Baryon spectroscopy with pion beams: presence and future

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Baryon spectrum: primary aim

Understand the nucleon structure in terms of elementary building blocks - quarks and gluons.

where we are ?

Theory

- Lattice QCD
- Dyson-Schwinger approach
- CQM and their extensions

Problems

Serious disagreement between theory and experiment in:

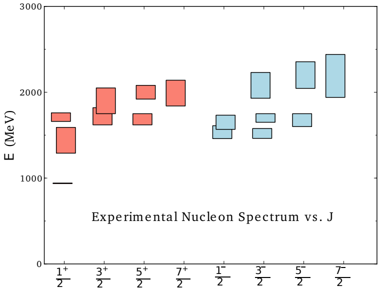
- number of excited states and
- their properties

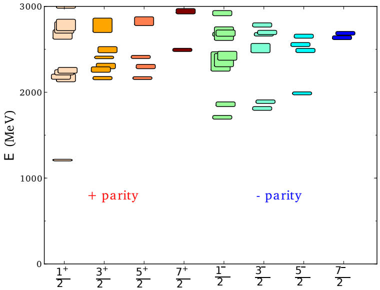
HADRON SPECTRUM COLLABORATION

Overall pattern of N* states

Expt. **** *** **

Lattice





Many more states in the lattice spectrum.

Baryon resonance analysis: general ideas

Resonaces are identified as poles in the scattering amplitude.
Analysis: TWO MAIN INGREDIENTS:

- Scattering amplitude (reaction theory) (includes resonance parameters).
- Experimental data (to fix N^* properties)

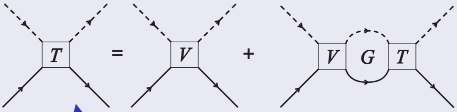
DEFINE THE SCATTERING AMPLITUDE

- parametrizations: Chew-Mandelstam, CMB:
  (SAID, MAID, BoGa, ...)
- dynamical models: calculate T solving scattering equations
  (GiM, Juelich, EBAC, ...)

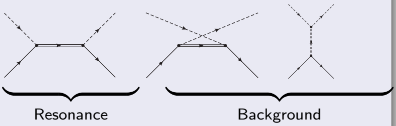
Giessen model. PRC71, 055206 (2005)

Bethe-Salpeter in K-matrix: dynamical model: based on eff. L_{mBB}

T-matrix



Interaction terms V_{ij}



multidimensional T-matrix

$$T = \begin{pmatrix} T_{\gamma N,\gamma N} & T_{\gamma N,\pi N} & T_{\gamma N,K\Lambda} & \cdots \\ T_{\pi N,\gamma N} & T_{\pi N,\pi N} & T_{\pi N,K\Lambda} & \cdots \\ T_{K\Lambda,\gamma N} & T_{K\Lambda,\pi N} & T_{K\Lambda,K\Lambda} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{pmatrix}$$

How many channels?

$\gamma N \to \gamma N$	$\pi N \to \pi N$
$\gamma N \to \pi N$	$\pi N \to 2\pi N$
$\gamma N \to \eta N$	$\pi N \to \eta N$
$\gamma N \to \omega N$	$\pi N \to \omega N$
$\gamma N \to K\Lambda$	$\pi N \to K\Lambda$
$\gamma N \to K\Sigma$	$\pi N \to K\Sigma$

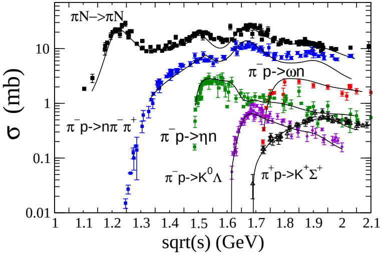
Partial wave version of optical theorem

constraints on partial wave cross sections

$$
Im T^{JP}_{\pi N \to \pi N} = \frac{k^2}{4\pi}(\sigma^{JP}_{\pi N \to \pi N} + \sigma^{JP}_{\pi N \to 2\pi N} + \sigma^{JP}_{\pi N \to \eta N}
+ \sigma^{JP}_{\pi N \to \omega N} + \sigma^{JP}_{\pi N \to K\Lambda} + \sigma^{JP}_{\pi N \to K\Sigma} + \ldots)
$$

all reaction data are linked

$\rightarrow$ need for coupled-channel unitary analysis



$$
T = \begin{pmatrix} T_{\gamma N,\gamma N} & T_{\gamma N,\pi N} & T_{\gamma N,K\Lambda} & \cdots \\ T_{\pi N,\gamma N} & T_{\pi N,\pi N} & T_{\pi N,K\Lambda} & \cdots \\ T_{K\Lambda,\gamma N} & T_{K\Lambda,\pi N} & T_{K\Lambda,K\Lambda} & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{pmatrix}
$$

