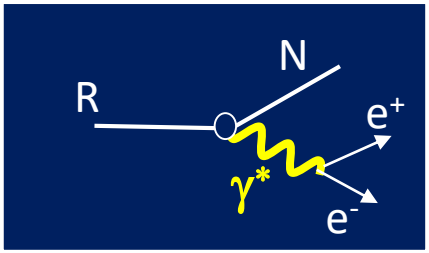
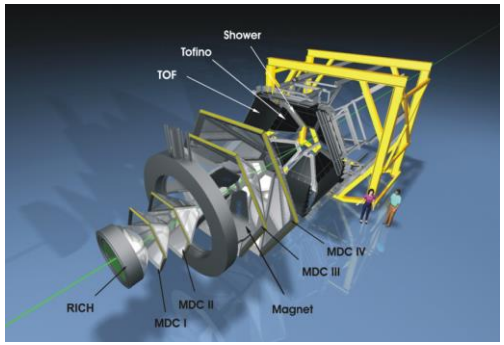
# *Time like baryon transition studies with HADES*

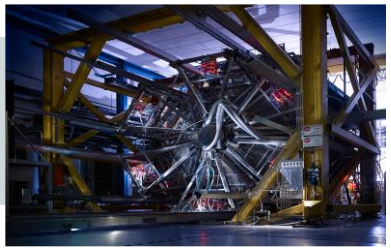
Béatrice Ramstein, IJCLab, Orsay, France
*for the HADES collaboration*

**QNP2022 - The 9th International Conference on Quarks and Nuclear Physics**



# Outline



- **General motivations of the HADES experiment at GSI**
  ***From dense hadronic matter to hadron structure studies***

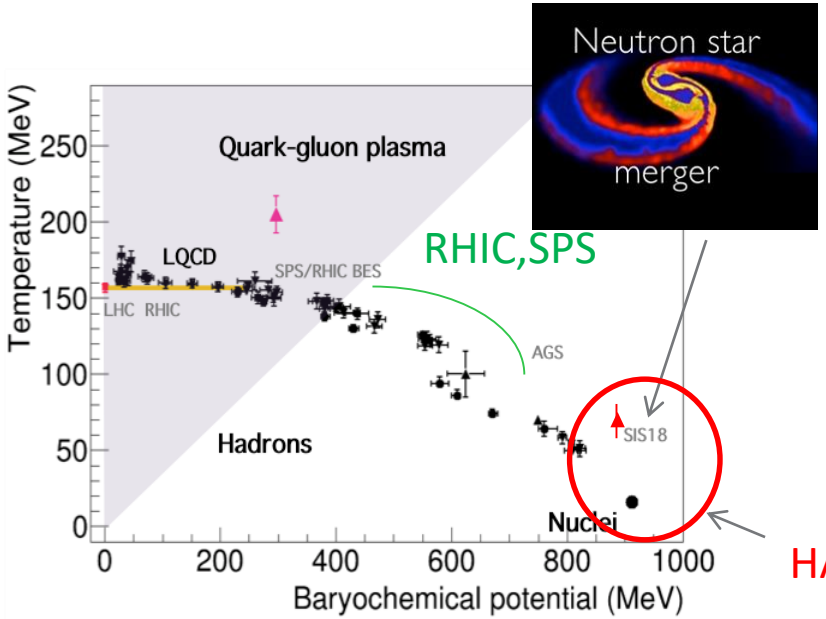
- **Results for time-like electromagnetic baryon transitions in pion beam experiments**

***to be completed by***

**Rafal Lalik** , Hadron structure , Sept.6 15:25 **Hyperon studies**
**Szymon Harabasz,** Heavy Ions, Sept.8 12:30 **medium effects in heavy-ion collisions**
**Fatima Hojeij**, Heavy Ions, Sept. 8 13:35, **exclusive channels in π−+C at 0.7 GeV/c**

- **Conclusions**

# HADES: exploring dense QCD matter




HADES

T. Galatyuk, NPA-D-18-00411 (2018) QM18

- ❑ Equation-of-State:

First order transition ? Search for a critical point

- ❑ Chiral symmetry restoration
- ❑ Microscopic structure of baryon dominated matte

Role of baryonic resonances, hyperons

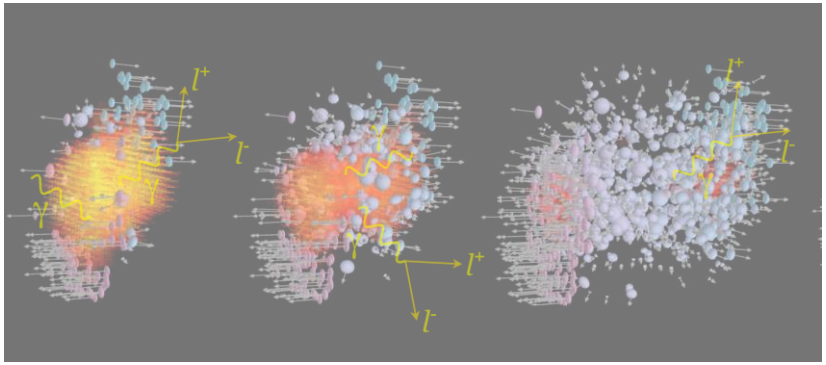
- ❑ Complementary to SPS,RHIC,..

A+A: 1-3A GeV

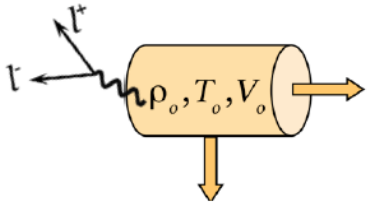
$\sqrt{s}$=2-2.4 GeV

Observables:

- ✓ Correlations and fluctuations
- ✓ Collective effects
- ✓ Strangeness
- ✓ Dileptons



# Emissivity of baryon rich matter



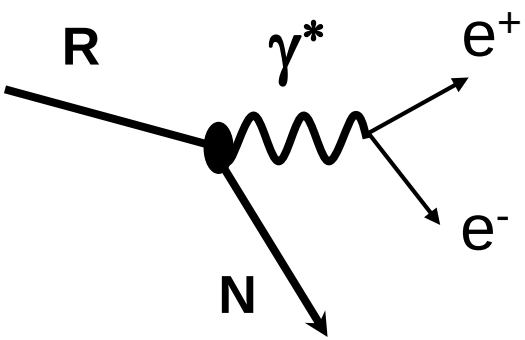

*McLerran, Toimela, PRD 31, 545 (1985)*

- Moderate temperatures: $T < 90\ MeV$
- Baryon-dominated system ($N_\pi/A_{\text{part}} \approx 10\%$)
- Important role of vector mesons for low mass dilepton production

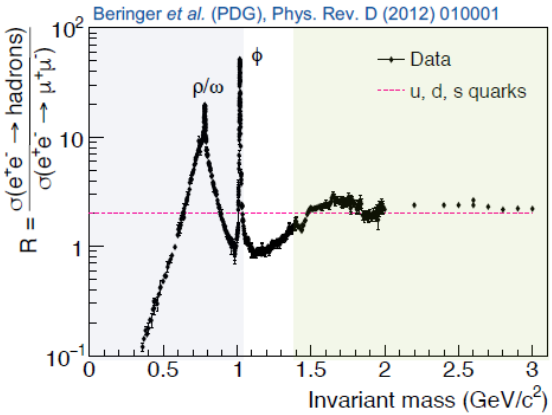
$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{em}^2}{\pi^3 M^2} L(M^2) f^B(q \cdot u; T)\ Im\Pi_{em}(M, q; \mu_B, T)$$

Lepton phase space factor — Thermal Bose distribution — Spectral function

## Baryon Dalitz decay




## Vector mesons

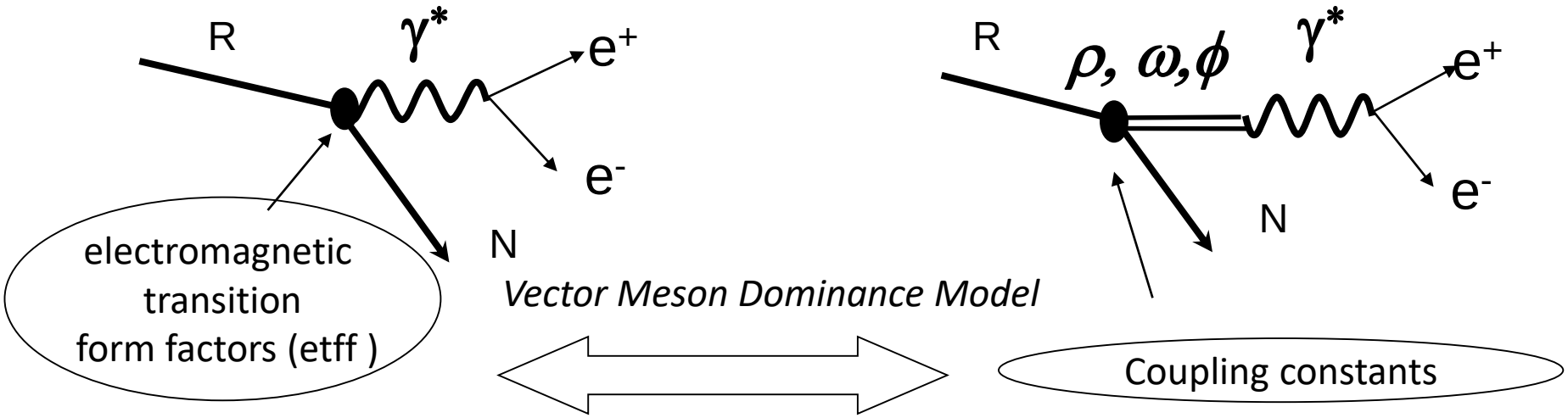



Coupling of baryons to vector mesons is crucial

# Vector Meson Dominance in the baryon sector (I)

Dalitz decay of baryonic resonances

vector meson decay




**Meson** Dalitz decays : (numerous data Crystal Ball/TAPS, A2, Na60 data)
many theoretical studies trying to connect VMD and the microscopic properties of QCD
*e.g. G. Adlarson et al., Phys. Rev. C95, 035208 (2017)*

