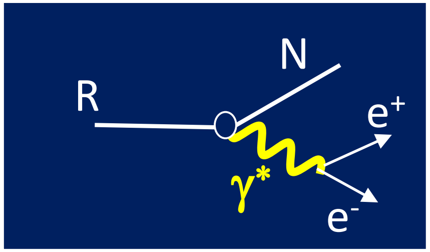
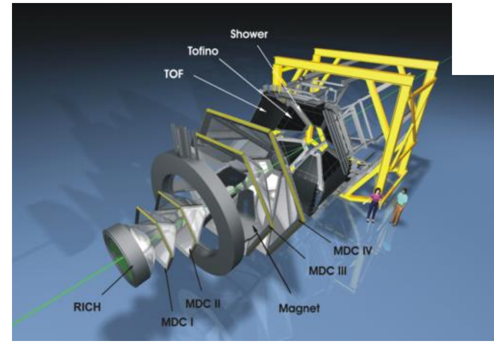
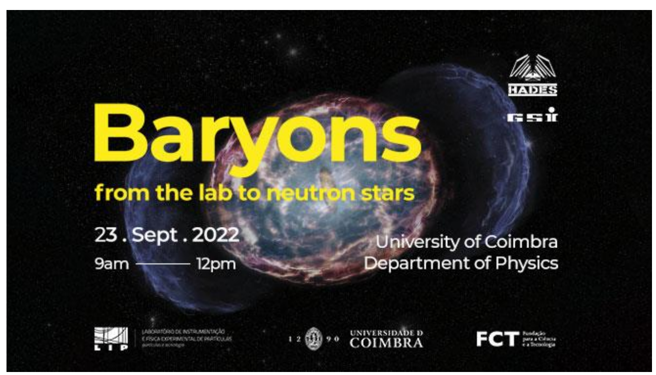


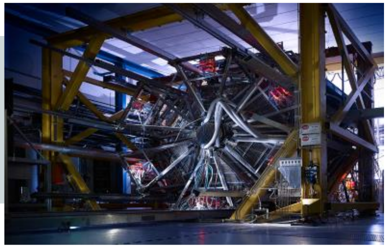


Time like baryon transition studies with HADES

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



Outline



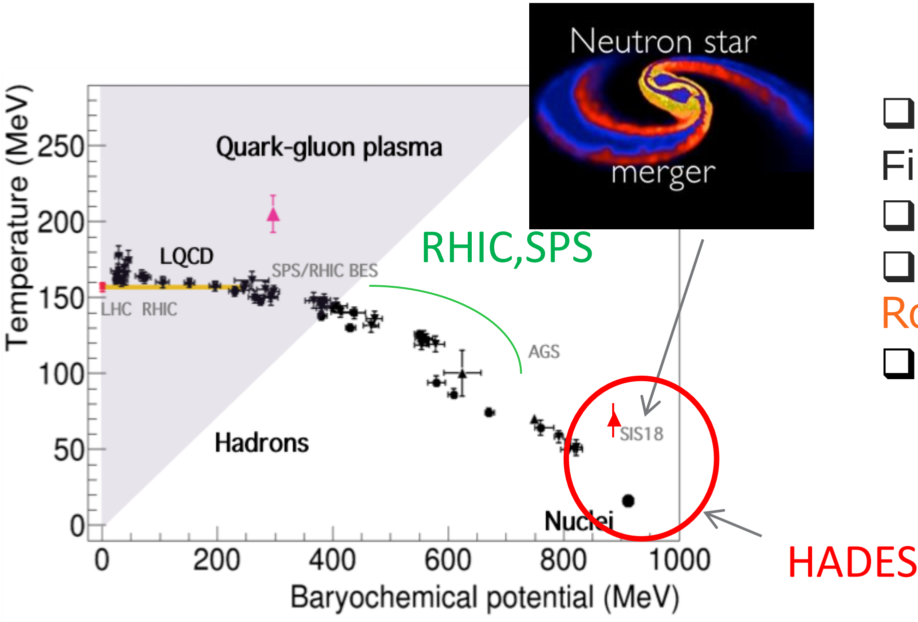
- **General motivations of the HADES experiment at GSI**
  From dense hadronic matter to hadron structure studies

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

- **Prospects for hyperon studies**

- **Conclusions**

HADES: exploring dense QCD matter



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

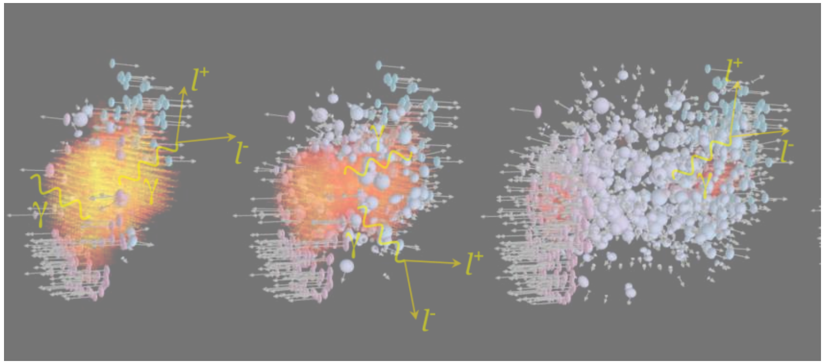
- ❑ Complementary to SPS,RHIC,..

A+A: 1-3A GeV

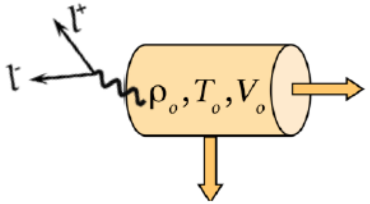
$\sqrt{s}$=2-2.4 GeV

Observables:

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



Emissivity of baryon rich matter



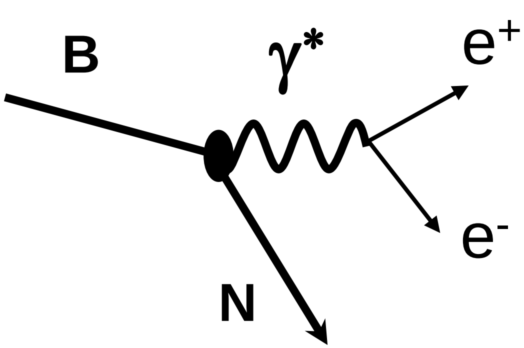
McLerran, Toimela, PRD 31, 545 (1985)

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

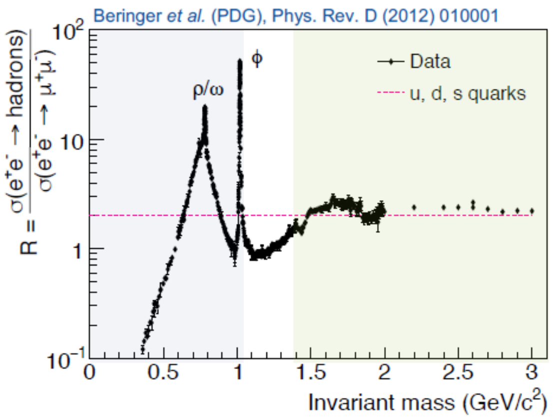
Lepton phase space factor — Thermal Bose distribution — Spectral function

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

Baryon Dalitz decay

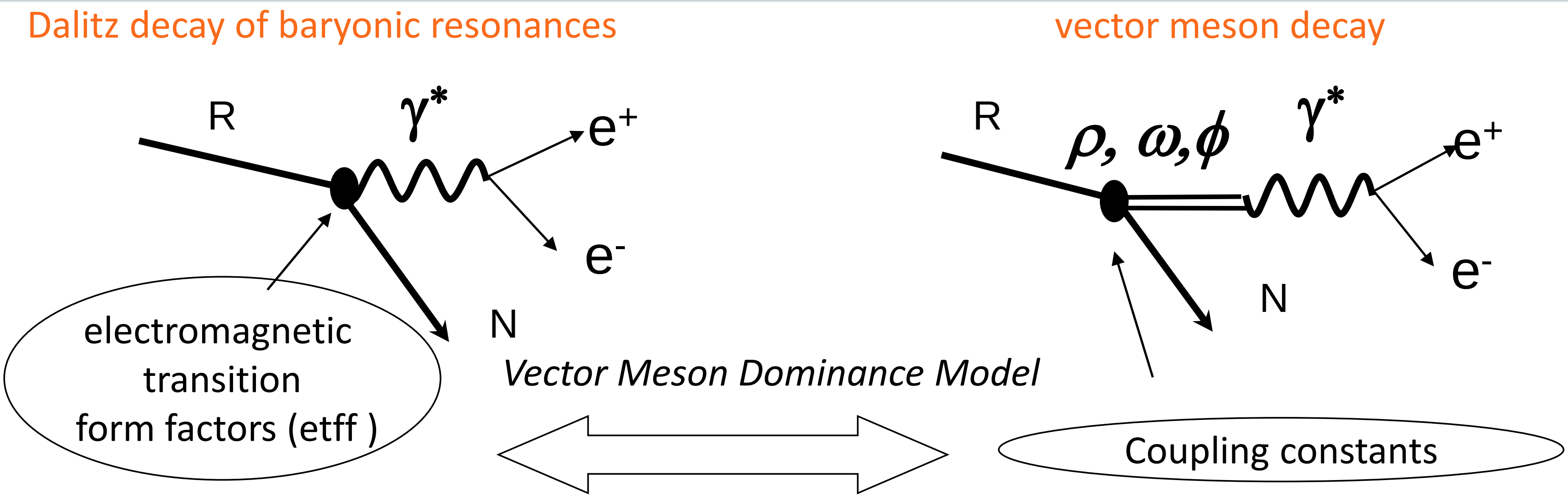


Vector mesons



Coupling of baryons to vector mesons is crucial

Vector Meson Dominance in the baryon sector (I)



