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UNIVERSITY OF
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2025 CAP Congress | Congrès de l'ACP 2025
June 8-13 juin

Jet Broadening and Photon Production in Viscous Quark-Gluon Plasma



University
of Regina

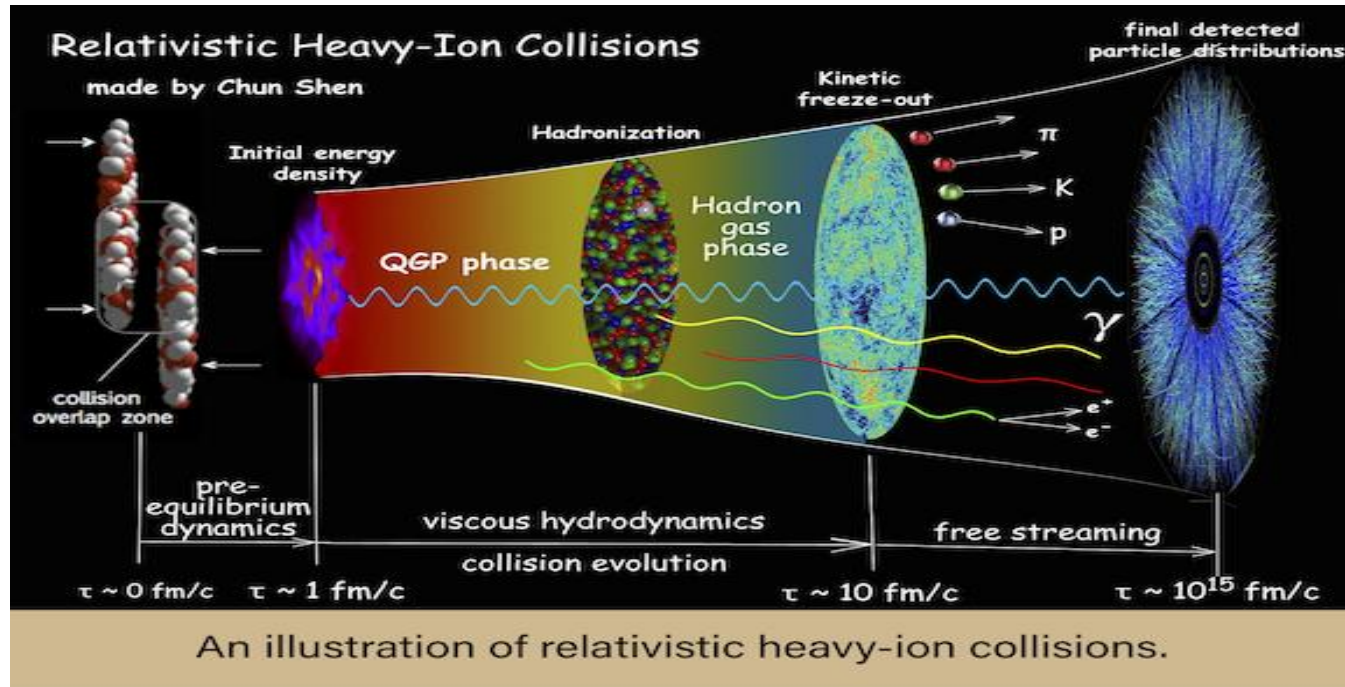
Hemanth Regi



10th June, 2025

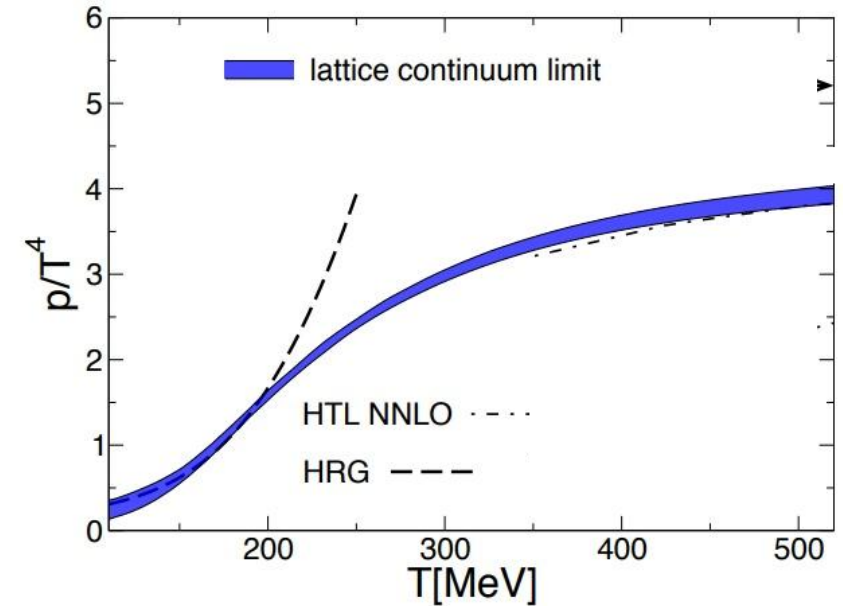
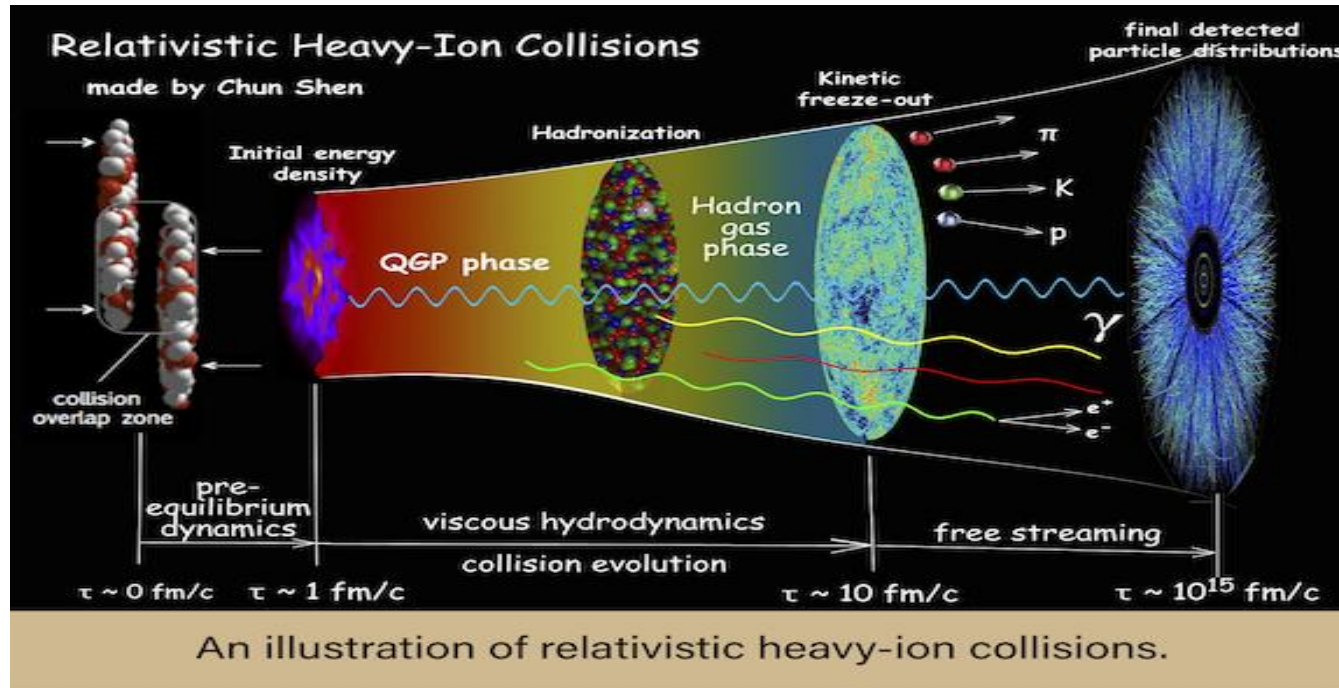
Supervisor: Dr. Gojko Vujanovic

