Symmetries and Hadron Form Factors

Egle Tomasi-Gustafsson
IRFU, SPhN-Saclay, and
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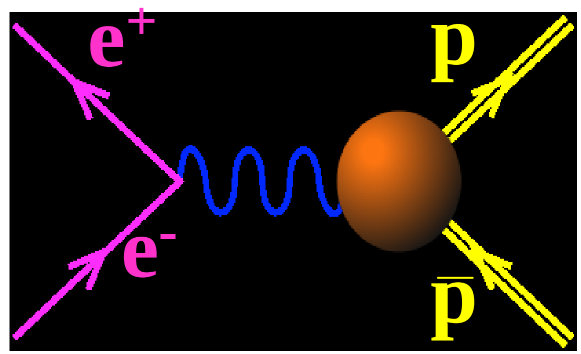
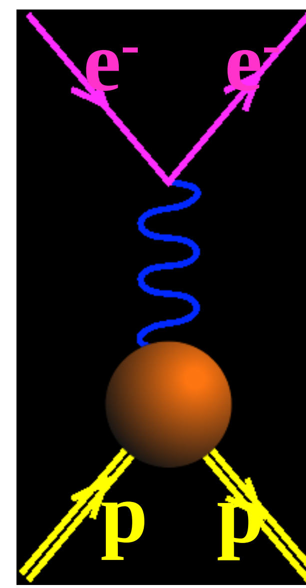
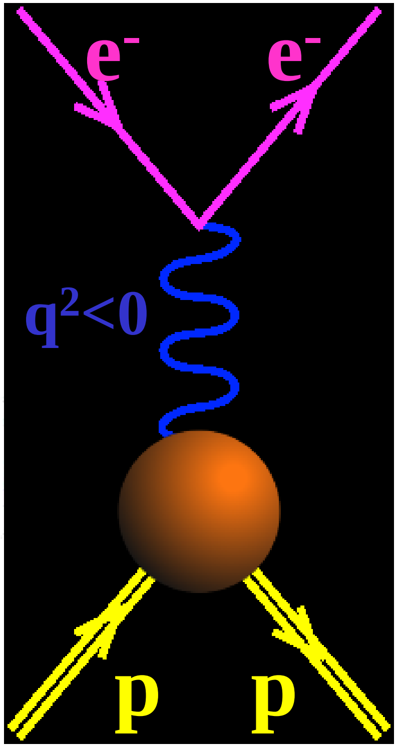




Hadron Electromagnetic Form factors

- Characterize the internal structure of a particle (≠ point-like)
- Elastic form factors contain information on the hadron ground state.
- In a P- and T-invariant theory, the EM structure of a particle of spin S is defined by 2S+1 form factors.
- Neutron and proton form factors are different.
- Deuteron: 2 structure functions, but 3 form factors.
- Playground for theory and experiment
- - at low q^2 probe the size of the nucleus,
- - at high q^2 test QCD scaling

Electromagnetic Interaction



The electron vertex is known, γ_μ

The interaction is carried by a virtual photon of mass q^2

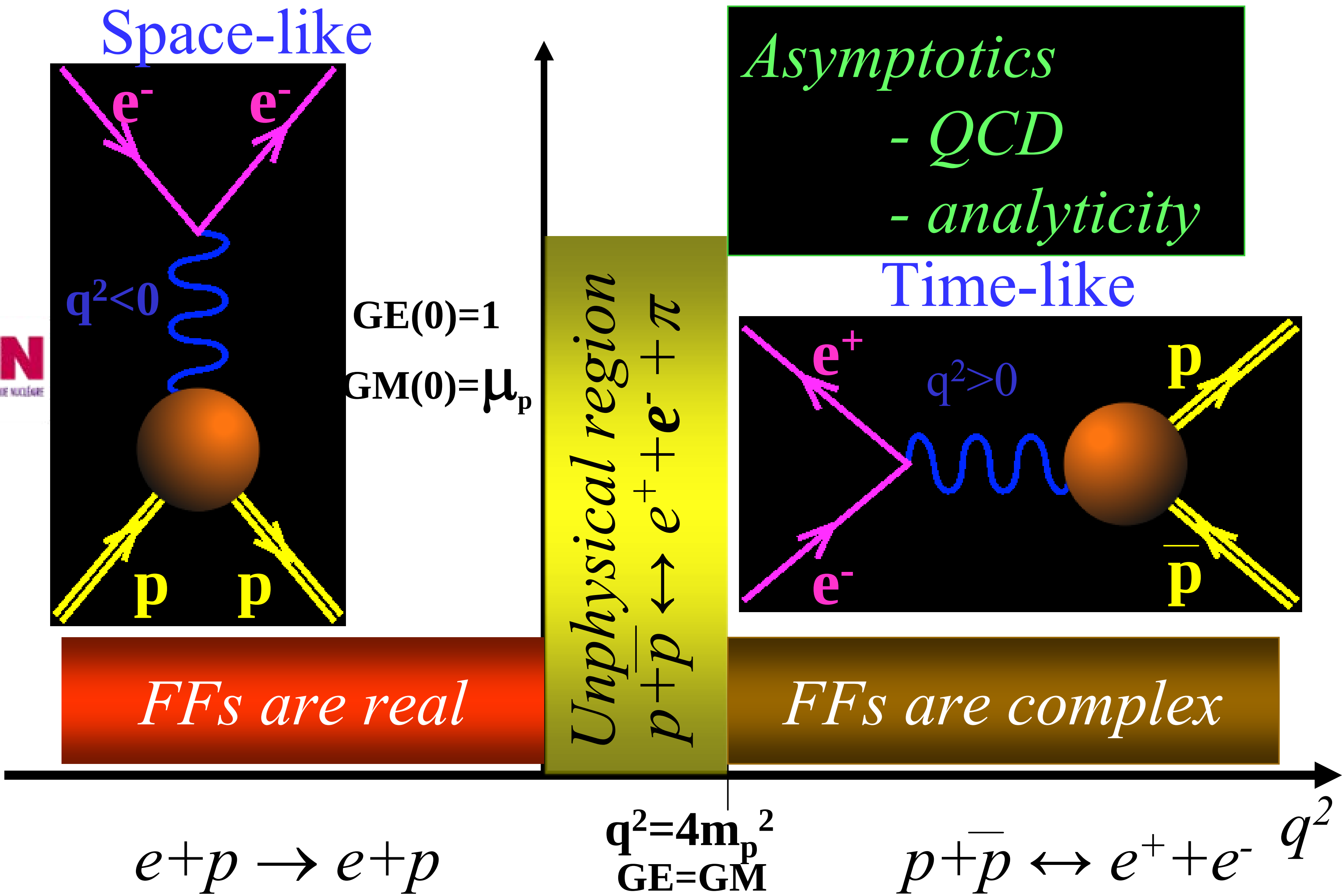
The proton vertex is parametrized in terms of FFs: Pauli and Dirac F_1, F_2

$$\Gamma_\mu = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu} q^\nu}{2M} F_2(q^2)$$

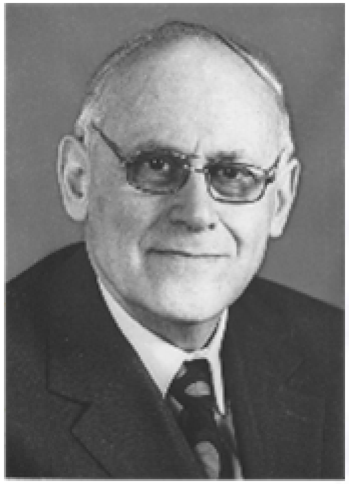
or in terms of Sachs FFs: $GE = F_1 - \tau F_2$, $GM = F_1 + F_2$, $\tau = -q^2/4M^2$

What about high order radiative corrections?

Analyticity



The polarization method (1967)



SOVIET PHYSICS – DOKLADY VOL. 13, NO. 6 DECEMBER, 1968

PHYSICS

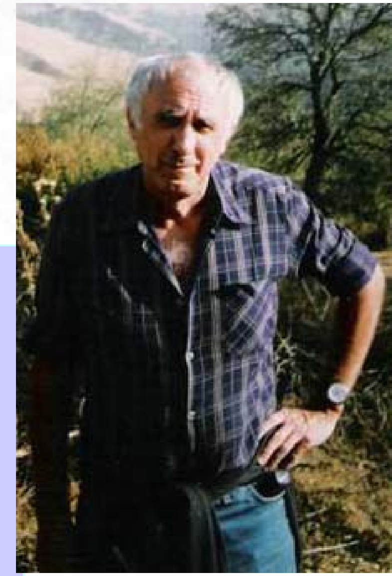
POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

Academician A. I. Akhiezer* and M. P. Rekalo

Physicotechnical Institute, Academy of Sciences of the Ukrainian SSR

Translated from Doklady Akademii Nauk SSSR, Vol. 180, No. 5, pp. 1081-1083, June, 1968

Original article submitted February 26, 1967

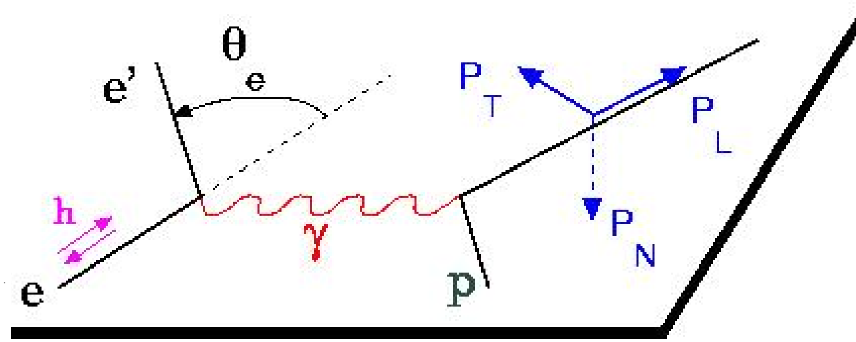


The polarization induces a term in the cross section proportional to $G_E\, G_M$

Polarized beam and target or

polarized beam and recoil proton polarization

$$s_2 \frac{d\sigma}{d\Omega_R} = 4p_2 \frac{(s\cdot q)}{1+\tau}\Gamma(\theta,\ \varepsilon_1)\Big[\tau G_M\,(G_M+G_E) - \frac{1}{4\varepsilon_1} G_M\,(G_E-\tau G_M)\Big],$$



Polarization experiments - Jlab

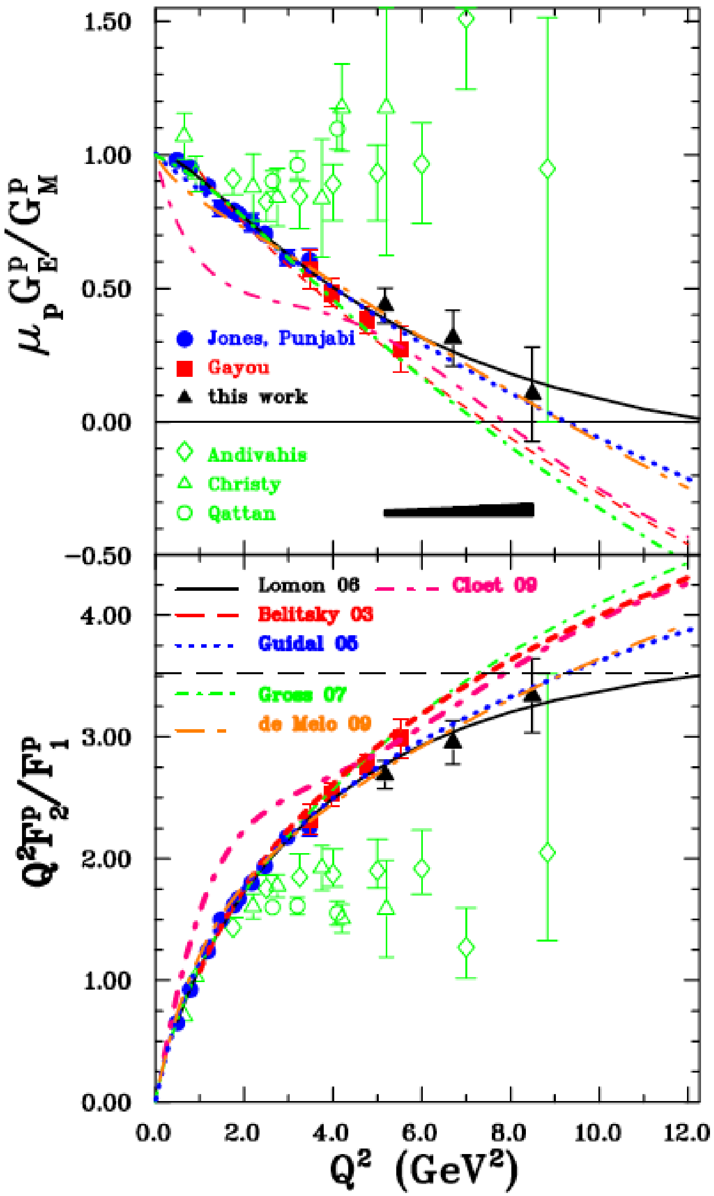
A.I. Akhiezer and M.P. Rekalo, 1967

GEp collaboration

1) "standard" dipole function for the nucleon magnetic FFs GMp and GMn
2) linear deviation from the dipole function for the electric proton FF Gep
3) QCD scaling not reached
3) Zero crossing of Gep?
4) ***contradiction between polarized and unpolarized measurements***

