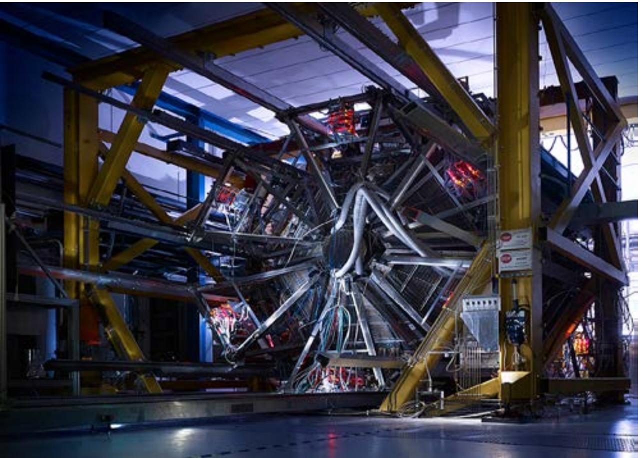
HADES investigations of baryon-photon couplings in pp and π p reactions

Contents

- ✓ Motivations(emissivity of QCD matter ->Low mass dileptons, ρ in-medium spectral function (SF) relations to chiral symmetry restoration → time-like baryon em. transitions)
- ✓ Measurements of baryon electromagnetic transitions in NN and πN reactions
- ✓ Summary & Outlook: perspectives for hyperon em. decays in HADES and new experiments with pion beams



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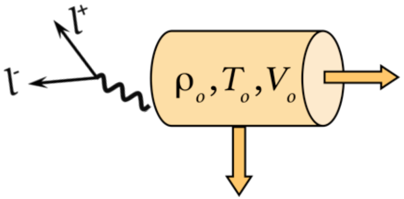
STRONG 2020

Emissivity of QCD matter with dileptons

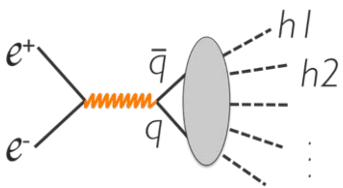
$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^{BE}(q_0,T)\,\mathrm{Im}\Pi_{em}(M,q,T,\mu_B)$$

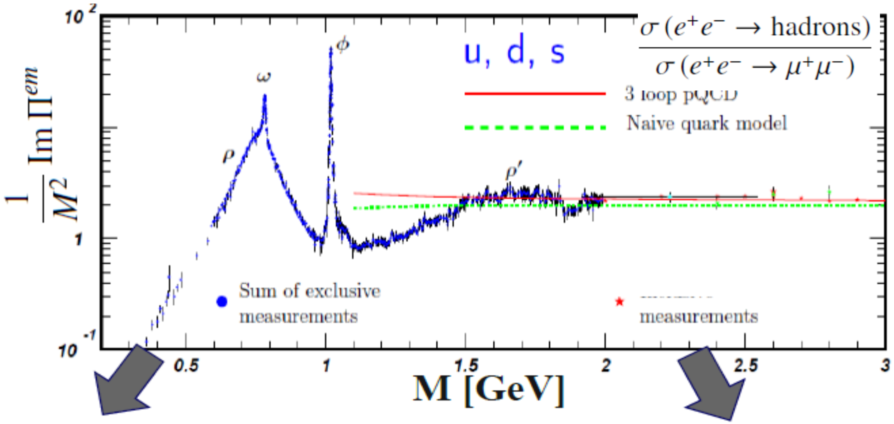


McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

In Vaccuum

$\Im m\Pi^{em}$





Low mass Region –Vector Mesons

• $q\bar{q}$ **Continuum**

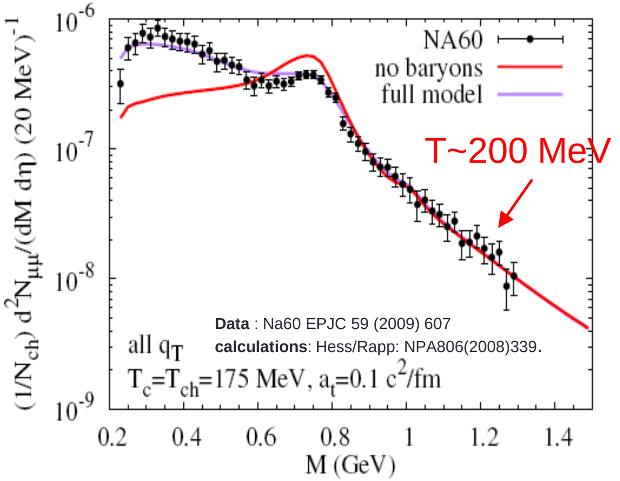
- ❑ Not disturbed by finite state interactions !
- ❑ Thermal distribution *f* ^{BE} (*T*) – *thermometer*

M > 1.5 GeV qq radiation pQCD ($\Im m\Pi_{em}$ *flat*) → *T*

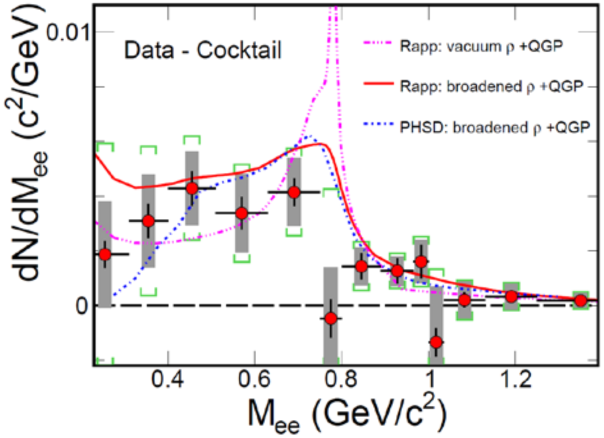
- ❑ $\Im m\,\Pi_{em}$: *M < 1 GeV - in- medium Vector Mesons (* **ρ** *) spectral functions*

Dielepton thermal rates from HIC SIS->RHIC

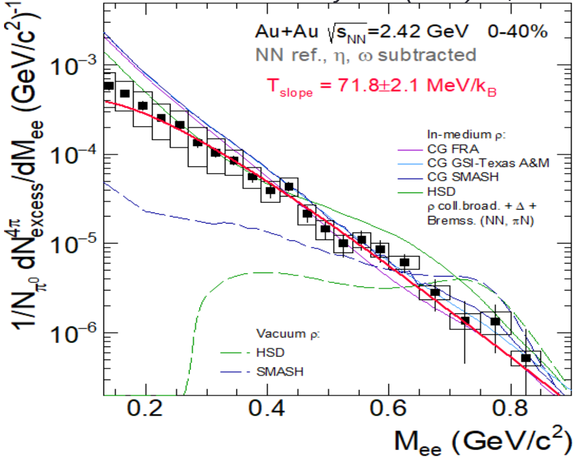
Na60 @ SPS In+In (μ+μ-) √s=17.3 GeV



STAR √s=200 GeV PRC92 (2015)



