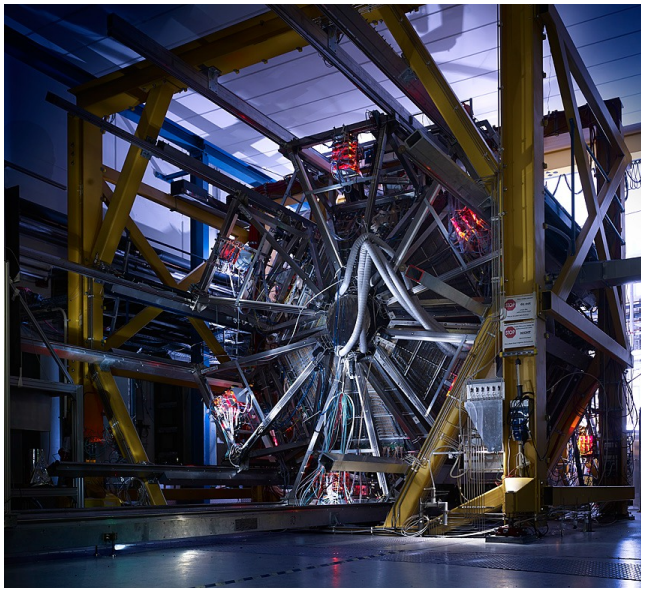
Studies of Baryon Transition Form Factors with HADES

GSI Helmholtzzentrum für Schwerionenforschung



OUTLINE:

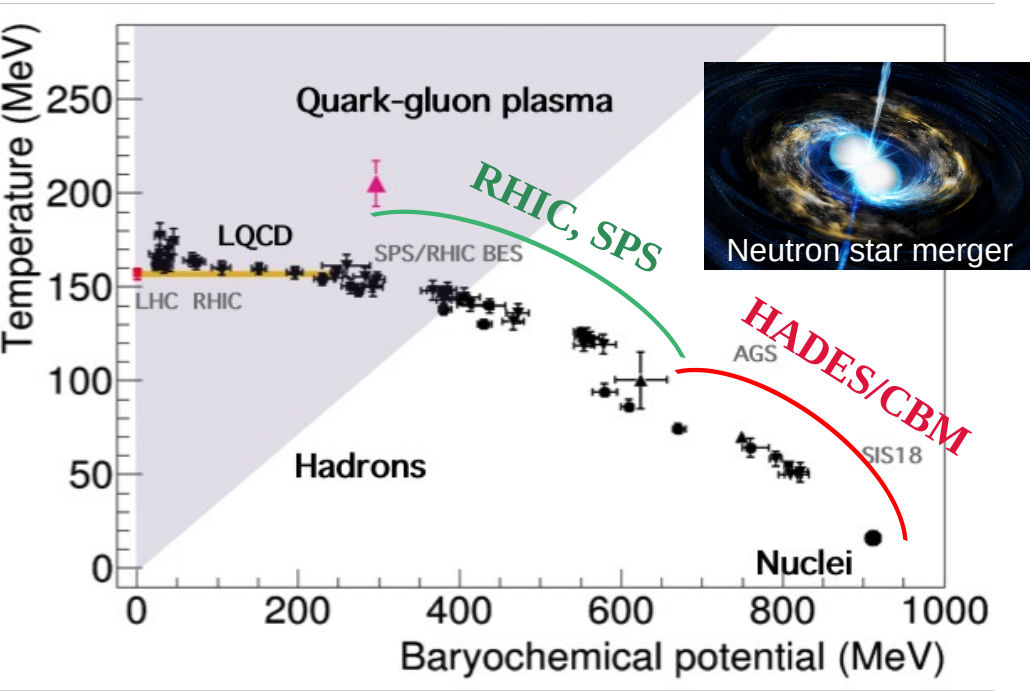
1) Motivations of the HADES experiment.
2) Electromagnetic structure of baryons.
3) Results on baryon time-like transition form factors from proton- and pion-induced reactions.
4) Studies of hyperons transition form factors.
5) Summary and outlook.

HADES

Izabela Ciepał

THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

Motivations



- Baryon dominated matter
- Similar conditions as expected in neutron star mergers

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

➔ Hadron properties in hot and dense nuclear matter

➔ Electromagnetic structure of hadrons

➔ Role of vector mesons, baryonic resonances, hyperons

➔ Complementary to SPS, RHIC,..

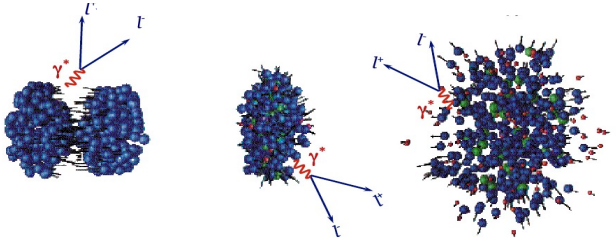
FAIR GSI

A+A: 1-3A GeV

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

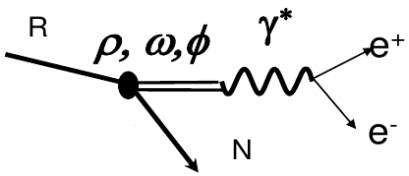
Di-leptons ($\gamma^* \rightarrow l^+l^-$)

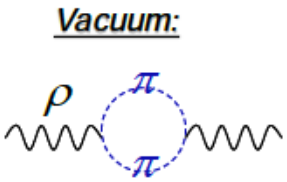
- carry information of each step of a collision
- immediately decouple from the strong interaction
- encode information on matter properties



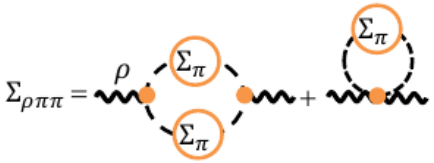
Motivations
HI & elementary collisions

➔ **important role of vector mesons**

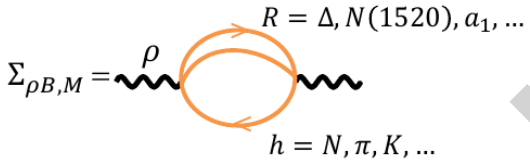


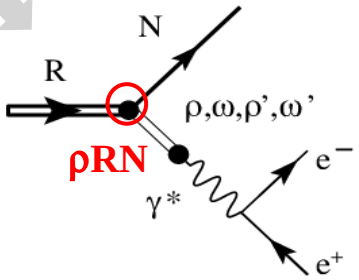


***Nuclear matter*: additional terms (ρ self-energies)**

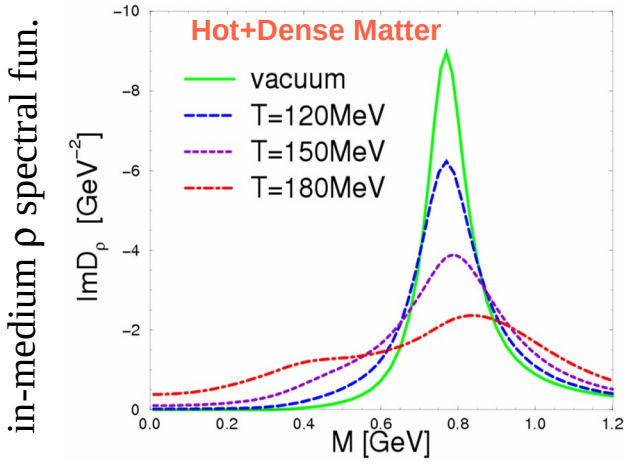


➔ **important role of barionic resonaces Δ, N***





ρ broadening

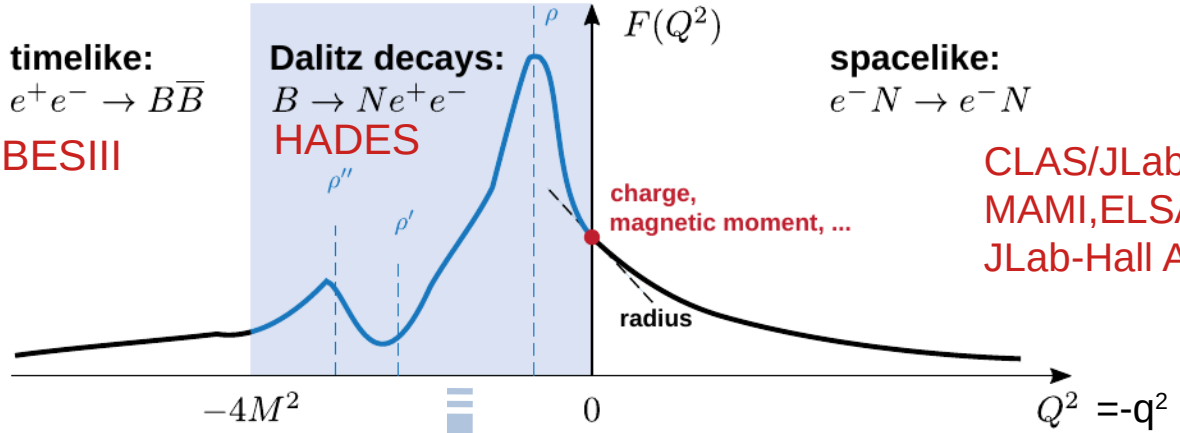


R. Rapp, J. Wambach, *Eur. Phys. J. A 6, 415 (1999)*

➢ in-medium spectral function (ImD_ρ) depends on ρRN coupling studied in $N^*(\Delta) \rightarrow Ne^+e^-$ Dalitz decays

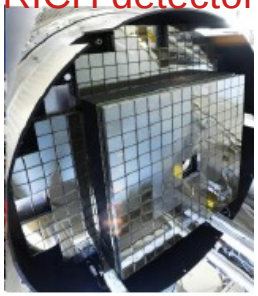
➔ **dedicated HADES hadron physics program to study Dalitz decays in NN and πN collisions**

Electromagnetic structure of baryons



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

RICH detector

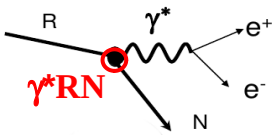


M. I. Krivoruchenko et. al
Annals Phys. 296, 299 (2002)

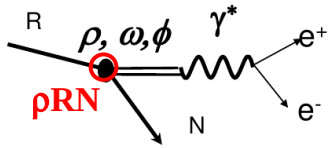
$$\frac{d\Gamma(\Delta \to Ne^+e^-)}{dq^2} = f\left(m_\Delta, q^2\right)\left(\left|G_M^2(q^2)\right| + 3\left|G_E^2(q^2)\right| + \frac{q^2}{2m_\Delta^2}\left|G_C^2(q^2)\right|\right)$$

