Diquarks in nucleons from a unified analysis of space and time-like Electromagnetic Form Factors

Egle Tomasi-Gustafsson

CEA, IRFU, DPhN and
Université Paris-Saclay, France

Diquark Correlations in Hadron Physics:
Origin, Impact and Evidence
ECT, September 23-27, 2019*

Plan

- Introduction
- Unified picture of space and time-like form factors
  - The space-like region
  - The time-like region:
    - Regular oscillations observed
    - Understanding the fourth dimension of the nucleon
- *Diquark configuration* in a picture of annihilation and scattering
- New data from BES
- Open questions and Conclusions

Introduction

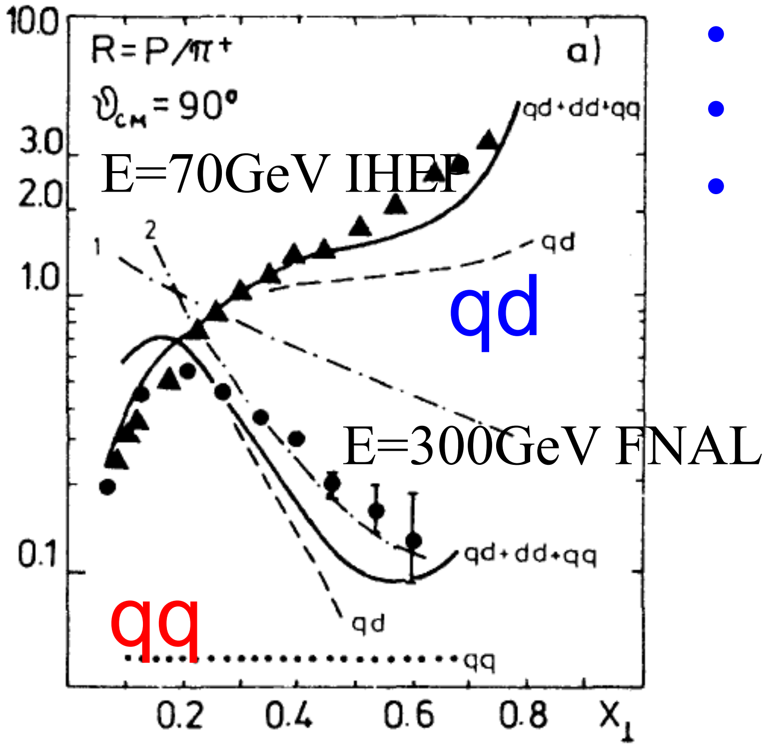
Modern Physics Letters A, Vol. 3, No. 9 (1988) 909–916

DIQUARKS AND DYNAMICS OF LARGE-$P_\perp$ BARYON PRODUCTION

V. T. KIM

Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 101000 Moscow

R=p/π^+ at 90°cms in pp scattering



- Scaling violation in hard pp scattering
- Hard constituent scattering model
- Di-quark scattering and fragmentation

qd+dd+qq	———
qd	- - - - -
qq	- - - - -

$$x_\perp = 2p_\perp/\sqrt{s}$$

q-d scattering at large x and at IHEP energies

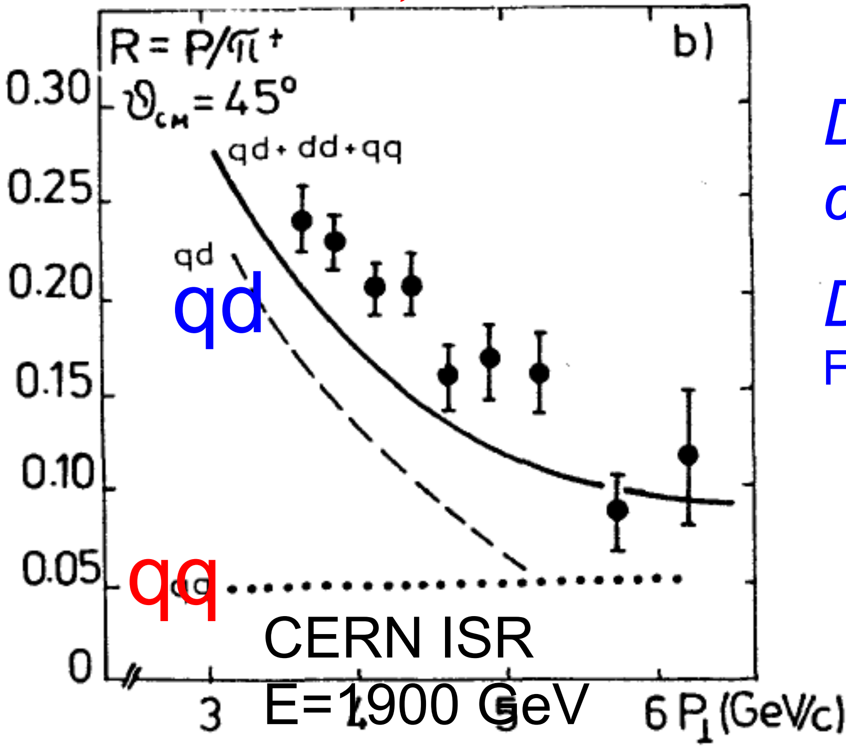
Modern Physics Letters A, Vol. 3, No. 9 (1988) 909–916

$A+B \rightarrow C+X$

$$\frac{E d\sigma}{d^3p} = \int_{x_{\min}}^{1} dx \int_{y_{\min}}^{1} dy\, G_a^A(x)\, G_b^B(y) \left(\frac{d\sigma}{d\hat{t}}\right)_{ab} \frac{D_C^c(z)}{\pi z},$$

G: distribution function of the constituent a,b in the hadron A or B

Diquark : $G_d^N \sim x(1-x)$
Quark : $G_q^N \sim (1-x)^3$



D: fragmentation function of the constituent c in the hadron C

$D_p^d(z)=0.4[1-\alpha+3\alpha(1-z)^2]$, $\alpha=0.57$
Field-Feynman FF

$\left(\frac{d\sigma}{d\hat{t}}\right)_{ab}$ *: cross section of the elastic scattering subprocess*

SCALING RULES

$$\left(\frac{d\sigma}{d\hat{t}}\right)_{qd} = \left(\frac{d\sigma}{d\hat{t}}\right)_{qq} \cdot f^2(Q^2),$$

$$\left(\frac{d\sigma}{d\hat{t}}\right)_{dd} = \left(\frac{d\sigma}{d\hat{t}}\right)_{qq} \cdot f^4(Q^2),$$

$$\left(\frac{d\sigma}{d\hat{t}}\right)_{qq} = -2300/\hat{s}\hat{t}^3 mbn\, \mathrm{GeV}^6.$$

$$Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2);$$

$$f(Q^2) = \frac{1}{1 + \frac{Q^2}{M^2}},$$

Diquark form factor:

- *M^2=12 GeV : diquark mass*
- *W=0.7: probability (q,d) in p*

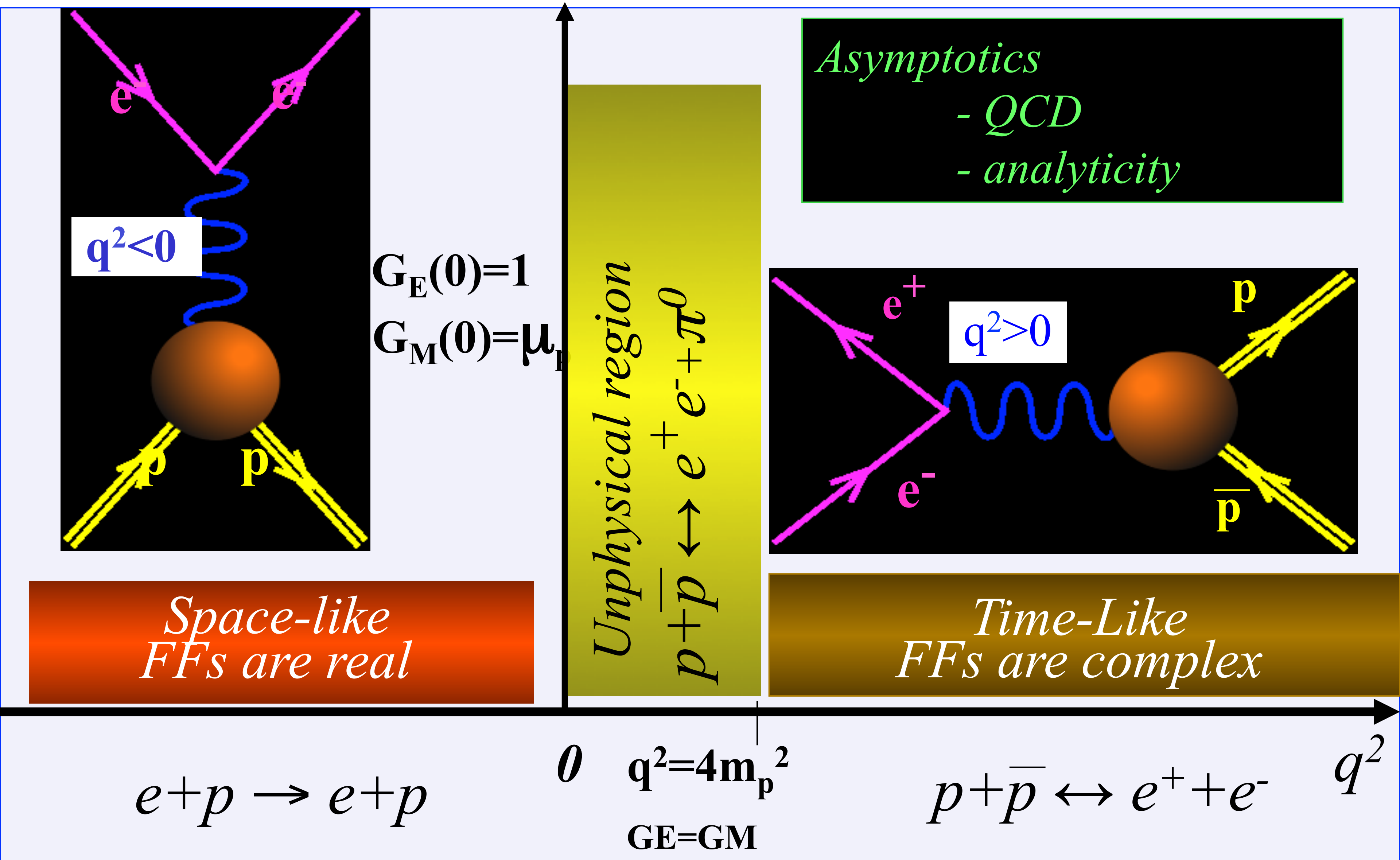
Diquark distribution function: $G_d^N \sim x(1-x)$

Quark: : $G_q^N \sim (1-x)^3$

Evidences…

- *M^2~12 GeV , size~0.2 fm :* a diquark is not a vector or scalar meson (ex.: quasi-deuteron, short range correlations in nuclei...)
- The quark dynamics is much more complex in non-perturbative regime: when scaling applies?
- *Hadron form factors : scattering & Creation and annihilation of p-pbar pairs:*

