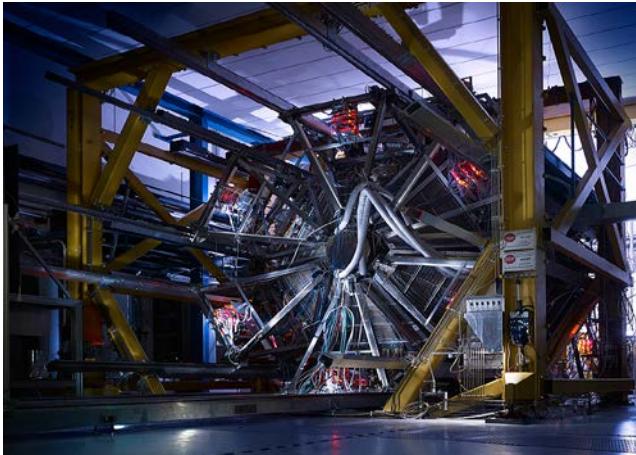
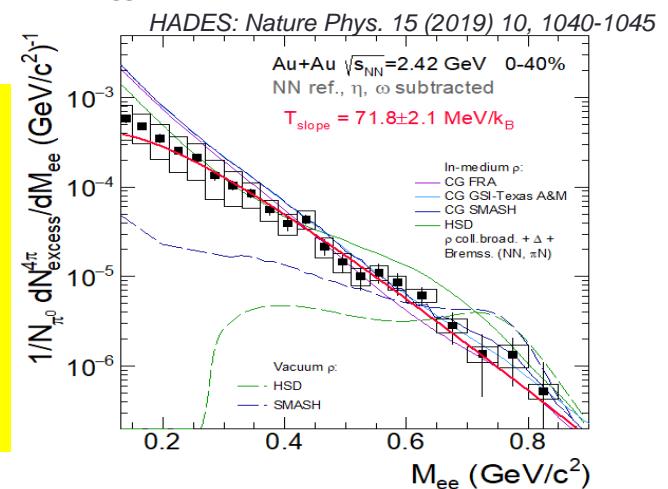
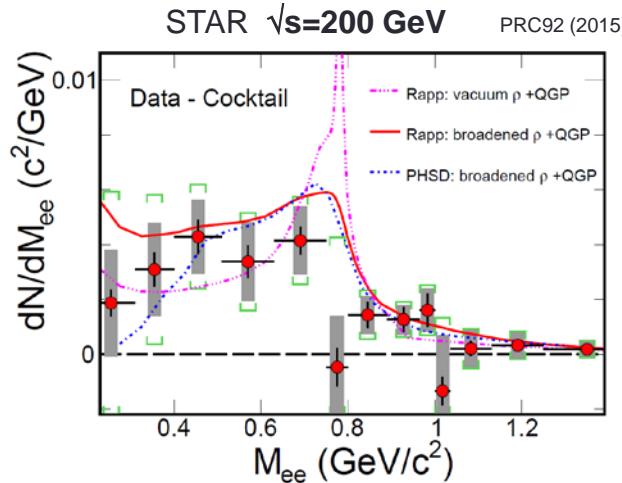
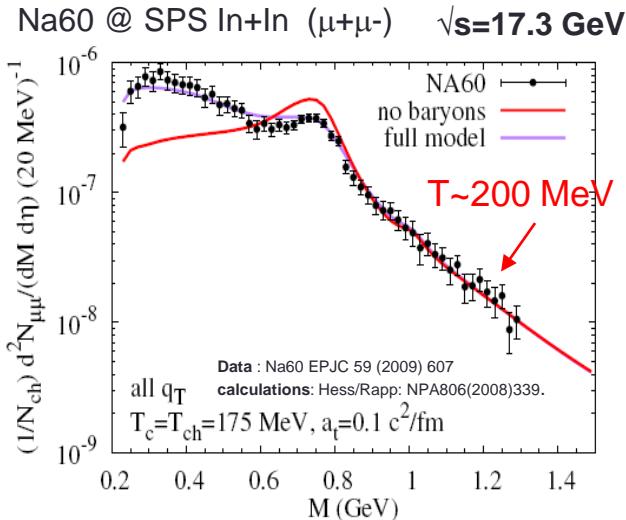


HADES investigations of baryon-photon coupling (baryon em. Form-Factors)

- ✓ Motivations(emissivity of QCD matter -> Low mass dileptons, ρ in-medium spectral function
→ time-like baryon em. transitions)
- ✓ Measurements of baryon electromagnetic transitions in NN and πN reactions
- ✓ Summary & Outlook: perspectives for hyperon em. decays in HADES and new experiments with pion beams



P. Salabura
M. Smoluchowski Institute of Physics
Jagiellonian University, Kraków
Poland

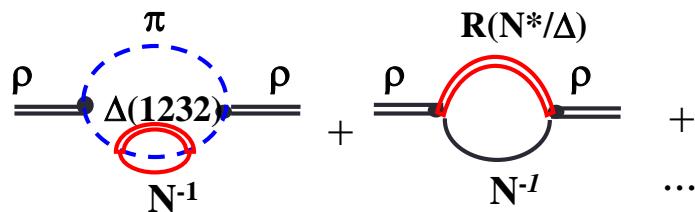


- ❑ Low Mass dileptons: dominated by thermal radiation from ρ
„melting“ of ρ due to **baryon- ρ interactions**
- ❑ Na60: $T \sim 200 \text{ MeV}$ - $\langle T \rangle$ of the early phase
- ❑ HADES $T \sim 70 \text{ MeV}$ „hot baryonic matter“
- ❑ LHC : important part of physics in ALICE (Run3 and beyond)

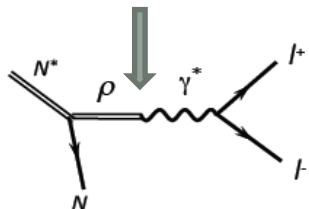
In medium ρ spectral function

$$D_\rho(M, q, T, \mu_B) = \frac{I}{M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}}$$

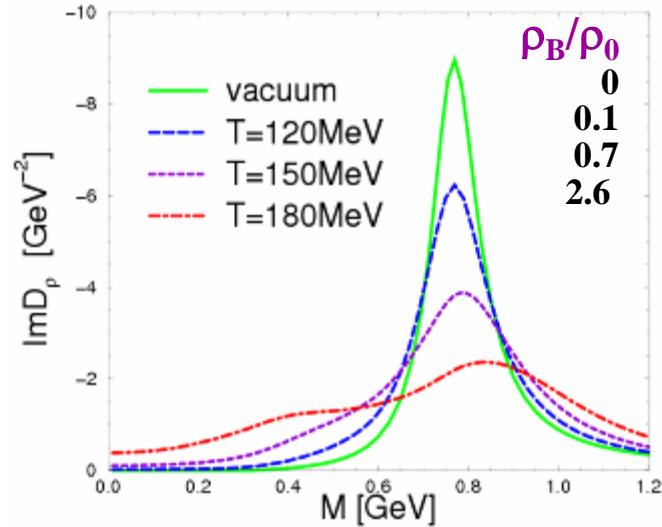
In Medium $\text{Im } \Sigma_\rho$:



dominant role of ρ - R couplings –
Vector Meson Dominance
 $R \rightarrow Ne^-e^-$ (Dalitz decays)



Rapp, Wambach, Adv. Nucl. Phys. A25 (2000)1

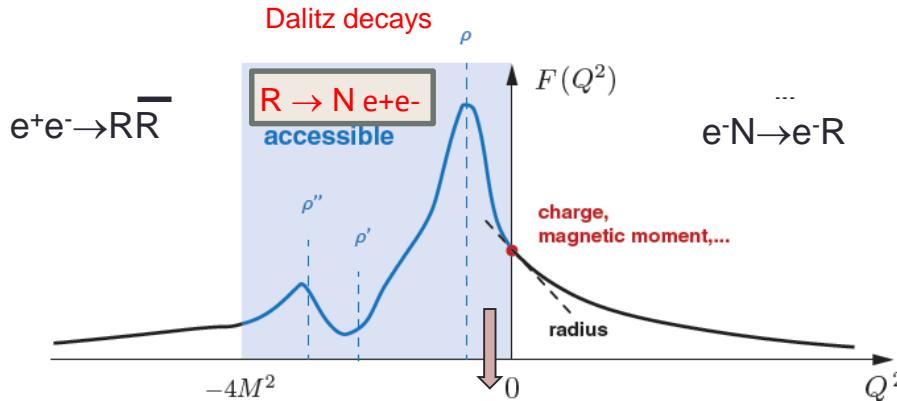


- connection to Chiral sym. restoration \rightarrow
 $\rho(760)/a_1(1260)$ become degenerate at
 $T \sim T_c, \mu_b = 0$

Weinberg QCD sum rules $\int ds (\rho_V - \rho_A) = -m_q \langle \bar{q}q \rangle$

Hohler and Rapp Phys.Lett. B731 (2014)

Baryon electromagnetic transitions

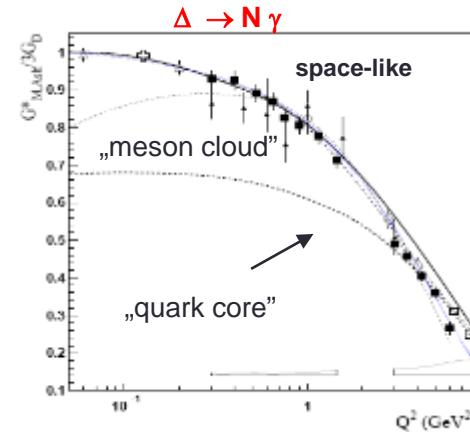
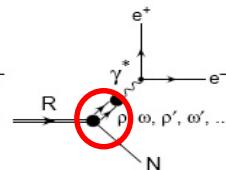


- Dalitz decays : **transition Form Factors (timelike)**
(complementary to spacelike region)

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

„QED“ Effective transition form-factor

Transitions of point-like particles



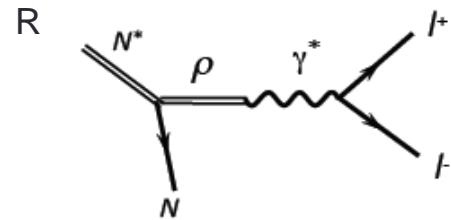
I. G. Aznauryan and V. D. Burkert,
Prog. Part. Nucl. Phys. 67, 1 (2012)

Main players for SIS/FAIR:
 $\Delta(1232)$, $N^*(1520)$, $\Delta(1600-1700)$,..