QED: transition of point-like particles

$G_{M/E/C}$: $R \to N\gamma^*$ transition Form-Factors ($A_{1/2}$, $A_{3/2}$, $S_{1/2}$) internal structure of hadrons **(various models)**



Vector Meson Dominance Model



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

Dalitz decays of baryon resonances

Vector Meson Dominance Models (VMD)

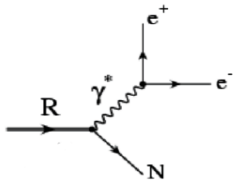
hadrons ⟷ photons

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

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

➔ **QED "point-like"**

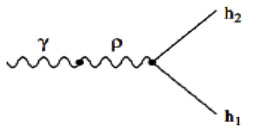
R-γ* vertex



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

➔ ***strict* VMD (VMD2)**

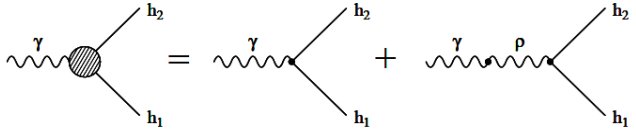
- Nρ coupling
- used in HI transport models



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

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

➔ **2-component VMD (VMD1)**



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

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

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

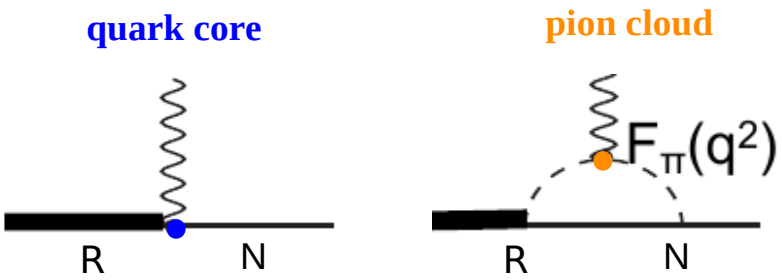
etFF of baryons: models

Covariant quark model +VMD

T. Pena & G. Ramalho

Review: *Prog. Part. Nucl. Phys. 136 (2024) 104097*

➔ N-Δ(1232), N-N*(1520), N-N*(1535)



quark FF's - are used to describe the quark e.m. current and they are parametrized based on VMD (ρ, ω, φ vector meson poles)

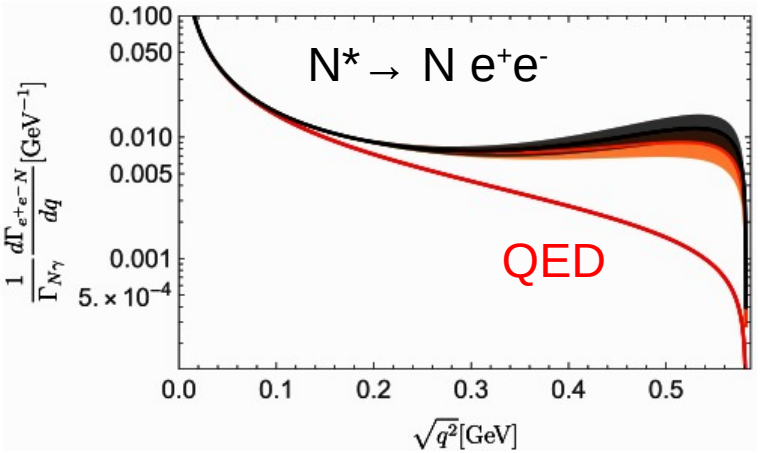
pion FF – pion electromagnetic FF (VMD)

Dispersion theory

S. Leupold et al.

arXiv:2401.17756 (2024)

- form factors are analytic functions in the complex plane
- partial-wave amplitudes for reactions/decays must be **unitary** and **analytic** (dispersion relations)
- **model-independent tool**



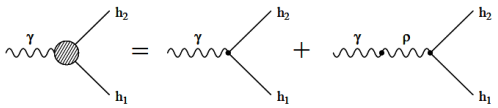
etFF of baryons: models

Two-component Lagrangian model

M. Zetenyi & G. Wolf

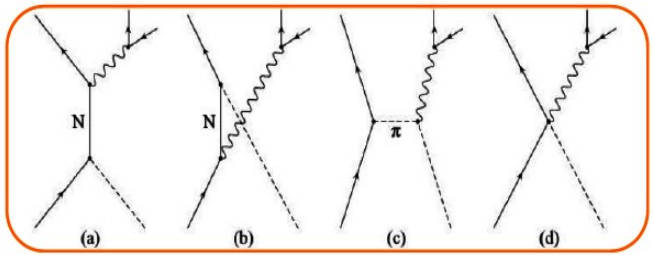
PRC 86, 065209 (2012)
PRC 104, 015201 (2021)

2-component VMD:

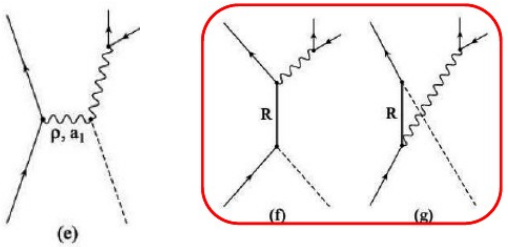


microscopic calculations of πN→ Ne+e-

Born terms

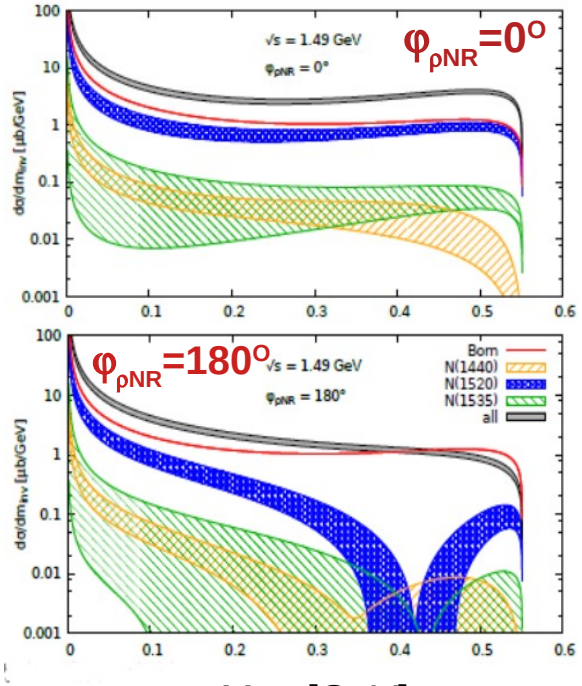


baryon resonances



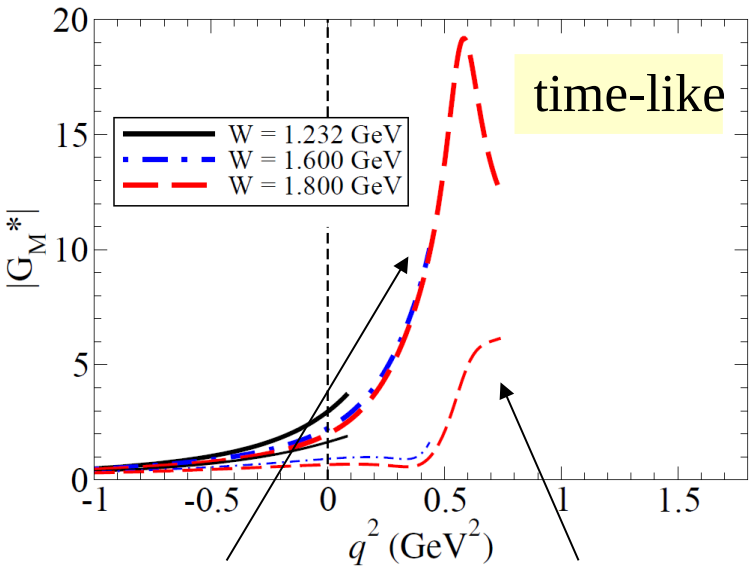
N*(1440)
N*(1520)
N*(1535)

