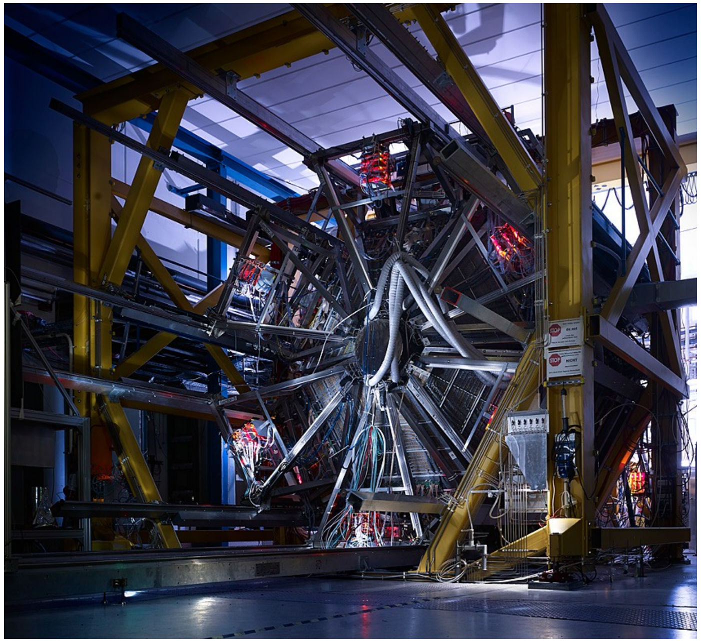
Studies of Pion Induced Reactions with the HADES Spectrometer



Izabela Ciepał

for the HADES Collaboration

Institute of Nuclear Physics PAS

Outline

1) Motivation of the HADES experiment,
2) Electromagnetic structure of baryons,
3) The HADES detector,
4) Sample results,
5) Pion beam @ GSI,
    - first measurement and results,
6) Outlook.

Motivations

two main pillars of HADES experiment

Heavy ion physics (A+A):

- in medium hadron properties
- nuclear matter at high μ_B, T

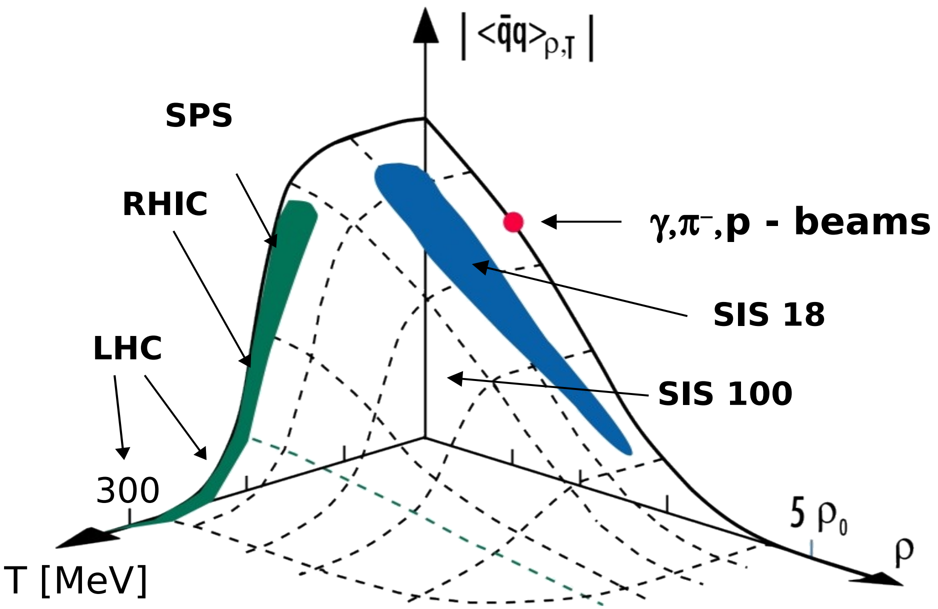
proton+A

Elementary collisions (proton-proton, pion-proton):

- vector meson baryon couplings
- cross sections..

Primary Motivations

Klimt, Lutz, Weise
Phys. Lett. B249 (1990) 386

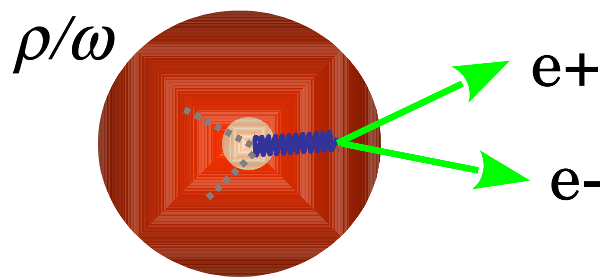


G.E. Brown / M. Rho: Scaling of masses with quark condensate - order parameter of Chiral Symmetry restoration (PRL 1989, 1991)

$$m^* \approx m\left[\langle \bar{q}q^* \rangle / \langle \bar{q}q \rangle\right]^u$$

short-lived mesons in medium

p/π/γ + A



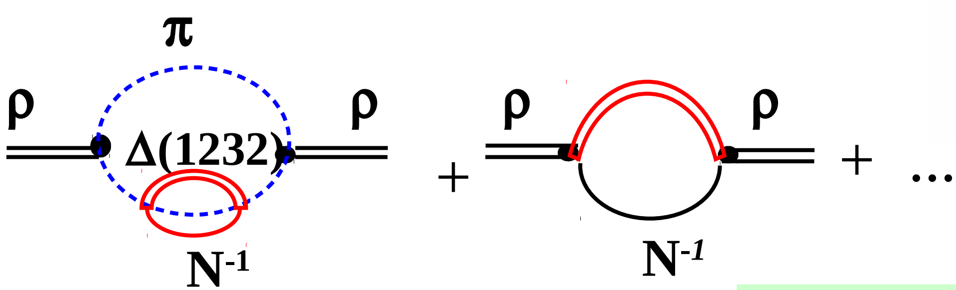
- **dileptons radiation** - rare probes (e^+e^- BR~10^{-5})
- **do not interact strongly** with nuclear matter

In Medium ρ Mas

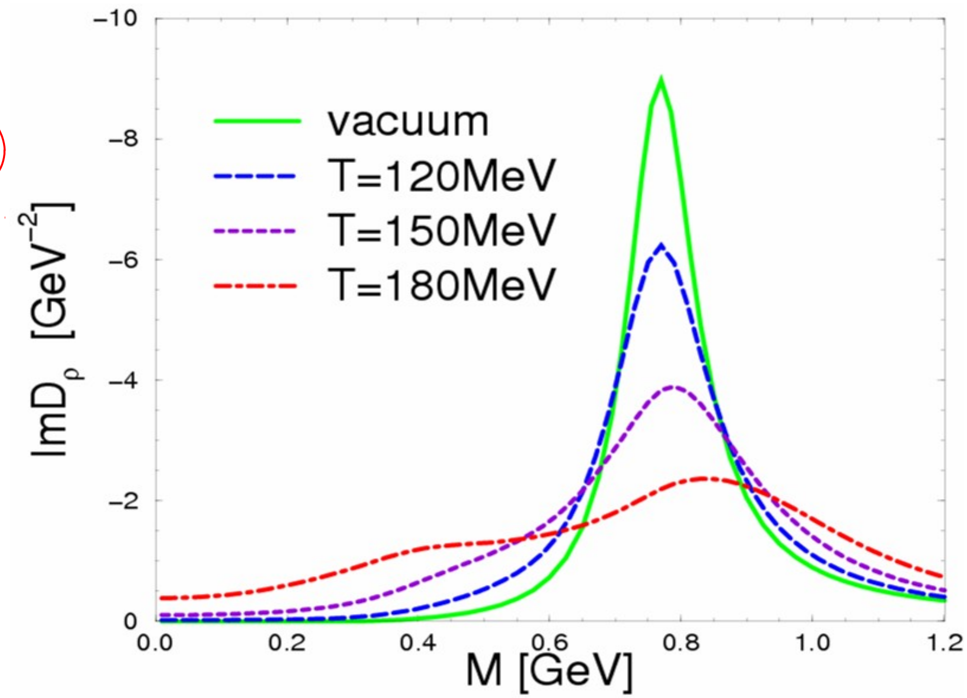
Thermal emission:

$$\frac{dN_{ee}}{d^4x\,d^4q} = \frac{\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T)\,\mathrm{Im}\,D_{\rho/\omega/\varphi}$$

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



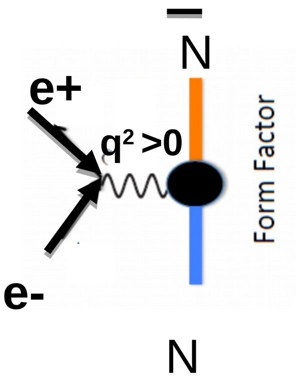
$\Sigma_{\rho\pi\pi}$ $\Sigma_{\rho R(\Delta,\, N^*)}$

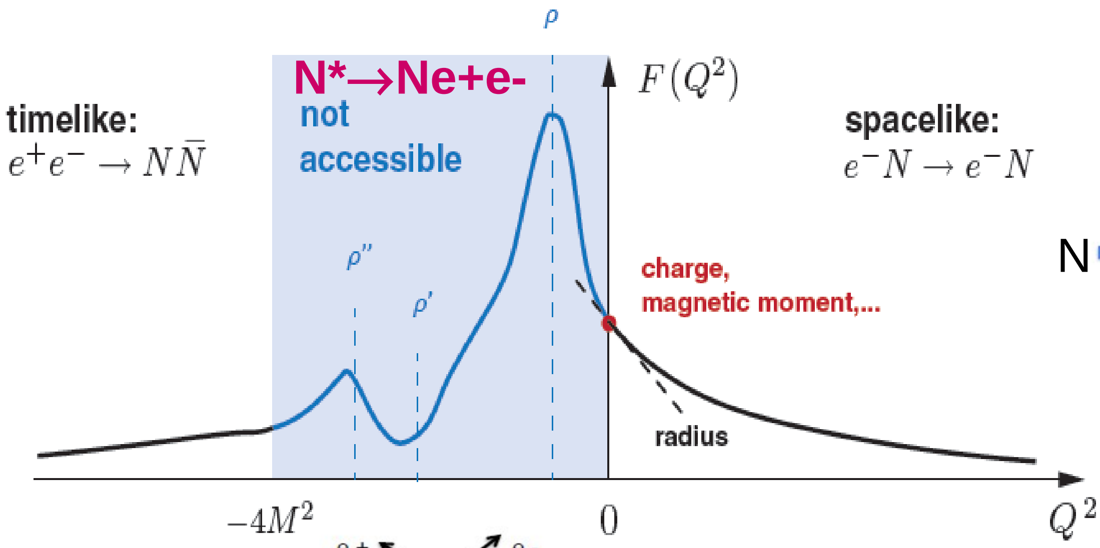


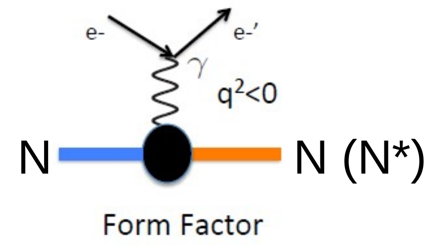
Rapp, Wambach, Adv. Nucl. Phys. A25 (2000)1

