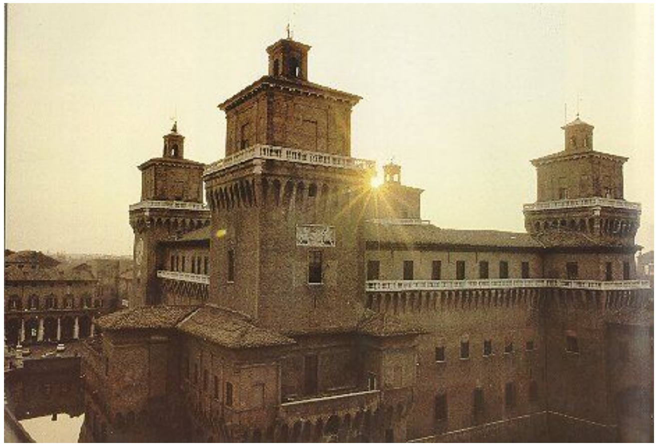
HADRON STRUCTURE and RADIATIVE CORRECTIONS

Egle Tomasi-Gustafsson
Saclay, France



Nucleon Structure at FAIR, Ferrara, 15 –X – 2007

PLAN

Experimental View and Models

- *space-like (ep-scattering)*
- *time-like (e+e- or ppbar annihilation)*

Model Independent Statements

- *Symmetry properties of fundamental interactions*
- *Kinematical constraints*

Exact Calculations ?

- *QED 'exact' calculations*
- *Radiative corrections*

Nucleon Structure and/or Reaction Mechanism?

Hadron Electromagnetic Form factors

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- Characterize the internal structure of a particle (≠ point-like)
- 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.
- Elastic form factors contain information on the hadron ground state.
- Playground for theory and experiment.
- New interest due to polarization data

Space-like and time-like regions

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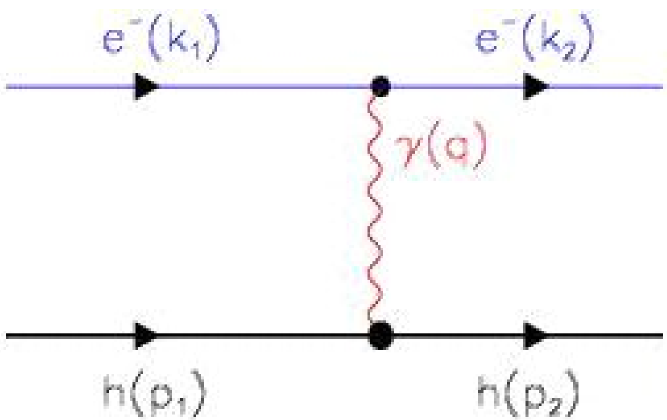
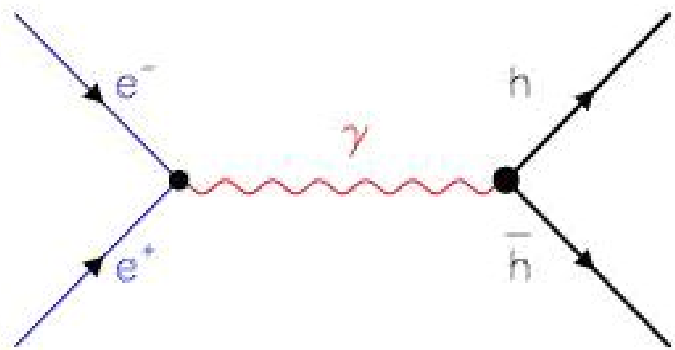
- FFs are analytical functions.
- In framework of one photon exchange, FFs are functions of the momentum transfer squared of the virtual photon, $t = q^2 = -Q^2$.

$t<0$ $t>0$

Scatterin





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

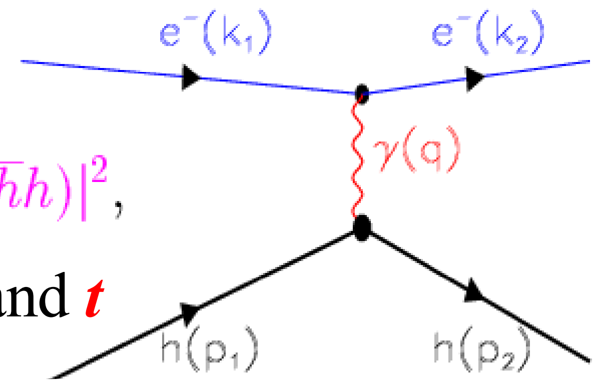
Form factors are *real in the space-like region*

and *complex in the time-like region*.

Crossing Symmetry

$e^- + h \rightarrow e^- + h$

Scattering and annihilation channels:



- 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***

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

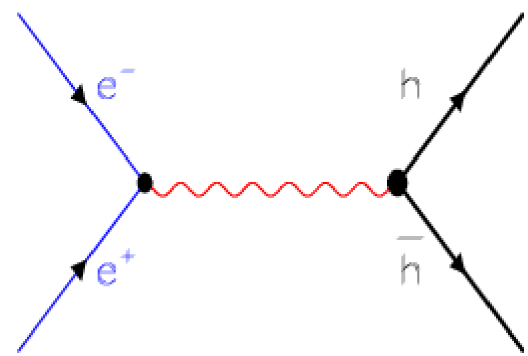
$e^- + e^+ \rightarrow \overline{h} + h$

- which scan different kinematical regions

$$k_2 \longrightarrow -k_2$$

$$p_2 \longrightarrow -p_1$$

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

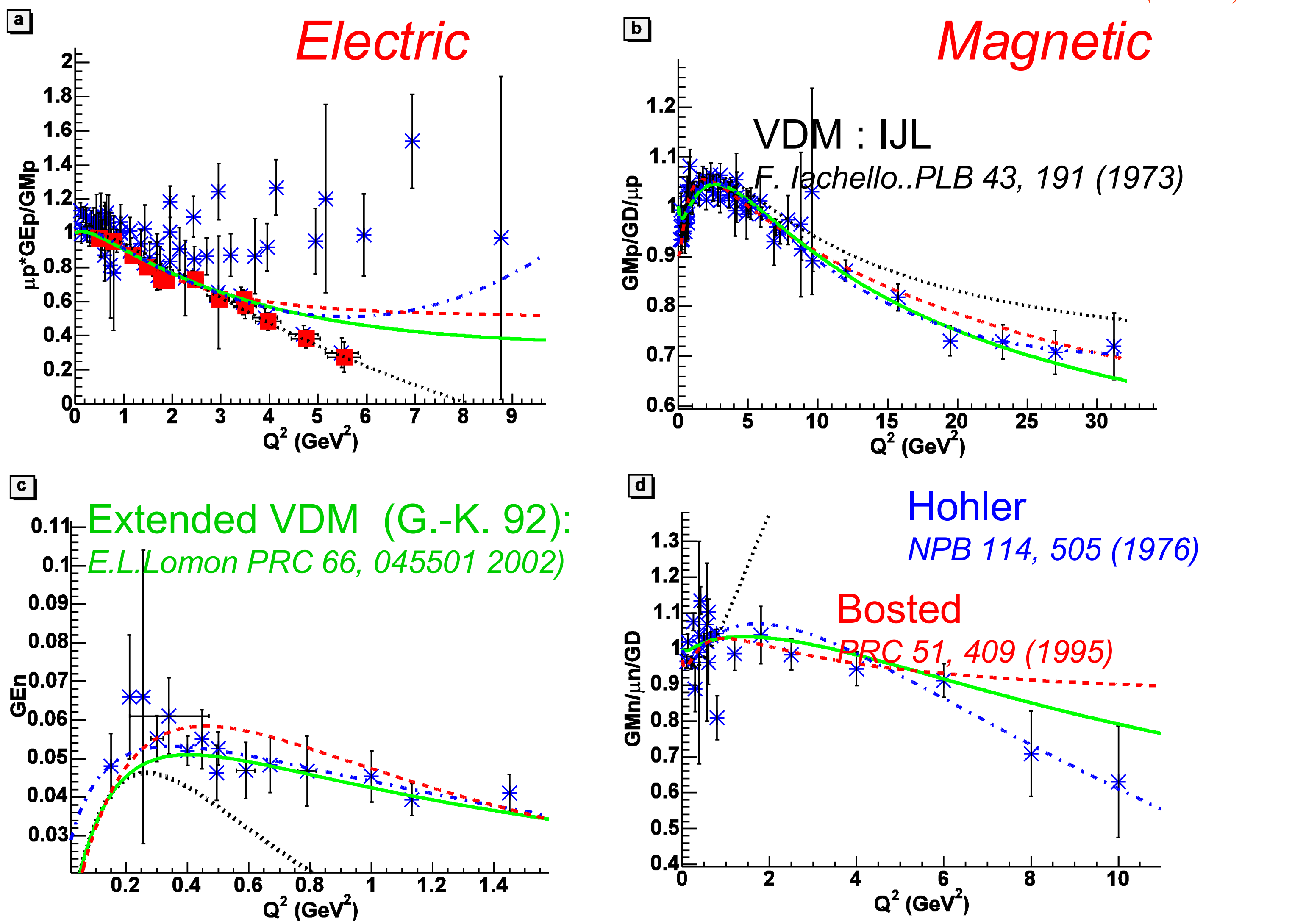


The nucleon form factors

E. T.-G., F. Lacroix, Ch. Duterte, G.I. Gakh, EPJA 24, 419 (2005)

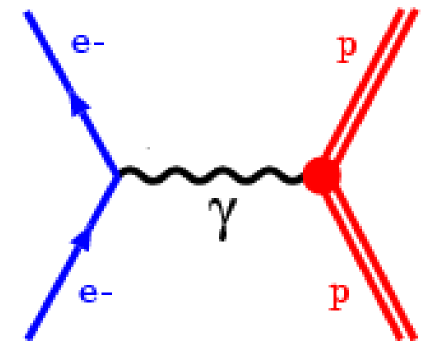
proton

neutron



The Rosenbluth separation (1950)

- Elastic ***ep*** cross section (1-γ exchange)

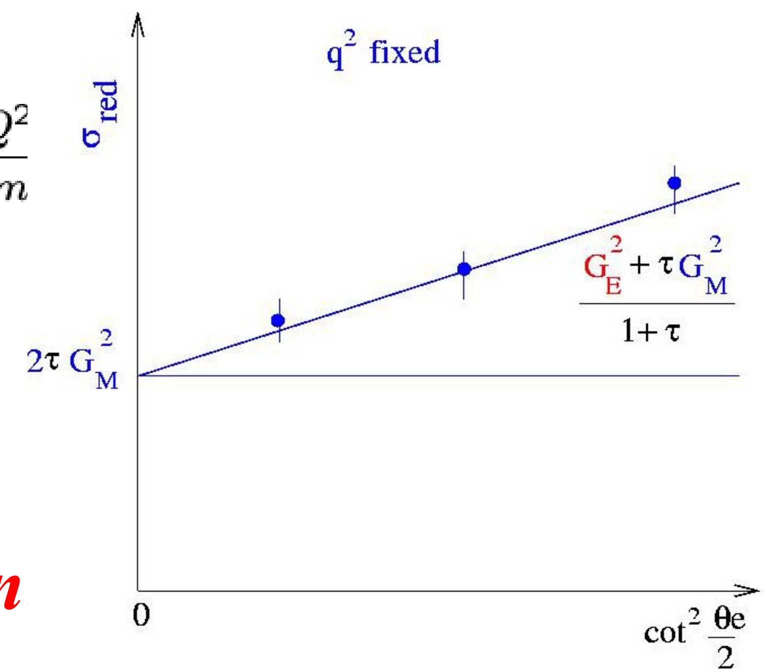


$$\frac{d\sigma}{d\Omega_e} = \sigma_M \left[2\tau G_M^2 \tan^2\frac{\theta_e}{2} + \frac{G_E^2 + \tau G_M^2}{1+\tau} \right]$$

- point-like particle: σ Mott

$$\sigma_M = \frac{4\alpha^2}{(-q^2)^2}\frac{\epsilon_2^3}{\epsilon_1}\cos^2\frac{\theta_e}{2} = \frac{4\alpha^2}{(-q^2)^2}\frac{\epsilon_2^2\cos^2\frac{\theta_e}{2}}{1+2\frac{\epsilon_1}{m}\sin^2\frac{\theta_e}{2}}, \ \tau = \frac{Q^2}{4m}$$

$$\sigma_{red} = \frac{\frac{d\sigma}{d\Omega_e}}{\frac{\alpha^2}{-q^2}\left(\frac{\epsilon_2}{\epsilon_1}\right)^2}$$



*Linearity of the **reduced cross section***

The polarization method (1967)

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

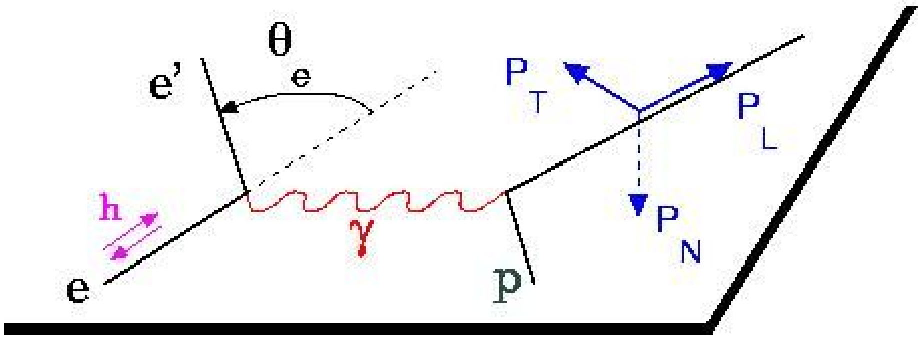
PHYSICS

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

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



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 RESULTS

Linear deviation from dipole

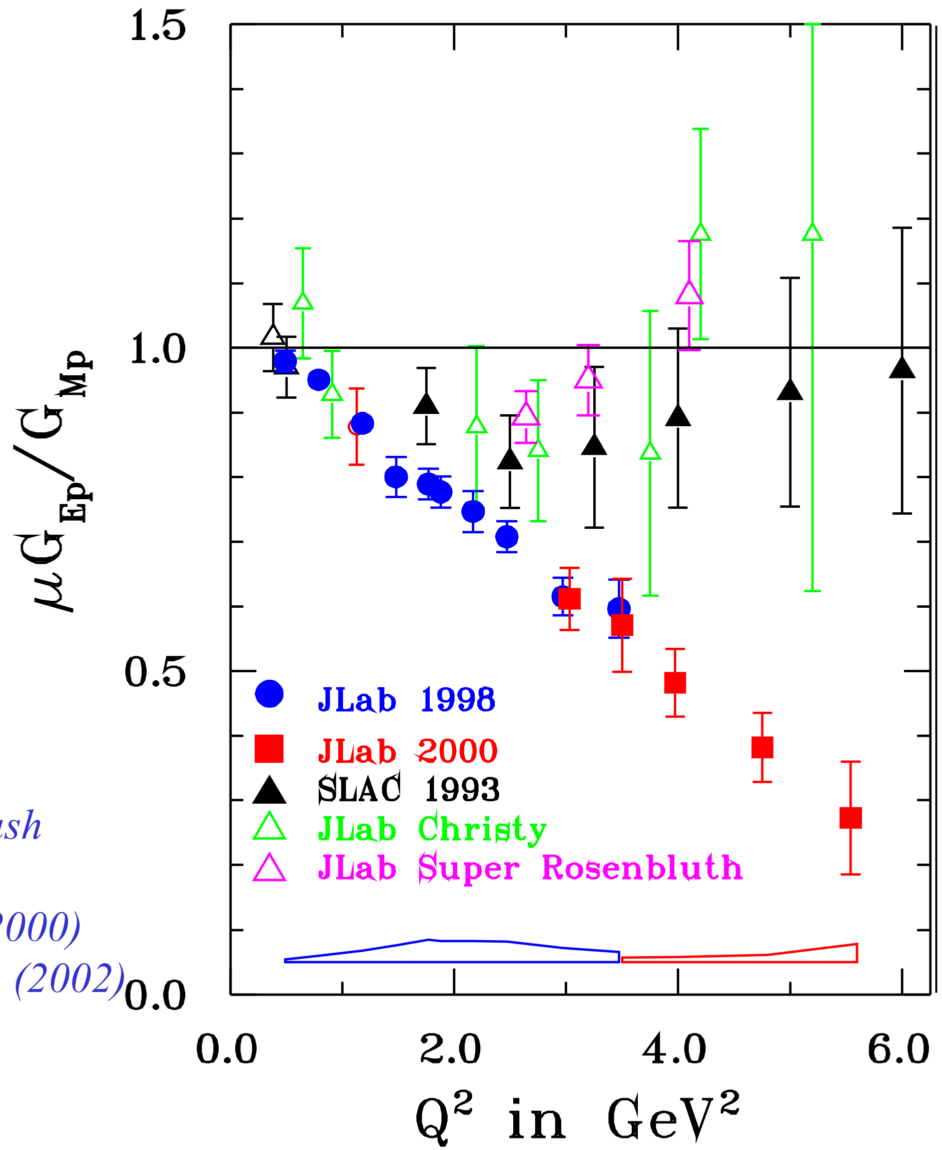
$\mu G_{Ep} \neq G_{Mp}$

Jlab E93-027 , E99-007

Spokepersons:

Ch. Perdrisat, V. Punjabi, M. Jones, E. Brash

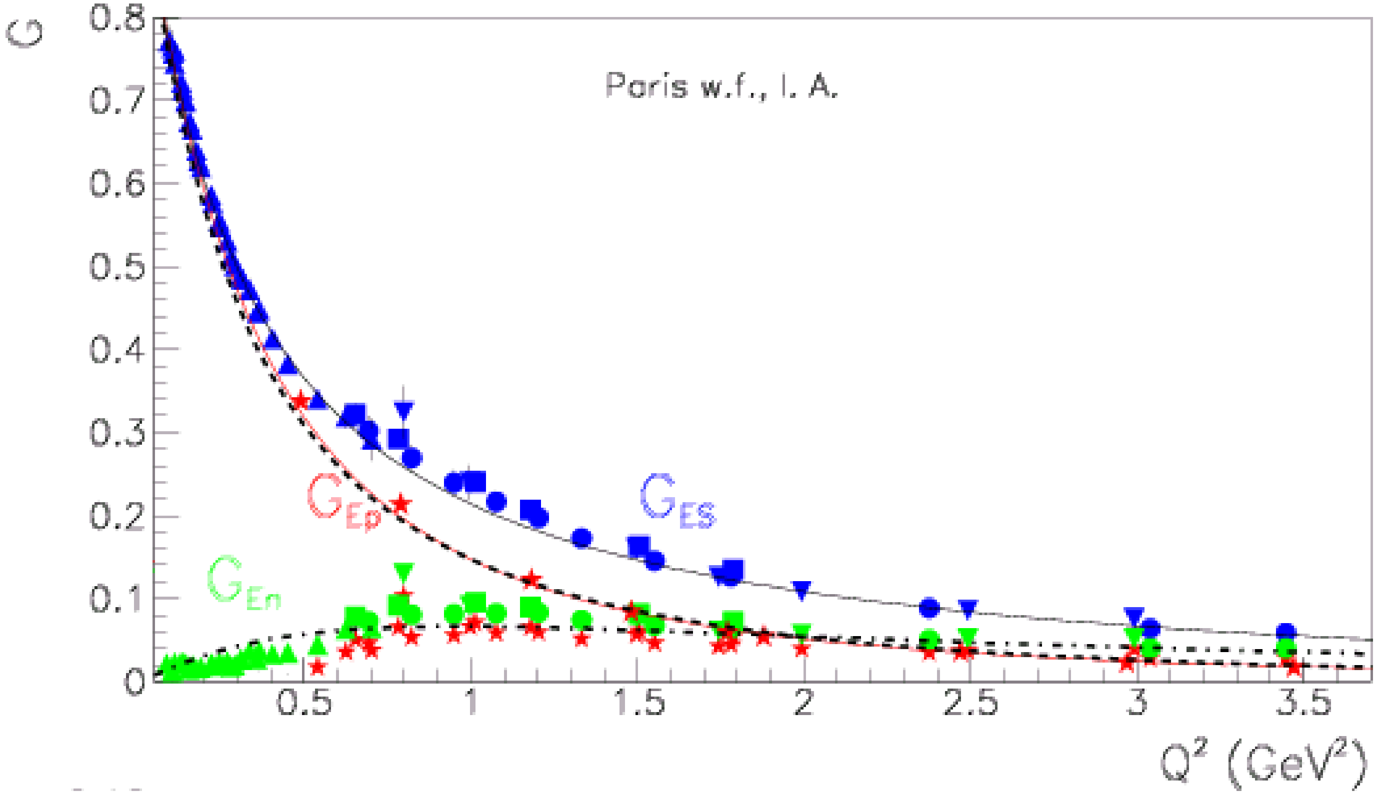
M. Jones et al., Phys. Rev. Lett. 84,1398 (2000)
O. Gayou et al., Phys. Rev. Lett. 88,092301 (2002)
V. Punjabi et al., Phys. Rev. C (2006)



Electric NEUTRON Form Factor

Smaller than for proton, but not so small

New results, also based on polarization method



E. T-G. and M. P. Rekalo, Europhys. Lett. 55, 188 (2001)

STATUS on EM Form factors

Space-like region

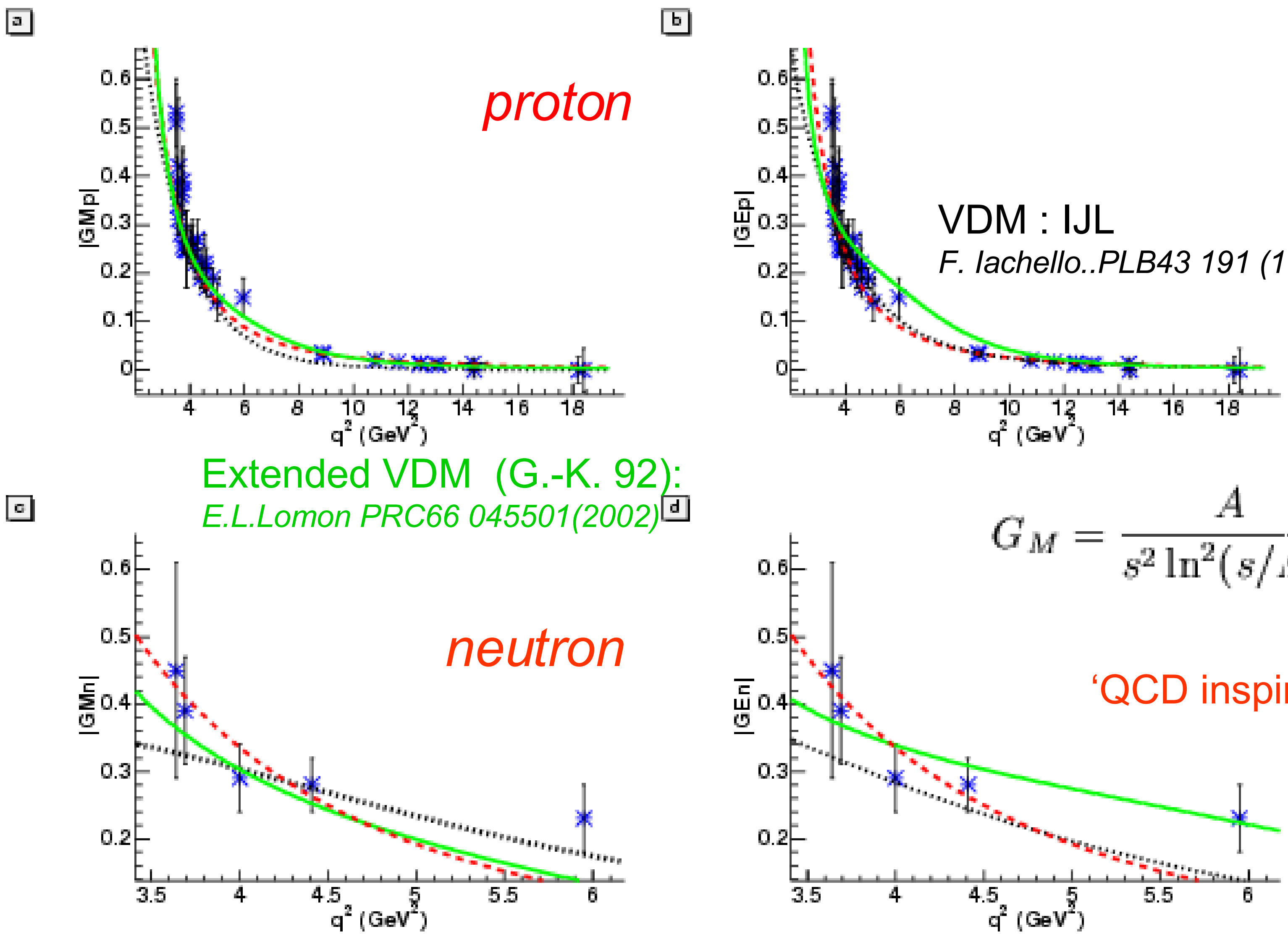
3) "standard" dipole function for the nucleon magnetic FFs GMp and GMn

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

3) *contradiction between polarized and unpolarized measurements*

4) non vanishing electric neutron FF, GEn.

Time-Like Region



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

E. T-G., F. Lacroix, C. Duterte, G.I. Gakh, EPJA 24, 419 (2005)

STATUS on EM Form factors

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Time-like region

4) No individual determination of GE and GM

5) Assume GE=GM (valid only at threshold) VMD or pQCD inspi
parametrizations (for p and n):

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

- A(p) = 56.3 GeV^4
- A(n) = 77.15 GeV^4

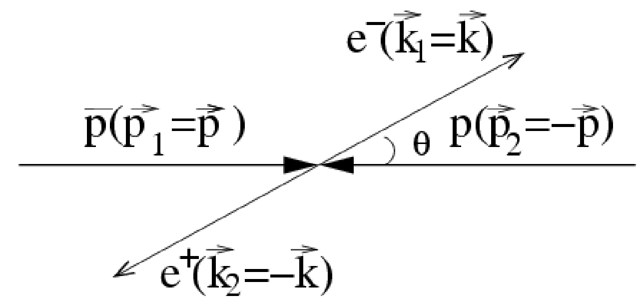
Λ=0.3 GeV is the QCD scale parameter

3) TL nucleon FFs are twice larger than SL FFs

4) Recent data from Babar (radiative return) :
   - interesting structures in the Q^2 dependence of GM(=GE)
   - GM≠GE.

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)

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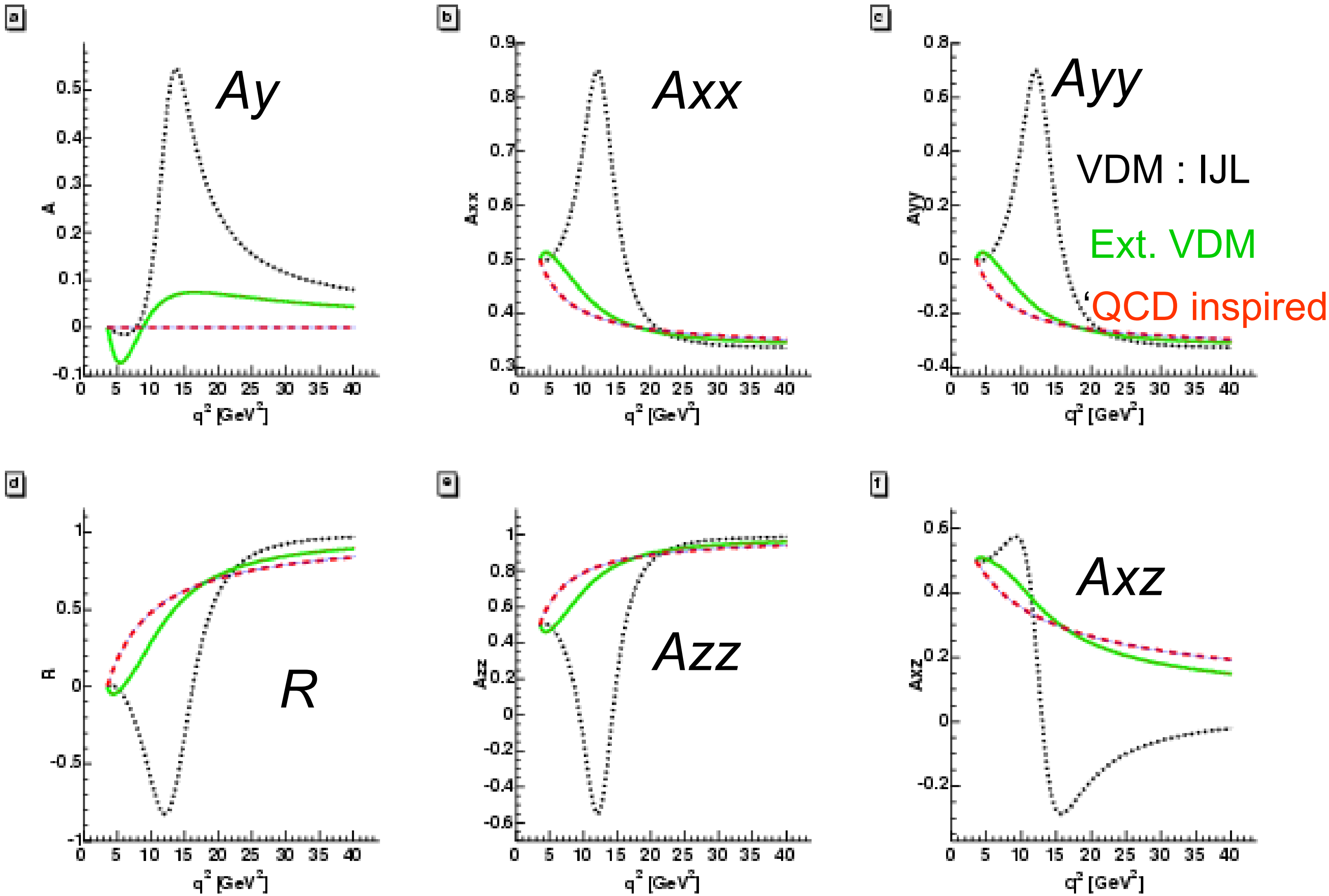
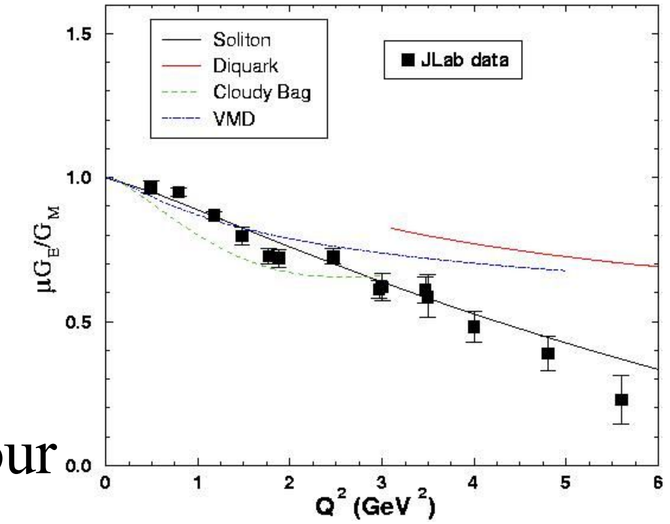


