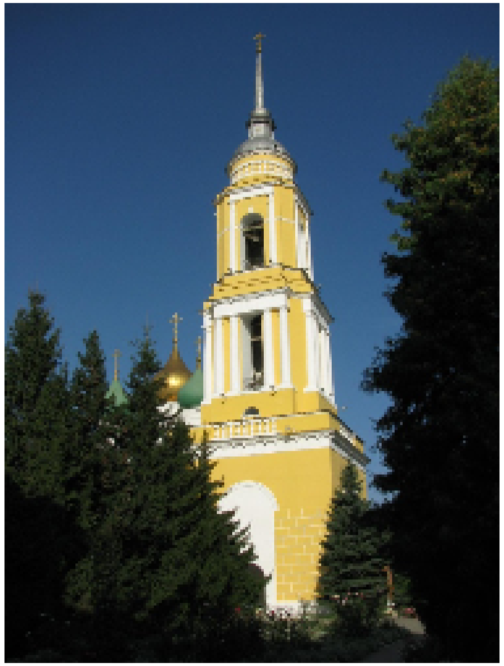
Test of QCD through hadron form factor measurements at large momentum transfer

Egle Tomasi-Gustafsson
IRFU, SPhN-Saclay, and
IN2P3- IPN Orsay France



QUARKS-2010
16th International Seminar on High Energy Physics
Kolomna, Russia, 6-12 June, 2010.

PLAN

- *Introduction*
- *What is new?*
  - *Space-like region : new data at JLab*
    - *Rosenbluth separation (unpolarized scattering)*
    - *Recoil proton polarization*
      (A.I. Akhiezer and M.P. Rekalo in 1968)
  - *Time-like region*
    - *Plans at BES-III*
    - *Plans at PANDA*

- *Global description in a wide kinematical region*
  - *Asymptotics*
  - *Counting rules*

Hadron Electromagnetic Form factors

The Nobel Prize in Physics 1961

"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the stucture of the nucleons"

Robert Hofstadter

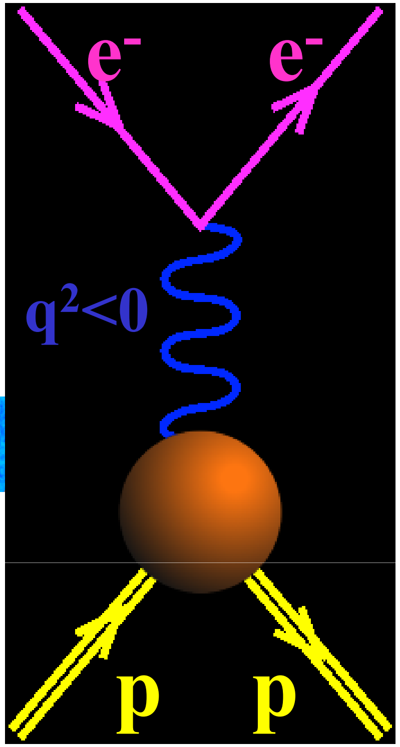
1/2 of the prize

USA

Stanford University
Stanford, CA, USA

- 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

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

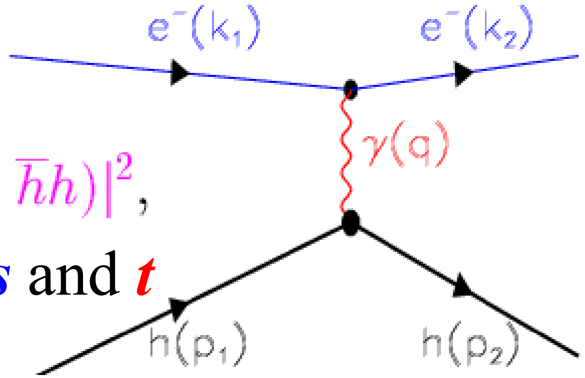
or in terms of Sachs FFs:
$GE = F_1 - \tau F_2$, $GM = F_1 + F_2$, $\tau = -q^2/4M^2$

What about high order radiative corrections?

Crossing Symmetry

Scattering and annihilation channels:

$e^- + h \to e^- + h$



- Described by the same amplitude :