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



- Low Mass dileptons: dominated by thermal radiation from ρ

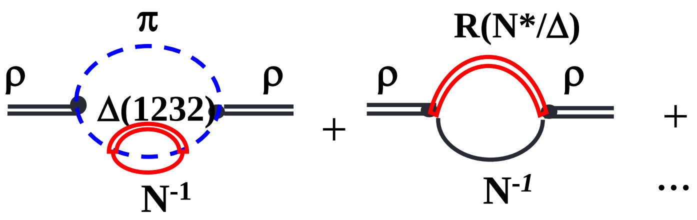
„Melting" of ρ due to **baryon-ρ interactions**

- Na60: T ~ 200 MeV - <T> of the early phase
- HADES T~ 70 MeV „hot baryonic matter"
- LHC : important part of Physics in ALICE (Run3 and beyond)

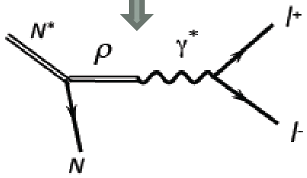
In medium ρ spectral function

$$A_\rho(M) = -\frac{2 Im\Sigma_\rho(M)}{[M^2 - m_\rho^2 - \mathrm{Re}\Sigma_\rho(M)]^2 + [Im\Sigma_\rho(M)]^2}$$

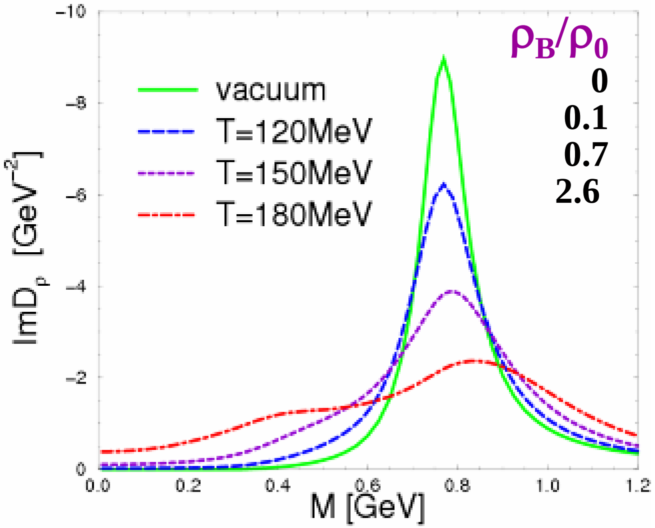
In Medium:



dominant role of ρ - R couplings –
Vector Meson Dominance
R → **Ne+e- (Dalitz decays)**



Rapp, Wambach, Adv. Nucl. Phys. A25 (2000)1



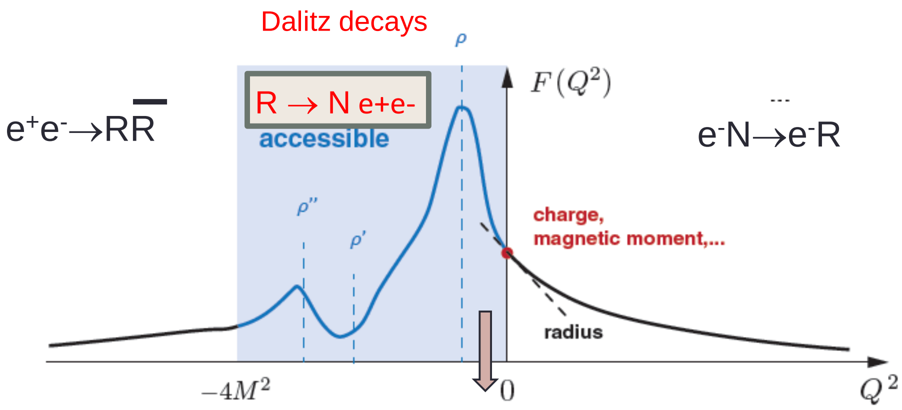
- connection to Chiral sym. restoration → ρ(760)/a_1(1260) become degenerate at T ~ T_c , μ_b =0

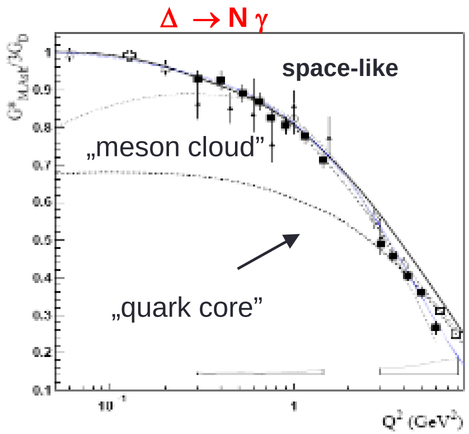
Weinberg QCD sum rules

$$\int ds\,(\rho_V - \rho_A) = -m_q\langle\bar{q}q\rangle$$

Hohler and Rapp Phys.Lett. B731 (2014)

Baryon electromagnetic transitions





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

- Dalitz decays : transition Form Factors (timelike)
  (complementary to spacelike region)

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

„QED”

Effective form-factor

Transitions
of point-like
particles

Main players for SIS/FAIR:
Δ(1232), N*(1520), Δ(1600-1700),..

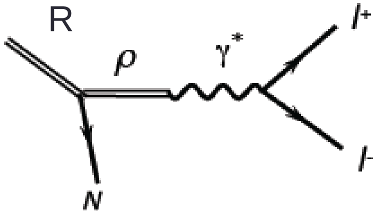
models:

M. I. Krivoruchenko, et. al. An. Phys. 296, 299 (2002)
Q. Wan and F. Iachello, Int. J. Mod. Phys. A 20 (2005) 1846.
G. Ramalho and M.T. Peña, PRD 80 (2009) 013008
M. Zetenyi, Gy. Wolf, Heavy Ion Phys. 17, 27 (2003).

pp $\to$ Rp $\to$pp$\gamma^*(e^+e^-)$ and

$\pi^- p \to R \to n\gamma*(e^+e^-)$

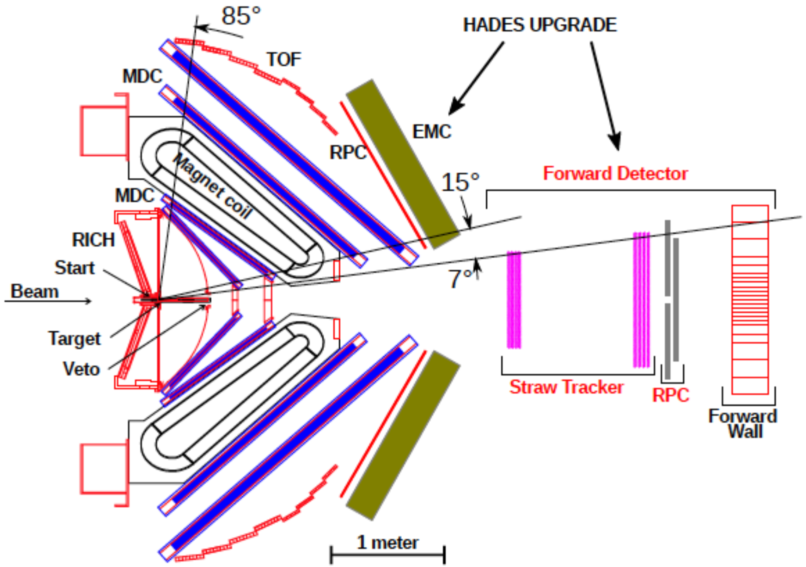
(exclusive channels)