**Baryon** Dalitz decays : almost unexplored, most calculations of etFF are based on Vector Meson Dominance.

# Vector Meson Dominance in the baryon sector (II)

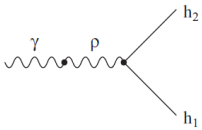
*O'Connell Prog. Part. Nucl. Phys., Vol. 39,pp. 201-252, 1997*

Various versions of VDM: equivalent for universal coupling

VDM2 : « strict VDM »

*Sakurai, Phys. Rev 22 (1969) 981*

- most commonly used in Heavy Ion transport models
- one single ρNN* coupling
- Overestimation of baryon radiative decays

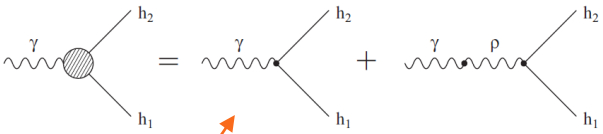



$$\Sigma_\rho^{VDM2} = \left(\frac{M_\rho}{M}\right)^2 \Sigma_\rho^0$$

VDM1 : »two-component »

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

- ρ contr. vanishes at $m_\gamma^*=0$,
- γN and ρN couplings fixed independently
- Phase between γ and ρ contributions to be fixed by data

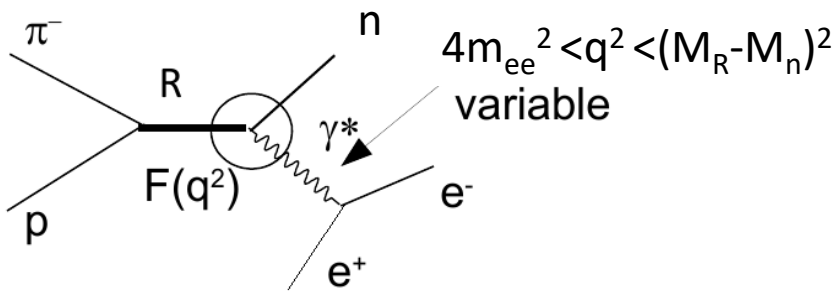



γ coupling

$$\Sigma_\rho^{VDM1} = \left(\frac{M}{M_\rho}\right)^2 \Sigma_\rho^0$$

# Baryon electromagnetic transitions

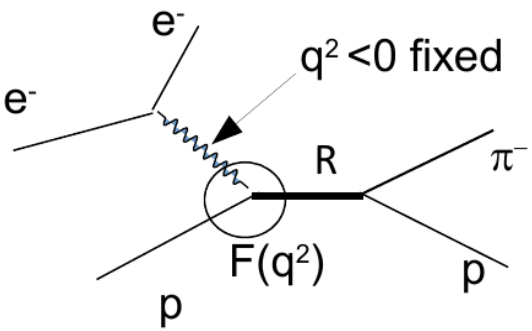
**Time-like electromagnetic form factors**




No data are available

Limit at $q^2$=0 given by real photon decay

**Space-like electromagnetic form factors**

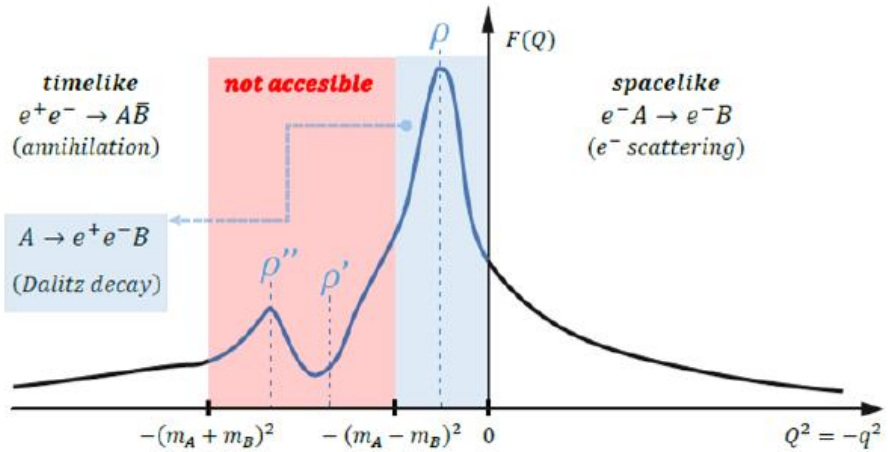



Data from Jlab (CLAS) up to $-q^2 = 4$ GeV$^2$

Exploration of higher $q^2$ with CLAS12

***A. D'Angelo Sept.5 10:30***

***K. Joo Sept.5 15:00***




Role of quark core and meson cloud in the TL region ?

# Time-like Electromagnetic baryon transition Form factor models

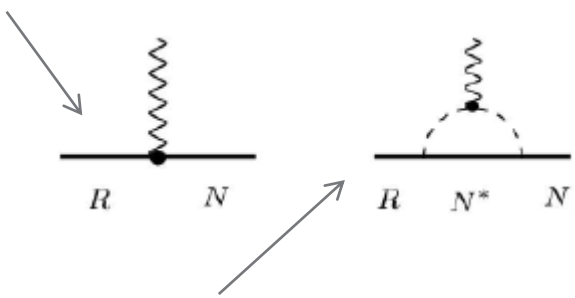
- Covariant model (*T. Pena and G. Ramalho*) quark core + meson cloud
- Parameters fitted to space-like data
- Predictions for the time-like region

T. Pena Sept. 9 12:00

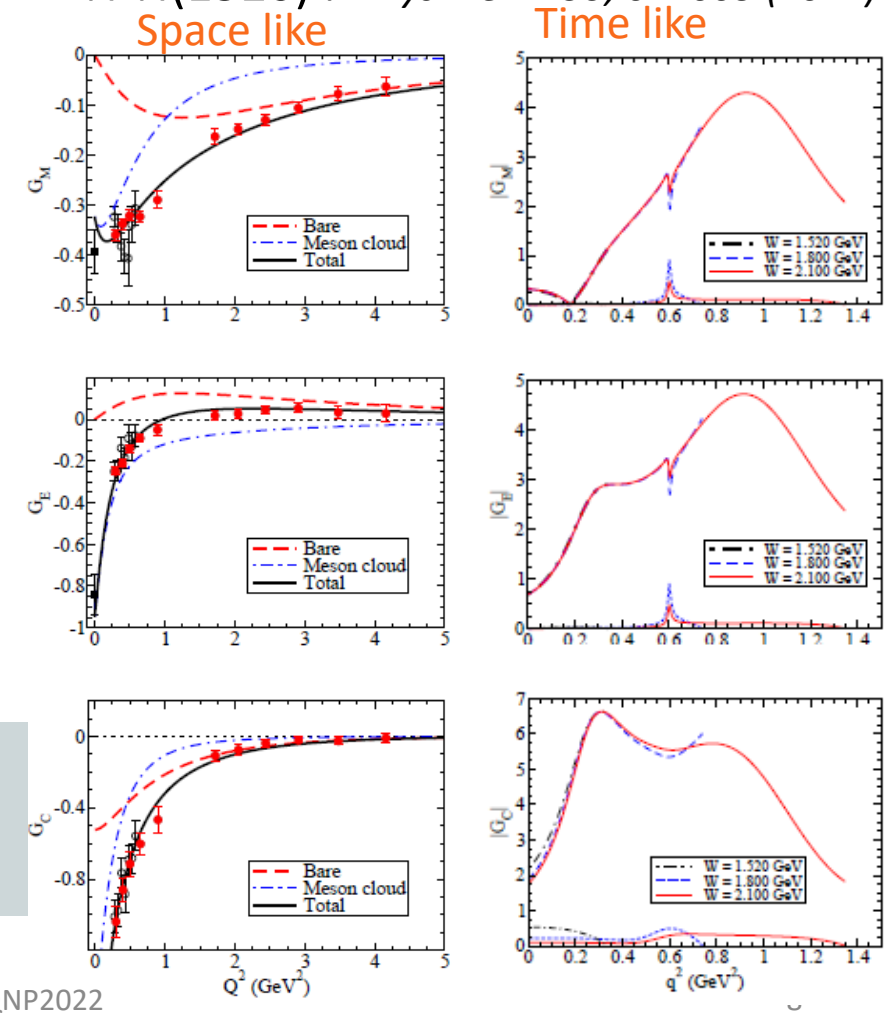
N-N(1520) : *Phys. Rev. D95, 014003 (2017)*

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

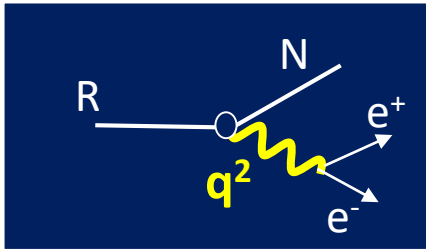
Quark core contribution :
- Quark form factors inspired by VDM




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



# Access to Time-like eTFF via baryon Dalitz decay (I)




- **$e^+e^-$ invariant mass distributions ($q^2 = M_{ee}^2$):**

$$\frac{d\Gamma^{N^\star\to Ne^+e^-}}{dM_{ee}} = \frac{2\alpha}{3\pi M_{ee}}\Gamma^{N^\star\to N\gamma^*}_{M_{N^\star}}(M_{ee}),$$

e.g. for $3/2^-$ and $1/2^-$

*M. Krivoruchenko et al., Ann. of Phys.* ***296****, 299–346 (2002)*

$$\Gamma^{N^*\to N\gamma} = \frac{\sigma_+^{3/2}\sigma_-^{1/2}}{m_+^{3/2}m_-^{1/2}}\frac{|G_T(q^2)|^2}{|G_T(0)|^2} \times \Gamma^{N^*\to N\gamma}$$

