Chiral Restoration and Electric Conductivity: Opportunities with Precision Dileptons at the LHC

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1.) Intro: EM Spectral Function to Probe Fireball

- Thermal Dilepton Rate

\[
\frac{dR}{d^4q} = \frac{-\alpha^2}{\pi^3 M^2} f^B(q_0, T) \Im \Pi_{em}(M,q; \mu_B,T)
\]

- Hadronic Resonances
  - change in degrees of freedom?
  - restoration of chiral symmetry?

- Continuum
  - temperature?

- Low-\(q_0\),\(q\) limit: transport coefficient (charge)?

- Total yields: fireball lifetime?
1.2 35 Years of Dileptons in Heavy-Ion Collisions

- Current understanding:
  QGP + hadronic radiation with *melting* $\rho$ resonance; $T > T_c$
1.3 Precision Physics with Thermal Dileptons

• **Spectral Information:** $M \sim 0.2-1.5$ GeV
  - Change in **degrees of freedom:** $\rho$ melts into partons?
  - **How is chiral restoration** realized? ($\rho$-$a_1$ degeneracy; “chiral mixing”)

• **Electric Conductivity:** very low $M$, $q$

\[
\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \left[ \text{Im} \, \Pi_{em}(q_0, q=0; T) / q_0 \right]
\]

as **fundamental** as $\eta/s$ and $D_s^{HF}$

• **Fireball Diagnostics**
  - Early **temperatures** ($M \geq 1.5$ GeV; no blue-shift distortion)
  - **Lifetime** of radiating phase (low-mass yield $M \sim 0.5$ GeV)
  - **Flow** ($p_T$ spectra and $v_2$ for **any** mass)
Outline

1.) Introduction

2.) Chiral Restoration and sQGP
   - QCD + Weinberg Sum Rules
   - Resonances above $T_c$?
   - Pre-equilibrium Radiation

3.) Transport Properties
   - Electric Conductivity

4.) Conclusions
2.1 Chiral Symmetry Breaking in Vacuum

- Mass **splitting** within chiral multiplets

- Quantitative: Sum Rules

\[
\begin{align*}
\int_0^\infty ds \frac{\Delta \rho(s)}{s^2} &= \frac{1}{3} f_\pi^2 \langle r_\pi^2 \rangle - F_A \\
\int_0^\infty ds \frac{\Delta \rho(s)}{s} &= f_\pi^2, \\
\int_0^\infty ds \Delta \rho(s) &= f_\pi^2 m_\pi^2 = -2m_q \langle \bar{q}q \rangle \\
\int_0^\infty ds s \Delta \rho(s) &= -2\pi \alpha_s \langle \mathcal{O}^{SB}_4 \rangle \\
\Delta \rho &= \rho_V - \rho_A
\end{align*}
\]

[Hohler+RR '12, Weinberg '67, Das et al '67, Kapusta+Shuryak '94]

- Sensitive to excited states: predict a\(_1\)(1950) state

[Hohler+RR '12]
2.2 Chiral Restoration in the Axial-/Vector Channels

Mechanism of chiral restoration:
- $\rho - a_1$ mass splitting “burns off” [also for $\pi - \sigma$, N-N*(1535) [Aarts et al ’17]]
- “chiral mixing” for $M=1-1.5$ GeV: $\pi - a_1$ annihilation or $\rho$’ broadening…?

Evaluate sum rules at finite $T$:
- In-medium $\rho$ spectral fct.
- Lattice-QCD for chiral order parameters

In-Medium Spectral Functions

[In-Medium Spectral Functions Diagram]

[Hohler+RR ‘13]
2.3 Where Does the $\rho$ Melt?

Hadronic Many-Body

QGP: $q\bar{q}$ T-Matrix

- Hadronic + partonic calculations match near $T_{pc}$ via broad $\rho$-resonance
- Nature of the medium ($s$QGP) above $T_{pc}$ ($D_s$, $\eta/s$, ...)?