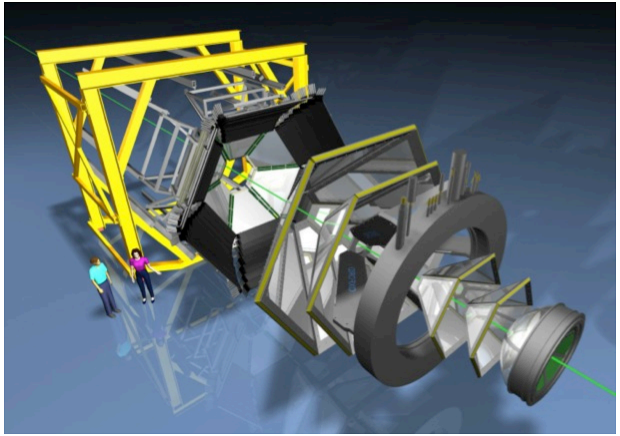


HADES

- ✓ Spectrometer with $\Delta M/M$ - 2% at ρ/ω @ GSI/FAIR
- ✓ electrons : RICH (hadron blind)
- ✓ hadrons: TOF & dE/dx vs p
- ✓ 2004-2014: HI (A+A $\sqrt{s}$~2.4-2.6 GeV)

p+p, d+p, p+A $\sqrt{s}$ =2.4-3.0 GeV π+p $\sqrt{s}$= 1.5 GeV





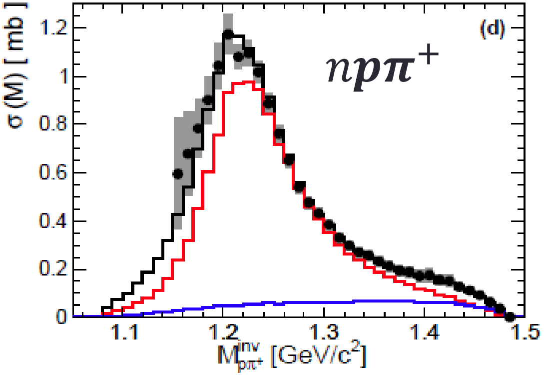
Upgrade 2018/2019

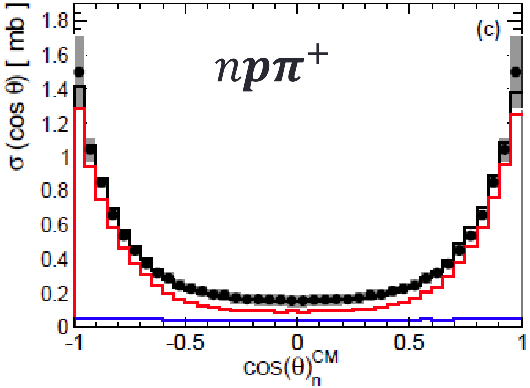
- New RICH photon det (HADES/CBM)
- Forward tracking straws +RPC – Λ/Ξ reconstruction in pp/pA (HADES/PANDA)
- Elec. Calorimiter (lead glass)- neutral mesons
- Planned: 200 kHz DAQ , **10 × count rate increase**

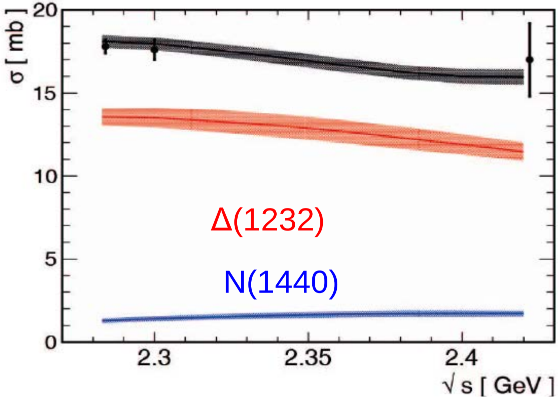
Δ (pπ⁺, pπ⁰) excitation in pp@ √s= 2.42 GeV

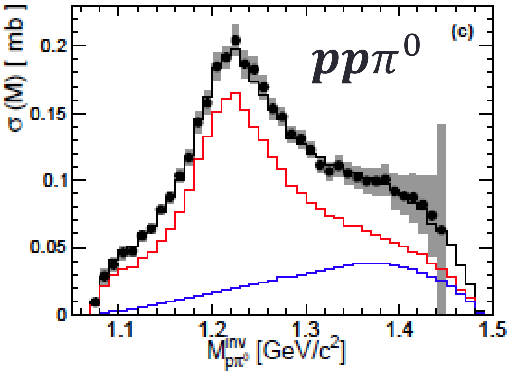
13 PNPI + 2 HADES data sets

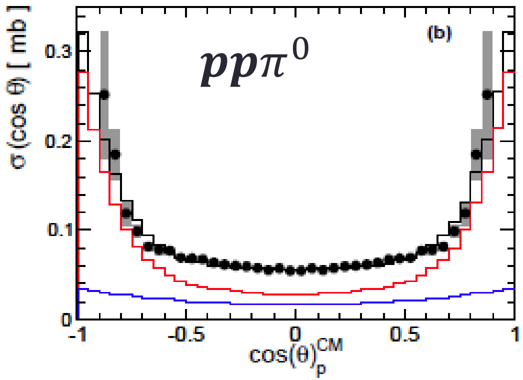
BnGa PWA solutions: resonances: Δ(1232) and N(1440)