$m_\pm = m_* \pm m_N$

$\sigma_\pm = m_\pm^2 - M_{ee}^2$

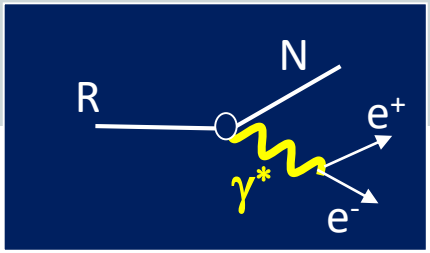
**effective form factor** **radiative decay width**

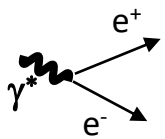
$J^P = \frac{1}{2}^-$ (e.g. N1535): $|G_T(q^2)|^2 = 2|G_E(q^2)|^2 + \frac{q^2}{2m_*^2}|G_C(q^2)|^2$

$J^P = \frac{3}{2}^-$ (e.g. N1520): $|G_T(q^2)|^2 = |G_E(q^2)|^2 + 3|G_M(q^2)|^2 + \frac{q^2}{2m_*^2}|G_C(q^2)|^2$

- **QED reference :** calculation for **constant covariant form factors** (point-like baryons) extrapolation of radiative decay at finite $q^2$

# Access to Time-like eTFF via baryon Dalitz decay (II)




- Additional information from **$e^+/e^-$ angular distributions:**
- **spin density matrix formalism**

*E. Speranza et al, Phys. Lett. B 764, 282 (2017)*
*M. Zetenyi et al. C 104, 015201 (2021)*
*A. Sarantsev priv. comm.*

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

**related to helicity amplitudes or electromagnetic transition form factors**

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

J=1/2

$$\lambda = \frac{\left|G^\pm_{E/M}\right|^2 - \left|G^\pm_C\right|^2}{\left|G^\pm_{E/M}\right|^2 + \left|G^\pm_C\right|^2}$$

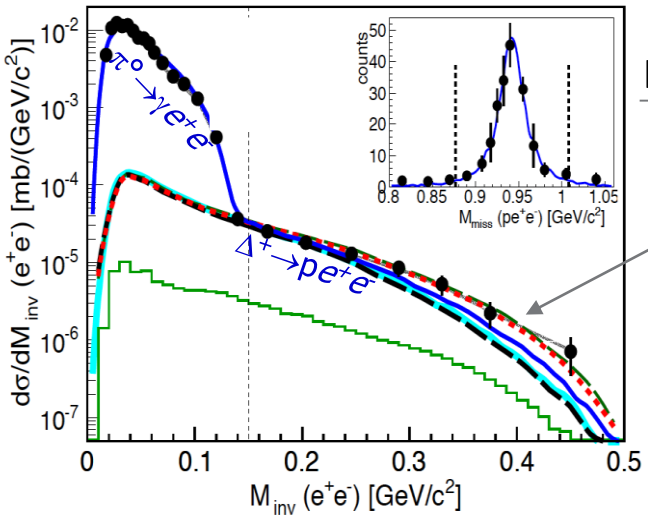
J>1/2

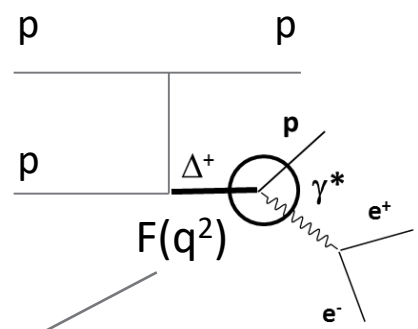
$$A_\perp = \frac{l+1}{l}\left|G^\pm_{M/E}\right|^2 + (l+1)(l+2)\left|G^\pm_{E/M}\right|^2$$
$$A_\parallel = \frac{M^2}{m_\star^2}\left|G^\pm_C\right|^2$$

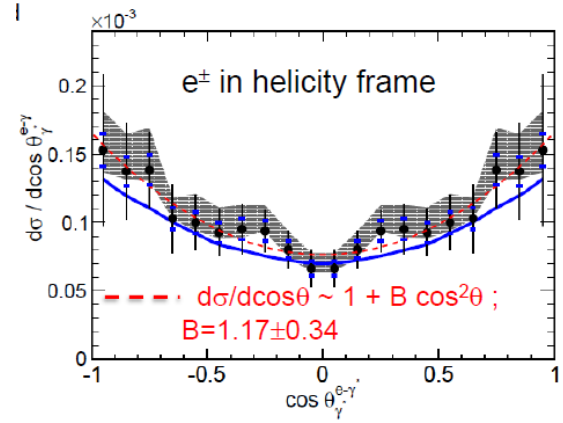
# Δ(1232) Dalitz decay studies with HADES

**E=1.25 GeV pp → ppe⁺e⁻**

*HADES PRC95, 065205 (2017)*



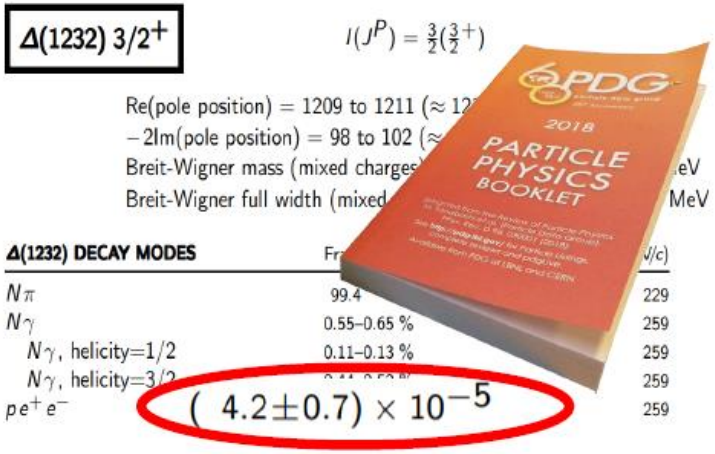

Dominance of magnetic transition (γ* are transversely polarized)

- First measurement of Δ (1232) Dalitz decay branching ratio (Δ⁺ →pe⁺e⁻)

*Using information from PWA (pnπ⁺, ppπ⁰)*

- Sensitivity to the electromagnetic structure (form factor) of the N-Δ transition

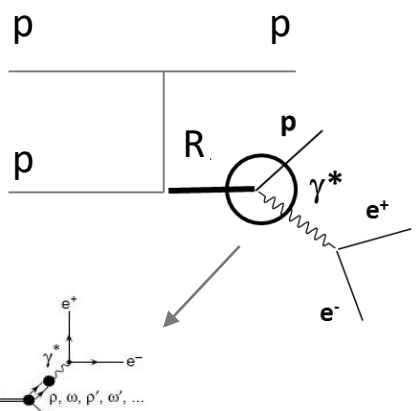
*Wan and Iachello, Int. J Mod. Phys. A20 (2005) 1846*
*T. Pena and G. Ramalho, Phys.Rev. D85 (2012) 113014*

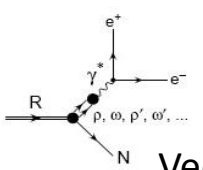


# Dalitz decay studies of heavier baryons with HADES

*G. Agakishiev et al.*
Eur.Phys.J. A50 (2014) 8

p+p →pp $e^+e^-$ 3.5 GeV



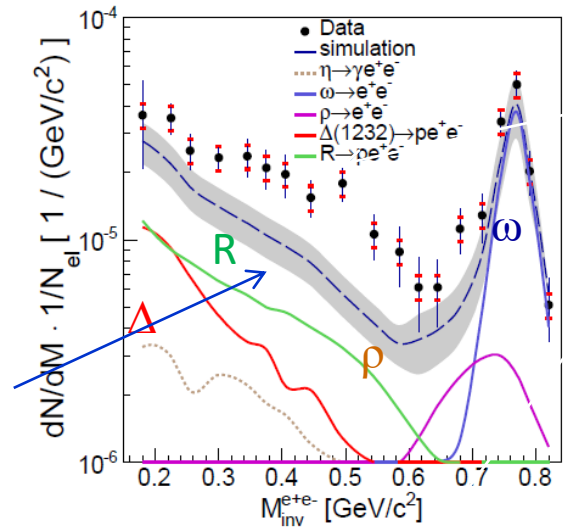

Vector Dominance Model

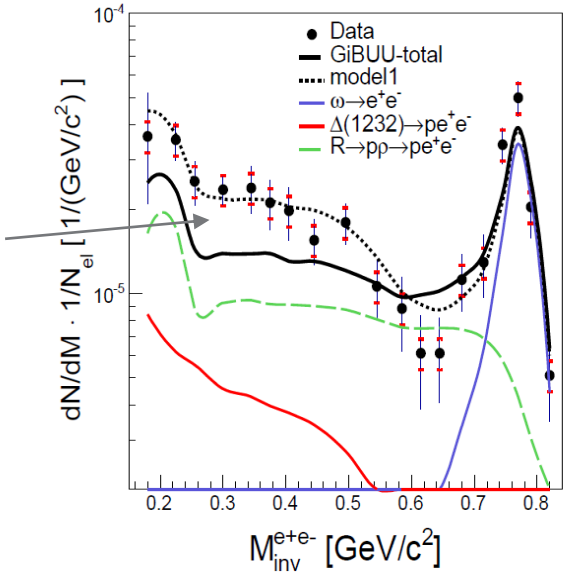
Δ(1232)
N*(1440)
N*(1520)
N*(1535)
N*(1680)
Δ(1620)
Δ(1700)
Δ(1910)

Dalitz decays of point-like baryonic resonances constrained by $pp\pi^0$ and $pn\pi^+$ channels : QED reference

