Polarization of dileptons in heavy-ion collisions

Hendrik van Hees

Goethe University Frankfurt

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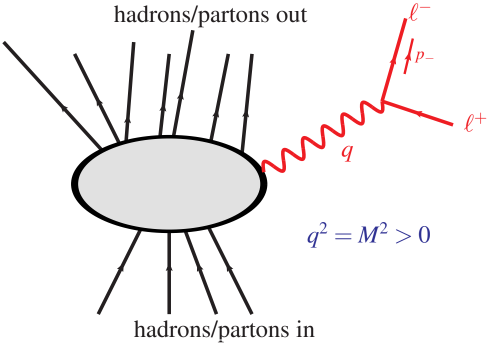
Outline

Production rates for dileptons



- Fermi's golden rule $\Rightarrow$ transition-matrix element for process $|i\rangle \to |f'\rangle = |f \ell^+ \ell^-\rangle$
- QED Feynman rules

The McLerran-Toimela formula

- result (in rest frame of dilepton!)

$$\frac{\mathrm{d}N_{\ell^+\ell^-}}{\mathrm{d}^4x\,\mathrm{d}^4q\,\mathrm{d}^2\Omega_\ell} = \frac{\alpha^2}{32\pi^3}\frac{1}{M^4}\sqrt{1-\frac{4m_\ell^2}{M^2}}L_{\mu\nu}\rho^{\mu\nu}n_{\mathrm{B}}(u\cdot q)$$

- spectral, thermal, and polarization of γ^* information!
- u: four-velocity of fluid cell, $\vec{q}^{*2}=(u\cdot q)^2-q^2$: γ^*-momentum in fluid rest frame
- $M^2=q\cdot q$: invariant mass, $u\cdot q$: energy of dilepton in rest frame of fluid cell
- $\mathrm{d}^2\Omega_\ell$: solid angle of lepton momentum, $\vec{p}_-$ (in rest frame of virtual photon)
- $L_{\mu\nu}=2[M^2\Theta_{\mu\nu}-2(p_\mu^- q_\nu+p_\nu^- q_\mu)+4p_\mu^- p_\nu^-]$: Lepton tensor
- in-medium electromagnetic current-current correlation function

$$\mathrm{i}\Pi^{\mu\nu}_{\mathrm{ret}}(q):=\int \mathrm{d}^4x\;\exp(\mathrm{i}q\cdot x)\left\langle\left[\mathbf{J}^\mu_{\mathrm{em}}(x),\mathbf{J}^\nu_{\mathrm{em}}(0)\right]\right\rangle_{T,\mu_B}\Theta(x^0)$$

- written in (local) rest frame of the medium:
  $\rho^{\mu\nu}=-2\,\mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{ret}}(M^2,|\vec{q}^*|)=\rho_{\mathrm{T}}(M,|\vec{q}^*|)\Theta^{\mu\nu}_{\mathrm{T}}+\rho_{\mathrm{L}}(M,|\vec{q}^*|)\Theta^{\mu\nu}_{\mathrm{L}}$

Radiation from thermal QGP: $q\overline{q}$ annihilation

- McLerran-Toimela formula for γ^* (integrate over $\mathrm{d}^2\Omega_\ell$)

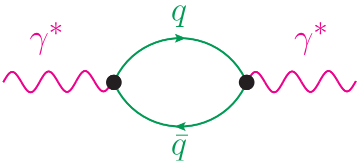
$$\frac{\mathrm{d}N_{\ell^+\ell^-}}{\mathrm{d}^4x\,\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{M^2+2m_\ell^2}{M^4}\sqrt{1-\frac{4m_\ell^2}{M^2}}\,g_{\mu\nu}\,\mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{ret}}(M,\vec{q})\,n_{\mathrm{B}}(u\cdot q)$$

- in-medium em. current-current correlation function

$$\mathrm{i}\Pi^{\mu\nu}_{\mathrm{ret}}(q) := \int \mathrm{d}^4x\;\exp(\mathrm{i}q\cdot x)\left\langle\left[\mathbf{J}^{\mu}_{\mathrm{em}}(x),\mathbf{J}^{\nu}_{\mathrm{em}}(0)\right]\right\rangle_{T,\mu_B}\Theta(x^0)$$

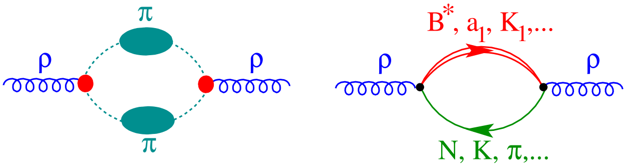
- Feynman diagrams: photon self-energy
- in QGP phase: $q\overline{q}$ annihilation
- hard-thermal-loop improved em. current-current correlator