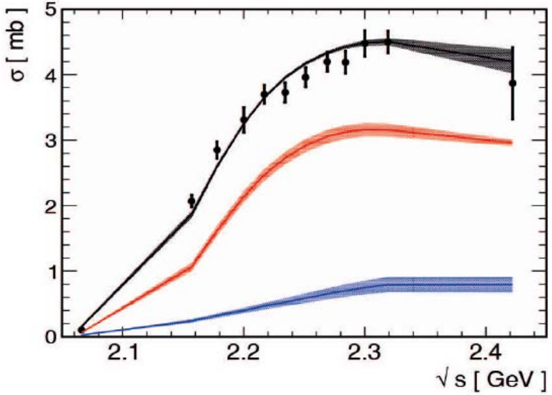










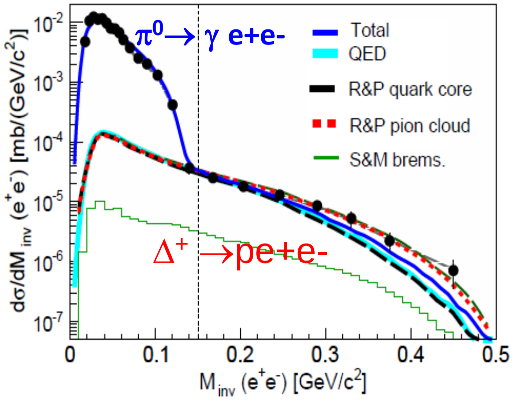


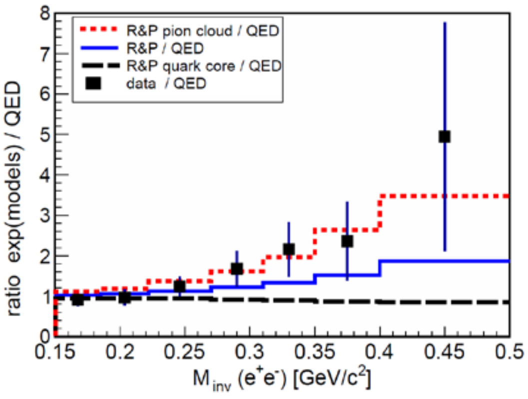
HADES :
Eur. Phys. J. A51 (2015) 137

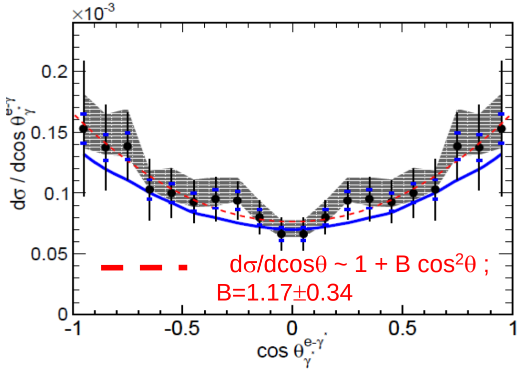
pp → p(Δ→pe⁺e⁻) Δ Dalitz decay

HADES Phys. Rev. C95 (2017) no.6, 065205)

$M_{e+e-} > M_\pi$





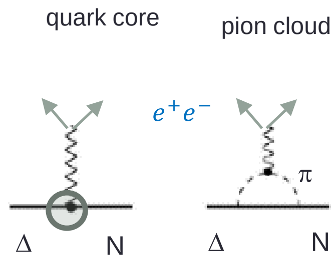


Lepton distribution in helicity frame

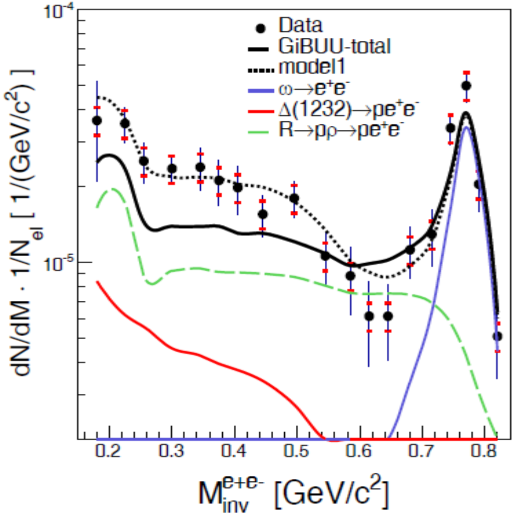
- ❑ **BR (Δ→pe+e-)= 4.19 10^{-5} ± 0.62 (sys) ± 0.32(stat)**
  (First measurement : PDG entry)

- ❑ Lepton angular distributions confirm dominance of G_M
  (transverse polarized γ* ->B=1)

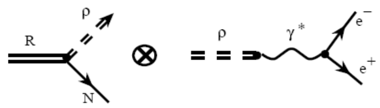
- ❑ Good agreement with 2 component model of TFF Ramahlo & Pehna (R &P) -> Slight rise v.s Mass due to VM(ρ) - pion cloud effect
  (constraints from spacelike region !)



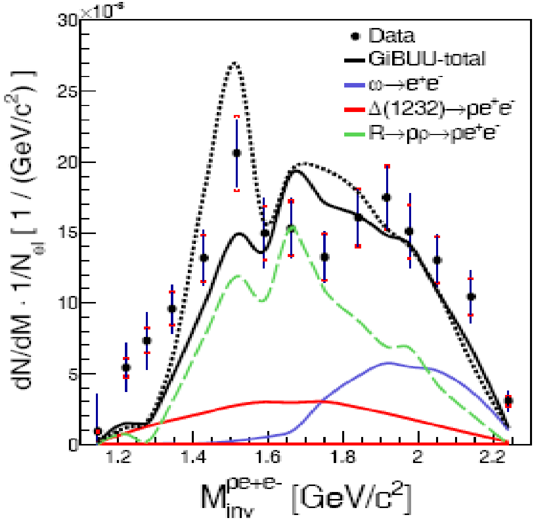
Higher mass resonances: pp→ppe+e- √s=3.1 GeV



Resonance model + „strict” VDM



$$\Gamma_{VDM}(M) = \frac{M_\rho}{M^3} \bullet \mathrm{BR}(M = M_\rho)$$



- Good description of one pion production by „HADES resonance model” $\rightarrow N^*, \Delta$ **contributions**
- **Comparison with VMD : works well .. but with lower BR for R→ Nρ than PDG** (upper limits from Bn-Ga)

2020 – no data on BR in PDG any more

pion beam !

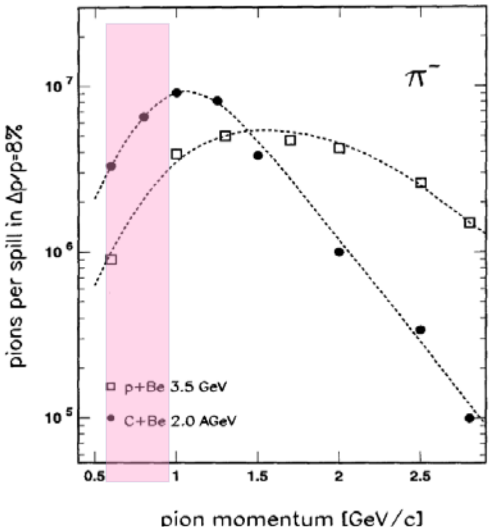
Resonance -> Nρ Branching Ratios

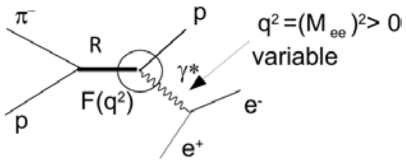
Contr. to e+e-	Resonances	GiBUU	UrQMD	KSU	BG	CLAS
38%	$N(1520)$	21	15	20.9(7)	10(3)	13(4)
15%	$\Delta(1620)$	29	5	26(2)	12(9)	16
22%	$N(1720)$	87	73	1.4(5)	10(13)	–
7%	$\Delta(1905)$	87	80	< 14	42(8)	–

