CRITICAL ANALYSIS OF TWO PHOTON EXCHANGE IN ELECTRON/POSITRON - PROTON ELASTIC SCATTERING

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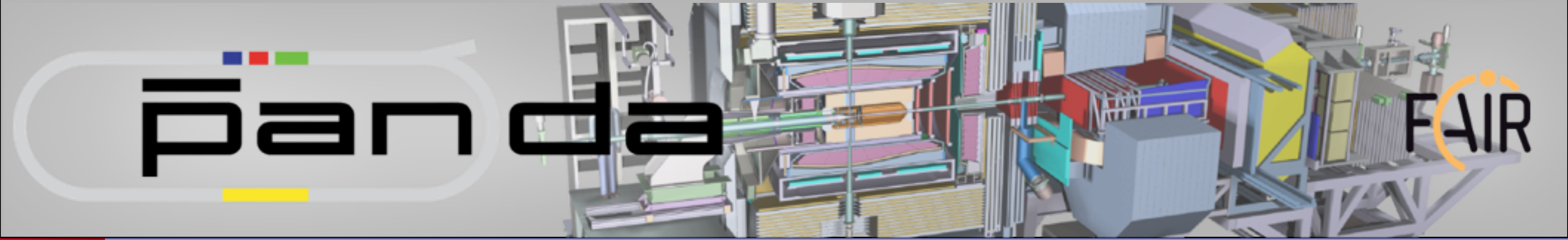
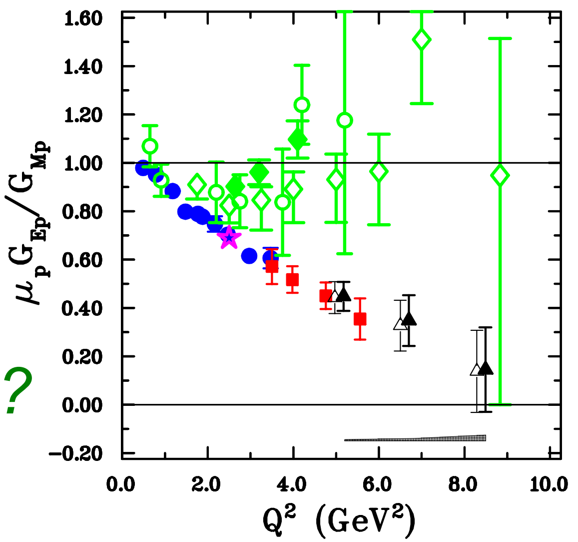


Plan

- Introduction

Last GEp results:
discrepancy between data from
Rosenbluth and Akhiezer-Rekalo methods

2γ-exchange as a solution??



- Why is it important for PANDA (TL FFs)?
- Is there any experimental evidence?
- Three new experiments on e^+p/e^-p cross sections ratio

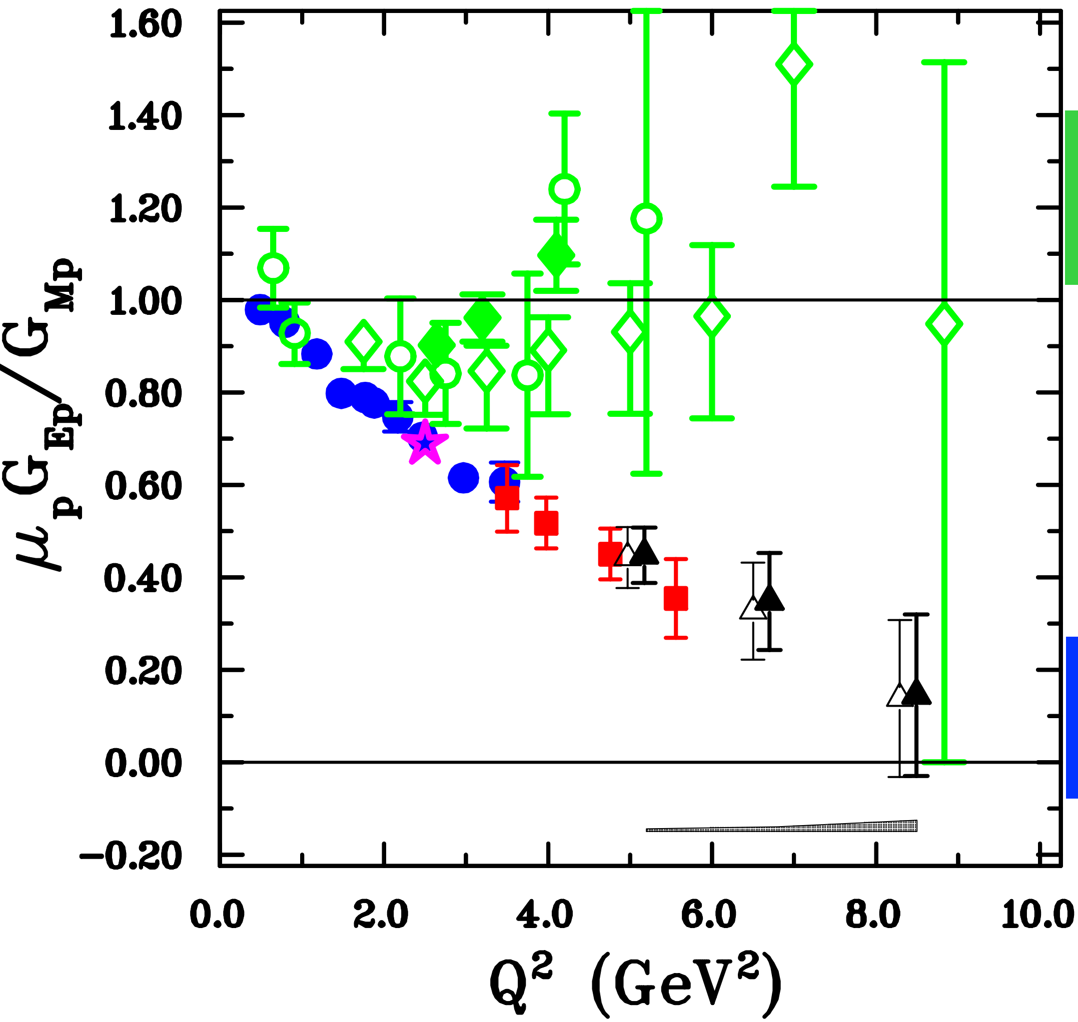
    VEPP (Novosibirsk)
    OLYMPUS (DESY)
    CLAS (Jlab)

- The consequences

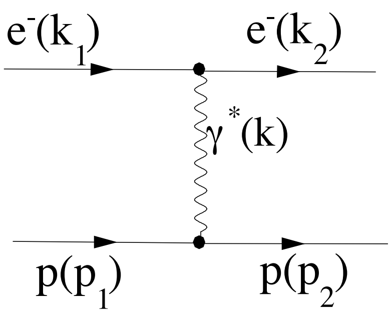
VEPP-3
Novosibirsk

Jefferson Lab

EM proton form factors



Unpolarized cross section
Rosenbluth method



Polarization Method
A.I. Akhiezer, M.P. Rekalo, 1967

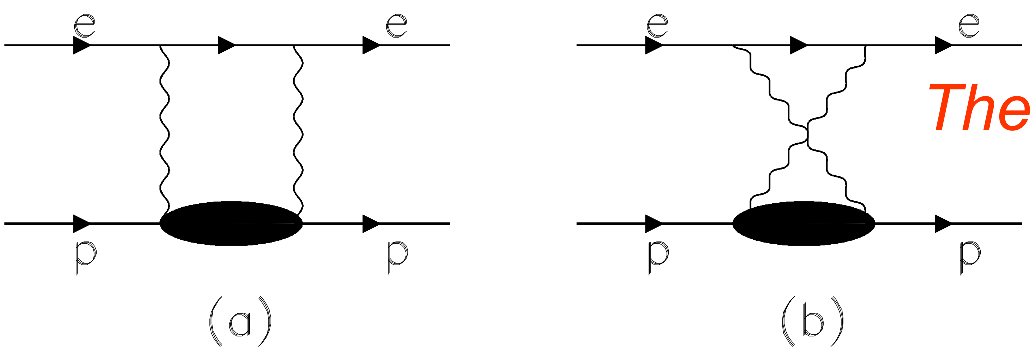
2γ exchange ?

A.J.R. Puckett et al, PRL (2010) , PRC (2012), PRC (2017)

Two photon exchange

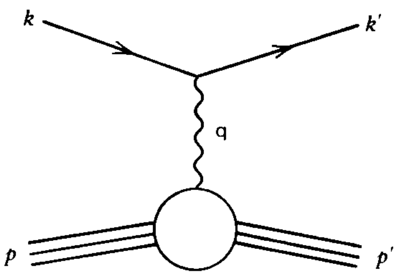
- *1γ-2γ interference is of the order of α=e²/4p=1/137*

- 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…] that, at large momentum transfer, the sharp decrease of the FFs, if the if the momentum is shared between the two photons, may compensate α
- The calculation of the box amplitude requires the description of intermediate nucleon excitation and of their FFs at any Q^2…
- Different calculations give quantitatively different results .



Theory not enough constrained!

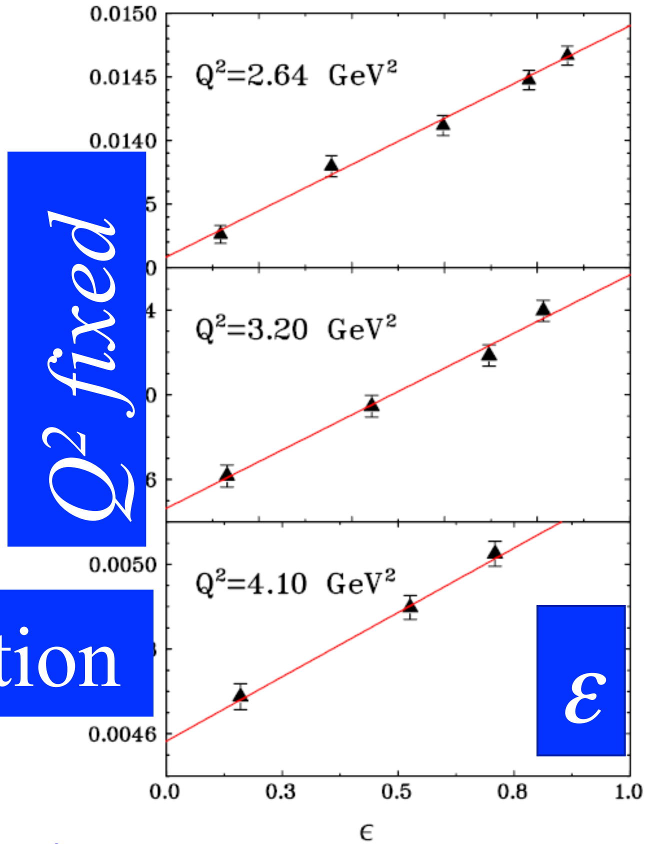
The Rosenbluth separation



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

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

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



PRL 94, 142301 (2005)

Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

→ Holds for 1γ exchange only

The polarization method (theory:1967)

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

PHYSICS

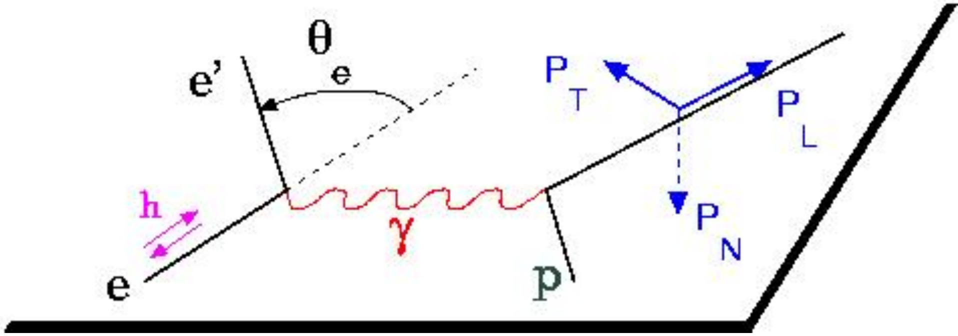
POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

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,

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



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

Polarized beam and target or

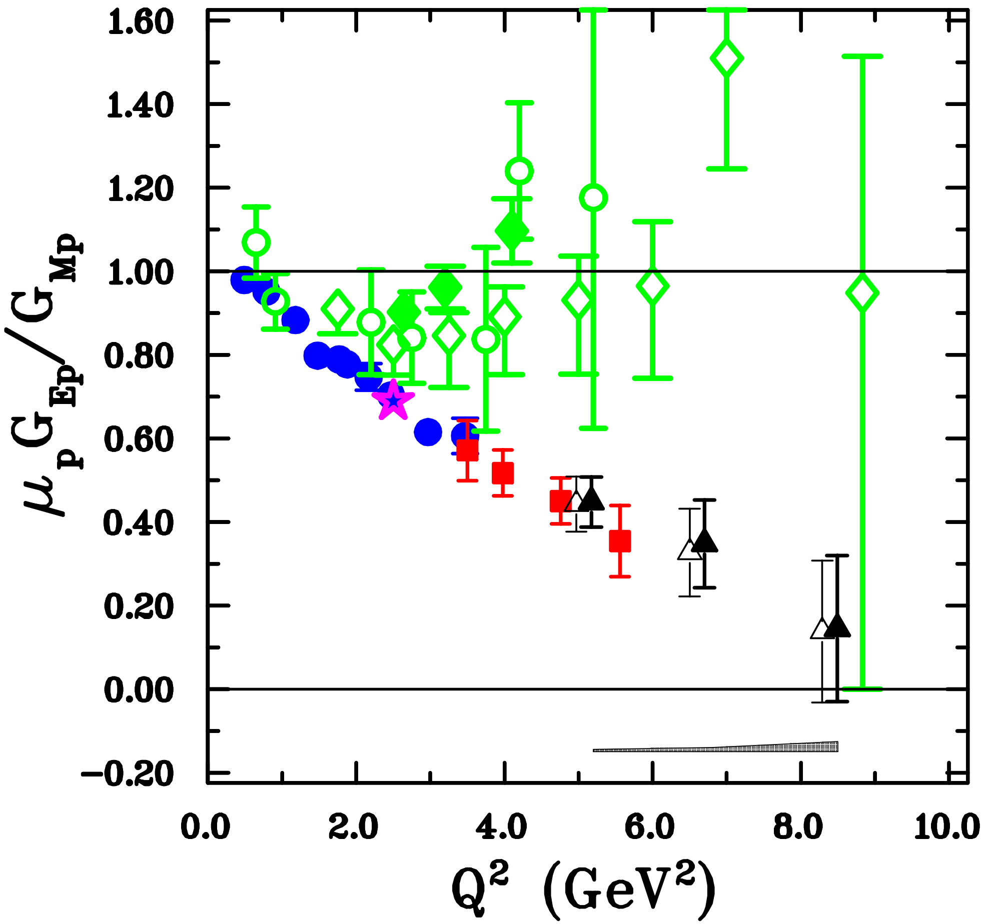
polarized beam and recoil proton polarization

Polarization Experiments

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

Jlab-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) , PRC (2012), PRC (2017)

Model independent statements

A sizable 2γ contribution would invalidate the FFs extraction as well as all experimental results based on the Born approximation.

•One-photon exchange:
- •Two (real) EM form factors
- •Functions of one variable (t)

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

- Breaks *the linearity of the Rosenbluth plot*
- Induces:
  - *charge-odd observables* (asymmetry in $e^{\pm}$ p cross section)
  - P-odd polarizations (Py)
- The expansion parameter is ($Z\alpha$), $\alpha = e^2/4\pi = 1/137$.
  - It is expected to increase
    - When Z increases
    - At small angles

electron/positron – proton elastic scattering

$$\frac{d\sigma^{e^\pm h \to e^\pm h}}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}\right]$$

Born approximation

$$|M^\pm|^2 = |\pm M_{1\gamma}|^2 = |M_{1\gamma}|^2$$

2γ exchange:

$$|M^\pm|^2 = |\pm M_{1\gamma} + M_{2\gamma}|^2 = |M_{1\gamma}|^2 \pm 2\,\mathrm{Re}\, M_{1\gamma}M^*_{2\gamma} + |M_{2\gamma}|^2$$

Asymmetry

$$A = \frac{\sigma(e^+p) - \sigma(e^-p)}{\sigma(e^+p) + \sigma(e^-p)} = \frac{2\,\mathrm{Re}\, M_{1\gamma}M_{2\gamma}}{\sigma_{Born}}$$

The effect is enhanced in the ratio

$$R = \frac{\sigma(e^+p)}{\sigma(e^-p)} = \frac{1+A}{1-A} \cong \sigma_{Born}(1 + 4\,\mathrm{Re}\, M_{1\gamma}M_{2\gamma})$$

Unpolarized cross section

-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.

