Production and decay of baryonic resonances in pion induced reactions

2-7 June 2016, Kraków

MESON 2016

Witold Przygoda

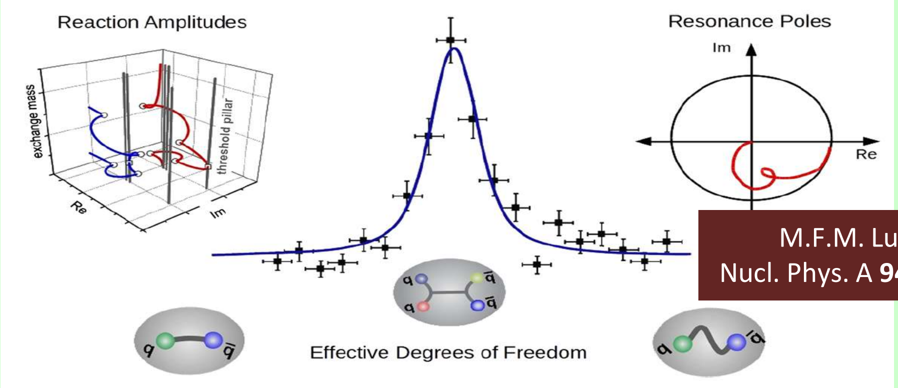
HADES Collaboration

„missing resonance"

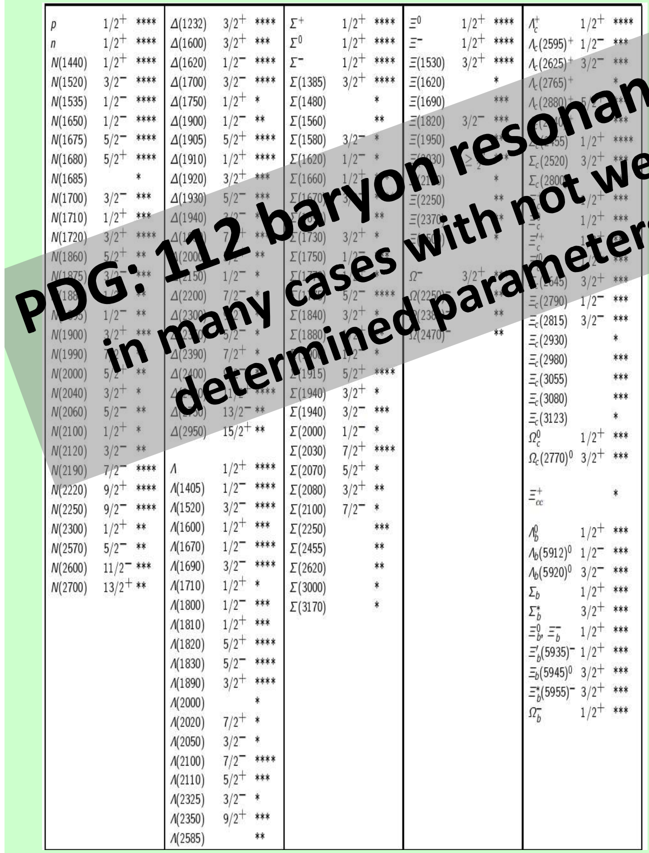
problem: SU(6)xO(3)

434 resonances

What are the relevant degrees of freedom for the resonance physics in QCD?



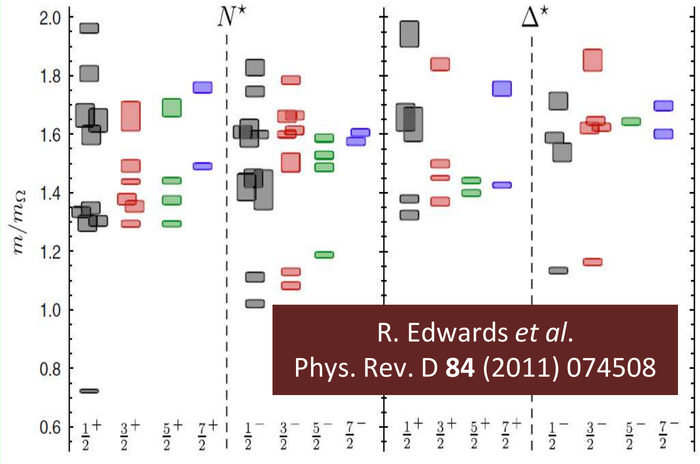
M.F.M. Lutz *et al*.
Nucl. Phys. A **948** (2016) 93



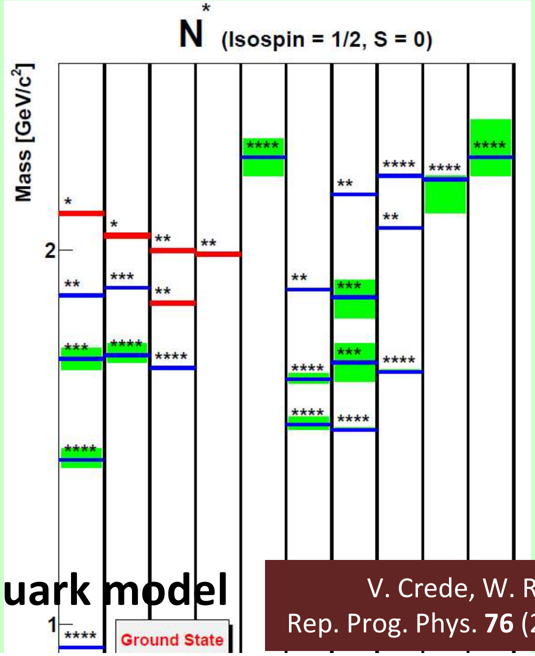
p	$1/2^+$	****	Δ(1232)	$3/2^+$	****	Σ^+	$1/2^+$	****	Ξ^0	$1/2^+$	****	Λ_c^+	$1/2^+$	****
n	$1/2^+$	****	Δ(1600)	$3/2^+$	***	Σ^0	$1/2^+$	****	Ξ^-	$1/2^+$	****	$\Lambda_c(2595)^+$	$1/2^-$	***
N(1440)	$1/2^+$	****	Δ(1620)	$1/2^-$	****	Σ^-	$1/2^+$	****	Ξ(1530)	$3/2^+$	****	$\Lambda_c(2625)^+$	$3/2^-$	***
N(1520)	$3/2^-$	****	Δ(1700)	$3/2^-$	****	Σ(1385)	$3/2^+$	****	Ξ(1620)		*	$\Lambda_c(2765)^+$		*
N(1535)	$1/2^-$	****	Δ(1750)	$1/2^+$	*	Σ(1480)		*	Ξ(1690)		***	$\Lambda_c(2880)^+$	$5/2^+$	***
N(1650)	$1/2^-$	****	Δ(1900)	$1/2^-$	**	Σ(1560)		**	Ξ(1820)	$3/2^-$	***	$\Lambda_c(2940)^+$		***
N(1675)	$5/2^-$	****	Δ(1905)	$5/2^+$	****	Σ(1580)	$3/2^-$	*	Ξ(1950)		***	$\Sigma_c(2455)$	$1/2^+$	****
N(1680)	$5/2^+$	****	Δ(1910)	$1/2^+$	****	Σ(1620)	$1/2^-$	*	Ξ(2030)	$\geq\frac{5}{2}?$	***	$\Sigma_c(2520)$	$3/2^+$	***
N(1685)		*	Δ(1920)	$3/2^+$	***	Σ(1660)	$1/2^+$	***	Ξ(2120)		*	$\Sigma_c(2800)$		***
N(1700)	$3/2^-$	***	Δ(1930)	$5/2^-$	***	Σ(1670)	$3/2^-$	****	Ξ(2250)		**	Ξ_c^+	$1/2^+$	***
N(1710)	$1/2^+$	***	Δ(1940)	$3/2^-$	**	Σ(1690)		**	Ξ(2370)		**	Ξ_c^0	$1/2^+$	***
N(1720)	$3/2^+$	****	Δ(1950)	$7/2^+$	****	Σ(1730)	$3/2^+$	*	Ξ(2500)		*	$\Xi_c'^+$	$1/2^+$	***
N(1860)	$5/2^+$	**	Δ(2000)	$5/2^+$	**	Σ(1750)	$1/2^-$	***				$\Xi_c'^0$	$1/2^+$	***
N(1875)	$3/2^-$	***	Δ(2150)	$1/2^-$	*	Σ(1770)	$1/2^+$	*	Ω^-	$3/2^+$	****	$\Xi_c(2645)$	$3/2^+$	***
N(1880)	$1/2^+$	**	Δ(2200)	$7/2^-$	*	Σ(1775)	$5/2^-$	****	$\Omega(2250)^-$		***	$\Xi_c(2790)$	$1/2^-$	***
N(1895)	$1/2^-$	**	Δ(2300)	$9/2^+$	**	Σ(1840)	$3/2^+$	*	$\Omega(2380)^-$		**	$\Xi_c(2815)$	$3/2^-$	***
N(1900)	$3/2^+$	***	Δ(2350)	$5/2^-$	*	Σ(1880)	$1/2^+$	**	$\Omega(2470)^-$		**	$\Xi_c(2930)$		*
N(1990)	$7/2^+$	**	Δ(2390)	$7/2^+$	*	Σ(1900)	$1/2^-$	*				$\Xi_c(2980)$		***
N(2000)	$5/2^+$	**	Δ(2400)	$9/2^-$	**	Σ(1915)	$5/2^+$	****				$\Xi_c(3055)$		***
N(2040)	$3/2^+$	*	Δ(2420)	$11/2^+$	****	Σ(1940)	$3/2^+$	*				$\Xi_c(3080)$		***
N(2060)	$5/2^-$	**	Δ(2750)	$13/2^-$	**	Σ(1940)	$3/2^-$	***				$\Xi_c(3123)$		*
N(2100)	$1/2^+$	*	Δ(2950)	$15/2^+$	**	Σ(2000)	$1/2^-$	*				Ω_c^0	$1/2^+$	***
N(2120)	$3/2^-$	**				Σ(2030)	$7/2^+$	****				$\Omega_c(2770)^0$	$3/2^+$	***
N(2190)	$7/2^-$	****	Λ	$1/2^+$	****	Σ(2070)	$5/2^+$	*						
N(2220)	$9/2^+$	****	Λ(1405)	$1/2^-$	****	Σ(2080)	$3/2^+$	**				Ξ_{cc}^+		*
N(2250)	$9/2^-$	****	Λ(1520)	$3/2^-$	****	Σ(2100)	$7/2^-$	*						
N(2300)	$1/2^+$	**	Λ(1600)	$1/2^+$	***	Σ(2250)		***				Λ_b^0	$1/2^+$	***
N(2570)	$5/2^-$	**	Λ(1670)	$1/2^-$	****	Σ(2455)		**				$\Lambda_b(5912)^0$	$1/2^-$	***
N(2600)	$11/2^-$	***	Λ(1690)	$3/2^-$	****	Σ(2620)		**				$\Lambda_b(5920)^0$	$3/2^-$	***
N(2700)	$13/2^+$	**	Λ(1710)	$1/2^+$	*	Σ(3000)		*				Σ_b	$1/2^+$	***
			Λ(1800)	$1/2^-$	***	Σ(3170)		*				Σ_b^*	$3/2^+$	***
			Λ(1810)	$1/2^+$	***							Ξ_b^0, Ξ_b^-	$1/2^+$	***
			Λ(1820)	$5/2^+$	****							$\Xi_b'(5935)^-$	$1/2^+$	***
			Λ(1830)	$5/2^-$	****							$\Xi_b(5945)^0$	$3/2^+$	***
			Λ(1890)	$3/2^+$	****							$\Xi_b^*(5955)^-$	$3/2^+$	***
			Λ(2000)		*							Ω_b^-	$1/2^+$	***
			Λ(2020)	$7/2^+$	*									
			Λ(2050)	$3/2^-$	*									
			Λ(2100)	$7/2^-$	****									
			Λ(2110)	$5/2^+$	***									
			Λ(2325)	$3/2^-$	*									
			Λ(2350)	$9/2^+$	***									
			Λ(2585)		**									

PDG: 112 baryon resonances in many cases with not well determined parameters

Lattice QCD



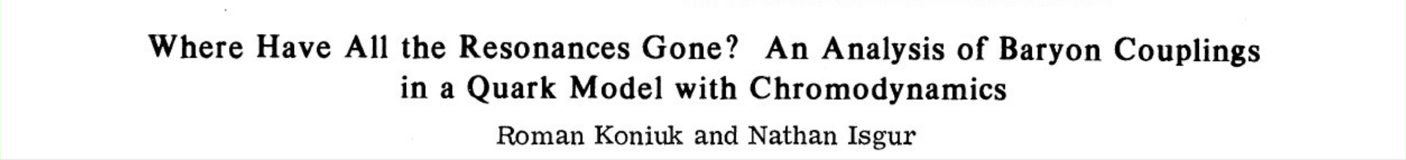
R. Edwards *et al*.
Phys. Rev. D **84** (2011) 074508



quark-diquark model

V. Crede, W. Roberts
Rep. Prog. Phys. **76** (2013) 076301

Quark models: many of the states expected by the models not seen



VOLUME 44, NUMBER 13 PHYSICAL REVIEW LETTERS 31 MARCH 1980

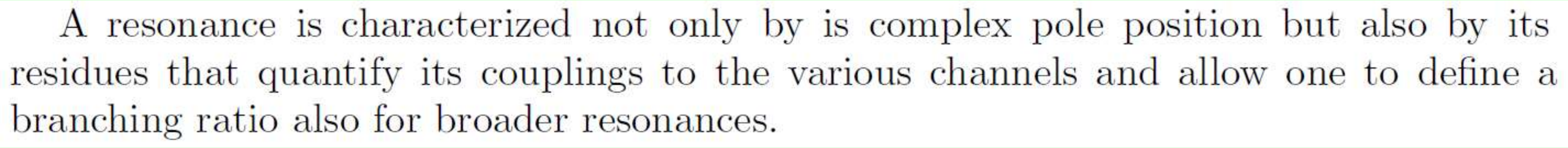
Where Have All the Resonances Gone? An Analysis of Baryon Couplings in a Quark Model with Chromodynamics

Roman Koniuk and Nathan Isgur

How to study N* and Δ?

Resonance is the peak located around a certain energy
found in differential cross sections of scattering experiments

Resonance is related to a pole on the unphysical second Riemann sheet: $M_{pole} + i\Gamma_{pole}/2$

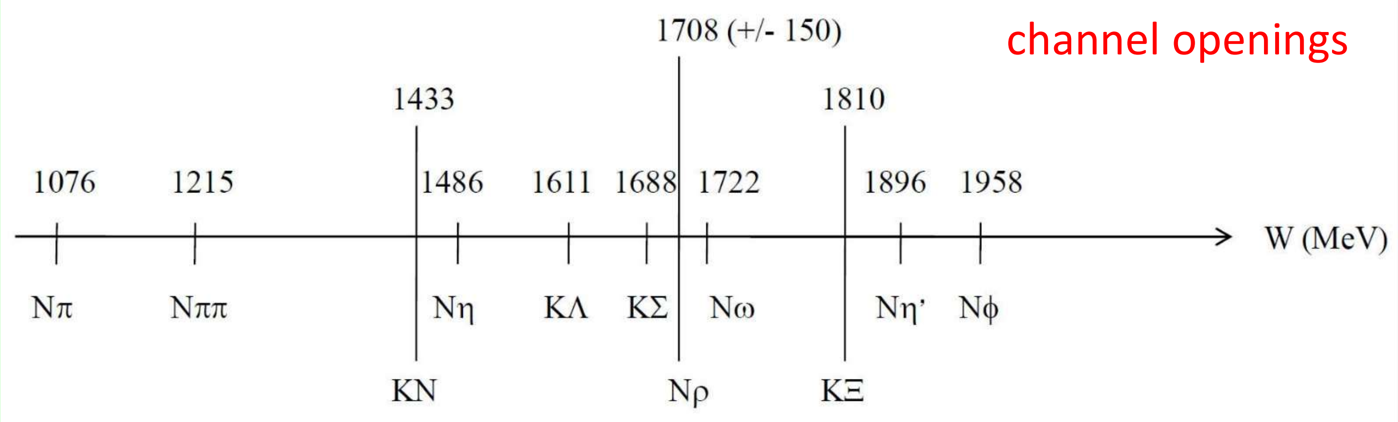


A resonance is characterized not only by is complex pole position but also by its residues that quantify its couplings to the various channels and allow one to define a branching ratio also for broader resonances.

experimental channels with different combinations of quantum numbers

$$\gamma N \rightarrow \pi N, \pi NN, \ldots$$
$$\gamma^* N \rightarrow \pi N, \pi NN, \ldots$$
$$\pi N \rightarrow \pi N, \pi NN, \ldots$$
$$pp \rightarrow pp\pi^0, pp\pi\pi, \ldots$$
$$J/\psi \rightarrow p\bar{p}\pi^0, p\bar{n}\pi^-, \ldots$$

+ analysis methods (PWA), coupled-channels models



PWA of πN total, elastic and **c**harge-e**x**change **s**cattering data

Karlsruhe-Helsinki

Carnegie-Mellon-Berkeley

George Washington (**SAID**)

G. Höhler (1983)
Pion-Nucleon Scattering
(Landolt-Börnstein vol I/9b2)

R. E. Cutkosky *et al.*
Phys. Rev. D **20** (1979) 2839

R. A. Arndt *et al.*
Phys. Rev. C **74** (2006) 045205

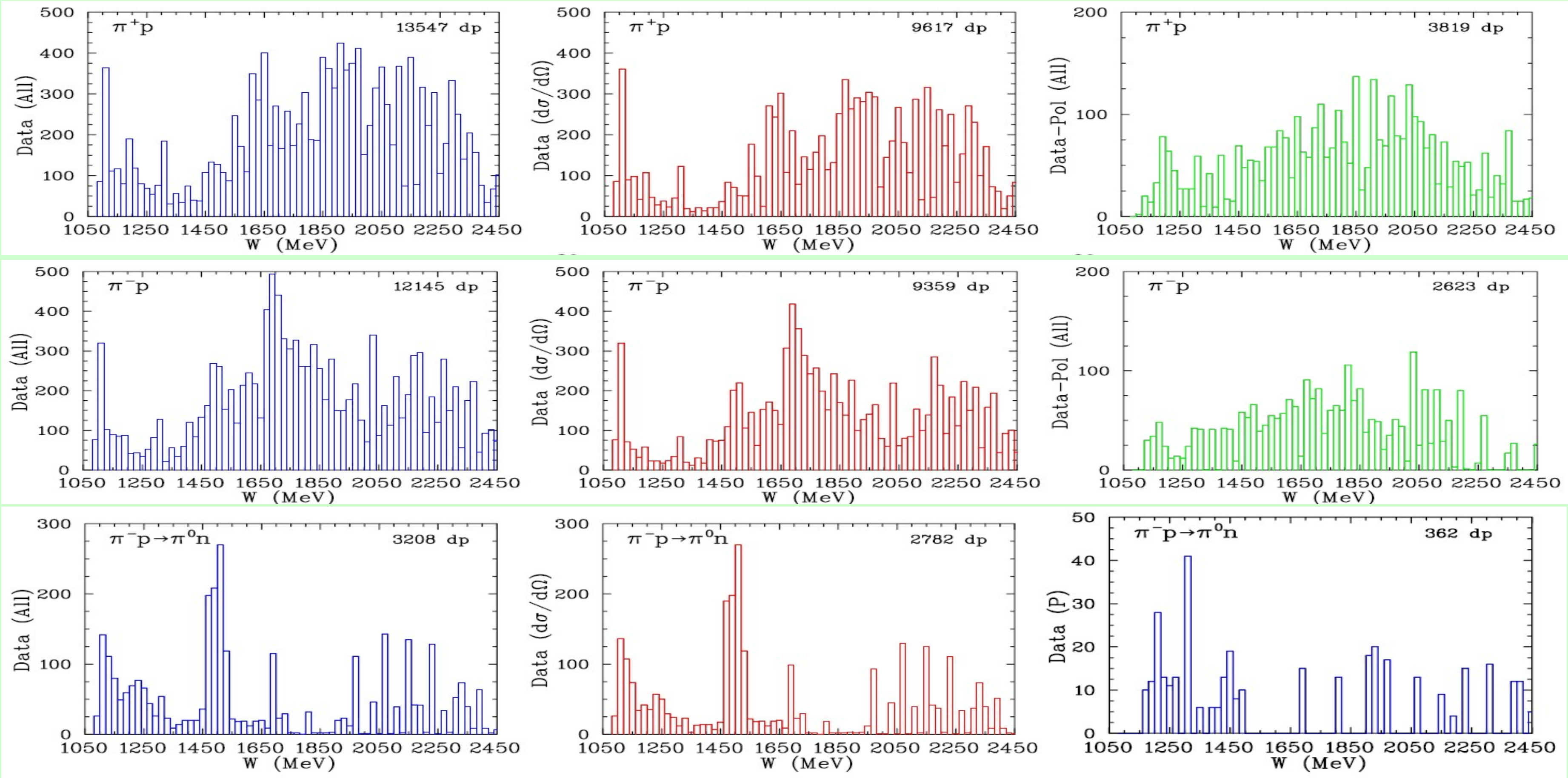
only experiments before 1980

10 k $\pi^{\pm}p \to \pi^{\pm}p$ each, 1.5 k $\pi^{-}p \to \pi^{0}n$, 17% pol.

