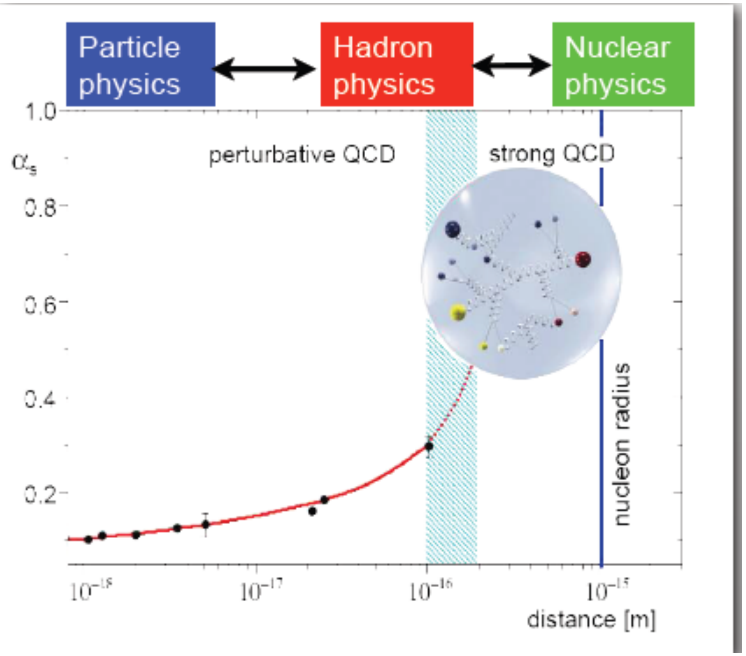
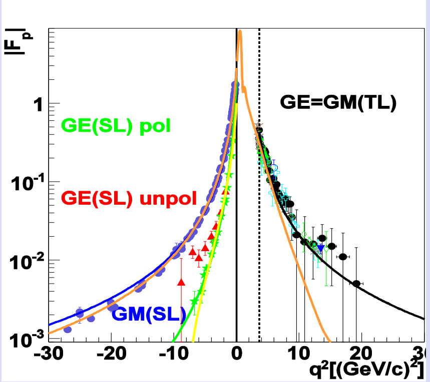
Open questions in QCD (some..)

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



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



Egle Tomasi-Gustafsson

IRFU, SPhN-Saclay,

In collaboration with :

S. Pacetti and R. Baldini-Ferroli

BLTP Bogoliubov Laboratory of Theoretical Physics

Dubna,13-2-2015

Plan

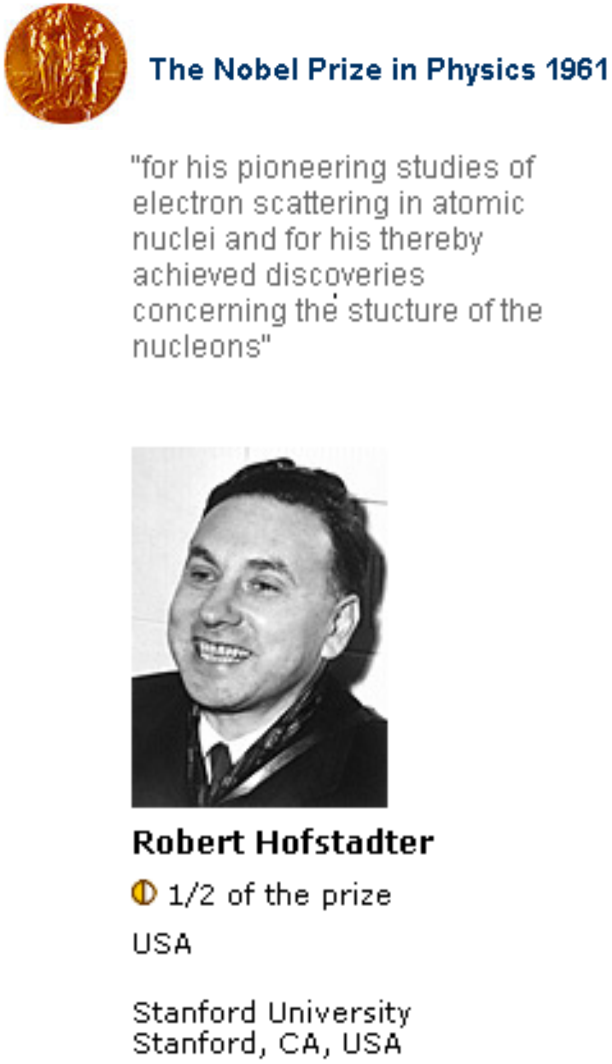
- Introduction
  - formalism

- The Experimental Status
  - The space-like region
    - Unpolarized experiments
    - Polarized experiments
    - Issues and open questions
  - The time-like region
    - The unphysical region
    - The threshold region
    - The asymptotics

- Interpretation(s)

- Future prospects and Conclusions

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.

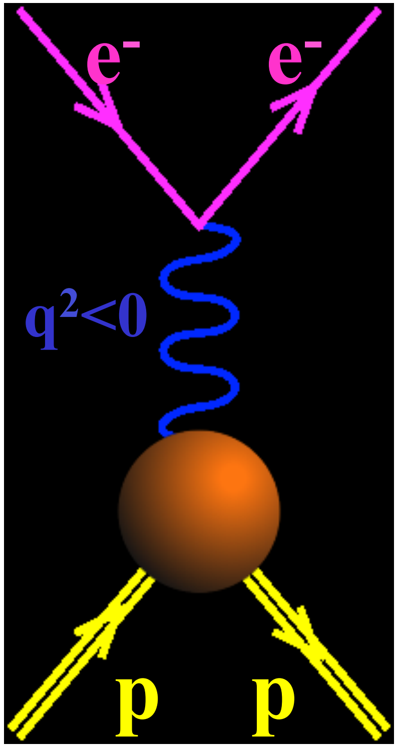
Neutron and proton form factors are different.

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

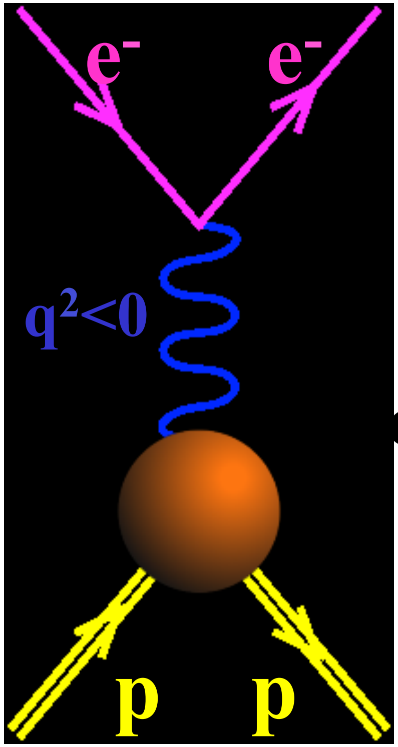
$$\Gamma_\mu = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M} F_2(q^2)$$

