Scattering and Annihilation Processes

Trento, ECT*, February 18-22, 2013

Time-like and Space-like Hadron Form Factors

Egle Tomasi-Gustafsson

Simone Pacetti

Marco Maggiora

Purpose of the workshop

Gather experimentalists and theoreticians from different communities: electron, hadron accelerators and colliders

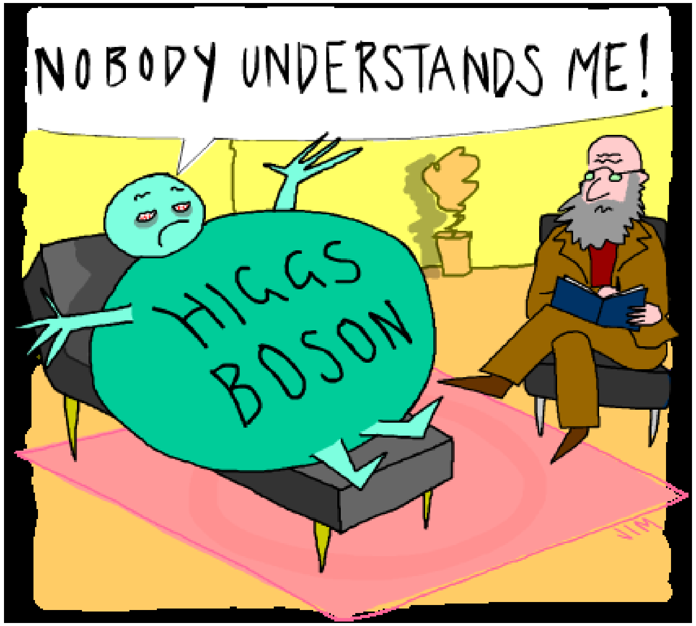
Progress on the way of having a unified and coherent description of hadron electromagnetic FFs in the whole kinematical region

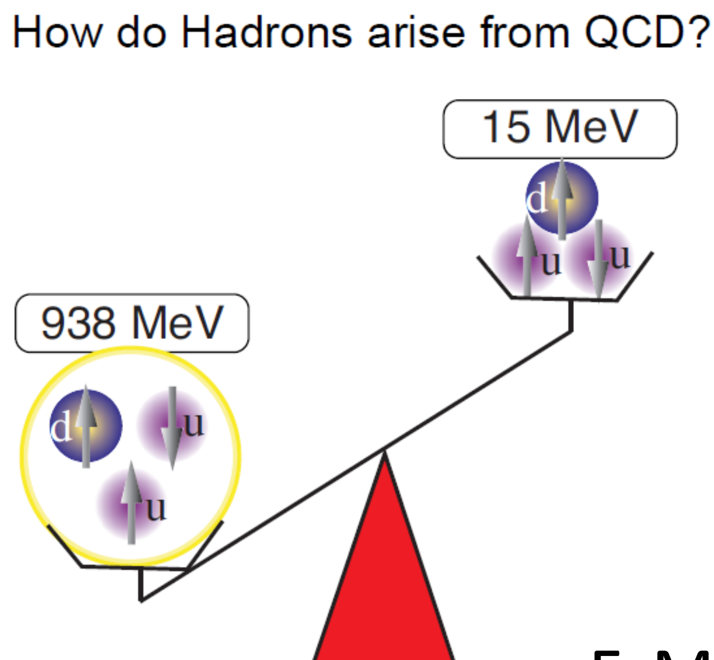
Triggered by recent precise data : ep-scattering (Jlab), e+e- (Novosibirsk, BESIII) and future pbar+p (PANDA, FAIR)

Three general introductory talks

Diego Bettoni, Frank Maas, Rinaldo Baldini

Le Monde, July 2012: the Word of the Month: HIGGS BOSON





F. Maas

Static:
Origin of nucleon mass
Quark and gluon condensate
Dynamics:
Structure of the nucleon: form factors

Hadron Form Factors: a long history

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.

factors: Playground for theory and experiment

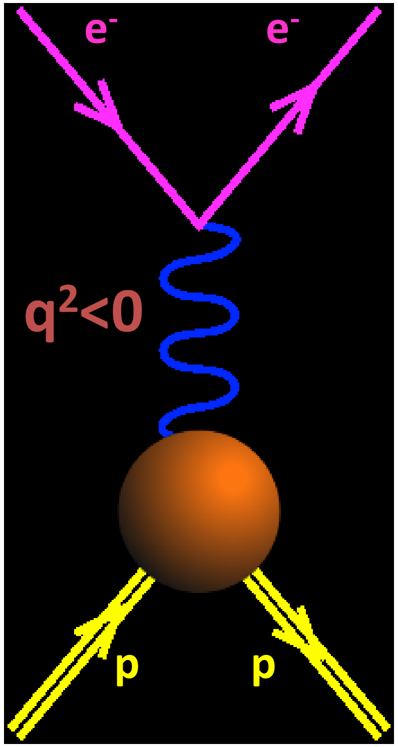
at low q^2 probe the size of the nucleus, at high q^2 test QCD scaling

...some names are UNAVOIDABLE
in references!

The 'Kharkov' school The 'Italian' school
The 'Russian' school

Experiments and Theory: France,Germany

Electromagnetic Interaction



The electron vertex is known, γ_μ

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

Physical meaning in decomposition of squares G_E^2 and G_M^2.

$$\sigma^{\delta,\delta} = G_E^2, \;\; \sigma^{-\delta,\delta} = \frac{\tau}{\varepsilon} G_M^2 \; . \tag{11}$$

The terms $\sigma^{\delta,\delta}$ and $\sigma^{-\delta,\delta}$ in Eq. (7), (11) are the cross sections without and with the spin-flip for the case where the initial and final protons are fully polarized in the direction of the motion of the final proton.
In the case when $\vec{c}_1 = \vec{n}_2$ and $\vec{c}_2 = \vec{n}_2$ we have $\sigma^{\delta,\delta} \rightarrow$ for non-spin-flip transition.
In the case when $\vec{c}_1 = \vec{n}_2$ and $\vec{c}_2 = -\vec{n}_2$ we have $\sigma^{-\delta,\delta} \;\; \rightarrow$ for spin-flip transition.

Consequently for the matrix elements of the proton current $J_p^{\pm\delta,\delta}$ we have

$$J_p^{\delta,\delta} = \sqrt{\sigma^{\delta,\delta}} \sim G_E \, , \; J_p^{-\delta,\delta} = \sqrt{\sigma^{-\delta,\delta}} \sim \sqrt{\tau}\, G_M \; . \tag{12}$$

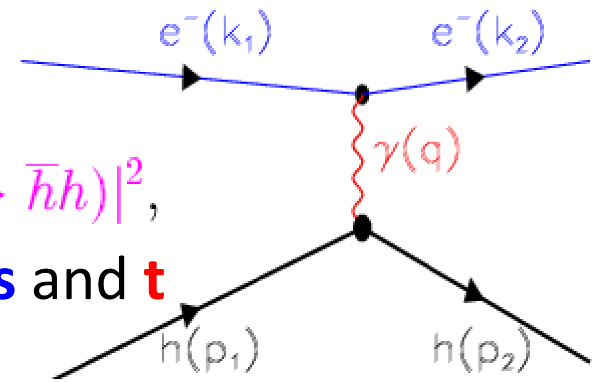
To prove the relations (11) and (12) we can offer three ways:

- Using the method for calculating of the QED matrix elements in the so-called "Diagonal Spin Basis" (DSB).
- Using the standard method for calculation of the QED cross sections.
- Using the textbook of F. Halzen and A. Martin "Quarks and leptons. An Introductory Course in Modern Particle Physics", 1984 (Page 178).

Crossing Symmetry

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

Scattering and annihilation channels:



- Described by the same amplitude :

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

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

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

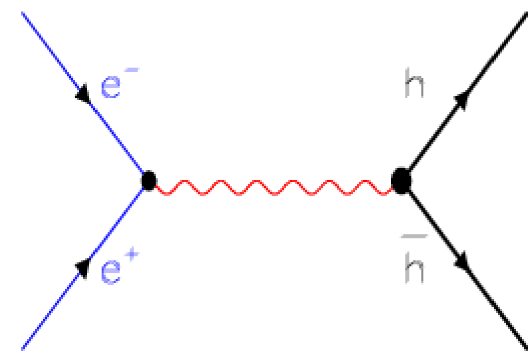
$e^- + e^+ \rightarrow \overline{h} + h$

- which scan different kinematical regions

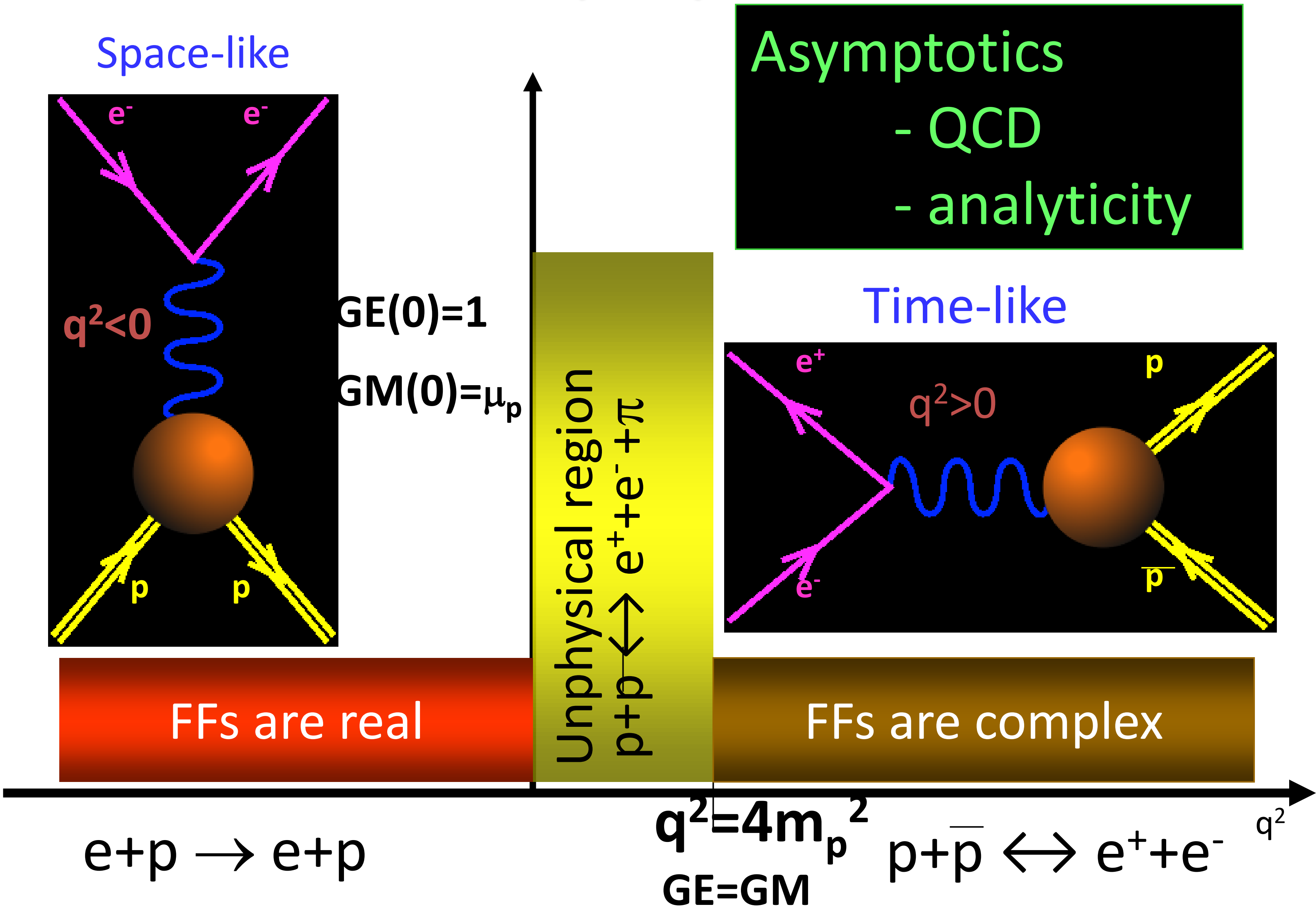
$k_2 \rightarrow -k_2$

$p_2 \rightarrow -p_2$

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



Analyticity



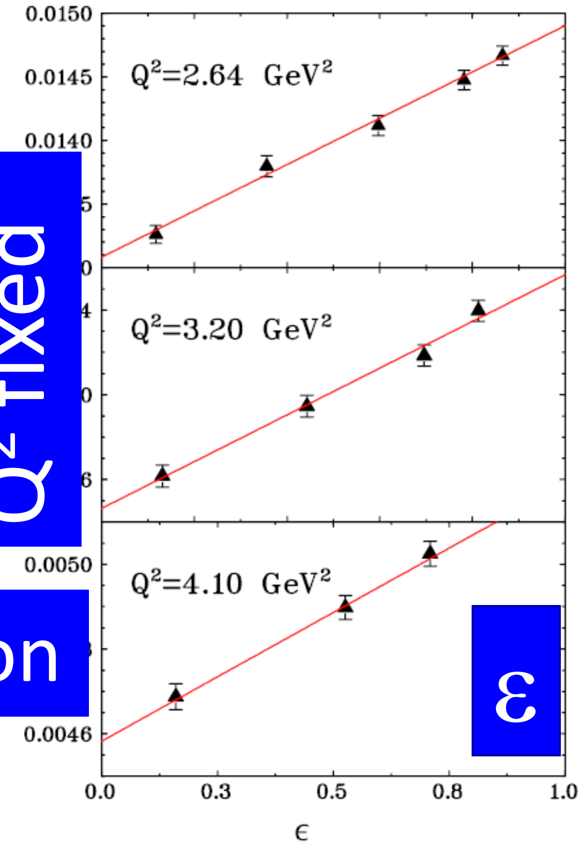
The Rosenbluth separation

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

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

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

Q^2 fixed



ε

PRL 94, 142301 (2005)

Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

→ Holds for 1γ exchange only

The polarization method (1967)

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

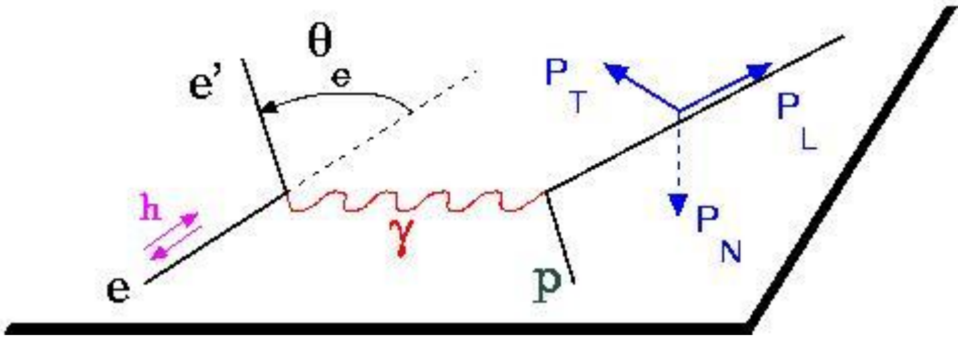
PHYSICS

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,

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



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)

C. Perdrisat et al, JLab-GEp collaboration

Transferred polarization is:

(Akhieze

$$P_n = 0$$

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

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

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

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

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

The simultaneous measurement of P_t and P_l reduces the systematic errors

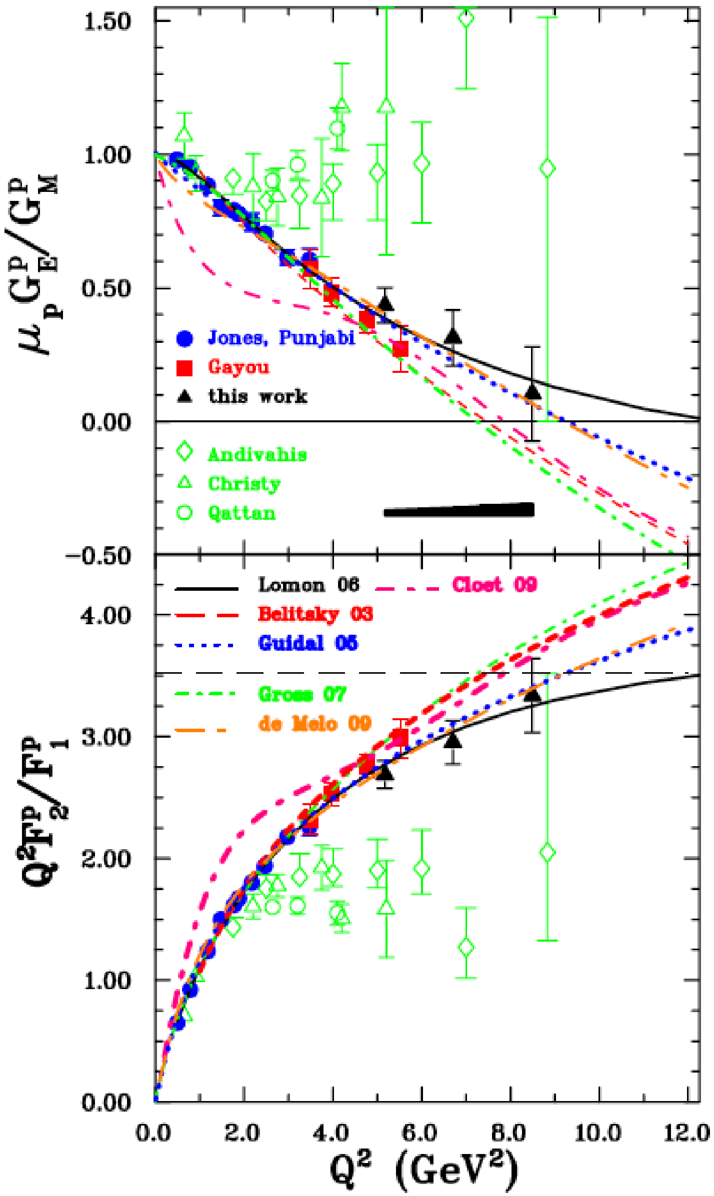
Polarization experiments - Jlab

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

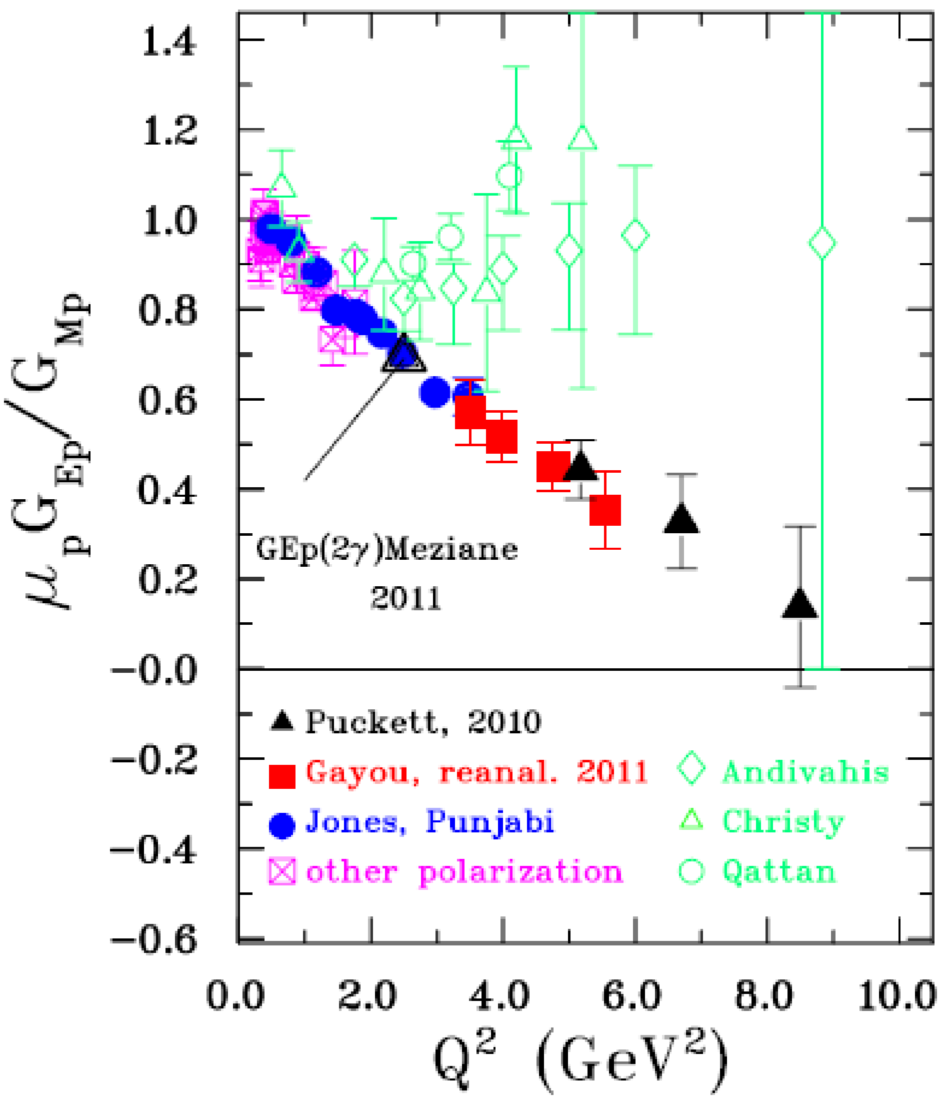
GEp collaboration

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)



