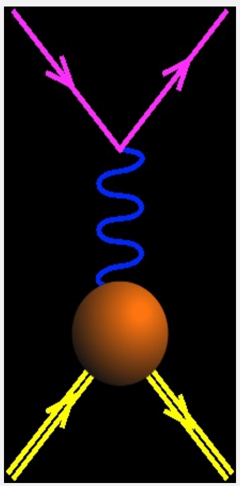
Exploring the Internal Structure of Composite Particles: Highlights on Proton Form Factors

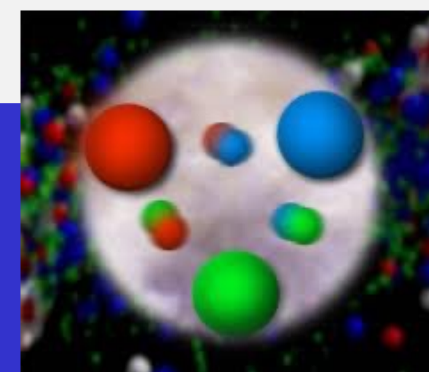


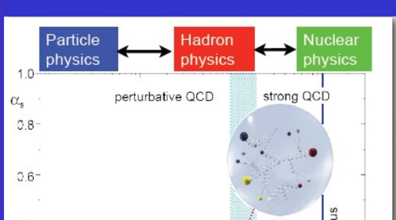
Egle Tomasi-Gustafsson

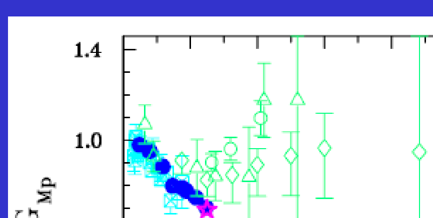
CEA, IRFU, DPhN

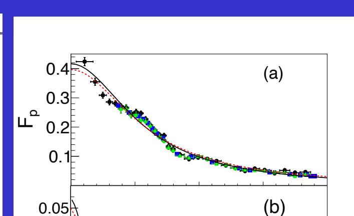
and

Université Paris-Saclay, France





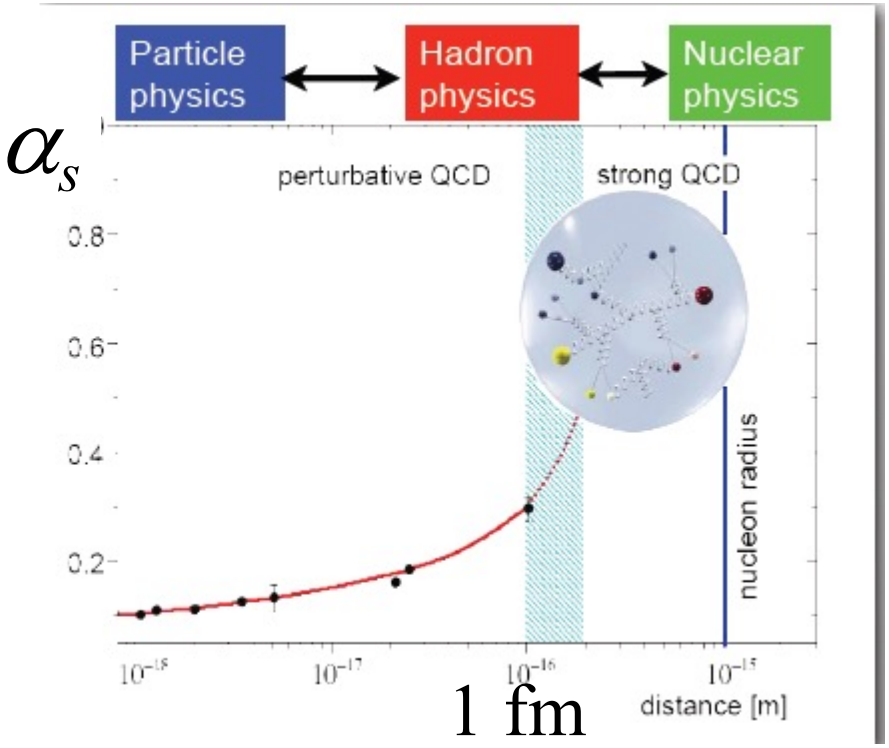




APC, 25 Juin 2021

Open questions in QCD (some)

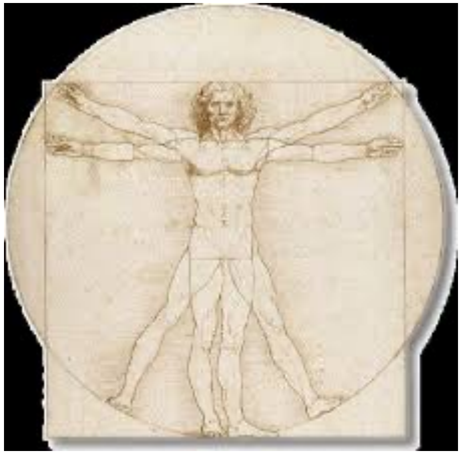
- Confinement: *why free quarks are not observed?*
- Origin of the hadron mass: the Higgs mechanism accounts for some percent of the hadron mass
- *How are* color neutral objects *formed?*
- Establish existence and properties of exotics, hybrids, glueballs
- Structure of the nucleon (charge, magnetic, spin distributions)



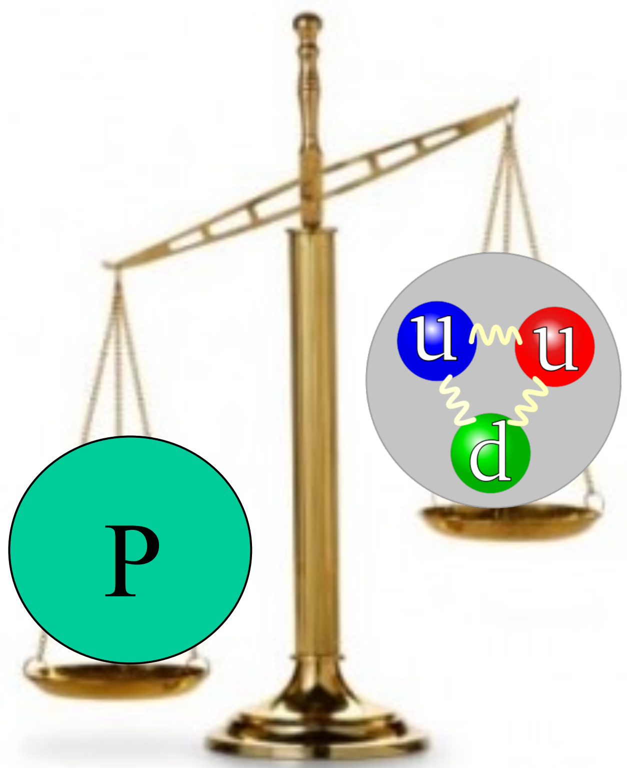
The proton

- Hadrons are >90% of visible matter
- Proton is the the most common particle in nature
- Its fundamental properties as
  - Mass
  - Spin
  - Size

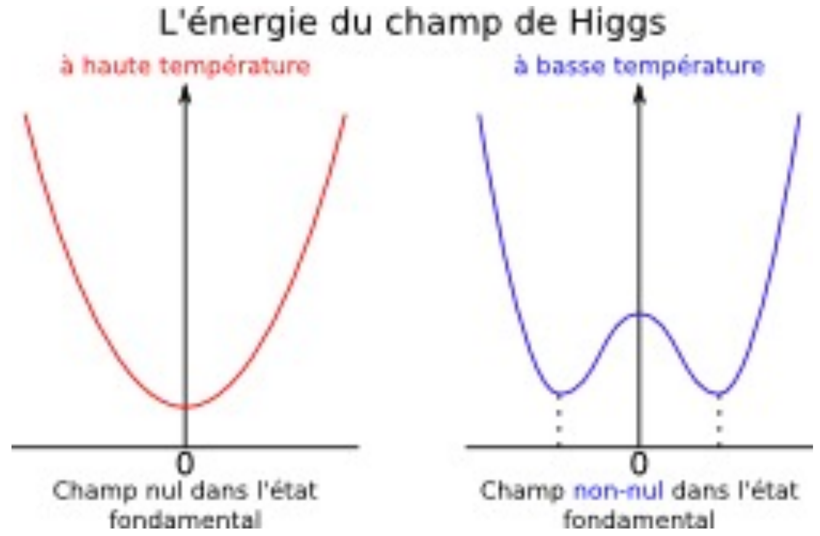
  are still object of controversy



The MASS of the proton



Mp=938,2720 MeV/c^2

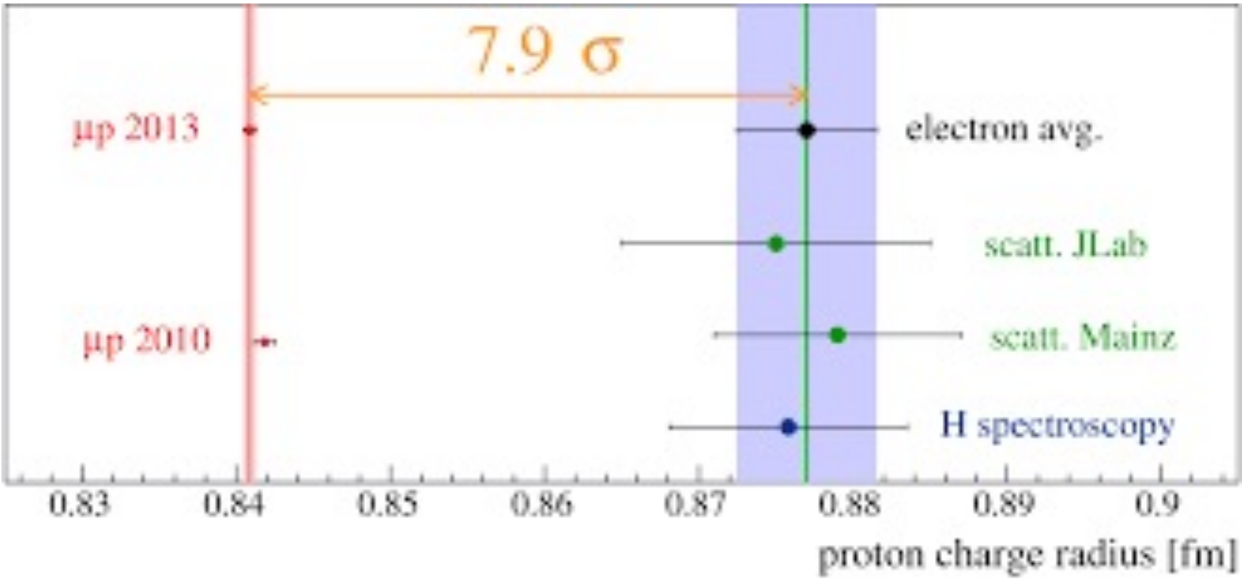


Masses
u-quark=1.5-4 MeV/c^2
d-quark=4-8 MeV/c^2

-dynamically created by the strong interaction
-antiproton-proton collisions: gluon rich environnement

panda @ FAIR SPD NICA EIC^2 EIC Center at Jefferson Lab

The SIZE of the proton

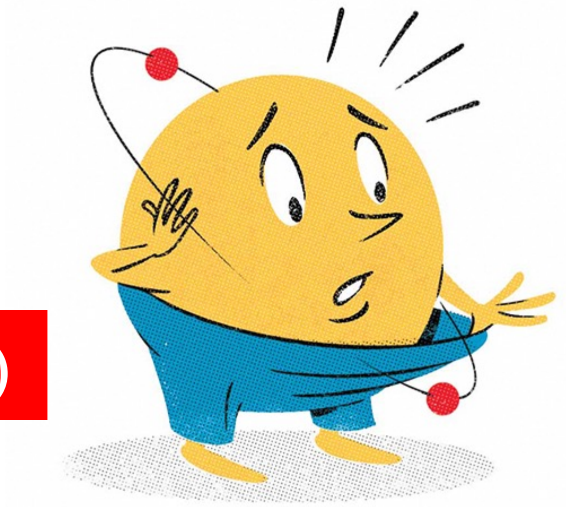


Rp=0.879(18) fm

Rp=0.8768(69) fm

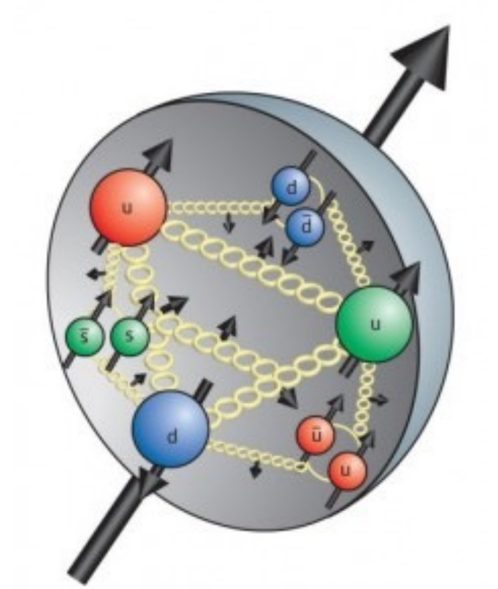
Rp=0.84184(67) fm (muonic H)

Rp=0.8335(95) fm (new H)



The New York Times

The SPIN of the proton



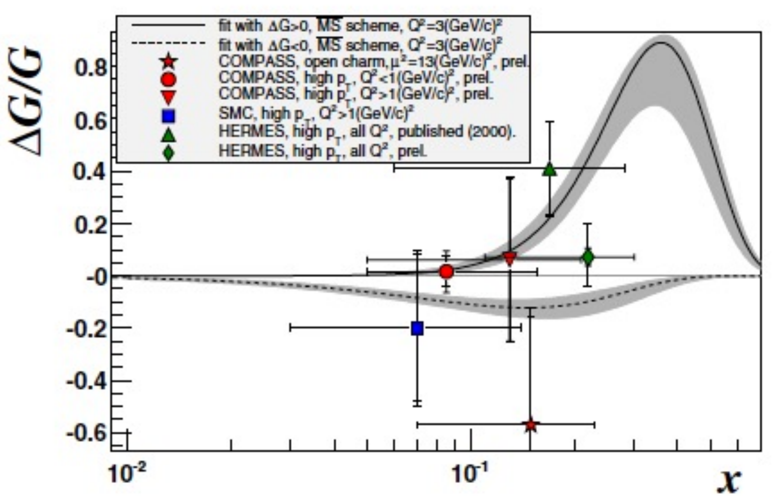
$S = 1/2$

$\Delta\Sigma \quad + \quad \Delta G \quad + \quad L$

Quarks

gluons

orbital momentum



Measured: ~ 1/4

L: spin-orbital correlations
TMD's, PDF's…

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

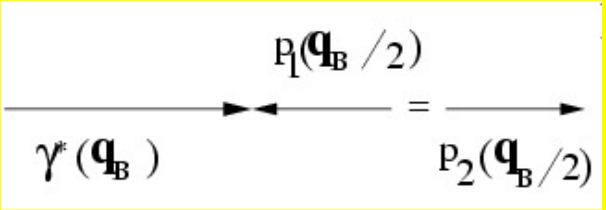
Stanford University
Stanford, CA, USA

- 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 (G_E,G_M)
- Playground for theory and experiment
  - at low q^2 probe the size of the nucleus,
  - at high q^2 test QCD scaling
- Assumption: dipole for GEp,GMp and GMn while GEn=0.

