Particle productions from chiral matter

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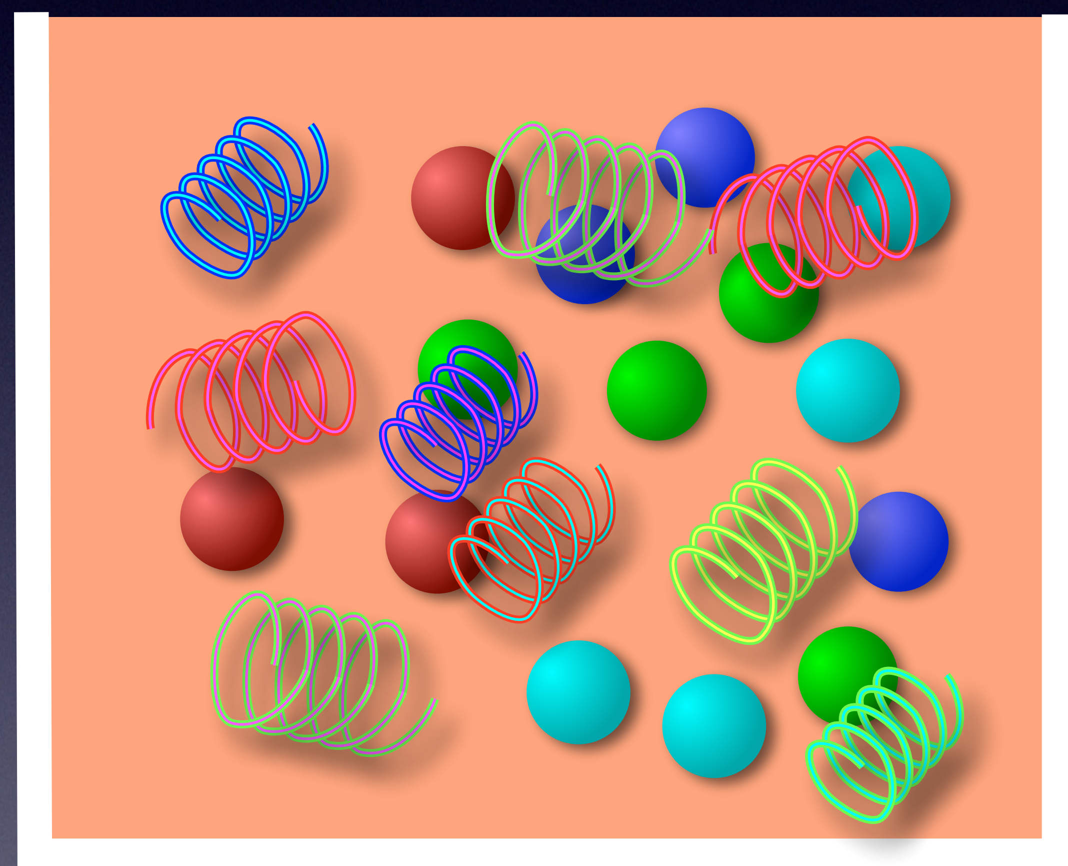
Quark gluon plasma as chiral matter



