Jet modification in A-A, p-A and D-A at RHIC and LHC
(within HT scheme)

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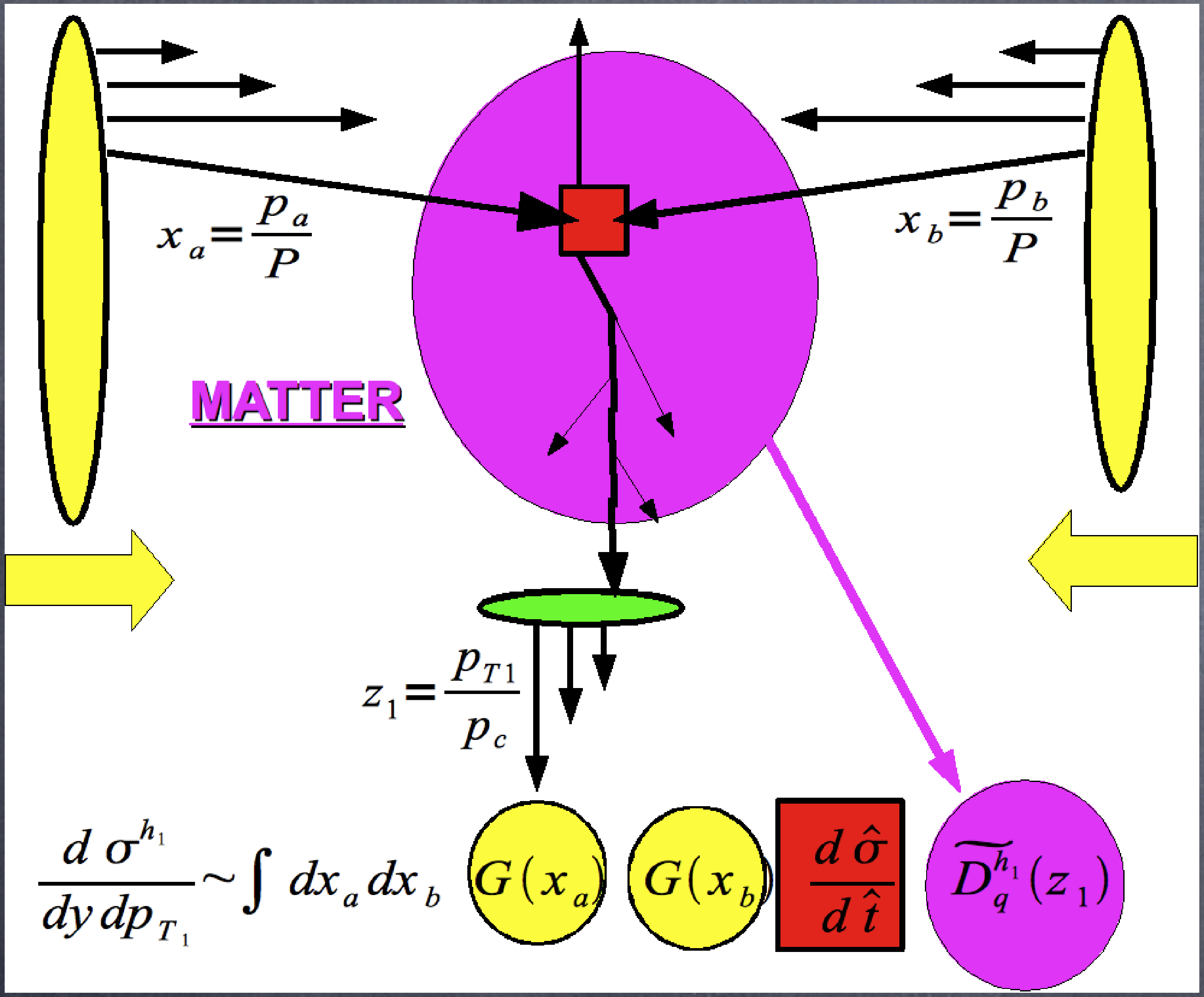
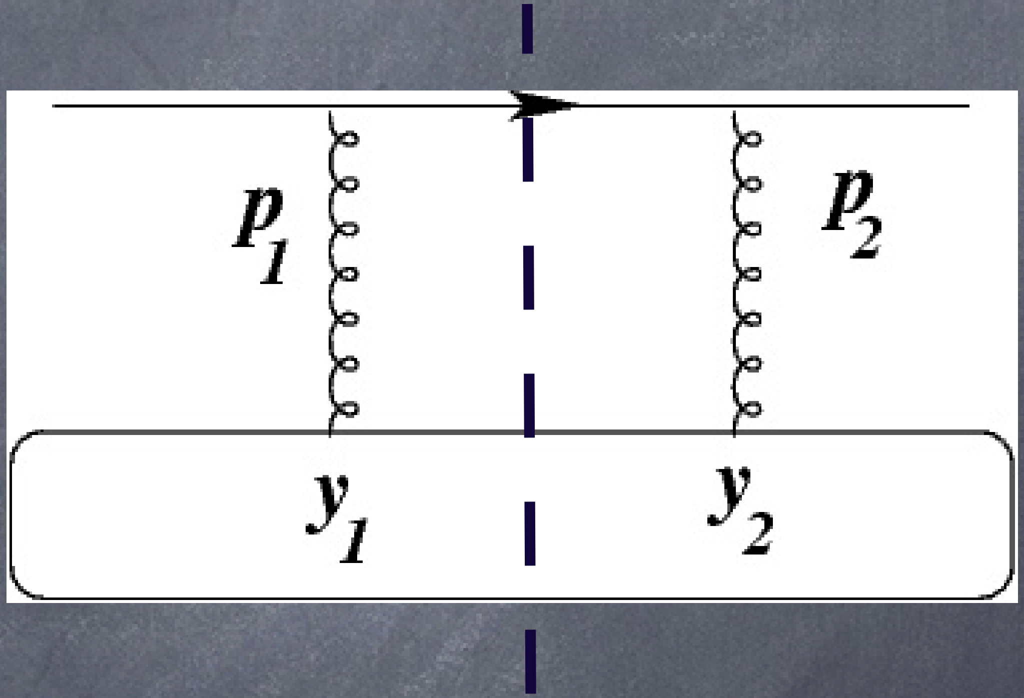
Outline

- The present status of HT jet modification
- Some background on HT E-loss + MC routines
- Observables that are easily understood
- Observables less easily understood
- Really difficult observables!
- What else are we doing...

What goes into HT-E-loss





Double factorized perturbative approach

What goes into this calculation

Modification derived in A-DIS and applied to HIC (implied factorization of hard scattering)

Jet scale assumed much harder than medium scale (factorization of jet from soft matrix element)

Multiple scatterings resummed in single gluon emission

Expansion in powers of Λ^2/Q^2

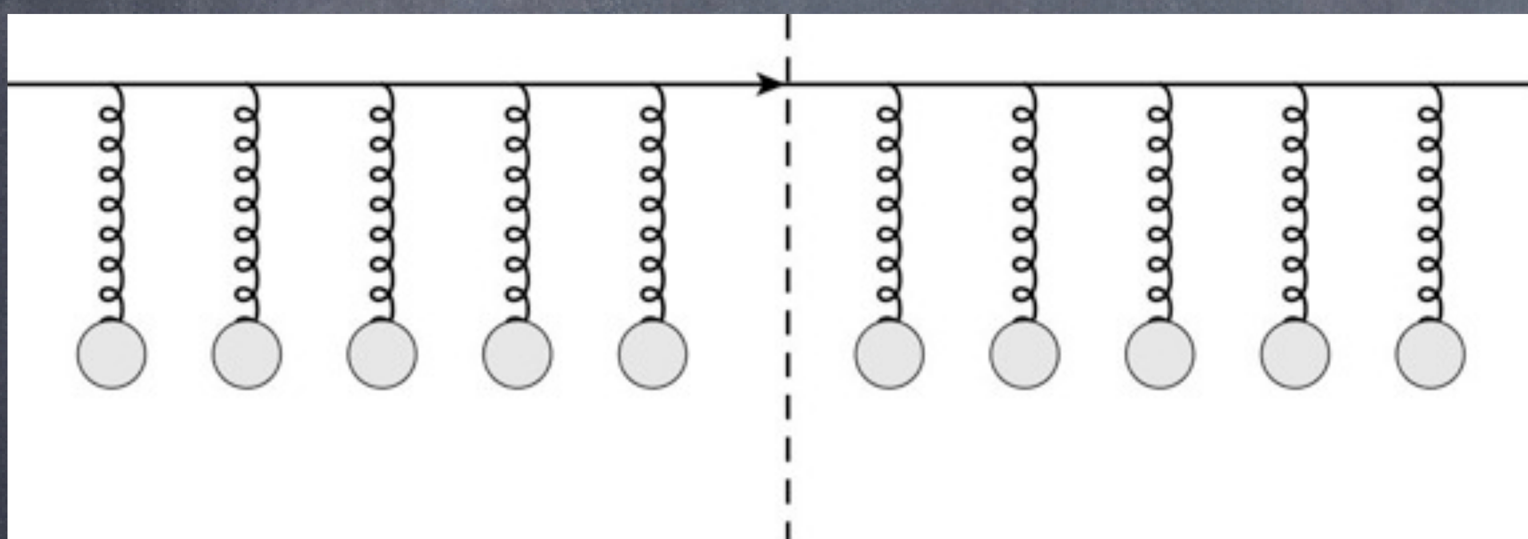
DGLAP k_T^2 systematics assumed for multiple emissions

Fluid dynamical simulation of medium and trans. coeffs.

How the medium affects the parton.

A parton in a jet shower, has momentum components

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



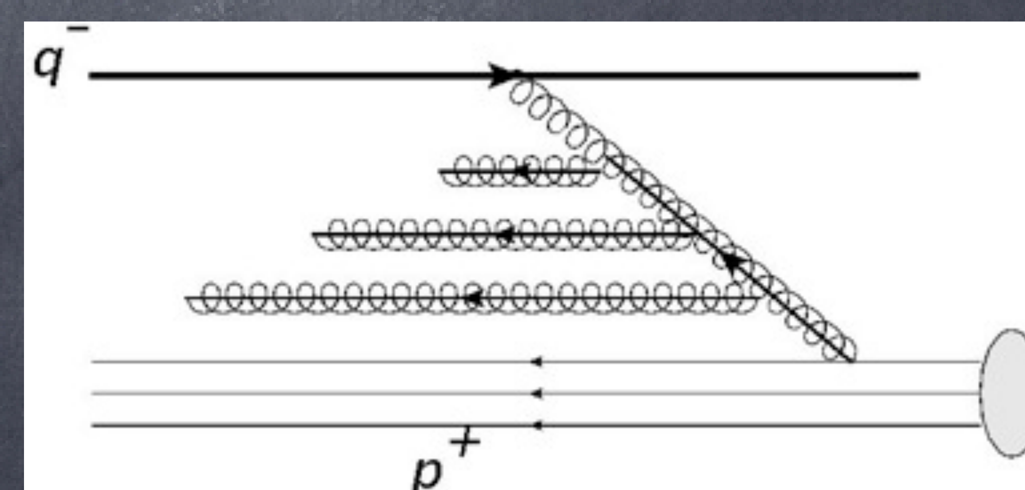
$$p^+ = \frac{p^0 + p_z}{\sqrt{2}}$$

$$p^- = \frac{p^0 - p_z}{\sqrt{2}}$$

hence, gluons have

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

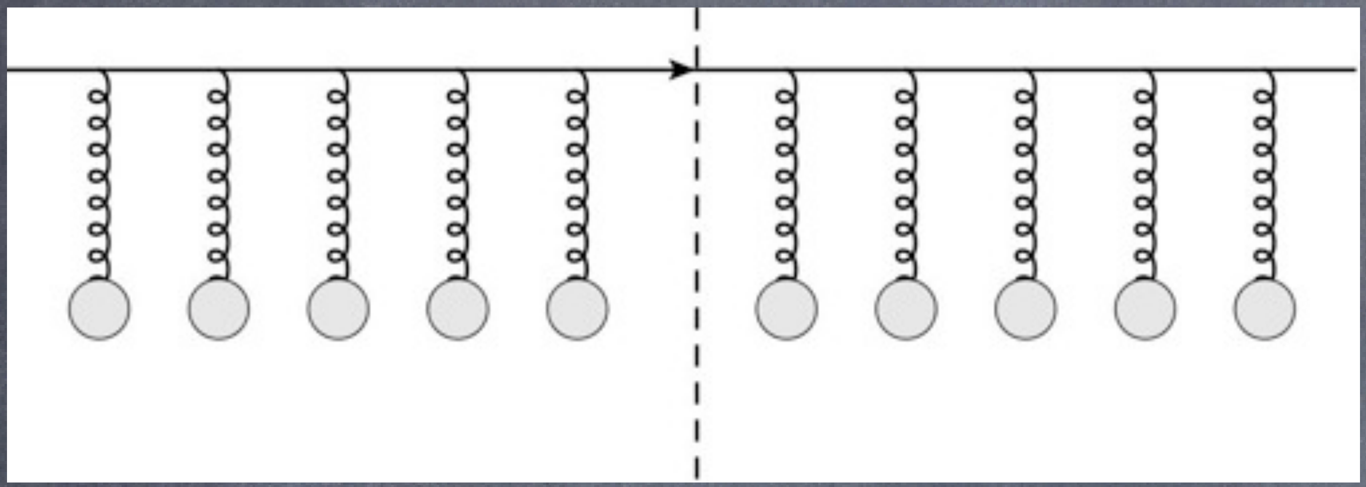
could also have $k^- \sim \lambda Q$



Idlilbi, Majumder PRD 80 054022 2008

So what do we get from resumming ?

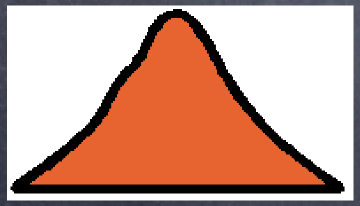
transverse broadening



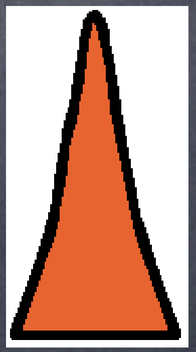
$$q^- \to \infty$$

Assuming independent scattering of nucleons gives a diff. equation

These cannot be soft, they must have transverse momentum, Glauber gluons.



$$\frac{\partial f(p_\perp, t)}{\partial t} = \nabla_{p_\perp} \cdot D \cdot \nabla_{p_\perp} f(p_\perp, t)$$

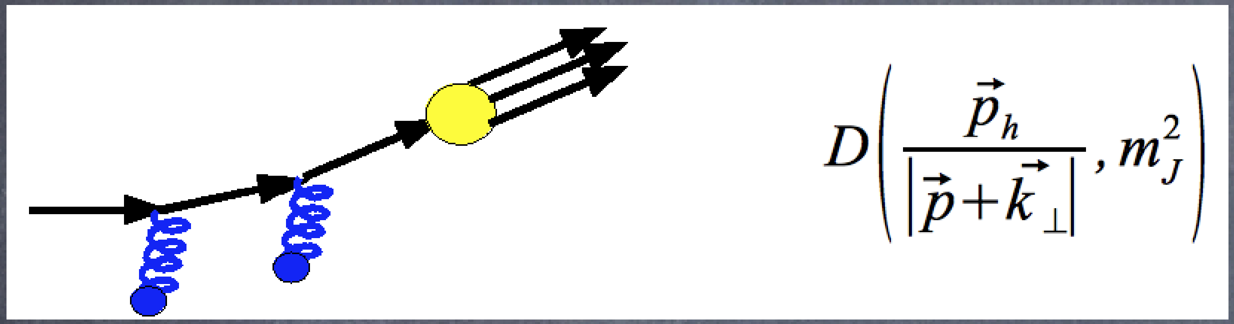


$$\langle p_\perp^2 \rangle = 4Dt$$

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

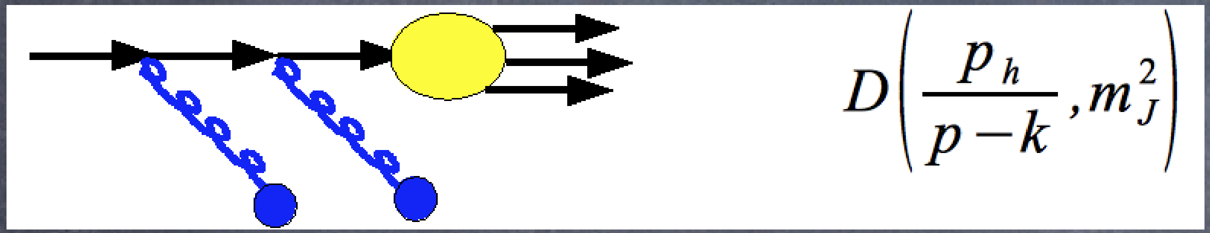
There are a bunch of medium properties which modify the parton and frag. func.

$\hat{q}$, $\hat{e}$ = dE/dL and f = dN/dL



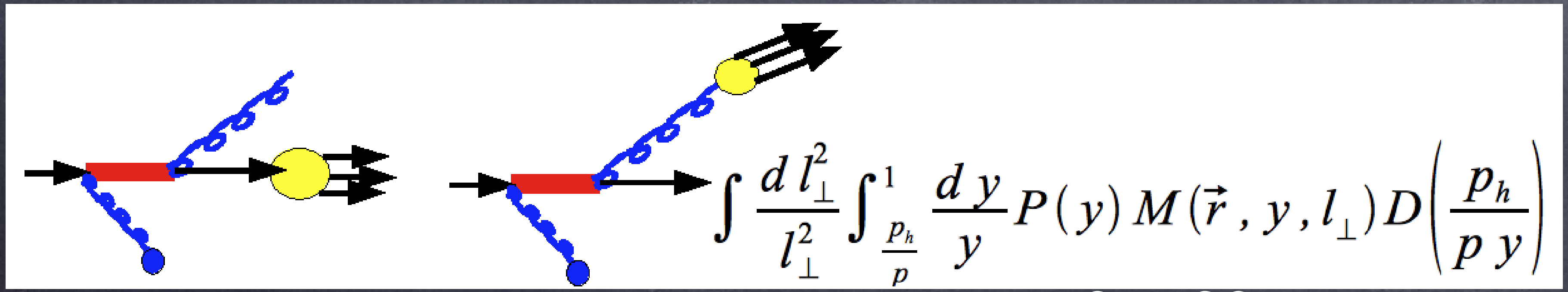
$$\hat{q} = \frac{\langle p_T^2 \rangle_L}{L}$$

Transverse momemtum diffusion rate



$$\hat{e} = \frac{\langle \Delta E \rangle_L}{L}$$

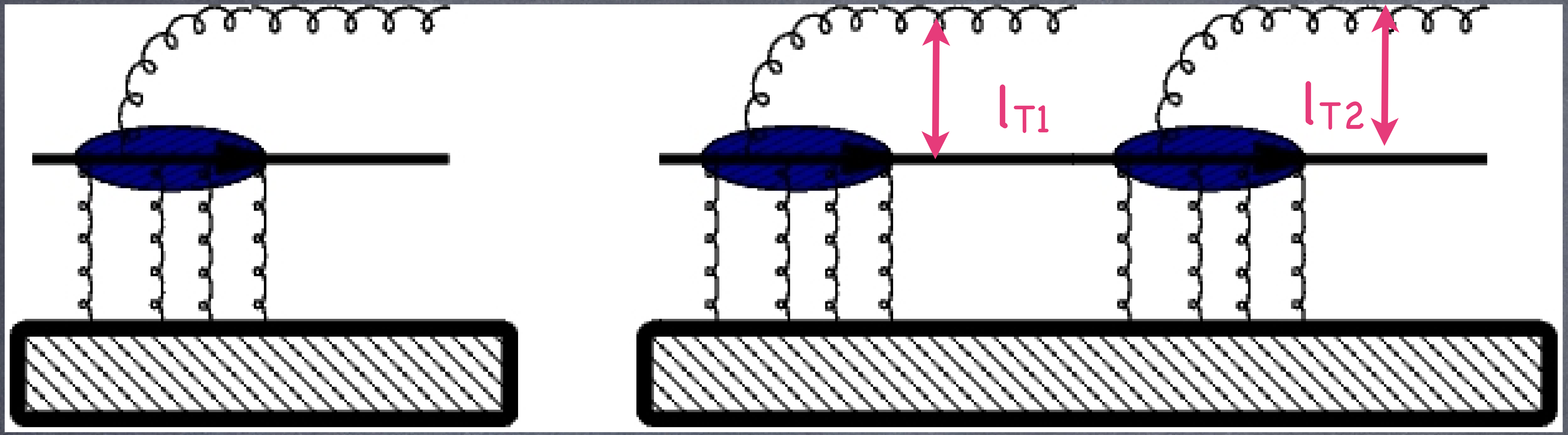
Elastic energy loss rate also diffusion rate e_2



Gluon radiation is sensitive to all these transport coefficients

And a bunch of off diagonal and higher order transport coefficients

Need to repeat the kernel



What is the relation between subsequent radiations ?

