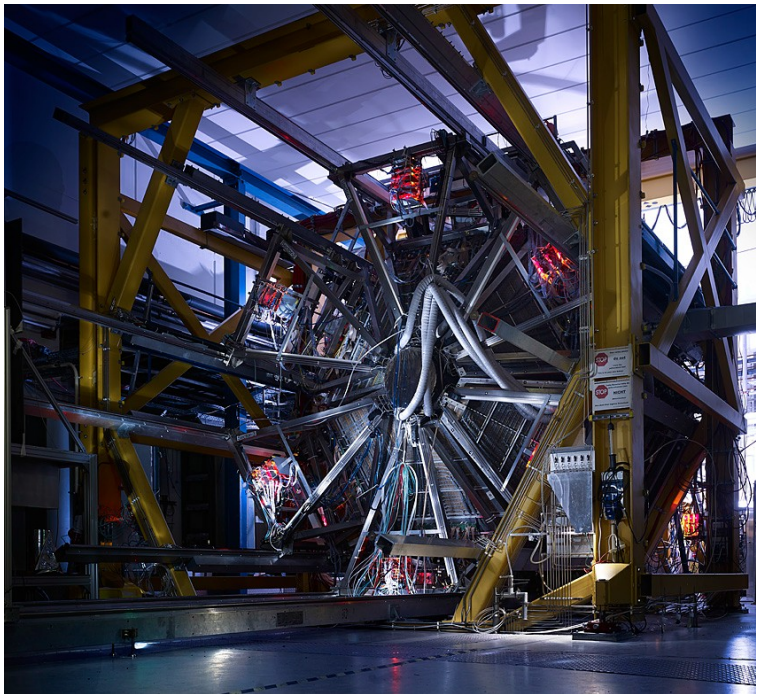
Studies of Two-Pion Production and Time-like Structure of Baryons in Pion-Induced Reactions

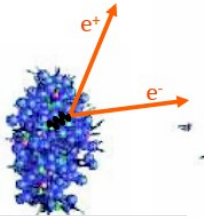


Outline:

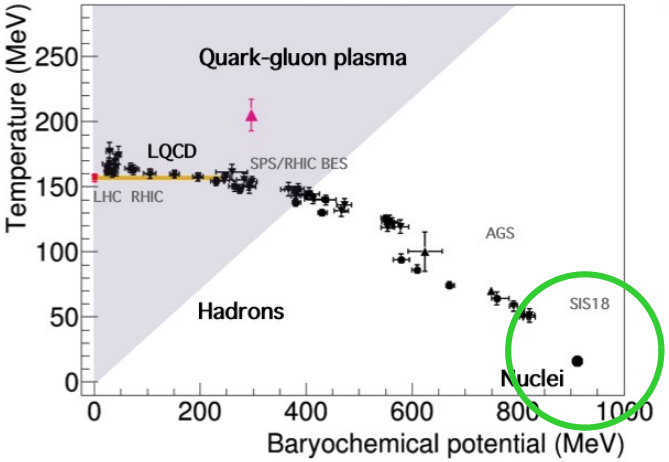
1) Motivations for experiments with pion beams,
2) HADES detector and pion beam @ GSI,
3) Results of PWA (BGa) for two pion channels,
4) Results for time-like em. transion of baryons in pion beam experiment,
5) Summary and outlook.

Izabela Ciepał, IFJ PAN Kraków
for the HADES Collaboration

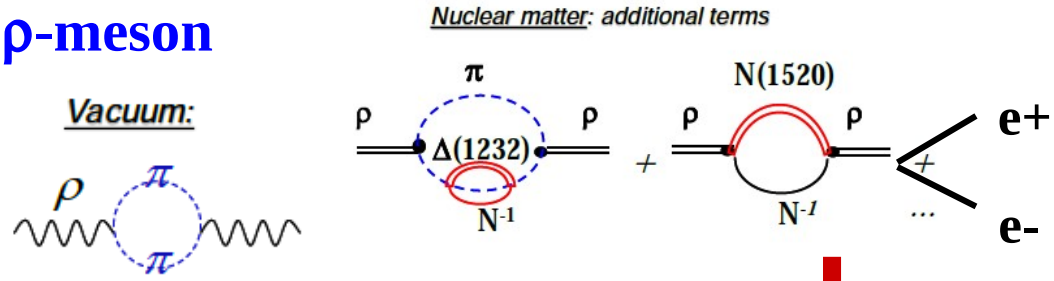
Motivations
HI & elementary collisions

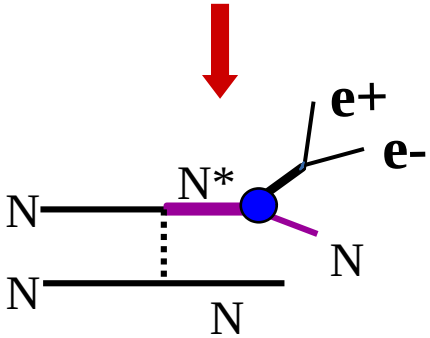


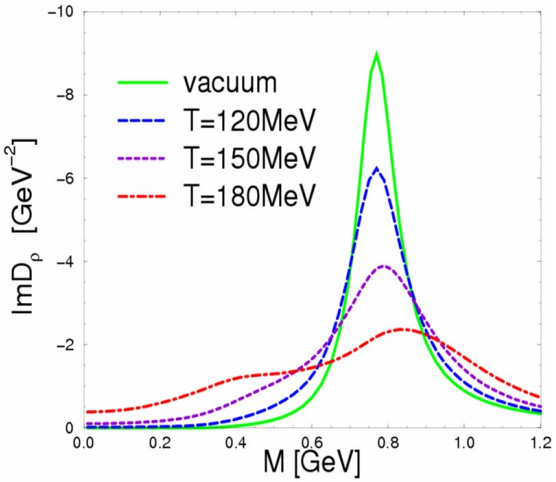
- ➔ hadron properties in hot and dense nuclear matter
- ➔ hadron electromagnetic structure
- ➔ role of vector mesons



ρ-meson







P. Hohler, R. Rapp, Phys. Lett. B 731 (2014) 103

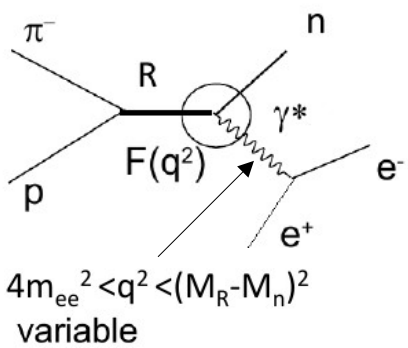
dominat role
of baryonic resonances

- ➔ **in-medium ρ broadening**
- ➔ **chiral symmetry restoration**

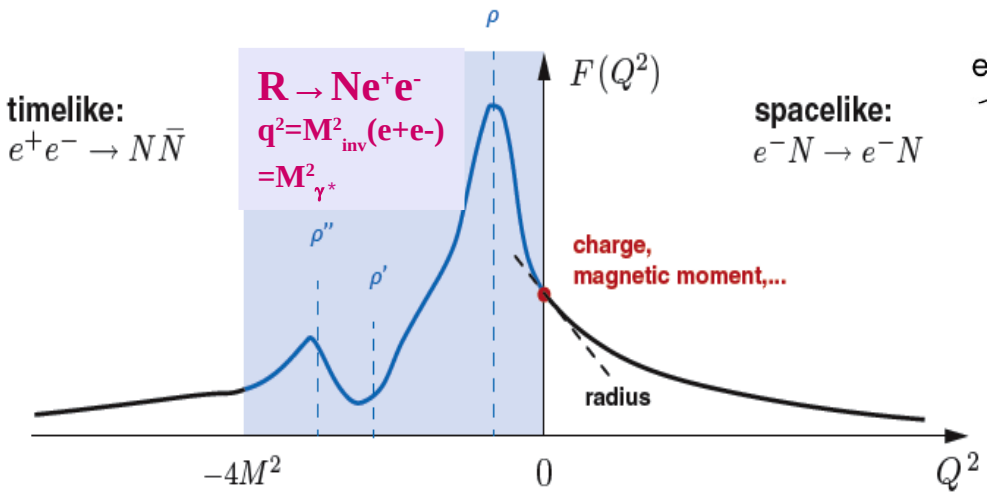
$\rho(760)/a_1(1260)$ become degenerate at $T \sim T_c$, $\mu_b = 0$

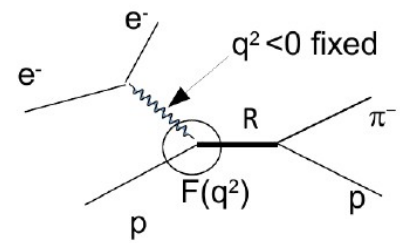
in-medium **spectral function** depends on **ρNN* coupling** (N(1520), Δ(1720), N(1910), ….) studied in **NN, πN collisions** via $N^*(\Delta) \rightarrow N e^+e^-$ Dalitz decays

Electromagnetic structure of baryons



no data available

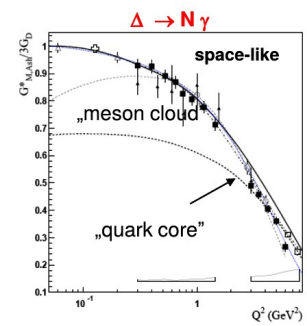




CLAS/Jlab, MAMI, ELSA, JLab-Hall A, ...

Dalitz decays - em. transition Form-Factor

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

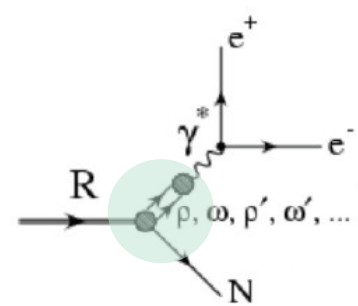


I. G. Aznauryan and V. D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)

Dalitz decays, appearance of intermediate vector mesons
ρ/ω/ϕ $J^{PC} = 1^{--}$ (= γ !)

