Polarization of virtual photons in ultrarelativistic heavy ion collisions

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Anisotropy in collisions polarizes both direct and virtual photons (detected via dileptons), and thus polarization is a probe of anisotropy at all stages of the collision.

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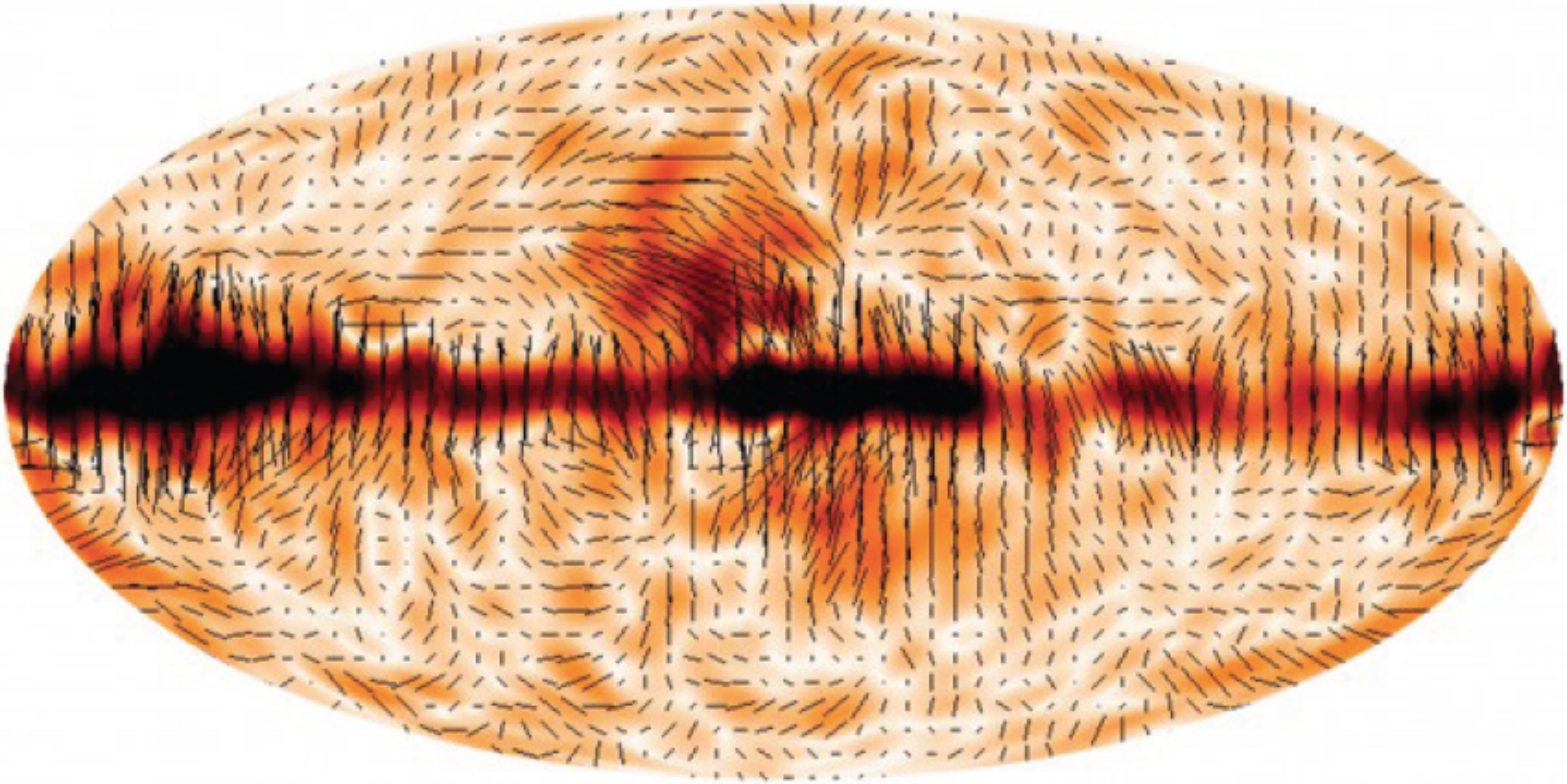
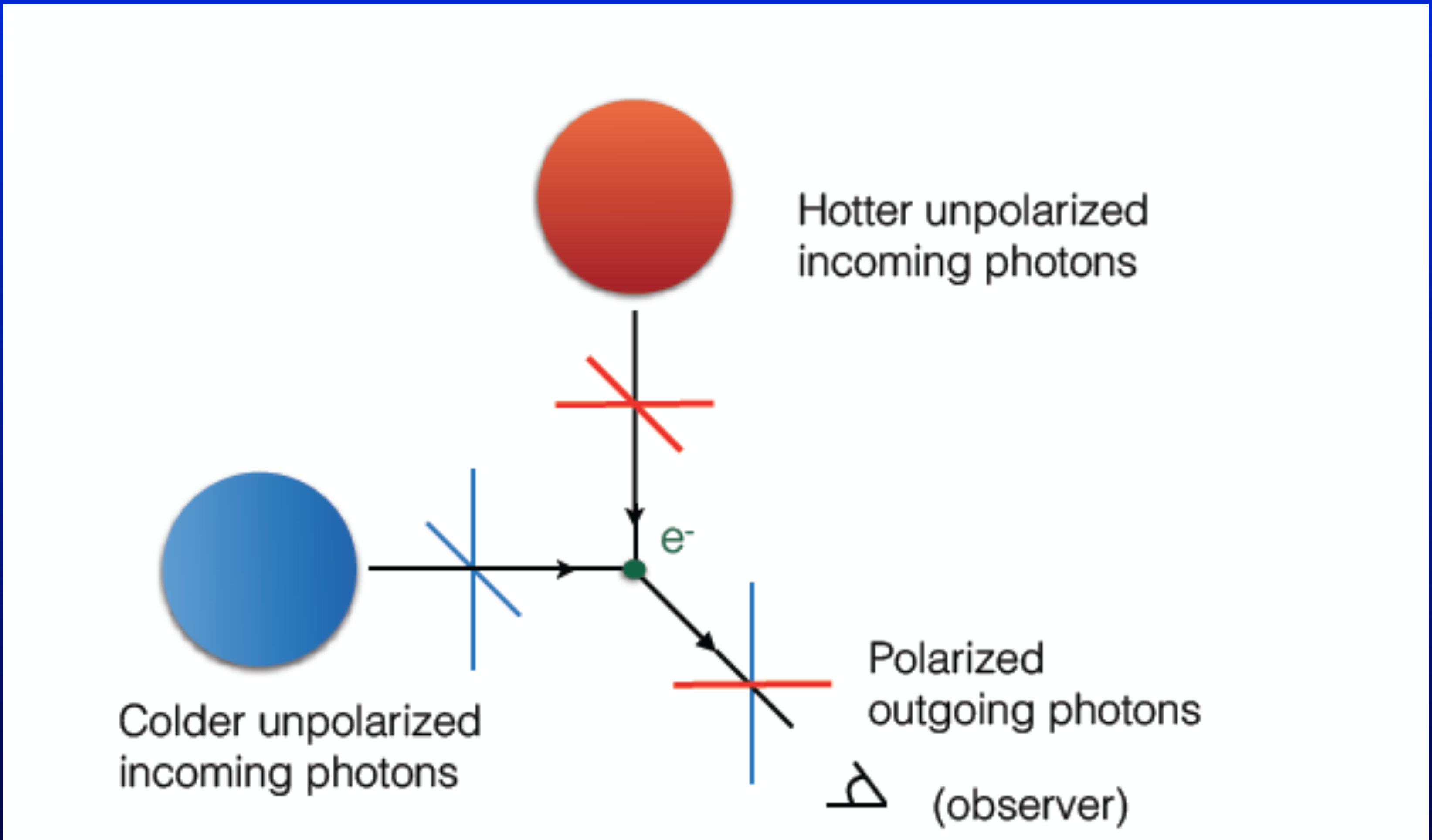
Polarization of cosmic microwave background