Proton Charge and Magnetic Distributions

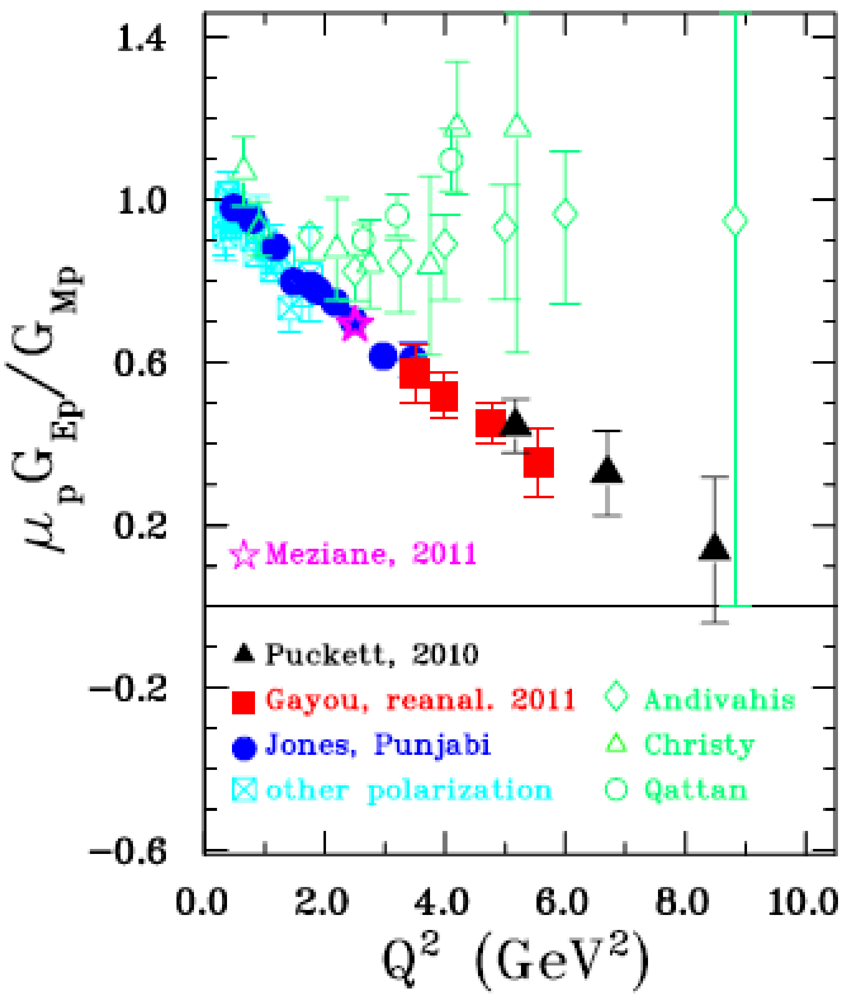


Polarization experiments @ Jlab

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

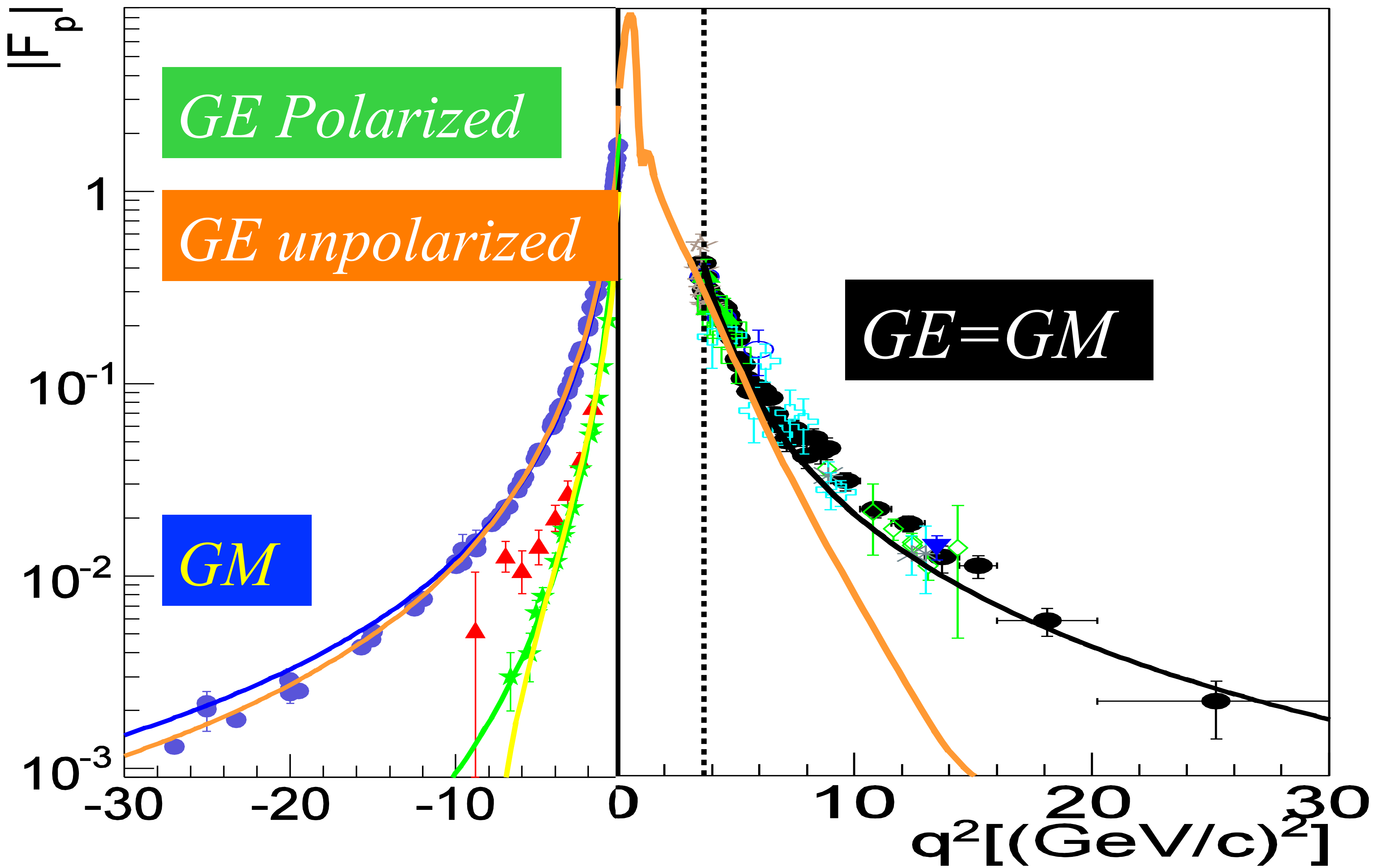
GEp collaboration

1) "standard" dipole function for the nucleon magnetic FFs GMp and GMn
2) linear deviation from the dipole function for the electric proton FF Gep
3) QCD scaling not reached
3) Zero crossing of Gep?
4) ***contradiction between polarized and unpolarized measurements***

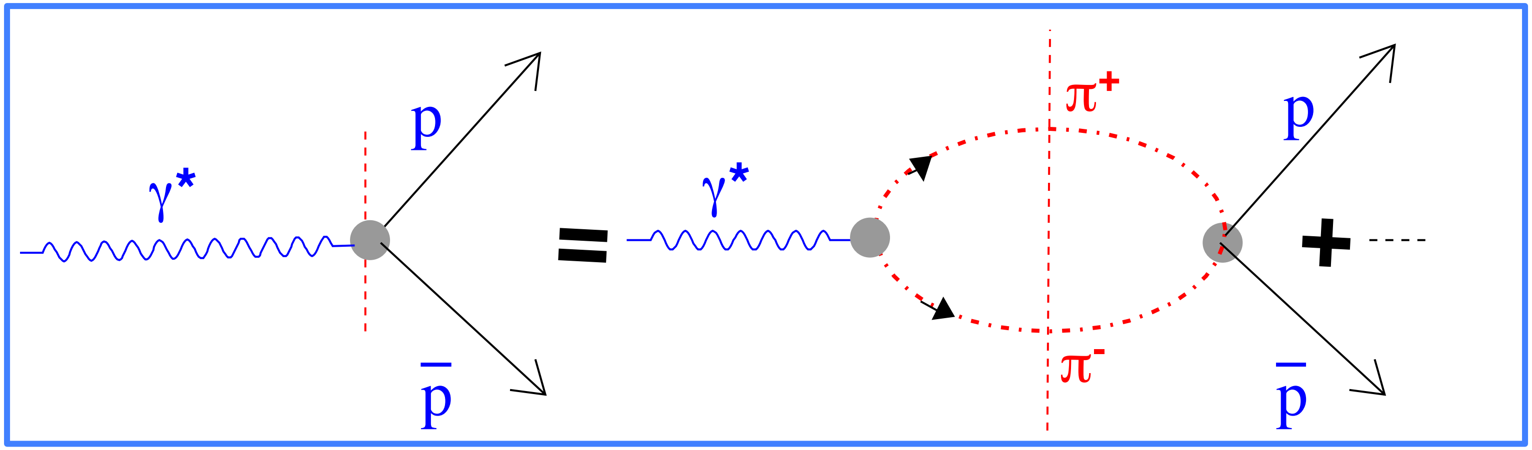


A.J.R. Puckett et al, PRL (2010), PRC (2012), PRC (2016)

Proton Electromagnetic Form Factors



Unitarity



ep elastic scattering:

The Rosenbluth Formula(1950)

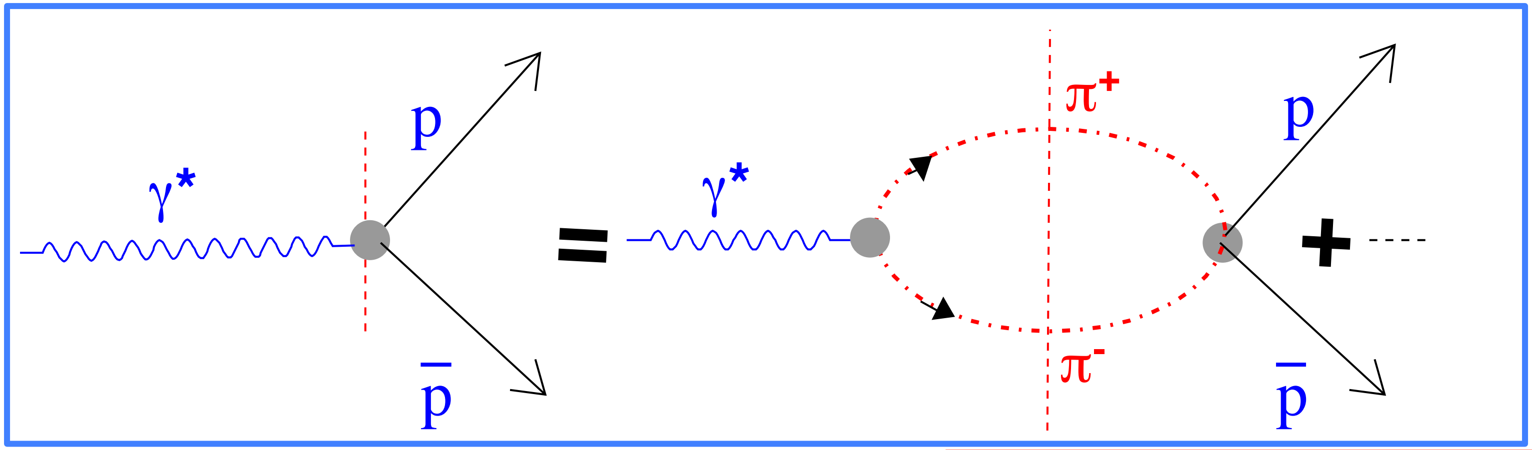
$$\frac{d\sigma}{d\Omega}=\left(\frac{d\sigma}{d\Omega}\right)_{Mott}\frac{1}{(1+\tau)}\left(G_E^2(Q^2)+\frac{\tau}{\varepsilon}G_M^2(Q^2)\right)$$

Annihilation (cms)

A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Il Nuovo Cimento XXIV, 170 (1962)

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

Unitarity



ep elastic scattering:
The Rosenbluth Formula (1950)

