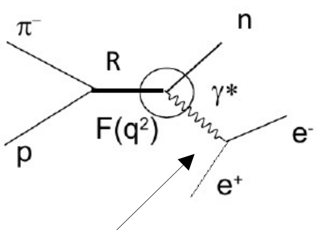
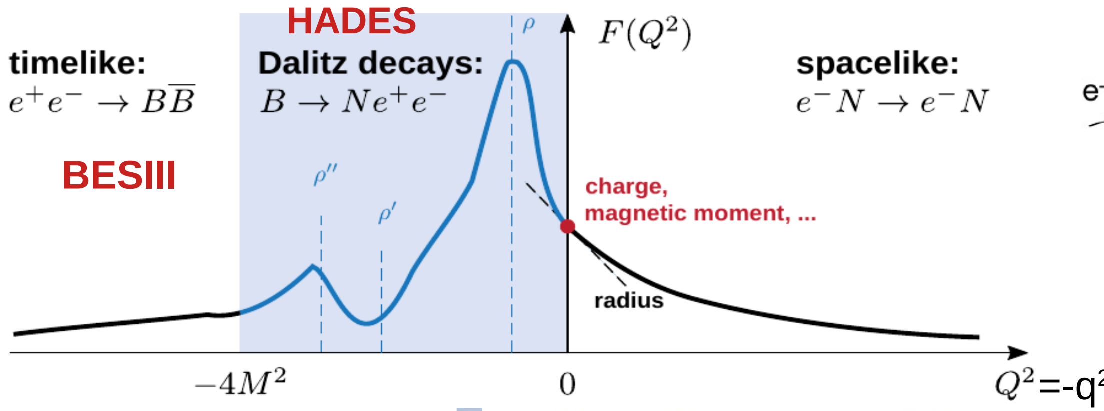
Studies of Time-like Baryon Transition Form Factors with HADES

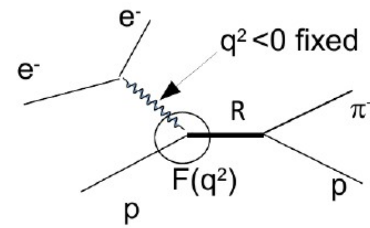
Izabela Ciepał

Electromagnetic structure of baryons



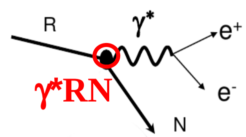
$4m_{ee}^2 < q^2 < (M_R - M_n)^2$ variable





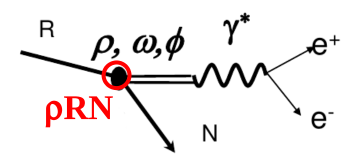
CLAS/JLab, MAMI, ELSA, JLab-Hall A, ...

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



R → N Transition Form Factor

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



QED
transition
of point-like
particles

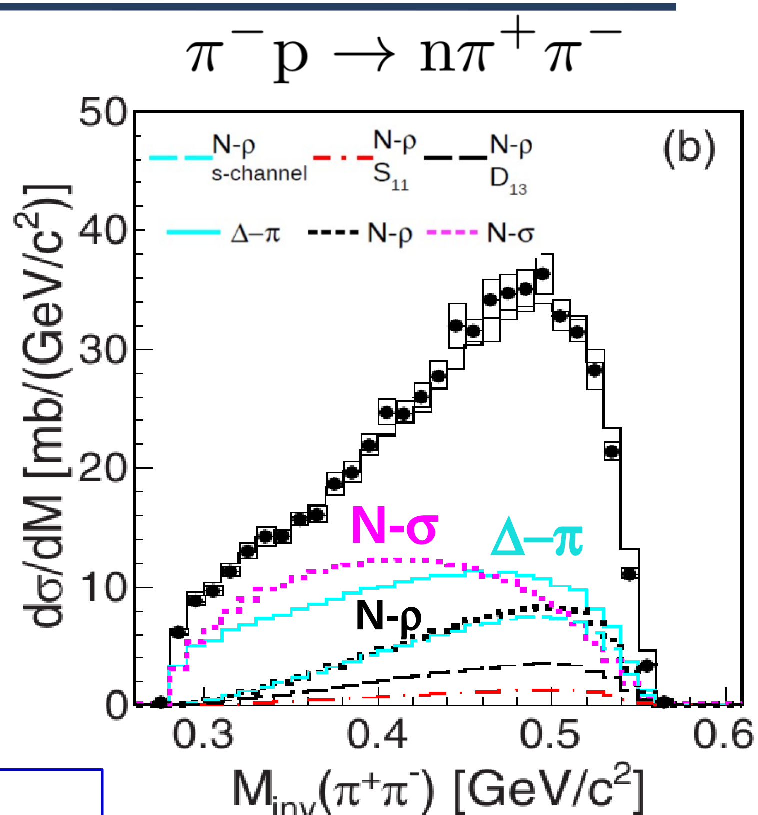
$G_{M/E/C}$: Form-Factors ($A_{1/2}$, $A_{3/2}$, $S_{1/2}$)
internal structure of hadrons

