From pion- and photon-nucleon scattering to vector mesons in nuclear matter

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- ✔ Vector mesons in nuclear matter and coupled channel analyses
- ✔ What is the nature of baryon resonances?
- ✔ Vector meson dominance assumption
- ✔ How to solve the Bethe-Salpeter equation
- ✔ Selection of results
- ✔ Summary

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based on work with Gy. Wolf and B. Friman, nucl-th/0112052, NPA in print

Introduction and motivation

- **Ultimate goal** : compute ρ, ω meson spectral functions in nuclear matter

- **Relevant experimental programs at Jefferson Lab, CERN, GSI and MAMI** :

  key observable: dilepton spectra from $\rho_0\,,\omega \to e^+\,e^-$ decay
  (e.g. CLAS, CERES, HADES, ...)

  $\rightarrow$ undistorted information of the vector meson properties in matter

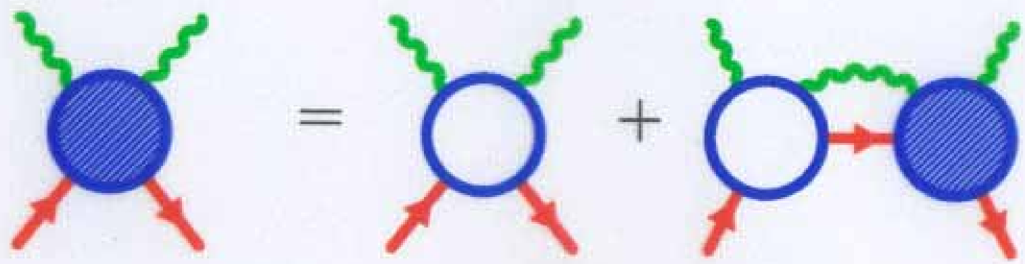
- **Strategy** :

  - small nuclear density: ρN and ωN scattering
  - use data on $\pi N \to \rho N\,, \omega N$, etc and $\gamma N \to \rho N\,, \omega N$, etc
  - coupled channel analyses for 1.4 GeV $< \sqrt{s} <$ 1.8 GeV
  - vector meson at rest in nuclear matter
    $\rightarrow$ s-wave ρN scattering $\rightarrow \pi N$ in s- and d-waves only

Coupled-channel Bethe-Salpeter equation

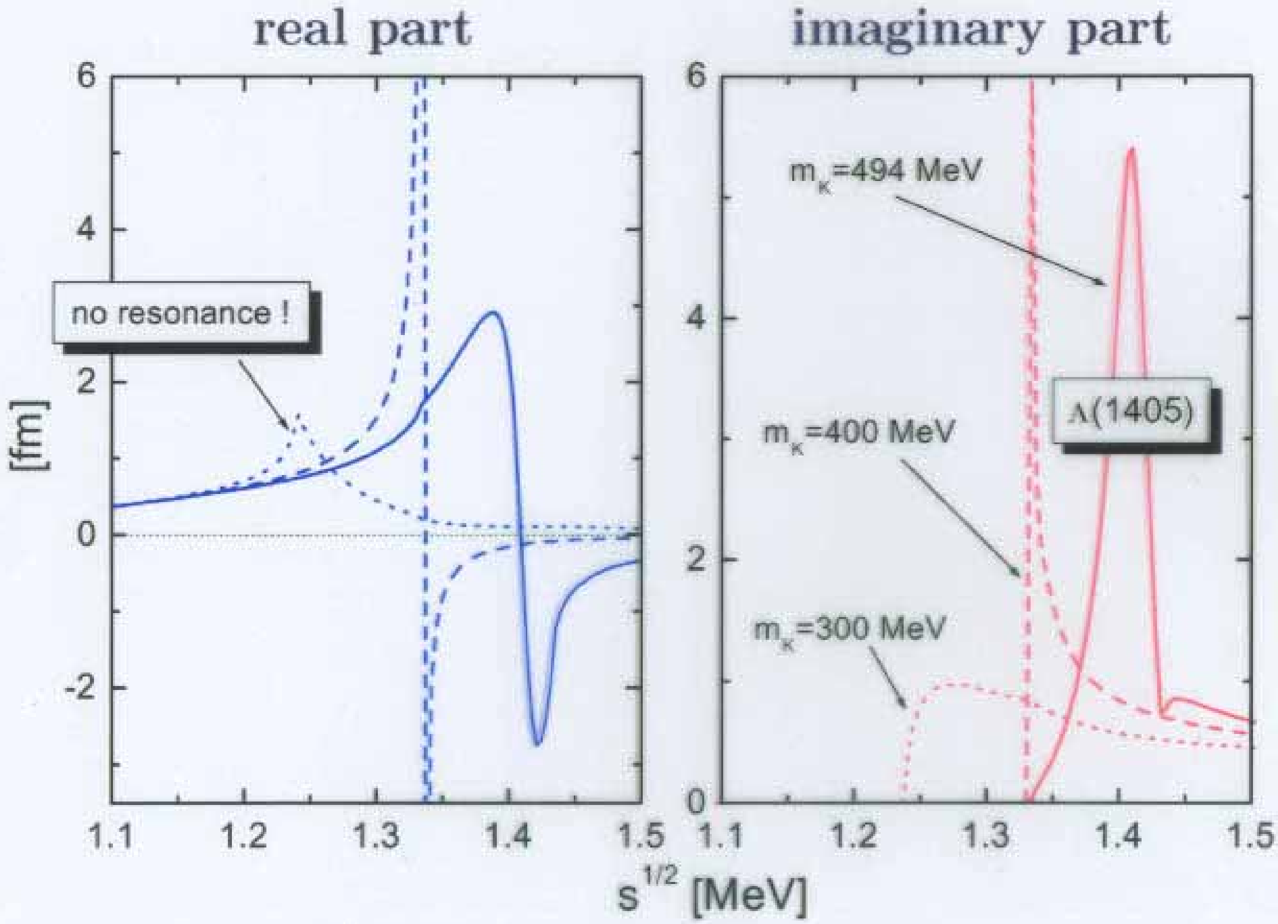
πN and γN scattering:

- non-perturbative in the resonance region!
- dynamic generation of baryon resonances?
- strong inelastic channels!



- ✔ included channels $\{M_\alpha, B_\alpha\} = (\pi N, \eta N, K\Lambda, K\Sigma\,, \pi\Delta\,, \rho N\,, \omega N)$
- ✔ interaction kernel  quasi-local two-body vertices
- ✔ analytic scattering amplitudes (covariant projector technique)

Chiral $SU(3)$ prediction for $\bar{K}N$ s-wave amplitude (Q^1)



- **Parameter free result** : use $f_\pi = 93$ MeV !
- $\Lambda(1405)$ **resonance dynamically generated** : disappears at $m_K = 300$ MeV !

