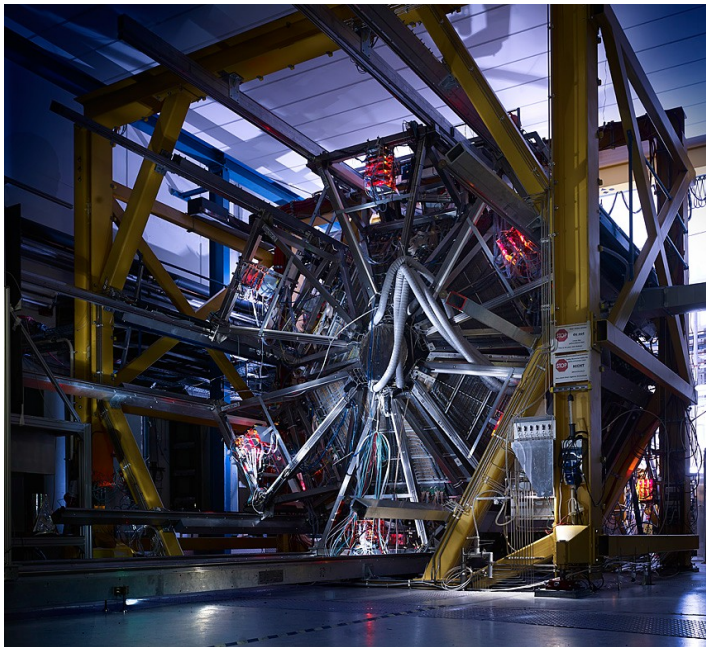
Studies of time-like electromagnetic structure of baryons with HADES

GSI Helmholtzzentrum für Schwerionenforschung



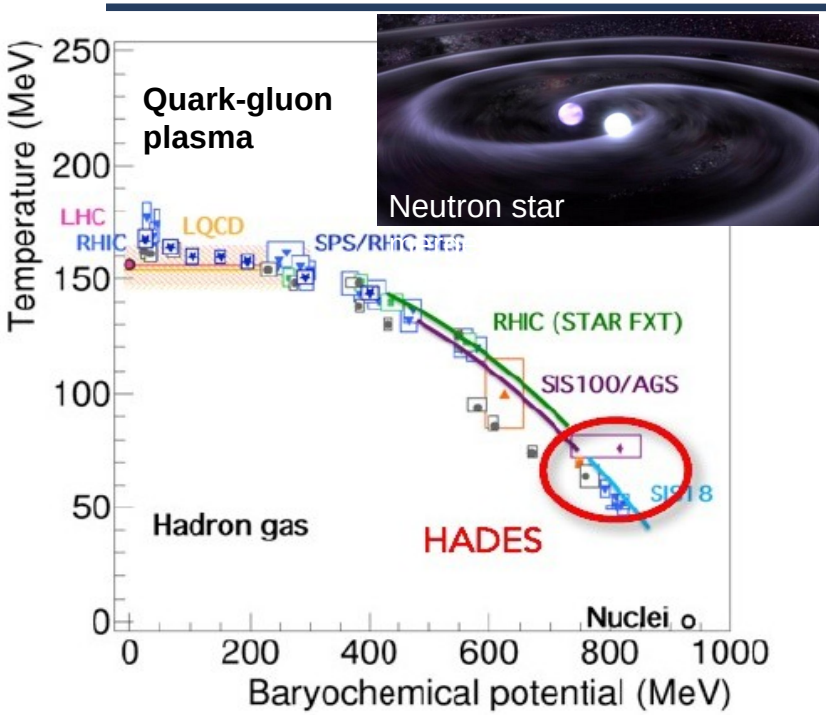
OUTLINE:

1) Motivations of the HADES experiment:
   - → emissivity of dense QCD matter with dileptons,
   - → electromagnetic structure of baryons.
2) HADES detector.
3) Results on baryon transition form factors from proton and pion induced reactions.
4) Summary and outlook.

Izabela Ciepał

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

HADES: exploring dense QCD matter

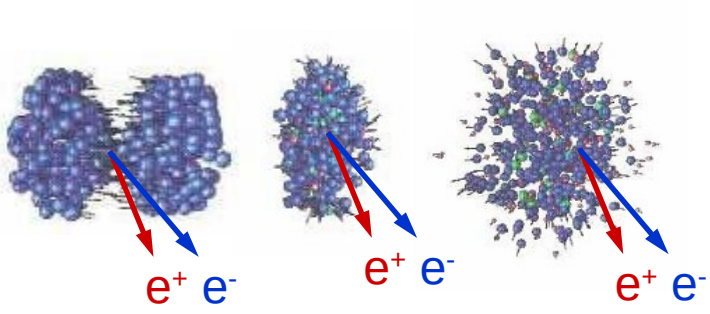


- Equation-of-State: First order transition ?
- Search for a critical point
- Chiral symmetry restoration
- Hadron properties in hot and dense nuclear matter
- Role of baryonic resonances, hyperons
- Complementary to SPS, RHIC,..

A+A: 1-3A GeV
√s=2-2.4 GeV

Observables:

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



Emissivity of QCD matter

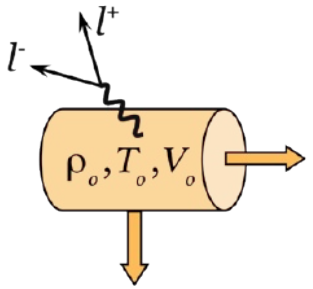
low-mass dilepton rate from a thermalized source

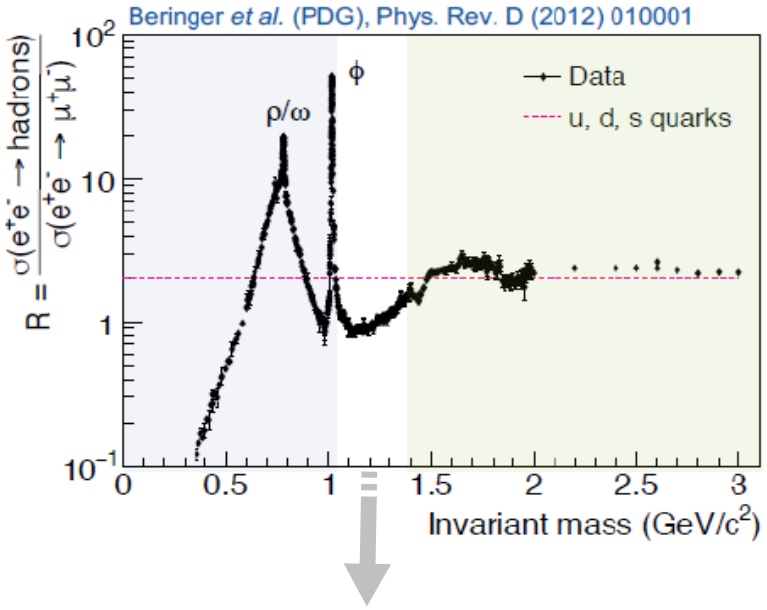
L.D. McLerran, T. Toimela, Phys. Rev. D 31, 545 (1985)

$$\frac{dN_{ee}}{d^4x d^4q} = \frac{-\alpha^2}{\pi^3 M^2} f^{BE}(T, q_0)\,\mathrm{Im}\,\Pi_{em}(M, q, T, \mu_B)$$

thermal Bose distribution

spectral function





transition region

spectral function in **VACUUM**:

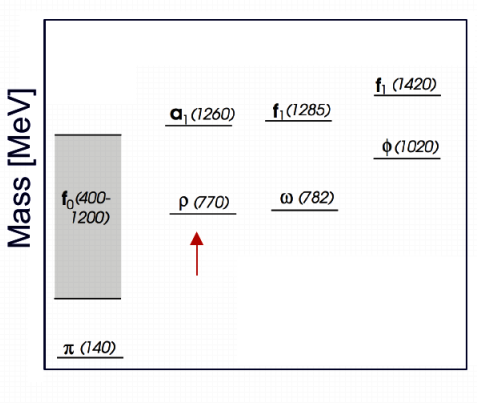
$$R = \frac{\sigma(e+e- \to hadrons)}{\sigma(e+e- \to \mu+\mu-)} \propto \frac{1}{M^2}\,\mathrm{Im}\,\Pi_{em}$$

- **LMR:** dileptons with M<1 GeV - spectral function saturated with vector mesons and mostly mediated by the vector meson **ρ (1⁻⁻)**

$$Im\Pi_{em}^{vac} = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 ImD_v^{vac}(M)$$

- **IMR:** M>1.5 GeV practically flat, q-$\bar{q}$ continuum (pQCD), stable termometer

Chiral symmetry restoration and low mass dileptons



➔ ρ–a_1 mass splitting ⇒ Chiral Symmetry Breaking

➔ a_1 (axial-vector) accessible only via ρ–a_1 mixing

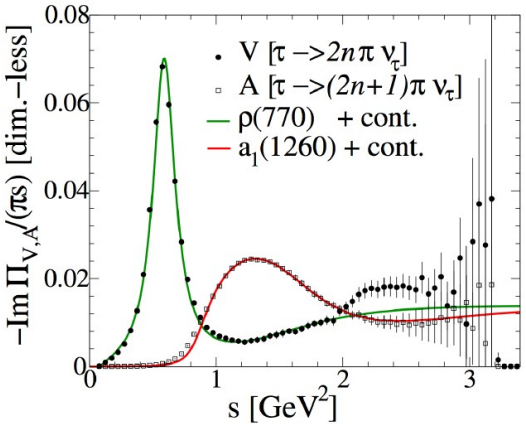
Winberg sum rules:

$$\int_0^\infty \frac{ds}{\pi}[\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