Dipole Approximation

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

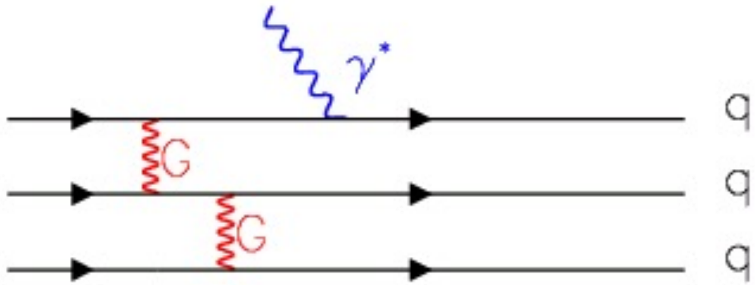
- Classical approach
  - Nucleon FF (in non relativistic approximation or in the Breit system) are Fourier transform of the charge or magnetic distribution.



Breit system

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

Dipole Approximation and pQCD



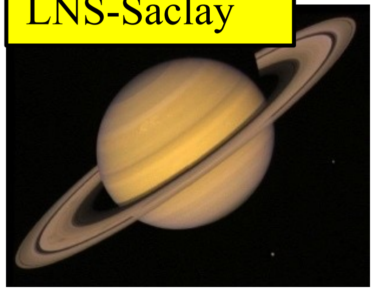
Dimensional scaling

- $F_n(Q^2) = C_n\,[1/(1+Q^2/m_n)^{n-1}]$,
  - $m_n = n\beta^2$, <quark momentum squared>
  - n is the number of constituent quarks
- Setting $\beta^2 = (0.471 \pm .010)$ GeV^2 *(fitting pion data)*
  - pion: $F_\pi(Q^2) = C_\pi\,[1/(1+Q^2/0.471\ \text{GeV}^2)^1]$,
  - nucleon: $F_N(Q^2) = C_N\,[1/(1+Q^2/0.71\ \text{GeV}^2)^2]$,
  - deuteron: $F_d(Q^2) = C_d\,[1/(1+Q^2/1.41\ \text{GeV}^2)^5]$

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

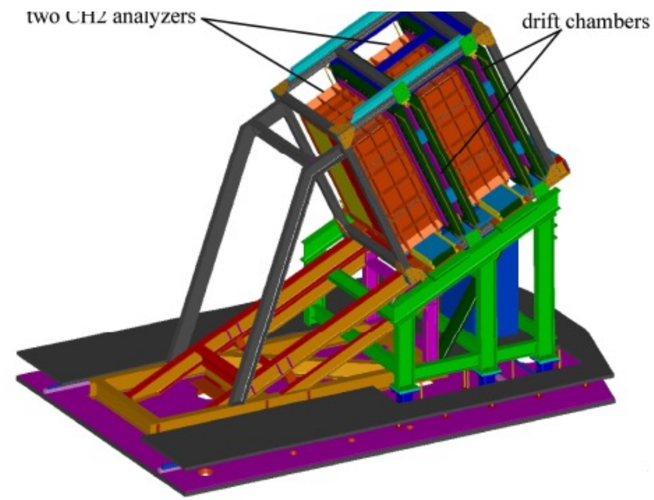
Recent experimental achievements: polarization

LNS-Saclay



Hadron polarimetry in the GeV range

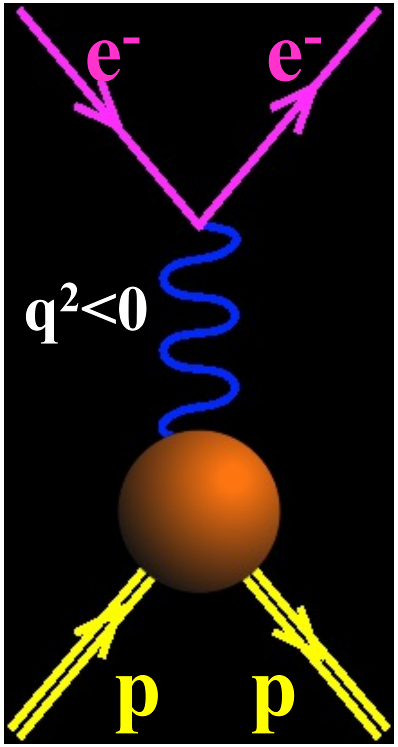
JINR-Dubna



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

VEPP-Novosibirsk

Electromagnetic Interaction



The electron vertex is known, γ_μ

The interaction is carried by a virtual photon of 4-mom q^2

The proton vertex is parametrized in terms of FFs: Pauli and Dirac F_1,F_2

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

$$q^2 = -4E_1E_2 \sin^2\theta/2$$

or in terms of Sachs FFs:

$G_E = F_1 + \tau F_2$, $G_M = F_1 + F_2$, $\tau = q^2/4M^2$

$G_E(0) = 1(e)$ $G_M(0) = \mu_N$

What about high order radiative corrections?

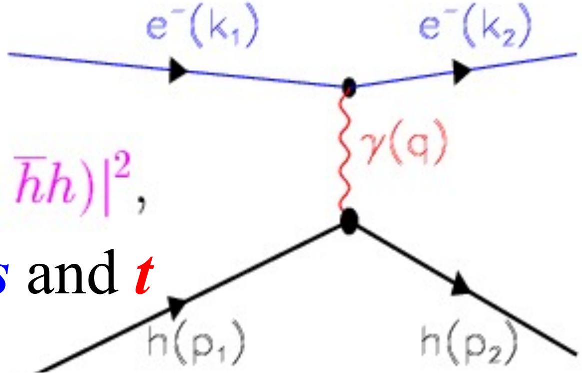
QED Radiative Corrections

Modify the absolute value of the experimental observables and their dependence from the relevant kinematical variables

Crossing symmetry

Scattering and annihilation channels:

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



- Described by the same amplitude :

$$|\overline{\mathcal{M}}(e^{\pm}h \rightarrow e^{\pm}h)|^2 = f(s,t) = |\overline{\mathcal{M}}(e^+e^- \rightarrow \bar{h}h)|^2,$$

- function of two kinematical variables, ***s*** and ***t***

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

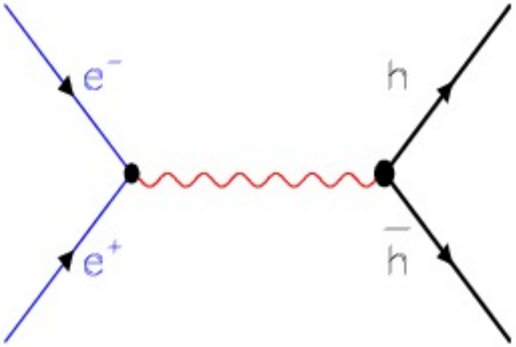
$e^- + e^+ \rightarrow \bar{h} + h$

- which scan different kinematical regions

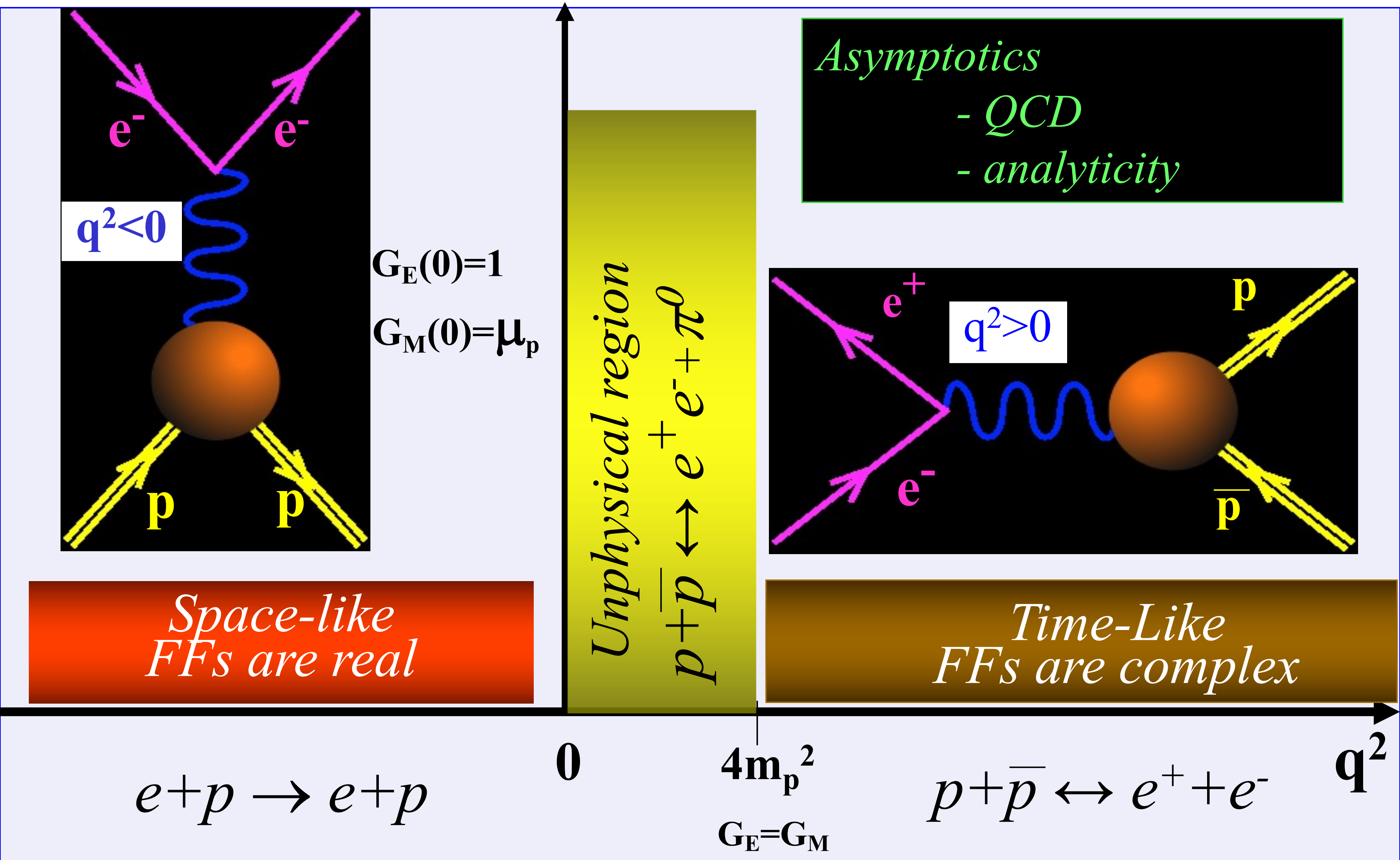
$$k_2 \longrightarrow -k_2$$

$$p_2 \longrightarrow -p_2$$

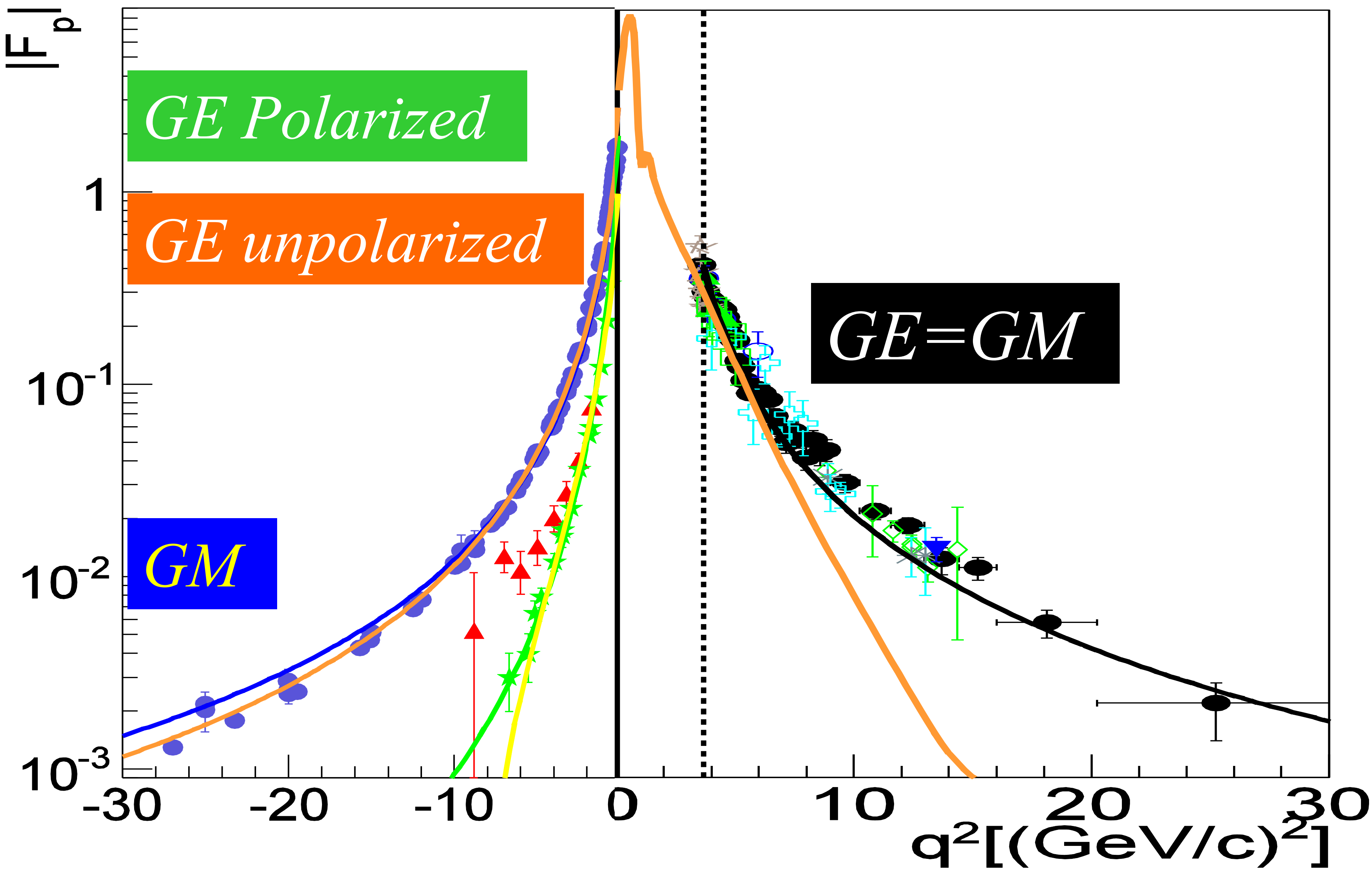
$$cos^2\tilde{\theta} = 1 + \frac{st + (s - M^2)^2}{t(\frac{t}{4} - M^2)} \rightarrow 1 + \frac{ctg^2\frac{\theta}{2}}{1+\tau}$$