Temperature

200 MeV

$\sim 2 \times 10^{13}$ K

Quarks are almost massless Dirac fermion

$m_q/T \sim 0.03$

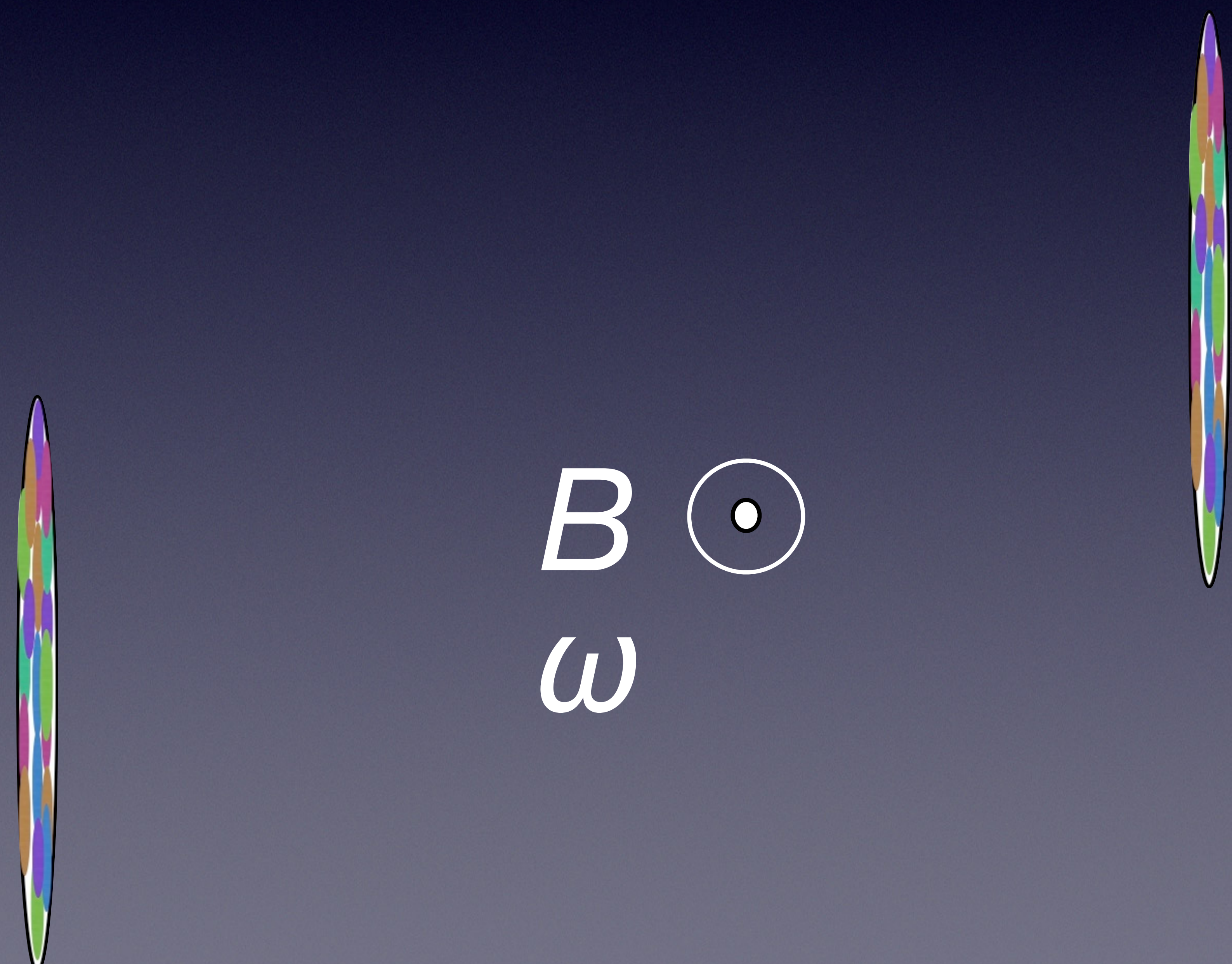
Two topics

Electric conductivity in a magnetic field

Dilution production in a magnetic field and vorticity

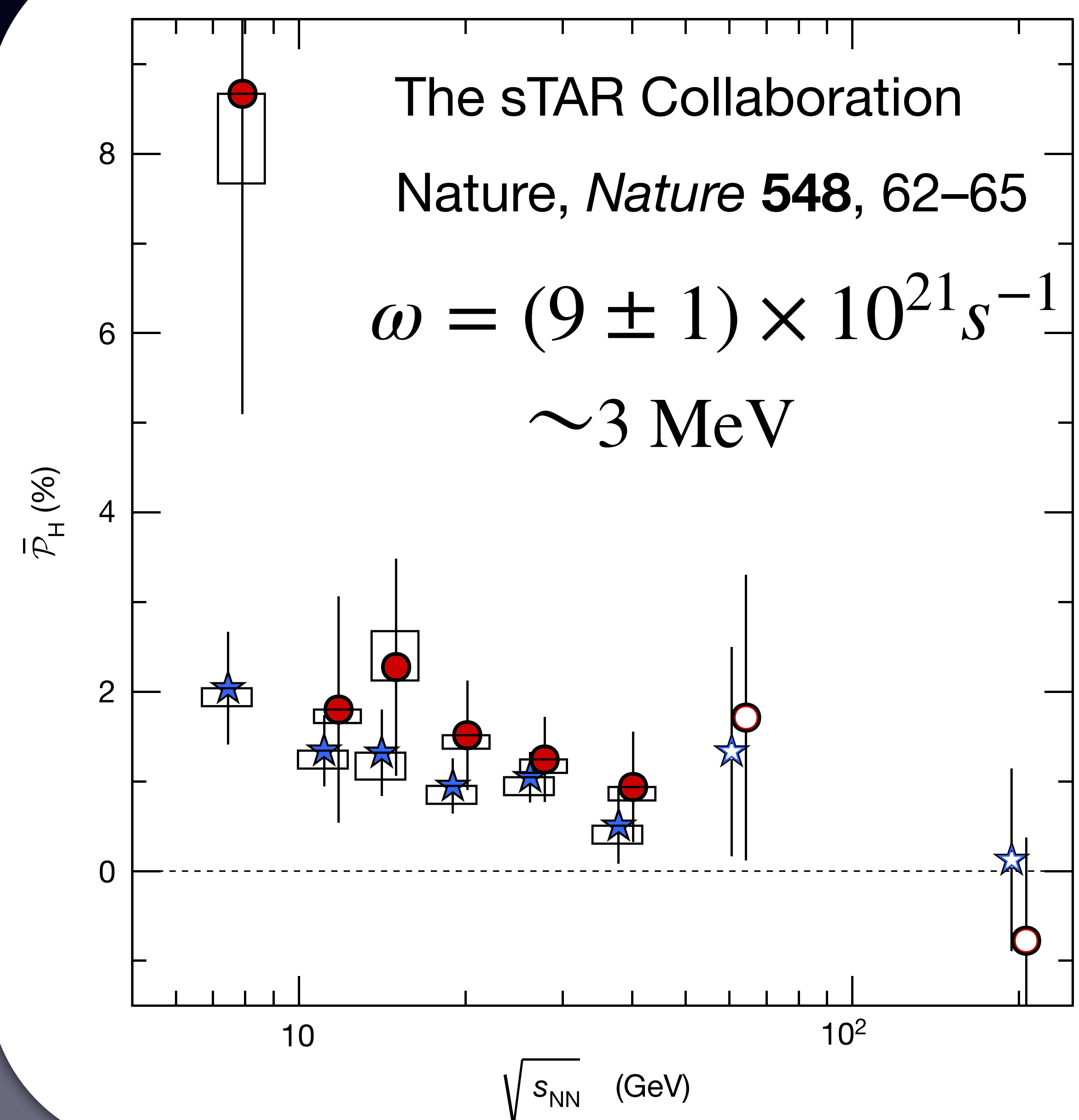
Motivation

Strong magnetic field and rotation
in heavy ion collisions



Vorticity in HIC

Lambda polarization

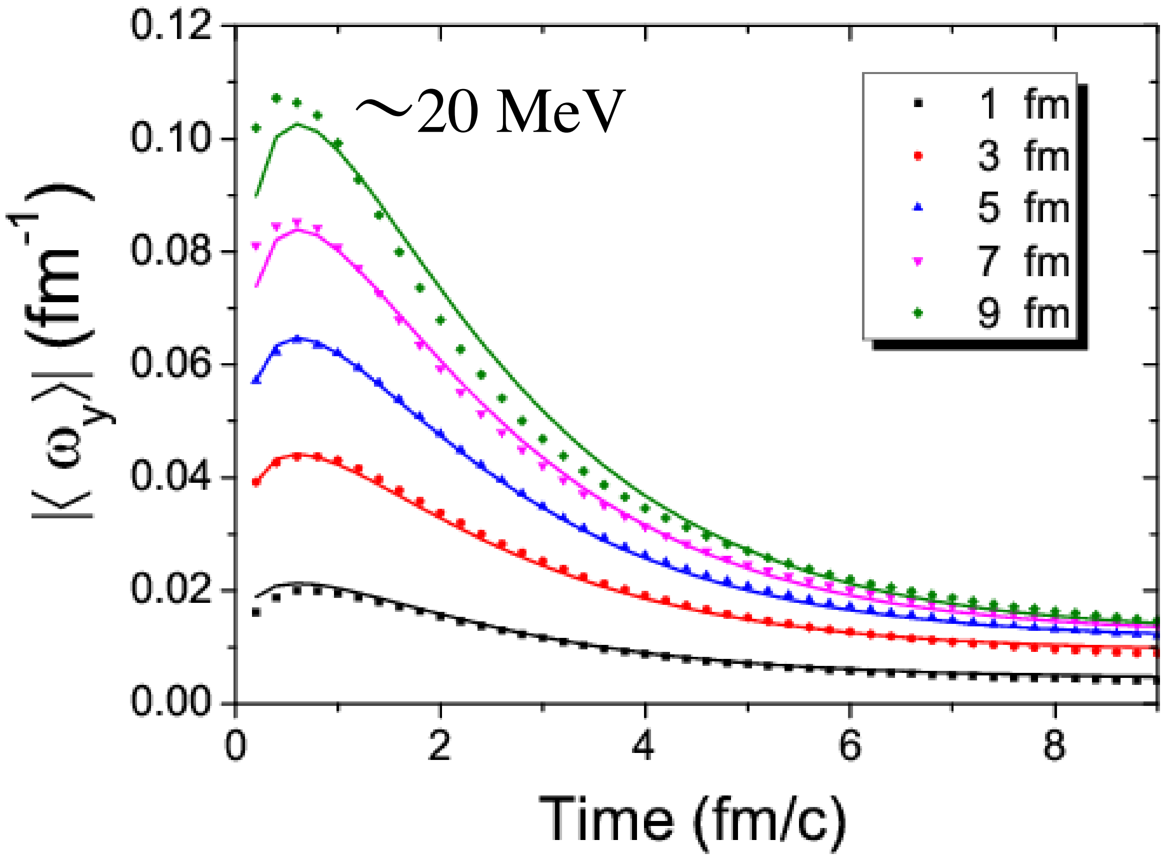


AMPT simulation

Jiang, Z. W. Lin and J. Liao

Phys. Rev. C 94, 044910 (2016)

Erratum: [Phys. Rev. C 95, no. 4, 049904 (2017)]



Chiral effect in QGP

$$\boldsymbol{J} = \xi_B \boldsymbol{B} + \xi_\omega \boldsymbol{\omega}$$

Chiral magnetic effect

Kharzeev, McLerran, Warringa ('08)
Fukushima, Kharzeev, Warringa ('08)

$$\xi_B \sim \mu_5$$

Chiral vortical effect

Son, Surowka ('09),
Landsteiner, Megias, Pena-Benitez (11)

$$\xi_\omega \sim \mu_5 \mu$$

$$\boldsymbol{J}_5 = \zeta_B \boldsymbol{B} + \zeta_\omega \boldsymbol{\omega}$$

Chiral separation effect

Son, Zhitnitsky ('04)
Metlitski, Zhitnitsky ('05)

related to chiral anomaly $\partial_\mu j_5^\mu = C\boldsymbol{E} \cdot \boldsymbol{B}$

Electric conductivity in B

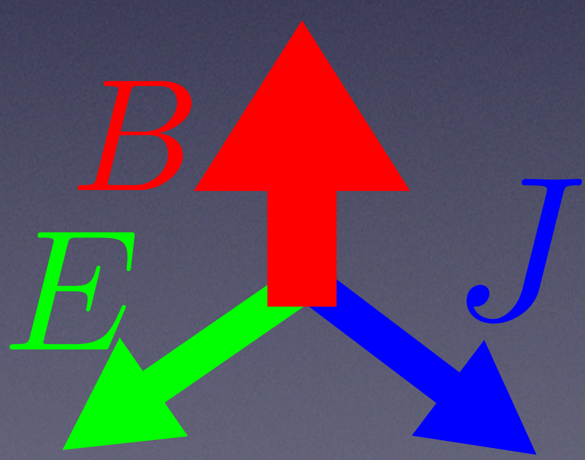
Fukushima YH , Phys. Rev. Lett. 120 (2018) no.16, 162301

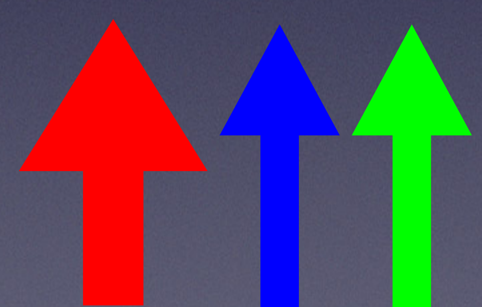
Current: $J^i = \sigma^{ij} E^j + \cdots$

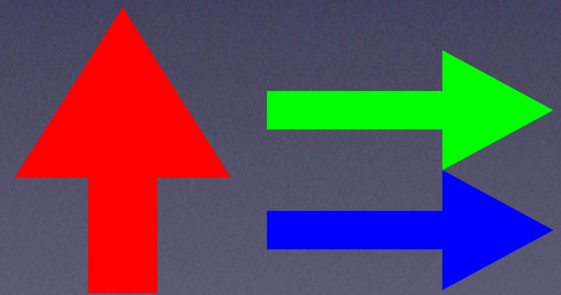
$$\sigma^{ij} = \sigma_H \epsilon^{ijk} \hat{B}^k + \sigma_{\parallel} \hat{B}^i \hat{B}^j + \sigma_{\perp} (\delta^{ij} - \hat{B}^i \hat{B}^j)$$

Hall　　　longitudinal　　　perpendicular

Related to CME







Strong B, chiral limit

Chiral anomaly

$$\partial_\mu j_5^\mu = C\boldsymbol{E}\cdot\boldsymbol{B} \Rightarrow n_5 \propto t\boldsymbol{E}\cdot\boldsymbol{B}$$

CME

$j_{\mathrm{CME}} \sim \mu_5 \boldsymbol{B} \sim n_5 \boldsymbol{B}$ implies $\sigma_\parallel \to \infty$

in cond-mat

Interaction with phonon or impurity

$t \to \tau_R$

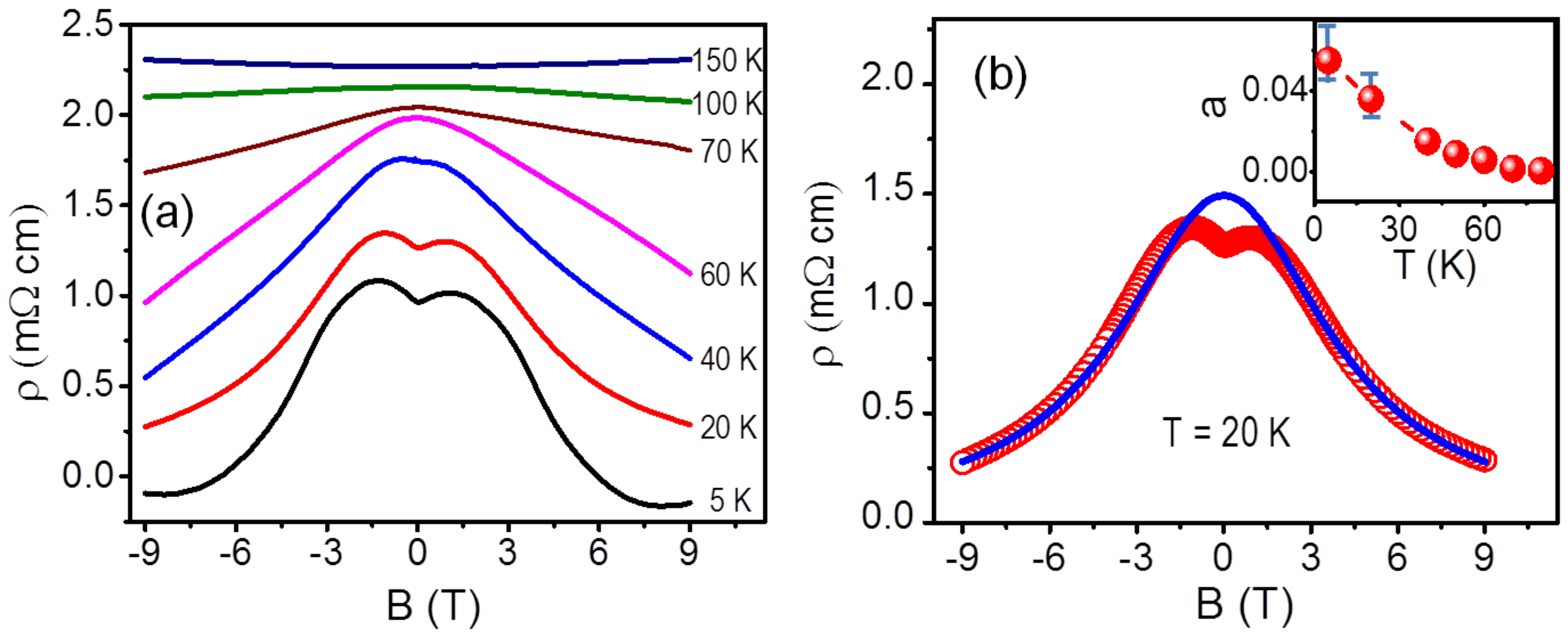
$\sigma_\parallel \propto \tau_R \boldsymbol{B}^2$ + Ohmic term

in QCD

explicit breaking by m_q

chiral magnetic effect in cond-mat.