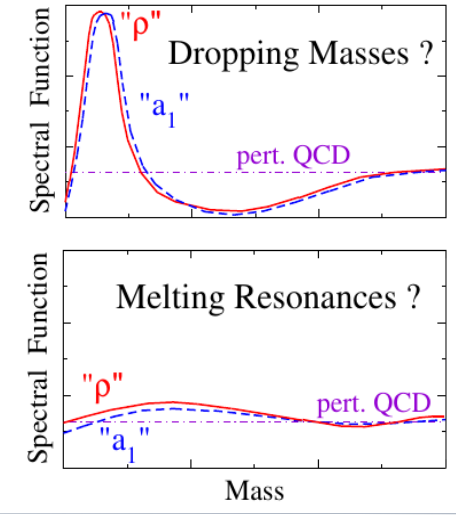
in-medium ρ broadening (RHIC, SPS, SIS18)

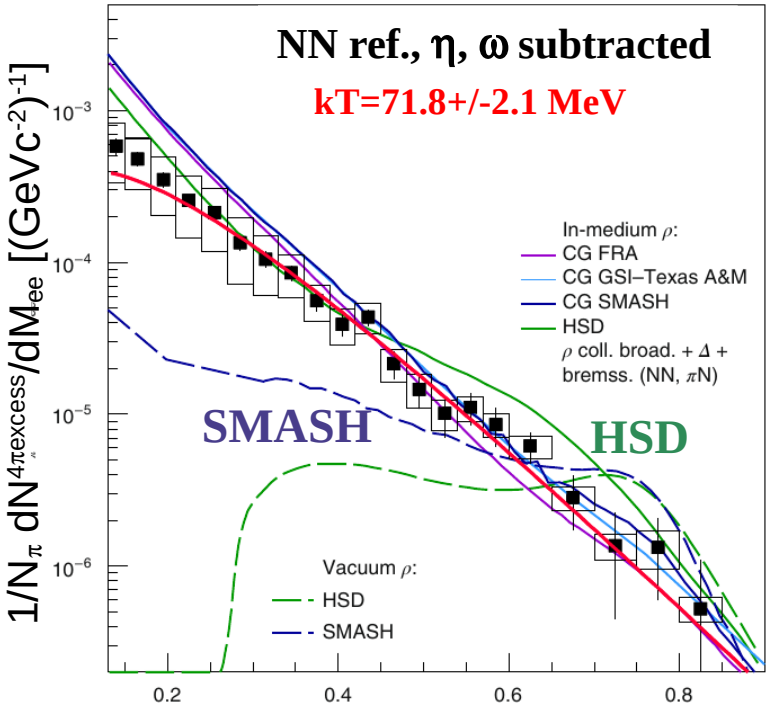
HADES Au+Au @ $\sqrt{s_{NN}}$=2.42 *GeV*

Axial-Vector in vacuum (ALEPH exp.)



at T_c: chiral restoration





HADES: Nature Phys. 15 (2019) 10, 1040

R. Rapp, J. Wambach EPJA 6 (1999) 415

In medium ρ spectral function – connection to baryon Dalitz decay

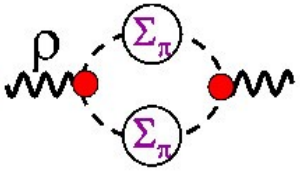
ρ meson propagator

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

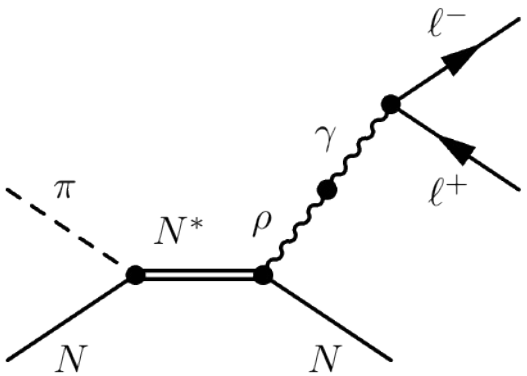
Vacuum:

Nuclear matter: additional terms (ρ selfenergies)

$\Sigma_{\rho\pi\pi}$ =



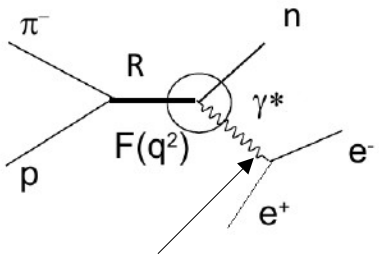
$\Sigma_{\rho B,M}$ =



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

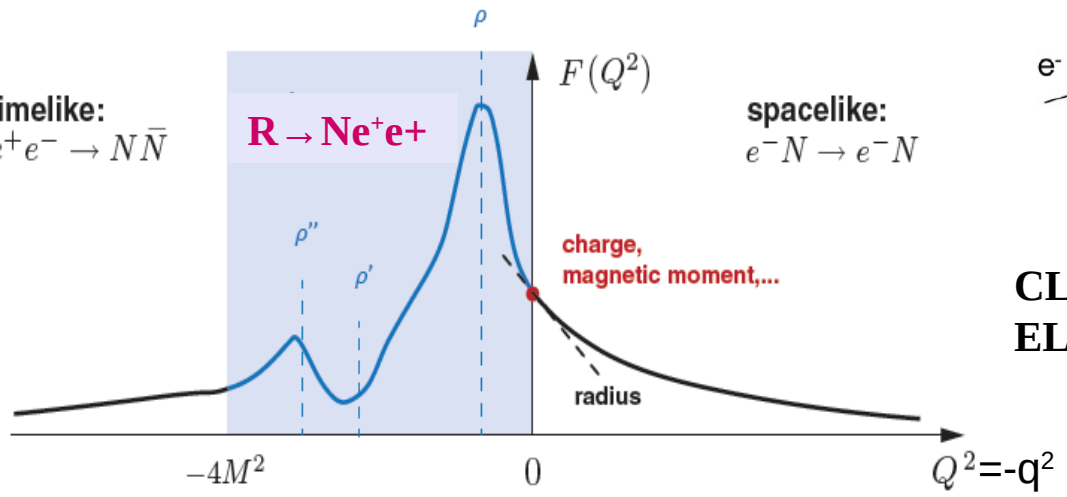
dedicated HADES hadron physics program

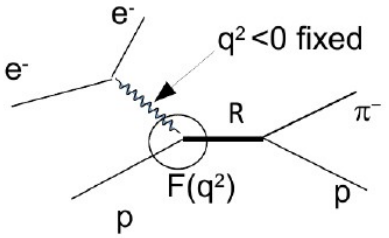
Electromagnetic structure of baryons



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

no data available





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

Rezonans → Nucleon Transition Form Factor – **baryon Dalitz decay**

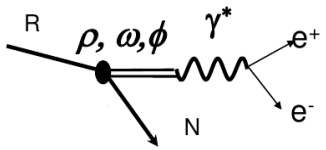
$$q^2 = M^2_{inv}(e^+e^-) = M^2_{\gamma^*} > 0$$

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

QED
transition of point-like particles

$G_{M/E/C}$: Form-Factors
internal structure of hadrons
(various models)

VMD: important role of vector mesons: $J^{PC} = 1^{--}$ (=γ)



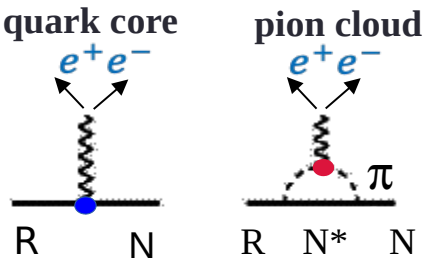
eTFF of baryons: models

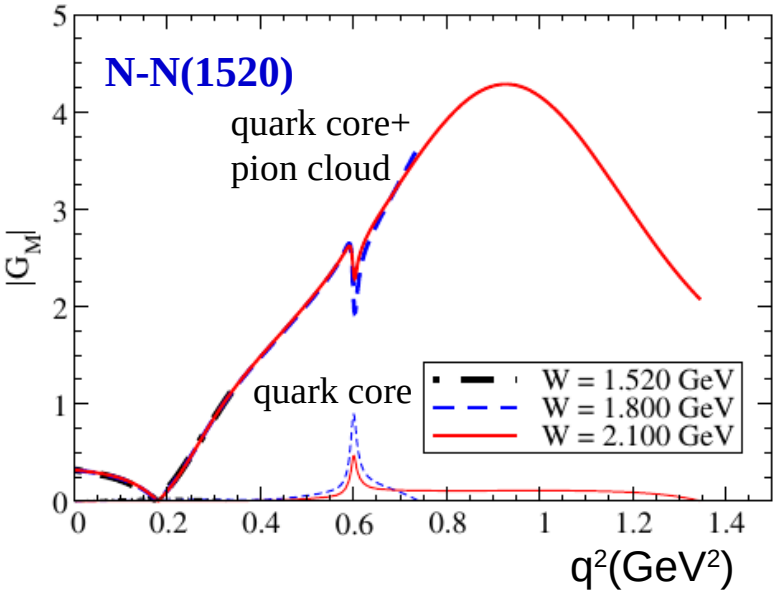
Covariant quark model +VMD

T. Pena & G. Ramalho

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

VMD:
quark FF
pion FF





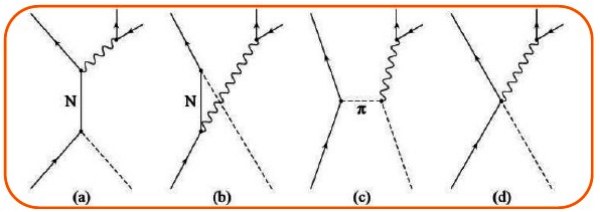
Two-component Lagrangian model

M. Zetenyi & G. Wolf

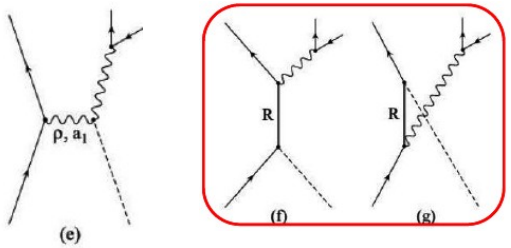
PRC 86, 065209 (2012)
PRC 104, 015201 (2021)

microscopic calculations of πN→ Ne+e-

Born terms

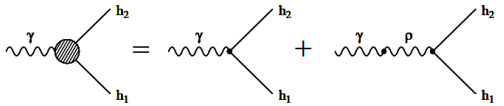


baryon resonances



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

2-component VMD:



Dalitz decays of baryon resonances

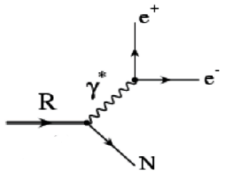
Vector Meson Dominance Models (VMD)

Mesons Dalitz decays – (Kloe, BesIII, A2, Na60 …), many theoretical calculations of eTFF (dispersive framework, effective Lagrangian, quark models, LQCD).

