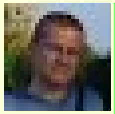
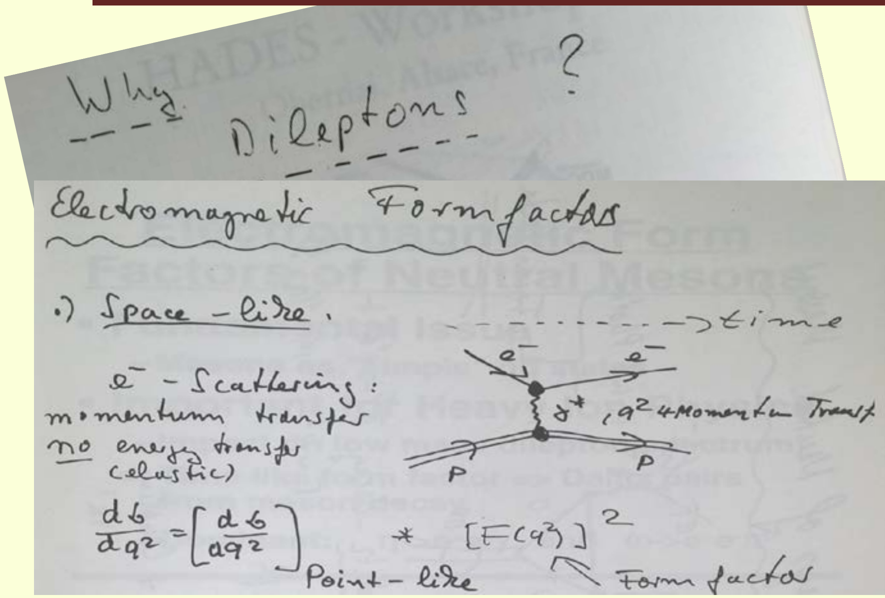
# Probing of dielectron decays of baryon resonances with HADES

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS 37th Course
Probing Hadron Structure with Lepton and Hadron Beams
16-24 September 2015, Erice



Witold Przygoda (HADES Collaboration)
Jagiellonian University in Kraków, Poland

# A bit of history… 20 years ago




## Why dileptons?

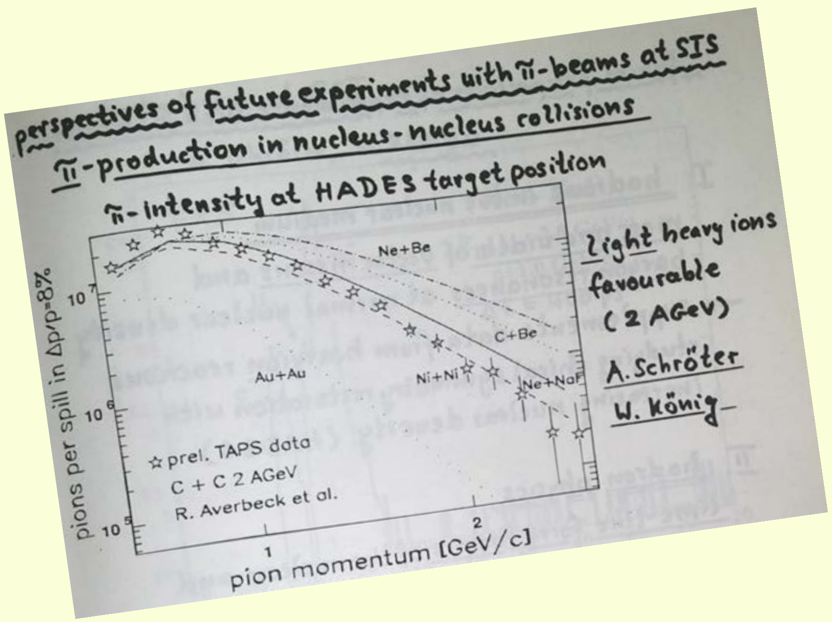
*Guy Roche*

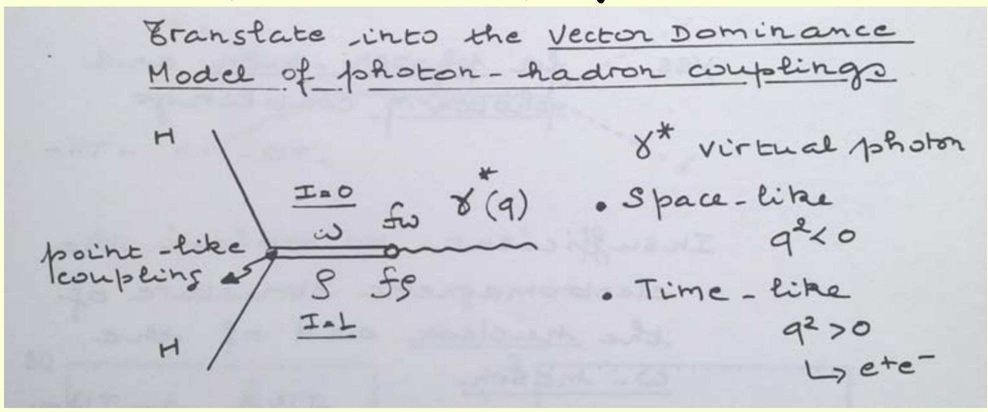
*( probe hadron strucure )*

## Dileptons from hadronic reactions

*Bengt Friman and Madeleine Soyeur*

*( Vector Dominance Model: working horse dilepton-hadron coupling )*

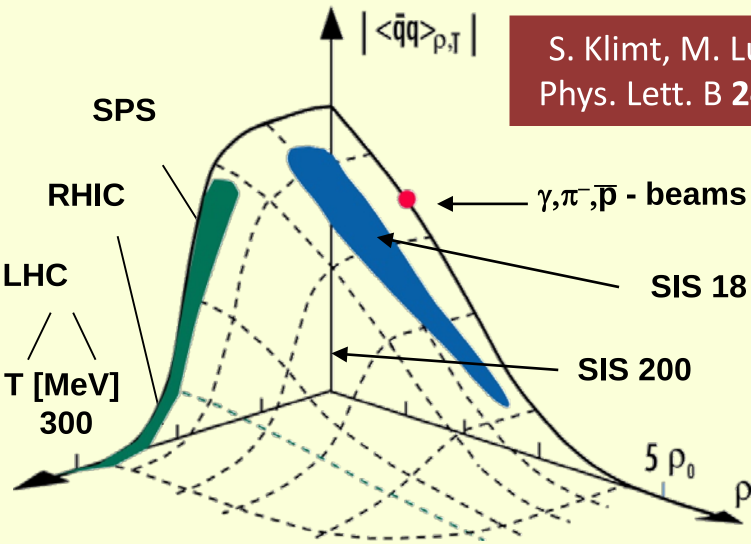



## Physics with Pion Beams at GSI

*Volker Metag*

# dileptons: probes of vector meson in medium




S. Klimt, M. Lutz, W. Weise
Phys. Lett. B **249** (1990) 386

## early motivations

G.E. Brown, M. Rho
Phys. Rev. Lett. **66** (1991) 2720

scaling of masses with $\chi$-condensate
order parameter of $\chi$S restoration

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

T. Hatsuda, S.H. Lee
Phys. Rev. C **46** (1992) 34

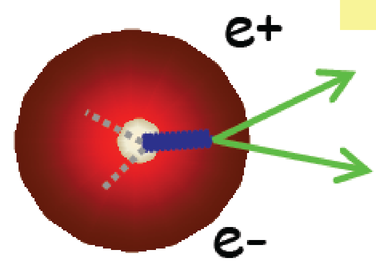
QCD sum rules

$$m^* = m(1 - \alpha\rho^* / \rho)$$

## « short-lived mesons in medium »

p/π/γ/A + A

$$m_{e+e-} = \sqrt{p_{e+}p_{e-}}\,\sin\frac{\vartheta_{e+e-}}{2}$$




best candidate
$\rho(770)$ $1^{--}$ $c\tau$ =1.3 fm/c
$\Gamma$=150 MeV

- **rare probes** $(e^+e^-\ BR{\sim}10^{-5})$

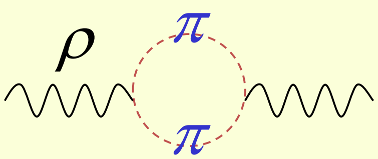
***but***

- **do not interact strongly** with nuclear matter

# ρ in-medium: hadronic models

## baryons are the main players

**« vacuum »**

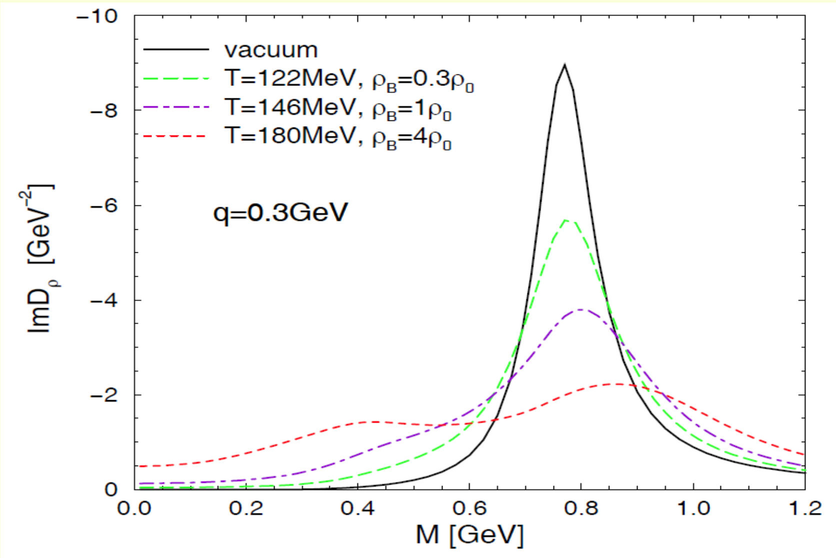



$$\Sigma_\rho(M) = -i m_\rho \Gamma_{\pi\pi}(m)$$
$$m_\rho = 0.77 GeV$$

S. Leupold, V. Metag, U. Mosel
Int. J. Mod. Phys. E **19** (2010) 147

**« in-medium broadening »**

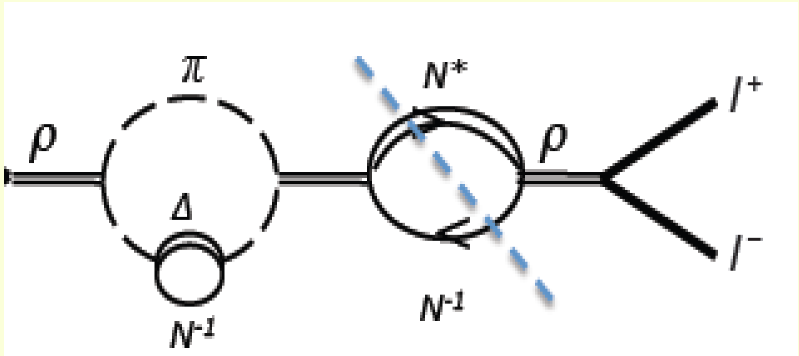
**in-medium spectral function depends on ρNN* coupling**
*main players:*
N(1520), Δ(1620) , N(1720), ….




