Jet Tomography at Lower Energies and the temperature dependence of Jet transport coefficients

A. Majumder

Wayne State University

Annual meeting of the Division of Nuclear Physics of the APS, New Port Beach, CA,

Jet modification in simple pictures

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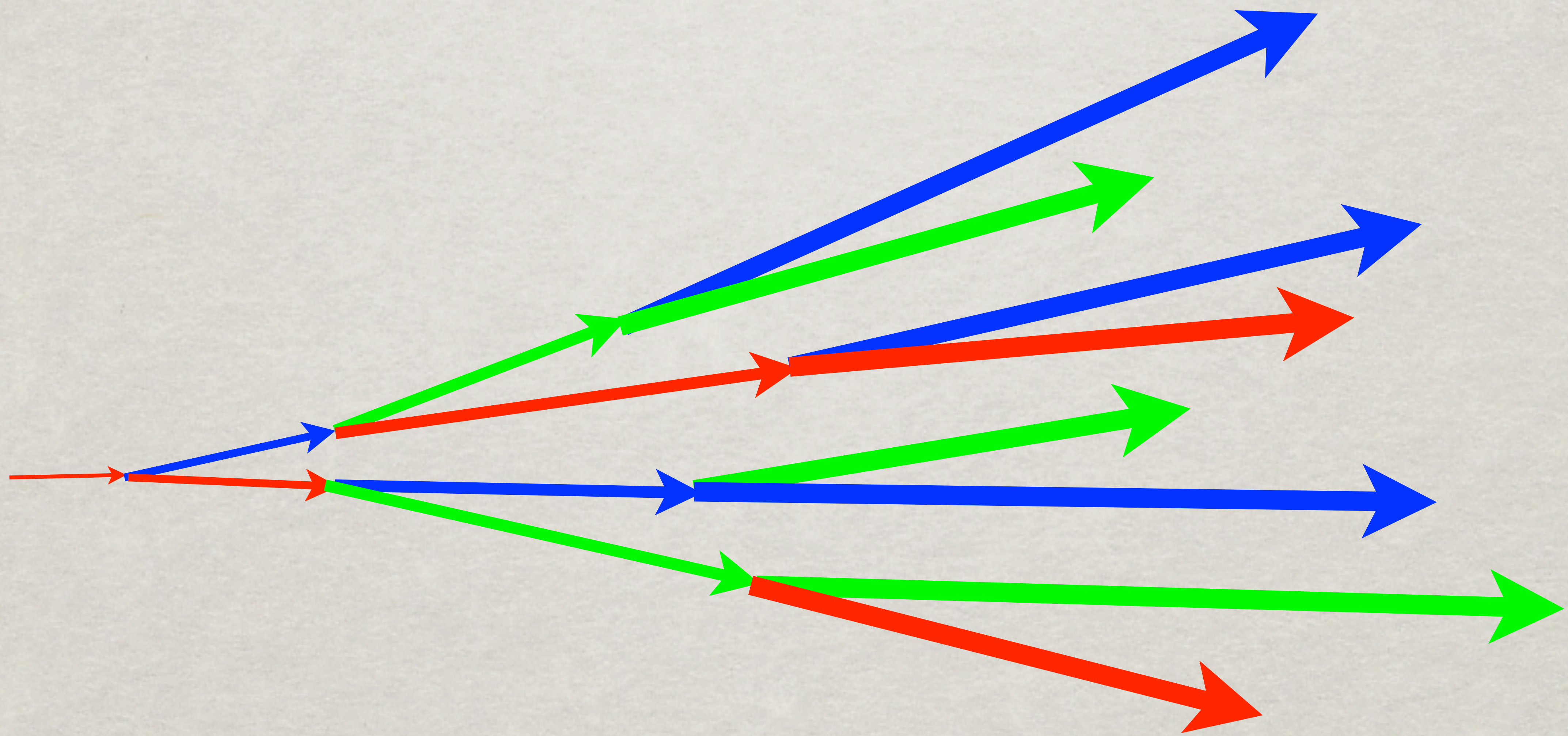
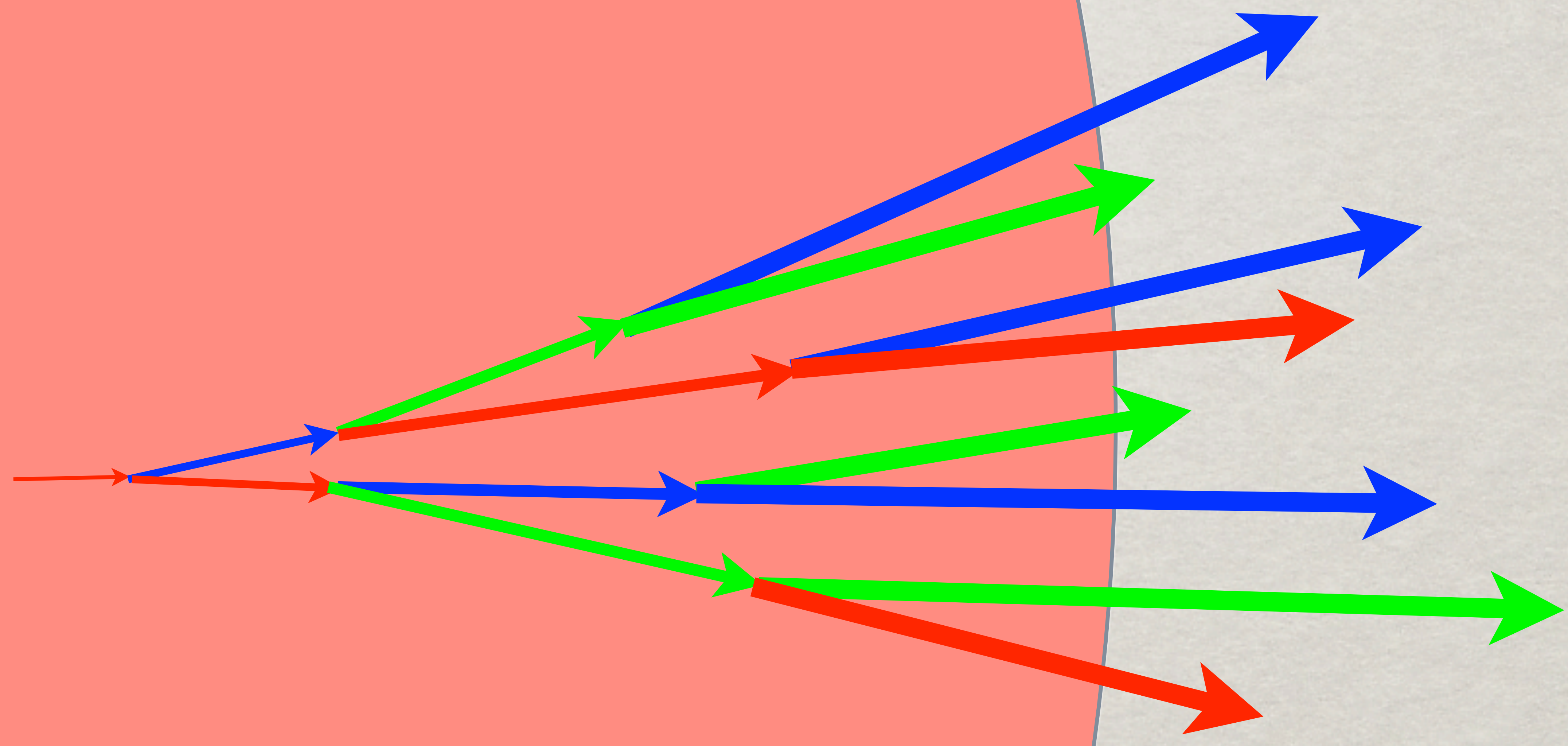


Jet modification in simple pictures



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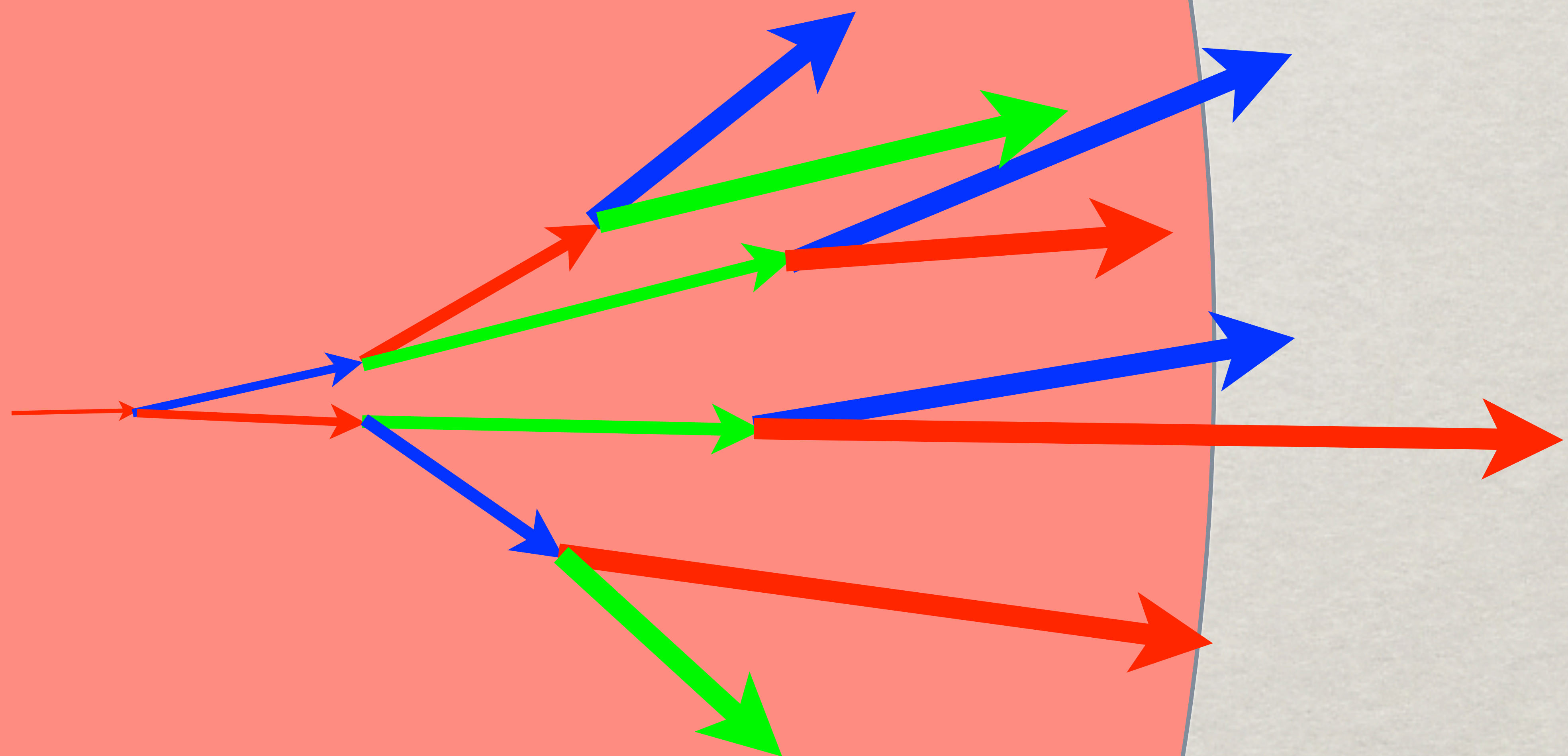

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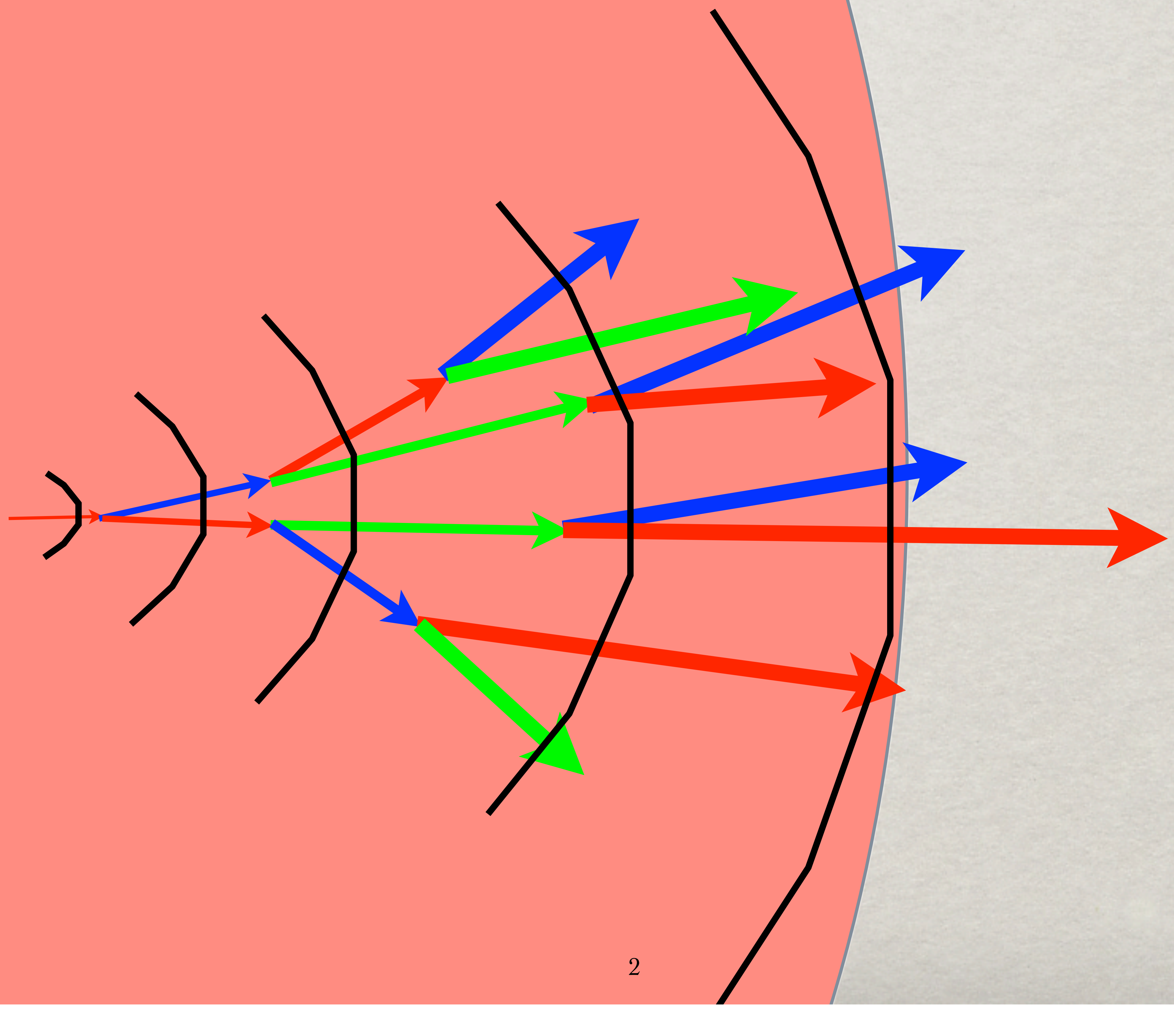