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

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



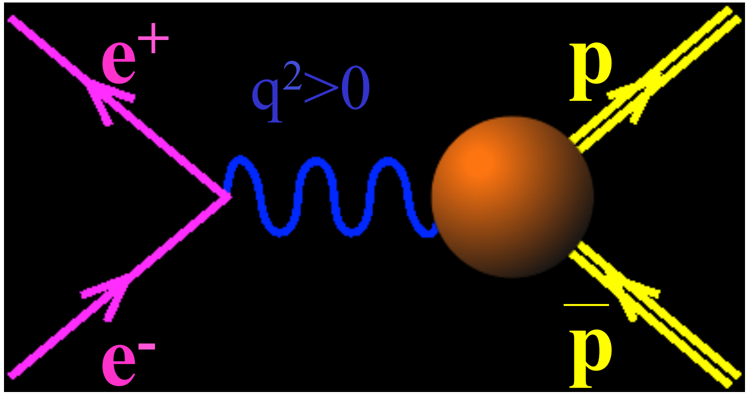
GE(0)=1

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

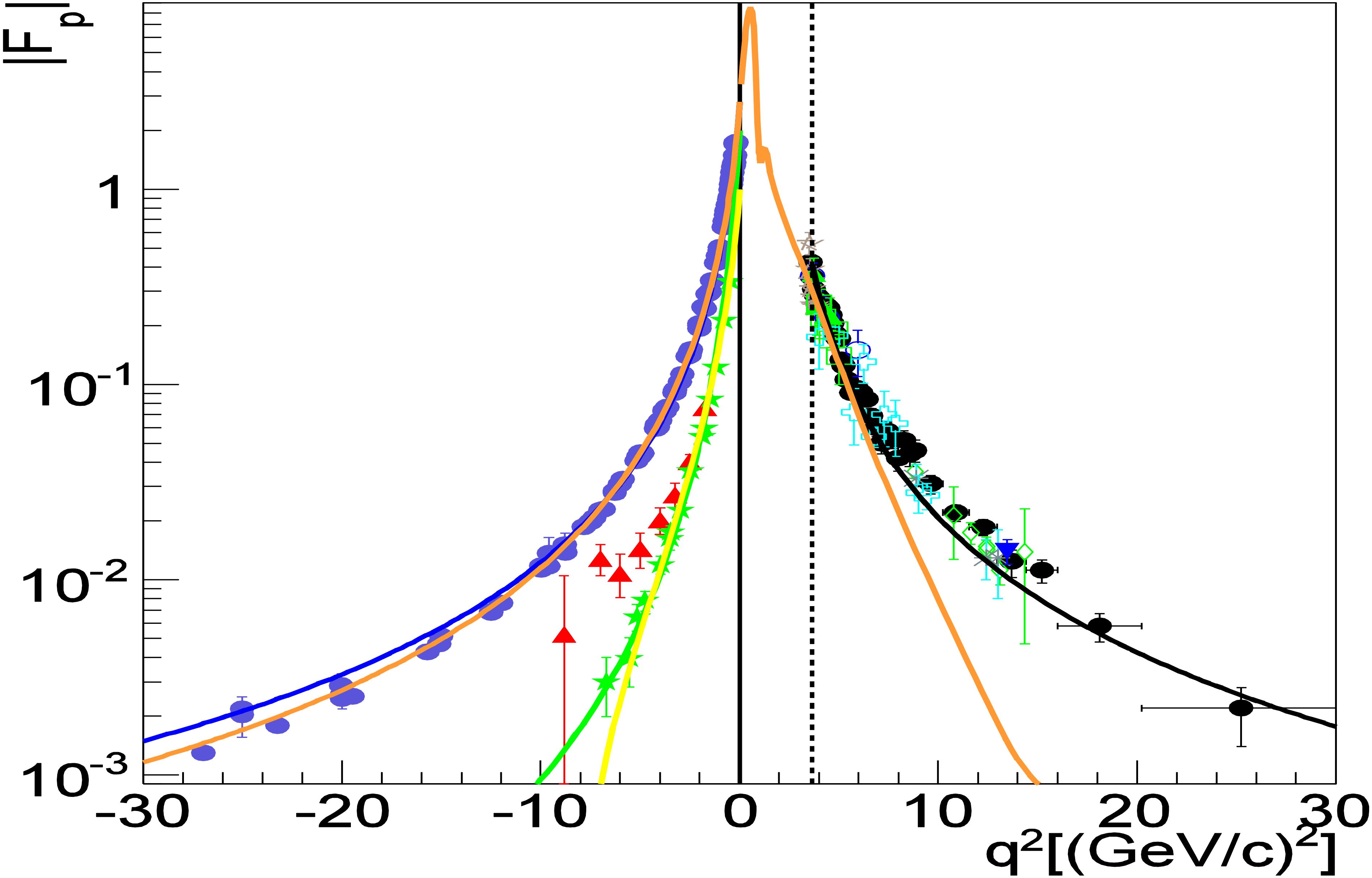
$e+p \rightarrow e+p$

$q^2=4m_p^2$
GE=GM

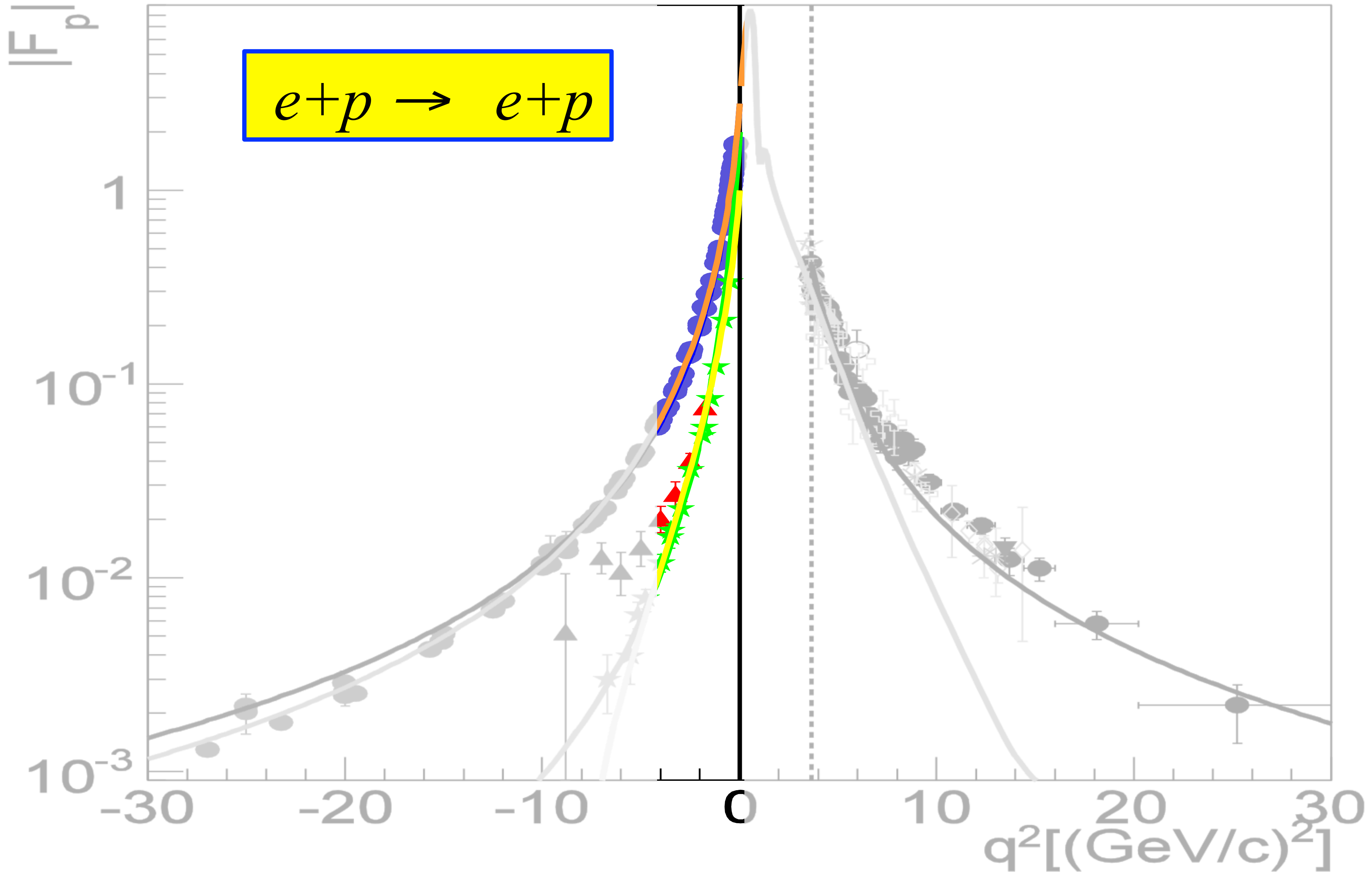
$p+\bar{p} \leftrightarrow e^+ + e^-$

q^2

Hadron Electromagnetic Form factors



The Space-Like region: low Q^2



Root mean square radius

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

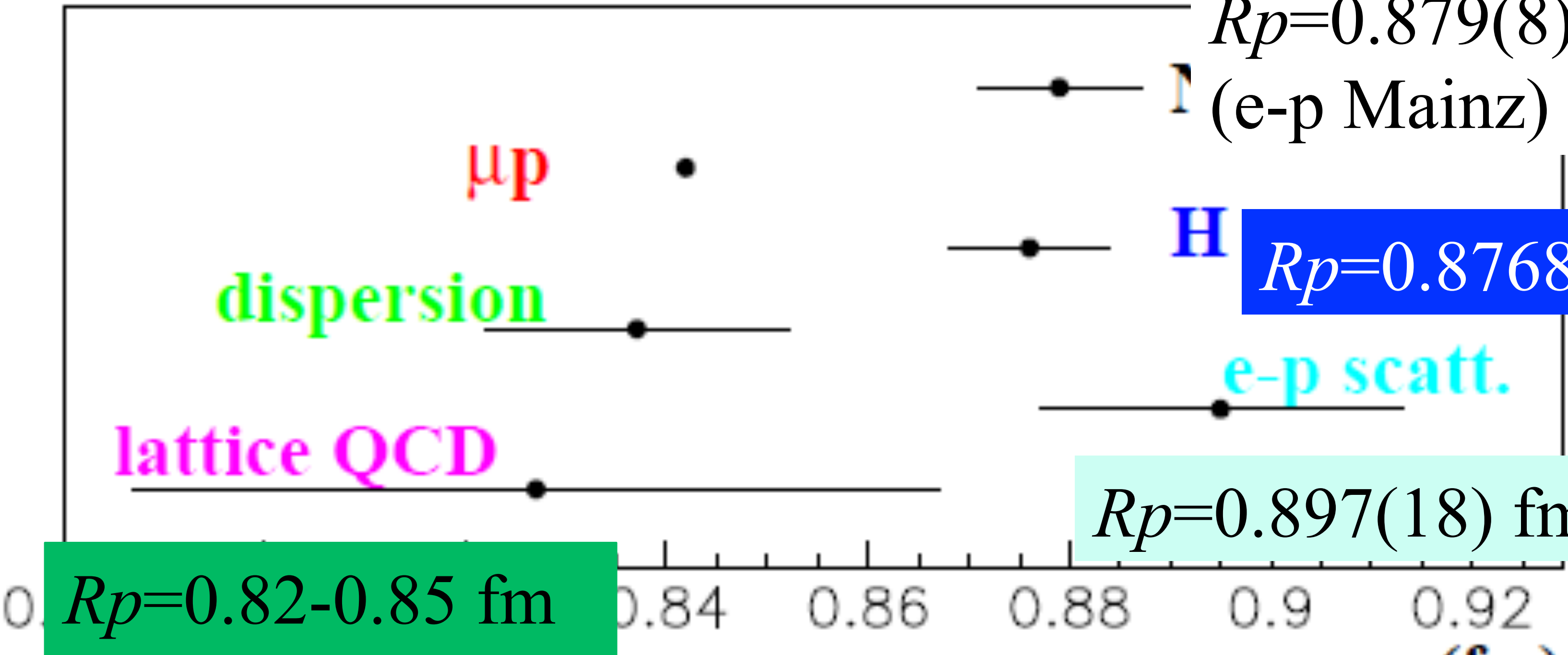
density $\rho(r)$	Form factor $F(q^2)$	r.m.s. $< r_c^2 >$	comments
δ	1	0	pointlike
e^{-ar}	$\frac{a^4}{(q^2+a^2)^2}$	$\frac{12}{a^2}$	dipole
$\frac{e^{-ar}}{r}$	$\frac{a^2}{q^2+a^2}$	$\frac{6}{a^2}$	monopole
$\frac{e^{-ar^2}}{r^2}$	$e^{-q^2/(4a^2)}$	$\frac{1}{2a}$	gaussian
ρ_0 for $x \leq R$ 0 for $r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

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

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

The Proton Radius

Rp=0.84184(67) fm (muonic atom)



Rp=0.879(8) fm
(e-p Mainz)

Rp=0.8768(69) fm

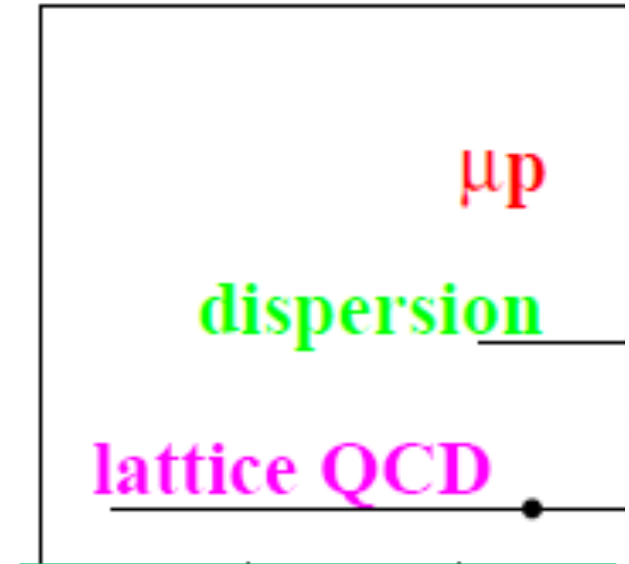
Rp=0.897(18) fm

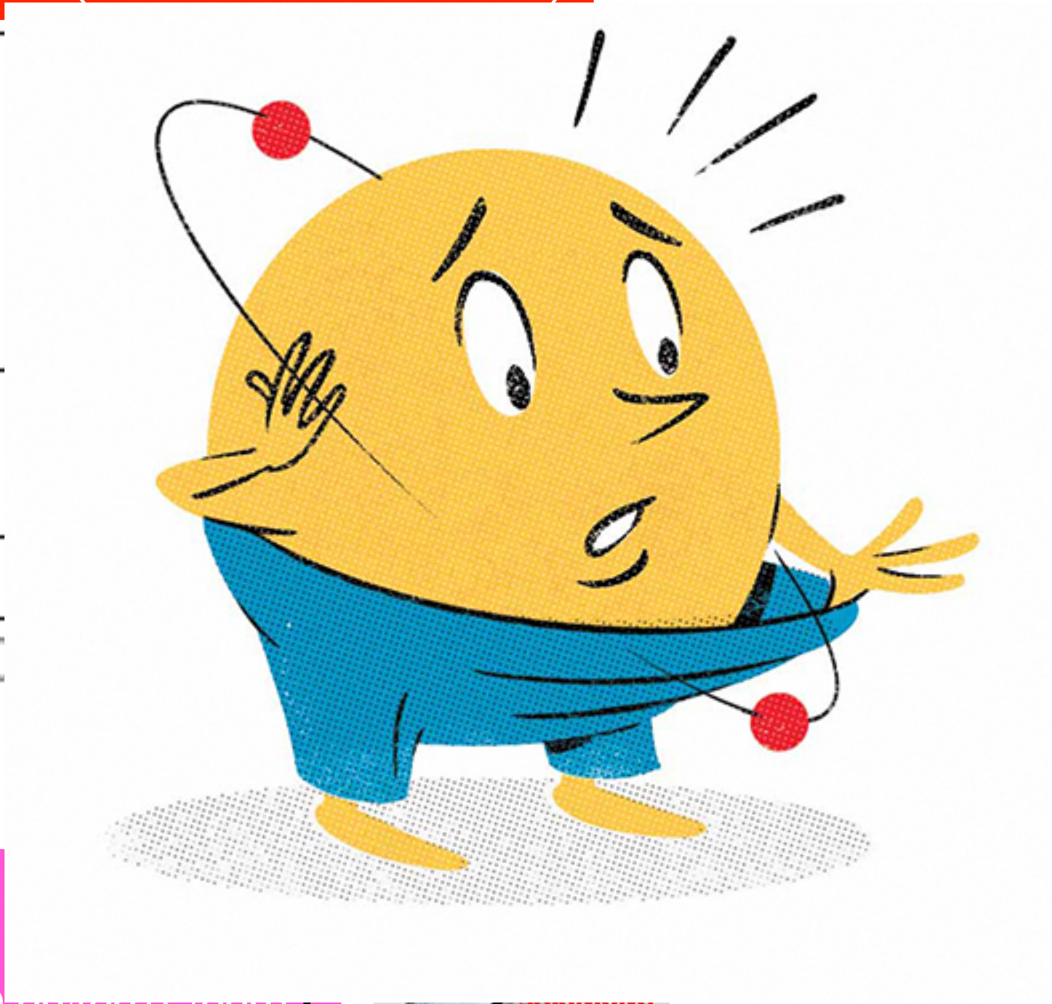
Rp=0.82-0.85 fm
(DR PRC75 035202(2007))

