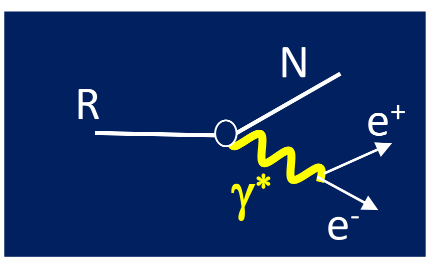
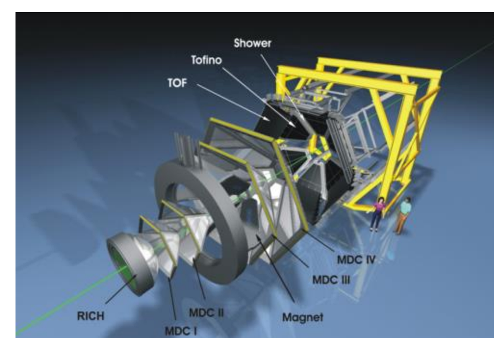
Space-like and Time-like Form Factors in Nucleon Resonance Production II

HADES results and prospects for Time-like baryon transition form factors

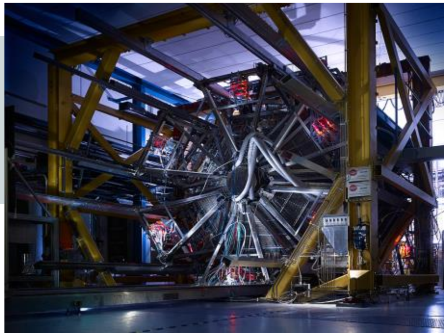
Béatrice Ramstein, IJCLab, Orsay, France

APCTP Focus Program in Nuclear Physics 2021 Part II: Science Opportunities with EIC





Outline



- **General motivations of the HADES experiment at GSI**

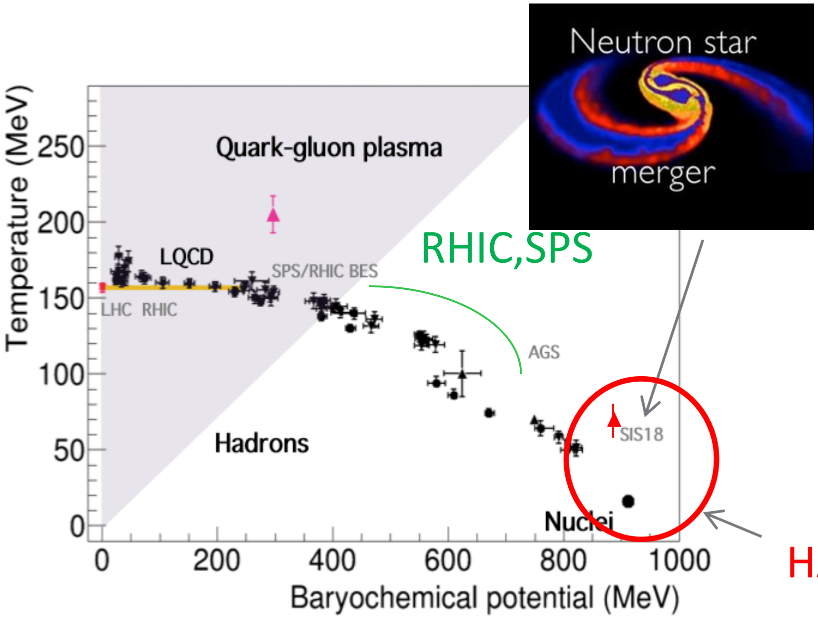
  Dense hadronic matter and hadron structure studies

- **Results for time-like electromagnetic baryon transitions in pp and πp reactions**

- **Prospects for hyperon studies**

- **Conclusions**

HADES: exploring dense QCD matter



HADES

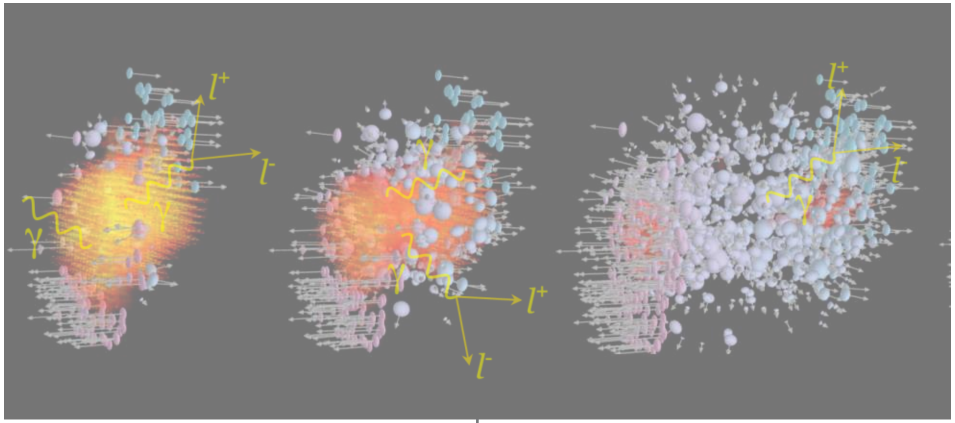
T. Galatyuk, NPA-D-18-00411 (2018) QM18

- ❑ Equation-of-State:
  First order transition ? Search for a critical point
- ❑ Chiral symmetry restoration
- ❑ Microscopic structure of baryon dominated matte
  Role of baryonic resonances, hyperons
- ❑ Complementary to SPS,RHIC,..

A+A: 1-3A GeV
√s=2-2.4 GeV

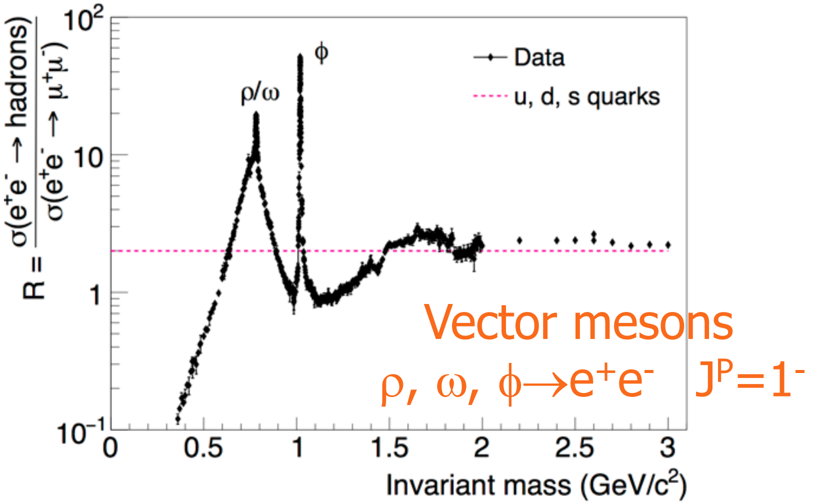
Observables:
- ✓ Correlations and fluctuations
- ✓ Collective effects
- ✓ Strangeness
- ✓ Dileptons

Emissivity of strongly interacting matter



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

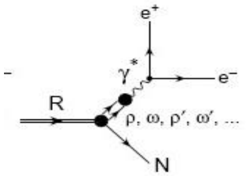
McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545



J. Beringer et al. (PDG), Phys. Rev. D (2012) 010001

Dilepton signal

- Encodes information (T,μ_B,τ) throughout the collisions
- Vector Dominance Model → Direct access to in-medium spectral functions



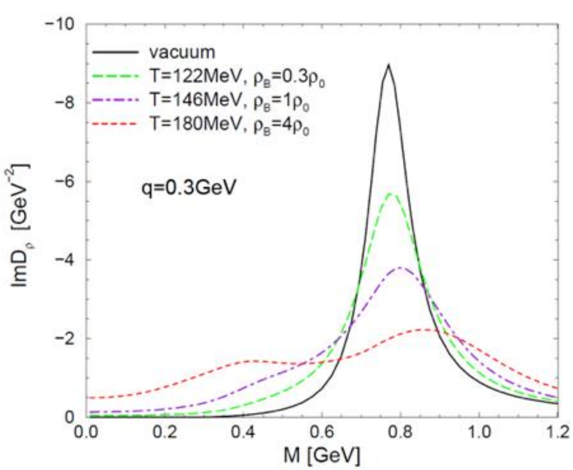
Chiral symmetry restoration at finite (ρ,T)

In medium vector meson spectral functions

inclusive e^+e^- production Au+Au @1.25A GeV

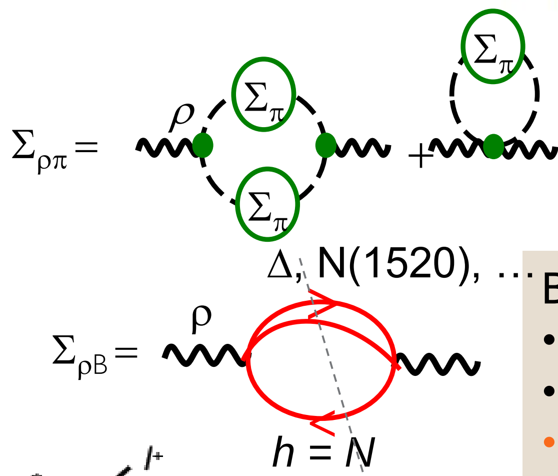
HADES Collab., Nature Phys. 15 (2019) 10, 1040-1045

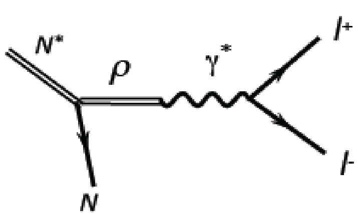
Strong broadening of **in medium ρ** spectral function due to its coupling with baryonic resonances.