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°

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

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 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

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

Symmetry relations (annihilation)

- Differential cross section at complementary angles:

The SUM cancels the 2γ contribution:

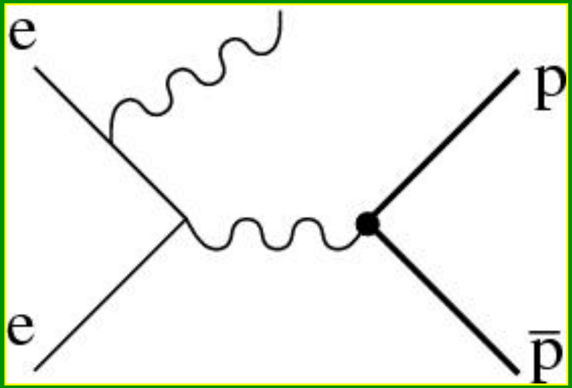
$$\frac{d\sigma_+}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi - \theta) = 2\frac{d\sigma^{Born}}{d\Omega}(\theta)$$

The DIFFERENCE enhances the 2γ contribution:

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

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

Radiative return (ISR)



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

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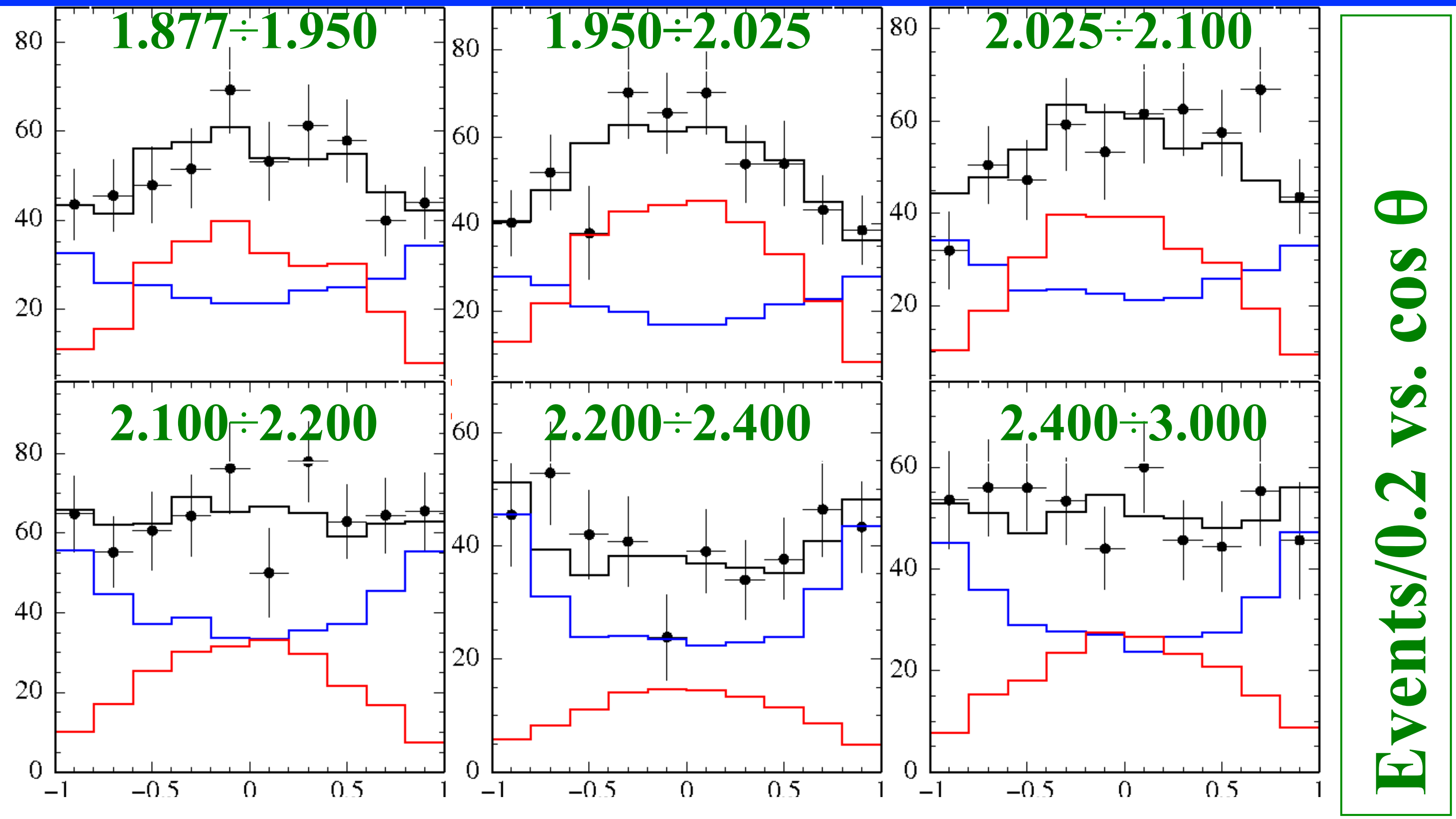
$$\frac{d\sigma(e^+e^- \rightarrow p\bar{p}\gamma)}{dm\, d\cos\theta} = \frac{2m}{s} W(s,x,\theta)\, \boxed{\sigma(e^+e^- \rightarrow p\bar{p})(m),} \quad x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{m^2}{s},$$

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

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

Radiative return (ISR)

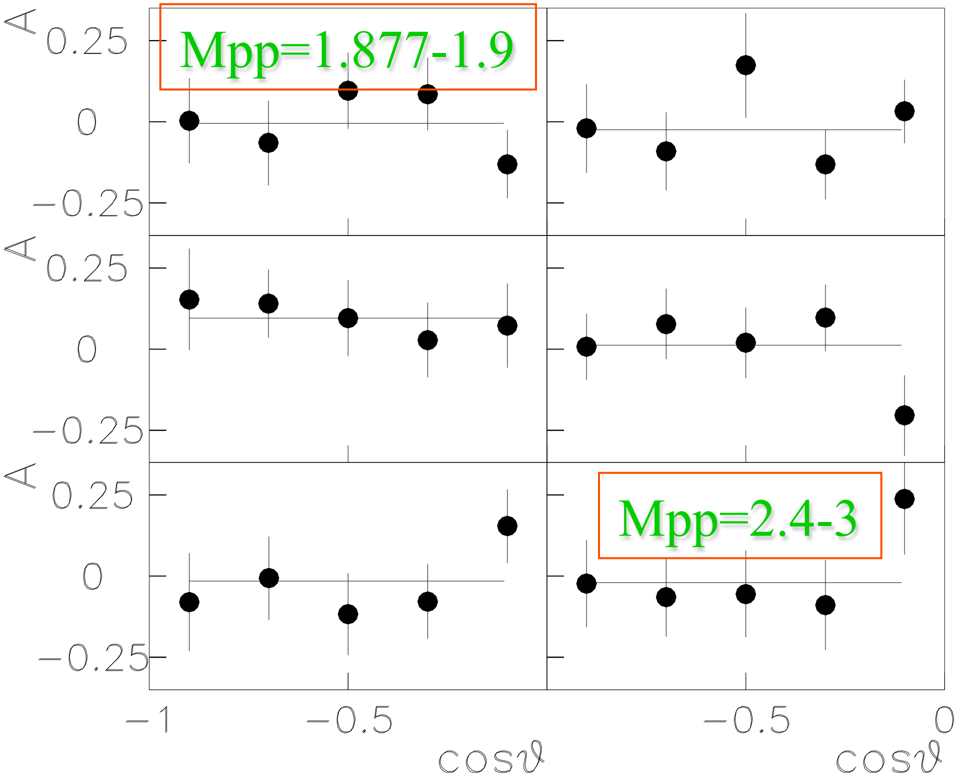


$$\frac{dN}{d\cos\theta_p} = A\left[H_M(\cos\theta, M_{p\bar{p}}) + \left|\frac{G_E}{G_M}\right|^2 H_E(\cos\theta, M_{p\bar{p}})\right]$$

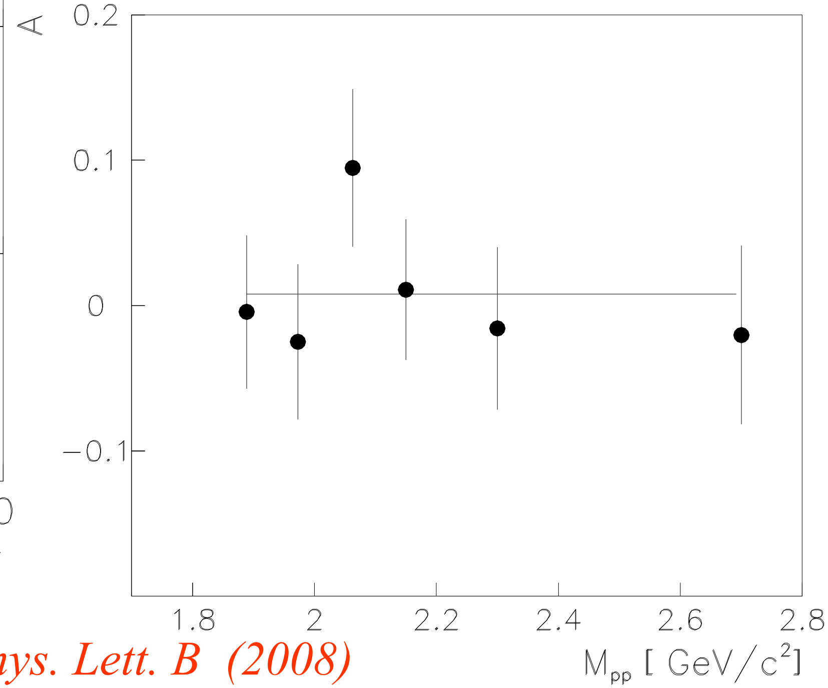
Angular Asymmetry

BABAR

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



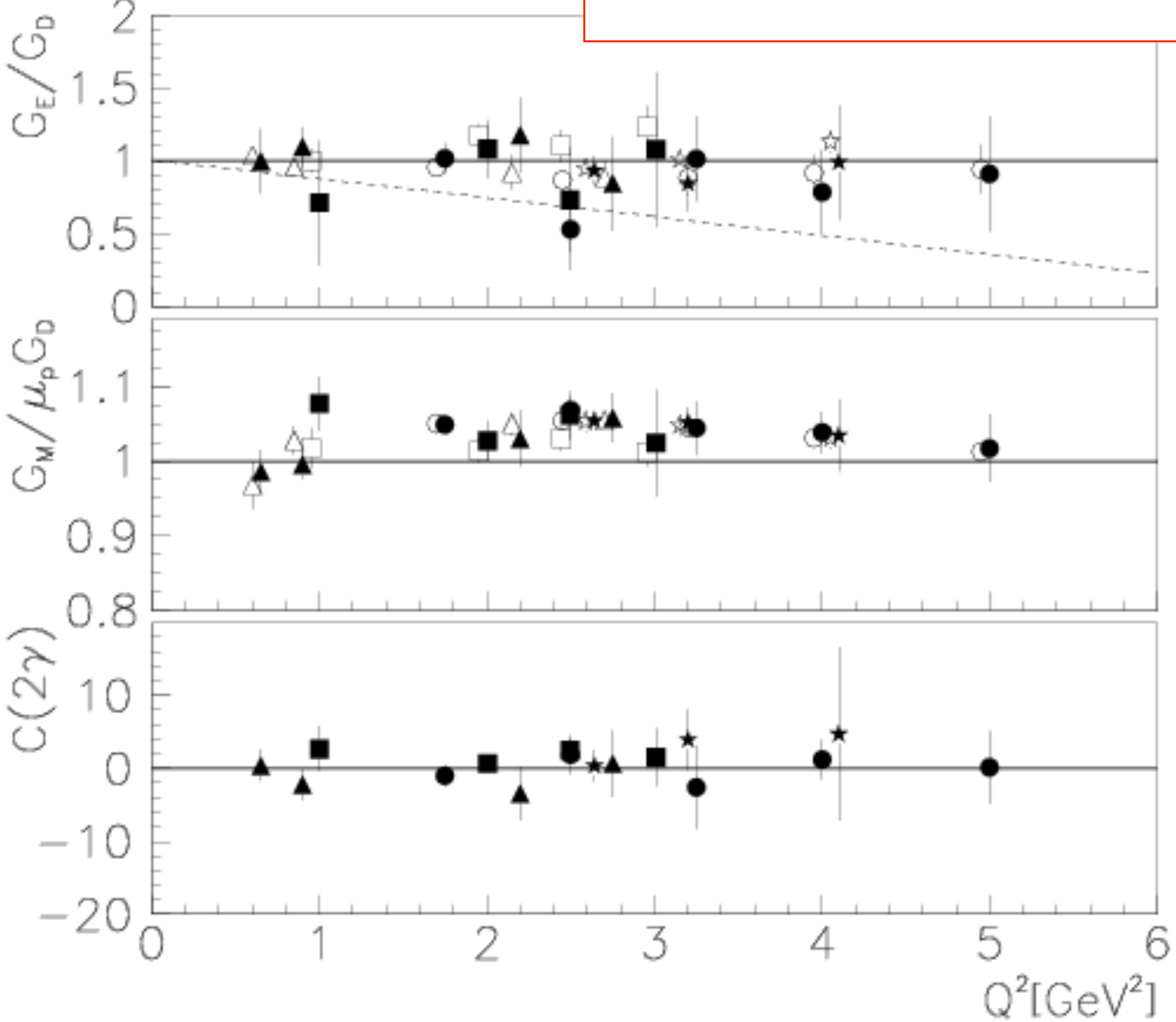
A=0.01±0.02



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

Check of linearity of the Rosenbluth plot

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



From the data:

<C> = 0.5 ± 0.6

deviation from linearity

<< 1%!

E. T.-G., G. Gakh, Phys. Rev. C72,015209 (2005)

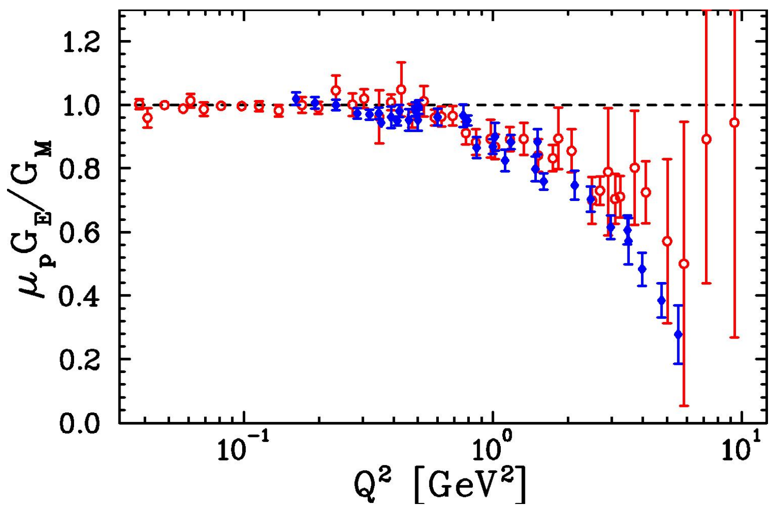
Check of ε-independence of G_E/G_M

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

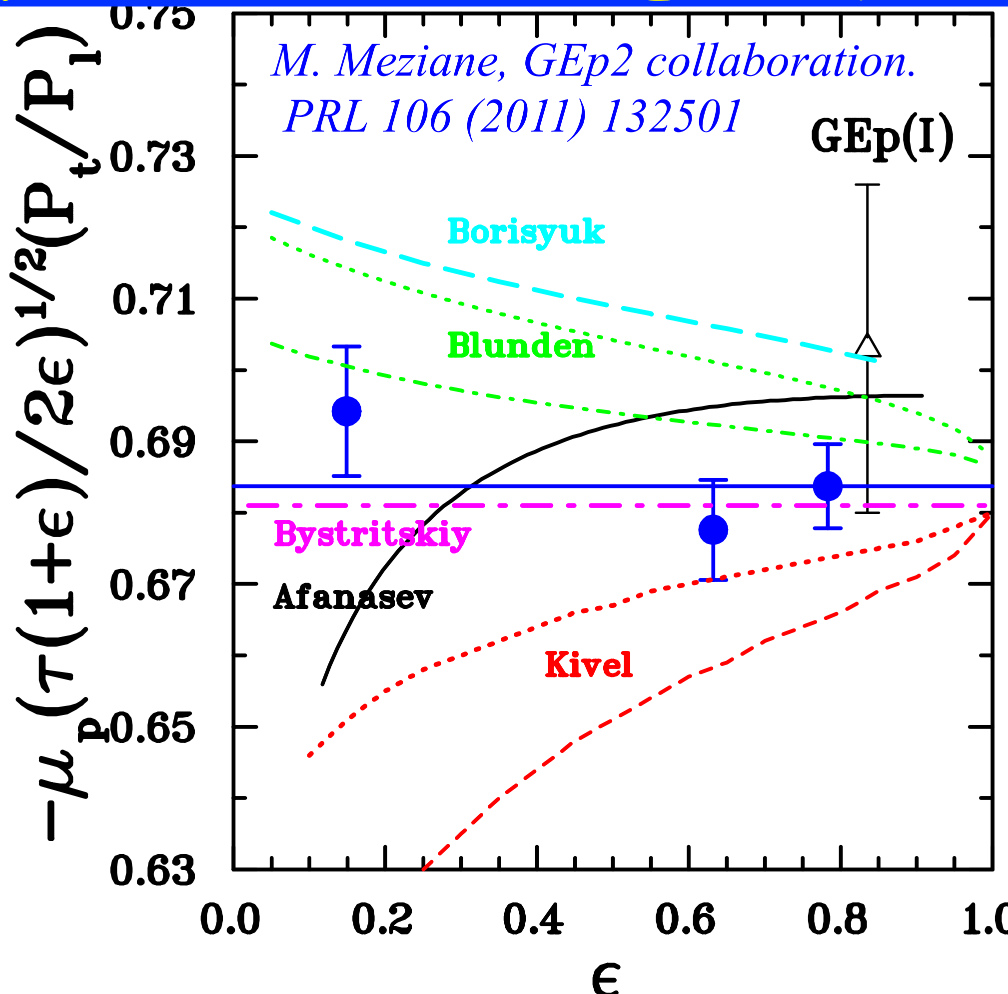
$$P_t = -hP_e\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{G_E G_M}{G_M^2+\frac{\epsilon}{\tau}G_E^2}$$

$$P_\ell = hP_e\sqrt{1-\epsilon^2}\frac{G_M^2}{G_M^2+\frac{\epsilon}{\tau}G_E^2}$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}.$$