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



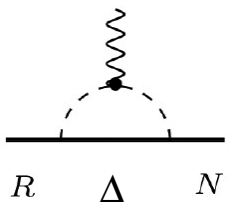
Meson cloud effect

$\Delta_{33}(J=3/2) \rightarrow N(J=1/2)$

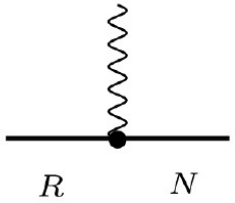


G. Ramalho, T. Peña
Phys. Rev. D 93, 033004 (2016)

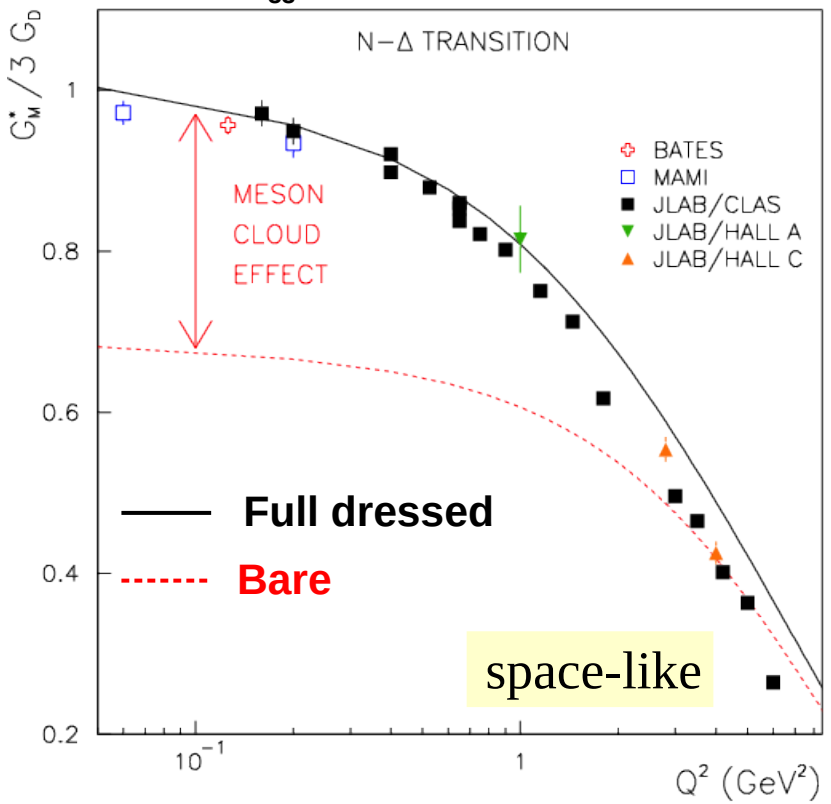
quark core + pion cloud



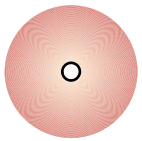
bare quark core

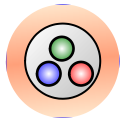


$\Delta_{33}(J=3/2) \rightarrow N(J=1/2)$



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





dressed quark core +dense meson clouds

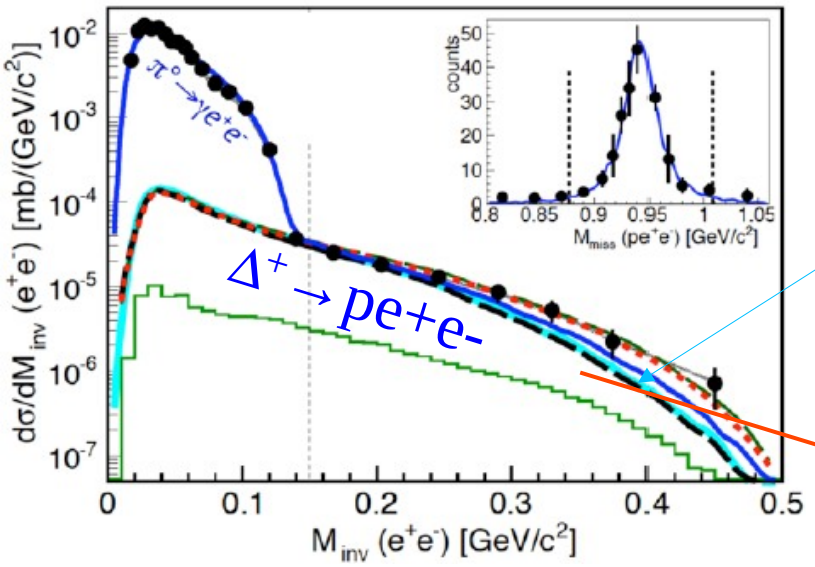
small meson cloud dressed quark core dominates

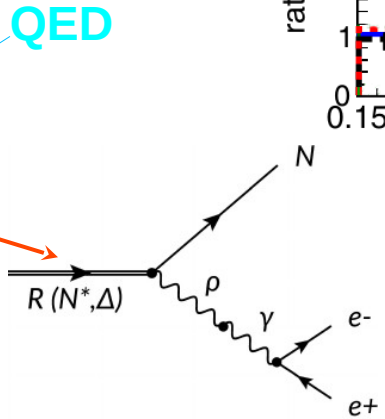
Δ (1232) resonance - exclusive pe+e- analysis

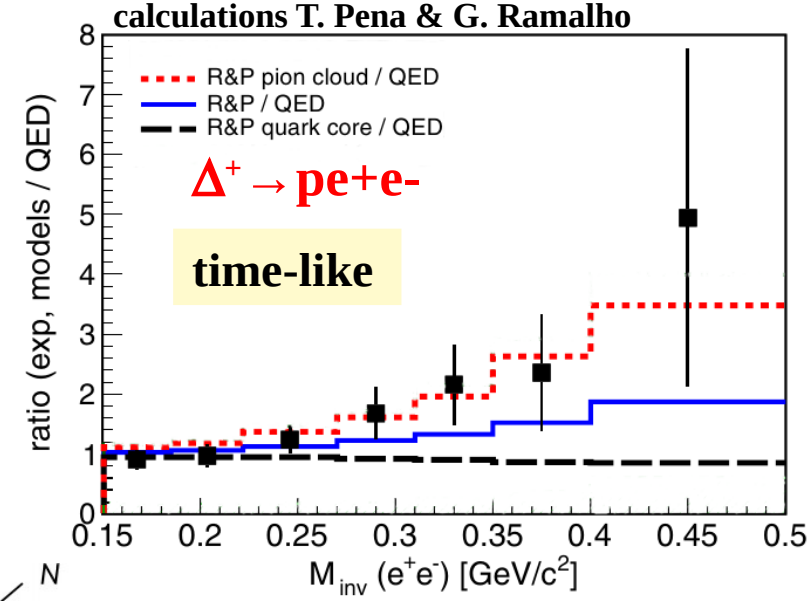
HADES: Phys. Rev. C 95, 065205 (2017)

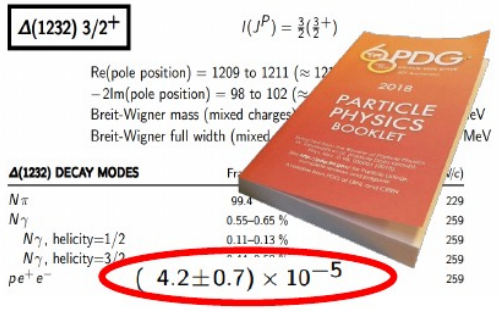
pp → ppe+e- @1.25 GeV

- energy below η production threshold
- cross sections for Δ^+ ($p\pi^+$, $p\pi^0$) from PWA









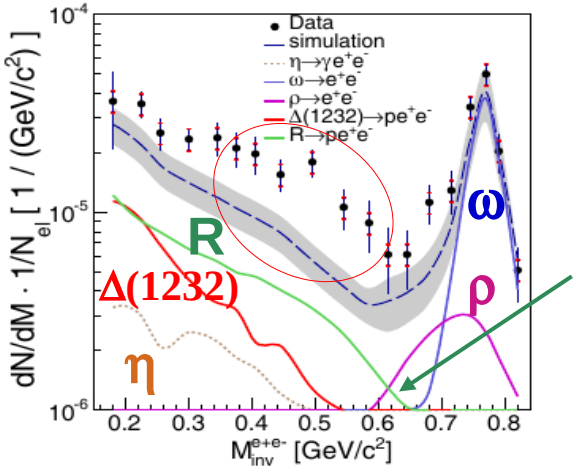
$$\frac{d\Gamma(\Delta \rightarrow N e^+ e^-)}{dq^2} = f\left(m_\Delta, q^2\right)\left(\left|G_M^2(q^2)\right| + 3\left|G_E^2(q^2)\right| + \frac{q^2}{2m_\Delta^2}\left|G_C^2(q^2)\right|\right)$$

effective eTFF

Dalitz decay studies of heavier baryons

HADES: EPJ A50, 82 (2014)

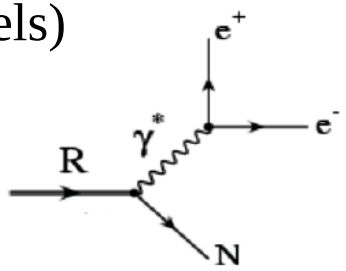
pp → ppe⁺e⁻ @3.5 GeV

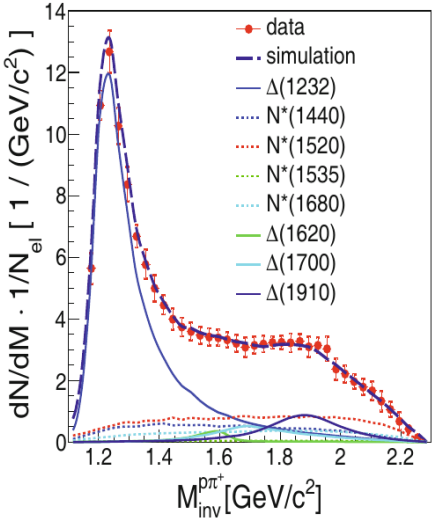


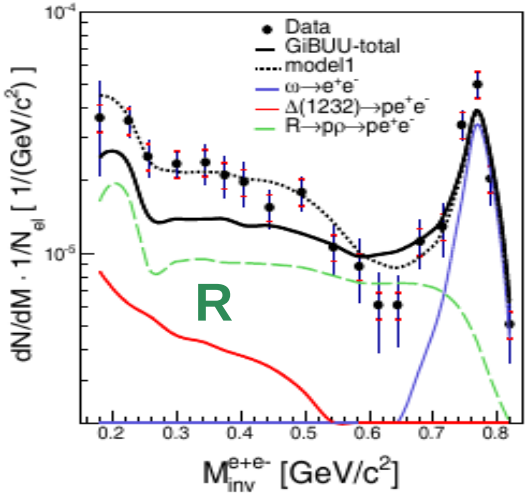
Dalitz decays of **point-like** baryonic resonances (constrained by ppπ⁰ and pnπ⁺ channels)

QED reference

R → pe+e-

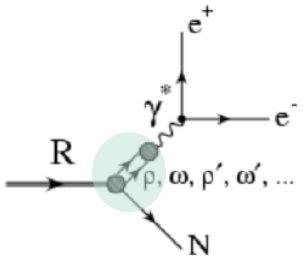






- comparison to GiBUU transport model with a 2-step process:

R → pρ → pe+e-



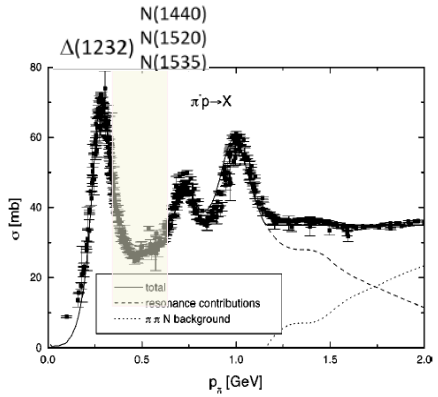
model 1 = GiBUU, but with modified cross sections (HADES simul.)