Planck map across the entire sky

In the early universe, momentum anisotropy of photons at last scattering leads to polarization of the cosmic microwave background



Essentially Thomson scattering preserves polarization to extent possible, keeping polarization transverse to momentum

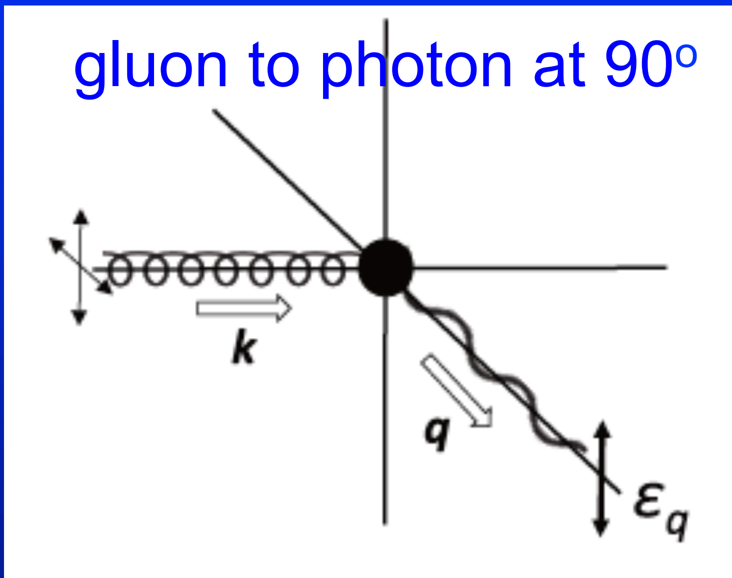
Ultrarelativistic heavy ion collisions

GB & T. Hatsuda, PTEP, 031D01 (2015)

CMB photons => initial conditions of universe. Similarly, direct and virtual photons in heavy ion collisions => information on initial state of HIC, including deviations from thermal eq. in hot plasma.

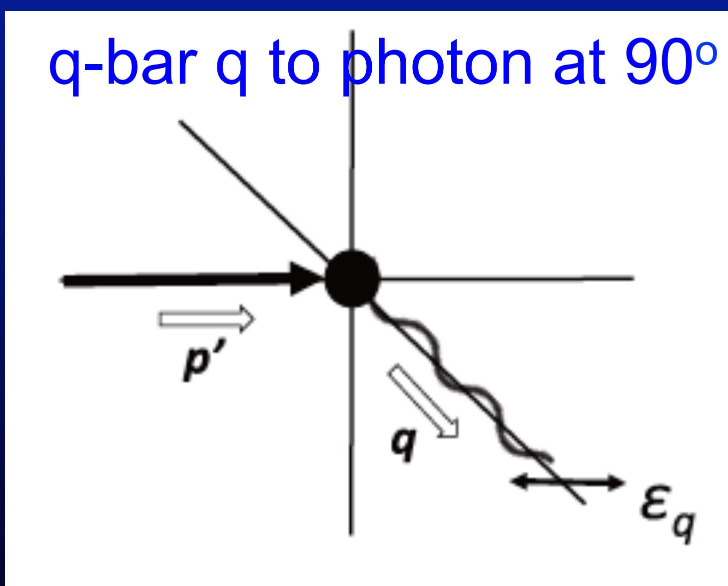
Large expected gluon anisotropy -- large flow along beam axis z -- strongly affects spectrum and polarization of photons! Detecting polarization probes anisotropy at all stages of collisions.

Origin of photon polarization: electric currents in collision



-- vertical gluon polarization shakes quark up and down => photon polarized out of scattering plane.

-- horizontal gluon polarization shakes quark in and out of plane, trying to produce (not possible) longitudinally polarized photon.



-- in rest frame of quark, the anti-quark generates current along its momentum => photon polarized along anti-quark momentum, in the scattering plane.

