Experimental study of the $\pi$-p→ne+e-
Hades strategy

• Study dilepton emission in dense and hot matter (cf. DLS/Berkeley)
  A+A reactions in the 1-2 AGeV energy range C+C, Ar+KCl, Au+Au (2012)
• Cold matter at normal nuclear density  p+Nb 3.5 GeV
  (cf KEK, Jlab, CBELSA/TAPS)
• Elementary collisions pp, dp and πp (2014)
  reference to heavy-ion spectra
  study different dilepton sources (exclusive channels)
  dilepton emission is probing time-like electromagnetic structure of hadronic transitions!

• Simultaneous measurements of hadronic channels (pp →NNπ, pp →NNππ)
  Cross-checks on known channels, detailed information on baryonic resonance production
• Strangeness measurement program: K-, K^0, φ, Σ(1385), Λ(1405) to be
  investigated also in πp and πA
• HADES@FAIR (2017): pp, pA, AA  E/A<8 AGeV
In medium modifications

Experimental results


- Strong broadening of in-medium $\rho$ spectral function due to its coupling with baryonic resonances (N(1520), $\Delta$(1620), N(1720), etc.)
- The coupling of $\rho$ to baryonic resonances can be studied directly in $\pi^-$-N interactions
Electromagnetic form factors

Time-like electromagnetic form factors

\[ q^2 = (M_{ee})^2 > 0 \]

Variable

No data are available

Space-like electromagnetic form factors

\[ q^2 < 0 \]

Fixed

Data from Jlab (CLAS) up to \(-q^2 = 4 \text{ GeV}^2\)

HADES detector

- Located at SIS18, GSI
- Beams: heavy-ions, protons, pions
- Fixed-target experiment
- Hadron and lepton identification
- Acceptance: 85% azimuthal coverage, 18-85° in polar angle
- Mass resolution 2 % (in $\rho/\omega$ region)
- 80,000 channels
- Fast DAQ: 50kHz event rate
Pion beams with HADES

Secondary $\pi$ momentum $p_\pi = 0.69$ GeV/c
- Access to the “second resonance region”
- Beam intensity $I = 3-4 \times 10^5 \pi/s$
- $\sigma_p = 2\%$
- Target: Polyethylene ($\text{CH}_2)_n$ and Carbon

- Primary beam: $8 \times 10^{10} \text{N}_2$ ions/spill
- $E = 2$ AGeV
- Spill: 4s cycle
- Total ~15 days of effective measurements
HADES programme for pion beam

Scan of N(1520) resonance region:

- **π⁺π⁻ production**
  Improve very poor π⁺π⁻ database. Manley analysis is based on only 240000 events (no differential distributions)

- **e⁺e⁻ production**
  No data are available
  Resonance Dalitz decays R→Ne⁺e⁻
  (Link to time-like transition electromagnetic structure)
Elastic scattering

W. Przygoda, MESON 2016, EPJ Web of Conferences Vol. 130 (2016)

- $\pi^- p \rightarrow \pi^- p$ (after C subtraction)
- Normalization via measured $\pi^- p$ elastic scattering of known $\sigma$
  (SAID partial wave solution)
PWA results (one example)

Bonn-Gatchina partial wave analysis (PWA) including
- HADES data (4 energies $\pi^+\pi^-$ and $\pi^0\pi^0$)
- $\pi$ and $\gamma$ database

HADES preliminary

- $\rho$ total
- $\rho$ s-channel
- $\rho$ $D_{13}(1520)$ ($N(1520)\rightarrow N\pi$)
PWA $\pi^+\pi^-$ inv. mass $\rho$ contribution

$\pi^-p \rightarrow \pi^+\pi^-n$ at 0.69 GeV/c

$N(1520)D_{13}$ coupling to $\rho N$: 12%

Total $\rho N$: 1.3 mb

- Dominated by s-channel
- Resonant D13(1520) production
- Strong interferences between $1/2^-$ states with isospin 1/2 and 3/2
Inclusive invariant mass spectrum (raw)

- Signal = $N_{e^+e^-} - CB$
- Same-event like-sign CB geometric and/or arithmetic mean

- CB rejection cuts:
  - Opening angle > 9°
  - Tracks with a not fitted track in the vicinity of 4° are excluded from further analysis

- Signal ($M<140$ MeV/c$^2$) = 37450
- Signal ($M>140$ MeV/c$^2$) = 3350

→ Efficiency corrections based on Monte Carlo simulations
Searching for $\pi^0$ and $\eta$ with full conversion method

Large uncertainties on experiment and theory side
Inclusive invariant mass spectrum
Comparison with simulation

Sources:
- $\sigma(\pi^- p \rightarrow \pi^0 X)$
  $\pi^0 \rightarrow e^+ e^- \gamma$
- $\pi p \rightarrow N(1520)$
  Dalitz decay with a constant form factor
- $\sigma(\pi^- p \rightarrow \eta X)$
  $\eta \rightarrow e^+ e^- \gamma$
- $\pi^+ C$ treated as a quasi-free process
- Cross sections taken from database (Landolt-Bornstein)
- Simulations filtered through the HADES acceptance
- Cocktail without $\rho$ contribution does not describe measured data!
Exclusive channel: $\pi^-p \rightarrow n e^+e^-$

$\rho$ contribution from PWA (partial wave analysis) of $\pi^+\pi^-$ HADES data and using the Strict Vector Dominance Model (VDM)