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

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

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

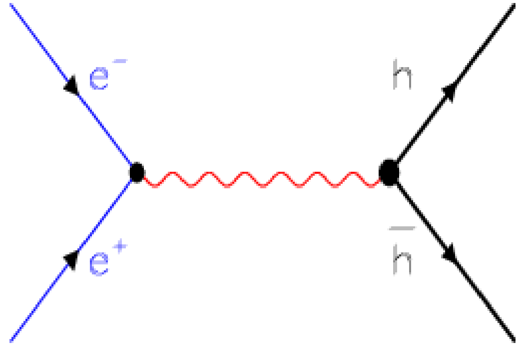
$e^- + e^+ \to \bar{h} + h$

- which scan different kinematical regions

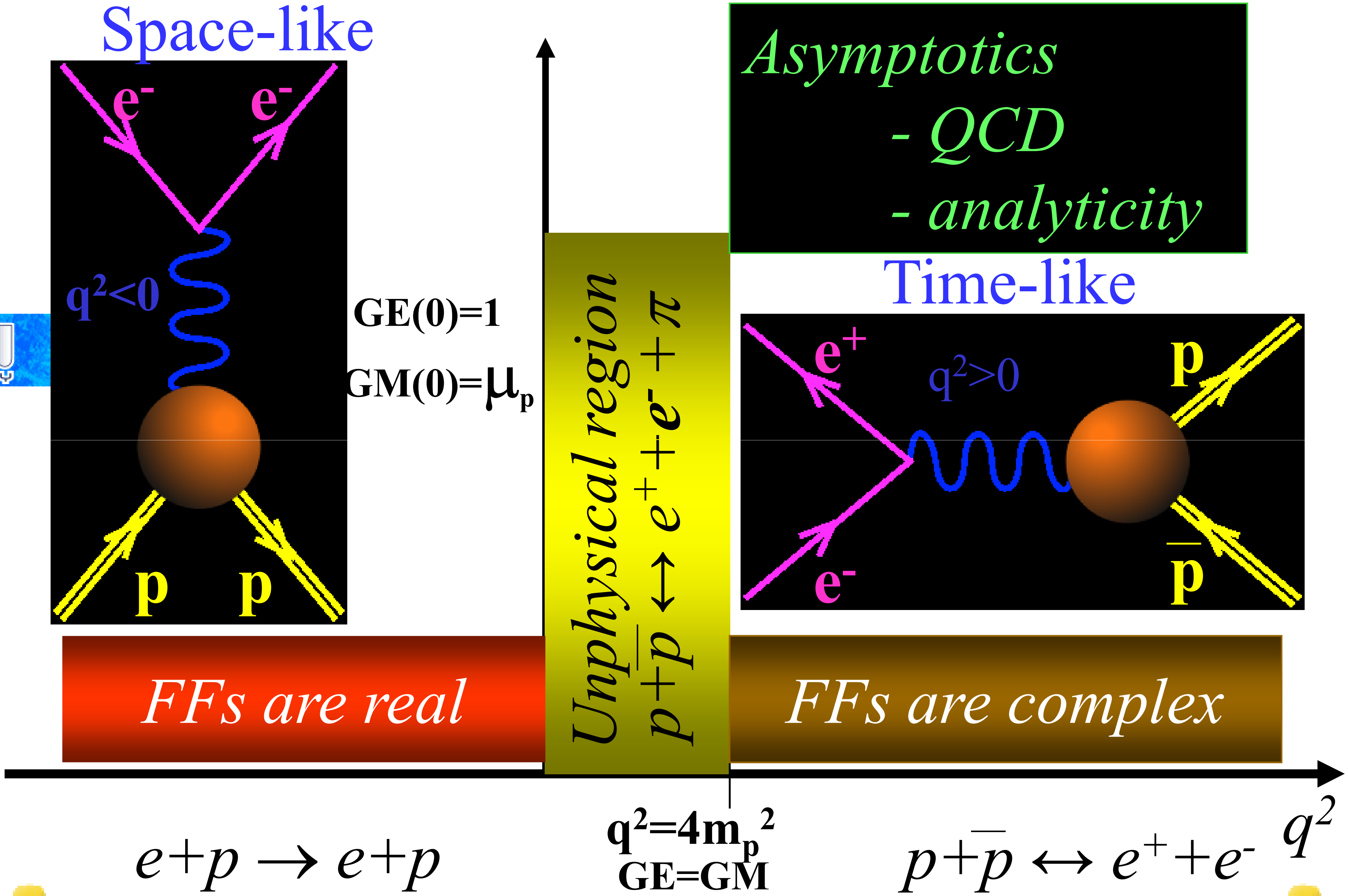
$$k_2 \longrightarrow -k_2$$

$$p_2 \longrightarrow -p_2$$

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

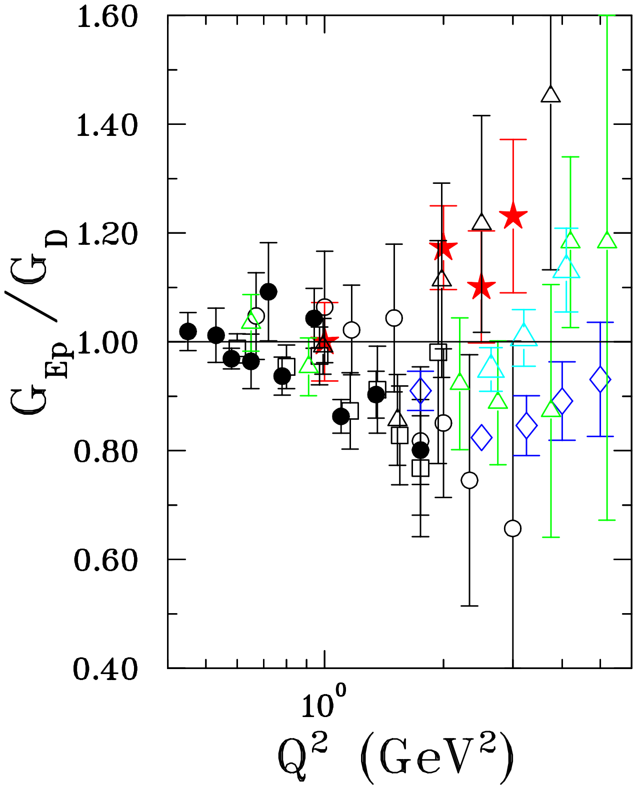


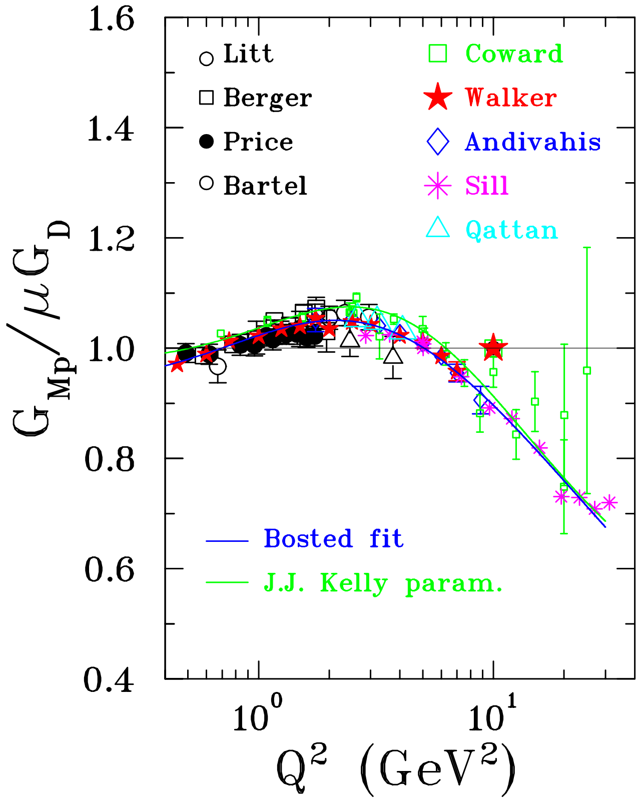
Analyticity



Proton Form Factors ...before

Dipole approximation: $G_D=(1+Q^2/0.71\ GeV^2)^{-2}$

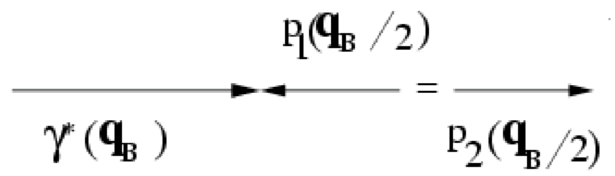




Rosenbluth separation/ Polarization observables

Dipole Approximation

- Classical approach
  - Nucleon FF (in the Breit system) are Fourier transform of the charge or magnetic distribution.

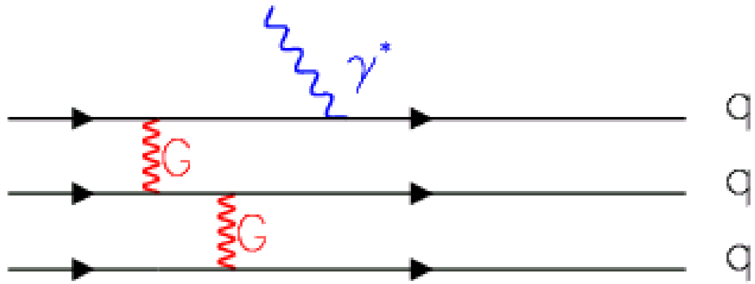


Dipole approximation: $G_D=(1+Q^2/0.71\ GeV^2)^{-2}$

- *The dipole approximation corresponds to an exponential density distribution.*
  - $\rho = \rho_0 \exp(-r/r_0)$,
  - $r_0^2= (0.24\ fm)^2$, $<r^2> \sim(0.81\ fm)^2$ $\leftrightarrow m^2_D = 0.71\ GeV^2$

Dipole Approximation and pQCD

Dimensional scaling



- $F_n(Q^2) = C_n\,[1/(1+Q^2/m_n)^{n-1}]$,
  - $m_n = n\beta^2$, <quark momentum squared>
  - n is the number of constituent quarks
- Setting $\beta^2 = (0.471 \pm .010)$ GeV^2 *(fitting pion data)*
  - pion: $F_\pi(Q^2) = C_\pi\,[1/(1+Q^2/0.471\text{ GeV}^2)^1]$,
  - nucleon: $F_N(Q^2) = C_N\,[1/(1+Q^2/0.71\text{ GeV}^2)^2]$,
  - deuteron: $F_d(Q^2) = C_d\,[1/(1+Q^2/1.41\text{GeV}^2)^5]$

V. A. Matveev, R. M. Muradian, and A. N. Tavkhelidze (1973), Brodsky and Farrar (1973), Politzer (1974), Chernyak & Zhitnisky (1984), Efremov & Radyuskin (1980)…