E. T-G., F. Lacroix, C. Duterte, G.I. Gakh, EPJA 24, 419(2005)

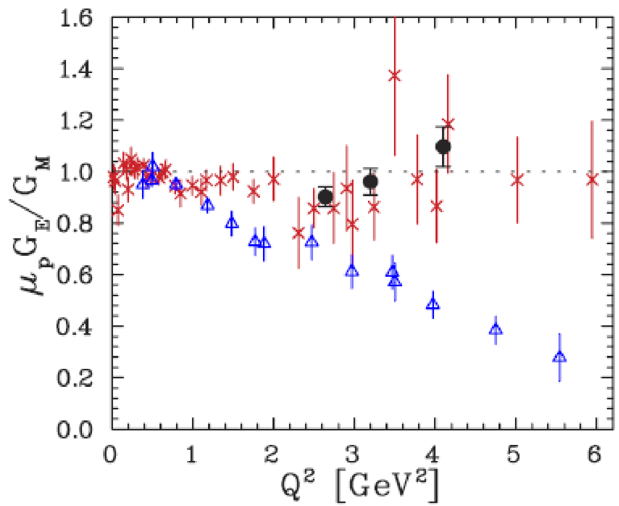
Issues

- 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



Perspectives in Time-Like region

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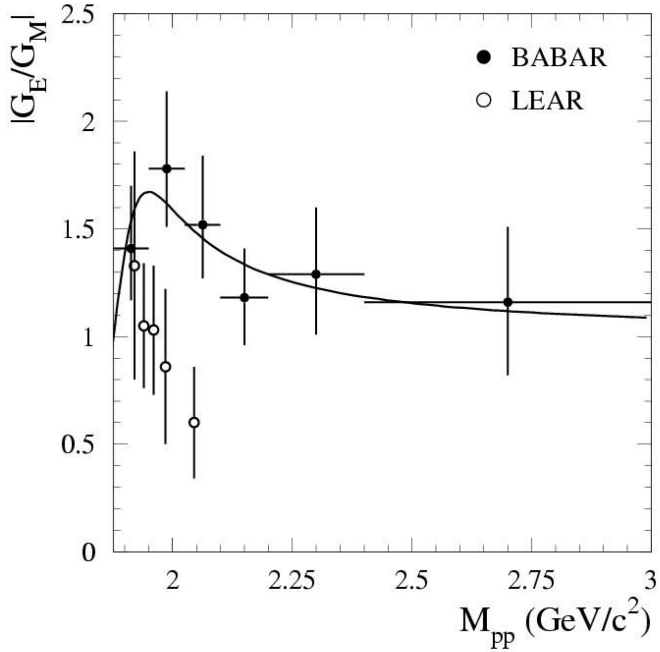
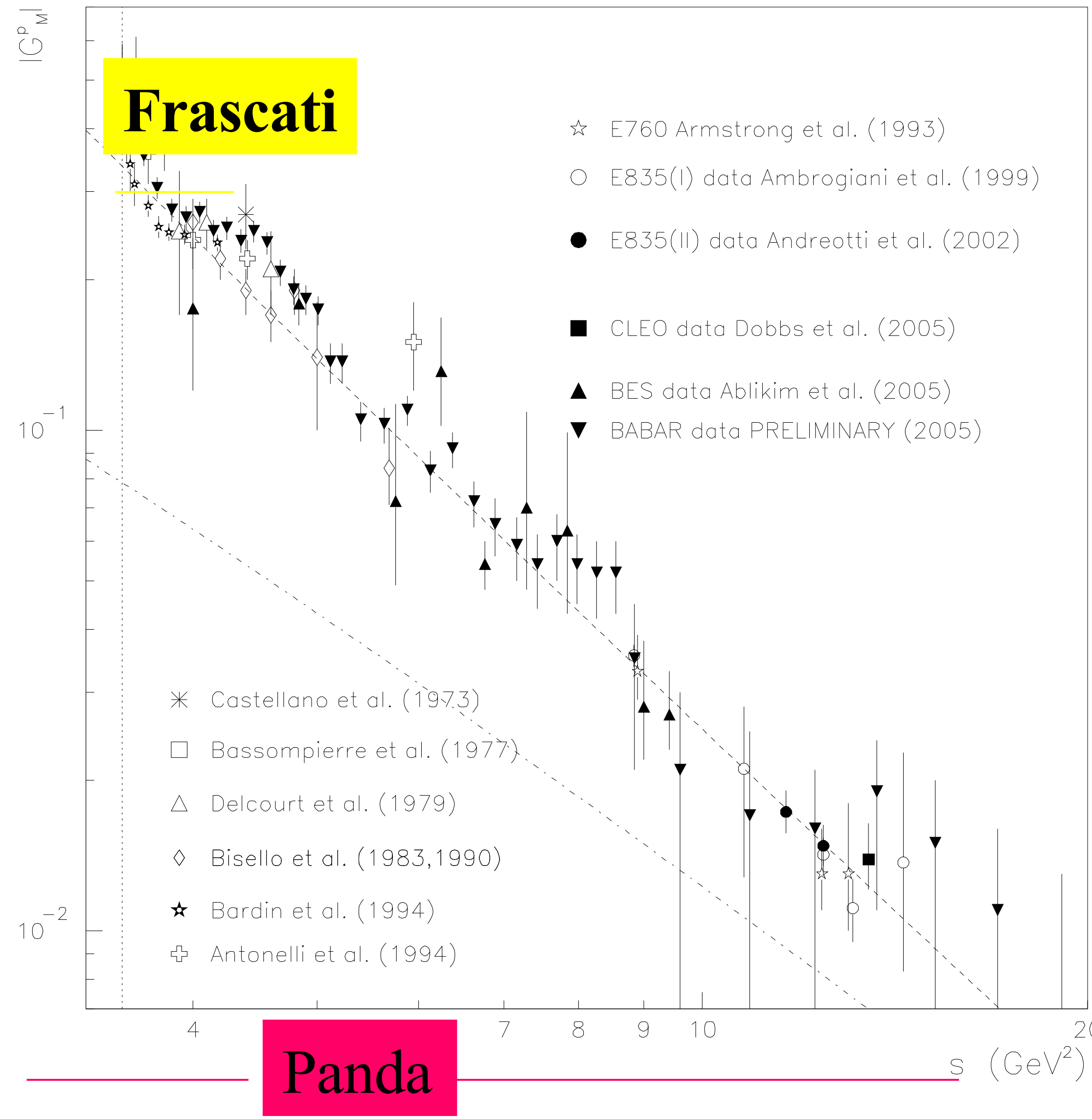
$$G_E = G_M\ ?$$





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

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-The cross section for $\overline{p}+p\rightarrow e^+ + e^-$ (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!

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

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-The Total Cross Section

$$\sigma(q^2) = \mathcal{N}\frac{8}{3}\pi\left[2|G_M|^2 + \frac{1}{\tau}|G_E|^2\right], \quad \mathcal{N} = \frac{\alpha^2}{4\sqrt{q^2(q^2-4m^2)}}$$

-The angular asymmetry, R

$$\frac{d\sigma}{d(\cos\theta)} = \sigma_0\left[1+\mathcal{R}\cos^2\theta\right], \quad \mathcal{R} = \frac{\tau|G_M|^2-|G_E|^2}{\tau|G_M|^2+|G_E|^2}$$

Cross section at 90^0

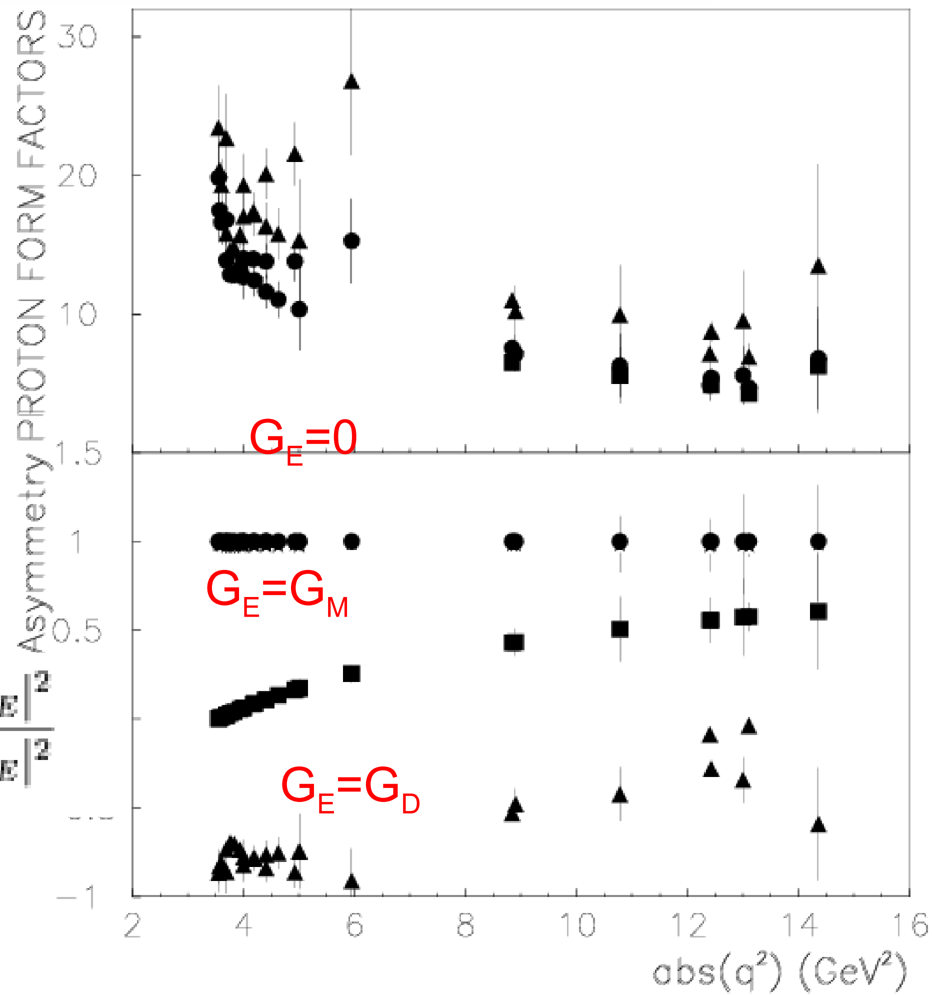
Due to limited statistics, no experimental determination of individual FFs in TL region, yet: $G_E=G_M$ or $G_E=0$

Time-Like Region

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

$| G_M |^2$

Asym



$$\frac{d\sigma}{d(\cos\theta)} = \sigma_0\left[1+\mathcal{R}\cos^2\theta\right], \ \mathcal{R} = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2}$$

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

Predictions for PANDA

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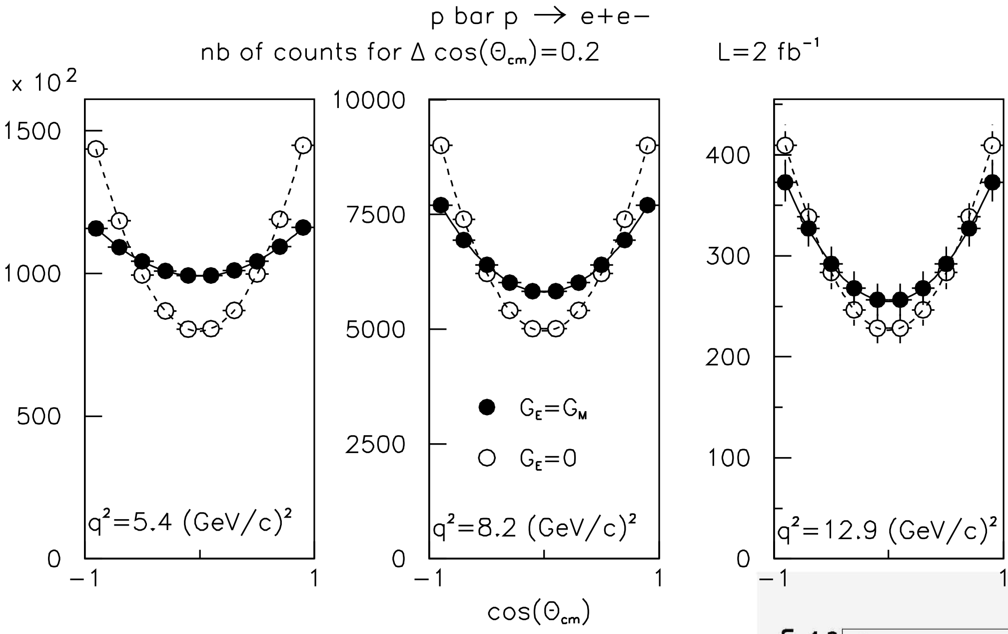
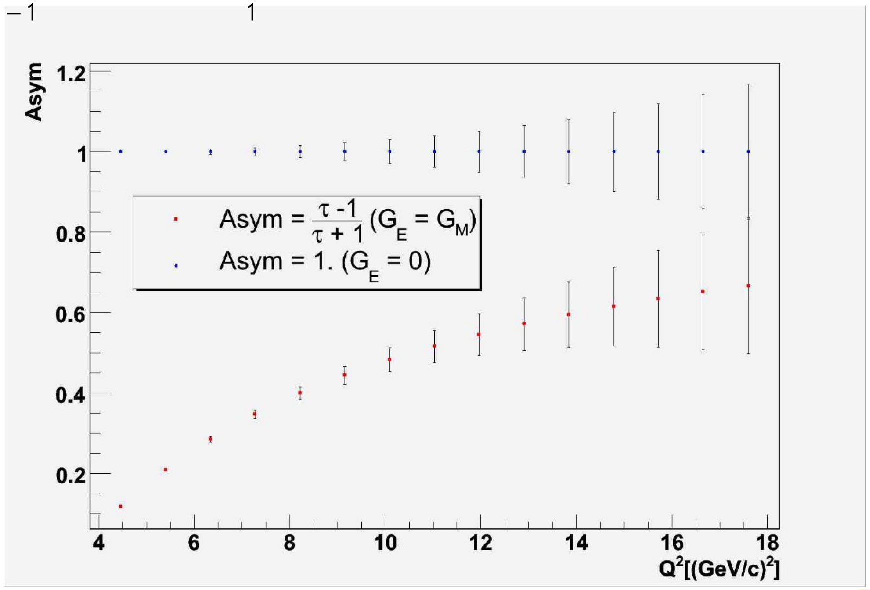
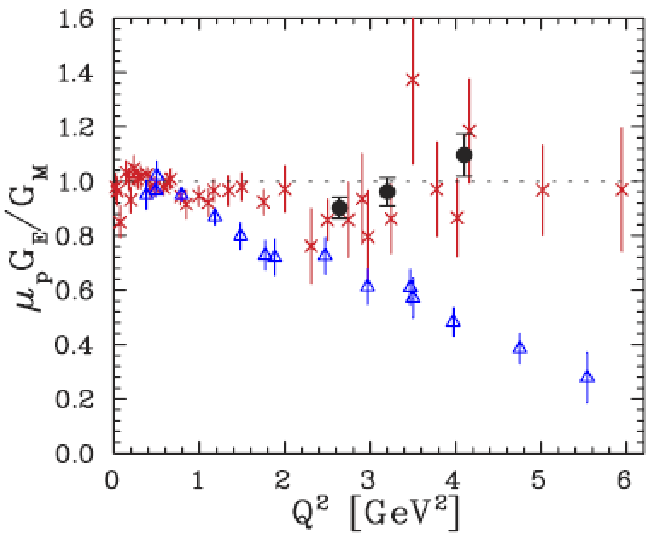




B. Ramstein, D. Marchand …

Two-photon exchange?

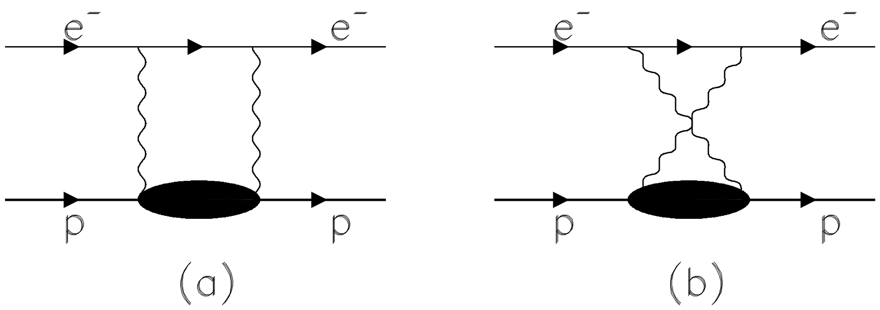
<u>Electric proton FF</u>



Different results with different experimental methods !!

- Both methods based on the same formalism
- Experiments repeated

New mechanism?



- 1γ-$2\gamma \sim \alpha=e^2/4\pi=1/137$
- 1970's: Gunion, Lev…

Two-Photon exchange

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- 1γ-2γ interference is of the order of $\alpha=e^2/4\pi=1/137$ (in usual calculations of radiative corrections, one photon is 'hard' and one is 'soft')

- In the 70's it was shown [*J. Gunion and L. Stodolsky, V. Franco, F.M. Lev, V.N. Boitsov, L. Kondratyuk and V.B. Kopeliovich, R. Blankenbecker and J. Gunion*] that, at large momentum transfer, due to the sharp decrease of the FFs, if the momentum is shared between the two photons, the 2 γ– contribution can become very large.