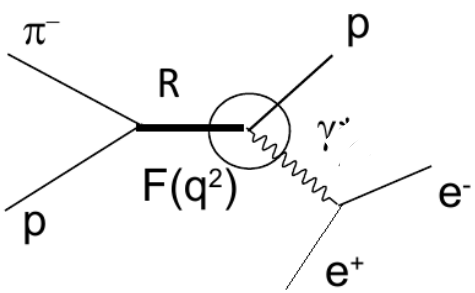
+ "direct" ρ and ω

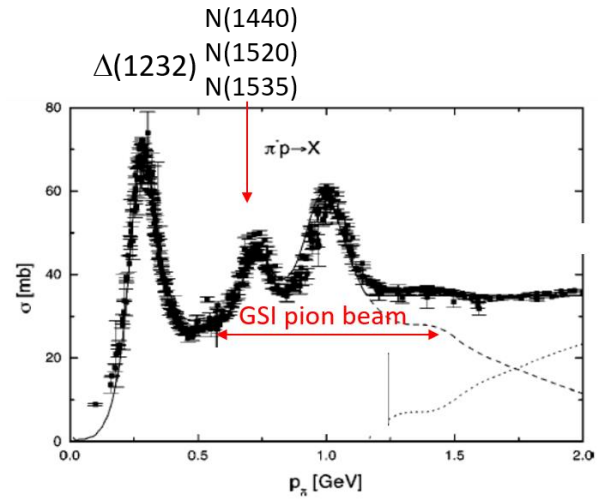
Effect of electromagnetic transition Form Factors for light baryonic resonances (N(1520),…)



# Specific motivations for pion beam experiments with HADES




Production of resonance with given mass in s-channel $M_R=\sqrt{s_{\pi p}}$

HADES + GSI pion beam is an ideal (unique in world) tool to

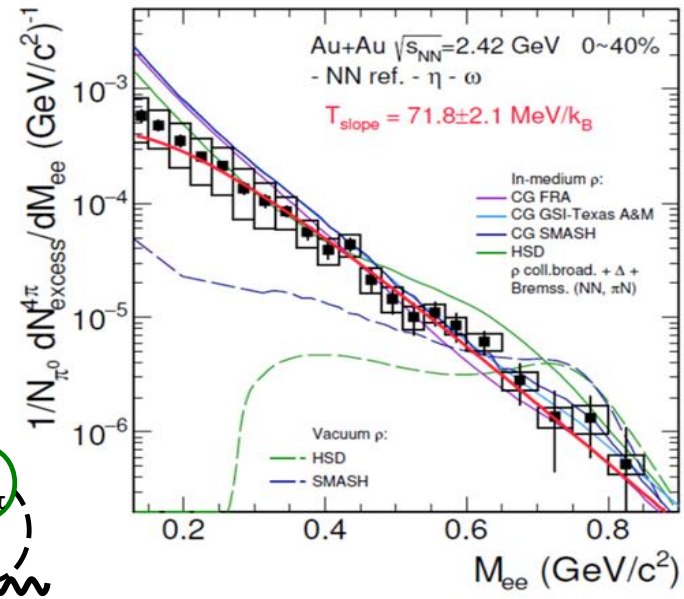
- ✓ Study the unknown time-like electromagnetic structure of baryons
- ✓ Complete the very scarce pion beam data base for hadronic couplings
- ✓ Test description of in-medium dilepton production

# In medium vector meson spectral functions

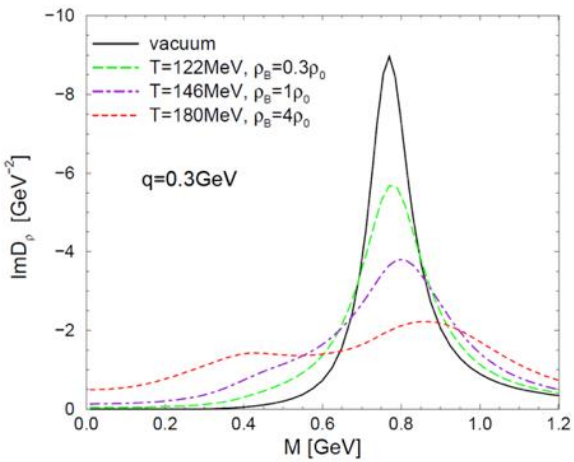
*HADES Collab., Nature Phys. 15 (2019) 10, 1040-1045*

*S. Harabasz Sept. 8 12:30*

Strong **broadening** of **in medium** ρ spectral fuction
**Observed from LHC to GSI energies !**



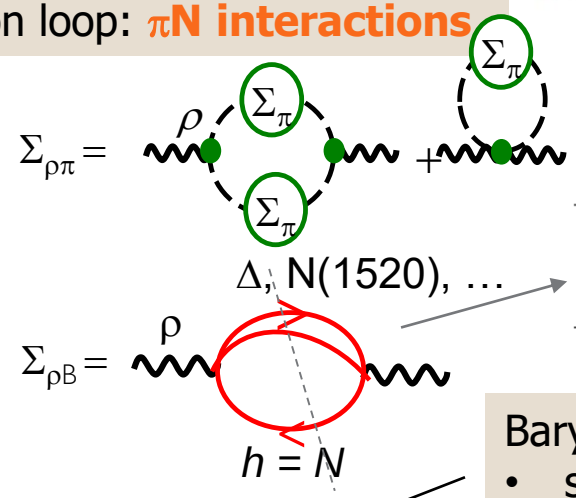

**Vector Meson Dominance**

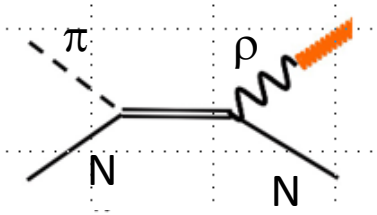



B. Friman et al. NPA617 (1997) 496.
R. Rapp and J. Wambach EPJA 6 (1999) 415

$$D_\rho(M,q,T,\mu_B) = \frac{1}{\left[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}\right]}$$

pion loop: **πN interactions**

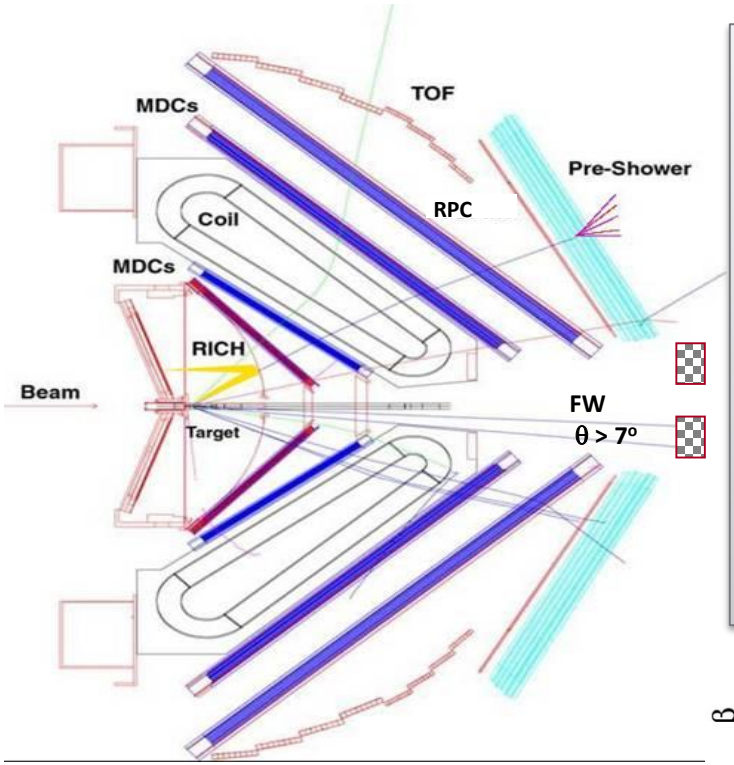



can be best accessed via πN reactions

Baryonic loop
- sensitive to **ρNN* couplings**
- related to **baryon Dalitz decay**
  **Δ/N*→Ne⁺e⁻**