Pion beam facility @ GSI

2π production in $\pi^- p$ @ $\sqrt{s} = 1.46 - 1.55\,GeV$

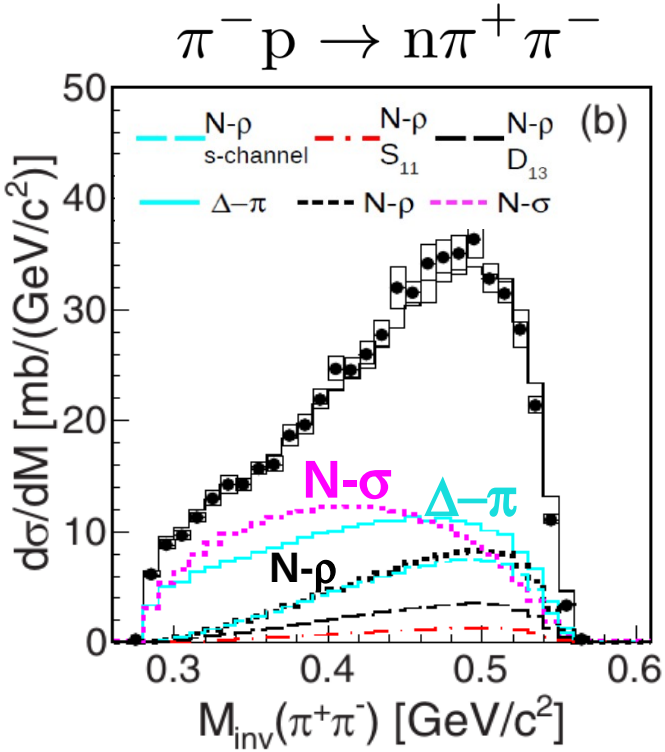
HADES: Phys. Rev. C 102, 024001, (2020)

2nd resonance region



→ more details: see talk by Ahmed Foda

- secondary pion beam (0.65-0.8 GeV/c)
- **PE $(CH_2)_n$** and **C** targets



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

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

→ cross section for N*(1520), N*(1535) ($n\pi^+\pi^-$, $p\pi^-\pi^0$) from PWA

ρ meson production:
s-channel D_{13} (N*(1520) 3/2⁻)

- N(1520) → Nρ BR=12.2 +/- 2 %
- N(1535) → Nρ BR=3.2 +/- 0.6 %

reference ρ mass spectrum for e+e- analysis

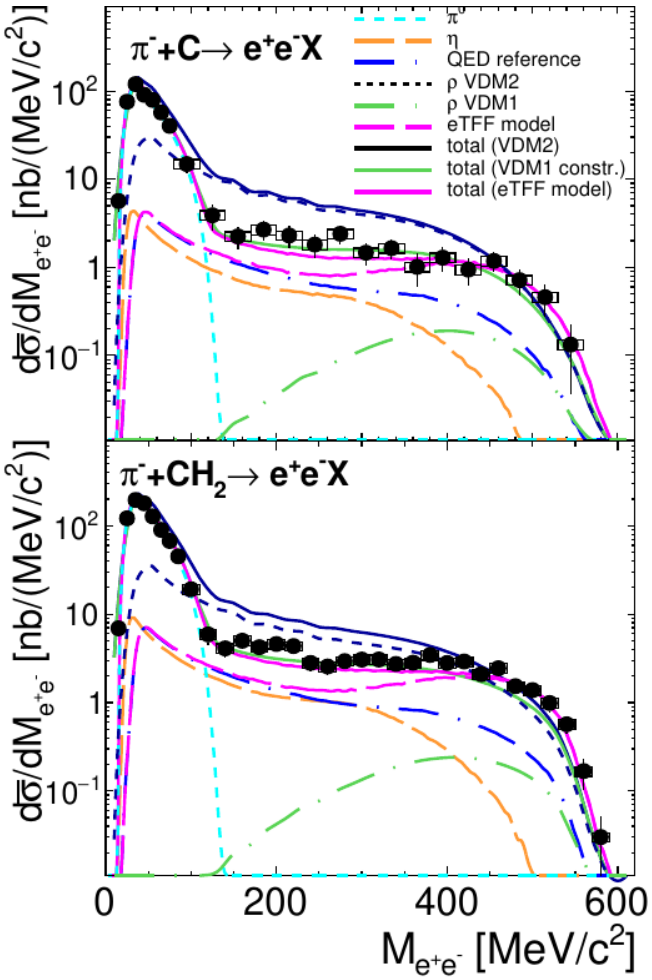
PDG particle data group

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

Inclusive e^+e^- cross sections

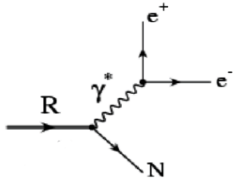
HADES Coll. arXiv:2309.13357 [nucl-ex]

e+e- cocktail @ $\sqrt{s} = 1.49 GeV$

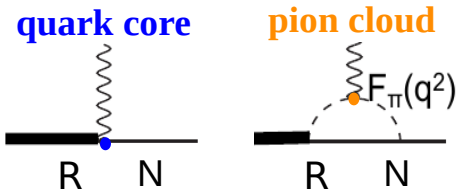


- quasi-free treatment of π^-C interaction

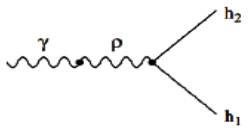
➔ **QED reference**



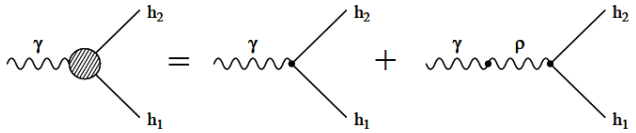
➔ **eTFF R&P: baryon Dalitz decay**
(N*(1520), N*(1535))



➔ **VMD2**

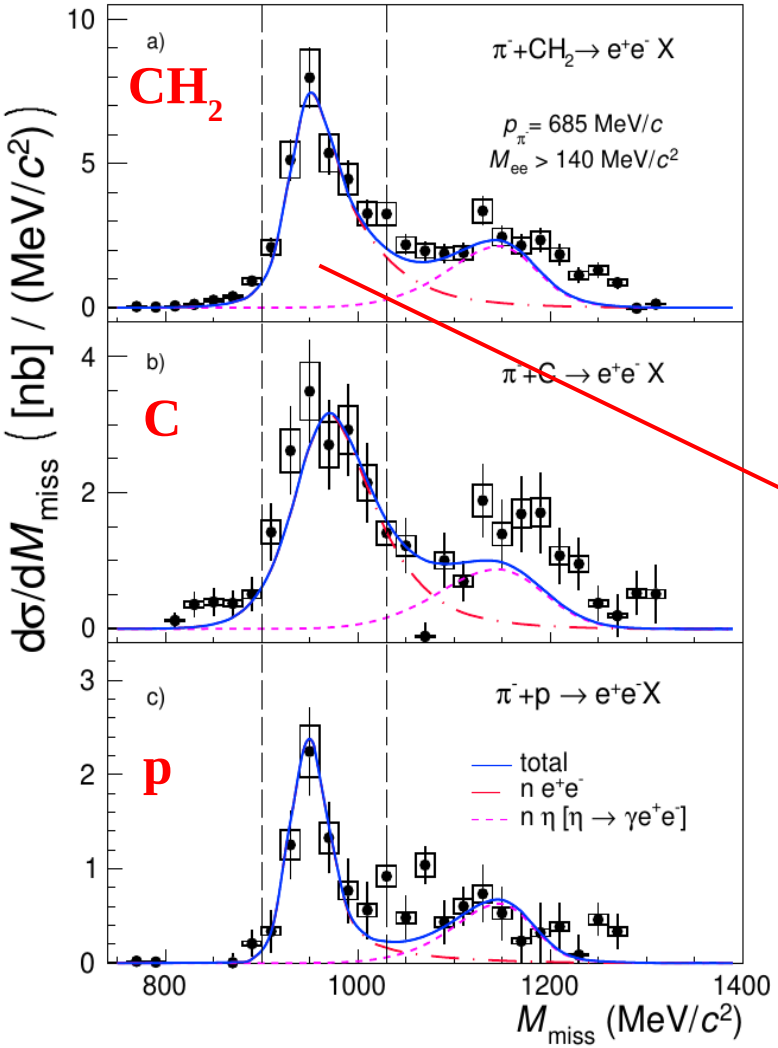


➔ **VMD1**

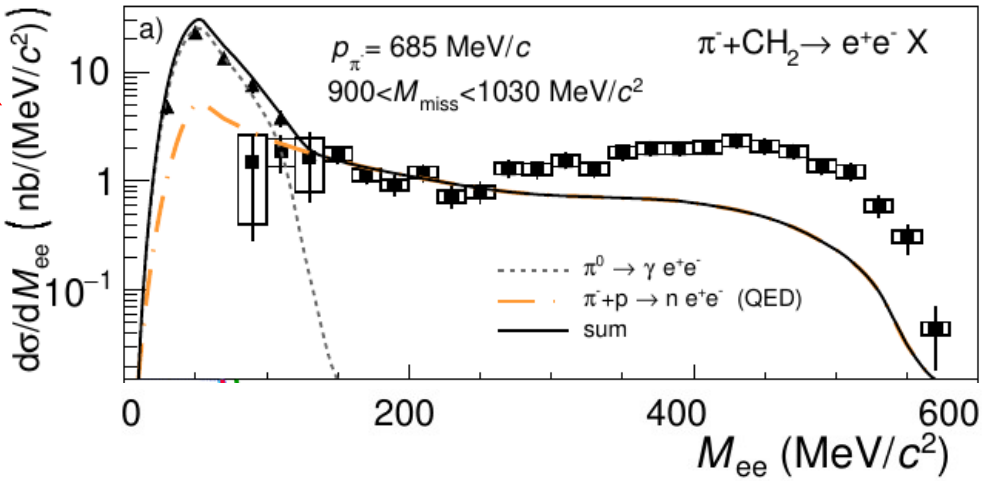


Selection of quasi-free $\pi^- p \rightarrow ne^+e^-$

HADES Coll. arXiv:2205.15914 [nucl-ex]