1γ-2γ interference

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

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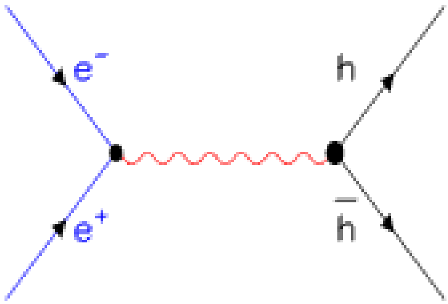

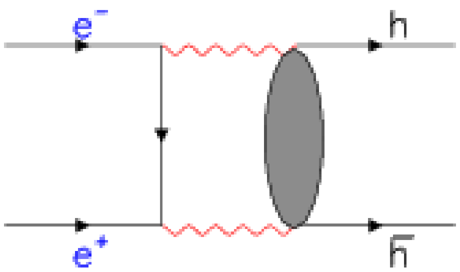

$C(\gamma)=-1$

$C(2\gamma)=+1$

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

$$\overline{|\mathcal{M}_1(e^+e^-\to\bar{h}h)|^2} = a(t) + \cos^2\tilde{\theta}\, b(t) \qquad Re\mathcal{M}_1\mathcal{M}_2^* = \cos\tilde{\theta}(a_0 + a_1\cos^2\tilde{\theta} + ..)$$

1γ 2γ

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

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The 1γ-2γ interference destroys the linearity of the Rosenbluth plot!

1γ-2γ interference (e-d)

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

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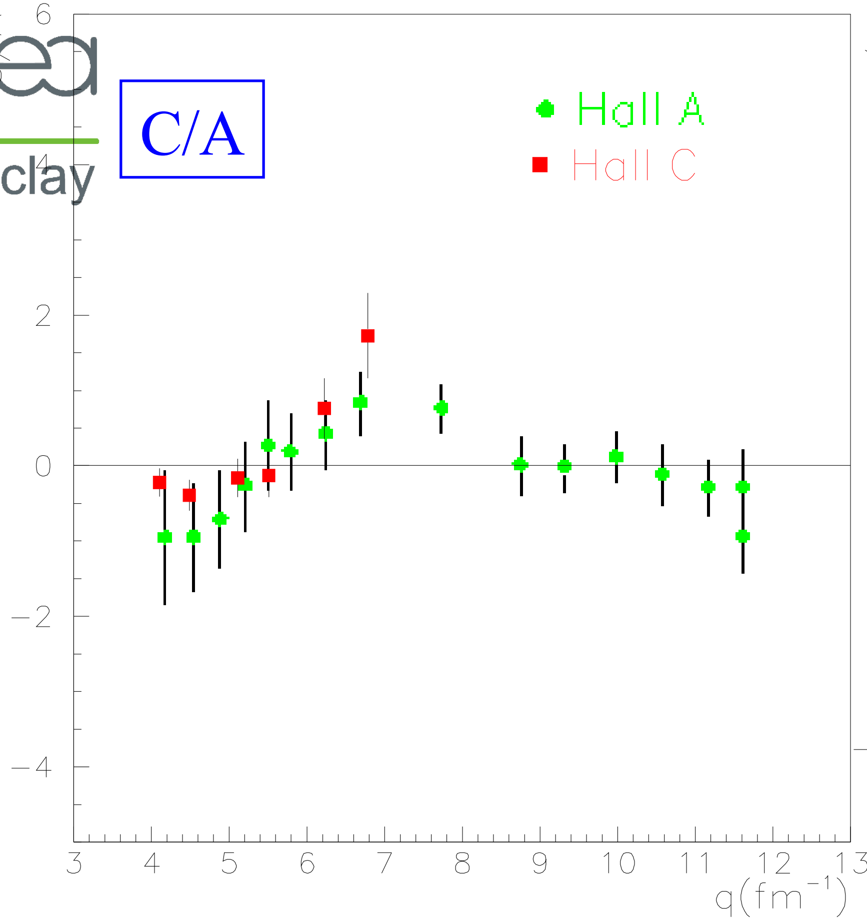
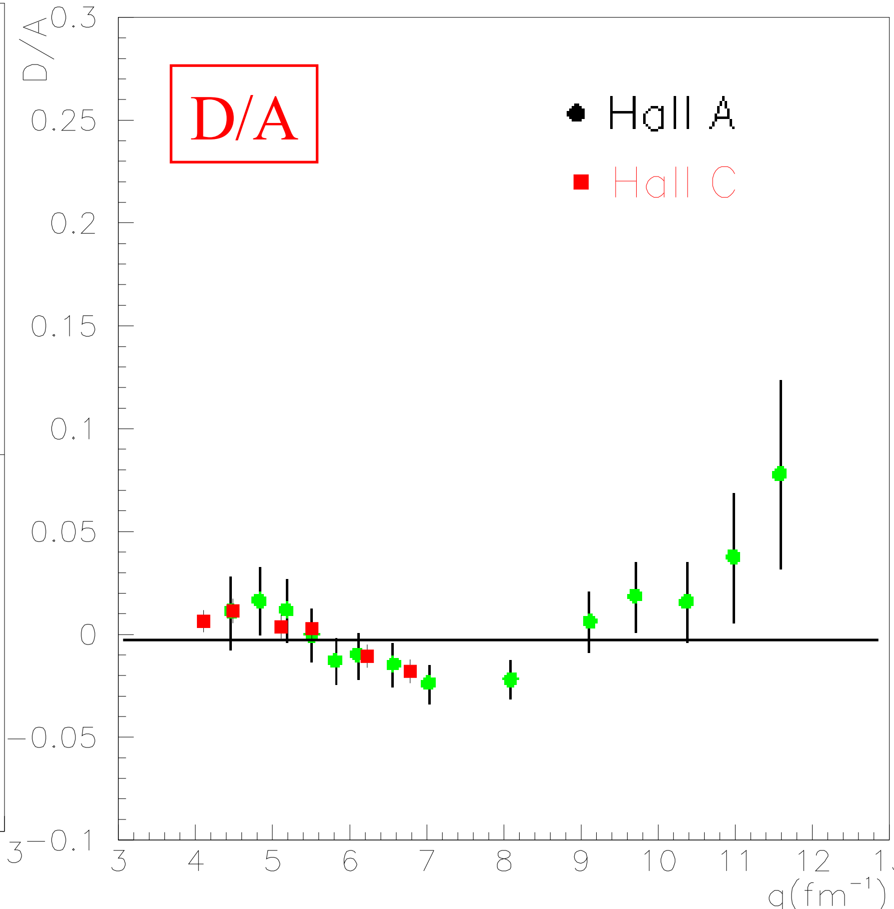


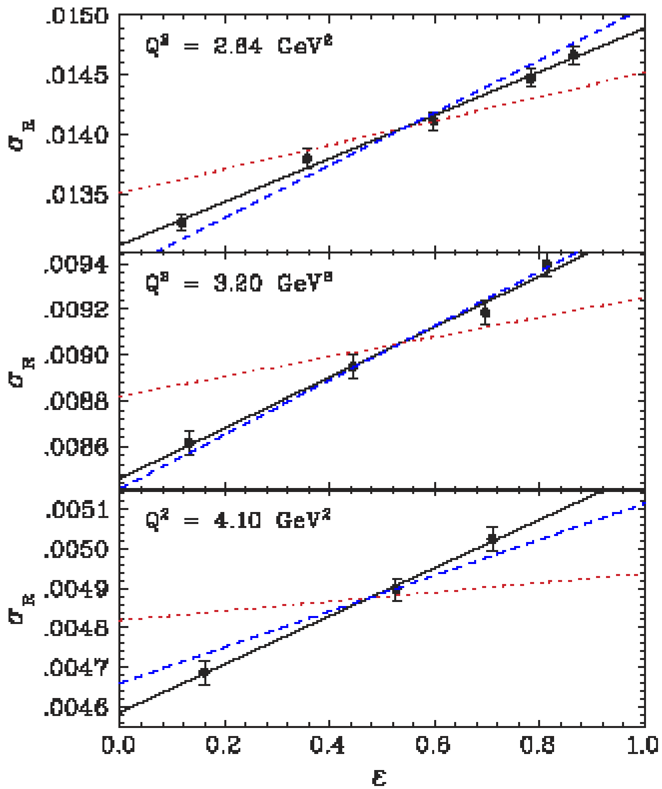


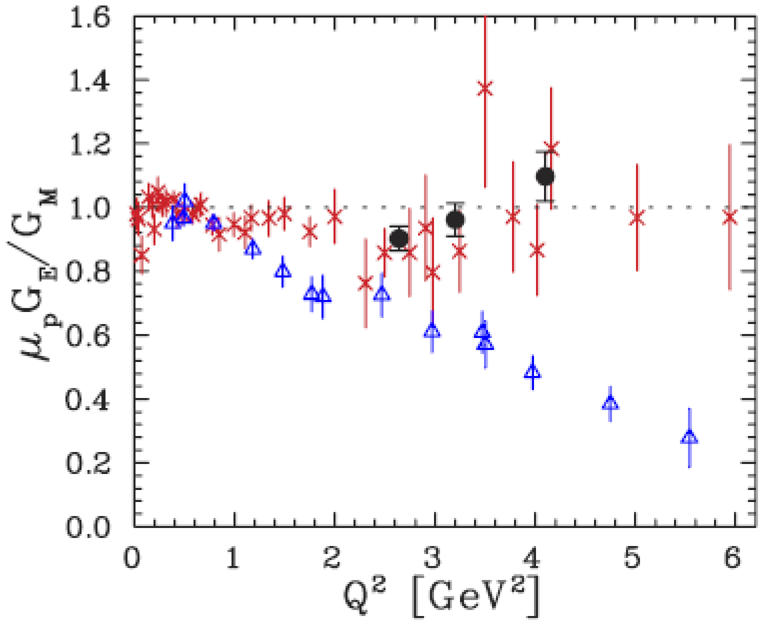
M. P. Rekalo, E. T-G and D. Prout, Phys. Rev. C60, 042202 (1999)

PRL 94, 142301 (2005) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2005

Precision Rosenbluth Measurement of the Proton Elastic Form Factors

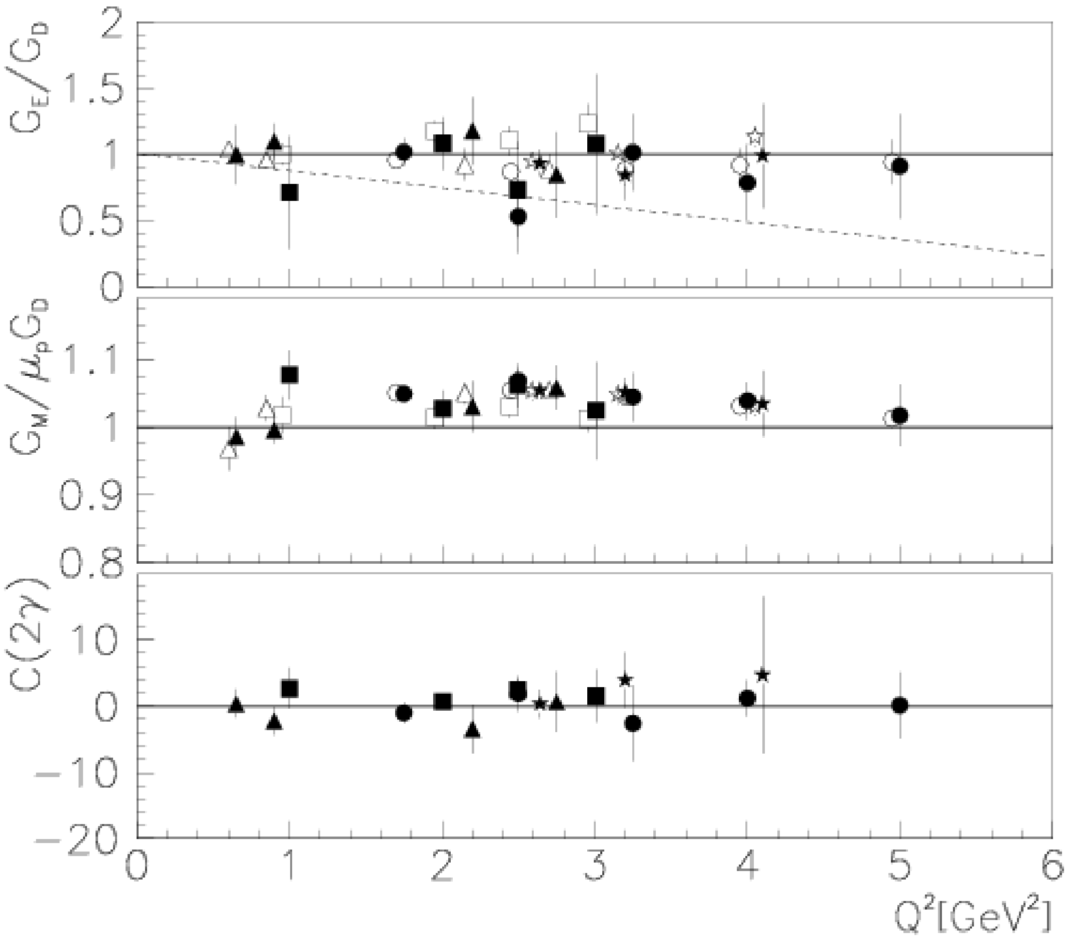
I. A. Qattan,[1,2] J. Arrington,[2] R. E. Segel,[1] X. Zheng,[2] K. Aniol,[3] O. K. Baker,[4] R. Beams,[2] E. J. Brash,[5] J. Calarco,[6] A. Camsonne,[7] J.-P. Chen,[8] M. E. Christy,[4] D. Dutta,[9] R. Ent,[8] S. Frullani,[10] D. Gaskell,[11] O. Gayou,[12] R. Gilman,[13,8] C. Glashausser,[13] K. Hafidi,[2] J.-O. Hansen,[8] D. W. Higinbotham,[8] W. Hinton,[14] R. J. Holt,[2] G. M. Huber,[5] H. Ibrahim,[14] L. Jisonna,[1] M. K. Jones,[8] C. E. Keppel,[4] E. Kinney,[11] G. J. Kumbartzki,[13] A. Lung,[8] D. J. Margaziotis,[3] K. McCormick,[13] D. Meekins,[8] R. Michaels,[8] P. Monaghan,[9] P. Moussiegt,[15] L. Pentchev,[12] C. Perdrisat,[12] V. Punjabi,[16] R. Ransome,[13] J. Reinhold,[17] B. Reitz,[8] A. Saha,[8] A. Sarty,[18] E. C. Schulte,[2] K. Slifer,[19] P. Solvignon,[19] V. Sulkosky,[12] K. Wijesooriya,[2] and B. Zeidman[2]





Parametrization of 2γ-contribution for e+p

$$\sigma^{red}(Q^2,\epsilon)=\epsilon G_E^2(Q^2)+\tau G_M^2(Q^2)+\alpha F(Q^2,\epsilon),$$



$$F(Q^2,\varepsilon)\rightarrow\sqrt{\frac{1+\varepsilon}{1-\varepsilon}}f^{(a)}(Q^2)$$

$$f^{(a)}(Q^2)=\frac{C_{2\gamma}G_D}{[1+Q^2[GeV]^2/m_a^2]^2}$$

From the data:
deviation from linearity
<< 1%!

E. T.-G., G. Gakh, Phys. Rev. C (2005)

Two-Photon exchange

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- The 2γ amplitude is expected to be mostly imaginary.
- In this case, the 1γ-2γ interference is more important in time-like region, as the Born amplitude is complex.