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

The Proton Radius

Rp=0.84184(67) fm (muonic atom)





n

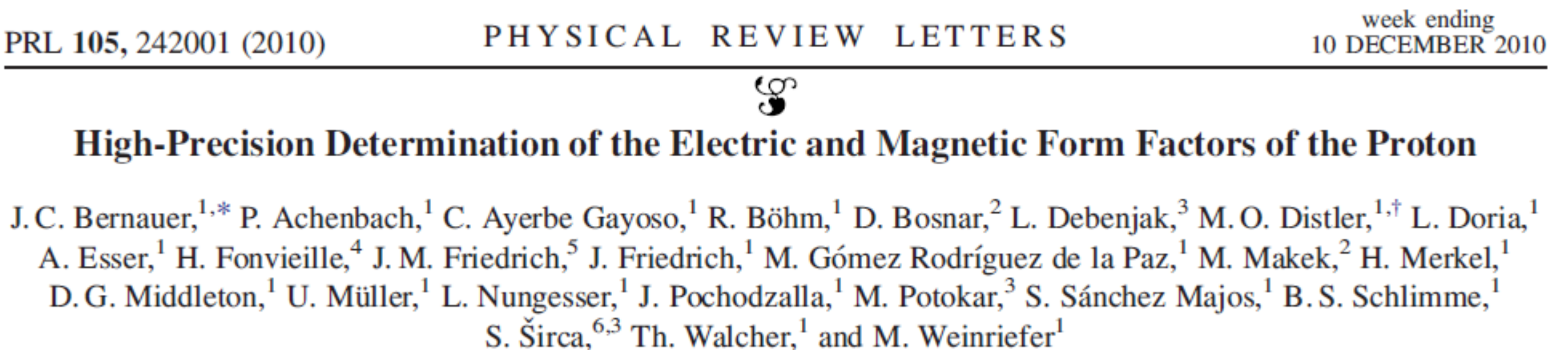
9) fm

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

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

SHRINKING THE PROTON

New value from exotic atom trims radius by four per cent



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)

$Q^2 > 0.004$ GeV^2

- Radiative corrections
- Two photon exchange
- Coulomb corrections

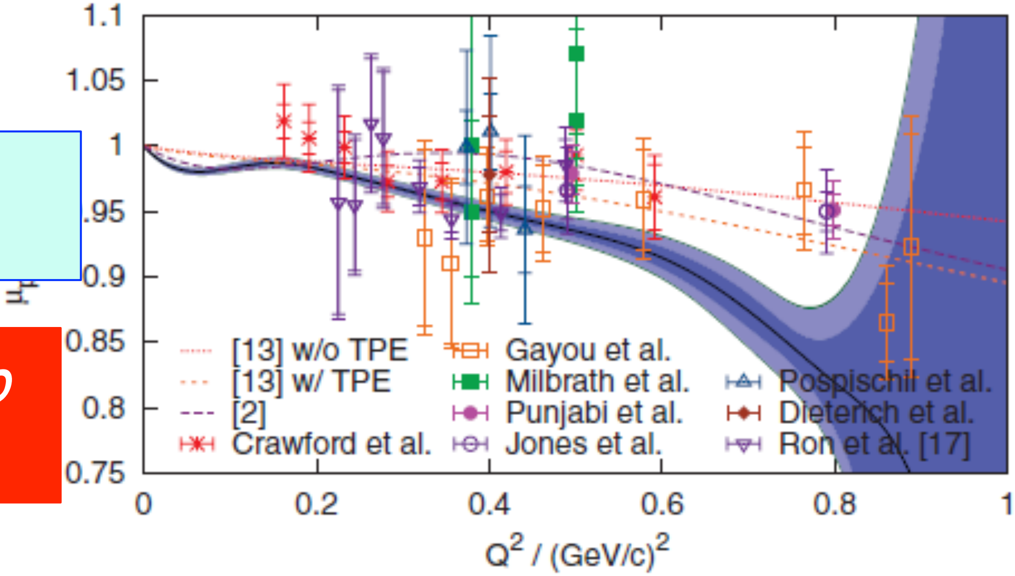
.....*comments*

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

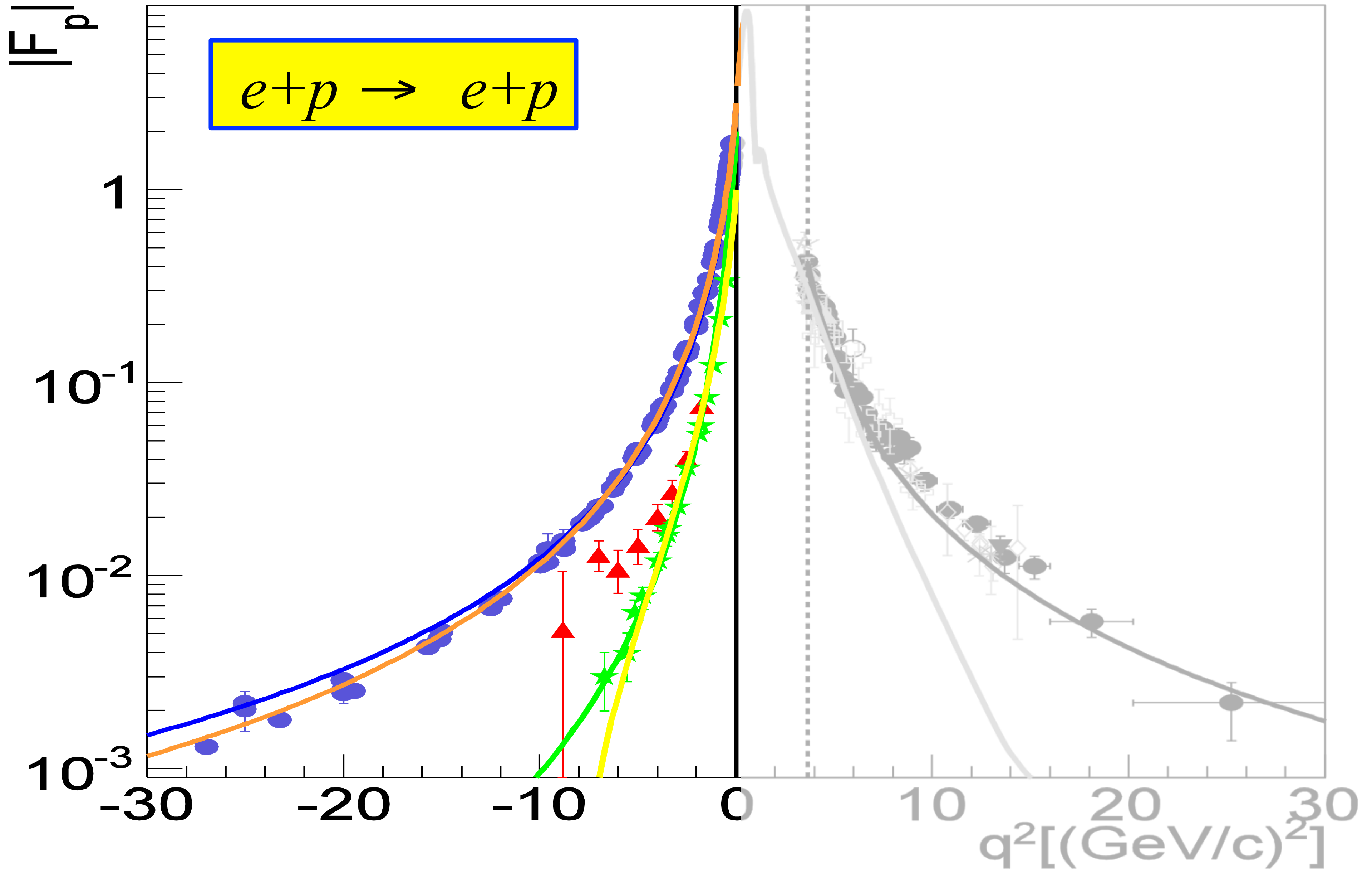
$$\langle r_M^2 \rangle^{1/2} = 0.777(13)_{\mathrm{stat}}(9)_{\mathrm{syst}}(5)_{\mathrm{model}}(2)_{\mathrm{group}}\ \mathrm{fm}.$$

- MUSE Experiment
- Jlab CLAS

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



The Space-Like region

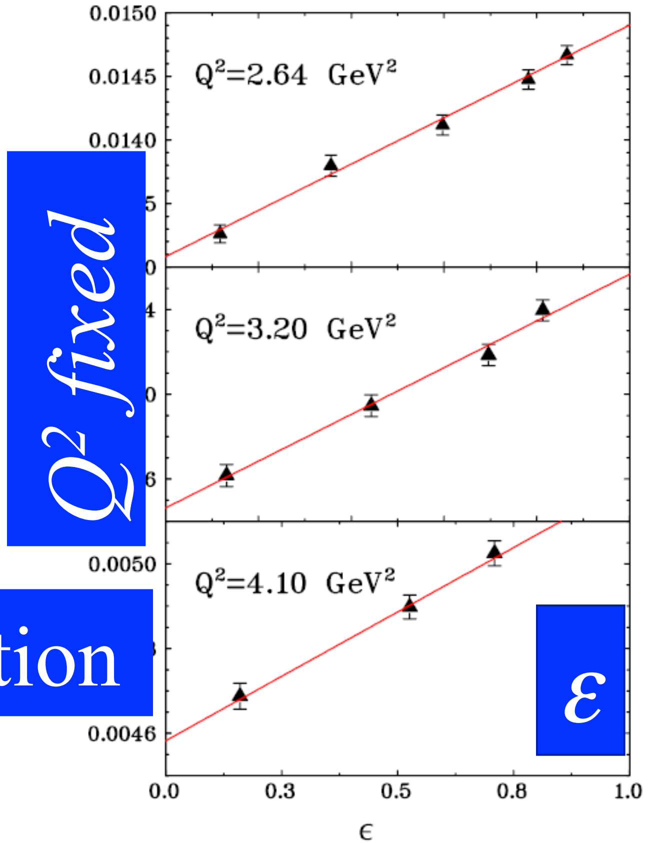


The Rosenbluth separation

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

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

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



Q^2 fixed

ε

Linearity of the reduced cross section

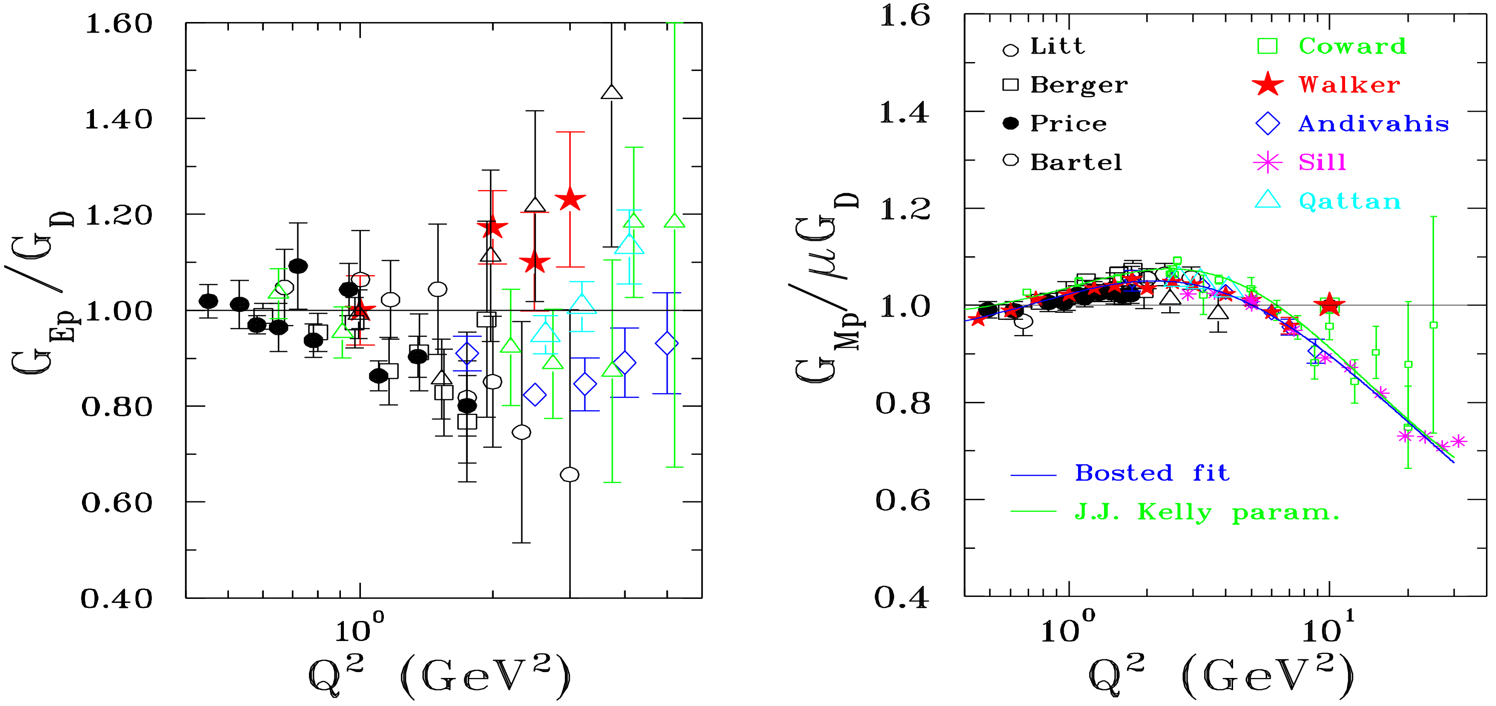
→ $\tan^2\theta_e$ dependence

→ Holds for 1γ exchange only

PRL 94, 142301 (2005)

