Hadronic and Electromagnetic interactions as probes for strongly interacting matter

Radhey Shyam

Saha Institute of Nuclear Physics

OUT LINE

Introduction
Hadronic Interactions
Electromagnetic Interactions
Summary

Invited talk in the workshop on NUCLEON-NUCLEON INTERACTION AND NUCLEAR MANY-BODY PROBLEM, Nov. 18-27, 2010, ICTS, TIFR, Mumbai

Exploration of strongly interacting matter

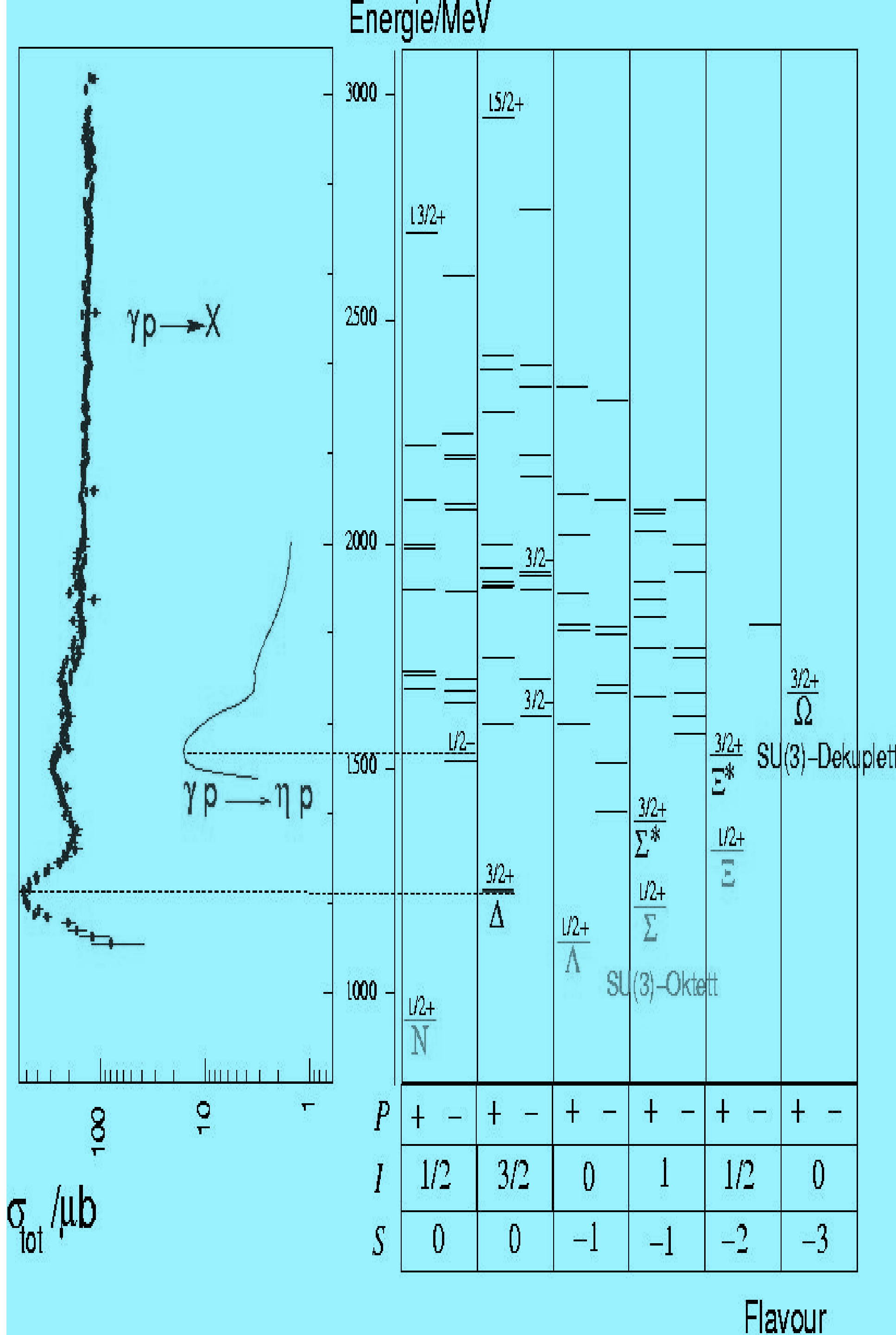
Study of strongly interacting Nucleons, and Meson (hadrons)

Quantum Chromodynamics (QCD)

Interaction between hadrons play a crucial role in understanding QCD

Properties of the basic constituents inferred indirectly, by studying the structure, decay, production and interactions of hadrons

N* program at several Labs.



How to study hadrons?

• Observe them as existing particles

γ / lepton beams are excellent probes (mostly of the nucleon)

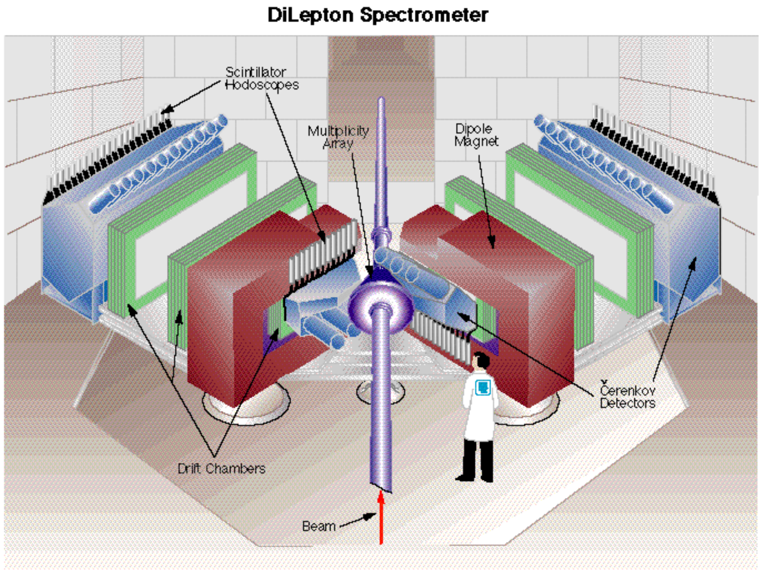
• Create them in a laboratory in a controlled manner

Hadron beams have high production cross sections but little control (except for antiprotons).

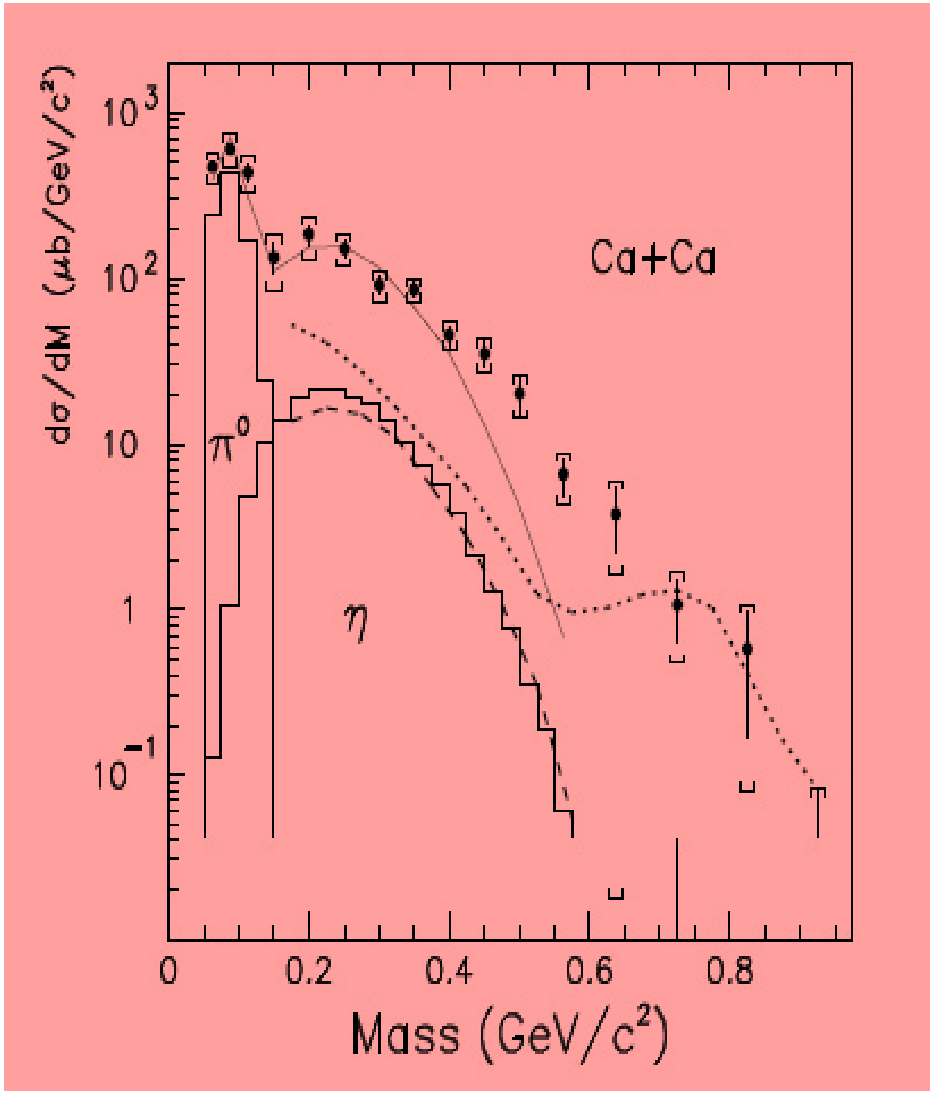
Motivation: obtain a description of scattering data at moderate energies where baryonic resonances enter as intermediate states whose properties are extracted by comparison of calculations with the experimental data

Dilepton production in hadronic collisions at 1-2 GeV/nucleon

DLS



R. J. Porter *et al.*,
Phys. Rev. Lett. 79 (1997) 1229.

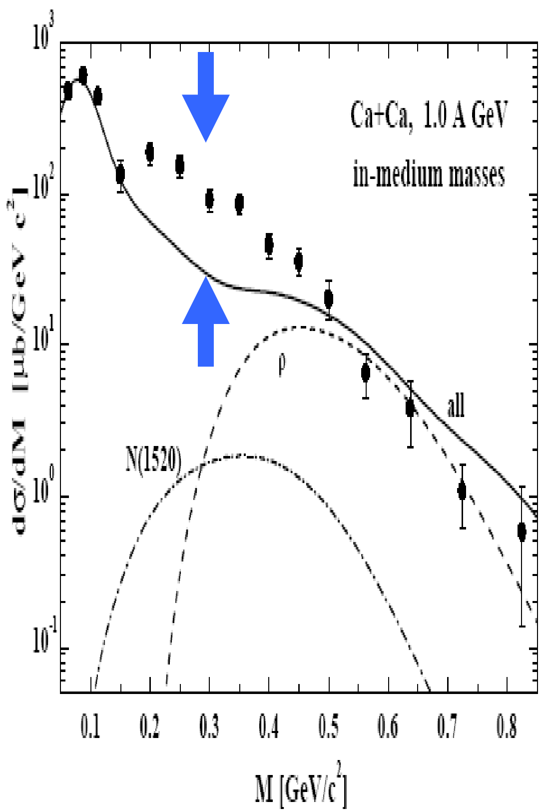


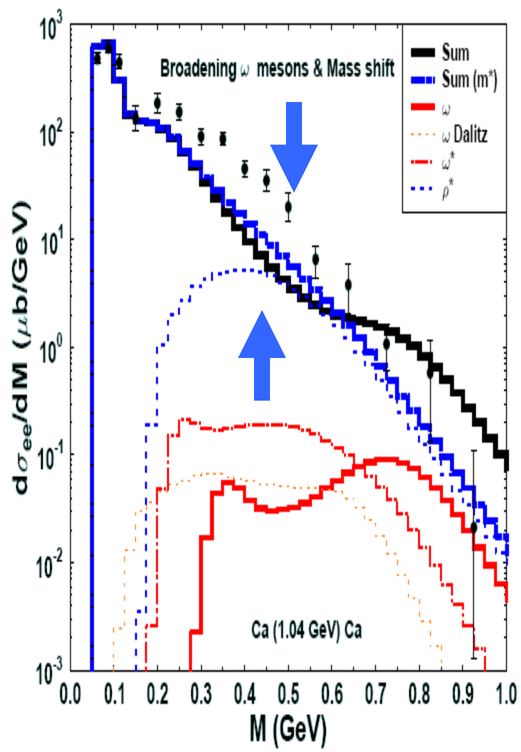
All attempts to reproduce the DLS results failed

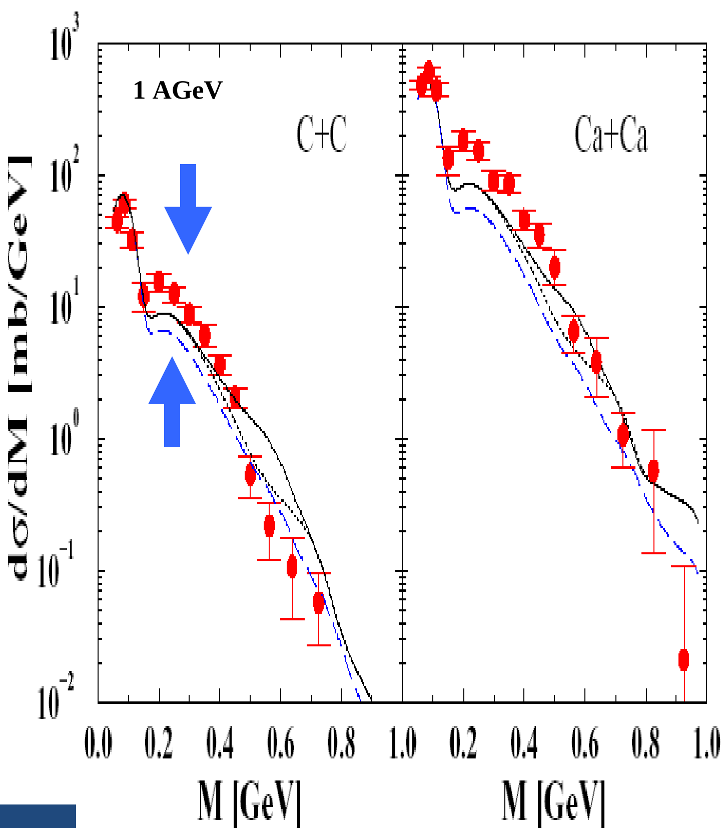
Calculation: E.L.Bratkovskaya et al.
Phys. Lett. B445 (1999) 265

Calculation: Ernst et al.
Phys. Rev. C58 (1998) 447

Calculation: C. Fuchs et al.
Phys. Rev. C68 (2003) 014904







DLS puzzle!

1. Is the DLS data wrong?

High acceptance di-electron spectrometer (HADES)

HADES studies confirmed the DLS data, no question against the data

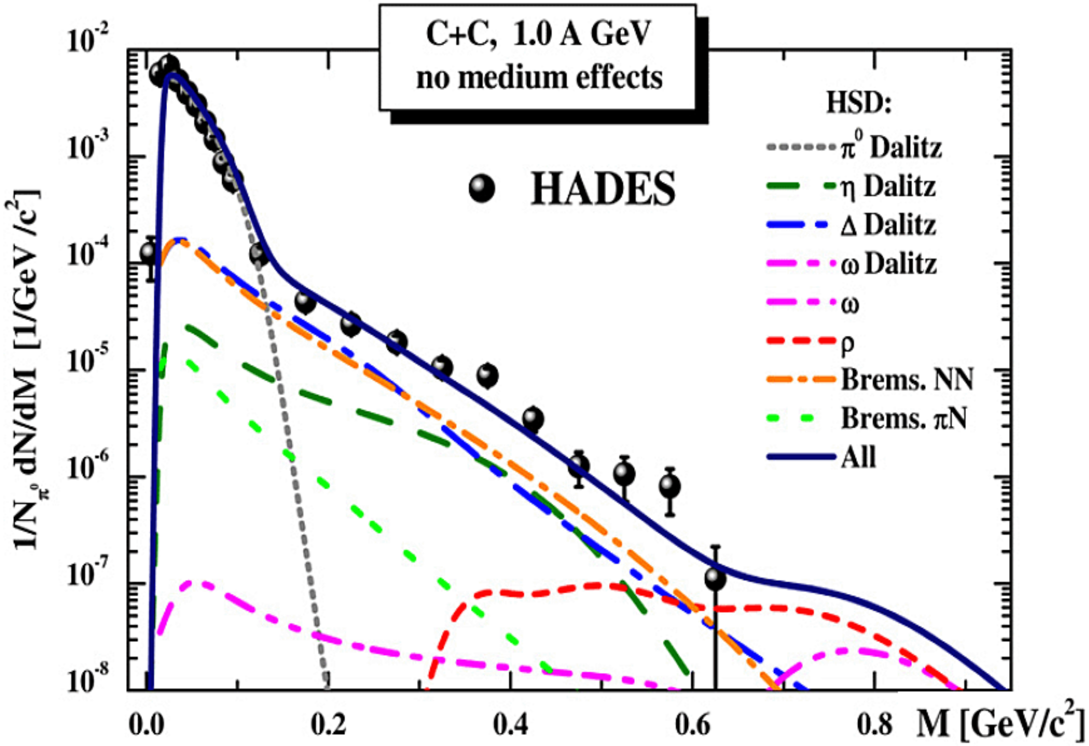
G. Agakichiev et al. Phys. Lett. B 663 (2008) 43

2. Is there something important missing in the theoretical calculations

Very important transport model study

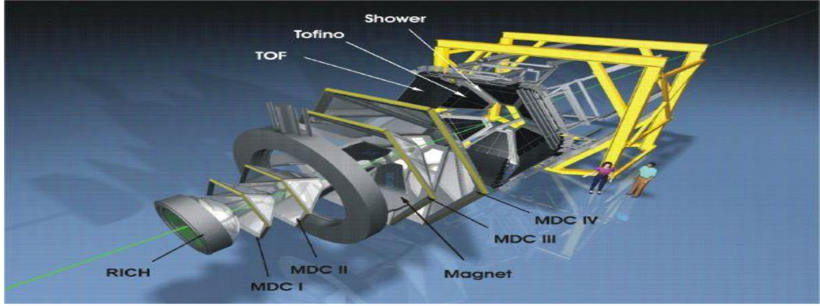
NPA 807 (2008) 214

Enhanced pn Bremsstrahlung cross sections (soft photon approx.)



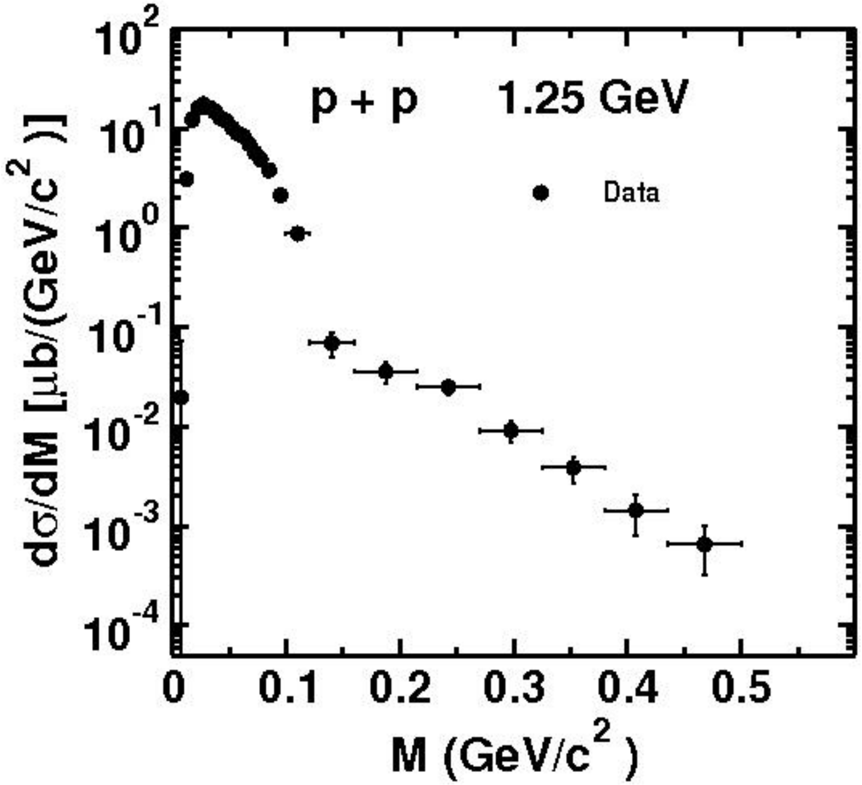
The puzzle seems to have reduced to an understanding of the dilepton production in elementary NN reactions

HADES DATA ON ELEMENTARY NN REACTIONS

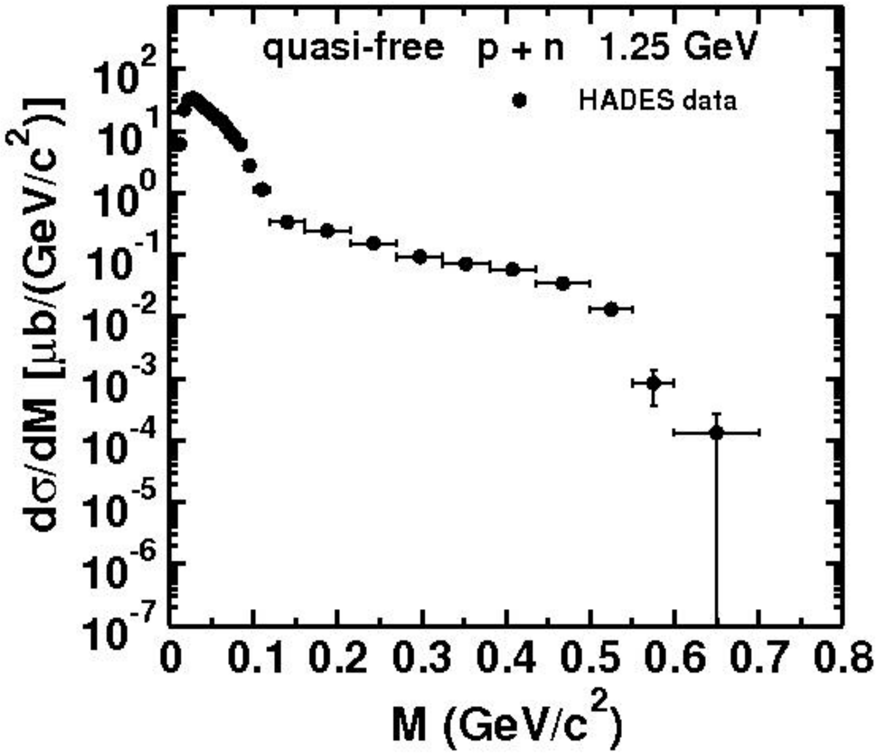


Phys. Lett. B 690 (2010) 118

p + p 1.25 GeV



quasi free p + n 1.25 GeV



Dilepton excess in the intermediate mass range 0.5-0.5 GeV/c^2 in C+C collisions can be described by a superposition of elementary p+p and p+n collisions.

