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UNDERSTANDING THE PROPERTIES OF THE FIREBALL WITH THE POLARIZATION SIGNATURE OF THERMAL DILEPTONS

Florian Seck
(TU Darmstadt)

in collaboration with B. Friman, T. Galatyuk, H. van Hees, R. Rapp, E. Speranza & J. Wambach

QM 2023

Quark Matter 2023, Houston

CRC–TR 211
Strong-interaction matter under extreme conditions

THERMAL DILEPTON RADIATION AS MULTIMETER OF THE FIREBALL

- Lifetime via low-mass yield
  → search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)

- Temperature via slope of invariant mass spectrum
  → **flattening** of caloric curve (T vs ε) sign for a **phase transition**

- Pressure anisotropies via dilepton flow
  → **access** to **EoS at high baryon density** via multi-differential measurements

- Electric conductivity probed in the limit p_{ee} = 0 MeV/c, M_{ee} → 0 MeV/c^2
  → **access** to **transport properties** of QCD matter

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T. Galatyuk, JPS Conf. Proc. 32 (2020), 010079
F. Seck *et al.*, Phys. Rev. C 106 (2022), 014904
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R. Chatterjee *et al.*, Phys. Rev. C 75 (2007), 054909
T. Reichert *et al.*, Phys. Lett. B 841 (2023) 137947

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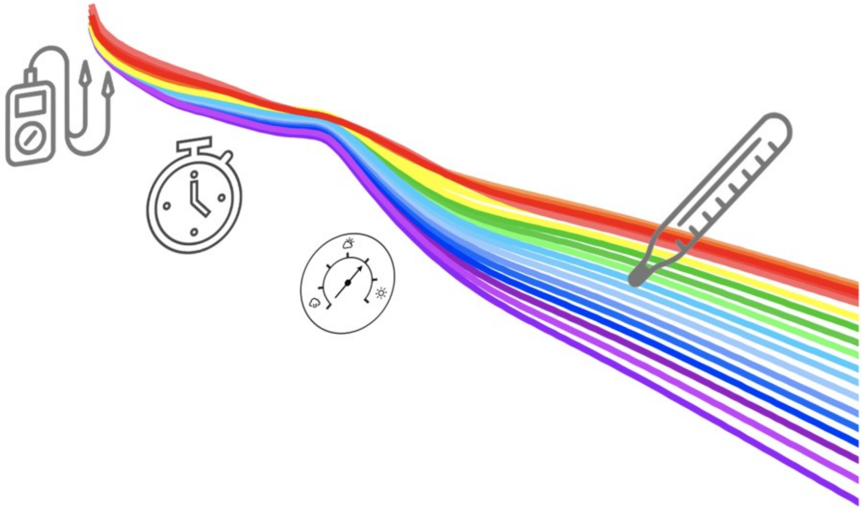

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- Electric conductivity probed in the limit p_{ee} = 0 MeV/c, M_{ee} → 0 MeV/c^2
  → **access** to **transport properties** of QCD matter

- Spin polarization allows to distinguish different sources of thermal dileptons
  → **access** information on **production mechanism**

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E. Bratkovskaya *et al.*, Phys. Lett. B 376, 12 (1996)
E. Speranza *et al.*, Phys. Lett. B 782, 395 (2018)
G. Baym *et al.*, Phys. Rev. C 95, 044907 (2017)
S. Hauksson, C. Gale, arXiv:2306.10307 [nucl-th] (2023)

KEY QUANTITY: EM EMISSIVITY

- EM emissivity of thermal QCD matter determined by the correlator of the EM current $\Pi^{\mu\nu}_{EM} = \langle j^{\mu}_{EM}\, j^{\nu}_{EM} \rangle_T$

- Dilepton emission rate given by

  $\frac{dN_{ll}}{d^4x\, d^4q} = \frac{\alpha^2\, L(M)}{6\,\pi^3\, M^2}\, f^B(q_0;\, T)\, g_{\mu\nu}\;\, \rho^{\mu\nu}_{EM}(M, |\vec{q}|;\, T, \mu_B)$ with $\rho^{\mu\nu}_{EM} = -2\, \mathrm{Im}\, \Pi^{\mu\nu}_{EM}$

- Decomposition using standard 4D projectors for a spin-1 particle $P^{\mu\nu}_{L,T}$

  $\rho^{\mu\nu}_{EM} = \rho_L\, P^{\mu\nu}_L + \rho_T\, P^{\mu\nu}_T$ with $g_{\mu\nu}\, \rho^{\mu\nu}_{EM} = \rho_L + 2\rho_T$

- Rotational symmetry of the medium broken by finite $|\vec{q}|$

- Angular distribution of single lepton in γ^* rest frame depends on polarization of γ^*:

  $$\frac{dN}{d^4x\, d^4q\, d\Omega} = \mathcal{N}\,(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda^\perp_\varphi \sin^2\theta \sin 2\varphi + \lambda^\perp_{\theta\varphi} \sin 2\theta \sin\varphi)$$

- λ coefficients related to **difference** between longitudinal and transverse spectral function components

  → for a static thermal medium in the helicity frame: $\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$

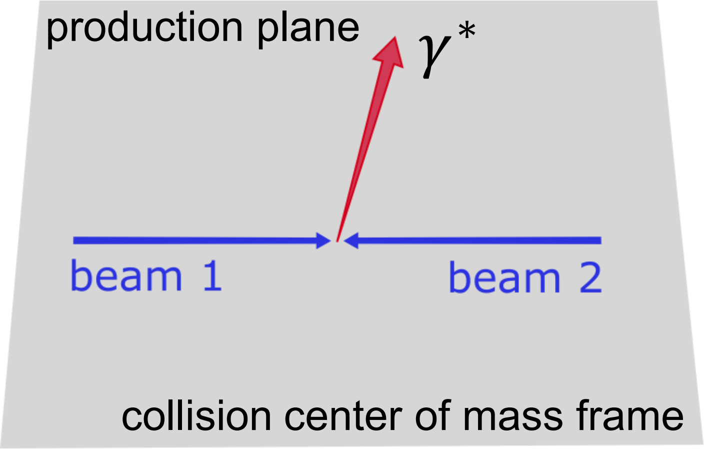
POLARIZATION FRAME

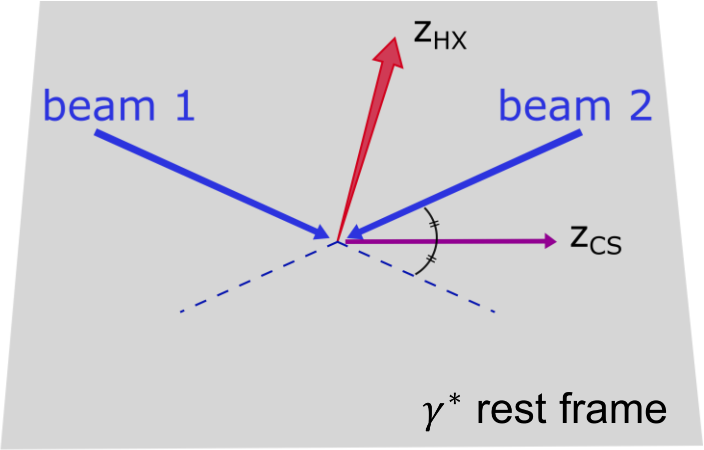
- Angular distribution of single lepton in γ^* rest frame depends on polarization of γ^*:

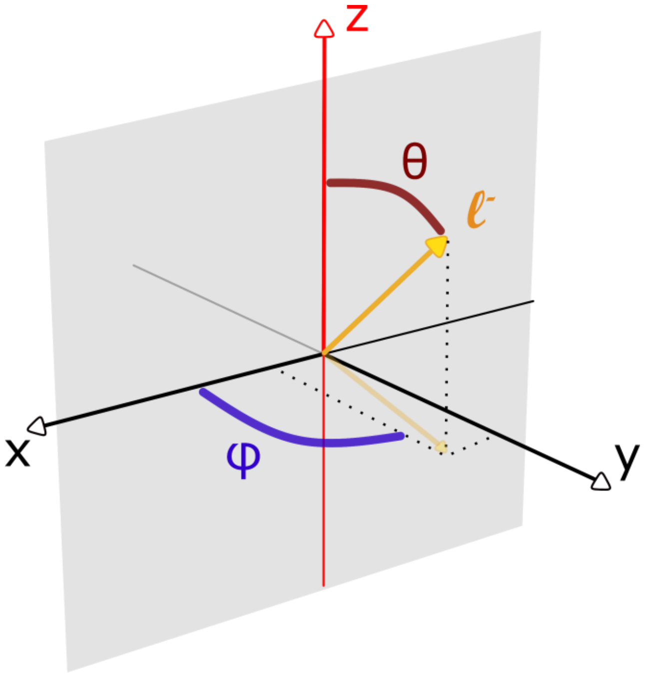
$$\frac{dN}{d^4x\, d^4q\, d\Omega} = \mathcal{N}\left(1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi^\perp \sin^2\theta \sin 2\varphi + \lambda_{\theta\varphi}^\perp \sin 2\theta \sin\varphi\right)$$

- Experiments have chosen different polarization axes for their measurements, e. g. Helicity frame (HX), Collins-Soper frame (CS) or Gottfried-Jackson frame (GJ)

- Anisotropy coefficients in different frames related via rotations







STATIC THERMAL MEDIUM

- Rotational symmetry only broken by virtual photon's momentum direction
- In the helicity frame HX the only non-zero coefficient is $\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$