QED
transition of point-like particles

Form-Factors
internal structure of hadrons
(various models)



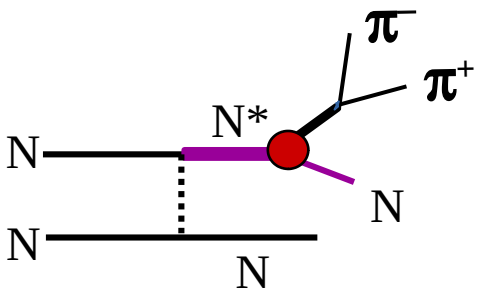
Vector Meson Dominance Model

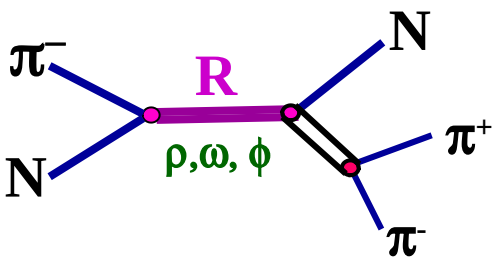
HADES Physics Program with Pion Beams

from I. Strakovsky

→ **selectivity:** resonances can be excited at given mass in s-channel by choosing the beam (pion) momentum, HADES starts with $\sqrt{s}$ = (1.46-1.55) GeV

→ 2nd resonance region,





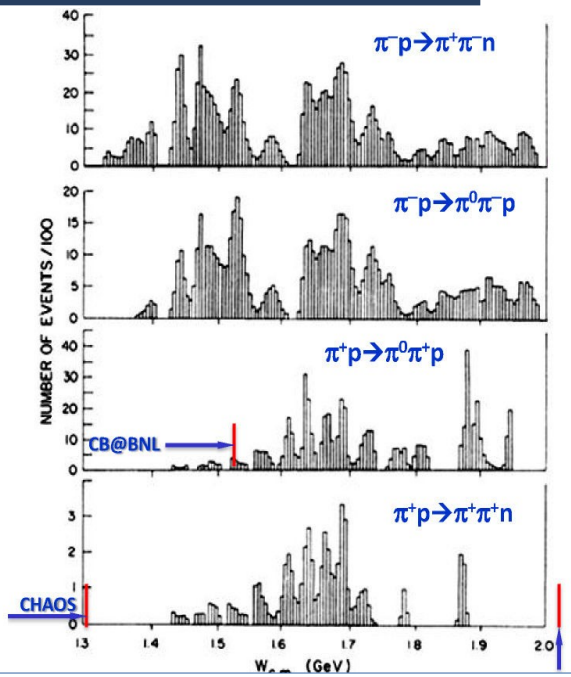
→ **$\pi^+\pi^-$, $\pi^+\pi^0$ production:** off-shell coupling of ρ to resonance, ρ → ππ (~100%) „golden channel",

→ **BR** of resonances in the ρN decay,

→ two-pion production channels,

→ **dilepton channel** R → N e+e-, never measured in pion induced reactions,

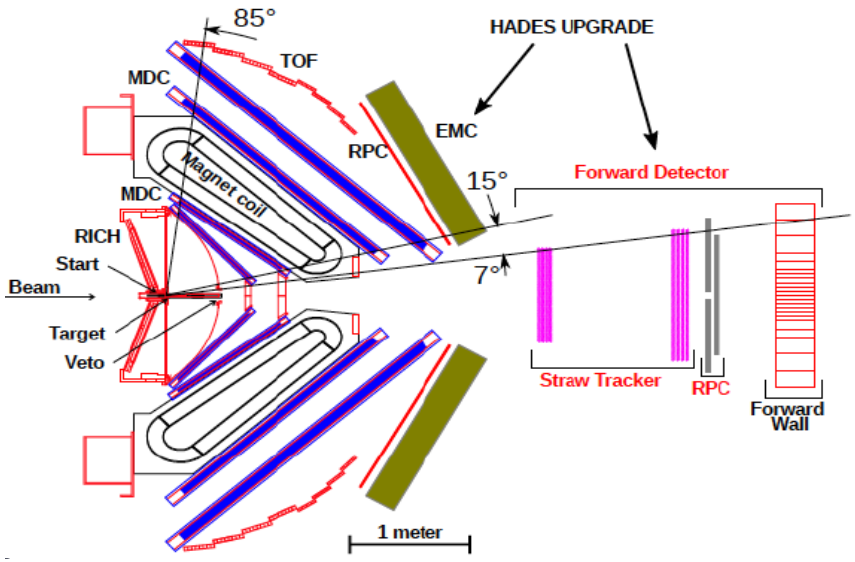
→ **very scarce data** base for pion-nucleon reactions.



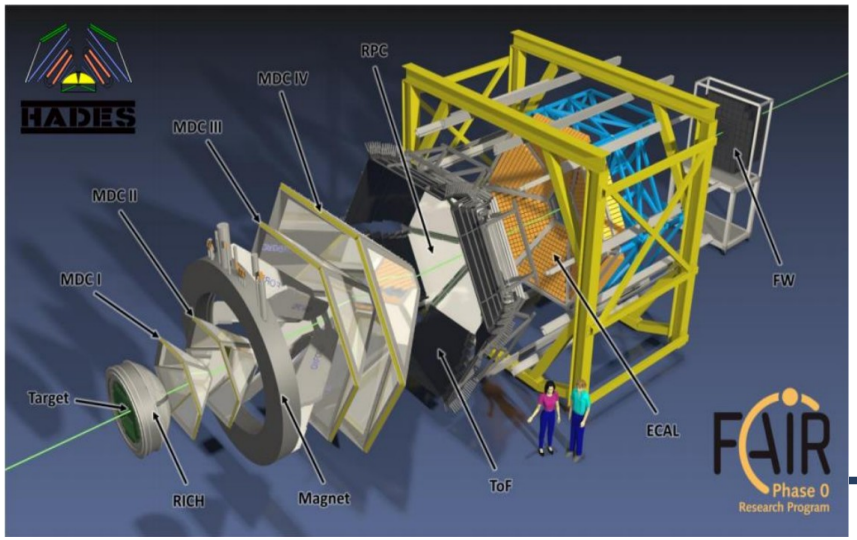
Manley *et. al* PRD30 (1984) 904, 241214 bubble chamber events analysed in isobar PWA model

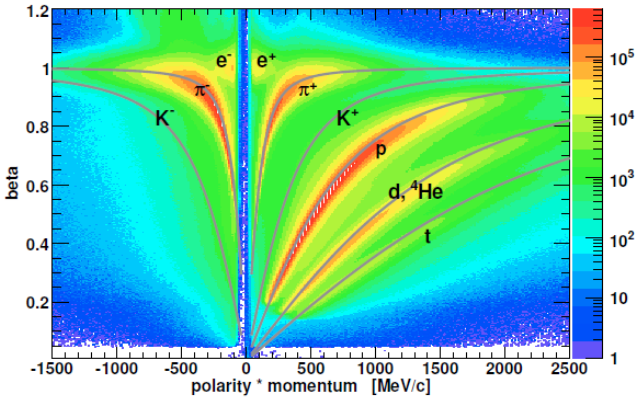
- Recent **post-Bubble Chamber** measurements:
  - **349,611** events for $\pi^-p\to\pi^0\pi^0n$ from **CB@BNL** at W = **1213** to **1527** MeV. [S. Prakhov *et al* Phys Rev C **69**, 045202 (2004)]
  - **20,000** events for $\pi^{+-}p\to\pi^{+-}\pi^{-+}n$ from TRIUMF **CHAOS@TRIUMF** at W = **1257**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

HADES Spectrometer



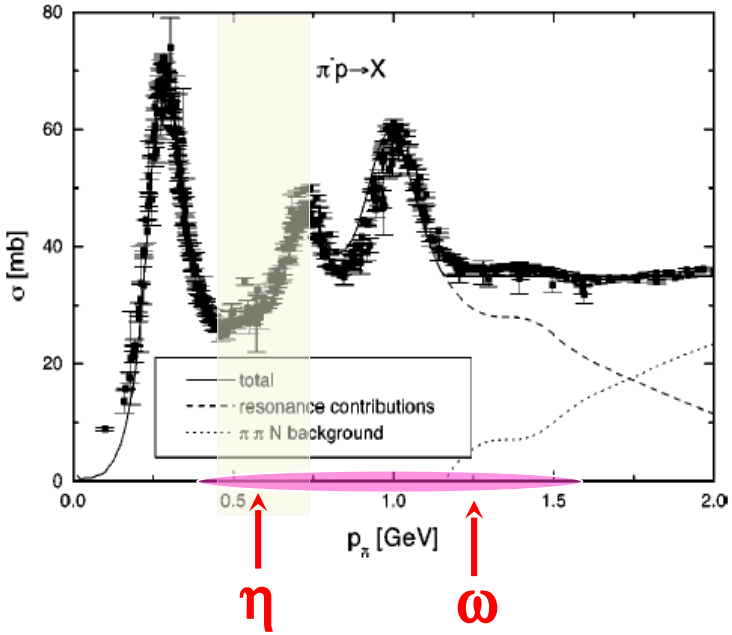
- ✓ SIS18 beams: protons (1-4.5GeV), nuclei (1-2AGeV), pions (0.4-2 GeV) secondary beam
- ✓ Spectrometer with $\Delta M/M \sim 2\%$ at ρ/ω
- ✓ PID (π/p/K): ToF (TOF/RPC, T0 detector), tracking (dE/dx)
- ✓ momenta, angles: MDC+ magnetic field
- ✓ electrons: RICH
- ✓ neutral particles: ECAL
- ✓ full azimuthal, polar angles 18° – 85°
- ✓ e+e- pair acceptance ~0.35



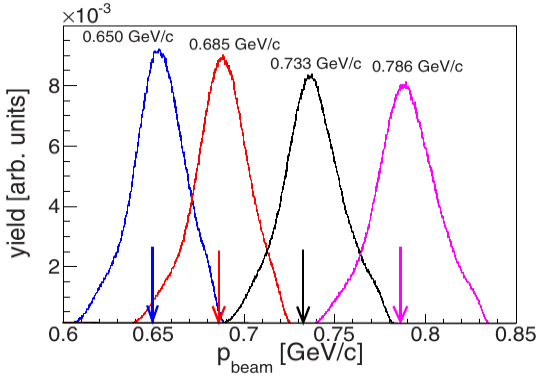


Pion Beam @ GSI

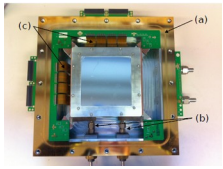
Eur. Phys. J. A 53, 188 (2017)

