



# **Baryonic Resonances at HADES**

**A. M. Foda**

**GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany**

**MESON 2026**

# Baryon Spectroscopy: Strategy



**Goal:** Non-perturbative QCD, resonance dynamics in the dense nuclear medium at FAIR.

**How:** Modular, open-source PWA framework (AmpTools<sup>1</sup>) unitary + analytic.

## $\pi^- p$ : K/D-Matrix Formalism

- Overlapping resonances (2nd/3rd region).
- Chew-Mandelstam unitarization + conformal Left-Hand Cuts (LHC).

## $pp$ : JüBo DCC Model

- Production couplings in baryon-meson channels.
- Dynamic Coupled-Channel; exact 2-body unitarity,  $L \leq 5$ ,  $M=[1,2.5]$  GeV.

*Framework available on GSI GitLab*

*Users can add their own reactions/amplitudes.*

<sup>1</sup>M. Shepherd *et al*, <https://doi.org/10.5281/zenodo.7336113>

# Baryon Spectroscopy: Strategy



**Goal:** Non-perturbative QCD, resonance dynamics in the dense nuclear medium at FAIR.

Earlier talk by J. Messchendorp

**How:** Modular, open-source PWA framework (AmpTools<sup>1</sup>) unitary + analytic.

## $\pi^- p$ : K/D-Matrix Formalism

- Overlapping resonances (2nd/3rd region).
- Chew-Mandelstam unitarization + conformal Left-Hand Cuts (LHC).

## $pp$ : JüBo DCC Model

- Production couplings in baryon-meson channels.
- Dynamic Coupled-Channel; exact 2-body unitarity,  $L \leq 5$ ,  $M=[1,2.5]$  GeV.

*Framework available on GSI GitLab*

*Users can add their own reactions/amplitudes.*

<sup>1</sup>M. Shepherd *et al*, <https://doi.org/10.5281/zenodo.7336113>

## Baryon-Meson couplings

( $\pi^- p \rightarrow (\pi\pi/\omega/\eta) N / K^0 \Lambda / K \Sigma$ )

- Sparse  $\pi$ -beam database (PWA)
- Baryon Structure: Cascade decays,  $\eta n$  couplings

## E.M. Baryon Transitions

( $\pi^- p \rightarrow n e^+ e^-$ )

- Broad range of  $q^2 = (M_{ee})^2 \rightarrow$  Time-Like
- Confirmation for VMD ( $\rho, \omega$ )
- Extract SDMEs
- Limited data available

## Cold Matter Studies (C, Ag Targets)

- $\omega$  absorption,  $\rho$  spectral function
- Strangeness production
- Limited data available

## Baryon-Meson couplings

( $\pi^- p \rightarrow (\pi\pi/\omega/\eta) N / K^0\Lambda / K\Sigma$ )

- Sparse  $\pi$ -beam database (PWA)
- Baryon Structure: Cascade decays,  $\eta n$  couplings

**APPROVED! 54 Shifts**

## E.M. Baryon Transitions

( $\pi^- p \rightarrow n e^+ e^-$ )

- Broad range of  $q^2 = (M_{ee})^2 \rightarrow$  Time-Like
- Confirmation for VMD ( $\rho, \omega$ )
- Extract SDMEs
- Limited data available

## Cold Matter Studies (C, Ag Targets)

- $\omega$  absorption,  $\rho$  spectral function
- Strangeness production
- Limited data available

## Baryon-Meson couplings

( $\pi^- p \rightarrow (\pi\pi/\omega/\eta) N / K^0 \Lambda / K\Sigma$ )

- Sparse  $\pi$ -beam database (PWA)
- Baryon Structure: Cascade decays,  $\eta n$  couplings

**APPROVED! 54 Shifts**

## Cold Matter Studies (C, Ag Targets)

- $\omega$  absorption,  $\rho$  spectral function
- Strangeness production
- Limited data available

## E.M. Baryon Transitions

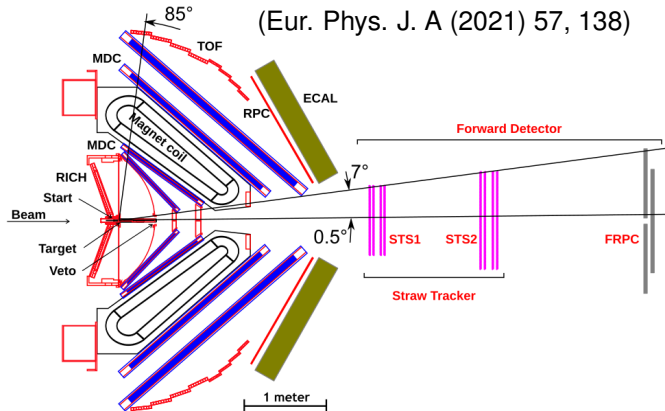
( $\pi^- p \rightarrow n e^+ e^-$ )

