About new data and BESIII individual determination of time-like form factors

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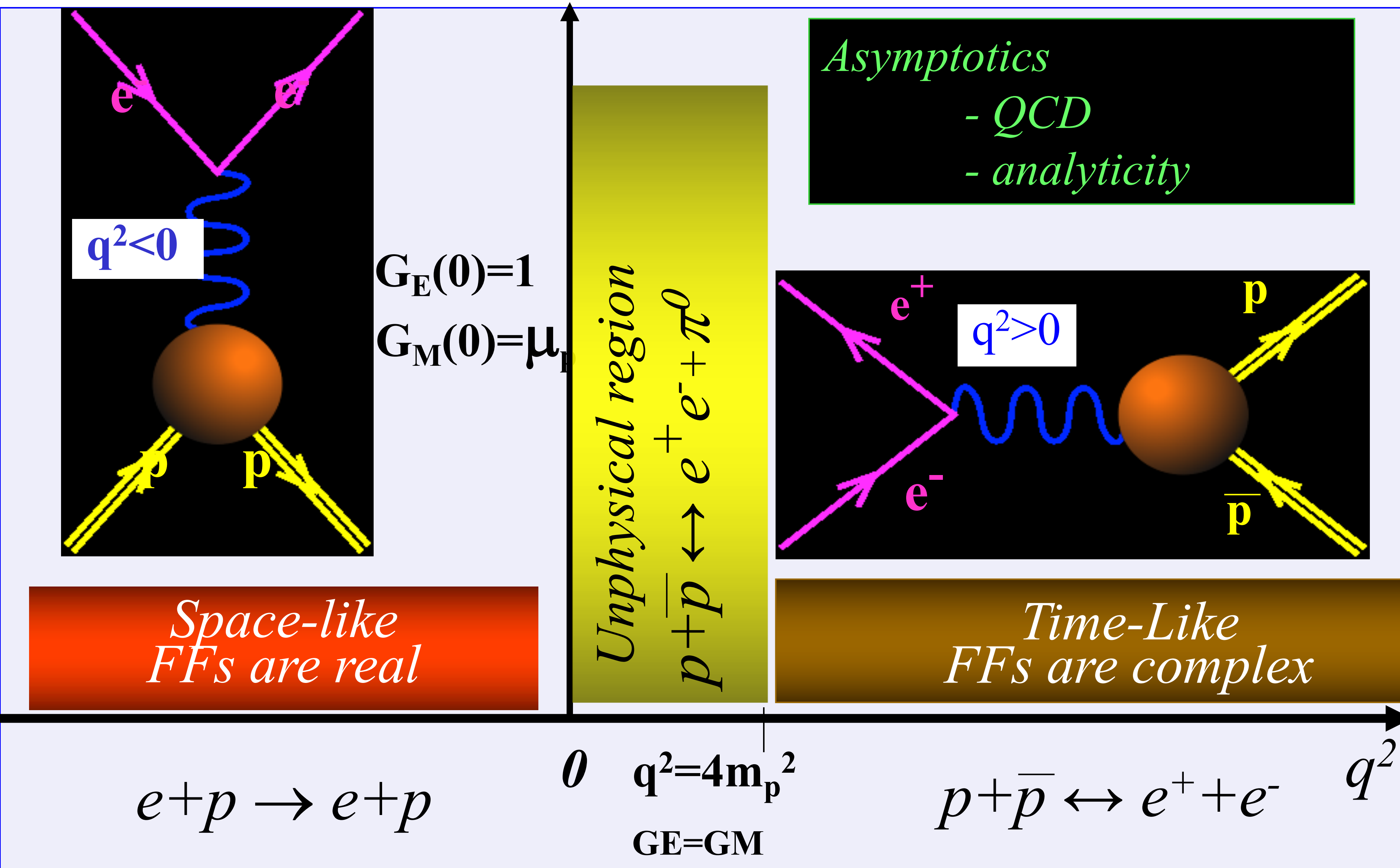
ArXiv: nucl-th / 2012.145656, to appear in Phys Rev. C

PANDA Coll. Meeting, EM Session, March 9, 2021

Proton Charge and Magnetic Distributions



CMS Cross section of $e^+e^-\to p\bar{p}$

$$\frac{d\sigma_{e^+e^-\to\bar{p}p}}{d\Omega}(s,\theta)=\frac{\alpha^2\beta\,\mathcal{C}(\beta)}{4s}\left[\left(1+\cos^2(\theta)\right)|G_M(s)|^2+\frac{1}{\tau}\sin^2(\theta)|G_E(s)|^2\right]$$

$$\tau=s/(4m_p^2)$$

A. Zichichi, S. Berman, N. Cabibbo, and R. Gatto, Nuovo Cim. 24, 170 (1962).

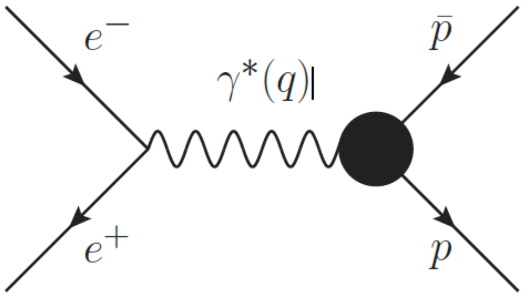
- Coulomb factor
  - *effective within < 1 MeV*
  - *insures finite cross section at threshold*
  - *not present in the time reverse reaction*

$$\mathcal{C}(\beta)=\frac{y(\beta)}{1-e^{-y(\beta)}}$$

$$y(\beta)=\frac{\pi\alpha}{\beta}\sqrt{1-\beta^2}$$

$\beta=\sqrt{1-1/\tau}$ is the proton velocity

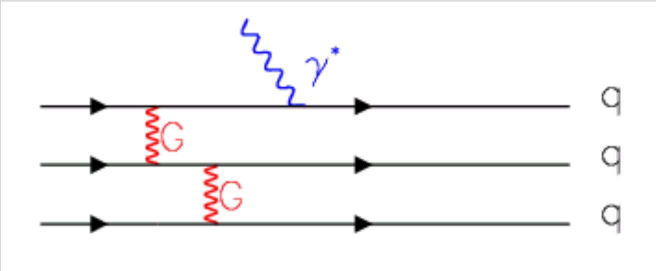
Assumes one-photon exchange : $\cos^2\theta$ – even



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 ?

