Model dependent and model independent considerations on two photon exchange

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Plan

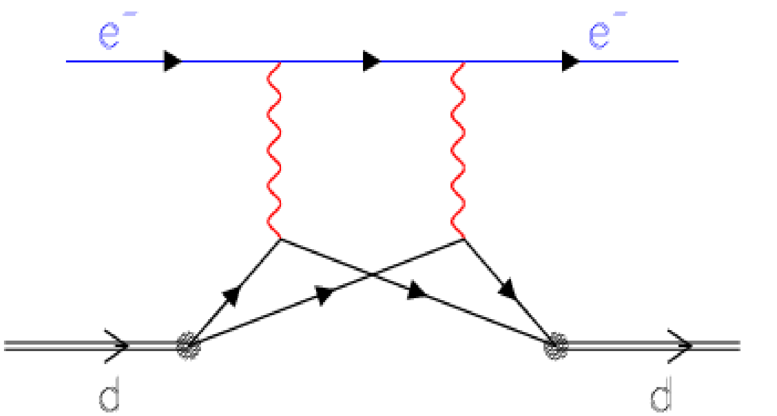
- Introduction
  - Generalities
- Model independent considerations
  - Space-like
  - Time-like
- Model dependent considerations
- What do data say?
- Which alternative for GEp problem?
- Conclusions

Two-Photon exchange

- *1γ-2γ interference is of the order of a=e2/4p=1/137 (in usual calculations of radiative corrections, one photon is 'hard' and one is 'soft')*
- *"Invent a mechanism" to enhance this contribution*
- *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 2γ-contribution can become very large.*
- *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.*

Qualitative estimation of 2γ exchange

*For **ed** elastic scattering:*



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

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

*From quark counting rules: Fd ~ t-5 and FN~t-2 . At **t** = 4* GeV2

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

$$t/m_x^2 \simeq 6$$

$$\frac{\mathcal{M}_2}{\mathcal{M}_1} \simeq 1500\ \alpha \rightarrow 10!$$

For d, 3He, 4He, 2γ effect should appear at ~1 GeV2,
for protons ~ 10 GeV2

Two-Photon exchange in ed-scatterng

- Discrepancy between the results from
  - Hall A [L.C. Alexa et al., P.R.L. 82, 1374 (1999)]
  - Hall C [D. Abbott et al., P.R.L. . 82, 1379 (1999)].

- Model-independent parametrization of the $2\gamma-$ contribution.
- Applied to **ed**-elastic scattering data.

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

Crossing Symmetry

Scattering and annihilation chan

- *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 va*

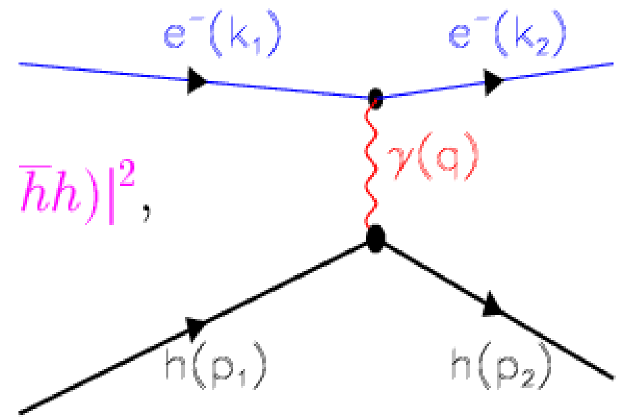
$$s = (k_1 + p_1)^2$$
$$t = (k_1 - k_2)^2$$

- *which scan different kinematical regions*

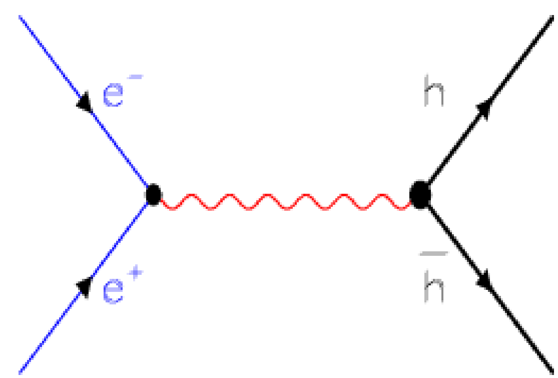
$$k2 \longrightarrow -k2$$
$$p2 \longrightarrow -$$

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

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

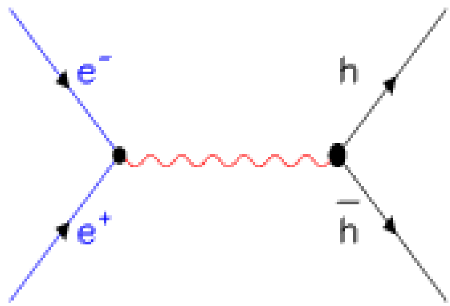


$$e^- + e^+ \rightarrow \overline{h} + h$$

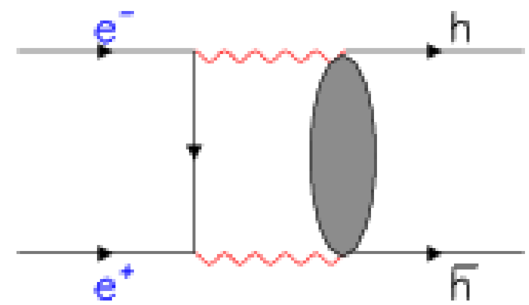


1γ-2γ interference

M. P. Rekalo, E. T.-G. an



$C(\gamma)=-1$



$C(2\gamma)=+1$

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

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

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

$$\frac{d\sigma}{d\Omega_e}(e^-h\to e^-h)=\sigma_0(\ \underbrace{A\cot^2\frac{\theta_e}{2}+B}_{1\gamma}+\underbrace{C\cot\frac{\theta_e}{2}+D\cot^3\frac{\theta_e}{2}}_{2\gamma}+..)$$

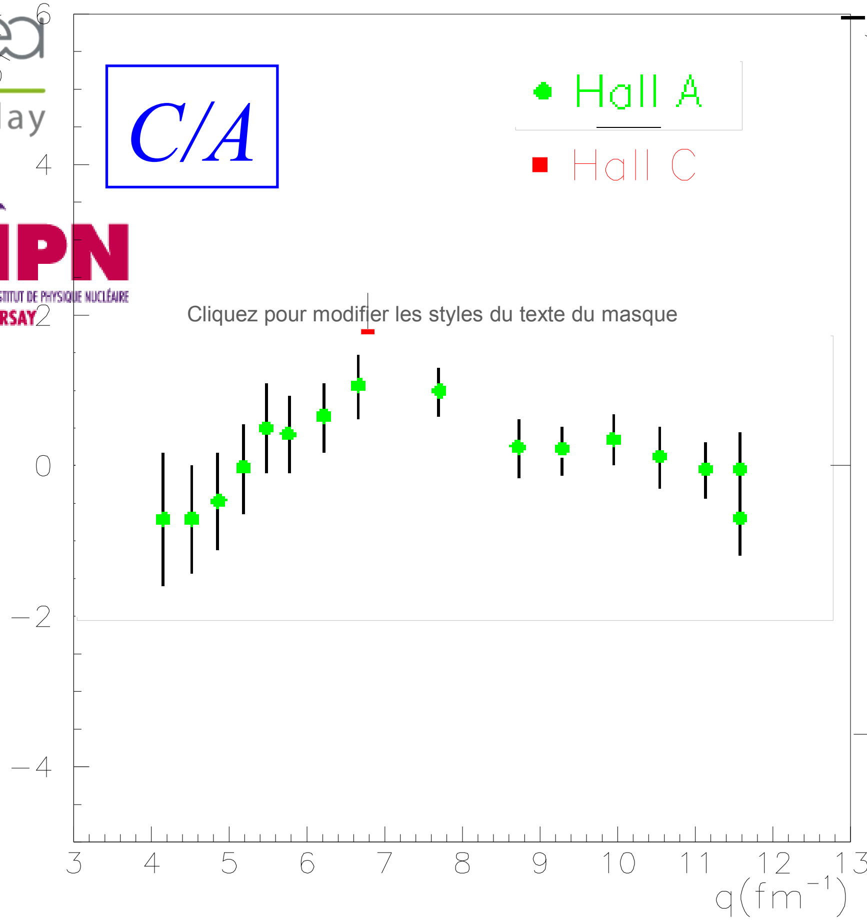
The 1γ-2γ interference destroys the linearity of the Rosenbluth plot!

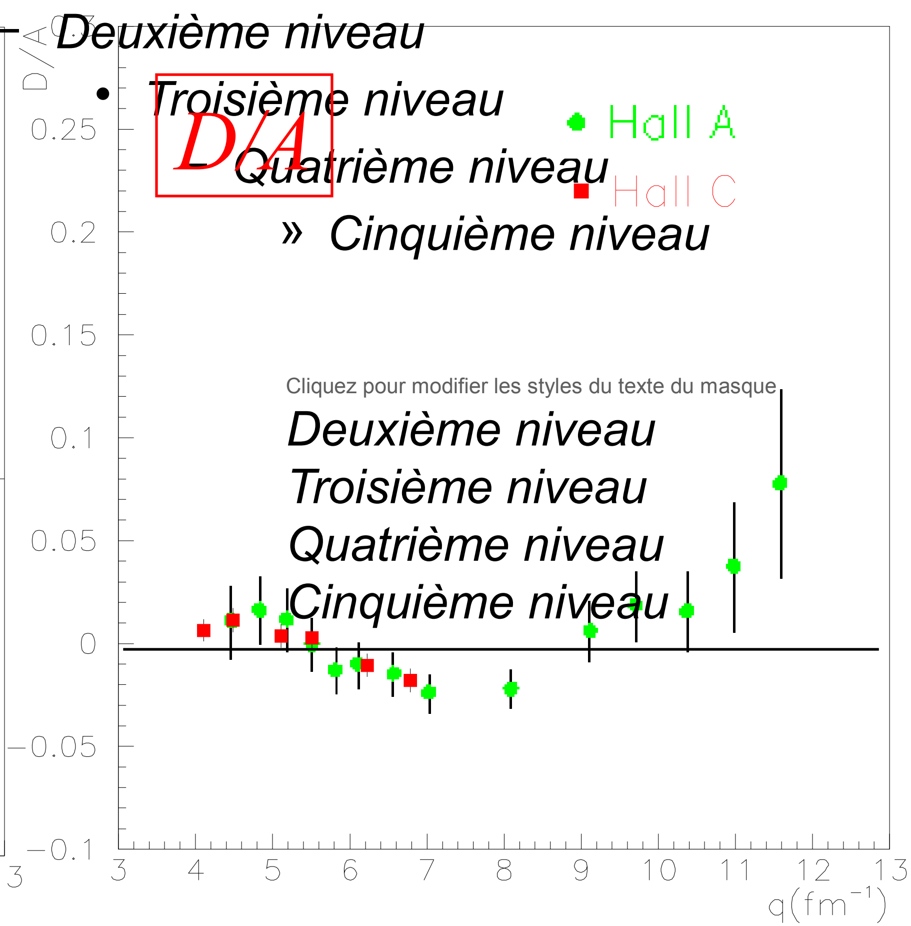
What about data?

1γ-2γ interference

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

- Cliquez pour modifier les styles du texte du masque
  - Deuxième niveau
    - Troisième niveau
      - Quatrième niveau
        - » Cinquième niveau



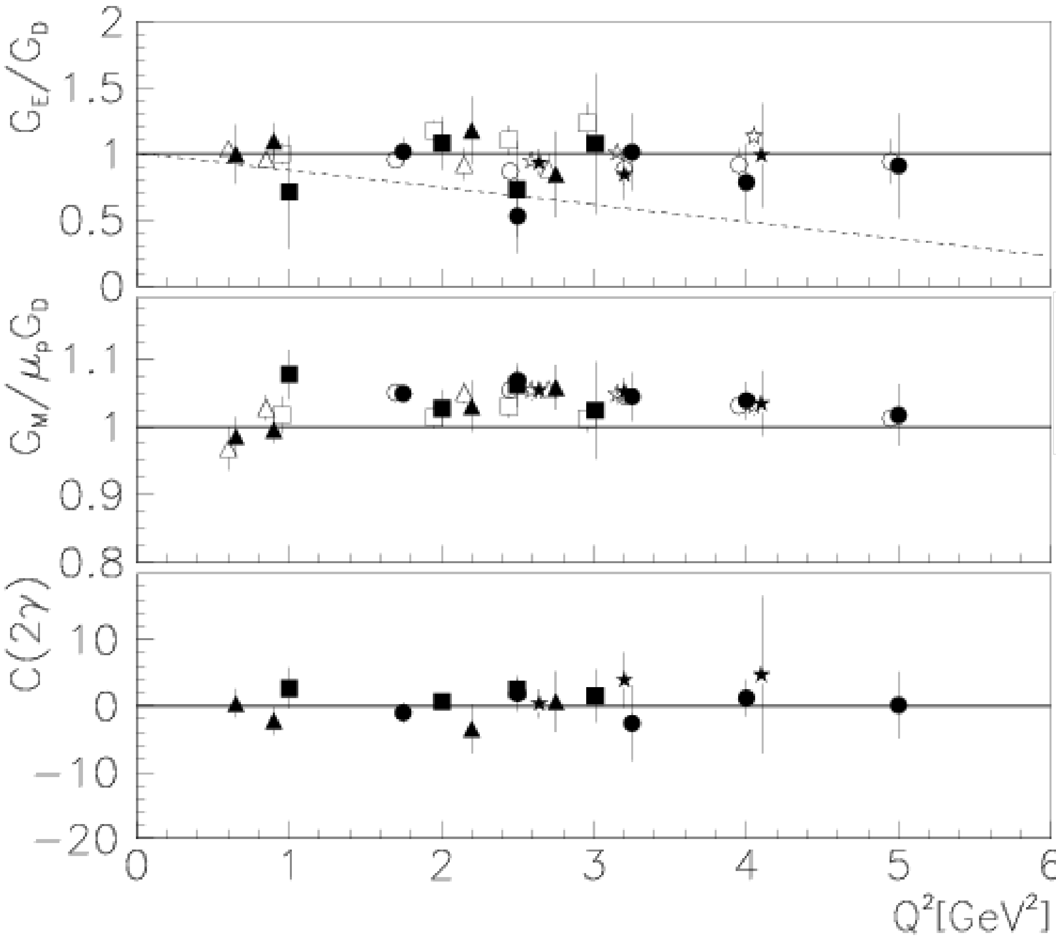


M. P. Rekalo, E. T-G and D. Prout, Phys. Rev. C60, 042202 (1999)

Parametrization of 2γ-contribution for e+p

Cliquez pour modifier le style du titre

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



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

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

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

E. T.-G., G. Gakh, Phys. Rev. C 72, 015209 (2005)

e+4He scattering

G.I Gakh, and E. T.-G., Nucl.Phys. A838 (2010) 50-60

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Spin 0 particle: F(q2) in Born approximation

$$\frac{d\sigma_{un}^{Born}}{d\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2\sin^4\frac{\theta}{2}}\left[1+2\frac{E}{M}\sin^2\frac{\theta}{2}\right]^{-1} F^2(q^2),$$