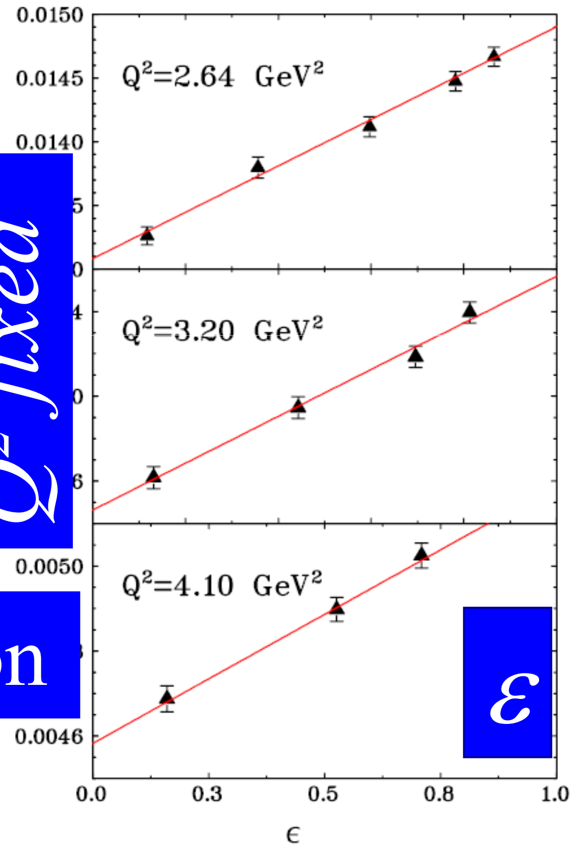
The Rosenbluth separation

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

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

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

Q^2 fixed



ε

PRL 94, 142301 (2005)

Linearity of the reduced cross section

→ *$\tan^2\theta_e$ dependence*

→ Holds for *1γ* exchange only

The polarization method (1967)

Irfu
cea
saclay

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

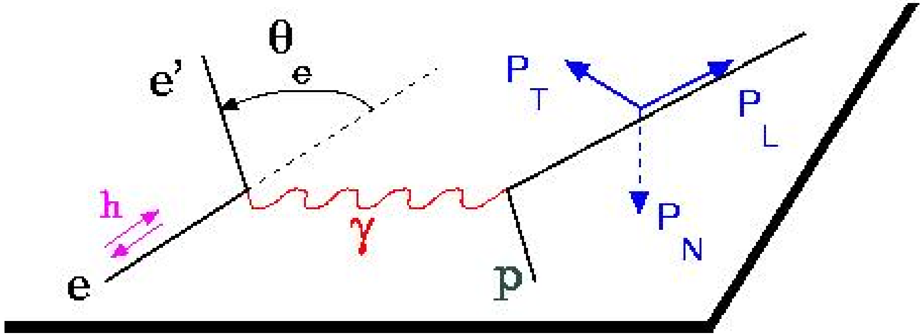
PHYSICS

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

$$S_2 \frac{d\sigma}{d\Omega_R} = 4p_2 \frac{(s\cdot q)}{1+\tau} \Gamma(\theta, \varepsilon_1) \Big[\tau G_M (G_M + G_E) - \frac{1}{4\varepsilon_1} G_M (G_E - \tau G_M) \Big],$$



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

The polarization method (exp)

Transferred polarization is:

C. Perdrisat et al, JLab-GEp collaboration

$$P_n = 0$$

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

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

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

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

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

The simultaneous measurement of P_t and P_l reduces the systematic errors

Polarization experiments - Jlab

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

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GEp collaboration

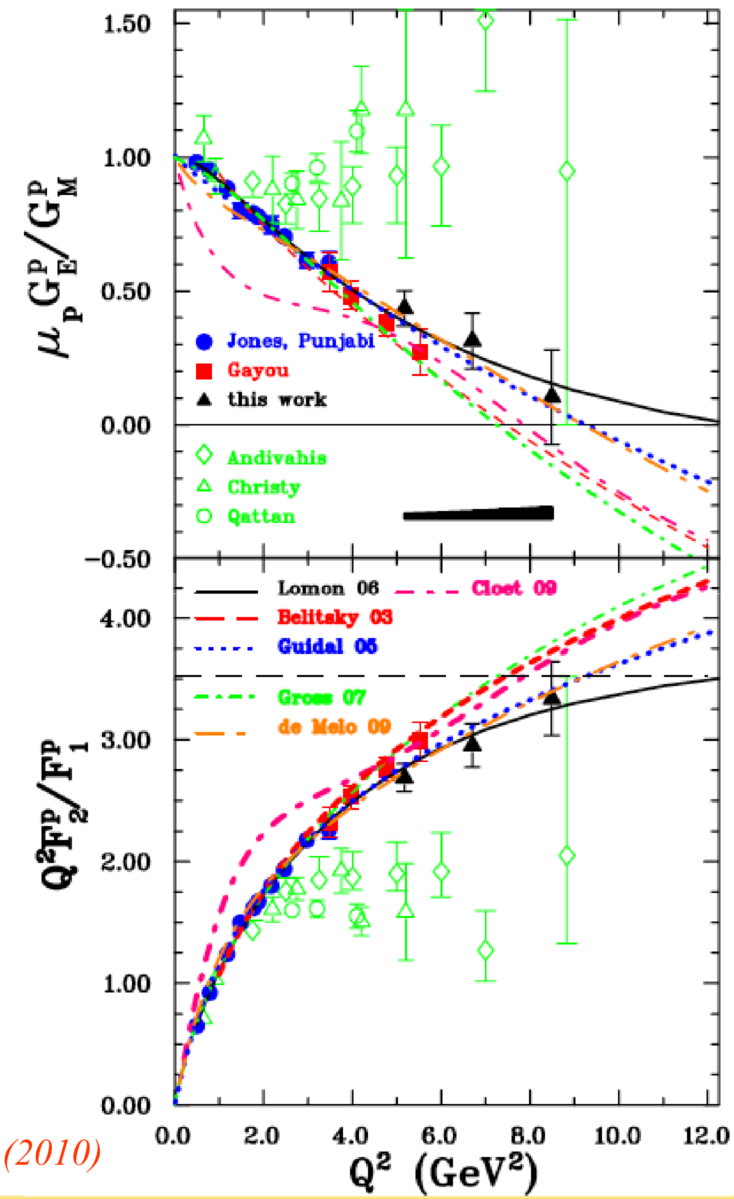
1) "standard" dipole function for the nucleon magnetic FFs GMp and GMn

2) linear deviation from the dipole function for the electric proton FF Gep

3) QCD scaling not reached

3) Zero crossing of Gep?

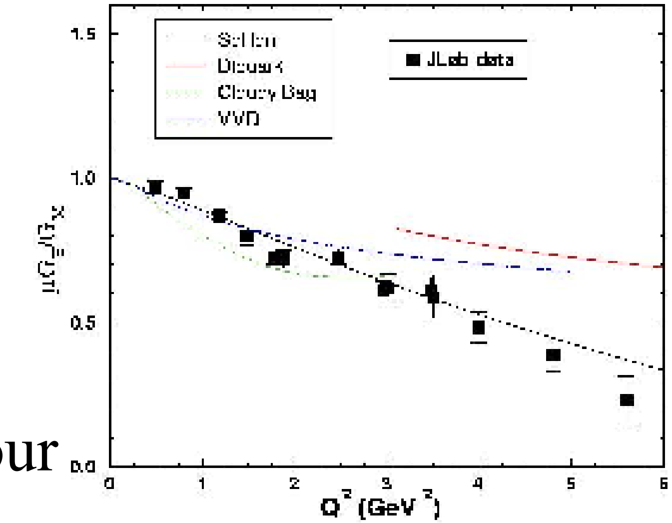
4) ***contradiction between polarized and unpolarized measurements***



