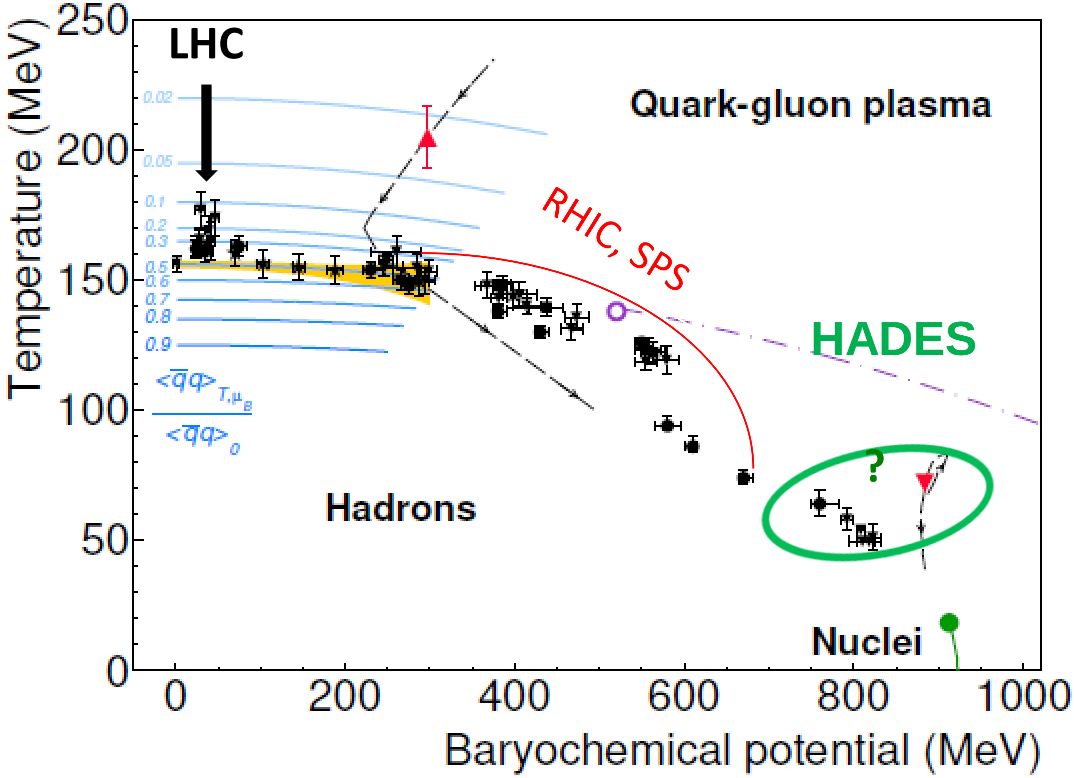
Transition Form Factors from HADES

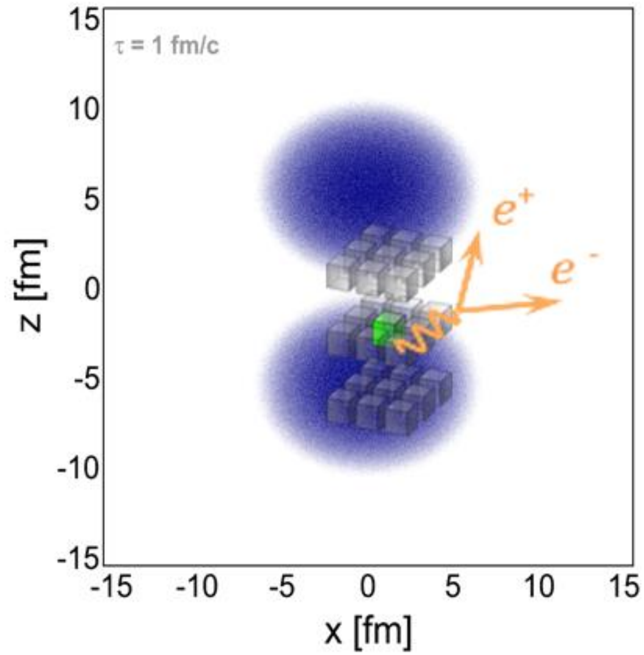
17 May 2021, Kraków

Witold Przygoda
HADES Collaboration

MESON 2021

QCD: phase diagram



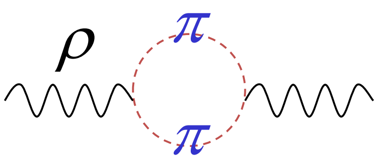


- HADES: primary goal: first measurement of Low Mass dileptons (e^+e^-) at high μ_B
- Complementary to studies with URHIC (LHC, RHIC, SPS)
- In-medium Vector Meson (ρ) spectral function
- Connection to Chiral symmetry restoration

ρ spectral function in-medium

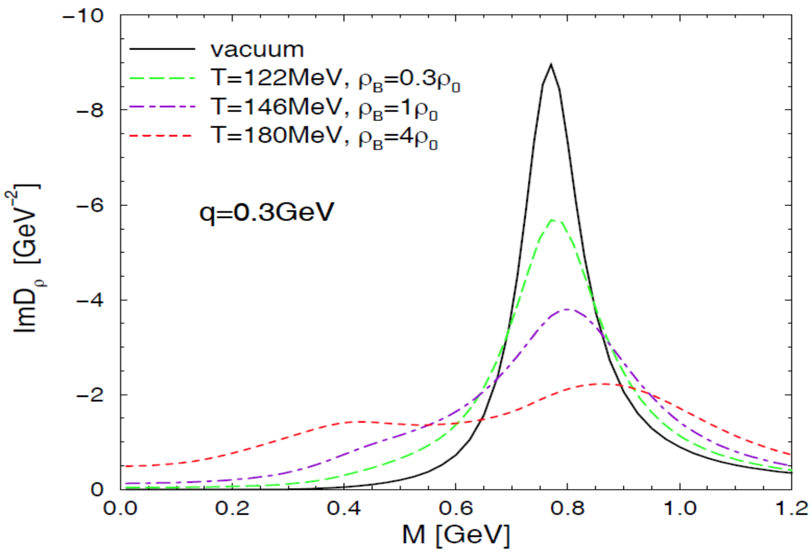
baryons are the main players

« vacuum »



$$\Sigma_\rho(M) = -i m_\rho \Gamma_{\pi\pi}(m)$$

$$m_\rho = 0.77 GeV$$



Explanation of dilepton spectra (RHIC, SPS, HADES)

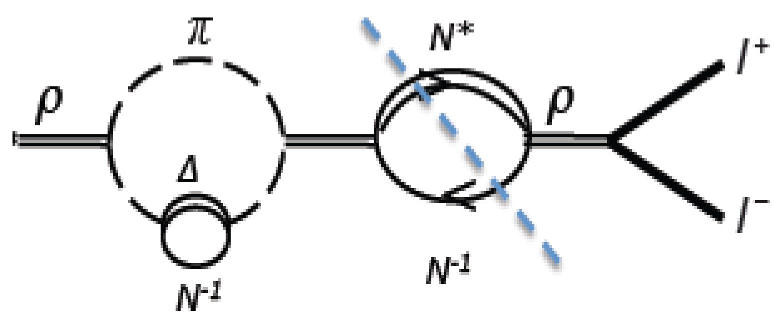
P. Hohler, R. Rapp
Phys. Lett. B **731** (2014) 103

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

R. Rapp, J. Wambach
Adv. Nucl. Phys. A**25** (2000) 1

« in-medium broadening »

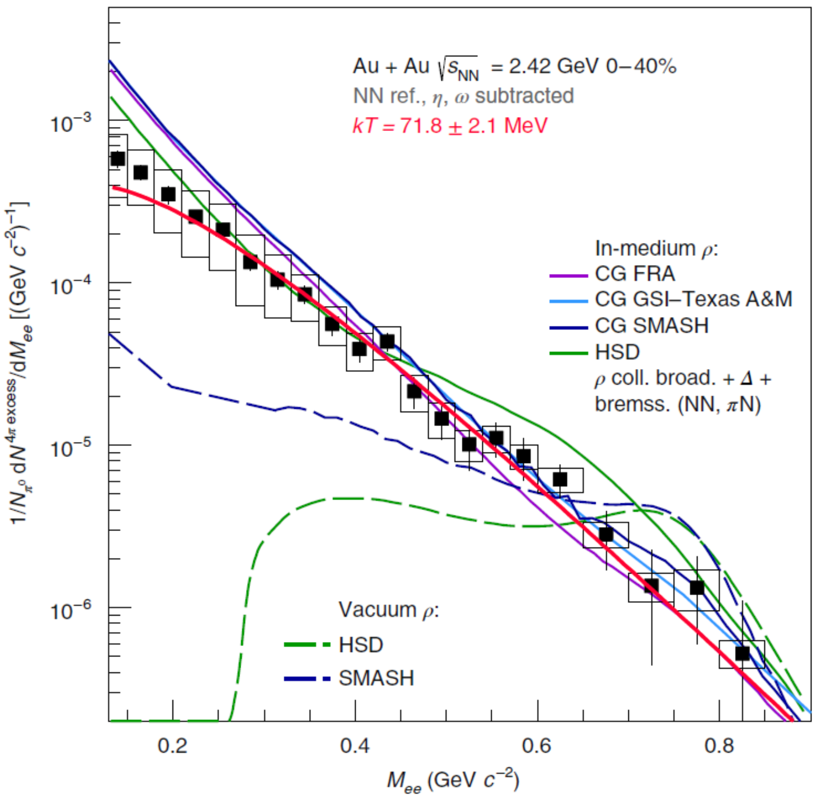
in-medium spectral function depends on ρNN* coupling
main players:
N(1520), Δ(1620) , N(1720), ….