$$-\mathrm{i}\Pi_{\mathrm{em,QGP}} =$$



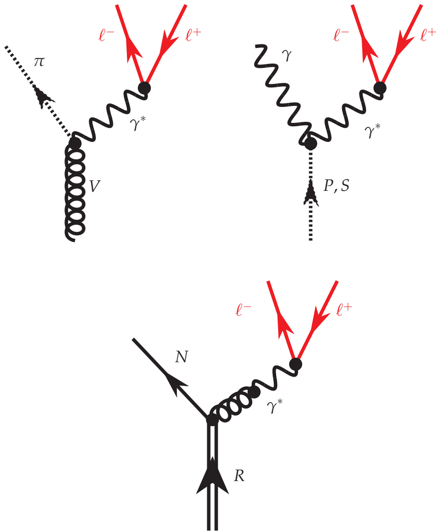
Hadronic many-body theory

- hadronic many-body theory (HMBT) of vector mesons
  [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, ...]
- $\pi\pi$ interactions and hadronic excitations
- effective hadronic models, implementing symmetries
- good approximation: vector-meson dominance, $J_{\text{em}}^{\mu} \propto \rho^{\mu}, \omega^{\mu}, \phi^{\mu}$
- dilepton/photon rates then $\propto \operatorname{Im} D_{\text{VM}}$ (VM-spectral functions)
- parameters fixed by phenomenology
  (photon absorption at nucleons and nuclei, $\pi N \rightarrow \rho N$)
- evaluated at finite temperature and density
- self-energies $\Rightarrow$ mass shift and broadening in the medium

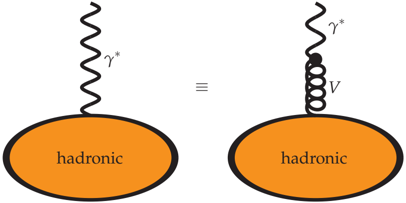


- Baryons important, even at low **net** baryon density $n_B - n_{\overline{B}}$
- reason: $n_B + n_{\overline{B}}$ relevant (CP inv. of strong interactions)

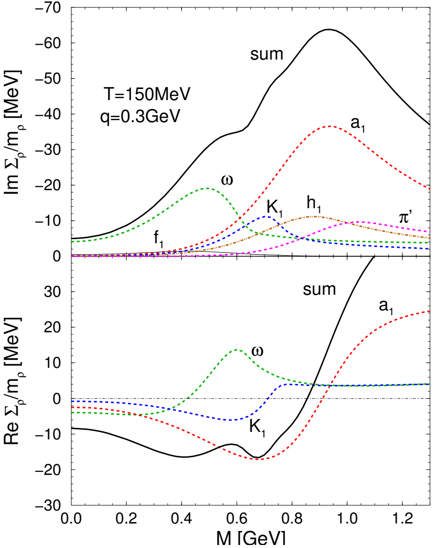
Dalitz decays



- Dalitz decay:
  1 particle $\longrightarrow$ 3 particles
- V: $\omega \to \pi + \gamma^* \to \pi + \ell^+ + \ell^-$
- P, S: $\pi, \eta \to \gamma + \gamma^* \to \gamma + \ell^+ + \ell^-$
- R: Baryon resonances
  $\Delta, N^* \to N + V \to N + \gamma^* \to N + \ell^+ + \ell^-$
- vector-meson dominance

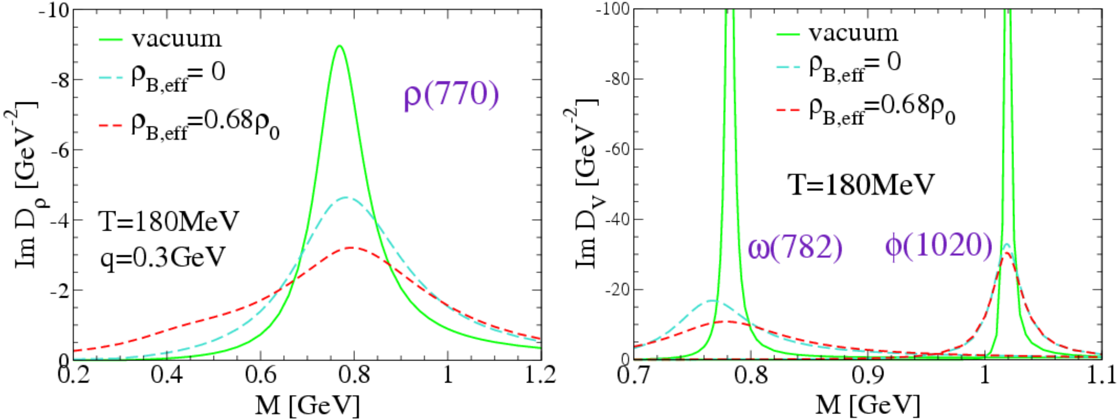


Meson contributions



[RG99]

In-medium spectral functions and baryon effects

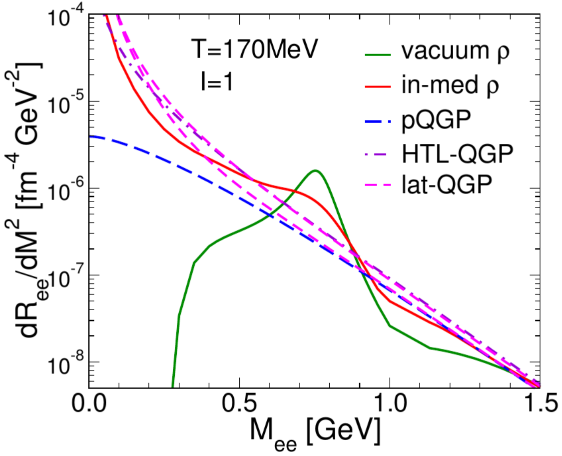


[RW99]

- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M

Dilepton rates: Hadron gas ⟷ QGP

- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?