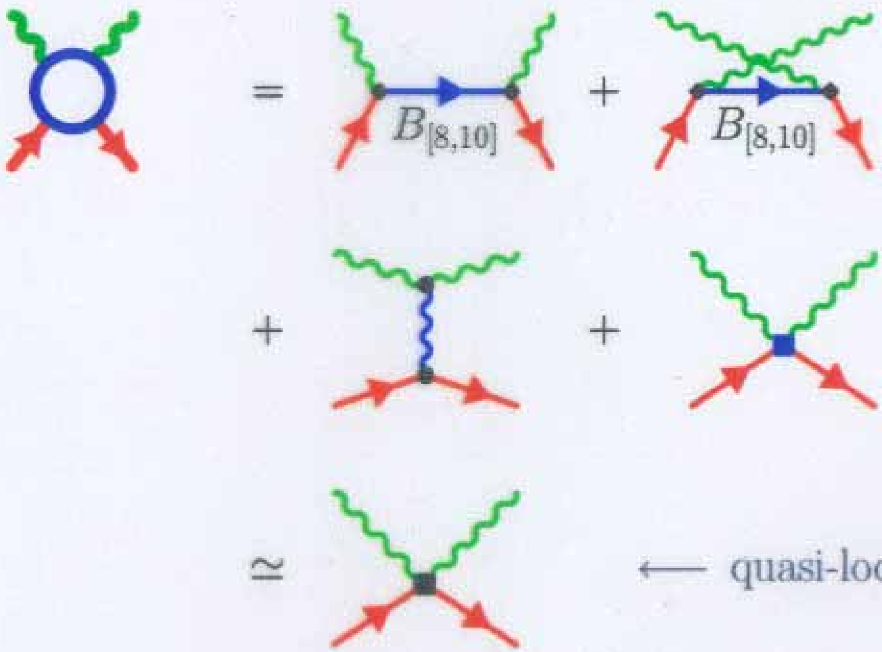
Baryon resonances relevant for s-wave VN scattering

- **S-wave** : N(1535), N(1650) and $\Delta(1620)$
- **D-wave** : N(1520) and $\Delta(1700)$
- **Observation** : part of the same p-wave $l = 1$ multiplet $(3^-, 70)$
- **Question** : $\Lambda(1405)$ generated by coupled channel chiral dynamics

  $\rightarrow$ generate also N(1535), N(1650), $\Delta(1620)$, N(1520) and $\Delta(1700)$?

Effective field theory for Bethe-Salpeter kernel

- **Meson exchange phenomenology**



$\longleftarrow$ s- and u-channel baryon exchange

$\longleftarrow$ t-channel exchange and background

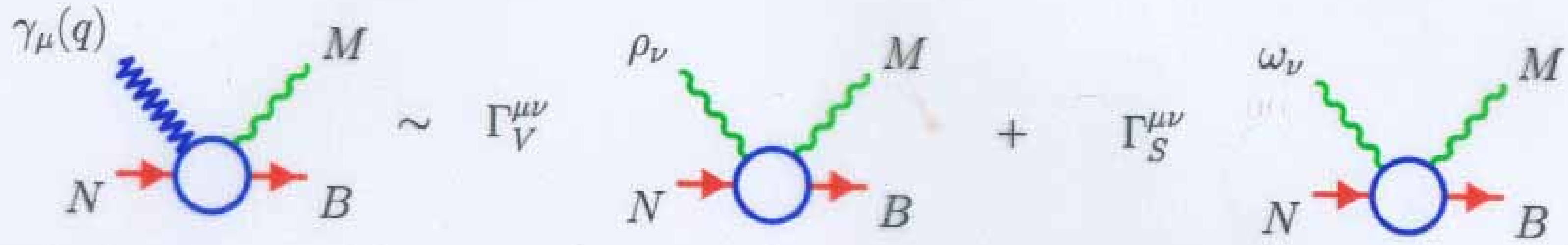
$\longleftarrow$ quasi-local vertices in the resonance region

- **πN s- and d-wave channels** : approximate kernel by quasi-local vertices !

  - no s-channel baryon exchange from the large-N_c groundstates of QCD ($B_{[8,10]}$)
  - if baryon resonances generated dynamically $\rightarrow$ smooth interaction kernel

Vector meson dominance assumption

- **Quasi-local production vertex**



- **Most general transition tensor** : constraints from gauge invariance!

$$\Gamma^{\mu\nu}_{S(V)}(q;w) = \Gamma^{\mu\nu,+}_{S(V)}(q;w) + \Gamma^{\mu\nu,-}_{S(V)}(q;w)\,,$$

$$\begin{aligned}\Gamma^{\mu\nu,\pm}_{S(V)}(q;w) &= \frac{g^{(\pm)}_{S(V),1}}{m_\omega}\,\frac{1}{2}\left(1 \pm \frac{\not{w}}{\sqrt{w^2}}\right)\left(\left(\not{q} - \frac{w\cdot q}{w^2}\not{w}\right) g^{\mu\nu} - q^\mu\left(\gamma^\nu - \frac{w^\nu}{w^2}\not{w}\right)\right) \\ &+ \frac{g^{(\pm)}_{S(V),2}}{m_\omega}\,\frac{1}{2}\left(1 \pm \frac{\not{w}}{\sqrt{w^2}}\right)\left(\frac{w\cdot q}{\sqrt{w^2}}\, g^{\mu\nu} - \frac{q^\mu\, w^\nu}{\sqrt{w^2}}\right) \\ &+ \frac{g^{(\pm)}_{S(V),3}}{m_\omega^2}\,\frac{1}{2}\left(1 \pm \frac{\not{w}}{\sqrt{w^2}}\right)\left(q^2\, g^{\mu\nu} - q^\mu\, q^\nu\right), \quad \text{where } s = w_\mu\, w^\mu\end{aligned}$$

Covariant projector approach

- **Covariant projection operators** define unique on-shell reduction

  e.g. projectors for elastic πN scattering:

$$Y_J^{(\pm)}(\bar{q},q;w) = \frac{1}{2}\left(\frac{w}{\sqrt{w^2}} \pm 1\right)\bar{Y}_{J+1/2}(\bar{q},q;w) - \frac{1}{2}(\bar{q}\cdot V\cdot\gamma)\left(\frac{w}{\sqrt{w^2}} \mp 1\right)(\gamma\cdot V\cdot q)\,\bar{Y}_{J-1/2}(\bar{q},q;w)\,,$$

$$\bar{Y}_n(\bar{q},q;w) = \sum_{k=0}^{[(n-1)/2]} \frac{(-)^k\,(2n-2k)!}{2^n\,k!\,(n-k)!\,(n-2k-1)!}\,(\bar{q}\cdot V\cdot q)^{n-2k-1}\,(q\cdot V\cdot q)^k\,(\bar{q}\cdot V\cdot\bar{q})^k\,,$$

$$V_{\mu\nu} = g_{\mu\nu} - \frac{w_\mu\,w_\nu}{w^2}$$

- **Uniqueness** of Projectors $Y_J^{(\pm)}(\bar{q},q;w)$ with $L = J \mp 1/2 \leftarrow$ regularity in q and $\bar{q}$

