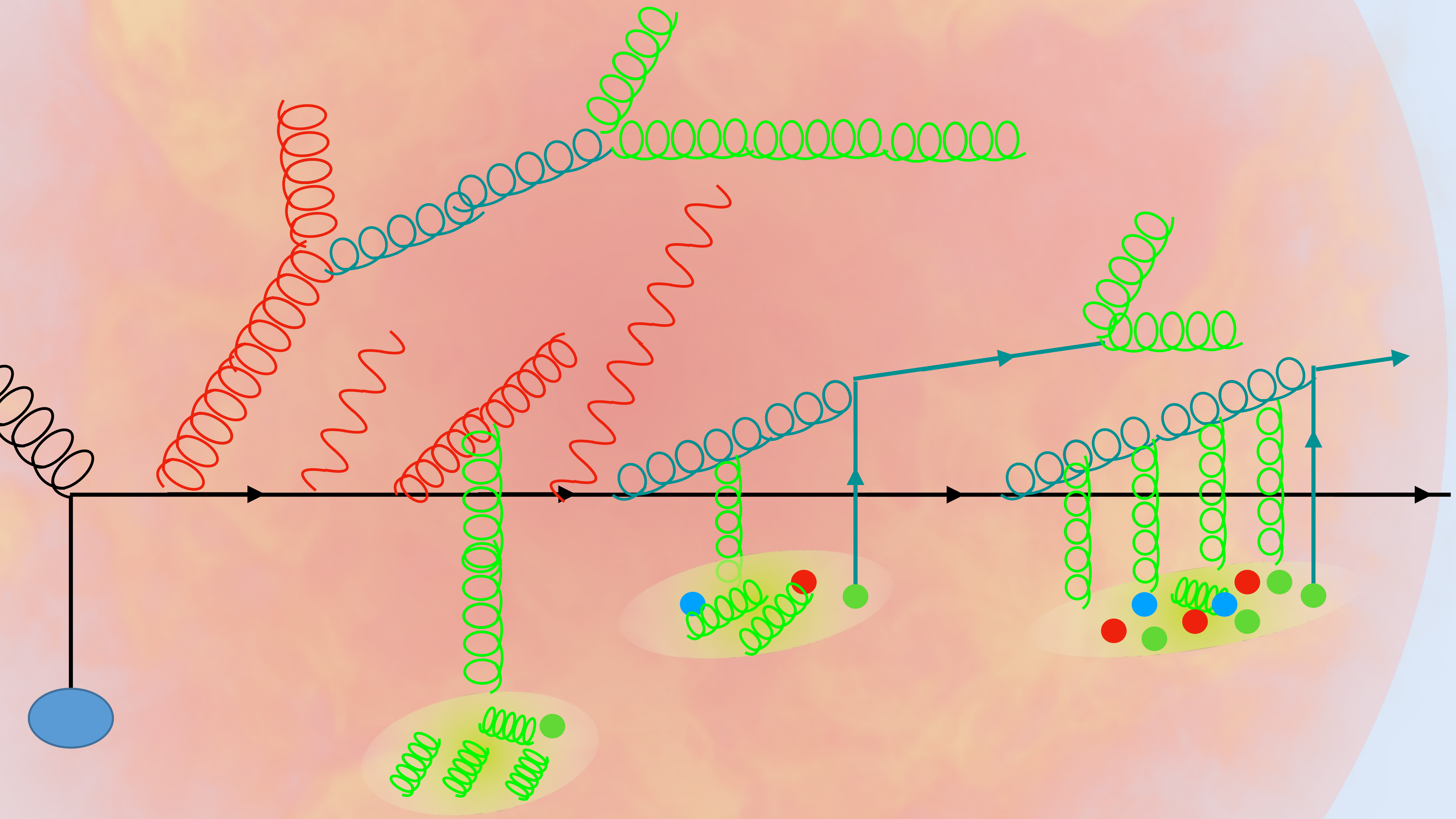
Winter Nuclear and Particle Physics Conference 2025

University of Regina



Photon contributions to parton energy loss at high Q^2

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Based on (arXiv:2502.02667)

In collaboration with Gojko Vujanovic

Feb 16th, 2025

CANADA RESEARCH CHAIRS
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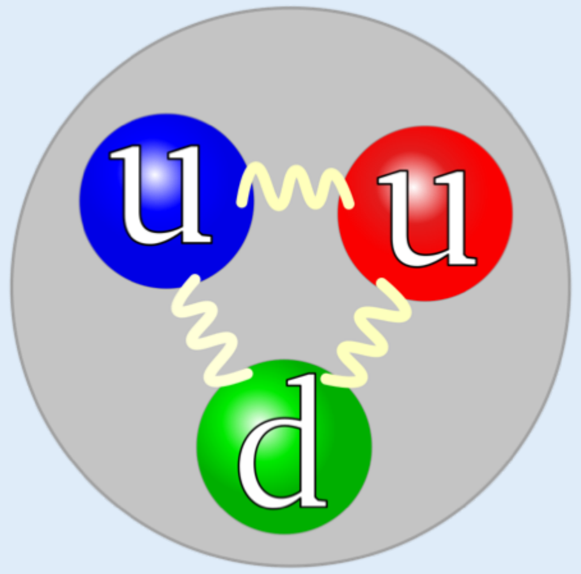
Outline

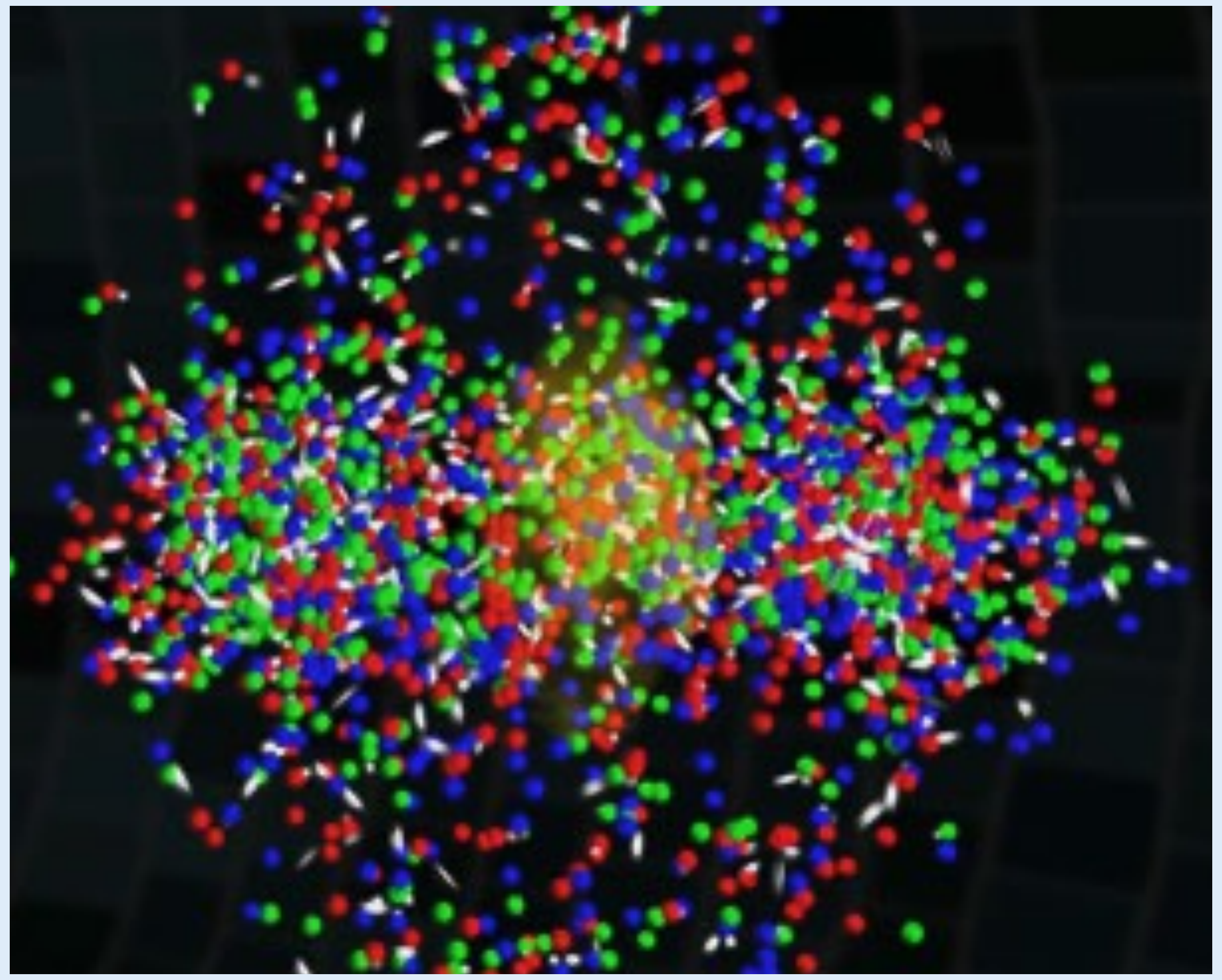
- ❑ **Introduction to Quark-Gluon plasma and jet quenching**
- ❑ **Stages of a parton shower and high virtuality sector**
- ❑ **Medium-induced single photon emission scattering kernel using perturbative QCD**
- ❑ **Fermion-to-Boson conversion process**
- ❑ **Heavy-quark energy loss and coherence effects**
- ❑ **Connections to Electron-Ion Collider (EIC) physics**

Nuclear matter under extreme condition

Hadrons: (At ordinary temperature)
Bound state of Quarks-Gluons



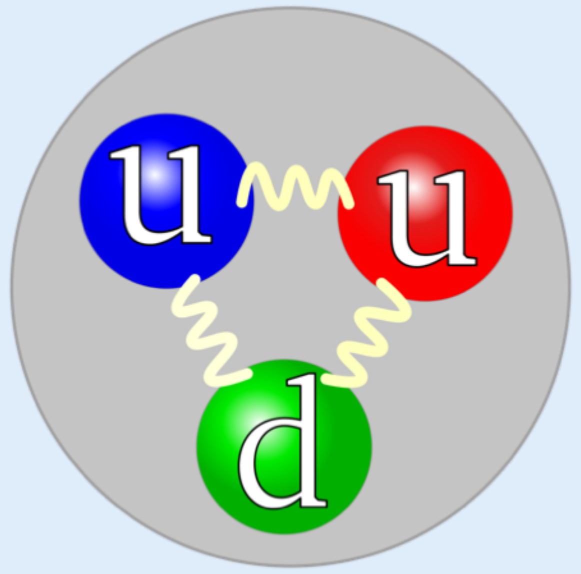
Quarks-Gluon Plasma



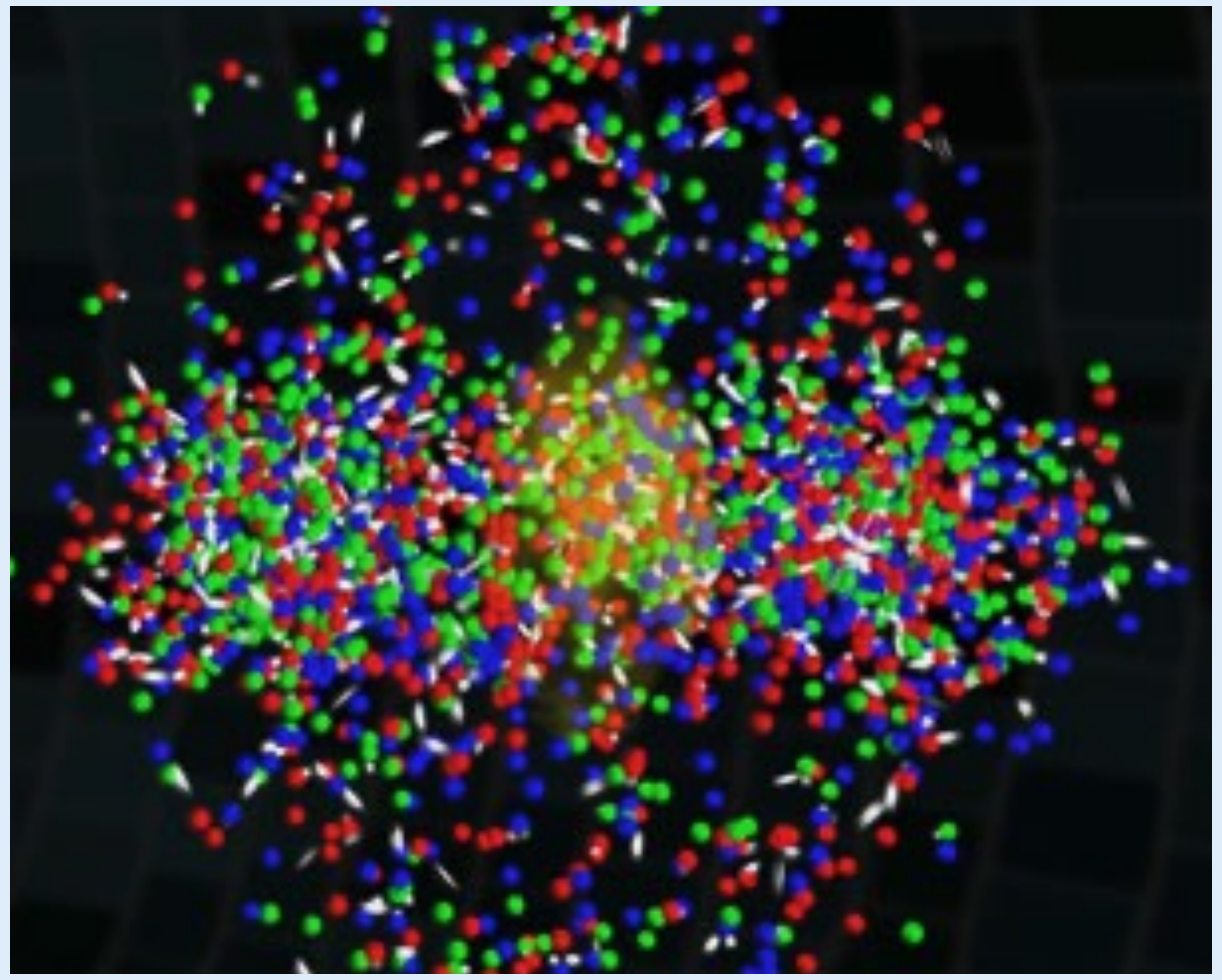
$T \gtrsim 200$ MeV

Nuclear matter under extreme condition

Hadrons: (At ordinary temperature)
Bound state of Quarks-Gluons

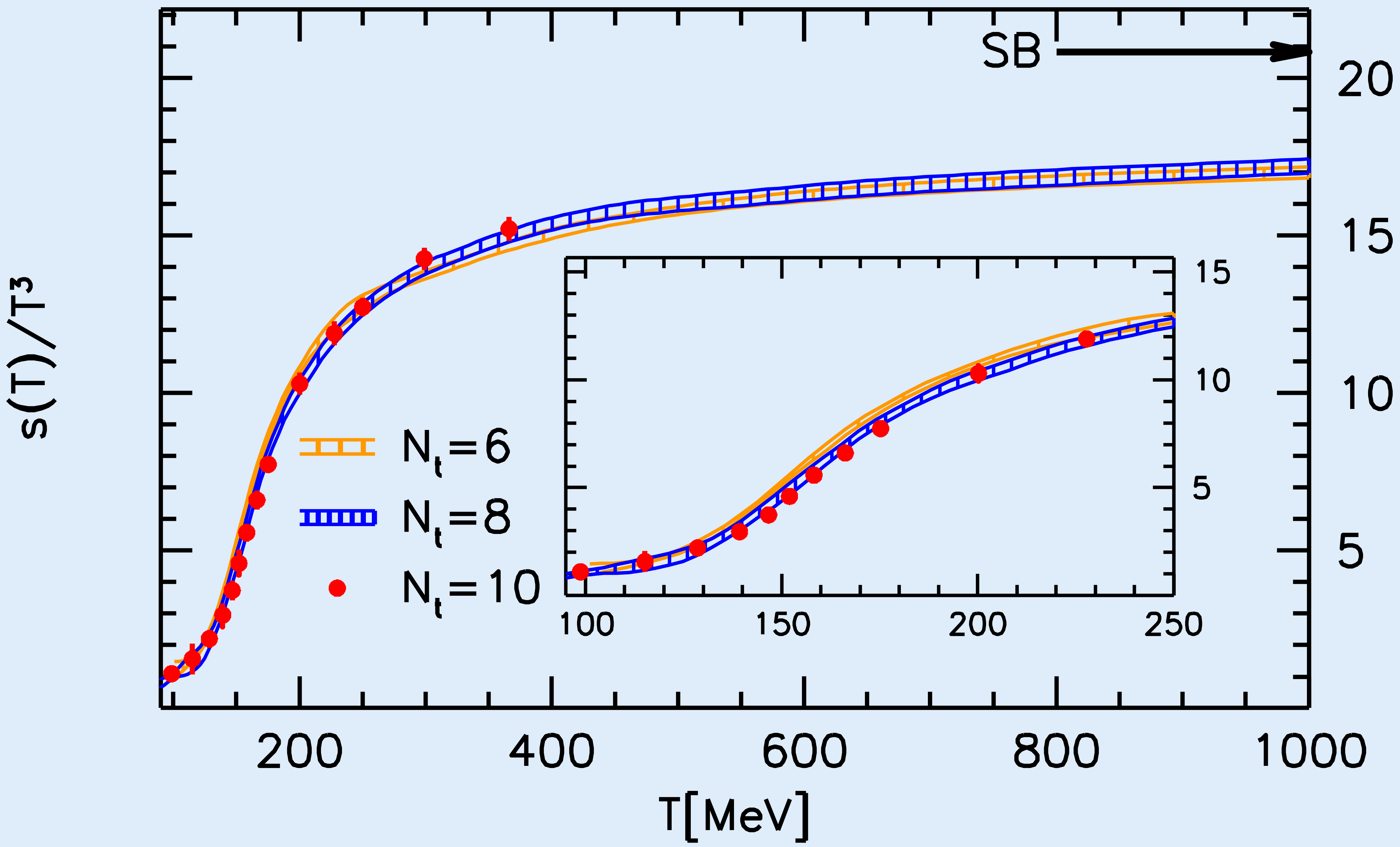


Quarks-Gluon Plasma



$T \gtrsim 200$ MeV

Entropy density prediction Lattice QCD (Equation of State)