contiuously updated

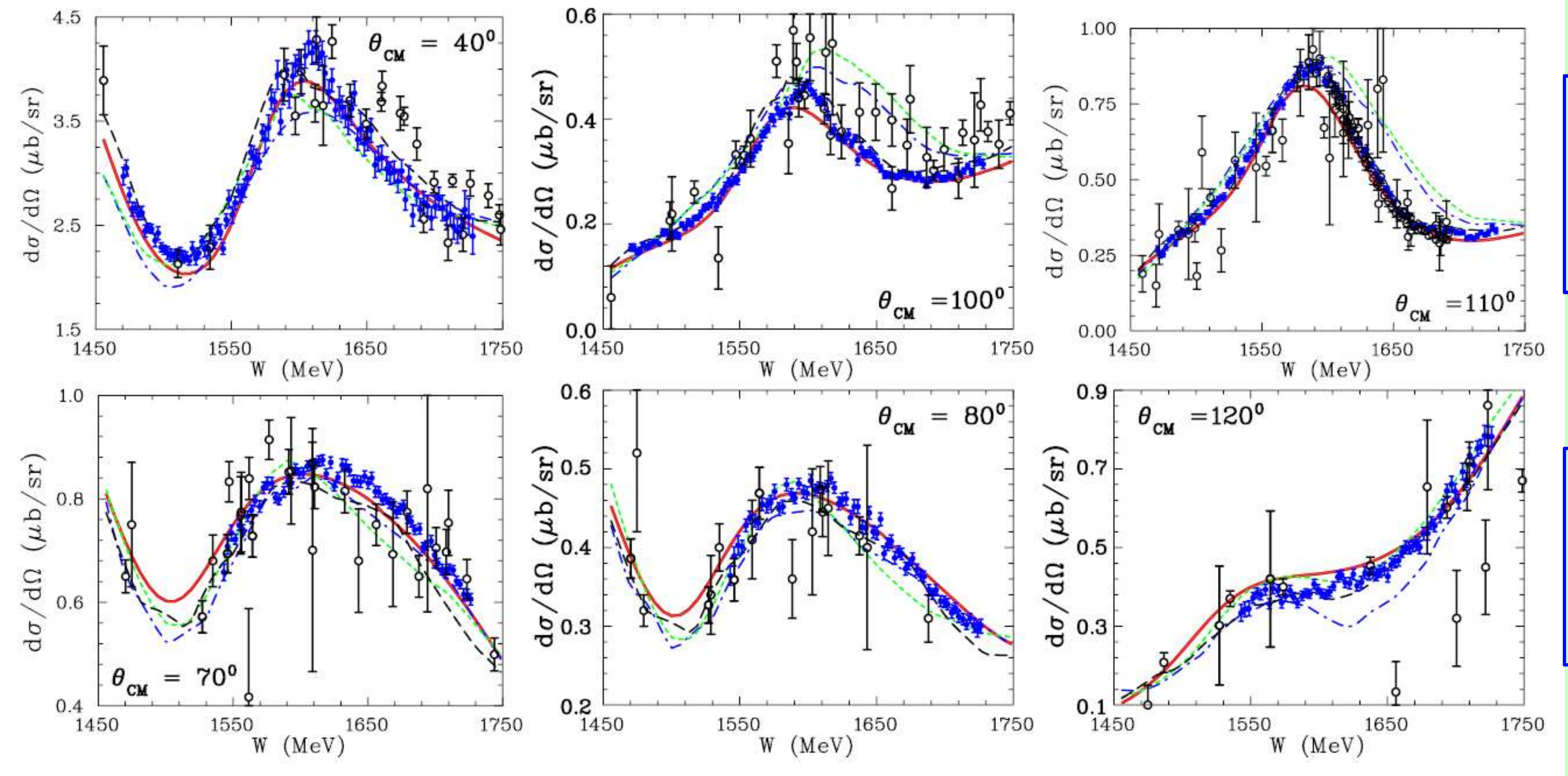
13 k $\pi^{\pm}p \to \pi^{\pm}p$ each, 3 k $\pi^{-}p \to \pi^{0}n$
0.25 k $\pi^{-}p \to \eta n$, 25% data polarized

scarce experimental situation…



πN→πN elastic (new data)

Example of dramatic improvement in statistics: $\Delta\theta_{CM} = \pm 1^{\circ}$



$\pi^- p \to \pi^- p$

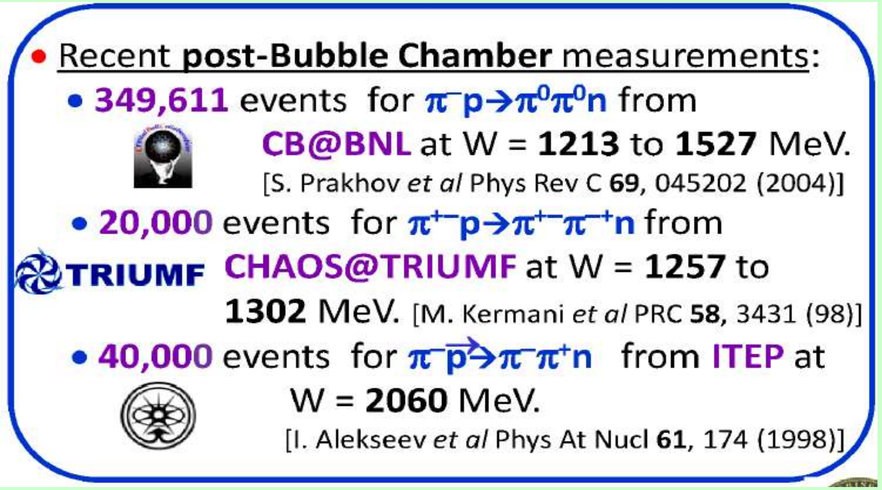
$\pi^+ p \to \pi^+ p$

I. G. Alexeev *et al*.
(EPECUR Collaboration)
Phys. Rev. C **91** (2015) 025205

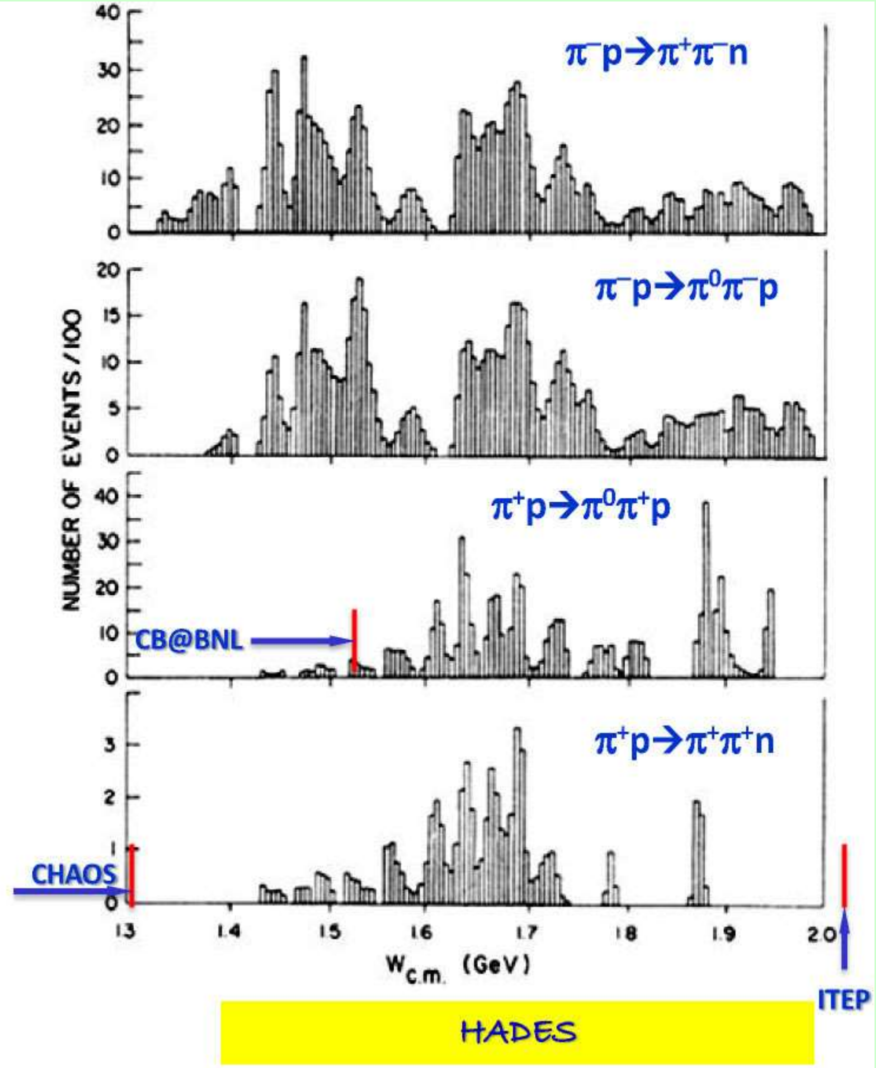
Similar improvement of the data for low energies **needed**!

$\pi N \to \pi\pi N$ status

- most of data $1.3 < \sqrt{s} < 2$ GeV from **Manley *et. al* PRD30 (1984) 904**
- **241214 bubble chamber events analyzed in isobar PWA model**
- knowledge on N* coupl. to ρN, Δπ, σN
- very scarce data base for pion-nucleon reactions
- differential distributions are even more scarce (or missing)
- more recent data do not help for $\pi^+\pi^-$ in **$1.3 < \sqrt{s} < 2$ GeV region**



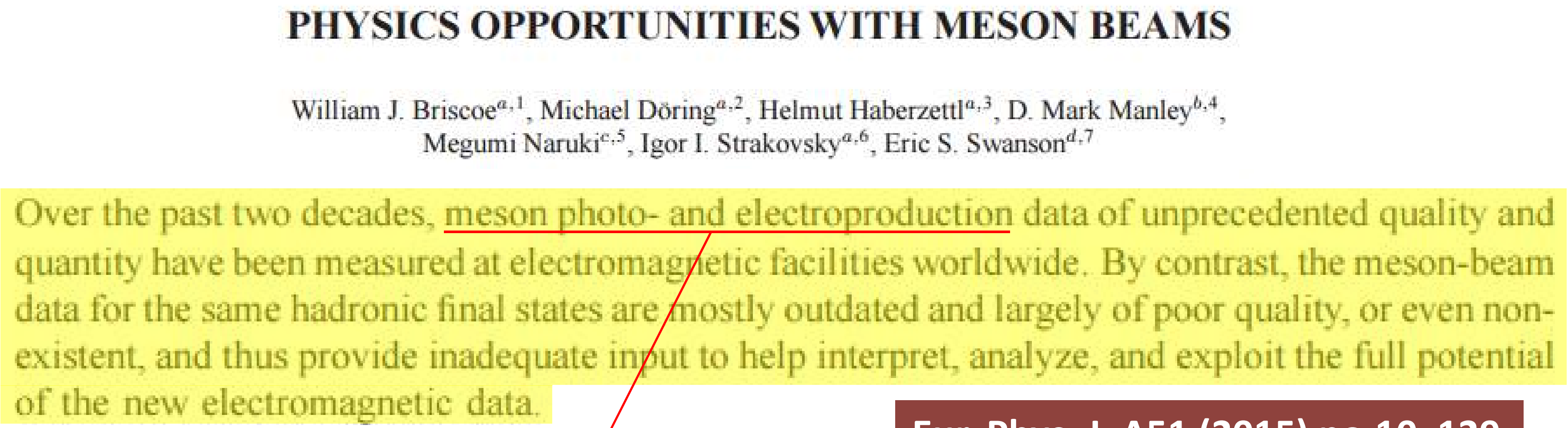
- Recent **post-Bubble Chamber** measurements:
  - **349,611** events for $\pi^- p \to \pi^0 \pi^0 n$ from **CB@BNL** at W = **1213** to **1527** MeV. [S. Prakhov *et al* Phys Rev C **69**, 045202 (2004)]
  - **20,000** events for $\pi^{+-} p \to \pi^{+-} \pi^{-+} n$ from **CHAOS@TRIUMF** at W = **1257** 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)]



Igor Strakovsky

RRTF Workshop, Darmstadt, Germany, Oct 2013

manifest – ”white book”



PHYSICS OPPORTUNITIES WITH MESON BEAMS

William J. Briscoe^{a,1}, Michael Döring^{a,2}, Helmut Haberzettl^{a,3}, D. Mark Manley^{b,4},
Megumi Naruki^{c,5}, Igor I. Strakovsky^{a,6}, Eric S. Swanson^{d,7}

Over the past two decades, meson photo- and electroproduction data of unprecedented quality and quantity have been measured at electromagnetic facilities worldwide. By contrast, the meson-beam data for the same hadronic final states are mostly outdated and largely of poor quality, or even non-existent, and thus provide inadequate input to help interpret, analyze, and exploit the full potential of the new electromagnetic data.

Eur. Phys. J. A51 (2015) no.10, 129

... there has been established a common agreement, that various efforts should converge in desctiption of data...

arxiv: 1604.05704 (19 Apr 2016)

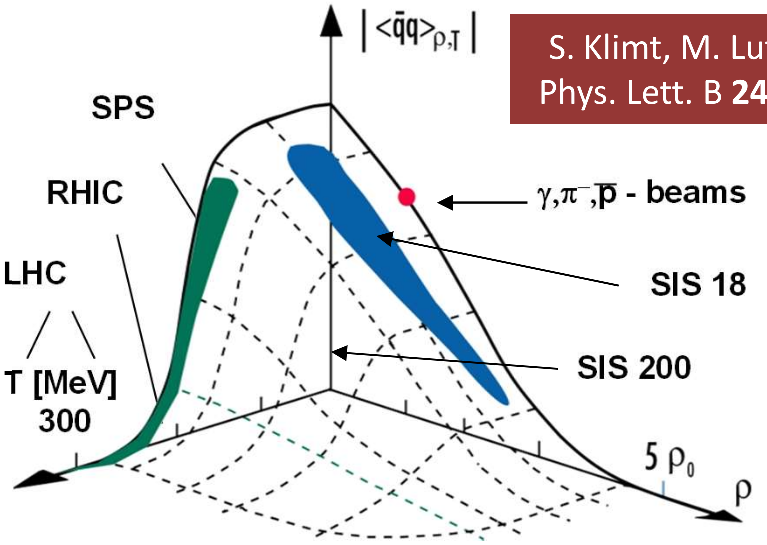
The Impact of New Polarization Data from Bonn, Mainz and Jefferson Laboratory on $\gamma p \to \pi N$ Multipoles

Bonn-Gatchina
Jülich-Bonn
MAID Mainz
SAID GWU

- comparison of the multipoles from fits made before new polarization data and with new data included: results get closer, the variance reduced x 2

Let us step back for some more motivation…

probes of vector meson in medium



S. Klimt, M. Lutz, W. Weise
Phys. Lett. B **249** (1990) 386

G.E. Brown, M. Rho
Phys. Rev. Lett. **66** (1991) 2720

scaling of masses with χ-condensate
order parameter of χS restoration

$$m^* \approx m\left[\langle \bar{q}\,q^* \rangle / \langle \bar{q}\,q \rangle\right]^{\alpha}$$

T. Hatsuda, S.H. Lee
Phys. Rev. C **46** (1992) 34

QCD sum rules

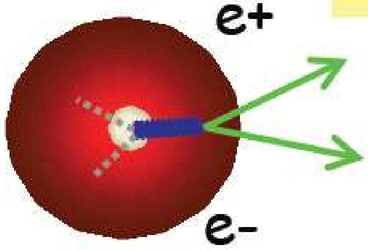
$$m^* = m\left(1 - \alpha\rho^*/\rho\right)$$

early motivations

« short-lived mesons in medium »

p/π/γ/A + A

$$m_{e+e-} = \sqrt{p_{e+}p_{e-}}\,\sin\frac{\vartheta_{e+e-}}{2}$$



best candidate
ρ(770) 1^{--} cτ =1.3 fm/c
Γ=150 MeV

- **rare probes** ($e^+e^-\ BR{\sim}10^{-5}$)

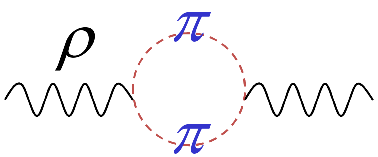
but

- **do not interact strongly** with nuclear matter

ρ in-medium: hadronic models

baryons are the main players

« vacuum »

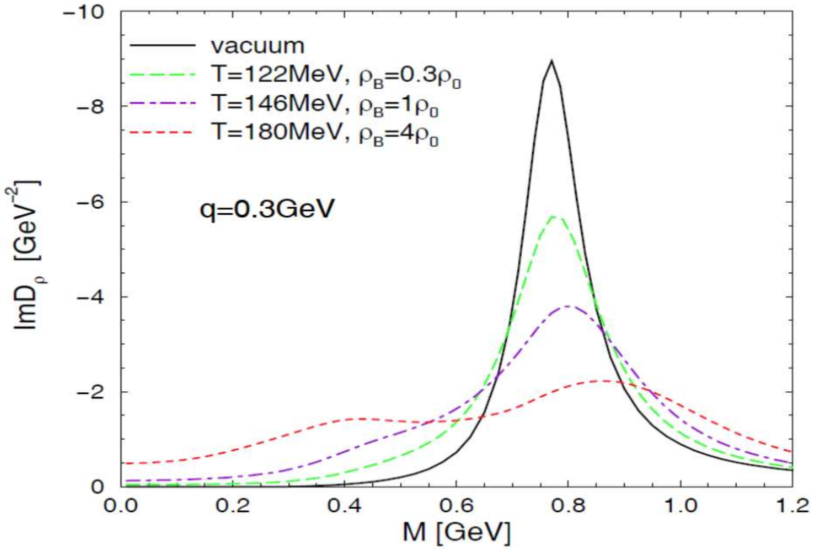


$$\Sigma_\rho(M) = -i m_\rho \Gamma_{\pi\pi}(m)$$
$$m_\rho = 0.77 GeV$$

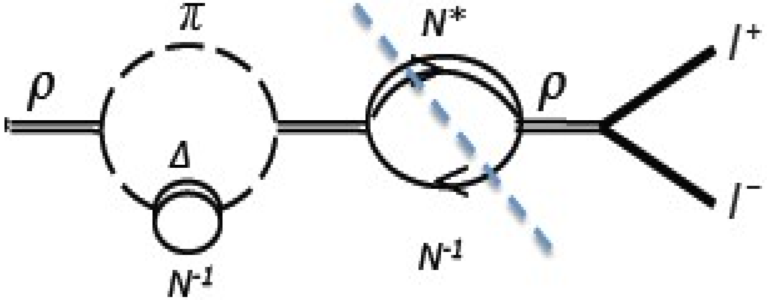
S. Leupold, V. Metag, U. Mosel
Int. J. Mod. Phys. E **19** (2010) 147

« in-medium broadening »

in-medium spectral function
depends on ρNN* coupling
main players:
N(1520), Δ(1620) , N(1720), ….



Explanation of dilepton spectra (RHIC, SPS, HADES)



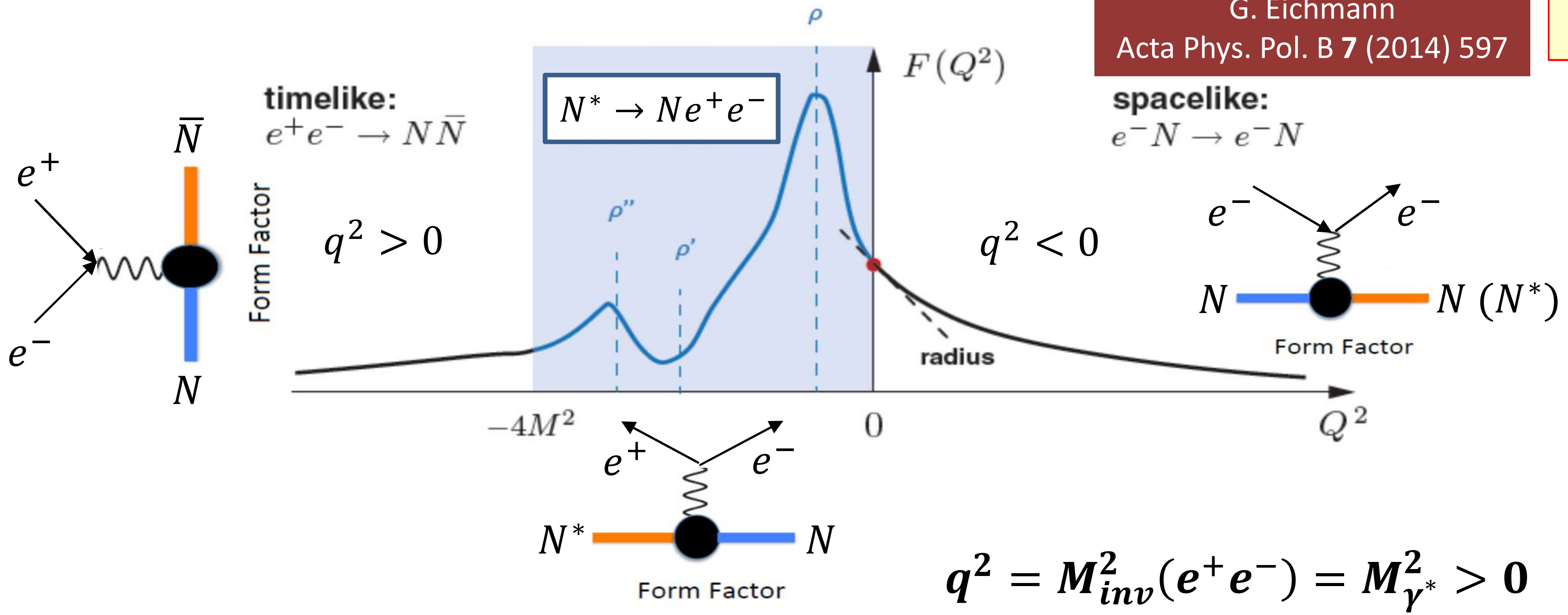
R. Rapp, G. Chanfray, J. Wambach
Nucl. Phys. A **617** (1997) 472

R. Rapp, J. Wambach
Eur. Phys. J. A **6** (1999) 415

Coupling of ρ to baryonic resonances can be **directly** studied in **NN** and **πN collisions** at 1-2 GeV via $N^*(\Delta) \rightarrow Ne^+e^-$ decays

relation to electromagnetic structure of baryons

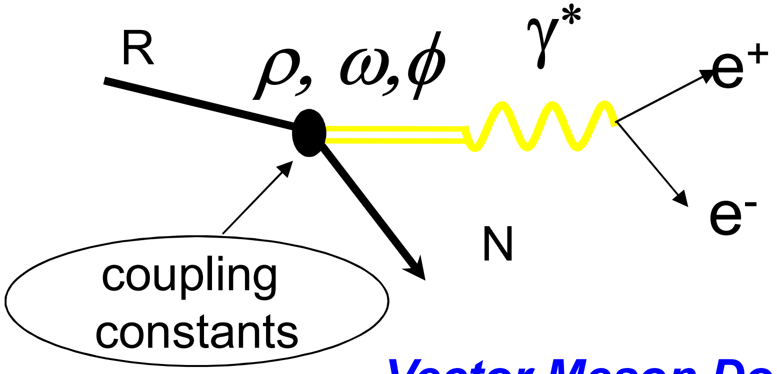
G. Eichmann
Acta Phys. Pol. B **7** (2014) 597



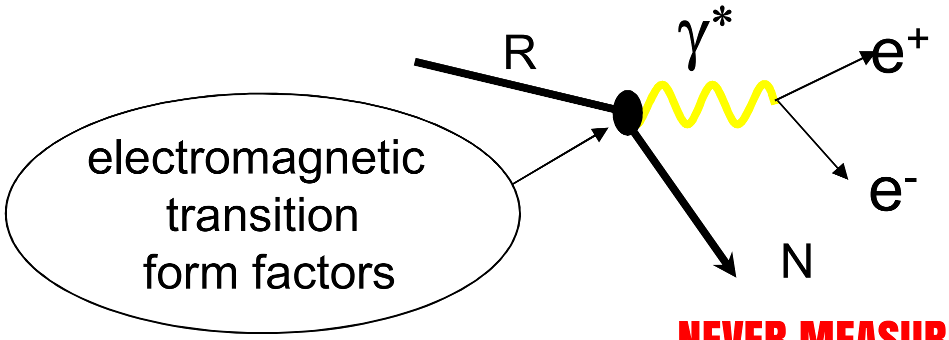
$$q^2 = M^2_{inv}(e^+e^-) = M^2_{\gamma^*} > 0$$

« **ρ** meson production and decay »

« Dalitz decay of baryonic resonances »



Vector Meson Dominance Model



NEVER MEASURED!