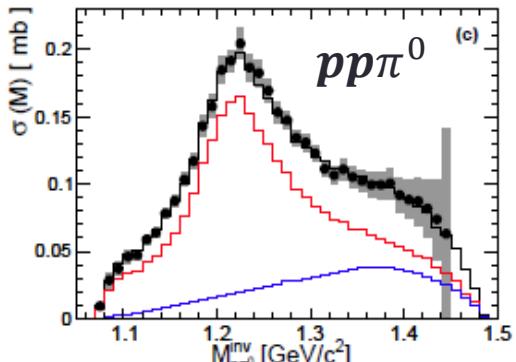
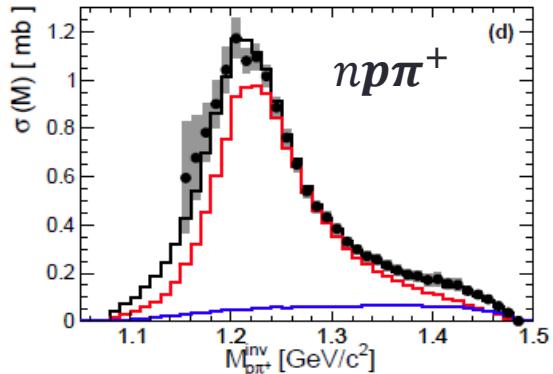
models:

- M. I. Krivoruchenko, et. al. An. Phys. 296, 299 (2002)
 Q. Wan and F. Iachello, Int. J. Mod. Phys. A 20 (2005) 1846.
 G. Ramalho and M.T. Peña, PRD 80 (2009) 013008
 T. Pena and G. Ramalho, Phys. Rev. D85 (2012) 113014
 M. Zetenyi, Gy. Wolf, Heavy Ion Phys. 17, 27 (2003).

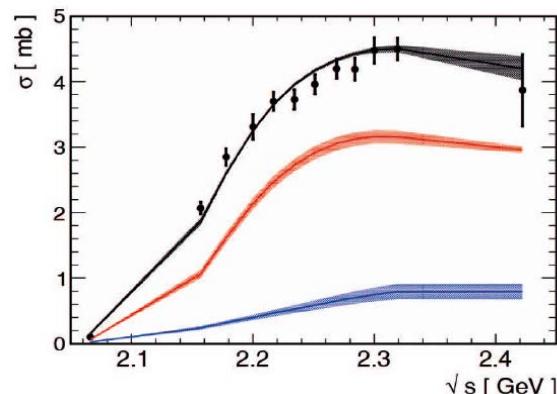
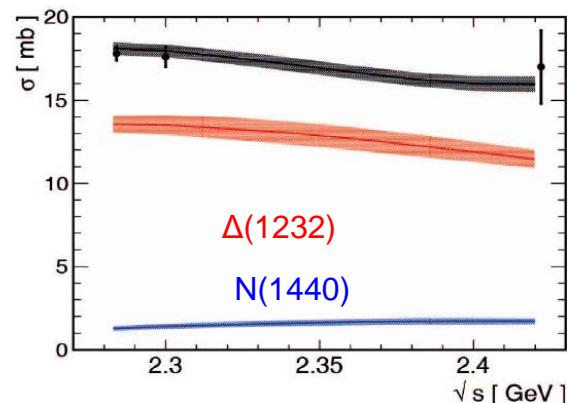
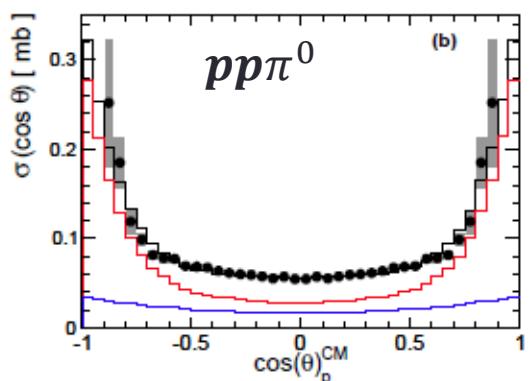
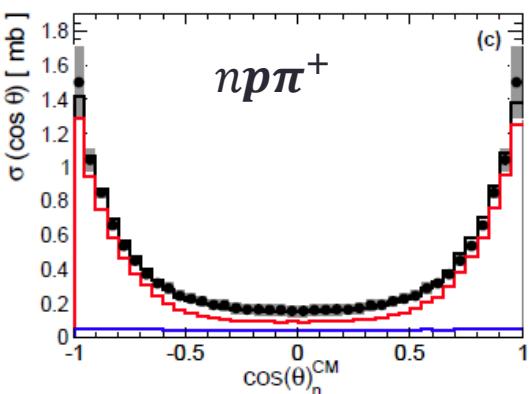
$pp \rightarrow Rp \rightarrow pp\gamma^*(e^+e^-)$ and
 $\pi^- p \rightarrow R \rightarrow n\gamma^*(e^+e^-)$
(exclusive channels)



13 PNPI + 2 HADES data sets

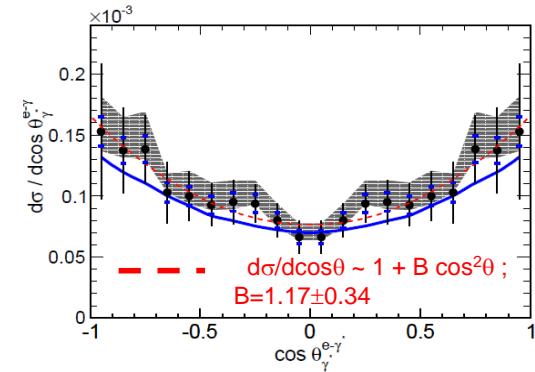
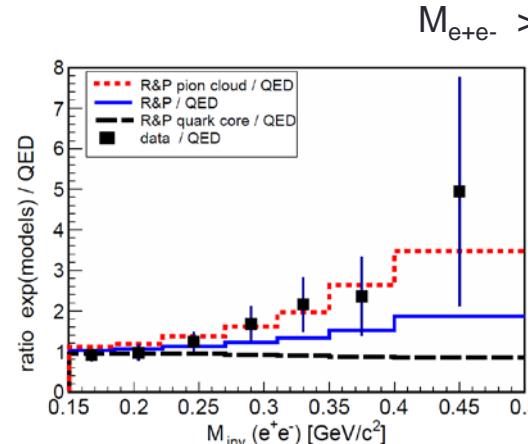
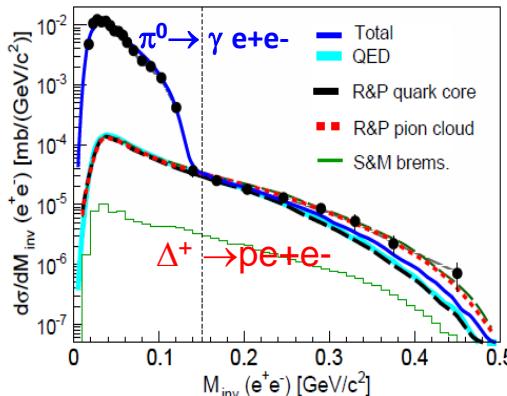


HADES : Eur. Phys. J. A51 (2015) 137

Bn-Ga PWA solutions: resonances: $\Delta(1232)$ and $N(1440)$ 

$pp \rightarrow p(\Delta \rightarrow pe^+e^-) \Delta$ Dalitz decay

HADES Phys. Rev. C95 (2017) no.6, 065205



Lepton distribution in helicity frame

□ BR ($\Delta \rightarrow pe+e^-$) = $4.19 \cdot 10^{-5} \pm 0.62$ (sys) ± 0.32 (stat)

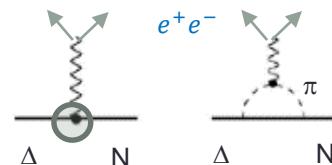
(First measurement : PDG entry)

□ Lepton angular distributions confirm dominance of G_M
(transverse polarized γ^* $\rightarrow B=1$)

□ Good agreement with 2 component model of TFF Ramalho &
Pehna (R &P) \rightarrow Slight rise v.s Mass due to VM(ρ) - pion cloud effect
(constraints from spacelike region !)

T. Pena and G. Ramalho, Phys. Rev. D85 (2012) 113014

quark core pion cloud



$pn \rightarrow p n \gamma^* \rightarrow p n e + e^-$

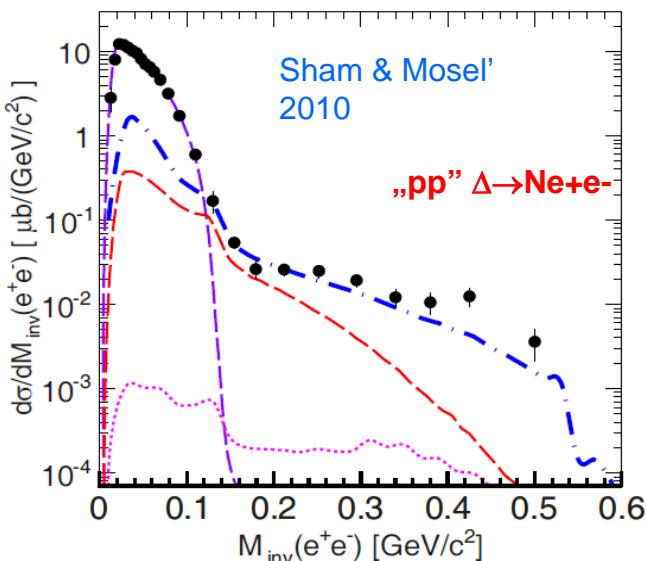
Many calculations (most recent only!):

R. Shyam/ U. Mosel *PRC* 82:062201, 2010

R. Shyam , U. Mosel *Phys. Rev. C* 82:062201, 2010

L.P. Kaptari, B. Kämpfer, *NPA* 764 (2006) 338

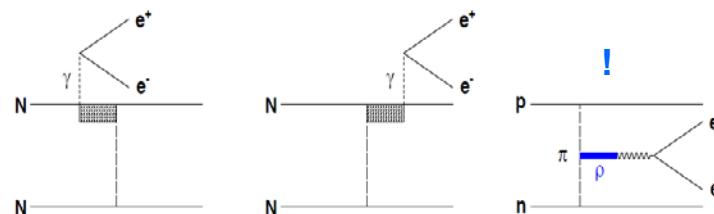
data: HADES PLB690 (2010)118 , EPJA 7, 149 (2017)