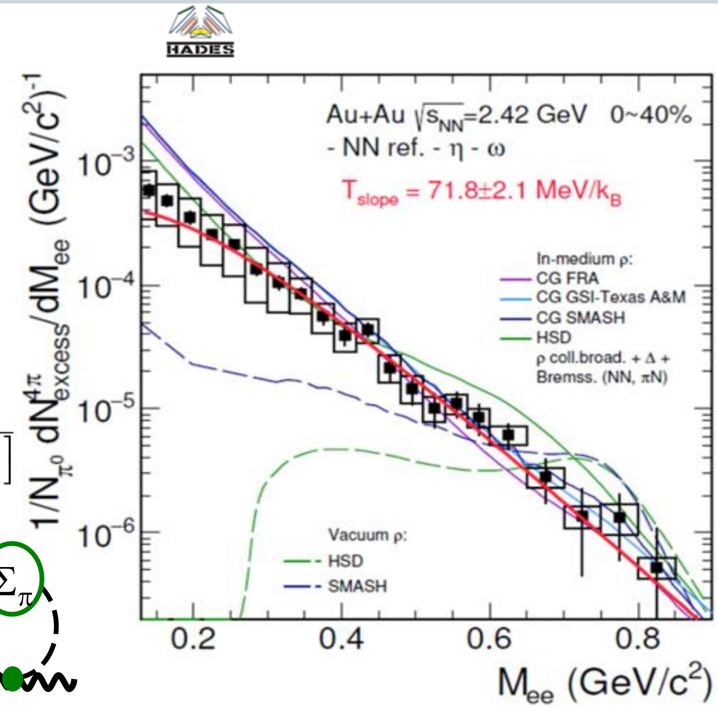


R. Rapp and J. Wambach EPJA 6 (1999) 415

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







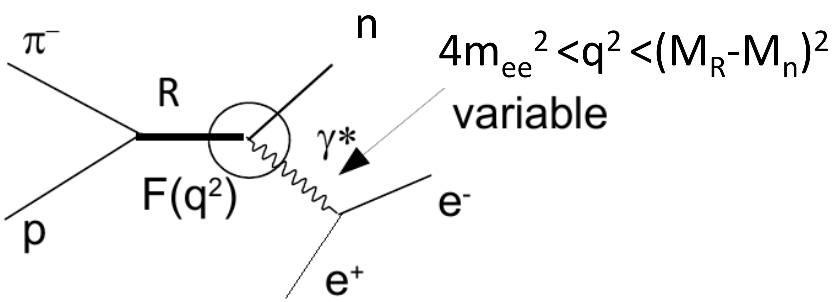
Baryonic loop

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

Can be tested using NN and πN collisions

Baryon electromagnetic transitions

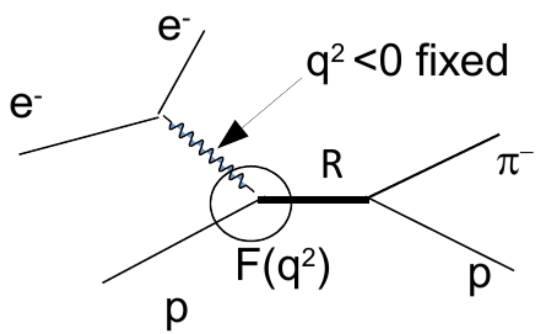
Time-like electromagnetic form factors



No data are available

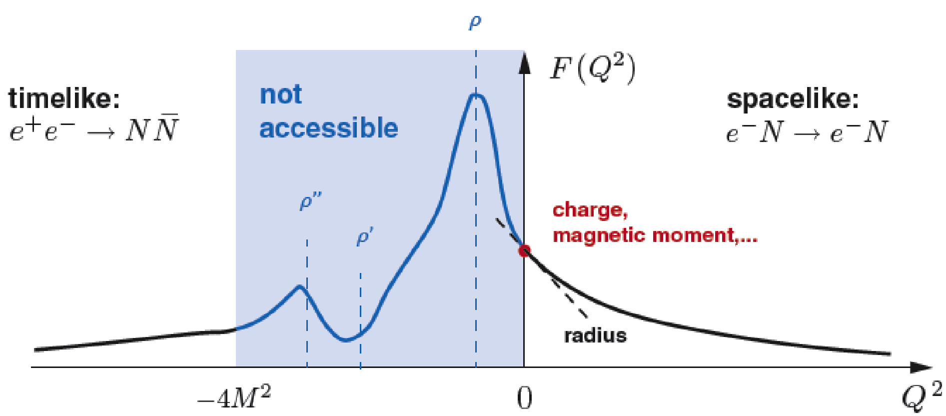
Limit at q^2=0 given by real photon decay

Space-like electromagnetic form factors



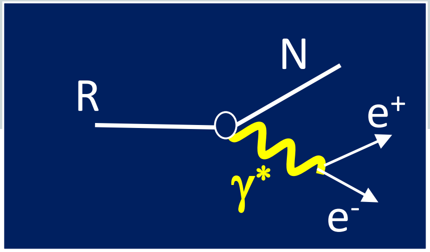
Data from Jlab (CLAS) up to $-q^2 = 4$ GeV^2

Exploration of higher q^2 with CLAS12



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

Time-like electromagnetic structure via baryon Dalitz decay



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

I=1/2

$$\Gamma^{N^*\to N\gamma^*}_{m_{N^*}}(q^2) = \frac{\alpha}{8m_\star}\sigma_\pm^{3/2}\sigma_\mp^{1/2}\times\left|G_T(q^2)\right|^2,$$
$$\text{where } q^2 = M_{ee}^2,$$
$$m_\pm = m_\star \pm m_N,$$
$$\sigma_\pm = m_\pm^2 - M_{ee}^2,$$
$$\text{and } \left|G_T(q^2)\right|^2 = 2\left|G_{E/M}(q^2)\right|^2 + \frac{q^2}{m_\star^2}\left|G_C(q^2)\right|^2$$

I>1/2 ℓ = I-1/2

$$\Gamma^{N^*\to N\gamma^*}(q^2) = \frac{9\alpha}{8}\frac{(l!)^2}{2^l(2l+1)!}\frac{m_\pm^2\sigma_\mp^{l+1/2}\sigma_\pm^{l-1/2}}{m_\star^{2l+1}m_N^2}\times\left|G_T(q^2)\right|^2,$$
$$\text{with } \left|G_T(q^2)\right|^2 = \frac{l+1}{2l}\left|G_{M/E}(q^2)\right|^2 + \tfrac{1}{2}(l+1)(l+2)\left|G_{E/M}(q^2)\right|^2 + \frac{q^2}{2m_\star^2}\left|G_C(q^2)\right|^2$$

Upper sign: $1/2^-, 3/2^+, 5/2^-$,... lower sign: $1/2^+, 3/2^-, 5/2^+$

- e^+/e^- angular distributions: spin density matrix coefficients

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

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

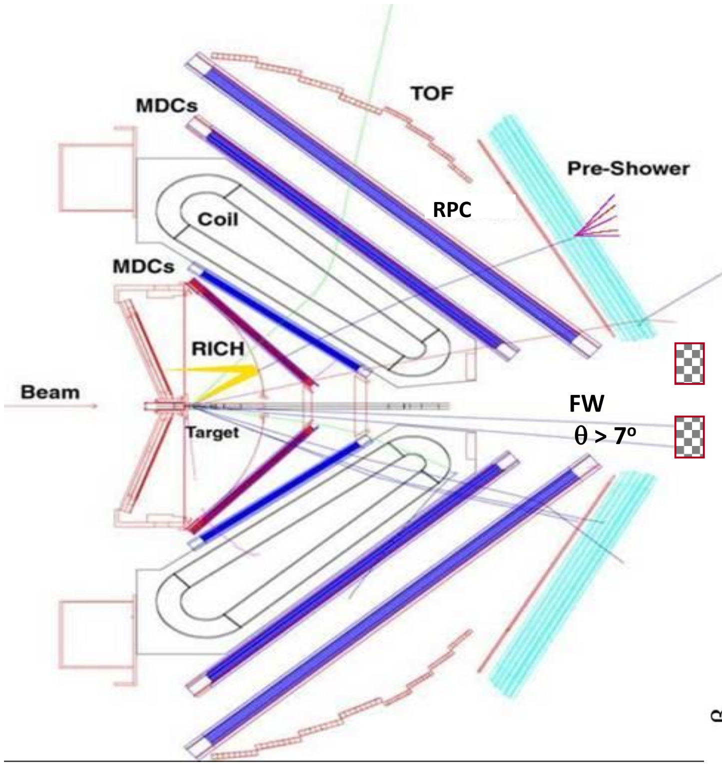
J=1/2

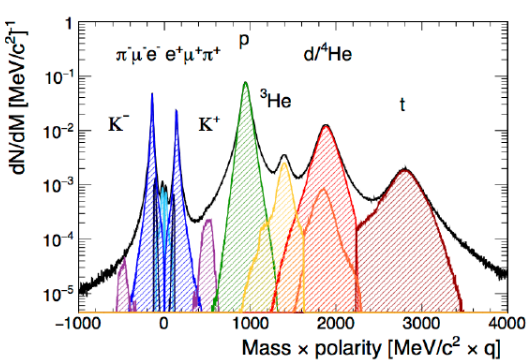
$$\lambda = \frac{\left|G_{E/M}^\pm\right|^2 - \left|G_C^\pm\right|^2}{\left|G_{E/M}^\pm\right|^2 + \left|G_C^\pm\right|^2}$$