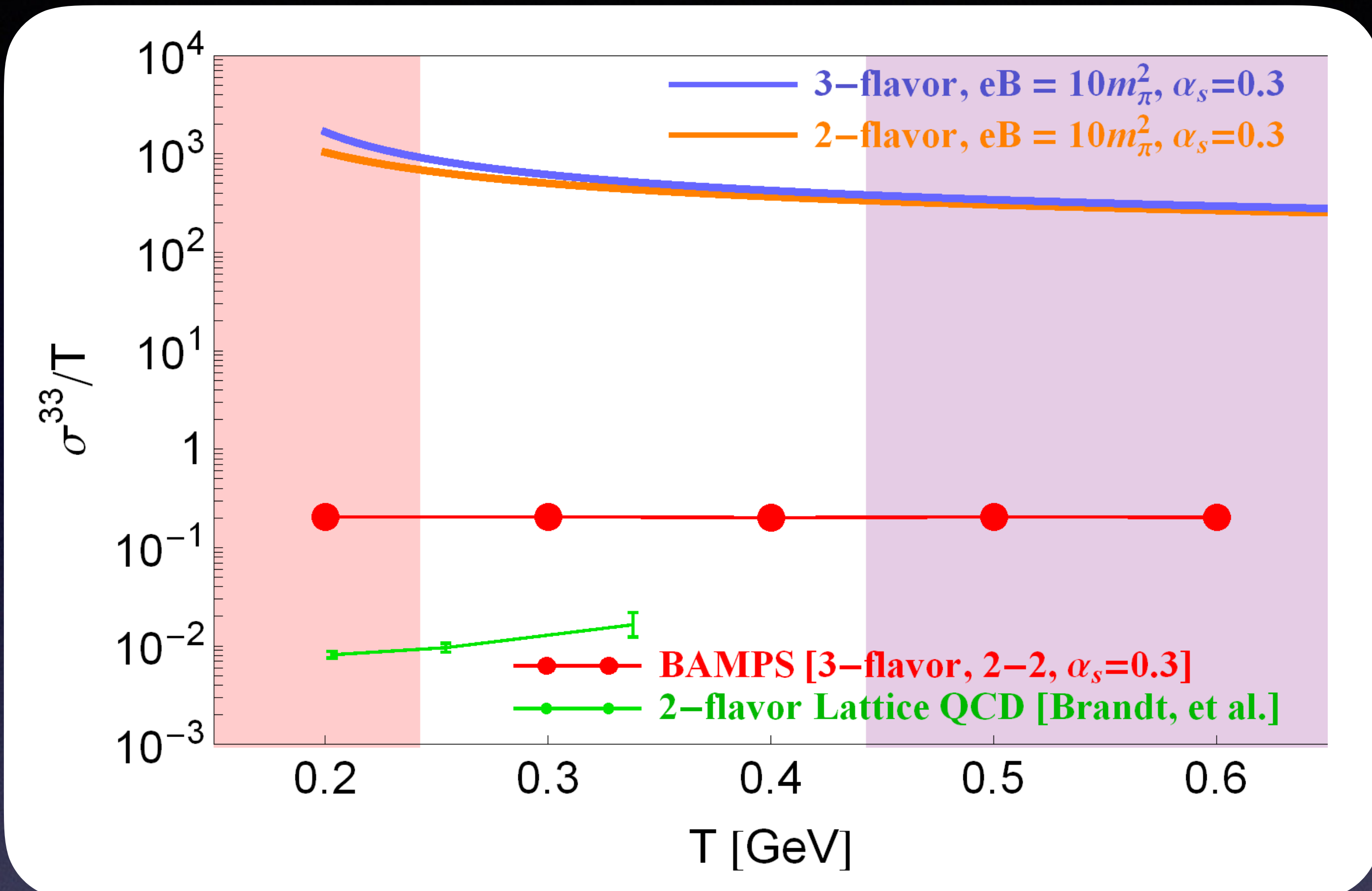
Q Li, et al, Nature Physics 12, 550-554 (2016)



resistance : $\rho = \dfrac{1}{\frac{\tau}{\chi}(CB)^2 + \sigma_{\mathrm{Ohm}}}$

Conductivity of QCD in strong B

Hattori, Satow, Phys. Rev. D94 (2016) 114032   Hattori, Li, Satow, Yee Phys.Rev. D95 (2017) no.7, 076008



$$\sqrt{eB} \gg T$$

$$\mu = 0$$

$$\sigma_{\parallel}/T \sim \frac{eB}{m_q^2 g^2}$$

Strong B

Effective 1+1 dynamics
+chiral symmetry

→ suppression of interactions

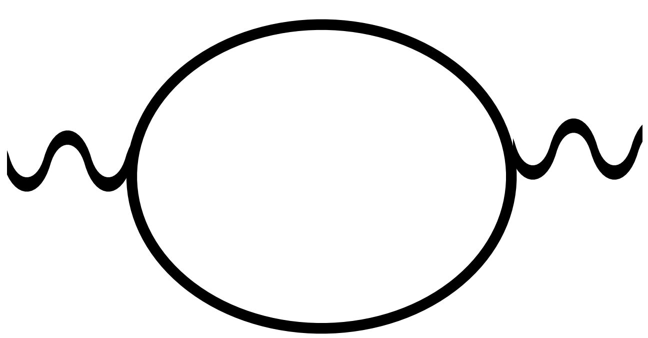
Electric conductivity in B

current $J^i = \sigma^{ij} E^j + \cdots$

$$\sigma^{ij} = \sigma_H \epsilon^{ijk} \hat{B}^k + \sigma_{\parallel} \hat{B}^i \hat{B}^j + \sigma_{\perp} (\delta^{ij} - \hat{B}^i \hat{B}^j)$$

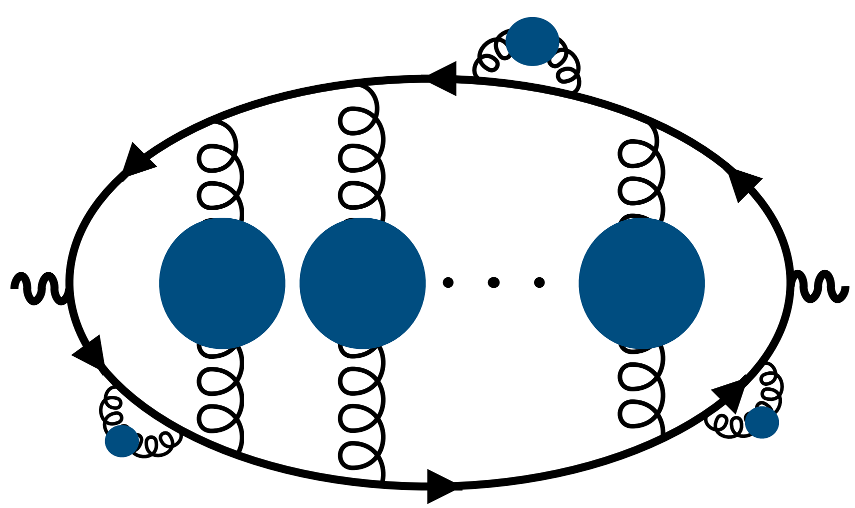
Hall longitudinal perpendicular

one-loop



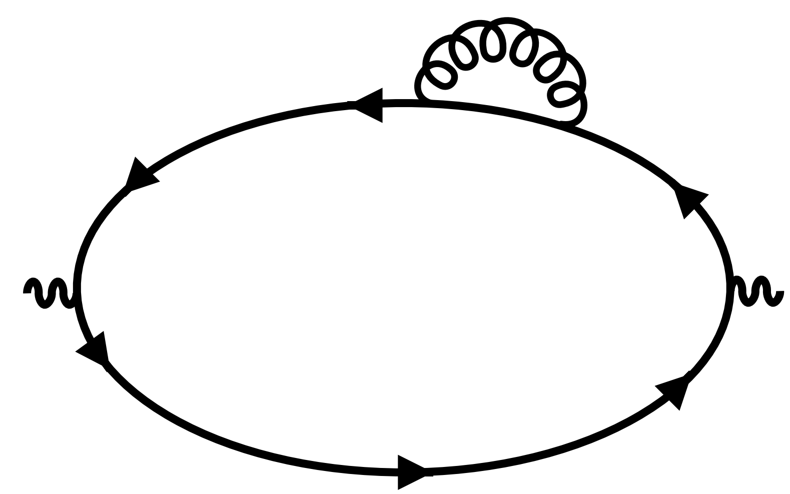
$$\sigma_H = \frac{n_e}{B}$$

resume



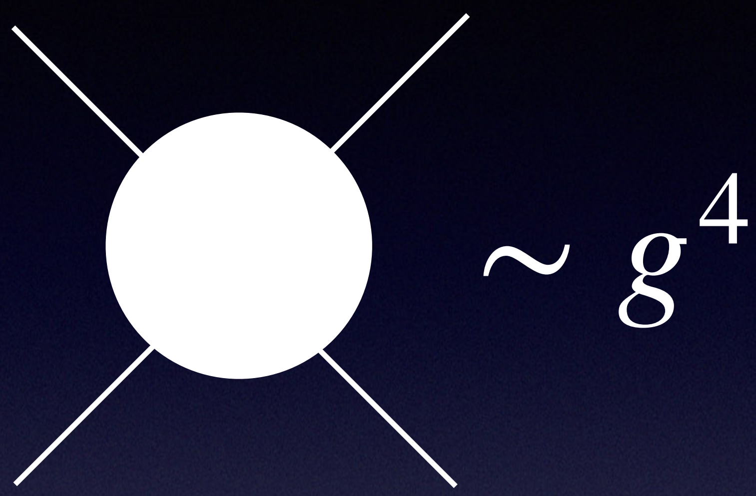
$$\frac{\sigma_{\parallel}}{T} \sim \frac{1}{g^n} F(T^2/eB)$$

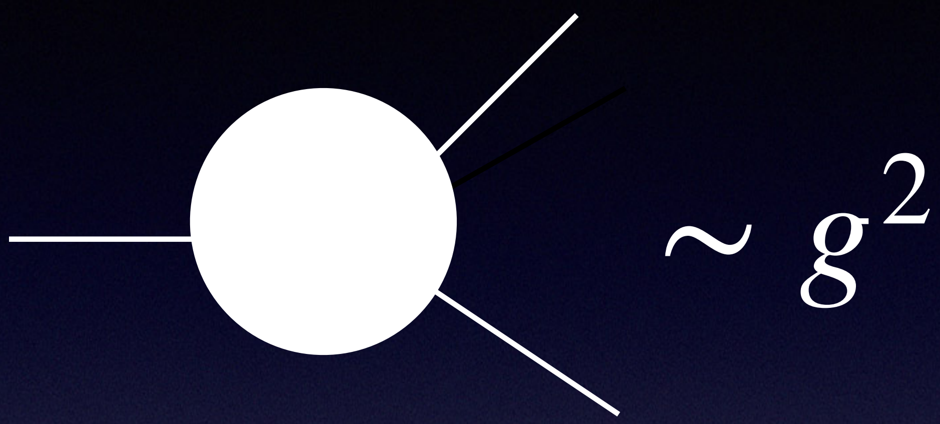
two loop



$$\frac{\sigma_{\perp}}{T} \sim \frac{g^2 T^2}{|eB|}$$

Scattering v.s. radiation





Leading contribution to conductivity

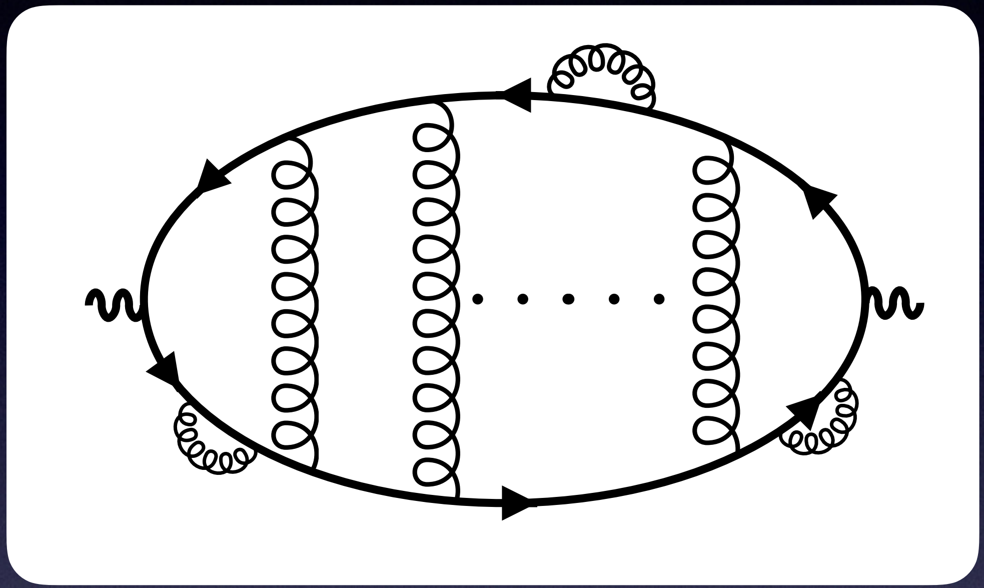
Usually suppress by kinematics

The situation is different in B!