„quasi-elastic p-n bremsstrahlung“

difficult theoretical problem faced since 80's

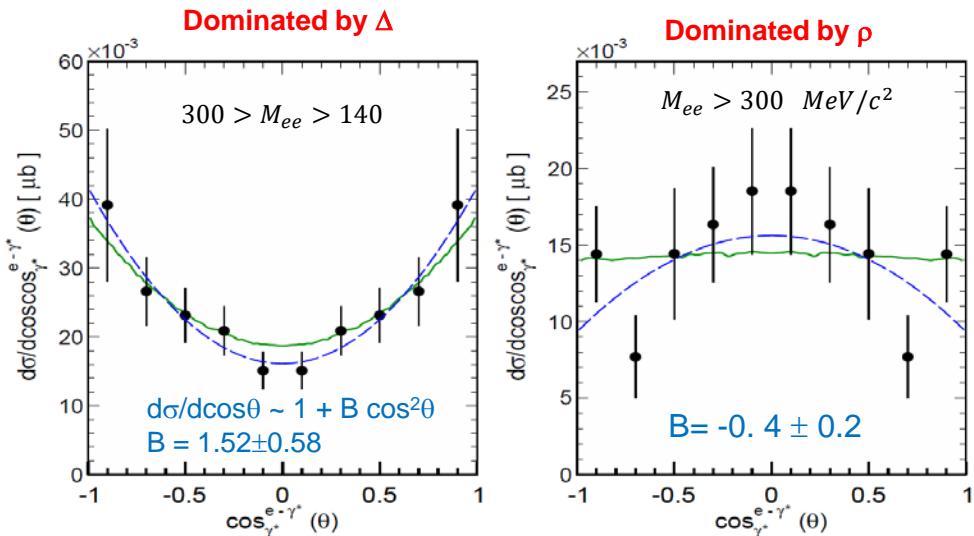
- off shell nucleon em. FF (in time-like region)
- nucleon-nucleon potential
- Conservation of gauge invariance in calculations
- Experimental finding : excess of p-n over p-p
(**p-p** fixed by Δ Dalitz Decay !)



Explanation Shym&Mosel 2010 : emission from charged pion exchange line..

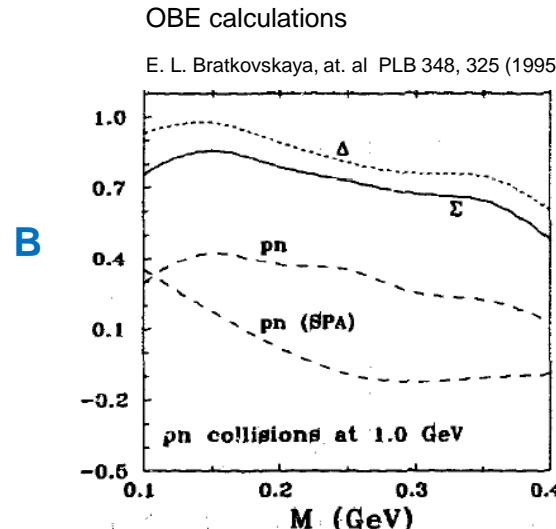
Simple picture: annihilation of pions from cloud in nucleon...

p-n data: γ^* polarization – e distributions (helicity) frame

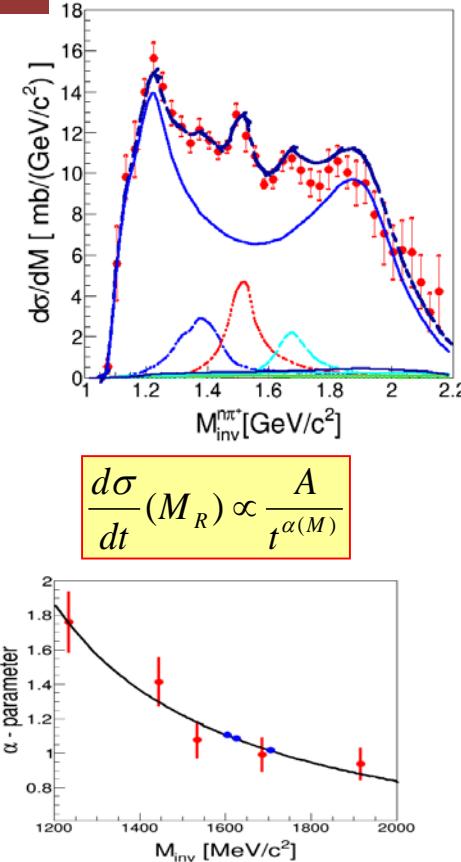
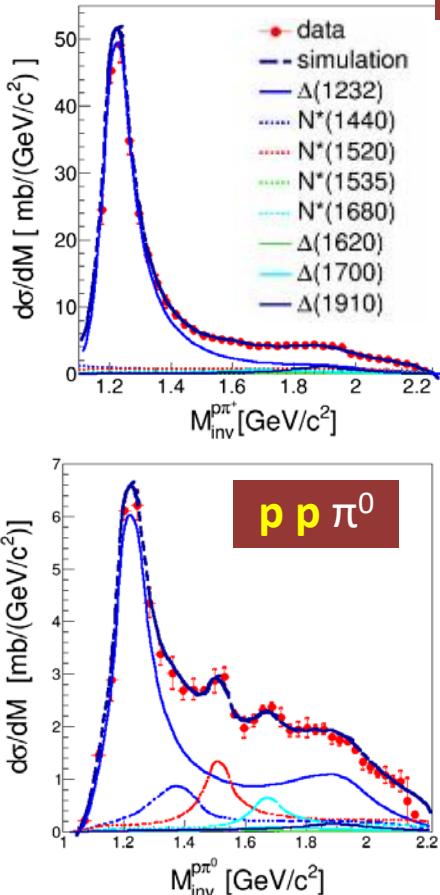


- $B \approx 1$ expected for $\Delta \rightarrow p + e^-$ dominance of G_M and transverse polarized photons

- change of angular distribution
- $B \approx 0$ expected for p-n bremsstrahlung (see right for OBE), $B \approx -1$ for ρ dominance



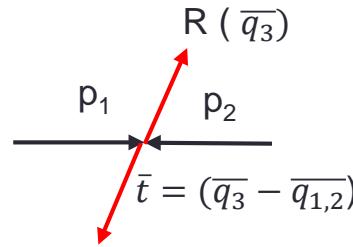
New d+p proposal
send to G-PAC



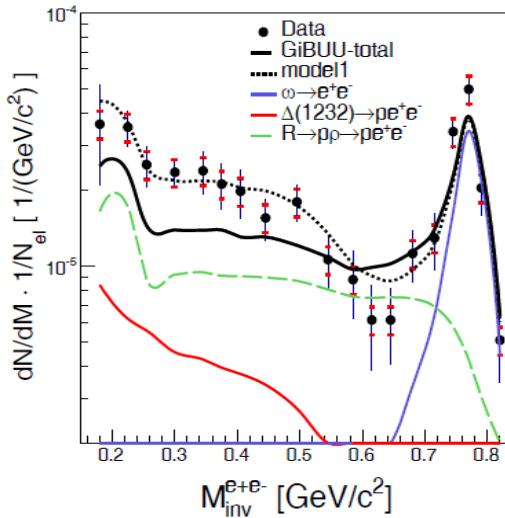
Resonance model:

Z. Teis et al., Z. Phys. A356 (1997) 421
 J. Weil et al. (GiBUU) Eur. Phys. J. A48 (2012) 111
 HADES : EPJA 50(2014) 42

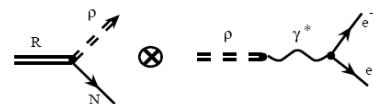
Incoherent sum of (Δ , N^*) resonances



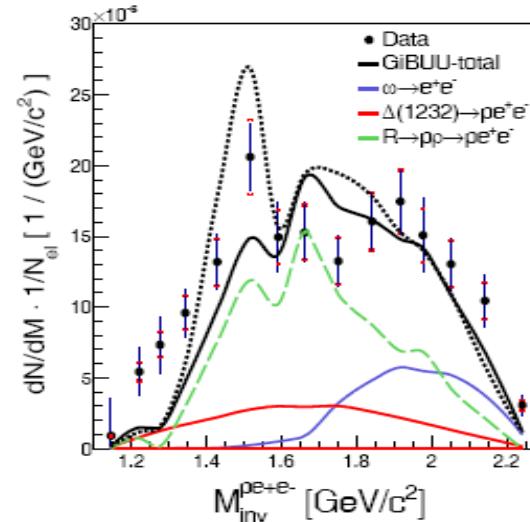
Empirical parametrisation of Resonance production as a function of
 $t(M_R)$
 t-channel dominance

Higher mass resonances: $pp \rightarrow ppe^+e^-$ $\sqrt{s}=3.1$ GeV

Resonance model + „strict” VDM



$$\Gamma_{VDM}(M) = \frac{M_\rho}{M^3} \cdot \text{BR}(M = M_\rho)$$



- Good description of one pion production by „HADES resonance model” $\rightarrow N^*, \Delta$ contributions
- Comparison with VMD : works well .. but with lower BR for $R \rightarrow N\rho$ than PDG (upper limits from Bn-Ga)
Since 2018 – no data on BR in PDG any more !

↓
pion beam !