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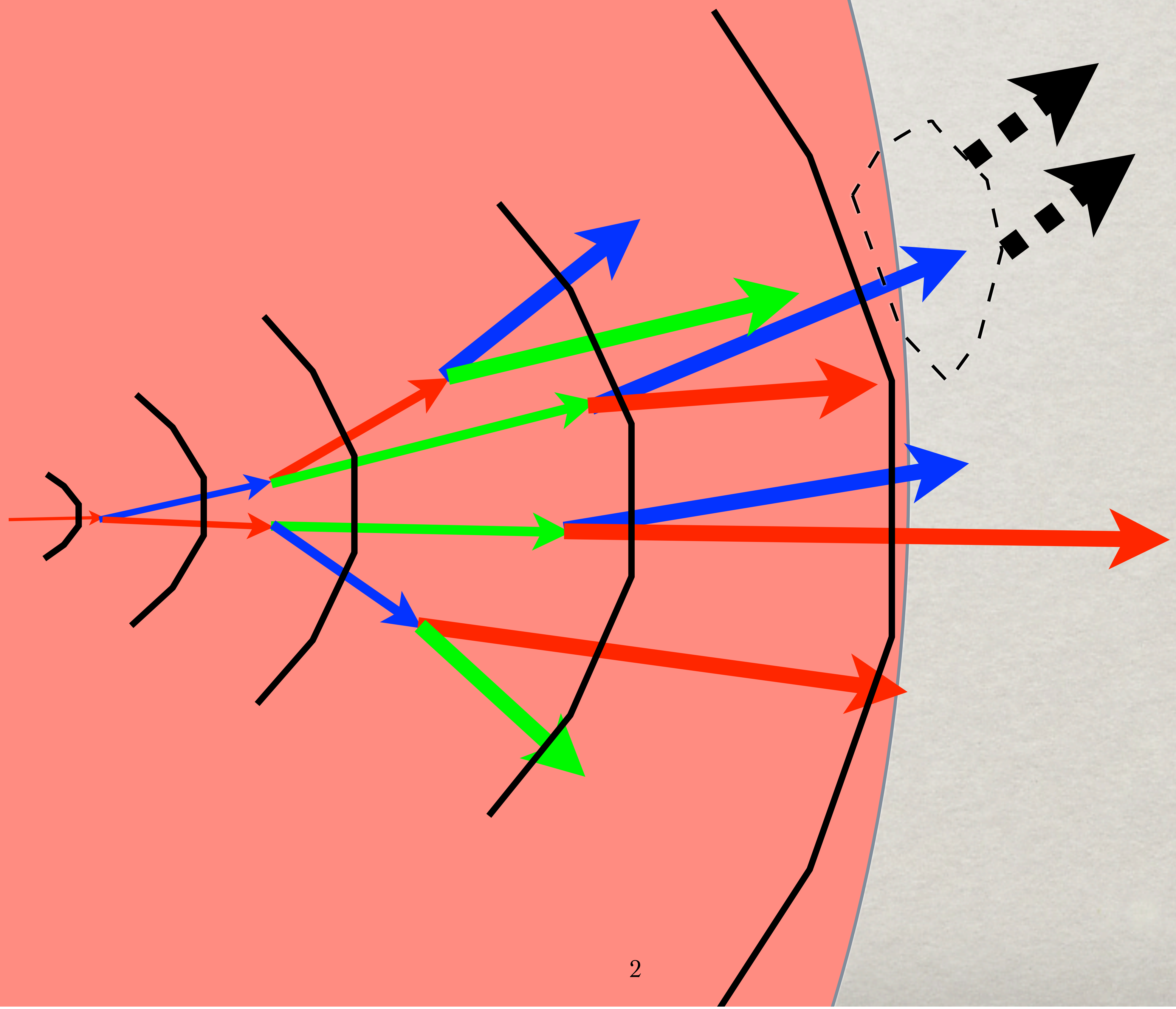

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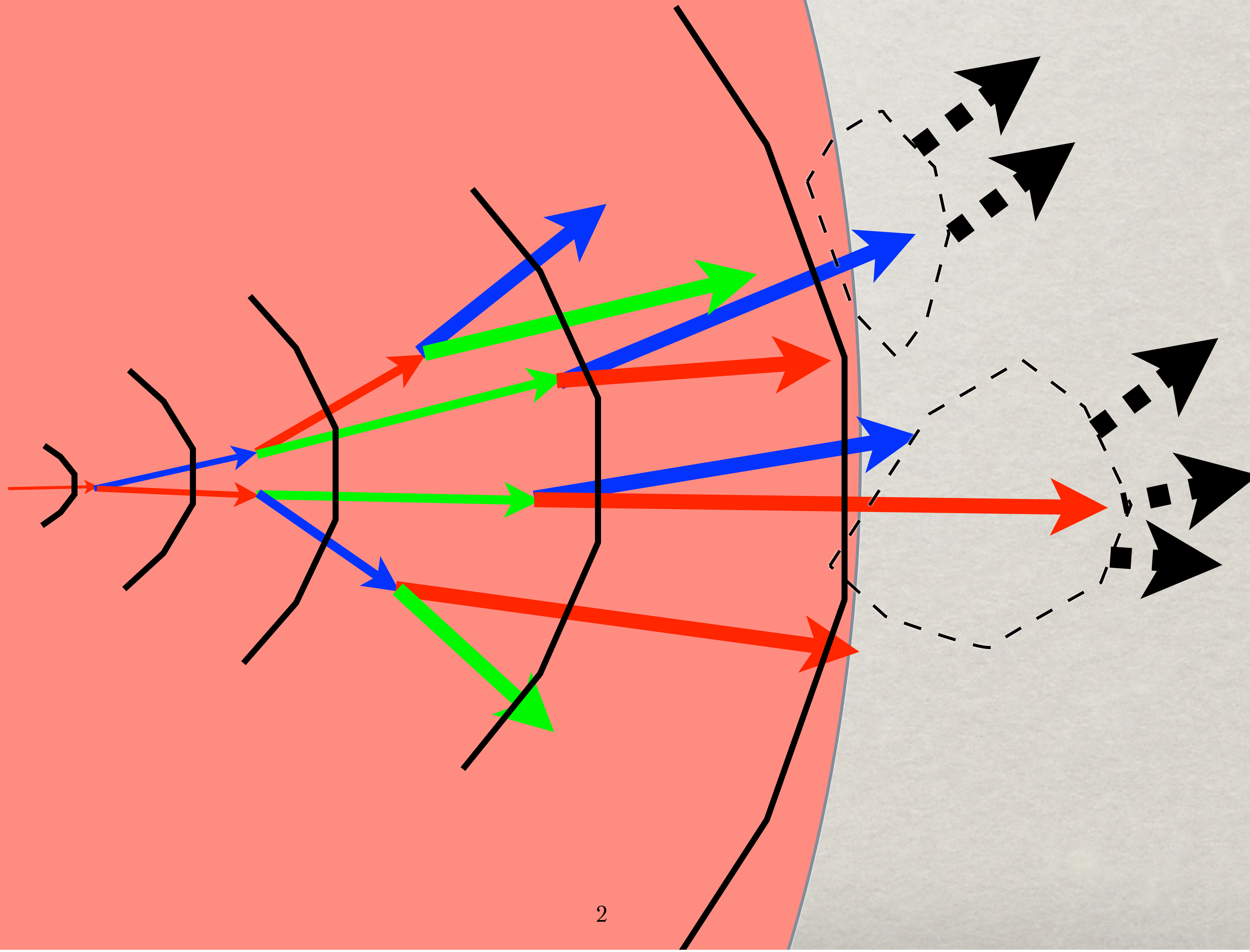
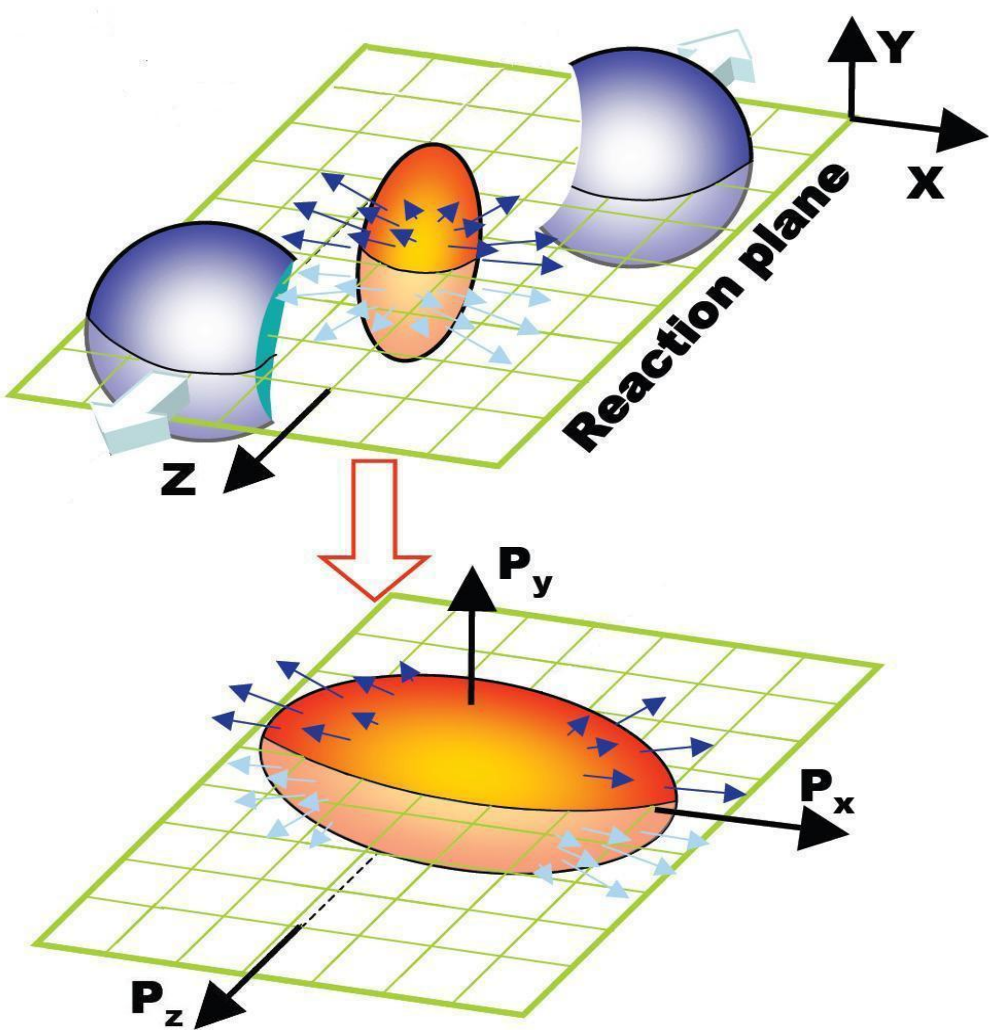
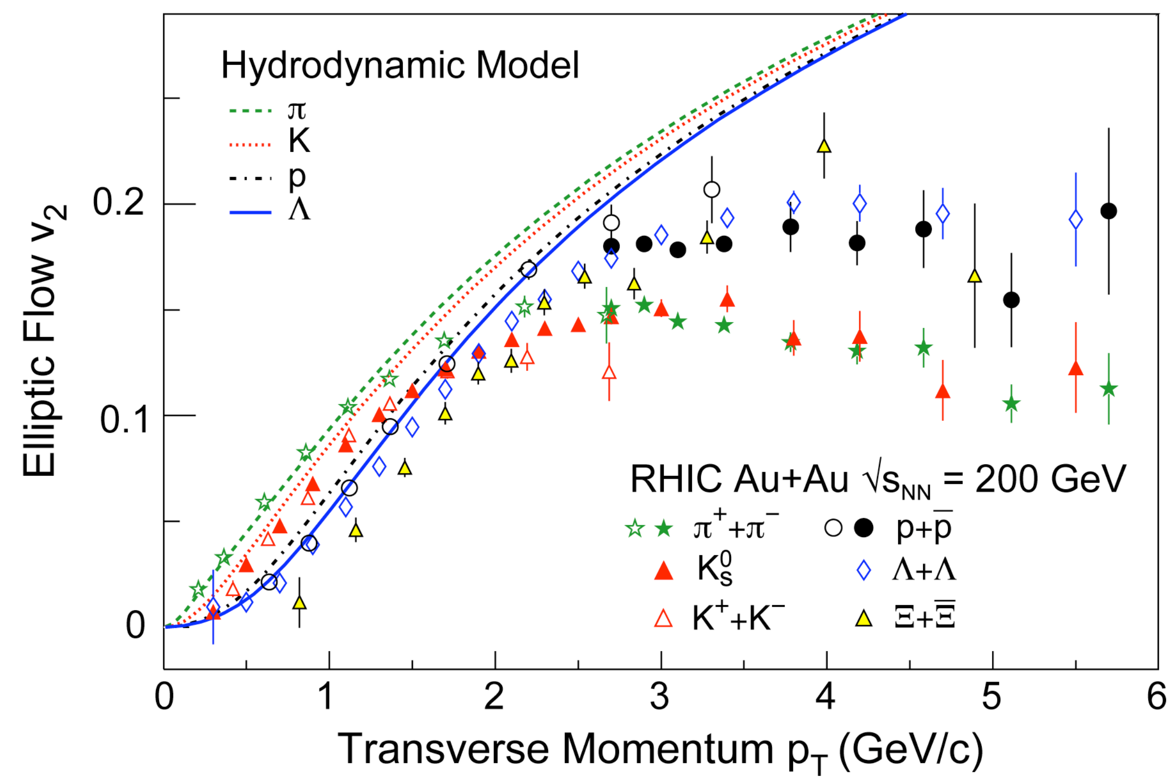


