Highligths in hadron physics:
New views on the proton structure

Egle Tomasi-Gustafsson
CEA, IRFU, DPhN,
Université Paris-Saclay
France

Women in Nuclear and Hadron Theoretical Physics: the last frontier - WTPLF 2018

10-11 December 2018 *Grand Hotel Savoia Genova*
Europe/Rome timezone

Open questions in QCD (some..)

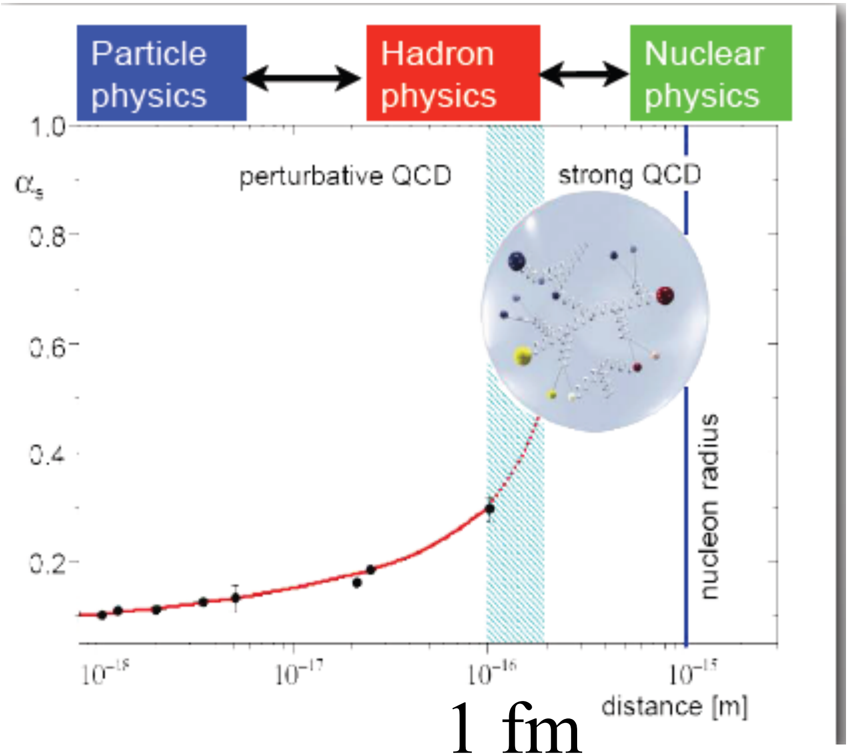
- Confinement: *why free quarks are not observed?*

- Origin of the hadron mass: the Higgs mechanism accounts for some percent of the hadron mass

- *How are* color neutral objects *formed?*

- Establish existence and properties of exotics, hybrids, glueballs

- Structure of the nucleon (charge, magnetic, spin distributions)

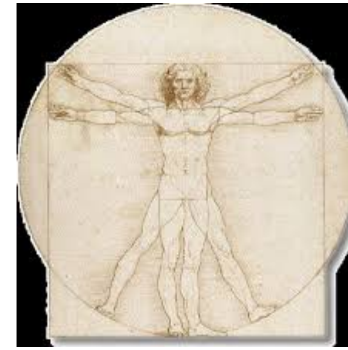


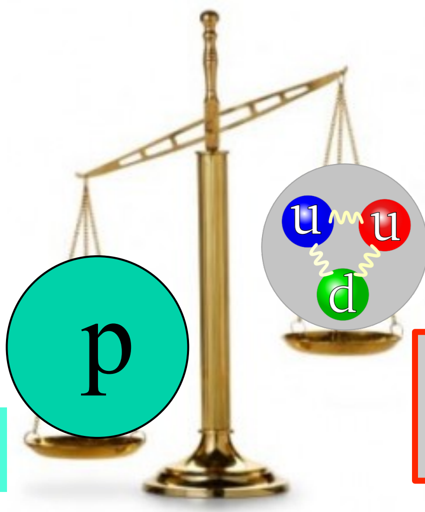
The proton

- Hadrons - particles submitted to the strong interaction – are the most abundant constituents of the visible matter
- Proton is the the most common particle in nature
- Its fundamental properties
  - Mass
  - Spin
  - Size

  are still *object of controversy*

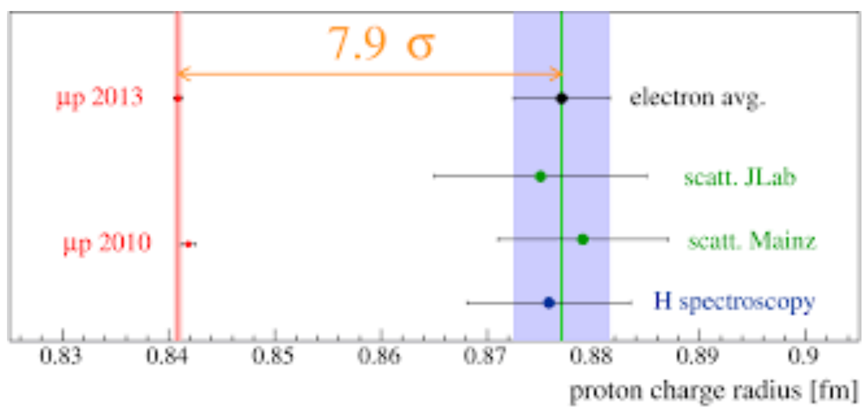
  Electromagnetic structure
  Elementary reactions





Mp=938,2720 MeV/c^2

u-quark=1.5-4 MeV/c^2
d-quark=4-8 MeV/c^2



Hadron Electromagnetic Form factors

The Nobel Prize in Physics 1961

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

Robert Hofstadter

1/2 of the prize

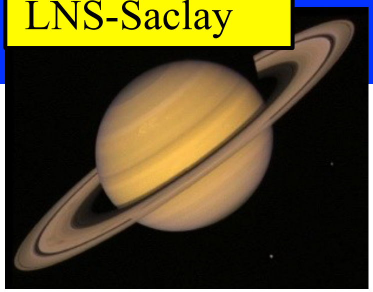
USA

Stanford University
Stanford, CA, USA

- Characterize the internal structure of a particle ($\neq$ point-like)
- Elastic form factors contain information on the hadron ground state.
- In a P- and T-invariant theory, the EM structure of a particle of spin S is defined by 2S+1 form factors.
- Neutron and proton form factors are different.
- Deuteron: 2 structure functions, but 3 form factors.
- Playground for theory and experiment
  - at low q^2 probe the size of the nucleus,
  - at high q^2 test QCD scaling

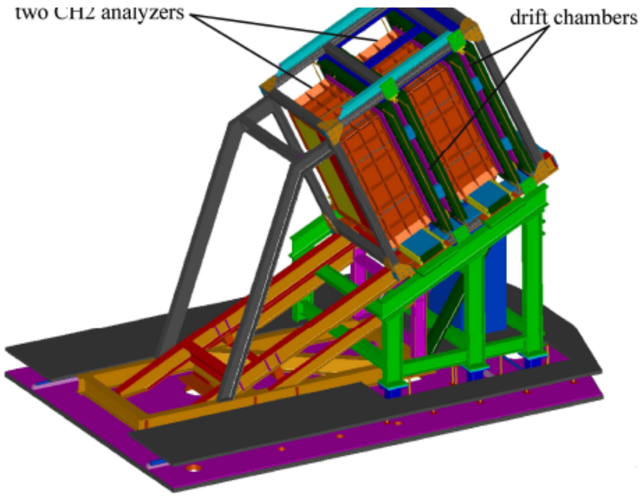
Recent experimental achievements: polarization

LNS-Saclay



JINR-Dubna

Hadron polarimetry in the GeV range

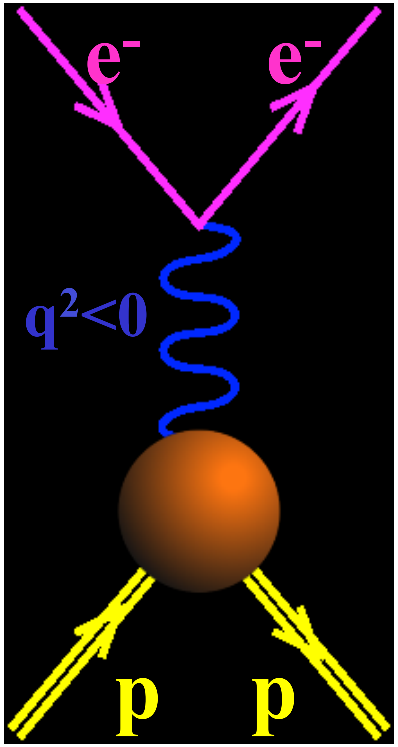


… and also: polarized sources and targets, high intensity e^- beams, high luminosity colliders, large acceptance spectrometers, high resolution 4p detectors…

panda BABAR BES mami MAINZER MIKROTRON Jefferson Lab EXPLORING THE NATURE OF MATTER

VEPP-Novosibirsk

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

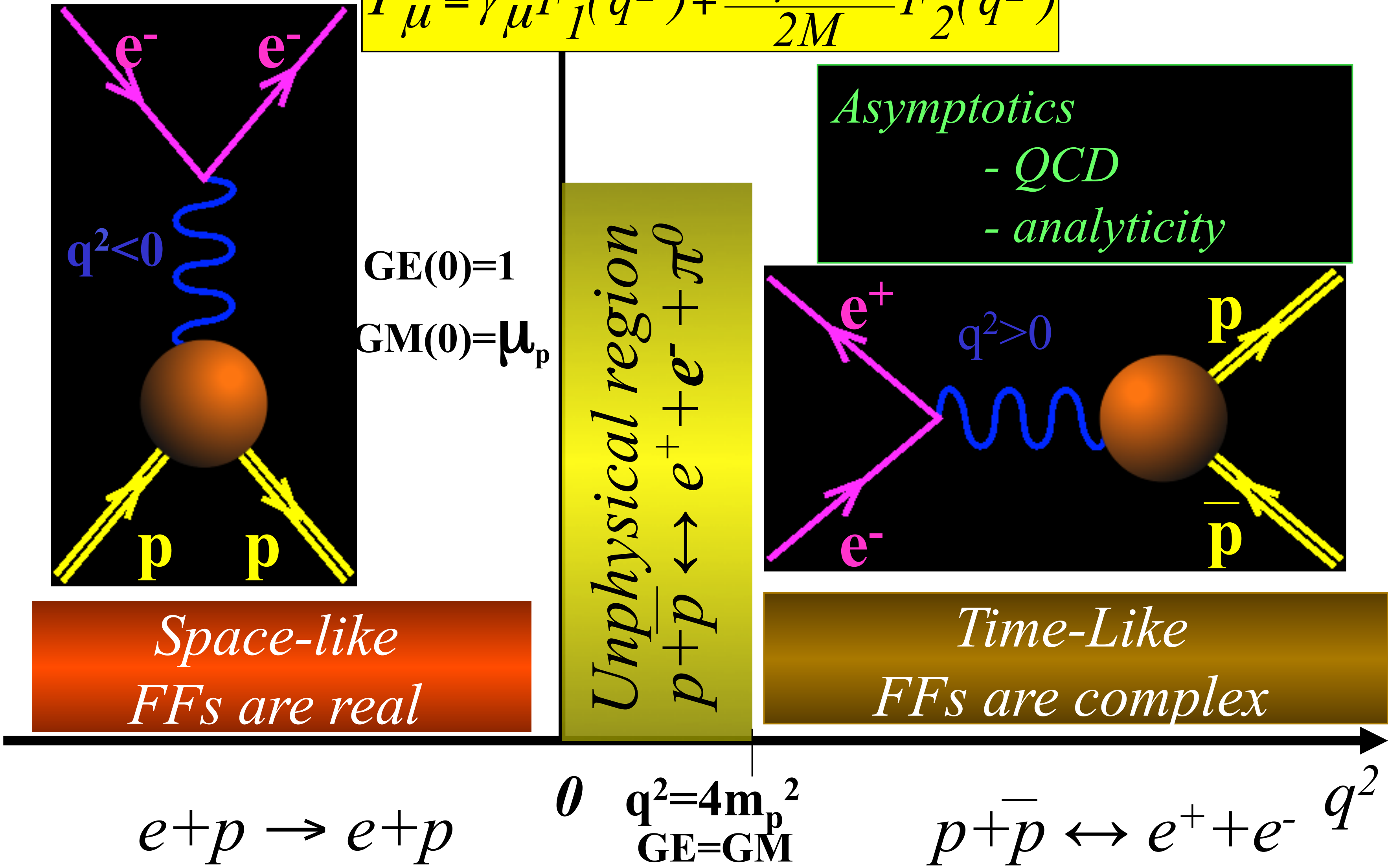
$$\Gamma_\mu = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu} q^\nu}{2M} F_2(q^2)$$

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

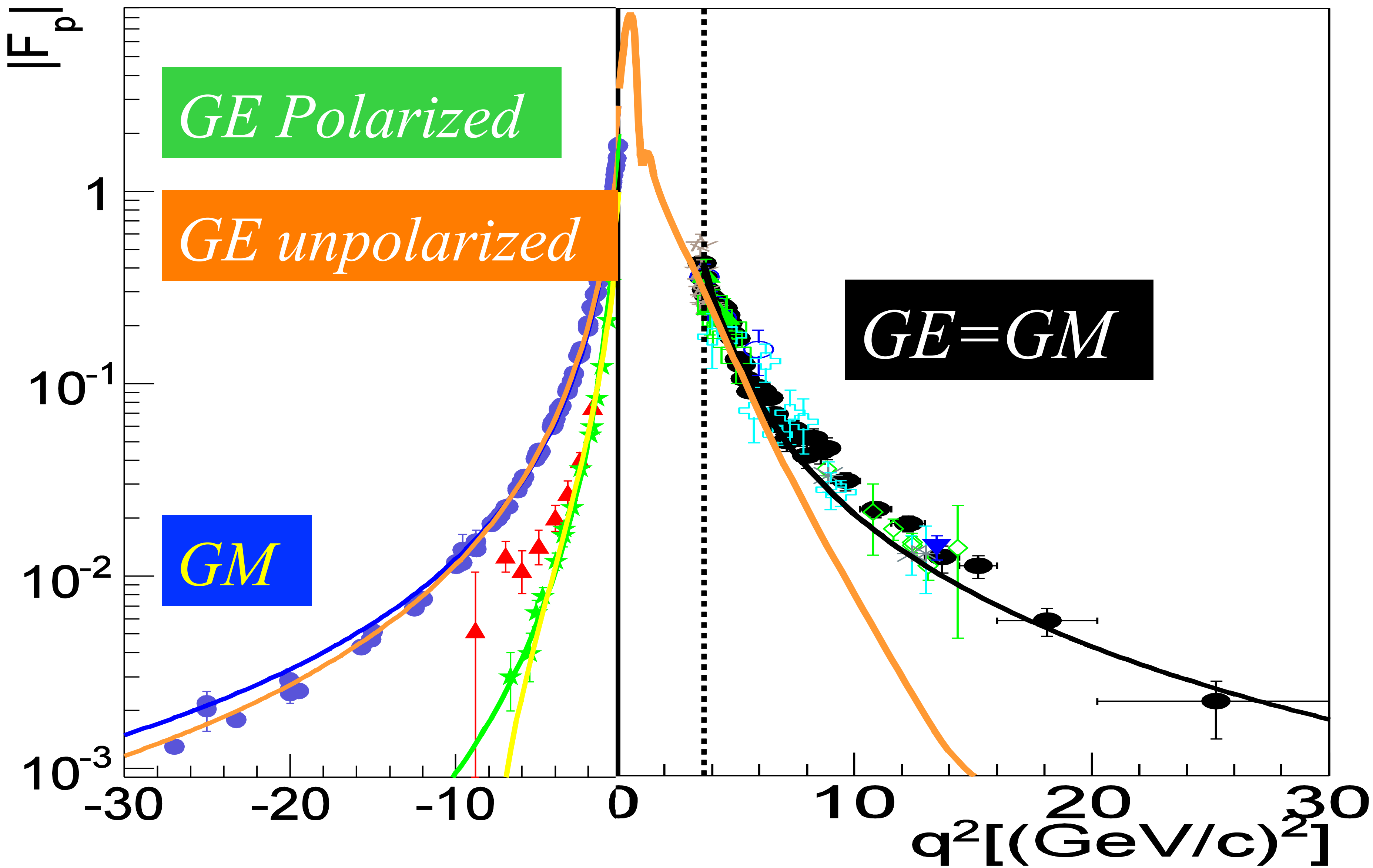
What about high order radiative corrections?