In the large Q^2 we can argue that there should be ordering of l_T.

$$if \;\; \hat{q}L \quad < \quad Q^2$$

$$\text{then} \qquad \frac{dQ^2}{Q^2}\left[1 + c_1 \frac{\hat{q}L}{Q^2}\right] \leq \frac{dQ^2}{Q^2}[1 + c_1]$$

A DGLAP formalism requires an upper scale and a lower scale

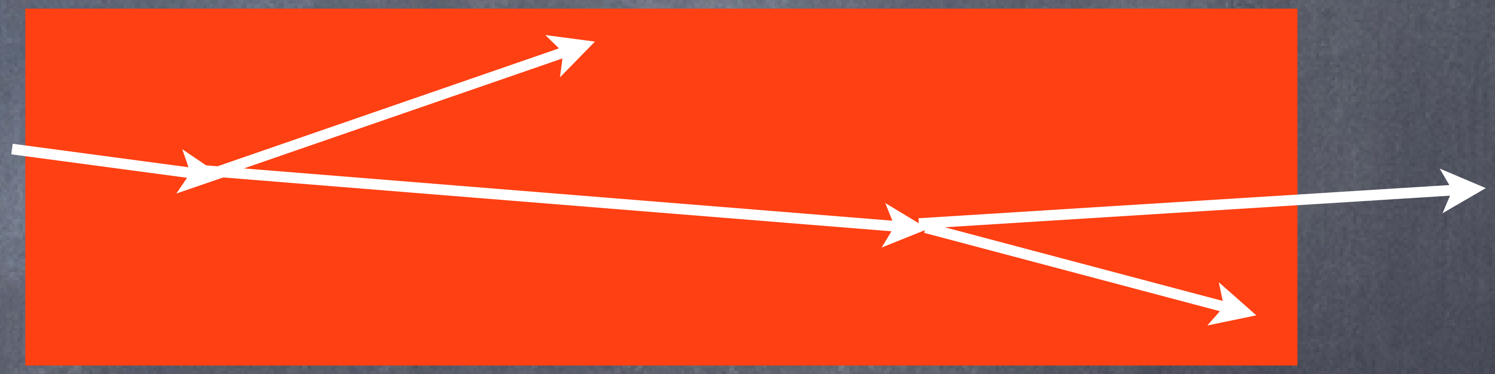
Upper scale is p_T^2 , same as in vacuum

What is the lower scale?

what is the virtuality of a parton on exit ?

Natural choice

$Q^2_{min} = E/L$



Realistically, this should be done for each path

In reality we average kernel over many paths

and calculate a mean distance based on the maximum length that the jet can travel in the representative brick

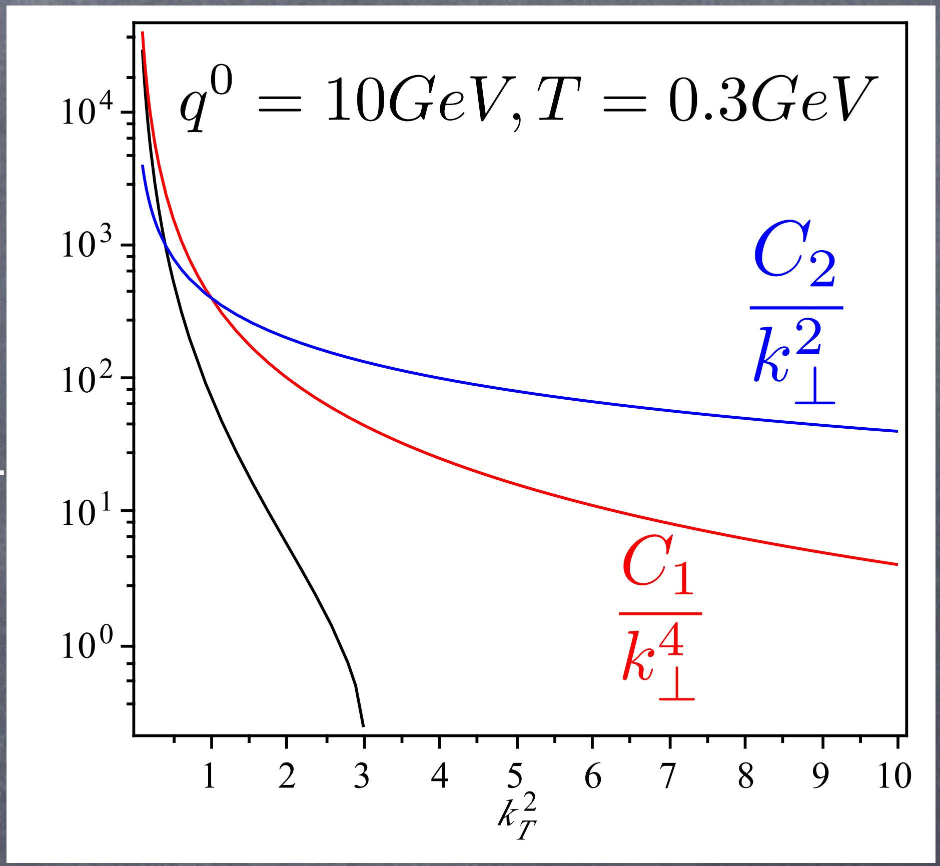
Gaussian distribution/temperature dependence/fit parameter !!!

Multiple scattering off any distribution samples a Gaussian

$$\hat{q} \sim T^3, s, \epsilon^{3/4}$$

is basically a model

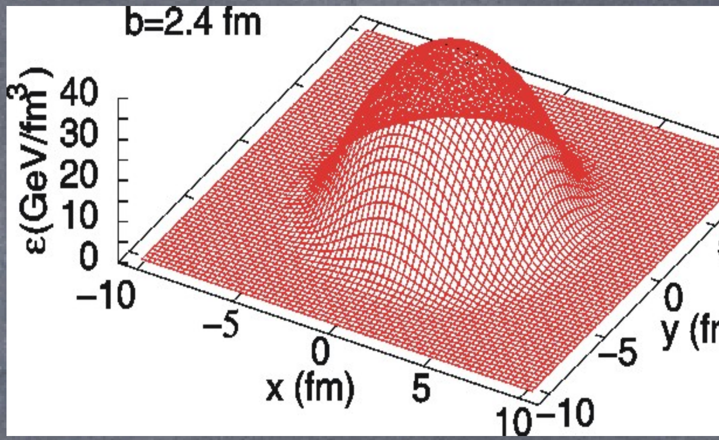
$$\frac{d\sigma}{dk_\perp^2}$$

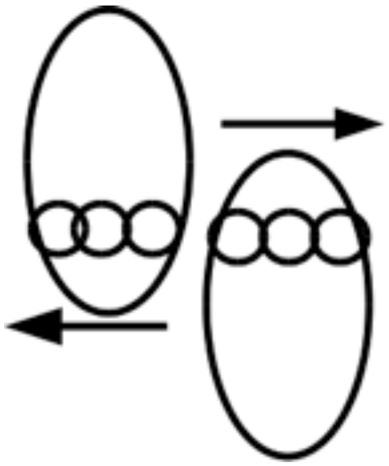


Ultimately you have to fit the normalization to 1 data point at one centrality, one value of p_T , one HIC energy

Bulk medium described by viscous fluid dynamics

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



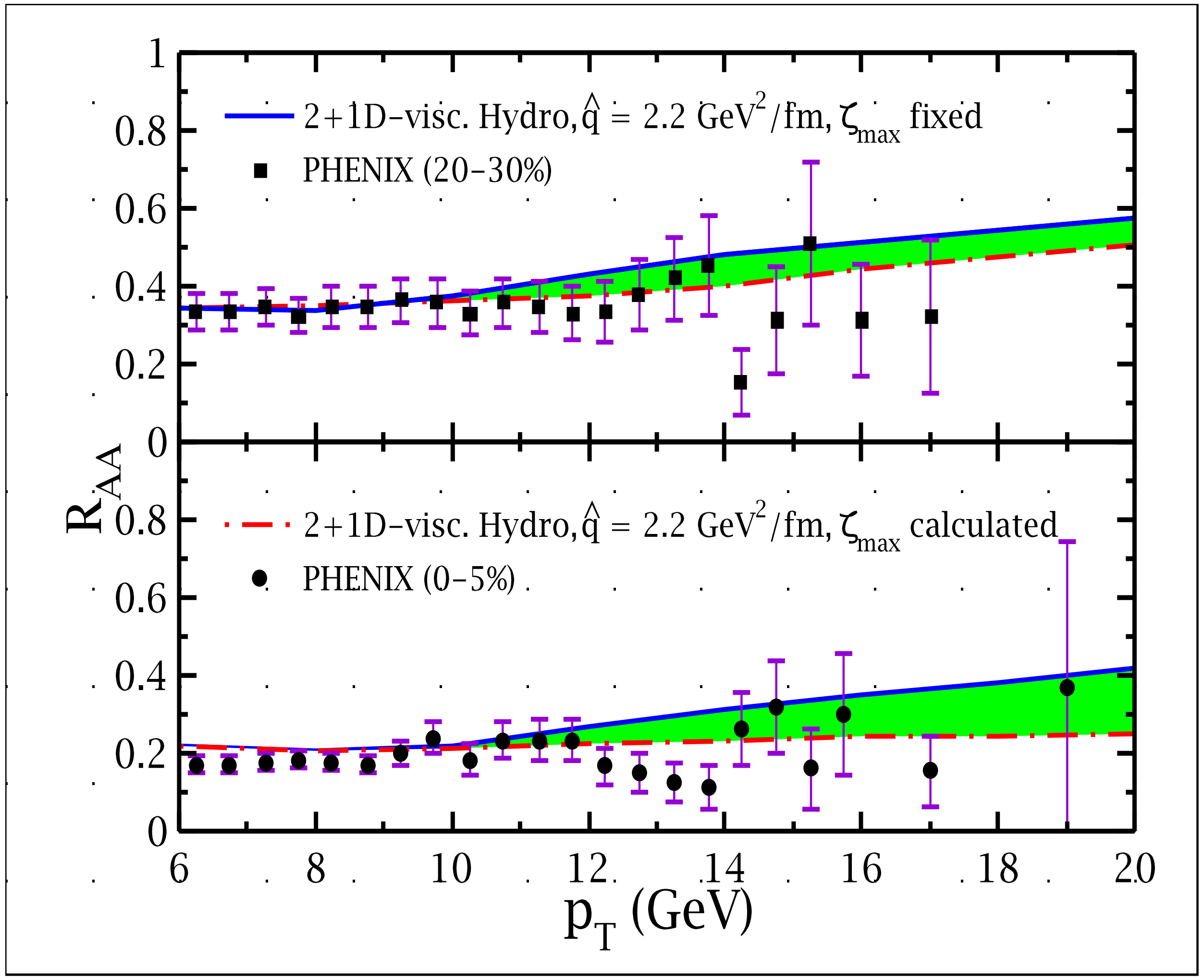


$$\hat{q}(\vec{r},t) = \hat{q}_0 \frac{s(\vec{r},t)}{s_0}$$

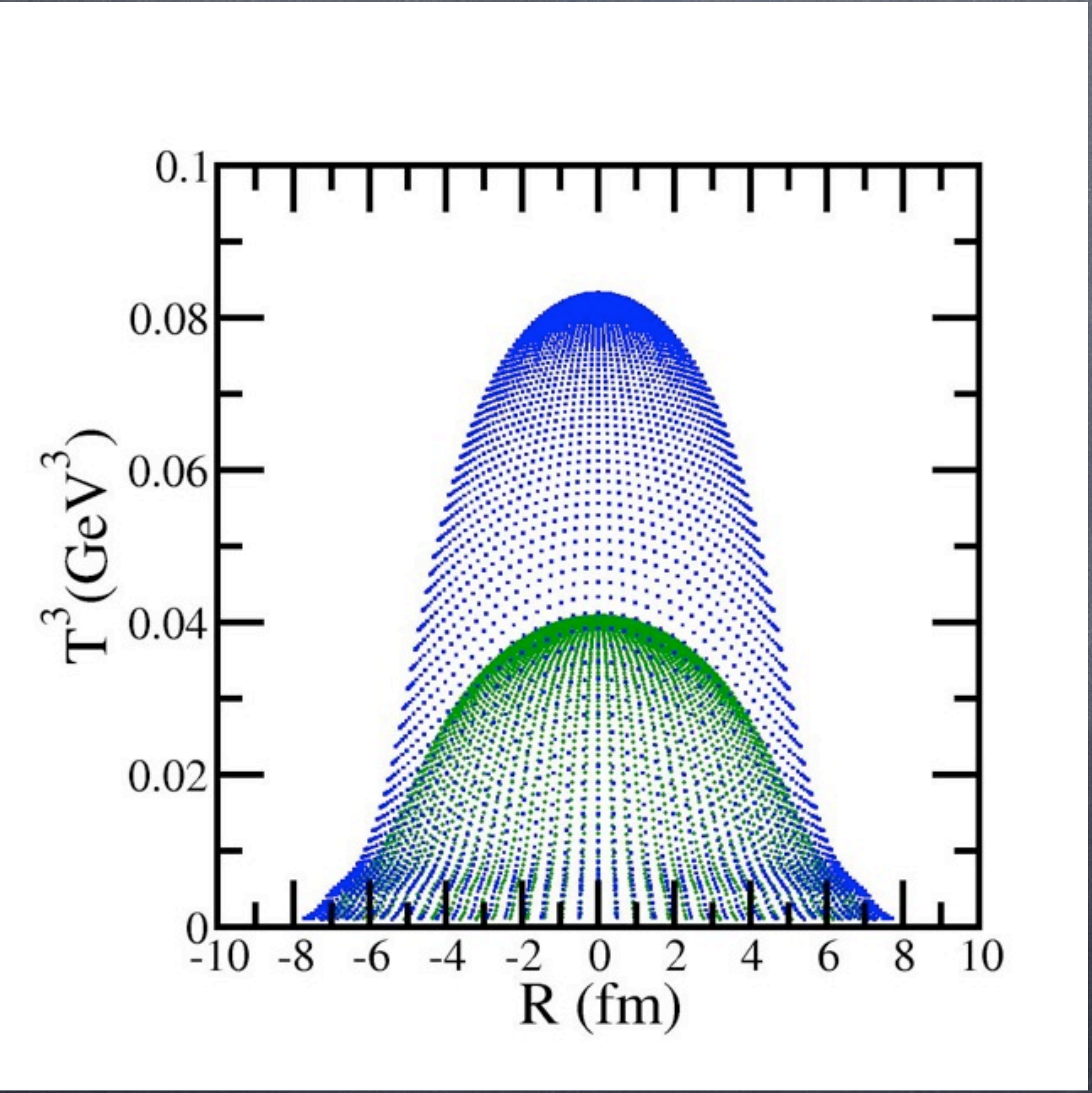
$$s_0 = s(T_0)$$

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

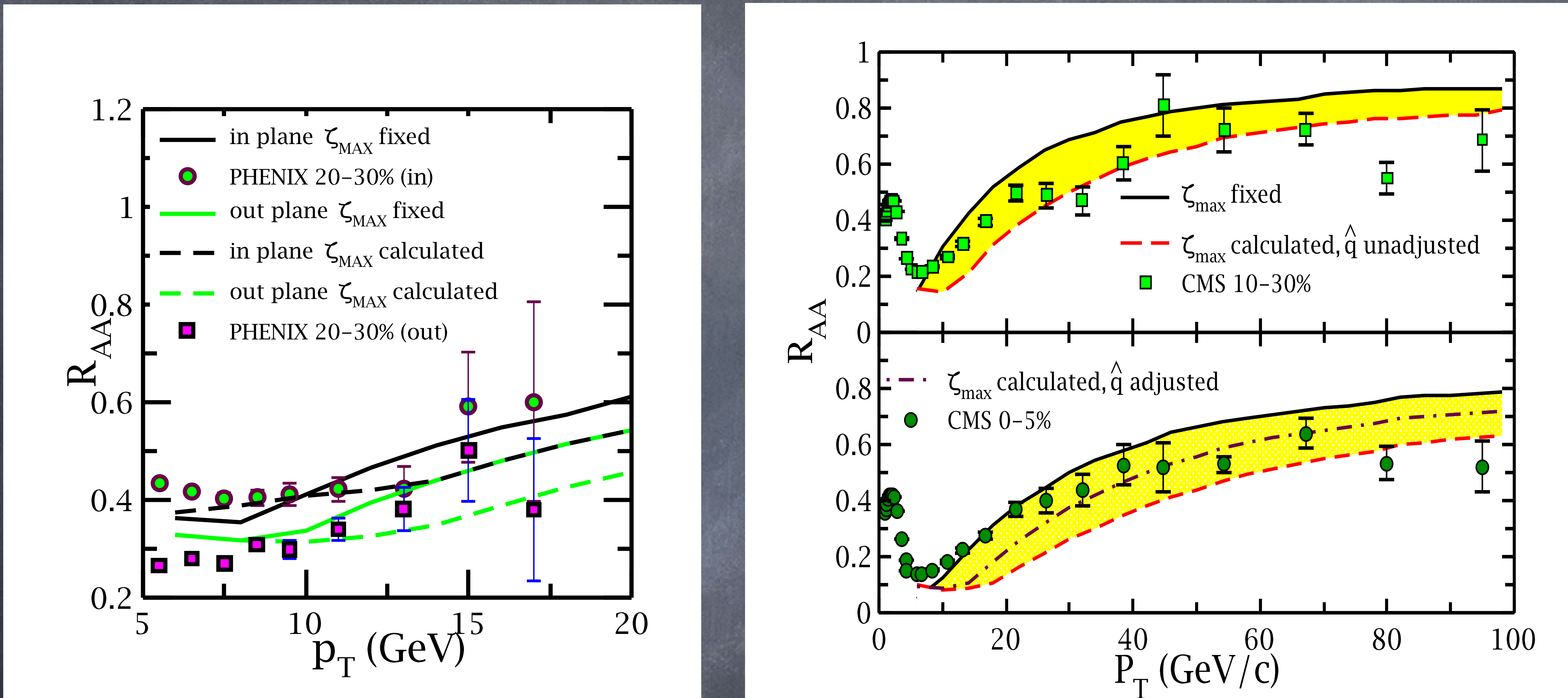
$$\hat{q}_0 \sim (10-20)\hat{q}_{Nucleus}$$



Note: no refitting between RHIC and LHC.