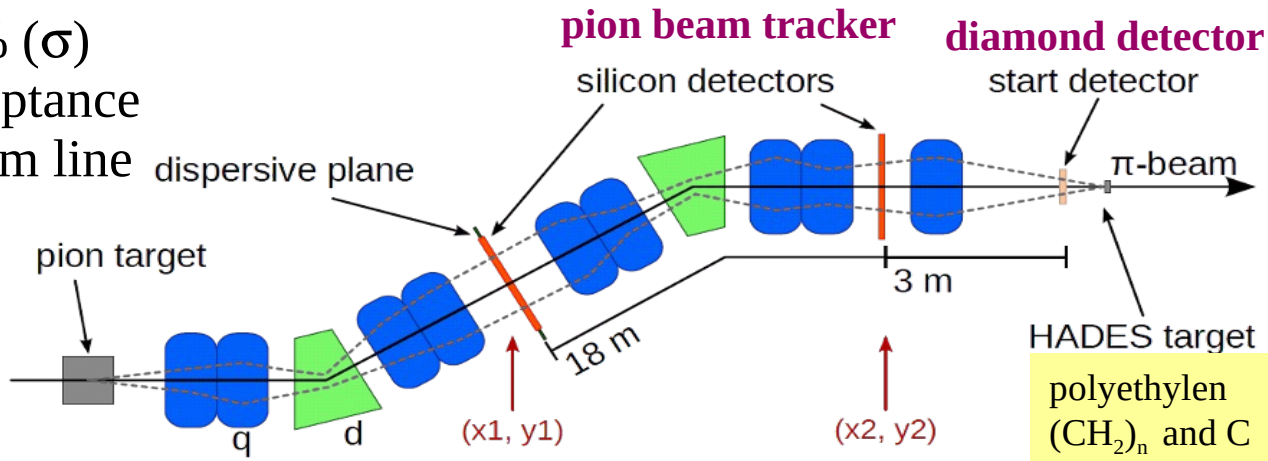


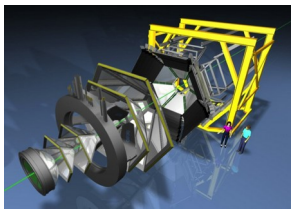
- reaction **N+Be**, 8-10*10^{10} N_2 ions/spill (4s)
- Secondary **π^-** with **I ~ 2-3 10^5/s**
- **p = 654, 686, 748, 787 (+/- 1) MeV/c**
- **PE $(CH_2)_n$** and **C** targets



- pion momentum $\Delta p/p$ =2.2% (σ)
- ~50% acceptance of pion beam line







polyethylen $(CH_2)_n$ and C

Bonn-Gatchina PWA

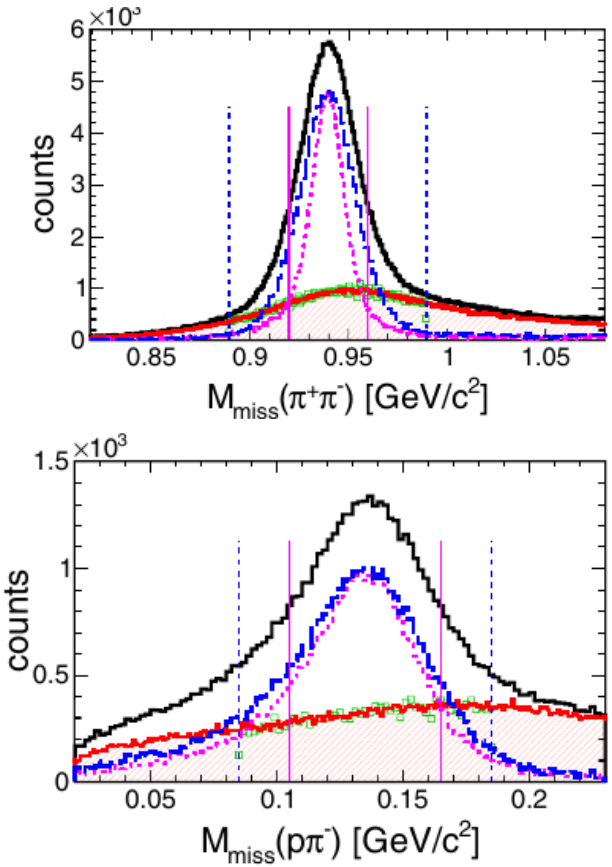
A. Sarantsev

exclusive analysis of 2π channels

2π data included in the fit

Reaction	Observable	W (GeV)	
$\gamma p \to \pi^0\pi^0 p$	DCS, Tot	1.2-1.9	MAMI
$\gamma p \to \pi^0\pi^0 p$	E	1.2-1.9	MAMI
$\gamma p \to \pi^0\pi^0 p$	DCS,Tot	1.4-2.38	CB-ELSA
$\gamma p \to \pi^0\pi^0 p$	P, H	1.45-1.65	CB-ELSA
$\gamma p \to \pi^0\pi^0 p$	T, P_x, P_y	1.45-2.28	CB-ELSA
$\gamma p \to \pi^0\pi^0 p$	P_x, P_x^c, P_x^s (4D)	1.45-1.8	CB-ELSA
$\gamma p \to \pi^0\pi^0 p$	P_y, P_y^c, P_y^s (4D)	1.45-1.8	CB-ELSA
$\gamma p \to \pi^+\pi^- p$	DCS	1.7-2.3	CLAS
$\gamma p \to \pi^+\pi^- p$	I^c, I^s	1.74-2.08	CLAS
$\pi^- p \to \pi^0\pi^0 n$	DCS	1.29-1.55	Crystal Ball
$\pi^- p \to \pi^+\pi^- n$	DCS	1.45-1.55	HADES
$\pi^- p \to \pi^0\pi^- p$	DCS	1.45-1.55	HADES

unique data set

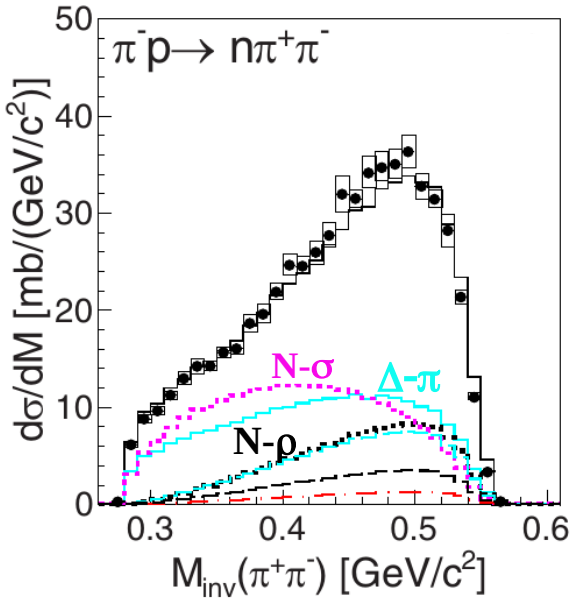


2π production in $\pi^- p \to n\pi^+\pi^-/p\pi^-\pi^0$

Bonn-Gatchina PWA

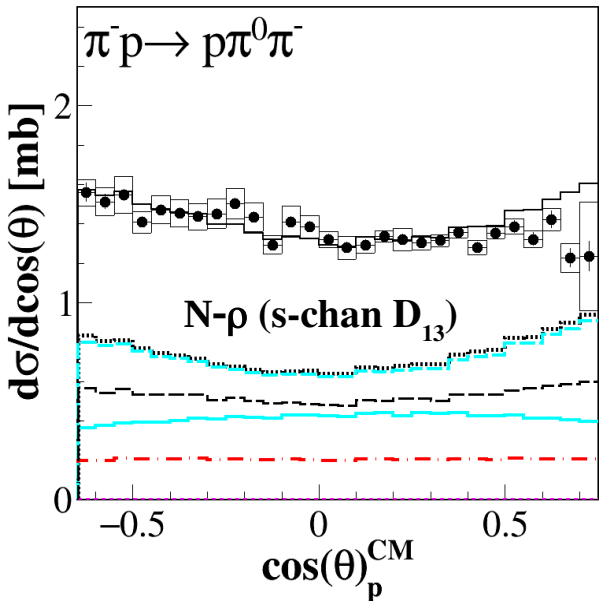
HADES: Phys. Rev. C 102, 024001, (2020)

inv. mass

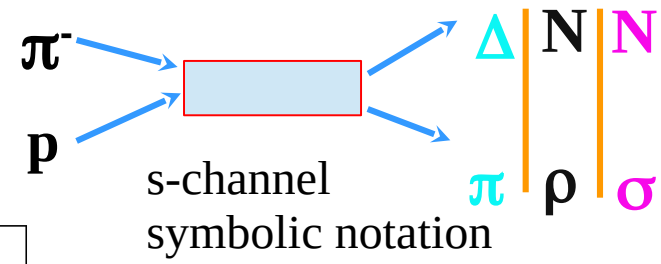


- Δ-π, N-σ dominat
- significant **N-ρ**, dominated by s-channels and N* (mainly D13)