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

Electromagnetic Structure of Baryons

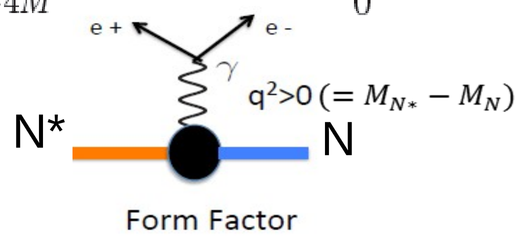




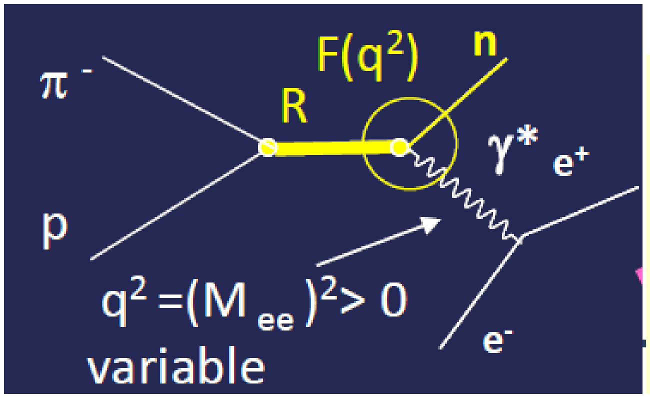


Transition Form Factors $F(Q^2)$

Time-Like electromagnetic form factors

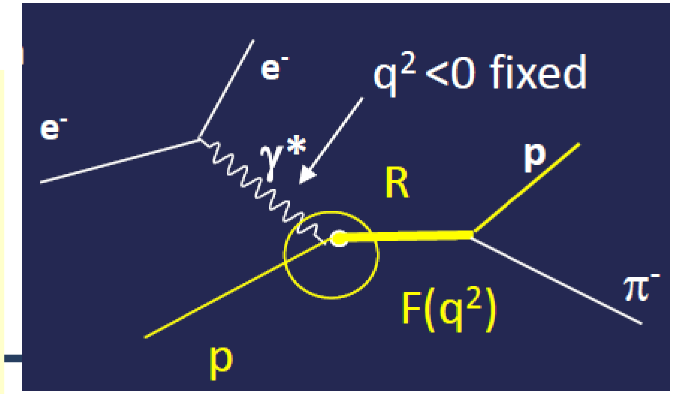


Space-Like electromagnetic form factors

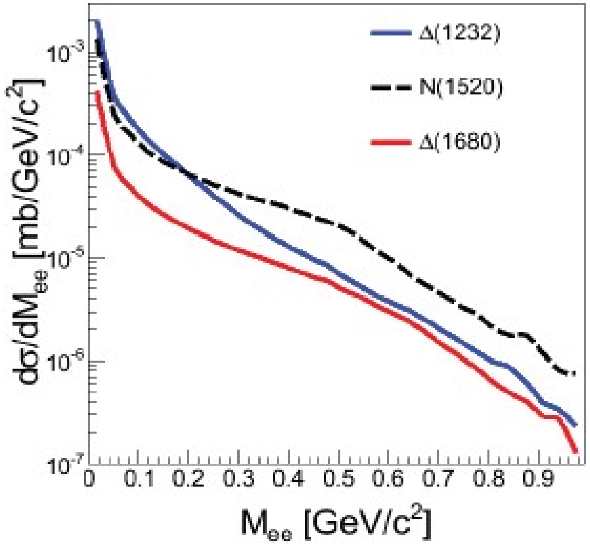


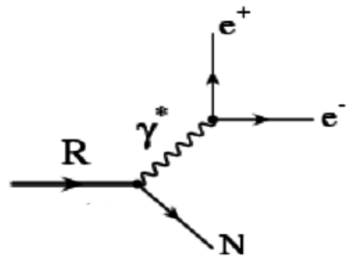
Dalitz decays, appearance of intermediate vector mesons!

ρ/ω/φ $J^{PC} = 1^{--}$ (=γ !)



Models for Dalitz Decays





- constant eTFF
- experimental cross section for ω/ρ used
- no off-shell coupling to vector mesons

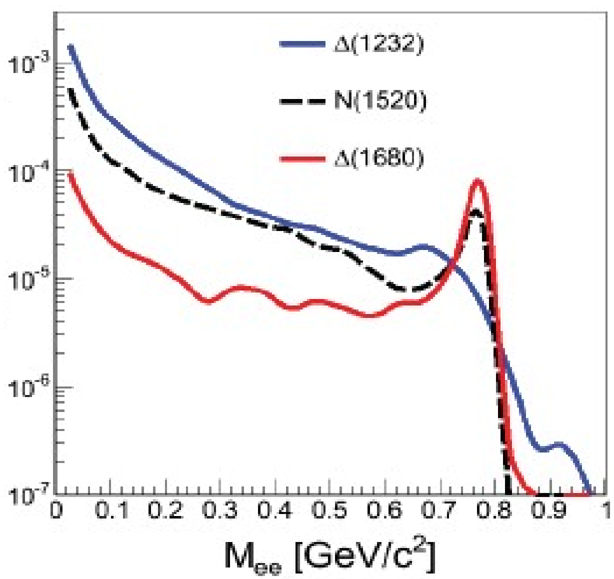
QED:

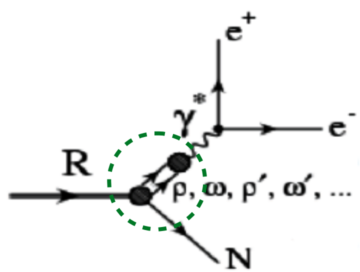
point-like R-γ^* vertex

M. Zetenyi/M. I. Krivoruchenko

$$d\Gamma\left(N^* \rightarrow e+e-\right) = \mathrm{QED}_{point-like} \times F\left(Q^2\right)_{QCD}$$

$$F\left(Q^2\right)_{QCD} \simeq 1 + \frac{1}{6q^2} < r^2 > \simeq \frac{1}{1 - q^2/\Lambda^2}$$





- off-shell coupling to vector mesons

VMD:

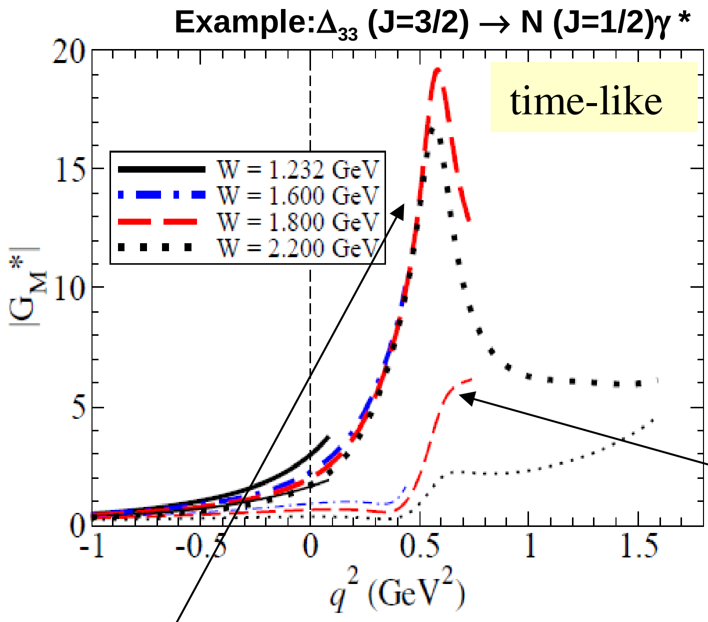
em. transition FF (M_{ee})