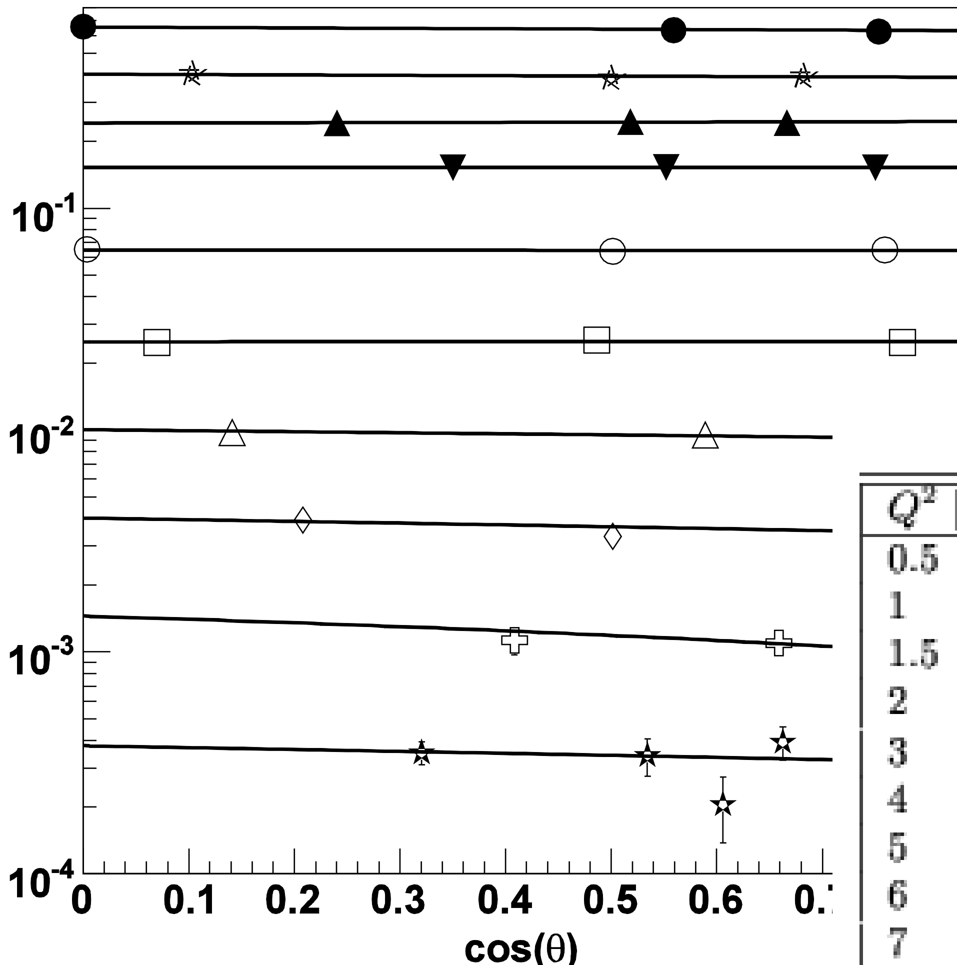
2γ exchange : F1(s,q2),F2(s,q2)=F(q2) +f(s,q2)

F(q2)~α0, F1(s,q2)~α $F_1^{Born}(s,q^2)=0,\ F_2^{Born}(s,q^2)=F(q^2),$

$$\frac{d\sigma_{un}}{d\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2\sin^4\frac{\theta}{2}}\left[1+2\frac{E}{M}\sin^2\frac{\theta}{2}\right]^{-1}\left\{F^2(q^2)+2F(q^2)Re\ f(s,q^2)+|f(s,q^2)|^2+ +\frac{m^2}{M^2}\left[\frac{M}{E}+(1+\frac{M}{E})\tan^2\frac{\theta}{2}\right]F(q^2)ReF_1(s,q^2)\right\}.$$

Linear fit to e+4He elastic scattering

G.I Gakh, and E. T.-G., Nucl.Phys. A838 (2010) 50-60



$$\sigma_{red}|_{\bar{Q}^2}(\theta) = a + \alpha\, b \cos\theta .$$

Q^2 [fm $^{-2}$]	a $\pm\Delta a$	b$\pm\Delta b$	χ^2
0.5	(66 ± 4) E-02	-6 ± 9	0.1
1	(0.40± 3) E-02	-3± 8	0.2
1.5	(0.24± 2) E-02	1.0 ± 0.1	0.1
2	(15 ± 2) E-03	0.0 ± 0.1	0.1
3	(65 ± 4) E-03	0.± 1	0.1
4	(25 ± 2) E-03	0.0± 0.4	0.1
5	(101± 8) E-04	-0.2± 0.2	0.5
6	(40± 5) E-04	-0.1± 0.1	0.6
7	(15± 3) E-04	-0.09± 0.07	1.0
8	(38± 9) E-05	-0.01± 0.03	1.0

Interaction of 4 spin ½ fermions

16 amplitudes in the general case.

- P- and T-invariance of EM interaction,
- helicity conservation,

- One-photon exchange:
  - Two form factors (real in SL, complex in TL)
  - Functions of one variable *(t)*

- Two-photon exchange:
  - Three (complex) amplitudes
  - Functions of two variables *(s,t)*

Is it still possible to extract the « real » FFs in presence of 2γ exchange?

Space-like region

Possible but difficult!

Model independent considerations for e± N scattering

Determination of EM form factors, in presence of 2γ exchange:

- electron and positron beams

  - longitudinally polarized ,
  - in identical kinematical conditions,

M. P. Rekalo, E. T.-G. , EPJA (2004), Nucl. Phys. A (2003)

Model independent considerations for e± N scattering

Determination of EM form factors, in presence of 2g exchange

- electron and positron beams,
- longitudinally polarized ,
- in identical kinematical conditions,

$$\frac{d\sigma^{(-)}}{d\Omega_e}+\frac{d\sigma^{(+)}}{d\Omega_e}=2\sigma_0\mathcal{N}=2\sigma_0\left[\epsilon G_E^2(Q^2)+\tau G_M^2(Q^2)\right],$$

$$\frac{1}{2}\mathcal{N}(P_x^{(+)}+P_x^{(-)})=-\lambda_e\sqrt{2\epsilon(1-\epsilon)\tau}G_E(Q^2)G_M(Q^2),$$

$$\frac{1}{2}\mathcal{N}(P_z^{(+)}+P_z^{(-)})=\lambda_e\tau\sqrt{(1-\epsilon^2)}G_M^2(Q^2),$$

Generalization of the polarization method (A. Akhiezer and M.P. Rekalo)

M. P. Rekalo and E. T-G Nucl. Phys. A740 (2004) 271,

M. P. Rekalo and E. T-G Nucl. Phys. A742 (2004) 322

If no positron beam…

Either three T-odd polarization observables….

- A_y: unpolarized leptons, transversally polarized target or
  P_y: outgoing nucleon polarization with unpolarized leptons, unpolarized target

- Depolarization tensor (D_{ab}): dependence of the **b-component of the final nucleon polarization** on the **a-component** of the nucleon target with longitudinally polarized leptons

M. P. Rekalo and E. T-G Nucl. Phys. A740 (2004) 271,
M. P. Rekalo and E. T-G Nucl. Phys. A742 (2004) 322

If no positron beam…

Either three T-odd polarization observables….

$$\mathcal{N} P_y = \mathcal{N} A_y = \sqrt{2\epsilon\tau(1+\epsilon)}\mathcal{I}_3(Q^2,\epsilon) + \sqrt{2\epsilon(1-\epsilon)(1+\tau)}\mathcal{I}_1(Q^2,\epsilon),$$

$$\mathcal{N} D_{xy}(\lambda_e) = \mathcal{N} D_{yx}(\lambda_e) = 2\lambda_e\epsilon\sqrt{\tau(1+\tau)}\mathcal{I}_2(Q^2,\epsilon),$$

$$\mathcal{N} D_{yz}(\lambda_e) = -\mathcal{N} D_{zy}(\lambda_e) = \lambda_e\sqrt{2\epsilon(1+\tau)(1+\epsilon)}\mathcal{I}_1(Q^2,\epsilon),$$

$$\mathcal{I}_1(Q^2,\epsilon) = Im G_E(Q^2)\mathcal{A}(Q^2,\epsilon),\ \mathcal{I}_2(Q^2,\epsilon) = Im G_M(Q^2)\mathcal{A}(Q^2,\epsilon),$$

$$\mathcal{I}_3(Q^2,\epsilon) = Im G_E(Q^2,\epsilon) G_M^*(Q^2,\epsilon).$$

$$\mathcal{R}_{EM}(Q^2) = \frac{\mathcal{I}_1(Q^2,\epsilon)}{\mathcal{I}_2(Q^2,\epsilon)} = \frac{G_E(Q^2)}{G_M(Q^2)}$$

M. P. Rekalo and E. T-G Nucl. Phys. A740 (2004) 271,

M. P. Rekalo and E. T-G Nucl. Phys. A742 (2004) 322

If no positron beam…

This ratio contains the 'TRUE 'form factors!

$$\mathcal{R}_{EM}(Q^2) = \frac{\mathcal{I}_1(Q^2,\epsilon)}{\mathcal{I}_2(Q^2,\epsilon)} = \frac{G_E(Q^2)}{G_M(Q^2)}$$

$$\mathcal{R}_{EM}(Q^2) = -\frac{\lambda_e}{D_{xy}(\lambda_e)}\left[P_y + \sqrt{\frac{1+\epsilon}{1-\epsilon}}\frac{D_{zy}(\lambda_e)}{\lambda_e}\right]\sqrt{\frac{1-\epsilon}{2\epsilon}\tau}.$$

Very difficult experiments

Three T-odd polarization observables….

Expected small, of the order of a, triple spin correlations

but… <u>Model independent way</u>

If no positron beam…

Either three T-odd polarization observables….

..or five T-even polarization observables….

among dσ/dΩ, Px(λe), Pz(λe), Dxx, Dyy, Dzz, Dxz

$$\frac{G_E(Q^2)}{G_M(Q^2)} = -\frac{1}{2\epsilon}\sqrt{\tau\frac{1-\epsilon^2}{2\epsilon}}\,\frac{\left[\sqrt{1+\epsilon}\,\frac{P_x(\lambda_e)}{\lambda_e} - D_{xz}\sqrt{1-\epsilon}\right]}{1+\frac{1-\epsilon}{2\epsilon}D_{xx} - \frac{1+\epsilon}{2\epsilon}D_{yy}},$$

Again very difficult experiments

Only Model independent ways (without positron beams)

M. P. Rekalo and E. T-G Nucl. Phys. A740 (2004) 271,
M. P. Rekalo and E. T-G Nucl. Phys. A742 (2004) 322

Is it still possible to extract the « real » FFs in presence of 2γ exchange?

Time-like region

much easier!

Time-like observables: | GE| 2 and | GM| 2

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

Cliquez pour modifier les styles du texte du masque

Deuxième niveau

Troisième niveau

Quatrième niveau

Cinquième niveau

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

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 q2 contained in FFs
- Even dependence on cos2θ (1γ exchange)
- No dependence on sign of FFs
- Enhancement of magnetic term

but TL form factors are complex!

Unpolarized cross section

Two Photon Exchange:

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

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

$$D = (1+\cos^2\theta)(|G_M|^2 \text{[redacted]}) + \frac{1}{\tau}\sin^2\theta(|G_E|^2 \text{[redacted]}) +$$

[redacted]

M.P. Rekalo and E. T.-G., EPJA 22, 331 (2004)

G.I. Gakh and E. T.-G., NPA761, 120 (2005)

Symmetry relations

- *Properties of the TPE amplitudes with respect to the transformation:* $\cos\theta = -\cos\theta$ *i.e.,* $\theta \rightarrow \pi - \theta$

(equivalent to non-linearity in Rosenbluth fit)

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

E. T.-G., G. Gakh, NPA (2007)

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:

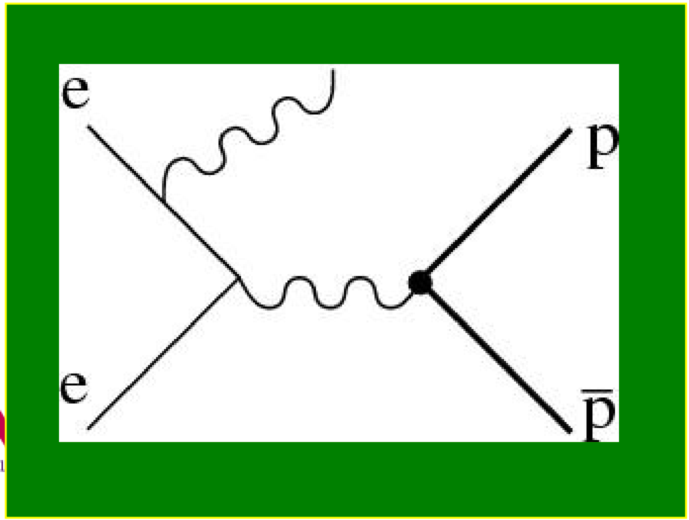
$$\frac{d\sigma_-}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi-\theta) = 4N\Big[(1+x^2)ReG_M\Delta G_M^* +$$

$$+\frac{1-x^2}{\tau}ReG_E\Delta G_E^* + \sqrt{\tau(\tau-1)}x(1-x^2)Re(\frac{1}{\tau}G_E - G_M)F_3^*\Big]$$

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

What do data say?