ONE BOSON EXCHANGE MODEL

The Effective Lagrangian based description

Production amplitudes with lowest order Feynman diagrams generated by effective Lagrangians that satisfy:

- ***the relevant Invariant Laws,***
- ***symmetries of the fundamental theory (QCD),***
- ***include only the effective degrees of freedom instead of quarks.***

Effective degrees of freedom are modeled by baryons and mesons

Cleaner insight into the underlying production mechanism,

RS ,U. Mosel, Phys. Rev. C67 (2003) 065202, C79 (2009) 035203, arxiv:1006.3873

PARTICLE PRODUCTION IN NN COLLISIONS

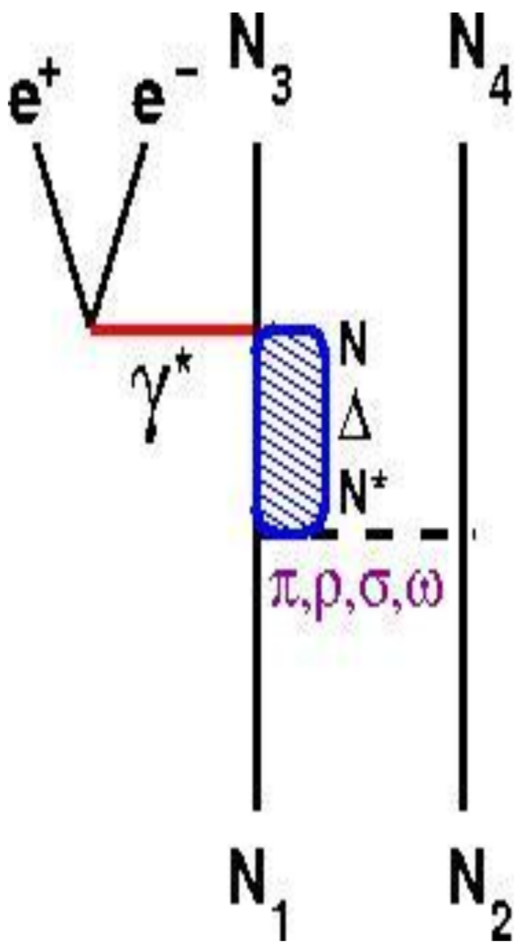
Initial NN interaction is modeled by effective** Lagrangians **based on exchange of** π, ρ, σ, ω **mesons.

Particle production ⟹ excitation propagation and decay of baryonic resonance intermediate states

- Effective Lagrangians at NNM, RNM and NNγ and RNγ vertices

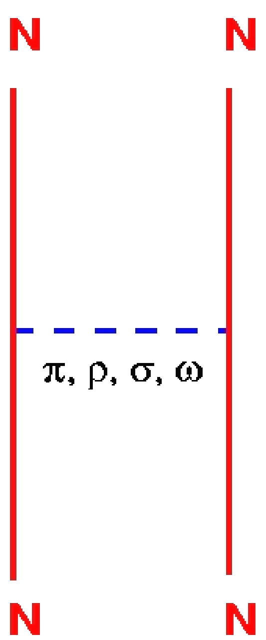
- Coupling constants and form factors

- Propagators for intermediate mesons and resonances



INITIAL NUCLEON-NUCLEON INTERACTION

Effective lagrangians



$$\ell_{NN\pi} = i\, g_{NN\pi}\, \bar{\Psi}_N \gamma_5 \tau.\Phi_\pi \Psi_N$$ **PS**

$$\ell_{NN\pi} = -(g_{NN\pi}/2m_N)\, \bar{\Psi}_N \gamma_5 \gamma_\mu \tau.(\partial^\mu \Phi_\pi)\, \Psi_N$$ **PV**

$$\ell_{NN\rho} = -g_{NN\rho}\, \bar{\Psi}_N [\gamma_\mu + (k_\rho/2m_N)\sigma_{\mu\nu}\partial^\nu]\, \tau.\rho^\mu\, \Psi_N$$

$$\ell_{NN\omega} = -g_{NN\omega}\, \bar{\Psi}_N [\gamma_\mu + (k_\omega/2m_N)\sigma_{\mu\nu}\partial^\nu]\, \omega^\mu\, \Psi_N$$

$$\ell_{NN\sigma} = g_{NN\sigma}\, \bar{\Psi}_N\, \sigma \Psi_N$$

At each interaction vertex Form Factor

$$F_i^{NN} = (\Lambda_i^2 - m_i^2)/(\Lambda_i^2 - q_i^2)$$

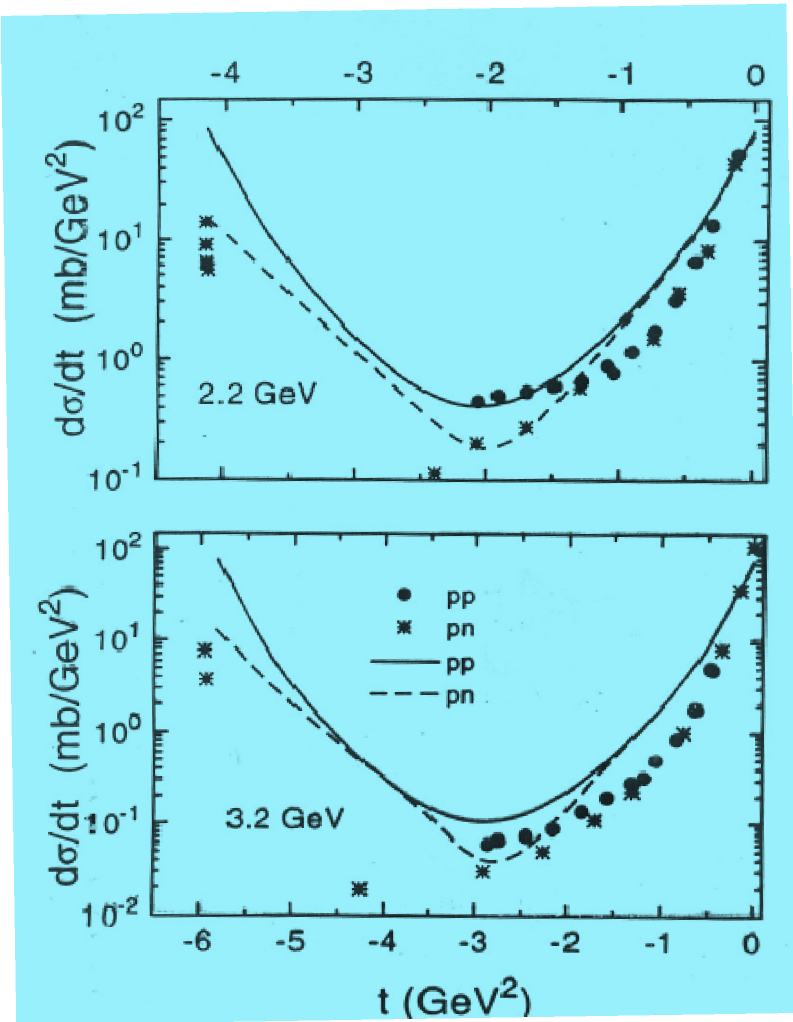
Energy dependence of Coupling constants

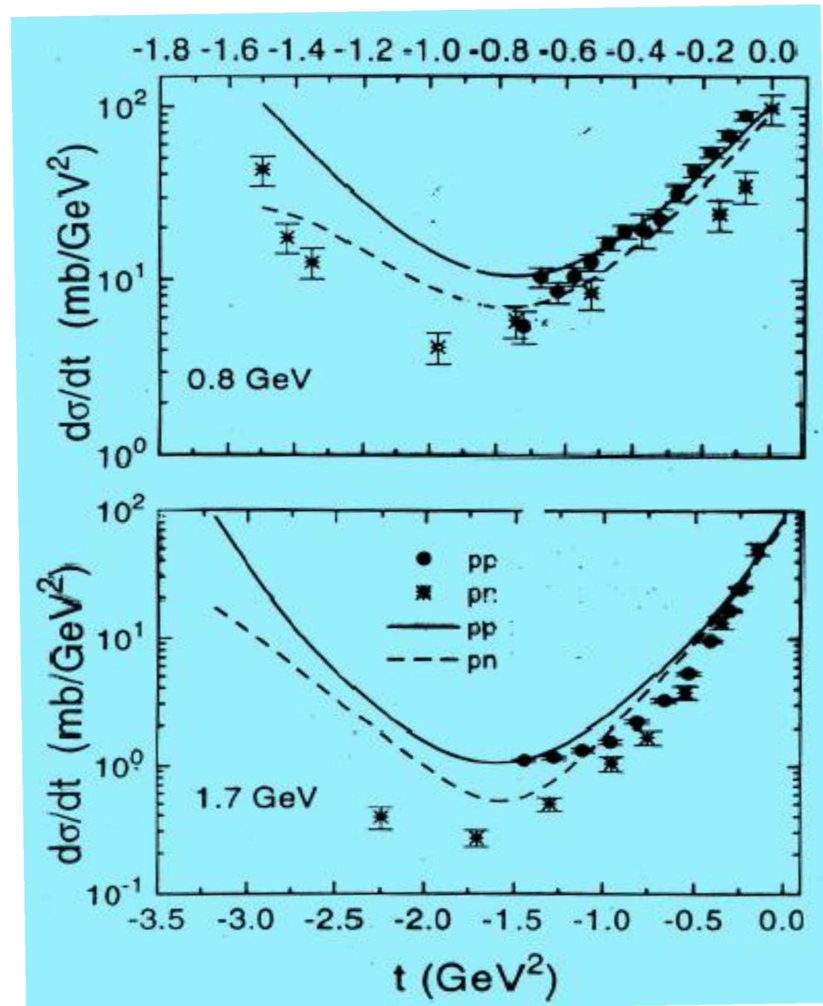
$$g_i(\sqrt{s}) = g_0 \exp(-\ell\sqrt{s})$$

Determination Nucleon-Nucleon-Meson vertex parameters

Describe the NN elastic scattering in the relevant energy region.

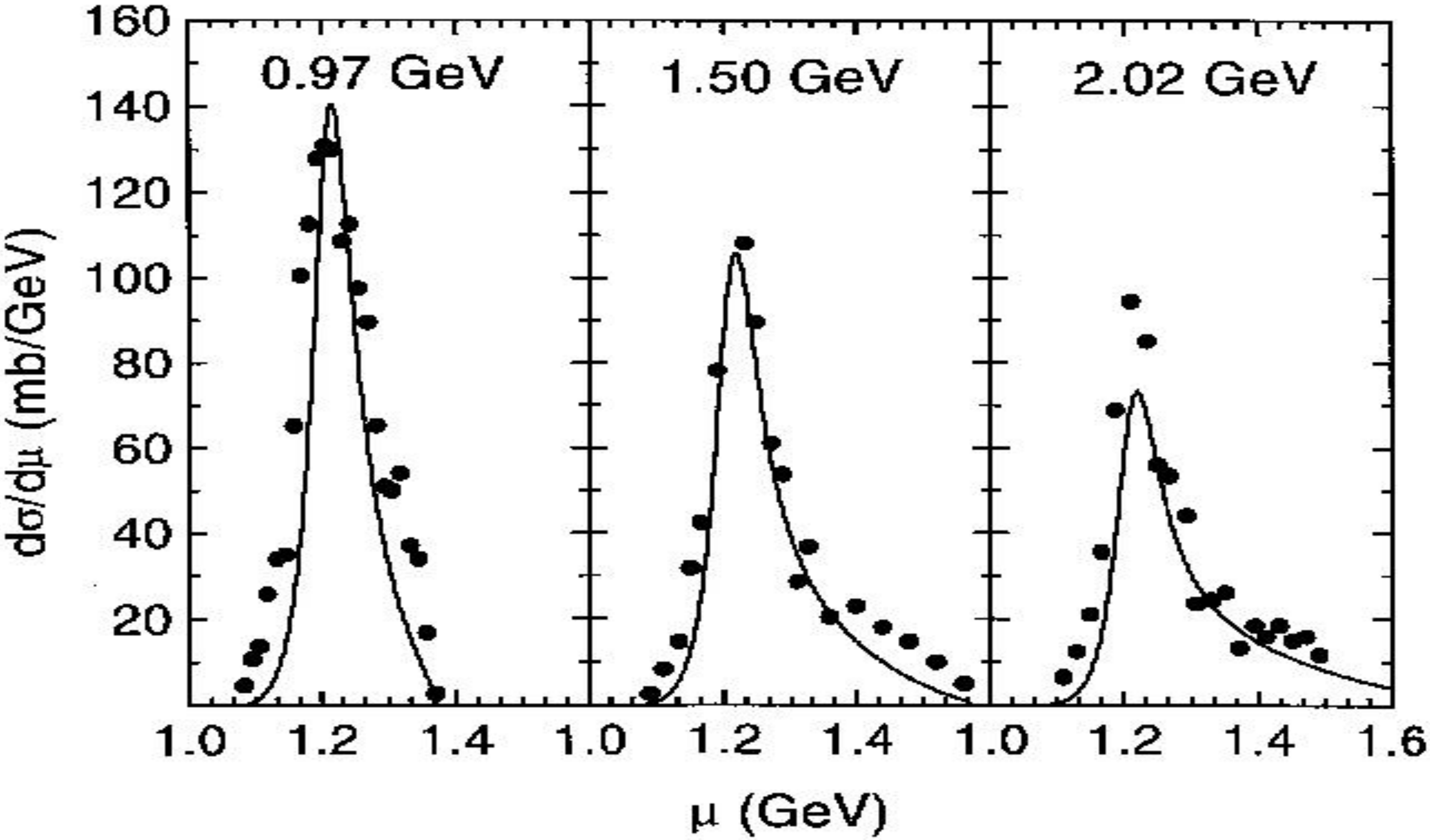
Coupling constants, shapes of the form factors, but not signs





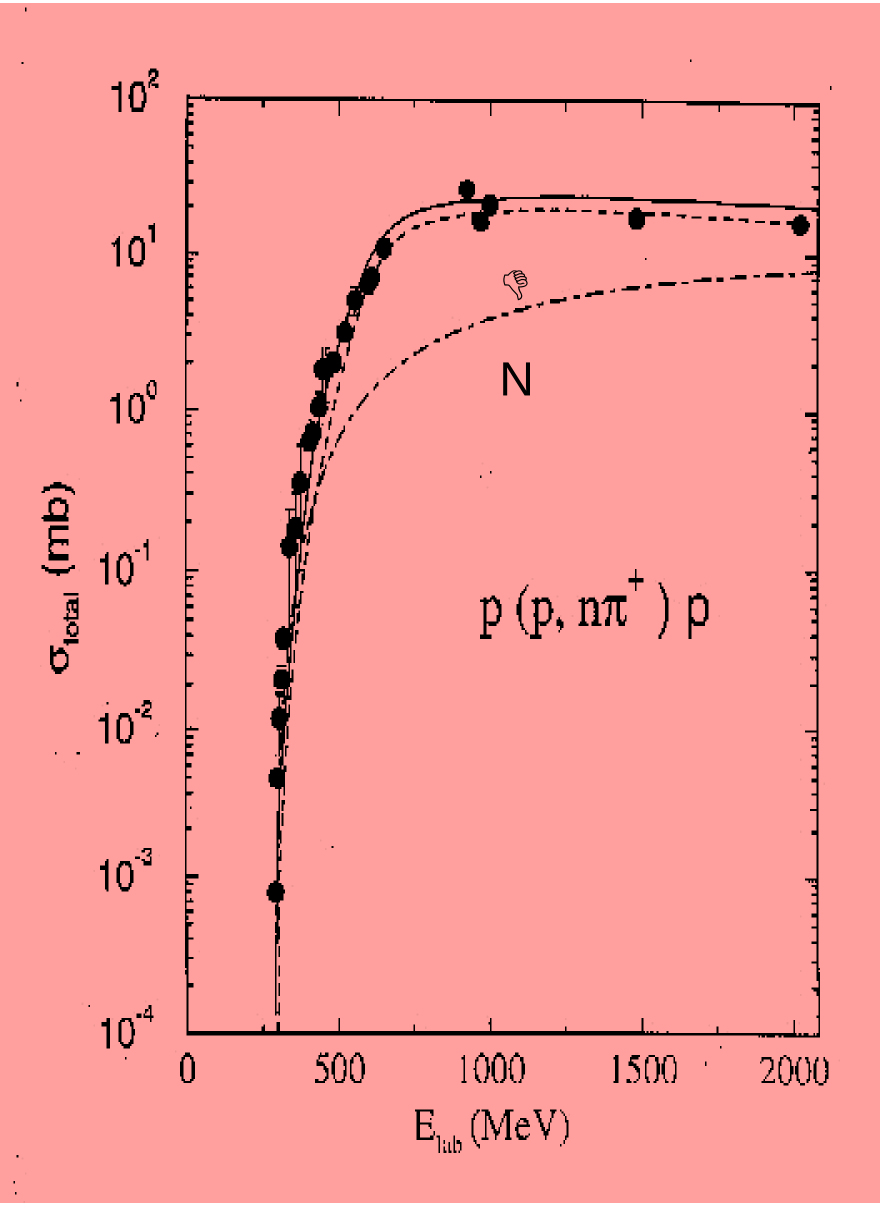
Determination of Delta vertex parameters