Versus reaction plane, versus energy



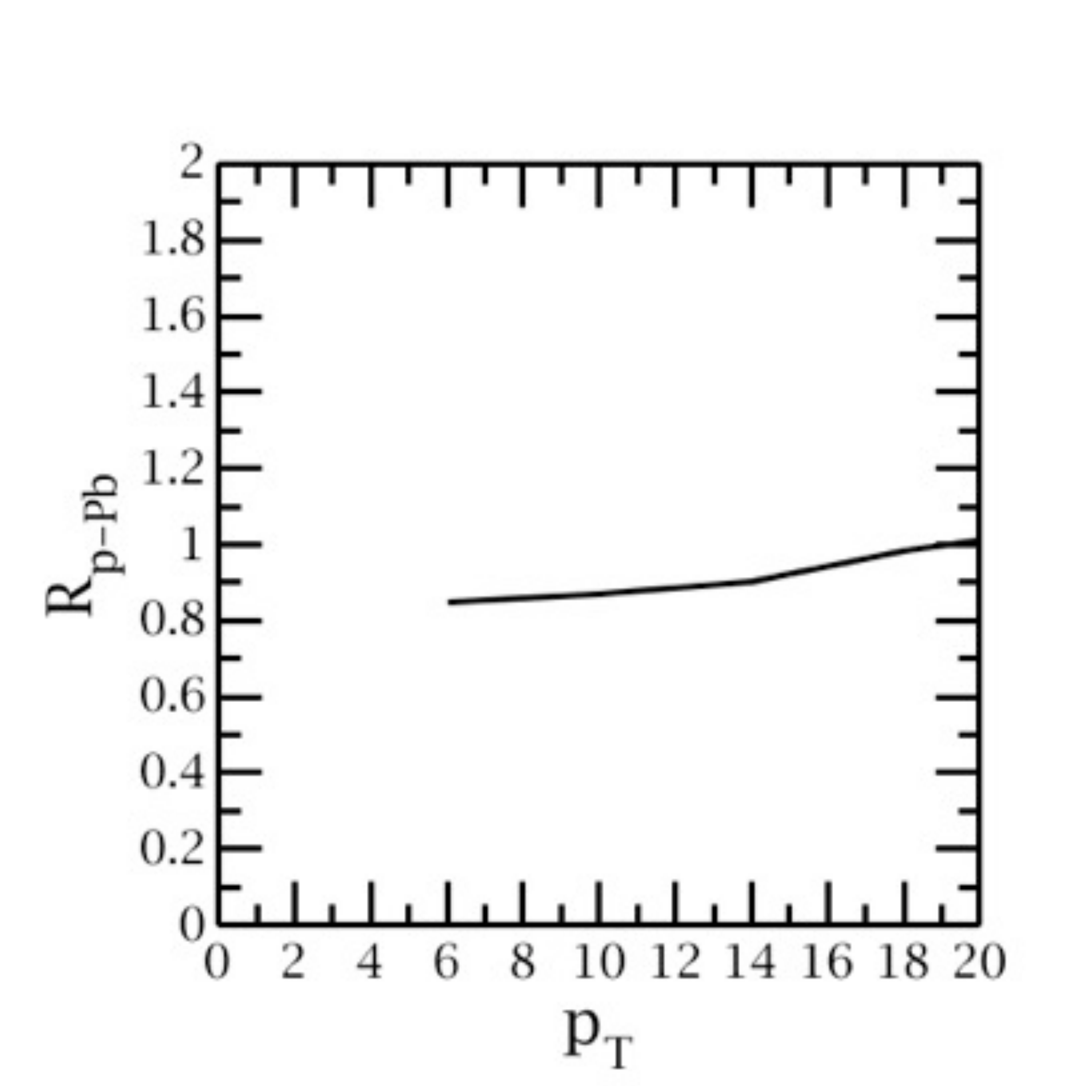
AM, C. Shen, PRL 109 202301 2012

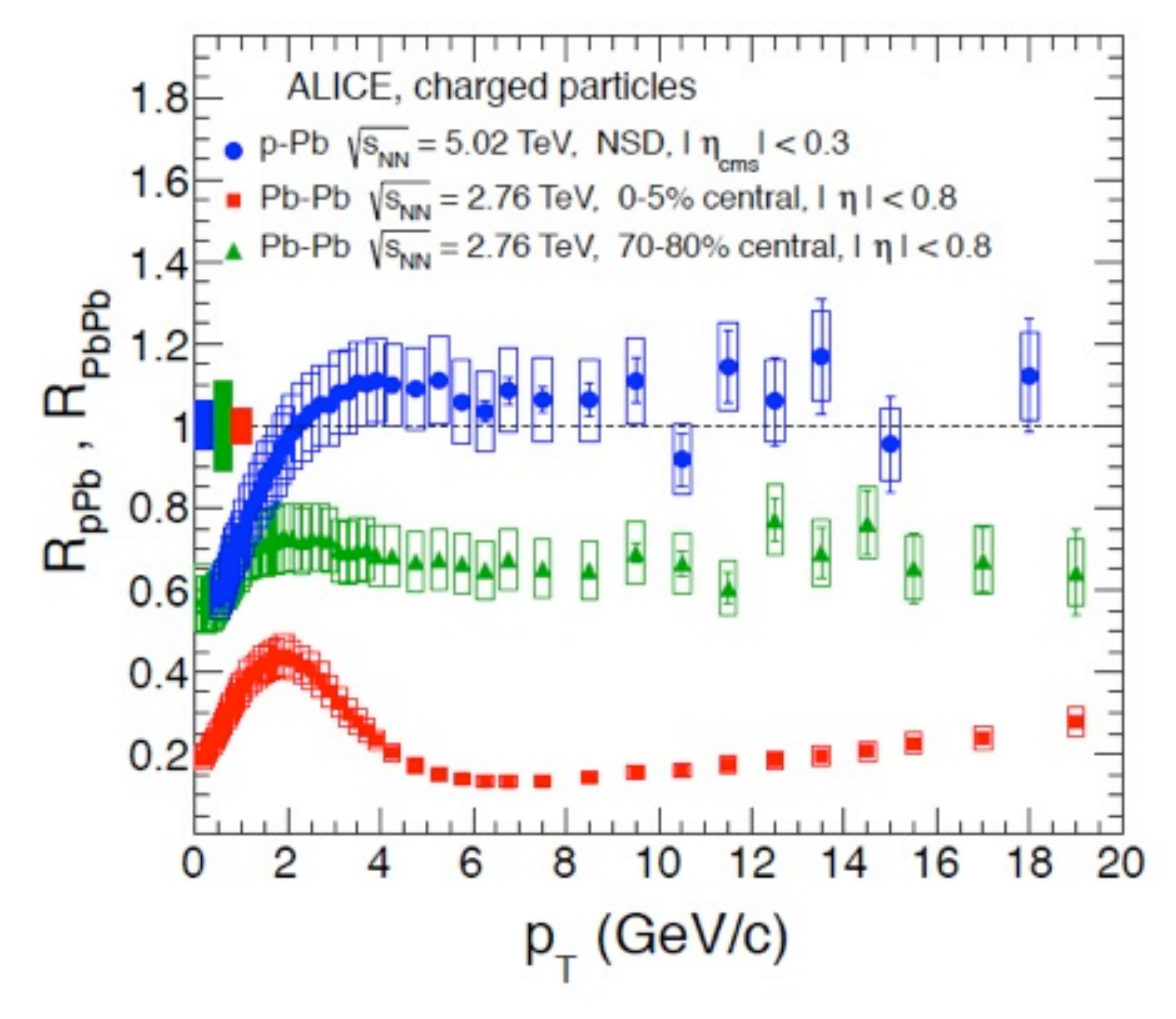
Reasonable agreement with data

The band is from the uncertainty in Q_{min}

Predictions for p-Pb R_{AA} at mid-rapidity

No surprises here!





This means that our baseline is in control
We can do more detailed analysis

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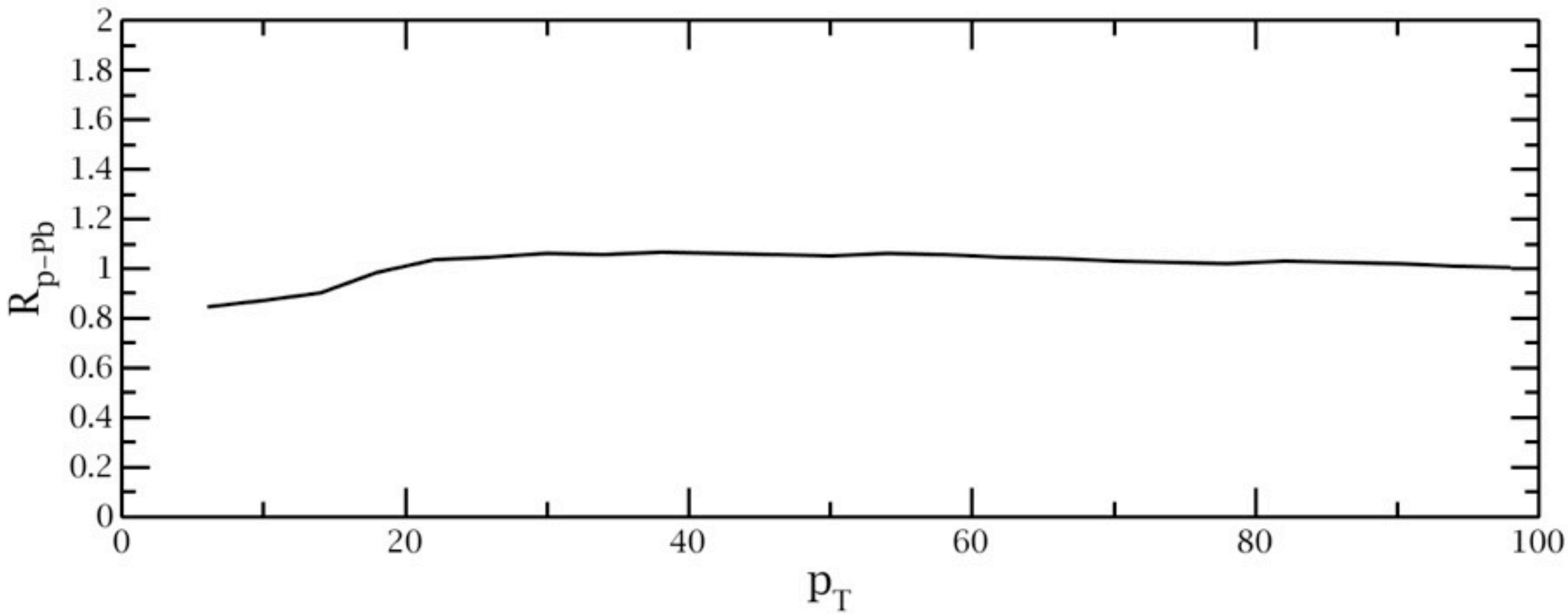

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Move from a few particles to full jets... Need MC

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Progress towards a first principles calculation... Lattice QCD

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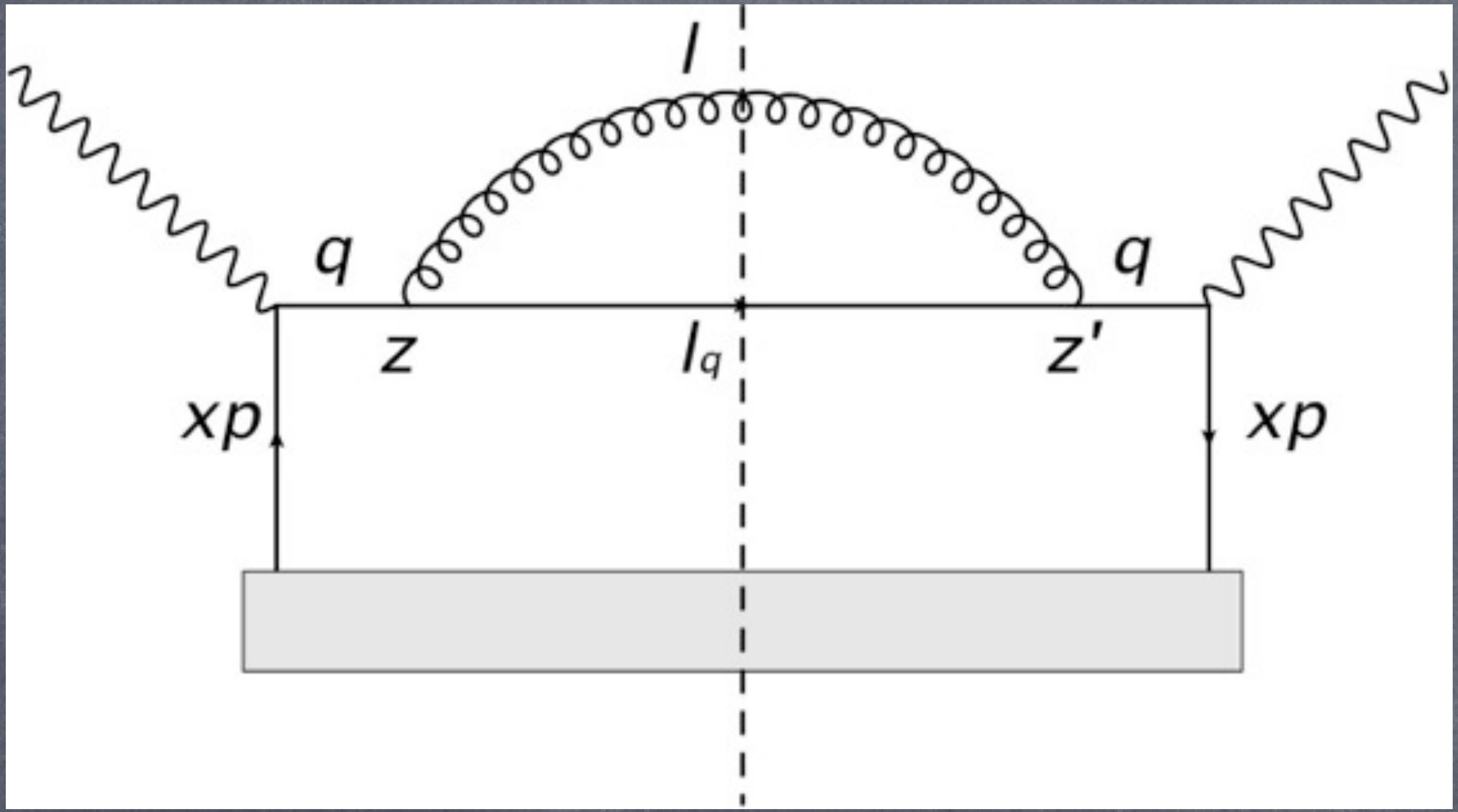
Study flavor/mass dependence... more transport coefficients

MATTER++ a HT based MC event generator

Main problem: Introducing distance into a DGLAP shower

No space-time in the usual Monte-Carlo showers

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



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

what is the role of z and z' ?

$$\int_0^\infty d^4\bar{z} \exp\left[i(\delta q)\bar{z}\right] \qquad \int d^4\delta z \exp\left[i\delta z(l + l_q - q)\right]$$

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

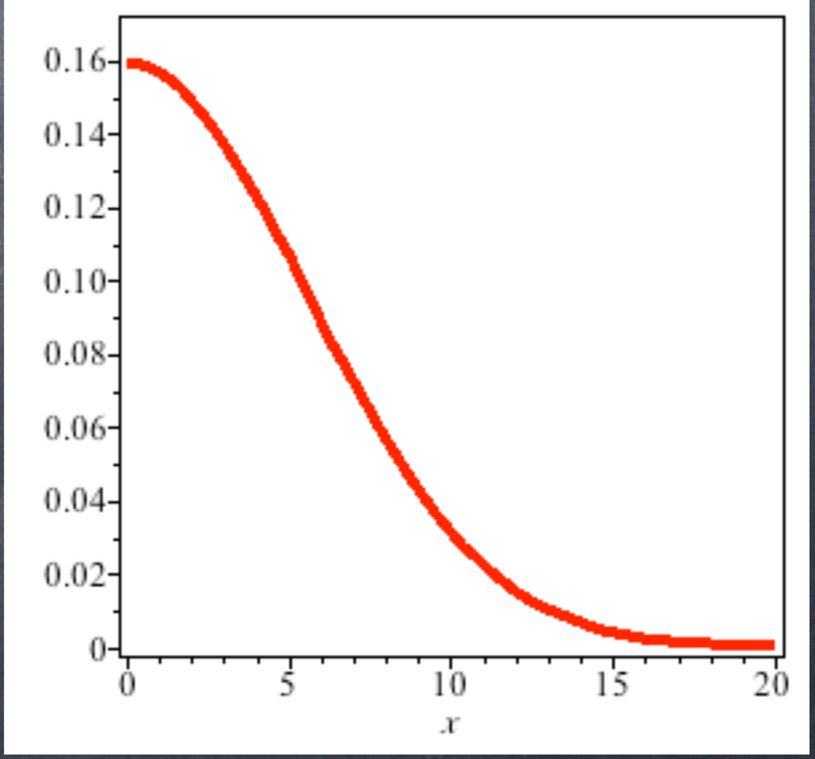
We set the form by insisting $\langle \tau \rangle = 2q^-/(Q^2)$

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

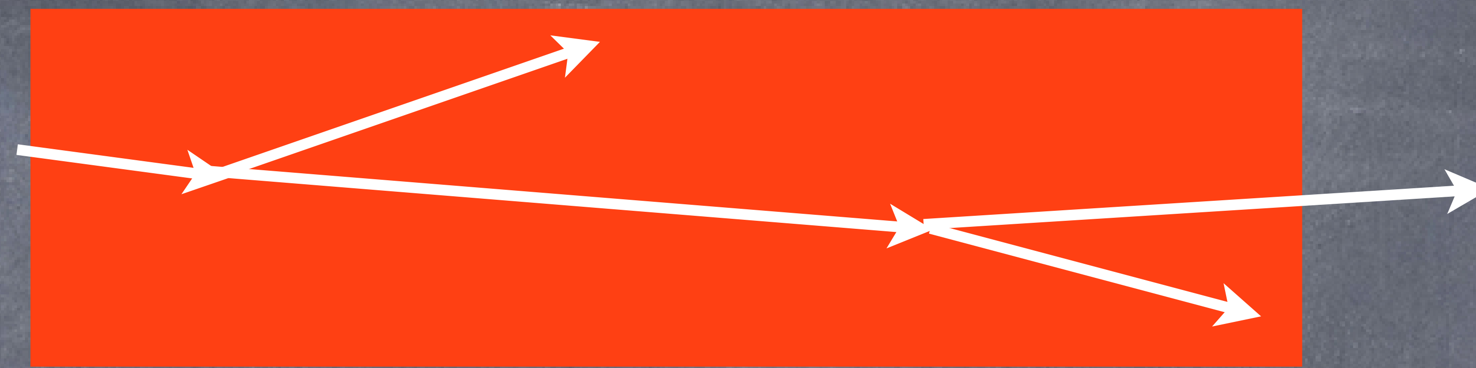
$$\rho(\delta q^+) = \frac{e^{-\frac{(\delta q^+)^2}{2[2(q^+)^2/\pi]}}}{\sqrt{2\pi[2(q^+)^2/\pi]}}$$