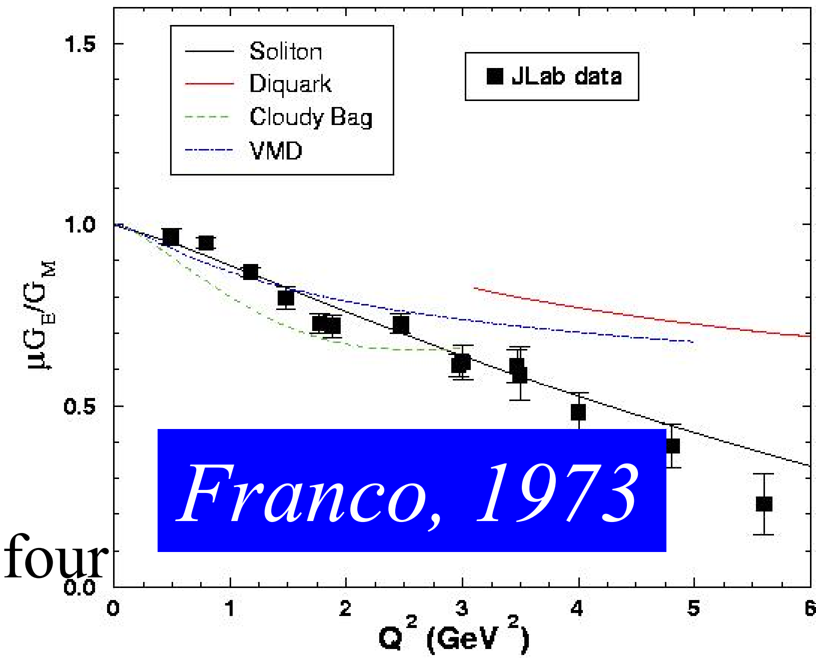
A.J.R. Puckett et al, PRL (2010)

PRC85 (2012) 045203



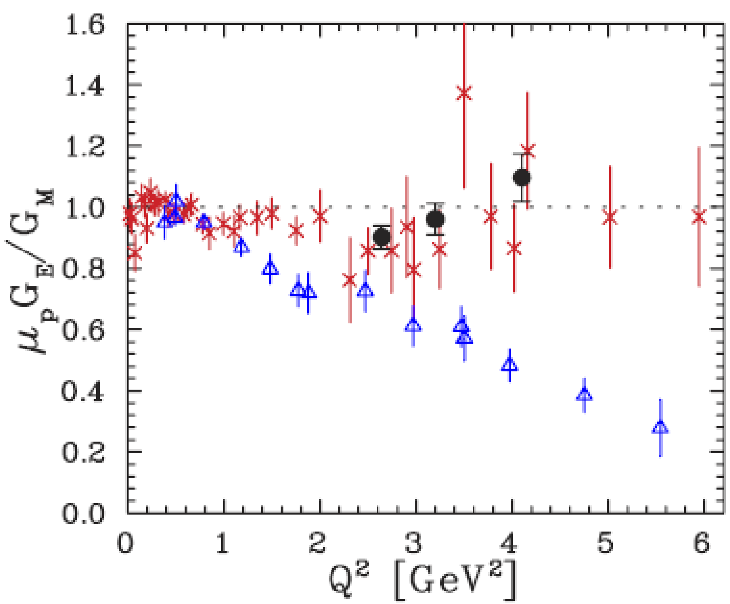
Issues

- Some models predicted such behavior before the data appeared



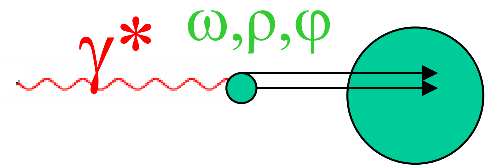
BUT

- Simultaneous description of the four nucleon form factors...
- ...in the space-like and in the time-like regions
- Consequences for the light ions description
- When pQCD starts to apply?
- Source of the discrepancy



Iachello, Jackson and Landé (1973)

Isoscalar and isovector FFs



$$F_1^s(Q^2) = \frac{g(Q^2)}{2}\left[(1-\beta_\omega-\beta_\phi)+\beta_\omega\frac{\mu_\omega^2}{\mu_\omega^2+Q^2}+\beta_\phi\frac{\mu_\phi^2}{\mu_\phi^2+Q^2}\right],$$

$$F_1^v(Q^2) = \frac{g(Q^2)}{2}\left[(1-\beta_\rho)+\beta_\rho\frac{\mu_\rho^2+8\Gamma_\rho\mu_\pi/\pi}{(\mu_\rho^2+Q^2)+(4\mu_\pi^2+Q^2)\Gamma_\rho\alpha(Q^2)/\mu_\pi}\right],$$

$$F_2^s(Q^2) = \frac{g(Q^2)}{2}\left[(\mu_p+\mu_n-1-\alpha_\phi)\frac{\mu_\omega^2}{\mu_\omega^2+Q^2}+\alpha_\phi\frac{\mu_\phi^2}{\mu_\phi^2+Q^2}\right],$$

$$F_2^v(Q^2) = \frac{g(Q^2)}{2}\left[(\mu_p-\mu_n-1)\frac{\mu_\rho^2+8\Gamma_\rho\mu_\pi/\pi}{(\mu_\rho^2+Q^2)+(4\mu_\pi^2+Q^2)\Gamma_\rho\alpha(Q^2)/\mu_\pi}\right],$$

$$g(Q^2) = \frac{1}{(1+\gamma e^{i\vartheta}Q^2)^2}$$

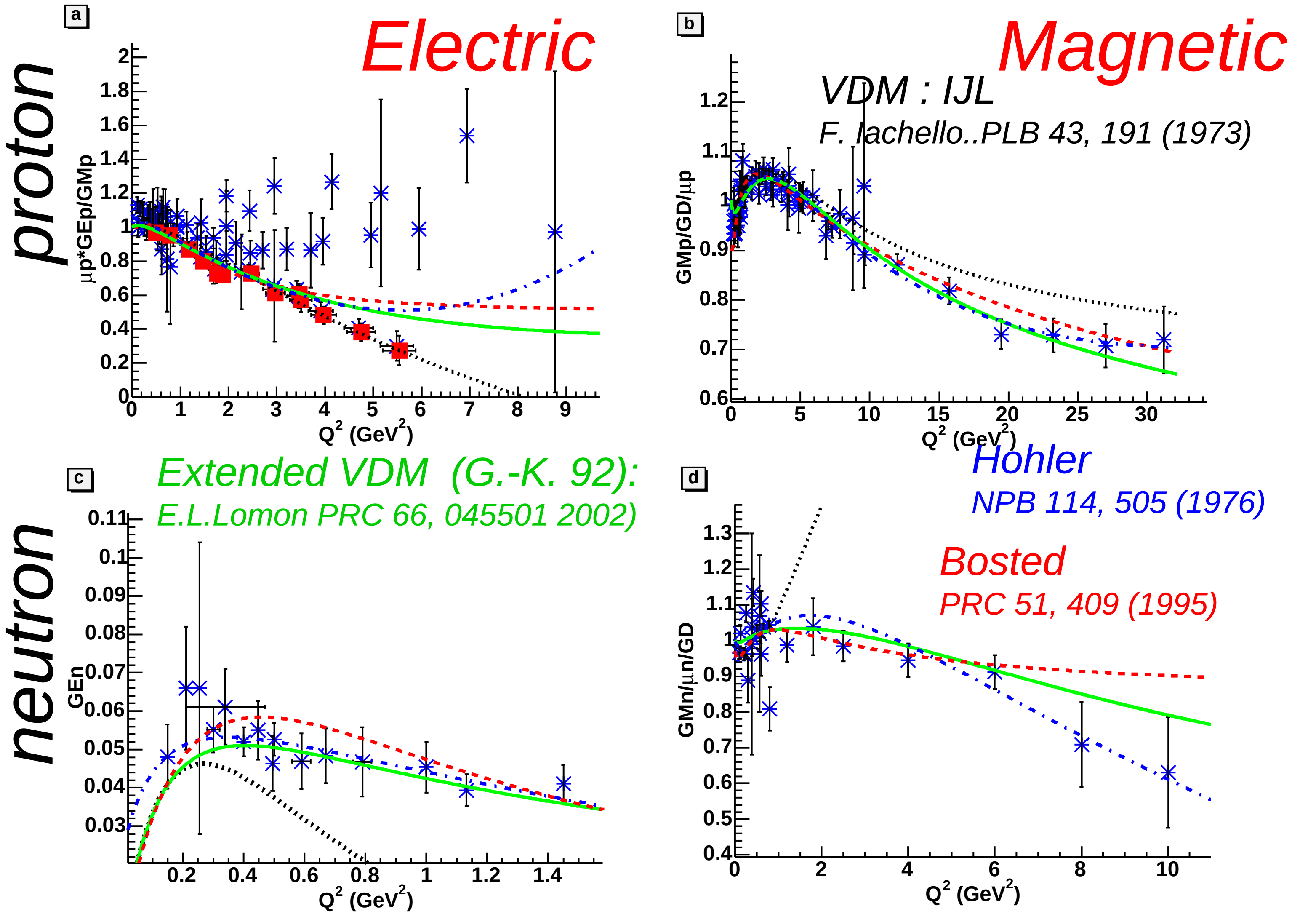
$$\alpha(Q^2) = \frac{2}{\pi}\sqrt{\frac{Q^2+4\mu_\pi^2}{Q^2}}\,ln\left[\frac{\sqrt{(Q^2+4\mu_\pi^2)}+\sqrt{Q^2}}{2\mu_\pi}\right]$$

$$2F_i^p = F_i^s + F_i^v,$$

$$2F_i^n = F_i^s - F_i^v$$

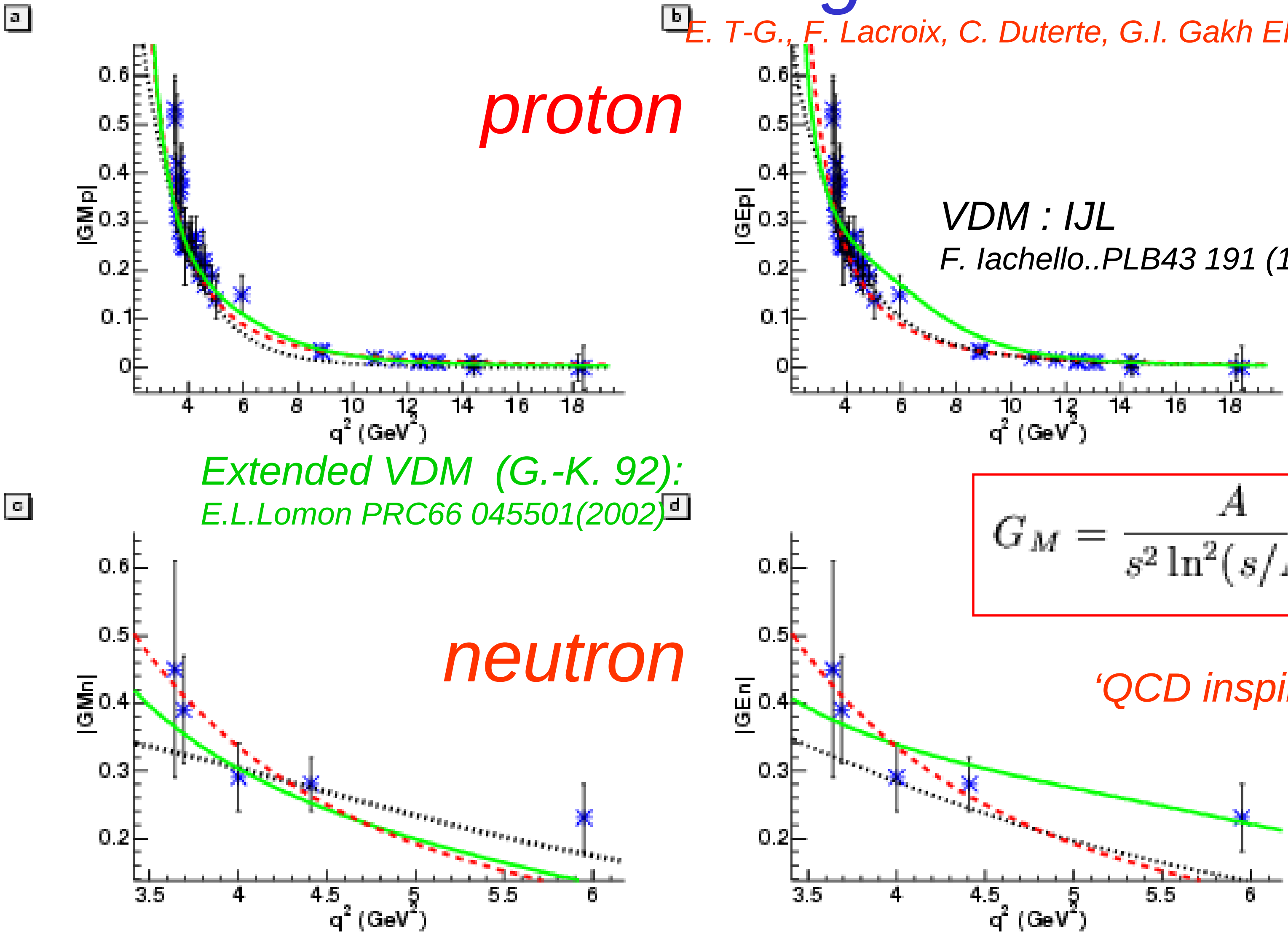
The nucleon form factors

E. T.-G., F. Lacroix, Ch. Duterte, G.I. Gakh, EPJA (2005)



Models in T.L. region

E. T-G., F. Lacroix, C. Duterte, G.I. Gakh EPJA 2005



proton

VDM : IJL

F. Iachello..PLB43 191 (1973)

Extended VDM (G.-K. 92):