J.Arrington, W Melnitchouk, J.A. Tjon, P.R. C76, 035205 (2007)



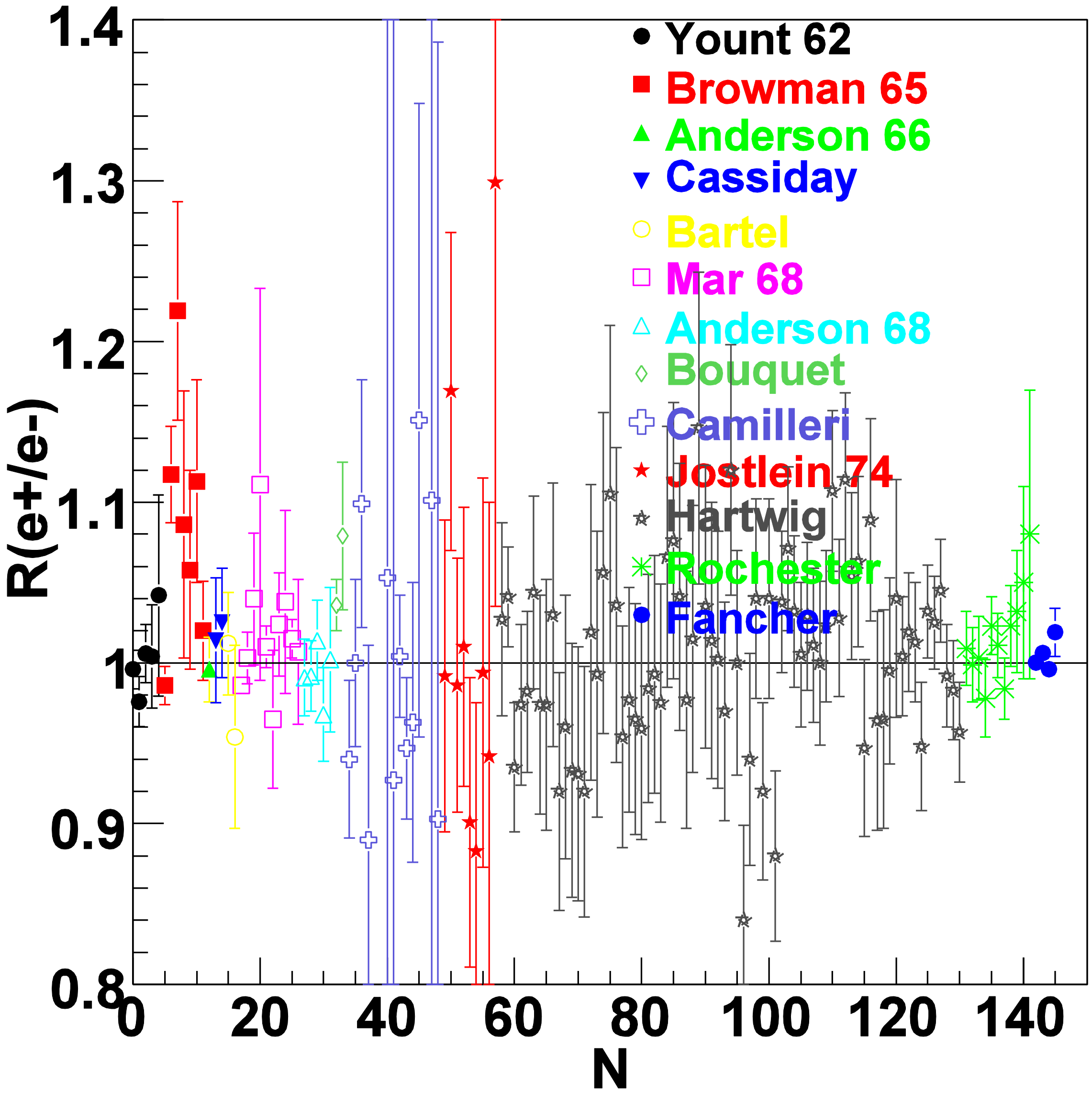
Y. Bystritskiy, E.A.Kuraev, E.T.-G, PRC.75, 015207 (2007)

P. Blunden et al., PRC 72,034612 (2005) (mainly GM)

A. Afanasev et al., PR.D 72,013008 (2005) (mainly GE)

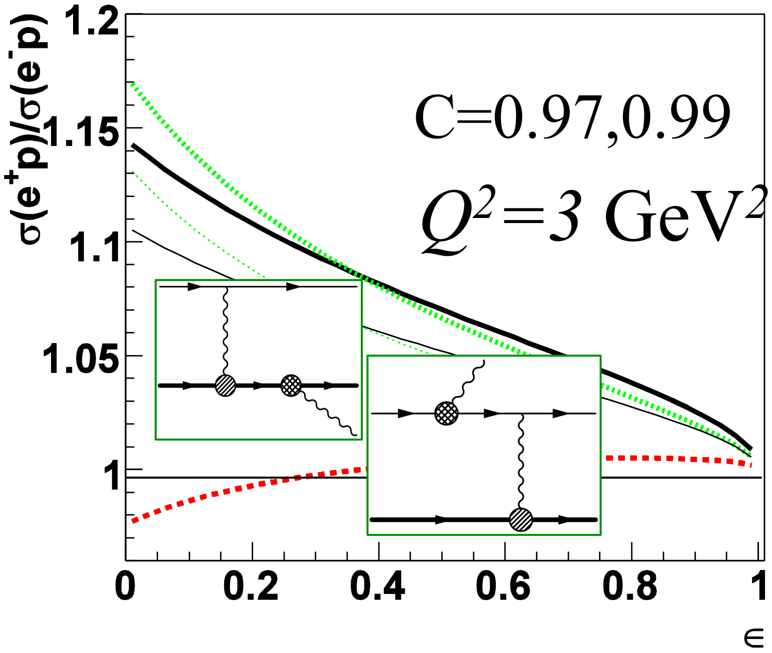
N.Kivel and M.Vanderhaeghen, P.R.L.103:092004 (2009)

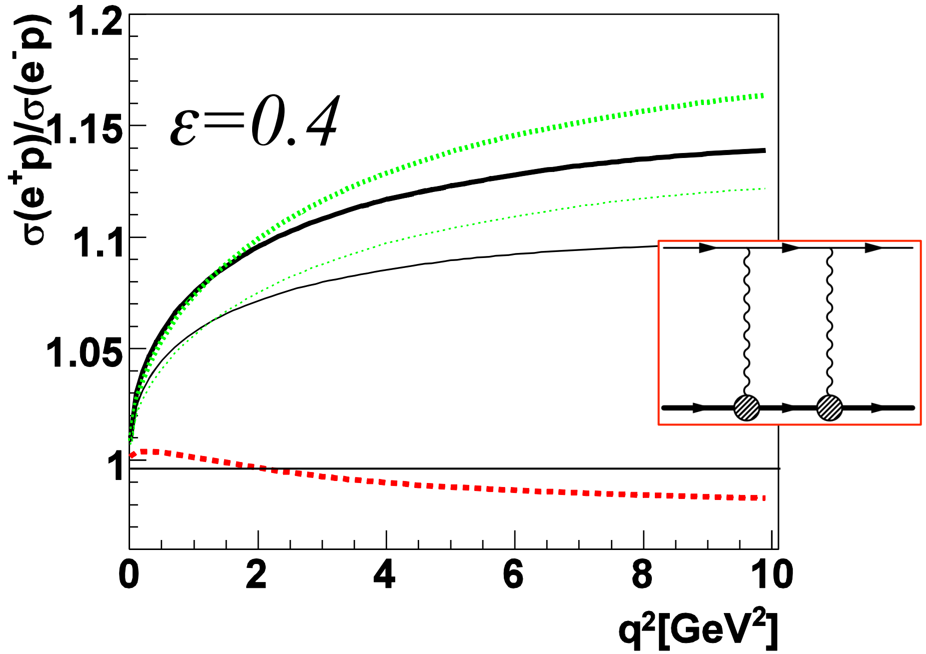
Word data on e^-/e^+ scattering



C-odd asymmetry in e^-/e^+ scattering

E.A. Kuraev, V.V. Bytev, S.Bakmaev and E.T-G, PRC 78, 015295 (2008).





Soft photon emission

2γ exchange

$$A^{odd} = \frac{d\sigma^{e^+p} - d\sigma^{e^-p}}{2d\sigma^B} =$$

$$= \frac{2\alpha}{\pi}\left[\ln\frac{1}{\rho}\ln\frac{(2\Delta E)^2}{ME} - \frac{5}{2}\ln^2\rho + \ln x\ln\rho + \mathrm{Li}_2\left(1-\frac{1}{\rho x}\right) - \mathrm{Li}_2\left(1-\frac{\rho}{x}\right)\right],$$

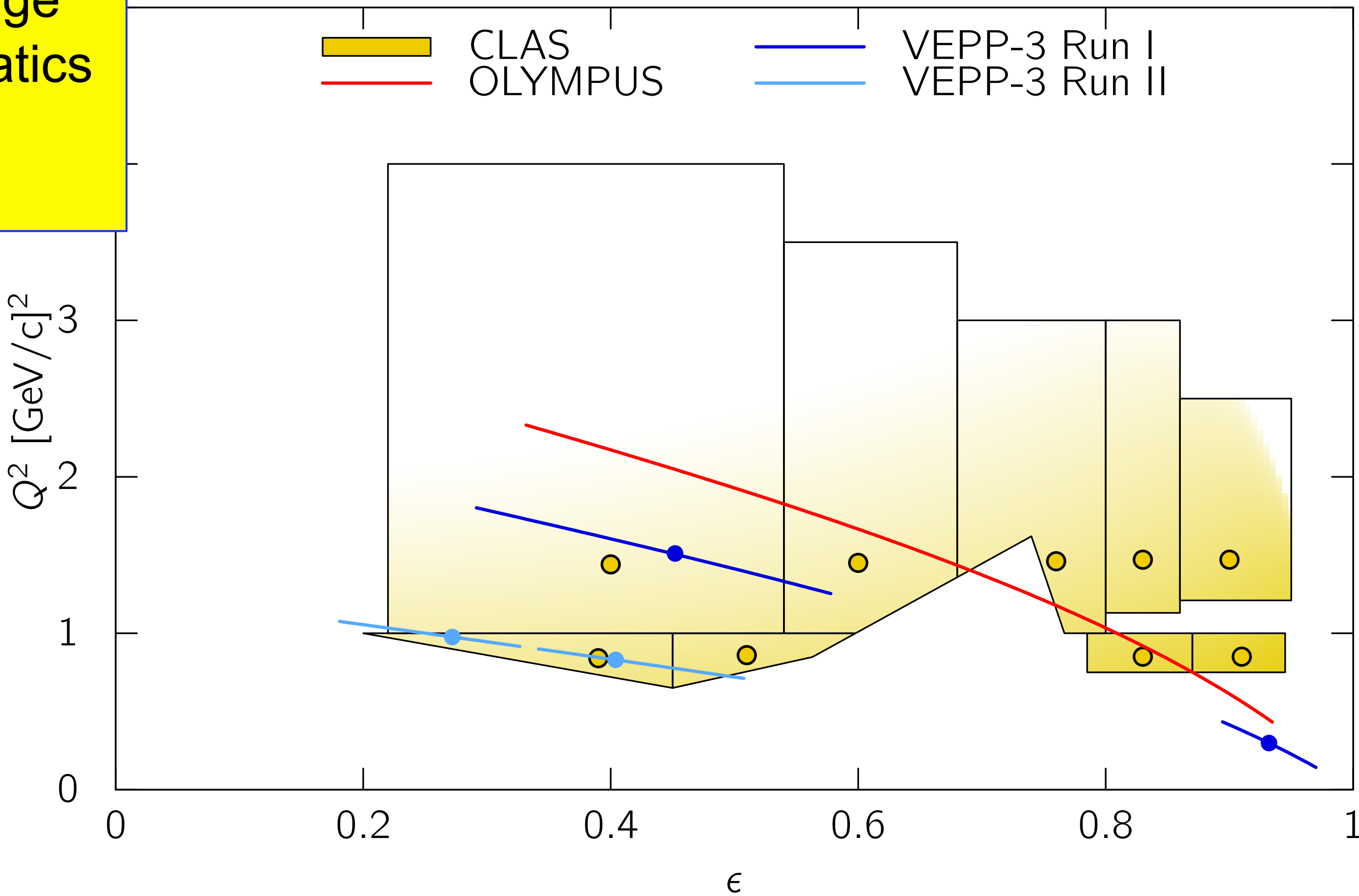
$$\rho = \left(1-\frac{Q^2}{s}\right)^{-1} = 1 + 2E/M\sin^2(\theta/2), \quad x = \frac{\sqrt{1+\tau}+\sqrt{\tau}}{\sqrt{1+\tau}-\sqrt{\tau}},$$

CLAS, VEPP-3, OLYMPUS….

- VEPP-3 @ Novosibirsk: E_{beam} = 1.6, 1.0 (and 0.6) GeV
- CLAS @ JLAB : E_{beam} = 0.5 – 4.0 GeV continuous
- OLYMPUS @ DESY: E_{beam} = 2.0 GeV

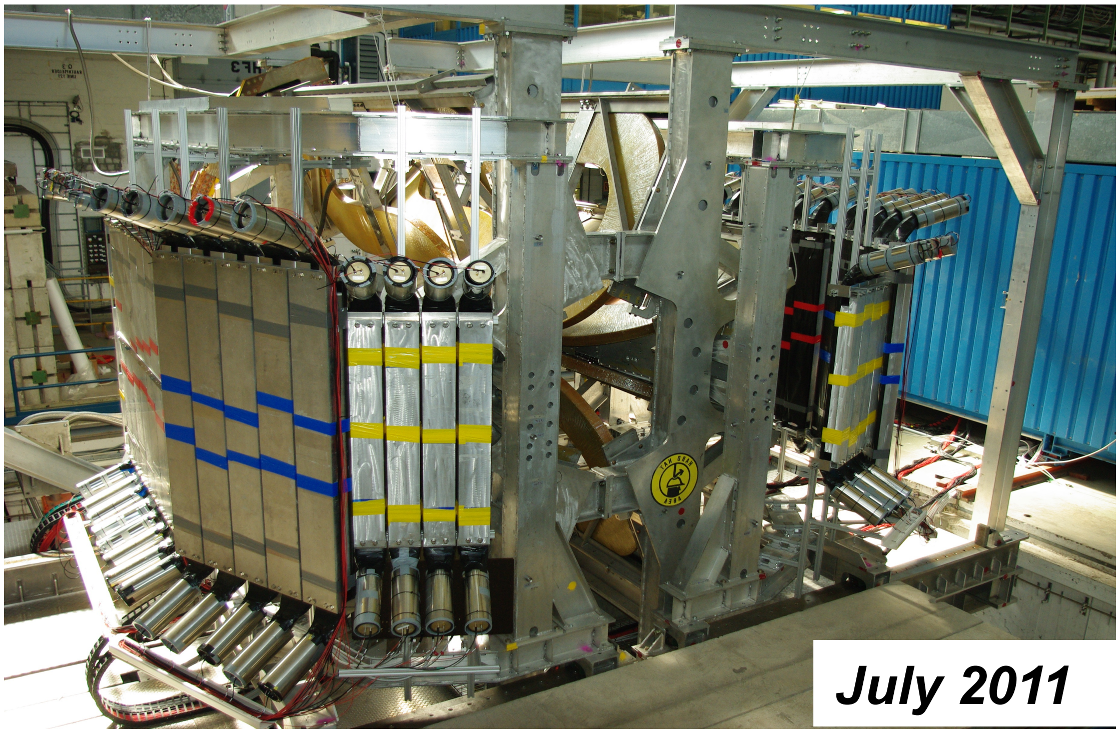
M. Kohl

- Low Q^2, large ε range
- Overlapping kinematics
- Claimed precision around 1%

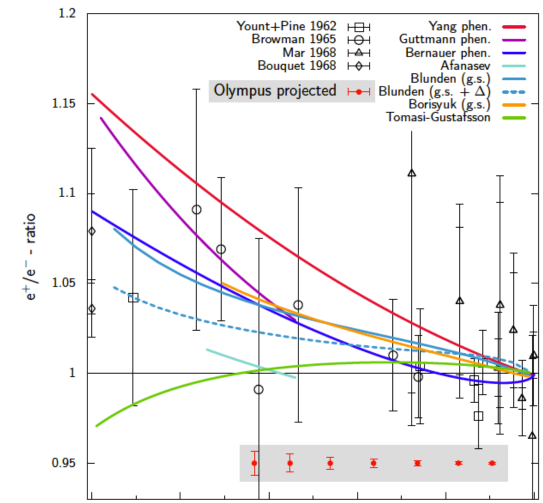


OLYMPUS @ DESY

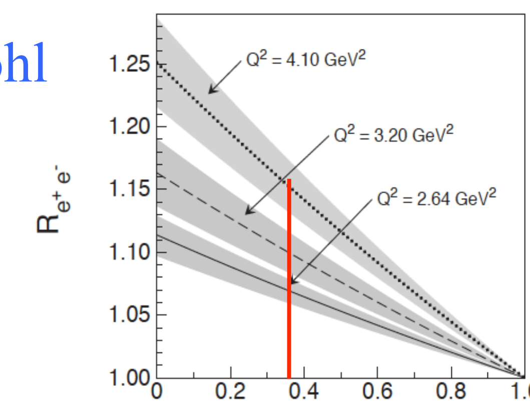
- Measure ratio of $e^{\pm}$-p cross to 1% total error
- unpolarized 2 GeV $e^{\pm}$ beams available at DORIS, DESY
- detector BLAST from MIT-Bates