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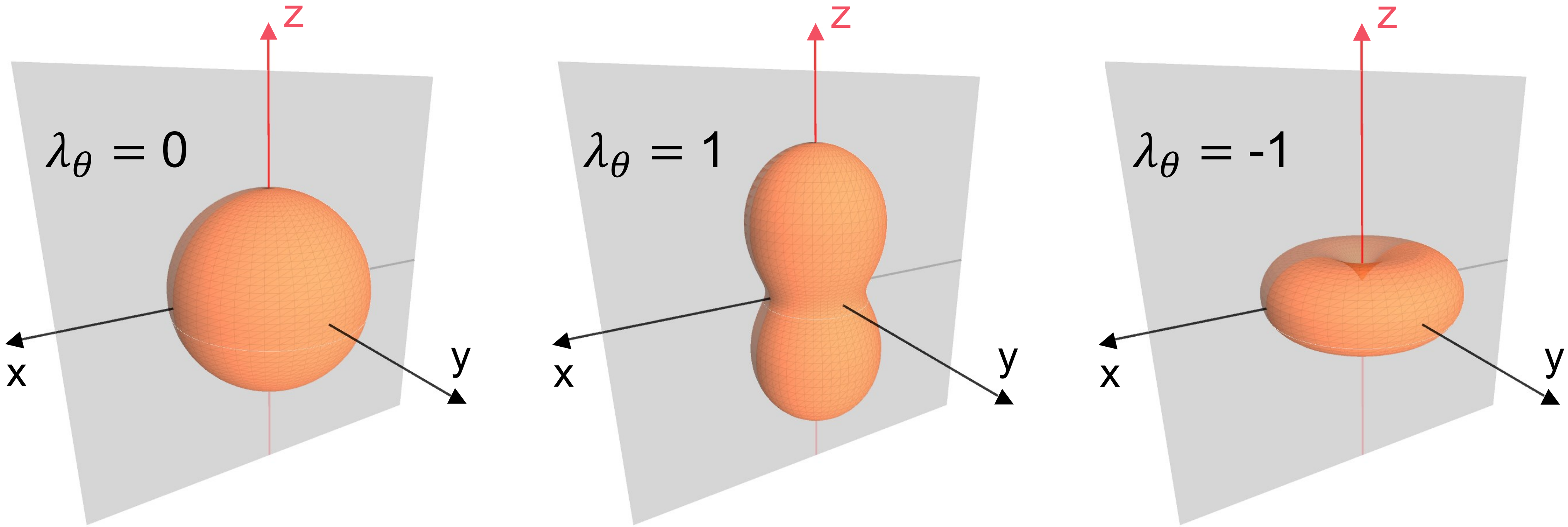

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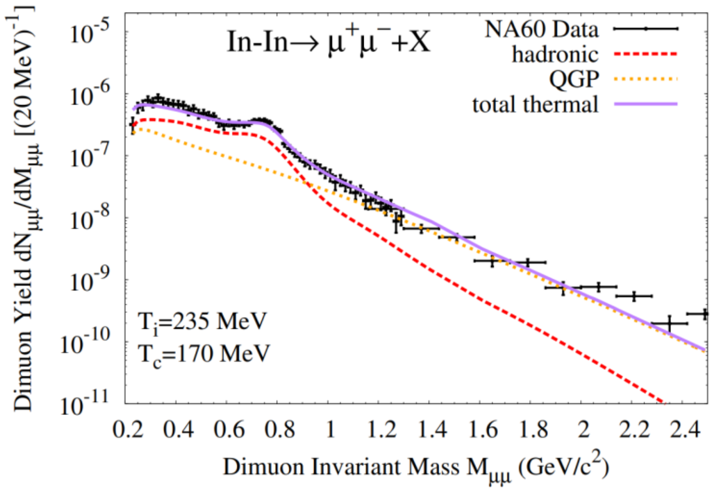
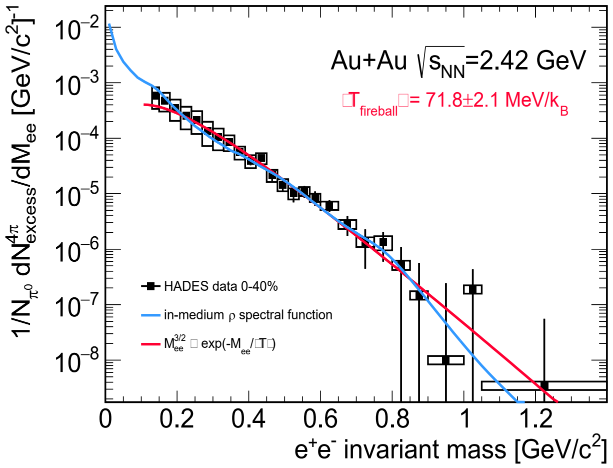
- Employ in-medium spectral functions that give fair description of available dilepton data





NA60 coll., Phys. Rev. Lett. 96, 162302 (2006)
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)

HADES coll., Nature Phys. 15(2019) 1040
T. Galatyuk *et al.*, Eur. Phys. J. A 52, 131 (2016)

- Hadronic emission with in-medium ρ-meson spectral function calculated from hadronic many-body theory based on effective Lagrangians

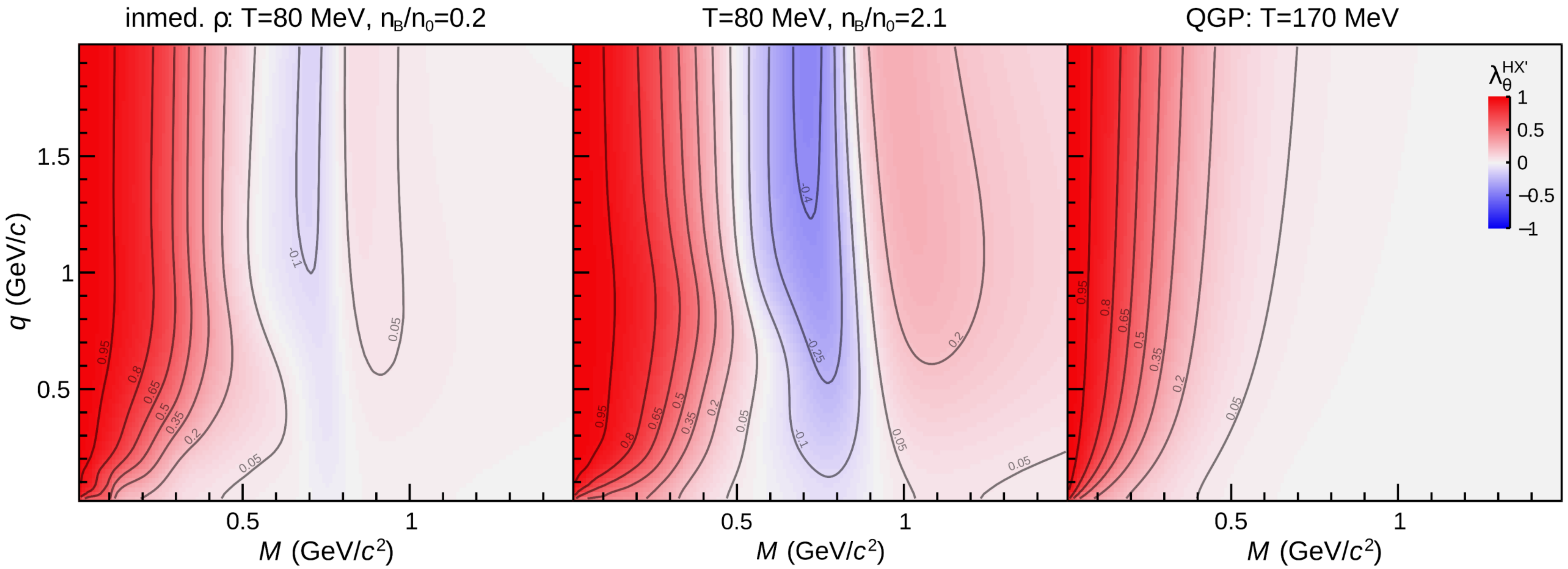
R. Rapp, J. Wambach, Eur. Phys. J. A 6, 415 (1999)
R. Rapp, G. Chanfray, J. Wambach, Nucl. Phys. A 617, 472 (1997)

- QGP emission based on perturbative $q\bar{q}$ annihilation with a low-energy transport peak constrained by lQCD data

R. Rapp, Adv. High Energy Phys. 2013, 148253 (2013)

POLARIZATION IN STATIC MEDIUM

- Strong dependence on mass, momentum and baryon density for hadronic medium
- Rather small polarization for QGP except for M_{ee} < 0.5 GeV/c^2 approaching the photon point