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)

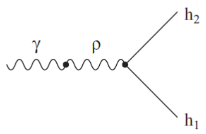
O'Connell Prog. Part. Nucl. Phys., Vol. 39,pp. 201-252, 1997

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

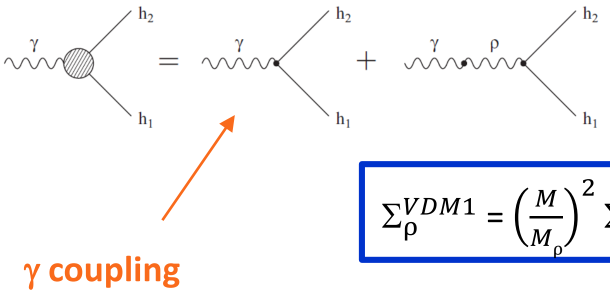


$$\Sigma_\rho^{VDM2} = \left(\frac{M_\rho}{M}\right)^2 \Sigma_\rho^0$$

VDM1 : »two-component »

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

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

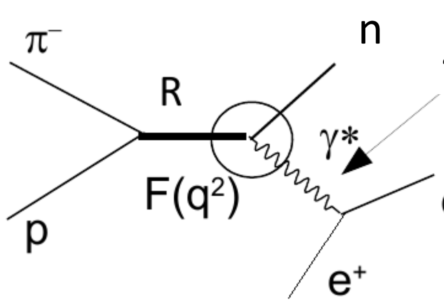


$$\Sigma_\rho^{VDM1} = \left(\frac{M}{M_\rho}\right)^2 \Sigma_\rho^0$$

6

Baryon electromagnetic transitions

Time-like electromagnetic form factors

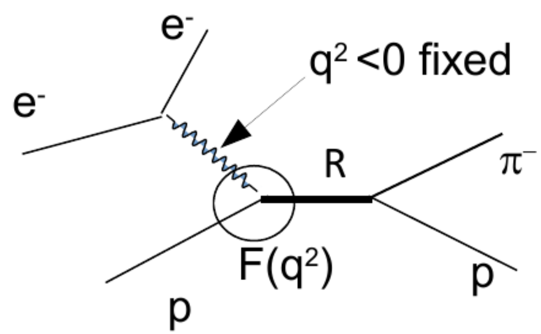


$4m_{ee}^2 < q^2 < (M_R - M_n)^2$ variable

No data are available

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

Space-like electromagnetic form factors



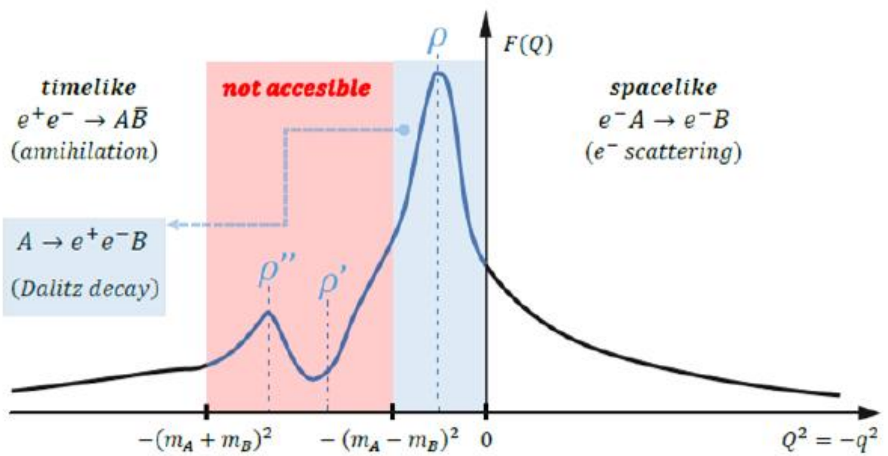
$q^2 < 0$ fixed

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 ?

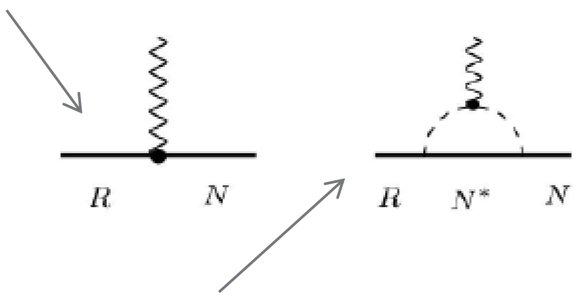
Time-like Electromagnetic baryon transition Form factor models

- 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-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

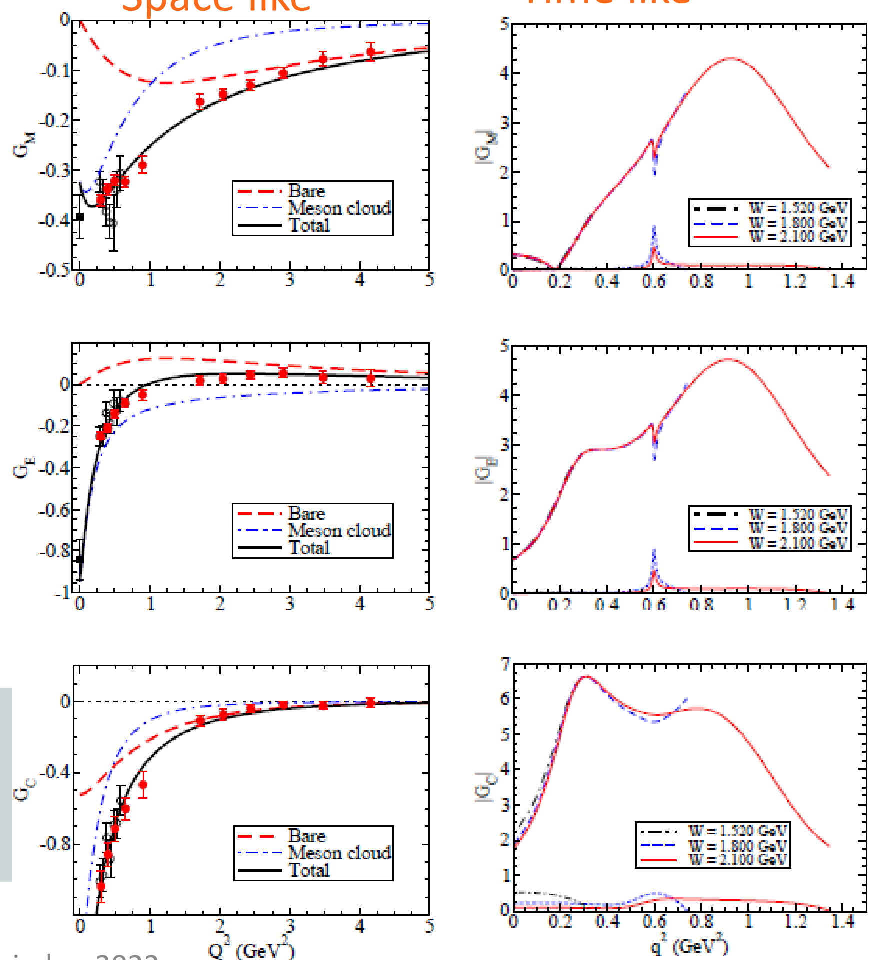


Meson cloud contribution:
- Based on pion electromagnetic form factor
- Dominant contribution in the time like region

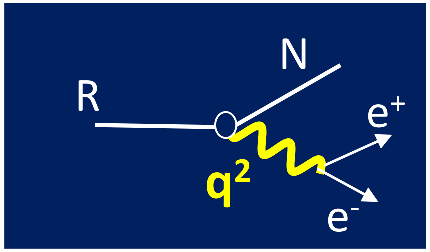
N-N(1520) : *Phys. Rev. D95, 014003 (2017)*

Space like

Time like



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



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

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

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

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

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

$m_\pm = m_* \pm m_N$

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

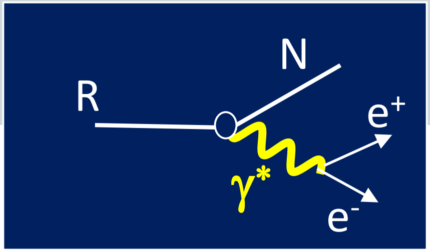
effective form factor — radiative decay width

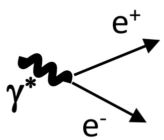
$J^P = \frac{1}{2}^-$ (e.g. N1535): $|G_T(q^2)|^2 = 2|G_E(q^2)|^2 + \frac{q^2}{2m*2}|G_C(q^2)|^2$

$J^P = \frac{3}{2}^-$ (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) extension 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

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

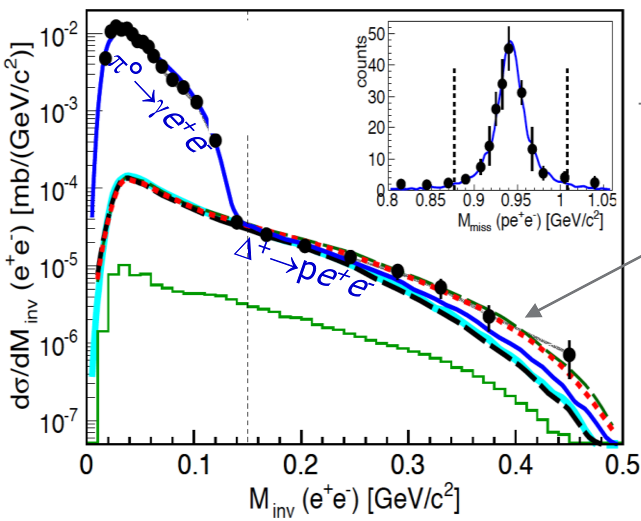
J=1/2
$$\lambda=\frac{\left|G^\pm_{E/M}\right|^2-\left|G^\pm_C\right|^2}{\left|G^\pm_{E/M}\right|^2+\left|G^\pm_C\right|^2}$$