Proton Form Factors … before

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



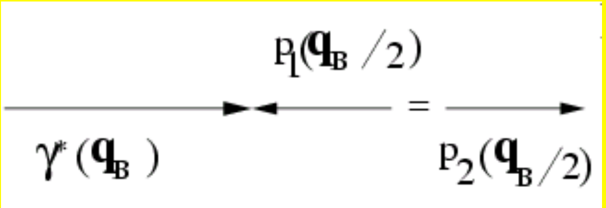
Rosenbluth separation/ Polarization observables

V. Punjabi, M. Jones,C. Perdrisat et al, JLab-GEp collaboration

Dipole Approximation

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

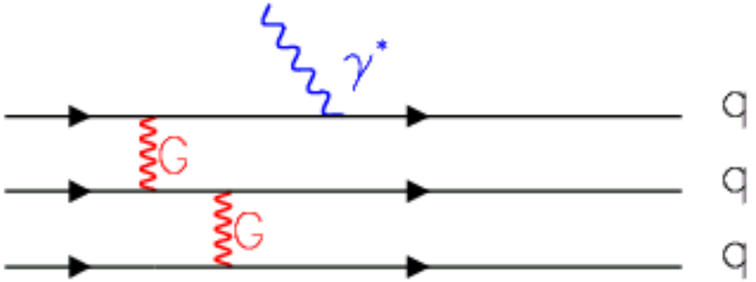
- Classical approach
  - Nucleon FF (in non relativistic approximation or in the Breit system) are Fourier transform of the charge or magnetic distribution.



Breit system

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

Dipole Approximation and pQCD



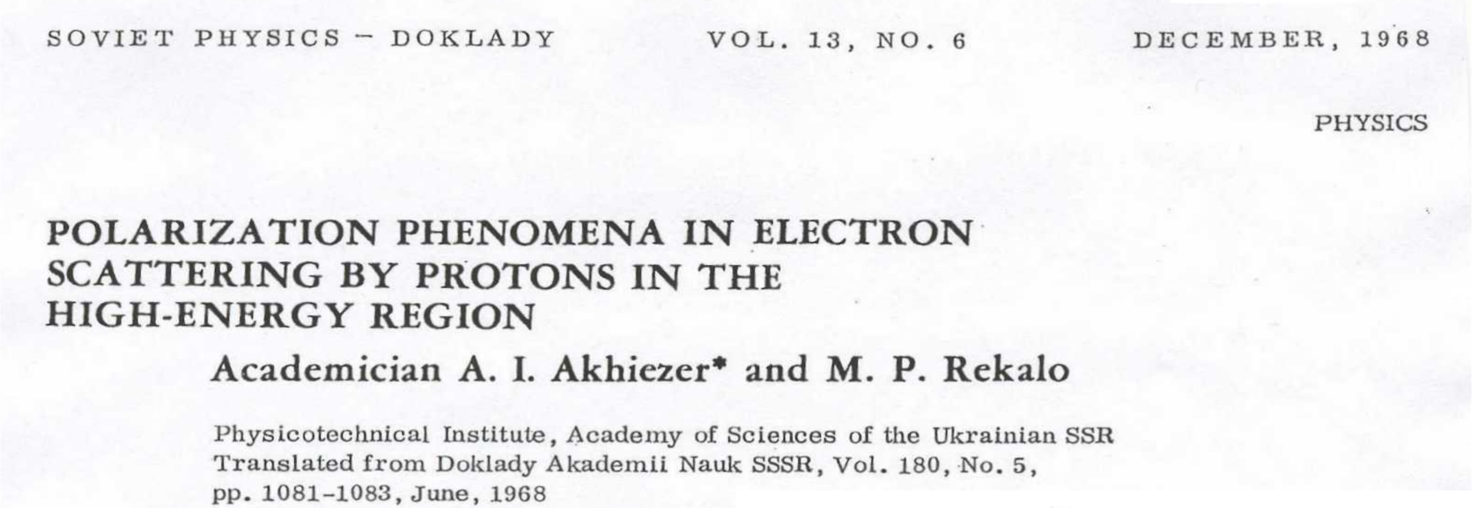
Dimensional scaling

- $F_n(Q^2) = C_n\,[1/(1+Q^2/m_n)^{n-1}]$,
  - $m_n = n\beta^2$, <quark momentum squared>
  - n is the number of constituent quarks

- Setting $\beta^2 = (0.471 \pm .010)$ GeV^2 *(fitting pion data)*
  - **pion**: $F_\pi(Q^2) = C_\pi\,[1/(1+Q^2/0.471\ \text{GeV}^2)^1]$,
  - **nucleon**: $F_N(Q^2) = C_N\,[1/(1+Q^2/0.71\ \text{GeV}^2)^2]$,
  - **deuteron**: $F_d(Q^2) = C_d\,[1/(1+Q^2/1.41\,\text{GeV}^2)^5]$

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

The polarization method (theory:1967)



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

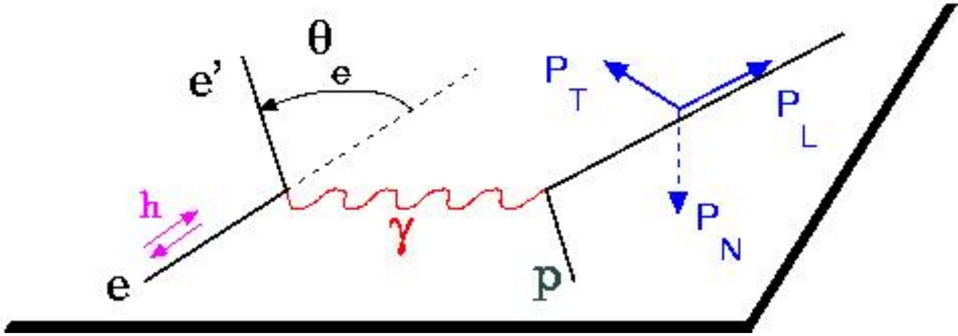
PHYSICS

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: 2000)

Transferred polarization is:

C. Perdrisat et al,
JLab-GEp collaboration

$$P_n = 0$$

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

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

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

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

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

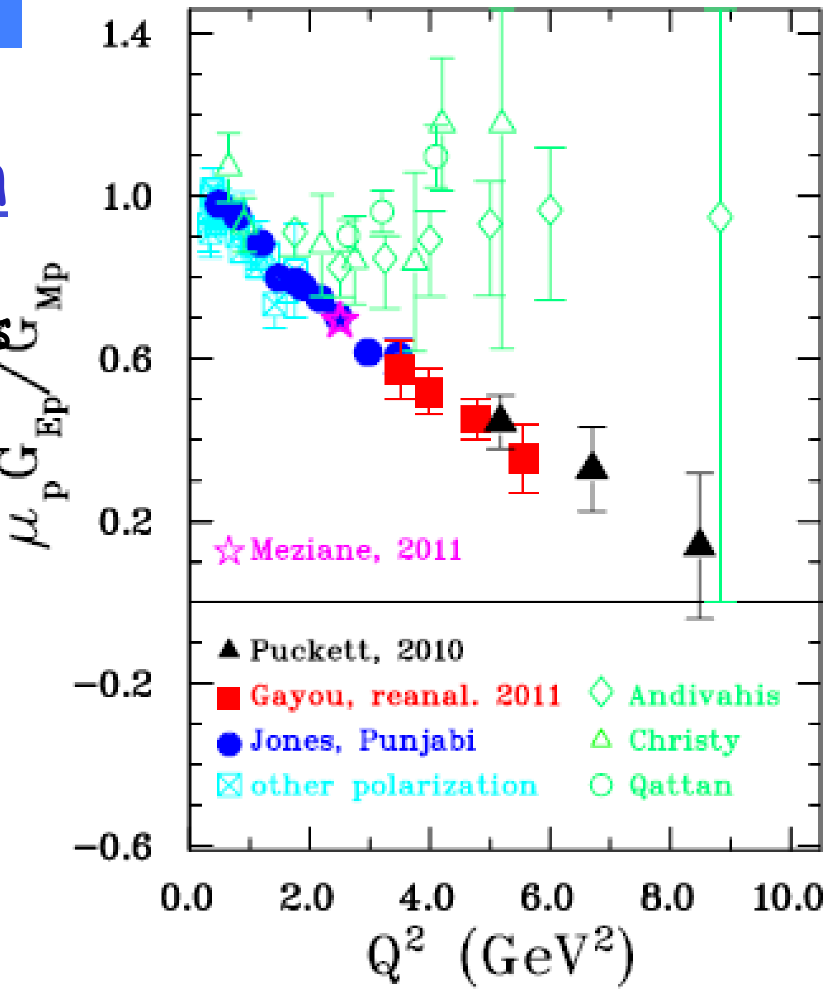
The simultaneous measurement of P_t and P_l reduces the systematic errors

Polarization experiments

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***



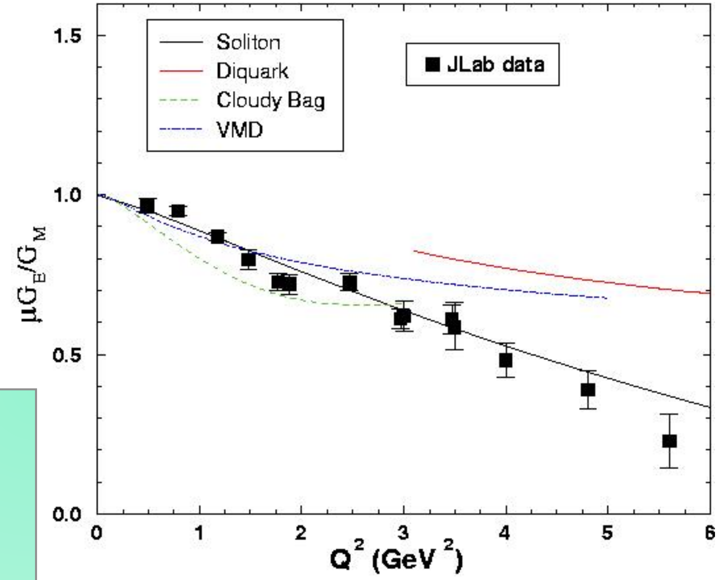
A.J.R. Puckett et al, PRL (2010), PRC (2012)