Bulk evolution with transport and coarse graining

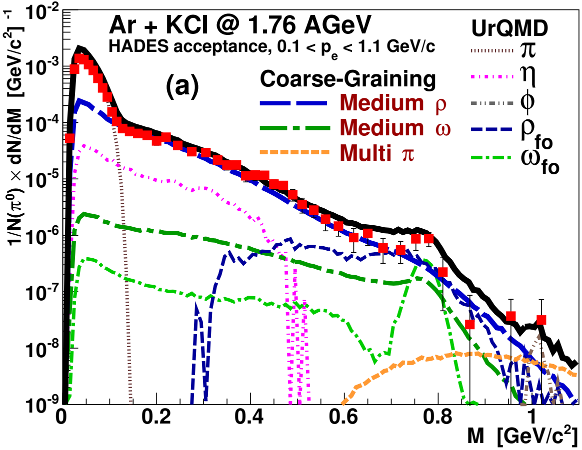
- established transport models for bulk evolution
  - e.g., UrQMD, GiBUU, BAMPS, (p)HSD,...
  - solve Boltzmann equation for hadrons and/or partons
- dilemma: need medium-modified dilepton/photon emission rates
- usually available only in equilibrium QFT calculations
- one way out:
  - UrQMD transport for entire bulk evolution
    $\Rightarrow$ use coarse graining in space-time cells $\Rightarrow$ extract $T, \mu_B, \mu_\pi, \ldots$
    $\Rightarrow$ use equilibrium rates locally
  - fit temperature, chemical potentials, flow-velocity field
    from anisotropic energy-momentum tensor [FMRS13]

$$T^{\mu\nu} = (\epsilon + P_\perp) u^\mu u^\nu - P_\perp g^{\mu\nu} - (P_\parallel - P_\perp) V^\mu V^\nu$$

  - thermal rates from partonic/hadronic QFT become applicable

Dielectrons (SIS/HADES)

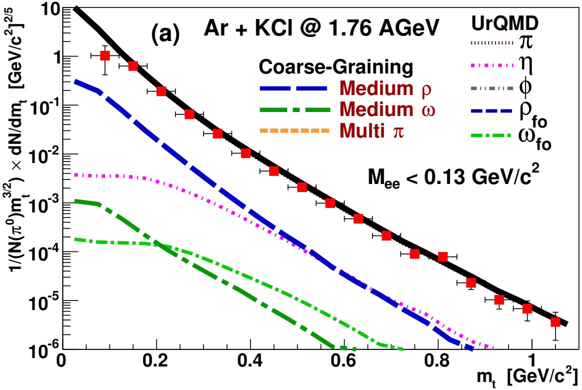
- coarse-graining method works at low energies!
- UrQMD-medium evolution + RW-QFT rates



[S. Endres, HvH, J. Weil, M. Bleicher] [EHWB15b]

CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra
- $M_{\mathrm{ee}} < 0.13\,\mathrm{GeV}$



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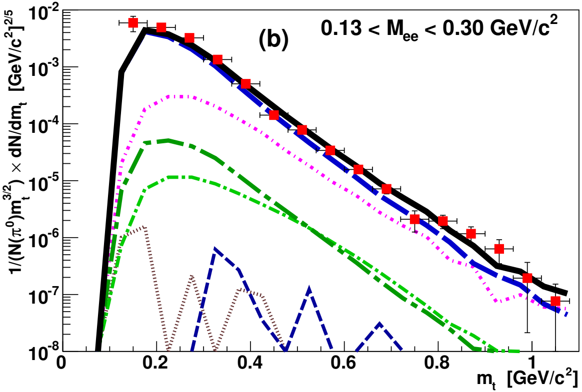
- m_t spectra
- $0.13\,\text{GeV} M_{ee} < 0.3\,\text{GeV}$



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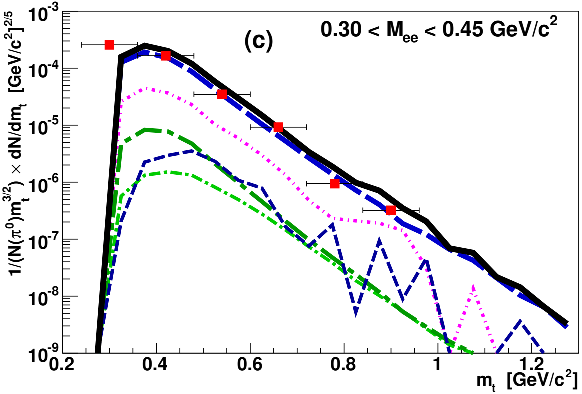
- m_t spectra
- $0.3\,\mathrm{GeV}\, M_{ee} < 0.45\,\mathrm{GeV}$



