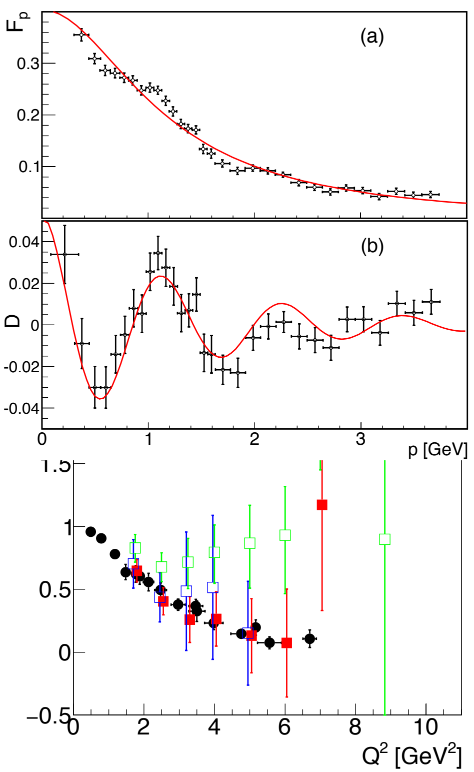
Frascati, May 20, 2016

Nucleon Form Factors Recent findings

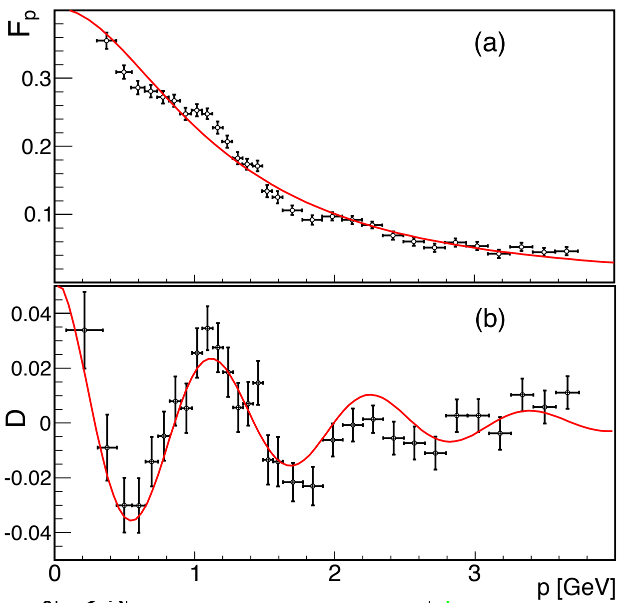
Egle Tomasi-Gustafsson
IRFU, SPhN-Saclay,



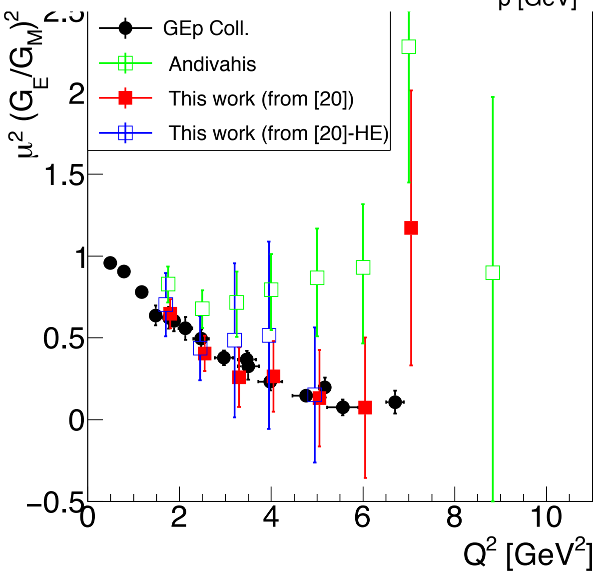
- *Accessing the hadron creation?*
- *Periodic structures in TL region*
- *Deviation from dipole in SL region?*

In collaboration with :
S. Pacetti and R. Baldini-Ferroli, Phys. Rep. 514 (2014) 1
A. Bianconi Phys Rev.Lett 114,232301 (2015)

Two questions

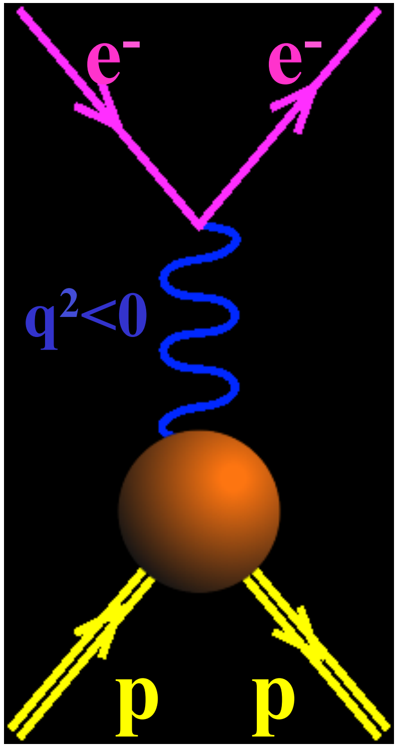


Periodic structures recently discovered in TL region
- *Hadron creation from vacuum?*
- *ISR?*
- *Resonances*



Discrepancy between polarized and unpolarized measurements of elastic EMFFs:
- *Is it real?*
- *Two photon echange?!*

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

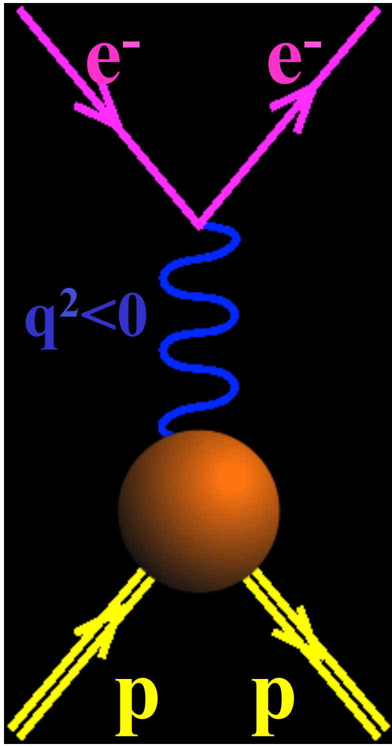
$$\Gamma_\mu = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu} q^\nu}{2M} F_2(q^2)$$

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?