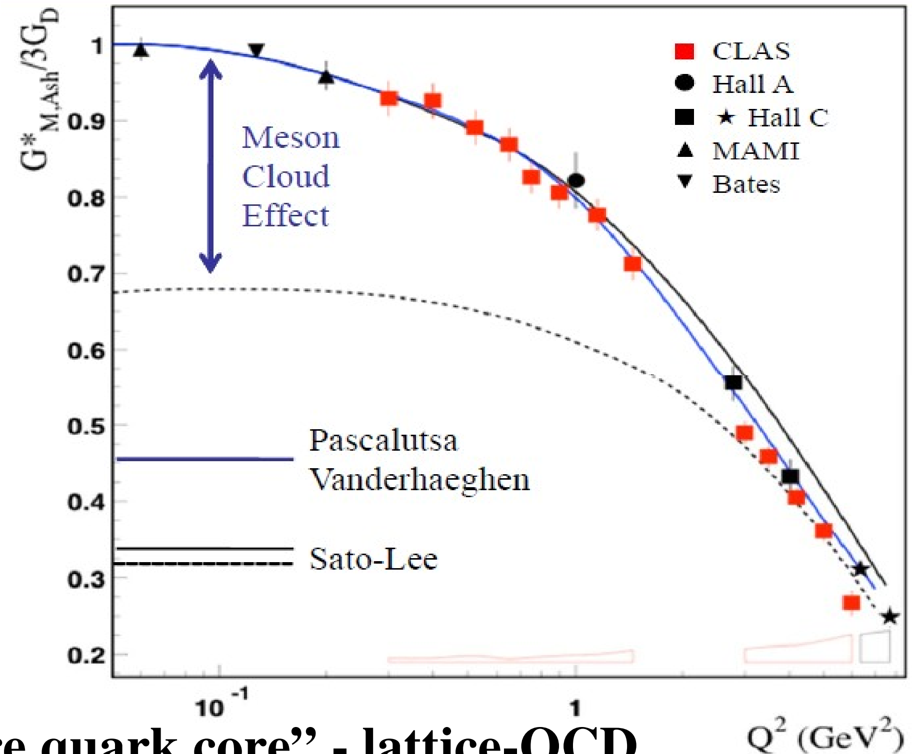
M. Zetenyi/M. I. Krivoruchenko

Electromagnetic Structure of Baryons

Role of meson cloud in baryons

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





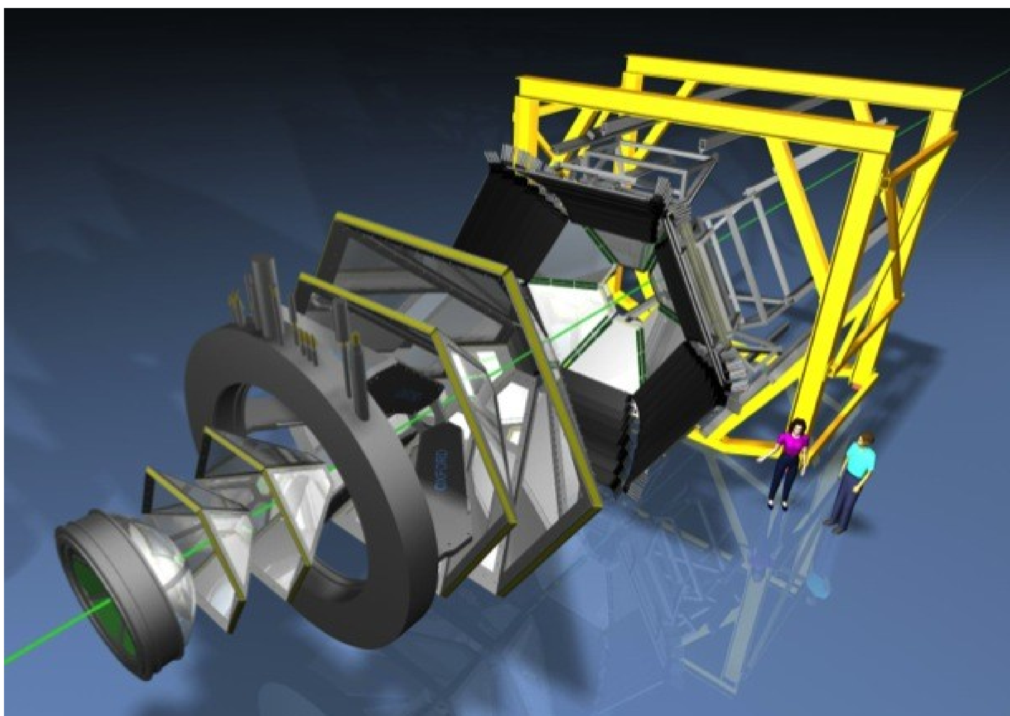
„bare quark core" - lattice-QCD

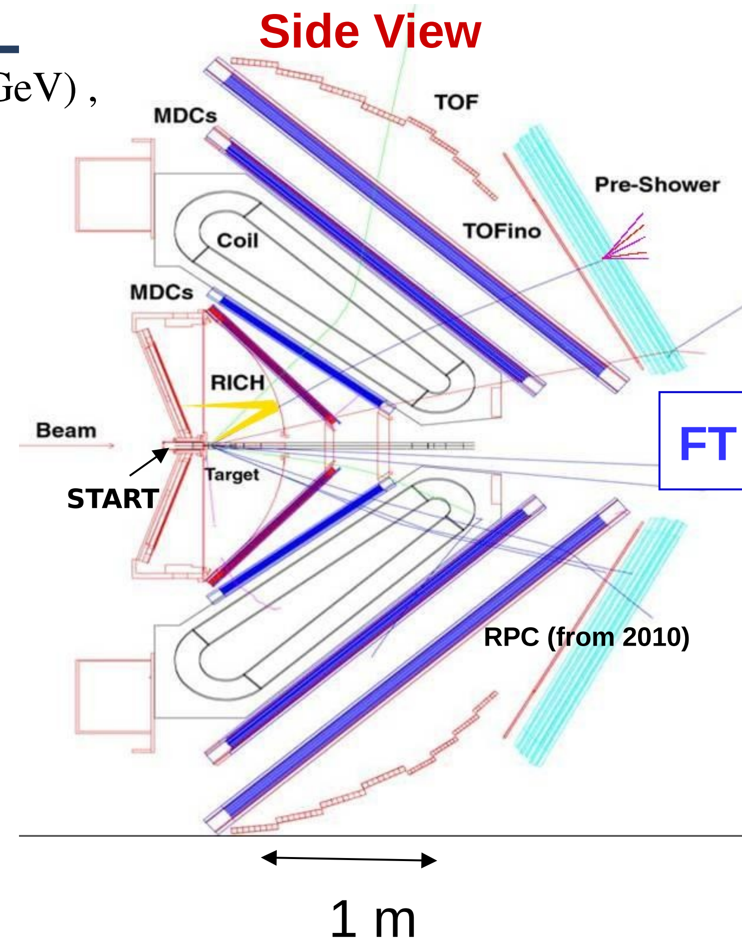
„quark core" + "pion cloud"

- Resonance - Nucleon transitions :
  em. Transition Form Factors : G_M (q^2), G_E (q^2) , G_C (q^2)
- Important role of pion cloud at small q^2

High Acceptance Di-Electron Spectrometer

- ✓ Beams from SIS18: 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
- ✓ π/p/K separation with TOF/tracking
- ✓ electrons : RICH (hadron blind), TOF/Pre-Shower
- ✓ Trigger: particle mult in TOF
- ✓ DAQ: ~20 KHz with Au+Au collisions

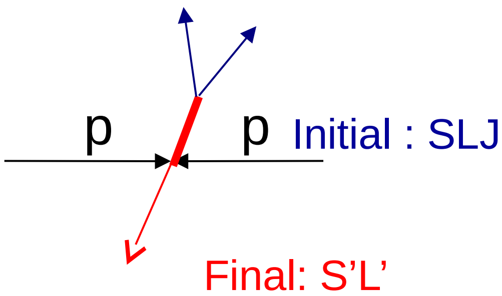




Geometry

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

p+p @ 1.25 GeV – Resonance Production



Partial Wave Analysis (PWA)

maximum log-likelihood event-by-event

A. V. Anisovich et al.
*Eur. Phys. J. A**34** (2007) 129*

- **Coherent sum** of partial waves
- Energy dependent solutions: many experimental sets treated together by max. log-likehood method event by event
- Detector acceptances taken into account

$$d\sigma = \frac{(2\pi)^4 |A|^2}{4|\vec{k}|\sqrt{s}} \, d\Phi_3(P, q_1, q_2, q_3)$$

$$A = \sum_{\alpha} A^{\alpha}_{tr}(s) Q^{in}_{\mu_1 \ldots \mu_J}(SLJ) A_{2b}(i, S_2L_2J_2)(s_i) Q^{fin}_{\mu_1 \ldots \mu_J}(i, S_2L_2J_2S'L'J)$$

initial NN system

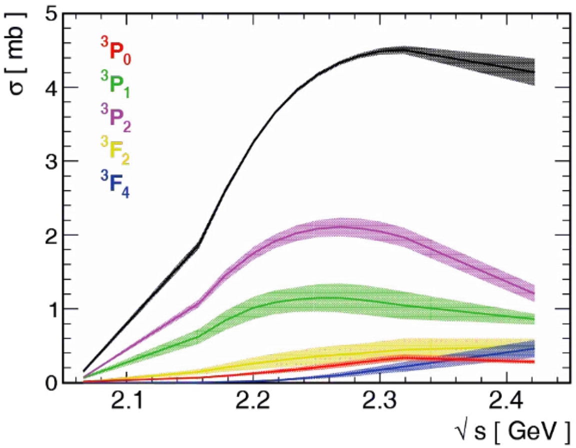
system of two final particles

transition amplitude

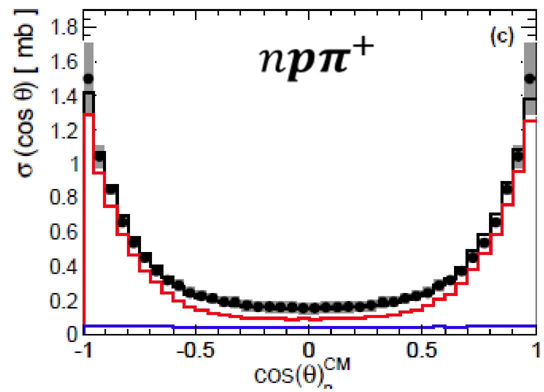
final state amplitude (resonant, non resonant)

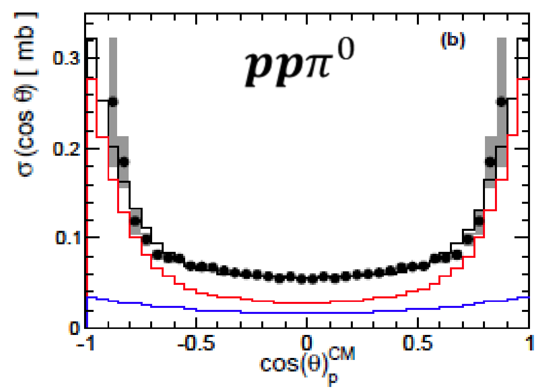
10

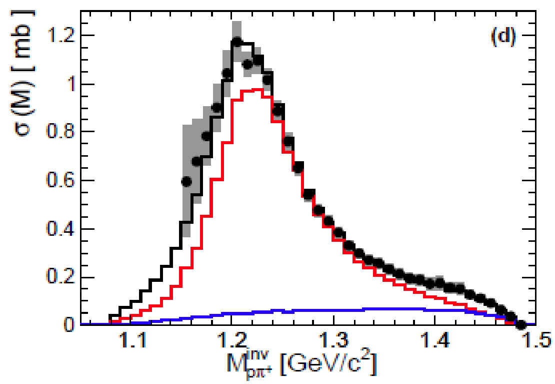
p+p @ 1.25 GeV – Resonance Production

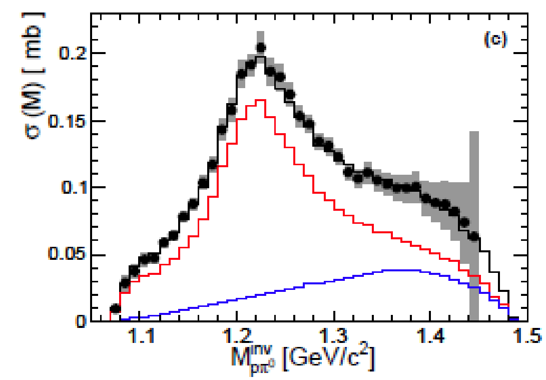


G. Agakishiev *et al.*
Eur. Phys. J. A (2015)



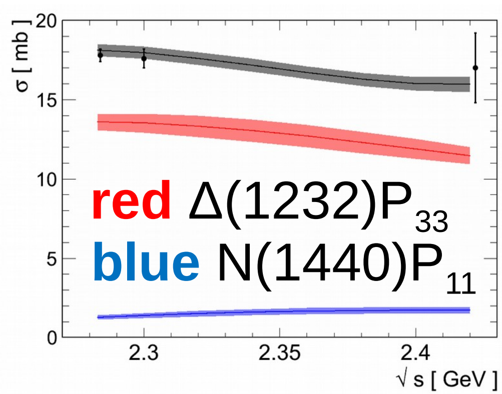


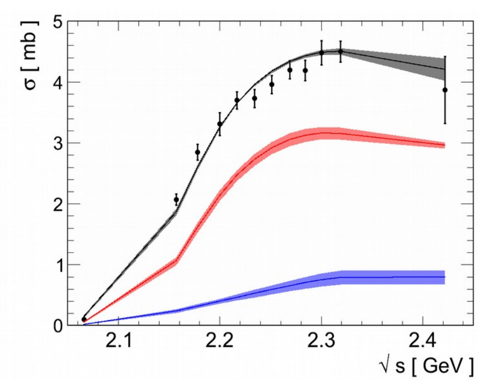




FINAL STATES

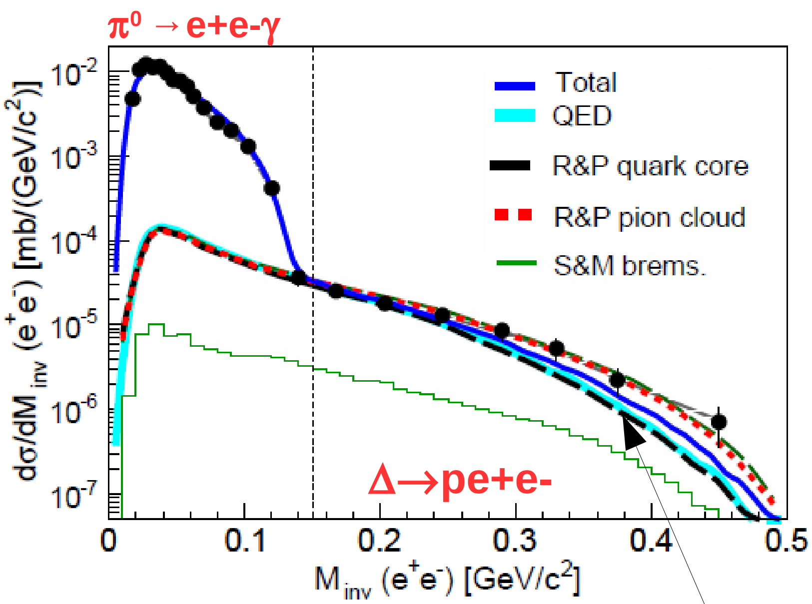
S-, P-, D-waves
in pp or pn-state
P_{33}(1232) and
P_{11}(1440) in πN state