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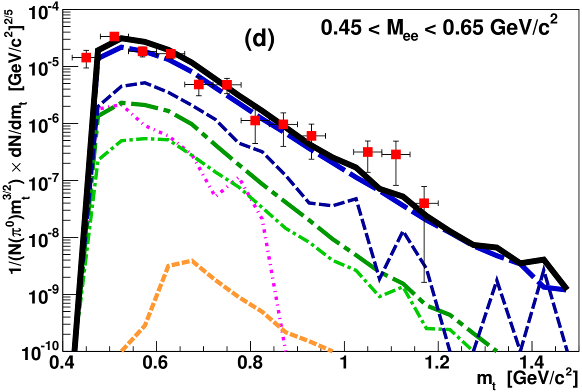
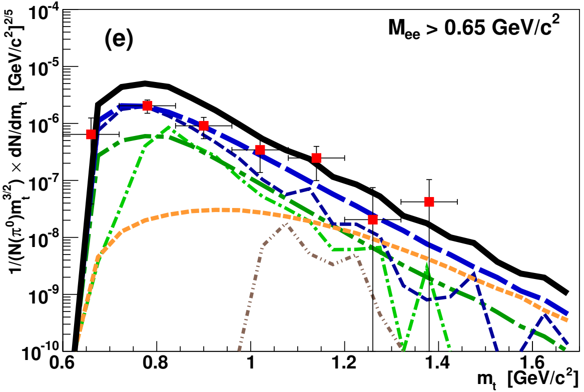
- dielectron spectra from $\text{Ar}+\text{KCl}(1.76\,A\text{GeV}) \rightarrow e^+e^-$ (SIS/HADES)
- m_t spectra
- $0.45\,\text{GeV} M_{ee} < 0.65\,\text{GeV}$



[S. Endres, HvH, J. Weil, M. Bleicher] [EHWB15b]

CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from Ar + KCl(1.76 *A*GeV) $\rightarrow e^+e^-$ (SIS/HADES)
- m_t spectra
- $M_{ee} > 0.65$ GeV



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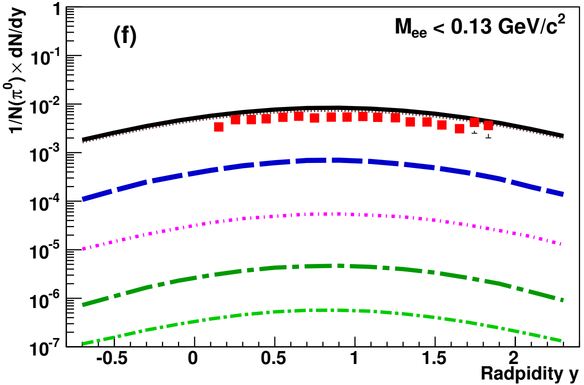
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

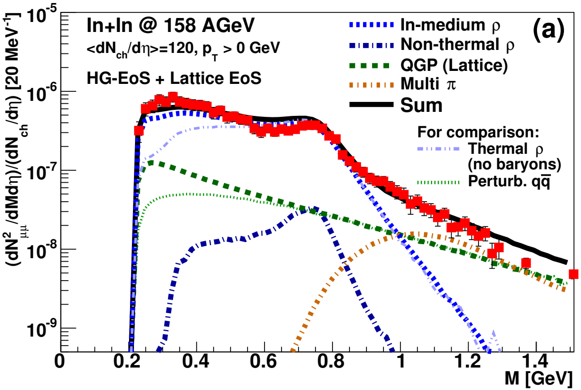
- dielectron spectra from $\mathrm{Ar} + \mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra
- rapidity spectrum ($M_{\mathrm{ee}} < 0.13$ GeV)



[S. Endres, HvH, J. Weil, M. Bleicher] [EHWB15b]

Dimuons (SPS/NA60)

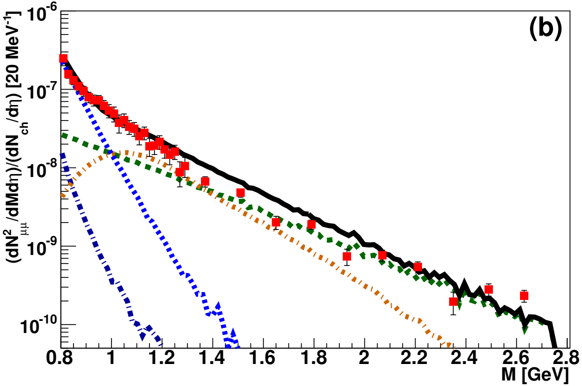
- dimuon spectra from In + In(158 AGeV) $\rightarrow \mu^+\mu^-$ (NA60) [EHWB15b]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)



[S. Endres, HvH, J. Weil, M. Bleicher] [EHWB15a]

CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from In + In(158 *A*GeV) → $\mu^+\mu^-$ (NA60) [EHWB15b]
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- higher IMR: provides averaged true temperature $\langle T \rangle_{1.5\,\mathrm{GeV} \lesssim M \lesssim 2.4\,\mathrm{GeV}} = 205\text{-}230\,\mathrm{MeV}$
- clearly above $T_c \simeq 150\text{-}160\,\mathrm{MeV}$ (no blueshifts in the invariant-mass spectra!)