Coupling of ρ to baryonic resonances can be **directly** studied in **NN** and **πN collisions** at 1-2 GeV via $N^*(\Delta) \rightarrow Ne^+e^-$ decays

HADES Au+Au $\sqrt{s}$=2.4 GeV

Excess yield fully corrected for acceptance



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

- Dielepton yield dominated by contribution from in medium ρ

Dileptons as thermometer

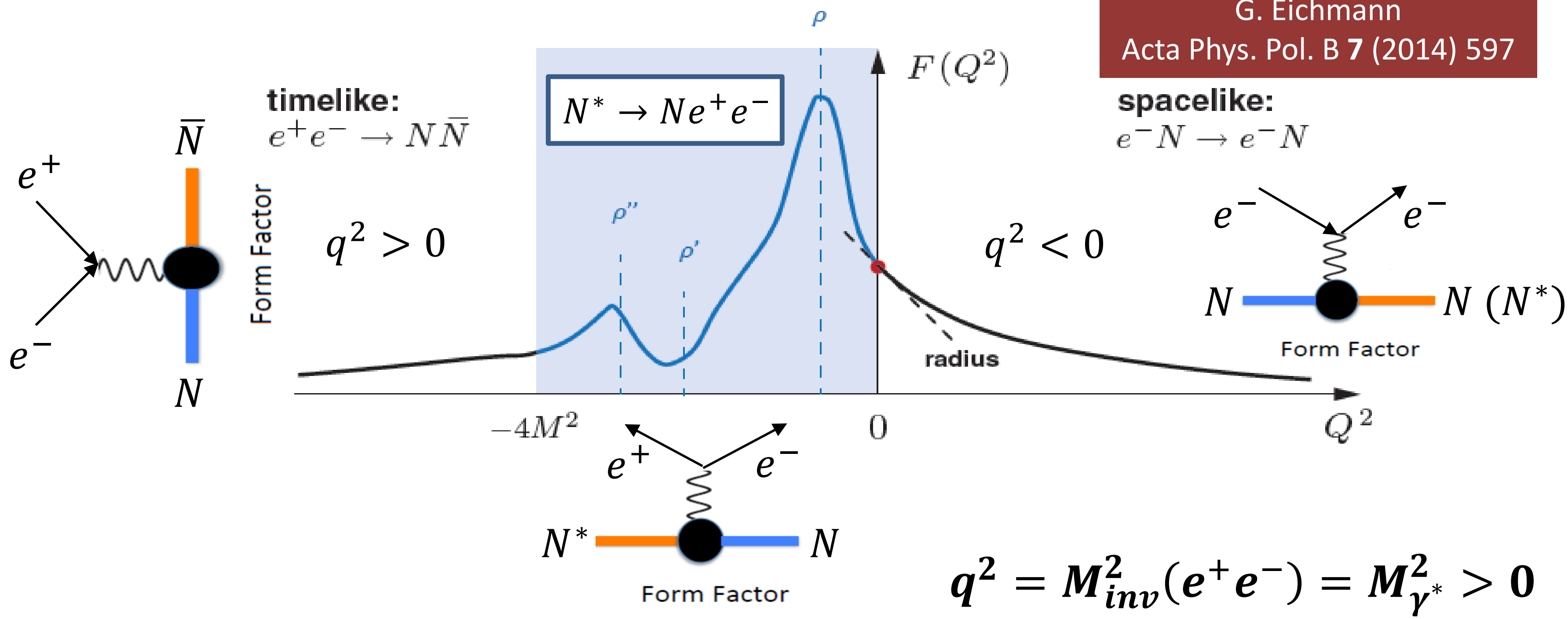
- Mass spectrum falls exponentially → "Planck-like"
- Fit $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$ in range M=0.2-0.8 GeV/c^2
- $\langle T \rangle_{\text{emitting source}}$ = 72 ± 2 MeV/k_B

- Strong melting of ρ meson
- In agreement with microscopic model of Rapp & Wambach (interactions with baryons)
- Same model describes also RHIC(STAR), SPS (CERES, Na60 data)

Robust understanding across QCD phase diagram

Relation to electromagnetic structure of baryons

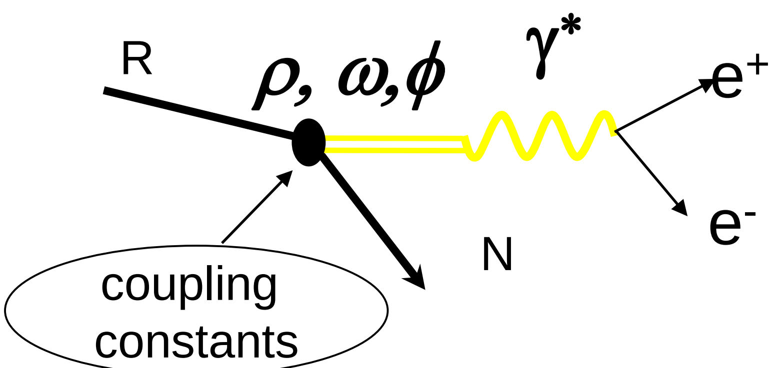
G. Eichmann
Acta Phys. Pol. B **7** (2014) 597

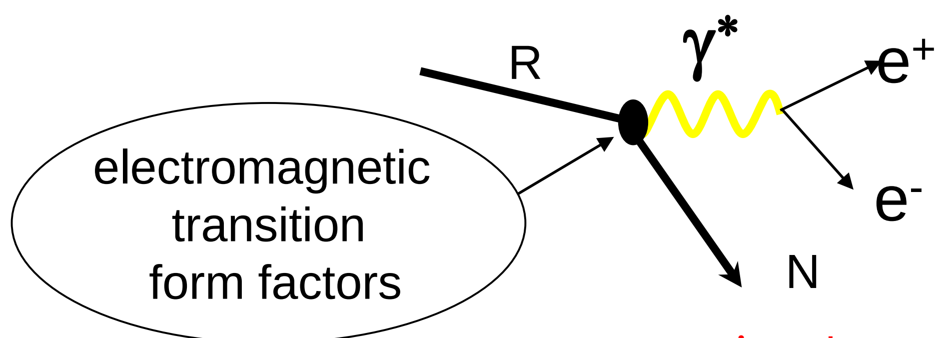


$$q^2 = M^2_{inv}(e^+e^-) = M^2_{\gamma^*} > 0$$

« ρ meson production and decay »

« Dalitz decay of baryonic resonances »





uniuqe!

Vector Meson Dominance Model

Resonances: description and Dalitz decays

Resonance description: W - arbitrary resonance mass

relativistic Breit-Wigner distribution $g_R(W) = A \frac{W^2 \Gamma_{tot}(W)}{(W^2 - M_R^2)^2 + W^2 \Gamma_{tot}^2(W)}$

with $\Gamma_{tot}(W) = \Gamma_{\pi N}(W) + \Gamma_{\gamma N}(W) + \boldsymbol{\Gamma_{e^+e^-N}(W)} + \;\ldots$

Dalitz decay requires a model for the form factors in the timelike region

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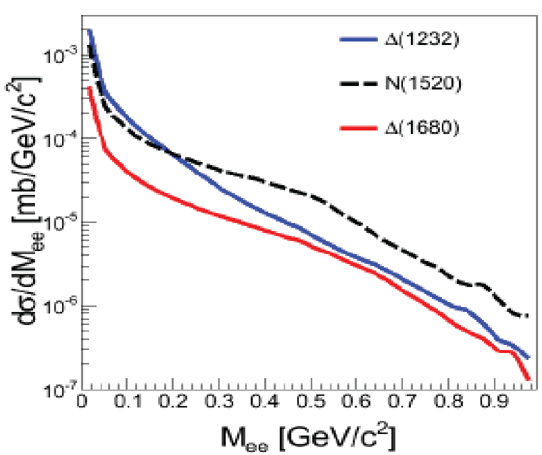
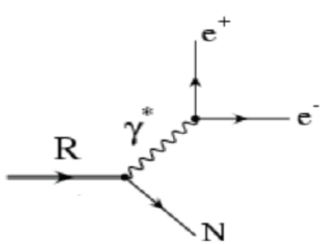
QED point-like $R\gamma^*$ vertex

M. Zetenyi, G. Wolf
Phys. Rev. C **67** (2003) 044002

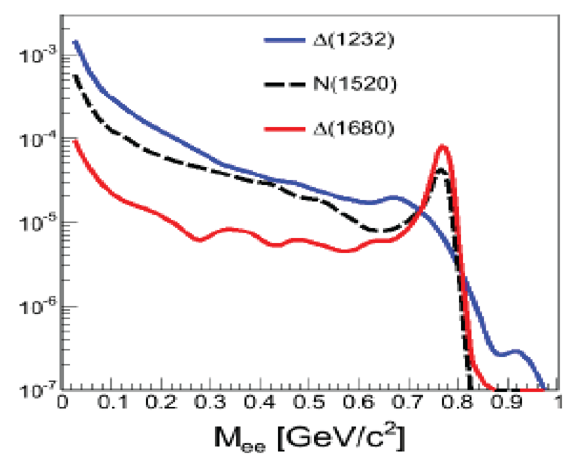
- coupling constants fixed from $R \rightarrow N\gamma$
- strong dependence on spin, parity

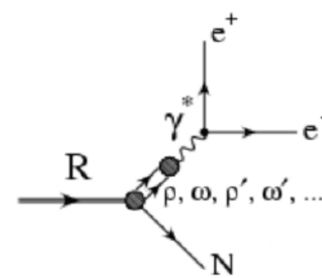




Extended VDM

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



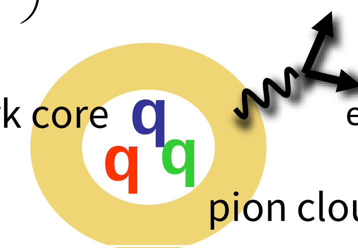


Example: $\Delta \rightarrow Ne^+e^-$

M.I. Krivoruchenko *et al.*
Phys. Rev. D**65** (2002) 017502

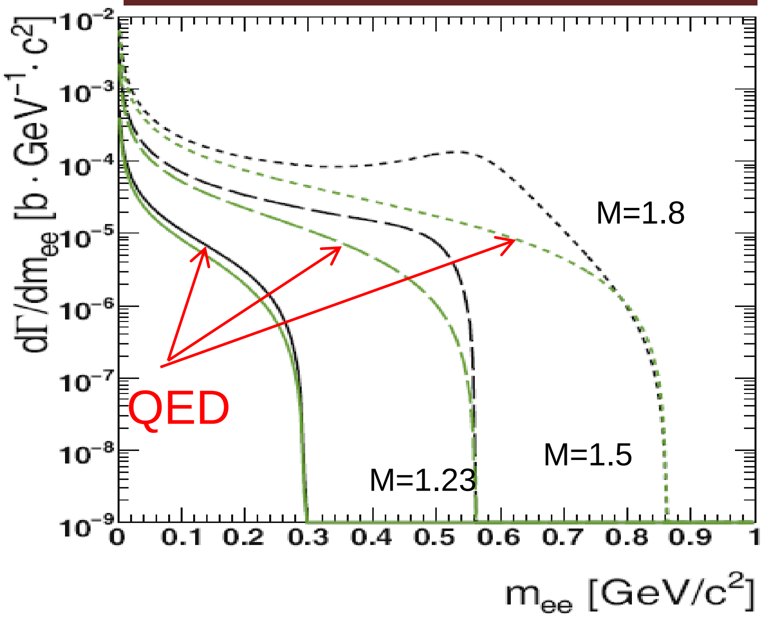
$$\frac{d\Gamma(\Delta \rightarrow Ne^+e^-)}{dq^2} = f\left(m_\Delta, q^2\right)\left(\left|G_M^2(q^2)\right| + 3\left|G_E^2(q^2)\right| + \frac{q^2}{2m_\Delta^2}\left|G_C^2(q^2)\right|\right)$$