E.L.Lomon PRC66 045501(2002)

$$G_M = \frac{A}{s^2 \ln^2(s/\Lambda^2)}$$

neutron

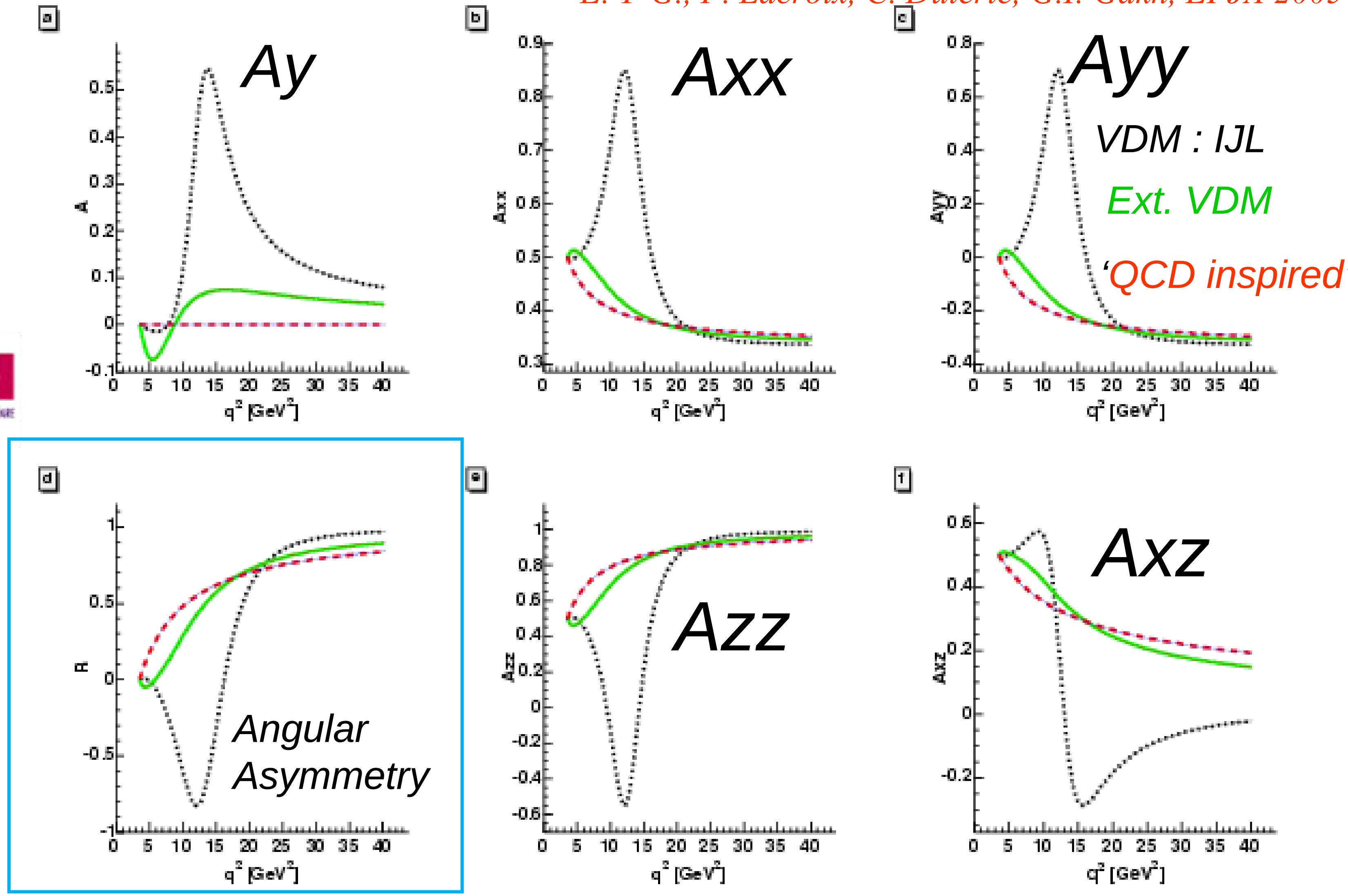
'QCD inspired'

R. Bijker and F. Iachello, Phys.Rev., C69 (2004) 068201

F. Iachello and Q. Wan, Phys.Rev., C69 (2004) 055204

Models in T.L. Region (polarization)

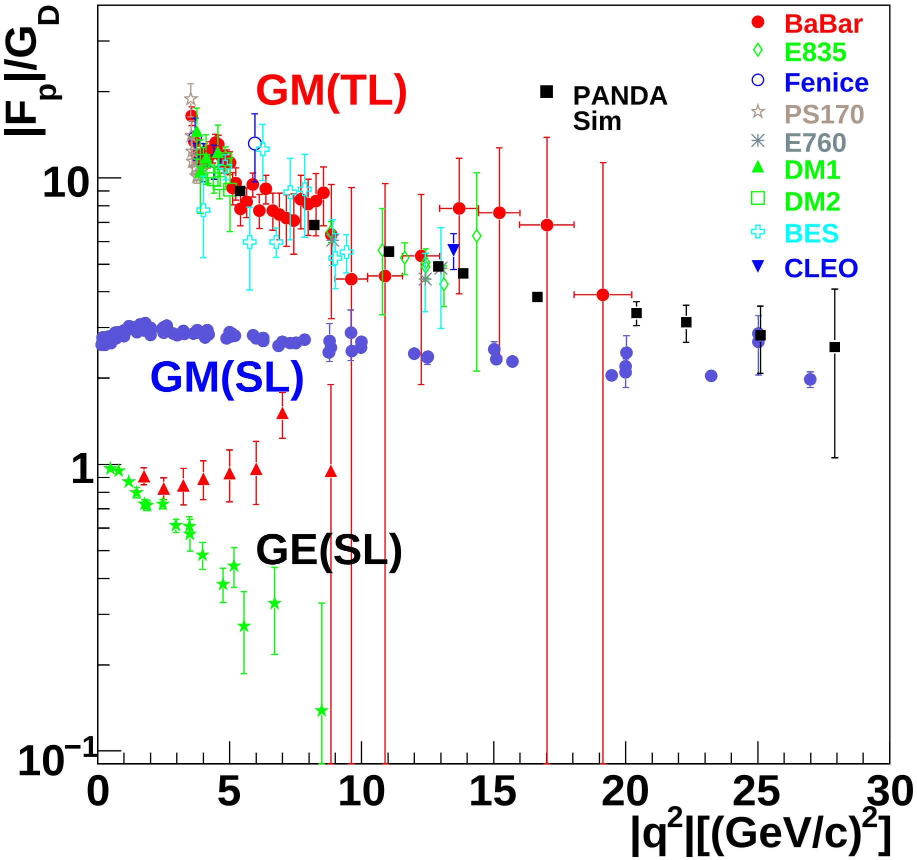
E. T-G., F. Lacroix, C. Duterte, G.I. Gakh, EPJA 2005

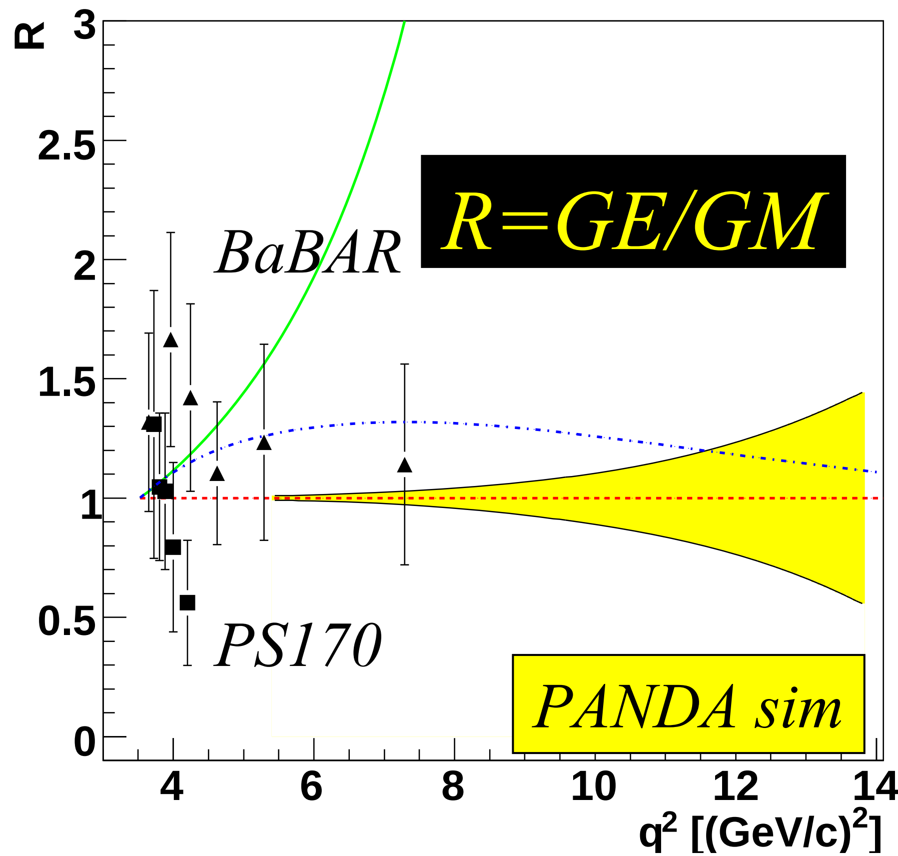


R. Bijker and F. Iachello, Phys.Rev., C69 (2004) 068201
F. Iachello and Q. Wan, Phys.Rev., C69 (2004) 055204

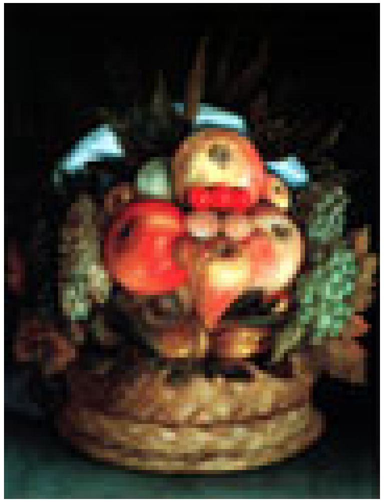
PREDICTIONS

$\mathscr{L}$ = 2x10^{32} cm^{-2}.s^{-1}, 10^{7} s (~100 days)

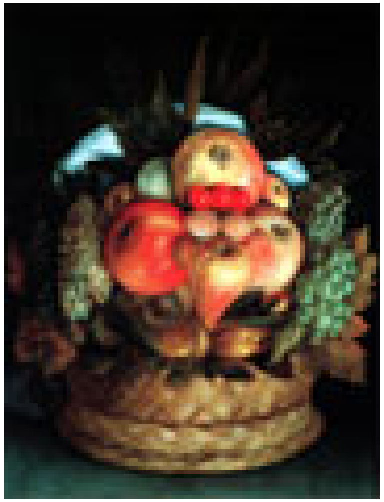




|GE| and |GM| individual determination up to large q^2

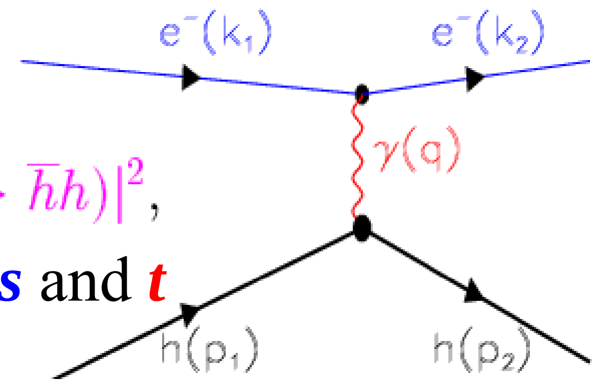




Symmetries


Crossing Symmetry

Scattering and annihilation channels: $e^- + h \rightarrow e^- + h$



- Described by the same amplitude :

$$|\overline{\mathcal{M}}(e^{\pm}h \rightarrow e^{\pm}h)|^2 = f(s,t) = |\overline{\mathcal{M}}(e^+e^- \rightarrow \overline{h}h)|^2,$$

- function of two kinematical variables, ***s*** and ***t***

$$s = (k_1 + p_1)^2$$
$$t = (k_1 - k_2)^2$$

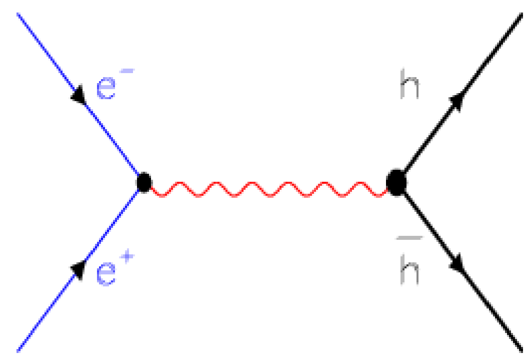
$e^- + e^+ \rightarrow \overline{h} + h$