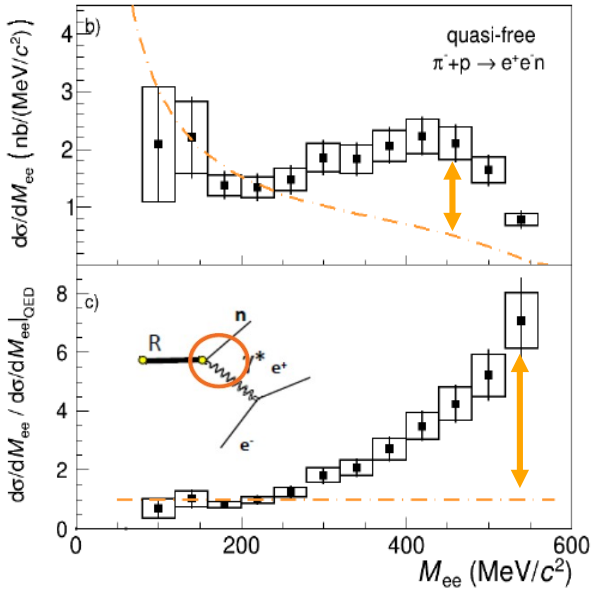
- cut on invMe$^+$e$^-$ >140 MeV (π^0 removed)
- selection of $\pi^- p \rightarrow ne^+e^-$ exclusive channel using **missing mass cut** (η removed)



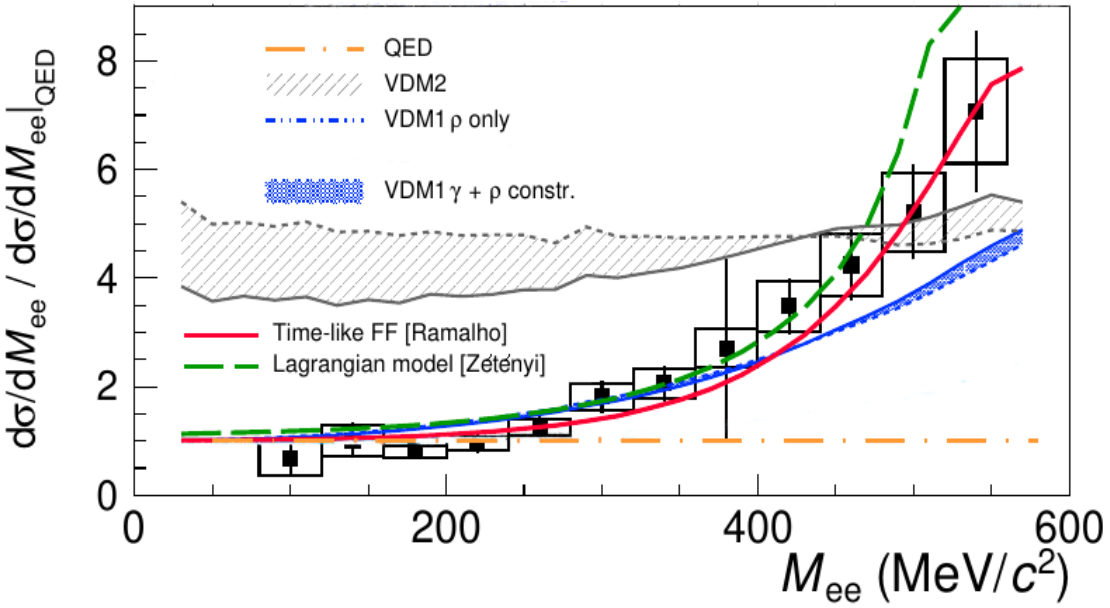
Effective time-like transition form factor

HADES Coll. arXiv:2205.15914 [nucl-ex]
HADES Coll. arXiv:2309.13357 [nucl-ex]

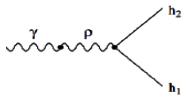
excess over point-like QED



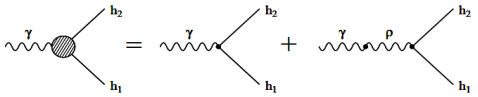
- M_{ee} < 200 MeV/c^2 data consistent with **QED**
- strong excess at large M_{ee} (up to factor 5)



- **VMD2** (*strict* VMD) overestimates data below 400 MeV (used in HI transport models)



- 2-component VMD (**VMD1**) 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)

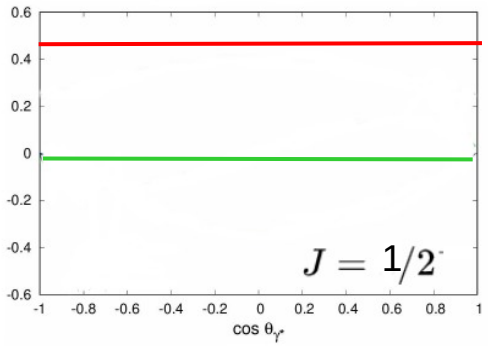
angular distribution of e+e- → polarization of γ* → spin density matrix elements ($\rho_{\Lambda\Lambda}$)

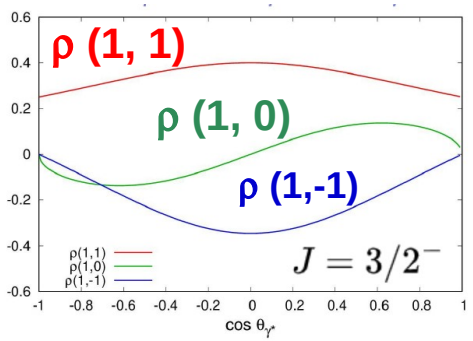
$\pi N \rightarrow N\gamma^* \rightarrow Ne^+e^-$ $\quad \frac{d^3\sigma}{dM_{ee}d\Omega_{\gamma_*}d\Omega_e} \sim |A|^2 = \frac{e^2}{Q^4}\sum_{\Lambda\Lambda'}\rho^{(H)}_{\Lambda\Lambda'}\rho^{(dec)}_{\Lambda\Lambda'}$ **QED: $\gamma^* \rightarrow e^+e^-$**

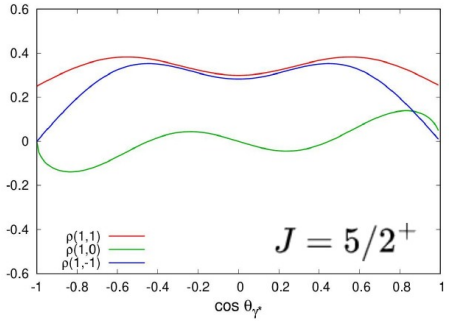
$R \rightarrow N + \gamma^*$

Angular distribution of the lepton pair:

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







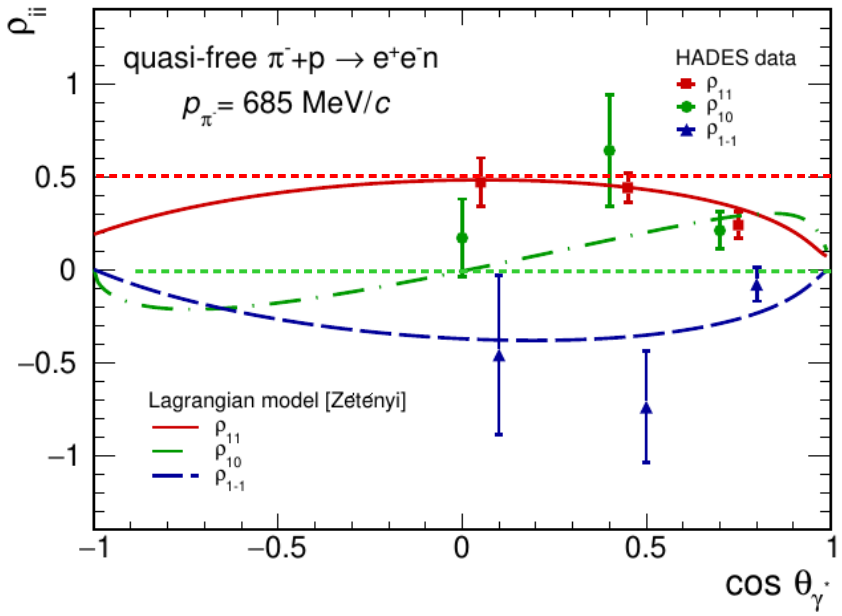
- ➔ $\rho_{\Lambda\Lambda}$ depends on γ* polarization
- ➔ $\rho_{\Lambda\Lambda}$ are combination of G_E, $G_{M,}$, G_C
- ➔ **the angular distribution is sensitive to J^P of the resonance**
- ➔ can be obtain from fit to the experimental angular distribution

Virtual photon polarization

HADES Coll. arXiv:2205.15914 [nucl-ex]

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

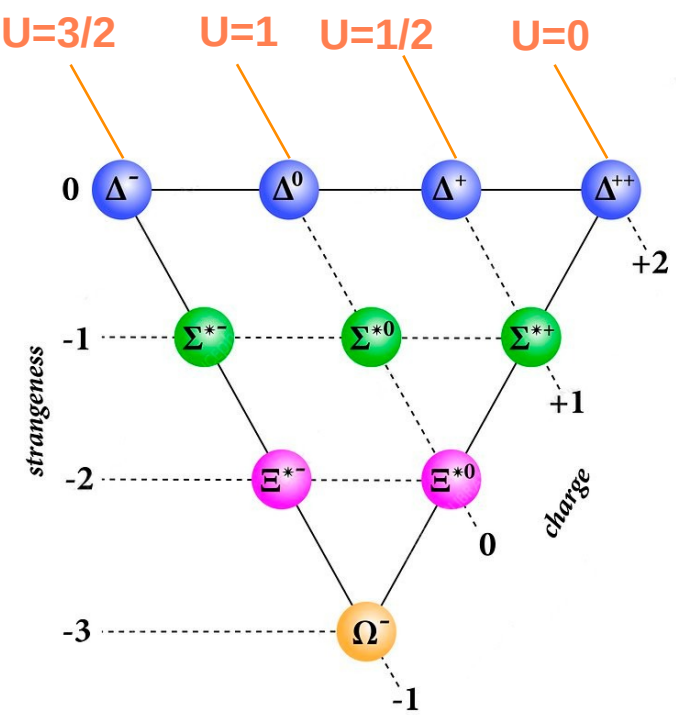
- **SDME ρ_{11}, ρ_{10}, ρ_{1-1} extracted from experiment taking into account acceptance and efficiency (A. Sarantsev) in 3 bins in cosθγ***