*Explanation of dilepton spectra (RHIC, SPS, HADES)*

R. Rapp, G. Chanfray, J. Wambach
Nucl. Phys. A **617** (1997) 472

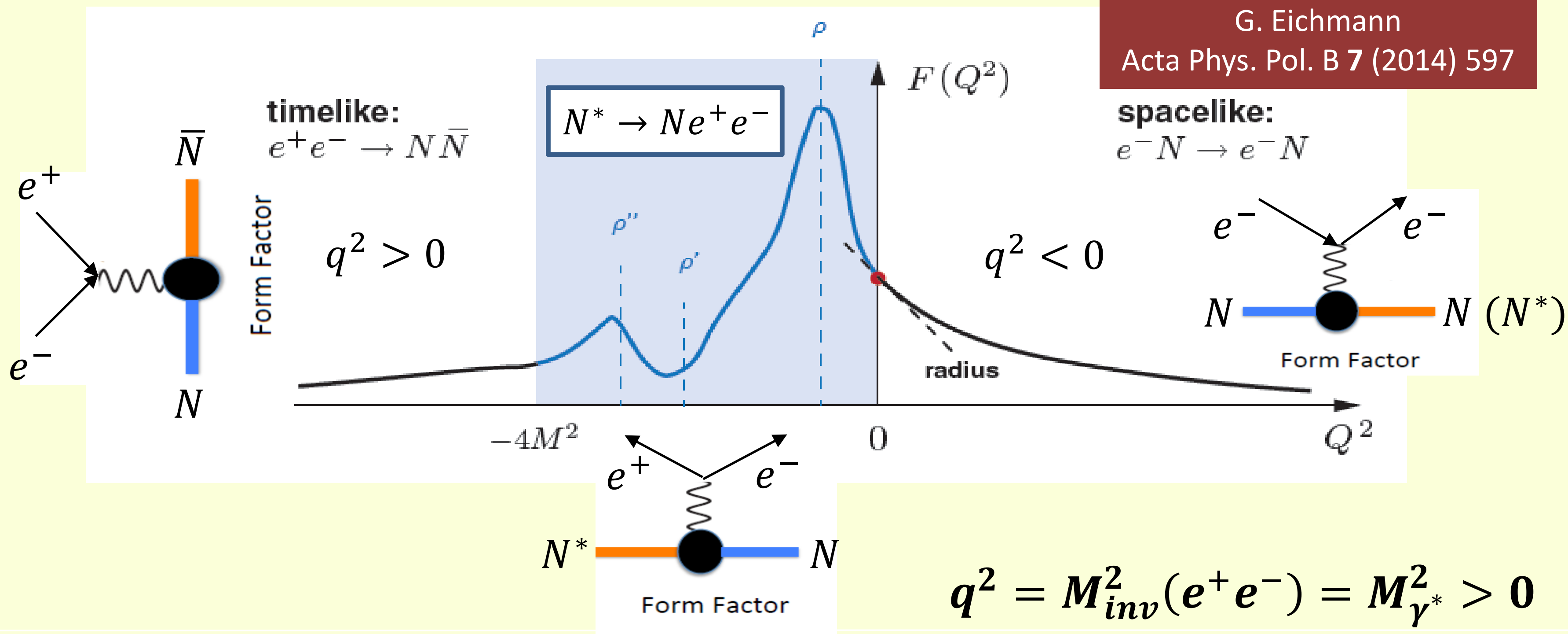
R. Rapp, J. Wambach
Eur. Phys. J. A **6** (1999) 415




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

# relation to electromagnetic structure of baryons

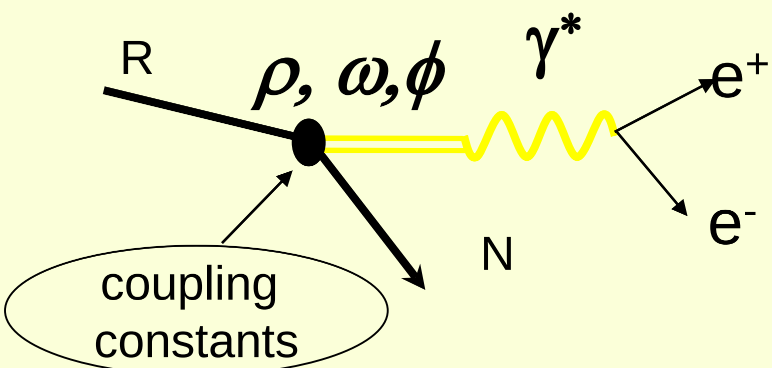
G. Eichmann
Acta Phys. Pol. B **7** (2014) 597

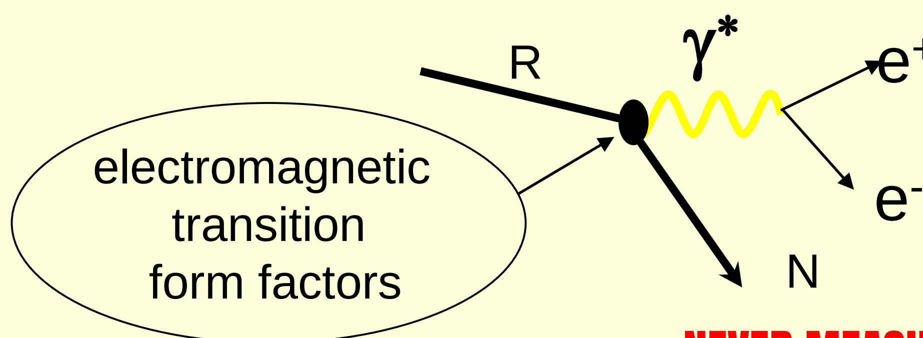



$$q^2 = M^2_{inv}(e^+e^-) = M^2_{\gamma^*} > 0$$

« ρ meson production and decay »

« Dalitz decay of baryonic resonances »




**NEVER MEASURED!**

***Vector Meson Dominance Model***

# Resonances: description and Dalitz decays

Resonance description: $W$ - arbitrary resonance mass

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

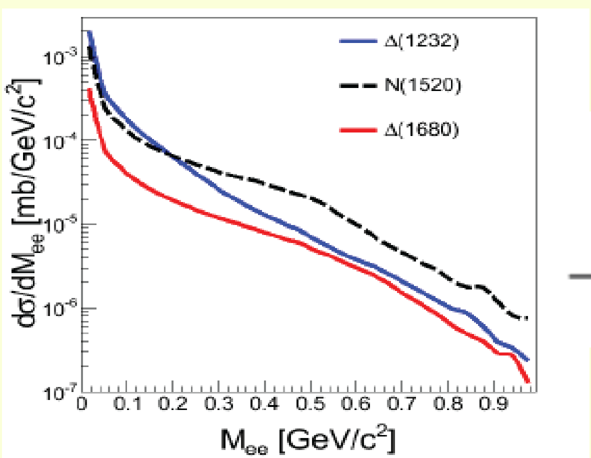
with $\Gamma_{tot}(W) = \Gamma_{\pi N}(W) + \Gamma_{\gamma N}(W) + \boldsymbol{\Gamma_{e^+e^-N}(W)} + \ ...$

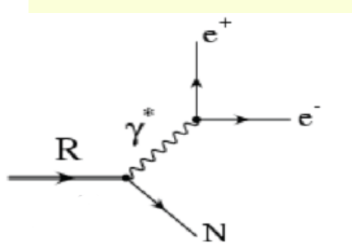
Dalitz decay requires a model for the form factors in the timelike region

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

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

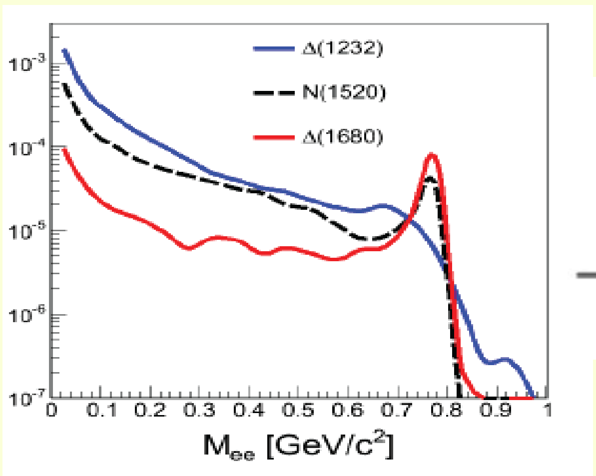
- coupling constants fixed from $R \to N\gamma$
- strong dependence on spin, parity

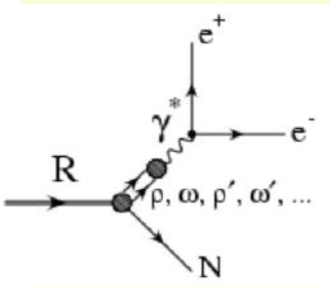



**Extended VDM**

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



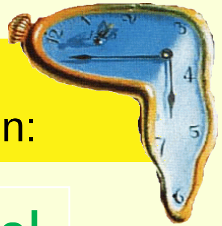



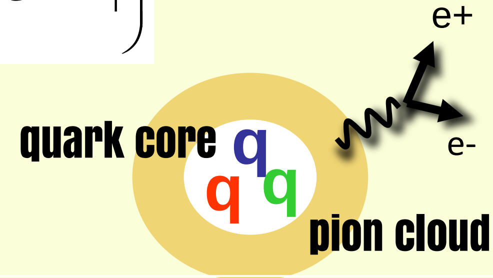
# Example: $\Delta \rightarrow Ne^{+}e^{-}$

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

$$\frac{d\Gamma(\Delta \rightarrow Ne^{+}e^{-})}{dq^{2}} = f\left(m_{\Delta}, q^{2}\right)\left(\left|G_{M}^{2}(q^{2})\right| + 3\left|G_{E}^{2}(q^{2})\right| + \frac{q^{2}}{2m_{\Delta}^{2}}\left|G_{C}^{2}(q^{2})\right|\right)$$