Scattering and Annihilation

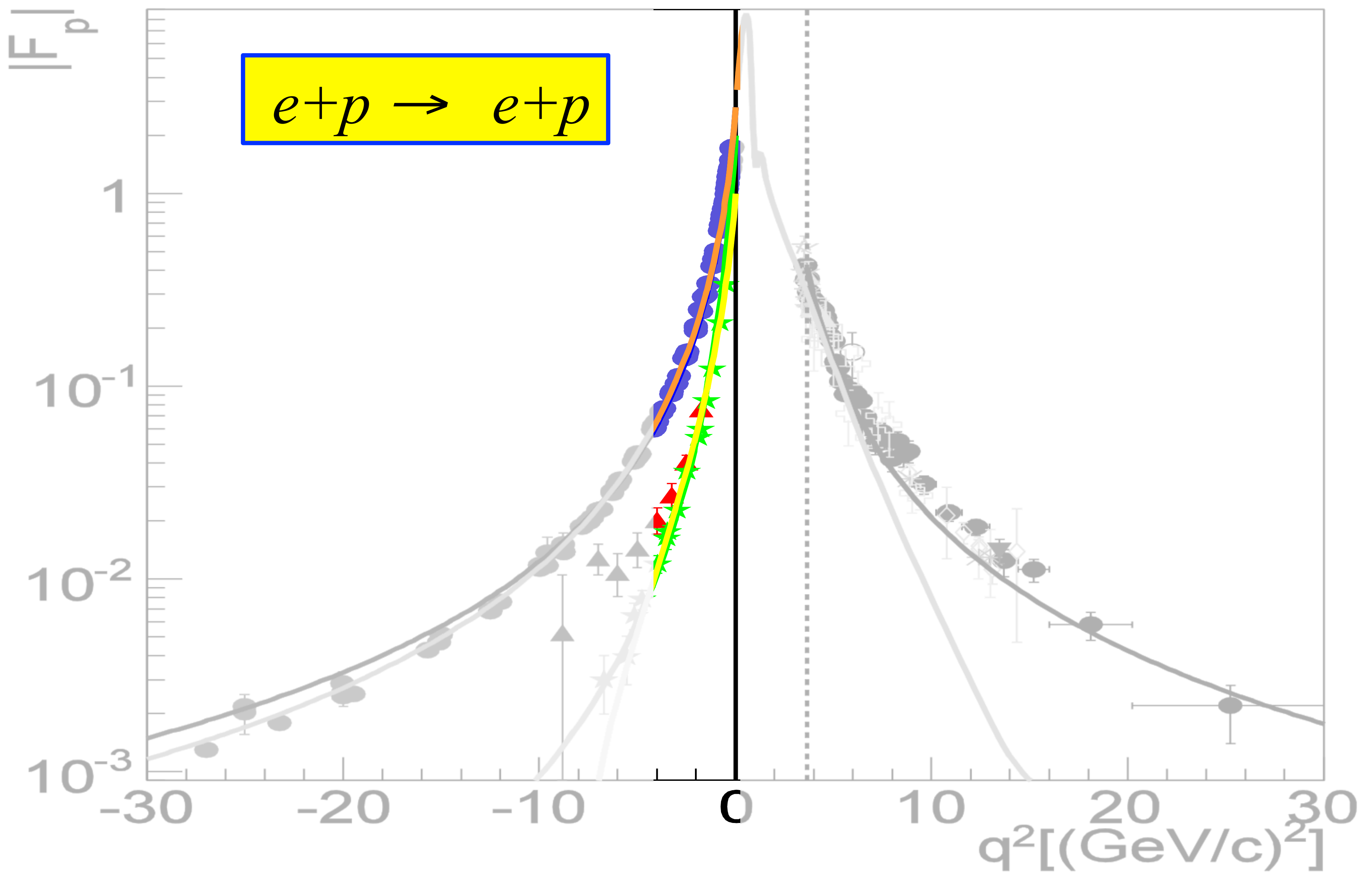
$$\Gamma_\mu = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu} q^\nu}{2M} F_2(q^2)$$



Hadron Electromagnetic Form Factors



The Space-Like region: low Q^2



ep-elastic scattering : Rosenbluth separation

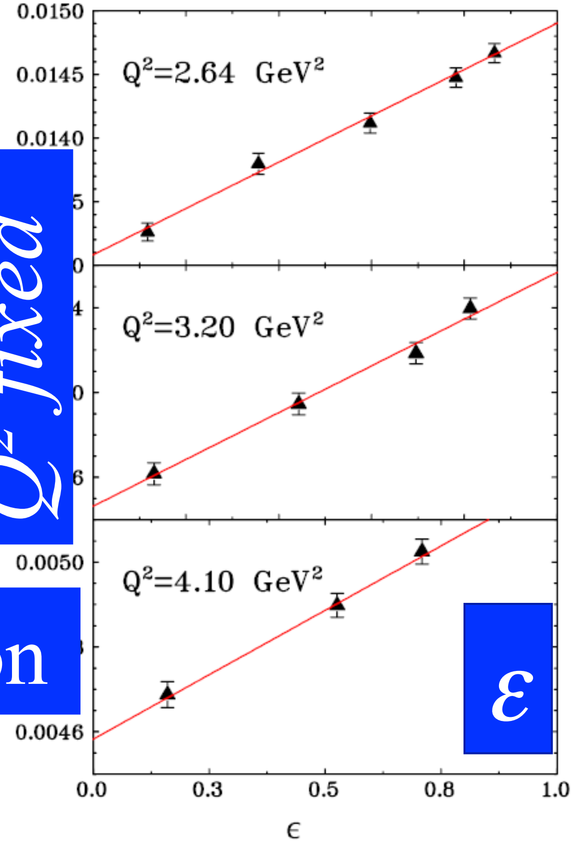
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{(1+\tau)}\left(G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right)$$

1950

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

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

Q^2 fixed



ε

PRL 94, 142301 (2005)

Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

→ Holds for 1γ exchange only

Root mean square radius

$$F(q) = \frac{\int_\Omega d^3\vec{x} e^{i\vec{q}\cdot\vec{x}} \rho(\vec{x})}{\int_\Omega d^3\vec{x} \rho(\vec{x})}.$$

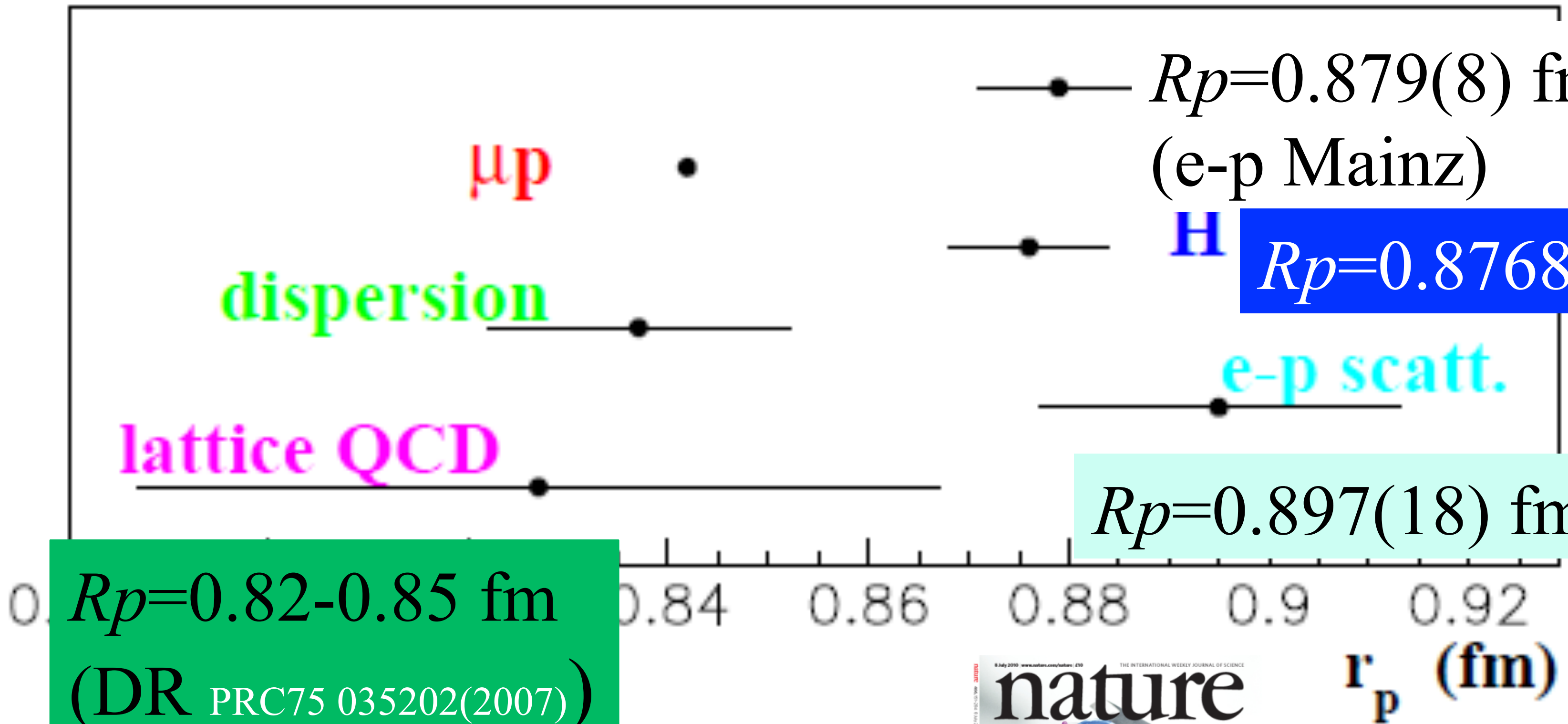
density $\rho(r)$	Form factor $F(q^2)$	r.m.s. $< r_c^2 >$	comments
δ	1	0	pointlike
e^{-ar}	$\frac{a^4}{(q^2+a^2)^2}$	$\frac{12}{a^2}$	dipole
$\frac{e^{-ar}}{r}$	$\frac{a^2}{q^2+a^2}$	$\frac{6}{a^2}$	monopole
$\frac{e^{-ar^2}}{r^2}$	$e^{-q^2/(4a^2)}$	$\frac{1}{2a}$	gaussian
ρ_0 for $x \leq R$ 0 for $r \geq R$	$\frac{3(\sin X - X\cos X)}{X^3}$ $X = qR$	$\frac{3}{5}R^2$	square well

$$F(q) \sim 1 - \frac{1}{6} q^2 < r_c^2 > + O(q^2),$$

$$< r_c^2 > = \frac{\int_0^\infty x^4 \rho(x) dx}{\int_0^\infty x^2 \rho(x) dx}.$$

The Proton Radius

Rp=0.84184(67) fm (muonic atom)



Rp=0.879(8) fm
(e-p Mainz)

Rp=0.8768(69) fm

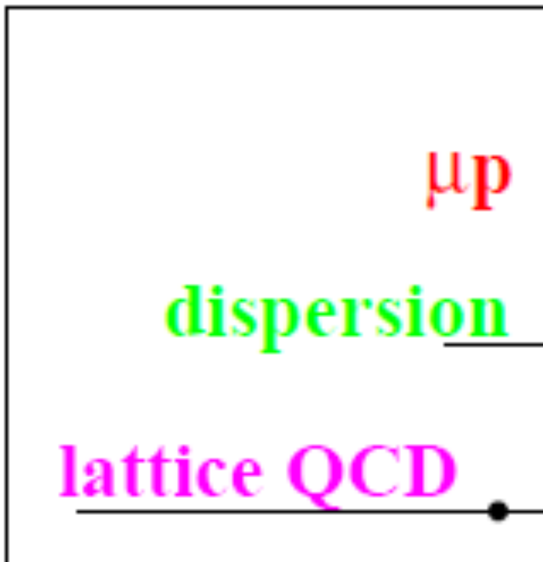
Rp=0.897(18) fm

Rp=0.82-0.85 fm
(DR PRC75 035202(2007))

