SA-CERN Excellence

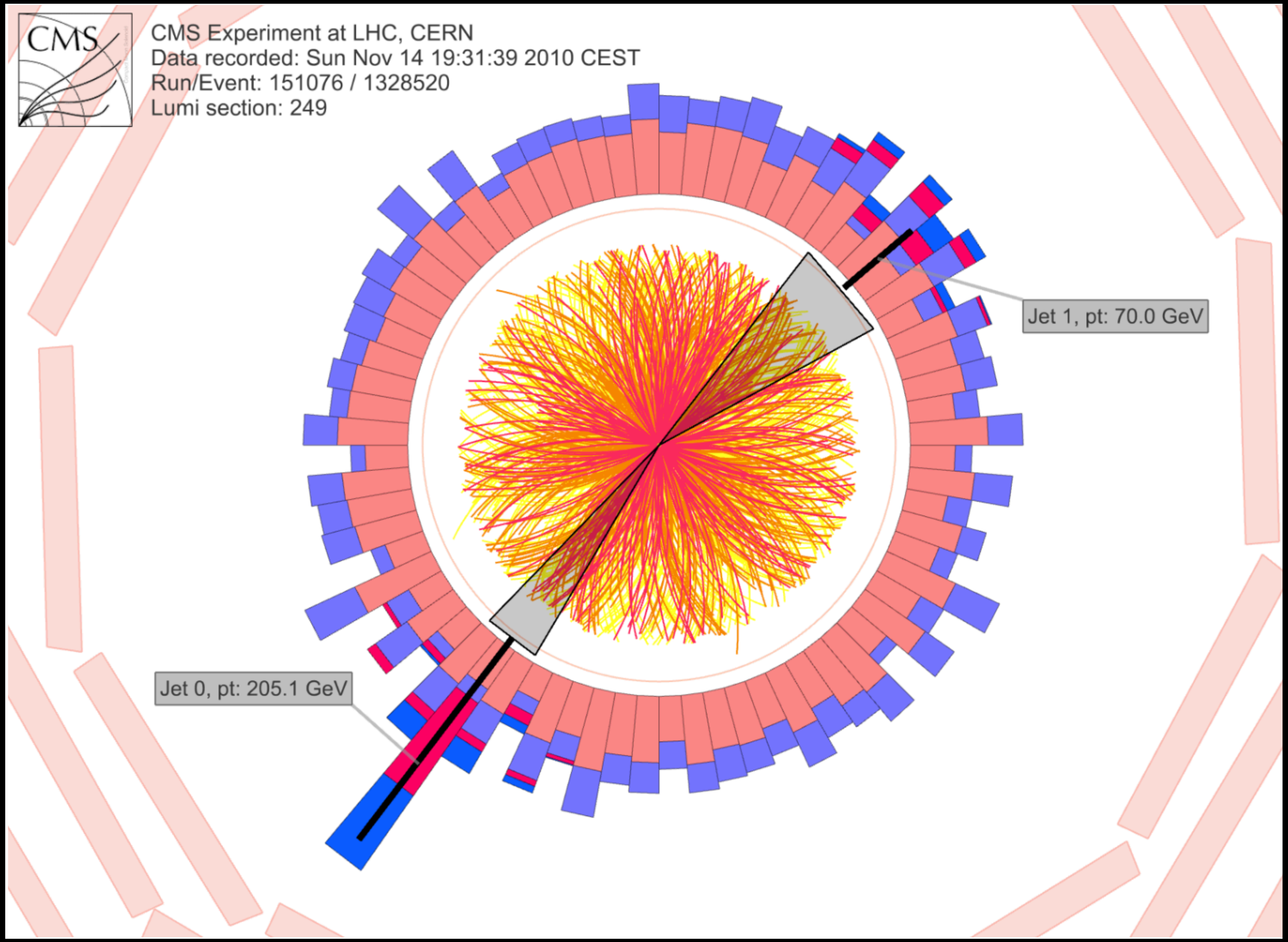
Momentum Broadening : All-Path-Length Corrections and Improved Regge Kinematics

Based on arXiv:2602.16450

70th Annual National Conference of the South African Institute of Physics (SAIP)

Dario van den Berg 08/07/2026

How do we know we have a QGP ?



Dijet imbalance

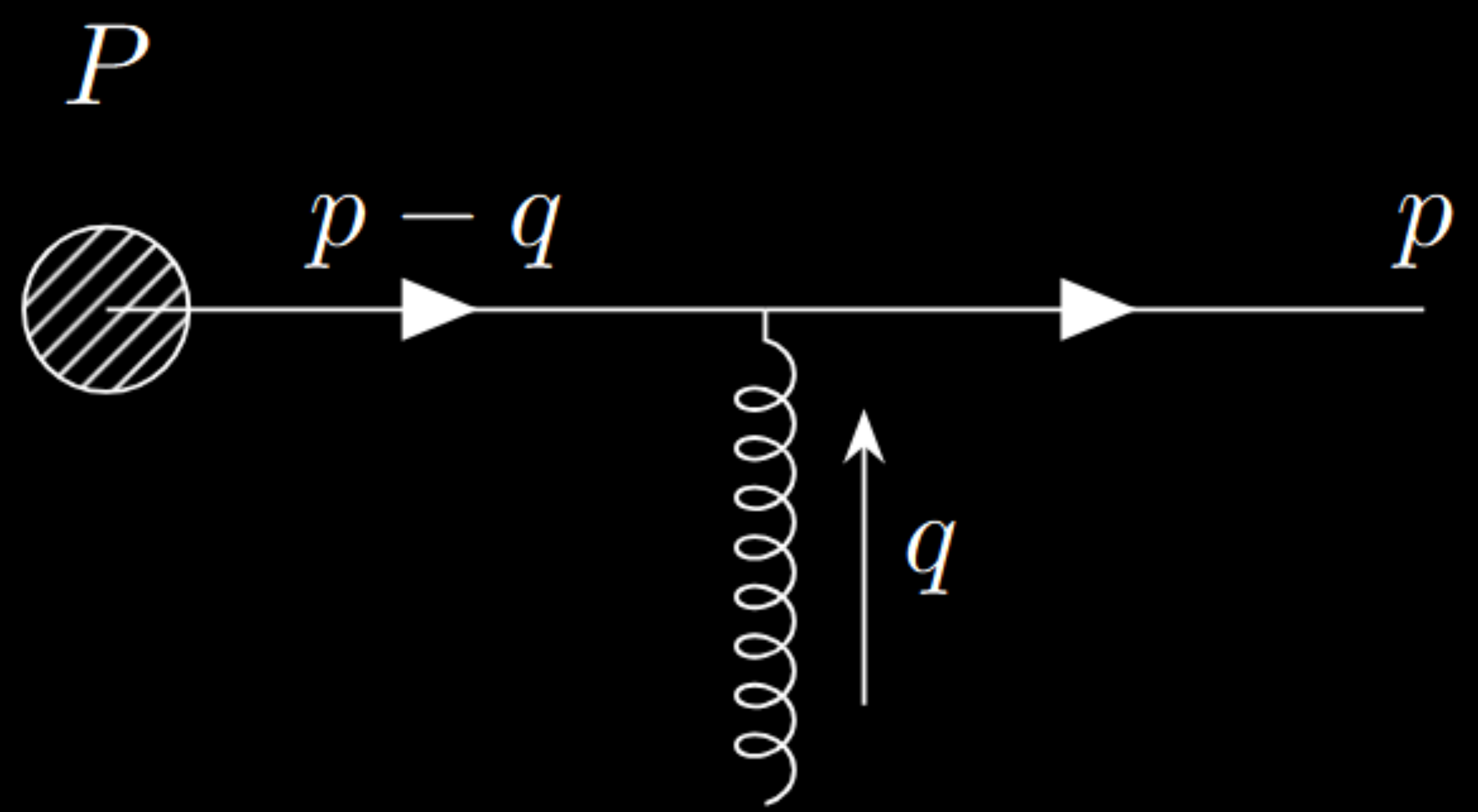
Jet Quenching !