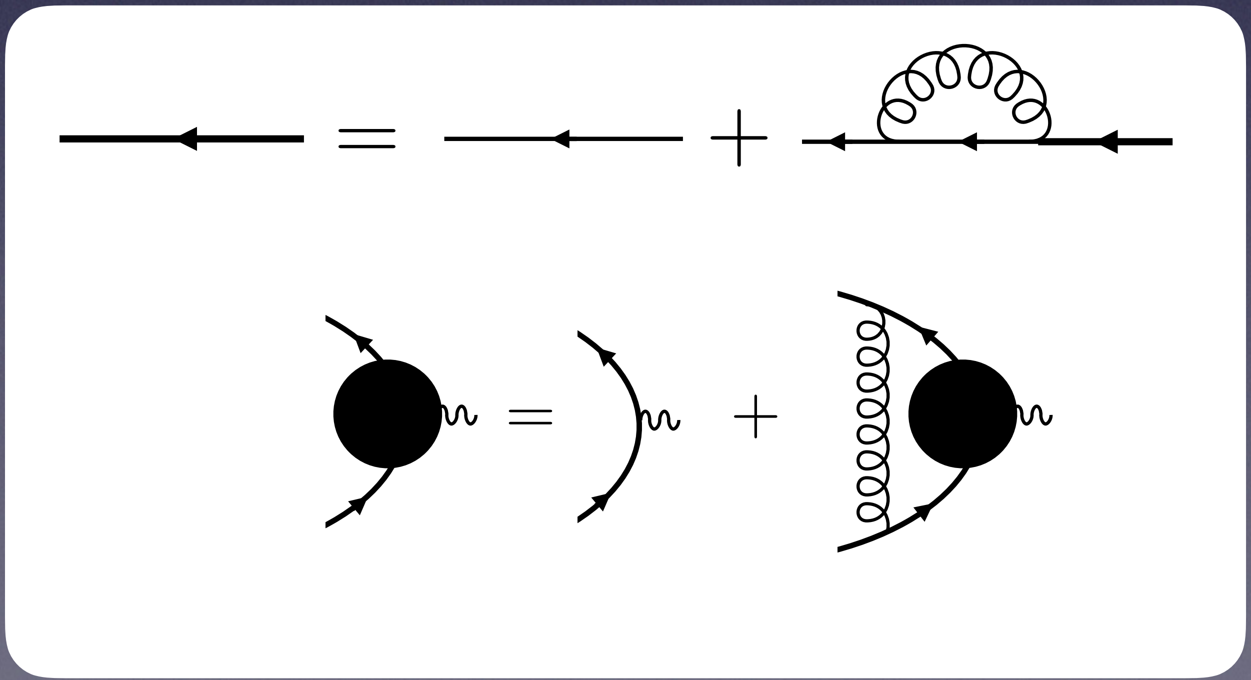
ex) Syncrotron radiation

Longitudinal conductivity $\sigma_\parallel$

Infinitely diagrams contribute to the conductivity



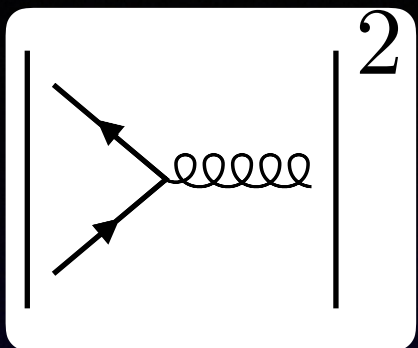
which is generated by



Solving linearized Boltzmann Eq.

cf. Jeon, Phys Rev. D 52 (1995) 3591
Hidaka, Kunihiro, Phys. Rev. D83 (2011) 076004
Fukushima, YH (2018)

Just complicated



$$\sim \sum_{l,s,c} \int \frac{d^2 p_\perp}{(2\pi)^2} |\mathscr{M}_{p+p'\to k}|^2 = X(n, n', \xi)$$

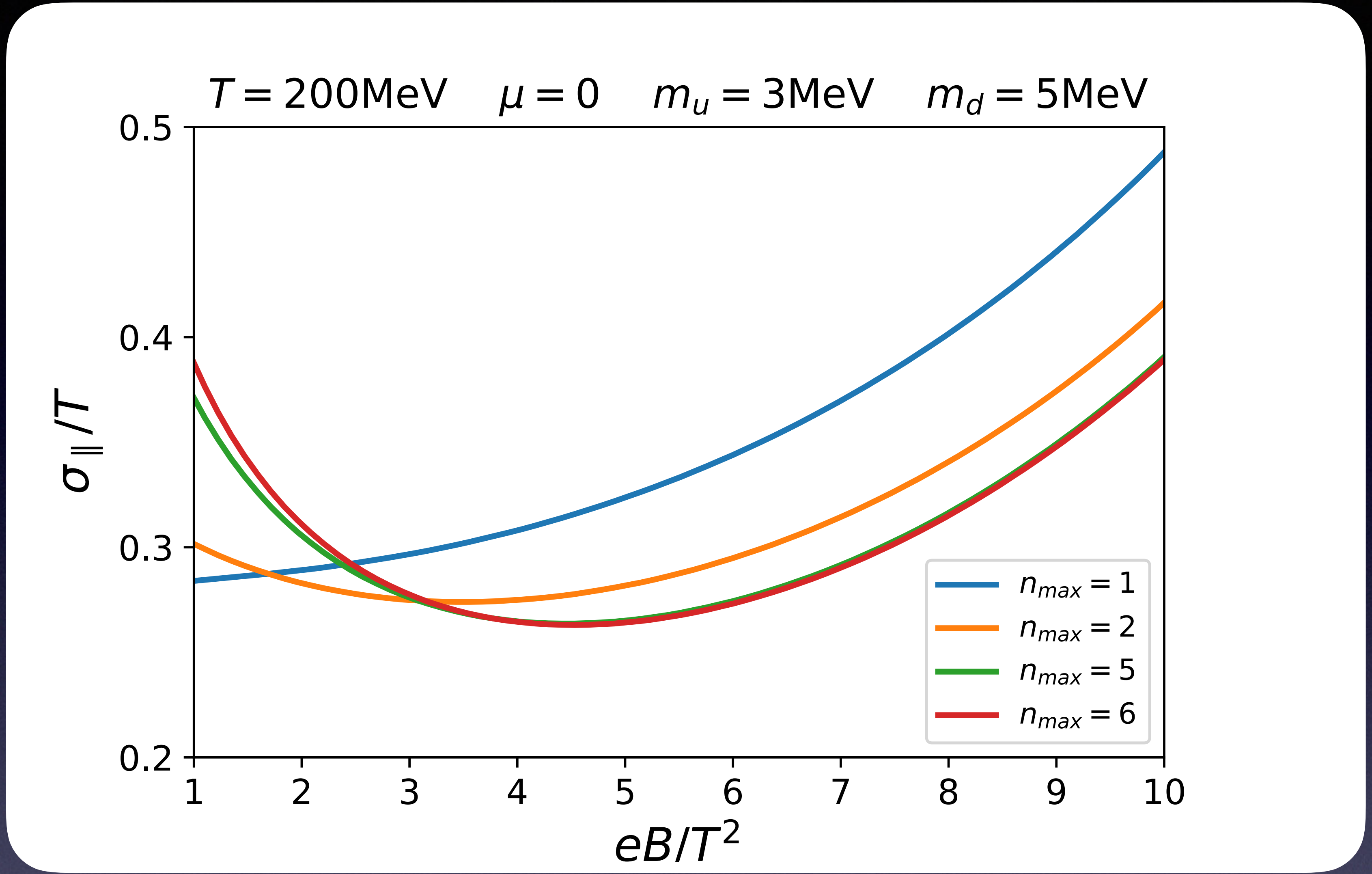
$$X(n,n',\xi) = g^2 N_c C_F \frac{|q_f B|}{2\pi} e^{-\xi} \frac{n!}{n'!} \xi^{n'-n}$$
$$\times \left\{ \left[4m_f^2 - 4|q_f B|(n + n' - \xi)\frac{1}{\xi}(n+n') \right] F(n,n',\xi) + 16|q_f B| n'(n+n')\frac{1}{\xi} L_n^{(n'-n)}(\xi) L_{n-1}^{(n'-n)}(\xi) \right\}$$

$$F(n,n',\xi) = \left[L_n^{(n'-n)}(\xi) \right]^2 + \frac{n'}{n} \left[L_{n-1}^{(n'-n)}(\xi) \right]^2$$

Laguerre Polynomials

$$\xi = \frac{(\varepsilon_{fn} + \varepsilon_{fn'})^2 - (p_z + p_z')^2}{2|q_f B|}$$