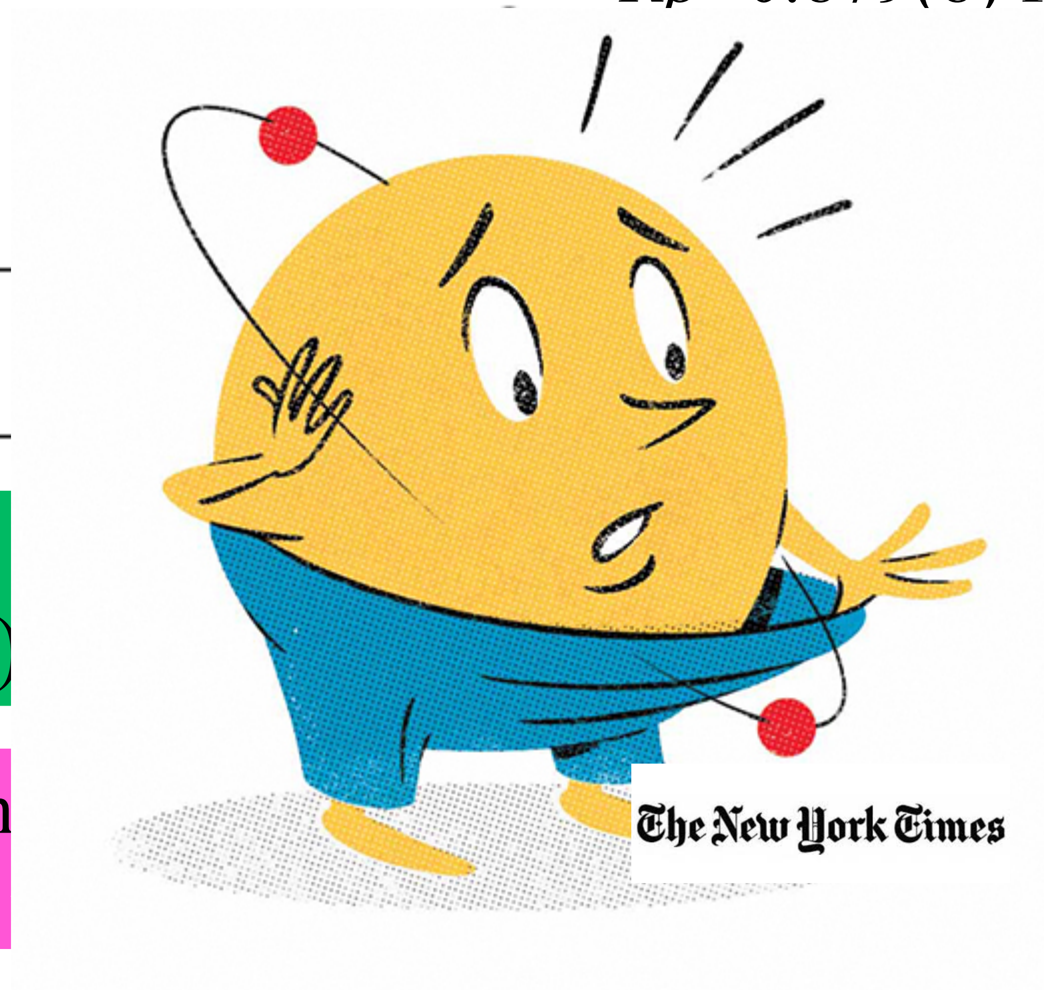
Rp=0.78-0.86 fm
(lattice QCD PRD 79 094001(2009))

The Proton Radius

Rp=0.84184(67) fm (muonic atom)



Rp=0.879(8) fm



(69) fm

Rp=0.82-0.85 fm
(DR PRC75 035202(2007))

Rp=0.78-0.86 fm
(lattice QCD PRD

PRL 105, 242001 (2010) PHYSICAL REVIEW LETTERS week ending 10 DECEMBER 2010

High-Precision Determination of the Electric and Magnetic Form Factors of the Proton

J. C. Bernauer,[1,*] P. Achenbach,[1] C. Ayerbe Gayoso,[1] R. Böhm,[1] D. Bosnar,[2] L. Debenjak,[3] M. O. Distler,[1,†] L. Doria,[1] A. Esser,[1] H. Fonvieille,[4] J. M. Friedrich,[5] J. Friedrich,[1] M. Gómez Rodríguez de la Paz,[1] M. Makek,[2] H. Merkel,[1] D. G. Middleton,[1] U. Müller,[1] L. Nungesser,[1] J. Pochodzalla,[1] M. Potokar,[3] S. Sánchez Majos,[1] B. S. Schlimme,[1] S. Širca,[6,3] Th. Walcher,[1] and M. Weinriefer[1]

Mainz, A1 collaboration (1400 points)

$Q^2 > 0.004\ \mathrm{GeV}^2$

- Radiative corrections
- Two photon exchange
- Coulomb corrections

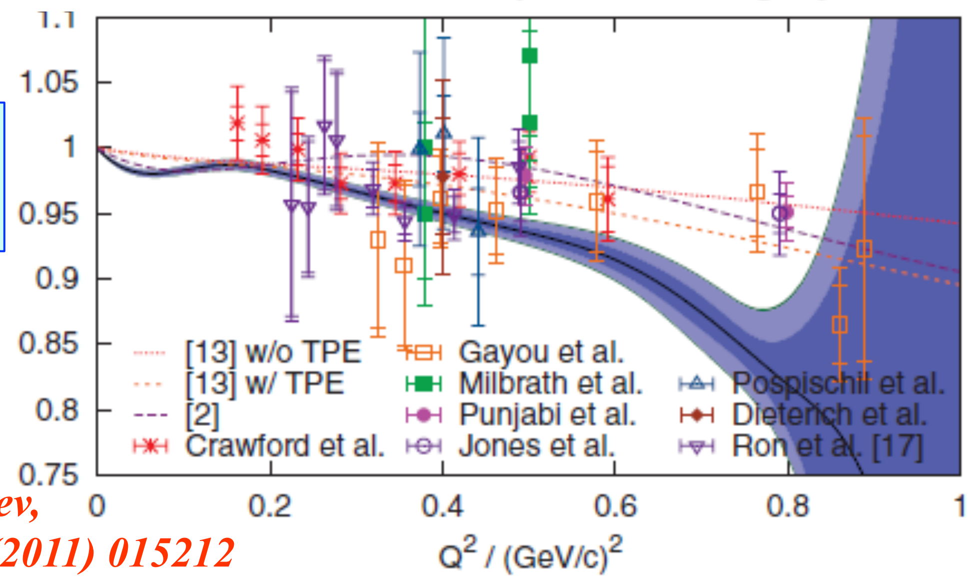
.....*comments*

$$\langle r_E^2 \rangle^{1/2} = 0.879(5)_{\mathrm{stat}}(4)_{\mathrm{syst}}(2)_{\mathrm{model}}(4)_{\mathrm{group}}\ \mathrm{fm},$$

$$\langle r_M^2 \rangle^{1/2} = 0.777(13)_{\mathrm{stat}}(9)_{\mathrm{syst}}(5)_{\mathrm{model}}(2)_{\mathrm{group}}\ \mathrm{fm}.$$

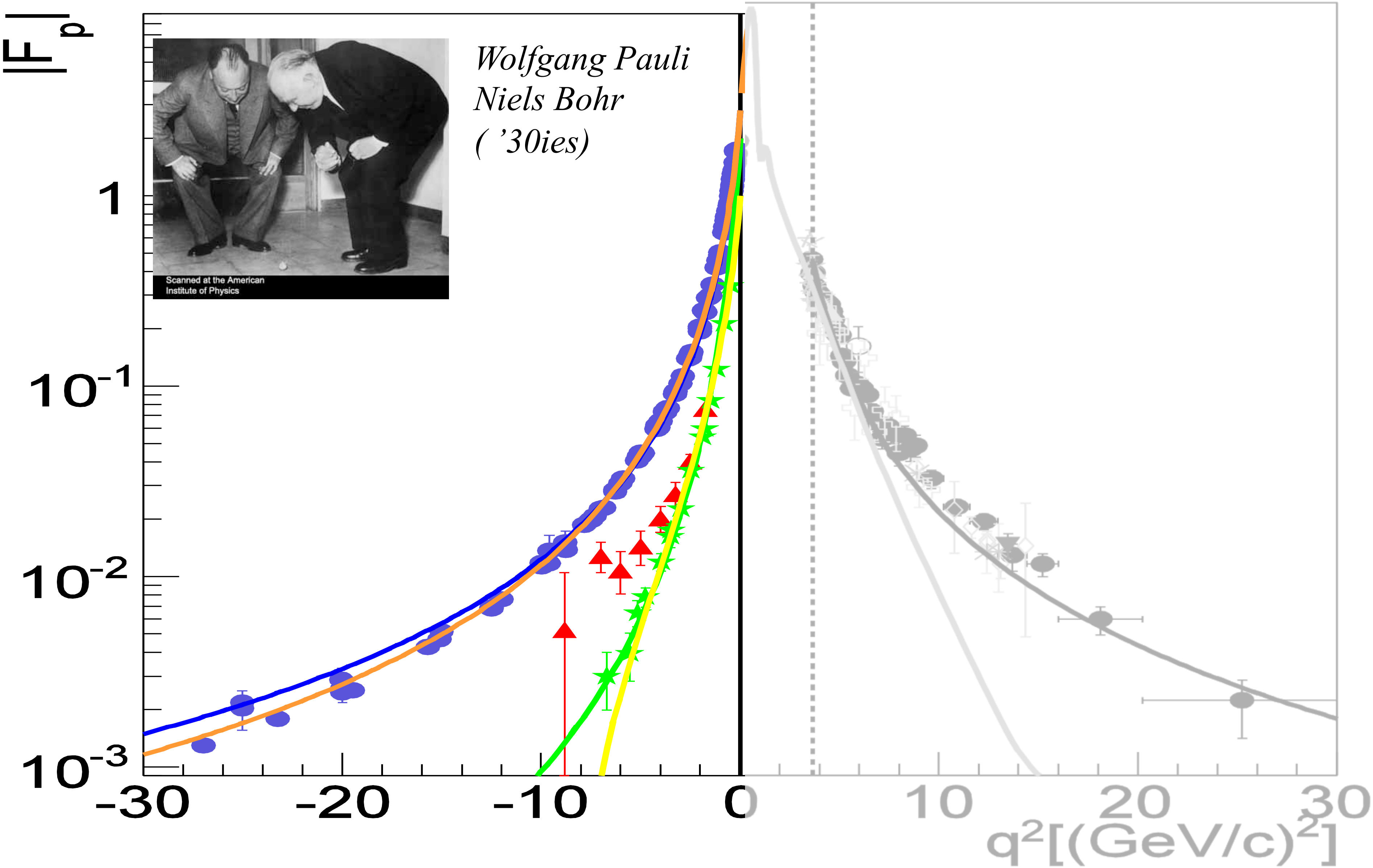
- MUSE Experiment
- Jlab CLAS

What about extrapolation to $Q^2 \to 0$?



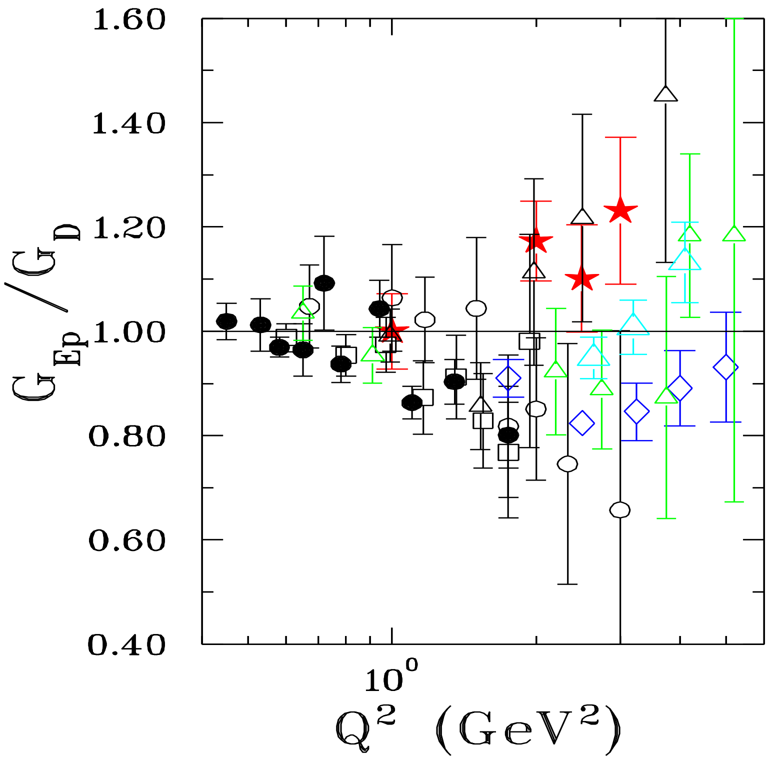
G.I. Gakh, A. Dbeyssi, E.T-G, D. Marchand, V.V. Bytev, Phys.Part.Nucl.Lett. 10 (2013) 393, Phys.Rev. C84 (2011) 015212

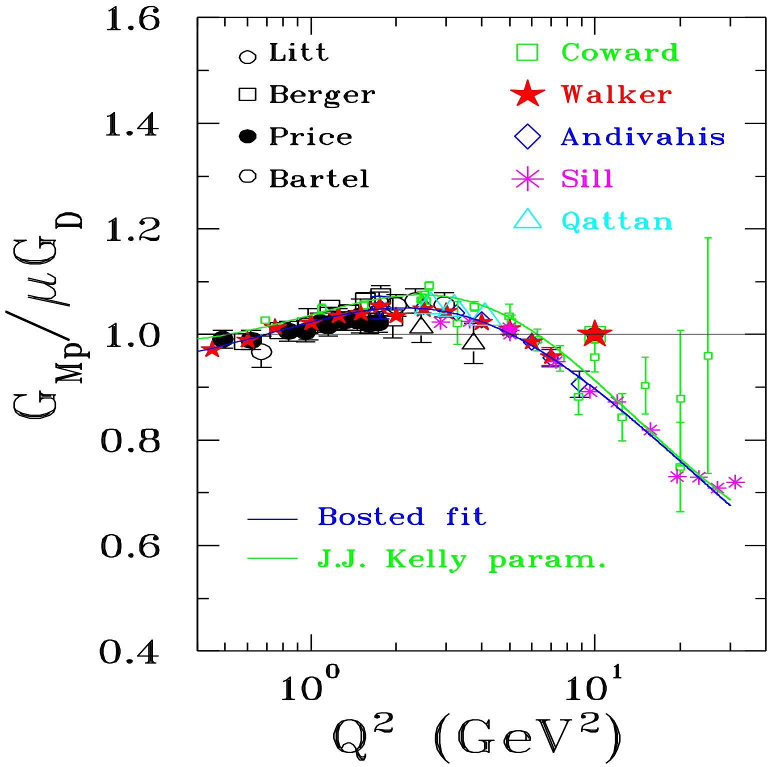
The Space-Like region



Proton Form Factors … before

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





Rosenbluth separation/ Polarization observables

V. Punjabi, M. Jones,C. Perdrisat et al, JLab-GEp collaboration

ep-elastic scattering : Akhiezer-Rekalo method

PHYSICS

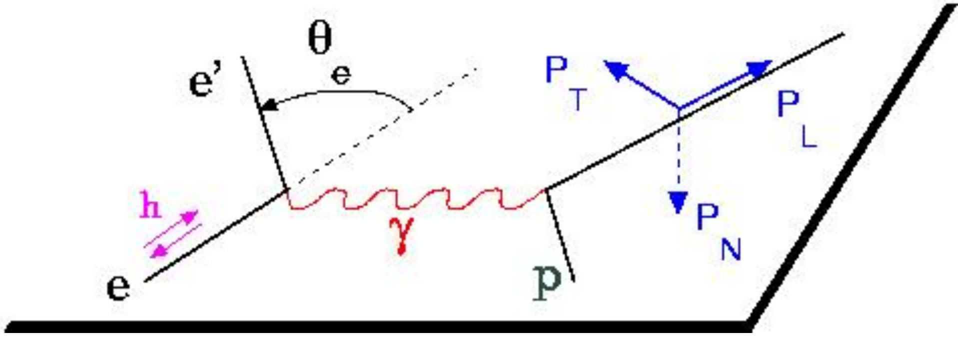
1967

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

The polarization method (exp: 2000)