- which scan different kinematical regions

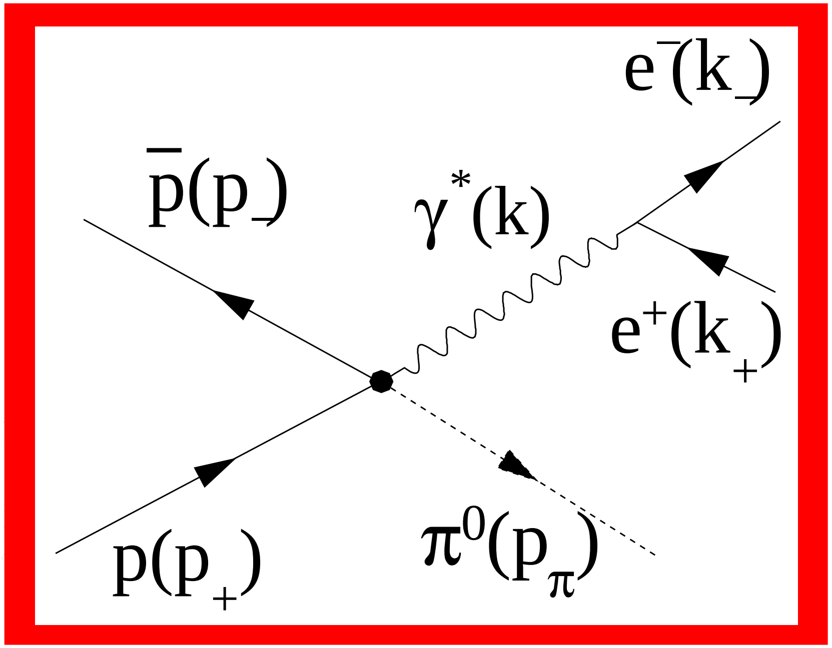
$$k_2 \longrightarrow -k_2$$

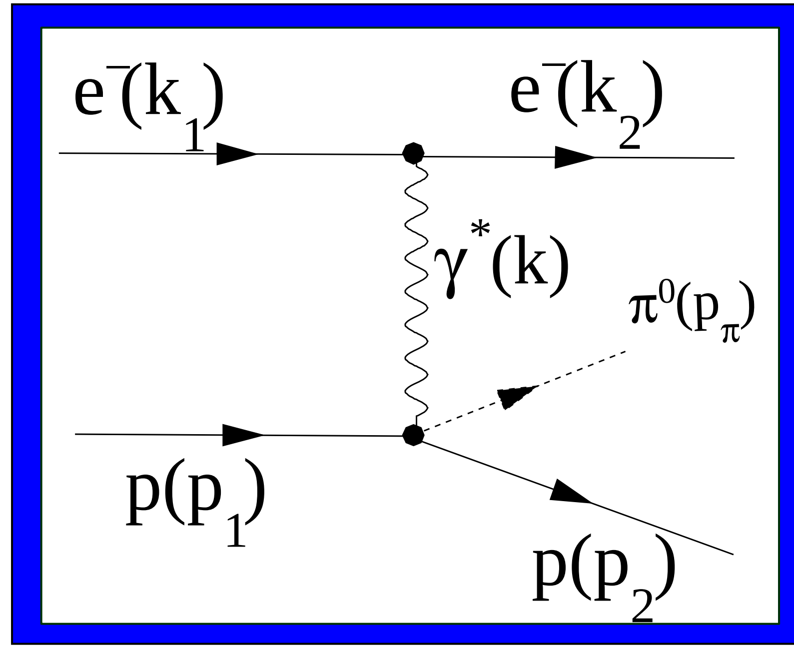
$$p_2 \longrightarrow -p_2$$

$$cos^2\tilde{\theta} = 1 + \frac{st + (s - M^2)^2}{t(\frac{t}{4} - M^2)} \rightarrow 1 + \frac{ctg^2\frac{\theta}{2}}{1+\tau}$$



$\bar{p} + p \rightarrow e^+ + e^- + \pi^0$ *and* $e^- + p \rightarrow e^- + p + \pi^0$





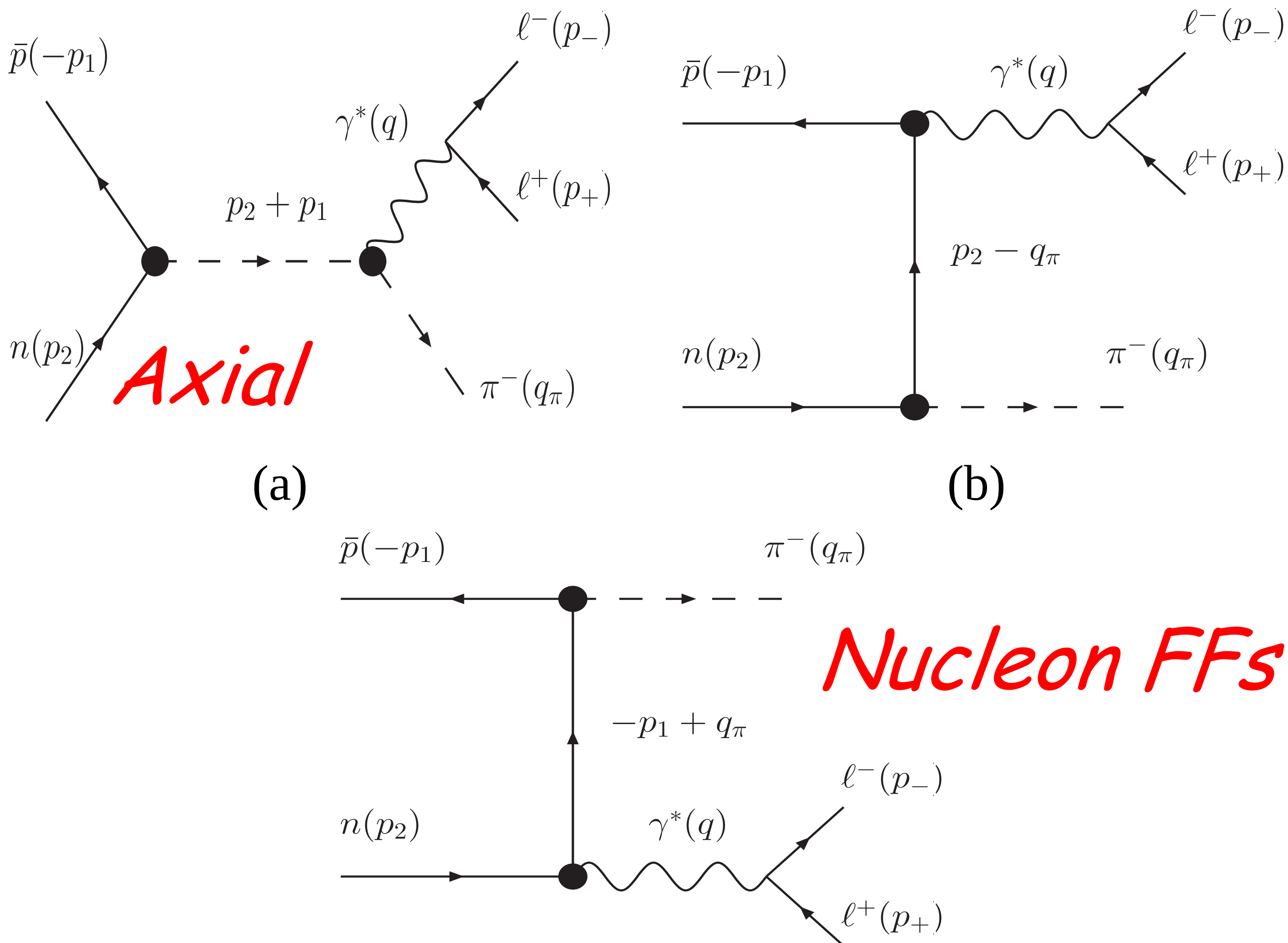
Described in general by 6 amplitudes which depend on 3 kinematical variables

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

M. P. Rekalo (1967)

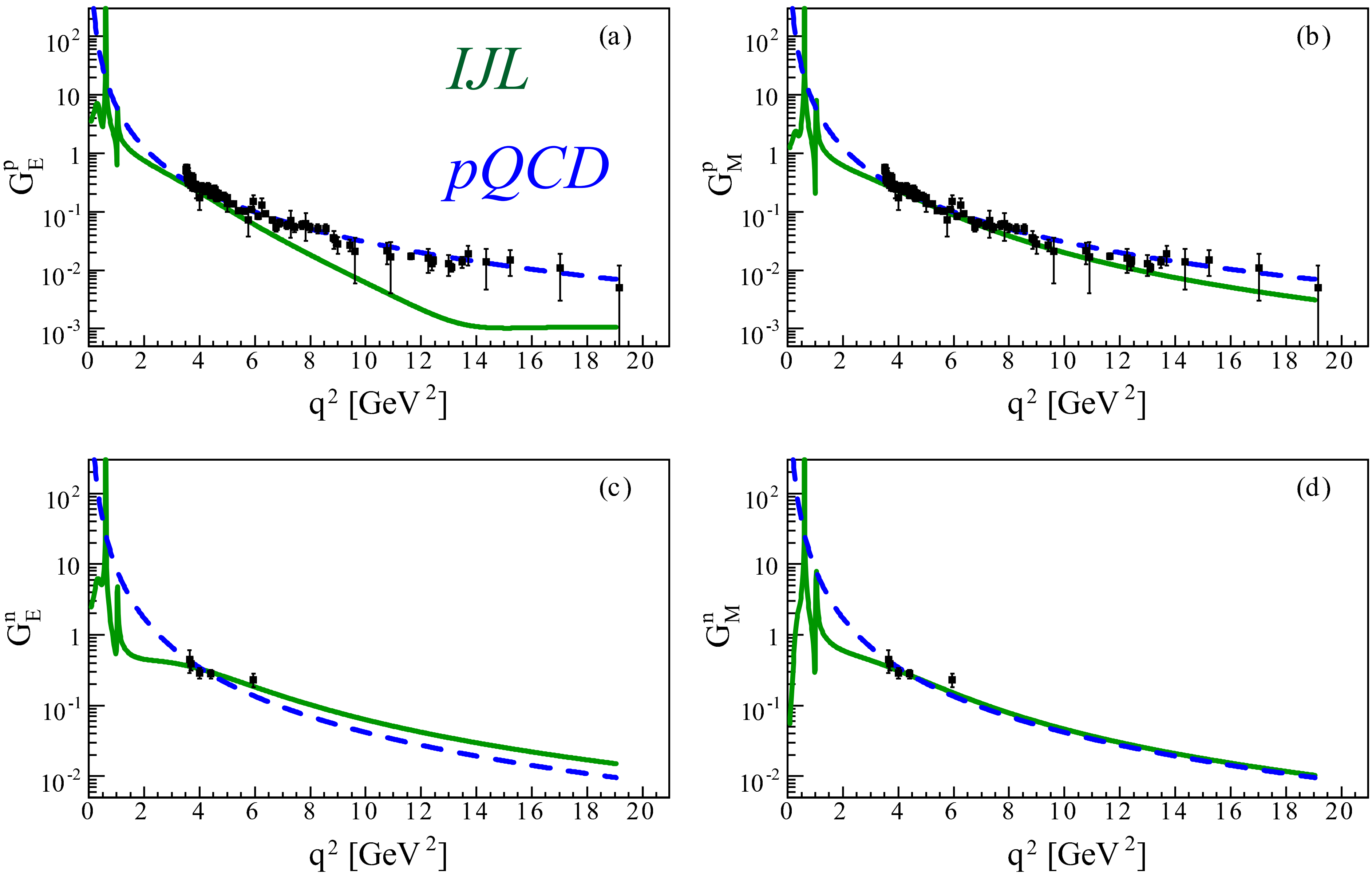
access the unphysical region

$\bar{p} + n \rightarrow e^+ + e^- + \pi^-$



FFs in the unphysical region

Time-like electromagnetic form factors



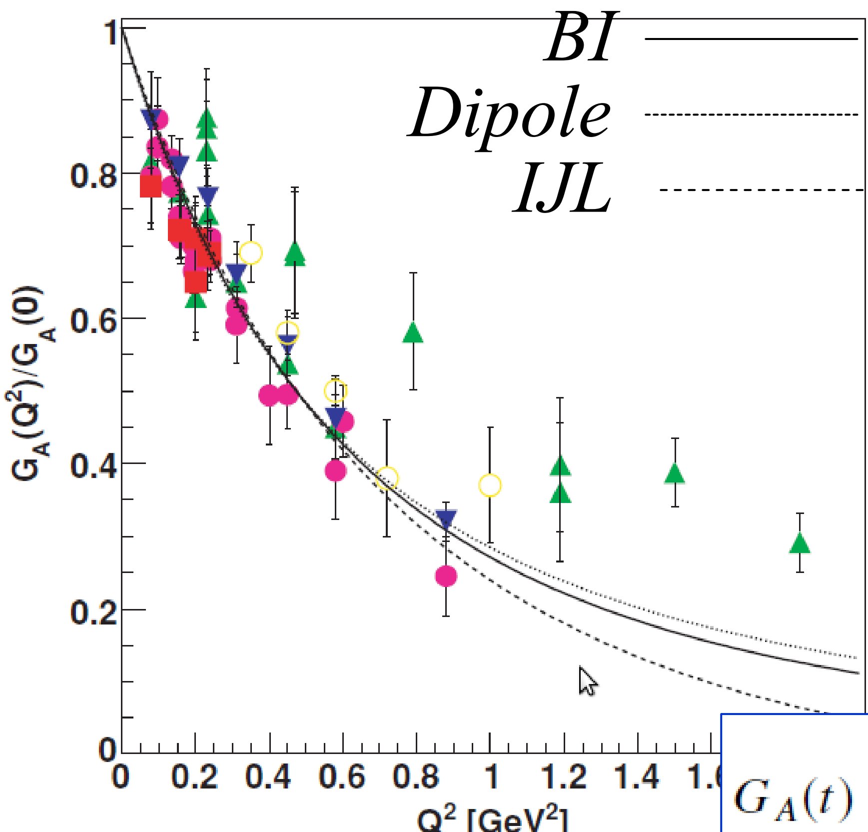
PHYSICAL REVIEW C **78**, 035201 (2008)