B dependence



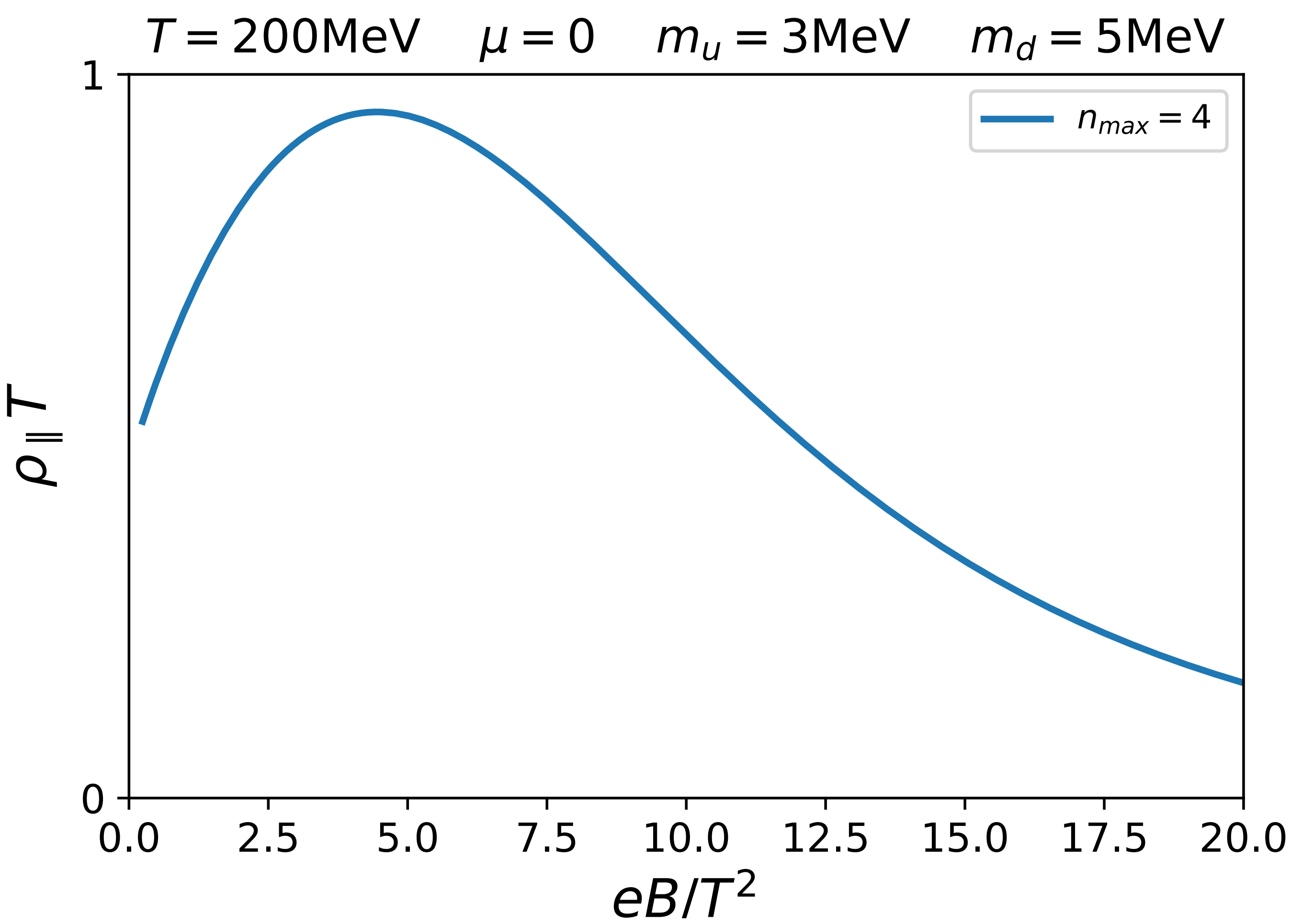
non-monotonic behavior

Degrees of freedom $\sim \dfrac{eB}{2\pi}$

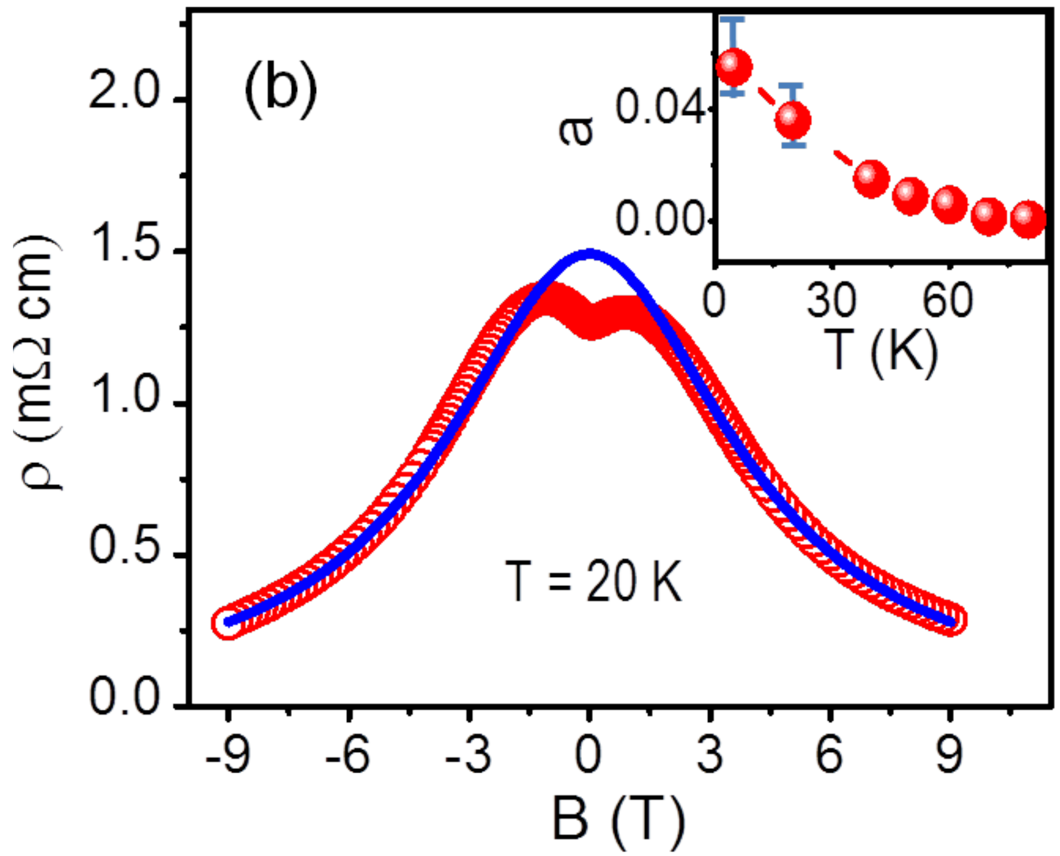
v.s.

Higher Landau level is suppressed by Boltzmann factor: $\exp(-\sqrt{eBn}/T)$

B dependence



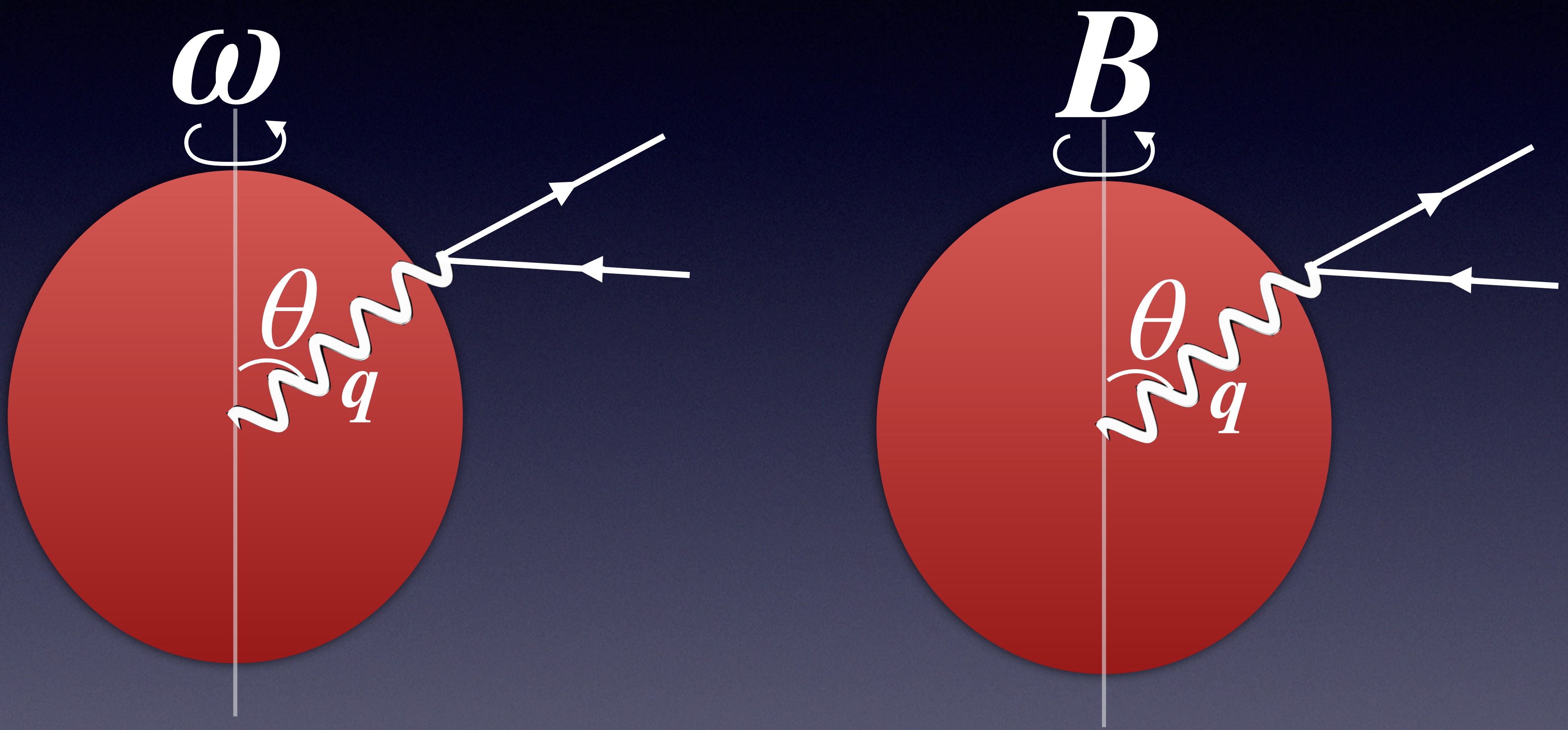
Li Li, Kharzeev, Zhang, Huang, Pletikosic, Fedorov, Zhong, Schneeloch, Gu, Valla, Nature Phys. 12, 550 (2016)



Similar behavior

although physical processes are different

Dilepton production



Chiral Kinetic theory

Son, Yamamoto ('12) Stephanov, Yin ('12)

Chiral kinetic equation (CKE)

$$(\partial_t + \dot{\boldsymbol{x}} \cdot \nabla_x + \dot{\boldsymbol{p}} \cdot \nabla_p) f = C[f]$$

Equations of motion $\dot{\boldsymbol{x}} = \hat{\boldsymbol{p}} + \dot{\boldsymbol{p}} \times \boldsymbol{\Omega}$

$$\dot{\boldsymbol{p}} = \dot{\boldsymbol{x}} \times \boldsymbol{B} + \boldsymbol{E}$$

Berry curvature $\boldsymbol{\Omega} = \nabla_p \times \boldsymbol{a} = \dfrac{\hat{\boldsymbol{p}}}{2p^2}$

Anomaly

$$\partial_\mu j^\mu = \frac{1}{4\pi^2} \boldsymbol{E} \cdot \boldsymbol{B}$$

Covariant version of Chiral kinetic equation (CKE)

YH, Shi Pu, Yang ('16) ('17)

$$\Delta_\mu S^{<\mu} = \Sigma^{<}_\mu S^{>\mu} - \Sigma^{>}_\mu S^{<\mu} \qquad \Delta_\mu = \partial_\mu + F_{\nu\mu}\partial_{p_\nu}$$

$$S^{<\mu} = 2\pi\epsilon(p\cdot n)\left[\delta(p^2)(p^\mu + S_n^{\mu\nu}\mathscr{D}_\nu) + p_\nu \tilde{F}^{\mu\nu}\delta'(p^2)\right]f$$

spin: $S_n^{\mu\nu} = \dfrac{1}{2}\epsilon^{\mu\nu\alpha\beta}\dfrac{p_\alpha n_\beta}{p\cdot n}$ $\qquad \mathscr{D}_\mu f = \Delta_\mu f + \Sigma^{<}_\mu f - \Sigma^{>}_\mu \bar{f}$

(local) Equilibrium

Current: $J^{\mu} = 2\int \frac{d^4p}{(2\pi)^4} S^{<\mu}(p, X)$

➡ $\boldsymbol{J} = n\boldsymbol{u} + \sigma_B \boldsymbol{B} + \sigma_\omega \boldsymbol{\omega}$

CME CVE

Dissipative current

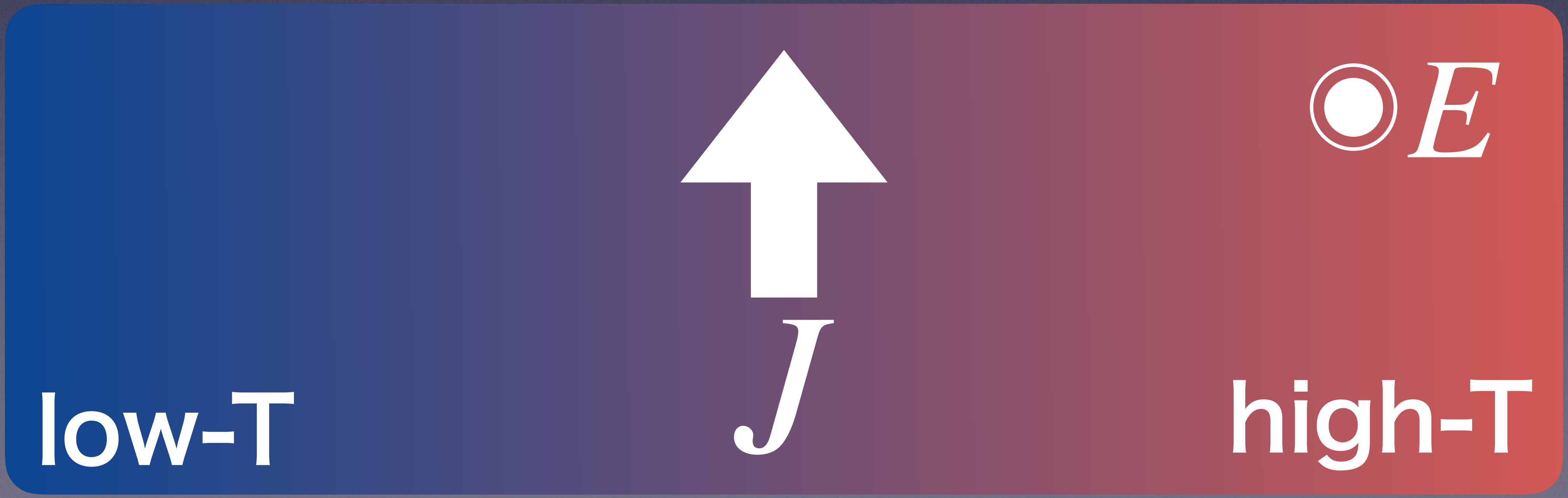
CKE with relaxation time approximation

Gorbar, Shovkovy, Vilchinskii, Rudenok, Boyarsky, Ruchayskiy ('16)
Chen, Ishii, Pu, Yamamoto ('16)
YH, Pu, Yang ('17)