Transferred polarization is:

C. Perdrisat, V. Punjabi, et al., JLab-GEp collaboration

$$P_n = 0$$

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

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

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

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

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

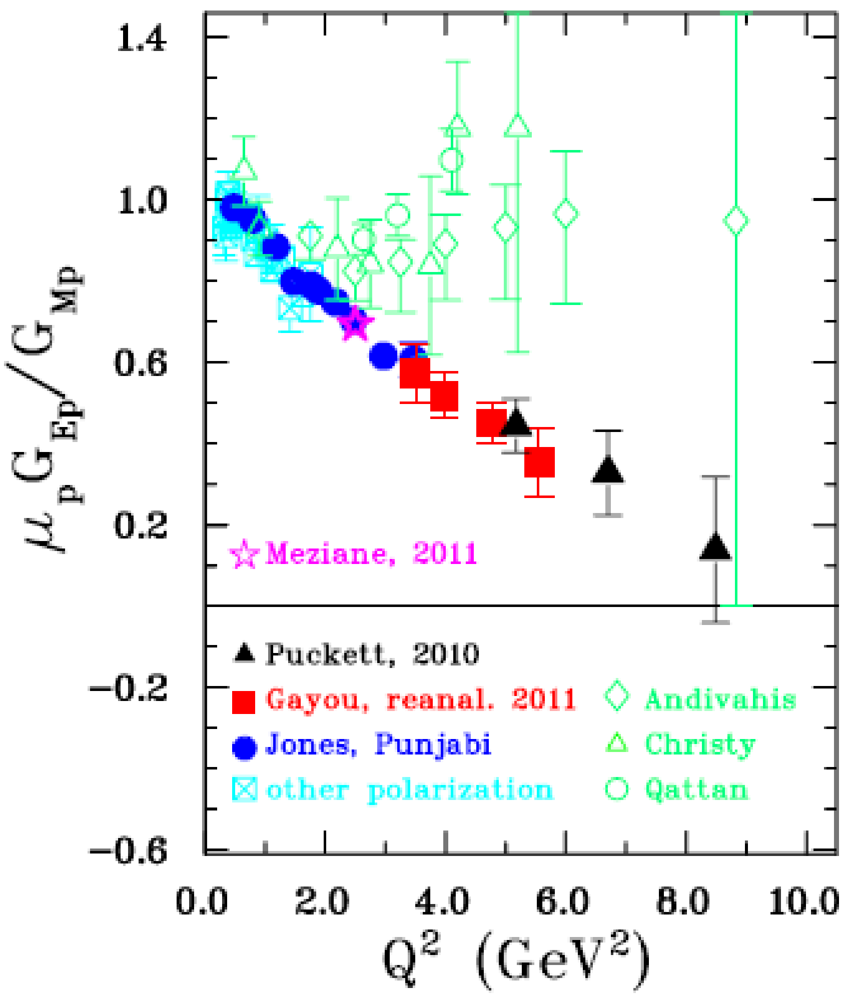
The simultaneous measurement of P_t and P_l reduces the systematic errors

Polarization Experiments

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***

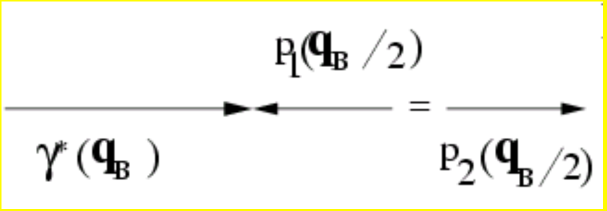


A.J.R. Puckett et al, PRL (2010), PRC (2012)

Dipole Approximation

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

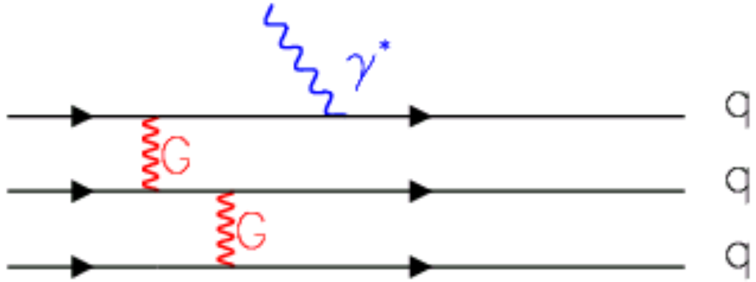
- Classical approach
  - Nucleon FF (in non relativistic approximation or in the Breit system) are Fourier transform of the charge or magnetic distribution.



Breit system

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

Dipole Approximation and pQCD



Dimensional scaling

– $F_n(Q^2) = C_n\,[1/(1+Q^2/m_n)^{n-1}]$,
  - $m_n = n\beta^2$, <quark momentum squared>
  - n is the number of constituent quarks

– Setting $\beta^2 = (0.471 \pm .010)$ GeV^2 *(fitting pion data)*
  - pion: $F_\pi(Q^2) = C_\pi\,[1/(1+Q^2/0.471\ \mathrm{GeV}^2)^1]$,
  - nucleon: $F_N(Q^2) = C_N\,[1/(1+Q^2/0.71\ \mathrm{GeV}^2)^2]$,
  - deuteron: $F_d(Q^2) = C_d\,[1/(1+Q^2/1.41\,\mathrm{GeV}^2)^5]$

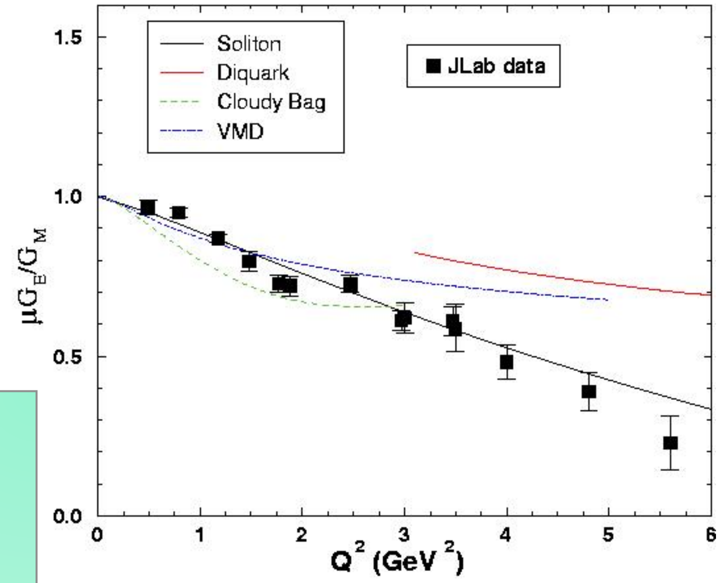
V. A. Matveev, R. M. Muradian, and A. N. Tavkhelidze (1973), Brodsky and Farrar (1973), Politzer (1974), Chernyak & Zhitnisky (1984), Efremov & Radyuskin (1980)…

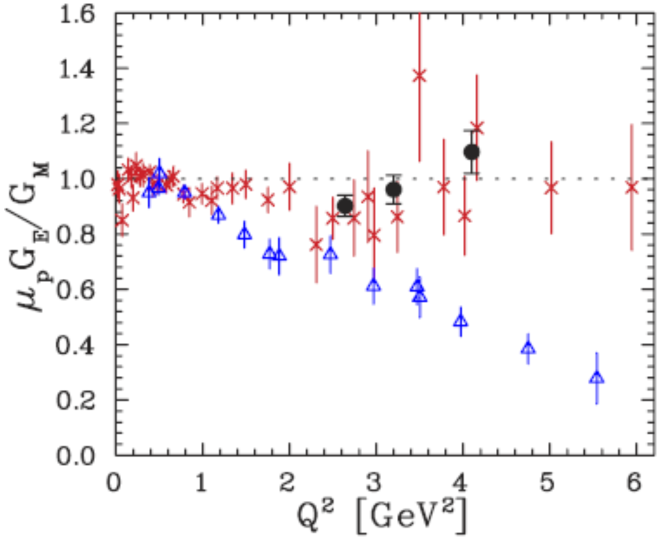
Issues

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

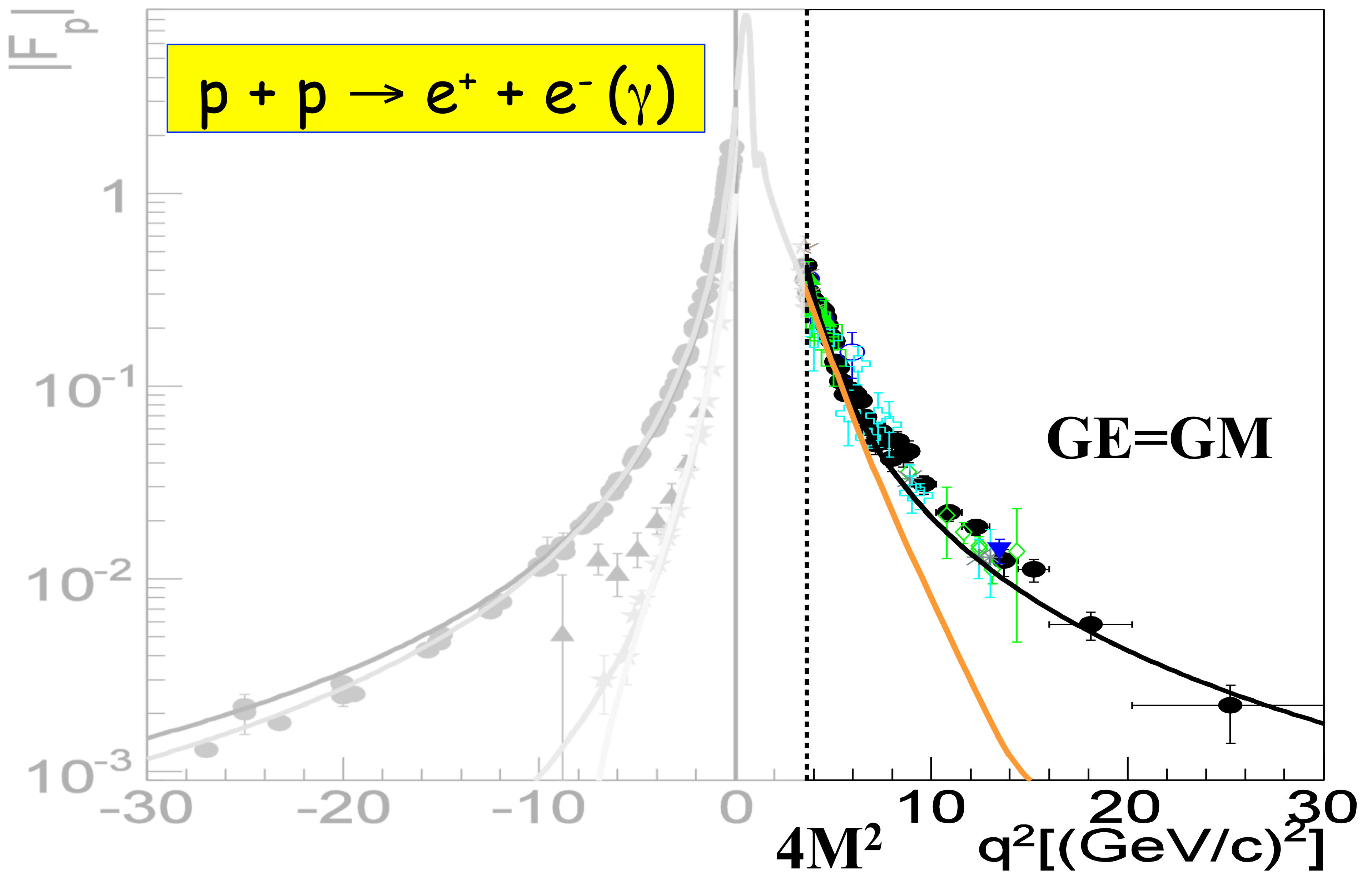
BUT

- Simultaneous description of the four nucleon form factors...
- ...in the space-like and in the time-like regions
- Consequences for the light ions description
- When pQCD starts to apply?
- Source of the discrepancy





The Time-Like region



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

-The cross section for $\bar{p} + p \to e^+ + e^-$ (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 $\bar{p}$ 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:

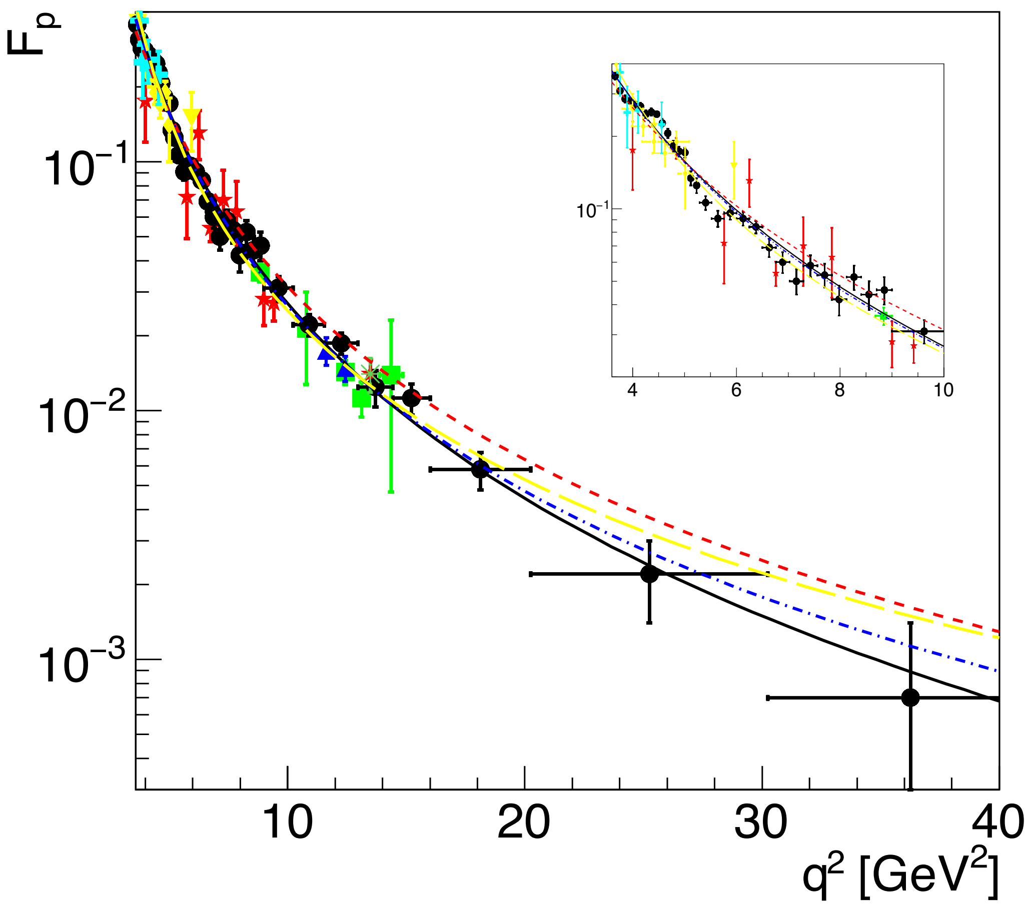
- Dependence on q^2 contained in FFs
- Even dependence on $\cos^2\theta$ (1γ exchange)
- No dependence on sign of FFs
- Enhancement of magnetic term

but TL form factors are complex!

The Time-like Region

GE=GM

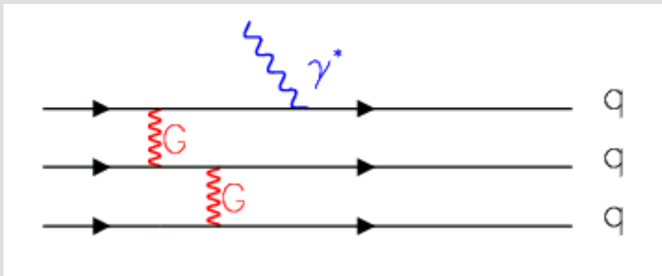
- The Experimental Status
  - No individual determination of GE and GM
  - TL proton FFs twice larger than in SL at the same Q^2
  - Steep behaviour at threshold
  - Babar:Structures? Resonances?



S. Pacetti, R. Baldini-Ferroli, E.T-G , Physics Reports, 514 (2014) 1

Panda contribution: *M.P. Rekalo, E.T-G , DAPNIA-04-01, ArXiv:0810.4245.*

The Time-like Region



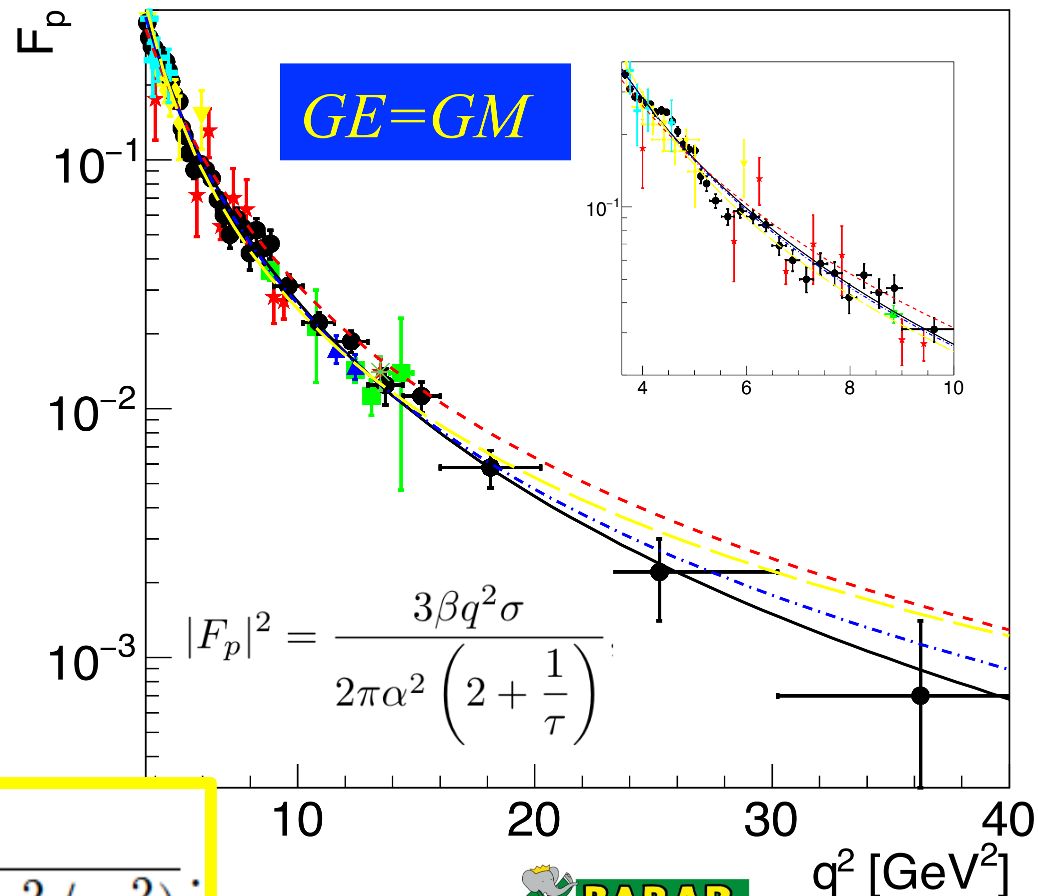
Expected QCD scaling $(q^2)^2$

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

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

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

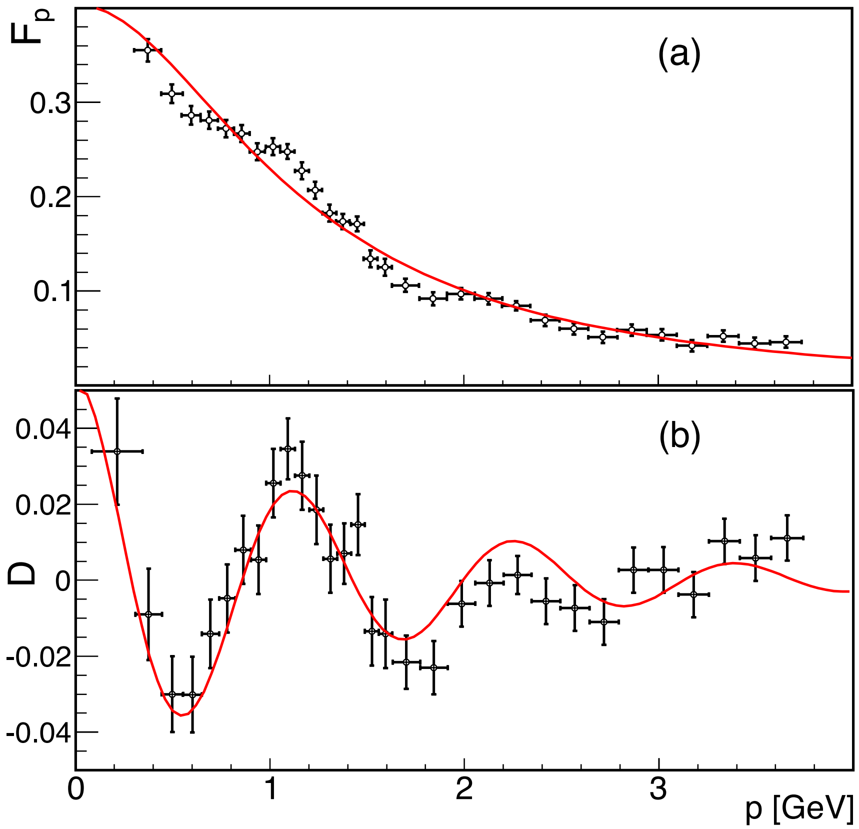
$$e^+ + e^- \rightarrow \bar{p} + p\,,$$
$$\bar{p} + p \rightarrow e^+ + e^-$$



BABAR

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)

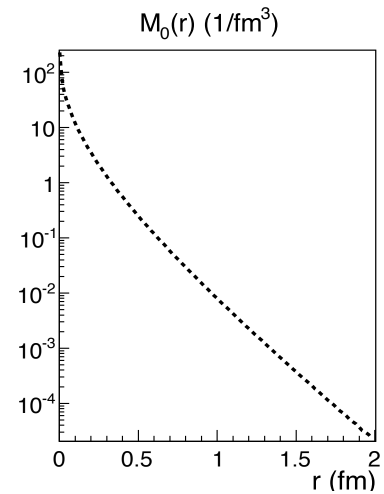
Fourier Transform

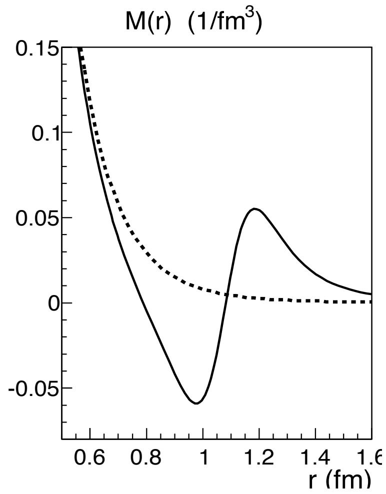
$$F_0(p) \equiv \int d^3\vec{r}\; exp(i\vec{p}\cdot\vec{r})\; M_0(r)$$

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

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

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

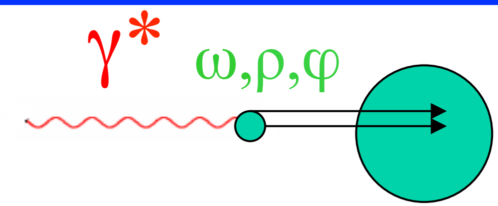




- *Rescattering processes*
- *Large imaginary part*
- *Related to the time evolution of the charge density?*

  (E.A. Kuraev, E. T.-G., A. Dbeyssi, PLB712 (2012) 240)
- *Consequences for the SL region?*
- *Data expected at BESIII, PANDA*

VMD: Iachello, Jakson and Landé (1973)



Isoscalar and isovector FFs

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

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

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

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

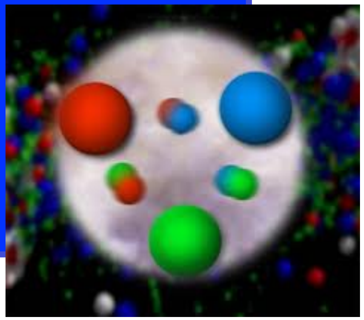
$$g(Q^2) = \frac{1}{(1+\gamma e^{i\theta}Q^2)^2}$$

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

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

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

The nucleon



3 valence quarks and a neutral sea of $q\bar{q}$ pairs

antisymmetric state of colored quarks

$$|p>\sim \epsilon_{ijk}|u^i u^j d^k>$$
$$|n>\sim \epsilon_{ijk}|u^i d^j d^k>$$

Main assumption

Does not hold in the spatial center of the nucleon: the center of the nucleon *is electrically neutral,* due to strong gluonic field

The neutral plasma acts on the distribution of the electric charge (not magnetic).

Prediction: additional suppression due to the neutral plasma similar behavior in SL and TL regions

Conclusions

• Large activity at all world facilities both in Space and Time-like regions

• Theory: unified models in SL and TL regions:

- *describe All FFs:* proton & neutron, electric & magnetic
- *understand* GE, GM(SL) < GE,GM(TL);

• Experiment: to measure

- zero crossing of GE/GM in SL? 2γ? Proton radius?
- GE and GM separately in TL
- complex FFs in TL region: polarization!
- new structures in TL: access to hadron formation?

Unpolarized cross section

-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.