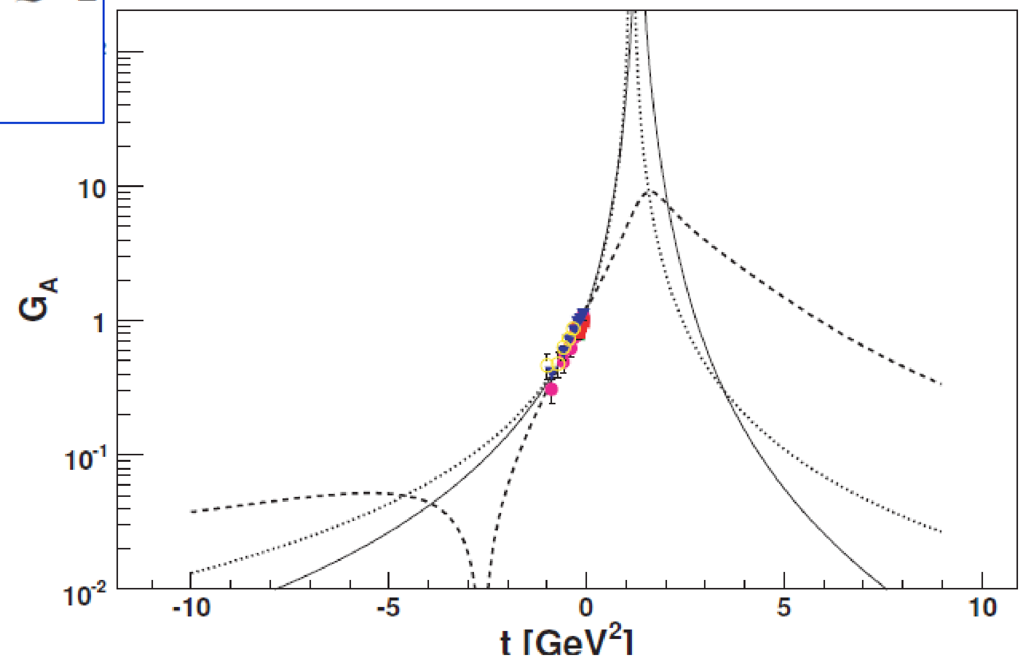
Two-component model for the axial form factor of the nucleon

C. Adamuscin, E. T-G,E. Santopinto, R. Bijker

$$G_A(Q^2) = G_A(0)g(Q^2)\left[1-\alpha+\alpha\frac{m_A^2}{m_A^2+Q^2}\right]$$

$$g(Q^2) = \left(1+\gamma Q^2\right)^{-2},$$





$$g(t) = \left(1-e^{i\delta}\gamma t\right)^{-2}$$

$$G_A(t) = G_A(0)g(t)\left[1-\alpha+\alpha\frac{m_A^2\left(m_A^2-t+im_A\Gamma_A\right)}{\left(m_A^2-t\right)^2+(m_A\Gamma_A)^2}\right]$$

S=1 form factors

The IA deuteron structure: S=1, T=0

$$G_c = G_{Es}C_E, \quad G_q = G_{Es}C_Q, \quad G_m = \frac{M_d}{M_p}\left(G_{Ms}C_S + \frac{1}{2}G_{Es}C_L\right)$$

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1) The nucleon form factors:

$$G_{Ms} = G_{Mp} + G_{Mn}$$

$$G_{Es} = G_{Ep} + G_{En}$$

$$C_E = \int_0^\infty dr\ j_0\left(\frac{Qr}{2}\right)\left[u^2(r) + w^2(r)\right],$$

$$C_Q = \frac{3}{\sqrt{2}\tau}\int_0^\infty dr\ j_2\left(\frac{Qr}{2}\right)\left[u(r) - \frac{w(r)}{\sqrt{8}}\right] w(r),$$

$$C_S = \int_0^\infty dr\left[u^2(r) - \tfrac{1}{2}w^2(r)\right] j_0\left(\tfrac{Qr}{2}\right) + \tfrac{1}{2}\left[\sqrt{2}u(r)w(r) + w^2(r)\right] j_2\left(\tfrac{Qr}{2}\right),$$

$$C_L = \frac{3}{2}\int_0^\infty dr\ w^2(r)\left[j_0\left(\frac{Qr}{2}\right) + j_2\left(\frac{Qr}{2}\right)\right],$$

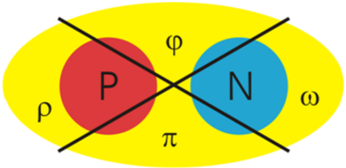
2) The S (u) and D (w) deuteron wave function

$$\int_0^\infty dr\ \left[u^2(r) + w^2(r)\right] = 1.$$

Deuteron VMD

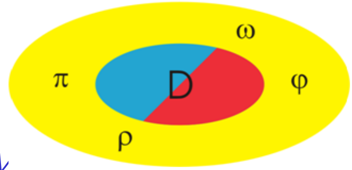
C. Adamuscin, G.I. Gakh and E.T-G. PRC ***73****, 045204 (2006)*

$$G_i(Q^2) = N_i g_i(Q^2) F_i(Q^2), \quad i = c, q, m$$



Intrinsic term

$$g_i(Q^2) = 1/[1 + \gamma_i Q^2]^{\delta_i},$$



Meson cloud: isoscalar vector meson only

$$F_i(Q^2) = 1 - \alpha_i - \beta_i + \alpha_i \frac{m_\omega^2}{m_\omega^2 + Q^2} + \beta_i \frac{m_\phi^2}{m_\phi^2 + Q^2},$$

Normalization

$$N_c = G_c(0) = 1,$$
$$N_q = G_q(0) = M^2 Q_d = 25.83,$$
$$N_m = G_m(0) = \frac{M}{m} \mu_d = 1.714,$$

Results

From 12 to 6 parameters fit

1) Constrains on the nodes:

Q^2_{0C}=1.7 GeV^2, Q^2_{0M}=2 GeV^2

$$\alpha_i = \frac{m_\omega^2 + Q_{0i}^2}{Q_{0i}^2} - \beta_i \frac{m_\omega^2 + Q_{0i}^2}{m_\phi^2 + Q_{0i}^2}.$$

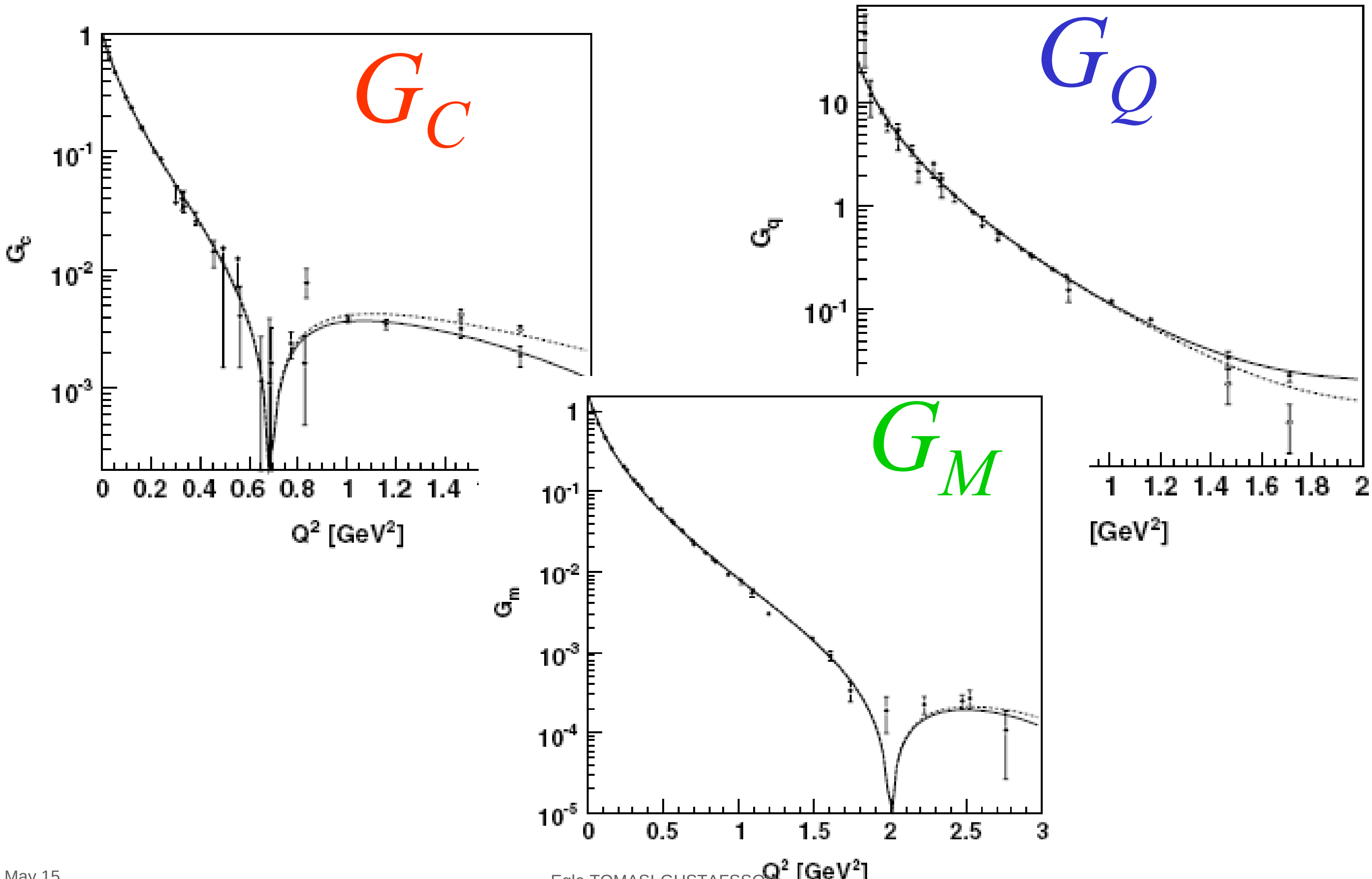
2) Intrinsic part common to the 3 FFs:

δ=1.04 ±0.03, γ=12.1 ± 0.5

	α	β	$\chi 2/ndf$
G_c (I)	5.75 ± 0.07	-5.11 ± 0.09	0.9
G_c (II)	5.50 ± 0.06	-4.78 ± 0.08	1.3
G_q(I)	4.21 ± 0.05	-3.41 ± 0.07	0.9
G_q(II)	4.08 ± 0.07	-3.25 ± 0.09	1.6
$G_m(I)$	3.77 ± 0.04	-2.86 ± 0.05	1.6
$G_m(II)$	3.74 ± 0.04	-2.83 ± 0.05	1.7

Results

C. Adamuscin, G.I. Gakh and E.T-G. PRC ***73****, 045204 (2006)*

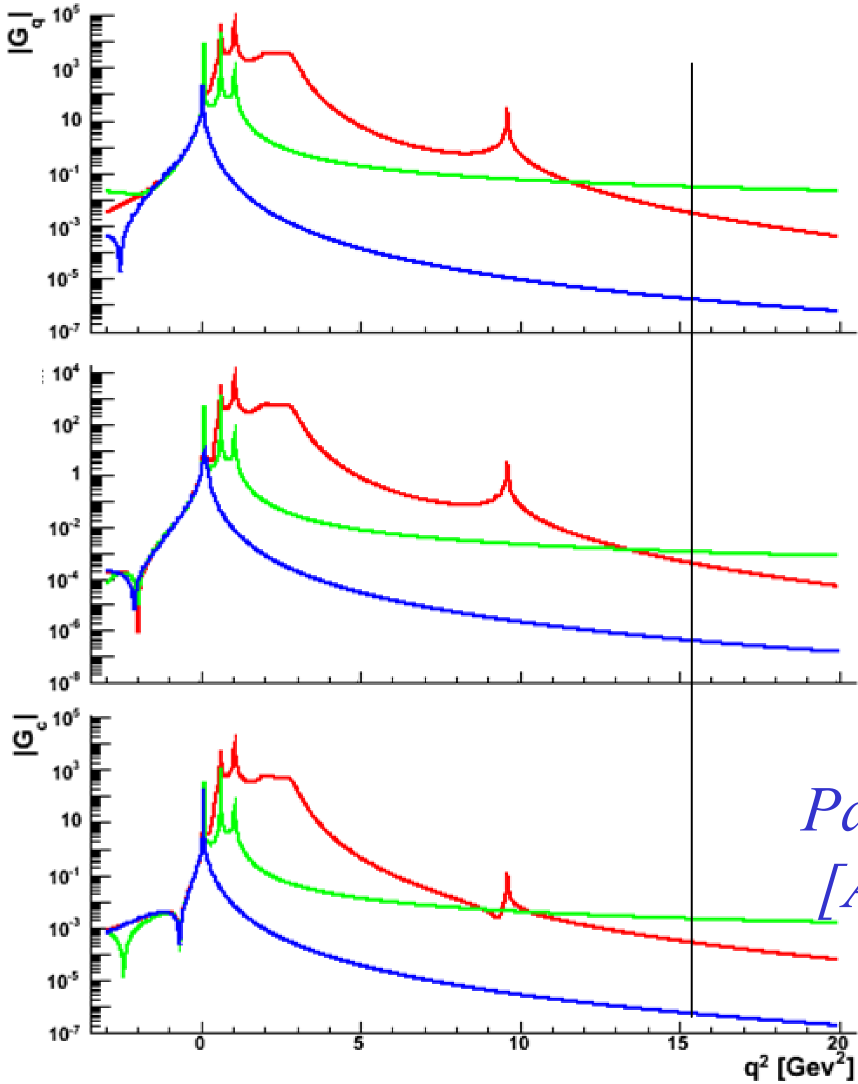


$e^+ + e^- \rightarrow d + \bar{d}$

$|G_Q|$

$|G_M|$

$|G_C|$



*PRC **74**, 025202 (2006)*

-Imaginary part from the intrinsic term

-No finite width for ρ,ω mesons)