Baryons Dalitz decays – (Hades), calculations of eTFF based on VMD:

➔ **QED "point-like"**

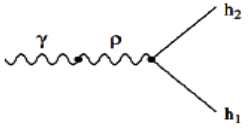
R-γ^* vertex



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

➔ ***strict* VMD**

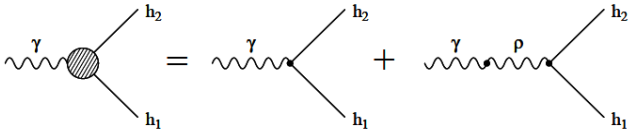
- Nρ coupling
- used in HI transport models



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

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

➔ **2-component VMD**



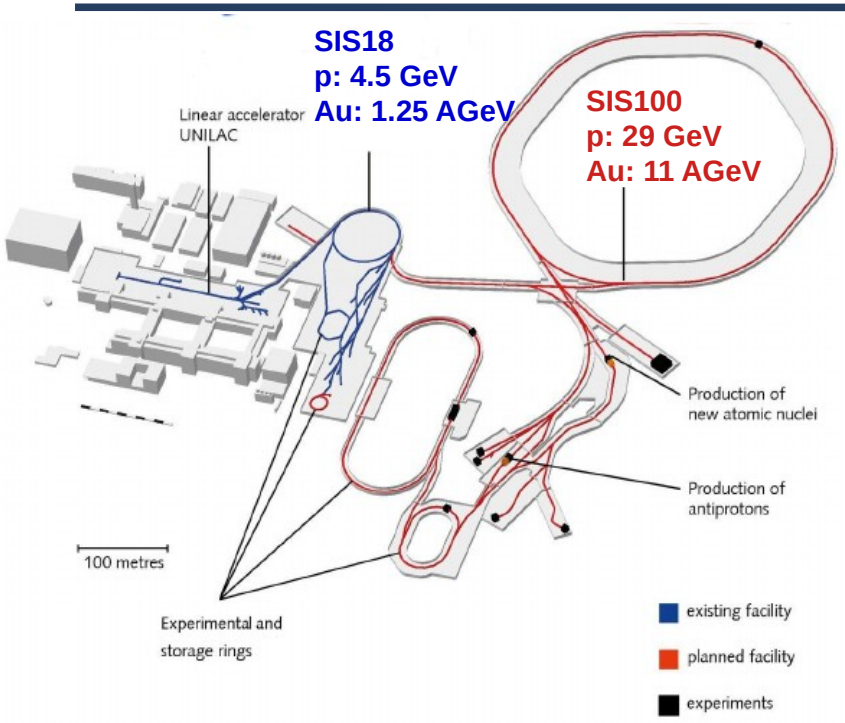
Kroll, Lee & Zuminio
Phys. Rev. 157, 1376 (1967)

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

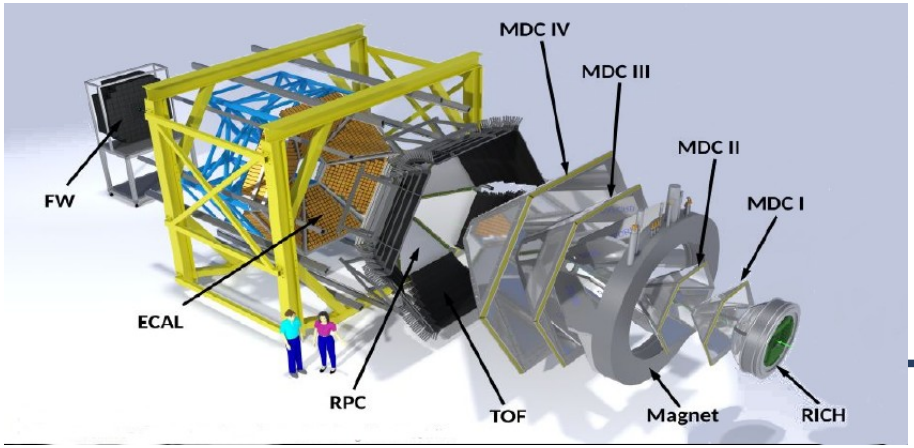
$$\Gamma_\rho^{VDM2} = \left(\frac{M_0}{M}\right)^3 \Gamma_\rho^0$$

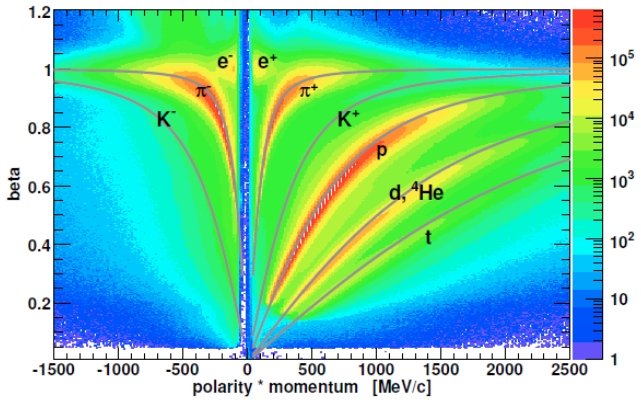
High Acceptance DiElectron Spectrometer

GSI Helmholtzzentrum für Schwerionenforschung



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



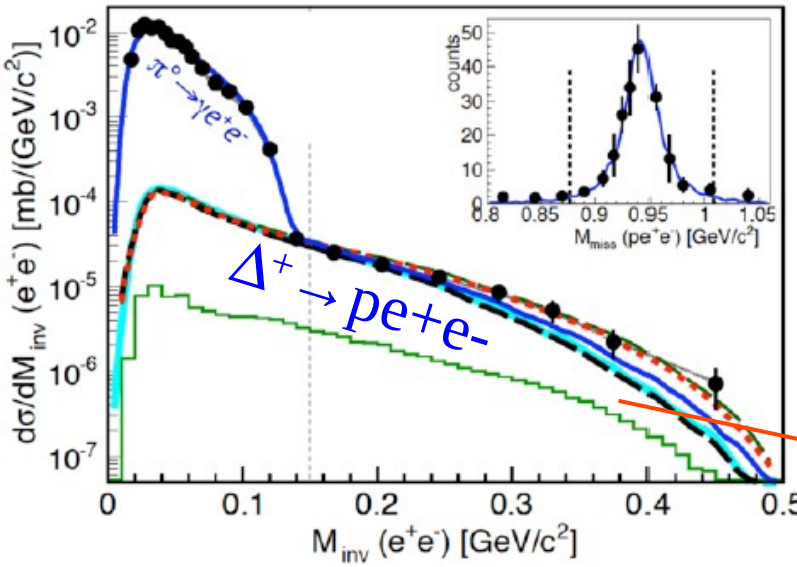


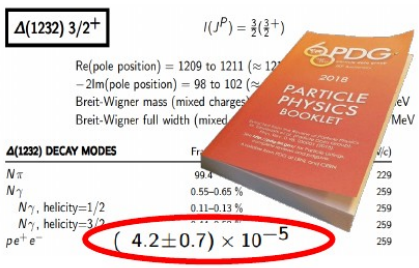
Δ (1232) resonance - exclusive pe+e- analysis

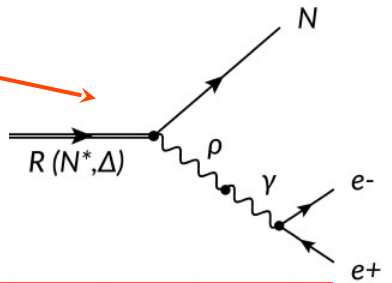
HADES: Phys. Rev. C 95, 065205 (2017)