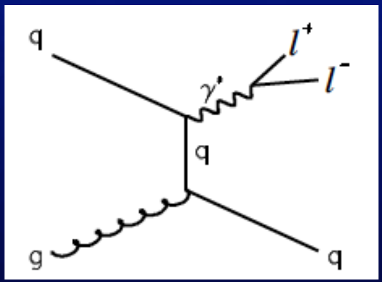
Polarizations from the two processes are perpendicular (but to see which is dominant requires detailed calculations)

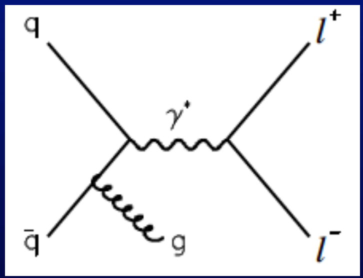
Experimental measurement of polarization

Measure angular distribution of lepton pairs, produced via

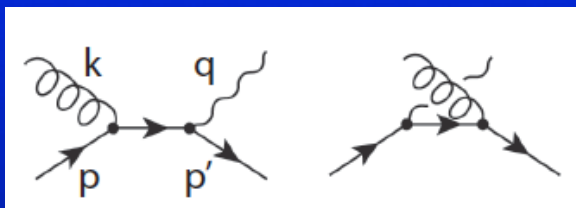
1) conversion of direct photons on foil to dilepton pairs
   Small opening angle of pairs, plus rescattering in foil => difficult (or impossible) to identify pairs and reconstruct polarization.

2) much more promising is to take advantage of internal conversion to measure decay of virtual photons to $\ell^+\ell^-$
   (Hoyer 1987, Bratkovskaya et al. 1995, Shuryak 2012)



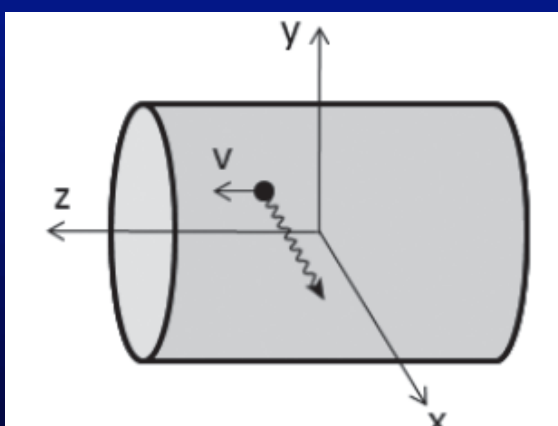


Toy model: Compton scattering on heavy quark scattering centers (GB + T. Hatsuda, PTEP 2015)



$$|\mathcal{M}_{\mathrm{C}}|^2 = \frac{e^2 g^2}{3}\left(\frac{\omega_g}{\omega_\gamma} + \frac{\omega_\gamma}{\omega_g} - 2 + 4\left(\vec{\varepsilon}_k \cdot \vec{\varepsilon}_q\right)^2\right)$$

Average Compton scattering rate over gluon polarizations



Anisotropy for photon along x direction at zero rapidity:

$$r(q_\perp, Y = 0) \equiv \frac{dN_{\hat{z}}/d\Gamma - dN_{\hat{y}}/d\Gamma}{dN_{\hat{z}}/d\Gamma + dN_{\hat{y}}/d\Gamma},$$

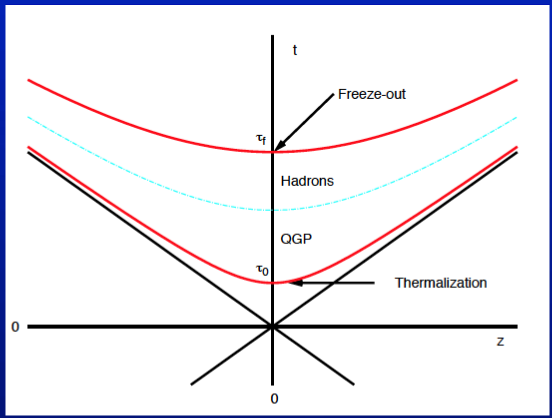
Simple parametrization of gluon anisotropy

P. Romatschke and M. Strickland, PRD 68, 036004 (2003)

In local rest frame $f_{\vec{k};\xi} = e^{-[k_x^2+k_y^2+(1+\xi)k_z^2]^{1/2}/T}$

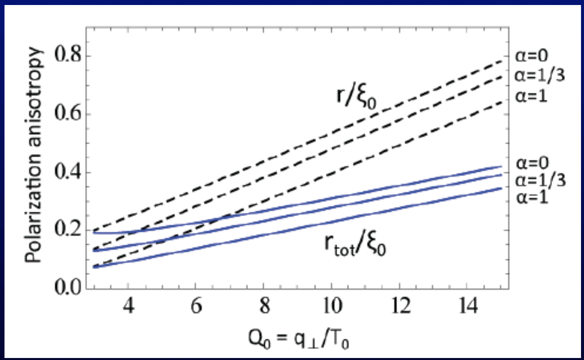
Boltzmann valid for k ~ GeV >>T

Lower gluon temperature along z:



Space-time averaging via Bjorken expansion

Estimated anisotropy: r_{tot} ~10-40%



More realistically (M. Strickland): r_{tot} ~3-5%

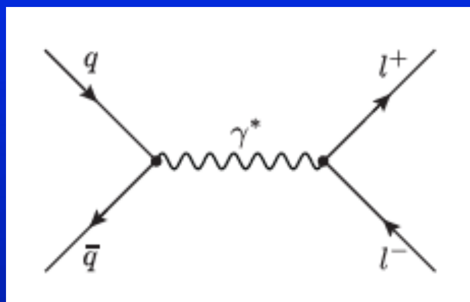
Given low polarization and difficulty in detecting direct photon polarization, turn to virtual photons:

Virtual photon polarization

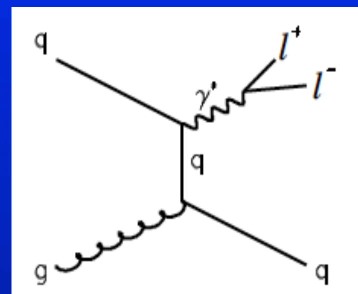
Off-shell photon, γ*, with $Q^2 > 0$

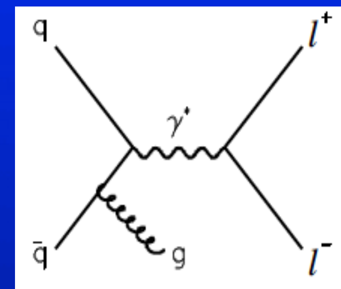
p, p' = lepton 4-momenta

Q = p+p'
s = p - p



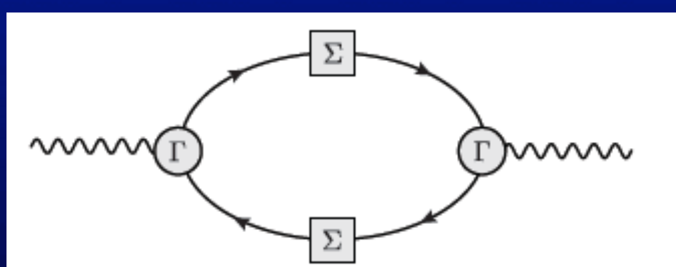
Drell-Yan

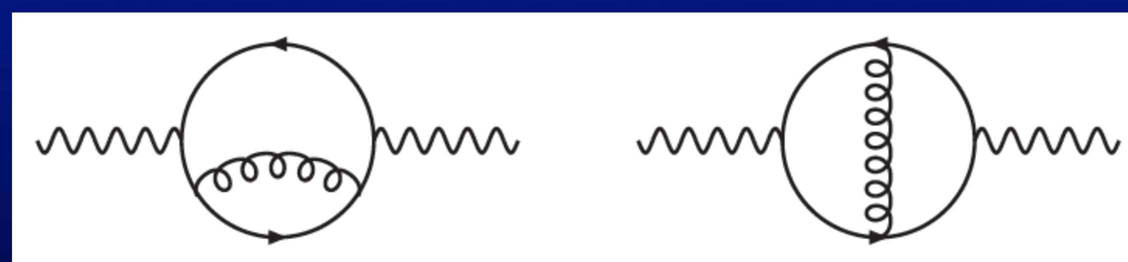




with gluons

Production rate of virtual photons ~ imaginary part of photon polarization diagram $\rho_{\mu\nu}(q)$





times ME squared $L^{\mu\nu}$ for making dilepton pair (Drell-Yan)

$$\frac{dR_{l^+l^-}}{d^3\bar{p}d^3\bar{p}'} = \frac{\alpha^2}{4\pi^4 Q^4}\, \rho_{\mu\nu}(q) L^{\mu\nu}(p,p')$$