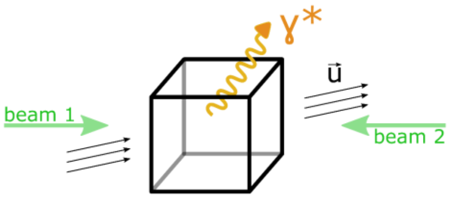


F. Seck *et al.*, submitted

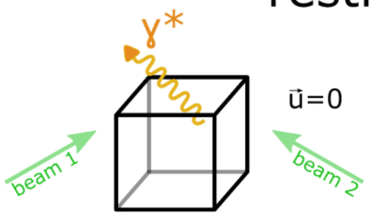
POLARIZATION IN MOVING MEDIUM

- Helicity frames (HX') of individual local fluid cells misaligned
- Transform polarization coefficients from each cell into a global frame accessible to experiment: HX, CS, …
- Integration over kinematic bins with yield-weighted mean

center of mass frame
of the collision
"lab"



local medium
restframe



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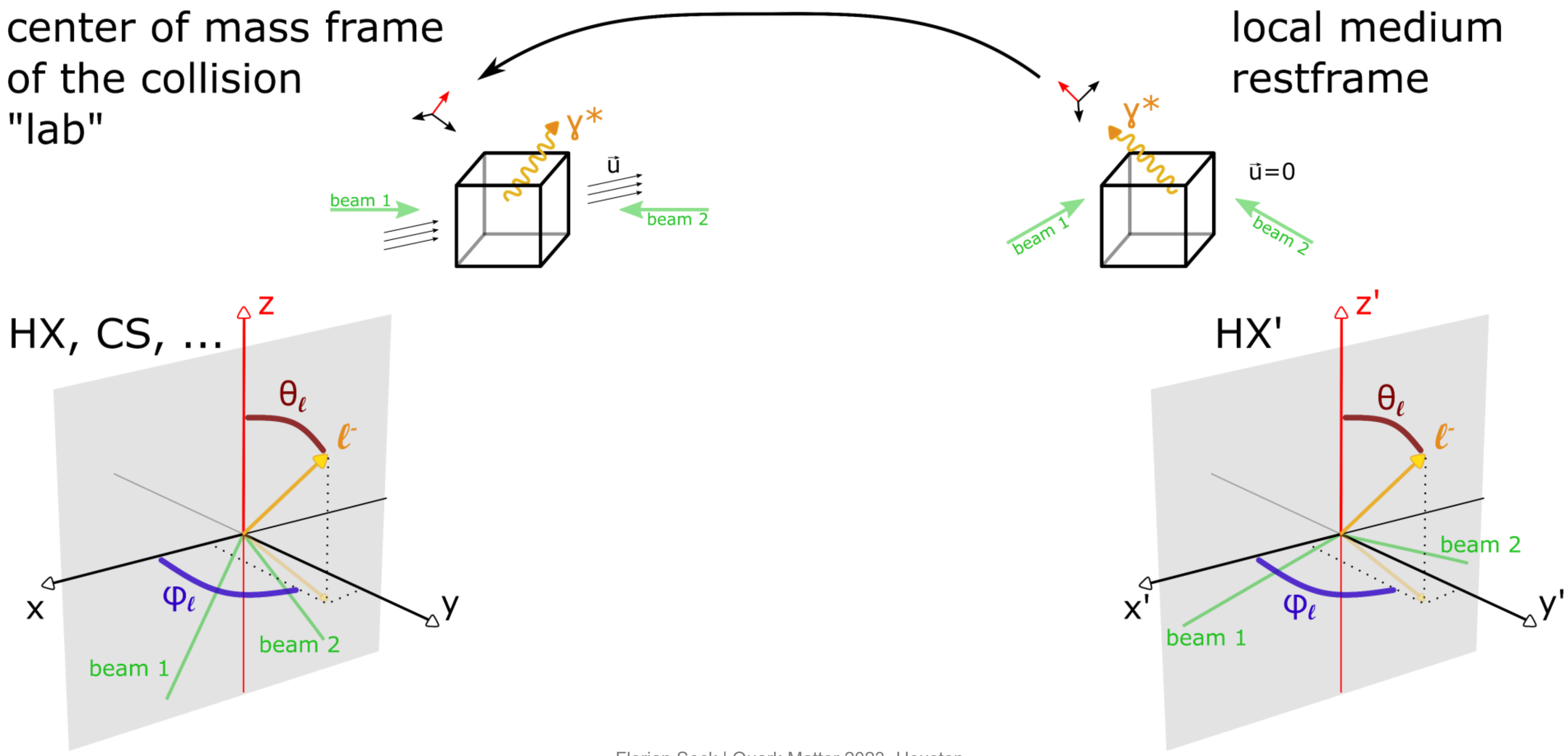

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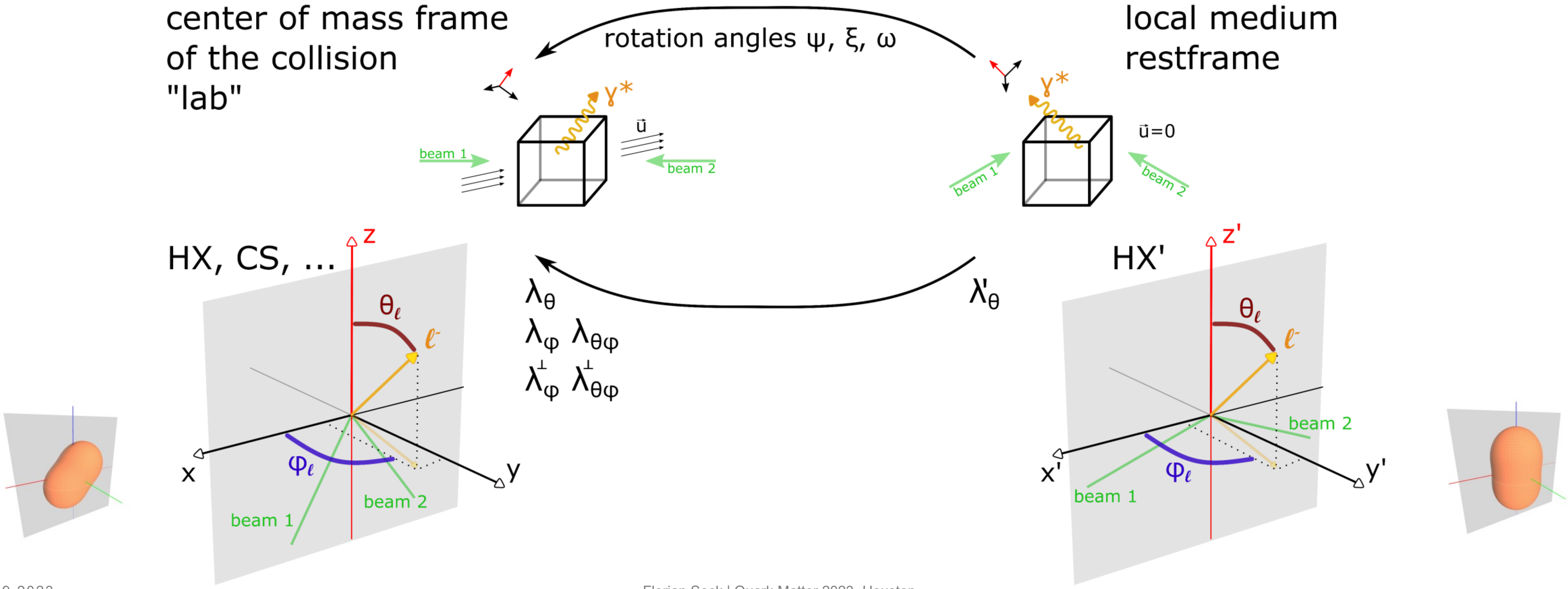


RESULTS FOR AR+KCL COLLISIONS AT SIS18 ENERGIES

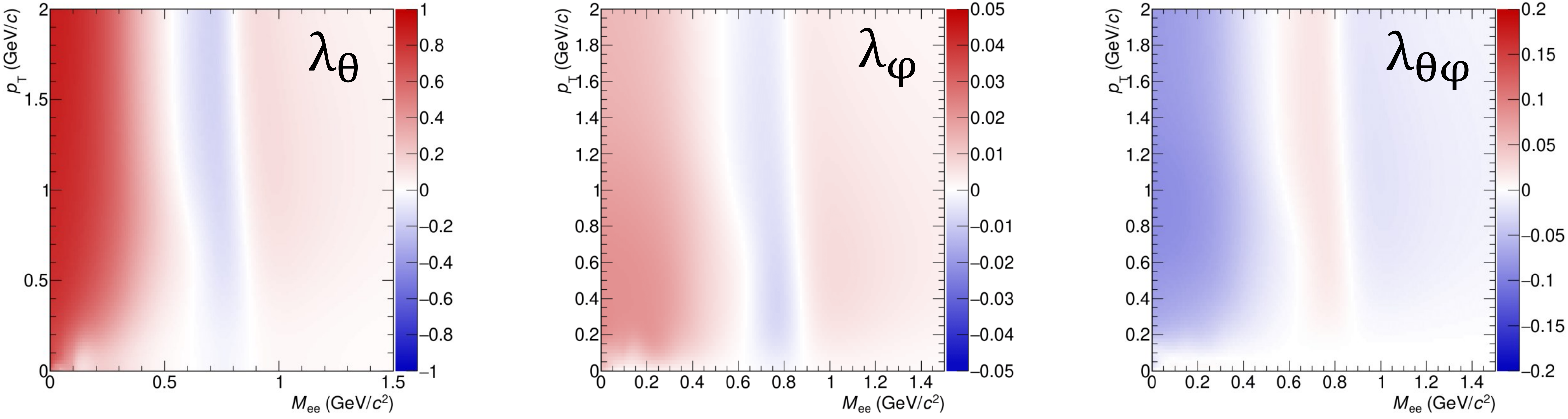
- HADES measured polarization coefficient λ_θ of excess radiation in the HX frame in Ar+KCl collisions at 1.76 AGeV beam energy

HADES coll,, Phys. Rev. C 84, 014902 (2011)