PDG @ 2015

Pion Beam @ GSI

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

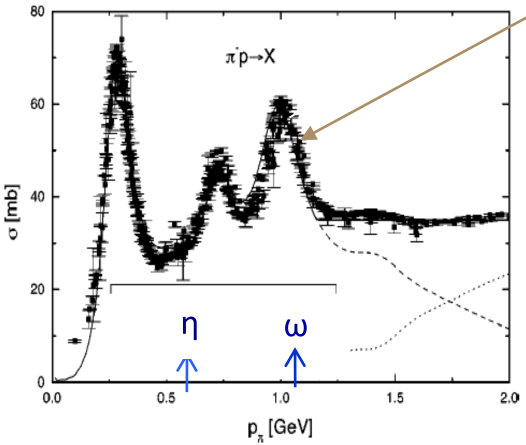


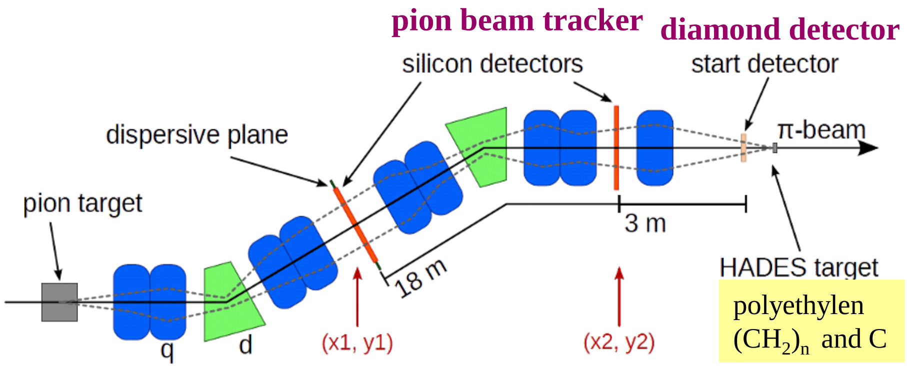


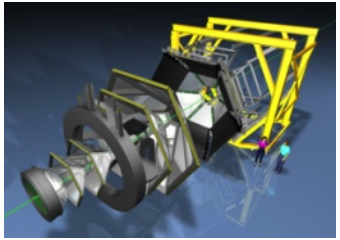
- reaction **N+Be**, 6×10^{10} N_2 ions/spill (4s)
- secondary π^- with **I ~ 2-3 10^5/s**
- pion momentum Δp/p =2.2% (σ)
- 50% acceptance of pion beam line

First run:

- **√s =1.46-1.55 GeV (4 points)**
- **PE $(CH_2)_n$** and **C** targets : 2-pion and e+e- production

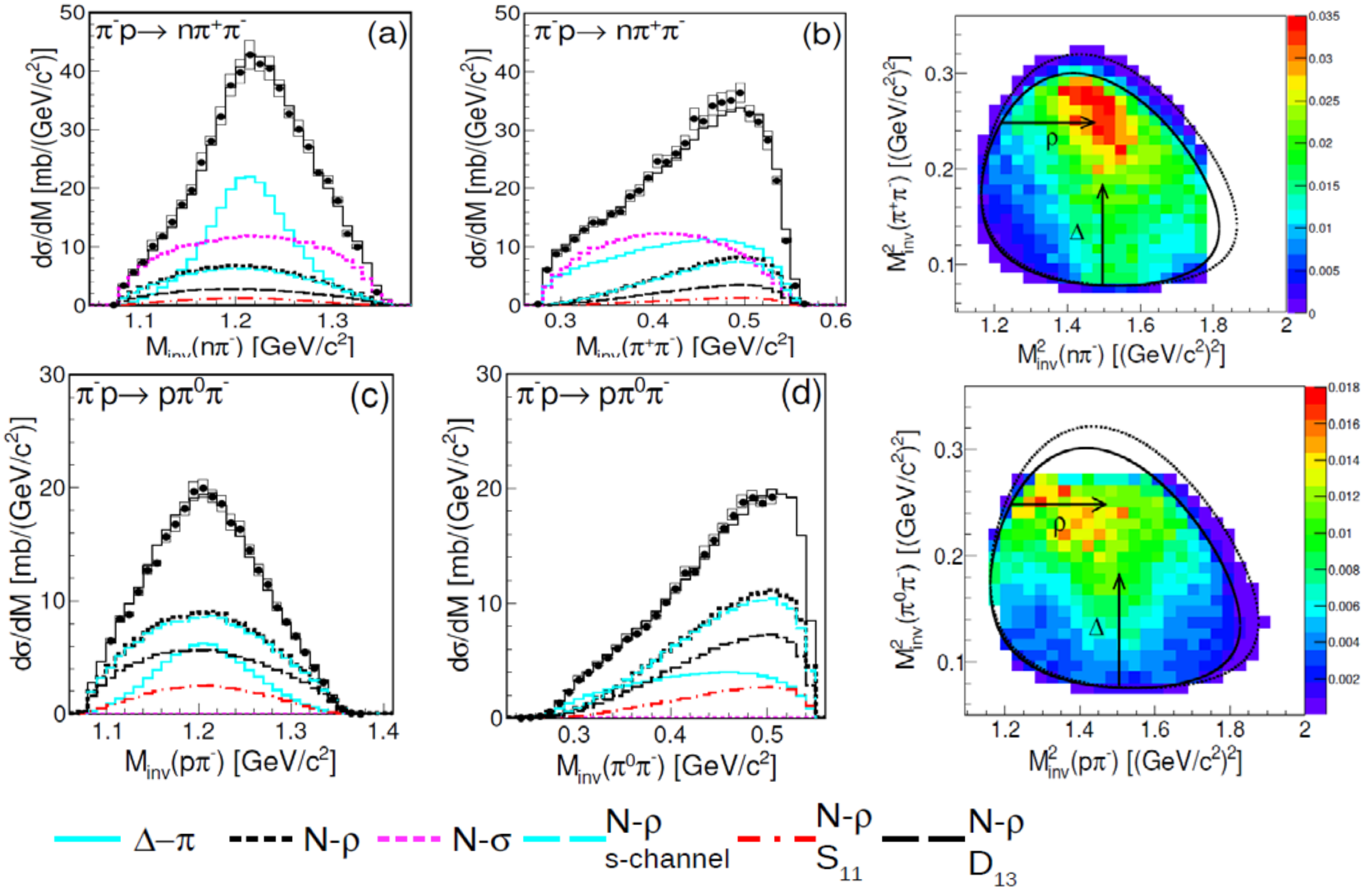






2 pion production: PWA (Bn-Ga) decomposition $\sqrt{s}$=1.49 GeV

„subthreshold" – no ρ peak in $\pi^+ \pi^{-,0}$ mass distributions



$n\pi^+\pi^-$

- **Δ-π dominant,**
- **significant N-σ**
- **N-ρ** s-channels I=1/2 (**D13**)