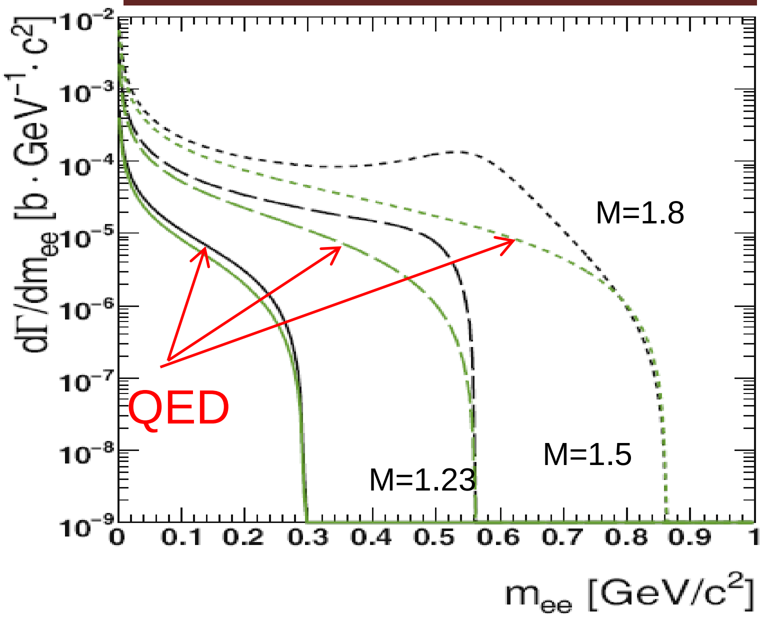
**Time Like** ($q^2 > 0$)
$\Delta$ (J=3/2) ->N (J=1/2) $\gamma^*$ transition:





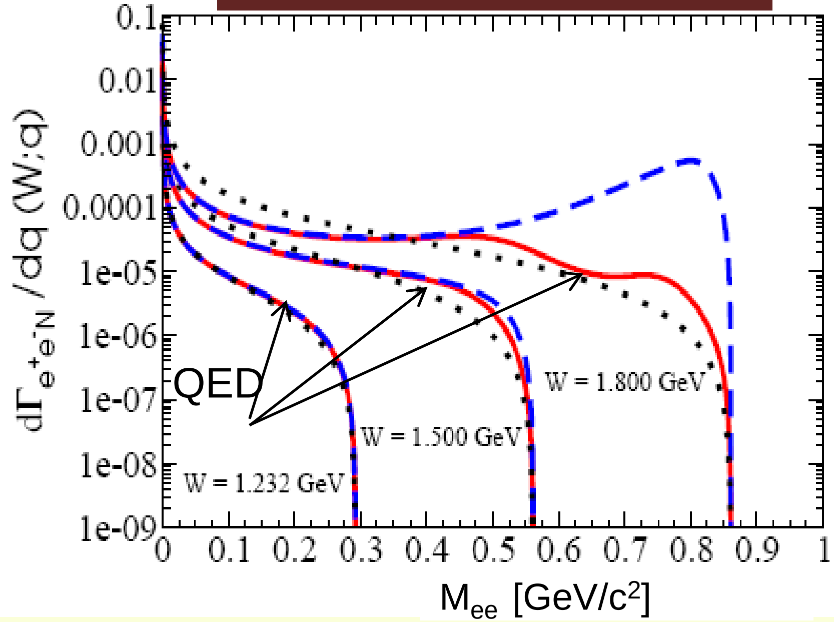

## two-component quark model

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

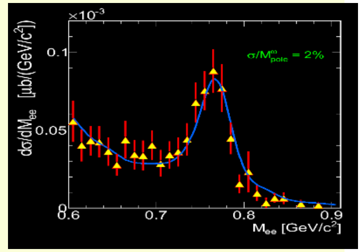


# HADES Spectrometer

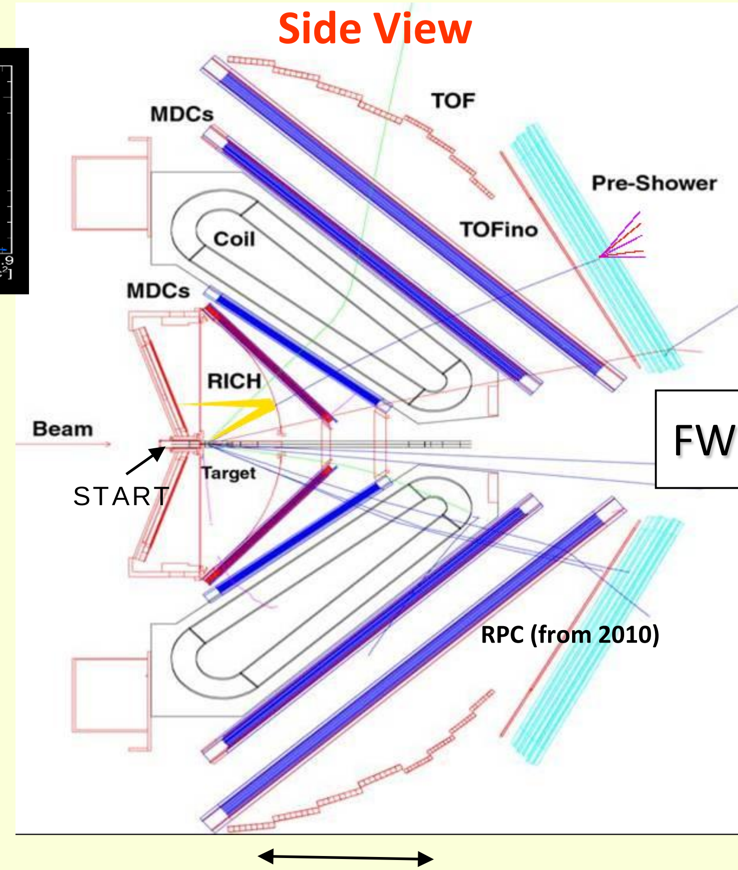
- SIS18 beams: protons (1-4 GeV), nuclei (1-2 AGeV) pions (0.4-2 GeV/c) – secondary beam
- spectrometer with $\Delta M/M$ - 2% at $\rho/\omega$
- **detector for rare probes:**

  dielectrons: e+, e-

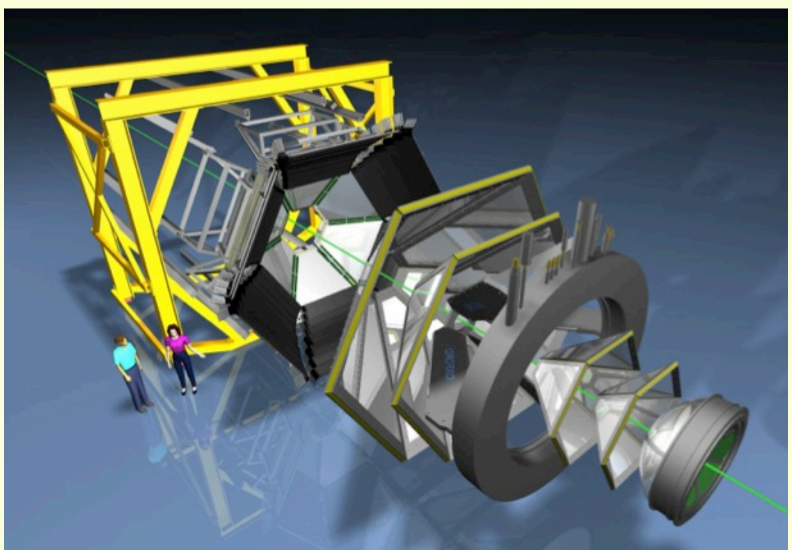
  strangeness: $\Lambda$, $K^{\pm,0}$, $\Xi^{-}$ , $\varphi$




- particle identification $\pi$/p/K – combined dE/dx (MDC) and TOF : $\sigma_{tof}$ ~80 ps (RPC)
  **electrons** : RICH (hadron blind), TOF/Pre-Shower
- upgrade(2010): new DAQ (~50 kHz) with Au+Au collisions




1 m



## Geometry

- full azimuthal, polar angles 18° - 85°
- $e^+e^-$ pair acceptance $\approx$ 0.35

HADES

p (1.25 GeV) + p

both hadron and dilepton exclusive channels measurement

- resonance production controlled via pion excitation
- resonance decay in dilepton exclusive channels

$\pi^- + p$

(0.656, 0.69, 0.748, 0.8 GeV/c)

p (3.5 GeV) + p

# p+p @ 1.25 GeV – resonance production

- **below ppη production threshold**

**Cross sections production extraction – one-pion channels identification**

## Resonance model

Z. Teis *et al.*,
Z. Phys. A**356** (1997) 421

V. Dmitriev *et al.*
Nucl. Phys. A**459** (1986) 503

- **incoheren**t sum of resonance contributions
- empirical angular distributions (t-channel)

G. Agakishiev *et al.*
Eur. Phys. J. A**48** (2012) 74

## Partial Wave Analysis

**Bonn-Gatchina group**

**maximum log-likelihood event-by-event**

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

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

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

**initial NN system**

**system of two final particles**

**two-final particle system and spectator**

**transition amplitude**

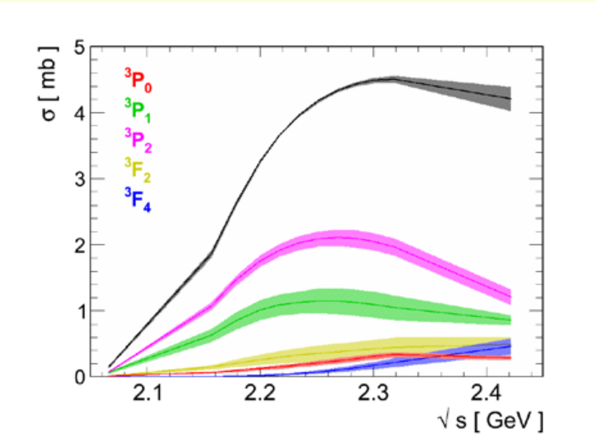
**final state amplitude (resonant, non resonant)**

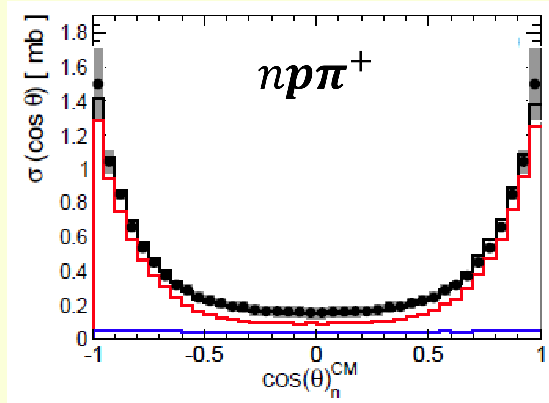
$$A^{\alpha}_{tr}(s) = \frac{a^{\alpha}_1 + a^{\alpha}_3\sqrt{s}}{s - a^{\alpha}_4}\, e^{i a^{\alpha}_2}$$