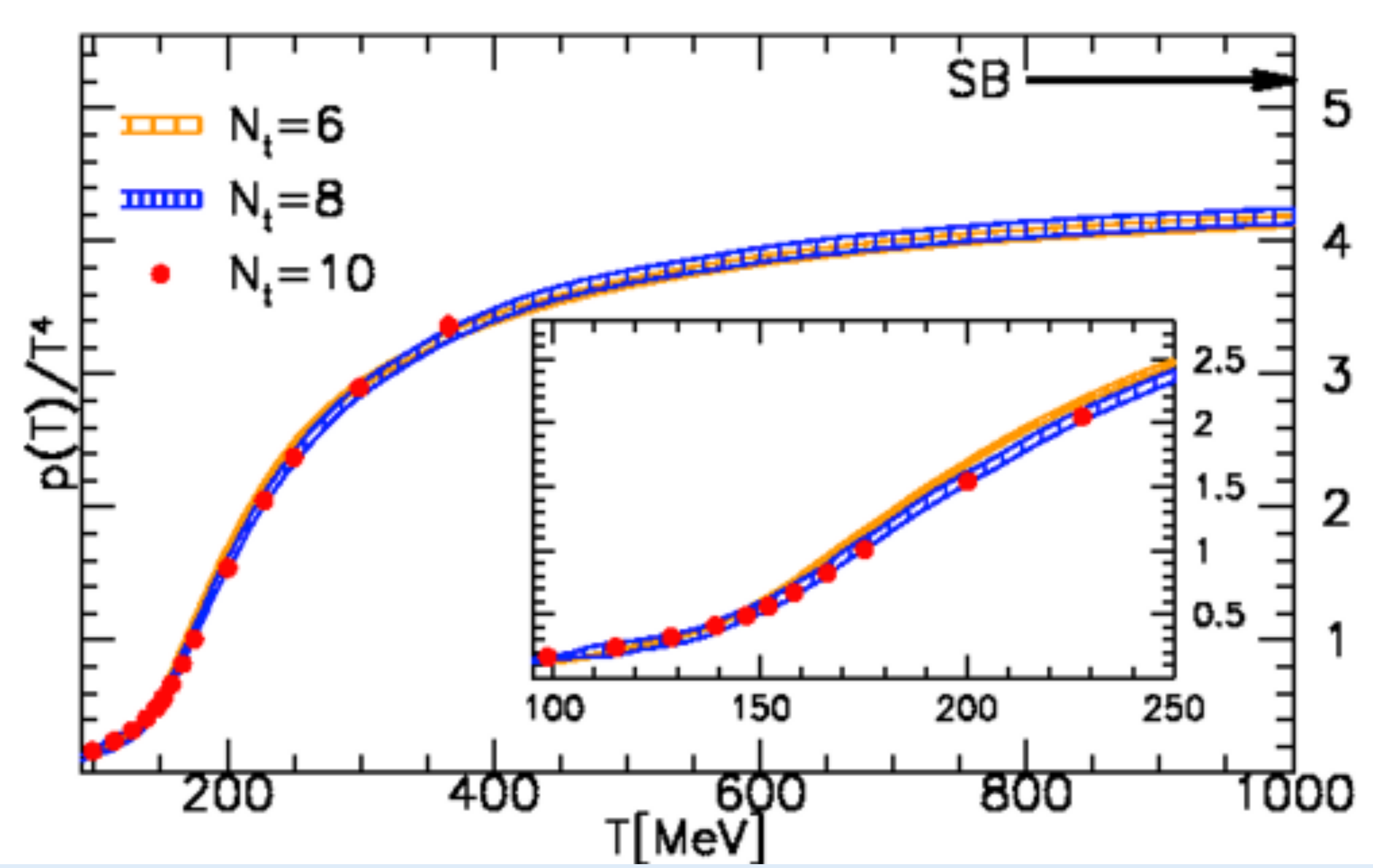


S. Borsanyi et al., JHEP 1011, 077 (2010)

- ❑ **Sudden increase in entropy density near the transition region**
- ❑ **Due to increase in the number of degrees of freedom (DOF)**
- ❑ **Interpreted as deconfinement of quarks and gluons**

Nuclear matter under extreme condition

Pressure density prediction Lattice QCD (Equation of State)



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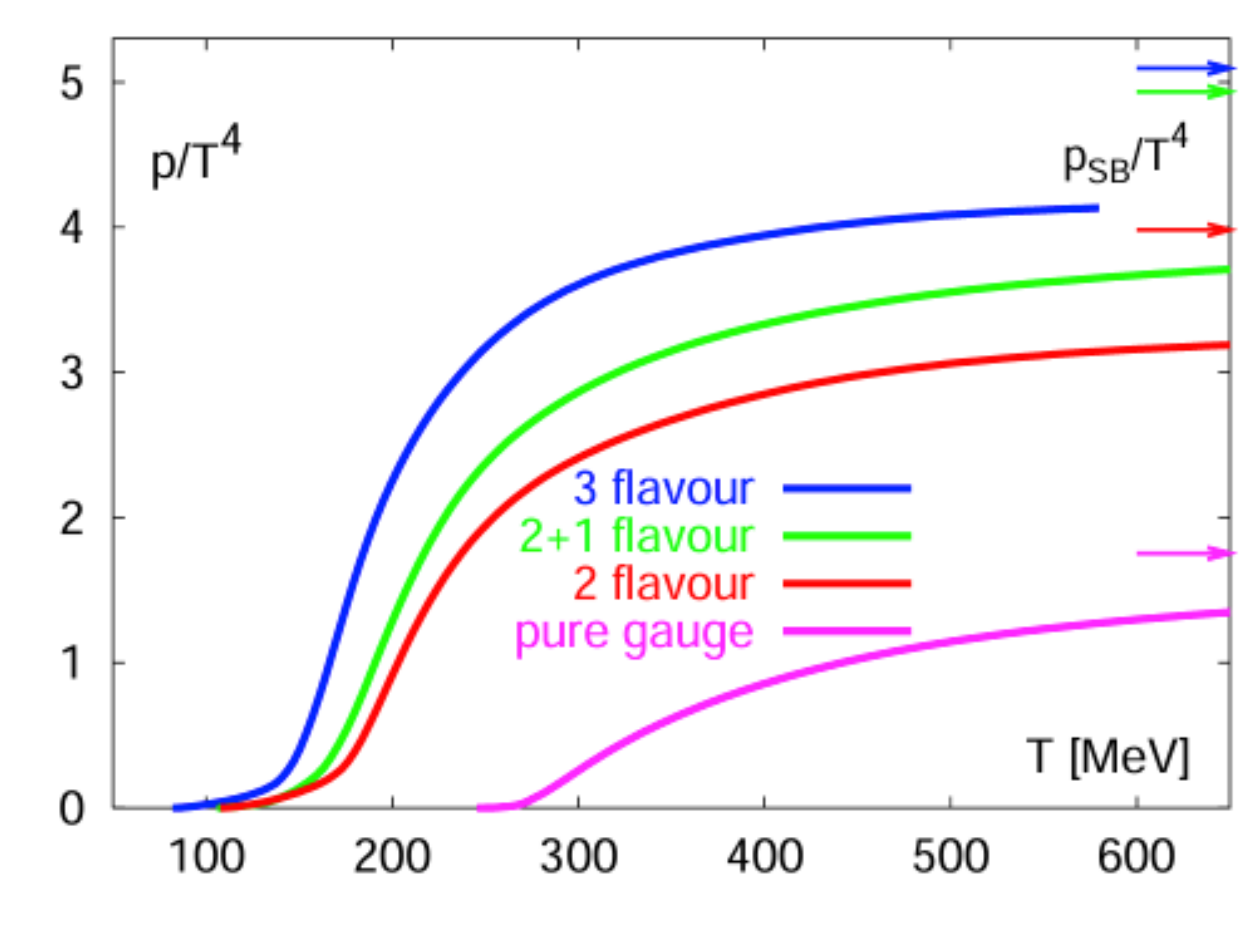
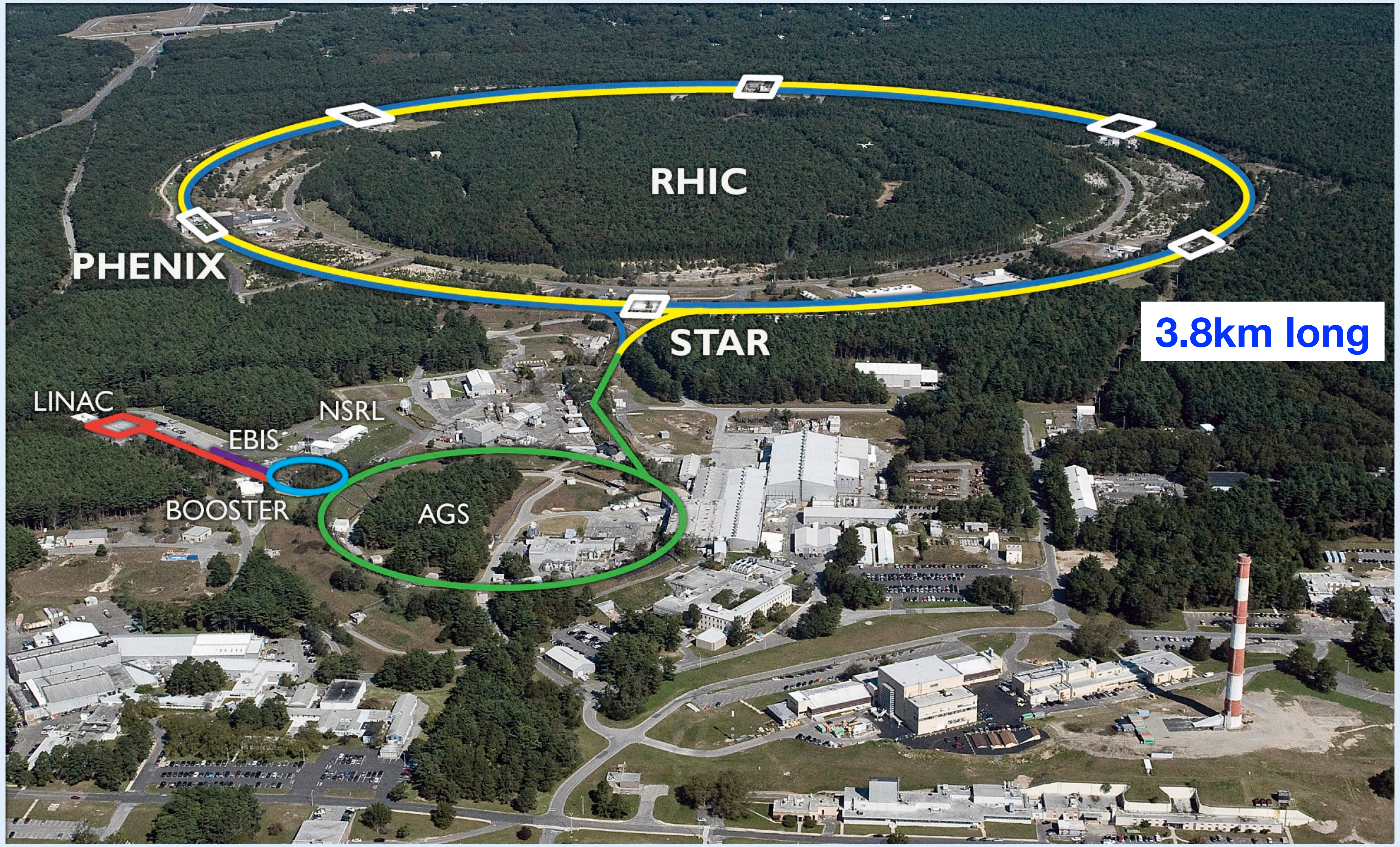


- ❑ **Sudden increase in pressure density near the transition region**
- ❑ **Due to increase in the number of degrees of freedom (DOF)**
- ❑ **Interpreted as deconfinement of quarks and gluons**

Quarks play significant role

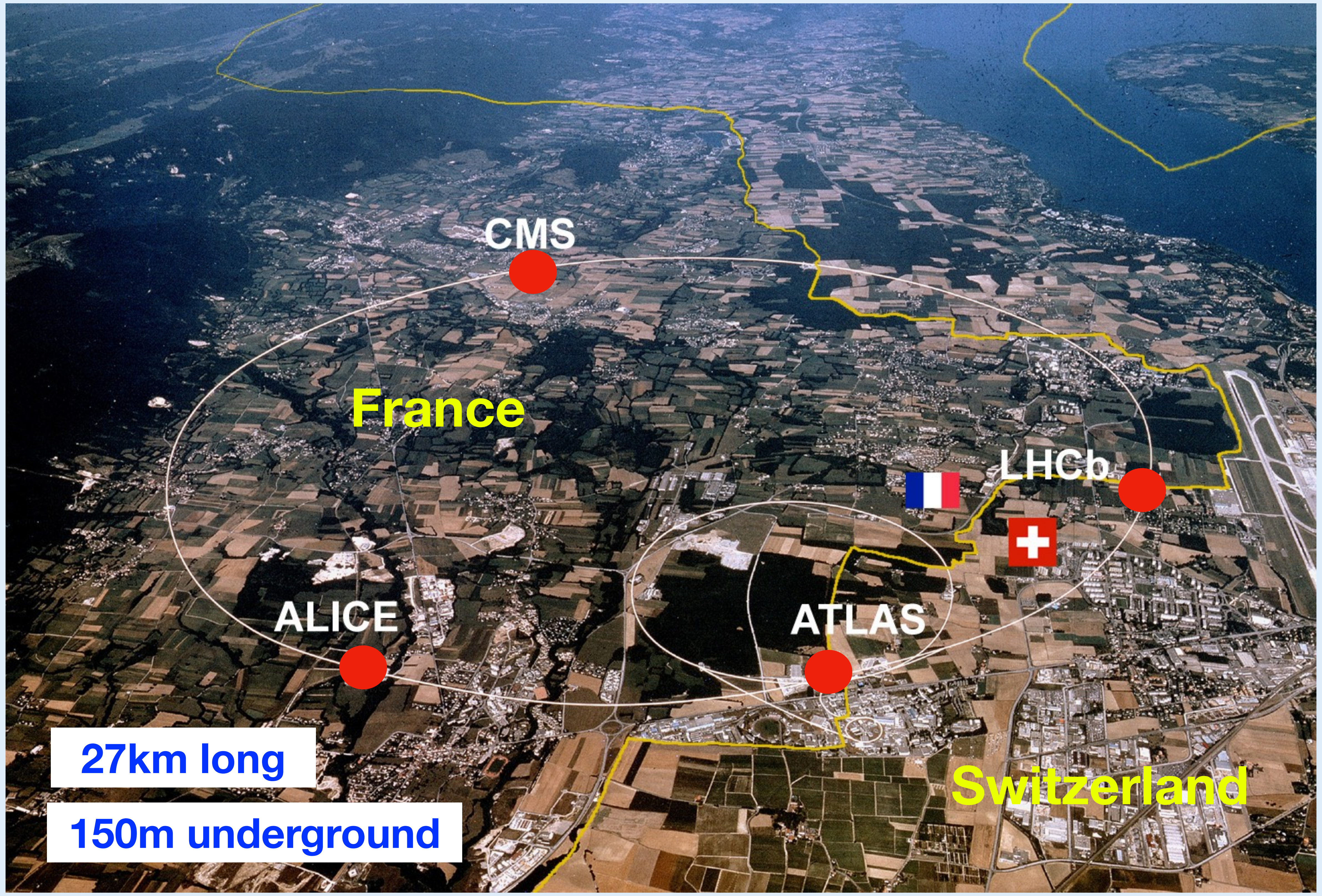
Creation of the Quark-Gluon Plasma (QGP)