J>1/2

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

High Acceptance Di-Electron Spectrometer





Experiments (2004-2019)

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:

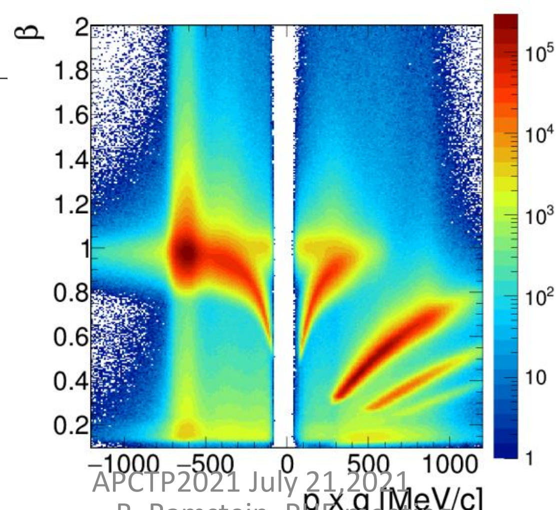
p+Nb 3.5 GeV, π^-+C/W 1.7 GeV/c

Elementary reactions:

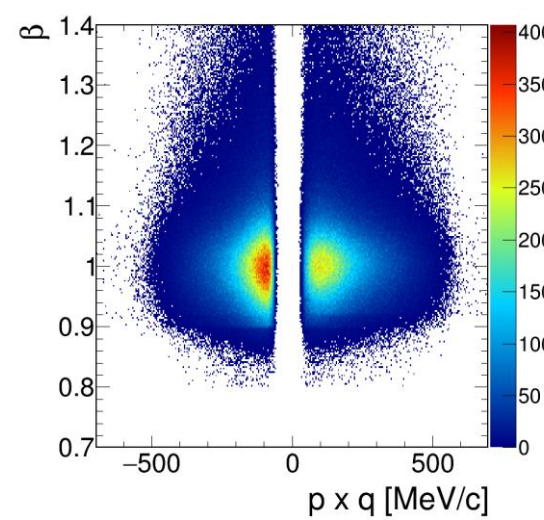
p+ p 1.25, 2.2 , 3.5 GeV, d+p 1.25 GeV/nucléon

π^-+CH_2/C 0.7 GeV/c

before lepton selection



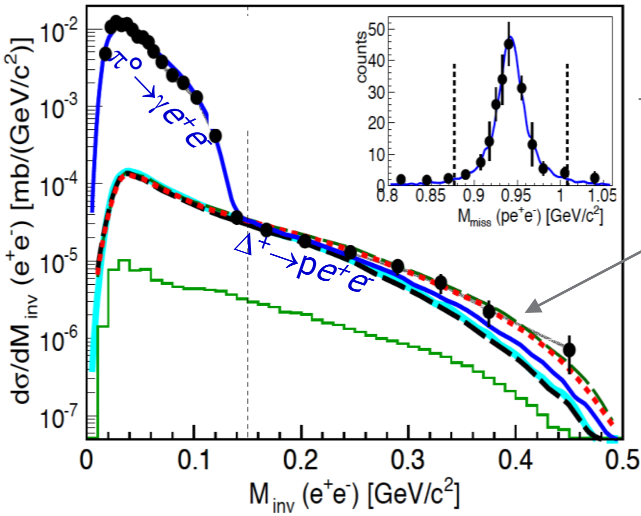
after lepton selection

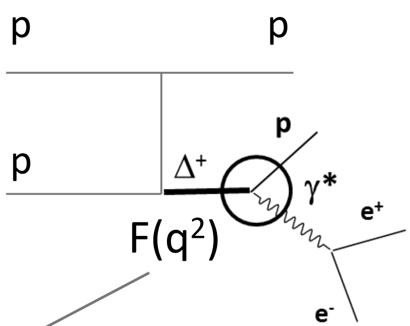


Δ(1232) Dalitz decay studies with HADES

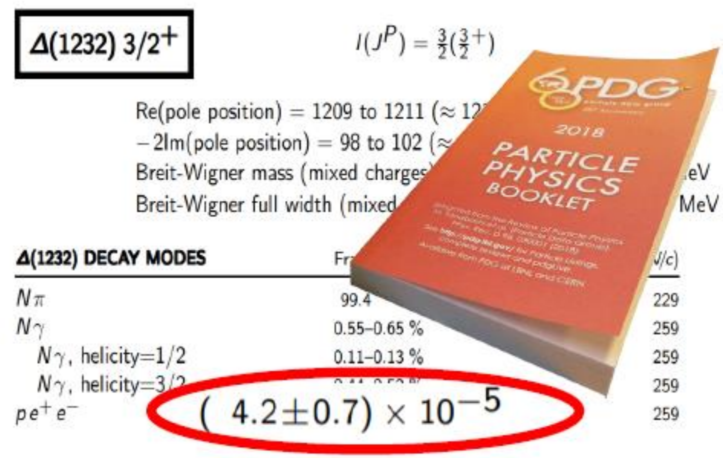
E=1.25 GeV pp → ppe⁺e⁻

HADES PRC95, 065205 (2017)





- Δ Production amplitudes from PWA of pp → ppπ° and pp → pnπ⁺
- Analysis of helicity angle distributions



- ❑ First measurement of Δ (1232) Dalitz decay branching ratio (Δ⁺ →pe⁺e⁻)
- ❑ Sensitivity to the electromagnetic structure (form factor) of the N-Δ transition

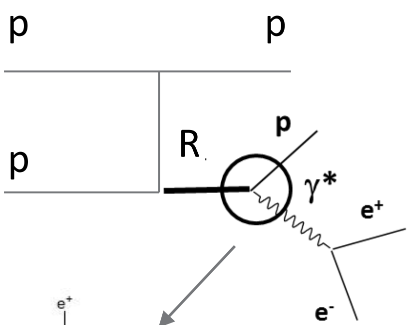
Wan and Iachello, Int. J Mod. Phys. A20 (2005) 1846
T. Pena and G. Ramalho, Phys.Rev. D85 (2012) 113014

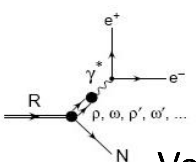
Dalitz decay studies of heavier baryons with HADES

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

p+p →pp e^+e^- 3.5 GeV

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



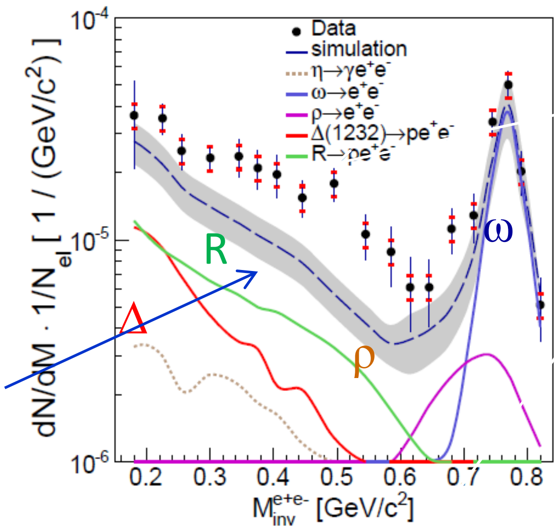


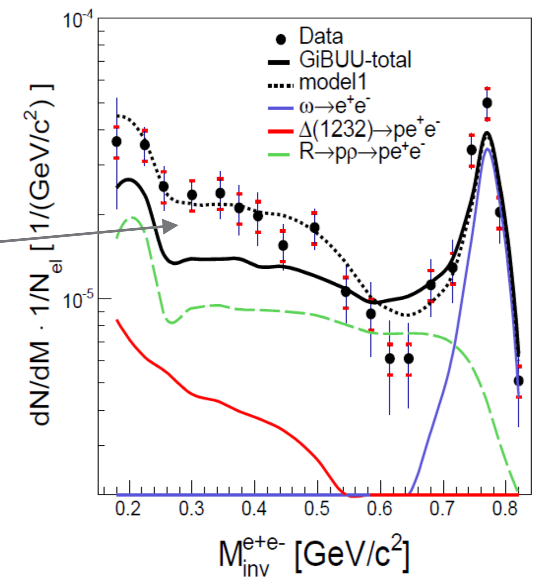
Vector Dominance Model

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

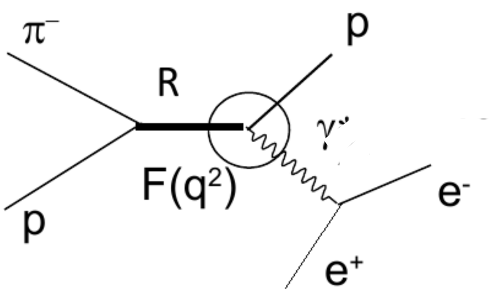
+ "direct" ρ and ω

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 (unique in world) is an ideal tool to