Quark-Gluon Plasma



- The goal of heavy-ion collisions is to melt the nucleus to form a system where quarks and gluons are quasi-free particles, i.e. to create a QGP.
- During the pre-equilibrium stage, the quarks and gluons produced will have very different energy scales.
- Highest energy partons give jets, and most (lower energy) partons will form the QGP.

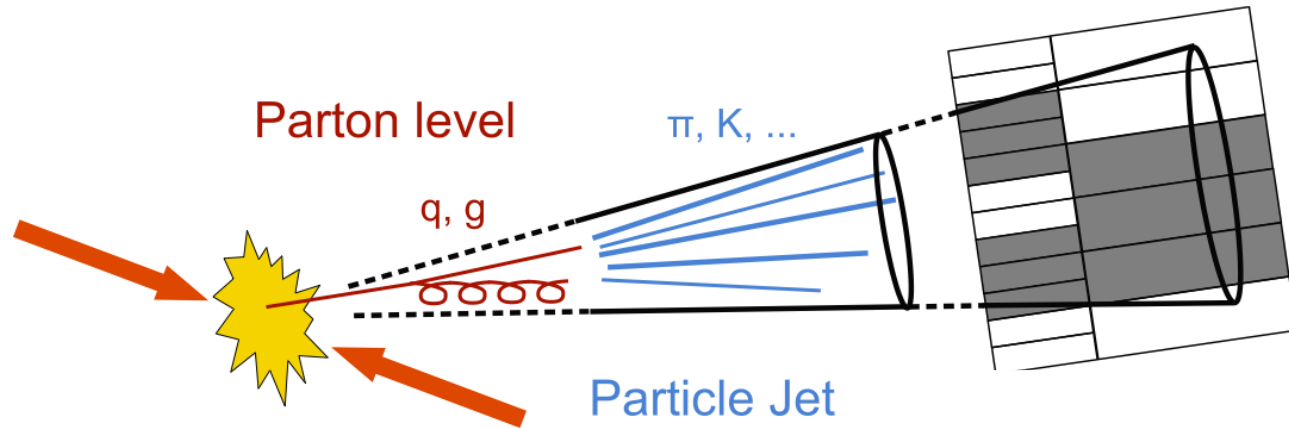
Quark-Gluon Plasma



Borsányi, Szabolcs, et al. *Physics Letters B* 730 (2014): 99-104.

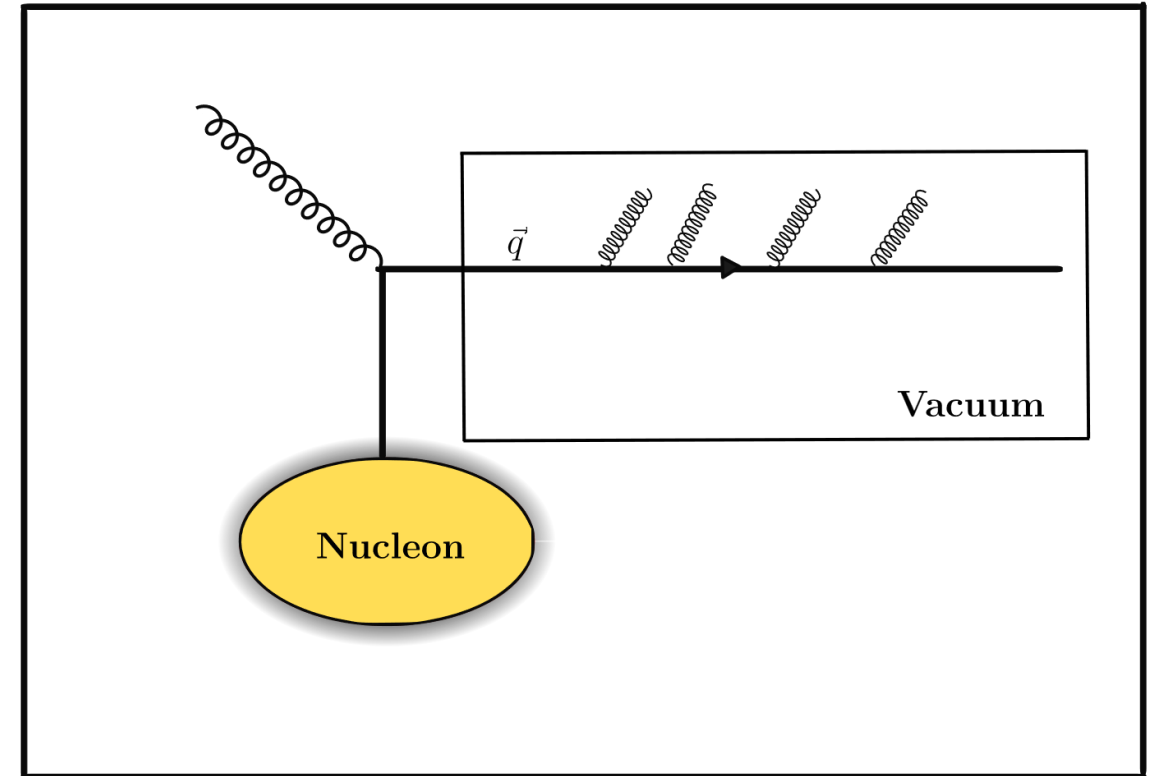
- Hydrodynamics describes QGP evolution, which requires an Equation of State from lattice QCD relating pressure to temperature.
- At temperatures below 200 MeV, the QCD EoS is well described by hadronic degrees of freedom (Perturbative EFT for hadrons).
- At $T > 350$, MeV behavior is similar to pQCD (Partonic degrees of freedom-quarks and gluons).
- The QCD EoS is well understood, showing a continuous (cross-over) transition from quark-gluon degrees of freedom at high temperatures to hadronic matter at lower temperatures.