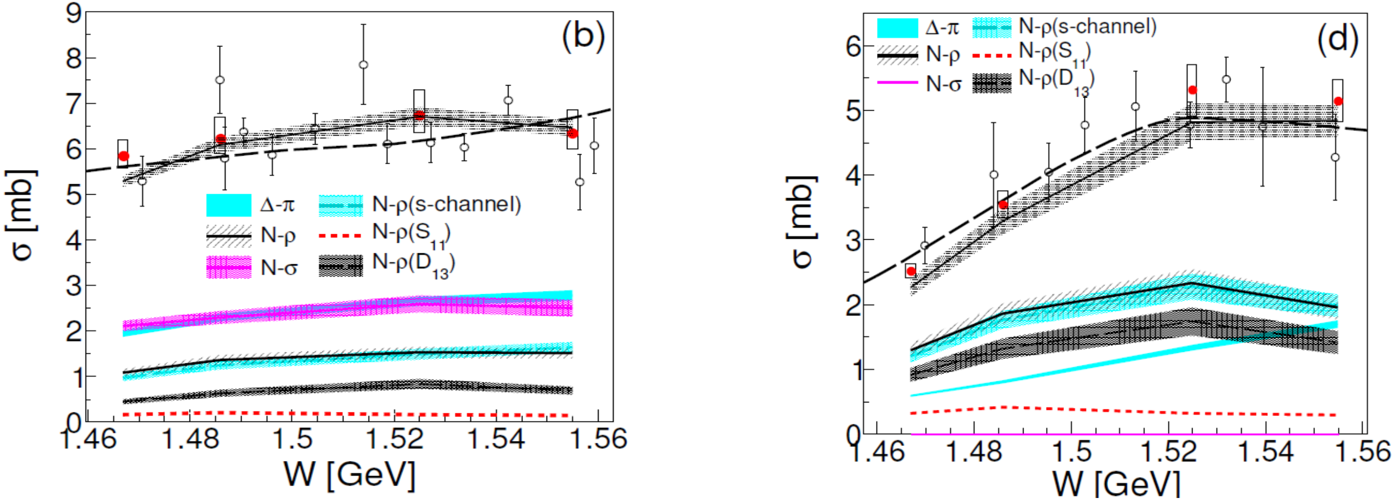
$p\pi^-\pi^0$

- **N-ρ** dominant (s-channels, **D13**)
- **Δ-π** smaller,
- **no N-σ**

HADES:PRC . *C102 (2020) 024001*

Total Cross Sections

$n\pi^+\pi^-$ $p\pi^-\pi^0$



○ world data ● HADES data — — PWA Refs. [8-9] PWA Bn-Ga

[8-9]

D. M. Manley *et al*. *Phys. Rev. D 30 (1984) 904*

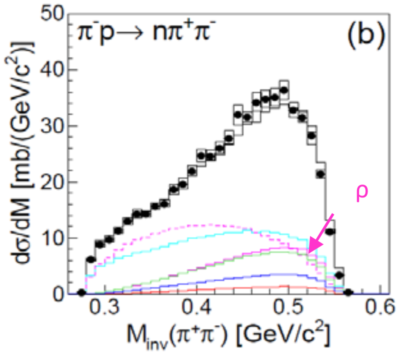
D. M. Manley and E.M. Saleski, Phys. Rev. D 45,

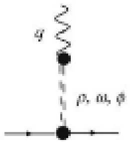
- ❑ consistent descripton of HADES and world data
- ❑ **N (1520) →N ρ BR =12.2 ± 2 % N(1535)** →N ρ **BR=3.2 ± 0.6 %**

+ BR for **Δπ** and **Nσ**

(8 new entries in PDG)

Test of Vector Dominance Model





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

Direct test of VDM models based on known ρ contribution

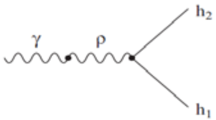
$$\left(\frac{d\sigma_{ee}}{dM_{ee}}\right)_{M_{ee}=M} = \left(\frac{d\sigma_{\pi\pi}}{dM_{\pi\pi}}\right)_{M_{\pi\pi}=M} \frac{\Gamma_{\rho\to e^+e^-}(M)}{\Gamma_{\rho\to\pi^+\pi^-}(M)}$$

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



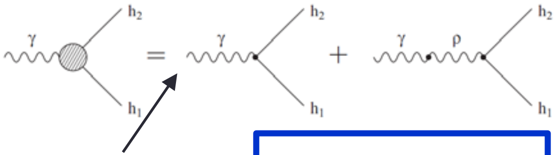
$$\Gamma_\rho^{VDM2} = \left(\frac{M_0}{M}\right)^3 \Gamma_\rho^0$$

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

- ρ contr. vanishes at $m_\gamma^*=0$,

γN and ρN couplings fixed independently

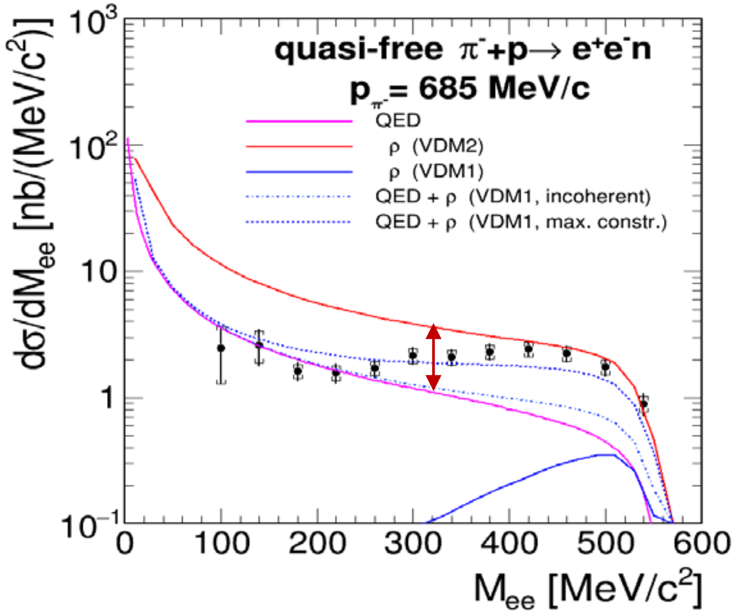
- Phase between γ and ρ contributions to be fixed by data



γ or point-like contribution

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

Data comparison with VDM2/VDM1 models



- **QED reference constrainted by** $\pi^- p \rightarrow n\gamma$ data and available Bn-Ga solutions

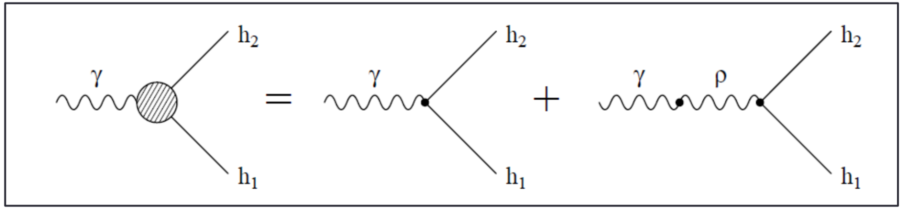
- **Model independent results:**

  - Strong excess with respect to the point-like contribution-QED reference (up to a factor 5)