Combined Partial Wave Analysis of hadronic 2-pion channels and Dalitz decays

Bn-Ga PWA: *pwa.hisp.uni-bonn.de*

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



ρ meson production:

- **s-channel D_{13} (N(1520) $3/2^-$) dominant contribution**
- N(1520)→ Nρ BR=12.2 +/- 2 %
- N(1535)→ Nρ BR=3.2 +/- 0.6 %

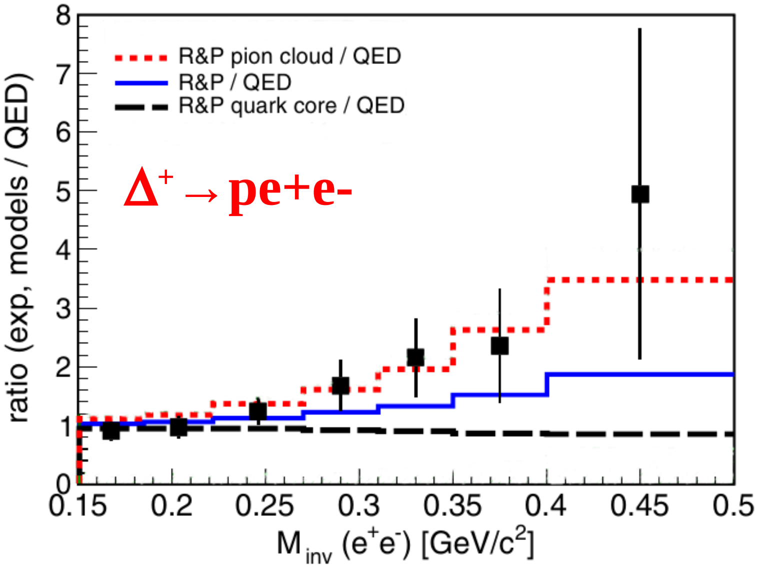
8 new entries:
branching ratios of
N(1440)
N(1535)
N(1520)
to 2π channels (Δπ, Nρ, Nσ)

reference ρ mass spectrum for e+e- analysis

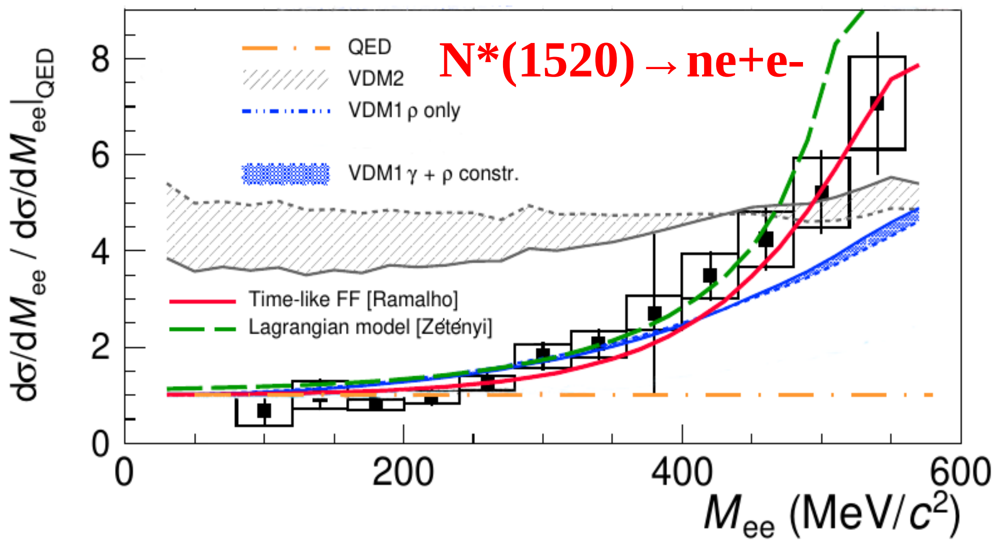
Time-like transition form factors for nucleon resonances

pp → ppe+e- @1.25 GeV

calculations T. Pena & G. Ramalho



π⁻p → ne+e- @0.7 GeV/c



- VMD2 (*strict* VMD) overestimates data below 400 MeV
- 2-component VMD (VMD1) gives reasonable description
- Z&W: Lagrangian model – very promising
- R&P: Time-like FF - dominant pion cloud contribution (pion emFF)