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

FT gives the following distribution in distance



Consider a jet moving through a QGP Brick



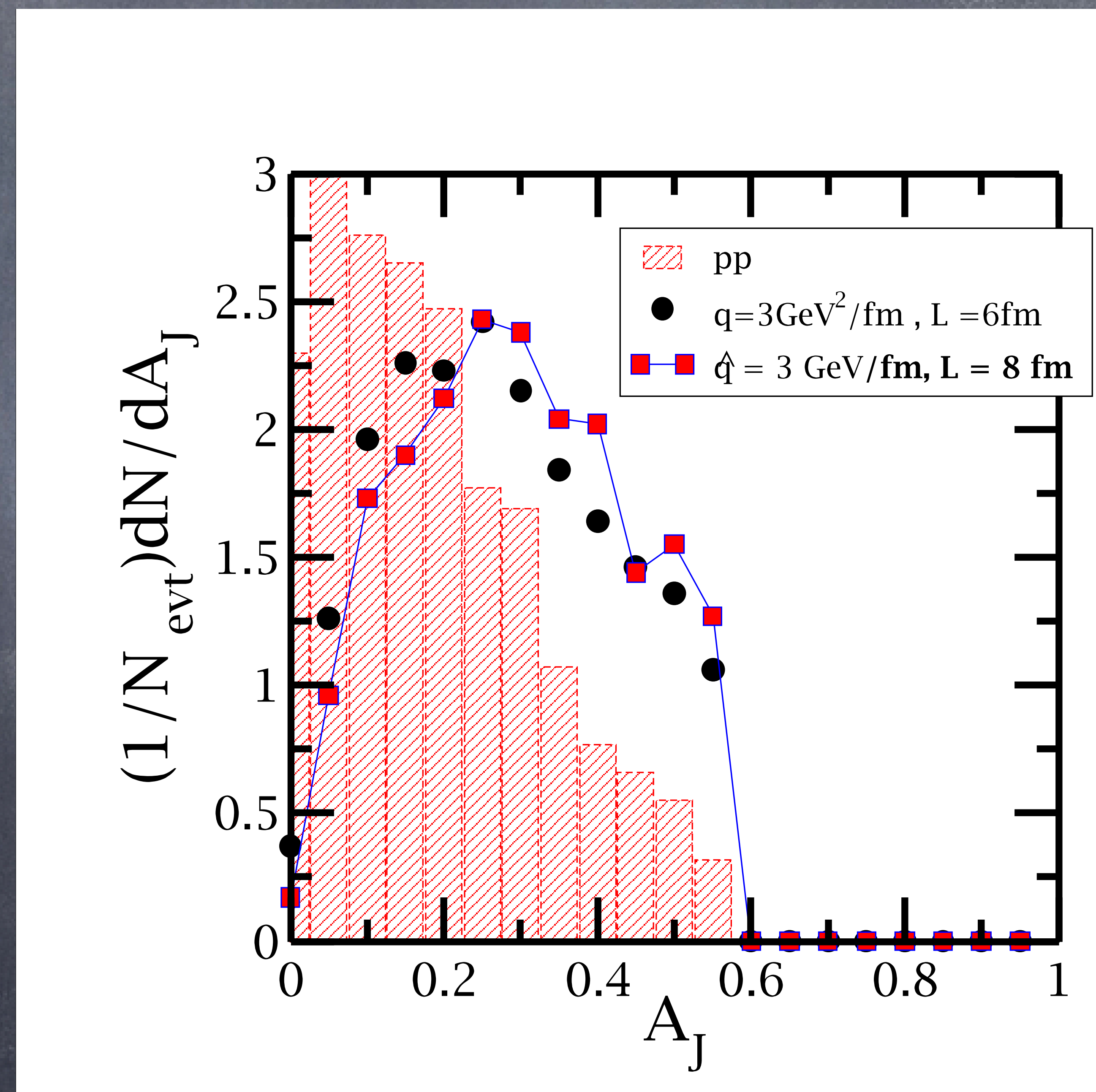
We now construct a Sudakov with the constraint

$$\frac{Q_0^2}{Q^2} < z < 1 - \frac{Q_0^2}{Q^2}$$

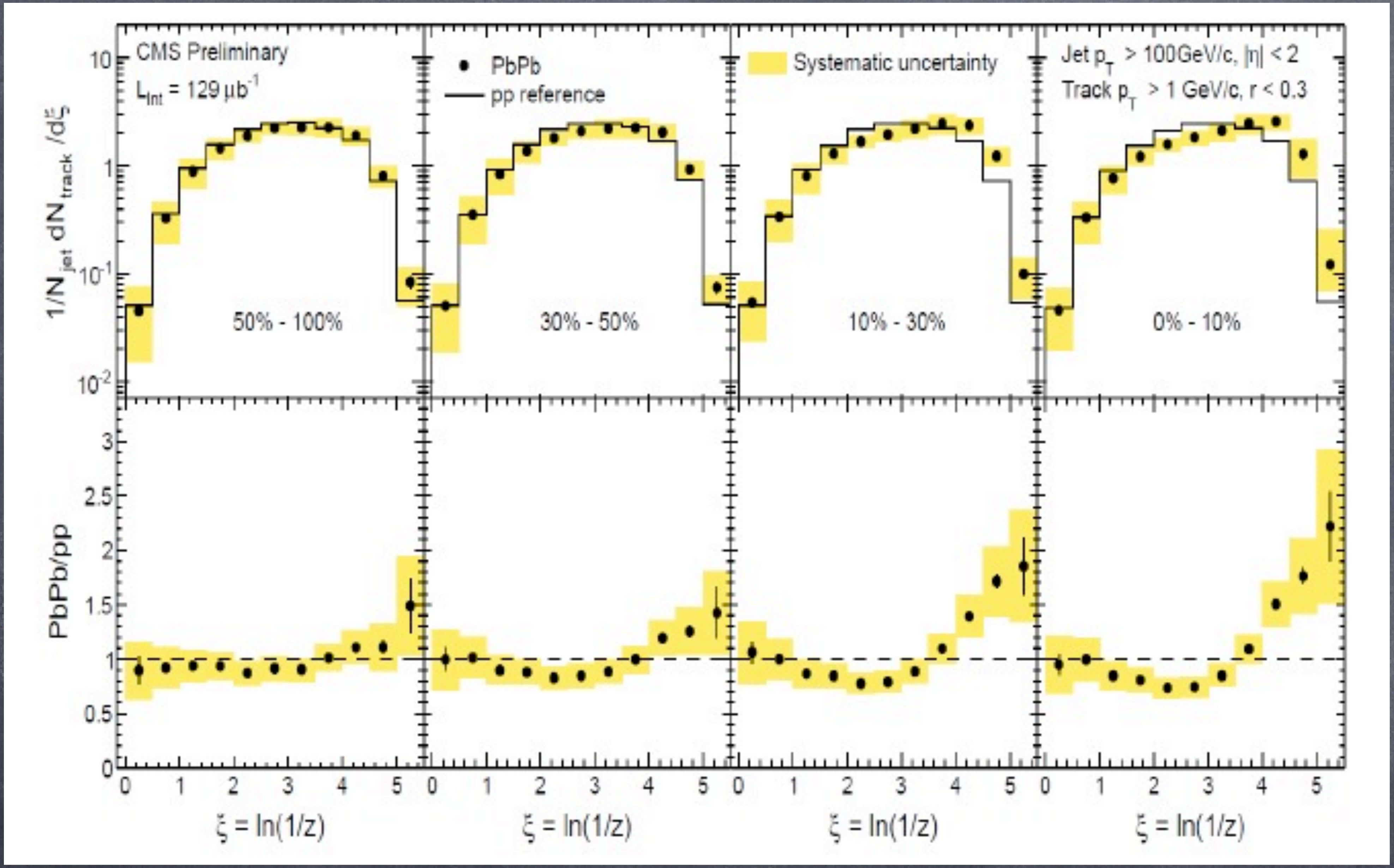
Have a distribution of locations of splittings

length dependent transverse broadening

Partons whose virtuality drops below 1 GeV are removed form cascade



Getting around to the CMS/ATLAS Fragmentation function



AM, arXiv:1301.5323 [nucl-th]

Brick MC, need E-by-E hydro and realistic hadronization

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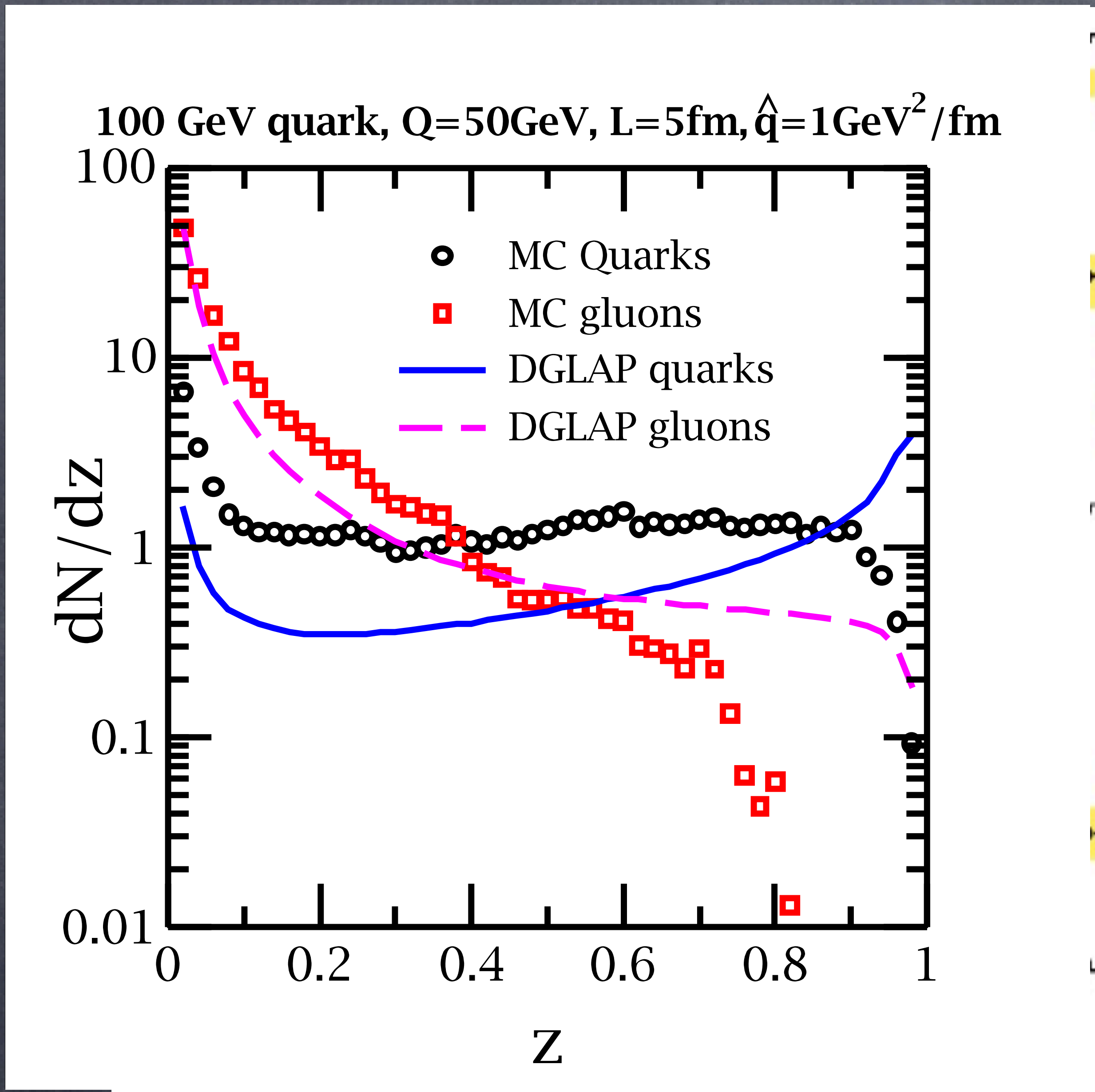

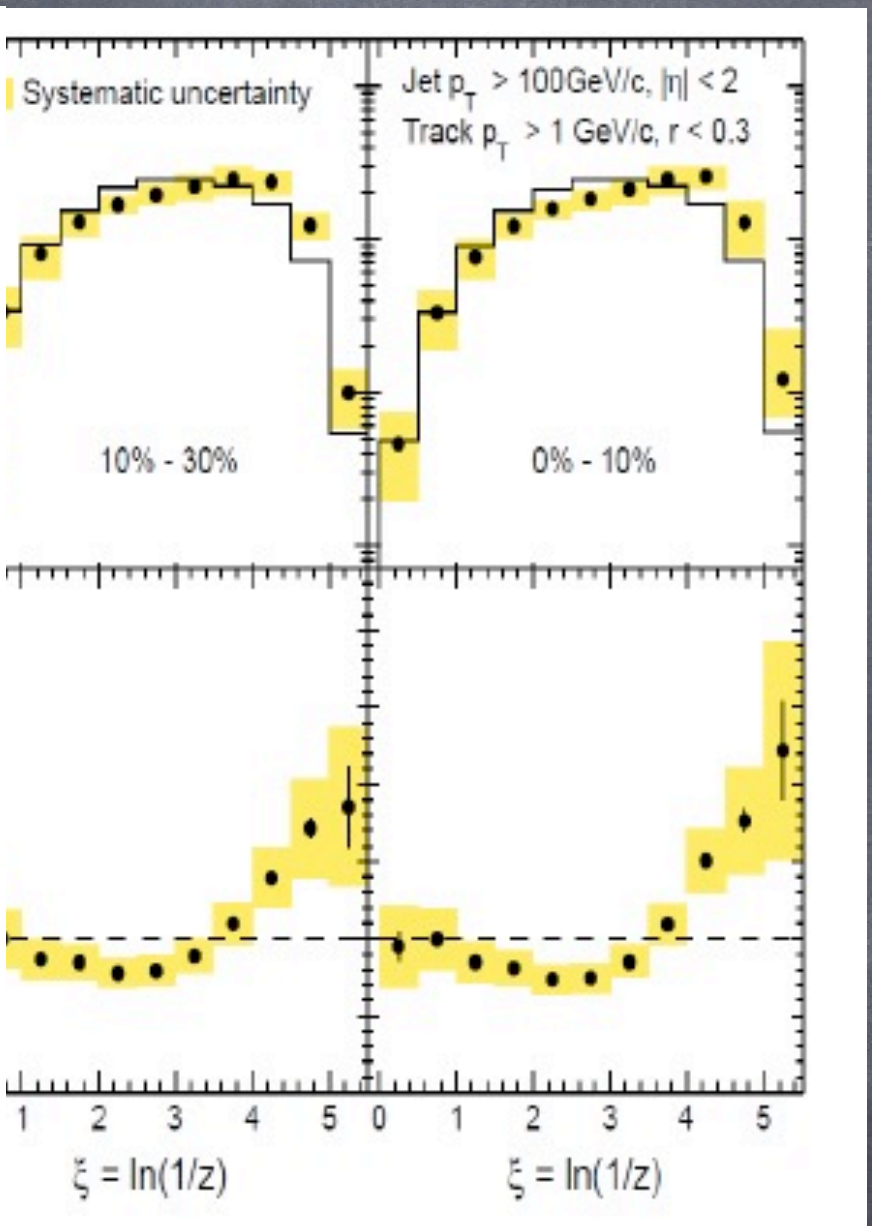

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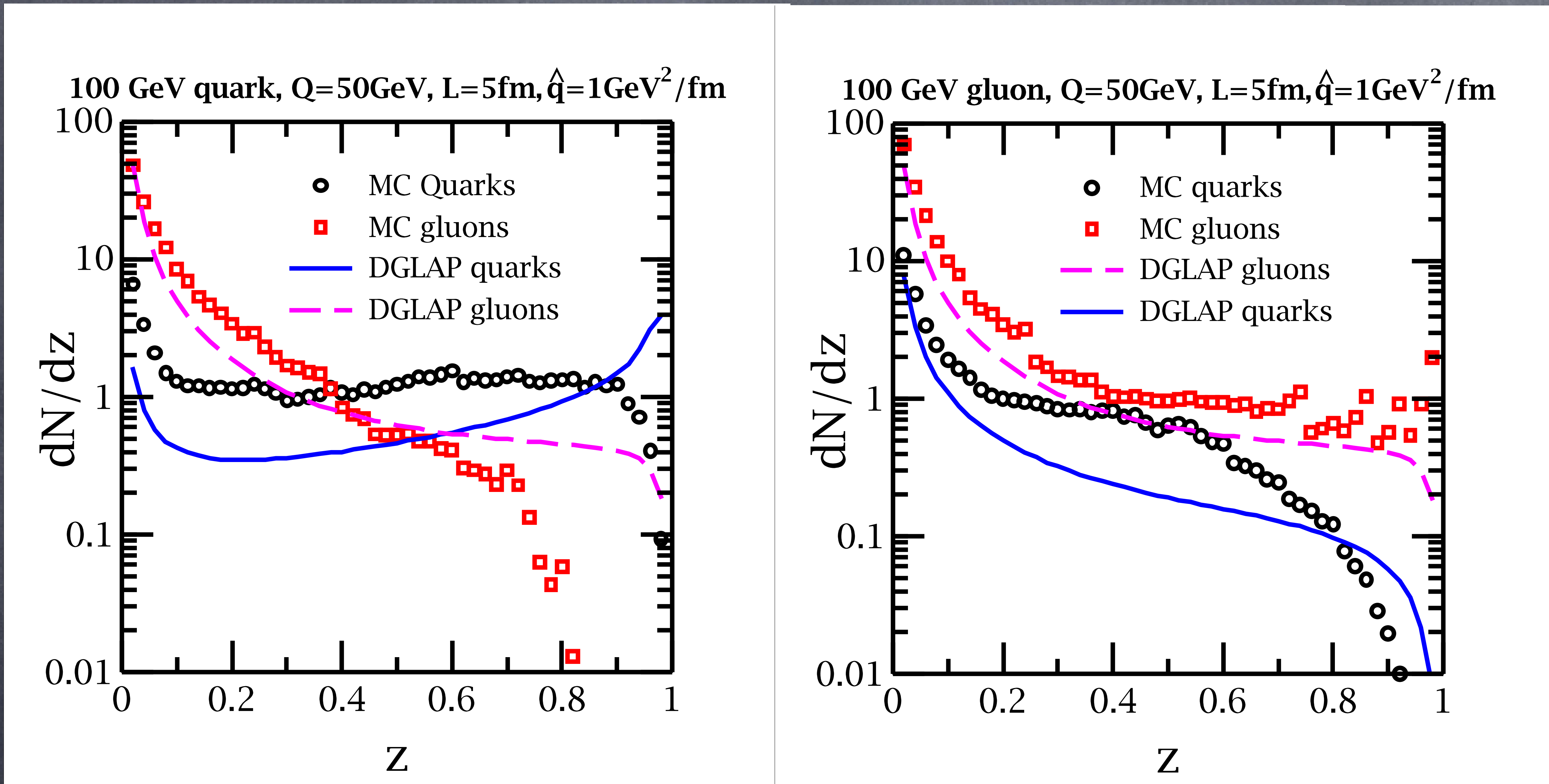

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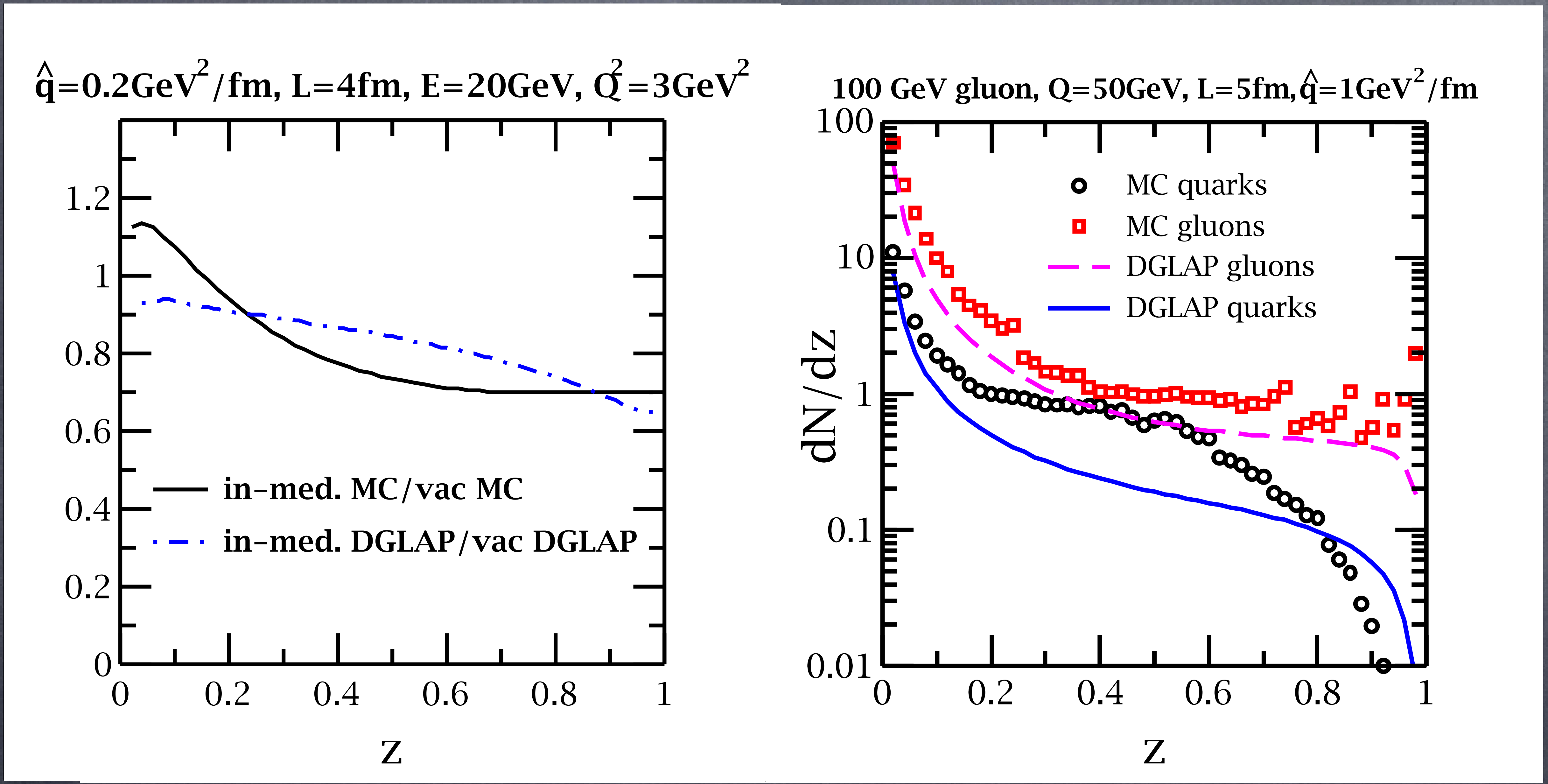