T. Galatyuk *et al.*, Eur. Phys. J. A 52, 131 (2016)

- Space-time evolution via coarse-grained UrQMD

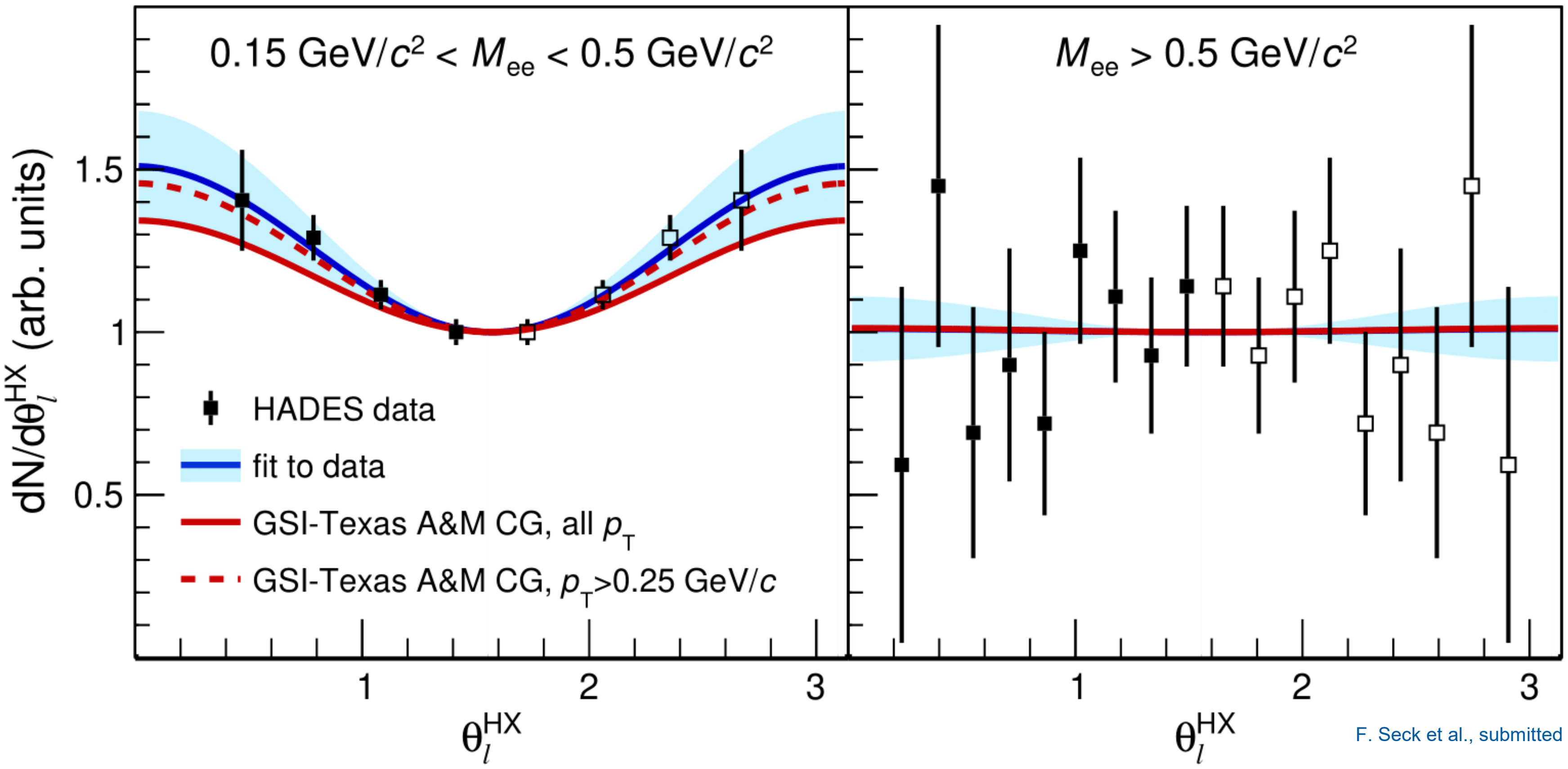
- Polarization largely survives evolution of the expanding medium



COMPARISON TO HADES DATA

- Good agreement between data and theory
- **Best fit** to data gives $\lambda_\theta = 0.51 \pm 0.17$ and $\lambda_\theta = 0.01 \pm 0.10$ in the two mass windows
- **Calculation** result gives $\lambda_\theta = 0.34$ and $\lambda_\theta = 0.01$ respectively

data points: HADES coll,, Phys. Rev. C 84, 014902 (2011)



F. Seck et al., submitted

RESULTS FOR IN+IN COLLISIONS AT SPS ENERGIES

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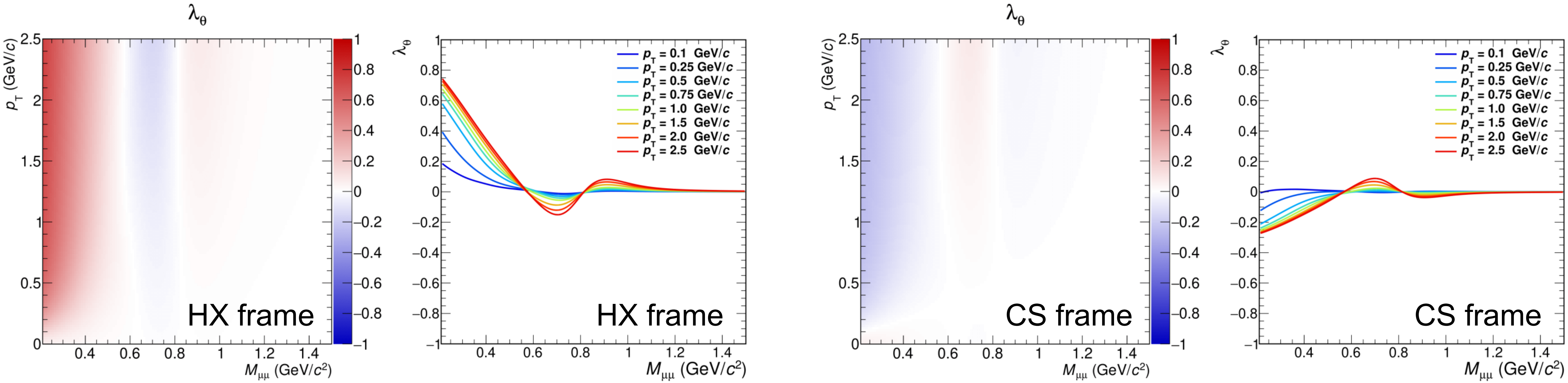
- NA60 measured polarization coefficients λ_θ, λ_φ and $\lambda_{\theta\varphi}$ of excess radiation in the CS frame in In+In collisions at 158 AGeV beam energy

NA60 coll., Phys. Rev. Lett. 96, 162302 (2006)
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)

- Space-time evolution via isentropic fireball model with transition from QGP to hadronic rates at T=170 MeV

- Strong dependence on the polarization frame as function of mass and momentum



COMPARISON TO NA60 DATA

- Good agreement between data and theory
  → size and trend

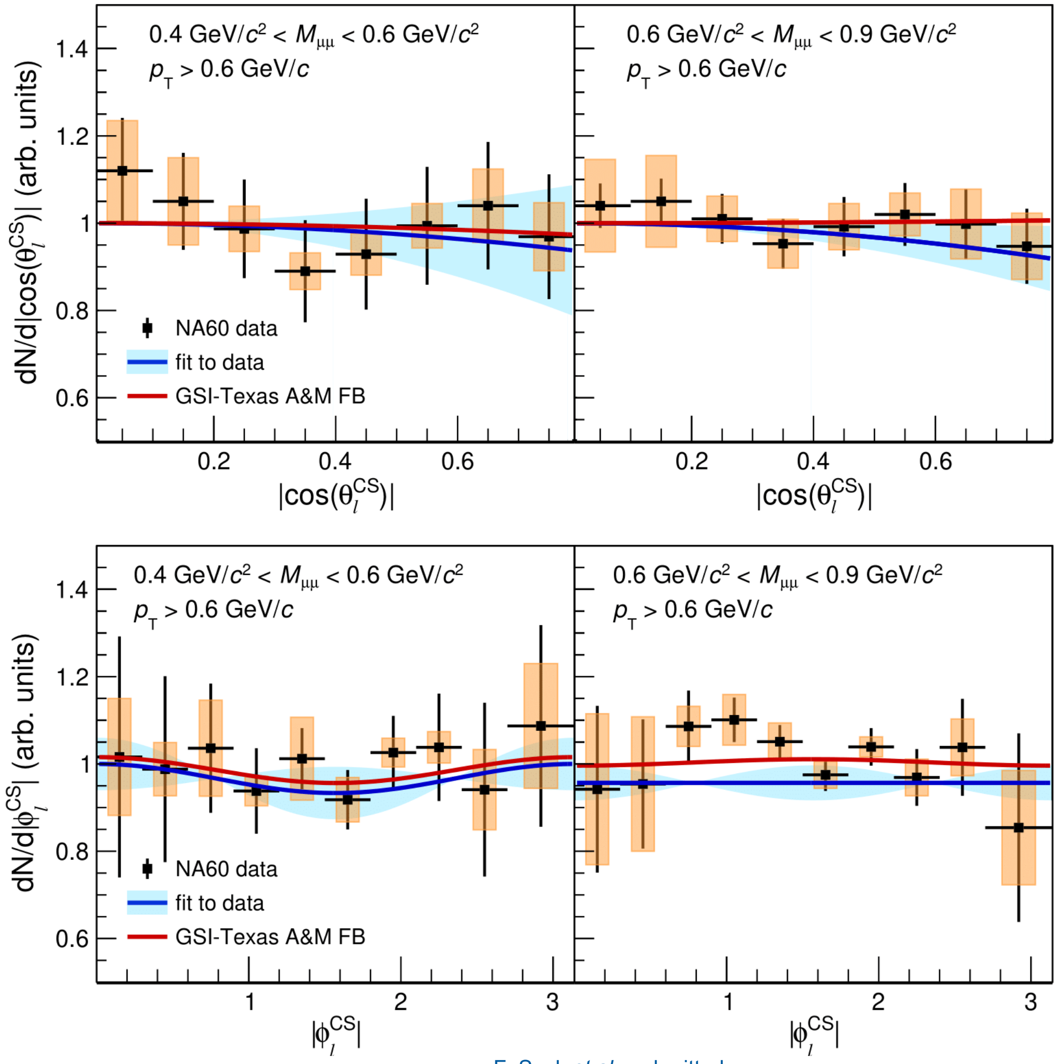
- Near absence of a net polarization
  - not related to thermal isotropy arguments
  - thermal properties of the EM spectral function