Relativistic Heavy-Ion Collider (RHIC) at BNL, NewYork, USA



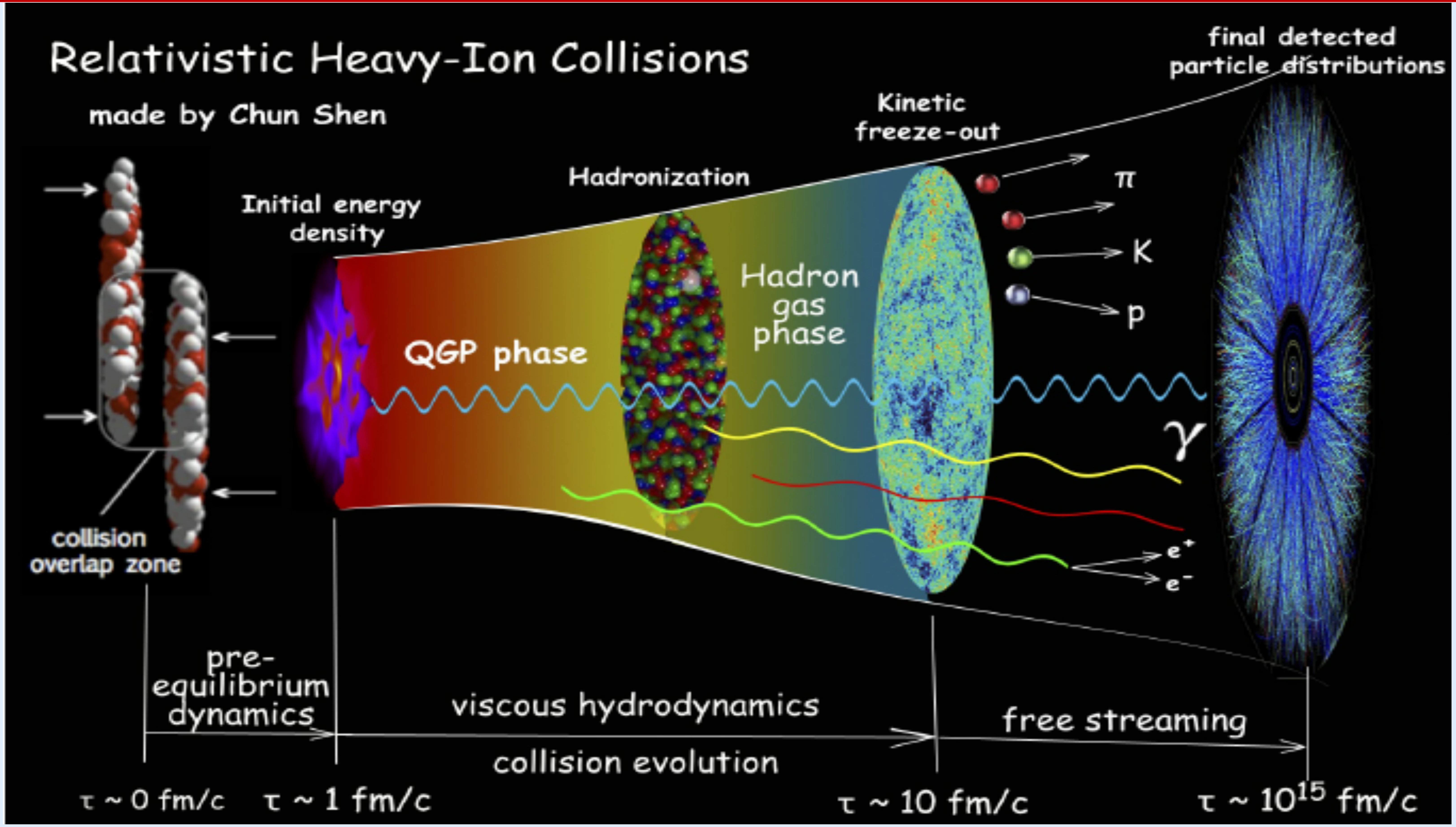
Collide two nuclei @ 5-200GeV per nucleon pair

Large Hadron Collider (LHC) at CERN, France-Switzerland border



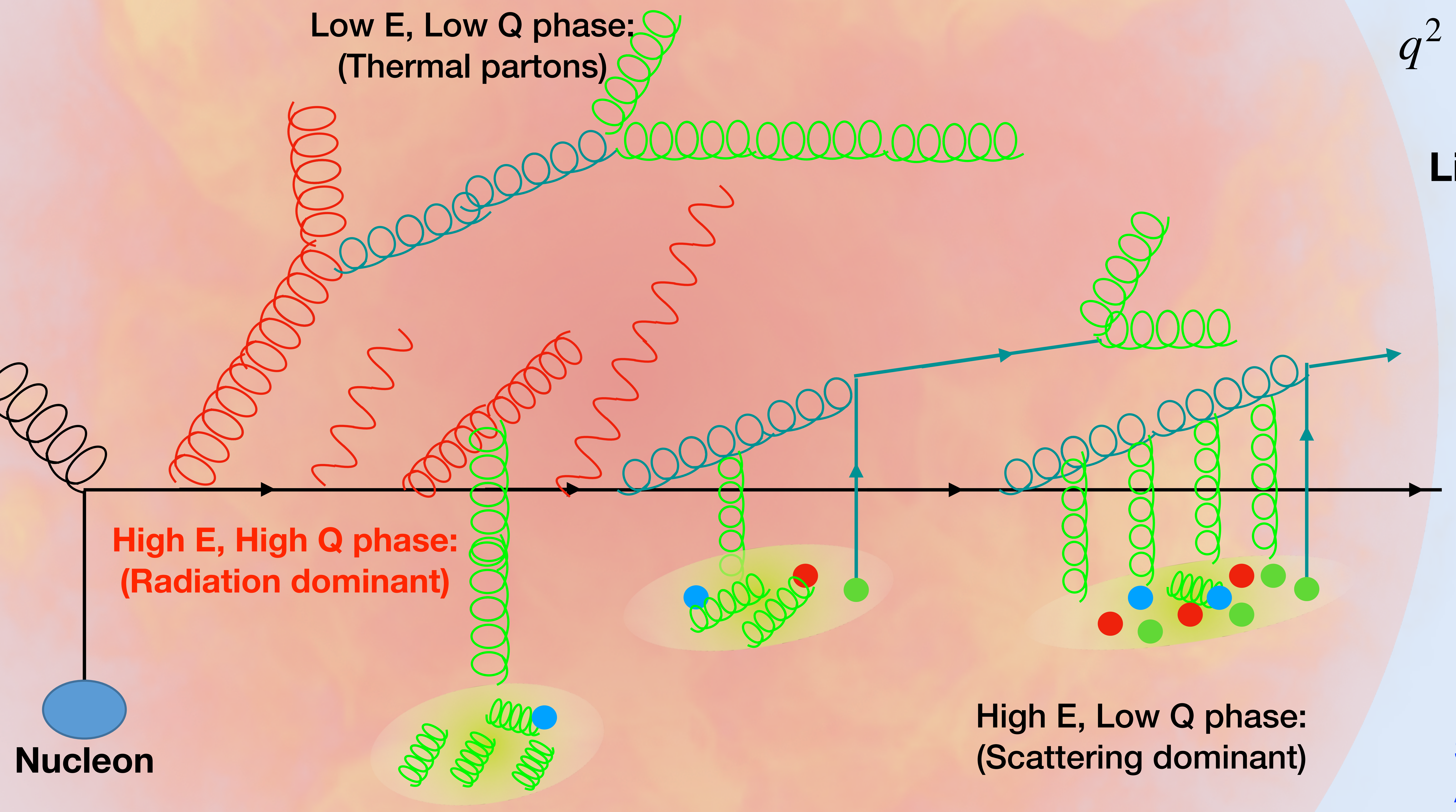
Collide two nuclei @ 2.76TeV/5TeV per nucleon pair

Creation of the Quark-Gluon Plasma (QGP)



- **Initial state:** Two Lorentz-contracted nuclei approach each other
- **Pre-equilibrium state:** undergo hard collisions produce hard probes and drive the system to thermalization in the form of QGP matter (quark density increases rapidly)
- **QGP phase:** the QGP expands hydrodynamically
- **Hadronization:** the QGP cools down and new hadrons are formed
- **Freeze-out:** hadron gas is so dilute that the interactions cease

Jet evolution in QGP a multi-scale phenomenon



Virtuality = Offshellness

$$q^2 = (q^0)^2 - |\vec{q}|^2 - m^2$$

Lifetime, $\tau_f = \dfrac{2E}{Q^2}$

Relevant theoretical framework

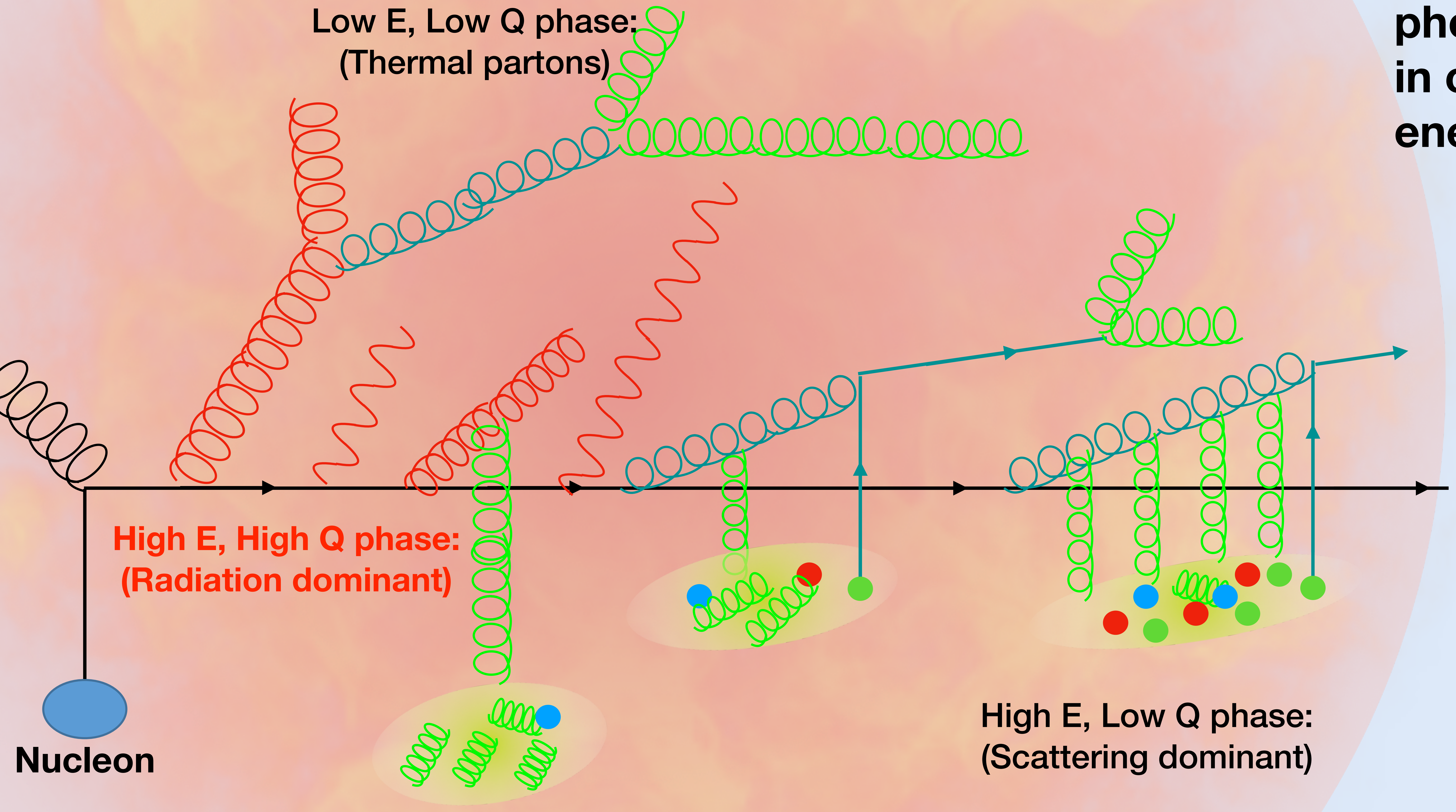
High E, High Q:
pQCD, Higher-twist approach

High E, low Q:
On-shell parton transport model

Low E, low Q:
Strong coupling formalism
AdS-CFT

QGP is gluon dominant in early stage.
Quark density increases in evolution

Jet evolution in QGP a multi-scale phenomenon



(1) Incomplete medium-induced photon emission rates are present in current Monte Carlo simulations energy loss models

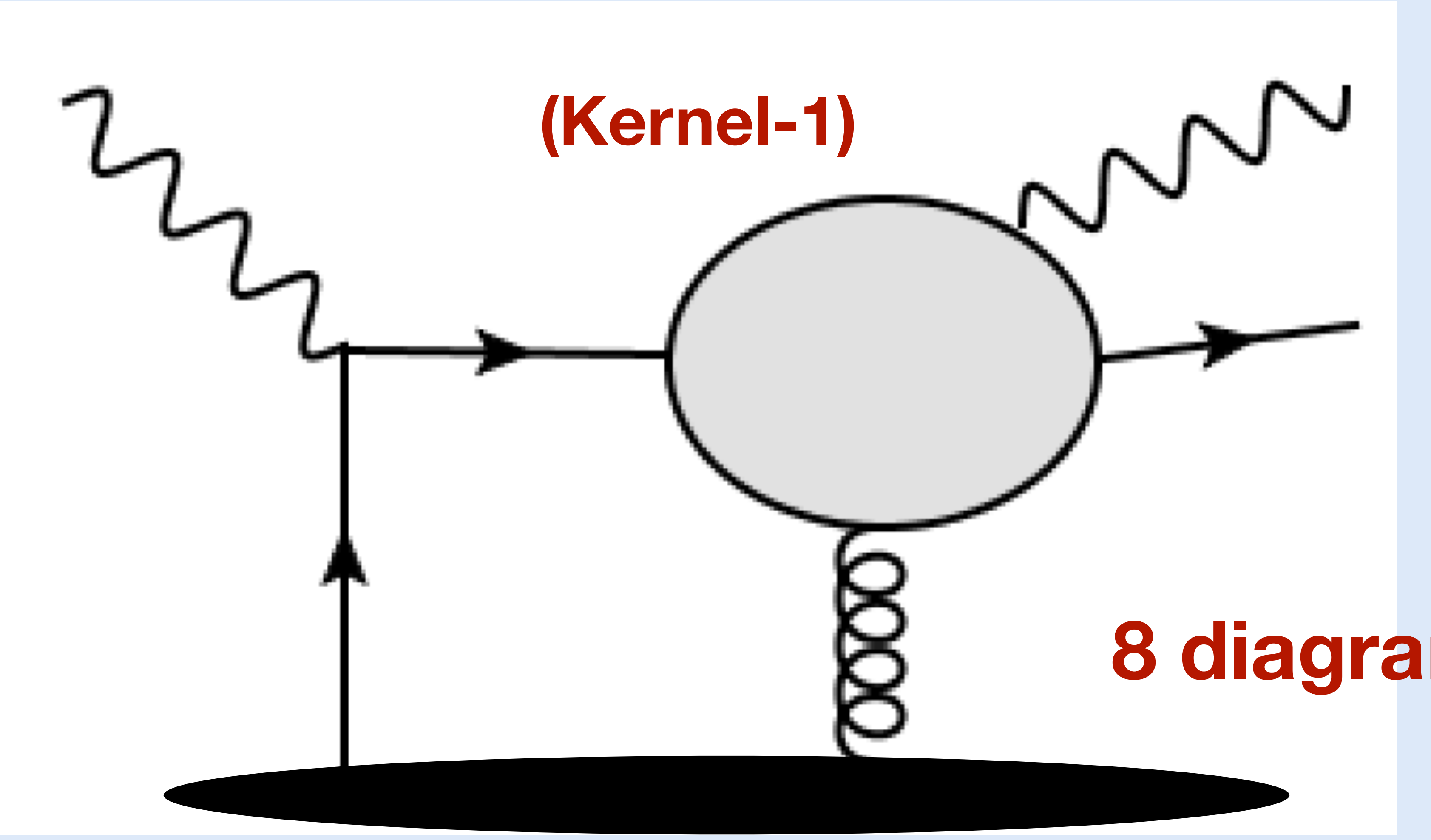
(2) Mechanism for heavy-quark energy loss in QGP?