- **Center of mass frame** $w_\mu = (\sqrt{s},0)$

$$\bar{Y}_n(\bar{q},q;w) \rightarrow p_{MB}^{2n-1}\,P_n'(\cos\theta)$$

Solution of Bethe-Salpeter equation

- **Algebraic solution of Bethe-Salpeter equation**

$$V(\bar{k}, k; w) \;=\; \sum_{J=1/2}^{\infty} \Big(V^{(+)}(\sqrt{s}; J)\, Y_J^{(+)}(\bar{q}, q; w) + V^{(-)}(\sqrt{s}; J)\, Y_J^{(-)}(\bar{q}, q; w) \Big)$$

- **Causal loop functions** : consistent with dimensional regularization

$$J_{MB}^{(\pm)}(\sqrt{s}; J)\, Y_J^{(\pm)}(\bar{q}, q; w) \stackrel{!}{=} \Big(Y_J^{(\pm)}(\bar{q}, l; w) \cdot G(l, w) \cdot Y_J^{(\pm)}(\bar{l}, q; w) \Big) \,,$$

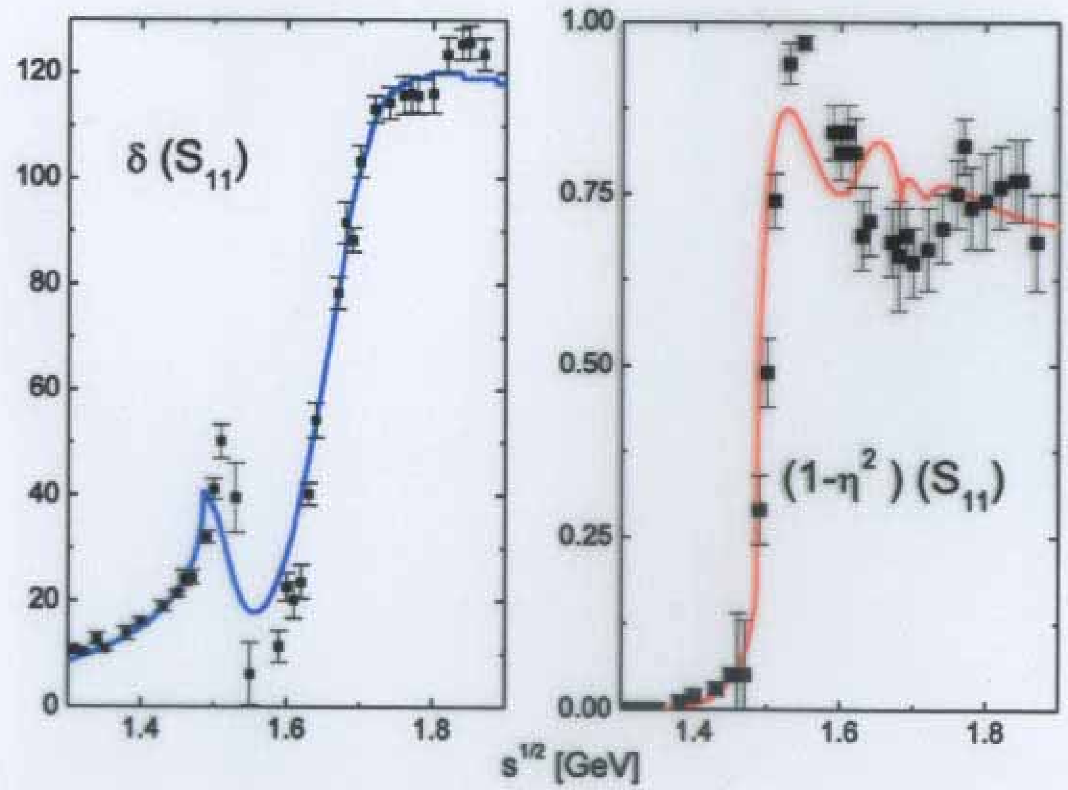
$$J_{MB}^{(\pm)}(\sqrt{s}; J) = p_{MB}^{2\,J-1} \left(E_B(\sqrt{s}\,) \pm m_B \right) \big(I_{MB}(\sqrt{s}) - I_{MB}(0) \big) \,,$$

- **Renormalization scheme** : move all tadpole contributions into Bethe-Salpeter kernel

$$I_{MB}(\sqrt{s}) = -i \int \frac{d^4 l}{(2\,\pi)^4} \frac{1}{l^2 - m_M^2} \frac{1}{(w-l)^2 - m_B^2} \,,$$

$$I_{MB}(0) = \frac{i}{m_B^2 - m_M^2} \int \frac{d^4 l}{(2\,\pi)^4} \Big(\frac{1}{l^2 - m_M^2} - \frac{1}{l^2 - m_B^2} \Big) \to 0$$

