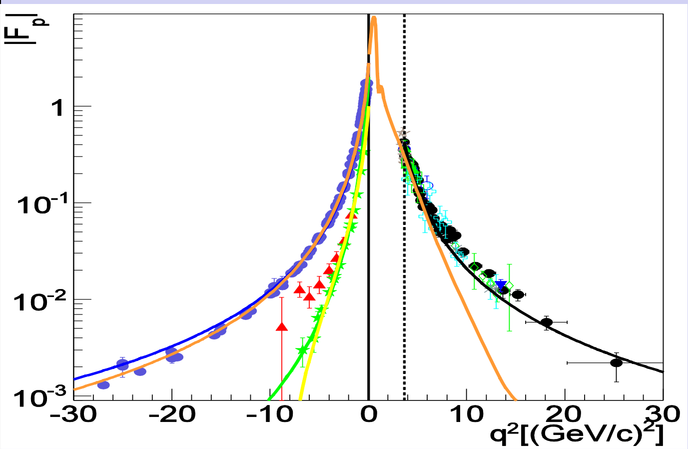
Hadron Form factors in space-like and time-like regions

Perspective



Egle Tomasi-Gustafsson
IRFU, SPhN-Saclay

AG-Theorie

IPN Orsay, 15-16 Decembre 2014

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

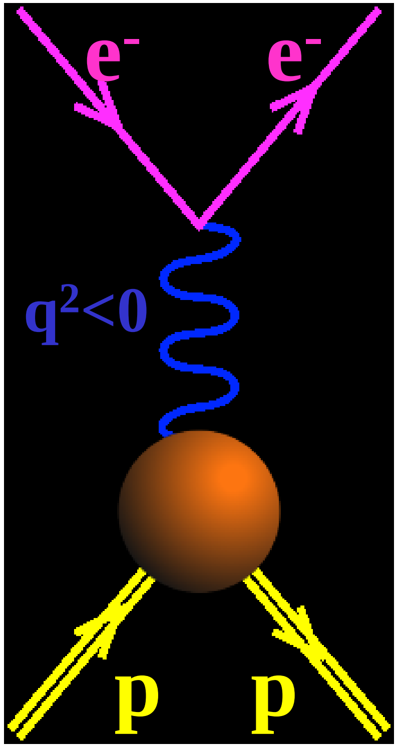
1/2 of the prize

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

Electromagnetic Interaction



The electron vertex is known, γ_μ

The interaction is carried by a virtual photon of mass q^2

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

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

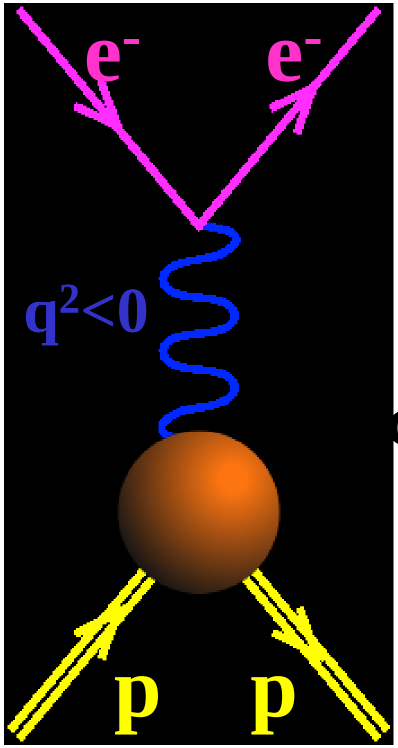
or in terms of Sachs FFs:

$GE = F_1 - \tau F_2$, $GM = F_1 + F_2$, $\tau = -q^2/4M^2$

What about high order radiative corrections?