Unpolarized cross section

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$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4q^2}\sqrt{\frac{\tau}{\tau-1}}D,$$

$$D = (1+\cos^2\theta)(|G_M|^2 + 2ReG_M\Delta G_M^*) + \frac{1}{\tau}\sin^2\theta(|G_E|^2 + 2ReG_E\Delta G_E^*) +$$
$$2\sqrt{\tau(\tau-1)}\cos\theta\sin^2\theta Re(\frac{1}{\tau}G_E - G_M)F_3^*.$$

2γ–contribution:

- **Induces four new terms**
- **Odd function of *θ*:**
- **Does not contribute at *θ*=90°**

Symmetry relations

•Properties of the TPE amplitudes with respect to the transformation: cos θ = - cos θ i.e., θ → π - θ

(equivalent to non-linearity in Rosenbluth fit)

$$\Delta G_{E,M}(q^2, -cos\theta) = -\Delta G_{E,M}(q^2, cos\theta),$$
$$F_3(q^2, -cos\theta) = F_3(q^2, cos\theta)$$

•Based on these properties one can remove or single out TPE contribution

Symmetry relations

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- Differential cross section at complementary angles:

The SUM cancels the 2γ contribution:

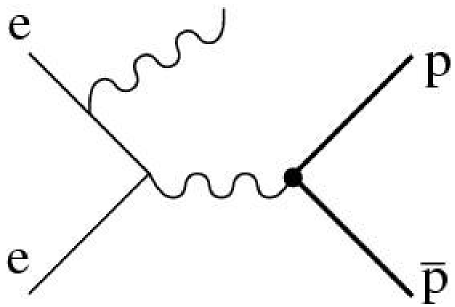
$$\frac{d\sigma_+}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi-\theta) = 2\frac{d\sigma^{Born}}{d\Omega}(\theta)$$

The DIFFERENCE enhances the 2γ contribution:

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

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

Radiative Return (ISR)



$e^+ + e^- \rightarrow p + p + \gamma$

$$\frac{d\sigma(e^+e^-\to p\bar{p}\gamma)}{dm\, d\cos\theta} = \frac{2m}{s} W(s,x,\theta)\,\sigma(e^+e^-\to p\bar{p})(m),\quad x=\frac{2E_\gamma}{\sqrt{s}} = 1-\frac{m^2}{s},$$

$$W(s,x,\theta)=\frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta}-\frac{x^2}{2}\right),\quad \theta>>\frac{m_e}{\sqrt{s}}.$$

Structure Function method

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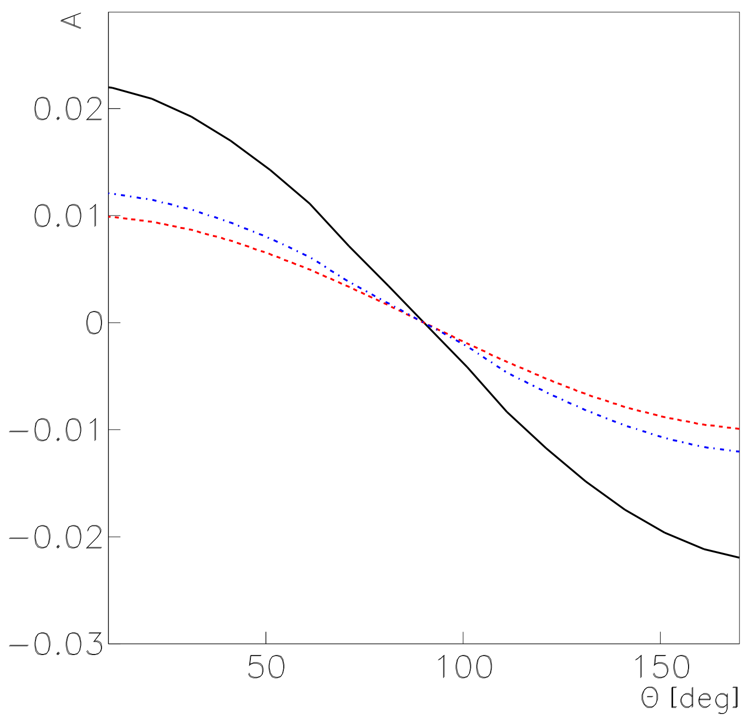
$$e^+ + e^- \to p + p + \gamma$$



$$A^{soft}(E) \simeq \frac{2\alpha}{\pi}\left(\ln\frac{1+\beta c}{1-\beta c}\ln\frac{\Delta E}{E}\right)$$

$$A^{tot} = A^{soft} + A^{hard} = \frac{2\alpha}{\pi}\psi(c,\beta),\ \ |A^{tot}| \leq 2\%,$$

$$\frac{d\sigma}{d\Omega}(c) \pm \frac{d\sigma}{d\Omega}(-c) \sim \int dx_1 \mathcal{D}(x_1,L)\mathcal{D}(x_2,L)dx_2\left(1+\frac{\alpha}{\pi}K\right)$$

$$\frac{d\sigma}{d\Omega}(c) + \frac{d\sigma}{d\Omega}(-c) = 2\frac{d\sigma_0}{d\Omega}\left[1+\frac{\alpha}{\pi}\left(\frac{3}{2}L - 2(L-1)\ln\frac{\Delta E}{E} + \frac{\pi^2}{3} - 2\right)\right],\ \ L = \ln\frac{t}{m^2},$$

Angular distribution

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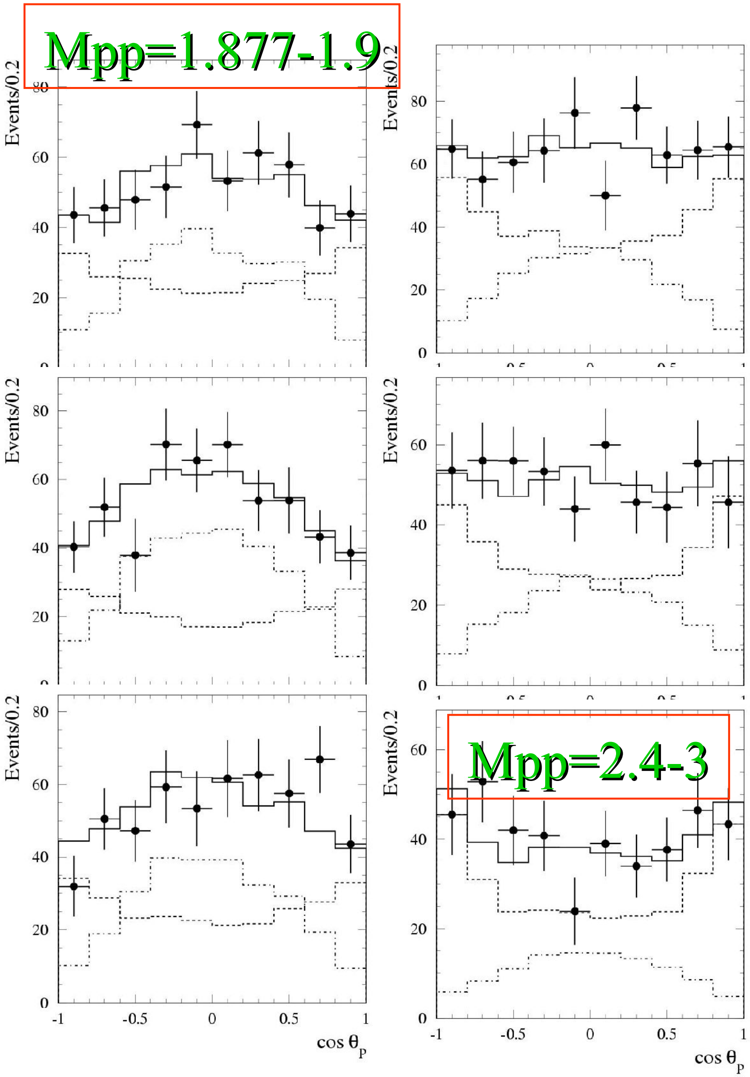

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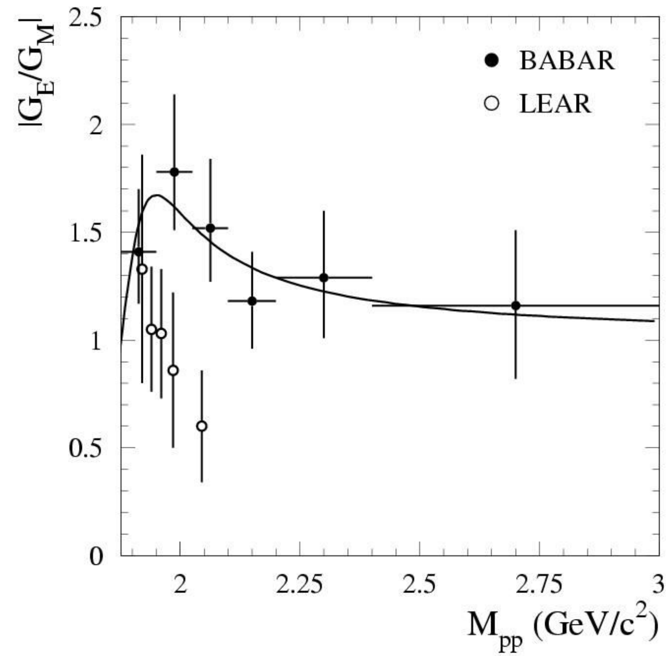
$$\frac{dN}{d\cos\theta_p} = A\left[H_M(\cos\theta, M_{p\bar{p}}) + \left|\frac{G_E}{G_M}\right|^2 H_E(\cos\theta, M_{p\bar{p}})\right]$$



BABAR

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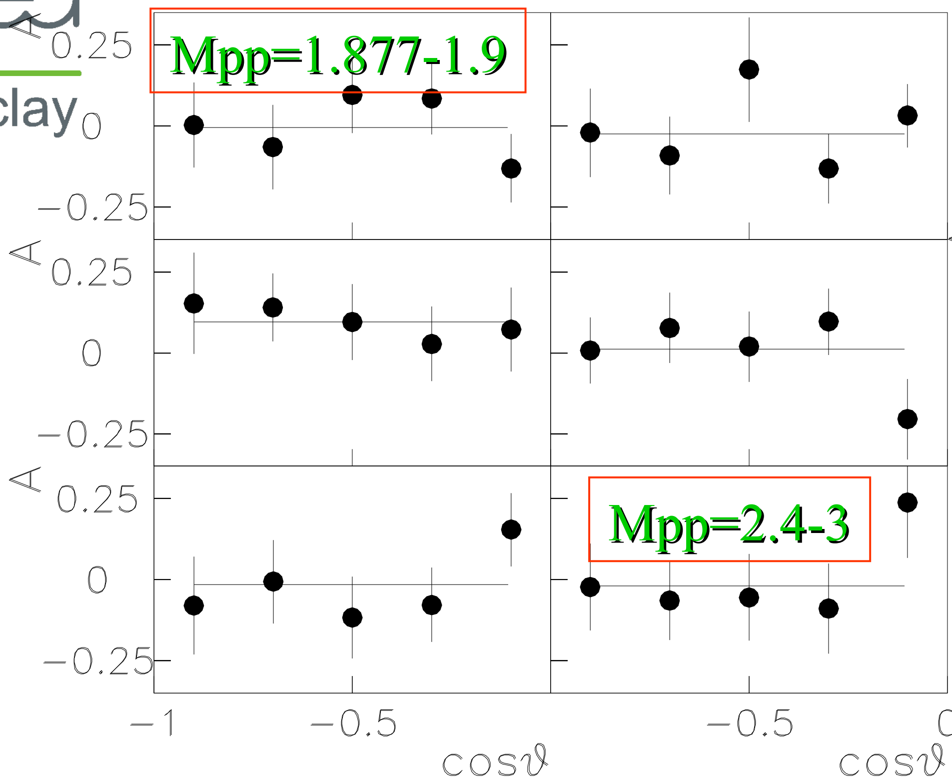
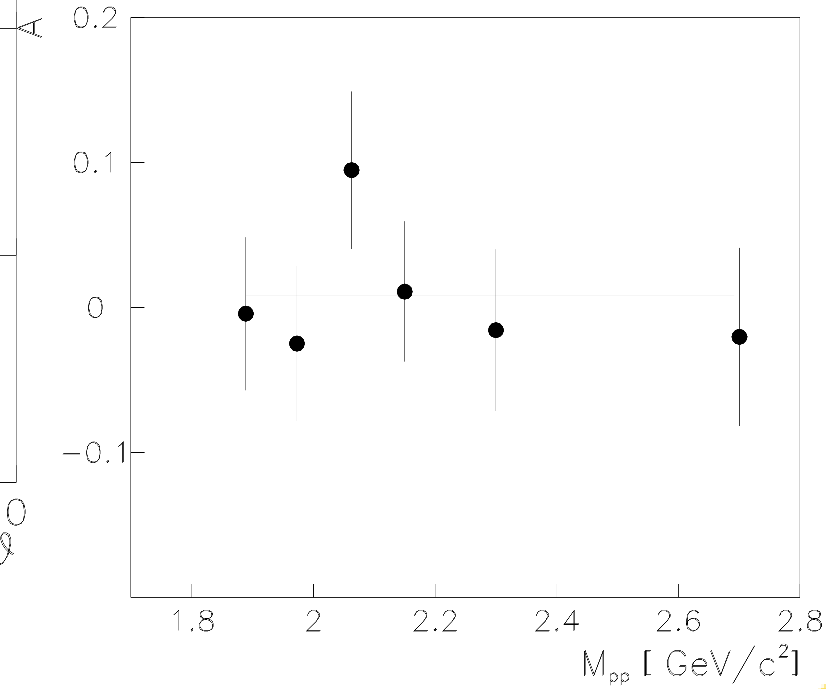


A=0.01±0.02



Radiative Corrections to the data

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- RC can reach 40% on σ
- Declared error ~1%
- Same correction for G_E and G_M
- Have a large ε-dependence
- Affect the slope

$\sigma_{el} = \sigma_{meas} \cdot RC$

$$\sigma^{red}_{meas}(Q^2,\epsilon) = \sigma^{red}(Q^2,\epsilon)[1-\delta_R(Q^2,\epsilon)] = G_M^2(Q^2)\left(\tau(Q^2) + \epsilon\frac{G_E^2(Q^2)}{G_M^2(Q^2)}\right)[1-\epsilon\delta'(Q^2)]$$

$$= G_M^2(Q^2)\left[\tau + \epsilon\left(\frac{G_E^2(Q^2)}{G_M^2(Q^2)} - \tau\delta'(Q^2)\right)\right]$$

slope

Slope negative if : $\delta' \geq \frac{G_E^2}{\tau G_M^2}$

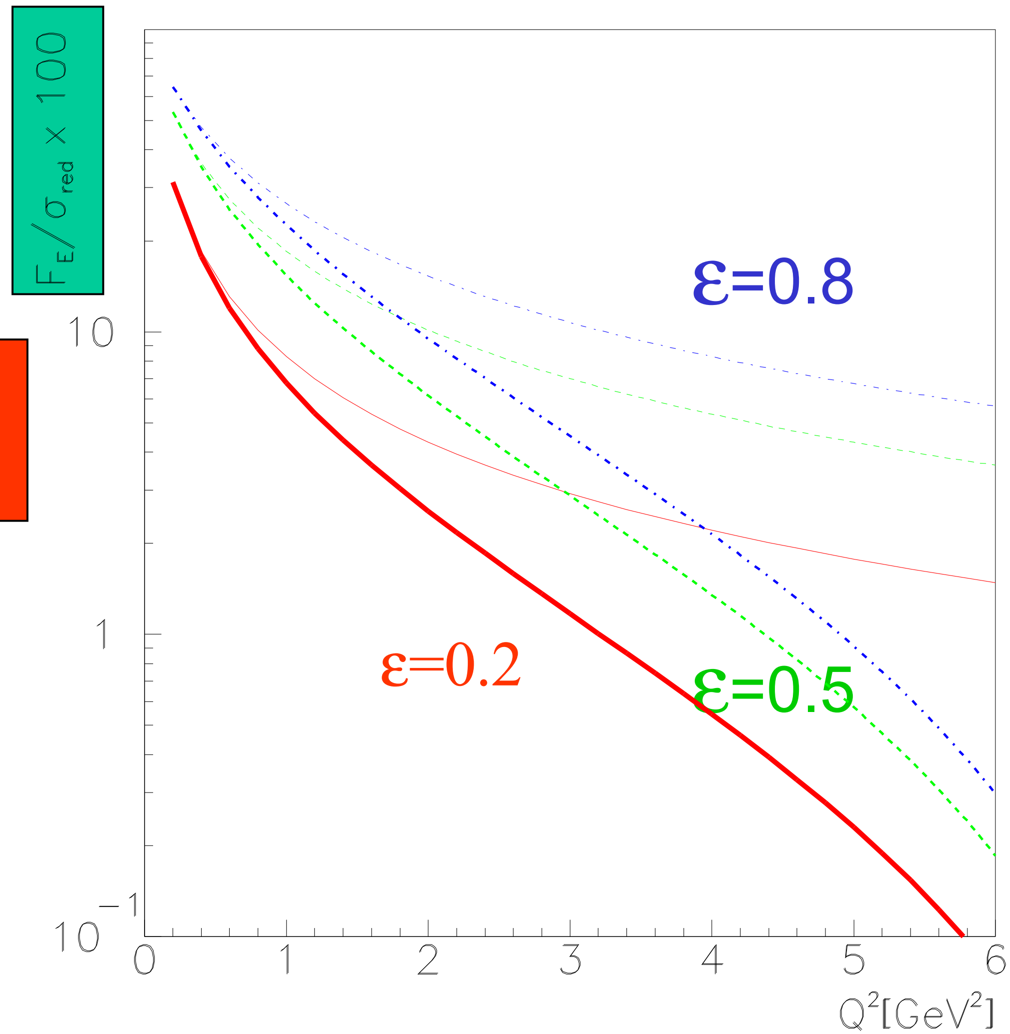
The slope is negative starting from 2-3 GeV²

