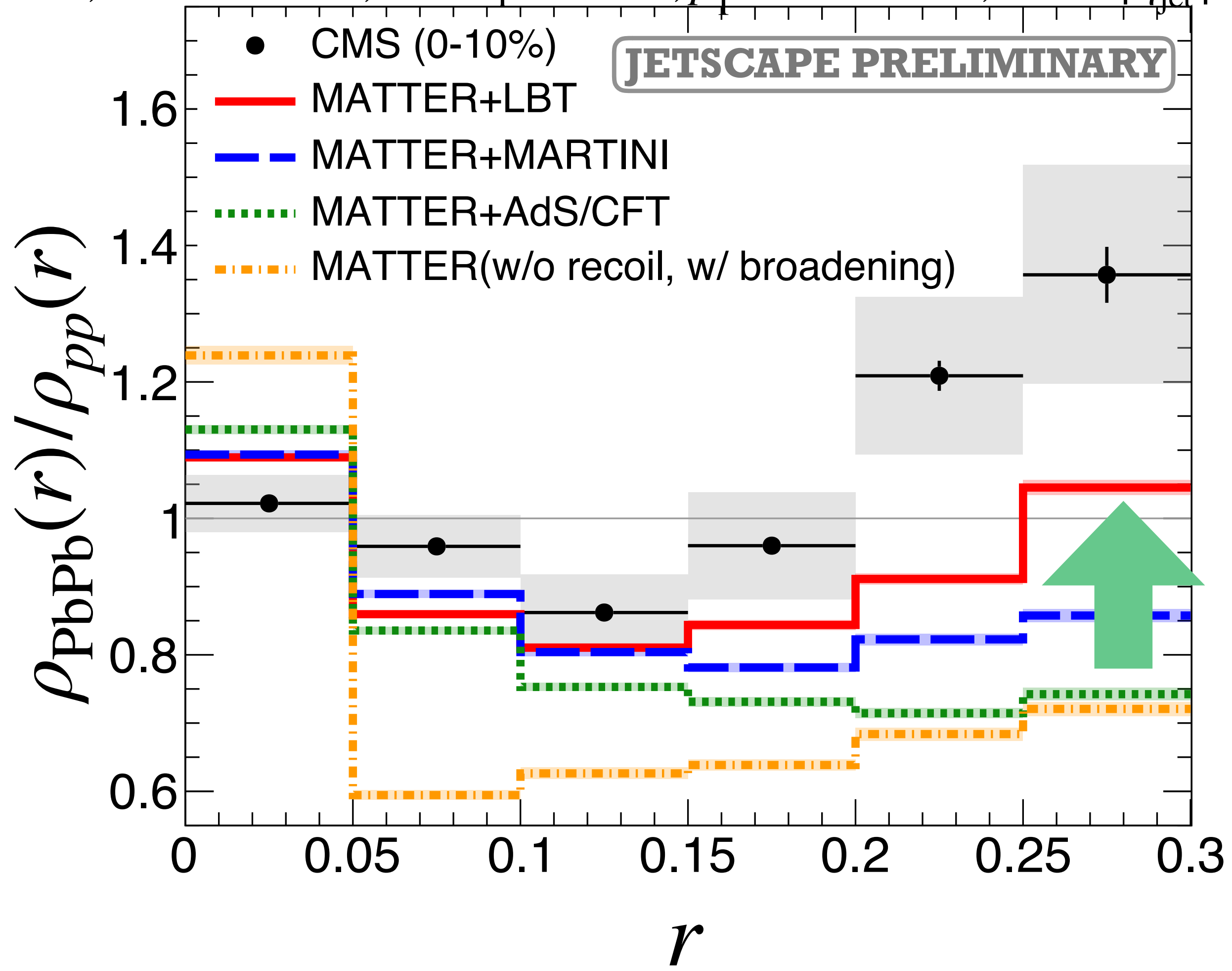