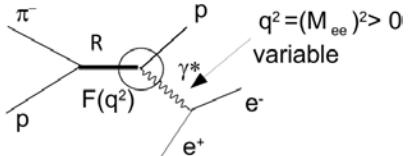
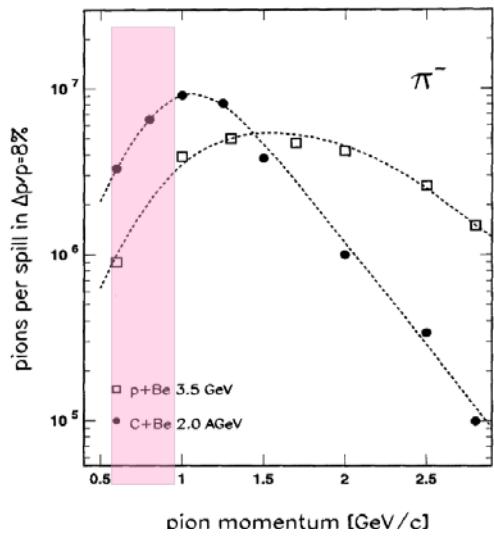
Contr.
to e^+e^- 38%
15%
22%
7%Resonance $\rightarrow N\rho$ Branching Ratios

Resonances	GiBUU	UrQMD	KSU	BG	CLAS
$N(1520)$	21	15	20.9(7)	10(3)	13(4)
$\Delta(1620)$	29	5	26(2)	12(9)	16
$N(1720)$	87	73	1.4(5)	10(13)	–
$\Delta(1905)$	87	80	< 14	42(8)	–

PDG @ 2015

Pion Beam @ GSI

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



- reaction **N+Be**, $6 \times 10^{10} \text{ N}_2$ ions/spill (4s)

- secondary π^- with **I** $\sim 2-3 \cdot 10^5/\text{s}$

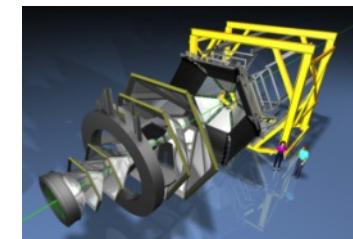
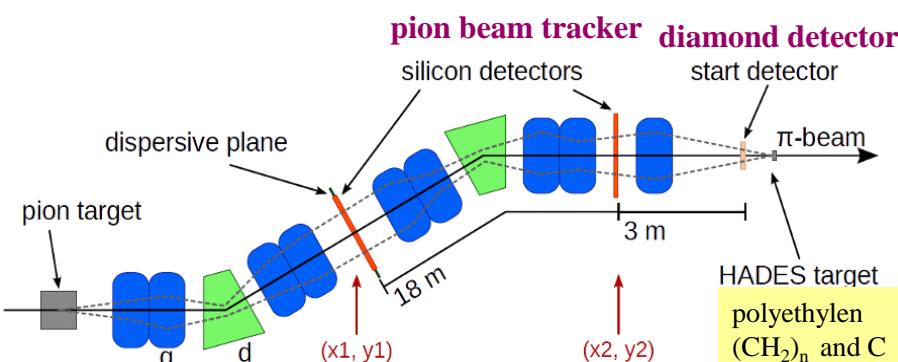
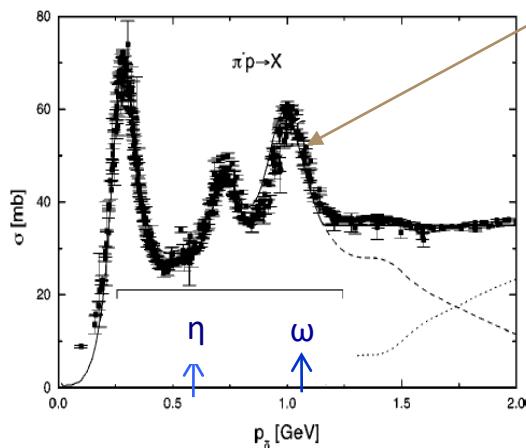
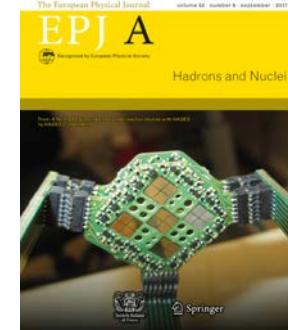
- pion momentum $\Delta p/p = 2.2\% (\sigma)$

- 50% acceptance of pion beam line

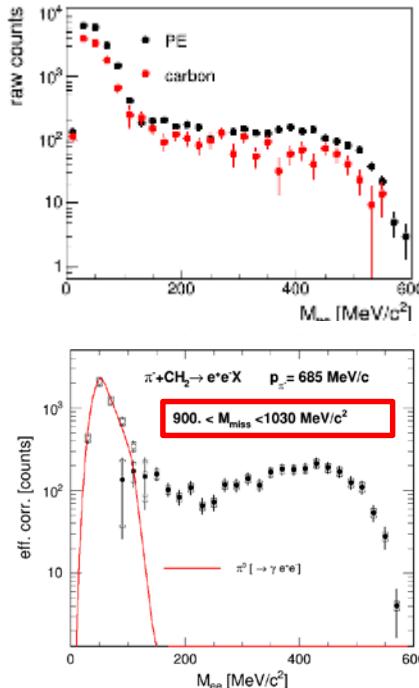
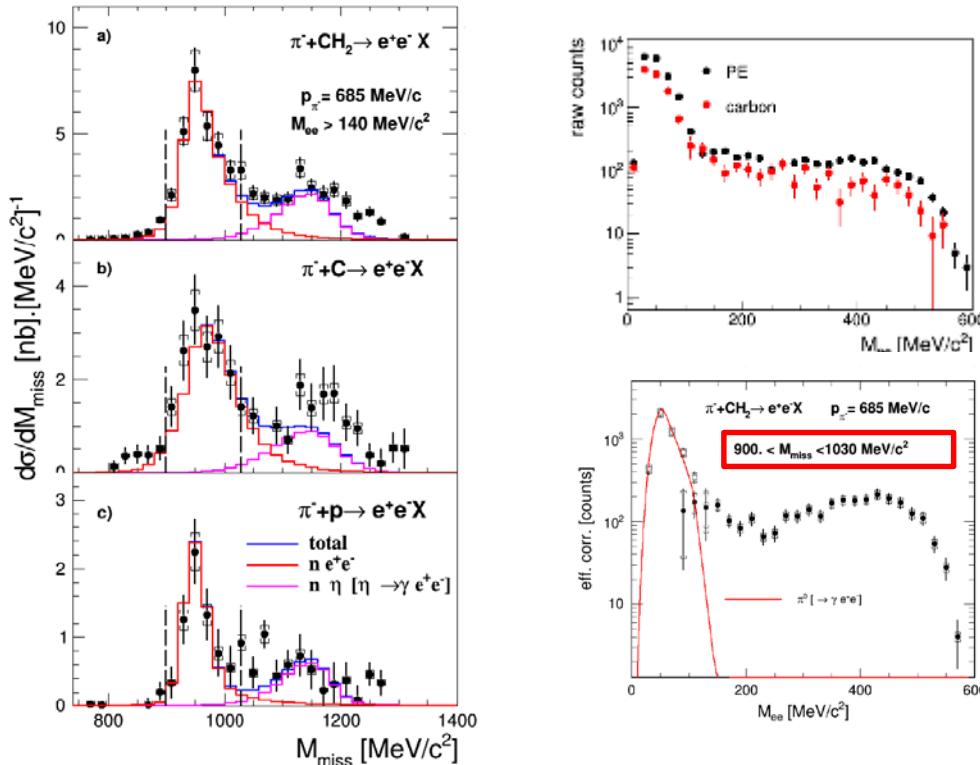
First run:

- $\sqrt{s} = 1.46-1.55 \text{ GeV}$ (4 points)

- PE** (CH_2)_n and **C** targets : 2-pion and e+e- production

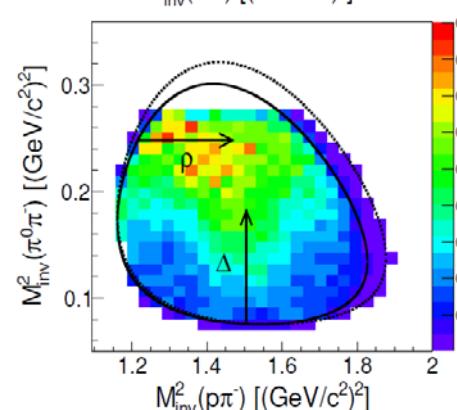
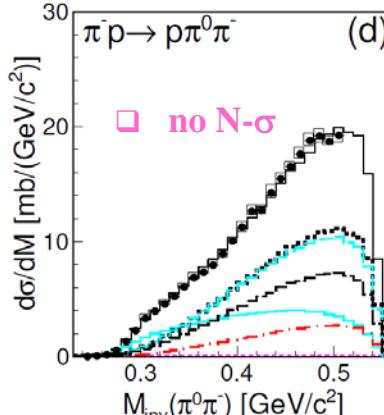
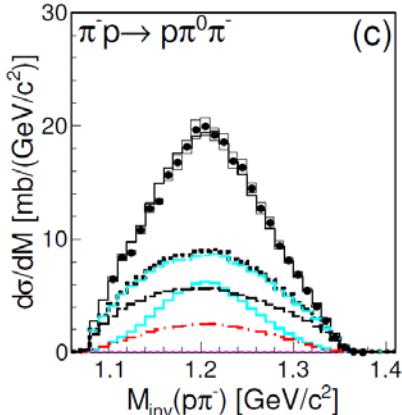
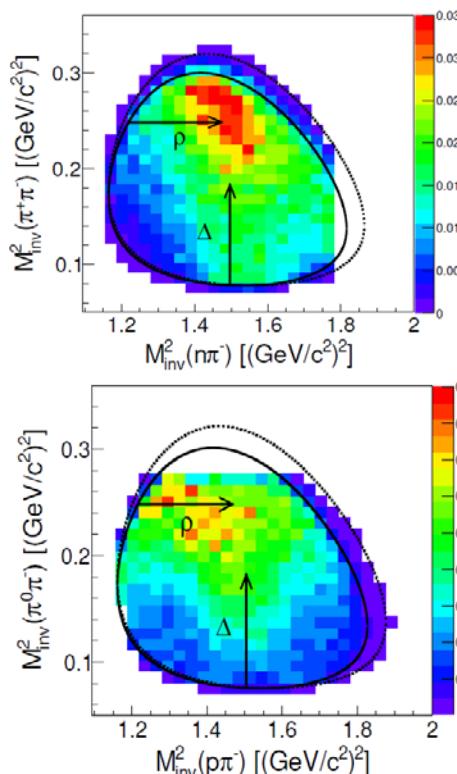
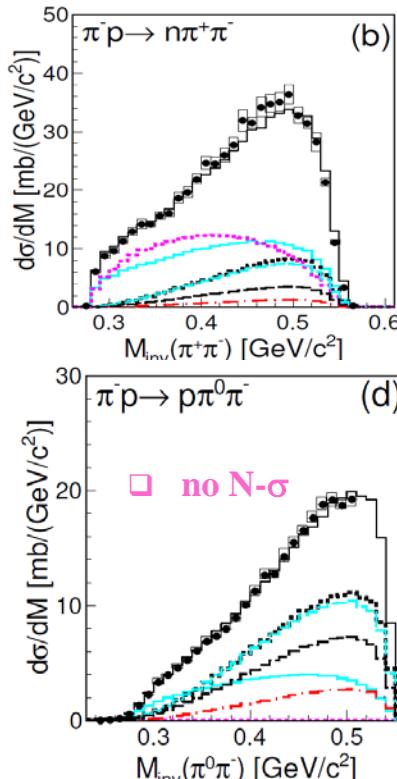
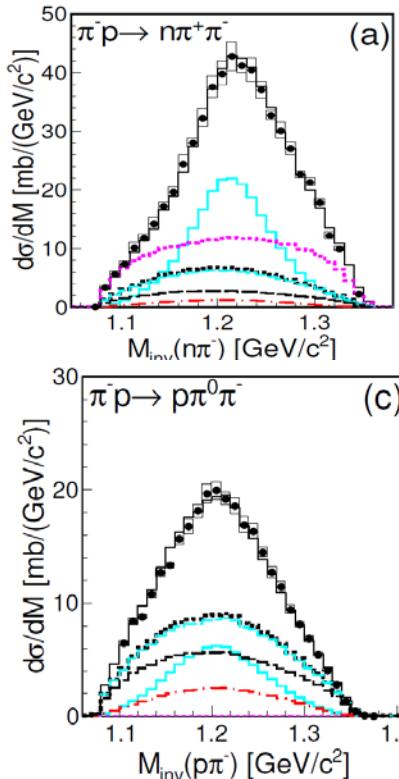