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

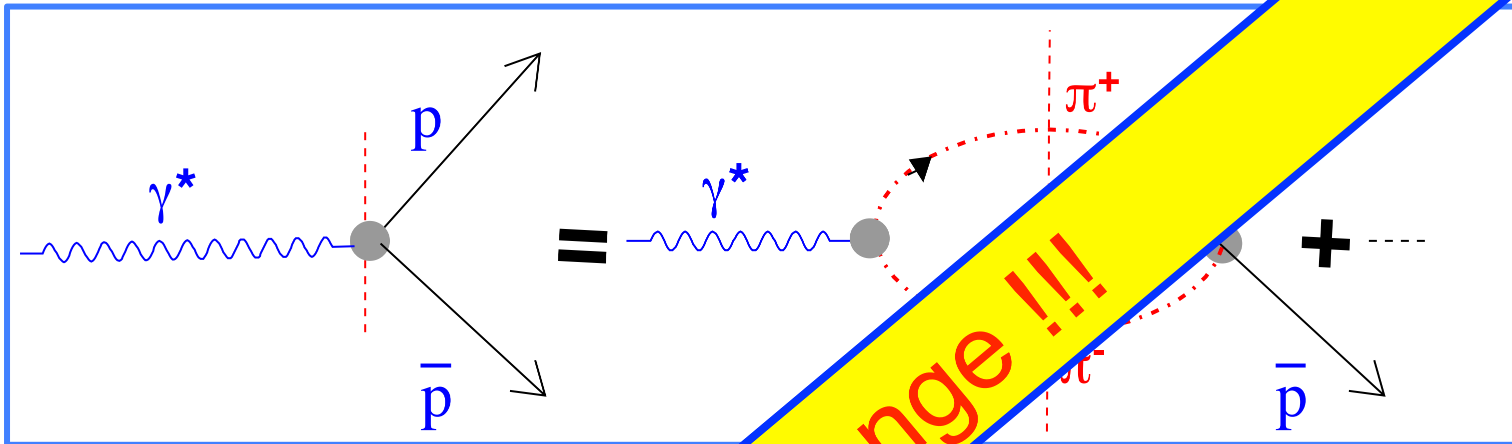
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{(1+\tau)}\left(G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right)$$

Annihilation (cms)

A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Il Nuovo Cimento XXIV, 170 (1962)

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

Unitarity



One-photon exchange !!!

ep elastic scattering:
The Rosenbluth Forn ... 950)

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

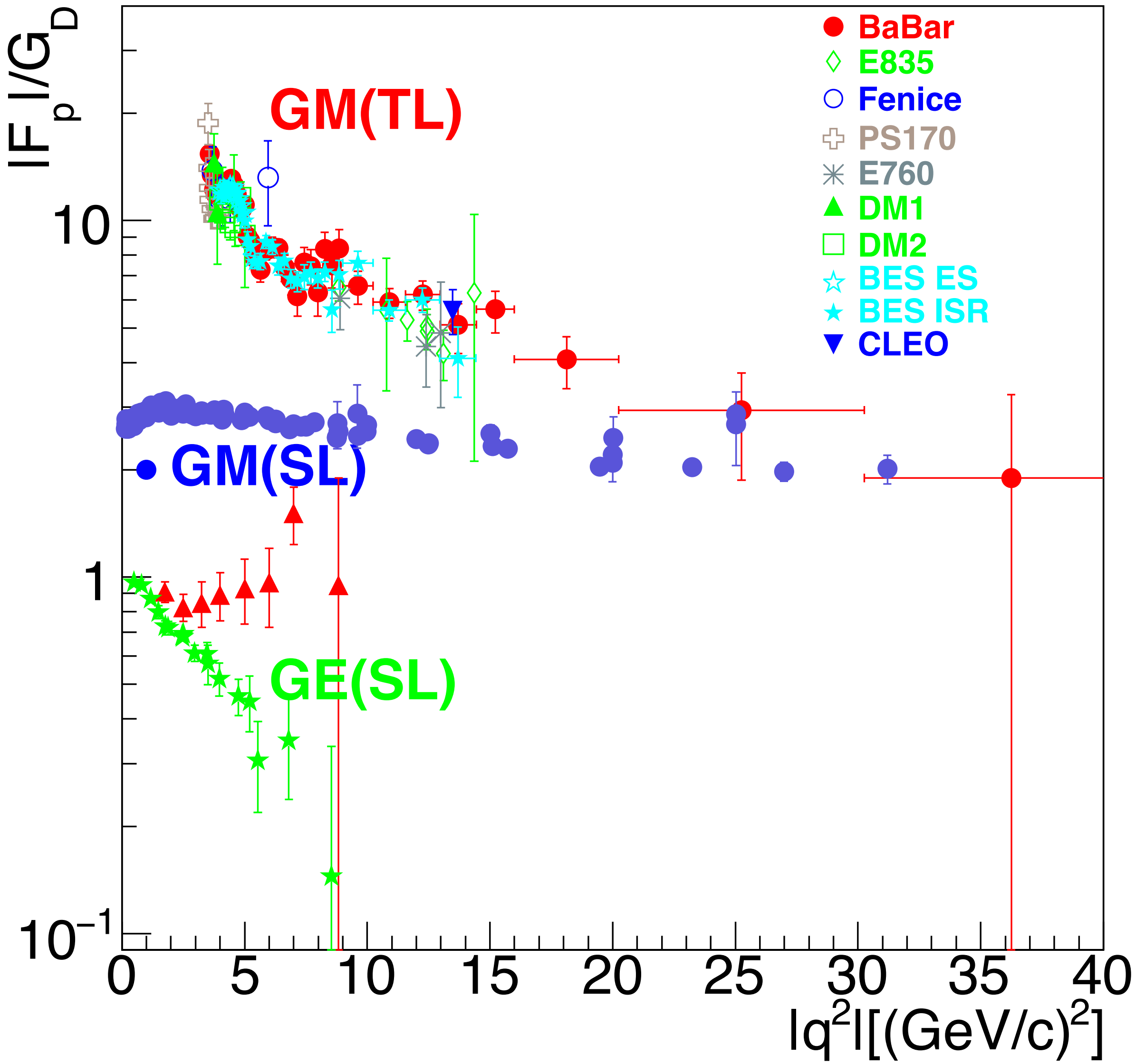
$$\varepsilon=\left(1+2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right)^{-1},\tau=\frac{Q^2}{4M^2}$$

Annihil ... (cms)

A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Il Nuovo Cimento XXIV, 170 (1962)

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

Asymptotics & Analyticity



Phragmèn-Lindelof Theorem for analytical functions

Connection with QCD asymptotics?

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

Form Factors and Frames

- In the Breit frame the expression of the Space-like EM current is simplified $E_{1B} = E_{2B} = E$

$$\begin{cases} \mathcal{J}_0 & = \overline{u}(p_2)\left[(F_1+F_2)\,\gamma_0 - \dfrac{(E_{1B}+E_{2B})}{2m}F_2\right]u(p_1), \\ \vec{\mathcal{J}} & = \overline{u}(p_2)\left[(F_1+F_2)\,\vec{\gamma} - \dfrac{(\mathbf{p_{1B}}+\mathbf{p_{2B}})}{2m}F_2\right]u(p_1) \\ & = (F_1+F_2)\,\overline{u}(p_2)\vec{\gamma}u(p_1). \end{cases}$$

$$\begin{aligned} \mathcal{J}_0 &= 2m\chi_2^\dagger\chi_1\,(F_1-\tau F_2) \\ \vec{\mathcal{J}} &= i\chi_2^\dagger\vec{\sigma}\times\mathbf{q_B}\chi_1\,(F_1+F_2) \end{aligned}$$

Identify the time component $\mathcal{J}_0$ with $G_E = F_1 - \tau F_2$

Identify the space component $\vec{\mathcal{J}}$ with $G_M = F_1 + F_2$

Fully relativistic derivation: Lecture Notes, M.P Rekalo, ETG ArXiv nucl-th/022025
A.I. Akhiezer, M. P Rekalo Sov.J.Part.Nucl. 4 (1974) 277

Form Factors and Frames

- In the Breit frame the expression of the Space-lik… …urrent is simplified $E_{1B} = E_{2B} = E$

$$\begin{cases} \mathcal{J}_0 = \overline{u}(p_2)\left[(F_1+F_2)\gamma_0 - \frac{(E_{1B}+E\ldots}{\ldots}\right. \\ \vec{\mathcal{J}} = \overline{u}(p_2)\left[(F_1+F_2)\vec{\gamma}\ldots\right. \\ \quad = (F_1+F_2)\,\overline{u}(\ldots \end{cases}$$

$\mathcal{J}_0$ … (F_1+F_2)

Sachs Form Factors: interpretation valid ONLY in BREIT Frame

Id… …ment $\mathcal{J}_0$ with $G_E = F_1 - \tau F_2$

Iden… …component $\vec{\mathcal{J}}$ with $G_M = F_1 + F_2$

The time-like region

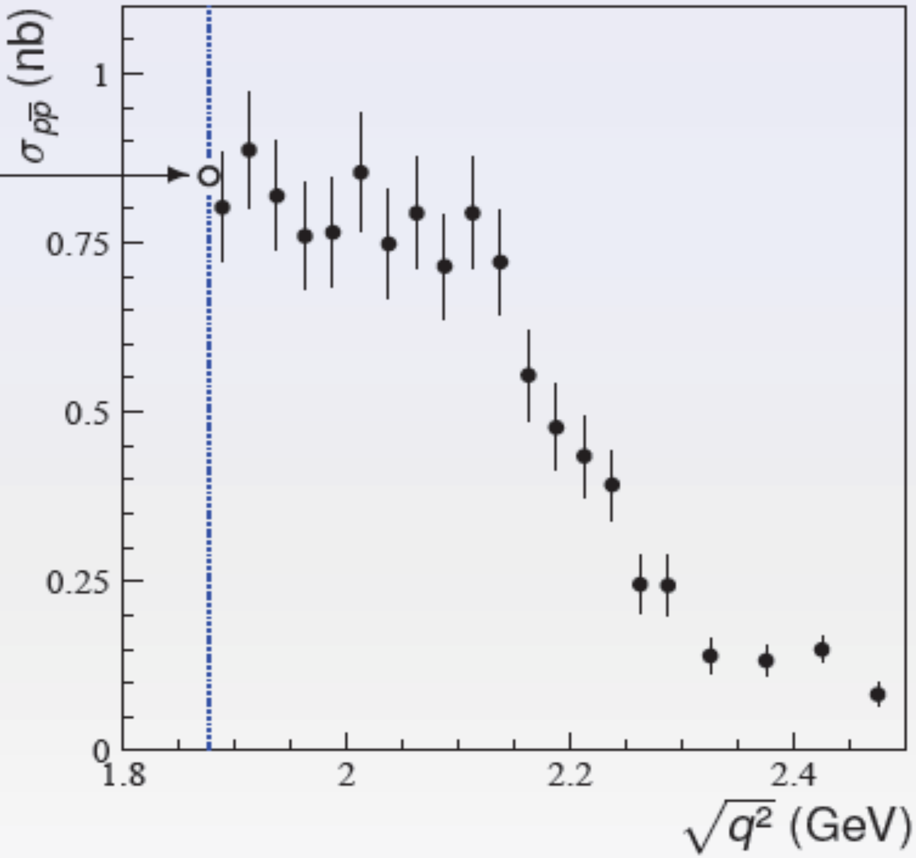
Point-like form factors?