- **Best fit** to data gives $\lambda_\theta = -0.10 \pm 0.24$ and $\lambda_\theta = -0.13 \pm 0.12$ in the two mass windows
- **Calculation** results in $\lambda_\theta = -0.04$ and $\lambda_\theta = 0.01$ respectively

- **Best fit** to data gives $\lambda_\varphi = 0.05 \pm 0.09$ and $\lambda_\varphi = 0.00 \pm 0.06$ in the two mass windows
- **Calculation** results in $\lambda_\varphi = 0.04$ and $\lambda_\varphi = -0.01$ respectively

- **Best fit** to data and **calculation** consistent with $\lambda_{\theta\varphi} = 0$ in both mass windows

data points: NA60 coll,, Phys. Rev. Lett. 102, 222301 (2009)

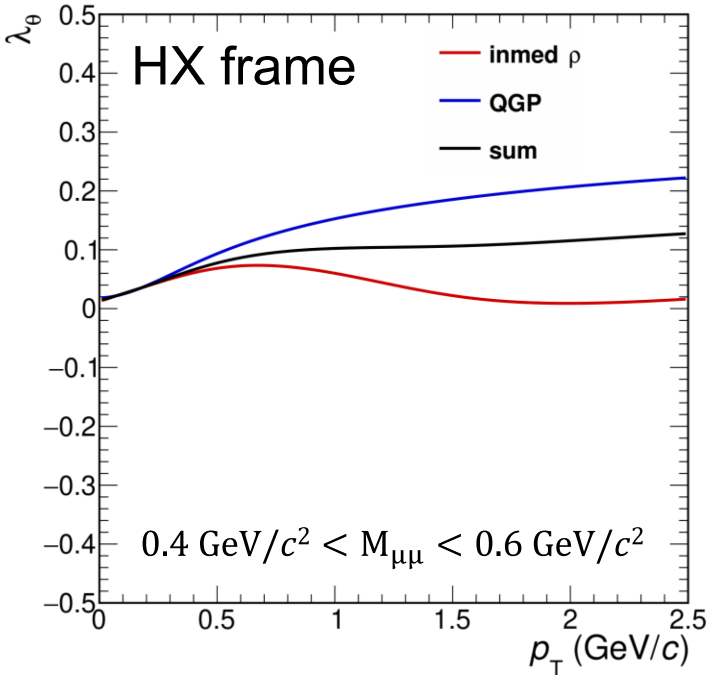


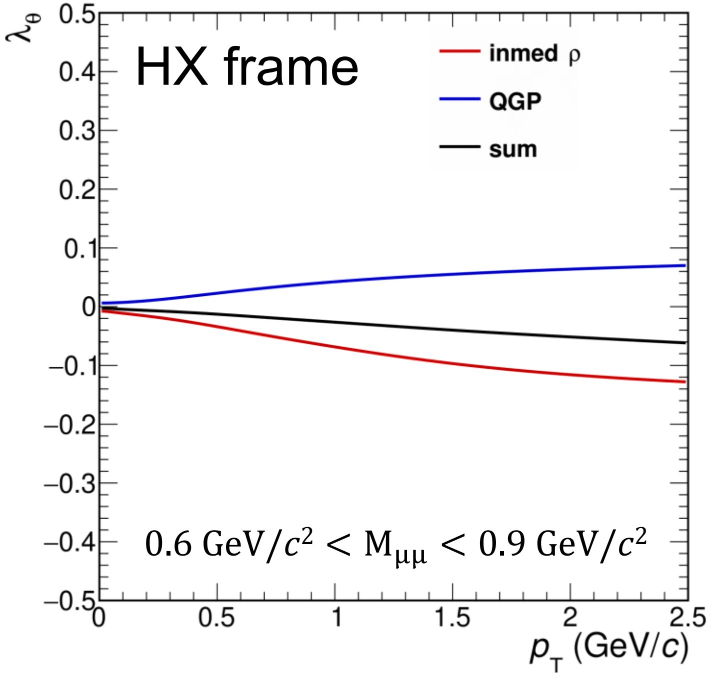
F. Seck *et al.*, submitted

PROSPECT OF DISENTANGLING HADRONIC AND PARTONIC SOURCES

- Polarization observables will play an increasingly important role in exploring the mechanisms underlying EM emission spectra in heavy-ion collisions

- Multidifferential measurements of the virtual photon polarization → large datasets needed
  - HADES, STAR and ALICE
  - future high-rate experiments CBM, NA60+ and ALICE3