The Time-like Region



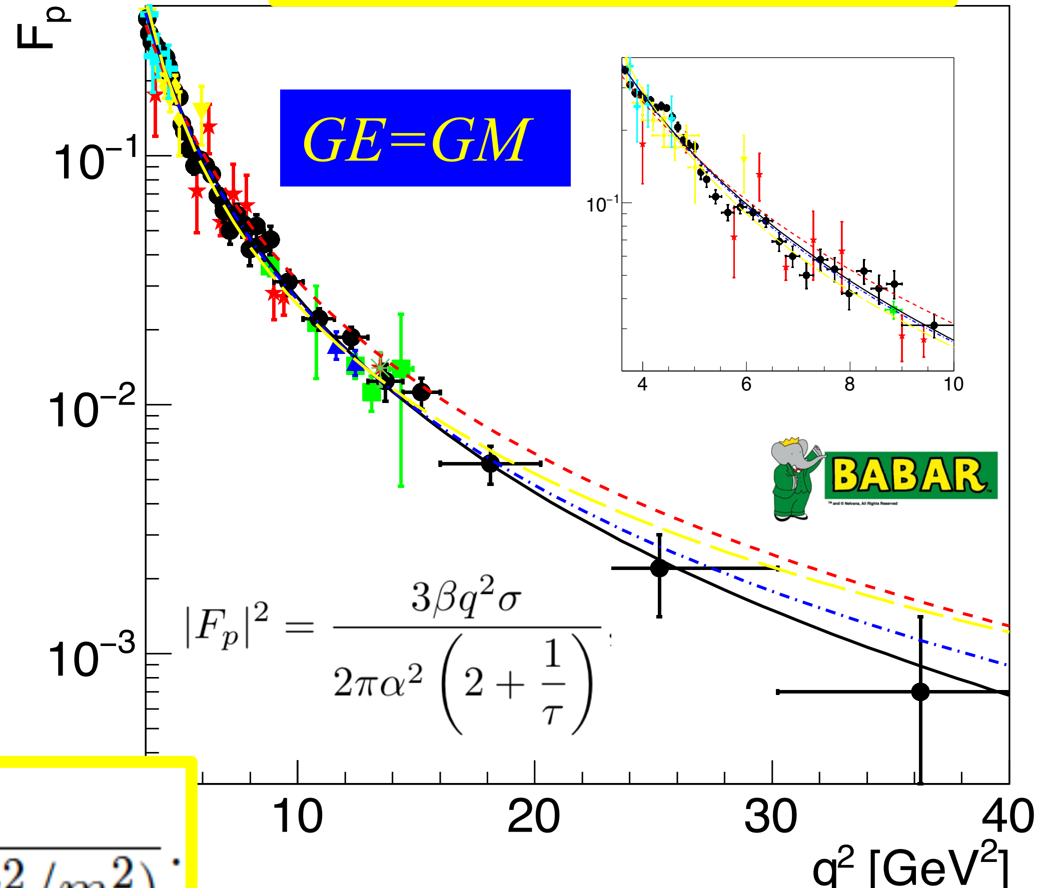
Expected QCD scaling $(q^2)^2$

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

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

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

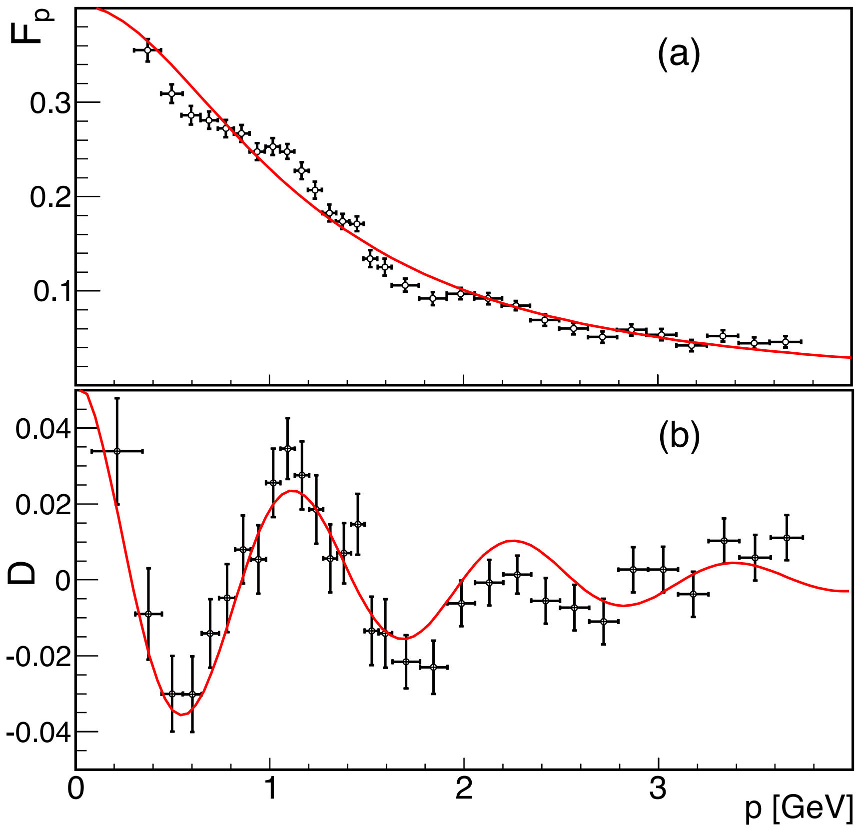
$$e^+ + e^- \to \bar{p} + p\,,$$
$$\bar{p} + p \to e^+ + e^-$$



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

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

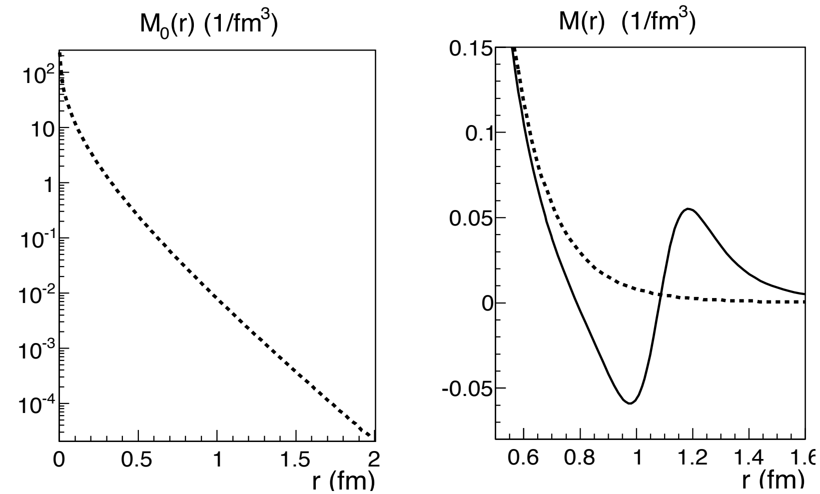
A.Bianconi, E. T-G.,
Phys. Rev. Lett. 114, 232301 (2015)