July 2011



M. Kohl

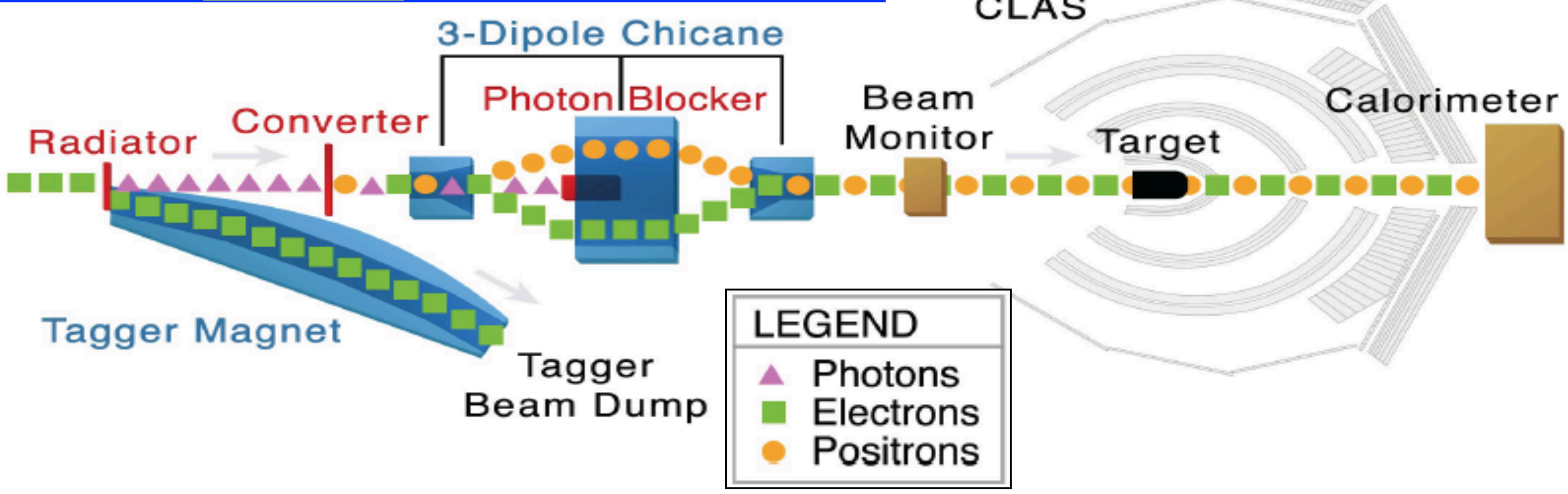


ε_{min}

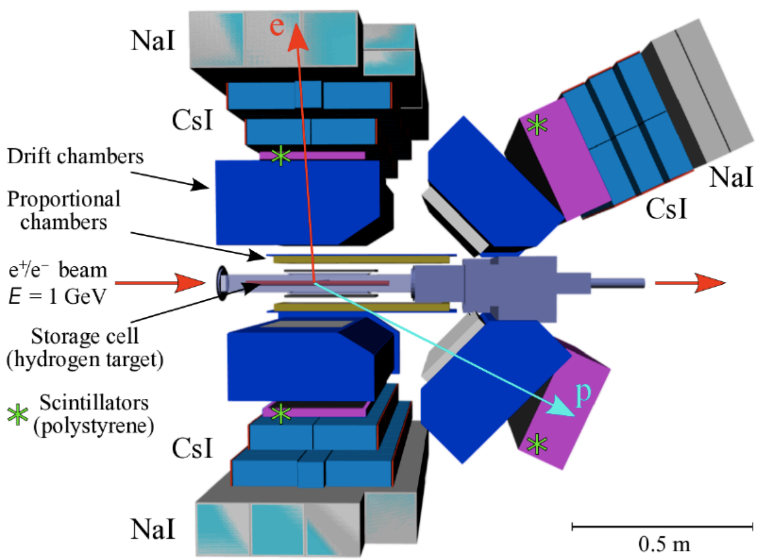
Expected ~6% effect at ε=0.4, Q^2=3.2 GeV^2

J. Guttmann, N. Kivel, M. Meziane, and M. Vanderhaeghen, EPJA 47, 77 (2011)

CLAS @ JLab



VEPP-3 @ Novosibirsk



E=1 and 1.6 GeV

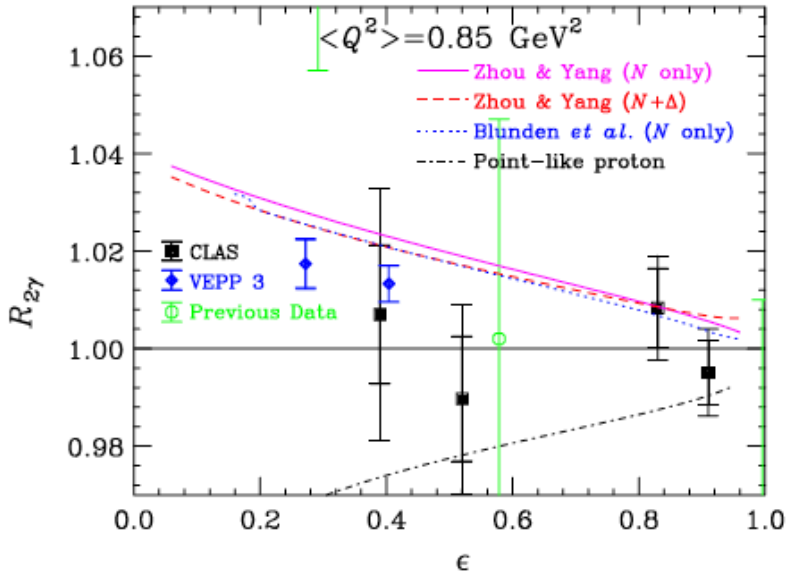
- Dedicated ESEPP generator *(A. Gramolin, V. Nikolenko, V. Fadin, R.E. Gerasimov…)*

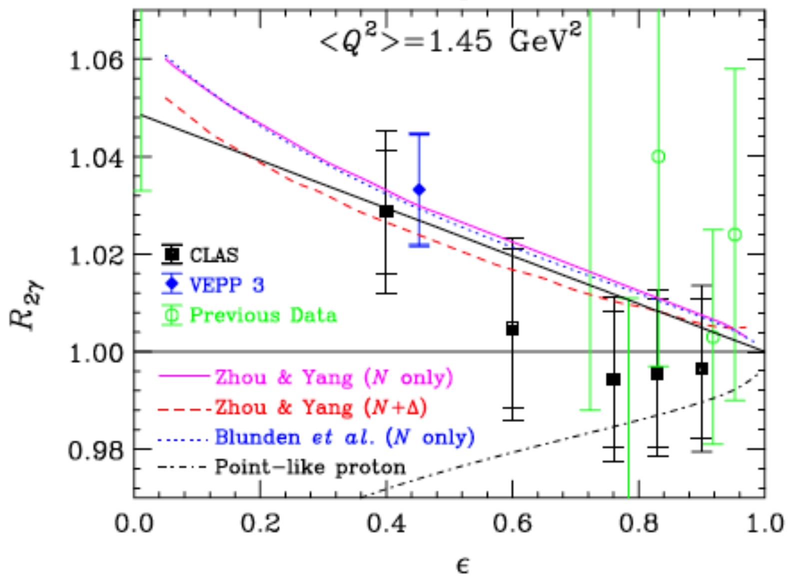
I.A. Rachek et al., PRL 114, 062005 (2015)

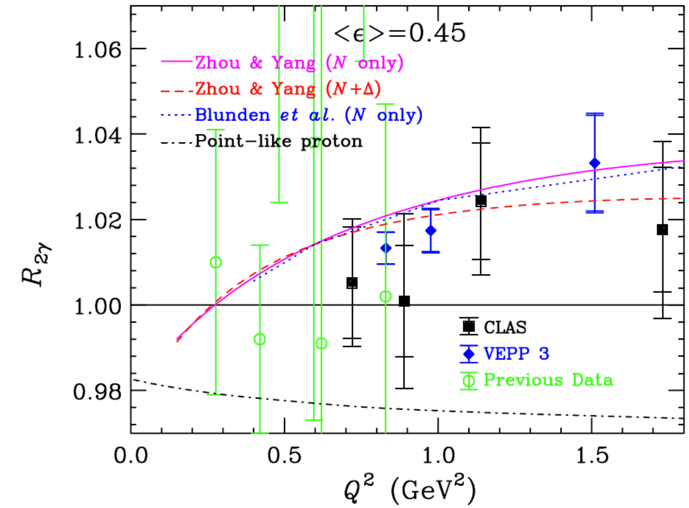
CLAS

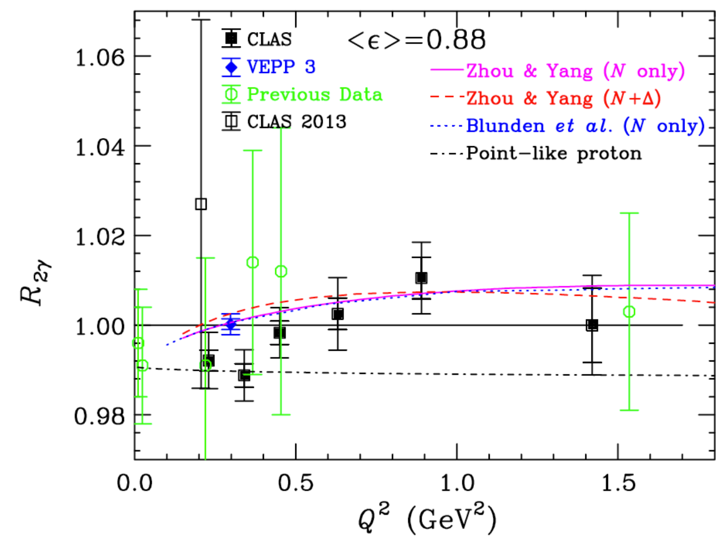
V. Rimal, PRC95, 065201 (2017)

- Q^2<2 GeV2
- Effect < 2%
- No evident increase with Q^2

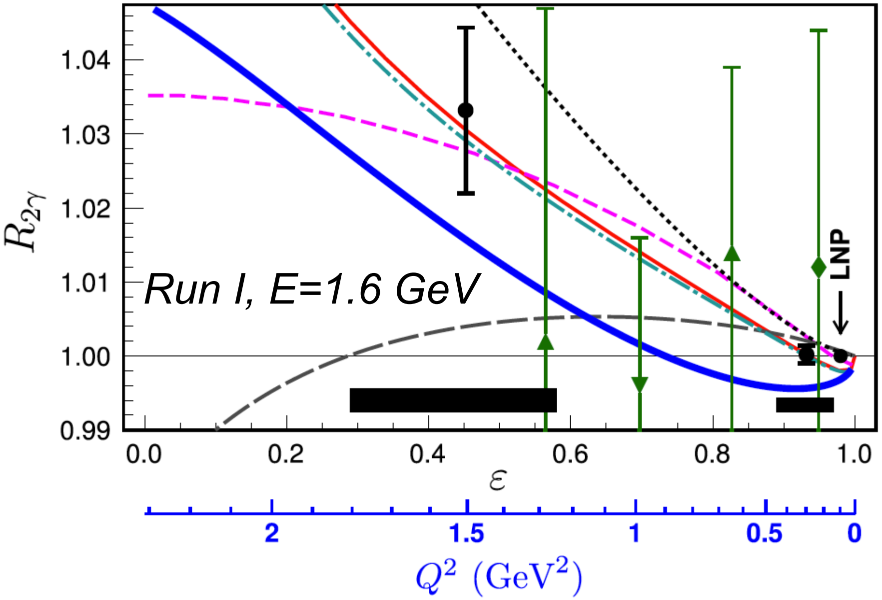


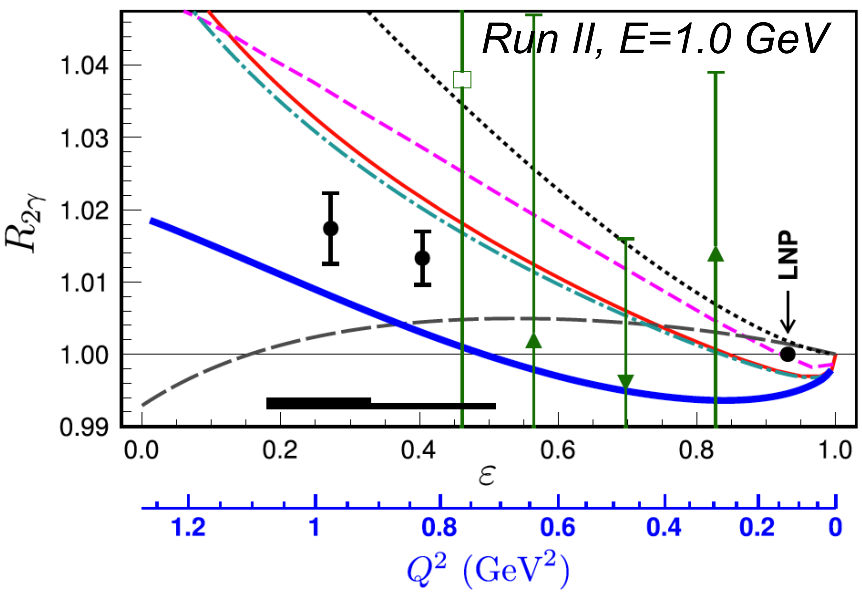






VEPP



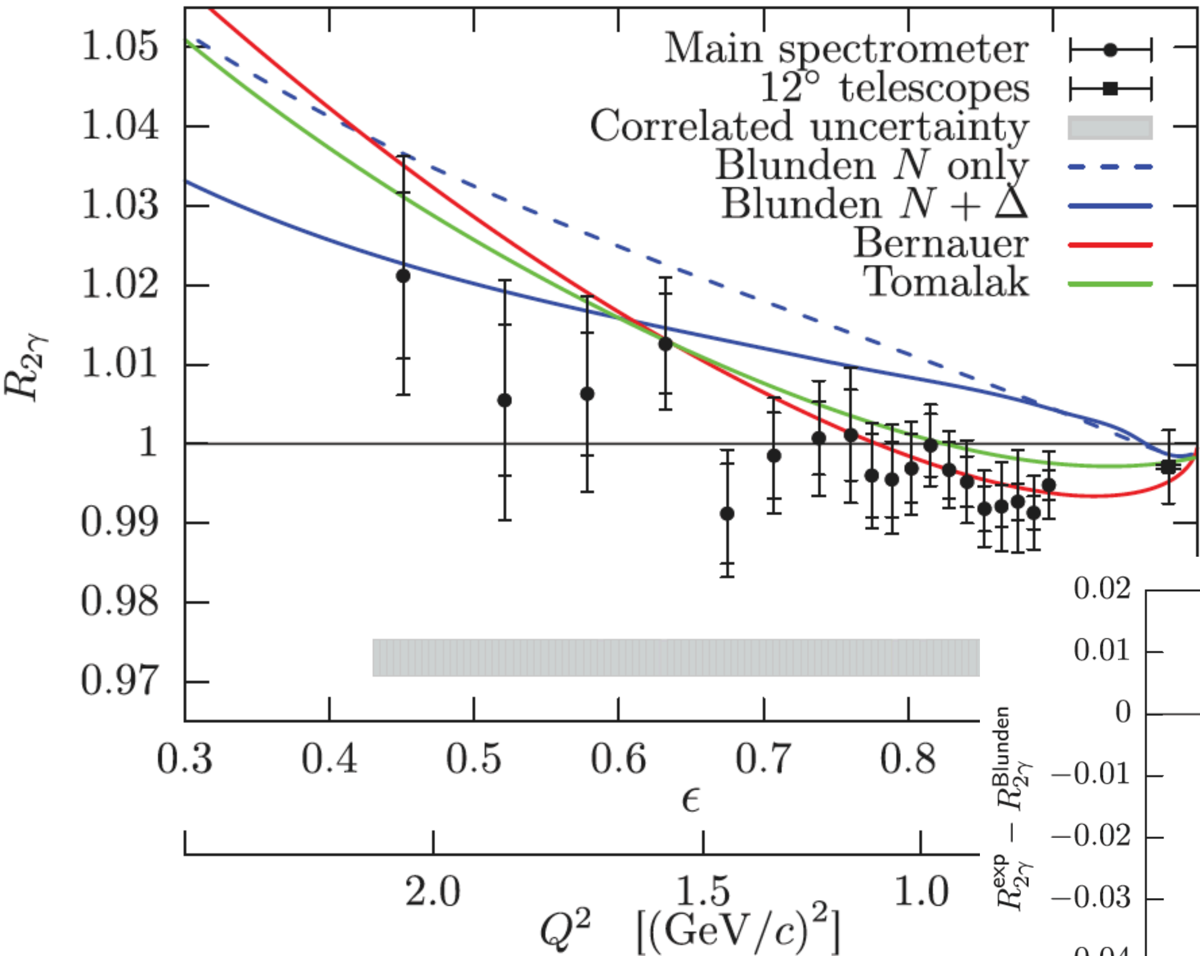


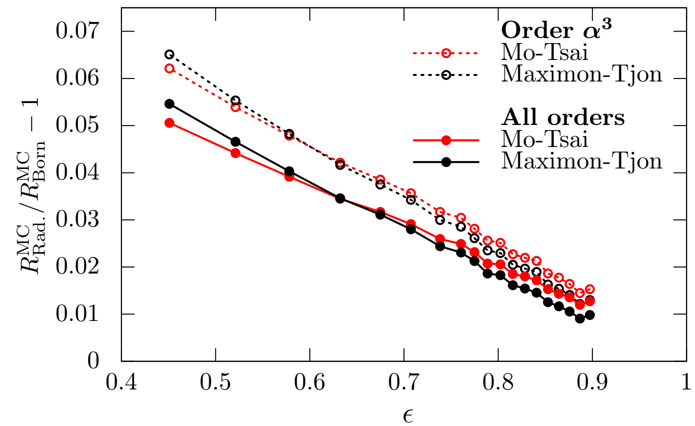
I.A. Rachek et al., PRL 114, 062005 (2015)