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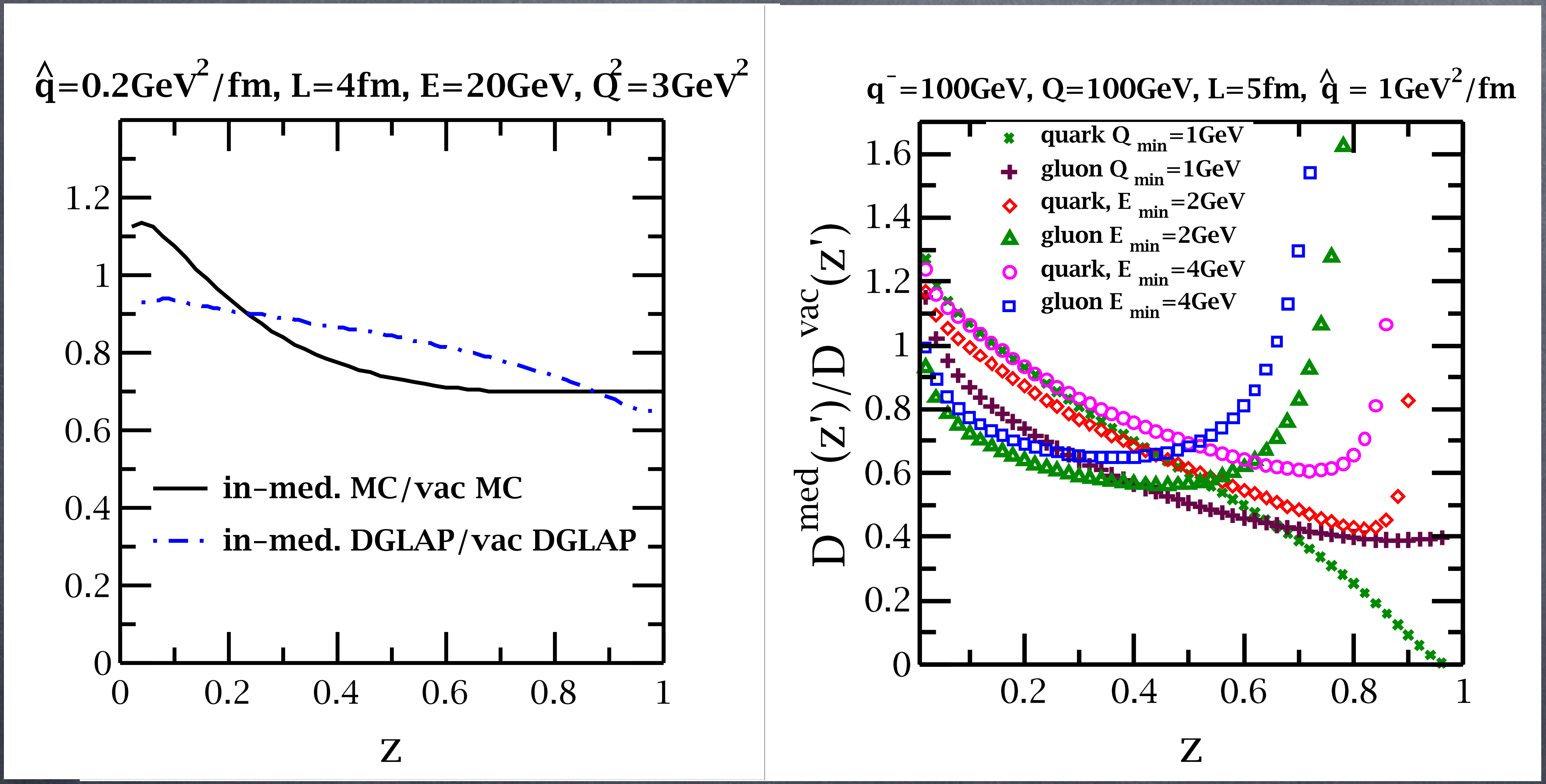

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Brick MC, need E-by-E hydro and realistic hadronization

Energy in and out of cone!

answering this question is not trivial!

From the surviving hard partons, very little energy ~ 5% is outside R=1 cone

A lot of the energy is lost as particles become less energetic or less virtual than 1 GeV, thus strongly interacting with the medium

So far cannot estimate in MC,
no Sudakov, which readjusts formation time
by removing deposited energy from shower

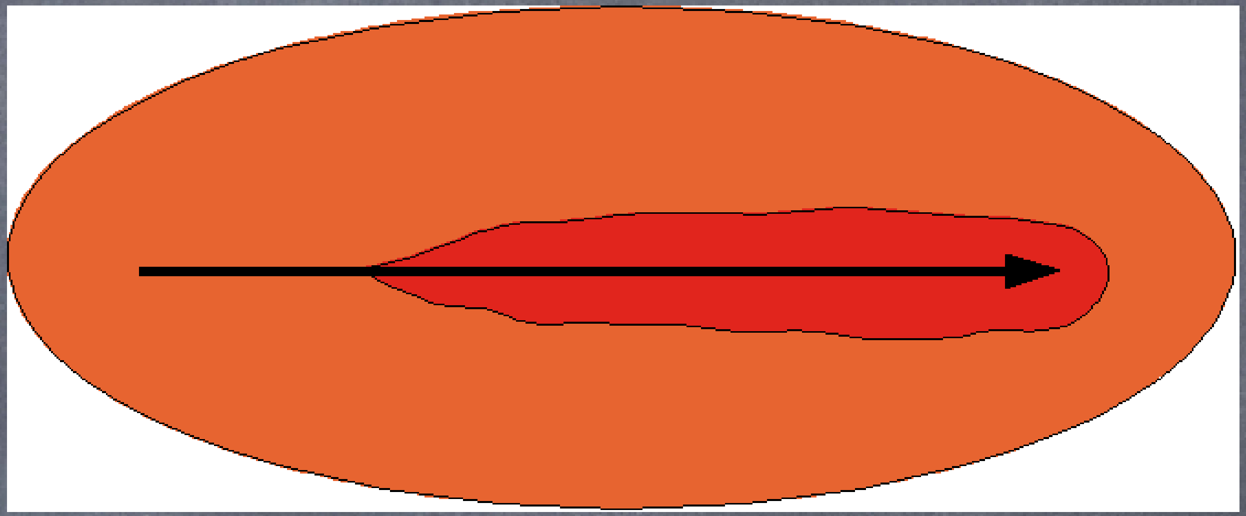
No single gluon emission with coherent drag calculation

G.Y. Qin, AM to appear

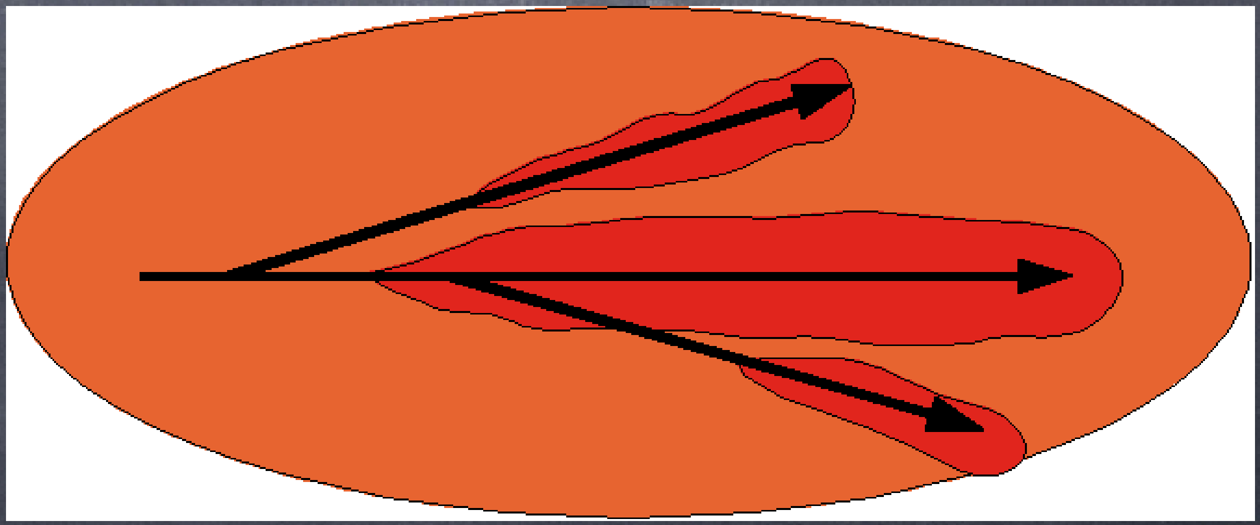
However, can be analytically estimated

At lower momentum need some no-pert. input

A single parton deposits energy and transverse momentum in medium. This just q and e



multiple radiation increases the sources of mom. dep. We know how much radiation as we already calculated it for energy loss

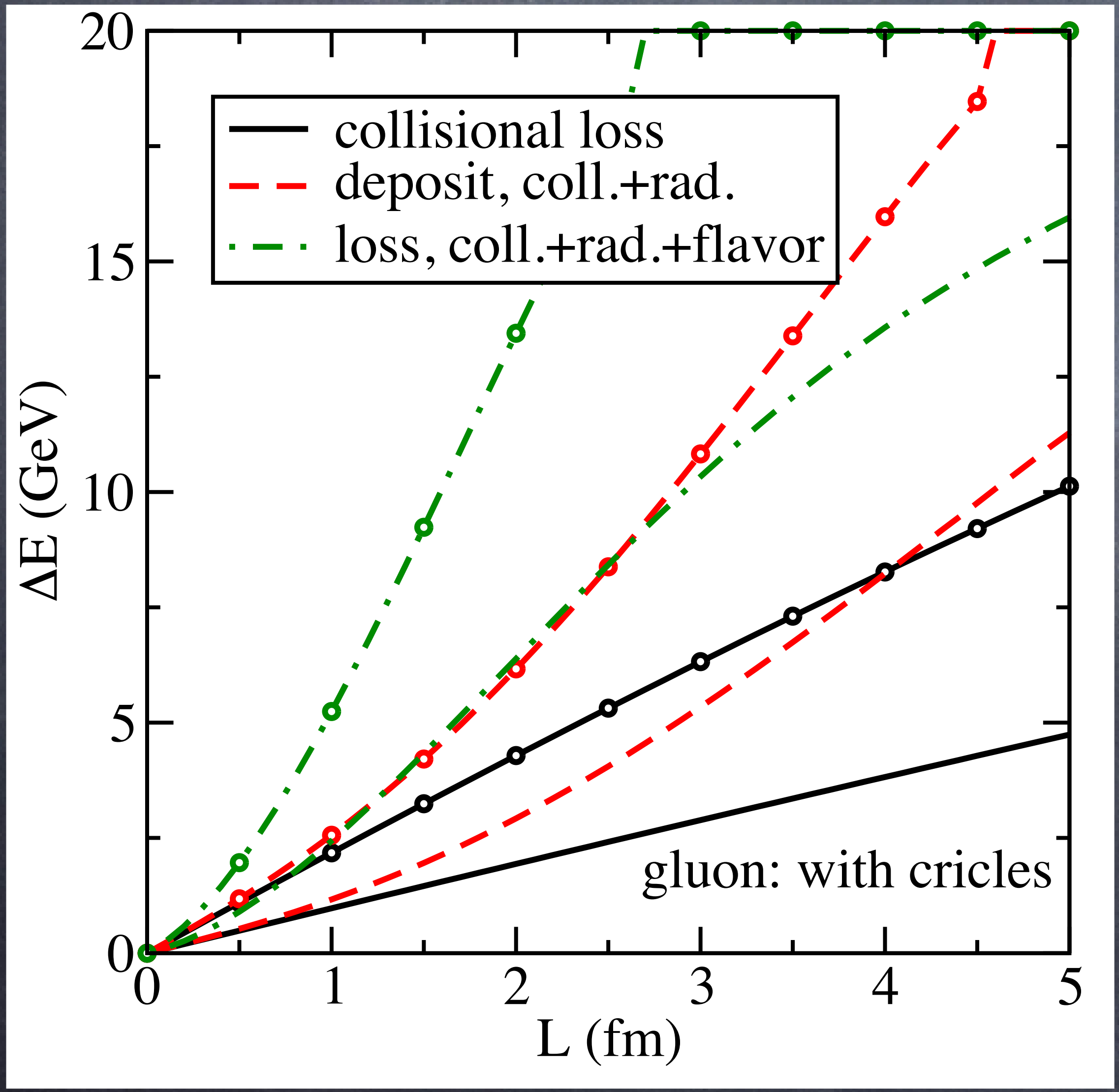


Radiative loss enhances the deposited energy

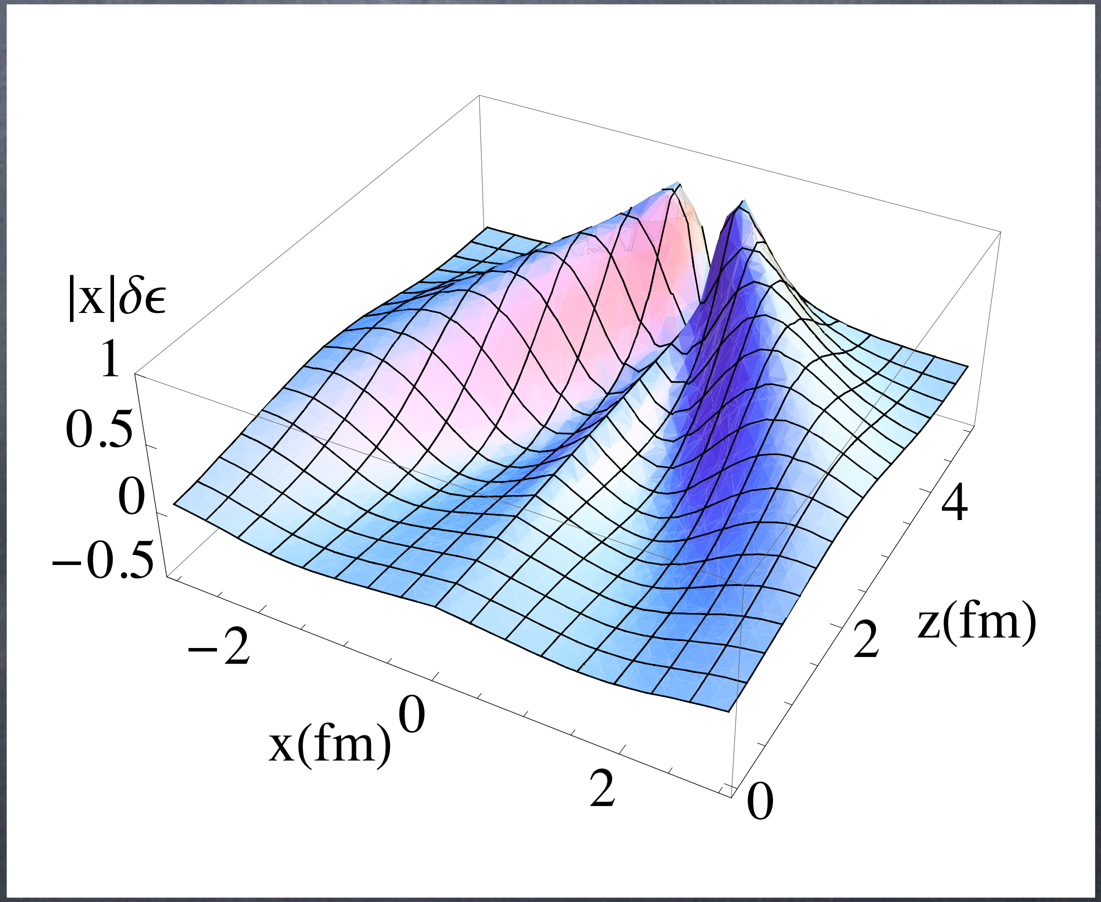
Do a DGLAP with $\Delta E = \hat{e}\, L$ as input

partons with E= 4T and Q<1GeV are added to medium

Energy



Deposited energy will thermalize and spread out

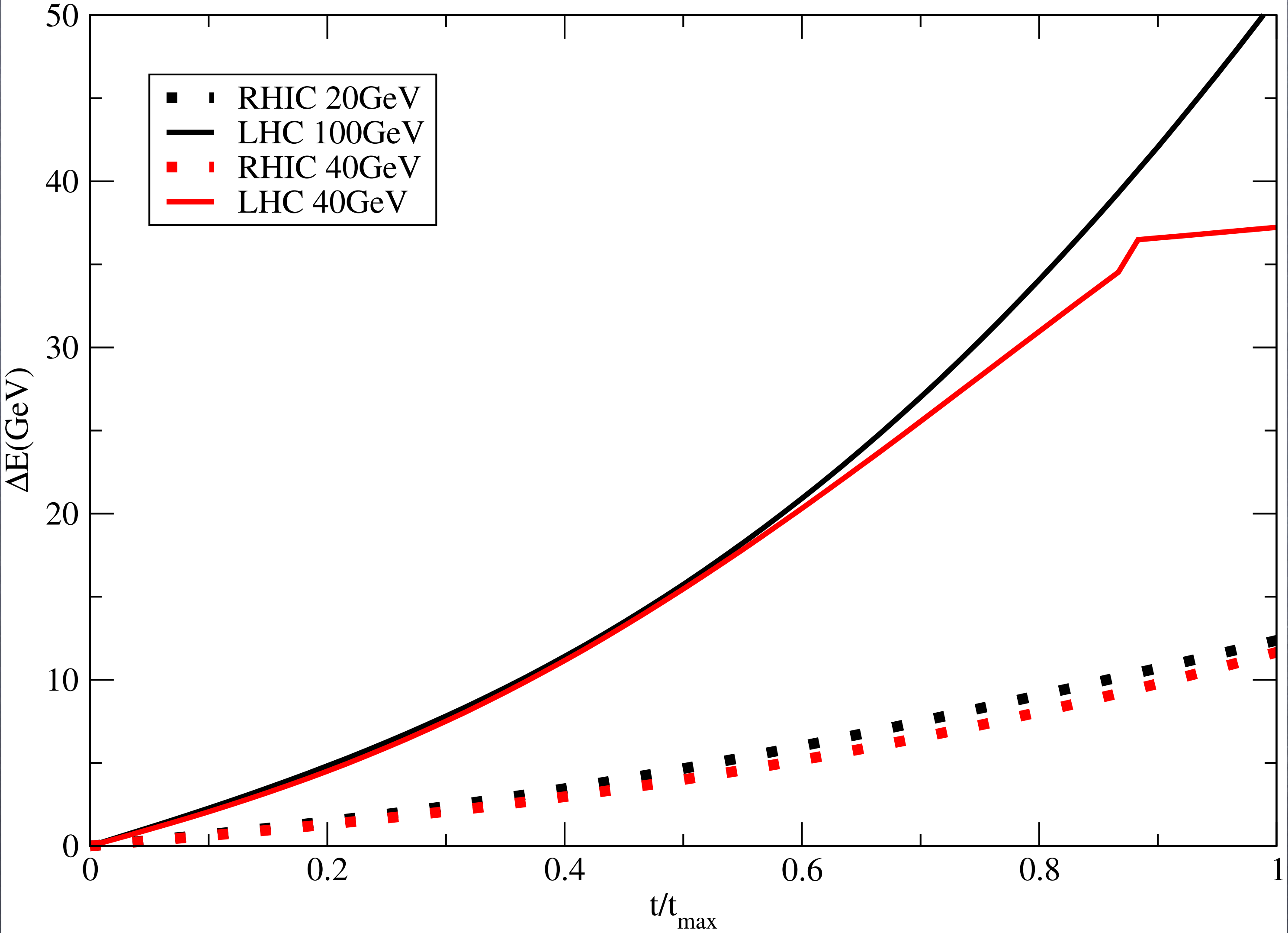


G.Y. Qin, AM, H. Song, U. Heinz, PRL **103 (2009) 152303**

A simple picture

Assign E deposited before L/2 as early deposition.