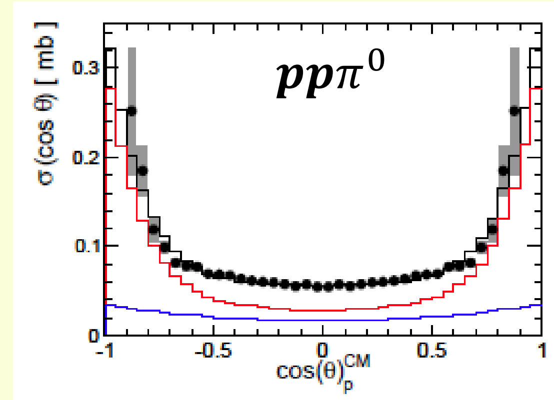
# PWA results: (π⁺, π⁰) production in pp@1.25 GeV

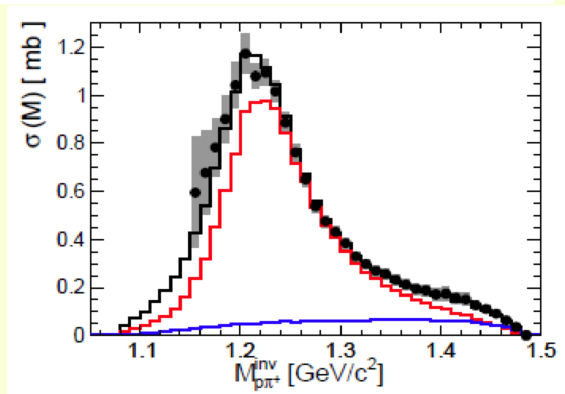
**13 PNPI + 2 HADES data sets**

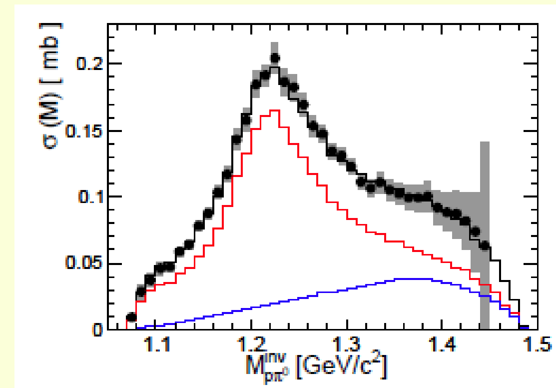
## J truncation (J=4)



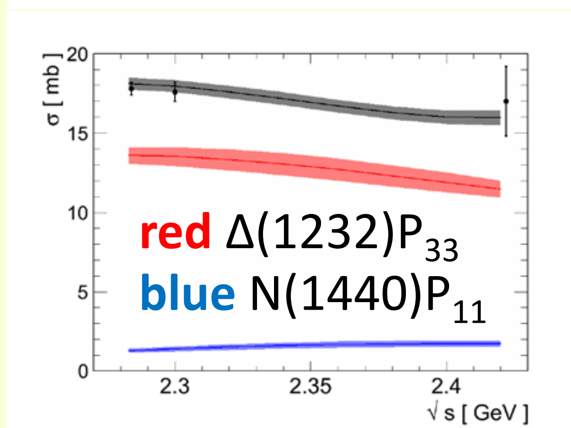



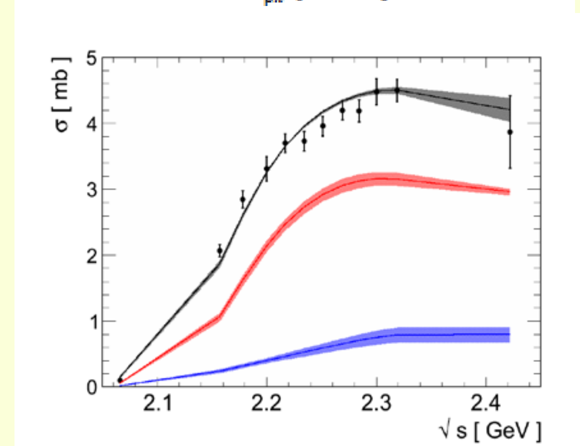




**FINAL STATES**

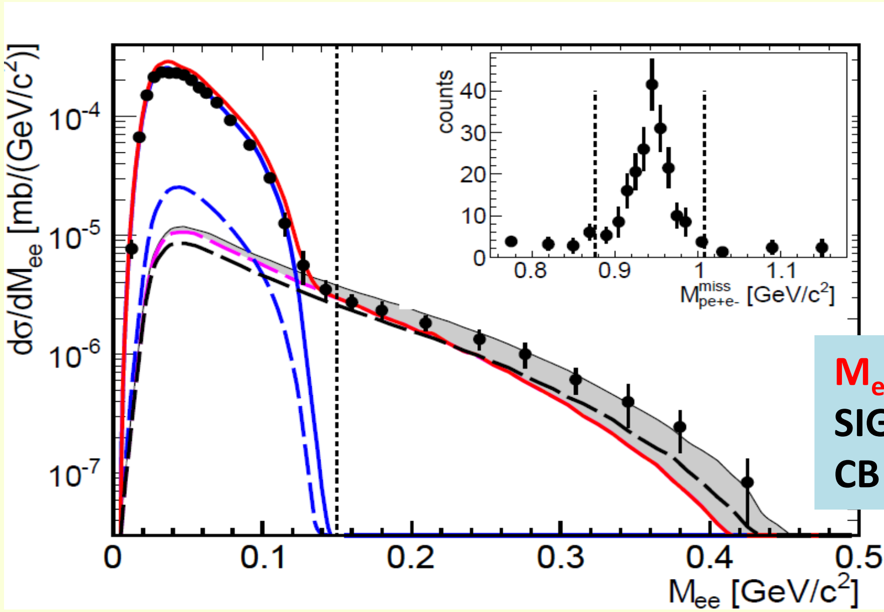
S-, P-, D-waves
in pp or pn-state
$P_{33}$(1232) and
$P_{11}$(1440) in πN state




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

# $\Delta^+$ Dalitz decay via $pn\Delta^+ \{\rightarrow pe^+e^-\}$




**red line** – total
**blue** – $\pi^0$ Dalitz
**magenta** – Δ Dalitz
grey band– (VMD)
dashed – Ramalho/Peña

**Δ Dalitz decay BR**

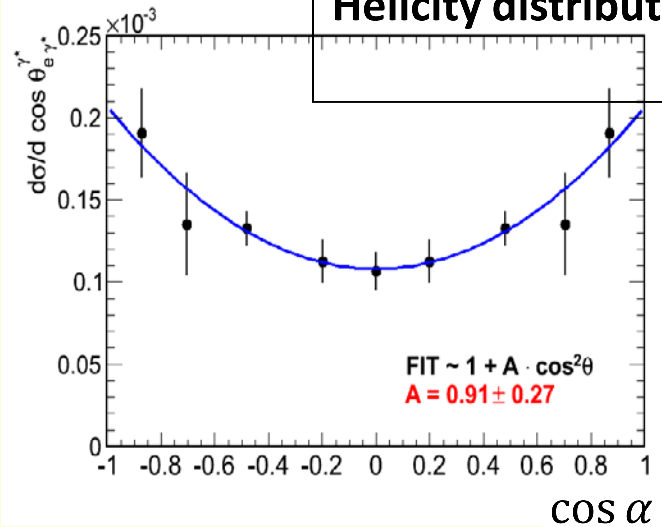
$G_M(0)$~3
$G_E(0)$~0
$G_C(0)$~0

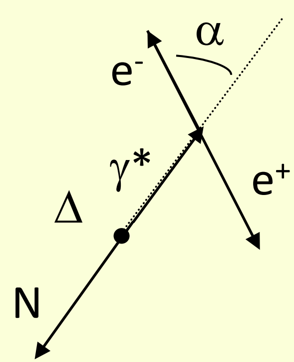
**$M_{ee}$ > 0.15**
**SIGNAL**: 200
**CB**: 15

**preliminary**

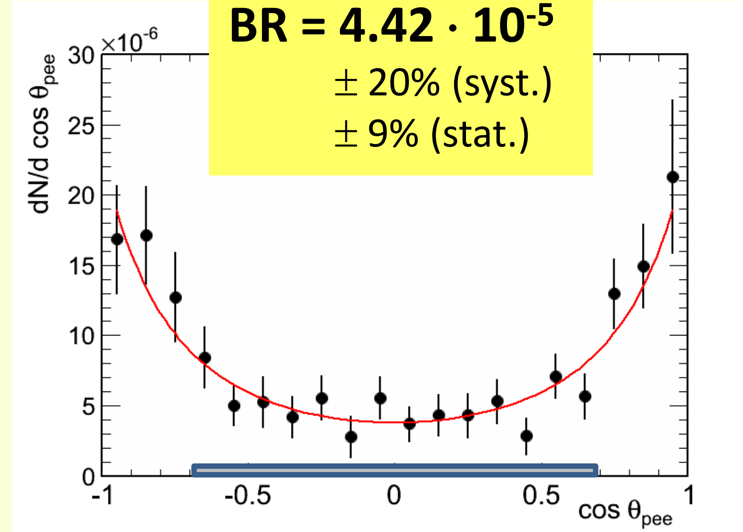
$$BR = \frac{N_{\Delta \rightarrow pe^+e^-}}{N_{\Delta \rightarrow p\pi^0}}$$