The current paradigm for high energy HIC

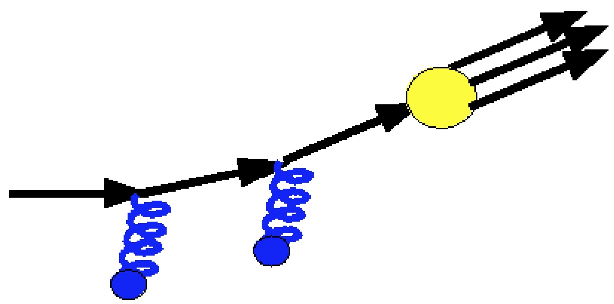
Soft medium described by viscous fluid dynamics,





Ideal Hydro calculations by P. Houvinen, also Kolb and Heinz, Teaney, Lauret, Shuryak, and Nonaka and Bass

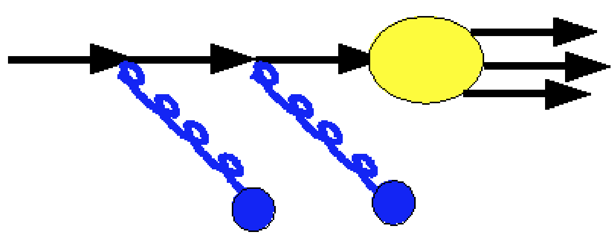
Hard jets described by pQCD
with factorized transport coefficients



$$D\left(\frac{\vec{p}_h}{|\vec{p}+\vec{k}_\perp|}, m_J^2\right)$$

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

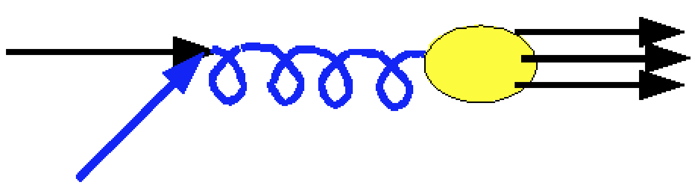
Transverse momemtum diffusion rate



$$D\left(\frac{p_h}{p-k}, m_J^2\right)$$

$$\hat{e} = \frac{\langle p_z \rangle_L}{L}$$

Elastic energy loss rate also diffusion rate e_2



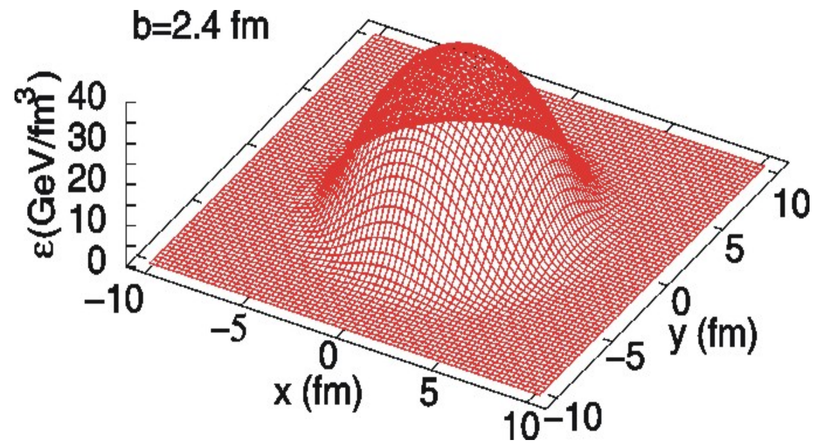
$$D_g\left(\frac{p_h}{p+k}, m_J^2\right)$$

$$\hat{f} = \frac{\langle \Delta N \rangle_L}{L}$$

Flavor (q $\leftrightarrow$ g) diffusion rate

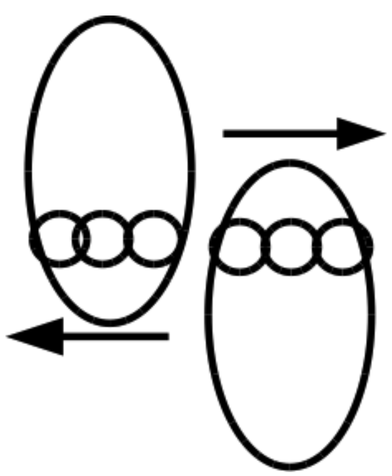
Non-perturbative transport coefficients represent medium's influence in jet quenching calculations

Fit the $\hat{q}$ for the initial T in the hydro in central coll.

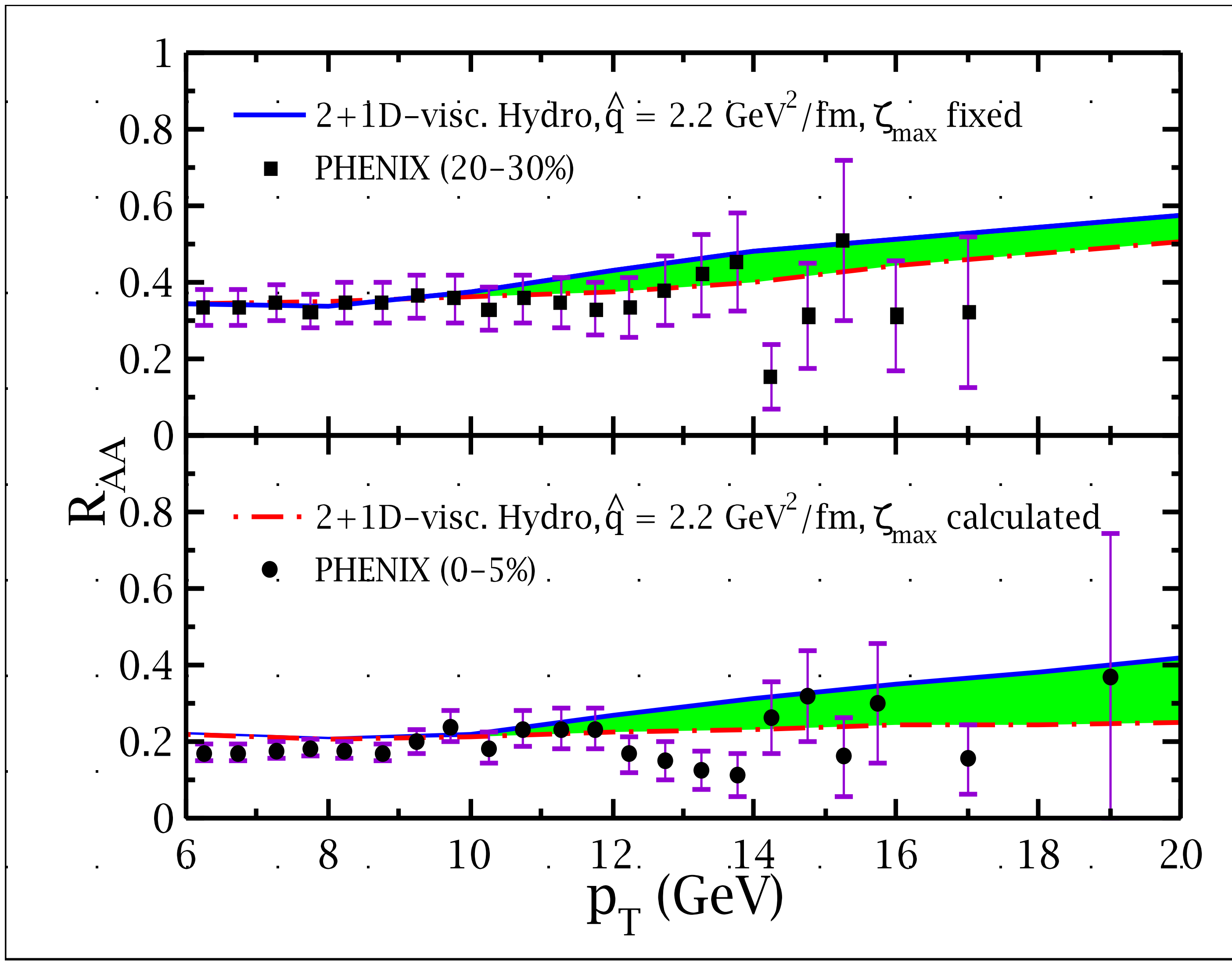


$$\hat{q}(\vec{r},t) = \hat{q}_0 \frac{s(\vec{r},t)}{s_0}$$

$$s_0 = s(T_0)$$



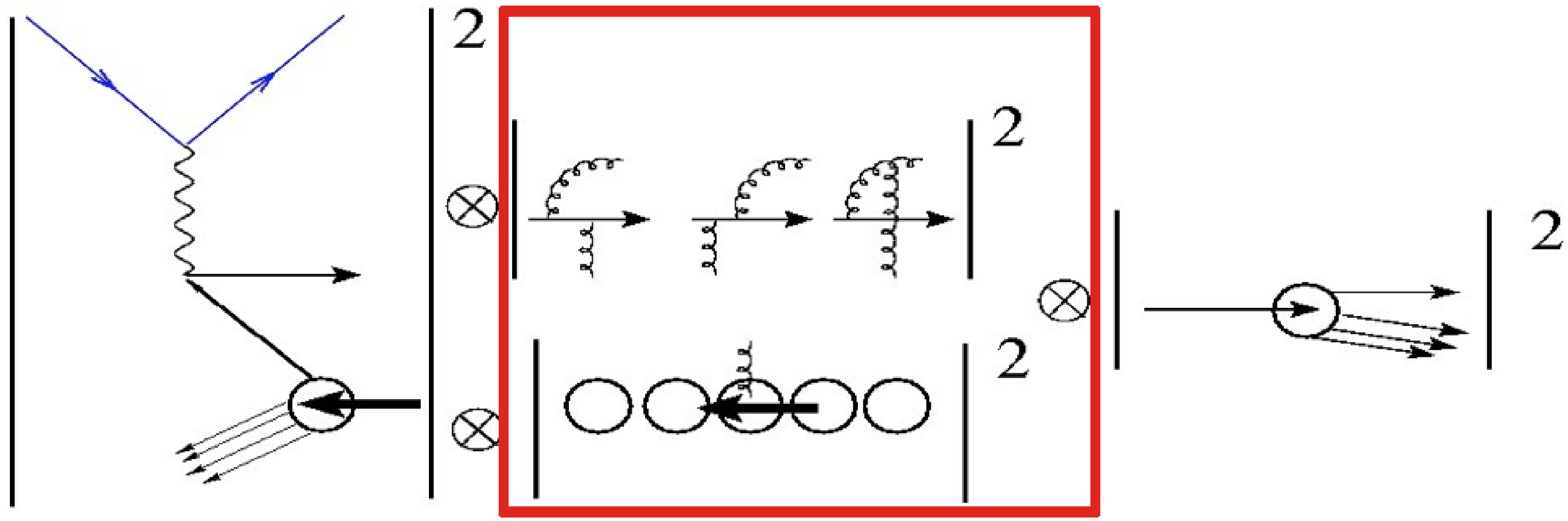
$$R_{AA} \sim \frac{\frac{dN_{AA}}{dp_T dy}}{N_{bin}\frac{dN_{pp}}{dp_T dy}}$$