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

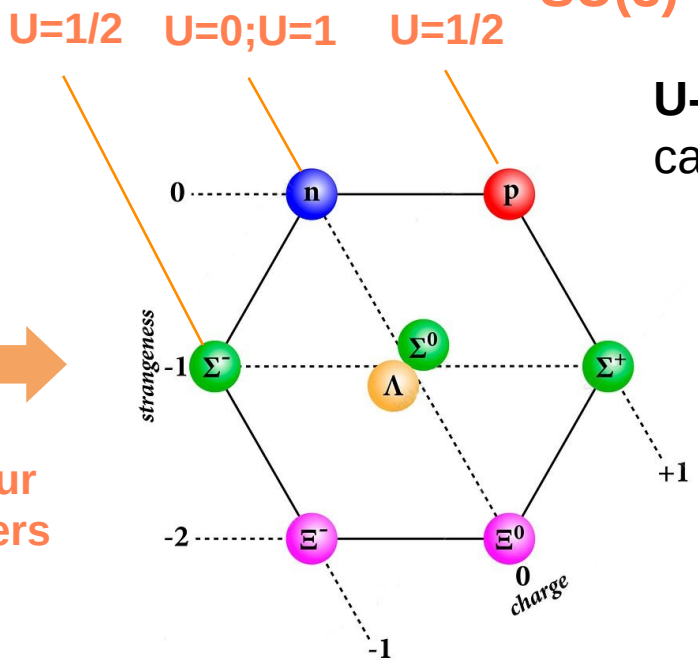
etFF of hyperons

$J^P=3/2^+$ decuplet



flavour partners

$J^P=1/2^+$ octet



SU(3) flavour sym.

U-spin states carry same charge

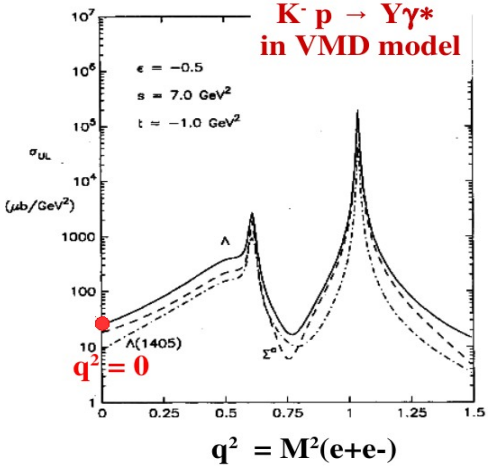
- Transitions **decuplet** ⟶ **octet** with conserved U-spin are allowed in SU(3)
- $\Sigma^*(1385) \rightarrow \Lambda\gamma^*$ ⟷ $\Delta(1232) \rightarrow N\gamma^*$
- $\Lambda(1520) \rightarrow \Lambda\gamma^*$ ⟷ $N^*(1520) \rightarrow N\gamma^*$

strange *vs* non-strange baryons

G. Ramalho, K. Tsushima
Phys. Rev. D 87, 093011 (2013)

etFF of hyperons
model predictions for the Dalitz decay

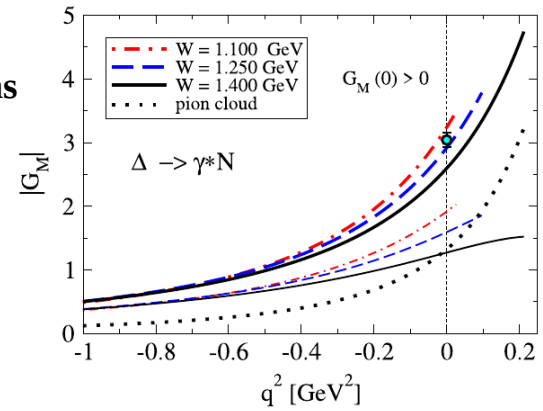
R. Williams et. al. PRC48, 1381 (1993)

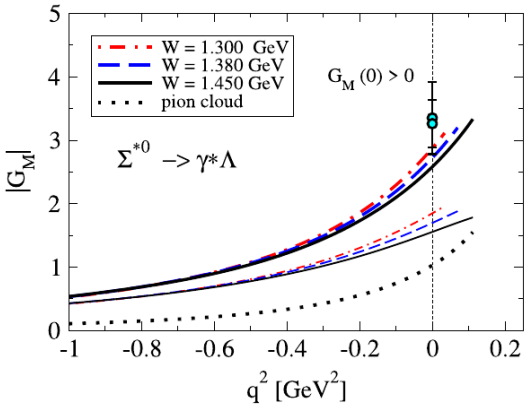


VMD:
large effect of vector mesons predicted

covariant spectator quark model (Σ*, Ξ*)

G. Ramalho, *Phys. Rev. D 102, 054016 (2020)*

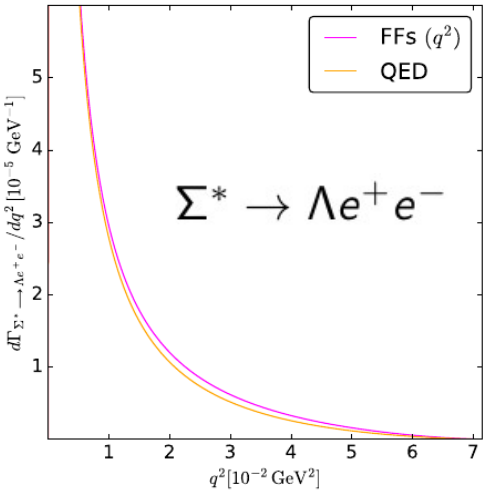


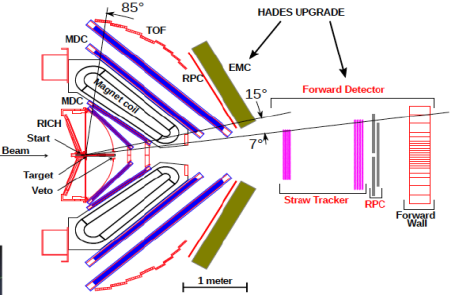


- pion cloud contribution
- kaon cloud contrib. ?

Dispersion theory

N. Salone, S. Leupold
Eur. Phys. J. A 57, 183 (2021)
O. Junker, S. Leupold et al.
Phys. Rev. C 101, 015206 (2020)





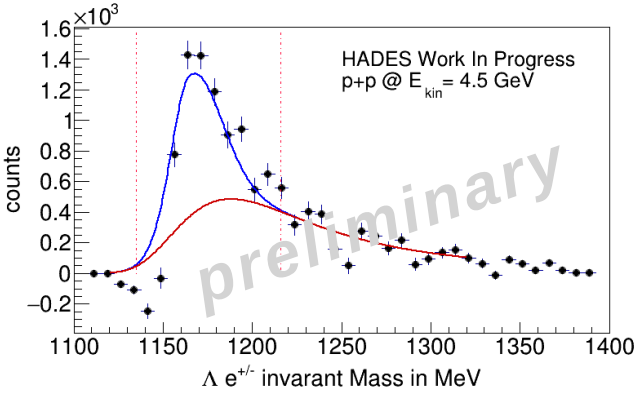
Hyperons @ HADES
pp @ 4.5GeV

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

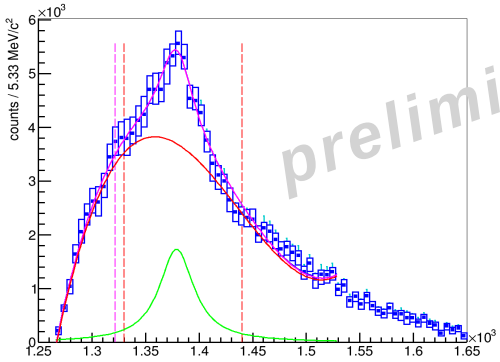
February 2022: beam time at SIS18 FAIR-Phase0

- Λ(1405), Λ(1520), Σ production cross sec., decays,...
- Σ, Λ(1405), Λ(1520) **Dalitz decays** → attempt to measure upper limits of branching ratios (obtained luminosity L~6 pb^{-1})
- the BR important information for future measurement **@CBM** and other hyperon factories
- information on hyperon structure, role of pion/kaon cloud

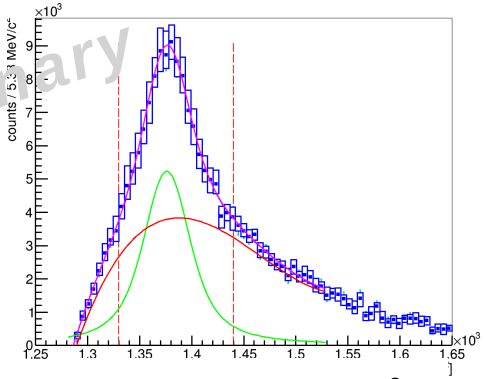
$\Sigma^0(1192) \rightarrow \Lambda\gamma^*$ Dalitz decay



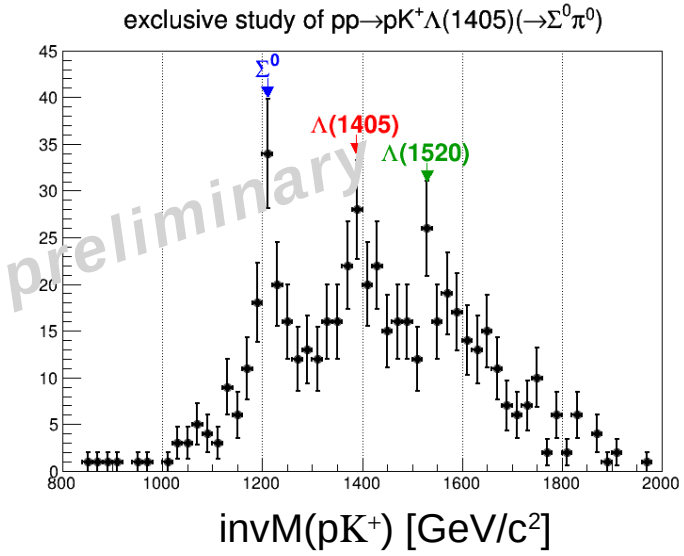
$\Sigma^{*-}(1385) \rightarrow \Lambda\pi^-$