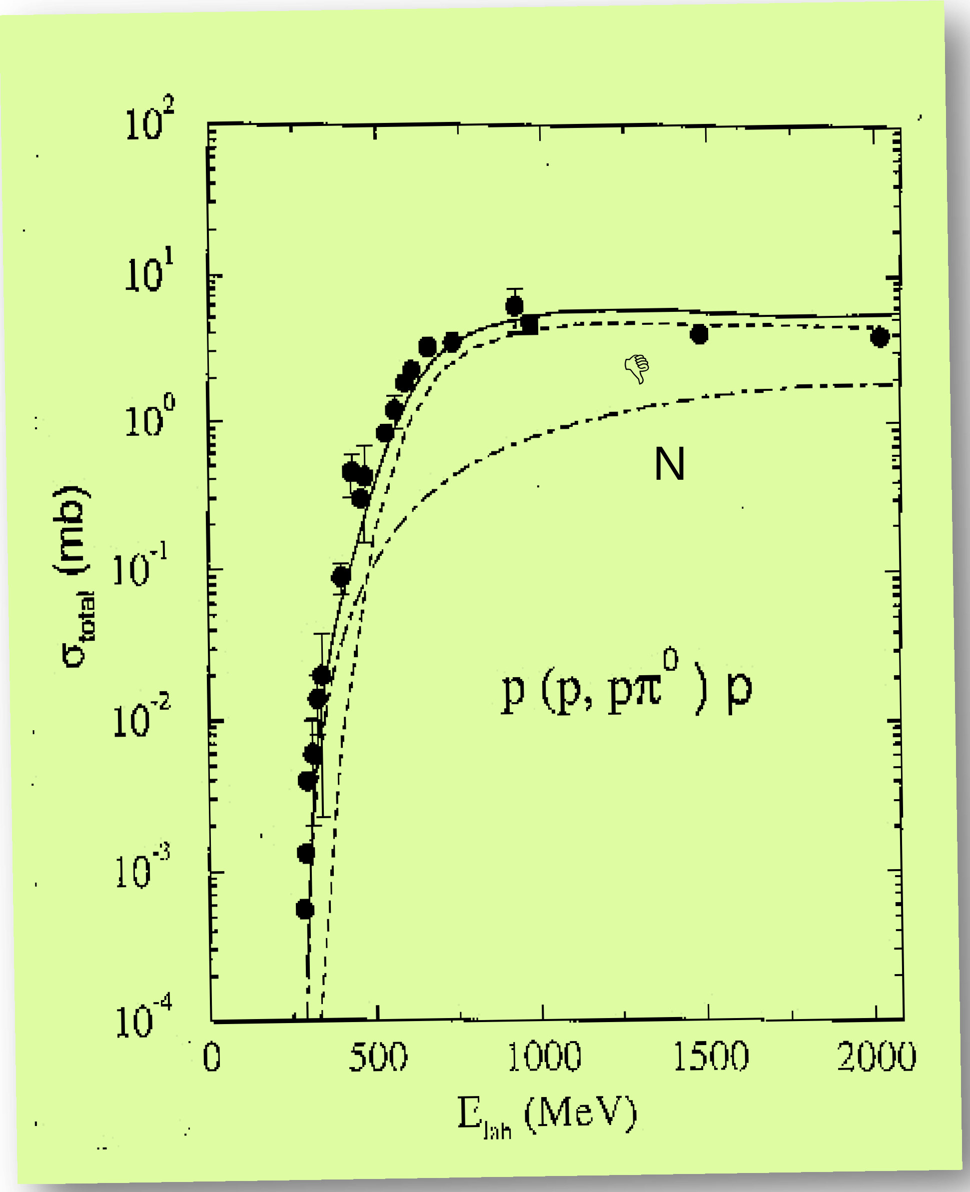
$pp \rightarrow n\Delta^{++}$

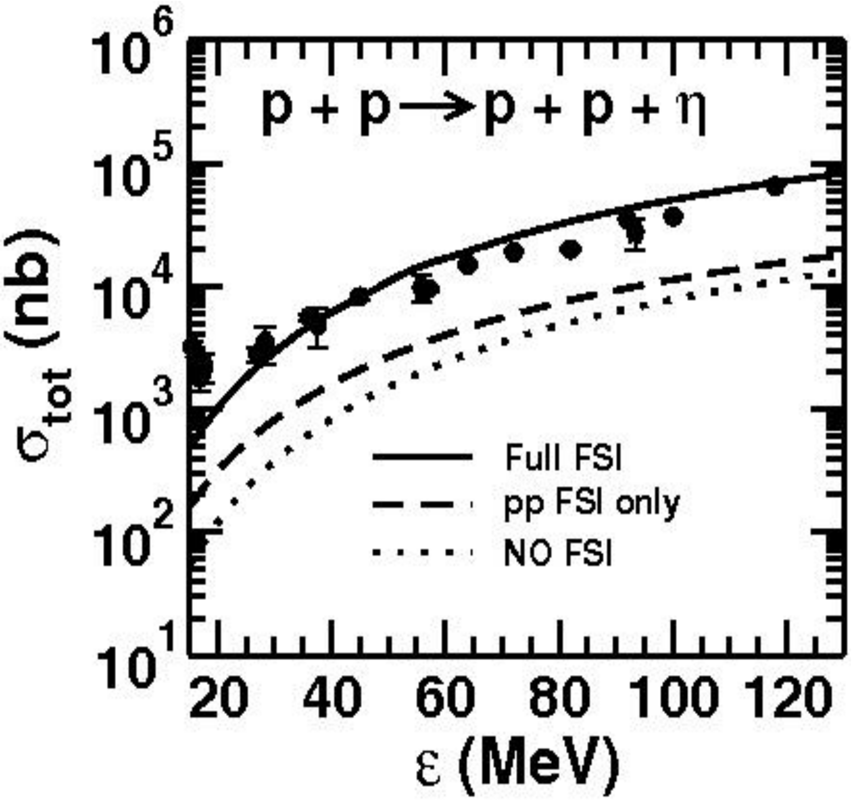


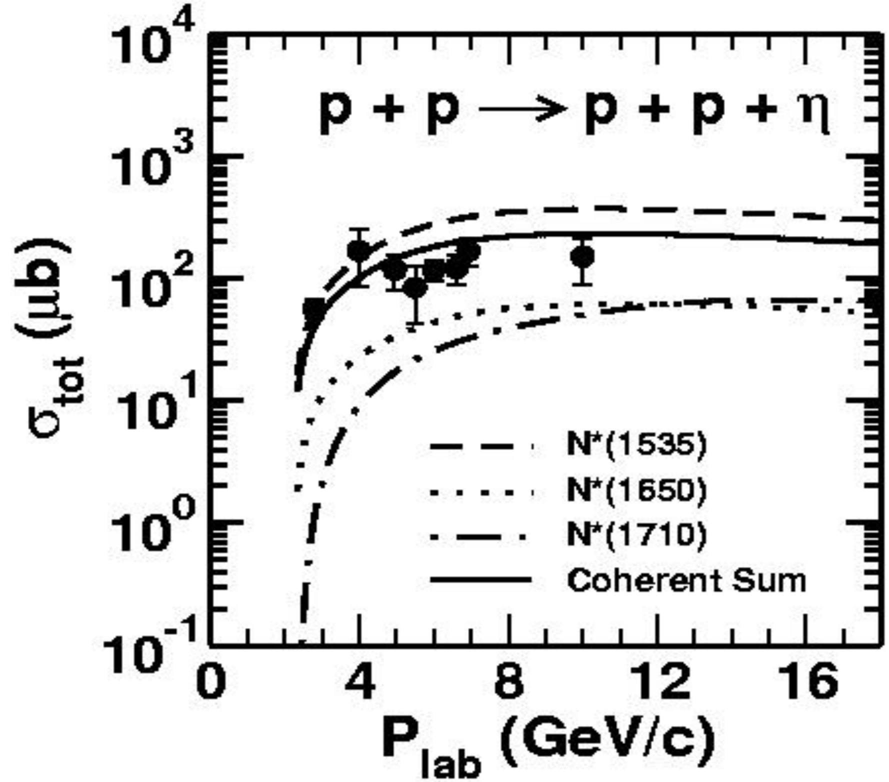
PION PRODUCTION

RS and U. Mosel, Phys. Lett.B 426 (1998) 1.





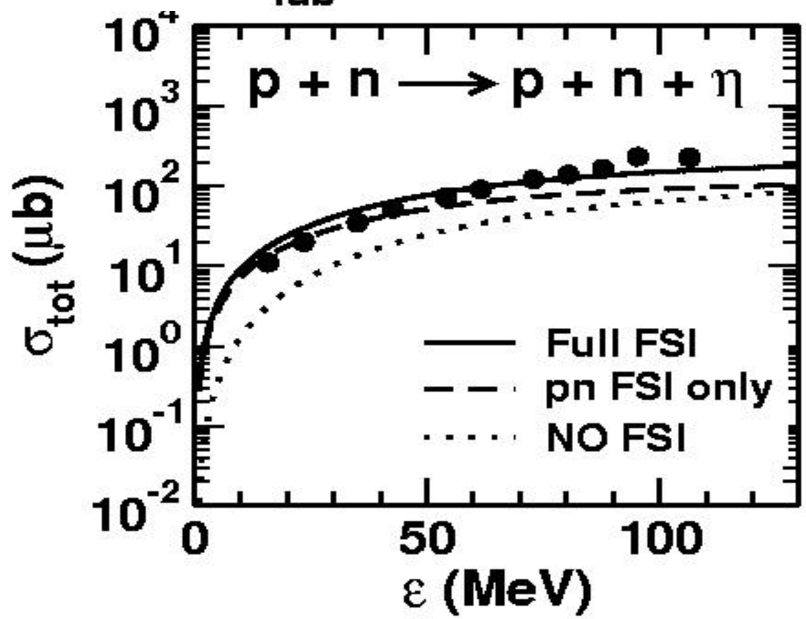




$\varepsilon = \sqrt{s} - 2m_p - m_\eta$

η Meson production

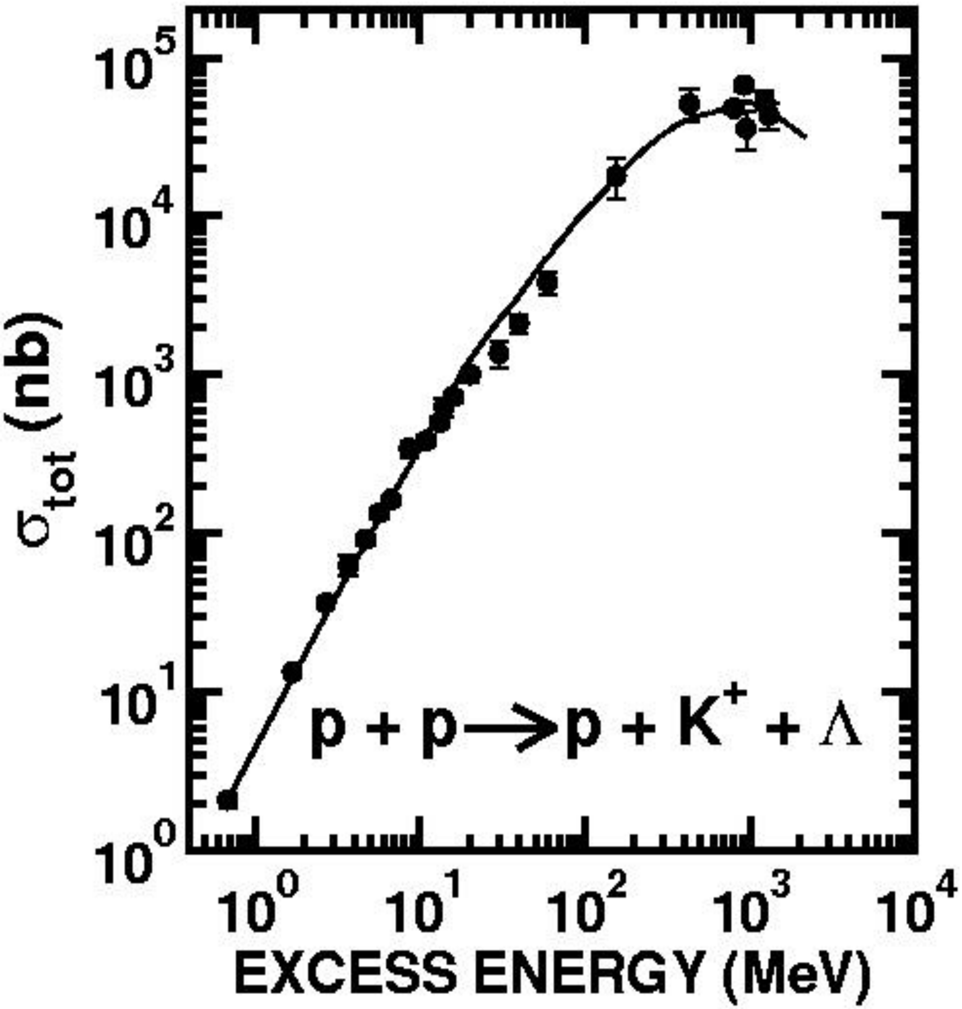
RS, Phys. Rev. C75, 055201 (2007)

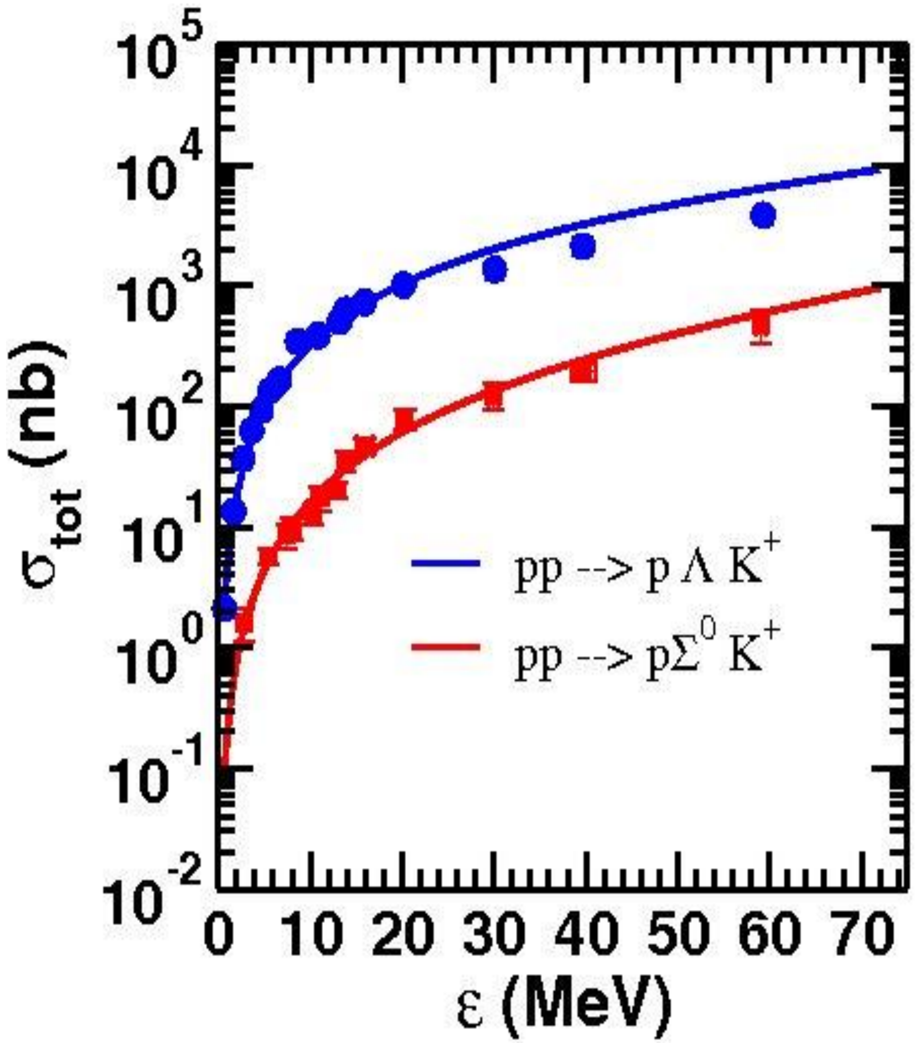


Associated Hyperon production

RS, H. Lenske and U. Mosel, Nucl. Phys. 764 (2006) 313

RS, Phys. Rev. C75, 055201 (2007)

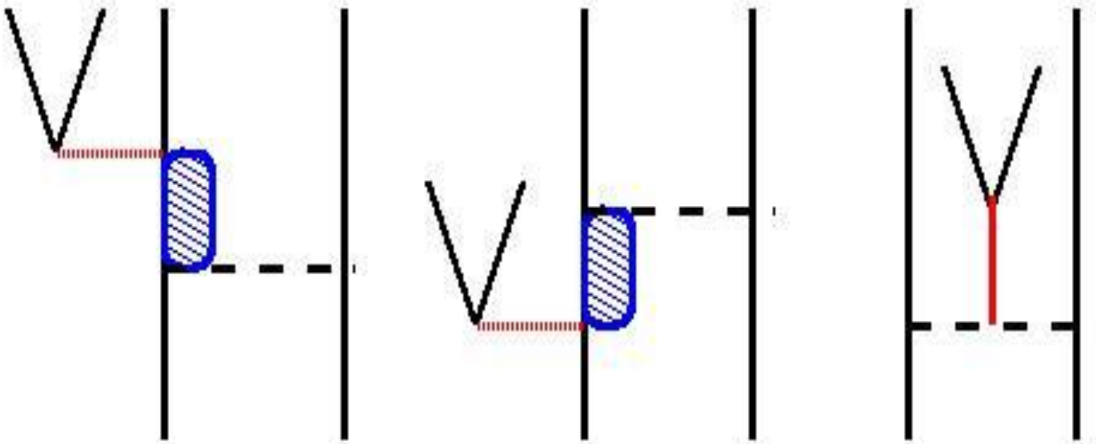




Coupling to electromagnetic field

$$\partial^\mu \to \partial^\mu - iem\boldsymbol{A}^\mu$$

m = +1, 0, -1

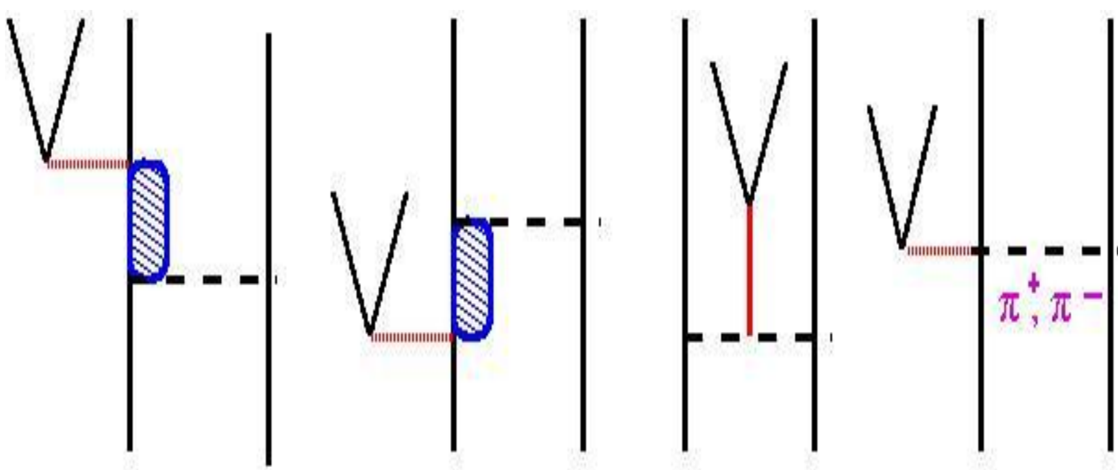


Pion exchange process

PS

gauge invariant

for point like



PV

Contact diagrams

Introduction of Strong Form Factors at hadronic vertices

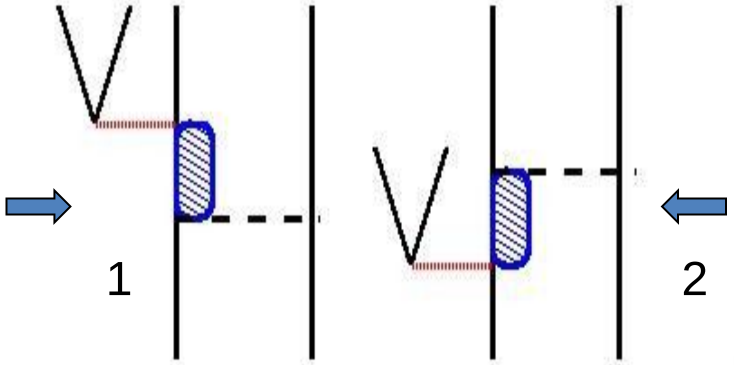
Couplings g's should be modified to reflect the finite size of nucleons

But make sure that gauge invariance is preserved

$$g_\alpha = g_\alpha f_\alpha \qquad f_\alpha(k^2) = (\Lambda_\alpha^2 - m_\alpha^2)/(\Lambda_\alpha^2 - k^2)$$

Multiply all the hadronic vertices by the same form factor.