[S. Endres, HvH, J. Weil, M. Bleicher] [EHWB15a]

γ^*-polarization observables

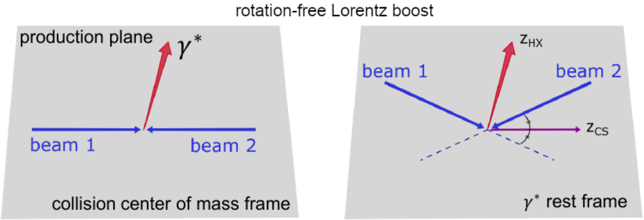
F. Seck, B. Friman, T. Galatyuk, HvH, E. Speranza, R. Rapp, J. Wambach

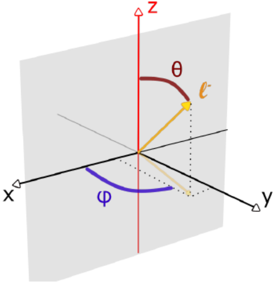
arXiv:2309.03189 [nucl-th]

Frames

- Helicity Frame HX, Collins-Soper Frame,... choice of “spin-quantization axis”

  [P. Faccioli and C. Lourenço, Particle Polarization in High Energy Physics, Springer, Cham (2022)] [FL22]





[F. Seck QM23 Talk]

- in γ^* rest frame (general form for parity-conserving decays of massive vector particles

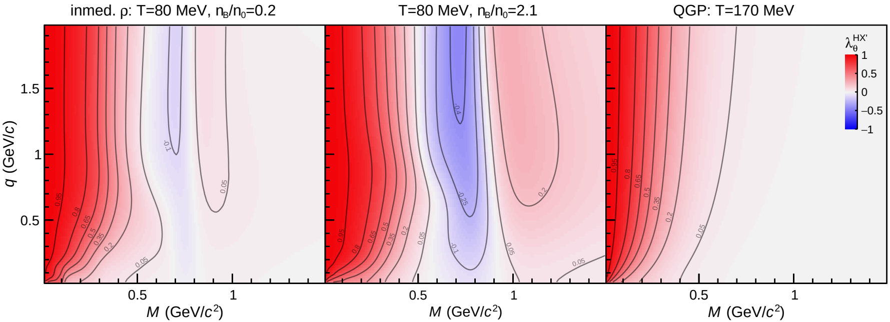
$$\frac{\mathrm{d}N_{\ell^+\ell^-}}{\mathrm{d}^4 x\,\mathrm{d}^4 q\,\mathrm{d}^2\Omega_\ell} = \mathcal{N}\Big(1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta)\cos\phi + \lambda_\phi^\perp \sin^2\theta \sin(2\phi) + \lambda_{\theta\phi}^\perp \sin(2\theta)\sin\phi\Big)$$

- λ’s depend on choice of “frame”! Transformation via corresponding rotations of axes

HX' frame

- for γ^*/dileptons from thermal medium $\Rightarrow$ "preferred frame" (local) rest frame of heat bath
- use $\vec{q}$ as quantization direction $\Rightarrow$ HX' frame
- in γ^* rest frame: only preferred direction is $\vec{u} \Rightarrow$ only $\lambda'_\theta \neq 0$:

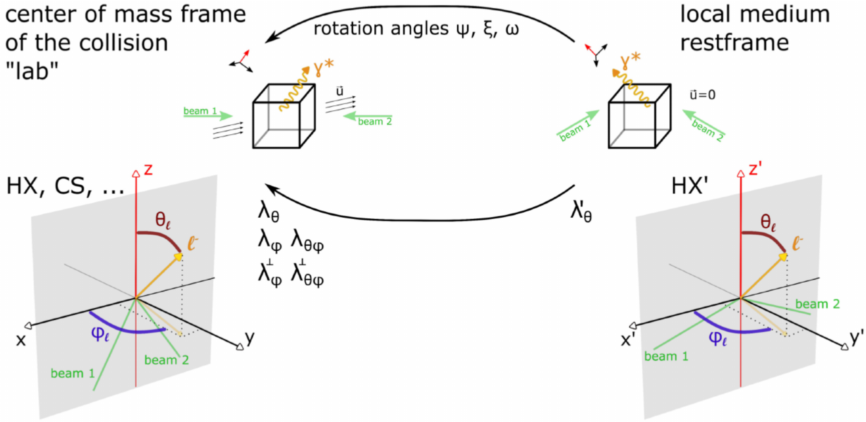
$$\lambda'_\theta = \frac{2(M^2 - 4m_\ell^2)(\rho_T - \rho_L)}{2M^2(\rho_L + \rho_T) + 8m_\ell^2 \rho_T} \underset{m_\ell \ll M}{\cong} \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$$



[F. Seck, B. Friman, T. Galatyuk, HvH, E. Speranza, R. Rapp, J. Wambach, arXiv:2309.03189 [nucl-th]] [SFG+23]

Dilepton polarization observables in heavy-ion collisions

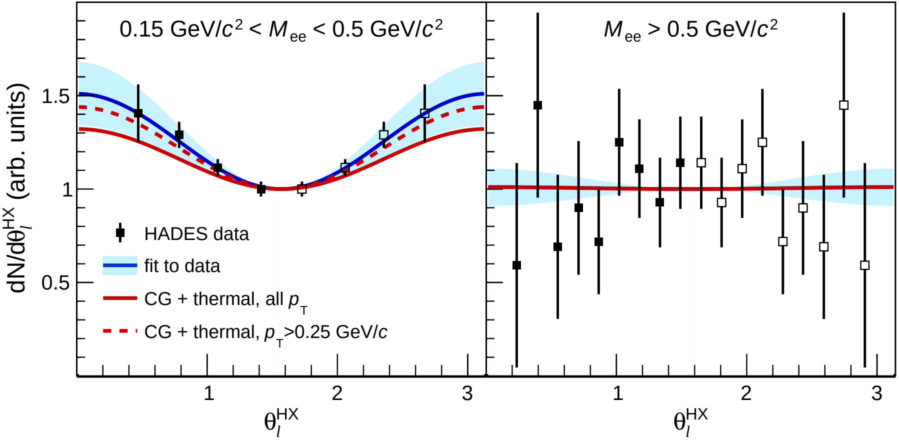
- fireball described as fluid (blast-wave model or coarse-grained transport)
- transform for each fluid cell by rotation from HX' to HX (for HADES experiment) or CS frame (for NA60 experiment)