U&A (Dubnicka)

Parametrization I (real part) [Abbott, EPJA 2000]

ρ–Meson Form Factors

Space-like

$$G_C(q^2) = \frac{G_C(0)(A+Bq^2)m_C^4}{(m_C^2-q^2)^2},$$

$$G_M(q^2) = \frac{G_M(0)m_M^4}{(m_M^2-q^2)^2},$$

$$G_Q(q^2) = \frac{G_Q(0)m_Q^4}{(m_Q^2-q^2)^2}.$$

A=1, B=0.33 from the node of Gc at q^2=-3 GeV^2

Time-like

Fit on light front calculation de Melo and Federico, PRC55,2043 (1997)

$$G_C(t) = \frac{(A+Bt)m_C^4}{(m_C^2-t-im_C\Gamma_C)^2},$$

$$G_M(t) = \frac{G_M(0)m_M^4}{(m_M^2-t-im_M\Gamma_M)^2},$$

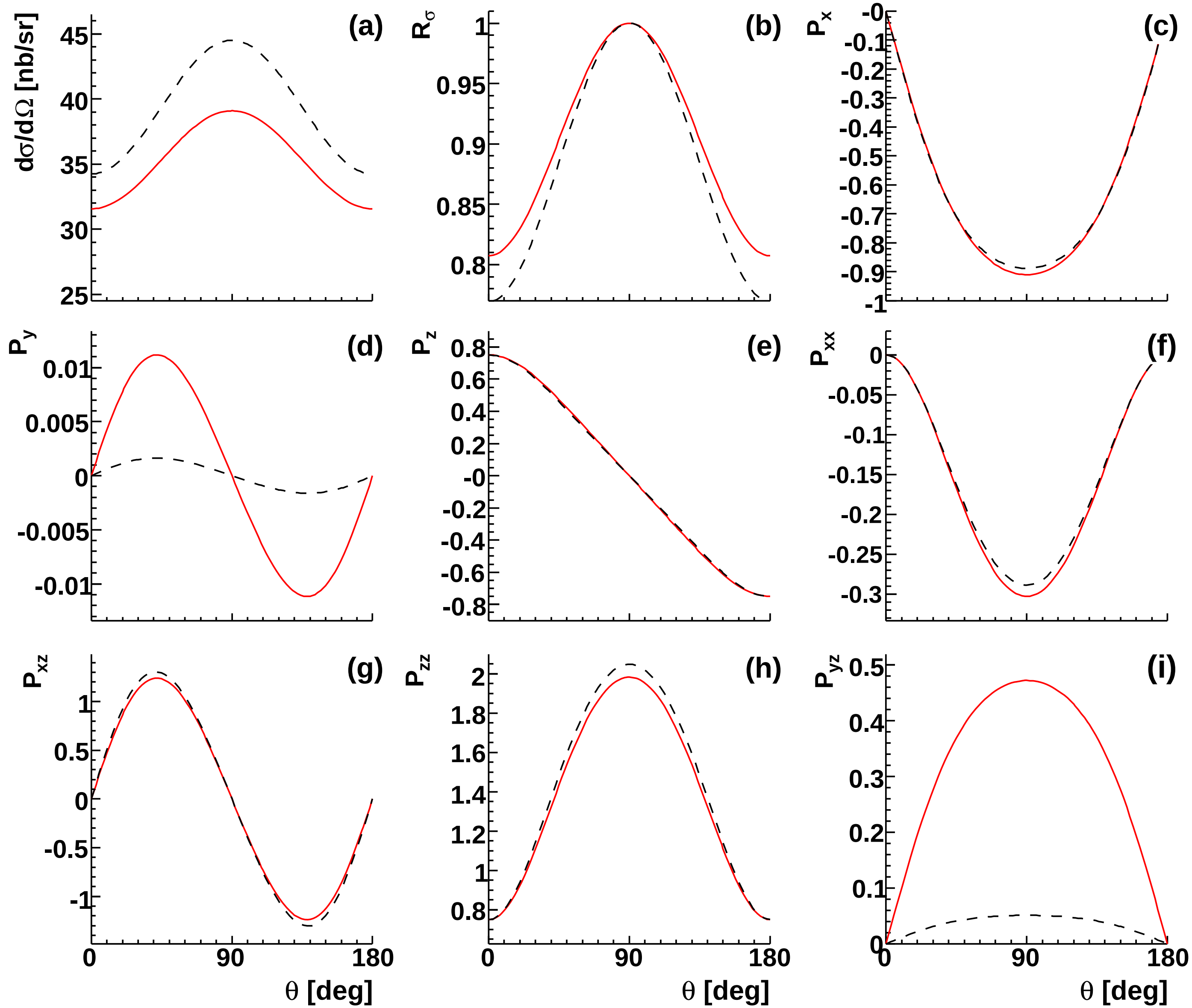
$$G_Q(t) = \frac{G_Q(0)m_Q^4}{(m_Q^2-t-im_Q\Gamma_Q)^2},$$

Analytical extension : imaginary part from the width ($\Gamma \sim$ 1% or 10% M)

...no experimental constraints, no new parameter

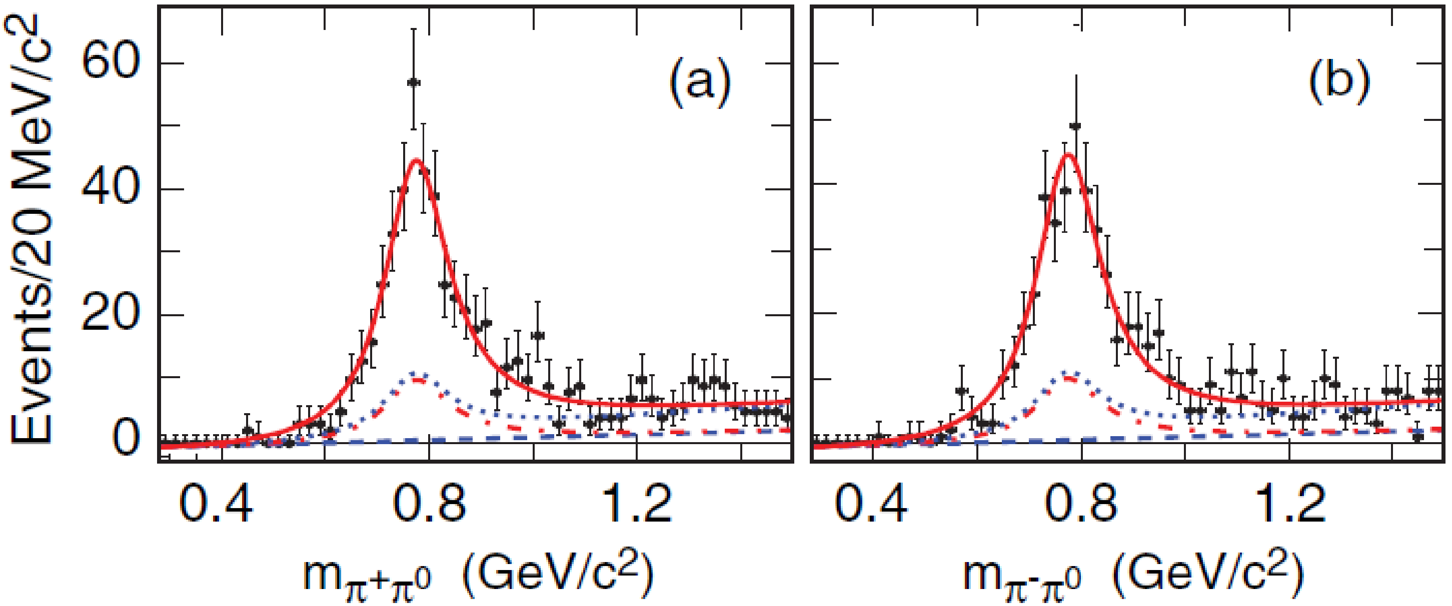
ρ - form factors : Observables

Spin 1



PHYSICAL REVIEW D **78,** 071103(R) (2008)

Observation of $e^+e^- \to \rho^+\rho^-$ near $\sqrt{s} = 10.58$ GeV

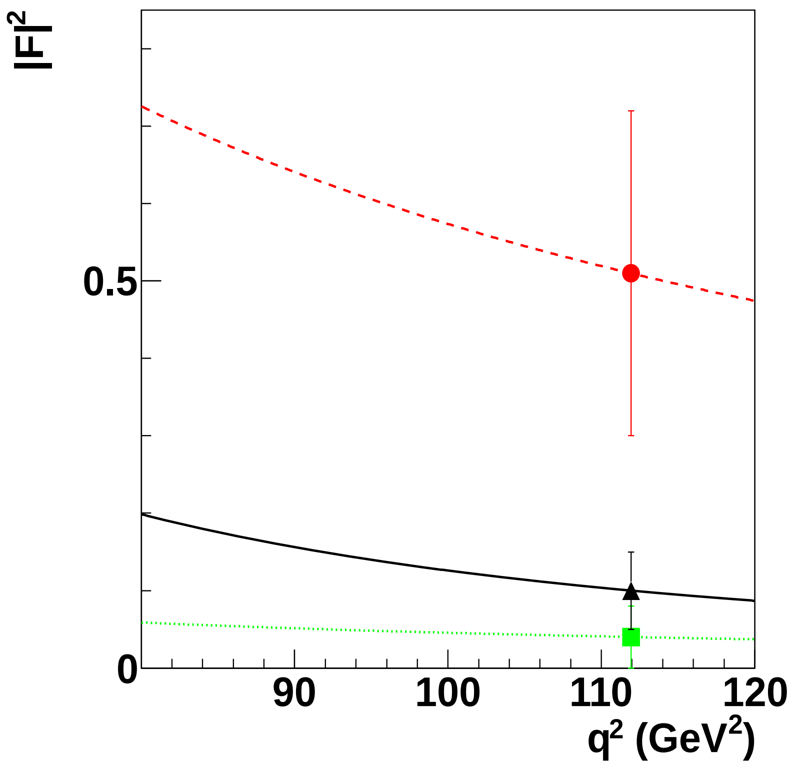


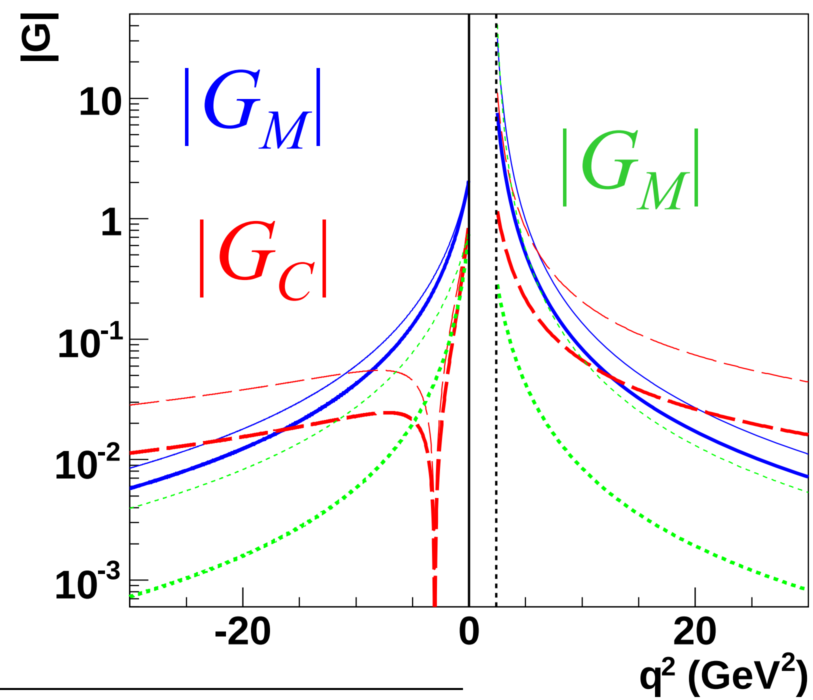
$|F_{00}|^2$:$|F_{10}|^2$:$|F_{11}|^2 = 0.51 \pm 0.14(\mathrm{stat}) \pm 0.07(\mathrm{syst})$:$0.10 \pm 0.04(\mathrm{stat}) \pm 0.01(\mathrm{syst})$:$0.04 \pm 0.03(\mathrm{stat}) \pm 0.01(\mathrm{syst})$.