pp → ppe+e- @1.25 GeV

→ cross sections for Δ ($p\pi^+$, $p\pi^0$) from PWA



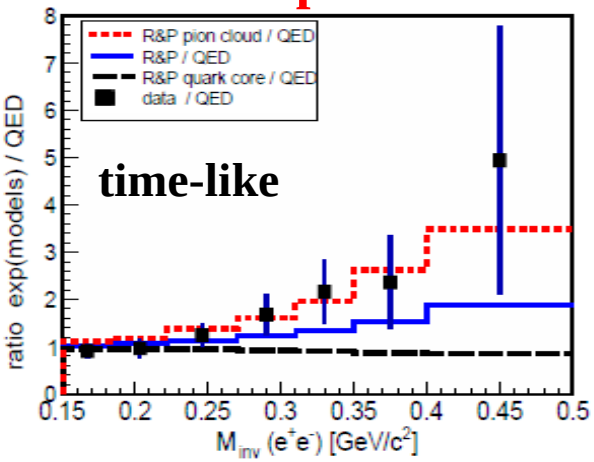




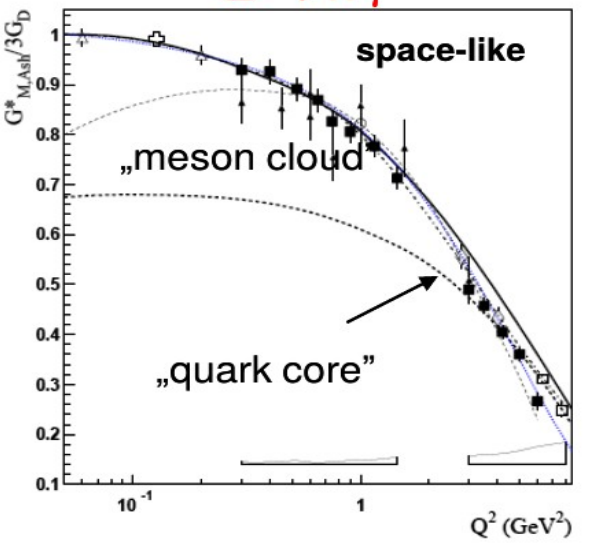
$$\frac{d\Gamma(\Delta \to Ne^+e^-)}{dq^2} = f\left(m_\Delta, q^2\right)\left(\left|G_M^2(q^2)\right| + 3\left|G_E^2(q^2)\right| + \frac{q^2}{2m_\Delta^2}\left|G_C^2(q^2)\right|\right)$$

effective eTFF

$\Delta^+ \to pe^+e^-$



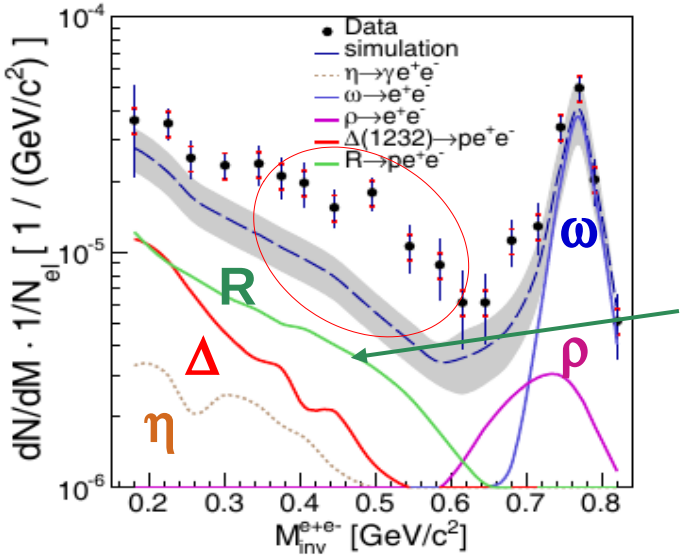
$\Delta \to N\gamma$



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

Dalitz decay studies of heavier baryons

HADES: EPJ A50, 82 (2014)

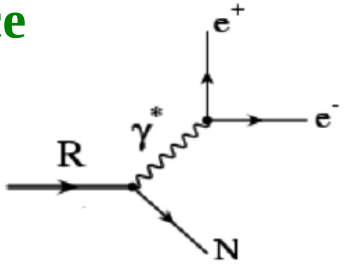


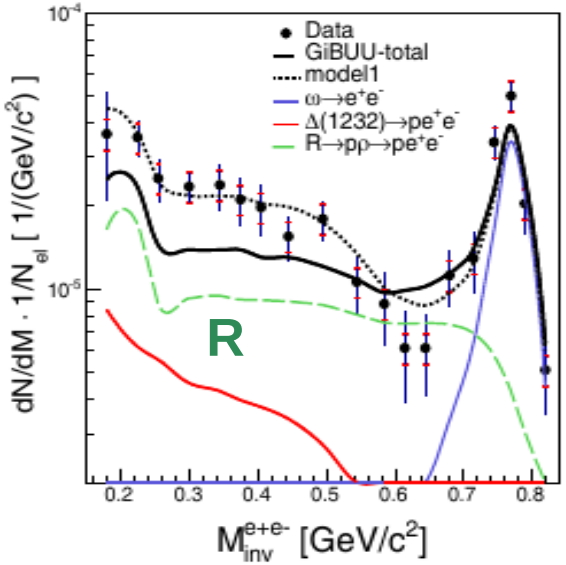
pp → ppe⁺e⁻ @3.5 GeV

Dalitz decays of **point-like** baryonic resonances (constrained by $pp\pi^0$ and $pn\pi^+$ channels)

QED reference

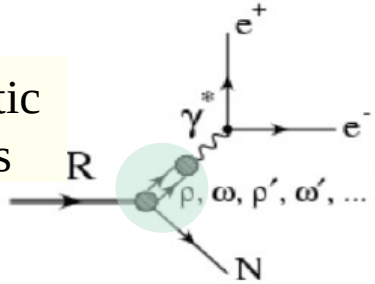
R → pe+e-





effect of electromagnetic transition Form Factors

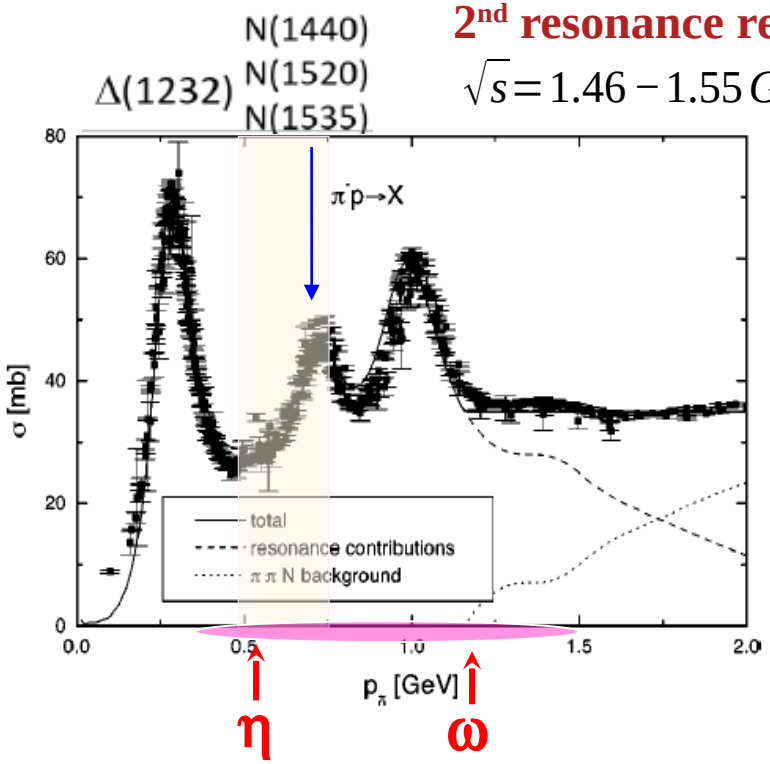
R → pρ → pe+e-



model 1 = GiBUU, but with modified cross sections (HADES simul.)

R= $\Delta^+(1232)$
$N^*(1440)$
$N^*(1520)$
$N^*(1535)$
$N^*(1680)$
$\Delta^+(1700)$
$\Delta^+(1910)$

Motivations for pion beam experiments with HADES

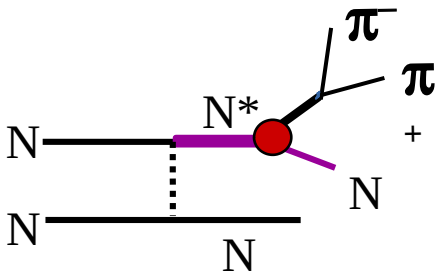


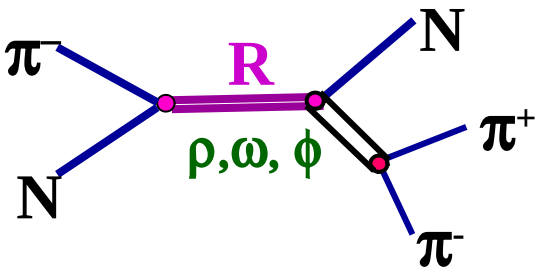
2nd resonance region

$\sqrt{s} = 1.46 - 1.55\,GeV$

selectivity:

producion of resonance with given mass in s-channel





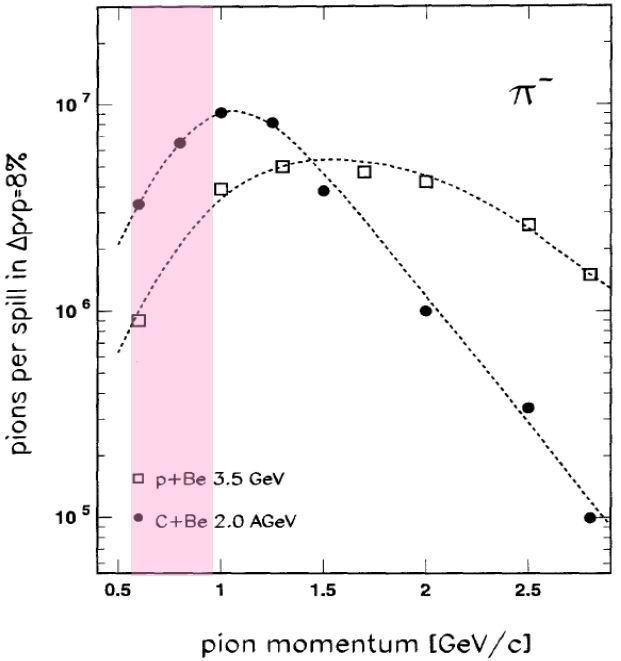
HADES + GSI pion beam is an ideal (unique in world) tool to:

- Study the time-like electromagnetic structure of baryons
- Complete the very scarce pion beam data base for hadronic couplings
- **Dilepton channel** R→ Ne+e-, **never** measured in pion induced reactions

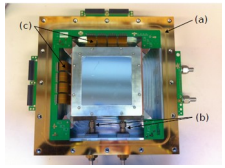
Pion beam facility @ GSI

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

- reaction **N+Be,** 8-10*10^{10} N_2 ions/spill (4s)
- secondary **π^-** with **I ~ 2-3 10^5/s**
- p = 650, **685**, 733, 786 (+/- 1) MeV/c
- **PE $(CH_2)_n$** and **C** targets

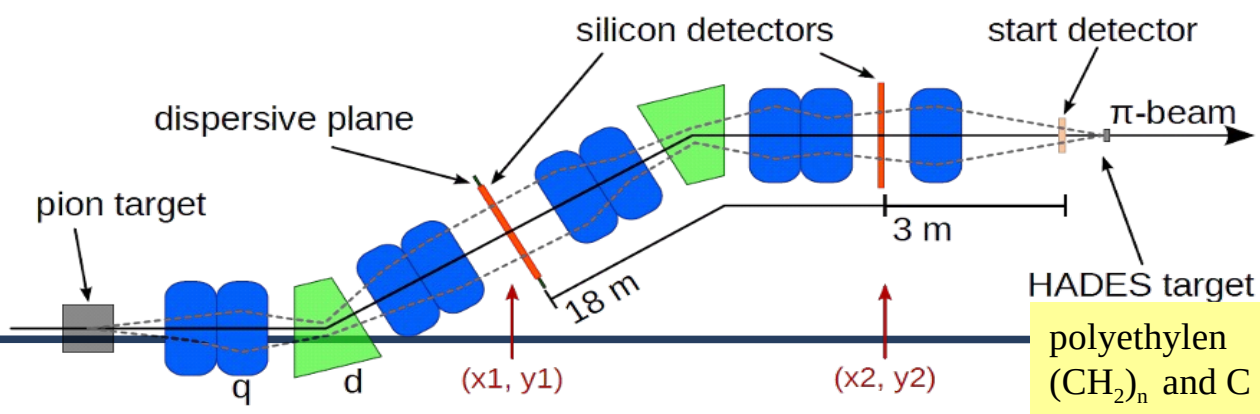


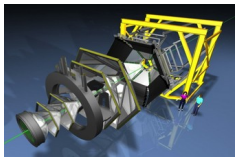
- pion momentum Δp/p =2.2% (σ)
- ~50% acceptance of pion beam line



pion beam tracker

diamond detector

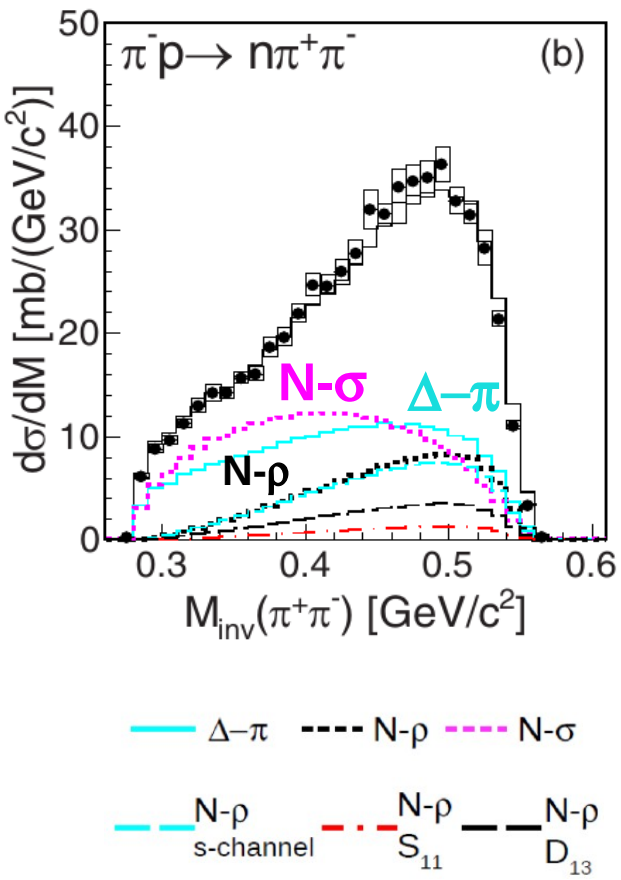




polyethylen $(CH_2)_n$ and C

2-pion production in π^-p

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

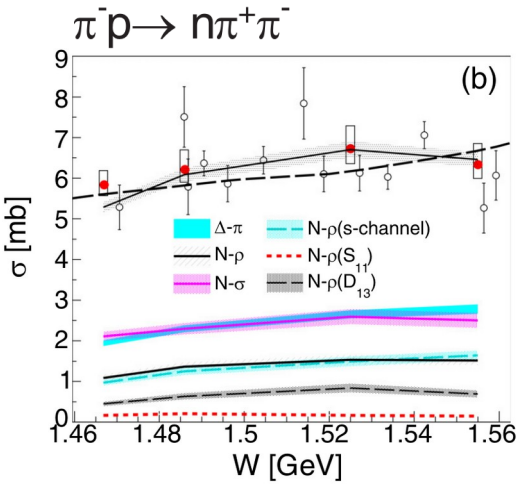


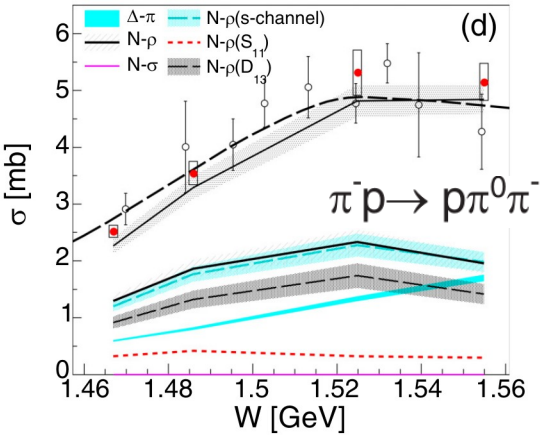
Bn-Ga PWA: *pwa.hisp.uni-bonn.de*

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

unique data set





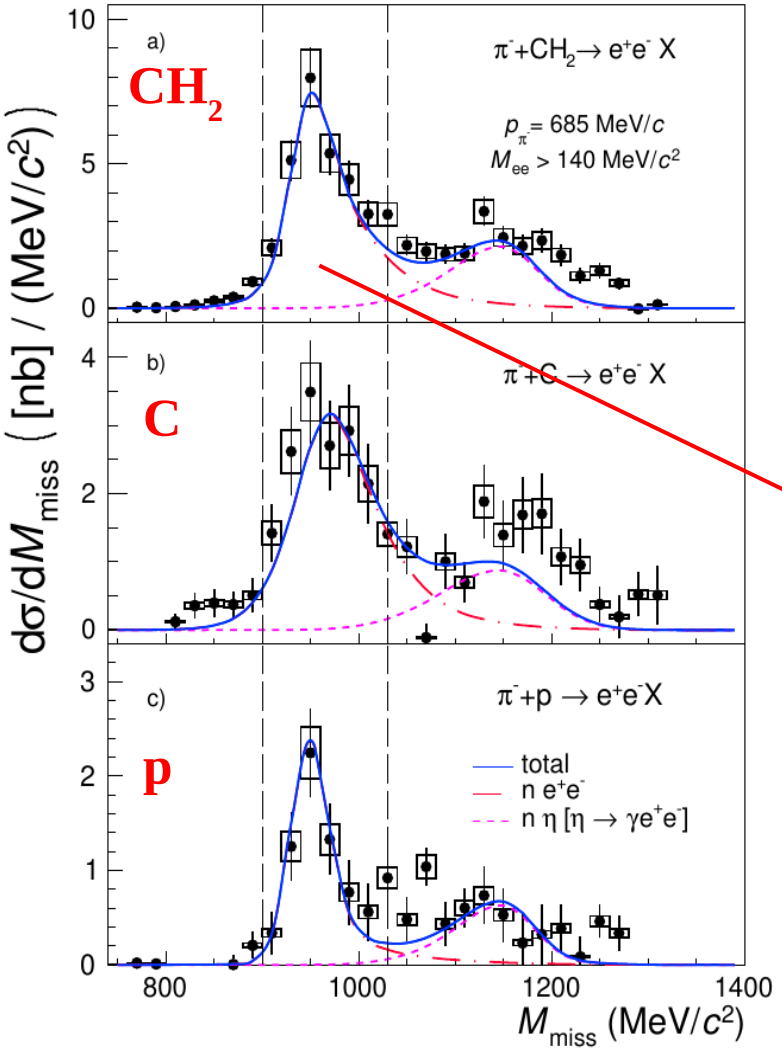
s-channel
N(1520) 3/2⁻
dominant contribution
BR=11.8 +/- 1.9 %
in **ρ** production

crucial for e+e- analysis

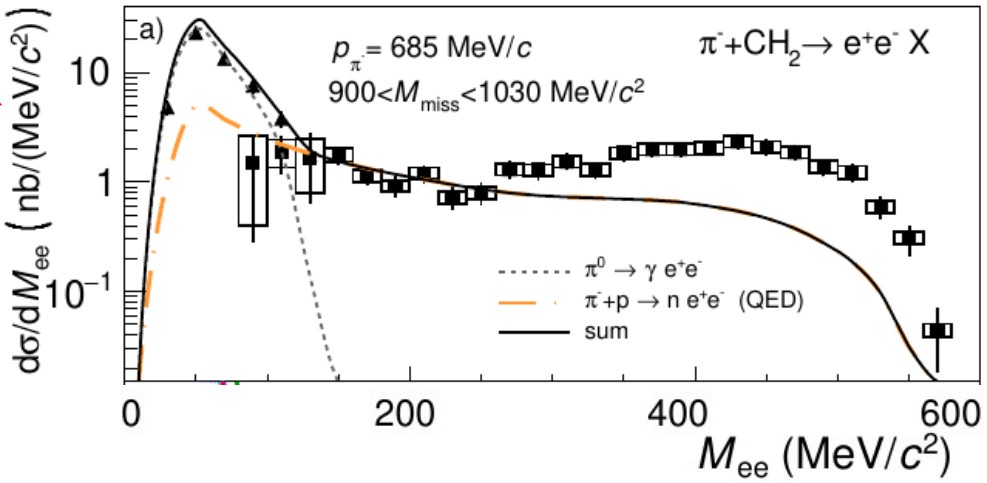
8 new entries: branching ratios of N(1440), N(1535), N(1520) to 2π channels (Δπ, Nρ, Nσ)