Resonances: description and Dalitz decays

Resonance description:

W - arbitrary resonance mass

relativistic Breit-Wigner distribution $g_R(W) = A\frac{W^2\Gamma_{tot}(W)}{(W^2-M_R^2)^2+W^2\Gamma_{tot}^2(W)}$

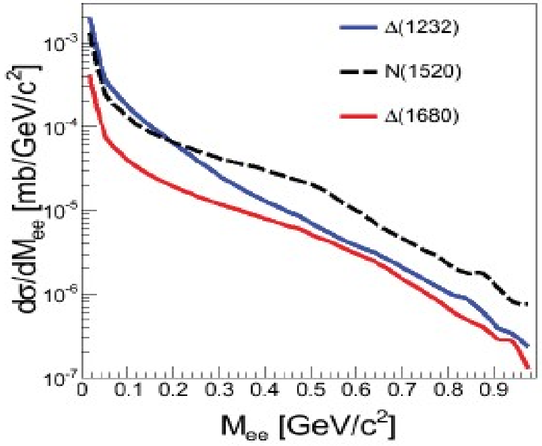
with $\Gamma_{tot}(W) = \Gamma_{\pi N}(W) + \Gamma_{\gamma N}(W) + \boldsymbol{\Gamma_{e^+e^-N}(W)} + \;\ldots$

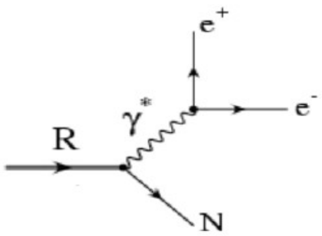
Dalitz decay requires a model for the form factors in the timelike region

QED point-like
$\boldsymbol{R\gamma^*}$ vertex

M. Zetenyi, G. Wolf
Phys. Rev. C **67** (2003) 044002

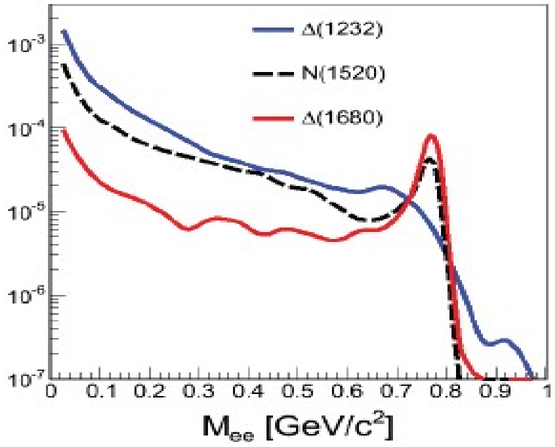
- coupling constants fixed from $R \rightarrow N\gamma$
- strong dependence on spin, parity

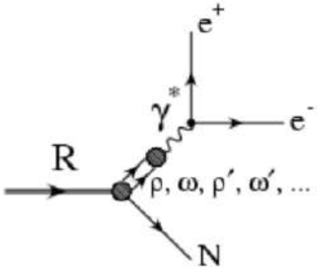




Extended
VDM

M.I. Krivoruchenko et al.
Ann. Phys. 296 (2002) 299



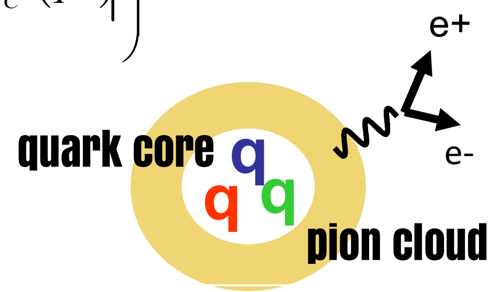


Example: $\Delta \to Ne^+e^-$

M.I. Krivoruchenko *et al.*
Phys. Rev. D**65** (2002) 017502

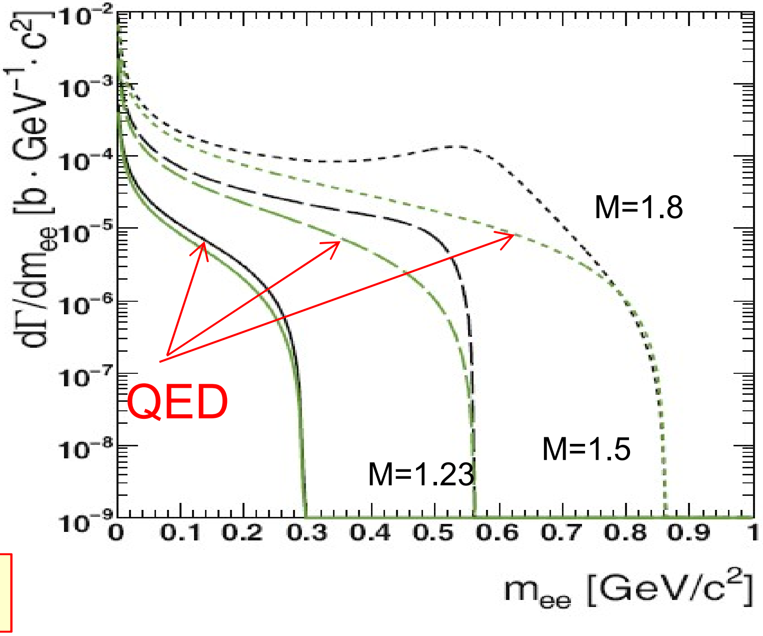
$$\frac{d\Gamma(\Delta \to Ne^+e^-)}{dq^2} = f\left(m_\Delta, q^2\right)\left(\left|G_M^2(q^2)\right| + 3\left|G_E^2(q^2)\right| + \frac{q^2}{2m_\Delta^2}\left|G_C^2(q^2)\right|\right)$$

Time Like ($q^2>0$)
Δ (J=3/2) ->N (J=1/2) γ^* transition:



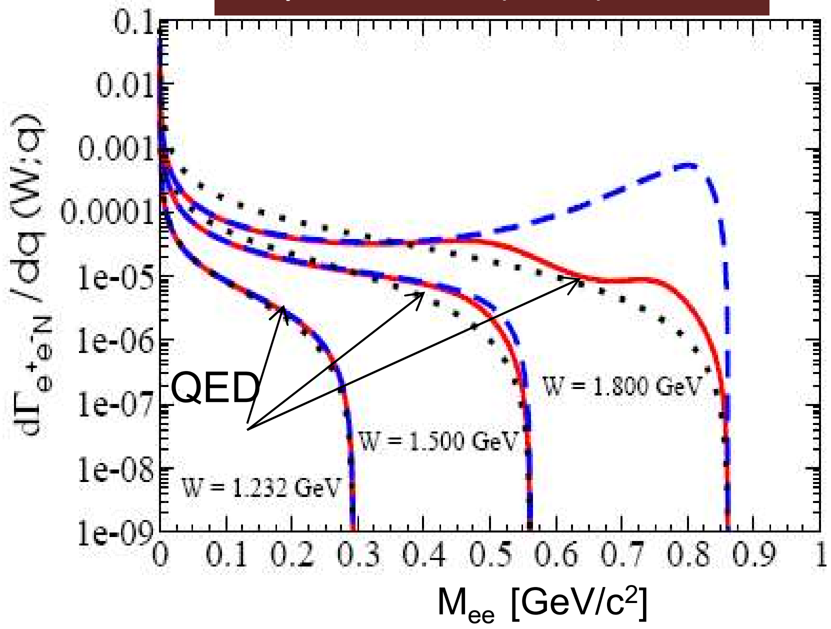
two-component quark model

Q. Wann, F. Iachello
Int. J. Mod. Phys. A**20** (2005) 1846



covariant constituent quark model

G. Ramalho, M. T. Peña
Phys. Rev. D**85** (2012) 113014

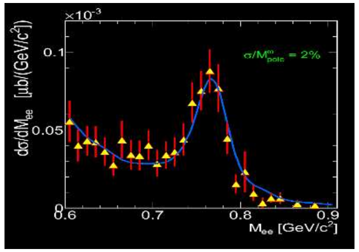


HADES Spectrometer

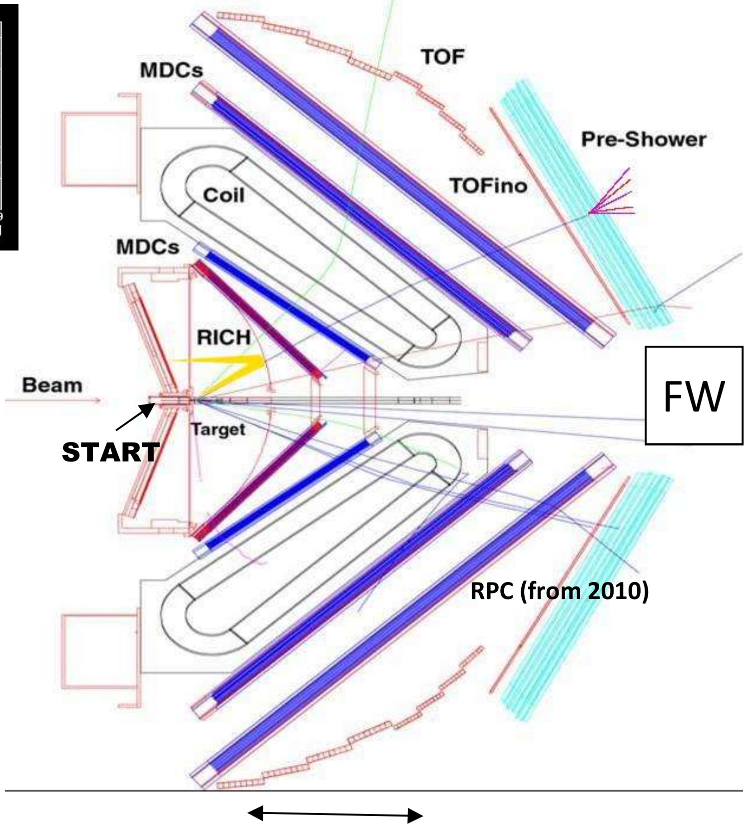
- SIS18 beams: protons (1-4 GeV), nuclei (1-2 AGeV)
  pions (0.4-2 GeV/c) – secondary beam
- spectrometer with $\Delta M/M$ - 2% at ρ/ω
- **detector for rare probes:**

  dielectrons: e+, e-

  strangeness: Λ, $K^{\pm,0}$, Ξ^-, φ
- particle identification π/p/K – combined dE/dx (MDC) and TOF : σ_{tof} ~80 ps (RPC)
  electrons : RICH (hadron blind), TOF/Pre-Shower
- upgrade(2010): new DAQ (~50 kHz) with Au+Au collisions



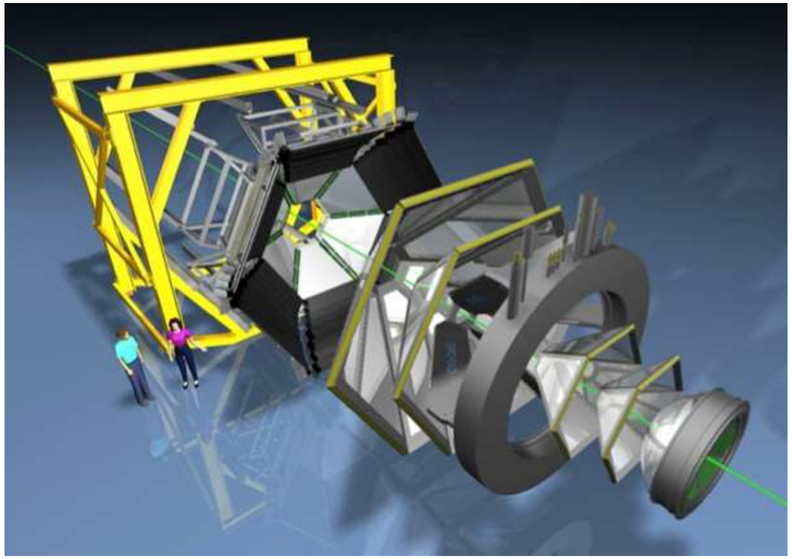
Side View



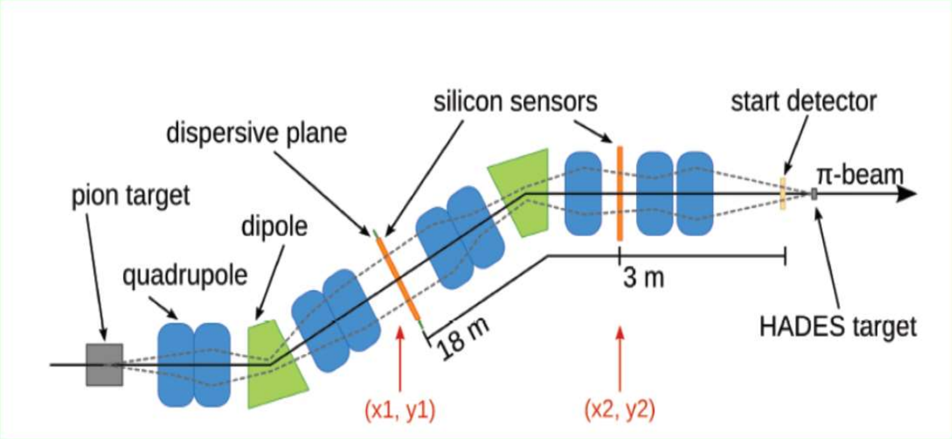
1 m

Geometry

- full azimuthal, polar angles 18° - 85°
- e^+e^- pair acceptance ≈ 0.35



HADES physics for pion beams (2014)

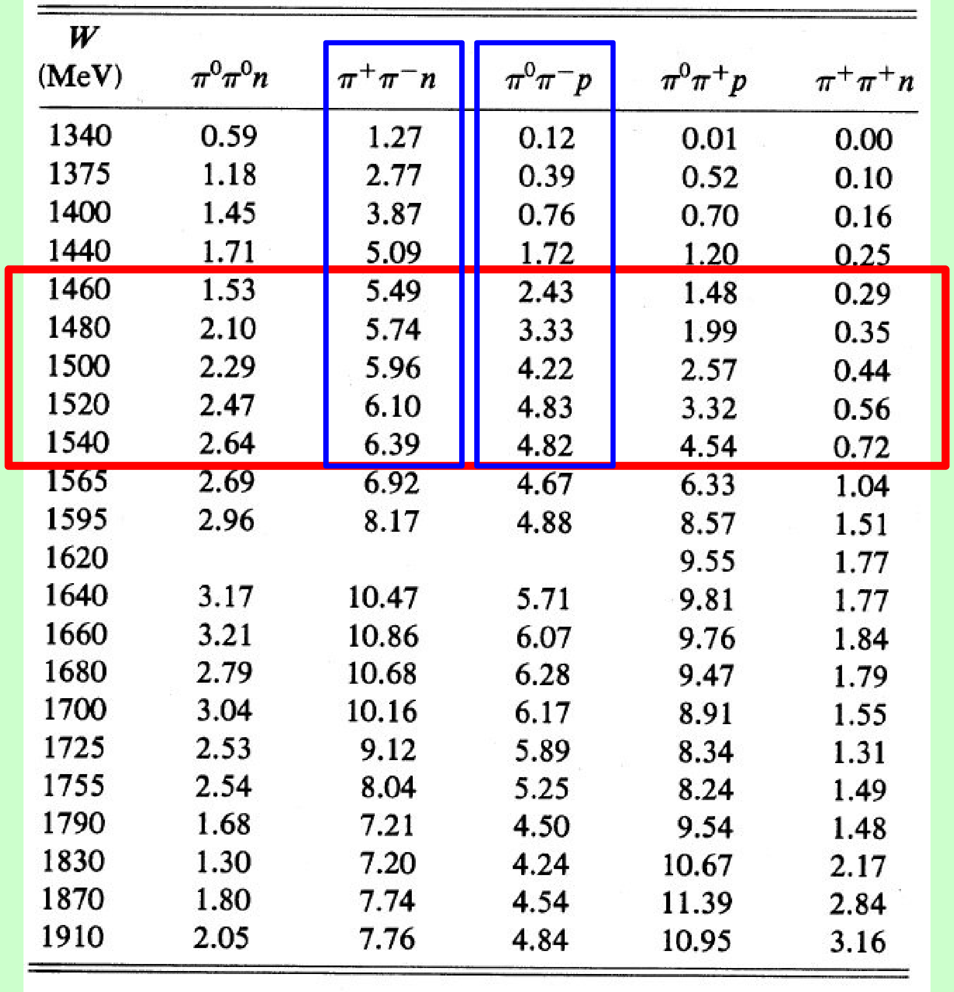


- reaction: N+Be 8-10 · 10^{10} N_2 ions/spill (4s)
- secondary π^- with I~3-4 · 10^5/spill @ 0.7 GeV/c
  - limited by the radioactivity safety
- pion momentum **Δp/p** = 2.2% (σ) and ~50% acceptance @ central momentum
- in beam tracking system: (X1,Y1/X2,Y2) for pion momentum determination: **Δp/p** = 0.3%

- resonance excitation can be controlled by the variation of the projectile (pion) momentum
- HADES starts with p = 0.656/0.69/0.748/0.8 GeV/c $\sqrt{s}$ = 1.46-1.55 GeV: N(1520)
- π+π- production: coupling of ρ to resonance
- e+e- never measured from pion induced reactions
- resonance Dalitz decays R→Ne+e- (reference for p+Nb)
- strangeness production of nucleus: $K^{\pm}$, K^0, φ
- high statistics differential distributions **needed**

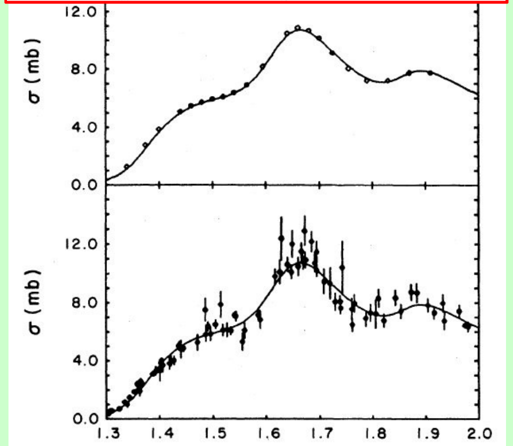
HADES physics for pion beams (2014)

D. M. Manley *et al.*
Phys. Rev. D 30 (1984) 904

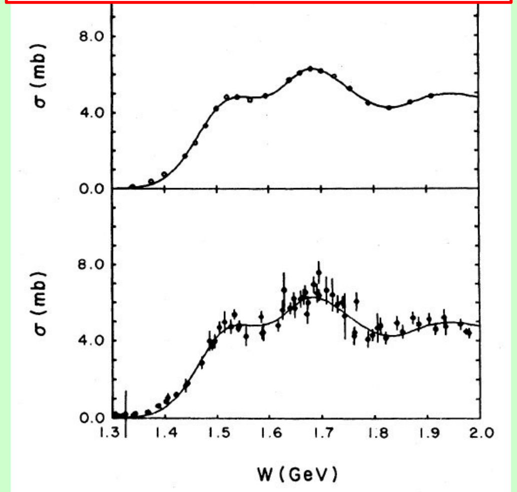


W (MeV)	$\pi^0\pi^0 n$	$\pi^+\pi^- n$	$\pi^0\pi^- p$	$\pi^0\pi^+ p$	$\pi^+\pi^+ n$
1340	0.59	1.27	0.12	0.01	0.00
1375	1.18	2.77	0.39	0.52	0.10
1400	1.45	3.87	0.76	0.70	0.16
1440	1.71	5.09	1.72	1.20	0.25
1460	1.53	5.49	2.43	1.48	0.29
1480	2.10	5.74	3.33	1.99	0.35
1500	2.29	5.96	4.22	2.57	0.44
1520	2.47	6.10	4.83	3.32	0.56
1540	2.64	6.39	4.82	4.54	0.72
1565	2.69	6.92	4.67	6.33	1.04
1595	2.96	8.17	4.88	8.57	1.51
1620				9.55	1.77
1640	3.17	10.47	5.71	9.81	1.77
1660	3.21	10.86	6.07	9.76	1.84
1680	2.79	10.68	6.28	9.47	1.79
1700	3.04	10.16	6.17	8.91	1.55
1725	2.53	9.12	5.89	8.34	1.31
1755	2.54	8.04	5.25	8.24	1.49
1790	1.68	7.21	4.50	9.54	1.48
1830	1.30	7.20	4.24	10.67	2.17
1870	1.80	7.74	4.54	11.39	2.84
1910	2.05	7.76	4.84	10.95	3.16