Radiative Return (ISR)



$$e+ +e- \rightarrow p + \overline{p} + \gamma$$

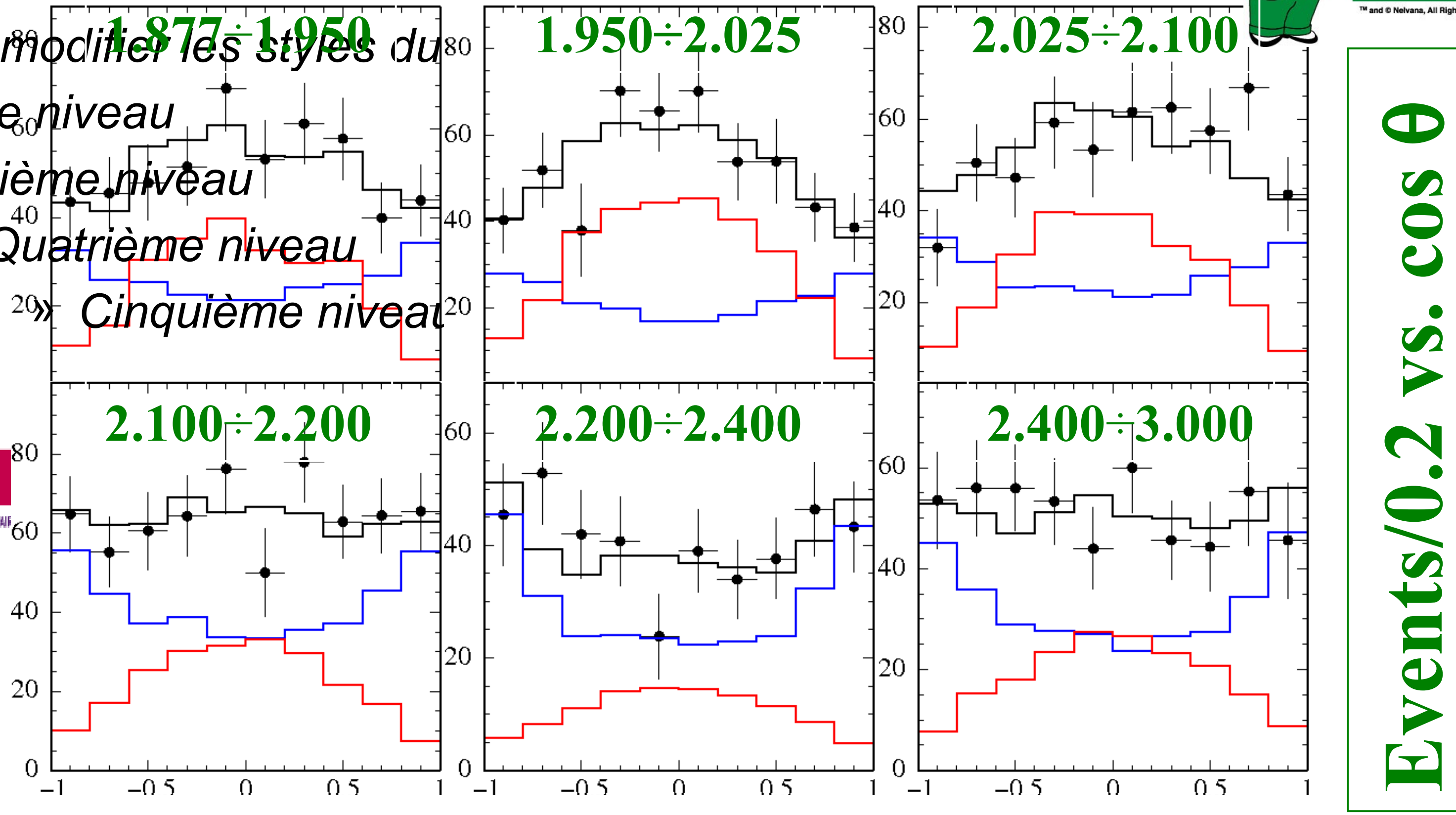
$$\frac{d\sigma\,(e^+e^- \rightarrow p\bar{p}\gamma\,)}{dm\;d\cos\theta} = \frac{2m}{s} W(s,x,\theta\,)\,\sigma\,(e^+e^- \rightarrow p\bar{p}\,)(m\,), \quad x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{m^2}{s},$$

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

B. Aubert (BABAR Collaboration) Phys Rev. **D73**, 012005 (2006)

Angular distribution

- …uez pour modifier les styles du…
  - Deuxième niveau
    - Troisième niveau
      - Quatrième niveau
        - » Cinquième niveau



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

2γ–exchange?

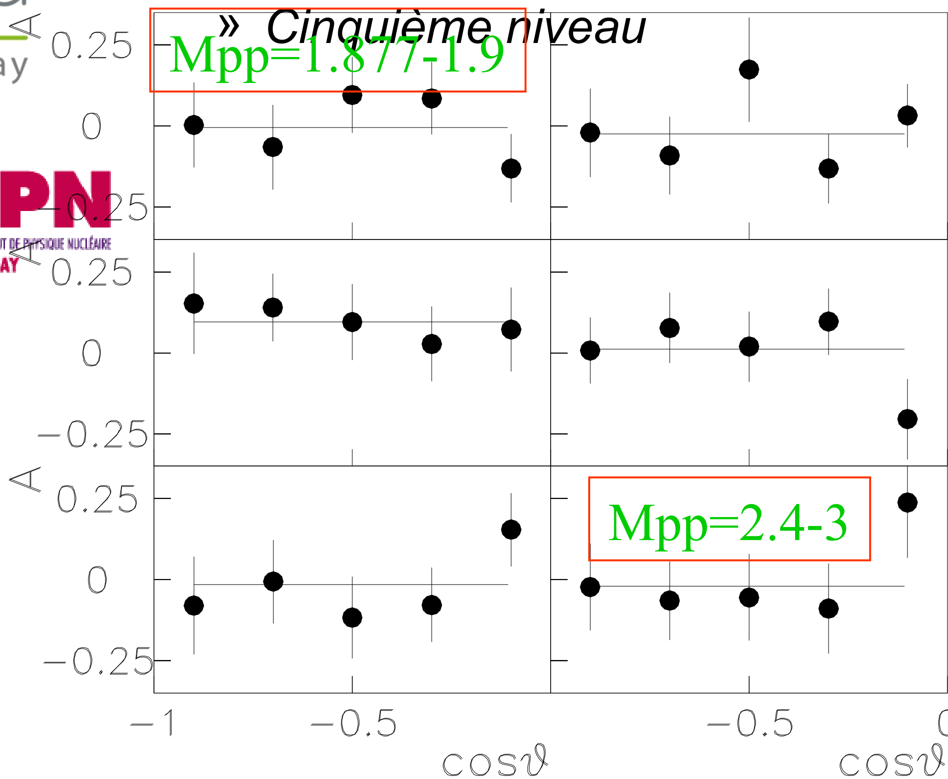
Angular Asymmetry

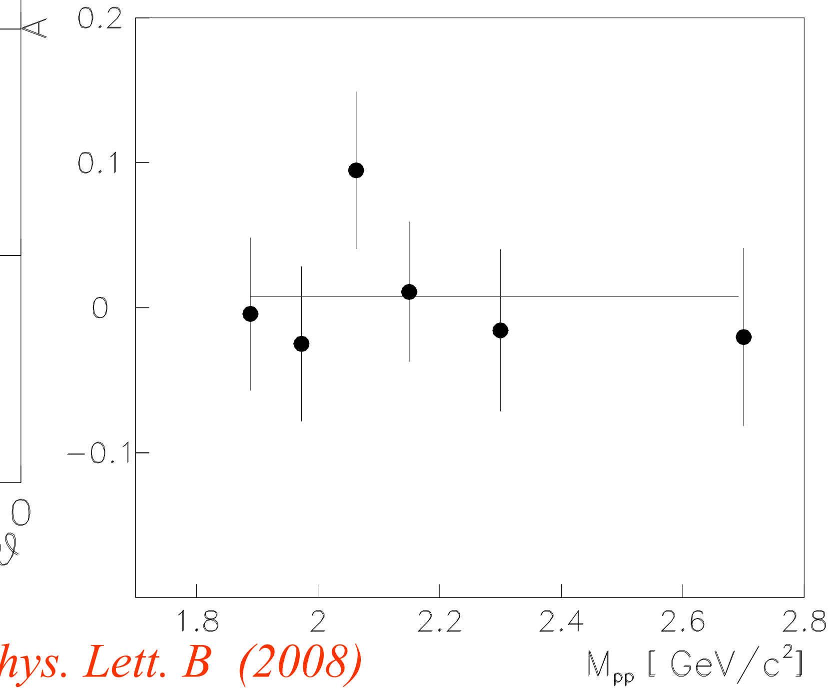
Cliquez pour modifier les styles du texte du masque

- Deuxième niveau
  - Troisième niveau
    - Quatrième niveau
      - » Cinquième niveau

$$\mathcal{A}(c) = \frac{\frac{d\sigma}{d\Omega}(c) - \frac{d\sigma}{d\Omega}(-c)}{\frac{d\sigma}{d\Omega}(c) + \frac{d\sigma}{d\Omega}(-c)}$$

A=0.01±0.02





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

Structure Function method

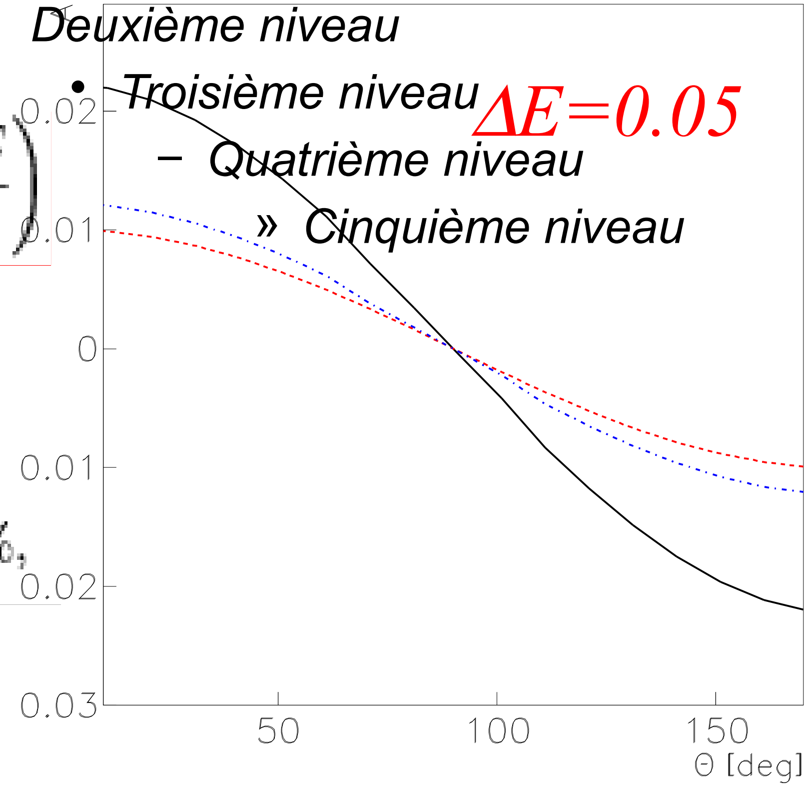
$e^+ + e^- \rightarrow p + \bar{p} + \gamma$

E.A. Kuraev, V. Meledin, Nucl. Phys. B

- Cliquez pour modifier les styles du texte du m
  - Deuxième niveau
    - Troisième niveau
      - Quatrième niveau
        - » Cinquième niveau

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

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



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

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

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

Fitting the angular distributions...

The form of the differential cross section:

is equivalent to:

Cross section at 900

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

Angular asymmetry

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

Fitting the angular distributions...

1 γ exchange:

→ *Linear Fit in* $\cos 2\theta$

$$y = a_0 + a_1 x \text{ with } x = \cos^2\theta,\ a_0 = \sigma_0,\ a_1 = \sigma_0 \mathcal{A}$$

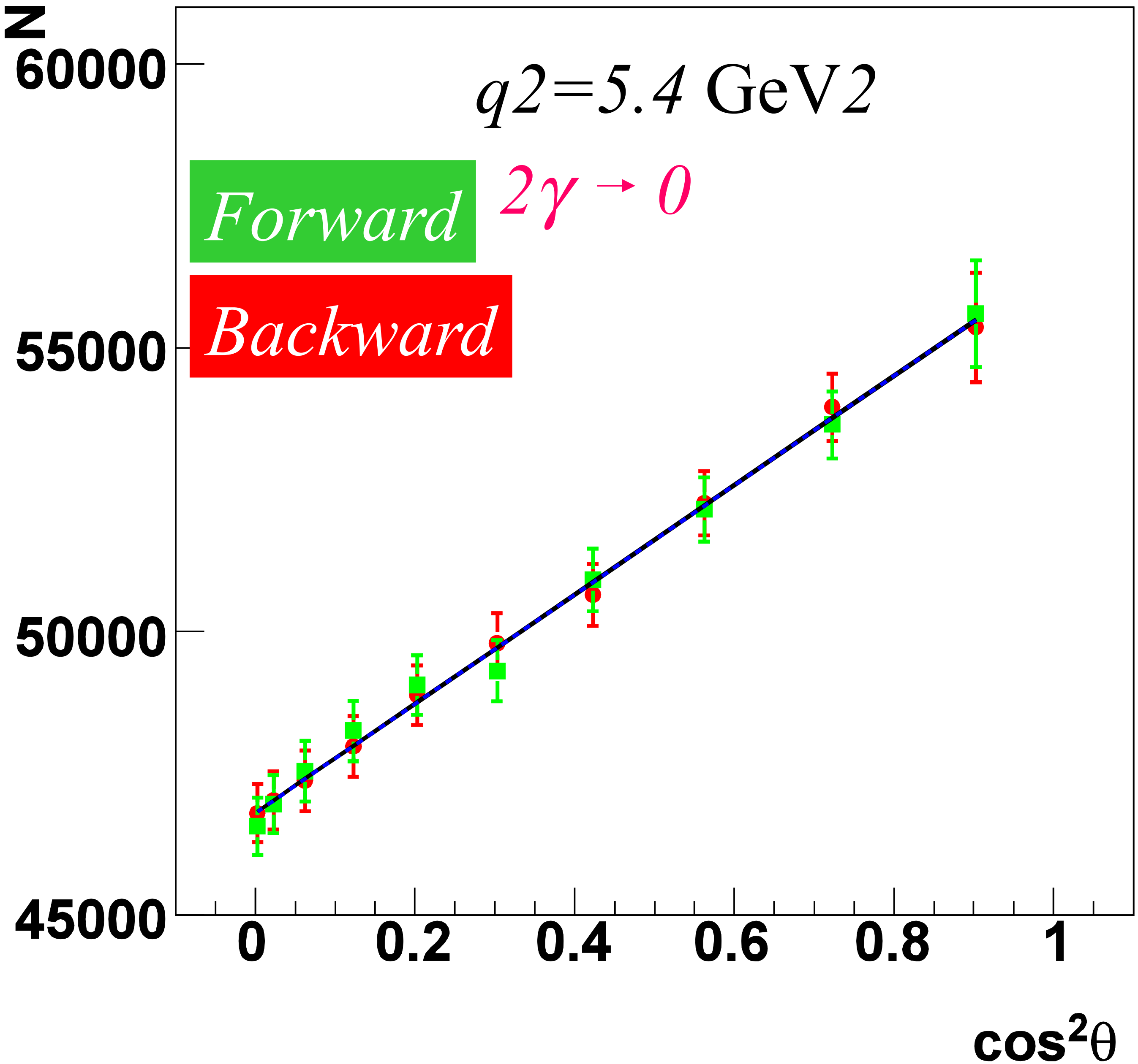
2 γ exchange → *Quadratic Fit in* $x = \cos\theta$