Hadron Electromagnetic Form factors

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



GE(0)=1

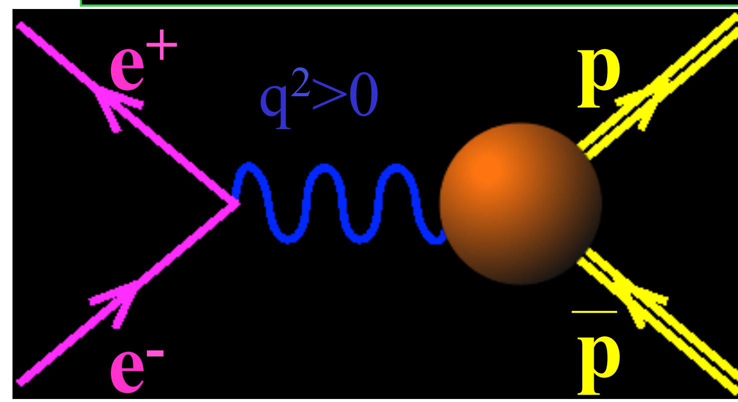
GM(0)=μ_p

Unphysical region

$p + \bar{p} \leftrightarrow e^+ + e^- + \pi^0$

Asymptotics

- *QCD*
- *analyticity*



Space-like

FFs are real

Time-Like

FFs are complex

$e + p \rightarrow e + p$

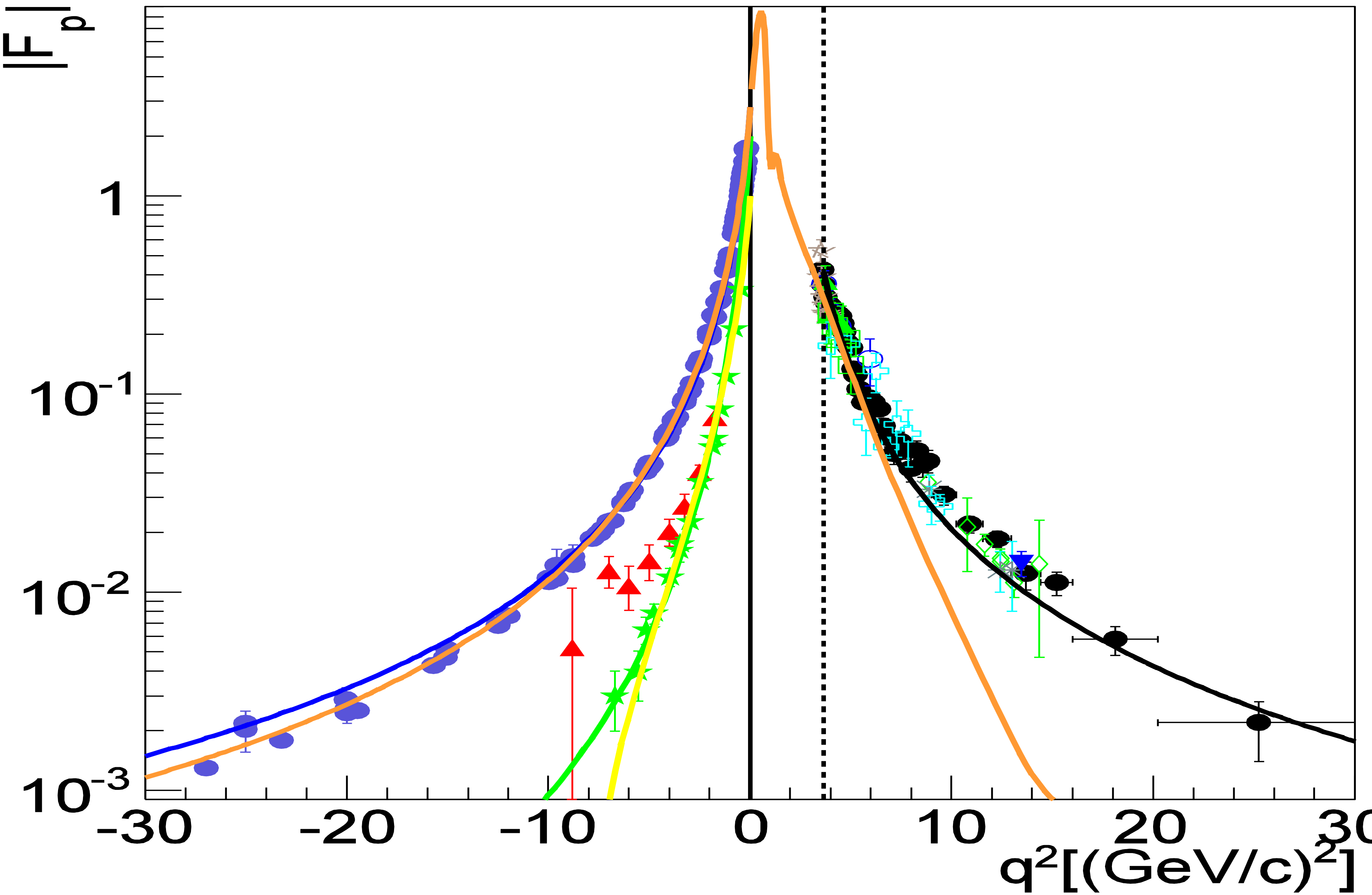
$q^2 = 4m_p^2$

GE=GM

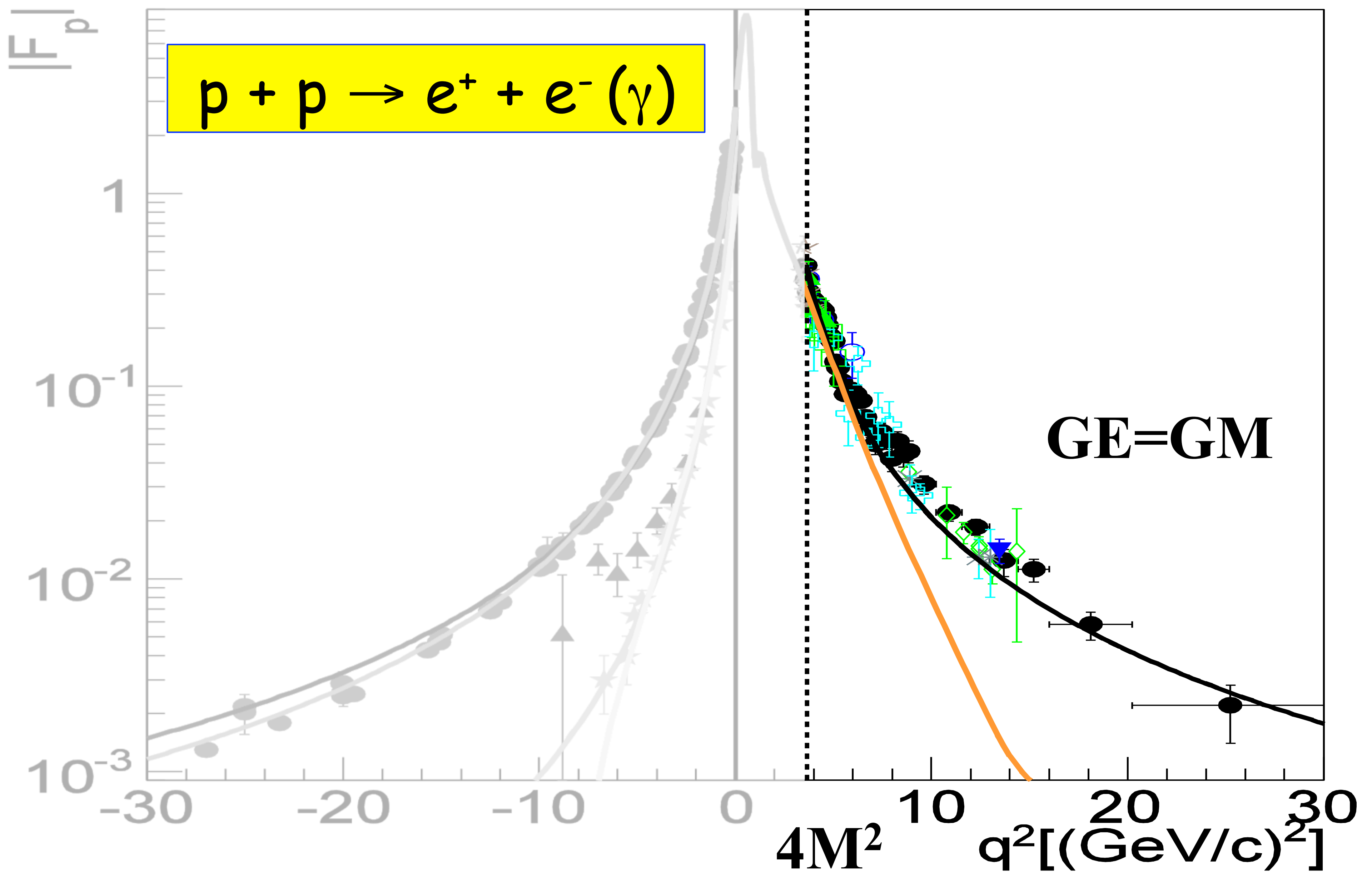
$p + \bar{p} \leftrightarrow e^+ + e^-$

q^2

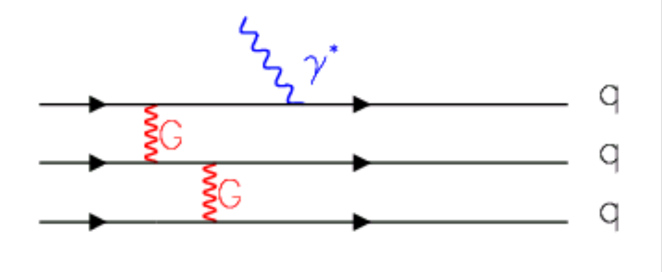
Proton Electromagnetic Form factors



The Time-Like region



The Time-like Region



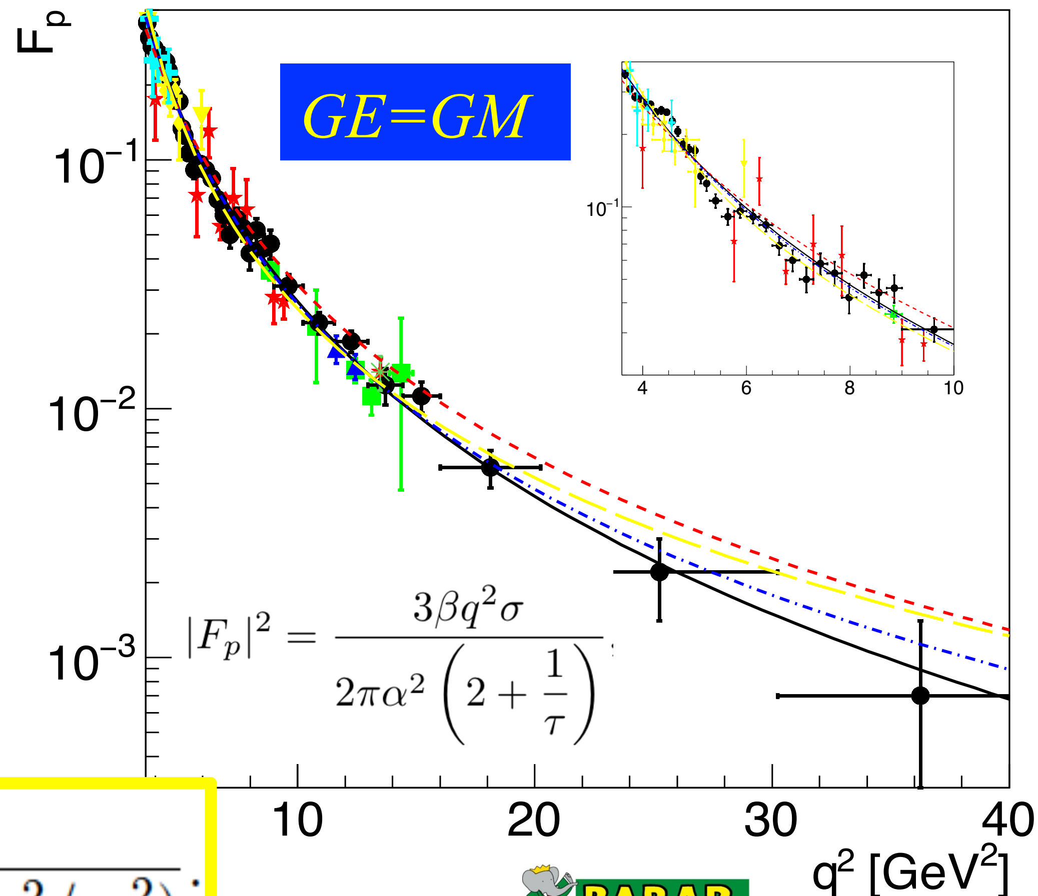
Expected QCD scaling $(q^2)^2$

$$\frac{\mathcal{A}}{(q^2)^2\left[\log^2(q^2/\Lambda^2)+\pi^2\right]}.$$

$$\frac{\mathcal{A}}{(1+q^2/m_a^2)\left[1-q^2/0.71\right]^2},$$

$$|F_{T3}(q^2)| = \frac{\mathcal{A}}{(1-q^2/m_1^2)(2-q^2/m_2^2)}.$$

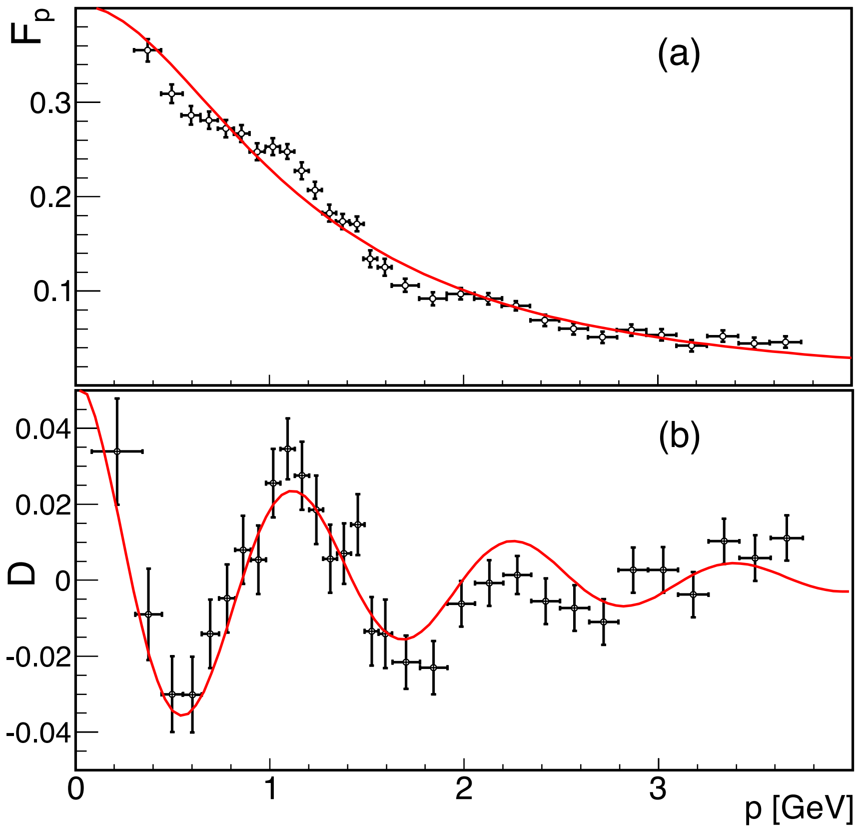
$$e^+ + e^- \to \bar{p} + p\,,$$
$$\bar{p} + p \to e^+ + e^-$$



$$|F_p|^2 = \frac{3\beta q^2\sigma}{2\pi\alpha^2\left(2+\frac{1}{\tau}\right)}$$

Oscillations : regular pattern in P_{Lab}

The relevant variable is p_{Lab} associated to the relative motion of the final hadrons.



$$F_{osc}(p) \equiv A \exp(-Bp) \cos(Cp + D).$$

$A \pm \Delta A$	$B \pm \Delta B$ $[GeV]^{-1}$	$C \pm \Delta C$ $[GeV]^{-1}$	$D \pm \Delta D$	$\chi^2/n.d.f$
0.05 ± 0.01	0.7 ± 0.2	5.5 ± 0.2	0.03 ± 0.3	1.2