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

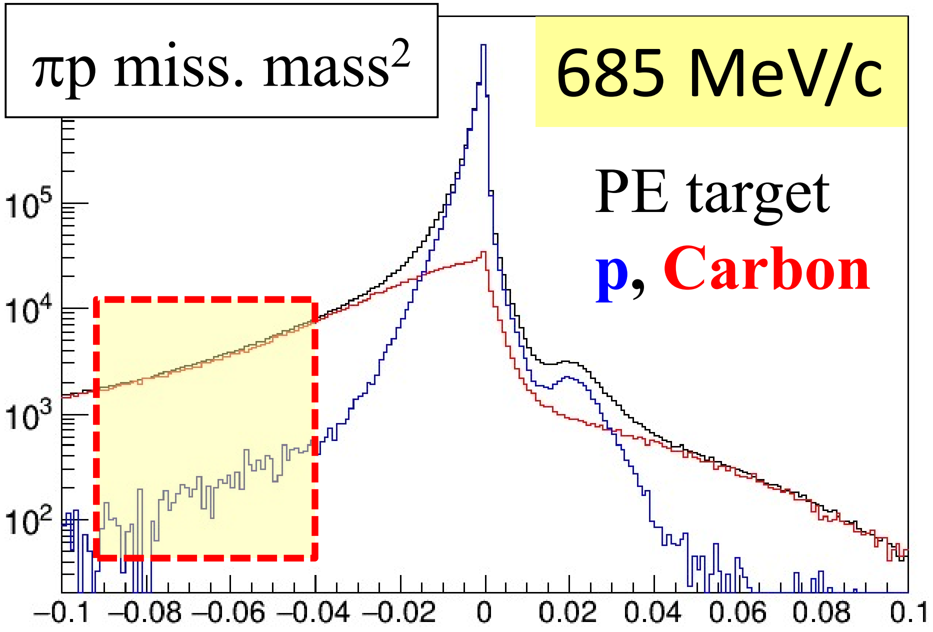


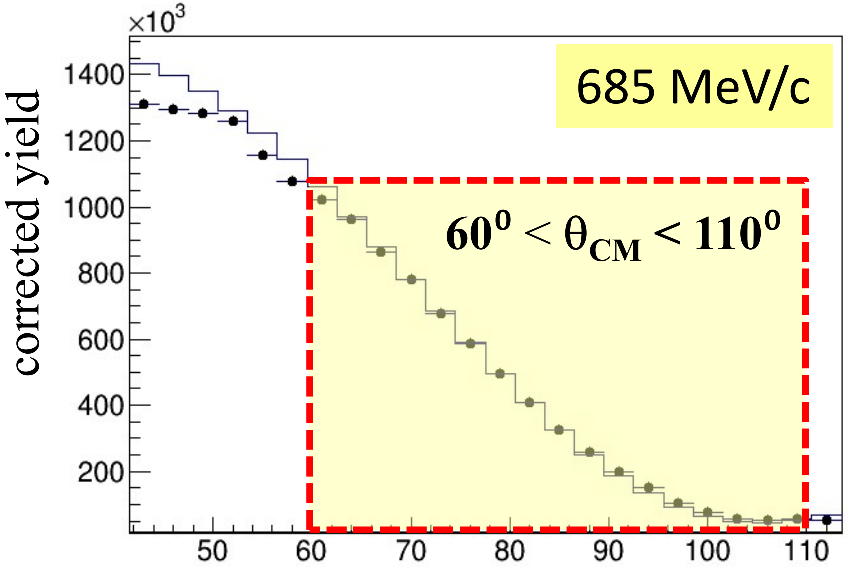
$\pi^- p \longrightarrow \pi^0\pi^- p$



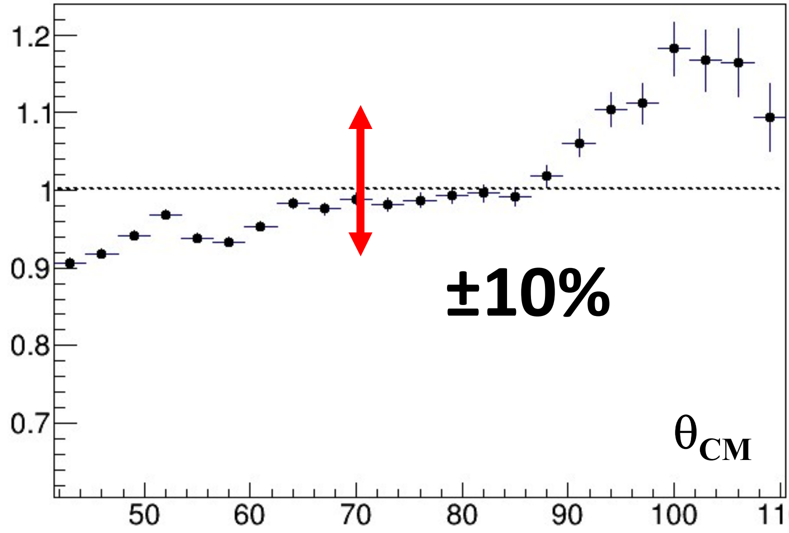
see also SAID database

elastic events (C subtr.) | SAID compared





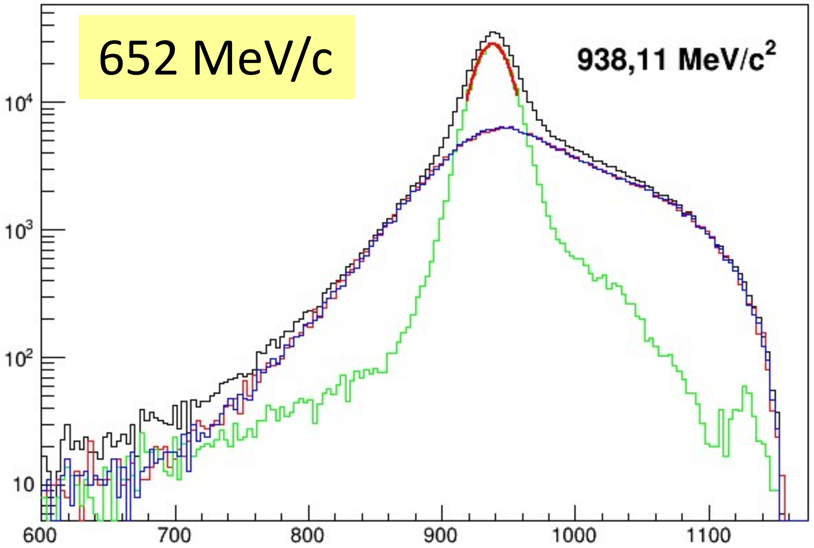
- MC simulation: acc & eff correction

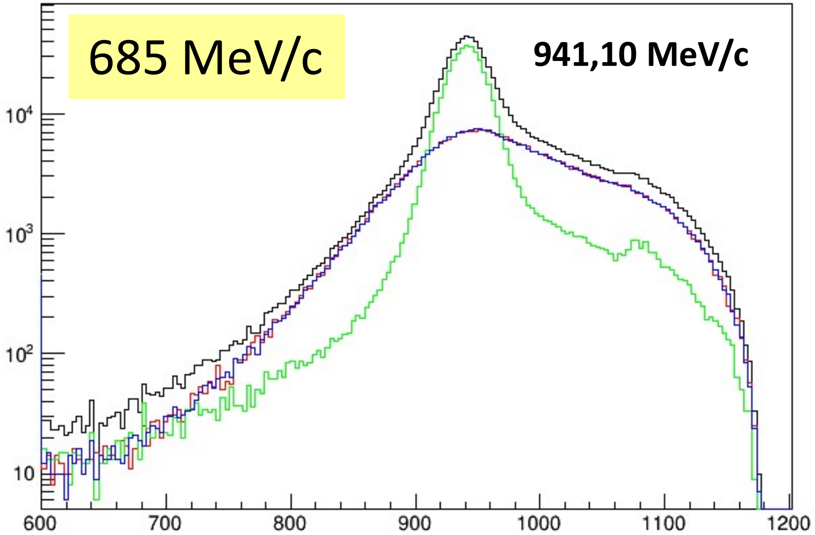


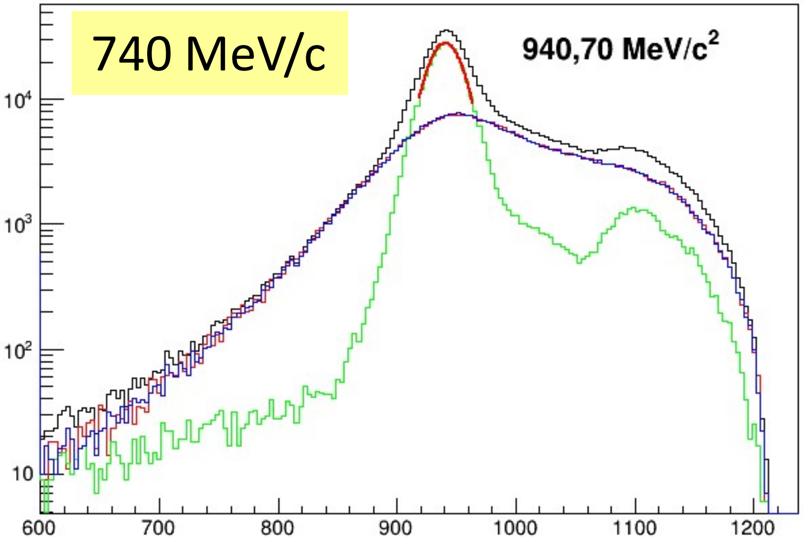
- exp normalized to the same area

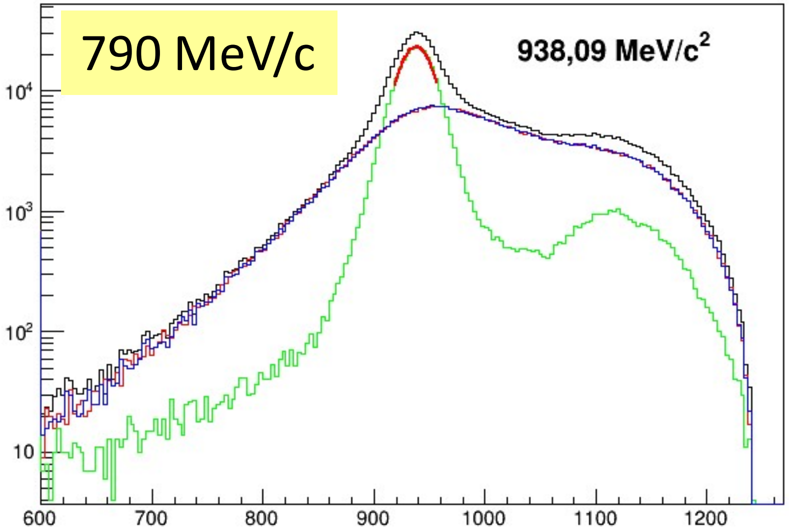
- **beam momenta adjusted to measured (HADES spectrometer) values:** **652, 685, 740, 790 MeV/c**
- **corrections for energy loss**
- **obtained scaling used then in $\pi^+\pi^-$, $\pi^0\pi^-$, e^+e^-**

(n $\pi^+\pi^-$) events – scaling from elastic





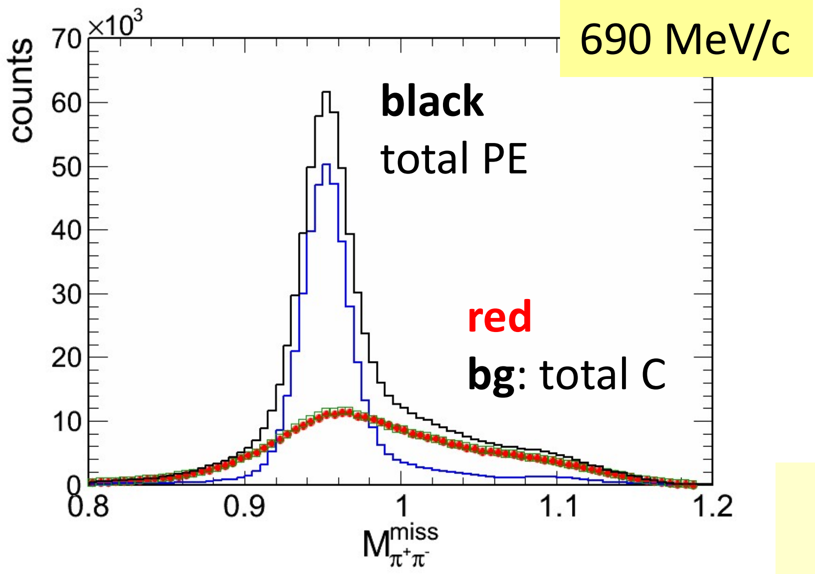


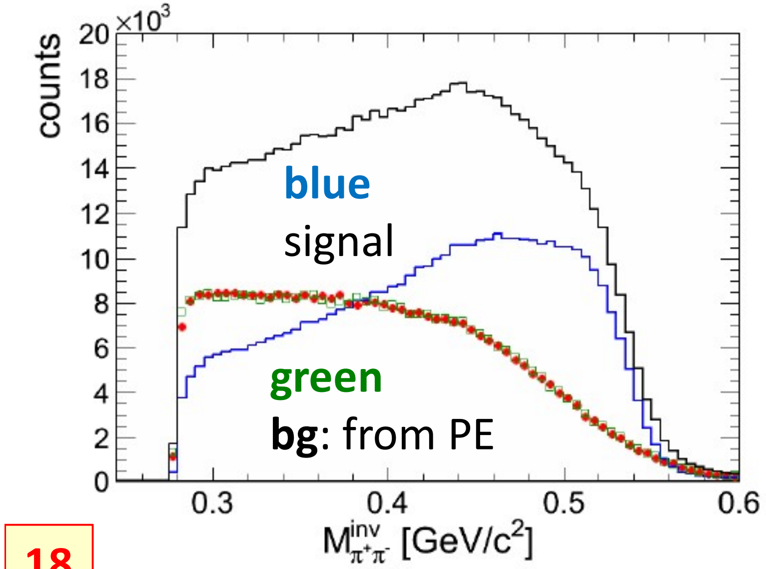


$\pi^+\pi^-$ *missing mass*

$\pi^+\pi^-$ *missing mass*

(n $\pi^+\pi^-$) – events with signal extracted





- **goal**: separate signal (**π^-p**) from background (**π^-C**) based on PE events and C events
- relative normalization of PE events and C events deduced from **π^-p** elastic scattering

procedure: event from C **correlated** with event from PE based on χ^2
(miss. mass + momentum of π^+, π^-, n)
(miss. mass + momentum of π^0, π^-, p)

PWA done with:

- ✓ **four ππ data samples from HADES**
- ✓ **photon- and pion-induced reactions**

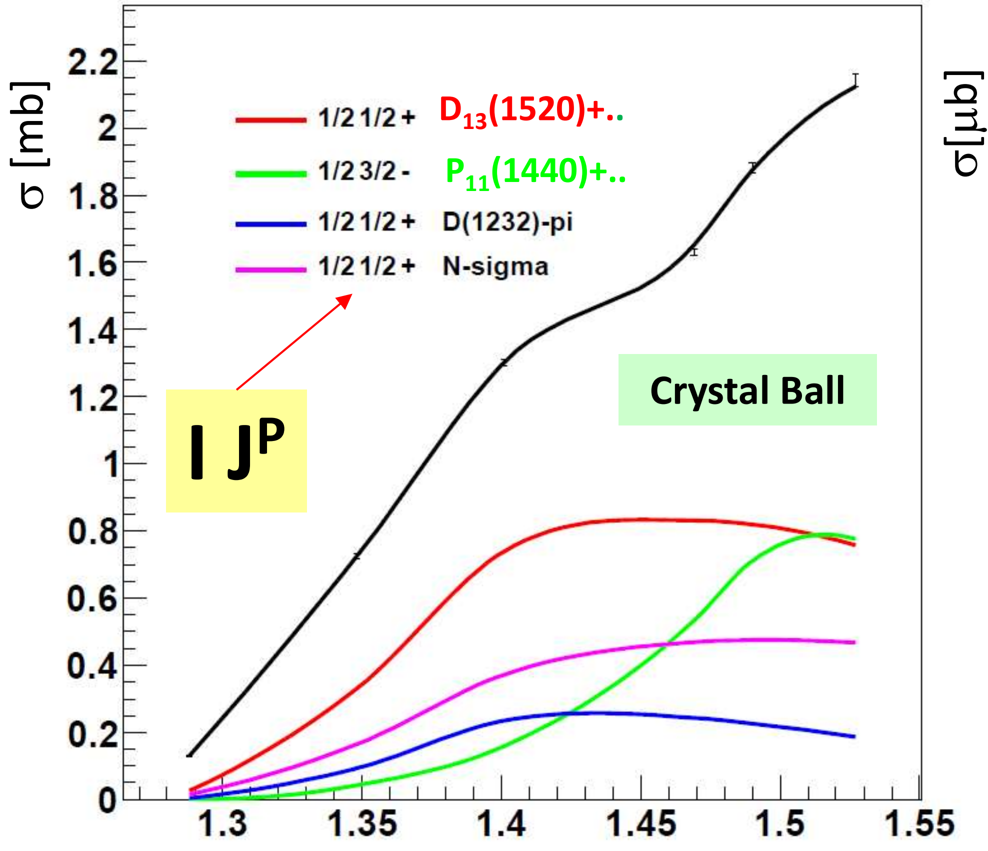
PWA coupled channel analysis

Baryon data base

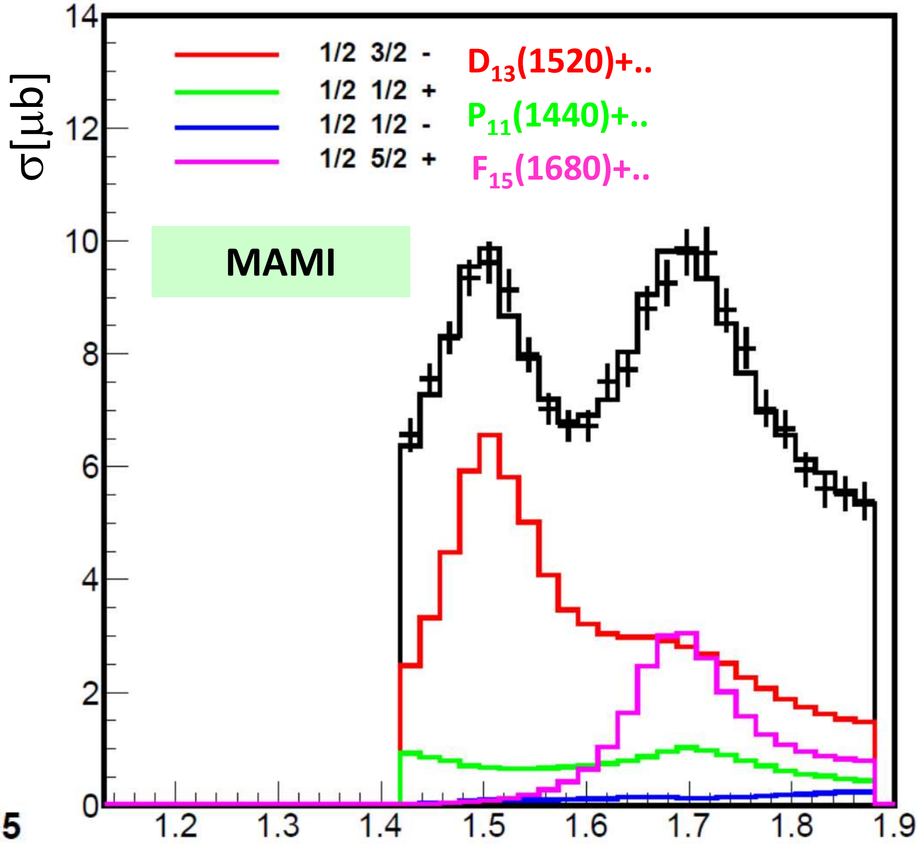
DATA	BG2013-2014	added in BG2014-2015
$\pi N \to \pi N$ ampl.	SAID or Hoehler energy fixed	
$\gamma p \to \pi N$	$\frac{d\sigma}{d\Omega}, \Sigma, T, P, E, G, H$	E, G, T, P (CB-ELSA, CLAS)
$\gamma n \to \pi N$	$\frac{d\sigma}{d\Omega}, \Sigma, T, P$	$\frac{d\sigma}{d\Omega} (MAMI)$
$\gamma n \to \eta n$	$\frac{d\sigma}{d\Omega}, \Sigma$	$\frac{d\sigma}{d\Omega}$ (MAMI)
$\gamma p \to \eta p$	$\frac{d\sigma}{d\Omega}, \Sigma$	T, P, H, E (CB-ELSA)
$\gamma p \to \eta' p$		$\frac{d\sigma}{d\Omega}, \Sigma$
$\gamma p \to K^+ \Lambda$	$\frac{d\sigma}{d\Omega}, \Sigma, P, T, C_x, C_z, O_{x'}, O_{z'}$	Σ, P, T, O_x, O_z (CLAS)
$\gamma p \to K^+ \Sigma^0$	$\frac{d\sigma}{d\Omega}, \Sigma, P, C_x, C_z$	Σ, P, T, O_x, O_z (CLAS)
$\gamma p \to K^0 \Sigma^+$	$\frac{d\sigma}{d\Omega}, \Sigma, P$	
$\pi^- p \to \eta n$	$\frac{d\sigma}{d\Omega}$	
$\pi^- p \to K^0 \Lambda$	$\frac{d\sigma}{d\Omega}, P, \beta$	
$\pi^- p \to K^0 \Sigma^0$	$\frac{d\sigma}{d\Omega}, P\ (K^0\Sigma^0)\ \frac{d\sigma}{d\Omega}\ (K^+\Sigma^-)$	
$\pi^+ p \to K^+ \Sigma^+$	$\frac{d\sigma}{d\Omega}, P, \beta$	
$\pi^- p \to \pi^0 \pi^0 n$	$\frac{d\sigma}{d\Omega}$ (Crystal Ball)	
$\pi^- p \to \pi^+ \pi^- n$		$\frac{d\sigma}{d\Omega}$ (HADES)
$\gamma p \to \pi^0 \pi^0 p$	$\frac{d\sigma}{d\Omega}, \Sigma, E, I_c, I_s$	
$\gamma p \to \pi^0 \eta p$	$\frac{d\sigma}{d\Omega}, \Sigma, I_c, I_s$	
$\gamma p \to \pi^+ \pi^- p$		$\frac{d\sigma}{d\Omega}, I_c, I_s$ (CLAS)
$\gamma p \to \omega p$		$\frac{d\sigma}{d\Omega}, \Sigma, \rho^0_{ij}, \rho^1_{ij}, \rho^2_{ij}, E, G$ (CB-ELSA)
$\gamma p \to K^*(890) \Lambda$		$\frac{d\sigma}{d\Omega}, \Sigma, \rho^0_{ij}$ (CLAS)

