Exploring time like transitions in pp(\(n\)), \(\pi p\) and AA reactions with HADES

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Content

✓ Emissivity of QCD matter
✓ Low mass dileptons and from HIC, ρ in-medium spectral function (SF) → relations to chiral symmetry restoration
✓ Connections to time-like baryon em. transitions
✓ Measurements of baryon electromagnetic transitions in NN and πN reactions
✓ Summary & Outlook
High Acceptance Di-Electron Spectrometer

- Spectrometer with $\Delta M/M - 2\%$ at $\rho/\omega$ @ GSI/FAIR
- Electrons: RICH (hadron blind)
- Hadrons: TOF & dE/dx vs p
- 2004-2014: HI (C+C, Ar+KCl, Au+Au $\sqrt{s}$~2.4-2.6 GeV)
  p+p, d+p, p+N $\sqrt{s}$=2.4-3.0 GeV $\pi$+p $\sqrt{s}$= 1.5 GeV

Upgrade 2018/2019
- New RICH photon det (HADES/CBM) – 2-3 $\otimes e_{\text{eff}}$
- Forward tracking straws +RPC – $\Delta/E_{\text{rec.}}$
in pp/pA (HADES/PANDA)
- el. Calorimeter (lead glass)-neutrals
- Planned: 200 kHz DAQ , 10$\otimes$ count rate increase
Various faces of QCD: phase diagram

LHC

Order par.: deconfinement

Lattice QCD

S. Borsnyi JHEP’2010

µ_B = 0

Order par.: Chiral symmetry restoration

- Primary goal: (first!) measurement of Low Mass dileptons (e+e-) at high µ_B
- Complementary to studies with URHIC (LHC, RHIC, SPS):

LM \rightarrow \text{in-medium Vector Meson (ρ) spectral function}
Emissivity of QCD matter with dileptons

\[
\frac{dN_{ll}}{d^4qd^4x} = -\frac{\alpha_{em}^2}{\pi^3} \frac{L(M^2)}{M^2} f^{BE}(q_0, T) \text{Im}\Pi_{em}(M,q,T,\mu_B)
\]


Not disturbed by finite state interactions!

Thermal distribution \( f^{BE}(T) \) – thermometer

\( q^2 > 1.2 \text{ GeV} \) qq radiation pQCD (\( \text{Im}\Pi_{em} \text{ flat} \) → T

\( \text{Low mass VectorMesons} \)

- qq Continuum

- Not disturbed by finite state interactions!

- Thermal distribution \( f^{BE}(T) \) – thermometer

- \( q^2 > 1.2 \text{ GeV} \) qq radiation pQCD (\( \text{Im}\Pi_{em} \text{ flat} \) → T

\( \text{Im}\Pi_{em} : q^2 < 1 \text{ GeV} \) - in-medium VM (\( \rho \)) spectral functions
Dielepton emission in HIC

HI collisions: total emission rate needs integration over full collision time \((T, \mu_B)\)

\[ \text{Compilati} \text{on F. Seck and T. Galatyuk} \]

„coarsed grained approach”

- energy \((\varepsilon)\) and baryon densities \((\rho_b)\) obtained in small cells \((\Delta x, \Delta t \sim 0.8\text{fm}, 0.2\text{ fm/c})\) in local rest frames with vanishing net baryon current
- EOS (hadron gas, QGP-lattice) used to relate \(\varepsilon\) with \((T, \rho_B)\)
- Apply emissivity formula with \textit{in medium} \(\varepsilon \mu B\text{em} \)
In medium $\rho$ spectral function

\[
A_{\rho}(M) = -\frac{2\text{Im} \Sigma_{\rho}(M)}{[M^2 - m_{\rho}^2 - \text{Re} \Sigma_{\rho}(M)]^2 + [\text{Im} \Sigma_{\rho}(M)]^2}
\]

In Medium:

- connection to ChSR $\rightarrow \rho(760)/a_1(1260)$ become degenerate at $T \sim T_c$, $\mu_b = 0$

$R \rightarrow \text{Ne}+\text{e}^-$ (Dalitz decays)


**Baryon electromagnetic transitions**

- Dalitz decays: transition Form Factors (timelike) (complementary to space-like region)

\[
\frac{d\Gamma(\Delta \rightarrow Ne^+e^-)}{dq^2} = f(m_\Delta, q^2) \left[ G_M^2(q^2) + 3G_E^2(q^2) + \frac{q^2}{2m_\Delta} G_C^2(q^2) \right]
\]

Main players in HADES: \(\Delta(1232), N^*(1520), \Delta(1600-1700),\ldots\)

Form-Factors - models

G. Ramalho and M.T. Peña, PRD 80 (2009) 013008
Results from HIC
Dilepton thermal rates from UrHIC SPS/RHIC

LMR dominated by thermal radiation from $\rho$ at $T \sim T_c$ (hadronic phase!)