$\nabla \mu, \nabla T$ correction

$$\delta J = C_1 E \times \nabla \mu + C_2 E \times \nabla T + C_3 \nabla \mu \times \nabla T$$

$$C_i \sim \tau_R$$

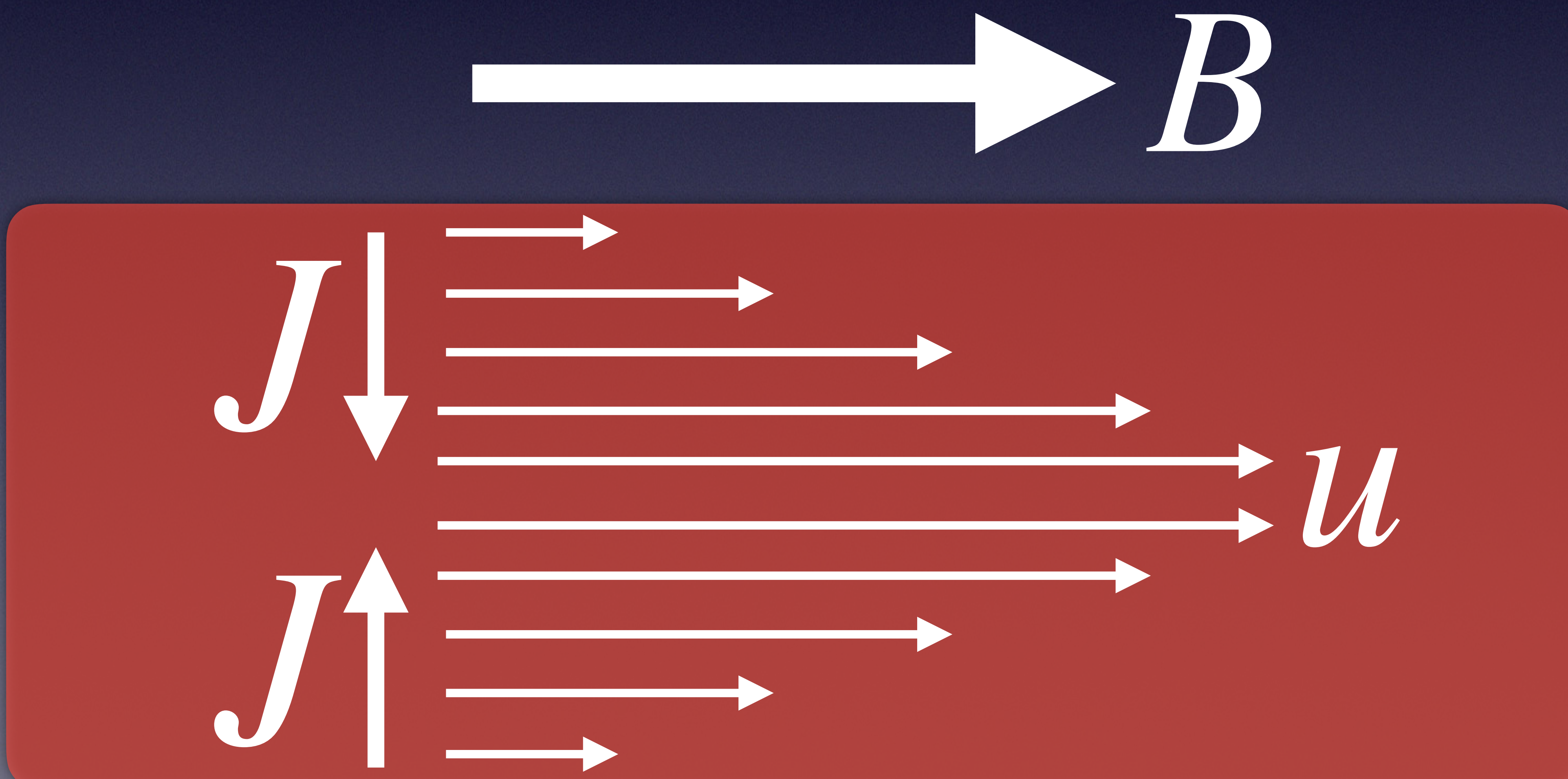


Dissipative current

YH, Yang ('18)

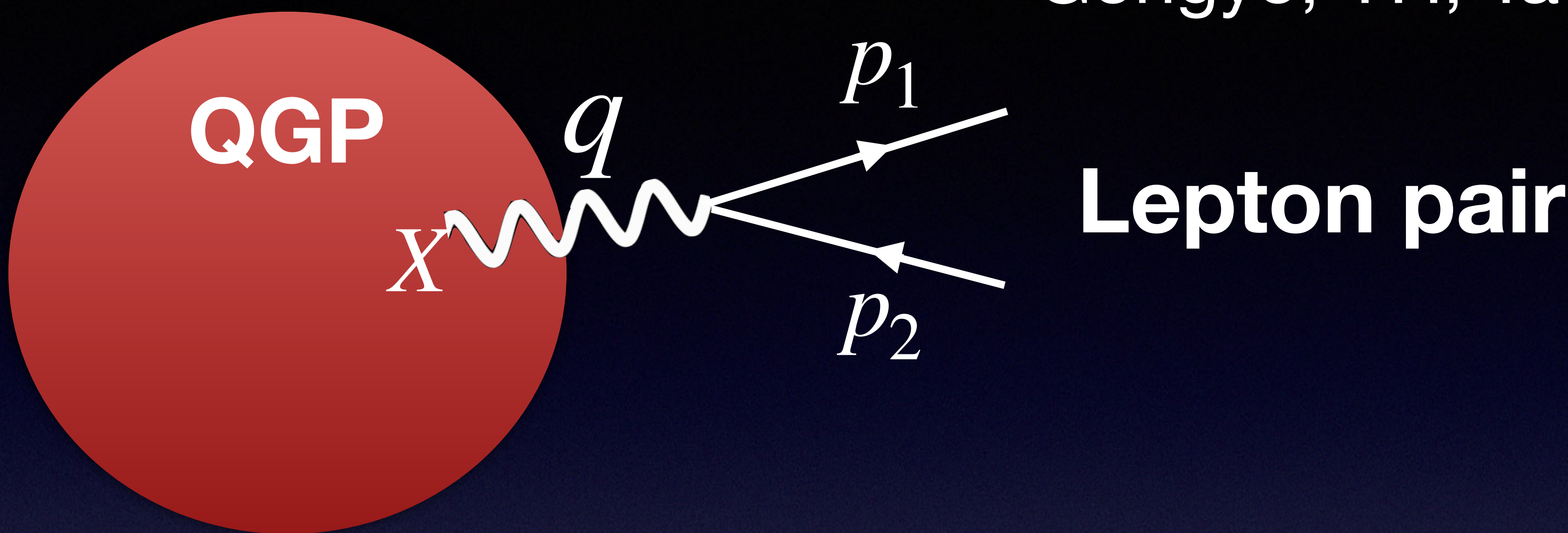
Shear and bulk correction

$$\delta J^i = C_4 \pi^{ij} B_j + C_5 \pi^{ij} \omega_j$$
$$+ C_6 (\nabla \cdot \boldsymbol{u}) B^i + C_7 (\nabla \cdot \boldsymbol{u}) \omega^i$$



Dilepton production

Gongyo, YH, Tachibana ('18)



Photon polarization funciton

$$\Pi^{<\mu\nu}(X,q) = \int d^4 s e^{iq\cdot s}\langle j^\nu(X - s/2) j^\mu(X + s/2)\rangle$$

Dilepton production rate

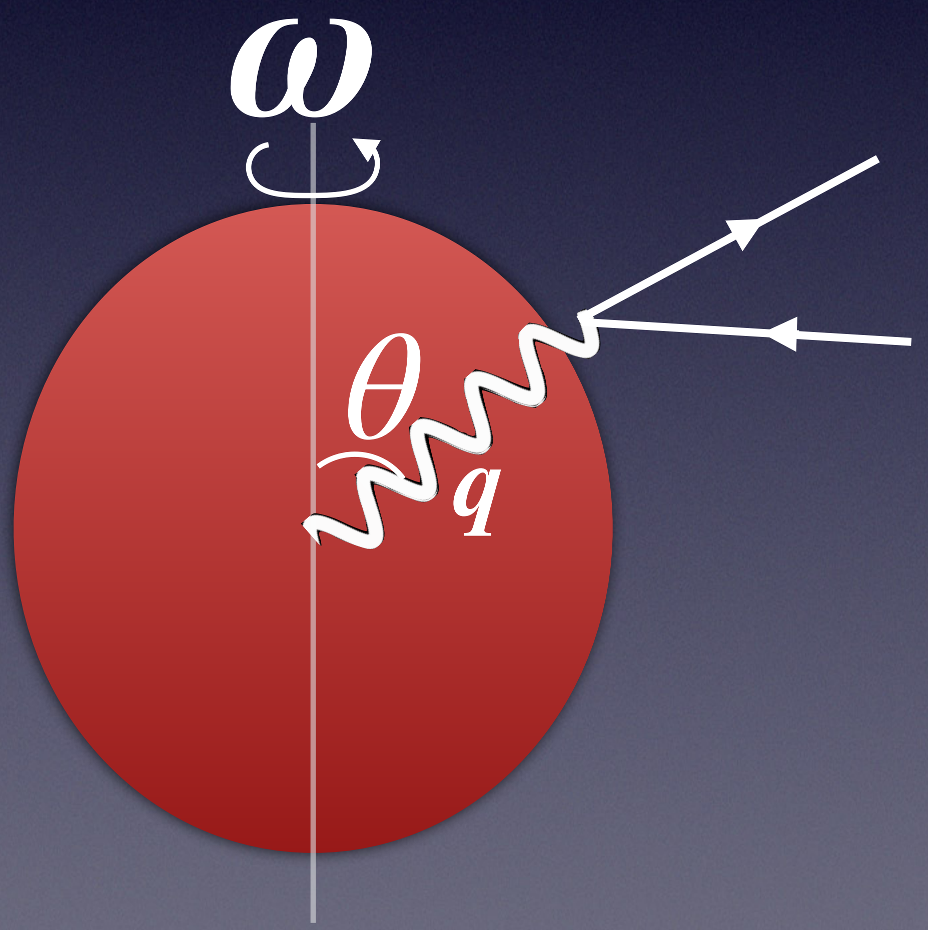
$$\frac{d\Gamma}{d^4q} = -\frac{\alpha}{24\pi^4}\Pi^{<\mu}{}_{\mu}(q,X)$$