BABAR: $e^+e^- \to p\bar{p}$

EPJA39, 315

S. Pacetti

Expected cross section with $|G_S^p(4M_p^2)| = 1$



At the threshold

$$\sigma_{p\bar{p}}(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\frac{\beta_p}{\beta_p}|G_S^p(4M_p^2)|^2$$

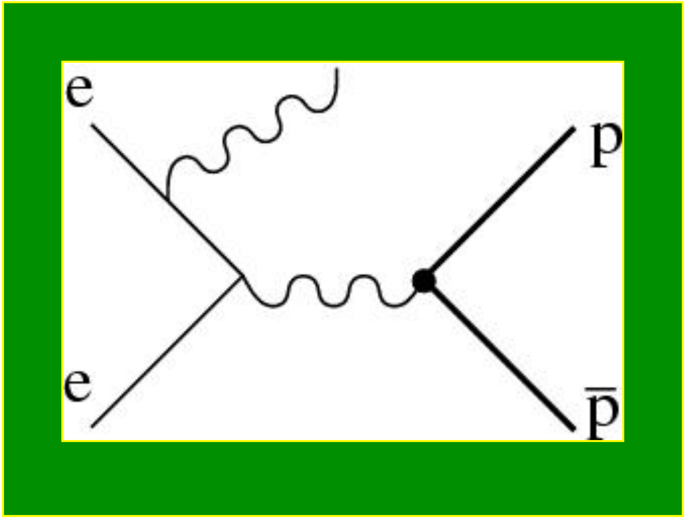
$$\sigma_{p\bar{p}}(4M_p^2) = 0.85\,|G_S^p(4M_p^2)|^2 \text{ nb}$$

$\Longrightarrow$

$|G_S^p(4M_p^2)| \equiv 1$

as pointlike fermion pairs!

Radiative return (ISR)



BABAR

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

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

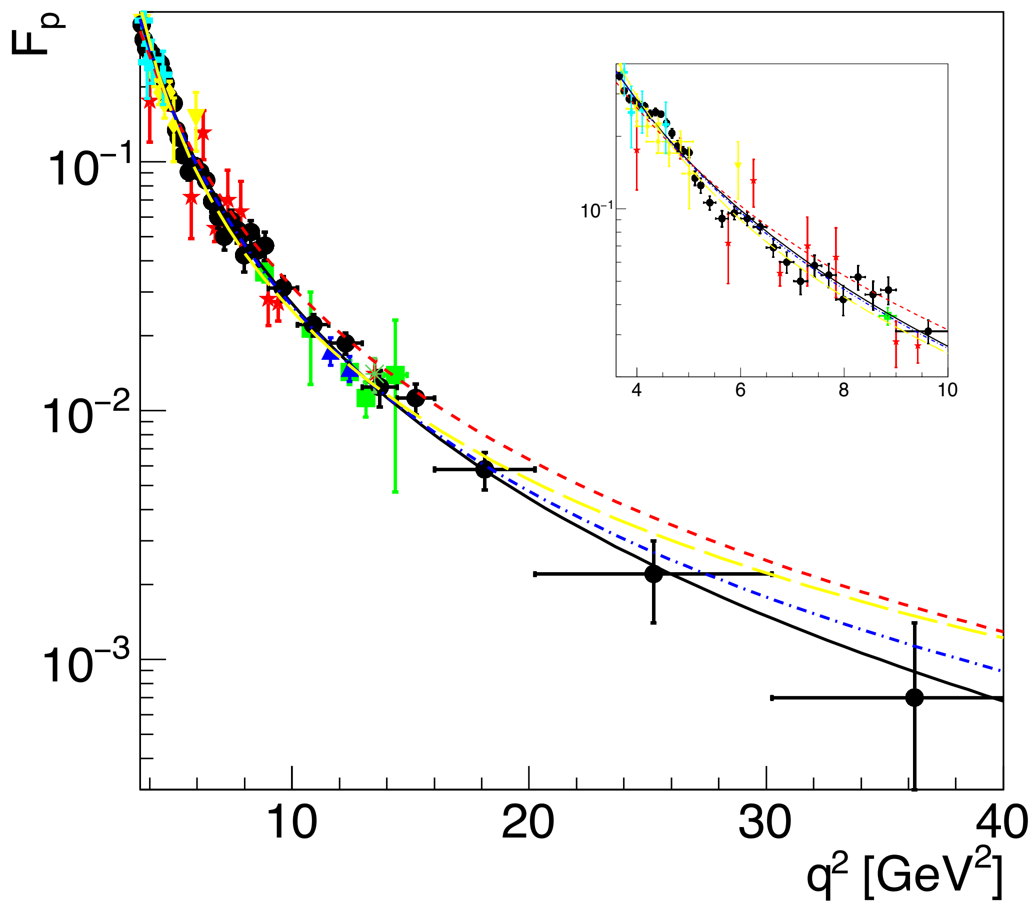
$$W(s,x,\theta) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta} - \frac{x^2}{2}\right), \quad \theta \gg \frac{m_e}{\sqrt{s}}.$$

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

The Time-like Region

GE=GM 'effective FF'

- The Experimental Status
  - No 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?



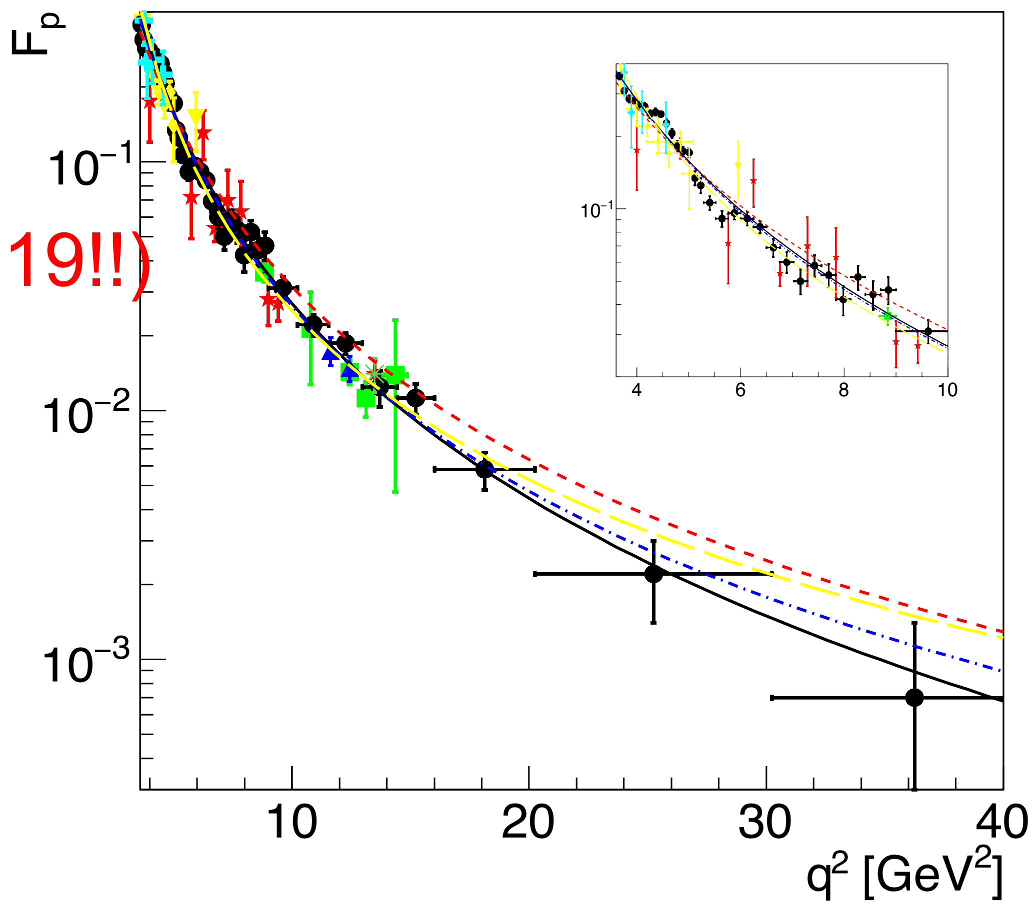
S. Pacetti, R. Baldini-Ferroli, E.T-G , Physics Reports, 514 (2014) 1

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

The Time-like Region

GE=GM 'effective FF'

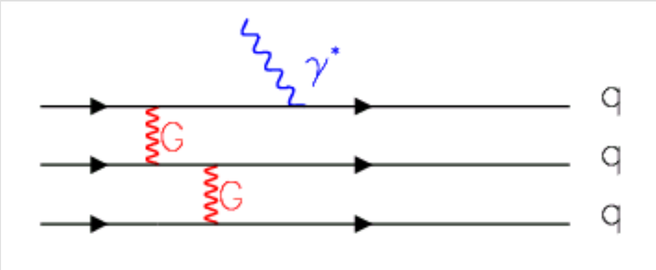
- The Experimental Status
  - ~~No determination of GE and GM~~ (since Mai 2019!!)
  - TL proton FFs twice larger than in SL at the same Q^2
  - Steep behaviour at threshold
  - Babar:Structures?
    Resonances?



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

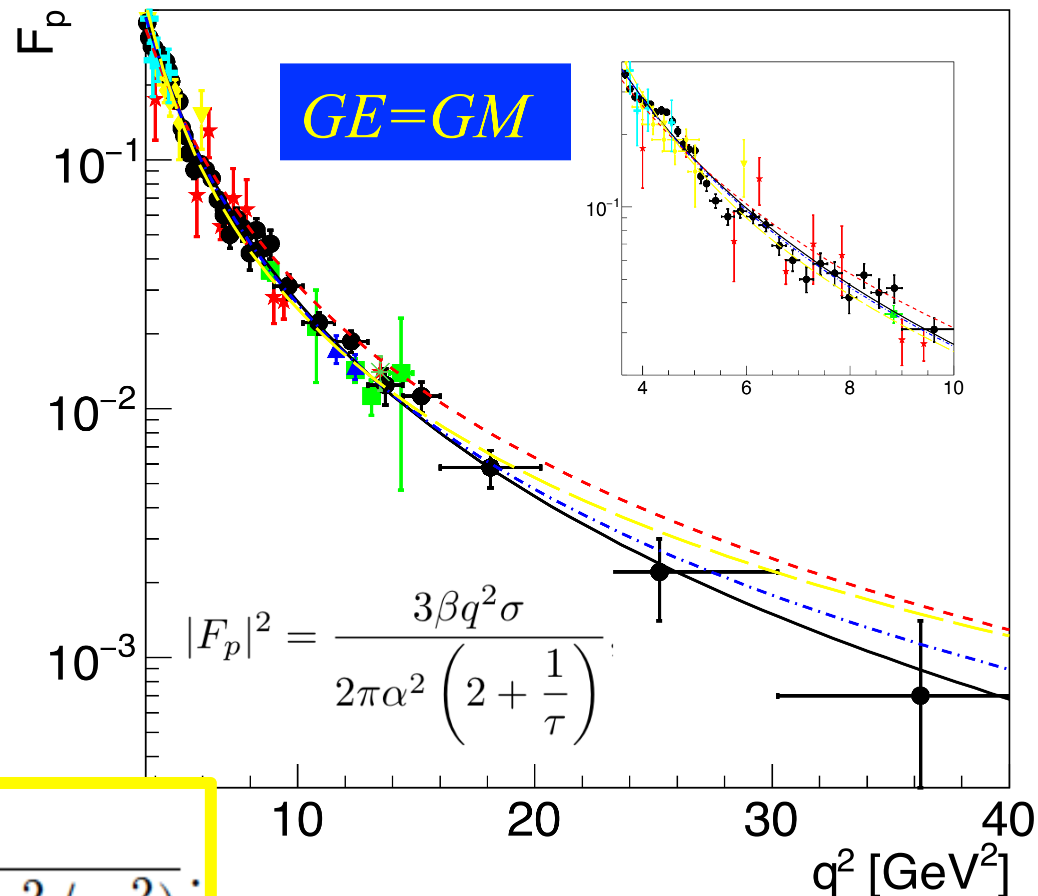


Expected QCD scaling $(q^2)^2$

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

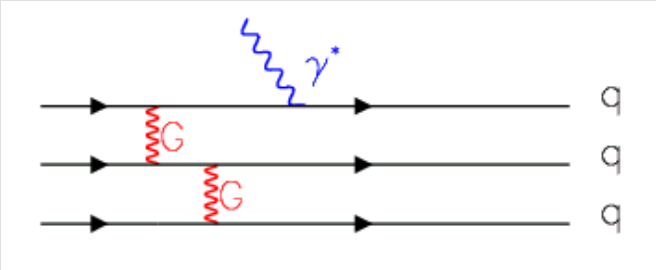
$$|F_{scaling}(q^2)| = \frac{\mathcal{A}}{(q^2)^2 \log^2(q^2/\Lambda^2)}$$