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

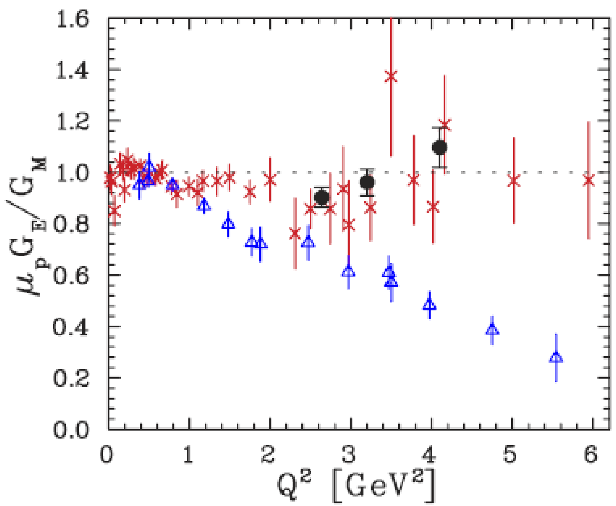
Issues

- Some models (IJL 73, Di-quark, soliton..) predicted such behavior before the data appeared



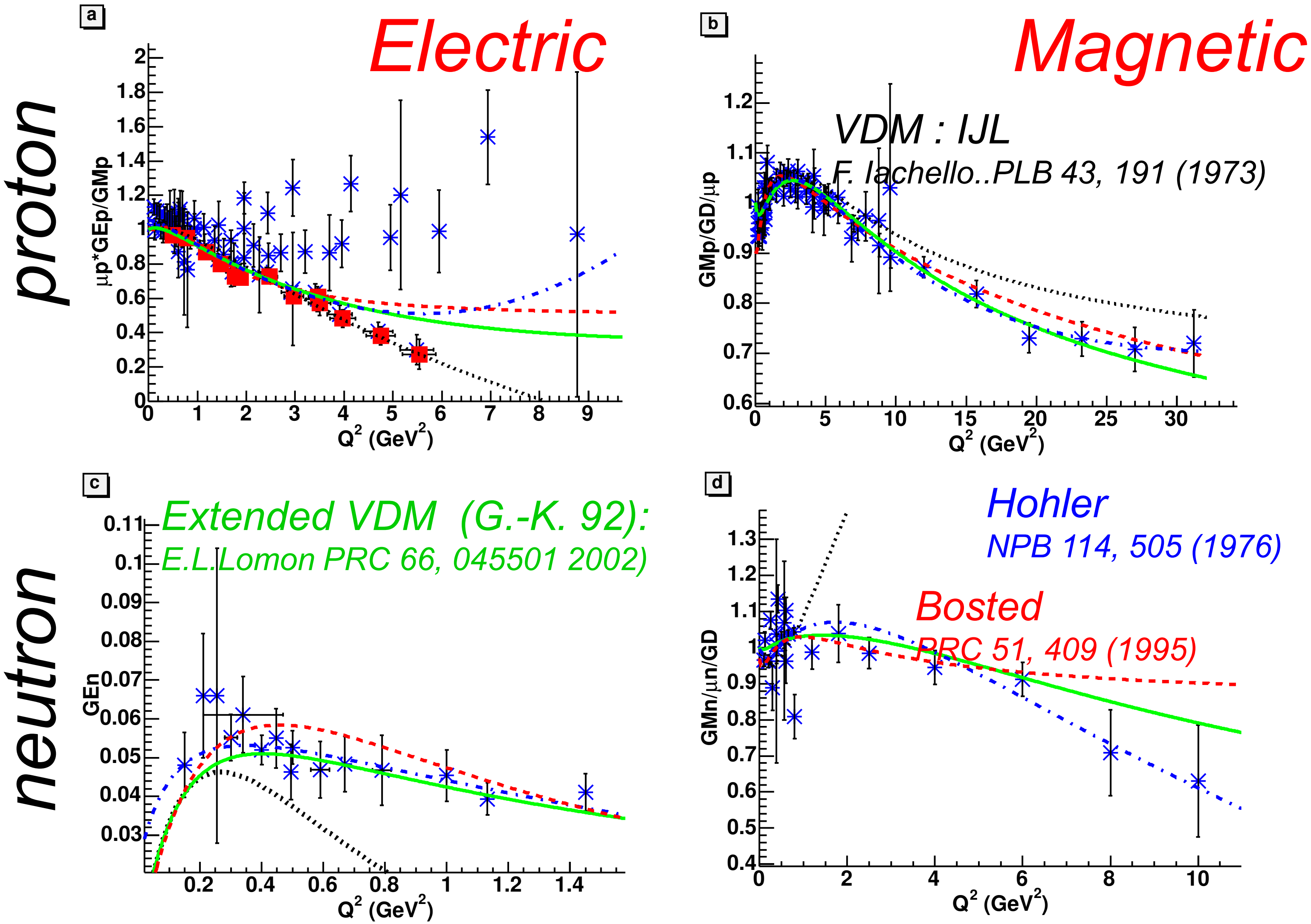
BUT

- 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

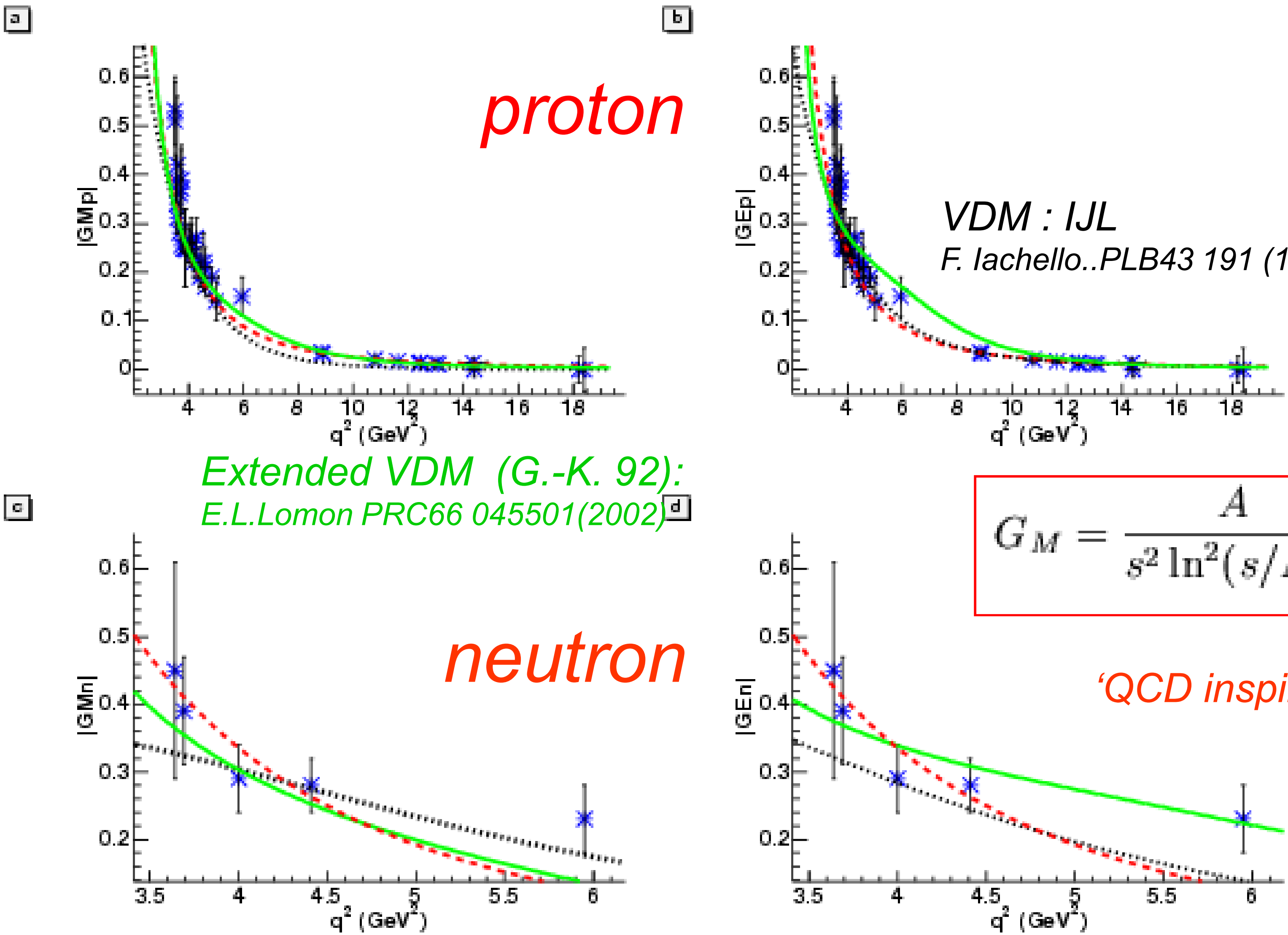


The nucleon form factors

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



Models in T.L. region



VDM : IJL
F. Iachello..PLB43 191 (1973)