$$y = a_0 + a_2 x + a_1 x^2$$

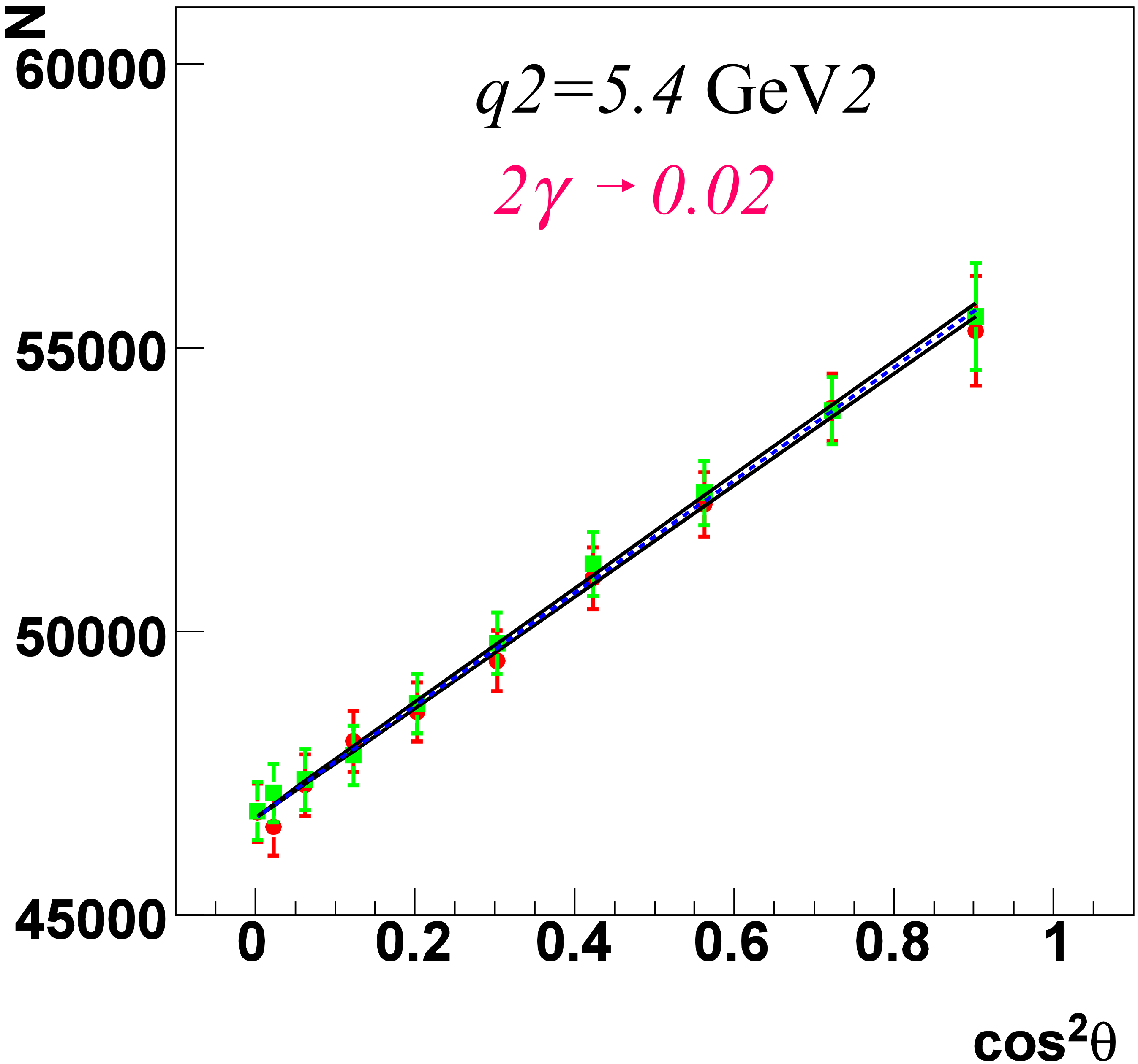
$$a_2 = \frac{2\sqrt{\tau(\tau-1)}(G_E - \tau G_M)F_3}{\tau|G_M|^2 + |G_E|^2}$$

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

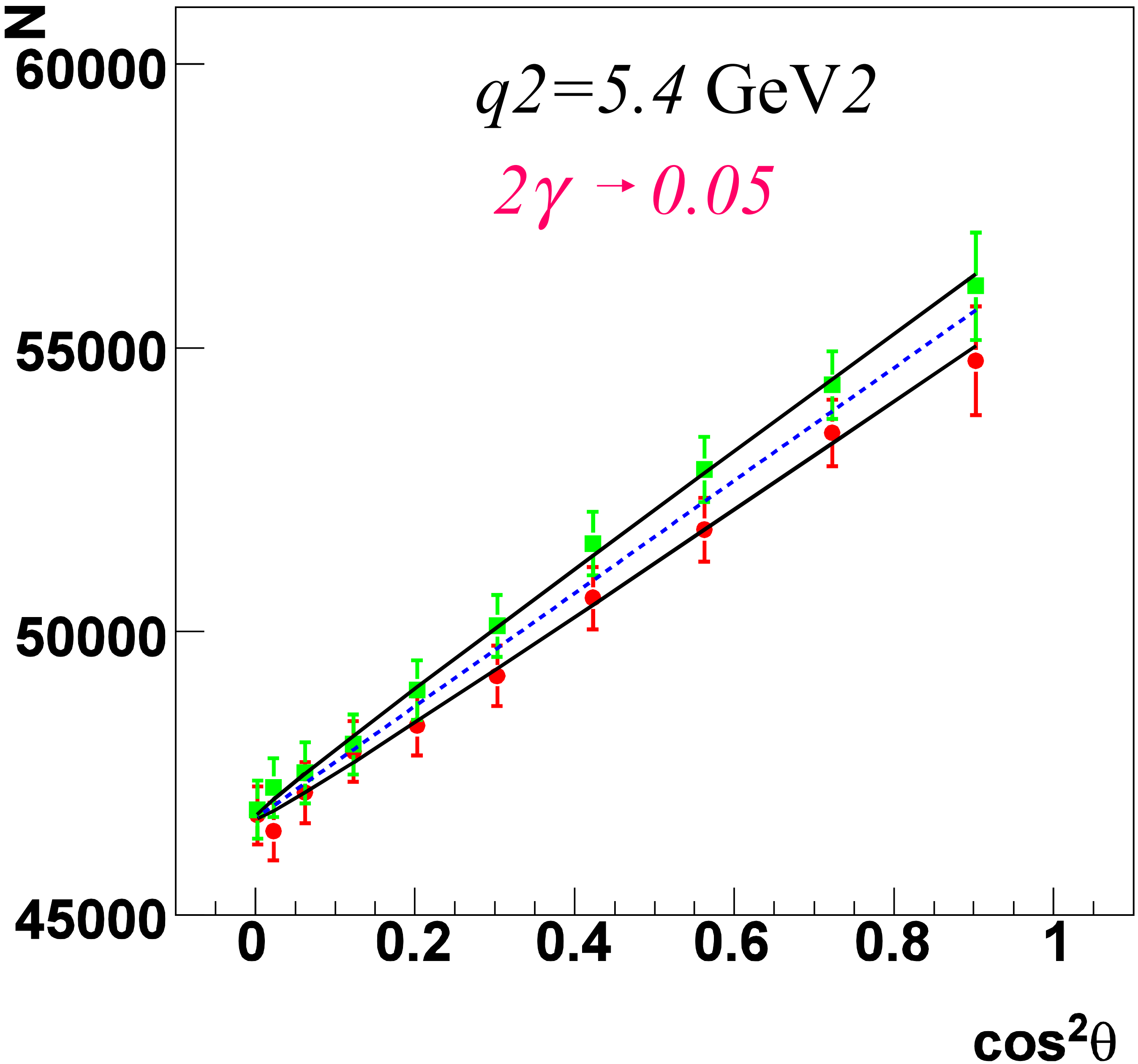
Fitting the angular distributions...



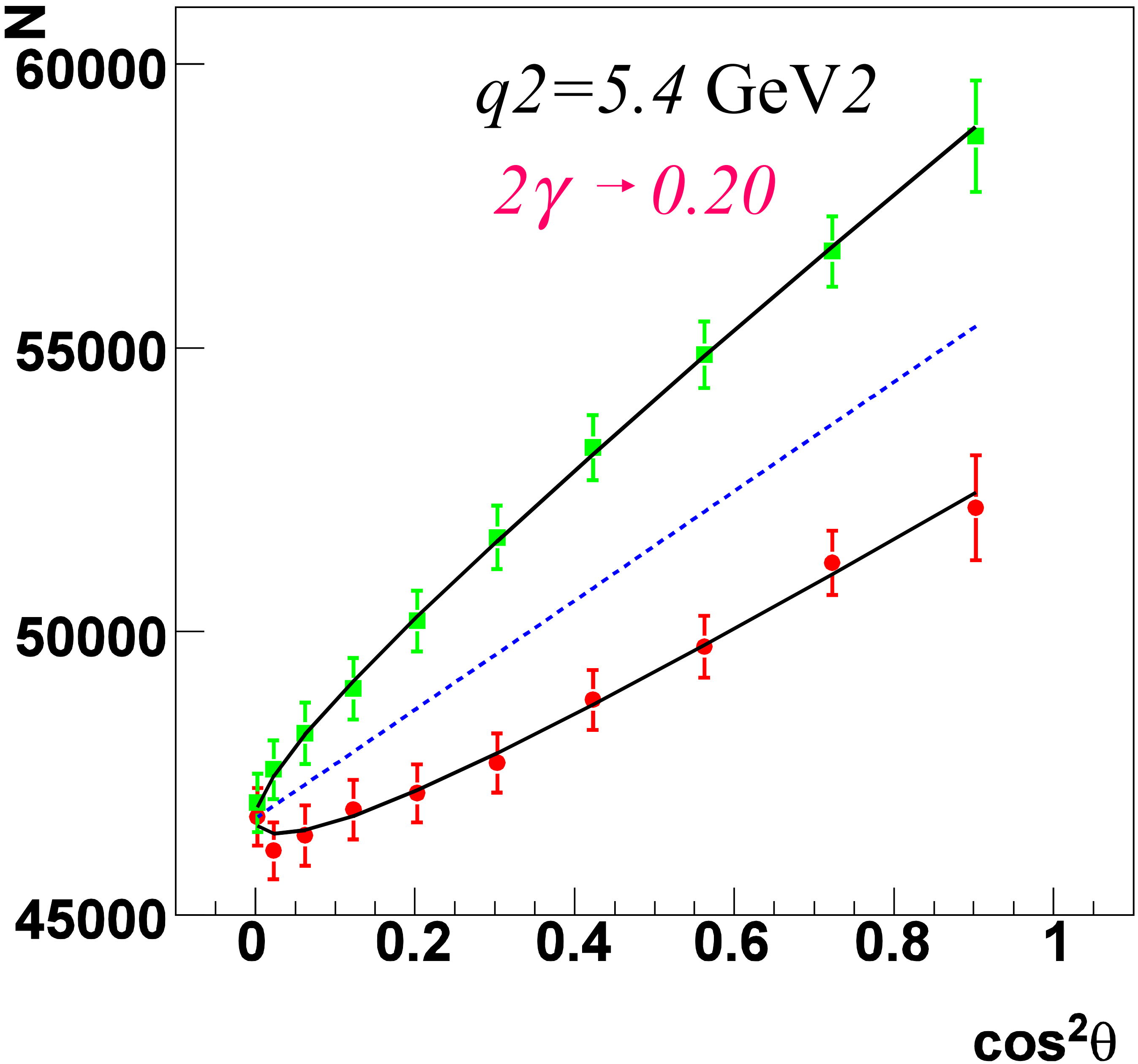
Fitting the angular distributions...



Fitting the angular distributions...



Fitting the angular distributions…



Which alternative for Gep?

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

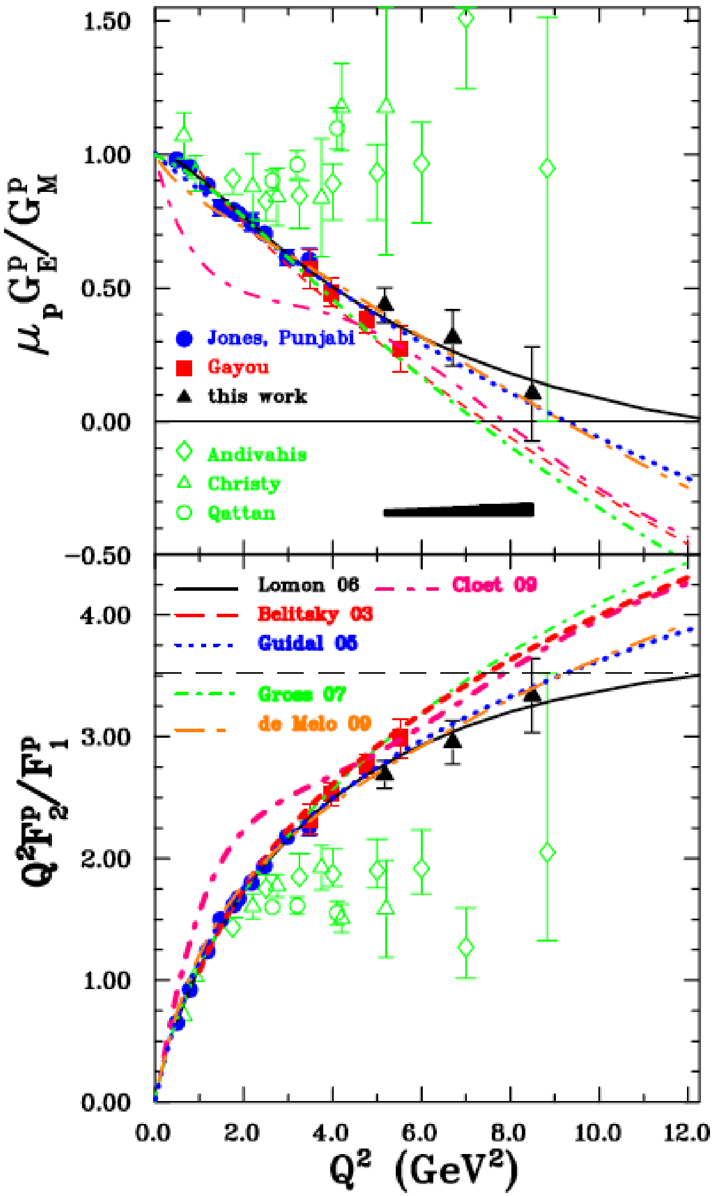
3) QCD scaling not reached

3) Zero crossing of Gep?