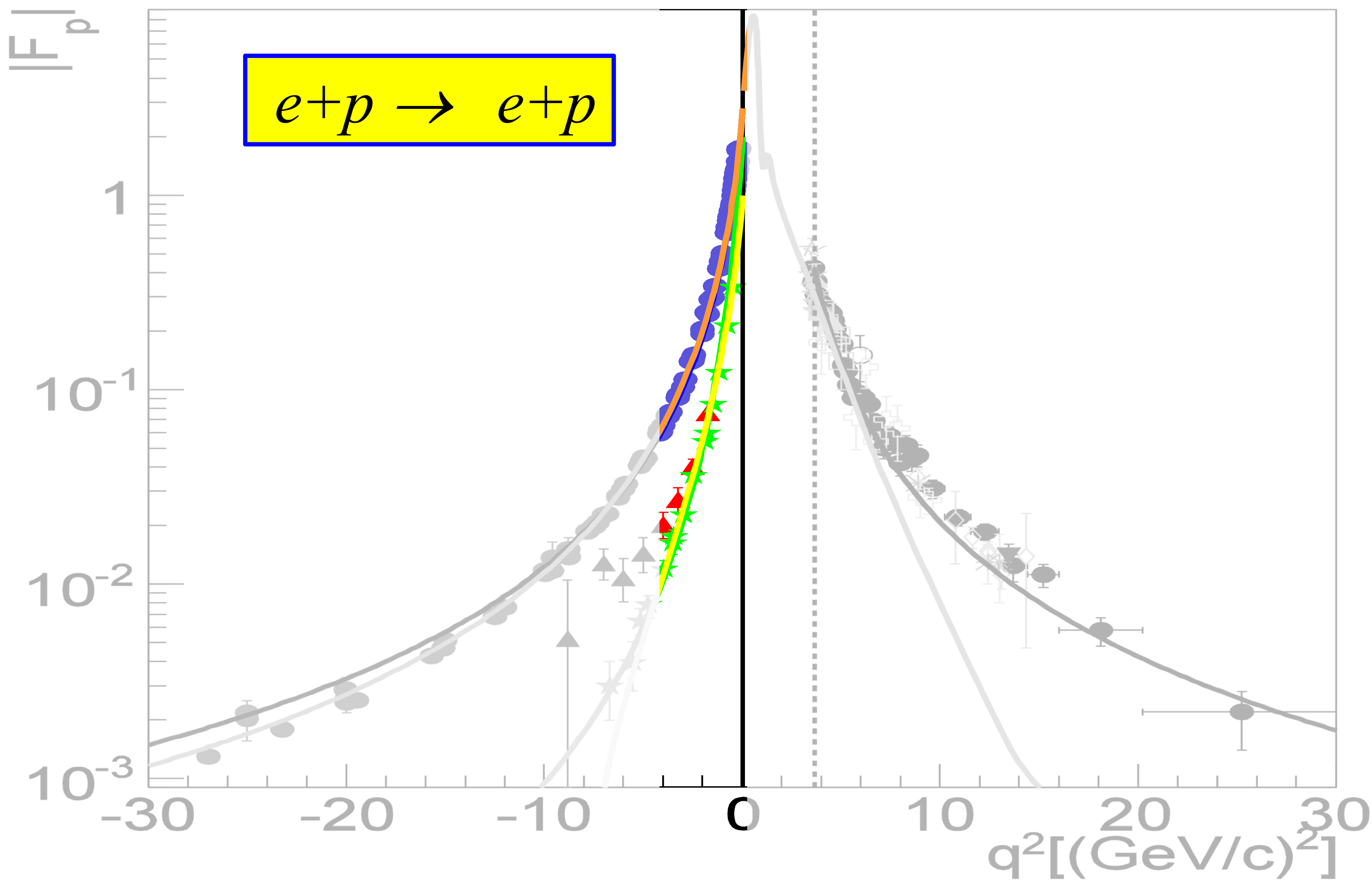
Proton Charge and Magnetic Distributions



Hadron Electromagnetic Form Factors



The Space-Like region: low Q^2



Root mean square radius

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

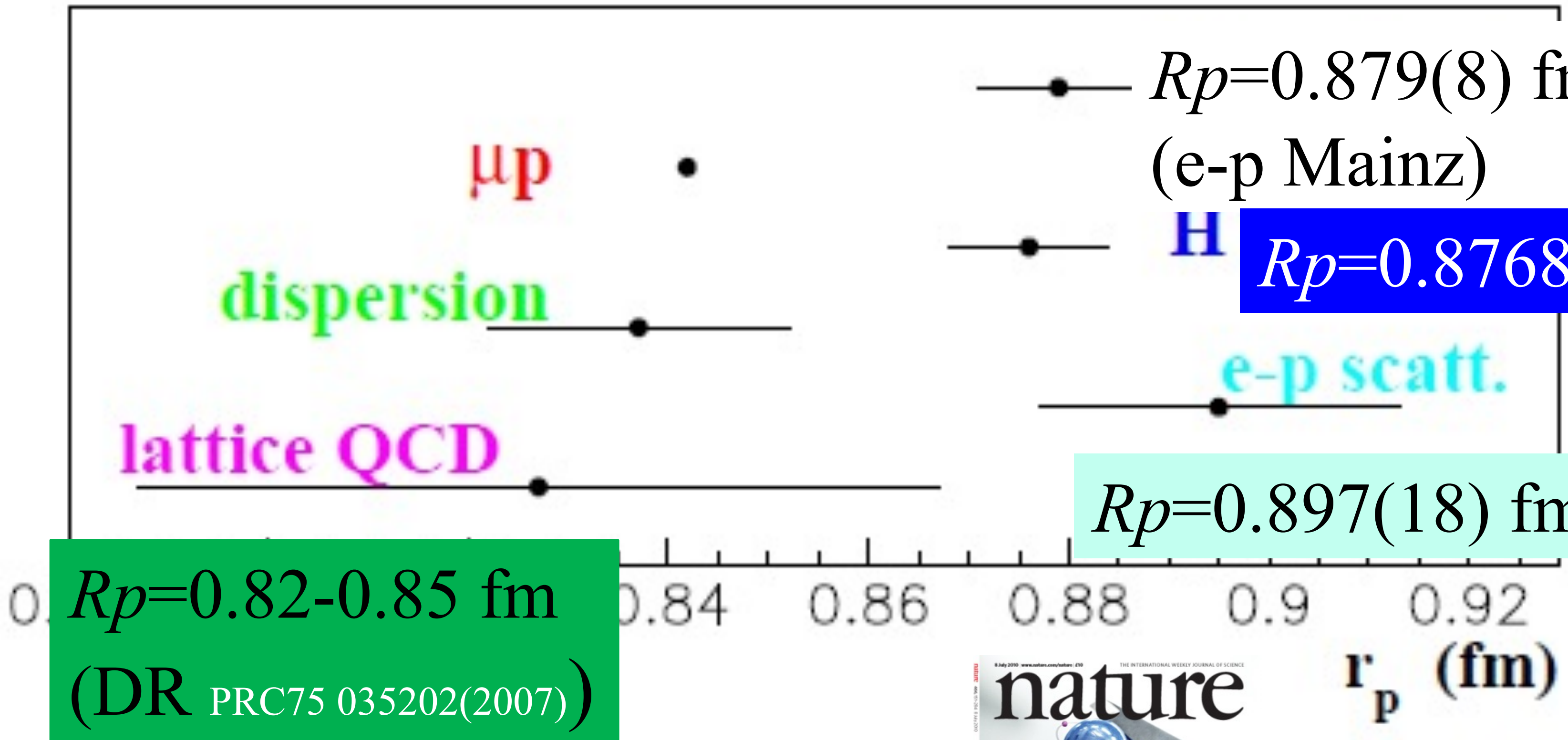
density $\rho(r)$	Form factor $F(q^2)$	r.m.s. $< r_c^2 >$	comments
δ	1	0	pointlike
e^{-ar}	$\frac{a^4}{(q^2+a^2)^2}$	$\frac{12}{a^2}$	dipole
$\frac{e^{-ar}}{r}$	$\frac{a^2}{q^2+a^2}$	$\frac{6}{a^2}$	monopole
$\frac{e^{-ar^2}}{r^2}$	$e^{-q^2/(4a^2)}$	$\frac{1}{2a}$	gaussian
ρ_0 for $x\le R$ 0 for $r\ge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

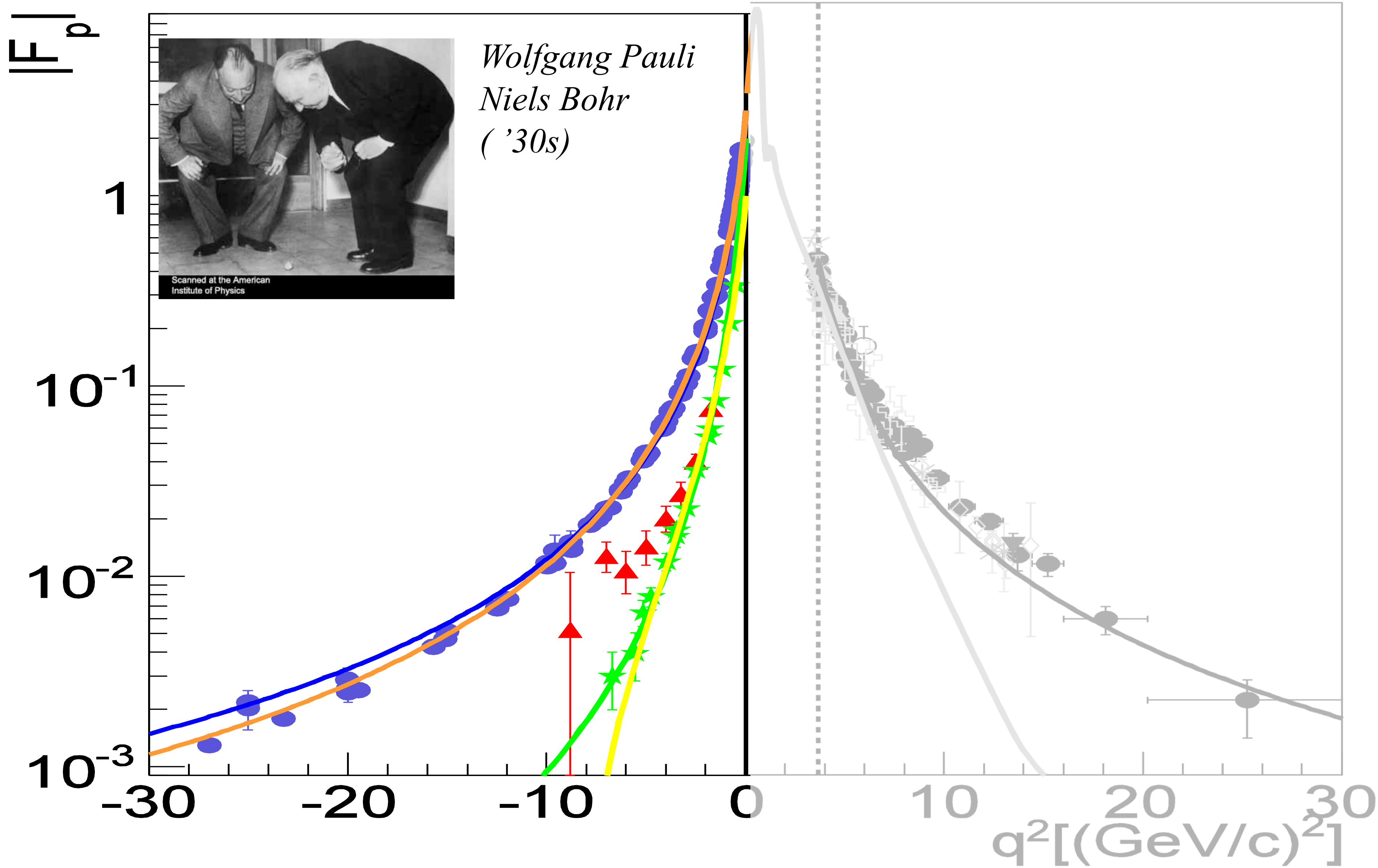
Rp=0.8768(69) fm

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 Space-Like region



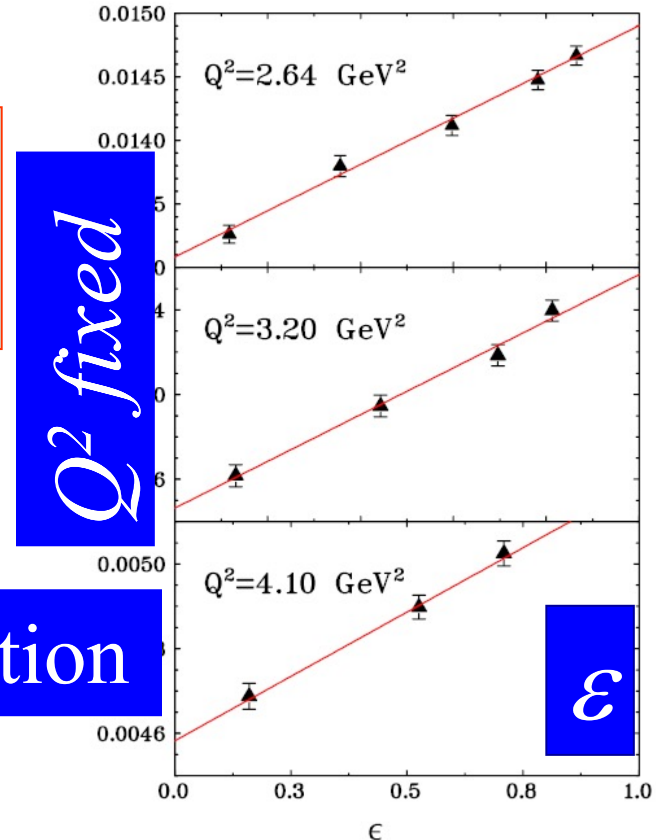
ep-elastic scattering : Rosenbluth separation

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

1950

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

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



Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

→ Holds for 1γ exchange only

PRL 94, 142301 (2005)

ep-elastic scattering : The Akhiezer-Rekalo method

PHYSICS

1967

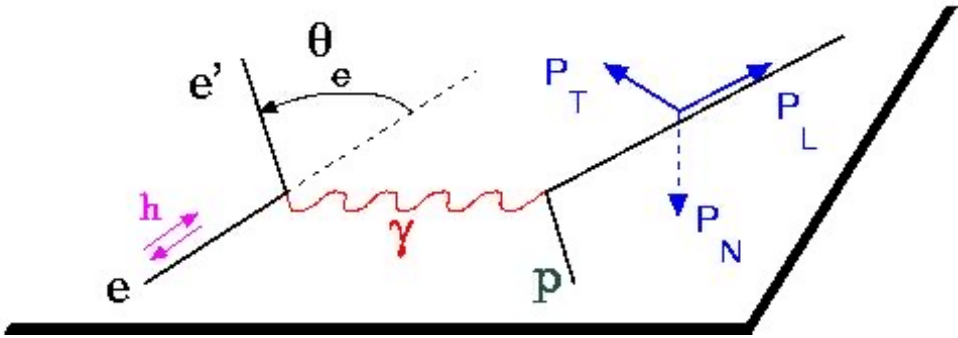
POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