**Helicity distributions $\gamma^* \rightarrow e^+e^-$**
**$d\sigma/d\Omega_e \sim 1+\cos^2\alpha$**

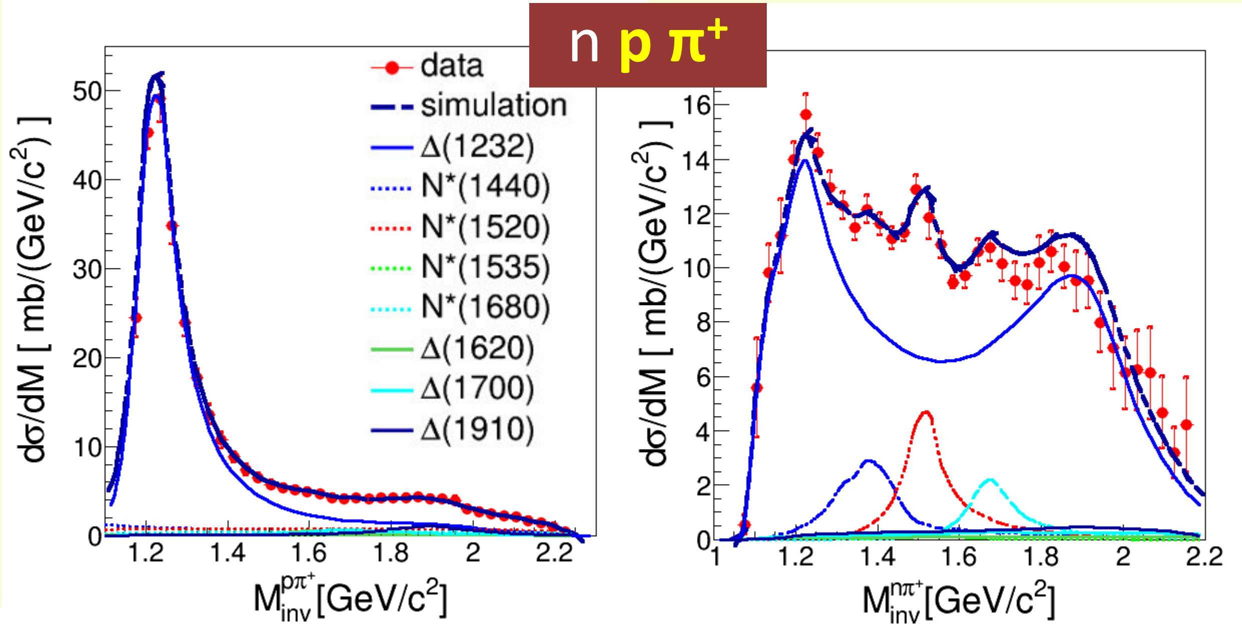


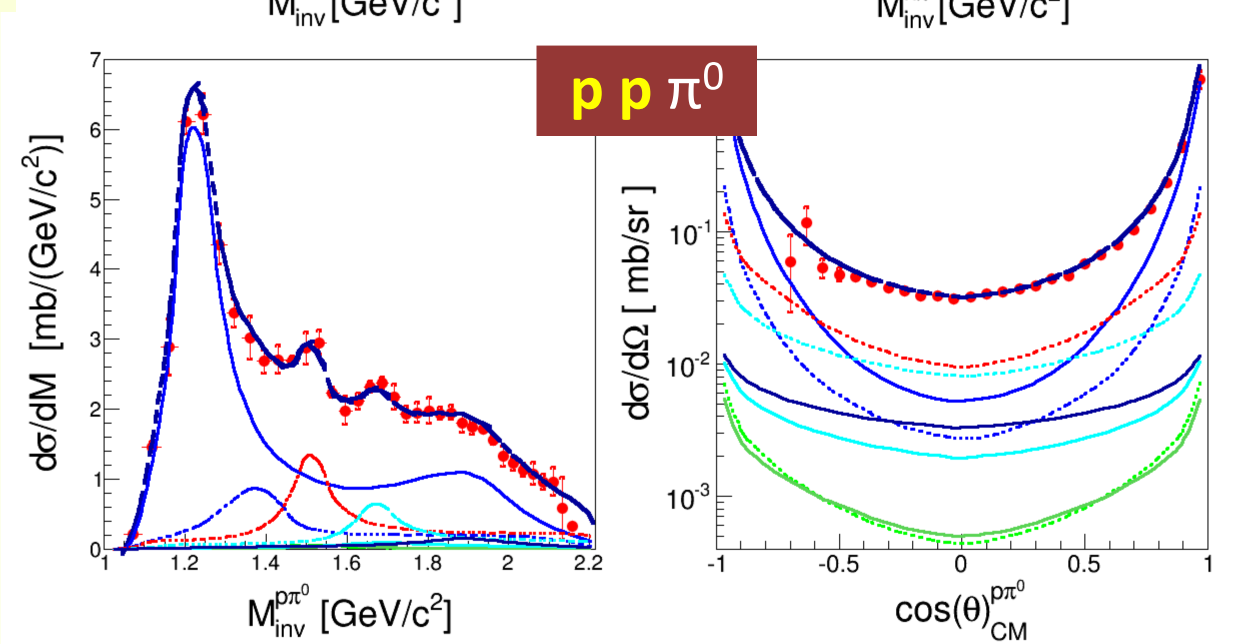




**BR = 4.42 · $10^{-5}$**
± 20% (syst.)
± 9% (stat.)



# Higher resonances: p+p @ 3.5 GeV



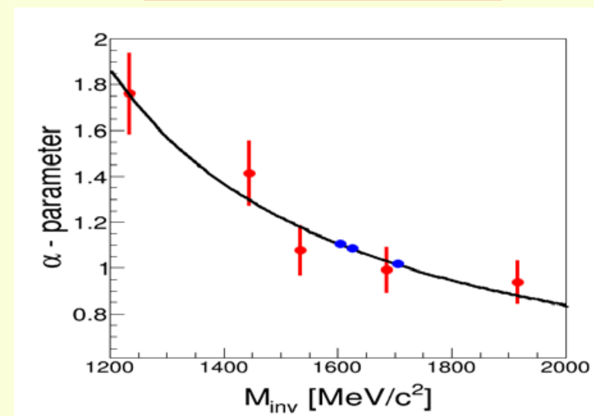




**Resonance model:**

$\Delta^{++}$ (1232)

*very good description of Δ-line shape ("Monitz" parameterization)*

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

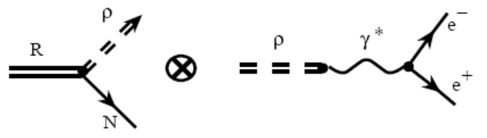


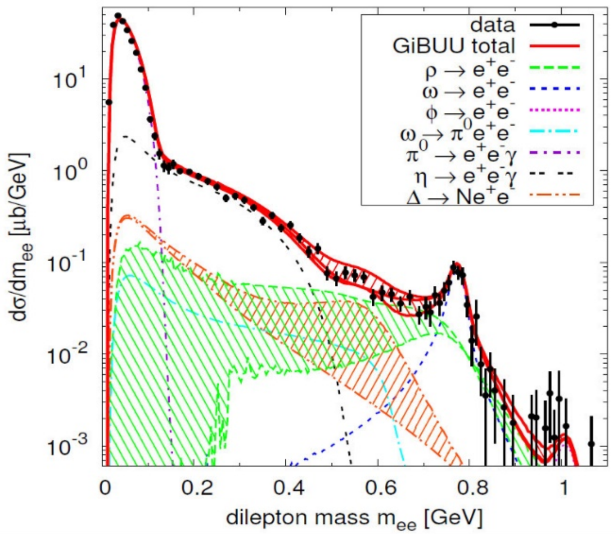

angular parametrisation as a function of ***t*** for **all resonances**

# Inclusive / Exclusive p+p @ 3.5 GeV (dileptons)

G. Agakishiev *et al.*
Eur. Phys. J. A **48** (2012) 64

- ρ mesons produced via baryonic resonances (**R → ρ N → e⁺ e⁻ N**)
- Resonance model with **electromagnetic Transition Form Factor** from model seems to describe nicely data – *only* Δ?



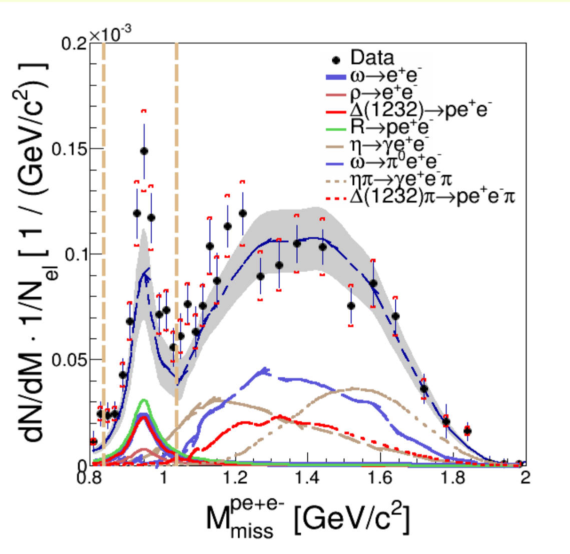




J. Weil *et al.* (**GiBUU**)
Eur. Phys. J. A**48** (2012) 111

**"QED model"**
**point-like R→Nγ* vertex**

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

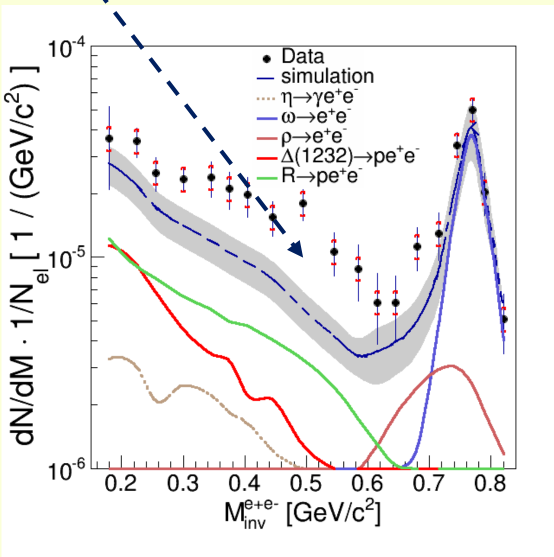
Effect of electromagnetic transition FF / coupling to ρ meson of light baryonic resonances (N(1520),…)




→ lower limit for e⁺e⁻ emission

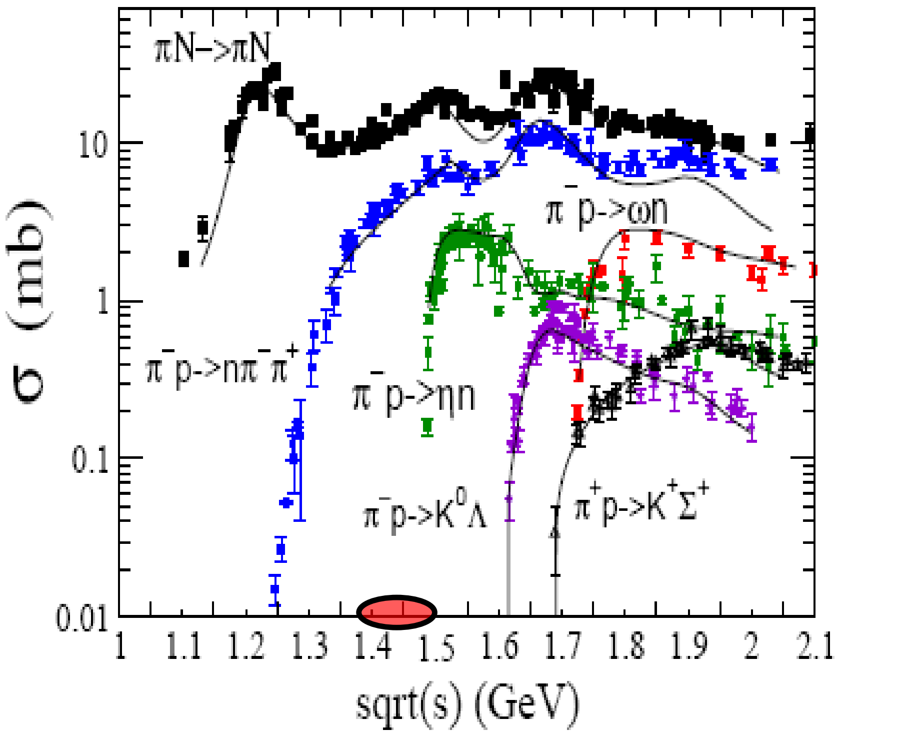
- constant eTTF
- no off-shell coupling to vector mesons
- experimental σ for ω/ρ used