L=4fm (RHIC) and L= 6fm (LHC)



G.Y. Qin, AM, J. Putschke

A complete understanding requires a MC and a new soft-hard transport coefficient

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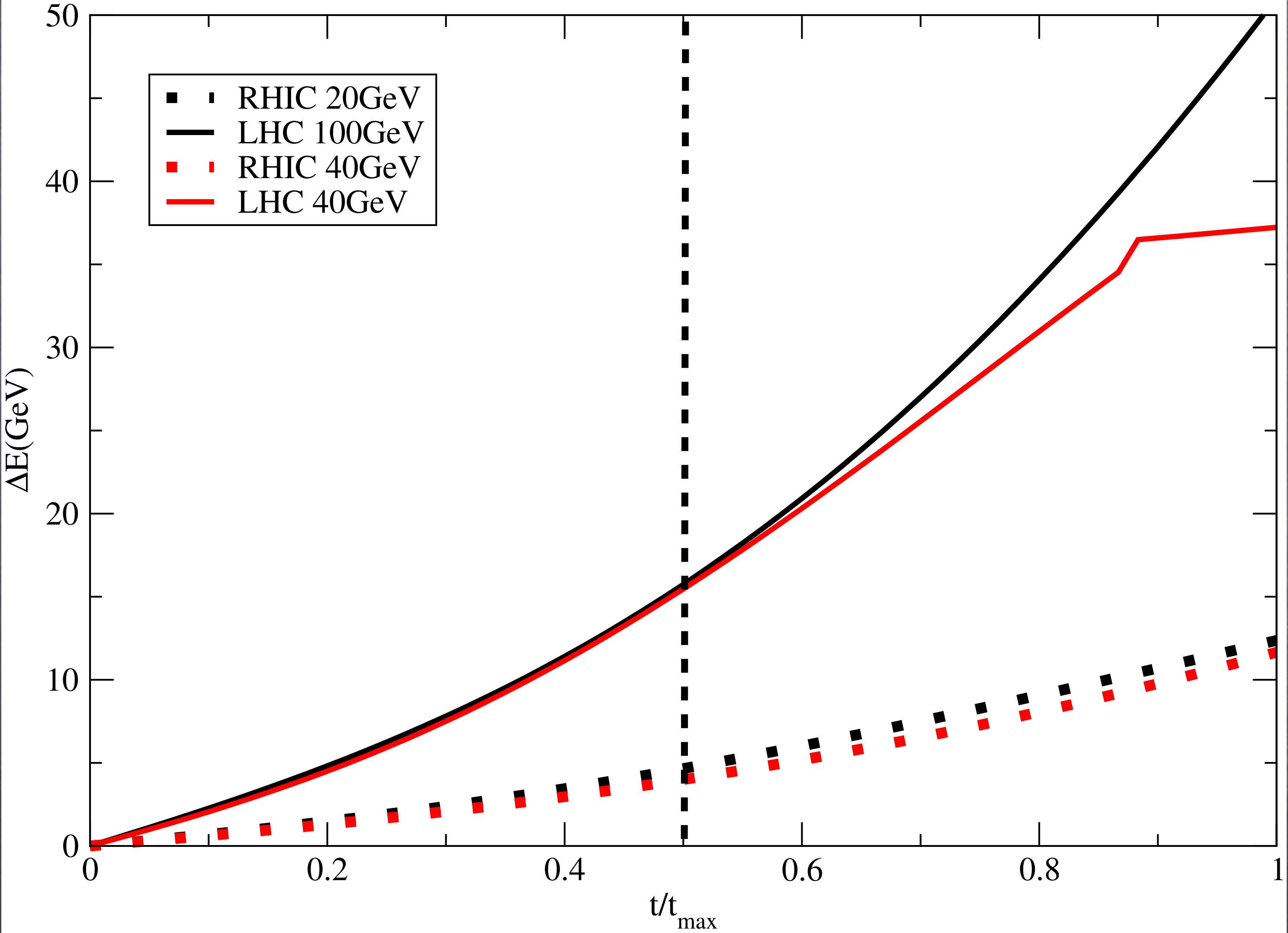
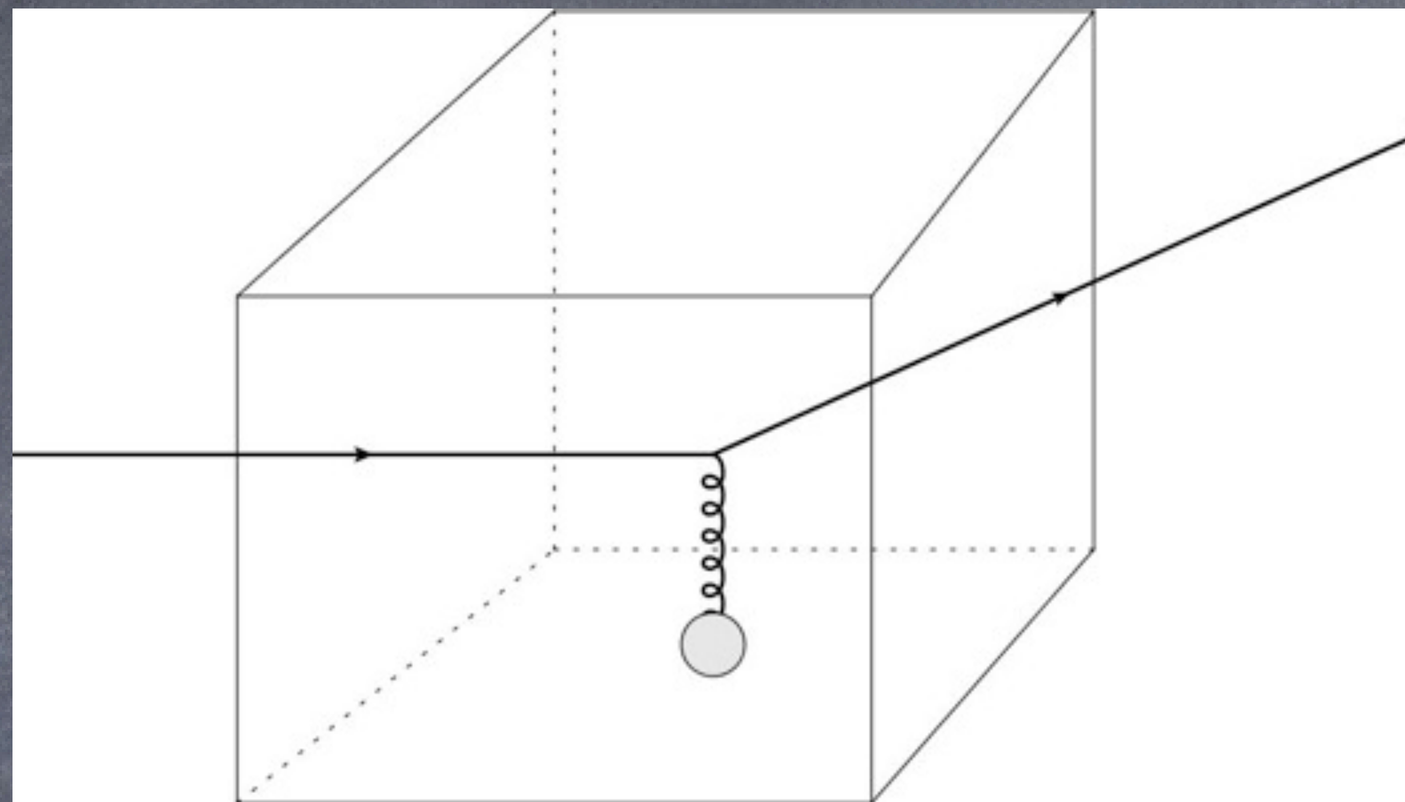


G.Y. Qin, AM, J. Putschke

A complete understanding requires a MC and a new soft-hard transport coefficient

Even with the best MC energy loss routine on the best E-by-E hydro The exchange momentum distribution of $\hat{q}, \hat{e}$ and their normalization are assumptions!

A first principles method to calculate $\hat{q}$



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

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

Final state is ``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

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

$$\langle n|\frac{e^{-\beta E_n}}{Z} F^{+,}{}_\perp(y^-) F_\perp^+(0)|n\rangle$$

physical $\hat{q}(q^-, q^+)$ where $q^+ \sim \lambda^2 Q$

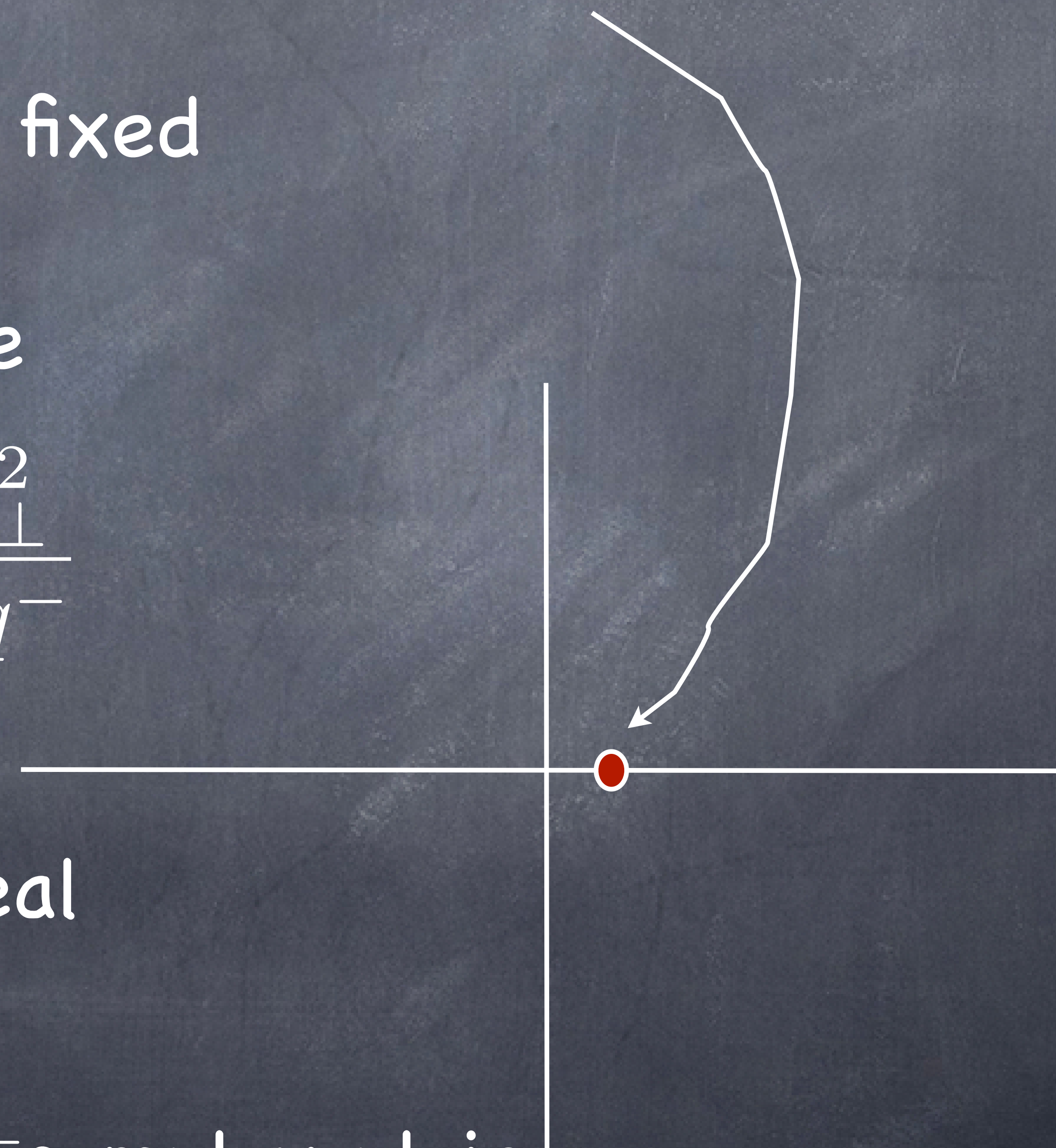
Consider a more general object

$$\hat{Q} = \frac{4\pi^2\alpha_s}{N_c}\int \frac{d^4y\,d^4k}{(2\pi)^4} e^{ik\cdot y}\,\frac{2(q^-)^2}{\sqrt{2}q^-}\,\frac{\langle M|F^{+\perp}(0)F^{+}_{\perp,}(y)|M\rangle}{(q+k)^2+i\epsilon}.$$

Consider q^- large (~Q) and fixed

Consider q^+ to be a variable

$\frac{d^2\hat{Q}}{dk_\perp^2}$ has a pole at $q^+ = \frac{k_\perp^2}{2q^-}$



$\hat{Q}$ has a branch cut on the real axis at $q^+ \sim \lambda^2 Q$

$\hat{q} = Im(\hat{Q})$

q^+complex plain

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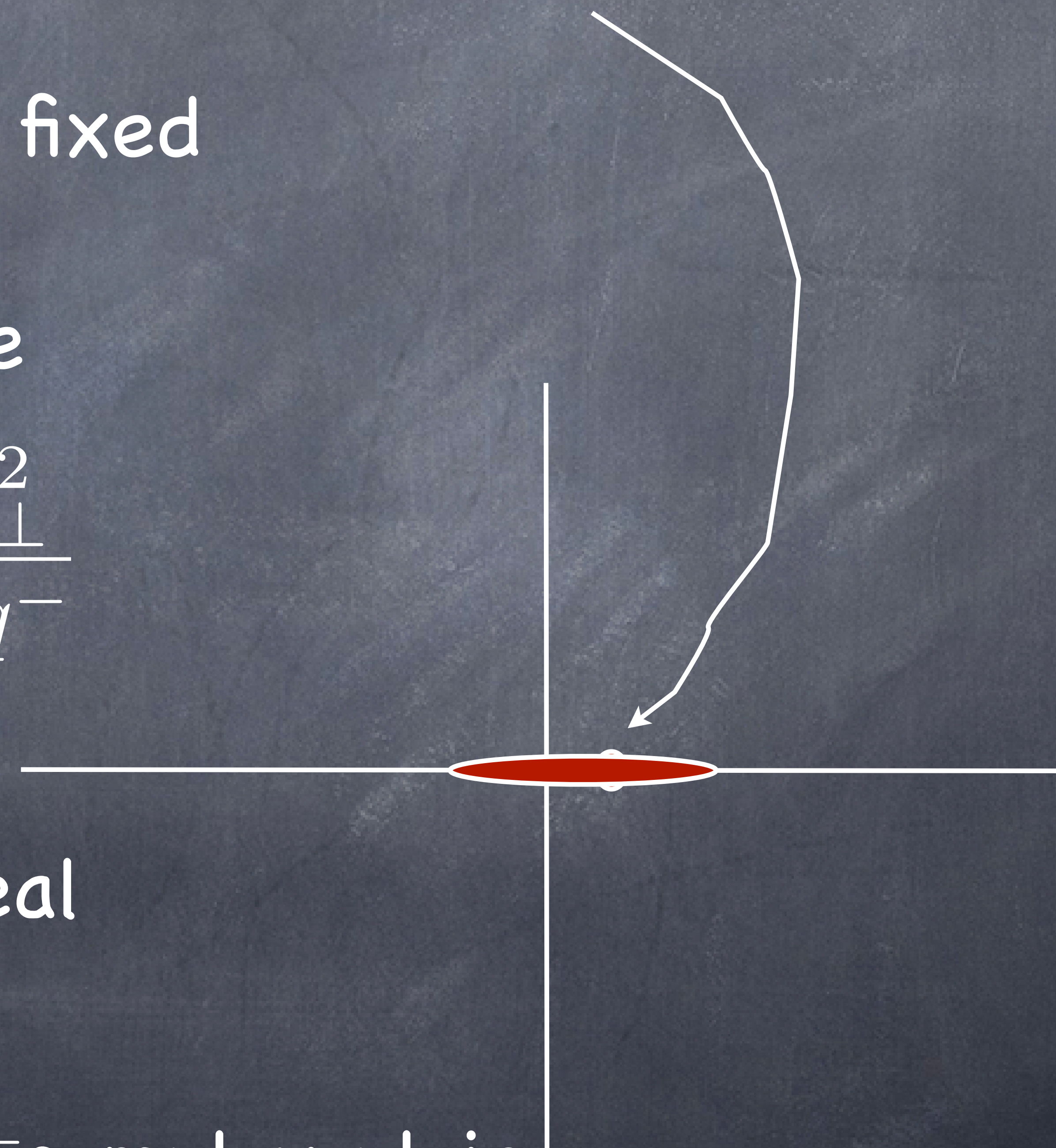

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$$I_1 = \oint \frac{dq^+}{2\pi i} \frac{\hat{Q}(q^+)}{(q^+ + Q_0)}$$

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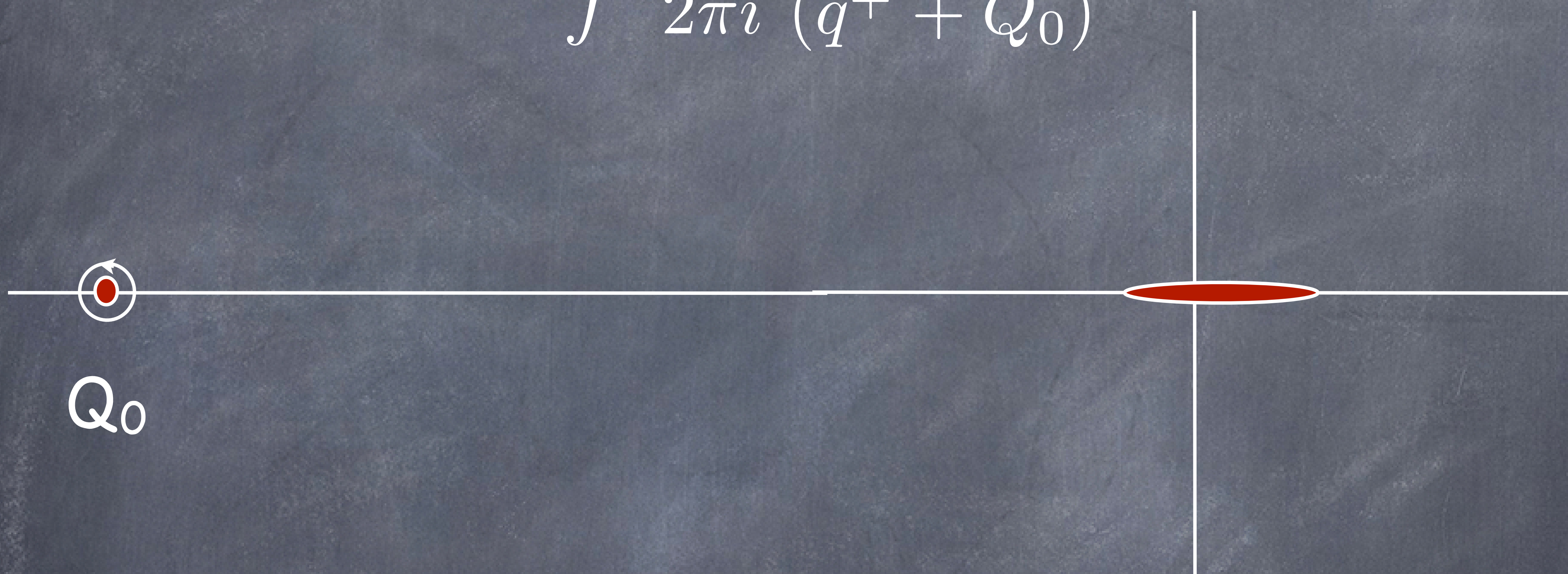

For $Q_0 \sim -Q$, can Taylor expand $\hat{Q}$ in terms of local operators

$$I_1 = \frac{4\sqrt{2}\pi^2 \alpha_s \langle M | F_\perp^{+\mu} \sum_{n=0}^{\infty} \left(\frac{-q \cdot i\mathcal{D} - \mathcal{D}_\perp^2}{2q^- Q_0} \right)^n F_{\perp,\mu}^{+} | M}{N_c 2 Q_0}$$

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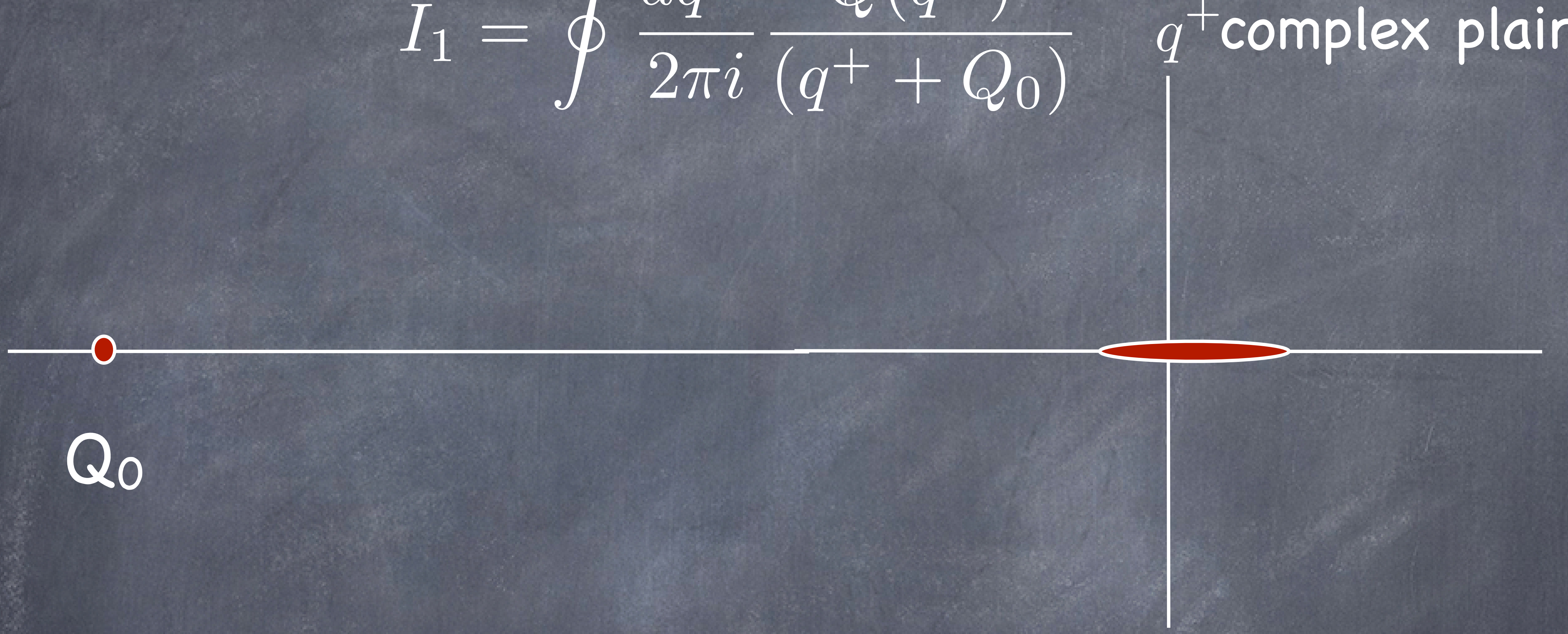

