9th International Symposium on HF Production in Hadron and Nuclear Collisions

The Heavy Quark Dynamics in the Presence of Magnetic Field and Chirality

Insights into QGP Dynamics from Recent Studies

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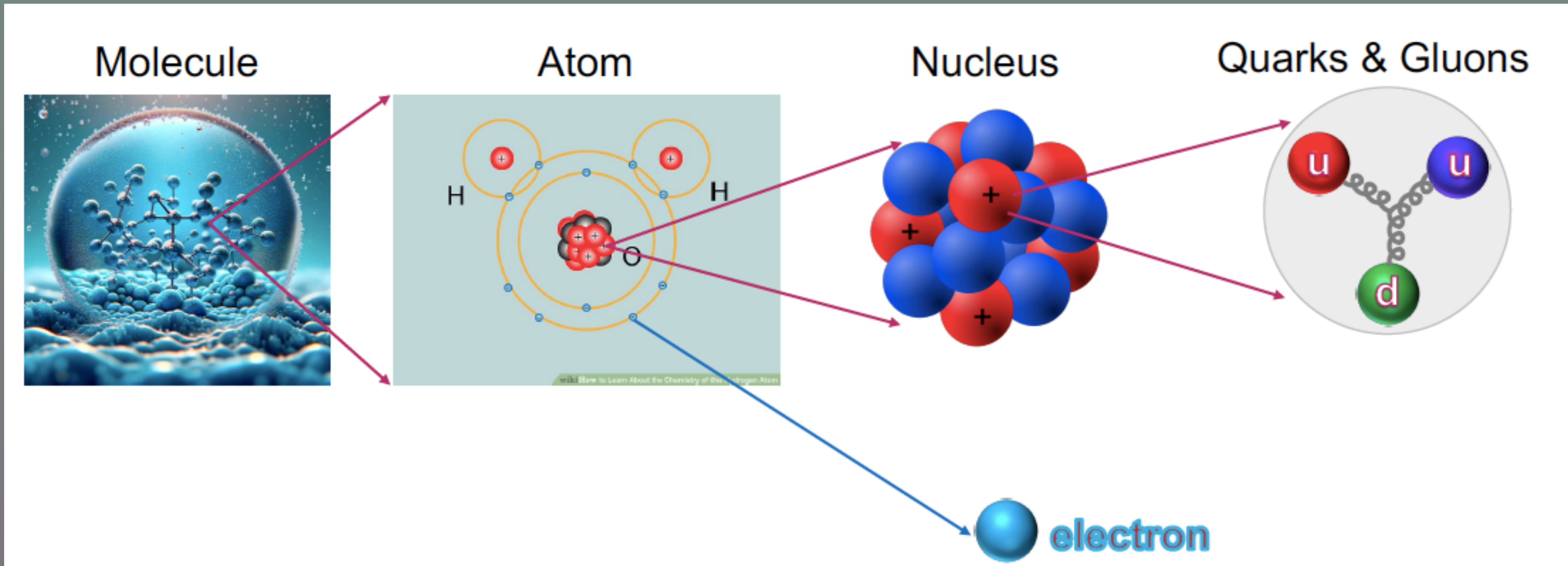
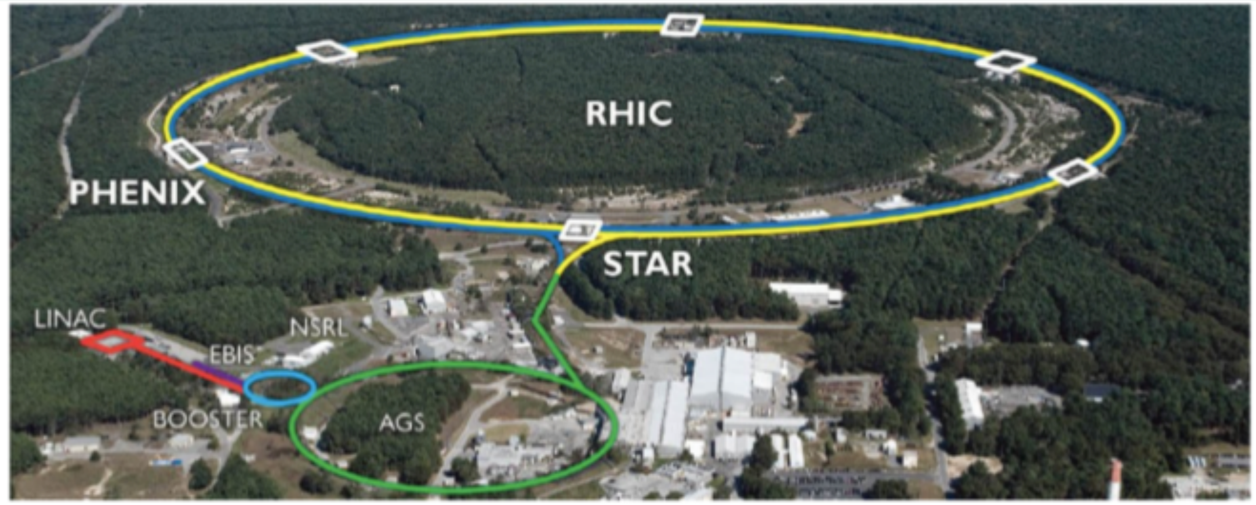
Evolution of Our Understanding of Matter