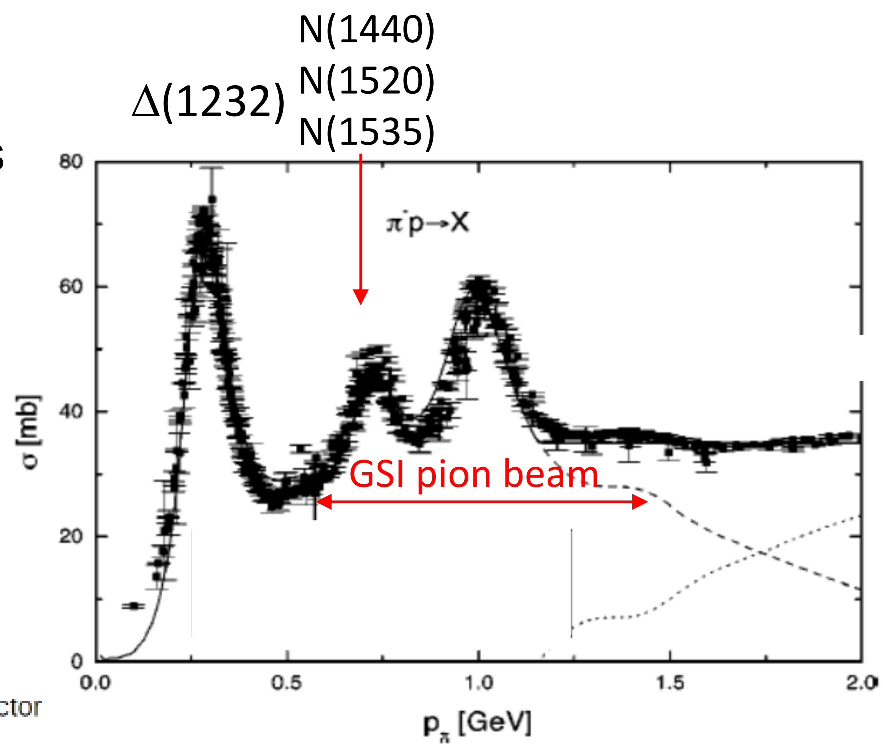
- ✓ study the unknown time-like electromagnetic structure of baryons
- ✓ complete the very scarce pion beam data base for hadronic couplings

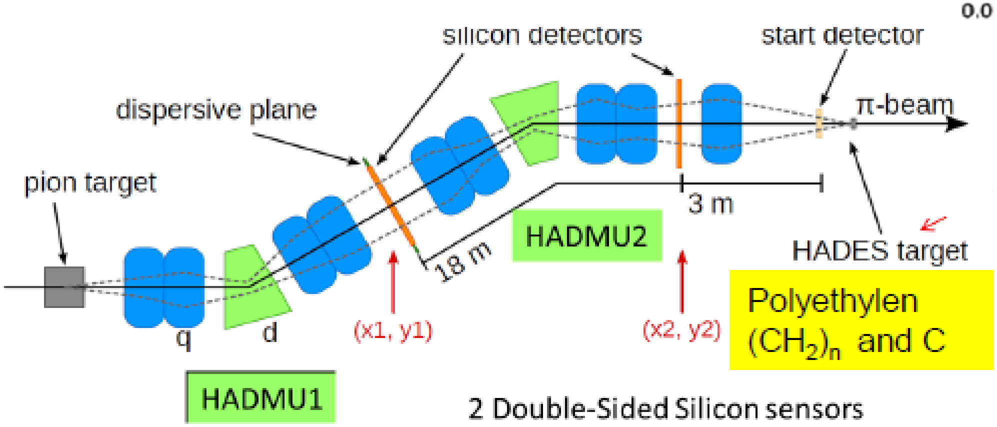
Specific interest for ρN couplings

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





2 Double-Sided Silicon sensors
100 x100mm², 300µm thick
2 x128 channels

Measurements on CH2 and C targets

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

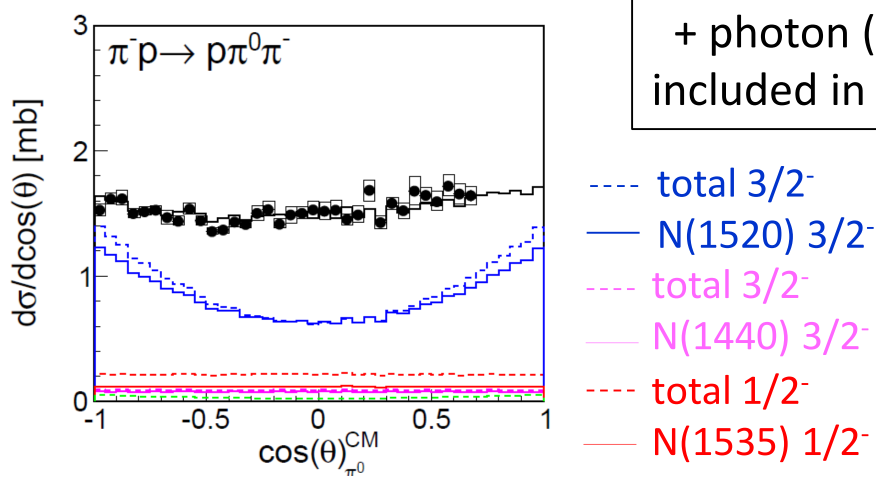
(4 measurements $\sqrt{s}$ =1.46-1.55 GeV/c^2)

- e^+e^- production $\sqrt{s}$ =1.49 GeV/c^2

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

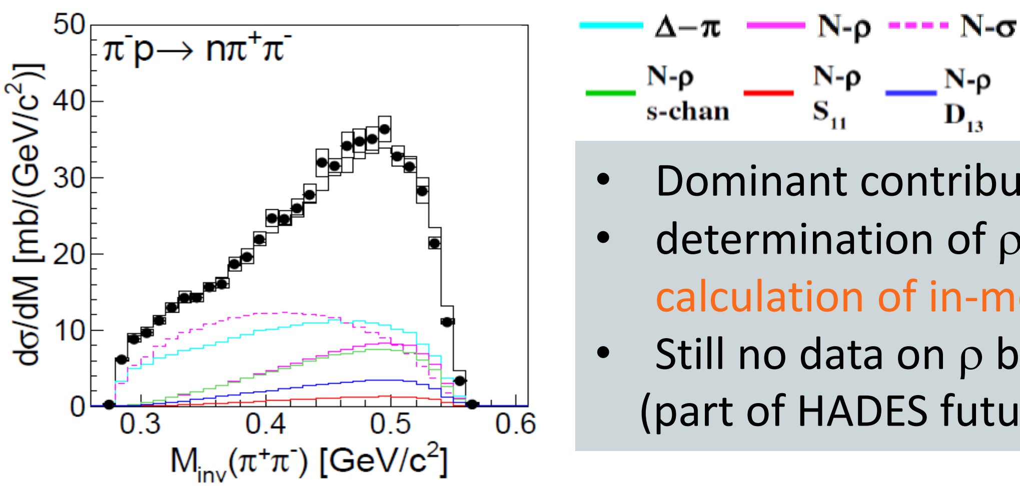


e.g. N(1520):

ρN coupling =12±2 %

PDG 2015 : 15-25%

PDG after 2016 : no information



- Dominant contribution from s-channel $3/2^-$ N(1520)
- determination of ρNN* couplings→ direct input for calculation of in-medium ρ meson spectral function
- Still no data on ρ between 1.54 and 1.75 GeV/c^2 (part of HADES future program)

PWA results–8 newPDG entries!

PDG Verification

particle data group

ρN coupling not present in PDG since 2016

$\Gamma(N(1520) \rightarrow \Delta(1232)\pi\,,\, S{-}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
12.1 ±2.1	ADAMCZEWSKI- 2020

$\Gamma(N(1520) \rightarrow \Delta(1232)\pi\,,\, D{-}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
6 ±2	ADAMCZEWSKI- 2020

$\Gamma(N(1520) \rightarrow N\rho\,,\, S{=}3/2\,,\, S{-}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
11.8 ±1.9	ADAMCZEWSKI- 2020

$\Gamma(N(1520) \rightarrow N\rho\,,\, S{=}1/2\,,\, D{-}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
0.4 ±0.2	ADAMCZEWSKI- 2020

$\Gamma(N(1520) \rightarrow N\sigma)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
7 ±3	ADAMCZEWSKI- 2020

$\Gamma(N(1535) \rightarrow \Delta(1232)\pi\,,\, D{-}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
3 ±1	ADAMCZEWSKI- 2020