# High Acceptance Di-Electron Spectrometer




**Experiments (2004-2022)**

**Hadronic matter studies**

C+C 1 and 2A GeV, Ar+ KCl 1.75A GeV,
Au+Au 1.25 AGeV, Ag+Ag 1.65A GeV

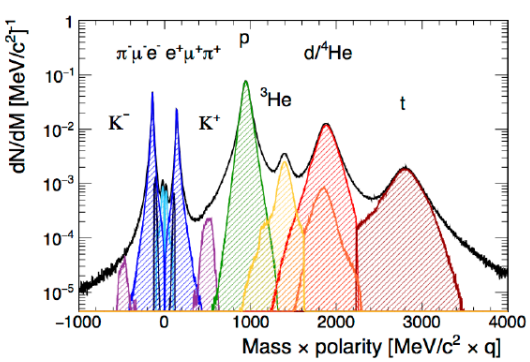
**Cold matter:**

p+Nb 3.5 GeV, $\pi^-$+C/W 1.7 GeV/c

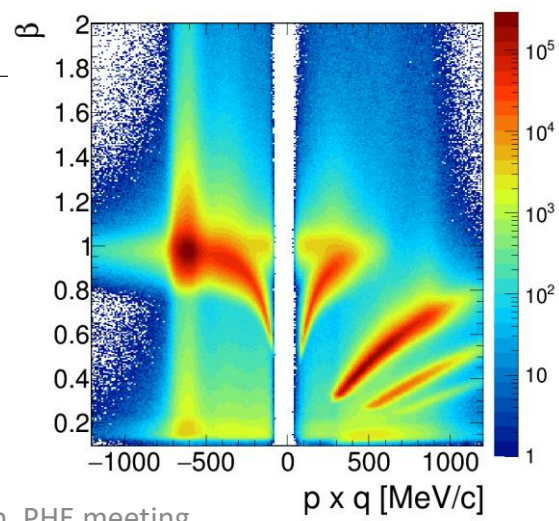
**Elementary reactions:**

p+ p 1.25, 2.2 , 3.5 GeV, 4.5 GeV d+p 1.25 GeV/nucleon

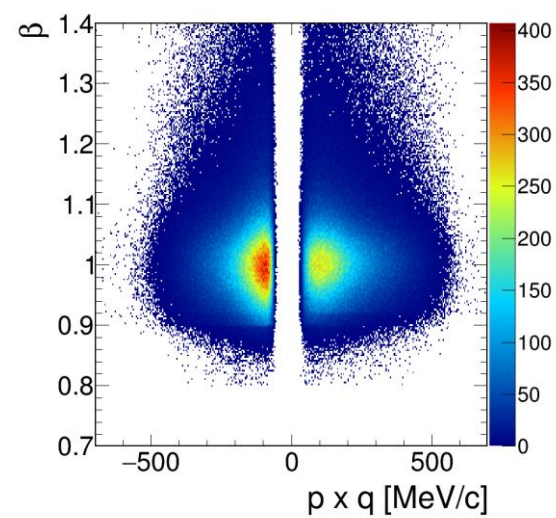
**$\pi^-$+$CH_2$/C 0.7 GeV/c**




*before lepton selection*



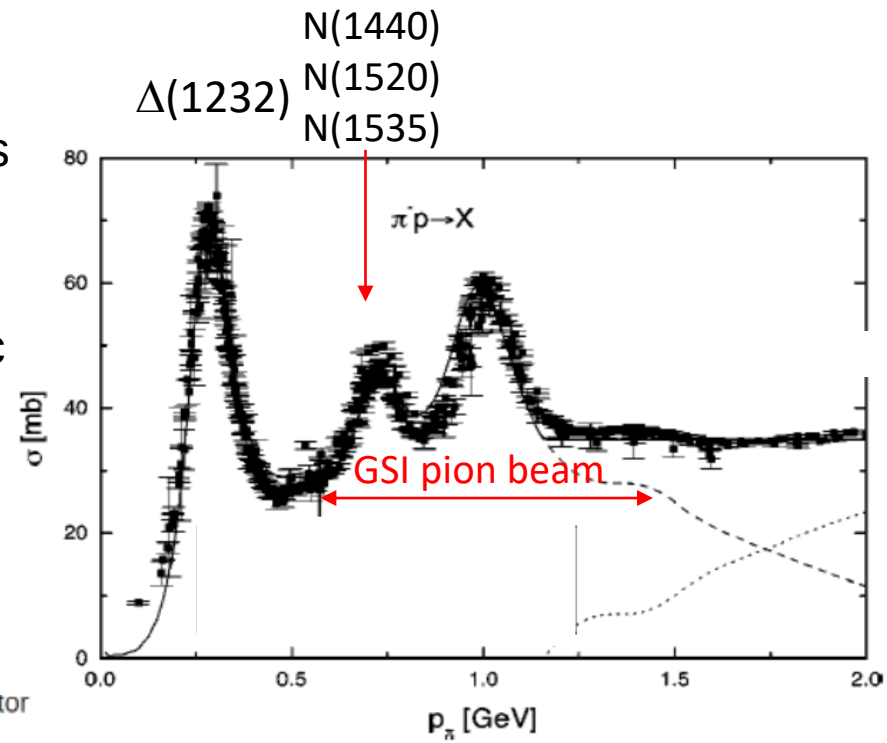

*after lepton selection*

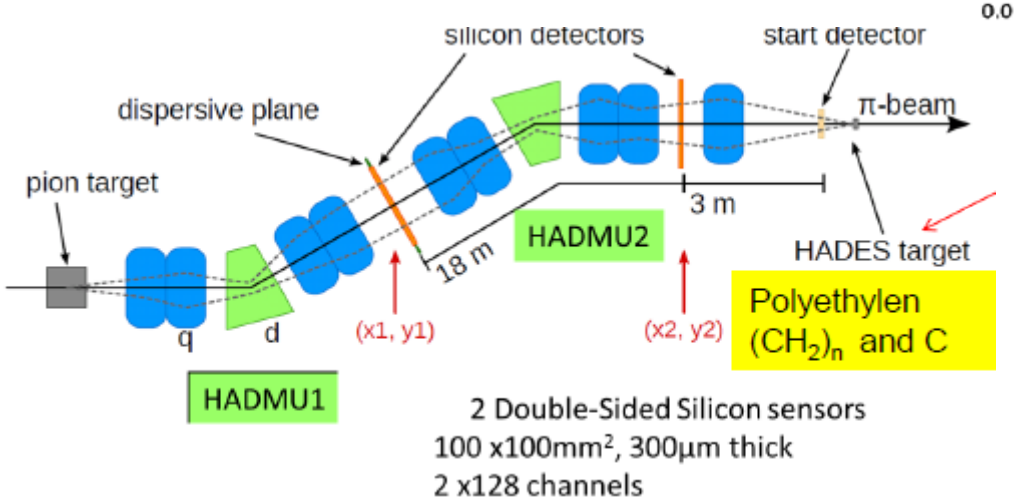


# Pion beam at GSI

- Primary beam: 6 × $10^{10}$ Nitrogen ions/s at E = 2*A* GeV
- Momentum acceptance = 2 % (rms)
- Momentum range $p_\pi$ = 0.65 – 1.5 GeV/c
- Secondary pion beam: 2 × $10^5$ $\pi$/s for $p_\pi$ around 0.7 GeV/c

*HADES coll. Eur. Phys. J. A (2017) 53: 18*




Measurements on CH2 and C targets

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

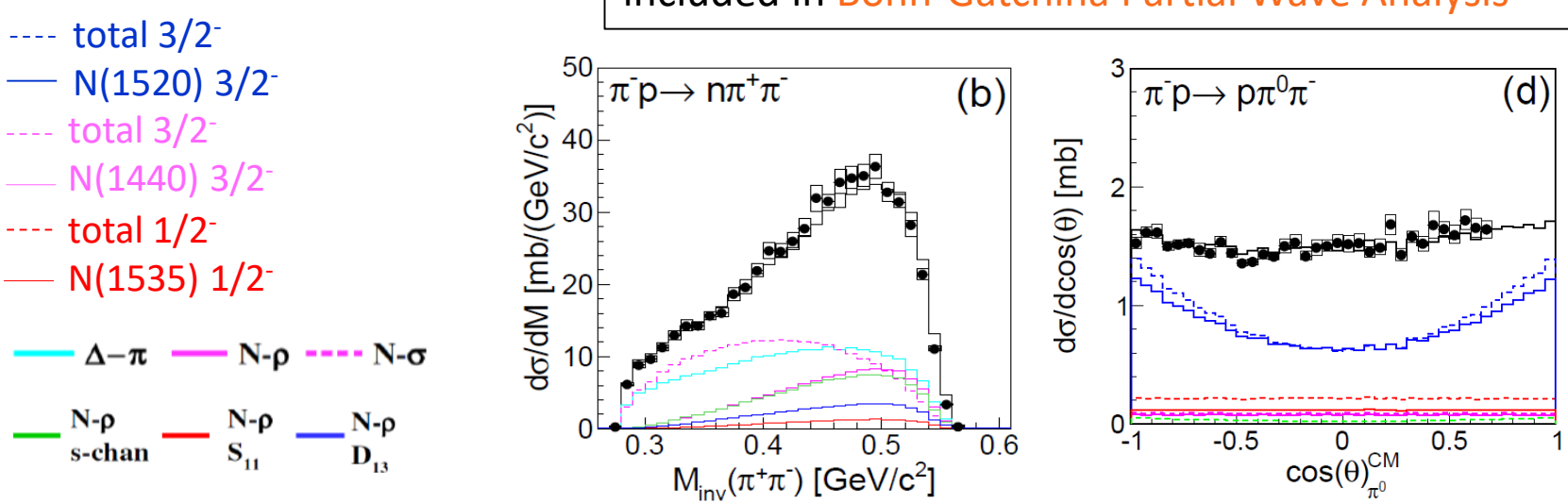
(4 measurements $\sqrt{s}$ =1.46-1.55 GeV/$c^2$)

- $e^+e^-$ production $\sqrt{s}$ =1.49 GeV/$c^2$
- data on C target also used for cold matter studies F. Hojeij , Sept. 8 13:35

# Partial Wave Analysis in 2π production channels

*HADES coll.* Phys.Rev.C 102 (2020) 2, 024001

HADES data ($\pi^- p \to n\pi^+\pi^-$ and $\pi^- p \to p\pi^0\pi^-$ at 4 energies )
+ photon (CB-ELSA,MAMI) and pion (Crystal Ball) data base
included in Bonn-Gatchina Partial Wave Analysis

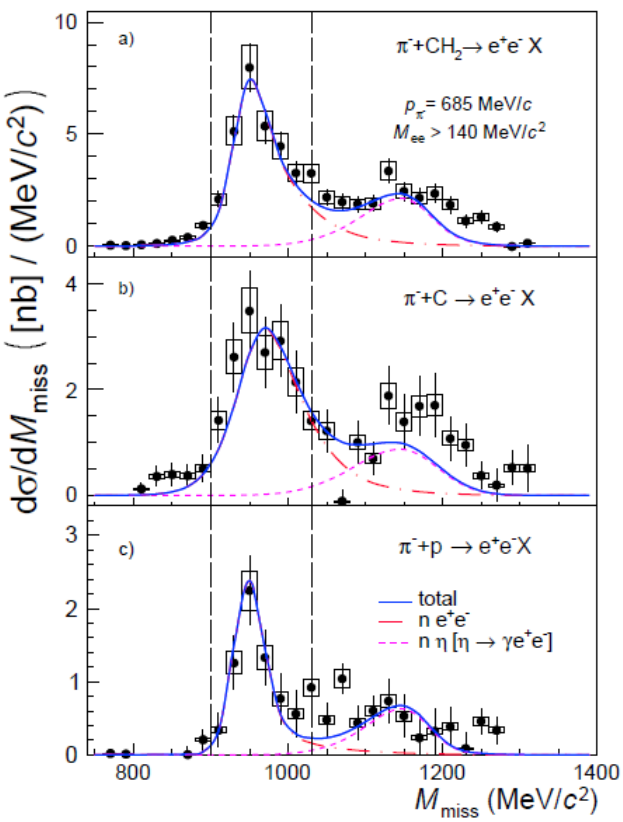



s-channel $3/2^-$ N(1520) is dominant

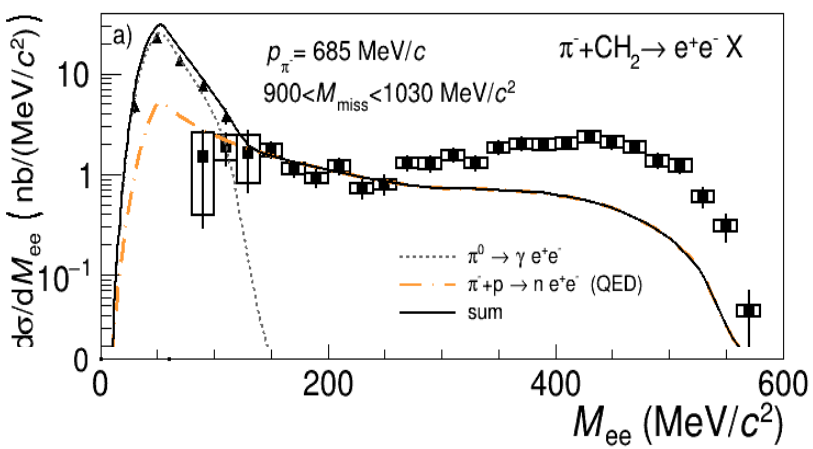
Branching ratios of N(1440), N(1535), N(1520) to 2π channels (Δ π, σN, ρN)
→ 8 new entries (4 first + 4 additional entries)