$\leftarrow$ Giessen Model vs experimental data

Baryon spectra

- PDG: most N^* properties from PWA of πN elastic scattering
- N.Isgur PRD21 1868 (1980): *"problem of missing states is not a problem - these states are only weakly coupled and should be eventually seen"*

Present status:

photoproduction $\gamma N \to \pi N$, $K\Lambda$, (ωN, $2\pi N$ etc), :

BoGa: indication for new states

GWU, EBAC, Giessen: no strong evidence

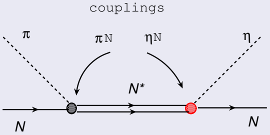
Main argument against pion-beams

- N^* weakly coupled to πN:
  can only be seen in photoproduction !
- there is enough information from old experiments

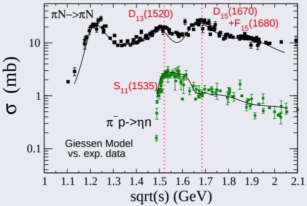
inelastic $\pi N \to \eta N$, ωN, ρN... etc scattering

My argument:

- $\pi N \to \eta N$ reaction $\frac{d\sigma}{d\Omega} \sim g^2_{\pi NN^*} g^2_{\eta NN^*}$
- N* with small πN coupling is visible if $g^2_{\eta NN^*}$ is large



- less screaning from $D_{13}(1520)$ with large πNN
- N* with small πN coupling no clean signal from $D_{13}(1520)$, $D_{15}(1680)$, $F_{15}(1680)$ in $\pi N \to \eta N$



N^* spectroscopy with pions:

Short summary :

Main argument against pion-beams

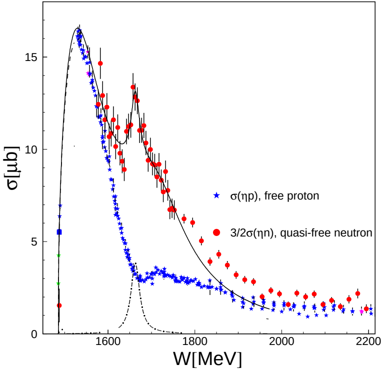
- ~~"missing resonances" are weakly coupled to πN: can only be seen in photoproduction~~ NO!
- The pion-induced inelastic reactions provide great possibility to study N^* spectra !

But

- What can we learn from old πN experiments ?

η-photoproduction on the neutron and on the proton

I.Jeagle, B. Krusche EPJA47, 89



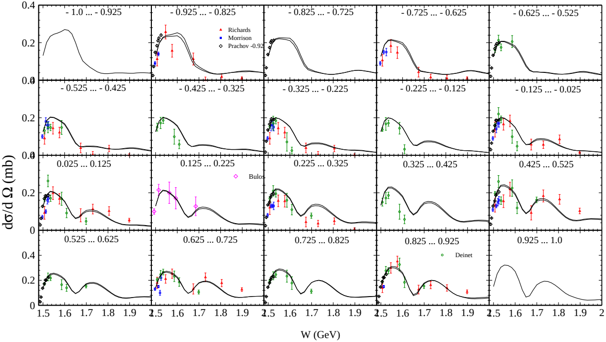
First peak: $S_{11}(1535)$

- $\gamma n \to \eta n$: resonance-like structure at 1.68 GeV
- $\gamma p \to \eta p$: dip at 1.68 GeV (well seen in new MAMI data PRC82,035208)

Main questions

- Shklyar et al PLB650 (2007),172: $\gamma n \to \eta n$: well known $S_{11}(1650)$, $P_{11}(1710)$
- Shklyar et al PRC 87 (2013): destructive interference between $S_{11}(1535)$, $S_{11}(1650)$

Results for the $\pi^- p \to \eta p$ production



$\pi^- p \to \eta\, n$: updated Giessen coupled-channel analysis

- overlap of $S_{11}(1535)$ and $S_{11}(1650)$ states - destructive interference - dip at 1.68 GeV
- contribution from $P_{11}(1710)$ - second peak
- interference between S_{11} and P_{11} partial waves - second peak at mostly forward angles.