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

HADES Coll. arXiv:2205.15914 [nucl-ex]



- cut on invMe$^+$e$^-$ >140 MeV (π^0 removed)
- selection of $\pi^- p \rightarrow ne^+e^-$ exclusive channel using missing mass cut (η removed)
- quasi-free treatment of π^-C interaction

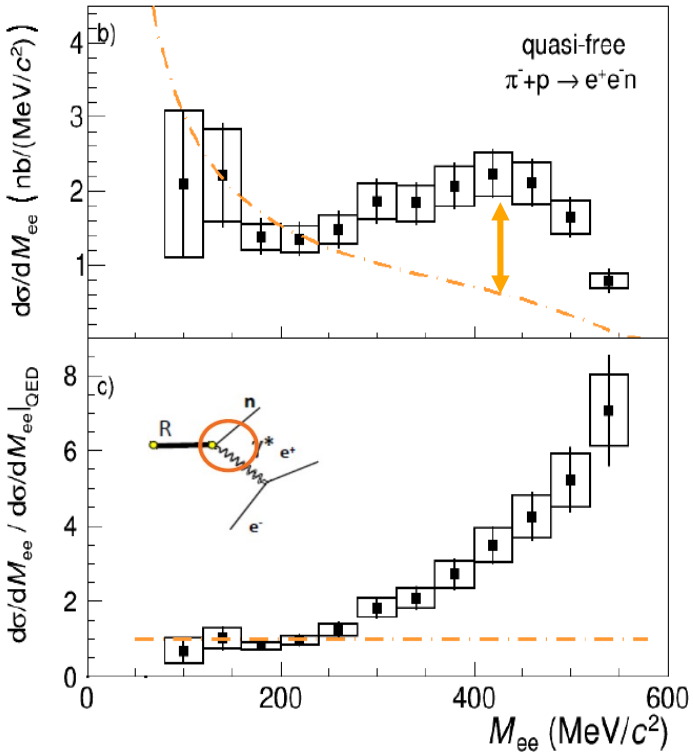


Effective time-like transition form factor

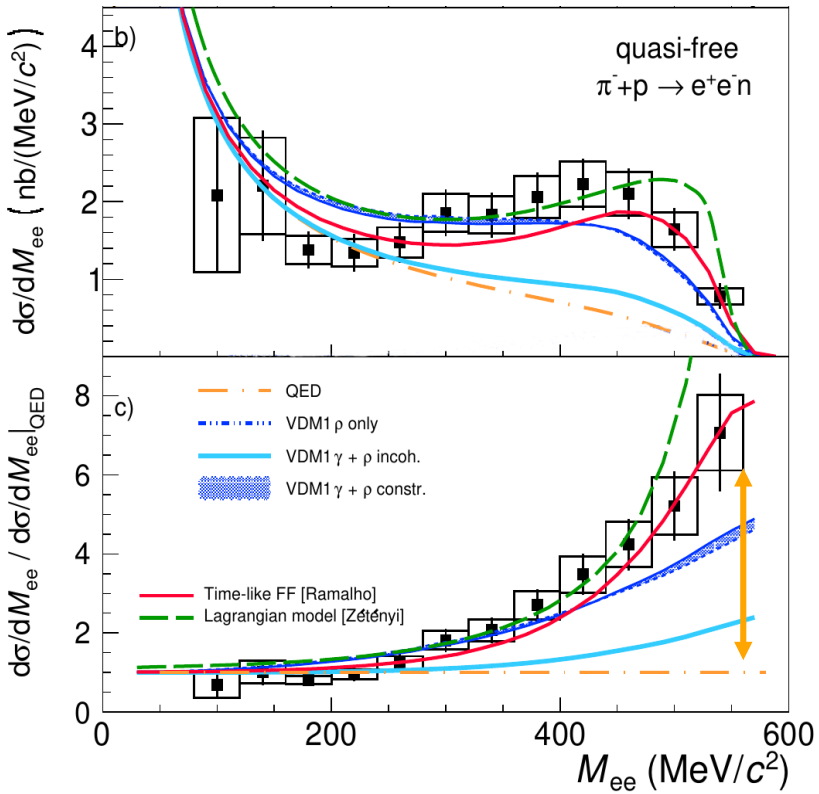
$R_{QED} = (d\sigma/dM)/(d\sigma/dM)_{QED}$

HADES Coll. arXiv:2205.15914 [nucl-ex]

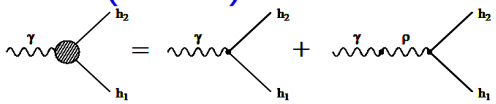
excess over point-like QED



- $M_{ee} < 200$ MeV/c^2 consistency with QED reference
- Strong excess at larger M_{ee} (up to a factor 5)



- 2-component VMD (VDM1)



gives reasonable description

- Lagrangian model – very promising
- Time-like FF - dominant pion cloud contribution (pion emFF)

Virtual photon polarization

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

$\pi N \rightarrow N\gamma^* \rightarrow Ne^+e^-$ spin density matrix elements (SDME)

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

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

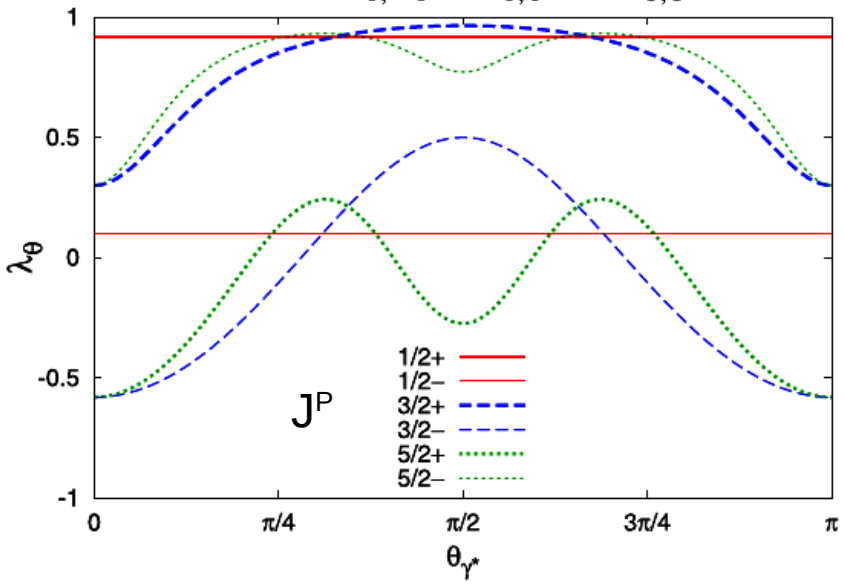
$R \rightarrow N + \gamma^*$

➔ $\rho_{\Lambda\Lambda}$ depends on γ^* polarization

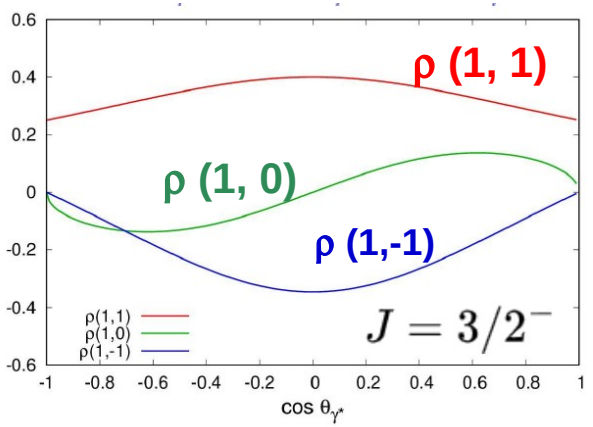
Angular distribution of the lepton pair:

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

$$\lambda_\theta = \frac{\rho^{had}_{-1,-1} + \rho^{had}_{1,1} - 2\rho^{had}_{0,0}}{\rho^{had}_{-1,-1} + \rho^{had}_{1,1} + 2\rho^{had}_{0,0}}$$



e.g. N(1520)