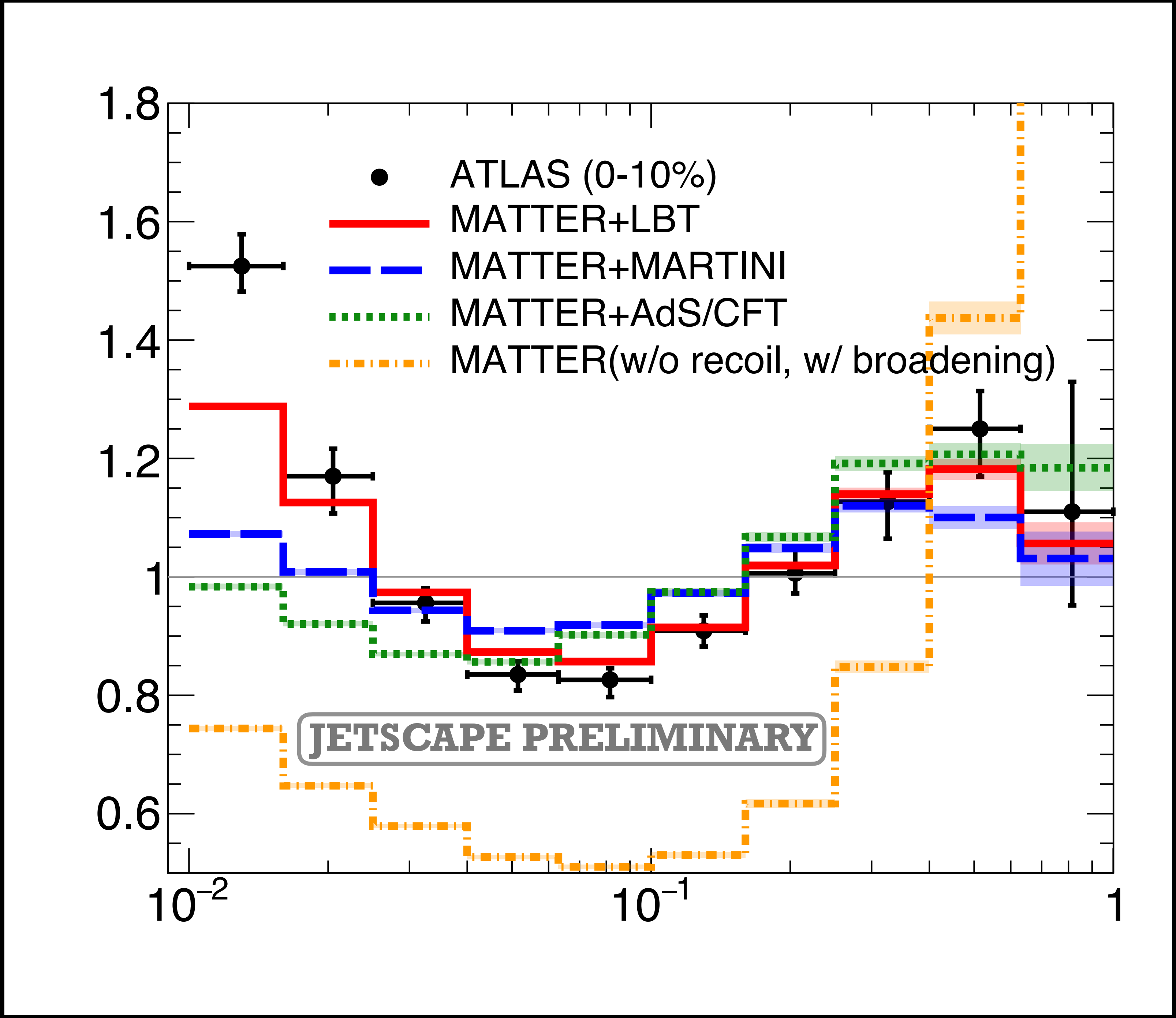