ωN-meson in-medium properties

Building block: ωN scattering amplitude

ωN scattering length

- $\bar{a} = -0.026 + i0.28$ fm, Giessen (coupled-channel) NPA780 187
- $\bar{a} = -0.44 + i0.20$ fm, Lutz, et al(coupled-channel, low partial waves) NPA706:431
- $\bar{a} = +1.60 + i0.30$ fm, Kling, Weise (single channel) NPA630:299

Common feature of above analysis:

- constrained by the $\pi N \to \omega N$ experimental data
- agrees on the value of the imaginary part of the scattering lengths

low density theorem: $i0.28$ corresponds to ≈ 60 MeV broading

but too small to explain the strong absorption of ω in medium

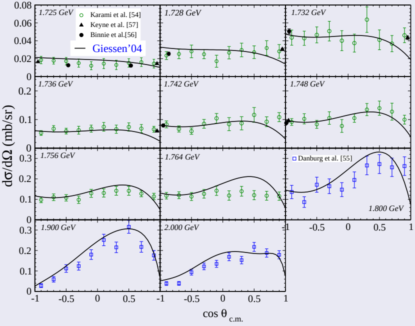
- theory: take in-medium corrections into account
- experiment: is everything clear with old $\pi N \to \omega N$ data?

Giessen model. Results for the $(\pi, \gamma)N \to \omega N$ reactions

ωN: coupled channel analysis Shklyar et al PRC 71:055206:

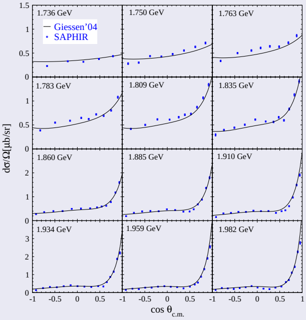
Aim: extract resonance coupling to ωN

$\pi N \to \omega N$



few measurements, low statistic

$\gamma N \to \omega N$

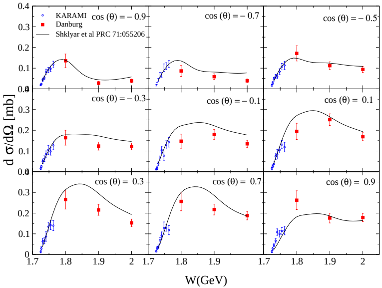


strong t-channel pion exchange shadow other reaction mechanisms

$\pi N \to \omega N$ database

- W=1.72 to 1.76 GeV: H. Karami, et al NPB154 503 (1979) : 80 datapoints threshold region
- W=1.8 to 2.1 GeV: J.S. Danburg, PR2, 2564(1970) from $\pi^+ D \to \pi^+\pi^-\pi^0 p(p)$: 41 datapoints Fermi-motion, final state interaction!

Shklyar et al, PRC 71:055206,2005

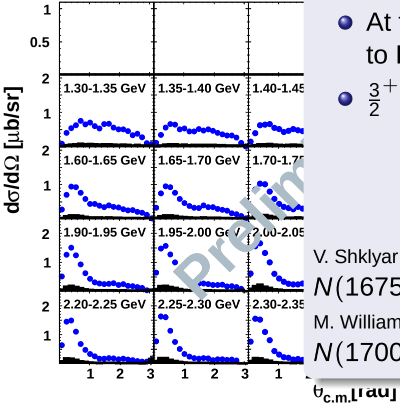


Difficulties:

- ωN has three helicities: need ω-polarization measurements
- Karami data - close to threshold
- region 1.76...2.0 GeV is almost empty - standard PWA not possible
- no polarization measurements
- Problem: N^* extraction ...

$\gamma p \to p\omega$

My own research $\to$ to be p



BnGa Analysis

- Pomeron exchange is large overall.
- At threshold, $\frac{3}{2}^-$ wave is equivalent to Pomeron exchange.
- $\frac{3}{2}^+$ and $\frac{5}{2}^-$ waves are significant.