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

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

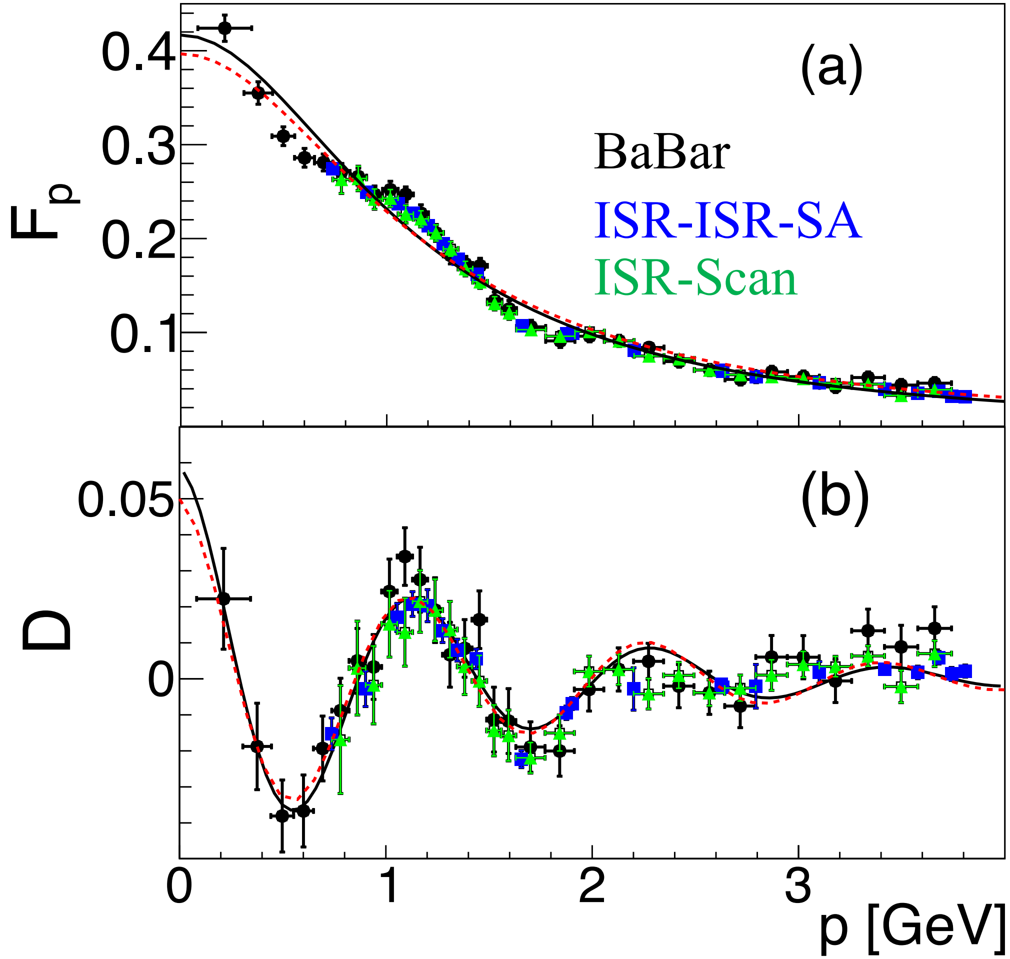
$$F_0 = \frac{\mathcal{A}}{(1 + q^2/m_a^2)\left[1 - q^2/0.71\right]^2},$$

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



- *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*

Confirmation of regular oscillations



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

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

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

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

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

Monopole Fit

Ref.	Exp.	N	F_0	m_a^2 (GeV^2)
[3, 5, 12]	BaBar	85	7.7 ± 0.3	15 ± 1
[3–6]	BaBar,BESIII-ISR,BESIII-SC	107	8.9 ± 0.2	8.8 ± 0.6

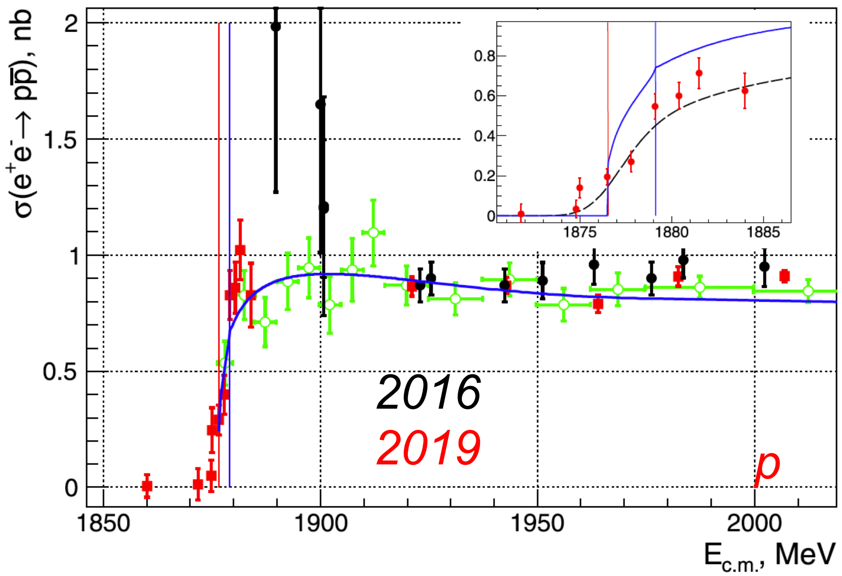
Damped Oscillatory Function

Ref.	Data set	$A \pm \Delta A$	$B \pm \Delta B$ (GeV^{-1})	$C \pm \Delta C$ (GeV^{-1})	$D \pm \Delta D$	$\chi^2/n.d.f$
[3, 5, 12]	BaBar	0.05 ± 0.01	0.59 ± 0.2	5.6 ± 0.1	0.2 ± 0.2	57/(55-4)= 1.1
[3–6]	BESIII-ISR,SC,BaBar	0.07 ± 0.01	0.93 ± 0.09	5.9 ± 0.1	0.1 ± 0.2	227/(107-4)=2.2

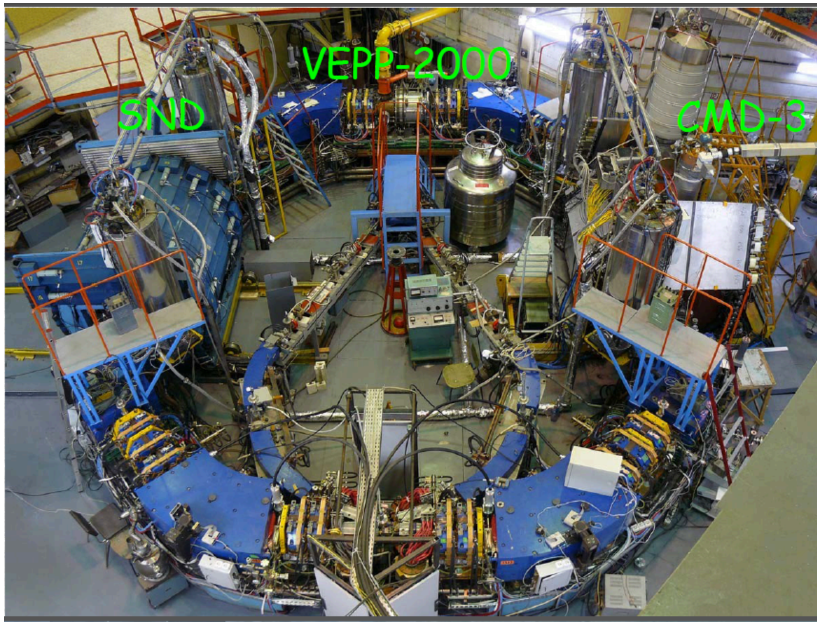
6-parameter Fit

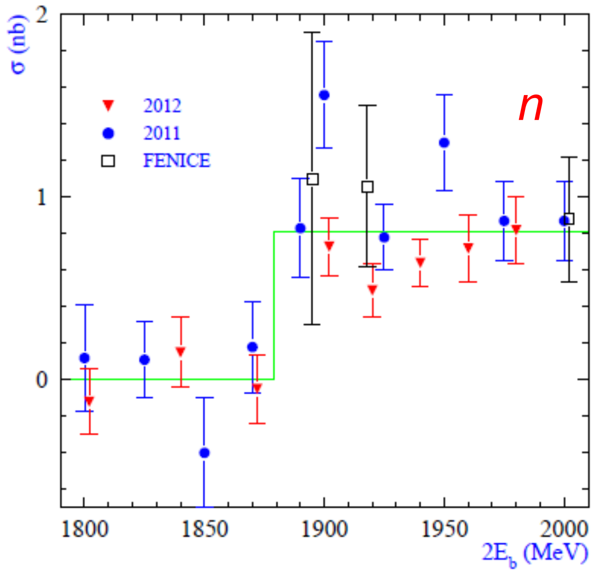
Ref.	F_0	m_a^2 (GeV^2)	A	B (GeV^{-1})	C (GeV^{-1})	D	$\frac{\chi^2}{\text{n.d.f.}}$
[3–6, 11]	9.7 ± 0.3	7.1 ± 0.5	0.073 ± 0.007	1.05 ± 0.07	5.51 ± 0.09	0.04 ± 0.1	$\frac{278}{118-6} = 2.5$