Fragmentation function



fraction of energy carried by hadrons in jet

Outcome from JETSCAPE

1) Very good description of most of the data
2) Minor discrepancies in p-p: need better tuning
3) Minor discrepancies in A-A: better phenomenology (modeling medium response)
4) Plain broadening or drag does not seem to work
5) Partonic recoil has a lot of success (Sensitivity to recoil kernel?)

Going from AA to eA

1) No hadronic energy loss
2) Minimal hadronic response
3) Hadronization in a hadronic medium?
4) Simulation of event activity
5) Simulation of TMDPDFs/GPDs/spin dependent objects

Modeling differences in leading hadrons

Assuming nuclear PDF =

A X nucleon p. d. f.

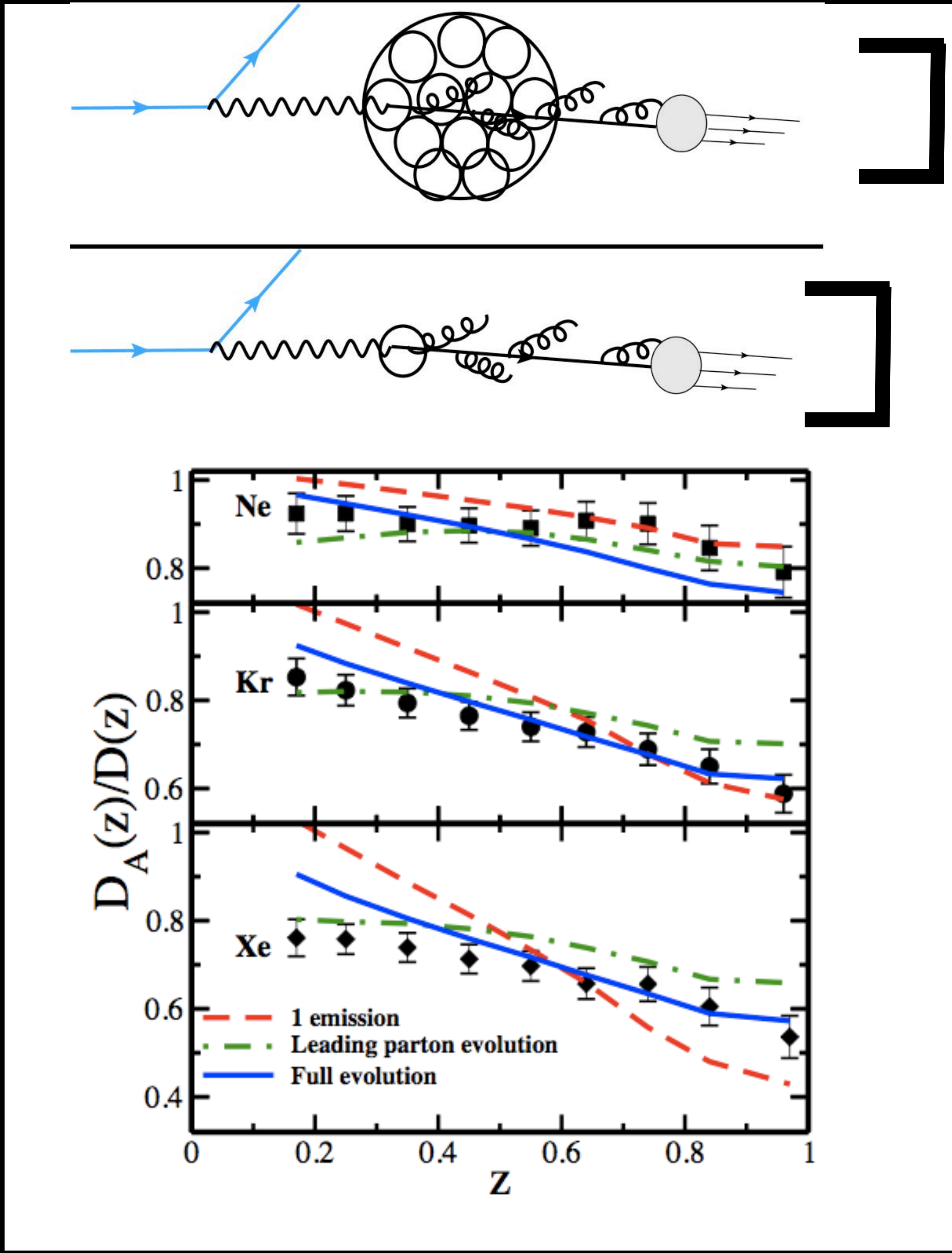
Data from HERMES at DESY

Three different nuclei

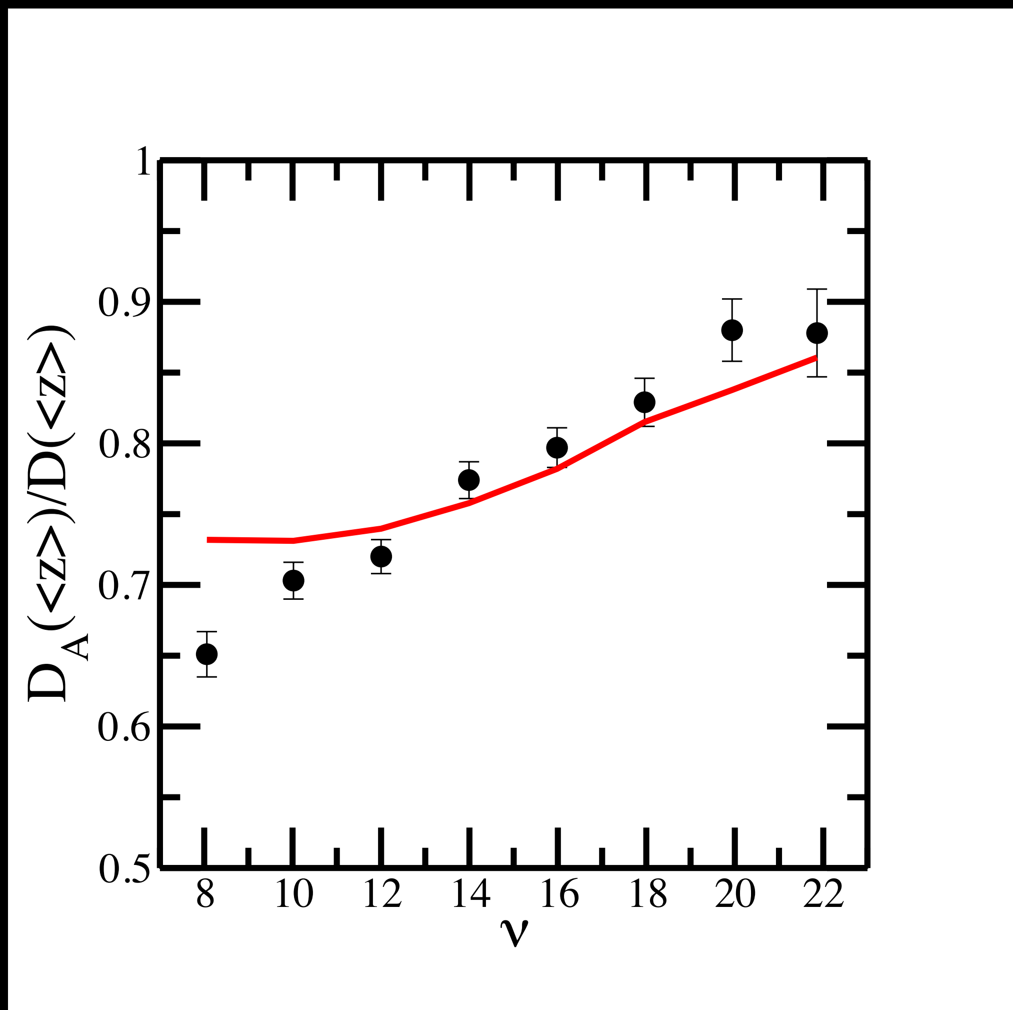
one $\hat{q}$ = 0.08GeV^2/fm

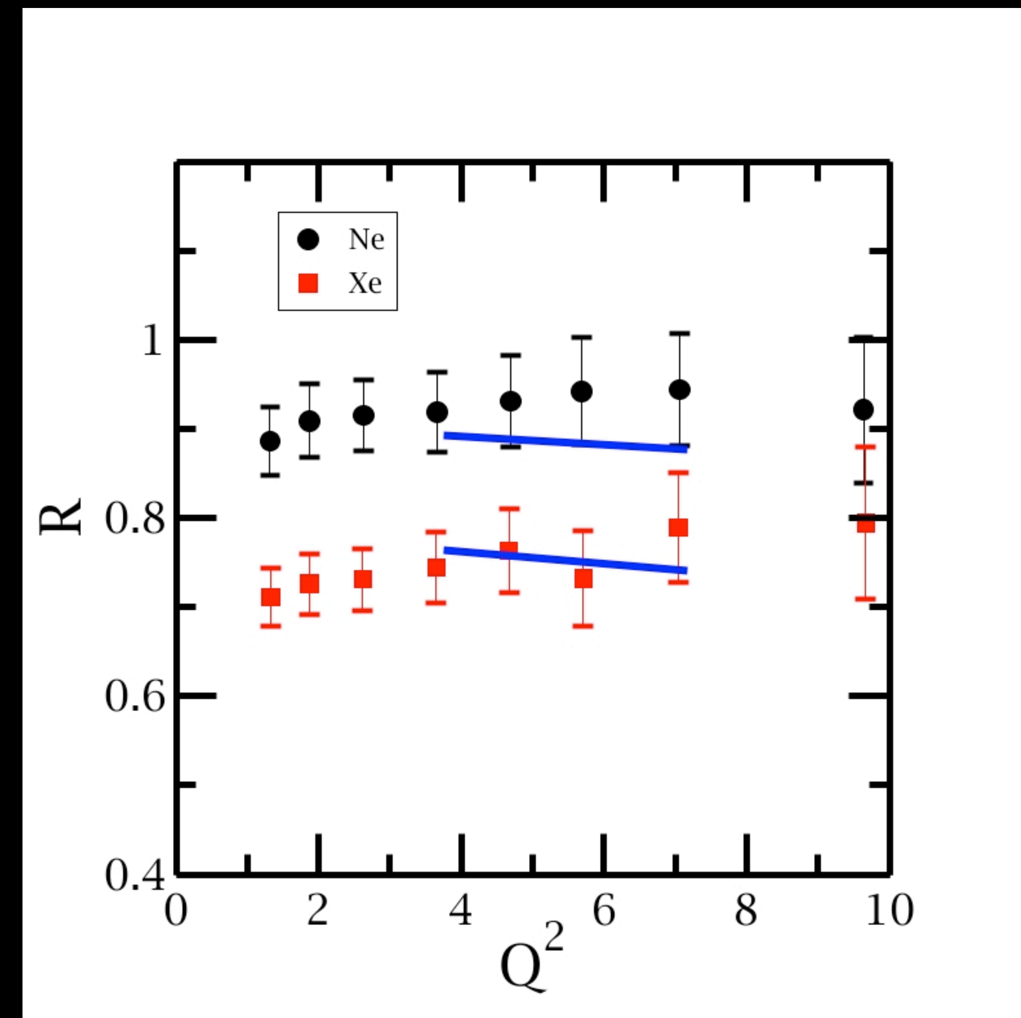
Fit one data point in Ne
everything else is prediction