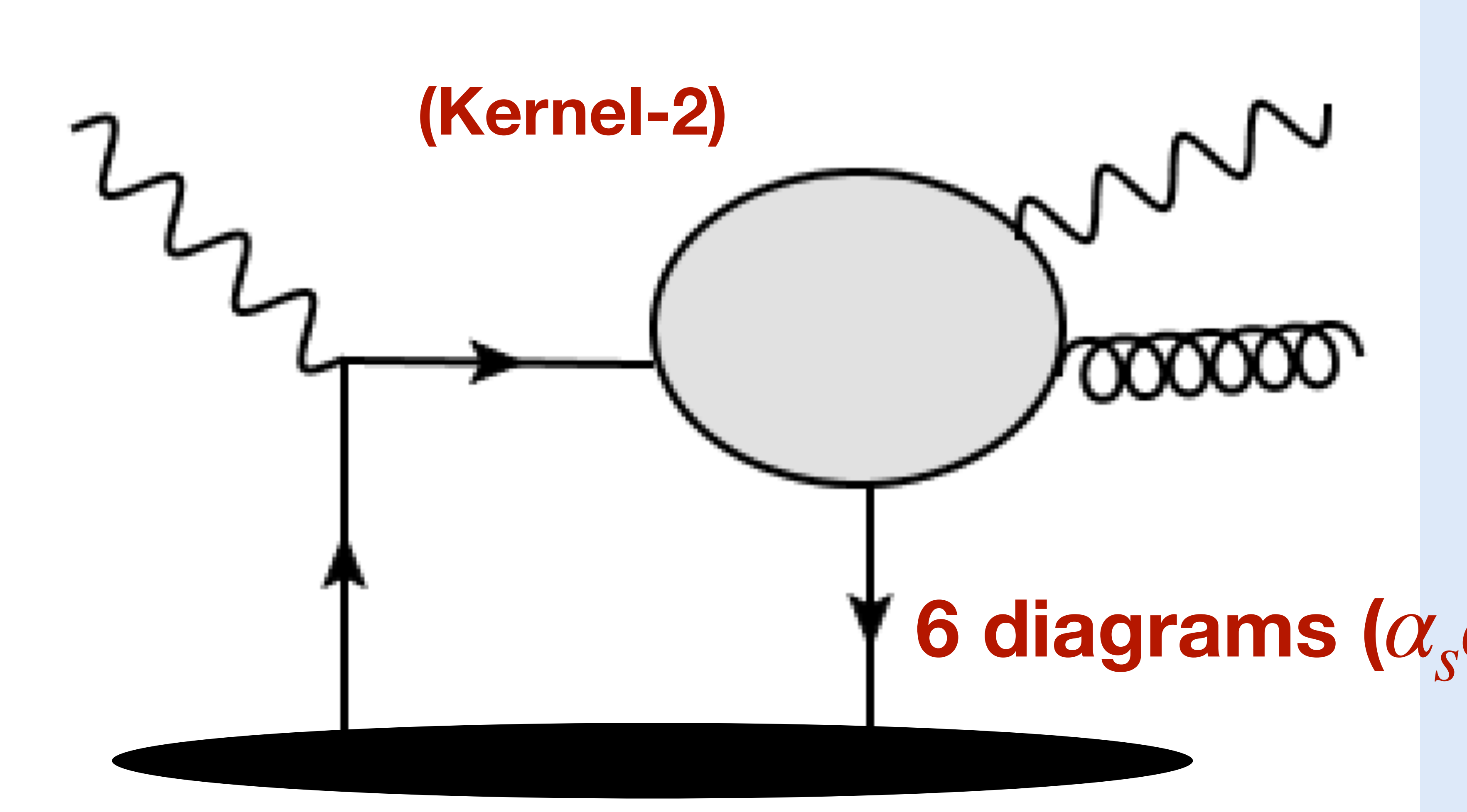
(3) Path length dependene of energy loss?

(4) Conversion processes: (QGP is gluon dominant at early stage then quarks generated)

Medium-induced single photon emission scattering kernels ($\alpha_{em}\alpha_s$)

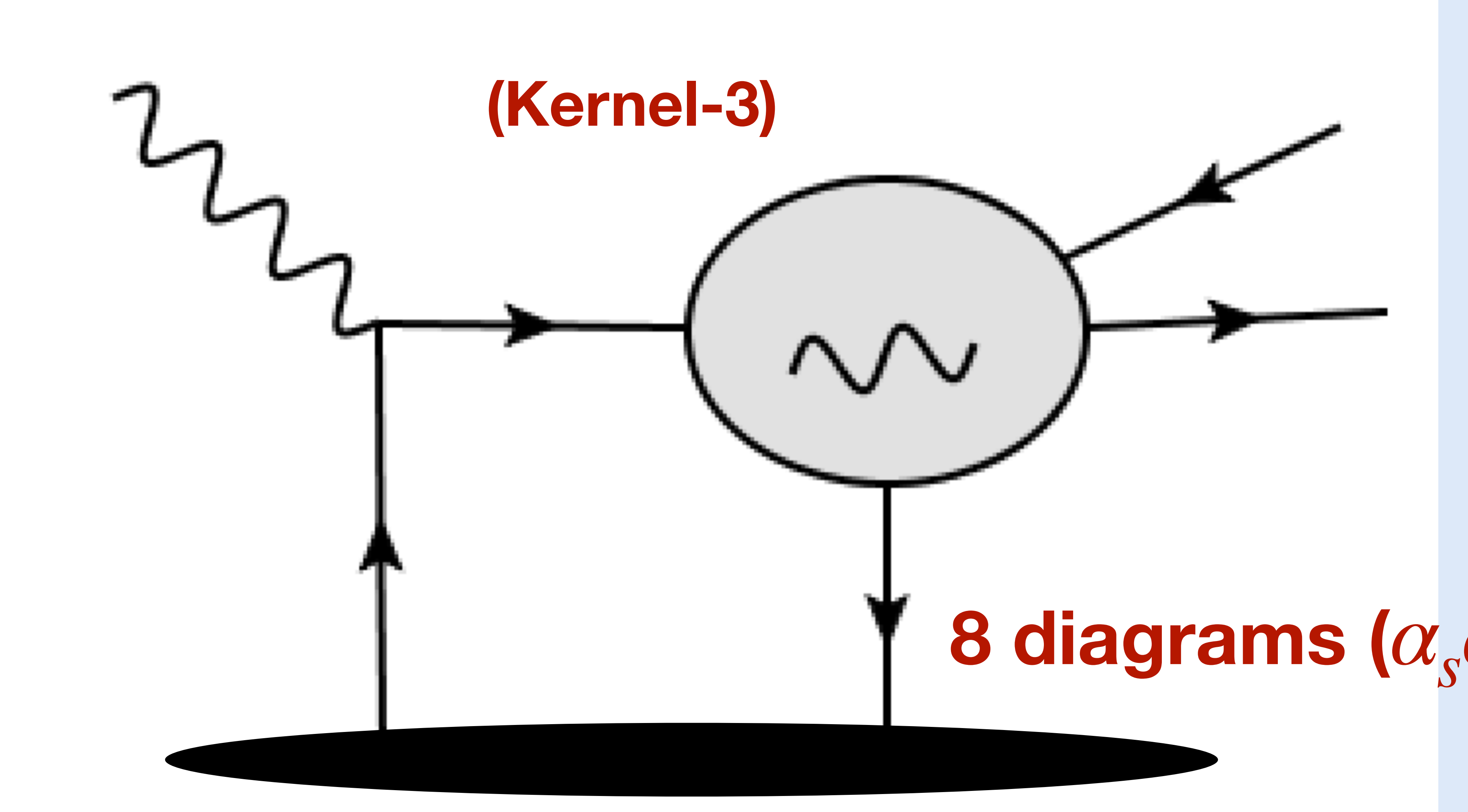
❑Bremsstrahlung photon emission Kernel

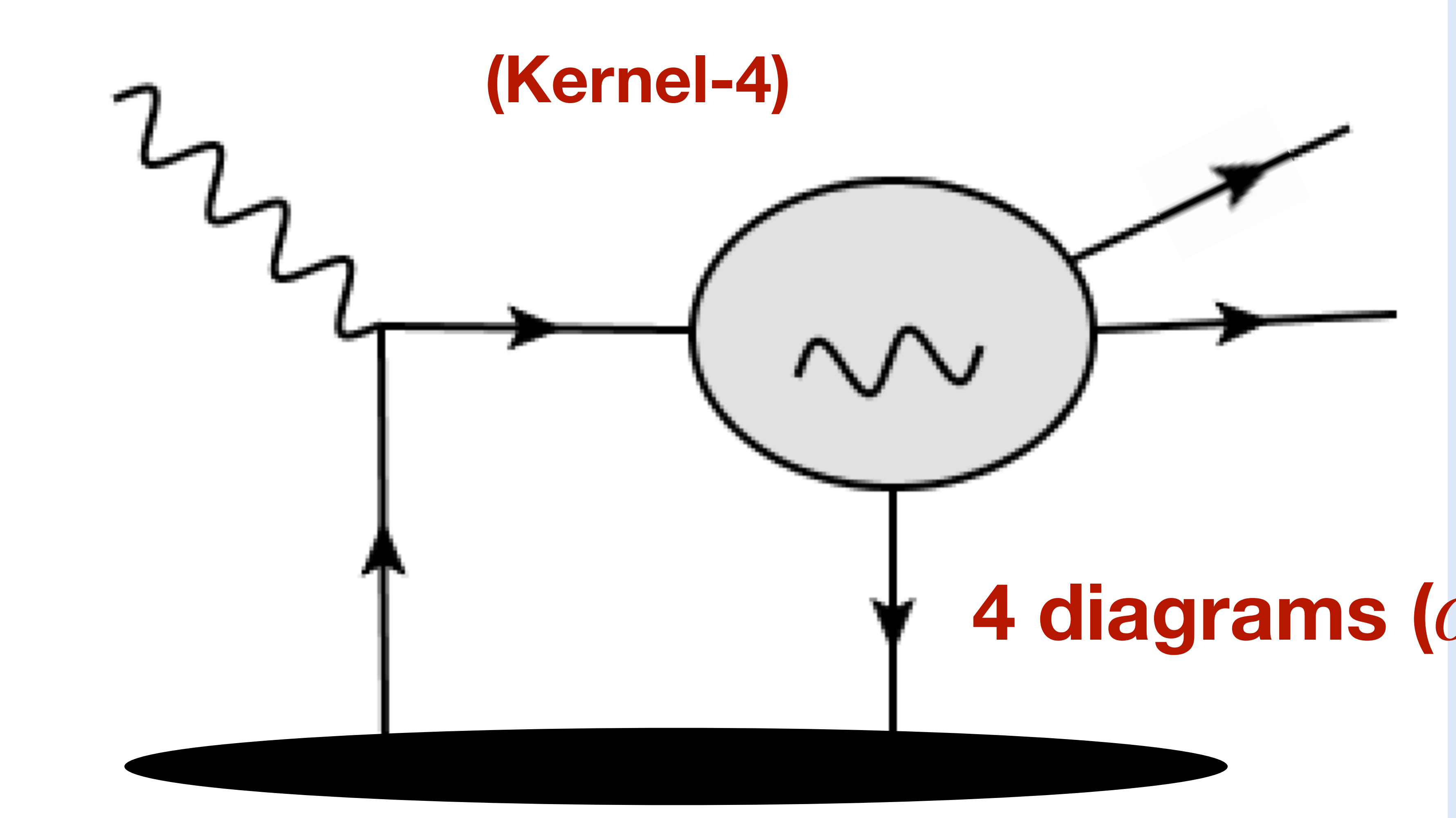




❑Virtual photon emission Kernel

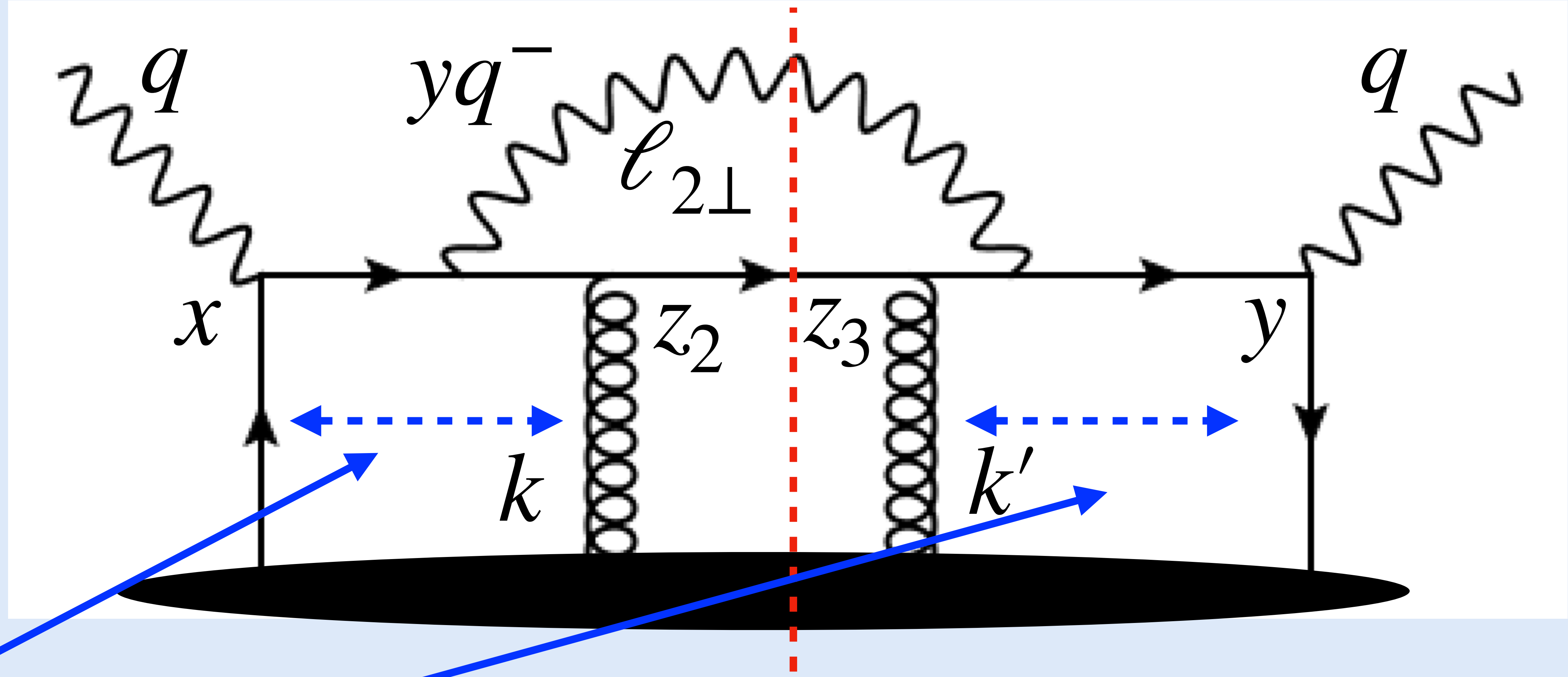
(Use perturbative QCD to evaluate Feynman Diagrams)





Single emission and single scattering kernel at high Q^2

- **Important Terms in the Scattering kernel:**



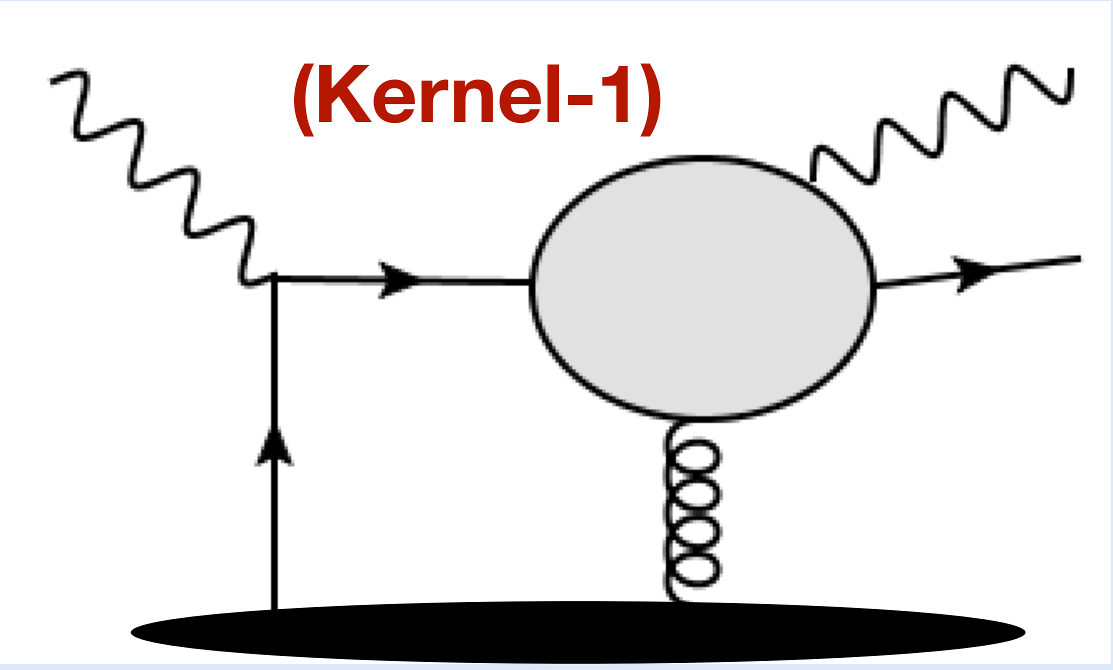
Path length

ζ^-

Forwad scattering diagram (Kernel-1)

Momentum scaling of in-medium parton (Glauber)