Selection of quasi-free $\pi^- p \rightarrow n e^+ e^-$



- Selection of the exclusive $\pi^- p \rightarrow n e^+ e^-$ channel using missing mass
- Quasi-free treatment of π^- C interactions $\sigma_C/\sigma_p = 3.3$ ($\sim Z^{2/3}$)
- Subtraction of residual π^0 contribution

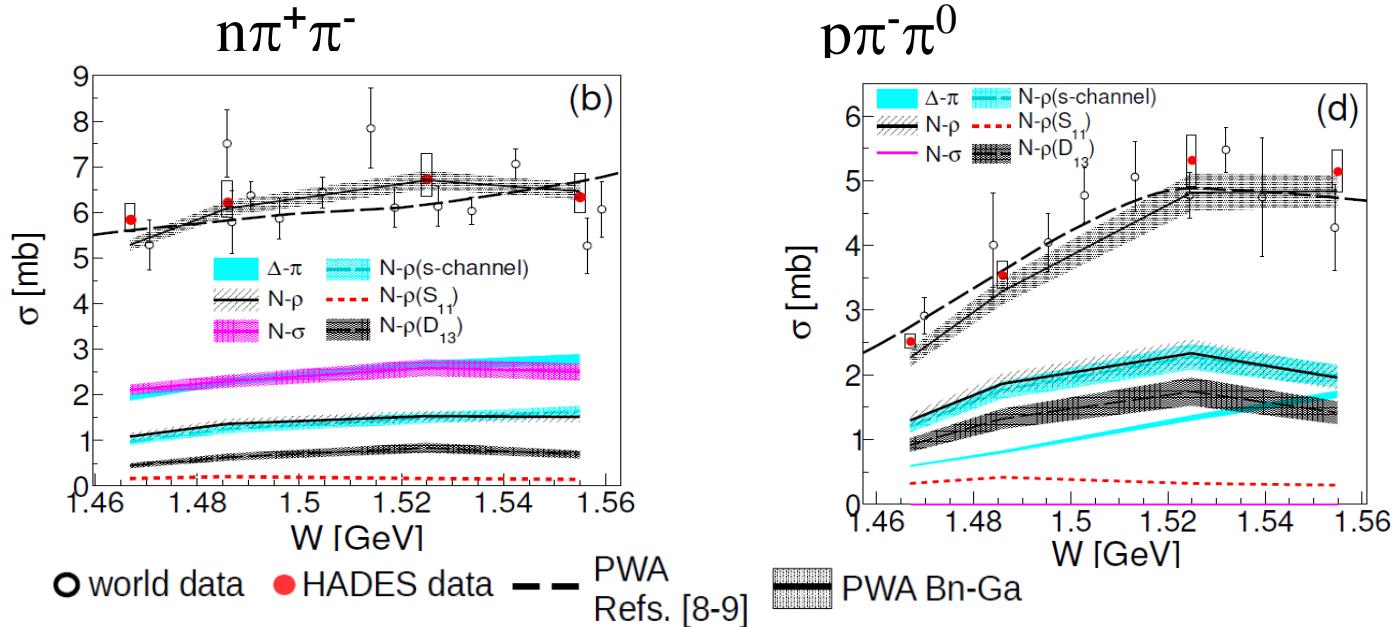
„subthreshold” – no ρ peak in $\pi^+ \pi^-$, $\pi^0 \pi^-$ mass distributions



Legend:
 — Δ-π - - - N-ρ - - - N-σ — N-ρ
 s-channel - - - N-ρ S₁₁ — N-ρ
 D₁₃

- Combined PWA fit with many other channels from $e^- p, \gamma p, Kp$ reactions
- Input solution: resonance properties fixed, except branches to VM
- Final solution (Log L) with HADES 2pion data Bn-Ga 2019
pwa.hisp.uni-bonn.de

Total Cross Sections



[8-9]

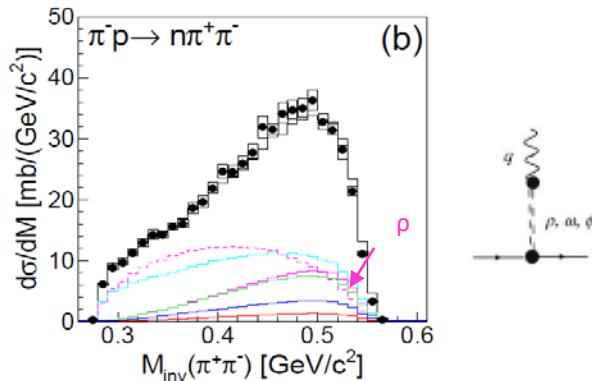
D. M. Manley *et al.* *Phys. Rev. D* 30 (1984) 904

D. M. Manley and E.M. Saleski, *Phys. Rev. D* 45,

- consistent description of HADES and world data
- $N(1520) \rightarrow N\pi$ BR = $12.2 \pm 2\%$ $N(1535) \rightarrow N\pi$ BR = $3.2 \pm 0.6\%$
- + BR for $\Delta\pi$ and $N\sigma$

(8 new entries in PDG'2020)

Test of Vector Dominance Model



Ideal case: $\rho \rightarrow \pi^+ \pi^-$ extracted from PWA
 Direct test of VDM models based on known ρ contribution

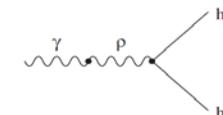
$$\left(\frac{d\sigma_{ee}}{dM_{ee}} \right)_{M_{ee}=M} = \left(\frac{d\sigma_{\pi\pi}}{dM_{\pi\pi}} \right)_{M_{\pi\pi}=M} \frac{\Gamma_{\rho \rightarrow e^+e^-}(M)}{\Gamma_{\rho \rightarrow \pi^+\pi^-}(M)}$$

Test of 2 VDM versions (equivalent for universal coupling $g_\rho = g_{\rho\pi\pi}$)

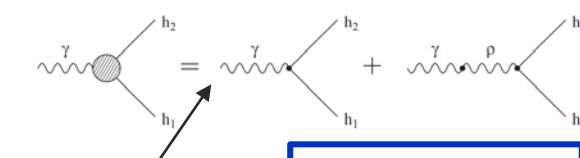
O'Connell Prog. Part. Nucl. Phys., Vol. 39, pp. 201-252, 1997

VDM2 : Sakurai, Phys. Rev 22 (1969) 981

- most commonly used in Heavy Ion models
- one single ρN coupling



$$\Gamma_\rho^{VDM2} = \left(\frac{M_0}{M} \right)^3 \Gamma_\rho^0$$



γ or point-like contribution

$$\Gamma_\rho^{VDM1} = \left(\frac{M}{M_0} \right) \Gamma_\rho^0$$

VDM1 : Kroll, Lee & Zuminio Phys. Rev. 157 (1967) 1376

- ρ contr. vanishes at $m_\gamma^*=0$,

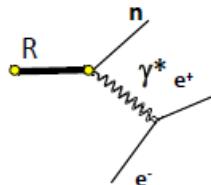
γN and ρN couplings fixed independently allows to fix $\text{BR}(R \rightarrow N\gamma)$ and $\text{BR}(R \rightarrow N\rho)$ consistently

B. Friman, H.J. Priner, Nucl. Phys. A 617 (1997) 496

- Phase between γ and ρ contributions to be fixed by data

QED reference

- Limit at $q^2=0$ given by $\pi^- p \rightarrow n \gamma$



Contribution of D13 to $\pi^- p \rightarrow \gamma n$ 27% (N1520 21%)
of S11 to $\pi^- p \rightarrow \gamma n$ 27% (N1535 15%)

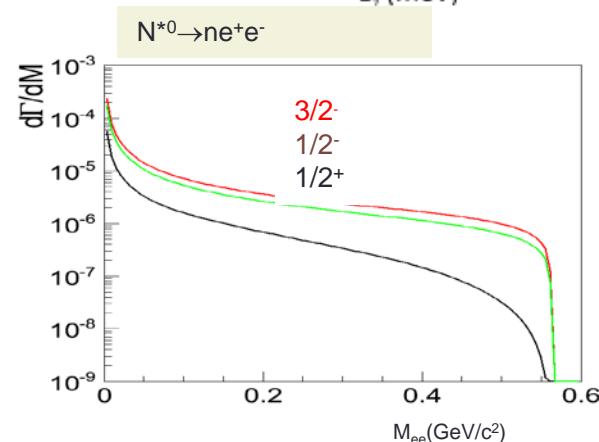
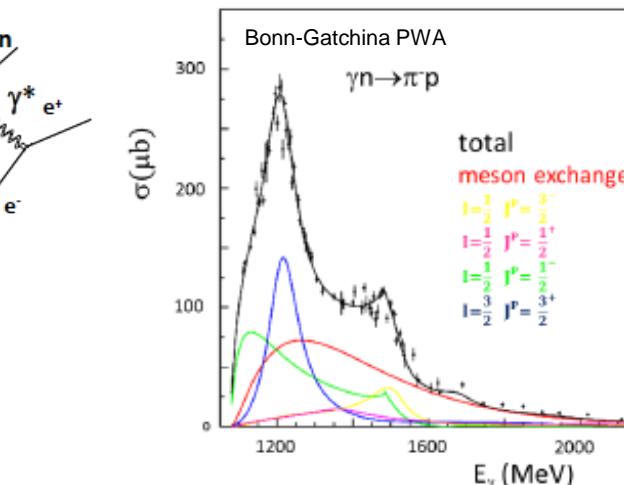
- Generalization to finite q^2 (QED)
M. Krivoruchenko et al., Ann. of Phys. 296, 299–346 (2002)