PWA: initial waves

$\pi^- p \to \pi^0\pi^0 n$



$\gamma p \to \pi^0\pi^0 p$



√s [GeV]

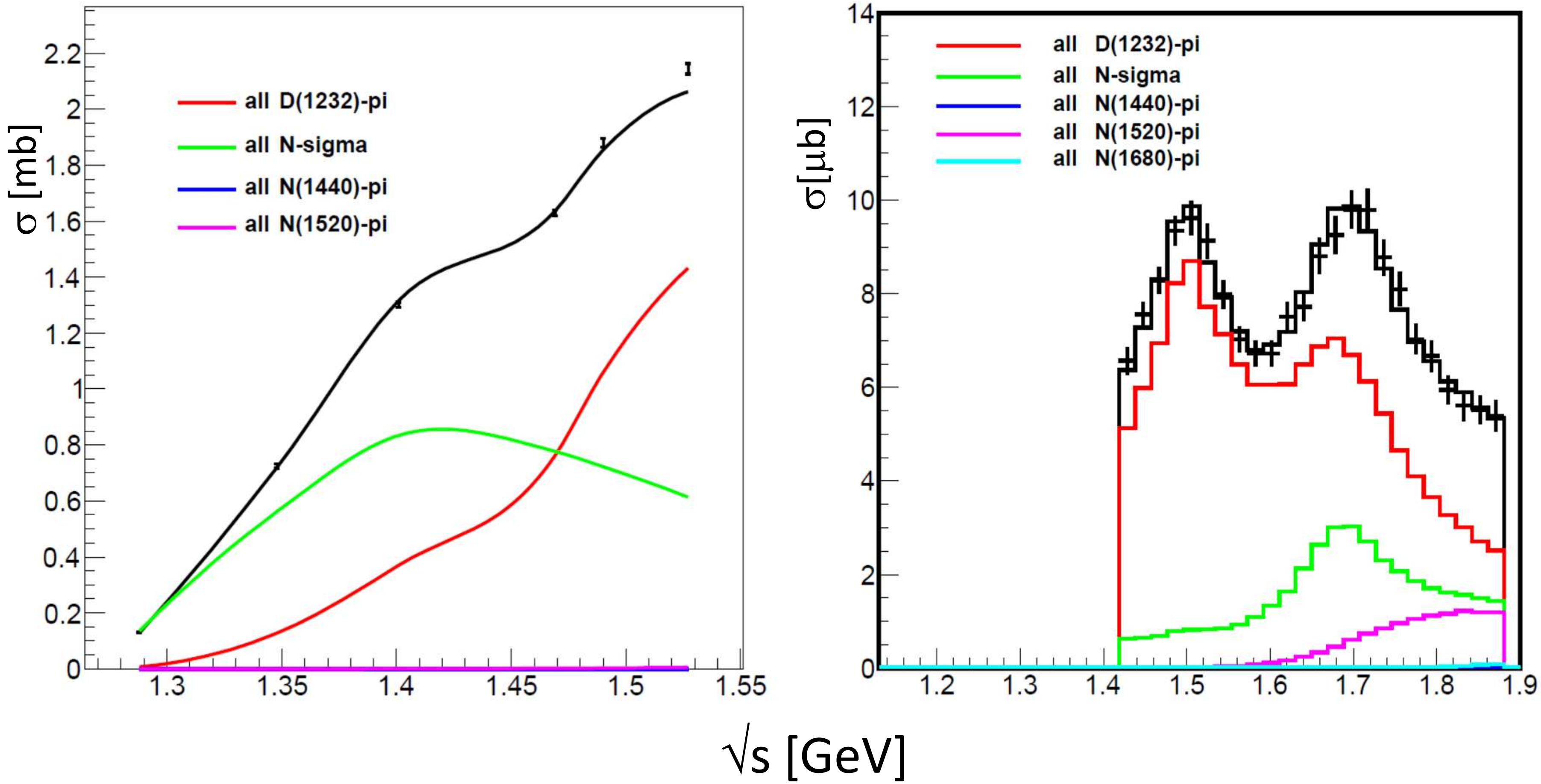
in energy range of **1.45 - 1.55 GeV**
in 2-pion production only few resonances
matter: **D_{13}(1520)**, **P_{11}(1440)**

$\xcancel{\rho \to \pi^0\pi^0}$

PWA: final states

$\pi^- p \rightarrow \pi^0\pi^0 n$

$\gamma p \rightarrow \pi^0\pi^0 p$

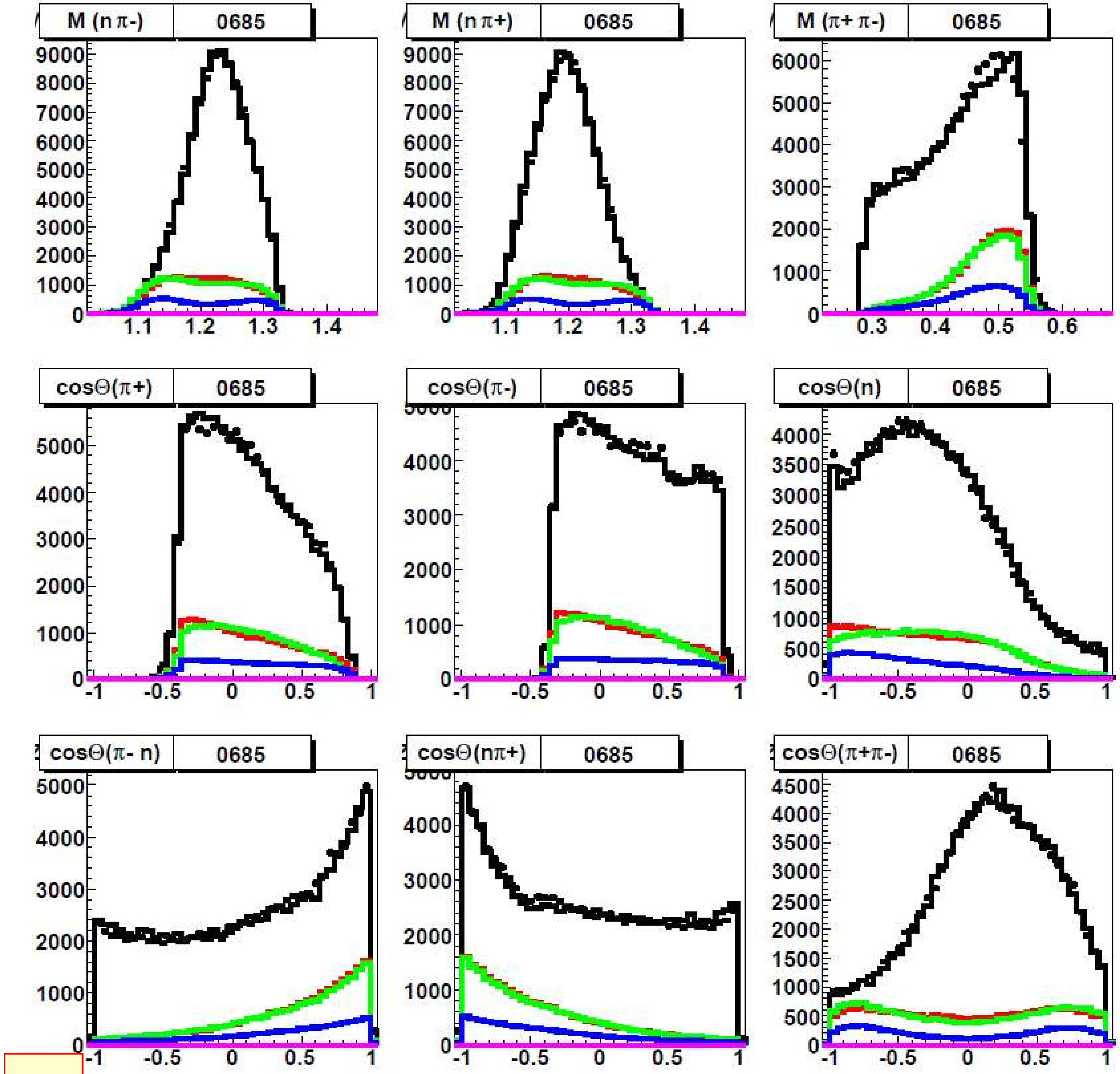


Dominat channels in $2\pi^0$ are: $\Delta\pi$ and $N\sigma$ ($2\pi^0$ in I = 0)

PWA example results (n $\pi^+\pi^-$)

in the acceptance

685 MeV/c



invariant masses
$n\pi^-, n\pi^+, \pi^+\pi^-$

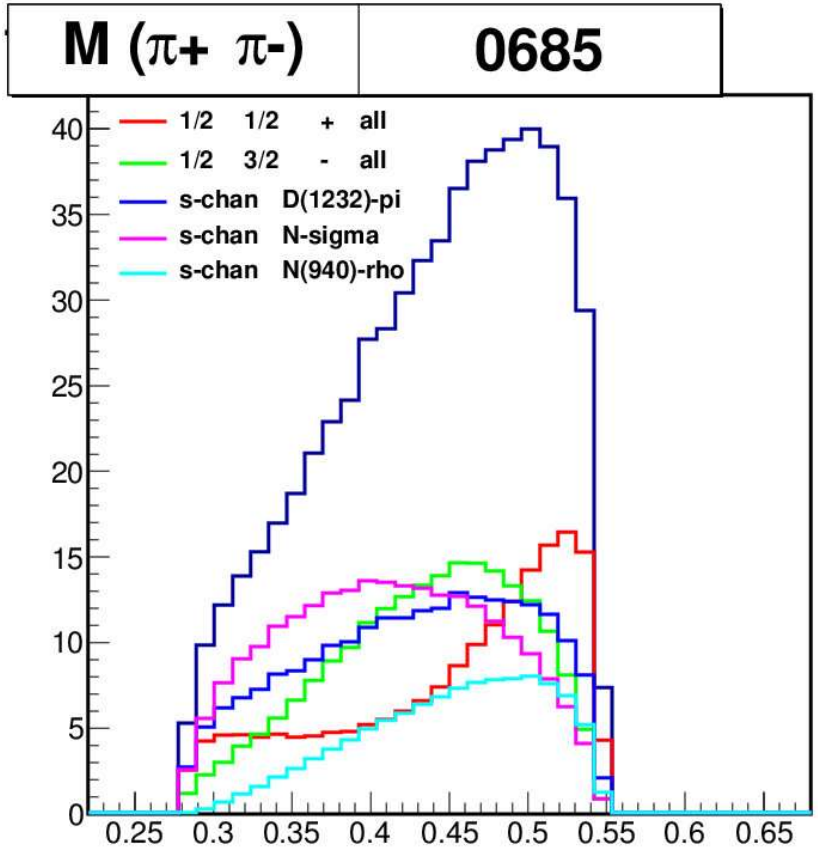
ρ – total
ρ – s-channel
ρ – D_{13}(1520)

angular distr. in CM
$\cos\theta$ **of** π^+, π^-, n

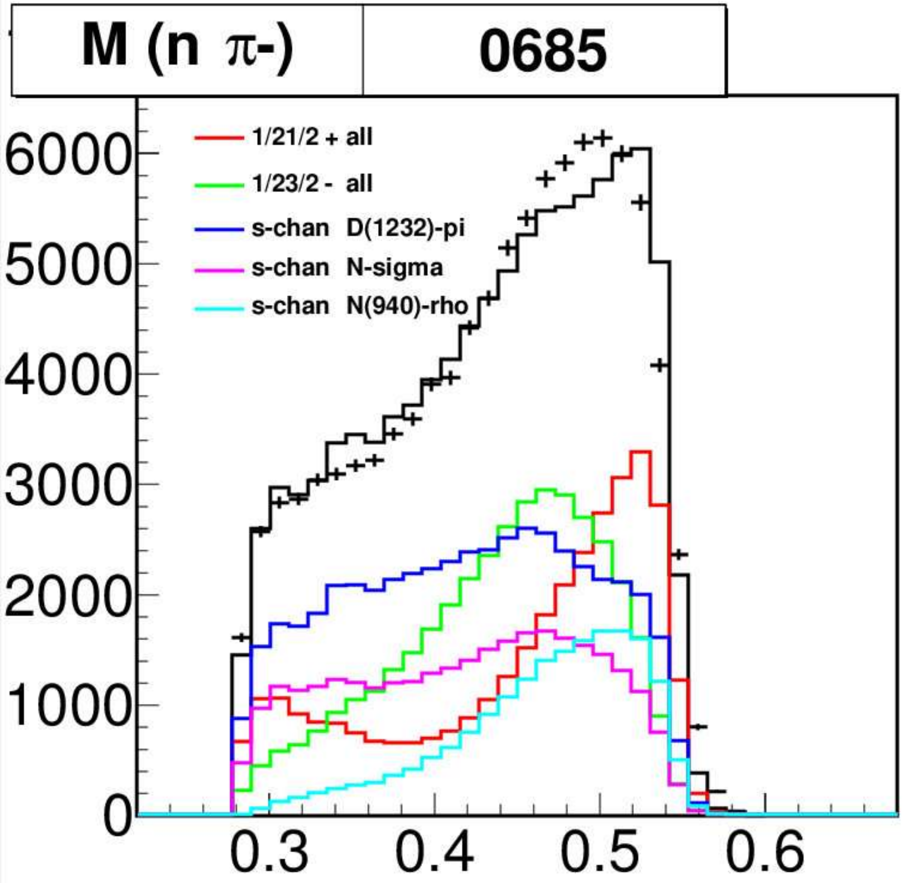
helicity (angular proj. of one of particles in the frame of $n\pi^-, n\pi^+, \pi^+\pi^-$**)**

PWA $\pi^+\pi^-$ inv. mass – main contributions

Total cross section (from PWA solution)



Inside HADES acceptance:

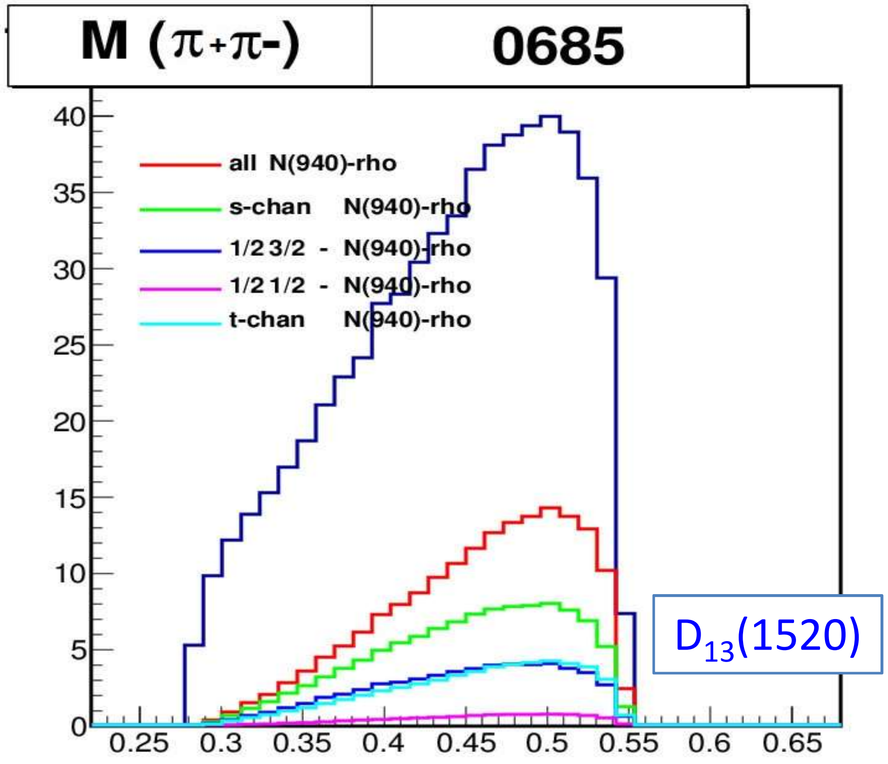


INPUT: $D_{13}(1520)$, $P_{11}(1440)$

OUTPUT: $\Delta\pi$, $N\sigma$, $N\rho$

PWA $\pi^+\pi^-$ inv. Mass – ρ contribution

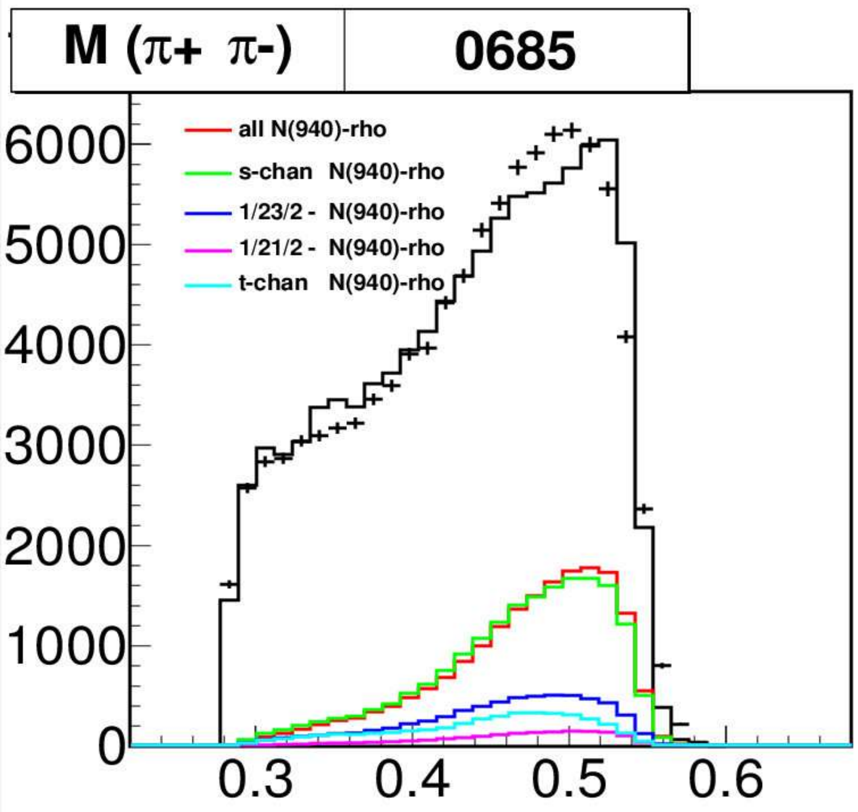
Total cross section (from PWA solution)



$D_{13}(1520)$

important non-resonant (t-channel contribution)

Inside HADES acceptance:



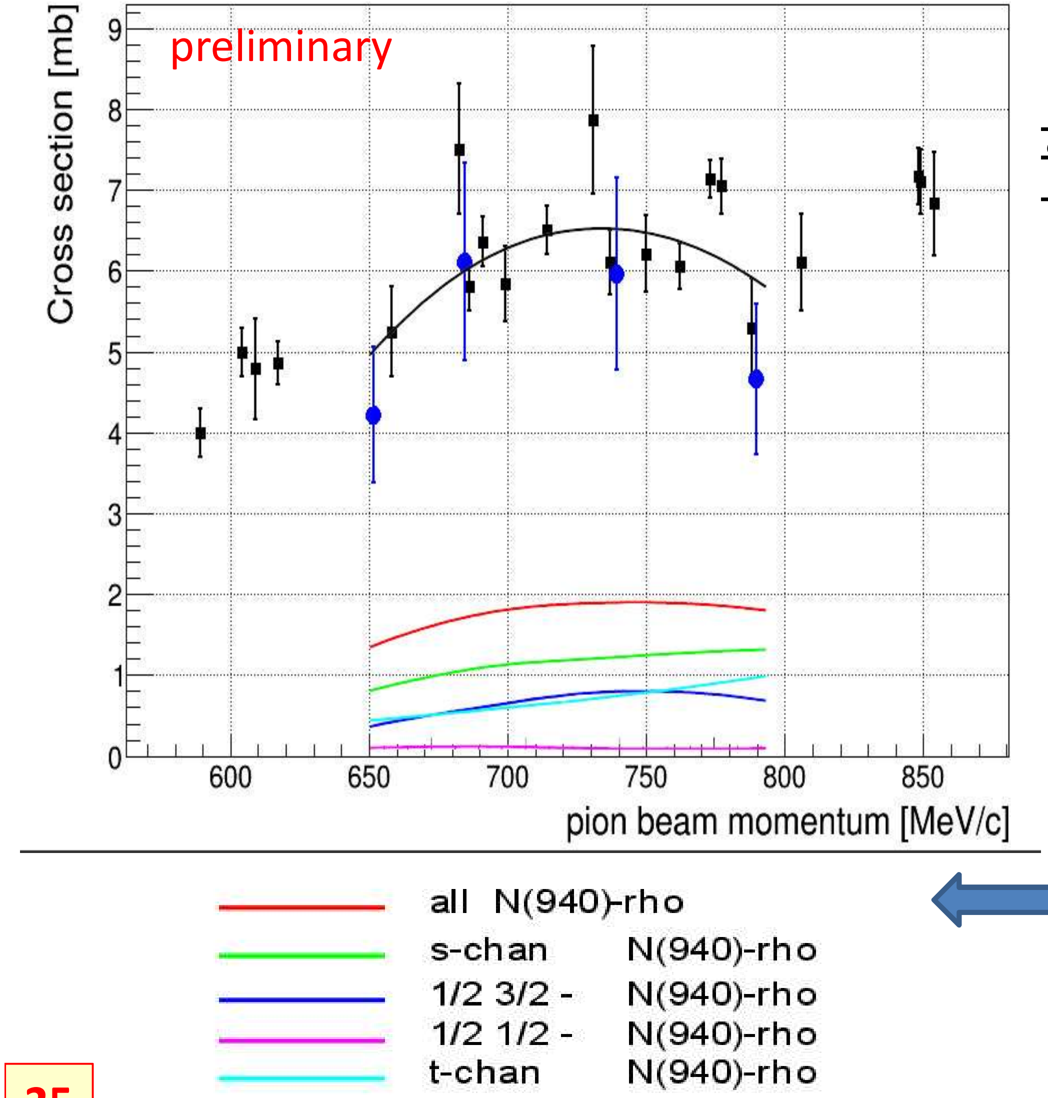
- **Dominated by s-channel**
  - resonant $D_{13}(1520)$ production
- **Strong interferences** between 1/2- states with izospin 1/2 and 3/2

FOR DILEPTON ANALYSIS:

$N(1520)D_{13}$ coupling to **ρN**: **17%**

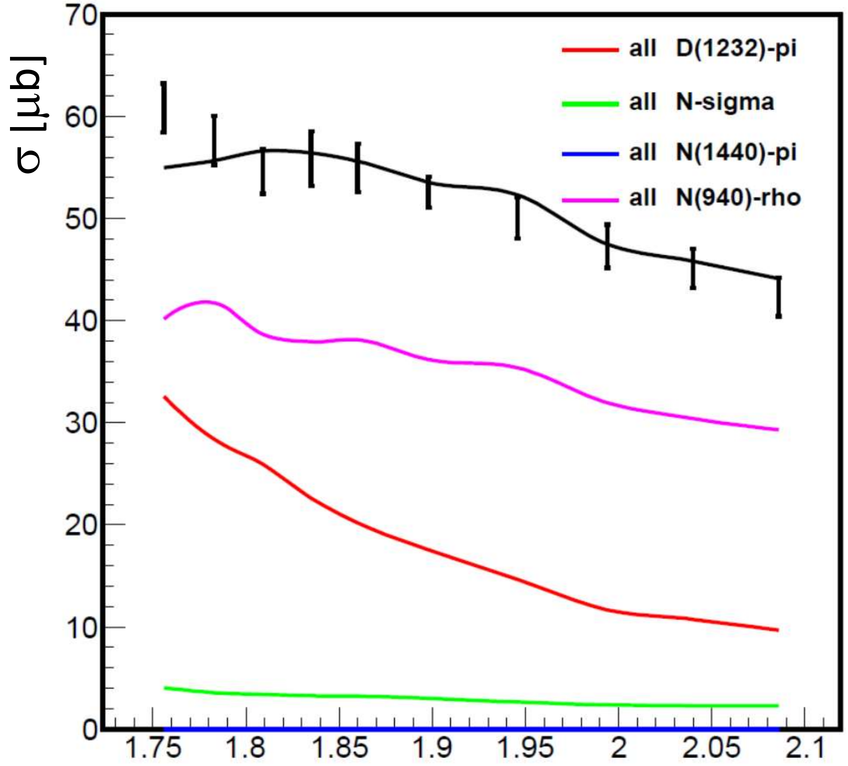
Total **ρN** : **2.3 mb** (for 685 MeV/c)

PWA results (n $\pi^+\pi^-$) – cross section



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

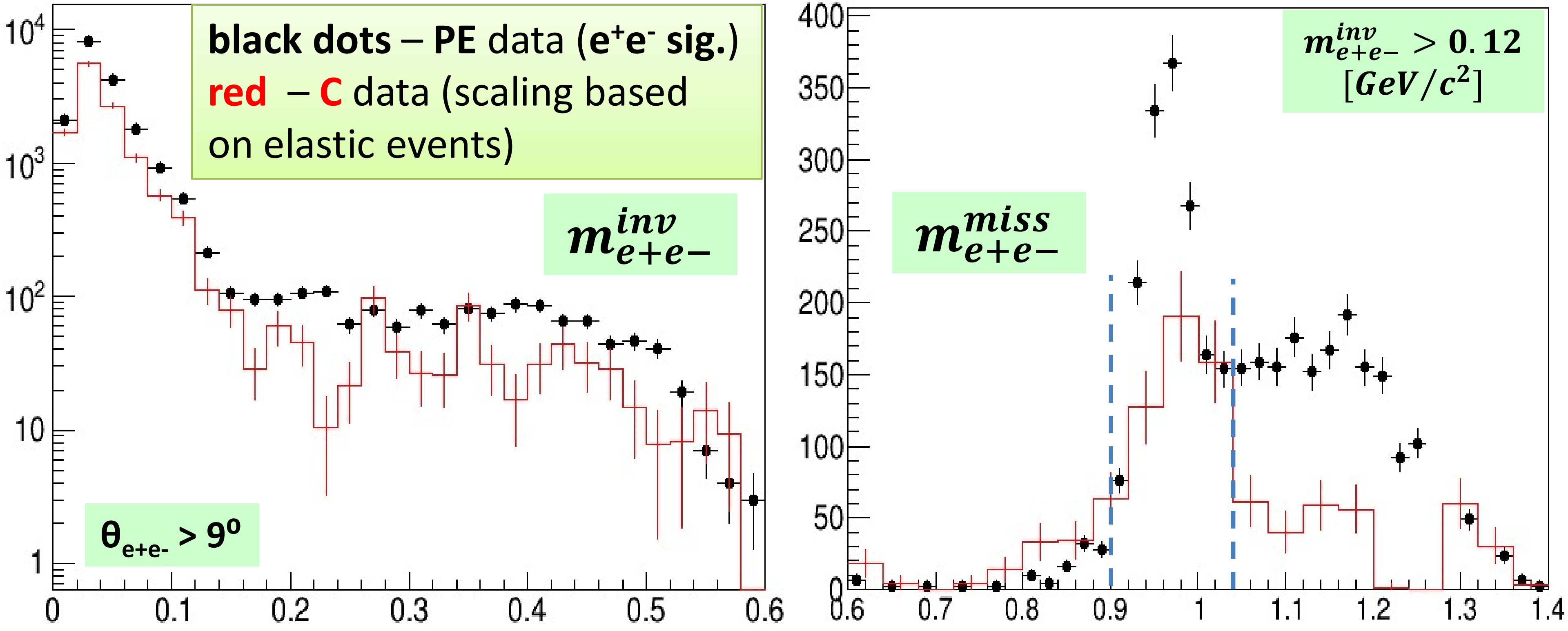
(SAPHIR, CLAS)



…mind the gap!

HADES data are really unique in this energy range!

e^+e^- inclusive – PE/C channels ratio



- statistics from carbon data too low for subtraction
- free + ”quasi-free” $\pi^- p \rightarrow e^+ e^- n$ events selected by miss. mass cut
- e^+e^- yield from proton to carbon ~ 1:2 (±20%)

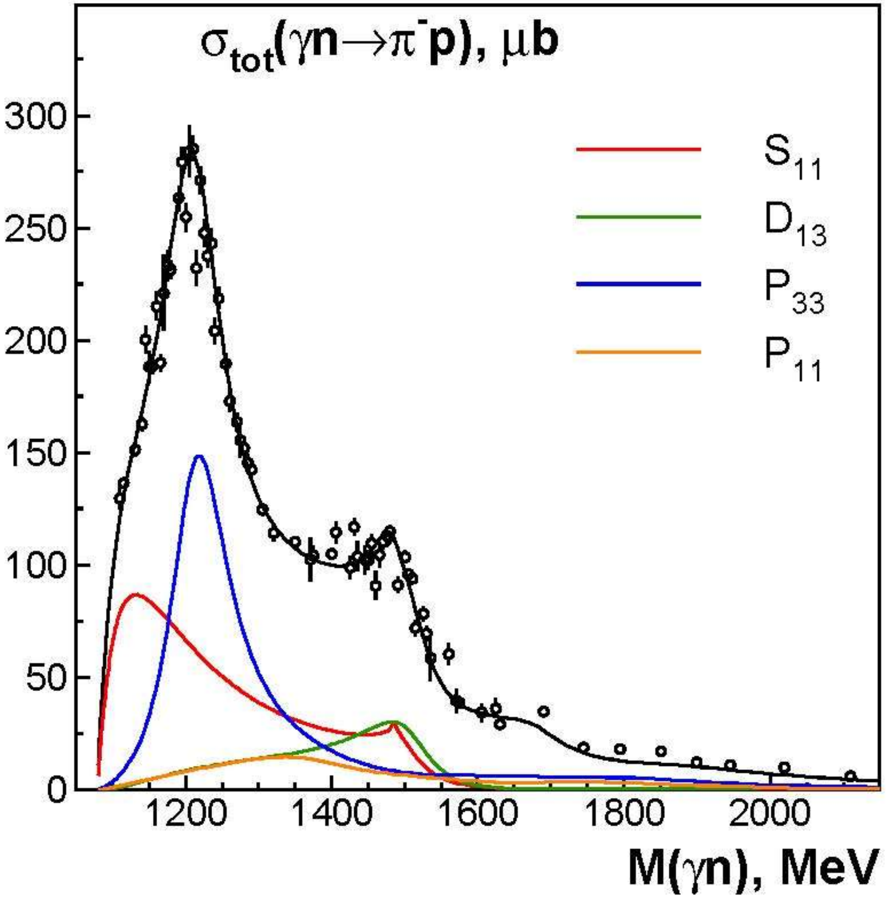
e^+e^- cocktail ingredients ”cookbook”

- **contributions from π^-p and π^-C added together (ratio 1 : 2** experimentally deduced**)**

π^-p mom. **0.69 GeV/c (√s=1.492 GeV)** **π^-C** average **√s=1.461 GeV (**mom. **0.65 GeV/c)**

channel	σ [mb]	data source	Model
π^0 *Dalitz* from: $\pi^- p \rightarrow n\pi^0$	**9.2**	Landolt-Börnstein constant (±1 mb) for 0.6 < p < 0.72 GeV/c	$N(1520) - 45\%$ $N(1440) - 45\%$ $N(1535) - 10\%$
single π^0 *Dalitz* from: $\pi^- p \rightarrow n\pi^0\pi^0$ $\pi^- p \rightarrow p\pi^-\pi^0$	2 x **1.8** **3.72** sum: **7.4**	Crystal Ball Landolt-Börnstein (for √s = 1.461 GeV 20% reduction)	$\Delta\pi^0 \rightarrow (N\pi)\pi^0$ $\rightarrow (N\pi)e^+e^-\gamma$
Δ *Dalitz* from: $\pi^- p \rightarrow \Delta\pi$	**8.4**	From single and double pion (isospin relations)	$\Delta^0\pi^0 \rightarrow ne^+e^-\pi^0$
N(1520) *Dalitz* from: $\pi^- p \rightarrow N(1520)$	**20.5**	Phys. Rev. C**86**, 065209 (2012)	Wolf / Zetenyi ”QED” model (pole) **BR = 4.0 · 10^{-5}** $N(1520) \rightarrow ne^+e^-$
η *Dalitz* from: $\pi^- p \rightarrow n\eta$	**0.3 (p)** **0.7 (C)**	Parameterization from Landolt-Börnstein (see next slide)	

Towards better cross sections



D_{13} is only part (50%) of the total cross section.

detailed balance theorem

(at equilibrium, each elementary process should be equilibrated by its reverse process)

$$|\boldsymbol{p}_1| = |\boldsymbol{p}_2|$$

$$= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

Real photon reactions decomposed:

N(1535)S_{11} + **t-channel** contribution
Δ(1232)P_{33}
N(1520)D_{13}
N(1440)P_{11}

Cross section estimation for reverse reaction: about × 2 times more „at real photon photon point” (no form factors here)
„virtual photon”: $\times \frac{1}{137}$

e^+e^- simulated (full analysis) cocktail

LEGEND

— total

— [9.2 mb] $\pi^0 \rightarrow e^+e^-\gamma$

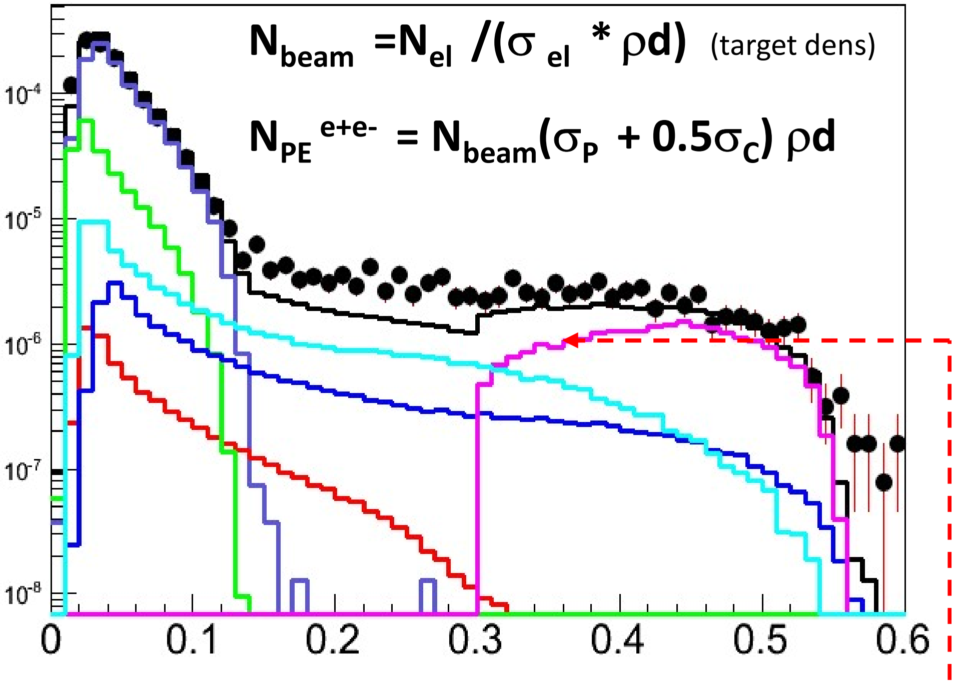
— [7.4 mb] $2{*}\pi^0(\rightarrow e^+e^-\gamma)$

— [1.0 mb] $\eta \rightarrow e^+e^-\gamma$

— [PWA: $D_{13} \times 2$]
$N(1520) \rightarrow n\, e^+e^-\ (QED)$

— [8.4 mb] $\Delta(1232) \rightarrow n\, e^+e^-\ (QED)$

CS need to be multiplied by BR



$N_{beam} = N_{el} / (\sigma_{el} * \rho d)$ (target dens)

$N_{PE}^{e+e-} = N_{beam}(\sigma_P + 0.5\sigma_C)\,\rho d$

Branching Ratios
π^0: 0.012, η: 0.006
$\mathbf{N(1520)}$: $4 \cdot 10^{-5}$, $\mathbf{\Delta(1232)}$: $4 \cdot 10^{-5}$

- **Large η contribution**
- **ρ(PWA) = 2.3 mb**
  VMD: $\sim 1/M^3 \rightarrow \times 4.6$

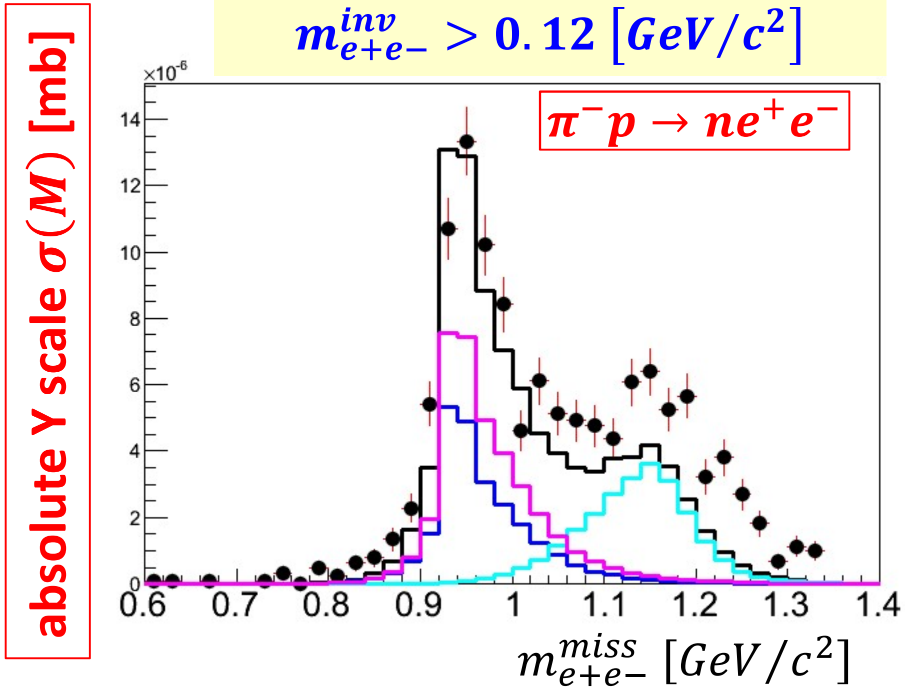
Dilepton cocktail

- **PLUTO event generator + full analysis**

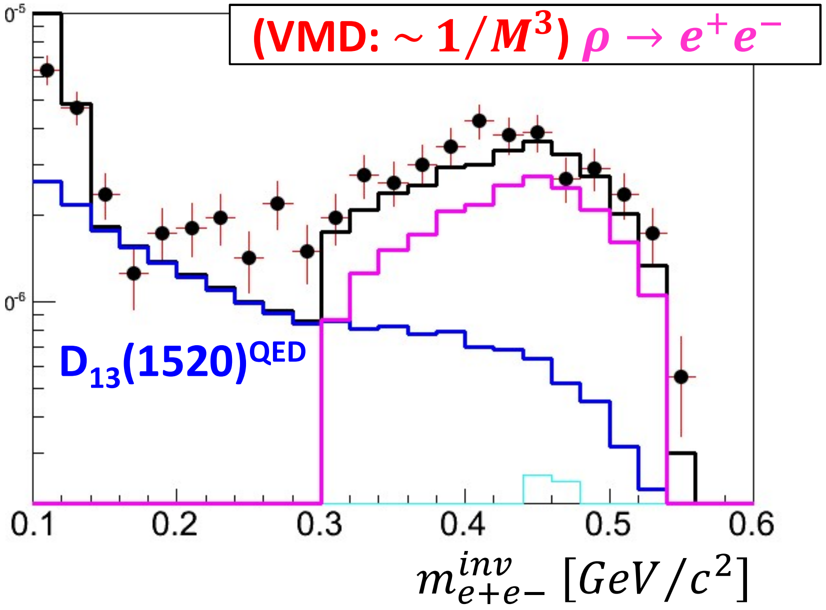
Ingo Fröhlich *et al.*
PoS ACTA2007 (2007) 076

Exclusive e^+e^- cocktail (PE target)

missing mass for
$m^{inv}_{e+e-} > 0.12\ [GeV/c^2]$



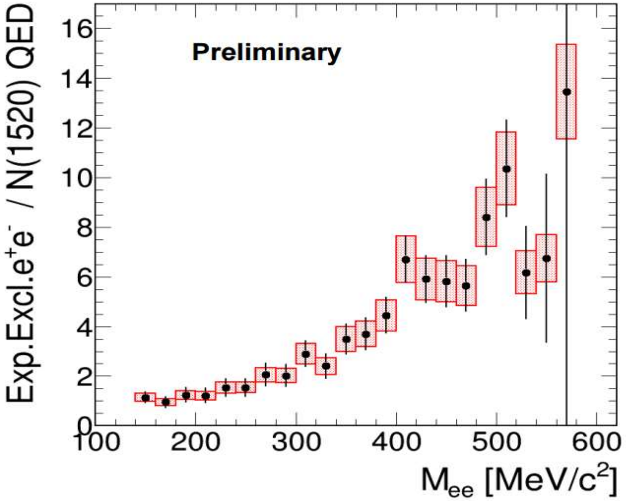
invariant mass for
$0.9 < m^{miss}_{e+e-} < 1.03\ [GeV/c^2]$