An aside on 2 underlying assumptions

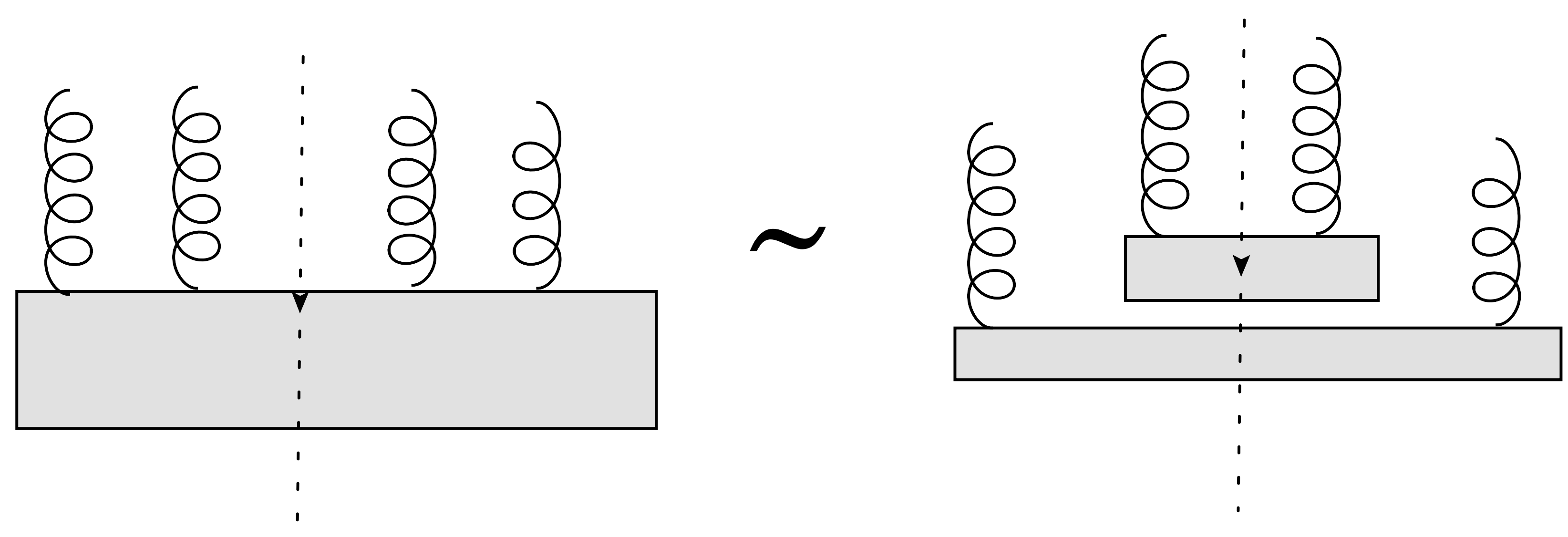
1) We will only consider very high Q^2 jets

In the maximally factorized region



2) We have assumed short correlation lengths in the medium

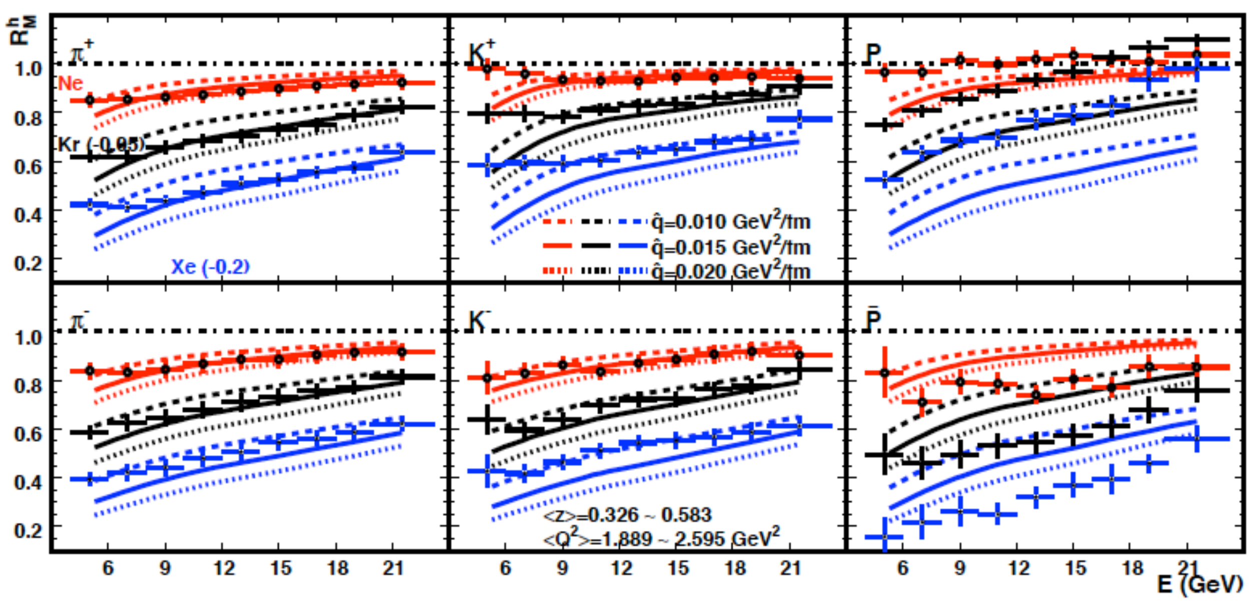
Multiple scattering 2N point correlators simplify to N 2-point correlators



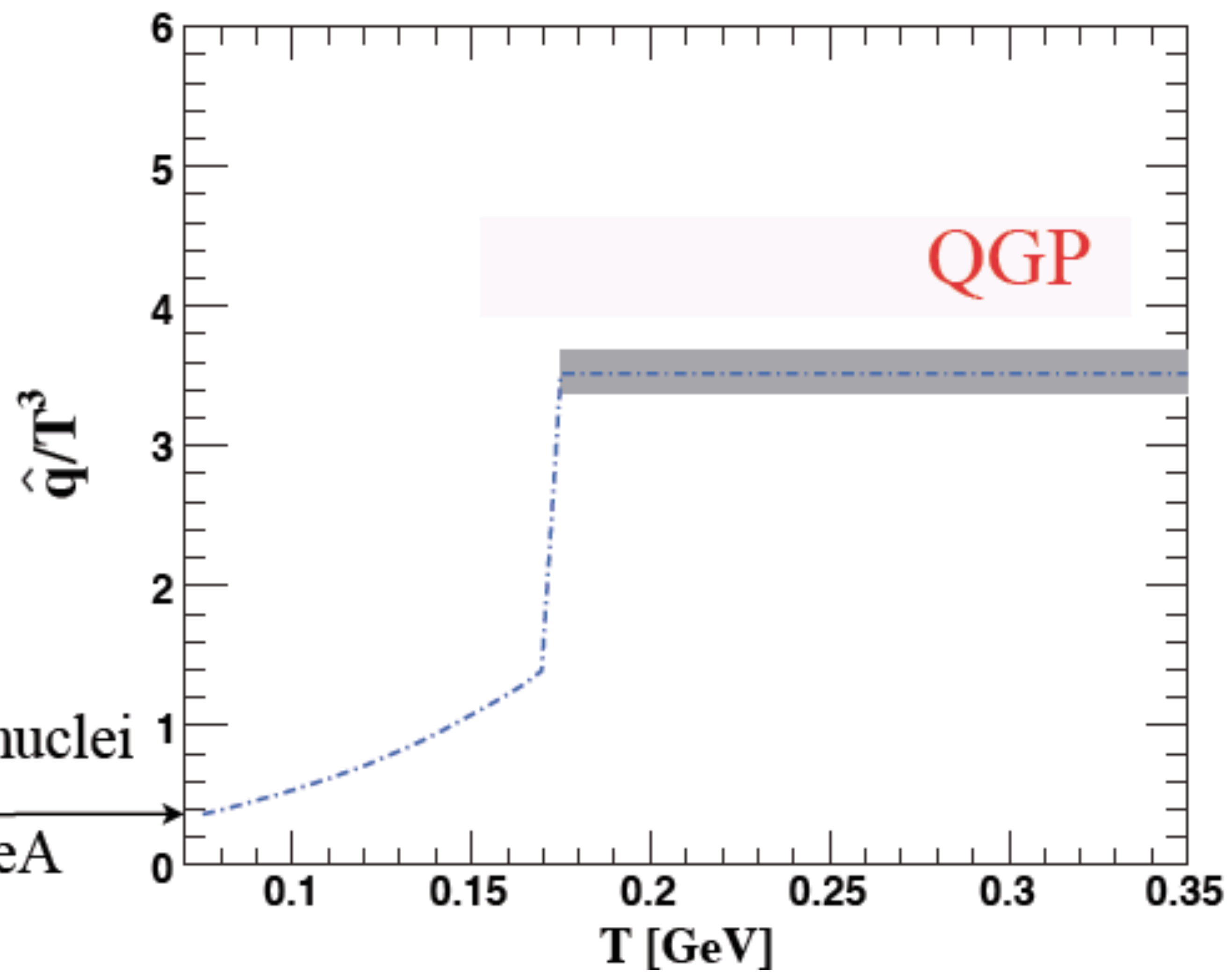
The temperature dependence of $\hat{q}$

Partly known and partly guessed!

$$\hat{q}=\frac{p_\perp^2}{t}=\frac{2\pi^2\alpha_s C_R}{N_c^2-1}\int d\tilde{t}\left\langle F^{\mu\alpha}(\tilde{t})v_\alpha F_\mu^\beta(0)v_\beta\right\rangle$$



From Deng, Chang and Wang



From Chen et. al.

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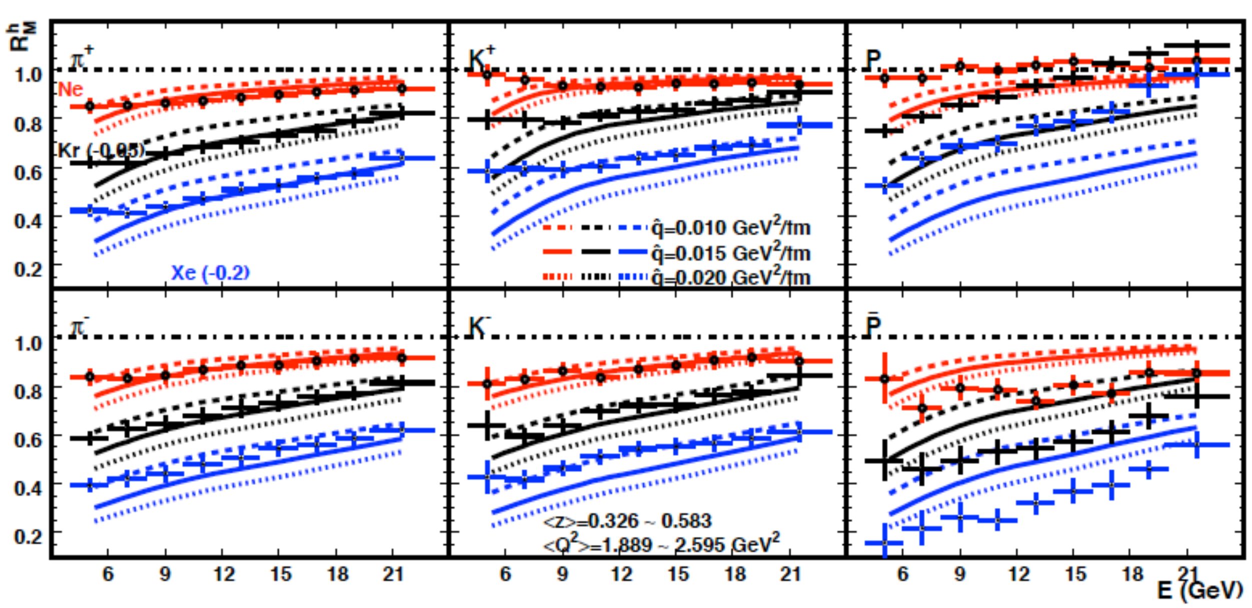

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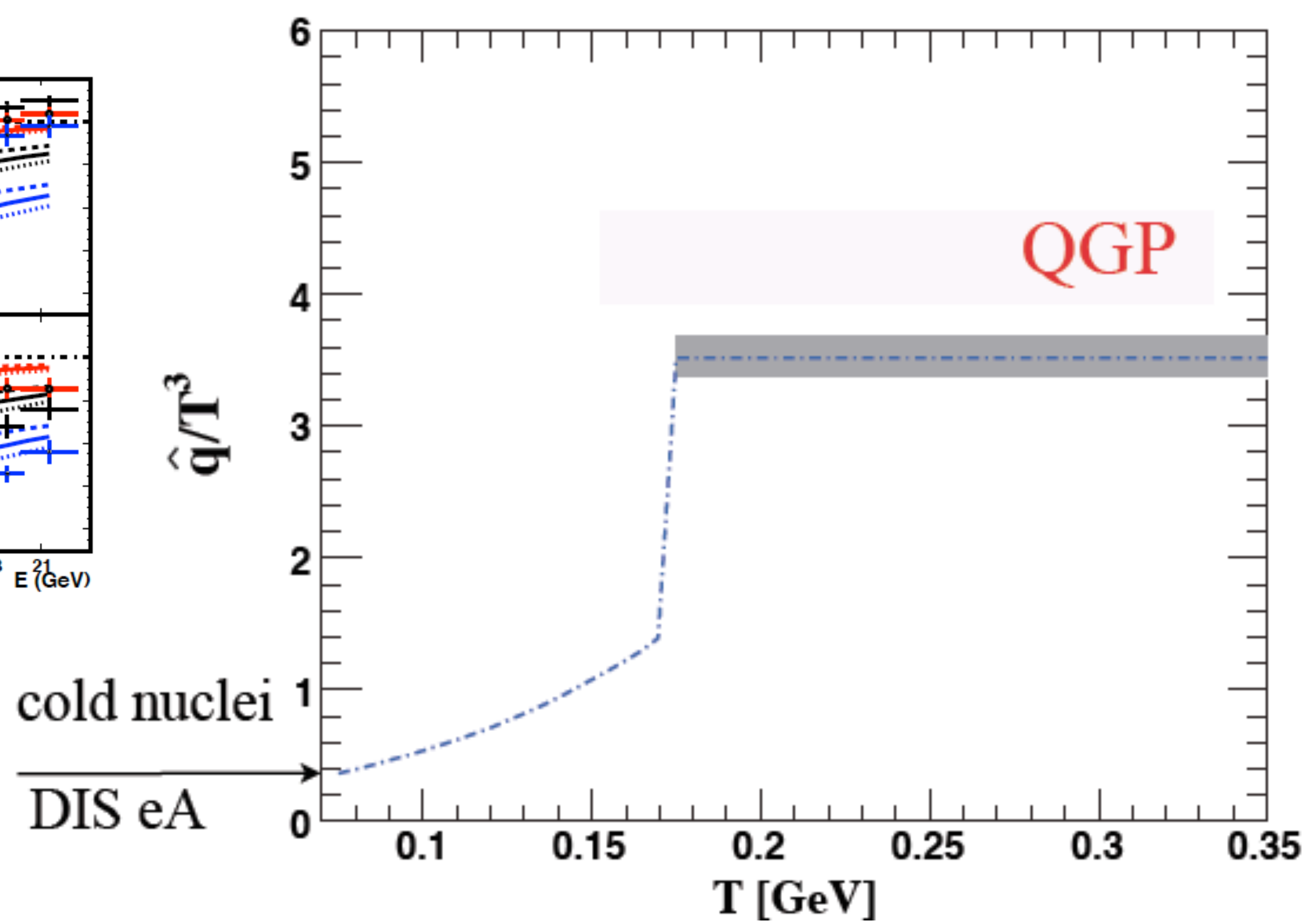

From Chen et. al.