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

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

PRC85 (2012) 045203



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

Precision Rosenbluth Measurement of the Proton Elastic Form Factors

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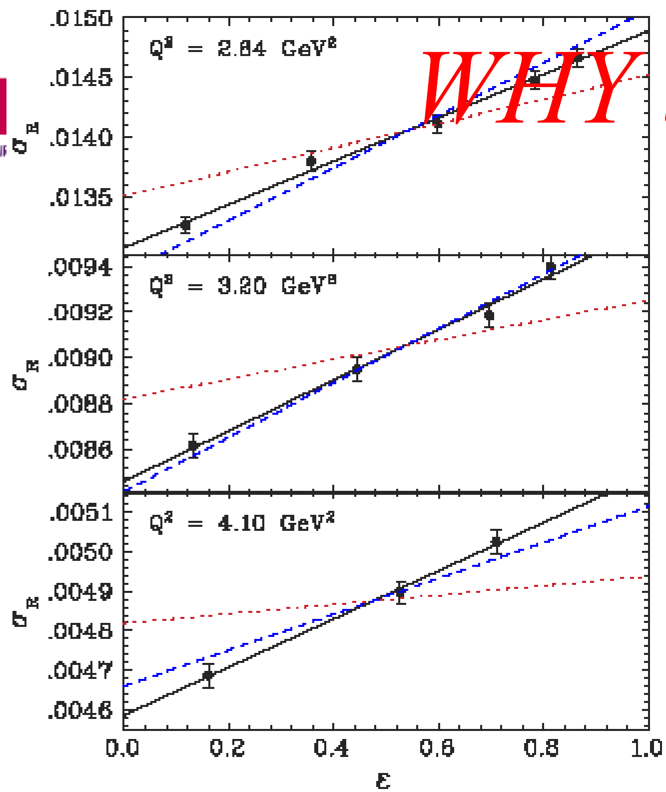
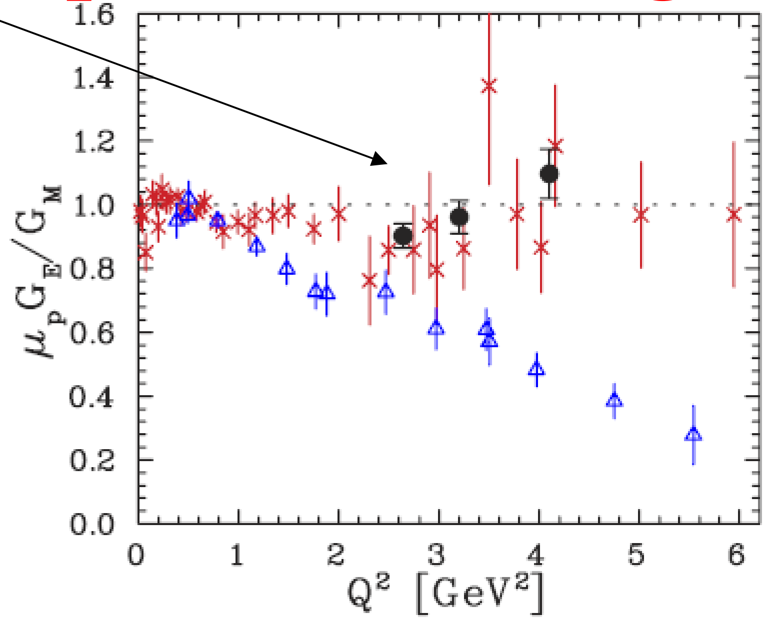


WHY these points are aligned?



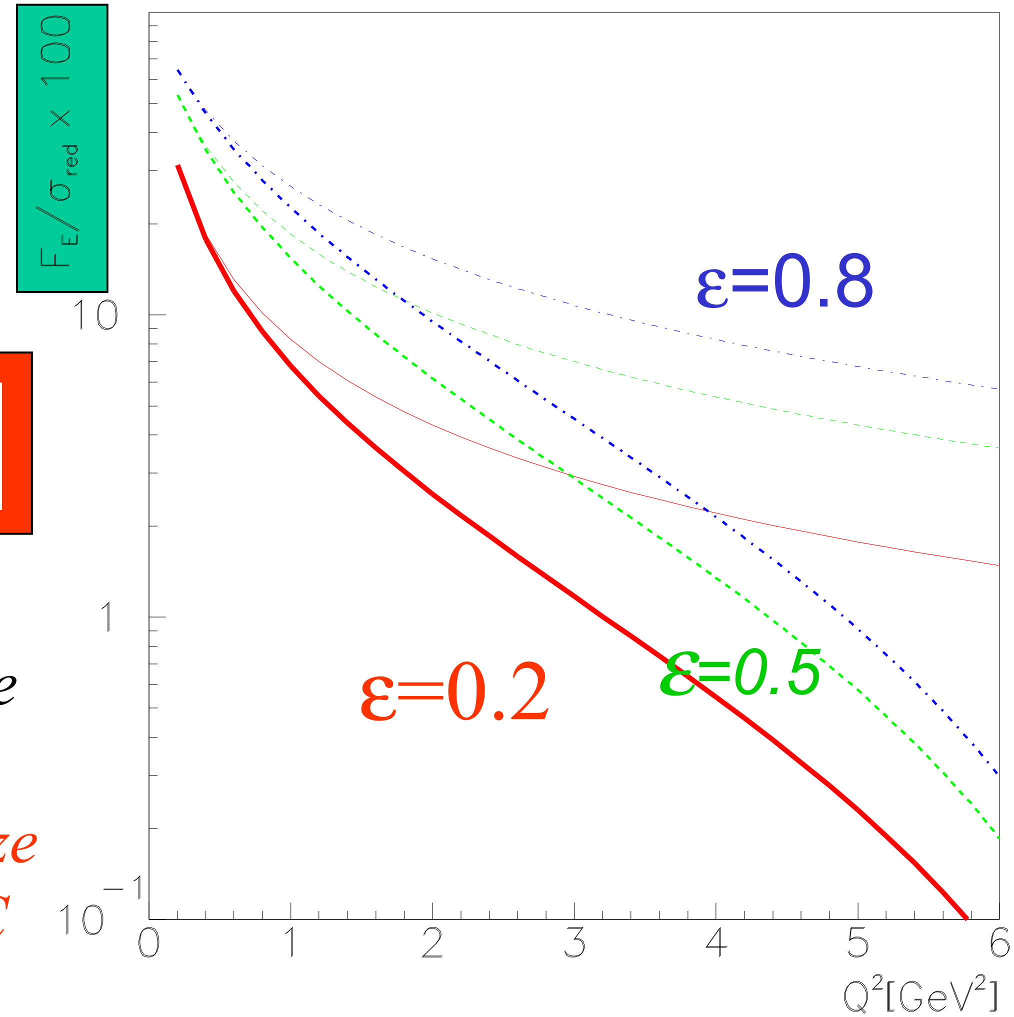
Rosenbluth separation

Contribution of the electric term

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

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

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



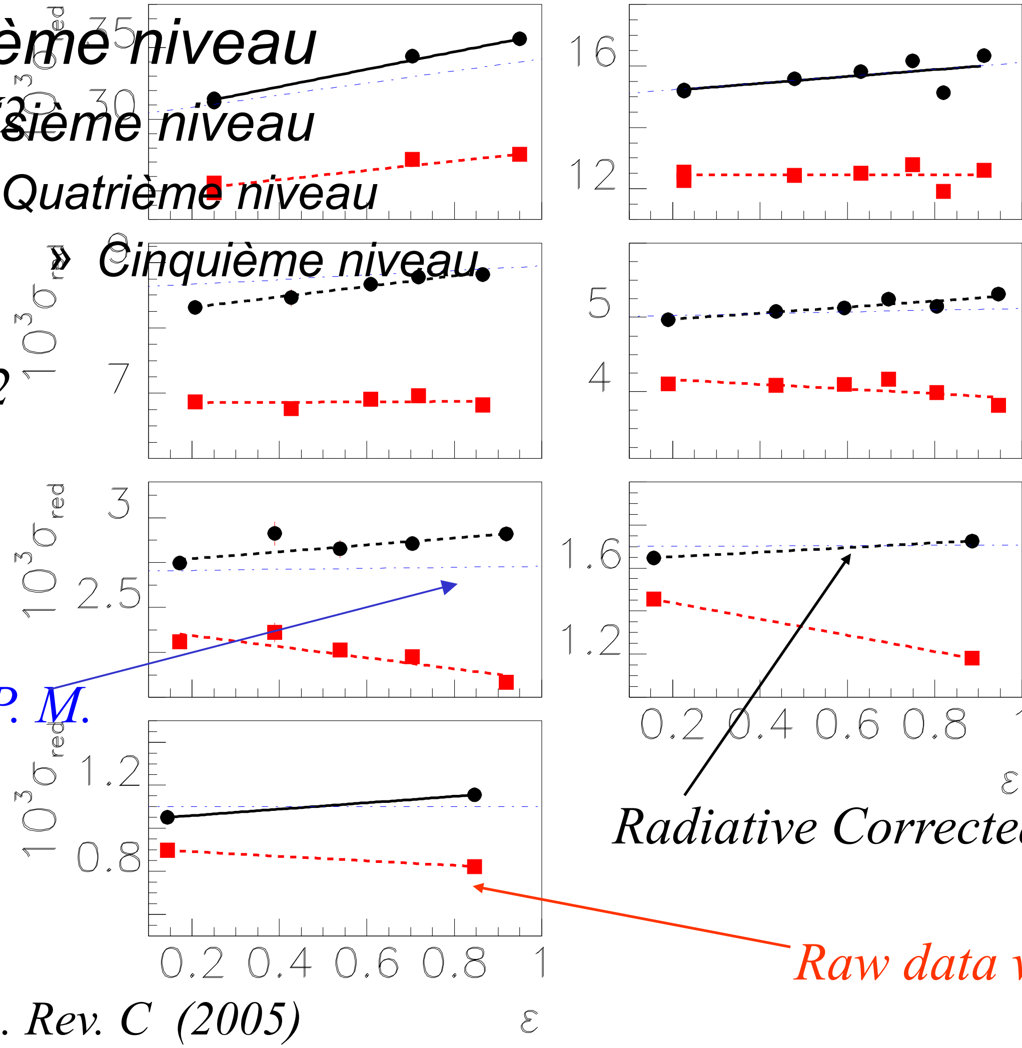
…to be compared to the absolute value of the error on σ and to the size and ε dependence of RC

E.T-G, Phys. Part. Nucl. Lett. ***4,*** *281 (2007)*

Reduced cross section and RC

- Cliquez pour modifier les styles du texte du masque
  - Deuxième niveau
    - Troisième niveau
      - Quatrième niveau
        - » Cinquième niveau

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



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

Radiative Corrections (ep)

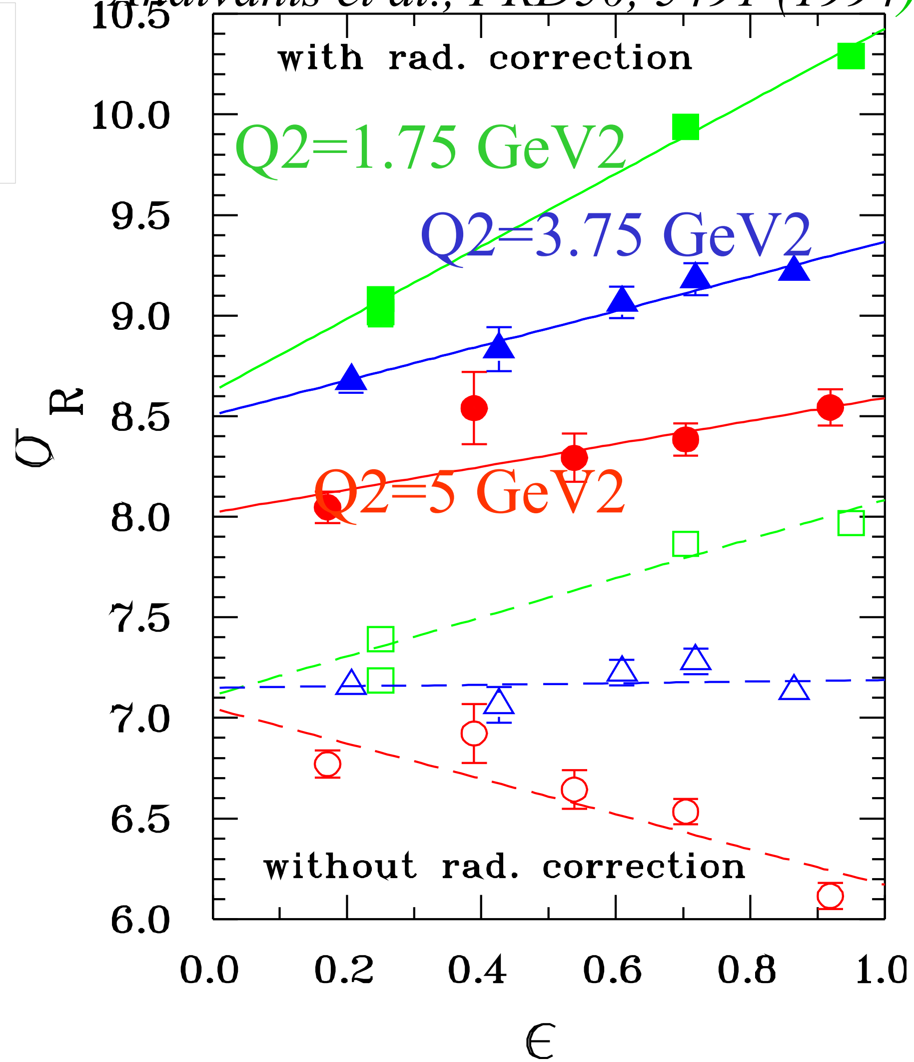
$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2$$

May change the slope of σR (and even the sign !!!)