Rosenbluth separation

Contribution of the electric term

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

...to be compared to the absolute value of σ and to the size and ε dependence of RC



The proton magnetic form factor

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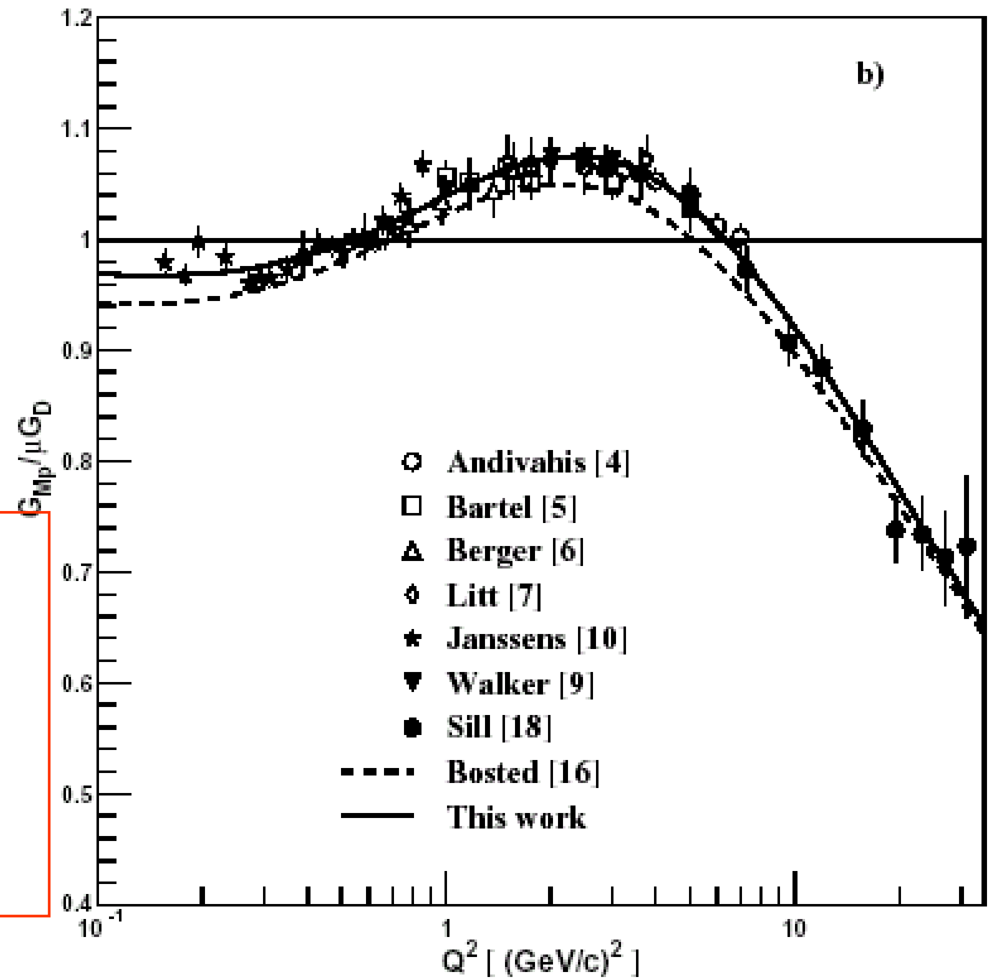
The polarization results induce 1.5-3% global effect

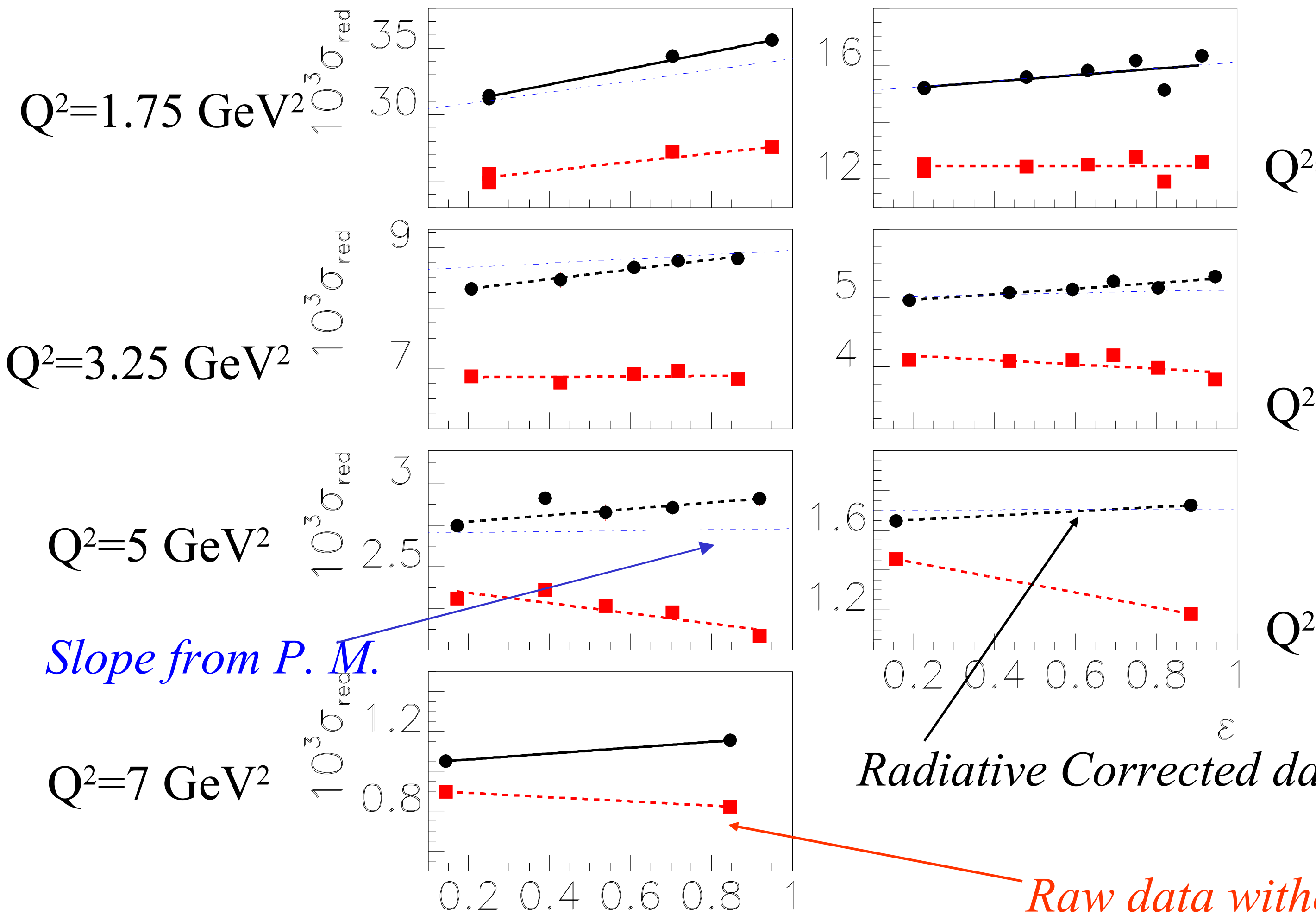


The difference is not at the level of the measured observables, but on the slope (derivative)!

E. Brash et al. Phys. Rev. C65, 051001 (2002)

Reduced cross section and RC

Data from L. Andivahis et al., Phys. Rev. D50, 5491 (1994)



E. T.-G., G. Gakh Phys. Rev. C (2005)

Experimental correlation

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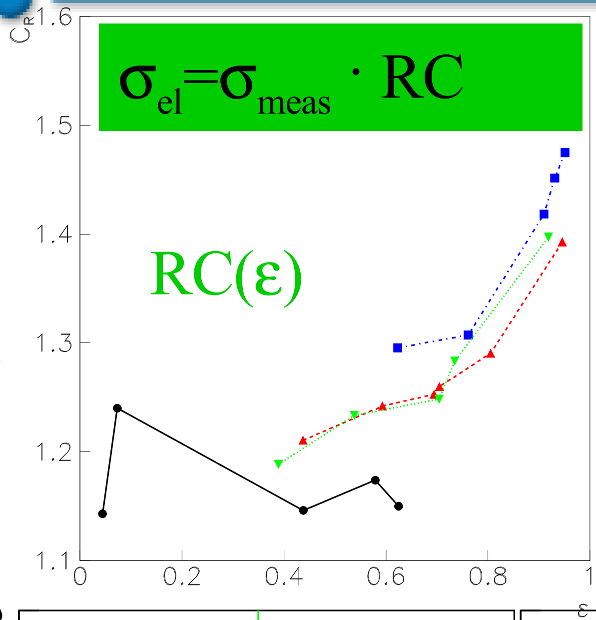
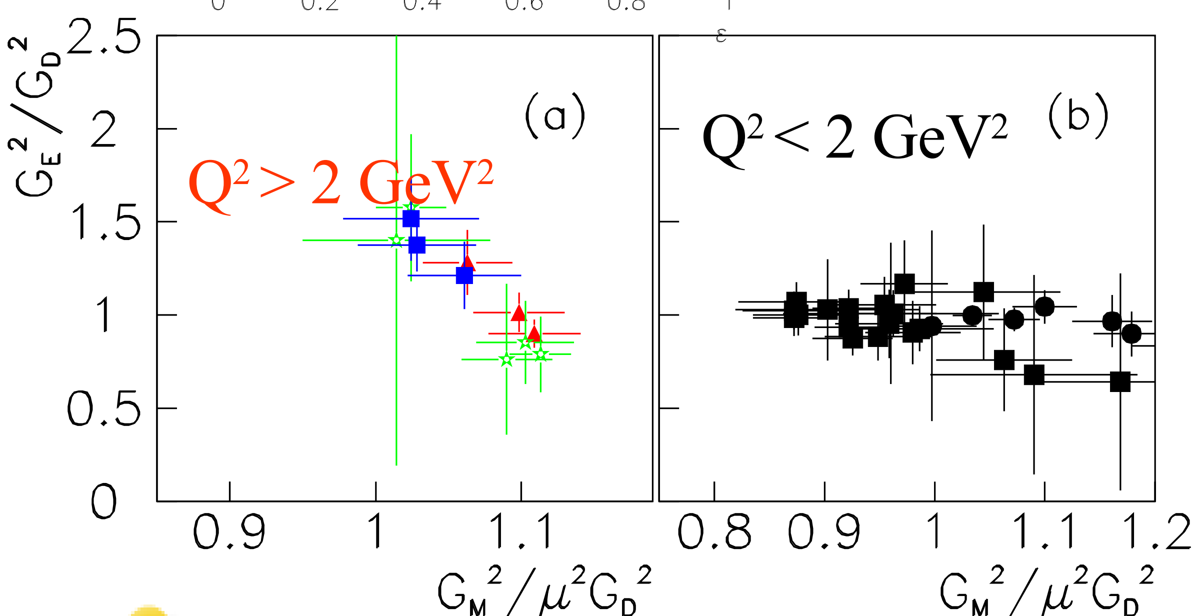
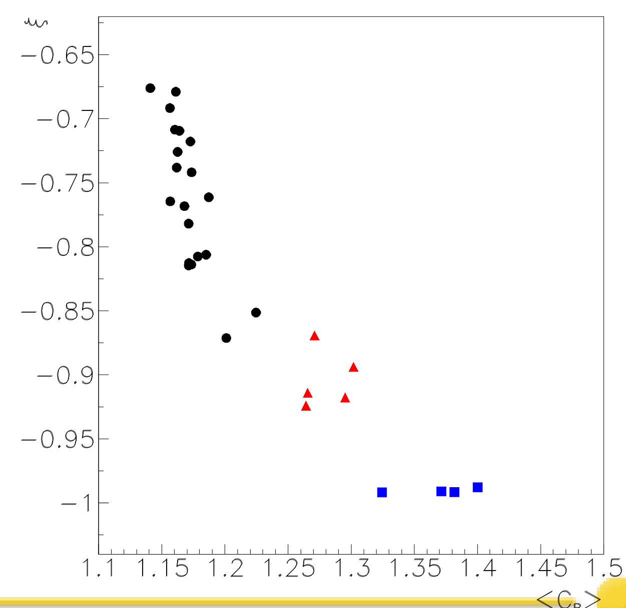


$$\sigma_{red} = \tau G_{Mp}^2 + \epsilon G_{Ep}^2$$

only published values!!



Correlation (<RC•ε>)



Scattered electron energy

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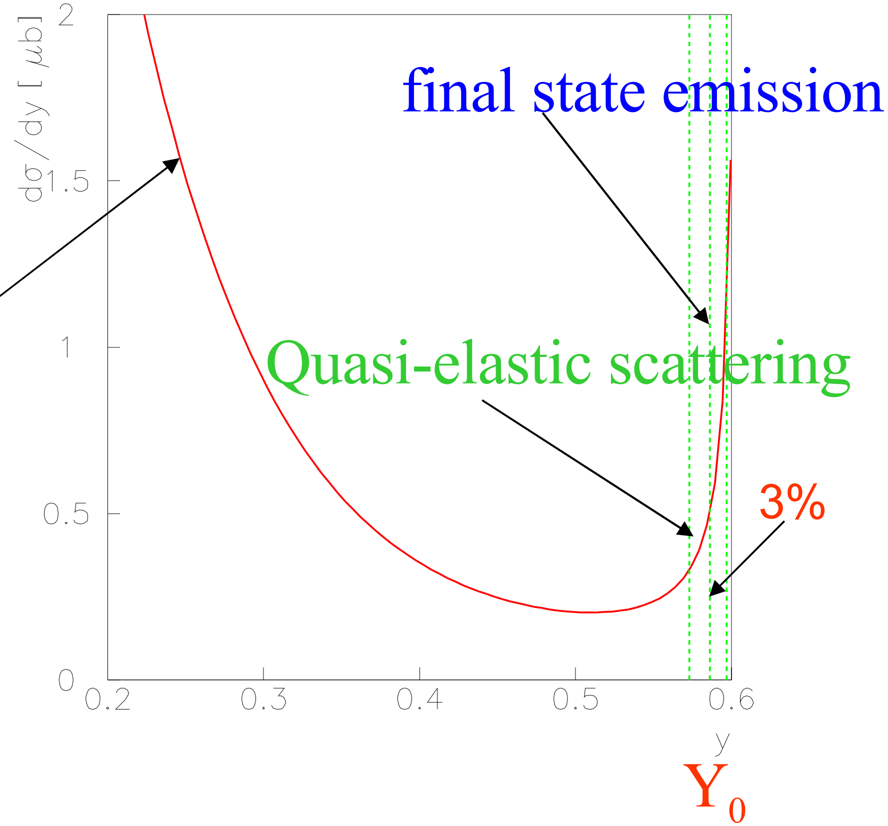
$$E'/E = y \; ; \; y_0 = \frac{1}{\rho}$$

$$\rho = 1 + \frac{2E}{m}\sin^2\theta/2 .$$

Initial state emission



$$\Delta \frac{d\sigma}{d\Omega} \sim \frac{d\sigma_0}{d\Omega} \cdot \frac{\alpha}{\pi} \ln \frac{E}{\Delta E} \ln \frac{2EM}{m_e^2} .$$

Not so small!