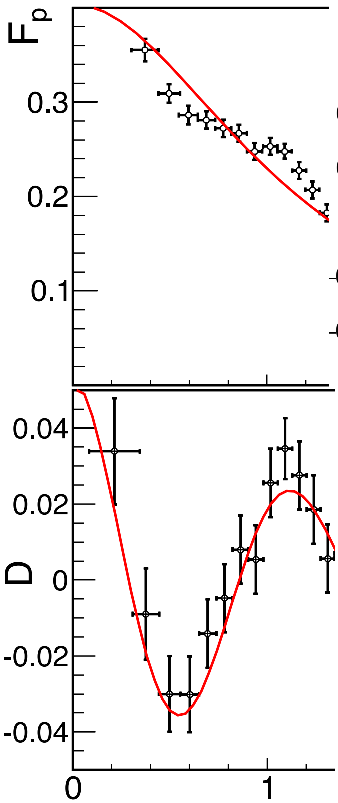
A: Small perturbation B: damping
C: r < 1fm D=0: maximum at p=0

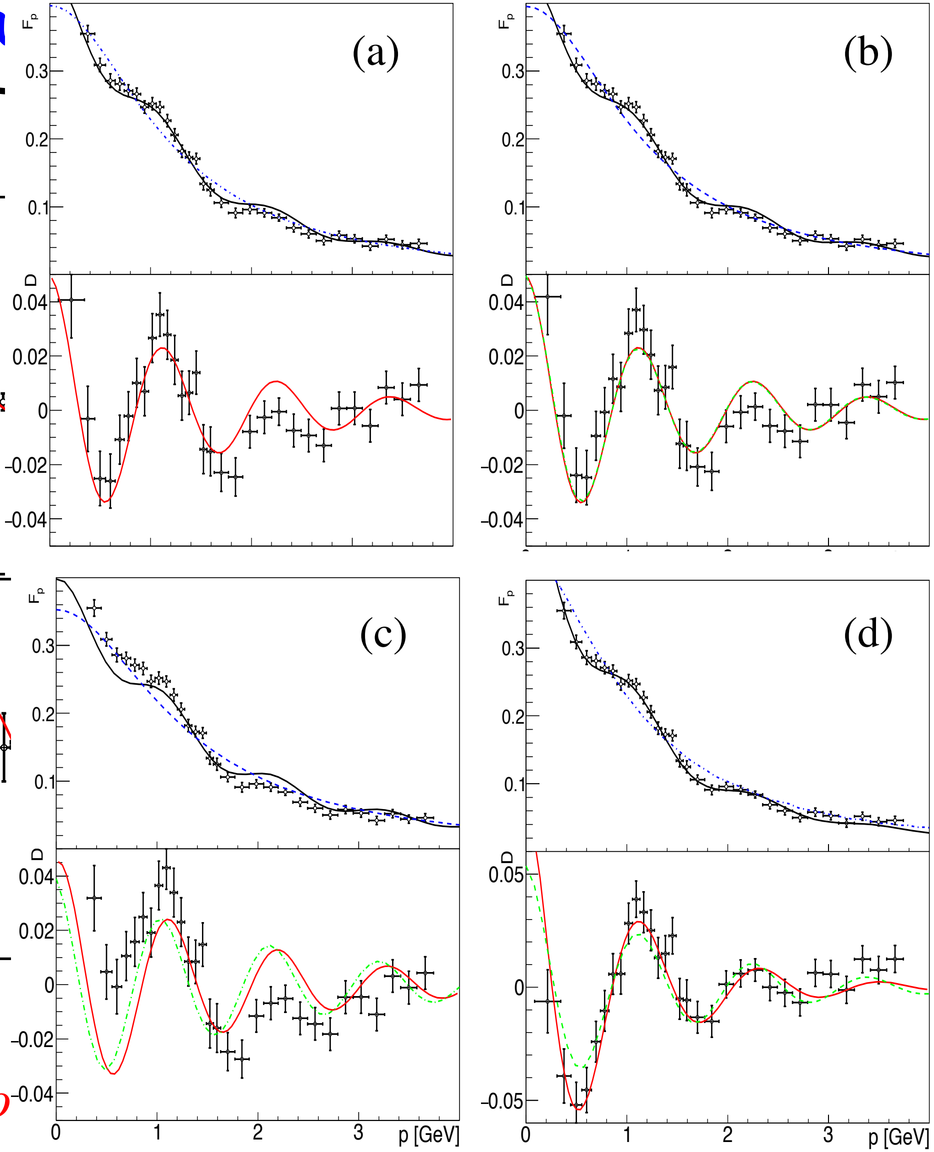
Simple oscillatory behaviour
Small number of coherent sources

A. Bianconi, E. T-G. Phys. Rev. Lett. 114,232301 (2015)

Oscillations : regular pattern in P_{Lab}

The releva … the relative motion of ·





$$\ldots p(-Bp)\ \cos(Cp + D).$$

$C \pm \Delta C$ $[GeV]^{-1}$	$D \pm \Delta D$	$\chi^2/n.d.f$
5.5 ± 0.2	0.03 ± 0.3	1.2

…on B: damping
D=0: maximum at p=0

…ory behaviour
…f coherent sources

A. Bianco…)

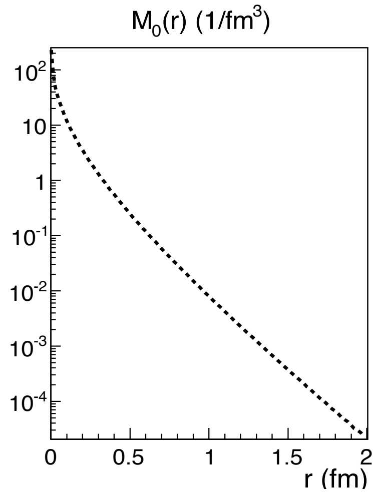
Fourier Transform

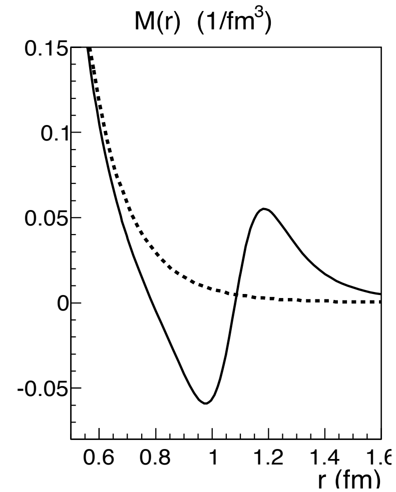
$$F_0(p) \equiv \int d^3\vec{r}\; exp(i\vec{p}\cdot\vec{r})\; M_0(r)$$

$$F(p) = F_0(p) + F_{osc}(p) \equiv \int d^3\vec{r}\; exp(i\vec{p}\cdot\vec{r}) M(r).$$

$$F_0 = \frac{\mathcal{A}}{(1+q^2/m_a^2)\,[1-q^2/0.71]^2},$$

$$F_{osc}(p) \equiv A\ \exp(-Bp)\ \cos(Cp + D).$$

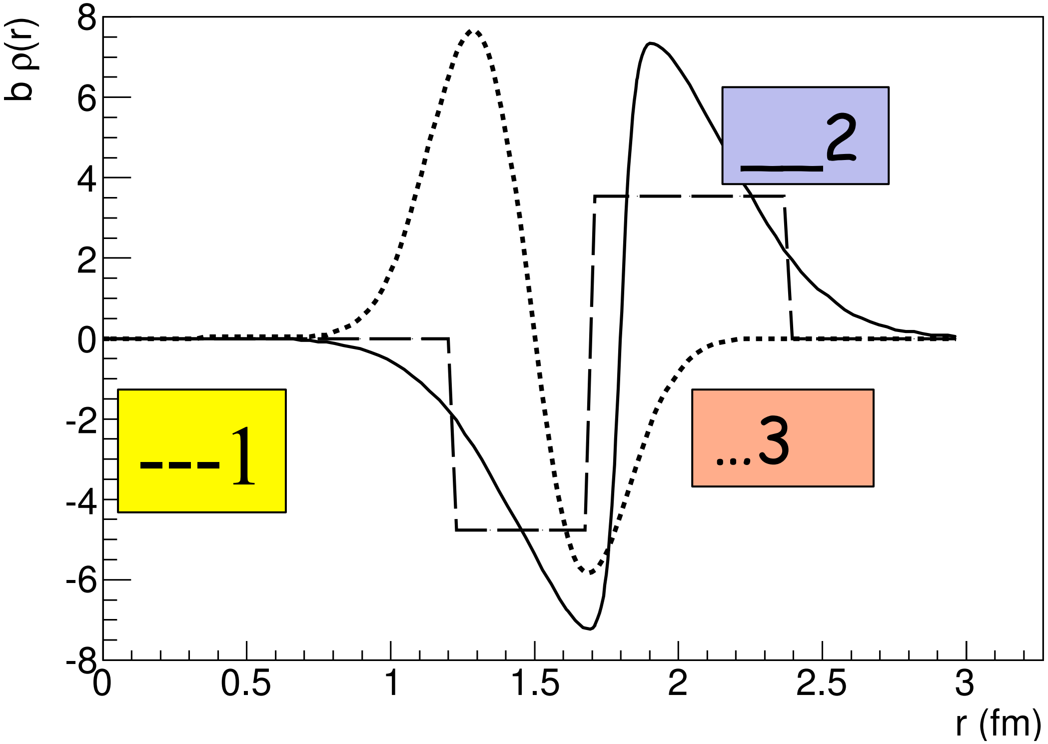




- *Rescattering processes*
- *Large imaginary part*
- *Related to the time evolution of the charge density?*
  (E.A. Kuraev, E. T.-G., A. Dbeyssi, PLB712 (2012) 240)
- *Consequences for the SL region?*
- *Data from BESIII confirm the structure*
- *Expected from PANDA*

Double layer potentials

<u>Double layer rescattering densities</u> : combination of two hollow potentials: one absorbing and one generating (imaginary potentials).



1) Multiple step function

2) Soft multistep

3) Two-gaussian opposite sign potential

A. Bianconi, E. T-G., Phys. Rev. C (2016)

Optical model analysis

Optical model analysis:

two component imaginary potential:

absorbing outside, regenerating inside

with steep change of sign.