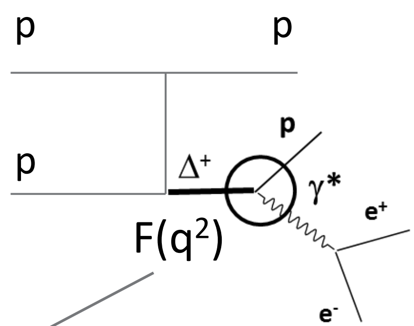
J>1/2
$$A_\perp = \frac{l+1}{l}\left|G^\pm_{M/E}\right|^2+(l+1)(l+2)\left|G^\pm_{E/M}\right|^2$$
$$A_\parallel = \frac{M^2}{m_\star^2}\left|G^\pm_C\right|^2$$

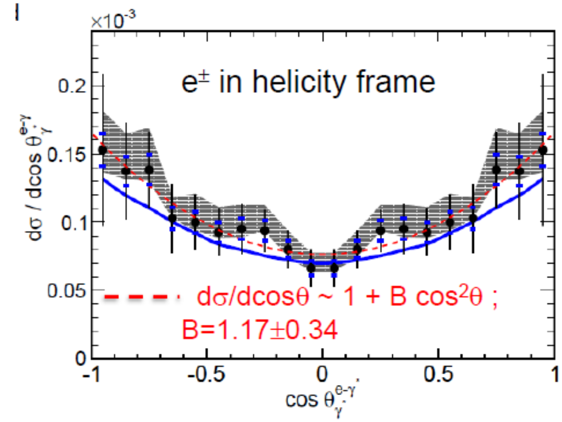
Δ(1232) Dalitz decay studies with HADES

E=1.25 GeV pp → ppe⁺e⁻

HADES PRC95, 065205 (2017)







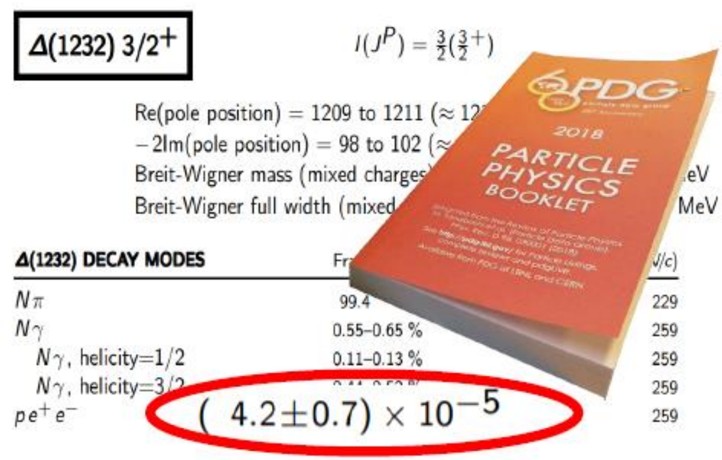
Dominance of magnetic transition (γ^* are transversely polarized)

- First measurement of Δ (1232) Dalitz decay branching ratio ($\Delta^+ \rightarrow pe^+e^-$)

Using information from PWA ($pn\pi^+$, $pp\pi^0$)

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

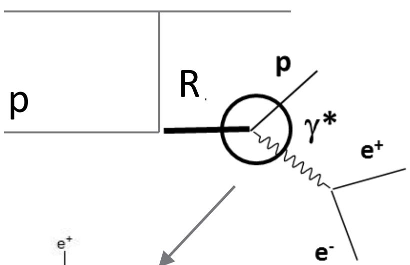
Wan and Iachello, Int. J Mod. Phys. A20 (2005) 1846
T. Pena and G. Ramalho, Phys.Rev. D85 (2012) 113014

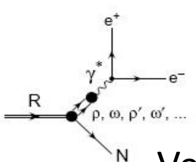


Dalitz decay studies of heavier baryons with HADES

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

p+p →pp e^+e^- 3.5 GeV



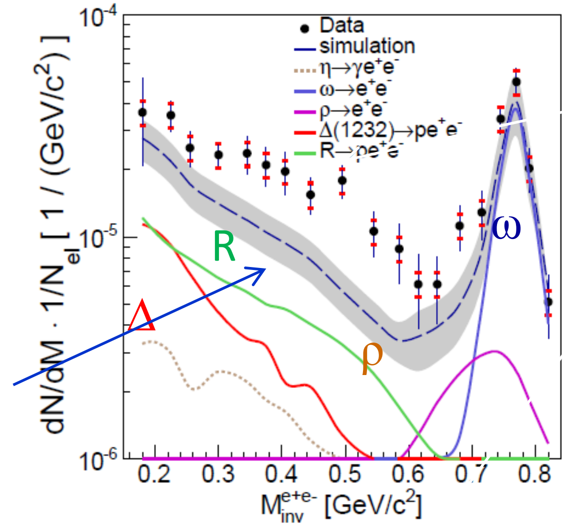


Vector Dominance Model

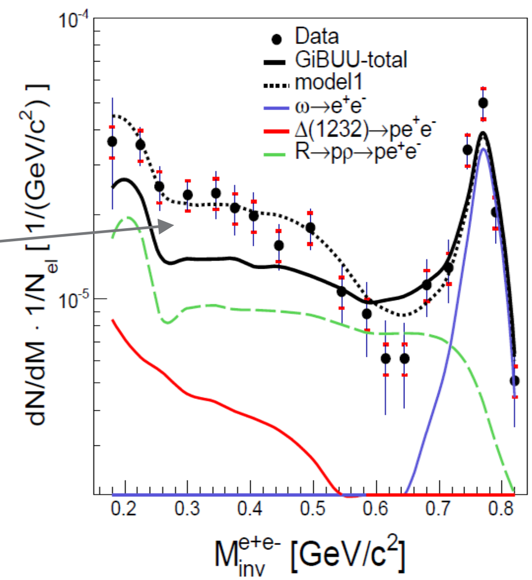
Δ(1232)
N*(1440)
N*(1520)
N*(1535)
N*(1680)
Δ(1620)
Δ(1700)
Δ(1910)

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

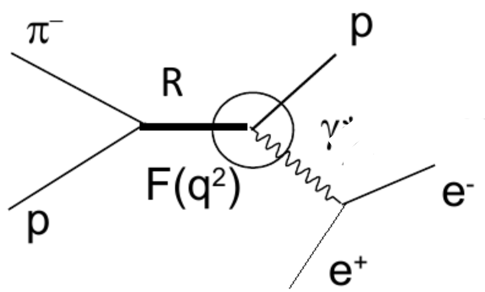
+ "direct" ρ and ω

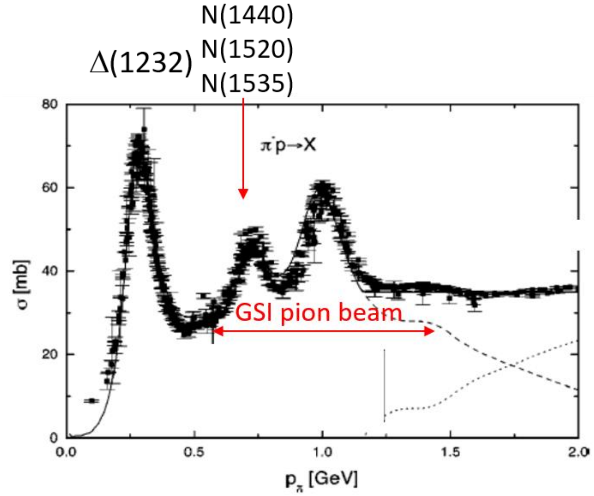


Effect of electromagnetic transition Form Factors for light baryonic resonances (N(1520),...)



Specific motivations for pion beam experiments with HADES





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

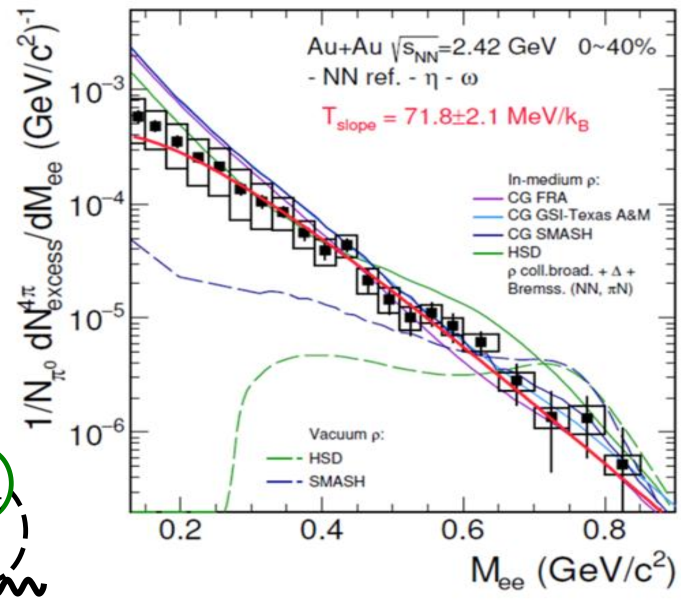
HADES + GSI pion beam is an ideal (unique in world) tool to

- ✓ 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

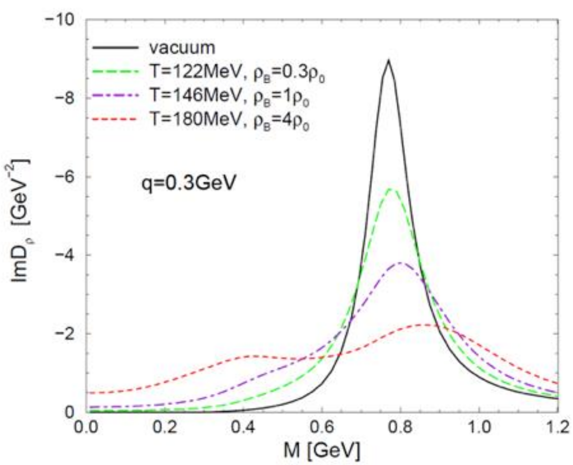
In medium vector meson spectral functions

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 !