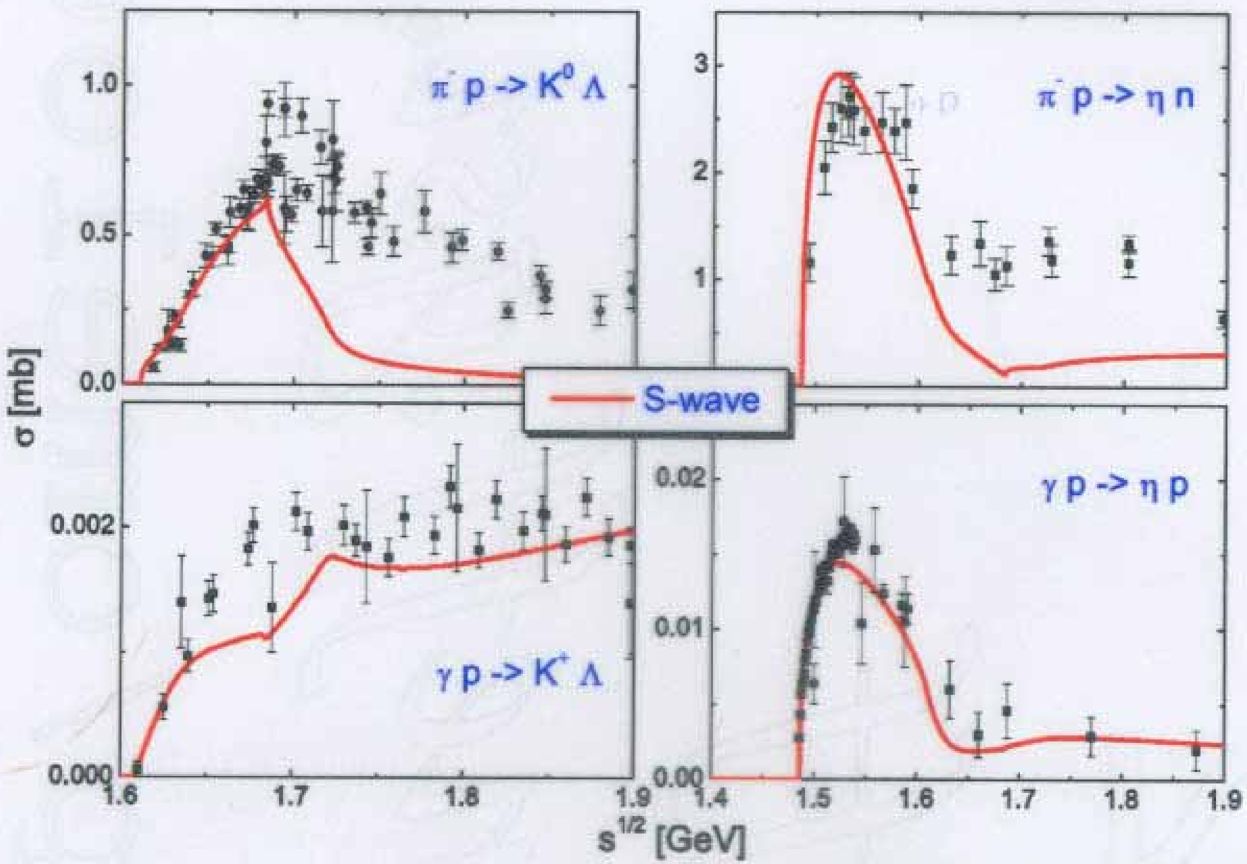
Pion nucleon scattering phase shifts



SP98 solution

- N(1535) and N(1650) generated dynamically
- Model justified only for 1.4 GeV $\leq \sqrt{s} \leq$ 1.8 GeV

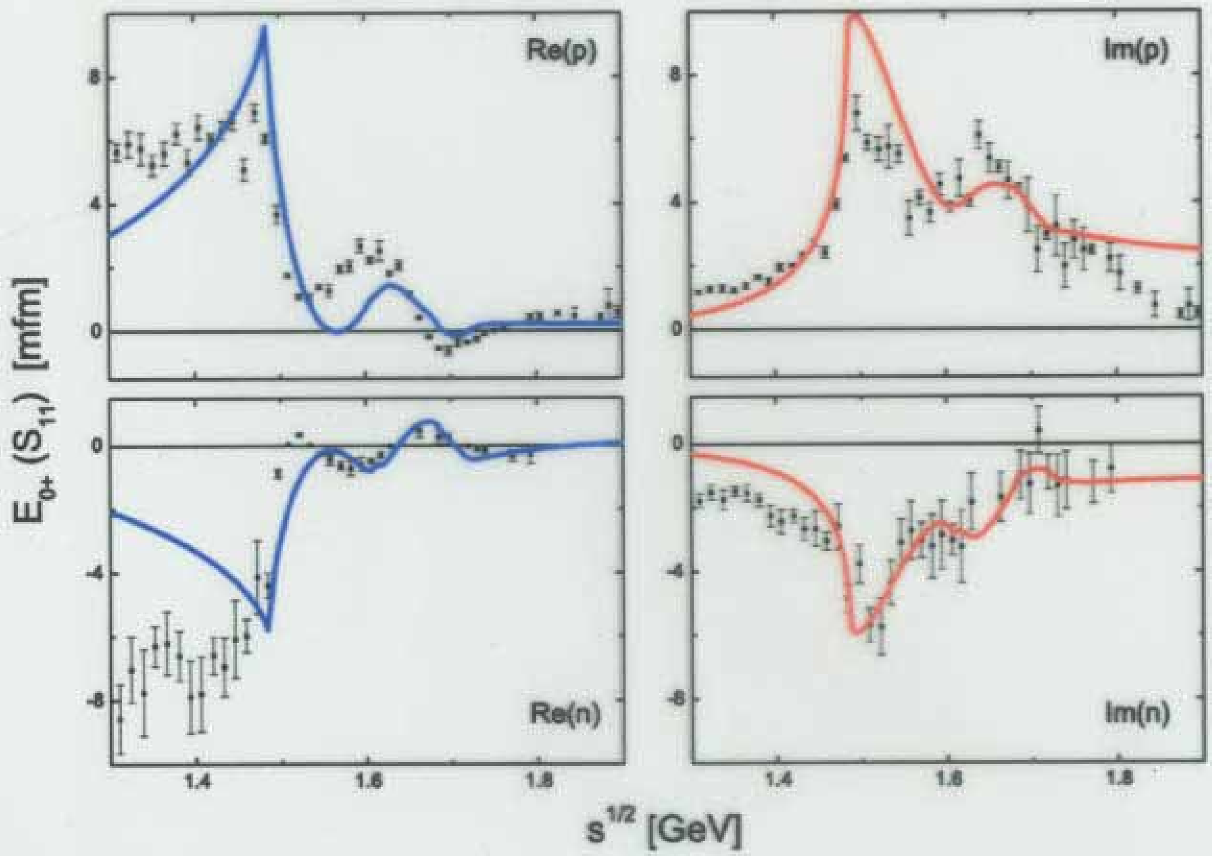
Pseudoscalar meson production



Phys. Rev. Lett. **74** (1995)
Phys. Lett. **B445** (1998)