Shift to LOWER Q^2

All orders of PT needed →

beyond Mo & Tsai approximation

Structure Function method

E. A. Kuraev and V.S. Fadin, Sov. J. of Nucl. Phys. 41, 466 (1985)

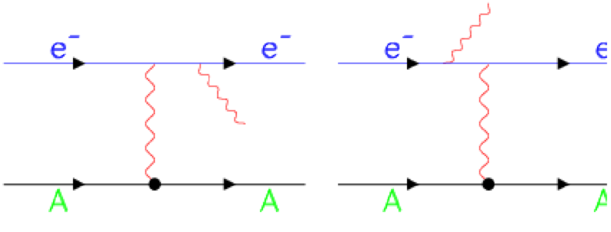
- SF method applied to QED processes: calculation of radiative corrections with precision of 0.1%.
- Takes into account the dynamics of the process
- Formulated in terms of parton densities (leptons, antileptons, photons) *Lipatov equations* (1975)
- Many applications to different processes

$$d\sigma(y) = \int_{x_0}^{1} \frac{dx}{x} \beta_x \frac{d\sigma_0(Ex)}{|1-\Pi(Q^2x)|^2} \mathcal{D}(x,L)\,\mathcal{D}\left(\frac{y\beta_x}{x}, L\right)\left(1+\frac{\alpha}{\pi}K\right)$$

$$L = \ln\frac{Q^2}{m_e^2}$$

Electron SF: probability to 'find' electron in the initial electron, with energy fraction x and virtuality up to Q^2

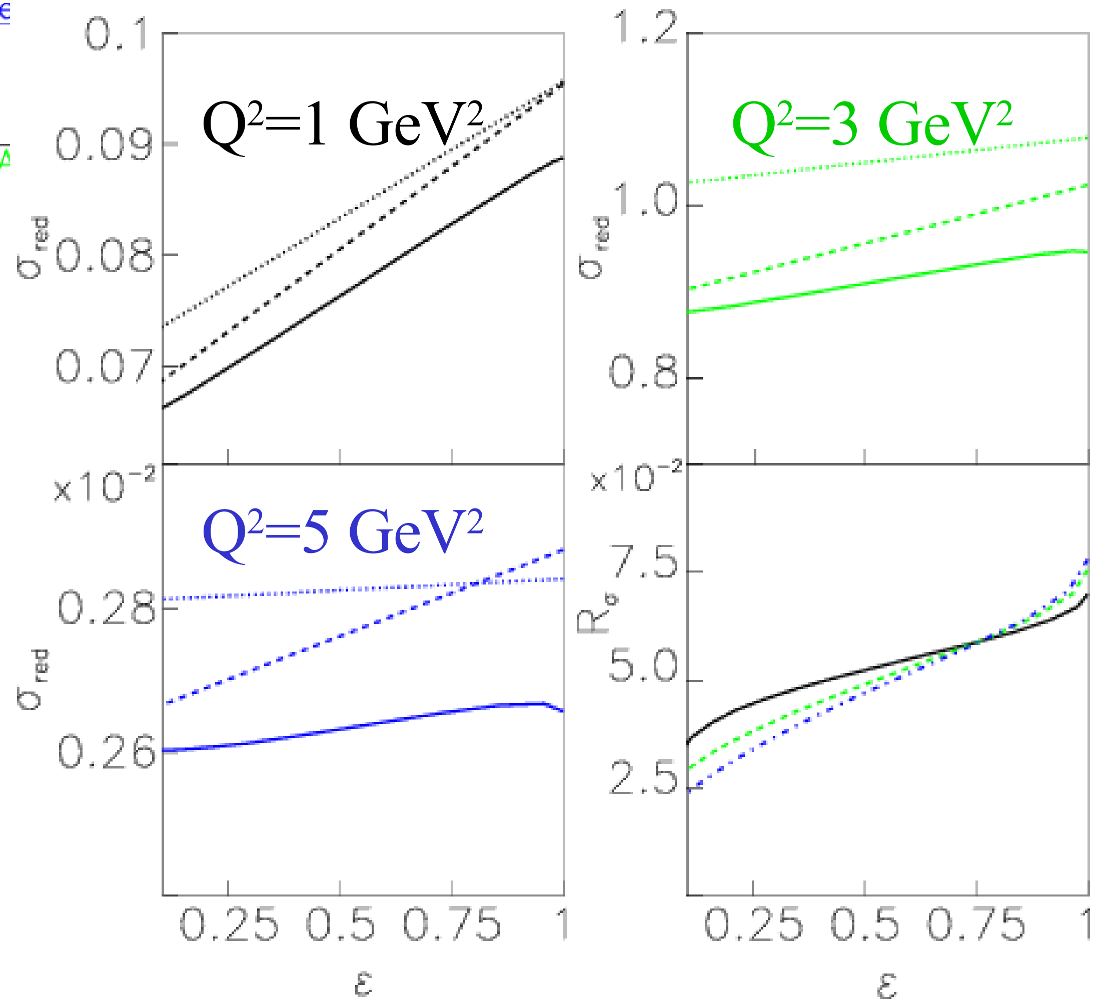
Results



SF Born

RC Born

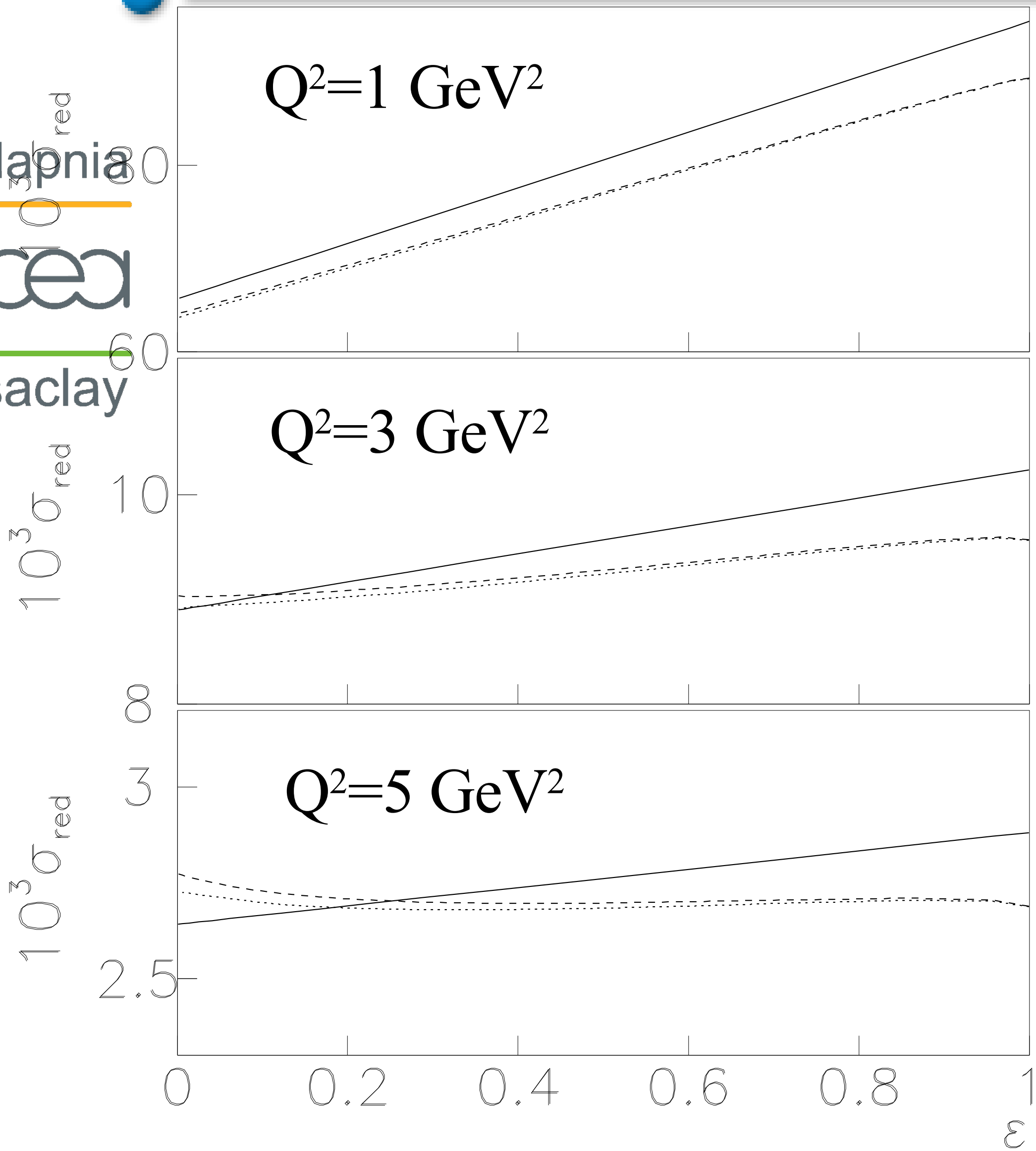
Polarization



Both calculations assume dipole FFs

The slope changes (due to different RC)

Unpolarized Cross section



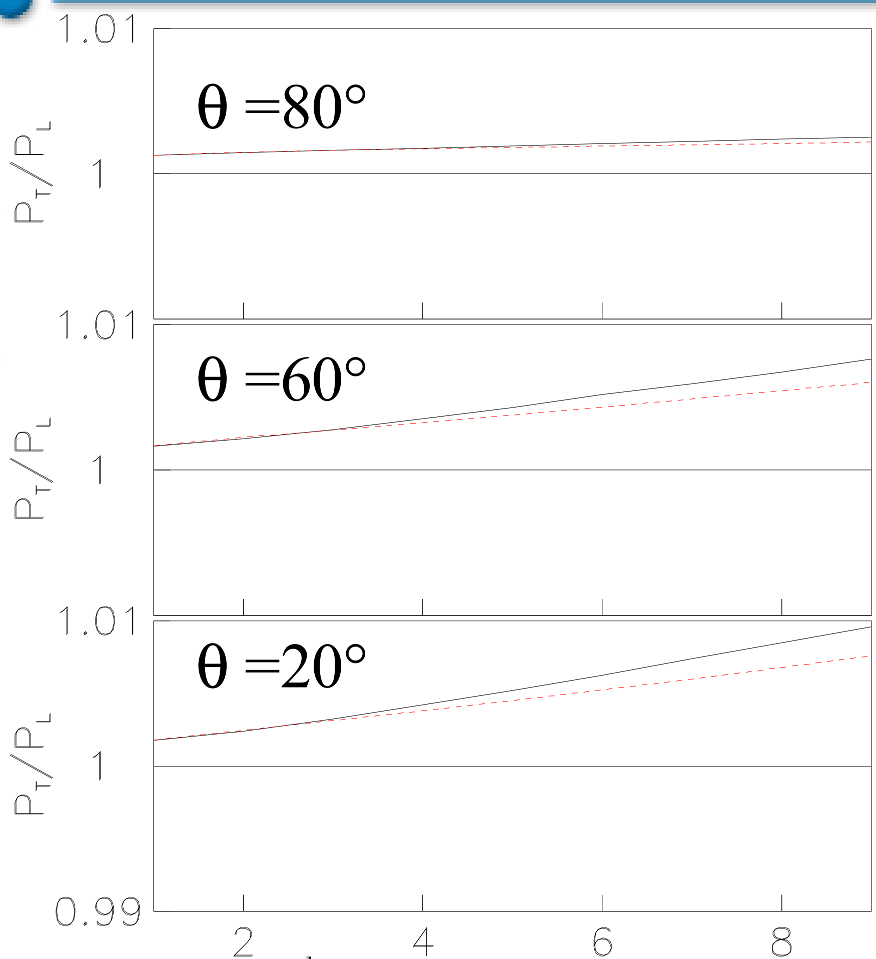
$$\sigma_{red} = \tau G^2_{Mp} + \epsilon G^2_{Ep}$$

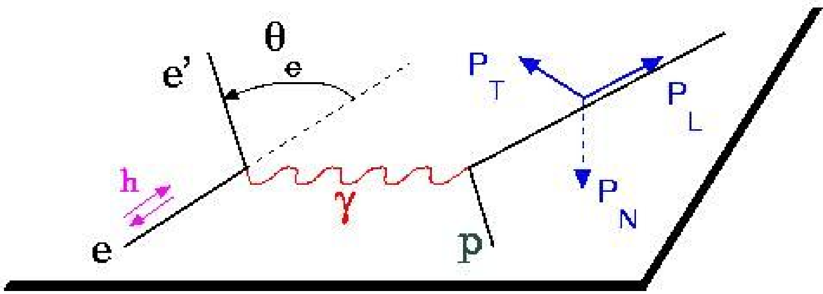
Born +dipole FFs ....
(=unpolarized experiment+Mo&Tsai)
SF (with dipole FFs)-------
SF+2γ exchange ....

SF: change the slope!

2γ exchange very small!

Polarization ratio





2γ exchange very small!

$$\left(\mathcal{P}_t\frac{d\sigma}{d\Omega}\right)_{corr}=-\lambda\int_{z_1}^{1}dz\frac{D(z,\beta)}{[1-\Pi(Q_z^2)]^2}\frac{\alpha^2}{Q_z^2}\left(\frac{1}{\rho_z}\right)^2\sqrt{\frac{\tau_z}{\tan^2(\theta/2)(1+\tau_z)}}G_E(Q_z^2)G_M(Q_z^2)\left(1+\frac{\alpha}{\pi}K_t\right);$$

$$\left(\mathcal{P}_\ell\frac{d\sigma}{d\Omega}\right)_{corr}=-\lambda\int_{z_1}^{1}dz\frac{D(z,\beta)}{[1-\Pi(Q_z^2)]^2}\frac{\alpha^2}{2M^2}\left(\frac{1}{\rho_z}\right)^2\sqrt{1+\frac{1}{\tan^2(\theta/2)(1+\tau_z)}}G_M^2(Q_z^2)\left(1+\frac{\alpha}{\pi}K_\ell\right).$$

Correction (SF method)

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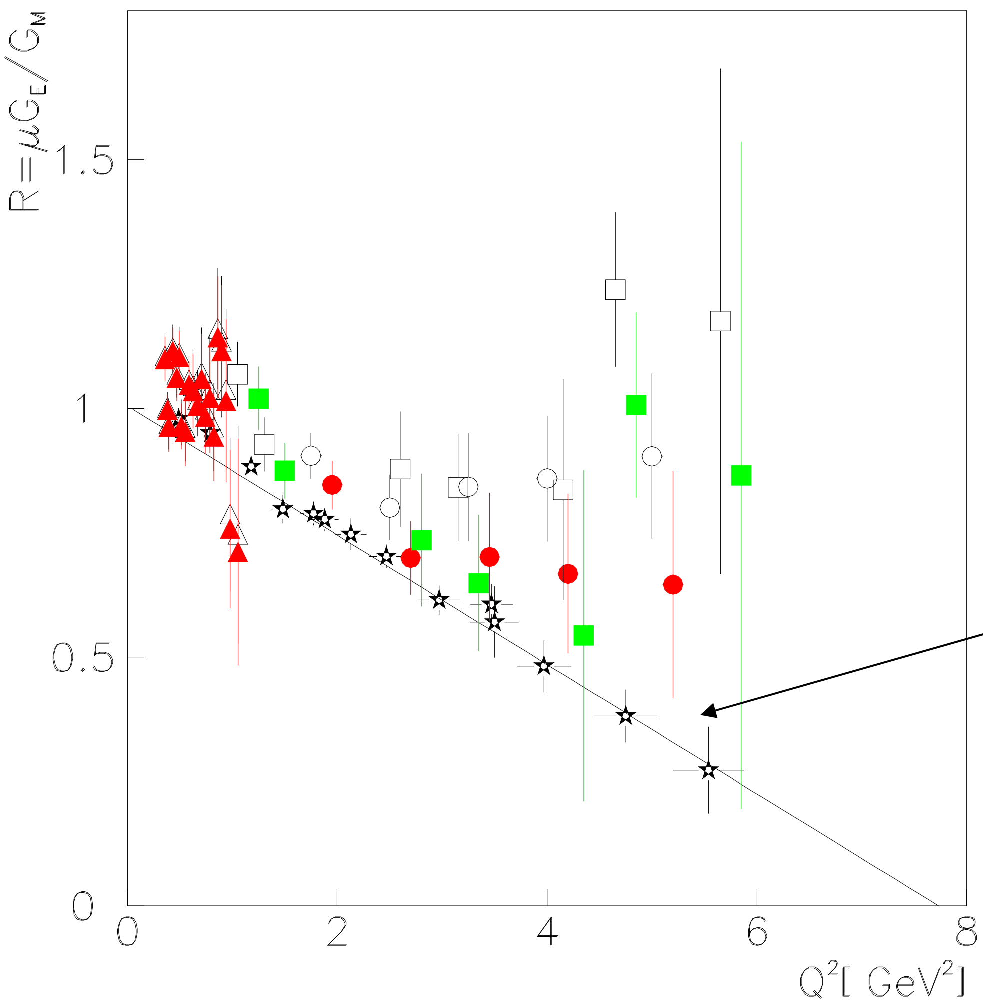


