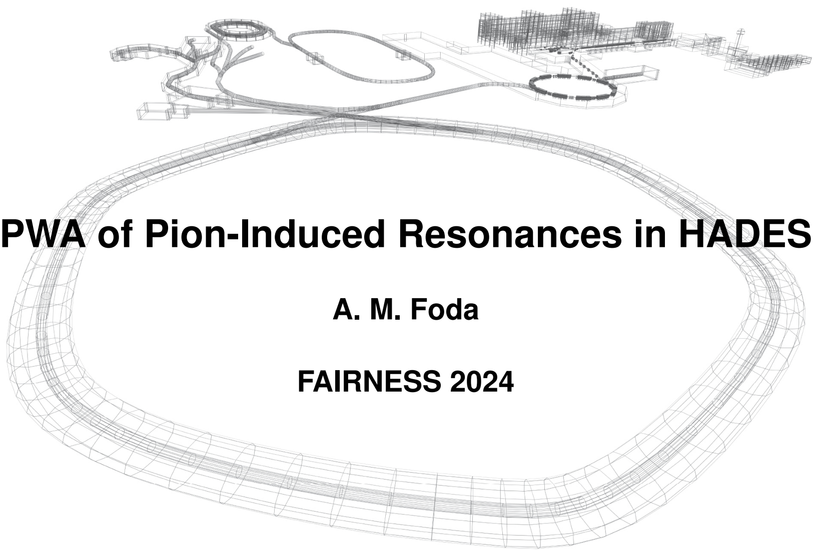


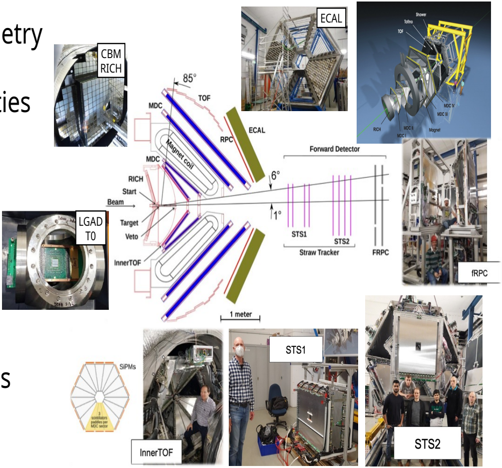
PWA of Pion-Induced Resonances in HADES

A. M. Foda

FAIRNESS 2024

HADES in a Nutshell

- Outstanding in dilepton spectrometry
- Excellent tracking & PID capabilities
- Modular at forward angles
- Additional photon detection
- Good angular coverage
- Designed for *various* SIS18 beams
- ...including pions!



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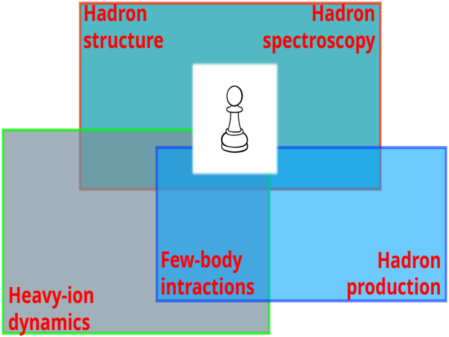
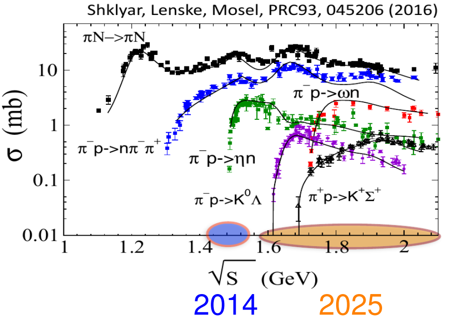
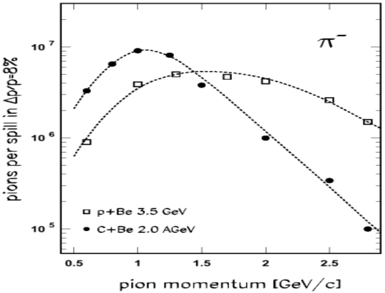