Time Like ($q^2 > 0$)
Δ (J=3/2) ->N (J=1/2) γ^* transition:



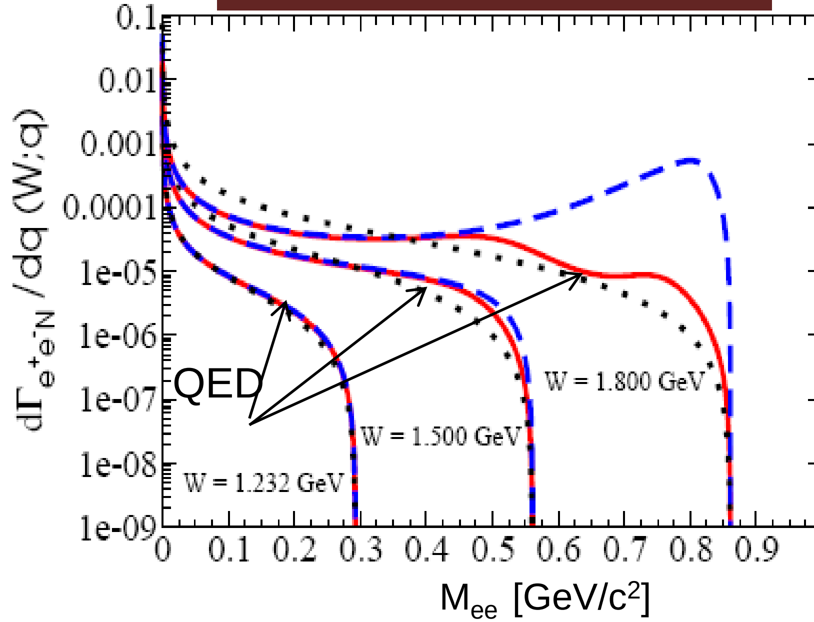
two-component quark model

Q. Wann, F. Iachello
Int. J. Mod. Phys. A**20** (2005) 1846



covariant constituent quark model

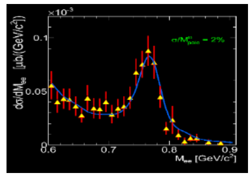
G. Ramalho, M. T. Peña
Phys. Rev. D**85** (2012) 113014



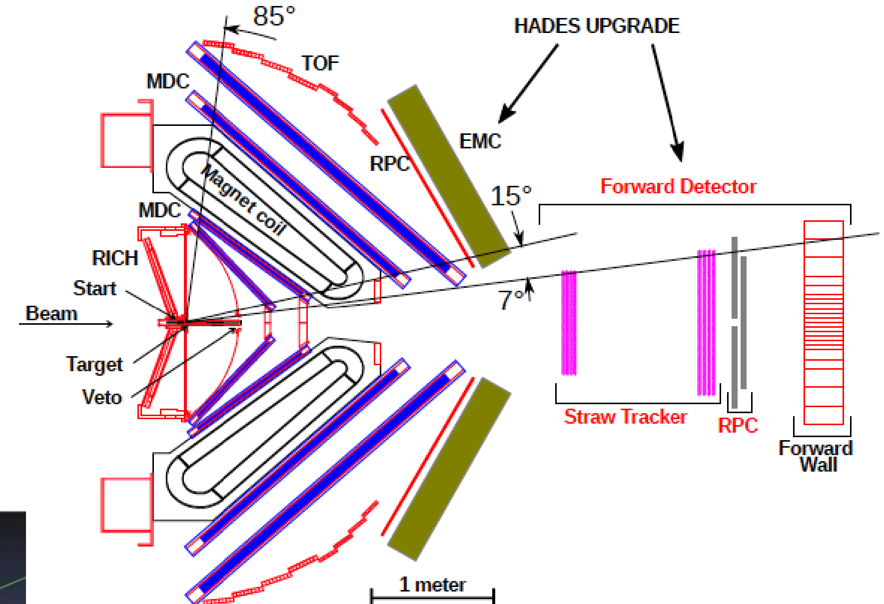
HADES Spectrometer

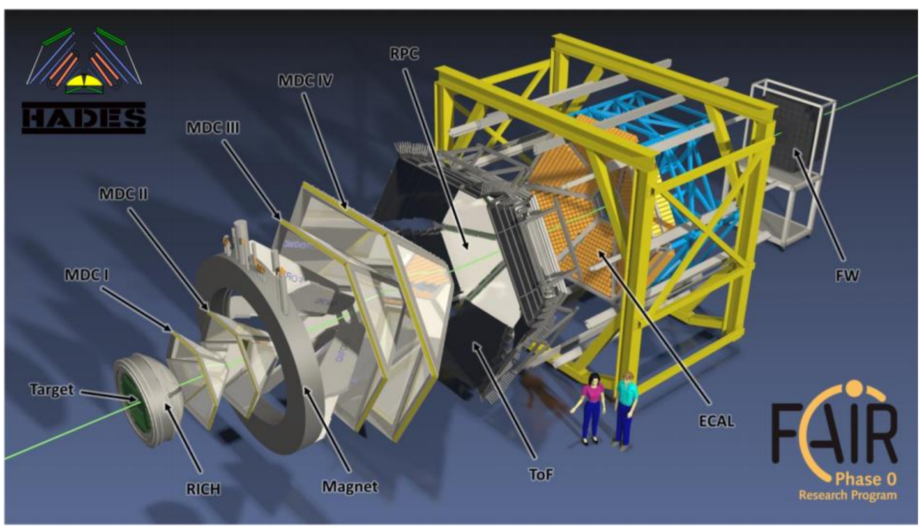
- SIS18 beams: protons (1-4 GeV), nuclei (1-2 AGeV) pions (0.4-2 GeV/c) – secondary beam
- spectrometer with $\Delta M/M$ - 2% at ρ/ω
- **detector for rare probes:**

  dielectrons: e^+, e^-
  strangeness: Λ, $K^{\pm,0}$, Ξ^-, φ



- particle identification π/p/K – dE/dx (MDC) and TOF : σ_{tof} ~80 ps (RPC)
  electrons : RICH (hadron blind), TOF/Pre-Shower
- neutral particles: ECAL





Geometry

- full azimuthal, polar angles 18° - 85°
- e^+e^- pair acceptance ≈ 0.35

HADES experimental program

- Dilepton emission in **dense and hot matter** (A+A reactions: 1-2 AGeV)
  C+C 1 and 2 GeV/nucleon, Ar+KCl 1.75 GeV/nucleon, Au+Au 1.25 GeV/nucleon, Ag+Ag 1.58 GeV/nucleon
- Cold matter at **normal nuclear density**
  p+Nb 3.5 GeV, π-+W/C 1.7 GeV/c

- **Elementary collisions** pp, dp and π-p
  - reference to heavy-ion spectra
  - time-like electromagnetic structure of hadronic transitions

- Simultaneous measurements of hadronic channels
  - inclusive and exclusive meson production 1π, 2π, η, ρ, ω ,…
  - production mechanism
  - baryon spectroscopy (baryonic resonance couplings)

- Partial Wave Analysis: pp$\rightarrow$ppπ 0, pp$\rightarrow$pnπ^+ , π^-p$\rightarrow$n π^+ π^-, π^-p$\rightarrow$p π^0 π^-
- Strangeness program: K^- , K0, ϕ, Σ(1385), Λ(1405), Λp corr.

Challenge for studies of EM baryon tansitions

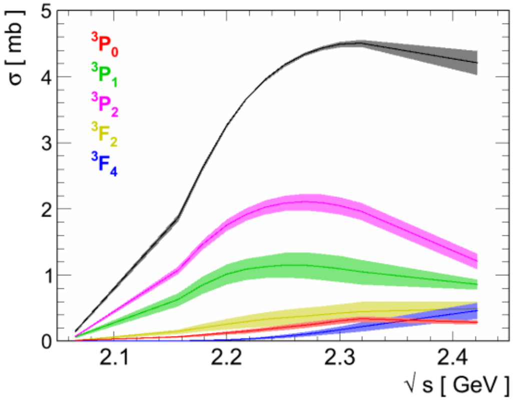
- Identification of resonances
- Production rates of Δ and N* resonances
- Interferences and non-resonant terms…

- ρ-meson coupling to R (resonances)
- Δ and N* electromagnetic transition form factors (in the timelike region)