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



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

The Time-like Region



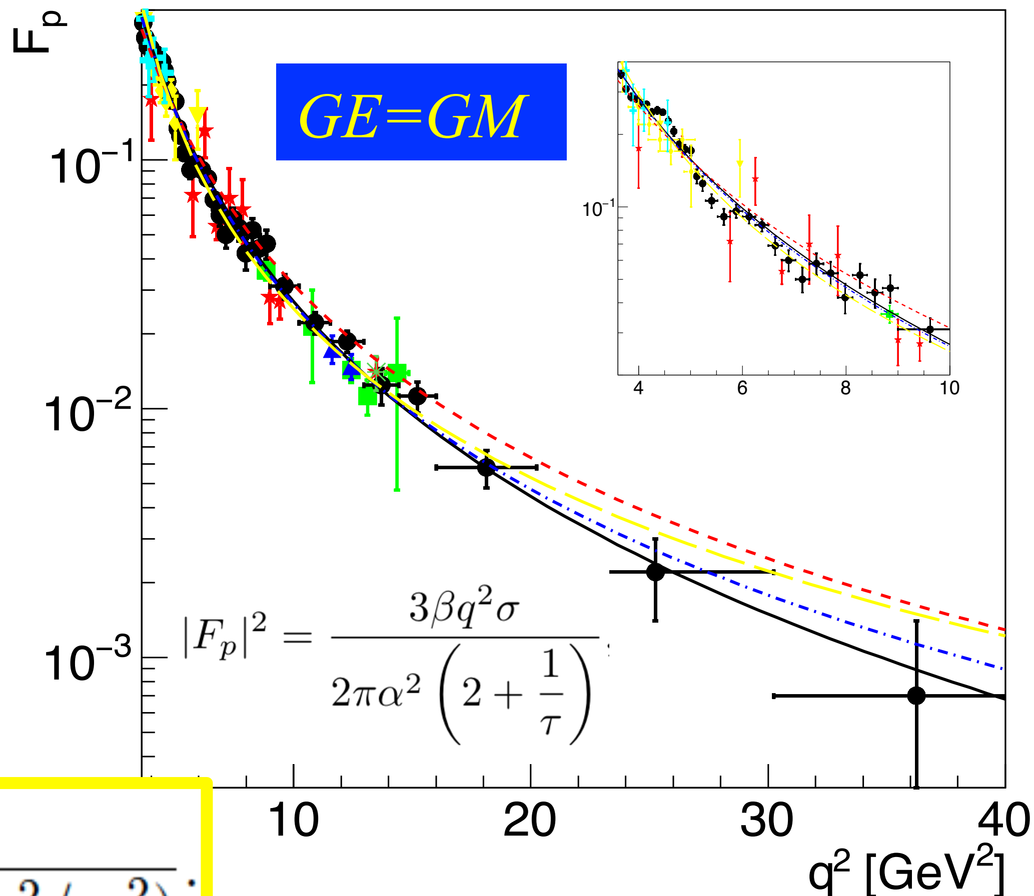
Expected QCD scaling $(q^2)^2$

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

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

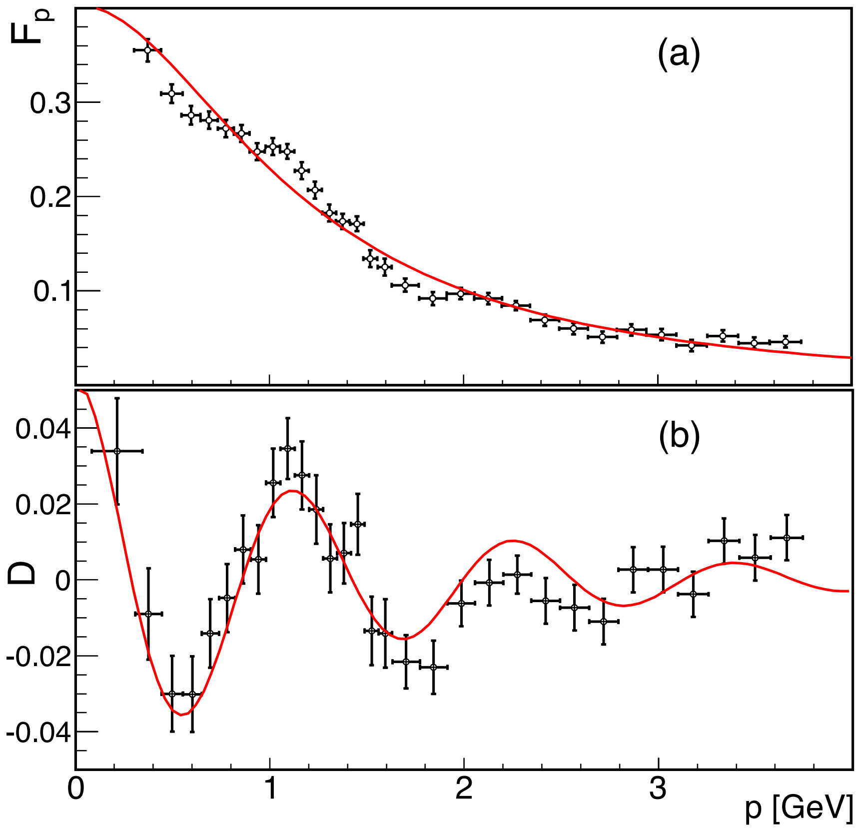
$$|F_{T3}(q^2)| = \frac{\mathcal{A}}{(1-q^2/m_1^2)(2-q^2/m_2^2)}.$$

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



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)

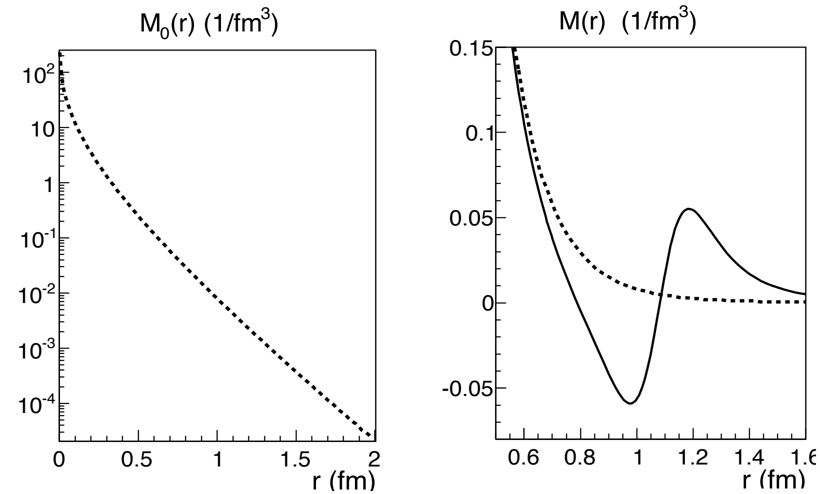
Fourier Transform

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

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

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

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



- *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 from BESIII, expected from PANDA*

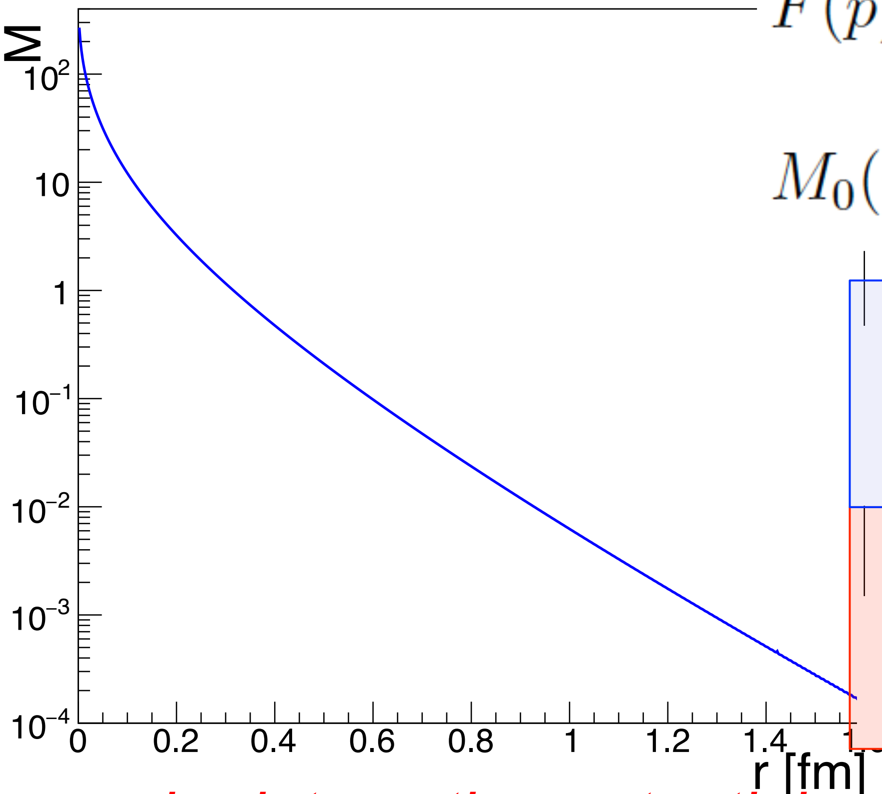
Optical Model Analysis

Fourier Transform

A. Bianconi, E. T-G., PRC 93, 035201 (2016)

$$F(p) = \frac{1}{(2\pi)^3} \int d^3\vec{r}\; e^{i\vec{p}\cdot\vec{r}} D(\vec{r}) M_0(r),$$

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



Rescattering - Distorted wave IA:

$$\psi_f(\vec{r}) = D(\vec{r}) \exp(i\vec{p}\cdot\vec{r}) \;\; (DWIA)$$

Glauber distortion factor:

$$D(x,y,z) = \exp\left(-ib \int_z^{\infty} \rho(x,y,z')dz' \right)$$

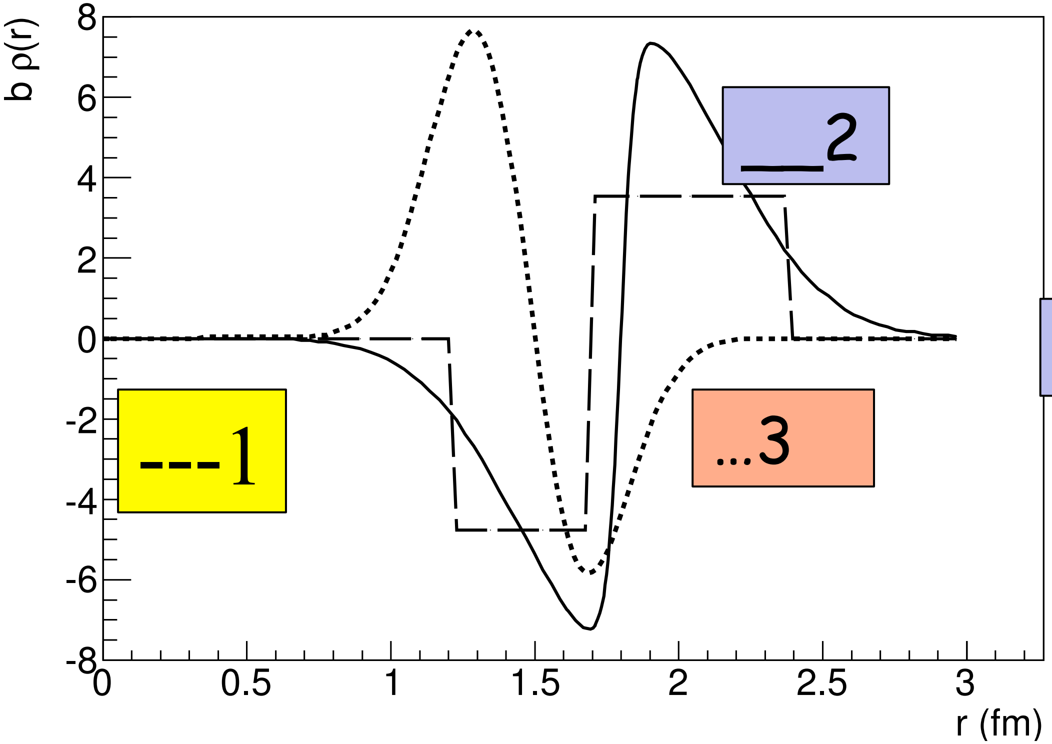
b~ interaction potential

real: elastic rescattering potential (attractive or repulsive)