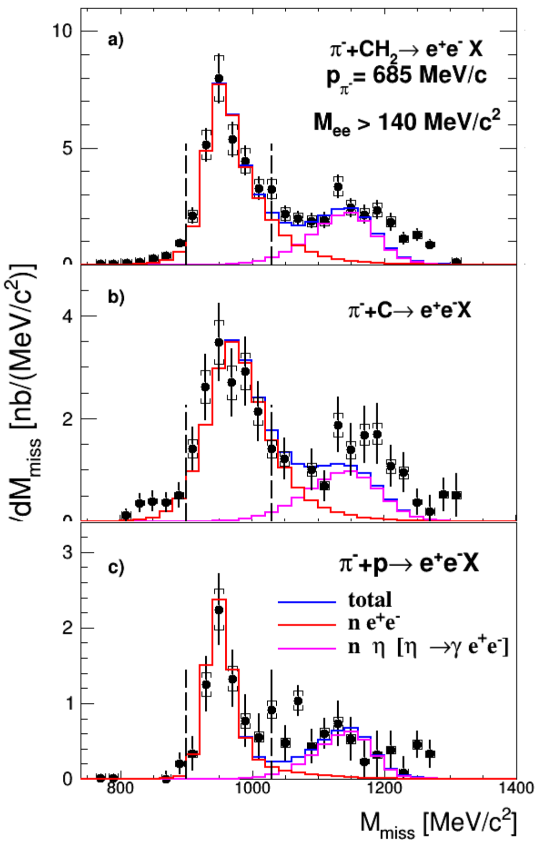
$\Gamma(N(1535) \rightarrow N\rho\,,\, S = 1/2)/\Gamma_{total}$

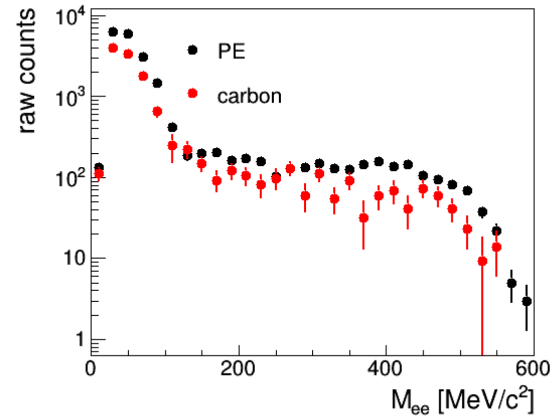
VALUE (%)	DOCUMENT ID
2.7 ±0.6	ADAMCZEWSKI- 2020

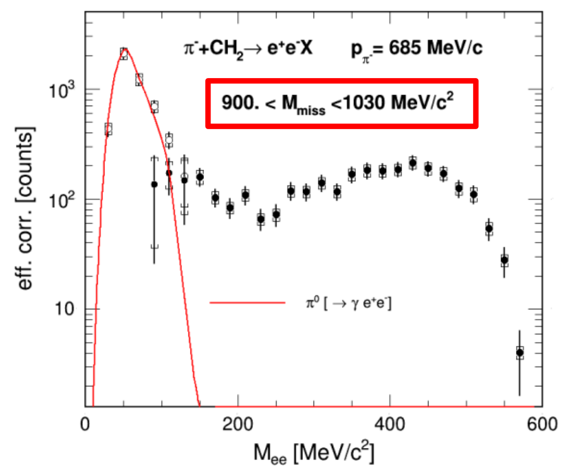
$\Gamma(N(1535) \rightarrow N\rho\,,\, S{=}3/2\,,\, D{-}wave)/\Gamma_{total}$

VALUE (%)	DOCUMENT ID
0.5 ±0.5	ADAMCZEWSKI- 2020

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



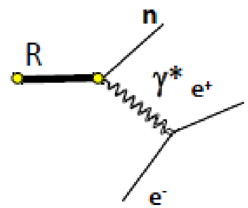




- Selection of the exclusive $\pi^- p \rightarrow n e^+ e^-$ channel using missing mass
- Quasi-free treatment of π^- C interactions σ_C/σ_p=3.3 (~$Z^{2/3}$)
- Subtracion of residual π^0 contribution

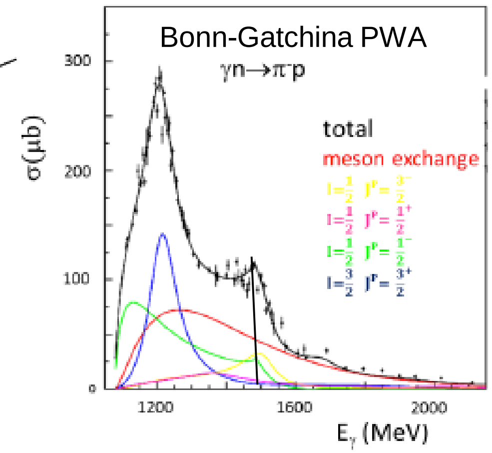
Baryon Dalitz decay in a point-like approach : QED reference

- Limit at q^2=0 given by $\pi^- p \to n\gamma$



Bonn-Gatchina PWA of $\pi^- p \to n\gamma$

cross sections (μb) for $\pi^- p \to \gamma n$						
	I =1/2 J^P=1/2$^-$		I =1/2 J^P=3/2$^-$		I =3/2 J^P=3/2$^+$	
total	total	N(1535)	total	N(1520)	total	Δ(1232)
220	60	34	60	47	13	18



Contribution of D13 to $\pi^- p \to \gamma n$ 27% (N1520 21%)
of S11 to $\pi^- p \to \gamma n$ 27% (N1535 15%)

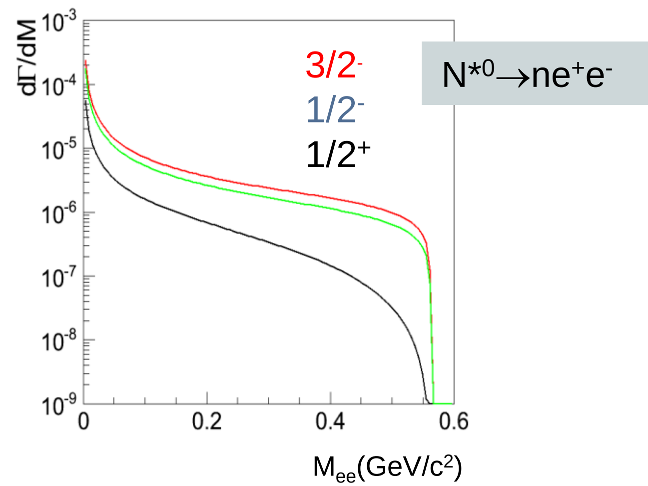
- Generalization to finite q^2 (QED)

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

→ "point-like" description of $R \to Ne^+e^-$

For M_R~1.50 GeV/c^2 : $\sigma(\pi^- p \to n e^+ e^-) \sim 1.35\ \alpha\ \sigma(\pi^- p \to n\gamma)$

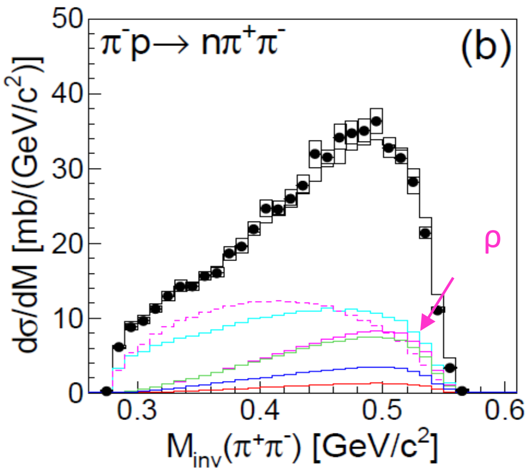
$\sigma(\pi^- p \to n e^+ e^-)$ = 2.1 μb
invariant mass distribution depends on J^P

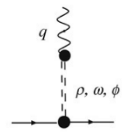


« γ « or « QED « reference

Test of Vector Dominance models

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





Ideal case: $\rho \to \pi^+\pi^-$ extracted from PWA

Direct test of VDM models based on known ρ contribution

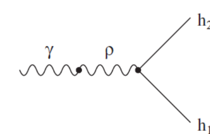
$$\left(\frac{d\sigma_{ee}}{dM_{ee}}\right)_{M_{ee}=M} = \left(\frac{d\sigma_{\pi\pi}}{dM_{\pi\pi}}\right)_{M_{\pi\pi}=M} \frac{\Gamma_{\rho\to e^+e^-}(M)}{\Gamma_{\rho\to\pi^+\pi^-}(M)}$$

Test of 2 VDM versions (equivalent for universal coupling $g_\rho = g_{\rho\pi\pi}$)

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

VDM2 : *Sakurai, Phys. Rev 22 (1969) 981*

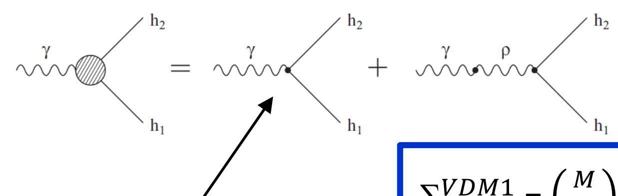
- most commonly used in Heavy Ion models
- one single ρN coupling