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

'QCD inspired'

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

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

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

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

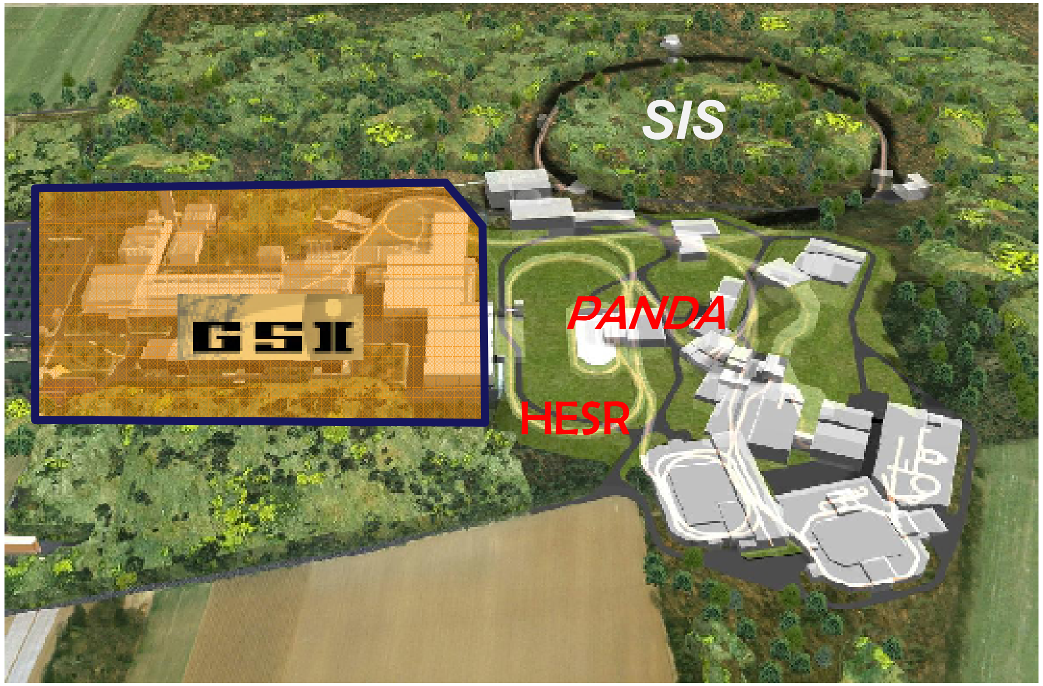
θ: angle between e^- and $\overline{p}$ in cms.

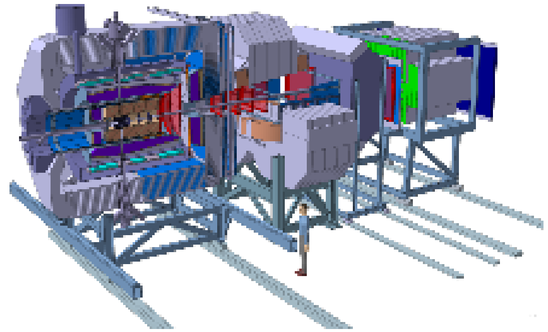
A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Il Nuovo Cimento XXIV, 170 (1962)
B. Bilenkii, C. Giunti, V. Wataghin, Z. Phys. C 59, 475 (1993).
G. Gakh, E.T-G., Nucl. Phys. A761,120 (2005).

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!

Proton-Antiproton Annihilation





need of
- *highest rates*
- *good resolution*
- *Good Particle Identification*

Parameters of HESR

http://www-panda.gsi.de/

- *Injection of p at 3.7 GeV*
- *Slow synchrotron (1.5-14.5 GeV/c)*
- *Storage ring for internal target operation*
- *Luminosity up to L~ $2x10^{32}$ cm-2s-1*
- *Beam cooling (stochastic & electron)*

Physical Background

M. Sudol et al, arXiv:0907.4478 [nucl-ex]

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

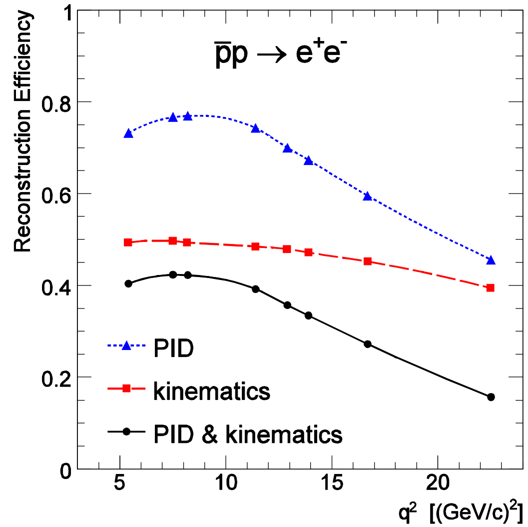
- **3 body reactions**
  - ➔ kinematical constraints
  - ➔ PID
- **2 body reactions (hadrons)**

  $\pi^+\pi^-$, K^+K^-

$$\frac{\sigma_{\pi^+\pi^-}}{\sigma_{e^+e^-}} \sim 10^6$$

High statistics GEANT4 simulations

- **< few $^0/_{00}$ misidentified events / $\cos\theta_{CM}$ bin**
- **< 1% on the total cross section up to 16 GeV^2**