"Melting" of $\rho$: baryon-$\rho$ interactions

IMR: $T \sim 200$ MeV - $\langle T \rangle$ of the early phase (QGP)
HADES Au+Au @ √s = 2.4 GeV

Excess yield fully corrected for acceptance

Accepted for pub. in Nature Phys. 2019

- Successful description with Coarse-Grained approach + emissivity formula
- Dileptons as thermometer
  - Mass spectrum falls exponentially → “Planck-like”
  - Fit \( \frac{dN}{dM} \sim M^2 \exp \left( -\frac{M}{T} \right) \) in range M=0.2-0.8 GeV/c^2
  - \( <T> \) emitting source = 72 ± 2 MeV/k_B
- Strong melting of \( \rho \) meson
- In agreement with microscopic model of Rapp & Wambach (interactions with baryons !)
- Same model describes also RHIC(STAR), SPS (CERES, Na60 data)

HADES Collab., submitted
CG FRA Endres et al.: PRC 92 (2015) 014911
CG SMASH: J. Staudenmaier et al., arXiv:1711.10297v1
$R \rightarrow N\gamma^*$ transition and $NN \rightarrow NN\gamma^*$ bremsstrahlung in $NN @ \sqrt{s} = 2.42$ GeV
$\Delta (p\pi^+, p\pi^0)$ excitation in pp@ $\sqrt{s} = 2.42$ GeV

13 PNPI + 2 HADES data sets

BnGa PWA solutions

FINAL STATES:
$P_{33}(1232)$ and $P_{11}(1440)$ in $\pi N$ state

HADES:
$pp \rightarrow ppe^+e^-$

BR ($\Delta \rightarrow pe+e^-$) = $4.19 \times 10^{-5} \pm 0.62$ (sys) $\pm 0.32$ (stat)
(First measurement PDG entry)

Good agreement with 2 component model of TFF Ramahlo & Pehna (R &P)
->Slight rise v.s Mass due to VM($\rho$) - pion cloud effect
Angular distributions for $\Delta \rightarrow pe+e^-$ and leptons

$\Delta (pe+e^-)$ angular distribution in CM

$e^\pm$ in helicity frame

$\Delta^+ \rightarrow pe+e^-$ : PWA solution for $\Delta$ production and Ramahlo & Pena model for Dalitz decay

$\Delta^+ \rightarrow pe+e^-$ : calc. assuming dominance of $G_M$ (transverse polarized $\gamma^*$)

Production and decay characteristics consistent with the expected for $\Delta^+ \rightarrow pe+e^-$
Many calculations (most recent only!):
R. Shyam/ U. Mosel \textit{PRC} 82:062201, 2010
L.P. Kaptari, B. K"ampfer, NPA 764 (2006) 338

\[ \text{pn} \rightarrow \text{pn} \gamma^* \rightarrow \text{pne}+\text{e}^- \quad \text{(bremmstrahlung)} \]

\textit{quasi-elastic p-n bremsstrahlung”}
difficult theoretical problem faced since 80’es
- off shell nucleon em. FF (in time-like region)
- nucleon-nucleon potential
- Conservation of gauge invariance in calculations

\[
\text{Strong excess of p-n over p-p (p-p } \Delta \text{ pe+)}!
\]

\textbf{Explanations} \textit{”off shell } \rho \text{” production:}
- emission from } \pi \text{ exchange line Shyam & Mosel

\[
\begin{align*}
\text{“} \Delta \Delta \text{”} \rightarrow \text{pnp} & \rightarrow \text{pne}+\text{e}^- & \text{Baskanov, Clement} \\
\end{align*}
\]

\[
\begin{align*}
\text{pp} & \rightarrow \text{Ne}+\text{e}^- \\
\end{align*}
\]
electron distributions in $\gamma^*$ rest (helicity) frame

As expected for $\Delta \rightarrow p\epsilon + e^-$

Change of angular distribution

Expected for "p-n bremsstrahlung" (OBE models) with contribution from emission from charge pion exchange
Dalitz decays of Higher mass resonances in pp @ $\sqrt{s}=3.1$ GeV
Resonance excitation $\sqrt{s}=3.1$

Incoherent sum of $(\Delta, N^*)$ resonances

$\mathcal{R}(\vec{q}_3)$

$p_1 \quad p_2$

$\bar{t} = (\vec{q}_3 - \vec{q}_{1,2})$

Empirical parametrisation of Resonance production as a function of $t(M_R)$

$t(M_R)$

$t$-channel dominance

Recently confirmed also by $\pi^+\pi^-$ channel

A. Belounnas talk
$p+p \rightarrow pp \ e^+e^- \ (\pi^+\pi^-)@ \sqrt{s}=3.1 \ GeV$

(exclusive channels)

HADES coll. EPJA50(2014) 82

A. Belounnas (preliminary)

- Excess above QED cocktail due to for subthreshold coupling of $R \rightarrow Np \rightarrow Ne+e^-$?
- (direct $\rho$ seen in 2 pion channel accounts only for small fraction of the $e^+e^-$ yield !)