[F. Seck, QM23 Talk]

Comparison to data: HADES

- $\theta^{(\mathrm{HX})}$ distribution measured by HADES in Ar+KCl collisions at $1.76A\mathrm{GeV}$ [A+11]



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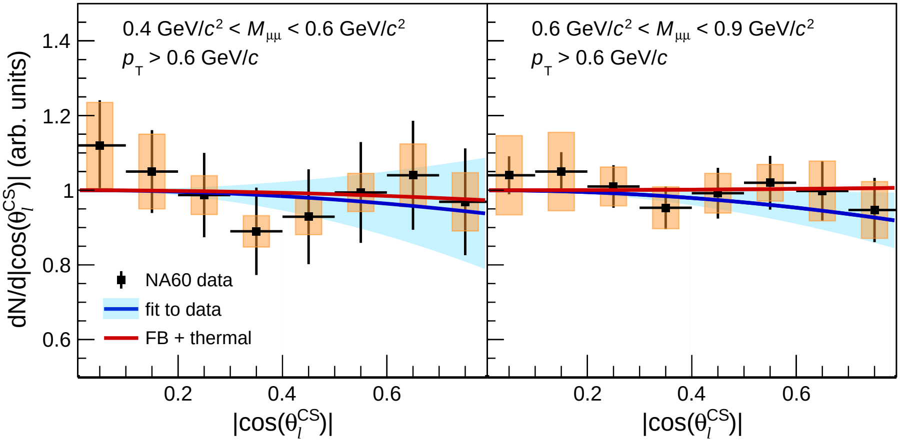
Comparison to data: NA60

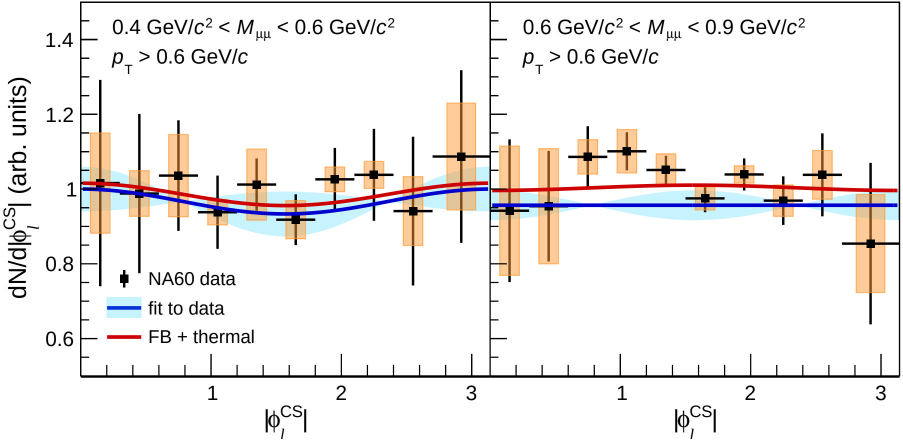
- $\lambda_\theta^{(\mathrm{CS})}$ measured by NA60 in In+In collisions at $158A\mathrm{GeV}$ [A+09]



[F. Seck, B. Friman, T. Galatyuk, HvH, E. Speranza, R. Rapp, J. Wambach, arXiv:2309.03189 [nucl-th]] [SFG+23]

Comparison to data: NA60

- $\theta^{(\mathrm{CS})}$ and $\phi^{(\mathrm{CS})}$ distributions measured by NA60 in In+In collisions at 158AGeV [A+09]



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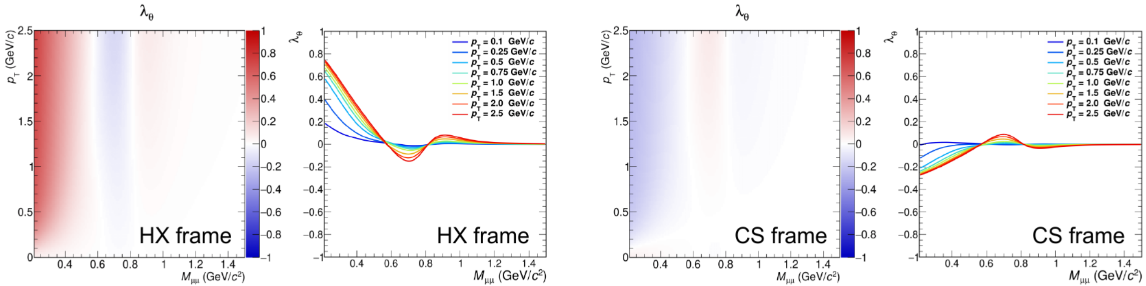
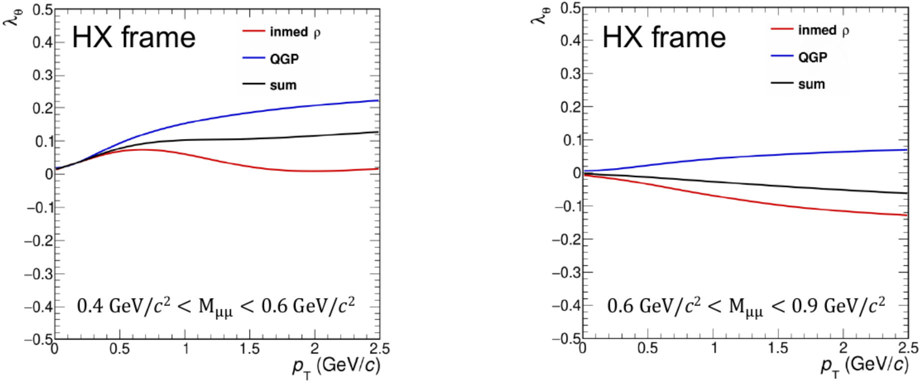
HX versus CS frame for NA60