→ “point-like” description of $R \rightarrow N e^+ e^-$:

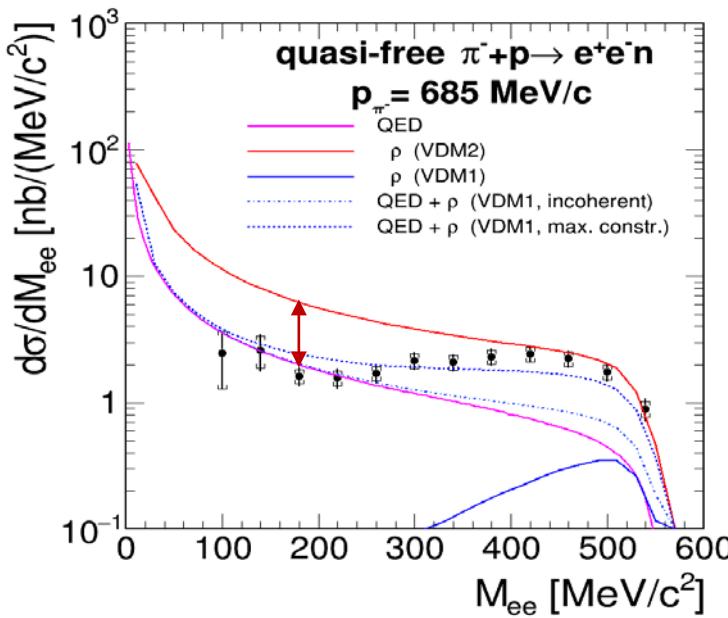
invariant mass distribution depends on J^P

$$\sigma(\pi^- p \rightarrow n e^+ e^-) \sim 1.35 \propto \sigma(\pi^- p \rightarrow n \gamma)$$

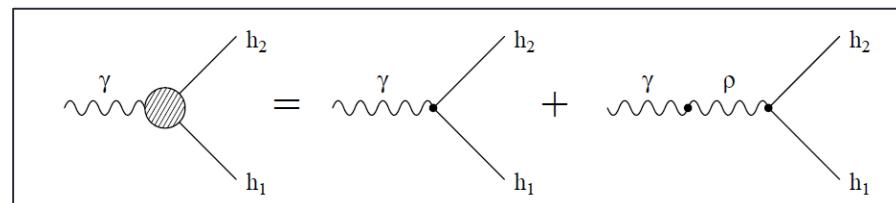
“ γ ” or “QED” reference



Data comparison with VDM2/VDM1 models



- QED reference constrained by $\pi^- p \rightarrow n \gamma$ data and available Bn-Ga solutions
- Model independent results:
 - Strong excess with respect to the point-like contribution-QED reference (up to a factor 5)
- VDM1/VDM2 test:
 - Large overestimation of measured yields with **VDM2**
 - Two component (**direct γ + VDM1**) with constructive interferences gives a **better description of the full spectrum**

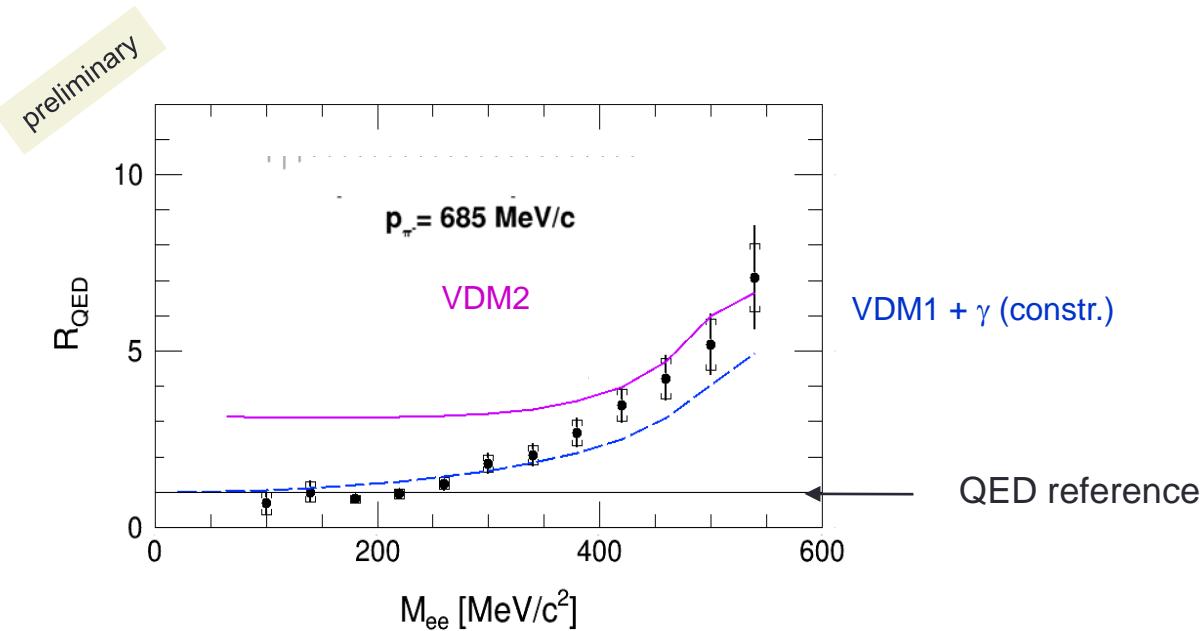


Effective Transition Form Factor

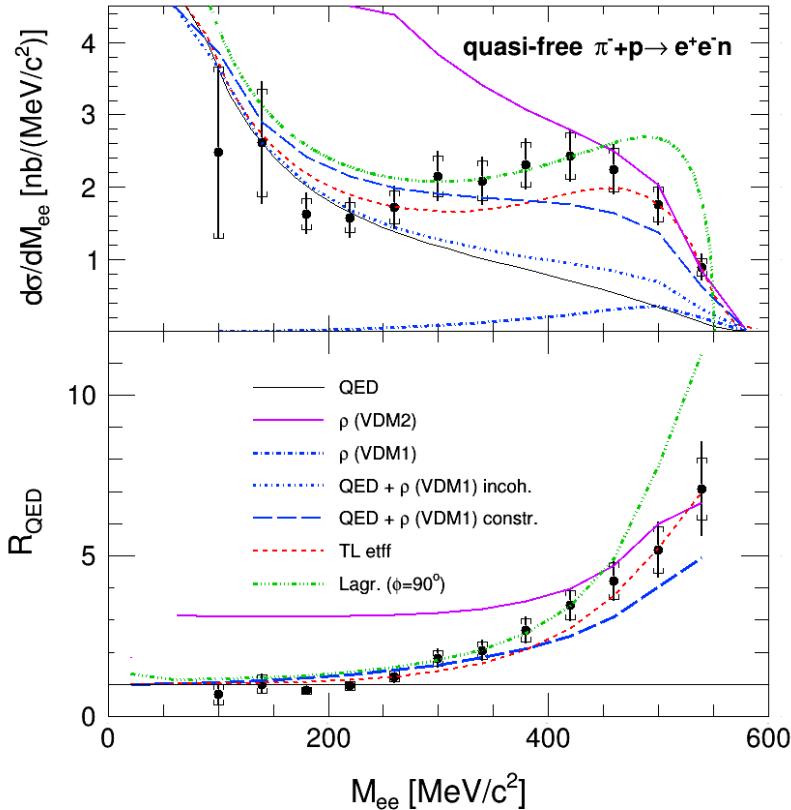
Effects of baryon time-like electromagnetic structure quantified by

$$R_{\text{QED}} = (d\sigma/dM) / (d\sigma/dM)_{\text{QED}}$$

« effective form factor » with strong contribution of N1520



Comparison to models (on-going)



Comparison with FF model:

G. Ramalho and M. T. Pena, Phys. Rev. D95, 014003 (2017)

- Dominant pion cloud contribution:
-> related to the pion electromagnetic form factor
(universal behavior of baryons ?)

Comparison with Lagrangian model:

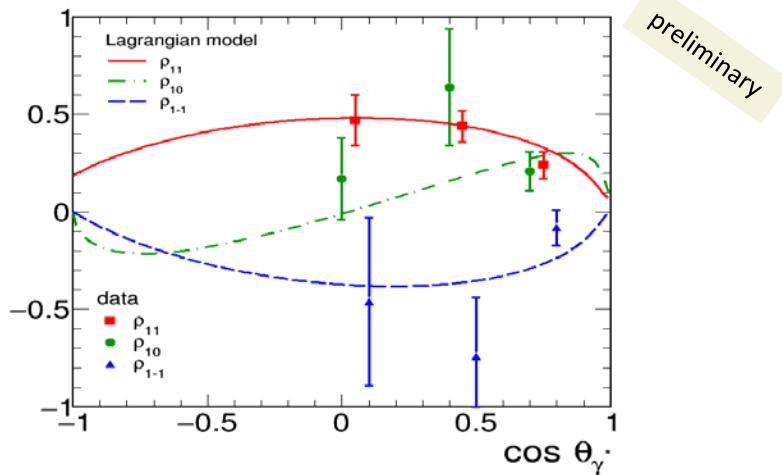
M. Zetenyi et al. PRC 104(2021) 1,015201

- based on VDM1, a coherent superposition of photon and ρ (shown with phase $\phi=90^\circ$)
- very promising, but needs to be confronted to $\pi\pi$ spectrum

spin density matrix elements from e^+e^- data

$$|A|^2 = 8p_{\gamma^*}^2(1 - \cos^2\theta_1 - \rho_{11}^H(3\cos^2\theta_1 - 1) + \sqrt{2}\sin(2\theta)\cos\varphi Re\rho_{10} + \sin^2\theta\cos(2\varphi)Re\rho_{1-1}^H)$$