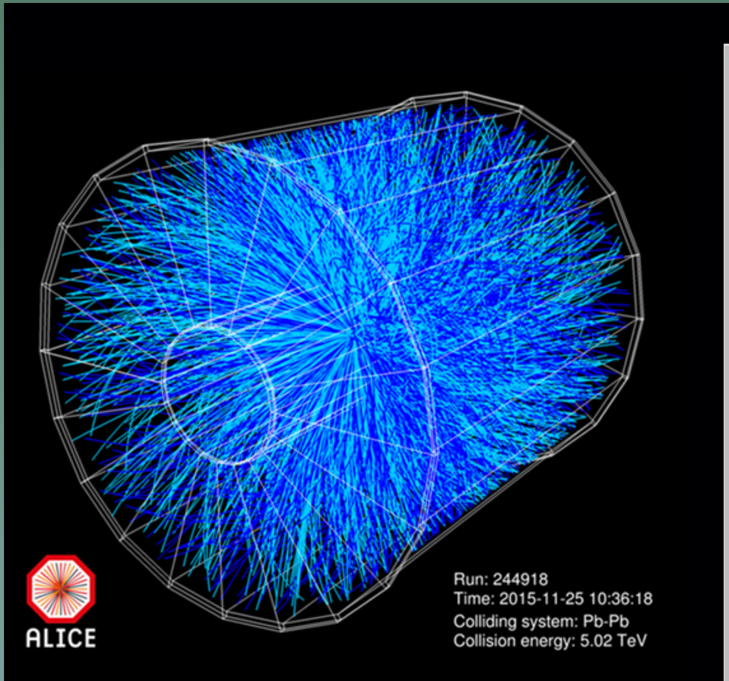
Heavy-ion Collision Experiments: RHIC and LHC



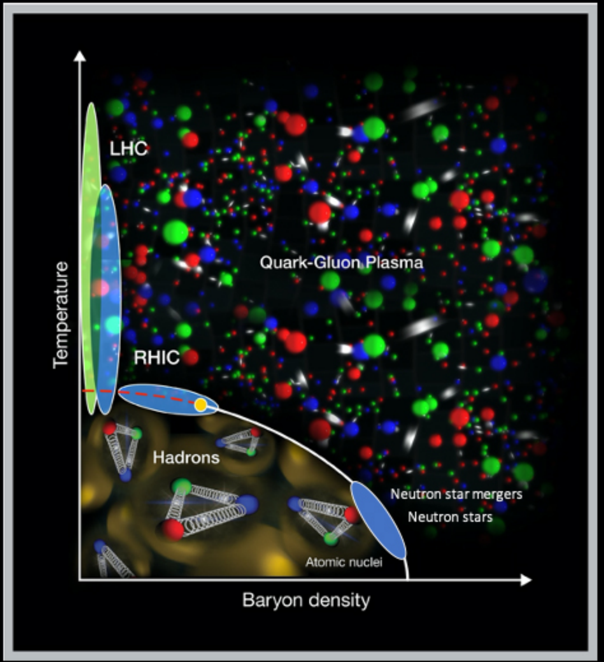
Relativistic Heavy Ion Collider (RHIC)
Brookhaven National Lab, Long Island, NY
2000-Present
Collision Energy ~ MeV