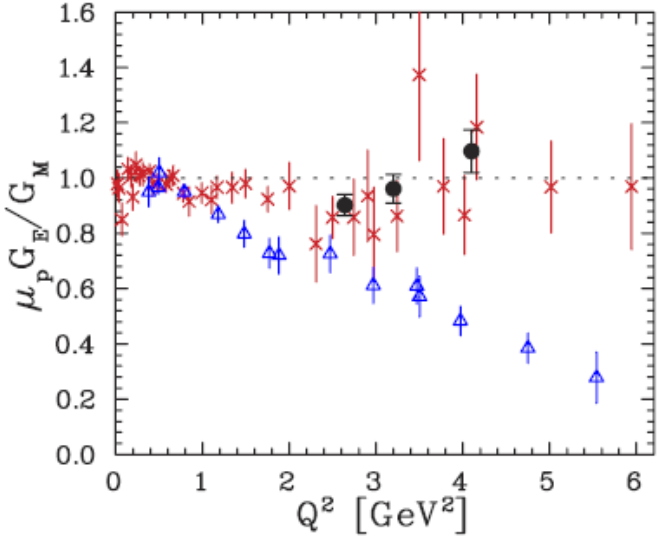
Issues

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

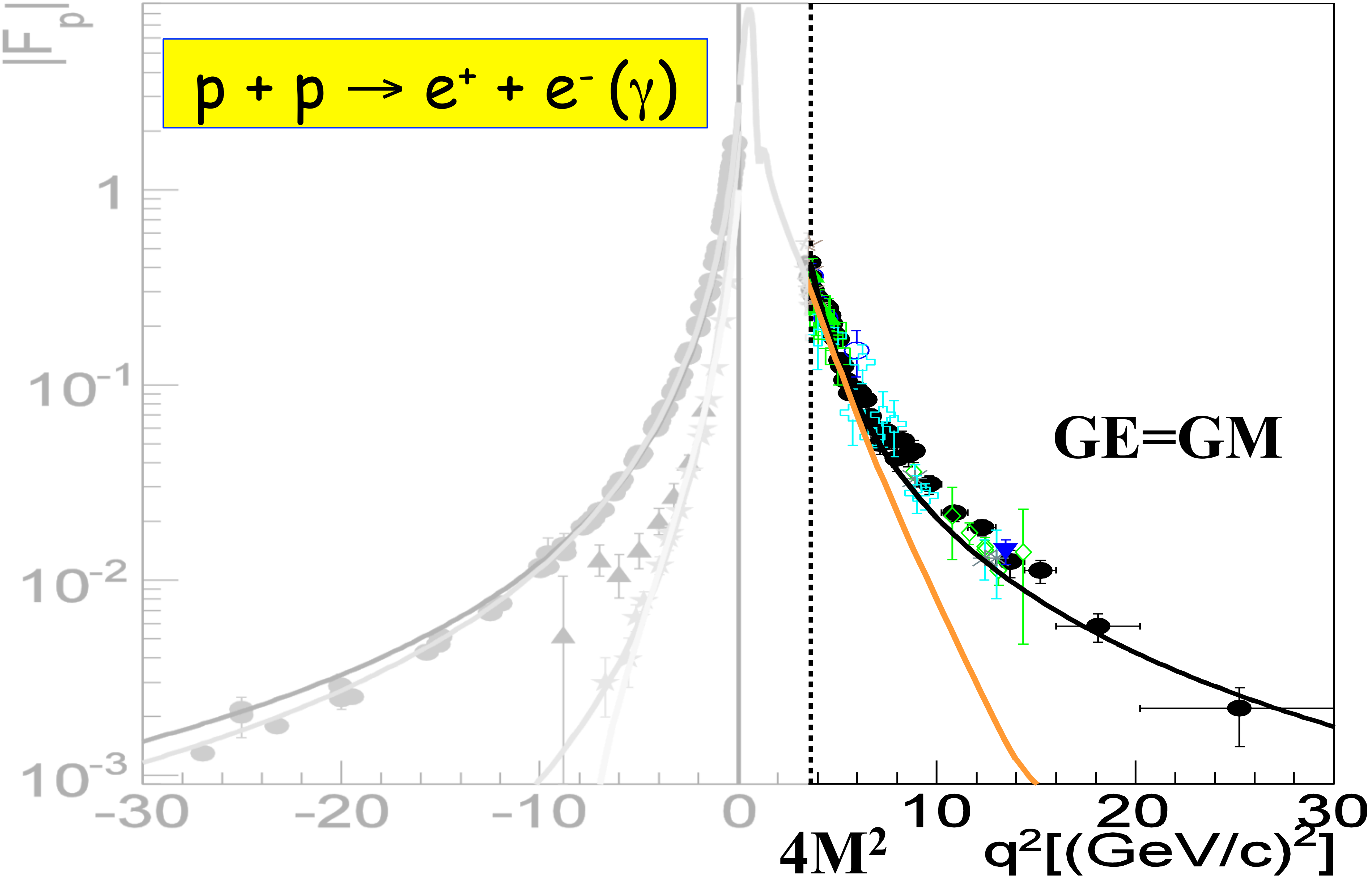
BUT

- 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 Time-Like region



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

Crossing symmetry

Scattering and annihilation channels:

- Described by the same amplitude :

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

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

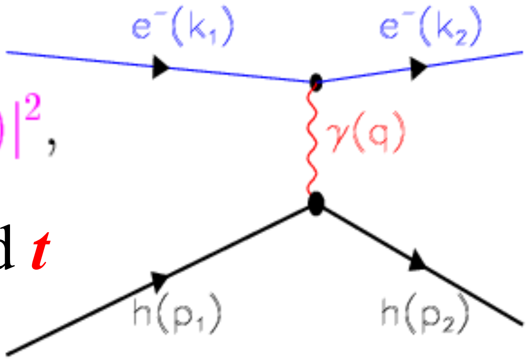
$$s = (k_1 + p_1)^2$$
$$t = (k_1 - k_2)^2$$

- which scan different kinematical regions

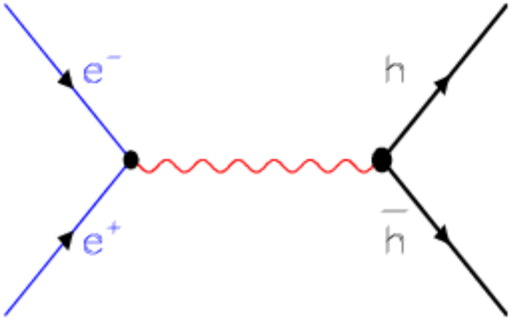
$$k_2 \longrightarrow -k_2$$
$$p_2 \longrightarrow -p_2$$

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

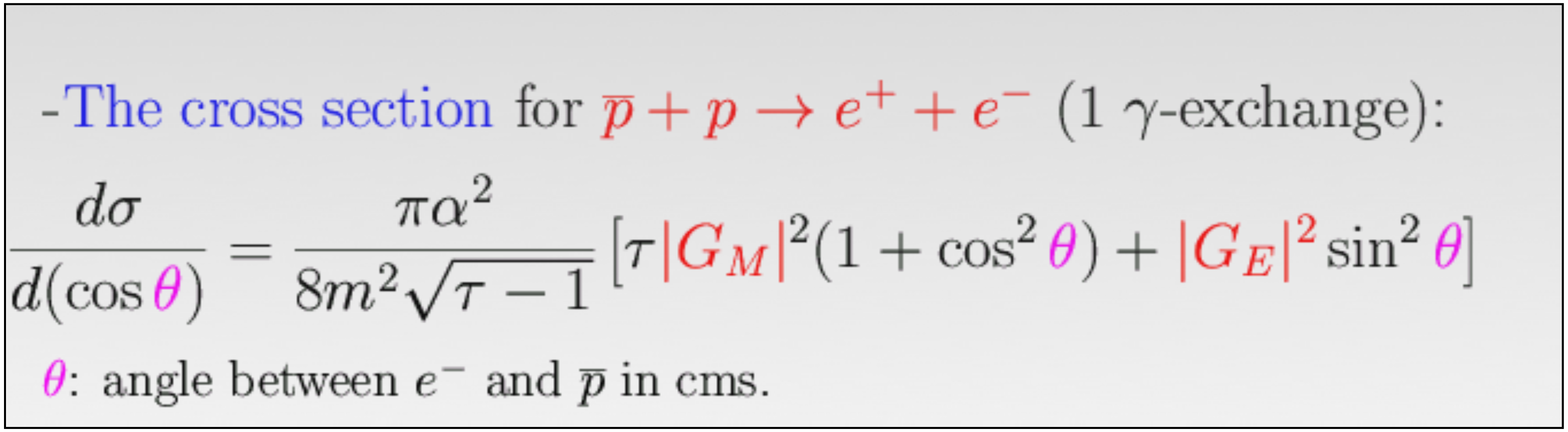
$$e^- + h \to e^- + h$$



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



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



-The cross section for $\bar{p}+p \to e^+ + e^-$ (1 γ-exchange):

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

θ: angle between e^- and $\bar{p}$ in cms.

A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Il Nuovo Cimento XXIV, 170 (1962)
B. Bilenkii, C. Giunti, V. Wataghin, Z. Phys. C 59, 475 (1993).
G. Gakh, E.T-G., Nucl. Phys. A761,120 (2005).

As in SL region:
- Dependence on q^2 contained in FFs
- Even dependence on $\cos^2\theta$ (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