Hadron Electromagnetic Form factors

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



GE(0)=1

GM(0)= μ_p

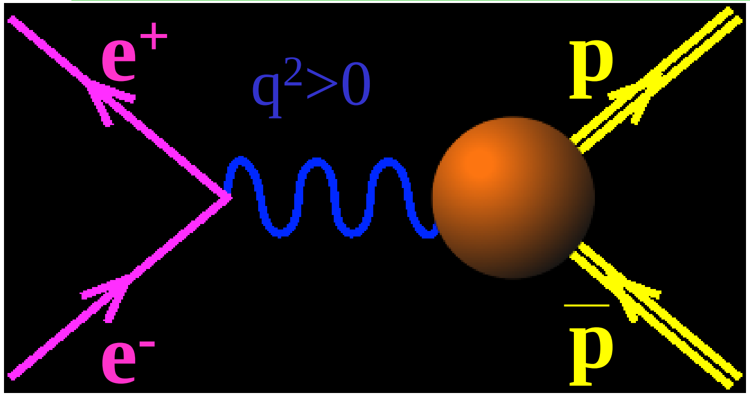
Unphysical region

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

Asymptotics

- QCD

- analyticity



Space-like

FFs are real

Time-Like

FFs are complex

q^2

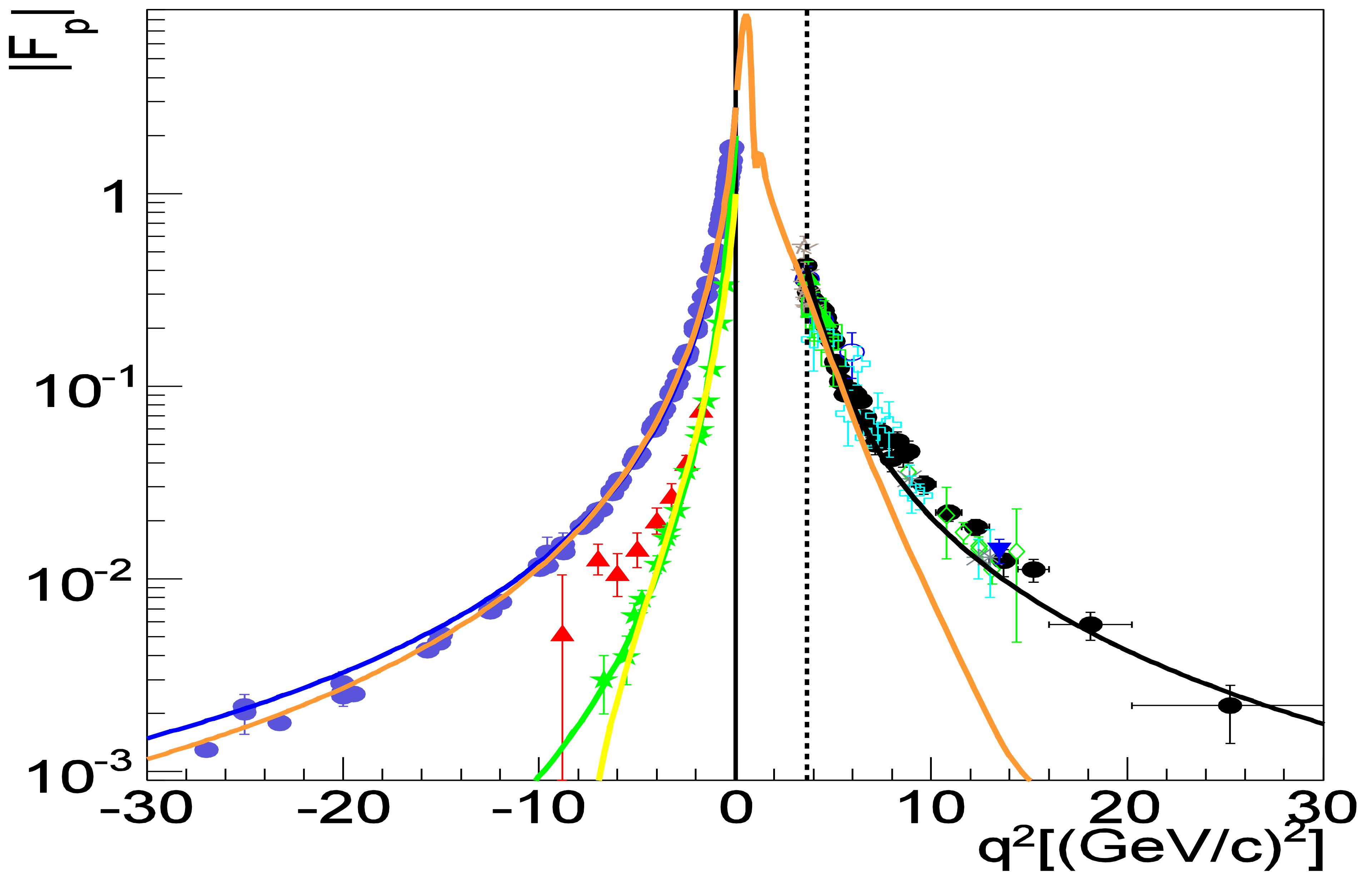
$e+p \rightarrow e+p$

$q^2=4m_p^2$

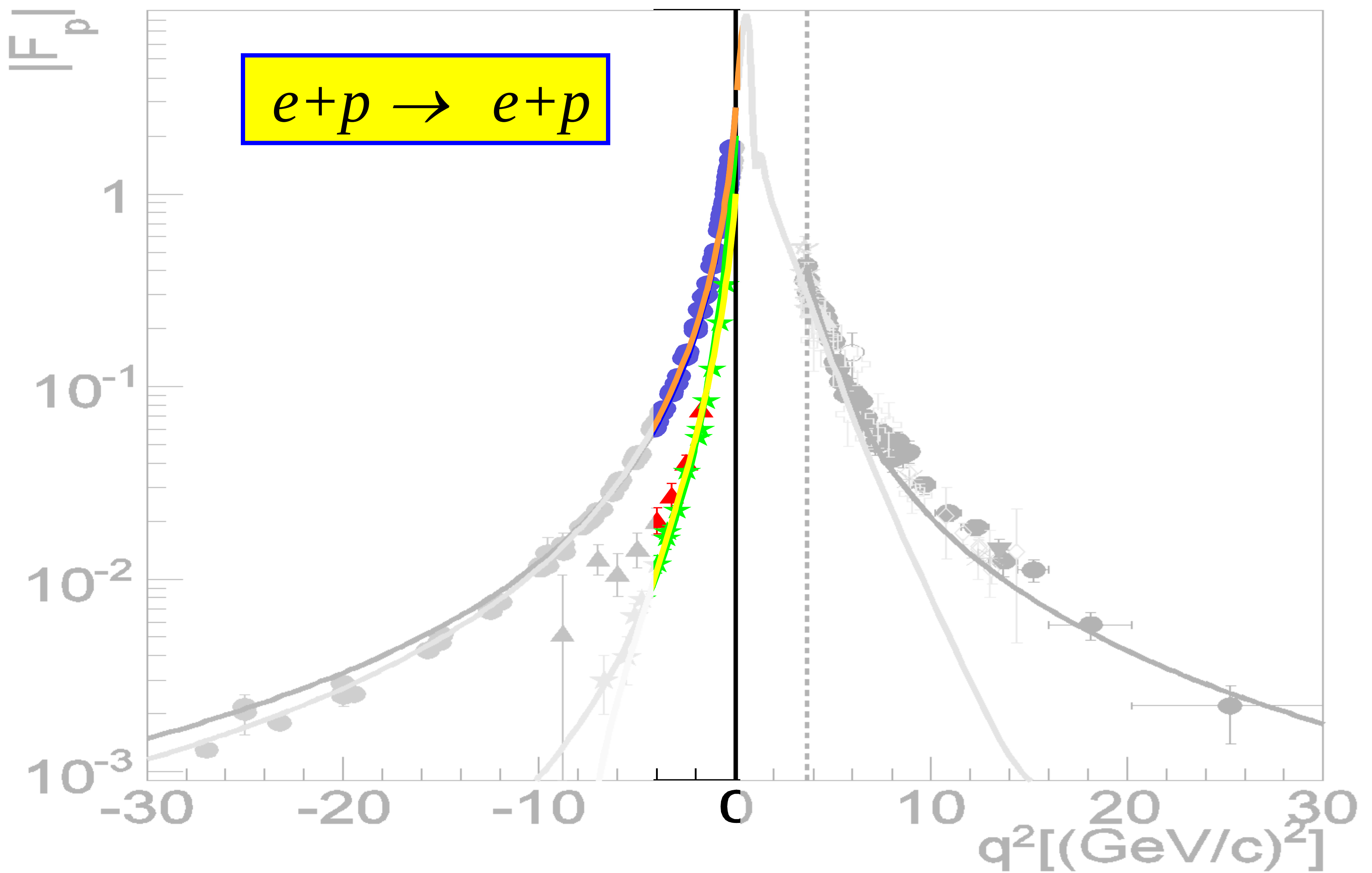
GE=GM

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

Hadron Electromagnetic Form factors



The Space-Like region: low Q^2

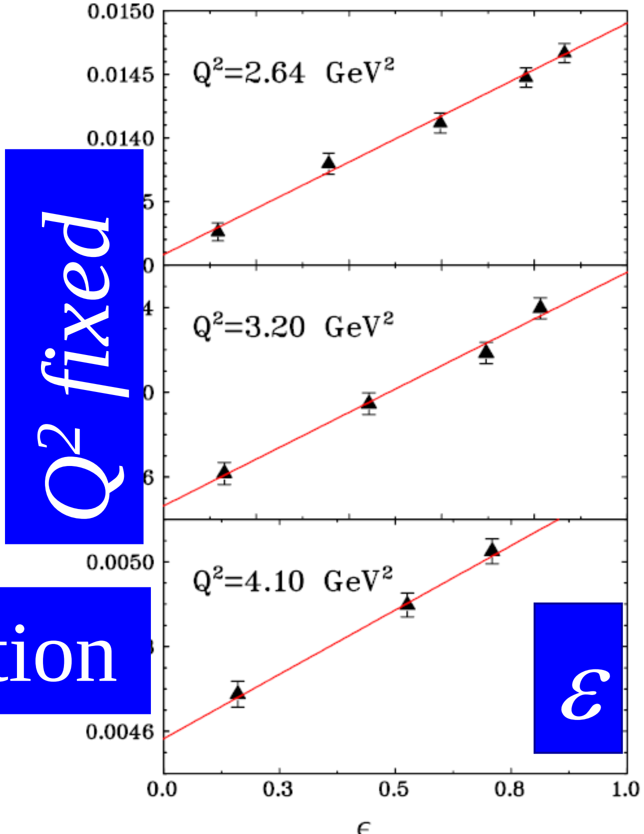


The Rosenbluth separation

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

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

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



PRL 94, 142301 (2005)

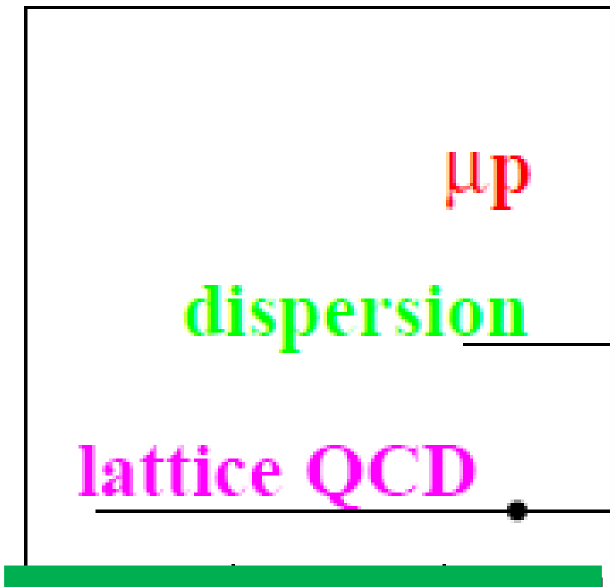
Linearity of the reduced cross section

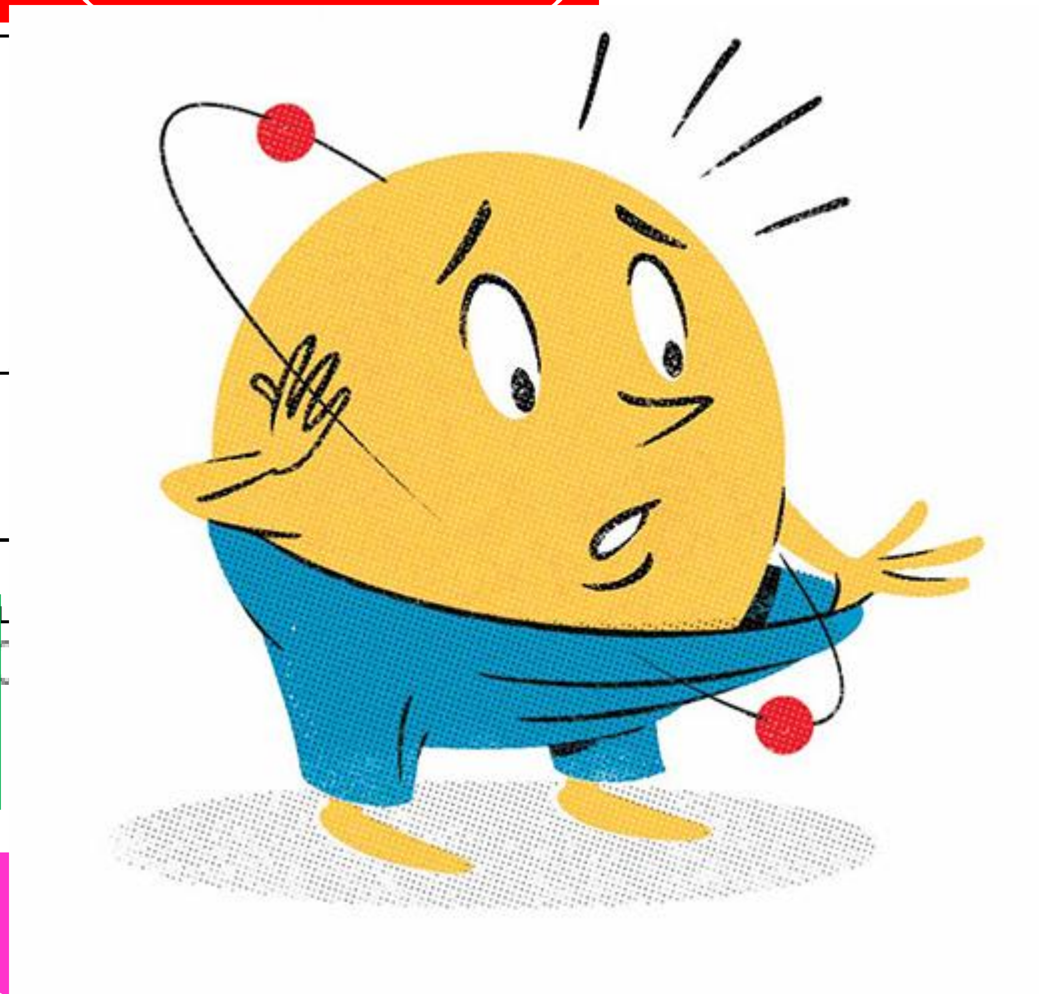
→ $\tan^2\theta_e$ dependence

→ Holds for 1γ exchange only

The Proton Radius

Rp=0.84184(67) fm (muonic atom)





n

9) fm

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

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

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)