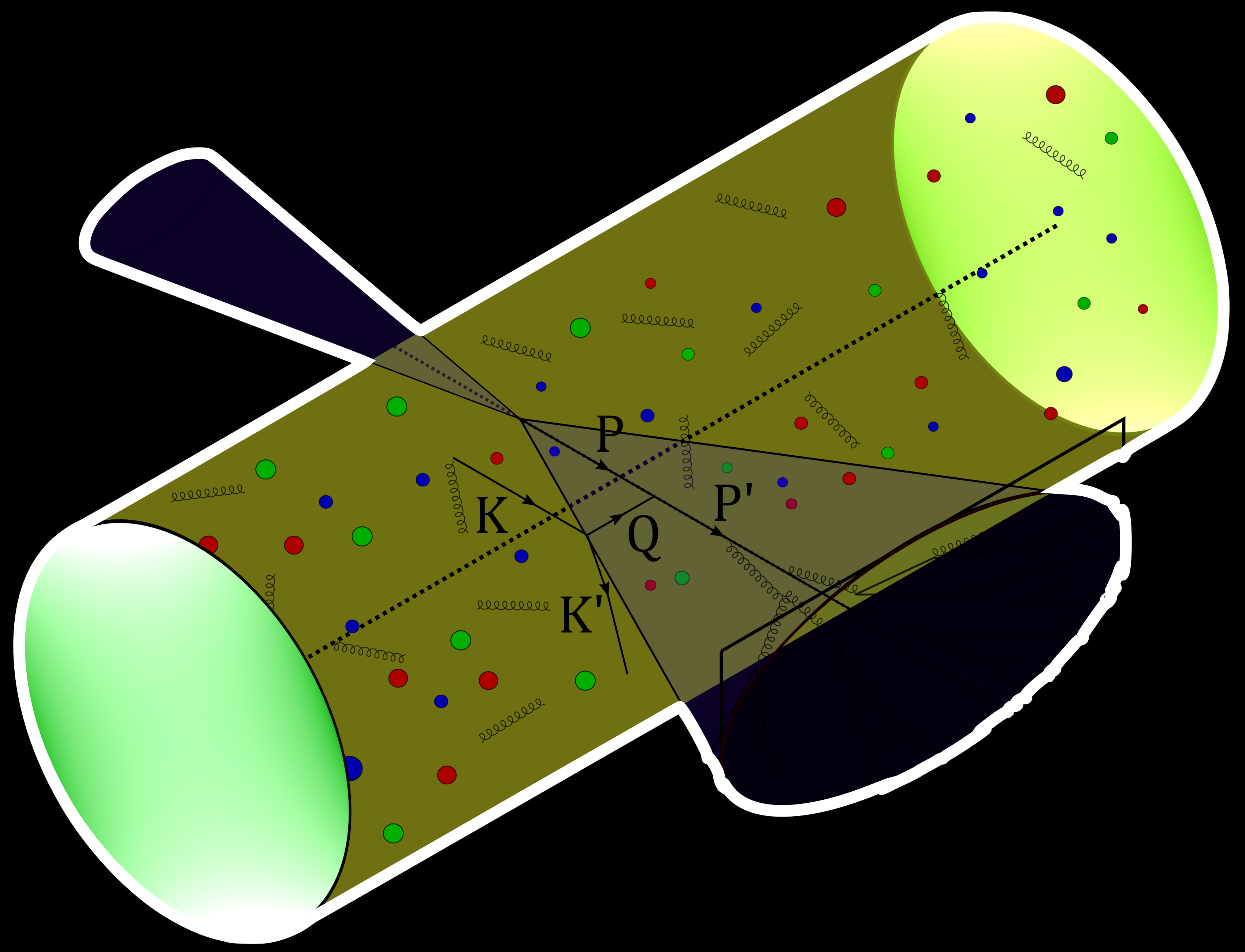
- Collimated sprays of hadrons are formed in high energy collisions and are known as jets.
- Two jets are formed with equal and opposite momentum.
- So how does Jet 0 have more energy than Jet 1 ?

How do jets get bigger ?

Jet momentum broadening!

Good old Scattering





Partons scatter off medium particles picking up transverse momentum.

This transverse momentum leads to a wider jet.

Motivation

Small collision systems and the absence of jet quenching have been a long standing mystery. Results from recent OO and NeNe runs at CERN present an ever growing need to understand possible Quark-Gluon Plasma (QGP) formation in small collision systems.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

CERN

CERN-EP-2025-203
02 Sep 2025

Evidence of nuclear geometry-driven anisotropic flow in OO and Ne–Ne collisions at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV

ALICE Collaboration*

Important Approximations

Large seperation distance approximation

$$\frac{1}{\mu_D} << \Delta z \sim \lambda_{mfp} << L$$

Large formation time approximation

$$\frac{1}{\mu_D} << \tau = \frac{xP^+}{k_\perp^2}$$

Relaxing

$$\frac{1}{\mu_D} \lesssim \Delta z \lesssim L$$

$$\Delta z \nsim \lambda_{mfp}$$

Relaxing

$$\frac{1}{\mu_D} \sim \tau_B = \frac{P^+}{q_\perp^2}$$

$$q_\perp \sim k_\perp$$

GLV Momentum Broadening Distribution

Momentum broadening distribution

$$\frac{dN^{(1)}}{d^3\vec{p}} = \left(\frac{1}{d_T} \mathrm{Tr}\langle |\mathcal{M}_1|^2 \rangle + \frac{2}{d_T} \mathrm{Re}\,\mathrm{Tr}\langle \mathcal{M}_2 \mathcal{M}_0^* \rangle \right)$$

Wave packet

Propagator

Color generators

$$\mathcal{M}_1 = i e^{ipx_0} \int \frac{d^4q}{(2\pi)^4} J(p-q) \frac{1}{(p-q)^2 + i\epsilon} 2\pi\delta(q^0) \frac{4\pi\alpha_s}{\vec{q}^2 + \mu_D^2} (2E) \sum_{j=1}^{N} e^{-iq(x_j - x_0)} T_a(j) T_a(R)$$