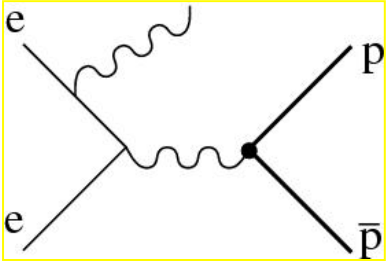
p̄anda

VEPP-Novosibirsk

IHEP

BES

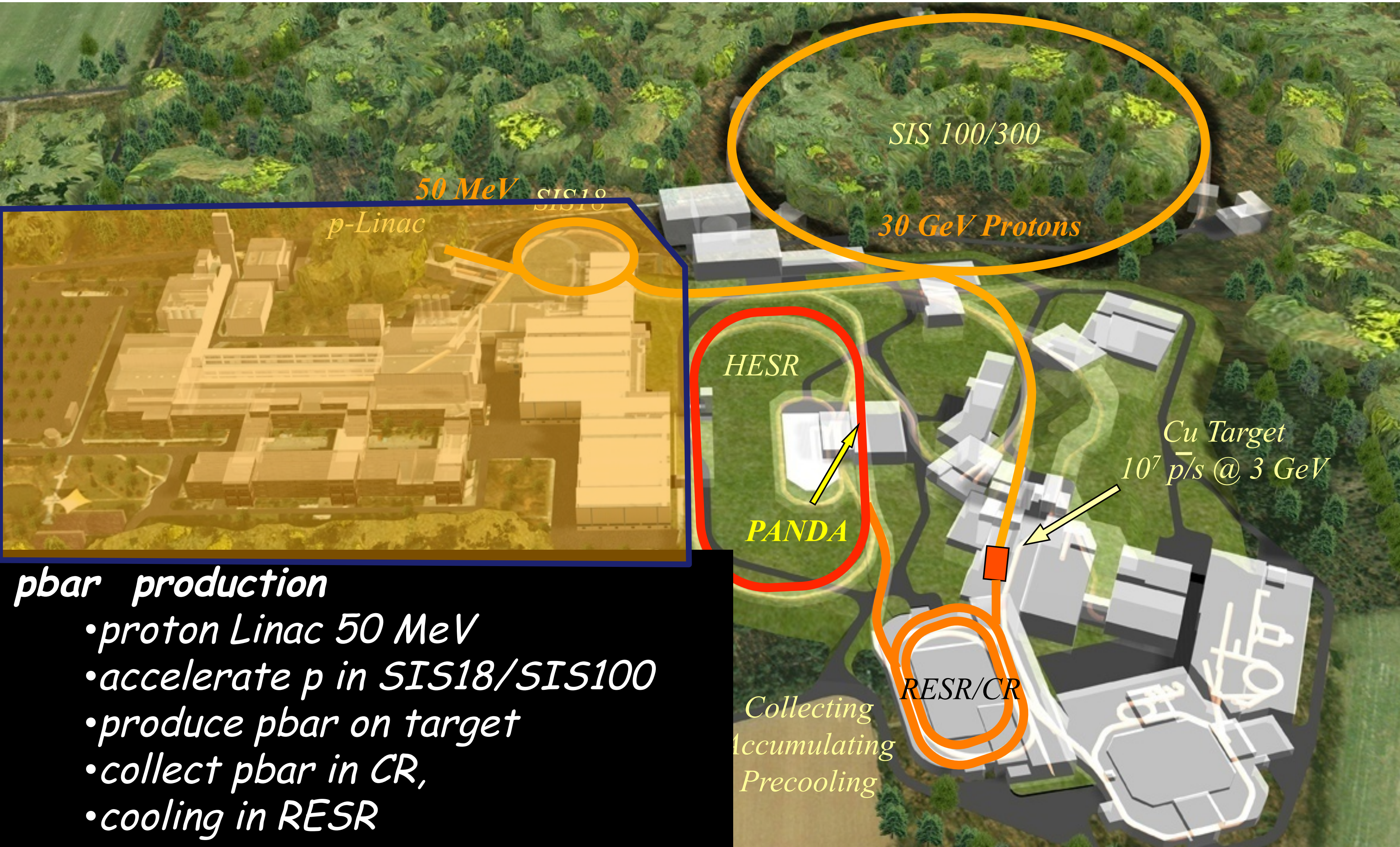
BABAR



Antiprotons at FAIR

http://www.fair-center.eu/

http://www-panda.gsi.de/



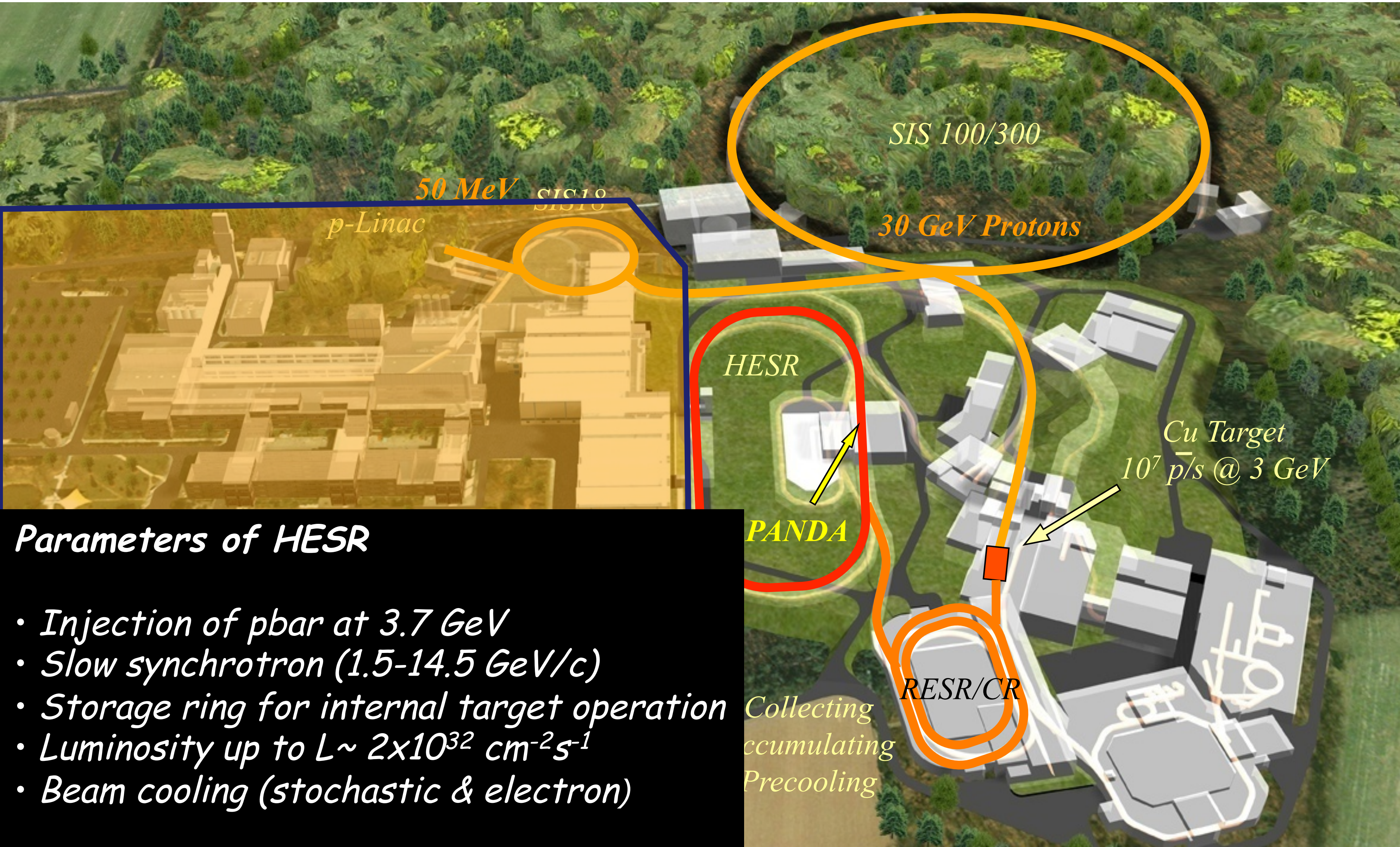
pbar production

- proton Linac 50 MeV
- accelerate p in SIS18/SIS100
- produce pbar on target
- collect pbar in CR,
- cooling in RESR

Antiprotons at FAIR

http://www.fair-center.eu/

http://www-panda.gsi.de/



Parameters of HESR

- *Injection of pbar at 3.7 GeV*
- *Slow synchrotron (1.5-14.5 GeV/c)*
- *Storage ring for internal target operation*
- *Luminosity up to L~ 2×10^{32} $cm^{-2}s^{-1}$*
- *Beam cooling (stochastic & electron)*

Hadron Physics with Antiprotons

- Dedicated experiments in the past decades for
  - Hadron spectroscopy
  - Hadron structure
  - Interaction of Hadrons

need of
- *Highest Rates*
- *Good Resolution*
- *Good Particle Identification*

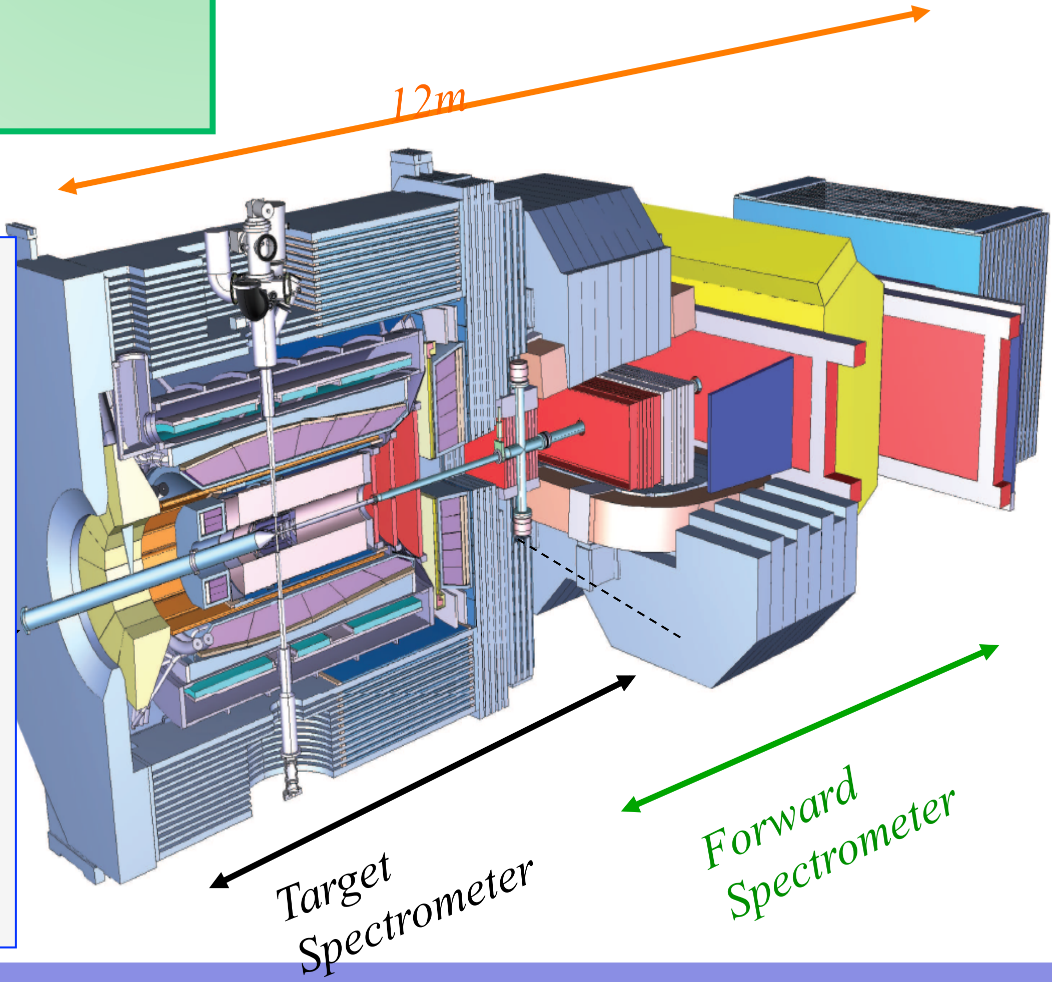
detector

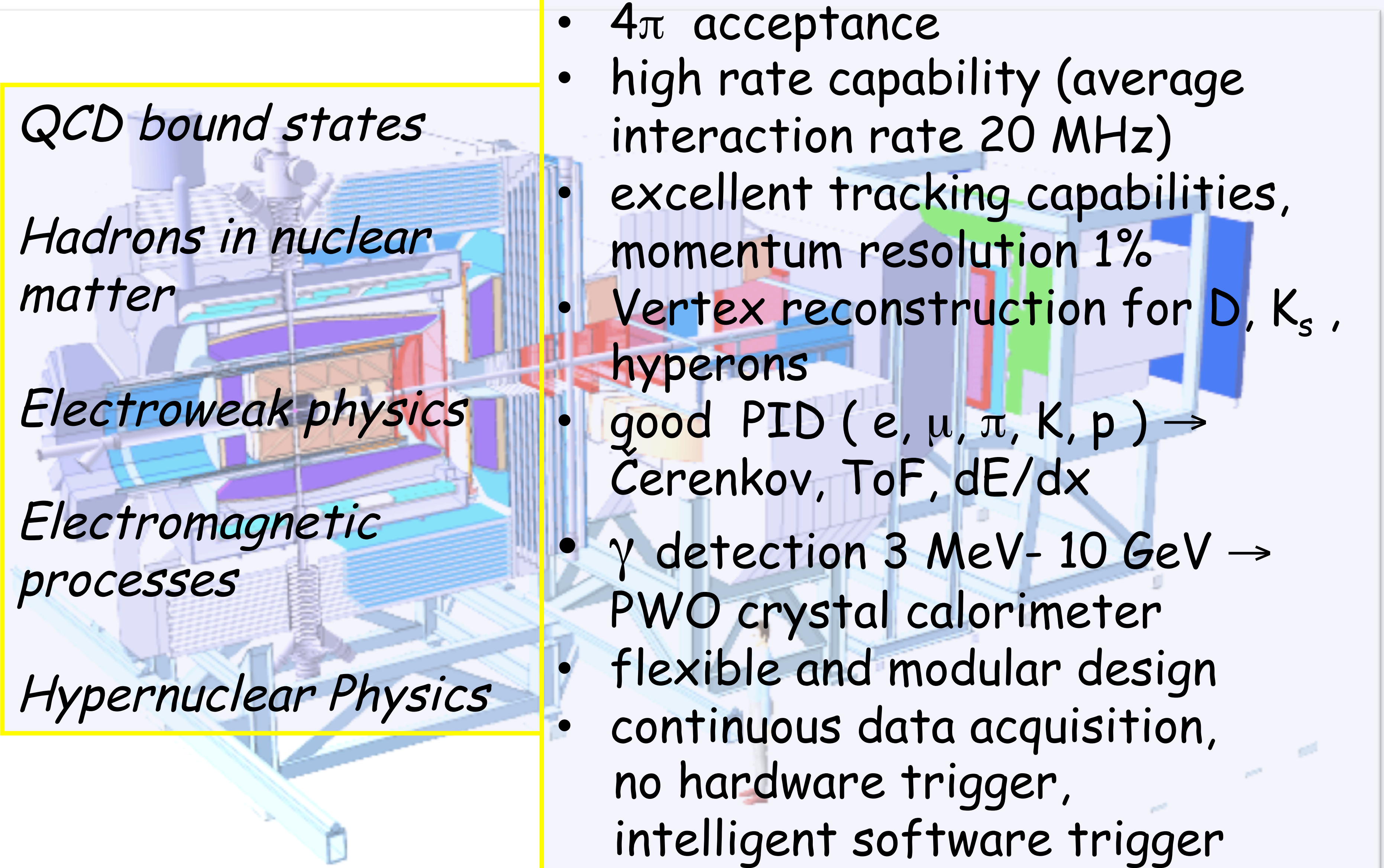
Fixed target experiment

<u>and</u>

Internal experiment in HESR storage ring (not interacting antiprotons recirculate)