- N(1535) generated dynamically

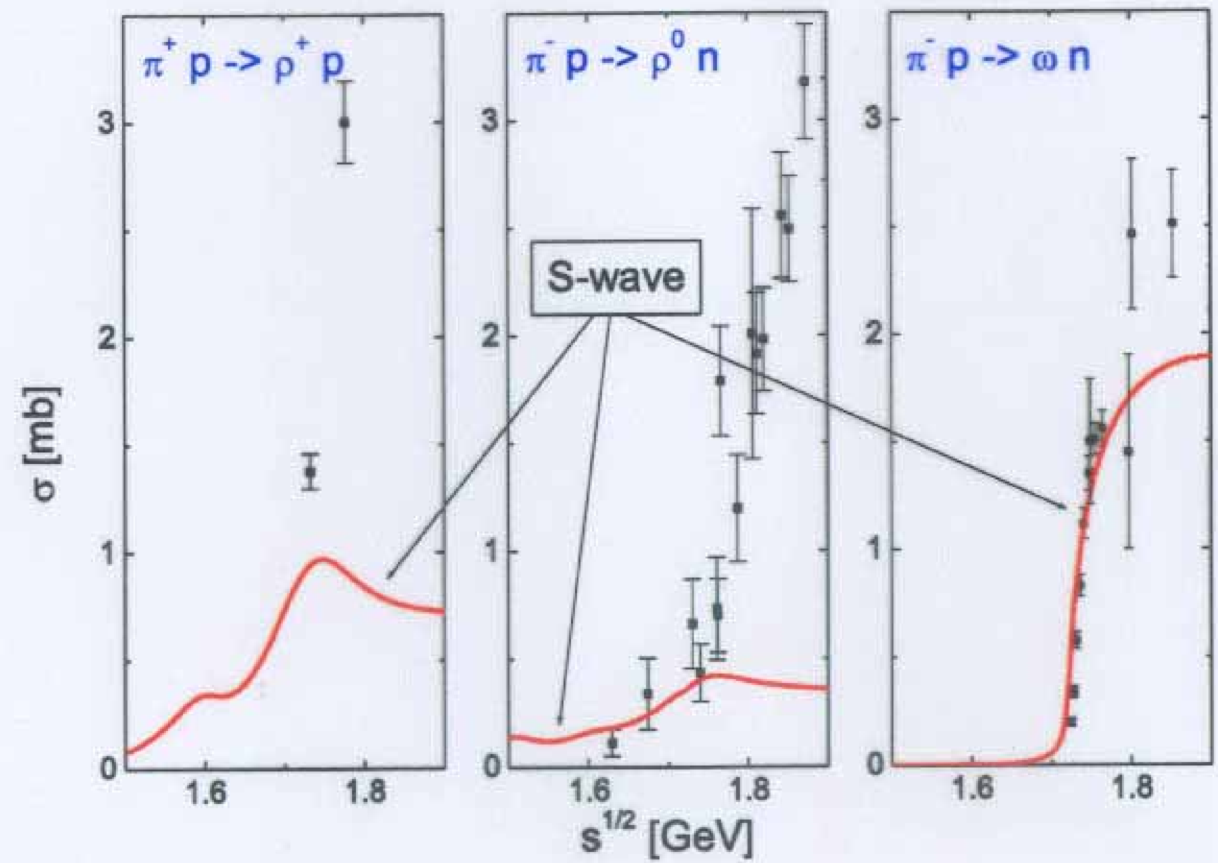
Photon induced pion production



SM00 solution

- N(1535) and N(1650) generated dynamically : include ρN and ωN states with $L \neq 0$!

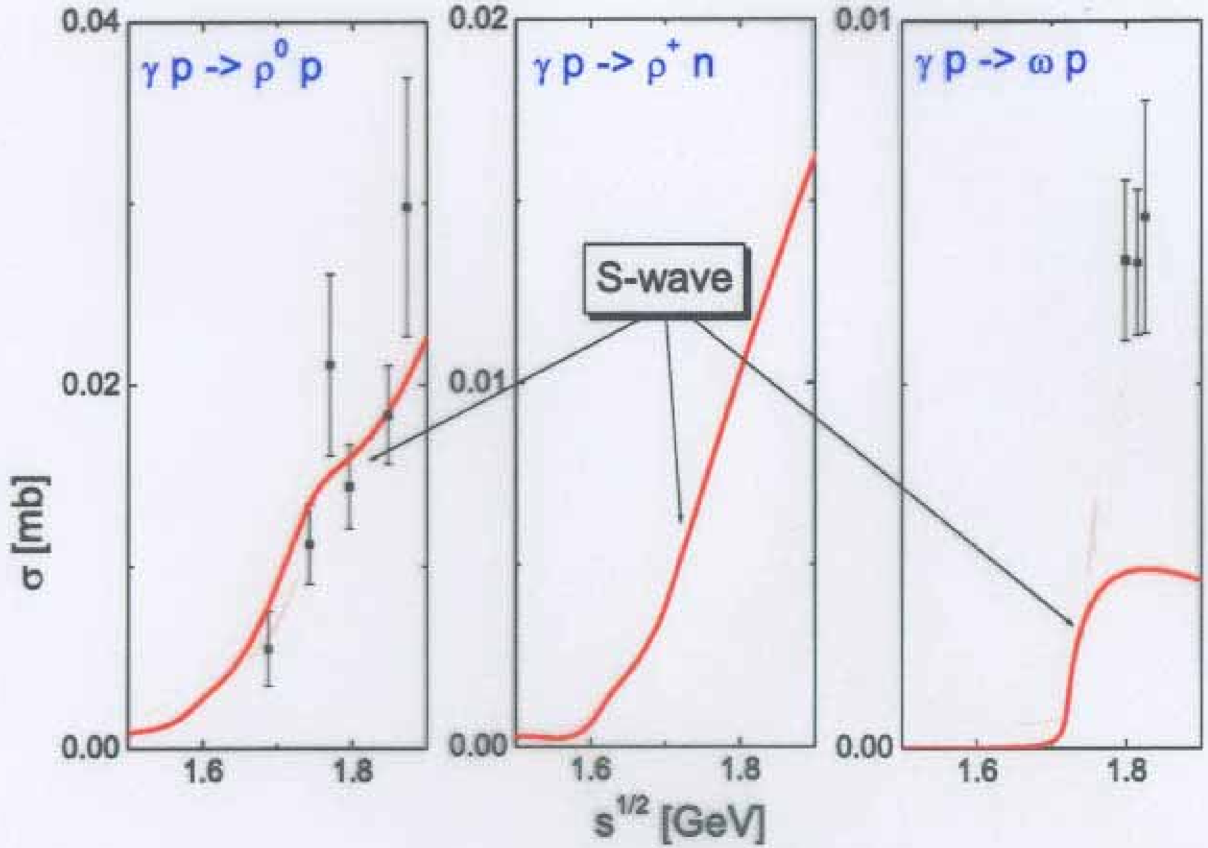
Pion induced vector meson production



Landolt Börnstein

- **S-wave dominance** : only if one-pion exchange (long-range) does not contribute !