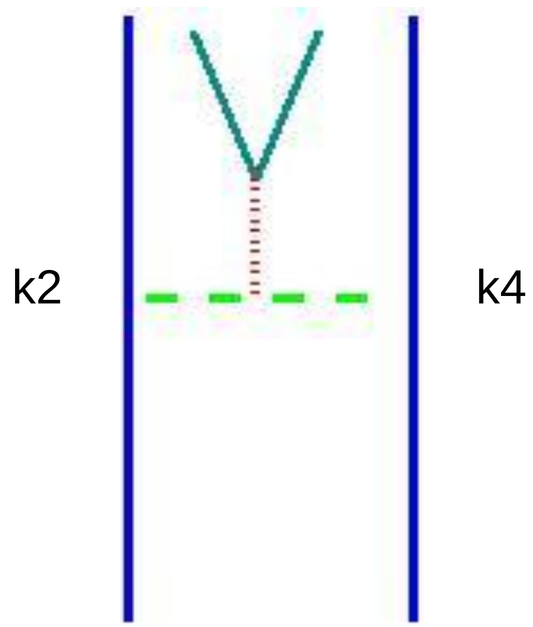
neutral meson exchange



$$q_\mu j^\mu = 0$$

Make use of Ward-Takahashi identity

For charged meson diagram 3 is needed

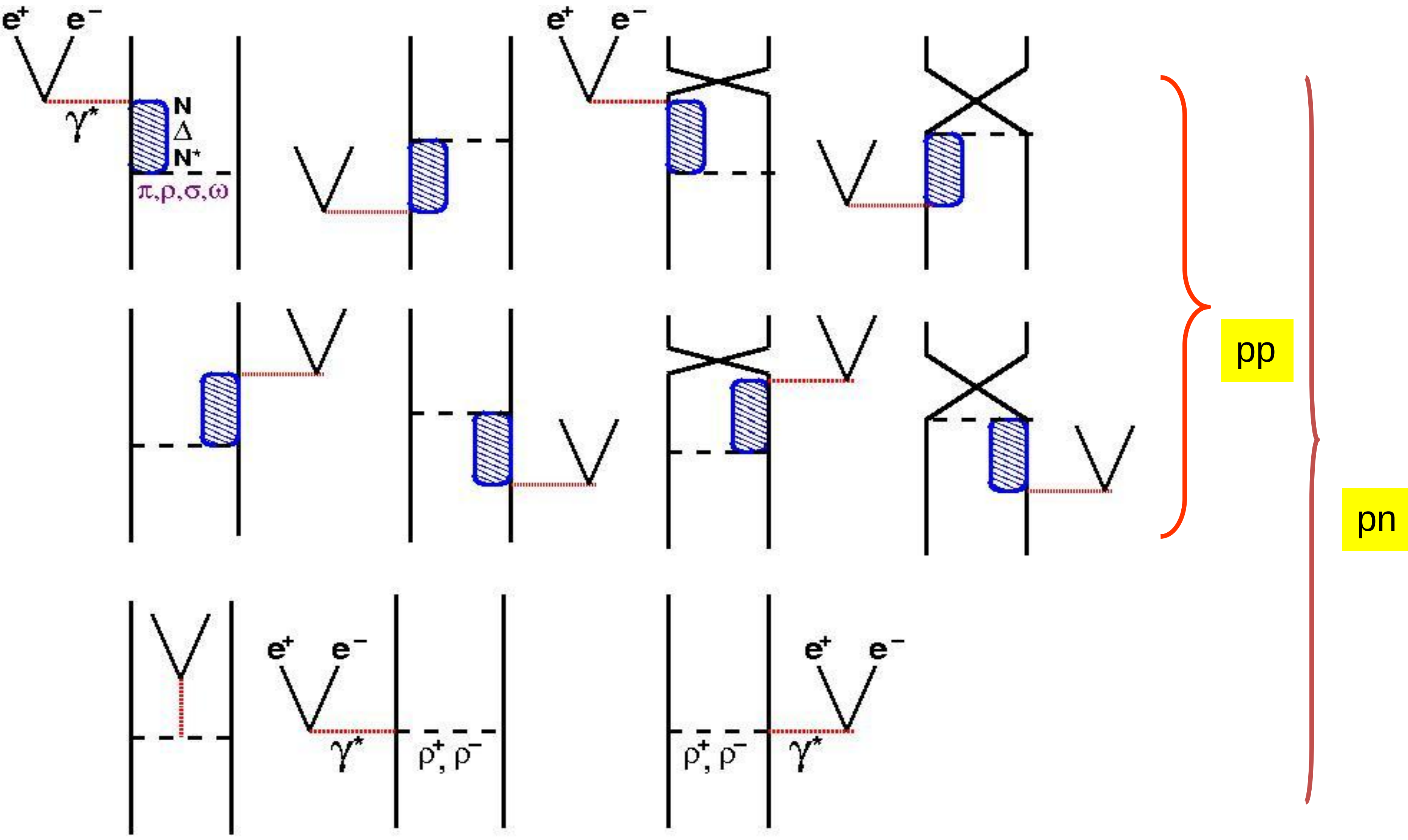


$f_\alpha(\Lambda_\pi) = f_\alpha(k_2^2)\, f_\alpha(k_4^2)$

$\times\,[1 + (k_2^2 - m_\pi^2)/(k_4^2 - \Lambda_\pi^2) + (k_4^2 - m_\pi^2)/(k_2^2 - \Lambda_\pi^2)]$

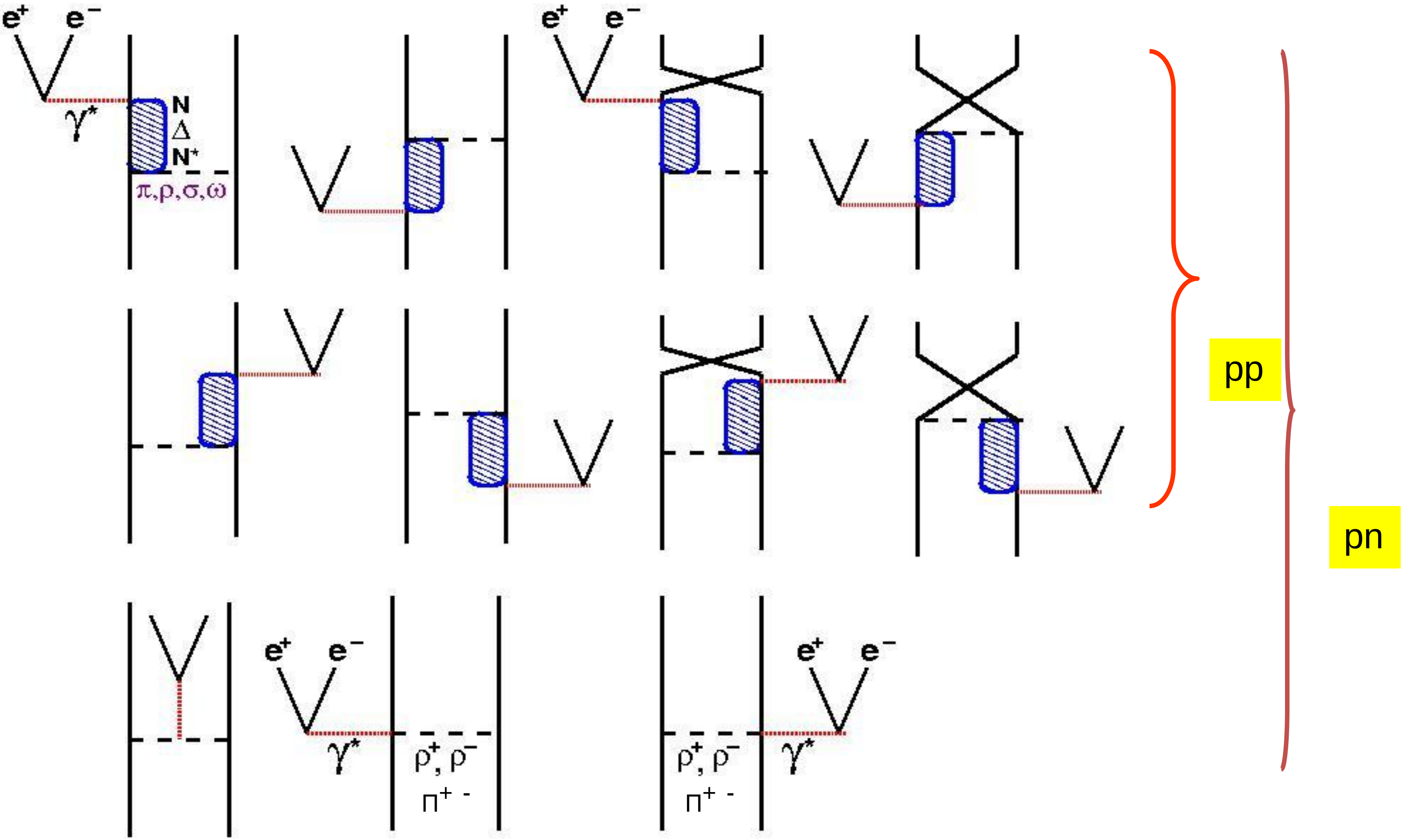
D.O. Riska, Progr. Part. Nucl. Phys. 11 (1984) 199

With PS NNπ coupling, no contact term for the dominant pion exchange processes in pn reaction



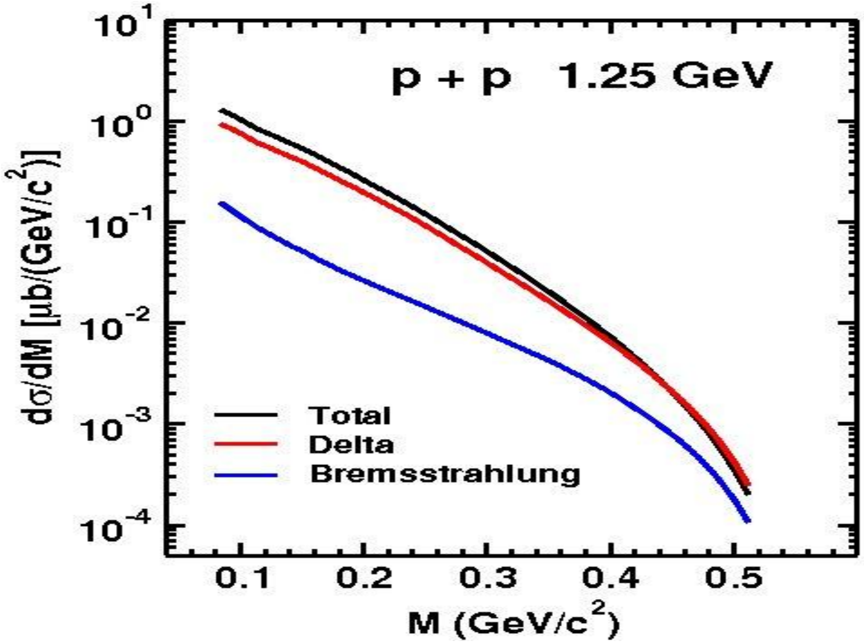
RS and U. Mosel, Phys. Rev. C79 (2009) 035203

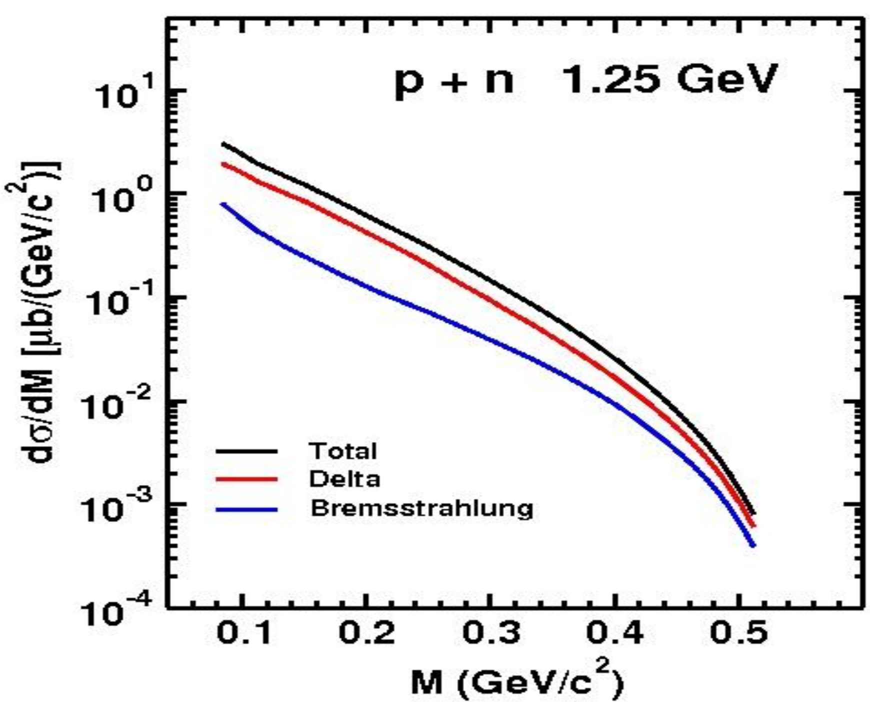
With PV NNπ coupling, contact term for the dominant pion exchange processes in pn reaction

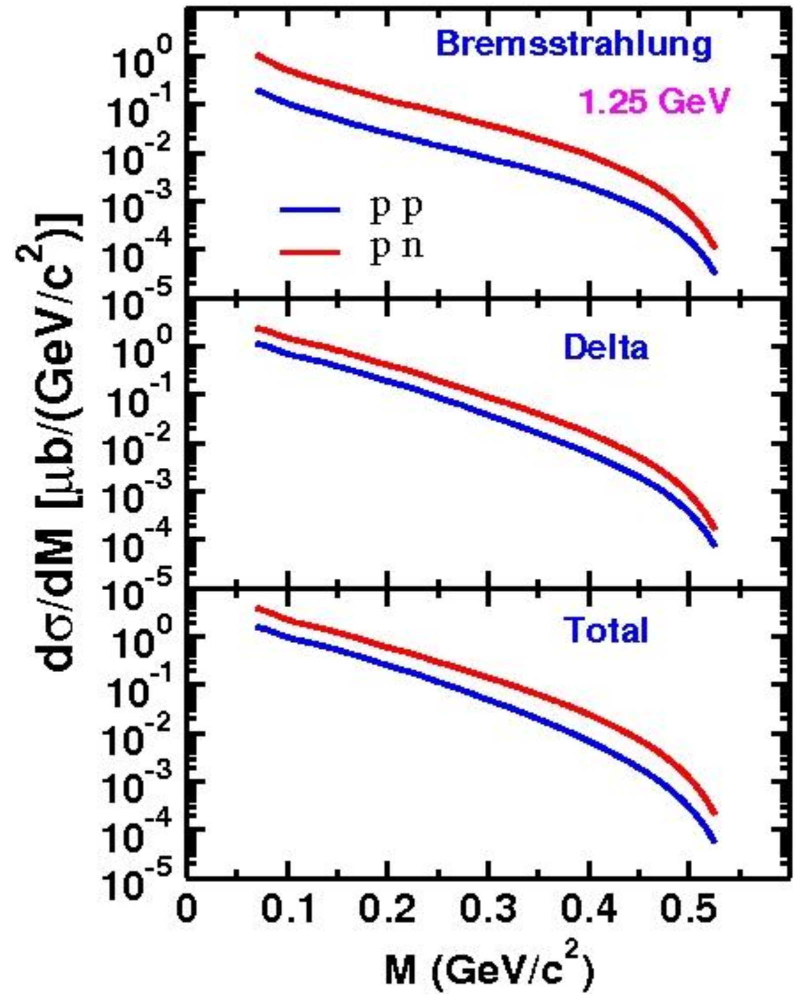


Kaptari, Kaempfer, Nucl. Phys. A764, 338 (2006)

Results at HADES energy



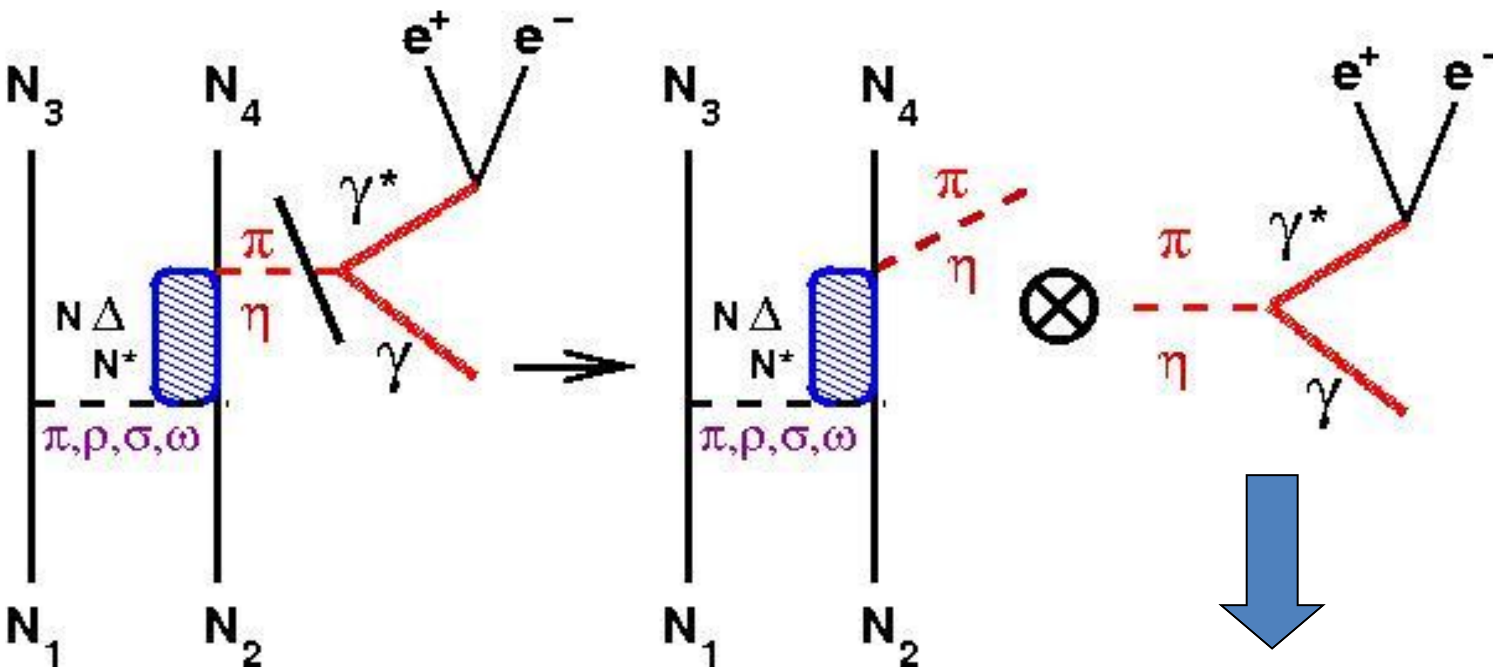




pn bremsstrahlung > pp (5-6)

pn total yield is larger than pp by factors around 3

Comparison with the data requires other contributions also



Meson Dalitz decay

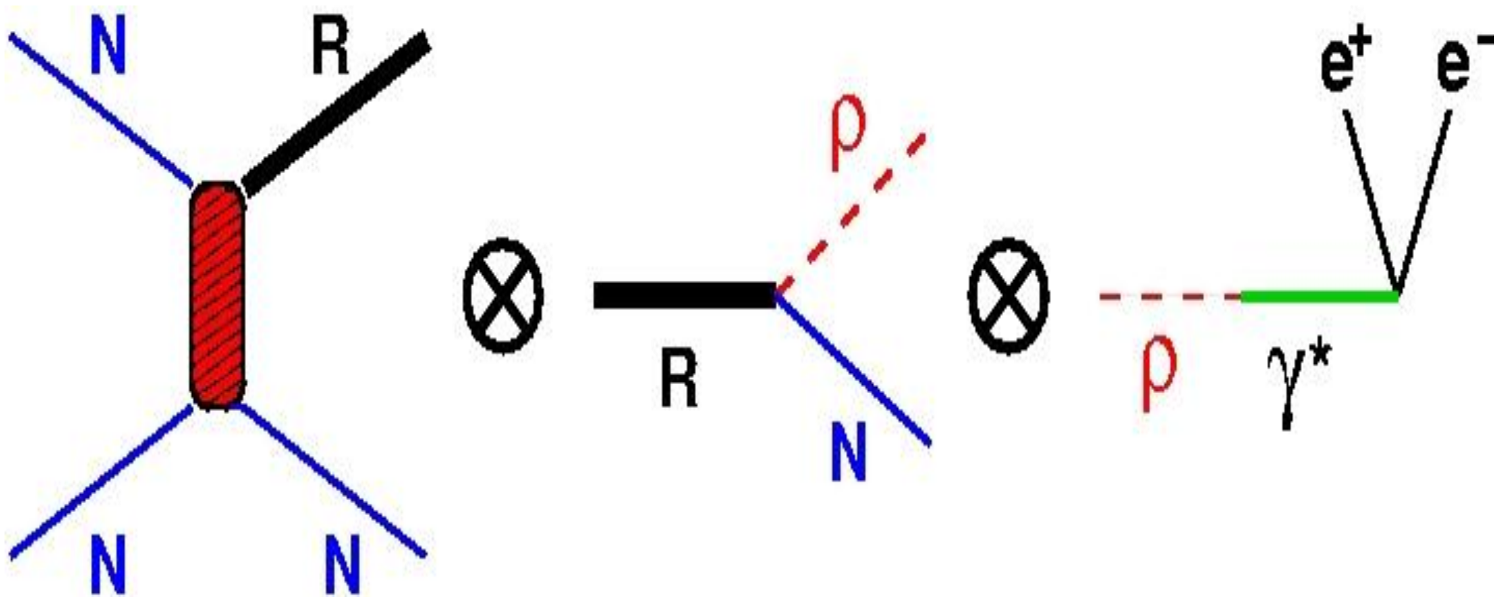
L.G. Landsberg, Phys. Rep. 128 (1985) 301