LEGEND
— total PE (p+C)
— N(1520) Dalitz
— η Dalitz
— Δ(1232) Dalitz
— ρ → e+e-

- **ρ cross sec. and mass shape derived from $\pi^- p \rightarrow n \pi^+ \pi^-$** empirical way of taking into account VDM form factors for electromagnetic decays

→ **excess consistent with $\rho \rightarrow e^+e^-$**



See: F. Scozzi talk (Friday, A4)

ρ/ω production from microscopic models

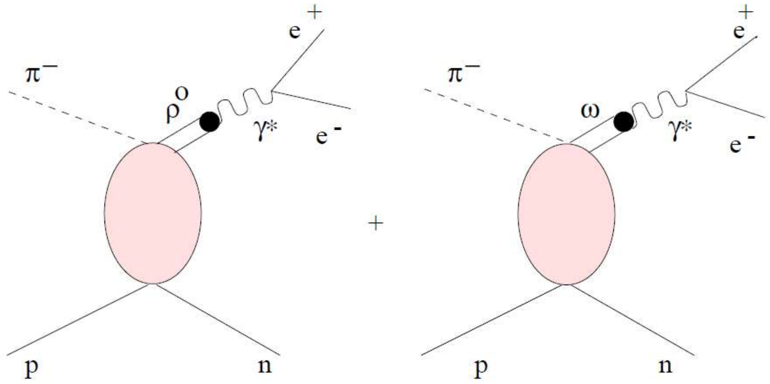
Relativistic unitary coupled-channel approach

M.F.M. Lutz, Gy. Wolf, B. Friman
Nucl. Phys. A **706** (2002) 431

$\pi N \rightarrow \rho^0 N$ (here $I = \frac{1}{2}, \frac{3}{2}$ and $J = \frac{1}{2}, \frac{3}{2}$)

$\pi N \rightarrow \omega N$ (here $I = \frac{1}{2}$ and $J = \frac{1}{2}, \frac{3}{2}$)

cross sections: amplitudes assuming VMD



investigated channels:

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

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

Effective Lagrangian
(vector meson-photon interaction terms)

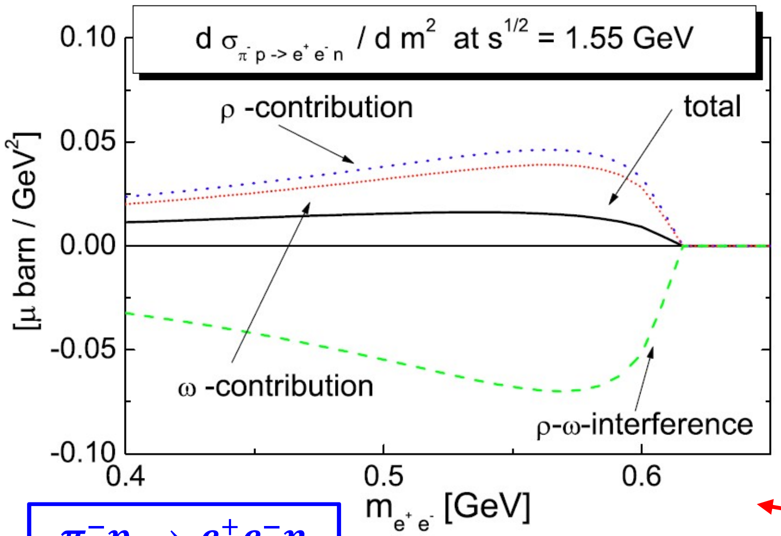
$$\mathcal{L}^{int}_{\gamma V} = \frac{f_\rho}{2M_\rho^2} F^{\mu\nu} \rho^0_{\mu\nu} + \frac{f_\omega}{2M_\omega^2} F^{\mu\nu} \omega_{\mu\nu}$$

- f_ρ, f_ω fixed by $\Gamma_{\rho/\omega \rightarrow e^+e^-}$
- relative sign fixed by the vector meson photoproduction amplitudes
- pion-nucleon resonances in S_{11}, S_{31}, D_{13} , D_{33} partial waves generated dynamically by solving Bethe-Salpeter eq.
- model valid below ρ/ω threshold tested for $1.4 < \sqrt{s} < 1.8$ GeV

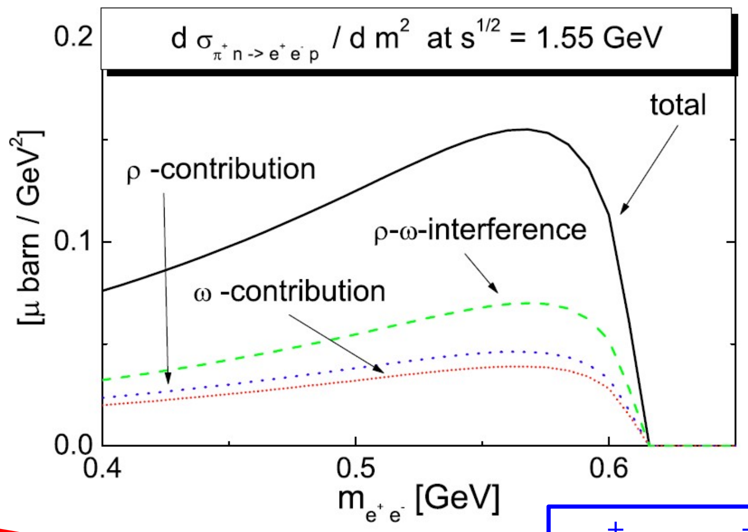
e^+e^- production from microscopic models

M.F.M. Lutz, B. Friman, M. Soyuer,Nucl. Phys. A **713** (2003) 97

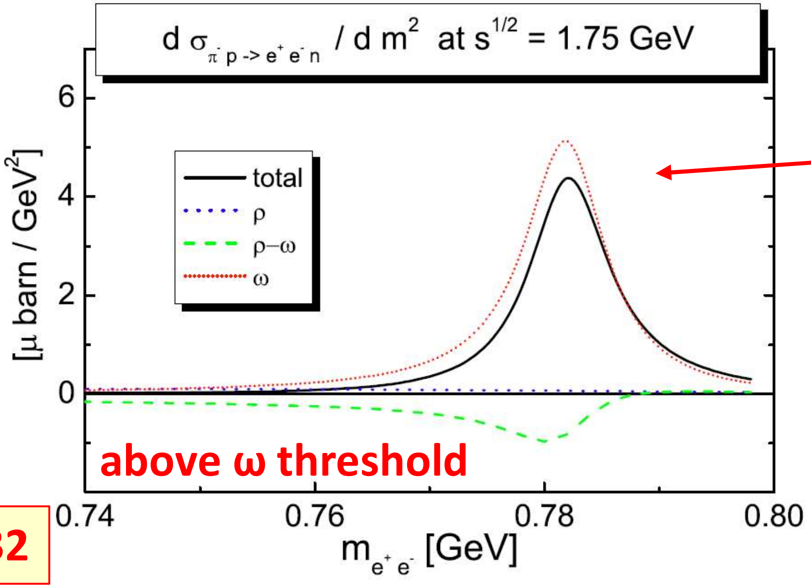
below ω threshold



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



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



above ω threshold

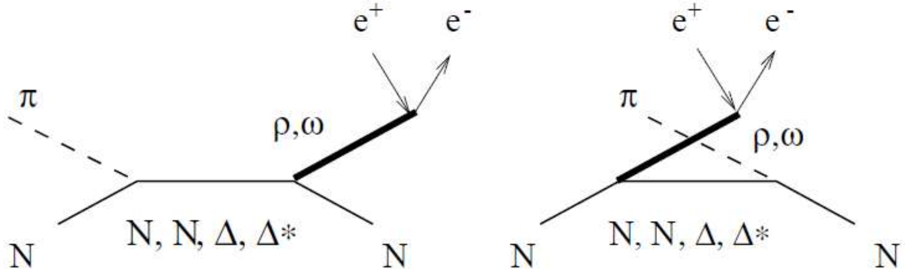
- below ω thr: huge **neg / pos interference effects!**
- above ω thr: inteference changes dramatically: two orders of magnitude! (dominated by ω)
- **$\rho N N^*$ couplings of resonances to vector meson-nucleon channel crucial !**

↓

- they are weaker than in Titov&Kämpfer model
  → despite interfer. **cross sections much larger**
  → **see**: **next slide**

e^+e^- production from microscopic models

Based on resonance model:



different quantum interference patterns:

$$T^{\pi^- p \rightarrow n e^+ e^-} \propto T^{\text{scalar}} + T^{\text{vector}}$$

$$T^{\pi^+ n \rightarrow p e^+ e^-} \propto T^{\text{scalar}} - T^{\text{vector}}$$

- valid just below ρ/ω threshold

- domiated by ***s*–** and ***u*–** channel nucleon and baryon resonance exchange
- included baryon resonances with masses ≤ 1.72 GeV (N, N^*, Δ)

Baryon	M_{B^*}	$f_{\pi N B^*}$	$g_{\omega N B^*}$	$g_{\rho N B^*}$	$\Gamma^0_{B^*}$	$B^\pi_{B^*}$
$N\frac{1}{2}^+ N$	940	1.0	10.35	3.0	–	–
$N\frac{1}{2}^+ P_{11}$	1440	0.39	6.34	1.78	350	0.65
$N\frac{3}{2}^- D_{13}$	1520	−1.56	8.88	5.0	120	0.55
$N\frac{1}{2}^- S_{11}$	1535	0.36	−5.12	−2.9	150	0.45
$N\frac{1}{2}^- S_{11}$	1650	0.31	2.56	−0.72	150	0.73
$N\frac{5}{2}^- D_{15}$	1675	0.10	10.87	−3.1	150	0.45
$N\frac{5}{2}^+ F_{15}$	1680	−0.42	−14.07	−19.8	130	0.65
$N\frac{3}{2}^- D_{13}$	1700	0.36	2.81	−0.45	100	0.10
$N\frac{3}{2}^+ P_{13}$	1720	−0.25	−3.17	−4.46	150	0.15
$\Delta\frac{3}{2}^+ P_{33}$	1232	2.21	–	17.32	120	0.99
$\Delta\frac{3}{2}^+ P_{33}$	1600	0.52	–	17.1	350	0.18
$\Delta\frac{1}{2}^- S_{31}$	1620	−0.17	–	0.88	150	0.25
$\Delta\frac{3}{2}^- D_{33}$	1700	1.32	–	1.53	300	0.15

A. Titov, B. Kämpfer
Eur. Phys. J A **12** (2001) 217

B. Kämpfer, A. Titov, R. Reznik
Nucl. Phys. A **721** (2003) 583

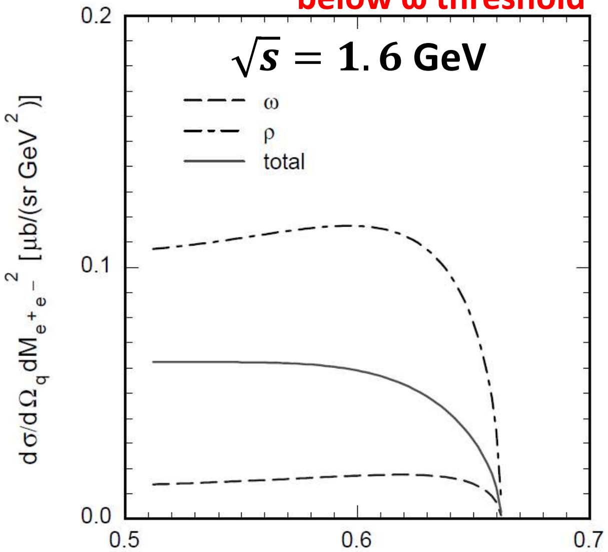
transition coupling constants
from a chiral quark model:

D. O. Riska, G. E. Brown
Nucl. Phys. A **679** (2001) 577

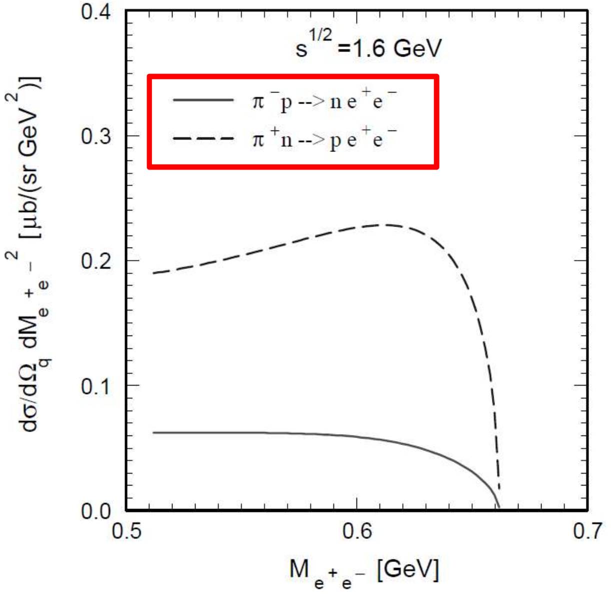
further attempt: deduction of $\boldsymbol{\rho N B^*}$ from $\Gamma_{B^* \rightarrow N\rho}$ has a **dramatic impact** on CS and angular projections!

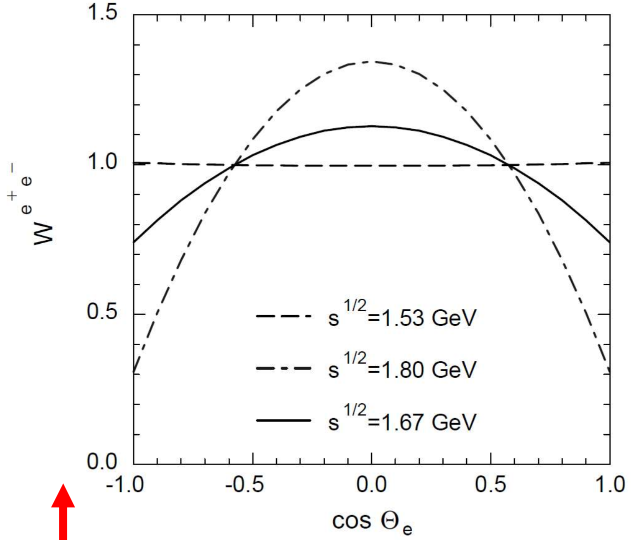
e^+e^- production from microscopic models

below ω threshold

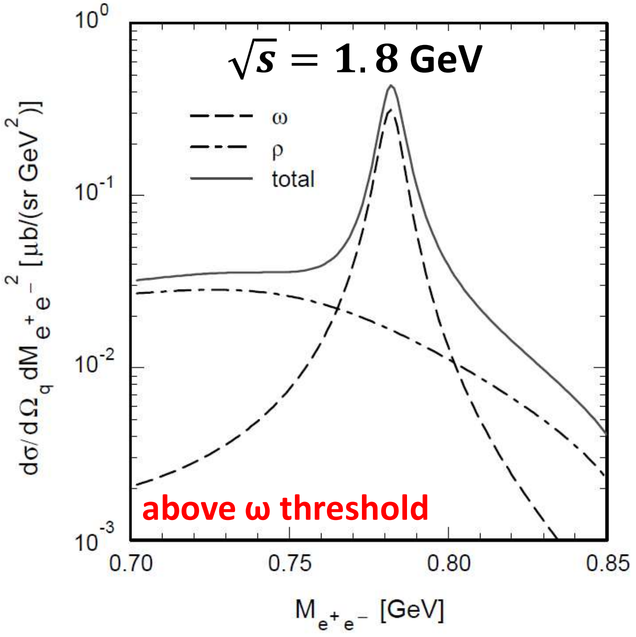


$\pi^- p \rightarrow e^+e^- n$





different ρNB^* = **different** angular projections!

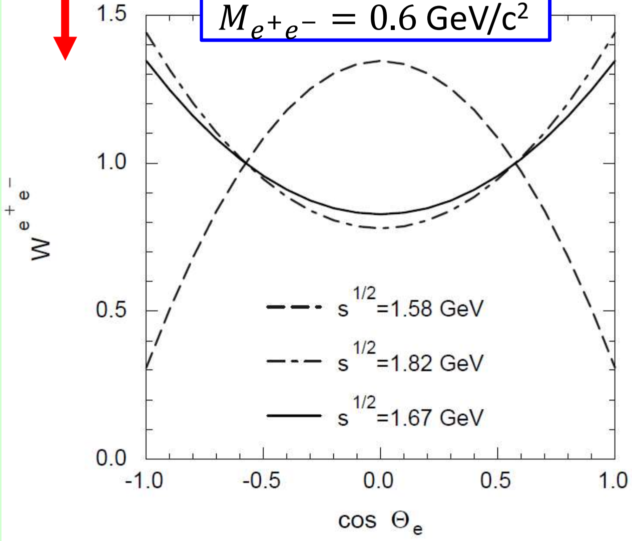


above ω threshold

decomposition into subequent resonacnce contributions available

MODELS: very large differences in e^+e^- yield up to factor 10!

$M_{e^+e^-} = 0.6$ GeV/c²

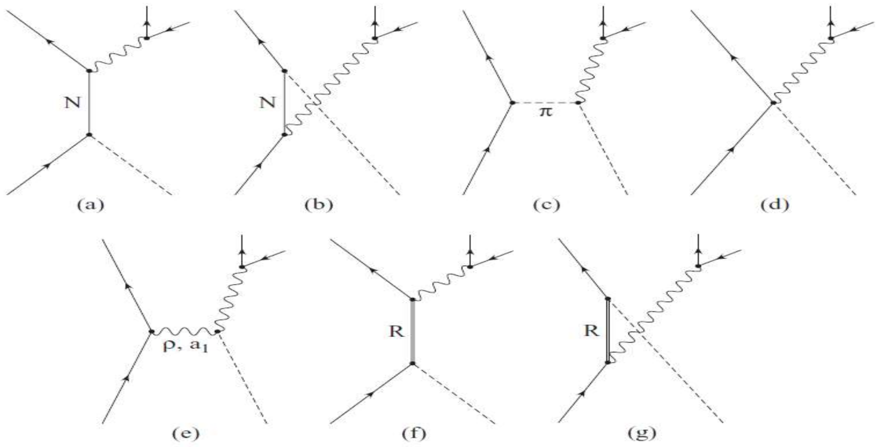


Dilepton production in pion-nucleon collisions in an effective field theory approach

$\boldsymbol{\pi + N \rightarrow N + e^{+} + e^{-}}$

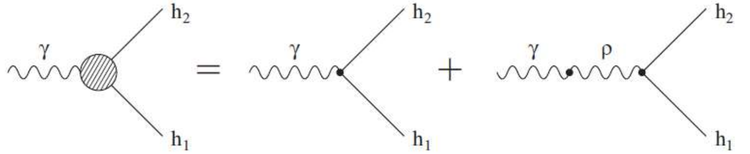
Miklós Zétényi* and György Wolf†

Phys. Rev. C **86** (2012) 065209

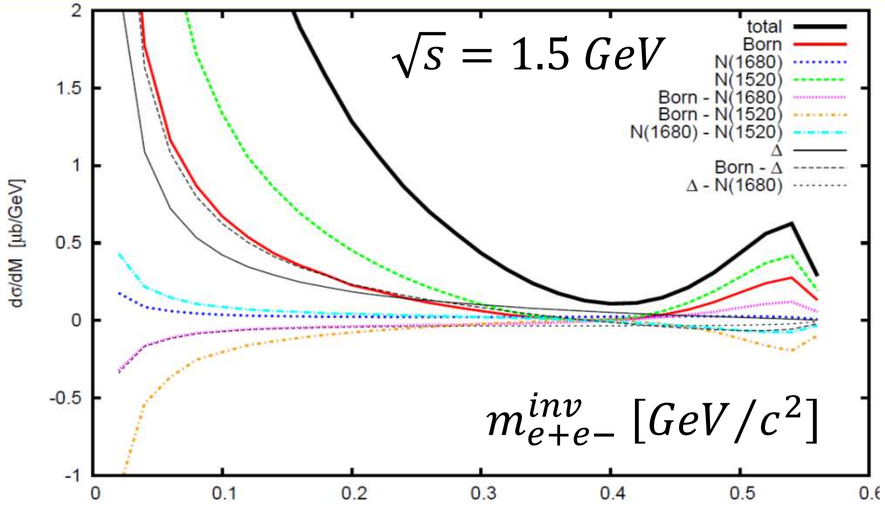


a) s- **b)** u- **c)** t-channel diagrams **d)** contact interaction
e) vector meson exchange diagram
f) s- **g)** u-channel baryon resonance contributions

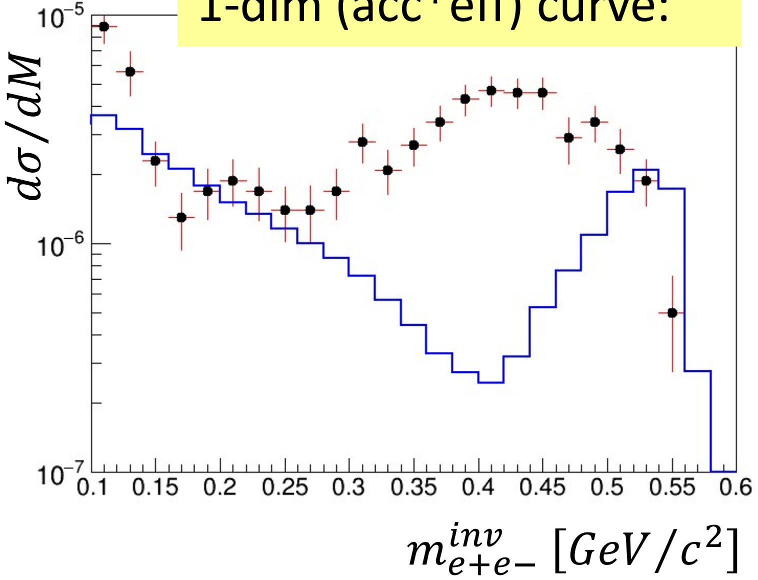
Lagrangian model: real γ+VMD coupling



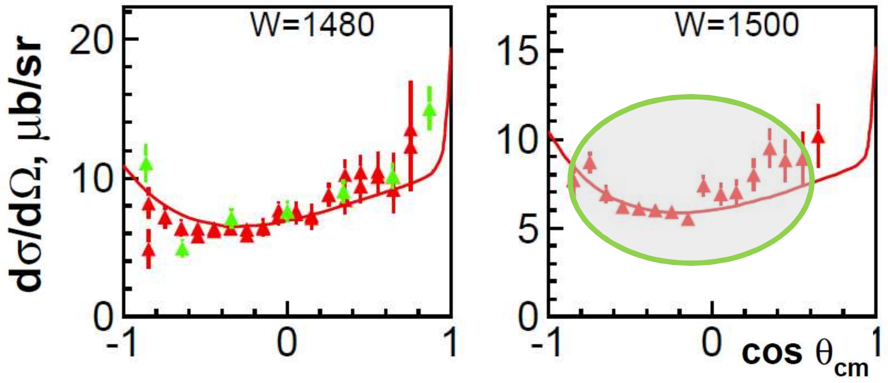
Z & W: higher $\sqrt{s} = 1.5\ GeV\ (\boldsymbol{\pi^{-}p})$
HADES: $\sqrt{s} = 1.492\ GeV\,(\boldsymbol{\pi^{-}p})$
and $\sqrt{s} = 1.461\ GeV\,(\boldsymbol{\pi^{-}C})$