RC to the cross section:

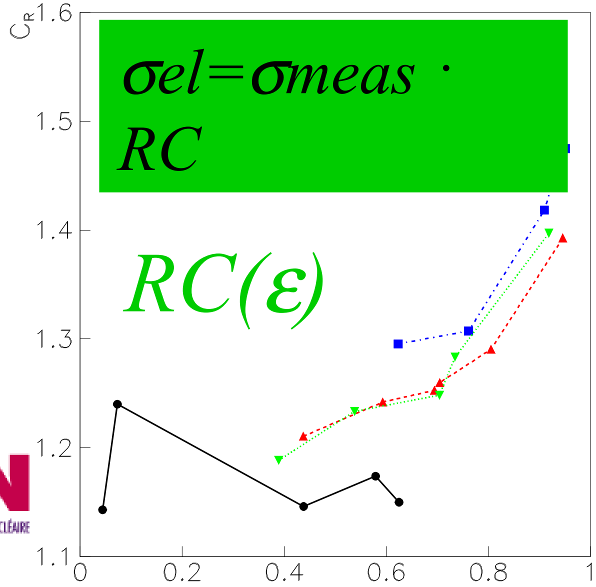
- *large (may reach 40%)*
- *ε and Q2 dependent*
- *calculated at first order*

Andivahis et al., PRD50, 5491 (1994)



C.F. Perdrisat,, Progr. Part. Nucl. Phys. 59,694 (2007)

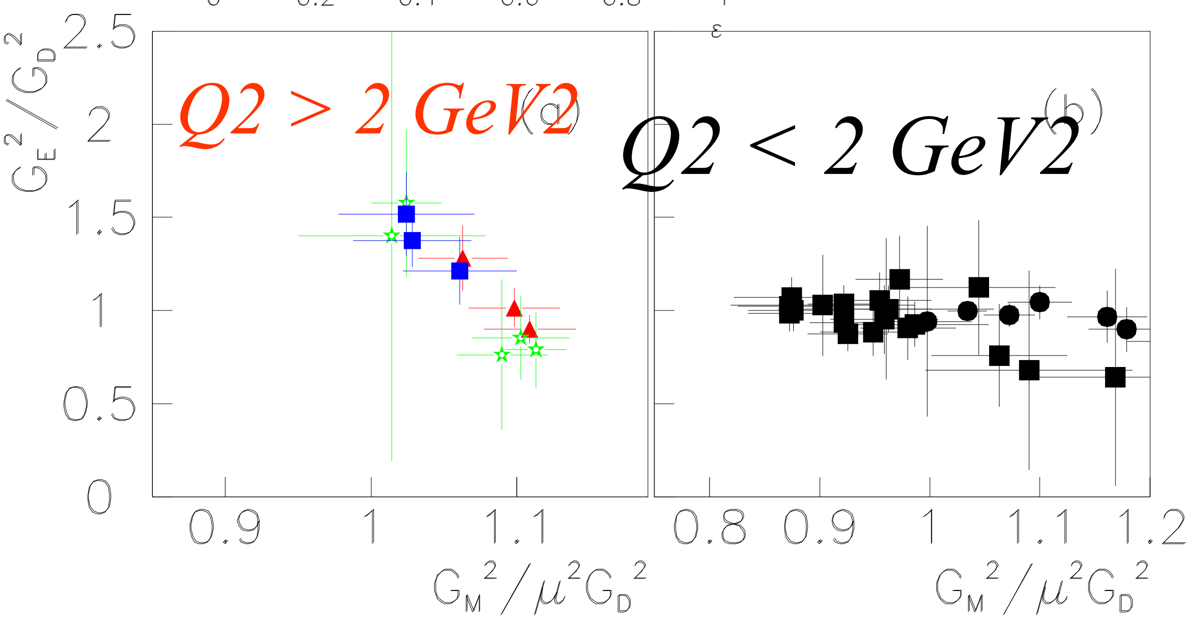
Experimental correlation

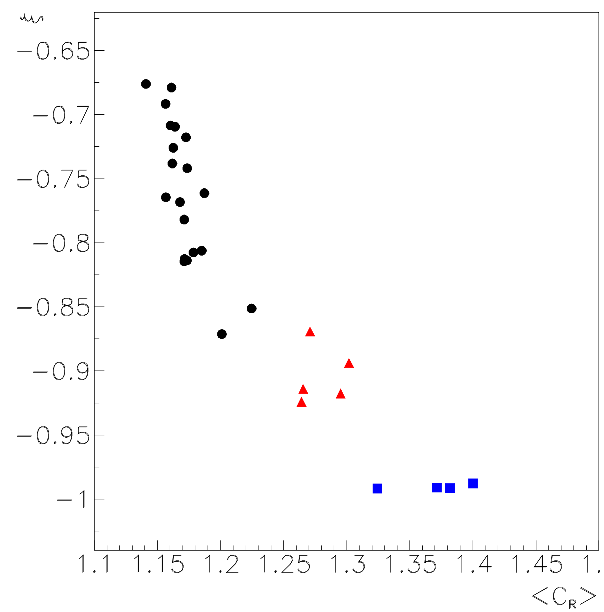


$$\sigma_{red} = \tau G^2_{Mp} + \epsilon G^2_{Ep}$$

only published values!!

Correlation (<RC•ε>)



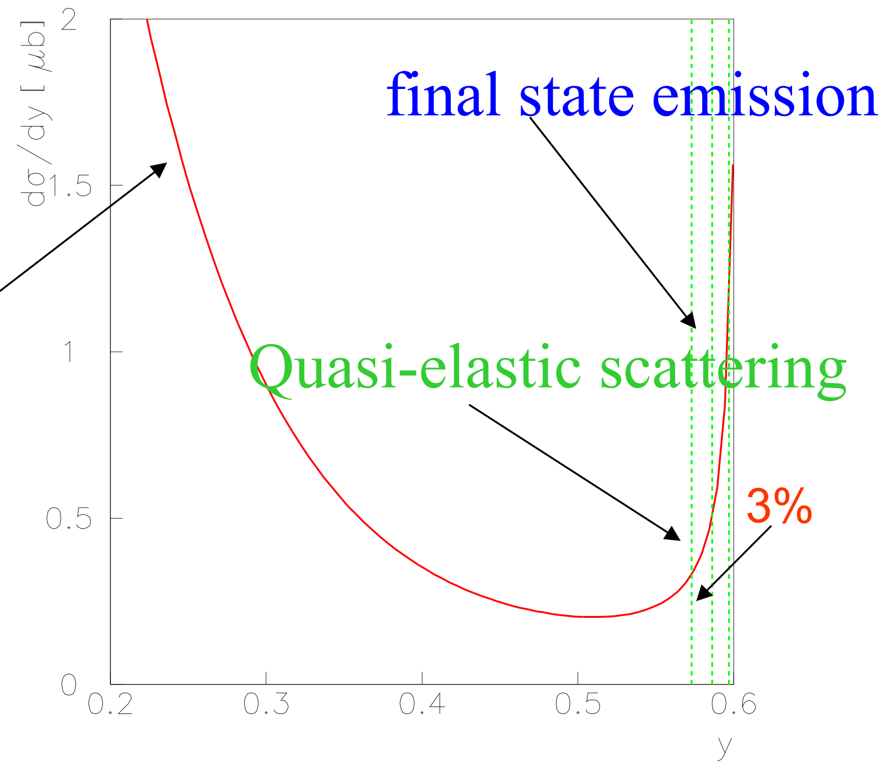


Scattered electron energy

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

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

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 Q2

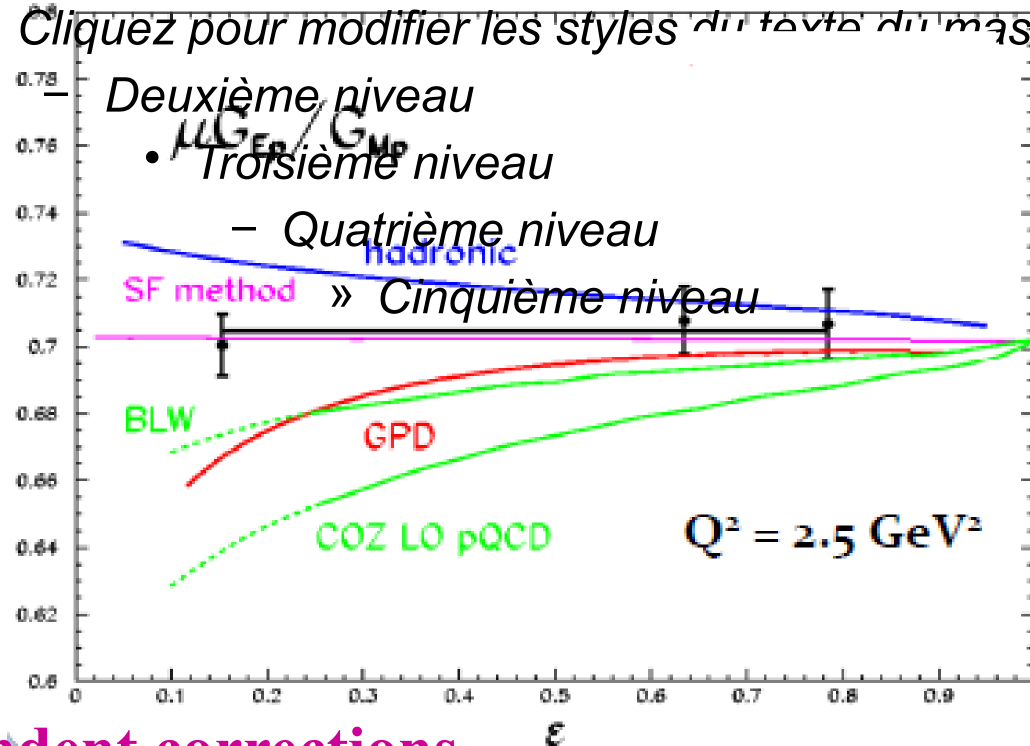
Y0

All orders of PT needed →

beyond Mo & Tsai approximation

Polarization ratio (ε-dependence)

- ***DATA: No evidence of ε-dependence at 1% level***
- ***MODELS: large correction (opposite sign) at small ε***



- Cliquez pour modifier les styles du texte du masque
  - Deuxième niveau
    - Troisième niveau
      - Quatrième niveau
        - » Cinquième niveau

- **SF method: ε-independent corrections**

- ***Theory: corrections to the Born approximation at Q2= 2.5 GeV2***

  Y. Bystritskiy, E.A. Kuraev and E.T.-G, Phys.Rev.C75: 015207 (2007)

  P. Blunden et al., Phys. Rev. C72:034612 (2005) ***(mainly GM)***

  A. Afanasev et al., Phys. Rev. D72:013008 (2005) ***(mainly GE)***

  N.Kivel and M.Vanderhaeghen, Phys. Rev. Lett.103:092004 (2009). (high Q2)

Summary

Our Suggestion for search of 2γ effects:

- Search for model independent statements (M.P. Rekalo, G. Gakh..)
- Exact calculation in frame of QED (p~μ)
- Prove that QED box is upper limit of QCD box diagram
- Study analytical properties of the Compton amplitude
- Compare to experimental data

Our Conclusions for elastic ep scattering

- Two photon contribution is negligible (real part) (E.A. Kuraev)
- Radiative corrections are huge: take into account higher order effects (Structure Functions method)) (Yu. Bystricky)

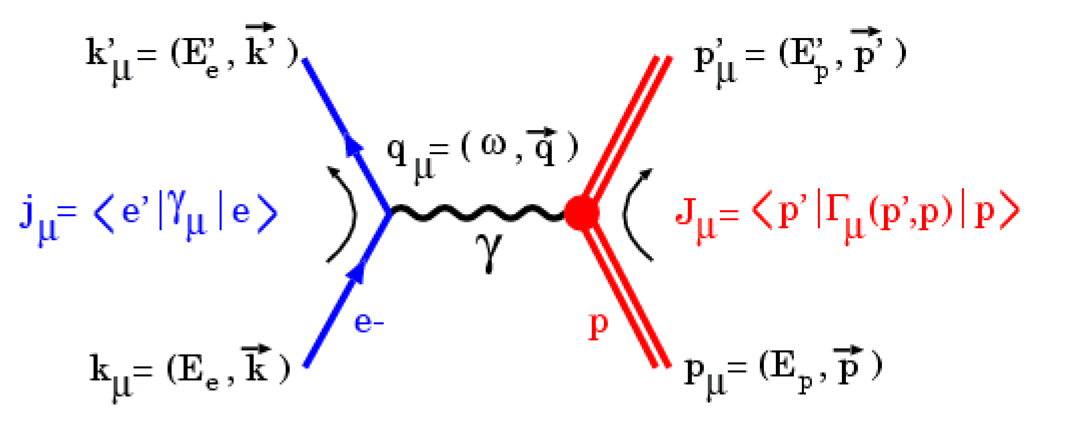
Look for Multiple Photon Exchange in e-A scattering

- Small angle e, or p or pbar - Heavy ion scattering

E.A. Kuraev, M. Shatnev, E.T-G., PRC80 (2009) 018201

2γ effects are expected to be larger in TL region (complex nature)

The Pauli and Dirac Form Factors



- The electromagnetic current in terms of the Pauli and Dirac FFs:

$$\Gamma_\mu(p',p) \quad = \quad \underbrace{F_1(Q^2)}_{Dirac}\gamma_\mu + \frac{i\kappa_p}{2M_p}\underbrace{F_2(Q^2)}_{Pauli}\sigma_{\mu\nu}q^\nu$$