Jets in Vacuum

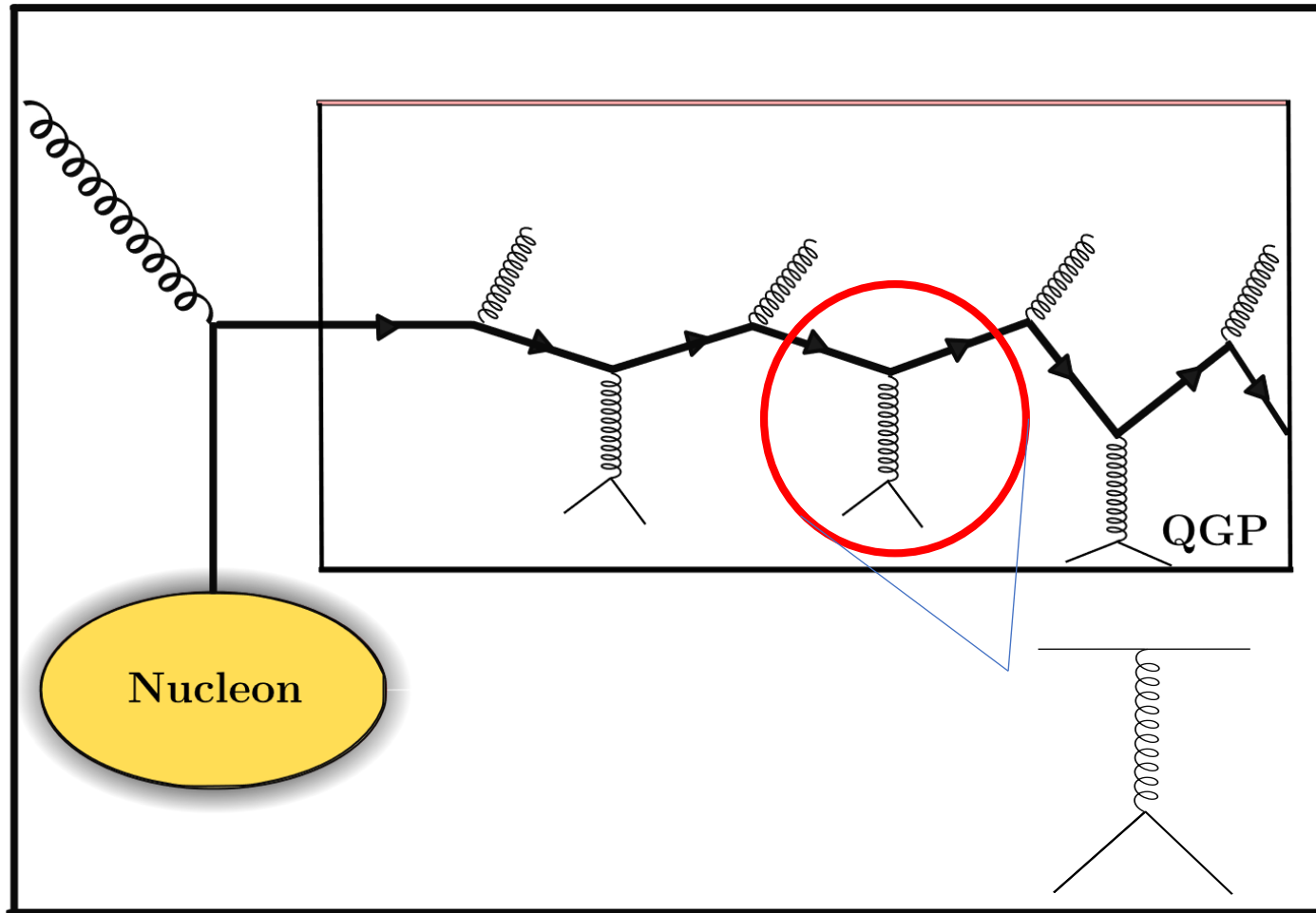


<https://cms.cern/news/jets-cms-and-determination-their-energy-scale>

- The evolution of a highly virtual quark in the vacuum is dominated by Bremsstrahlung radiation of gluons.
- Extensively studied in electron-positron collisions in vacuum. Thus jets are vacuum-calibrated probes.
- Heavy quarks are further unique jet probes as we can tag on them.

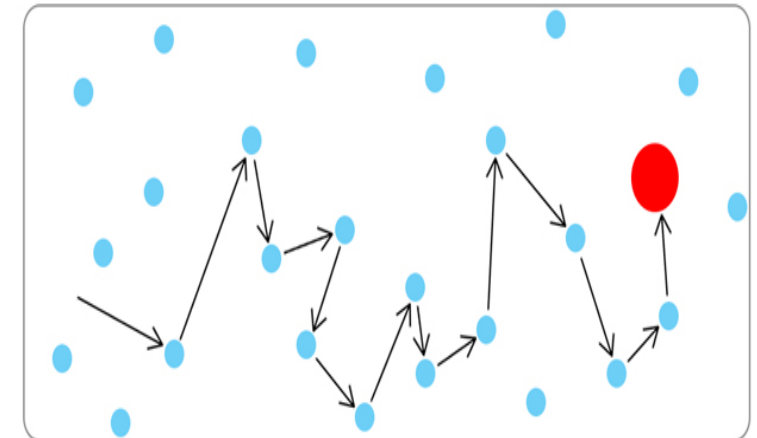


Jets in Medium



- Jet passing through QGP deviates from its path due to collisions with particles in the medium.
- These collisions would ultimately lead to **Brownian** motion of particles in the jet... however we have hadronization
- Collision can be described using the transport coefficient \hat{q} : the average squared transverse momentum broadening per unit length, in the medium.

Brownian Motion



● Fluid molecule ● Suspended particle

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GO FAR, Together.

Boltzmann Equation of Parton Transport

- The multiple scattering of jet partons in the QGP is described by the Boltzmann equation.
- Applicable for weakly interacting and dilute systems.
- In vacuum, the scattering rate can be obtained from the collision kernel as:

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{m} \cdot \nabla f = C[f]$$

$$N = \int d^4x \int \frac{d^3p_1}{(2\pi)^3 2E_1} \frac{d^3p_2}{(2\pi)^3 2E_2} \frac{d^3p_3}{(2\pi)^3 2E_3} \frac{d^3p_4}{(2\pi)^3 2E_4} |M|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)$$

Luminosity

Cross-section

- In the medium, this gets modified as

$$\frac{d^4N}{d^4x} = dR = \int \frac{d^3p_1}{(2\pi)^3 2E_1} f(p_1) \frac{d^3p_2}{(2\pi)^3 2E_2} f(p_2) \frac{d^3p_3}{(2\pi)^3 2E_3} [1 \pm f(p_3)] \frac{d^3p_4}{(2\pi)^3 2E_4} [1 \pm f(p_4)] |M|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)$$

where f is the Bose-Einstein/Fermi-Dirac distribution function of particles in thermal equilibrium.

- In reality, jets don't thermalize due to the (small) size of the QGP, its viscosity, as well as the rapid onset of hadronization. These effects inhibit the jet's momentum distribution from isotropizing.