- Broad range of  $q^2 = (M_{ee})^2 \rightarrow$  Time-Like
- Confirmation for VMD ( $\rho, \omega$ )
- Extract SDMEs
- Limited data available

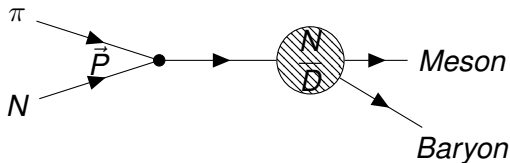
Earlier talk by M. Kohls

# High-Acceptance Di-Electron Spectrometer (HADES)

- GSI, SIS18
- $\pi$ ,  $\rho$ , Heavy-Ion beam



- Acceptance: 15-85° + Forward Upgrades 1-7°
- Precise spectroscopy of  $\gamma$ ,  $e^+ e^-$  pairs & charged hadrons



$$A_{ab} = \sum_{\alpha, \beta} P_a^{(\alpha)} d_{\alpha\alpha} D_{\alpha\beta} g_b^{L(\beta)}$$

$$\hat{D} = \hat{d}(\hat{I} - \hat{B}\hat{d})^{-1}, \quad B(s) = B_{\text{RHC}}(s) + B_{\text{LHC}}(s)$$

$d_{\alpha\alpha}$  propagators (resonant & non-resonant)

$g_a^\alpha$  coupling of channel a to state  $\alpha$  a, b, j: channels,  $\alpha, \beta$ : bare states

<sup>2</sup>PhysRevD.84.076001

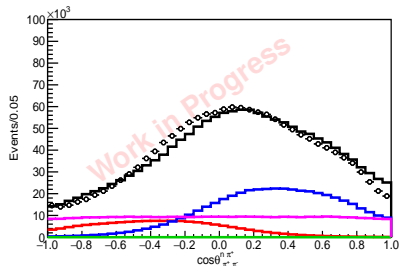
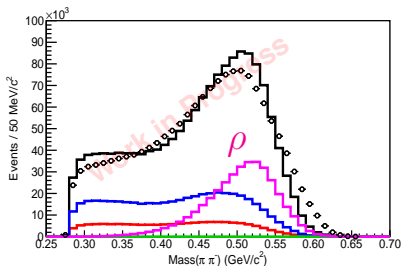
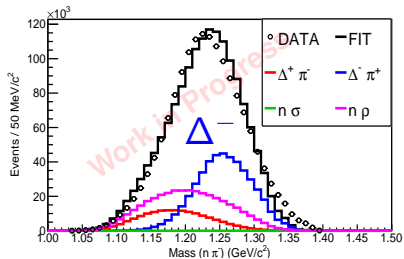
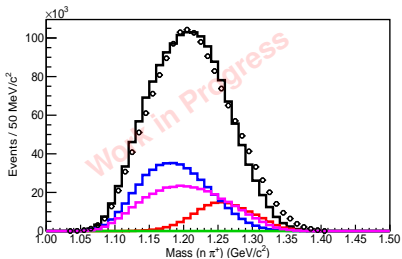
$$\pi^- p \rightarrow n\pi^+\pi^-$$

Channels:  $\Delta^+\pi^-$ ,  $\Delta^-\pi^+$ ,  $n\sigma$ ,  $n\rho$

Resonances (Poles): N(1440), N(1520) & N(1535)

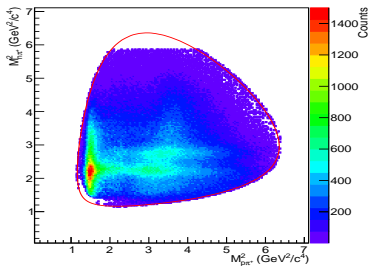
- 4 energy bins:  $\sqrt{s} = 1.47 - 1.55$  GeV
- Spectral function description of  $\Delta$ ,  $\sigma$  &  $\rho$ .
- Dispersion Matrix: - bare resonance mass  
- Total width =  $\Sigma$  partial widths.
- Fit Parameters: production & decay couplings (energy independent).
- Left-hand cuts disabled.