The emerging picture in the temperature dependence of viscosity

PRL **97,** 152303 (2006) PHYSICAL REVIEW LETTERS week ending 13 OCTOBER 2006

Strongly Interacting Low-Viscosity Matter Created in Relativistic Nuclear Collisions

Laszlo P. Csernai,[1,2] Joseph I. Kapusta,[3] and Larry D. McLerran[4]
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[2]*MTA-KFKI, Research Institute of Particle and Nuclear Physics, 1525 Budapest 114, P. O. Box 49, Hungary*
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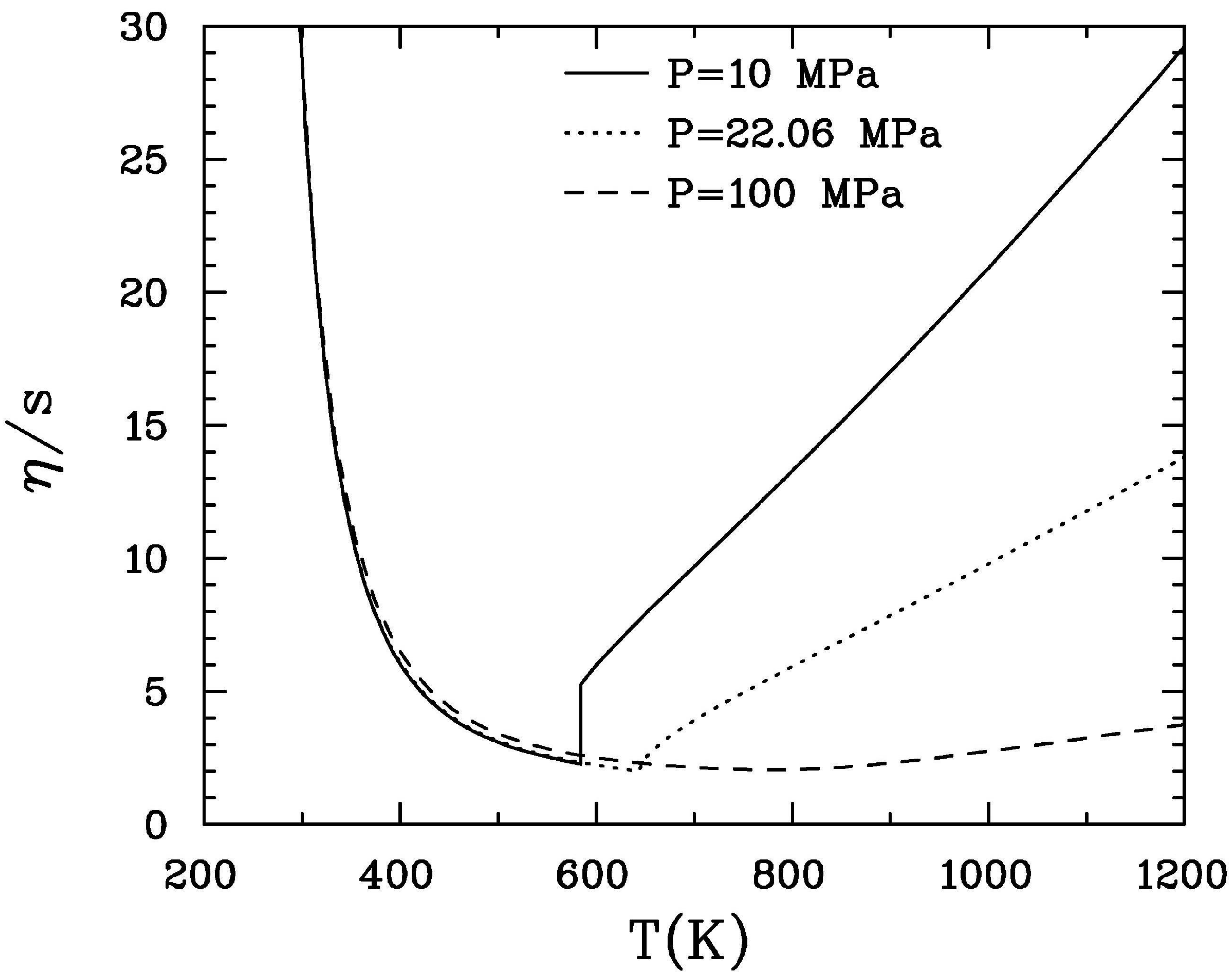
[4]*Nuclear Theory Group and Riken Brookhaven Center, Brookhaven National Laboratory, Bldg. 510A, Upton, New York 11973, USA*
(Received 12 April 2006; published 12 October 2006)



Is there a relationship between η and $\hat{q}$?

PRL **99,** 192301 (2007) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2007

Small Shear Viscosity of a Quark-Gluon Plasma Implies Strong Jet Quenching

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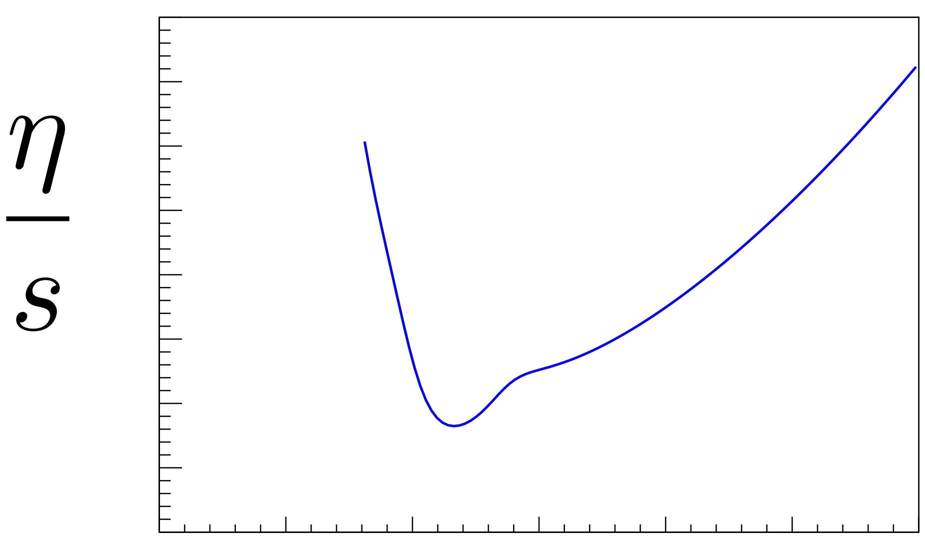
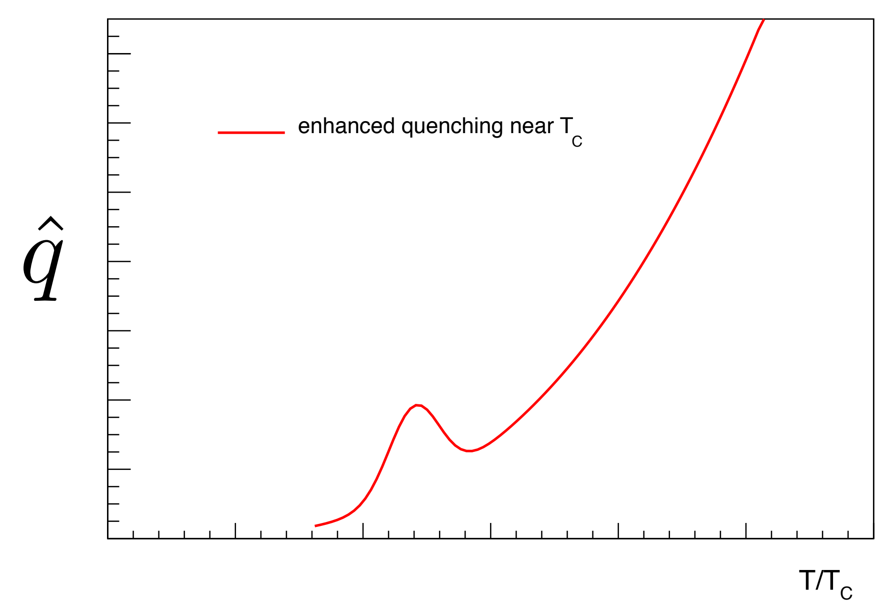
[2]*Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 10 March 2007; revised manuscript received 13 June 2007; published 7 November 2007)

$$\frac{\eta}{s} \sim \frac{T^3}{\hat{q}}$$

For a weakly coupled medium, proportionality constant ~ 1





Where else in nature does something similar happen

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Pretty much everywhere !

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Critical opalescence

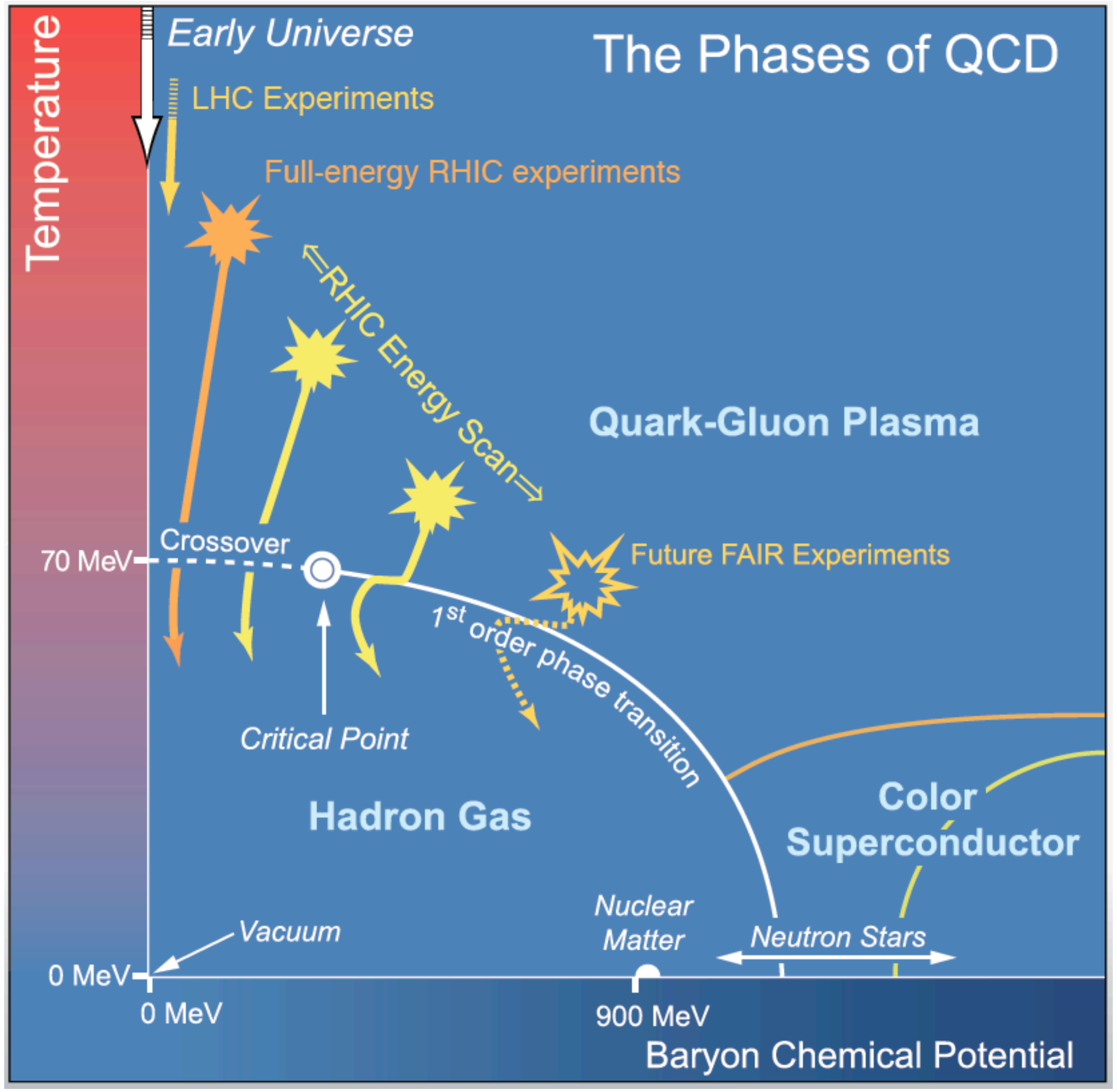
Where else in nature does something similar happen

Pretty much everywhere !

Critical opalescence

Does QCD show Critical opalescence ?