→ S. Leupold: FF based on dispersive framework

effective eTFF

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

QED

Virtual photon polarization

HADES Coll. arXiv:2205.15914 [nucl-ex]

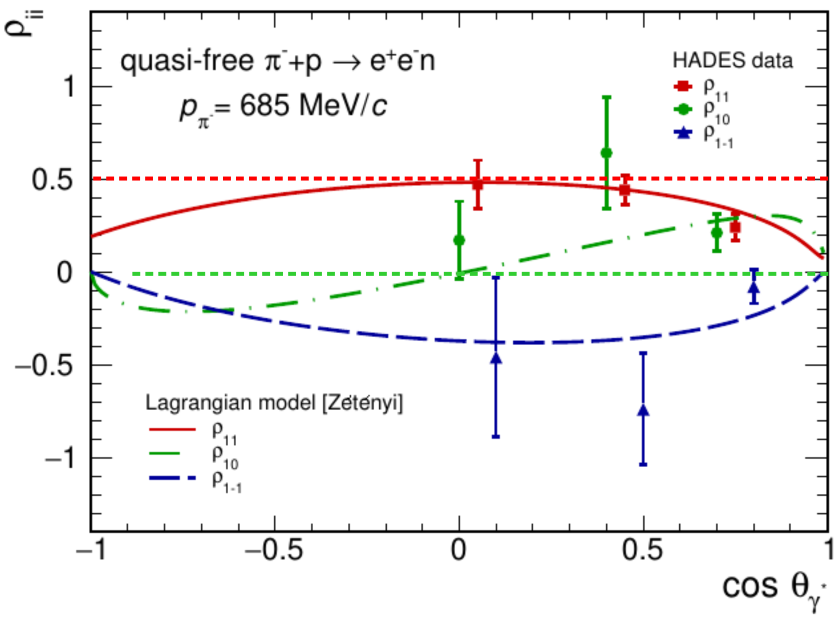
$$\frac{d^3\sigma}{dM_{ee}\,d\Omega_{\gamma_*}\,d\Omega_e} \sim |A|^2 = \frac{e^2}{Q^4}\sum_{\Lambda\Lambda'} \rho^{(H)}_{\Lambda\Lambda'}\,\rho^{(dec)}_{\Lambda\Lambda'}$$

QED: $\gamma^* \rightarrow e^+e^-$

$R \rightarrow N + \gamma^*$

$$|A|^2 \propto 8k^2\left[1-\rho_{11}+(3\rho_{11}-1)\cos^2\Theta+\sqrt{2}Re\rho_{10}\sin 2\Theta\cos\phi+Re\rho_{1-1}\sin^2\Theta\cos 2\phi\right]$$

- **SDME ρ_{11}, ρ_{10}, ρ_{1-1} extracted from experiment taking into account acceptance and efficiency (A. Sarantsev) in 3 bins in $\cos\theta_{\gamma^*}$**