[Liu+RR ‘18]
2.3 Dilepton Spectra and Chiral Restoration

- Precision data sensitive to $\rho$-meson spectral shape
- Is the $\rho$-meson really melted above $T_{pc}$ at the LHC?
- “Chiral mixing” discernible at $M \sim 0.9-1.5$ GeV

SPS

$$T_s \sim 200 \text{ MeV}$$

$$\mu_B \sim 220 \text{ MeV}$$

LHC

$$T_s \sim 300 \text{ MeV}$$

$$\mu_B \sim 0 \text{ MeV}$$
4.1 QGP Radiation and Pre-Equilibrium

Hadronic vs. QGP: Elliptic Flow

- Transition hadronic $\rightarrow$ QGP in M-dep. of radial + elliptic flow
- Pre-equilibrium radiation: $M>2$ GeV, sensitive to viscosity + quark chemistry

QGP vs. Pre-equilibrium

$T_s \sim 220$ MeV

[Schlichting et al '21]
Outline

1.) **Introduction**

2.) **Chiral Restoration and sQGP**
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   - Pre-equilibrium Radiation

3.) **Transport Properties**
   - Electric Conductivity

4.) **Conclusions**
3.) **Electric Conductivity**

- Generic transport coefficient (charge): \( \sigma_{el}/T \sim 4\pi \eta/s \sim 2\pi T \mathcal{D}_s^{HF} \)
- Probes timelike long-wavelength limit of EM spectral function:

\[
\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \left[ \text{Im} \mathcal{I}_{em}(q_0, q=0; T)/q_0 \right]
\]

- Kinetic theory:

\[
\sigma_{el} = \frac{1}{3T} \sum_{i=1}^{N_{\text{species}}} q_i^2 n_i \tau
\]

\[\text{pQCD} \quad [\text{Moore+Robert '06}]\]
3.1 Conductivity Peak in Hadronic Matter

- Conductivity peak at zero energy
  stronger interaction $\rightarrow$ broadening reduces peak + enhances shoulder
- Peak quickly disappears at finite 3-momentum (non-zero energies)
conductivity with $\pi$-baryon interactions: $\sigma_{el} \sim 10$-40 MeV or $\sigma_{el}/T \sim 0.1$-0.2

$\Rightarrow$ inefficient in reducing $\sigma_{el}$

much reduced upon inclusion of thermal-pion interactions
3.3 Thermal Dileptons: **No Single-e± Cuts**

- Factor ~2 increase due to reduced $\sigma_{el}$
- Factor ~3 for $q_{t}^{ee} < 200$ MeV
- Factor ~4 for $q_{t}^{ee} < 30$ MeV
4.) Conclusions

• Precise measurement of dilepton spectral shape
  - Chiral restoration of hadron masses and “chiral mixing”
  - $\rho$ spectral shape above $T_{pc}$ and nature of sQGP?

• Very-low-mass dileptons
  - probe electric conductivity consistent with low-mass dileptons

• Dilepton radiation at intermediate mass
  - mass dependent $v_0$ and $v_2$: transition hadronic $\rightarrow$ QGP
  - early temperature vs. pre-equilibrium: $\eta/s$, quark chemistry
5.2 Fireball Temperature

Slope of Intermediate-Mass Excess Dileptons

- unique "early" temperature measurement (no blue-shift!)
- $T_s$ approaches $T_i$ toward lower energies
- first-order "plateau" at BES-II/CBM?
2.2 Transverse-Momentum Dependence

$p_T$-Sliced Mass Spectra

- spectral shape as function of pair-$p_T$
- entangled with transverse flow (barometer)
3.) Polarization Observables

- little explored for thermal radiation
- Non-trivial even for isotropic medium: depend on **transverse** vs. **longitudinal** modes of spectral function

\[
\frac{dR_{l^+l^-}}{d^4q} = -\frac{\alpha^2}{\pi^3M^2} f^B(q_0; T)^{\frac{1}{3}} [2 \text{ Im } \Pi_T + \text{ Im } \Pi_L]
\]

\[
\propto (1 + \lambda \cos^2\theta + \mu \sin2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos2\phi)
\]

- angle between electron and photon momentum

\[
\lambda_{\theta} = \frac{\text{ Im } \Pi_T - \text{ Im } \Pi_L}{\text{ Im } \Pi_T + \text{ Im } \Pi_L}
\]

[Hoyer ‘87, Baym et al ‘18, Speranza+Friman ‘18]
3.2 Polarization Coefficients from ρ Spectral Fct.