PWA results: (π^+, π^0) production in pp@1.25 GeV

13 PNPI + 2 HADES data sets

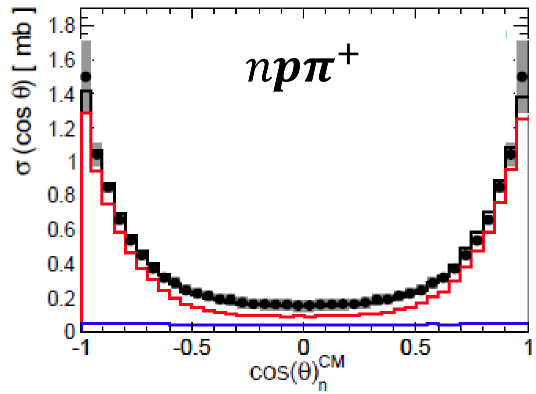
Bonn-Gatchina

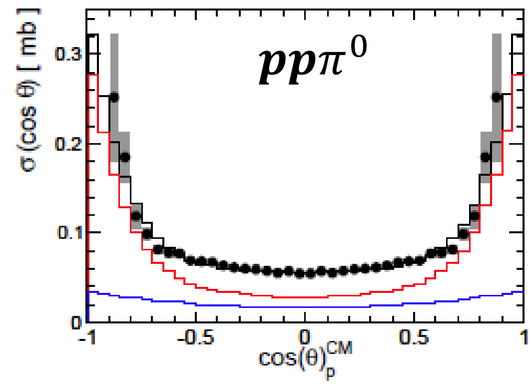


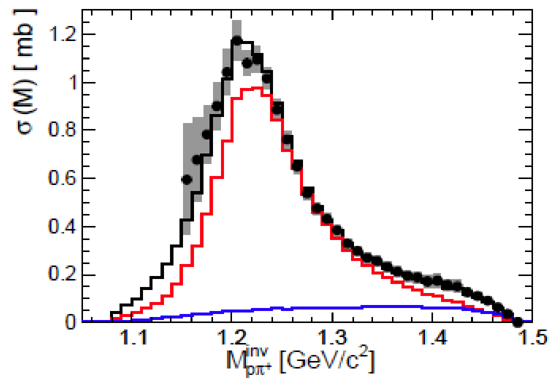
FINAL STATES

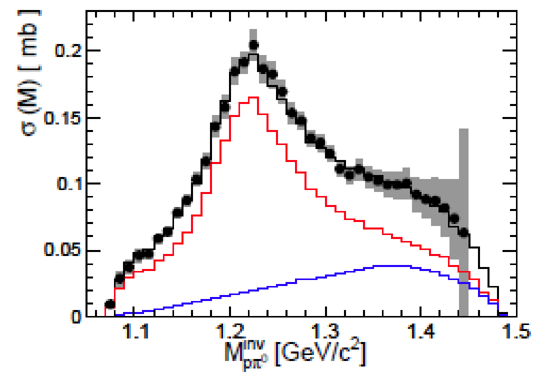
S-, P-, D-waves
in pp or pn-state
P_{33}(1232) and
P_{11}(1440) in πN state

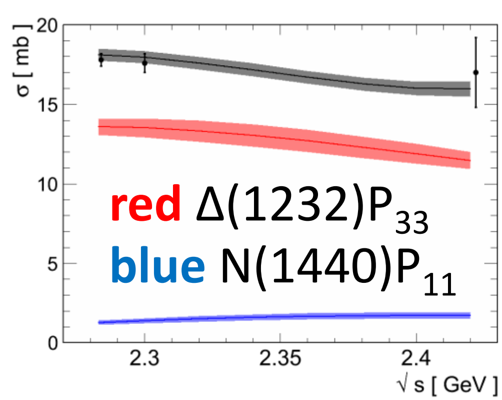
G. Agakishiev *et al.*
Eur. Phys. J. A51 (2015) 137

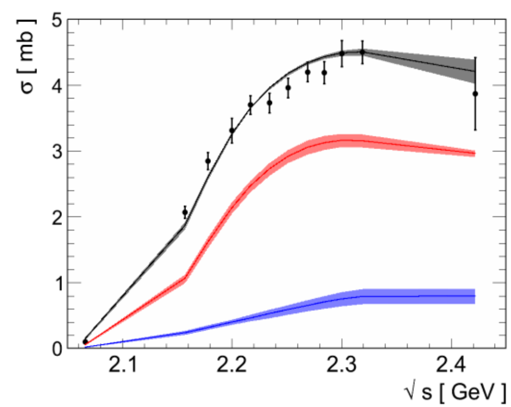




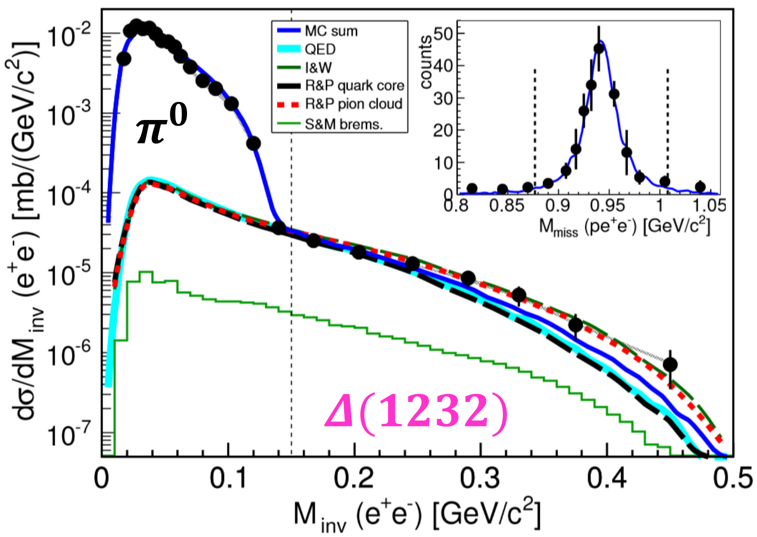


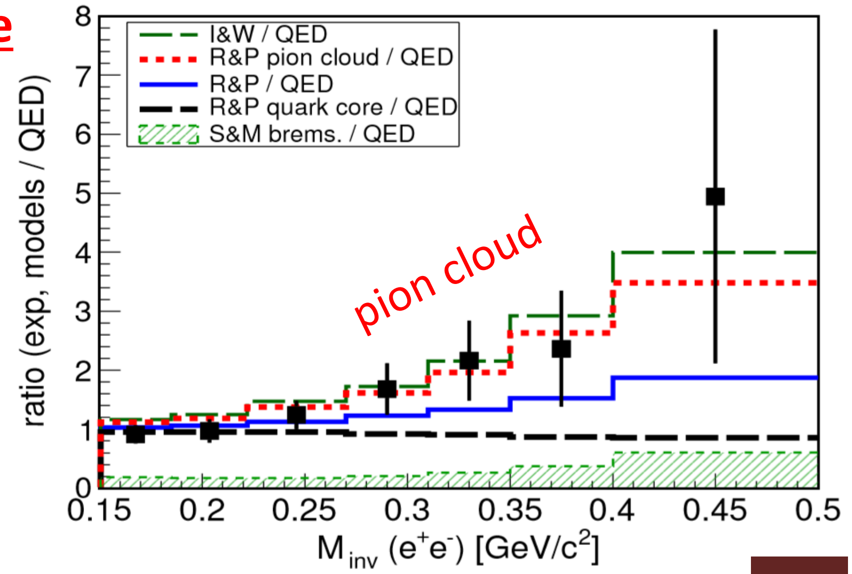






Δ(1232) Dalitz decay measured for the first time

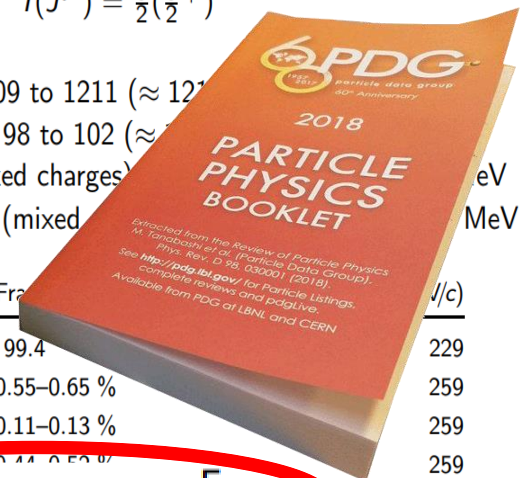




G. Ramalho and M. T. Peña, Phys. Rev. **D93** (2016) 033004

Δ(1232) 3/2+

$I(J^P) = \frac{3}{2}(\frac{3}{2}^+)$

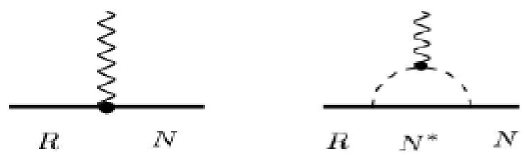


Re(pole position) = 1209 to 1211 (≈ 12
−2Im(pole position) = 98 to 102 (≈
Breit-Wigner mass (mixed charges) ... eV
Breit-Wigner full width (mixed ... MeV

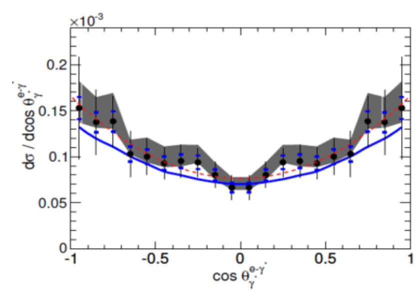
Δ(1232) DECAY MODES	Fr...	.../c)
$N\pi$	99.4	229
$N\gamma$	0.55–0.65 %	259
$N\gamma$, helicity=1/2	0.11–0.13 %	259
$N\gamma$, helicity=3/2	[illegible]	259
pe^+e^-	$(4.2\pm0.7)\times10^{-5}$	259

✓ **Two-component model of eTFF**

Quark core   Pion cloud



Angular distributions important!