Quark Mass effects



A. Kumar and G. Vujanovic (arXiv:2502.02667) (2025)

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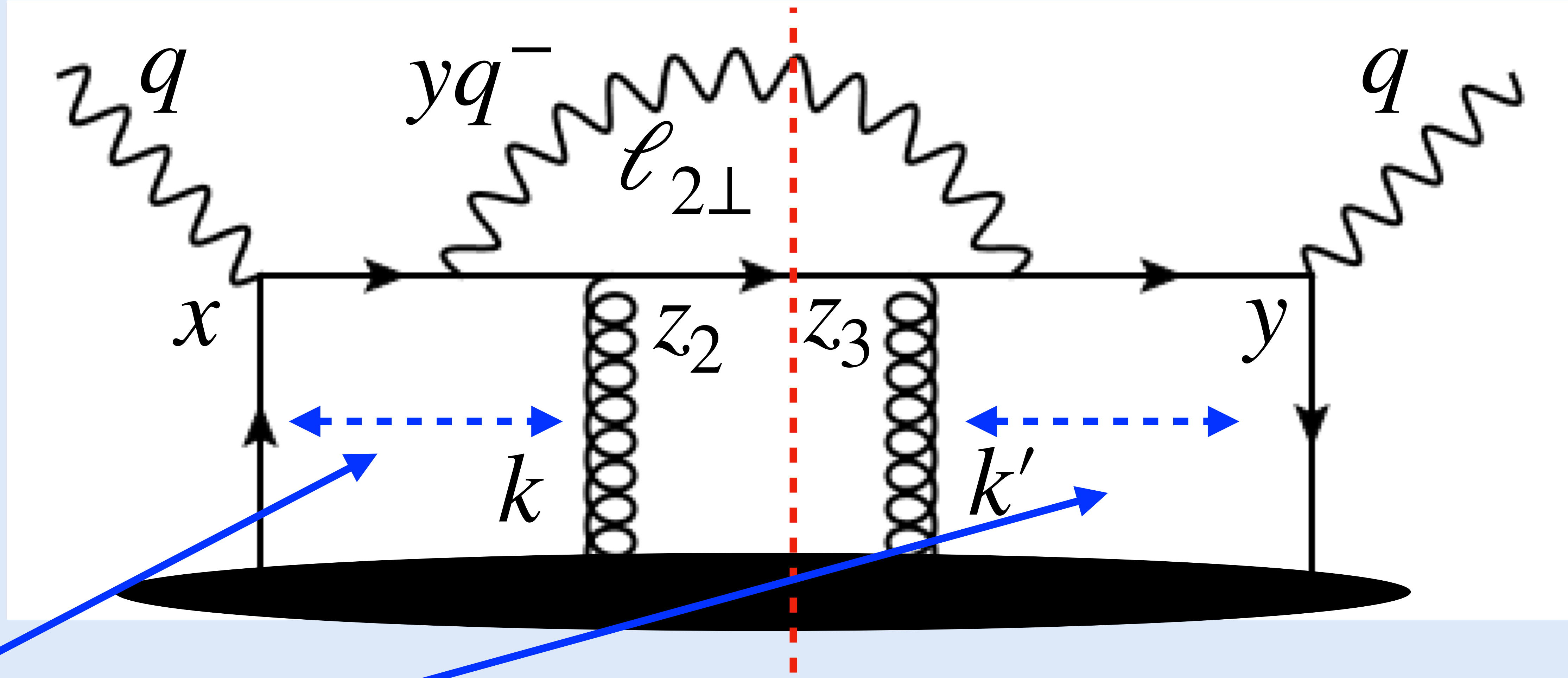


Forwad scattering diagram (Kernel-1)

✦**Splitting Function** $\left[\frac{1+(1-y)^2}{y}\right]$

✦**Phase interefence (positive definite)**

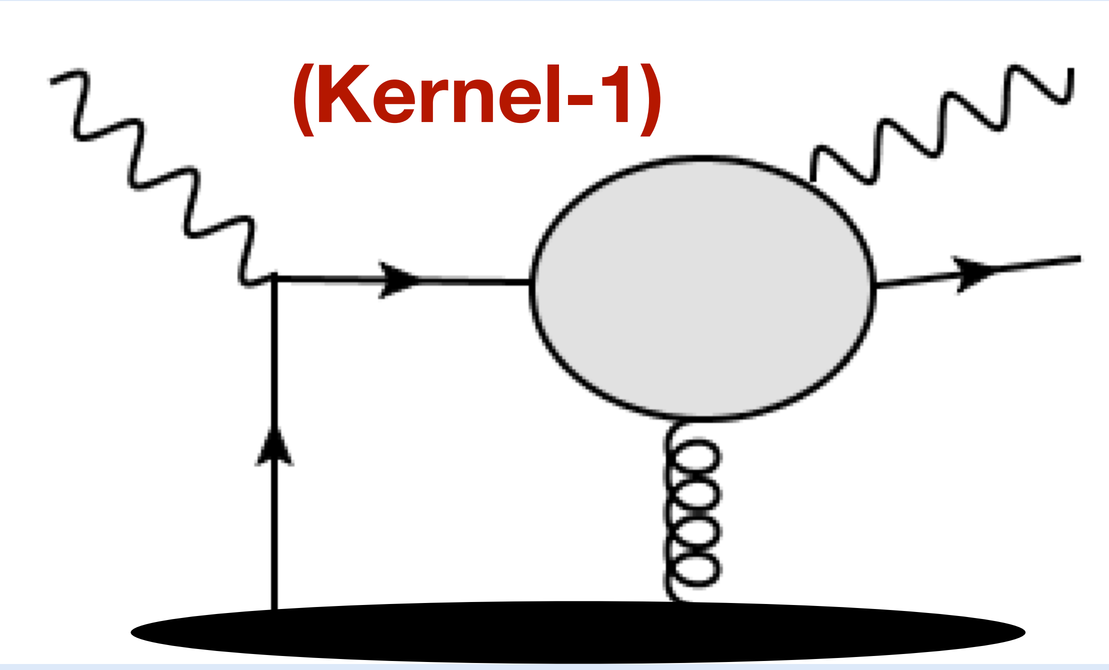
Path length ζ^-

$$\left[\frac{2-2\cos\left\{\frac{(\ell_{2\perp}^2+y^2M^2)}{2y(1-y)q^-}\zeta^-\right\}}{\ell_{2\perp}^2}\right]$$

(Positive matrix element)

Momentum scaling of in-medium parton (Glauber)

Quark Mass effects



✦**Non-perturbative in-medium operators**

$$\langle P_{A-1}|A^+(\zeta^-,\Delta z^-,\Delta z_\perp)A^+(\zeta^-,0)|P_{A-1}\rangle\ e^{i\Delta z^-\left[\frac{\vec{\ell}_{2\perp}^2-yM^2}{2yq^-}+\frac{\left(\vec{\ell}_{2\perp}-\vec{k}_\perp\right)^2+M^2}{2q^-(1-y+\eta y)}\right]}$$

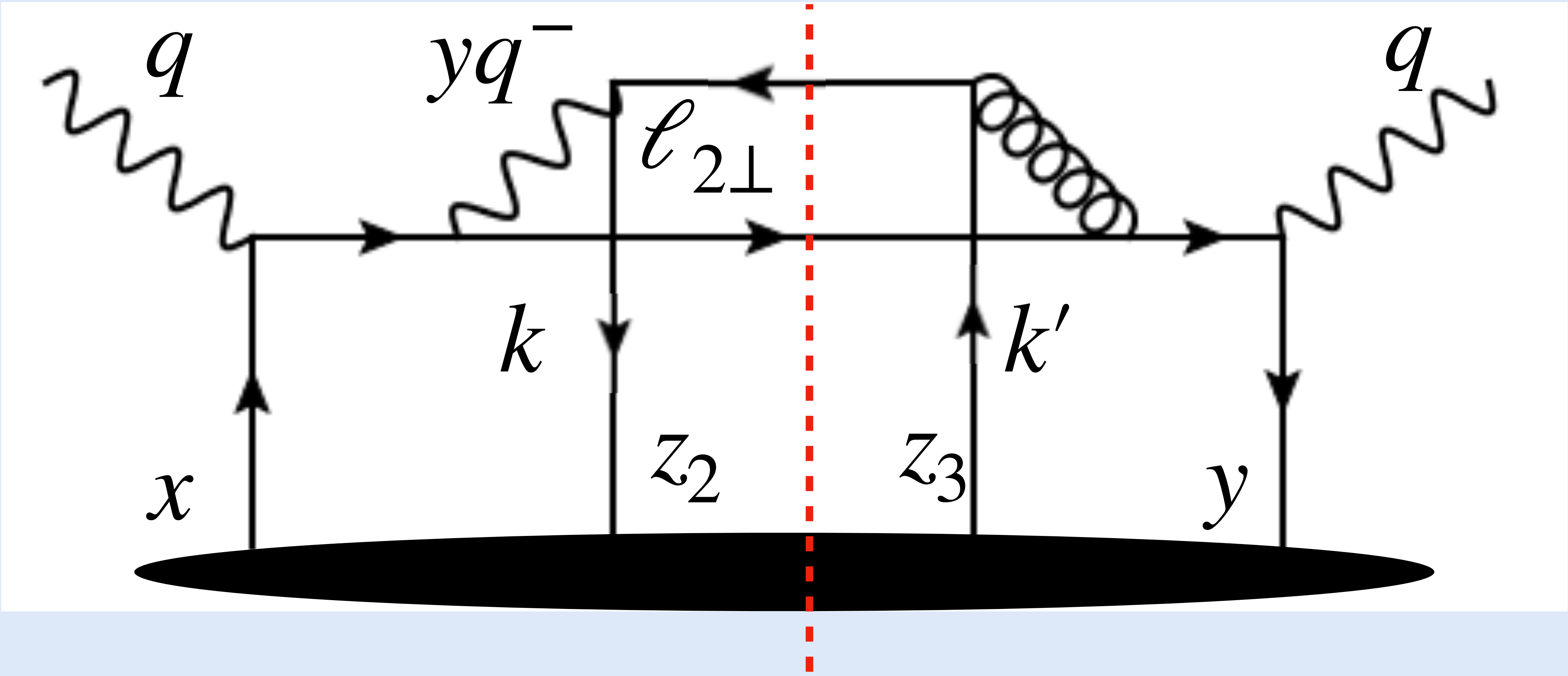
Contains transverse momentum dependence in addition to collinear momentum

(TMD-like phase space)

A. Kumar and G. Vujanovic (arXiv:2502.02667) (2025)

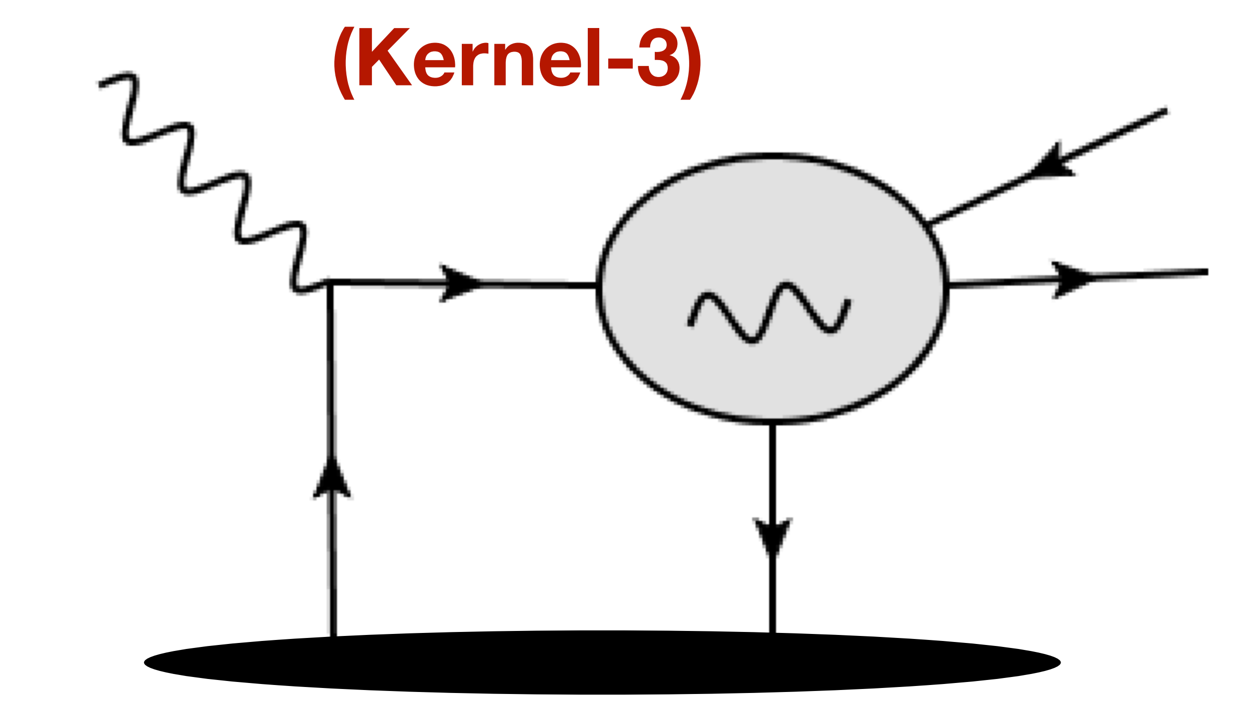
Single emission and single scattering kernel at high Q^2

- **Important Terms in Scattering kernel:**



Forwad scattering diagram (Kernel-3)

Momentum scaling of in-medium parton (Glauber)
Quark Mass effects
Conversion processes (Suppressed by energy)



TMD-like phase space

Single emission and single scattering kernel at high Q^2

❑ Important Terms in Scattering kernel:

✦**Splitting Function** $\left[\frac{1+(1-y)^2}{y}\right]$

✦**Phase coherence effect**

$$\left[\frac{2-2\cos\left\{\frac{(\ell_{2\perp}-k_\perp)^2+y^2M^2}{2y(1-y)q^-}\zeta^-\right\}}{(\ell_{2\perp}-k_\perp)^2}\right]$$

$\ell_{2\perp} \approx k_\perp$, amplitude square is maximum
In-medium quark can resolve the splitting

✦**Non-perturbative in-medium operators**

$$\frac{1}{yq^-}\left\langle P_{A-1}\left|\bar{\psi}(\zeta^-,0)\frac{\gamma^+}{4}\psi\left(\zeta^-,\Delta z^-,\Delta\vec{z}_\perp\right)\right|P_{A-1}\right\rangle e^{i\Delta z^-\left[\frac{\vec{\ell}^2_{2\perp}-yM^2}{2yq^-}+\frac{\left(\vec{\ell}_{2\perp}-\vec{k}_\perp\right)^2+M^2}{2q^-(1-y+\eta y)}\right]}$$

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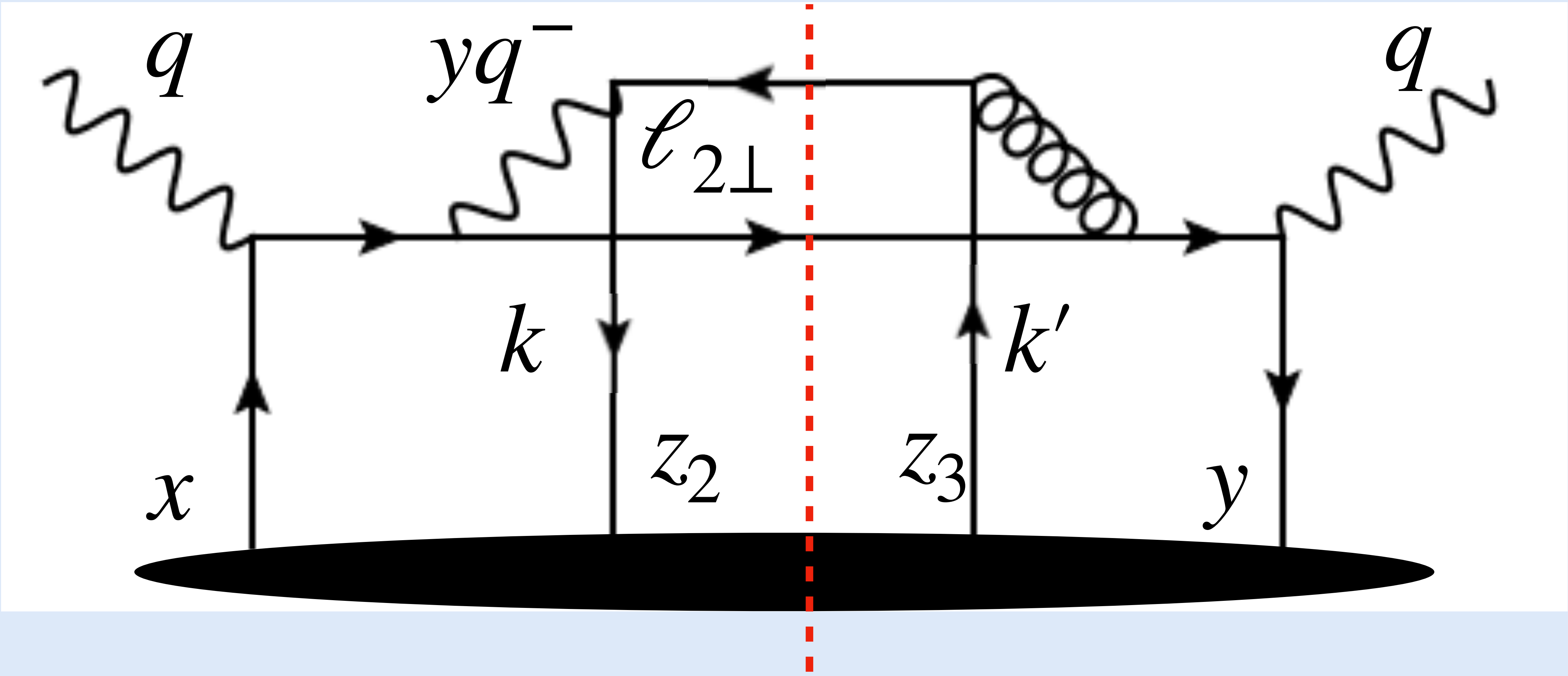