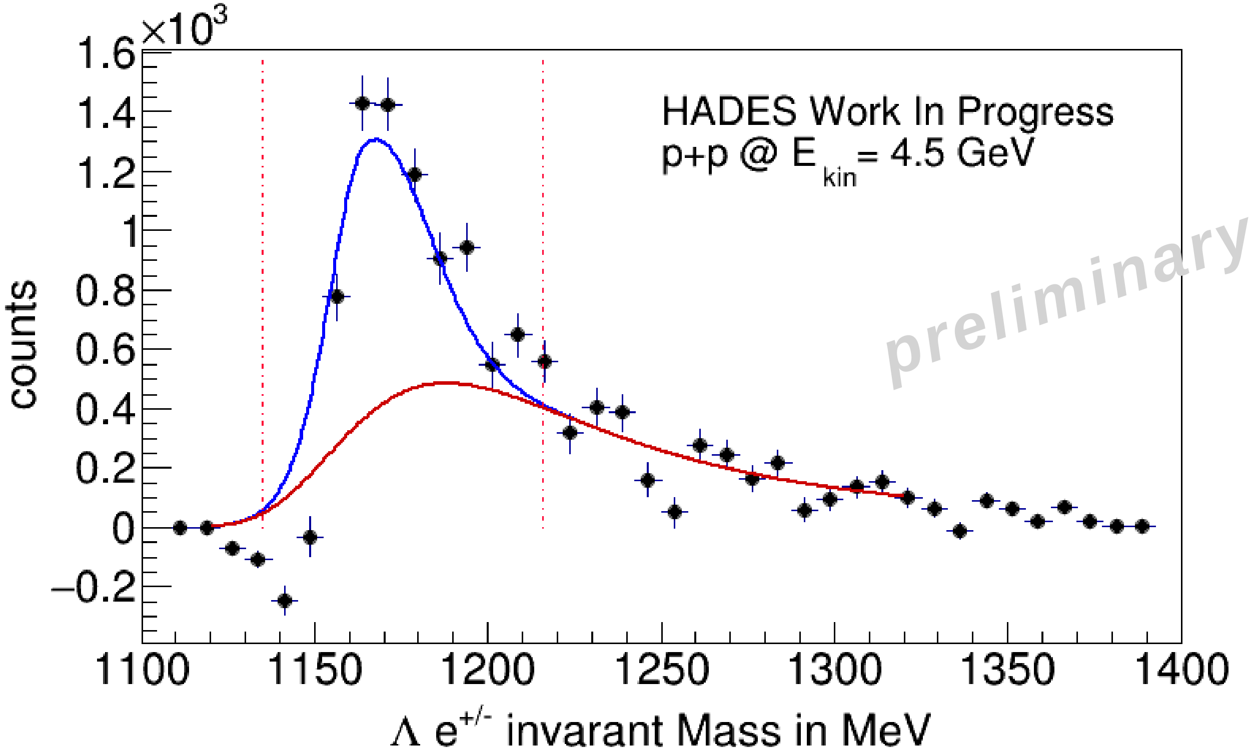
- $\rho_{11}=0.5$, $\rho_{10}=0$ for transverse polarization
- (real photon)
- we see angular dependence
  => contribution from a virtual photon
- => contributions of spins larger than ½: N(1520) resonance
- **more precise data needed !**

Backup

Time-like transition form factors for hyperons

$pp \rightarrow pp\pi^- e^+e^-$ @4.5 GeV — ***Jana Rieger (PhD)***

$\Sigma^0(1192) \rightarrow \Lambda e^+e^-$ Dalitz decay



Dalitz decays of baryon resonances

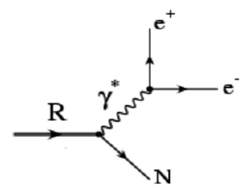
Vector Meson Dominance Models (VMD)

hadrons ⟷ photons

Meson Dalitz decays: (Crystal Ball/TAPS, A2, Na60 data), many theoretical studies

Baryons Dalitz decays: (Hades), most of the calculations of eTFF are based on VMD

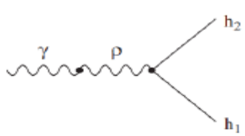
➔ **QED "point-like"** R-γ^* vertex



M. Zetenyi et al., PRC 67, 044002 (2003)

➔ ***strict* VMD (VMD2)**

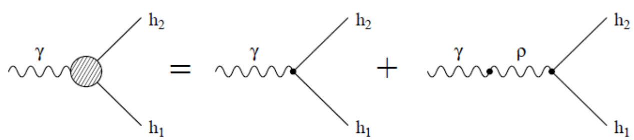
- Nρ coupling
- used in HI transport models



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

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

➔ **2-component VMD (VMD1)**



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

- Nρ and Nγ couplings
- used in calculations of in-medium spectral functions

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

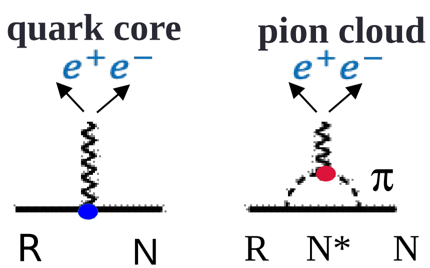
etFF of baryons: models

Covariant quark model +VMD

T. Pena & G. Ramalho

N-Δ(1232): *Phys.Rev. D93, 033004 (2016)*
N-N(1520): *Phys. Rev. D95, 014003 (2017)*
N-N(1535): *Phys.Rev. D101, 114008 (2020)*