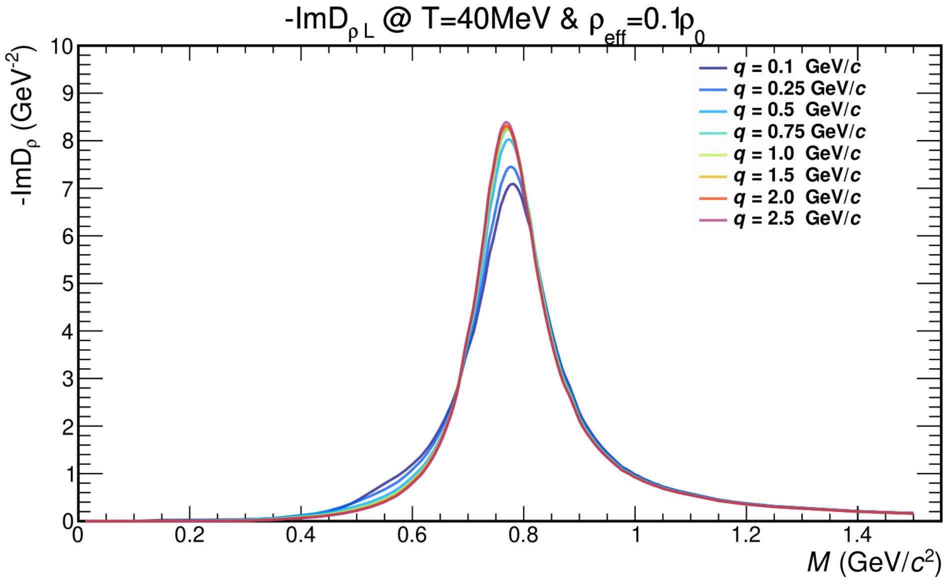


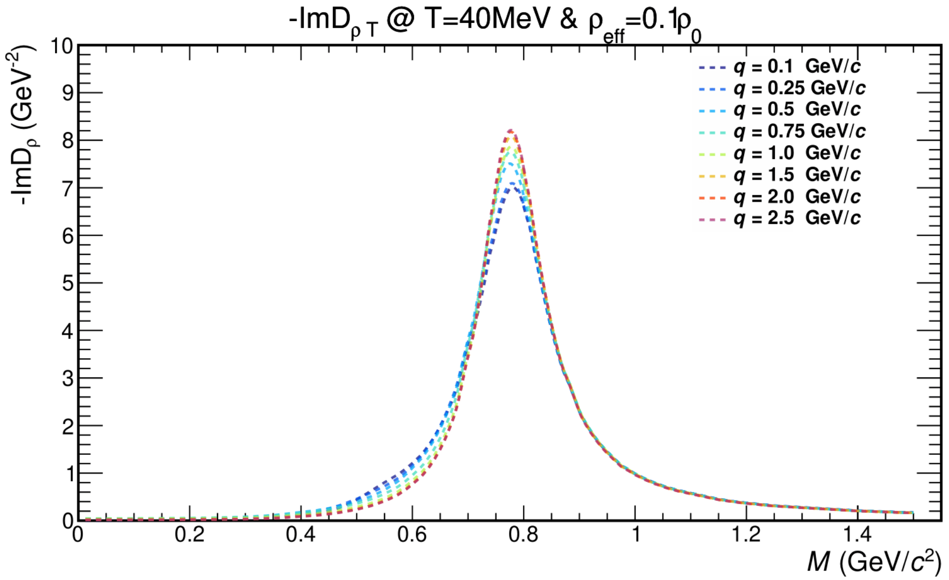
SUMMARY

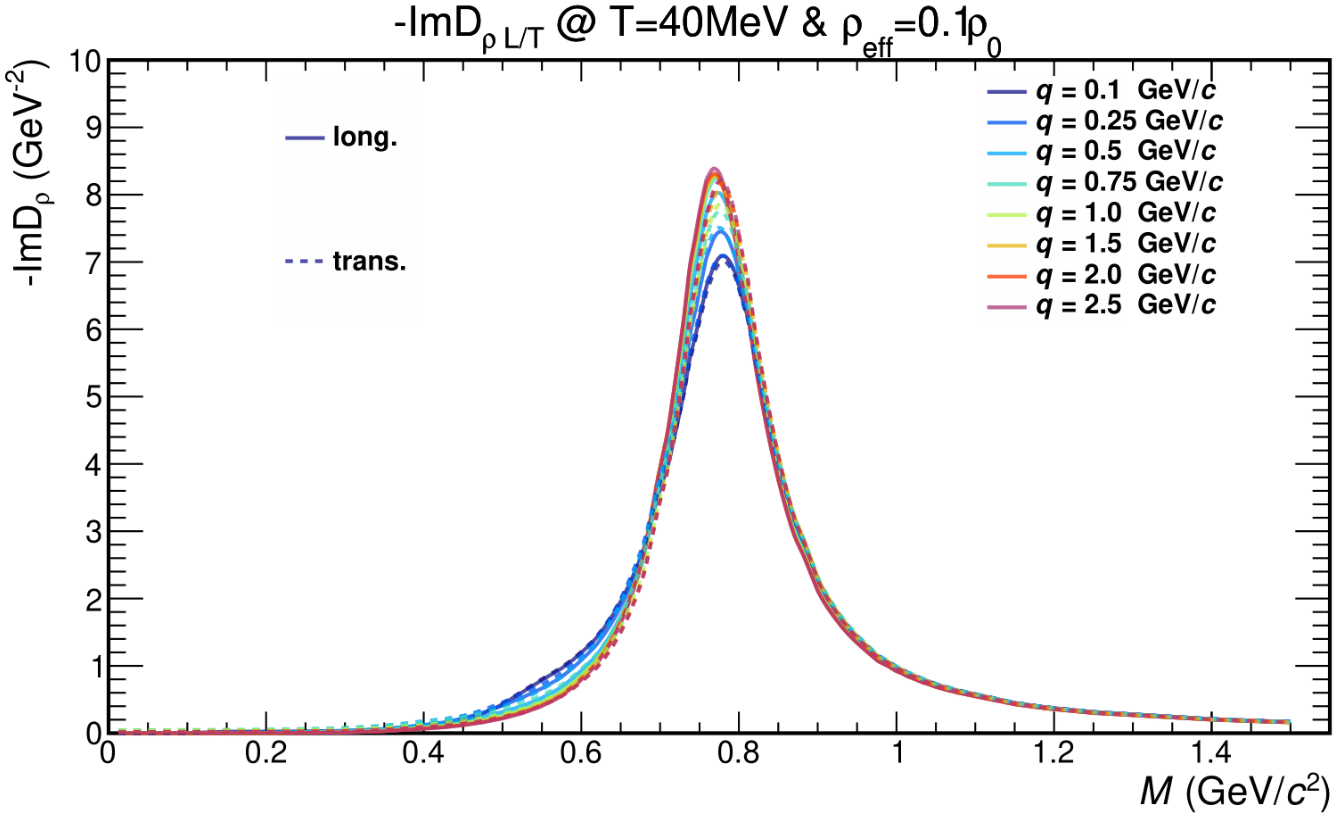
- Polarization properties of virtual photons from electromagnetic spectral functions of QCD matter
  - Sensitive to difference of longitudinal and transverse components of the spectral function
- Polarization of hadronic matter transits from transverse at low masses into longitudinal in the ρ-meson mass region
  - Less pronounced structure at high temperatures and low baryon density
  - More closely resembles polarization of QGP emission
- Transformations from the thermal frame into angular variables observable in the lab frame
  - Good agreement between our predictions and both HADES and NA60 data
- Polarization observables to play an increasingly important role in exploring the mechanisms underlying EM emission
  - Multidifferential measurements: HADES, STAR, ALICE, CBM, NA60+ and ALICE3

BACKUP

SPECTRAL FUNCTION COMPONENTS: LOW TEMPERATURE & LOW DENSITY







SPECTRAL FUNCTION COMPONENTS: MID TEMPERATURE & MID DENSITY

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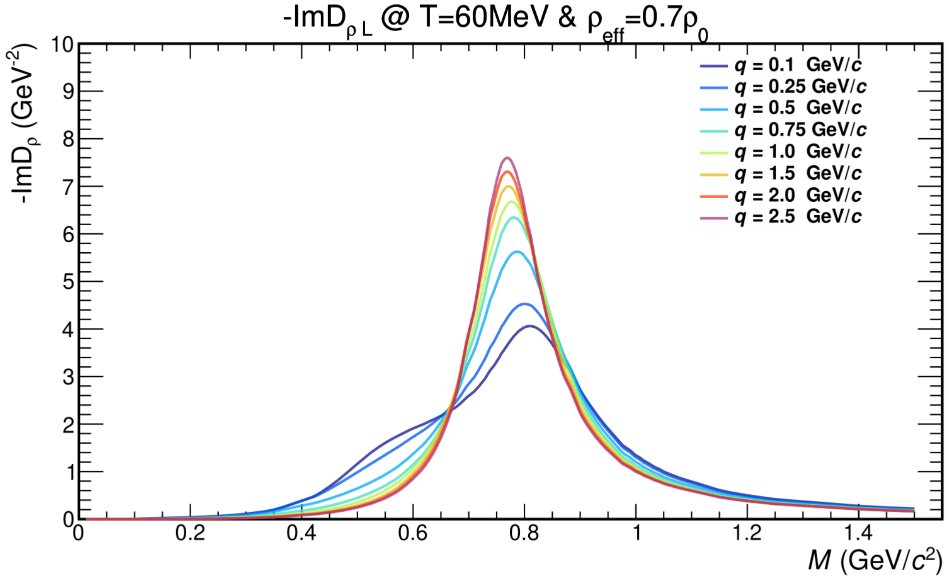
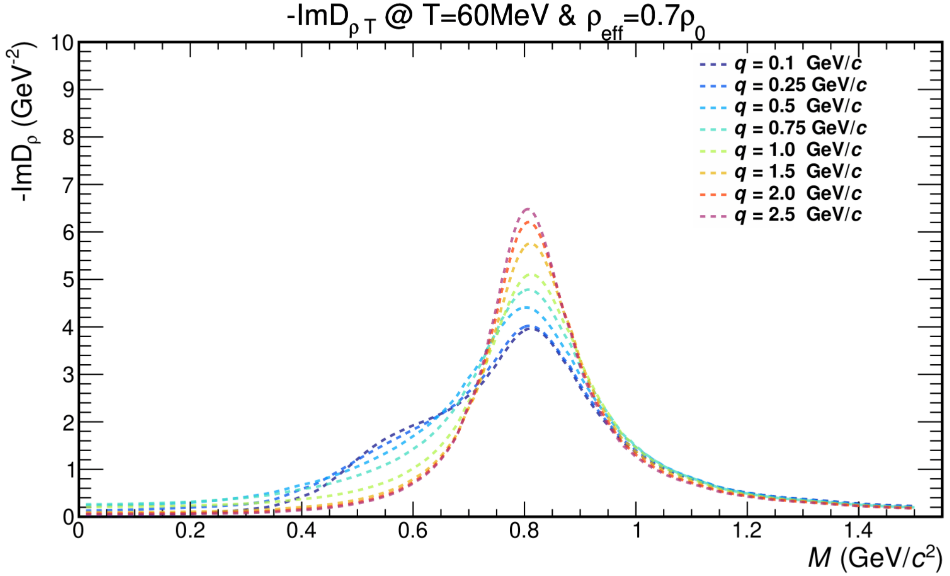
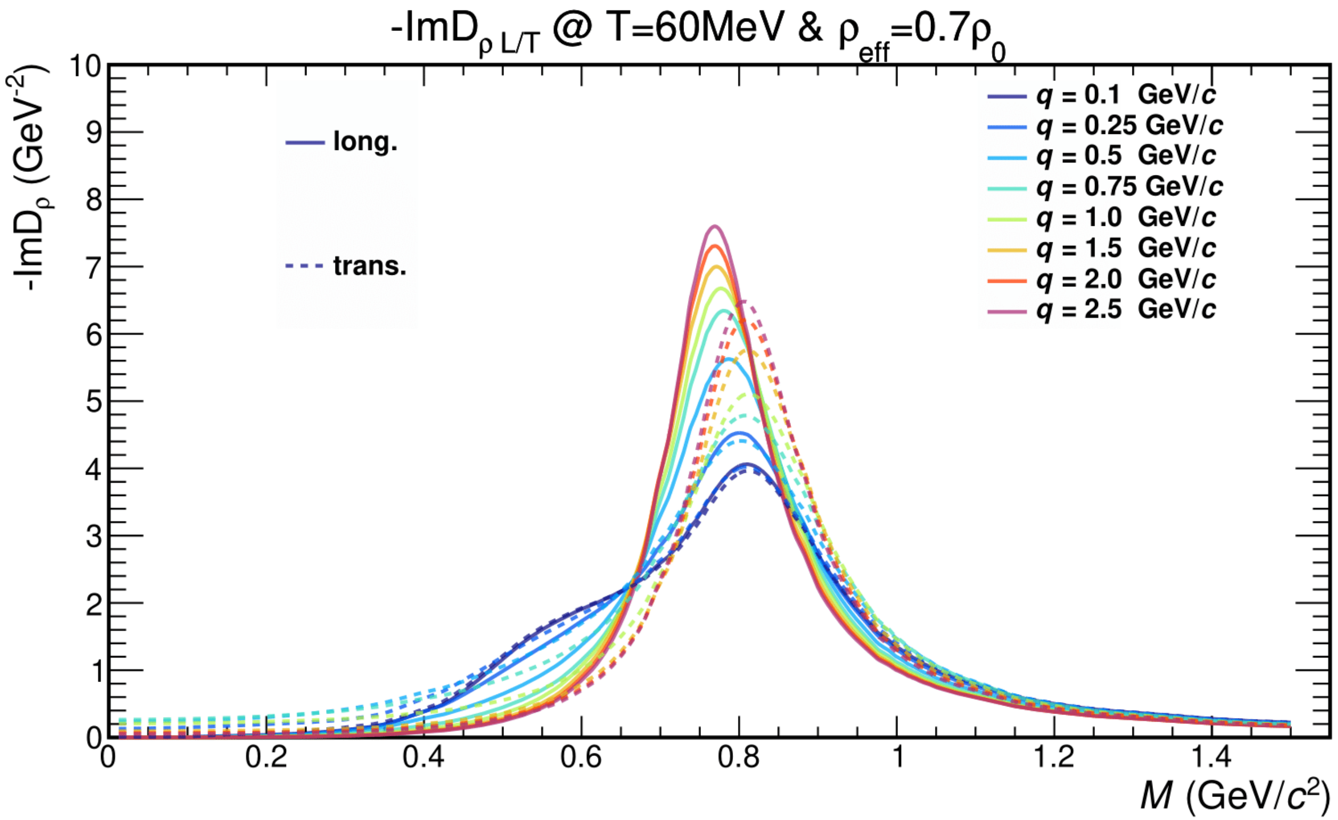
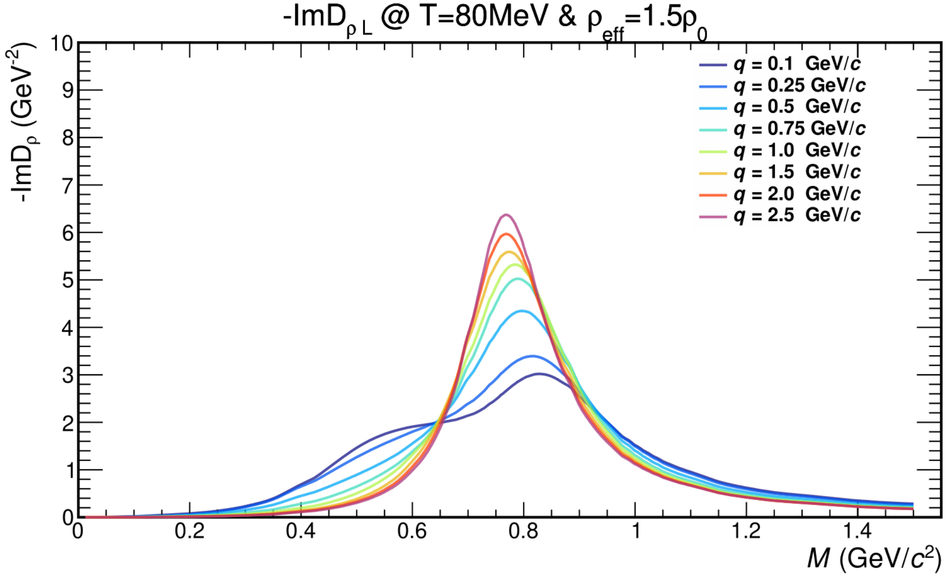
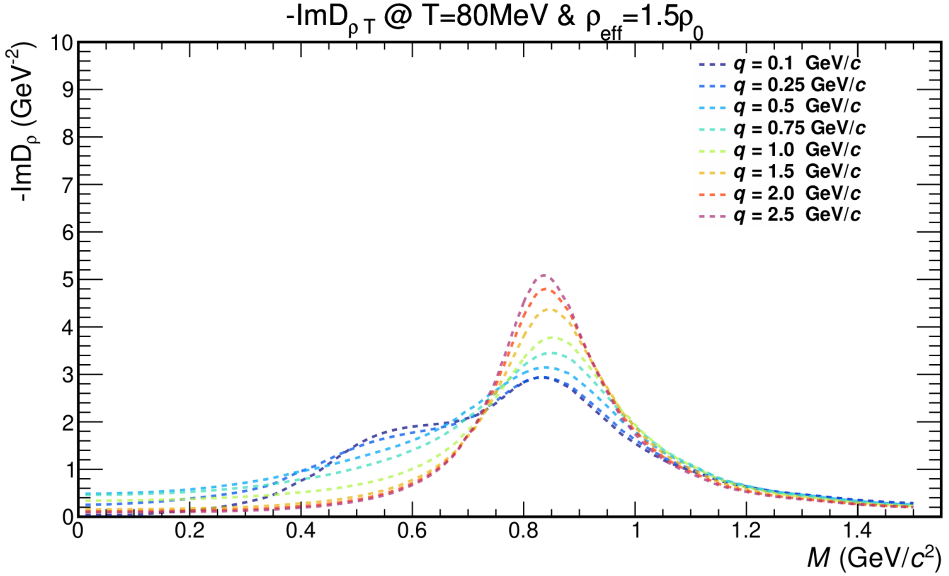