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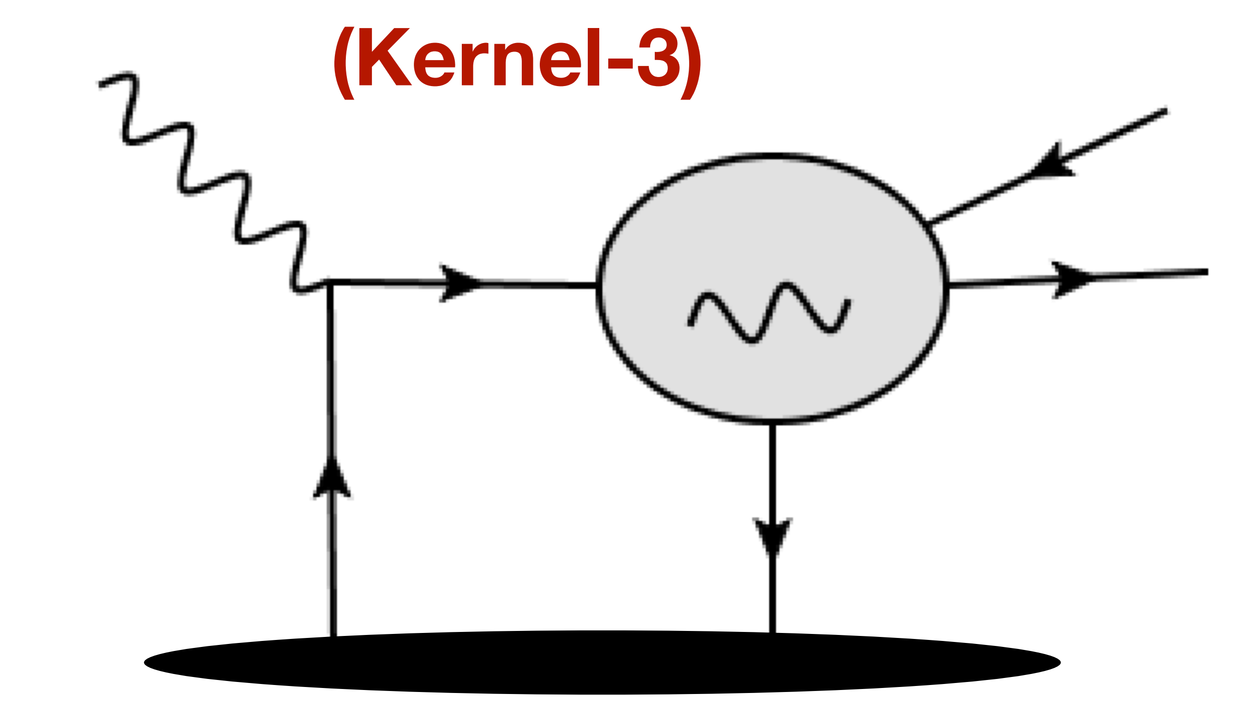
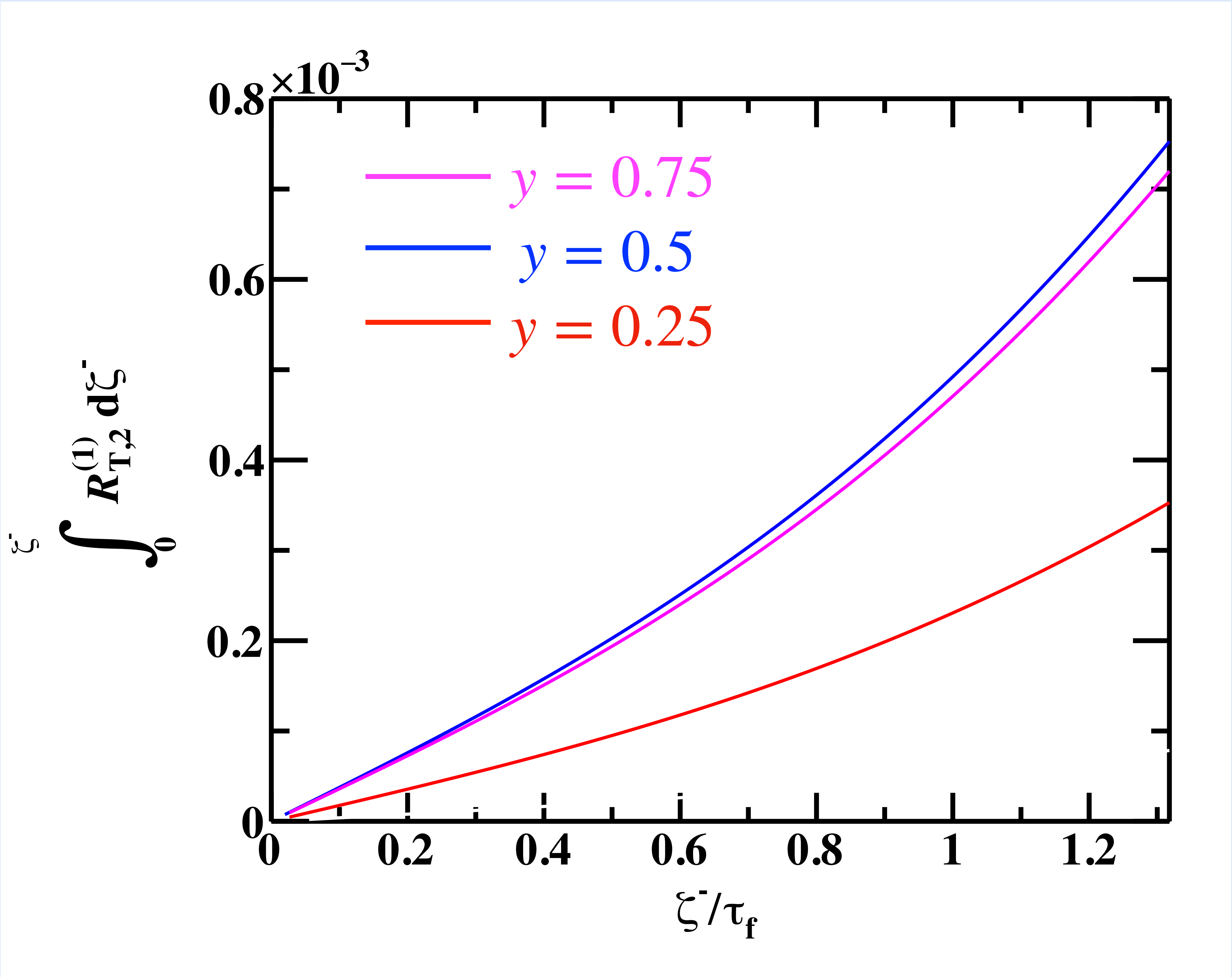
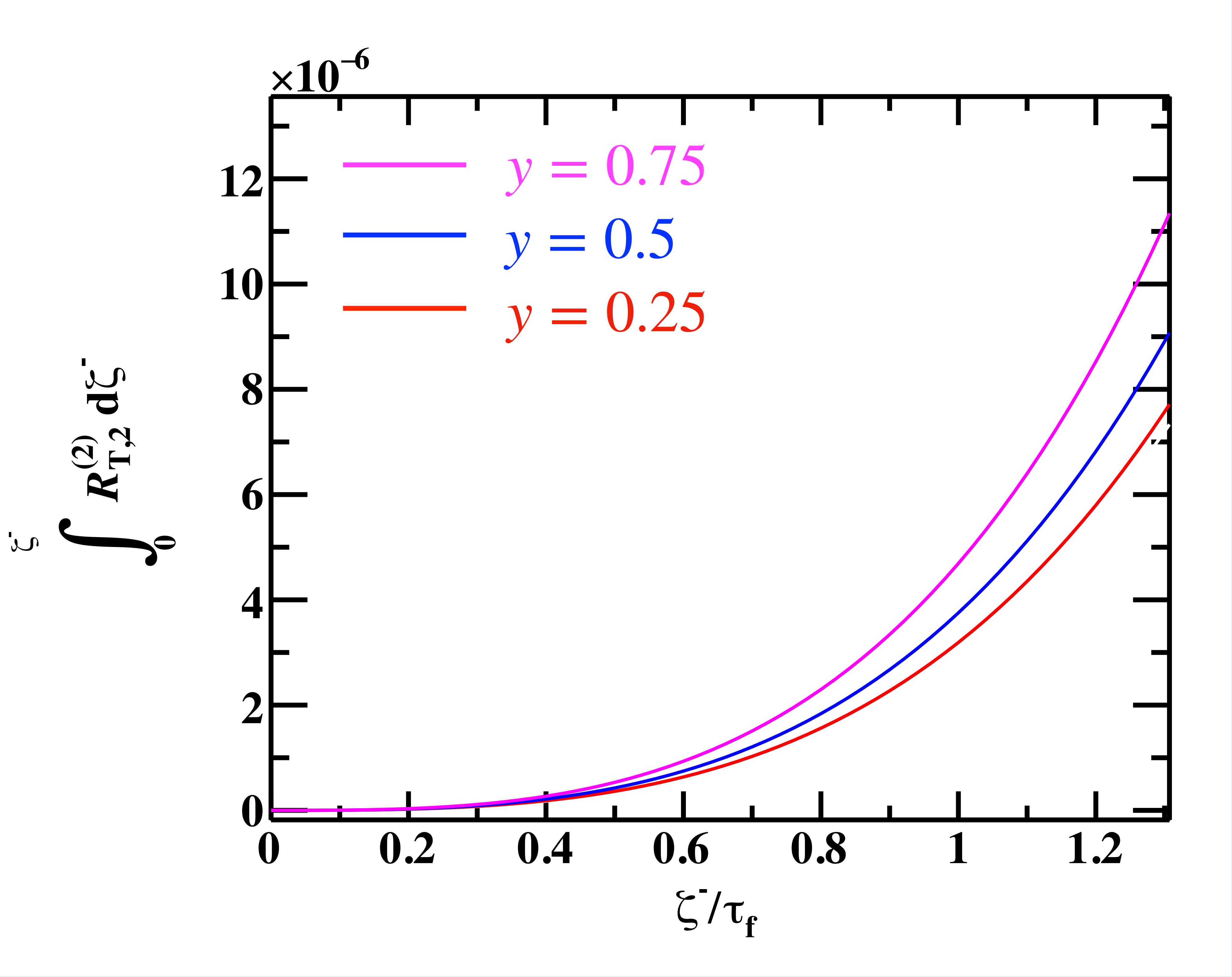


TMD-like phase space

Path length dependence of scattering kernel

- ❑ **Bremsstrahlung photon emission, single scattering kernel for quark mass $M = 0$**





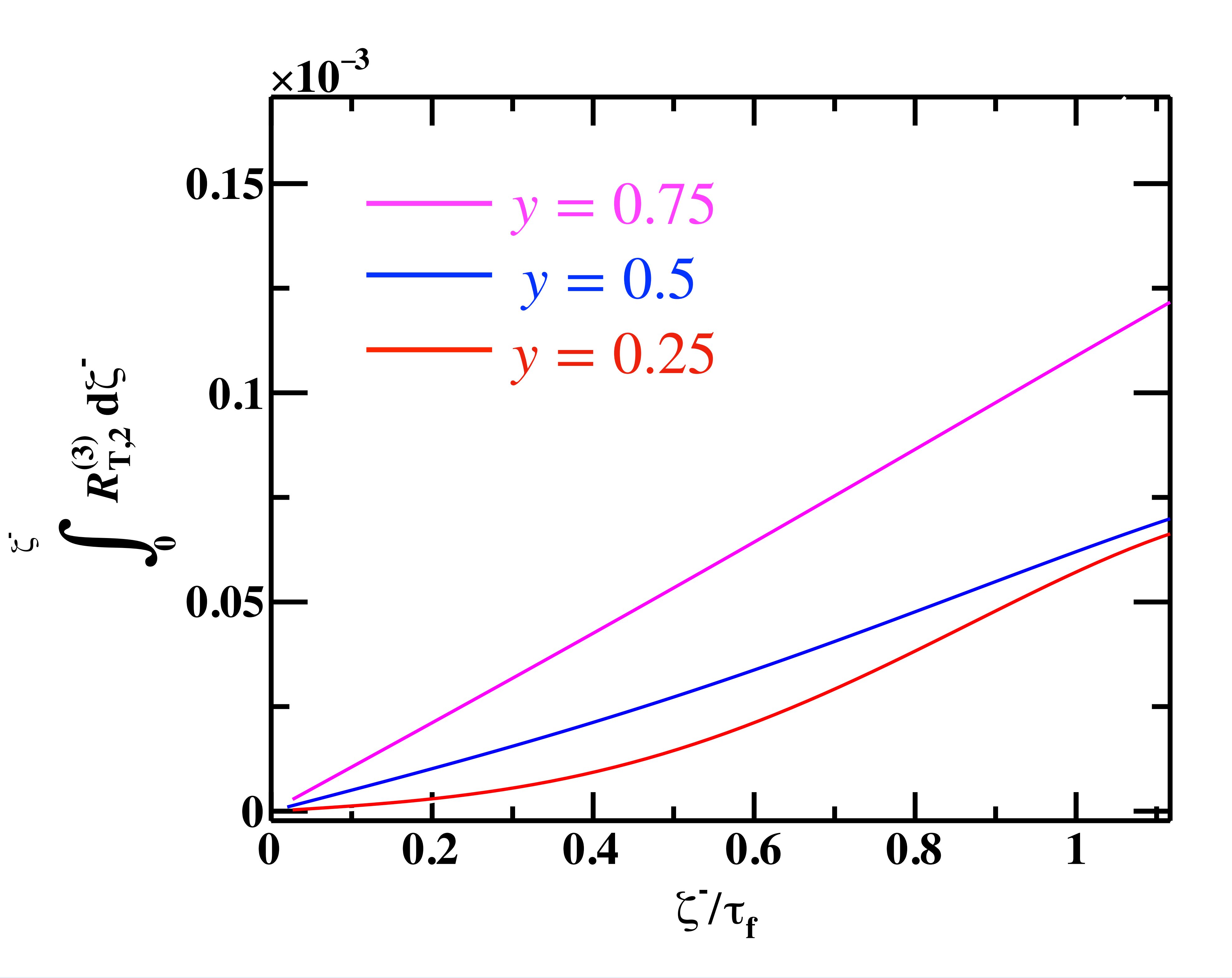
Kernel-1 **(Length integrated kernel)** **Kernel-2**

- ❑ **Kernel shows positive and increasing trend with the path length traversed**

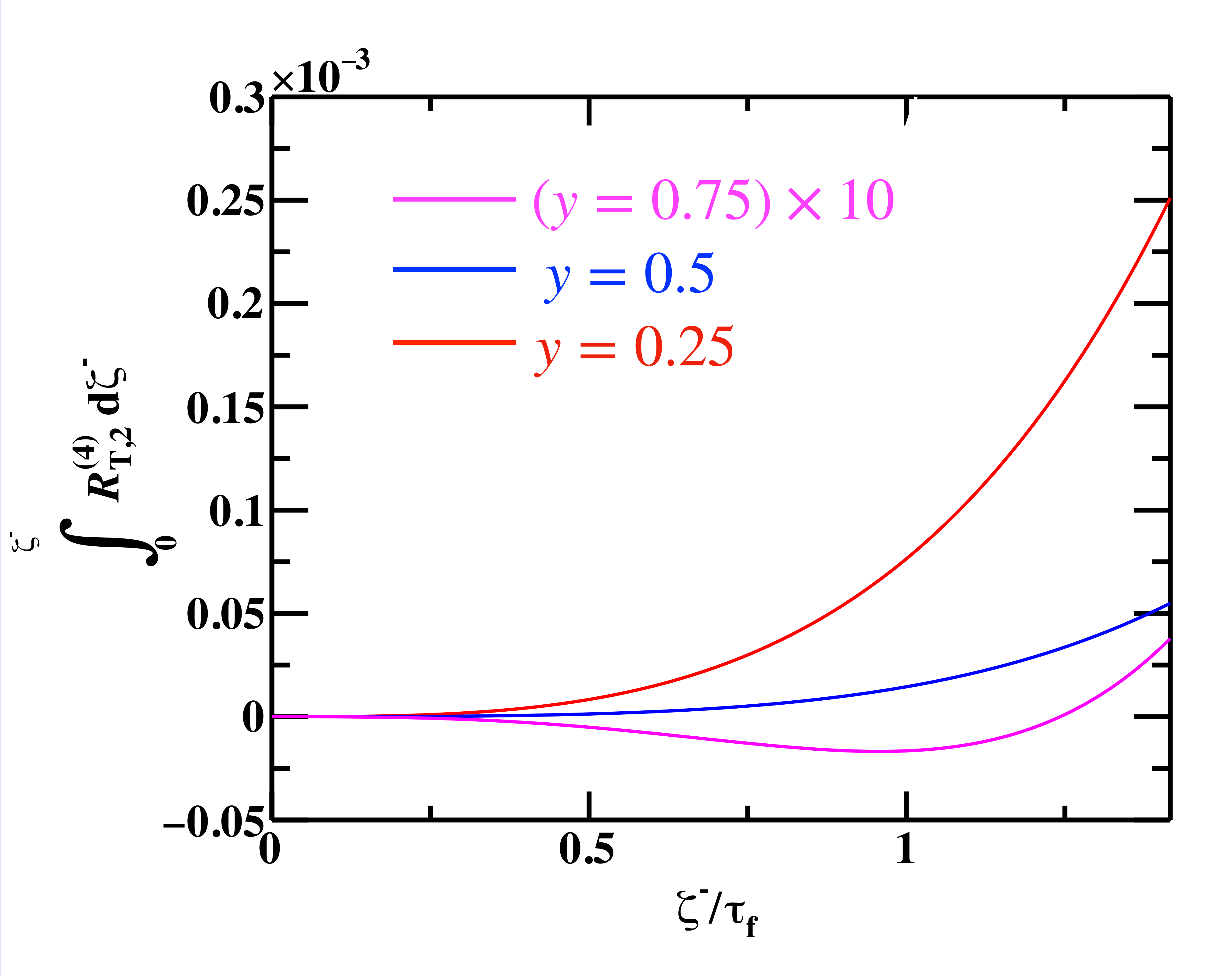
A. Kumar and G. Vujanovic (arXiv:2502.02667) (2025)

Path length dependence of scattering kernel (conti.)