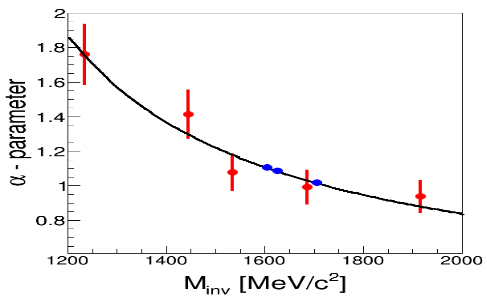


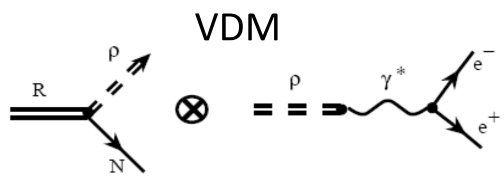
Helicity angles
$\gamma^* \rightarrow e^+e^-$
$d\sigma/d\Omega_e \sim 1 + B\cos^2\alpha$
Fit : B=1.17 ±0.34

Higher resonances | VDM | p+p @ 3.5 GeV

Resonance model: Δ and N* incoherent sum + ang. param.

$$\frac{d\sigma}{dt}(M_R) \propto \frac{A}{t^{\alpha(M)}}$$





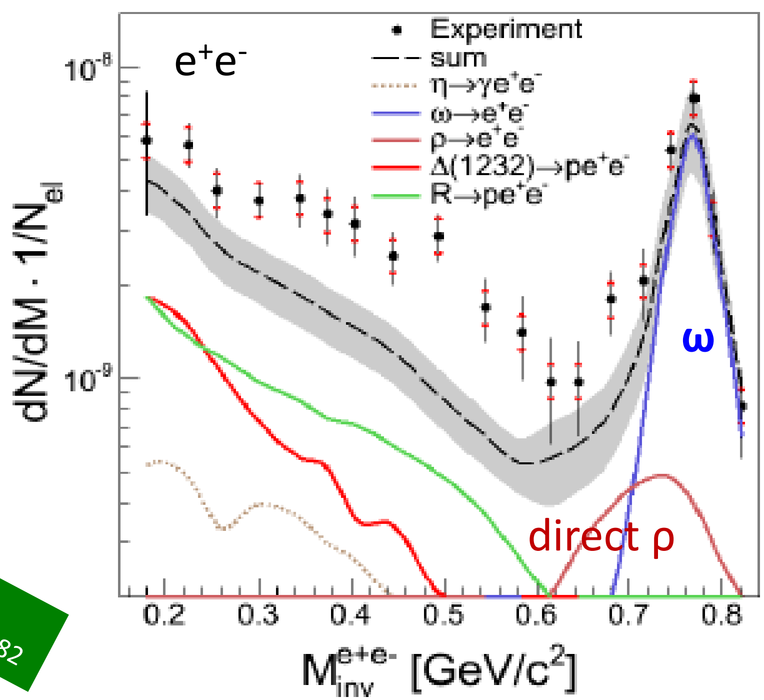
$$\frac{d\Gamma}{dM} = \frac{M_\rho}{M^3}\mathrm{BR}(M = M_\rho)$$

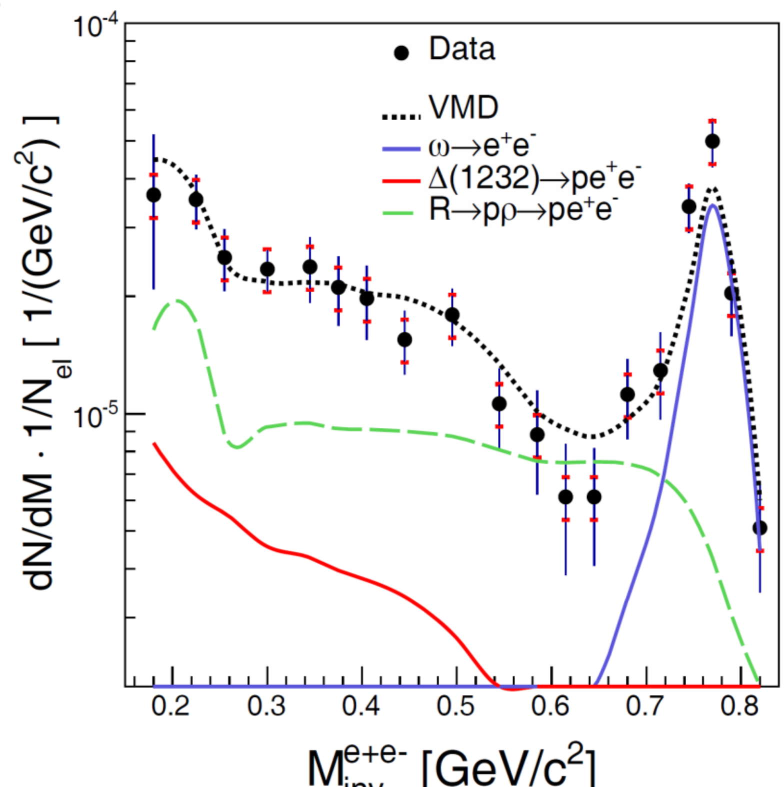
Good description within „HADES resonance model" **but with BR for R→ Nρ** from BnGa (upper limits)

(reduced as compared to PDG 2014)

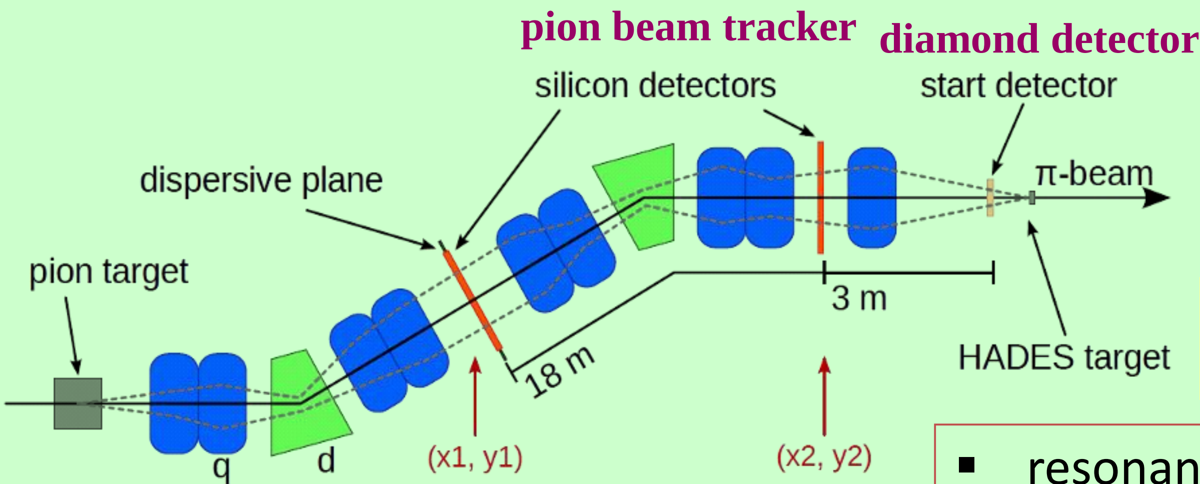
Excess above QED cocktail: off-shell coupling of $R \rightarrow N\rho \rightarrow Ne^+e^-$

G. Agakishiev et al. Eur. Phys. J. A50 (2014) 82





HADES physics for pion beams



polyethylen $(CH_2)_n$ and C

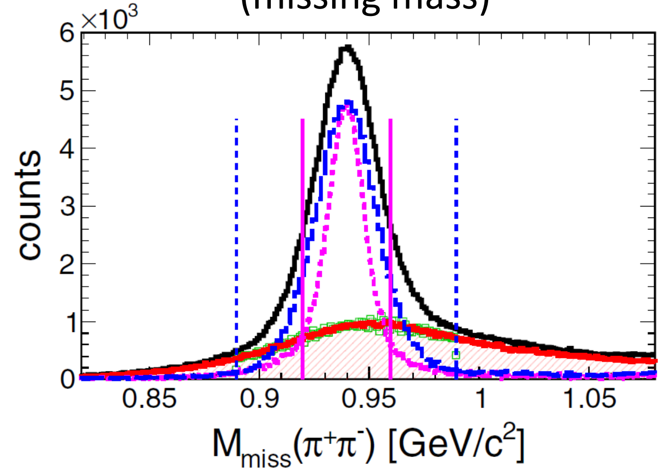
- resonance excitation can be controlled by the variation of the projectile (pion) momentum
- p = 0.656/0.69/0.748/0.8 GeV/c $\sqrt{s}$ = 1.45-1.55 GeV: N(1520)
- $\pi^+\pi^-$ production: coupling of ρ to resonance
- e^+e^- never measured from pion induced reactions
- resonance Dalitz decays $R \rightarrow N e^+ e^-$ (reference for p+Nb)

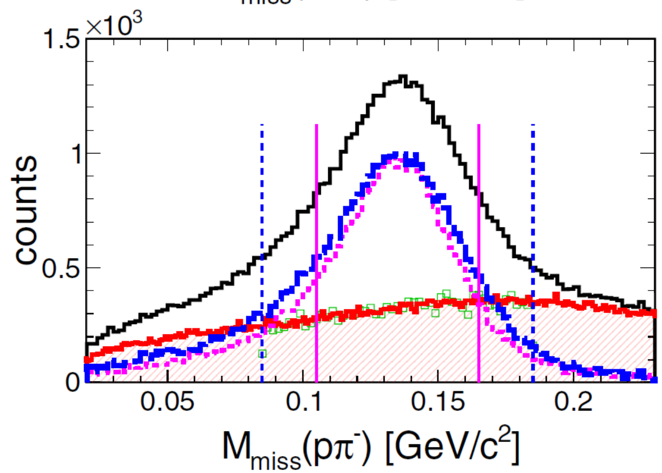
- reaction: N+Be 8-10 · 10^{10} N_2 ions/spill (4s)
- secondary π^- with I~3-4 · 10^5/spill @ 0.7 GeV/c
- pion momentum **Δp/p** = 2.2% (σ) and ~50% acceptance @ central momentum

PWA coupled channel analysis

Reaction	Observable	W (GeV)	Experiment
$\gamma p \to \pi^0\pi^0 p$	$d\sigma/d\Omega$, σ_{tot}	1.2–1.9	MAMI
$\gamma p \to \pi^0\pi^0 p$	E	1.2–1.9	MAMI
$\gamma p \to \pi^0\pi^0 p$	$d\sigma/d\Omega$, σ_{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
$\pi^- p \to \pi^0\pi^0 n$	$d\sigma/d\Omega$	1.29–1.55	Crystal Ball
$\pi^- p \to \pi^+\pi^- n$	$d\sigma/d\Omega$	1.45–1.55	HADES (this work)
$\pi^- p \to \pi^0\pi^- p$	$d\sigma/d\Omega$	1.45–1.55	HADES (this work)

two-pion
exclusive channels
(missing mass)