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

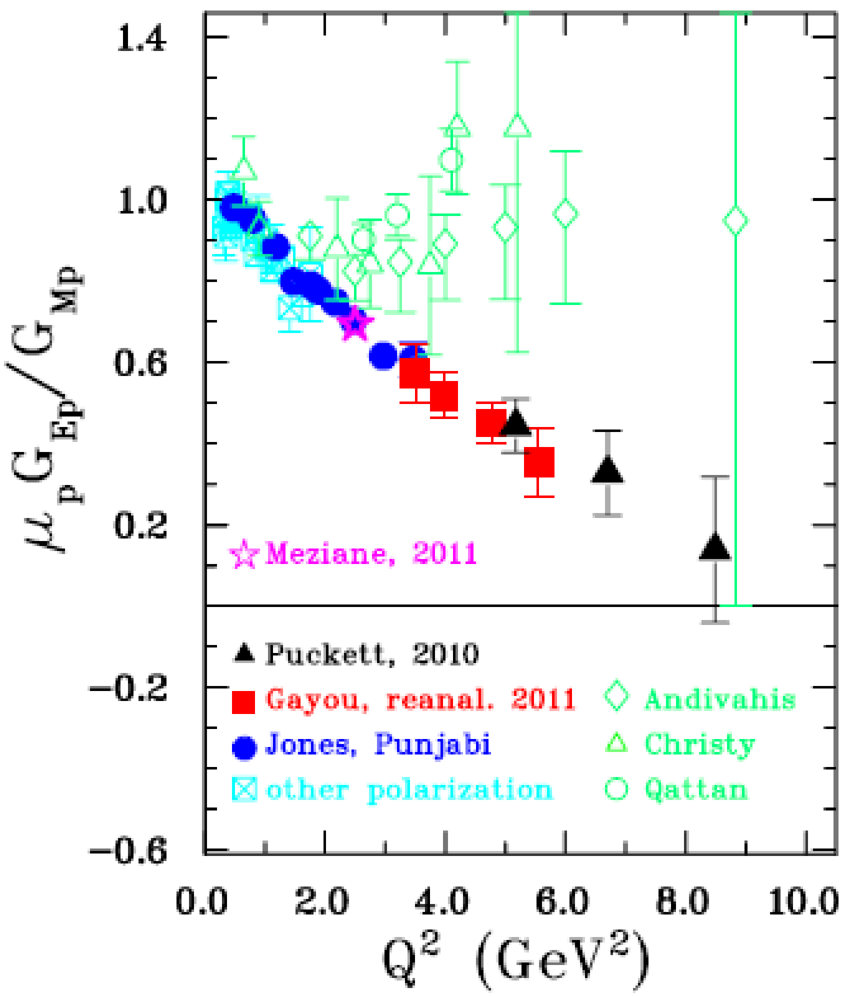
$$I_0 = (G_E^p(Q^2))^2 + \frac{\tau}{\epsilon}(G_M^p(Q^2))^2$$

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

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 (>2000)

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***

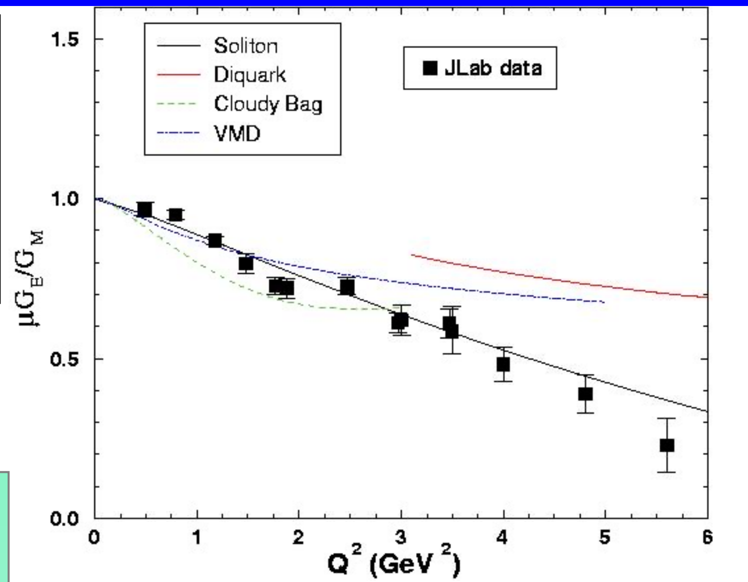
A.J.R. Puckett et al, Phys. Rev. ***C96,*** *055203 (2017).*

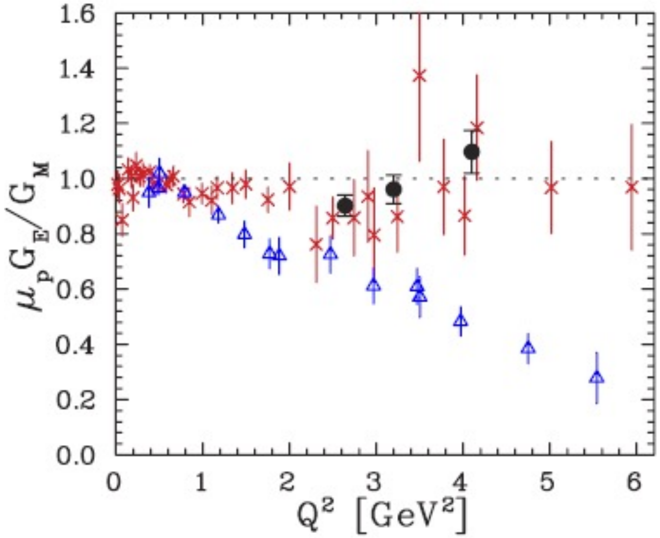
Issues

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

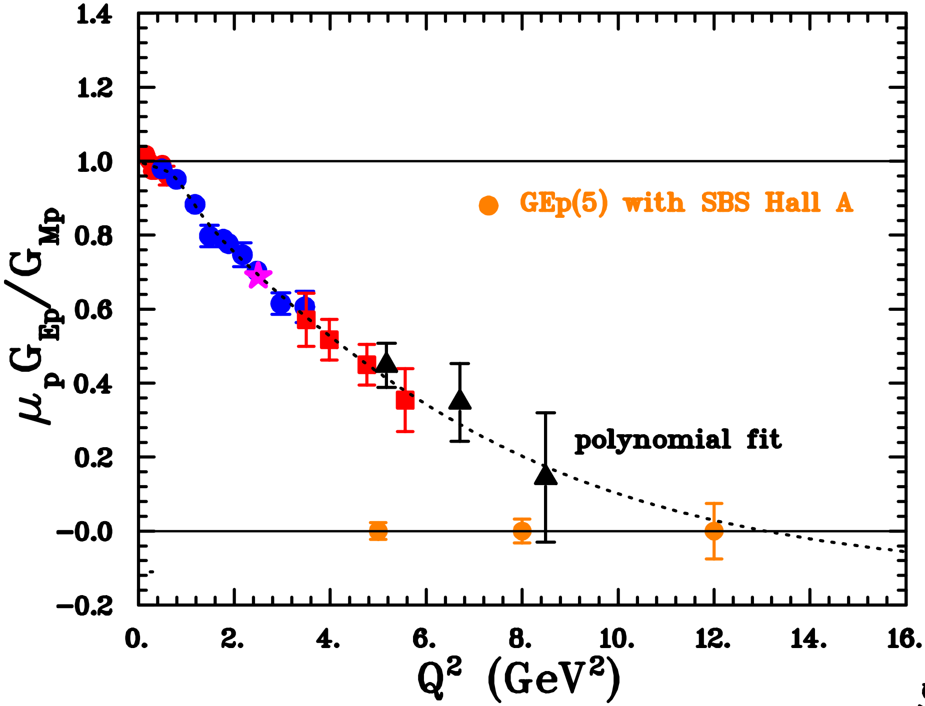
BUT

- 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



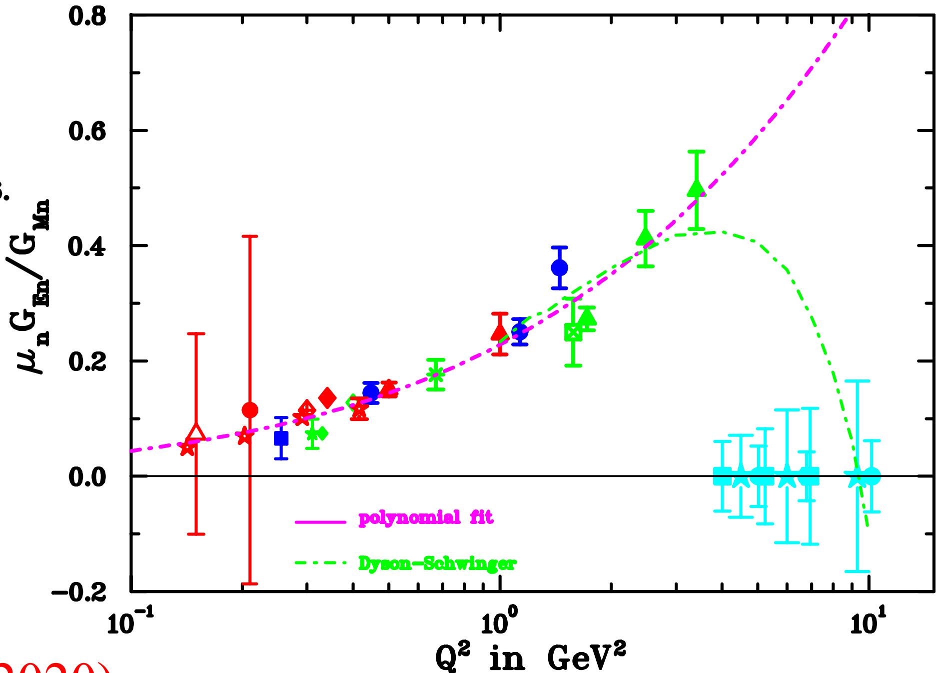


...and future plans



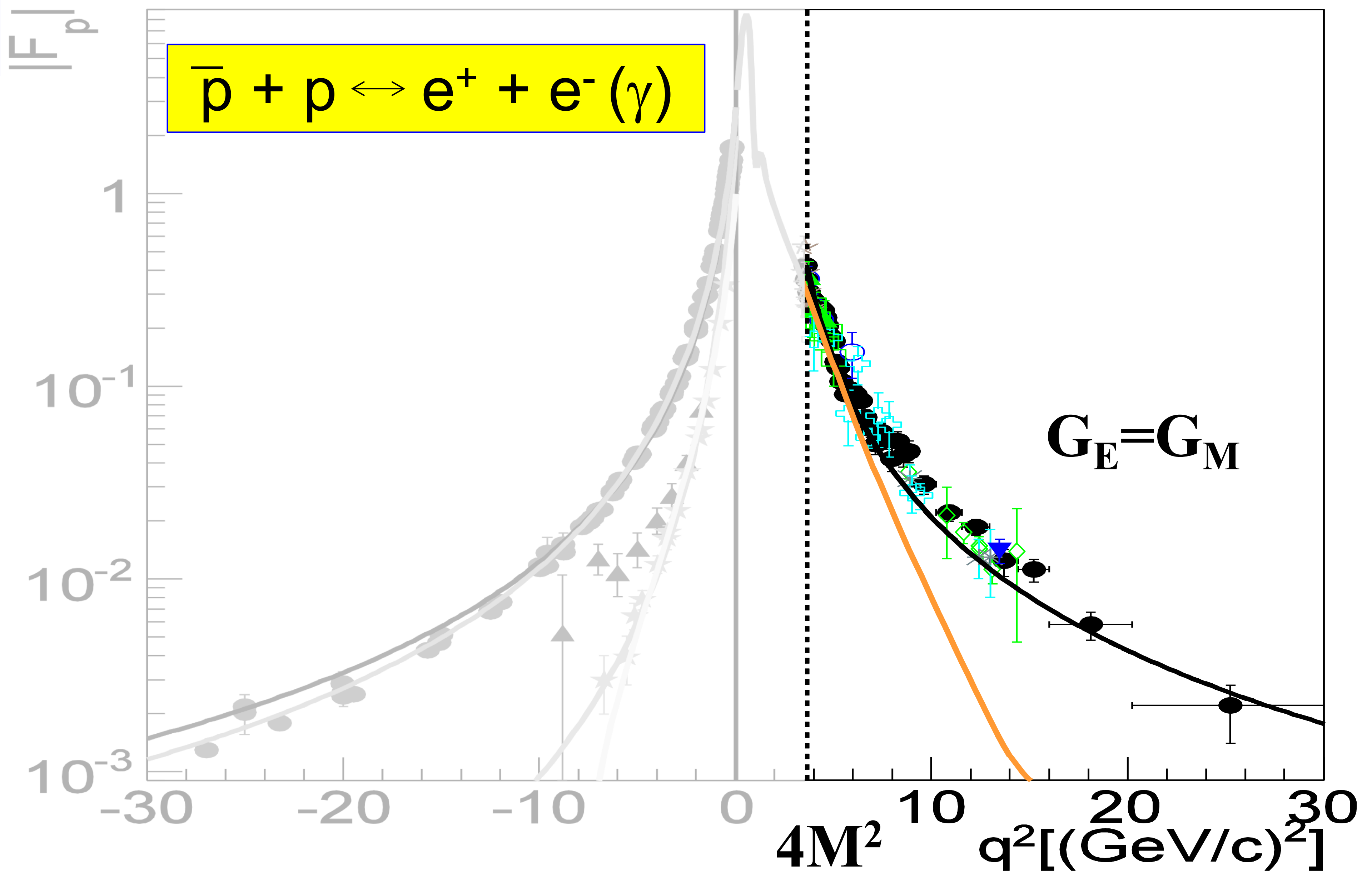
Ch. Perdrisat, Jlab PR12-07-109

J. Anderson Jlab PR12-09-009
J. Annand Jlab PR12-09-019



S.N. Basilev et al, Eur.Phys.J.A 56 (2020)

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 $\cos^2 q$ (1g exchange)
- No dependence on sign of FFs
- Enhancement of magnetic term

but TL form factors are complex!

Total Cross Section from $e^+e^- \to p\bar{p}$

$$\sigma_{e^+e^-\to\bar{p}p}(s) = \frac{4\pi\alpha^2\beta\,\mathcal{C}(\beta)}{3s}\left(|G_M(s)|^2 + \frac{1}{2\tau}|G_E(s)|^2\right)$$

- Effective FF: $\sigma_{Tot} \sim F_p^2$

$$F_p(s)^2 = \frac{2\tau|G_M(s)|^2 + |G_E(s)|^2}{2\tau+1}$$

- Equivalent to:

$$|G_E(s)| = |G_M(s)| \equiv F_p(s)$$

Strictly valid at threshold, where only one amplitude is present

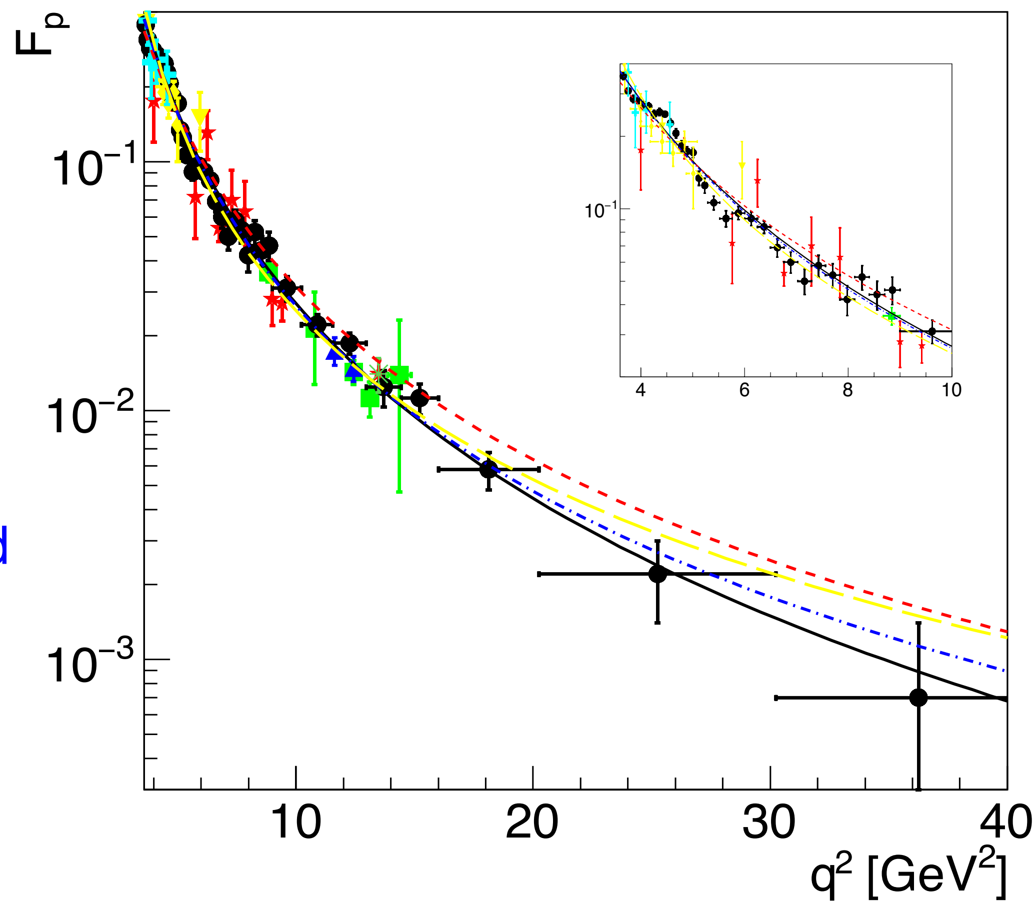
The Time-like Region

$G_E = G_M$

The Experimental Status

- Individual determination of GE and GM : only recently!
- TL proton FFs twice larger than in SL at the same Q^2
- Steep behaviour at threshold
- BaBAR:Structures?
  Resonances?