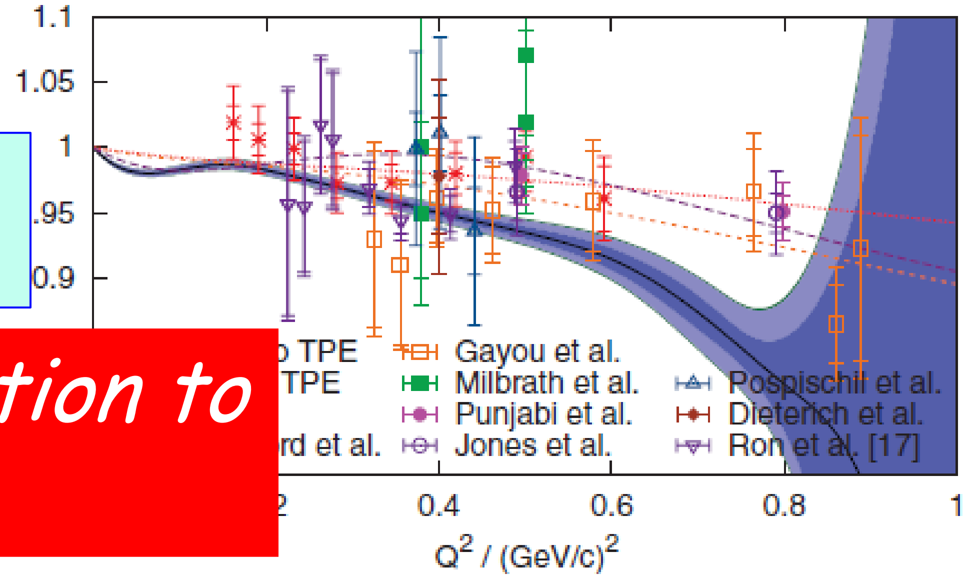
$Q^2 > 0.004\ \mathrm{GeV}^2$

- Radiative corrections
- Two photon exchange
- Coulomb corrections

.....*comments*

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

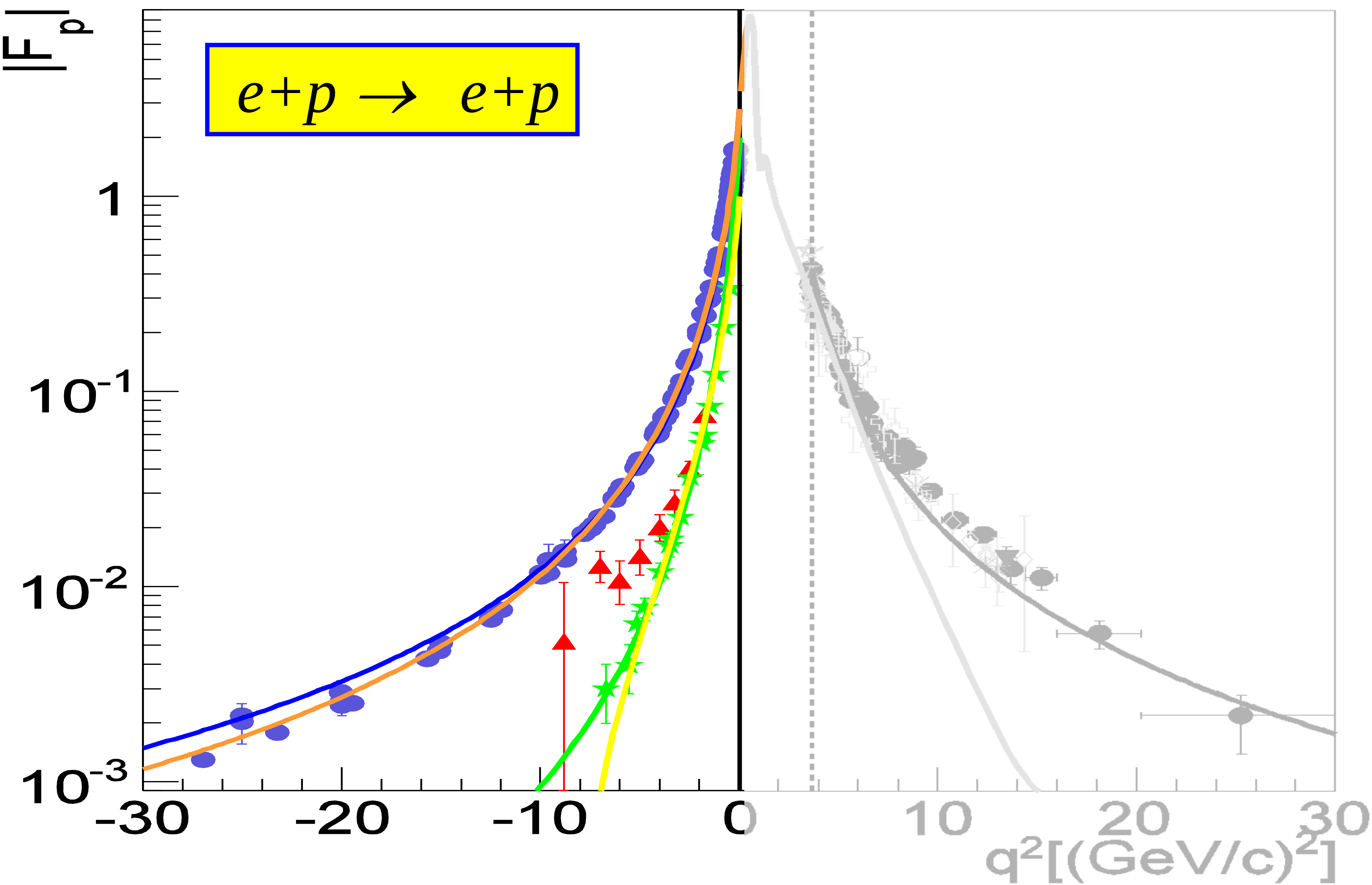
$$\langle r_M^2 \rangle^{1/2} = 0.777(13)_{\rm stat}(9)_{\rm syst}(5)_{\rm model}(2)_{\rm group}\ \mathrm{fm}.$$



- MUSE Experiment
- Jlab CLAS

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

The Space-Like region



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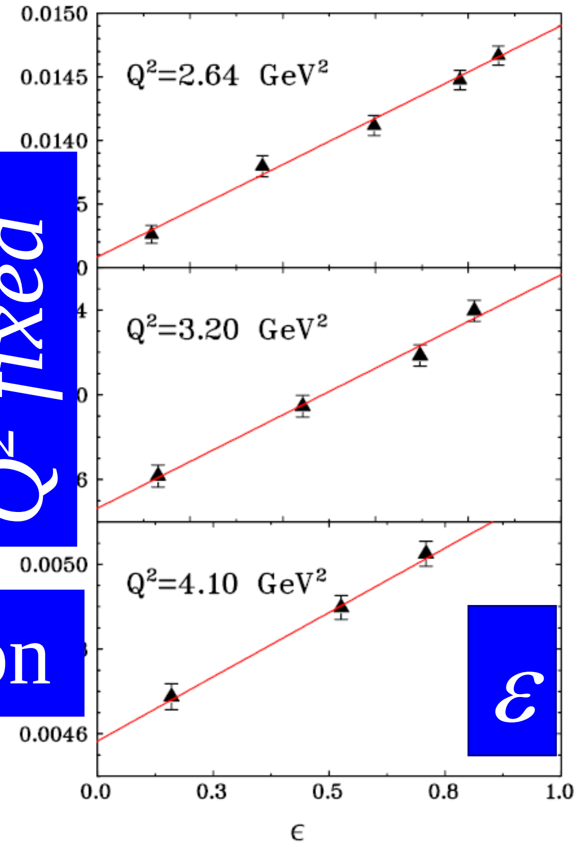
$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}, \tau = \frac{Q^2}{4M^2}$$

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



Q^2 fixed

ε

PRL 94, 142301 (2005)

Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

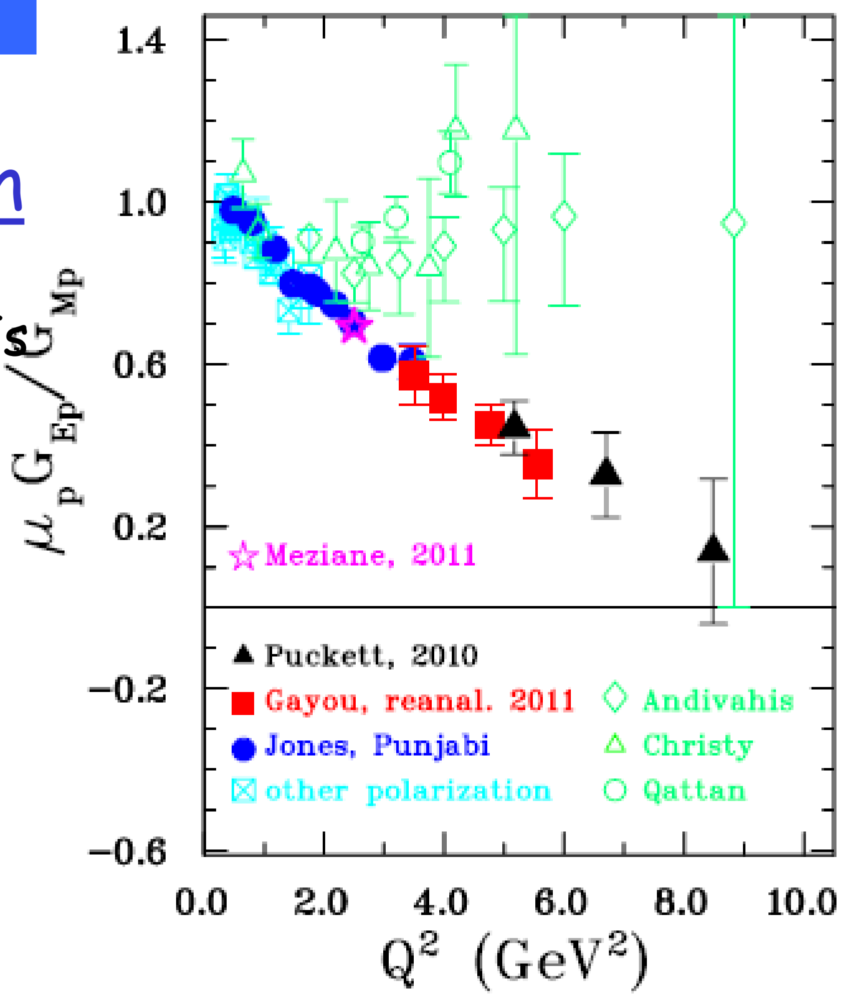
→ Holds for 1γ exchange only

Polarization experiments

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

Jlab-GEp collaboration

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



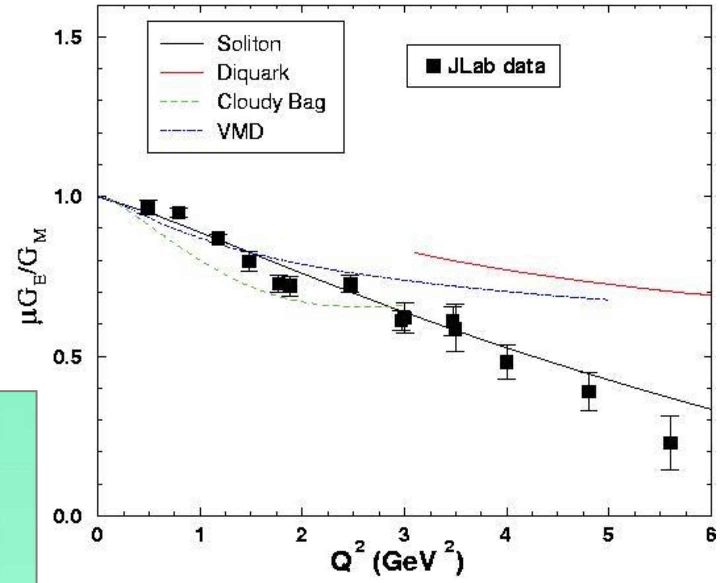
A.J.R. Puckett et al, PRL (2010), PRC (2012)

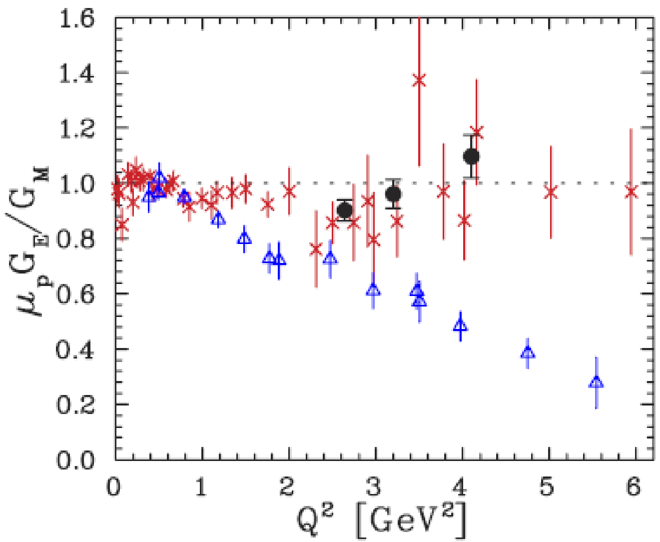
Issues

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

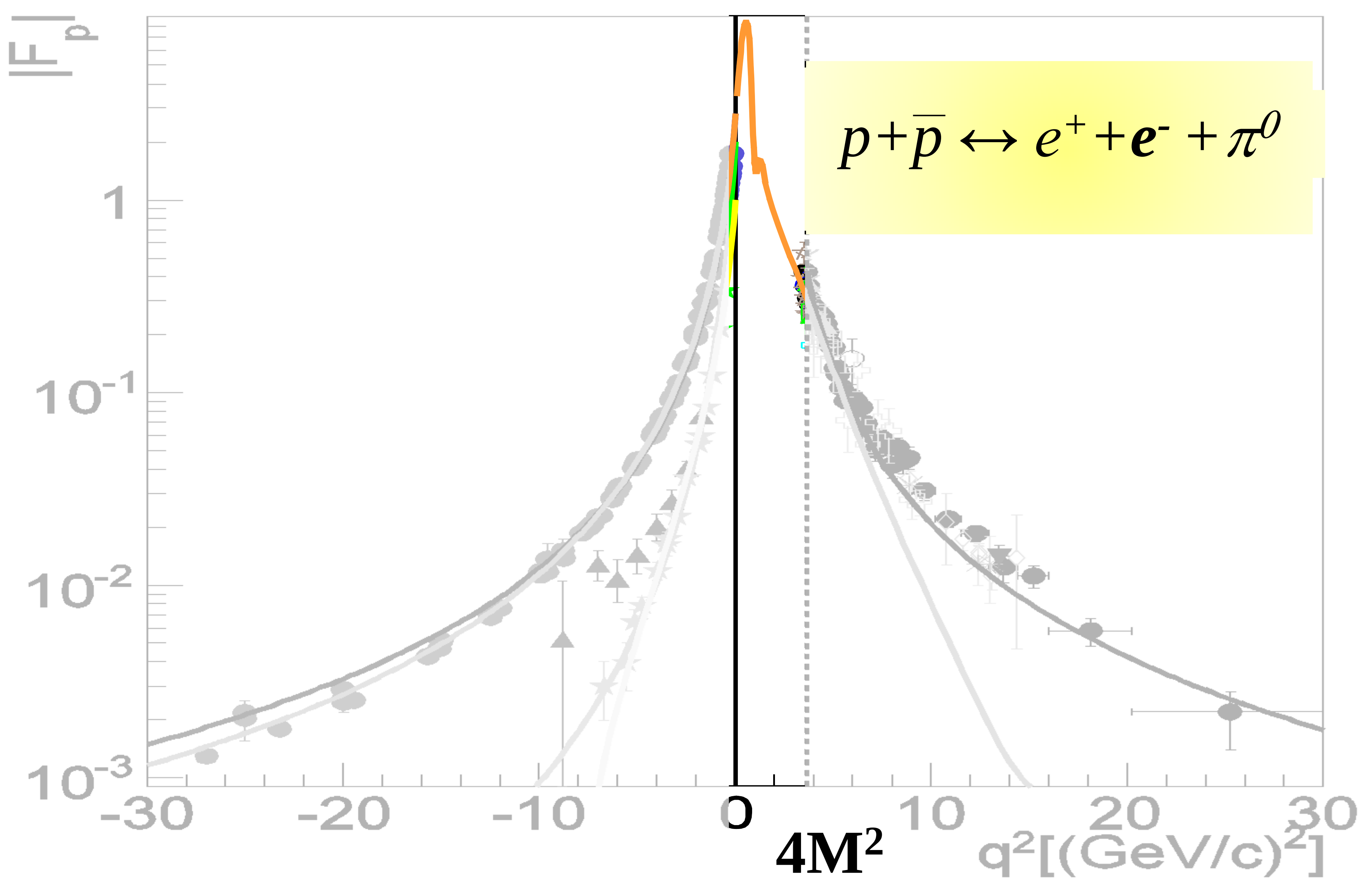
BUT

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





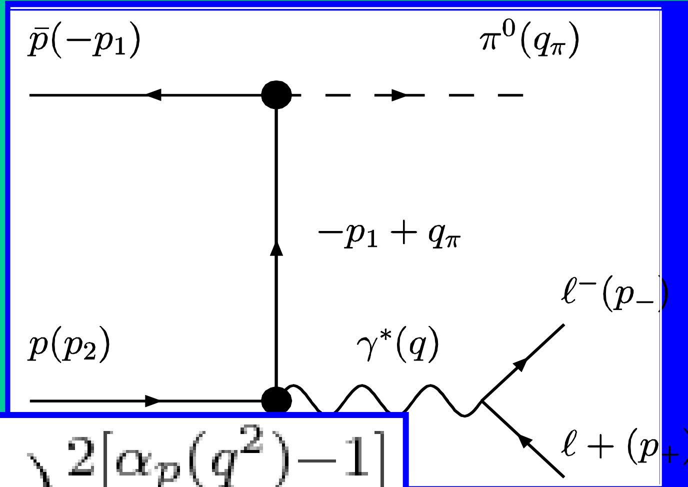
The "unphysical region"