It is possible to discriminate e^+e^- from $\pi^+\pi^-$

Expected Results

Irfu

cea

saclay

$\mathscr{L} = 2 \cdot 10^{32}\ cm^{-2}\,s^{-1}$

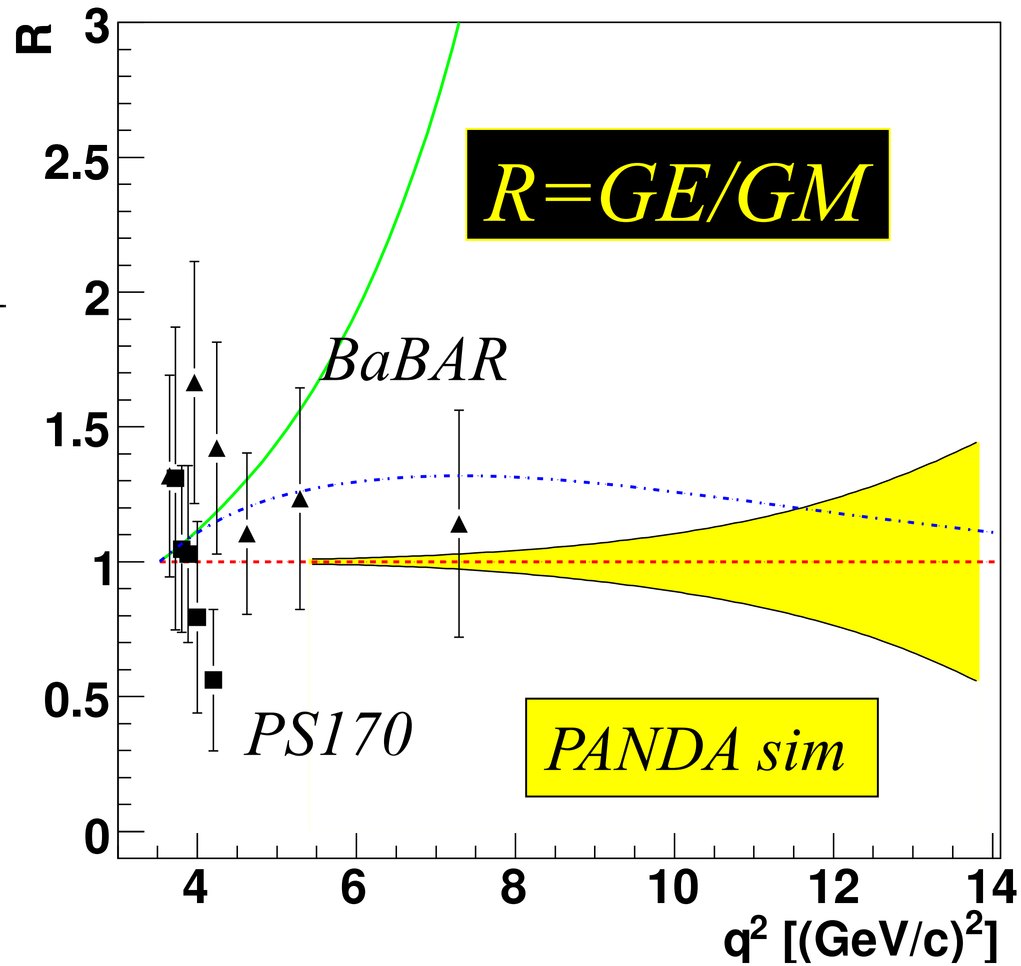
100 jours

panda

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

Individual determination of GE and GM up to large Q^2

M. Sudol et al, EPJA 2010, arXiv:0907.4478 [nucl-ex]



$\bar{p} + p \rightarrow e^+ + e^-$ *Angular Distributions*

The form of the differential cross section:

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

is equivalent to:

$$\frac{d\sigma}{d(\cos\theta)} = \sigma_0\left[1 + \mathcal{A}\cos^2\theta\right]$$

Cross section at 90^0

$$\sigma_0 = \frac{\alpha^2}{4q^2}\sqrt{\frac{\tau}{\tau-1}}\left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right)$$

Angular asymmetry

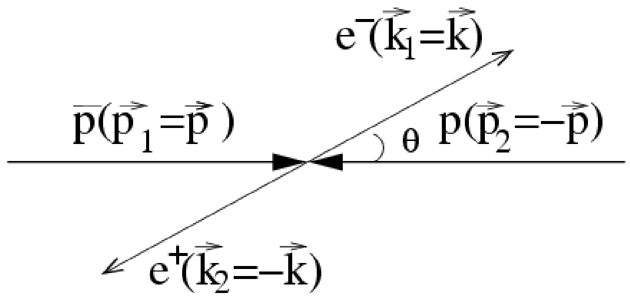
$$\mathcal{A} = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2} = \frac{\tau - \mathcal{R}^2}{\tau + \mathcal{R}^2}.$$

$$\mathcal{R} = |G_E|/|G_M|$$

E. T-G. and M. P. Rekalo, Phys. Lett. B 504, 291 (2001)

Spin Observables

Analyzing power, A



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

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

Double spin observables

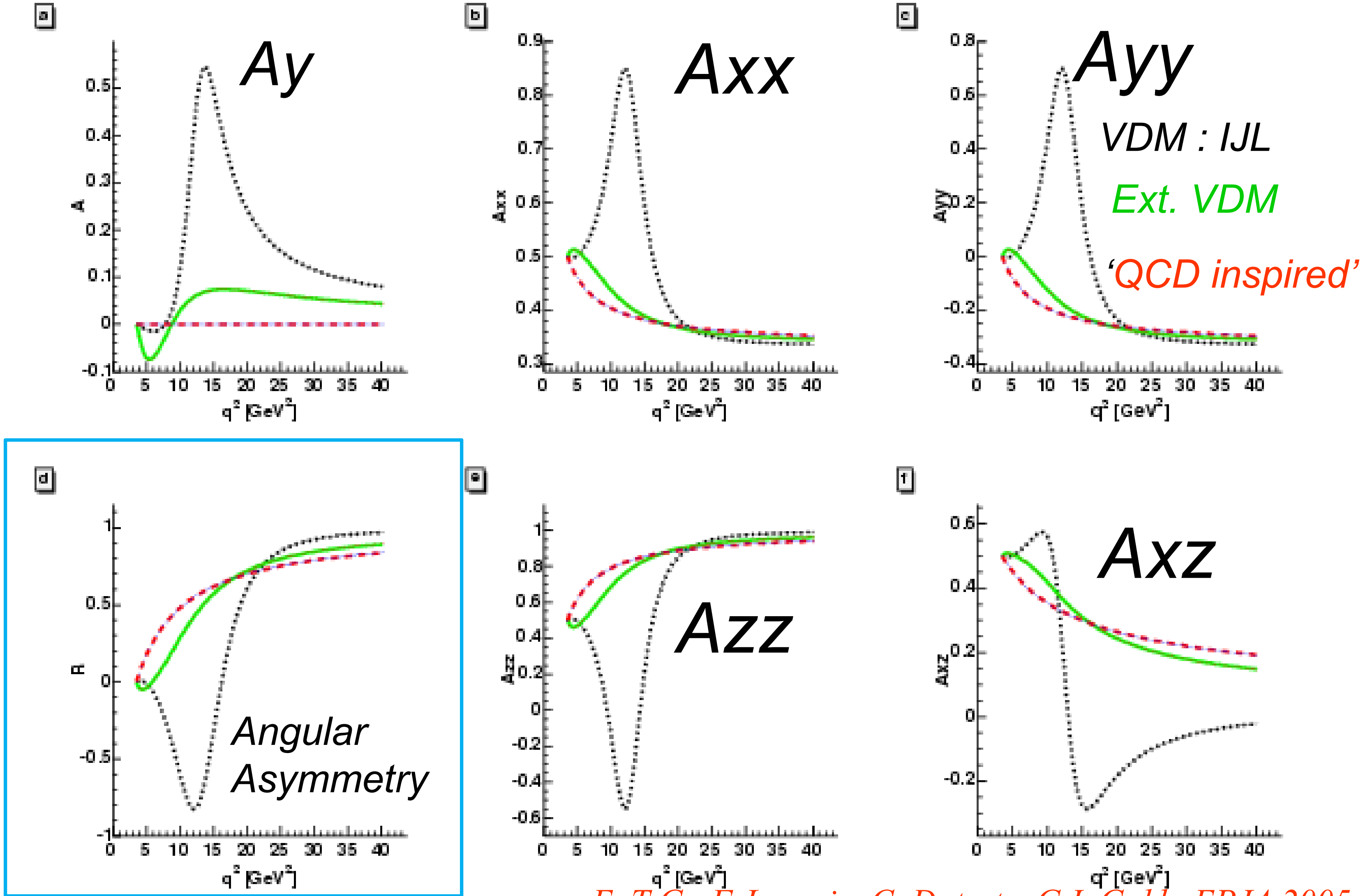
$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xx} = \sin^2\theta \left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right)\mathcal{N},$$

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

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

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

Models in T.L. Region (polarization)



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

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.