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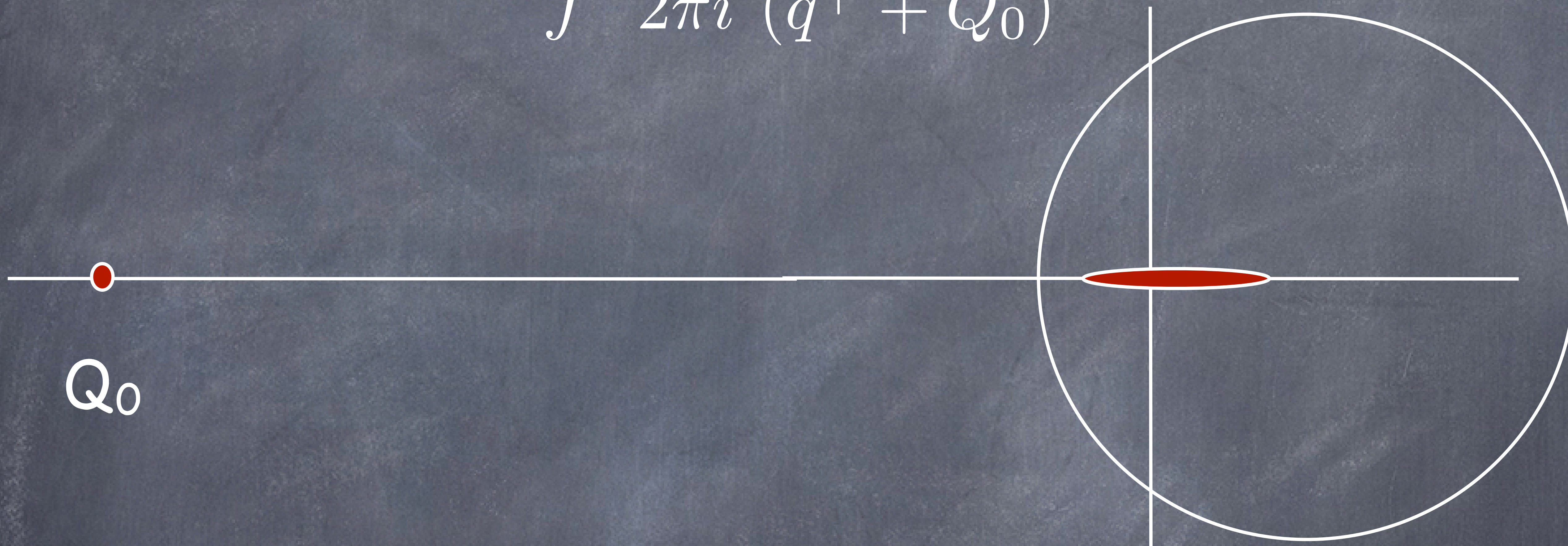

For Q_0 ~ $-Q$, can Taylor expand $\hat{Q}$ in terms of local operators

$$I_1 = \frac{4\sqrt{2}\pi^2 \alpha_s \langle M| F_\perp^{+\mu} \sum_{n=0}^{\infty} \left(\frac{-q\cdot i\mathcal{D} - \mathcal{D}_\perp^2}{2q^- Q_0} \right)^n F^{+}_{\perp,\mu} |M}{N_c 2 Q_0}$$

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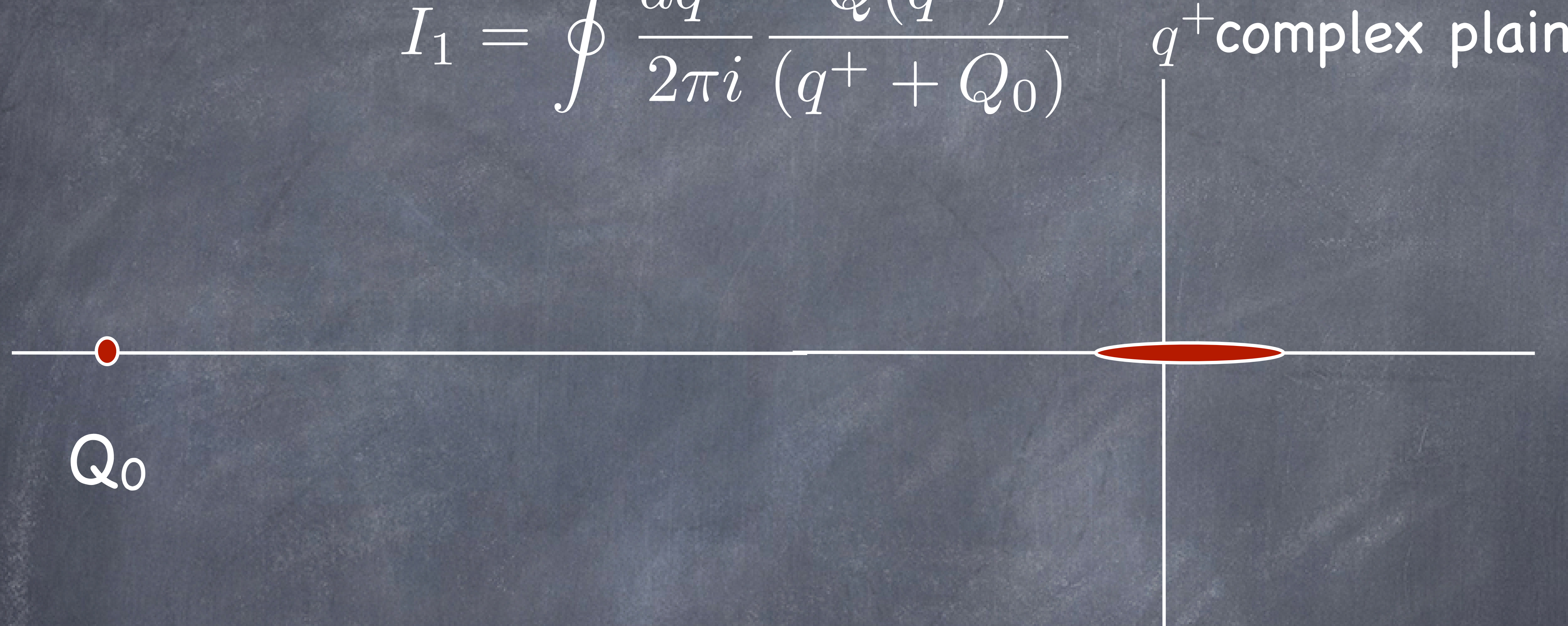

For $Q_0 \sim -Q$, can Taylor expand $\hat{Q}$ in terms of local operators

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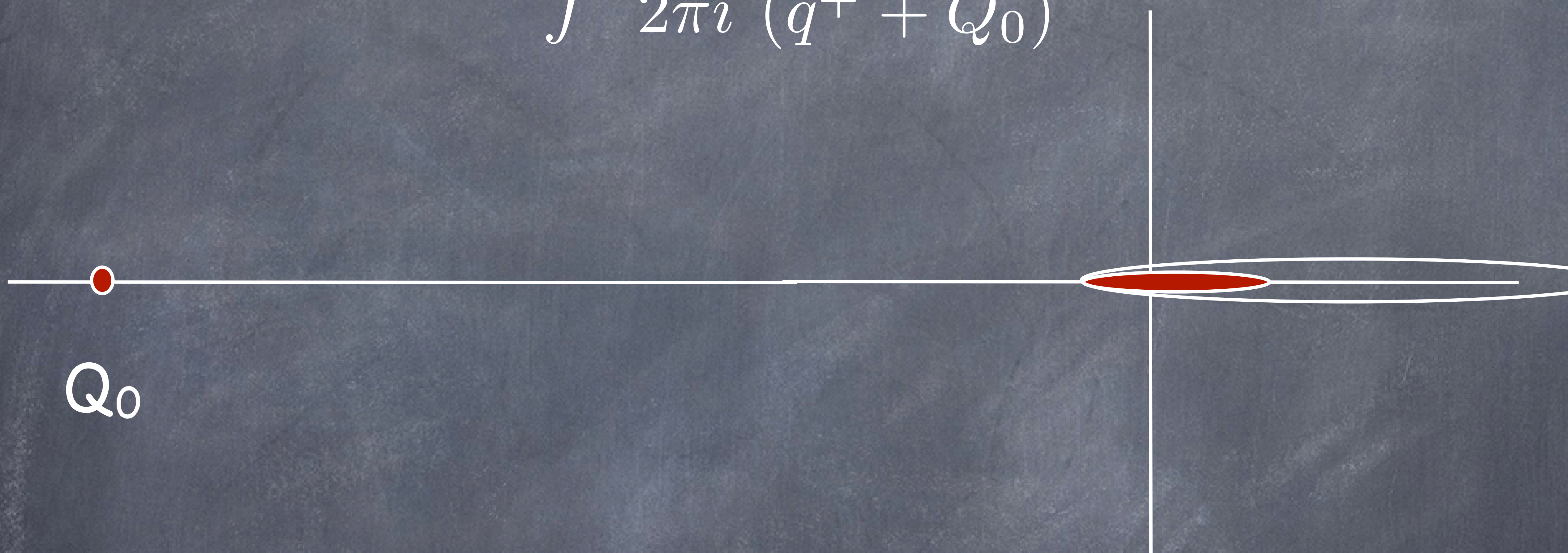
q^+complex plain



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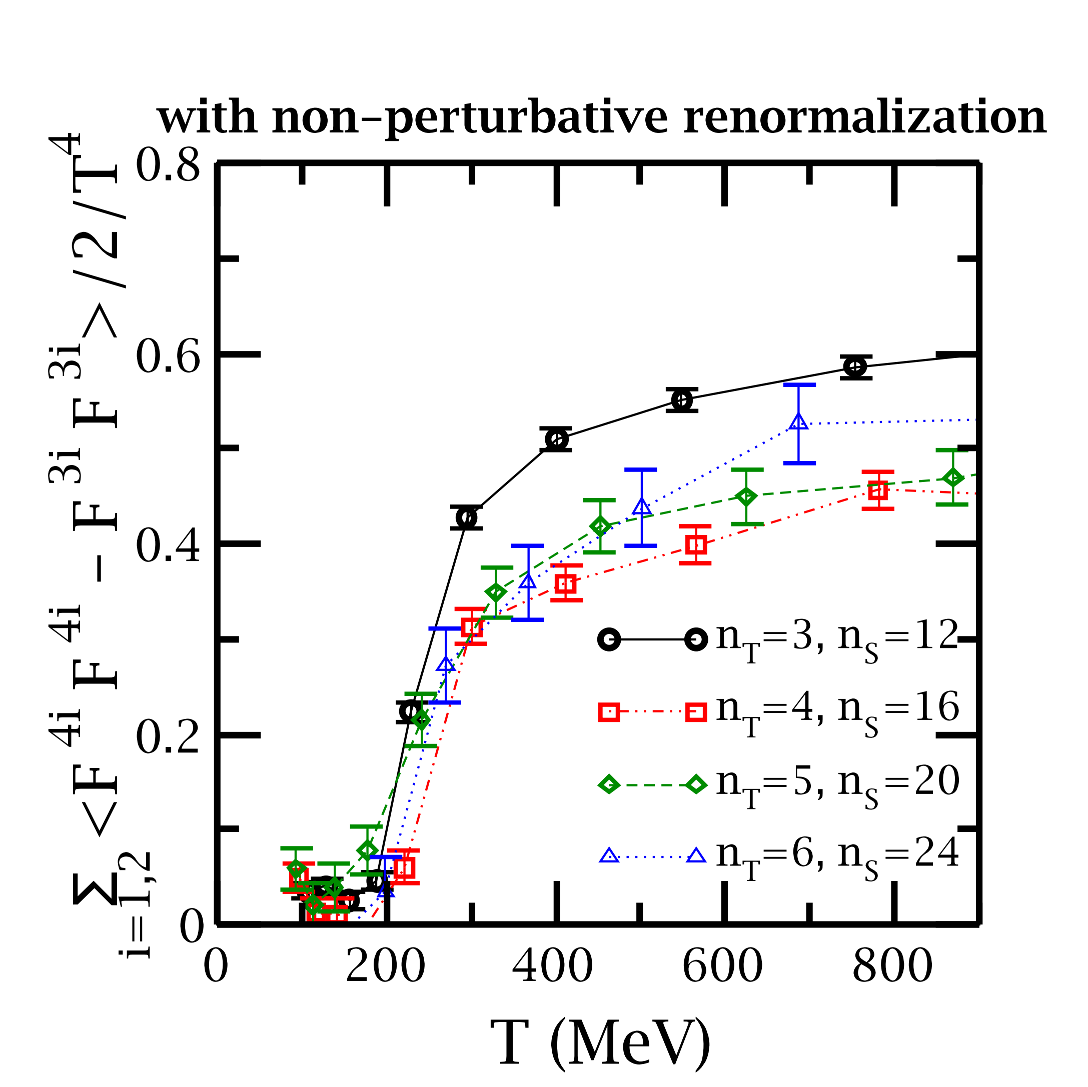
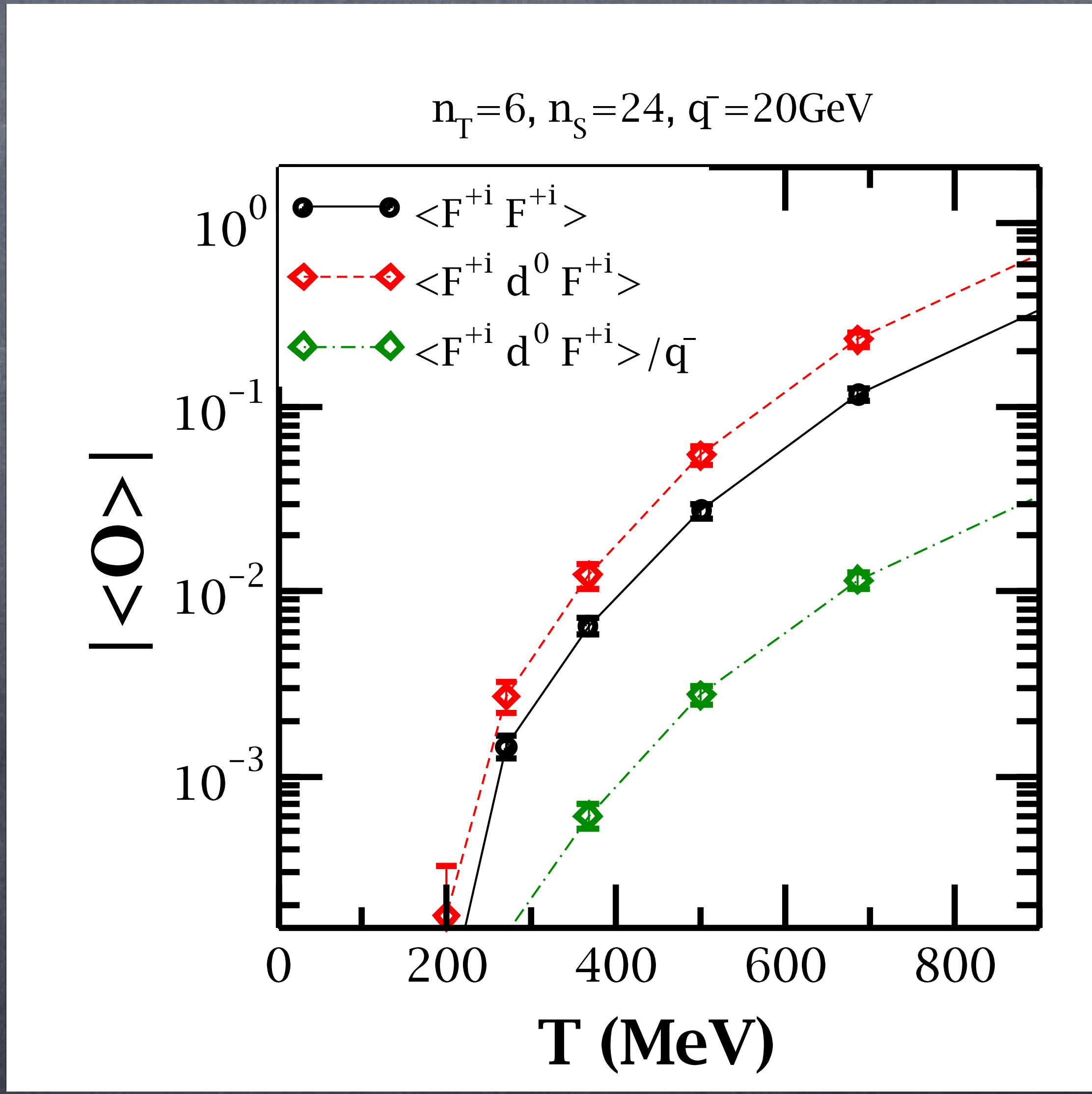
Rotating everything to Euclidean space and calculating

$$x^0 \to -ix^4 \text{ and } A^0 \to iA^4$$

$$\to F^{0i} \to iF^{4i}$$

Calculate in quark less SU(2) gauge theory





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Concluding and Extrapolating !