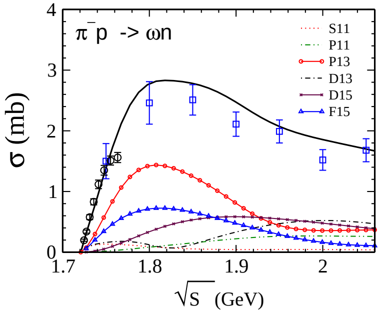
Earlier Analyses
Threshold Contributions

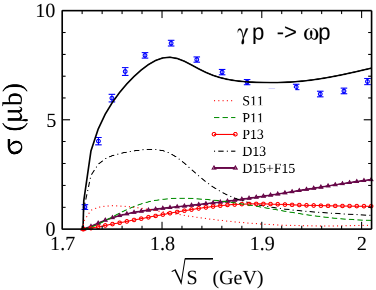
V. Shklyar *et al.*,Phys. Rev. C **71** (2005) 055206.
$N(1675)\frac{5}{2}^-$, $N(1680)\frac{5}{2}^+$

M. Williams *et al.* Phys. Rev. C **80** (2009) 065209.
$N(1700)\frac{3}{2}^-$, $N(1685)\frac{5}{2}^+$

Labeled with incoming photon energy.

Giessen model, Shklyar et al, PRC 71:055206,2005





- P_{13}: interference between resonance and background
- strong $N^*(\frac{5}{2})$ coupling to ωN
- D_{13} shows minor influence

- strong Born and π^0-exchange contributions
- D_{13} is due to π^0-exchange

$\Longrightarrow$ hard to see any resonance contribution !

Summary of $(\pi/\gamma)N \to \omega N$ reactions

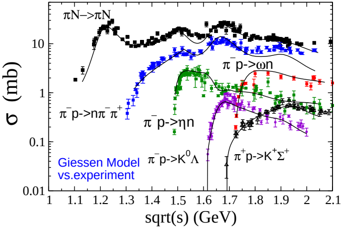
- $\gamma p \to \omega p$: strong t-channel background $\to$ other reaction mechanisms are shadowed: hard to see any resonance contributions
- $\pi N \to \omega N$: almost NO data in the region region 1.76...2.0 GeV - standard PWA not possible
- contributions from many groups: Lutz, Wolf, Friman, Titov, Sibirtsev, Zhao, Shklyar, Mosel, Penner - no general conclusion on N^* contributions

NEED $\pi^- p \to \omega p$ measurements in order to

- get information on N^* couplings to ωN - fill white pages in PDG
- construct microscopical model of ω-dynamics in nuclear medium; explain large collisional broading

$\pi N \to 2\pi N$ reaction

$\pi N \to 2\pi N$: strong contribution to the πN inelasticity.

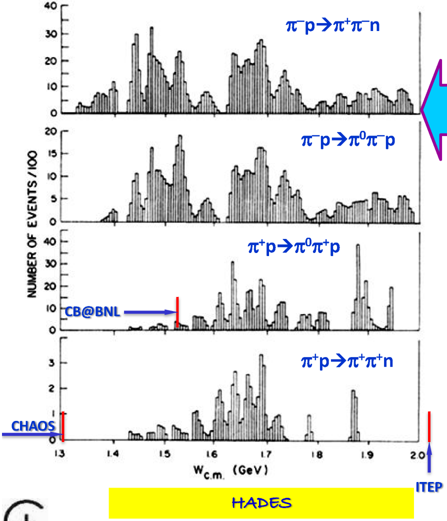


$\pi N \to 2\pi N$ strong resonance contributions

All what we know about N^* couplings to ρN, $\pi\Delta$, σN channel is due to Manley, Arndt, Goradia, Teplitz PRD**30**,(1984) 904.

- based on 240000 events from old bubble-chamber experiments W = 1.2...2 GeV: $\approx$ 9000 events per energy/angular (θ, ϕ) bin
- non-unitary
- amplitudes $\pi N \to \rho N$, $\pi\Delta$ at fixed isobar masses

Previous $\pi N \to \pi\pi N$ Measurements



- **241,214** **Bubble Chamber** events for $\pi N \to \pi\pi N$ have been analyzed in **Isobar-model PWA** at W = **1320** to **1930** MeV.
  [D.M. Manley, **R. Arndt**, Y. Goradia, V. Teplitz, Phys Rev D **30**, 904 (1984)]