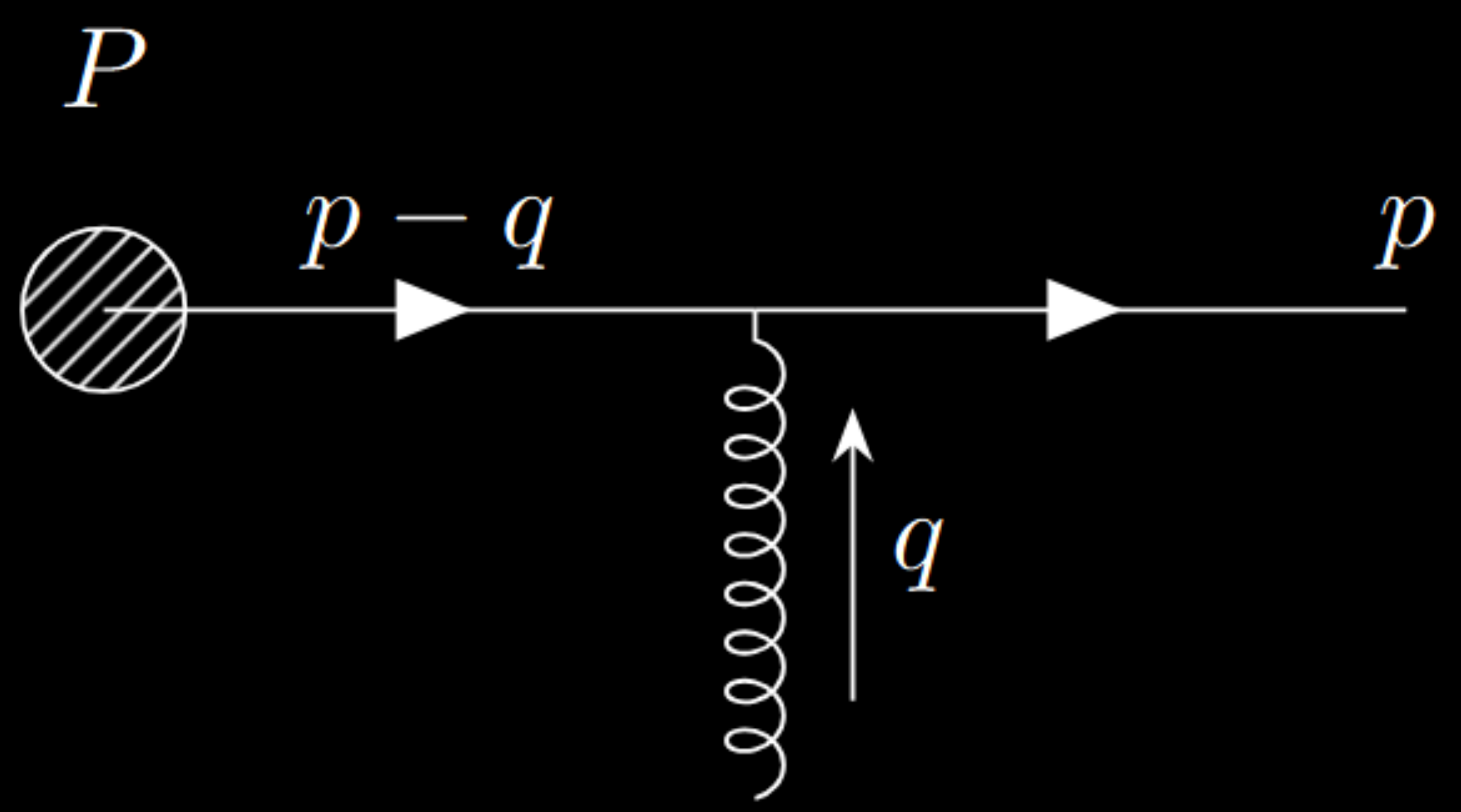
Source

Potential

Regge Kinematics

The Regge kinematical regime :

$$s \gg t$$



Our case in terms of Mandelstam variables :

$$s = (P + q)^2 \qquad t = (P - p)^2 = q^2$$

$$s \approx P^2 \gg q^2 = t$$

Kinematics

Standard Regge Kinematics

in light cone coordinates.

$$p^\mu = \left[P^+, -\frac{1}{\sqrt{2}} q_z, \vec{q}_\perp\right]$$

Relaxed LFT approximation.

$$\frac{1}{\mu_D} \sim \boxed{\tau_B} = \frac{P^+}{q_\perp^2}$$

Sub-Regge correction "smells" like $\boxed{\tau_B}$.

Sub-Regge Kinematics

in light cone coordinates.

$$p^\mu = \left[P^+\left(1 + \frac{q_z}{\sqrt{2}P^+}\right), -\frac{1}{\sqrt{2}} q_z, \vec{q}_\perp\right]$$

Sub-Regge correction.

The Poles

Standard Regge Poles

for single scattering

$$q_z = -i\mu_\perp$$

$$q_z = \frac{\sqrt{2}}{2}\frac{q_\perp^2}{P^+} - i\epsilon$$

Sub-Regge Poles

for single scattering

$$q_z = -i\mu_\perp$$

$$q_z = -\frac{\sqrt{2}}{2}P^+(1-\gamma) - i\epsilon$$

Where

$$\mu_\perp = \sqrt{q_\perp^2 + \mu_D^2} \text{ and } \gamma = \sqrt{1 - \frac{2}{\tau_B P^+}}$$

Momentum Broadening Results

$$\underline{GLV} = \frac{N}{A_\perp}\frac{1}{d_A}C_2(R)C(R)(4\pi\alpha_s)^2\int\rho(\Delta z)\int\frac{d^2q_\perp}{(2\pi)^2}\left(|J(p-q_\perp)|^2-|J(p)|^2\right)\frac{1}{\mu_\perp^4}$$

$$(\underline{GLV}+\underline{APL}) = \left(\cdots\right)\frac{1}{\mu_\perp^4}\boxed{\left(1-\frac{1}{2}e^{-\mu_\perp\Delta z}\right)^2}$$