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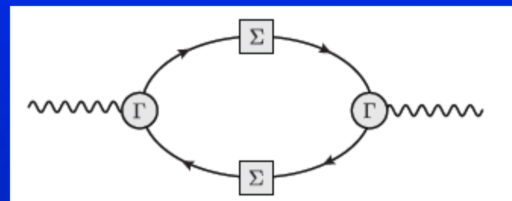
Photon polarization:

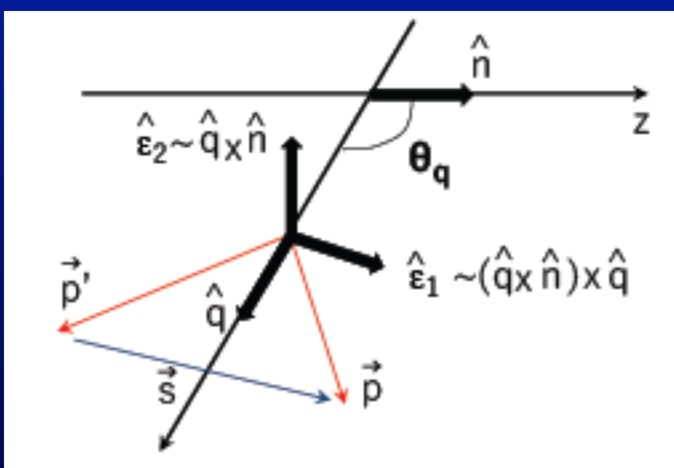


$$\Pi_{\mu\nu}(\vec{q},z) = e^2\int_{-\infty}^{\infty}\frac{dq^0}{2\pi}\,\frac{\rho_{\mu\nu}(\vec{q},q^0)}{z-q^0}$$

General structure of $\rho_{\mu\nu}(q)$: **q** = photon 3-momentum

$\hat{n}$ = beam (anisotropy) axis.

$$n^\mu = (0,\hat{n})$$



Transverse polarization vectors

$$\hat{\varepsilon}_1 \equiv (\vec{q}\times\hat{n})\times\vec{q}/|\vec{q}\times\hat{n}| \qquad \hat{\varepsilon}_2 \equiv \vec{q}\times\hat{n}/|\vec{q}\times\hat{n}| \qquad \varepsilon_i^\mu = (0,\hat{\varepsilon}_i)$$

Longitudinal polarization

$$\varepsilon_{\rm L}^\mu \equiv \frac{1}{\sqrt{Q^2}}(|\vec{q}|,q^0\hat{q})$$

Construct basis of four 4-vectors

$$g^{\mu\nu} = \frac{q^\mu q^\nu}{Q^2} - \varepsilon_1^\mu\varepsilon_1^\nu - \varepsilon_2^\mu\varepsilon_2^\nu - \varepsilon_{\rm L}^\mu\varepsilon_{\rm L}^\nu$$

$$\rho_{\mu\nu} \sim a\varepsilon_{\mathrm{L}}^{\mu}\varepsilon_{\mathrm{L}}^{\nu} + b\varepsilon_{1}^{\mu}\varepsilon_{1}^{\nu} + c(\varepsilon_{1}^{\mu}\varepsilon_{\mathrm{L}}^{\nu} + \varepsilon_{\mathrm{L}}^{\mu}\varepsilon_{1}^{\nu}) + d\varepsilon_{2}^{\mu}\varepsilon_{2}^{\nu}$$

No terms ~ $q^\mu q^\nu$

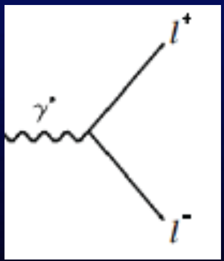
Anisotropy 4-axis orthogonal to q^μ : $\mathcal{N}^{\mu} = n^{\mu} - (qn)q^{\mu}/Q^{2}$

$$\rho^{\mu\nu} = \varepsilon_{\mathrm{L}}^{\mu}\varepsilon_{\mathrm{L}}^{\nu}\rho^{\mathrm{L}} + \varepsilon_{1}^{\mu}\varepsilon_{1}^{\nu}\rho_{1}^{\mathrm{T}} + \varepsilon_{2}^{\mu}\varepsilon_{2}^{\nu}\rho_{2}^{\mathrm{T}} + \mathcal{N}^{\mu}\mathcal{N}^{\nu}\rho_{n}$$