Gep III results (2010)



QED Radiative Corrections

Modify the <u>absolute value</u> of the experimental observables <u>and their dependence</u> from the relevant kinematical variables

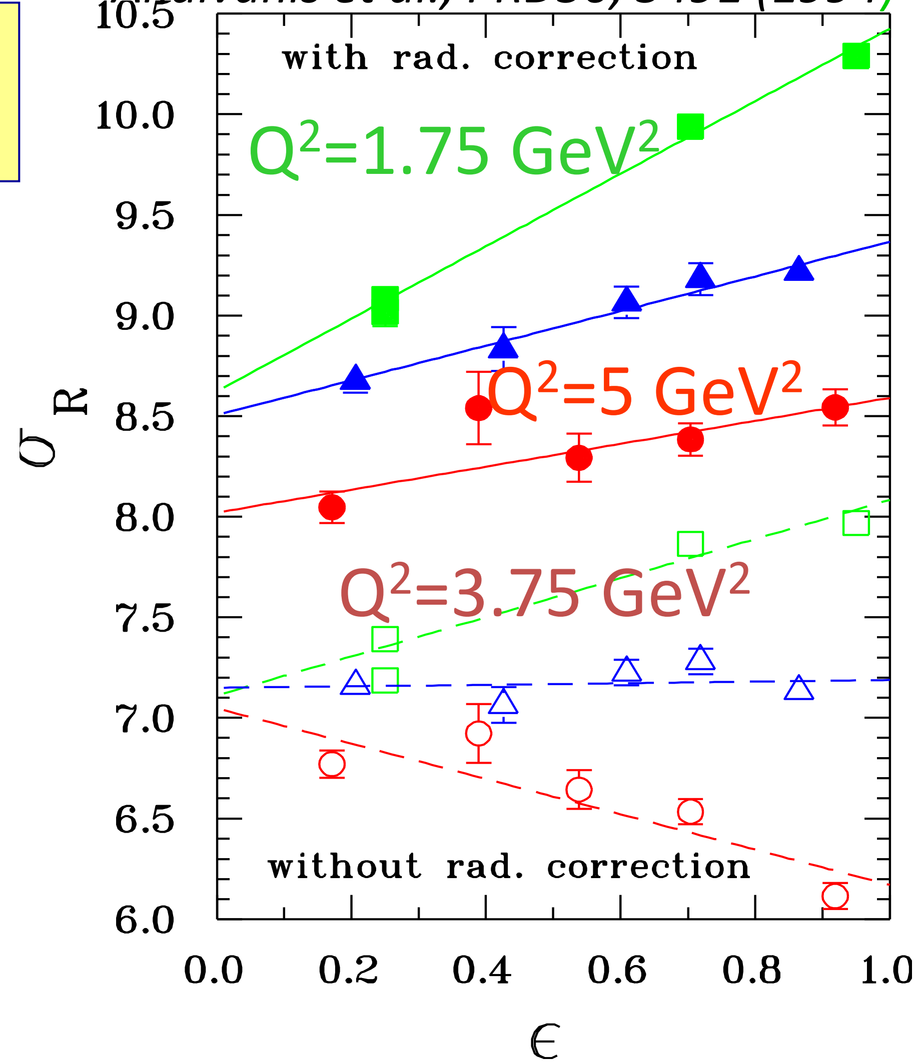
Radiative Corrections (ep)

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

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

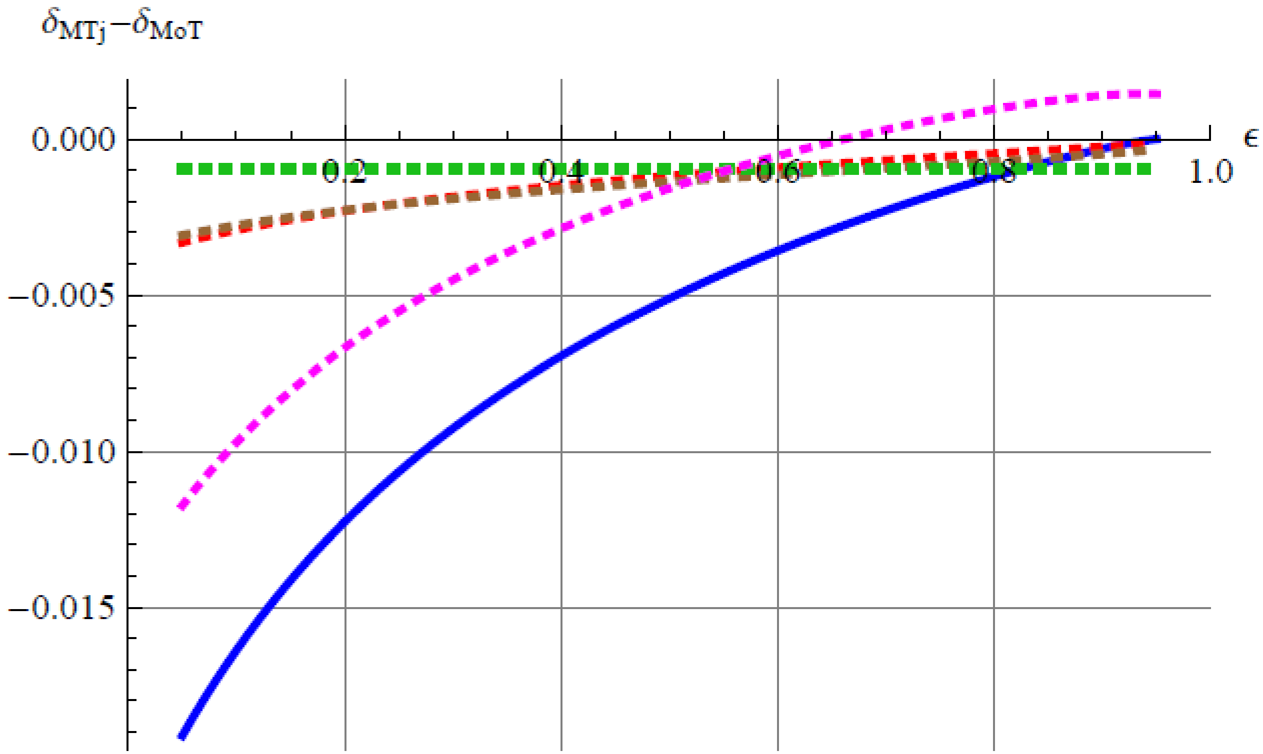
RC to the cross section:
– large (may reach 40%)
– ε and Q^2 dependent
– calculated at first order

Andivahis et al., PRD50, 5491 (1994)



E. T.-G., G. Gakh, PRC72, 015209 (2005), C.F Perdrisat et al, Progr.Part.Nucl.Phys.(2010)

First order Radiative Corrections (ep)
Mo&Tsai (1969) - Maximon&Tjon (2000)



V. Fadin

Q^2=5 GEV^2

The difference

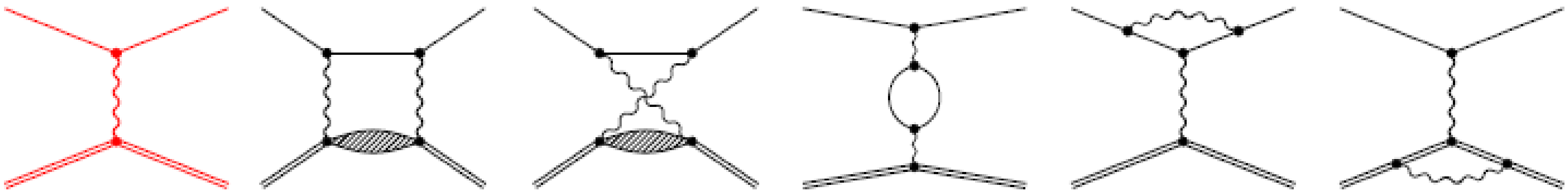
- is epsilon-dependent
- increases with Q^2

E.A. Kuraev et al,

e-Print: arXiv:0805.3623 [hep-ph] |

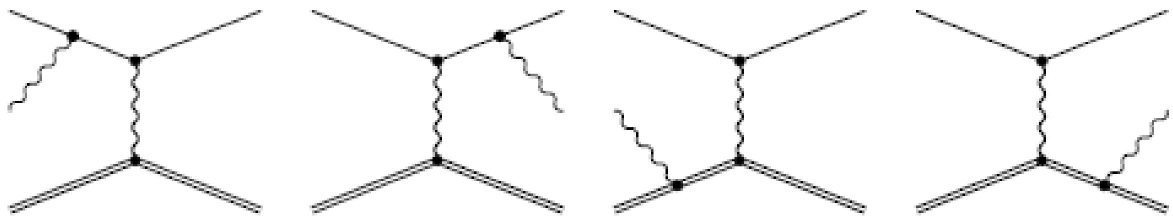
Born cross section and radiative corrections of order α

"Elastic" scattering ($e^{\pm}p \to e^{\pm}p$):



$\mathcal{M}_{\text{Born}}$ $\mathcal{M}_{2\gamma}$ $\mathcal{M}_{\text{vac}}$ $\mathcal{M}^{\ell}_{\text{vert}}$ $\mathcal{M}^{p}_{\text{vert}}$

Bremsstrahlung ($e^{\pm}p \to e^{\pm}p\,\gamma$):



$\mathcal{M}^{\ell}_{\text{brems}}$ $\mathcal{M}^{p}_{\text{brems}}$

$$\sigma(e^{\pm}p) = |\mathcal{M}_{\text{Born}}|^2 \pm 2\,\text{Re}\left(\mathcal{M}^{\dagger}_{\text{Born}}\mathcal{M}_{2\gamma}\right) +$$

$$+\,2\,\text{Re}\left(\mathcal{M}^{\dagger}_{\text{Born}}\mathcal{M}_{\text{vac}}\right) + 2\,\text{Re}\left(\mathcal{M}^{\dagger}_{\text{Born}}\mathcal{M}^{\ell}_{\text{vert}}\right) + 2\,\text{Re}\left(\mathcal{M}^{\dagger}_{\text{Born}}\mathcal{M}^{p}_{\text{vert}}\right) +$$

$$+\,|\mathcal{M}^{\ell}_{\text{brems}}|^2 + |\mathcal{M}^{p}_{\text{brems}}|^2 \pm 2\,\text{Re}\left(\mathcal{M}^{\ell\dagger}_{\text{brems}}\mathcal{M}^{p}_{\text{brems}}\right)$$

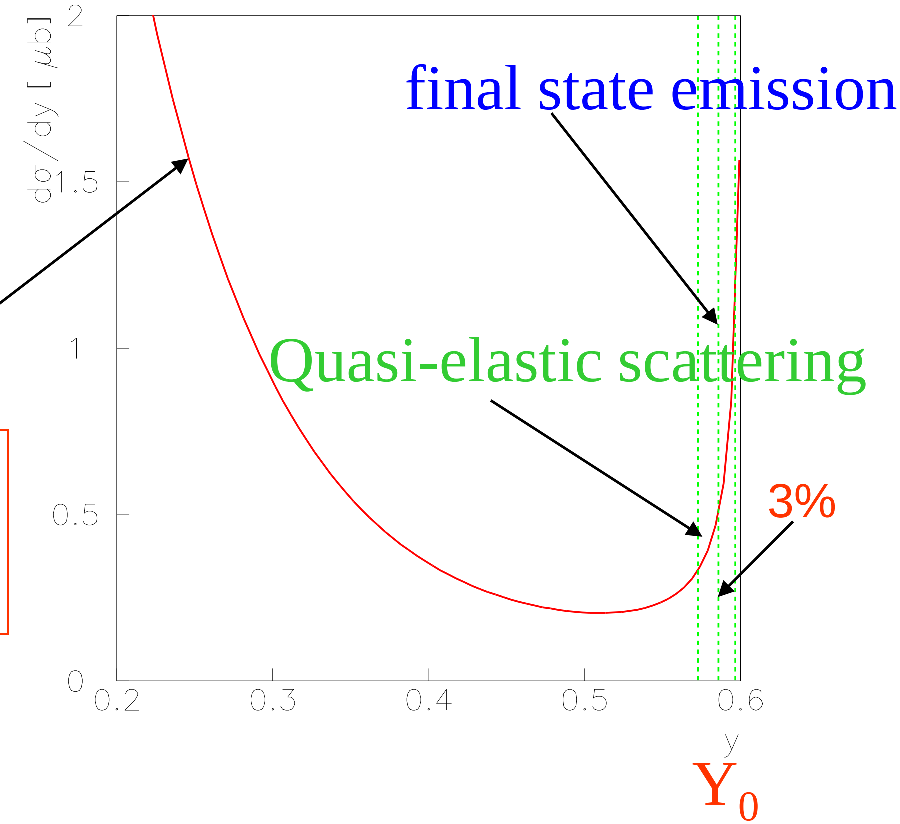
✓ Cancellation of infrared divergences (corresponding terms are marked in color)

✓ Some of the terms are of different signs ("$\pm$") for $e^{+}p$ and $e^{-}p$ scattering

Why higher orders?

$$E'/E = y \; ; \; y_0 = \frac{1}{\rho}$$

$$\rho = 1 + \frac{2E}{m}\sin^2\theta/2 .$$



$$\boxed{\Delta \frac{d\sigma}{d\Omega} \sim \frac{d\sigma_0}{d\Omega} \cdot \frac{\alpha}{\pi} \ln\frac{E}{\Delta E} \ln\frac{2EM}{m_e^2} .}$$

Not so small!

Shift to LOWER Q^2

All orders of PT needed →

beyond Mo & Tsai approximation

The Structure Function Method

E. A. K. and V.S. FADIN, Sov. J. of Nucl. Phys. 41, 466 (1985)

Distinguish:

-leading contributions of higher order $\sim \left(\frac{\alpha}{\pi} L\right)^n$

-non leading ones $\sim \frac{\alpha}{\pi}\left(\frac{\alpha}{\pi} L\right)^n$ $\quad \boxed{L = \ln \frac{Q^2}{m_e^2}}$

The SF method is based on:

- Renormalization group evolution equation
- Drell-Yan parton picture of the cross section in QCD

$$\boxed{d\sigma(y) = \int_{x_0}^{1} \frac{dx}{x} \rho_x \frac{d\sigma_0(Ex)}{|1-\Pi(Q^2 x)|^2} \mathcal{D}(x,L)\, \mathcal{D}\left(\frac{y\beta_x}{x}, L\right)\left(1+\frac{\alpha}{\pi}K\right)}$$

$\boxed{\mathcal{D}(x,L)}$ **Electron SF: probability to ‘find’ electron in the initial electron, with energy fraction *x* and virtuality up to Q^2**

The LSF cross section (for ep)

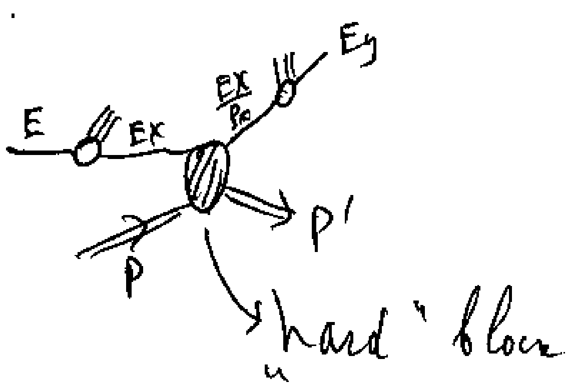
- If the electron is detected in a calorimeter:$\rightarrow$ the cross section is integrated over the scattered electron energy fraction:

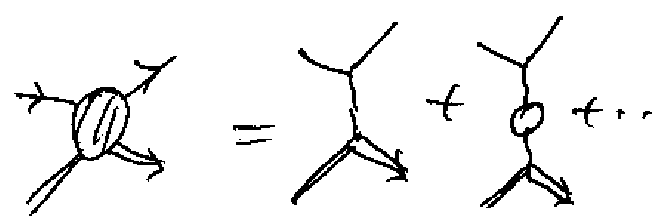
$$\int_0^1 dz\, D(z,\beta) = 1$$

$$\frac{d\sigma}{d\Omega} = \sigma_M \int_{z_1}^{1} dz D(z,\beta) \frac{\Phi(z)}{[1-\Pi(Q_z^2)]^2} \left(1 + \frac{\alpha}{\pi} K_{unp}\right)$$

$$D(z) = \frac{\beta}{2}\left[(1+\frac{3}{8}\beta)(1-z)^{\frac{\beta}{2}-1} - \frac{1}{2}(1+z)\right] + O(\beta^2),\ \ \beta = \frac{2\alpha}{\pi}\left[\ln\frac{Q^2}{m_e^2} - 1\right]$$

- The K-factor includes all non leading contributions (2γ,…):





LSF: ‰ precision

E. A. K. and V.S. FADIN, Sov. J. of Nucl. Phys. 41, 466 (1985)

LLA (Leading Logarithm Approximation)

$$\boxed{\frac{\alpha}{\pi} L \approx 1 , L = \ln \frac{Q^2}{m_e^2}}$$

Precision of LLA

$$\boxed{\left(\frac{\alpha}{\pi}\right)\left(\frac{\alpha}{\pi} L\right) \approx \frac{1}{400} \approx 0.2 \%}$$

Including K-factor

$$\boxed{\left(\frac{\alpha}{\pi}\right)^2 \left(\frac{\alpha}{\pi} L\right) \leq 0.01 \%}$$

Even when corrections in first order PT are $\delta \sim 100\%$,
the accuracy of higher order RC (LSF) is $\alpha/\pi\ \delta \leq 1\%$!