Need to calculate in SU(3)
Better renormalization prescription
More complicated processes on the lattice
Need to do a higher order perturbative calculation
But lets estimate anyways

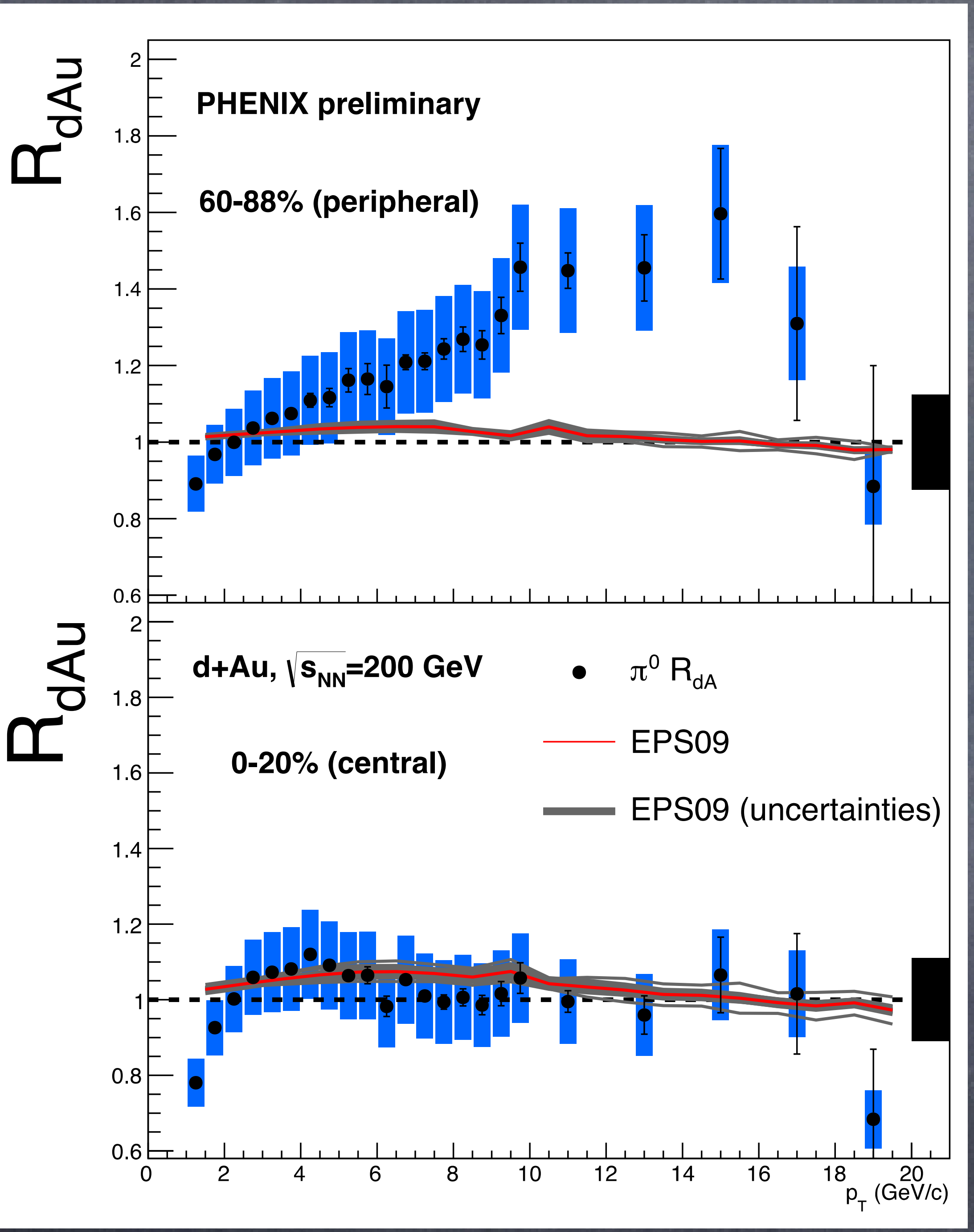
at T=400, FF = 0.01 GeV^4
Lattice size ~ 2fm, E = 20 GeV, $\mu^2 = 1.3$ GeV^2

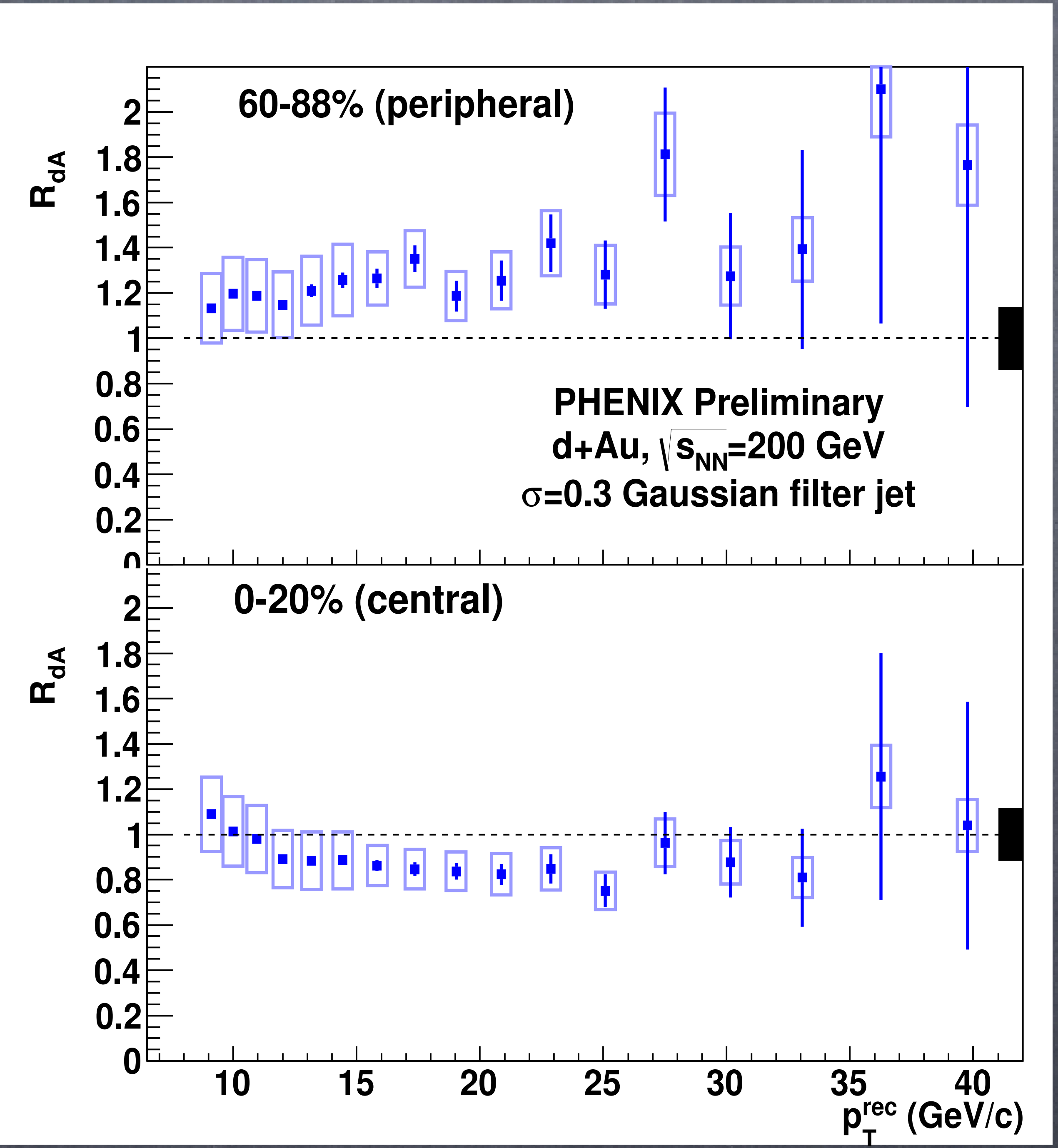
Gluon $\hat{q}$ is C_A/C_F of quark $\hat{q}$

SU(2) has 3 gluons, SU(3) has 8,
and 6 quarks + antiquarks

$$\hat{q}(T = 400\text{MeV}) = 1\text{GeV}^2/\text{fm} - 2\text{GeV}^2/\text{fm}$$

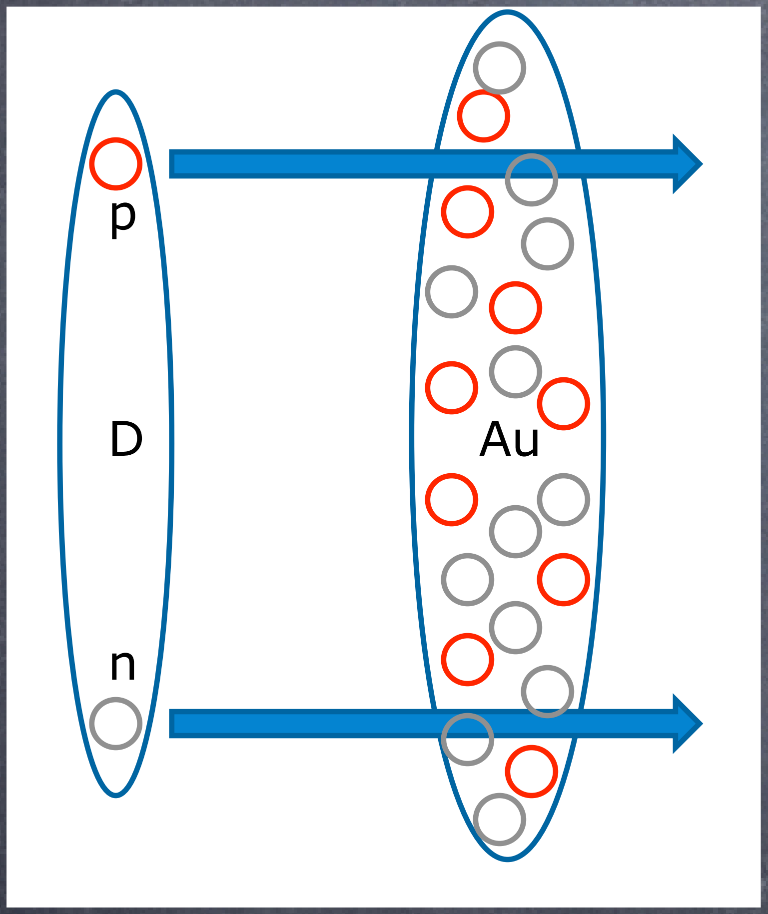
A lingering problem with D-Au

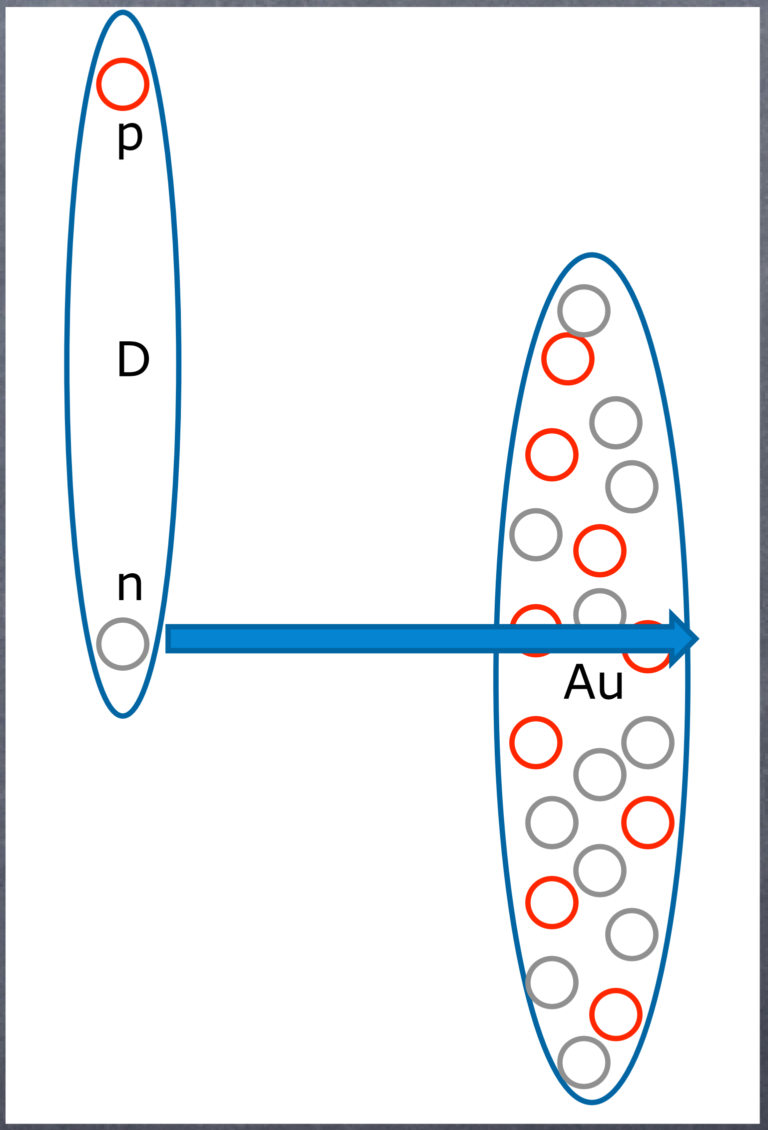




Why does this happen ?

Are there more scatterings per nucleon in peripheral vs. central D-Au



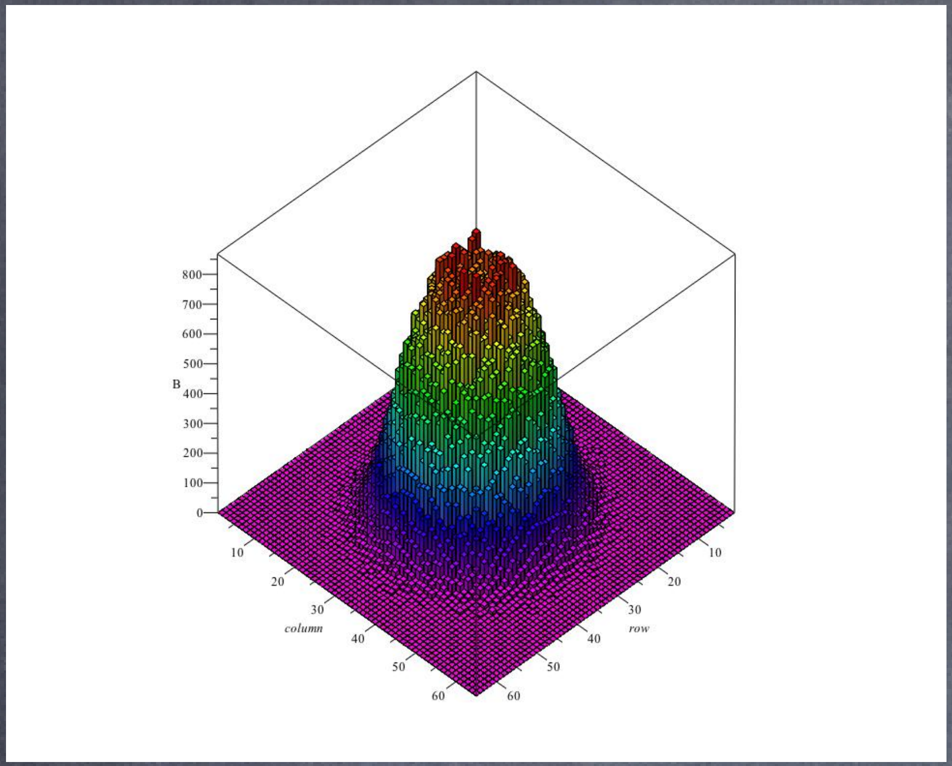


No, but the numbers are very close.

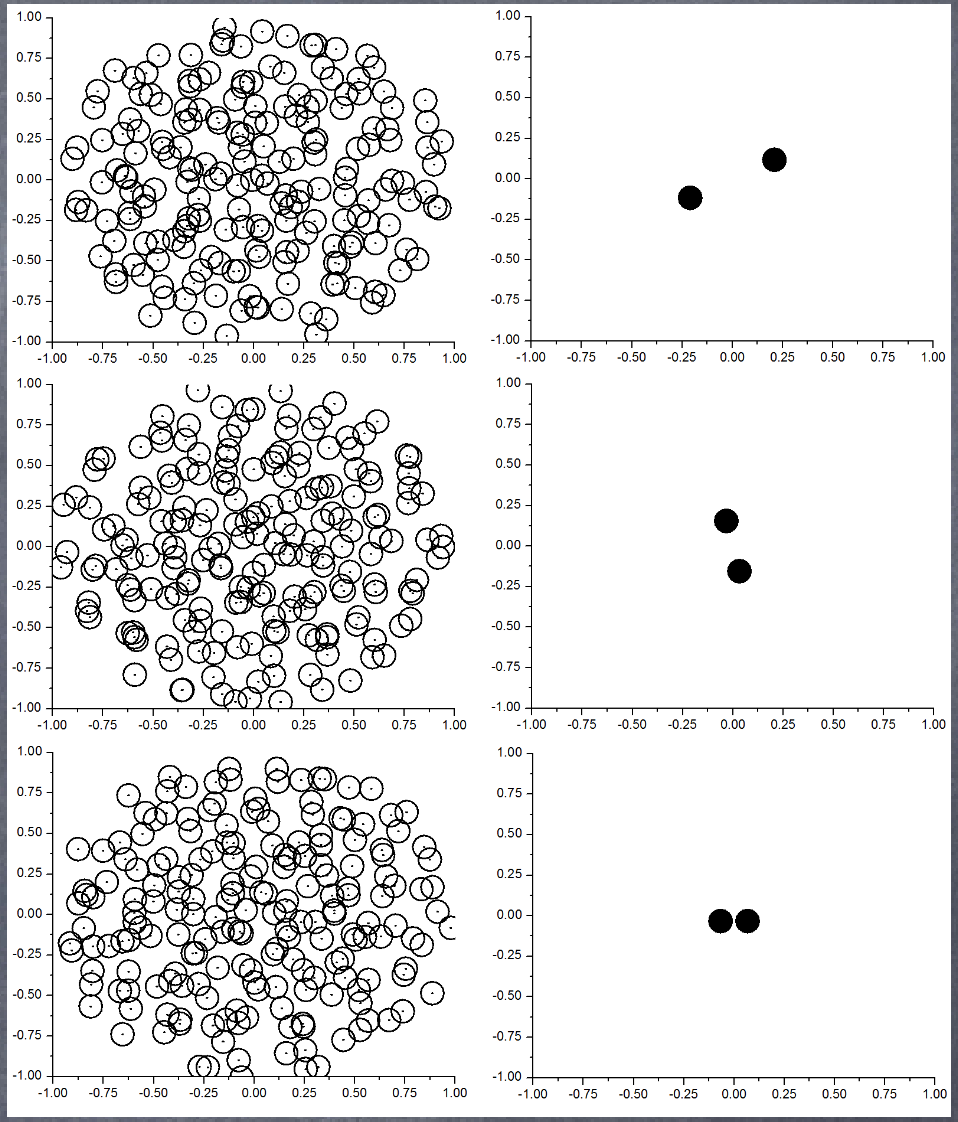
Testing to see if correlated initial state and final state scattering can explain the data.

M. Kordell, AM and S. Gavin

Done more carefully than you would think!

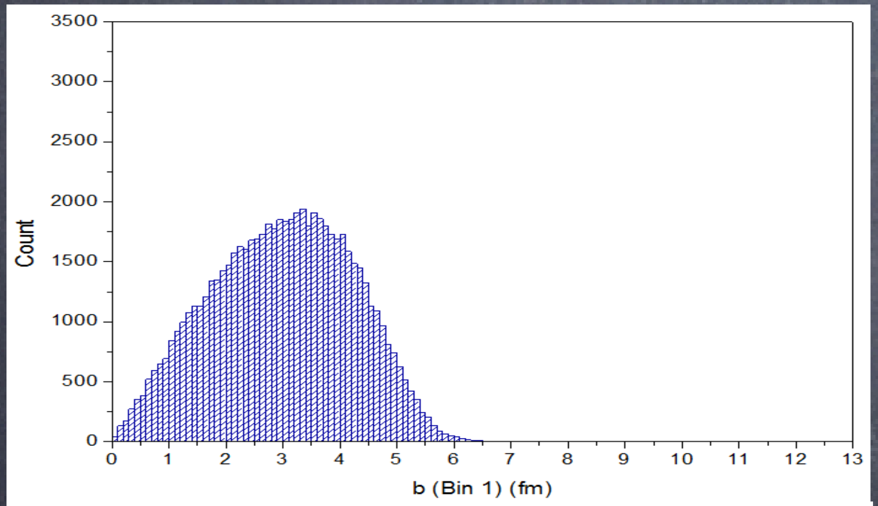


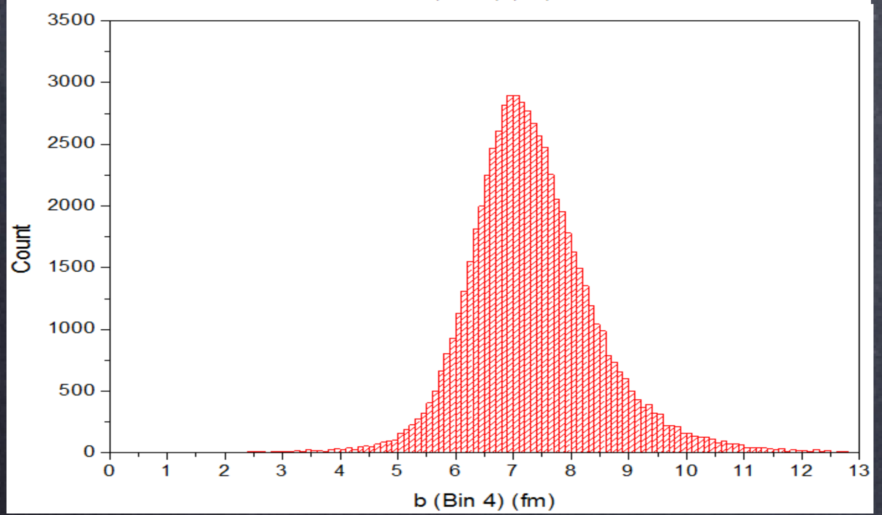
Hulthen for D
Woods-Saxon for A
Shell model for A



Sum of 1M events
Distribution of b for each N_{bin}

A new e-by-e shadowing





Summary

After R_{AA} test HT energy loss scheme on the expansion

Full Jet MC being incorporated with E-by-E hydro

Energy deposition calculations being developed

Lattice QCD calculations of transport parameters

Detailed phenomenology for D-A and AA being set up

Interesting issues with heavy-quarks and NLO

Jets at Detroit, part II