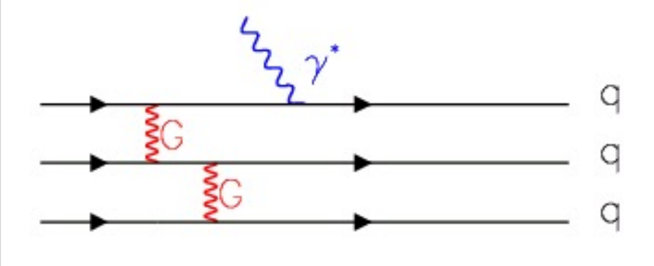
Confirmed by BES



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



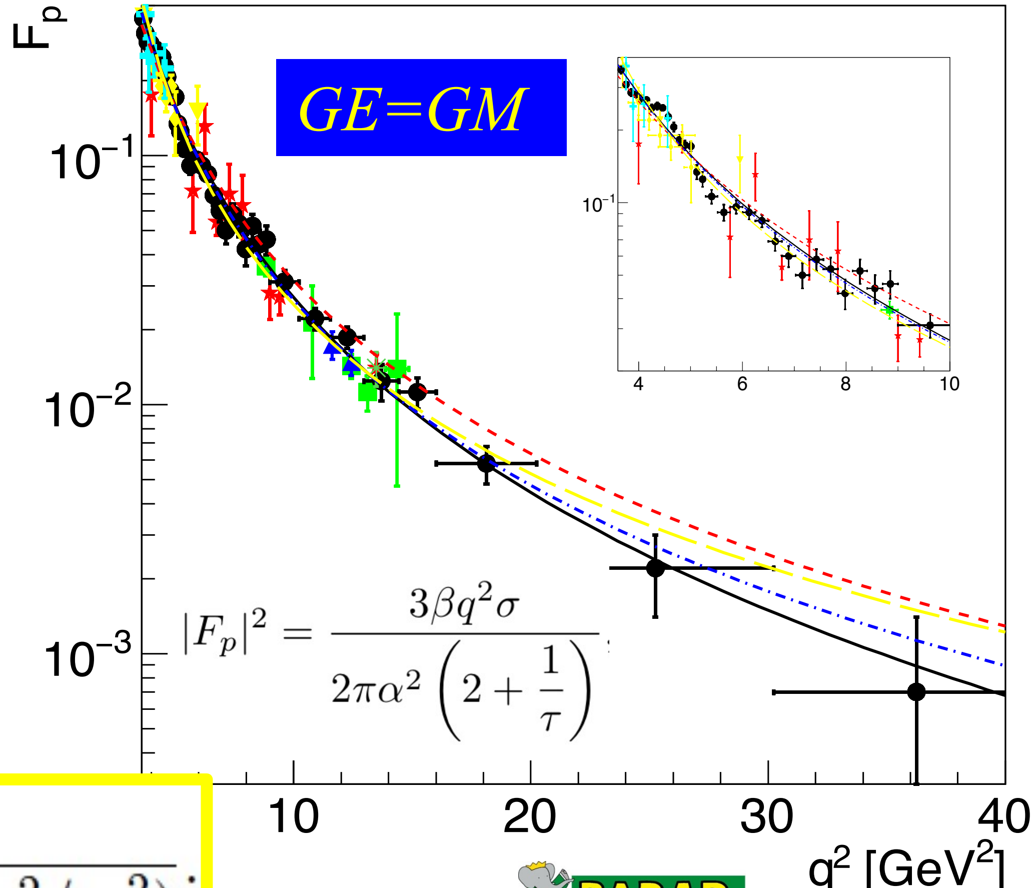
Expected QCD scaling $(q^2)^2$

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

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

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

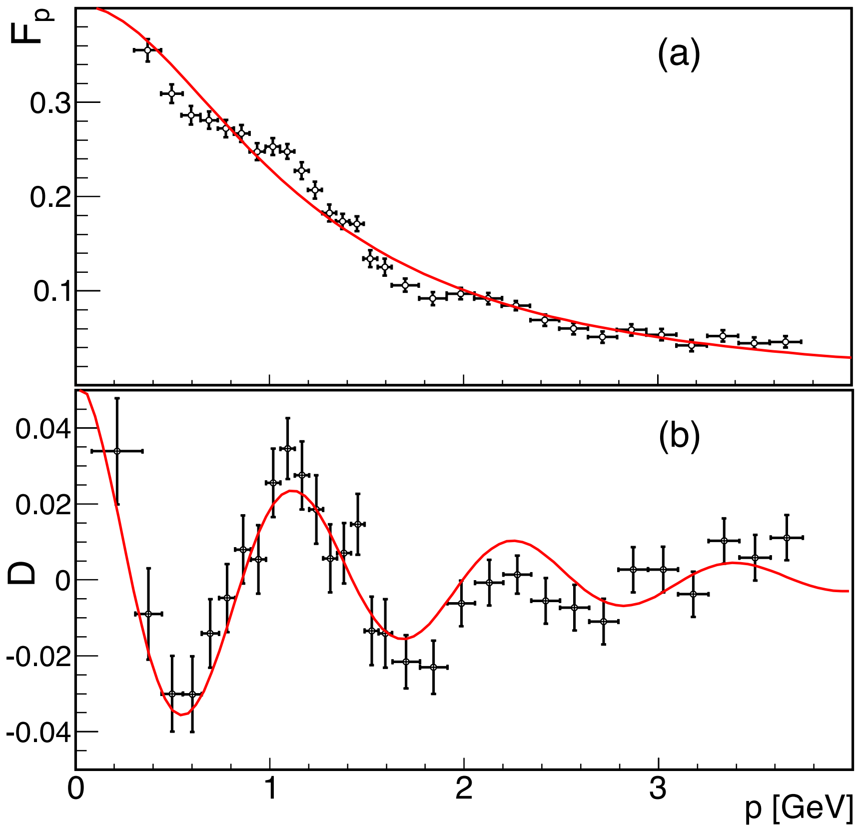
$$e^+ + e^- \to \bar{p} + p\,,$$
$$\bar{p} + p \to e^+ + e^-$$



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)

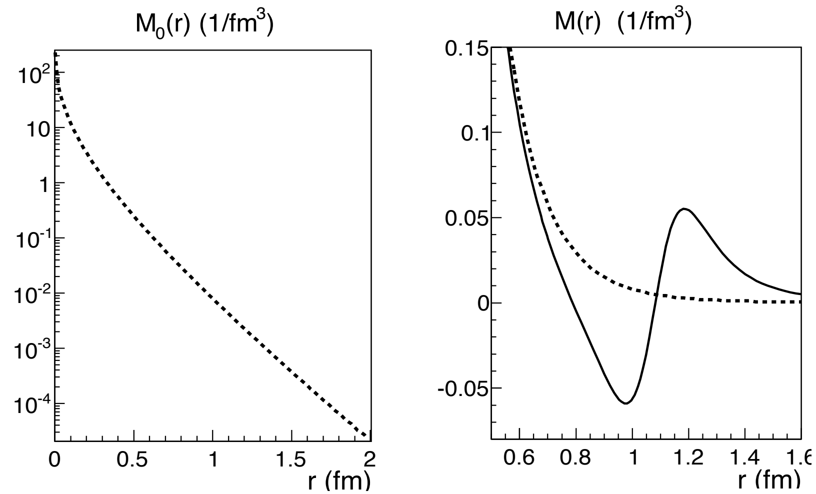
Fourier Transform

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

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

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

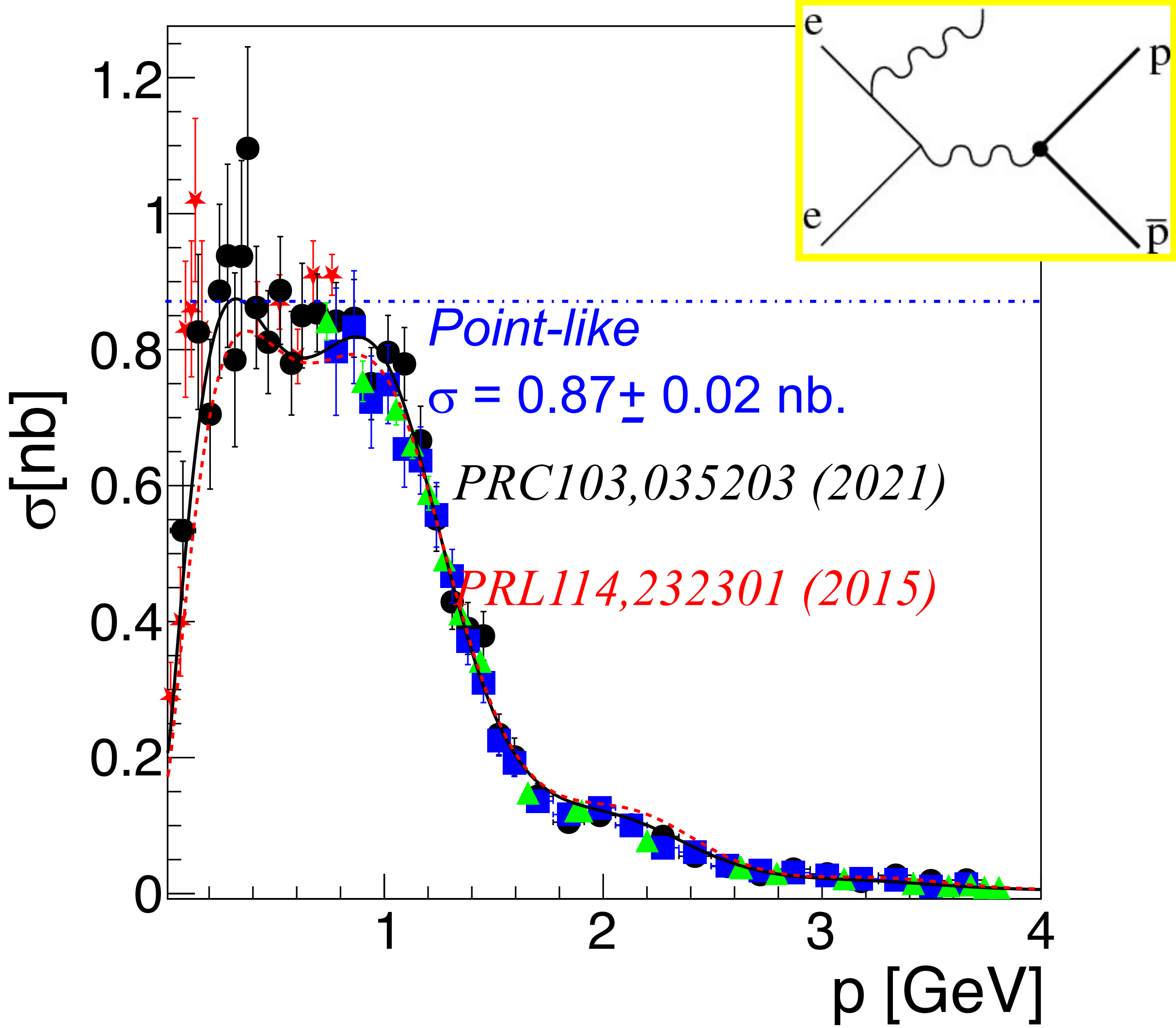
$$F_{osc}(p) \;\equiv\; A\;\exp(-Bp)\;\cos(Cp\;+\;D).$$



- *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*

Cross section from $e^+e^- \to p\bar{p}\ (\gamma)$



Novosibirsk 38pt
1.9<2E<4.5
PLB794,64 (2019)

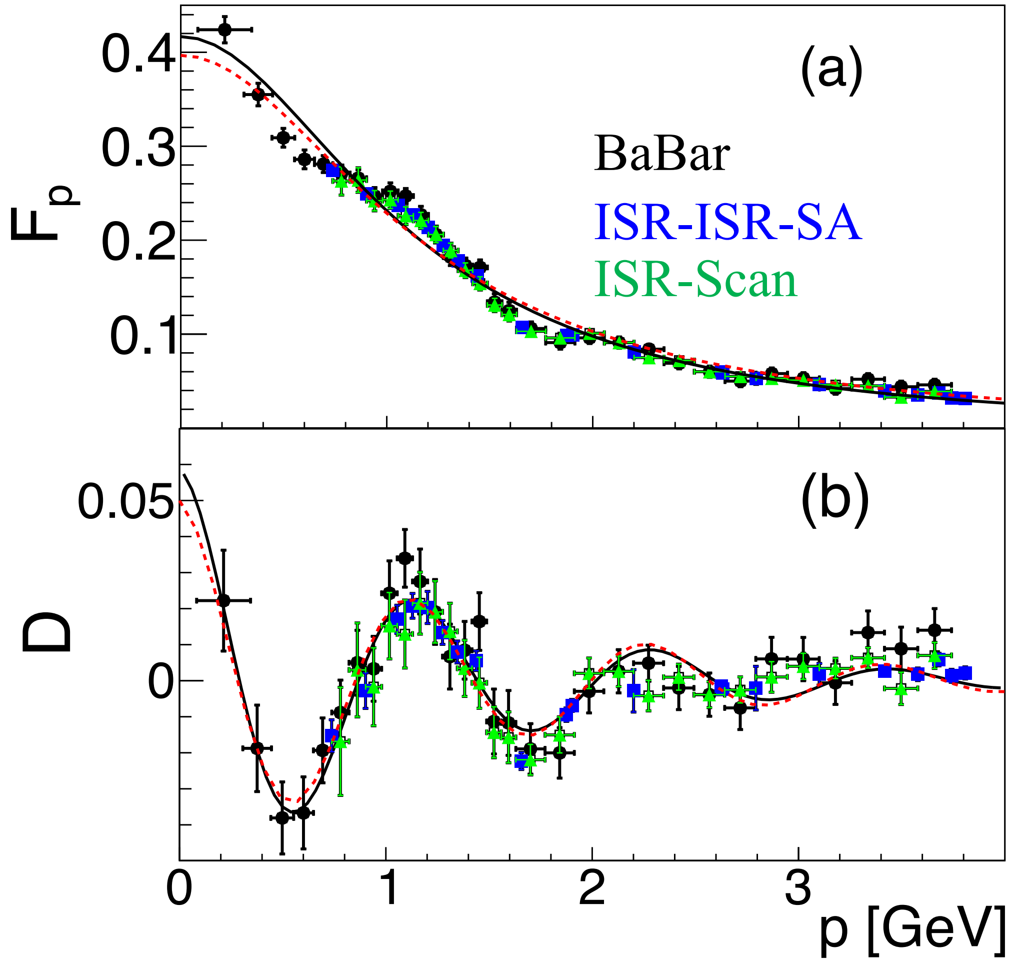
BaBar 85pt
1.9<2E<4.5
PRD87,092005 (2013)