But this happens at the critical point



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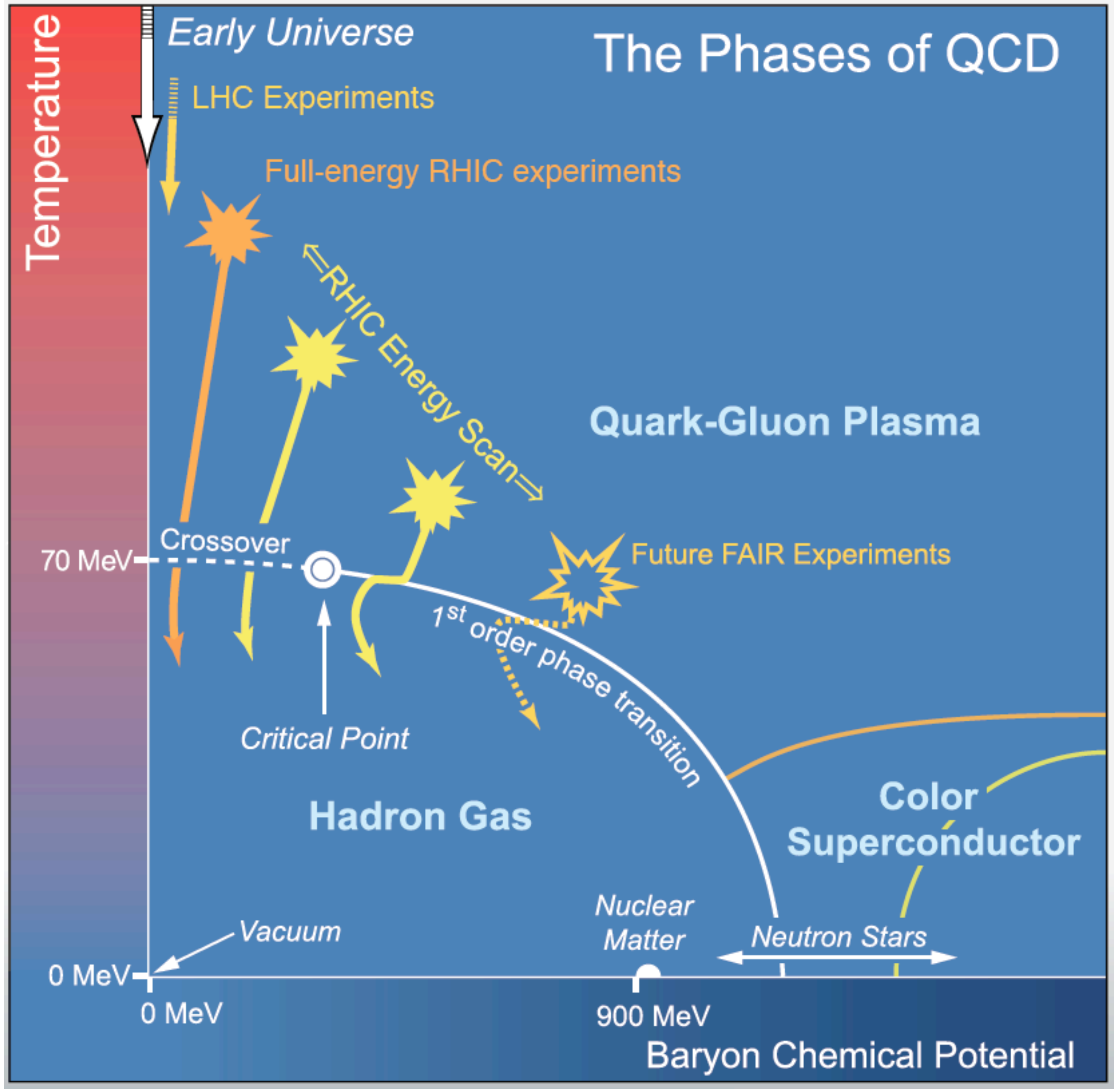
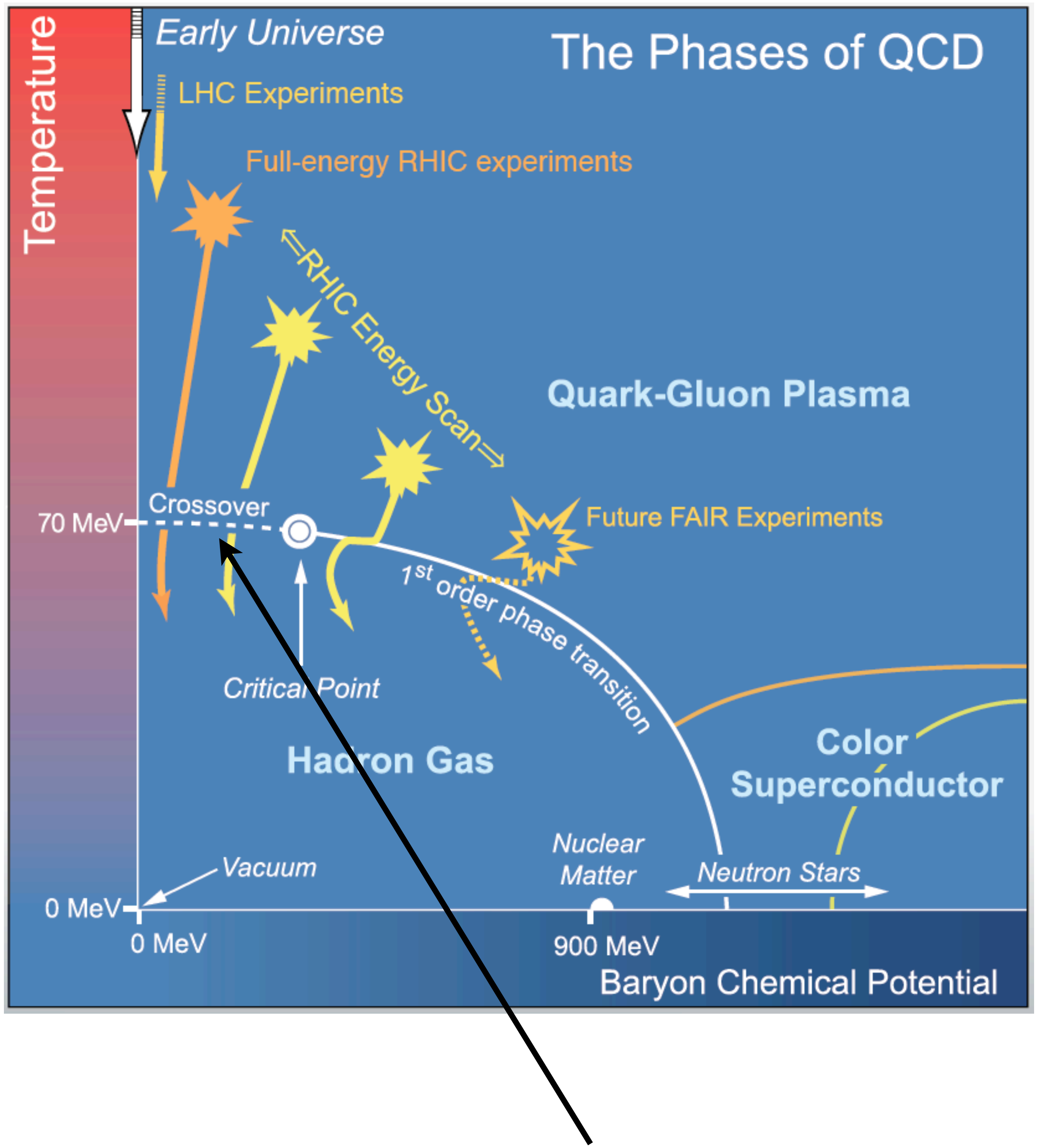


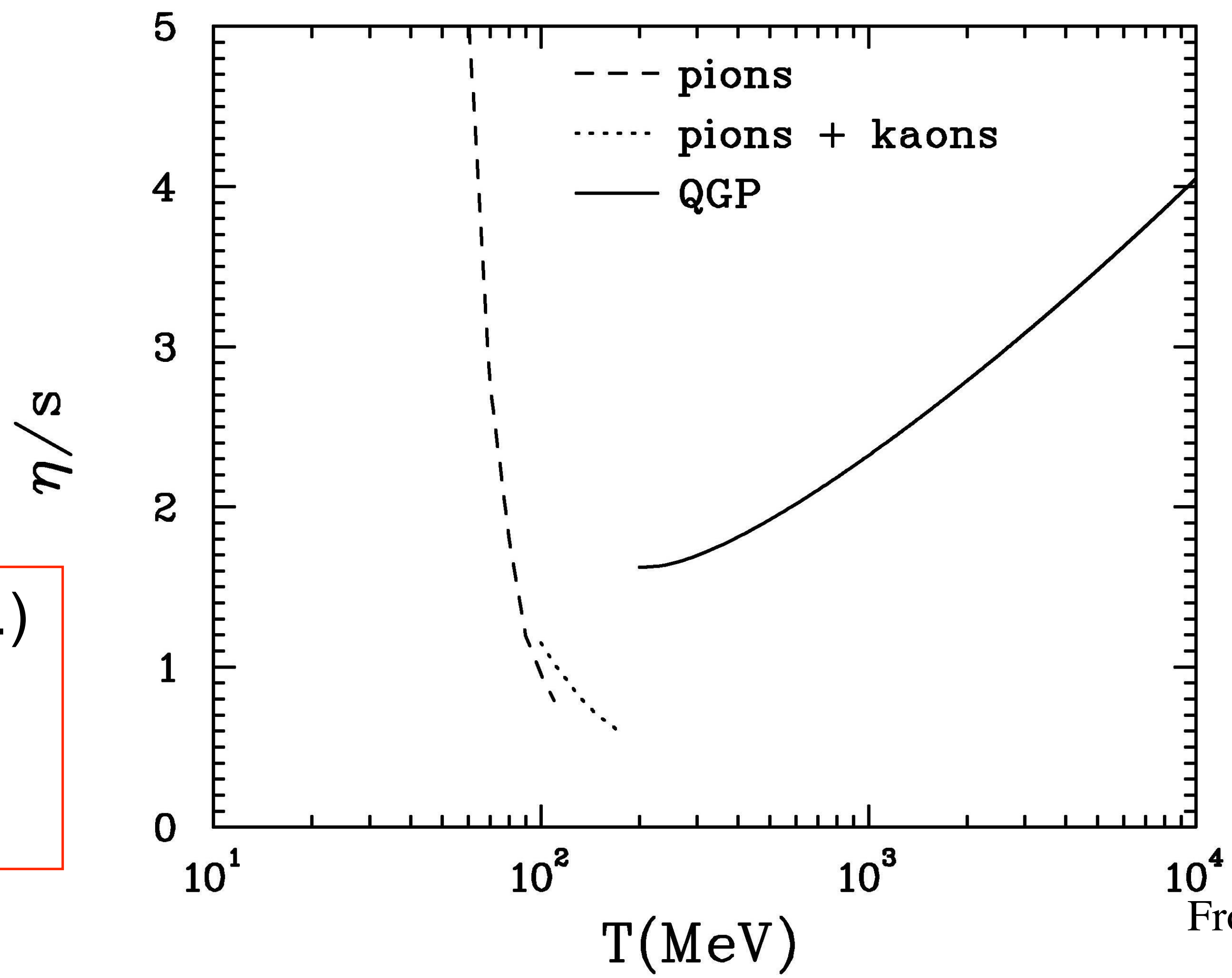
There may be remnant extremal behavior at smaller μ_B

But this happens at the critical point



There may be remnant extremal behavior at smaller μ_B

Remnants of extremal behavior at $\mu \to 0$



Low T (*Prakash et al.*) using experimental data for 2-body interactions.

High T (Yaffe *et al.*) using perturbative QCD.

From talk by J. Kapusta at QM2006

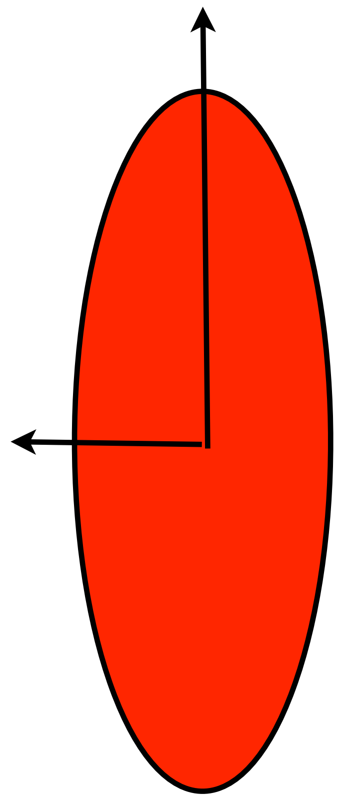
QCD matter at RHIC and LHC is far from the critical point

Yet one still expects a minimum, at least theoretically!

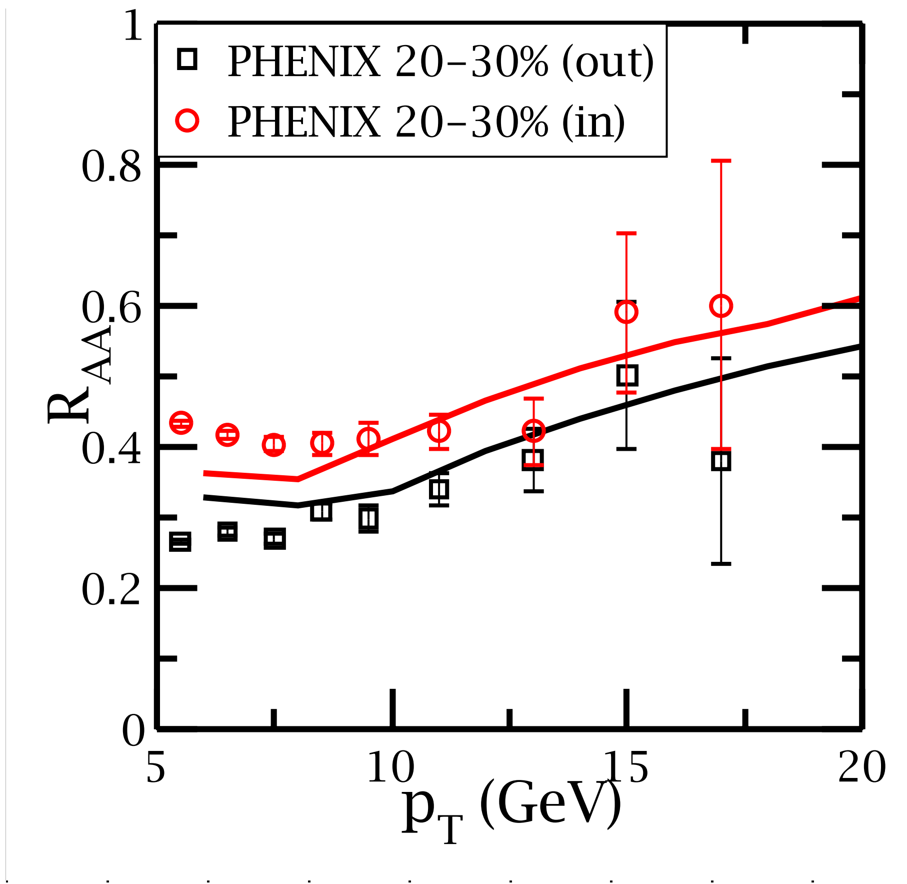
Not inconsistent with any bulk measurement at RHIC/LHC

Any reason to expect a bump in $\hat{q}/T^3$?