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

$space - like \quad (e^- + p \to e^- + p)$ $\qquad$ $time - like \quad (e^+ + e^- \leftrightarrow \overline{p} + p)$

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

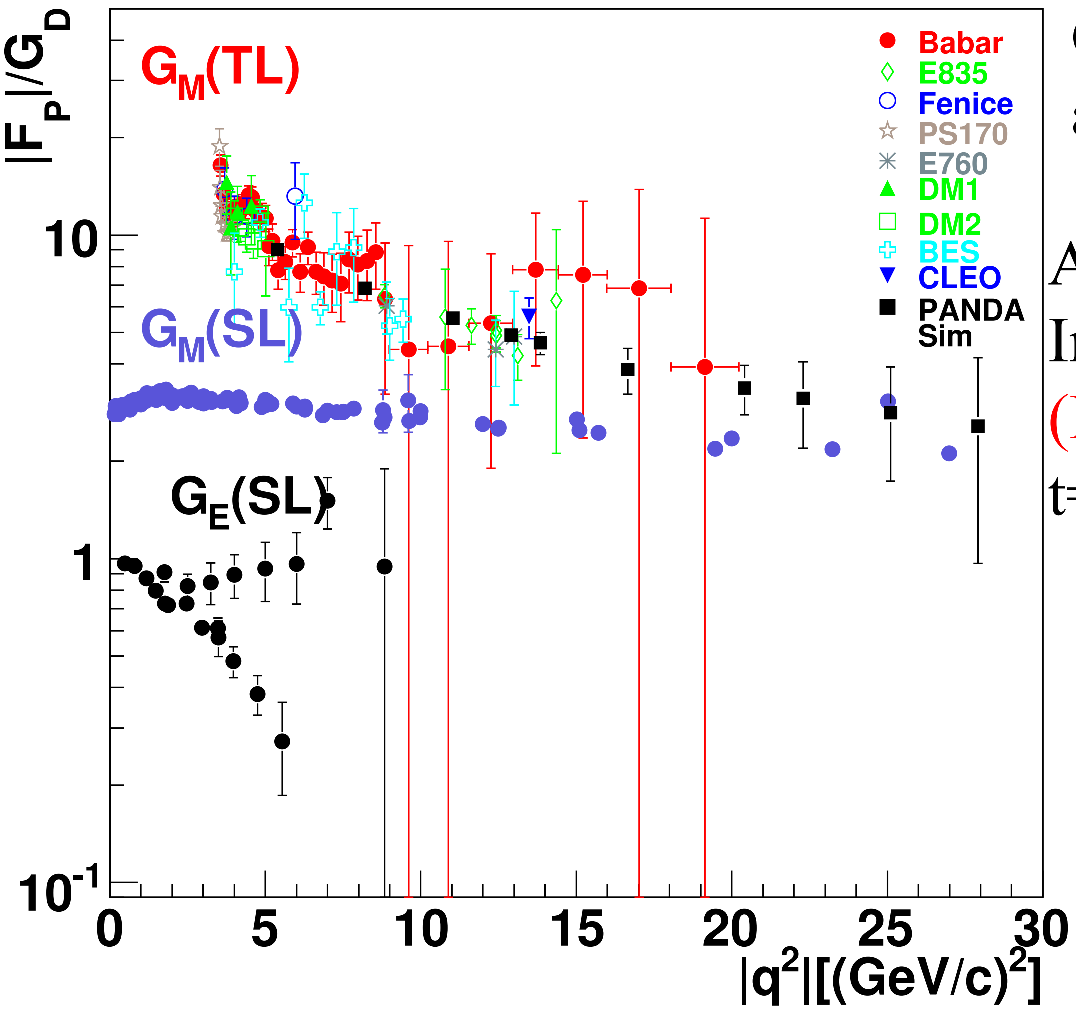
$$\mathcal{F} = |Im(F_2/F_1)|/|Re(F_2/F_1)| = \Delta$$

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

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

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

Phragmèn-Lindelöf theorem



Connection with QCD asymptotics?

Applies to NN and $\overline{N}N$ Interaction

(Pomeranchuk theorem)

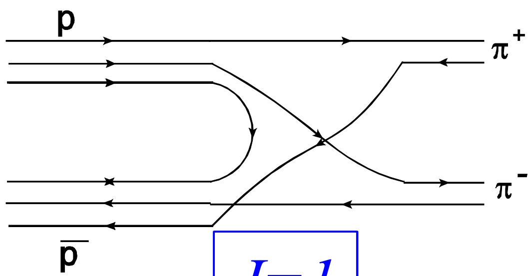
t=0 : not a QCD regime!

E. T-G. and M. P. Rekalo, Phys. Lett. B 504, 291 (2001)
E. T-G. e-Print: ***arXiv:0907.4442*** *[nucl-th]*

Exclusive processes: hadronic ratios

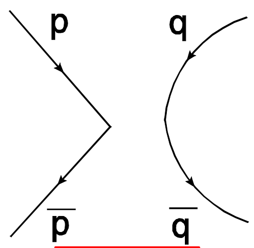
$$R_s = \frac{(p\bar{p})_{\mathcal{J}=0} \to K\bar{K}}{(p\bar{p})_{\mathcal{J}=0} \to \pi^+\pi^-}, \quad R_p = \frac{(p\bar{p})_{\mathcal{J}=1} \to K\bar{K}}{(p\bar{p})_{\mathcal{J}=1} \to \pi^+\pi^-}$$

Threshold region (L=0): $R_p \ll R_S \simeq 1$



J=1

Quark rearrangement



J=0

Excited vacuum

$$\frac{Y_{KK}}{Y_{\pi\pi}} = \frac{1/2}{3+1/2}\frac{\beta_K}{\beta_\pi}\left(\frac{\beta_s}{\beta_u}\right)^2 = 0.108$$

Experimental value at LEAR:

$$R = f(K^+K^-)/f(\pi^+\pi^-) = 0.108 \pm 0.007.$$

E.A. Kuraev, E.T-G, PRD 81,017501 (2010)

Conclusions

- Comparison of *scattering* and *annihilation* channels: model independent statements

- Study of the *validity of one photon exchange approximation:* basic question for deriving information on the hadron structure *: in annihilation processes all FFs information is contained in a precise measurement of the angular distribution.*

- Determination of time-like form factors up to large q2
  Tests of validity of pQCD and analiticity.

Polarization observables?

- *basic program with anti-proton beams:*
  Panda Physics Performance Report
  e-Print: **arXiv:0903.3905** [hep-ex]

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:

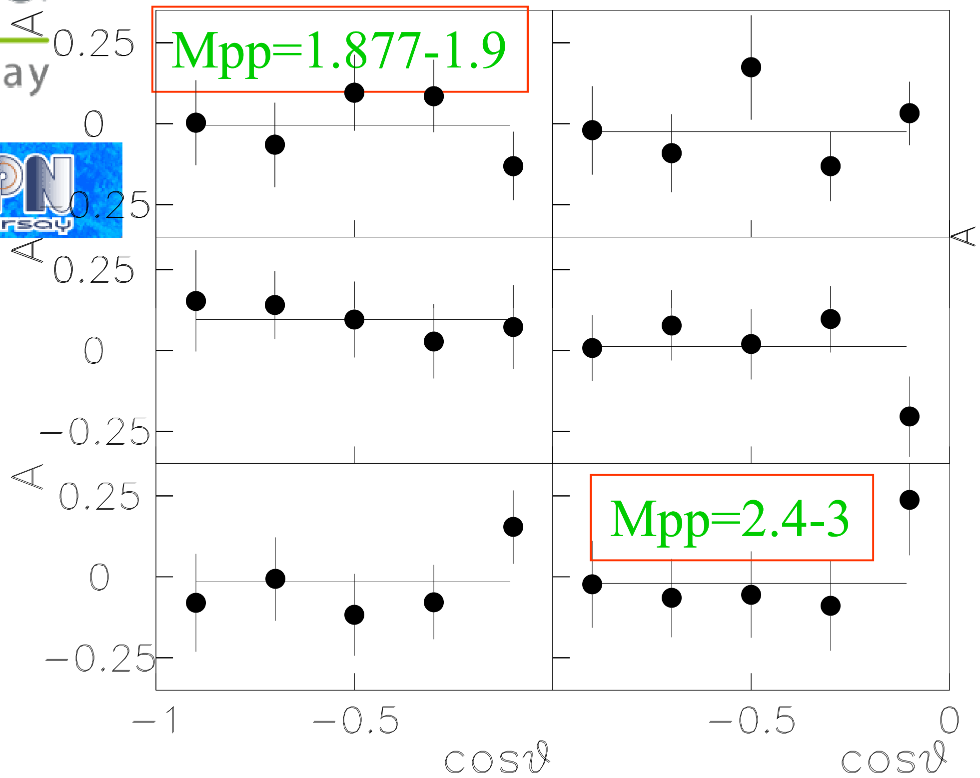
$$\frac{d\sigma_-}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi-\theta) = 4N\Big[(1+x^2)ReG_M\Delta G_M^* + \frac{1-x^2}{\tau}ReG_E\Delta G_E^* + \sqrt{\tau(\tau-1)}x(1-x^2)Re(\frac{1}{\tau}G_E - G_M)F_3^*\Big]$$

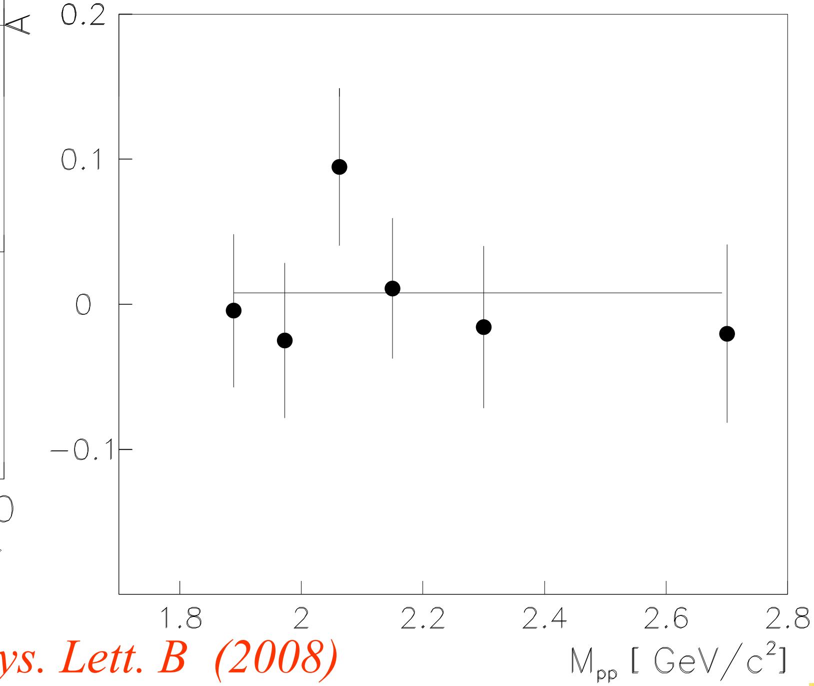
$$\tau = \frac{q^2}{4m^2}, \quad x = cos\theta$$

BABAR

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

A=0.01±0.02





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

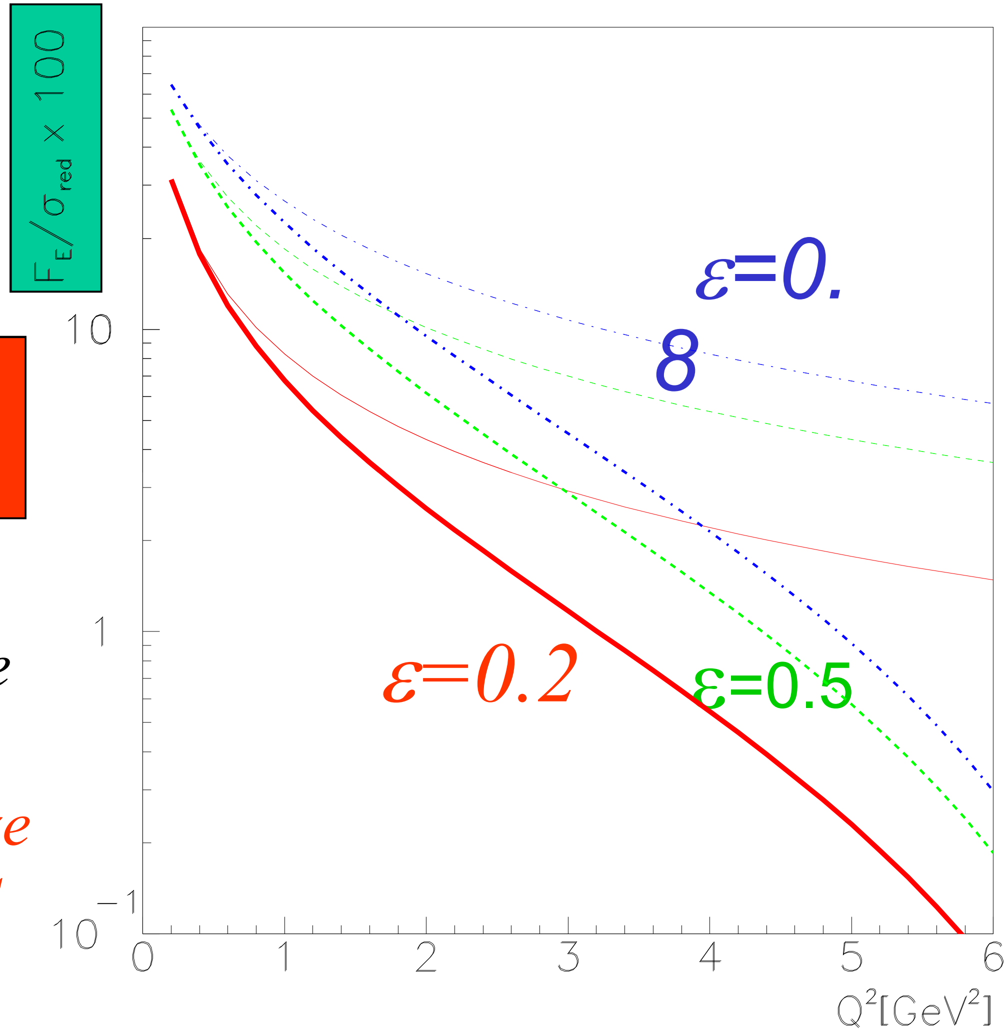
Rosenbluth separation

Contribution of the electric term

$$\epsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta_e}{2}},$$

$$\tau = \frac{q^2}{4m^2}$$

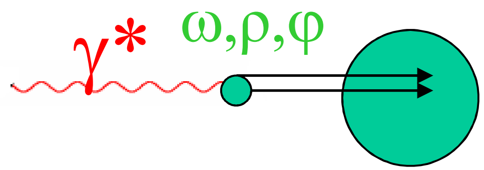
$$\sigma_{red} = \tau G_{Mp}^2 + \boxed{\epsilon G_{Ep}^2}$$



…to be compared to the absolute value of the error on σ and to the size and ε dependence of RC

Iachello, Jakson and Landé (1973)

Isoscalar and isovector FFs



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

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

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

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

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

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

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

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