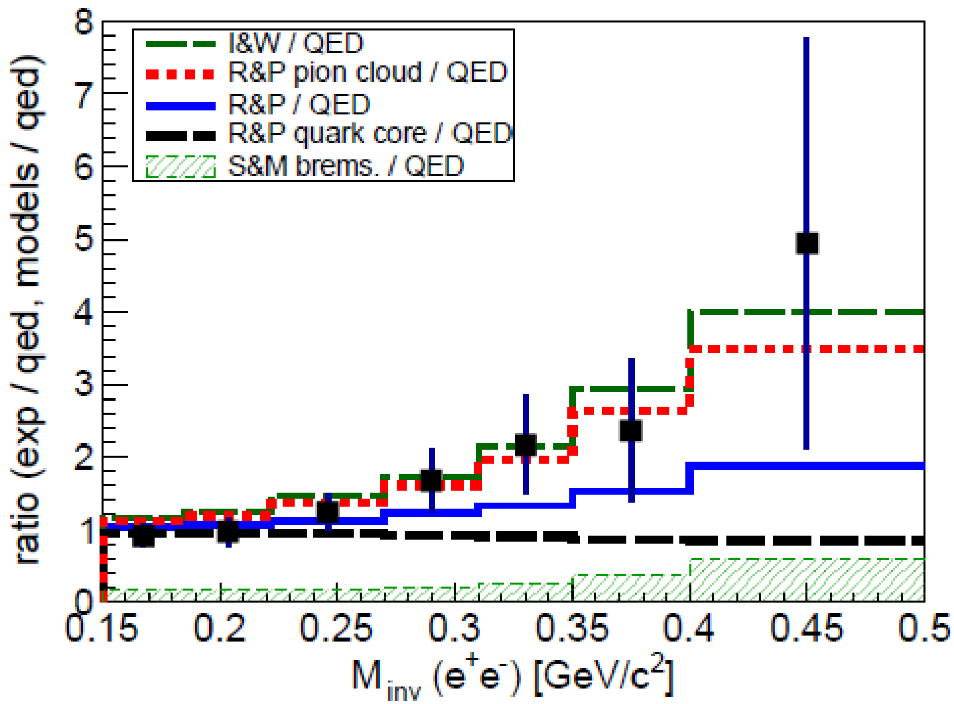
p+p @ 1.25 GeV
Δ^+ (1232) { → pe^+e^- } Dalitz Decay

First detailed study of a timelike em. baryon transition in p+p: BR($\Delta \rightarrow pe^+e^-$) = 4.2×10^{-5}



„bare quark core"

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

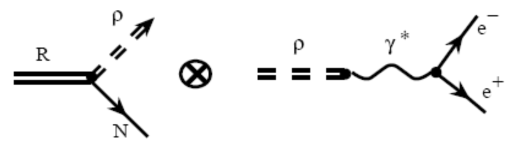


p+p@ 3.5 GeV – Higher Resonances

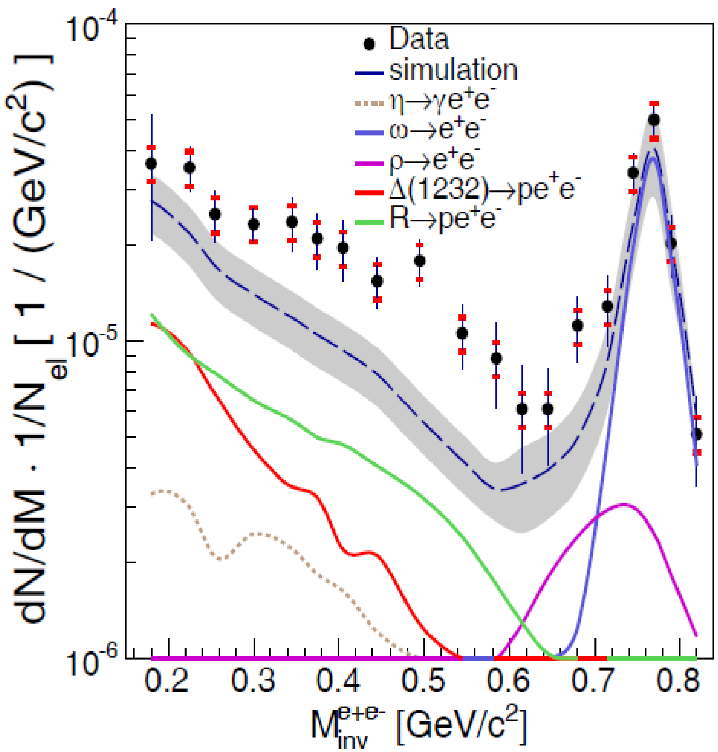
pp → ppe+e-

HADES Coll., EPJ A50 (2014) 82

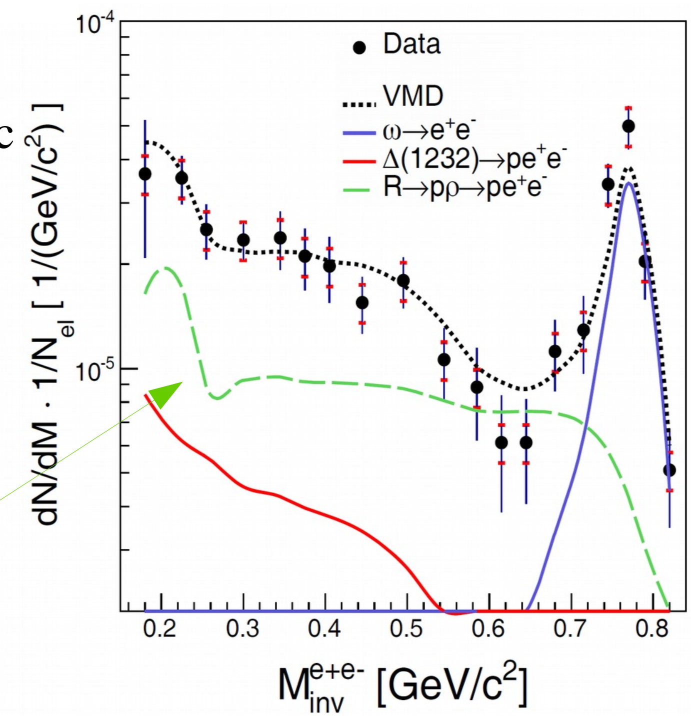
"QED" –point like decay



Vector Meson Dominance



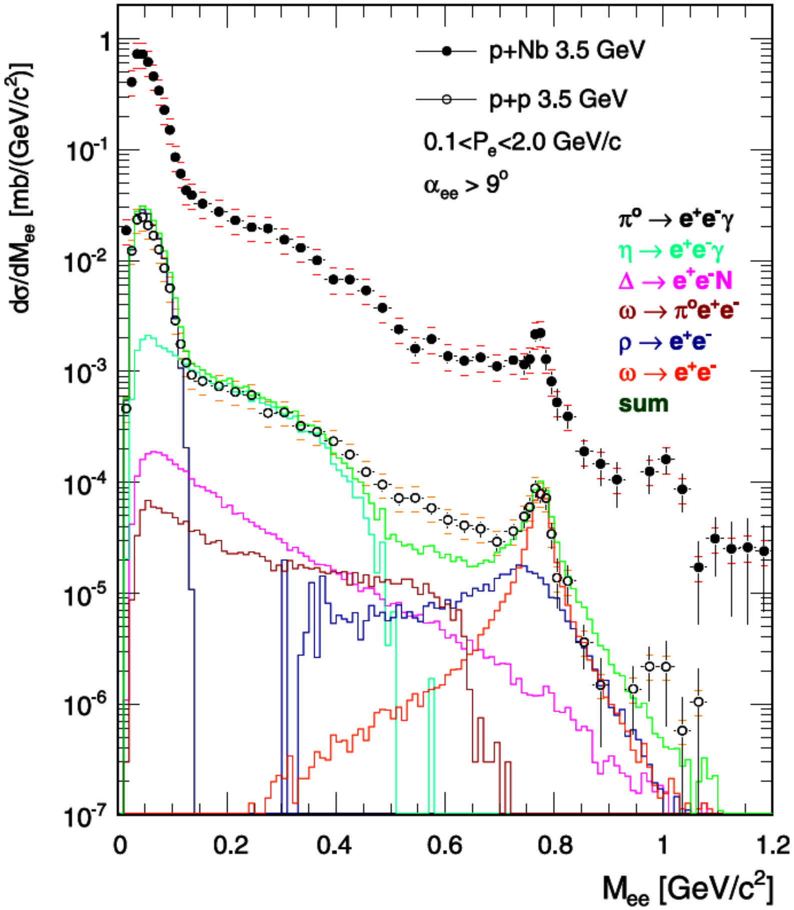
Effect of electromagnetic transition FF
- coupling to ρ meson of light baryonic resonances R



- several contributing resonances **R:** N*(1520), N*(1720), Δ(1620), Δ(1905), ...
- excess above „QED" cocktail can be explained by VDM