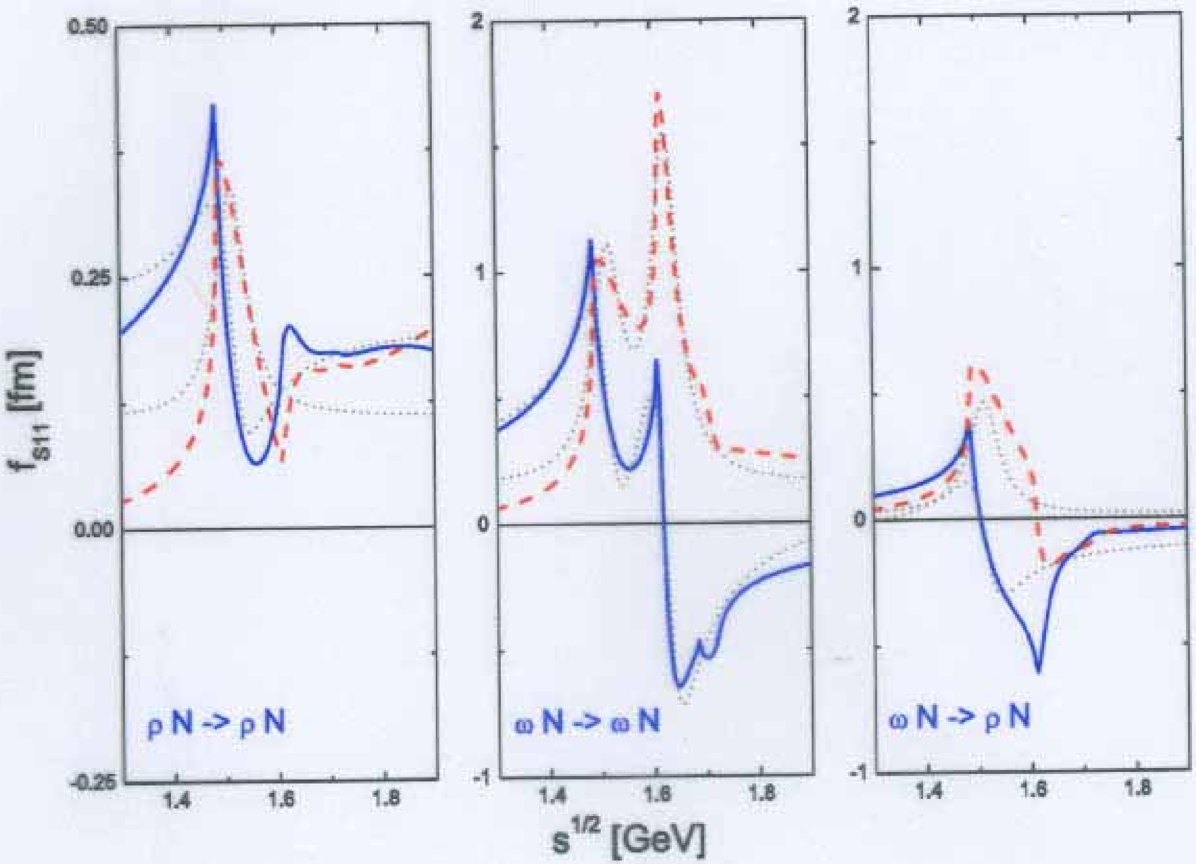
Photon induced vector meson production



Phys. Rev. **175** (1968)

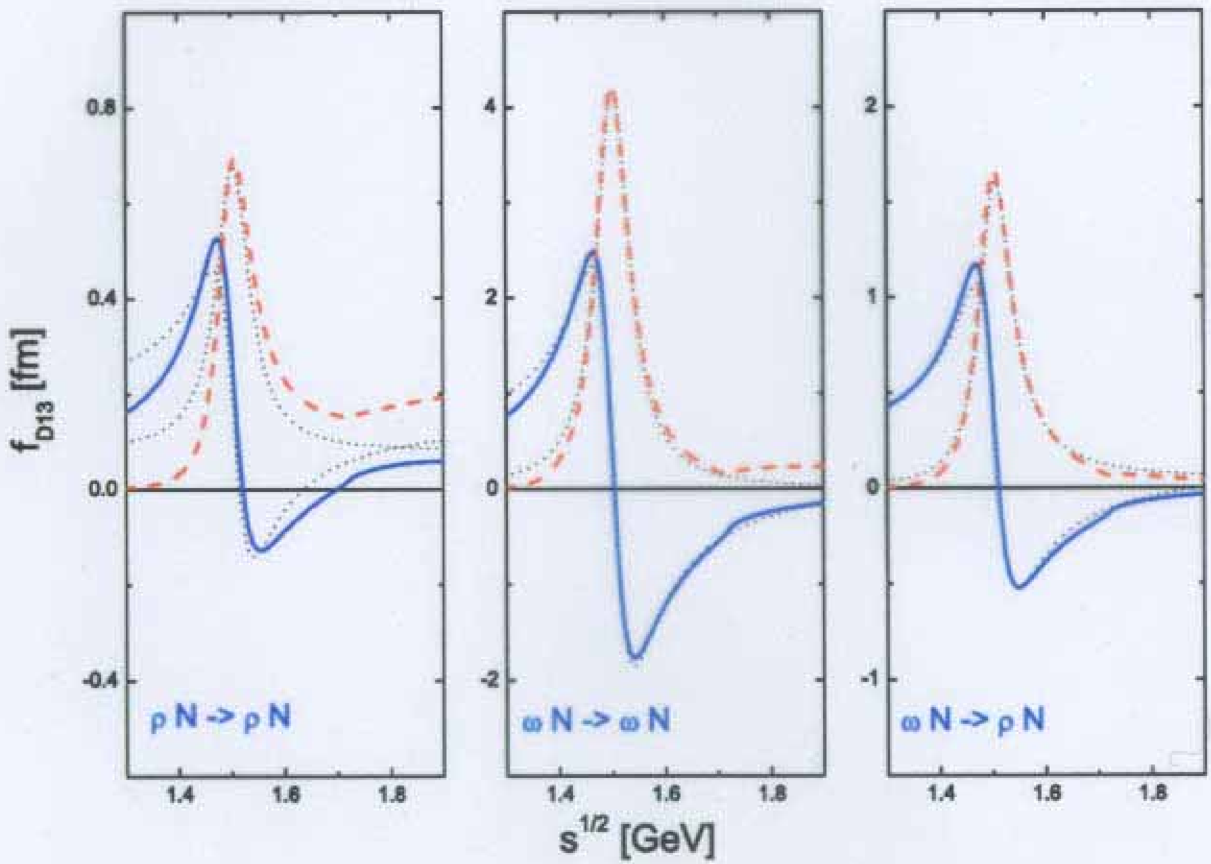
- **S-wave dominance** : only if one-pion exchange (long-range) is suppressed !