A common effort for RC and Monte Carlo tools

~60 participants, 13 countries

www.lnf.infn.it/wg/sighad

Eur. Phys. J. C (2010) 66: 585–686
DOI 10.1140/epjc/s10052-010-1251-4

THE EUROPEAN PHYSICAL JOURNAL C

Review

Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data

Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies

S. Actis[38], A. Arbuzov[9,e], G. Balossini[32,33], P. Beltrame[13], C. Bignamini[32,33], R. Bonciani[15], C.M. Carloni Calame[35], V. Cherepanov[25,26], M. Czakon[1], H. Czyż[19,a,f,i], A. Denig[22], S. Eidelman[25,26,g], G.V. Fedotovich[25,26,e], A. Ferroglia[23], J. Gluza[19], A. Grzelińska[8], M. Gunia[19], A. Hafner[22], F. Ignatov[25], S. Jadach[8], F. Jegerlehner[3,19,41], A. Kalinowski[29], W. Kluge[17], A. Korchin[20], J.H. Kühn[18], E.A. Kuraev[9], P. Lukin[25], P. Mastrolia[14], G. Montagna[32,33,b,d], S.E. Müller[22,f], F. Nguyen[34,d], O. Nicrosini[33], D. Nomura[36,h], G. Pakhlova[24], G. Pancheri[11], M. Passera[28], A. Penin[10], F. Piccinini[33], W. Płaczek[7], T. Przedzinski[6], E. Remiddi[4,5], T. Riemann[41], G. Rodrigo[37], P. Roig[27], O. Shekhovtsova[11], C.P. Shen[16], A.L. Sibidanov[25], T. Teubner[21,h], L. Trentadue[30,31], G. Venanzoni[11,c,i], J.J. van der Bij[12], P. Wang[2], B.F.L. Ward[39], Z. Was[8,g], M. Worek[40,19], C.Z. Yuan[2]

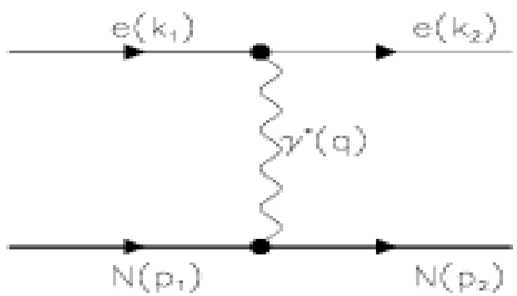
(next meeting 11-12 April 2013, ECT*) – G. Venanzoni

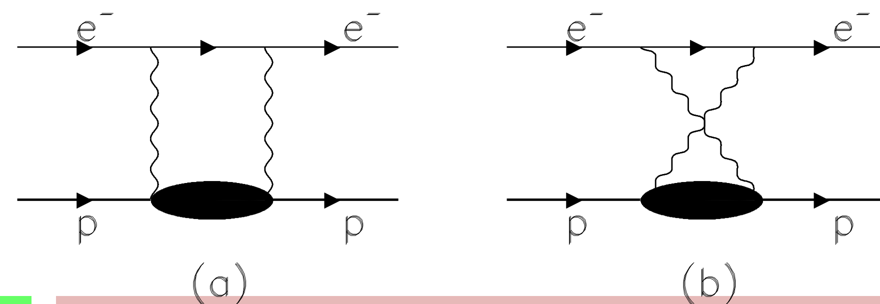
$e^{\pm} + p \rightarrow e^{\pm} + p$

4 spin ½ fermions → 16 amplitudes in the general case.

- T-invariance of EM interaction,
- identity of initial and final states,
- helicity conservation,
- unitarity

1. Interference 1γ- 2γ
2. 'Hard' 2γ box
3. 6% effect needed





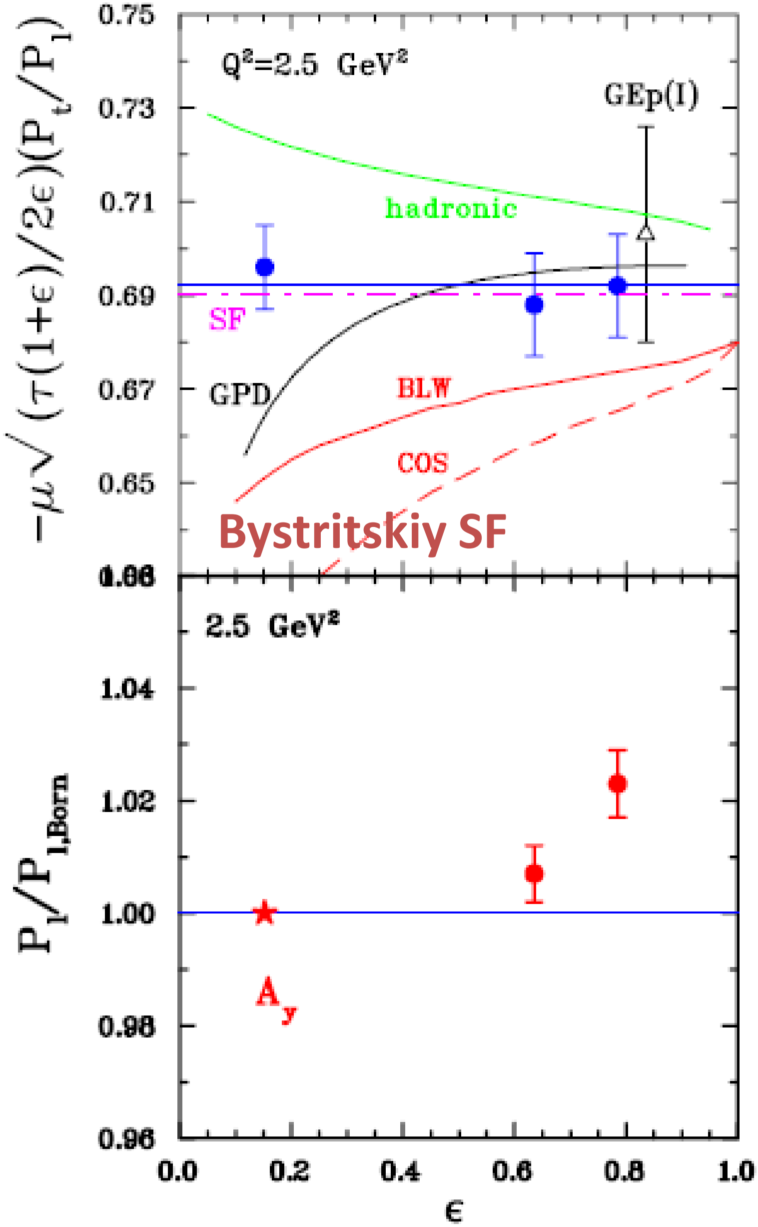
- **Two EM form factors**
- **Real (in SL region)**
- **Functions of one variable (*t*)**
- **Describe e⁺ and e⁻ scattering**

1γ exchange

- **Three structure functions**
- **Complexe**
- **Functions of TWO variables (*s*,*t*)**
- **Different for e⁺ and e⁻ scattering**

2γ exchange

Gep III results (2010)



At Jefferson Lab the 2γ experiment measured P_t/P_ℓ at Q^2=2.5 GeV² for 3 values of ε, with unprecedented small error bars.

Also, obtained P_ℓ for two values of ε, the third being used to determine the analyzing power.

Data published: M. Meziane et al. PRL 106, 132501 (2011)

COZ BLW nuclear distribution amplitudes: Kivel and Vanderhaeghen
GPD Afanasev et al.
Hadronic Blunden et al.
SF Bystritskiy et al, shifted down!

No evidence of large two photon effects

No radiative corrections applied to the data

Comparison of three TPE experiments

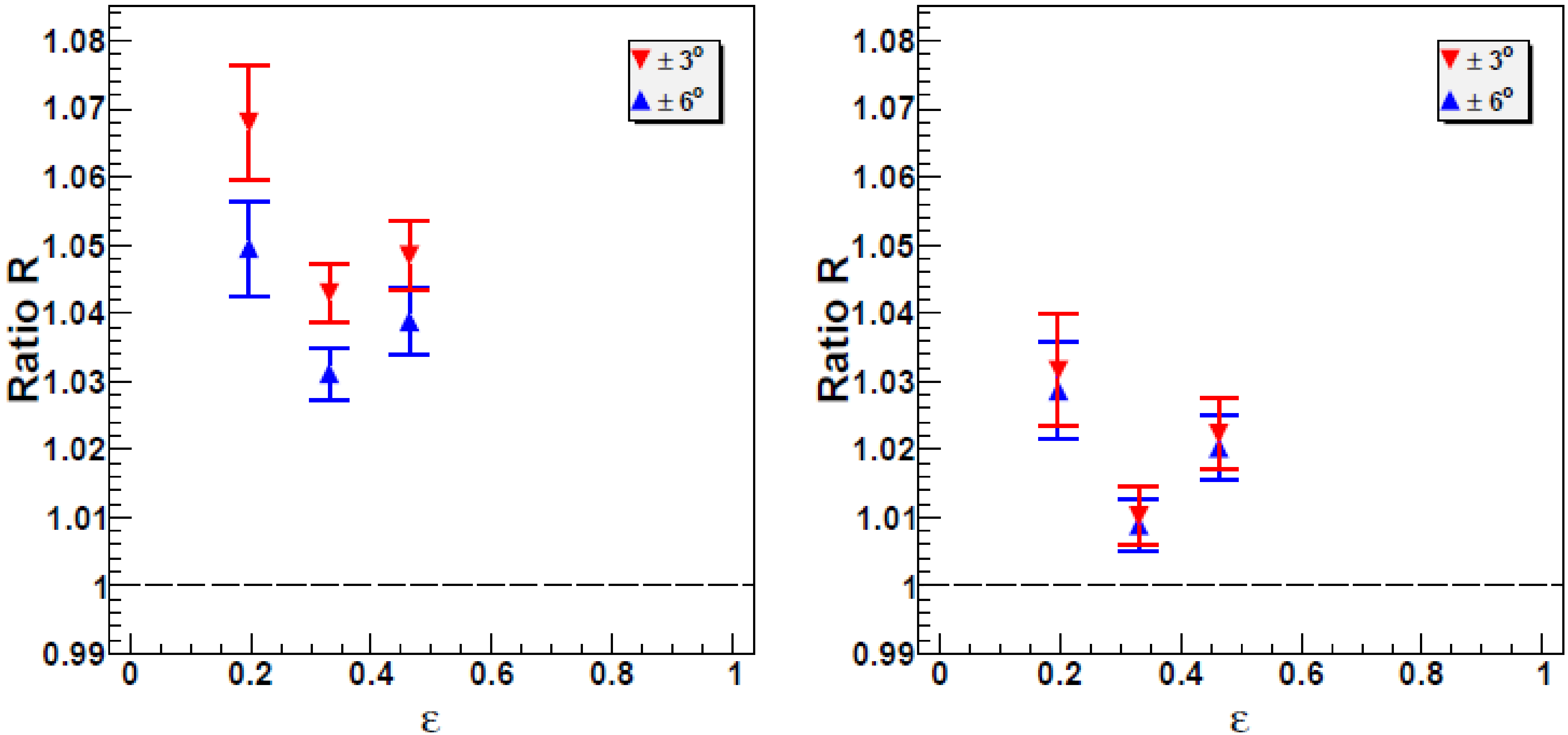
	VEPP-3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
Beam energy	3 fixed	1 fixed	wide spectrum
equality of $e^{\pm}$ beam energy	measured precisely	assumed (measured?)	reconstructed
e^+/e^- swapping frequency	half-hour	8 hours	simultaneously
e^+/e^- lumi monitor	elastic low-Q^2	elastic low-Q^2, Möller/Bhabha	from simulation
energy of scattered $e^{\pm}$	EM-calorimeter	mag. analysis	mag. analysis
proton PID	$\Delta E/E$, TOF	mag. analysis, TOF	mag. analysis, TOF
e^+/e^- detector acceptance	identical	big difference	big difference
luminosity	1.0×10^{32}	2.0×10^{33}	2.5×10^{32}
systematic error	$< 0.3\%$	1%	1%

- Novosibirsk experiment is inferior to the other two in experimental luminosity and in quality of particle ID;
- However, the detector performance is sufficient for reliable identification of elastic scattering events;
- Non-magnetic detector, measurement of beams energy, frequent swapping of e^+/e^- beams allow lowest systematic error;
- Novosibirsk is the first to provide results on precise measurement of $R(e^{\pm}p)$ ratio.

Ratio R as a function of kinematic cuts

RUN II

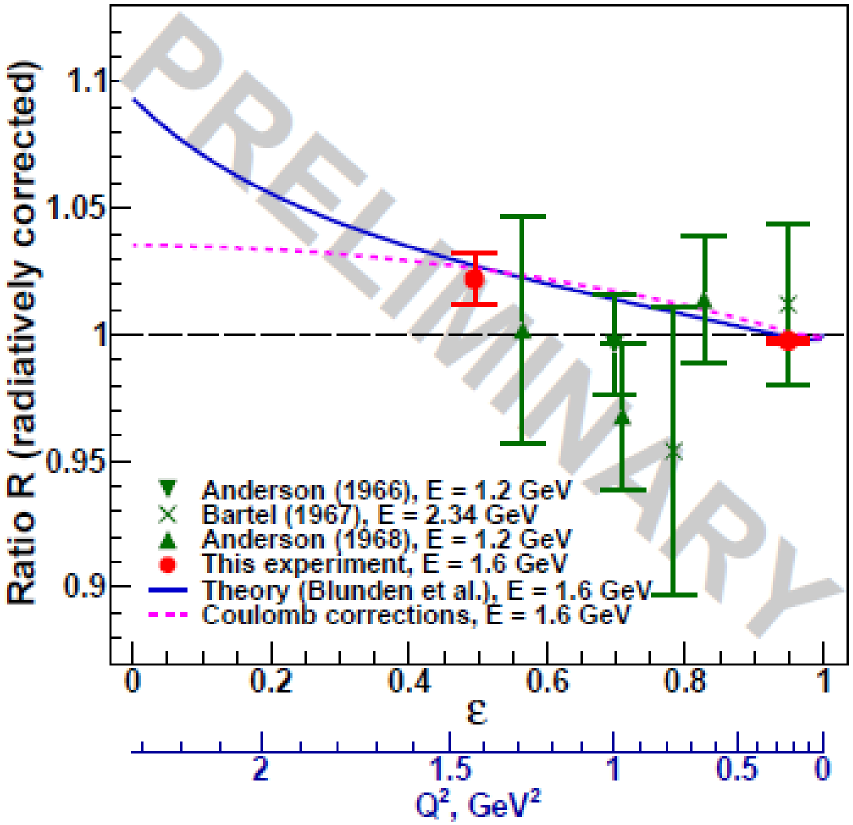
Raw data for the ratio R: Radiatively corrected ratio R:



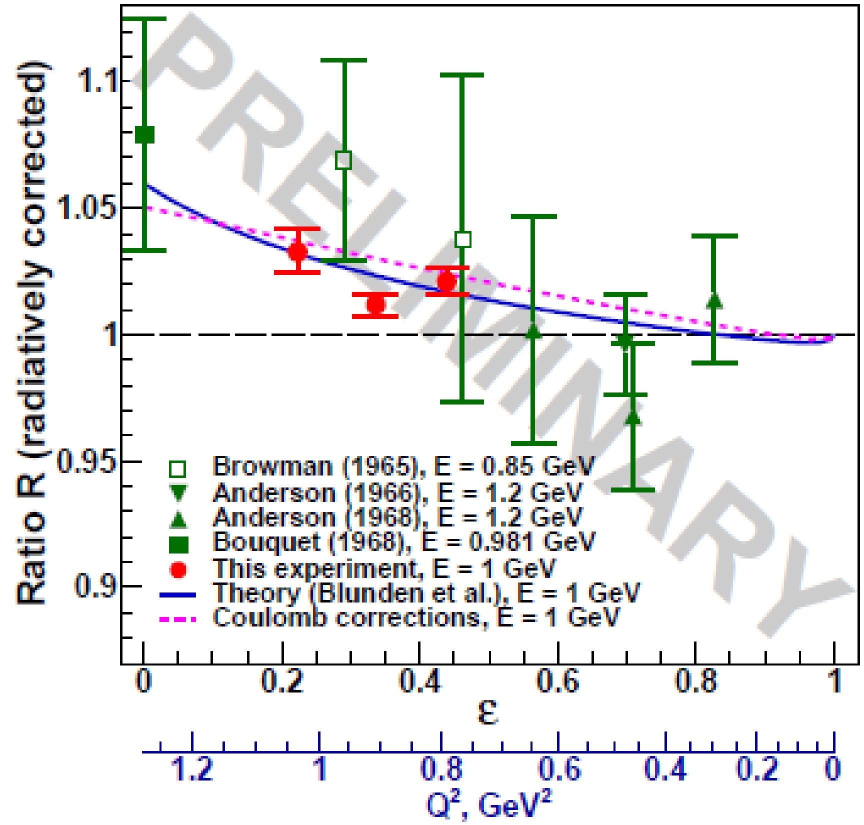
The experimentally measured ratio R before (left figure) and after (right figure) taking into account the radiative corrections (FF model). Red markers correspond to the cut $\Delta\theta = \Delta\phi = 3^\circ$ on the angular correlations, blue markers correspond to the cut $\Delta\theta = \Delta\phi = 6^\circ$ (data for LA range of the Run II).