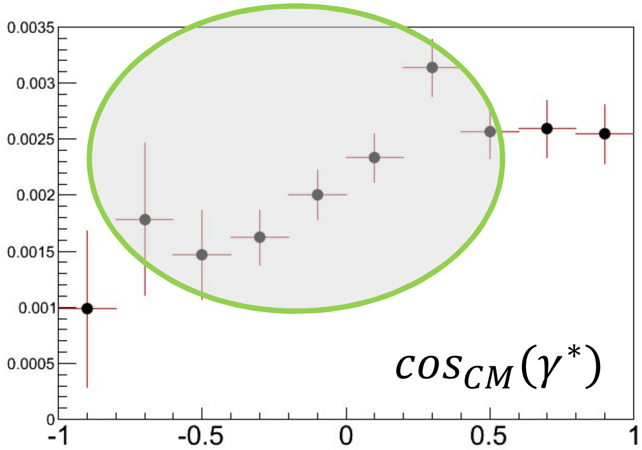
Folding the model with
1-dim (acc*eff) curve:



Exclusive e^+e^- - more observables



$\gamma n \rightarrow p\pi^-$ (for **real** photon, no FF)

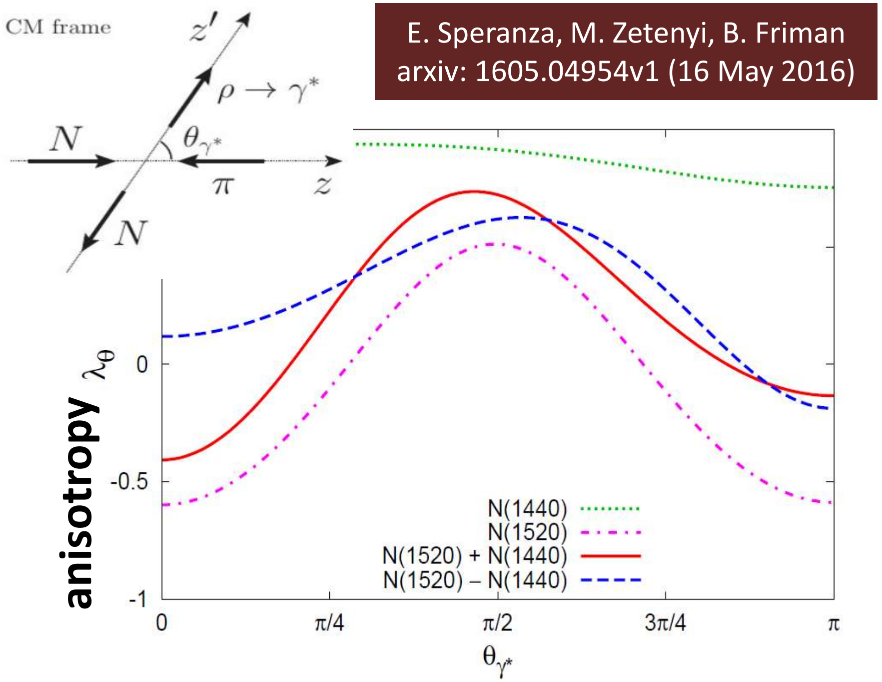


(for **virtual** photon, FF plays a role)

For: $m_{e+e-}^{inv} > 0.12\ [GeV/c^2]$

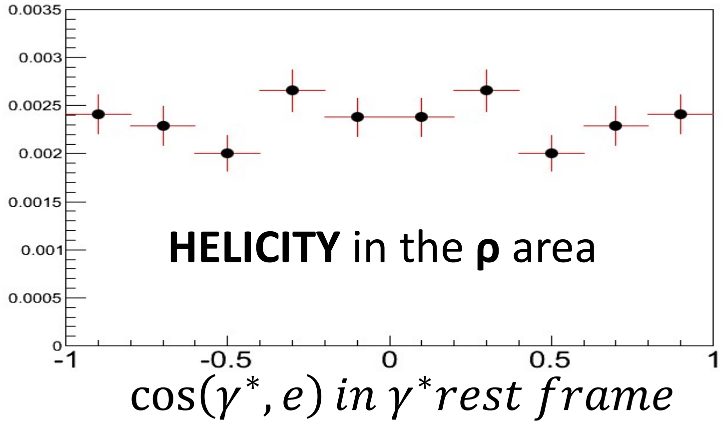
$0.9 < m_{e+e-}^{miss} < 1.03\ [GeV/c^2]$

E. Speranza, M. Zetenyi, B. Friman
arxiv: 1605.04954v1 (16 May 2016)



sensitivity to intereferences between amplitudes from different contribution

very preliminary



SUMMARY

- HADES & **pion beam** is an unique tool
  to understand in details baryon - ρ couplings
- Significant off-shell ρ contribution originating from $N(1520)D_{13}$ shown by combined PWA and e^+e^- data

Future activity (now and 2018+):

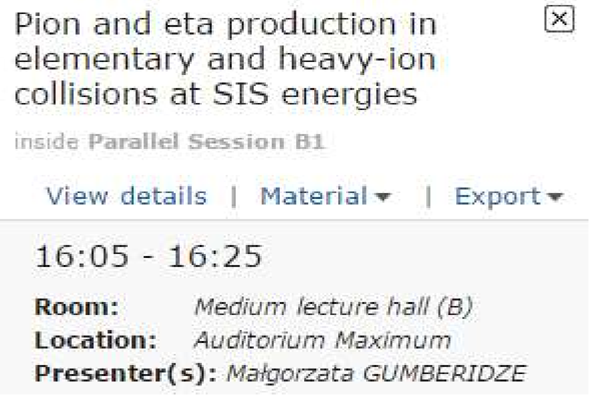
- Joint venture of **PWA analysis (Bo-Ga) and dilepton channels**
- **High statistics beam energy scan**:

  continuation and extension to third resonance region
- Hadronic final states, one-pion, two-pion, hyperon production to control resonance excitation
- HADES upgrade: **electromagnetic calorimeter** - neutral final states: η / π / ω
- Di-electron measurements : ρR couplings $S_{13}(1620)$, $D_{33}(1700)$, $P_{13}(1720)$

The HADES Collaboration

Special thanks to **Andrey V. Sarantsev** (Bonn-Gatchina group)

More HADES talks / poster:

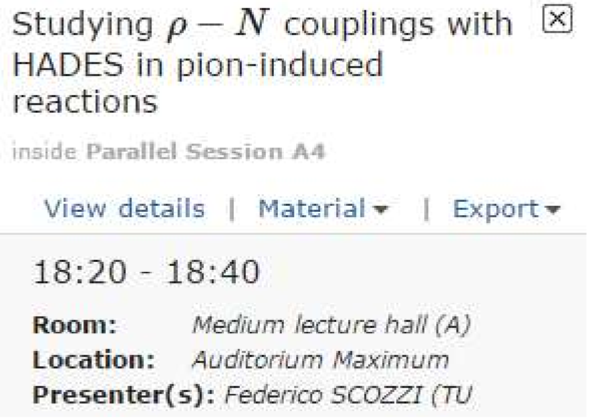


Pion and eta production in elementary and heavy-ion collisions at SIS energies

inside **Parallel Session B1**

16:05 - 16:25

Room: *Medium lecture hall (B)*
Location: *Auditorium Maximum*
Presenter(s): *Małgorzata GUMBERIDZE*

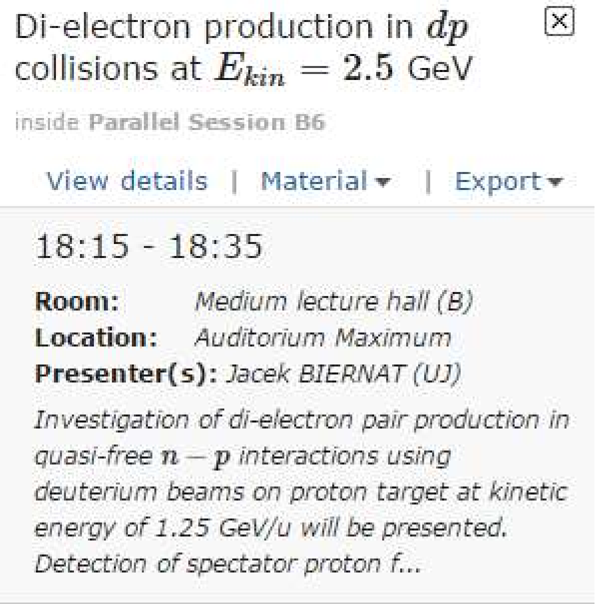


Studying $\rho - N$ couplings with HADES in pion-induced reactions

inside **Parallel Session A4**

18:20 - 18:40

Room: *Medium lecture hall (A)*
Location: *Auditorium Maximum*
Presenter(s): *Federico SCOZZI (TU*



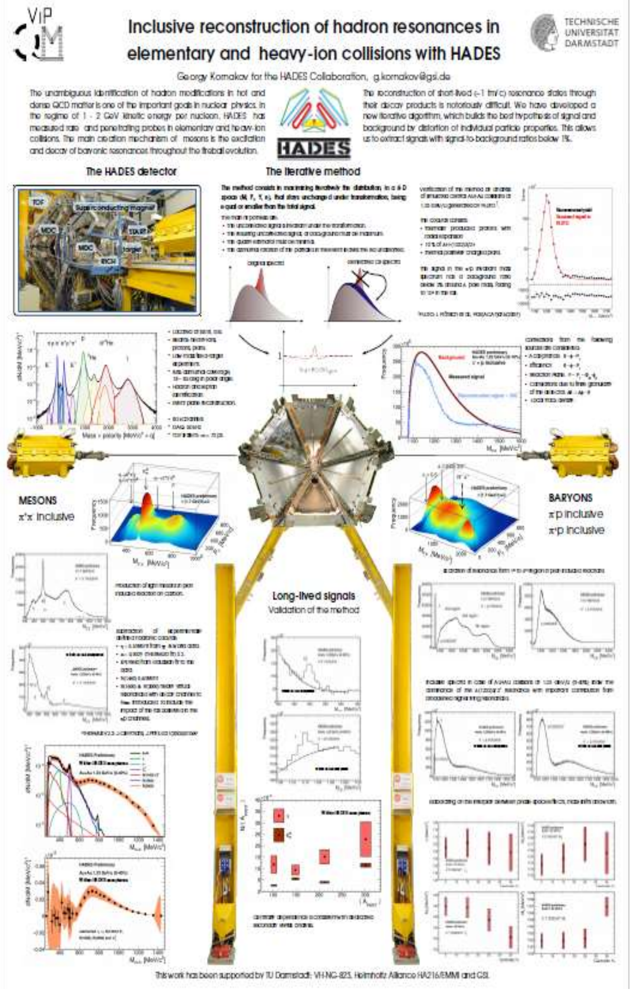
Di-electron production in dp collisions at $E_{kin} = 2.5$ GeV

inside **Parallel Session B6**

18:15 - 18:35

Room: *Medium lecture hall (B)*
Location: *Auditorium Maximum*
Presenter(s): *Jacek BIERNAT (UJ)*

Investigation of di-electron pair production in quasi-free $n - p$ interactions using deuterium beams on proton target at kinetic energy of 1.25 GeV/u will be presented. Detection of spectator proton f...



Inclusive reconstruction of hadron resonances in elementary and heavy-ion collisions with HADES

Georgy Kornakov for the HADES Collaboration, g.kornakov@gsi.de

The unambiguous identification of hadron modifications in hot and dense QCD matter is one of the important goals in nuclear physics. In the regime of 1 - 2 GeV kinetic energy per nucleon, HADES has measured rare and penetrating probes in elementary and heavy-ion collisions. The main creation mechanism of mesons is the excitation and decay of baryonic resonances throughout the fireball evolution.

The reconstruction of short-lived (~1 fm/c) resonance states through their decay products is notoriously difficult. We have developed a new iterative algorithm, which builds the best hypothesis of signal and background by distortion of individual particle properties. This allows us to extract signals with signal-to-background ratios below 1%.

The HADES detector

The iterative method

MESONS

BARYONS

Long-lived signals

Validation of the method

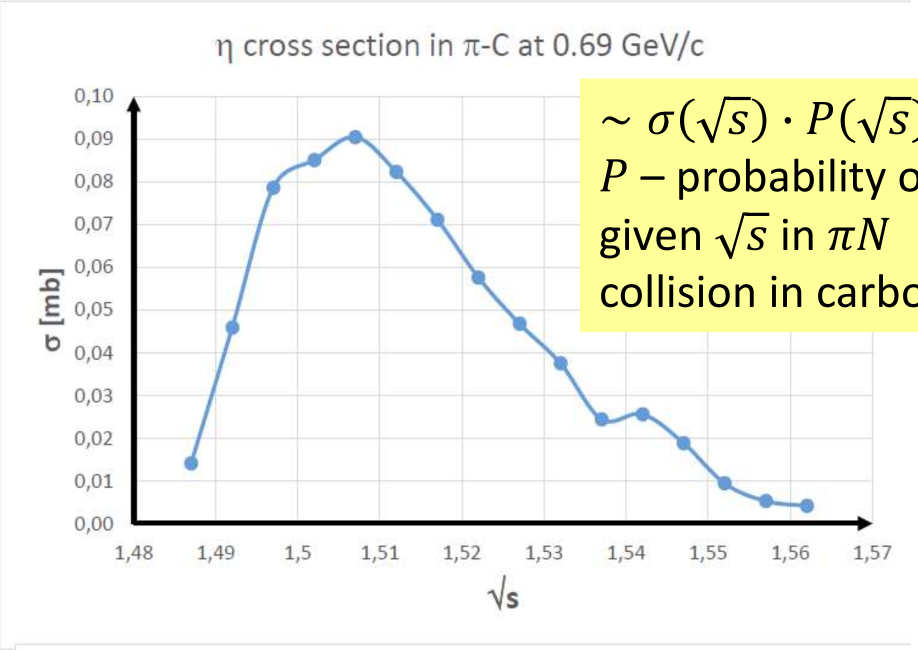
This work has been supported by TU Darmstadt, VH-NG-823, Helmholtz Alliance HA216/EMMI and GSI.

BACKUP

η contribution (mainly from C)

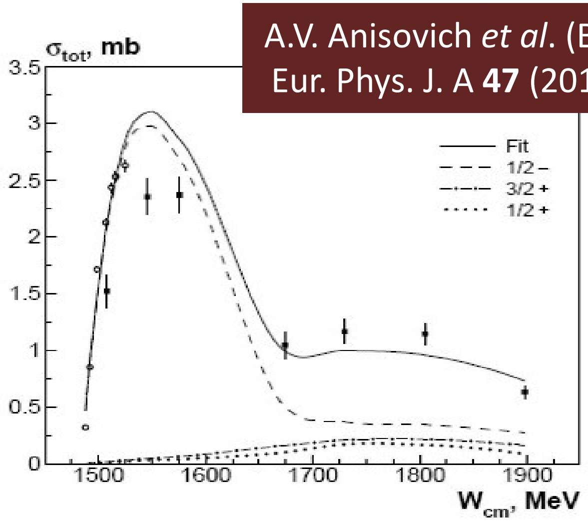
Landolt-Börnstein

bin	sqrt(s)	p(sqrt(s))	XS_eta	product
98	1,487	4,70E-02	0,3	0,0141
99	1,492	5,10E-02	0,9	0,0459
100	1,497	4,47E-02	1,76	0,078672
101	1,502	3,87E-02	2,2	0,08514
102	1,507	3,74E-02	2,42	0,090508
103	1,512	3,05E-02	2,7	0,08235
104	1,517	2,48E-02	2,87	0,071176
105	1,522	1,96E-02	2,94	0,057624
106	1,527	1,56E-02	3	0,0468
107	1,532	1,21E-02	3,1	0,03751
108	1,537	7,88E-03	3,1	0,024428
109	1,542	8,00E-03	3,2	0,0256
110	1,547	5,88E-03	3,2	0,018816
111	1,552	2,94E-03	3,2	0,009408
112	1,557	1,64E-03	3,2	0,005248
113	1,562	1,29E-03	3,2	0,004128
			SUM	0,697408



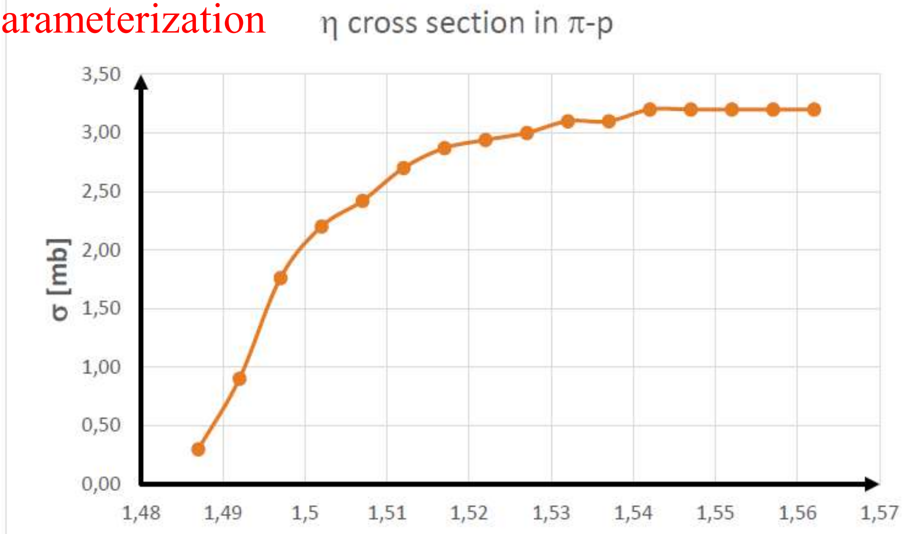
$\sim \sigma(\sqrt{s}) \cdot P(\sqrt{s})$

P – probability of given $\sqrt{s}$ in πN collision in carbon



A.V. Anisovich *et al.* (Bn-Ga)
Eur. Phys. J. A **47** (2011) 27

parameterization



ρ contribution (off-shell)

- **contribution from $\pi^+\pi^-$ channel (PWA analysis): cross section 1.54 mb**
  - **VDM predicts scaling $\sim 1/M^3$ resulting in much higher BR as compared to the value at pole**

Line #1

mass	rho_XS	VDM (1/m3)	product
3,04E-01	4,19E-03	15,61366255	6,55E-02
3,14E-01	1,05E-02	14,20091609	1,49E-01
3,26E-01	1,68E-02	12,66505858	2,12E-01
3,37E-01	2,10E-02	11,50844232	2,41E-01
3,48E-01	2,52E-02	10,41514376	2,62E-01
3,59E-01	3,14E-02	9,455788455	2,97E-01
3,68E-01	3,14E-02	8,842060636	2,78E-01
3,81E-01	3,77E-02	7,96530894	3,01E-01
3,90E-01	4,19E-02	7,382426161	3,10E-01
4,01E-01	5,03E-02	6,813086495	3,43E-01
4,11E-01	5,56E-02	6,301052508	3,50E-01
4,24E-01	6,18E-02	5,73892679	3,55E-01
4,34E-01	6,60E-02	5,360496552	3,54E-01
4,46E-01	8,07E-02	4,959360928	4,00E-01
4,57E-01	9,01E-02	4,597528169	4,14E-01
4,67E-01	1,01E-01	4,314782768	4,34E-01
4,78E-01	1,07E-01	4,013707862	4,29E-01
4,90E-01	1,15E-01	3,739926802	4,31E-01
5,00E-01	1,16E-01	3,50778875	4,08E-01
5,12E-01	1,19E-01	3,278724205	3,92E-01
5,21E-01	1,22E-01	3,098015318	3,77E-01
5,33E-01	1,22E-01	2,903650904	3,53E-01
5,43E-01	1,07E-01	2,73782466	2,93E-01
5,54E-01	9,75E-02	2,584269529	2,52E-01
5,66E-01	7,23E-02	2,42132848	1,75E-01
5,77E-01	2,94E-02	2,281757596	6,70E-02
5,89E-01	7,34E-03	2,152336802	1,58E-02
SUM	**1,74E+00**		**7,96E+00**

Landolt-Börnstein

$$|\mathcal{M}(\pi^+\pi^- \to \rho^0 \to e^+e^-)|^2 = \frac{m_\rho^2 \Gamma_{\pi^+\pi^-} \Gamma_{e^+e^-}}{(s - m_\rho^2)^2 + m_\rho^2 \Gamma_\rho^2}$$

$$\Gamma_{e^+e^-} = bk/M^3_{e^+e^-}$$

even 4 times more