PHYSICAL REVIEW C 85, 048201 (2012)

Experimental constraint on the ρ-meson form factors in the time-like region

A. Dbeyssi, E.T-G,G.I.Gakh,C.Adamuscin





Ref.	m_C (GeV)	m_M (GeV)	m_Q (GeV)
[3]	1.34 ± 2	1.42 ± 0.5	1.51 ± 0.1
This work (I)	$1.05^{+0.05}_{-0.09}$	$1.28^{+0.06}_{-0.08}$	$0.97^{+0.02}_{-0.01}$
This work (II)	$0.77^{+0.05}_{-0.02}$	$1.28^{+0.06}_{-0.08}$	$1.12^{+0.05}_{-0.08}$

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Tanti Auguri,
Franco!

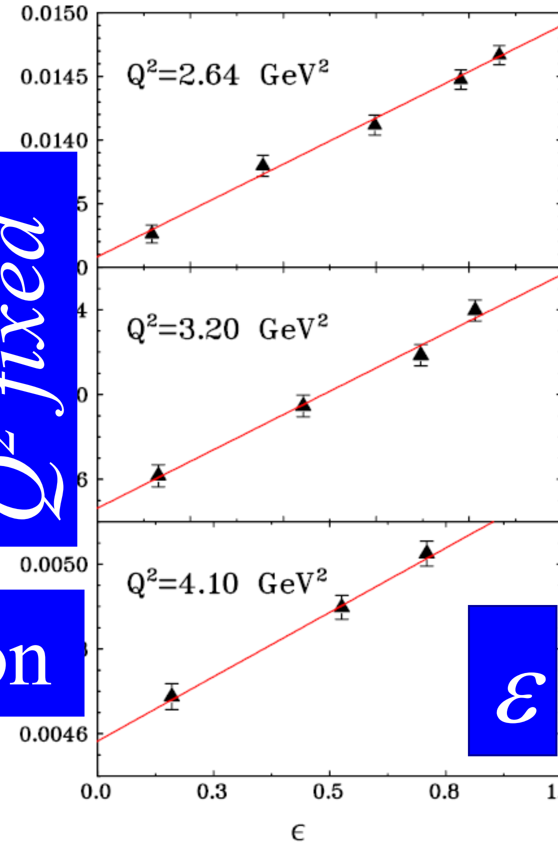
The Rosenbluth separation

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{(1+\tau)}\left(G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right)$$

$$\varepsilon = \left[1+2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}, \quad \tau = \frac{Q^2}{4M^2}$$

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2$$

Q^2 fixed



ε

PRL 94, 142301 (2005)

Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

→ Holds for 1γ exchange only

From Space-Like to Time-Like

$$Q^2 = -q^2 = q^2 e^{-i\pi} \implies \begin{cases} \ln(Q^2) = \ln(q^2) - i\pi, \\ \sqrt{Q^2} = e^{\frac{-i\pi}{2}} \sqrt{q^2}. \end{cases}$$

The sign is important for polarization observables

Phenomenological parametrizations must include an imaginary part

SL and TL generalized form factors

E.A. Kuraev et al., arXiv:1106.1670

Definition: $$F(q^2) = \int_{\mathcal{D}} d^4x e^{iq_\mu x^\mu} \rho(x),\ q_\mu x^\mu = q_0 t - \vec{q}\cdot\vec{x}$$

$\rho(x) = \rho(\vec{x}, t)$ *space-time distribution of the electric charge in the space-time volume D*

In SL- Breit frame (zero energy transfer):

$$F(q^2) = \delta(q_0) F(Q^2),\ Q^2 = -(q_0^2 - \vec{q}^2) > 0.$$

In TL-(CMS):

$$F(q^2) = \int_{\mathcal{D}} dt e^{i\sqrt{q^2}t} \int d^3\vec{r} \rho(\vec{r}, t) = \int_{\mathcal{D}} dt e^{i\sqrt{q^2}t} Q(t),$$

$Q(t)$ *: time evolution of the charge distribution in the domain* $\mathcal{D}$.

Time-like observables: $|G_E|^2$ and $|G_M|^2$.

-The cross section for $\bar{p} + p \to e^+ + e^-$ (1 γ-exchange):

$$\frac{d\sigma}{d(\cos\theta)} = \frac{\pi\alpha^2}{8m^2\sqrt{\tau - 1}}\left[\tau|G_M|^2(1+\cos^2\theta) + |G_E|^2\sin^2\theta\right]$$

θ: angle between e^- and $\bar{p}$ in cms.

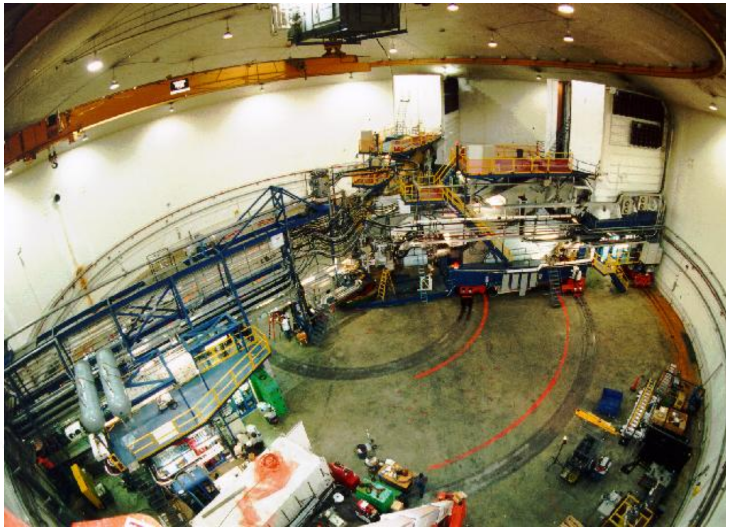
A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Il Nuovo Cimento XXIV, 170 (1962)
B. Bilenkii, C. Giunti, V. Wataghin, Z. Phys. C 59, 475 (1993).
G. Gakh, E.T-G., Nucl. Phys. A761,120 (2005).

As in SL region:
- Dependence on q^2 contained in FFs
- Even dependence on $\cos^2\theta$ (1γ exchange)
- No dependence on sign of FFs
- Enhancement of magnetic term

but TL form factors are complex!

The polarization method (exp)

JLab, Hall A



Transferred polarization is:

(Akhiezer & Rekalo and Arnold, Carlson & Gross):

$$P_n = 0$$

$$\pm h P_t = \mp h\, 2\sqrt{\tau(1+\tau)}\, G_E^p G_M^p \tan\left(\frac{\theta_e}{2}\right) / I_0$$

$$\pm h P_l = \pm h (E_e + E_{e'}) (G_M^p)^2 \sqrt{\tau(1+\tau)} \tan^2\left(\frac{\theta_e}{2}\right) / M / I_0$$

Where, $h = |h|$ is the beam helicity

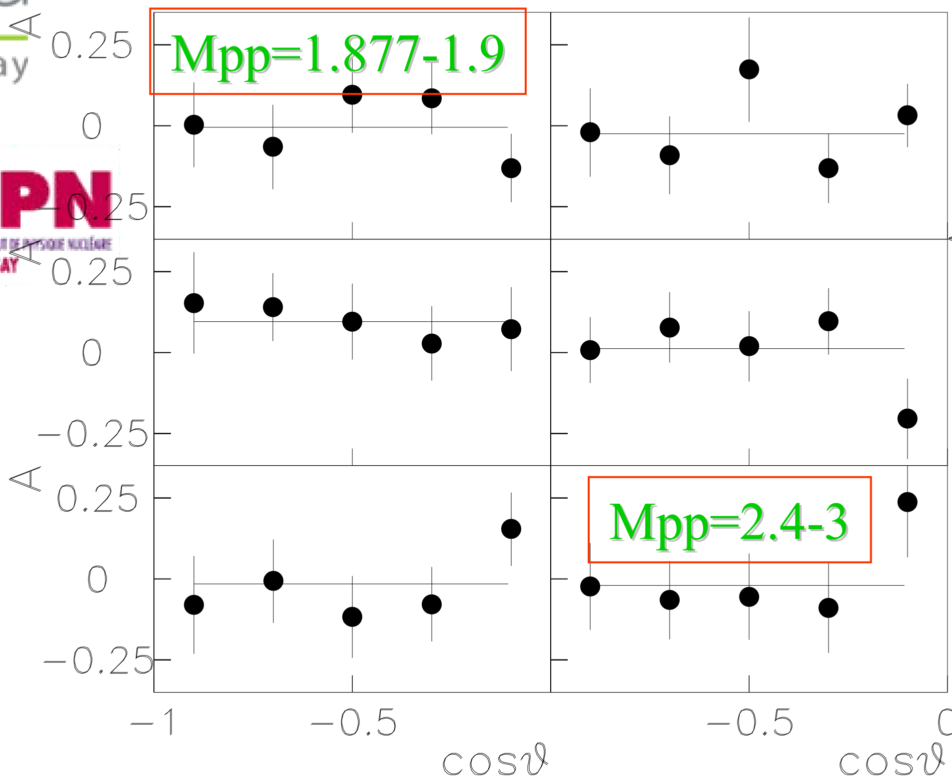
$$I_0 = (G_E^p(Q^2))^2 + \frac{\tau}{\epsilon} (G_M^p(Q^2))^2$$

$$\Longrightarrow \frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l} \frac{E_e + E_{e'}}{2M} \tan\left(\frac{\theta_e}{2}\right)$$

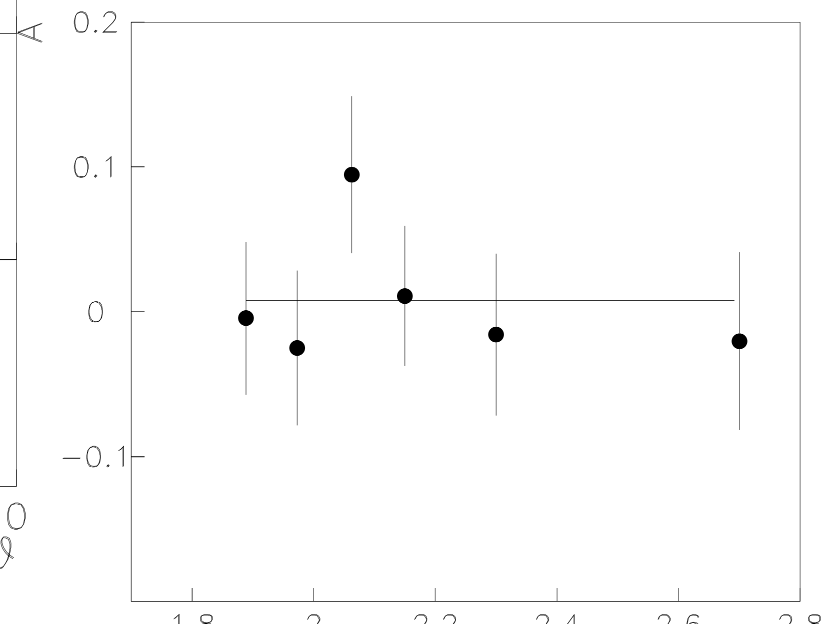
C. Perdrisat et al, JLab-GEp collaboration (2000)

The simultaneous measurement of P_t and P_l reduces the systematic errors

$$\frac{d\sigma_-}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi - \theta)$$



A=0.01±0.02



E. T.-G., E.A. Kuraev, S. Bakmaev, S. Pacetti, Phys. Lett. B (2008)

Phragmèn-Lindelöf theorem

Asymptotic properties for analytical functions

If f(z) →a as z→∞
along a straight line,
and f(z) →b as z→∞
along another
straight line,
and f(z) is regular
and bounded
in the angle between,
then a=b and f(z) →a
uniformly in the angle.

$$\lim_{q^2\to-\infty} F^{(SL)}(q^2) = \lim_{q^2\to\infty} F^{(TL)}(q^2)$$

$$space-like \qquad time-like$$

$$(e^- + p \to e^- + p) \qquad (e^+ + e^- \leftrightarrow \bar{p} + p)$$

$$- F^{(TL)}(q^2) \ \to \ real, \text{ if } q^2 \to \infty$$

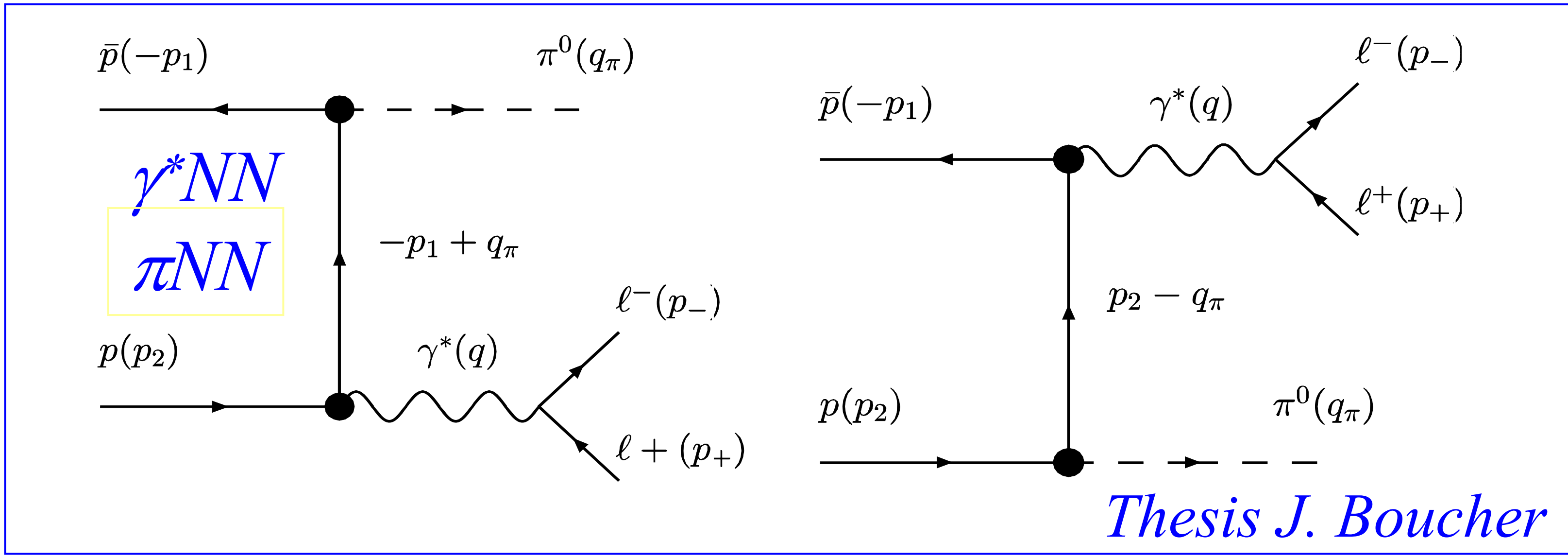
$$\mathcal{F} = |Im(F_2/F_1)|/|Re(F_2/F_1)| = \Delta$$