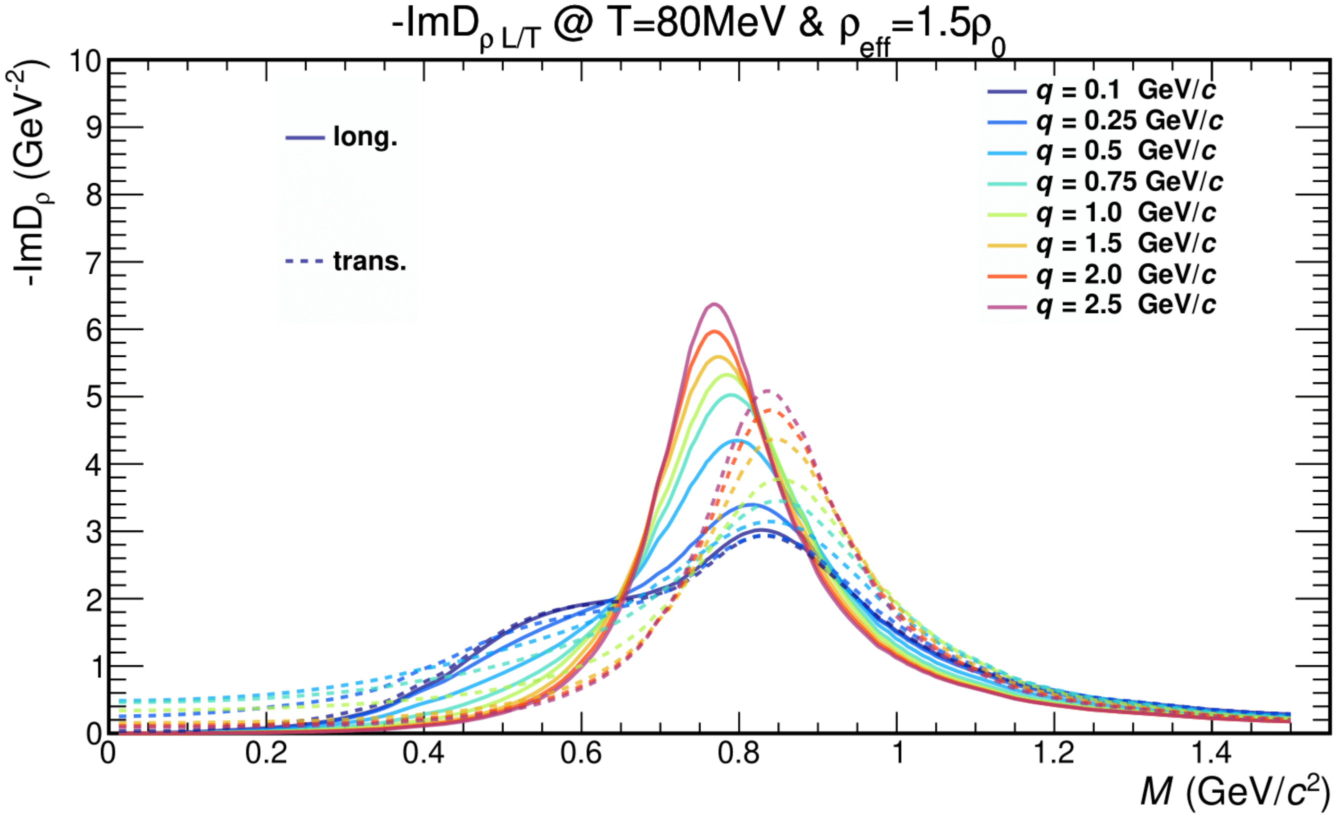




SPECTRAL FUNCTION COMPONENTS: HIGH TEMPERATURE & HIGH DENSITY







- ψ -- rotation around z'-axis: rotated y-axis perpendicular to final z-axis
- ξ -- rotation around new y''-axis: align initial and final z-axes
- ω -- rotation around z-axis: give x- and y-axes their orientation

VIRTUAL PHOTON POLARIZATION

based on: P. Faccioli, Particle Polarization in High Energy Physics, Springer 2023

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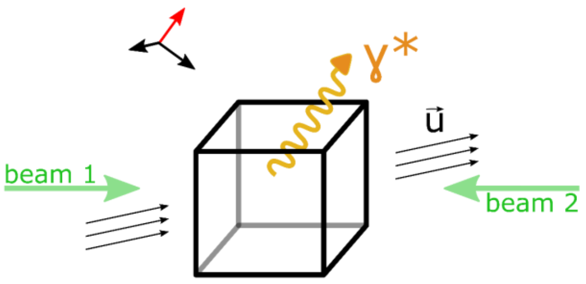
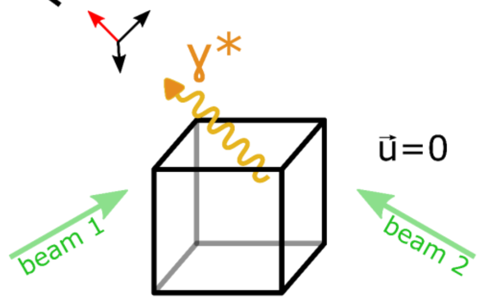
rotation angles ψ, ξ, ω