ISR-ISR-SA 30pt
2<2E<3.6
PRD99,092002 (2019)

ISR-Scan 22pt
2<2E<3.1
PRL124,042001 (2020)

E.T.-G., A. Bianconi, S. Pacetti, Phys.Rev.C 103 (2021) 3, 035203

Confirmation of regular oscillations



$$F_p^{\text{fit}}(s) = F_{3\text{p}}(s) \; + \; F_{\text{osc}}(p(s))$$

$$F_{3\text{p}}(s) = \frac{F_0}{\left(1 + \frac{s}{m_a^2}\right)\left(1 - \frac{s}{m_0^2}\right)^2},$$

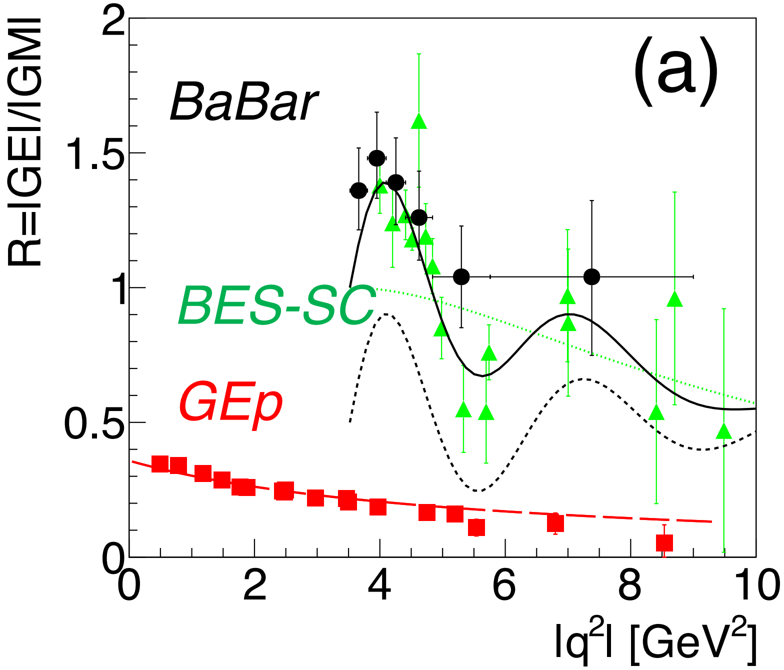
$$F_{\text{osc}}(p(s)) = Ae^{-Bp}\cos(Cp + D).$$

$$s = 2m_p\left(m_p + \sqrt{p^2 + m_p^2}\right),$$

$$p = \sqrt{s\left(\frac{s}{4m_p^2} - 1\right)}.$$

E.T.-G., A. Bianconi, S. Pacetti, Phys.Rev.C 103 (2021) 3, 035203

Form Factor Ratio R=|GE|/|GM|

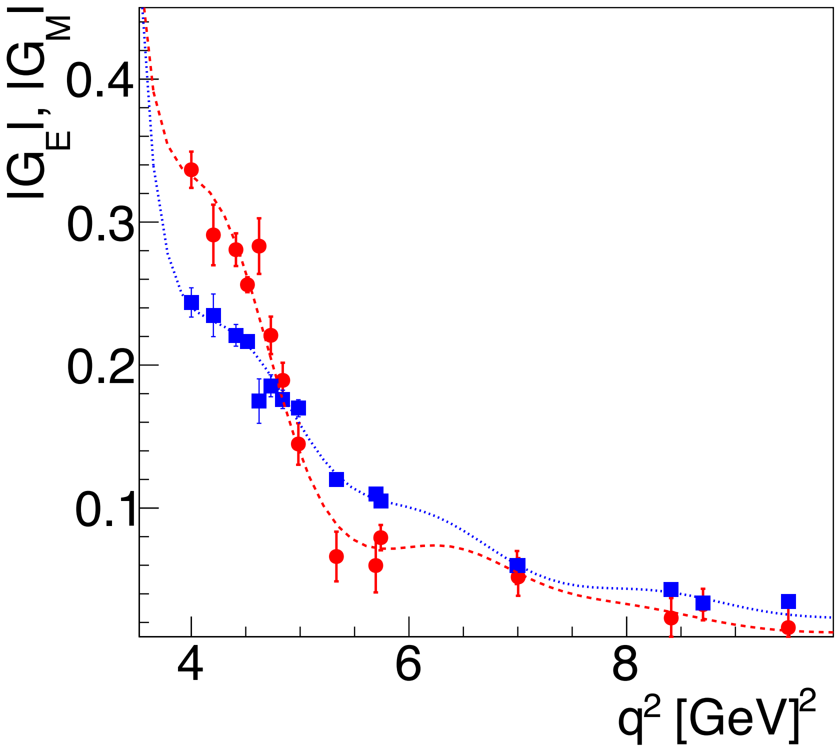


- Precise data from BESIII
- Dip at $|q^2|$~5.8 GeV^2
- Comparison with SL (Jlab-GEp data)
- Oscillations on top of a monopole: from GE or GM?

$$F_R(\omega(s)) = \frac{1}{1+\omega^2/r_0}\left[1 + r_1 e^{-r_2\omega}\sin(r_3\omega)\right], \;\; \omega = \sqrt{s} - 2m_p\,,$$

Sachs form factors: $|G_E|$, $|G_M|$

From the fit on Fp and the fit on R,
the Sachs FFs (moduli) can be reconstructed



$$|G_E(s)| = F_p(s)\sqrt{\frac{1+2\tau}{R^2(s)+2\tau/R^2(s)}}$$

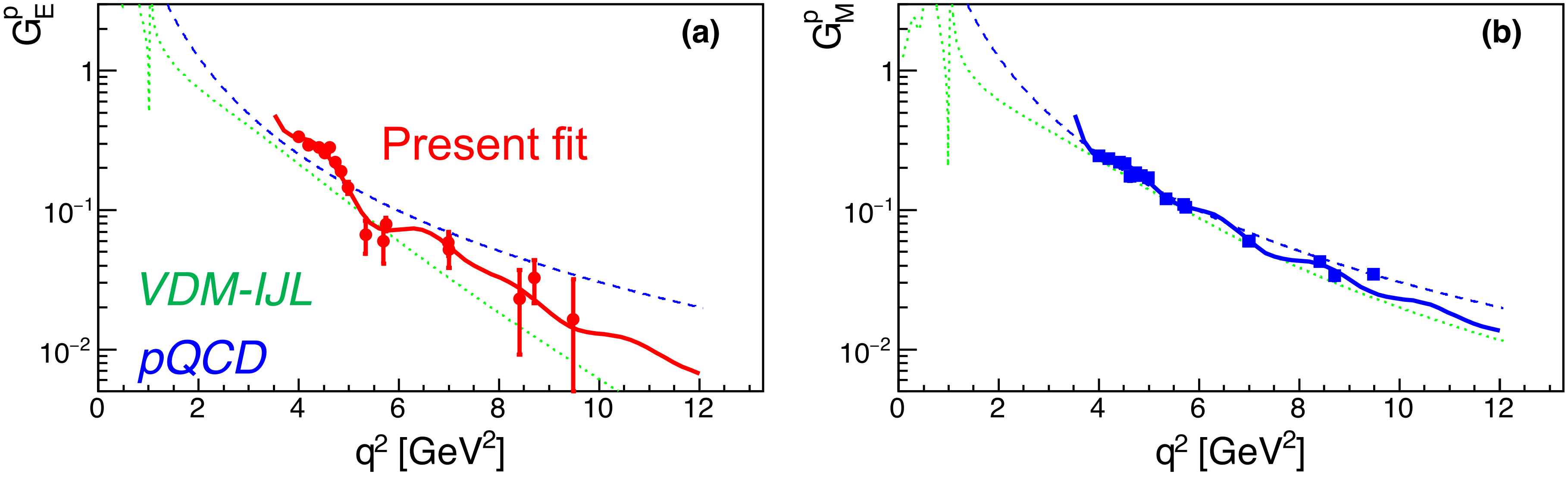
$$|G_M(s)| = F_p(s)\sqrt{\frac{1+2\tau}{R^2(s)+2\tau}}.$$

Threshold constrain R=1 for $\tau=1$
The fit gives :
$|G_E| = |G_M| = 0.48$

E.T.-G., A. Bianconi, S. Pacetti, Phys.Rev.C 103 (2021) 3, 035203

Models

Parametrizations have been determined by fitting Fp



|GE|: more pronounced oscillations
faster q^2-decrease

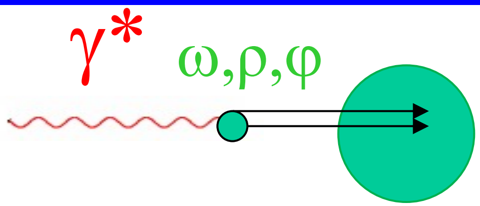
Threshold constrain R=1 for $\tau=1$

The fit gives : pQCD : 0.34

$|G_E| = |G_M| = 0.48$ VDM-IJL : 0.29

E.T.-G., A. Bianconi, S. Pacetti, Phys.Rev.C 103 (2021) 3, 035203

VMD: Iachello, Jakson and Landé (1973)



Isoscalar and isovector FFs

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

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

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

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

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

Intrinsic factor

Meson Cloud

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

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

Few # parameters, with physical meaning

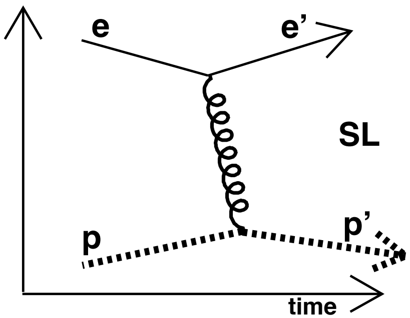
Naturally arising TL imaginary part

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

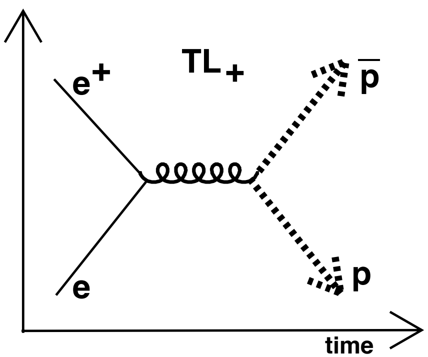
Unified definition of TL-SL Form Factors

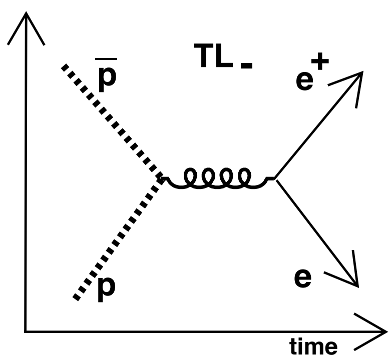
$$F(q^2) = \int_{\mathcal{D}} d^4x e^{iq_\mu x^\mu} \rho(x),\ \ q_\mu x^\mu = q_0 t - \vec{q}\cdot\vec{x}$$

$\rho(x) = \rho(\vec{x}, t)$ space-time distribution of the electric charge in the space-time volume $\mathcal{D}$.



SL photon 'sees' a charge density

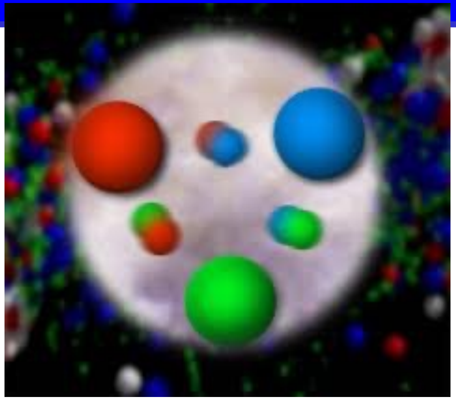




TL photon can NOT test a space distribution

How to connect and understand the amplitudes?

The nucleon



3 valence quarks and a neutral sea of qq pairs

Antisymmetric state of colored quarks:

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

Assumption:

Does not hold in the spatial center of the nucleon: the center of the nucleon *is electrically neutral,* due to strong gluonic field
Inner region: gluonic condensate of clusters with randomly oriented chromo-magnetic field (Vainshtein, 1982)

Charge screening in a plasma

E.A. Kuraev, E. T-G, A. Dbeyssi, Phys.Lett. B712 (2012) 240

Predictions for SL and TL

Quark counting rules apply to the vector part of the potential

$$G_M^{(p,n)}(Q^2) = \mu G_E(Q^2);$$
$$G_E^{(p,n)}(Q^2) = G_D(Q^2) = \left[1 + Q^2/(0.71\,\mathrm{GeV}^2)\right]^{-2}$$

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

Additional suppression due to the neutral plasma

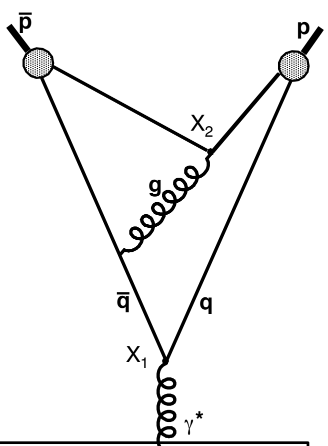
$$G_E(Q^2) = \frac{G_M(Q^2)}{\mu}\left(1 + Q^2/q_1^2\right)^{-1}$$

Similar behavior in SL and TL regions

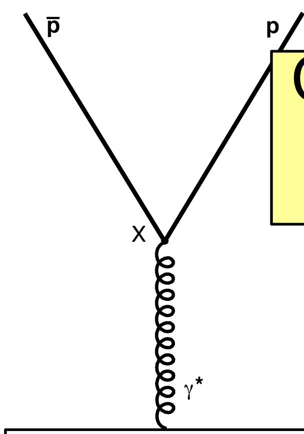
Photon-Charge coupling

$\rho(\vec{x})$ Fourier transform of a stationary charge and current distribution