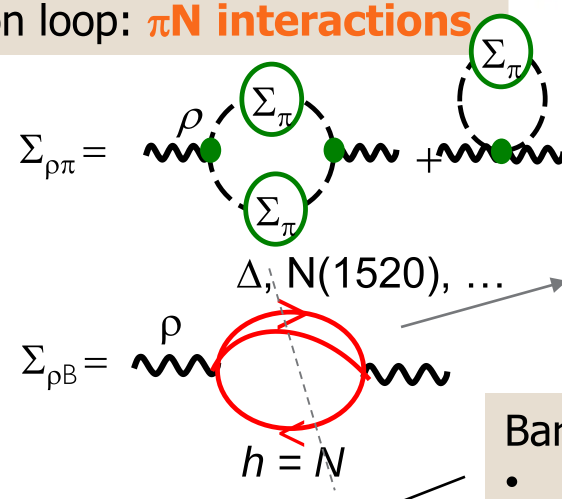


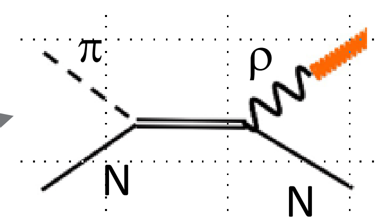
Vector Meson Dominance (VDM1)



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

pion loop: **πN interactions**



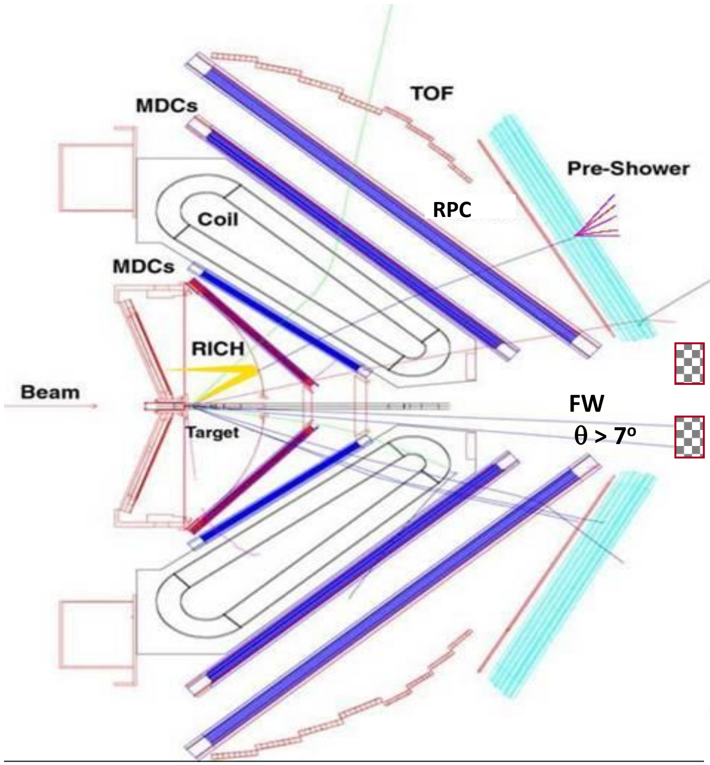


B. Friman et al. NPA617 (1997) 496.
R. Rapp and J. Wambach EPJA 6 (1999) 415

can be best accessed via πN reactions

Baryonic loop
- sensitive to **ρNN* couplings**
- related to **baryon Dalitz decay** **$\Delta/N^* \rightarrow Ne^+e^-$**

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

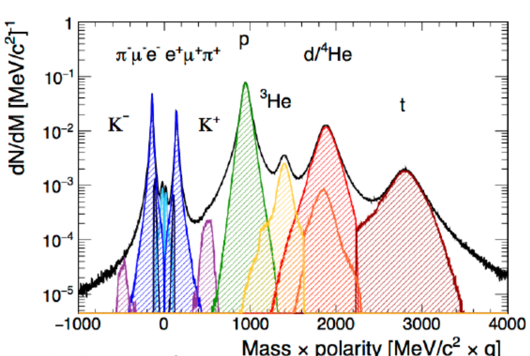
Cold matter:

p+Nb 3.5 GeV, π^-+C/W 1.7 GeV/c

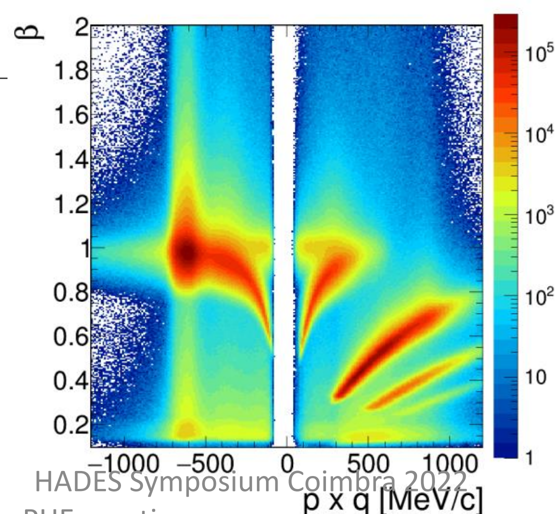
Elementary reactions:

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

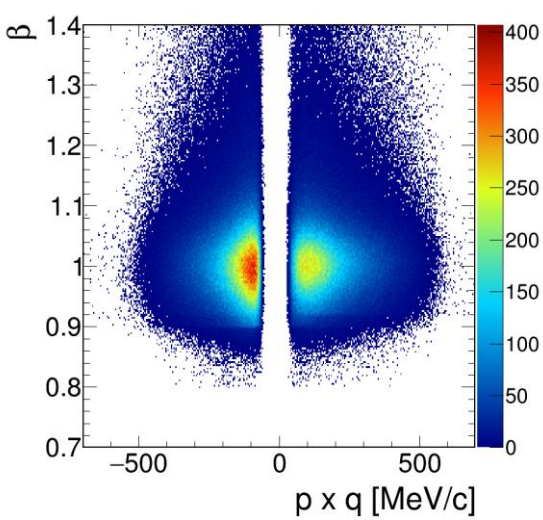
π^-+CH_2/C 0.7 GeV/c



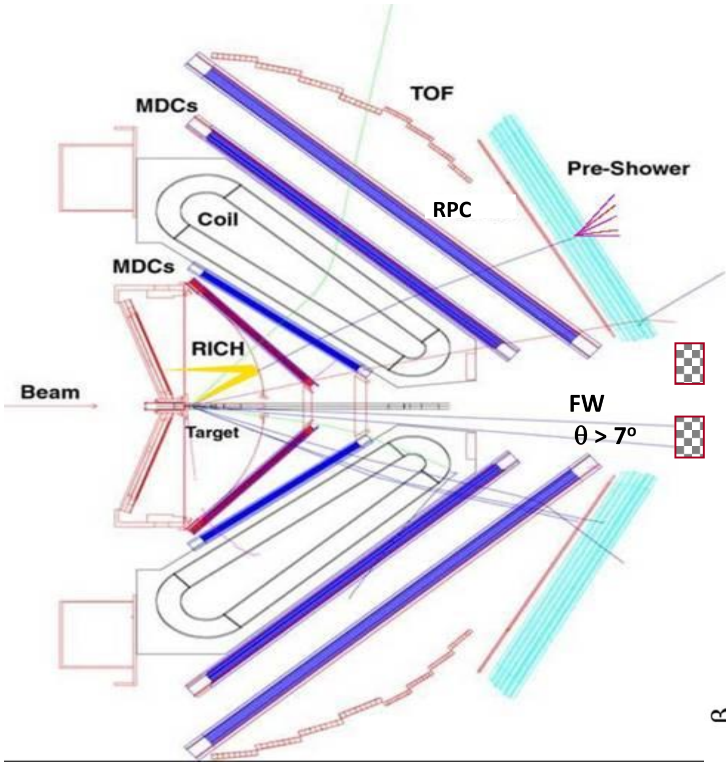
before lepton selection



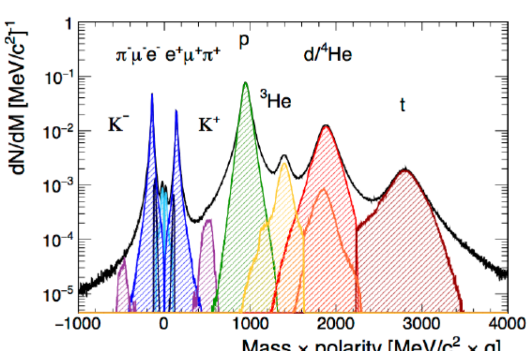
after lepton selection



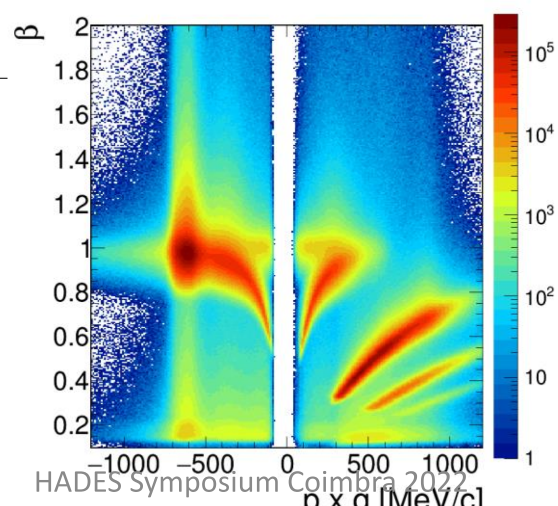
High Acceptance Di-Electron Spectrometer