Threshold physics



VEPPII, Novosibirsk





- The beam energy is measured at 0.1 MeV precision (back scattering laser light system).
- The energy spread due to radiation and energy resolution is small enough to differentiate the proton and neutron thresholds.

$$\sigma_{Born}(E_{c.m.}) = A + B\left[1 - \exp\left(-\frac{(E_{c.m.} - E_{thr})}{\sigma_{thr}}\right)\right],$$

Point-like form factors?

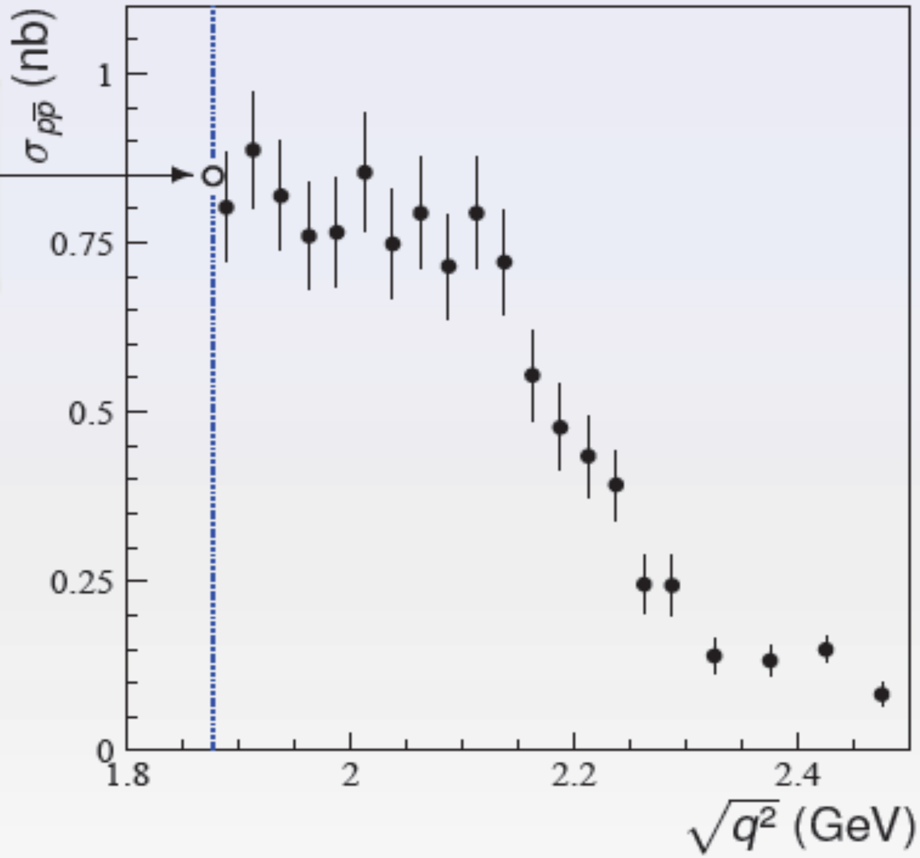
BABAR: $e^+e^- \to p\bar{p}$

EPJA39, 315

S. Pacetti

EPJA 39, 315 (2009)

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



At the threshold

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

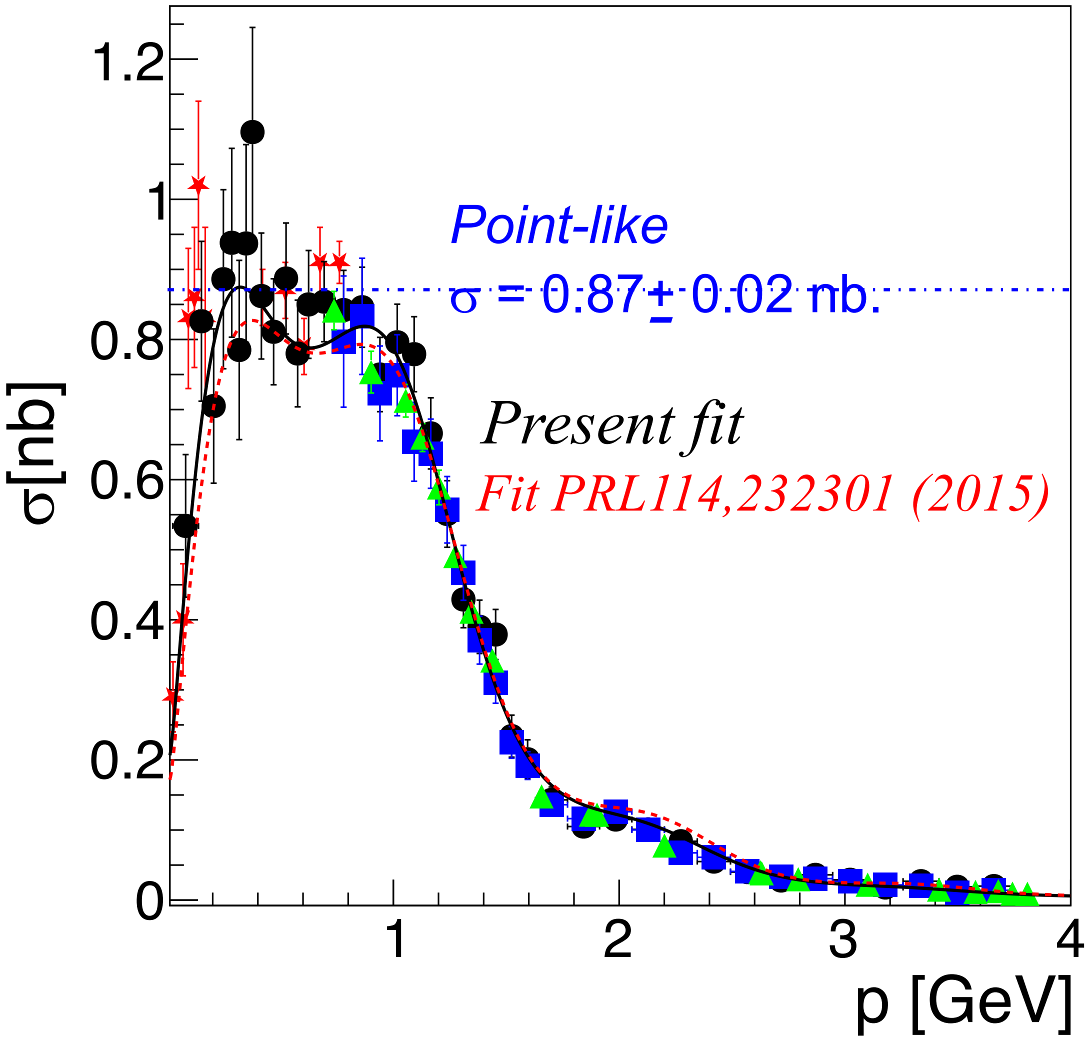
$$\sigma_{p\bar{p}}(4M_p^2) = 0.85\,|G_S^p(4M_p^2)|^2 \text{ nb}$$

$\Longrightarrow$

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

as pointlike fermion pairs!