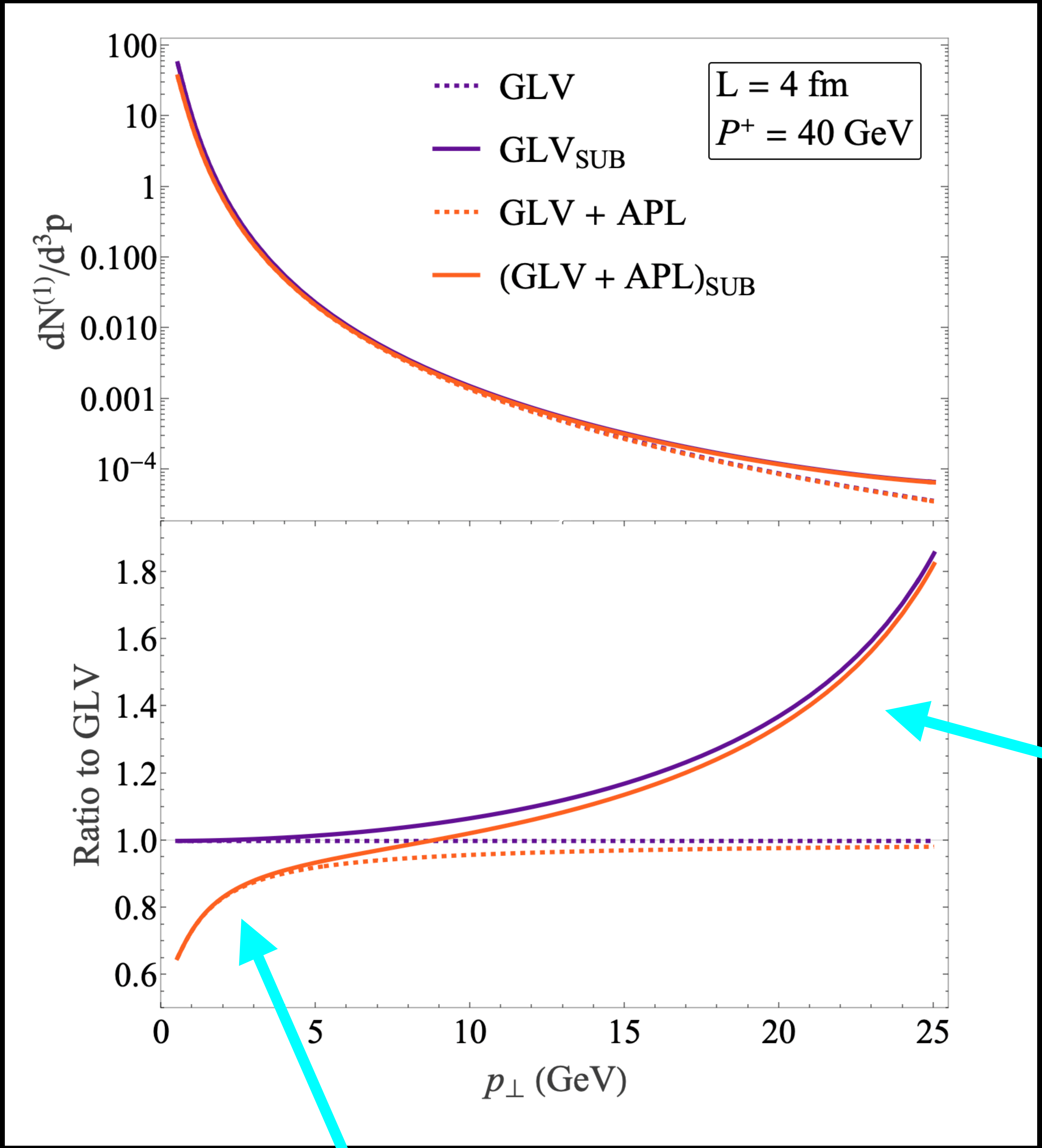
APL correction

$$\underline{(GLV)}_{\underline{SUB}} = \left(\cdots\right)\boxed{\frac{4}{(1+\gamma)^2}}\frac{1}{\mu_\perp^4}$$

SUB correction

$$(\underline{GLV}+\underline{APL})_{\underline{SUB}} = \left(\cdots\right)\boxed{\frac{4}{(1+\gamma)^2}}\frac{1}{\mu_\perp^4}\boxed{\left(1-\frac{1}{2}e^{-\mu_\perp\Delta z}\right)^2}$$