G. Agakishiev *et al.*
Eur. Phys. J. A **50** (2014) 82



# HADES physics for pion beams (2014)

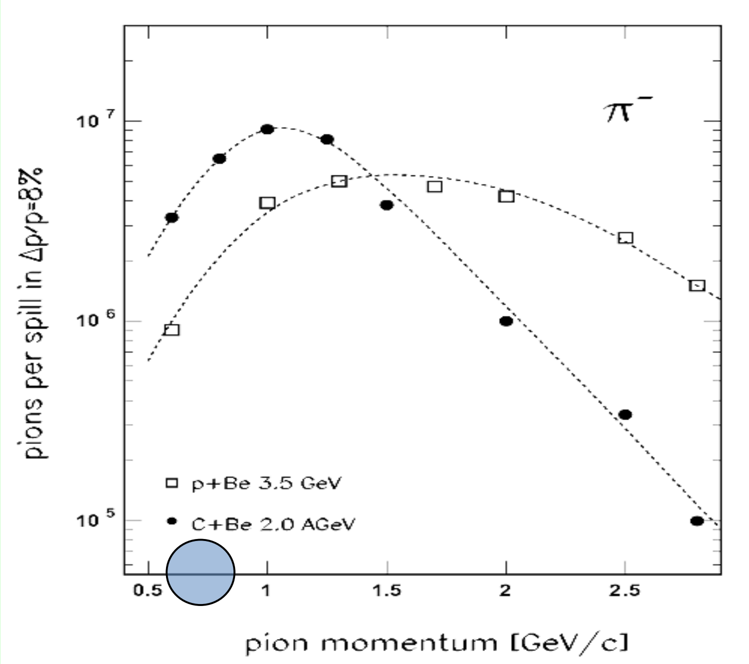
V. Shklyar *et al.* (GiBUU coupled-channel model)
arxiv: 1409.7920v1



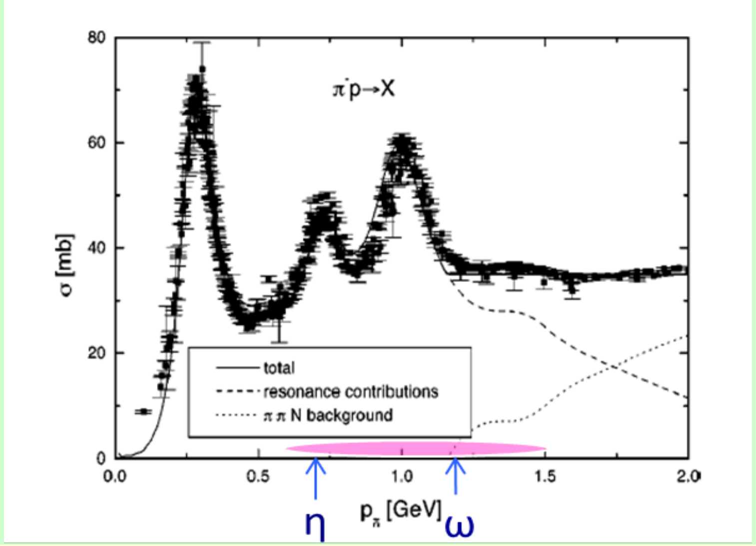

- improve the very scarce data base for pion-nucleon reactions
- differential distributions are even more scarce (or missing)

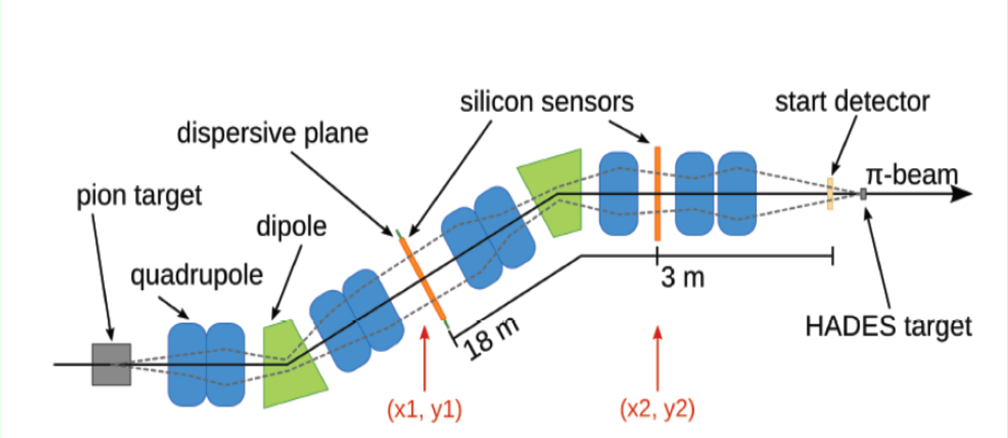
- resonance excitation can be controlled by the variation of the projectile (pion) momentum
- HADES starts with $p = 0.656/0.69/0.748/0.8$ GeV/c $\sqrt{s} = 1.46$-$1.55$ GeV: N(1520)
- $\pi^+\pi^-$ production: coupling of $\rho$ to resonance
- most of data $1.3 < \sqrt{s} < 2$ from Manley *et. al* PRD30 (1984) 904 based on 240.000 events (no differential distributions)
- e+e- never measured from pion induced reactions
- resonance Dalitz decays $R \rightarrow Ne^+e^-$ (reference for p+Nb)
- strangeness production of nucleus: $K^{\pm}$, $K^0$, $\phi$

# pion beam for HADES (2014)




- reaction: N+Be 8-10 · $10^{10}$ $N_2$ ions/spill (4s)
- secondary $\pi^-$ with I~3-4 · $10^5$/spill @ 0.7 GeV/c
  - limited by the radioactivity safety
- pion momentum **Δp/p** = 2.2% (σ) and ~50% acceptance @ central momentum
- in beam tracking system: (X1,Y1/X2,Y2) for pion momentum determination: **Δp/p** = 0.3%



# tools & strategy & objectives

* analysis of single and double meson production in photon- and pion-induced reactions

$$\gamma p \rightarrow \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N, \pi\eta N$$
$$\pi N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma, \pi\pi N$$

* energy dependent approach
* partial wave aplitude parametrization (poles: BW – i.e. energy depentend)
* combined analysis of lareg number of reactions (HADES, CLAS, …)
* D-matrix analysis

* $\pi^- p$ measured with: **$(CH_2)_n$** polyethylene target, **PE** and carbon (**C**) target
* four beam momenta: **656**, **690** (large statistics), **748**, **800** MeV/c
* elastic scattering

  identification: $\pi^- p \rightarrow \pi^- p$

  events from C target identified in PE events

  comparison with SAID database & solution

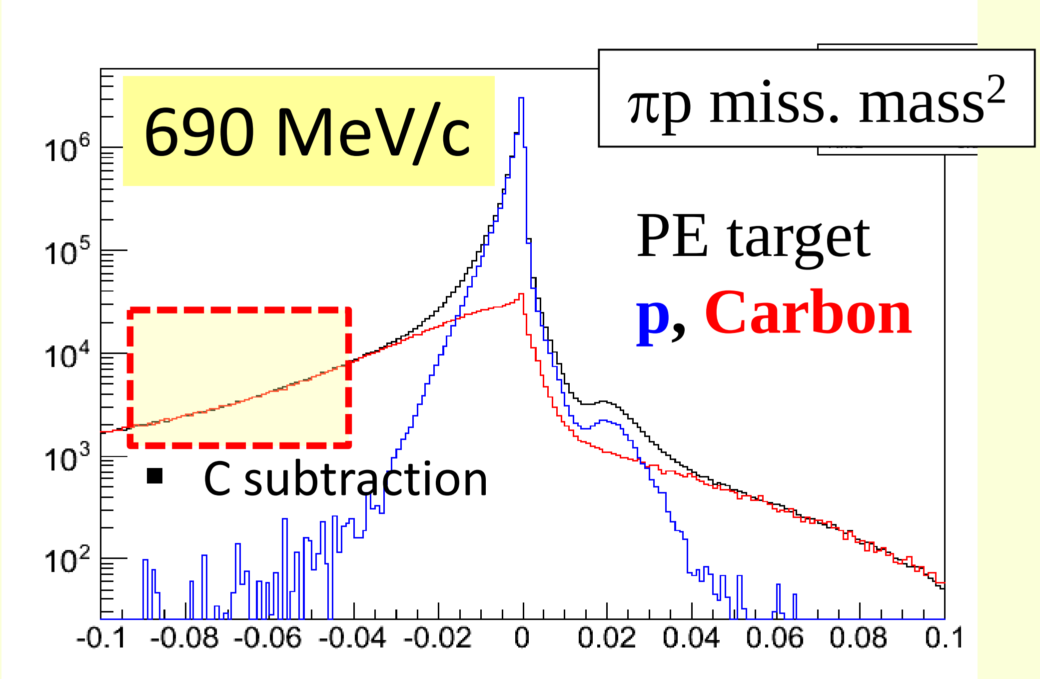
  luminosity extraction : $N_{beam} \otimes \rho\, d_{targ}$

  absolute normalization of other channels via $\sigma_{el}/N_{el}$
* two-pion identification in channel: $n\pi^+\pi^-$ (exclusive channel via missing mass)

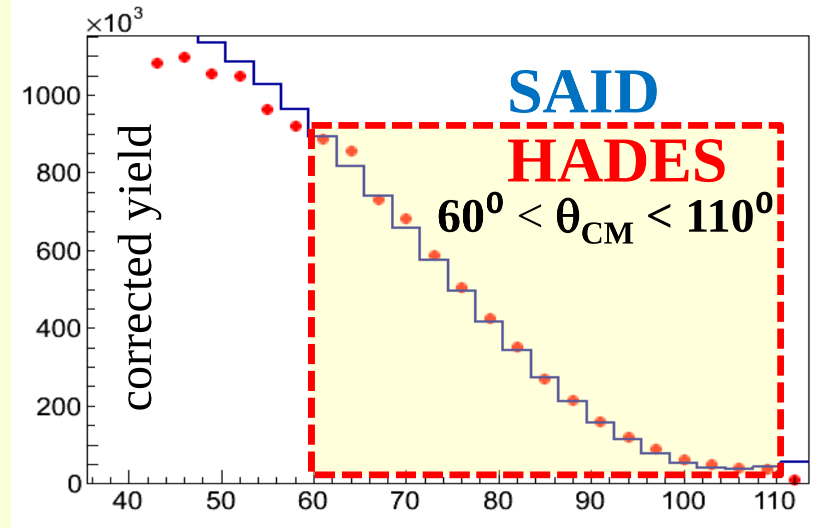
  partial wave analysis focused on N(1520) and **ρ** production
* dilepton identification in channel: $ne^+e^-$ (quasi-exclusive channel)