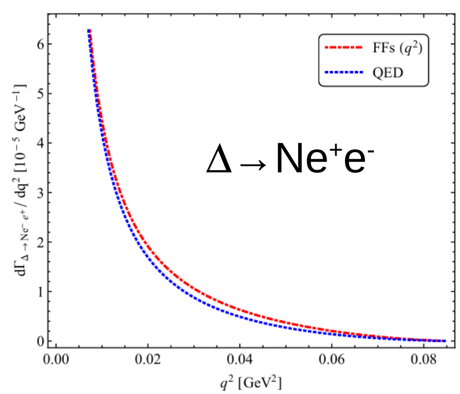
VMD:
quark FF
pion FF



Dispersion theory

S. Leupold et al.

S. Leupold
arXiv:2401.17756 (2024)



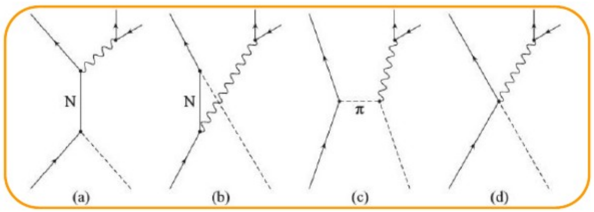
Two-component Lagrangian model

M. Zetenyi & G. Wolf

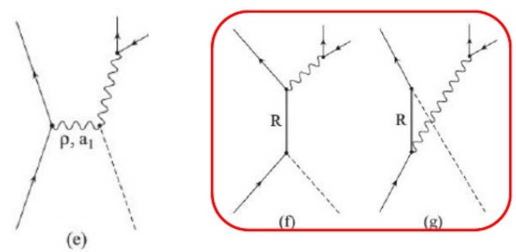
PRC 86, 065209 (2012)
PRC 104, 015201 (2021)

microscopic calculations of $\pi N \rightarrow Ne^+e^-$

Born terms

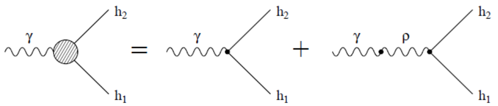


baryon resonances



N*(1440)
N*(1520)
N*(1535)

2-component VMD:



interference between γ and ρ contributions

Virtual photon polarization

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

angular distribution of e+e- → polarization of γ* → spin density matrix elements ($\rho_{\Lambda\Lambda}$)

πN → Nγ* → Ne+e-

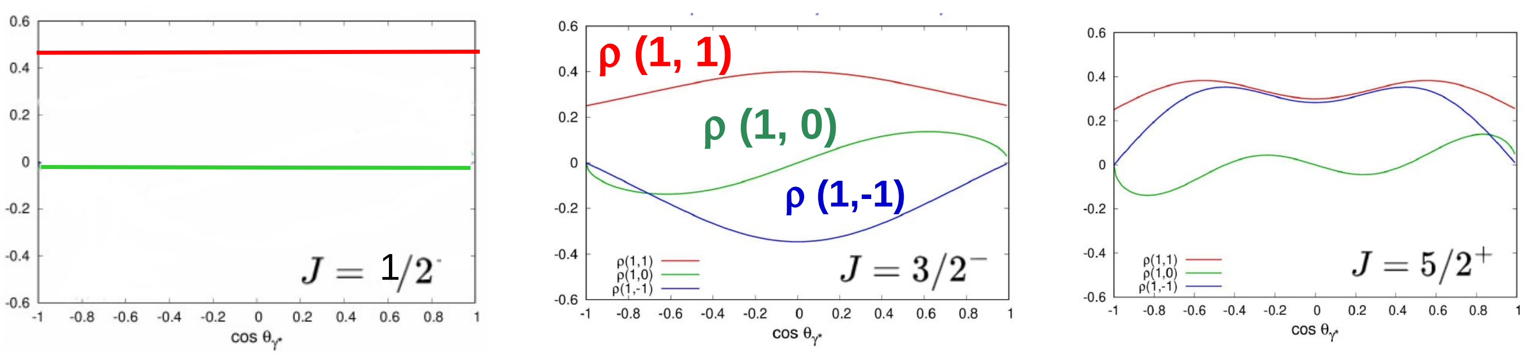
$$\frac{d^3\sigma}{dM_{ee}\,d\Omega_{\gamma_*}\,d\Omega_e} \sim |A|^2 = \frac{e^2}{Q^4}\sum_{\Lambda\Lambda'} \rho^{(H)}_{\Lambda\Lambda'}\,\rho^{(dec)}_{\Lambda\Lambda'}$$