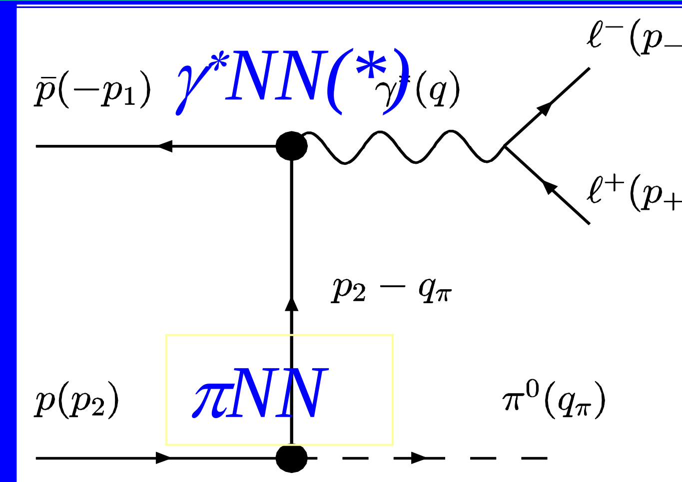


$$p+\bar{p} \leftrightarrow e^{+}+\boldsymbol{e}^{-}+\pi^{0}$$

The reaction $p + \bar{p} \rightarrow e^+ + e^- + \pi^0$

E.A. Kuraev, PRC, 2008
JETP, 2012
G.I.Gakh et al, PRC, 2011

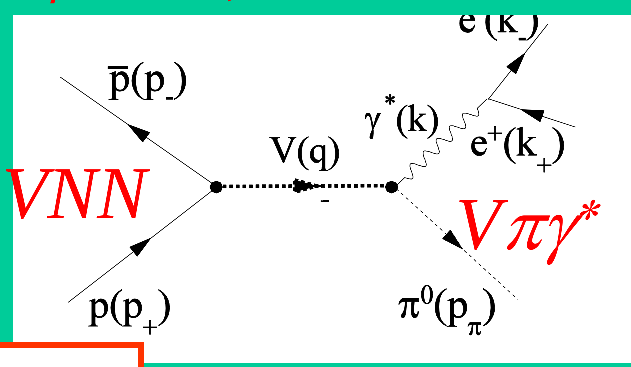




M. P. Rekalo, 1967

$$d\sigma_s \propto \frac{1}{q^2}\left(\frac{s}{M^2}\right)^{2[\alpha_p(q^2)-1]}$$

$V = \rho, \omega, \phi, J/\Psi, ..$



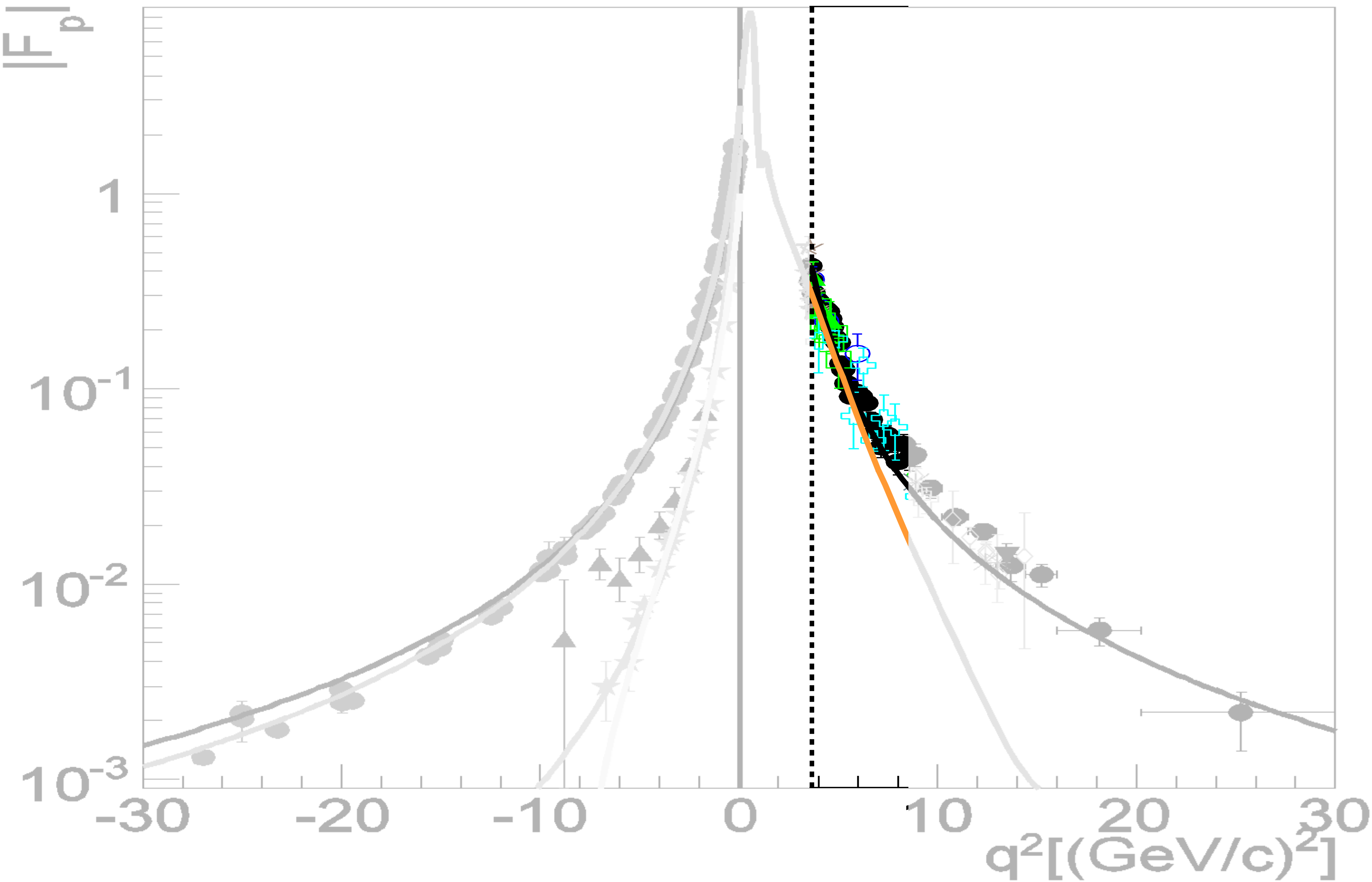
$$d\sigma_a \propto 1/s$$

Forward/backward
Regge trajectory of the proton

$$\frac{d\sigma_s}{d\sigma_a} \propto \left(\frac{s}{M^2}\right)^{2[\alpha_p(q^2)-1]} \ll 1$$