Diagram showing $dN/dM \cdot 1/N_{el}$ and $d\sigma/dM$ for $e^+e^-$ versus $M_{inv}^{e^+e^-}$ and $M_{inv}(\pi^+\pi^-)$.
Comparison to models with strict VDM

Good description by “HADES resonance model” but with BR for $R \rightarrow N\rho$ from BnGa (upper limits) (reduced as compared to PDG’ 2014)

Needs pion beam!

$\frac{d\Gamma}{dM} = \frac{M_\rho}{M^3} \text{BR}(M = M_\rho)$

Resonance -> $N\rho$ Branching Ratios

<table>
<thead>
<tr>
<th>Resonances</th>
<th>GiBUU</th>
<th>UrQMD</th>
<th>KSU</th>
<th>BG</th>
<th>CLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(1520)$</td>
<td>21</td>
<td>15</td>
<td>20.9(7)</td>
<td>10(3)</td>
<td>13(4)</td>
</tr>
<tr>
<td>$\Delta(1620)$</td>
<td>29</td>
<td>5</td>
<td>26(2)</td>
<td>12(9)</td>
<td>16</td>
</tr>
<tr>
<td>$N(1720)$</td>
<td>87</td>
<td>73</td>
<td>1.4(5)</td>
<td>10(13)</td>
<td>–</td>
</tr>
<tr>
<td>$\Delta(1905)$</td>
<td>87</td>
<td>80</td>
<td>&lt; 14</td>
<td>42(8)</td>
<td>–</td>
</tr>
</tbody>
</table>

PDG Status 2014!
Pion Beam @ GSI

- Reaction $N+Be$, $8\times10^{10}$ $N_2$ ions/spill (4s)
- Secondary $\pi^-$ with $I \sim 2-3 \times 10^5$/s
- $P = 654, 687, 737, 787$ MeV/c ($\sqrt{s} \sim 1.5$ GeV)
- PE $(CH_2)_n$ and C targets

- Pion momentum $\Delta p/p = 2.2\%$ ($\sigma$)
- $\sim 50\%$ acceptance of pion beam line

Talks: I. Ciepal
B. Ramstein
2 pion production: PWA (BnGa) decomposition

Final States @ $\sqrt{s}=1.49$ GeV

„subthreshold” – no peak in $\rho \rightarrow \pi^+ \pi^-\pi^0$ mass distributions

- $\Delta-\pi$ dominant,
- significant $N-\rho$
  - dominant: $s$-channels I=1/2 (mainly D13)

- $\Delta-\pi$ smaller,
- $N-\rho$ dominant
  - $s$-channels, D13

**M(n\pi^-)**

**M(\pi^+\pi^-)**

**M(p\pi^0)**

**M(\pi^0\pi^-)**

- $\Delta-\pi$
- $N-\rho$
- $N-\sigma$

$\rho\pi^-\pi^0$

$\rho\pi^+\pi^-$
Total Cross Sections

\[ n\pi^+\pi^- \quad \text{and} \quad p\pi^-\pi^0 \]

\[ \sigma [\text{mb}] \]

- world data
- PWA Manley
- HADES
- PWA total
- \( \Delta-\pi \)
- N-\( \rho \)
- N-\( \sigma \)
- N-\( \rho \) (s-chan)
- N-\( \rho \) (S11)
- N-\( \rho \) (D13)

consistent description of HADES data and ~ 130 other reactions with BnGa (A. Sarantsev)

- \( D_{13} (1520) \) dominant contribution to \( \rho \) production
  - \( \text{BR} = 12 \pm 2 \% \)
$\pi^- p \rightarrow e^+ e^- n \ @ \ \sqrt{s} = 1.49 \ \text{GeV}$

**Exclusive channel**

$\pi^- + \text{CH}_2 \rightarrow e^+ e^- X \ (\text{eff. corr.})$

$\rho_\pi = 685 \ \text{MeV/c}$

- N(1520)
- N(1535)
- $\rho$
- total

$\rho \rightarrow e^+ e^-$ calculated as $\frac{d\sigma}{dM_{\pi^+ \pi^-}} \frac{M_\rho}{M^3} \ BR(q \rightarrow e^+ e^-)$