[F. Seck, QM23 Talk]

- polarization coefficients pretty sensitive to choice of frame!

Outlook: more high-precision differential dilepton spectra



[F. Seck, QM23 Talk]

- sensitivity to kind of source!?!

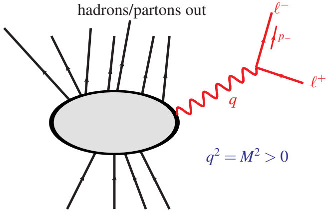
Conclusions and Outlook

- General ideas
  - em. probes $\Leftrightarrow$ in-medium electromagnetic current-correlation function
  - dual rates around T_c (compatible with χ symmetry restoration)
  - medium modifications of ρ, ω, ϕ
  - importance of baryon-resonance interactions
- Application to dileptons in HICs
  - successful description from SIS to RHIC energies
  - consistent description of M and m_T spectra!
  - effective slope of M spectra ($1.5\,\text{GeV} < M < M_{J/\psi}$) provides $\langle T \rangle$
  - polarization observables need more differential measurements of dilepton spectra
  - models also here in good agreement with existing data (HADES Ar+KCl electrons, NA60 In+In muons)
- Outlook
  - better understanding of dilepton-production mechanisms with polarization observables
  - sensitivity to phase diagram?
  - relation to vorticity of medium and/or magnetic field?

Transversal projectors

- for q^μ (four-momentum of a massive vector boson/virtual γ/dilepton with invariant mass, $M^2 = q \cdot q = q_\mu q^\mu$)
$$\Theta_{\mu\nu} = \eta_{\mu\nu} - \frac{q_\mu q_\nu}{M^2}.$$
- in rest-frame of heat bath, $(u^\mu) = (1,0,0,0)$, this is further decomposed into 3D longitudinal and transverse parts
$$\Theta_{\text{T}}^{*\mu\nu} = \begin{pmatrix} 0 & \vec{0}^{\text{T}} \\ \vec{0} & \left(-\delta^{ij} + q^j q^k / \vec{q}^2\right) \end{pmatrix}, \quad \Theta_{\text{L}}^{*\mu\nu} = \Theta^{\mu\nu} - \Theta_{\text{T}}^{*\mu\nu}.$$
- in covariant form (valid in any frame)
$$\Theta_{\text{T}}^{\mu\nu} = \eta^{\mu\nu} - u^\mu u^\nu - \frac{q_\perp^\mu q_\perp^\nu}{q_\perp^2}, \quad \Theta_{\text{L}}^{\mu\nu} = \Theta^{\mu\nu} - \Theta_{\text{T}}^{\mu\nu} = u^\mu u^\nu - \frac{q^\mu q^\nu}{M^2} + \frac{q_\perp^\mu q_\perp^\nu}{q_\perp^2}.$$
- with $q_\perp^\mu = q^\mu - u^\mu (u \cdot q)$

Differential dilepton production rate



- in rest-frame of dilepton

$$\frac{\mathrm{d}N_{\ell\ell}}{\mathrm{d}^4x\,\mathrm{d}^4q\,\mathrm{d}^2\Omega_-} = L_{\mu\nu}\frac{\alpha_{\text{em}}^2}{32\pi^4}\frac{1}{M^4}\sqrt{1-\frac{4m_\ell^2}{M^2}}\rho^{\mu\nu}(q) f_{\text{B}}(u\cdot q)$$

- m: lepton mass
- in-medium spectral function of electromagnetic current-current correlation function

$$\rho^{\mu\nu} = -2\,\mathrm{Im}\,\Pi_{\text{ret}}^{\mu\nu} = \rho_{\text{T}}(M, u\cdot q)\Theta_{\text{T}}^{\mu\nu} + \rho_{\text{L}}(M, u\cdot q)\Theta_{\text{L}}^{\mu\nu}$$

- “lepton tensor”

$$L_{\mu\nu} = 2\left[M^2\Theta_{\mu\nu} - 2(p_\mu^- q_\nu + p_\nu^- q_\mu) + 4p_\mu^- p_\nu^-\right]$$