Large Hadron Collider (LHC)
CERN, Geneva, Switzerland/France
2010-Present
Collision Energy ~ TeV

Hot and Dense Matter: Heavy Ion Collision



Picture Credit: Brookhaven National Laboratory



QCD: theory of strong interaction where elementary degrees of freedom are quarks and gluons

Quark Confinement: at low energies

Asymptotic Freedom: at high energies: de-confined Nuclear matter: Quark Gluon Plasma

Gross, Wilczek PRL (1973)
H. D. Politzer PRL (1973)

The Problem

Small size ~ $5-10$ fm

Short Lifetime ~ 10^{-22} Sec

Temp: $\geq 2 * 10^{12}$ °C

How to explore?

Theoretical Study:

Phenomenological study:

We know QGP is:

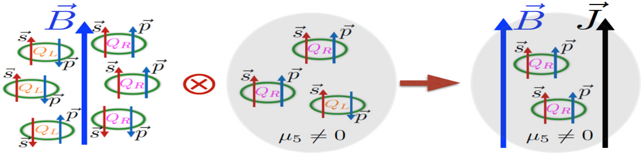
Hottest,
Most Dense,
Most Vortical and
Most Perfect Fluid
Ever created in the lab.

Chiral Asymmetry and Magnetic Fields

Chiral Magnetic Effect

The interplay between Chirality, Magnetic Fields, and the Chiral Anomaly gives rise to this fascinating phenomenon.

- Chiral asymmetry arises due to imbalances between left- and right-handed fermions, described by the chiral chemical potential μ_5.
- The CME leads to an electric current parallel to the magnetic field, arising from the chiral imbalance.



arXiv:1511.04050

Experiment

A chiral QGP may be created locally in HICs through a variety of mechanisms (e.g. topological fluctuations in the gluonic sector, glasma flux tubes, etc) and observed experimentally in the analysis of γ correlator. M. Anderson, *et al.* NIMA **499**, 659-678 (2003)

Research Goal and Framework

Goal

- To observe the effect of Chirality and Magnetic field on the propagation of a fast-moving parton.
- We target the energy loss of a fast-moving parton in the QGP medium having the influence of Chirality and Magnetic field.

Framework

- Soft Contribution
- Static Medium
- Strong Magnetic Field

Research Methodology: Wong Equations and Energy Loss

Wong equations

They describe the motion of a color-charged particle in a non-Abelian gauge field:

$$\frac{dX^\mu}{d\tau} = V^\mu, \tag{1}$$

$$\frac{dP^\mu}{d\tau} = g_s q^a F_a^{\mu\nu} V_\nu, \tag{2}$$

$$\frac{dq^a}{d\tau} = -g_s f^{abc} V^\mu A_\mu^b q^c, \tag{3}$$

$X^\mu/V^\mu/P^\mu$ is the position/velocity/momentum of the parton,
$F_a^{\mu\nu}$ is the gluon field strength tensor,
q^a is the parton's color charge.

Energy Loss

The equations modify to give the energy loss of parton/heavy quark:

$$\left\langle \frac{dE}{dx} \right\rangle = i \frac{1}{|\mathbf{v}|} g_s^2 C_F v^i v^j \int \frac{d^3\mathbf{k}}{(2\pi)^3} \omega \Delta^{ij} \tag{4}$$

C_F is the Casimir invariant of $\mathrm{SU}(N_c)$ and $\omega = \mathbf{k}\cdot\mathbf{v}$.