- Recent **post-Bubble Chamber** measurements:
  - **349,611** events for $\pi^- p \to \pi^0 \pi^0 n$ from **CB@BNL** at W = **1213** to **1527** MeV.
    [S. Prakhov *et al* Phys Rev C **69**, 045202 (2004)]
  - **20,000** events for $\pi^{+-} p \to \pi^{+-} \pi^{-+} n$ from TRIUMF **CHAOS@TRIUMF** at W = **1257** to **1302** MeV. [M. Kermani *et al* PRC **58**, 3431 (98)]
  - **40,000** events for $\pi^- \vec{p} \to \pi^- \pi^+ n$ from **ITEP** at W = **2060** MeV.
    [I. Alekseev *et al* Phys At Nucl **61**, 174 (1998)]

Resonance → $N\rho$ Branching Ratios

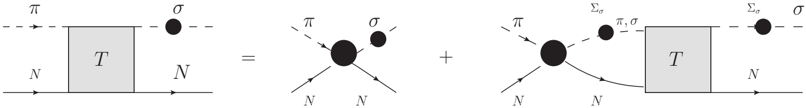
	GiBUU12	UrQMD09	KSU12	KSU92	BnGa12	CLAS12	PDG12	
$N(1520)3/2^-$	21	15	20.9(7)	21(4)	10(3)	12.7(4.3)	20(5)	D13
$N(1720)3/2^+$	87	73	1.4(5)	87(5)	10(13)	47.5(21.5)	77.5(7.5)	P13
$\Delta(1620)1/2^-$	29	5	26(2)	25(6)	12(9)	37(12)	16(9)	S31
$\Delta(1905)5/2^+$	87	80	<6	86(3)	42(8)		>60	F35

Partial courtesy of Piotr Salabura, Sept 2013

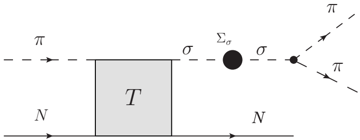
CLAS12: V. Mokeev *et al*, Phys Rev C **86**, 035203 (2012); V. Mokeev, PC
BnGa12: A.V, Anisovich *et al*, Eur Phys J A **48**, 15 (2012)
GiBUU12: J. Weil *et al*, Eur Phys J A **48**, 111 (2012); J. Weil, PC
KSU92: D.M. Manley and E.M. Saleski, Phys Rev D **45**, 055203 (1992)
KSU12: M. Shrestha and D.M. Manley, Phys Rev D **86**, 055203 (2012)
PDG12: J. Beringer *et al* [RPP] Phys Rev D **86**, 010001 (2012)
UrQMD09: K. Schmidt *et al*, Phys Rev C **79**, 4002 (2009)

BSE in the isobar approximation:

system of coupled-channel integral equations



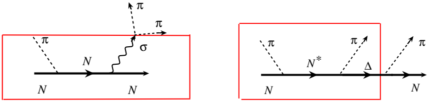
$\pi N \to 2\pi N$ amplitude from BSE



$+ \pi N \to \rho N$, $\pi N \to \pi\Delta$ etc

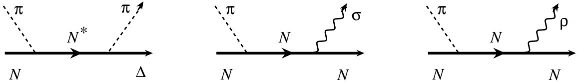
Next step: improve description of the $2\pi N$ channel

$\pi N \to 2\pi N$ reaction via ρN, $\pi\Delta$ channels

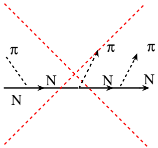


Assumptions

- decays $N^* \to \rho N$, σN, $\pi\Delta$ drive the $\pi N \to 2\pi N$ channel



- two-step diagrams are neglected



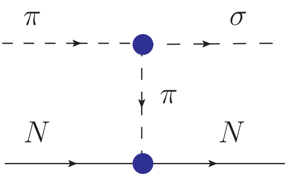
$\pi N \to 2\pi$ channel in the first resonance energy region

Roper resonance N(1440) properties:

- Manley & Saleski PRD30 904, $Br(\Delta\pi) = 22\%$ $Br(\sigma N) = 9\%$
- Vrana et al PRPL328, $Br(\Delta\pi) = 16\%$ $Br(\sigma N) = 12\%$
- Sarantsev et al PLB659,94, $Br(\Delta\pi) = 17\%$ $Br(\sigma N) = 21\%$