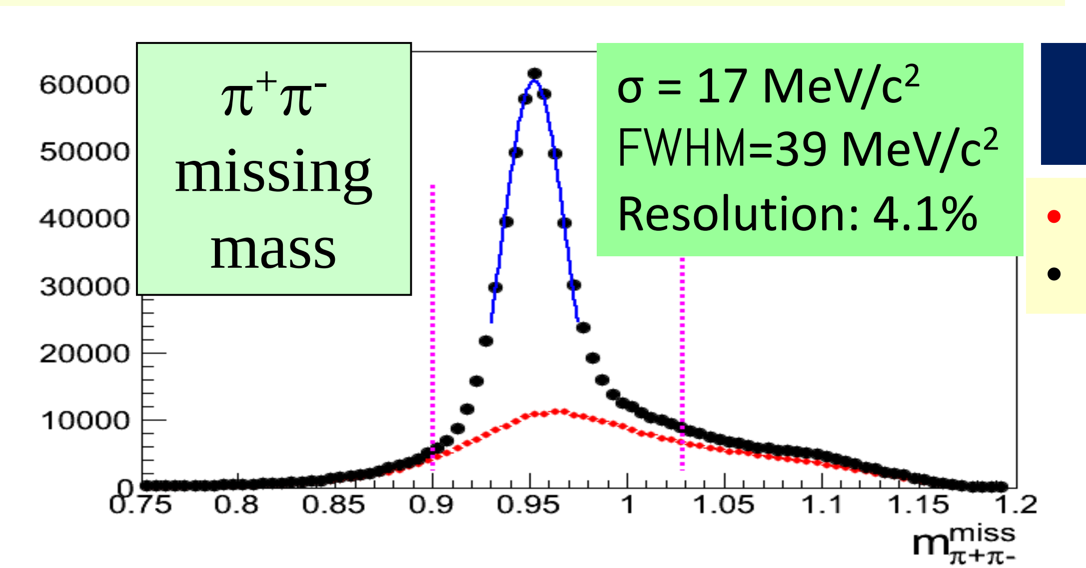
  baryon resonance Dalitz decays and two-body **ρ** decay

# elastic events – comparison to SAID




- MC simulation: acc & eff correction
- exp normalized to the same area



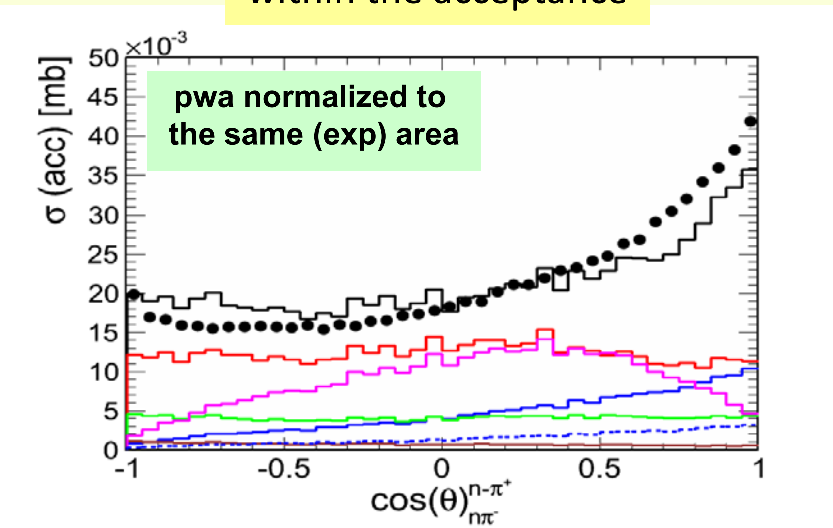

## n $\pi^+\pi^-$ events

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

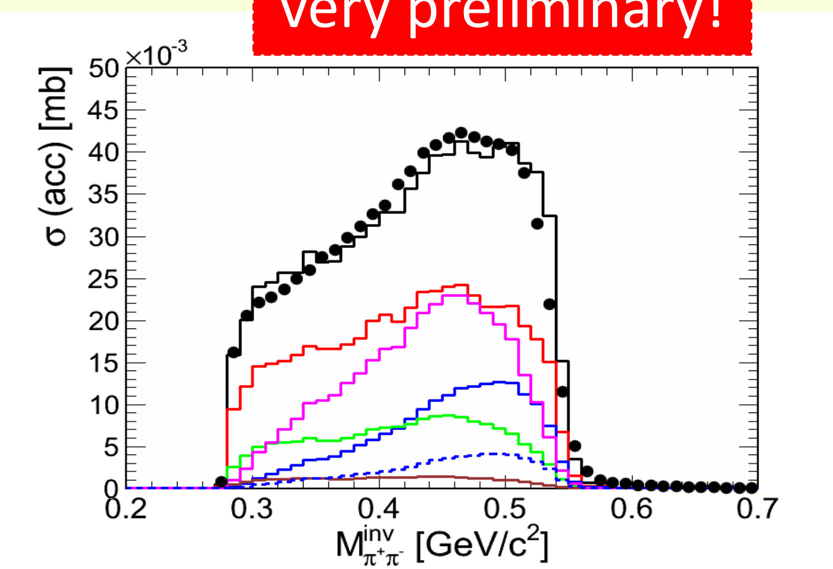
statistics of existing data base increased by more than 2 orders of magnitude (>4 $10^7$ events for each √s)

# PWA results (n $\pi^+\pi^-$) – towards N(1520)

within the acceptance




very preliminary!




**LEGEND**

- Δ(1232)π
- N(1520)
- - - ρN
- ρN(939)
- σN(939)
- N(1400)π

**PWA**: 4 HADES data samples and huge photon and pion database

**GOAL:** extraction of **N(1520)$D_{13}$** BR to **Δπ, ρN, σN**

INPUT FOR DILEPTON ANALYSIS

Total **ρN** contribution:

**1.54 mb** (for 690 MeV/c)

Manley PWA analysis

( Phys. Rev. D**30** (1984) 904 )

predicted much more (~5 mb)

# $e^+e^-$ simulated cocktail

**LEGEND**

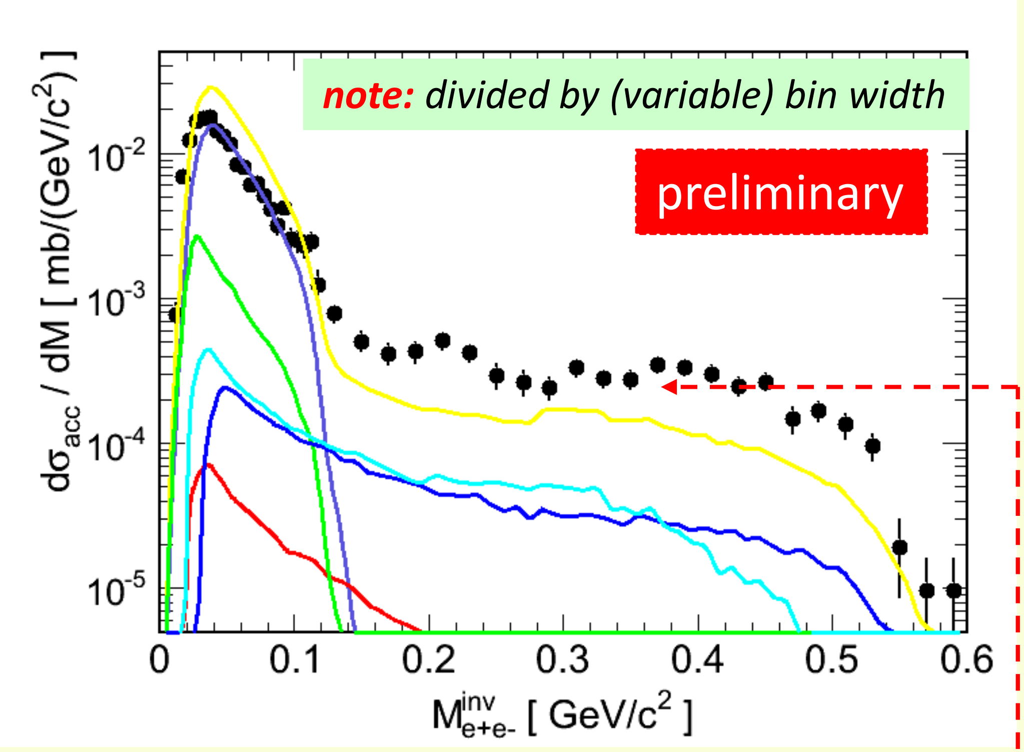
- total (yellow)
- [9.2 mb] $\pi^0 \rightarrow e^+e^-\gamma$
- [7.4 mb] $2{*}\pi^0(\rightarrow e^+e^-\gamma\,)$
- [1.0 mb] $\eta \rightarrow\ e^+e^-\gamma$
- [20.5 mb] $\mathrm{N}(1520) \rightarrow \mathrm{n}\ e^+e^-$
- [8.4 mb] $\Delta(1232) \rightarrow \mathrm{n}\ e^+e^-$

**CS need to be multiplied by BR**

**Branching Ratios**

$\boldsymbol{\pi^0}$: 0.012, $\boldsymbol{\eta}$: 0.006

$\mathbf{N(1520)}$: $4 \cdot 10^{-5}$, $\mathbf{\Delta(1232)}$: $4 \cdot 10^{-5}$




- Meson production: Landolt-Börnstein
- Cocktail of point-like sources
  → (high $m_{e+e-}$ underestimated)
- Strong η contribution