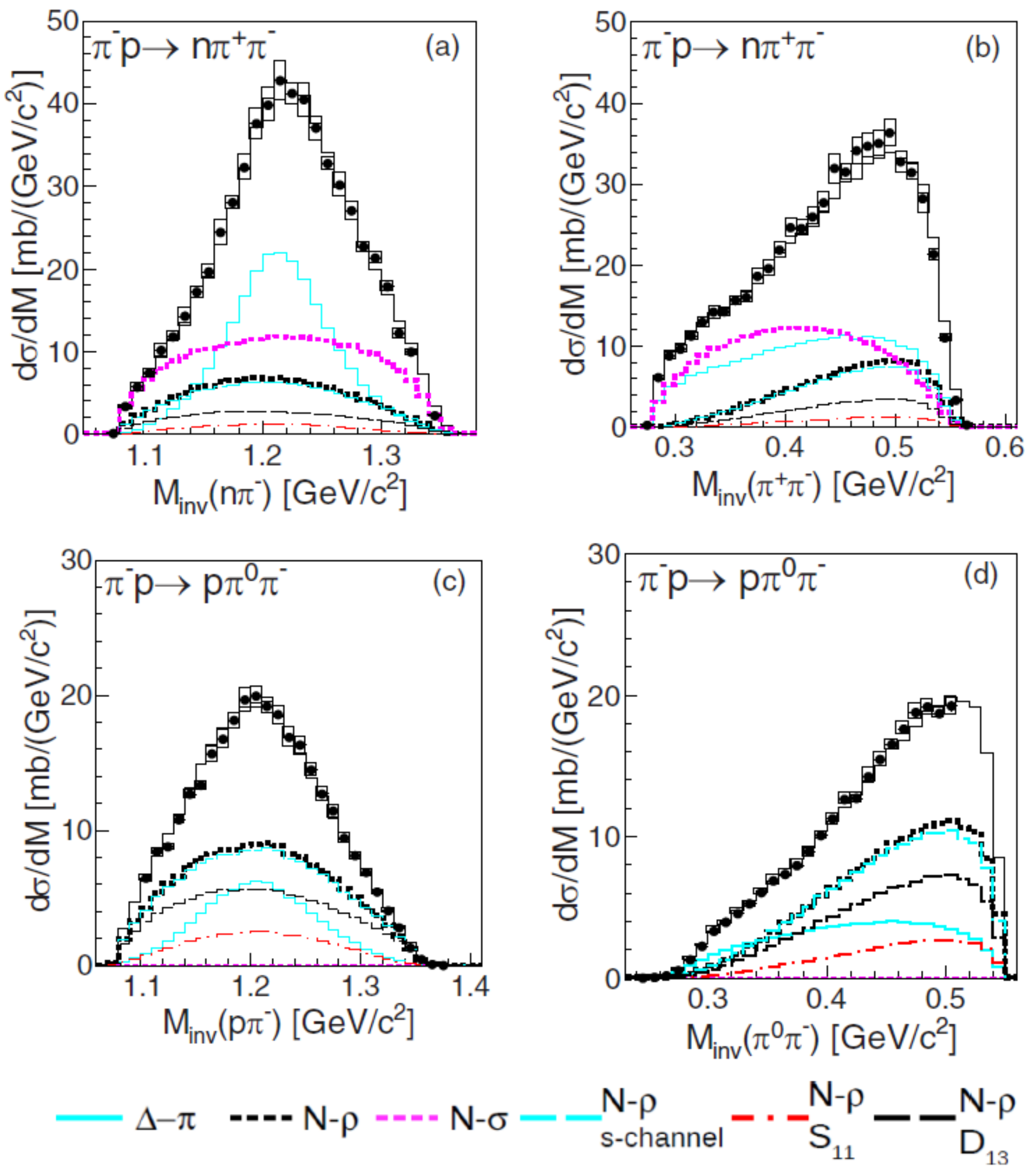




in energy range of **1.45 - 1.55 GeV**
in 2-pion production only few resonances matter: **D_{13}(1520)**, **P_{11}(1440)**

Dominant channels in $2\pi^0$ are: $\Delta\pi$ and $N\sigma$ ($2\pi^0$ in I = 0)

Two-pion production: PWA decomposition



$\sqrt{s}$=1.49 GeV

$n\pi^+\pi^-$

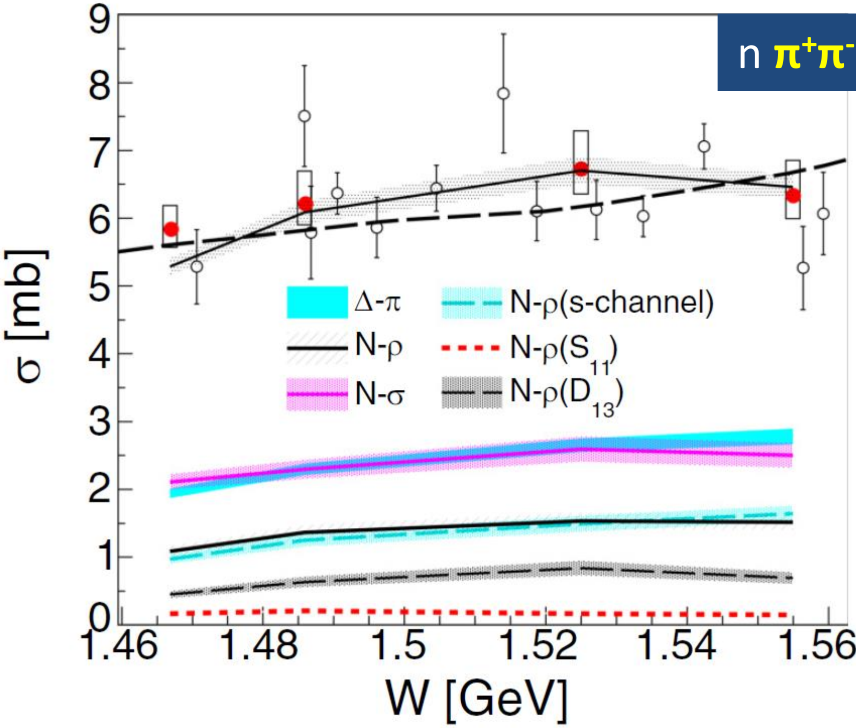
ρ subthreshold
no peak in $\rho \to \pi^+\pi^{-,0}$

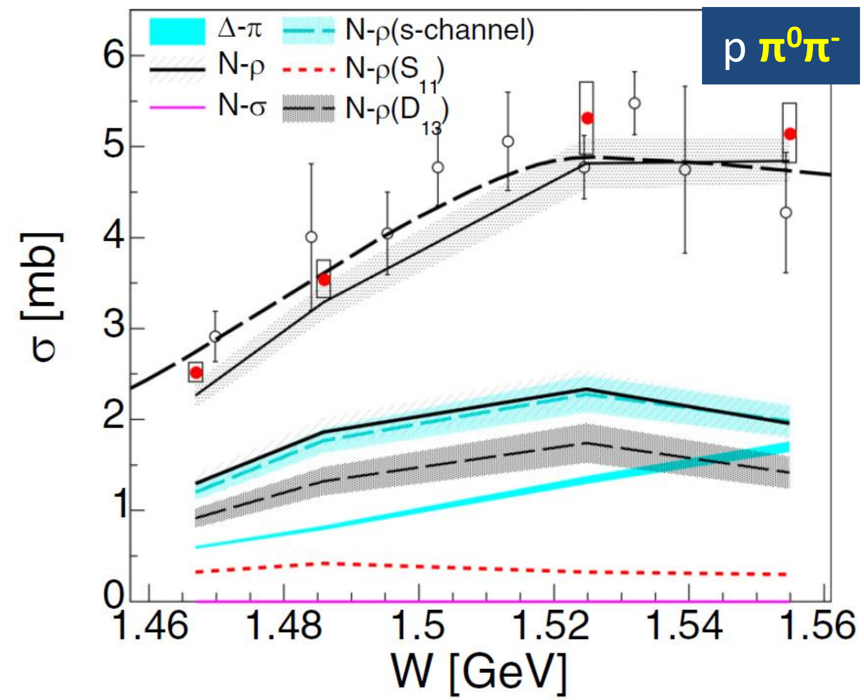
- **Δ-π** dominant,
- significant **N-ρ** dominat : s-channels I=1/2 (mainly D_{13})

$p\pi^-\pi^0$

- **Δ-π** smaller,
- **N-ρ** dominant (s-channels, D_{13})

Two-pion – total cross section





world data
(open points)

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

$N(1520)\frac{3}{2}^{-}$ dominant contribution to ρ production:

$$BR = 12.2 \pm 1.9\ \%$$

PWA results – 8 new PDG entries!

PDG· Verification
particle data group

ρN coupling not present in PDG since 2016

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

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

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

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

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

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

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

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

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

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

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

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

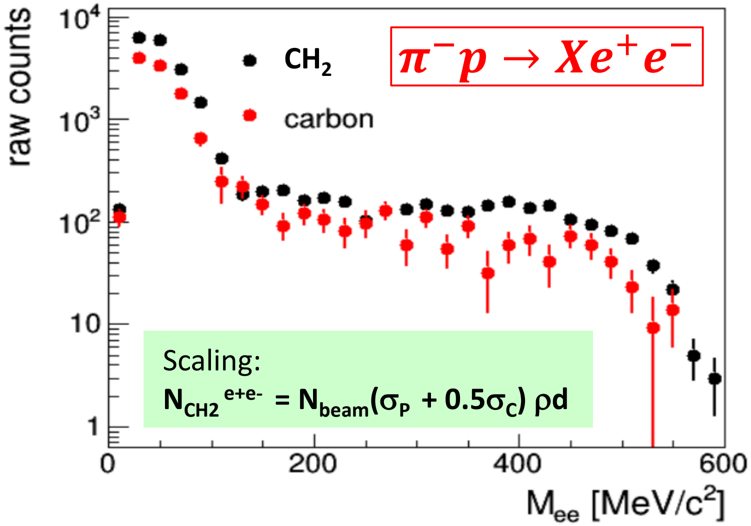
$\Gamma(\ N(1535) \to N\rho\ ,\ S = 1/2)/\Gamma_{\text{total}}$

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

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

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

Inclusive e^+e^- cocktail (CH_2 target)