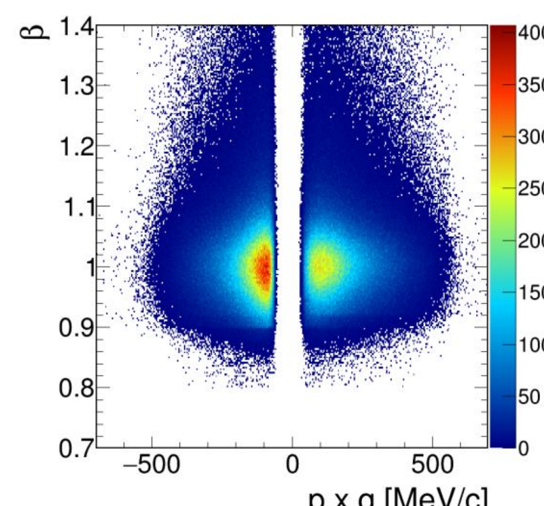
Acceptance: Full azimuth, polar angles 18° - 85°
Momentum measurement
Magnet: $\int B dl$ = 0.1- 0.34 Tm
MDC: 24 Mini Drift Chambers
Leptons: $\Delta x \sim 140\ \mu$ per cell, $\Delta p/p \sim$ 1-2 %
Particle identification: e^+/e^-, π^+/π^-, K^+/K^-, p
RICH, Time Of Flight, Pre-Shower (pad chambers & lead converter) (also MDC (K^-))
Trigger: ~ 50 kHz



before lepton selection



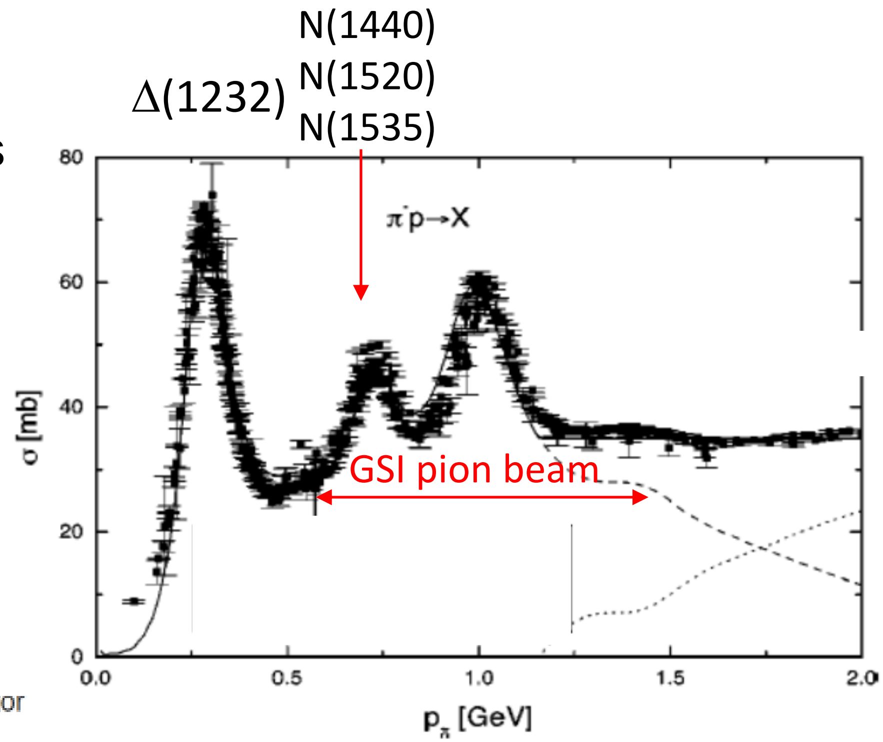
after lepton selection

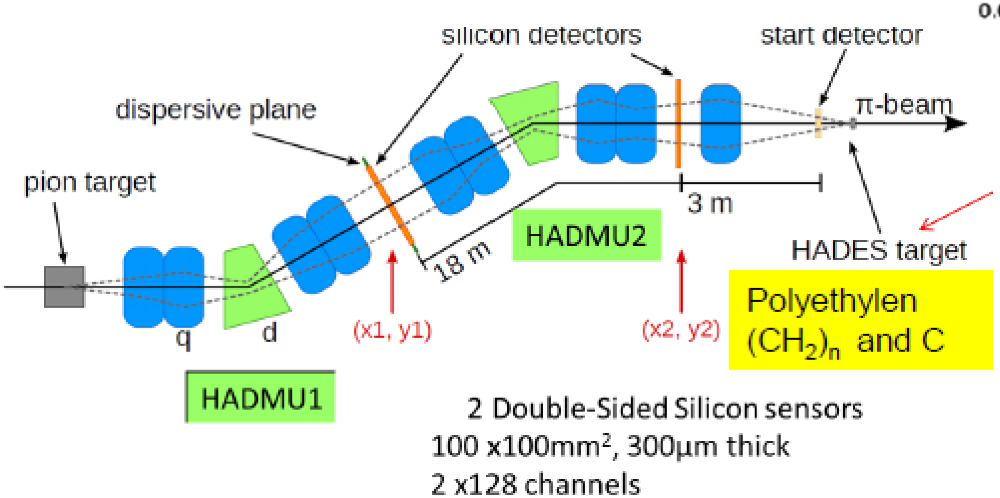


Pion beam at GSI

- ☐ 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 π/s for p_π 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)

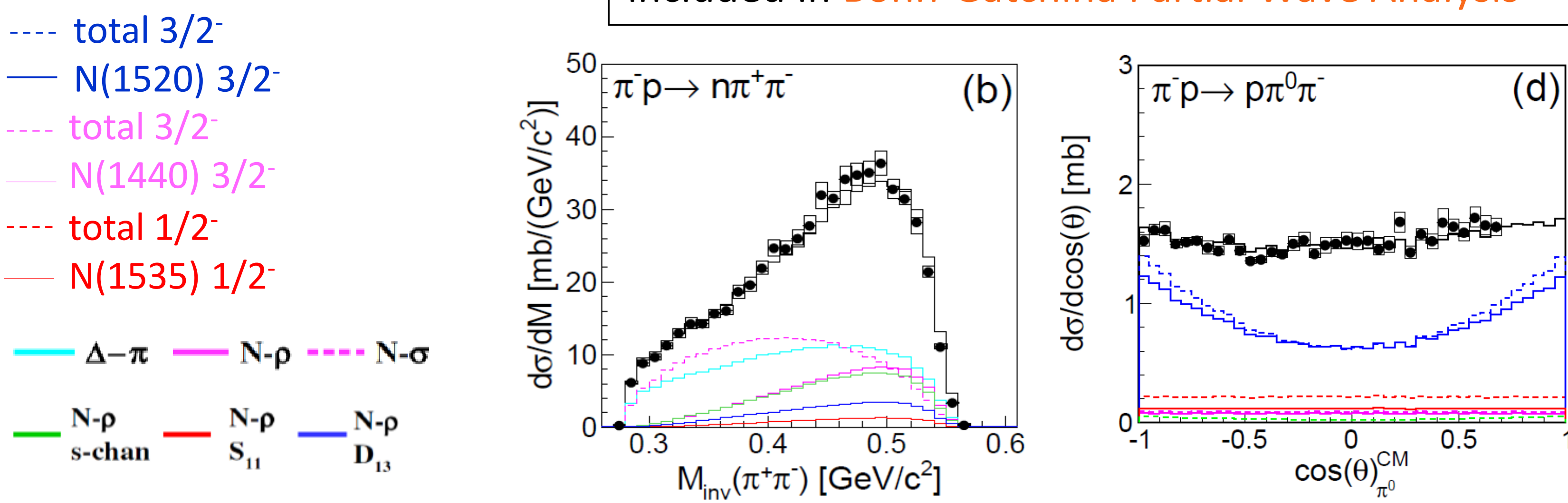
- e^+e^- production $\sqrt{s}$ =1.49 GeV/c^2
- data on C target also used for