***π* and *η* production cross sections**

R. Shyam and U. Mosel, Phys. Lett. B426 (1998) 1

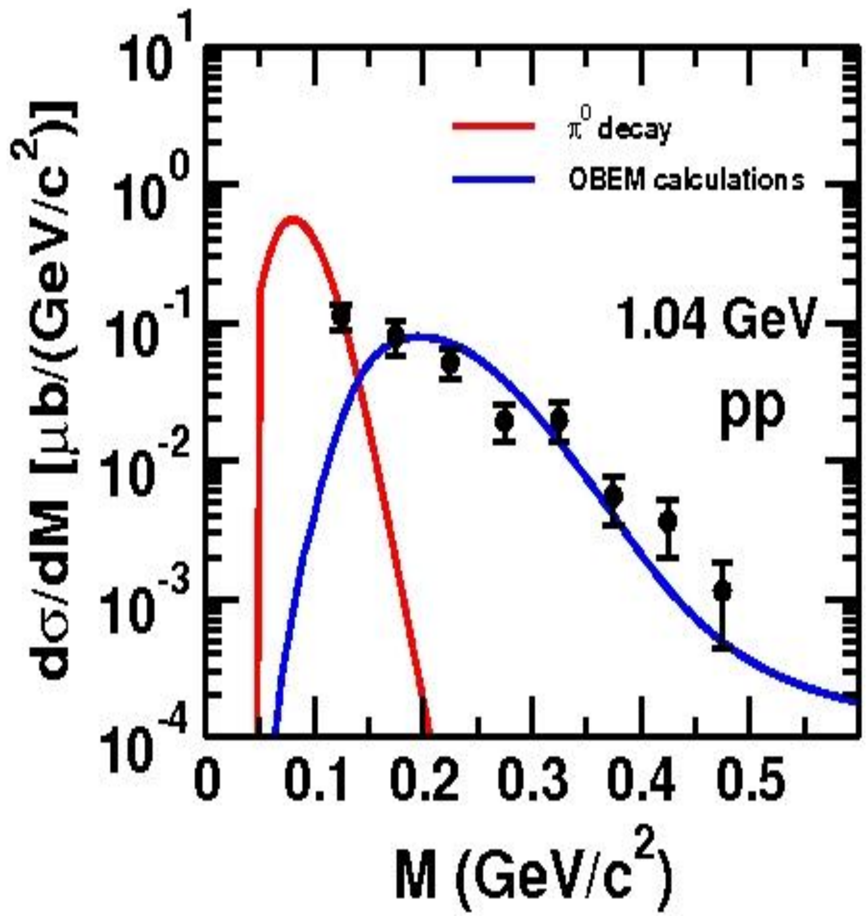
R. Shyam, Phys. Rev. C 75 (2007) 055201

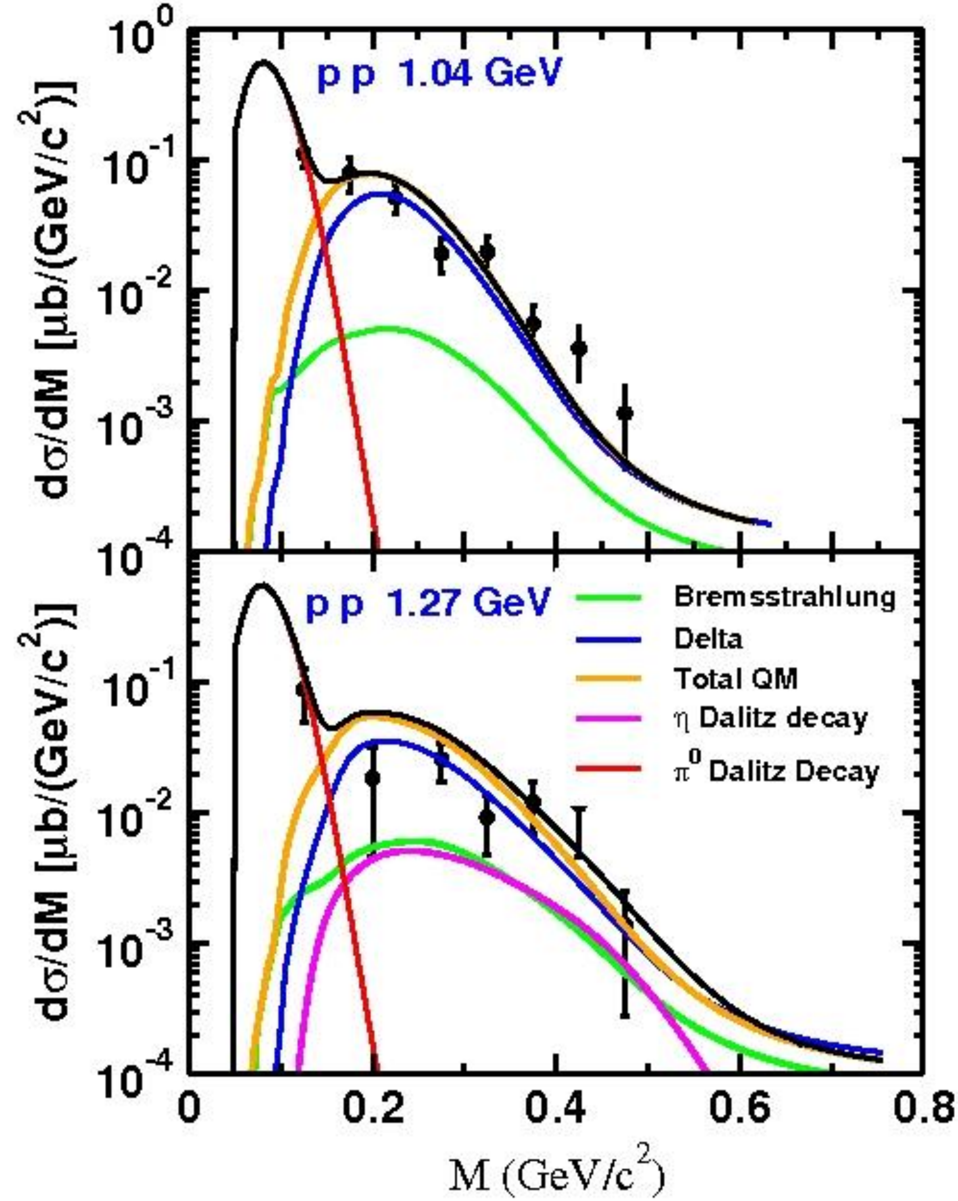
Dilepton yields from the production and decay of subthreshold □0 meson via the baryonic resonances



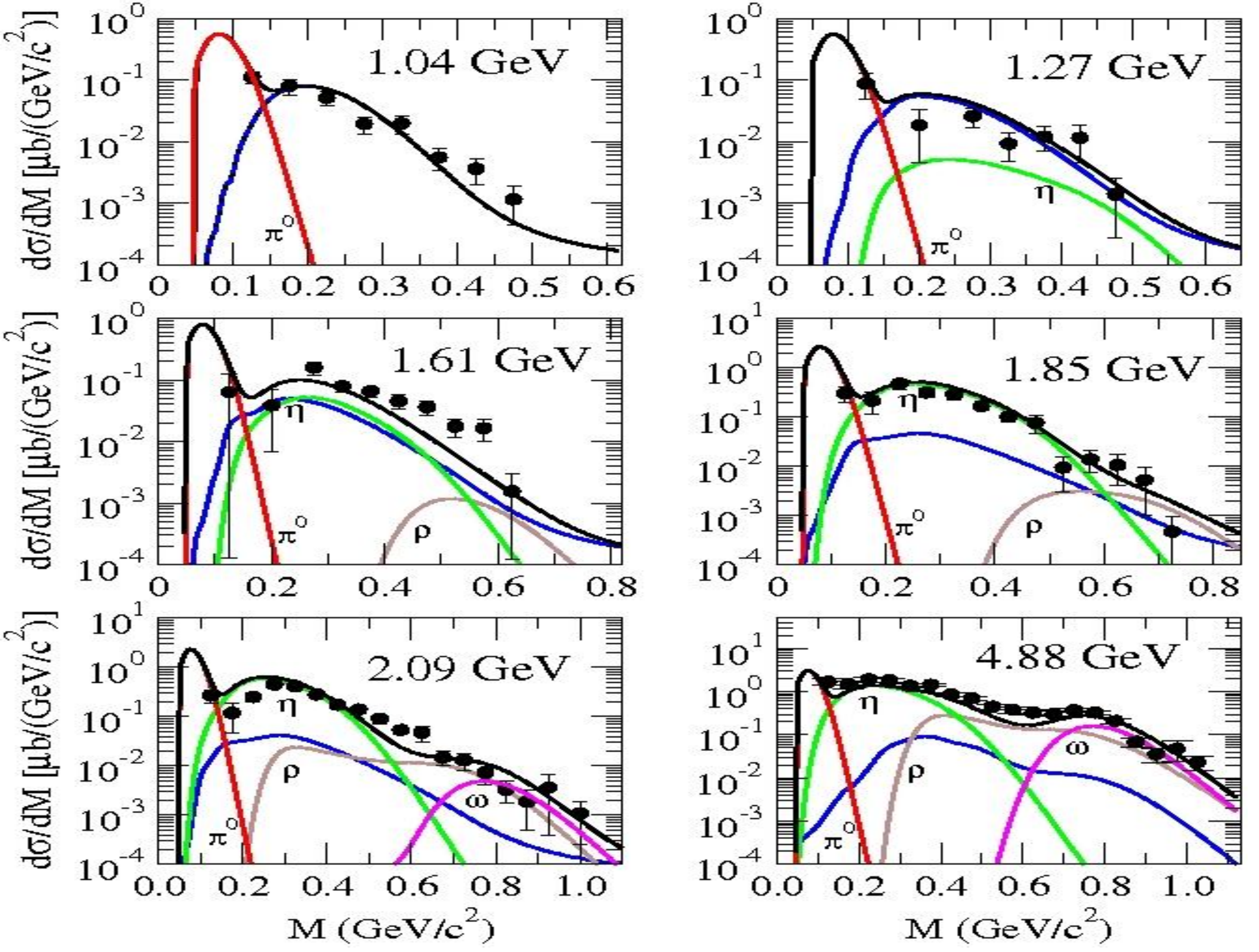
We consider only N*(1520) resonance in our calculations

Comparison with the DLS data



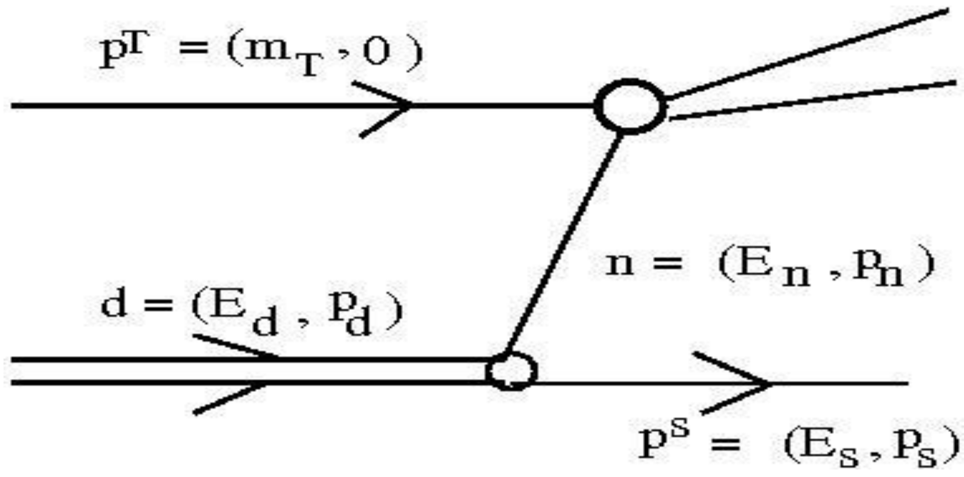


Comparison with the DLS data at higher energies



Extracting p+n cross sections from the d+p experiment

$p_n = - p_s = p_f$



Available energy in c.m. is smeared to include neutron momentum distribution in deuteron using Argonne V18 potential

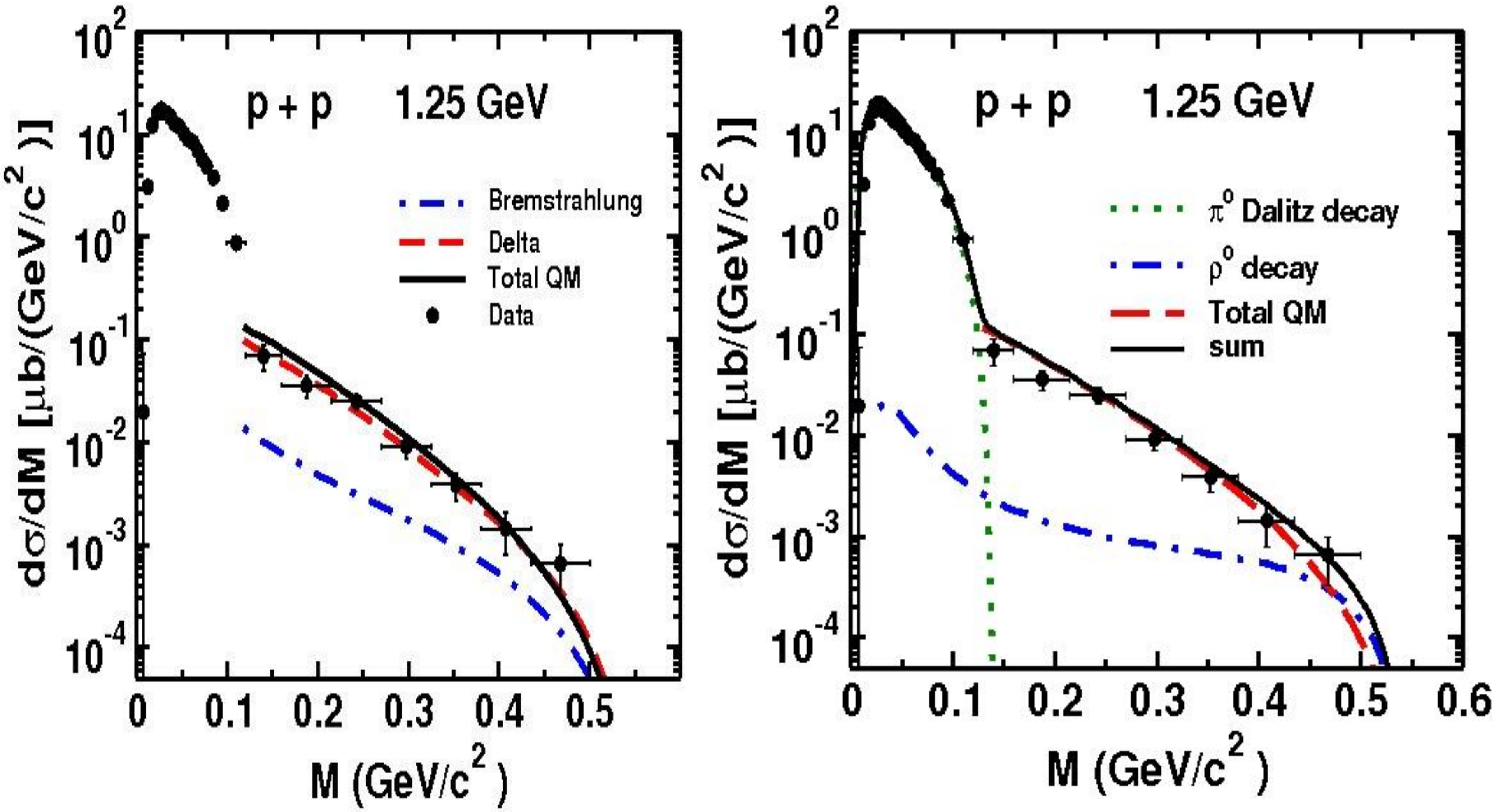
Dileptons measured in d + p reaction → In a smeared n + p reaction

↓

with cm energies in excess of 1.25 GeV

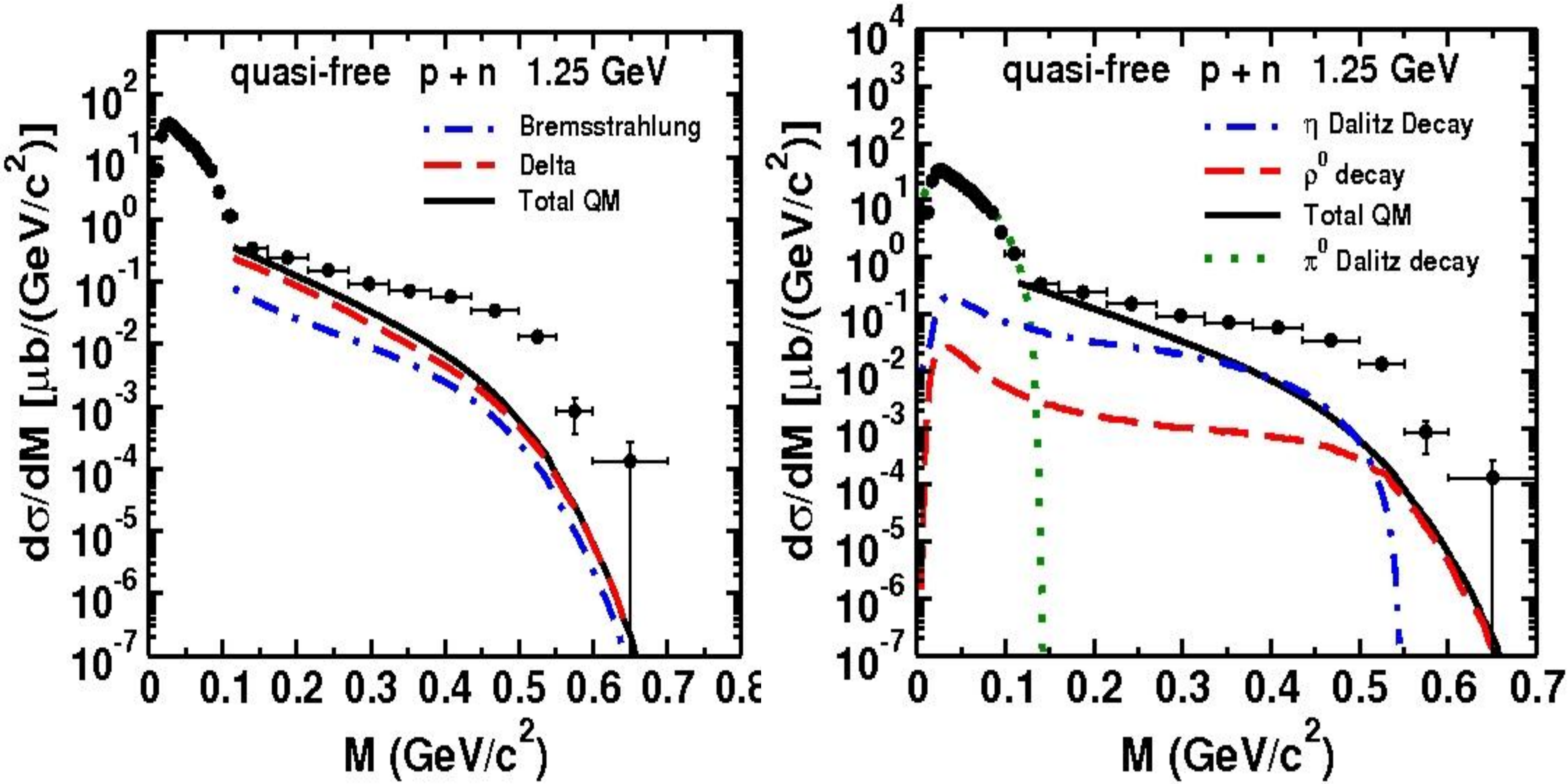
η production channel opens up

HADES pp data as compared with our calculations



Data: HADES coll. Phys. Lett. B 690 (2010) 118

HADES quasi-free pn data as compared with calculations



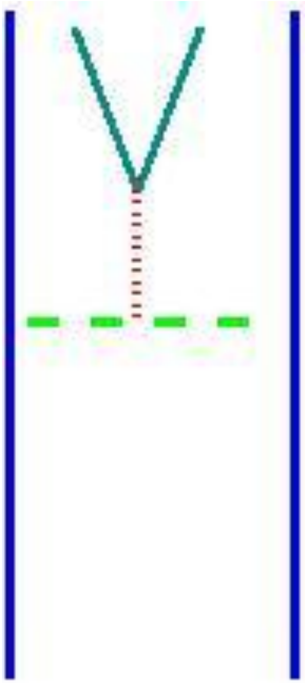
Has been termed as a New Puzzle, HADES puzzle!!