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



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)

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

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

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

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

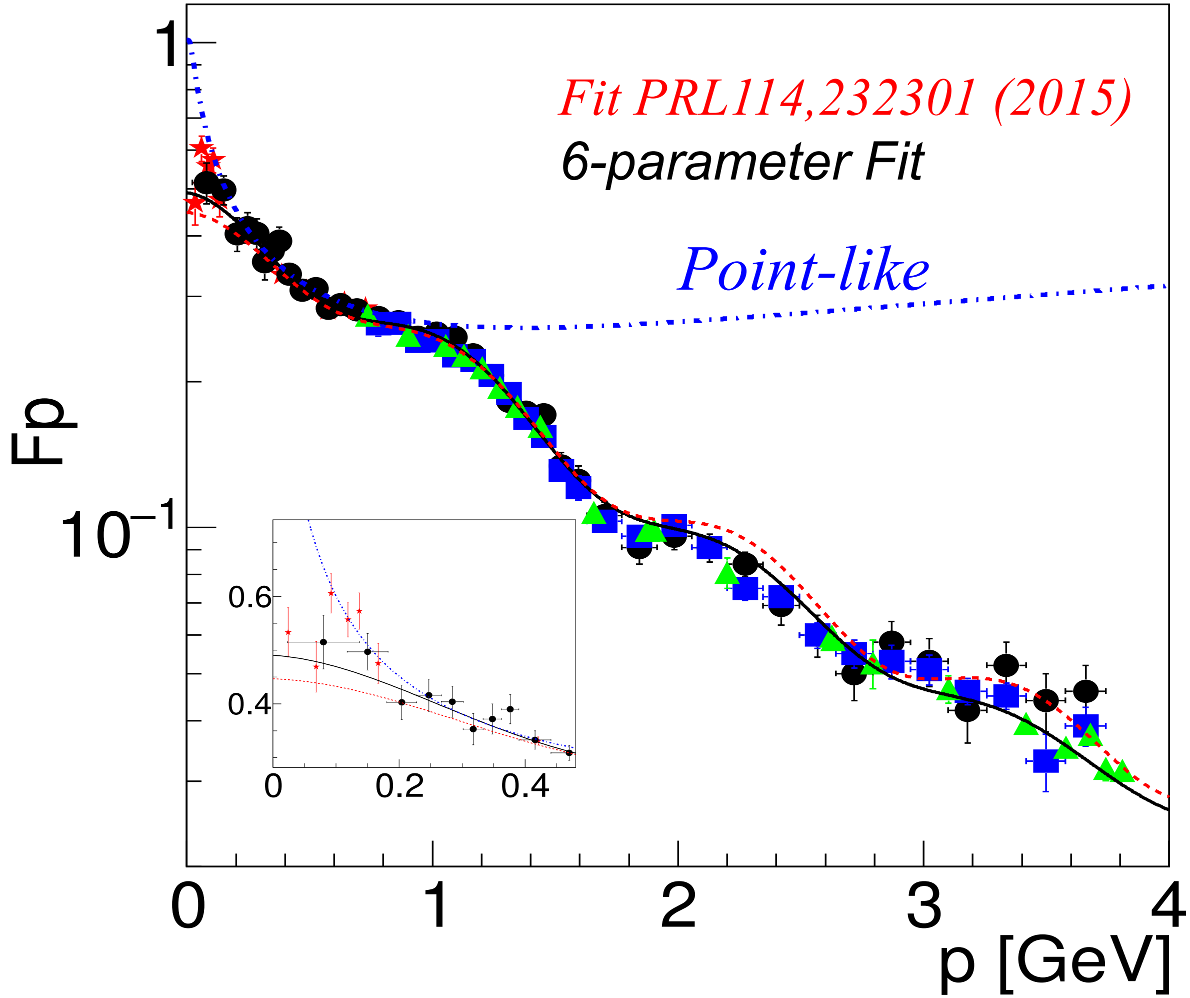
- Equivalent to:

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

Strictly valid at threshold, where only one amplitude is present

Generalized Form Factor

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



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

PHYSICS

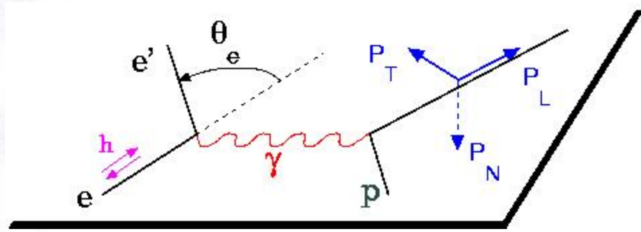
POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

Academician A. I. Akhiezer* and M. P. Rekalo

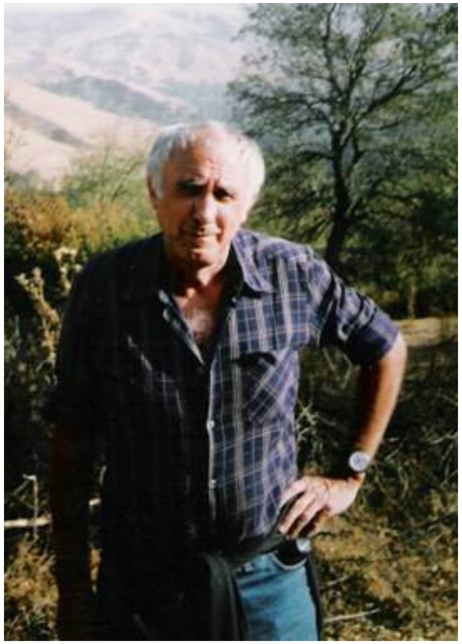
Physicotechnical Institute, Academy of Sciences of the Ukrainian SSR

Translated from Doklady Akademii Nauk SSSR, Vol. 180, No. 5, pp. 1081–1083, June, 1968

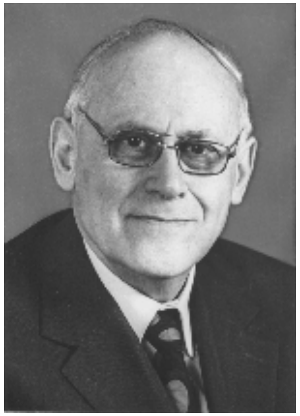
Original article submitted February 26, 1967



M.P. Rekalo (1938-2004)



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



A.I. Akhiezer (1911-2000)