- **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**

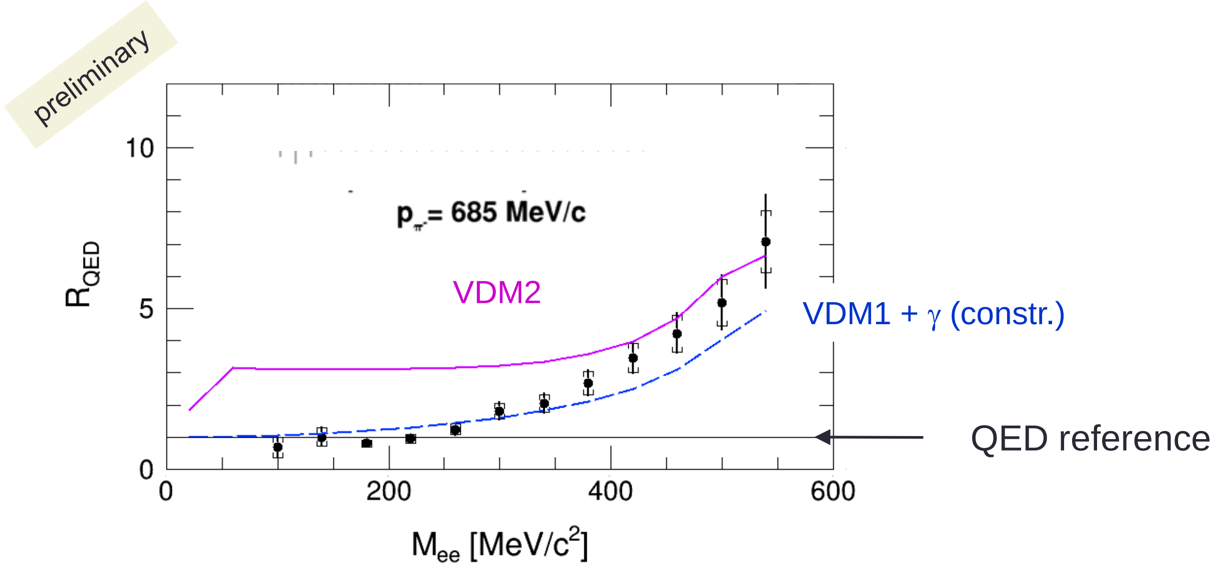


Effective Form Factor

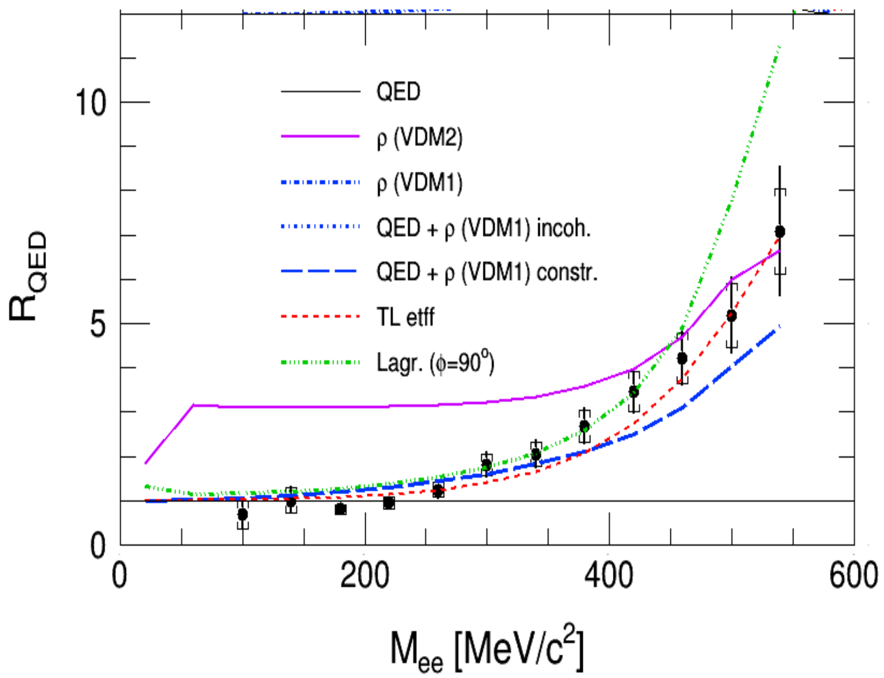
Effects of baryon time-like electromagnetic structure quantified by

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

« effective form factor » with strong contribution of N1520



Comparison to models (on-going)



Comparison with FF model:

G. Ramalho and M. T. Pena,

Phys. Rev. D95, 014003 (2017)

- Dominant pion cloud contribution:

-> 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, a coherent superposition of photon and ρ

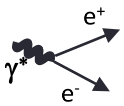
  (shown with phase ϕ=90)

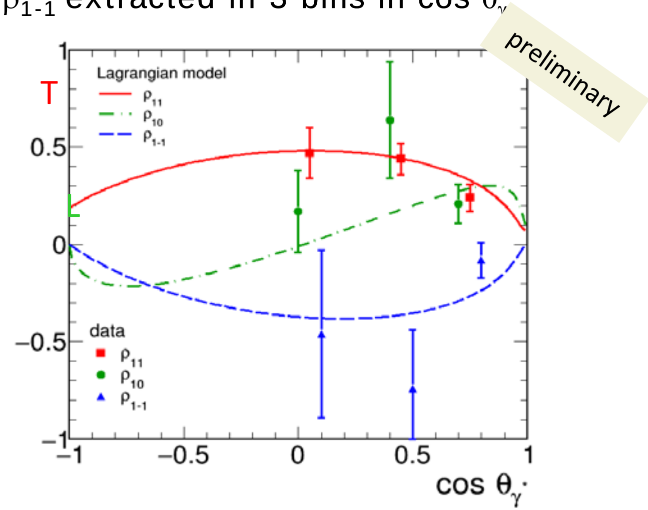
- very promising, but needs to be confronted to ππ spectrum

spin density matrix elements from e^+/e^- data

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

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

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

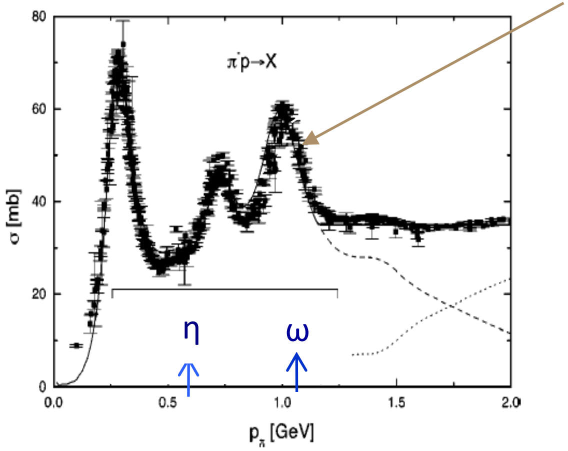
J=1/2 $$\lambda = \frac{\left|G^{\pm}_{E/M}\right|^2 - |G^{\pm}_C|^2}{\left|G^{\pm}_{E/M}\right|^2 + |G^{\pm}_C|^2}$$

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

- Spin >1/2 contributions : consistent with dominance of N1520
- Good agreement with Lagrangian model (predictions!)
- **More precise data needed**

Outlook : experiments with pion beam

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



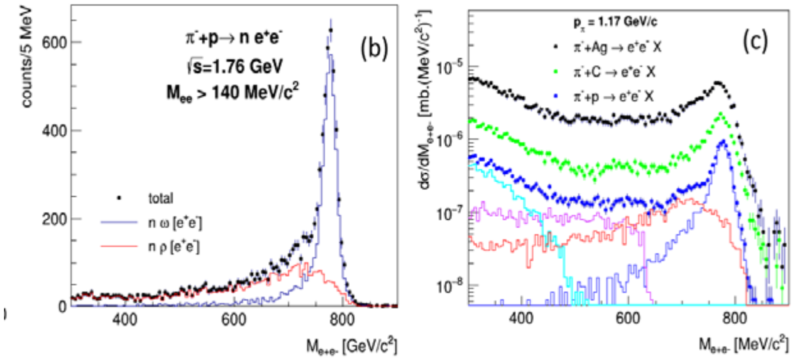
1. Baryon meson couplings $\pi\pi N$, ωn, ηn , $K^0\Lambda$, $K\Sigma$,….

