Theory and phenomenology of electromagnetic probes

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Quark Matter 2022
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Direct probes of the QCD medium

• **Why study electromagnetic probes of the QGP?**
  • Emitted at all stages of a collision (w/ negligible re-scattering) ⇒ precise information about the QGP
  • Virtual photons/dileptons are particularly interesting because of their invariant mass $M$
Direct probes of the QCD medium

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- In experiment however...
  
  ![Graph showing data comparison between measured and modeled distributions.
  ALICE, Phys. Rev. C 102, 055204 (2020)]
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[STAR, Phys. Rev. Lett. 113 (2014) 2, 022301]
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  ![Graph 1](STAR, J. Phys. Conf. Ser. 535, 012006 (2014))

  ![Graph 2](STAR, Phys. Rev. Lett. 113 (2014) 2, 022301)

  ![Graph 3](G.V. et al., Phys. Rev. C 101, 044904 (2020))

• Detailed study of QGP: measure $dN/dM$ and $v_2(M)$, especially $M \gtrsim 1 \text{ GeV}$!
Direct probes of the QCD medium

- A high precision measurement of dileptons: **NA60 dimuon experiment**

[NA60, Prog. Part. Nucl. Phys. 62, 486 (2009)]

- Described by theory (via blast wave), but can do better:
Direct probes of the QCD medium

- A high precision measurement of dileptons: NA60 dimuon experiment

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⇒ Hydrodynamics, hadronic transport, ...
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  • Can ask detailed questions ✓
    e.g. shear viscosity (η)?
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    e.g. shear viscosity ($\eta$)?

- Measurement of dilepton $v_2(M)$
  - HADES: Quark Matter 2022 [N. Schild, Wed 19:18]
  - upcoming from ALICE and NA60+

- Exploring sources of EM radiation

[N60, Prog. Part. Nucl. Phys. 62, 486 (2009)]
Sources of EM probes

• Onset of collisions:
  • Prompt photons [C. Sirimanna, Wed 18:42; R. Modarresi-Yazdi, Thu 18:10]
  • Drell-Yan dileptons [M. Coquet, Wed 19:06]
  • Heavy Quarkonia
  • Open Heavy Flavor

• Pre-hydrodynamical evolution/jet-medium interaction
  • EM production coming from various partonic processes
    [J.-F. Paquet, Wed 18:34; C. Sirimanna, Wed 18:42; S. Park, Thu 16:00; R. Modarresi-Yazdi, Thu 18:10]

• Hydrodynamical evolution
  • EM production coming from partonic and hadronic processes

• Transport evolution
  • EM production from hadronic interactions
EM probes and the QGP

• Bayesian analysis simulating various stages for soft hadronic observables are starting to inform us about transport coefficients.
EM probes and the QGP

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Bayesian Analysis by the JETSCAPE Simulations Group
EM probes and the QGP

• Bayesian analysis simulating various stages for soft hadronic observables are starting to inform us about transport coefficients.


• Soft hadron observables give a better description at low T.

Bayesian Analysis by the JETSCAPE Simulations Group
Bayesian analysis simulating various stages for soft hadronic observables are starting to inform us about transport coefficients.


- Soft hadron observables: not enough?

Bayesian Analysis by the JETSCAPE Simulations Group

- $\nu_n$ of EM probes $\Rightarrow$ directly probe microscopic d.o.f. of nuclear matter and can better constrain $\frac{\eta}{s}, \frac{\zeta}{s}$
Dilepton emission
Electromagnetic radiation from QCD medium

- Finite Temperature Field Theory
  - Dilepton production rate
    \[ \frac{d^4 R}{d^4 k} \propto -\alpha_{EM}^2 Im \left[ \begin{array}{c} \gamma \\ \gamma \end{array} \right] \]
    \[ k^2 = M^2 \geq 0 \]
  - Photon production rate
    \[ k^0 \frac{d^3 R}{d^3 k} \propto -\alpha_{EM} Im \left[ \begin{array}{c} \gamma \\ \gamma \end{array} \right] \]
    \[ k^2 = M^2 = 0 \]

\[ Im \left[ \begin{array}{c} \gamma \\ \gamma \\ \gamma \\ \gamma \end{array} \right] = EM \text{ Spectral Function} \]
Electromagnetic radiation from QCD medium

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    \]

- EM spectral function in pQCD or on the Lattice
  \[
  G_V(\tau) = \int \frac{dk^0}{\pi} K(k^0, \tau) Im \left[ \begin{array}{c} \gamma \\gamma \end{array} \right] ; \quad K(k^0, \tau) = \frac{\cosh\{k^0[1/(2T) - \tau]\}}{\sinh(k^0/2T)}
  \]