$\rho_{11}, \rho_{10}, \rho_{1-1}$ extracted in 3 bins in $\cos\theta_\gamma$



sdme sensitive to :

- J^P : for $J=1/2$ no dependence on θ_γ
- $\rho_{10} = 0$ (only transverse polarization ρ_{11})
- Combination of G_E, G_M, G_C

$$\rho_{11} = \frac{1 + \lambda}{3 + \lambda} = \frac{A_\perp}{2A_\perp + A_\parallel}$$

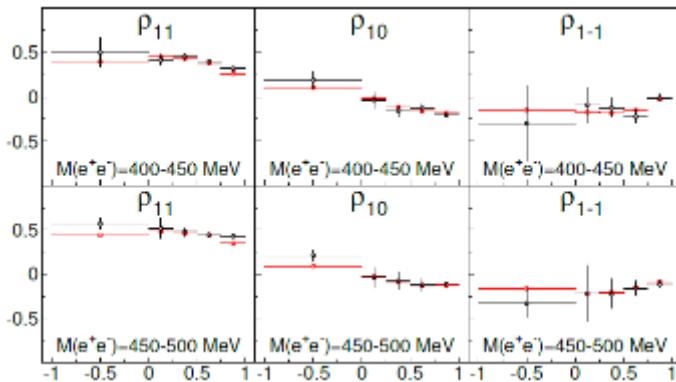
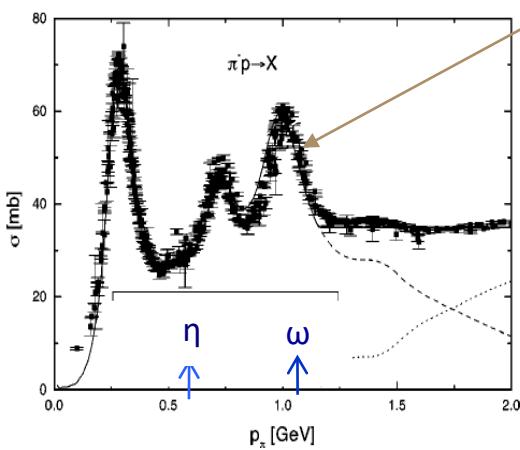
$$\lambda = \frac{\left|G_{E/M}^\pm\right|^2 - \left|G_C^\pm\right|^2}{\left|G_{E/M}^\pm\right|^2 + \left|G_C^\pm\right|^2}$$

$$\begin{aligned} J=1/2 \quad & A_\perp = \frac{l+1}{l} \left|G_{M/E}^\pm\right|^2 + (l+1)(l+2) \left|G_{E/M}^\pm\right|^2 \\ & A_\parallel = \frac{M^2}{m_*^2} \left|G_C^\pm\right|^2 \end{aligned}$$

Outlook : experiments with pion beam

21

Exp. proposal at GSI/SIS18 : 2023-2025: explore the **third resonance region** ($\sqrt{s} \sim 1.7 \text{ GeV}/c^2$)



1. Baryon meson couplings $\pi\pi N$, ωn , ηn , $K^0\Lambda$, $K\Sigma$, ...

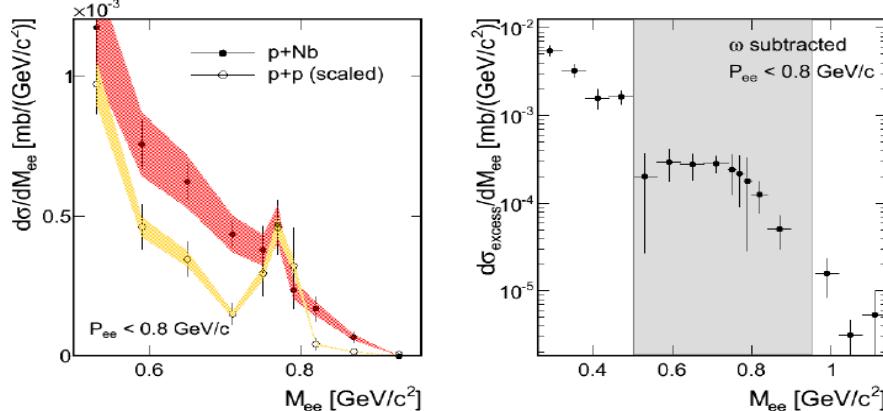
→ Inputs for Partial Wave Analysis

→ Many baryon structure issues: confirmation of $N'(1720)$, Cascade decays ($R \rightarrow R' \pi \rightarrow N \pi \pi$), „missing resonances“

2. Time-like electromagnetic baryon transitions $\pi p \rightarrow ne^+e^-$

- Broad range of $q^2 = (M_{ee})^2 \rightarrow$ sensitivity to form factors
- Check of Vector Dominance (both for p and ω)
- High prec. measurements of photon polarization - spin density matrix elements

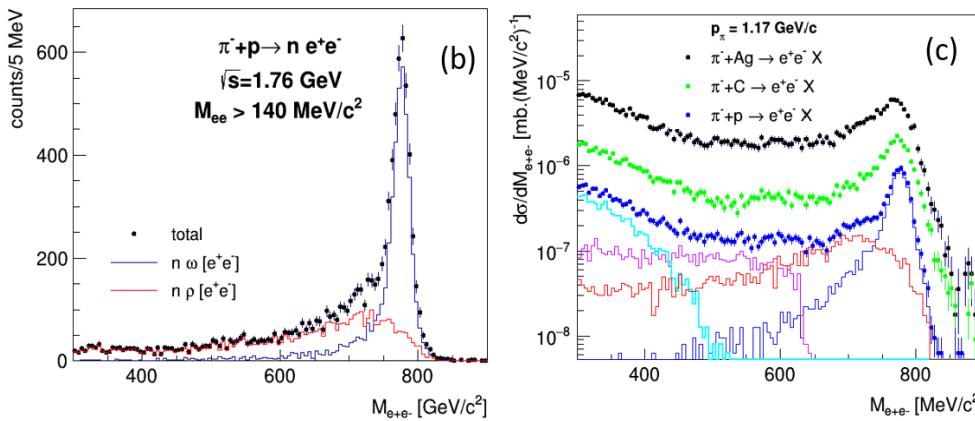
expected sensitivity for $N^*(1520)$



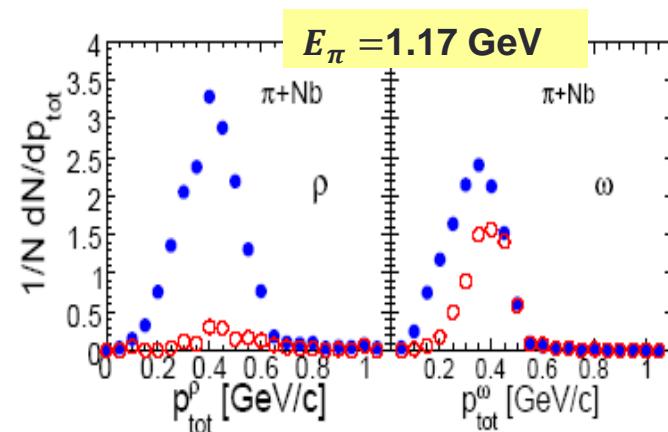
HADES PL715 (2012) 304

- $p + \text{Nb}$ @ 3.5 GeV
- Significant cold matter effect for slow γ^* ($p < 0.8 \text{ GeV}/c$)
- due to secondary πN reactions?

Projections for π^-A



- π^-A better sensitivity to **inside decays** and low momentum

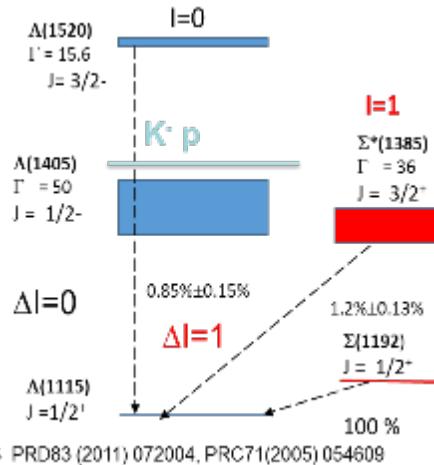


Outlook: p+p @ 4.5 GeV

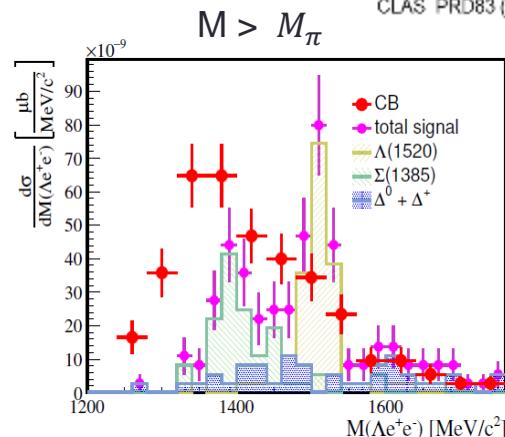
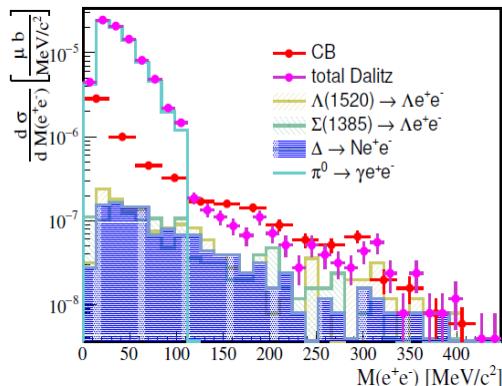
- **February 2022:** pp @ 4.5GeV

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

- Hyperon Dalitz decays: $\text{pp} \rightarrow \text{pK}^+ \Lambda(1520)$ [$\Lambda e^+ e^-$] [$\Lambda \gamma$]
 $\text{pp} \rightarrow \text{pK}^+ \Sigma(1385)$ [$\Lambda e^+ e^-$] [$\Lambda \gamma$]
- Ξ , $\Lambda(1405)$, $\Lambda(1520)$ production and decays
- Λ - Λ correlations
- dilepton production (higher mass baryon resonance decays, pair production above ϕ , mass,...)