❑ Virtual photon emission scattering kernel for quark mass $M = 0$



Kernel-3



Kernel-4

(Length integrated kernel)

Here, y is momentum fraction carried away by radiated photon

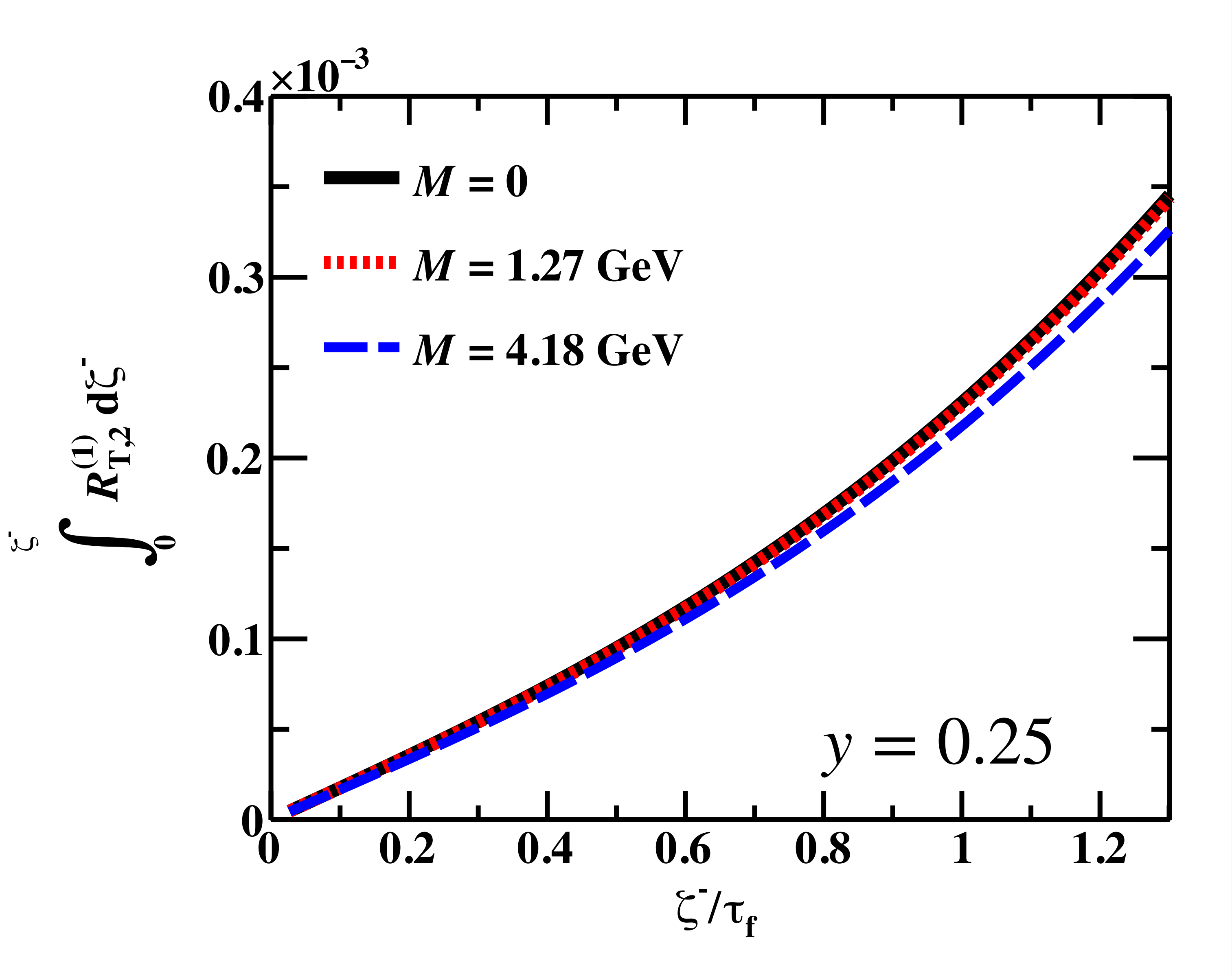
❑ Kernel shows positive and increasing trend with the path length traversed

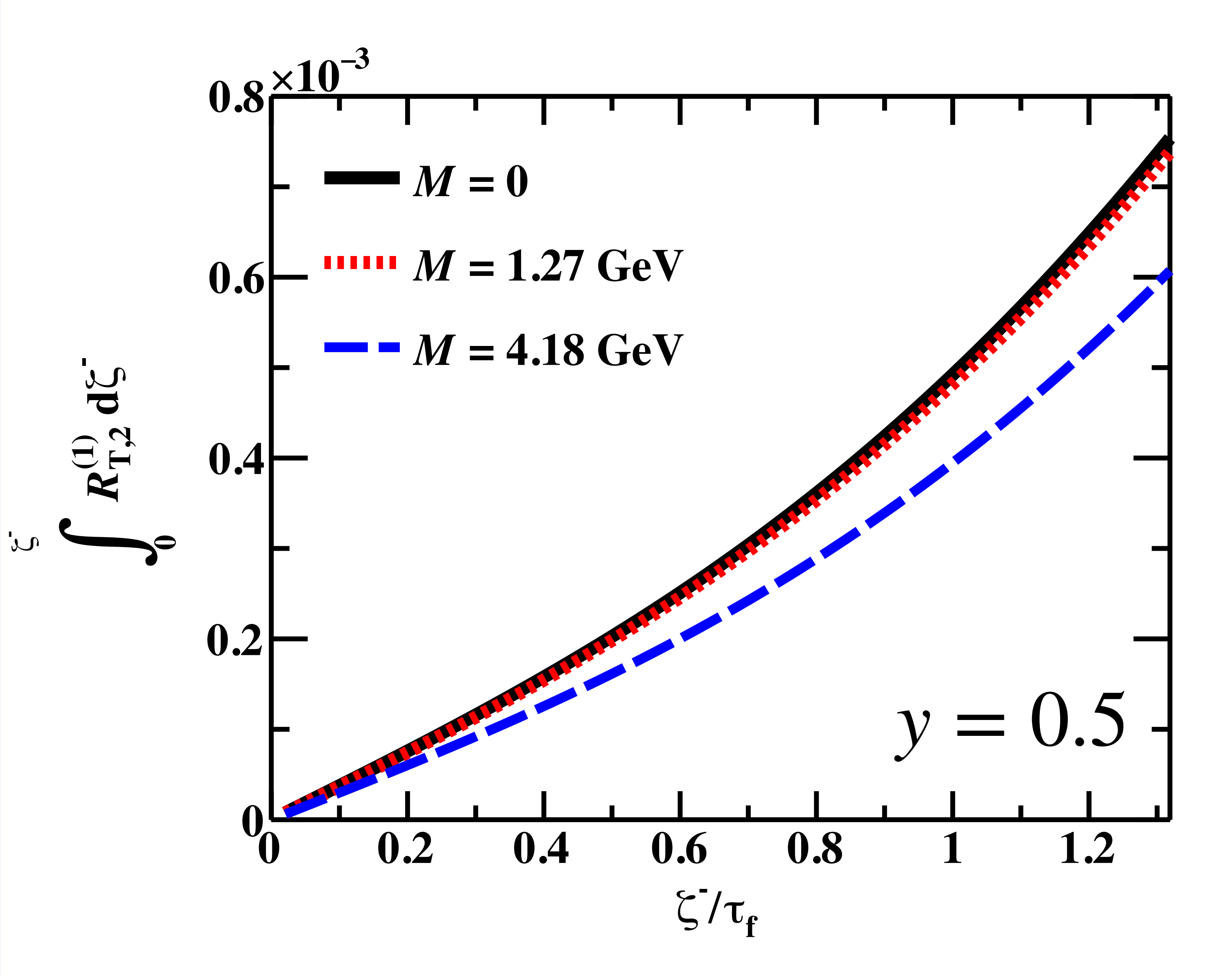
❑ Interference term

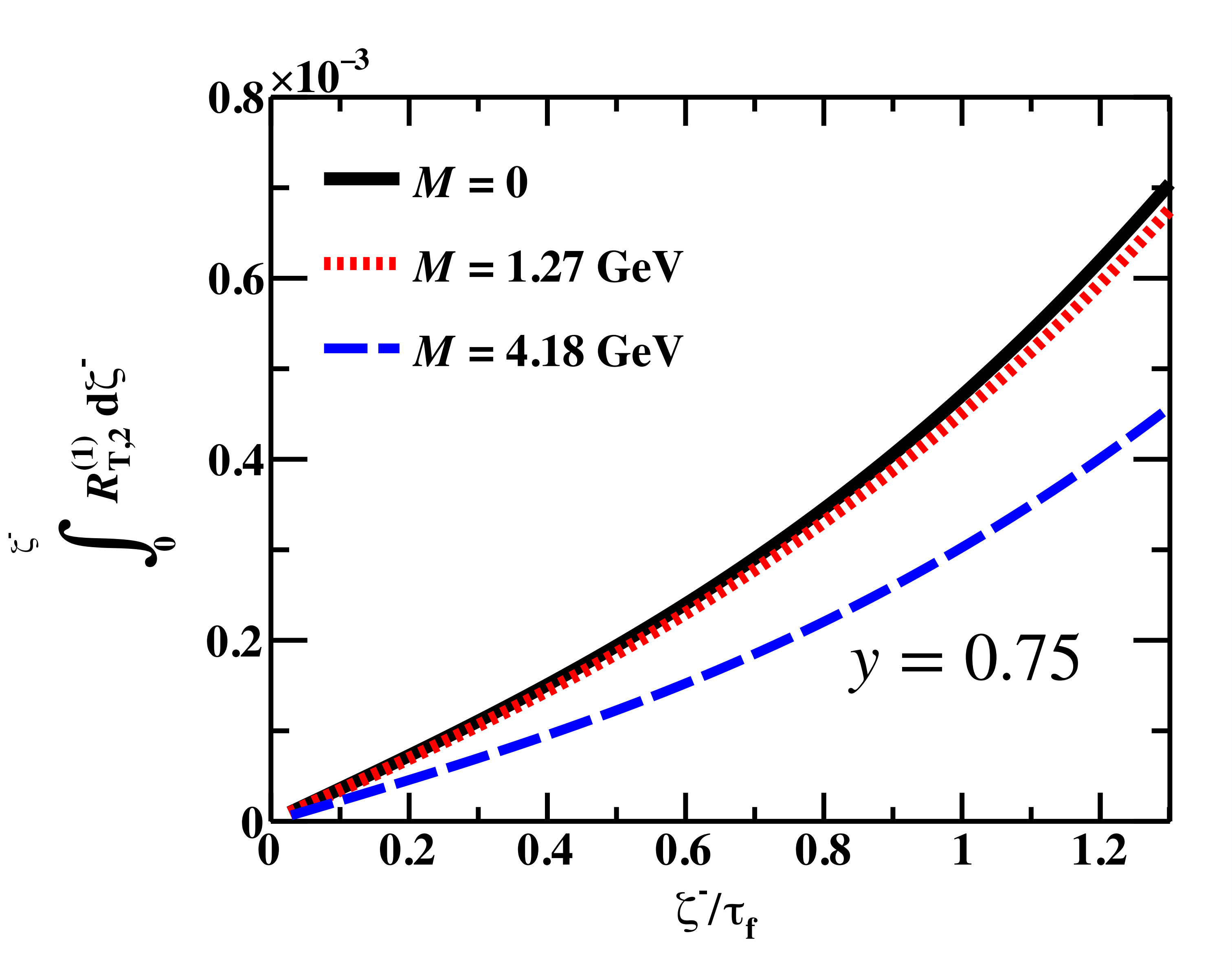
A. Kumar and G. Vujanovic (arXiv:2502.02667) (2025)

Path length dependence of scattering kernel for heavy-quarks

❑ **Bremsstrahlung photon emission, single scattering kernel for charm and bottom quark mass**