Two Photon Exchange:

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

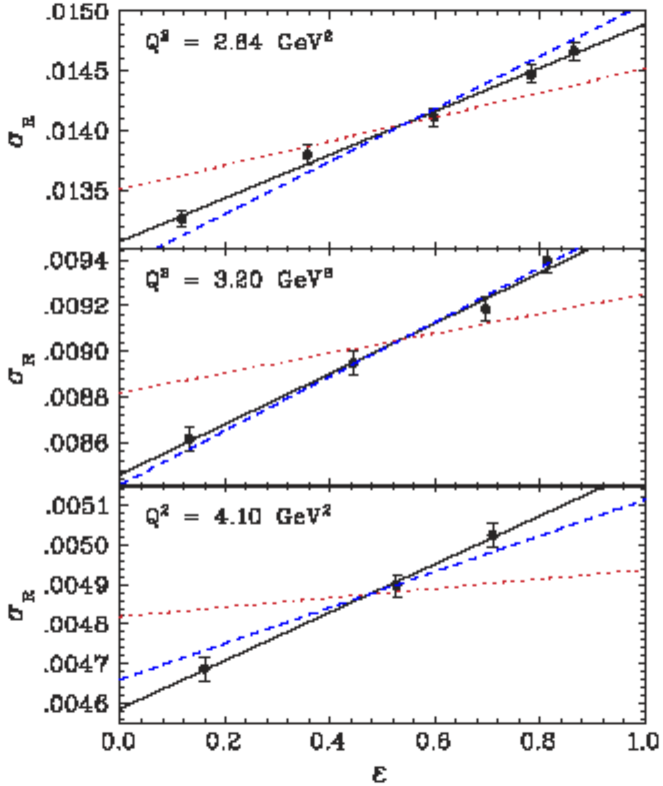
- Induces four new terms
- Odd function of θ:
- Does not contribute at θ=90°

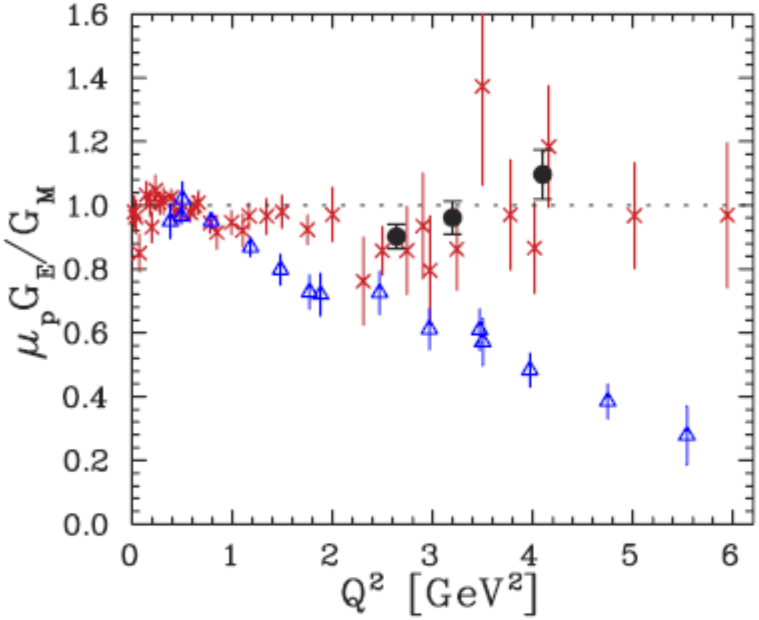
$$D=(1+\cos^2\theta)(|G_M|^2+2ReG_M\Delta G_M^*)+\frac{1}{\tau}\sin^2\theta(|G_E|^2+2ReG_E\Delta G_E^*)+$$
$$2\sqrt{\tau(\tau-1)}\cos\theta\sin^2\theta Re(\frac{1}{\tau}G_E-G_M)F_3^*.$$

M.P. Rekalo and E. T.-G., EPJA 22, 331 (2004)
G.I. Gakh and E. T.-G., NPA761, 120 (2005)

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]





Symmetry Relations(annihilation)

- Differential cross section at complementary angles:

The SUM cancels the 2γ contribution:

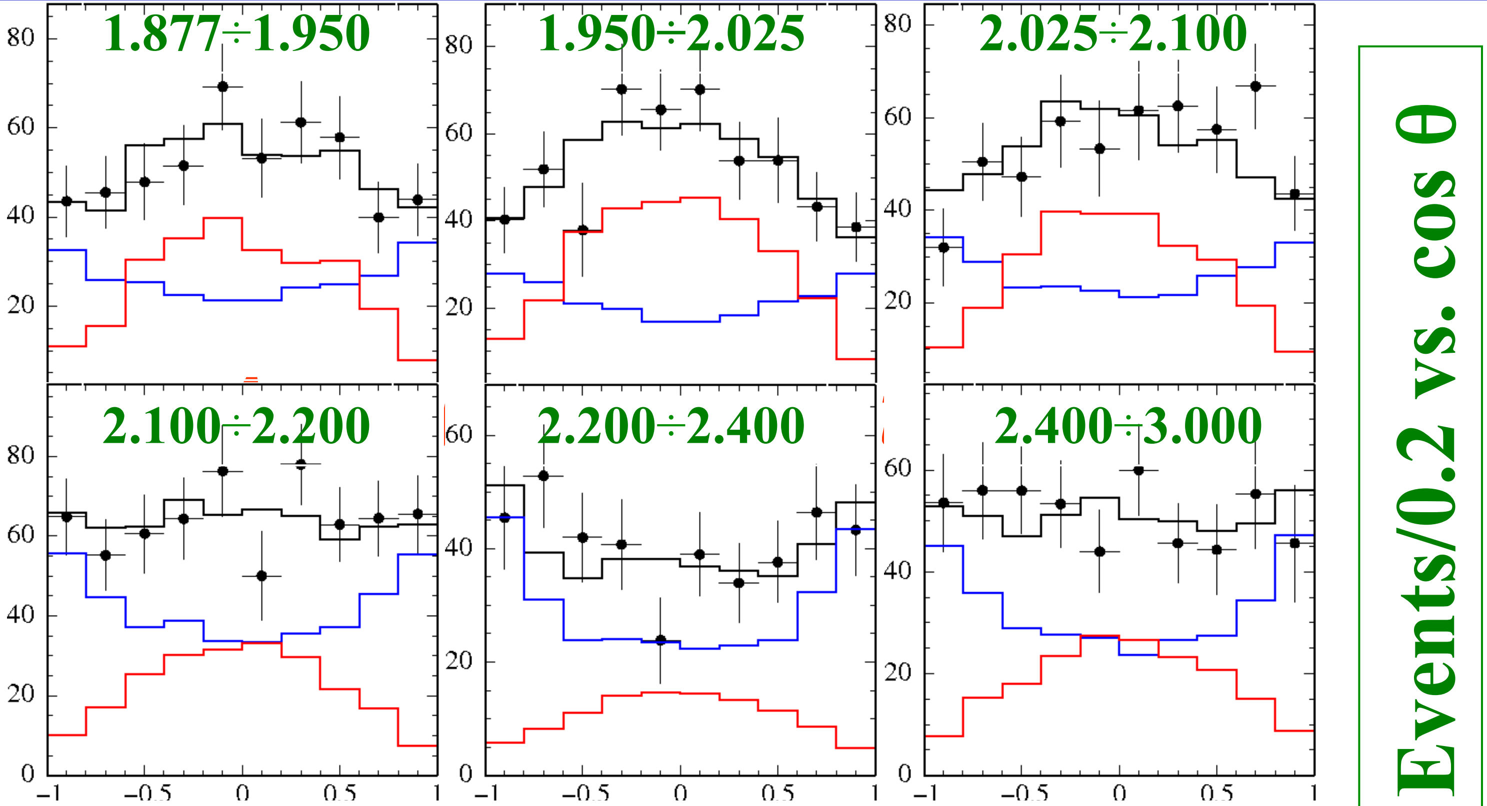
$$\frac{d\sigma_+}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi - \theta) = 2\frac{d\sigma^{Born}}{d\Omega}(\theta)$$

The DIFFERENCE enhances the 2γ contribution:

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

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

Angular Distributions



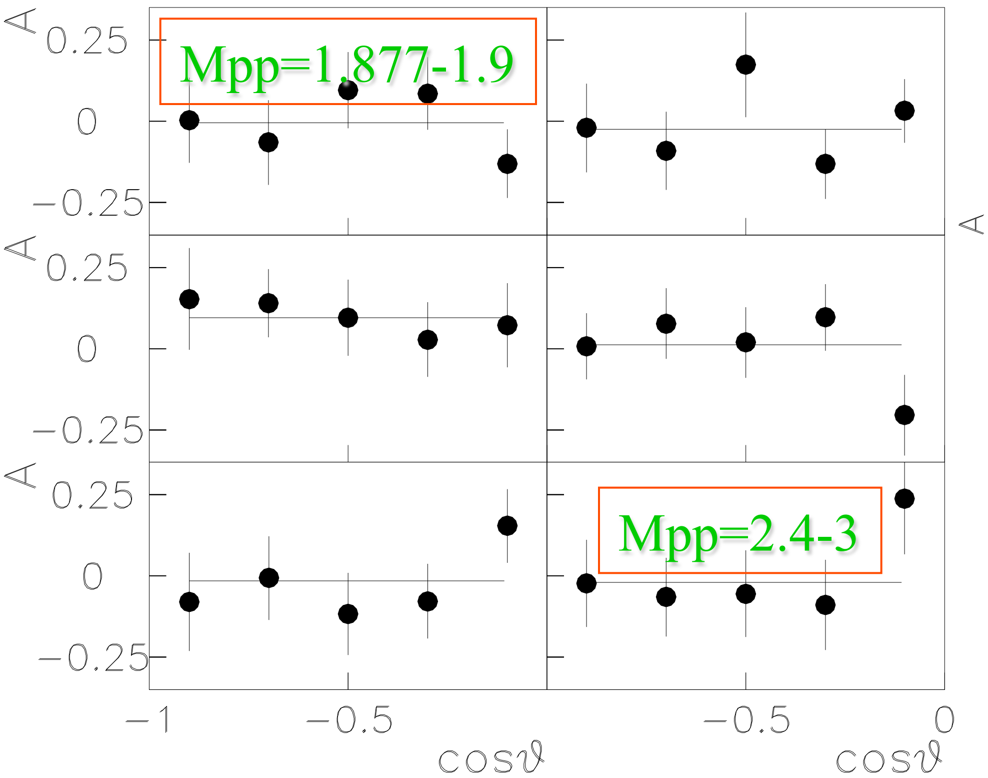
$$\frac{dN}{d\cos\theta_p} = A\left[H_M(\cos\theta, M_{p\bar{p}}) + \left|\frac{G_E}{G_M}\right|^2 H_E(\cos\theta, M_{p\bar{p}})\right]$$

BABAR

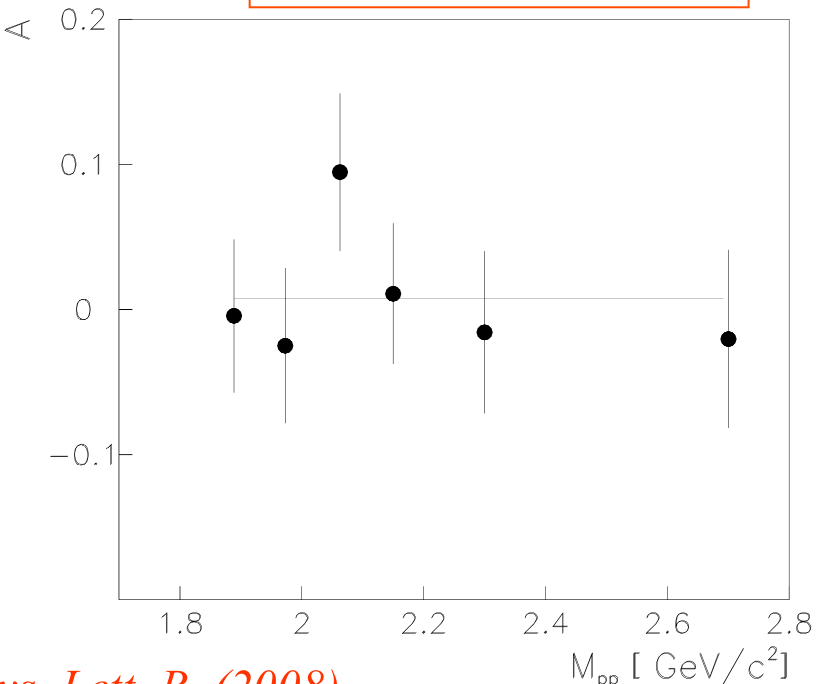
2γ–exchange?

Angular Asymmetry

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

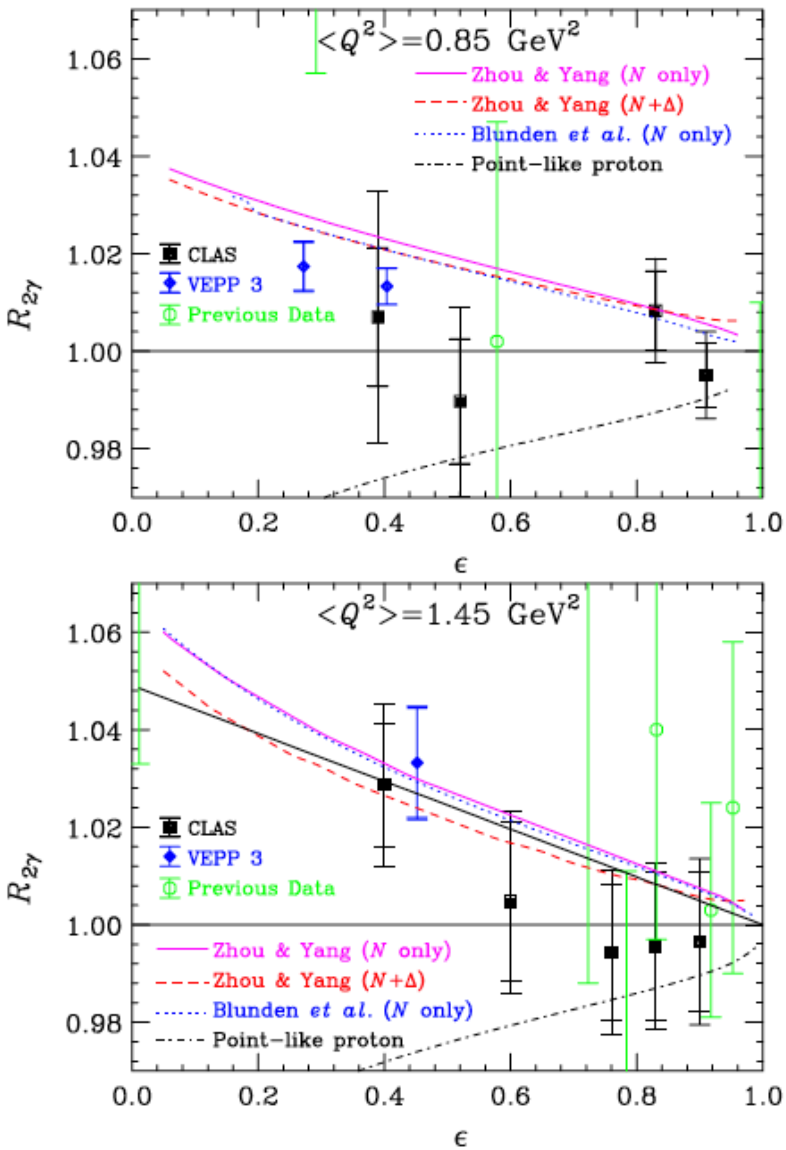


A=0.01±0.02



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

CLAS, VEPP, OLYMPUS….