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

HADES coll. arXiv:2205.15914 [nucl-ex]



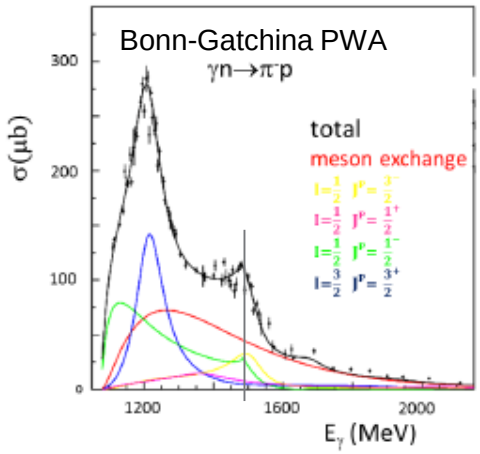

- Selection of the exclusive $\pi^- p \rightarrow n e^+ e^-$ channel using missing mass
- Quasi-free treatment of $\pi^-$ C interactions
  $\sigma_C/\sigma_p = 3.3$ ($\sim Z^{2/3}$)
- Subtraction of residual $\pi^0$ contribution



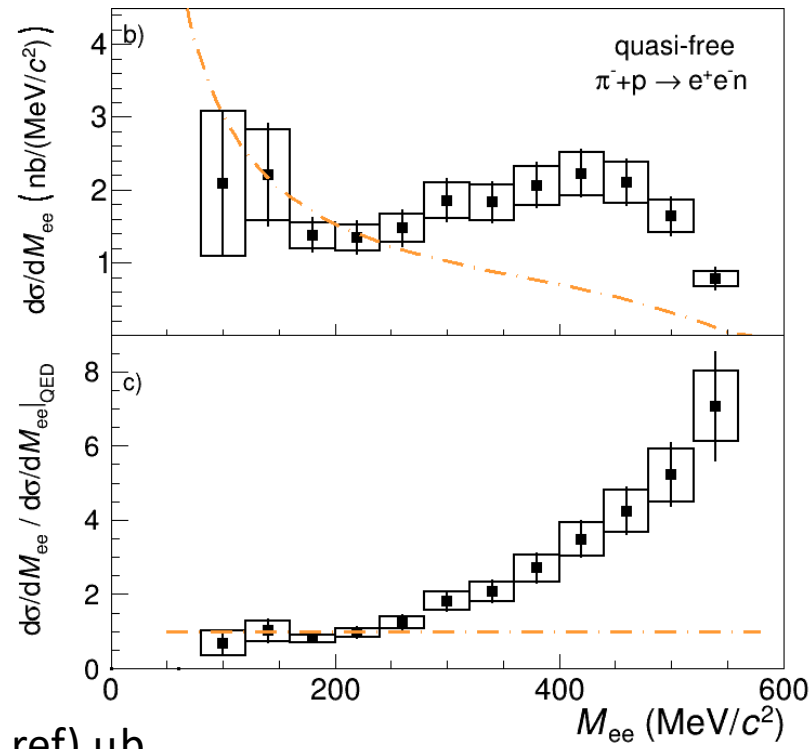
# Comparison to the QED reference

QED reference:

- Dalitz decay of $J^P=3/2^-$ or $1/2^-$ (largest contr. to $\pi^- p \leftrightarrow n\gamma$ and $\pi^- p \rightarrow \rho n$) with constant covariant form factors
- Cross section deduced from $\sigma(\pi^- p \rightarrow n\gamma)$



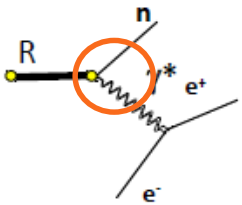

HADES coll. arXiv:2205.15914 [nucl-ex]




- $\sigma(\pi^- p \rightarrow n e^+ e^-) = 2.14 \pm 0.06$ (data) $\pm 0.23$ (QED ref) $\mu$b

  $\sigma = 1.16 * \sigma_{QED}$
- $M_{ee} < 200$ MeV/$c^2$ consistency with QED reference
- Strong excess at larger $M_{ee}$ (up to a factor 5)
- Effective time-like transition form factor

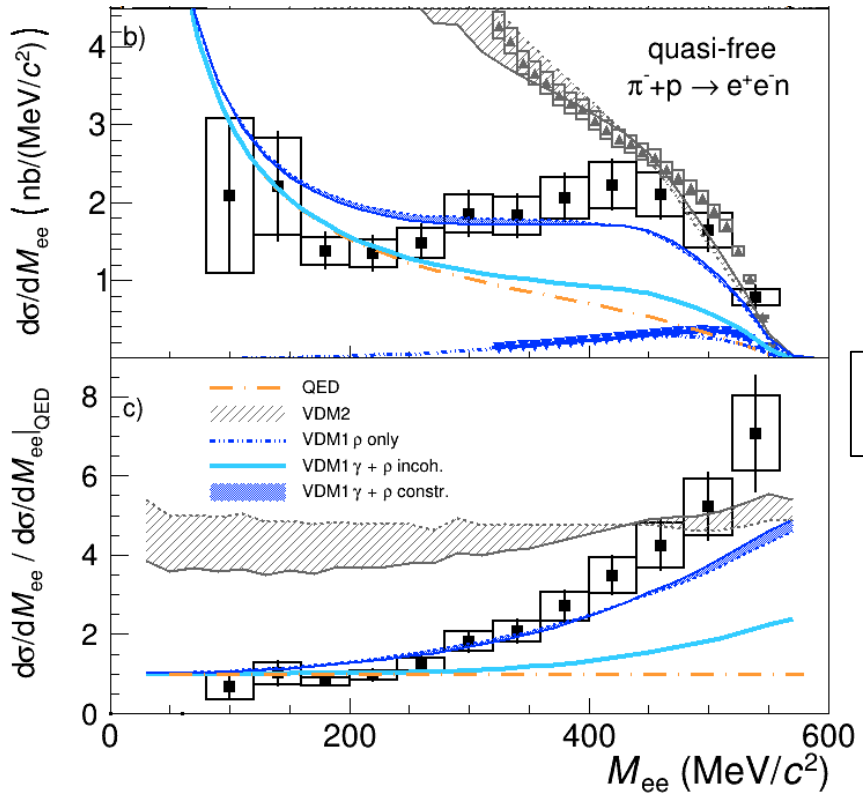
  $R_{QED} = (d\sigma/dM)/(d\sigma/dM)_{QED}$



# Data comparison with VDM2/VDM1 models

HADES coll. arXiv:2205.15914 [nucl-ex]

*HADES collab., Phys.Rev. C102 (2020) 024001*

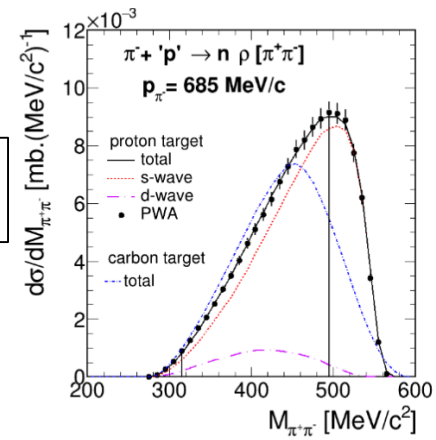



Ideal case:

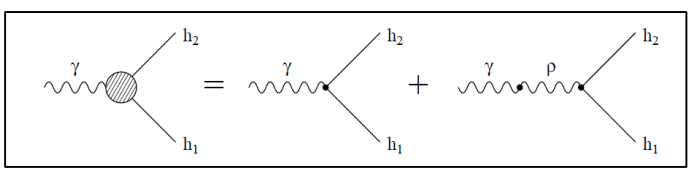
$\rho \rightarrow \pi^+\pi^-$ extracted from the same experiment (PWA)

Direct test of VDM models based on known ρ contribution

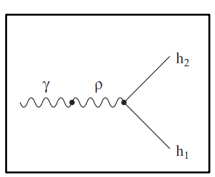
$$\left(\frac{d\sigma_{ee}}{dM_{ee}}\right)_{M_{ee}=M} = \left(\frac{d\sigma_{\pi\pi}}{dM_{\pi\pi}}\right)_{M_{\pi\pi}=M} \frac{\Gamma_{\rho\to e^+e^-}(M)}{\Gamma_{\rho\to\pi^+\pi^-}(M)}$$