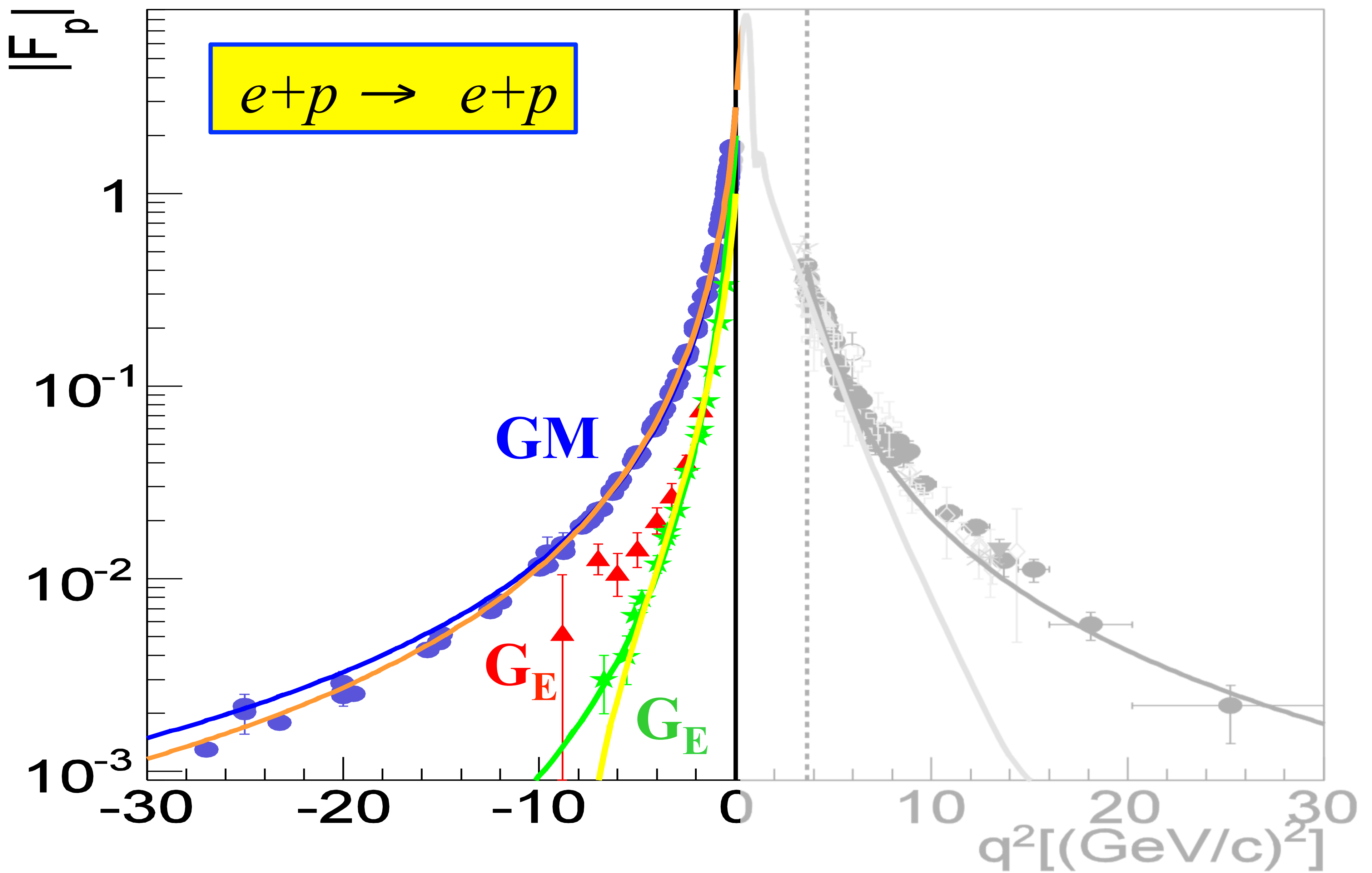
From the pbar-p point of view, the coupling with the other channels transforms into an imaginary potential that

- destroys flux (absorption – negative potential)
- generates flux (creation – positive potential)

The excited vacuum created by e+e- annihilation decays in multi-quark states: pbar-p is one of them

- feeding at small r by decay of higher mass states in pbar p
- depletion at large r from pbar-p annihilation into mesons

The Space-Like region



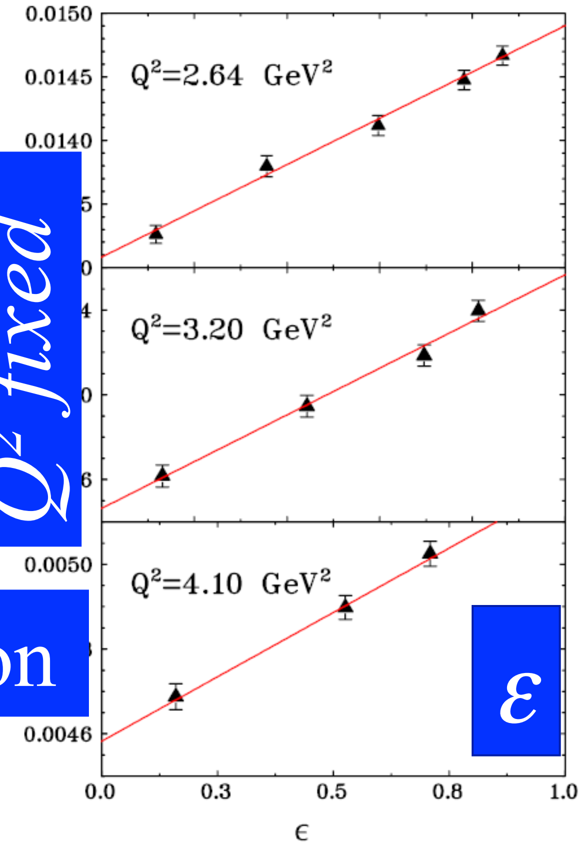
The Rosenbluth separation

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

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

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

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 (theory:1967)

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

PHYSICS

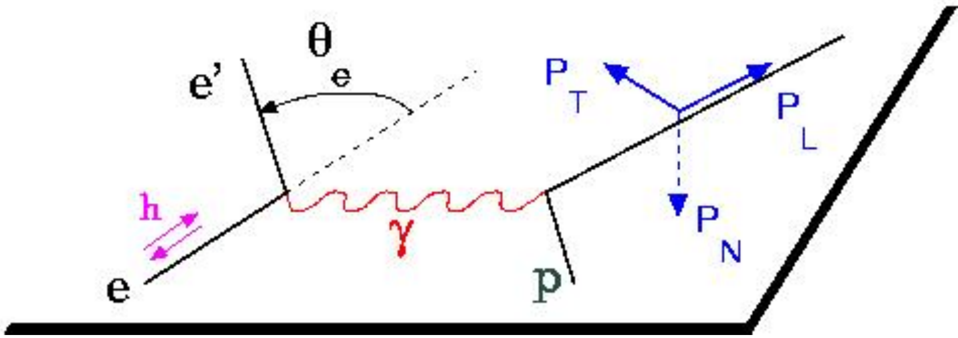
POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

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

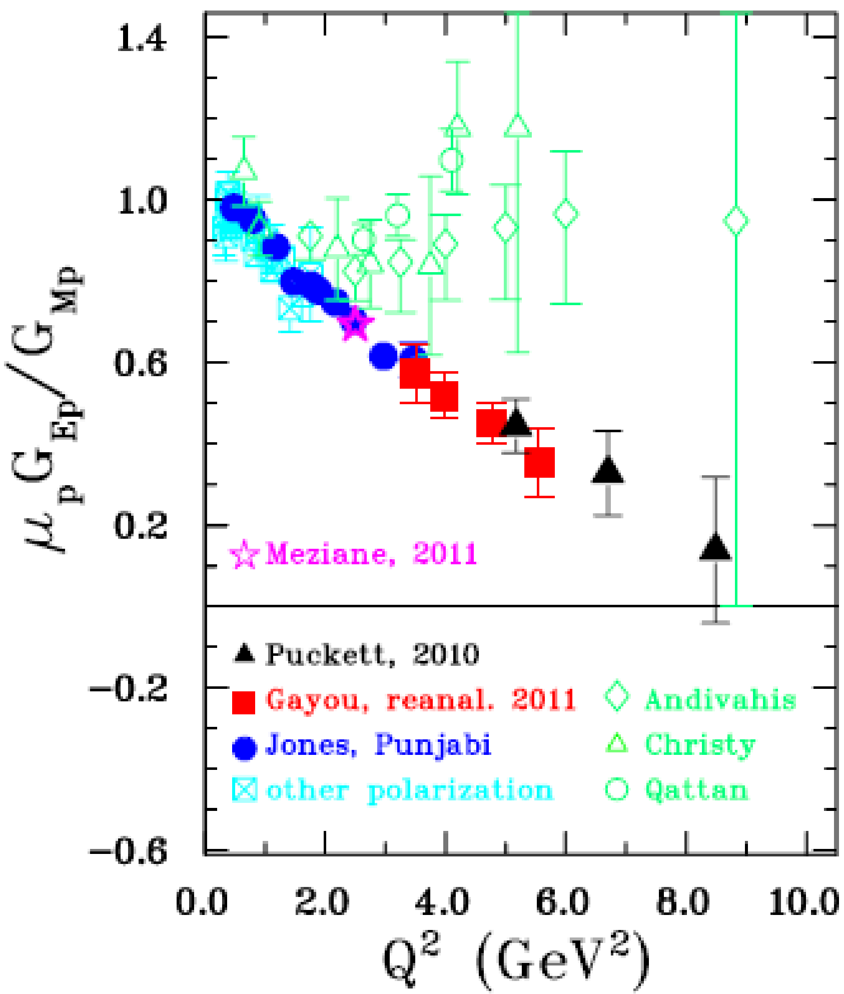
polarized beam and recoil proton polarization

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***



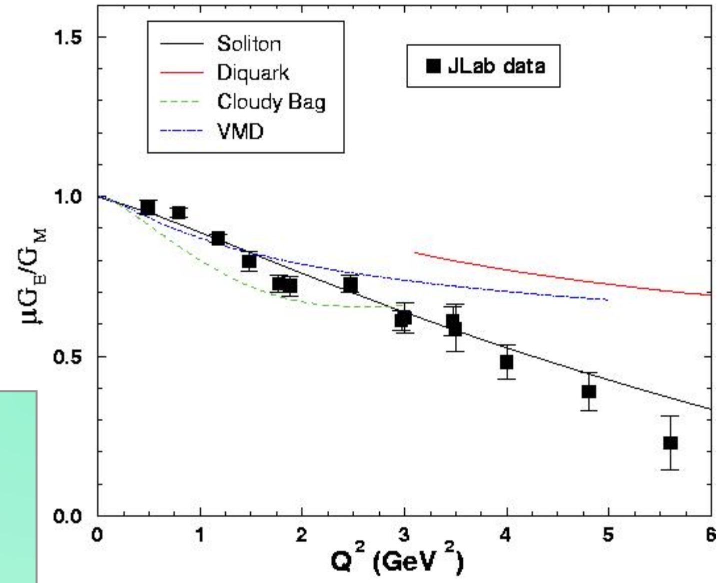
A.J.R. Puckett et al, PRL (2010), PRC (2012)

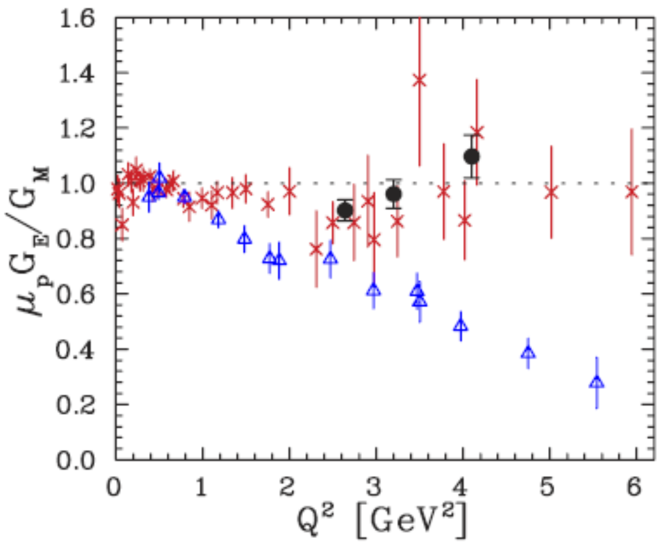
Issues

- 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





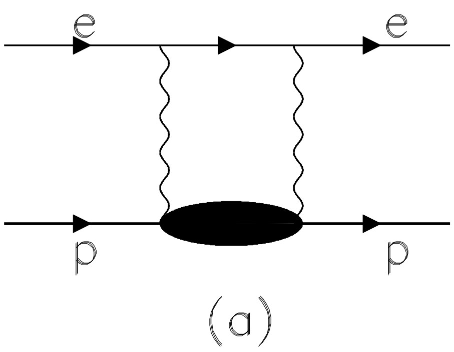
Reaction mechanism:
1γ-2γ interference ?