Good description using a cocktail of point-like baryons+$\rho$ contribution

$$\frac{d\sigma}{dM_{ee}} = \frac{d\sigma}{dM_{\pi\pi}} C_p \left( \frac{m_\rho}{m_{ee}} \right)^3$$

$C_p = 4.7 \times 10^{-5}$
Deviation from point-like behaviour

- Ratio between:
  - Efficiency corrected exclusive $e^+e^-$ spectra
  - $N(1520)$ QED calculation, filtered through the HADES acceptance

- Clear deviation from unity in the high mass region!
- Indication for VDM like form factors
Comparison with GiBUU model

- BUU-type hadronic transport model
- Incoherent sum of the cocktail components
  - $\sigma_p (\pi^0) = 19 \text{ mb}$
  - $\sigma_p (\eta) = 0.9 \text{ mb}$
  - $\sigma_p (\Delta) = 4.24 \text{ mb}$
- Some overestimation in $\pi^0$ region and above 140 MeV/c$^2$ dominated by N(1520) and $\eta$
Comparison with GiBUU model

Exclusive spectrum $\pi p \rightarrow ne^+e^-$

- $N(1520)\rightarrow N\rho \rightarrow Ne^+e^-$ with $\rho \rightarrow e^+e^-$ following pure VDM form factor for $N(1520)$

$\rightarrow$ Overestimation points to problem with strict VDM at small invariant mass (close to real photon emission)
e^+e^- production in microscopic models

Resonance contribution N*/Δ + Interference effects (important ≤ ρ/ω threshold!)


G. Wolf, M. Zetenyi, PRC86 (2012)
Exploiting angular distribution

- Invariant mass shows deviation from point-like baryon transitions
- Additional information on the electromagnetic transitions can be provided by the angular distribution
- General formula for \( \gamma^* \rightarrow e^+e^- \) angular distribution:
  \[
  |A|^2 = 8|k|^2 \left[ 1 - \rho_{11}^{(H)} + \cos^2 \theta (3\rho_{11}^{(H)} - 1) + \sqrt{2} \sin(2\theta) \cos \phi \text{Re}\rho_{10}^{(H)} + \sin^2 \theta \cos(2\phi) \text{Re}\rho_{1-1}^{(H)} \right]
  \]
- Coefficients depend on \( M_{e^+e^-} \) and \( \gamma^* \) angle
- The estimation of the coefficients is performed via a log-likelihood event-by-event approach
Fit results in HADES acceptance

\[ \cos \theta_{CM} < 0 \text{ and } M_{inv} > 400 \text{ MeV/c}^2 \]

\[ 0 < \cos \theta_{CM} < 0.5 \text{ and } M_{inv} > 400 \text{ MeV/c}^2 \]

\[ \cos \theta_{CM} > 0.5 \text{ and } M_{inv} > 400 \text{ MeV/c}^2 \]
Model predictions

- Microscopic model including N(1440) and N(1520) excitations in s and u-channels and VDM electromagnetic form factors (E. Speranza, M. Zetenyi, B. Friman, Physics Letters B 764 (2017) 282–288)

\[
\lambda_\theta = \frac{3\rho_{11} - 1}{1 - \rho_{11}}
\]

\[
\frac{d\sigma}{dM d\cos\gamma \cdot d\cos_\theta} \propto \Sigma_{\perp} (1 + \cos^2 \theta_\gamma) + \Sigma_{\parallel} (1 - \cos^2 \theta_\gamma) \\
\propto A(1 + B(\theta_\gamma, M) \cos^2 \theta_\gamma)
\]

Distribution of virtual photon angle in CM: sensitive to interference between amplitudes for different contributions

Distribution of helicity angle: for each contribution, it reflects the electromagnetic structure of the transition
Model predictions
Comparison with data

- Comparison of density matrix coefficients extracted from the data and in the microscopic model in the same $M_{ee}$ and $\theta_{\gamma^*}$ ranges

![Graph showing comparison of $\rho_{11}$ coefficients](image)

**HADES Preliminary**

Only transverse

1: $-1 < \cos \theta_{cm} < 0$
2: $0 < \cos \theta_{cm} < 0.5$
3: $0.5 < \cos \theta_{cm} < 1$
Model predictions
Comparison with data

- Model independent statements: transverse photons give $\rho_{11}=1/2$, $\rho_{10}=0$
- Data indicate significant contribution of longitudinal virtual photons, especially for $\cos \theta_{cm}$ in $[-1,0]$ and $[0.5,1]$.
- Consistent with pure contribution of $N(1520)$
- Points to a too large $N(1440)$ contribution (also supported by PWA of $\pi^- p \rightarrow n\pi^+\pi^-$ channel)
- Effects of non-resonant terms to be studied
Summary and outlook

- HADES – Di-Electron spectrometer in combination with pion beam is an unique tool to understand in details baryon-$\rho$ couplings using both $e^+e^-$ and $\pi^+\pi^-$ measurements

- Measurement of $e^+e^-$ invariant mass spectra for inclusive and exclusive channels

- Good agreement with a cocktail of point-like source + $\rho$ contribution deduced from PWA of $\pi^+\pi^-$ data

- Comparison to GiBUU points to too large $N(1520)$ contributions (due to VDM model?)

- Despite low statistics, angular distributions show sensitivity to time-like electromagnetic structure of the transitions and allows for a comparison to models

- Future plan to continue pion induced reactions at higher energies with an electromagnetic calorimeter and new RICH detector