$R(t)$ Amplitude for creating *charge-anticharge pairs* at time t



Resolved

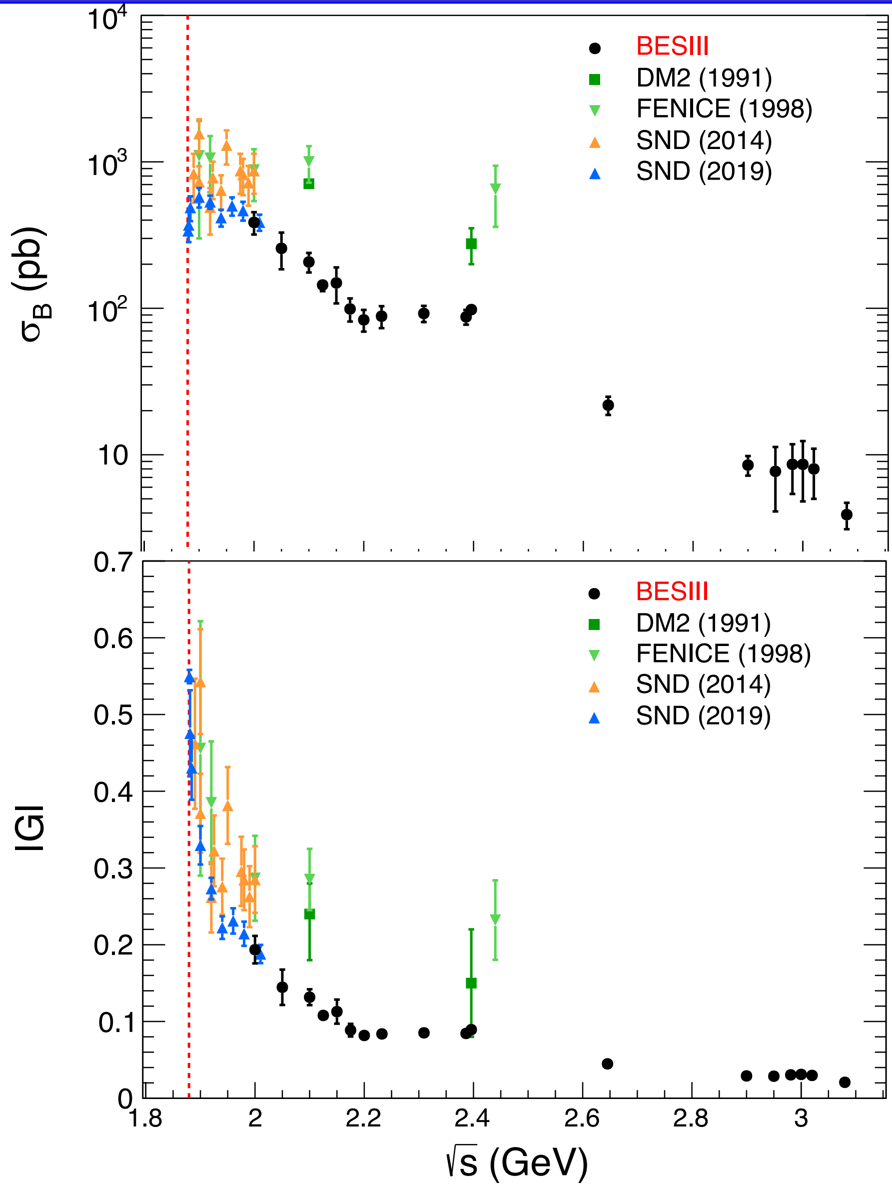


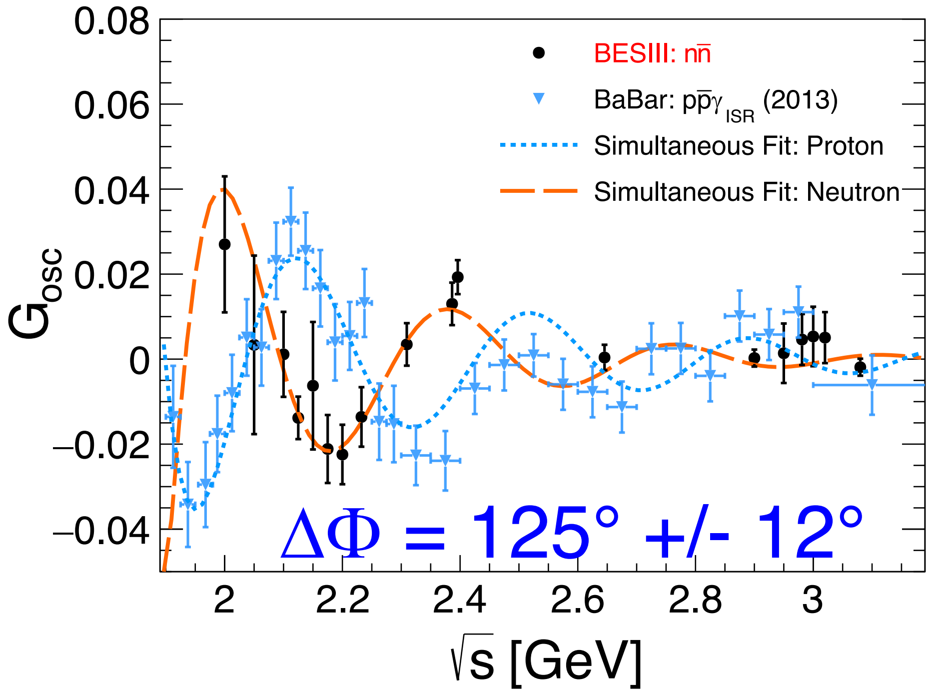
Unresolved *representation*

Charge distribution: distribution in time of
$\gamma^* \longrightarrow$ *charge-anticharge vertices*

The simplest picture: qq pair + compact di-quark

Cross section from $e^+e^- \to n\bar{n}$





ArXiv:2103.12486 [hep-ex]

Conclusions

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

• Theory: unified models in SL and TL regions:

- *describe all 4 FFs:*

  proton and neutron, electric and magnetic

• Experiment: to measure

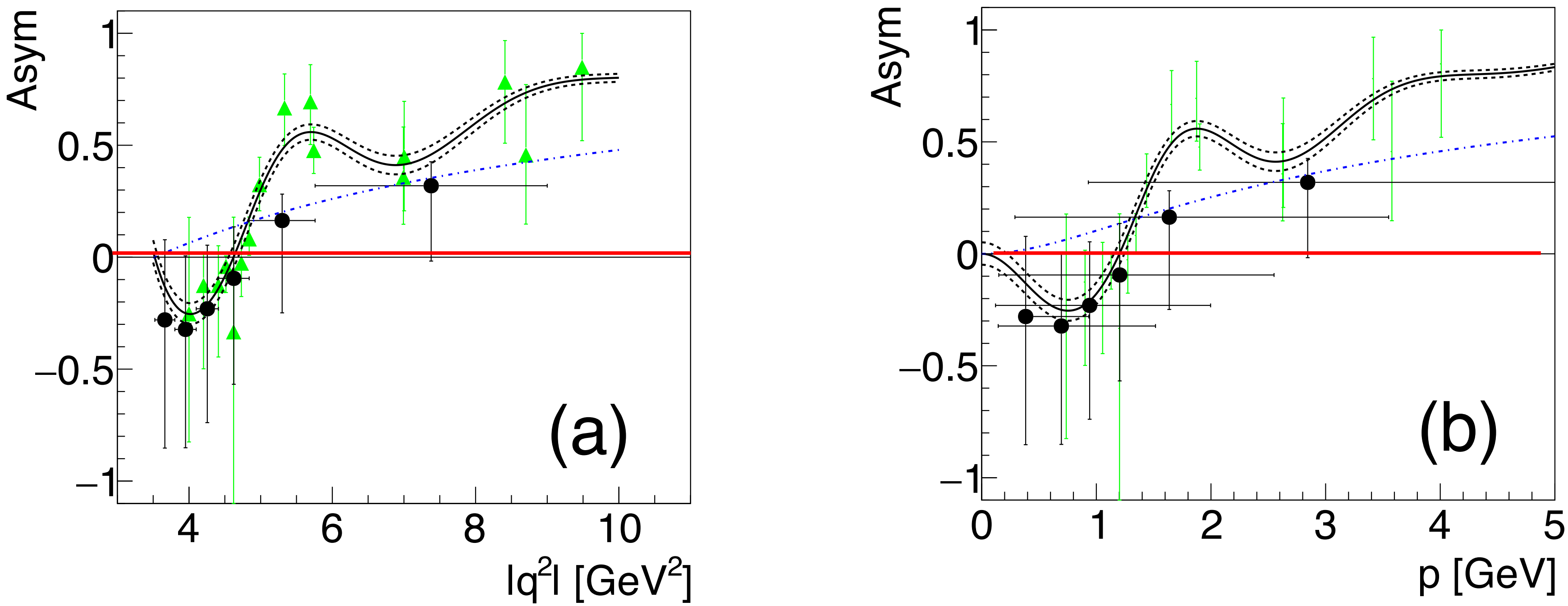
- zero crossing of GE/GM in SL? Proton radius?
- complex FFs in TL region: polarization!
- new structures in TL: access to hadron formation?

Space and Time structure of the nucleon

…. the 4^{th} dimension of the nucleon

Thank you for the attention!

Angular Asymmetry



$$\frac{d\sigma_{e^+e^-\to\bar{p}p}}{d\Omega}(s,\theta)=\sigma_0(s)\left[1+\mathcal{A}(s)\cos^2(\theta)\right]$$

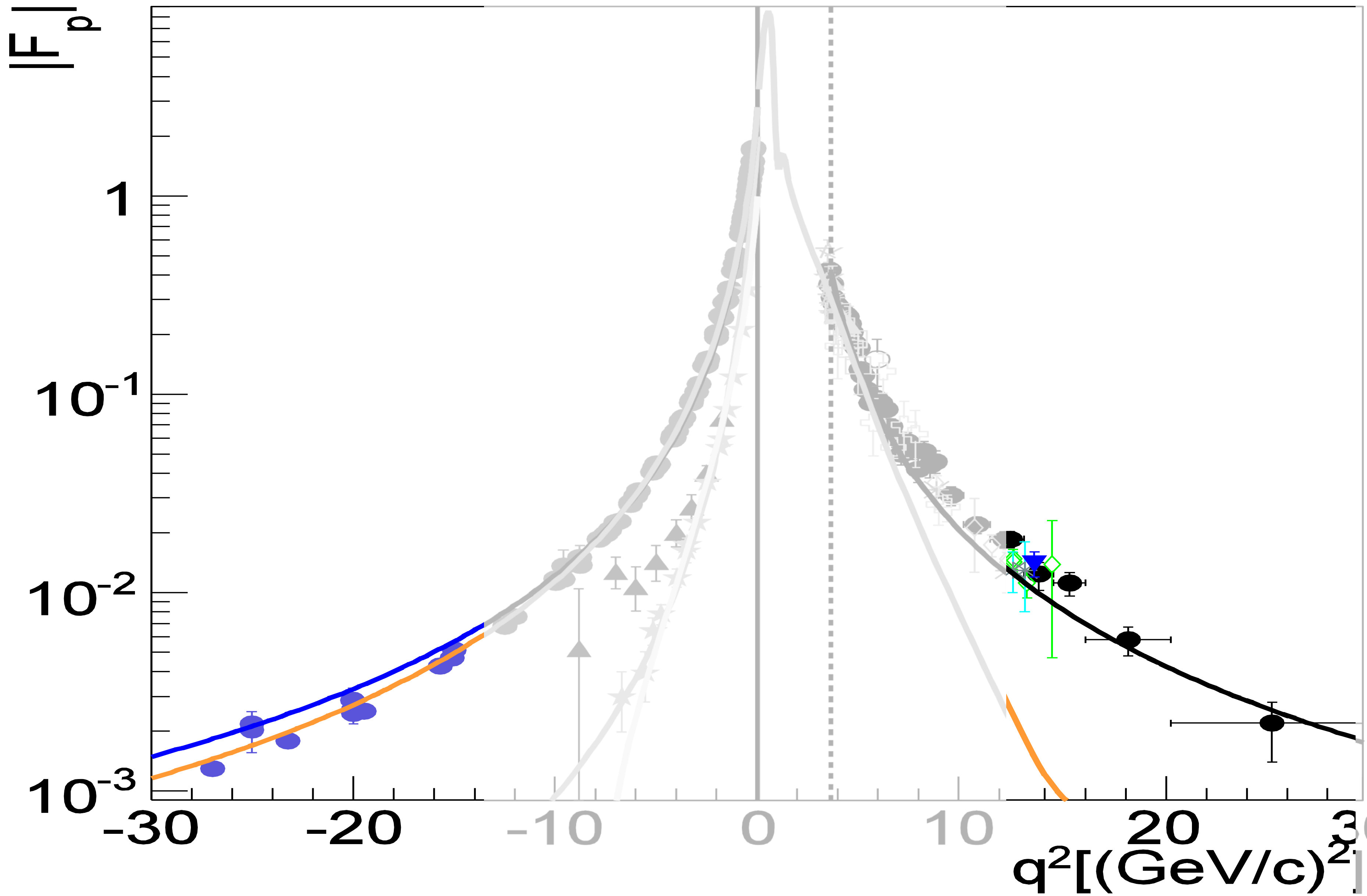
$$\sigma_0(s)=\frac{\alpha^2\beta\mathcal{C}(\beta)}{4s}\left(|G_M(s)|^2+\frac{1}{\tau}|G_E(s)|^2\right)$$

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

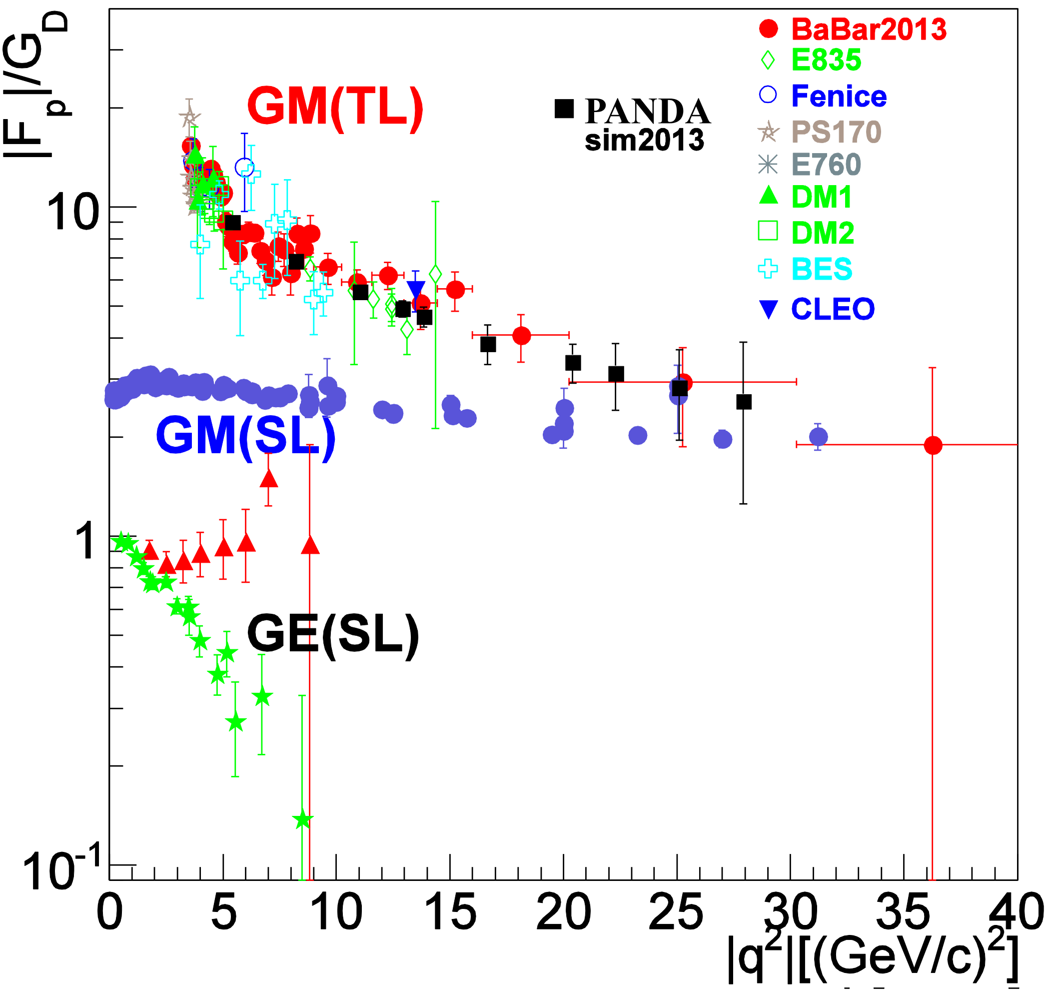
$q^2 = (4.60 \pm 0.07)$ GeV^2
$p = (1.20 \pm 0.04)$ GeV

Zero of the angular asymmetry

The asymptotic region



Large q^2 : where the extremes meat



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

Phragmèn-Lindelöf theorem

$$\lim_{q^2\to-\infty} F^{(SL)}(q^2) = \lim_{q^2\to\infty} F^{(TL)}(q^2)$$

space – like $(e^- + p \to e^- + p)$ — *time – like* $(e^+ + e^- \leftrightarrow \bar{p} + p)$

$- F^{(TL)}(q^2) \to real$, if $q^2 \to \infty$

Applies to NN and $N\bar{N}$ Interaction
(Pomeranchuk theorem)
t=0 : not a QCD regime!