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

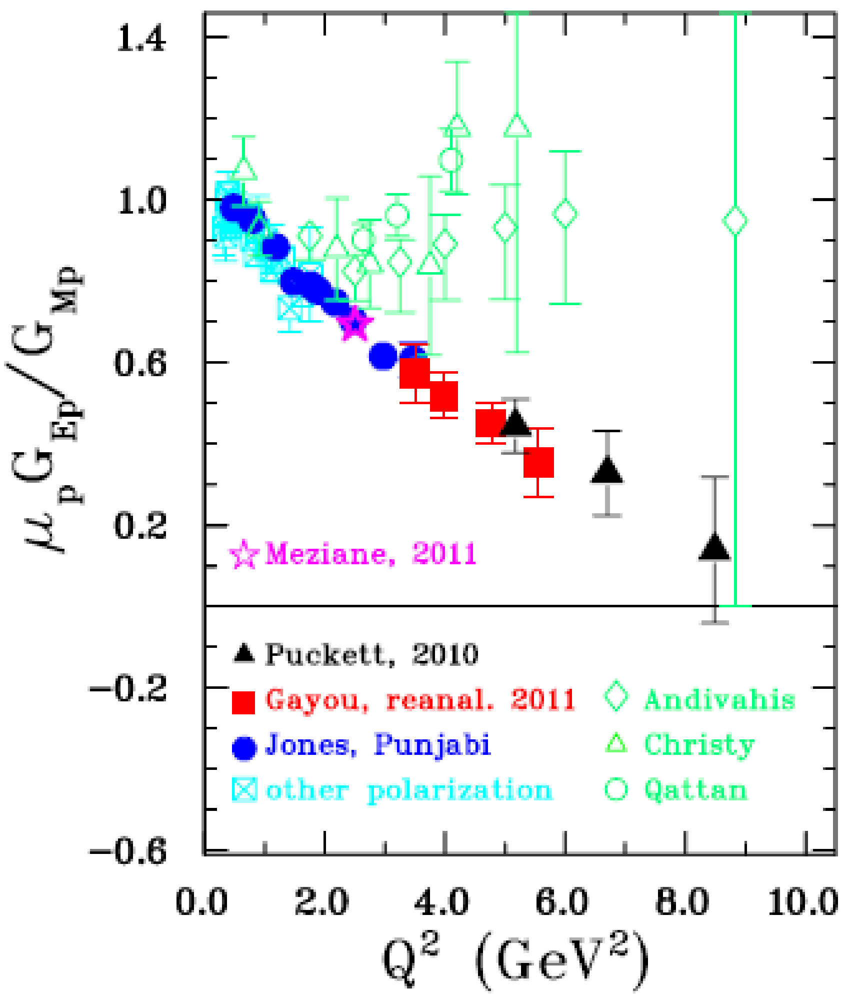
Polarized beam and target or polarized beam and recoil proton polarization

Polarization experiments @ JLab

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

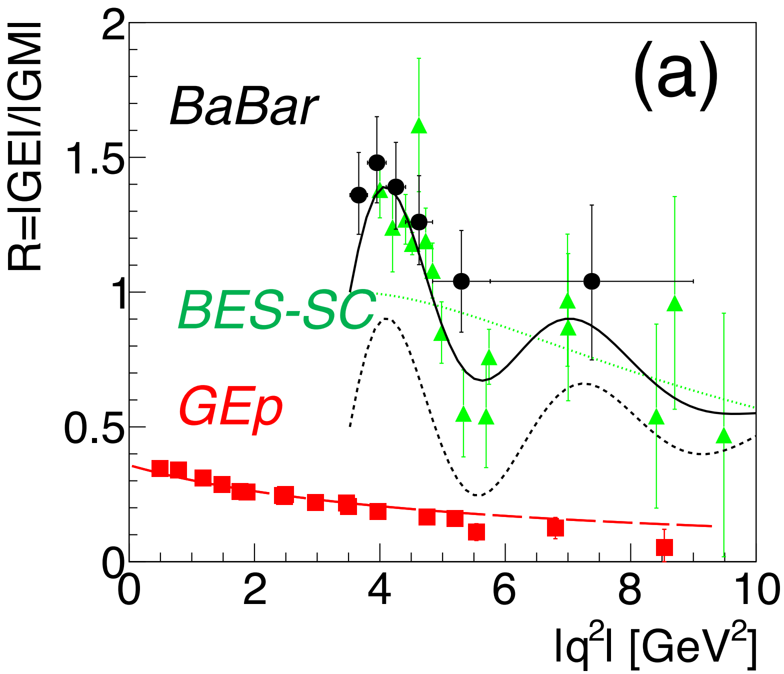
GEp collaboration

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



JLab-GEp Collaboration
.J.R. Puckett et al, PRC 96, 055203 (2017)

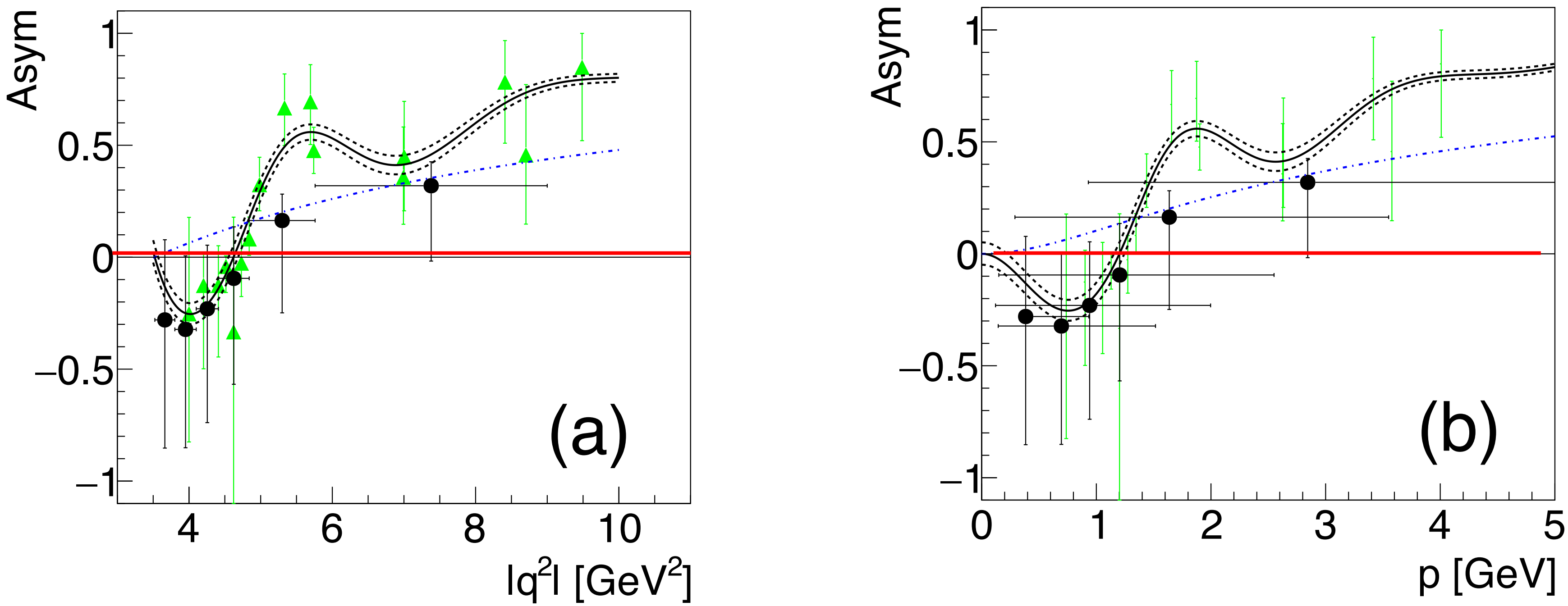
Form Factor Ratio R=|GE|/|GM|



- 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?