Look at the R_{AA} vs reaction plane



plot from Majumder and Shen



At low p_T hard to describe the reaction plane dependence

Note: at low p_T many higher power corrections become important

these have so far been ignored

A non-monotonic behavior in $\hat{q}/T^3$

PRL 102, 202302 (2009) PHYSICAL REVIEW LETTERS week ending 22 MAY 2009

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement near the QCD Phase Transition

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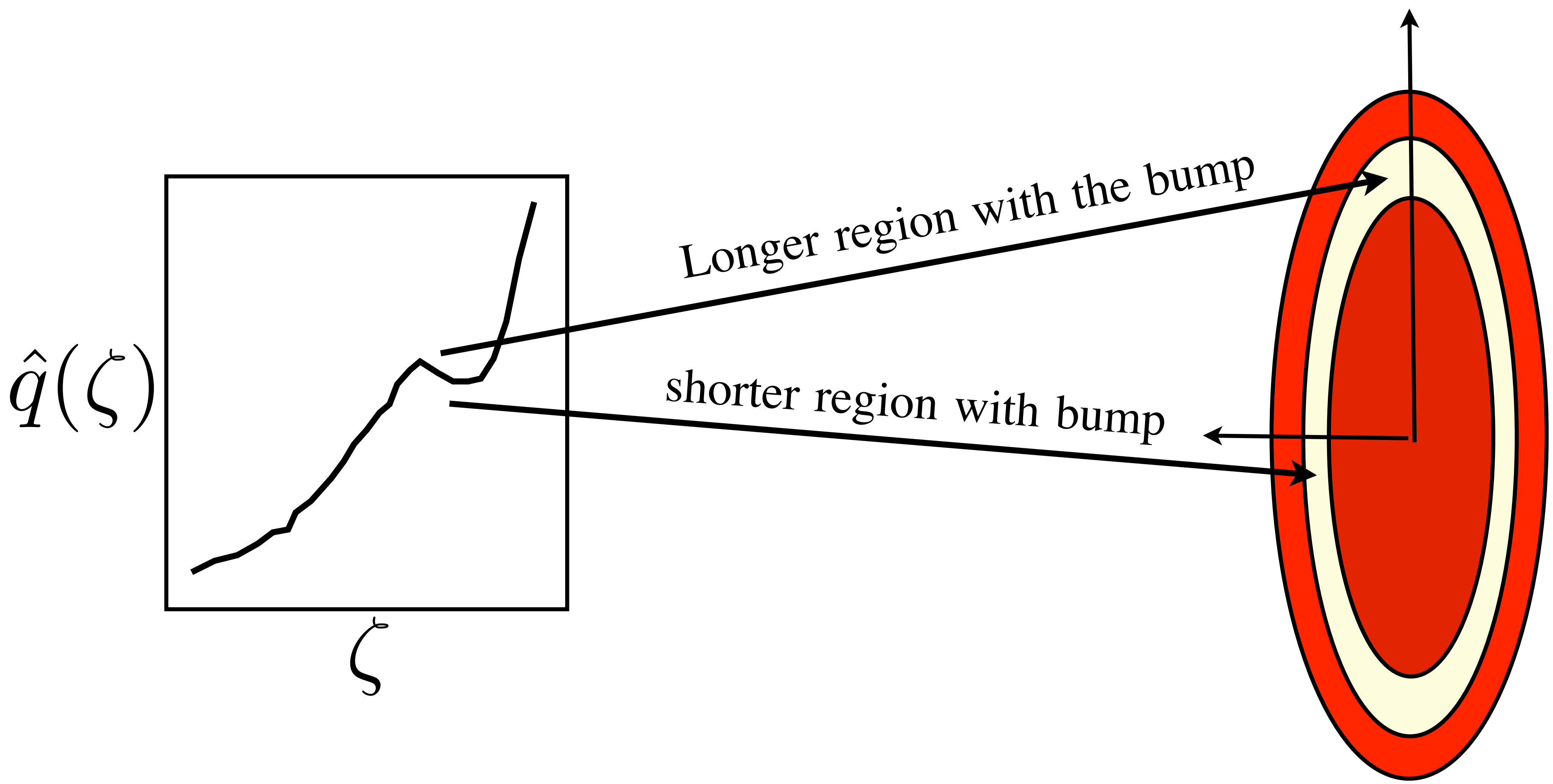
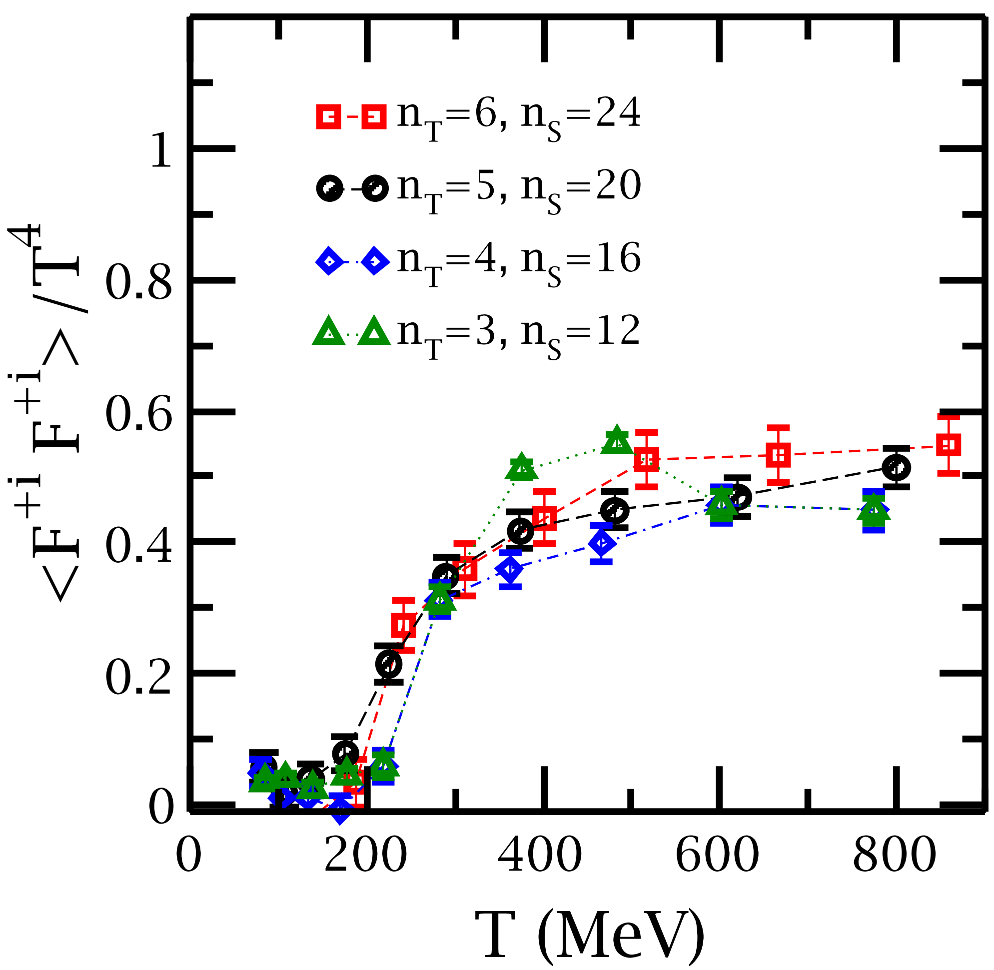
(Received 22 October 2008; revised manuscript received 19 February 2009; published 22 May 2009)

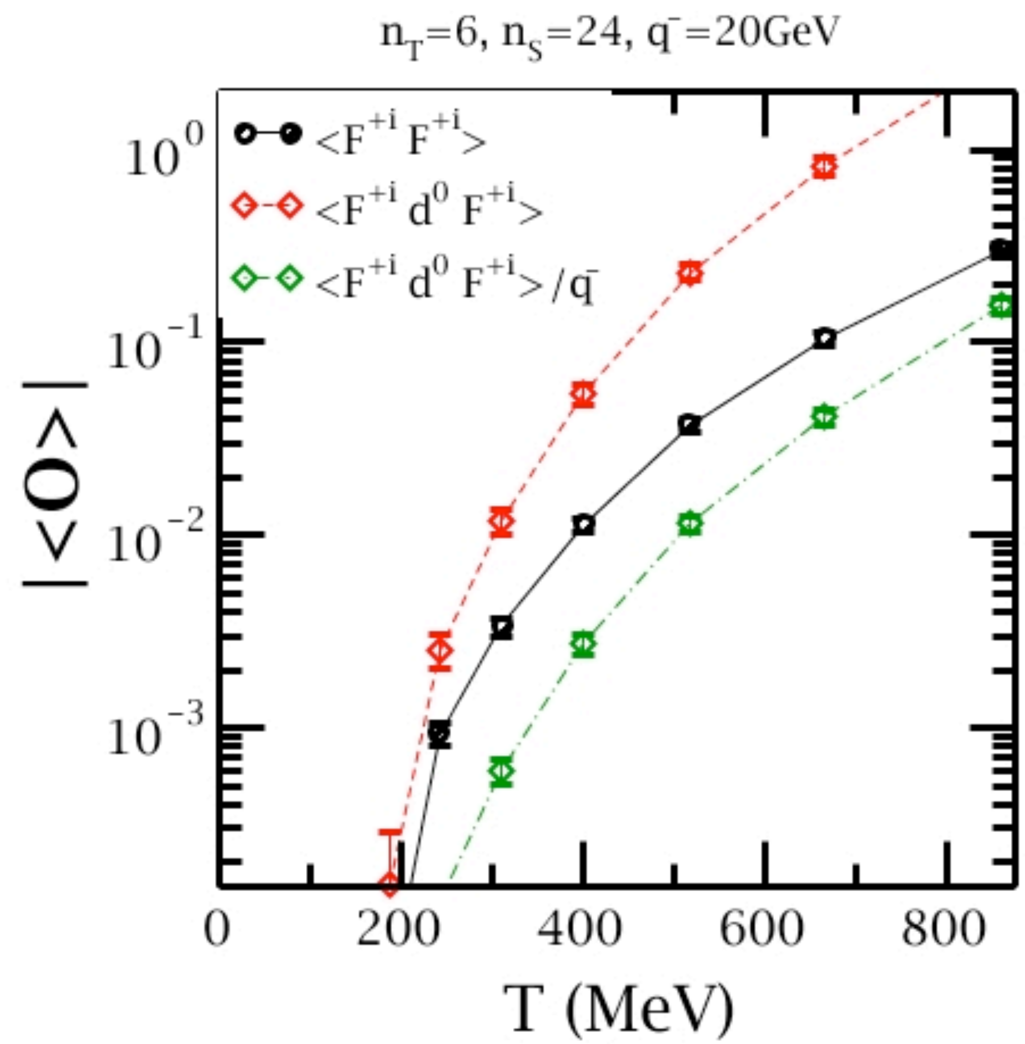


A Lattice calculation of $\hat{q}$

Long story short: can analytically continue $\hat{q}$ to euclidean space and evaluate as a series

$$\langle M | F_{\perp}^{+\mu} \sum_{n=0}^{\infty} \left(\frac{-q \cdot i\mathcal{D} - \mathcal{D}_{\perp}^{2}}{2q^{-}Q_0} \right)^{n} F_{\perp,\mu}^{+} | M \rangle$$

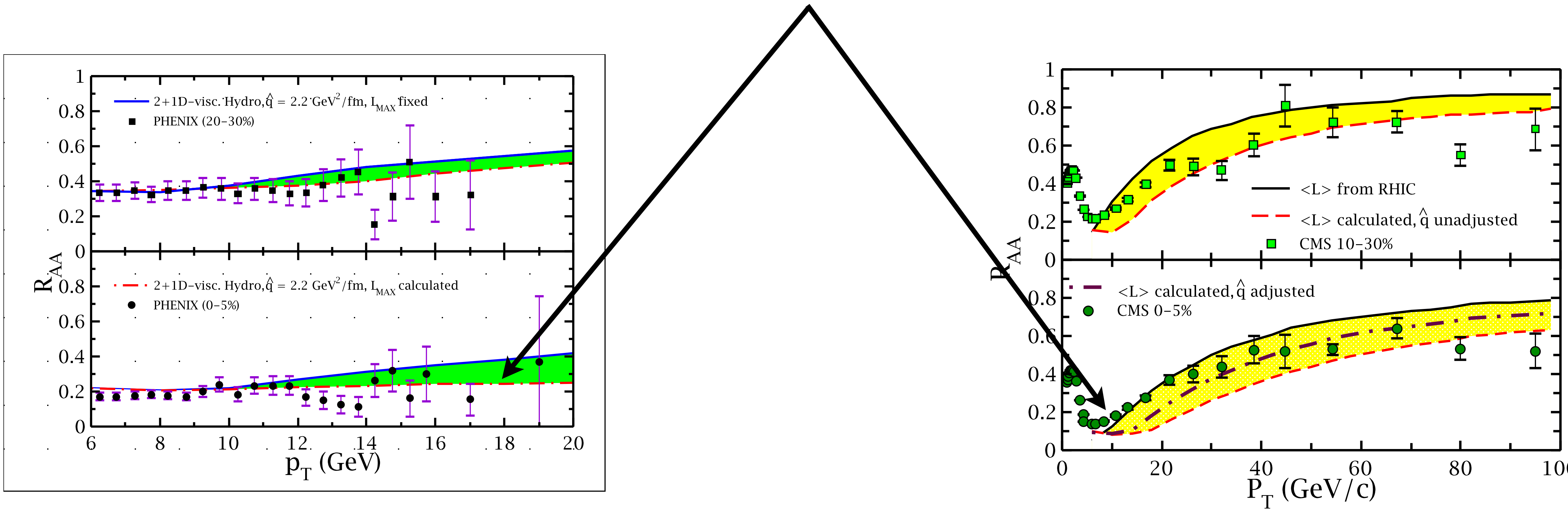




Note: quenched SU(2), results not inconsistent with a bump above T_C.