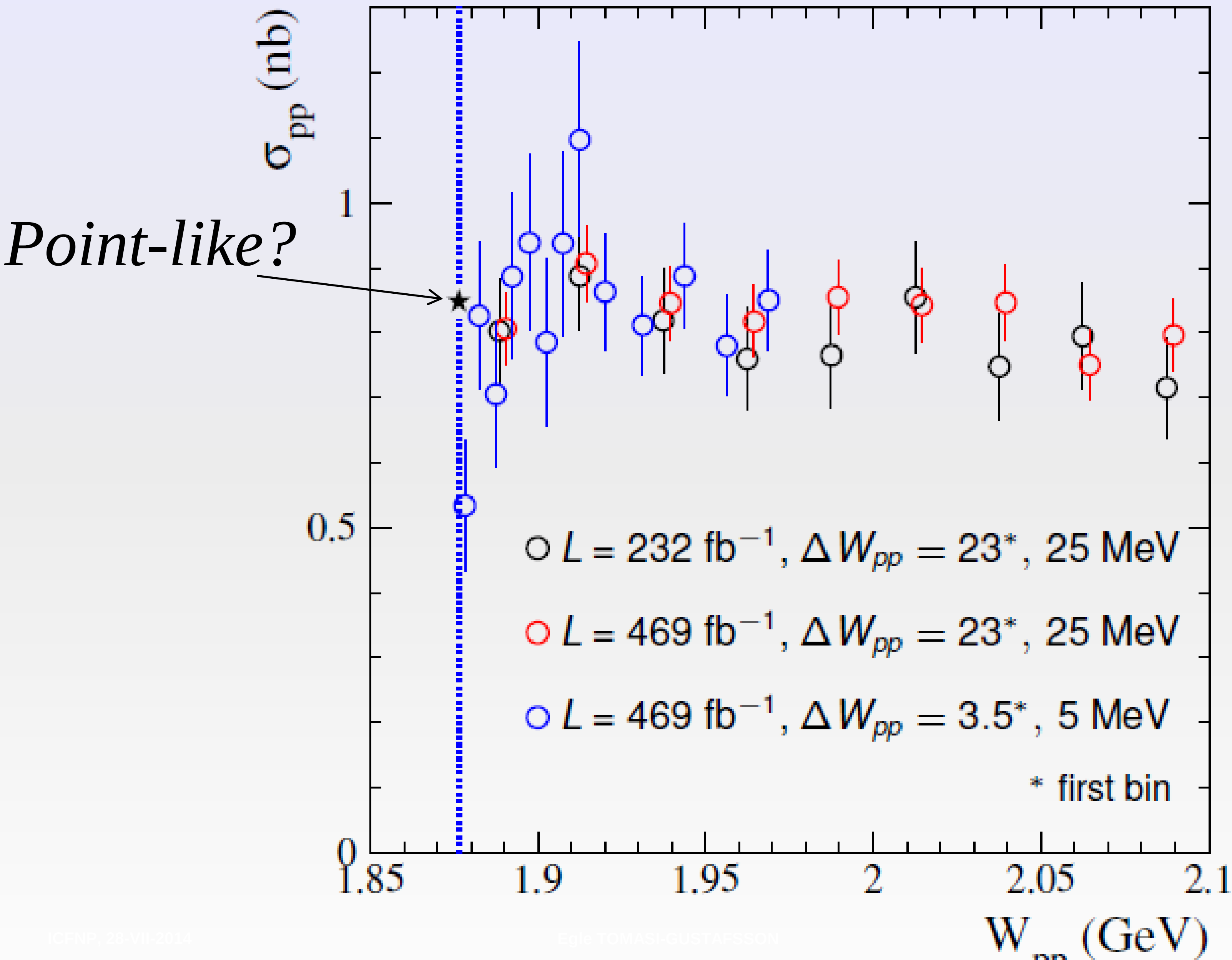
Large angle: VM exchange

The Time-like region: the threshold

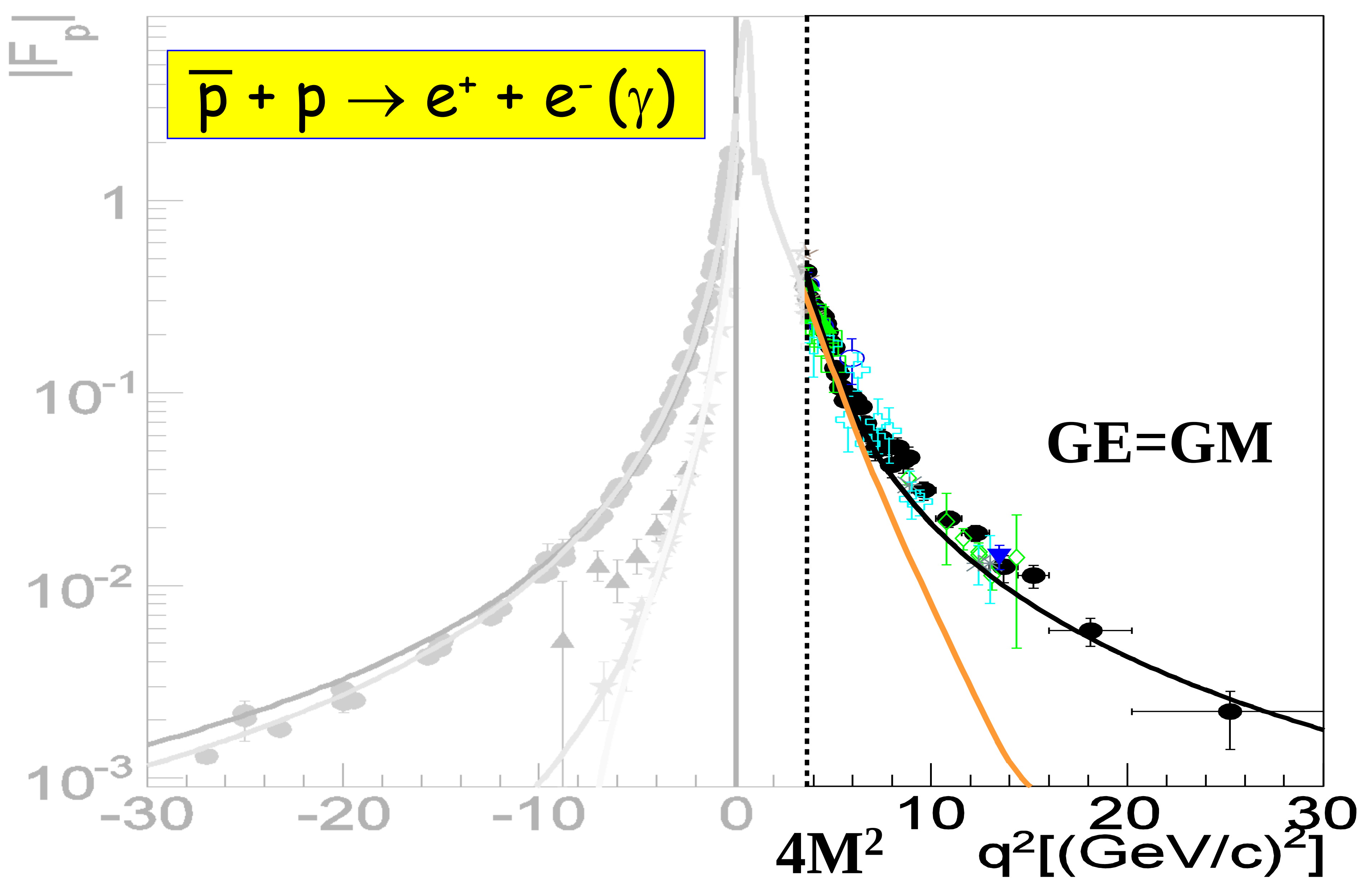


BABAR 2013: $e^+e^- \rightarrow p\bar{p}$

PRD73-012005, arXiv:13



The Time-Like region



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

-The cross section for $\overline{p}+p \to e^+ + e^-$ (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 $\overline{p}$ 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 Experimental facilities

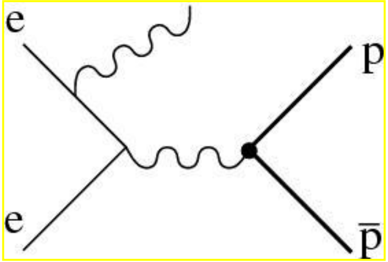
- Antiproton-proton colliders:
    - LEAR, FERMILAB, PANDA
- Electron –positron colliders
    - FENICE, VEPP, BABAR, BES
- Initial State Radiation
    - BABAR, BES