Data: HADES coll. Phys. Lett. B 690 (2010) 118

What is the solution

One possibility

Present in pn but not in pp case



Pions have electromagnetic structure

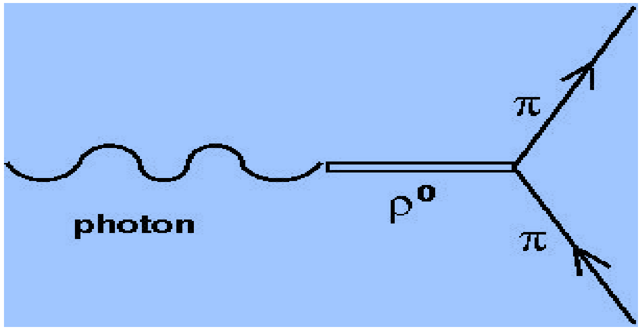
Include pion electromagnetic form factor

But preserve the gauge invarinace

Gross and Riska, Phys. Rev. C 36 (1987) 1928

FF1

Ericson and Weise, Pions and Nuclei



$$F_\pi\ (M^2) = [m_\pi^2 / (m_\pi^2 - M^2 - i m_\pi \Gamma_\pi)],$$

$\Gamma_\pi = \rho \to \pi\pi$ decay width

Reproduces the main features of pion form factors both in space- and time-like regions

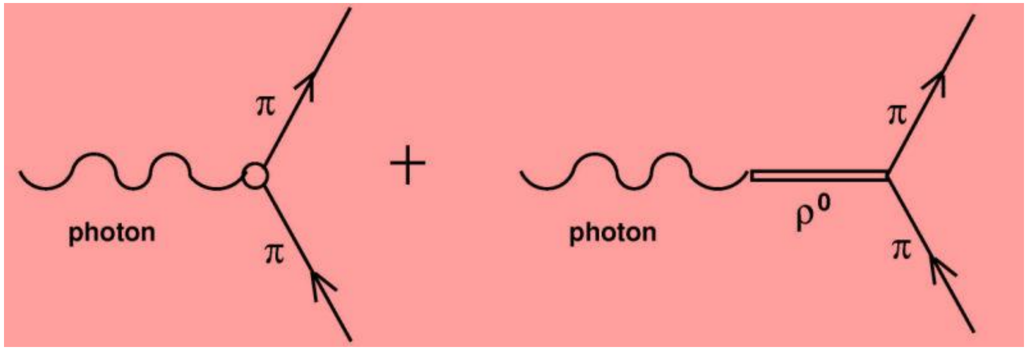
FF2

Brown, Rho and Weise, Nucl. Phys. A454 (1986) 669

Provides good fit to pion form factors both in space- and time-like regions

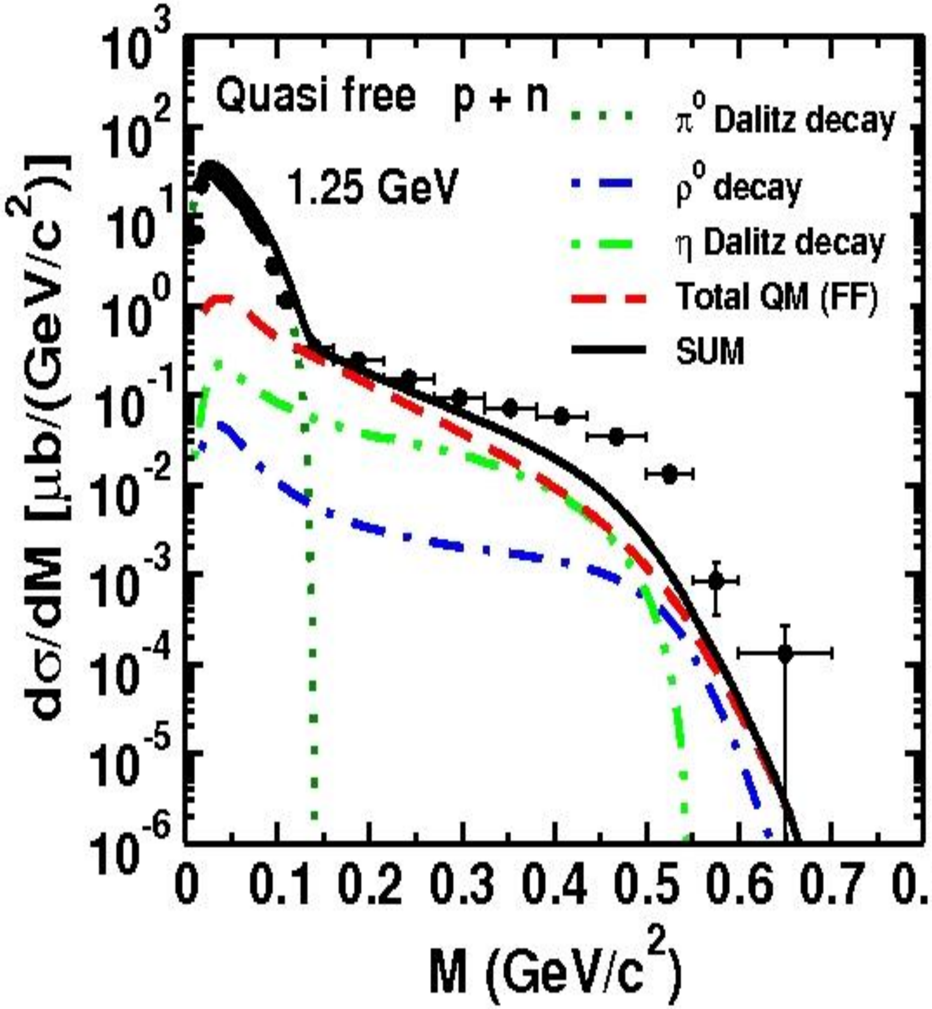
$$F_\pi\ (M^2) = 0.4/(1 - M^2/\lambda^2) + 0.6/(1 - M^2/2m_\pi^2) \times m_\pi^2/(M^2 - m_\pi^2 - i m_\pi \Gamma_\pi)$$

$\lambda^2 = 1.9\ GeV^2$

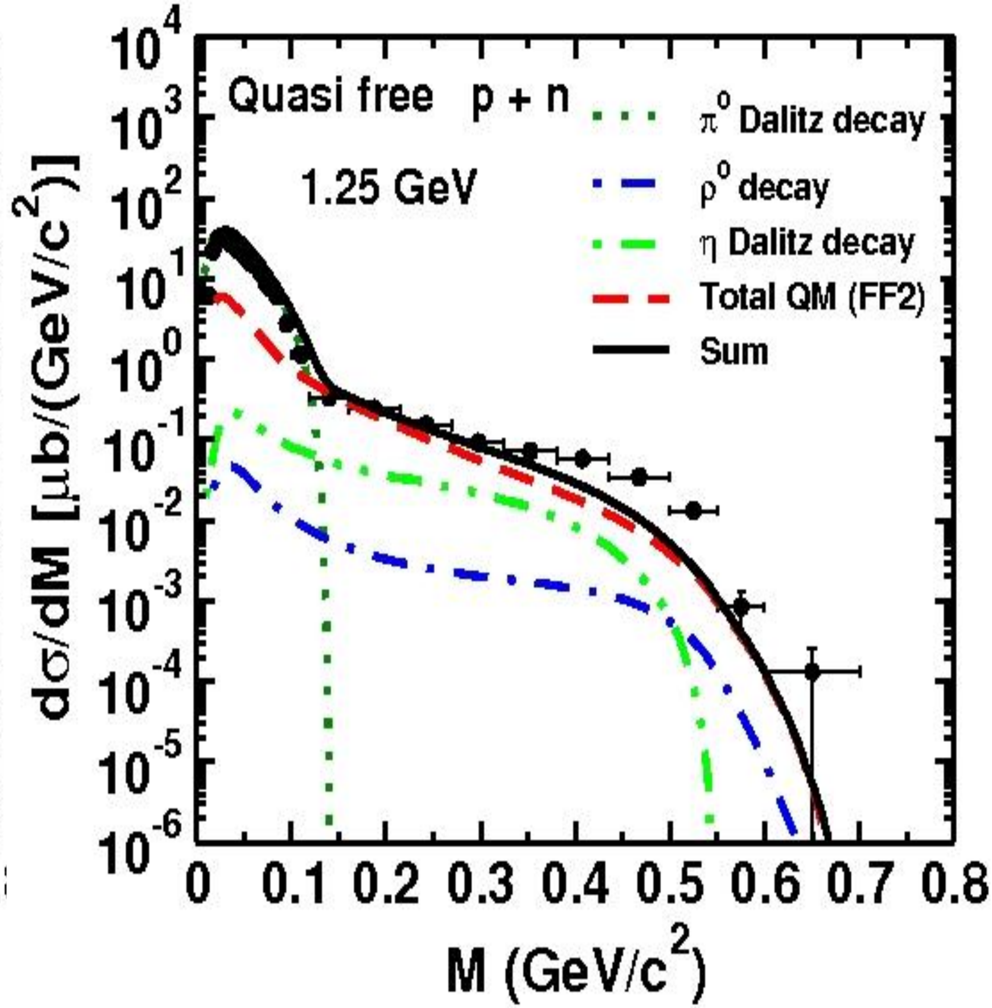


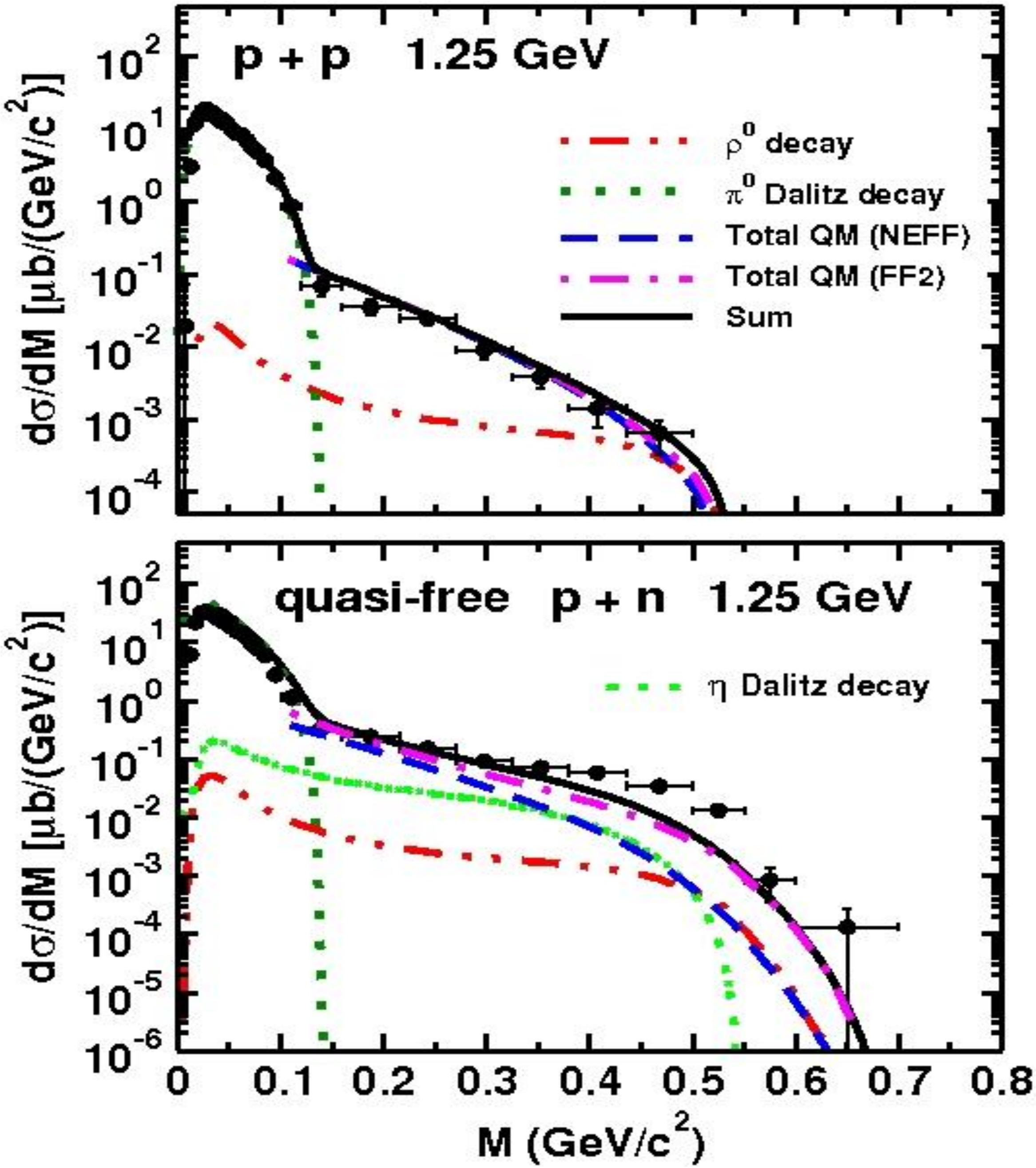
photon couples directly to Internal structure of pion ~ 50%

Form factor FF1



Form factor FF2





Data: HADES coll.
Phys. Lett. B 690 (2010) 118

RS and U. Mosel,
arXiv:1006.3873,

Phys. Rev. *C* (Rapid Comm.
In press)

Hades pp data is in agreement with our model

With inclusion of pion electromagnetic form factor, the quasi-free pn data can also be largely explained, so there may no longer be a puzzle.

DLS puzzle

→ Experimentally resolved

→ Theoretically is also almost resolved

Photon induced meson production Reactions

Determination of nucleon resonance properties from experimental data.

Benchmark for testing predictions of LQCD.

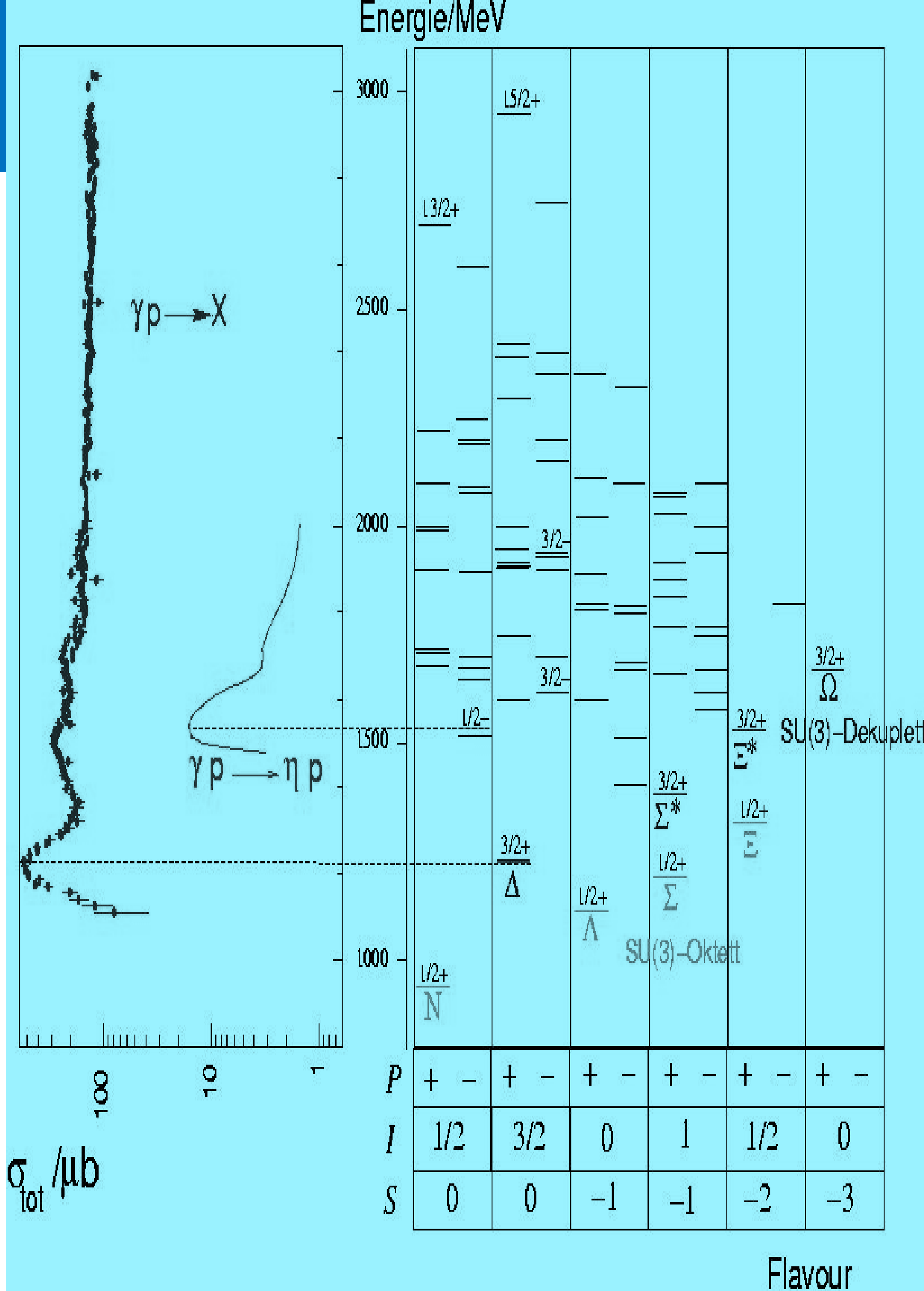
LQCD is still not fully amenable to intermediate energy scattering.

Use effective Methods.

Describe simultaneously all the reaction channels using a single Lagrangian

Satisfy the symmetries of the fundamental theory QCD while using only meson and nucleon degrees of freedom.

Relativistic invariance, Unitarity, gauge invariance, analyticity



The K-matrix model

- **Full coupled channels in large model space**
- **Non-perturbative**
- **Unitary**
- **Gauge invariant**
- **Covariant**
- **Crossing symmetric**

Bethe-Saltpeter Equation and K-matrix approximation

$S = 1 + 2iT$ T ➡ scattering amplitude (T matrix)

If T is a solution of the Bethe-Saltpeter equation,

$T = V + VGT$, V ➡ potential, G ➡ propagator (meson and nucl.)

Then the S matrix fulfills most of the constrains mentioned above.

$$G = i\delta + G^R$$

Pole contribution, on-shell nucleon or meson ($i\delta$)

Principal-value part, one or both particles in the int. state are off-shell (G^R)

Define

$K = V + VG^R K$ ➡ $T = K + K\, i\delta\, T$ ➡ $T = (1 - i\delta K)^{-1} K$

$K = V$ K matrix approximation

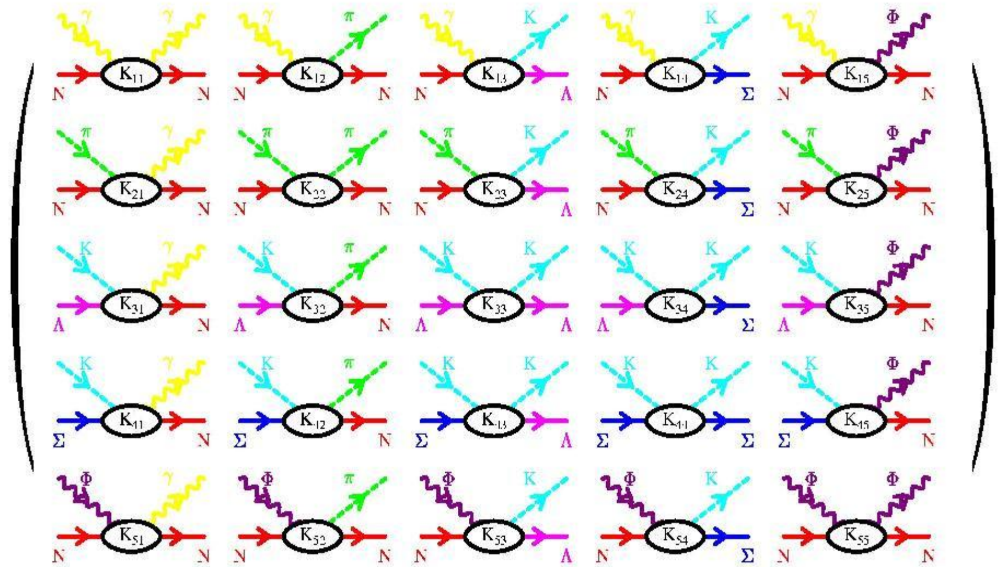
Construct K starting from effective Lagrangians that describe coupling between all the channels.