→ Inputs for Partial Wave Analysis

→ Many baryon structure issues: confirmation of N'(1720), Cascade decays (R→R'π→ Nπ π), ηn couplings

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

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



3. Vector meson in cold matter

$\pi^- A \to e^+ e X$

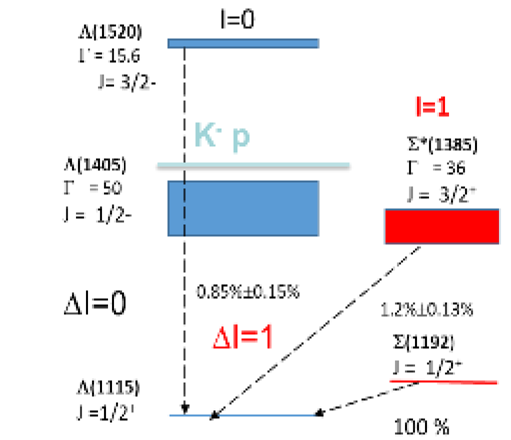
- Studies of low momentum ρ and ω propagation in nuclear matter

Outlook: p+p @ 4.5 GeV

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

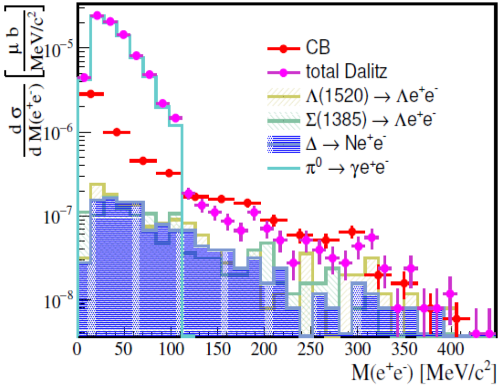
HADES: Eur. Phys. J. A57, 138 (2021) ***feasibility study***

- Hyperon Dalitz decays: $pp \rightarrow pK^{+}\Lambda(1520)$ $[\Lambda e^{+}e^{-}]$ $[\Lambda\gamma]$
  $pp \rightarrow pK^{+}\Sigma(1385)$ $[\Lambda e^{+}e^{-}]$ $[\Lambda\gamma]$
- Ξ, $\Lambda(1405)$, $\Lambda(1520)$ production and decays
- Λ–Λ correlations
- dilepton production (higher mass baryopn resonance decays, pair Production above ϕ, mass,..)

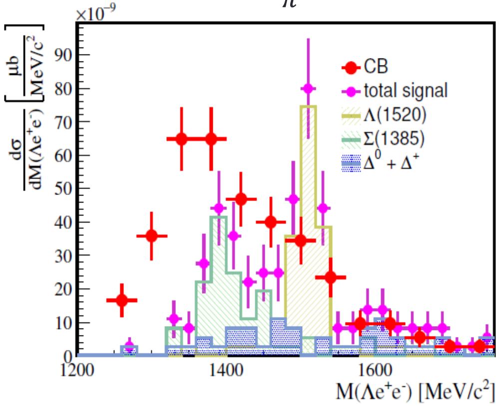


CLAS PRD83 (2011) 072004, PRC71(2005) 054609

Projections for Hyperon Dalitz decays



$M > M_\pi$



Summary

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

$\rightarrow$ improved knowledge of hadronic couplings

$\rightarrow$ 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

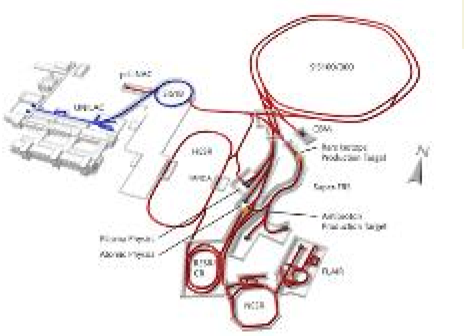
$\rightarrow$ Basic inputs for medium effects of ρ meson calculations

✓ 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

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

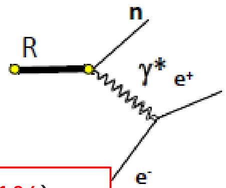
✓ After 2027: HADES experiments in new location (CBM cave) at FAIR

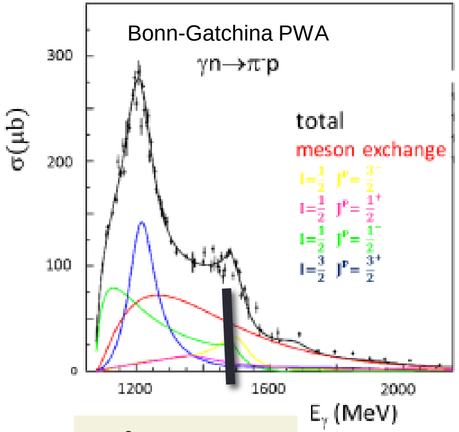


Back-up

QED reference

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





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

- Generalization to finite q^2 (QED)

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

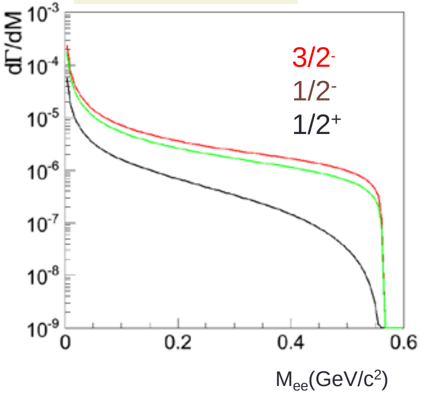
→ "point-like" description of $R \rightarrow Ne^+e^-$:

invariant mass distribution depends on J^P

$$\sigma(\pi^- p \rightarrow n e^+ e^-) \sim 1.35\ \alpha\ \sigma(\pi^- p \rightarrow n\gamma)$$

« γ « or « QED « reference

$N^{*0} \rightarrow n e^+ e^-$



PWA results–8 newPDG entries!

PDG Verification

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

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

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

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

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

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

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

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

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

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

ρN coupling not present in PDG since 2016

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

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

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

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

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

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