Preliminary results of the Novosibirsk TPE experiment

Run I (2009):
$E_{\text{beam}} = 1.6$ GeV



Run II (2011–2012):
$E_{\text{beam}} = 1$ GeV

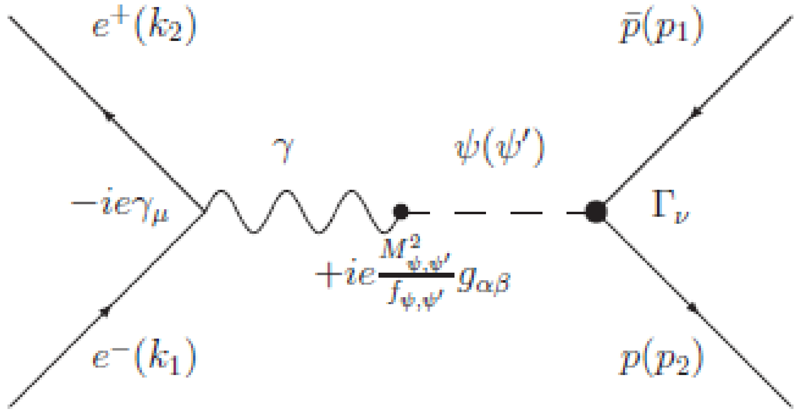


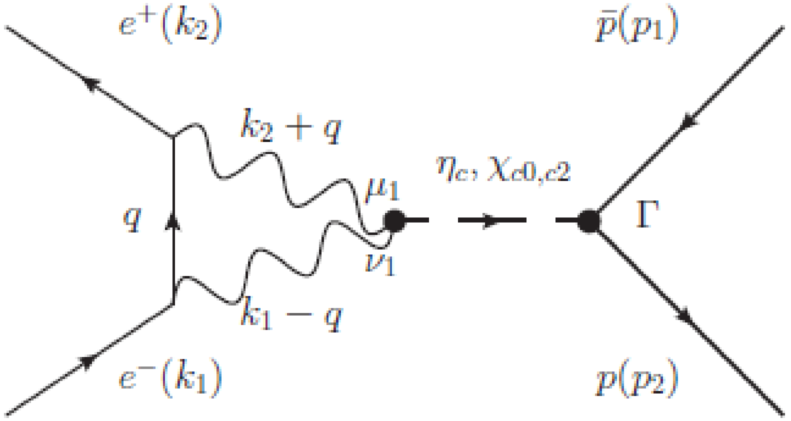
Theory: *J. Arrington and I. Sick*, Phys. Rev. **C70** (2004) 028203
P. G. Blunden, et al., Phys. Rev. **C72** (2005) 034612

- *Only statistical errors are shown.*
- *The radiative corrections are taken into account.*
- *Some minor corrections have not yet been made.*

Resonance enhanced two-photon contributions

In a recent paper H.-Q. Zhou and B.-S. Zou, Nucl. Phys. **A883**, 49 (2012) it was proposed that a large C-odd effect could arise in the electron-positron annihilation into a hadron pair through two photon exchange which couple to resonances such as $\Phi = \eta,\ \eta_C,\ \chi_0,\ \chi_2,\ \rho,\ a_1$. In one loop level, taking into account the two-photon intermediate state, there is the possibility to access the $^1S_0$, $^3P_0$, $^3P_2$ quarkonium intermediate states, which are bound states of charm quark and antiquark.

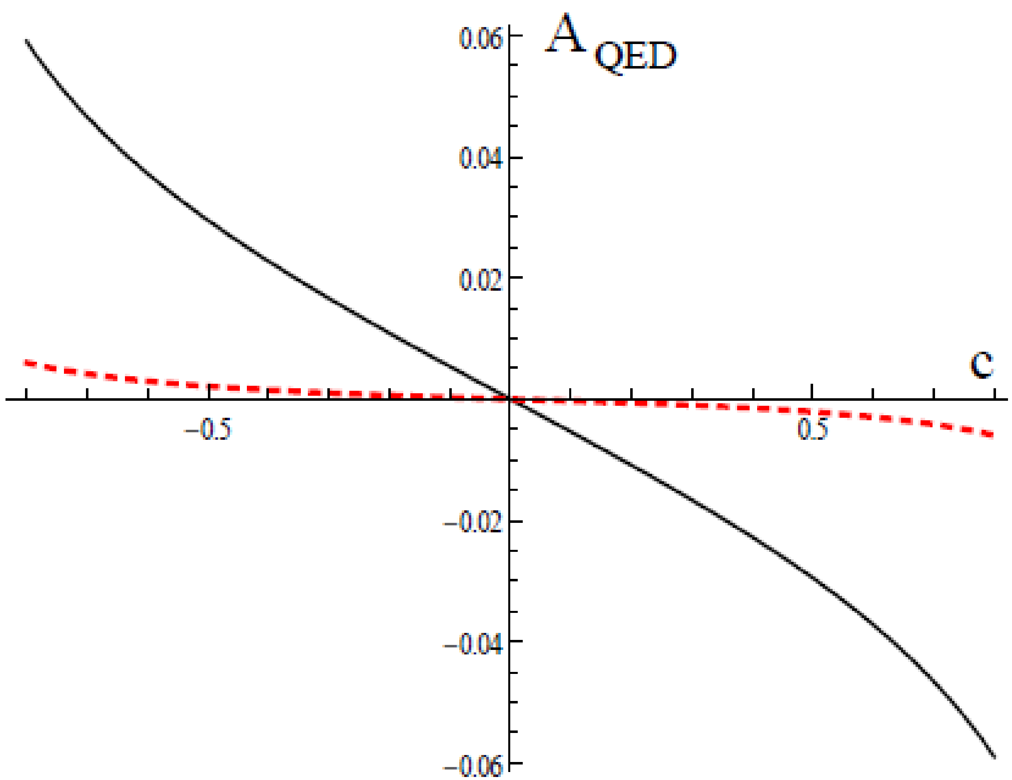




It was shown in Zhou'2012 and D. Ebert, R. Faustov, and V. Galkin, Mod. Phys. Lett. **A18**, 601 (2003) that the contribution to the asymmetry arising from the intermediate states $^1S_0$, $^3P_0$ is proportional to the ratio of the electron mass to the proton mass and it is negligible. The intermediate state with quantum numbers $^3P_2(3556) = \chi_2$ can be produced by two virtual photons, which arise from the annihilation subprocess of electron and positron.

Pure QED asymmetry

Besides the two considered sources of the asymmetry, there is also a pure QED source, A_{QED}. The total contribution to the odd part of the cross section was previously considered in E. A. Kuraev and G. V. Meledin, Nucl. Phys. B122, 485 (1977) and A. I. Ahmadov, V. V. Bytev, E. A. Kuraev, and E. Tomasi-Gustafsson, Phys. Rev. D82, 094016 (2010). The angular dependence of the asymmetry corresponding to this calculation, is plotted below for $\sqrt{s} = M_\chi$. The dashed curve corresponds to the interference of the Bo e box ones, and it is very small. The dominant contribution arises from the s oton emission from initial and final states (solid line).

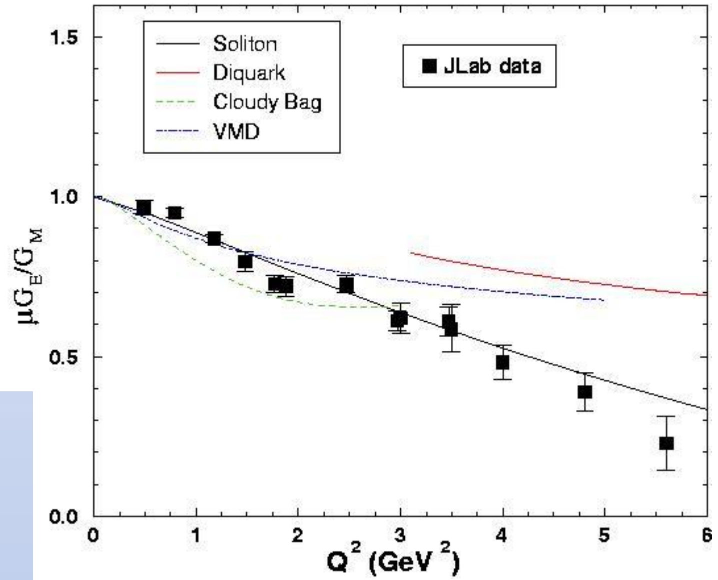


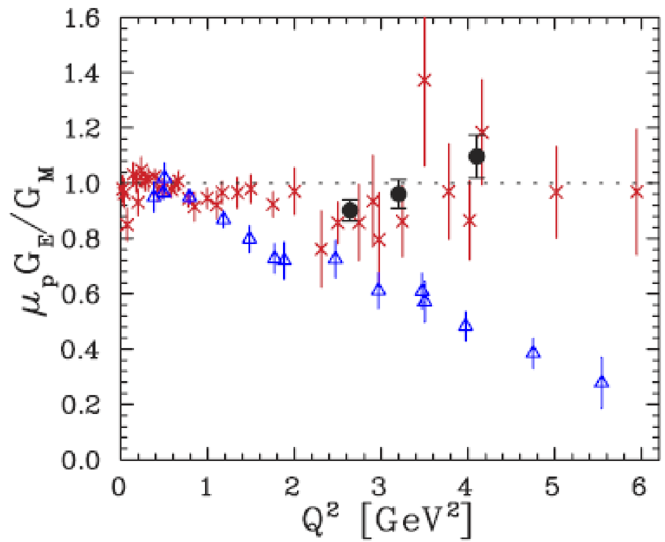
Issues

- 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

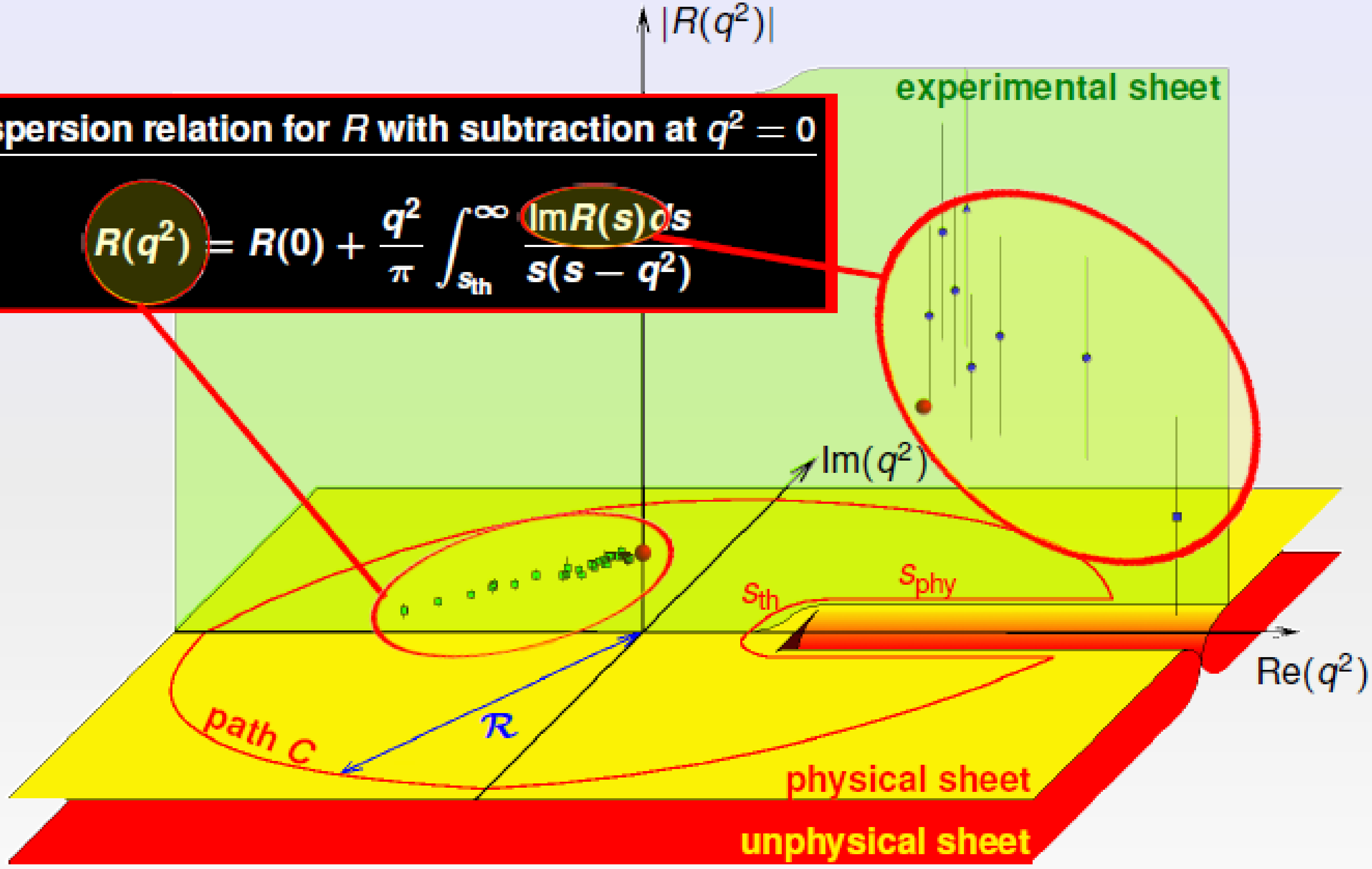




$R(q^2)$ in the complex plane

Dispersion relation for R with subtraction at $q^2 = 0$

$$R(q^2) = R(0) + \frac{q^2}{\pi}\int_{s_{th}}^{\infty} \frac{\mathrm{Im}R(s)\,ds}{s(s-q^2)}$$



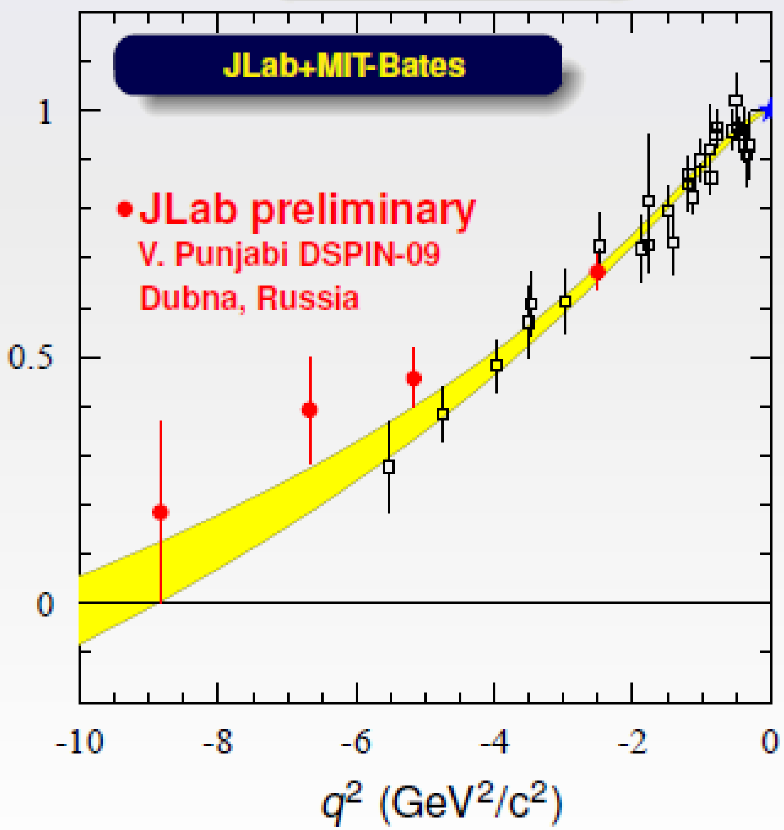
$R(q^2)$

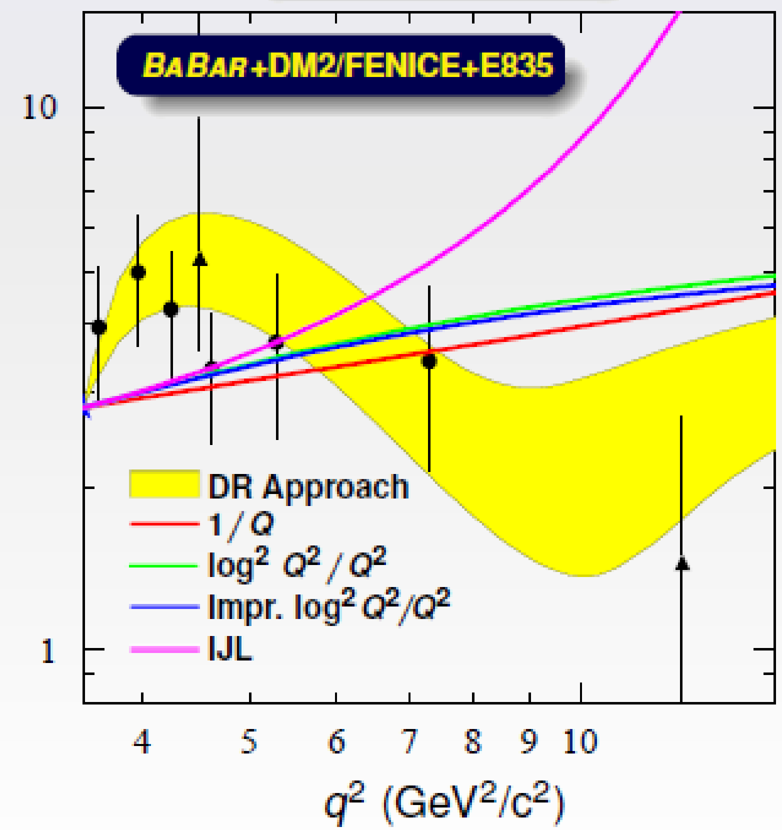
$$R(q^2) = R(0) + \frac{q^2}{\pi}\int_{4M_\pi^2}^{\infty} \frac{\mathrm{Im}R(s)}{s(s-q^2)}ds$$

$\mathrm{Re}\,q^2$

$R(q^2)$ space-like

$|R(q^2)|$ time-like





Point-like form factors?