Q^2=3-4 GeV^2, ν=16-20 GeV



The ν and Q^2 dependence





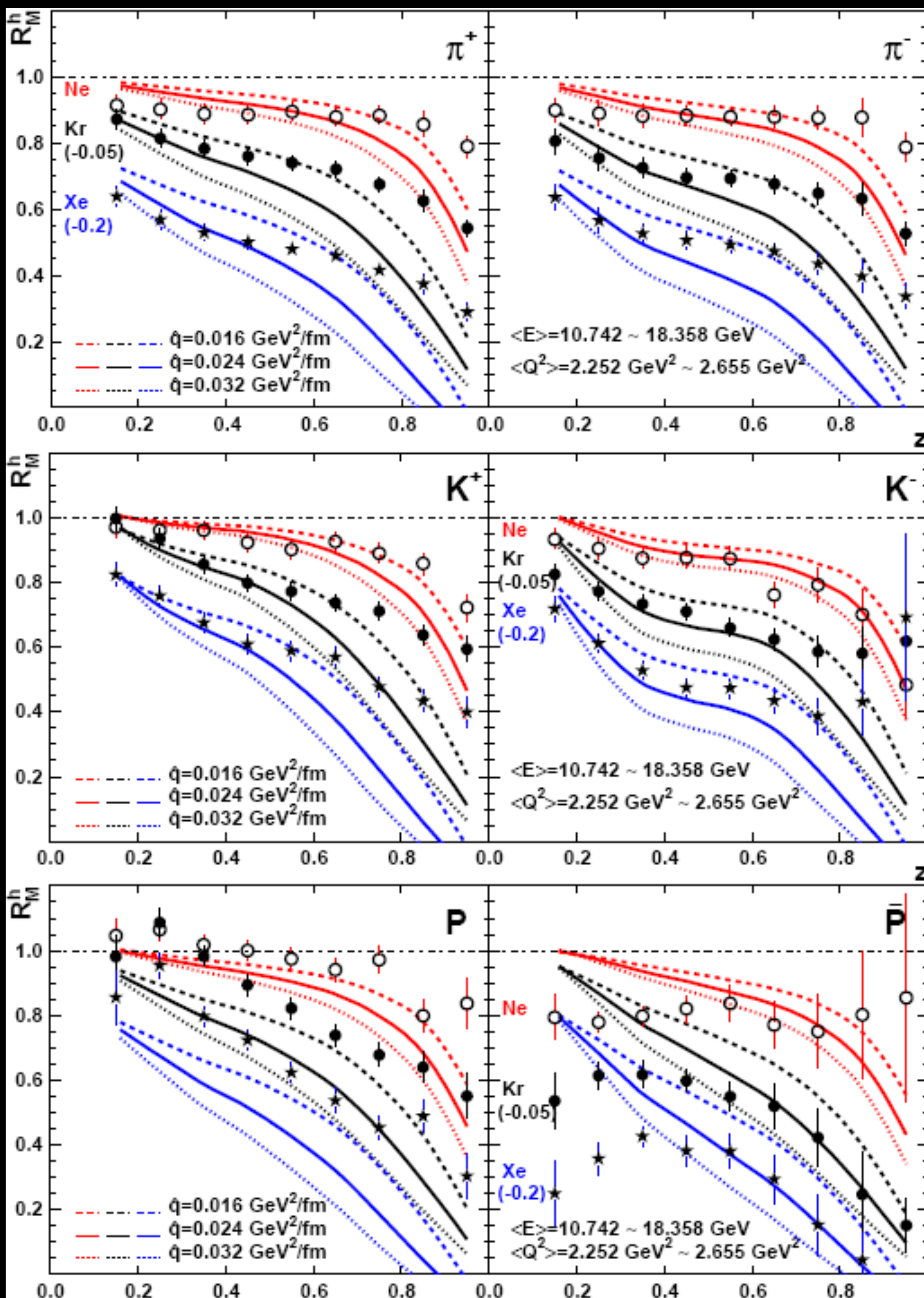
Modeling approximations made!

$$\tilde{D}(z, Q^2, \nu)\Big|_{\zeta}^{\zeta_f} \rightarrow \tilde{D}(z, Q^2, \nu)\Big|_{\zeta_i}^{\zeta_f}$$