Relativistic Hydrodynamics and Viscosity

- The link between the microscopic distribution function f and the macroscopic stress-energy tensor is given by:

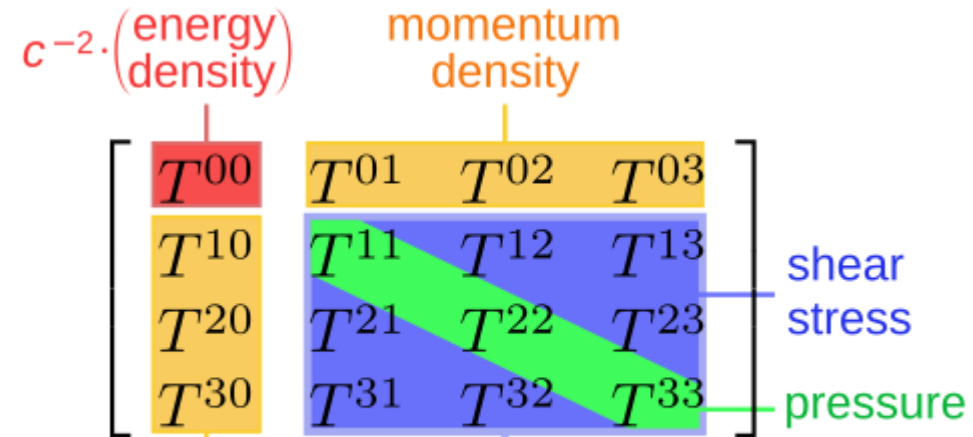
$$T_0^{\mu\nu} + \pi^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3 2E} p^\mu p^\nu f_0(p \cdot u) + \int \frac{d^3p}{(2\pi)^3 2E} p^\mu p^\nu \delta f(p \cdot u)$$

- The equilibrium (ideal) part of stress-energy tensor is given by f_0
 - For an ideal fluid, only diagonal terms remain in the stress-energy tensor.
- The viscous part of the stress-energy tensor is encoded in δf .
 - For non-ideal fluids, off-diagonal terms become important.
- These off-diagonal contributions are also present in the scattering rate, through the viscous correction to the distribution function:

$$\frac{d^4N}{d^4x} = dR(f_1, f_2, f_3, f_4) \rightarrow dR(f_1, f_2 + \delta f_2, f_3, f_4 + \delta f_4)$$

where,

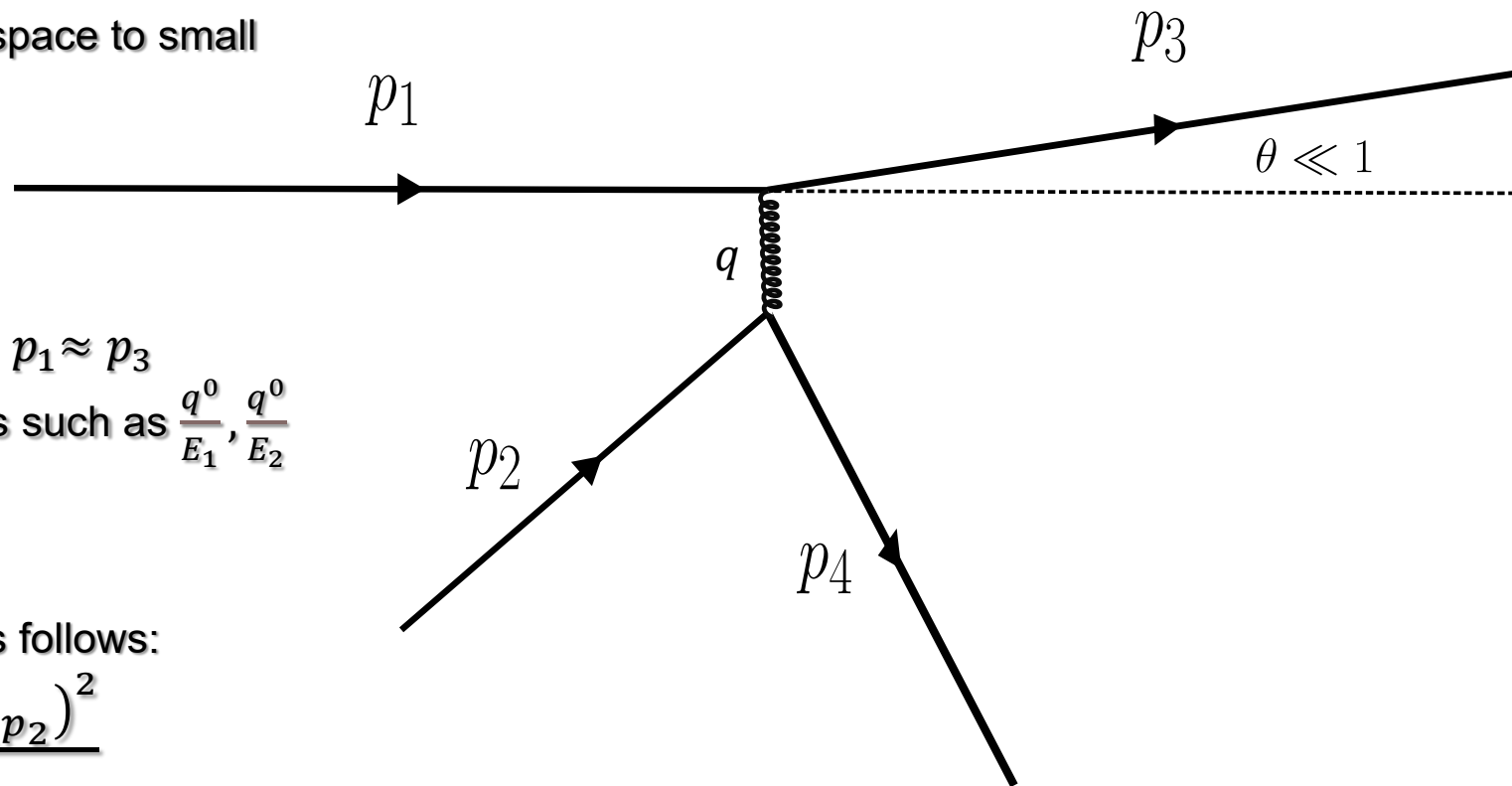
$$\delta f(p) = \frac{c}{2} f(p) (1 \pm f(p)) \frac{p^\alpha p^\beta}{T^2} \frac{\pi_{\alpha\beta}}{\epsilon + P}$$



[arXiv:0909.0754](https://arxiv.org/abs/0909.0754) [nucl-th]

Forward Scattering Approximation

- Computing the rate in general is challenging. We will use the FSA approximation.
- FSA restricts the scattering phase space to small angles only.



- According to FSA:

$$p_1 \gg p_2 \gg q \Rightarrow p_1 \approx p_3$$

- Consequently, we will neglect terms such as $\frac{q^0}{E_1}, \frac{q^0}{E_2}$ etc.