Analyticity: connection with QCD asymptotics?

The nucleon

Inner region: gluonic condensate of clusters with randomly oriented chromo-magnetic field (Vainshtein, 1982):

Intensity of the gluon field in vacuum:

$$< 0|\alpha_s/\pi(G^a_{\mu\nu})^2|0 >\sim E^2 - B^2 \sim E^2 = 0.012 \text{ GeV}^4.$$

$$G^2 \simeq 0.012\, \pi/\alpha_s GeV^4, \text{ i.e., } E \simeq 0.245\, GeV^2. \quad \alpha_s/\pi \sim 0.1$$

In the internal region of strong chromo-magnetic field, the color quantum number of quarks does not play any role, due to stochastic averaging

$< G\|u^i u^j\|G >\sim \delta_{ij}$	proton
$d^i d^j$	neutron

Colorless quarks: Pauli principle

Model

Antisymmetric state of colored quarks

Colorless quarks: Pauli principle

1) uu (dd) quarks are repulsed from the inner region
2) The 3rd quark is attracted by one of the identical quarks, forming a compact di-quark
3) The color state is restored

Formation of di-quark: competition between attraction force and stochastic force of the gluon field

$$\frac{Q_q^2 e^2}{r_0^2} > e|Q_q|\,E.$$

proton: (u) Qq=-1/3

neutron: (d) Qq=2/3

attraction force >stochastic force of the gluon field

Model

$$\frac{Q_q^2 e^2}{r_0^2} > e|Q_q|\,E.$$

attraction force > stochastic force of the gluon field

$$p_0 = \sqrt{\frac{E}{e|Q_q|}} = 1.1\ \text{GeV}.$$

Proton: r_0=0.22 fm, p_0^2 = 1.21 GeV^2

Neutron: r_0=0.31 fm, p_0^2 = 2.43 GeV^2

Applies to the scalar part of the potential

Model

Quark counting rules apply
to the vector part of the potential

$$G_M^{(p,n)}(Q^2) = \mu G_E(Q^2);$$
$$G_E^{(p,n)}(Q^2) = G_D(Q^2) = \left[1 + Q^2/(0.71\ \mathrm{GeV}^2)\right]^{-2}$$

$$G_E^{(p,n)}(0) = 1, 0, G_M^{(p,n)}(0) = \mu_{p,n}$$

Model

Additional suppression for the scalar part due to colorless internal region: "charge screening in a plasma":

$$\Delta\phi = -4\pi e \sum Z_i n_i,\ n_i = n_{i0} exp\left[-\frac{Z_i e\phi}{kT}\right]$$

Boltzmann constant

Neutrality condition: $\sum Z_i n_{i0} = 0$

$$\Delta\phi - \chi^2\phi = 0,\ \phi = \frac{e^{-\chi r}}{r},\ \chi^2 = \frac{4\pi e^2 Z_i^2 n_{i0}}{kT}$$

Additional suppression (Fourier transform)

$$G_E(Q^2) = \frac{G_M(Q^2)}{\mu}\left(1 + Q^2/q_1^2\right)^{-1}$$

$q_1(\equiv \chi)$

fitting parameter

Fourier Transform

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

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 $x \le R$ 0 for $r \ge R$	$\frac{3(\sin X - X\cos X)}{X^3}$ $X = qR$	$\frac{3}{5}R^2$	square well

Root mean square radius

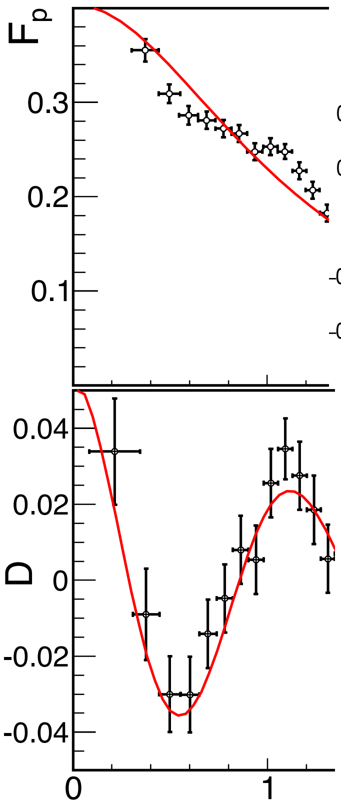
$$F(q) \sim 1 - \frac{1}{6} q^2 < r_c^2 > + O(q^2),$$

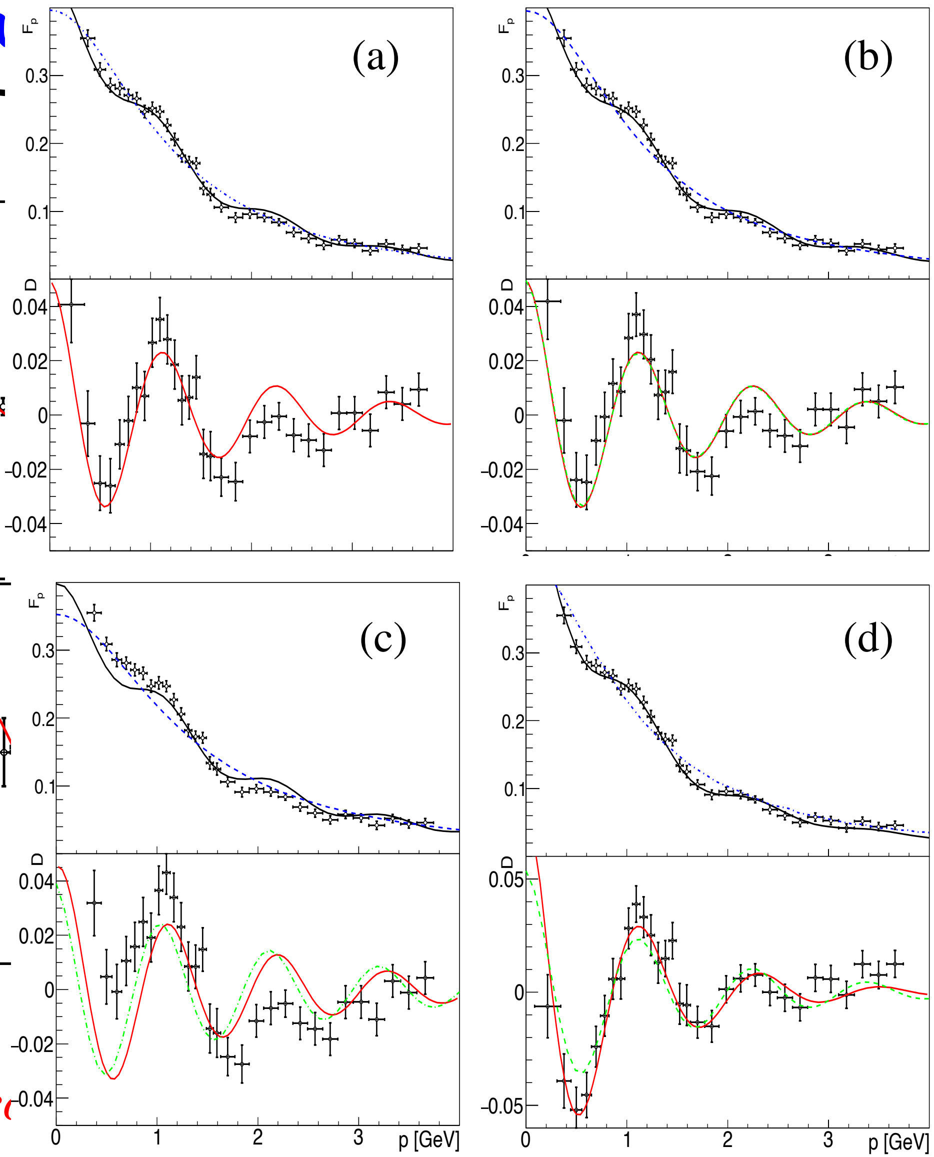
$$< r_c^2 > = \frac{\int_0^\infty x^4 \rho(x) dx}{\int_0^\infty x^2 \rho(x) dx}.$$

Oscillations : regular pattern in P_{Lab}

The releva … the relative

motion of ·





$$\text{xp}(-Bp)\ \cos(Cp\ +\ D).$$

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

on B: damping
D=0: maximum at p=0

ory behaviour
of coherent sources

A. Bianc… 5)

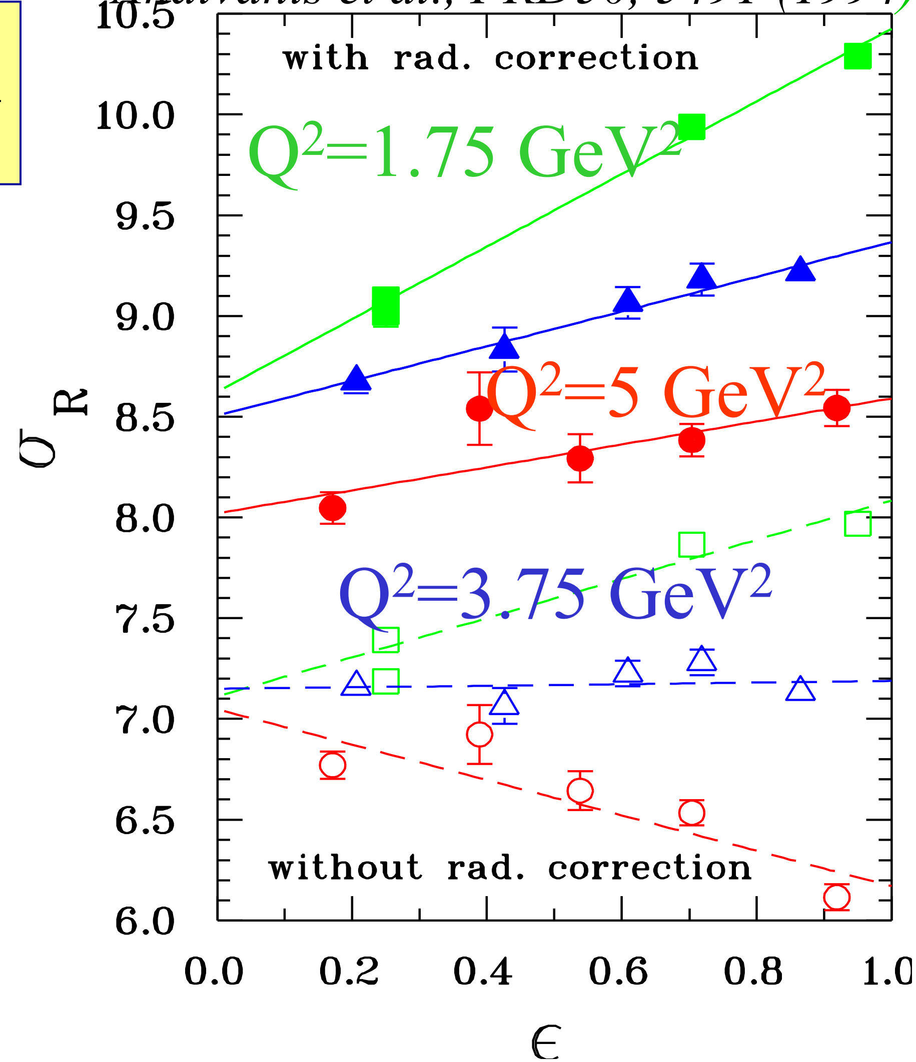
Radiative Corrections (ep)

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

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

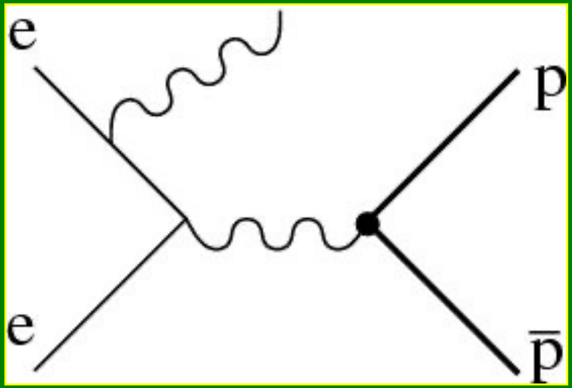
RC to the cross section:
- *large (may reach 40%)*
- *ε and Q^2 dependent*
- *calculated at first order*

Andivahis et al., PRD50, 5491 (1994)



E. T.-G., G. Gakh, PRC72, 015209 (2005), C.F Perdrisat et al, Progr.Part.Nucl.Phys.(20

Radiative return (ISR)



BABAR

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

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

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

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

Nucleon Form Factor Experiments

Hall	Exp#	Title	E_e	Q^2_{max}
A	E12-07-108	Precision Measurement of the **Proton Elastic Cross Section** at High Q^2	6.6 8.8 11	17,5 (14)
A	E12-07-109	Large Acceptance **Proton Form Factor Ratio Measurements** at 13 and 15 $(GeV/c)^2$ using **Recoil Polarization Method**	6.6 8.8 11	12(14)
A	E12-09-019	Precision Measurement of the **Neutron Magnetic Form Factor** up to $Q^2 = 18.0$ $(GeV/c)^2$ by the Ratio Method	4.4 6.6 8.8 11	13.5 (18)
A	E12-09-016	Measurement of the **Neutron Electromagnetic Form Factor Ratio** G^n_E / G^n_M at High Q^2	4.4 6.6 8.8	10.2
B	E12-07-104	Measurement of the **Neutron Magnetic Form Factor** at High Q^2 Using the Ratio Method on Deuterium	11	14
C	E12-11-009	The **Neutron Electric Form Factor** at Q^2 up to 7 $(GeV/c)^2$ from the Reaction 2H(e,e'n)1H via Recoil Polarimetry	4.4 6.6 11	7