# Example Fit



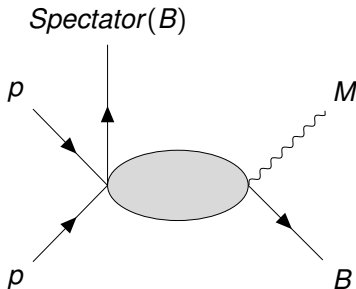
- **Exclusive production  $N^*$**   
 $\Delta$ : Differential cross-section & coupling strengths.
- **Rescattering effects:**  
Resolve overlapping contributions.

Next talk by S. K. Sahu



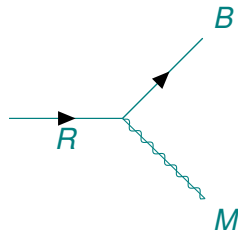
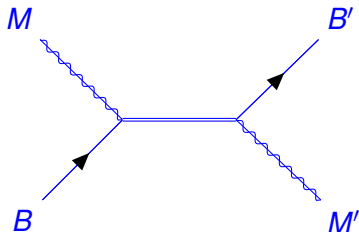
$p p \rightarrow p \pi^+ (n)$

- JuBo: Dynamical coupled-channel (DCC) model for meson-baryon reactions.
- $\pi N, \eta N, K\Lambda, K\Sigma, \pi\Delta, \rho N, \sigma N^3$ .
- Partial Waves: Up to  $L=5$ , Resonances: 1.07-2.5 GeV
- Exact 2 body unitarity, 3-body unitarity through  $\sigma N, \pi\Delta, \rho N$ .
- Left-hand cuts:  $t$ - and  $u$ -channel exch. ( $\rho, \sigma, K^*, N, \Lambda, \Sigma$ ).



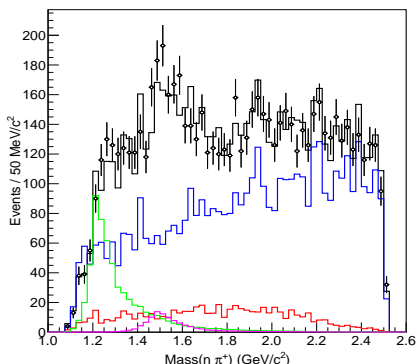
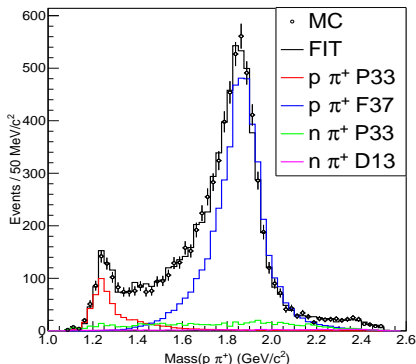
- The total amplitude is constructed as:

$$\begin{aligned}
 \mathcal{A}(L, I, J, s, E) = & \alpha_0 + \alpha_1(E - E_{\text{thr}}) + \sum_k^{\text{Channels}} \alpha_k \Gamma_k(E) \\
 & + \sum_{i=1}^{\text{Resonances}} \gamma_i \Gamma_i^{(R)}(E)
 \end{aligned}$$



# JuBo Model - Proof of Concept

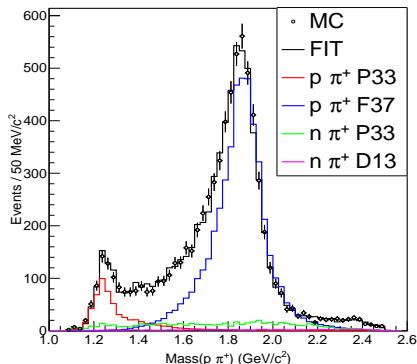
- MC simulation for  $pp \rightarrow p \pi^+ (n) (\sqrt{s} = 3.47 \text{ GeV})$ .
- $p\pi^+$ :  $\Delta^{++}(1232)$  ( $P_{33}$ ),  $\Delta(1950)$  ( $F_{37}$ )
- $n\pi^+$ :  $\Delta^+(1232)$  ( $P_{33}$ ),  $N(1520)$  ( $D_{13}$ )
- Perfect acceptance.