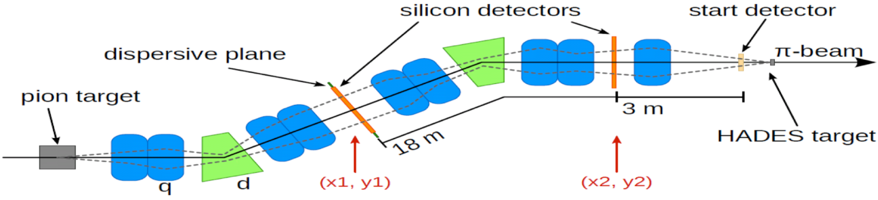
$$L_{QCD} = \sum_q \bar{\psi}_q \left(i\gamma_\mu D^\mu - m_q \right) \psi_q - \frac{1}{2} Tr\left[\bar{G}_{\mu\nu} \bar{G}^{\mu\nu} \right]$$

➡ Enabling a rich QCD program integrating heavy-ion, hadron (and

π Beam Facility at SIS18



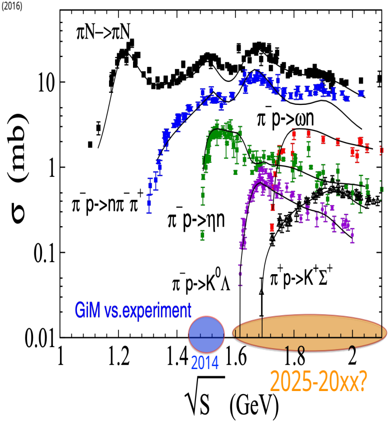




Pion Beam Facility

- Unique combination of pion beam *and* dilepton spectrometer + more!
- $\sqrt{s}$ coverage up to ~2 GeV
- 'Simple' initial state with spin-zero (Goldstone) pion, s-channel
- 'Simple' final states, 2/3-bodies
- Sizeable xsecs for strangeness production w.r.t. light hadrons
- Promising tool for *precision* PWAs & probing (e.m.) decay properties of various baryons/mesons/...

Shklyar, Lenske, Mosel, PRC93, 045206 (2016)

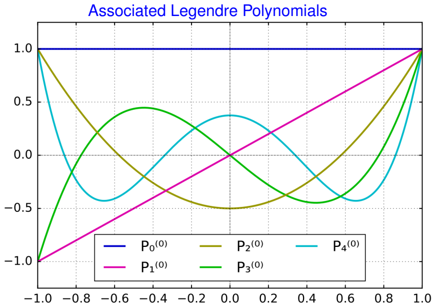


What is Partial Wave Analysis?

$$\mathcal{I}(x^\mu) = \overbrace{\sum_\sigma}^{\text{Coh. Sum}} |\overbrace{\sum_\alpha}^{\text{Amp.}} V_{\sigma,\alpha}\, A_{\sigma,\alpha}(x^\mu)|^2$$

x^μ Kinematics vector, σ Coherent sum terms, α Indistinguishable proces
$V_{\sigma,\alpha}$ Production coefficients, $A_{\sigma,\alpha}$ Amplitudes

- Expand cross-section in terms of Spin-Parity states.
- Search for optimum fit: Systematically switching production amplitudes on & check if that improves the fit.
- Ambiguity: More than one set of amplitudes produce equally acceptable fits for the data.



Towards A Modular Approach

Goal: K/D-Matrix formalism (BnGa) in an open source modular package

- AmpTools: A general interface (library) for PWA fits
  - Developed at Indiana University.
- **Developing: amplitudes for πp reactions**
  - K/D-Matrix
  - Covariant Tensor Angular Dist.
  - in collaboration with Bonn-Gatchina group.
- Will be available on GitLab (GSI)
  Users can report problems or add amplitudes.