Polarization parameters in HX' frame

- "heat-bath-helicity frame" HX' frame defined for dileptons from a thermalized medium
- polarization axis: $\parallel \vec{q}\,' = Q' \vec{e}_3\,'$ in rest-frame of heat bath, $u' = (1,0,0,0)$
- boost to rest-frame of dilepton: $q = (M,0,0,0)$, $u = \gamma(1,0,0,-\beta)$, $\beta = Q'/E'_{\gamma^*} = Q'/\sqrt{M^2 + Q'^2}$, $p_- = (\sqrt{m_\ell^2 + P^2}, P\sin\theta\cos\phi, P\sin\theta\sin\phi, P\cos\theta)$

$$\frac{\mathrm{d}N_{\ell\ell}}{\mathrm{d}^4x\,\mathrm{d}^4q\,\mathrm{d}^2\Omega_-} = L_{\mu\nu}\frac{\alpha_{\mathrm{em}}^2}{32\pi^4}\frac{1}{M^4}\sqrt{1-\frac{4m_\ell^2}{M^2}}\rho^{\mu\nu}(q) f_{\mathrm{B}}(u\cdot q)$$
$$= \mathcal{N} A(1+\lambda'_\theta \cos^2\theta).$$

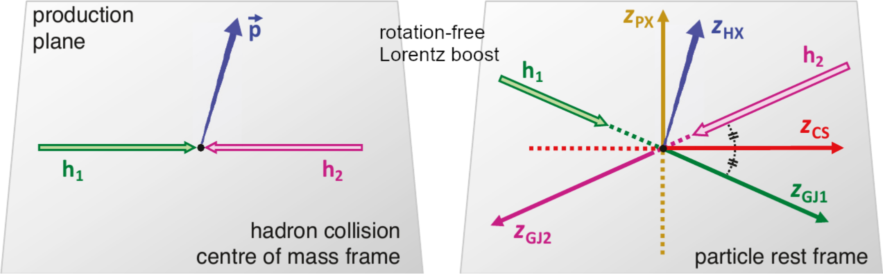
- with

$$\mathcal{N} = \frac{\alpha_{\mathrm{em}}^2}{32\pi^4}\frac{1}{M^4}\sqrt{1-\frac{4m_\ell^2}{M^2}} f_{\mathrm{B}}(u\cdot q),$$
$$A = 2M^2(\rho_{\mathrm{L}}+\rho_{\mathrm{T}}) + 8m_\ell^2\rho_{\mathrm{T}}, \quad B = A\lambda'_\theta = 2(M^2-4m_\ell^2)(\rho_{\mathrm{T}}-\rho_{\mathrm{L}}),$$
$$\lambda'_\theta = \frac{B}{A} = \frac{2(M^2-4m_\ell^2)(\rho_{\mathrm{T}}-\rho_{\mathrm{L}})}{2M^2(\rho_{\mathrm{L}}+\rho_{\mathrm{T}})+8m_\ell^2\rho_{\mathrm{T}}} \underset{m\ll M}{\cong} \frac{\rho_{\mathrm{T}}-\rho_{\mathrm{L}}}{\rho_{\mathrm{T}}+\rho_{\mathrm{L}}}$$

- check: integrate over $\mathrm{d}^2\Omega_-$ $\Rightarrow$ McLerran-Toimela formula!

Polarization parameters in arbitrary frame

- polarization axis determined in center-momentum frame of hadron collision
- different choices HX (helicity frame), CS (Collins-Soper frame), GJ (Gottfried-Jackson frame), PX (perpendicular helicity frame)...



[FL22]

Polarization parameters in arbitrary frame

- theory: start with $\vec{q}' = Q' \vec{e}_3'$ (now in cm frame of collision!); then boost to rest-frame of dilepton
- rotate $\vec{u}$ to basis of chosen polarization frame using Euler angles ω, ξ, ψ [Faccioli:2022peq]

$$\vec{u} = \gamma \hat{R}_3(\omega)\hat{R}_2(\xi)\hat{R}_3(\psi)(0,0,-\beta)^{\mathrm{T}} = \beta\gamma(\sin\xi\cos\omega, -\sin\xi\sin\omega, -\cos\xi)^{\mathrm{T}}.$$

- use general expression for differential production rate

$$\frac{\mathrm{d}R_{ll}}{\mathrm{d}^4 q\,\mathrm{d}^2\Omega_-} = \mathcal{N} A(1+\Lambda)\Big(1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta\cos 2\phi + \lambda_{\theta\phi}\sin 2\theta\cos\phi + \lambda_\phi^\perp \sin^2\theta \sin 2\phi + \lambda_{\theta\phi}^\perp \sin 2\theta \sin\phi\Big),$$

- with

$$\Lambda = \frac{1}{2}\lambda_\theta' \sin^2\xi, \quad \lambda_\theta = \frac{\lambda_\theta'}{1+\Lambda}\left(1 - \frac{3}{2}\sin^2\xi\right),$$
$$\lambda_\phi = \frac{1}{2}\frac{\lambda_\theta'}{1+\Lambda}\cos(2\omega)\sin^2\xi, \quad \lambda_\phi^\perp = -\frac{1}{2}\frac{\lambda_\theta'}{1+\Lambda}\sin(2\omega)\sin^2\xi,$$
$$\lambda_{\theta\phi} = -\frac{1}{2}\frac{\lambda_\theta'}{1+\Lambda}\cos\omega\sin(2\xi), \quad \lambda_{\theta\phi}^\perp = \frac{1}{2}\frac{\lambda_\theta'}{1+\Lambda}\sin\omega\sin(2\xi).$$

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