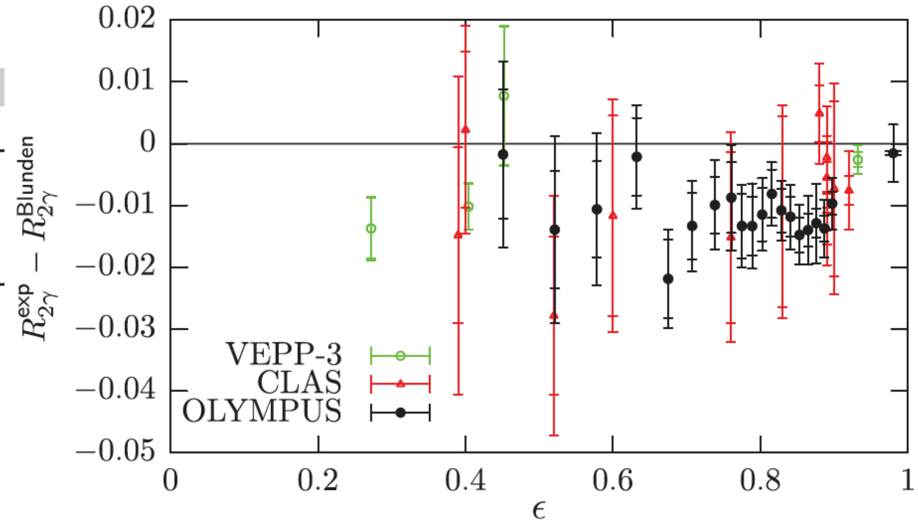
- Large asymmetry in the raw data
- Big effort on radiative calculations

OLYMPUS

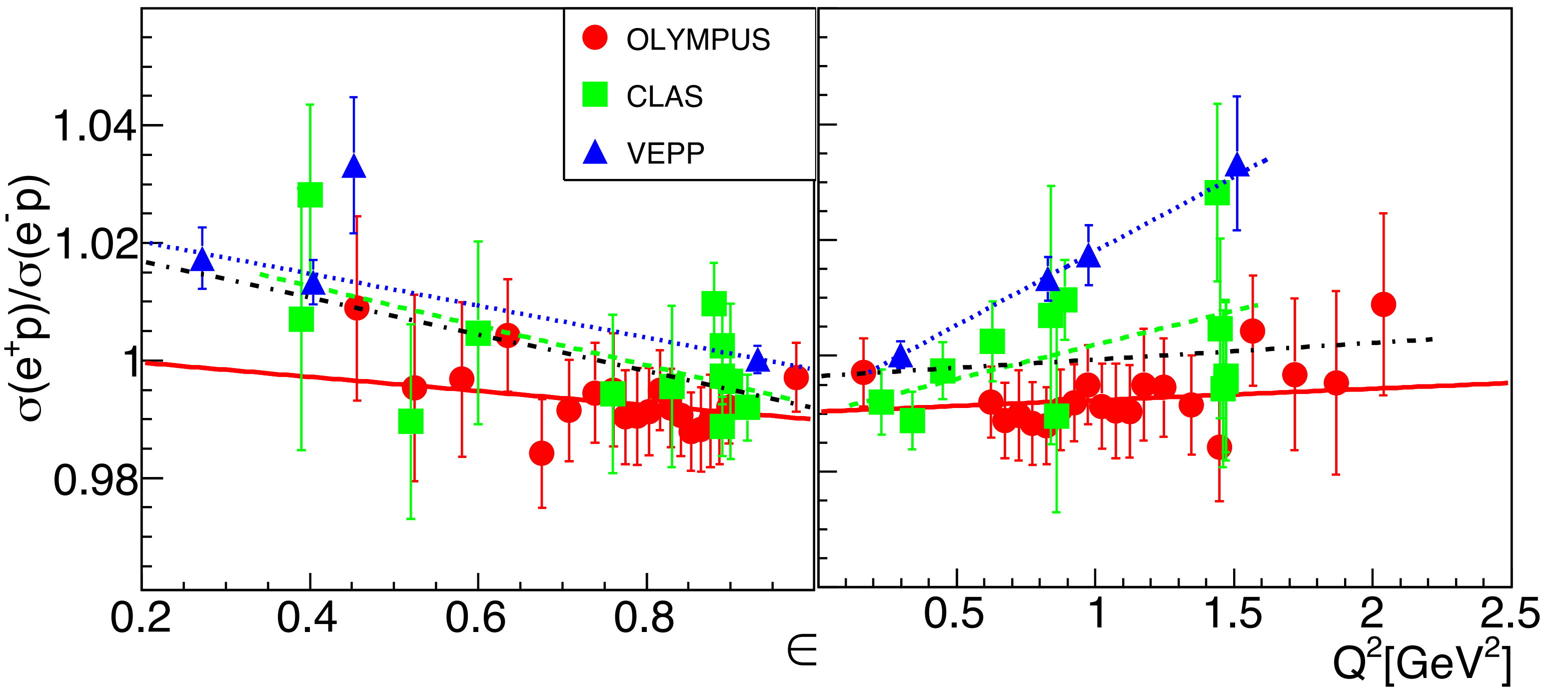
B.S. Henderson et al., PRL 118, 092501 (2017)





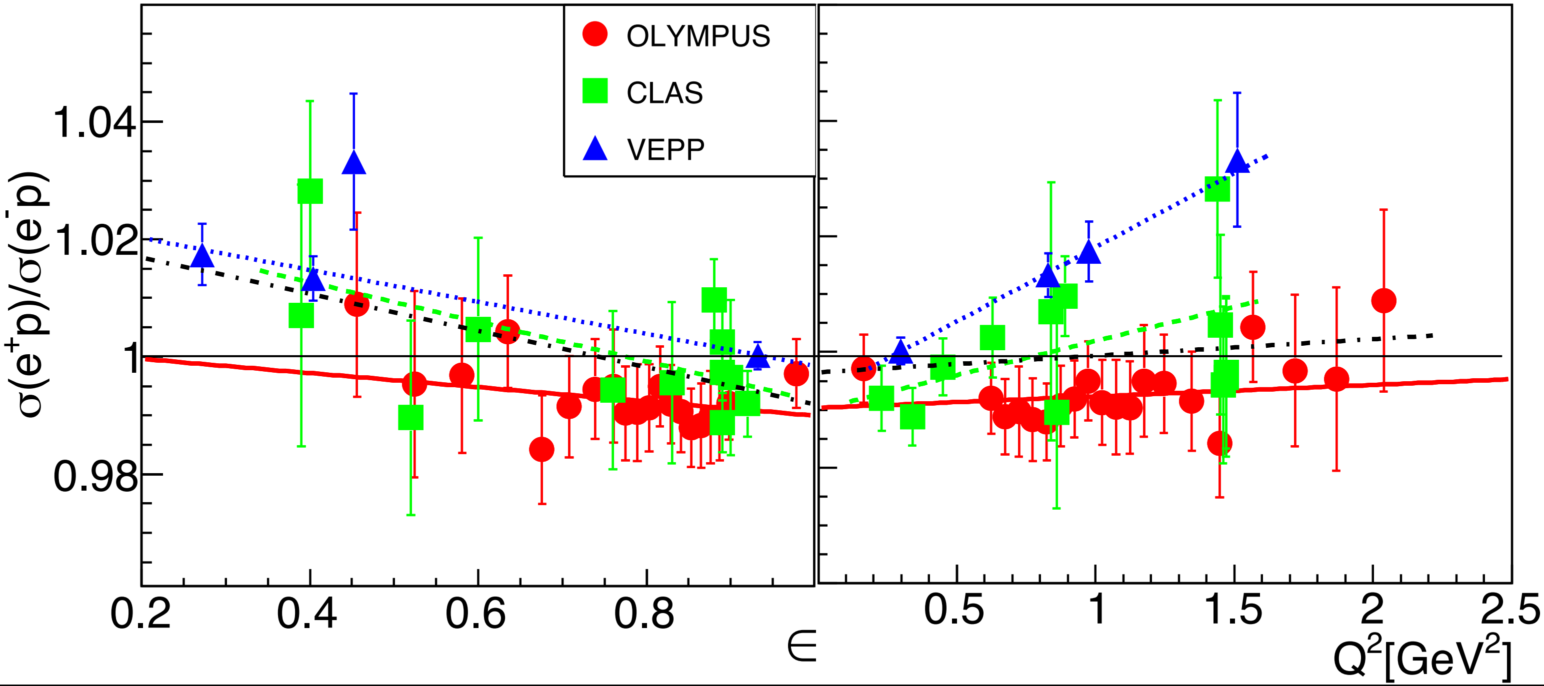


All Data



Compatible with unity?

All Data



	All data	OLYMPUS	CLAS	VEPP
	Experiment			
$< R_{2\gamma} >$	0.999± 0.001	0.999± 0.001	0.997 ± 0.002	1.006± 0.002
$\chi^2/N(1)$	69.3/35=1.98	19/19=1.00	12.1/11=1.1	23.7/3=7.9

From Experiment to Theory

- C-odd asymmetry:

$$A^{odd} = \frac{d\sigma(e^+p \to e^+p) - d\sigma(e^-p \to e^-p)}{d\sigma(e^+p \to e^+p) + d\sigma(e^-p \to e^-p)} = \frac{\delta_{odd}}{1+\delta_{even}} = \frac{R-1}{R+1}, \quad R = \frac{1+A_{odd}}{1-A_{odd}}$$

- Measured Ratio:

$$R^{meas} = \frac{d\sigma^{meas}(e^+p \to e^+p)}{d\sigma^{meas}(e^-p \to e^-p)} = \frac{1+\delta_{even}-\delta_{2\gamma}-\delta_s}{1+\delta_{even}+\delta_{2\gamma}+\delta_s}.$$

- Published 'Hard contribution'

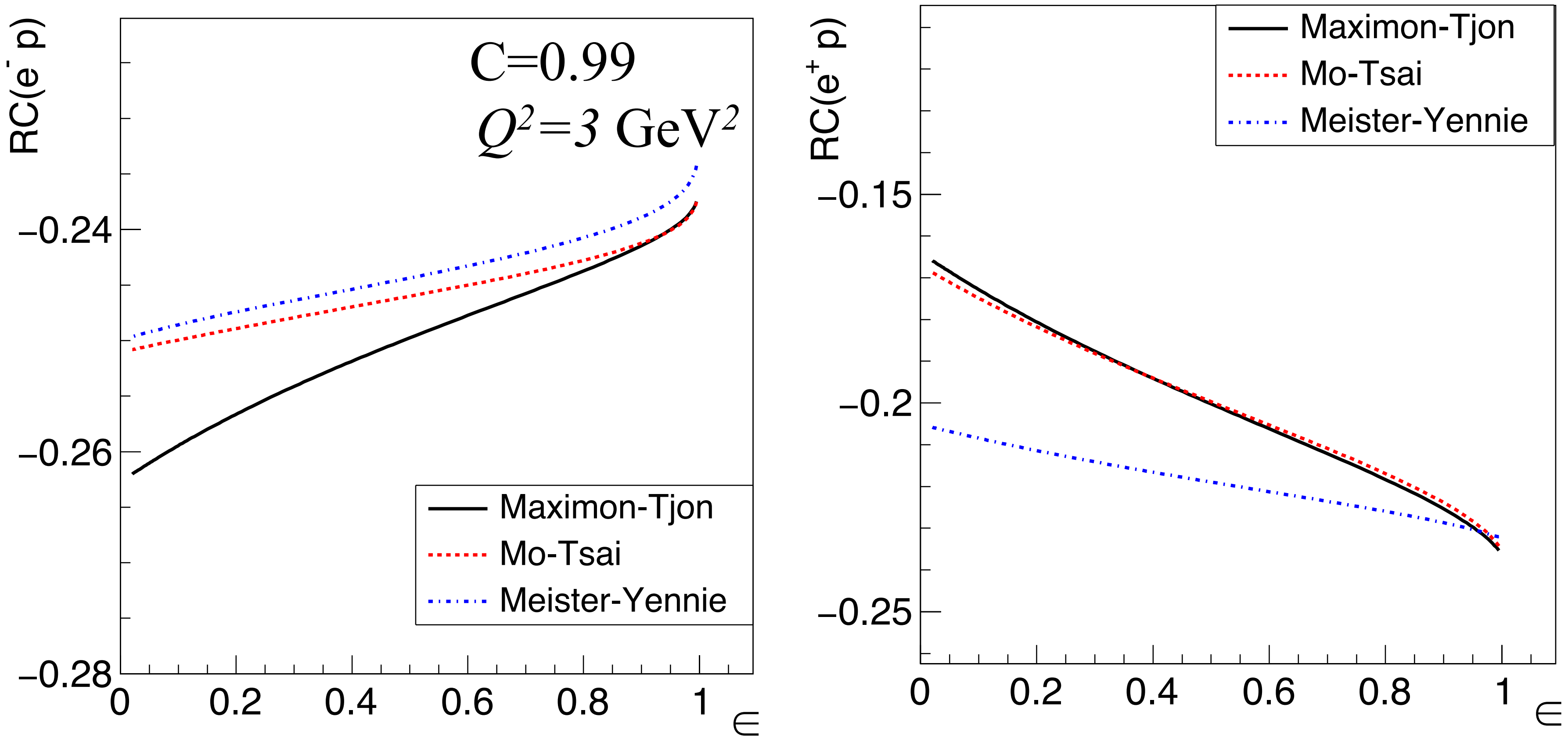
$$R_{2\gamma} \simeq \frac{1-\delta_{2\gamma}}{1+\delta_{2\gamma}};$$

- To be compared with theory:

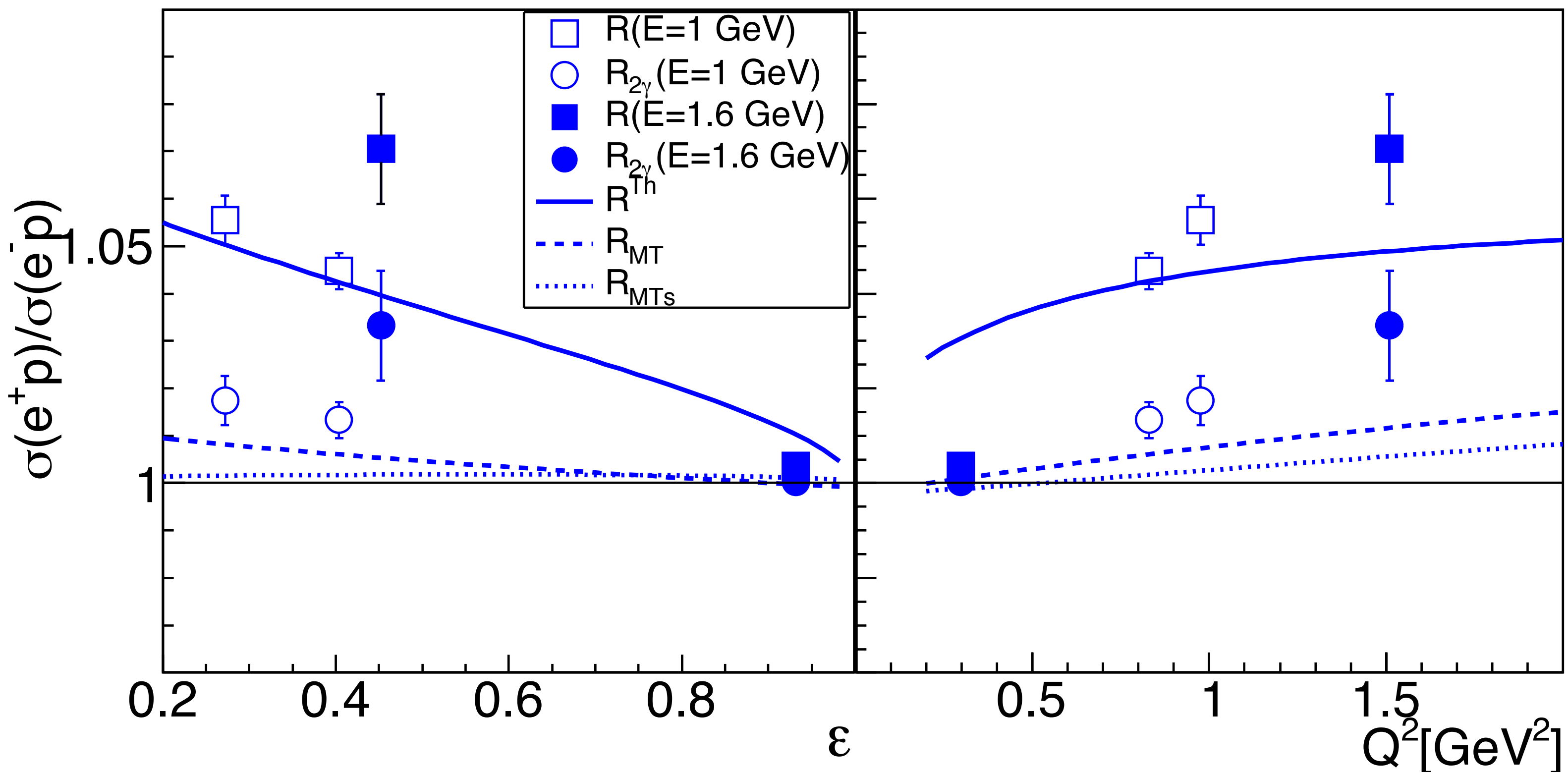
$$R_{2\gamma}^K = \frac{1-A_{odd}^K(1+\delta_{even})+\delta_M}{1+A_{odd}^K(1+\delta_{even})-\delta_M},$$