cold matter studies

Partial Wave Analysis in 2π production channels

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

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

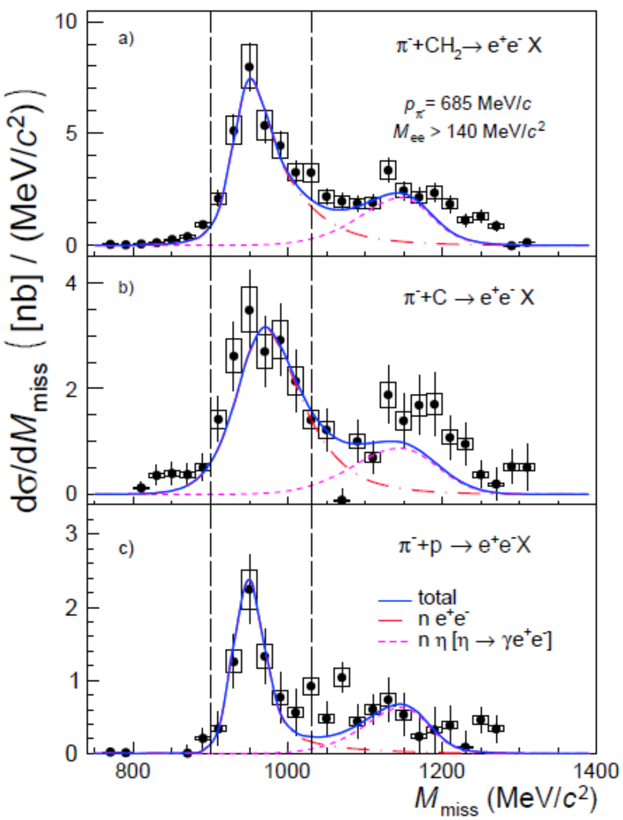


s-channel $3/2^-$ N(1520) is dominant

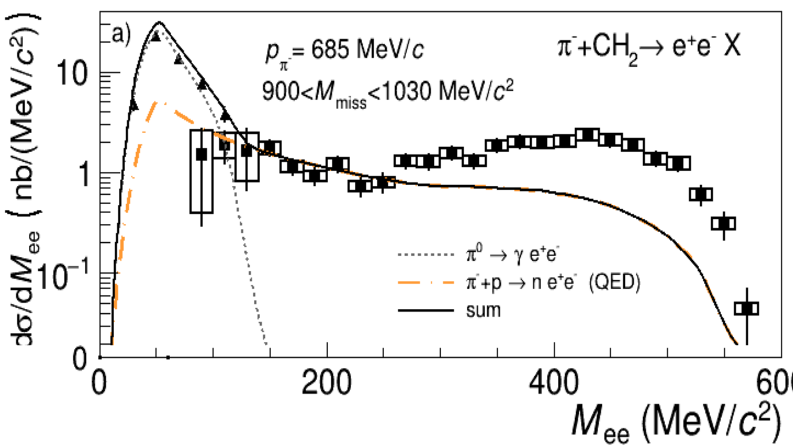
Branching ratios of N(1440), N(1535), N(1520) to 2π channels (Δ π, σN, ρN)
→ 8 new entries (4 first + 4 additional entries)

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

HADES coll. arXiv:2205.15914 [nucl-ex]



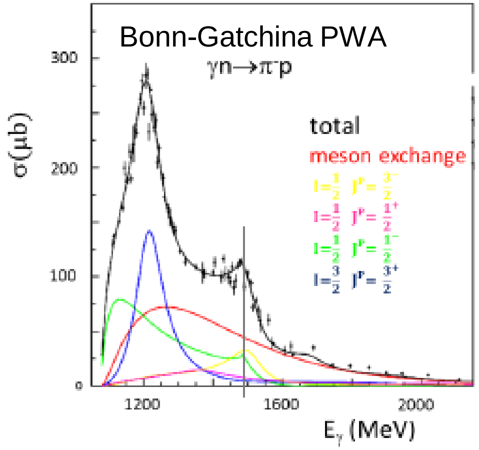
- Selection of the exclusive $\pi^- p \to n e^+ e^-$ channel using missing mass
- Quasi-free treatment of π^- C interactions
  σ_C/σ_p=3.3 (~$Z^{2/3}$)
- Subtraction of residual π^0 contribution



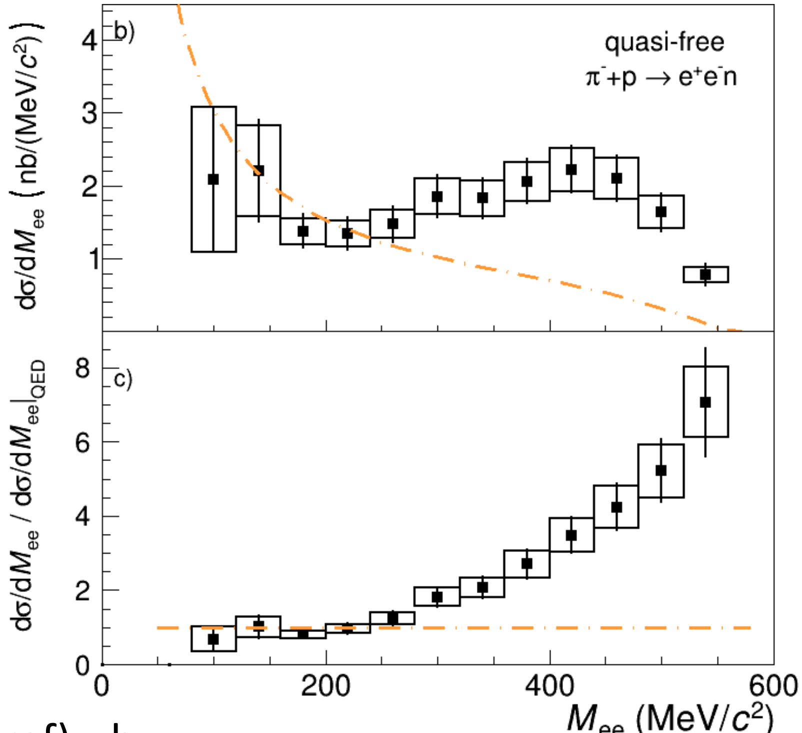
Comparison to the QED reference

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 $\sigma(\pi^-p \rightarrow n\gamma)$



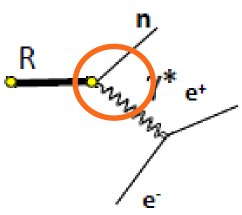
HADES coll. arXiv:2205.15914 [nucl-ex]



- $\sigma(\pi^-p \rightarrow ne^+e^-) = 2.14 \pm 0.06$ (data) ± 0.23 (QED ref) μb

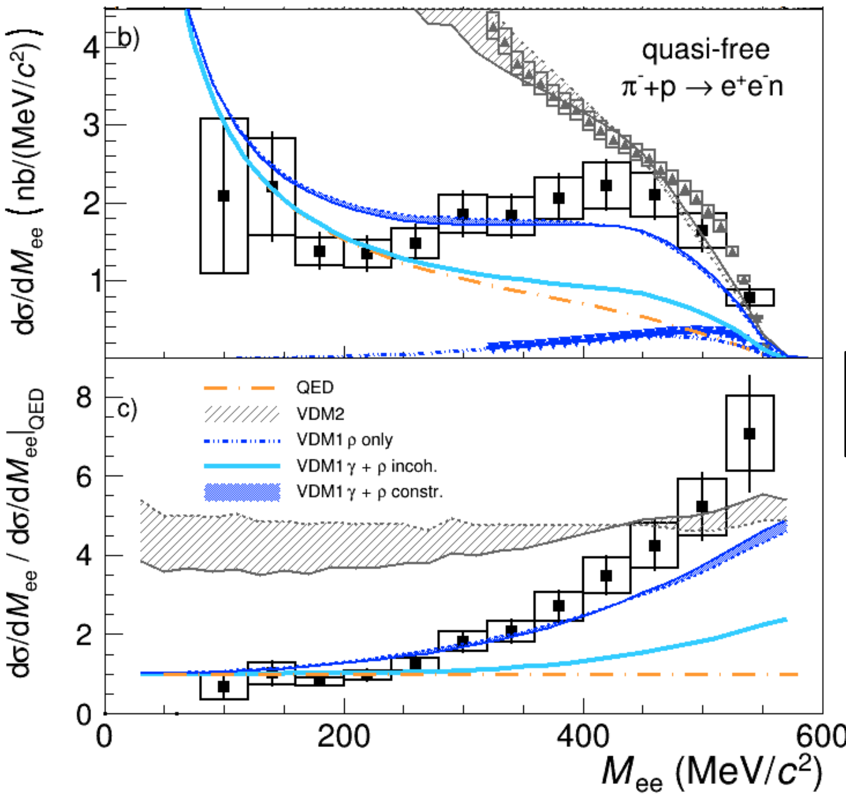
  $\sigma = 1.16 * \sigma_{QED}$
- $M_{ee} < 200$ MeV/c^2 consistency with QED reference
- Strong excess at larger M_{ee}
- Effective time-like transition form factor

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



Data comparison with VDM2/VDM1 models

HADES coll. arXiv:2205.15914 [nucl-ex]



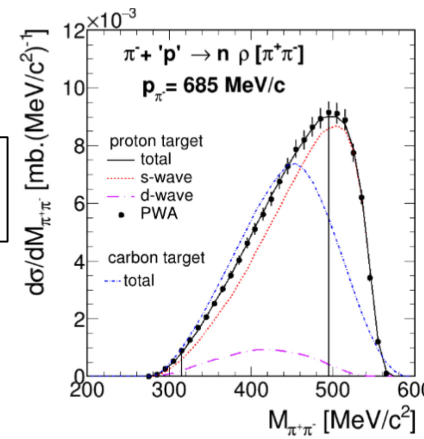
HADES collab., Phys.Rev. C102 (2020) 024001

Ideal case:

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

Direct test of VDM models based on known ρ contribution

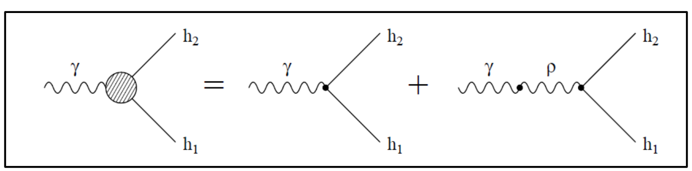
$$\left(\frac{d\sigma_{ee}}{dM_{ee}}\right)_{M_{ee}=M} = \left(\frac{d\sigma_{\pi\pi}}{dM_{\pi\pi}}\right)_{M_{\pi\pi}=M} \frac{\Gamma_{\rho\to e^+e^-}(M)}{\Gamma_{\rho\to\pi^+\pi^-}(M)}$$