$$= -(g^{\mu\nu} - q^{\mu}q^{\nu}/Q^{2})\rho^{\mathrm{L}} + \varepsilon_{1}^{\mu}\varepsilon_{1}^{\nu}(\rho_{1}^{\mathrm{T}} - \rho^{\mathrm{L}}) + \varepsilon_{2}^{\mu}\varepsilon_{2}^{\nu}(\rho_{2}^{\mathrm{T}} - \rho^{\mathrm{L}}) + \mathcal{N}^{\mu}\mathcal{N}^{\nu}\rho_{n}$$

Have 4 spectral functions, $\rho_1^T, \rho_2^T, \rho_L, \rho_n$, vs. 2 for real photons

If $\hat{n}$ enters as an axis (reflection invariance along beam axis and not a direction (e.g., AA' collisions) then $\rho_n \equiv 0$



Lepton matrix elements squared:

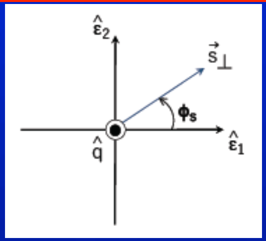
$$L_{\mu\nu}(q,s) \sim \sum_{spins} (\bar{u}_p\gamma_\mu u_{p'})(\bar{u}_{p'}\gamma_\nu u_p) = 2\left(q_\mu q_\nu - g_{\mu\nu}Q^2 - s_\mu s_\nu\right)$$

Dilepton rate

$$\frac{dR_{l^+l^-}}{d^3\bar{p}d^3\bar{p}'} = \frac{\alpha^2}{4\pi^4 Q^4}\,\rho_{\mu\nu}(q)L^{\mu\nu}(p,p')$$

$$\frac{1}{2}\rho^{\mu\nu}L_{\mu\nu} \;=\; 2Q^2\bar{\rho}^{\rm T} + \left(s_\perp^2 + 4m^2\right)\rho^{\rm L} + \left(Q^2 + (qn)^2 - (sn)^2\right)\rho_n - s_\perp^2\left(\bar{\rho}^{\rm T} + \delta\rho^{\rm T}\cos 2\phi_s\right)$$

$$\bar{\rho}^{\rm T} \equiv (\rho_1^{\rm T} + \rho_2^{\rm T})/2 \qquad \delta\rho^{\rm T} \equiv (\rho_2^{\rm T} - \rho_1^{\rm T})/2 \qquad \vec{s}_\perp = s_1\vec{\varepsilon}_1 + s_2\vec{\varepsilon}_2$$



Real photon emission

$$\frac{dR_\gamma}{d^3\bar{q}} = \frac{\alpha}{2\pi^2}\left(\bar{\rho}^{\rm T} + \delta\rho^{\rm T}\cos 2\phi_\varepsilon\right)$$

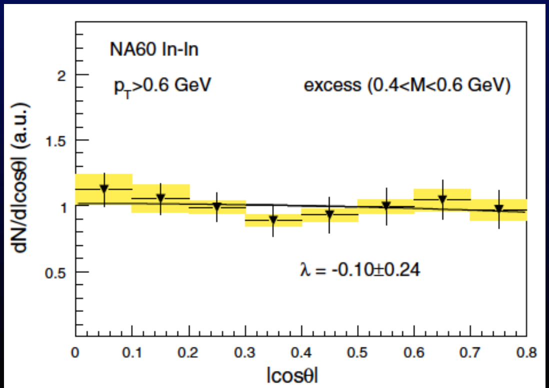
$$d^3\bar{q} = d^3q/2|\vec{q}|$$

$$(\varepsilon\varepsilon_1) \equiv -\cos\phi_\varepsilon$$

Dilepton angular distribution

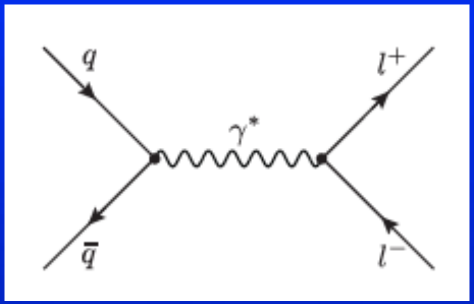
$$\propto 1 + \lambda\cos^2\theta_s + \mu\sin 2\theta\cos\phi_s + (\nu/2)\sin^2\theta\cos 2\phi_s$$