- very sensitive to production process:
  - $q\bar{q}$ vs. $\pi\pi$ annihilation vs. Dalitz decay vs. partial wave

[Speranza et al in prog]
5.3 Low-Mass Dileptons in p-Pb (5.02GeV)

- Thermal radiation at ~10% of cocktail
- follows excess-lifetime systematics
- photons [Shen et al ‘15]
3.1 Conductivity Peak in Hadronic Matter

- Conductivity peak at zero energy
  stronger interaction $\rightarrow$ broadening reduces peak + enhances shoulder
- Peak quickly disappears at finite 3-momentum (non-zero energies)
5.1 Fireball Lifetime

Excitation Function of Low-Mass Dilepton Excess Yield

- Low-mass excess tracks lifetime well (medium effects!)
- Tool for critical point search?
2.) Dilepton Rates and Degrees of Freedom

\[ \frac{dR_{ee}}{dM^2} \sim \int d^3q / q_0 f^B(q_0; T) \text{Im} \Pi_{em} / M^2 \]

- ρ-meson resonance “melts"
- spectral function merges into QGP description

⇒ Direct evidence for transition
hadrons → quarks + gluons

\[ \frac{dR_{ee}}{d^4q} \quad 1.4T_c \quad (\text{quenched}) \quad q=0 \]

[R, Wambach et al '99]

[Ding et al '10]
4.4 Elliptic Flow of Dileptons at RHIC

- maximum structure due to late $\rho$ decays
  
  [Chatterjee et al '07, Zhuang et al '09]
  
  [He et al '12]
4.5 QGP Barometer: Blue Shift vs. Temperature

- QGP-flow driven increase of $T_{\text{eff}} \sim T + M \left( \beta_{\text{flow}} \right)^2$ at RHIC
- high $p_t$: high $T$ wins over high-flow $\rho$’s $\rightarrow$ minimum (opposite to SPS!)
- saturates at “true” early temperature $T_0$ (no flow)
2.2 Chiral Condensate + \( \rho \)-Meson Broadening

\[
\langle \langle \bar{q}q \rangle \rangle(T, \mu_B) = \frac{1 - \sum_h \frac{g_h^{\Sigma_h}}{m_{\pi}^2 f_{\pi}^2}}{\langle \langle \bar{q}q \rangle \rangle}
\]

- \( \Sigma_h = m_q \langle \langle h|\bar{q}q|h \rangle \rangle > 0 \) contains quark core + pion cloud

- \( \Sigma_h = \Sigma_h^{\text{core}} + \Sigma_h^{\text{cloud}} \sim \) matches spectral medium effects: resonances + pion cloud

- resonances + chiral mixing drive \( \rho \)-SF toward chiral restoration
baryon effects important even at $\rho_{B,\text{tot}} = 0$:
sensitive to $\rho_{B,\text{tot}} = \rho_B + \rho_{\bar{B}}$ ($\rho$-$N$ and $\rho$-$\bar{N}$ interactions identical)
• $\omega$ also melts, $\phi$ more robust ↔ OZI
3.2 Massive Yang-Mills in Hot Pion Gas

Temperature progression of vector + axialvector spectral functions

- supports "burning" of chiral-mass splitting as mechanism for chiral restoration [as found in sum rule analysis]
3.2 Massive Yang-Mills Approach in Vacuum

- Gauge $\rho + a_1$ into chiral pion lagrangian:
\[
\mathcal{L}_{\text{MYM}} = \frac{f_\pi^2}{8} (\text{Tr}[D_\mu U^+ D^\mu U] + m_\pi^2 \text{Tr}[U + U^+ - 2]) - \frac{1}{2} \text{Tr}[F^2_L + F^2_R] + m_0^2 \text{Tr}[A_L^2 + A_R^2] - i \xi \text{Tr}[D_\mu U D_\nu U^+ F_L + D_\mu U^+ D_\nu U F_R] + \gamma \text{Tr}[F_L U F_R U^+] ,
\]

- problems with vacuum phenomenology → global gauge? [Urban et al ‘02, Rischke et al ‘10]

- Recent progress:
  - full $\rho$ propagator in $a_1$ selfenergy
  - vertex corrections to preserve PCAC:
  \[
  \int \frac{(-\text{Im} \Pi_A^L)}{\pi s} ds = \frac{F_\pi^2}{2}
  \]