imaginary: potential inducing flux absorbtion or creation

Double layer potentials

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



1) Multiple step function

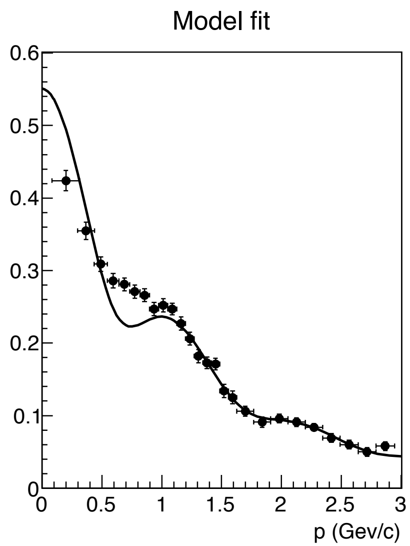
2) Soft multistep

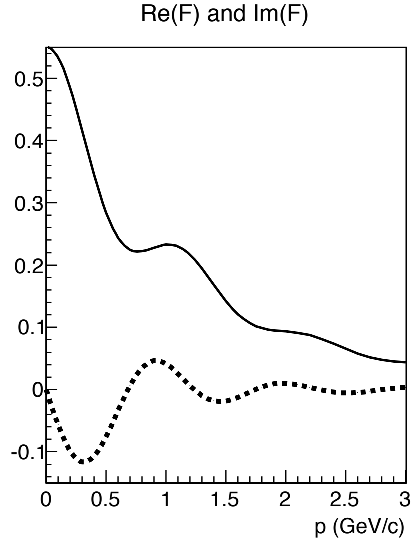
3) Two-gaussian opposite sign potential

A. Bianconi, E. T-G., PRC 93, 035201 (2016)

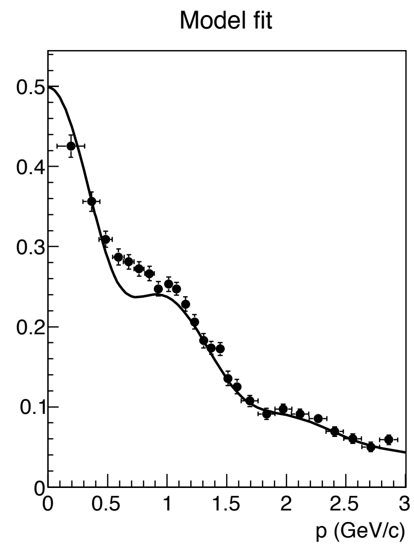
Optical model analysis

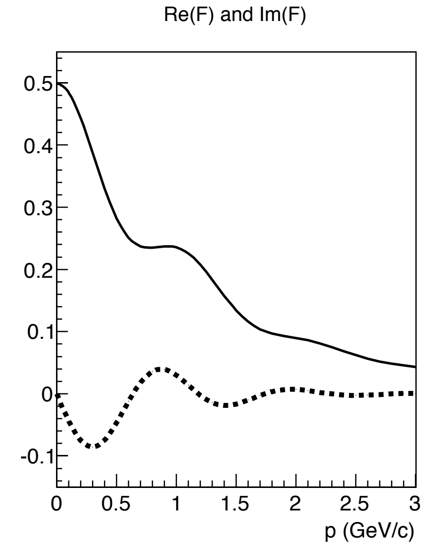
1) Multiple step function





2) Soft multistep





- At large r: purely absorptive
- At small r: the product D(r)M(r)“resonates” with the FT factor
- Importance of the steep behavior (oscillation period)
- Related to threshold enhancement

Optical model analysis

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

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)

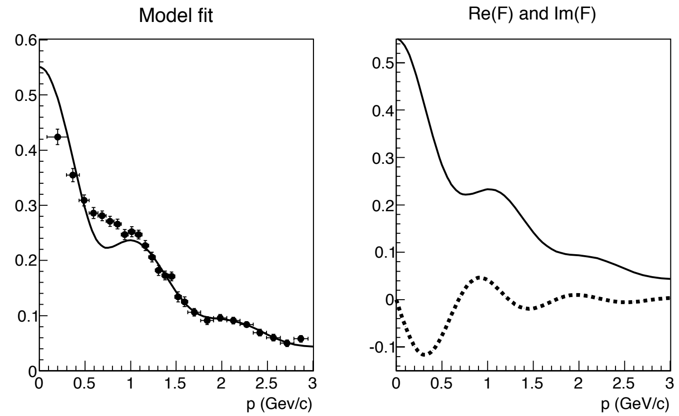
Optical model :

2 component imaginary potential:

absorbing outside,

regenerating inside,

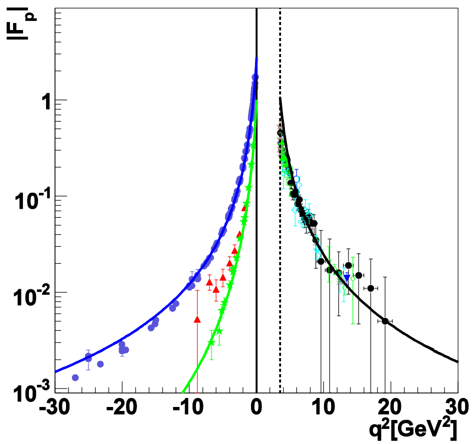
with steep change of sign



The model

Should explain:

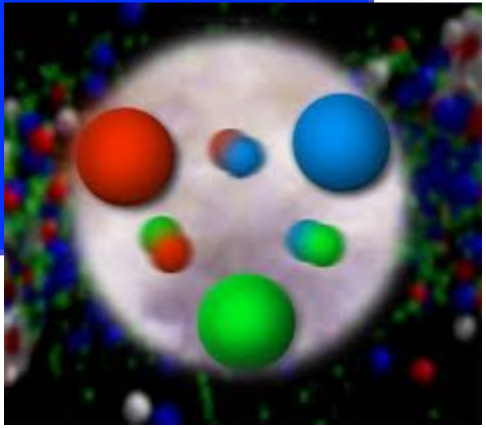
- Scattering & annihilation dynamics
- Decrease of R (Q^2) in SL
- $|G_E|=|G_M|=1$ at threshold



Predictions for TL…

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

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 the strong gluonic field

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

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, $p_0^2 = 1.21\ \text{GeV}^2$

Neutron: $r_0 = 0.31$ fm, $p_0^2 = 2.43\ \text{GeV}^2$

Applies to the scalar part of the potential

Model

V. A. Matveev, R.M. Muradian, A.N. Tavkhelidze, Nuovo Cimento Lett. 7 (1973) 719
S.J. Brodsky, G.R. Farrar, Phys. Rev. Lett. 31 (1973) 1153.

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

Model: generalized form factors

Definition:

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

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

In SL- Breit frame (zero energy transfer):

$$F(q^2) = \delta(q_0) F(Q^2), \; Q^2 = -(q_0^2 - \vec{q}^2) > 0.$$

In TL-(CMS):

$$F(q^2) = \int_{\mathcal{D}} dt e^{i\sqrt{q^2}t} \int d^3\vec{r} \rho(\vec{r}, t) = \int_{\mathcal{D}} dt e^{i\sqrt{q^2}t} Q(t),$$

$Q(t)$: time evolution of the charge distribution in the domain $\mathcal{D}$.

The annihilation channel: $e^+ + e^- \to \gamma^*(q) \to p + \bar{p}$.

1) Creation of a $p\bar{p}$ state through $^3S_1 = < 0|J^\mu|p\bar{p} >$ intermediate state with $q = (\sqrt{q^2}, 0, 0, 0)$.

2) The vacuum state transfers all the released energy to a state of matter consisting of:

- 6 massless valence quarks
- Set of gluons
- Sea of current $q\bar{q}$ pairs of quarks with energy $q_0 > 2M_p$, J=1, dimensions $\hbar/(2M_p) \sim 0.1$ fm.

3) Pair of p and $\bar{p}$ formed by three bare quarks:

- Structureless
- Colorless

→ pointlike FFs !!!

The annihilation channel: $e^+ + e^- \to \gamma^*(q) \to p + \bar{p}$.

- The point-like hadron pair expands and cools down: the current quarks and antiquarks absorb gluon and transform into constituent quarks

- The residual energy turns into kinetic energy of the motion with relative velocity $2\beta = 2\sqrt{1 - 4M_p^2/q_0^2}$.

- The strong chromo-EM field leads to an effective loss of color. Fermi statistics: identical quarks are repulsed. The remaining quark of different flavor is attracted to one of the identical quarks, creating a compact diquark (*du*-state)

The annihilation channel: $e^+ + e^- \to \gamma^*(q) \to p + \bar{p}$

At larger distances, the inertial force exceeds the confinement force: p and $\bar{p}$ start to move apart with relative velocity β

p and $\bar{p}$ leave the interaction region: at larger distances the integral of Q(t) must vanish.

For very small values of the velocity $\alpha\pi/\beta \simeq 1$ FSI lead to the creation of a bound $\bar{N}N$ system .

The annihilation channel: $e^+ + e^- \rightarrow \gamma^*(q) \rightarrow p + \bar{p}$.

The repulsion of p and p̅ with kinetic energy

$$T = \sqrt{q^2} - 2M_p c^2$$

is balanced by the confinement potential

$$q_0 - 2M_p c^2 = (k/2)R^2$$

- The long range color forces create a stable colorless state of proton and antiproton
- The initial energy is dissipated from current to constituent quarks originating on shell $\bar{p}p$ separated by R.