$$\lambda = \frac{\bar{\rho}^{\rm T} - \rho^{\rm L}}{\bar{\rho}^{\rm T} + \rho^{\rm L}}, \qquad \nu = 2\frac{\delta\rho^{\rm T}}{\bar{\rho}^{\rm T} + \rho^{\rm L}} \qquad \mu = 0$$



cf. NA60 (In-In at 158GeV/A SPS, PRL102, 2009) find λ, μ, ν consistent with 0. But average of data over all directions of total dilepton pair momenta loses anisotropy information.

Drell-Yan rate as illustrative example



rate for quark pair to produce virtual photon

$$H_{\mu\nu}(q,t) = 2(q_\mu q_\nu - g_{\mu\nu}Q^2 - t_\mu t_\nu)$$

$$t = k - k'$$

$$\rho^{\mu\nu}(q) = 2(q_\mu q_\nu - g_{\mu\nu}Q^2)\langle 1\rangle - 2\langle t_\mu t_\nu\rangle$$

$$\langle X\rangle \equiv 3\sum_{\rm f}\frac{e_{\rm f}^2}{4\pi^2}\int d^3\bar{k}d^3\bar{k}'\; X\,\delta^{(4)}(q-k-k')f(\vec{k})\bar{f}(\vec{k}')$$

$$\begin{aligned}\rho_1^{\rm T} + \sin^2\theta\,\rho_n &= 2Q^2\langle 1\rangle - 2\langle(\varepsilon_1 t)^2\rangle,\\ \rho_2^{\rm T} &= 2Q^2\langle 1\rangle - 2\langle(\varepsilon_2 t)^2\rangle,\\ \rho^{\rm L} + (\bar{q}^0)^2\cos^2\theta\,\rho_n &= 2Q^2\langle 1\rangle - 2\langle(\varepsilon_{\rm L} t)^2\rangle\end{aligned}$$

$$\rho_n = -\frac{4}{\bar{q}^0\sin 2\phi}\langle(\varepsilon_1 t)(\varepsilon_{\rm L} t)\rangle \Rightarrow 0$$

Assume angular dep. temperature

$$f(\vec{k}) = \frac{1}{e^{\beta(\hat{k})k}+1}.$$

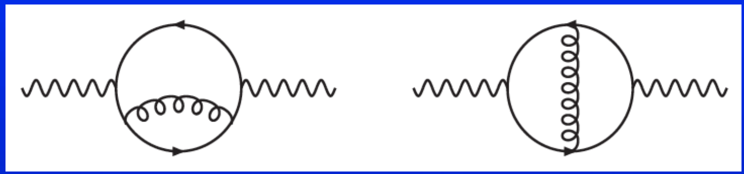
Weak anisotropy:

$$\delta\rho^{\rm T} \sim \beta_2 = \frac{1}{2}\int_{-1}^{1} d\cos\theta\,\beta(\theta)P_2(\cos\theta)$$

Dileptons measure the second spherical harmonic of temperature

Looking ahead: realistic calculations

GB, T. Hatsuda, A. Ipp, M. Strickland, L. Bhattacharya



With full framework for relating polarization information in dilepton distributions to underlying space-time dependent gluon and quark distributions in collisions.

Include polarization dependent Compton and annihilation to generalize
B. Schenke and M. Strickland PRD 76, 025023 (2007)
(*Photon production from an anisotropic quark-gluon plasma*):
Full 3+1d anisotropic hydro codes (M. Strickland, NPA 926, 92 (2014))
=> space-time evolution with anisotropic quark, antiquark and gluon distributions, hard (thermal loop) and soft scale processes.

Eventually include:

- initial gluon polarization, longitudinal gluons, finite screening effects
- strong initial gluon anisotropies, e.g., from color glass condensate
- effects of off-shell gluons (bremsstrahlung).

Large initial gluon anisotropy => true signal in heavy ion is suppression of direct and virtual photon polarization as system thermalizes!