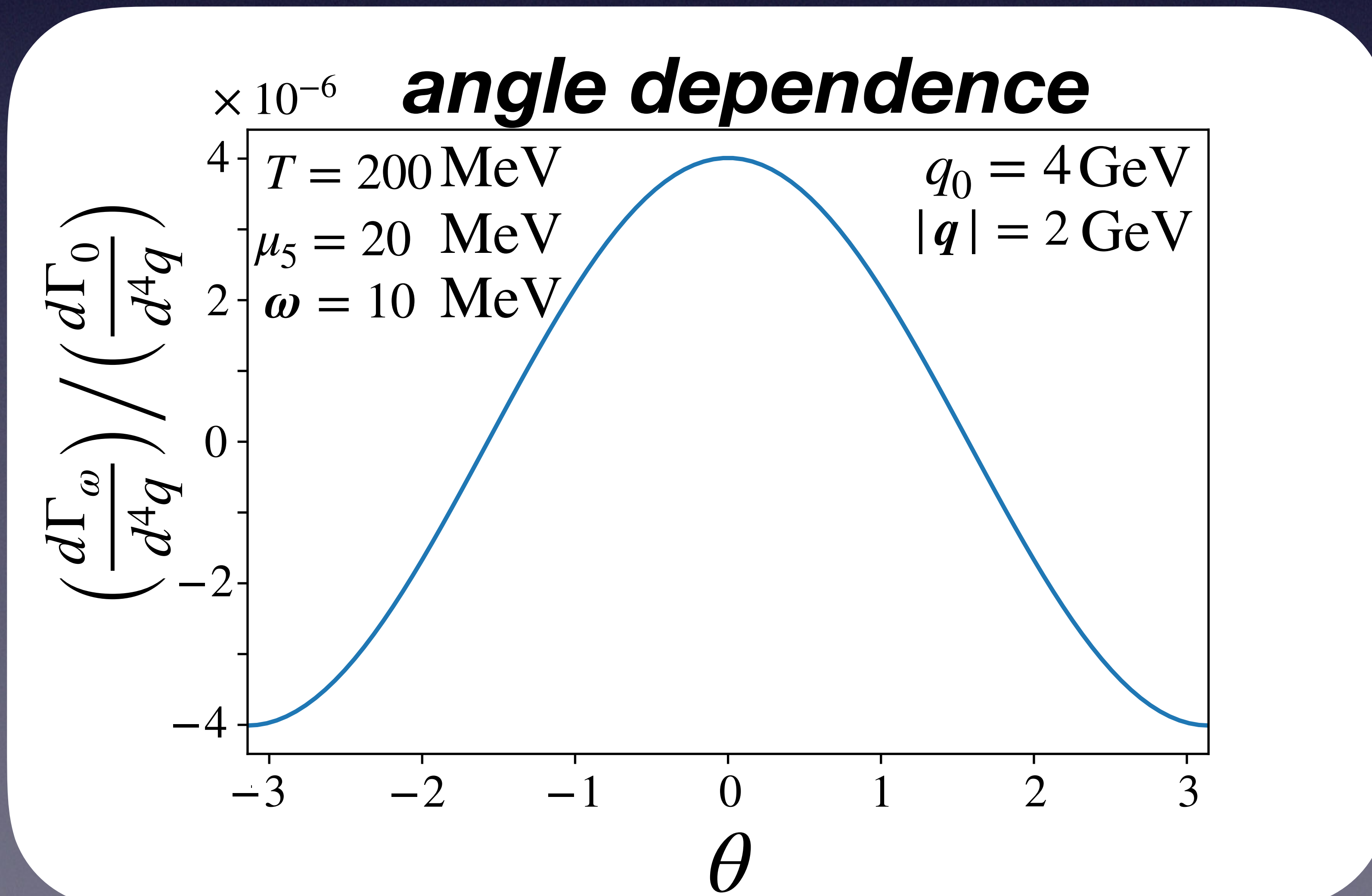
Di-lepton production in ω

Gongyo, YH, Tachibana ('18)

$$\frac{d\Gamma}{d^4q} = \frac{d\Gamma_0}{d^4q} + \frac{d\Gamma_\omega}{d^4q} \quad \textbf{with} \quad \frac{d\Gamma_\omega}{d^4q} = (\boldsymbol{\Omega}_\gamma \cdot \boldsymbol{\omega}) C_\omega(q)$$

$$C_\omega \sim \mu_5 \quad \boldsymbol{\Omega}_\gamma = \frac{\hat{\boldsymbol{q}}}{|\boldsymbol{q}|^2}$$



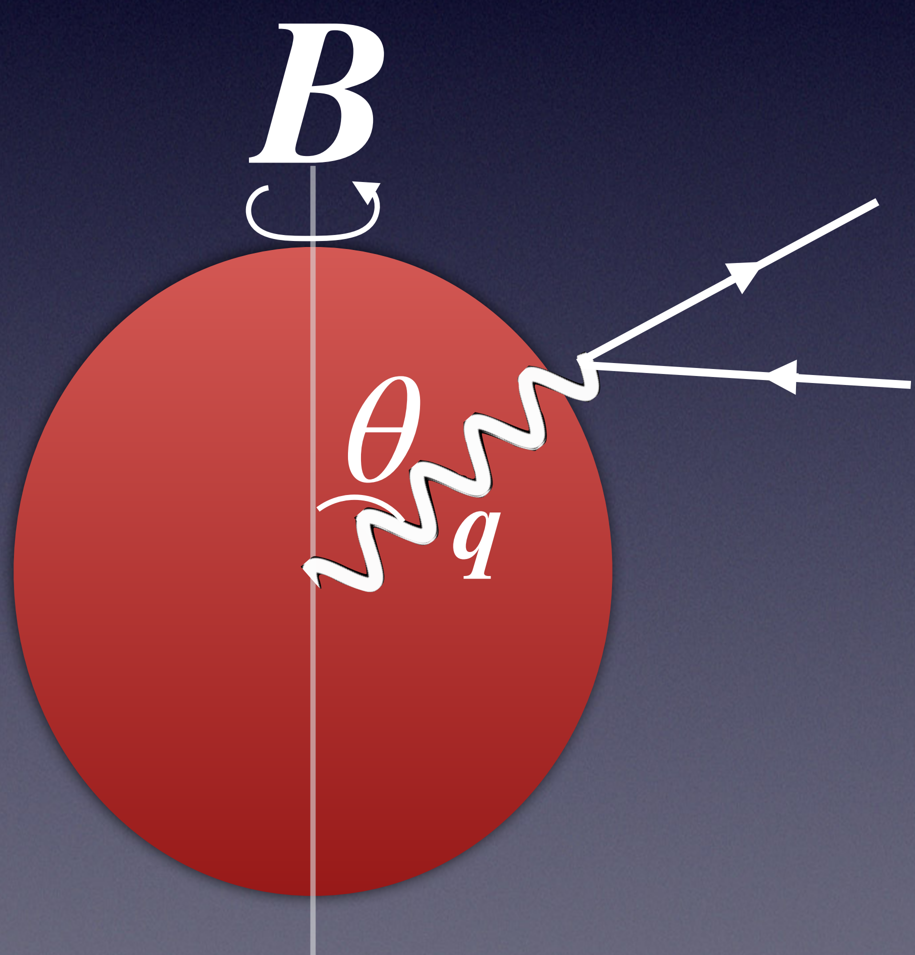


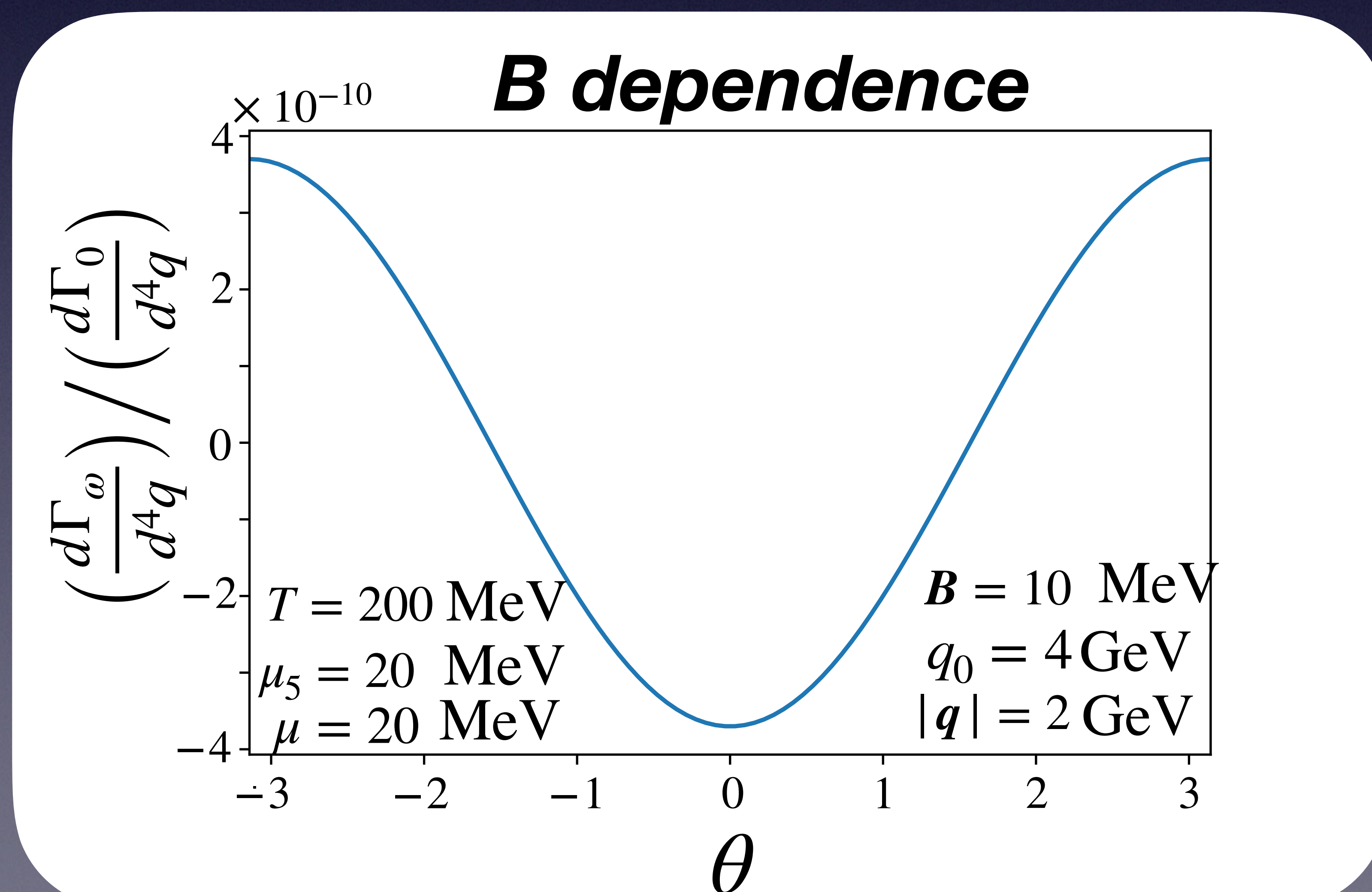
Di-lepton production in B

Gongyo, YH, Tachibana ('18)

$$\frac{d\Gamma}{d^4q} = \frac{d\Gamma_0}{d^4q} + \frac{d\Gamma_B}{d^4q} \quad \textbf{with} \quad \frac{d\Gamma_B}{d^4q} = (\boldsymbol{\Omega}_\gamma \cdot \boldsymbol{B}) C_B(q)$$