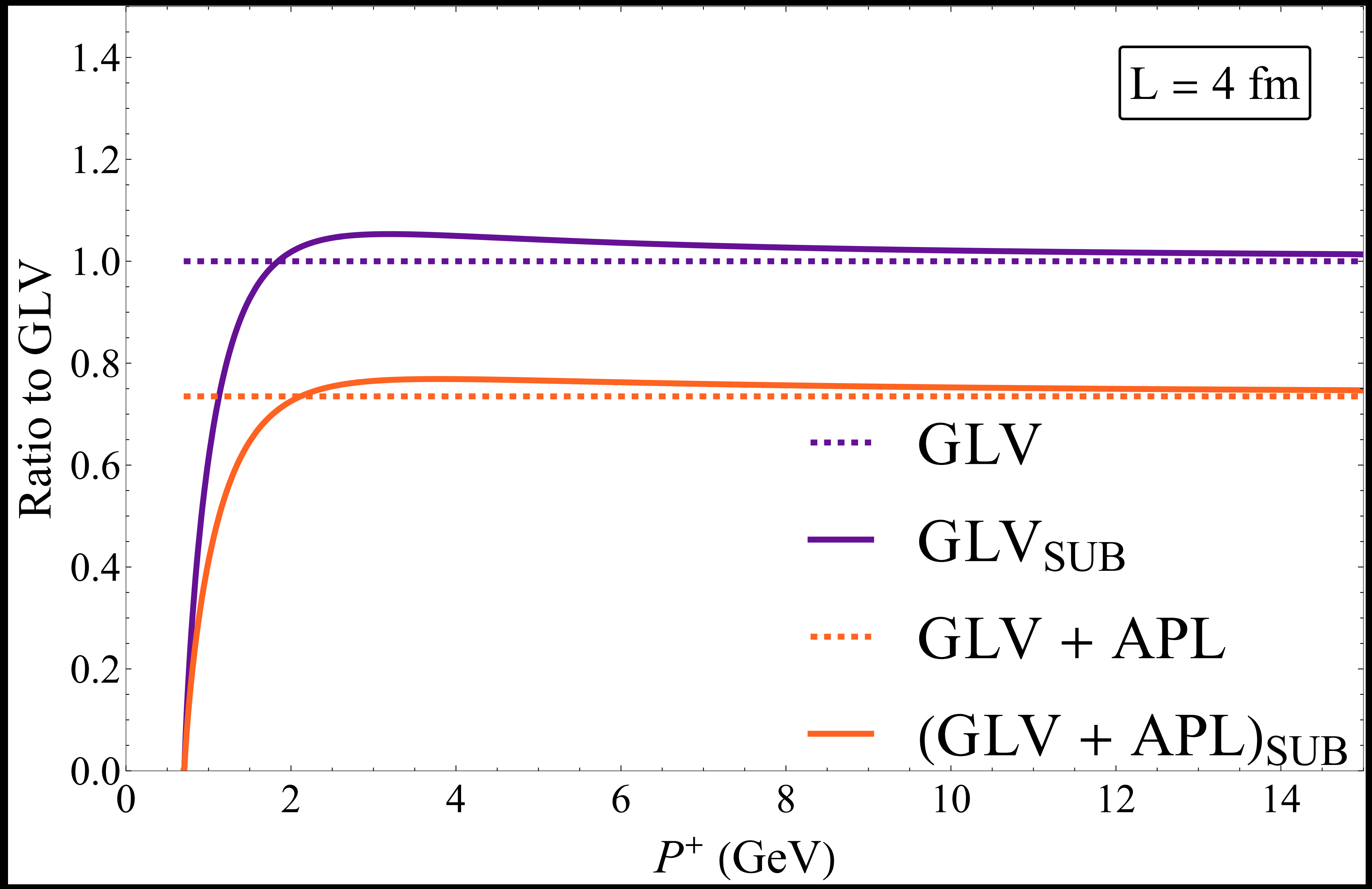
Results



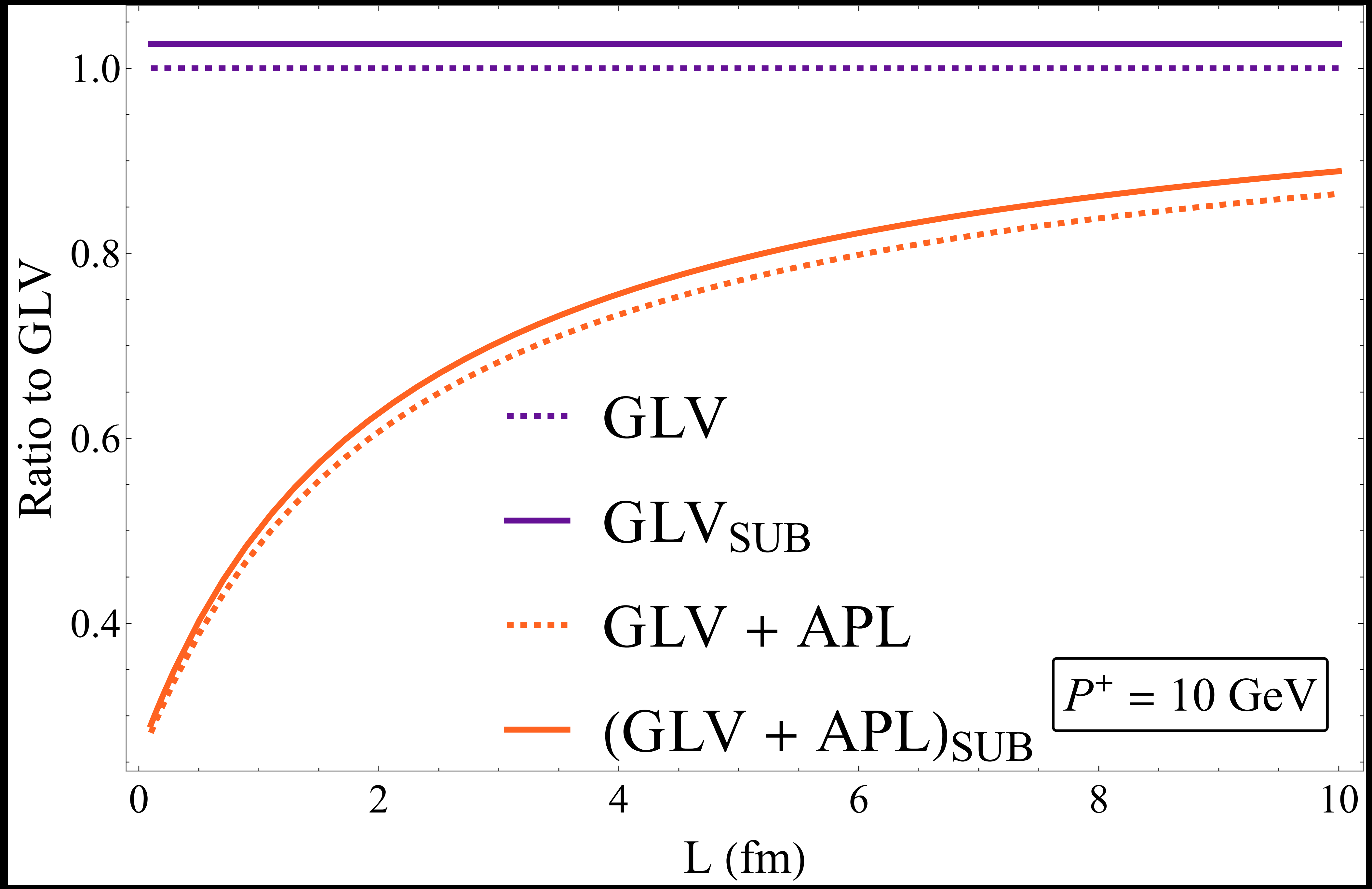
Sub-Regge correction dominates

All-path-length correction dominates

Results



Ratio of approximation schemes to GLV plotted against P^+.



Ratio of approximation schemes to GLV plotted against L.

Momentum Broadening ($\hat{q}$)

Single interaction distribution

Generalized expectation value

$$\langle \cdots \rangle = \frac{\int d^2p_\perp (\cdots) \frac{dN^{(1)}}{d^3\vec{p}}}{\int d^2p_\perp \frac{dN^{(0)}}{d^3\vec{p}}}$$