Radiative corrections

- 1st order radiative corrections usually applied to the data

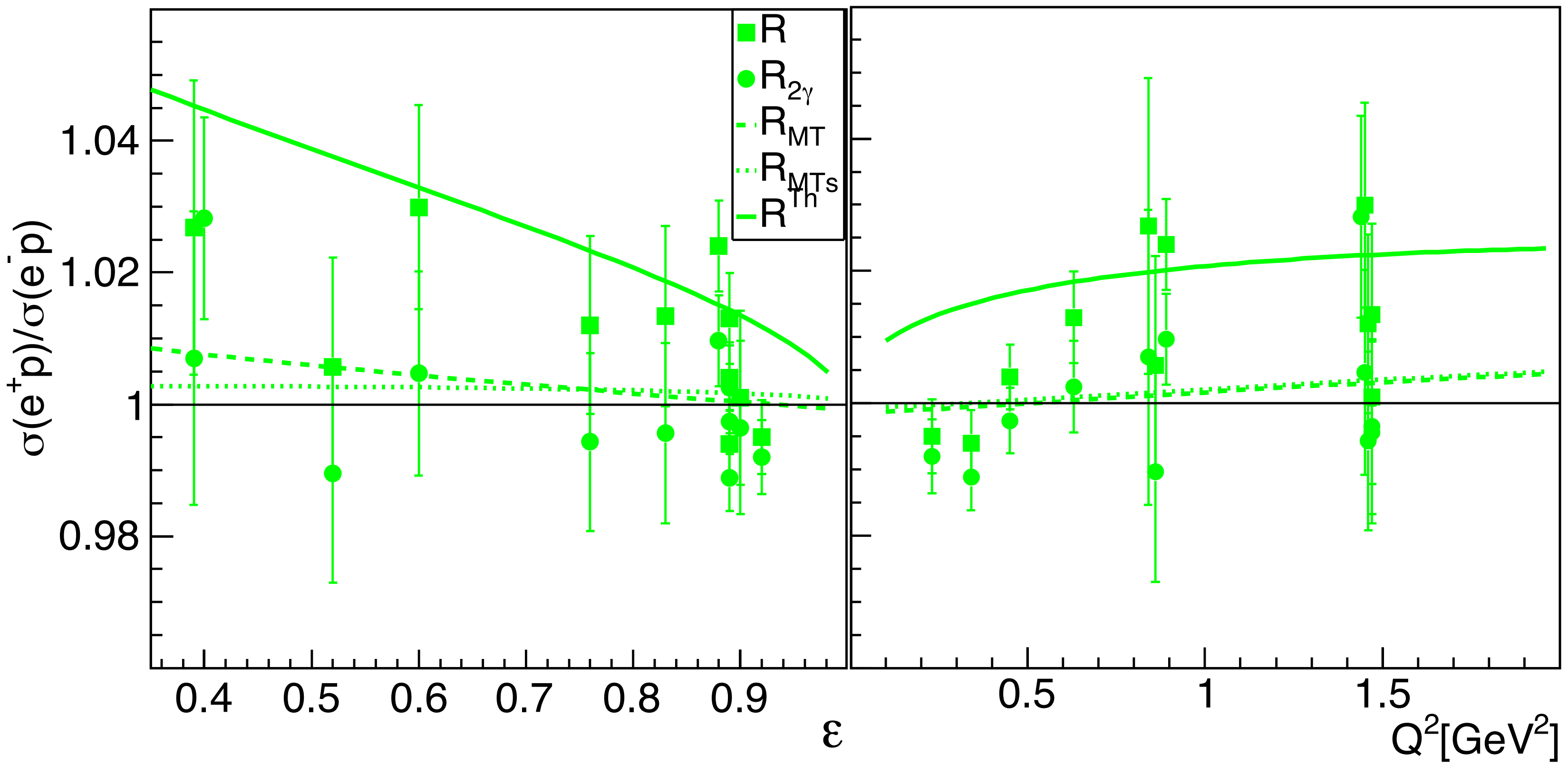


Radiative corrections: VEPP



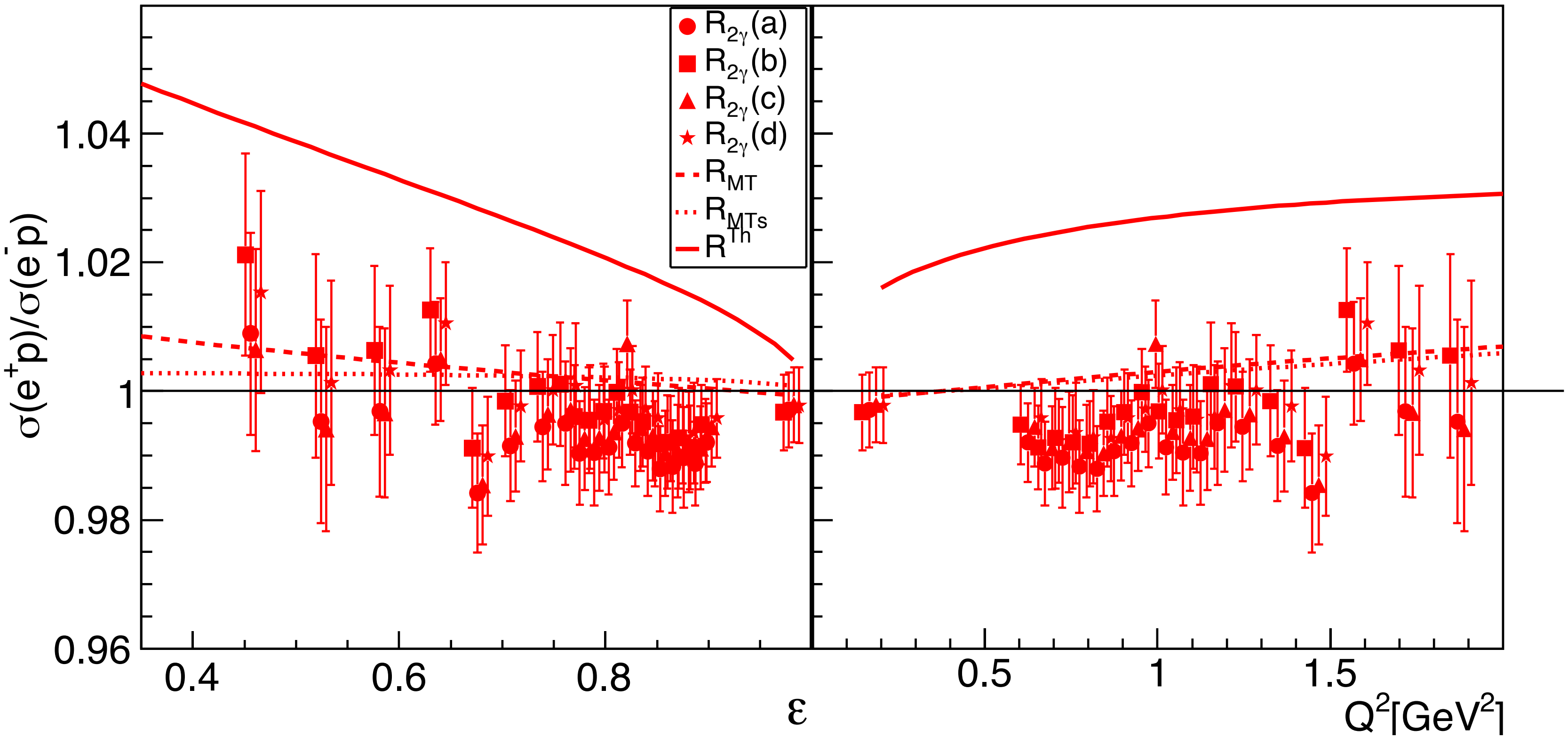
$<Q^2>=1$ GeV^2 $<\varepsilon>=1$ GeV^2

Radiative corrections (CLAS)



$<Q^2>=1$ GeV^2 $\quad$ $<\varepsilon>=1$ GeV^2

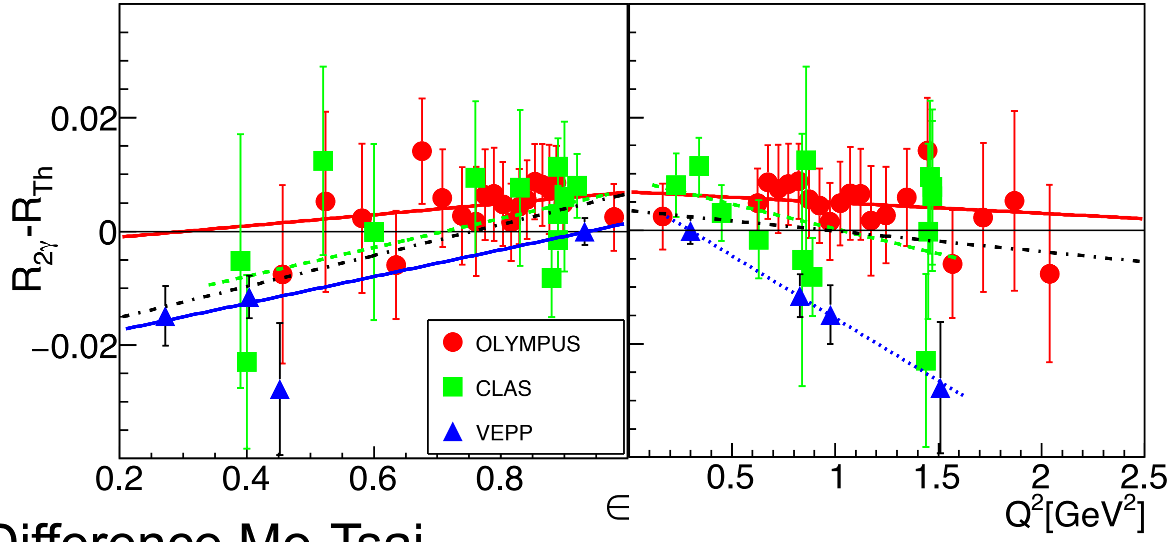
Radiative corrections (OLYMPUS)



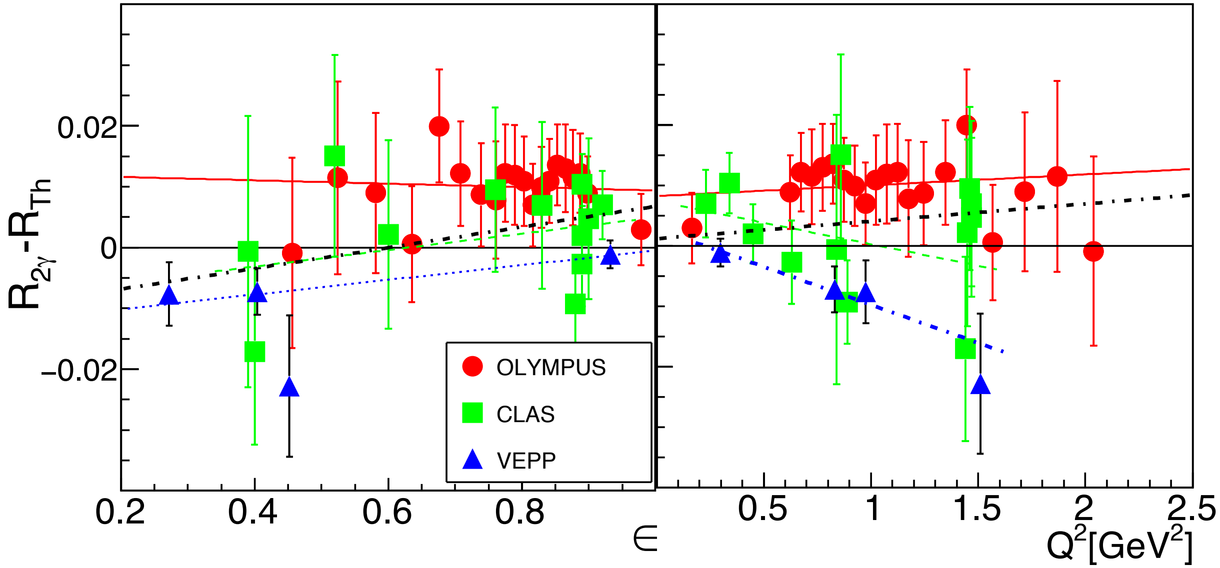
<Q^2>=1 GeV^2 <ε>=0.7 GeV^2

Difference Exp-Theory

- Difference Maximon-Tjon



- Difference Mo-Tsai



- Difference < 2%
- No evident increase with ε, Q^2

Conclusion - Discussion

•Experimental results DO NOT favor a large 2γ effect

•Other explanations are likely

- *•Radiative corrections*
- *•Normalization, correlations in experimental data*

•Models should be developed in all Q2 range

•Large effort in Space- and Time – like regions is ongoing to measure form factors more precisely in a wider kinematical range

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panda

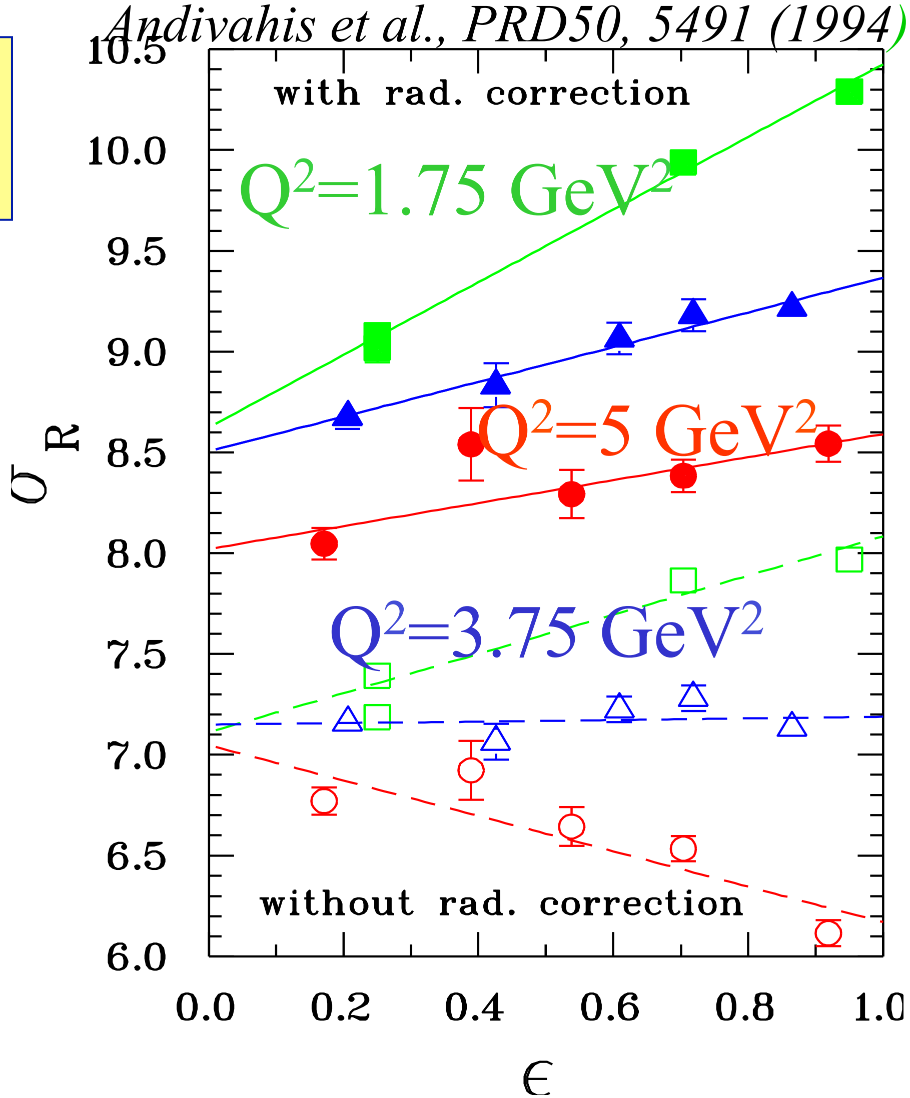
BABAR

Radiative Corrections ($e^- p$)

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

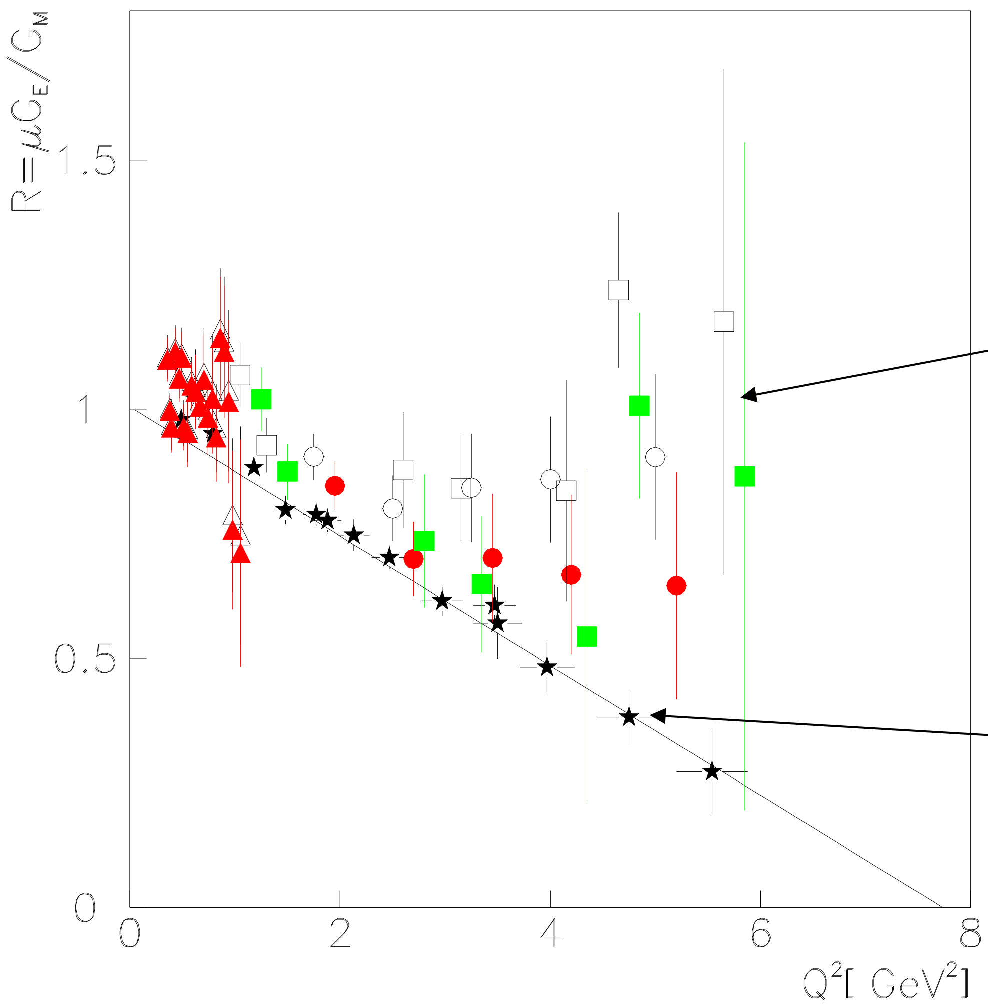
May change the slope of σ_R (and even the sign !!!)