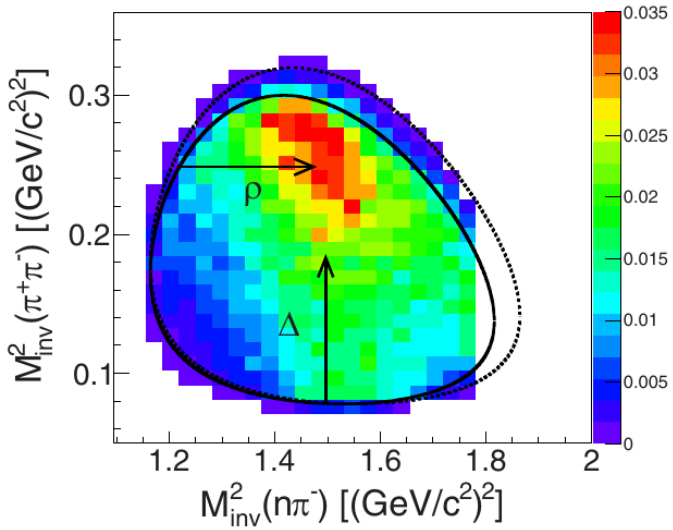
$\cos\theta^{CM}_{p(\pi^-\pi^0)}$



- Δ-π smaller,
- **N-ρ** dominat (s-chan. D_{13})
- no N-σ



s-channel symbolic notation



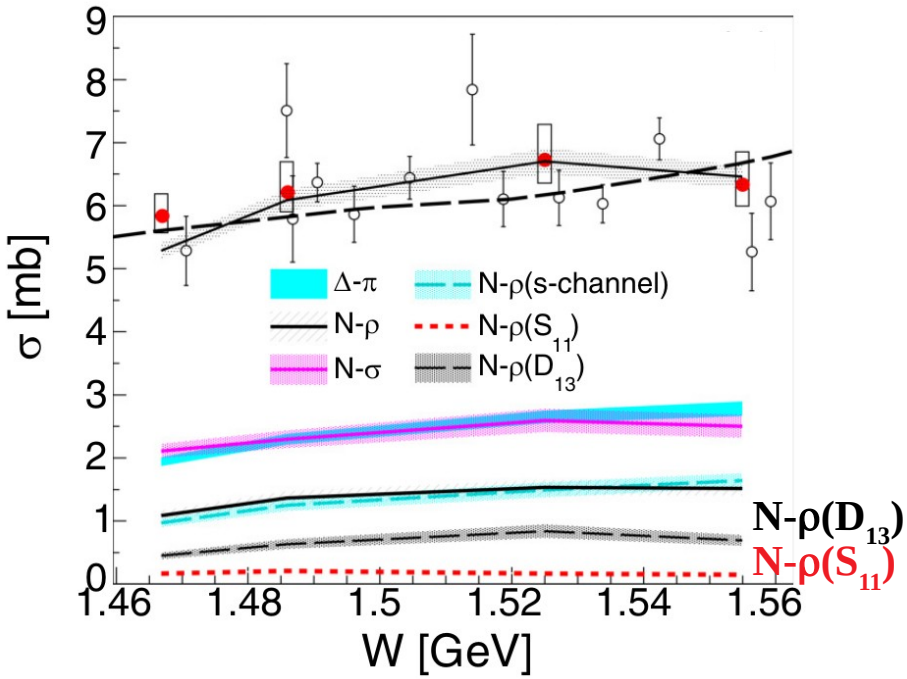
Δ–π N-ρ N-σ N-ρ s-channel N-ρ S_{11} N-ρ D_{13}

2π production in $\pi^- p \rightarrow n\pi^+\pi^-/p\pi^-\pi^0$

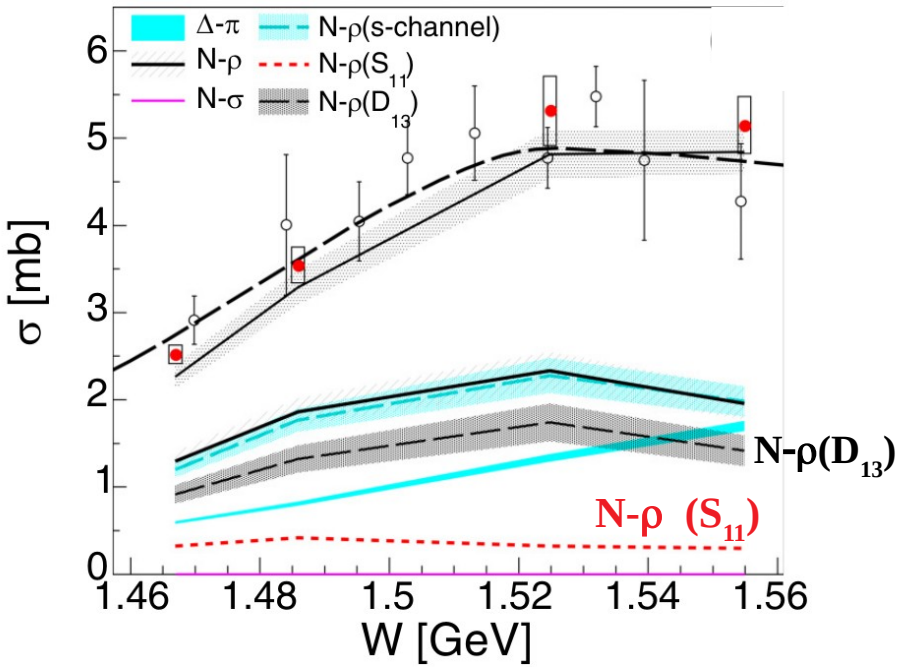
total cross sections

HADES: Phys. Rev. C 102, 024001, (2020)

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



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



- ➔ D_{13} (N*(1520)) dominant contribution in ρ production
- ➔ D_{13} (1520) coupling to ρN: 12+/-2 %

crucial for e+e- analysis

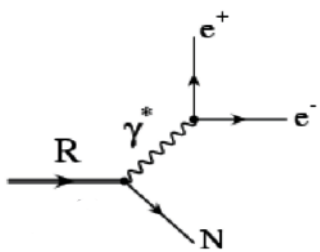
8 new entries

branching ratios of N(1440), N(1535), N(1520) to 2π channels (Δπ, Nρ, Nσ)

Dalitz decays of Baryon resonance

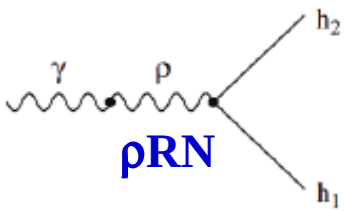
QED "point-like"

R-γ^* vertex



M. Zetenyi et al.,
PRC 67, 044002 (2003).
M. I. Krivoruchenko et al.,
Ann. Phys. 296, 299 (2002).

VDM2 "strict VDM"

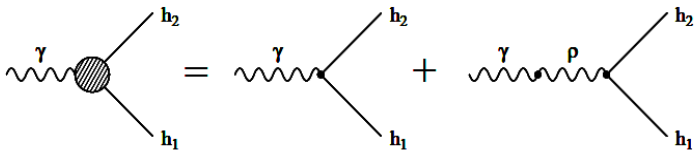


ρRN

Sakurai,
Phys. Rev 22 (1969) 981
M. I. Krivoruchenko et al.,
Ann. Phys. 296, 299 (2002)

$$\Gamma(M_{e^+e^-}) = \Gamma_0 (M_0/M_{e^+e^-})^3$$

extended VDM1 two component

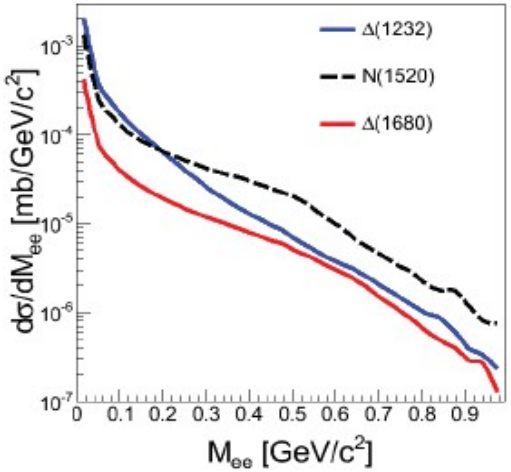


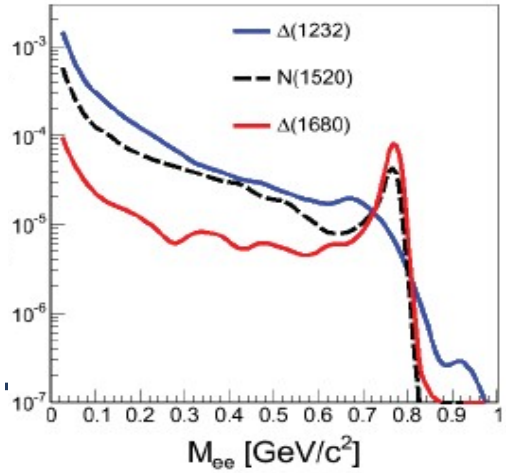
ρN, γN fixed independently
vanishing ρ → e+e- at q^2~0

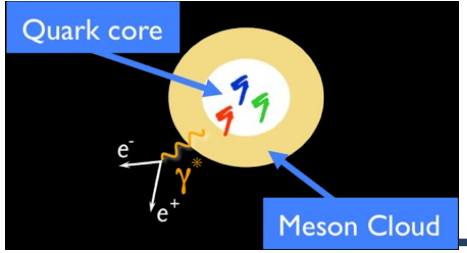
Kroll, Lee & Zuminio
Phys. Rev. 157, 1376 (1967)

$$\Gamma(M_{e^+e^-}) = \Gamma_0 M_{e^+e^-}/M_0$$

this scheme is implemented
in Rapp and Wambach calculations
of in-medium ρ spectral functions







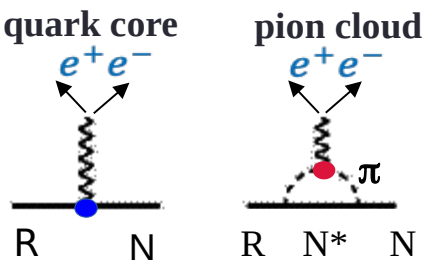
Implementation of VDMs

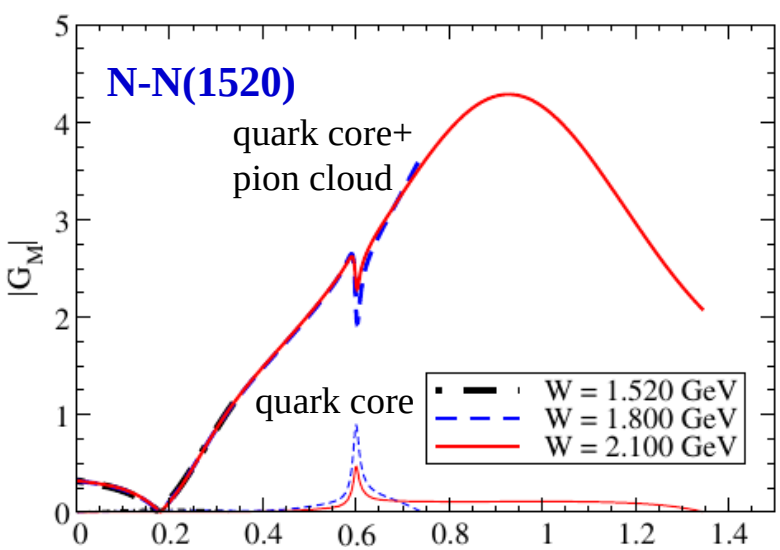
Covariant quark model +VMD

T. Pena and G. Ramalho

N-Δ(1232): ***Phys.Rev. D85 (2012) 113014***
N-N(1520): ***Phys. Rev. D95, (2017) 014003***
N-N(1535): ***Phys.Rev. D101 (2020)114008***