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

VDM1 : *Kroll, Lee & Zuminio Phys. Rev. 157 (1967) 1376*

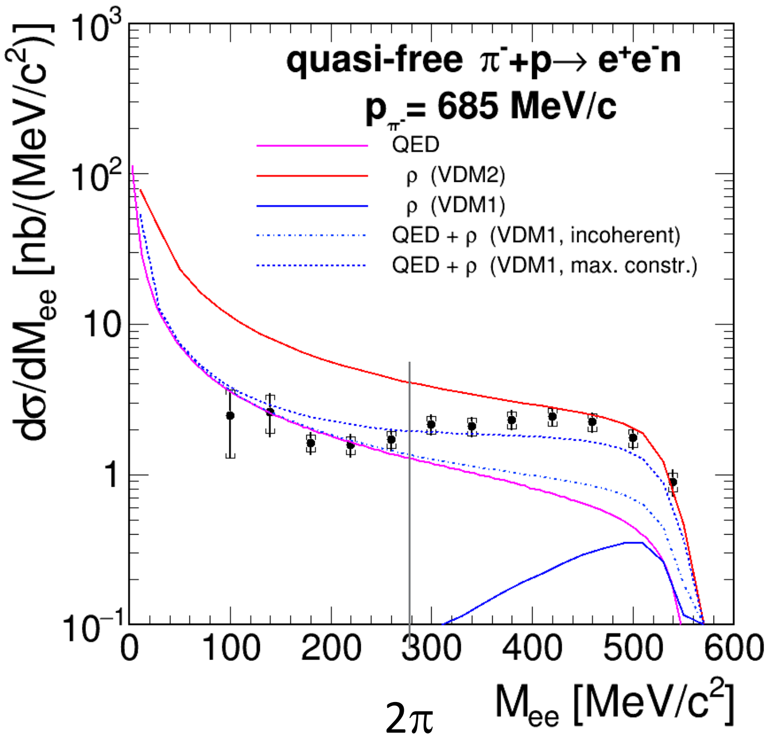
- ρ contr. vanishes at $m_\gamma{}^*=0$, γN and ρN couplings fixed independently
- Phase between γ and ρ contributions to be fixed by data



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

γ or point-like contribution

Data comparison with VDM2/VDM1 models



- **Model independent results:**
  - Strong excess with respect to the point-like contribution (up to a factor 5)
  - Extrapolated cross section

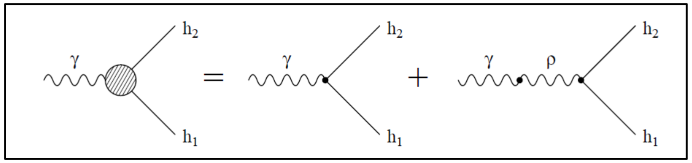
σ =2.14 ± 0.06 (data) ± 0.23 (QED ref) μb

σ = 1.16 * σ $_{QED}$

- **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**

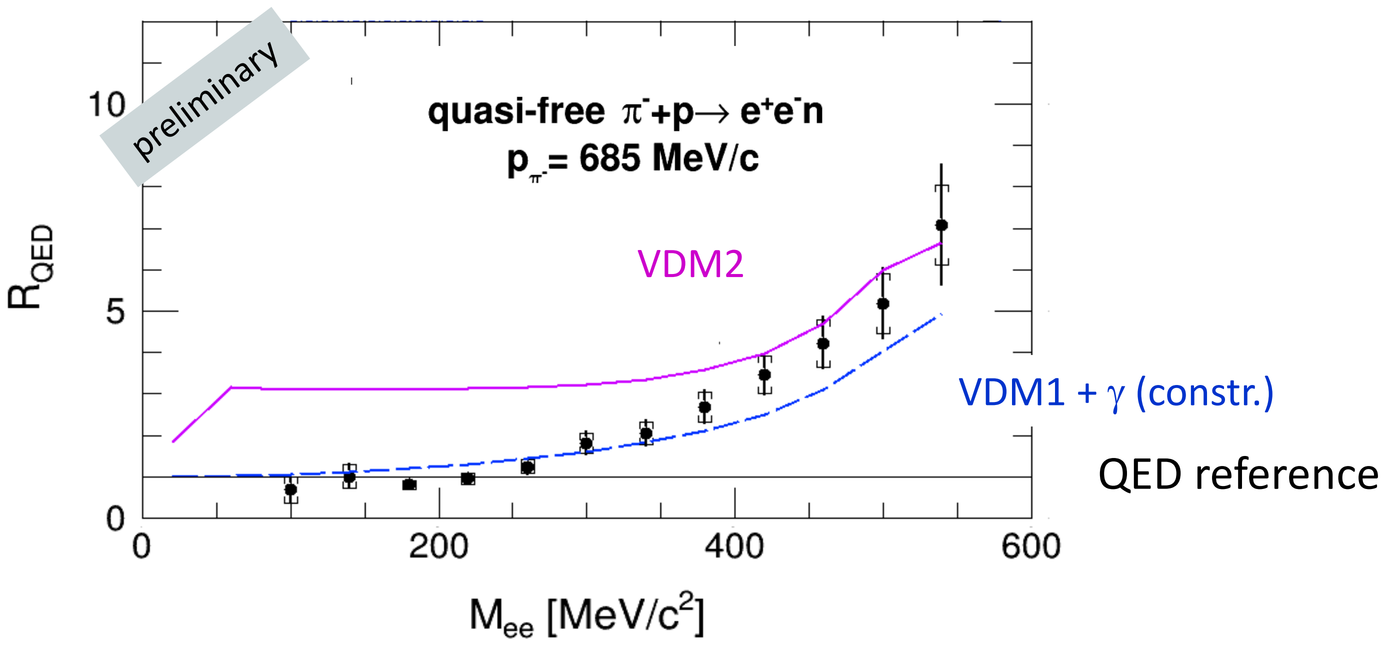


Effective Form Factor

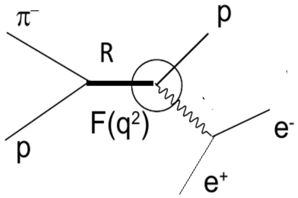
Effects of baryon time-like electromagnetic structure quantified by

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

« effective form factor » with strong contribution of N1520

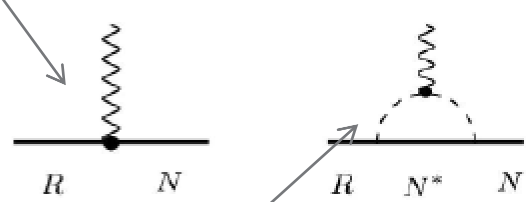


Baryon Dalitz decay: Form factor models



Recent model for N-N(1520) transition
G. Ramalho and M. T. Pena,
Phys. Rev. D95, 014003 (2017)

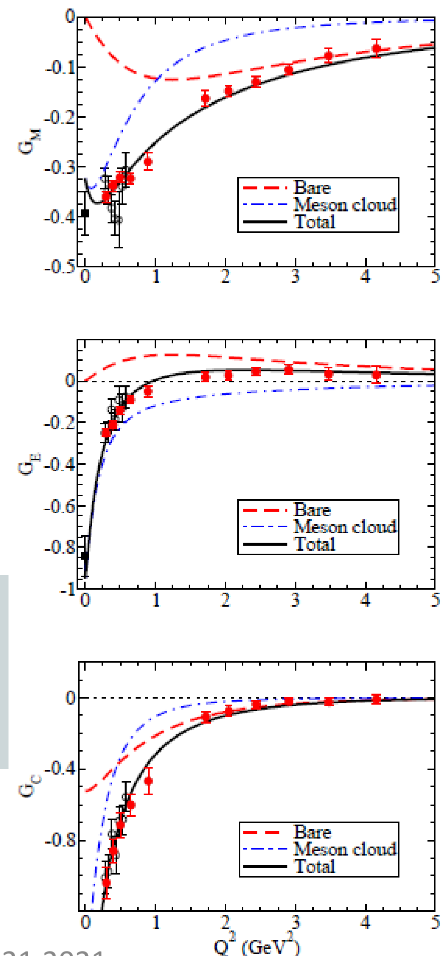
Quark core contribution :
- Quark form factors inspired by VDM



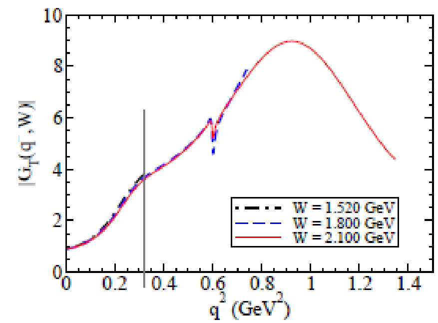
Meson cloud contribution:
- Based on pion electromagnetic form factor
- Dominant contribution in the time like region

Similar model for N-N(1535) transition
Phys.Rev. D101 (2020)114008

Parameters of the model fitted to space-like data

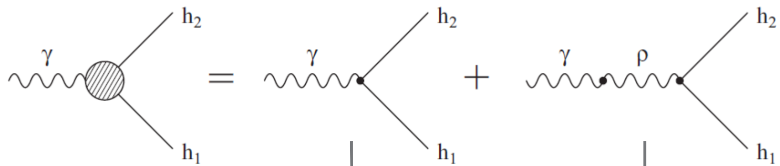


Predictions for the time-like region



$$|G_T(q^2,W)|^2 = 3|G_M(q^2,W)|^2 + |G_E(q^2,W)|^2 + \frac{q^2}{2W^2}|G_C(q^2,W)|^2.$$