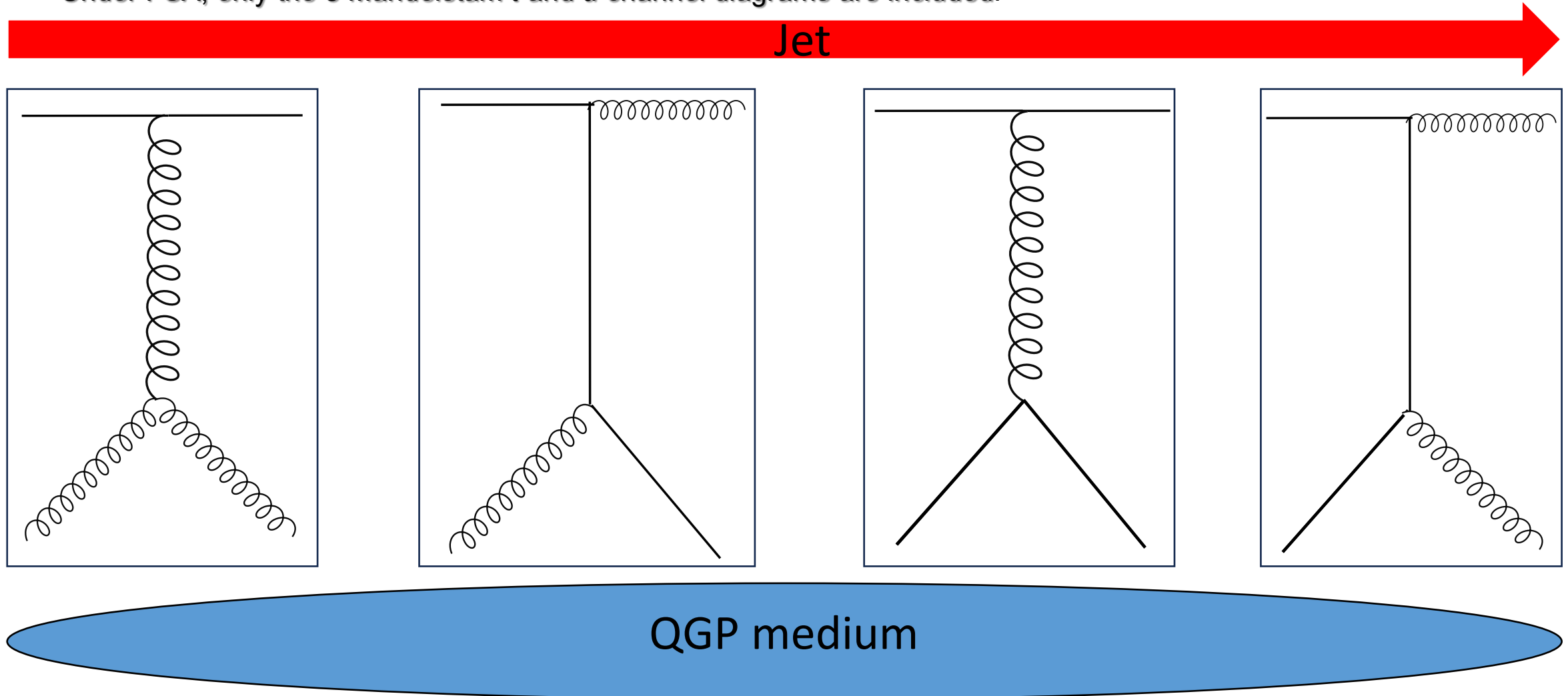
- FSA modifies the matrix element as follows:

$$\frac{s^2}{t^2} \approx \frac{(1 - \cos \theta_{p_1 p_2})^2}{q_{\perp}^4}$$

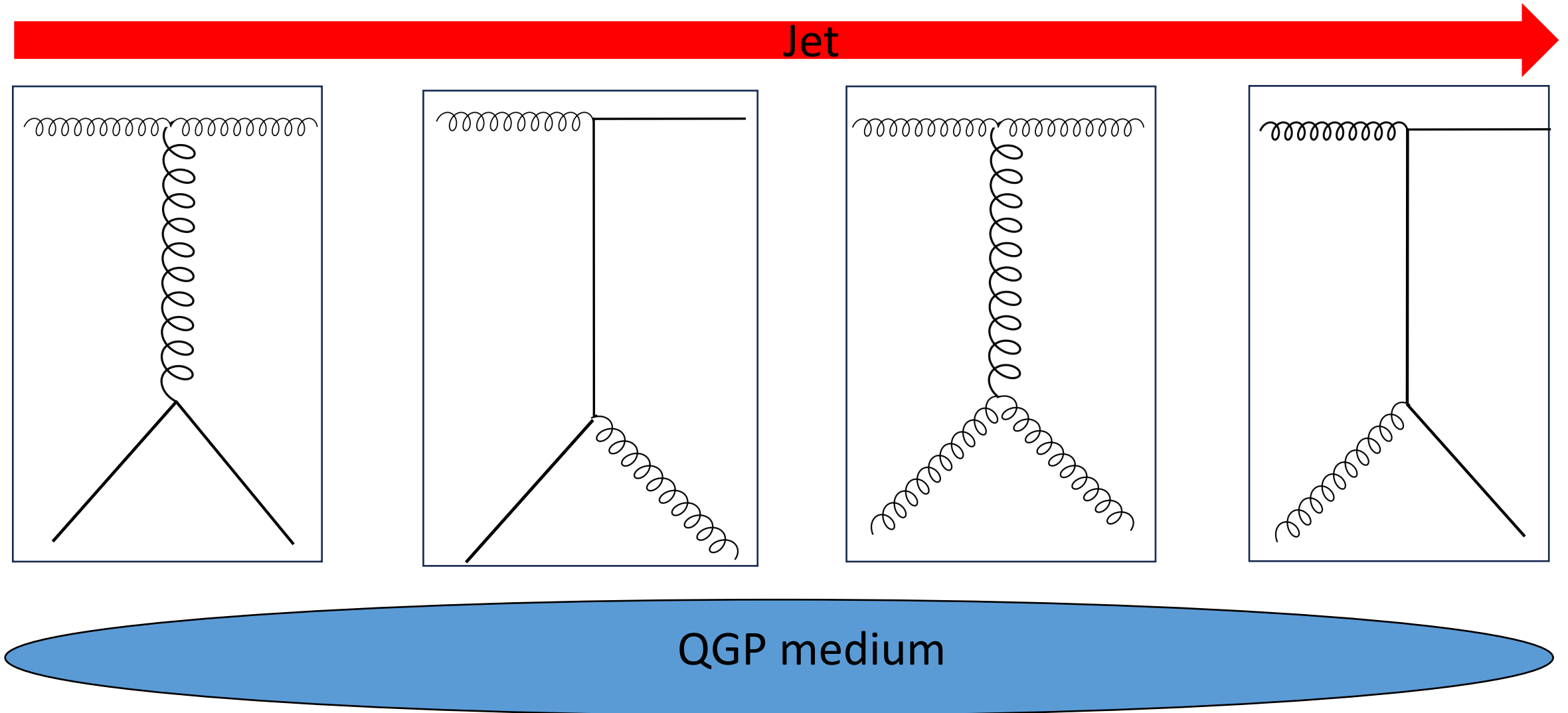
- Mass corrections – no explicit mass terms inside the matrix element.
- Heavy flavour mass corrections appear in the rate calculations through phase space integrals.

Scattering Channels for Jet-Medium Interactions

- Under FSA, only the 8 Mandelstam t and u channel diagrams are included.