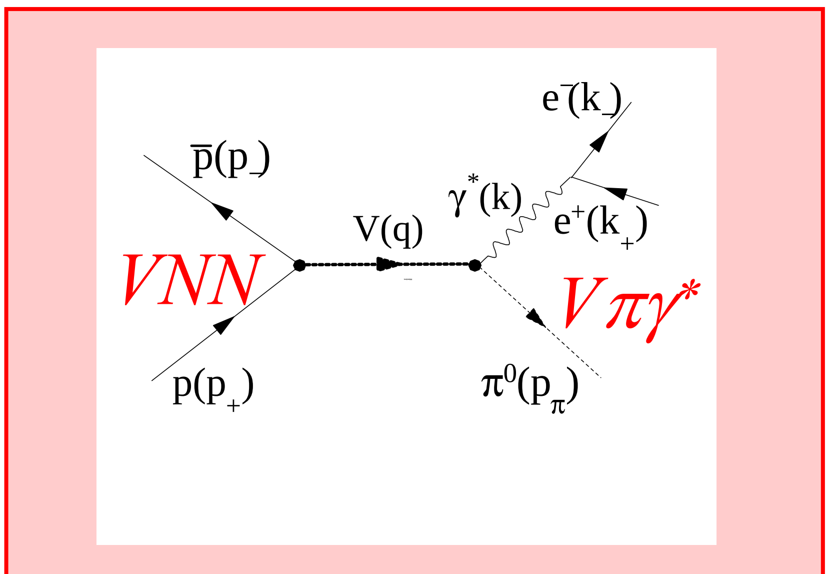
$$|P_y| = \Delta \quad \Delta=0.05,\ 0.1$$

$$\mathcal{R} = |F_2/F_1|_{TL}/|F_2/F_1|_{SL} = 1 + \Delta$$

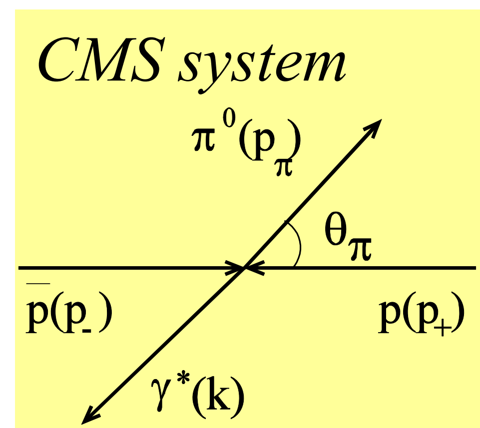
E. T-G. and G. Gakh, Eur. Phys. J. A 26, 265 (2005)

The reaction $p + \bar{p} \to e^+ + e^- + \pi^0$



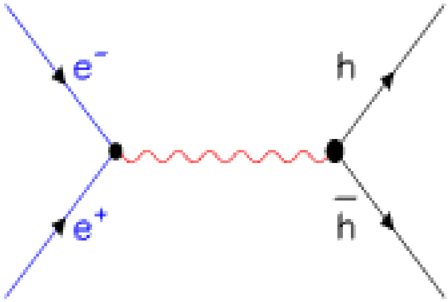


$V=\rho,\omega,\phi, J/\Psi, ..$

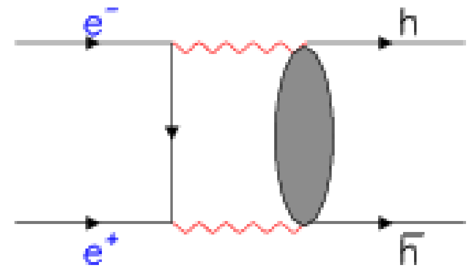


1γ-2γ interference

M. P. Rekalo, E. T.-G. and D. Prout, Phys. Rev. C60, 042202 (1999)



$C(\gamma)=-1$



$C(2\gamma)=+1$

$S=1,\ \ell=0$ and $S=1,\ \ell=2$ with $\mathcal{J}^P=1^-$,

$$\overline{|\mathcal{M}_1(e^+e^-\to\bar{h}h)|^2}=a(t)+\cos^2\tilde{\theta}\ b(t)$$

$$Re\mathcal{M}_1\mathcal{M}_2^*=\cos\tilde{\theta}(a_0+a_1\cos^2\tilde{\theta}+..)$$

1γ 2γ

$$\frac{d\sigma}{d\Omega_e}(e^-h\to e^-h)=\sigma_0(\ A\ \cot^2\frac{\theta_e}{2}+B+\ C\ \cot\frac{\theta_e}{2}+D\ \cot^3\frac{\theta_e}{2}+..)$$

Symmetry relations (annihilation)

- Differential cross section at complementary angles:

The SUM cancels the 2γ contribution:

$$\frac{d\sigma_+}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi-\theta) = 2\frac{d\sigma^{Born}}{d\Omega}(\theta)$$

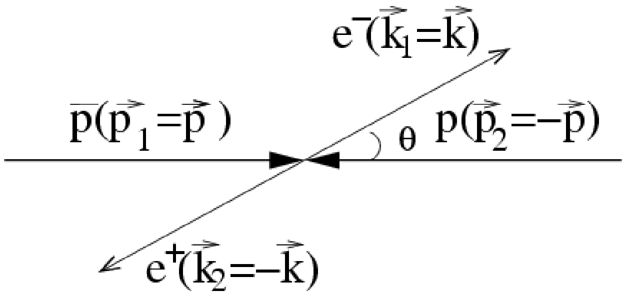
The DIFFERENCE enhances the 2γ contribution:

$$\frac{d\sigma_-}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi-\theta) = 4N\Big[(1+x^2)ReG_M\Delta G_M^* + \\ +\frac{1-x^2}{\tau}ReG_E\Delta G_E^* + \sqrt{\tau(\tau-1)}x(1-x^2)Re(\frac{1}{\tau}G_E - G_M)F_3^*\Big]$$

$$\tau = \frac{q^2}{4m^2}, \quad x = cos\theta$$

Spin Observables

Analyzing power, A



$$\frac{d\sigma}{d\Omega}(P_y)=\left(\frac{d\sigma}{d\Omega}\right)_0[1+\mathcal{A}P_y],$$

$$\mathcal{A}=\frac{\sin 2\theta\, Im G_E^* G_M}{D\sqrt{\tau}},\ \ D=|G_M|^2(1+\cos^2\theta)+\frac{1}{\tau}|G_E|^2\sin^2\theta$$

Double spin observables

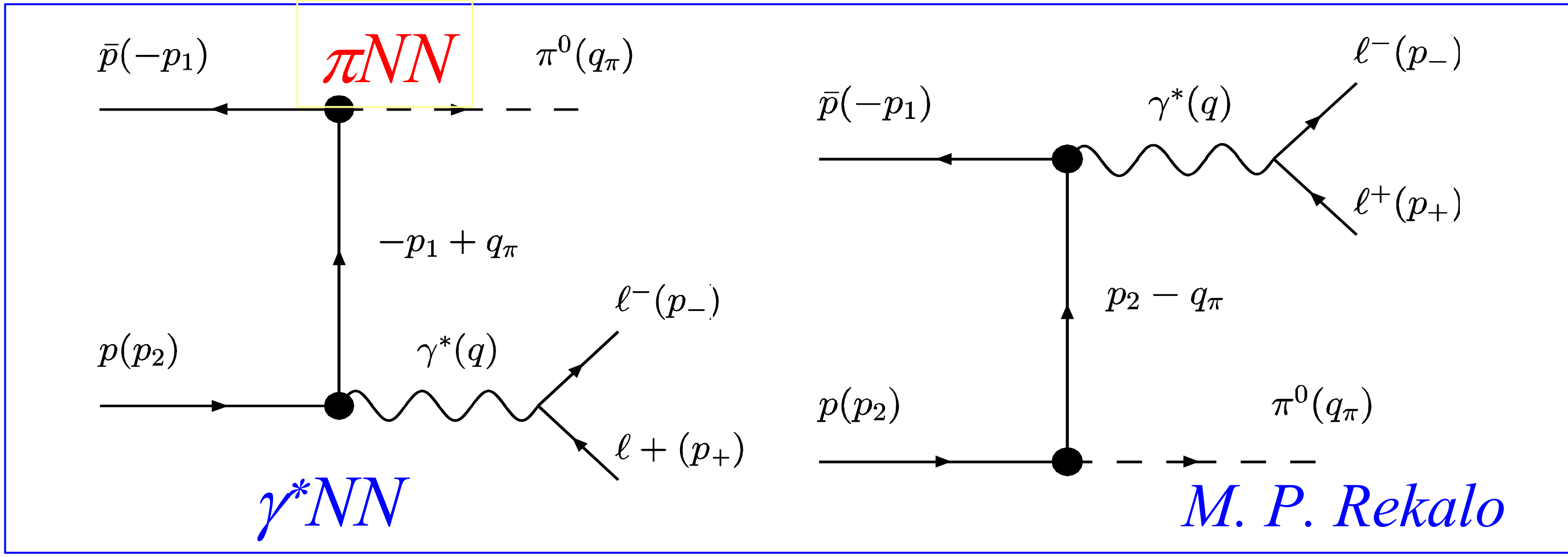
$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xx} = \sin^2\theta\left(|G_M|^2+\frac{1}{\tau}|G_E|^2\right)\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{yy} = -\sin^2\theta\left(|G_M|^2-\frac{1}{\tau}|G_E|^2\right)\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{zz} = \left[(1+\cos^2\theta)|G_M|^2-\frac{1}{\tau}\sin^2\theta|G_E|^2\right]\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xz} = \left(\frac{d\sigma}{d\Omega}\right)_0 A_{zx}=\frac{1}{\sqrt{\tau}}\sin 2\theta\, Re G_E G_M^*\mathcal{N}.$$

The reaction $p + \bar{p} \to e^+ + e^- + \pi^0$



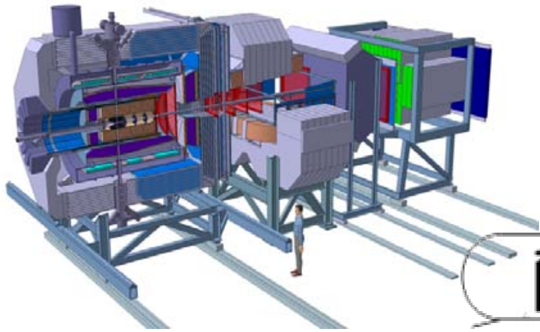
$$< N(p')|\Gamma_\mu(q)^N|N(p) >= \bar{u}(p')\left[F_1^N(q^2)\gamma_\mu + \frac{F_2^N(q^2)}{4M}(\hat{q}\gamma_\mu - \gamma_\mu\hat{q})\right]u(p)$$

$$d\sigma^i = \frac{\alpha^2}{6s\pi r}\frac{\beta(q^2+2\mu^2)}{(q^2)^2}\mathcal{D}^i\frac{d^3q_\pi}{2\pi E_\pi},$$

$$\mathcal{D}^i = \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)\frac{1}{4}Tr(\hat{p}_1 - M)O^i_\mu(\hat{p}_2 + M)(O^i_\nu)^*,\ i = 0, -$$

$$O^0_\mu = \Gamma^p_\mu(q)\frac{\hat{p}_1 - \hat{q} - M}{(p_1-q)^2 - M^2}\gamma_5 g(m_\pi^2) - \gamma_5\frac{\hat{p}_2 - \hat{q} + M}{(p_2-q)^2 - M^2}\Gamma^p_\mu(q)g(m_\pi^2)$$

STATUS on Time-like EM Form factors



1) No individual determination of |GE| and |GM|

2) Assume GE=GM (valid only at threshold)

3) TL nucleon FFs are twice larger than SL FF

VMD or pQCD inspired parametrizations (for p and n):

$$G_M = \frac{A}{s^2[\pi^2 + \ln^2(s/\Lambda^2)]}$$

A(p) = 56.3 GeV^4

A(n) = 77.15 GeV^4

Λ_{QCD} =0.3 GeV