Two-component Lagrangian model



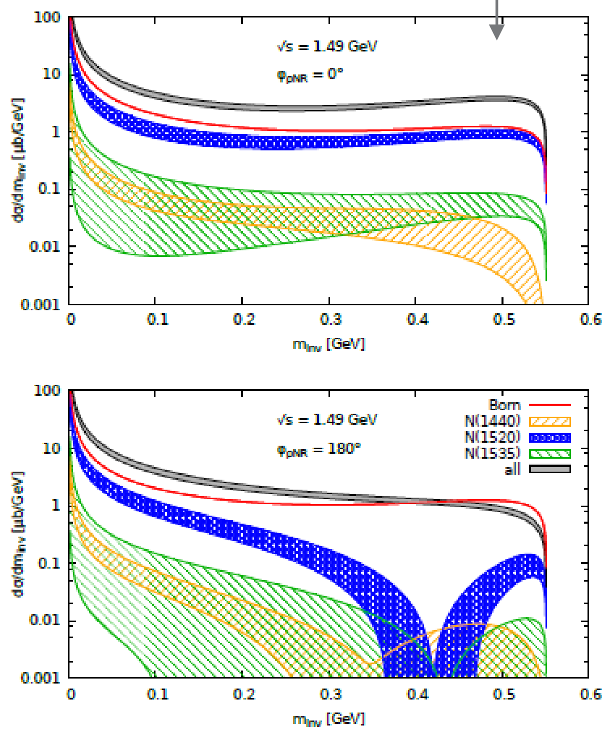
- Various non-resonant (Born term) and resonant (N(1520),N(1440), N(1535),..)
- **Strong contribution of the Born term**

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

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

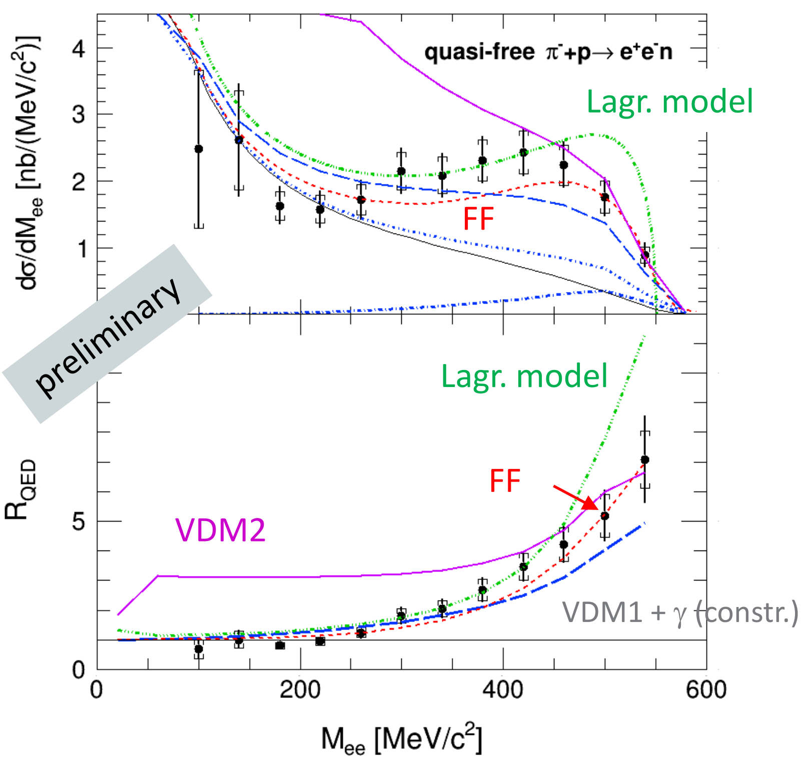
*M. Zetenyi and G. Wolf, Phys. ReV. C **86**, 065209 (2012)*

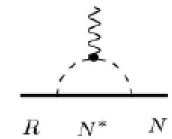
M. Zetenyi, et al. arXiv:2012.07546[nucl-th], 2020



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

Invariant mass distribution: comparison to models





Comparison with FF model:

G. Ramalho and M. T. Pena,
Phys. Rev. D95, 014003 (2017)

- Dominant pion cloud contribution:

baryon transition form factor strongly related to the pion electromagnetic form factor (universal behavior of baryons ?)

Comparison with Lagrangian model:

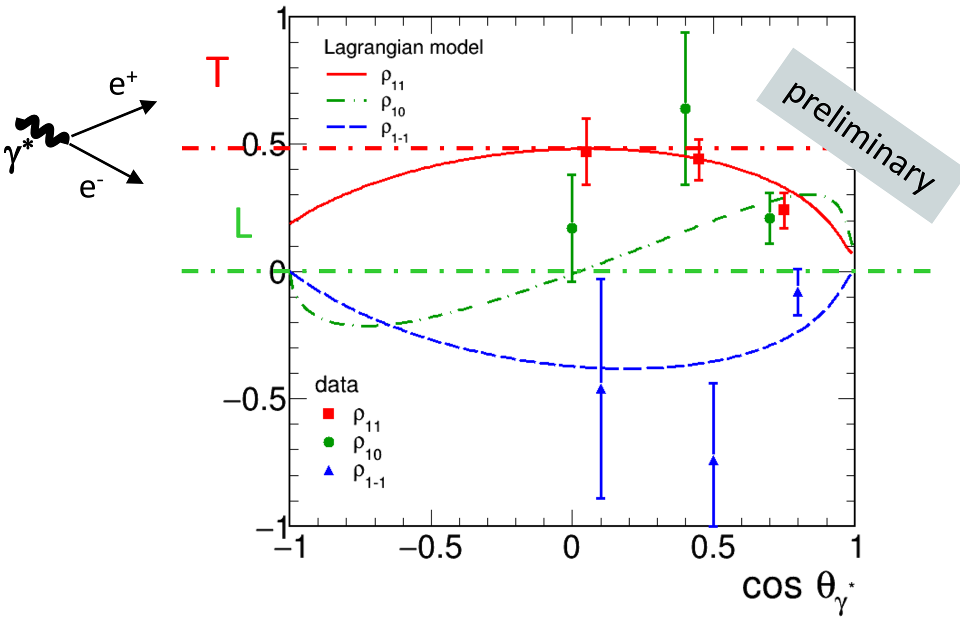
M. Zetenyi et al. arXiv:2012.07546 [nucl-th]

- based on VDM1, takes into account the different contributions (resonant, non-resonant, photon, rho,..) in a coherent way *shown with phase* ϕ*=90*
- very promising, but needs to be confronted to ππ spectrum

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

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

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

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

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 $$A_\perp = \frac{l+1}{l}\left|G^{\pm}_{M/E}\right|^2 + (l+1)(l+2)\left|G^{\pm}_{E/M}\right|^2$$

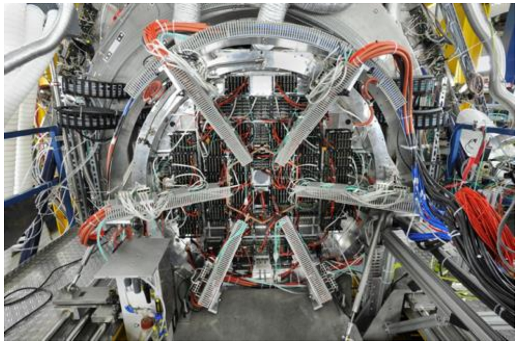
$$A_\parallel = \frac{M^2}{m_\star^2}\left|G^{\pm}_{C}\right|^2$$

- Significant transverse contributions:
- Spin >1/2 contributions : consistent with strong N1520 contribution
- Good agreement with Lagrangian model
- **More precise data needed**

HADES upgrade: FAIR-Phase0

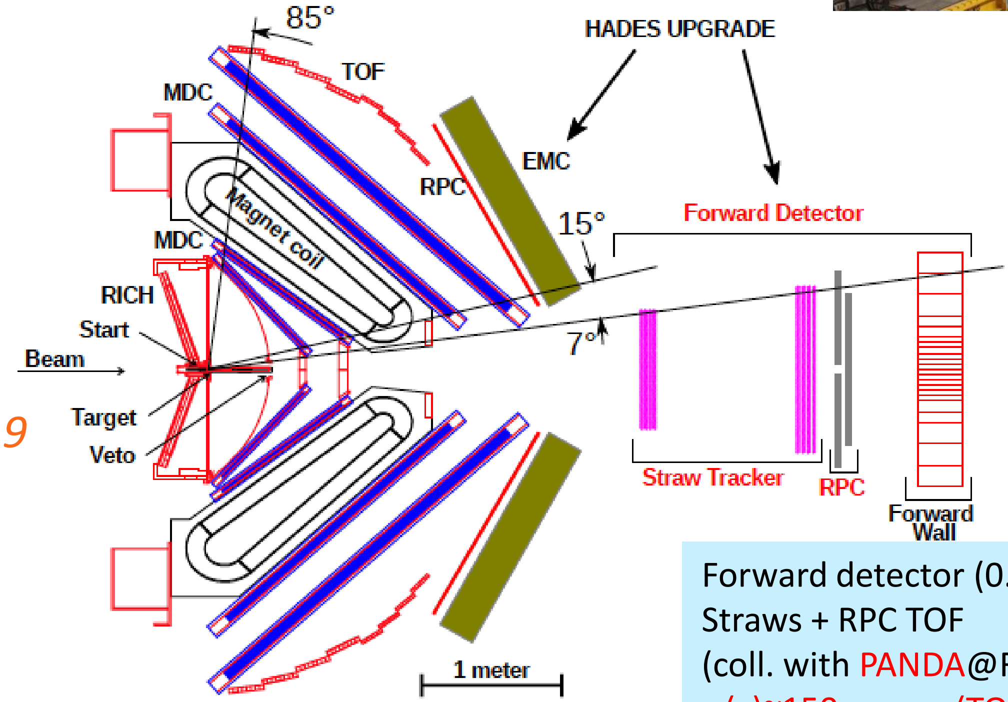
New ECAL (lead glass)
$\Delta E/E$ ~5%
γ and e^+/e^- detection