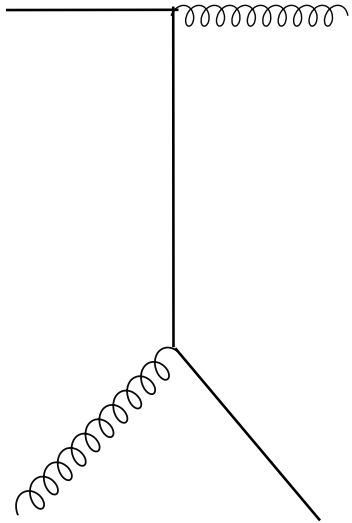


Scattering Channels for Jet-Medium Interactions

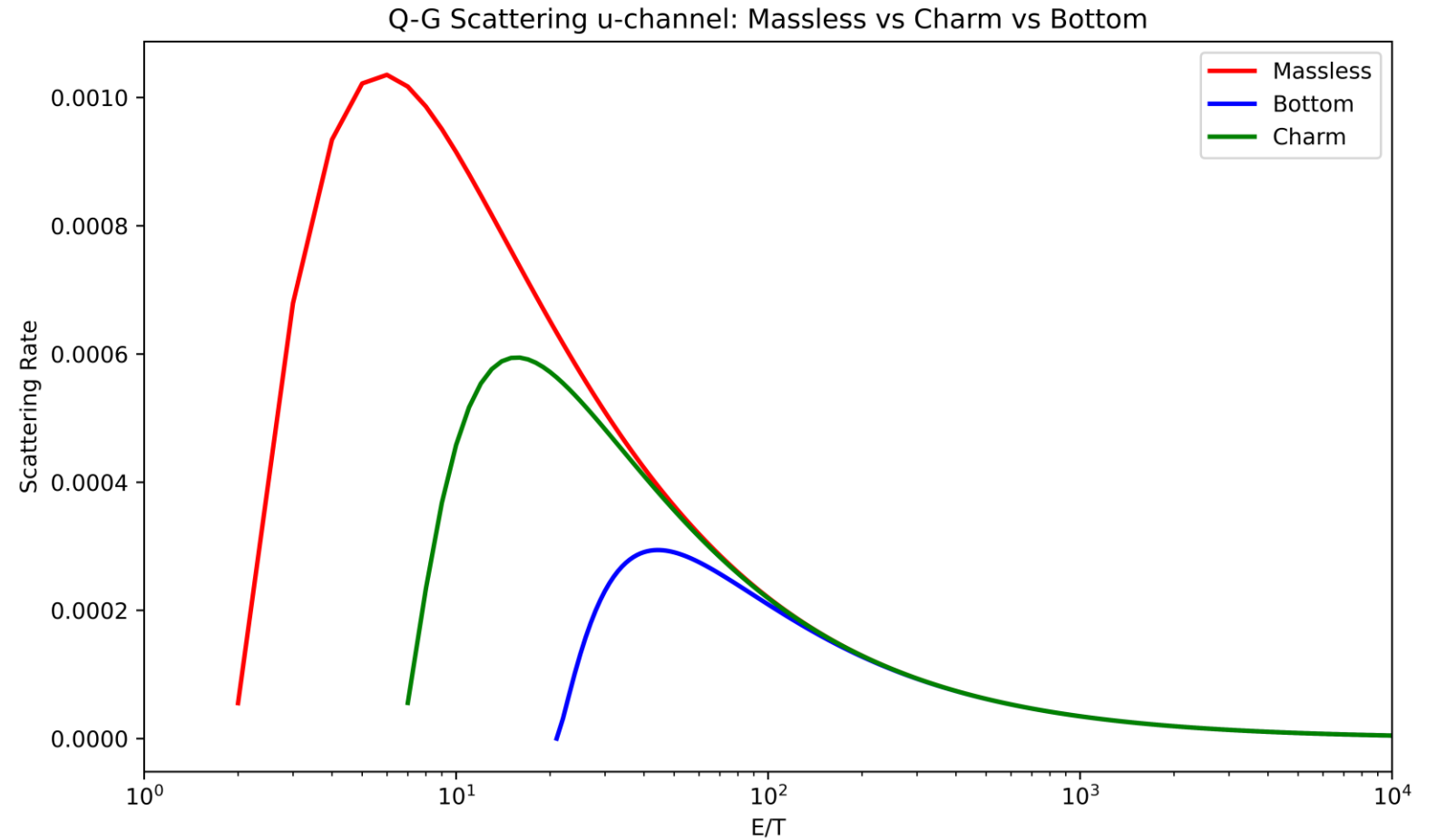


Results

Illustrative example: Quark-Gluon scattering in the u-channel

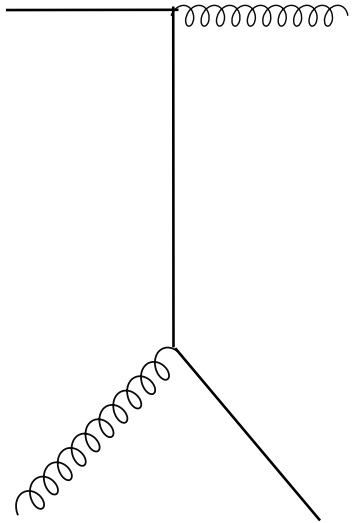


Mass effects introduce significant change in viscous rate.