- enables fit to $\tau$-decay data!
- local-gauge approach viable
- starting point for addressing chiral restoration in medium [Hohler +RR ‘14]
3.2 Lattice-QCD Results for N(940)-N*(1535)

Euclidean Correlator Ratios

“Nucleon”  “N*(1535)”

- Also indicates $M_{N^*}(T) \rightarrow M_N(T) \approx M_N^{\text{vac}}$

- See also talk by R.-A. Tripolt

Exponential Mass Extraction

<table>
<thead>
<tr>
<th>$T/T_c$</th>
<th>$m_+$ [GeV]</th>
<th>$m_-$ [GeV]</th>
<th>$\Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.21</td>
<td>1.20(3)</td>
<td>1.9(3)</td>
<td>0.209(28)(082)</td>
</tr>
<tr>
<td>0.76</td>
<td>1.18(9)</td>
<td>1.6(2)</td>
<td>0.138(29)(130)</td>
</tr>
<tr>
<td>0.84</td>
<td>1.08(9)</td>
<td>1.6(1)</td>
<td>0.197(39)(054)</td>
</tr>
<tr>
<td>0.95</td>
<td>1.12(14)</td>
<td>1.3(2)</td>
<td>0.052(35)(190)</td>
</tr>
</tbody>
</table>

$R = \int (G^+-G^-)/(G^++G^-)$

[Aarts et al ‘15]
4.2 Thermal Photon Rates

- "Cocktail" of hadronic sources (available in parameterized form) [Heffernan et al ’15]
- Sizable new hadronic sources: pr → gw, pw → gr, rw → gp
- Hadronic emission rate close to QGP-AMY
- semi-QGP much more suppressed [Pisarski et al ‘14]

Graph showing thermal photon rates from QCD matter. Inset shows detailed comparison with different sources.
4.3.2 Photon Puzzle!? 

- $T_{\text{slope}}$ excess $\sim 240$ MeV
- blue-shift: $T_{\text{slope}} \sim T \sqrt{(1+\beta)/(1-\beta)}$
  $\Rightarrow T \sim 240/1.4 \sim 170$ MeV
4.1 Prospects I: Spectral Shape at $\mu_B \sim 0$

STAR Excess Dileptons [STAR ‘14]

- rather different spectral shapes compatible with data
- QGP contribution?
2.3 Low-Mass $e^+e^-$ Excitation Function: 20-200 GeV

- compatible with predictions from melting $\rho$ meson
- “universal” source around $T_{pc}$

P. Huck et al. [STAR], QM14
4.1 Initial Flow + Thermal Photon-\(v_2\)

**Bulk-Flow Evolution**

- **Ideal Hydro 0-20% Au-Au**
  - New thin line: default azhydro

  [Image of graph showing bulk-flow evolution]

  

**Direct-Photon \(v_2\)**

- 0-20%, Au-Au, 200AGeV
  - PHENIX dir \(\gamma\) (BBC)
    - Total
    - Thermal

  [Image of graph showing direct-photon \(v_2\)]

- **\(v_2\) characteristics**
  - Initial radial flow: - accelerates bulk \(v_2\)
    - Harder radiation spectra
      (pheno.: coalescence, multi-strange f.o.)
  - Much enhances thermal-photon \(v_2\)

[He et al '14]
3.1.2 Transverse-Momentum Spectra: Barometer

Effective Slope Parameters

### SPS

- Qualitative change from SPS to RHIC: flowing QGP
- True temperature “shines” at large $m_T$

### RHIC

[Deng, Wang, Xu+Zhuang ‘11]
5.2 Chiral Restoration Window at LHC

- low-mass spectral shape in chiral restoration window:
  \( \sim 60\% \) of thermal low-mass yield in “chiral transition region”
  \( (T=125-180\text{MeV}) \)

- enrich with (low-) \( p_t \) cuts
3.3.2 Fireball vs. Viscous Hydro Evolution

- very similar!

[van Hees, Gale+RR ’11]
[S.Chen et al ‘13]
4.3 Comparison to Data: RHIC

- same rates + intial flow $\Rightarrow$ similar results from various evolution models
4.2 Low-Mass Dileptons: **Chronometer**

- first “explicit” measurement of interacting-fireball **lifetime**: 
  \[ \tau_{FB} \approx (7 \pm 1) \text{ fm/c} \]