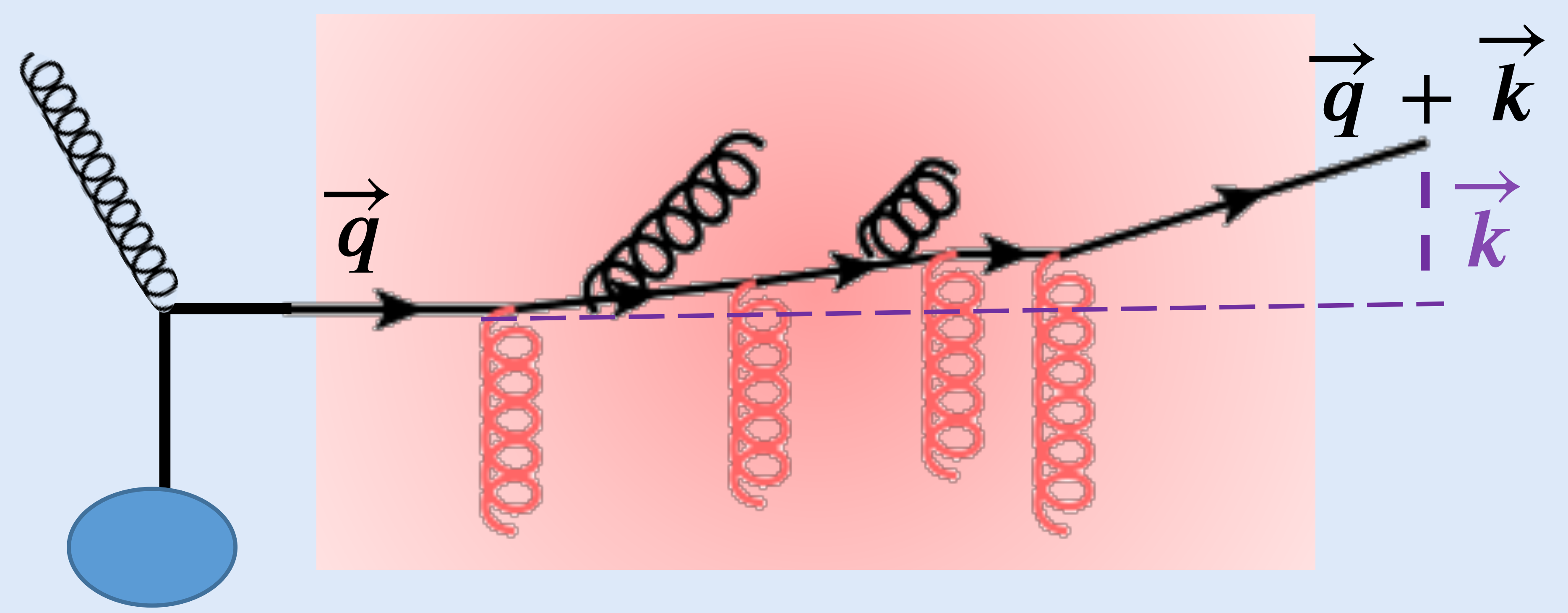
Kernel-1 **(Length integrated kernel)**

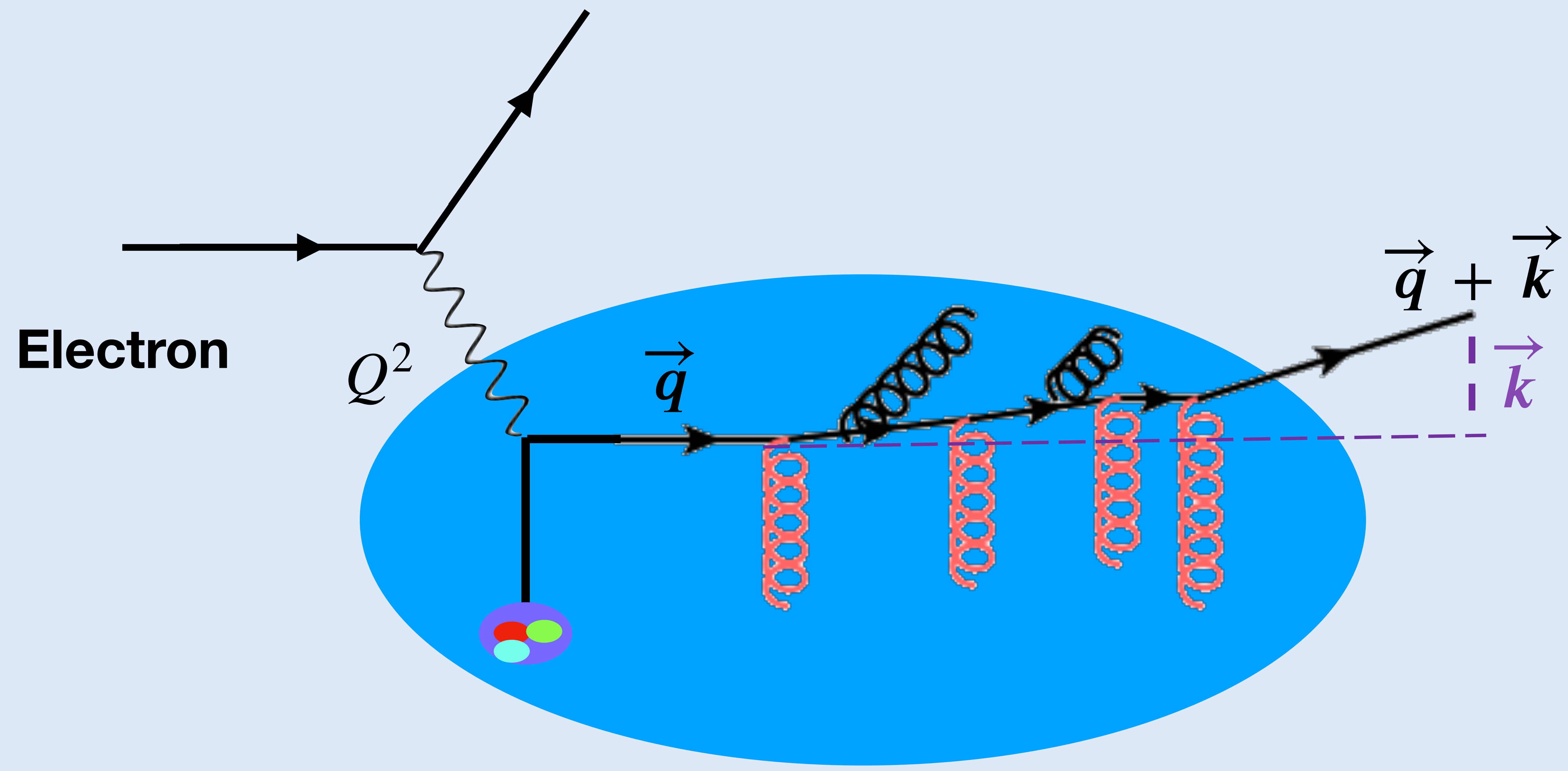
❑ **Bottom quark demonstrates large mass effects compared to charm quark**
❑ **Kernel-3 and kernel-4 also show similar behavior**

A. Kumar and G. Vujanovic (arXiv:2502.02667) (2025)

Jet transport coefficients in cold nuclear medium

- ❑ Factorized approach to jet evolution





- ❑ Transport coefficient $\hat{q}$:

$$\hat{q}(\vec{r},t) = \frac{\langle \vec{k}_\perp^2 \rangle}{L} \propto \langle M | F_\perp^+(y^-, y_\perp) F^{+\perp}(0) | M \rangle$$

- ❑ Transport coefficient $\hat{e}$:

$$\hat{e}(\vec{r},t) = \frac{\langle k_z \rangle}{L} \propto \langle M | \partial^- A^+(y^-, y_\perp) A^+(0) | M \rangle$$

- ❑ Transport coefficient $\hat{e}_2$:

$$\hat{e}_2(\vec{r},t) = \frac{\langle k_z^2 \rangle}{L} \propto \langle M | F^{+-}(y^-, y_\perp) F^{+-}(0) | M \rangle$$

- ✦ Transport coefficient arise from pQCD based calculations
- ✦ Replace QGP thermal state with hadronic nuclear state

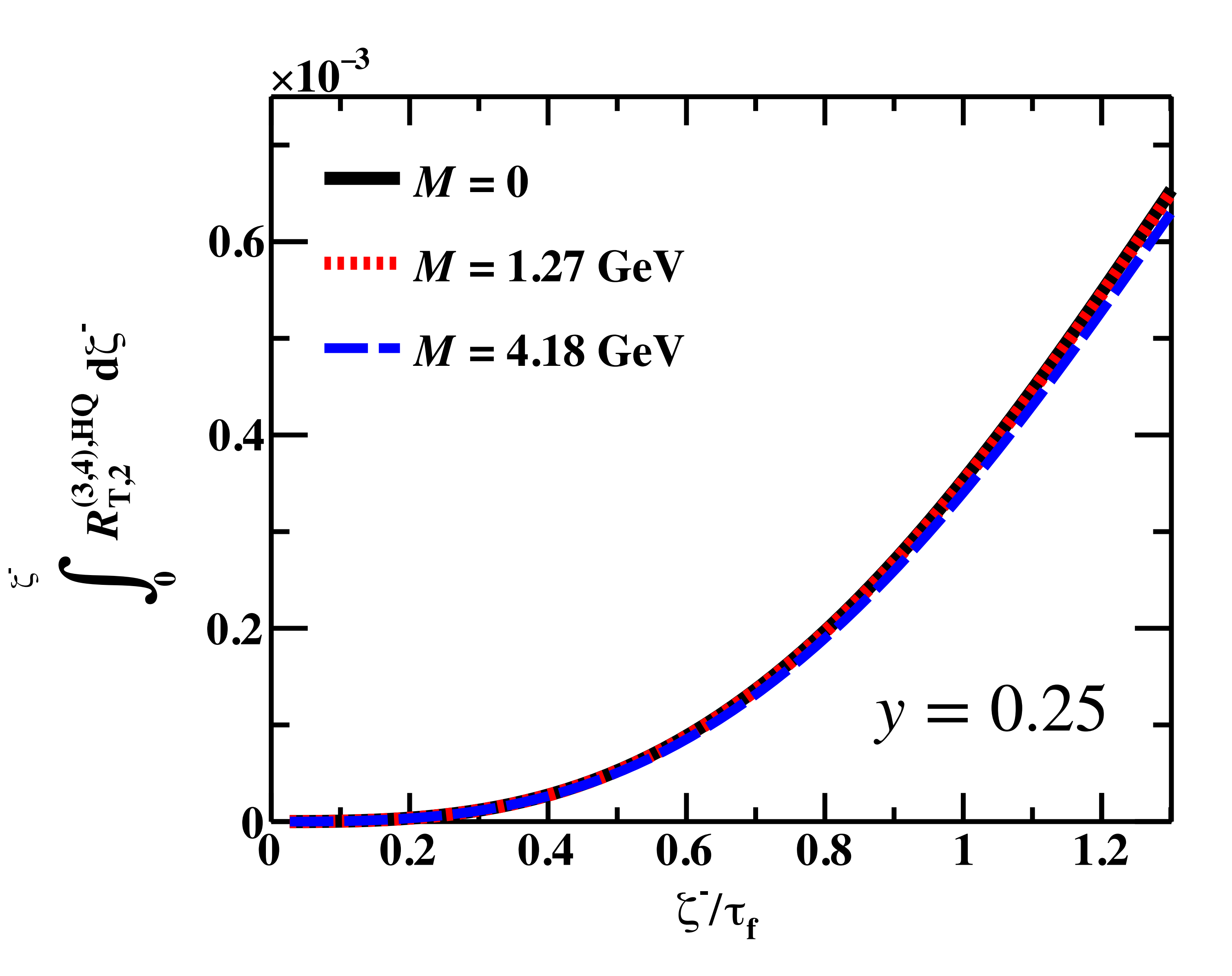
$\Longrightarrow$ Energy loss calculation can be extened to Electron-Ion Physics

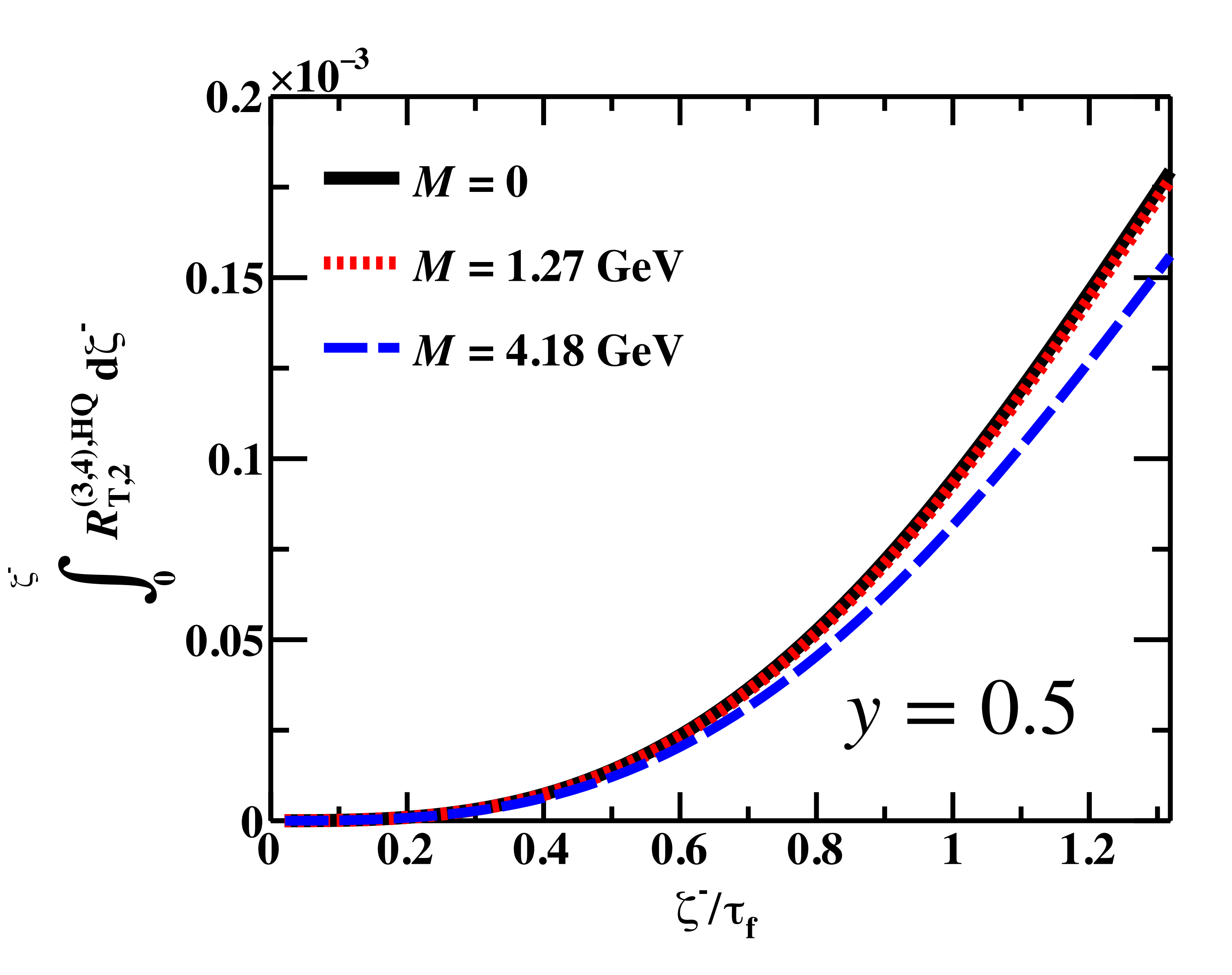
Summary

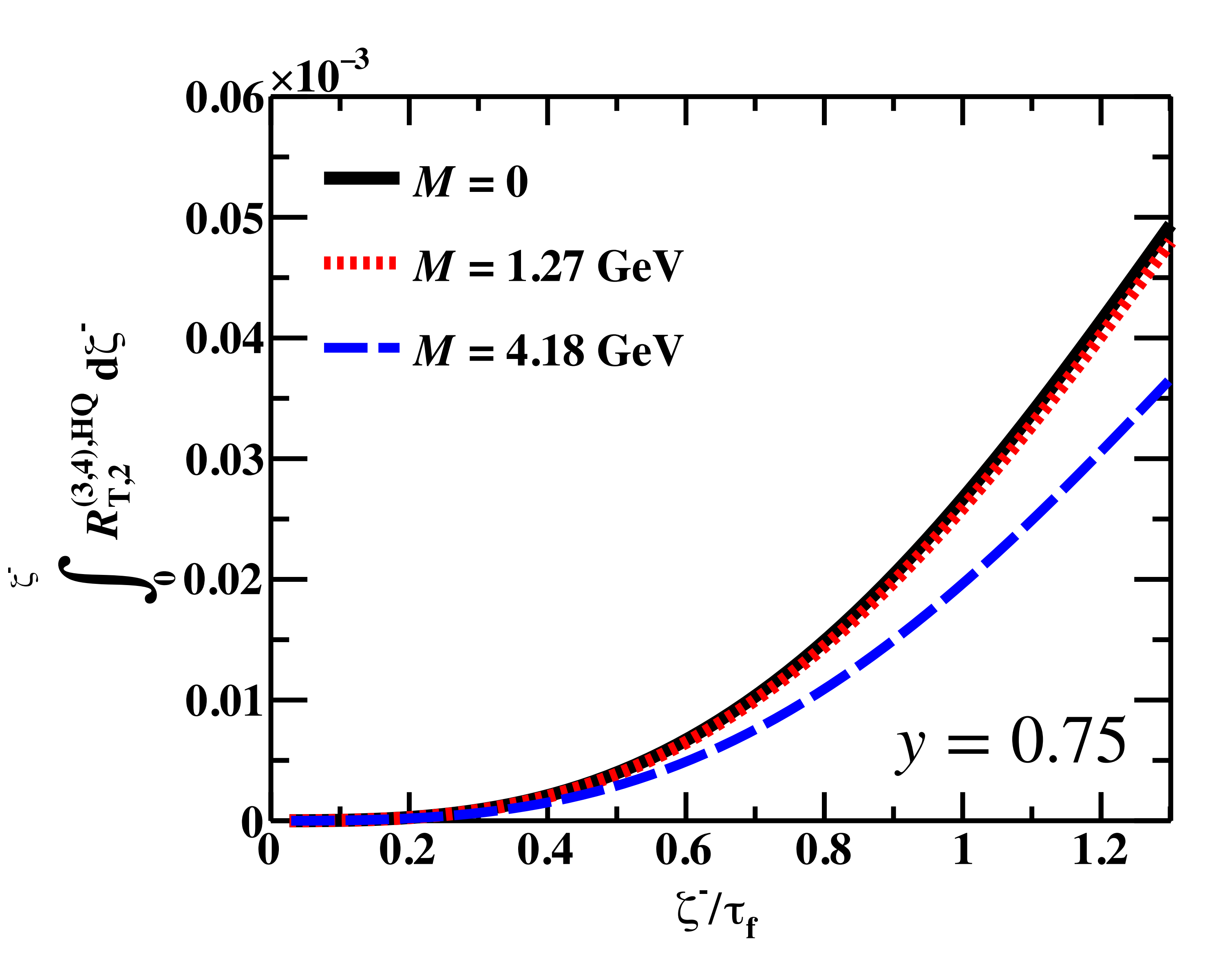
- ❑ First effort to derive Bremmstralung photon scattering kernel at high Q^2
  - ✦ Real photon and a quark final state
  - ✦ Real photon and a gluon final state
  - ✦ virtual photon contributions
- ❑ Interference/coherence effects
- ❑ Incorporated Fermion-to-Boson conversion processes
- ❑ Demonstrated Heavy-quark energy loss effects on scattering kernel
- ❑ Connections to Electron-Ion Collider (EIC) physics

Path length dependence of scattering kernel for heavy-quarks

❑ **Virtual photon emission scattering kernel for charm and bottom quark mass**







Kernel-3 and 4 **(Length integrated kernel)**

❑ **Bottom quark demonstrates large mass effects compared to charm quark**