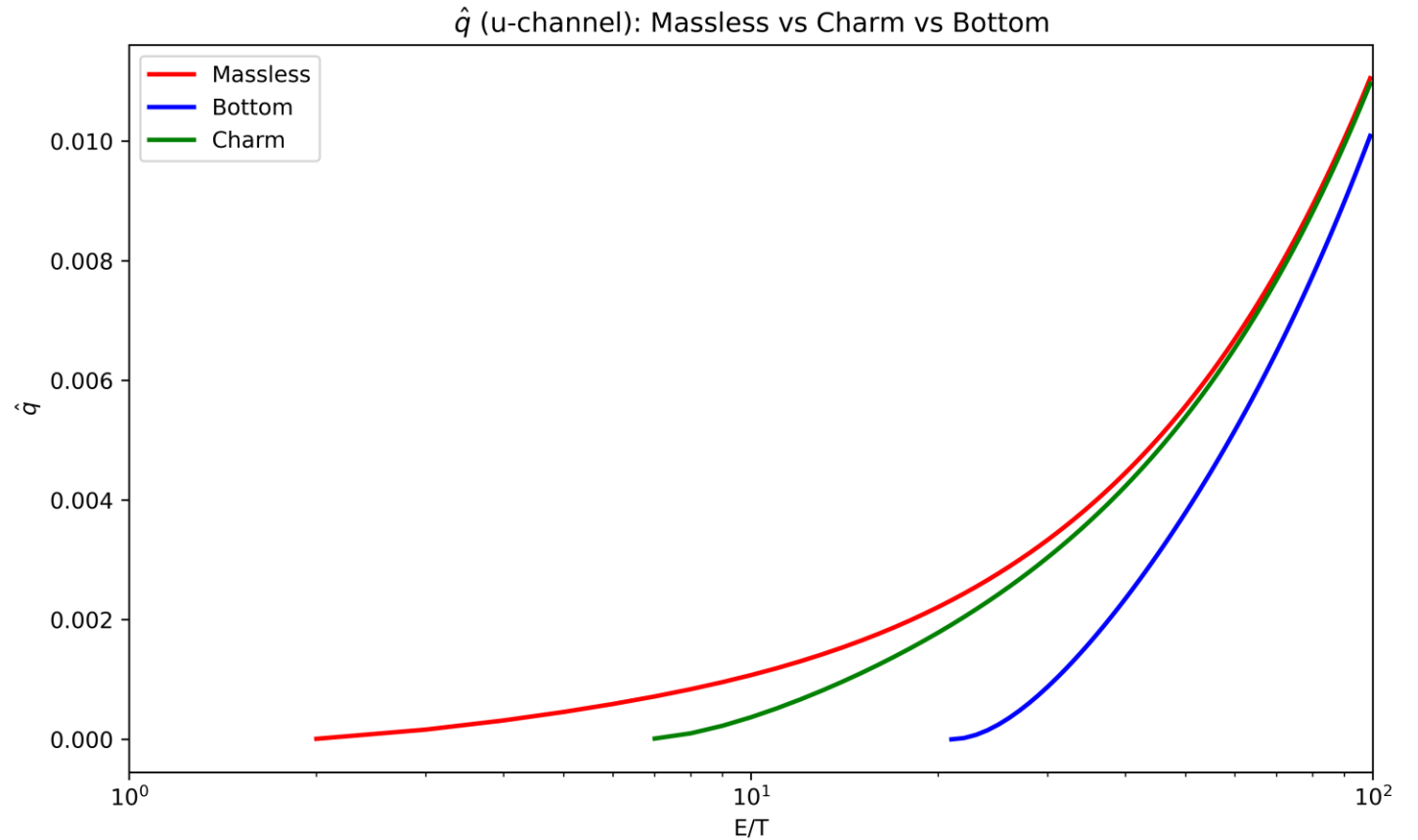


Results

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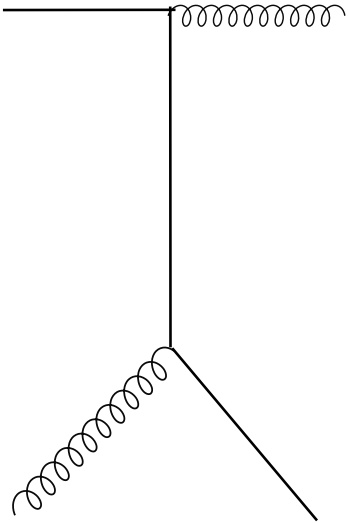


Inviscid transverse momentum broadening is also affected.

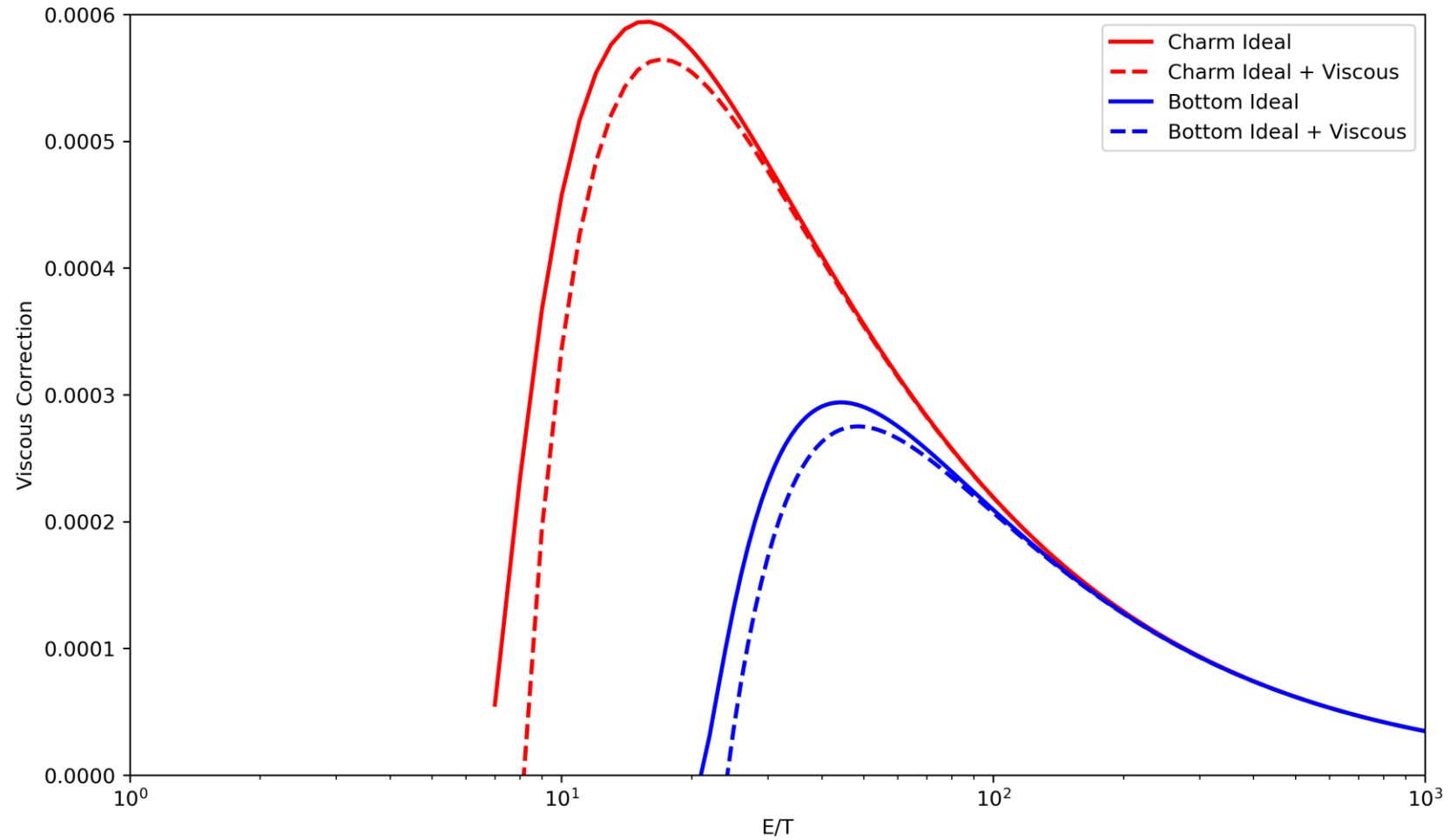


Results

Quark-Gluon scattering in u channel

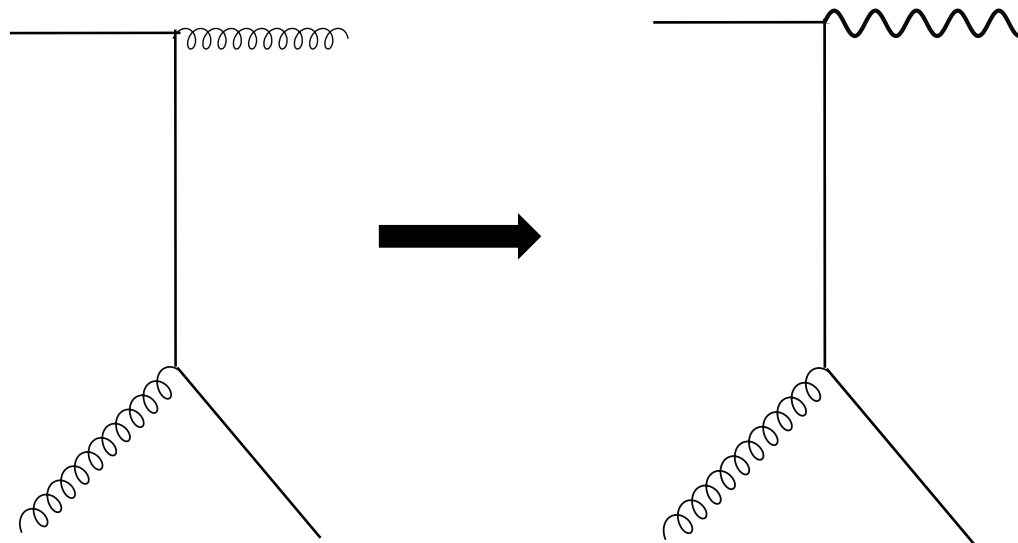


Viscous correction further suppresses the mass corrected ideal rate.