Sommerfeld Enhancement and Resummation Factors

S. Pacetti
R. Baldini

Coulomb Factor $\mathcal{C}$ for S-wave only:

- Partial wave FF: $G_S = \dfrac{2G_M\sqrt{q^2/4M^2} + G_E}{3}$ $\quad G_D = \dfrac{G_M\sqrt{q^2/4M^2} - G_E}{3}$
- Cross section: $\sigma(q^2) = 2\pi\alpha^2\beta\,\dfrac{4M^2}{(q^2)^2}\left[\mathcal{C}\,|G_S(q^2)|^2 + 2|G_D(q^2)|^2\right]$

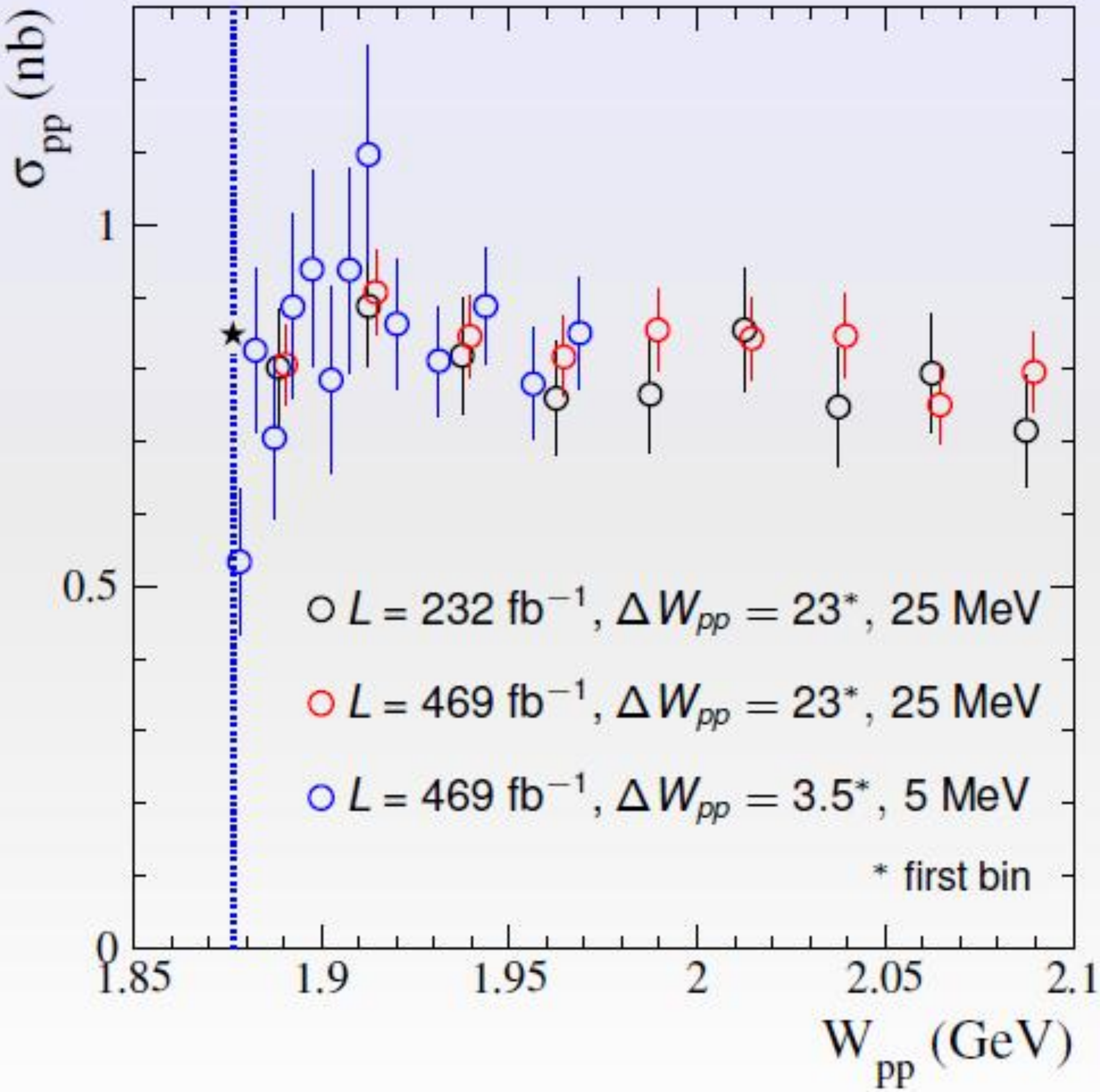
$$\boxed{\mathcal{C} = \mathcal{E} \times \mathcal{R}}$$

- Enhancement factor: $\mathcal{E} = \pi\alpha/\beta$
- Step at threshold: $\sigma_{p\bar{p}}(4M_p^2) = \dfrac{\pi^2\alpha^3}{2M^2}\dfrac{\cancel{\beta}}{\cancel{\beta}}|G_S^p(4M_p^2)|^2 = 0.85\,|G_S^p(4M_p^2)|^2$ nb

- Resummation factor: $\mathcal{R} = 1/[1 - \exp(-\pi\alpha/\beta)]$
- Few MeV above threshold: $\mathcal{C} \simeq 1 \;\Rightarrow\; \sigma_{p\bar{p}}(q^2) \propto \beta\,|G_S^p(q^2)|^2$

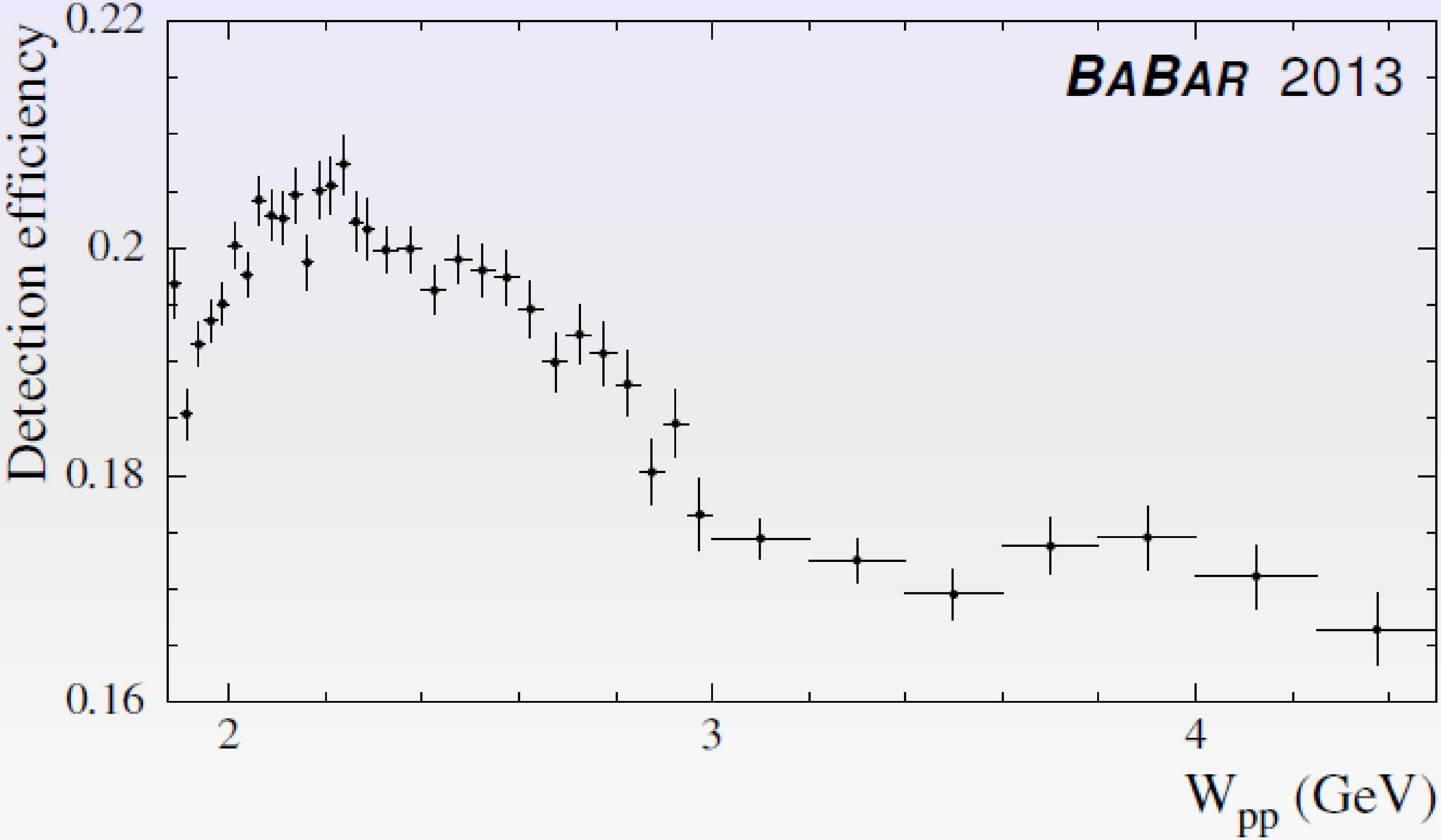
BABAR 2013: $e^+e^- \to p\bar{p}$

PRD73-012005, arXiv:1302.0055



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

arXiv:1302.0055



E. A. Kuraev

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

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

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

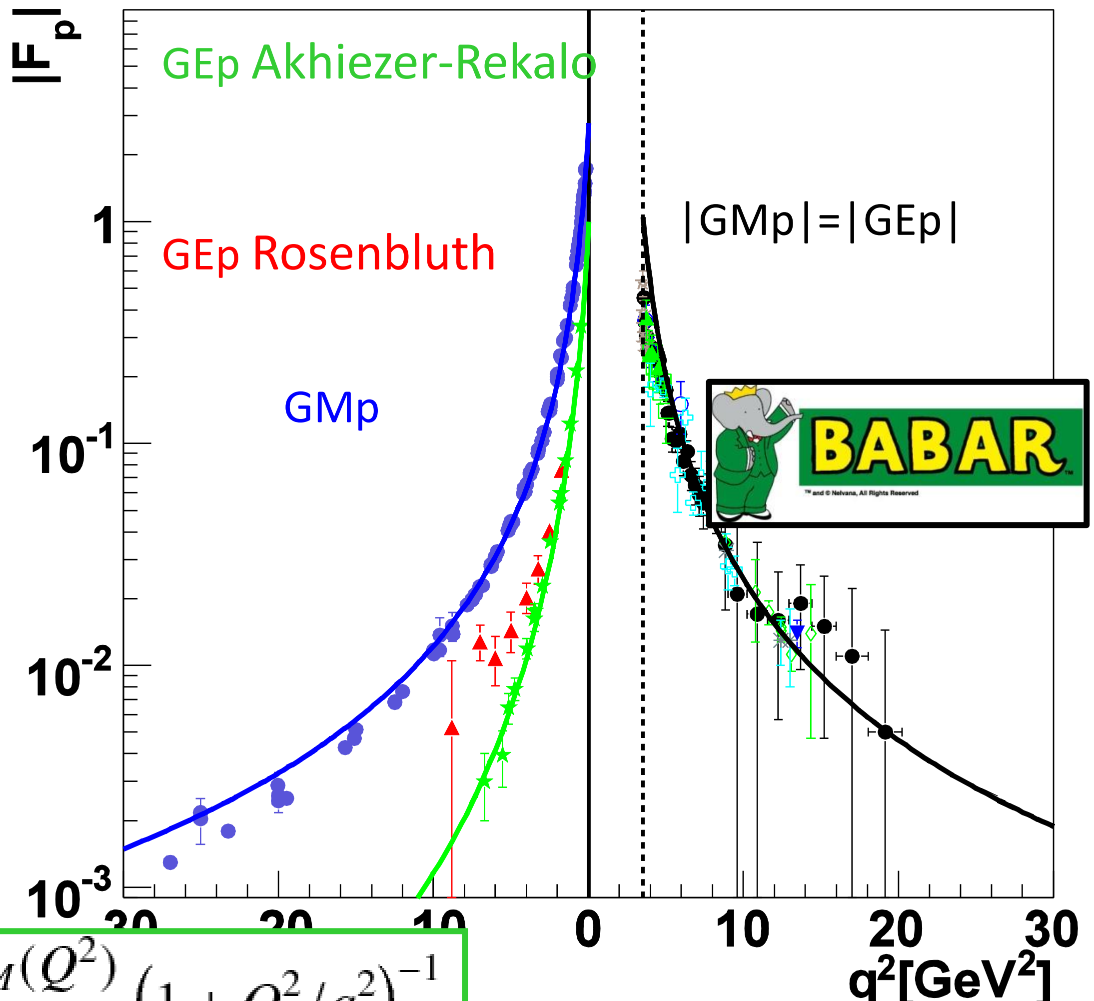
$$|G_M(q^2)| = [1 + (q^2 - 4M_p^2)/q_2^2]^{-2}\Theta(q^2 - 4M_p^2),$$
$$|G_E(q^2)| = |G_M(q^2)|[1 + (q^2 - 4M_p^2)/q_1^2]^{-1}\Theta(q^2 - 4M_p^2),$$

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

E.A. Kuraev et al., Phys.Lett. B712 (2012) 240-244

Proton Form Factors

E.A. Kuraev et al., Phys.Lett. B712 (2012) 240-244



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

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

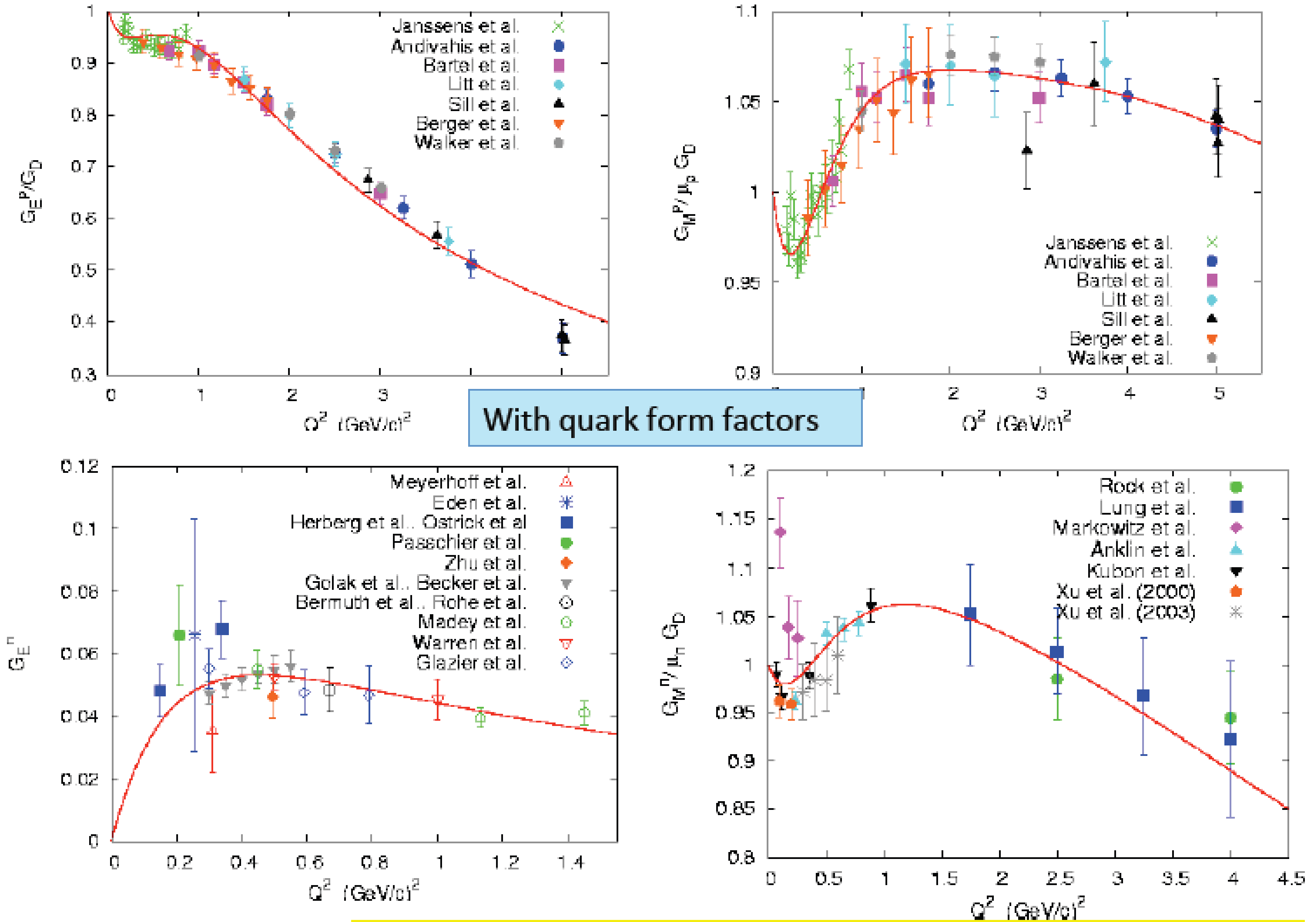
Relativistic constituent quark models

E. Santopinto

Main points

- Unquenching quark model:we have constructed the formalism in an explicit way, also thanks to group theory tecniques. Now, it can be applied to any quark model.
- We think we have maked up the problems of quark models adding the coupling with the continuum, thus opening the possibilty of many, many applications

- Future: application to open problems in hadron structure and spectroscopy : helicity amplitudes, strong decays,and so on.



With quark form factors

De Sanctis, Giannini, Santopinto, Vassallo Phys. Rev. C76, 062201 (2007)

Skyrme model with vector mesons

Meissner, Keiser, Wirzba, Weise

ρ and w are gauge bosons of a hidden symmetry SU(2) x U(1)

$$\mathrm{L} = \frac{f_\pi^2}{4}\mathrm{Tr}(\mathrm{D}_\mu U\, \mathrm{D}^\mu U^\dagger) - \frac{f_\pi^2}{2}\mathrm{Tr}[\mathrm{D}_\mu U^{1/2}(U^\dagger)^{1/2} + \mathrm{D}_\mu (U^\dagger)^{1/2} U^{1/2}]^2$$
$$-\frac{1}{2g^2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + \mathrm{L}_{WZ} + \mathrm{L}_M \,.$$

$$\mathrm{D}_\mu = \partial_\mu - \frac{ig}{2}(\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu + \omega_\mu)$$

Generalizing the hedgehog ansatz

$$\omega_\mu(\mathbf{r}) = \omega(r)\,\delta_{\mu 0} \qquad \rho_{0a}(\mathbf{r}) = 0 \qquad \rho_{ia}(\mathbf{r}) = \frac{1}{g}\varepsilon_{ija}\,\hat{r}^j\, G(r)$$

A. Drago

Main results of the analytic continuation

- At $Q^2 = -9\ m_\pi^2$ a log singularity develops
- For $Q^2 < -9\ m_\pi^2$ we obtain an imaginary part
- The log singularity is well inside the non-accessible region $-4\ M^2 < Q^2 < 0$
- BIG problem: the behaviour for $Q^2 << -9\ m_\pi^2$ is strongly unstable: a tiny variation of the parameters used to fit the current corresponds to a huge variation of the TLFFs

G. Salmè

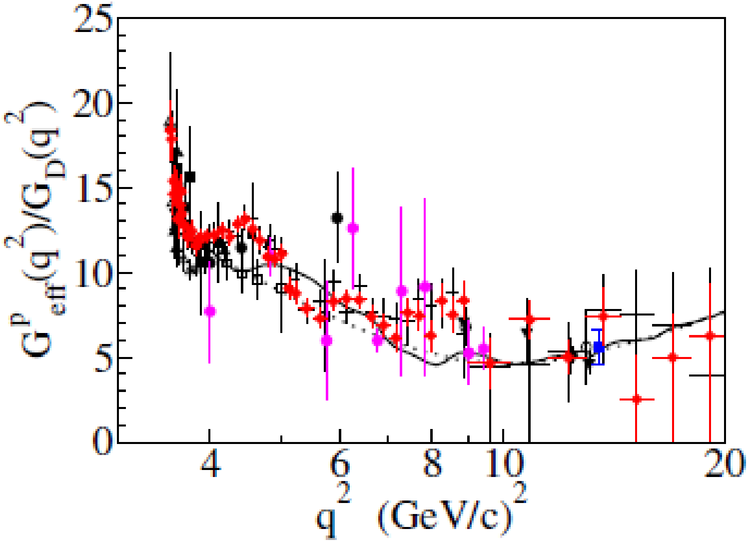
The Light-front constituent quark model and the electromagnetic properties of the nucleon: beyond the valence component ?