Xin-Nian's version

instead of vacuum FF as input

use a real Medium modified FF

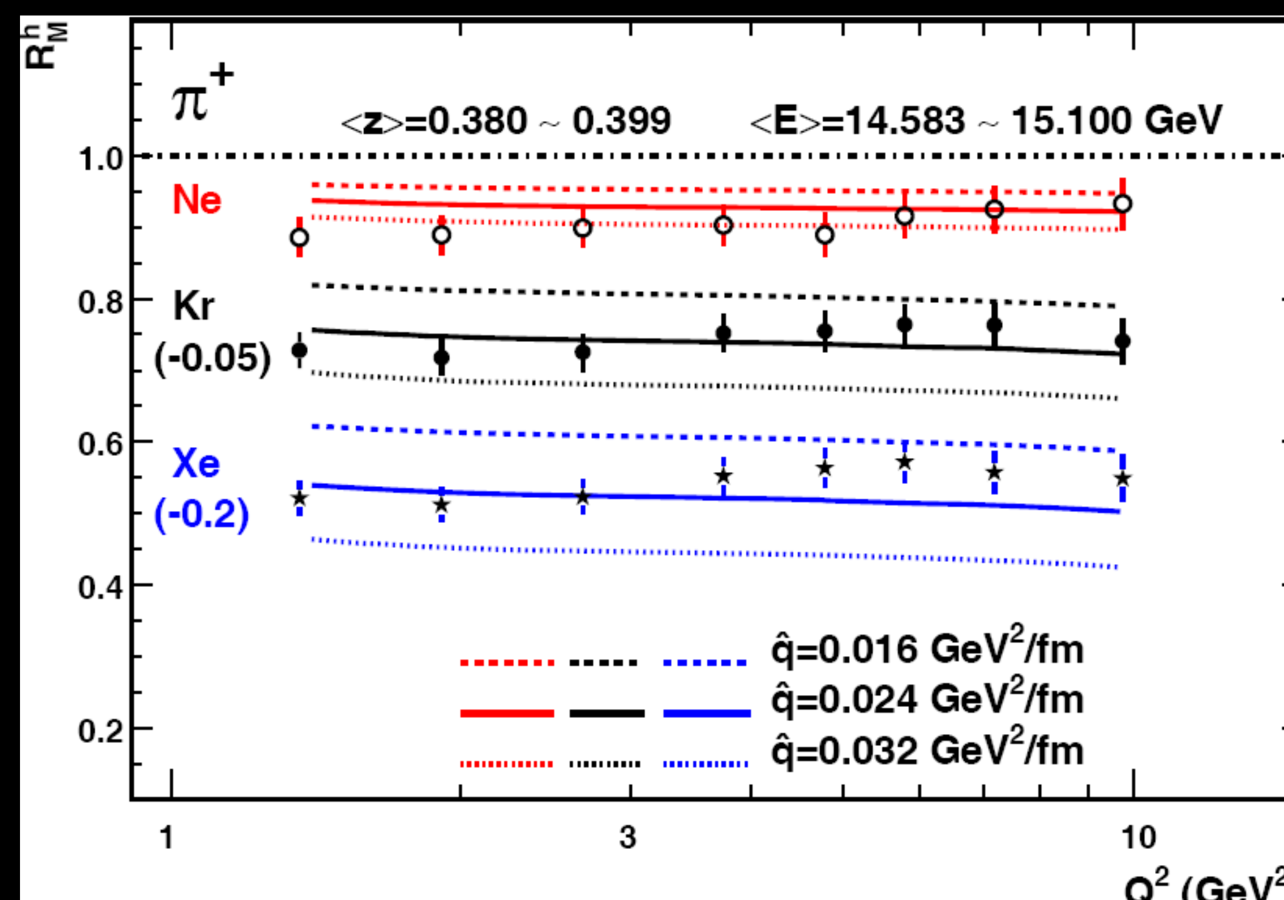


Idea:Jet never drops below

μ = 1 GeV

in principle the MMFF input

has to be measured in expt.



Thank you for your attention!