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

Angular Asymmetry



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

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

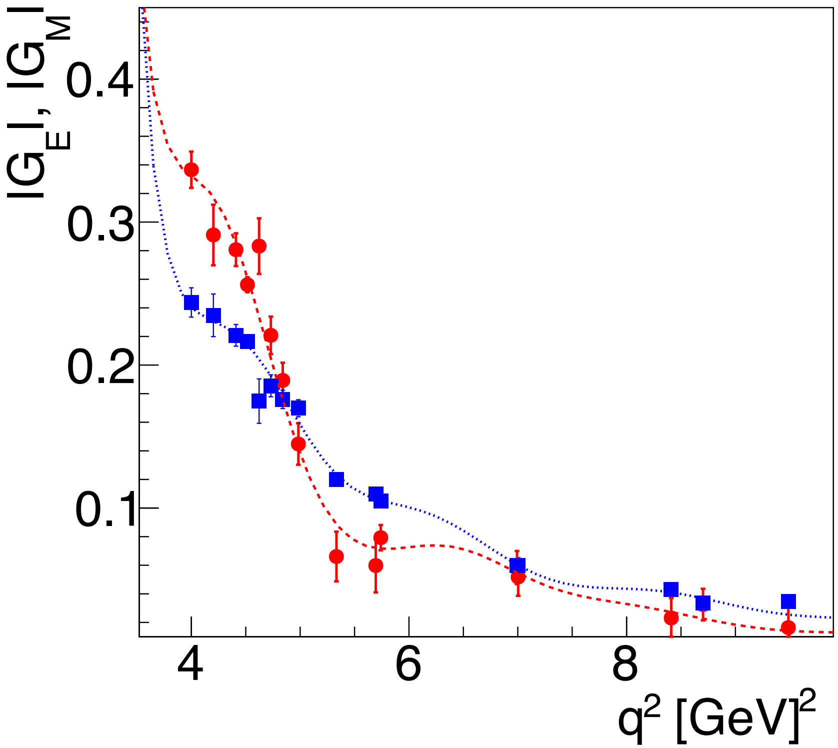
$$\mathcal{A}(s) = \frac{\tau|G_M(s)|^2-|G_E(s)|^2}{\tau|G_M(s)|^2+|G_E(s)|^2} = \frac{\tau-R(s)^2}{\tau+R(s)^2}$$

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

Zero of the angular asymmetry

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

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



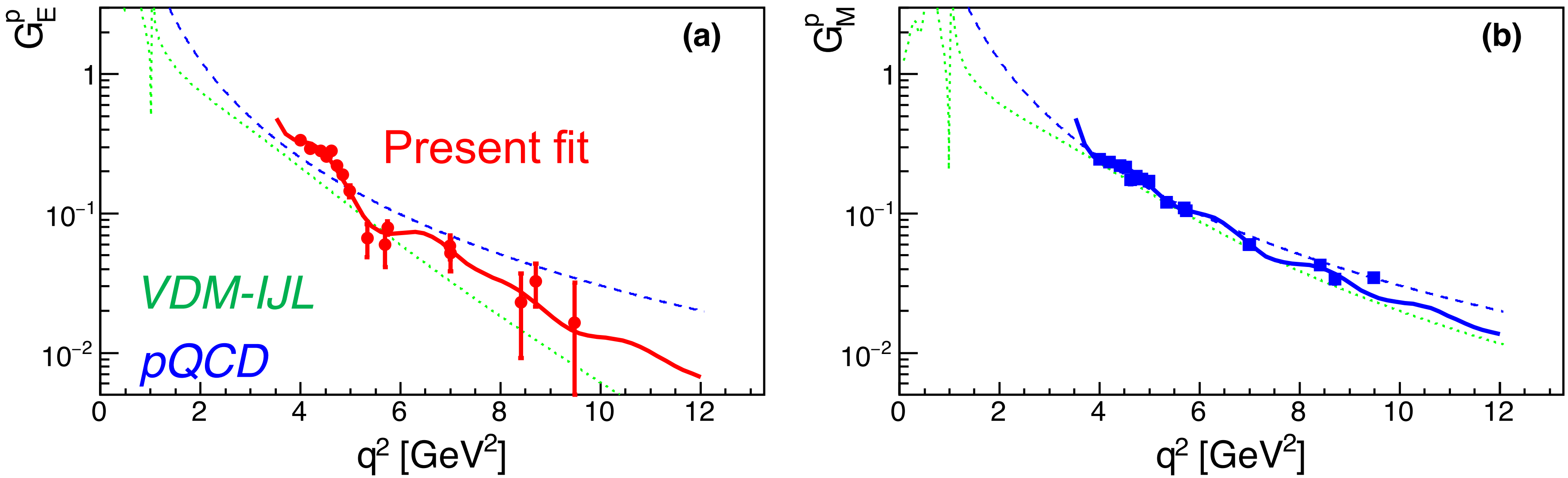
$$|G_E(s)| = F_p(s)\sqrt{\frac{1+2\tau}{R^2(s)+2\tau/R^2(s)}}$$

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

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

Models

Parametrizations have been determined by fitting Fp



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

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

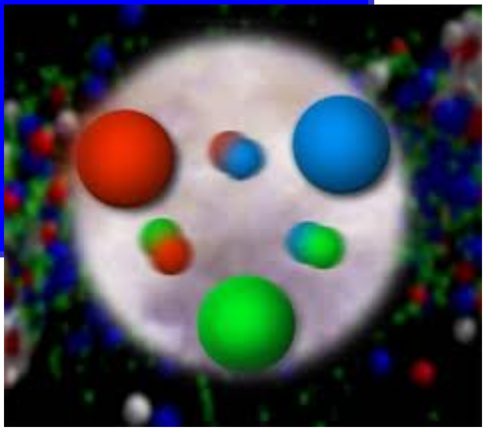
The fit gives :

$|G_E| = |G_M| = 0.48$

pQCD : 0.34

VDM-IJL : 0.29

The nucleon



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

antisymmetric state of colored quarks

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

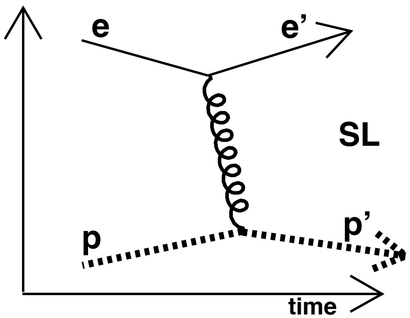
Main assumption

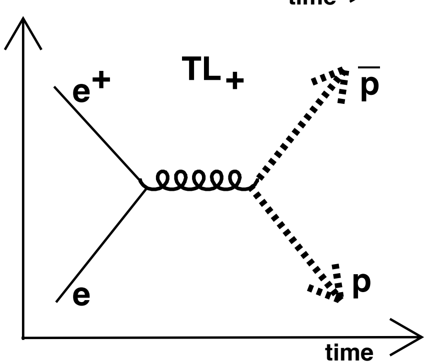
Does not hold in the spatial center of the nucleon: the center of the nucleon *is electrically neutral,* due to the strong gluonic field