VDM1




VDM2




**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

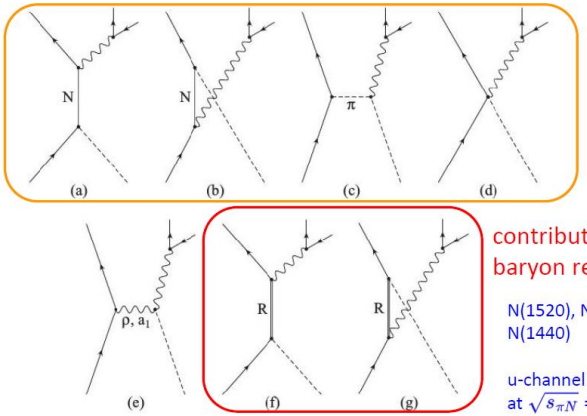
# Two-component Lagrangian model

Microscopic calculation of $\pi^- p \to n e^+ e^-$

*M. Zetenyi and G. Wolf,*
*Phys. ReV. C **86**, 065209 (2012)*

*M. Zetenyi et al, Phys. Rev. C 104, 015201 (2021)*

Born terms

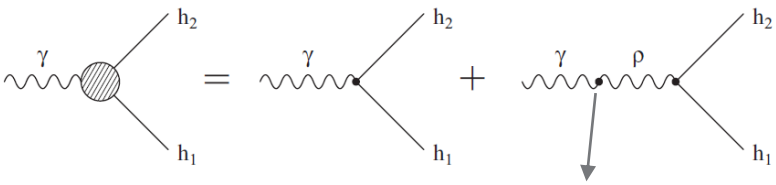



contributions of baryon resonances

N(1520), N(1535), N(1440)

u-channel unimportant at $\sqrt{s_{\pi N}}$ = 1.5 GeV

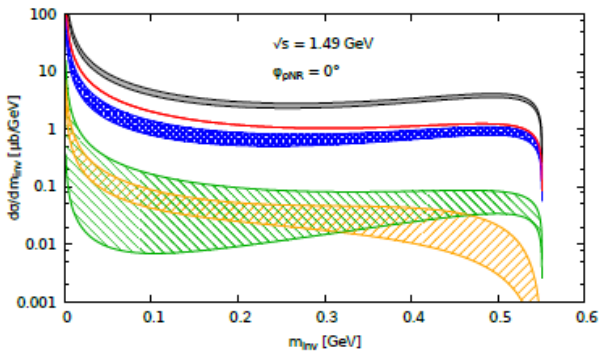
**Strong contribution of the Born terms**

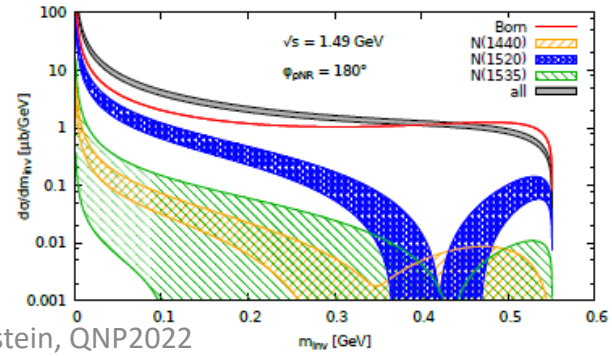



$$\mathcal{L}_{\rho\gamma} = -\frac{e}{2g_\rho} F^{\mu\nu} \rho^0_{\mu\nu},$$

Here, « Kroll-Lee-Zuminio »
**« VDM1 » Lagrangian** is use

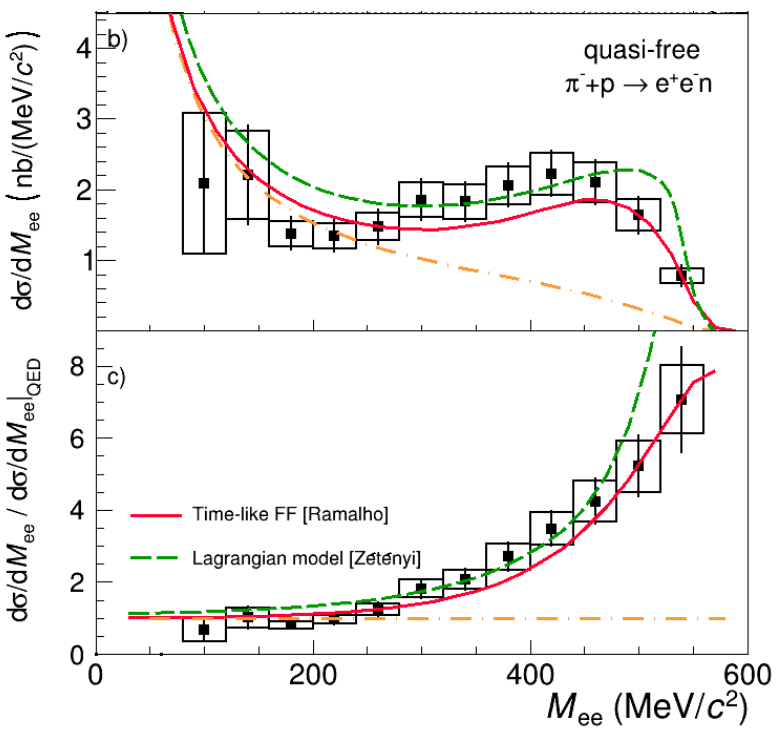
→ Shape and yield sensitive to the interference between the γ and ρ contributions



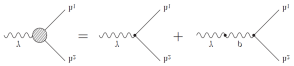



# Invariant mass distribution: comparison to models

HADES coll. arXiv:2205.15914 [nucl-ex]




**Lagrangian model:**



*M. Zetenyi et al. Phys.Rev. C 104, 015201 (2021)*

- *based on VDM1 for various baryon transitions*
- *shown with phase $\phi$=90°*
- very promising, **but needs to be confronted to $\pi^- p \rightarrow \pi\pi N$ data**

**Covariant form factor model** (quark core+meson cloud)

*G. Ramalho and M. T. Pena, Phys. Rev. D95, 014003 (2017)*
*Phys. Rev. D101, 114008 (2020)*

- *n-N1520 and n-N1535 transitions*
- dominant pion cloud contribution:

baryon transition form factor strongly related to the **pion electromagnetic form factor**

T. Pena Sept. 9 12:00

**More calculations**:

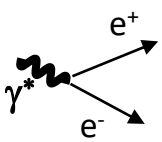
- *A. I. Titov and B. Kämpfer, EPJ.A12, 668 217 (2001)* ($\rho/\omega$ prod. amplitudes)
- *M. Lutz, B. Friman & M. Soyeur NPA713, 97 (2003)* ($\rho/\omega$ prod. amplitudes)
- *A. Ierusalimov & G. Lykasov Phys. Part. Nucl. Lett. 15, 457 (2018) ; 1907.10298 [hep-ph]*
  Inverse Pion Electroproduction (dipole or Gaussian FF)

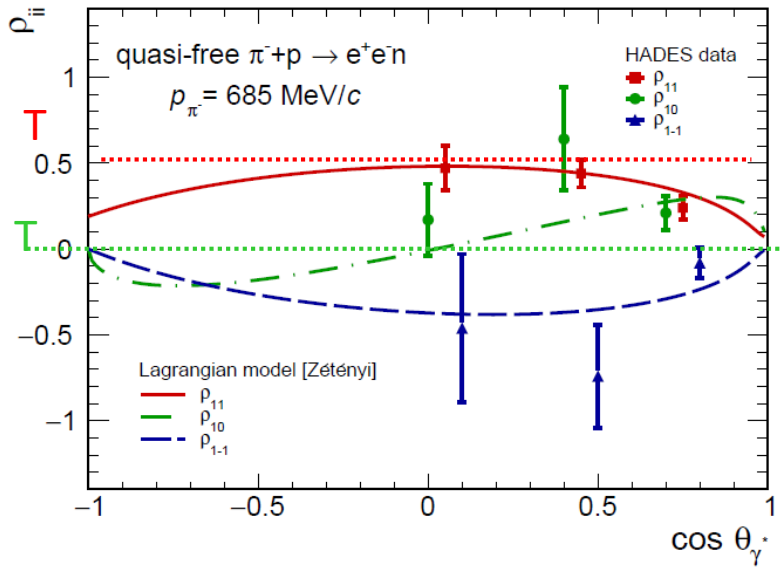
# Analysis of $e^+/e^-$ angular distribution spin density matrix elements

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

*Algorithm taking into account acceptance and efficiencny developed by A. Sarantsev*

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



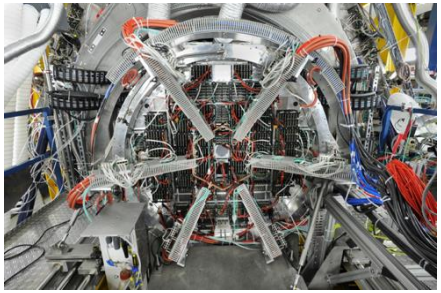

sdme sensitive to

- $J^P$ : *e.g.* no dependence on $\theta_\gamma$ for J=1/2
- electromagnetic structure of the transition

*e.g.* $\rho_{11}$ =0.5 and $\rho_{10}$ =0 for transverse polarization

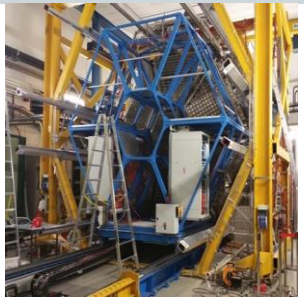
- Significant longitudinal contributions at finite $q^2$
- Angular dependence of $\rho_{10}$ consistent with strong N1520 contribution
- Good agreement with Lagrangian model
- **More precise data needed !**