Pion Beam 2025: ($\sqrt{s}$ = 1.67 - 1.79 GeV)

Baryon-Meson couplings

- $\pi\pi$N, ωn, ηn , $k^0\Lambda$, KΣ, ...
- Sparse π-beam database (PWA)
- Baryon Structure: Cascade decays, ηn couplings, N(1720) Double Resonance

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E.M. Baryon Transitions (π^-p$\rightarrow$ne^+e^-)

- Broad range of $q^2 = (M_{ee})^2$ $\rightarrow$ Time-Like
- Confirmation for VMD (ρ, ω)
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- No data available

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Cold matter studies (C, Ag targets)

- ω absorption, ρ spectral function
- Strangeness production
- No data available

N(1720) Double Resonance

Final Fit Results from CLAS for the Combined Data:

Resonance states	Mass [GeV]	Total Width [MeV]	Branching fraction for decays into $\Delta\pi$	Branching fraction for decays into $N\rho$
$N(1720)3/2^+$	1.743-1.753	114 ± 6	38-53%	31-46%
$N'(1720)3/2^+$	1.715-1.735	120 ± 6	47-62%	4-10%

Jan Gollub, Ruhr-Universität Bochum

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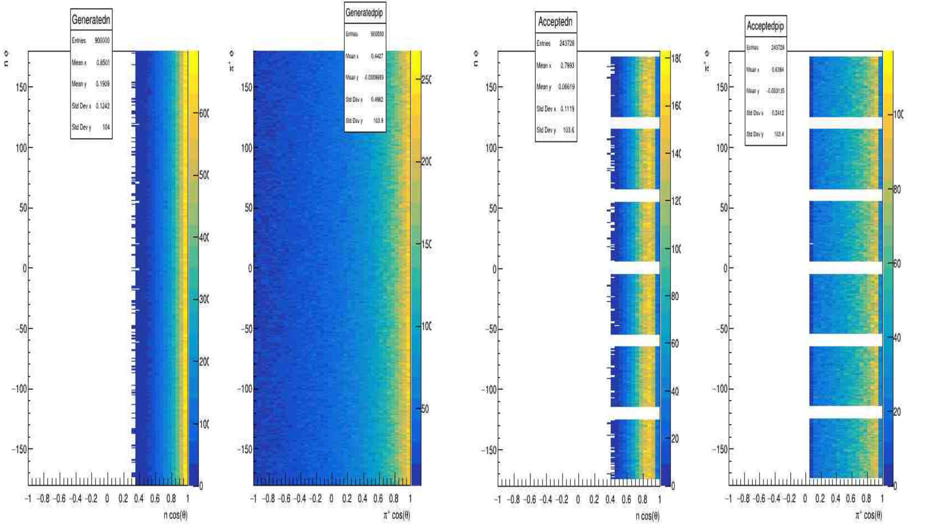
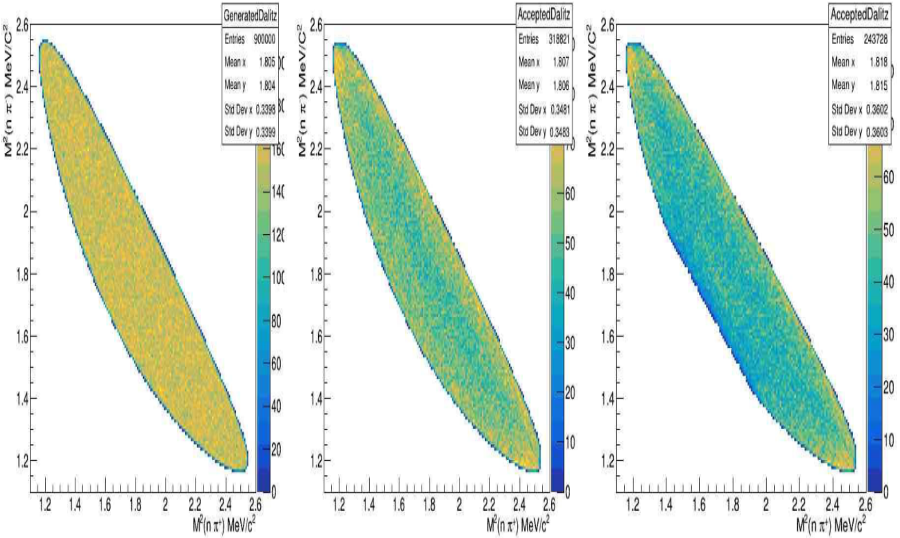
Could the proposed HADES experiment using a pion beam provide conclusive evidence for the $N'(1720)$?