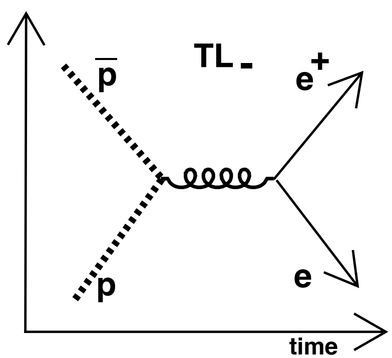
E.A. Kuraev, E. T-G, A. Dbeyssi, Phys.Lett. B712 (2012) 240

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

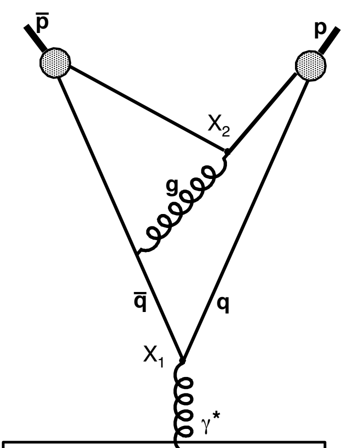
and in the Breit frame or at small x:

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

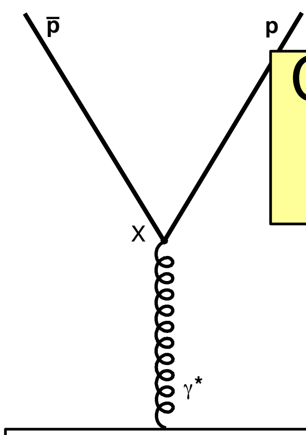
Photon-Charge coupling

$\rho(\vec{x})$ 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

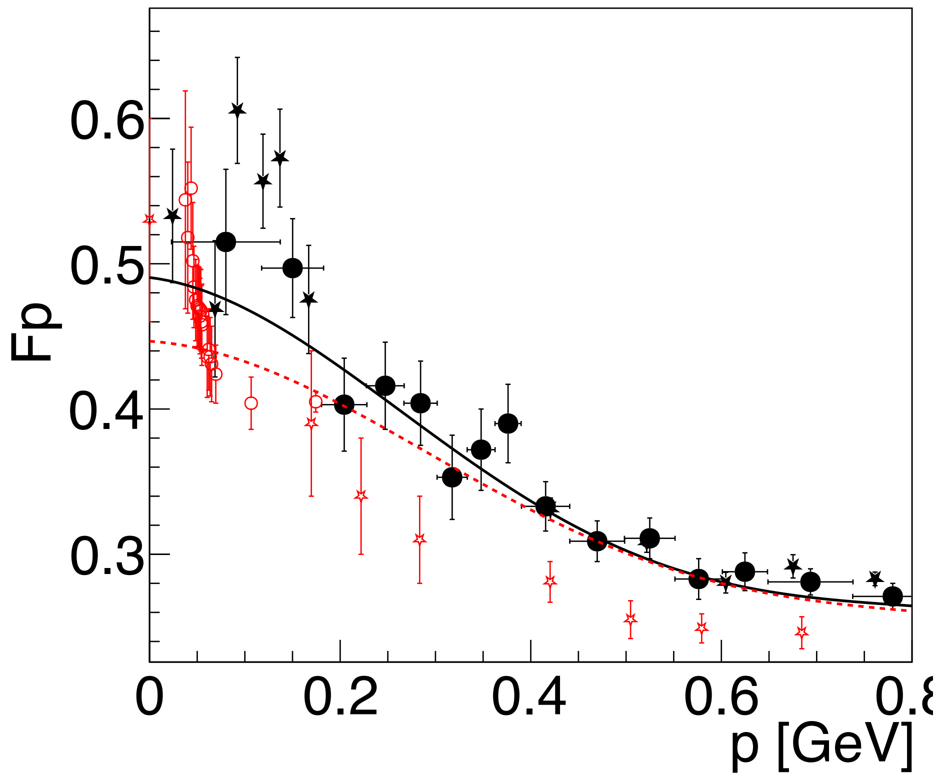
Conclusions

- New, precise data on time-like form factors and *first determination of individual FFs ($|G_E|$ and $|G_M|$)*

- New data on *FFs ratio* and *angular asymmetry*
- *FFs ratio:* damped oscillations around a monopole decrease
- Oscillations more pronounced in $|G_E|$.
- Origin of oscillatory phenomena ? Di-quark as a necessary step towards hadron creation?

- Time reversal holds for 'elastic' annihilation channels: *are the two channels really equivalent* in the whole q^2-region?

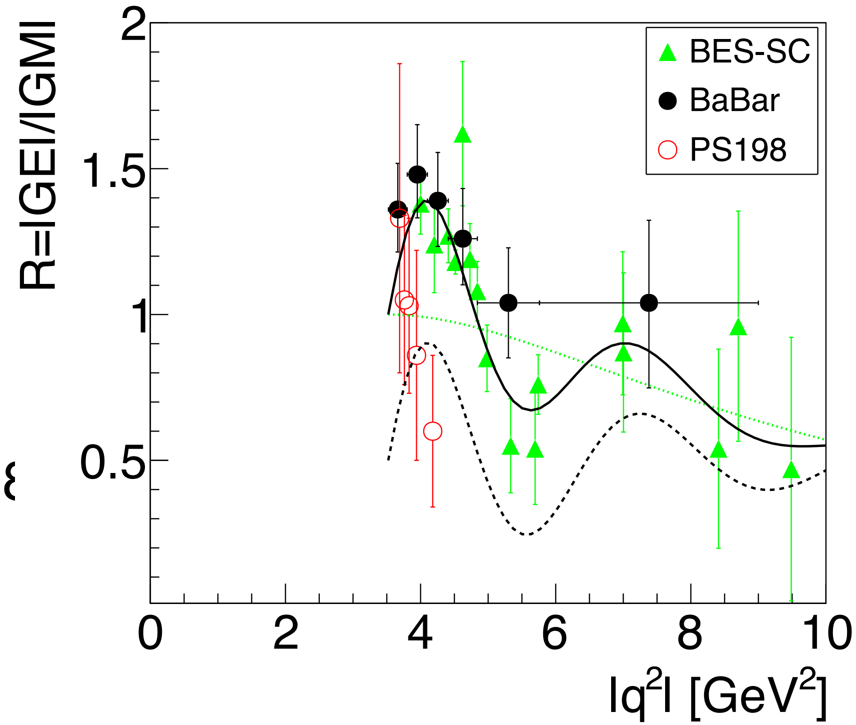
Data…



LEAR: antiproton

BaBar, Novosibirsk

BESIII



Thank you for your attention