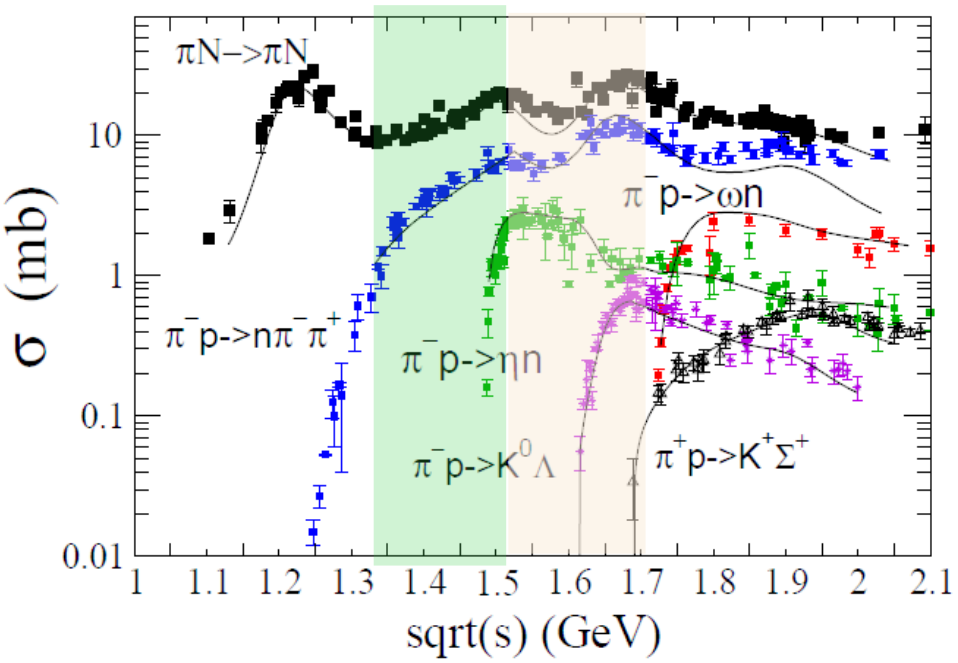
$\Sigma^{*+}(1385) \rightarrow \Lambda\pi^+$



exclusive study of $pp \rightarrow pK^+\Lambda(1405)(\rightarrow\Sigma^0\pi^0)$



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



Beam energy scan 2025: 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) Hyperon polarization: Λ, Σ

3) Exotic states:

→ the lowest glueballs, 4q systems, hybrids , bound states of mesons: $f_0(500)$, $f_0(980)$, $a_0(980)$, f0(1370),…

→ unknown region of invM(ππ) ~1 GeV very precise data needed !

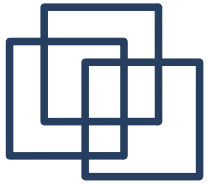
CBM@ SIS100 pp @ 30 GeV

- prod. cross sec. higher than at SIS18: σ (Σ*,Λ*) ~1 mb
- much higher luminosity

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.
- Studies of hyperon structure @CBM.

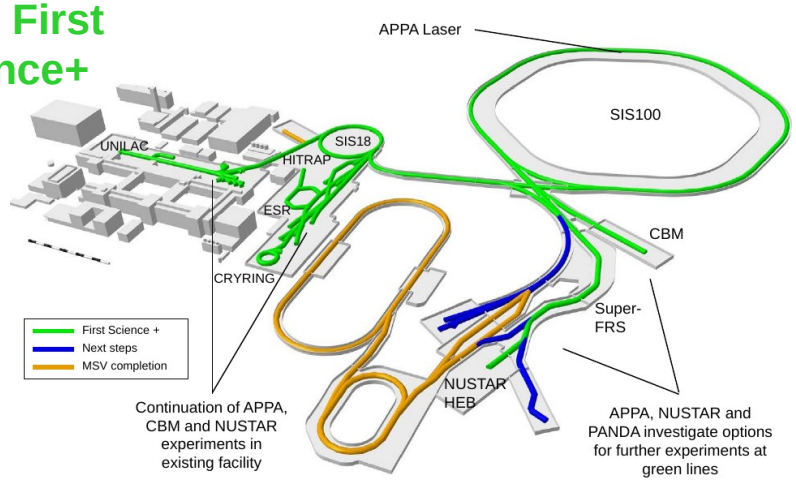
Thank You for Your Attention !



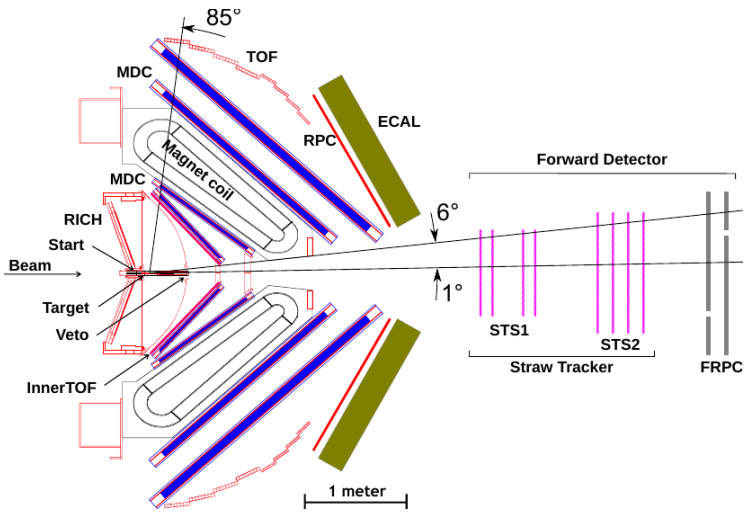
HADES - High Acceptance DiElectron Spectrometer

GSI Helmholtzzentrum für Schwerionenforschung

FAIR First Science+

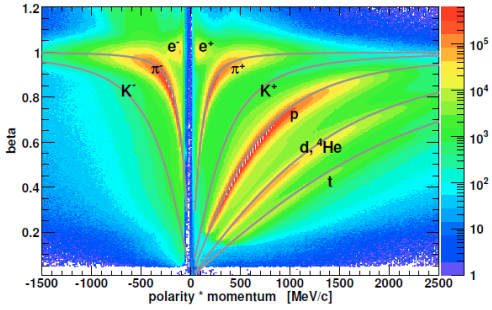


- ✓ SIS18 beams: protons (1-4.5GeV), nuclei (1-2AGeV), pions (0.4-2 GeV) secondary beam
- ✓ Spectrometer with $\Delta M/M \sim 2\%$ at ρ/ω
- ✓ PID (π/p/K): ToF (TOF/RPC, T0 detector), tracking (dE/dx)
- ✓ momenta, angles: MDC+ magnetic field
- ✓ e+,e-: RICH
- ✓ neutral particles: ECAL
- ✓ full azimuthal,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



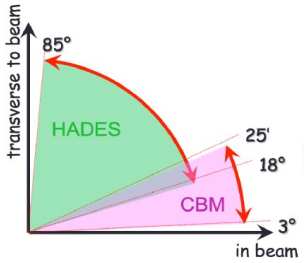
FAIR - Phase0 upgrade:

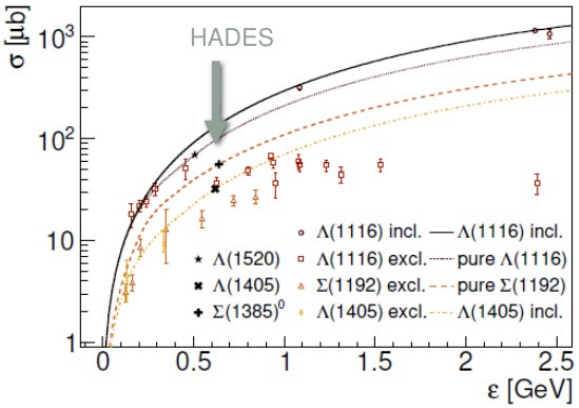
- → **ECAL** (2017-2021)
- → RICH (2018)
- → **Forward Detector** (2021)
- → **iTOF** (2021)
- → START - LGAD



proton-CBM

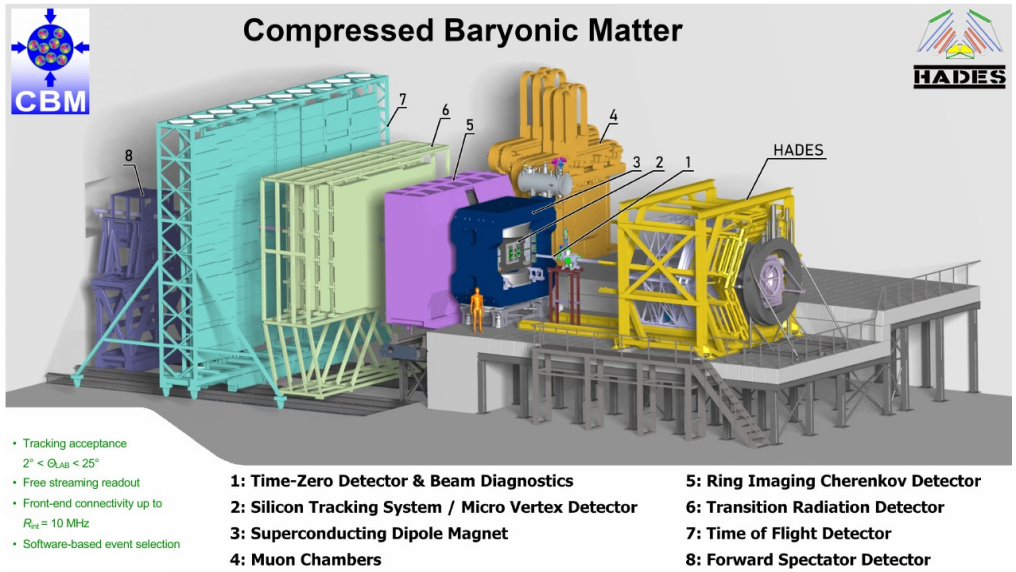
- structure and spectroscopy of hadrons (hyperons)
- mass distribution of barionic resonances with strange and charm content
- strangeness and charm production
- intrinsic charm in the proton





CBM@ SIS100 pp @ 30 GeV

- prod. cross sec. higher than at SIS18: σ (Σ*,Λ*) ~1 mb
- much higher luminosity