Jan Gollub, Ruhr-Universität Bochum

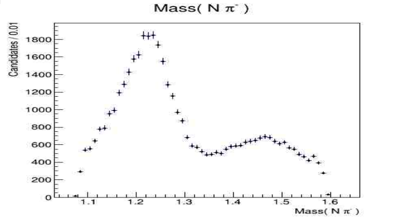
N(1720) Double Resonance

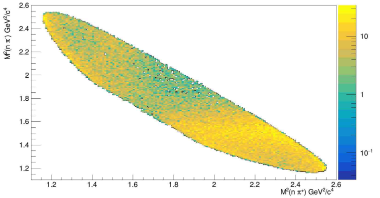


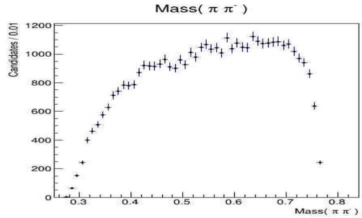
N(1720) Double Resonance

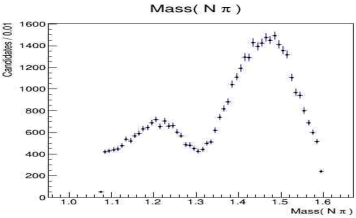


Physics of the Dalitz Plot



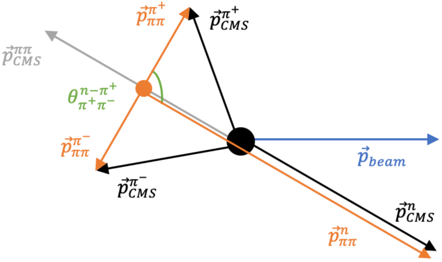






N(1720) Double Resonance

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



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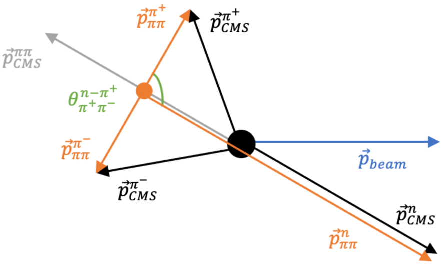
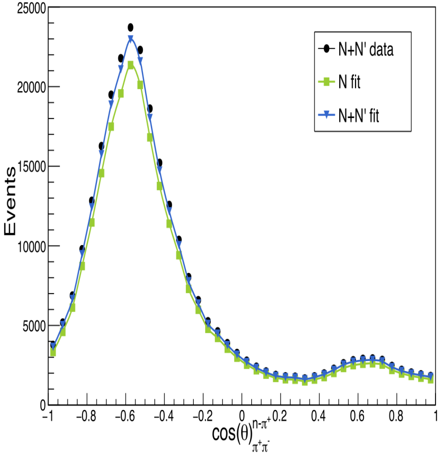




N Fit $\rightarrow \chi^2/NDF = 144$

N+N' Fit $\rightarrow \chi^2/NDF = 14$

Jan Gollub, Ruhr-Universität Bochum

N(1720) Double Resonance

Defining the two cases based on the Branching Fractions

→ Case A:

N	N'
BF(Δπ) ~ 53%	BF(Δπ) ~ 47%
BF(Nρ) ~ 31%	BF(Nρ) ~ 10%
BF(Nπ) ~ 16%	BF(Nπ) ~ 43%

Fit Parameters:

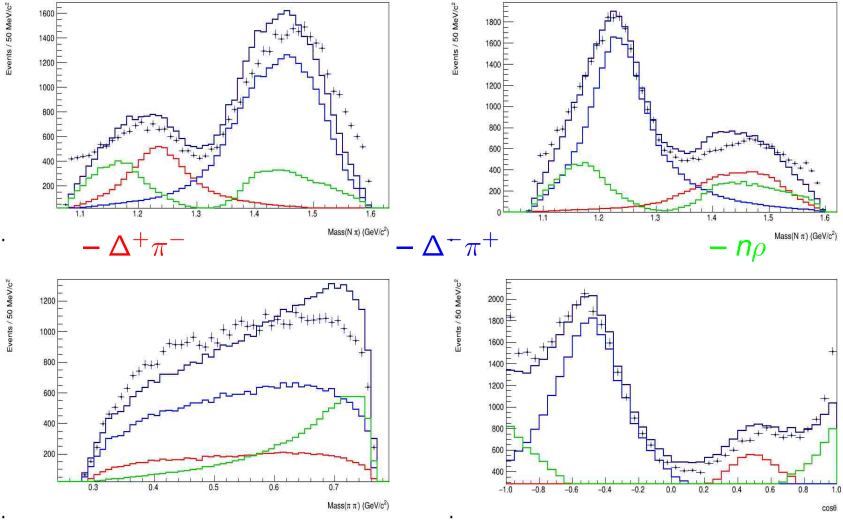
Fixed Parameters	Free Parameters
${}^{N}g_{\Delta\pi}$, ${}^{N'}g_{\Delta\pi}$, ${}^{N}g_{N\rho}$, ${}^{N'}g_{N\rho}$, ${}^{N}g_{N\pi}$	V, ${}^{N'}g_{N\pi}$

→ Case B:

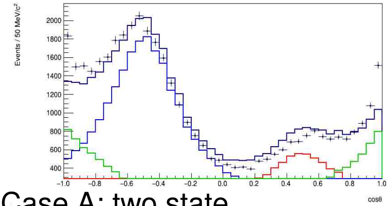
N	N'
BF(Δπ) ~ 38%	BF(Δπ) ~ 62%
BF(Nρ) ~ 46%	BF(Nρ) ~ 4%
BF(Nπ) ~ 16%	BF(Nπ) ~ 34%

Fixed Parameters	Free Parameters
${}^{N}g_{\Delta\pi}$, ${}^{N'}g_{\Delta\pi}$, ${}^{N}g_{N\rho}$, ${}^{N'}g_{N\rho}$, ${}^{N}g_{N\pi}$, ${}^{N'}g_{N\pi}$	V