K-Matrix, Unitarity

$$S = 1 + 2iT$$

$$T = \frac{K}{1 - iK} =$$

$$= K + iK \times K + \cdots K =$$

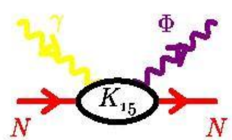


K = sum of tree-level diagrams;

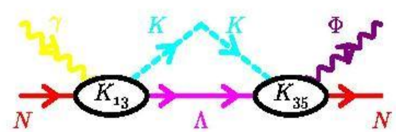
Gauge invariant

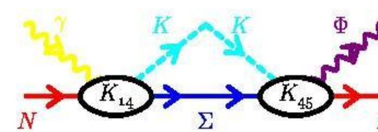
Processes Contributing to $p + \gamma \to p + \Phi$

Order K



Some diagrams of order $iK \times K$





Consistency among all channels !!!!!

Covariant, Gauge, Unitarity and Crossing symmetry

Strength K-matrix approach

Unitarity S

- K-matrix formalism:

$T = \frac{K}{1 - i\,K}$

thus: $S = \frac{1 + i\,K}{1 - i\,K}$ Unitary !

$K =$ Hermitian

Gauge invariance

- Current conservation

$\nabla \vec{J} = \frac{\partial \rho}{\partial t} \Longrightarrow k_\mu J^\mu = 0$

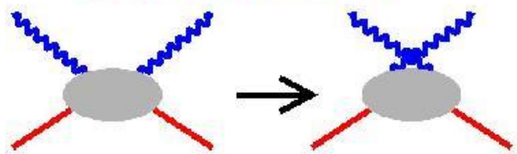
Covariance

- Relativistic kinematics
- 4-vector notation

Vectors transform properly under Lorentz boosts

s-u Crossing Symmetry

- symmetry under



Obeyed in K-matrix formalism

(Provided K is cross. sym.)

Weakness K-matrix approach

Causality ~ Analyticity ~ Dispersion relations

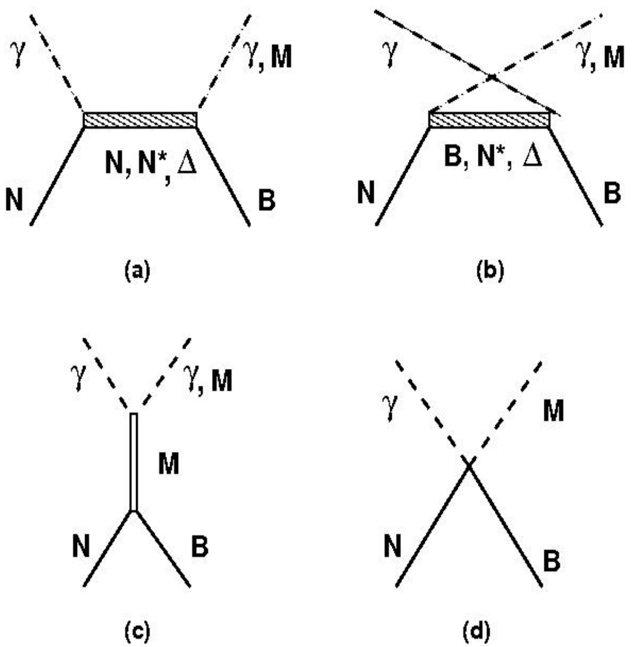
violated

Cauchy theorem $\Rightarrow$ Dispersion relation: $\mathrm{Re} f(\omega) = \frac{\mathcal{P}}{\pi} \int_{-\infty}^{+\infty} d\omega' \frac{\mathrm{Im} f(\omega')}{\omega' - \omega}$

Model ingredients

Channel Space (two-body final channels)

(N+γ), (N+π), (N+η), (N+ϕ), (N+ρ), (Λ+K), (Σ+K)



t-channel Contact terms ⇨ Gauge invariance

S- and u-channels

N, Λ, Σ, S_{11} (1535), S_{11}(1650), S_{31}(1620), P_{11}(1440), P_{11}(1710), P_{13} (1720), P_{33}(1232), P_{33}(1600), D_{13} (1520), D_{13}(1700), D_{33}(1700),

t-channels

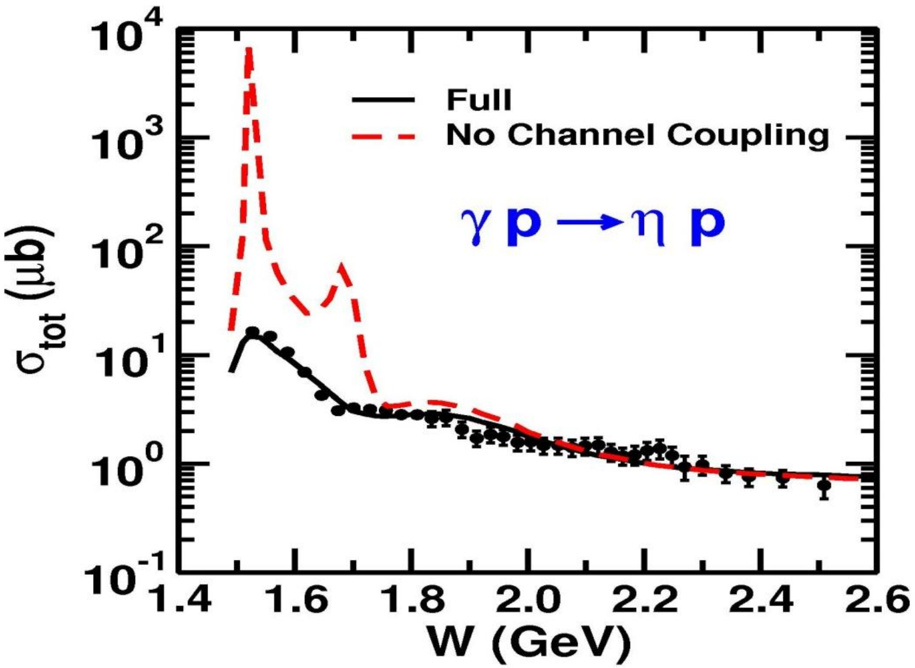
π, η, ρ, ϕ, ω, σ, K, K^* , mesons

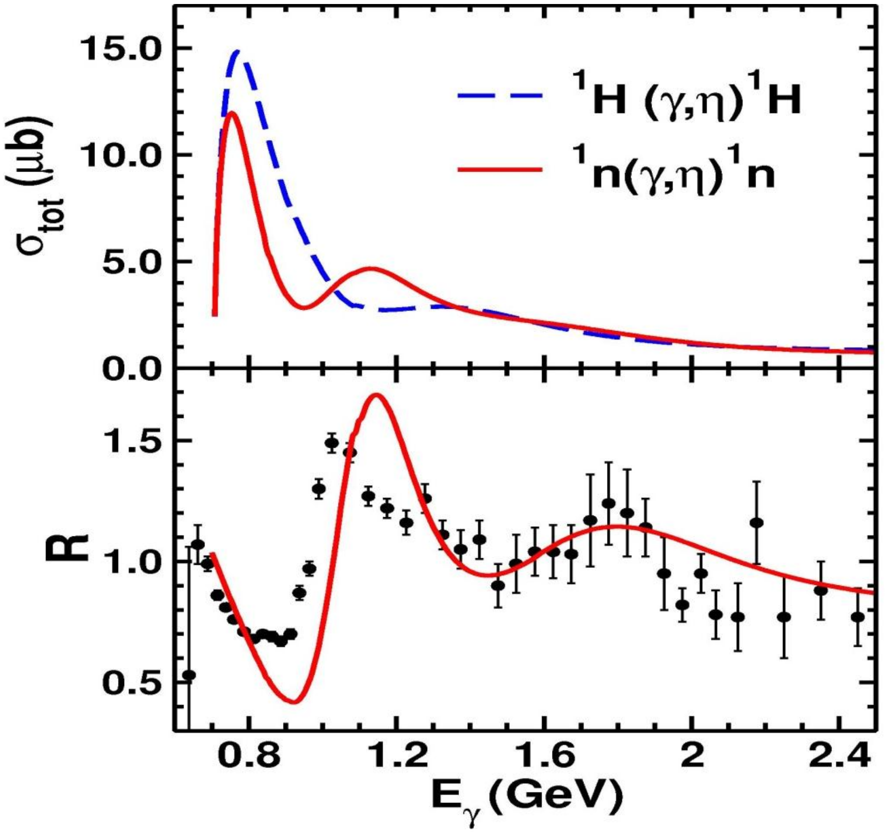
Advantage: background contributions are created dynamically
no additional parameters

Photo-induced η production I

No Coupled channels: amplitudes of various processes are simply added together, modifications to the widths of resonances due to CC is ignored

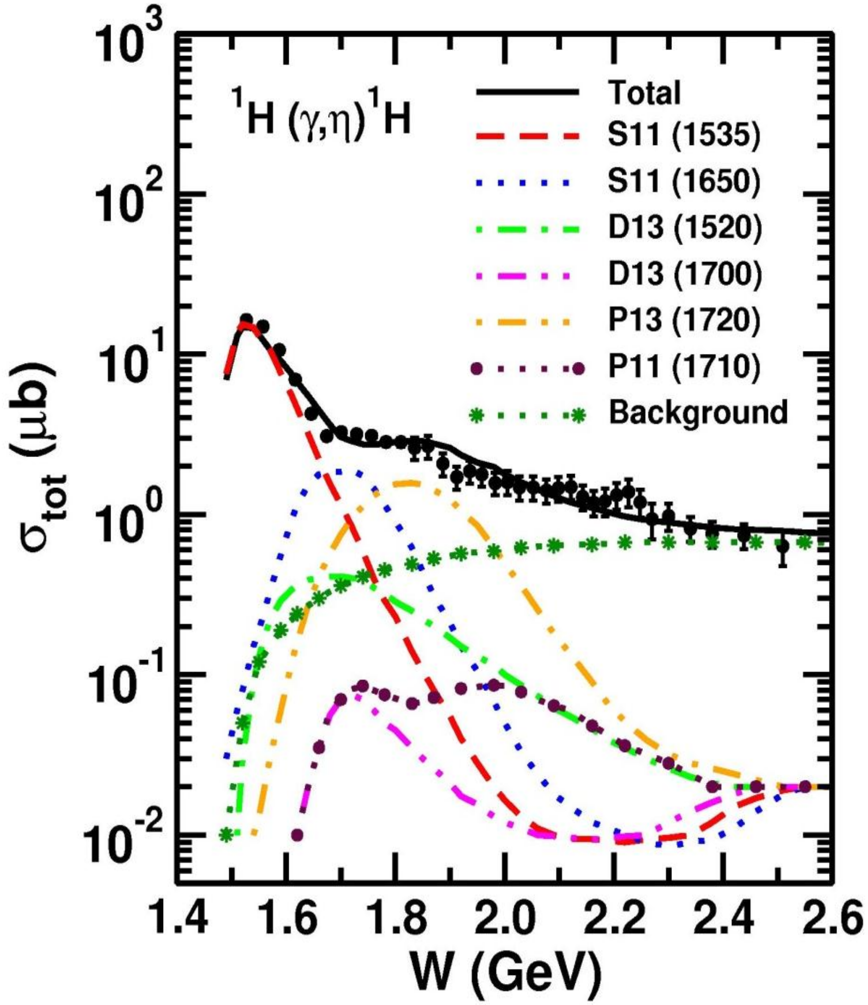
CB-ELSA data

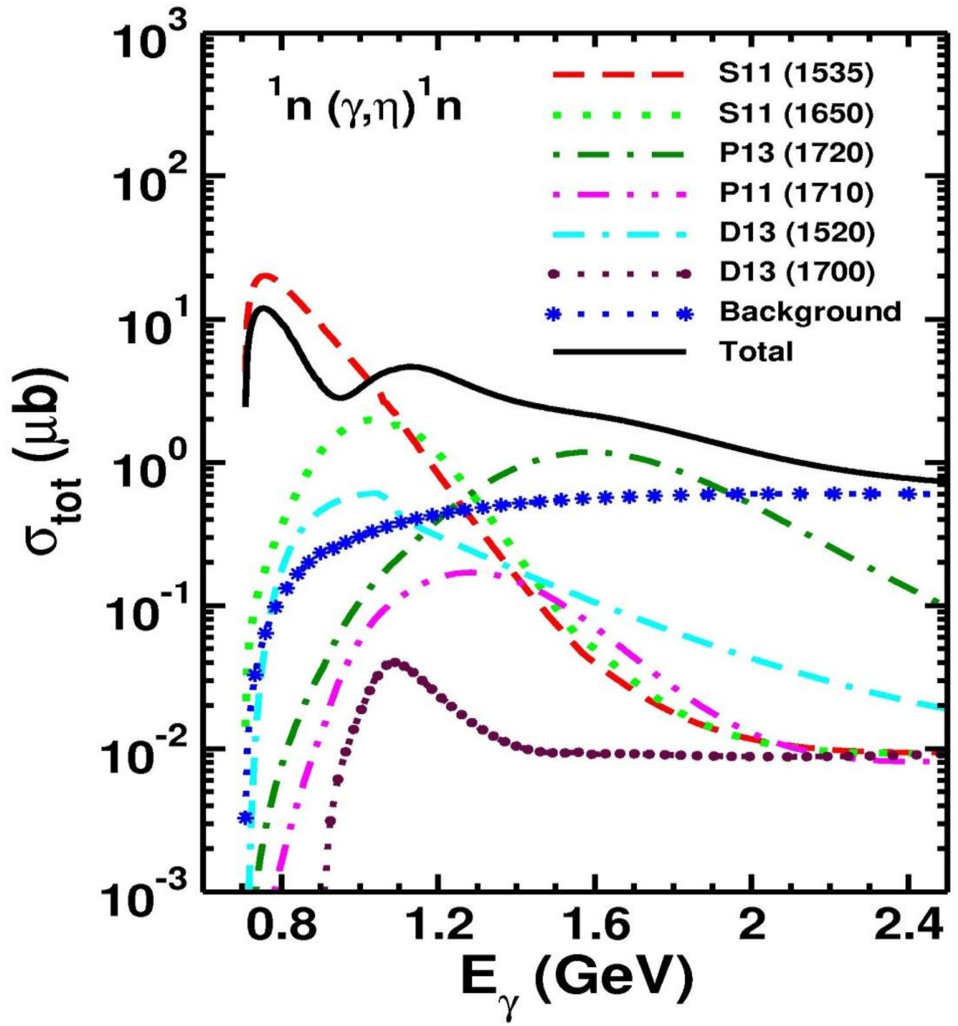




R. S. AND Olaf Scholten, PHYS REV C **78**, 065201 (2008)

Photo-induced η production

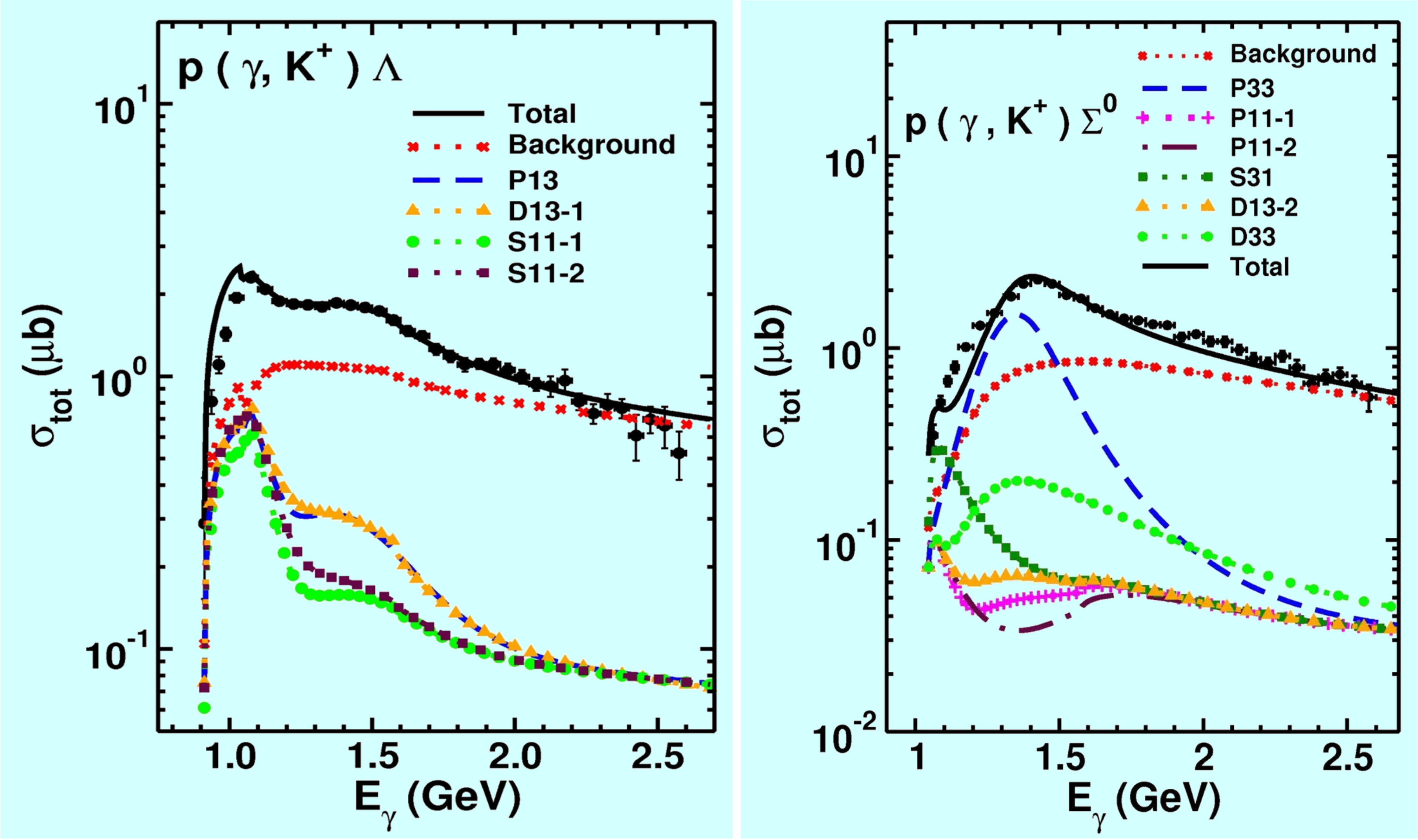




R. S. AND Olaf Scholten, PHYS REV C **78**, 065201 (2008)

CB-ELSA data

Photo-induced K+Λ & K+Σ



RS, O. Scholten, H. Lenske, Phys. Rev. C **81**, 015201 (2010)