used in Au+Au exp. March 2019



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

used in Au+Au exp. March 2019

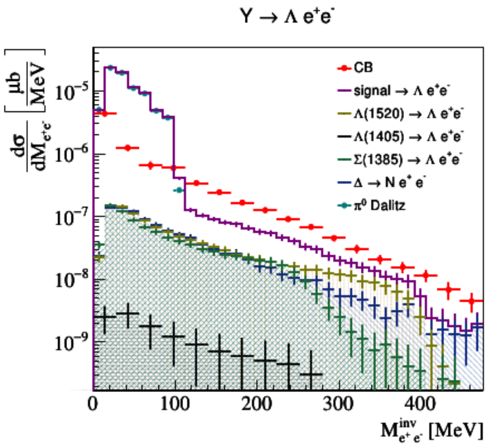


Forward detector (0.5-6.5°)
Straws + RPC TOF
(coll. with PANDA@FAIR)
$\sigma(x)$~150 μm σ(TOF)~70 ps

Future experiments at SIS18

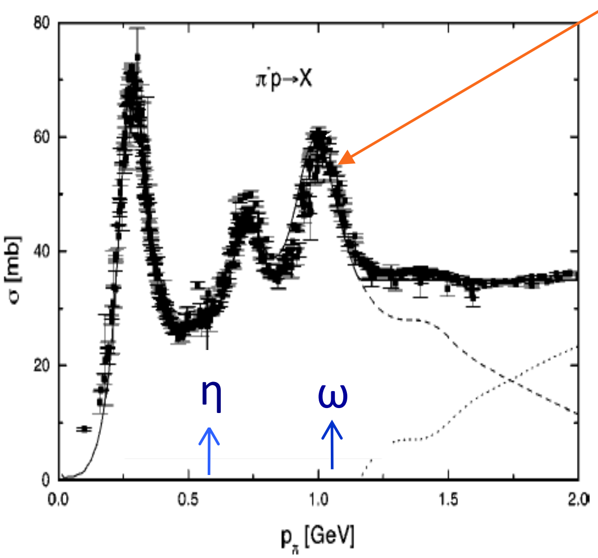
- **February 2022**: pp @ 4.5GeV

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



Hyperon Dalitz decays: $pK^+\Lambda(1520)\ [\Lambda e^+e^-]$
$pK^+\Sigma(1385)\ [\Lambda e^+e^-]$
Ξ, $\Lambda\Lambda$, Λ, $\Sigma\rightarrow\Lambda\gamma$

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
→ Inputs for Partial Wave Analysis
→ Many baryon structure issues: confirmation of N'(1720), Cascade decays ($R\rightarrow R'\pi\rightarrow N\pi\ \pi$), ηn couplings

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

Conclusion

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

→ improved knowledge of hadronic couplings

→ very new information on time-like electromagnetic baryon transitions

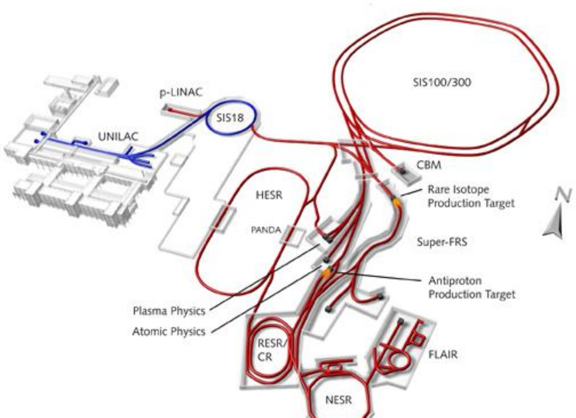
First test of Vector Dominance Model below 2π threshold and time-like electromagnetic form factor models

→ Basic inputs for medium effects calculations

✓ 2022: Electromagnetic decays of hyperons in pp reactions : $Y \rightarrow \Lambda\gamma$, $Y \rightarrow \Lambda e^+e^-$ using Forward Detector + Electromagnetic Calorimeter

✓ 2023 and later : pion beam experiment in the third resonance region
→ Investigate heavier resonances N(1620), N(1720),…in e^+e^- channels and many hadronic channels, e.g. $\pi^- p \rightarrow \eta n$, $K^0\Lambda$, $K\Sigma$,….

✓ After 2027: HADES experiments at FAIR ion and proton beams

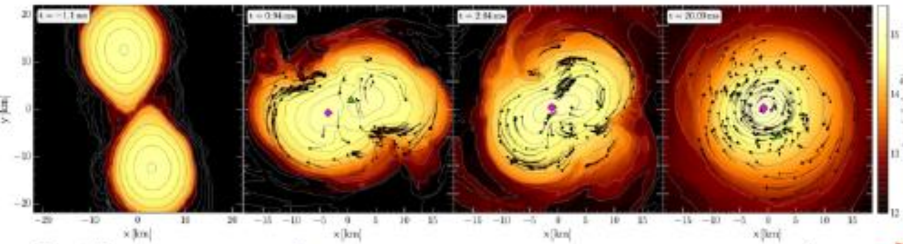


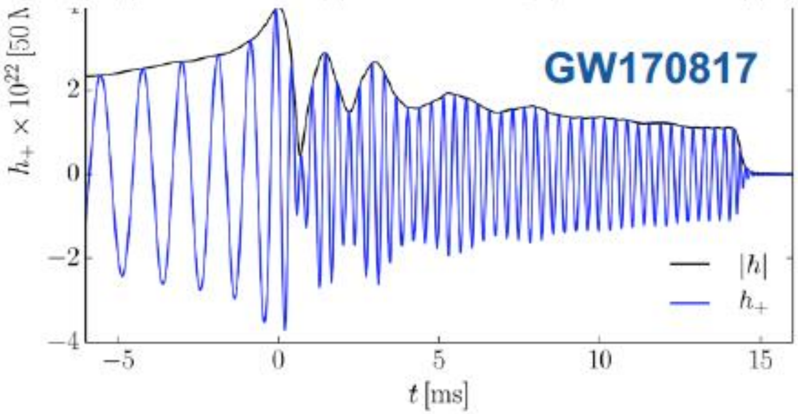
HADES Collaboration, Feb 22nd 20018

Thank you

LABORATORY STUDIES OF THE MATTER PROPERTIES (EoS) IN COMPACT STELLAR OBJECTS

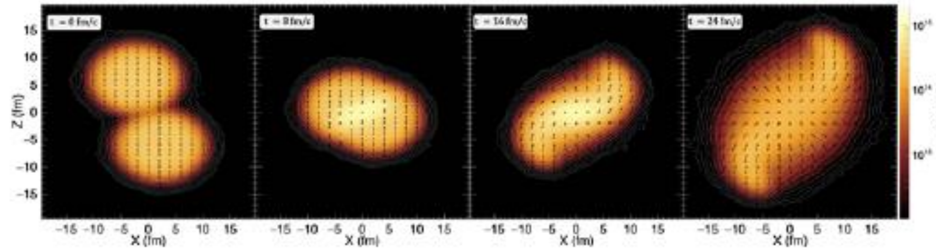
Neutron Star merger (model calculations)





M. Hanauske, Journal of Phys.: Conf. Series 878 (2017) 012031
L. Rezzolla *et al.*, Phys. Rev. Lett. 122, no. 6, 061101 (2019)

Au+Au $\sqrt{s_{NN}} = 2.4\ GeV$ (UrQMD)



- T < 70 MeV, $\rho < 3\rho_0$ for both (note the different isospin)
- Role of YN, YY phase shifts in EOS!
  HADES Collab. Phys.Rev. C94 (2016) 025201
  ALICE Collab. Phys.Rev.C 99 (2019) 2, 024001

Strong connections between the fields

electron angular distributions: fit results in HADES acceptance

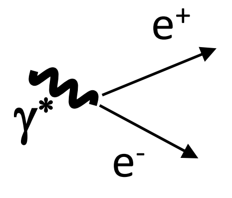
Similar procedure as Bonn-Gatchina PWA (collaboration with A. Sarantsev)

- ☐ Monte Carlo includes acceptance and efficiency of the detector
- ☐ The estimation of the coefficients is performed via a log-likelihood event-by-event approach
- ☐ 3 bins in cos θ_γ

Quasi-free exclusive process

$\pi^{-'}p' \rightarrow n\, e^+e^-$ $\sqrt{s}$=1.49 GeV/c^2

M_{ee} > 300 MeV/c^2



weighted Monte Carlo events compared to the data

cos θ_γ <0. | 0.< cos θ_γ<0.5 | 0.5 < cos θ_γ < 1.