Research Methodology: Gluon Propagator

- To obtain the propagator, we begin with the linearized Yang-Mills equation:

$$-ik_\nu F_a^{\nu\mu}(K) = j^\mu_{a,ind}(K) + j^\mu_{a,ext}(K), \tag{5}$$

where $K^\mu = (\omega, \mathbf{k}) \equiv K$ and the induced current $j^\mu_{a,ind}(K)$ is given by:

$$j^\mu_{a,ind}(K) = \Pi^{\mu\nu}(K) A_{a,\nu}(K), \tag{6}$$

One can rewrite the Yang-Mills equation:

$$\left[K^2 g^{\mu\nu} - k^\mu k^\nu + \Pi^{\mu\nu}(K)\right] A_{a,\nu}(K) = -j^\mu_{a,ext}(K). \tag{7}$$

- The gluon propagator can be obtained as:

$$\Delta^{ij} = [(|\mathbf{k}|^2 - \omega^2)\delta^{ij} - k^i k^j + \Pi^{ij}(K)]^{-1} \tag{8}$$

with the external current

$$j^j_{a,ext}(K) = \frac{ig_s q^a v^j}{\omega - \mathbf{k}\cdot\mathbf{v} + i\epsilon}, \tag{9}$$

Energy Loss in Chiral Asymmetric Medium

The self-energy

$$\Pi^{ij}(K) = \Pi^{ij}_{+}(K) + \Pi^{ij}_{-}(K) \tag{10}$$

- $\Pi^{ij}_{+}(K)$/ $\Pi^{ij}_{-}(K)$ are parity even / odd parts of self-energy obtained as:

$$\Pi^{ij}_{+}(K) = \frac{m_D^2\omega}{4\pi}\int d\mathbf{u}\,\frac{u^i u^j}{U\cdot K + i\epsilon}, \tag{11}$$

$$\Pi^{ij}_{-}(K) = \frac{\mu_5 g_s^2}{4\pi^2} i\epsilon^{ijk}k^k\left(1-\frac{\omega^2}{|\mathbf{k}|^2}\right)\left[1-\frac{\omega}{2|\mathbf{k}|}\ln\left(\frac{\omega+|\mathbf{k}|}{\omega-|\mathbf{k}|}\right)\right]. \tag{12}$$

$U^\mu = (1, \mathbf{u})$ with $\mathbf{u} = \frac{\mathbf{k}}{|\mathbf{k}|}$

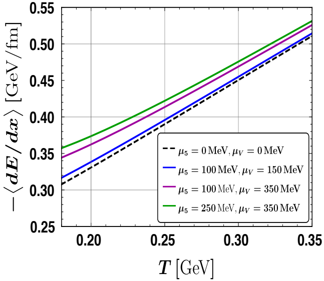
The Debye mass in the chiral medium

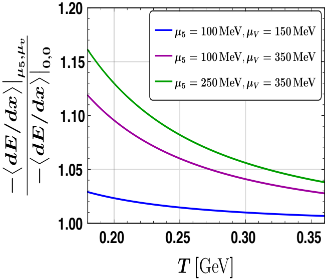
$$m_D^2 = (N_f + 2N_c)\frac{g_s^2 T^2}{6} + N_f\,\frac{g_s^2}{2\pi^2}(\mu_R^2 + \mu_L^2). \tag{13}$$

Energy Loss in Chiral Asymmetric Medium: Results

Observations

- At a fixed temperature, the energy loss increases with the chirality.
- At a fixed chiral chemical potential, the loss increases with the temperature.
- Chiral effect on energy loss suppressing at a higher temperature.





R. Ghosh, M. Y. Jamal and M Kurian, PRD 108, 054035 (2023)

Energy Loss in Magnetized Medium

The self-energy

$$\Pi^{ij} = a\,N^{ij} + b\,B^{ij} + c\,R^{ij} + d\,Q^{ij}, \tag{14}$$

The projection operators can be defined as,

$$N^{ij} = -\frac{\hat{k}^i \tilde{n}^j + \hat{k}^j \tilde{n}^i}{\sqrt{\tilde{n}^2}}, \tag{15}$$

$$B^{ij} = \frac{k^i k^j}{|\mathbf{k}|^2}, \tag{16}$$

$$R^{ij} = -\delta^{ij} + \frac{k^i k^j}{|\mathbf{k}|^2} - \frac{\tilde{n}^i \tilde{n}^j}{\tilde{n}^2}, \tag{17}$$