Projections for Hyperon Dalitz decays



CLAS PRD83 (2011) 072004, PRC71(2005) 054609

Summary

- ✓ VM (ρ) do play an important role in baryon – virtual photon couplings
- ✓ Baryon resonance studies with the GSI pion beam + HADES detector (2nd resonance region $\sqrt{s} \sim 1.5$ GeV)
 - improved knowledge of hadronic- meson (ρ) couplings (new BR measurements!)
 - very new information on time-like electromagnetic baryon transitions

First test of Vector Dominance Model below 2π threshold and time-like electromagnetic transition form factor models → Important inputs for medium effects of ρ meson calculations

- ✓ 2022: Electromagnetic decays of higher mass N^*/Δ resonances and hyperons $Y \rightarrow \Lambda\gamma$, $Y \rightarrow \Lambda e^+e^-$ in pp reactions

2023-2025 : pion beam experiment in the third resonance region

- Investigate heavier resonances $N(1620)$, $N(1720), \dots$ in e^+e^- channels and many hadronic channels, e.g. $\pi^- p \rightarrow \omega/\rho n$, $\pi^- p \rightarrow \eta n$, $K^0 \Lambda$, $K \Sigma, \dots$
- Cold matter effects for VM with πA

Back-up

Polarisation of resonances in pion induced reactions

Z- CMS quantization axis

$$\vec{L} \perp \text{R.P}$$

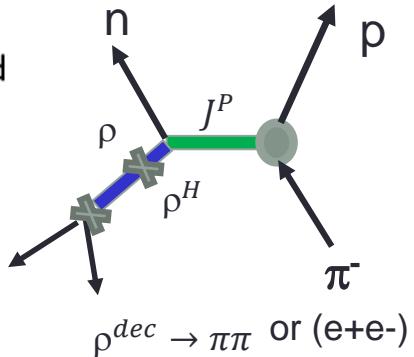
- π is spinless hence

$$J_Z^{N*} = S_z^N = \pm \frac{1}{2}$$

- Polarization for $J^{N*} \geq \frac{3}{2}$ expected (only spin projections $\pm \frac{1}{2}$) allowed

$$|A|^2 = \sum_{\Lambda\Lambda'} \rho_{\Lambda\Lambda'}^{(H)} \rho_{\Lambda\Lambda'}^{(dec)}$$

for $e+e-$



$$\rho^{dec} \rightarrow \pi\pi$$
 or $(e+e-)$

ρ^{dec} known, find ρ^H from data

$$|A|^2 = 8p_{\gamma*}^2 (1 - \cos^2\theta_1 - \rho_{11}^H (3\cos^2\theta_1 - 1) + \sqrt{2}\sin(2\theta)\cos\varphi \operatorname{Re}\rho_{10} + \sin^2\theta\cos(2\varphi) \operatorname{Re}\rho_{1-1}^H)$$

Models: GSI/Budapest

E.Speranza et al.. PLB 764(2017)282

$$\rho^{dec}$$

$$(e+e-)$$

$$\rho^H$$

$$\rho_{10}$$

$$\rho_{1-1}^H$$

$$\rho_{1-1}$$

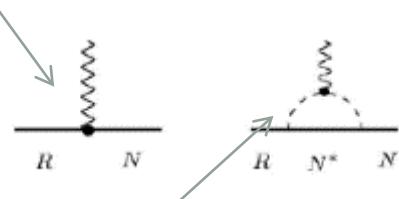
$$\rho_{1-1}</$$

Baryon Dalitz decay: Form factor models

Recent model for N-N(1520) transition *G. Ramalho and M. T. Pena, Phys. Rev. D95, 014003 (2017)*

Quark core contribution :

- Quark form factors inspired by VDM

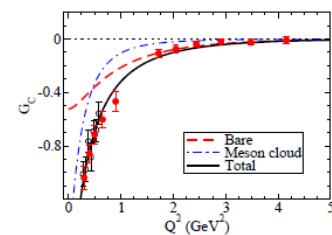
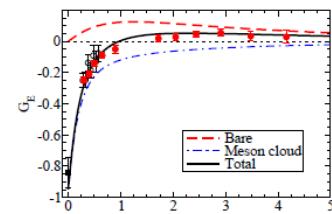
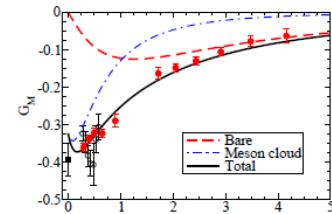


Meson cloud contribution:

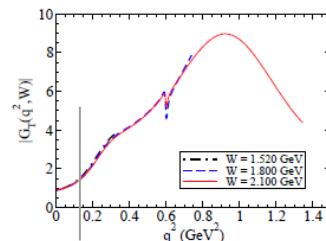
- Based on pion electromagnetic form factor
- Dominant contribution in the time like region

Similar model for N-N(1535) transition
Phys. Rev. D101 (2020) 114008

Parameters of the model fitted to space-like data

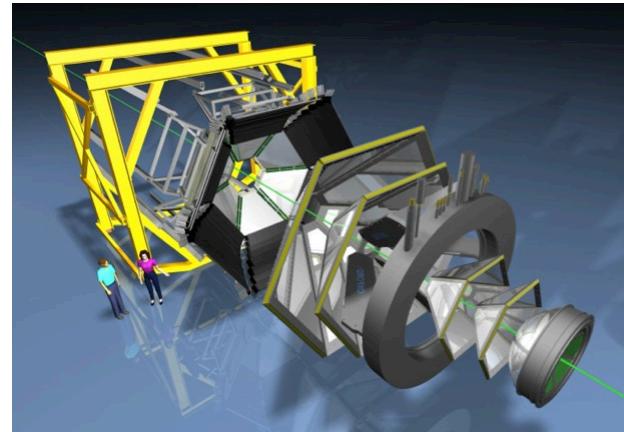
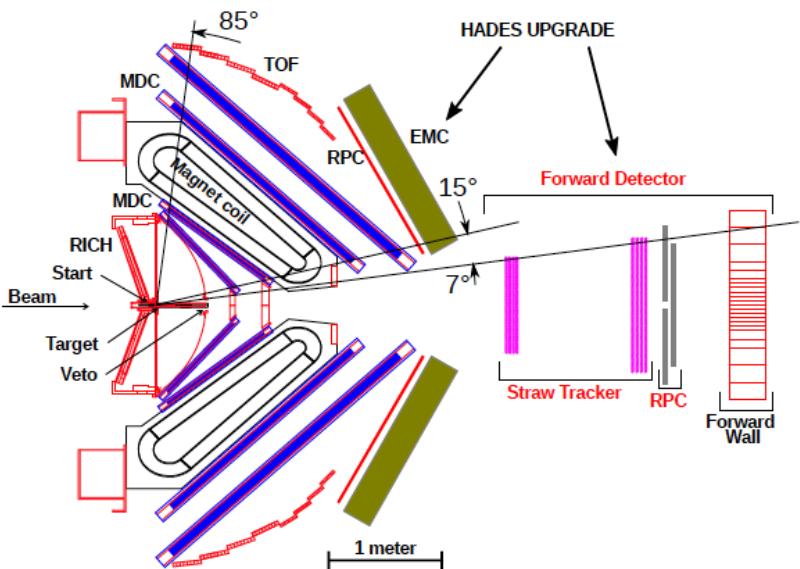


Predictions for the time-like region



$$|G_T(q^2, W)|^2 = 3|G_M(q^2, W)|^2 + |G_E(q^2, W)|^2 + \frac{q^2}{2W^2}|G_C(q^2, W)|^2.$$

- ✓ Spectrometer with $\Delta M/M - 2\%$ at p/ω @ GSI/FAIR
- ✓ electrons : RICH (hadron blind)
- ✓ hadrons: TOF & dE/dx vs p
- ✓ **2004-2014:** HI (A+A $\sqrt{s} \sim 2.4\text{-}2.6$ GeV)
- $p+p, d+p, p+A \sqrt{s} = 2.4\text{-}3.0$ GeV $\pi+p \sqrt{s}= 1.5$ GeV



Upgrade 2018/2019

- New RICH photon det (HADES/CBM)
- Forward tracking straws +RPC – Λ/Ξ reconstruction in pp/pA (HADES/PANDA)
- Elec. Calorimiter (lead glass)- neutral mesons
- Planned: 200 kHz DAQ , **10 × count rate increase**

PWA results—8 newPDG entries!



$$\Gamma(N(1520) \rightarrow \Delta(1232)\pi, S\text{-wave})/\Gamma_{\text{total}}$$

VALUE (%)	DOCUMENT ID
12.1 ±2.1	ADAMCZEWSKI- 2020

$$\Gamma(N(1520) \rightarrow \Delta(1232)\pi, D\text{-wave})/\Gamma_{\text{total}}$$

VALUE (%)	DOCUMENT ID
6 ±2	ADAMCZEWSKI- 2020

$$\Gamma(N(1520) \rightarrow N\rho, S=3/2, S\text{-wave})/\Gamma_{\text{total}}$$

VALUE (%)	DOCUMENT ID
11.8 ±1.9	ADAMCZEWSKI- 2020

$$\Gamma(N(1520) \rightarrow N\rho, S=1/2, D\text{-wave})/\Gamma_{\text{total}}$$

VALUE (%)	DOCUMENT ID
0.4 ±0.2	ADAMCZEWSKI- 2020

$$\Gamma(N(1520) \rightarrow N\sigma)/\Gamma_{\text{total}}$$

VALUE (%)	DOCUMENT ID
7 ±3	ADAMCZEWSKI- 2020

ρN coupling not present in PDG since 2016

$$\Gamma(N(1535) \rightarrow \Delta(1232)\pi, D\text{-wave})/\Gamma_{\text{total}}$$

VALUE (%)	DOCUMENT ID
3 ±1	ADAMCZEWSKI- 2020

$$\Gamma(N(1535) \rightarrow N\rho, S = 1/2)/\Gamma_{\text{total}}$$

VALUE (%)	DOCUMENT ID
2.7 ±0.6	ADAMCZEWSKI- 2020

$$\Gamma(N(1535) \rightarrow N\rho, S=3/2, D\text{-wave})/\Gamma_{\text{total}}$$

VALUE (%)	DOCUMENT ID
0.5 ±0.5	ADAMCZEWSKI- 2020