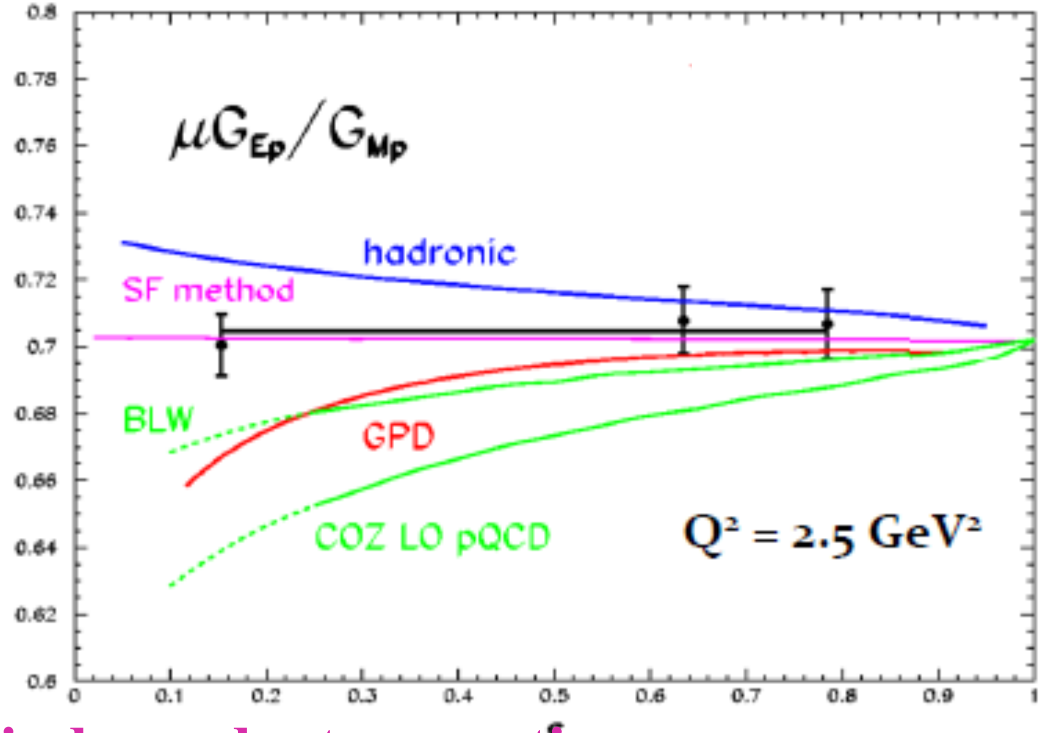
V. Rimal, ArXiv 1603. 00315l

- 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)

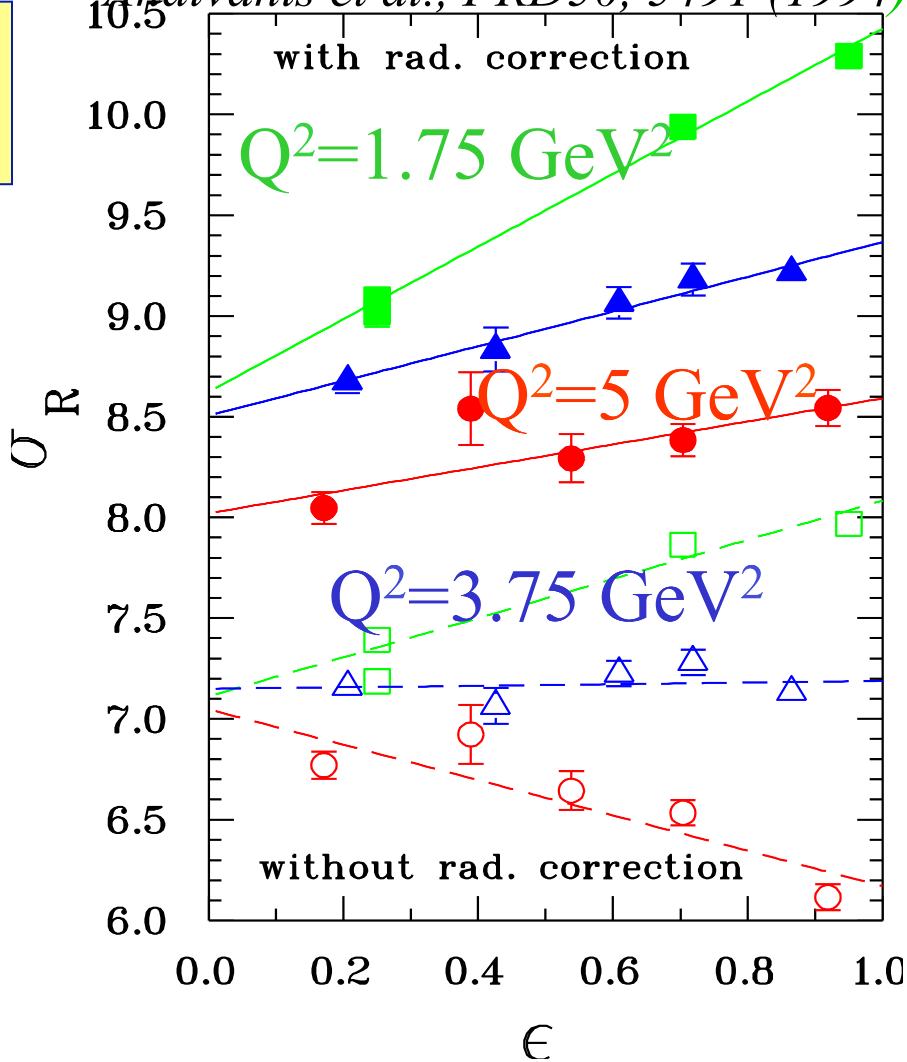
Radiative Corrections (ep)

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

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

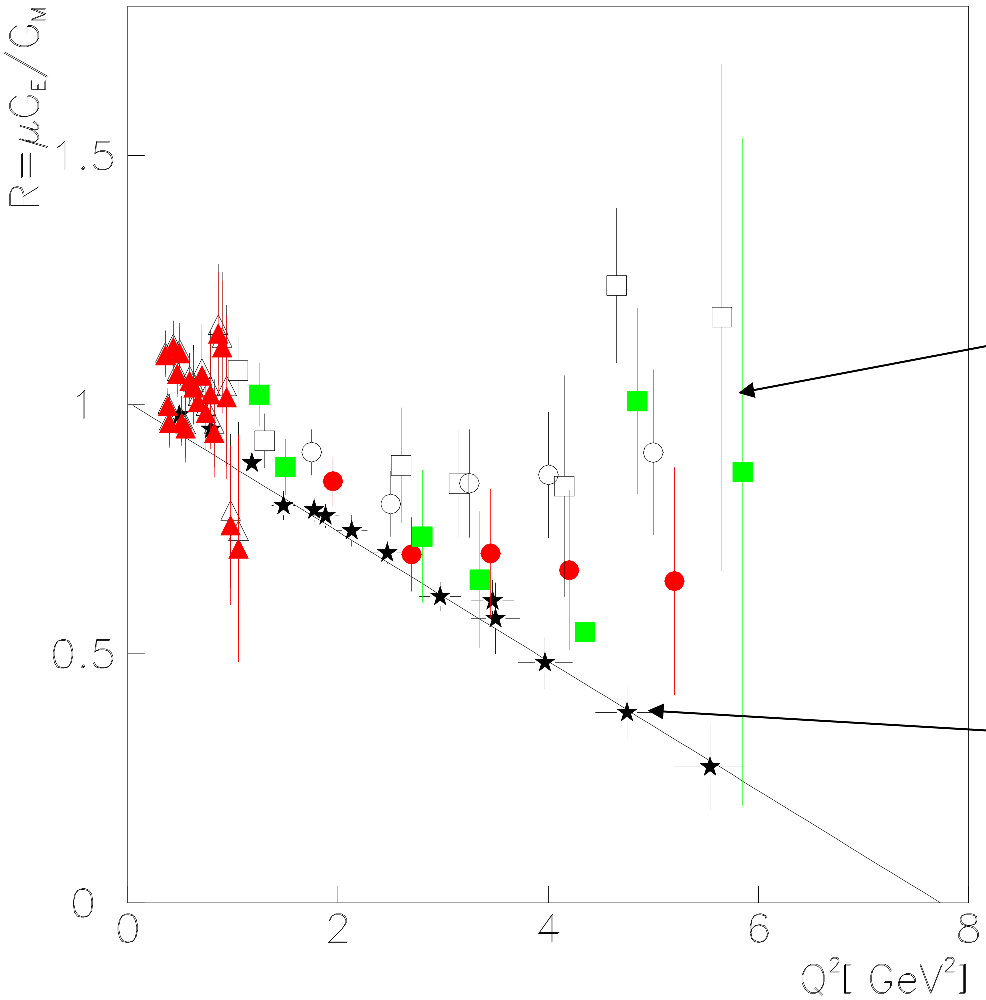
RC to the cross section:
- *large (may reach 40%)*
- *ε and Q^2 dependent*
- *calculated at first order*

Andivahis et al., PRD50, 5491 (1994)



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

Radiative Corrections (SF method)



Andivahis et al., PRD50, 5491 (1994)

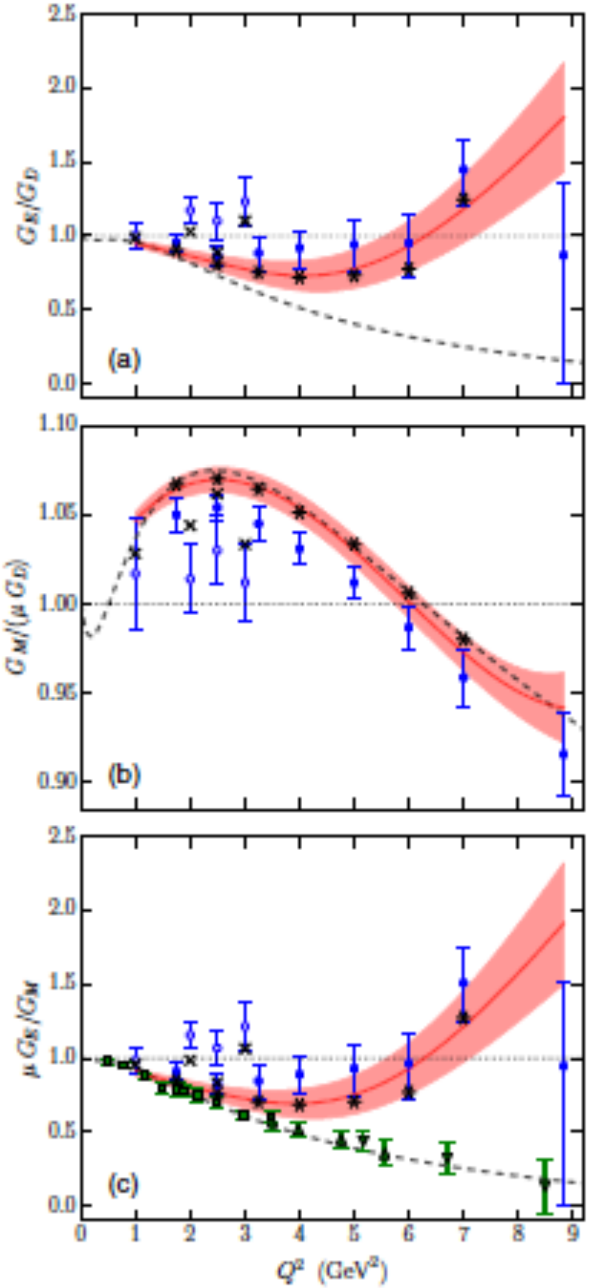
SLAC data

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

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

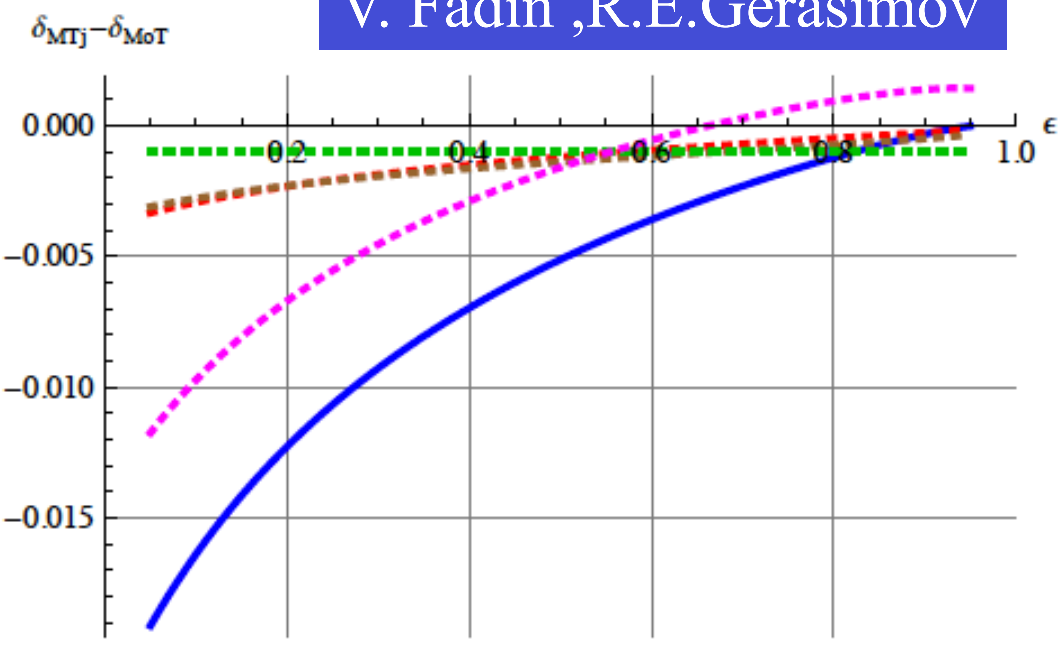
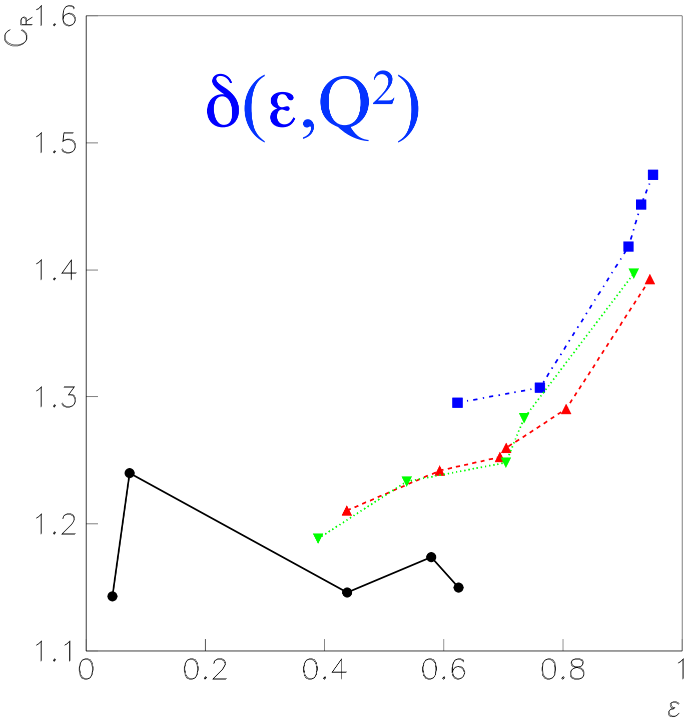


Figure 3: Difference at $Q^2 = 5\ GeV^2$.