$$Q^{ij} = \frac{\tilde{n}^i \tilde{n}^j}{\tilde{n}^2}. \tag{18}$$

a, b, c, and d are Lorentz-invariant form factors

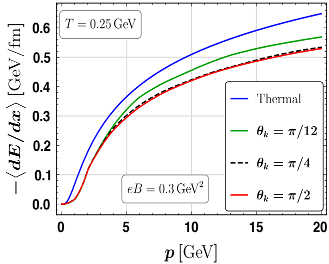
$$a = \frac{1}{2} N^{ij}\Pi^{ij}, \qquad b = B^{ij}\Pi^{ij}, \tag{19}$$

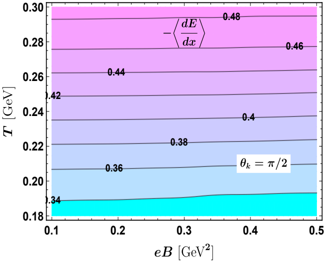
$$c = R^{ij}\Pi^{ij}, \qquad d = Q^{ij}\Pi^{ij}. \tag{20}$$

Energy Loss in Magnetized Medium: Results

Observations

- The energy loss depends on the angular direction (θ_k) between the motion of the parton and the direction of the field.
- The energy loss is suppressed in the presence of the magnetic field as compared to the isotropic case.
- At a fixed temperature, the loss increases with the magnetic field.
- At a fixed magnetic field strength, the loss increases with temperature.





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Summary and Future Directions

Take Away Points

- The propagation of a parton is significantly influenced by the presence of Chirality in the QGP medium.
- The Magnetic field strength further affects its propagation.
- The orientation of the parton's motion relative to the magnetic field also plays an important role.

Future Directions

- The current study can be extended with the generalized magnetic field.
- One further needs to consider the expanding medium.
- To incorporate the current analysis with the hard collisions.
- To obtain the experimental observables R_{AA} and v_2.

Thank You for Your Attention!

Any questions or further discussion are welcome.

Details about the Chiral Medium

$$\Pi_{+}^{ij}(K) = \frac{m_D^2 \omega}{4\pi} \int d\mathbf{u} \frac{u^i u^j}{U \cdot K + i\epsilon}, \tag{21}$$

$$\Pi_{-}^{ij}(K) = \frac{\mu_5 g_s^2}{4\pi^2} i\epsilon^{ijk} k^k \left(1 - \frac{\omega^2}{|\mathbf{k}|^2}\right) \left[1 - \frac{\omega}{2|\mathbf{k}|} \ln\left(\frac{\omega + |\mathbf{k}|}{\omega - |\mathbf{k}|}\right)\right]. \tag{22}$$

where $U^\mu = (1, \mathbf{u})$ with $\mathbf{u} = \frac{\mathbf{k}}{|\mathbf{k}|}$
The Debye mass in the chiral medium takes the form as

$$m_D^2 = (N_f + 2N_c) \frac{g_s^2 T^2}{6} + N_f \frac{g_s^2}{2\pi^2} (\mu_R^2 + \mu_L^2). \tag{23}$$

At finite μ_5, the gluon propagator can be written as,

$$\Delta^{ij} = \frac{C_T}{C_T^2 - C_A^2} A^{ij} + \frac{1}{C_L} B^{ij} - \frac{C_A}{C_T^2 - C_A^2} C^{ij}, \tag{24}$$

Details about the Chiral Medium

Transfer Projection: $A^{\mathrm{ij}} = \delta^{\mathrm{ij}} - \frac{k^i k^j}{|\mathbf{k}|^2}$
Longitudinal Projection: $B^{\mathrm{ij}} = \frac{k^i k^j}{|\mathbf{k}|^2}$
Anti-symmetric part: $C^{ij} = i\epsilon^{ijk}\frac{k^k}{|\mathbf{k}|}$.