VEPP-Novosibirsk

IHEP

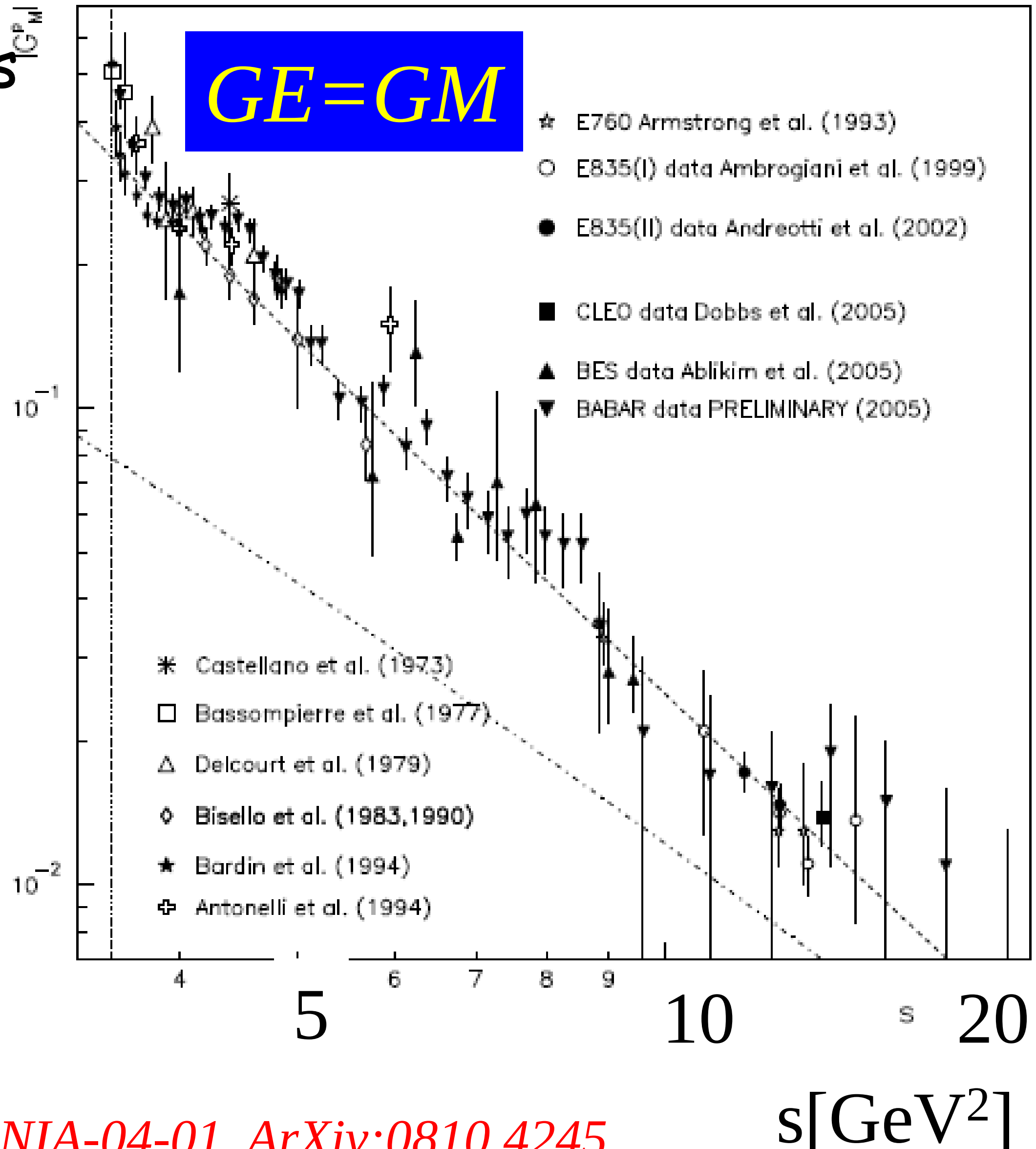
BES

BABAR



The Time-like region

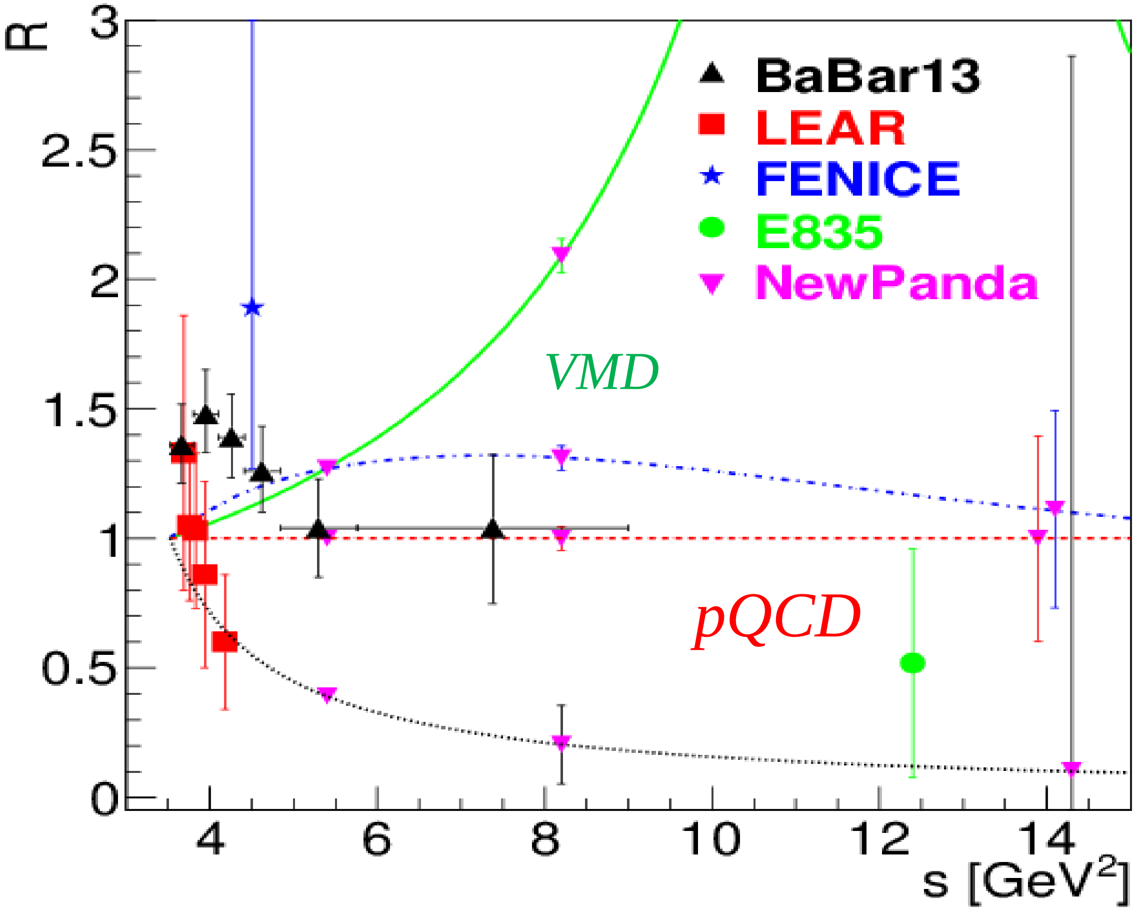
- The Experimental Status
  - No individual determination of GE and GM
  - TL proton FFs twice larger than in SL at the same Q^2
  - Steep behaviour at threshold
  - Babar:
    Structures?
    Resonances?
  - -> Panda contribution



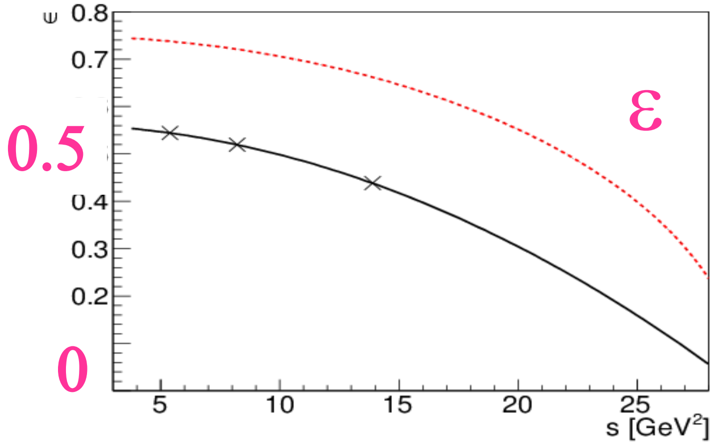
MP. Rekalo, E.T-G., preprint DAPNIA-04-01, ArXiv:0810.4245.

Individual determination of $|G_E|$ and $|G_M|$

A.Dbeyssi
PhD 2013

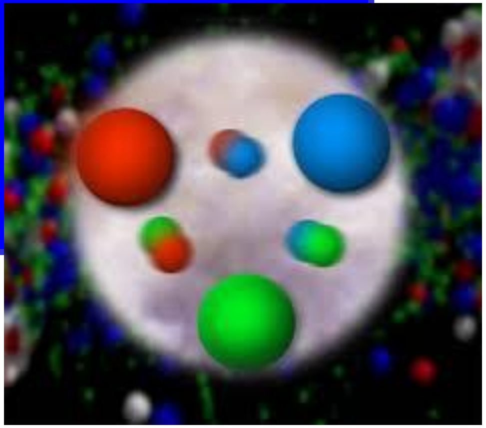


$\varepsilon \leq 50\%$



F. Iachello et al., Phys. Rev. C 69 (2004) 055204
E. L. Lomon, Phys. Rev. C 66 (2002) 045501
E. A. Kuraev et al., Phys. Lett. B 712, (2012)
V. A. Matveev, S. J. Brodsky , D. V. Shirkov….

The nucleon



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

antisymmetric state of colored quarks

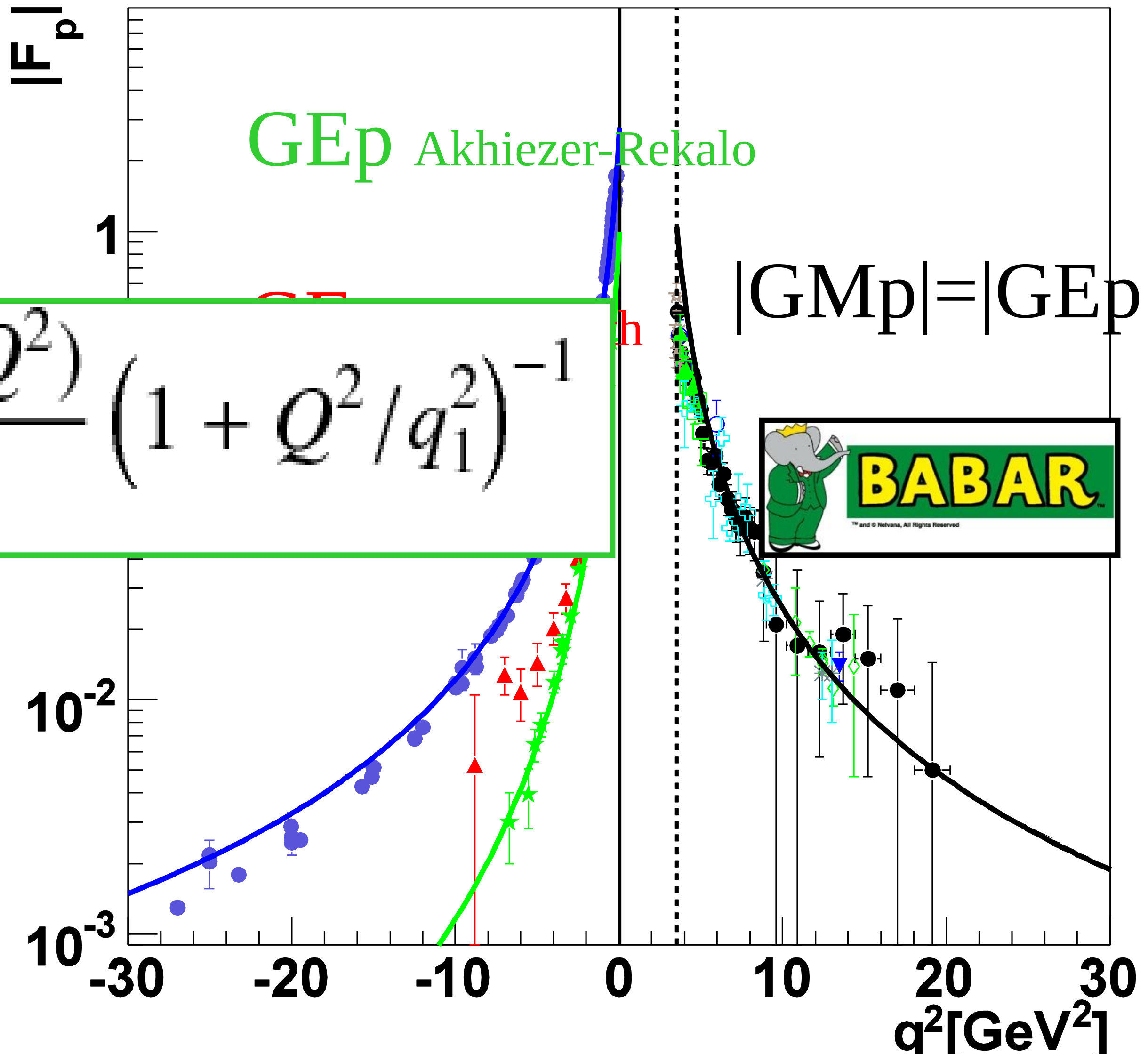
$$|p> \sim \epsilon_{ijk}|u^i u^j d^k>$$
$$|n> \sim \epsilon_{ijk}|u^i d^j d^k>$$