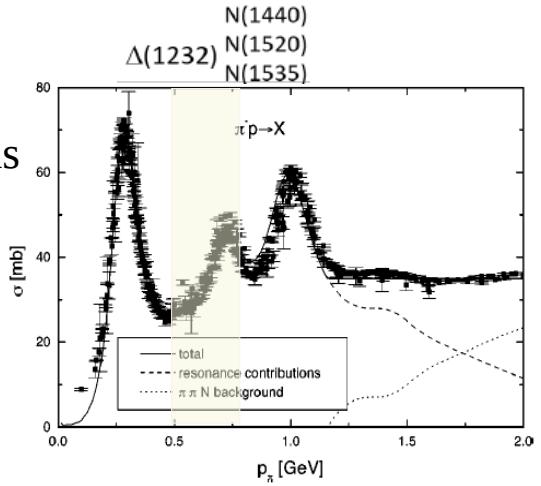


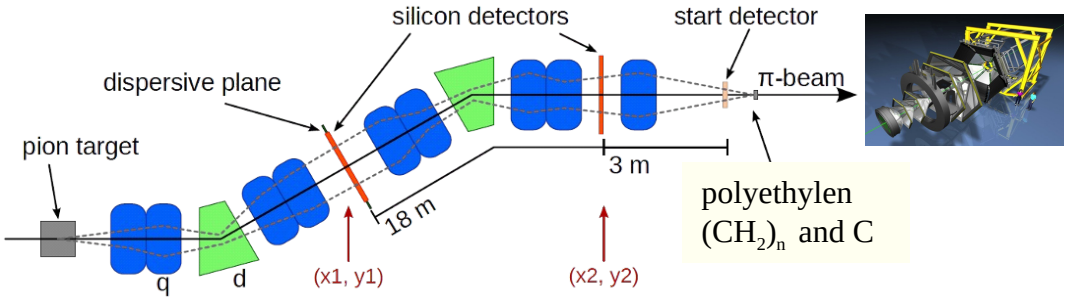
Pion beam facility @ GSI

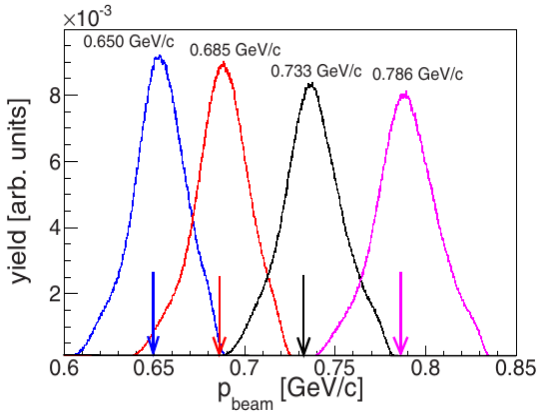
Eur. Phys. J. A 53, 188 (2017)

- **selectivity:** producion of resonance with given mass in s-channel
- 2-pion channels: $\pi^- p \rightarrow n\pi^+\pi^-$, $\pi^- p \rightarrow p\pi^-\pi^0$ $(\sqrt{s} = 1.46 - 1.55\, GeV)$
  - complete the very scarce pion beam data base for hadronic couplings
- dilepton channel R → Ne+e-, **never** measured in pion induced reactions
  - time-like electromagnetic structure of baryons

2nd resonance region

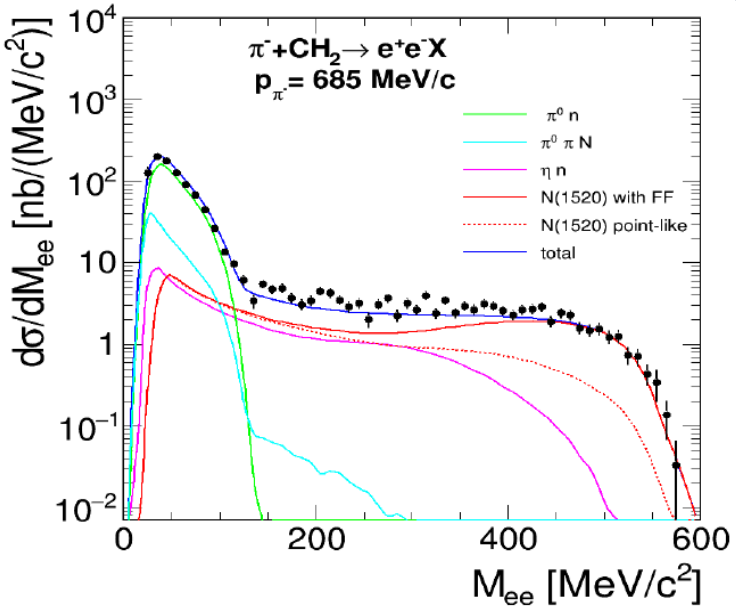






- reaction **N+Be,** 8-10*10^{10} N_2 ions/spill (4s)
- secondary **π^-** with **I ~ 2-3 10^5/s**
- p = 650, **685**, 733, 786 (+/- 1) MeV/c
- **PE $(CH_2)_n$** and **C** targets

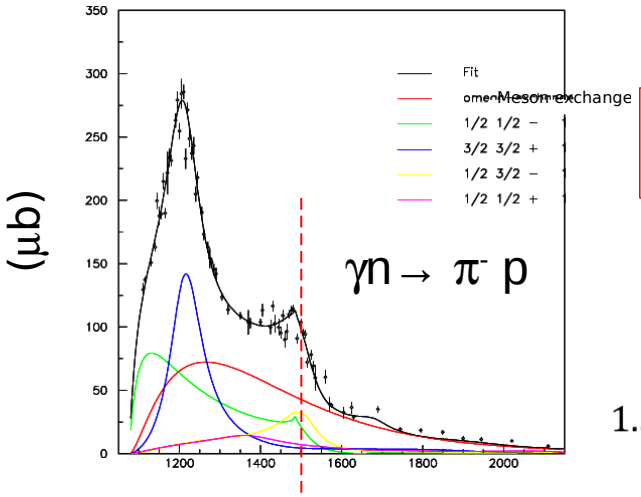
Inclusive e+e- cocktail
Fixing cocktail ingredients



$\pi^- p \rightarrow n\pi^0$ [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]

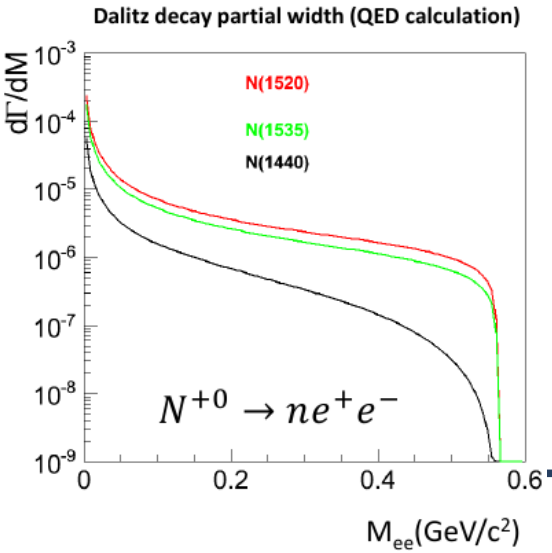
Arndt et al., PRC**72** (2005) 045202

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%

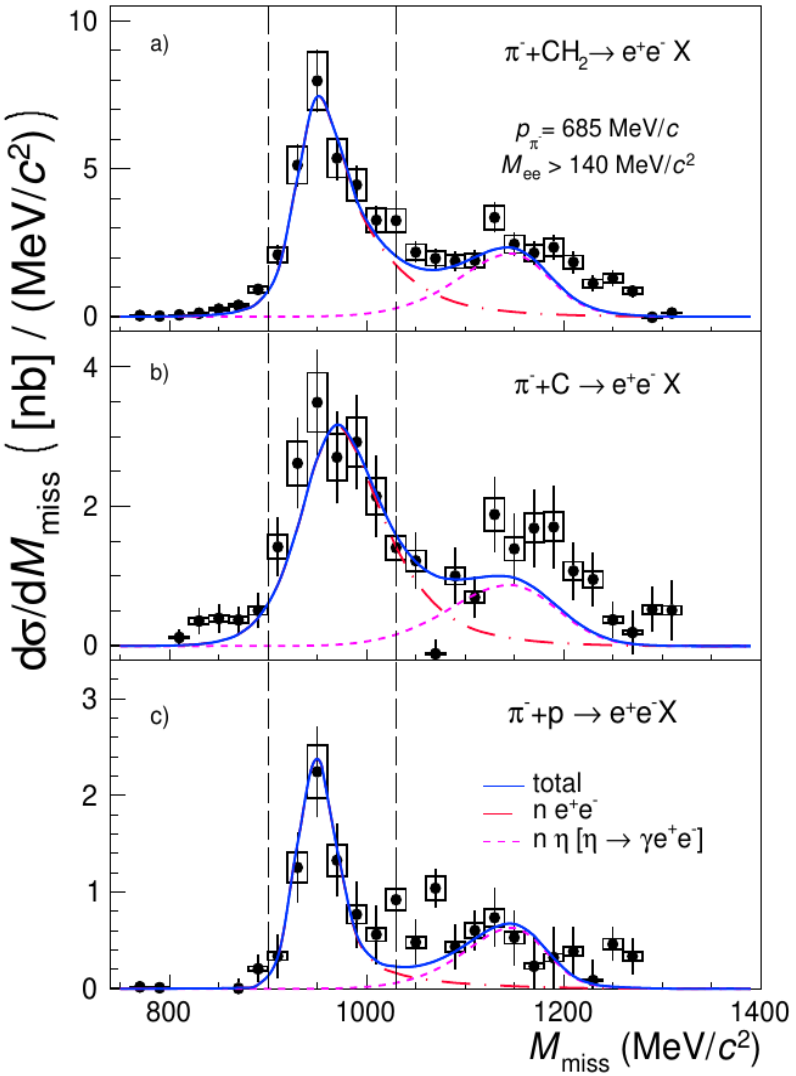


$\sigma(\pi^- p \rightarrow ne^+e^-) \sim$
$1.35\ \alpha\ \sigma(\pi^- p \rightarrow n\gamma) = 2\ \mu b$

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

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

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)

- **π^-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:

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