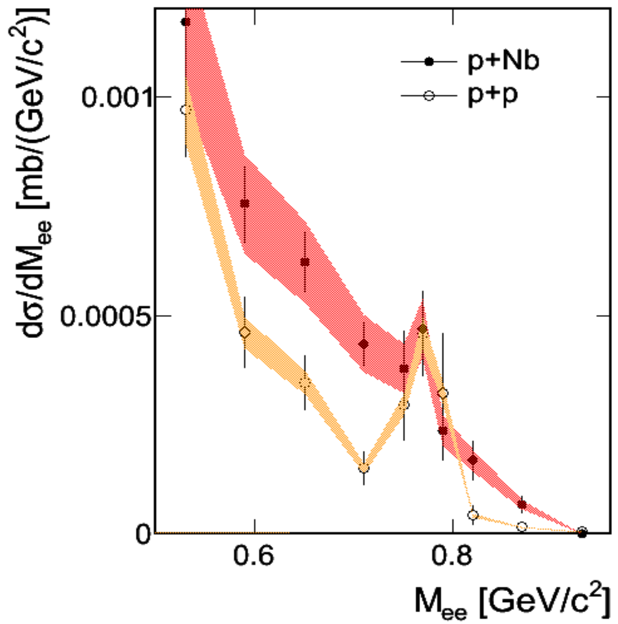
p+p vs p+Nb @ 3.5 GeV

HADES Coll., PLB 715 (2012) 304



pp data scaled by „A$_{part}$" scaling

„slow sources" p_{e+e-}< 0.8 GeV/c

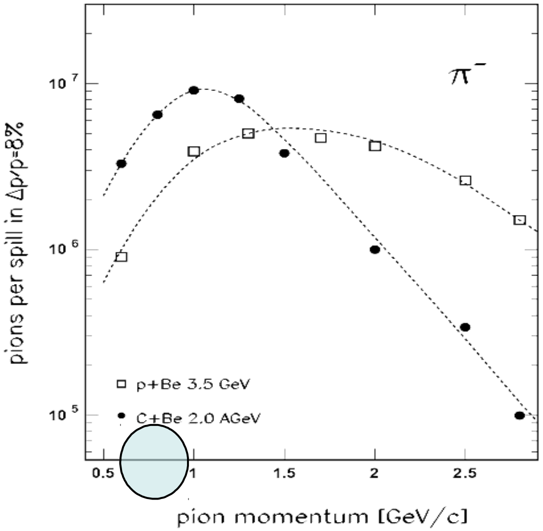


$$R_{pA} = \frac{d\sigma^{pNb}/dp}{d\sigma^{pp}/dp} \times \frac{\langle A^{pp}_{part}\rangle}{\langle A^{pNb}_{part}\rangle} \times \frac{\sigma^{pp}_{reaction}}{\sigma^{pNb}_{reaction}}.$$

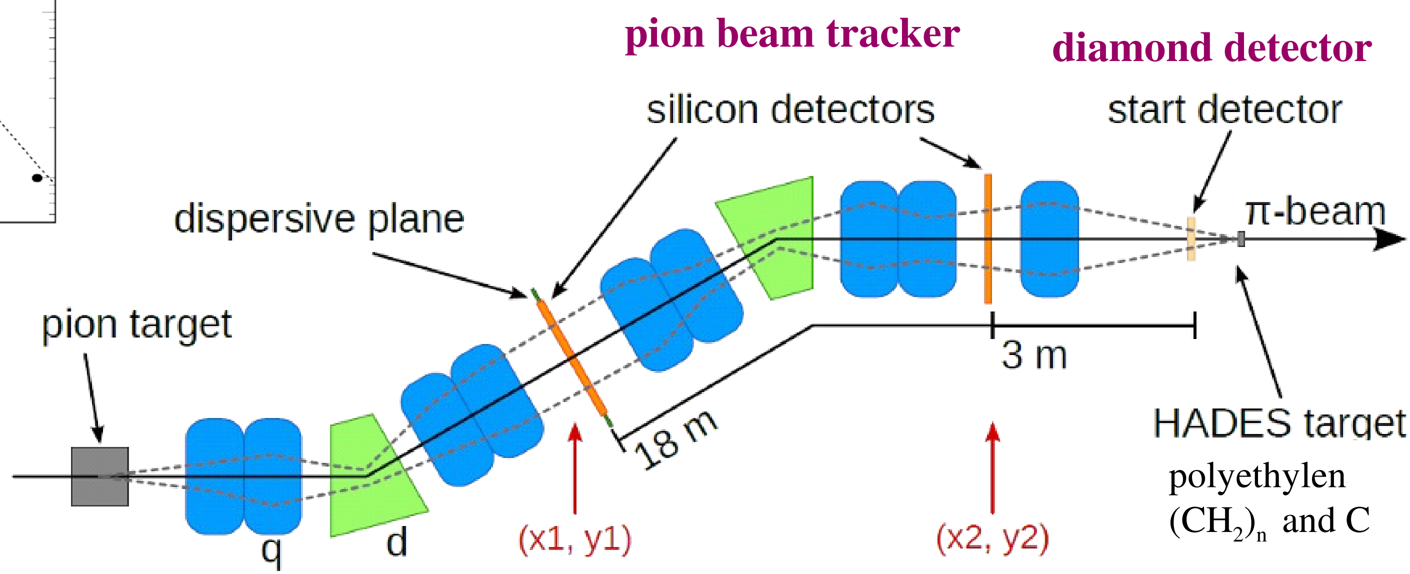
nuclear modification factor

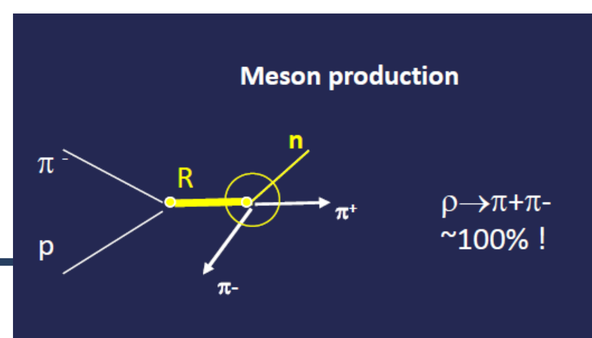
- p+p cockail : based on known sources fixed to data π^0 /η/ ω/ ρ , Δ
- remarkable difference between p+p, p+A : **reduction of ω, broadening of ρ**

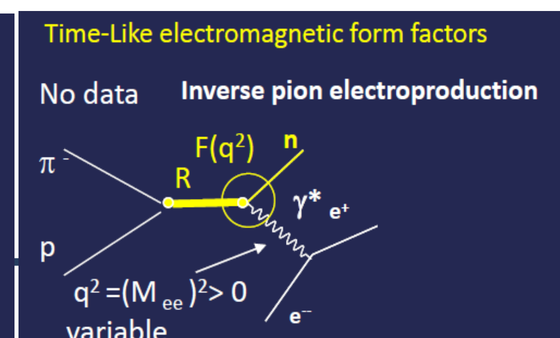
Pion Beam @ GSI



Unique possibility to investigate em. resonance decays via **combined** Partial Wave Analysis of hadronic and electromagnetic final states







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

HADES Physics Programe'2014 with Pion Beams

Main advantages of pion beams:

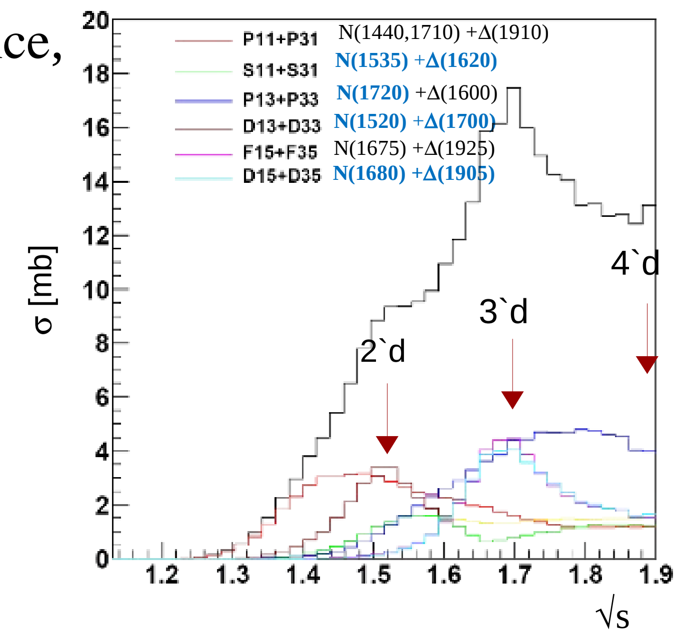
1) **selectivity:** resonances can be excited at given mass by choosing the beam (pion) momentum,
HADES starts with $\sqrt{s}$=(1.46-1.55) GeV – N*(1520) resonance region
data obtained at 4 momenta: 0.656, 0.69, 0.748, 0.8 GeV/c

2) **π+ π- production:** off-shell coupling of ρ to resonance, ρ→ π+ π- (~100%) „golden channel",

Most of π+π- data 1.3 <√s <2 come from Manley et al., PRD30, (1984) 904 based on 240 000 events (differential distributions not available)

3) **dilepton channel** R → e+e-, e+e- never measured in pion induced reactions.