- Related to the Sachs FFs :

$$G_E(Q^2) = F_1(Q^2) - \kappa_p \frac{Q^2}{4M_p^2} F_2(Q^2)$$

$$G_M(Q^2) = F_1(Q^2) + \kappa_p F_2(Q^2)$$

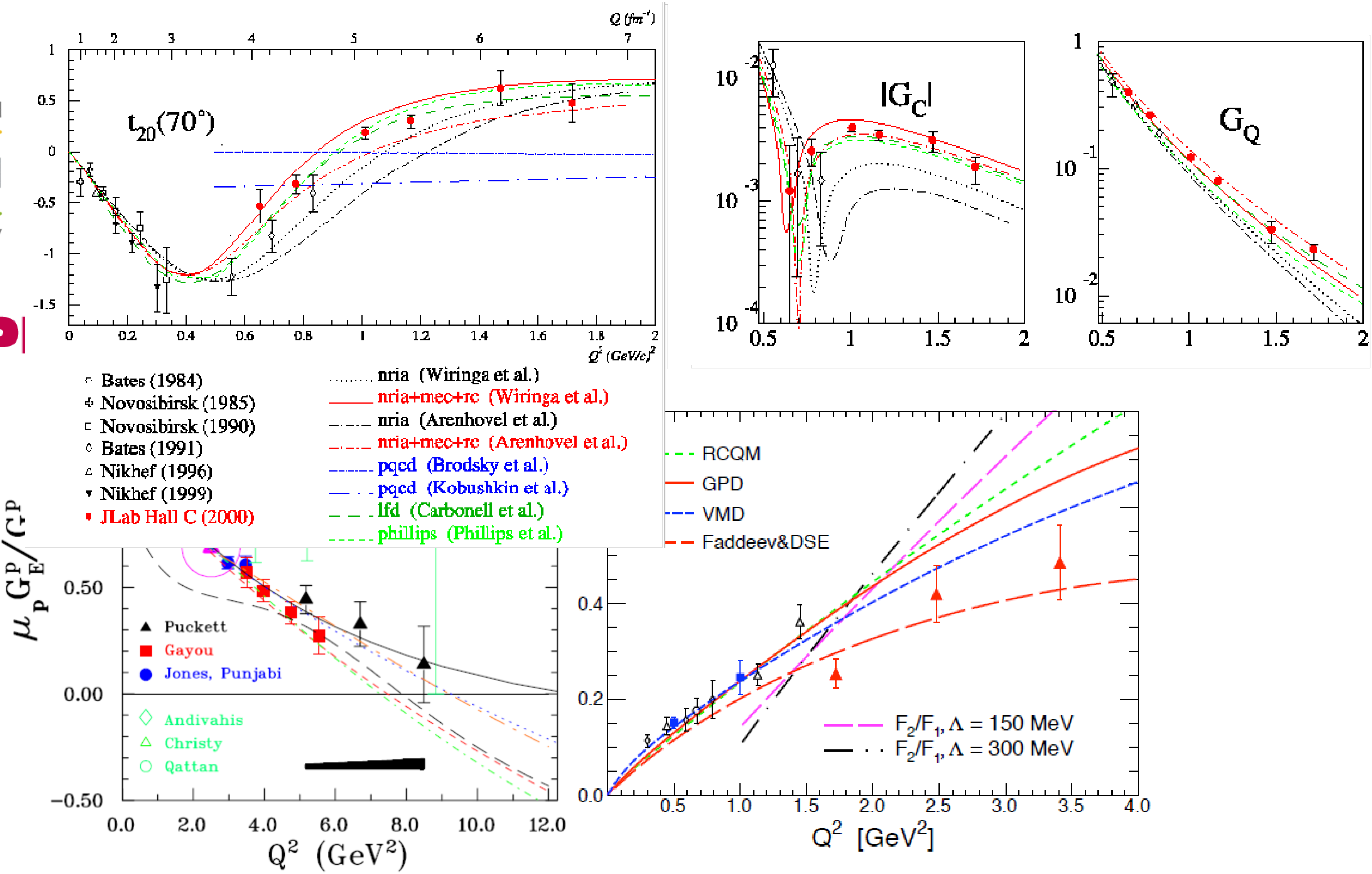
Normalization

F1p(0)=1, F2p(0)= κp

GEp(0)=1,

GMp(0)=μp=2.79

Systematics



Differential cross section (SF)

$$\bar{p}(p_-) + p(p_+) \longrightarrow e_+(y_+) + e_-(y_-) + (\gamma(k))$$

Energy fractions of the leptons

$$\frac{d\sigma}{dc\,dy_+dy_-} = \int dx_+dx_-\mathcal{D}(x_+, L_s)\mathcal{D}(x_-, L_s) \times \frac{d\sigma_B(x_-p_-, x_+p_+, z_+, z_-)}{dc}\frac{1}{|\Pi(sx_+x_-)|^2} \times \left(1 + \frac{\alpha}{\pi}K\right)\frac{1}{z_+z_-}\mathcal{D}\left(\frac{y_+}{z_+}, L_e\right) \times \mathcal{D}\left(\frac{y_-}{z_-}, L_e\right) + \left(\frac{d\sigma}{dc}\right)^{\text{odd}},$$

K-factor

Partition function

Odd term

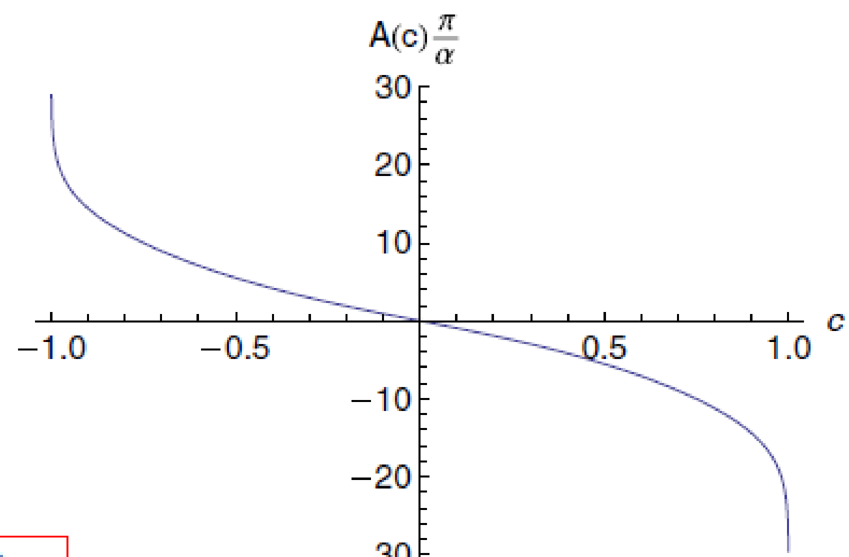
- *The structure function of the lepton*

$$\mathcal{D}(x, L) = \frac{1}{2}b(1-x)^{(b/2)-1}\left(1 + \frac{3b}{8}\right) - \frac{1}{4}b(1+x) + O(b^2), \qquad b = \frac{2\alpha}{\pi}(L-1).$$

Charge Asymmetry

$$\frac{d\sigma^{\mathrm{odd}}}{dc} = \frac{\alpha^3}{2s} F(c),$$

$$F(c) = c\left(-6 - \frac{\pi^2}{3} + 2\ln\frac{2}{1+c}\ln\frac{2}{1-c} + \ln\frac{4}{1-c^2}\right) + 3(1-2c^2)\ln\frac{1+c}{1-c} + \frac{6}{1-c} \times\left(-1 + \frac{2}{1-c}\ln\frac{2}{1+c}\right) - \frac{6}{1+c} \times\left(-1 + \frac{2}{1+c}\ln\frac{2}{1-c}\right) + 4(1+c^2) \times\left[\mathrm{Li}_2\left(\frac{1-c}{2}\right) - \mathrm{Li}_2\left(\frac{1+c}{2}\right)\right].$$



$$A(c) = \frac{d\sigma(c) - d\sigma(-c)}{d\sigma(c) + d\sigma(-c)} = \frac{\alpha}{\pi}\frac{F(c)}{1+c^2}$$

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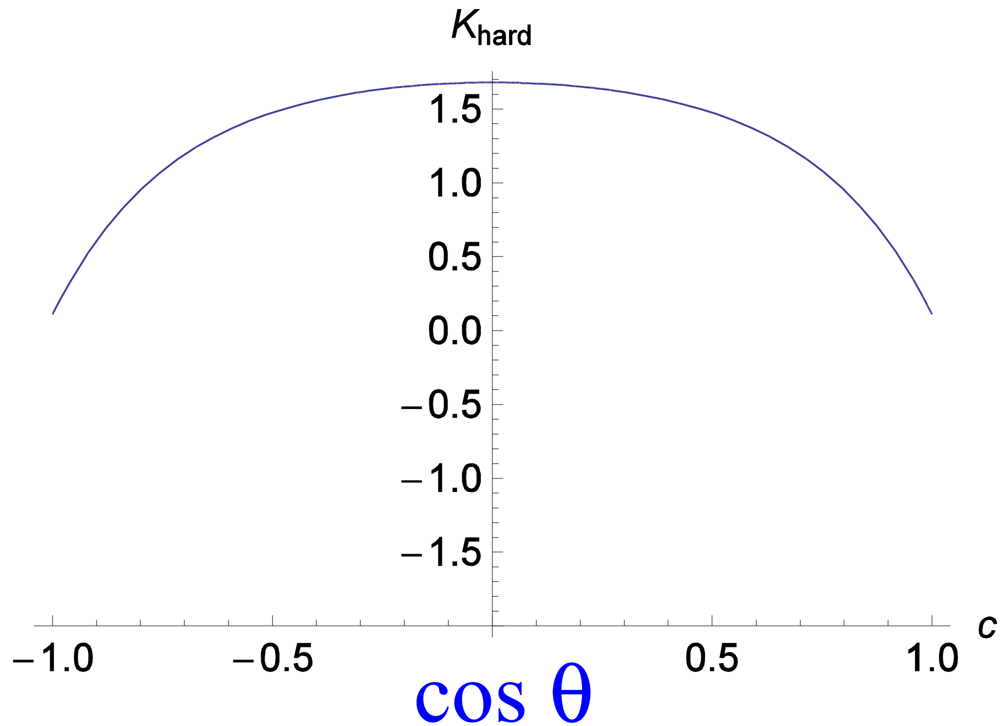
K-factor (hard)

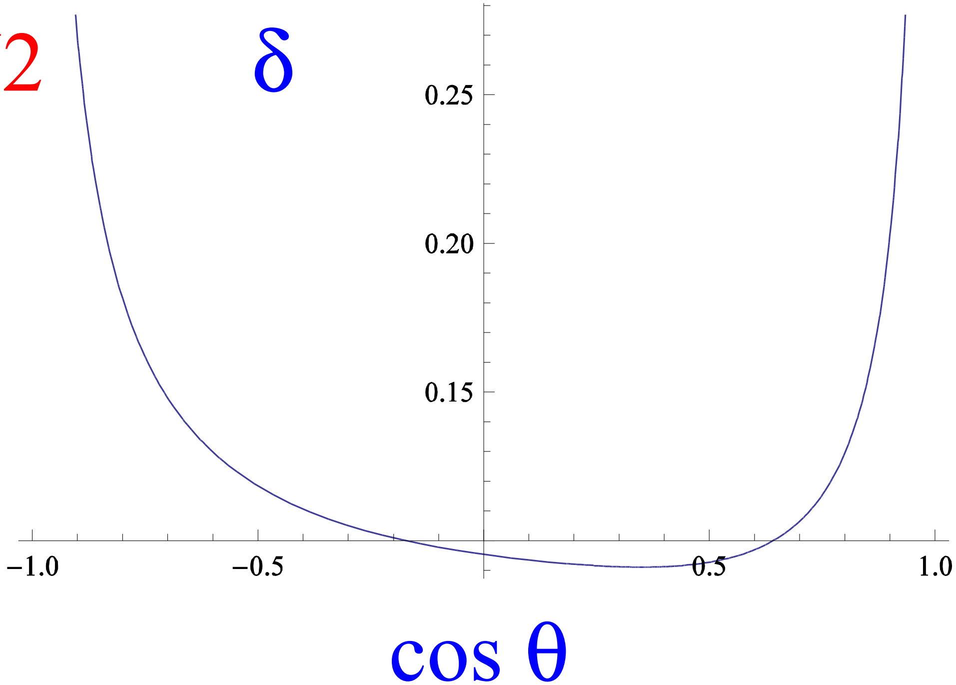


1. of the order of one
2. from the even part of the cross section

Radiative correction factor

Ncorr=Nraw(1+δ)

s=10 GeV2



Integrated in all phase space for γ
Proton structureless

QED versus QCD

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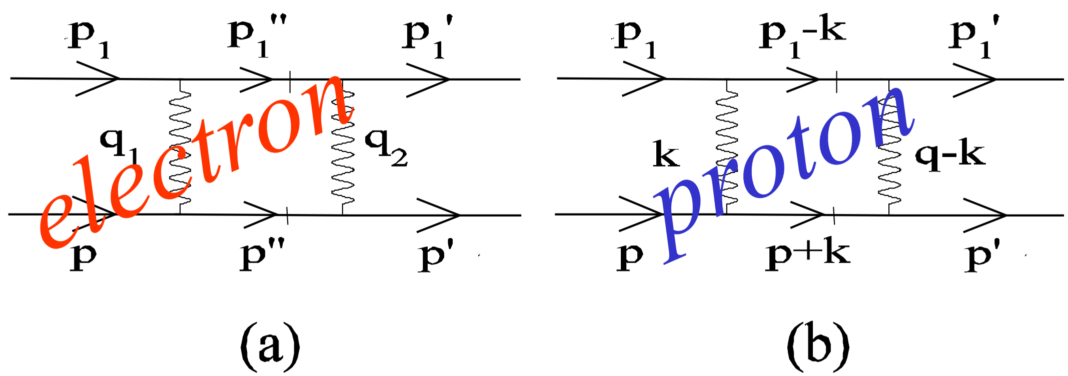


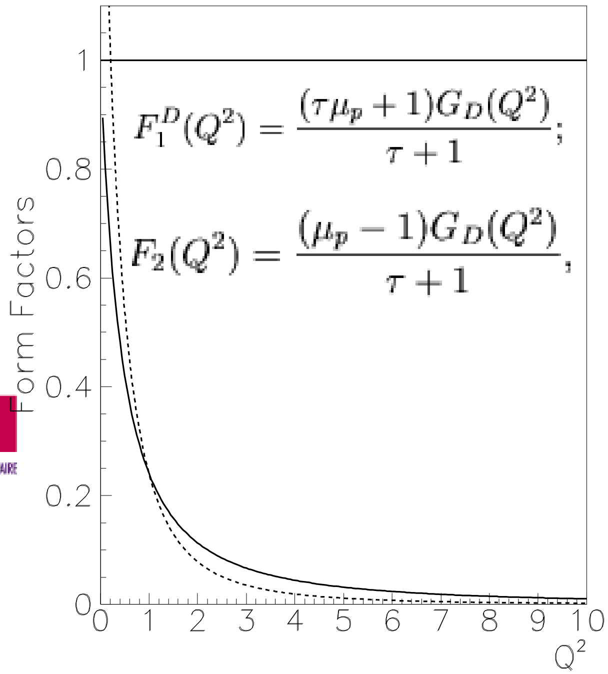
Imaginary part of the 2γ amplitude

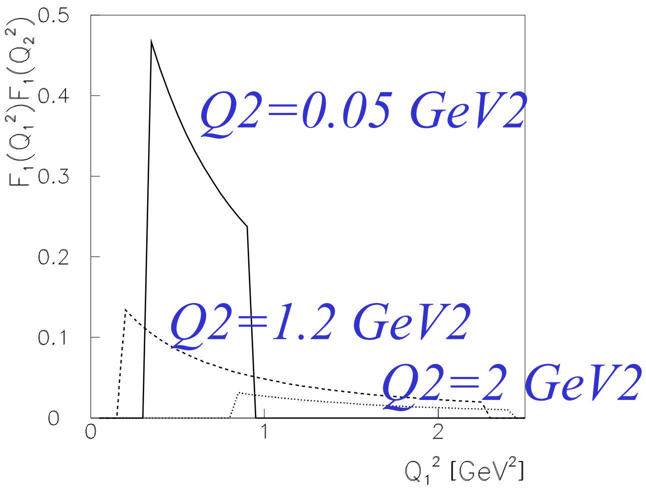
$$\mathcal{M}_{1a} = \frac{1}{\sqrt{8s}} \int \frac{dQ_1^2 dQ_2^2}{\sqrt{\mathcal{D}_1}(Q_1^2+\lambda^2)(Q_2^2+\lambda^2)}$$