"QED" (point-like) constrained by $\pi^- p \rightarrow n \gamma$

PWA BnGa

Strong increase with mass – signature of VDM

Yield consistent with $\rho$ contribution expected from $\pi \pi$ (BnGa)

Consistent with 2 component model of D13(1520) $\rightarrow$ ne+e- (Ramalho & Pena)
Polarisation of resonances in pion induced reactions

Z- CMS quantization axis

\[ \vec{L} \perp \text{R.P} \]

- \( \pi \) is spinless hence

\[ J_{Z}^{N^*} = S_{Z}^{N} = \pm \frac{1}{2} \]

- Polarization for \( J^{N^*} \geq \frac{3}{2} \)

expected (only spin projections \( \pm \frac{1}{2} \)) allowed

\[ |A|^2 = \sum_{\Lambda \Lambda'} \rho_{\Lambda \Lambda'}^{(H)} \rho_{\Lambda \Lambda'}^{(dec)} \]

for e+e-

\[ |A|^2 = 8p_{\gamma^*}^2(1 - \cos^2 \theta_1 - \rho_{11}^H (3\cos^2 \theta_1 - 1) + \sqrt{2} \sin(2\theta) \cos \varphi \text{Re}\rho_{10} + \sin^2 \theta \cos(2\varphi) \text{Re}\rho_{1-1}^H ) \]

Models: GSI/Budapest

E.Speranza et al. PLB 764(2017)282

Talk by Denis Nitt
A. Sarantsev (priv. Comm)
Results for $\rho_{11}$ $\rho_{10}$ $\rho_{1-1}$ from $e^+e^-$ and $\pi\pi$

- consistent description of $e^+e^-$ data with VDM * model (GSI/Budapest) for D13
- consistent description of $e^+e^-$ data with $\rho \rightarrow \pi\pi$ from BnGa
- dominance of D13
Summary

• Dilepton radiation (excess yield) in Low Mass Range in HIC can be described by emission form hot and dense phase using emissivity approach with strongly modified SF of ρ meson
  ▪ Modeling of SF requires detailed knowledge of elementary processes involving baryon- meson interactions - $R \rightarrow N \gamma^*$ transitions (em. Transition Form Factors) are directly related to hadronic loops in self-energy calculations
  ▪ Results of studies performed with NN and πN reactions demonstrate important role of intermediate ρ meson in em. transitions for $\Delta$, $D13$, along Vector Meson Dominance
  ▪ Angular distributions (triple differential cross sections) are important observable to discriminate between different contributions
Exp. proposals at GSI/SIS18 (FAIR0 phase 2019-2022) explore the third resonance region ($\sqrt{s} \sim 1.7$ GeV/$c^2$) with pion beams:

$\pi^- p \to n e^+ e^-$, $\pi^- p \to \pi\pi N$, $\omega n$, $\eta n$, $K^0 \Lambda$, $K\Sigma$,....+photons (new electromagnetic calorimeter, Forward Detector (0-7), new Photon Detector RICH (better e+e- eff.))

• Experiments with protons beams $E=4.5$ GeV at SIS18/FAIR to search for Hyperon dilepton transitions $Y^* \to \Lambda e^+ e^-$ (common project with PANDA)
**Hyperon decays**

- Hyperons are narrow ($\Gamma=15-40$ MeV) : can be studied in pp, pA with HADES (and later pp with PANDA at FAIR).
- Radiative decays of hyperons $Y \rightarrow \Lambda \gamma$
  - Badly known
  - High sensitivity to internal (quark,bag models,..)
- Dalitz decays of hyperons $Y \rightarrow \Lambda e^+e^-$ (BR~$10^{-5}$)
  - No measurement.

Relevance of Vector Dominance in the hyperon sector?

E.g. $\Sigma^*(1385) \rightarrow \Lambda \gamma^*$ is anologue of $\Delta(1232) \rightarrow N \gamma^*$ transition (measured by HADES)
**ρ/a₁ - VM : connection to χSR**

**Weinberg Sum rules**

[Weinberg ’67, Das et al ’67; Kapusta+Shuryak ‘94]

\[
\int ds \frac{1}{s} (\rho_V - \rho_A) = f_\pi^2
\]

\[
\int ds (\rho_V - \rho_A) = -m_q \langle \bar{q}q \rangle
\]

\[
\int ds s (\rho_V - \rho_A) = c\alpha_s \langle (\bar{q}q)^2 \rangle
\]

- **ρ/a₁ splitting in vacuum**
  
  ![Graph showing ρ/a₁ splitting in vacuum](image)

- **evolution of ρ SF from microscopic model** Rapp & Wambach
- **a₁ SF predicted from QCD constraints (sum rules) and lattice data**

- **Merging of ρ/a₁ SF at T ~ T_c**
  
  (calculations for μ_b = 0)