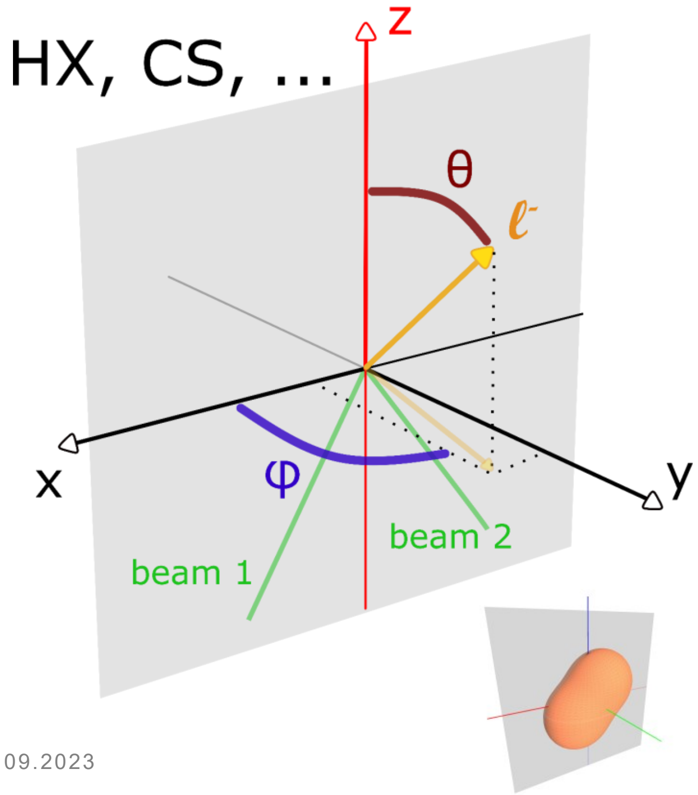
center-of-mass frame of the collision "lab"



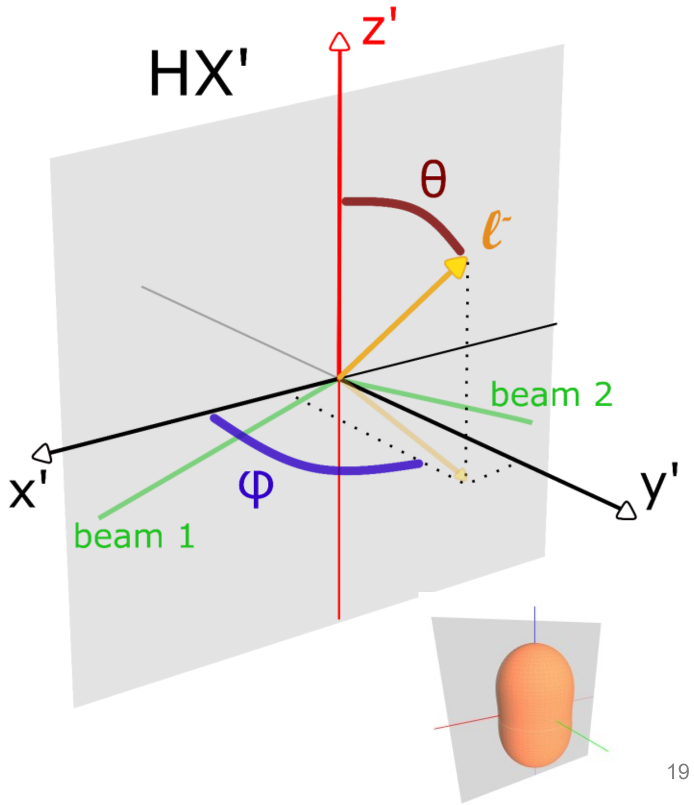


local fluid rest frame

HX, CS, …



HX'



λ_θ

λ_φ $\lambda_{\theta\varphi}$

$\lambda_\varphi^\perp$ $\lambda_{\theta\varphi}^\perp$

λ'_θ

$$\lambda_\theta = \frac{\lambda'_\theta}{1+\Lambda}\left(1 - \frac{3}{2}\sin^2\xi\right)$$

$$\Lambda = \frac{1}{2}\lambda'_\theta \sin^2\xi$$

$$\lambda_\varphi = \frac{\lambda'_\theta}{1+\Lambda}\left(\frac{1}{2}\sin^2\xi\ \cos 2\omega\right) \qquad \lambda_{\theta\varphi} = \frac{\lambda'_\theta}{1+\Lambda}\left(-\frac{1}{2}\sin 2\xi\ \cos\omega\right)$$

$$\lambda_\varphi^\perp = \frac{\lambda'_\theta}{1+\Lambda}\left(-\frac{1}{2}\sin^2\xi\ \sin 2\omega\right) \qquad \lambda_{\theta\varphi}^\perp = \frac{\lambda'_\theta}{1+\Lambda}\left(\frac{1}{2}\sin 2\xi\ \sin\omega\right)$$

RESULTS FOR IN+IN COLLISIONS IN SPS ENERGY REGIME: LAMBDA THETA

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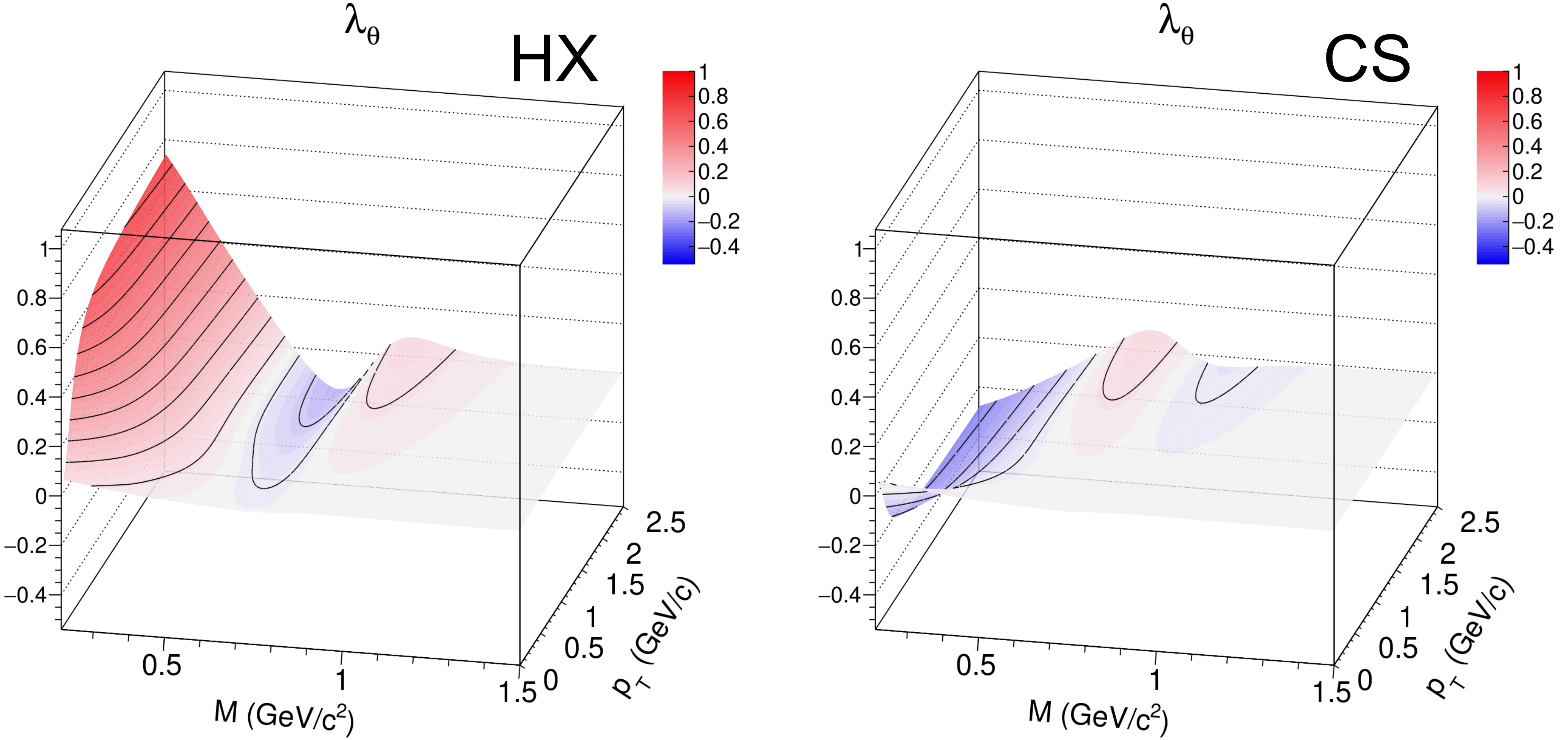
- Strong dependence on the polarization frame as function of mass and momentum



RESULTS FOR IN+IN COLLISIONS IN SPS ENERGY REGIME: LAMBDA THETA

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- Polarization observables will play an increasingly important role in exploring the mechanisms underlying EM emission spectra in heavy-ion collisions