QED: γ* → e+e-

R → N + γ*

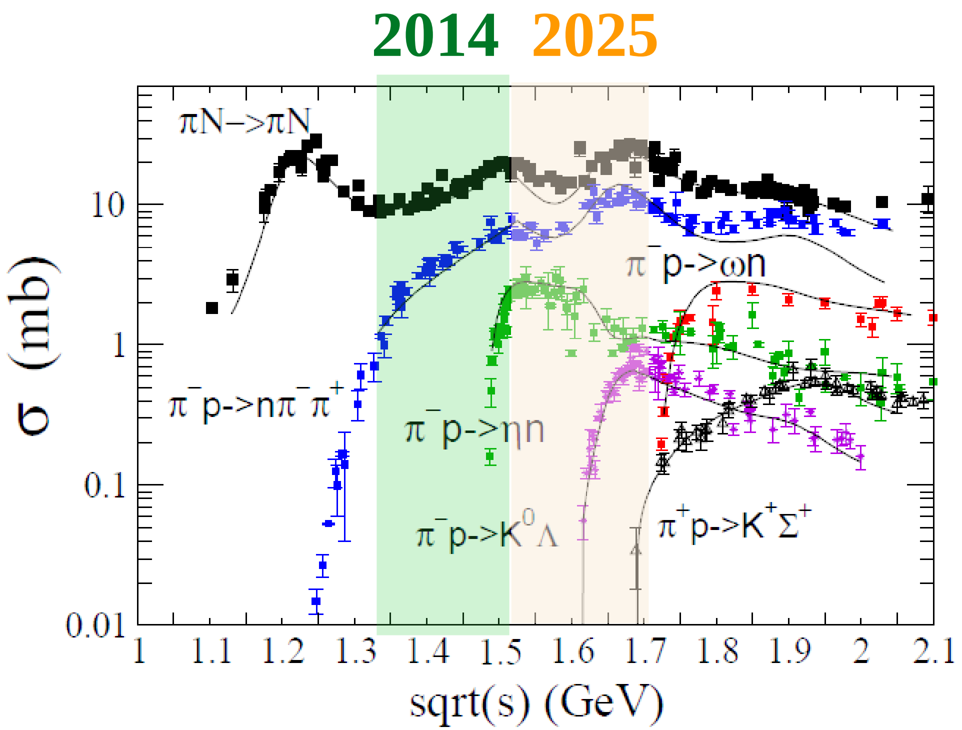
Angular distribution of the lepton pair:

$$|A|^2 \propto 8k^2\left[1-\rho_{11}+(3\rho_{11}-1)\cos^2\Theta+\sqrt{2}Re\rho_{10}\sin 2\Theta\cos\phi+Re\rho_{1-1}\sin^2\Theta\cos 2\phi\right]$$



- $\rho_{\Lambda\Lambda}$ depends on γ* polarization
- $\rho_{\Lambda\Lambda}$ are combination of G_E, G_{M}, G_C
- **the angular distribution is sensitive to J^P of the resonance**
- can be obtain from fit to the experimental angular distribution

OUTLOOK
HADES Physics Program with Pion Beams
explore the 3rd resonance region $\sqrt{s} = 1.7$ GeV/c^2



Beam energy scan 2025: continuation and extension to 3rd resonance region

1) Baryon-meson couplings:

2) → ππN, ωn, ηn, $K^0\Lambda$, $K^0\Sigma$, …

3) including neutral mesons (ECAL),
→ ρR couplings S31(1620),

4) D33(1700), P13(1720),..

5) Hyperon polarization: Λ, Σ

6) Exotic states:
→ the lowest glueballs, 4q systems, hybrids , bound states of mesons: $f_0(500)$, $f_0(980)$, $a_0(980)$, f0(1370),…
→ unknown region of invM(ππ) ~1 GeV very precise data needed !

CBM@ SIS100 pp @ 30 GeV
- prod. cross sec. higher than at SIS18: σ (Σ*,Λ*) ~1 mb
- much higher luminosity