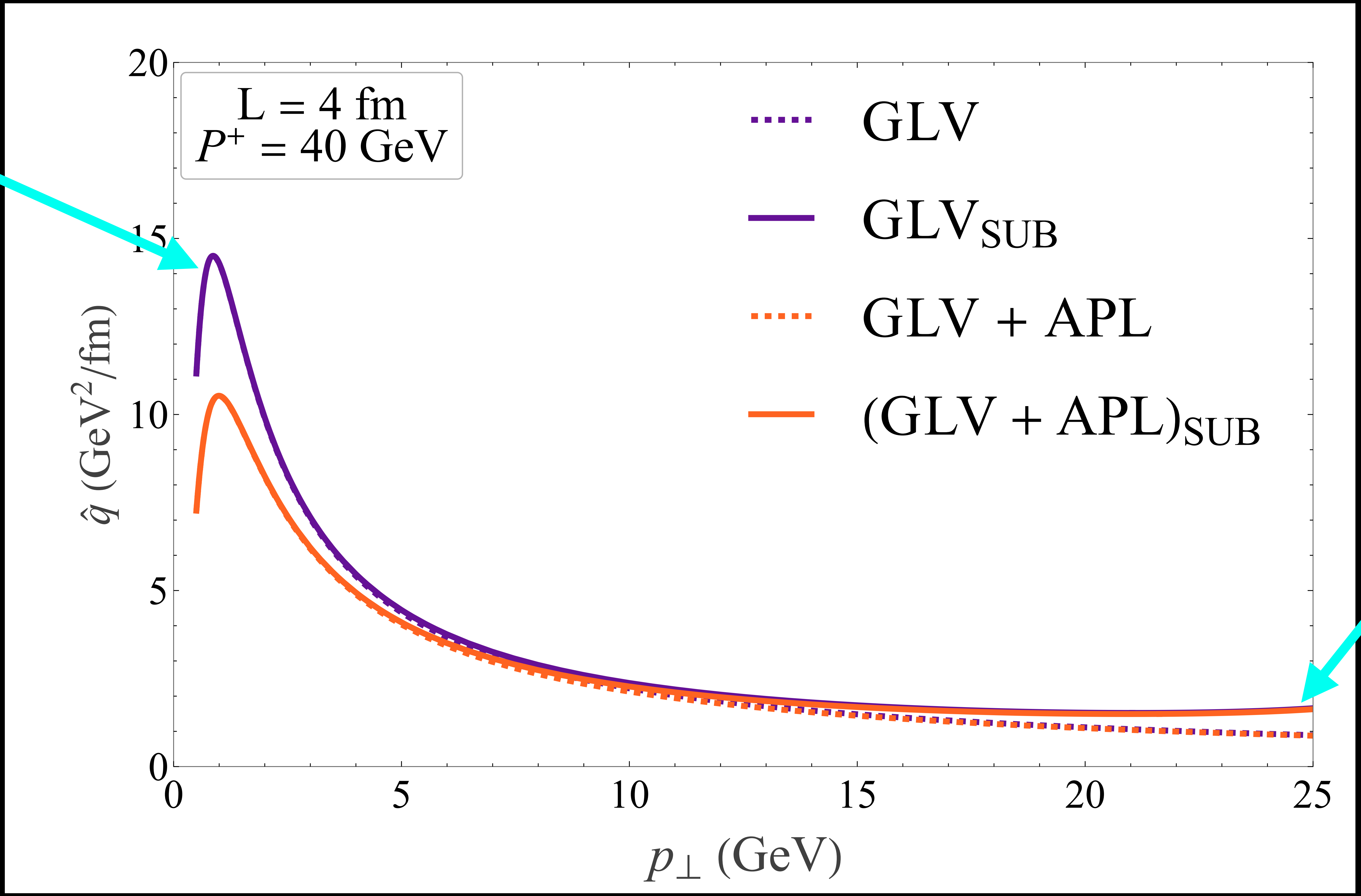
Non-interaction distribution

Allows one to define the momentum broadening :

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

$\hat{q}$ Results

APL curves show broadening suppression



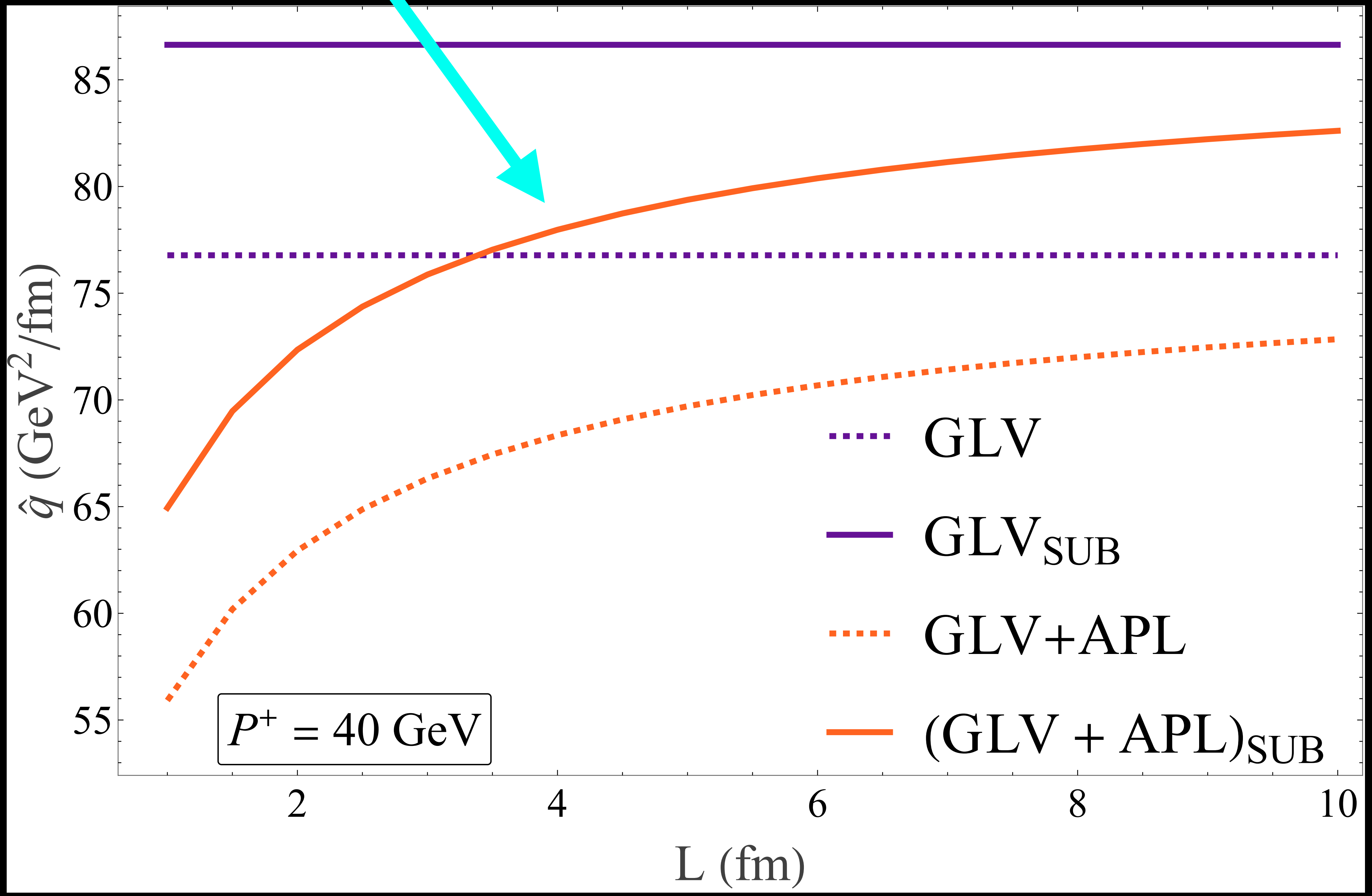
Sub-Regge curves show broadening enhancement