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

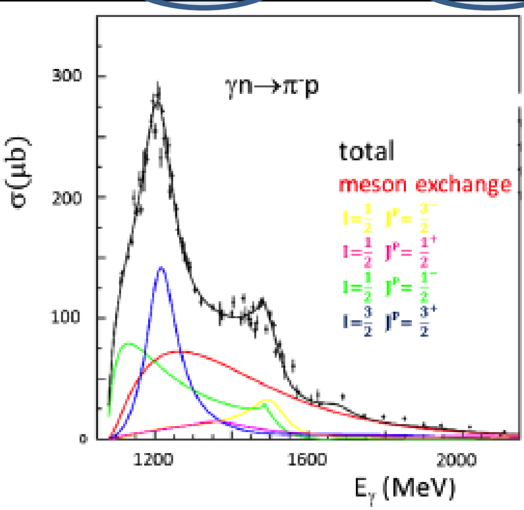
Arndt et al., PRC**72** (2005) 045202

Dalitz Decay BR
π^0: 0.012
η: 0.006

"Pointlike" resonance $R \to Ne^+e^-$
- inv. mass fixed by QED
- M_R and J^P resonance dependence

cross sections (μb) for π^-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

Based on: Anisovich et al., Eur.Phys.J. **A49** (2013) 67



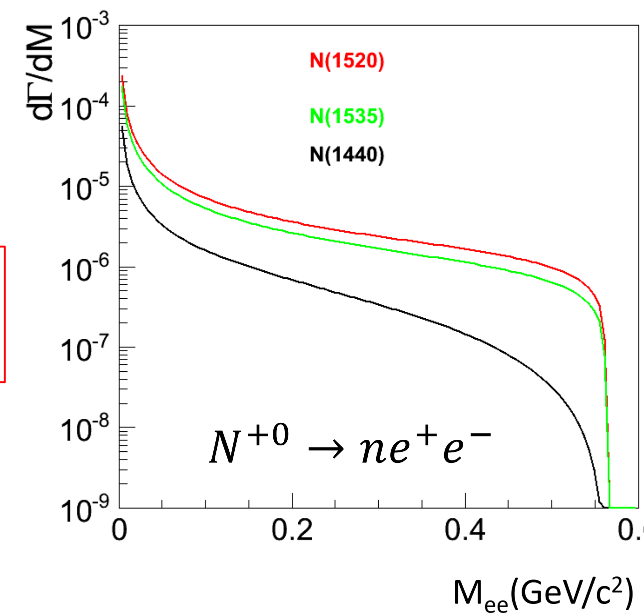
Bonn-Gatchina PWA

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

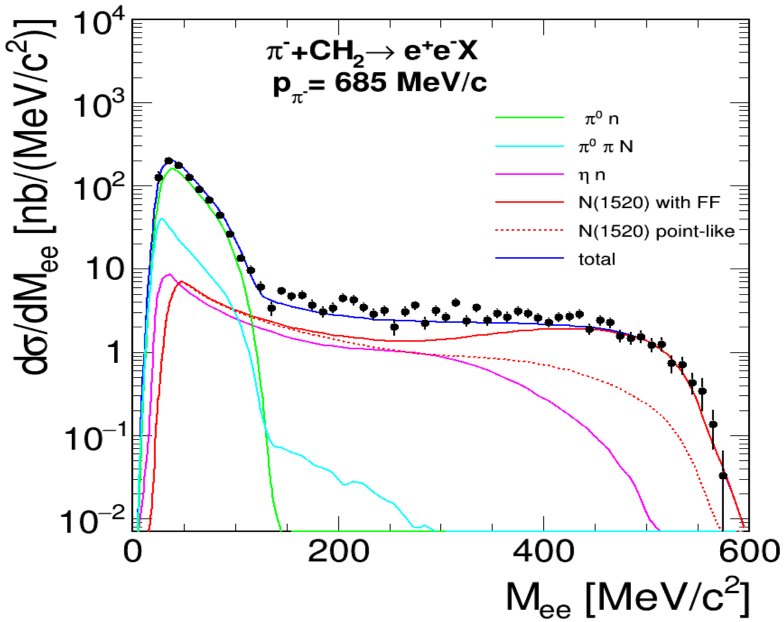
$$M_R \sim 1.5\ \mathrm{GeV}/c^2$$

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

Dalitz decay partial width (QED calculation)



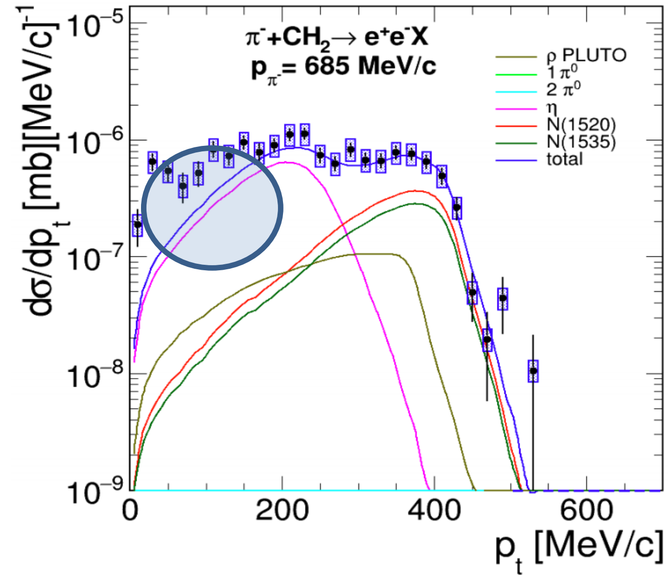
$\pi^- p \rightarrow e^+e^- X$ production

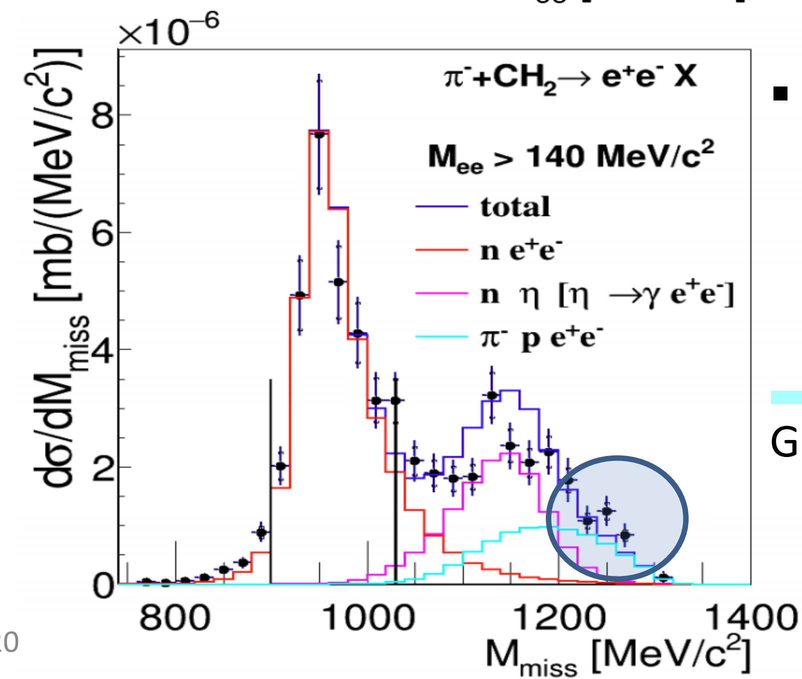


- **good π^0 description**
- **large η contribution**
- **huge excess over N(1520) point-like**

$$140 < m^{inv}_{e+e-} < 300\ [\mathrm{MeV/c^2}]$$

- low $\mathbf{p_T}$ excess



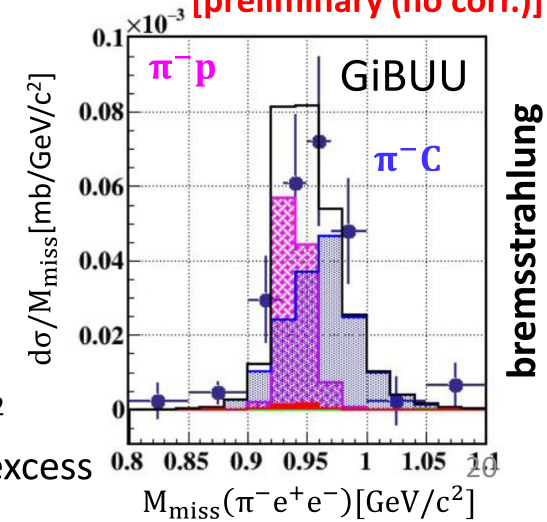


- clear neutron (miss. mass) peak

GiBUU π^-N bremsstr. sim

- for: $M_{inv} > 140$ MeV/c^2
$M_{miss} > 1200$ MeV/c^2 excess

[preliminary (no corr.)]



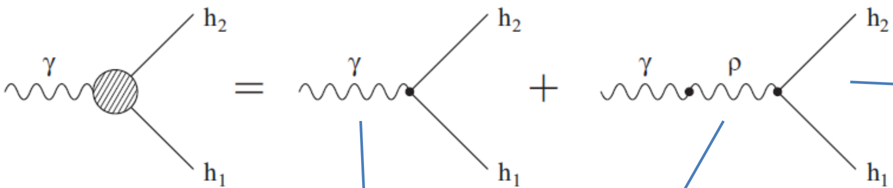
Dilepton production in pion-nucleon collisions in an effective field theory approach