Summary and Outlook

- In the Forward Scattering Approximation (FSA), gluon and light-flavour quark scatterings receive **no viscous corrections**.
- Viscous effects arise only when heavy-flavor mass contributions are included within the FSA.
- **Outlook:**
- How good is the forward scattering approximation?
 - Compute the viscous rate without the forward scattering approximation.
- After evaluating the scattering rate, photon production offers a cleaner probe of QGP viscosity. Photons are not in thermal equilibrium with the medium, and escape it largely unmodified when produced.



Thank You

Questions?

Backup Slides

QGP Probes

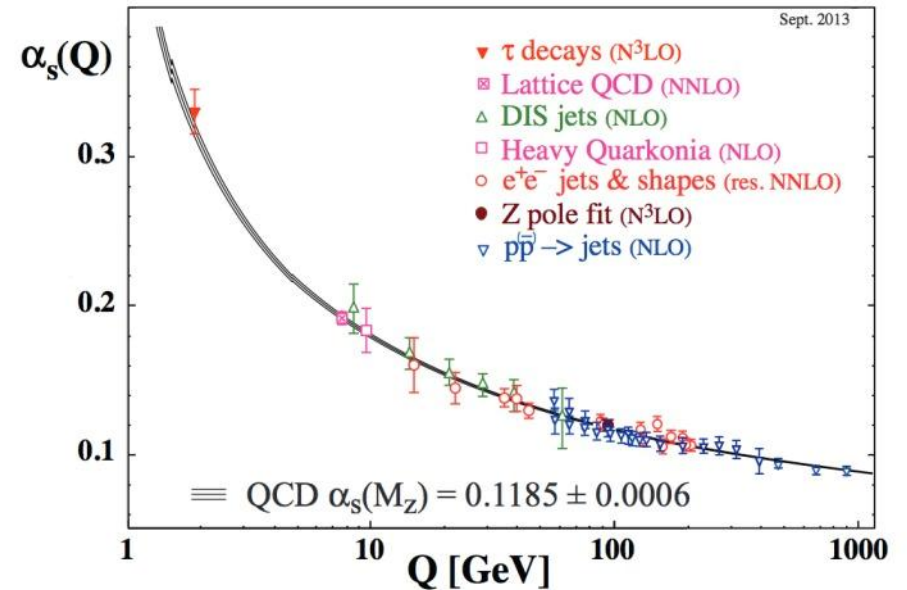
- A **probe** is any particle, process, or observable that interacts with or passes through a system (like the QGP) in a way that encodes measurable information about the system's internal properties.
- The two main probes of QGP are **Jets** and **Photons**:

| Jets | Photons |
|---|--|
| <ul style="list-style-type: none">• Highly collimated spray of hadrons formed from high-momentum quarks and gluons. | <ul style="list-style-type: none">• Electromagnetic probes produced from electromagnetic interactions in high-energy nuclear collisions. |
| <ul style="list-style-type: none">• Strongly interact with the medium and undergo multiple scatterings. | <ul style="list-style-type: none">• Minimal interactions with QGP and escapes almost unmodified. |
| <ul style="list-style-type: none">• Produced early in hard scatterings. | <ul style="list-style-type: none">• Production spans from early stage and continues throughout the evolution of QGP. |
| <ul style="list-style-type: none">• Provides insights about transport coefficients. | <ul style="list-style-type: none">• Provides information about the evolution of QGP. |

QCD Coupling and Asymptotic Freedom

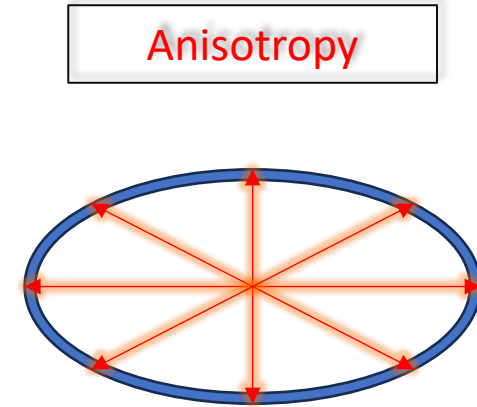
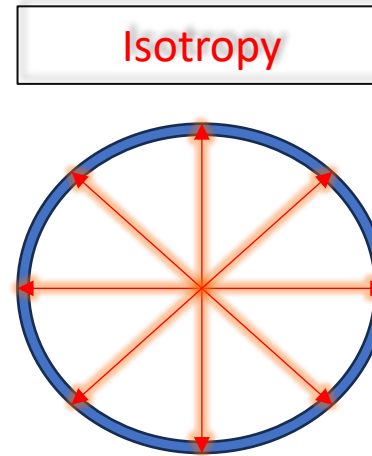
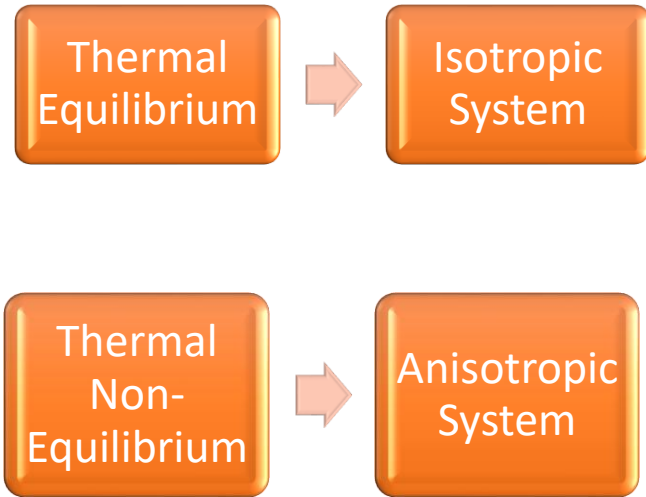
- Jet partons have much higher energy scales than the temperature of the QGP.
- At those energy scales, there is a significant running of the strong coupling.
- In fact, for $Q > \sim 10$ GeV, α_s is small enough for perturbation theory to work. This is because of the asymptotic freedom of QCD.
- Partons at these high energies, will see a very dilute QGP, given that α_s is so small.
- This allows the use of perturbation theory when describing how jet partons interact with QGP partons.
- Let's explore how jet partons evolve in the vacuum vs the QGP medium.

$$\alpha_s(Q^2) \sim \frac{1}{\ln Q^2/\Lambda_{QCD}^2}$$



Particle Data Group, K. Olive et al., Chin.Phys. C38, 090001 (2014).

Thermal Equilibrium and Isotropy



- System in thermal equilibrium is isotropic (spherically symmetric) in momentum space.
- The Boltzmann equation allows for the system to go away from thermal equilibrium.
- Going off-equilibrium manifests as the momentum distribution becoming anisotropic.
- An anisotropic momentum distribution of particles at the microscopic scale generates viscous effects in the (macroscopic) fluid.
- The goal of my work is to constrain the viscosity of the QGP by studying how jets are quenched in the QGP.