The annihilation channel: $e^+ + e^- \to \gamma^*(q) \to p + \bar{p}.$

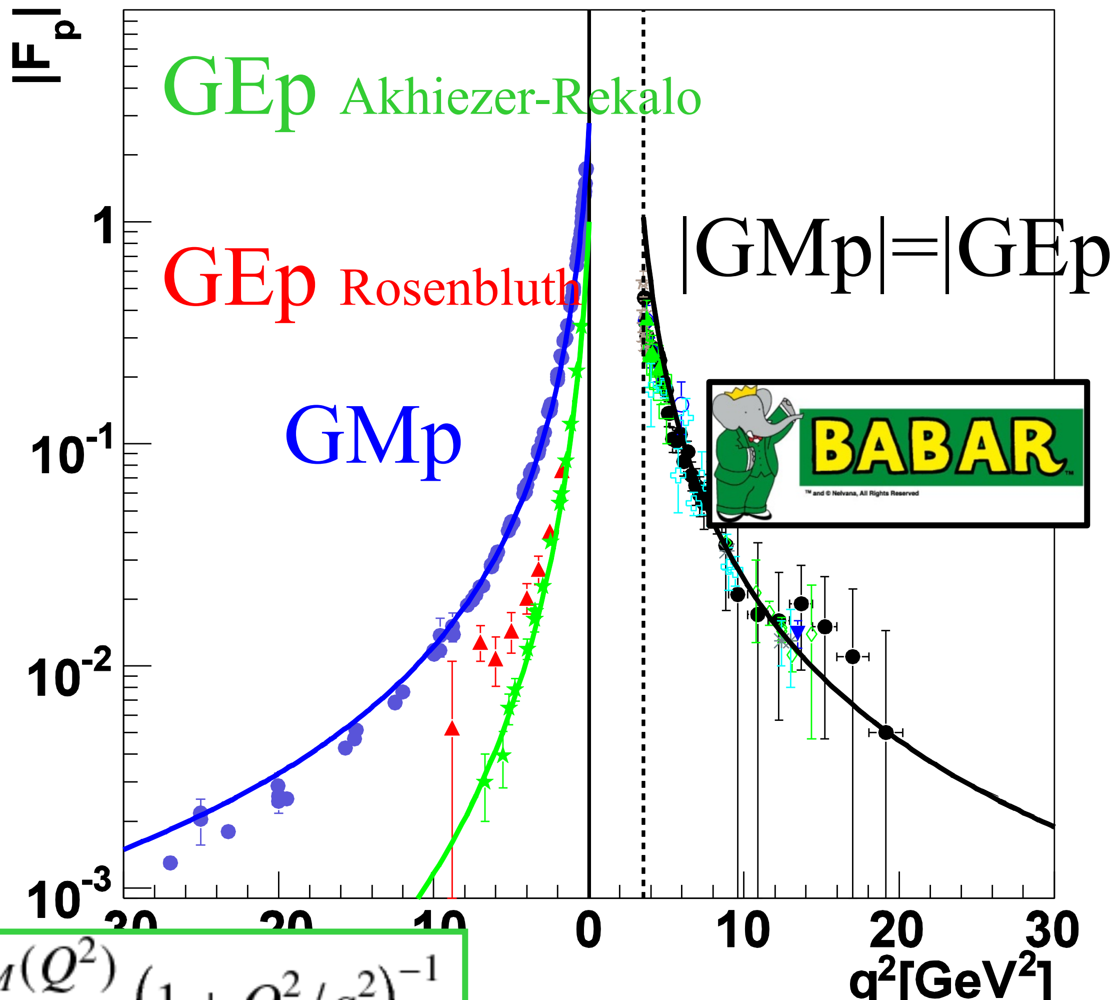
The neutral plasma acts on the distribution of the electric charge (not magnetic).

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

$$
\begin{aligned}
|G_M(q^2)| &= [1 + (q^2 - 4M_p^2)/q_2^2]^{-2}\Theta(q^2 - 4M_p^2), \\
|G_E(q^2)| &= |G_M(q^2)|[1 + (q^2 - 4M_p^2)/q_1^2]^{-1}\Theta(q^2 - 4M_p^2),
\end{aligned}
$$

- *Implicit normalization at* $q^2=4M_p^2$: |GE|=|GM| =1
- *No poles in the unphysical region*

Proton Form Factors



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

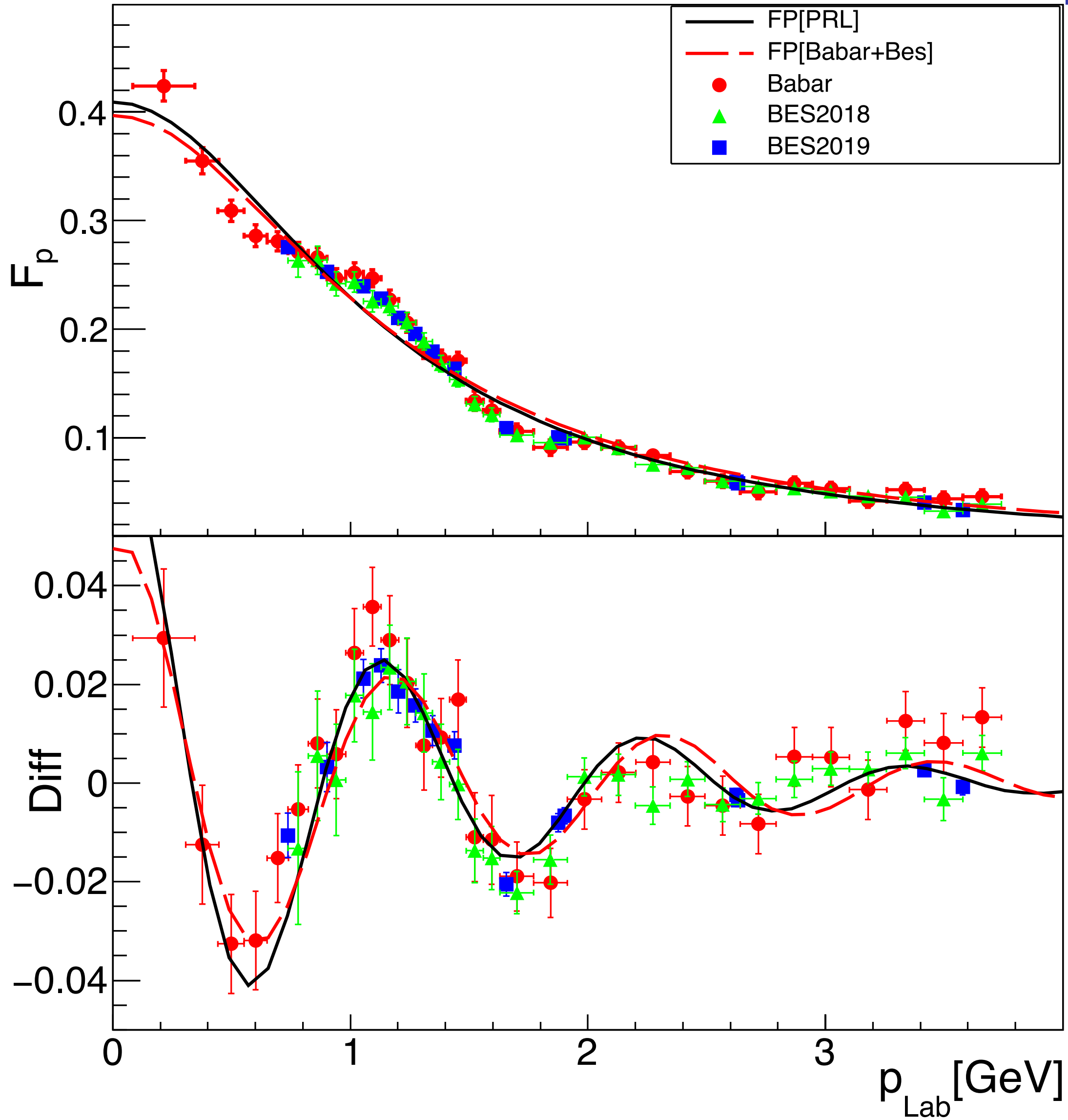
$$|G_M(q^2)| = [1 + (q^2 - 4M_p^2)/q_2^2]^{-2}\Theta(q^2 - 4M_p^2),$$

$$|G_E(q^2)| = |G_M(q^2)|[1 + (q^2 - 4M_p^2)/q_1^2]^{-1}\Theta(q^2 - 4M_p^2)$$

BES IHEP

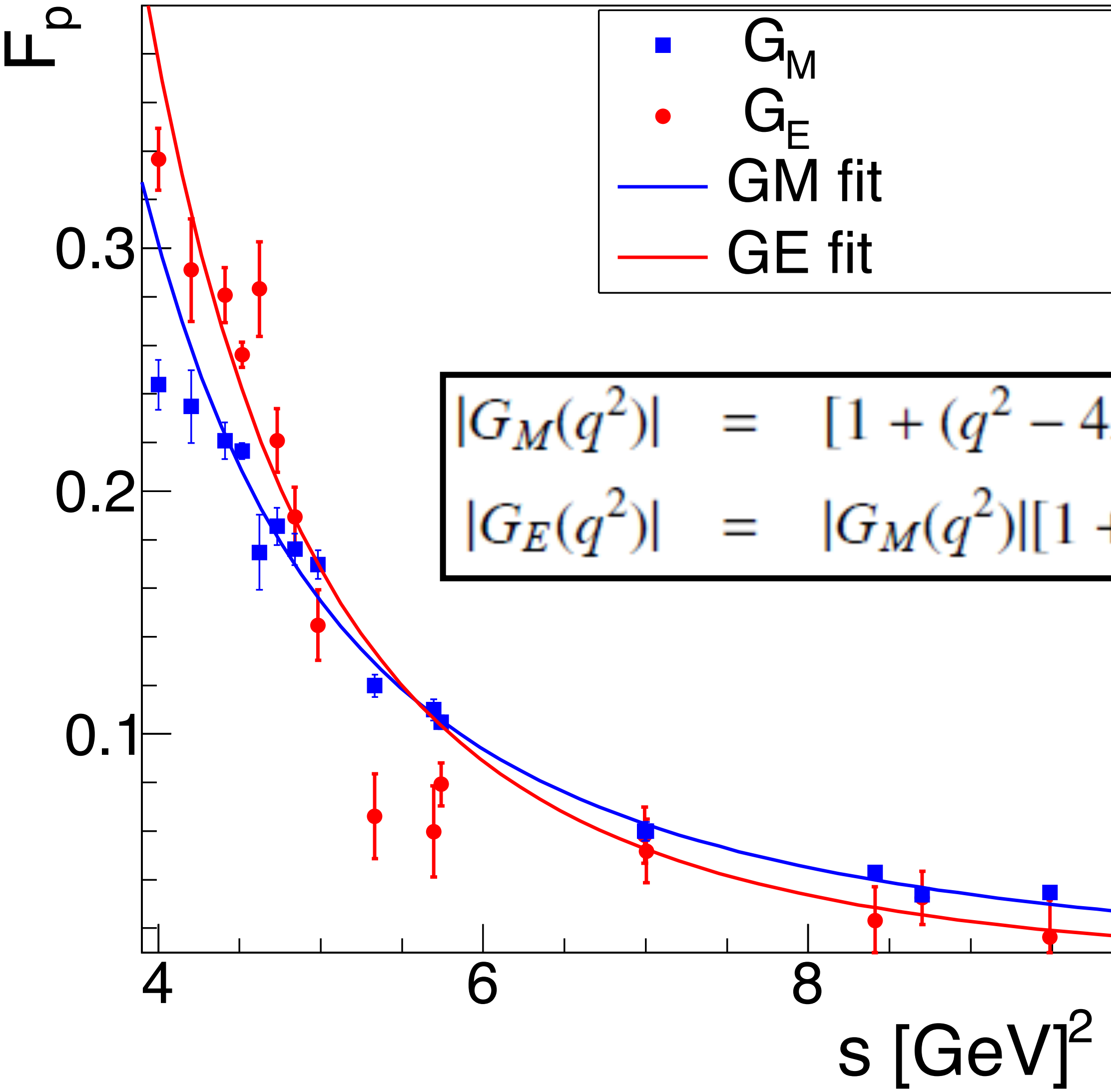
New Data in Time-like

Effective Form Factor



- Regular oscillations confirmed by BES (ISR and scan)
- Does not change fit parameters (within errors)
- BES2019: First individual determination of GE &GM in TL region!!