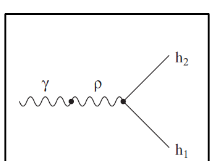
VDM1/VDM2 test:

- Large overestimation of measured yields with VDM2
- Two component (direct γ + VDM1) with constructive interferences gives a better description of the full spectrum

VDM1



VDM2

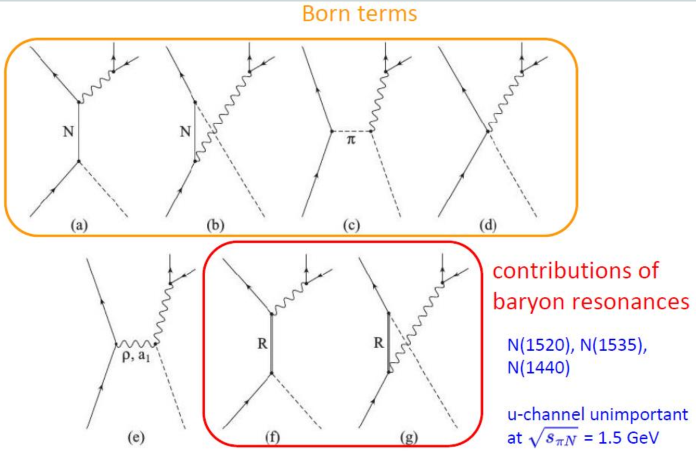


Two-component Lagrangian model

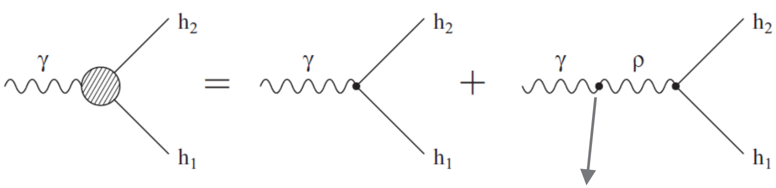
Microscopic calculation of $\pi^- p \rightarrow n e^+ e^-$

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

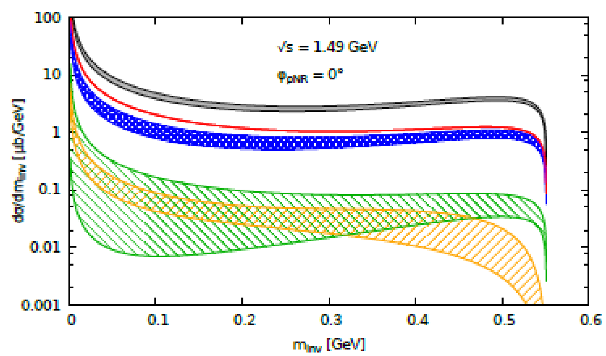
M. Zetenyi et al, Phys. Rev. C 104, 015201 (2021)



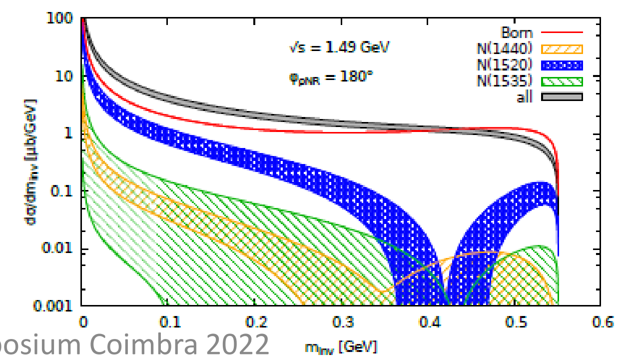
Strong contribution of the Born terms



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



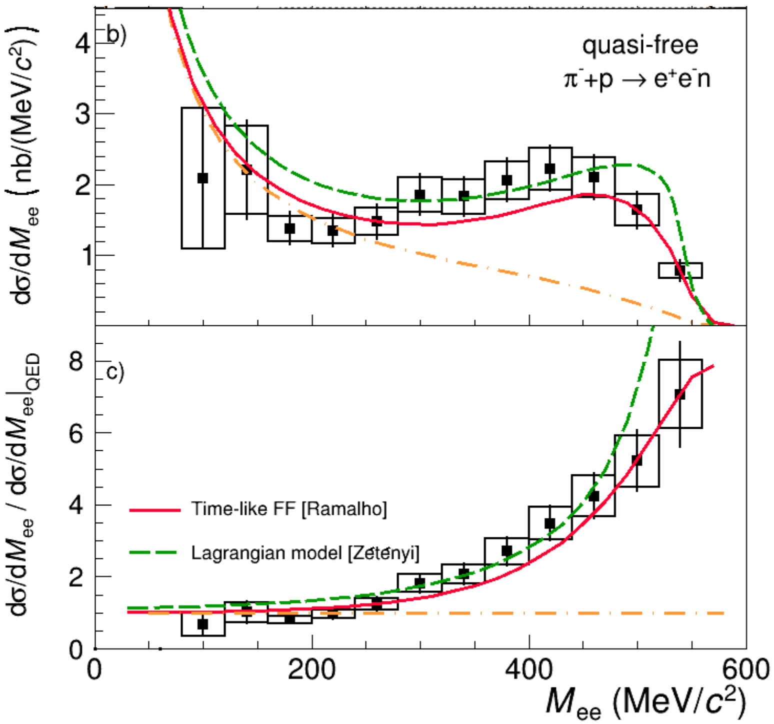
Here, « Kroll-Lee-Zuminio »
« VDM1 » Lagrangian is use

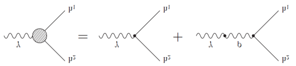


→ Shape and yield sensitive to the interference between the γ and ρ contributions

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 ϕ=90°*
- very promising, **but needs to be confronted to π^-p→ππN 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**

More calculations:

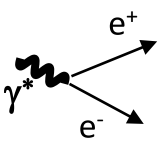
- *A. I. Titov and B. Kämpfer, EPJ.A12, 668 217 (2001)* (ρ/ω prod. amplitudes)
- *M. Lutz, B. Friman & M. Soyeur NPA713, 97 (2003)* (ρ/ω prod. amplitudes)
- *A. Ierusalimov & G. Lykasov Phys. Part. Nucl. Lett. 15, 457 (2018) ; 1907.10298 [hep-ph]*
  Inverse Pion Electroproduction (dipole or Gaussian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

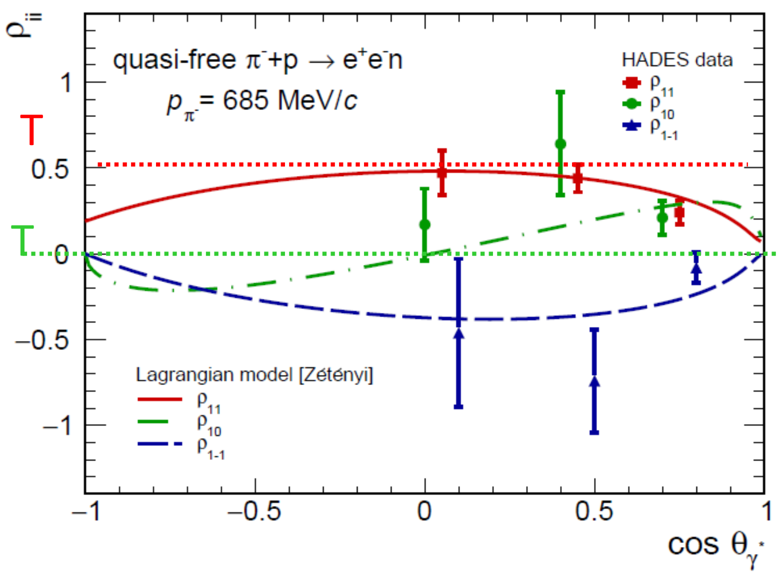
Analysis of e⁺/e⁻ angular distribution spin density matrix elements

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

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

ρ_{11} , ρ_{10}, ρ_{1-1} extracted in 3 bins in cos θ_γ





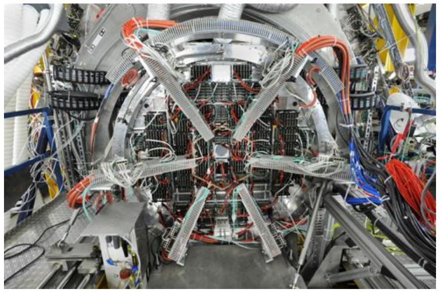
sdme sensitive to

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

e.g. ρ_{11} =0.5 and ρ_{10} =0 for transverse polarization

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

HADES upgrade: FAIR-Phase0

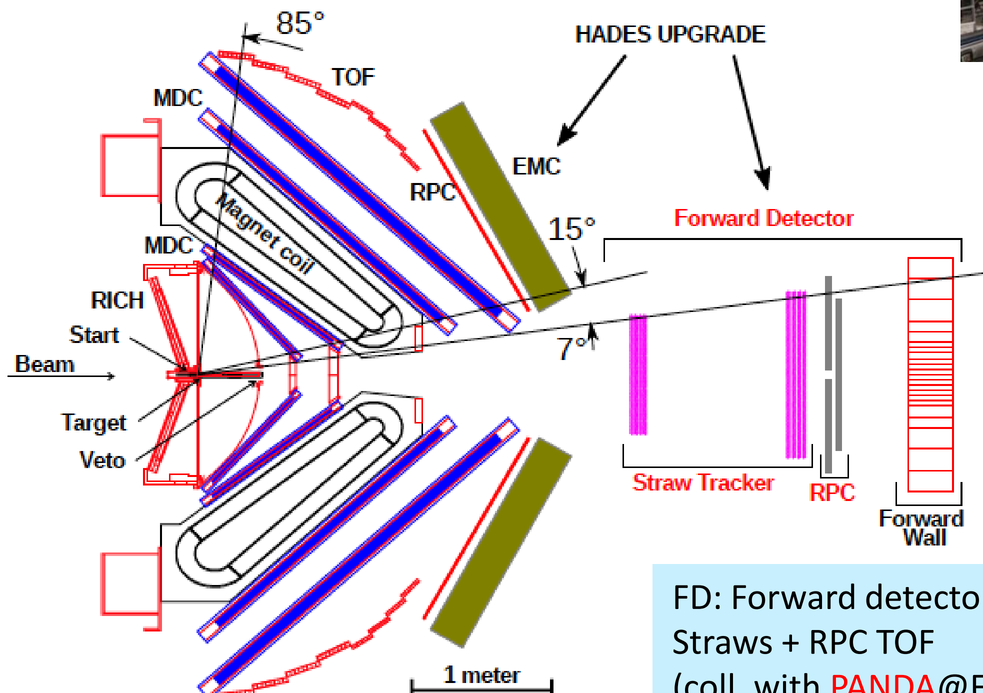


New RICH photon detector
& read-out
(coll. with CBM@FAIR)
Gain in e^+e^- efficiency x5