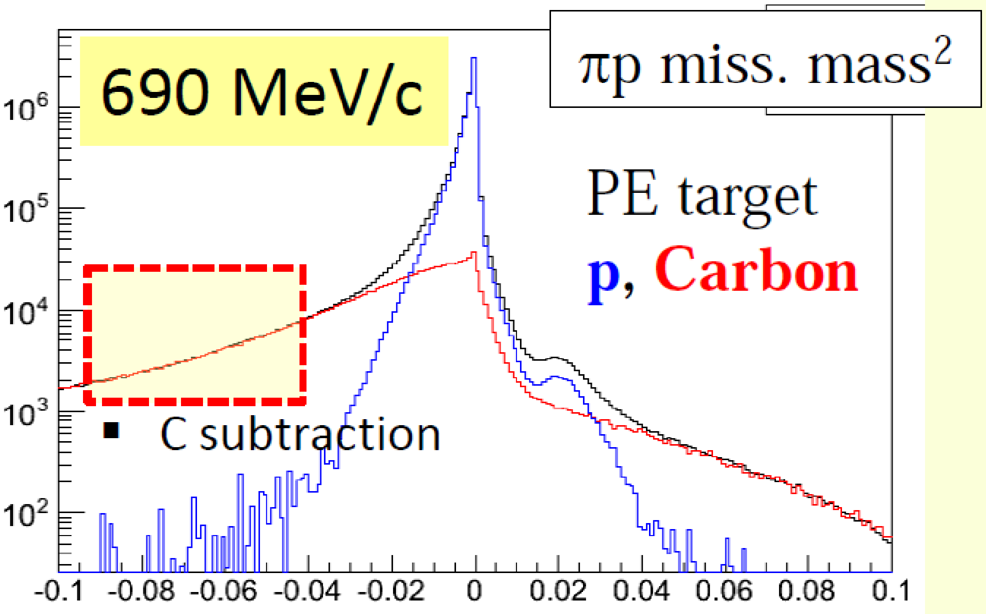
πN→2πN: Bonn/Gatchina PWA

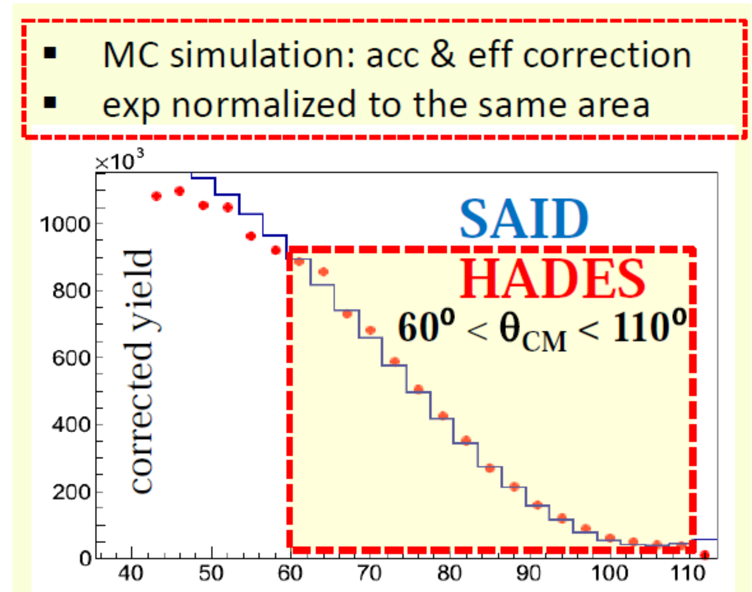


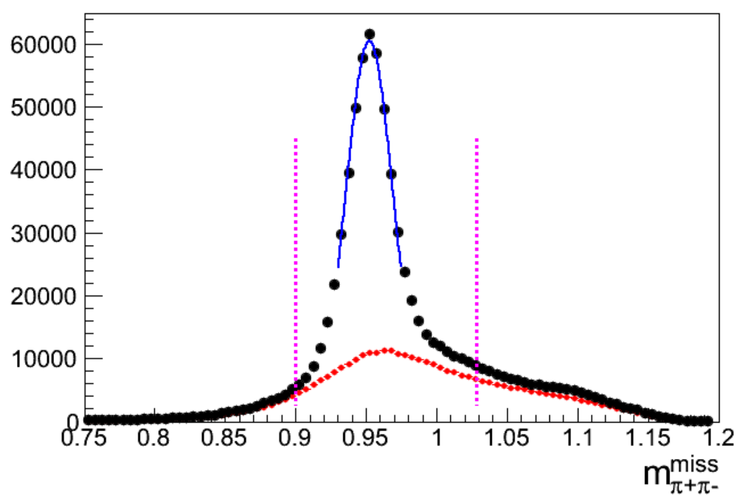
π^- p @ 0.656, 0.69, 0.748, 0.8 GeV/c

- (CH2)n polyethylene target, PE and carbon(C) target,
- **elastic scattering identification**: **$\pi^- p \rightarrow \pi^- p$,**
- **two-pion identification** in channel: **$n\pi^+\pi^-$, $p\pi^-\pi^0$** (exclusive channels via missing mass), partial wave analysis focused on N(1520) and ρ production,
- **dilepton identification** in channel: **ne^+e^-** (quasi-exclusive channel) baryon resonance Dalitz decays and two-body ρ decay.

π- p @ 0.656, 0.69, 0.748, 0.8 GeV/c



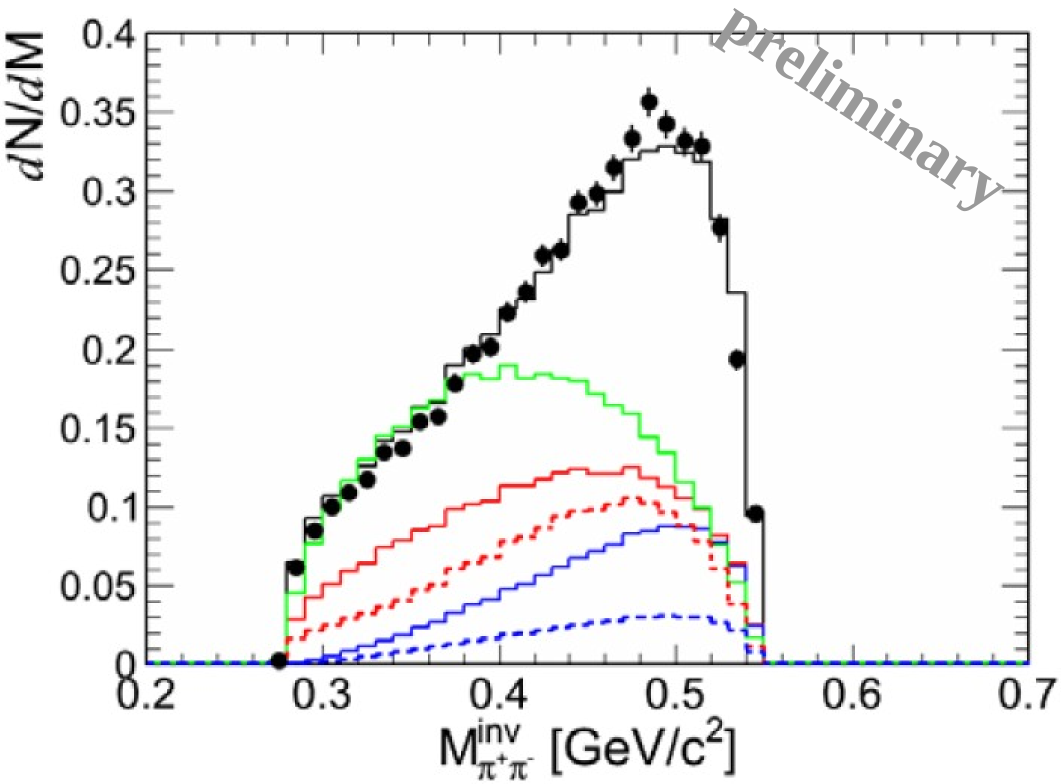




- red: 35-42% C backgr. (quasi-free πp)
- peak shift due to energy loss in a target

statistics of existing database increased by more than 2 orders of magnitude (> 4*10⁷ events for each √s)

PWA Results (n π+π-) by Bonn-Gatchina Group



GOAL:

extraction of

N(1520) BR

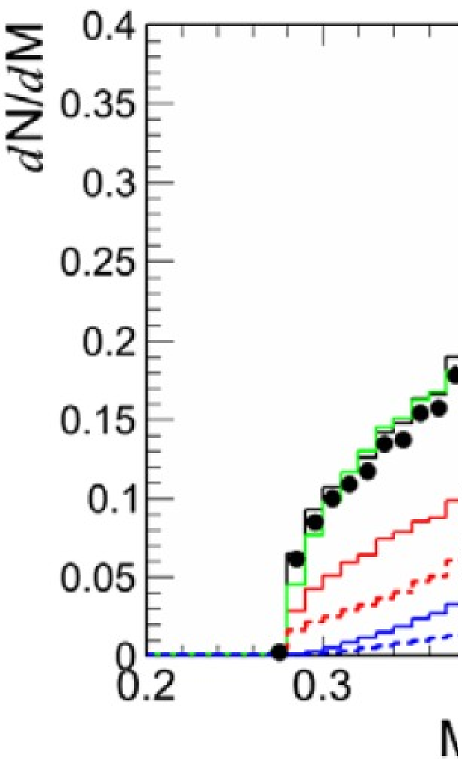
to Δπ, ρN,

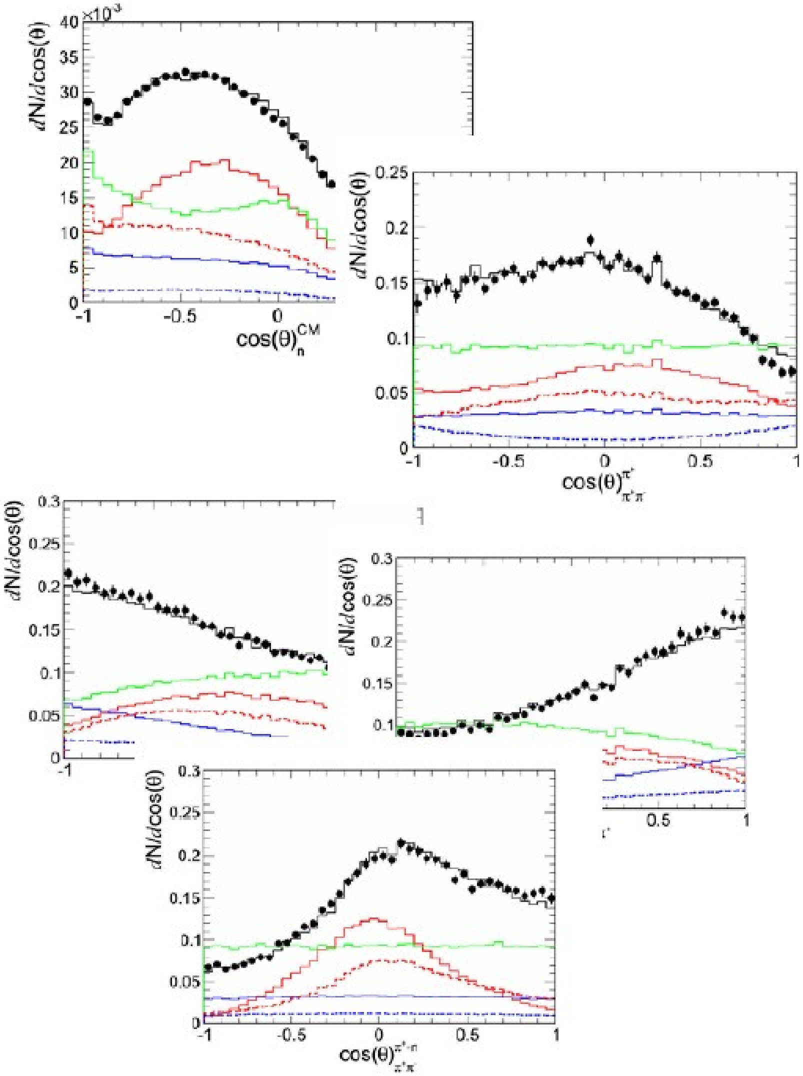
σN

ρN - **input for dilepton analysis**

— σN(939) — Δ(1232)π — ρN(939) | - - - N(1520) - - - ρN

PWA Results (n π+π-)





L:

ction of

20) BR

, ρN,

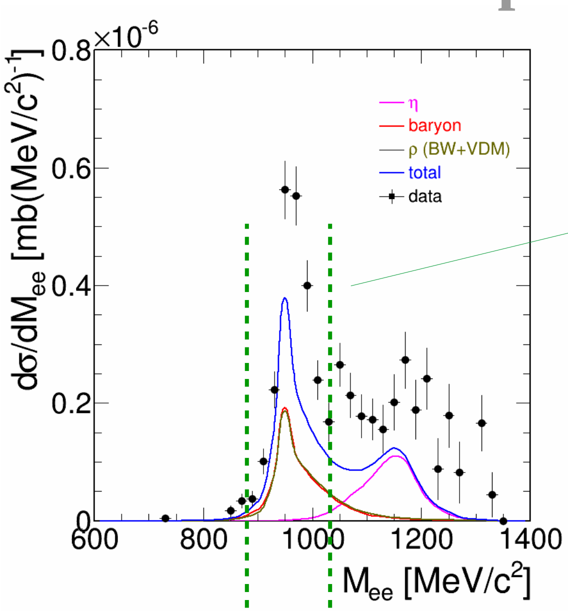
nput for dilepton

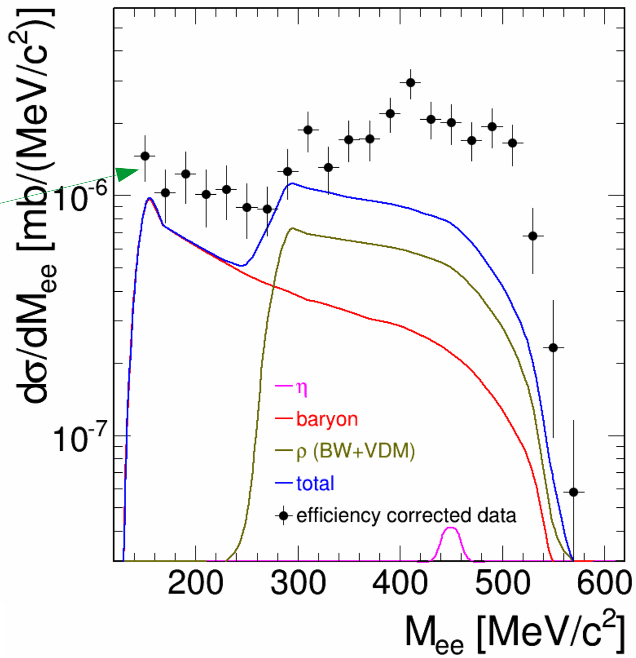
nalysis

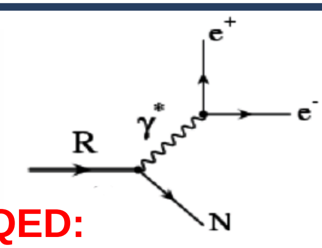
σN(939) - - N(1520) - - - ρN

Exclusive π^- $p \rightarrow e^+e^- n$ @ $\sqrt{s}$~1.5 GeV

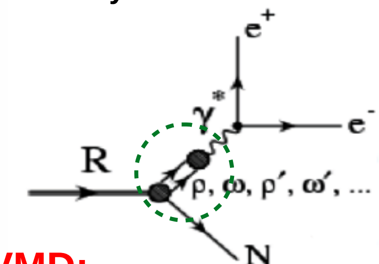
preliminary







QED:
point-like R-γ^* vertex
M. Zetenyi/M. I. Krivoruchenko



VMD:
em. transition FF (M_{ee})