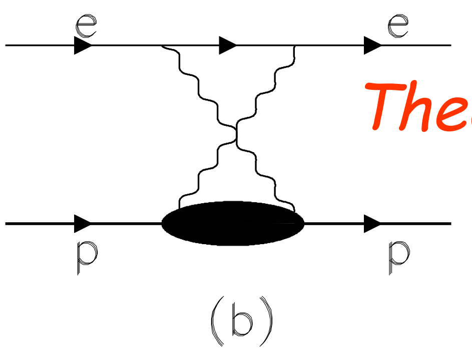
Radiative corrections?

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 .

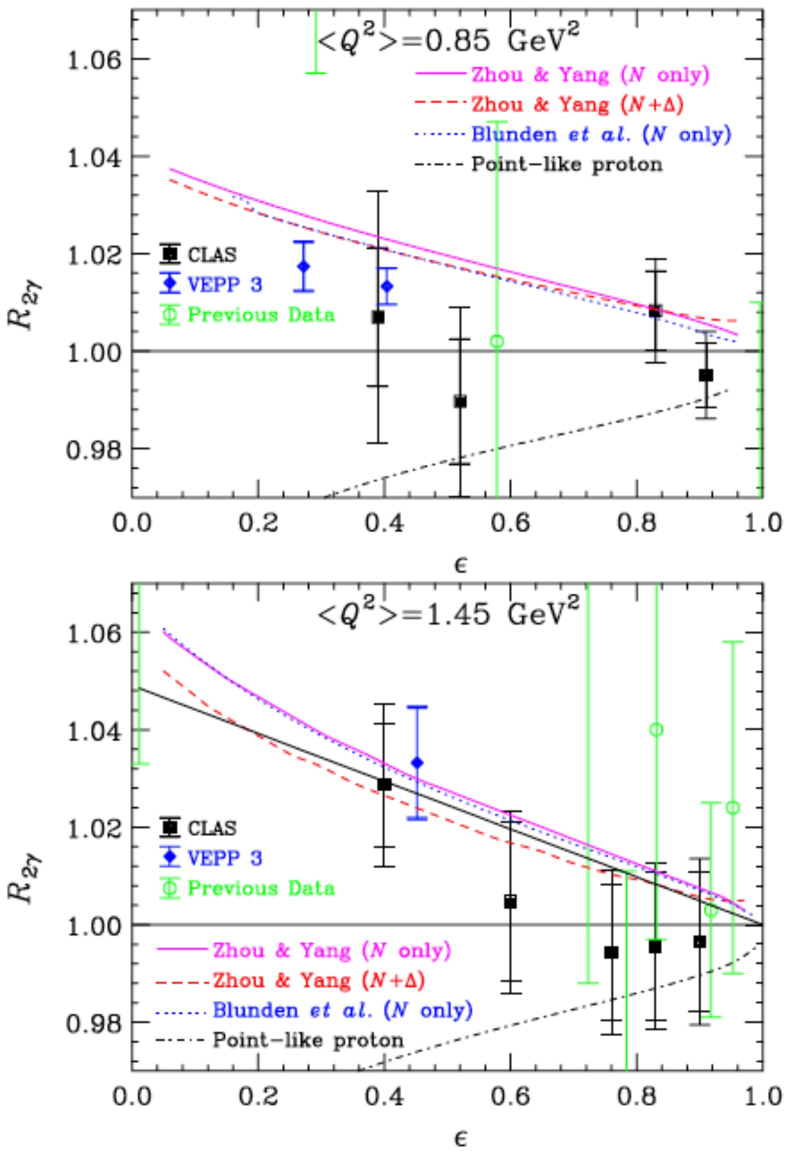




Theory not enough constrained!

CLAS, VEPP, OLYMPUS….

V. Rimal, ArXiv 1603. 003151

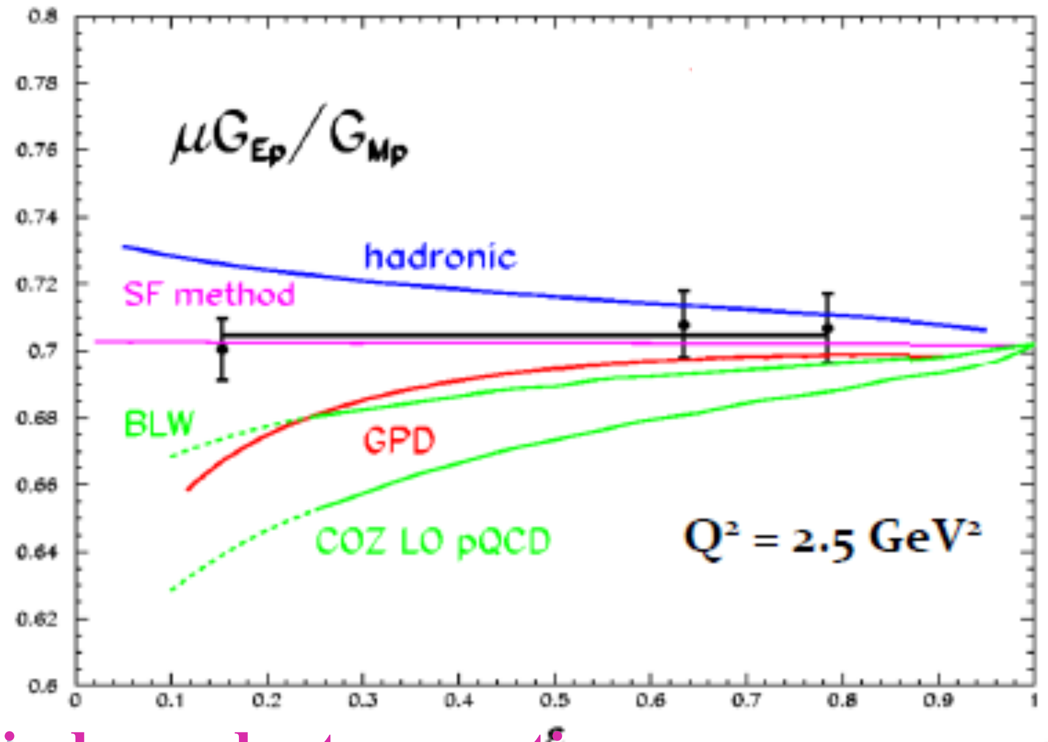


- Q^2<2 GeV2
- Effect < 2%
- No evident increase with Q^2

Polarization ratio (ε-dependence)

- *DATA: No evidence of ε-dependence at 1% level*

- *MODELS: large correction (opposite sign) at small ε*



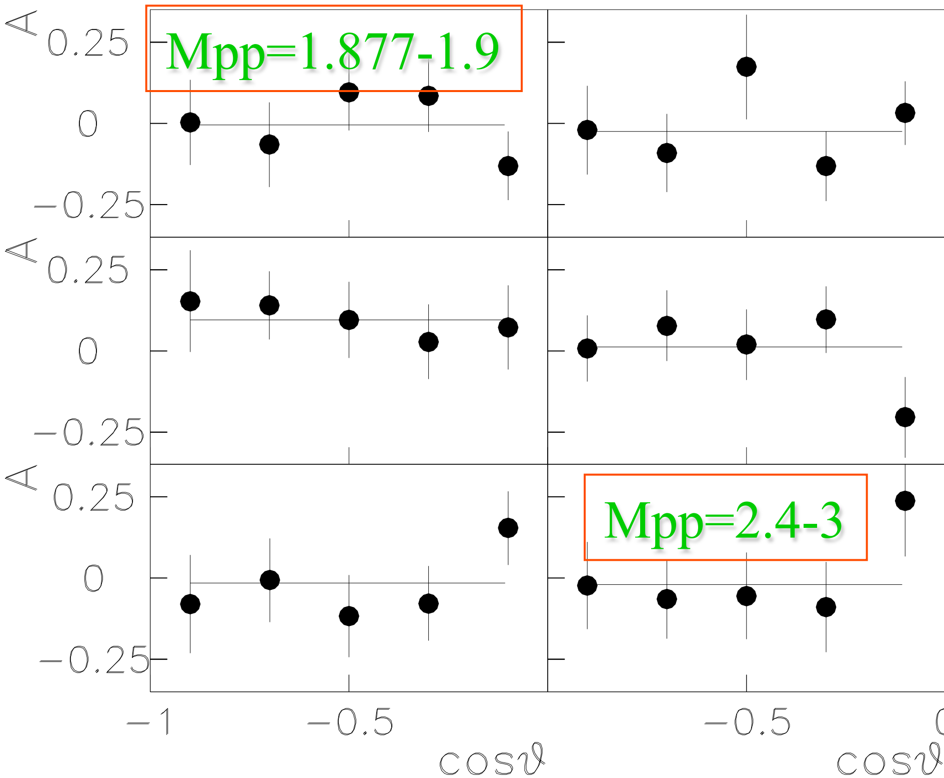
•SF method: ε-(almost)independent corrections

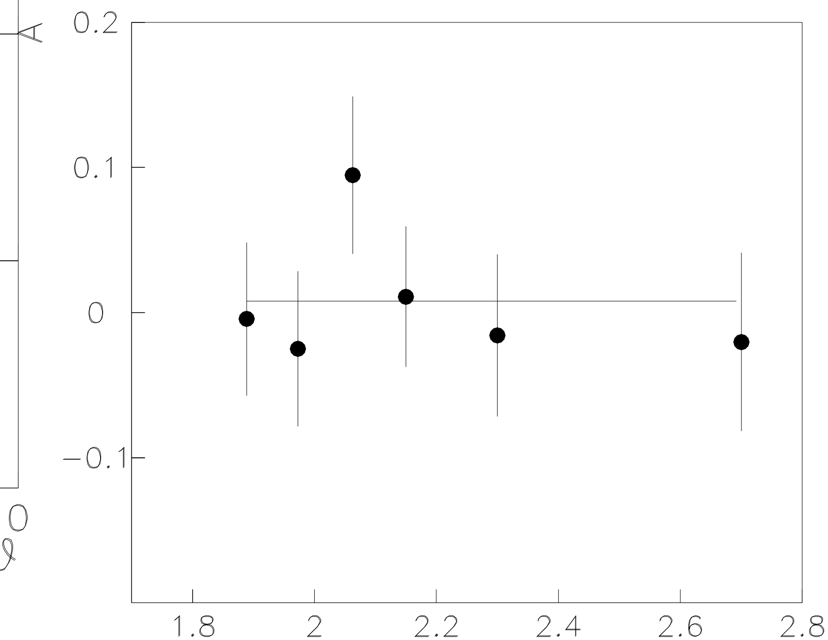
- *Theory: corrections to the Born approximation at Q2= 2.5 GeV2*
  - *Y. Bystritskiy, E.A. Kuraev and E.T.-G, Phys.Rev.C75: 015207 (2007)*
  - *P. Blunden et al., Phys. Rev. C72:034612 (2005) (mainly GM)*
  - *A. Afanasev et al., Phys. Rev. D72:013008 (2005) (mainly GE)*
  - *N.Kivel and M.Vanderhaeghen, Phys. Rev. Lett.103:092004 (2009). (high Q_2)*