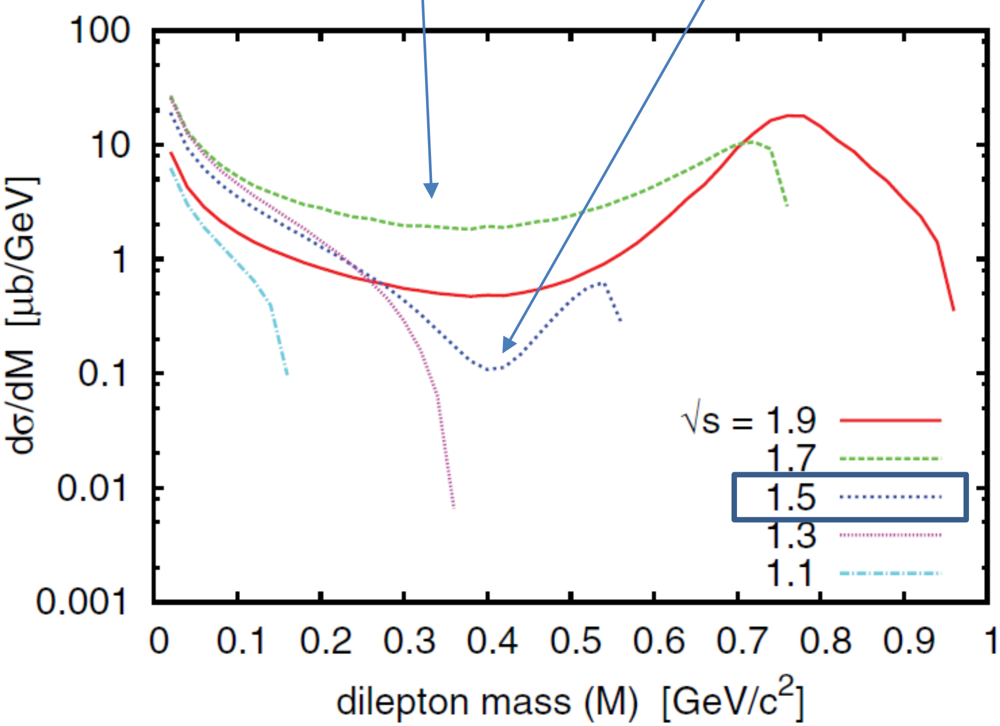
$\pi + N \rightarrow N + e^{+} + e^{-}$

Miklós Zétényi* and György Wolf†

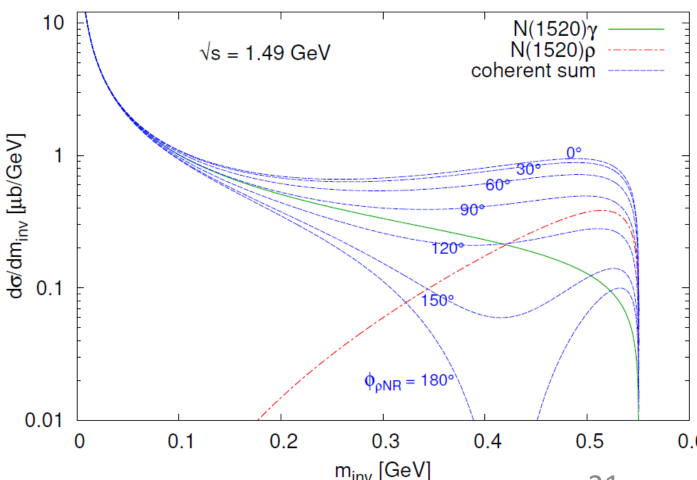
Lagrangian model: real γ+VMD coupling

Phys. Rev. C **86** (2012) 065209



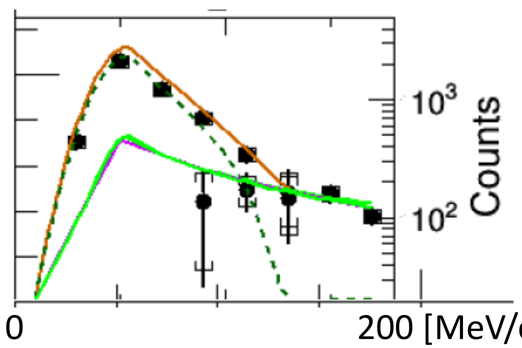


- vanishing contribution at q^2=0
- dip between γ and ρ contributions due to the destructive interference
- dip can be reduced by changing the phase between the two contributions:



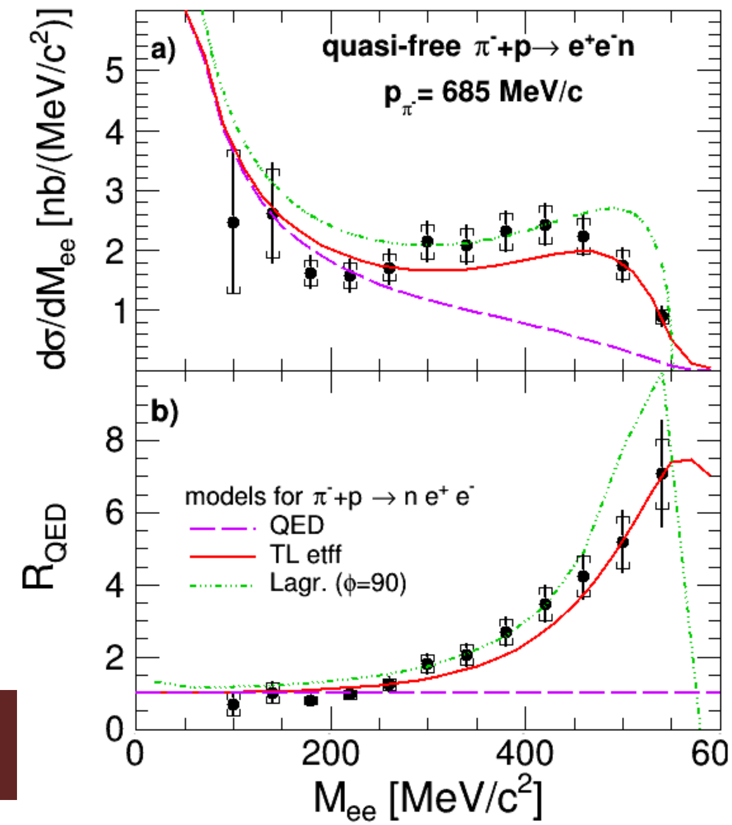
Exclusive e^+e^- cocktail (CH_2 target)

$m_{e+e-}^{inv} < 0.14\ [GeV/c^2]$



- total quasi-free
- $\pi^- p \to n\pi^0[\gamma e^+ e^-]$
- quasi-free $\pi^- p \to n e^+ e^-$

invariant mass for
$0.9 < m_{e+e-}^{miss} < 1.03\ [GeV/c^2]$

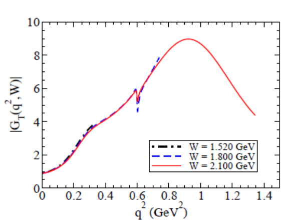


$m_{e+e-}^{inv} > 0.14\ [GeV/c^2]$

- η contribution suppressed
- quasi-free $\pi^- p \to e^+ e^- n$ signal extracted
- huge excess over point-like QED
- off-shell $\rho \to \pi^+\pi^-$

G. Ramalho and M. T. Peña, Phys. Rev. D**95** (2017) 014003

G. Ramalho and M. T. Peña, Phys. Rev. D**101** (2020) 114008



- eTTF models for N(1520) and N(1535)
- Lagrangian model with VDM form factors

Nature of eTFFs: angular distributions

M. Zetenyi, D. Nitt, M. Buballa, and T. Galatyuk
arXiv:2012.07546[nucl-th], 2020

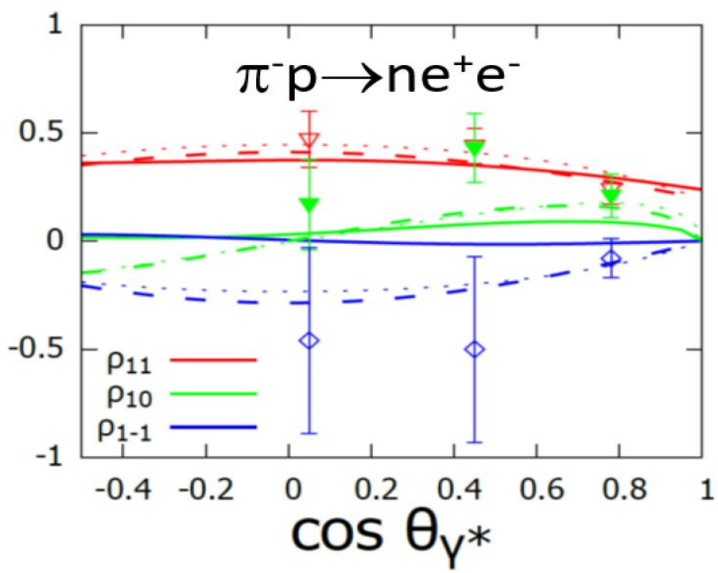
E. Speranza, M. Zetenyi, B. Friman
Phys. Lett. B764 (2017) 282

Density matrix formalism:

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

$$|A|^2 \propto 4k^2[2\rho_{00}(1-\cos^2\theta) + 2\rho_{11}(1+\cos^2\theta) + 2\sqrt{2}\sin(2\theta)\cos\phi Re\rho_{10} + 2\sin^2\theta Re\rho_{1-1}\cos(2\phi)]$$

ρ_{00}, ρ_{11}, ρ_{1-1} coefficients
(sensitive to spin of the transition and parity – eTTFs) FIT TO DATA:



- ✓ e+e- data with VDM (GSI/Budapest) for D_{13}
- ✓ e+e- data with $\rho \to \pi\pi$ from PWA BnGa
- ✓ dominance of D_{13} confirmed

$\pi^- p \to n e^+ e^-$ **CS: 2.54 ± 0.33** μb
BR $N(1520) \to n e^+ e^-$ $(2.65 \pm 0.13) \times 10^{-5}$

SUMMARY

- Modeling of SF requires detailed knowledge of elementary processes involving baryon-meson interactions - R→N γ^* transitions (*em*. Transition Form Factors) are directly related to hadronic loops in self-energy calculations
- Results of studies performed with NN and πN reactions demonstrate important role of intermediate ρ meson in *em*. transitions for Δ , D_{13} , along with **V**ector **M**eson **D**ominance
- Angular distributions (differential cross sections) are important observable to discriminate between different contributions

HADES & related talks

May 2021

18 Tuesday

Alexandr Prozorov
Neutral meson production in AgAg@1.58 A GeV
parallel **C2 17:15**

Manuel Lorentz
Results on hadron properties in pion, p, A+A collisions from HADES
plenary **15:15**

19 Wednesday

Krzysztof Piasecki
New systematics of strange hadron production from HADES
parallel **C3 18:25**

20 Thursday

Krzysztof Nowakowski
$\Lambda(1520)$ **production in proton-proton and proton-nucleus collisions with HADES**
parallel **C4 17:15**

Gilberto Ramalho **THE LAST TALK**
Covariant calculations of Dalitz decays of nucleon resonances and hyperons
parallel **C4 18:15**