Correlations

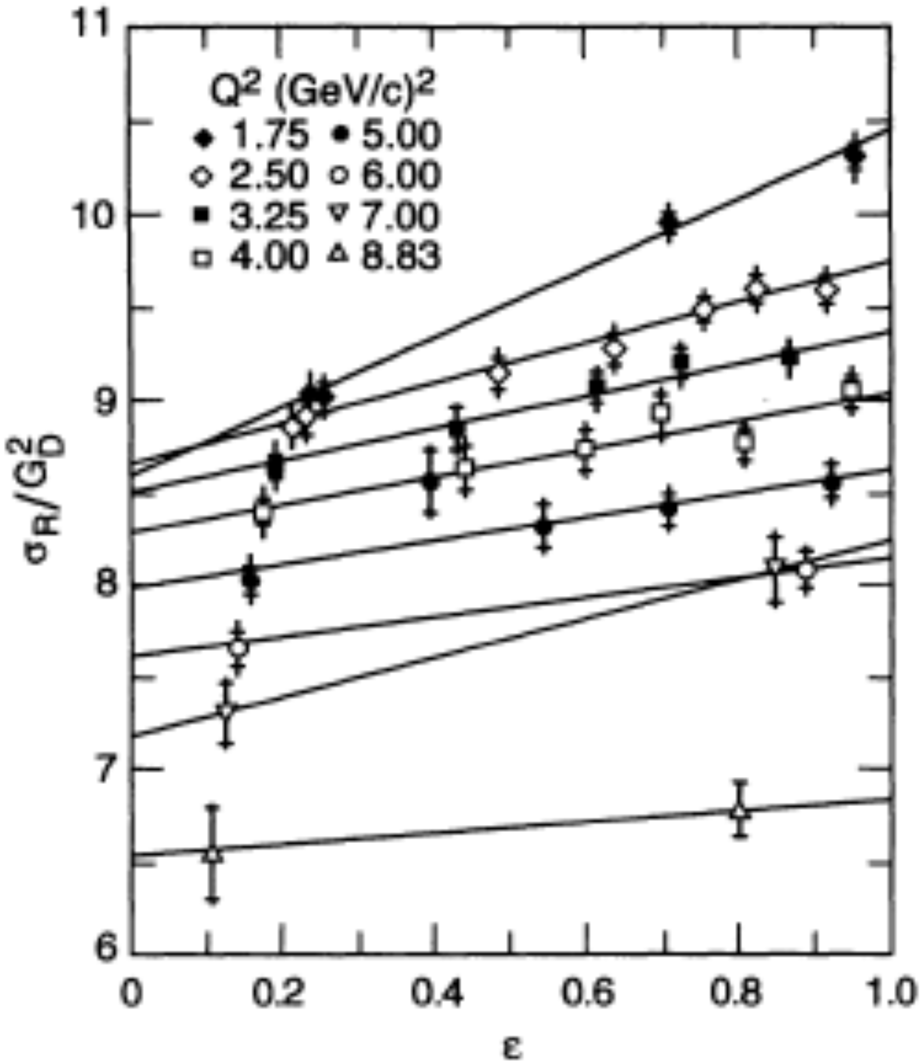
$$\sigma=\sigma_0(1+\delta(\varepsilon,Q^2))$$



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

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)

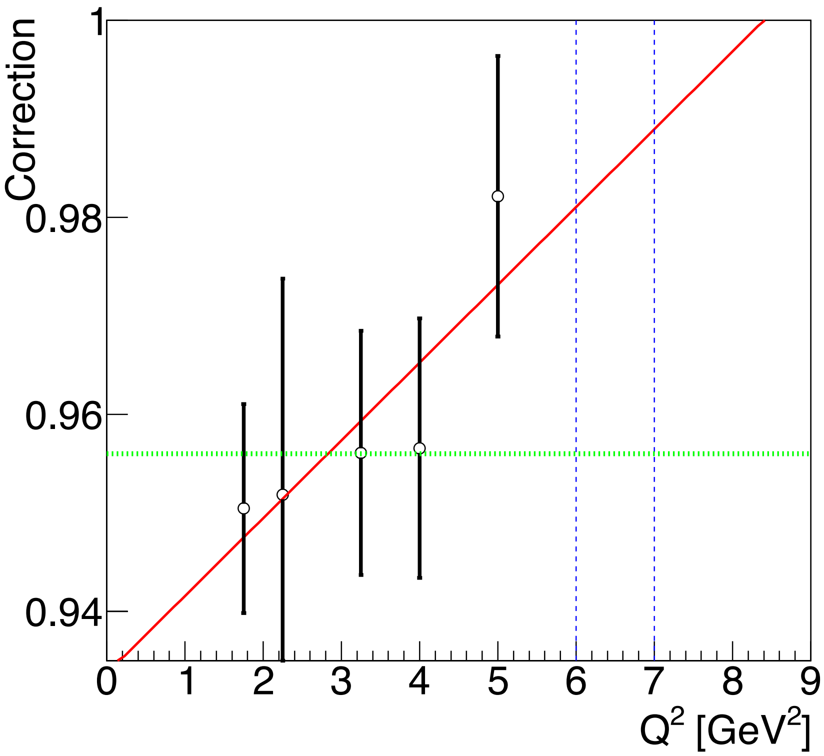
Increases the slope!

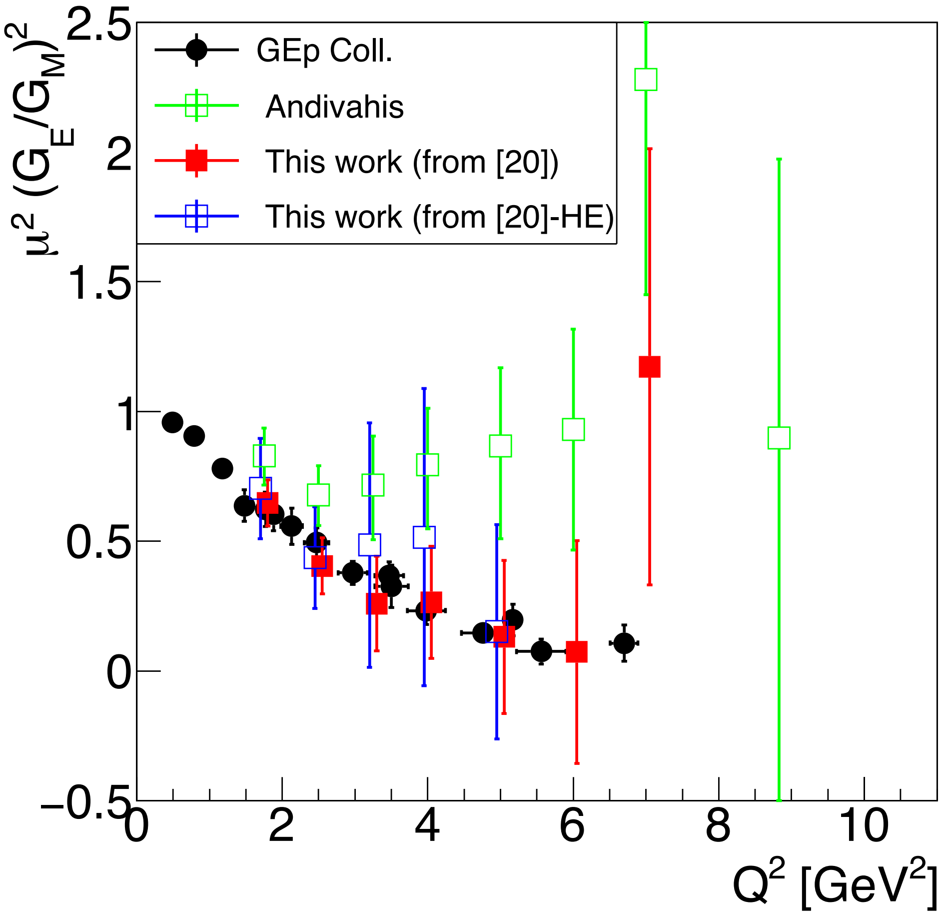
$G_E \approx G_D$

Direct extraction of the Ratio

Andivahis et al., PRD50, 5491 (1994)

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





Conclusion - Discussion

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

Jefferson Lab

VEPP-3
Novosibirsk

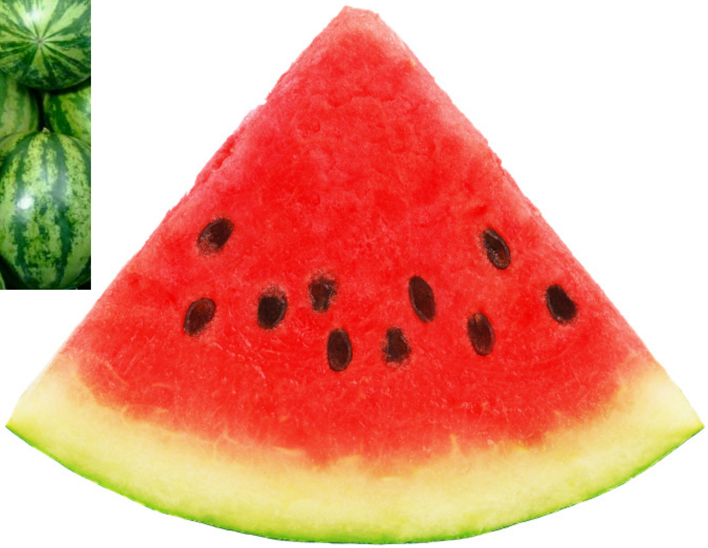
• Unified models in SL and TL

To explore:

- Neutron/proton EM structure: FFs contain essential information in SL and TL
- Effect of deviation of both GE and GM from dipole

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

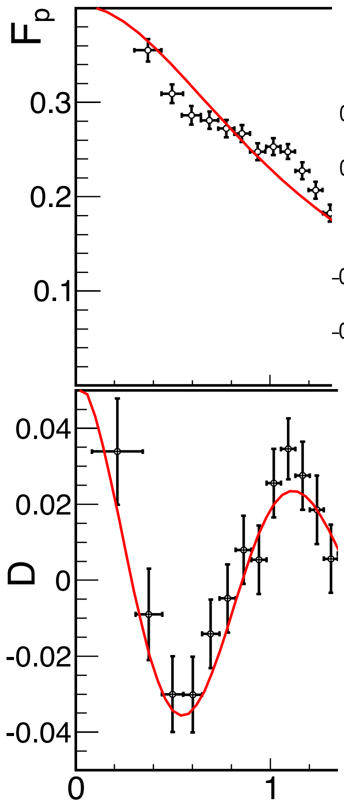
Distribution of the Proton Charge

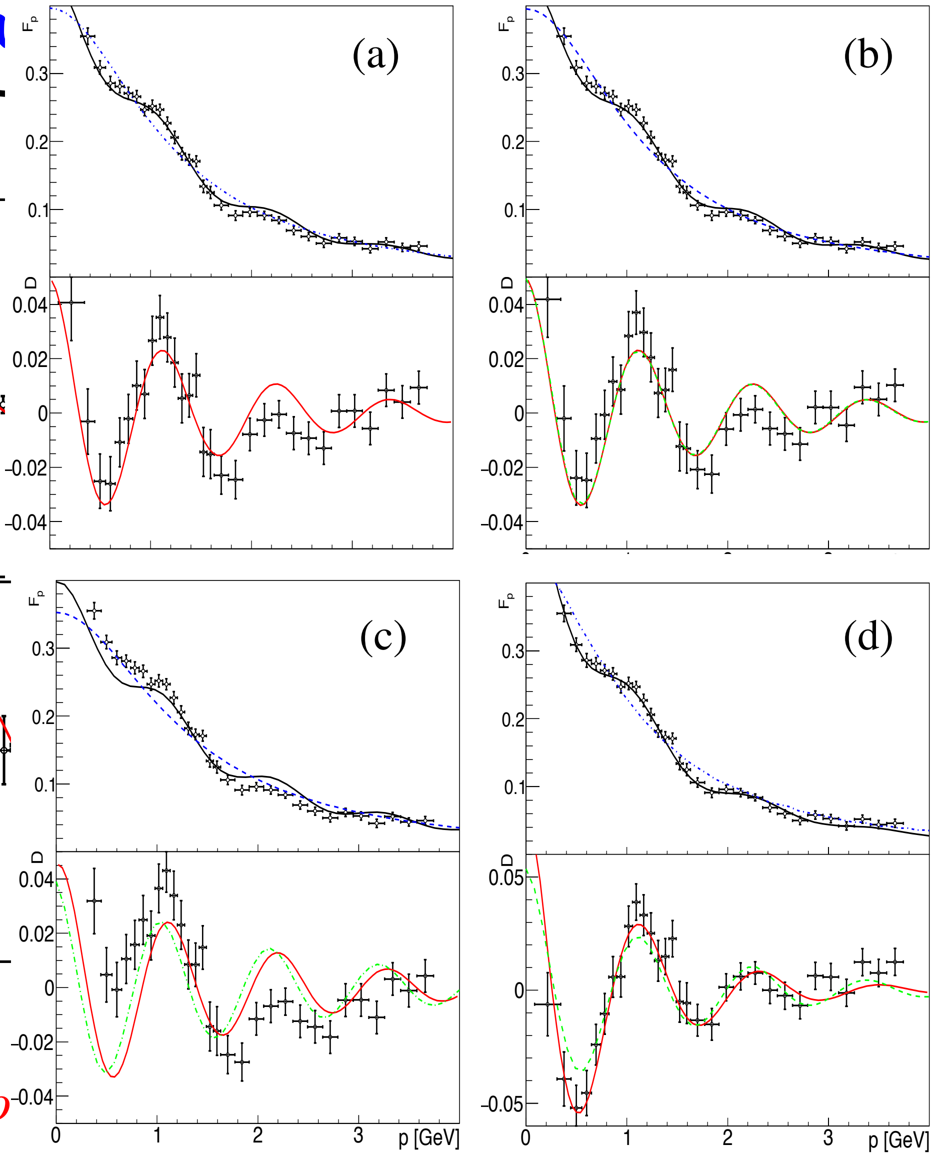


Oscillations : regular pattern in P_{Lab}

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…)