Angular Asymmetry

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

A=0.01±0.02





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

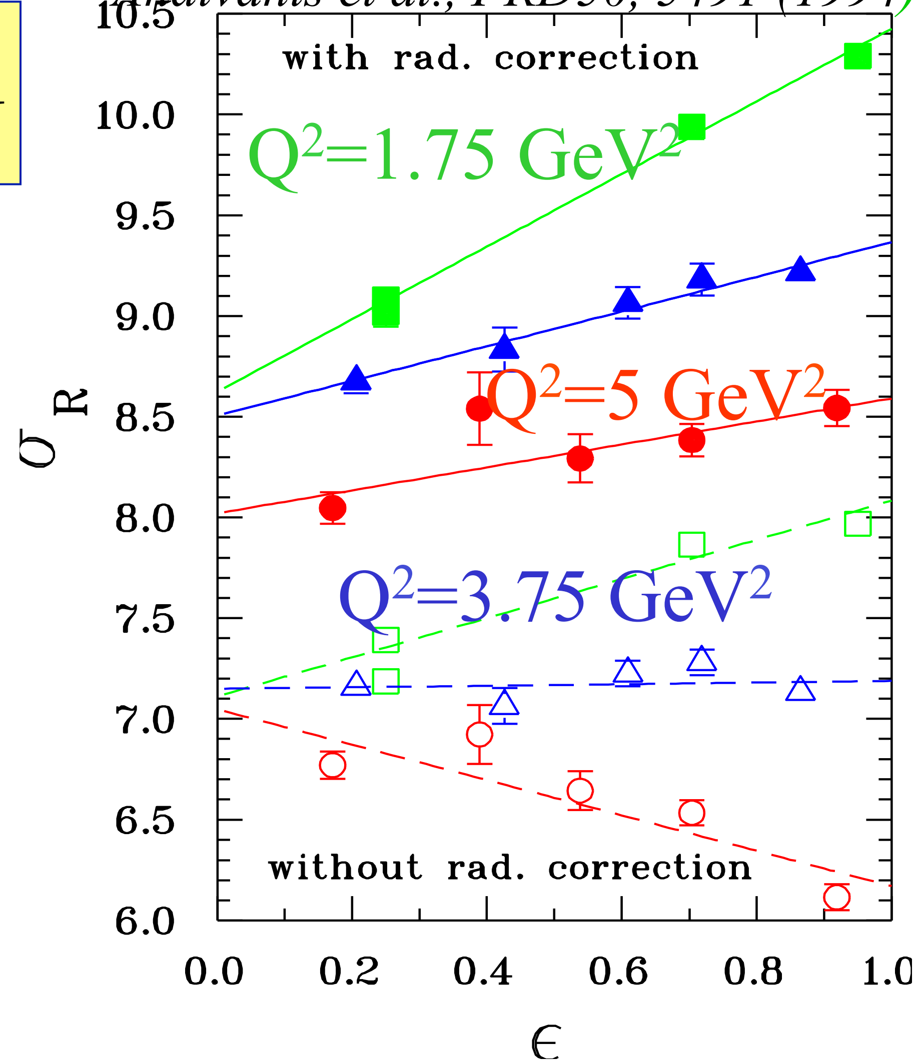
Radiative Corrections (ep)

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

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*

Andivahis et al., PRD50, 5491 (1994)



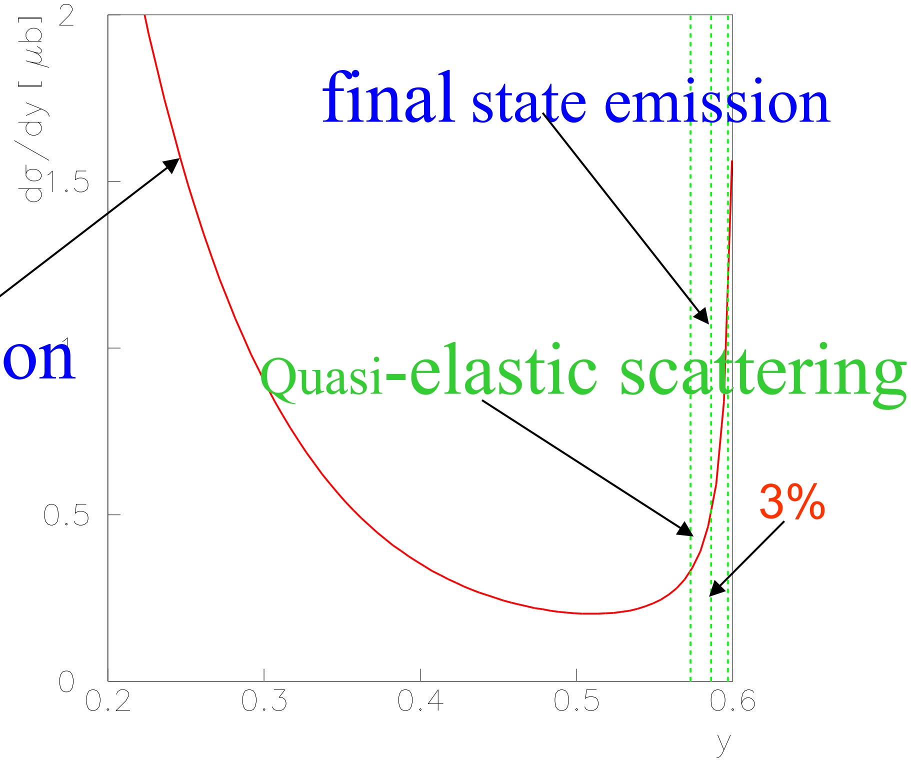
E. T.-G., G. Gakh, PRC 72, 015209 (2005)

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!

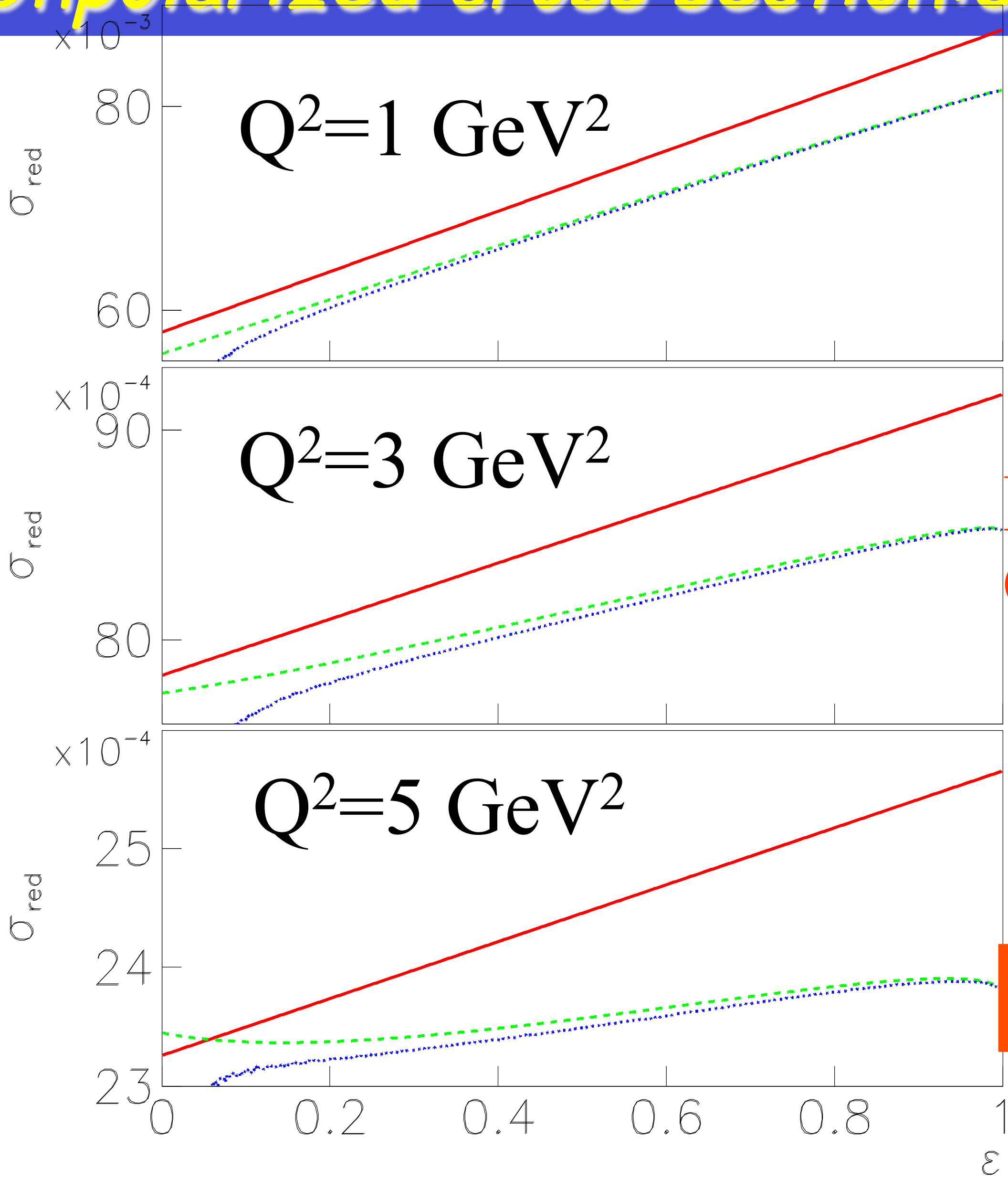
Shift to LOWER Q^2

Y_0

All orders of PT needed →

beyond Mo & Tsai approximation!

Unpolarized cross section:ep elastic scattering



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

Born +dipole FFs

(=unpolarized experiment+Mo&Tsai)

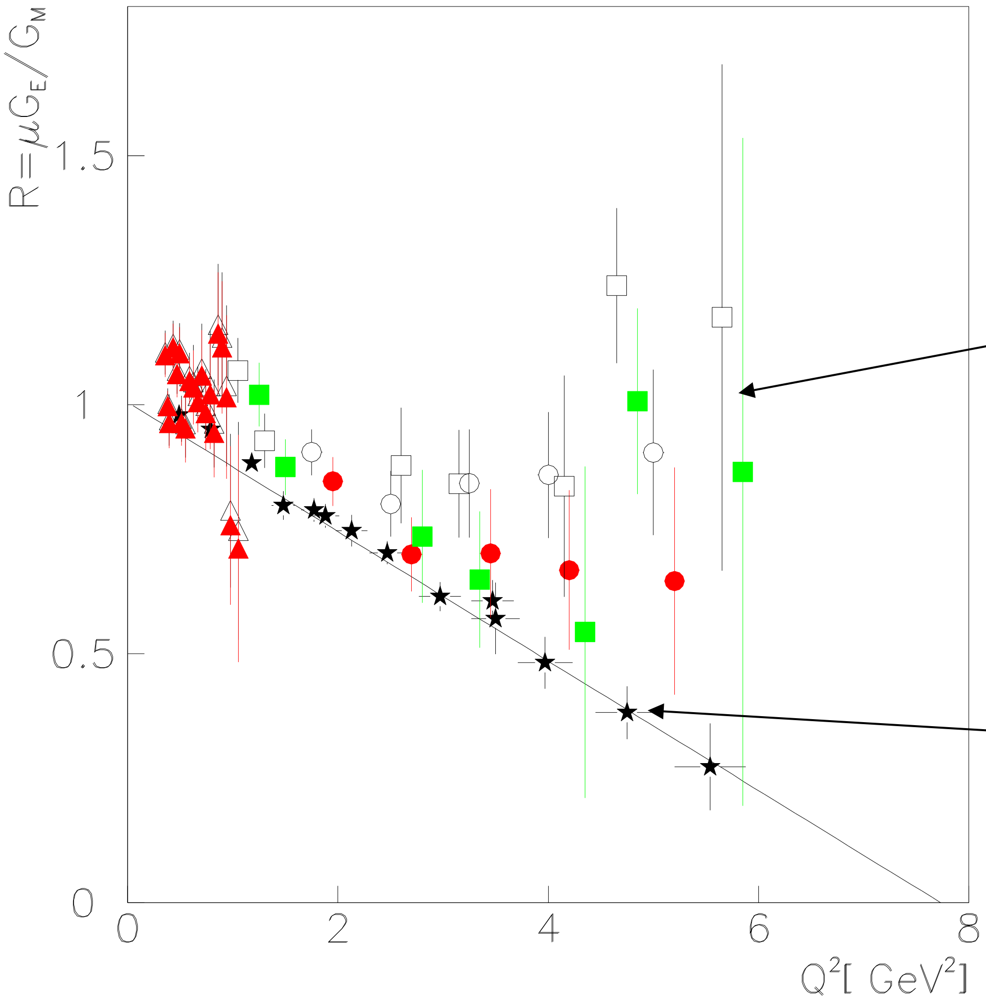
SF (with dipole FFs)

SF+2γ exchange

SF: change the slope!