- Hadronic sector, sensitive to chiral symmetry breaking
Dilepton production from pQCD & lattice QCD ✓

- Quite good agreement between pQCD and lattice QCD in the (un-)quenched.

\[ T = 1.1T_c, N_f = 0 \]  
\[ T = 1.2T_c, N_f = 2 \]

- Entering the era for precision calculations of EM spectral functions; with extension to $\mu_B > 0$. 

\[ G_V / G_{\text{norm}}, V \]

\[ G_H / T^3 \]
Dilepton production from hadronic interactions

- EM spectral function via vector mesons

\[ \text{Im} \left[ \begin{array}{c} \gamma \\ \gamma \end{array} \right] = \text{Im} \left[ \begin{array}{c} \frac{m_{V}^{2}}{g_{V}} \\ V = \rho, \omega, \phi \end{array} \right] \]

- Many-body effective Lagrangians

\[ \text{Im} [D_{\rho}] = \text{Im} \left[ \begin{array}{c} \rho \\ \rho \end{array} \right] \]

\[ \text{Mesons} \quad \text{Baryons} \]


Mesons only

Mesons & Baryons

\[ \text{Im} D_{\rho} \text{ [GeV}^{2}] \]

\[ M \text{ [GeV]} \]

\[ \mu_{B} = 330 \text{MeV} \]

\[ T = 120 \text{MeV} \quad T = 150 \text{MeV} \quad T = 180 \text{MeV} \]

\[ \mu_{B} = 330 \text{MeV} \]
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\[
\text{Im} \left[ \frac{m_V^2}{gV} \gamma \right] = \text{Im} \left[ \frac{m_V^2}{gV} \gamma \right] = \text{Im} \left[ \frac{m_V^2}{gV} \gamma \right]
\]

- Many-body effective Lagrangians

\[
\text{Im}[D_\rho] = \text{Im} \left[ \gamma \rho \right]
\]

- Many-body effective Lagrangians now include the chiral partner of \( \rho \), the \( a_1 \)
  - \( \rho \) & \( a_1 \) agree at high \( T \) ⇒ encouraging for understanding chiral symmetry restoration from a hadronic perspective.


Dilepton production in a viscous medium

- Theory ⇒ Experimental observables

\[ \frac{d^4N}{d^4k} = \int d^4 x \frac{d^4R}{d^4k}[u^\mu(x), T(x), \pi^{\mu\nu}(x), \Pi(x)] \]

\[ T_{eq.}^{\mu\nu} + \pi^{\mu\nu} - \Pi^{\mu\nu} = \int \frac{d^3k}{(2\pi)^3 k_0} k^\mu k^\nu[n_{eq.} + \delta n^{shear} + \delta n^{bulk}] \]

- Dileptons from (hadronic) scattering theory

\[ \frac{d^4R}{d^4k} \propto \text{Im} \]

- Dileptons from LO pQCD

\[ \frac{d^4R}{d^4k} \propto \text{Im} \]

Dileptons as “timer”, thermometer & viscometer

- Size of $\int \frac{dN}{dM} \in 0.3 < M < 0.7 \text{ GeV}$

- Slope of $\frac{dN}{dM} \in 1.5 < M < 2.5 \text{ GeV}$


[NA60, Phys. Rev. Lett. 100, 022302 (2008)]
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- Size of $\int \frac{dN}{dM} \in 0.3 < M < 0.7$ GeV
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- Size of $v_2(M)$ [or $v_n(M)$]


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- Size of \( \nu_2(M) \) [or \( \nu_n(M) \)]

\[
\eta/s = \frac{\text{dil.}}{\text{hadrons}}
\]

- A joint Bayesian analysis (dileptons & hadrons) to help constrain on \((\eta/s)(T)\).


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- A joint Bayesian analysis (dileptons & hadrons) to help constrain on \( \frac{\eta}{s}(T) \).
- An accurate measurement of dilepton \( \nu_2 \) is needed at high \( \sqrt{s} \) ⇒ possible following ALICE upgrade

\[ \text{[G.V. et al., Phys. Rev. C 98, 014902 (2018)]} \]

\[ \text{[D. Everett et al., Phys. Rev. Lett. 126, 242301 (2021)]} \]

\[ \text{[G.V. et al., Phys. Rev. C 98, 014902 (2018)]} \]
Dileptons from transport

- At lower $\sqrt{S_{NN}}$, more dileptons from transport


[R. Hirayama, Wed 19:10]
Dileptons from transport & hydrodynamics

- At lower $\sqrt{s_{NN}}$, more dileptons from transport & hydrodynamics at $\mu_B > 0$ with 1st order PT EoS


[R. Hirayama, Wed 19:10]