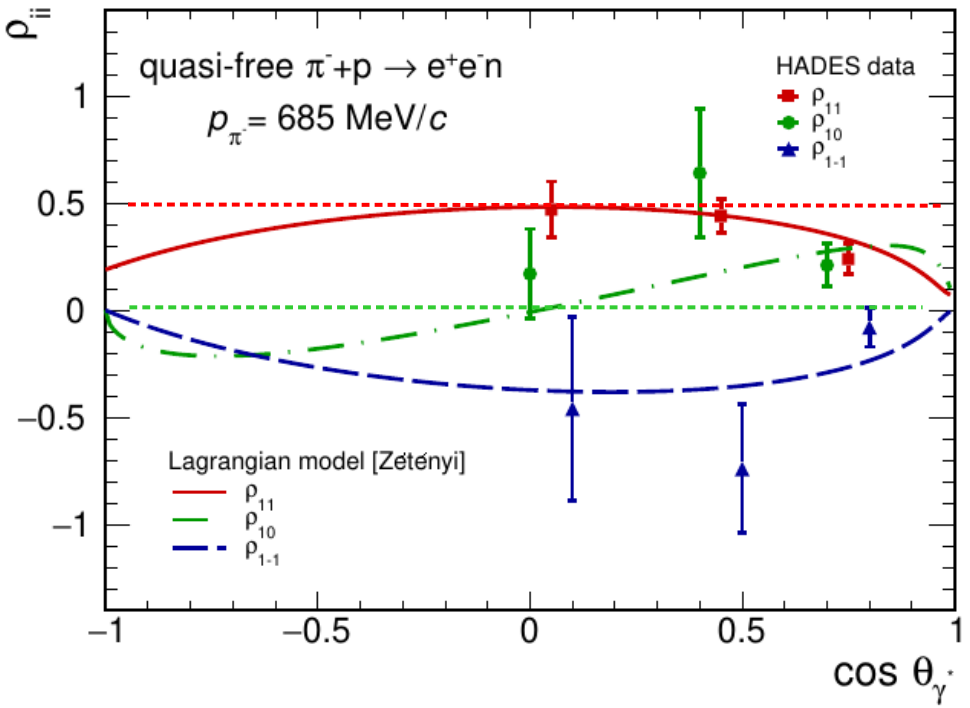


Virtual photon polarization

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

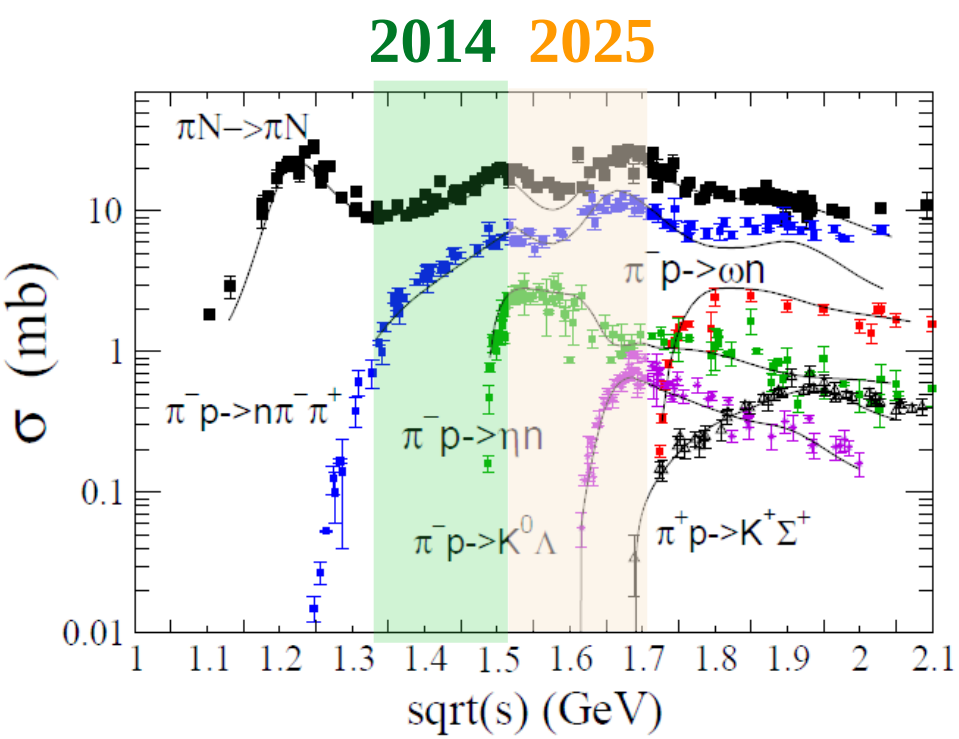
$$\frac{|A|^2}{\sigma} = \frac{1}{N}\left(8m_e^2 + 8|\mathrm{k}|^2\left[1 - \tilde{\rho}_{11}^{(H)} + \cos^2\theta(3\tilde{\rho}_{11}^{(H)} - 1) + \sqrt{2}\sin(2\theta)\cos\phi\,\mathrm{Re}\tilde{\rho}_{10}^{(H)} + \sin^2\theta\cos(2\phi)\,\mathrm{Re}\tilde{\rho}_{1-1}^{(H)}\right]\right)$$

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



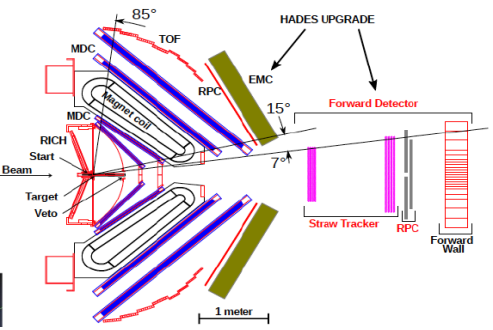
- $\rho_{11} = 0.5$, $\rho_{10} = 0$ for transverse polarization (real photon) => contribution from virtual photon
- angular dependence
  → contributions of spins larger than ½: N(1520) resonance
- **more precise data needed !**

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



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

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

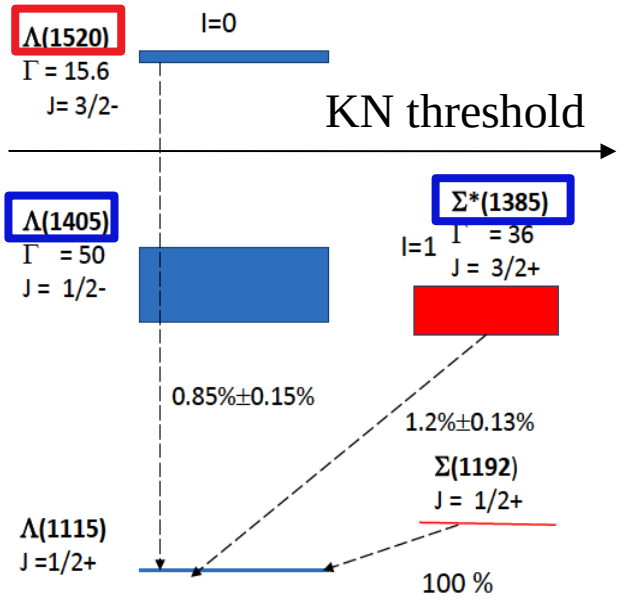


Outlook (II): eTFF of hyperons

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

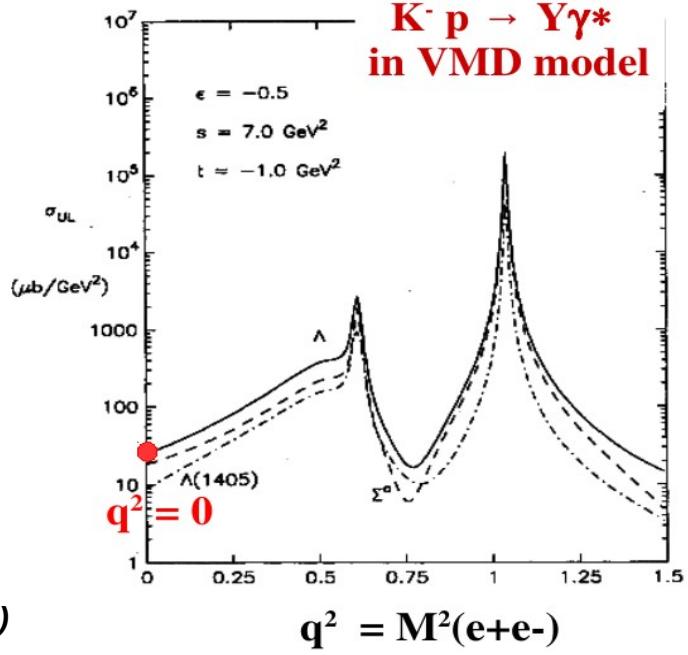
Intrinsic interest of pp:

- eTFF of Λ(1520), Σ(1385) in pp @ 4.5GeV



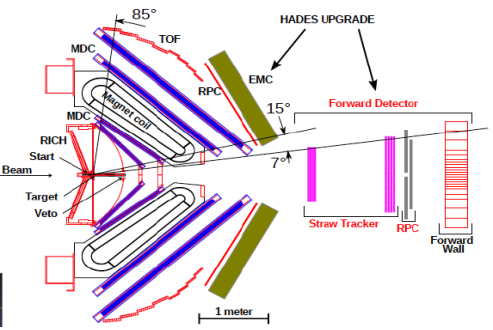
VMD:
large effect of vector mesons predicted

S. Leupold
Eur. Phys. J. A 57, 183 (2021)
G. Ramalho
Phys. Rev. D 102, 054016 (2020)



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

- narrow states, easier to identify but lower production cross sections
- attempt to measure branching ratios with HADES