Photon Induced η Meson production

CB-ELSA data

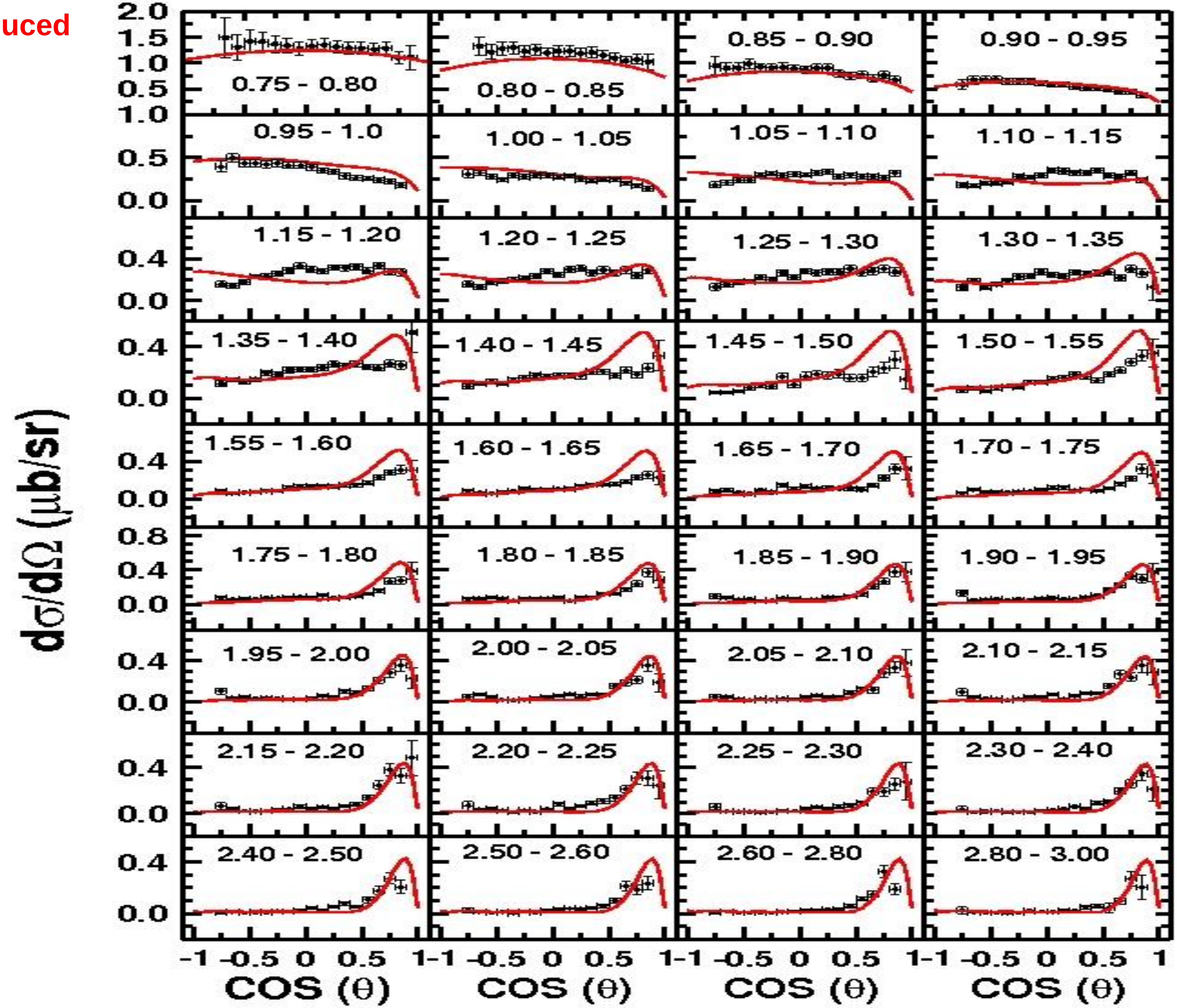
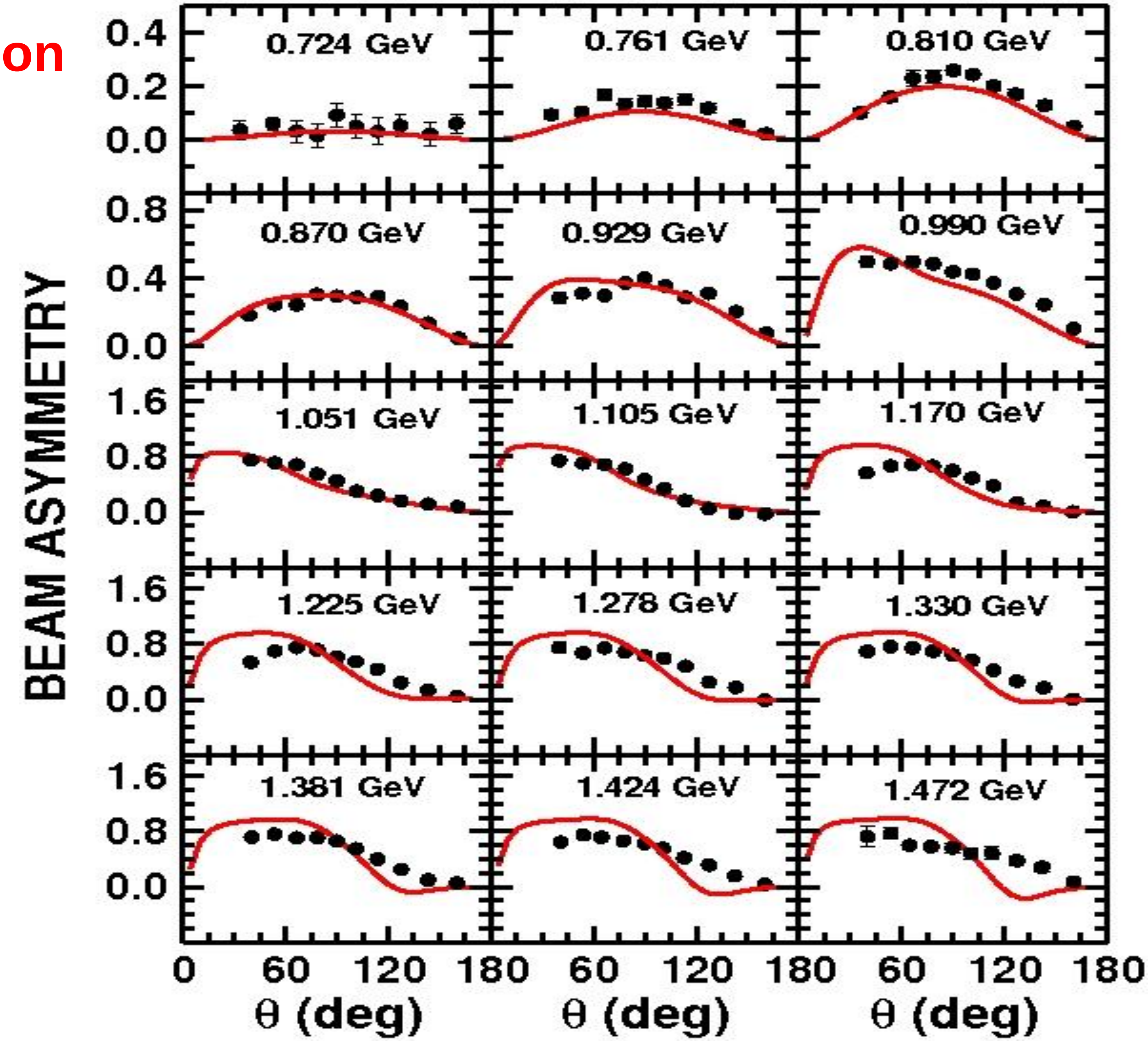


Photo production of η meson

CB-ELSA data

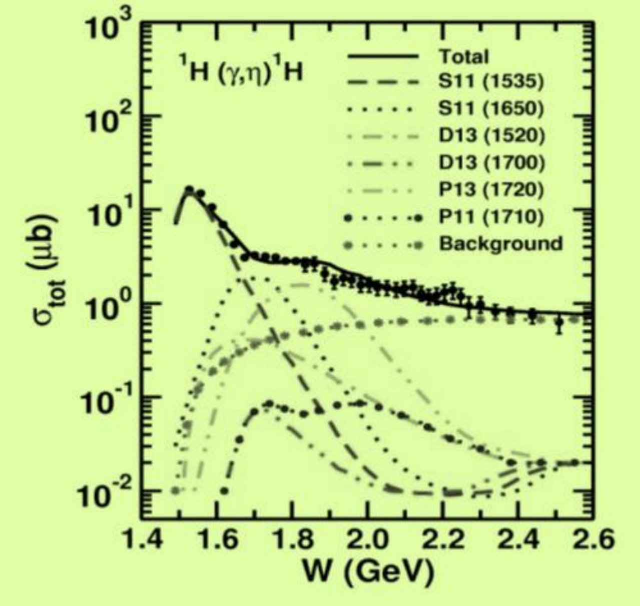


Summary

- **Coupled channels effects are large**
  - **Lambda K and Sigma K photo-production**
  - **eta-meson photo-production**

- **Good reproduction of cross section and Polarization data is obtained in effective-Lagrangian based K matrix approach.**
  - **need complete set of polarization observables**
  - **may help to implement causality in theory**

Coupled channels K-matrix



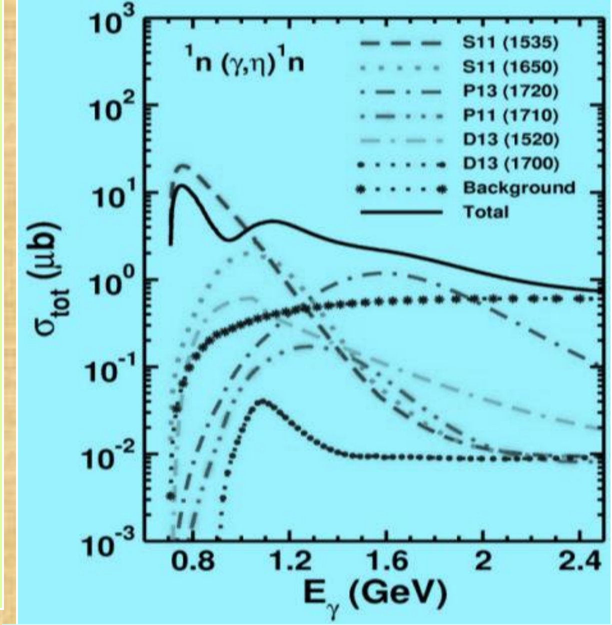
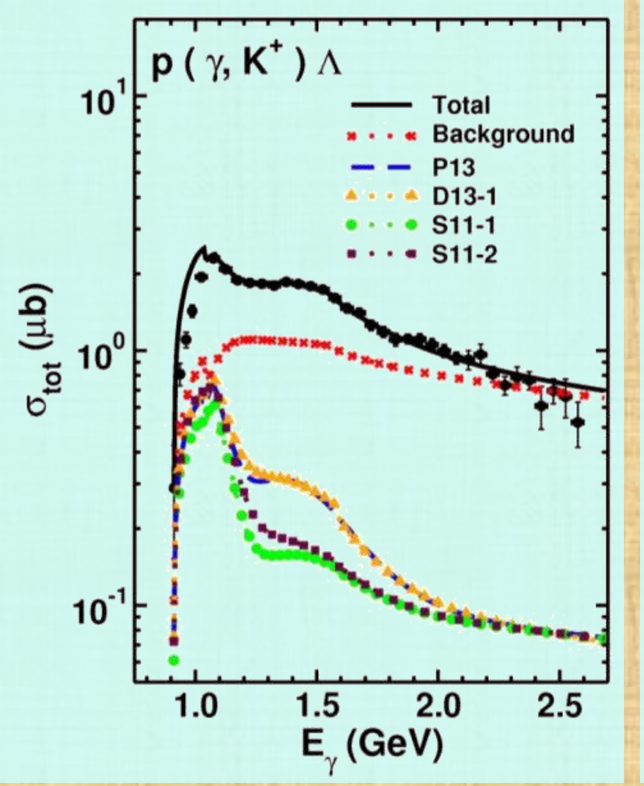


Photo-induced η production

RS and O. Scholten, phys. Rev. C **78**, 065201 (2008)



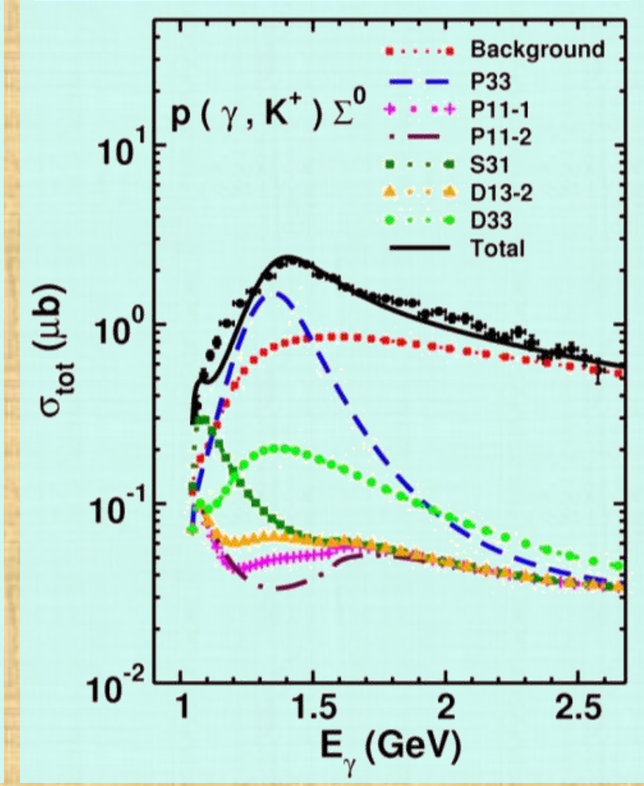
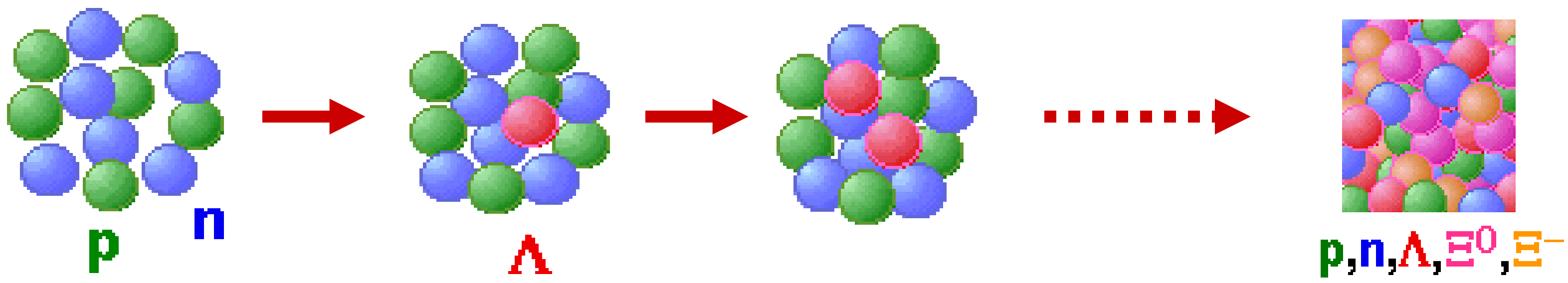


Photo-induced associated strangeness production

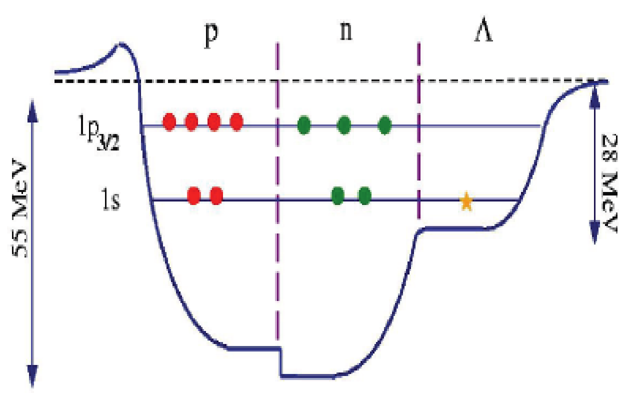
RS, O. Scholten, H. Lenske, Phys. Rev. C **81**, 015201 (2010)

What are Hypernuclei

Hypernuclei are the systems where at least one nucleon in one of its orbits are replaced by A hyperson (e.g. ☹). Hypernuclei are a laboratory to study the hyperon-nucleon interaction.



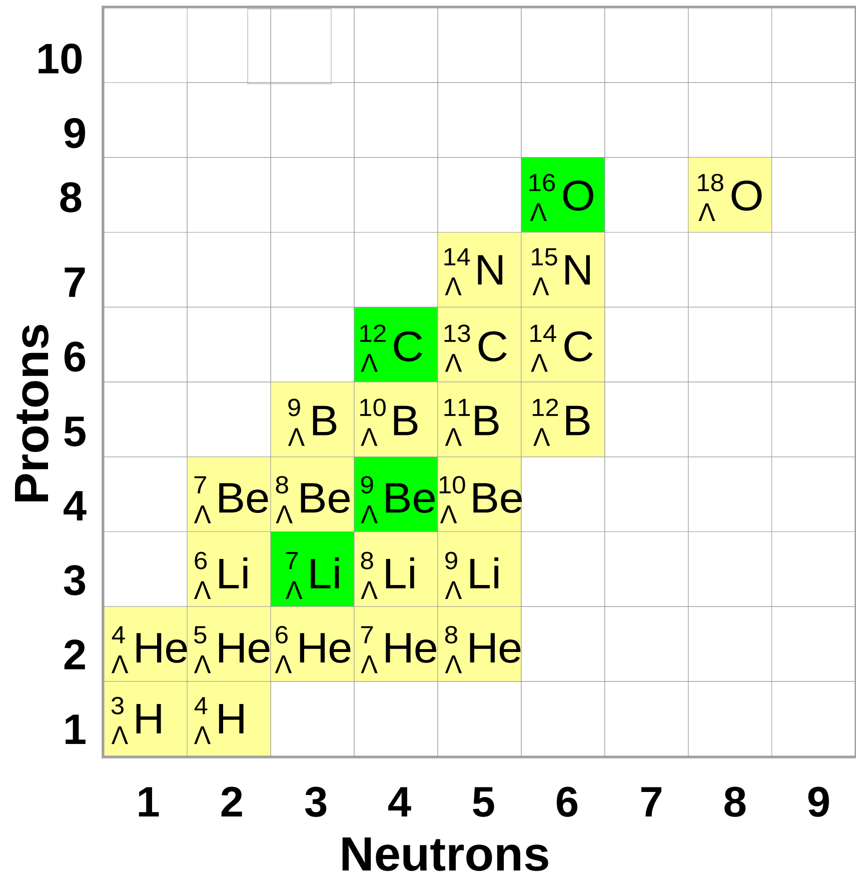
- Internal nuclear shell are not Pauli-blocked for hyperons.



A hypernucleus can be considered the outcome of a genetic engineering manipulation applied to the nuclear physics domain

The introduction of 1 (or 2) hyperons in a nucleus may give rise to various changes of the nuclear structure

- **changes of the size and of the shape**
- **changes of the cluster structure**
- **manifestation of new symmetries**
- **change of collective motions**

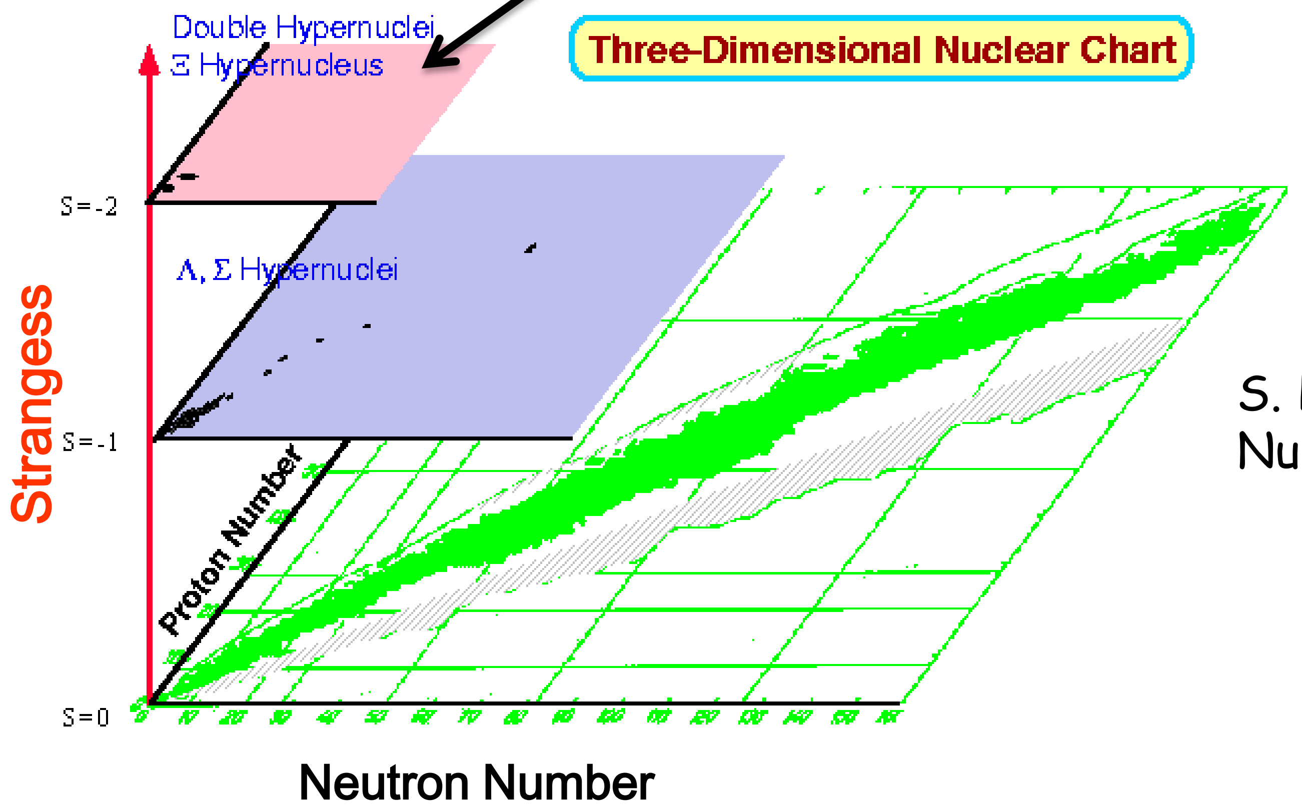


S = -2 systems study is not just a simple extension of what has been done for S = -1 system

S = -2 systems

A detailed and consistent understanding of the quark aspect of the baryon-baryon force will not be possible unless information on YY systems is available

Production of ✠ Hypernuclei at J-PARC by (K-, K+) reaction



Work in India
M. Soeb (stru)
R. Shyam (prod.)

S. Bender, RS, H. Lenske
Nucl. Phys., **A839** (2010) 51.