RC to the cross section:
- *large (may reach 40%)*
- *ε and Q^2 dependent*
- *calculated at first order*



E. T.-G., G. Gakh, PRC 72, 015209 (2005)

Radiative Corrections (SF method)



Andivahis et al., PRD50, 5491 (1994)

SLAC data

SLAC data

corrected by SF

Jlab Polarization data

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

PHYSICAL REVIEW C 93, 055201 (2016)

Reanalysis of Rosenbluth measurements of the proton form factors

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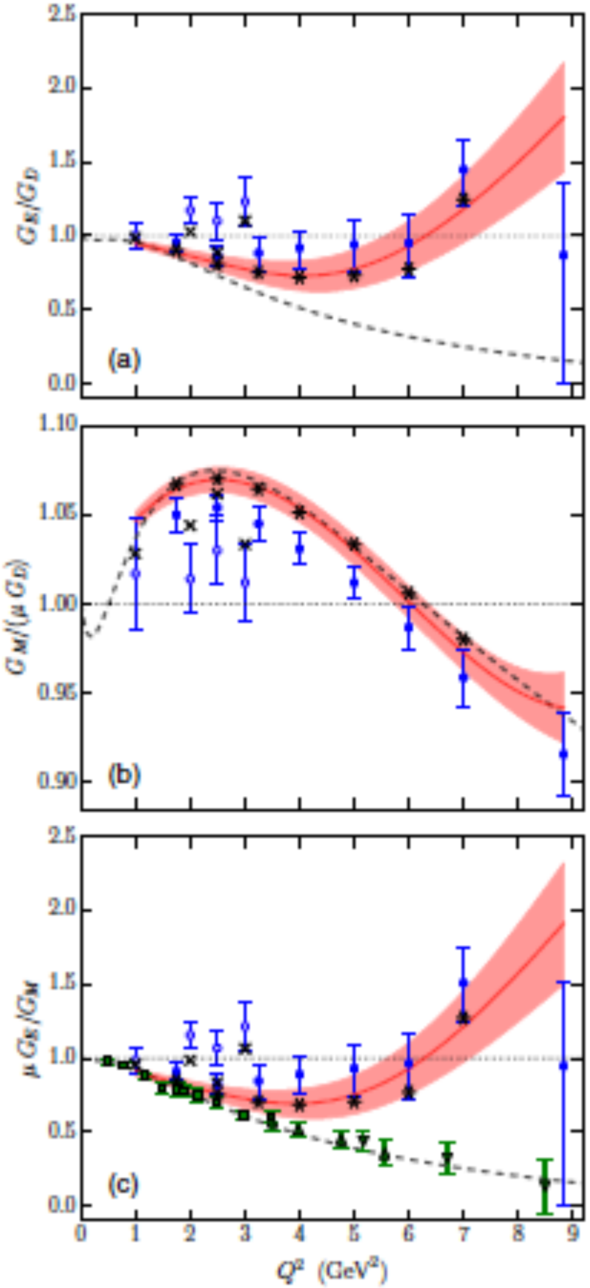
(Received 28 March 2016; published 10 May 2016)



V. Fadin ,R.E.Gerasimov

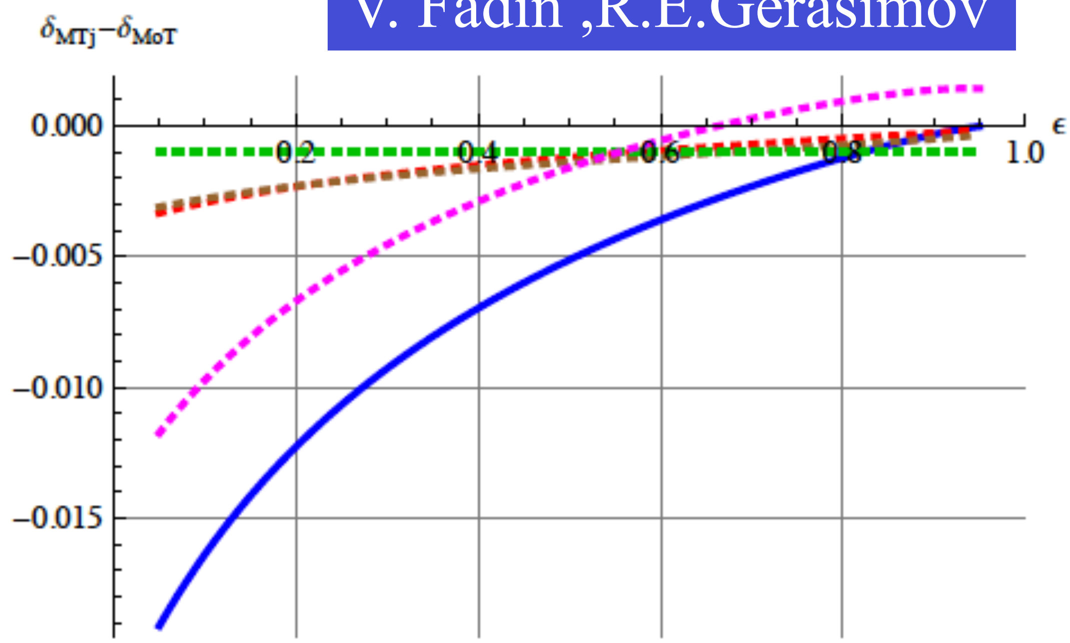
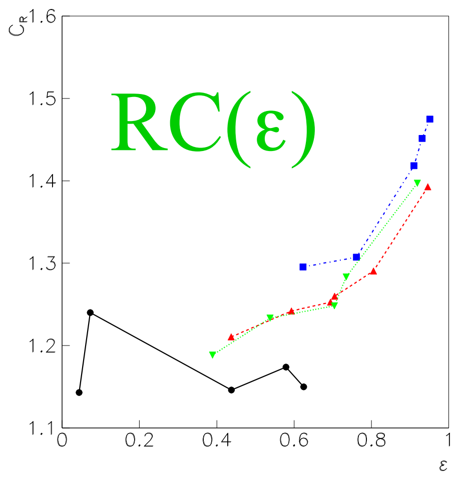


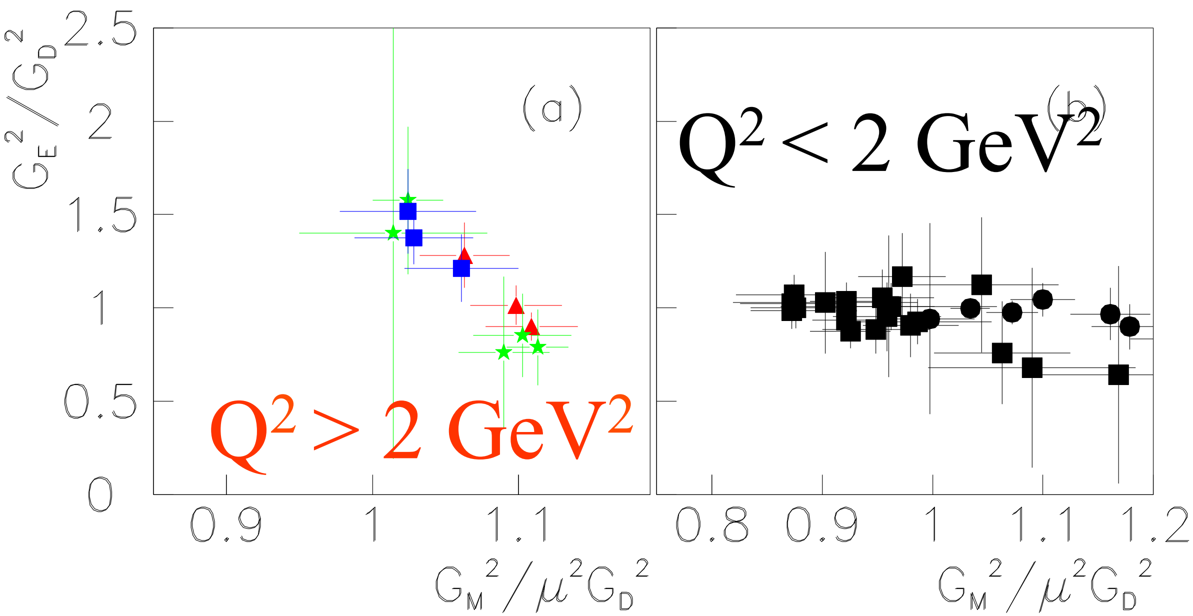
Figure 3: Difference at $Q^2 = 5\ GeV^2$.

Other issues in data

- Correlations



G_E^2 versus G_M^2

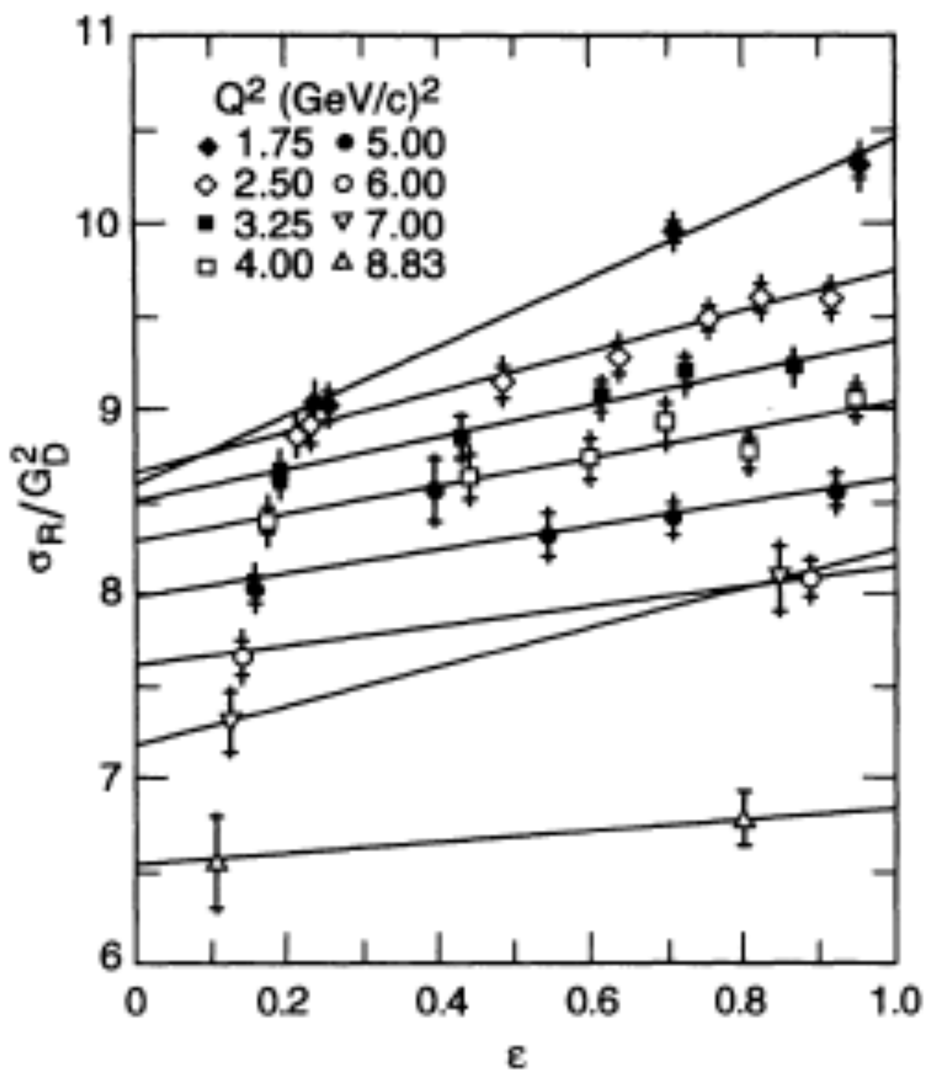


E.T-G, Phys. Part. Nucl. Lett. ***4,*** *281 (2007)*

- Normalizations
  - of different sets of data
  - within a set of data

Normalization

Andivahis et al., PRD50, 5491 (1994)



Two spectrometers (8 and 1.6 GeV)

2 points at low ε

Fixed renormalization for the lowest ε point c=0.956 (acceptance correction)

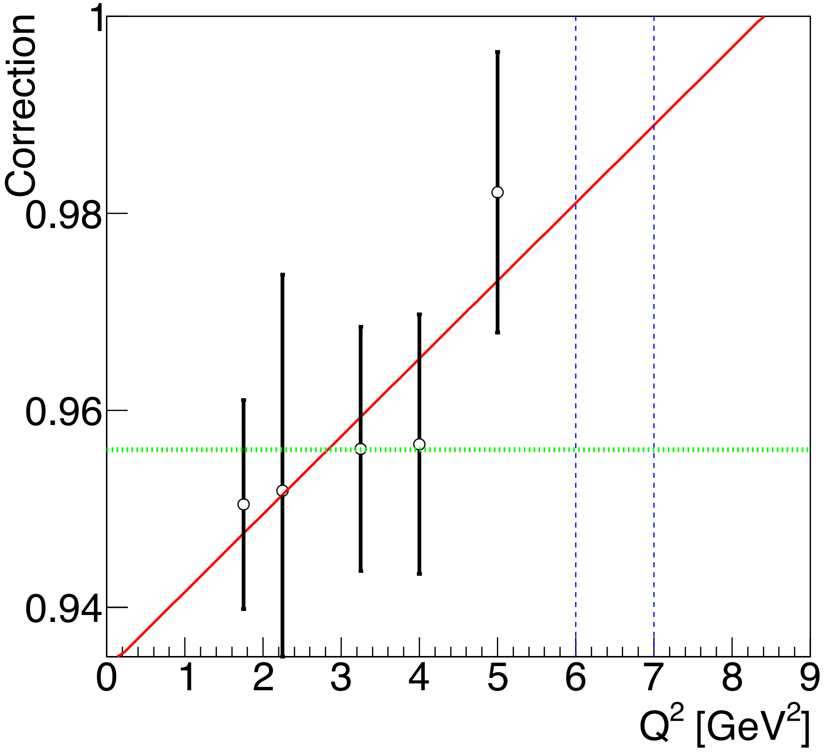
Increases the slope!