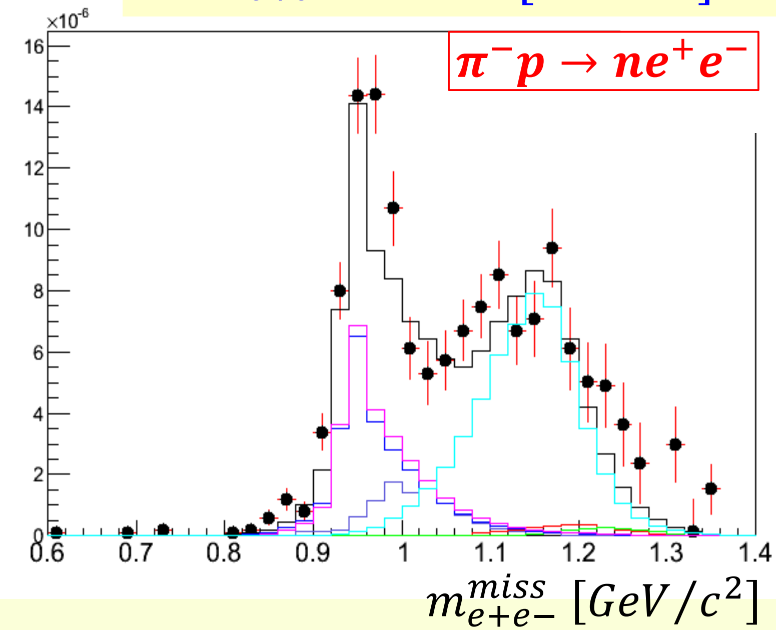
## Dileptoncocktail

- **PLUTO event generator** Ingo Fröhlich *et al.* PoS ACTA2007 (2007) 076 **+ (acc * eff) filters**
  (includes realistic momentum distribution of nucleons in carbon)

# Exclusive $e^+e^-$ cocktail (PE target)

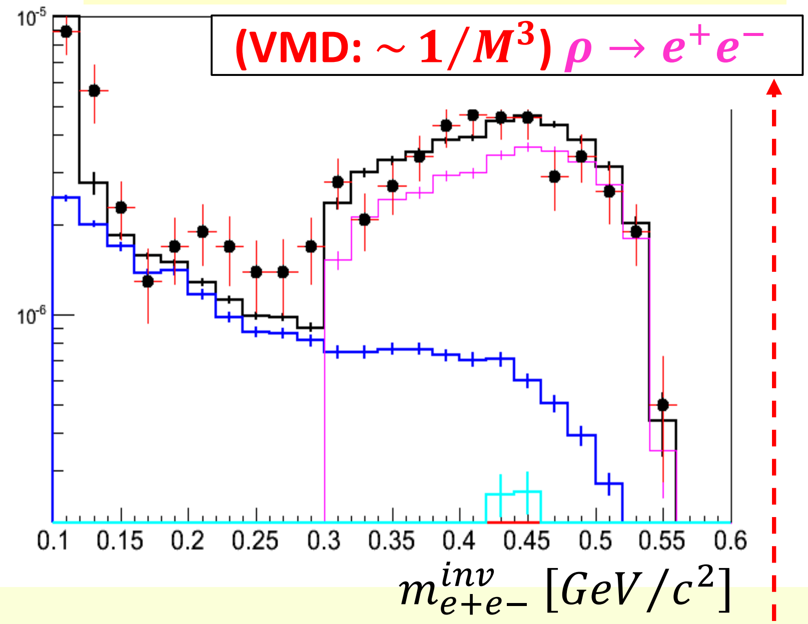
absolute Y scale $\sigma(M)$ [mb]

**missing mass for**
$m^{inv}_{e+e-} > 0.12\ [GeV/c^2]$




preliminary!

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

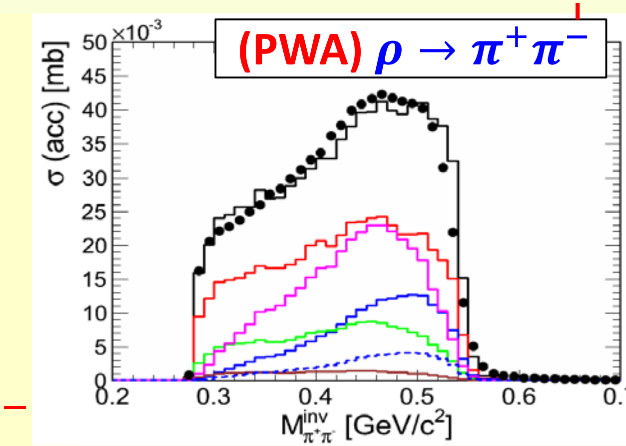



**LEGEND**

- total PE (p+C)
- N(1520) Dalitz
- η Dalitz
- Δ(1232) Dalitz
- ρ → e+e-

- **ρ cross sec. and mass shape derived from $\pi^- p \rightarrow n\pi^+\pi^-$ measured in the same experiment !**
- empirical way of taking into account VDM form factors for electromagnetic decays

**→ excess consistent with $\rho \rightarrow e^+e^-$**



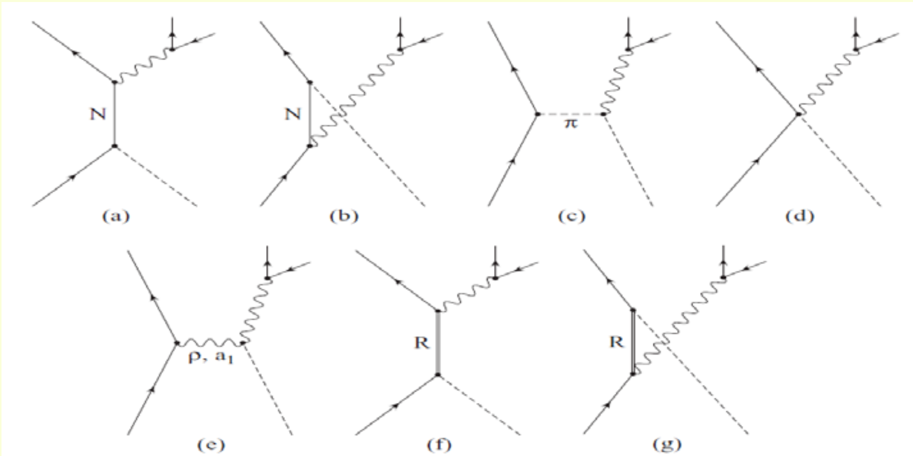
# Dilepton production in pion-nucleon collisions in an effective field theory approach

22

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

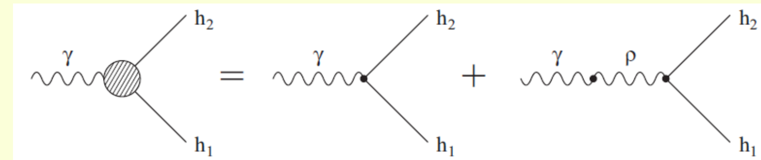
Miklós Zétényi* and György Wolf†

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

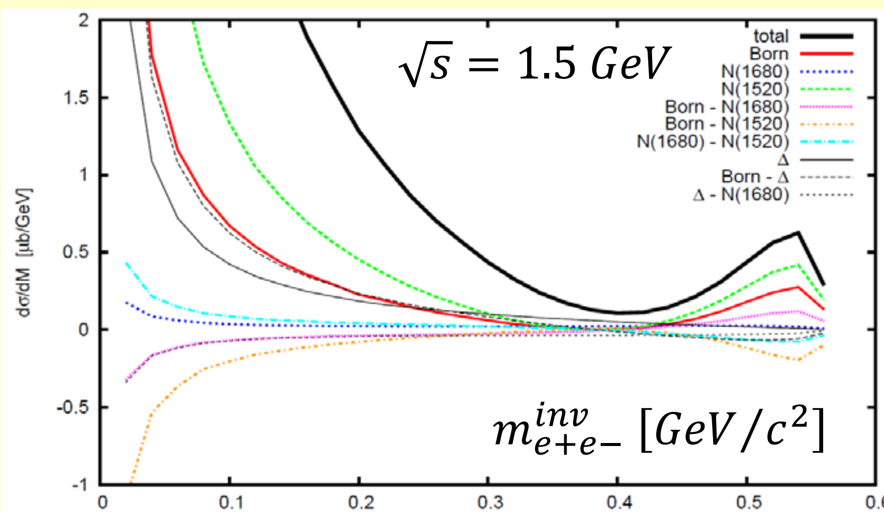



a) s- b) u- c) t-channel diagrams d) contact interaction
e) vector meson exchange diagram
f) s- g) u-channel baryon resonance contributions

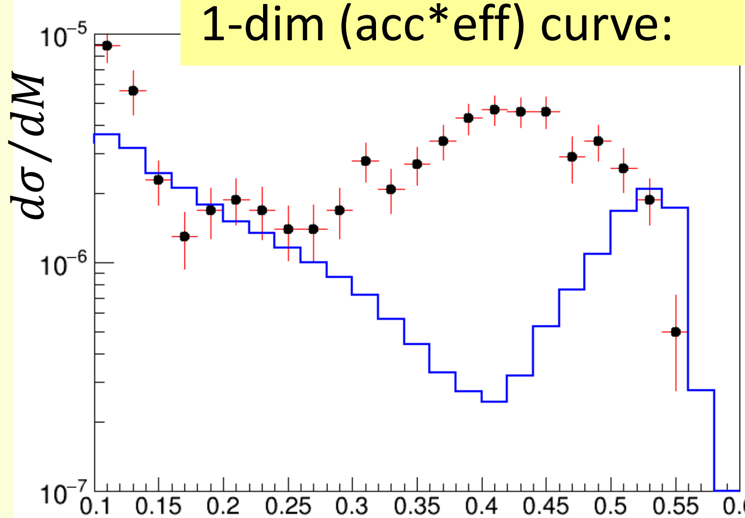
Lagrangian model: real $\gamma$+VMD coupling




**Z & W**: higher $\sqrt{s} = 1.5\ GeV\ (\pi^{-}p)$
**HADES**: $\sqrt{s} = 1.492\ GeV(\pi^{-}p)$
and $\sqrt{s} = 1.461\ GeV(\pi^{-}C)$




**Folding the model** with 1-dim (acc*eff) curve:




$m^{inv}_{e+e-}\ [GeV/c^2]$

# FUTURE PLANS

- extend PWA to p+p @ 3.5 GeV (one-pion) and complete for the pion beam (two-pion)
- > 2018: 2-3 year time slot for pion beam experiments at SIS 18 (before the start of FAIR)

FAIR:

- higher statistics measurements (pp), liquid H target
- investigation of heavier resonances
- electromagnetic calorimeter (better electron identification, radiative decays, $\pi^0, \eta, \omega$ reconstruction for PWA and in-medium studies)
- > 2021: HADES at FAIR(p and ion beams, possibly pions…)

# SUMMARY

- resonance production in NN and πN via exclusive chanels within PWA (Bonn-Gatchina approach)
- selective study of $e^+e^-$ production from Dalitz decay of resonances $\rightarrow$ *sensitivity to baryonic resonances* ( time-like electromagnetic structure / coupling to ρN )

## Recent pion beam experiment:

- promising data: $\pi^+\pi^-$ and $e^+e^-$ (important constraint for models) – strong off-shell ρ contribution
- PWA: expected determination of N(1520) coupling to ρN
- verification of model predictions on ω/ρ interferences
- continuation at SIS18 in 2017-18 (with ECAL)

# CREDITS

## *The HADES Collaboration*

*Special thanks to* **Andrey V. Sarantsev** (Bn-Ga group)