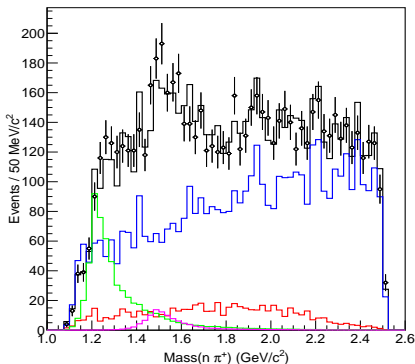
# JuBo Model - Proof of Concept



- MC simulation for  $pp \rightarrow p \pi^+ (n) (\sqrt{s} = 3.47 \text{ GeV})$ .
- $p\pi^+$ :  $\Delta^{++}(1232)$  ( $P_{33}$ ),  $\Delta(1950)$  ( $F_{37}$ )
- $n\pi^+$ :  $\Delta^+(1232)$  ( $P_{33}$ ),  $N(1520)$  ( $D_{13}$ )
- Perfect acceptance.



Next talk by S. K. Sahu



## PWA @ HADES: Modular partial wave analysis

- K-/Dispersion-matrix amplitudes, Chew-Mandelstam self-energy, Left-Hand Cuts, Production Vector.
- **Channels:**  $\pi p \rightarrow \{\pi N, \pi \Delta, \rho N, \sigma N\}$
- **In progress:** HADES 2014 data

## JuBoAmp: Event-by-event unitary analytic low comp cost coupled-channel analysis.

- **Channels:**  $pp \rightarrow \{\pi N, \eta N, K\Lambda, K\Sigma, \pi \Delta, \rho N, \sigma N\}$
- **Resonance Range:** 1.07–2.5 GeV; Partial waves  $L = 5$
- **In progress:**  $pp(@4.5 \text{ GeV}) \rightarrow: \{p\pi^+n, p\pi^0p, \Delta K\Lambda\}$

## PWA @ HADES: Modular partial wave analysis

- Fine Tune 2014 Fit: Left-hand cuts
- Covariant Tensor Formalism
- $p\pi^-\pi^0$  data, More channels ( $\pi^0\Delta^0, \eta N$ )

## JuBoAmp: Event-by-event unitary analytic low comp cost coupled-channel analysis.

- $\pi^0 p, K^+\Lambda$

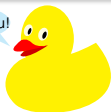
## PWA @ HADES: Modular partial wave analysis

- Fine Tune 2014 Fit: Left-hand cuts
- Covariant Tensor Formalism
- $p\pi^-\pi^0$  data, More channels ( $\pi^0\Delta^0, \eta N$ )

## JuBoAmp: Event-by-event unitary analytic low comp cost coupled-channel analysis.

- $\pi^0 p, K^+\Lambda$

Thank You!



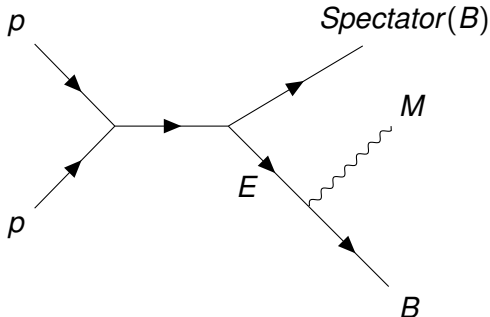
[a.foda@gsi.de](mailto:a.foda@gsi.de)

# **Extra Slides**

- The total amplitude is constructed as:

$$\mathcal{A}(L, I, J, s, E) = \mathcal{A}_{\text{bgd}}(s, E) + \mathcal{A}_{\text{res}}(s, E)$$

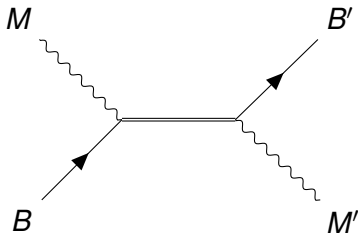
- **Background** and **resonance** amplitudes are pre-calculated based on JuBo fit.
- Each amplitude is a complex number.



- The background contribution is calculated as:

$$\mathcal{A}_{\text{bgd}} = \alpha_0 + \alpha_1(E - E_{\text{thr}}) + \sum_k^{\text{Channels}} \alpha_k \Gamma_k(E)$$

- $\Gamma_k(E)$ : complex amplitudes.
- $\alpha_k$ : decay channel fit parameters.
- $\alpha_k$ : same for all analyses.



- The resonance contribution to the amplitude is constructed as:

$$\mathcal{A}_{\text{res}} = \sum_{i=1}^{\text{Resonances}} \gamma_i \Gamma_i^{(R)}(E)$$

- $\Gamma_i^{(R)}(E)$ : complex resonance amplitudes.
- $\gamma_i$ : resonance coupling.
- User can choose which resonances to include.