2γ exchange very small!

Radiative Corrections (SF method)



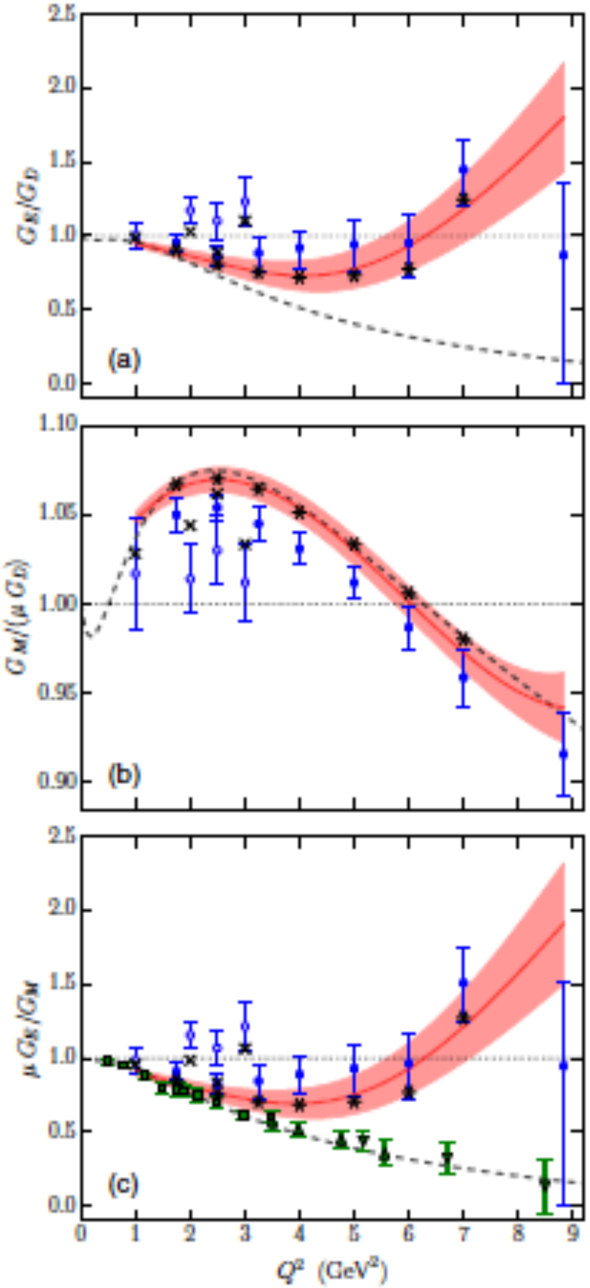
SLAC data

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

A. V. Gramolin* and D. M. Nikolenko

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

(Received 28 March 2016; published 10 May 2016)

V. Fadin ,R.E.Gerasimov

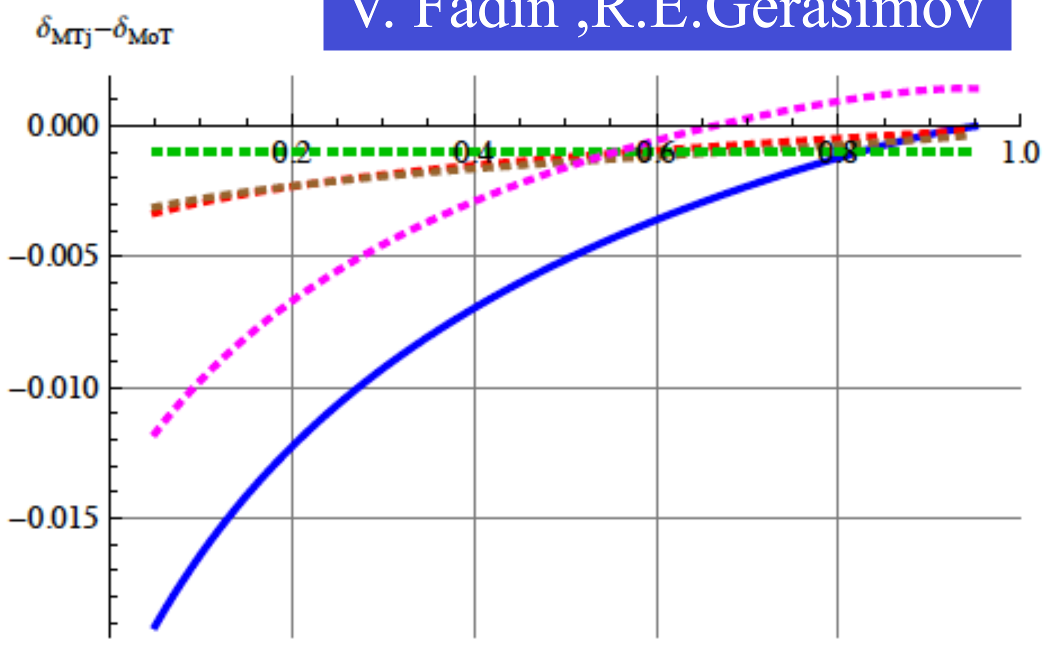


Figure 3: Difference at $Q^2 = 5\ GeV^2$.

Other issues in data

- Correlations

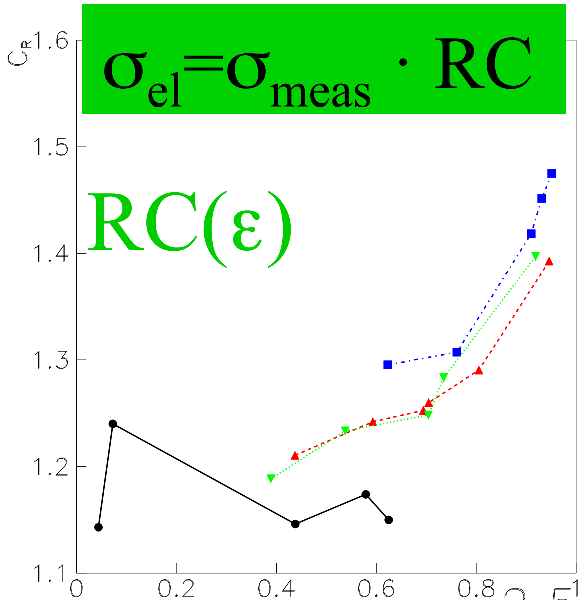
- Normalizations
  + of different sets of data
  + in a series

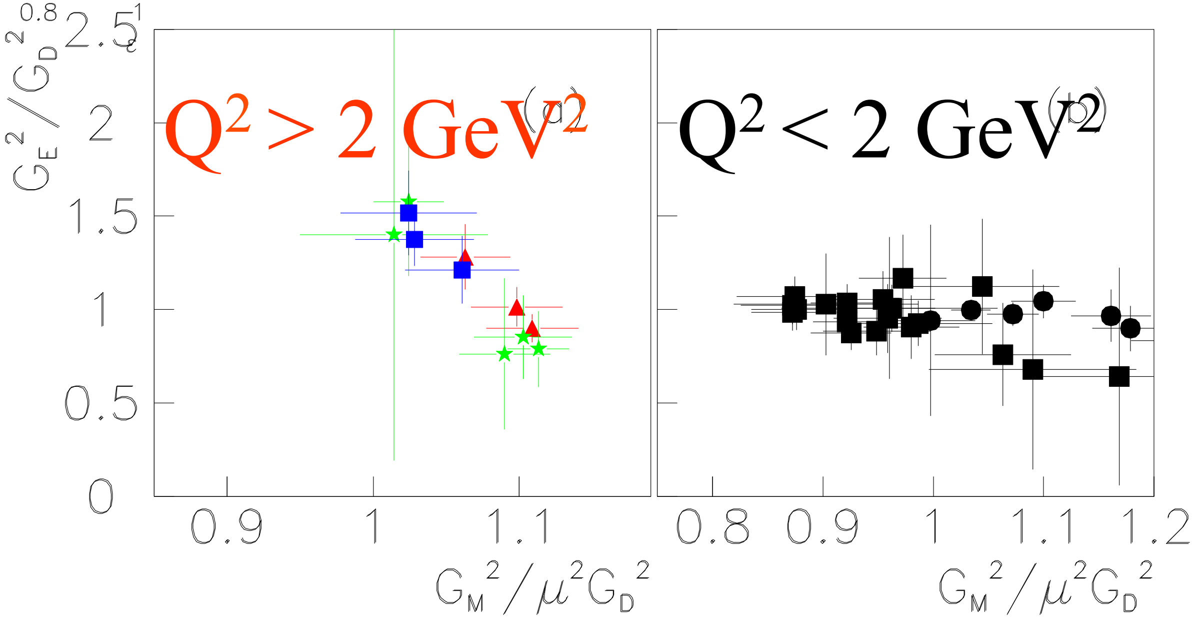
Experimental correlation

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

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

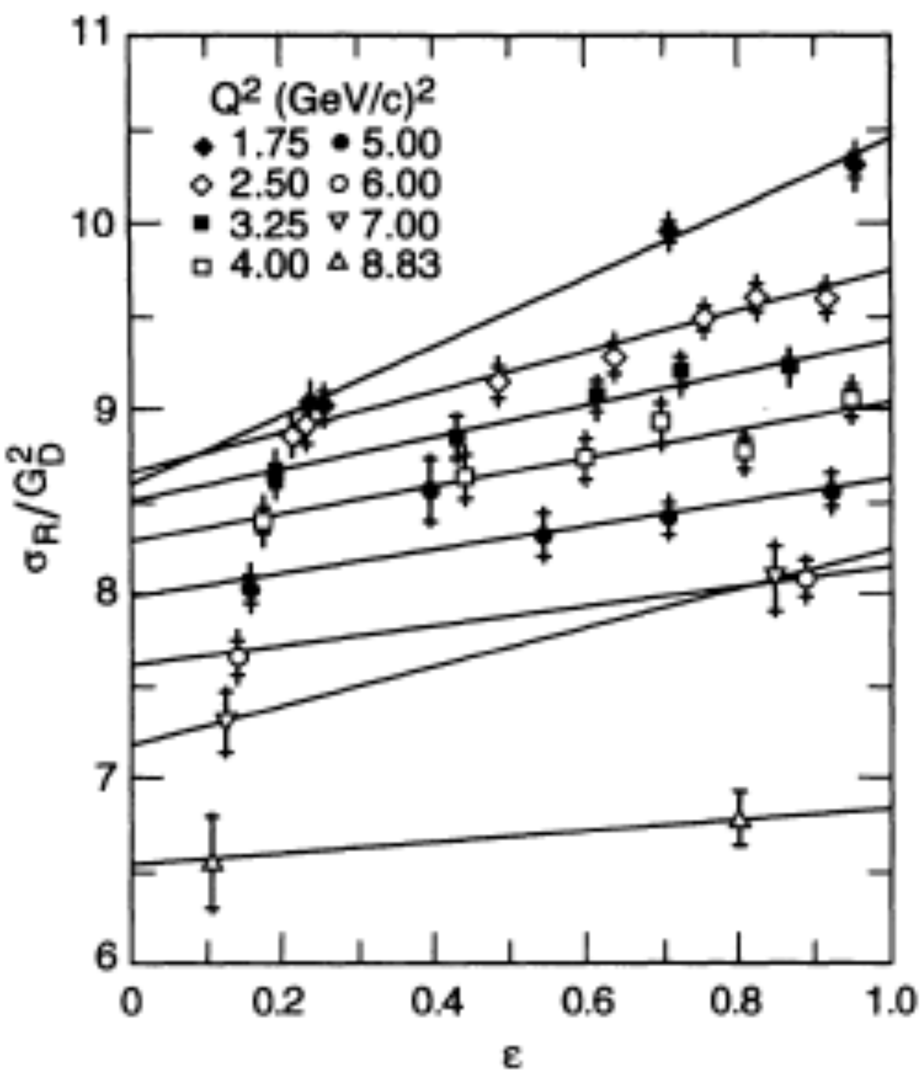
only published values!!