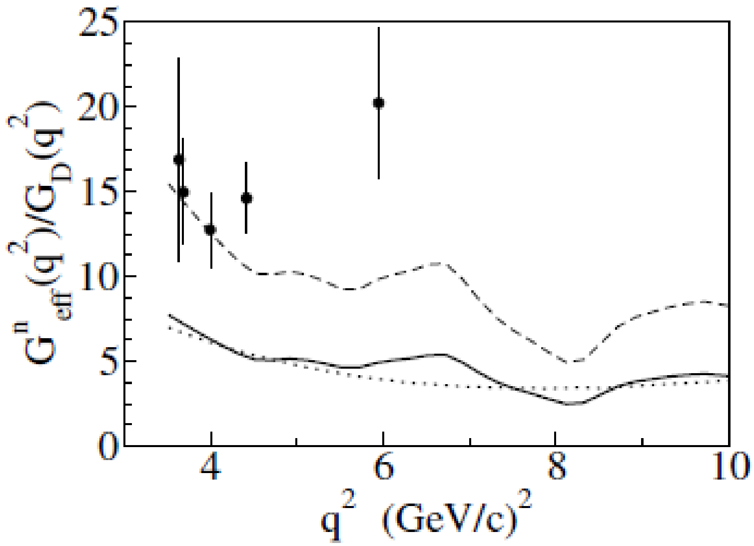
- A relativistic Constituent Quark Model, based on phenomenological Ansatzes for the hadron Bethe-Salpeter amplitudes, have been applied for evaluating both pion and nucleon em form factors, in SL and TL regions.

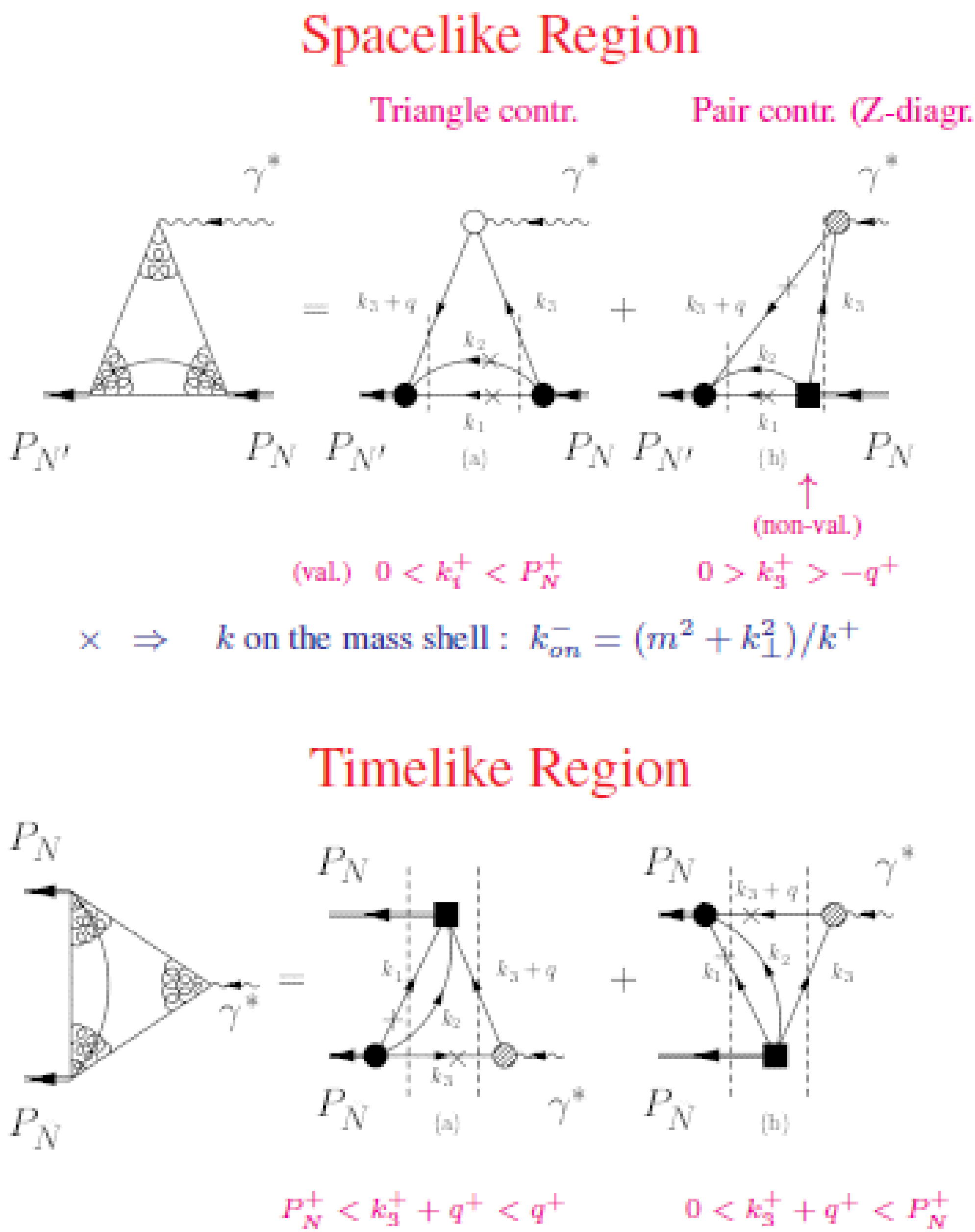
- A microscopical Vector Meson Dominance model has been devised, exploiting masses and eigenfunction of a relativistic mass operator, able to reproduce the vector meson mass in PDG 08.

Extension to time-like!

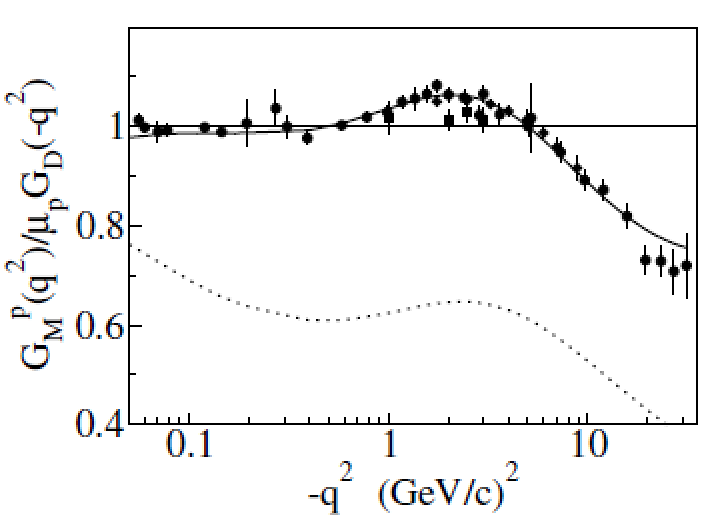
Time-like *G. Salmè*

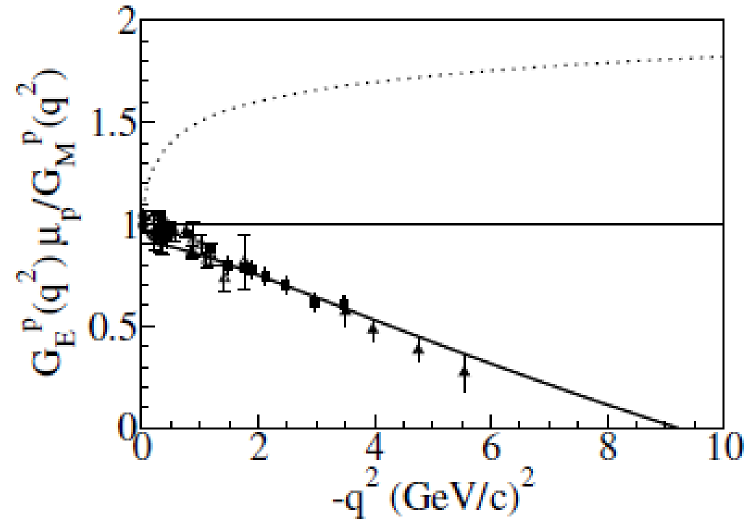


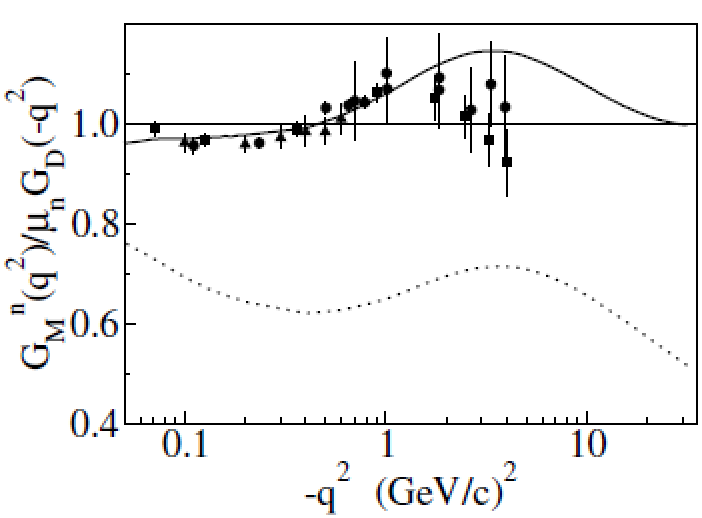


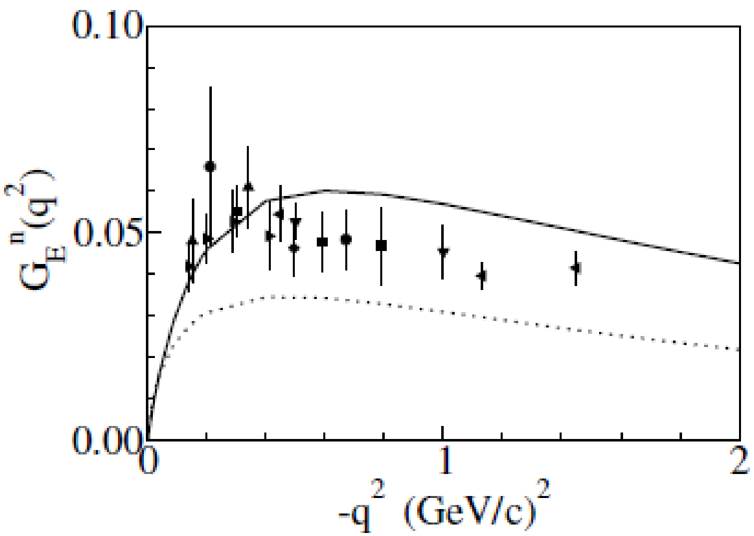


Space-like







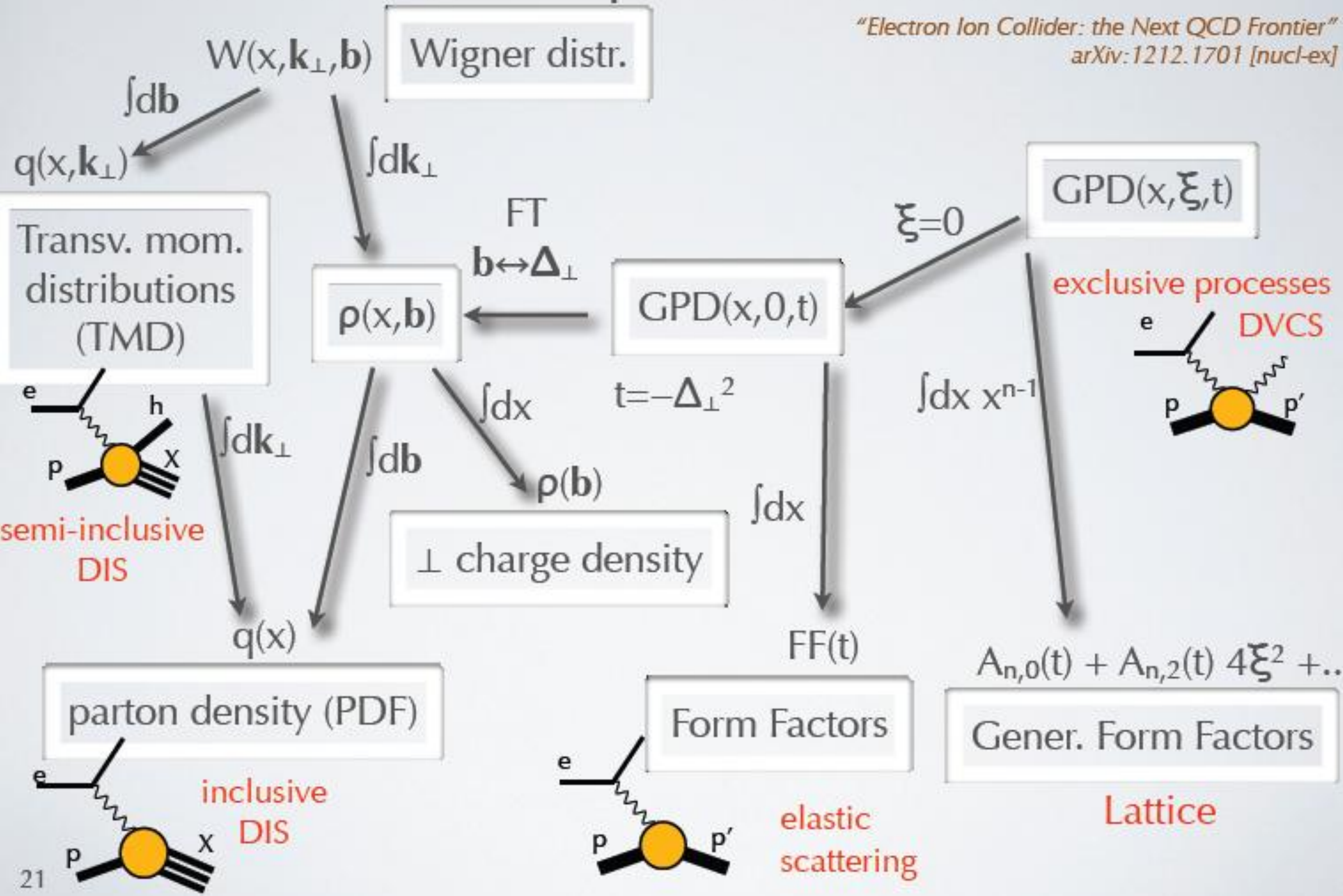


G. Salmè

Multi-dimensional "picture" of N structure

M. Radici

"Electron Ion Collider: the Next QCD Frontier"
arXiv:1212.1701 [nucl-ex]



In the limit $\xi \to 0$ no long. change $P'^{+}=P^{+}$ $P^{+} \gg |\mathbf{P}_\perp|$

$t \neq 0$ but change in $\mathbf{P}'_\perp \neq \mathbf{P}_\perp$ (IFM)

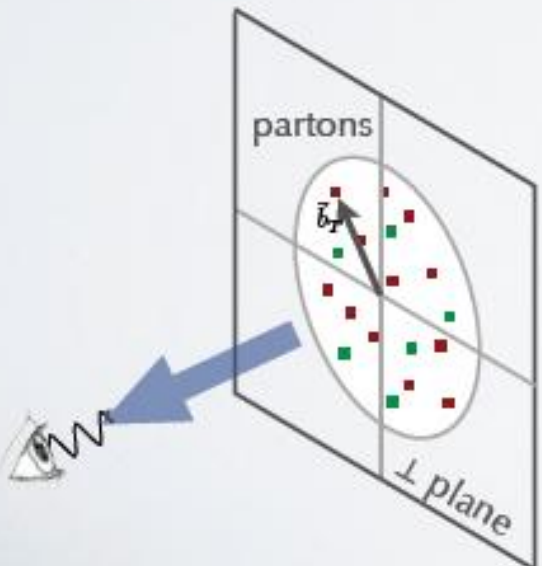
$$H(x,0,t=-(\mathbf{P}'-\mathbf{P})^2) = \sum_\lambda \int \frac{dx^-}{2\pi} e^{ixP^+x^-} \langle P^+, \mathbf{P}'_\perp, \lambda | \, \bar{q}(-\frac{x^-}{2}, 0, \mathbf{0}) \, \gamma^+ \, q(\frac{x^-}{2}, 0, \mathbf{0}) \, | P^+, \mathbf{P}_\perp, \lambda \rangle$$

$$q(x,\mathbf{b}) = \int \frac{d\mathbf{q}}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} H(x,0,t=-\mathbf{q}^2)$$

$\lambda = \pm 1/2$ N helicity

q(x,**b**) is a density in **b** $\leftrightarrow$ $\mathbf{q}=\mathbf{P}'_\perp-\mathbf{P}_\perp$ Fourier transformed

valid for all x $\Rightarrow$ integrate in x $\Rightarrow$ $\perp$ charge density $\rho(\mathbf{b})$



$$\rho^0(\mathbf{b}) = \int dx \int \frac{d\mathbf{q}}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} H(x,0,t=-\mathbf{q}^2)$$
$$= \int \frac{d\mathbf{q}}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} F_1(Q^2=\mathbf{q}^2)$$

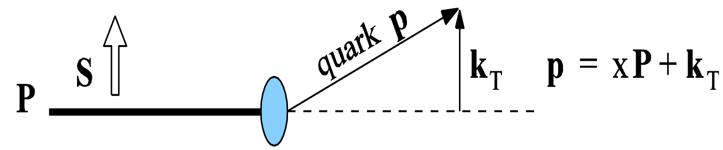
Breit $\langle J^0 \rangle \leftrightarrow G_E$

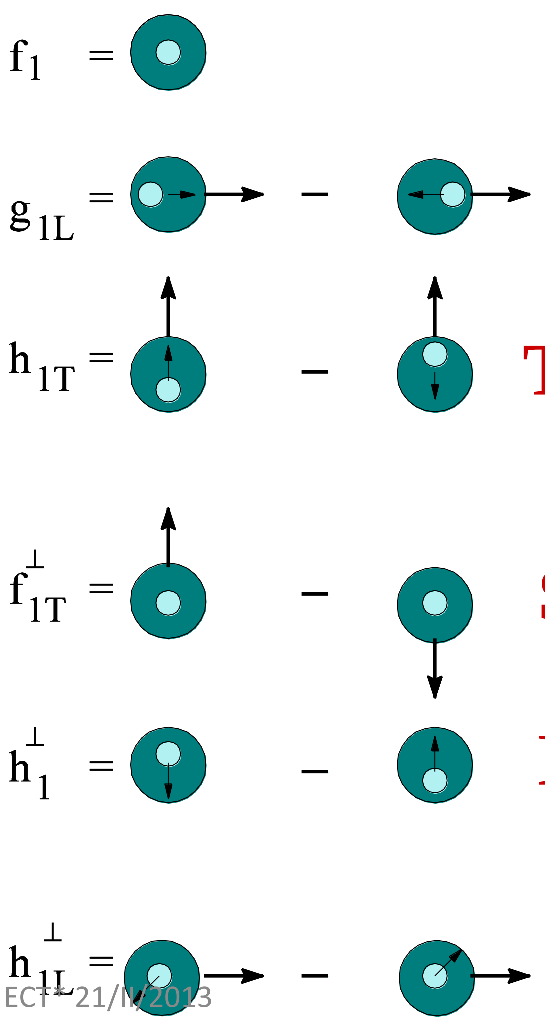
IMF $\langle J^+ \rangle \leftrightarrow F_1$