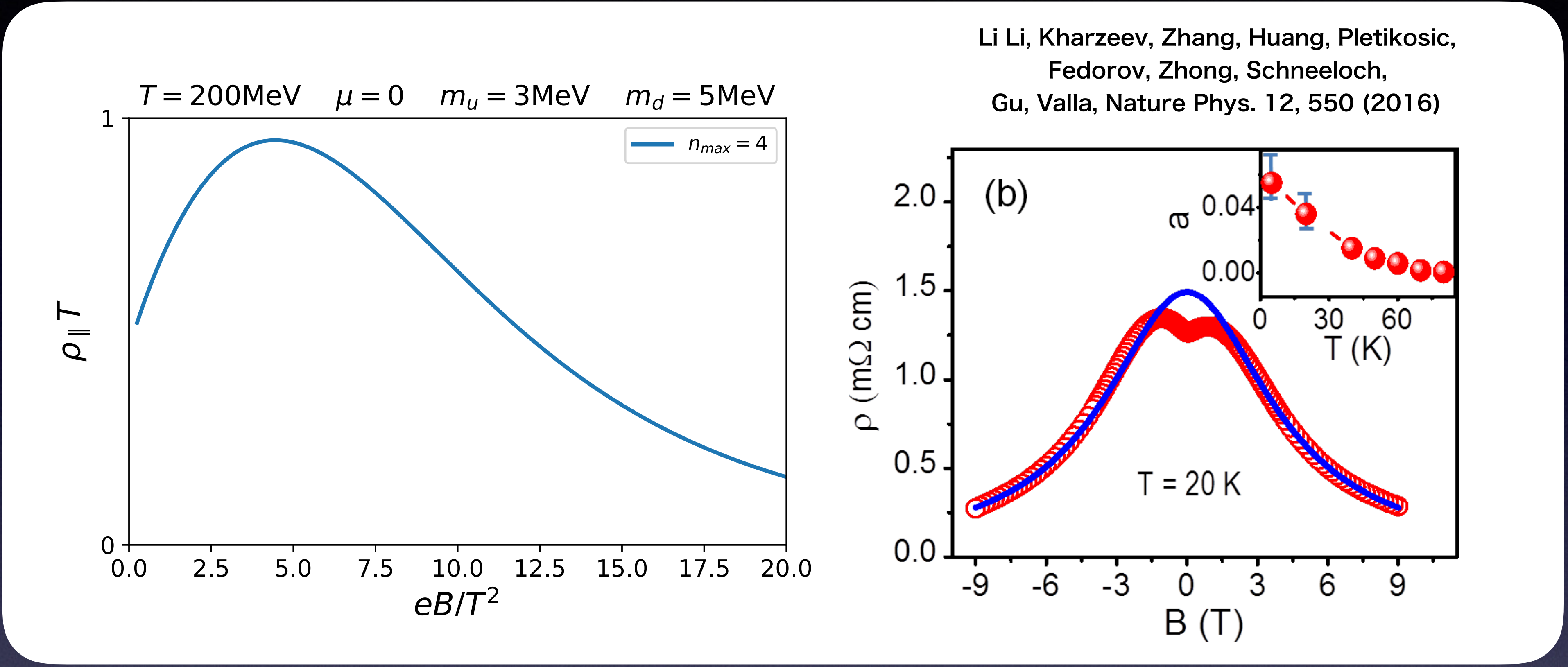
$$C_\omega \sim \mu_5 \mu \qquad \boldsymbol{\Omega}_\gamma = \frac{\hat{\boldsymbol{q}}}{|\boldsymbol{q}|^2}$$





Summary

Electric conductivity



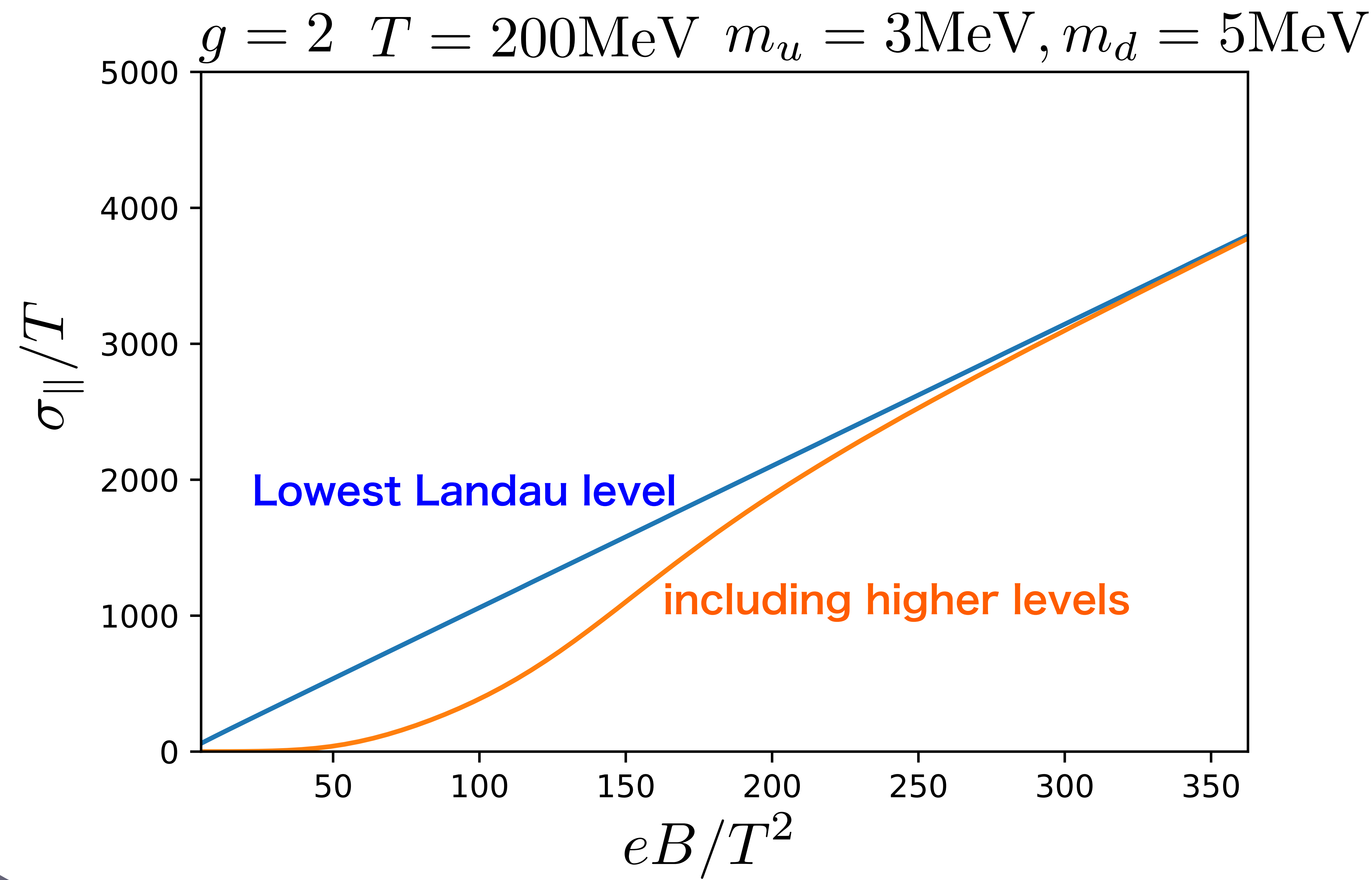
Particle production: Novel chiral effects:

$$\frac{d\Gamma_\omega}{d^4q} = (\boldsymbol{\omega} \cdot \boldsymbol{\Omega}_\gamma) C_\omega \qquad \frac{d\Gamma_B}{d^4q} = (\boldsymbol{B} \cdot \boldsymbol{\Omega}_\gamma) C_B$$

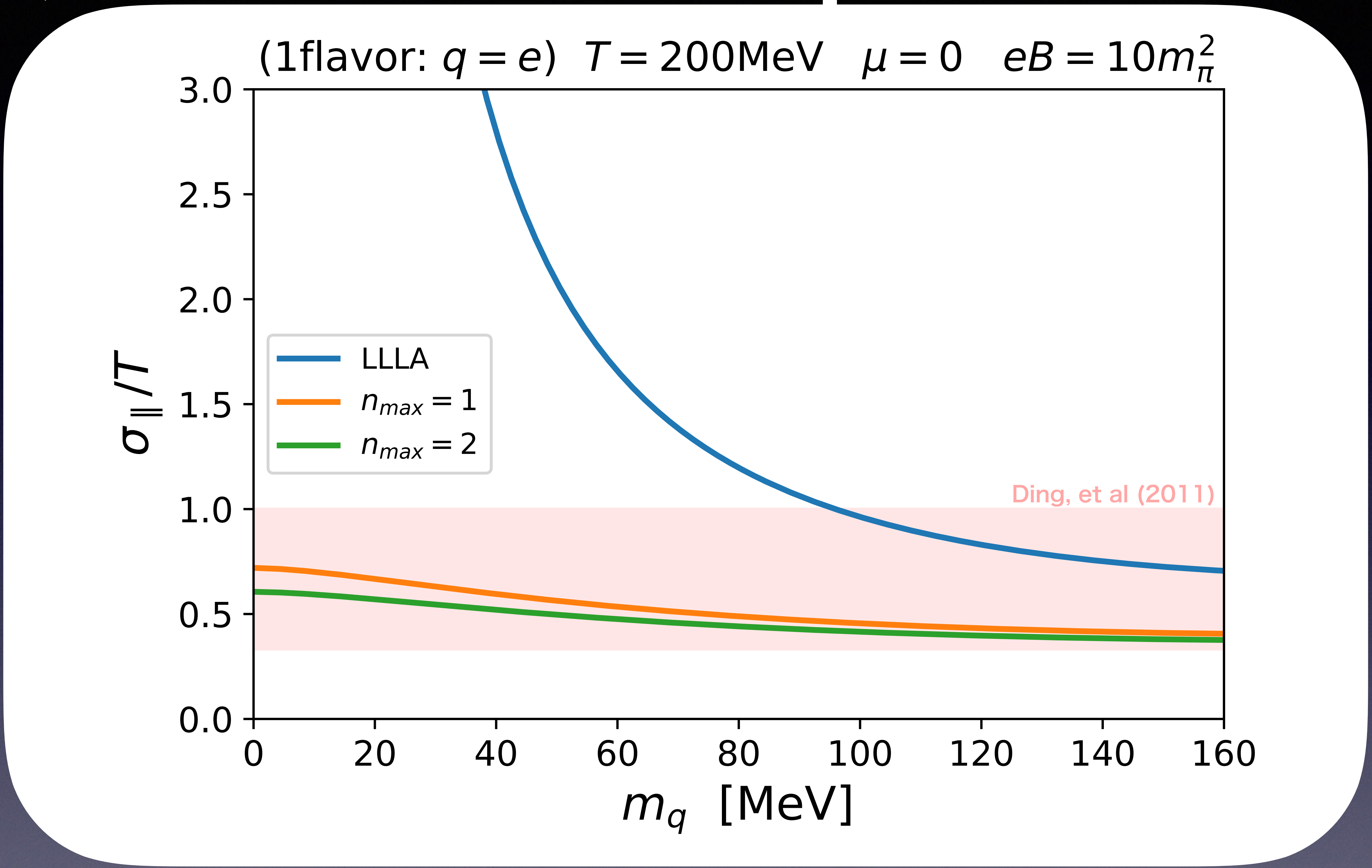
$$\boldsymbol{\Omega}_\gamma = \frac{\hat{\boldsymbol{q}}}{|\boldsymbol{q}|} \quad C_\omega \sim \mu_5 \quad C_B \sim \mu_5 \mu$$

Backup

Large B behavior



Quak mass dependence



For small current mass, higher Landau levels are important

$$\frac{d\Gamma_\omega}{d^4q} = (\boldsymbol{\Omega}_\gamma \cdot \boldsymbol{\omega})C(q)$$