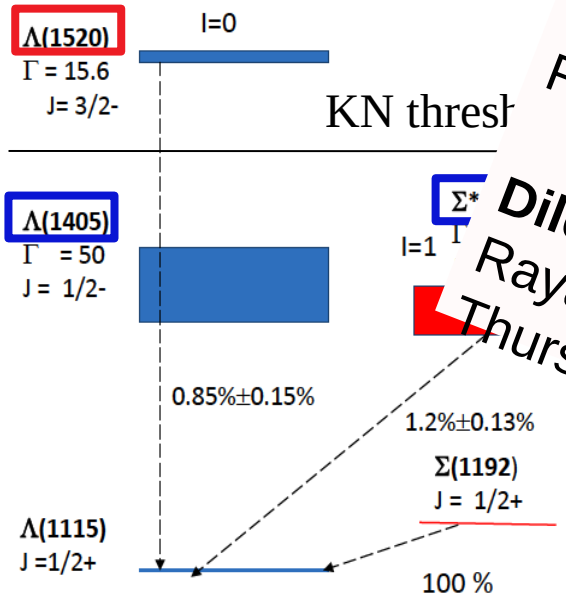


Outlook (II): etFF of hyperons

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

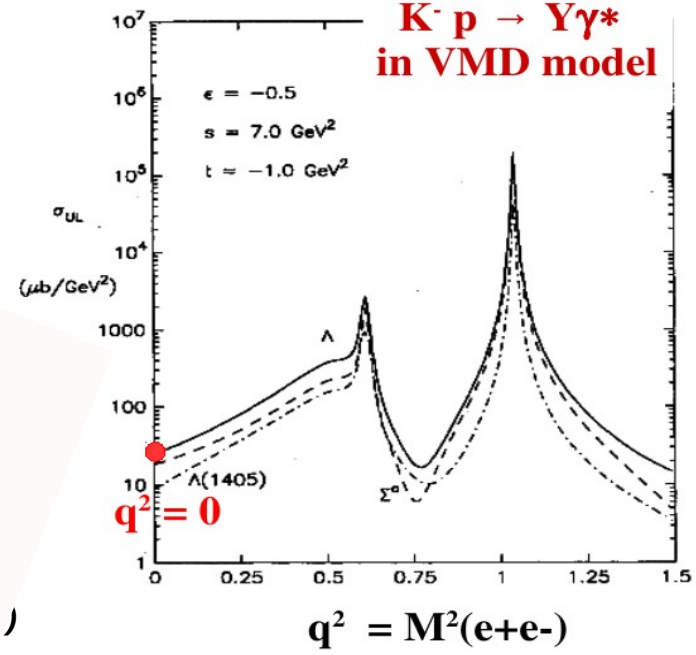
Intrinsic interest of pp:

- etFF of Λ(1520), Σ(1… … @ 4.5GeV



Hyperons:
Jana Rieger
Konrad Sumara
Friday, parallel session

Dileptons:
Rayane Abou Yassine
Thursday, parallel session



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

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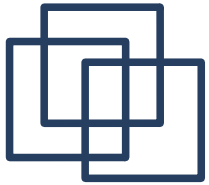
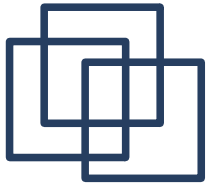
Summary

- HADES & **pion beam** is an unique tool to understand in details baryon-ρ couplings:
  → significant off-shell contribution originating from N(1520)D_{13} shown by combined PWA (D_{13}(1520) coupling to ρ-N: 12+/-2 %),
  → improved knowledge of baryon resonances- meson (ρ) couplings (new BR measurements),
  → very new information on electromagnetic baryon transitions in the time-like region,
- 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

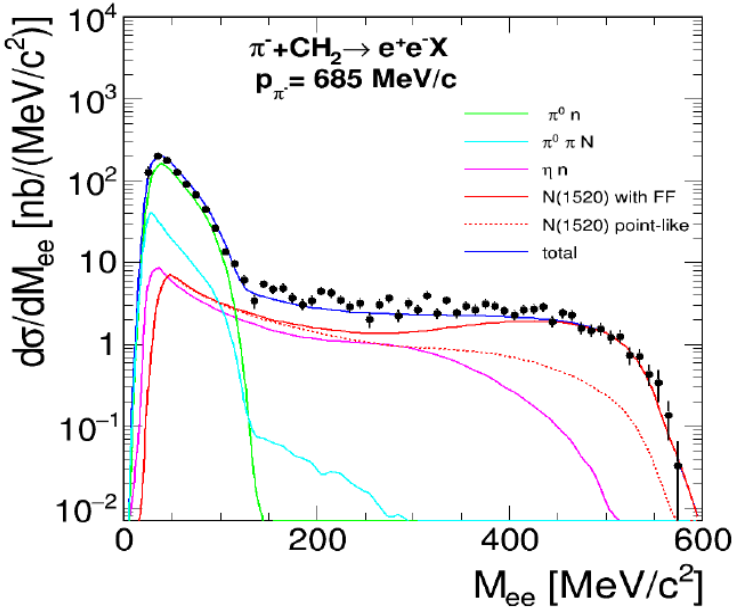
- Studies of etFF of hyperons in pp@ 4.5 GeV.
- Proposal for pion beam experiment in 2025 in the third resonance region.

Thank You for Your Attention !





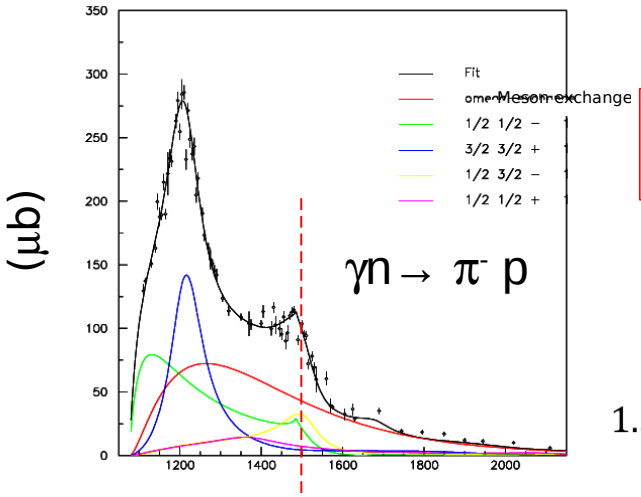
Inclusive e+e- cocktail
Fixing cocktail ingredients



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

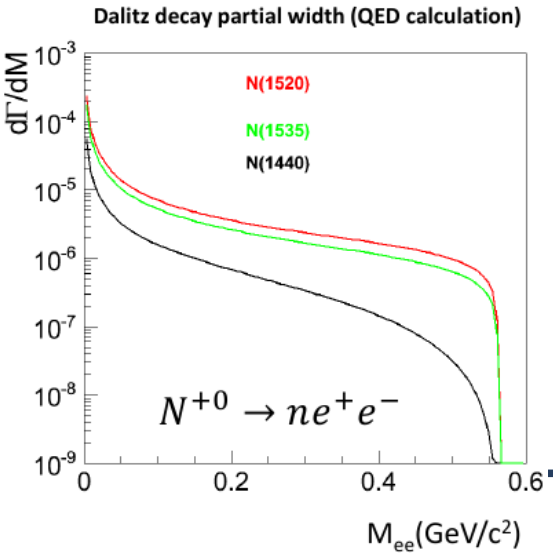
Arndt et al., PRC**72** (2005) 045202

Dalitz Decay BR
π^0: 0.012
η: 0.006



Bonn-Gatchina PWA

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

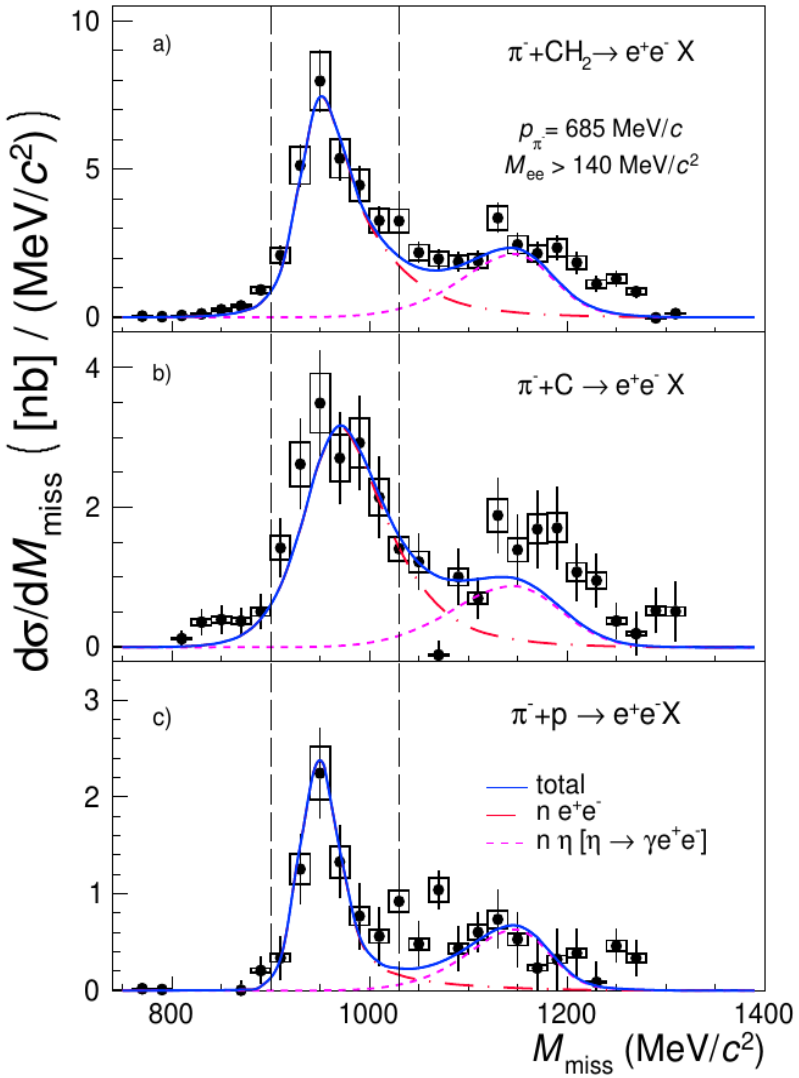


$\sigma(\pi^- p \rightarrow ne^+e^-) \sim$
$1.35\ \alpha\ \sigma(\pi^- p \rightarrow n\gamma) = 2\ \mu b$

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

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

HADES coll. arXiv:2205.15914 [nucl-ex]



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

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

- **CH_2** target:

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