The accelerator and the detector are built and optimized together for the best performances





Physic topics

QCD bound states

Hadrons in nuclear matter

Electroweak physics

Electromagnetic processes

Hypernuclear Physics

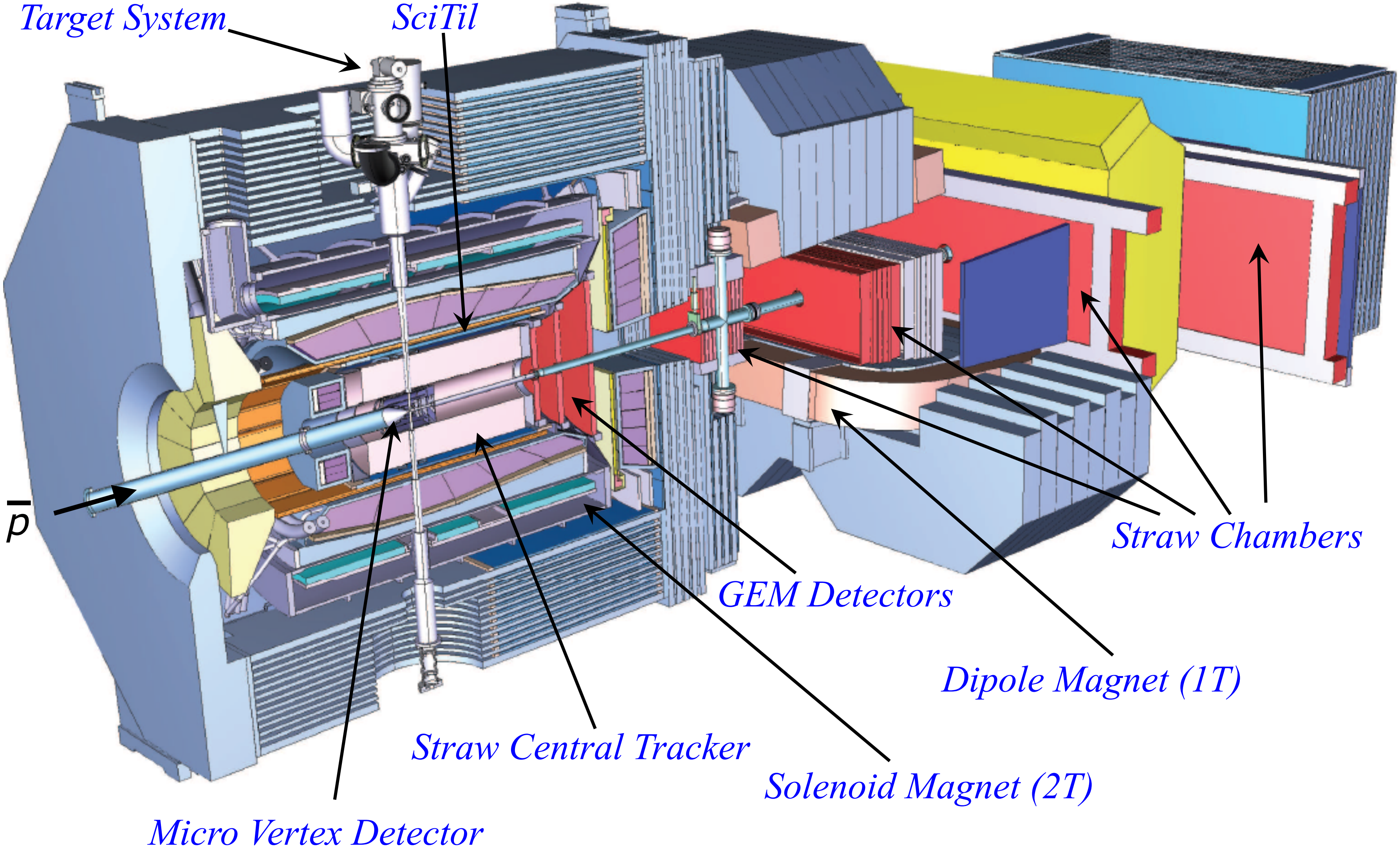
Detector requirements

- 4π acceptance
- high rate capability (average interaction rate 20 MHz)
- excellent tracking capabilities, momentum resolution 1%
- Vertex reconstruction for D, K_s , hyperons
- good PID (e, μ, π, K, p) → Čerenkov, ToF, dE/dx
- γ detection 3 MeV- 10 GeV → PWO crystal calorimeter
- flexible and modular design
- continuous data acquisition, no hardware trigger, intelligent software trigger