Vector-meson nucleon scattering amplitudes



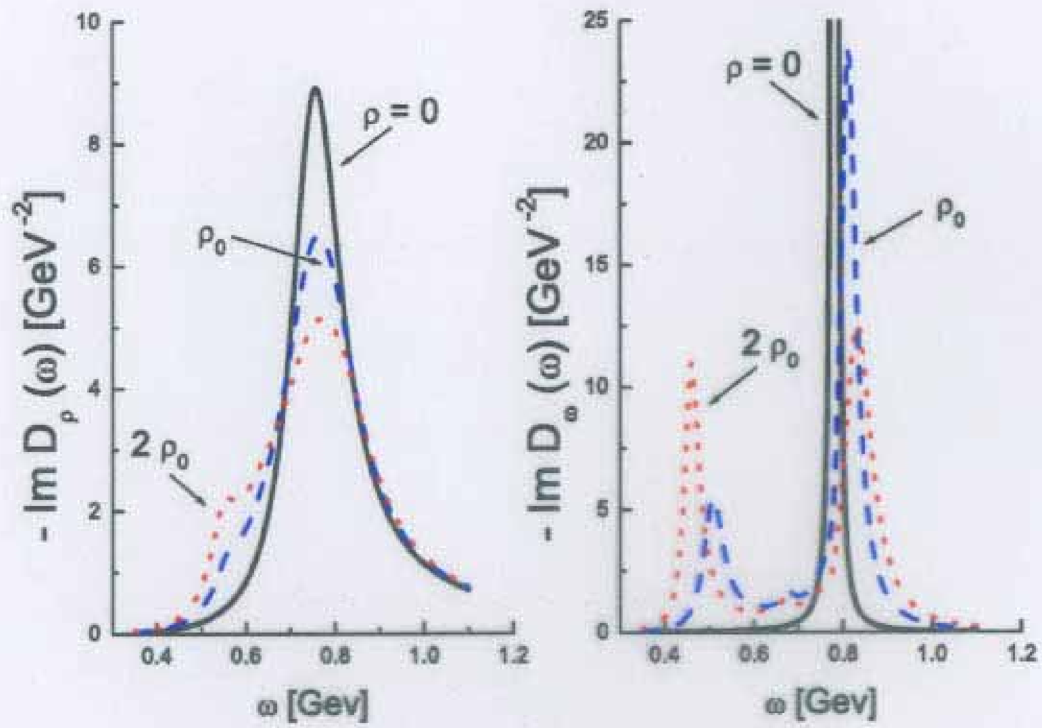
- N(1535) and N(1650) : generated dynamically!

Vector-meson nucleon scattering amplitudes



- N(1520) : generated dynamically!

Vector meson spectral functions: leading order in density



vector meson at rest

- **N(1520) nucleon-hole state** : strong in ω but weak in ρ

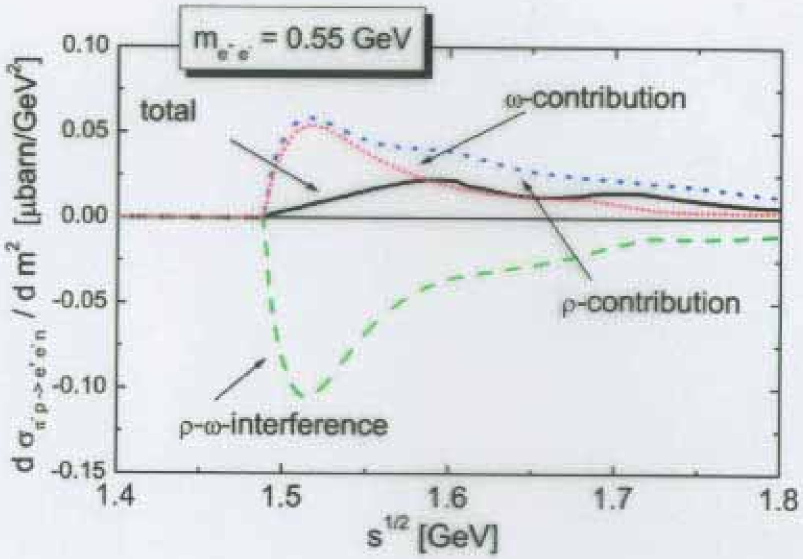
Pion induced dilepton production

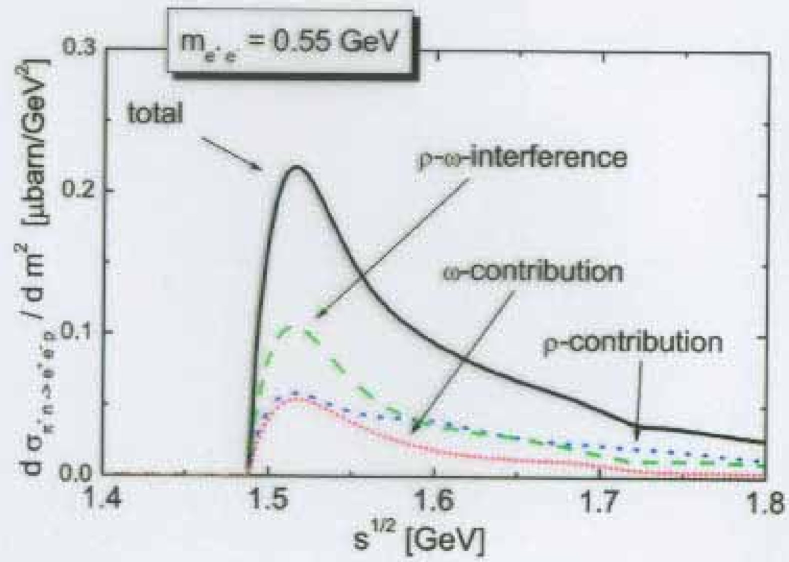
study $$\pi^- p \to \rho^0 n, \omega n \to e^+ e^- n\,,$$

$$\pi^+ n \to \rho^0 p, \omega p \to e^+ e^- p$$

- **Gain improved understanding of $\pi N \to \rho N, \omega N$ amplitudes**
  - avoid competing processes with pions in the final state, e.g. $\pi\Delta, \rho N$
- **Basic process for $\pi A \to e^+ e^- X$ reaction**
  - vector meson propagation in nuclear matter
- **Phenomenological constraints on $\rho N N^*$ and $\omega N N^*$ couplings**
  - strong or weak $\rho\, N\, N(1520)$ and $\omega\, N\, N(1520)$ vertex ?
- **Measurement feasible in the near future**
  - pion beam and large acceptance $e^+ e^-$ detector (HADES) at GSI available