[ArKCl at 1.76A GeV]
- $\phi \rightarrow e^+ e^-$
- $\pi^0 \rightarrow \gamma e^+ e^-$
- $\eta \rightarrow \gamma e^+ e^-$
- CG--$\omega$
- CG--$\rho$
- non-CG
- HADES

[STAR data]
- Coarse-graining
- UrQMD
- $p_t^* > 0.2$ GeV/c
- $|y| < 1$, $|y_{cin}| < 1$
- STAR data

[SMASH]

[Au+Au at 1.23A GeV]
- Ideal hydro+1st order EoS

[M. Wiest, Wed 19:14]
Dileptons from transport & hydrodynamics

- At lower $\sqrt{S_{NN}}$, more dileptons from transport & hydrodynamics at $\mu_B > 0$ with 1st order PT EoS

- Consistent description at all beam energies ⇒ combining transport & hydrodynamical calculations.
Dileptons from transport & hydrodynamics

- At lower $\sqrt{s_{NN}}$, more dileptons from transport & hydrodynamics at $\mu_B > 0$ with 1st order PT EoS

- Consistent description at all beam energies $\Rightarrow$ combining transport & hydrodynamical calculations.

- No more jets at lower $\sqrt{s_{NN}}$: only penetrating probes sensitive to QCD dofs are EM.
Dileptons from transport & hydrodynamics ✓

- At lower $\sqrt{S_{NN}}$, more dileptons from transport & hydrodynamics at $\mu_B > 0$ with 1st order PT EoS

- Consistent description at all beam energies ⇒ combining transport & hydrodynamical calculations.

- No more jets at lower $\sqrt{S_{NN}}$: only penetrating probes sensitive to QCD dofs are EM.

- Bayesian comparisons of dileptons at various $\sqrt{S_{NN}}$ ⇒ learn more dilepton production mechanisms
  - Exclude rates w/o chiral symmetry restoration by comparison with data?
  - Determine uncertainties of calculations & accurate measurements
Dilepton calculations compared to data

- **Comparison with data**


  - RHIC data is better described if charm exchanges energy & momentum w/ QGP

  - $\sqrt{s_{NN}} = 200$ GeV
  - Au+Au 0-10%


  ![Graph showing dilepton calculations compared to data](image-url)
Dilepton calculations compared to data

- Comparison with data

Cocktail+Thermal nor Cocktail+Charm w/ Lagenvin are not enough to explain data ⇒ all three are sources needed, in fact...

Au+Au 0-10% \( \sqrt{S_{NN}} = 200 \text{ GeV} \)

\[ \text{G.V. et al., Phys. Rev. C 89, 034904 (2014)} \]
Dilepton calculations compared to data

- Comparison with data

NLO pQCD dilepton rates are needed to explain the data.

Dilepton yield and $\nu_2$ at intermediate $M$

- Comparison with data

\[
\frac{dN}{dM} \text{ and } \nu_2 \text{ in } 1 < M < 3 \text{ GeV must be consistent with heavy flavor } R_{AA} \text{ and } \nu_2.
\]

This is non-trivial as dileptons follow the HF pair traversing the QGP.

- Another handle on heavy flavor transport coefficients (e.g. $\hat{q}_{QCD}$).

- RHIC data is better described if charm exchanges energy & momentum w/ QGP

- Charm’s interaction w/ QGP generates dilepton $\nu_2$.

Dilepton yield and \( \nu_2 \) at intermediate \( M \)

- Comparison with data

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This is non-trivial as dileptons follow the HF \textit{pair} traversing the QGP.

- Another handle on heavy flavor transport coefficients (e.g. \( \hat{q}_{QCD} \)).

- Dilepton \( \nu_2 \) is simultaneously sensitive to \( \hat{q}_{QCD} \) and \textit{viscosities}!
Dilepton flow at $M \gtrsim 1$ GeV as probe of QGP

- A heavy flavor tracker can reduce/remove HF signal exposing direct QGP radiation ($M \gtrsim 1$ GeV)
- Need to measure $\frac{dN}{dM}$ and $v_2$!  