$\hat{q}$ Results

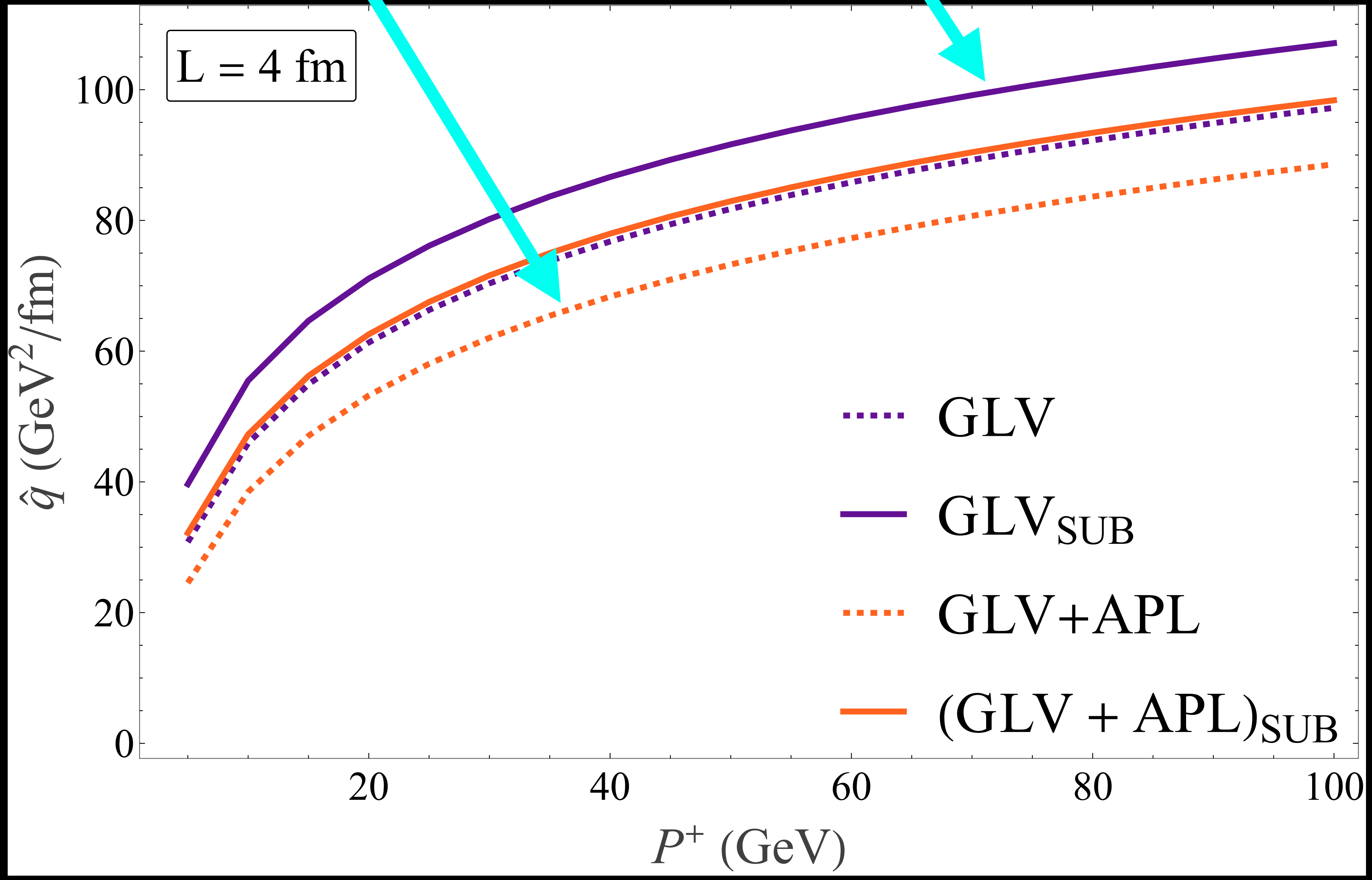
Suppression across system sizes

Suppression across Parton momentum

Enhancement across Parton momentum



$\hat{q}$ plotted as a function of L.

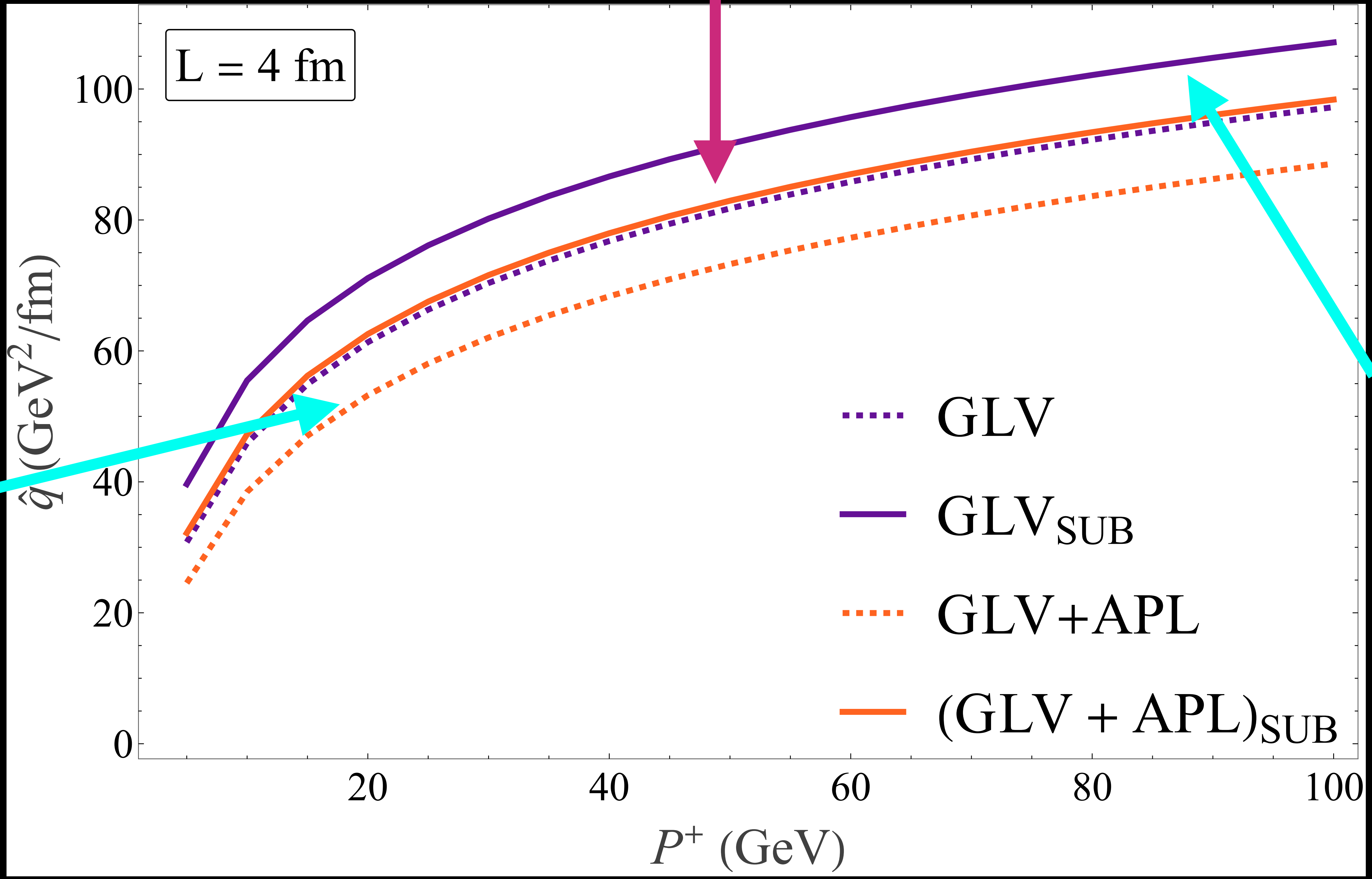


$\hat{q}$ plotted as a function of P^+.

$\hat{q}$ Results

Crucially, Sub-Regge mitigates the APL suppression

Suppression across Parton momentum



Enhancement across Parton momentum

$\hat{q}$ plotted as a function of P^+.