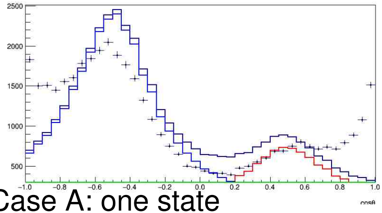
N(1720) Double Resonance



Example Fits

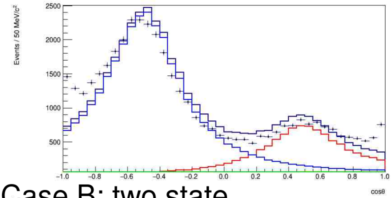


Case A: two state

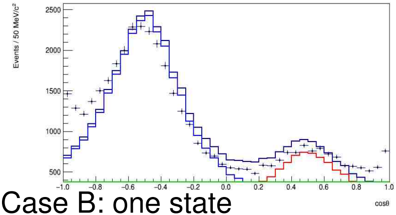


Case A: one state

– $\Delta^+\pi^-$ – $\Delta^-\pi^+$ – $n\rho$

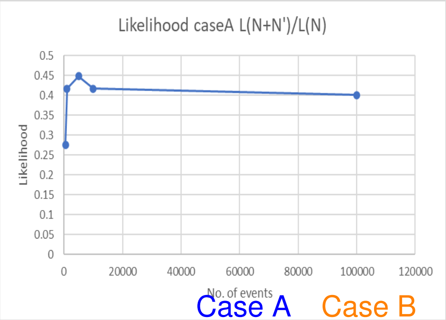


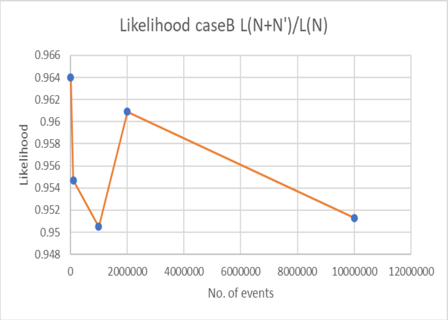
Case B: two state



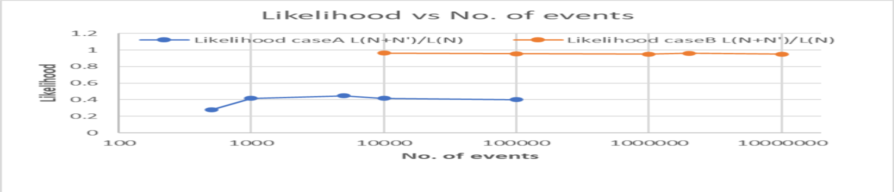
Case B: one state

Events vs Likelihood



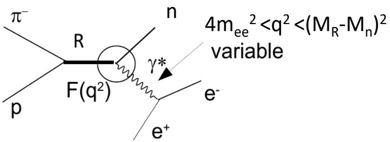


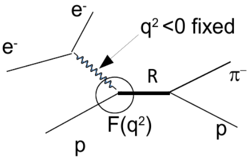
Case A Case B



E.M. Time-like Transitions Form Factors

Time-like electromagnetic form factors	Space-like electromagnetic form factors

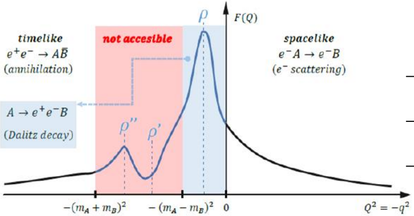




Limit at q^2=0 given by real photon decay

Data from Jlab (CLAS) up to $-q^2 = 4$ GeV²

Exploration of higher q^2 with CLAS12



- → Confirmation for VMD (ρ, ω)
- → Extract SDMEs
- → No data available

Role of quark core and meson cloud in the TL region ?

Courtesy of Béatrice Ramstein, IJCLab, Orsay, France

Summary

π Beam @ HADES $\rightarrow$ Unique combination with great potential for hadron spectroscopy.

- PWA @ HADES: A modular approach for PWA fit & visualization.
- Under Development:
  - K/D-Matrix amplitudes.
  - Covariant operator angular distribution.
  - e^+e^- (form factors)

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K-Matrix (PhysRevD.84.076001)

$$\hat{A} = \hat{K}(\hat{I} - i\rho\hat{K})^{-1}$$
$$K_{aj} = \sum_\alpha \frac{g_a^{R(\alpha)} g_j^{L(\alpha)}}{(M_\alpha - s)^2} + NR$$

ρ_j phase volume, K_{aj} off-shell elementary interaction,

- Fit several reaction channels simultaneously
- Correct analytical properties & unitarity of all amplitudes included.
- Ambiguity: Contributions of left-hand cuts

D-Matrix (PhysRevD.84.076001)

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

$$\hat{D} = \hat{d}(\hat{I} - \hat{B}\hat{d})^{-1}, \tilde{\rho}(s) = \rho(s) ln \frac{1-\rho(s)}{1+\rho(s)}$$

$$B(s) = ReB(M^2) + \frac{g^2}{\pi}[\tilde{\rho}(s) - \tilde{\rho}(M^2)] + i\rho(s)g^2$$

$d_{\alpha\alpha}$ propagators (resonant & non-resonant)
g_a^{α} coupling of channel a to state α

a, b, j: channels, α, β: bare states

- No false kinematical singularities in the Amplitudes
- Theoretically better founded than K-Matrix
- Understanding the stability & limitations of the obtained results is not trivial