EM probes sensitivity to transport coefficients

• Understanding (non-)hydrodynamical signal: better sensitivity to transport coefficients

  • Sensitivity to $\tau_\pi = b_\pi \eta/(\varepsilon + P)$

Sensitivity to electrical conductivity using spectral function from EM current in hydro


\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

Au-Au 20-40%

\[ \sqrt{s_{NN}} = 5020 \text{ GeV} \]

Pb-Pb 0-5%

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

Au-Au 20-40%

\[ \sqrt{s_{NN}} = 5020 \text{ GeV} \]

Pb-Pb 0-5%

[S. Floerchinger, Wed 19:18]
Photon emission
Photon sources

• Photons probing early dynamics:
  • Primodial photons / Jet-medium photons [C. Sirimanna, Wed 18:42; R. Modarresi-Yazdi, Thu 18:10]
  \[
k^0 \frac{d^3 \sigma_{A+A \rightarrow \gamma + X}}{d^3 k} = \sum_{a,b,c} f_{a/A}(x_a, Q^2_{fact}) \otimes f_{b/A}(x_{\bar{q}}, Q^2_{fact}) \otimes k^0 \frac{d^3 \hat{\sigma}_{a+b \rightarrow c+\gamma}(Q^2_{ren})}{d^3 k}
  \]
  \[
  + \sum_{a,b,d} f_{a/A}(x_a, Q^2_{fact}) \otimes f_{b/A}(x_{\bar{q}}, Q^2_{fact}) \otimes k^0 \frac{d^3 \hat{\sigma}_{a+b \rightarrow c+d}(Q^2_{ren})}{d^3 k} \otimes D_{\gamma/c}(Q^2_{frag})
  \]
  • Photons from pre-hydrodynamics [J.-F. Paquet, Wed 18:34]
  • Photons as probes of charge stopping [S. Park, Thu 16:00]

• Photons emitted during hydrodynamics
  • Photons from hadronization [C. Nonaka, Thu 18:30]

• Photons from hadronic transport
  • Same photon matrix elements as in hydrodynamical calculations [O. Garcia-Montero, Wed 18:58]
Photon production at intermediate $p_T$

- Conversion and bremsstrahlung photons contribute significantly at intermediate $p_T$
  [R. Modarresi-Yazdi, Thu 18:10]

Photons $5 < p_T < 8$ GeV:
- Total yield dominated by prompt photons
- Significant contribution from jet-medium $\approx 30\%$
  - Conversion $\approx 12\%$
  - Bremsstrahlung $\approx 18\%$

- Jet-medium photons are directly sensitive to $\hat{q}_{QCD}$, avoiding hadronization effects.
Photons from SMASH

- Total photon yield from (Hydro+SMASH) is comparable to that obtained from hydro running to lower temperature (T=120 MeV).

\[ [O. Garcia-Montero, Wed 18:58] \]

- Non-equilibrium dynamics increase \( v_2(p_T) \) at low \( p_T \) ⇒ better comparison with photon data, once a more complete calculation is obtained.
Photon calculations vs data & Bayesian analysis

- Match $T^{\mu\nu}_{\text{IP-Glasma}} \Rightarrow T^{\mu\nu}_{\text{KOMP\ST}} \Rightarrow T^{\mu\nu}_{\text{Hydro}}$

- Photons are sensitive dynamics of quarks production
  CGC $\rightarrow$ hydrodynamics

- Different sources are continuously being included, need to include theoretical uncertainties
Photon calculations vs data & Bayesian analysis

- Match $T^{\mu\nu} (\text{IP-Glasma}) \Rightarrow T^{\mu\nu} (\text{K\O MP\O ST}) \Rightarrow T^{\mu\nu} (\text{Hydro})$

- Photons are sensitive dynamics of quarks production
  CGC $\rightarrow$ hydrodynamics

- Different sources are continuously being included, need to include theoretical uncertainties

- Bayesian Analysis using EM & hadron probes can hopefully constrain better the transport coefficients of QCD

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[J.-F. Paquet, Wed 18:34]

[S. Floerchinger, Wed 19:18]
Summary & Outlook

✔ What was/can be done
  • Dynamics of quark generation can be explored via EM probes
  • EM probes possess simultaneous sensitivity to hydrodynamical transport coefficients (e.g. $\eta$, $\sigma_{EM}$) and jet-related transport coefficient $\hat{q}_{QCD}$ (via jet-medium photons and open heavy flavor dileptons)

✔ Improved rates
  • NLO pQCD comparable with lattice QCD; hadronic rates agree with pQCD at high $T$
  • Hadronic rates are now including chiral symmetry restoration effects

✔ Better medium simulations
  • Pre-hydrodynamical production of photons (dileptons to come...)
  • Hydrodynamic production of EM probes include off-equilibrium dynamics (i.e. viscous effects)
  • Off-equilibrium photon radiation from hadronic transport (improves $\nu_2$ at $p_T < 1.5$ GeV)

➢ Future directions
  • Determine uncertainties of EM probes calculations (e.g. viscous corrections) for better estimation of transport coefficients such as viscosities
  • Bayesian analysis using hadron & EM probes with more precise data
  • More measurements of dilepton $\nu_2$ needed, and removal of HF signal in dileptons
Thank you

Questions?