VDM:
quark FF
pion FF



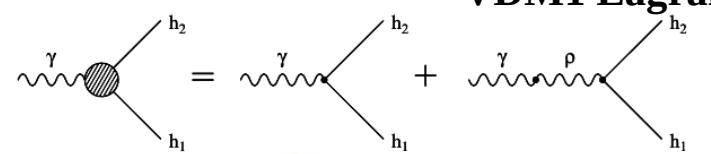


Two-component Lagrangian model

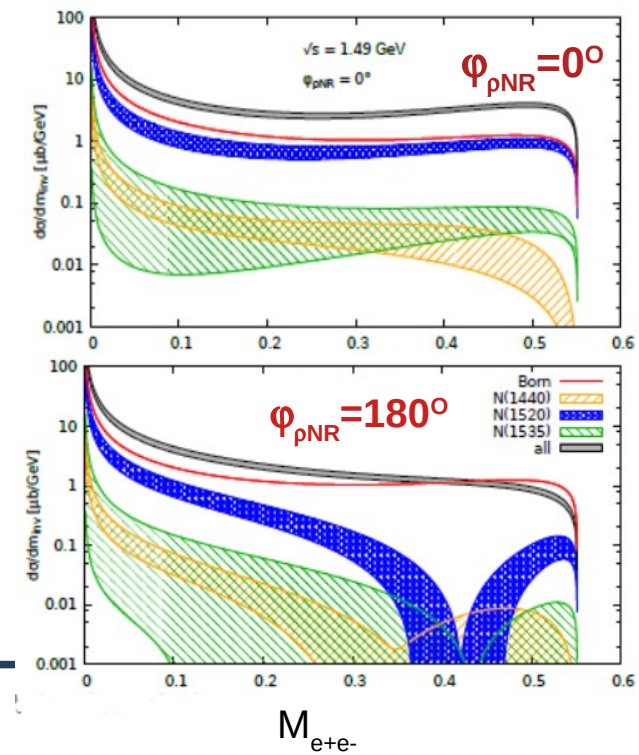
M. Zetenyi and G. Wolf

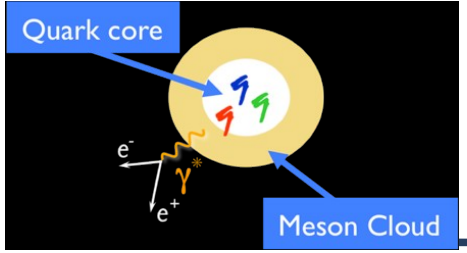
Phys. ReV. C 86, 065209 (2012)
Phys. Rev. C 104, 015201 (2021)

VDM1 Lagrangian



Shape and yield sensitive to the interference between the γ and ρ contributions





Implementation of VDMs

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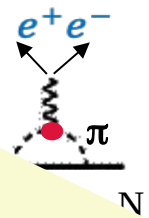
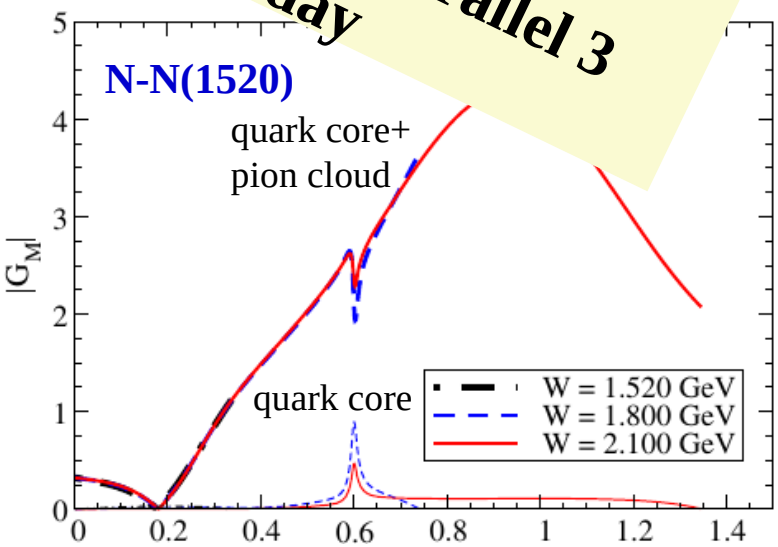
N-N(1535): ***Phys.Rev. D101 (2020)114008***

VDM:
quark F
pion F

quark core pion cloud



T. Pena talk on Parallel 3 Tuesday



Two-component Lagrangian model

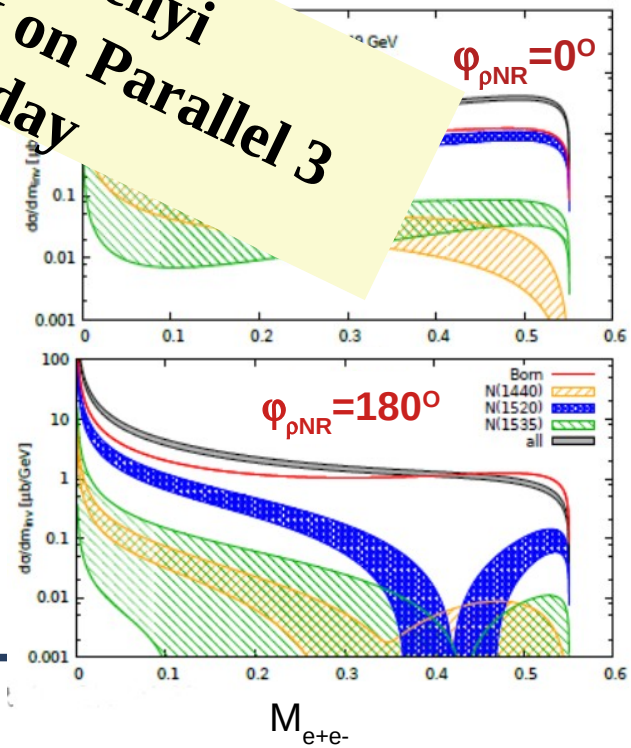
M. Zetenyi and G. Wolf

Phys. ReV. C 86, 065209 (2012)
Phys. Rev. C 104, 015201 (2021)

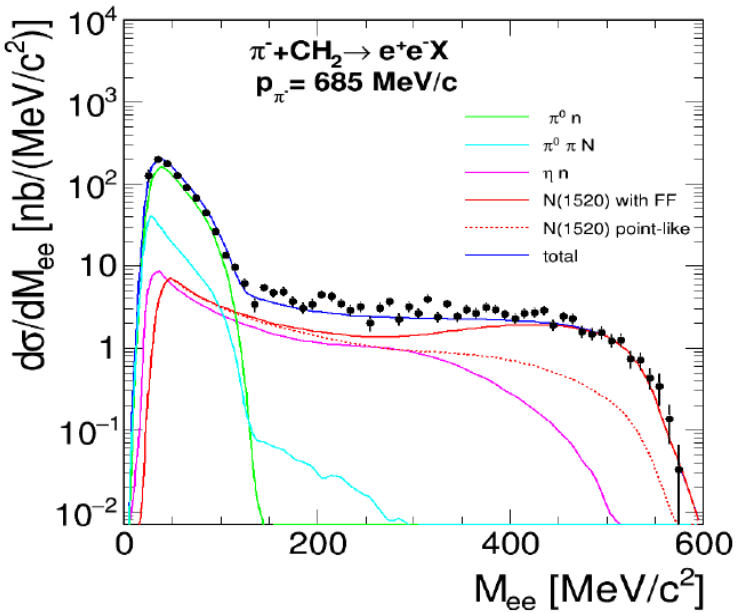
VDM1 Lagrangian

M. Zetenyi talk on Parallel 3 Tuesday

Shape and yield sensitive to the interference between the γ and ρ contributions



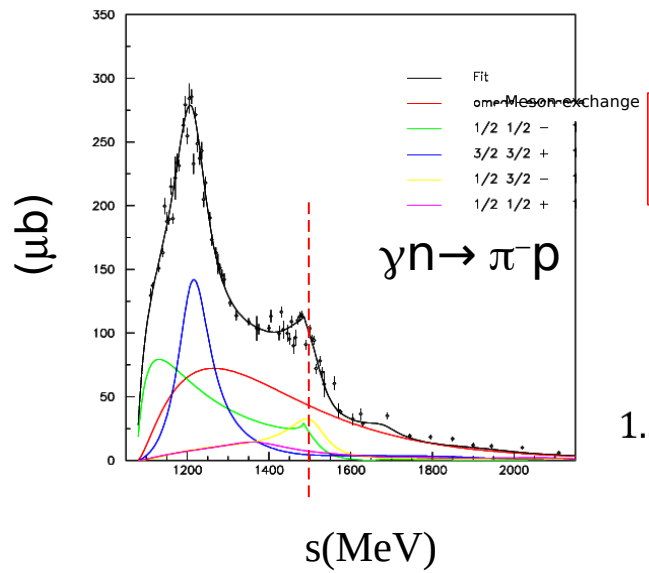
Inclusive e+e- cocktail
Fixing cocktail ingredients



$\pi^- p \rightarrow n\pi^0$ [9 mb] (SAID)
$\pi^- p \rightarrow n\pi^0\pi^0$ [1.9 mb] (L.-B.)
$\pi^- p \rightarrow p\pi^0\pi^-$ [4.0 mb] (L.-B.)
$\pi^- p \rightarrow n\eta$ [0.83 mb]