used in Au+Au exp. March 2019

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

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 Dalitz decays

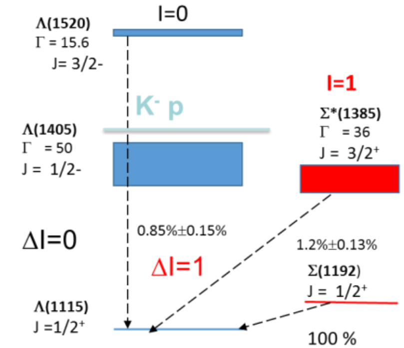
- Hyperons are narrow (Γ=15-40 MeV) : can be studied in pp, pA with HADES (and later p$\bar{p}$ with PANDA at FAIR).

Radiative decays of hyperons Y $\rightarrow\Lambda\gamma$

- Poorly known
- High sensitivity to internal structure (quark correlations)

Dalitz decays of hyperons Y $\rightarrow\Lambda$ e^+e^- (BR~10^{-5})

- No measurement.
- Role of meson cloud ?
- Relevance of Vector Dominance in the hyperon sector?



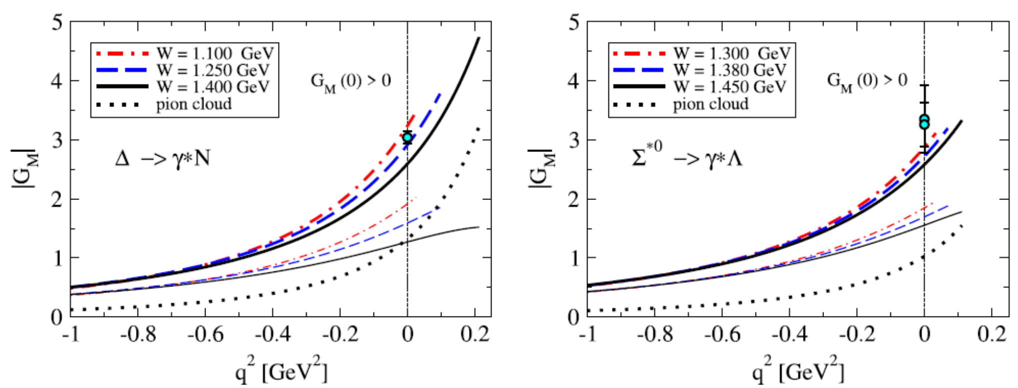
CLAS PRD83 (2011) 072004, PRC71(2005) 054609

Existing calculations

$\Sigma\rightarrow\Lambda e^+e^-$ dispersive theory C. Granados et al. Eur. Phys. J.A54(2018)1

$\Sigma(1385)\rightarrow\Lambda e^+e^-$ constituent quark model G. Ramalho, Phys. Rev. D 102, 054016 (2020)

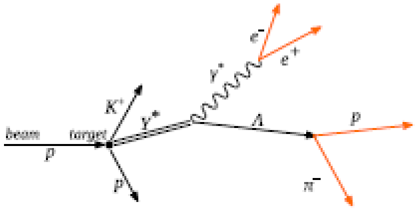
e.g. $\Sigma^*(1385)\rightarrow\Lambda\gamma^*$ is anologue of $\Delta(1232)\rightarrow N\gamma^*$ (measured by HADES)



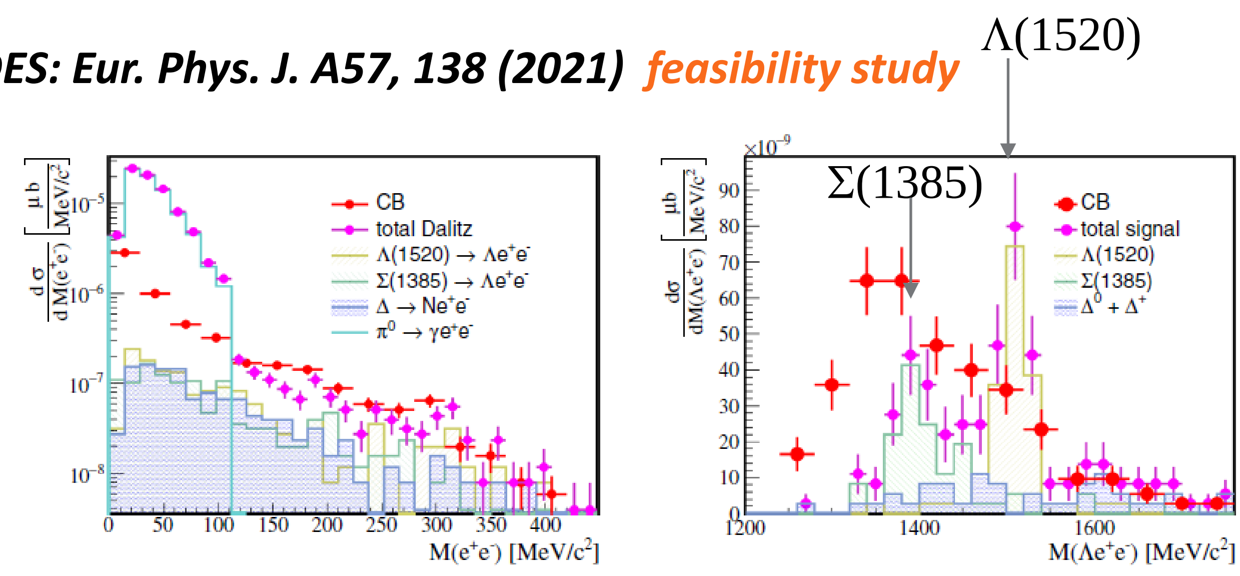
Hyperon studies in pp@4.5 GeV

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

Ξ, ΛΛ, Λ, Σ→Λγ
Hyperon Dalitz decays: $pK^+\Lambda(1520)$ [Λe^+e^-]
$pK^+\Sigma(1385)$ [Λe^+e^-]



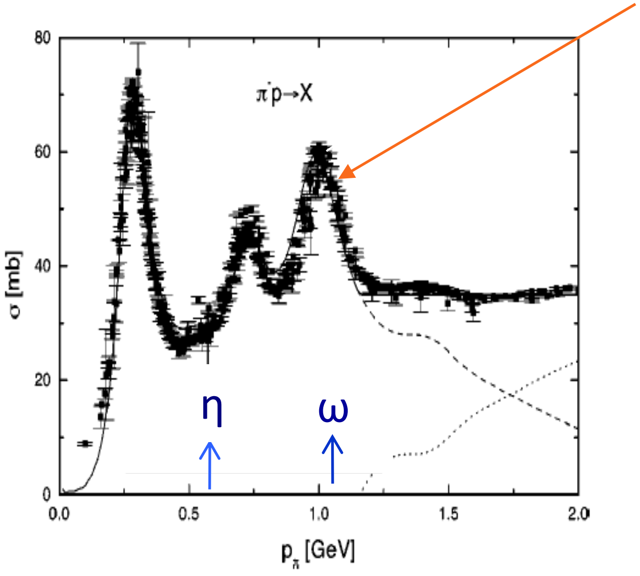
HADES: Eur. Phys. J. A57, 138 (2021) ***feasibility study***



Analysis is on-going….

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 $\pi\pi N$, ωn, ηn , $K^0\Lambda$, $K\Sigma$,….
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 ($R \to R'\pi/\eta \to N\pi\pi/ N\pi\eta$), ηn couplings

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

- Broad range of $q^2=(M_{ee})^2$ → 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 (2^{nd} 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

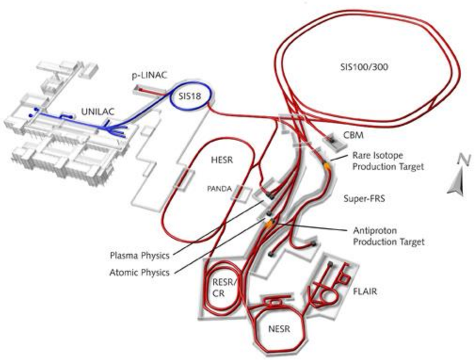
✓ Proposal for pion beam experiment in 2023 in the third resonance region

→ 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



HADES Collaboration, Feb 22nd 20018

Thank you

Precision data require accurate analysis procedures to establish the baryon spectrum

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