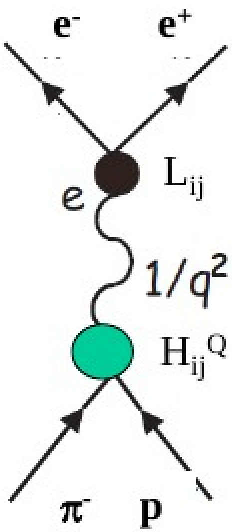
Models - coctail simulations:

- **baryon (?)** – "QED" calculated as only D13(1520) Dalitz (with σ of π^- $p \rightarrow n\gamma$),
- very strong contribution from **ρ** (**using strict VMD**),
- ρ meson contribution derived from PWA of 2 pion channels ($n\pi^+\pi^-$, $p\pi^-$ π^0)

measured in the same experiment !

$\pi^- p \rightarrow e^+ e^- n$ – Formula for Lepton Production

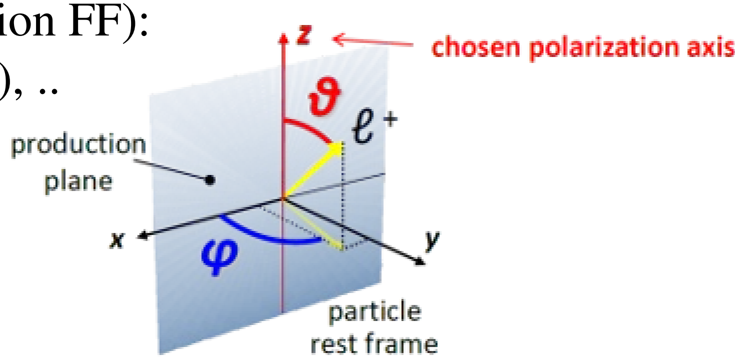
$$d\sigma = \frac{(2\pi)^4}{4|k|\sqrt{s}} \left(H_{\mu\nu} \frac{e^2}{Q^4} L^{\mu\nu} \right) d\Phi^3_{ne+e-},$$



$H_{\mu\nu}$ (hadronic tensor) - hadron production and decay to γ^* (dependence on spin and parity of the transition FF): input either from theory or from data (PWA), ..

$L_{\mu\nu}$ (lepton tensor) - transition $\gamma^* \rightarrow$ e+e- (**known from QED !**)

$d\Phi$ - phase space factor



E. Speranza et al., Phys.Lett.B764 (2017) 282-288

$$d\sigma \sim \sum_{pol} |A|^2 = \sum_{\lambda,\lambda'} \rho^{had}_{\lambda,\lambda'} \rho^{lep}_{\lambda,\lambda'}$$

Spin Density Matrix Elements (SDME):

$\rho^{had}_{\lambda,\lambda'} = \epsilon^{\mu}(k,\lambda) H_{\mu\nu} \epsilon^{\nu}(k,\lambda')^*$ hadron decay to γ^*

$\rho^{lep}_{\lambda,\lambda'} = \epsilon^{\mu}(k,\lambda) L^{\mu\nu} \epsilon^{\nu}(k,\lambda')^*$ γ^* decay to e+e- (QED)

virtual photon polarization (in the helicity basis):

transverse $\epsilon^{\mu}(k,-1) = \frac{1}{\sqrt{2}}(0,1,-i,0)$

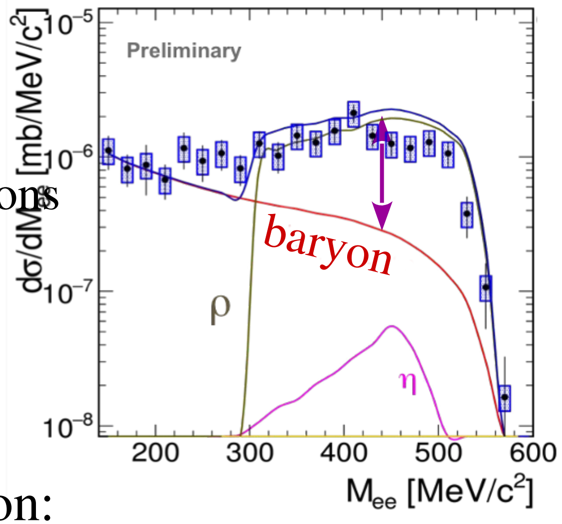
longitudinal $\epsilon^{\mu}(k,0) = (0,0,0,1)$

transverse $\epsilon^{\mu}(k,+1) = \frac{1}{\sqrt{2}}(0,1,i,0)$

$\pi^- p \rightarrow e^+ e^- n$ – Angular Distributions

$$\frac{d\sigma}{dM d\cos\theta_{\gamma^*} d\cos\theta_e} \sim \sum_{\lambda,\lambda'} \rho^{had}_{\lambda,\lambda'} \rho^{lep}_{\lambda,\lambda'}$$

known from QED



- invariant mass shows deviation from point-like baryon transitions
- additional information on the electromagnetic transitions can be provided by the angular distribution
- SDME depend on m_{γ^*}, $z = \cos\theta^{\gamma^*}_{CM}$

general formula for $\gamma^* \rightarrow e^+e^-$ angular distribution:

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

4 parameters: $\theta_{e+,e-}, \varphi_{e+,e-}, m_{\gamma^*}, z = \cos\theta^{\gamma^*}_{CM}$

→ SDME can be extracted from fit to the angular distributions

Separation of Resonance Contributions

→ microscopic model including N(1440) and N(1520) excitations in s and u-channels and VDM electromagnetic form factors

E. Speranza et al., Phys.Lett.B764 (2017) 282-288

$$\frac{d\sigma}{dMd\cos\theta_{\gamma^*}d\cos_e} \propto \Sigma_\perp(1+\cos^2\theta_e) + \Sigma_\parallel(1-\cos^2\theta_e)$$

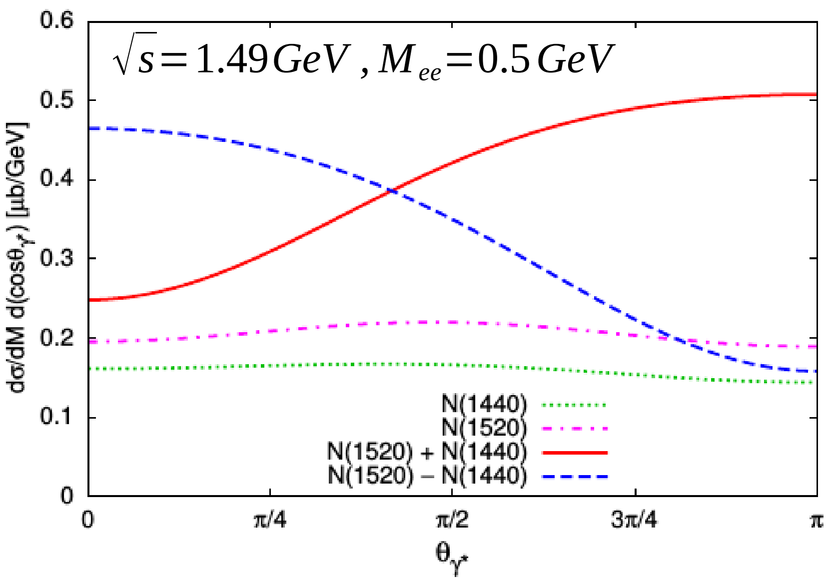
$$\propto A(1+\lambda_\theta(\theta_{\gamma^*},M)\cos^2\theta_e)$$

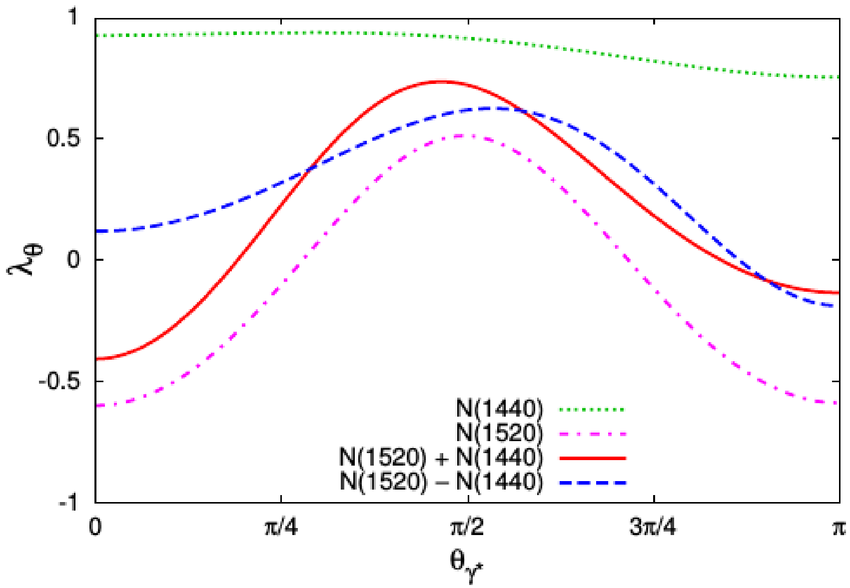
$$\lambda_\theta = \frac{3\rho_{11}-1}{1-\rho_{11}}$$