$C_T = -\omega^2 + |\mathbf{k}|^2 + \Pi_T$, $C_L = -\omega^2 + \Pi_L$ and

$$C_A \equiv \Pi_A = \mu_5 \frac{g_s^2|\mathbf{k}|}{4\pi^2}\left(1 - \frac{\omega^2}{|\mathbf{k}|^2}\right)\left[1 - \frac{\omega}{2|\mathbf{k}|}\ln\left(\frac{\omega + |\mathbf{k}|}{\omega - |\mathbf{k}|}\right)\right]. \tag{25}$$

where Π_L and Π_T are the longitudinal and transverse form factors, respectively, given as,

$$\Pi_T(K) = m_D^2 \frac{\omega^2}{2|\mathbf{k}|^2}\left[1 - \frac{K^2}{2\omega|\mathbf{k}|}\ln\left(\frac{\omega + |\mathbf{k}|}{\omega - |\mathbf{k}|}\right)\right], \tag{26}$$

$$\Pi_L(K) = -m_D^2 \frac{\omega^2}{k^2}\left[1 - \frac{\omega}{2k}\ln\left(\frac{\omega + k}{\omega - k}\right)\right], \tag{27}$$

Main Slide

Details about the Magnetized Medium

$$\Pi^{ij} = a\, N^{ij} + b\, B^{ij} + c\, R^{ij} + d\, Q^{ij}, \tag{28}$$

where the projection operators can be defined as follows,

$$N^{ij} = -\frac{\hat{k}^i \tilde{n}^j + \hat{k}^j \tilde{n}^i}{\sqrt{\tilde{n}^2}}, \tag{29}$$

$$B^{ij} = \frac{k^i k^j}{|\mathbf{k}|^2}, \tag{30}$$

$$R^{ij} = -\delta^{ij} + \frac{k^i k^j}{|\mathbf{k}|^2} - \frac{\tilde{n}^i \tilde{n}^j}{\tilde{n}^2}, \tag{31}$$

$$Q^{ij} = \frac{\tilde{n}^i \tilde{n}^j}{\tilde{n}^2}. \tag{32}$$

Here, a, b, c, and d are Lorentz-invariant form factors and can be obtained from the following relations,

$$a = \frac{1}{2} N^{ij} \Pi^{ij}, \qquad b = B^{ij} \Pi^{ij}, \tag{33}$$

$$c = R^{ij} \Pi^{ij}, \qquad d = Q^{ij} \Pi^{ij}. \tag{34}$$

Details about the Magnetized Medium

$$a = \sum_f \frac{g_s^2 q_f B}{4\pi^2} e^{-k_\perp^2/2q_f B} \; \frac{\omega\, k_z}{\omega^2 - k_z^2} \sqrt{\frac{k_\perp^2\, K^4}{\omega^2\, |\mathbf{k}|^4}}, \tag{35}$$

$$b = \frac{N_c\, g_s^2 T^2}{3} \left(\frac{K^4}{\omega^2\, |\mathbf{k}|^2} \right) [1 - \mathcal{T}_K(\omega, |\mathbf{k}|)] - \sum_f \frac{g_s^2 q_f B}{4\pi^2} \left(\frac{K^4}{\omega^2\, |\mathbf{k}|^2} \right) e^{-k_\perp^2/2q_f B} \; \frac{k_z^2}{\omega^2 - k_z^2}, \tag{36}$$

$$c = \frac{N_c\, g_s^2 T^2}{3} \frac{1}{2} \left[\frac{\omega^2}{|\mathbf{k}|^2} - \frac{K^2}{|\mathbf{k}|^2} \mathcal{T}_K(\omega, |\mathbf{k}|) \right], \tag{37}$$

$$d = \frac{N_c\, g_s^2 T^2}{3} \frac{1}{2} \left[\frac{\omega^2}{|\mathbf{k}|^2} - \frac{K^2}{|\mathbf{k}|^2} \mathcal{T}_K(\omega, |\mathbf{k}|) \right] + \sum_f \frac{g_s^2 q_f B}{4\pi^2} \left(\frac{K^4}{\omega^2\, |\mathbf{k}|^2} \right) e^{-k_\perp^2/2q_f B} \; \frac{k_z^2}{\omega^2 - k_z^2}, \tag{38}$$

Main Slide