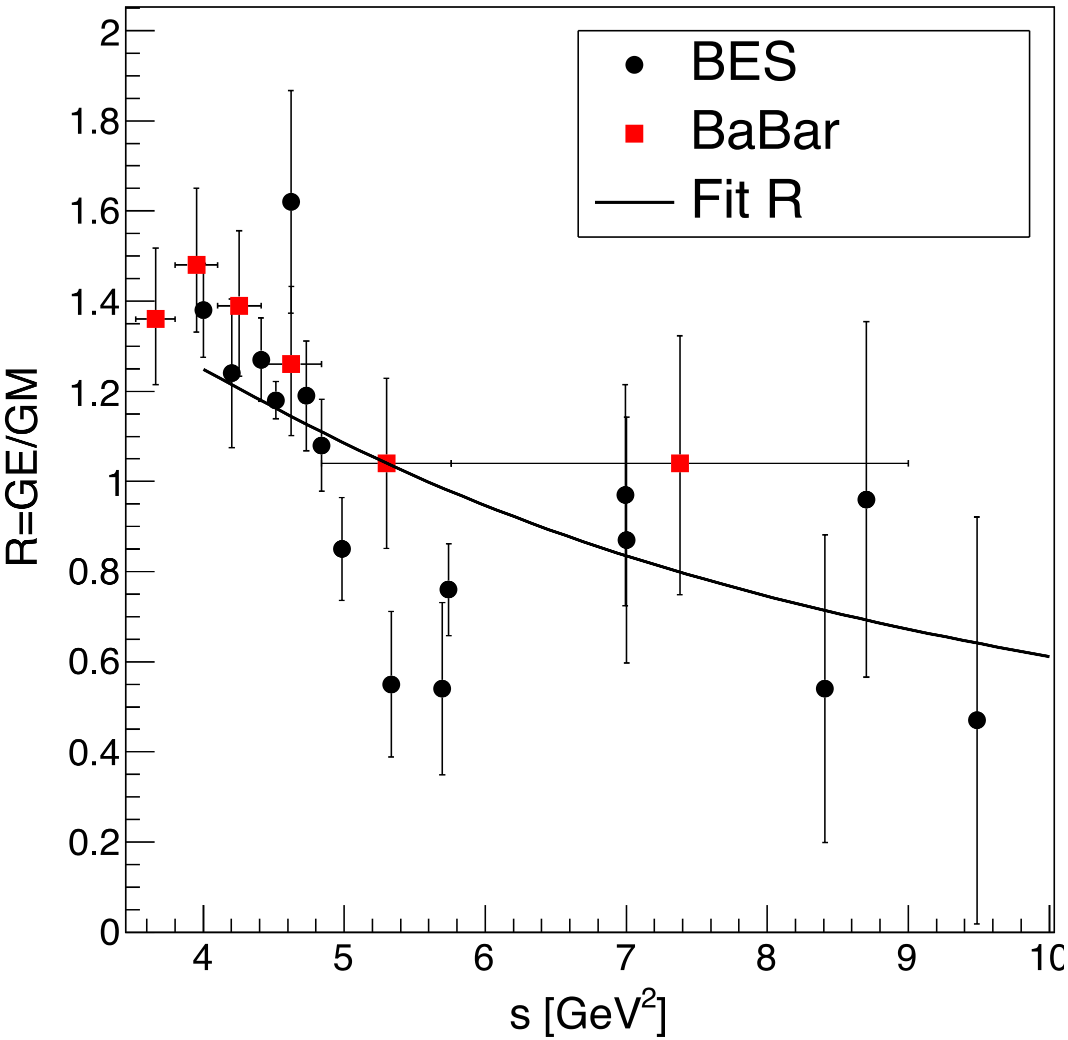
Time-like Proton Form Factors



$$|G_M(q^2)| = [1 + (q^2 - 4M_p^2)/q_2^2]^{-2}\Theta(q^2 - 4M_p^2),$$

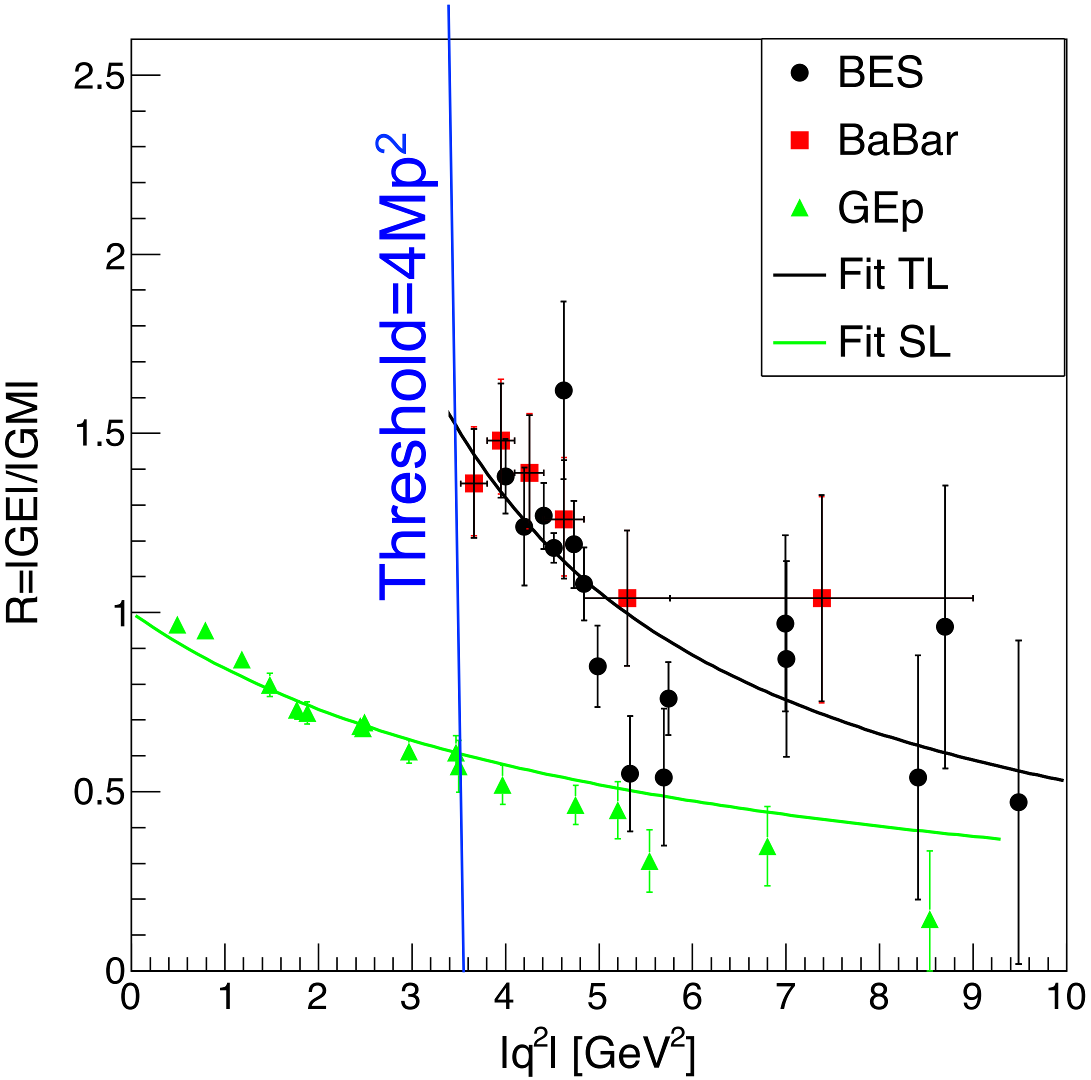
$$|G_E(q^2)| = |G_M(q^2)|[1 + (q^2 - 4M_p^2)/q_1^2]^{-1}\Theta(q^2 - 4M_p^2),$$

Time-like Proton Form Factor Ratio



- $|R|=1$ at threshold
- For s= 5-6 GeV^2
  - Minimum?
  - Oscillation?
  - Node?

Proton Form Factor Ratio (SL,TL)

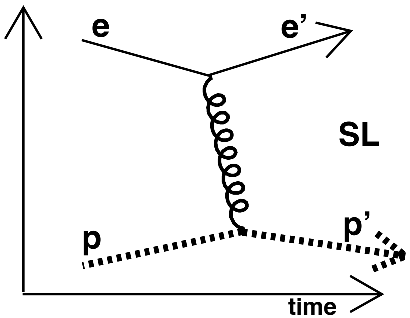


- $|R(TL)|=2.5\mu_p R(SL)$
- Minimum for s= 5-6 GeV²

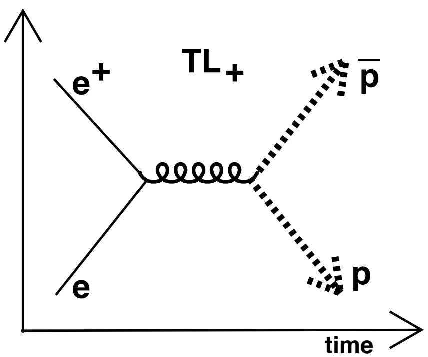
$$R \sim (1+|q^2|/q_1^2)^{-1}$$

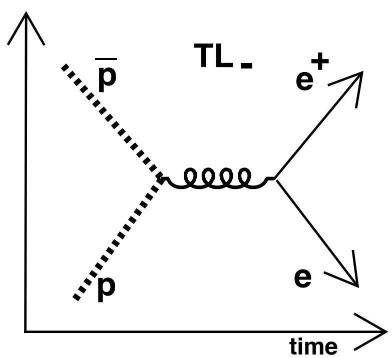
Definition of TL-SL Form Factors

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



$\rho(x) = \rho(\vec{x}, t)$ 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?

ρ(x) in the space-like region

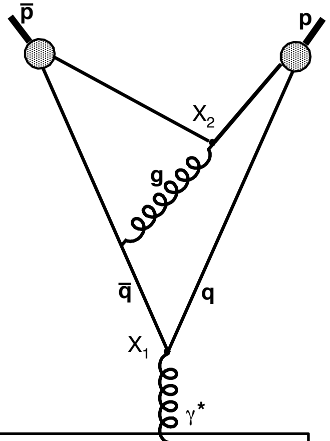
and in the Breit frame or at small x:

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

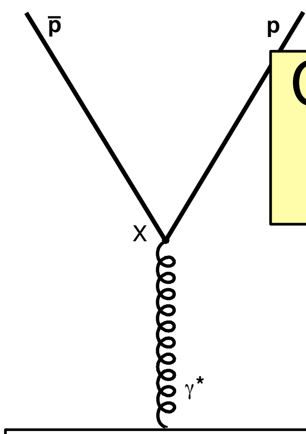
Charge: photon-charge coupling

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

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



Resolved



Unresolved

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

The simplest picture: qq pair + compact di-quark representation

Oscillations

- Recent and precise data on the proton time-like form factors show a systematic sinusoidal modulation in the near-threshold region.
- The relevant variable is the momentum *p* associated to the relative motion of the final hadrons.
- The periodicity and the simple shape of the oscillations point to a unique interference mechanism, which occurs when the hadrons are separated by about 1 fm.
- The hadronic matter is distributed in non-trivial way.
- The oscillation period corresponds to hadronic-scale
  - ➢ scaling-violating parameter
  - ➢ origin ?

Conclusion

- New understanding of Form Factors in the Time-like region: time distribution of quark-antiquark pair creation vertices

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

- The distributions tested by the virtual photon are projections in orthogonal 1 and 3-dim spaces of the function F(x): $R(t)$ and $\rho(\vec{x})$

- Di-quark as a necessary step towards hadron creation?
- Origin of oscillatory phenomena ?

Thank you for the attention

Modern Physics Letters A, Vol. 3, No. 9 (1988) 909–916

DIQUARKS AND DYNAMICS OF LARGE-$P_\perp$ BARYON PRODUCTION

V. T. KIM

Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 101000 Moscow

5) In the present work, we are not concerned with the scaling violation problem in the deep inelastic lepton-nucleon scattering. The point is that the diquark contributions can partly be cancelled with other contributions of higher twists. The theoretical situation with the twist-4 and especially with twist-6 is not completely clear now.

Best evidence from pbar-p annihilation?