anisotropy coefficient

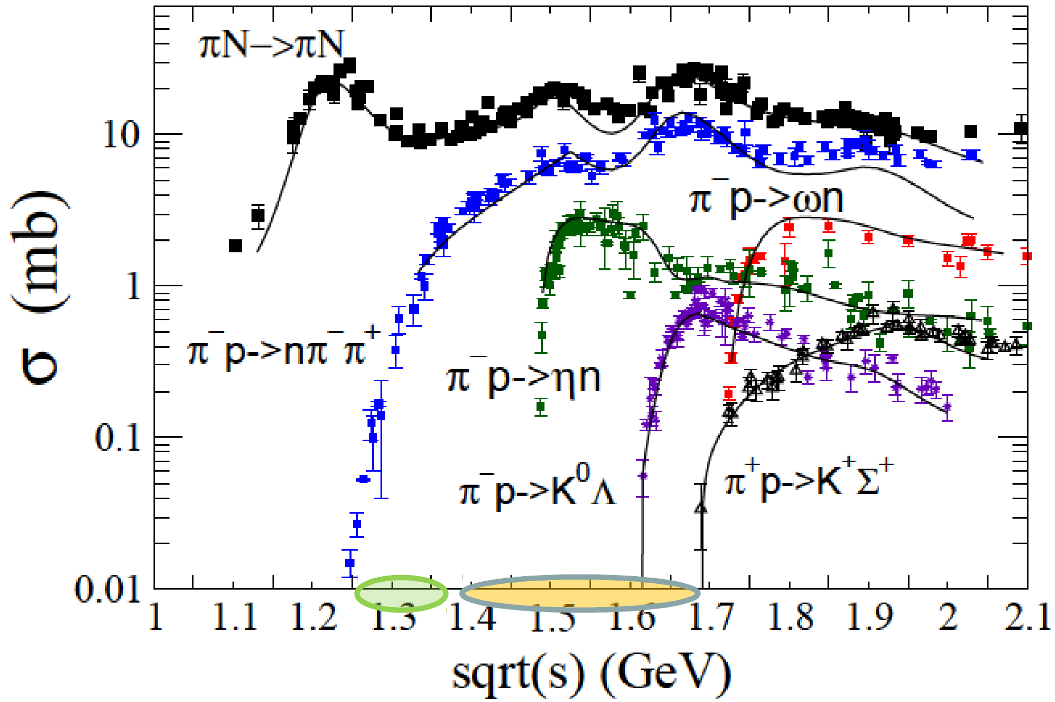
→ info on the virtual photon polarization

angular distributions depends on spin and parity of resonance state (λ_θ from the model):





HADES Physics Program with Pion Beams – Near Future



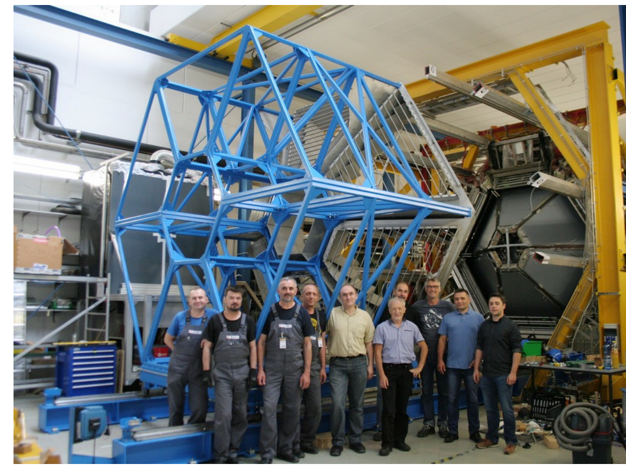
2014 2019 (?)

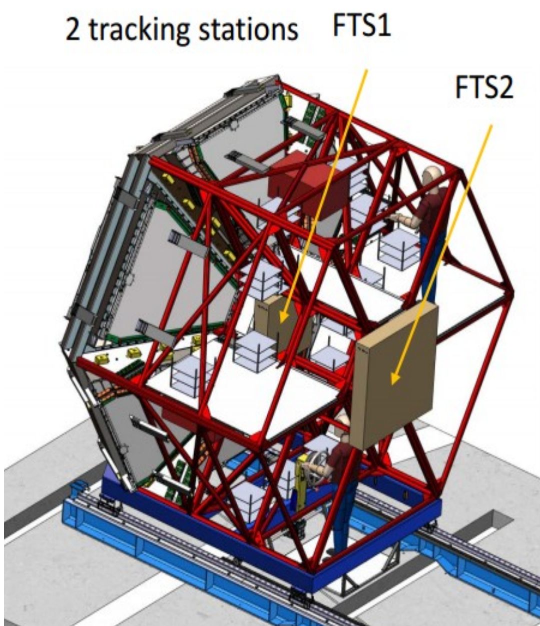
- High statistics beam energy scan : continuation and extension to third resonance region
- Hadronic final states, one pion, 2 pion, hyperon production to control resonance excitation (HADES upgrade with el. calorimeter ! neutral final states: η/π/ ω)
- Dielectron measurements : ρR couplings S31(1620), D33(1700), P13(1720),..

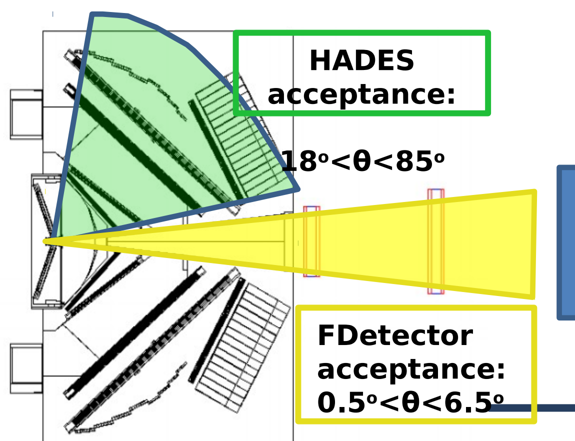
Outlook
Phase 0/FAIR : joined effort with PANDA/CBM

- **Tracking stations** (FTS1, FTS2) based PANDA Straw technology (Krakow)(IFJ, UJ, AGH)
- **Forward TOF** based on RPC
- New **ECAL (lead glass)**
- New **RICH photon detector**

- **π +p /π+A**
- p+p, p+A @ max energy @ SIS18 (4.5 GeV)
- A+A

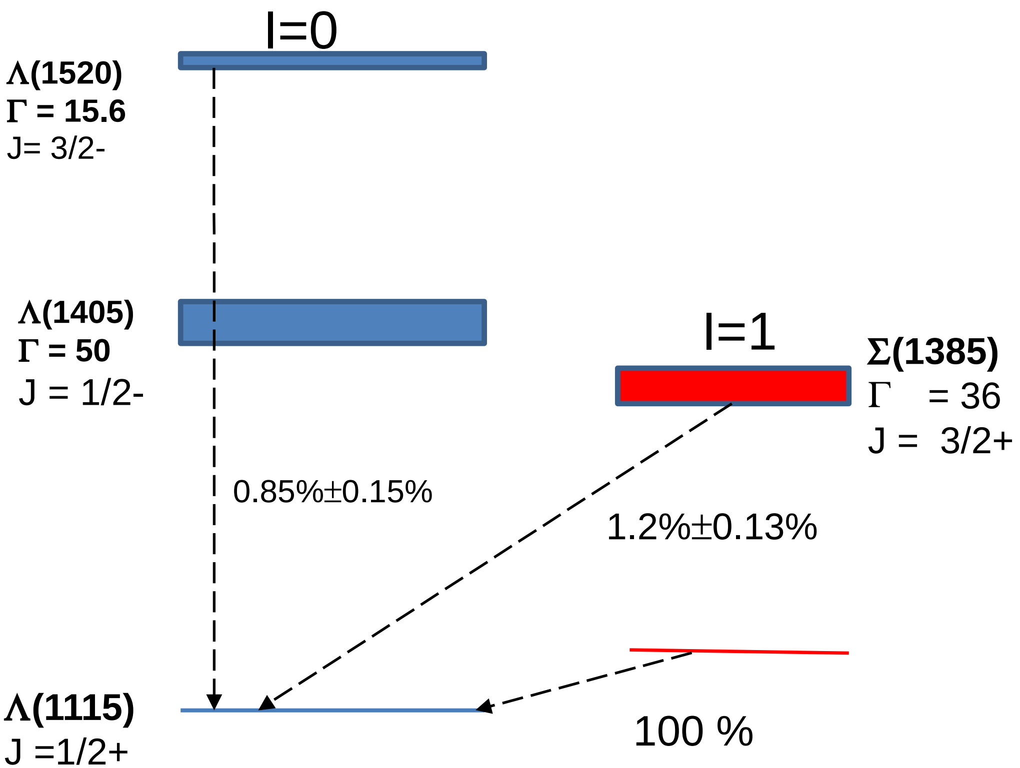




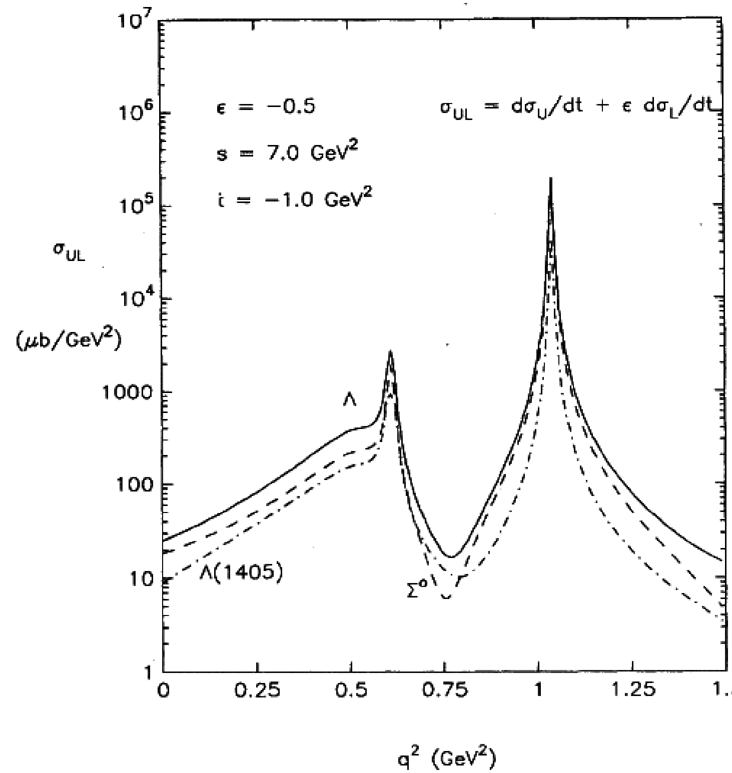


Electromagnetic Decays of Hyperons

- Em. Decays are important for baryon structure
- Possible with upgraded HADES detector (DAQ/ECAL/Forward Detector) at SIS18,SIS100
- Complementary to PANDA programme of Hyperon Spectroscopy in p-pbar



Predictions for K-p→Y*→Ye+e-



VMD:R. Williams et. al. PRC48(1993)

Very strong VM contribution

- Only very few Y→Λγ transitions are known !
- No Y→Λe+e- ever measured

Summary

- **HADES & pion beam** is an unique tool to understand in details baryon ρ couplings and em. decays of baryon resonances,
- Strong contribution to e+e- production from resonance decays along the VDM but more detail investigations will follow (microscopic models, PWA with e+e-..),
- Large impact on interpretation of e+e- production in pA and AA,
- Exciting possibility to continue this physics with upgraded HADES at FAIR.

Thank You

for

Your Attention