Recap

- Jet Quenching is one of the main observables of the QGP.
- Traditional momentum broadening calculations use a series of approximations valid for large systems.
- Relaxing such approximations leads to APL and Sub-Regge kinematical corrections.
- Sub-Regge kinematics leads to an enhancement of momentum broadening.
- APL correction leads to a suppression of momentum broadening.
- Crucially, Sub-Regge kinematics leads to a mitigation of the APL correction.

Kidding…

Thank you for listening!

Any Questions ?

Important Approximations

Large formation time approximation

$$\frac{1}{\mu_D} << \tau = \frac{xP^+}{k_\perp^2}$$

Approximation : τ is much larger than the Debye screening length.

However in small systems one my have that

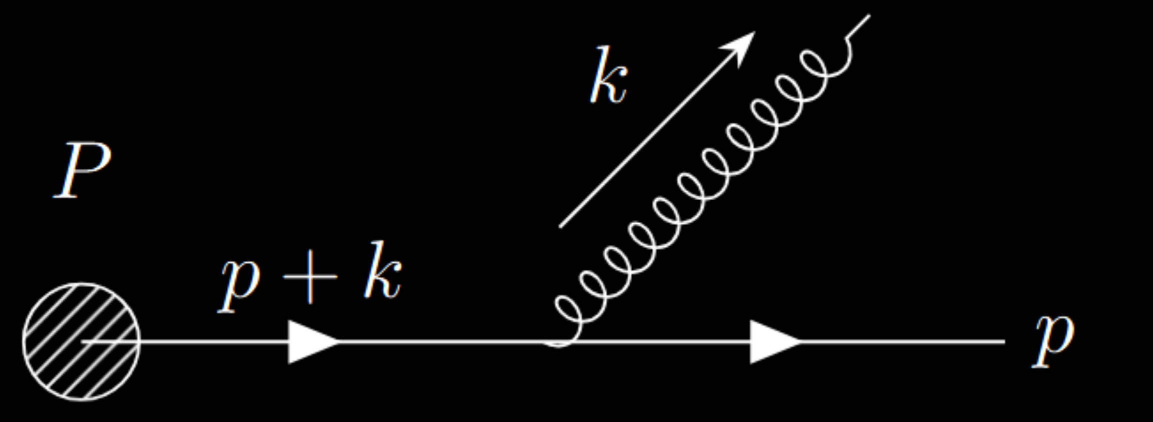
$$\frac{1}{\mu_D} \sim \tau$$

Important Approximations

Large formation time approximation

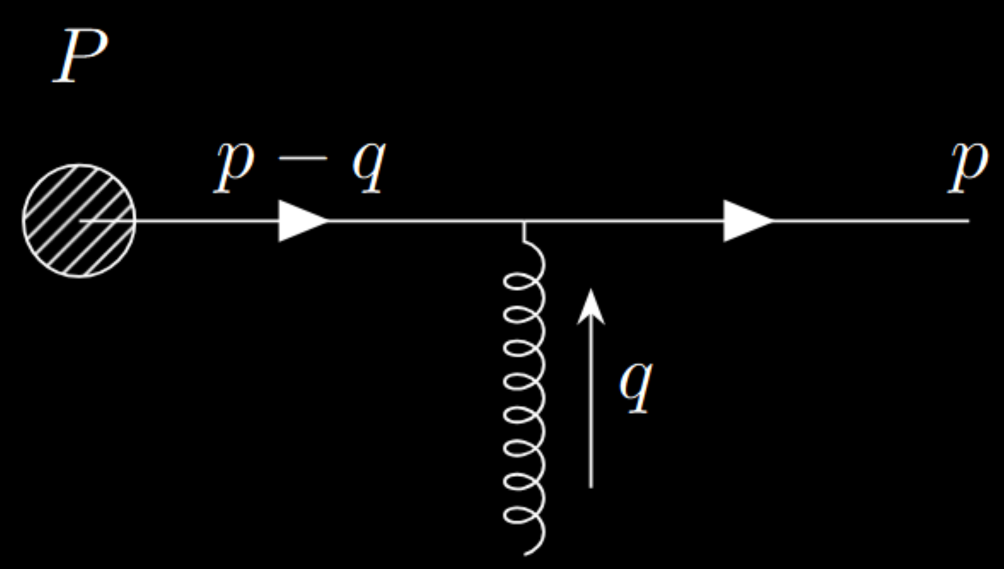
However relaxing the large formation time approximation in the radiative case is incredibly daunting. We can gain insight by looking at the broadening analogue of formation time,

$$\frac{1}{\mu_D} \sim \tau_B = \frac{P^+}{q_\perp^2}$$



since

$$k_\perp \sim q_\perp$$



Momentum Broadening Results

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$$(\underline{GLV}+\underline{APL}) = \left(\cdots\right)\int\rho(\Delta z)\int\frac{d^2q_\perp}{(2\pi)^2}\left(|J(p-q_\perp)|^2-|J(p)|^2\right)\frac{1}{\mu_\perp^4}\boxed{\left(1-\frac{1}{2}e^{-\mu_\perp\Delta z}\right)^2}$$

$$(\underline{GLV})_{\underline{SUB}} = \left(\cdots\right)\int\rho(\Delta z)\int\frac{d^2q_\perp}{(2\pi)^2}\left(|J(p-q_\perp)|^2-|J(p)|^2\right)\boxed{\frac{4}{(1+\gamma)^2}}\frac{1}{\mu_\perp^4}$$

APL correction

SUB correction

$$(\underline{GLV}+\underline{APL})_{\underline{SUB}} = \left(\cdots\right)\int\rho(\Delta z)\int\frac{d^2q_\perp}{(2\pi)^2}\left(|J(p-q_\perp)|^2-|J(p)|^2\right)\boxed{\frac{4}{(1+\gamma)^2}}\frac{1}{\mu_\perp^4}\boxed{\left(1-\frac{1}{2}e^{-\mu_\perp\Delta z}\right)^2}$$

Important Approximations

Large seperation distance approximation

$$\frac{1}{\mu_D} < < \Delta z \sim \lambda_{mfp} < < L$$

Approximation : distance between production point z_0 and position of first scattering z_1 is sufficiently larger than the Debye screening length $1/\mu_D$.

However is smaller systems one has that

$$\frac{1}{\mu_D} \sim \Delta z$$

Unitarity

In order to guarantee Unitarity the result from $\mathrm{Tr}\langle\, |\mathscr{M}_1|^2 \rangle$ need to be the same as that from $2Re\mathrm{Tr}\langle \mathscr{M}_2 \mathscr{M}_0^* \rangle$.

This result guarantees the factorised form of the broadening distribution to be consistent with unitarity,

$$J(p-q)f(q_\perp) - J(p)f(q_\perp) = \Big(J(p-q) - J(p)\Big)f(q_\perp).$$

Unitarity can be checked by performing the integral over p. When performing this integral one has a shift in coordinates $p \to p + q$ that allows the sources to cancel.