Pion induced dilepton production of the nucleon



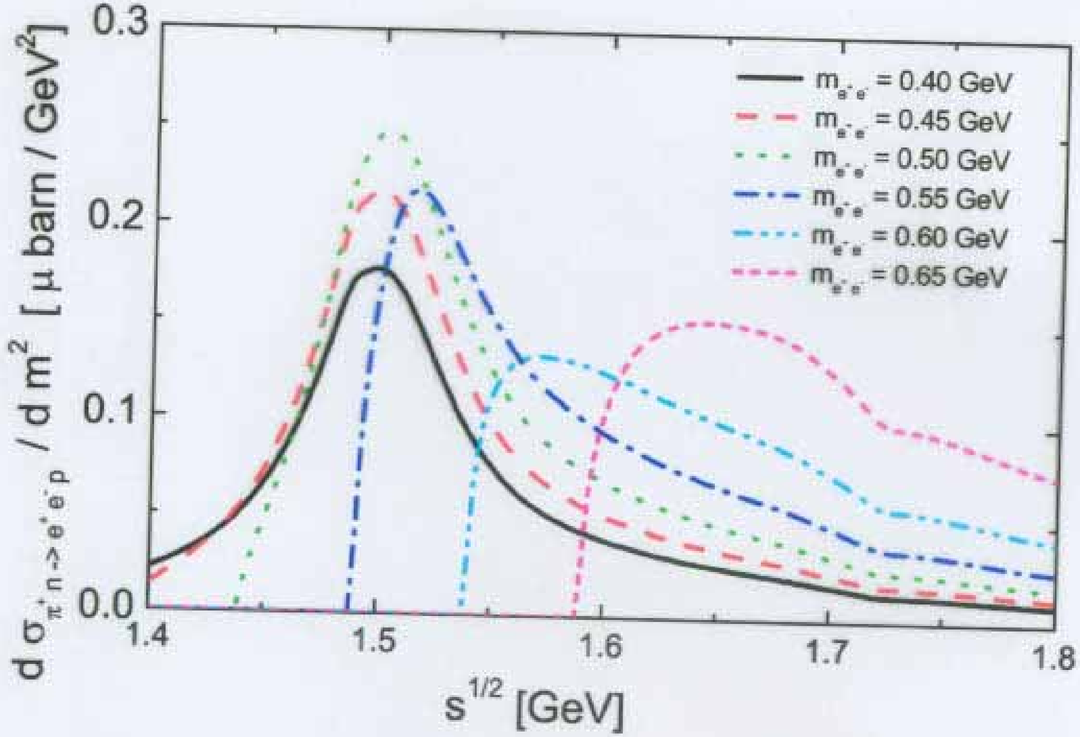


- **important $\rho - \omega$ interference pattern**

$$M_{\pi^- p \to \rho^0 p} = - M_{\pi^+ n \to \rho^0 p}, \qquad M_{\pi^- p \to \omega p} = + M_{\pi^+ n \to \omega p}$$

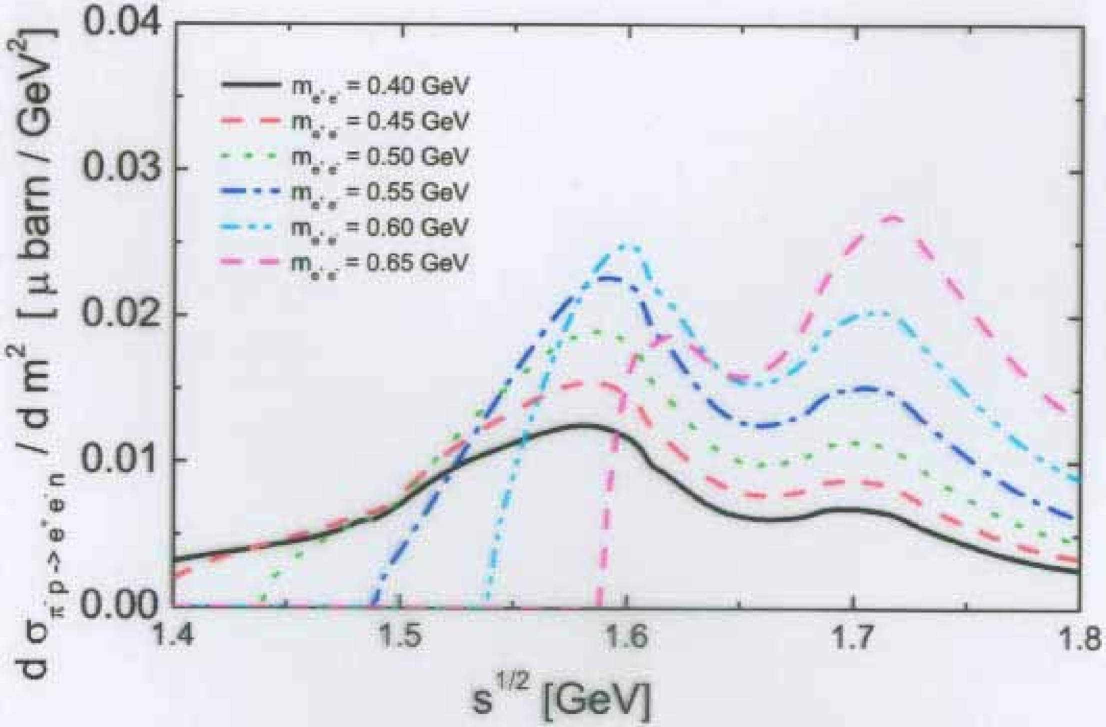
- $\pi^- p$: destructive interference
- $\pi^+ n$: constructive interference

Pion induced dilepton production of the neutron



- **constructive interference** : large cross section

Pion induced dilepton production of the proton



- **destructive interference** : significantly reduced cross section

Summary

- ✔ coupled channel analysis of γN and πN scattering
  - use quasi-local interaction vertices for 1.4 GeV $< \sqrt{s} <$ 1.8 GeV
  - assume vector meson dominance
  - obtain covariant and analytic scattering amplitudes
  - baryon resonances generated dynamically
- ✔ 54 parameters adjusted to describe
  - πN phase shifts: $S_{11}, S_{31}, D_{13}, D_{33}$
  - inelastic reactions: $\pi N \to \omega N, \rho N, \eta N, K\Lambda, K\Sigma$ (s-wave only!)
  - $\gamma N \to \pi N$ multipoles: $E_{0+}^{(p,n)}(S_{11}, S_{31})$, $E_{2-}^{(p,n)}(D_{13}, D_{33})$, $M_{2-}^{(p,n)}(D_{13}, D_{33})$
  - inelastic reactions: $\gamma N \to \omega N, \rho N, \eta N, K\Lambda, K\Sigma$ (s-wave only!)
- ✔ predict s-wave vector-meson nucleon scattering amplitudes
  - computed vector meson spectral functions to leading order in the density
  - find strong (weak) N(1520) nucleon-hole component for ω (ρ)
  - predict pion induced dilepton production cross sections off the nucleon