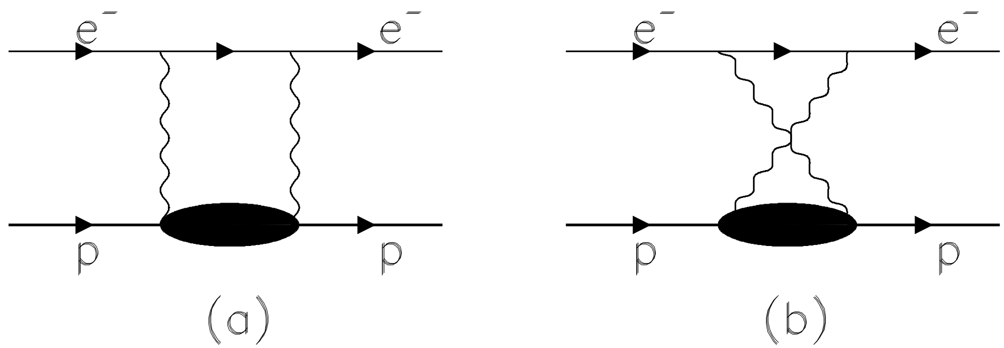
SLAC data

JLab data

Polarization data

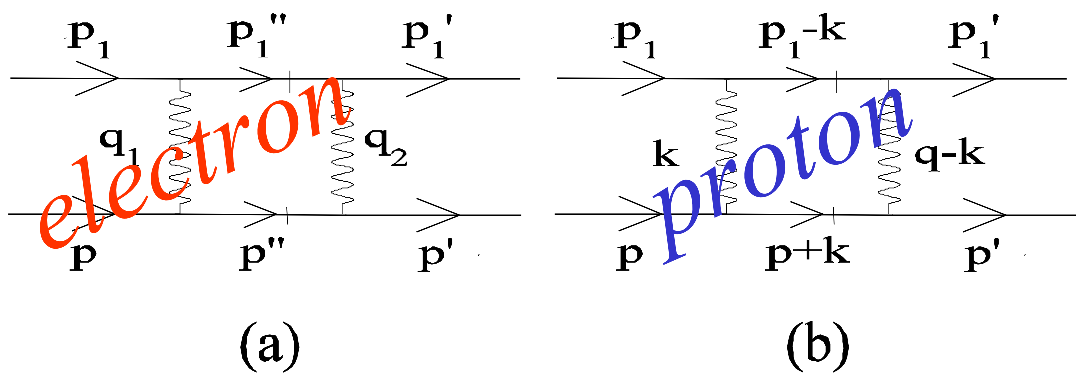
Yu. Bystricky, E.A.Kuraev, E. T.-G, Phys. Rev. C 75, 015207 (2007)

Interference of 1γ ⊗2γ exchange



- Explicit calculation for structureless proton
  - The contribution is small, for unpolarized and polarized ep scattering
  - Does not contain the enhancement factor *L*
  - The relevant contribution to *K* is ~ 1

E.A.Kuraev, V. Bytev, Yu. Bystricky, E.T-G Phys. Rev. D74 013003 (1076)



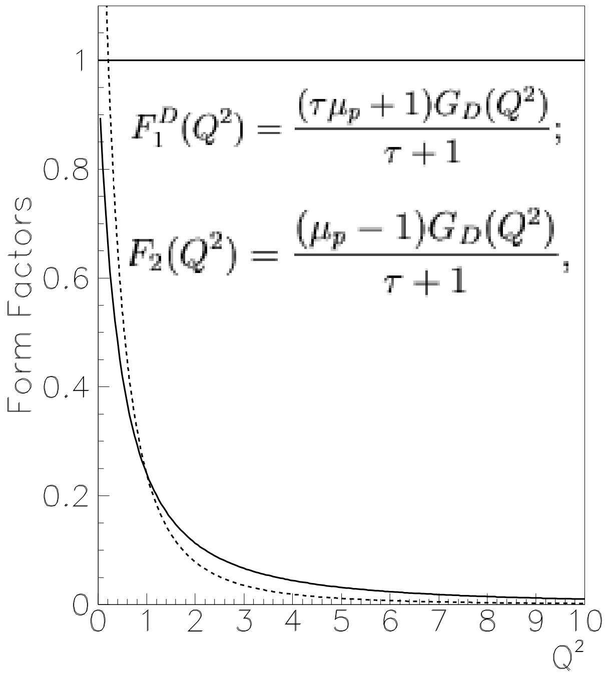
Imaginary part of the 2γ amplitude

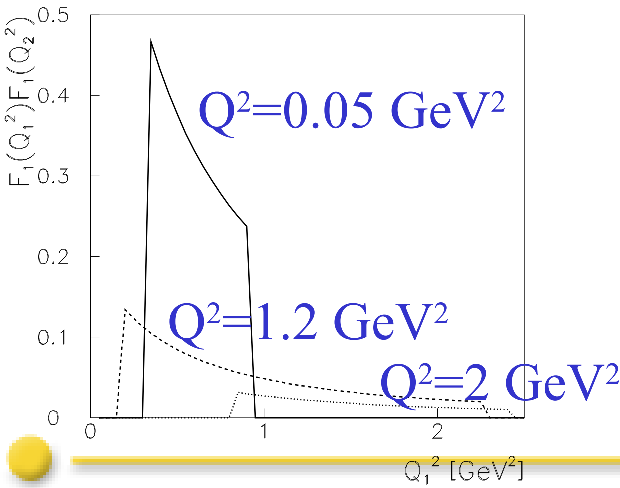
$$\mathcal{M}_{1a} = \frac{1}{\sqrt{8s}} \int \frac{dQ_1^2 dQ_2^2}{\sqrt{\mathcal{D}_1}(Q_1^2+\lambda^2)(Q_2^2+\lambda^2)}$$

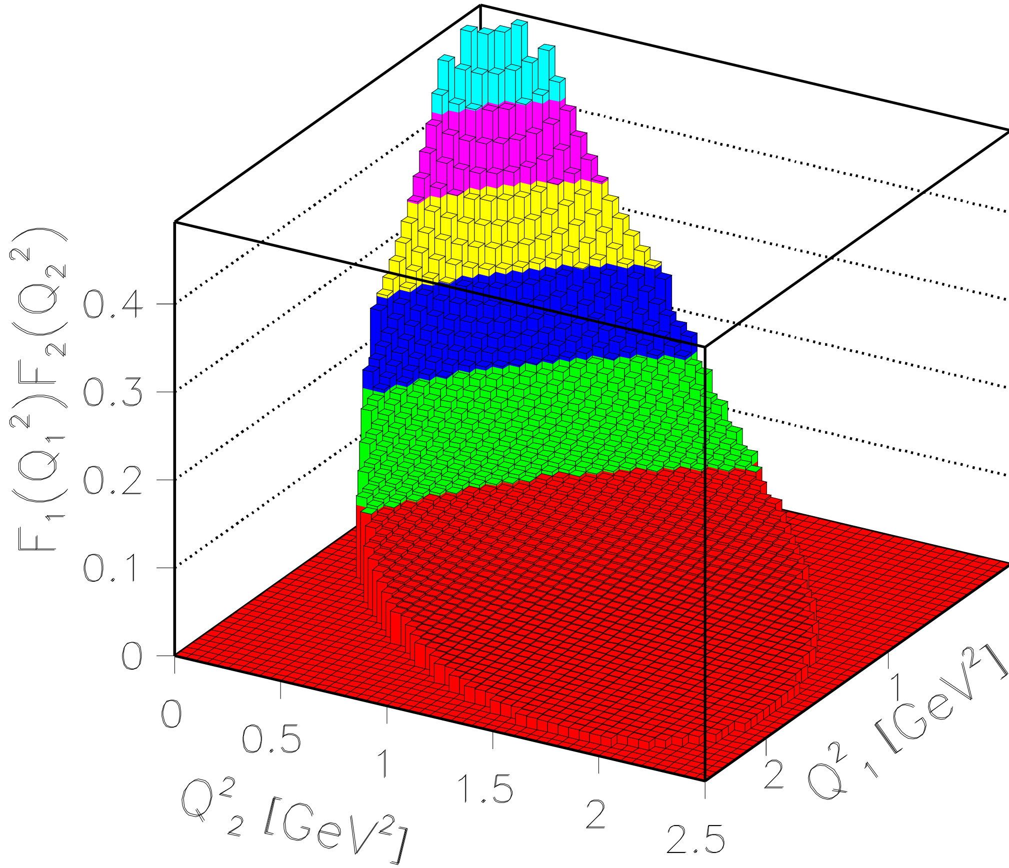
$$\mathcal{M}_{1b} = \frac{1}{\sqrt{8s}} \int \frac{dQ_1^2 dQ_2^2 F(Q_1^2) F(Q_2^2)}{\sqrt{\mathcal{D}_1}(Q_1^2+\lambda^2)(Q_2^2+\lambda^2)}$$

$$dO_1'' = \frac{2dQ_1^2 dQ_2^2}{\sqrt{\mathcal{D}_1 Q_0^2}}, \quad \mathcal{D}_1 = 2(Q_1^2+Q_2^2)Q^2Q_0^2 - 2Q^2Q_1^2Q_2^2 - (Q_1^2-Q_2^2)Q_0^2 - (Q^2)^2Q_0^2$$

QED versus QCD







$$F(Q_1^2)F(Q_2^2) < 1$$

Perspectives and Conclusions

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•Fundamental measurement: the electric and the magnetic distributions of the proton are different in SL region.

What about TL ? *Separation of G_E and G_M via angular dependence of differential cross section*

• Clarify reaction mechanism: *2γ exchange by model independent symmetry requirements*

• Unified description in TL and SL region : *zero of GEp?*

• Asymptotic properties : *QCD and analyticity*

Model independent properties
Lessons from QED

Nucleon form factor ratio

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- The ratio of the FFs moduli is given by the following expression:

$$\frac{d\sigma_+}{d\Omega}(\theta_1) : \frac{d\sigma_+}{d\Omega}(\theta_2) = \frac{\tau(1+x_1^2)+(1-x_1^2)R^2}{\tau(1+x_2^2)+(1-x_2^2)R^2}$$

$$x_i = cos\theta_i, \quad R = \frac{|G_E|}{|G_M|}$$

Model independent considerations for $\bar{p}+p\rightarrow e^{+}+e^{-}$

M. L. Goldberger, Y. Nambu and R. Oehme, Ann. Phys 2, 226 (1957)
P. Guichon and M. Vanderhaeghen, P. R.L. 91, 142303 (2003)
M.P. Rekalo and E. Tomasi-Gustafsson, EPJA 22, 331 (2004)

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The hadronic current:

$$J_{\mu}=\bar{u}(-p_2)[\tilde{G}_M(q^2,t)\gamma_{\mu}+\frac{P_{\mu}}{m}\tilde{F}_2(q^2,t)+\frac{P_{\mu}}{m^2}\hat{K}F_3(q^2,t)]u(p_1)$$

$$K=\frac{k_1+k_2}{2},\ \mathcal{P}=\frac{p_1+p_2}{2},$$

Decomposition of the amplitudes:

$$\tilde{G}_M(q^2,t)=G_M(q^2)+\Delta G_M(q^2,t);$$
$$\tilde{G}_E(q^2,t)=G_E(q^2)+\Delta G_E(q^2,t).$$

For 1γ-exchange:

$$\tilde{G}_M^{Born}(q^2,t)=G_M(q^2),\ \tilde{F}_2^{Born}(q^2,t)=F_2(q^2),\ F_3^{Born}(q^2,t)=0$$

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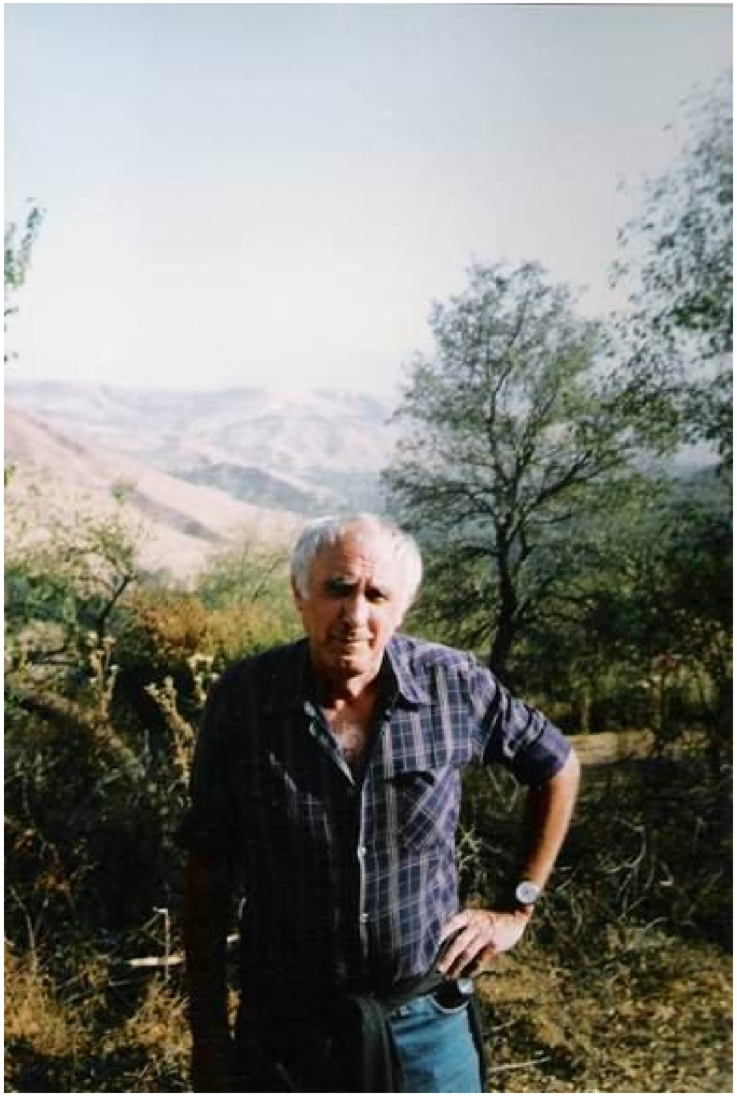

The work presented here was initiated in a collaboration with Prof. M. P. REKALO

Qualitative estimation of Two-Photon exchange (for ed)

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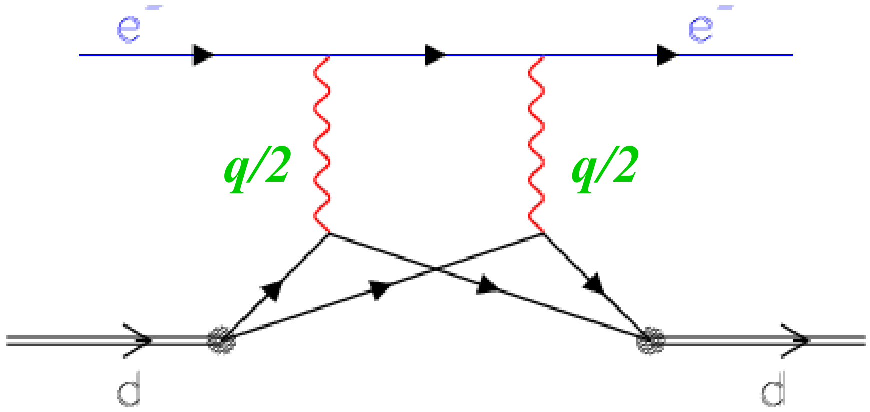

$$\mathcal{M}_1 = \alpha F_d(t).$$

$$\mathcal{M}_2 = \alpha^2 F_N^2 \left(\frac{t}{4}\right).$$

Form factors → quark counting rules: $F_d \sim t^{-5}$ and $F_N \sim t^{-2}$

$$\frac{\mathcal{M}_2}{\mathcal{M}_1} = \alpha F_N^2 / F_d(t) = 256\ \alpha t / m_x^2$$

For $t = 4$ GeV^2, $t/m_x^2 \simeq 6$ $\frac{\mathcal{M}_2}{\mathcal{M}_1} \simeq 1500\ \alpha \rightarrow 10!$

For d, ^{3}He, ^{4}He, 2γ effect should appear at ~1 GeV^2, for protons ~ 10 GeV^2