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)

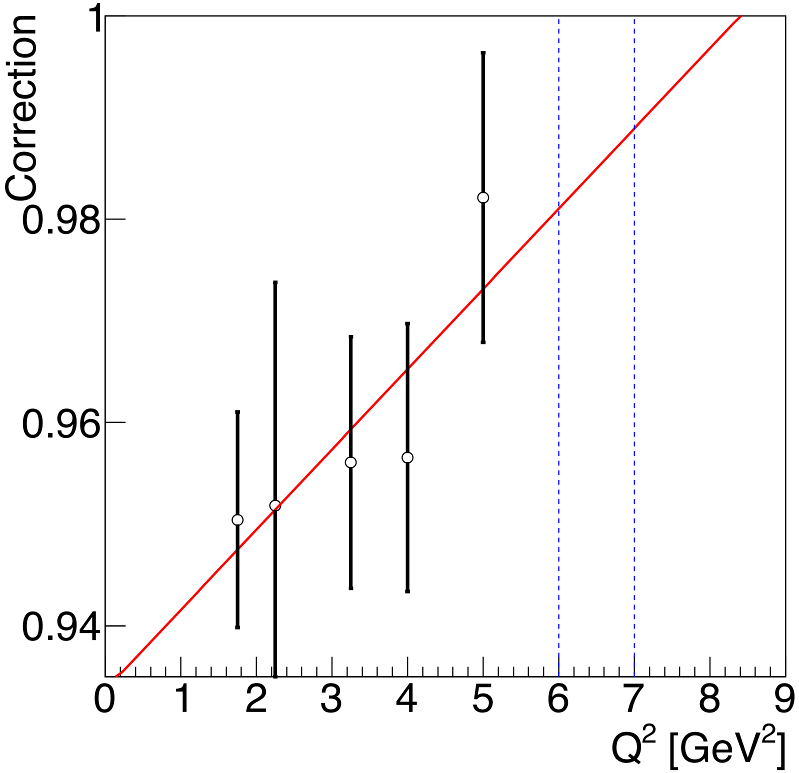
Increases the slope!

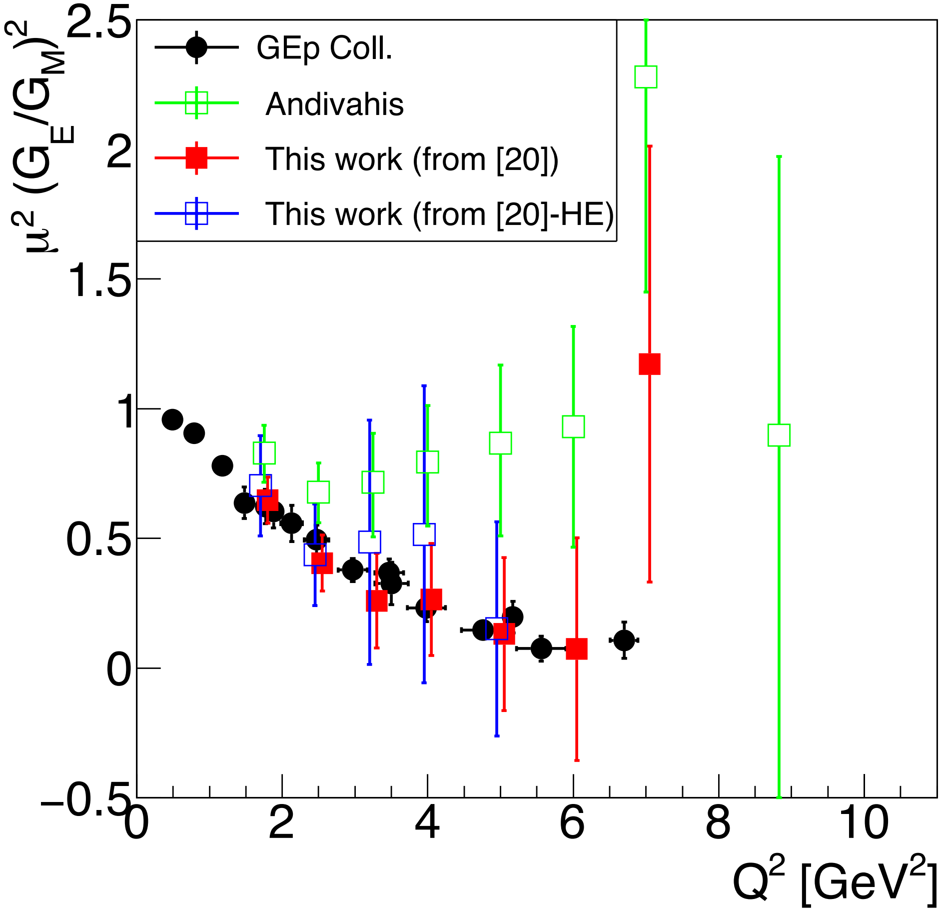
$$G_E \approx G_D$$

Direct extraction of the Ratio

Andivahis et al., PRD50, 5491 (1994)

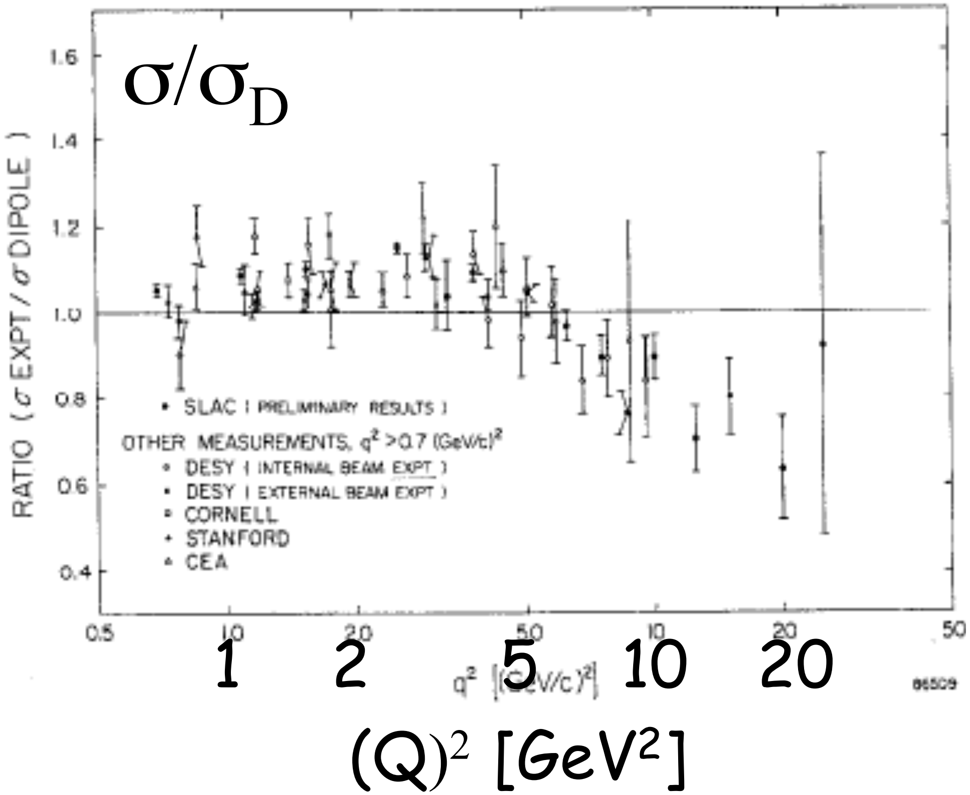
$$\sigma_{\rm red} = G_M^2(R^2\epsilon + \tau),$$

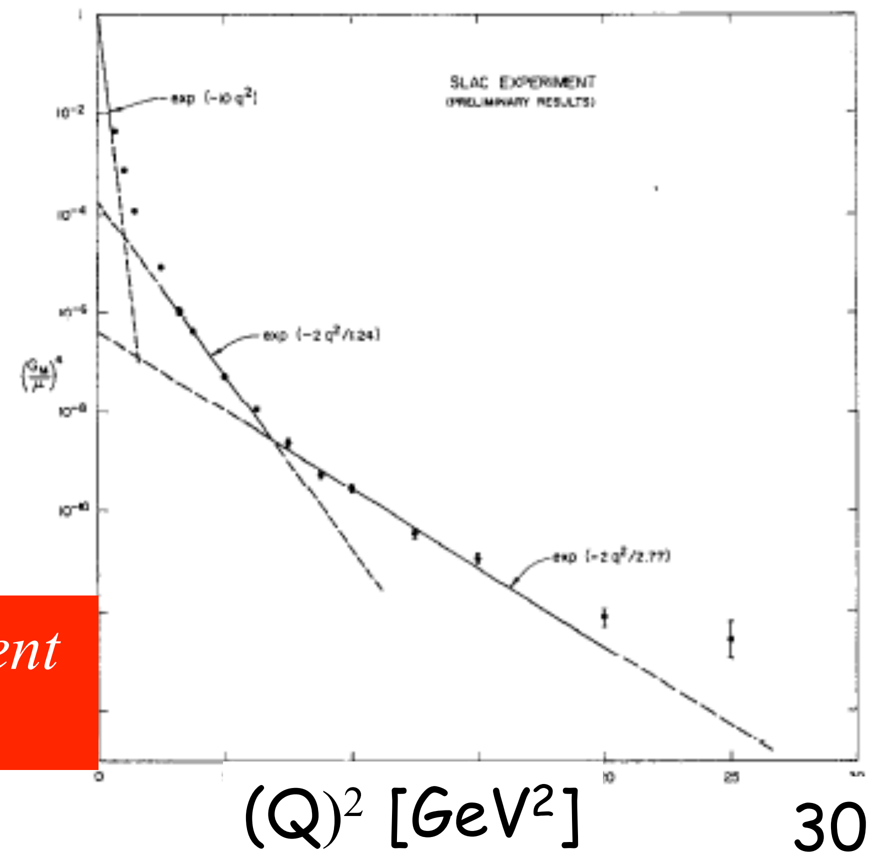




Nucleon FFs above 6 GeV

SLAC-PUB-372
September 1967





…which makes evident any disagreement with the dipole prediction

R. Taylor

Conclusion - Discussion

•Large activity in Space and Time-like regions increase precision or extend q^2 range

Jefferson Lab

VEPP-3
Novosibirsk

•Unified models in SL and TL

To explore:

- *Neutron/proton EM structure: FFs contain essential information*
- *Effect of deviation of GE and GM from dipole*

- *If problems were not in observables… but in derivatives?*