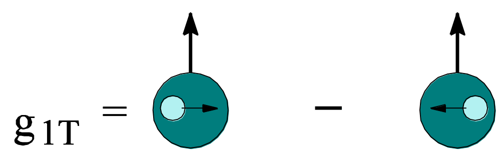
M. Radici

TMD: K_T-dependent Parton Distributions

Twist-2 PDFs $\quad f_1(x) = \int d^2k_T\, f_1(x, k_T)$



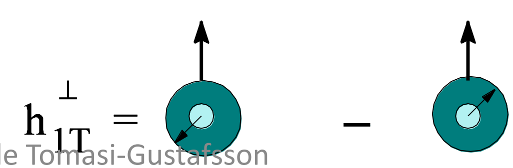




Transversity

Sivers

Boer-Mulders

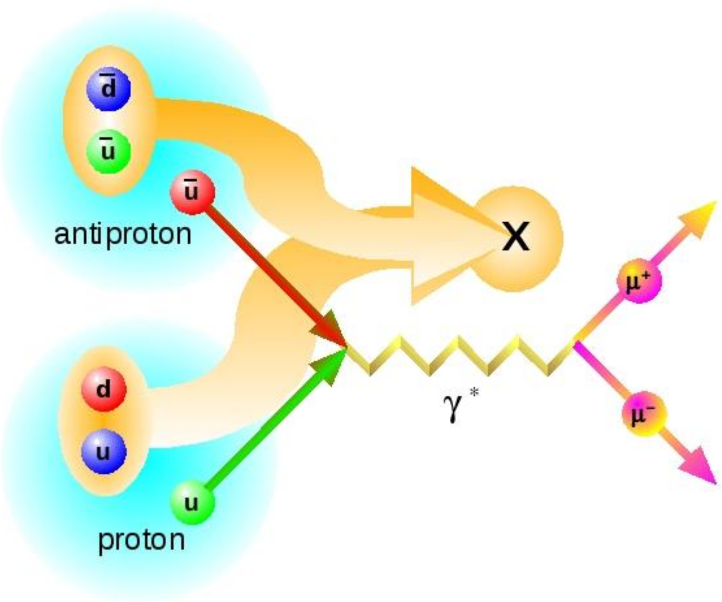


Distribution functions		Chirality even	Chirality odd
Twist-2	U	f_1	$h_1^{\perp}$
	L	g_1	$h_{1L}^{\perp}$
	T	$f_{1T}^{\perp}, g_{1T}$	$h_1, h_{1T}^{\perp}$

M. Destefanis

Drell-Yan Process

- Drell-Yan: $p\bar{p} \rightarrow \mu^+\mu^- X$



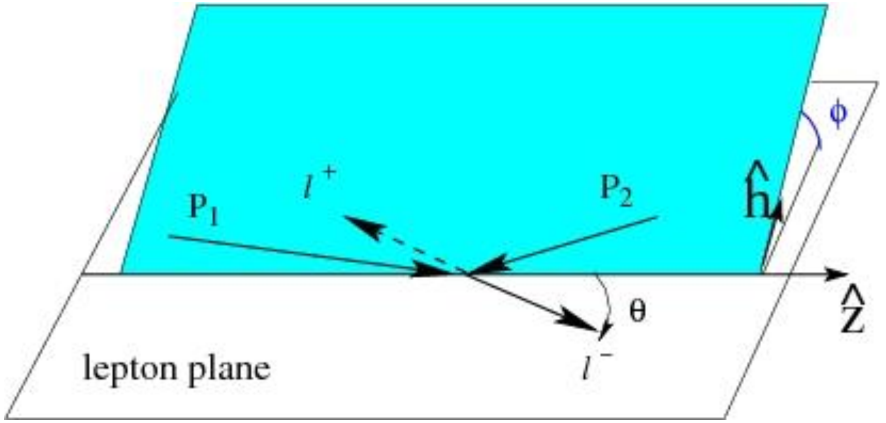
Kinematics

$x_{1,2}$ = mom fraction of parton$_{1,2}$

$\tau = x_1 \bullet x_2 = M^2/s$

$x_F = x_1 - x_2$

Collins-Soper frame



Collins-Soper frame: Phys. Rev. D16 (1977) 2219.

Drell-Yan Cross Section

UNPOLARISED

$$\frac{d\sigma^o}{d\Omega dx_1 dx_2 d\mathbf{q}_T} = \frac{\alpha^2}{12Q^2}\sum_f e_f^2 \Bigg\{ (1+\cos^2\theta)\,\mathcal{F}\left[\bar{f}_1^f f_1^f\right] + f\,\sin^2\theta\,\cos 2\phi\,\mathcal{F}\left[\left(2\hat{\mathbf{h}}\cdot\mathbf{p}_{1_T}\,\hat{\mathbf{h}}\cdot\mathbf{p}_{2_T} - \mathbf{p}_{1_T}\cdot\mathbf{p}_{2_T}\right)\frac{\bar{h}_1^{\perp f} h_1^{\perp f}}{M_1 M_2}\right]\Bigg\}$$

SINGLE-POLARISED

$$\frac{d\Delta\sigma^{\uparrow}}{d\Omega dx_1 dx_2 d\mathbf{q}_T} = \frac{\alpha^2}{12sQ^2}\sum_f e_f^2 |\mathbf{S}_{2_T}| \Bigg\{ (1+\cos^2\theta)\,\sin(\phi-\phi_{S_2})\,\mathcal{F}\left[\hat{\mathbf{h}}\cdot\mathbf{p}_{2_T}\frac{\bar{f}_1^f f_{1T}^{\perp f}}{M_2}\right] - \sin^2\theta\,\sin(\phi+\phi_{S_2})\,\mathcal{F}\left[\hat{\mathbf{h}}\cdot\mathbf{p}_{1_T}\frac{\bar{h}_1^{\perp f} h_{1T}^f}{M_1}\right] - \sin^2\theta\,\sin(3\phi-\phi_{S_2})\,\mathcal{F}\left[\left(4\hat{\mathbf{h}}\cdot\mathbf{p}_{1_T}(\hat{\mathbf{h}}\cdot\mathbf{p}_{2_T})^2 - 2\hat{\mathbf{h}}\cdot\mathbf{p}_{2_T}\,\mathbf{p}_{1_T}\cdot\mathbf{p}_{2_T} - \hat{\mathbf{h}}\cdot\mathbf{p}_{1_T}\,\mathbf{p}_{2_T}^2\right)\frac{\bar{h}_1^{\perp f} h_{1T}^{\perp f}}{2M_1 M_2^2}\right]\Bigg\}$$

DOUBLE-POLARISED

$$\frac{d\sigma^{\uparrow\uparrow}}{dx_1\,dx_2\,d\Omega} = \frac{\alpha^2}{12q^2}\Bigg[(1+\cos^2\theta)\sum_f e_f^2\,\bar{f}_1^f(x_1)\,f_1^f(x_2) + \sin^2\theta\,\cos 2\phi\,\frac{\tilde{\nu}(x_1,x_2)}{2} + |\mathbf{S}_{T1}|\,|\mathbf{S}_{T2}|\,\sin^2\theta\,\cos(2\phi-\phi_{S_1}-\phi_{S_2})\sum_f e_f^2\,\bar{h}_{1T}^f(x_1)\,h_{1T}^f(x_2) + (1\leftrightarrow 2)\Bigg]$$

R.D. Tangerman and P.J. Mulders, Phys. Rev. D51, 3357-3372 (1995)

Azimuthal Asymmetries

- Unpolarized $\cos 2\varphi$
- Single polarized $\sin(\varphi - \varphi_{S_2}),\ \sin(\varphi + \varphi_{S_2})$
- Double polarized $\cos(2\varphi - \varphi_{S_1} - \varphi_{S_2})$

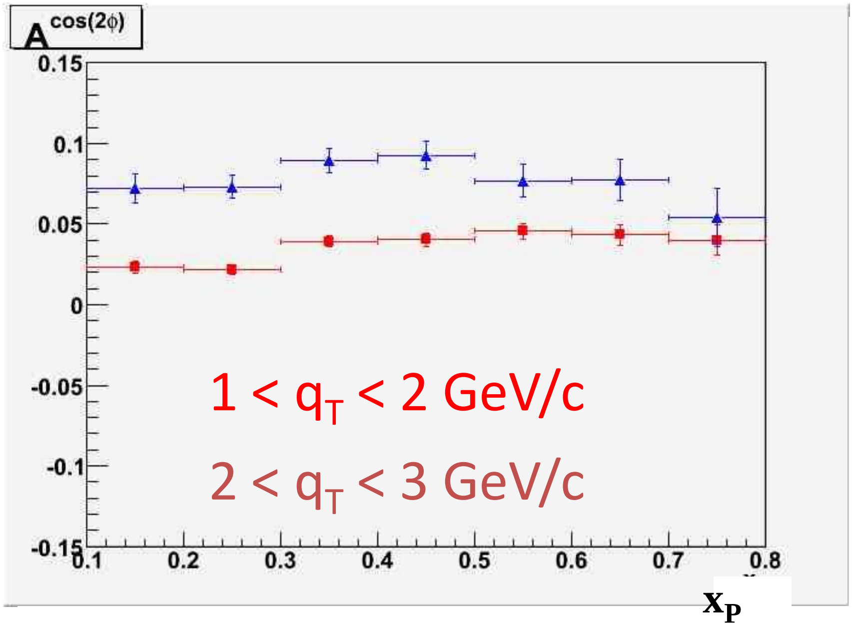
U = N(cos2ϕ>0)

D = N(cos2ϕ<0)

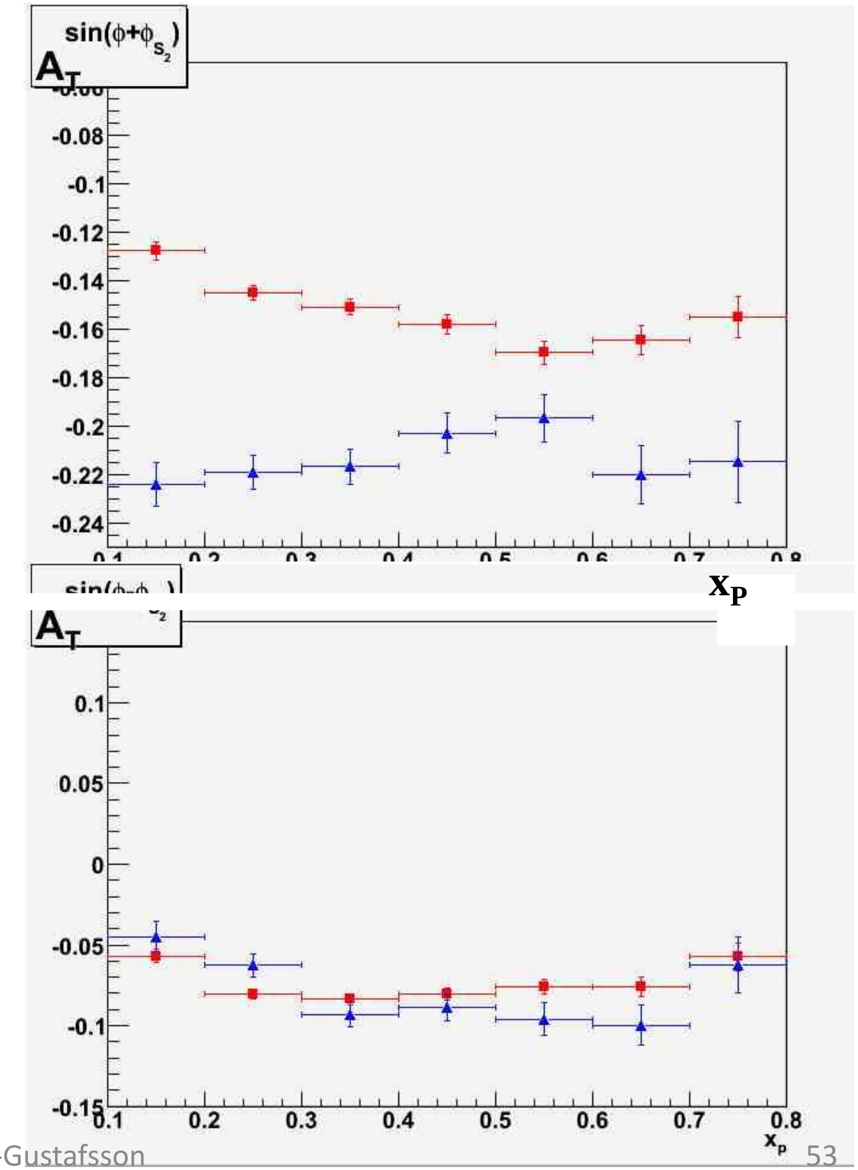
Asymmetry $$A = \frac{U - D}{U + D}$$

DY Asymmetries @ Vertex

UNPOLARISED



SINGLE-POLARISED



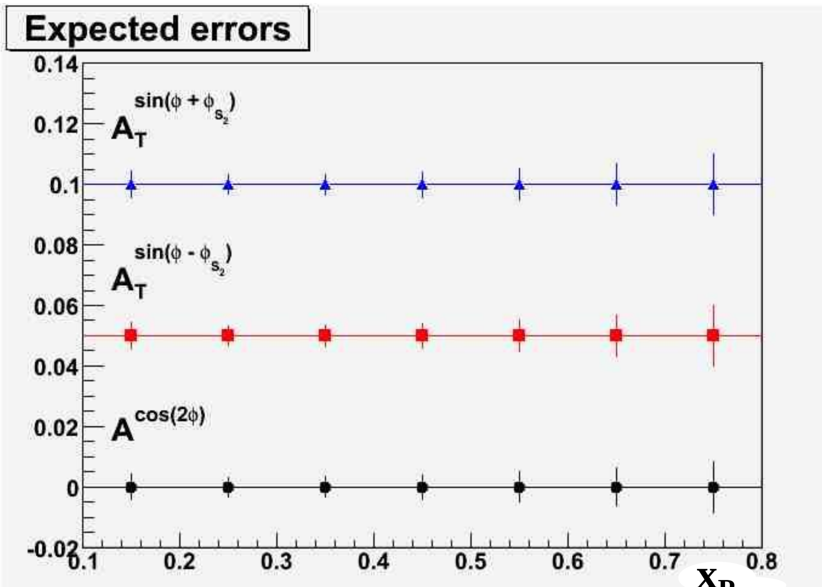
500KEv included in asymmetries

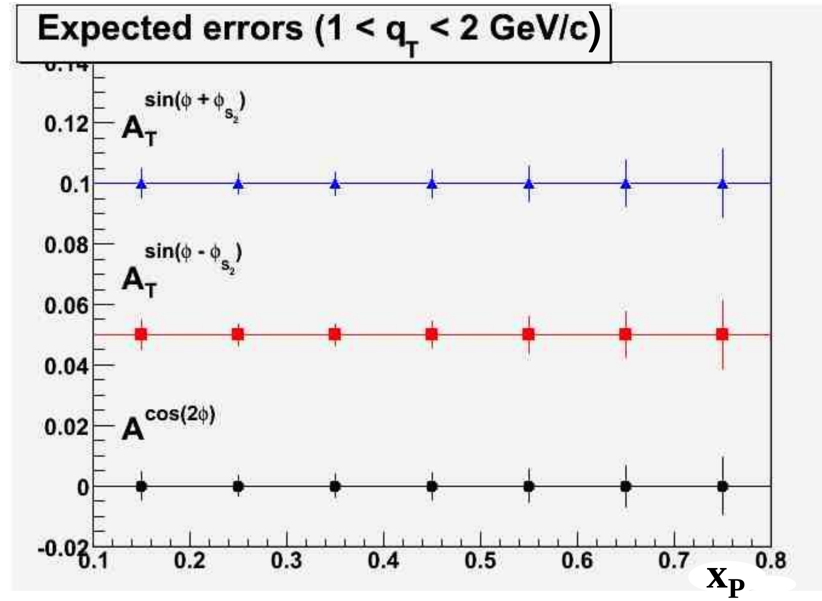
Acceptance corrections crucial!