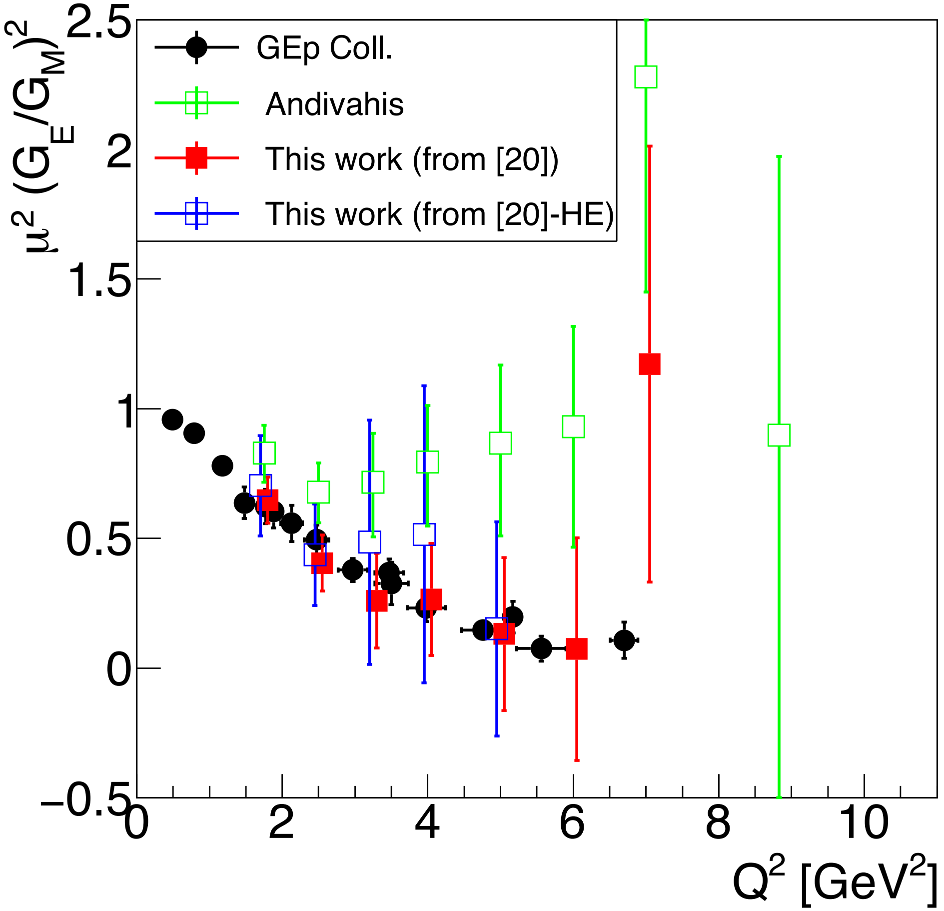
$$G_E \approx G_D$$

Direct extraction of the Ratio

Andivahis et al., PRD50, 5491 (1994)

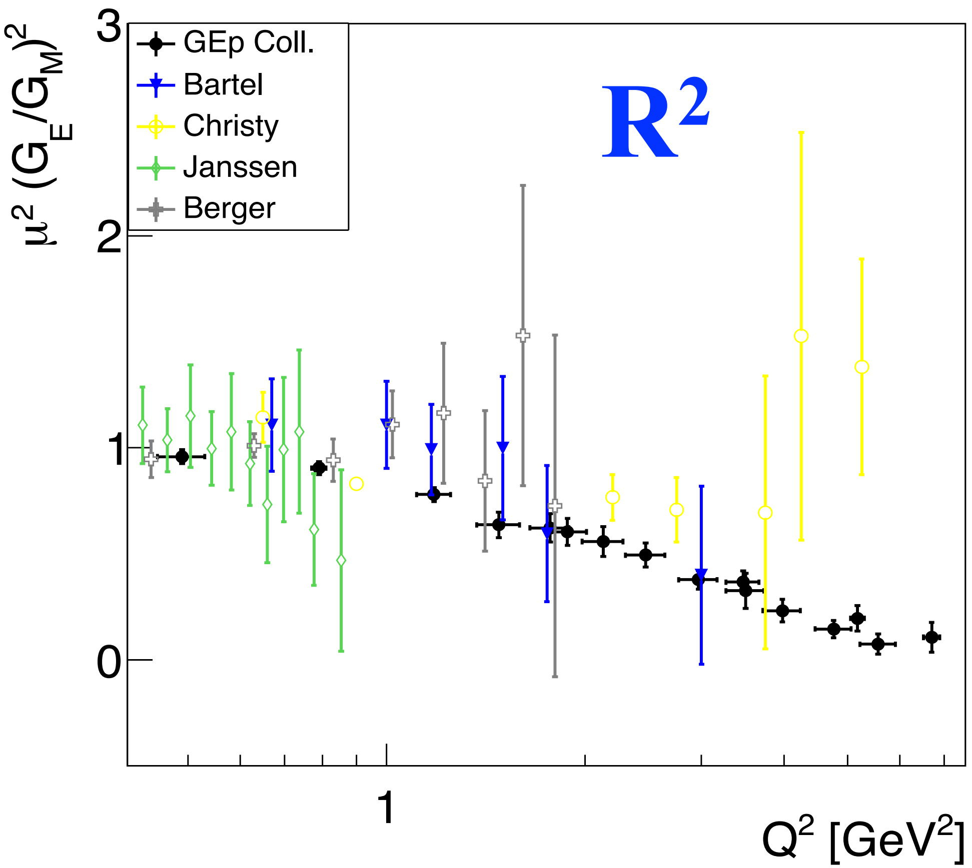
$$\sigma_{\rm red} = G_M^2(R^2\epsilon + \tau),$$

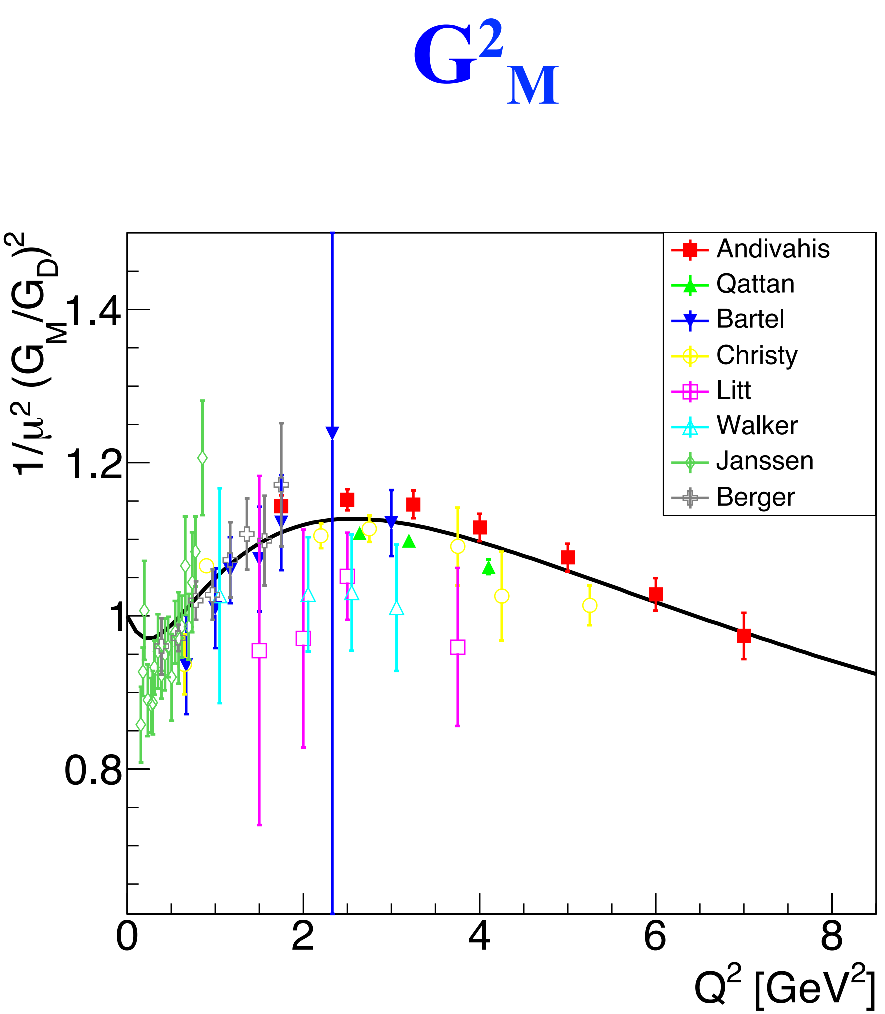




S. Pacetti and E.T-G., P.R.C. 94 (2016) 055202

Different Data Sets

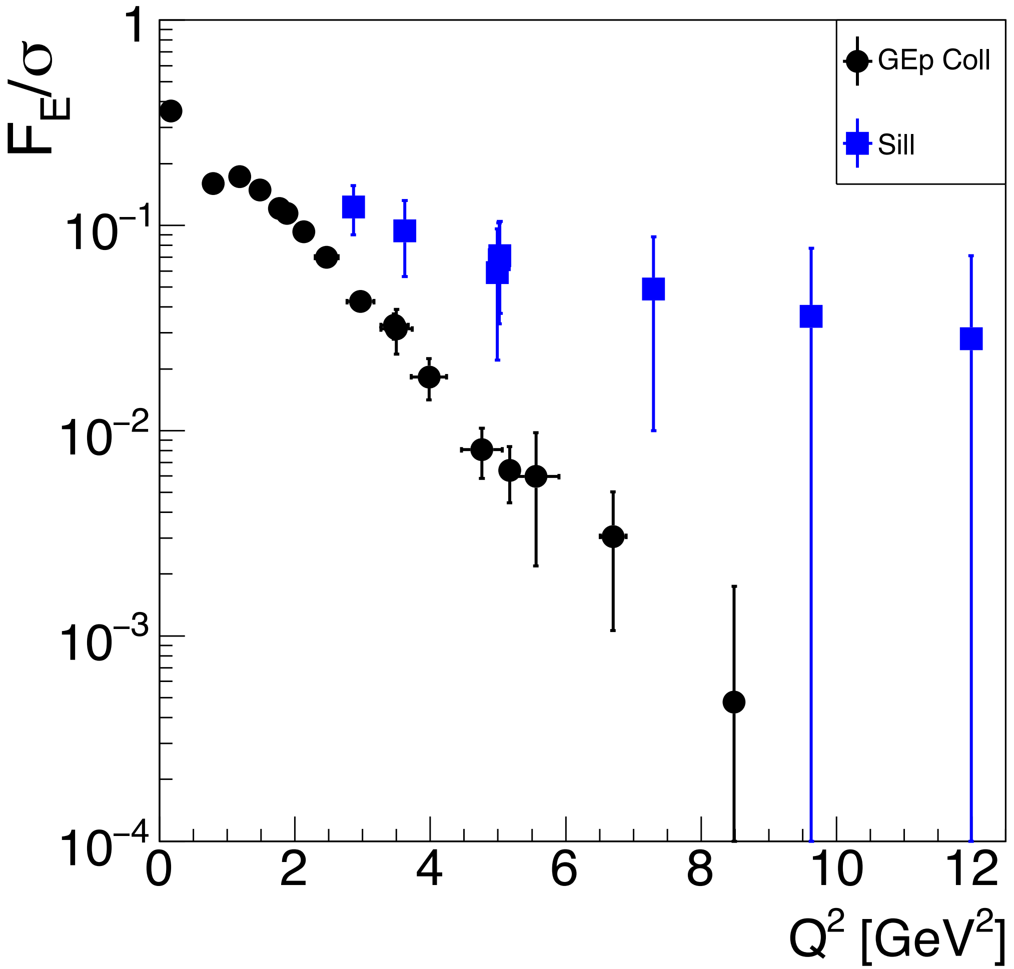




Electric contribution to ep cross section

$$F_E = \frac{\epsilon G_E^2}{1 + \tau/(\epsilon R^2)}.$$

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



$G_E \approx G_D$

$G_E < G_D$

Fitting the 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

Angular asymmetry

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

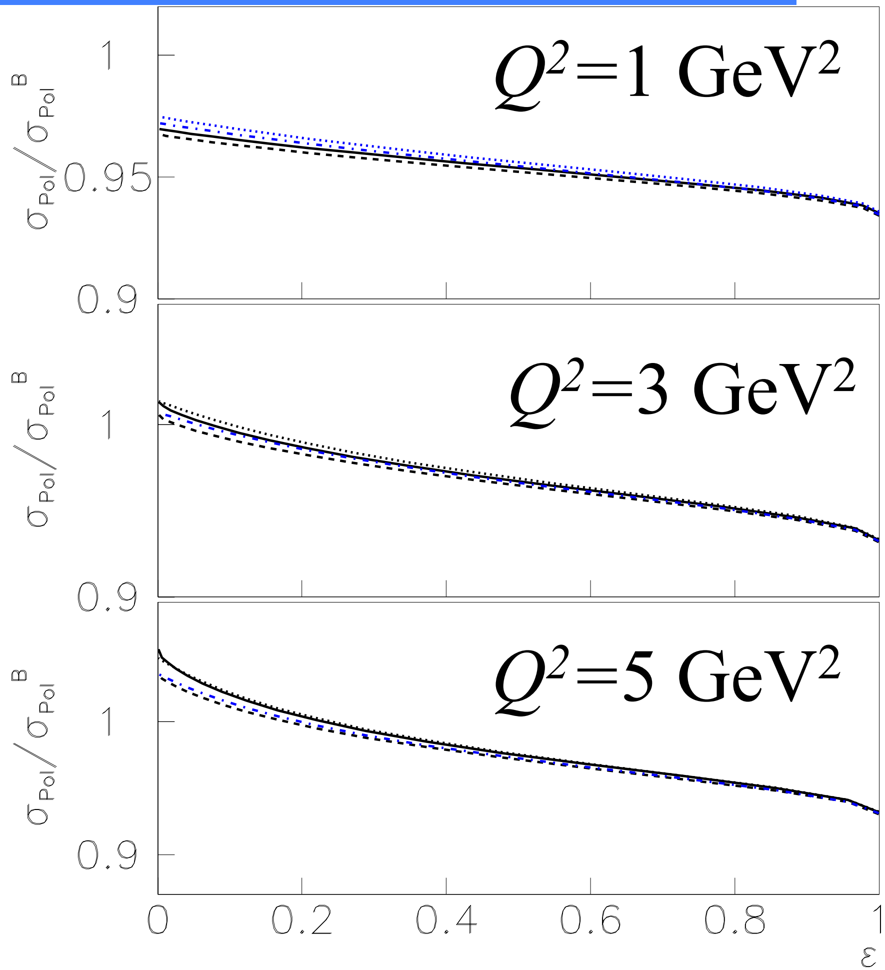
$$\mathcal{A} = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2} = \frac{\tau - \mathcal{R}^2}{\tau + \mathcal{R}^2}.$$

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

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

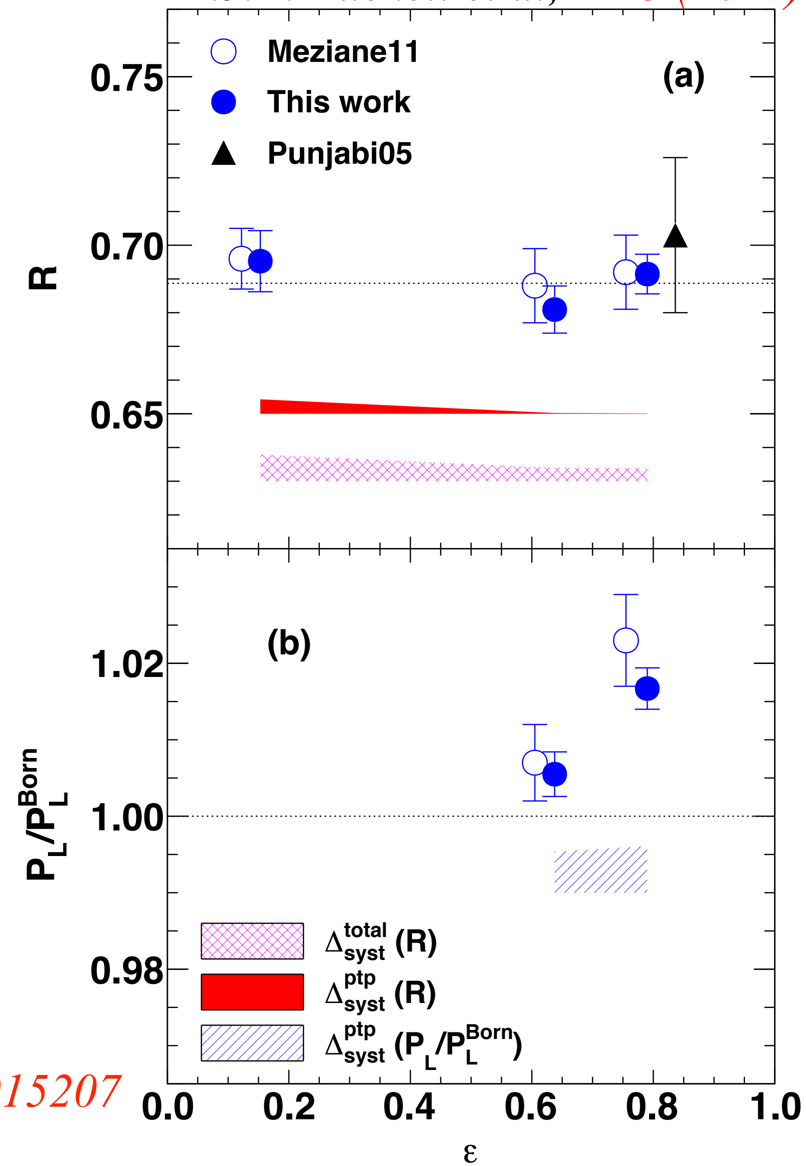
Polarization Experiments

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



Yu.M. Bystritskiy E.A. Kuraev, E. T-G., PRC75 (2007) 015207

A.J.R. Puckett et al, PRC (2017)



Check of linearity of the Rosenbluth plot

Simple parametrization:

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

$$F(Q^2,\epsilon) \to \epsilon\sqrt{\frac{1+\epsilon}{1-\epsilon}} f^{(T)}(Q^2).$$

$$f^{(T,A)}(Q^2) = \frac{C}{[1+Q^2(\mathrm{GeV})^2/0.71]^2[1+Q^2(\mathrm{GeV})^2/m_{T,A}^2]^2},$$

1γ 2γ interference is charge-odd!

$$F(Q^2,x) = -F(Q^2,-x).$$

$$x = [\sqrt{(1+\epsilon)/(1-\epsilon)}]$$

$$\frac{\sigma(e^-p)-\sigma(e^+p)}{\sigma(e^-p)+\sigma(e^+p)} = \frac{\alpha F(Q^2,\epsilon)}{\epsilon G_E^2(Q^2)+\tau G_M^2(Q^2)}.$$

E. T.-G., G. Gakh, Phys. Rev. C72,015209 (2005)