What exactly are we looking for?

Note: The QGP at RHIC and LHC already very opaque to most jets



Jets tend to disintegrate as they propagate through the QGP

We need very specific range of parameters to see a maximal scaled opacity $(\hat{q}/T^3)$.

A couple of things to keep in mind

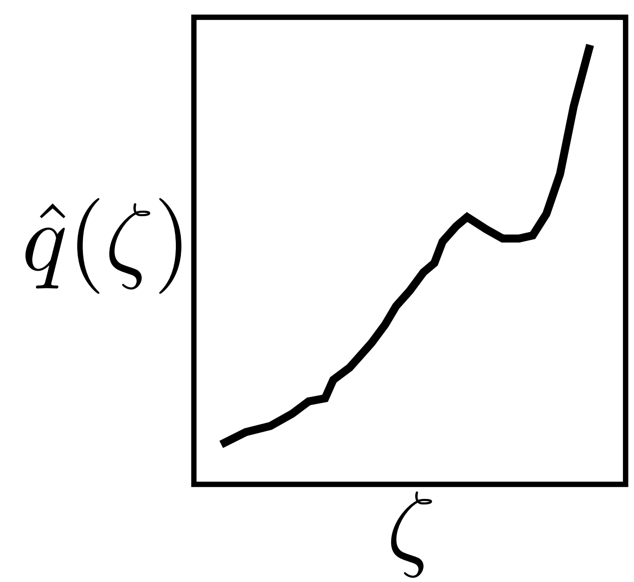
(I) Jet quenching is sensitive to

$$\int_{\text{Origin}}^{\text{Exit}} d\zeta q(\zeta)$$

And not to the scaled quantity

$$\int_{\text{Origin}}^{\text{Exit}} d\zeta \frac{q(\zeta)}{T^3(\zeta)}$$

Thus, we are looking for a wiggle in a steeply falling curve



(II) At very high p_T a small R_{AA} does not mean the modification to the jet is as large as at lower p_T

If there is a wiggle at T_C, RHIC is a better place to look

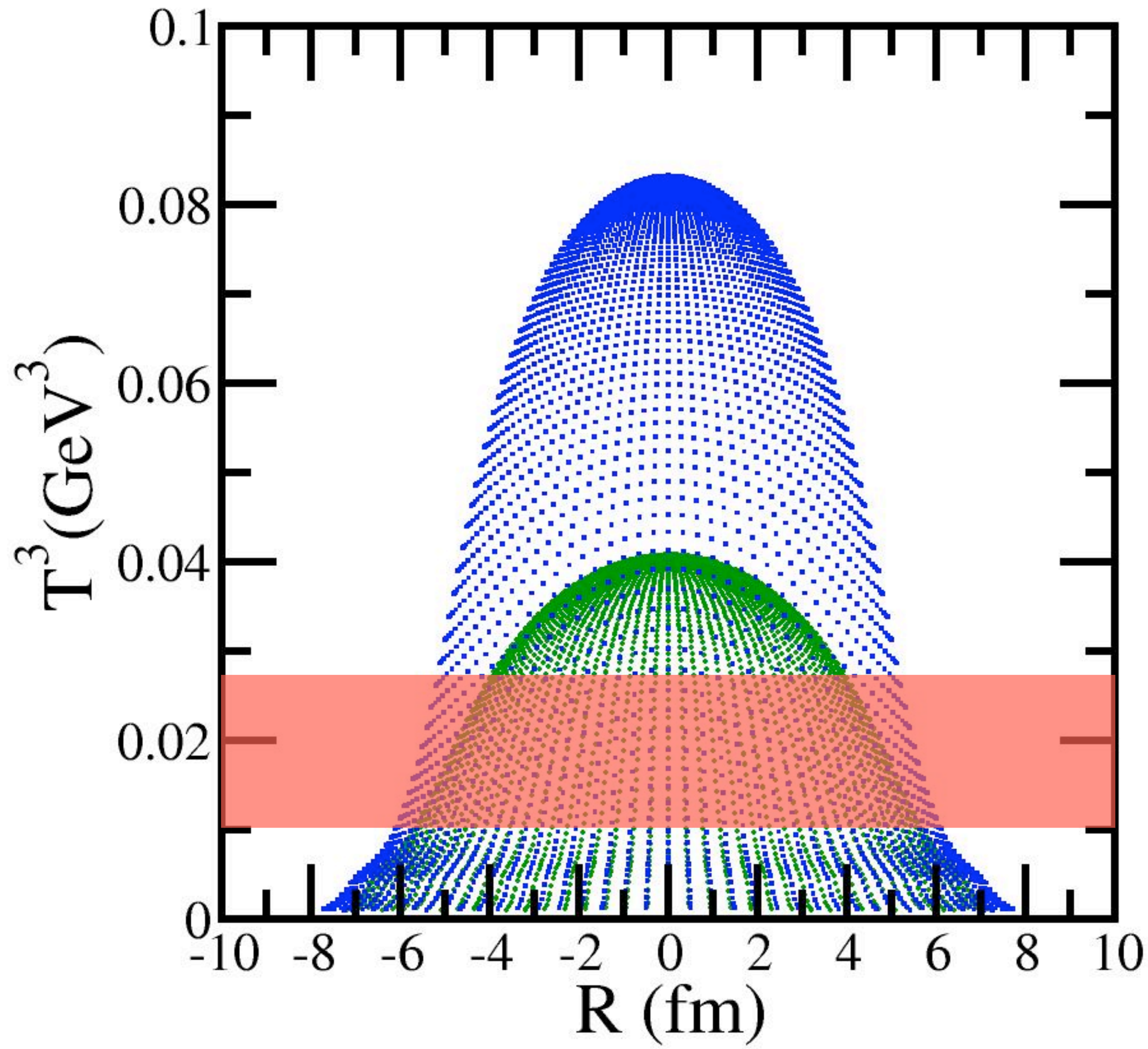
T^3 profiles from

the OSU 2+1 D hydro, 0-5% evts

At LHC, region of non-monotonic

behavior suppressed by much

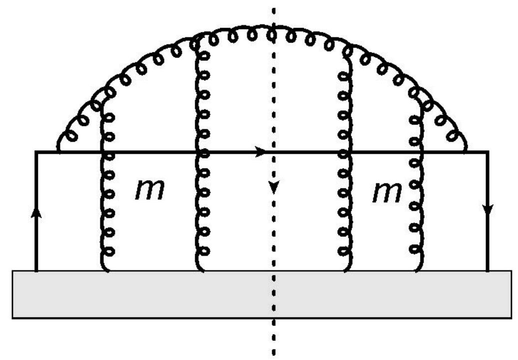
larger $\hat{q}$ values at earlier times



Region stretches for about

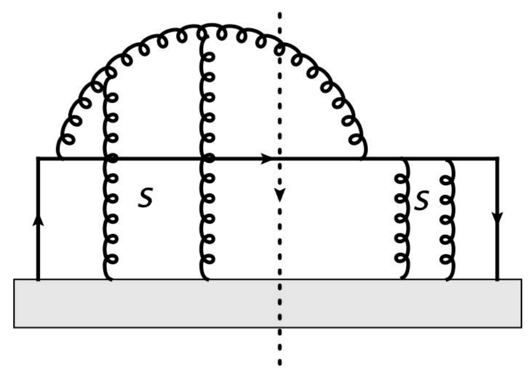
2fm/c at RHIC and 1fm/c at LHC

What kind of jets are best suited for probing this region

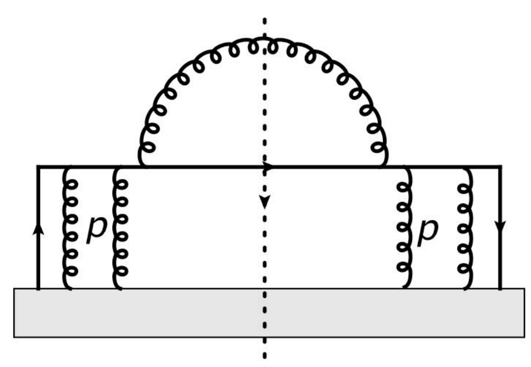


$$\sim C_A^m \int dy \frac{l_\perp^2}{l_\perp^2} P(y) \int d\zeta \frac{2\hat{q}}{l_\perp^2} \left[2 - 2\cos\left(\frac{l_\perp^2}{2E} \zeta \right) \right]$$

Results from a multiple scattering single emission calculation



$$\sim -\left(\frac{C_A}{2} \right)^s \int dy \frac{l_\perp^2}{l_\perp^2} y P(y) \int d\zeta \frac{\hat{q}}{l_\perp^2} \left[2 - 2\cos\left(\frac{l_\perp^2}{2E} \zeta \right) \right]$$



$$\sim (C_F)^p \int dy \frac{l_\perp^2}{l_\perp^2} y^2 P(y) \int d\zeta \frac{\hat{q_Q}}{l_\perp^2} \left[2 - 2\cos\left(\frac{l_\perp^2}{2E} \zeta \right) \right]$$

The modification is controlled by the parameter $\dfrac{\hat{q}L}{Q^2}$

If this is too small then jets not modified

If its too big then jets are completely quenched, ideal value ~ 0.1

Some estimates!

In the region of the bump, $q_q \sim 0.5\ \text{GeV}^2/\text{fm}$

$q_g \sim 1\ \text{GeV}^2/\text{fm}$

Length is about 2fm at RHIC, thus qL ~1-2 GeV^2

Thus we need a $Q^2 \sim 10 - 20\ \text{GeV}^2$

If we want the jet to emit once in this region then

Formation time ~ $$\frac{E}{Q^2} \sim 1fm = 5GeV^{-1}$$

$$\Rightarrow E \sim 50 - 100GeV$$

At LHC, length of region is like 1fm, then qL ~0.5-1 GeV^2

thus for a $Q^2 \sim 5 - 10\ \text{GeV}^2$, need E ~ 25 - 50 GeV

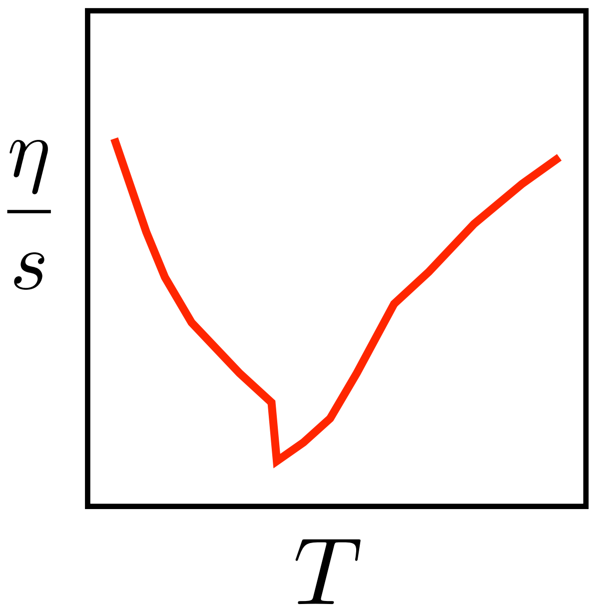
Virtuality driven MCs

These are very hand wavy estimates

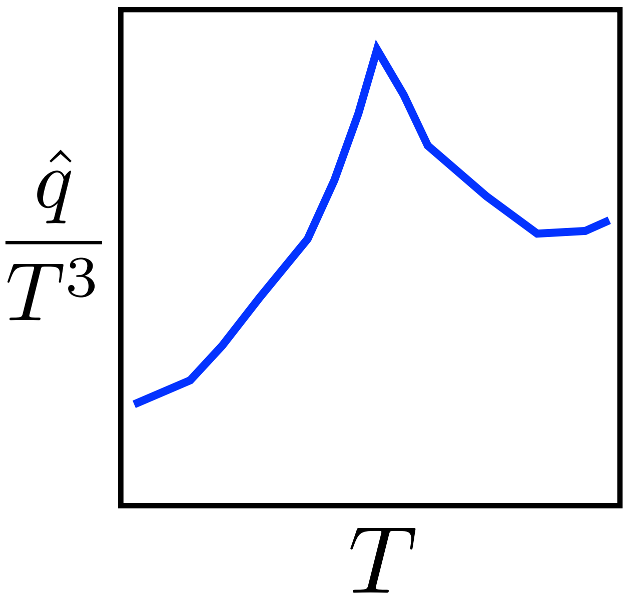
However, we now have the technology to
test these with virtuality driven MC on a medium
with a bump in $\hat{q}$

Results will appear soon!

Back up



$\frac{\eta}{s}$
T



$\frac{\hat{q}}{T^3}$
T