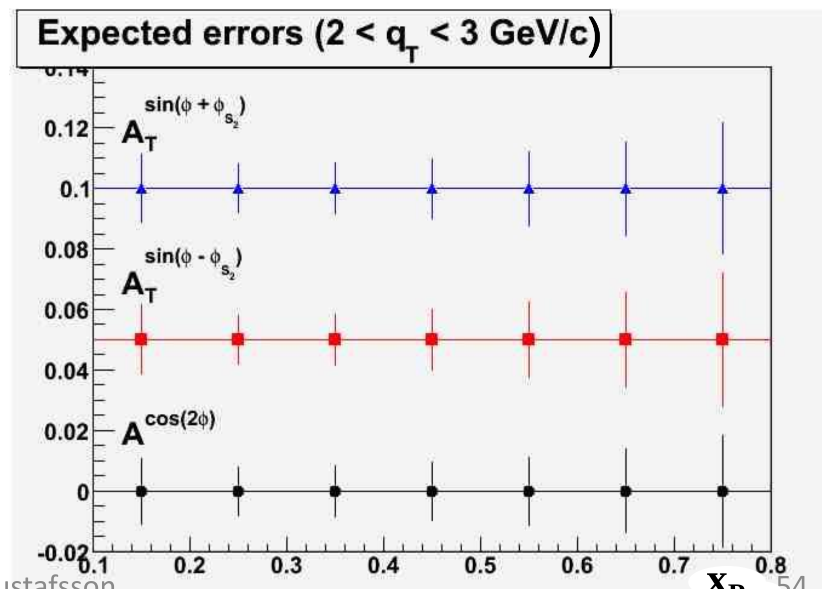
Physics Performance Report for PANDA arXiv:0903.3905

DY Asymmetries @ Vertex

Statistical errors for 500KEv generated







$R = \mathcal{L} \cdot \sigma \cdot \varepsilon$

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

$\times\ 0.8 \cdot 10^{-33} cm^2 \times 0.33$

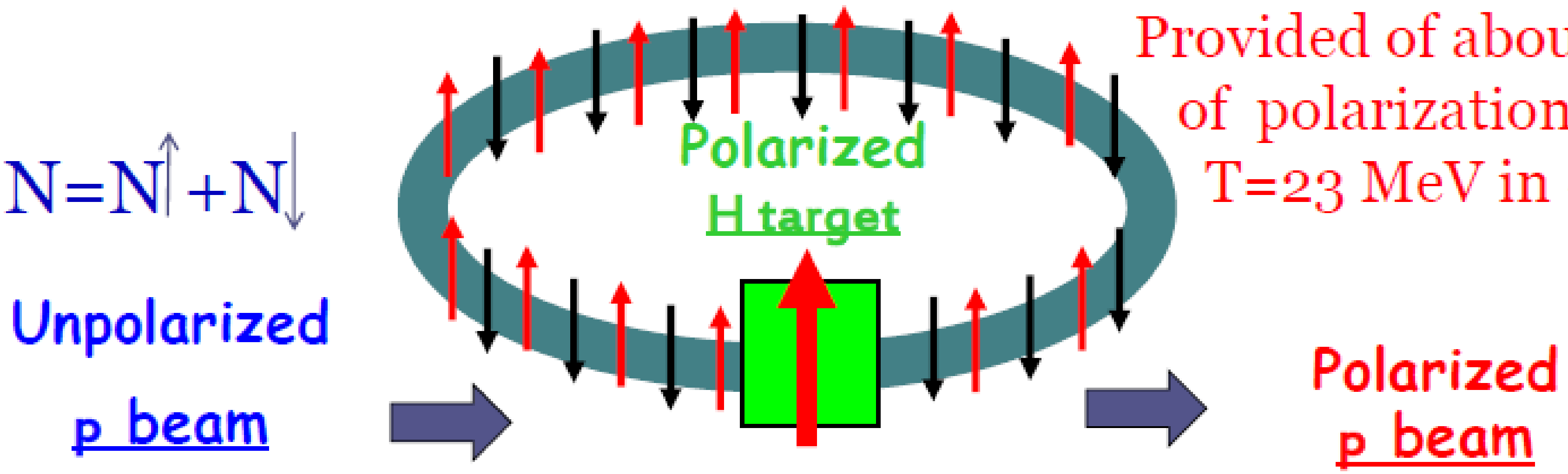
$= 0.05\ s^{-1}$ ~ 130 Kev/month

Physics Performance Report for PANDA arXiv:0903.3905

Polarized (Anti)Proton Beam: Spin selective

By repeated traversal of a beam through a polarized hydrogen target in a storage rings (Rathmann PRL 71 (1993))

$N = N^{\uparrow} + N^{\downarrow}$



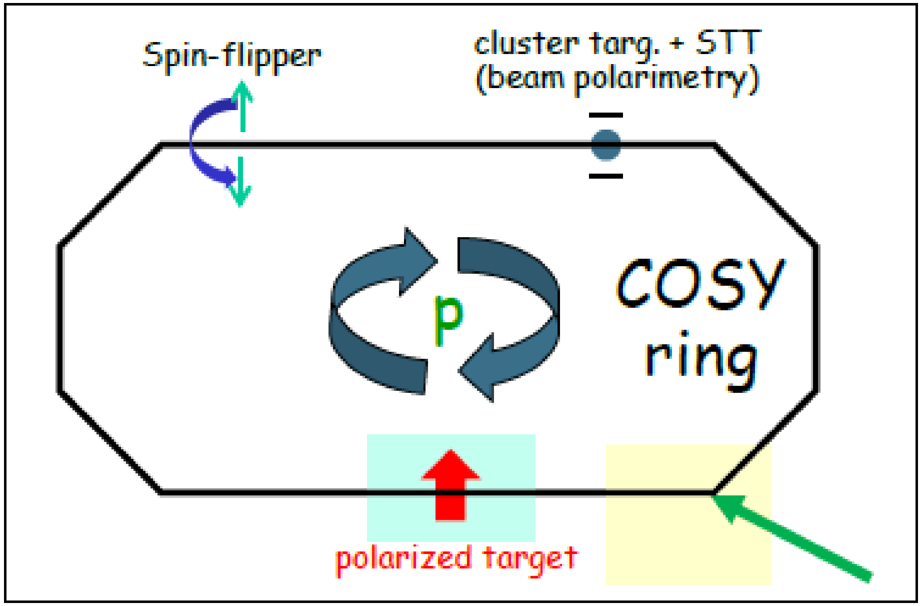
Provided of about 2% of polarization at T=23 MeV in ~ 2h

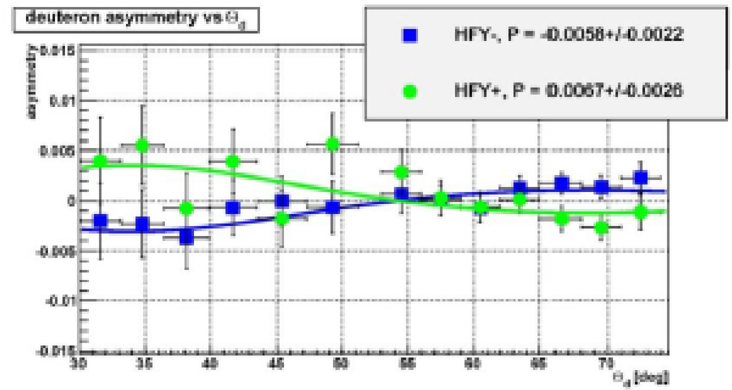
- Spin Filter: selective removal through **pp** scattering beyond the acceptance.
- Spin Flip: selective reversal the spin of the particle in one spin state.

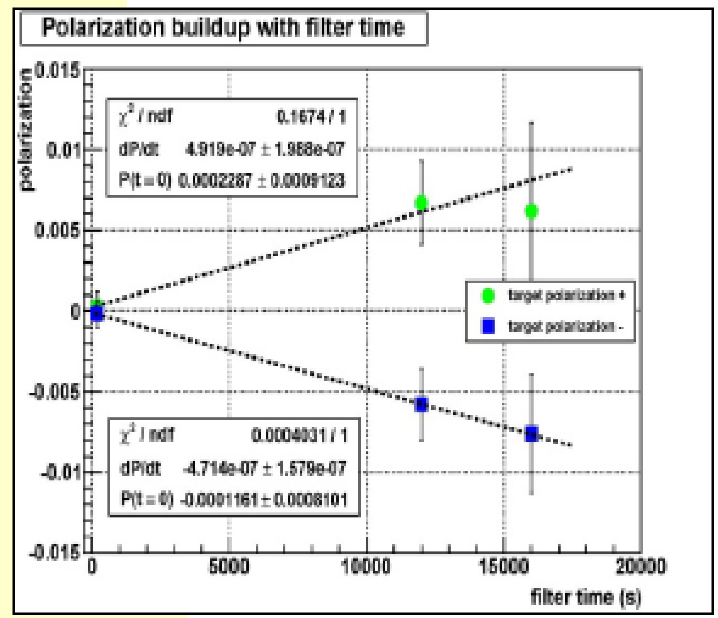
Spin Transfer: from polarized electrons.

A. Dbeyssi

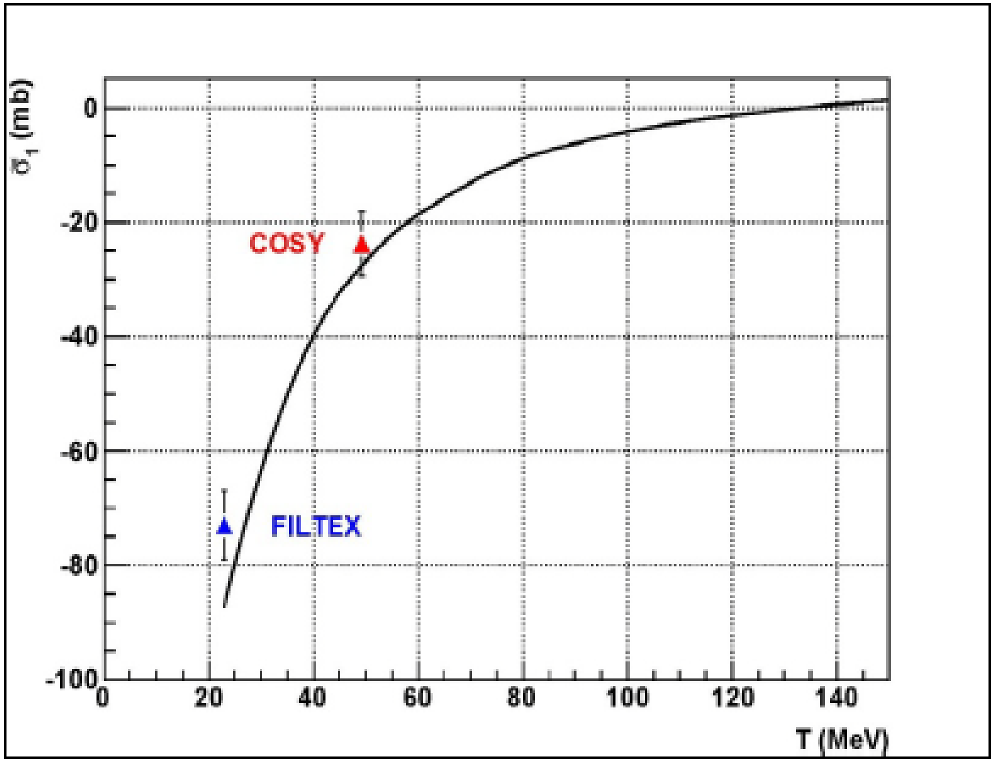
2011: Spin-filtering measurement





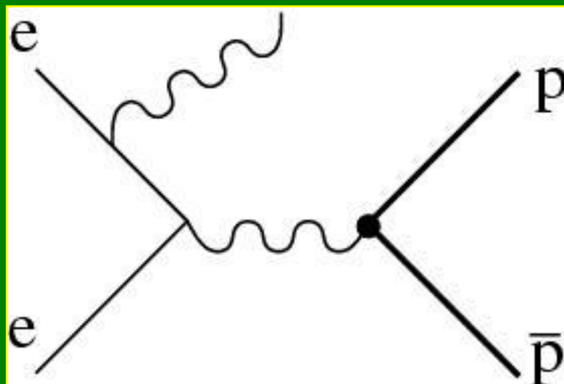


Result



- Milestone for the field!
  - Confirms understanding of spin-filtering as a viable method to polarize a stored beam.
  - Confirms complete control of the systematics of the experiment
  - Does not cover for the lack of knowledge of the pbar-p interaction.

Radiative Return (ISR)



$$e^+ + e^- \rightarrow p + p + \gamma$$

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

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

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

Application to BES-III presented by:
F. Maas on behalf of C. Morales

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!

Expected Results

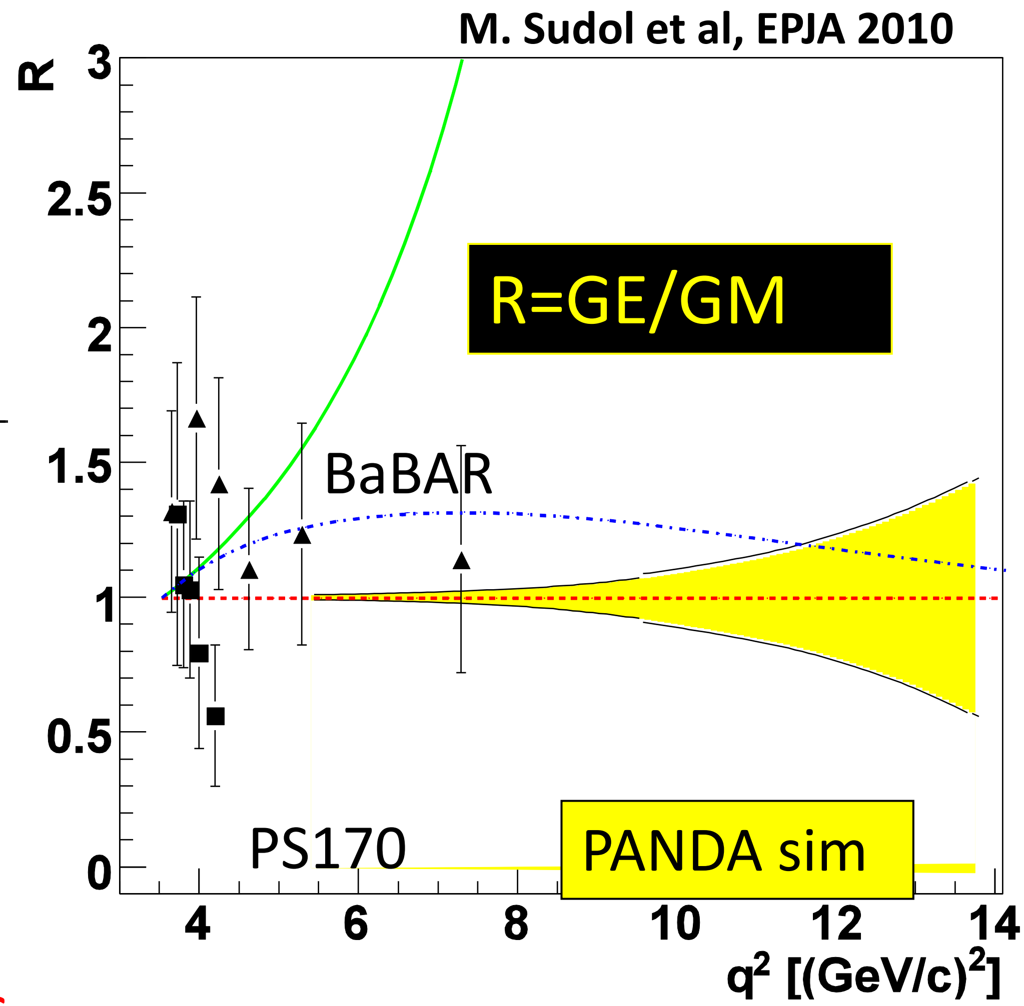
$\mathscr{L} = 2 \cdot 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

100 days

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

Individual determination of GE and GM up to large Q^2

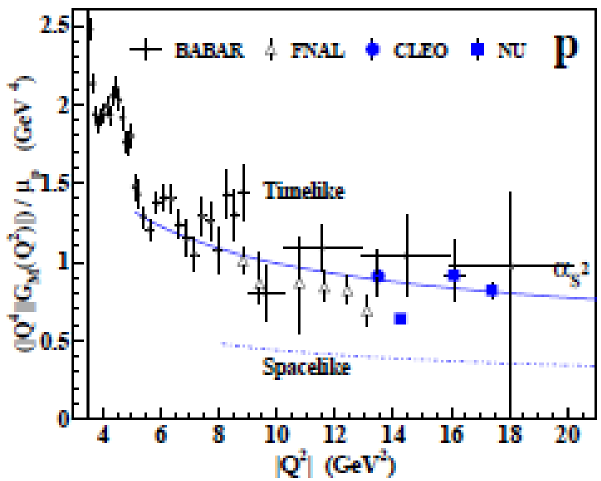
new PandaRoot analysis
Mainz, Orsay

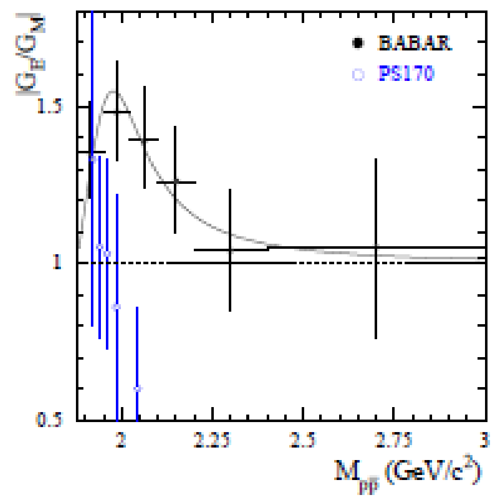


D. Khaneft

PROTONS

I promised not to say much about protons. So, I will only present the latest results, including our results (PRL 110, 022002 (2013)) published **one month ago**, and the BaBar results (arXiv:1302.0055) listed **two weeks ago**.





I want to draw your attention to three points.

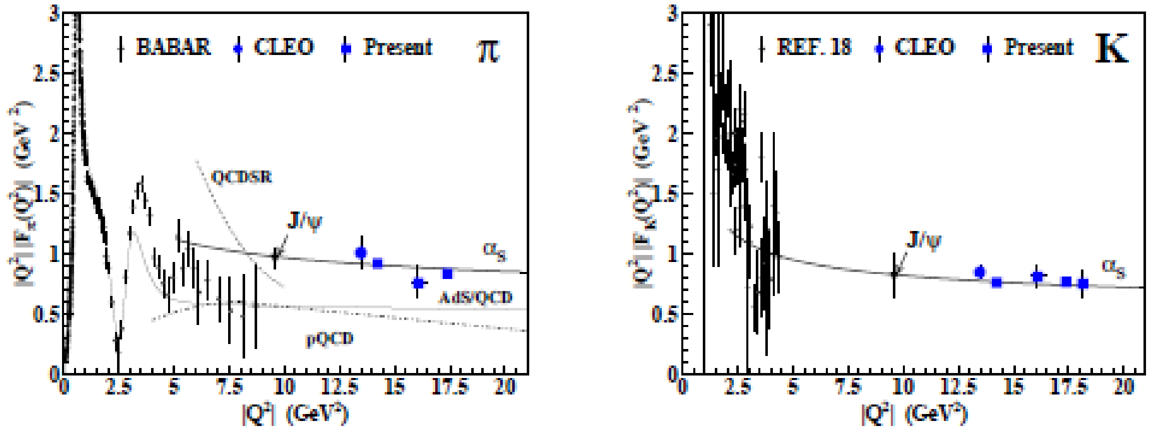
1. Irrespective of some of the large error bars, it is clear that

$$\text{FF(timelike)} \approx 2 \times \text{FF(spacelike)}$$

This feature, first observed in Fermilab $p\bar{p} \to e^+e^-$ measurements, and confirmed by CLEO measurements, is still unexplained. Diquark–quark structure of the proton remains a contender.

Added material following the discussion

Pion and Kaon Form Factors



The important experimental results are:

1. There is a remarkable agreement of the form factors for both pions and kaons with the **dimensional counting rule prediction of QCD** that $|Q^2|F_{\pi,K}$ are nearly constant, varying with $|Q^2|$ only weakly as $\alpha_S(|Q^2|)$.
2. The existing theoretical predictions **underpredict the magnitude** of $F_\pi(|Q^2|)$ at large $|Q^2|$ by large factors, ≥ 2. More about this later.
3. $\boldsymbol{F_\pi(14.2\ \text{GeV}^2)/F_K(14.2\ \text{GeV}^2) = 1.21 \pm 0.03}$,
   $\boldsymbol{F_\pi(17.4\ \text{GeV}^2)/F_K(17.4\ \text{GeV}^2) = 1.09 \pm 0.04 \neq (f_\pi/f_K)^2 = 0.67 \pm 0.01}$.
   More about this later.

Added material following the discussion

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

Patrizia Rossi ECT* Trento – February 18-22, 2013 9 Jefferson Lab

Hadron Form Factors: Conclusions

Large activity in Space-like and Time-like regions

Jefferson Lab

VEPP-3 Novosibirsk

IHEP

Unified models in SL and TL regions:

- reproduce proton, neutron, electric, magnetic
- pointlike behavior at threshold?
- GEn, GMn(SL) $<$ GEn,GMn(TL);

To measure:

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


Thank you for attention