Arndt et al., PRC**72** (2005) 045202

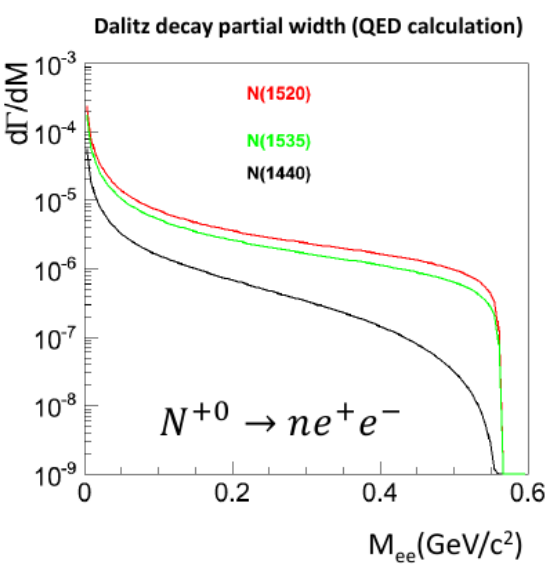
Dalitz Decay BR
π^0: 0.012
η: 0.006



Bonn-Gatchina PWA

N(1520) to $\pi^- p \rightarrow \gamma n$: 21%
N(1535) to $\pi^- p \rightarrow \gamma n$: 15%

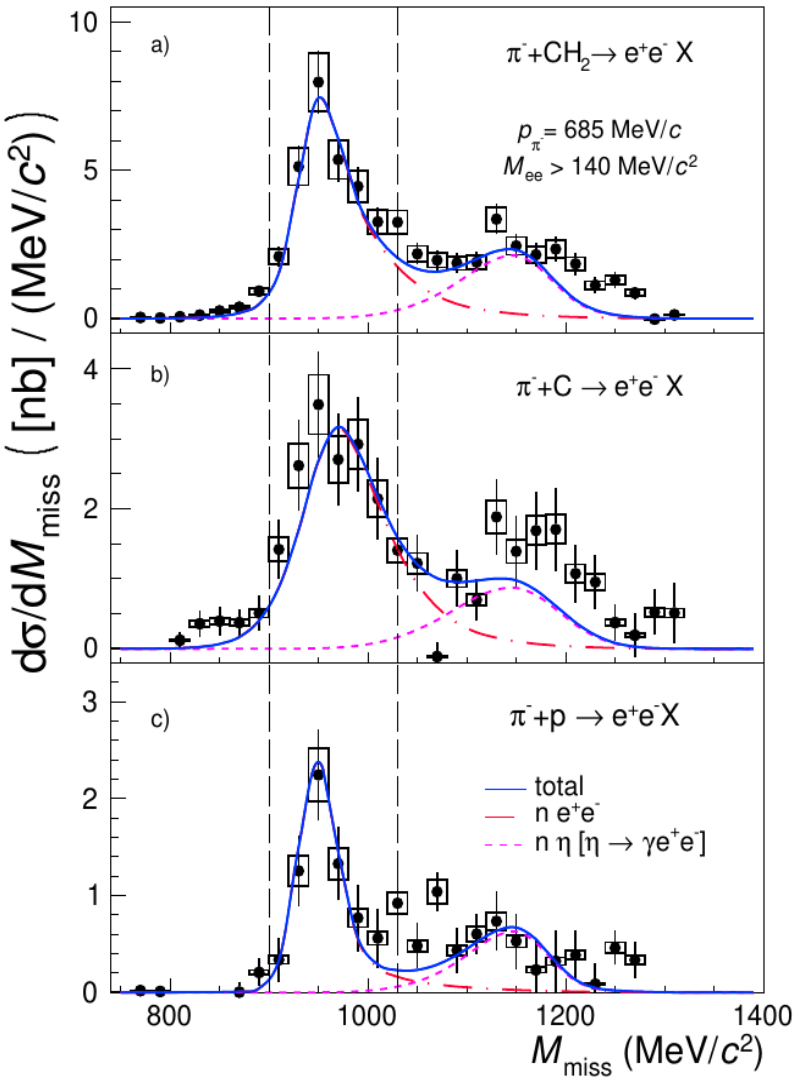
$$\sigma(\pi^- p \rightarrow n e^+ e^-) \sim 1.35\, \alpha\, \sigma(\pi^- p \rightarrow n\gamma) = 2\ \mu b$$



input for $\pi^- p \rightarrow \gamma^*(e^+e^-)n$
QED Dalitz decay contribution

Selection of quasi-free $\pi^- p \rightarrow ne^+e^-$

HADES coll. arXiv:2205.15914 [nucl-ex]



- cut on **invMe$^+$e$^-$** >140 MeV (above π^0 mass)
- missing mass cut on $\mathbf{M_{miss}}$ (η removed)

- **$\pi^- C$** simulations using Pluto (qfs participant-spectator model)
- production cross sec. on C for: π^0, η, ρ, γ deduced from the scaling: $R_{C/H} = \sigma_C / \sigma_H$

- **CH_2** target:

$$\left(\frac{d\sigma}{dM_{ee}}\right)_{CH_2} = \left(\frac{d\sigma}{dM_{ee}}\right)_C + 2\left(\frac{d\sigma}{dM_{ee}}\right)_H$$

Selection of quasi-free $\pi^- p \rightarrow ne^+e^-$

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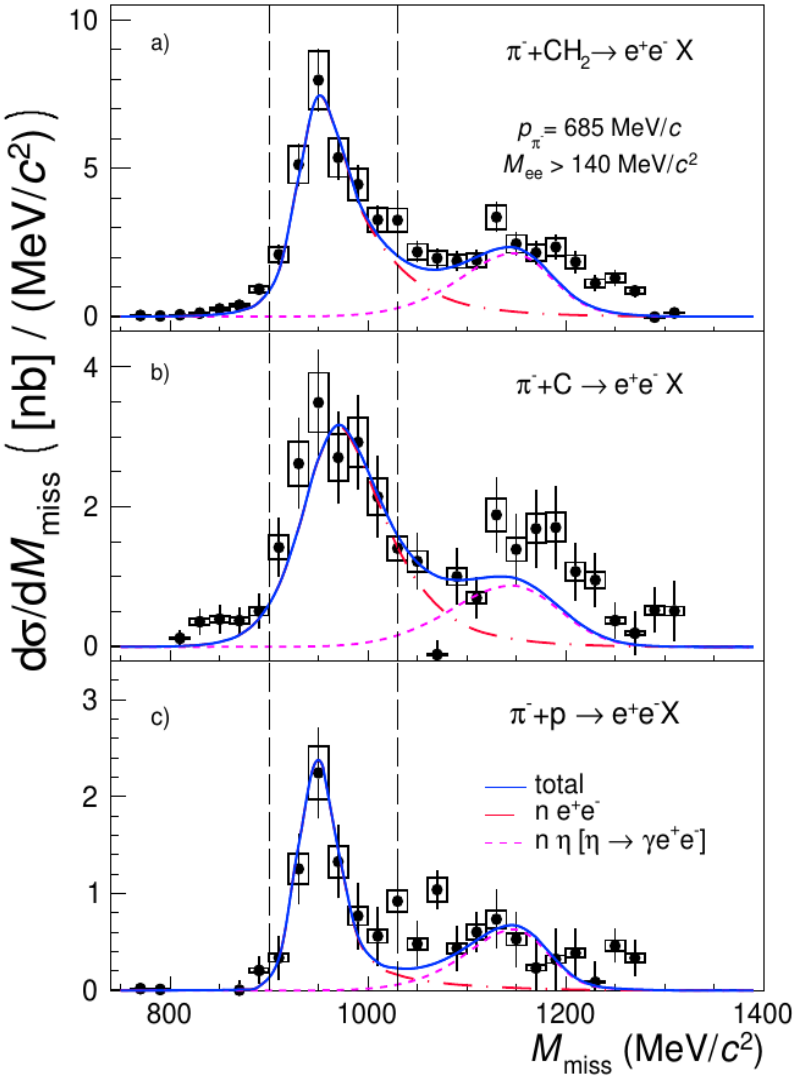


- cut on **invMe$^+$e$^-$** >140 MeV (above π^0 mass)
- missing mass cut on $\mathbf{M_{miss}}$ (η removed)

pion and proton production on C target
F. Hojeij
this session

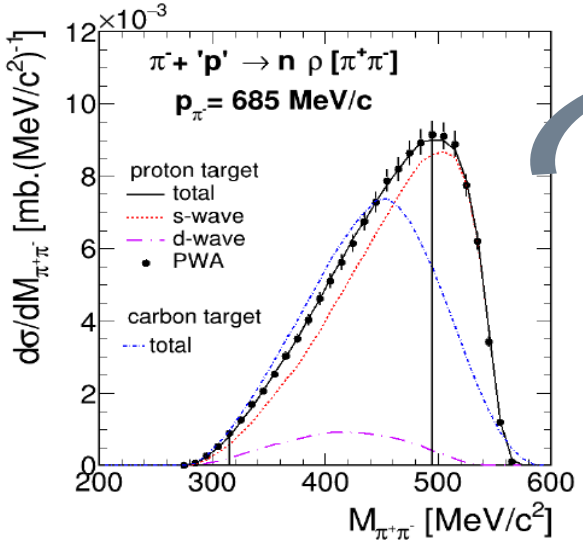
- **π^-C** sim… …ticipant-spectato…
- produc… deduced from …

- **CH_2** target:

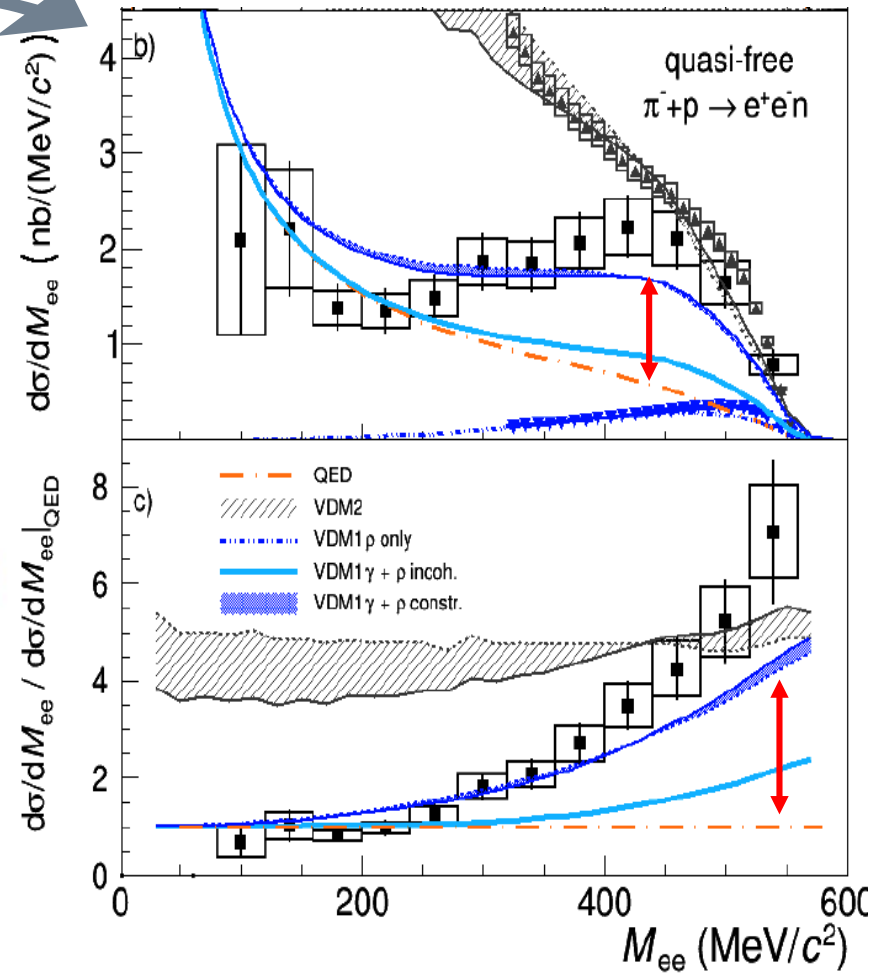
$$\left(\frac{d\sigma}{dM_{ee}}\right)_{CH_2} = \left(\frac{d\sigma}{dM_{ee}}\right)_{C} + 2\left(\frac{d\sigma}{dM_{ee}}\right)_{H}$$

Exclusive e+e- cocktail

comparison to VMD1 and VDM2

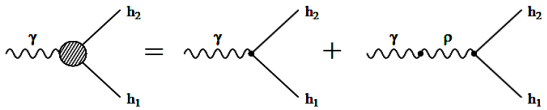


HADES coll. arXiv:2205.15914 [nucl-ex]



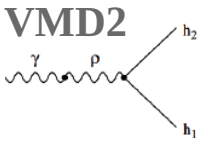
$$\left(\frac{d\sigma_{ee}}{dM_{ee}}\right)_{M_{ee}=M} = \left(\frac{d\sigma_{\pi\pi}}{dM_{\pi\pi}}\right)_{M_{\pi\pi}=M} \frac{\Gamma_{\rho\to e^+e^-}(M)}{\Gamma_{\rho\to\pi^+\pi^-}(M)}$$

VMD1



reasonable description

VMD2



large overestimation

Exclusive e+e- cocktail

comparison to the Lagrangian and covariant quark models

HADES coll. arXiv:2205.15914 [nucl-ex]

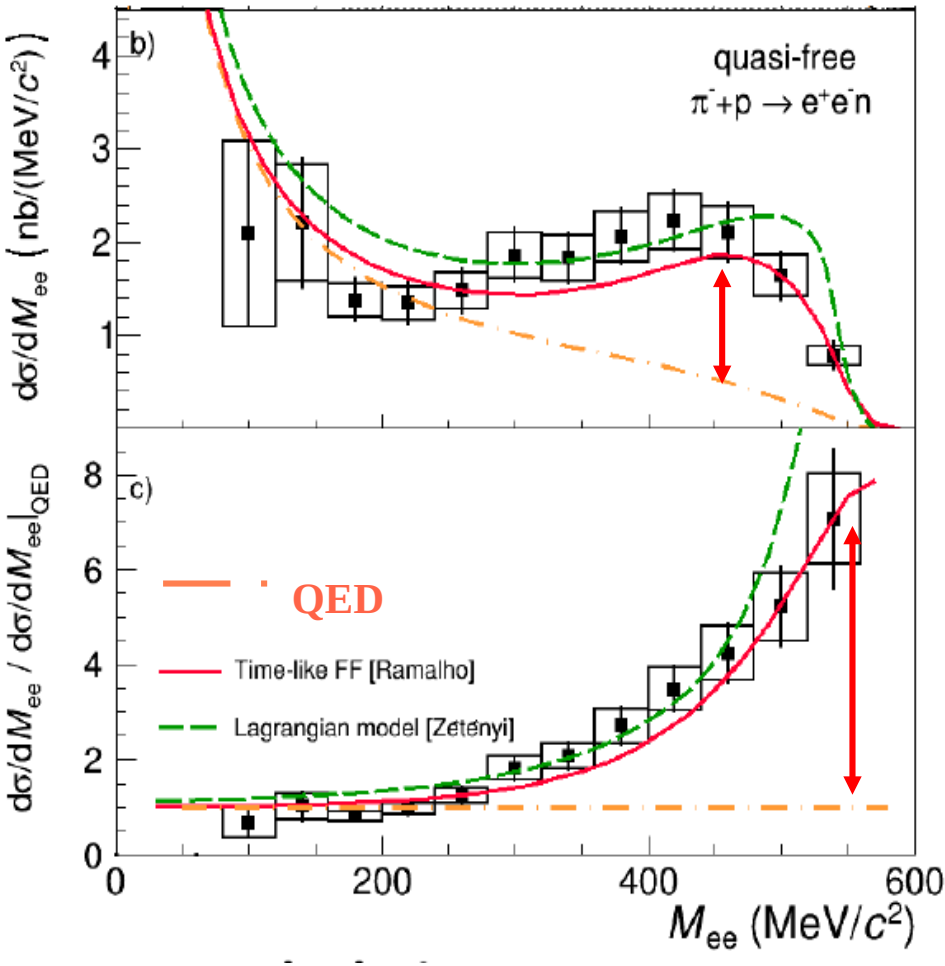
Lagrangian model:

- based on VDM1
- shown with phase $\varphi=90^o$
- needs to be confronted to $\pi^- p \to \pi\pi N$ data

Covariant form factor model:

- n-N(1520) and n-N(1535) transitions
- **dominant pion cloud contribution**: baryon transition form factor strongly related to the pion electromagnetic form factor

huge excess over point-like QED



Structure of Baryon Transitions
Lagrangian Model

E. Speranza et al. Phys. Lett. B764, 282 (2017)

πN → Ne+e-

spin density matrix elements (SDME)

information on photon polarization

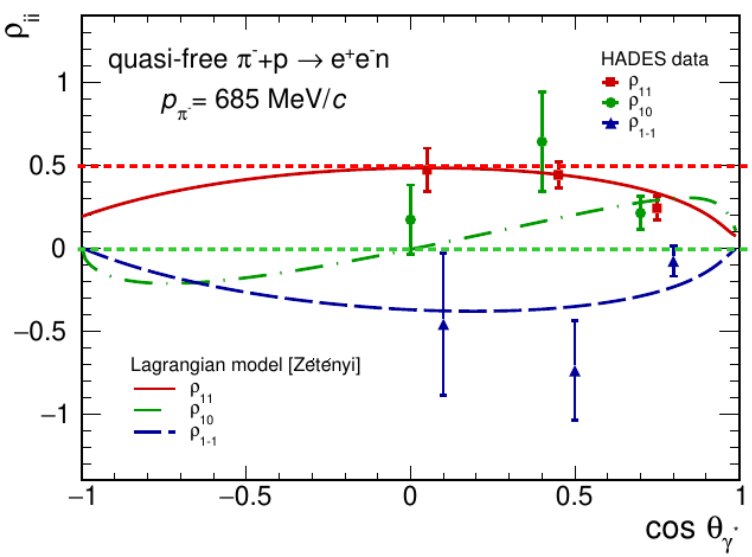
$$\frac{d^3\sigma}{dM_{ee}d\Omega_{\gamma_*}d\Omega_e} \sim |A|^2 = \frac{e^2}{Q^4}\sum_{\Lambda\Lambda'} \rho^{(H)}_{\Lambda\Lambda'}\rho^{(dec)}_{\Lambda\Lambda'}$$

QED: γ* → e+e-

hadron decay to γ*

$$\frac{|A|^2}{\sigma} = \frac{1}{N}\left(8m_e^2 + 8|\mathrm{k}|^2\left[1 - \tilde{\rho}^{(H)}_{11} + \cos^2\theta(3\tilde{\rho}^{(H)}_{11} - 1) + \sqrt{2}\sin(2\theta)\cos\phi\,\mathrm{Re}\tilde{\rho}^{(H)}_{10} + \sin^2\theta\cos(2\phi)\,\mathrm{Re}\tilde{\rho}^{(H)}_{1-1}\right]\right)$$

SDME ρ_{11}, ρ_{10}, ρ_{1-1} extracted taking into account acceptance and efficiency (A. Sarantsev) in 3 bins in cosθγ

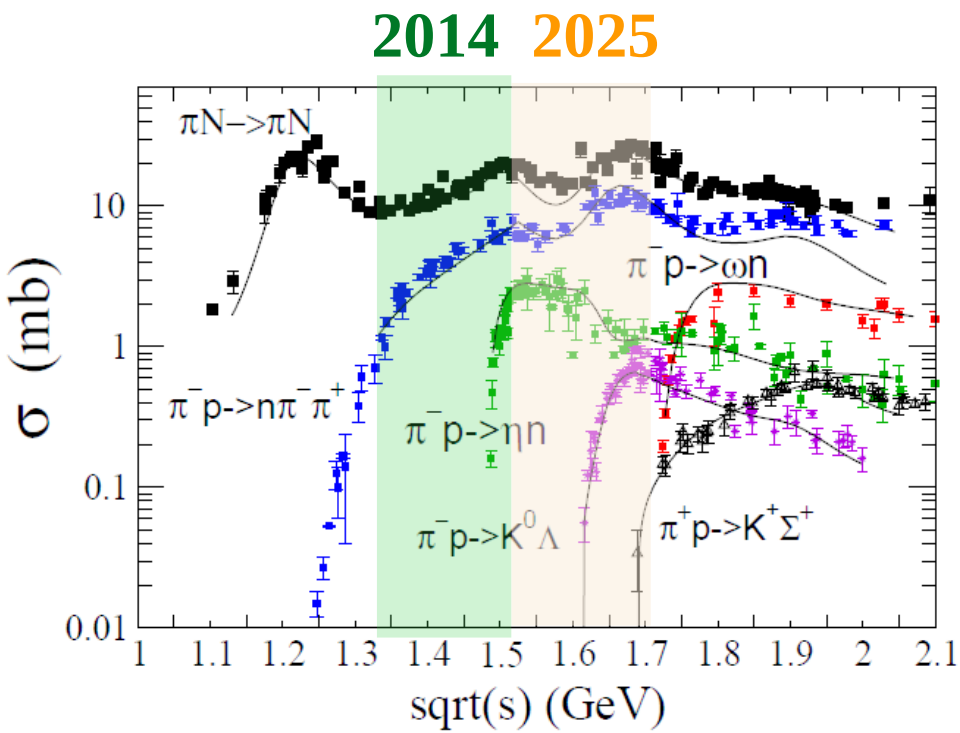


SDME sensitive to:

- resonance J^P (for s=1/2 no dependence on θγ)
- ρ_{11}=0.5, ρ_{10}=0 for transverse polarization (real photon)
- angular dependence → contributions of spins larger than ½: N(1520) resonance
- more precise data needed

M. Zetenyi talk on Parallel 3 Tuesday

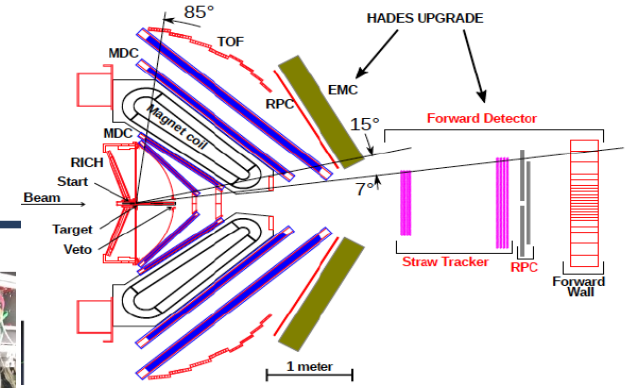
HADES Physics Program with Pion Beams
explore the 3rd resonance region $\sqrt{s} = 1.7$ GeV/c²



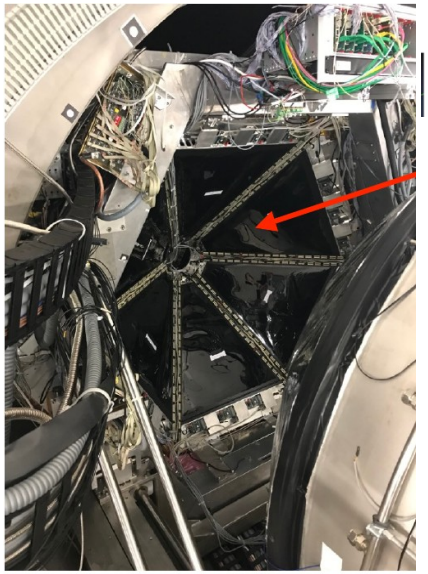
High statistics beam energy scan: continuation and extension to 3rd resonance region

1) **Baryon-meson couplings:**
   - → ππN, ωn, ηn, $K^0\Lambda$, $K^0\Sigma$, …
     including neutral mesons (ECAL),
   - → ρR couplings S31(1620), D33(1700), P13(1720),..
2) **Time-like em. baryon transitions**
   - → $\pi^- p$ → ne+e-,
   - → test of VMD for ρ and ω,
   - → spin-density matrix elements,
3) **Cold nuclear matter studies:**
   - → ω absorption
   - → ρ spectral function
   - → strangeness production

HADES Spectrometer UPGRADE

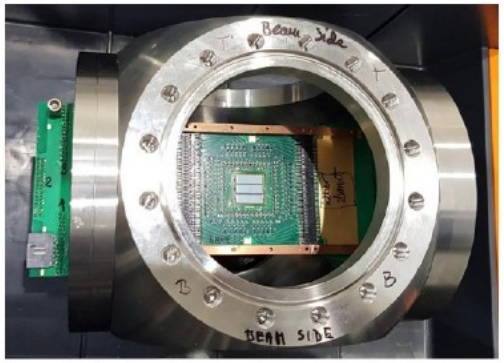


HODO, fRPC, STS2, STS1



innerTOF (fast trigger)

- START T0 detector

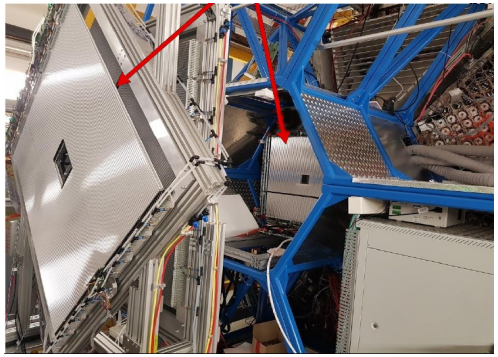


Low Gain Avalanche Detectors for the HADES reaction time (T) detector upgrade (Eur. Phys. J. A (2020) 56: 183)

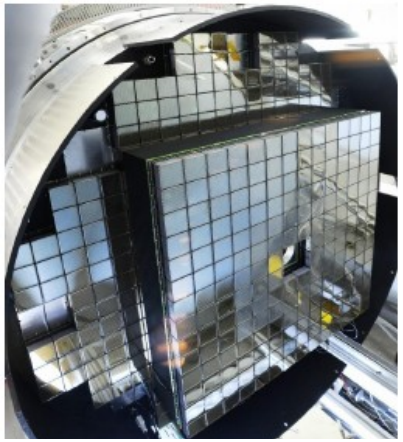
- timing < 100 ps
- PCB in the beam vacuum
- rate capability 10^8 p/s
- 2 cm x 2 cm, 96 channels
- pitch 387 µm

- ECAL (lead glass)

STS2 STS1



- new RICH



MWPC → MAPMT

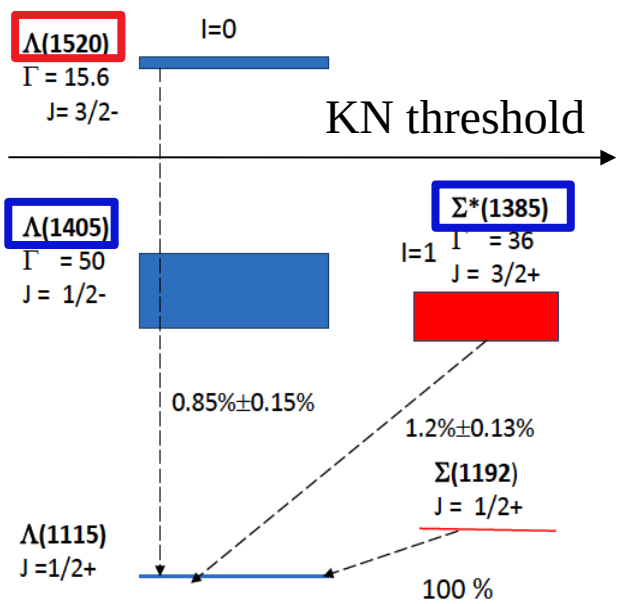
Strangeness studies with HADES
pp@ 4.5 GeV (Feb 2022)

HADES: Eur. Phys. J. A57, 138 (2021)

Intrinsic interest of pp:

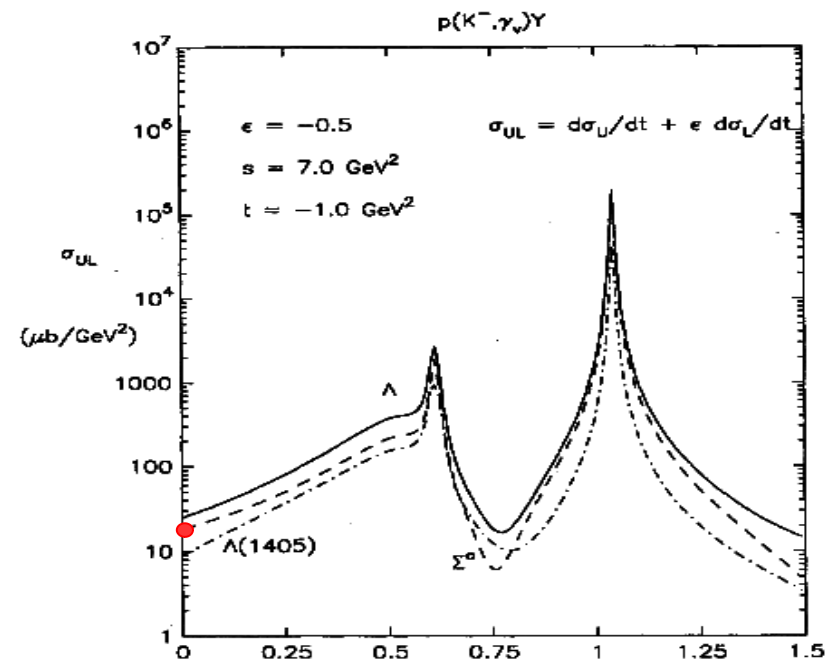
- Structure of strange baryons (Λ, Σ)

– measurement @SIS
February 2022: pp @ 4.5GeV



VMD:
huge effect of vector mesons predicted

$K^- p \rightarrow Y\gamma^*$
in VMD model



R. Williams et. al.
PRC48, 1381 (1993)

Summary and Outlook

- HADES & **pion beam** is an unique tool to understand in details baryon-couplings:
  → significant off-shell contribution originating from N(1520)D_{13} shown by combined PWA,
  → D_{13}(1520) coupling to ρ-N: 12+/-2 %,
  → very new information on electromagnetic baryon transitions in the time-like region,
- On-going analysis for hyperon Dalitz and radiative decays in pp reaction at 4.5 GeV
- Proposal for pion beam experiment in 2025 in the third resonance region
  → investigate heavier resonances N(1620), N(1720),...in e+e- channels and many hadronic channels, e.g. $\pi^- p \rightarrow n$, $K^0\Lambda$, $K^0\Sigma$,....

Thank You
for
Your Attention