- Julich Model: PRC62: pion exchange is responsible for a large amount of attraction: P(1440) is dynamically generated
- Crystal Ball PRL91(2003): PWA of the $2\pi^0$-subsystem: σ-meson production via pion exchange is small
- Crystal Ball PRL69(2004): measurement of the $\pi N \to 2\pi^0 N$-reaction: no direct evidence for a strong σN subchannel

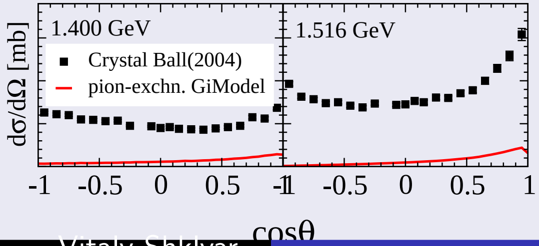
t-channel pion exchange: σN how large?



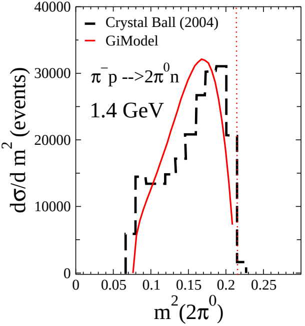
- coupling constants are well fixed
- $g_{\pi NN} = 13$, $g_{\sigma\pi\pi} = 2$ correspond to $m_\sigma^0 = 600\text{MeV}$, $\Gamma_{\sigma\pi\pi} = 600\text{MeV}$
- contribution from the t-channel diagram is well fixed

- shed light on the σ-meson dynamics
- background mechanism in $\pi N \to 2\pi N$ reaction

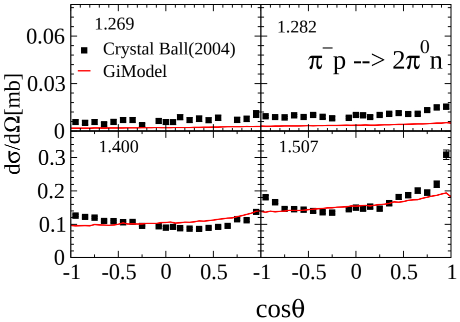
$\pi^- p \to \pi^0\pi^0 n$: t-channel pion exchange: very small !

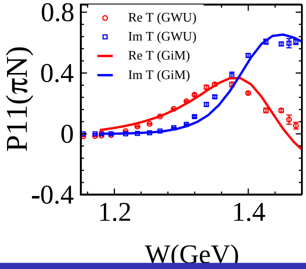


Giessen Model vs. Crystal Ball data



Roper resonance





- good description of the $\pi^- p \to 2\pi^0 n$ data
- three-body unitarity is maintained

$$\mathrm{Im}\, T^{11}_{\pi N} = \frac{k^2}{4\pi}(\sigma^{11}_{\pi N} + \sigma^{11}_{2\pi^0 N})$$

GIModel for $\pi^- p \to \pi^0 \pi^0 n$ reaction

- model space is extended to include σN, $\pi\Delta$, and ρN channels
- $t-$channel pion exchange in σN channel is very weak - underestimate the data.
- do not rule out dynamical pole; however if it exists the contribution to the production cross section should be small
- calculation with a genuine Roper resonance: nice description of the CB-measurements

Summary of the $\pi N \rightarrow 2\pi N$ reactions

- important for understanding ρ-meson dynamics and resonance couplings
- could solve many puzzles in non-strange baryon spectroscopy: origin and properties of the $P_{11}(1440)$, $P_{11}(1710)$, $D_{13}(1520)$ etc.

Theory

- analysis of Manley et. al. can be extended!

Experiment

- need for new measurements $\pi N \rightarrow 2\pi N$ in region 1.2...2.GeV

Challange for HADES

ρN dynamics: N(1520)$\frac{3}{2}^{-}$, N(1720)$\frac{3}{2}^{+}$, D(1620)$\frac{1}{2}^{-}$, D(1905)$\frac{5}{2}^{+}$

- $\pi^- p \to \pi^+ \pi^- n$ with 21106000 events (114000 existing)
- $\pi^- p \to \pi^+ \pi^0 p$ with 15106000 events (72000 existing)
- $\pi^- p \to \pi^- \eta p$

direct access to time-like E.M. formfactors

- $\pi^- p \to e^+ e^- n$

PDG: indications for new N^* states from $\gamma p \to K^+ \Lambda$

- $\pi^- p \to K^0 \Lambda^0$: great impact on hadron spectroscopy