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

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

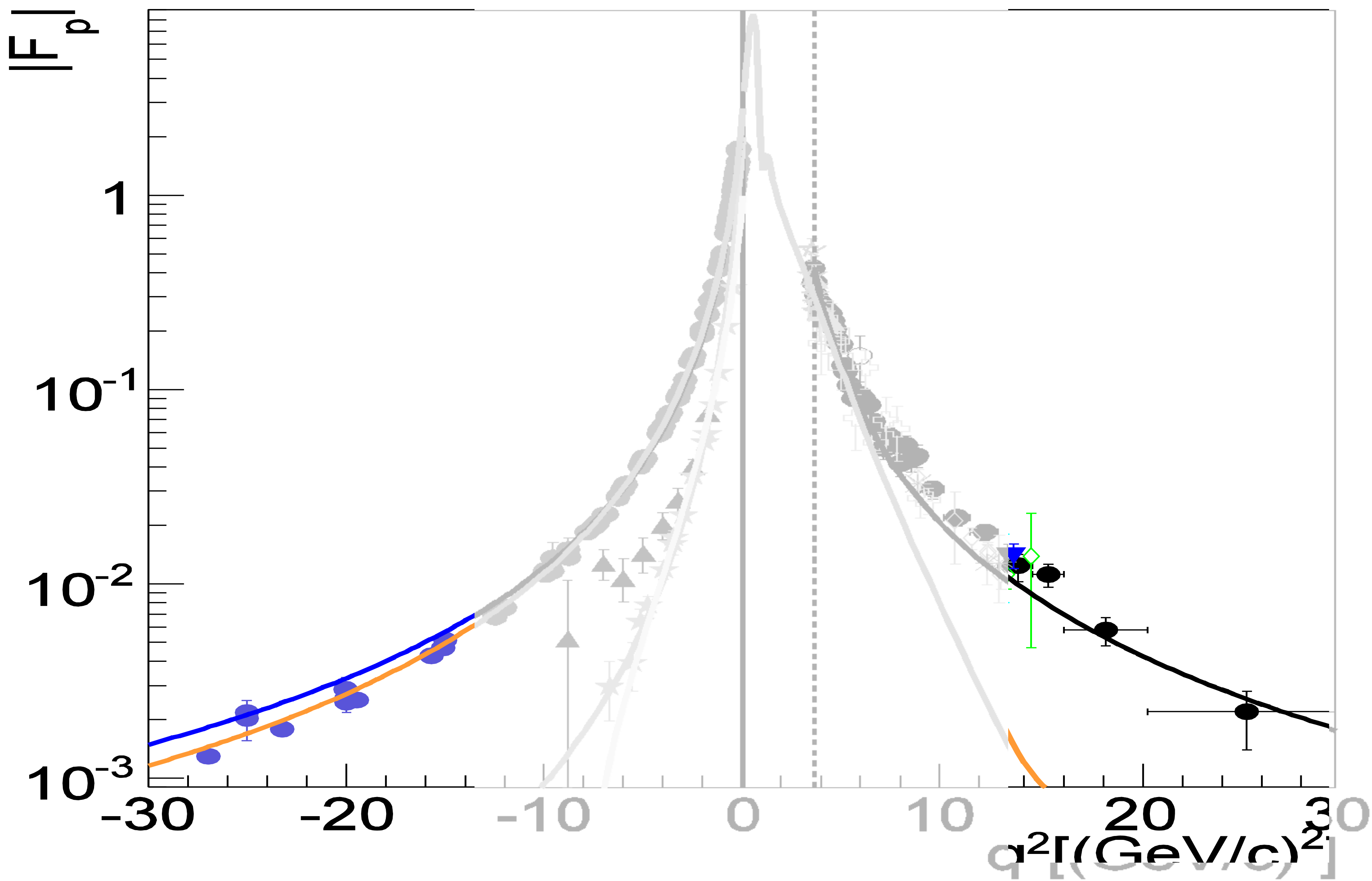
Proton Form Factors



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

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

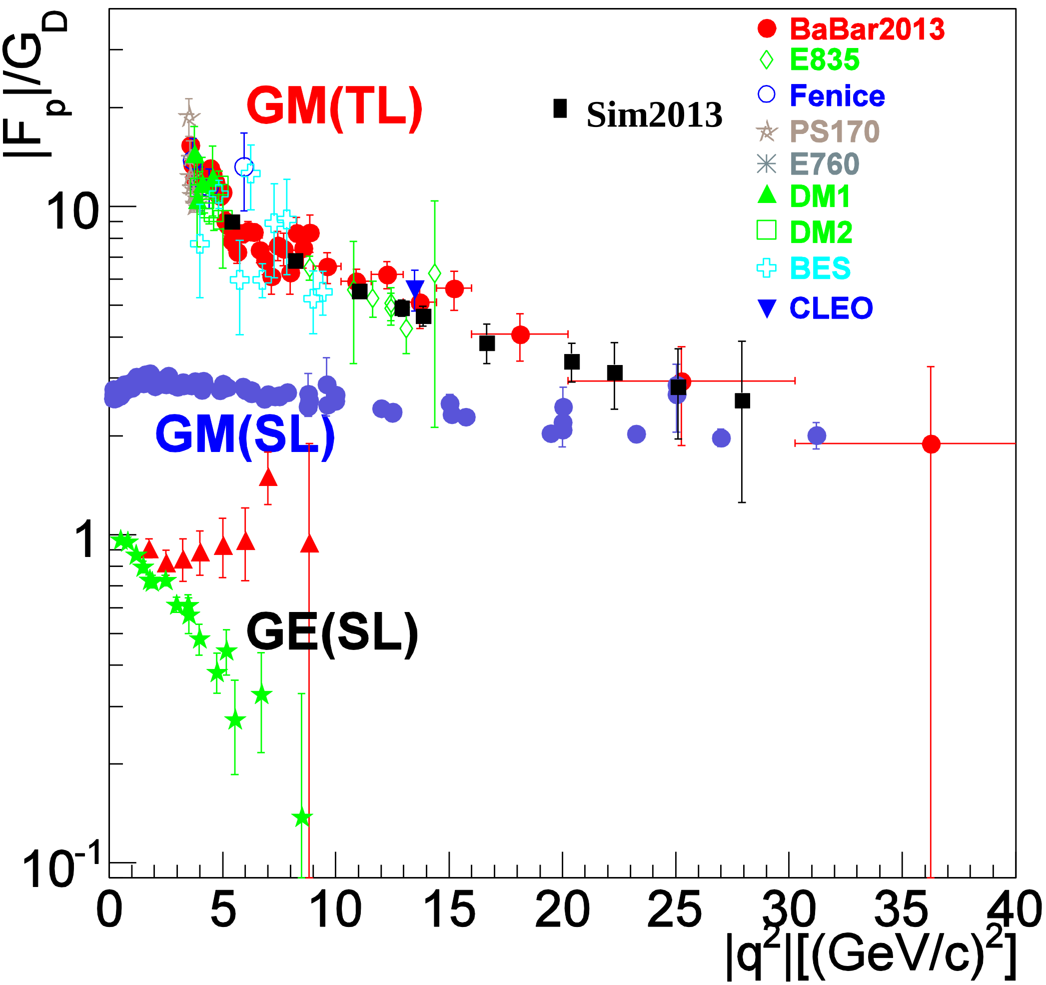
The asymptotic region



Proton form factors at large q^2

$\mathscr{L} = 2 \cdot 10^{32}\ cm^{-2}\ s^{-1}$

100 days



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	time – like
$(e^- + p \to e^- + p)$	$(e^+ + e^- \leftrightarrow \overline{p} + p)$

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

Applies to NN and N$\overline{\text{N}}$ Interaction

(Pomeranchuk theorem)

t=0 : not a QCD regime!

Analyticity

Connection with QCD asymptotics?

Conclusions

•<u>Large activity</u> both in Space and Time-like regions

Jefferson Lab

VEPP-3 Novosibirsk

IHEP BES

•<u>Unified models in SL and TL regions:</u>

- *describe* proton, neutron, electric, magnetic FFs
- pointlike behavior at threshold?
- *understand* GE, GM(SL) < GE,GM(TL);

•<u>To measure</u>

- zero crossing of GE/GM in SL? 2γ? Proton radius?
- GE and GM separately in TL (PANDA)
- complex FFs in TL region: polarization

Thank you for your attention