# HADES upgrade: FAIR-Phase0



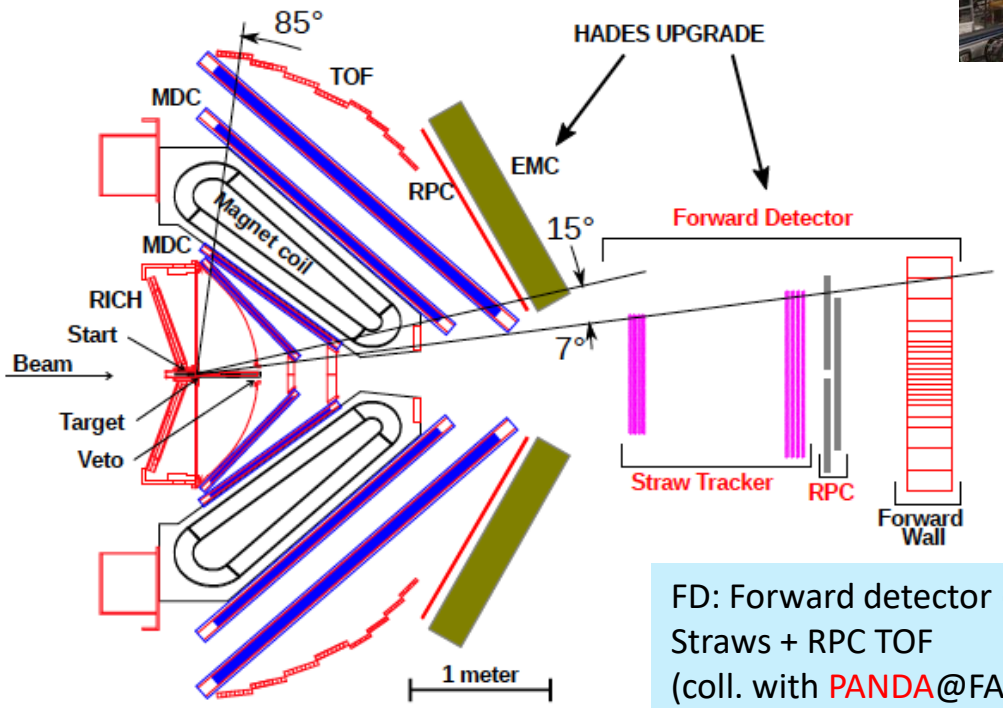
New ECAL (lead glass), $\Delta E/E$ ~5%
$\gamma \rightarrow$ neutral mesons
and $e^+/e^-$ detection

*used in Au+Au exp. March 2019*



New RICH photon detector
& read-out
(coll. with CBM@FAIR)
Gain in $e^+e^-$ efficiency x5

*used in Au+Au exp. March 2019*



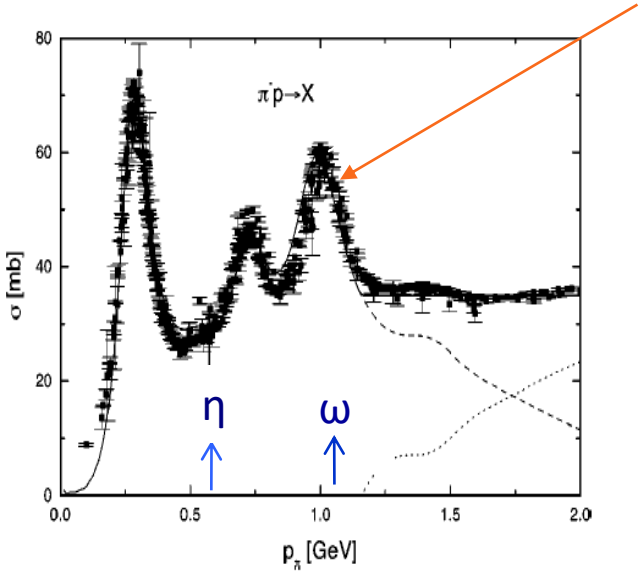

FD: Forward detector (0.5-6.5°)
Straws + RPC TOF
(coll. with PANDA@FAIR)
$\sigma(x)$~150 μm $\sigma$(TOF)~70 ps

*used in p+p 4.5 GeV Feb. 2022*

*« Hyperon electromagnetic form factors with HADES »* $Y \rightarrow \Lambda e^+e^-$ , $Y \rightarrow \Lambda\gamma$
*Rafal Lalik (JU Krakow), Hadron structure, Sept.6 15:25*

# Future pion beam experiments at SIS18

**Exp. proposal** at GSI/SIS18 : 2023-2024: explore the **third resonance region** ($\sqrt{s}$~1.7 GeV/$c^2$)




1. Baryon meson couplings $\pi\pi N$, $\omega n$, $\eta n$ , $K^0\Lambda$, $K\Sigma$,....

*Including neutral mesons thanks to the ECAL*

*→ Improve the poor pion beam data base (PWA)*

*→ Many baryon structure issues: confirmation of N'(1720), Cascade decays ($R \to R'\pi/\eta \to N\pi\pi/ N\pi\eta$ ), $\eta n$ couplings*

*A. Thiel Sept.6 8:30*

2. Time-like electromagnetic baryon transitions $\pi^- p \to n e^+ e^-$

- Broad range of $q^2=(M_{ee})^2 \to$ sensitivity to form factors
- Check of Vector Dominance (both for ρ and ω)
- Spin density matrix elements

3. Cold matter studies: C, Ag targets

- ω absorption
- ρ spectral function
- Strangeness production

# Conclusion

✓ Baryon resonance studies with the GSI pion beam + HADES detector (2nd resonance region $\sqrt{s}$~1.5 GeV)

→ improved knowledge of hadronic couplings

→ very new information on electromagnetic baryon transitions in the time-like region

→ phenomenological to be developed to extract information for single baryon transition!

✓ On-going analysis for hyperon Dalitz and radiative decays in pp reaction at 4.5 GeV

✓ Proposal for pion beam experiment in 2023 in the third resonance region

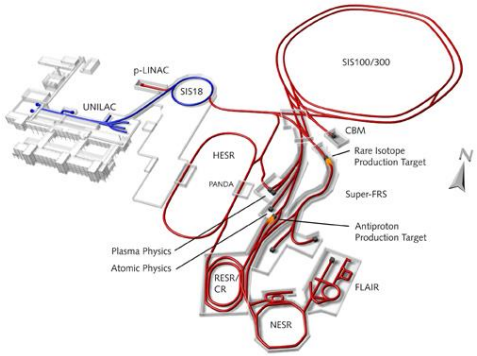
→ Investigate heavier resonances N(1620), N(1720),…in $e^+e^-$ channels and many hadronic channels, e.g. $\pi^- p \rightarrow \eta n$ , $K^0\Lambda$, $K\Sigma$,….

✓ Experimental program at SIS18:

Au+Au (0.2-0.8 GeV) (subm. proposal), p+A at 4.5 GeV, d+p energy scan,……

✓ After 2028: HADES experiments at FAIR with ion and proton beams

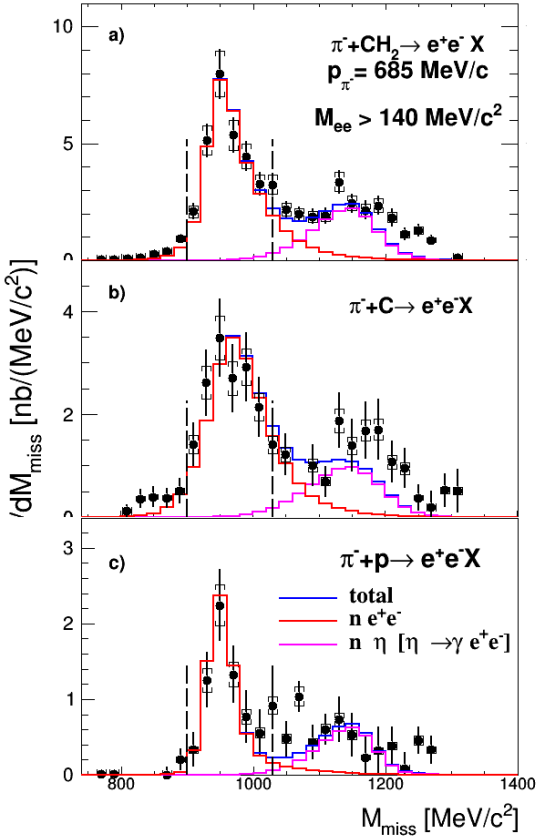
Status of FAIR: Y. Leifels Sept.7 9:00

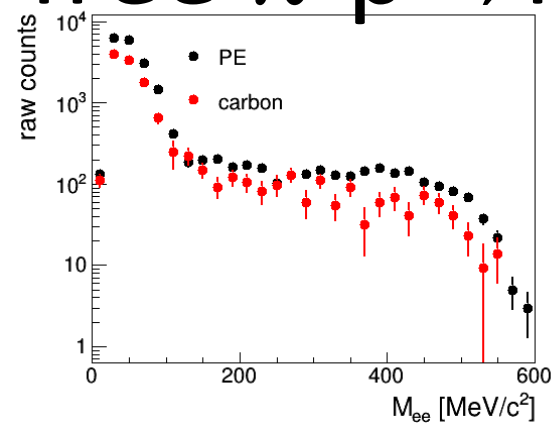


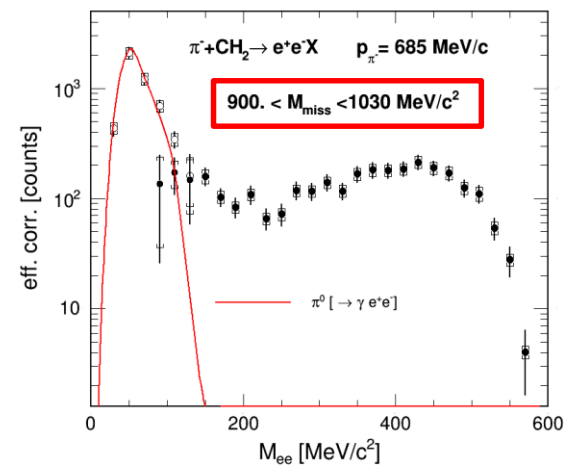

The HADES collaboration
HADES Collaboration, Feb 22nd 20018

# Thank you

# Selection of quasi-free π-p→ne+e-




- Selection of the exclusive π-p→ne+e- channel using missing mass
- Quasi-free treatment of π- C interactions σC/σp=3.3 (~Z2/3)
- Subtracion of residual π0 contribution

**Precision data require accurate analysis procedures to establish the baryon spectrum**

V.D. Burkert., T.S.-H. Lee
IJMP E13 (2004)