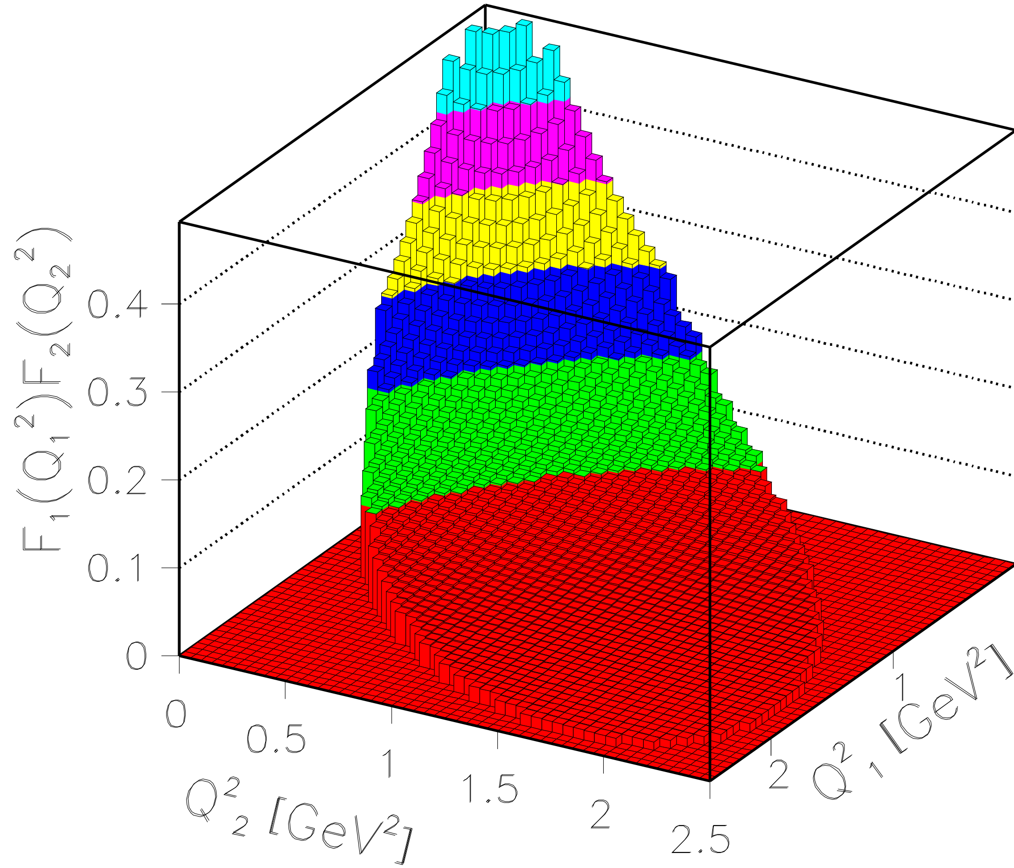
$$\mathcal{M}_{1b} = \frac{1}{\sqrt{8s}} \int \frac{dQ_1^2 dQ_2^2 F(Q_1^2) F(Q_2^2)}{\sqrt{\mathcal{D}_1}(Q_1^2+\lambda^2)(Q_2^2+\lambda^2)}$$

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

QED versus QCD



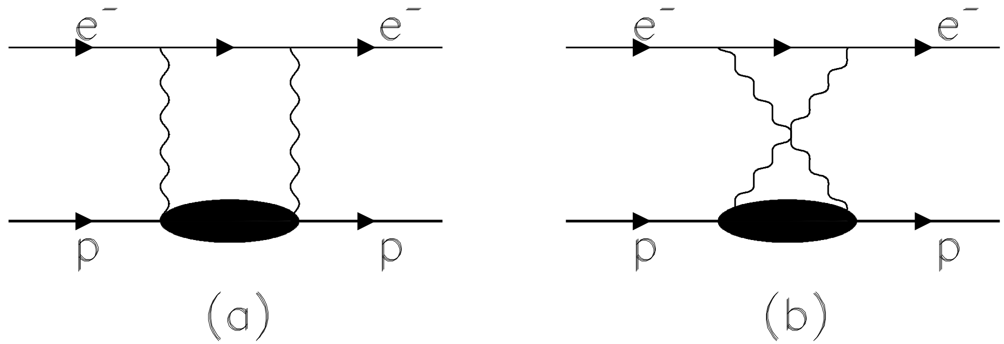




$F_1(Q_1^2)F_2(Q_2^2) < 1$

- Cliquez pour modifier les styles du texte du mas
  - Deuxième niveau
    - Troisième niveau
      - Quatrième niveau
        - » Cinquième niveau

Interference of $1\gamma \otimes 2\gamma$ 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*

- *eμ (elastic) scattering is upper limit for ep*

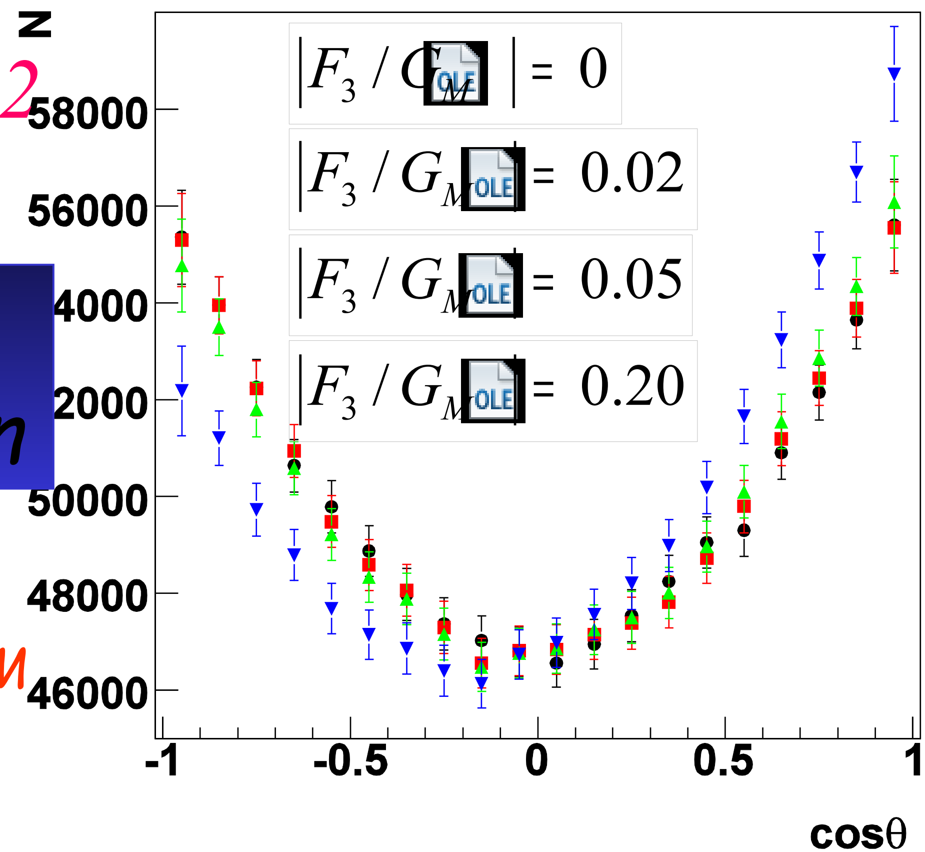
E.A.Kuraev, V. Bytev, Yu. Bystricky, E.T-G , Phys. Rev. D74 013003 (1076)

Simulations

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

$q2$=5.4,8.2,13.8 GeV2

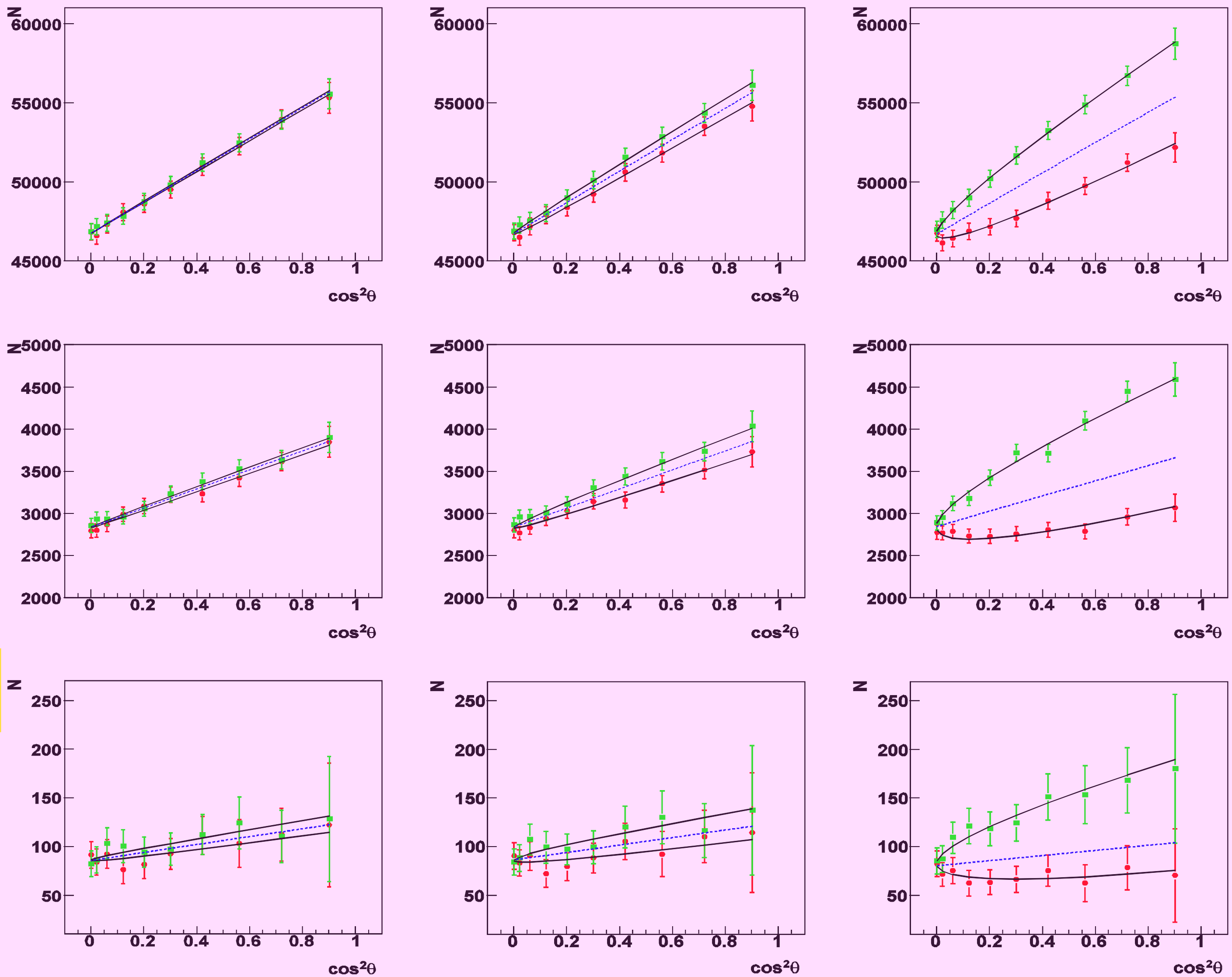
Main effect:
odd cosθ–distribution



Approximations:

- Neglect contributions to GE,GM
- Consider only real part

2γ 0.02 0.05 0.20



ni
n
a

$N = a0 + a2 \cos\theta \sin\theta + a1 \cos 2\theta,\ a2 \sim 2\gamma$

q^2 (GeV^2)	case	a_0		a_2	χ^2	χ^2/N_f	$\mathcal{R}$	$\mathcal{A}$
5.4		46798 ± 182		9927 ± 485	1.94	0.11	$1/00 \pm 0.017$	0.21 ± 0.01
		46713 ± 182		9926 ± 485	1.45	0.09	0.997 ± 0.017	0.21 ± 0.01
	$2\gamma \cdot 0.05$	46714 ± 182	662 ± 240	9924 ± 485	1.47	0.09	0.998 ± 0.017	0.21 ± 0.01
	$2\gamma \cdot 0.20$	46710 ± 182	3398 ± 240	9933 ± 485	1.13	0.07	0.997 ± 0.017	0.21 ± 0.01
8.2		2832 ± 30		1128 ± 85	3.66	0.22	1.001 ± 0.095	0.398 ± 0.030
		2833 ± 29		1130 ± 85	3.78	0.22	1.000 ± 0.095	0.399 ± 0.030
	$2\gamma \cdot 0.05$	2830 ± 30	163 ± 42	1136 ± 85	3.49	0.21	0.998 ± 0.096	0.401 ± 0.030
	$2\gamma \cdot 0.20$	2842 ± 30	805 ± 42	1106 ± 84	6.54	0.38	1.012 ± 0.092	0.389 ± 0.030
13.84		85 ± 5		39 ± 19	4.49	0.26	1.149 ± 1.09	0.469 ± 0.230
		86 ± 5		41 ± 19	3.36	0.19	1.133 ± 1.116	0.481 ± 0.228
	$2\gamma \cdot 0.05$	86 ± 5	16 ± 9	41 ± 19	3.67	0.22	1.137 ± 1.107	0.478 ± 0.228
	$2\gamma \cdot 0.20$	82 ± 5	59 ± 9	55 ± 18	2.12	0.12	0.848 ± 2.121	0.672 ± 0.233