Target System and Tracking Devices

detector

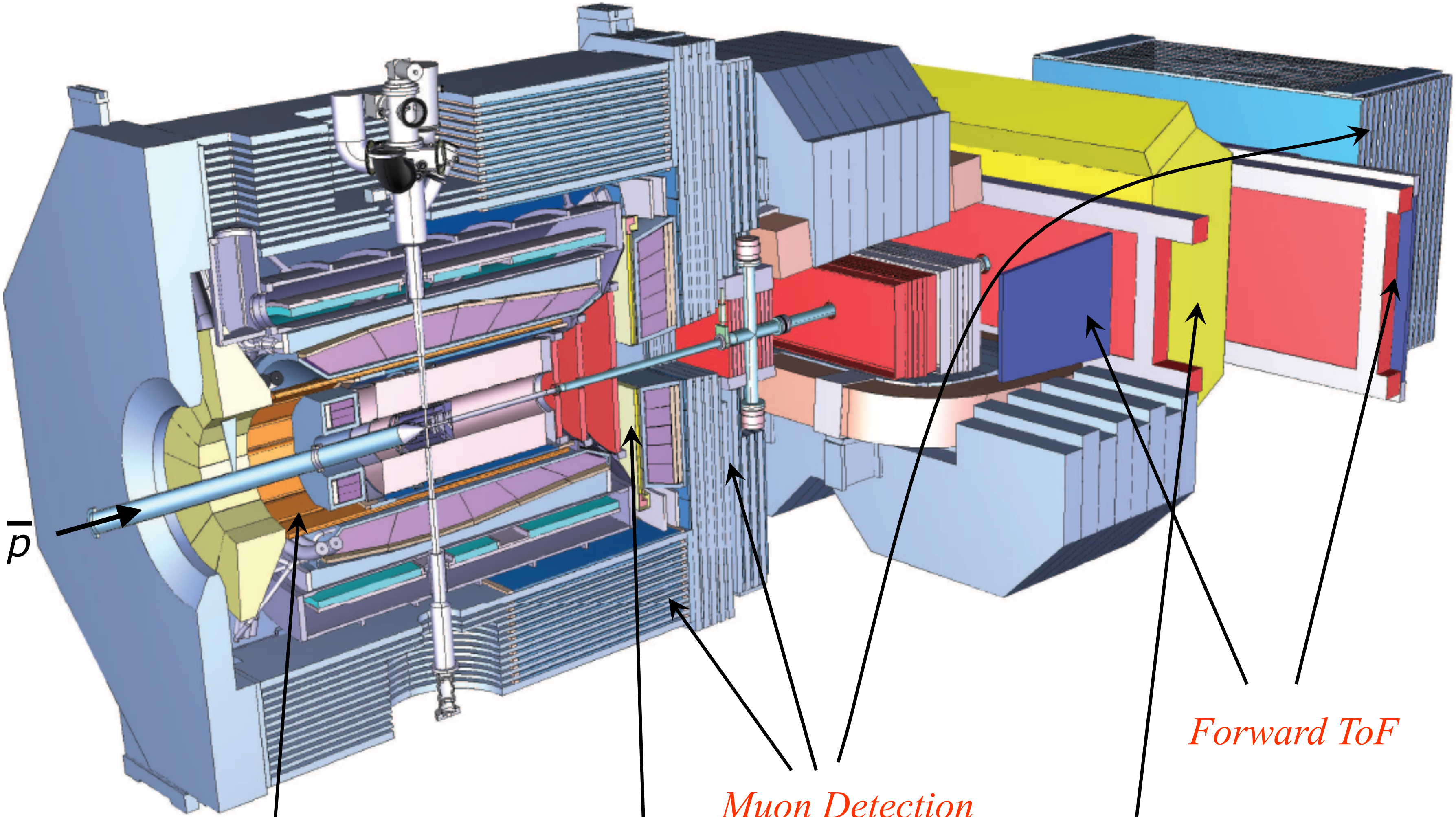
G.Boca GSI, Germany & U. Pavia, Italy



Particle ID detectors

p̄anda *detector*

G.Boca GSI, Germany & U. Pavia, Italy



$\bar{p}$

Forward ToF

Muon Detection

Barrel DIRC

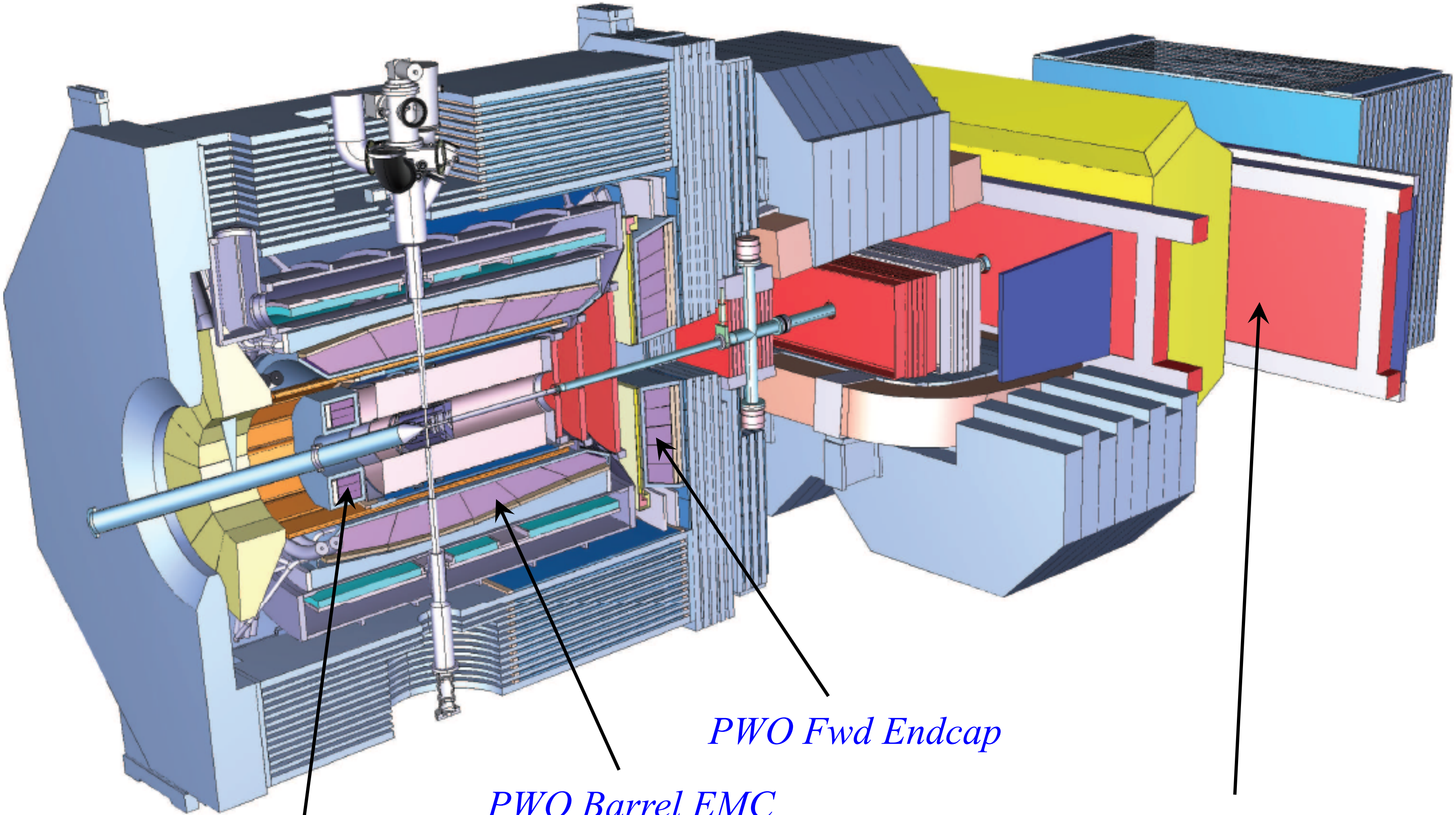
Disc DIRC

Forward RICH

Calorimetry

panda ***detector***

G.Boca GSI, Germany & U. Pavia, Italy



PWO Fwd Endcap

PWO Barrel EMC

Forward EM Calorimeter

PWO Backward Endcap

Antiproton facilities

Experiment	Years	Intensity $\bar{p}/s$	Momentum range [GeV/c]	$\Delta p/p$
CERN -LEAR	1983-1996	$2 \cdot 10^6$	0.06-1.94	10^{-3}
FermiLab 45% polarized $\bar{p}$	1985-2011	$2 \cdot 10^6$ 10^4		10^{-4}
PANDA	2017-...	$2 \cdot 10^7$	1.5-15	10^{-5}

Panda will have:

- *Better luminosity*
- *Better beam momentum resolution*
- *Better detector (coverage, PID,magnetic field..)*

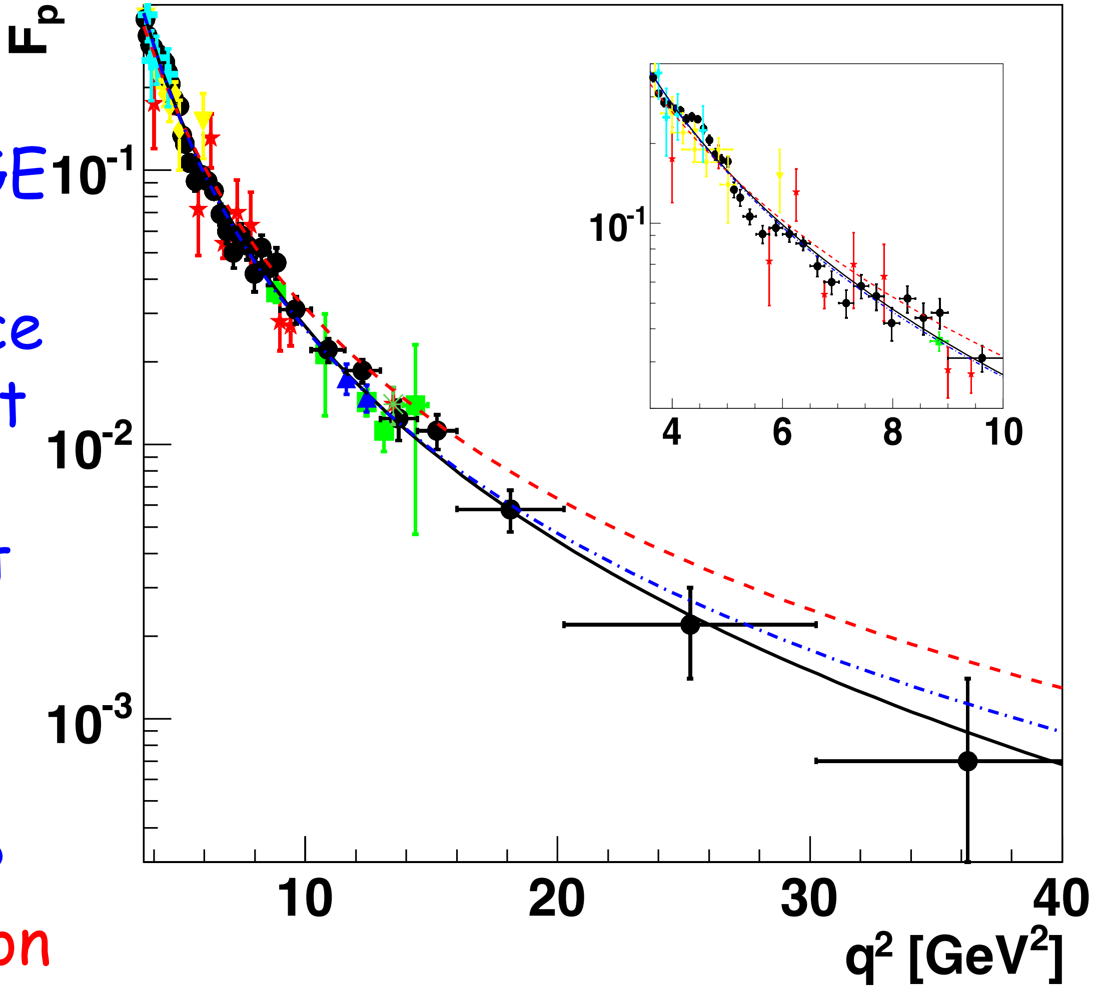
The Time-like region

GE=GM

- 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:

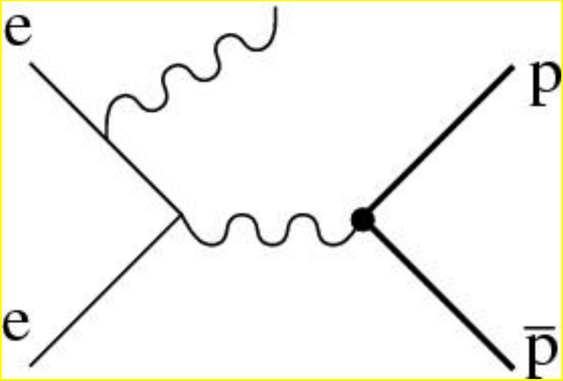
    Structures?

    Resonances?
  - -> Panda contribution



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

Radiative return (ISR)



BABAR

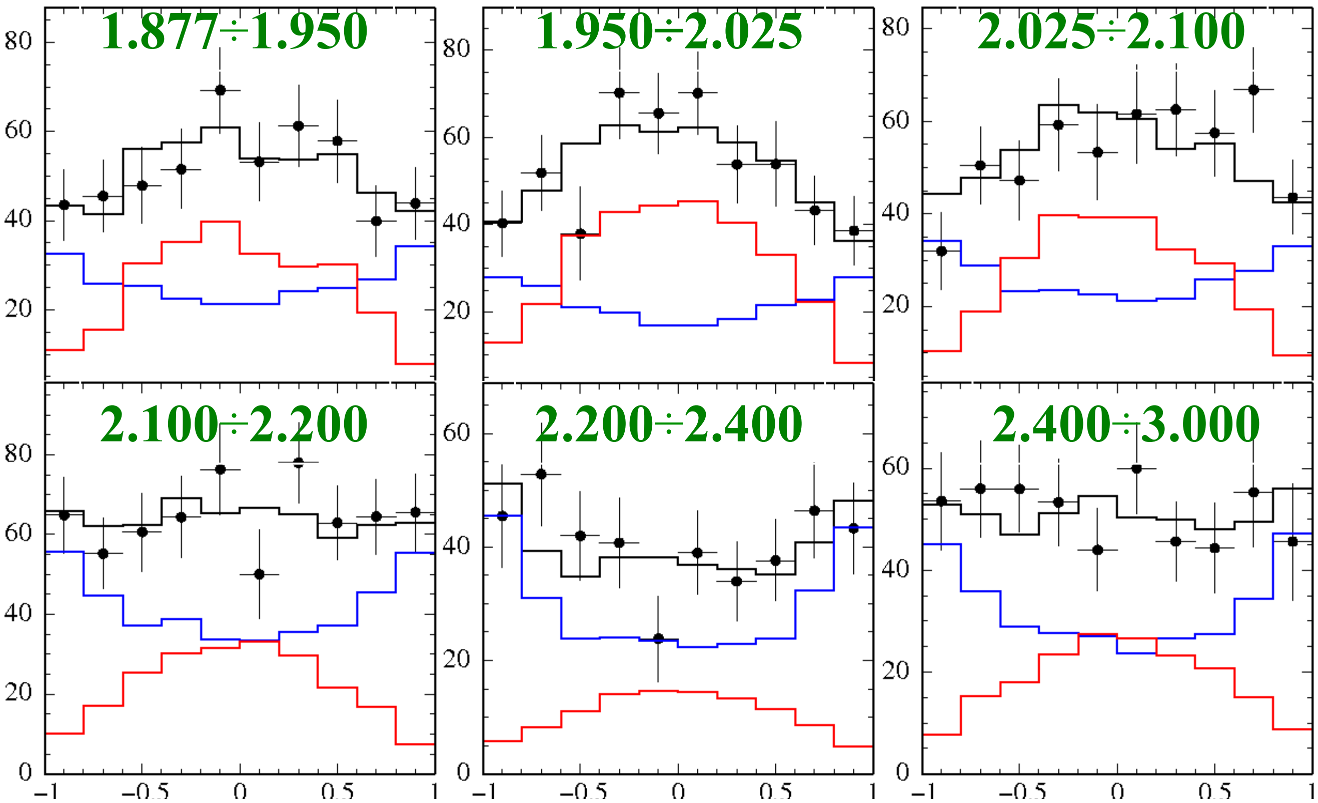
$$e^+ + e^- \longrightarrow p + \bar{p} + \gamma$$

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

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

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

Angular distribution



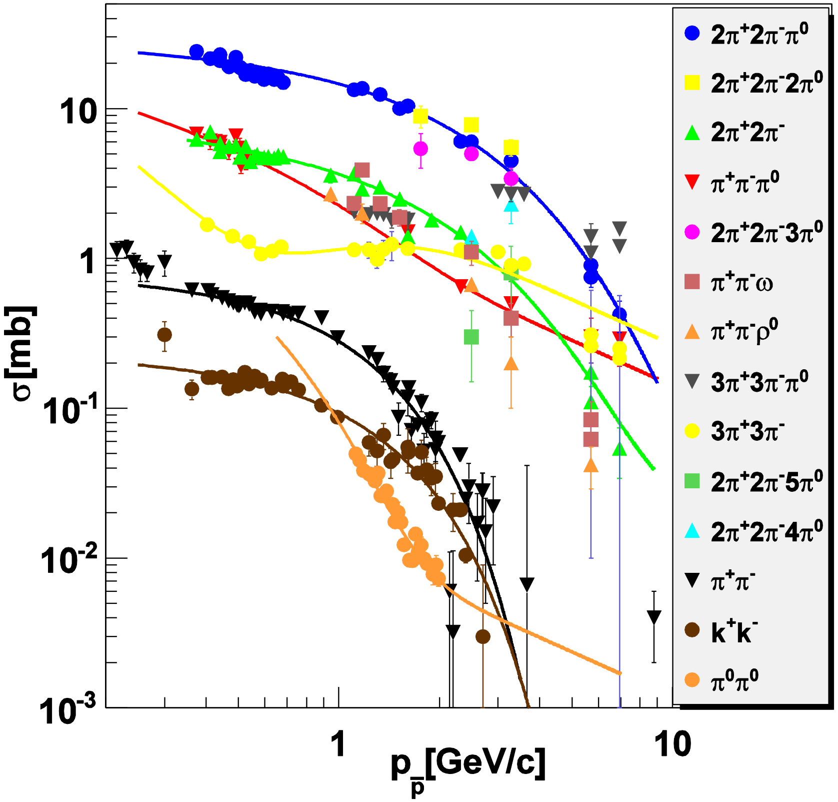
Events/0.2 vs. cos θ

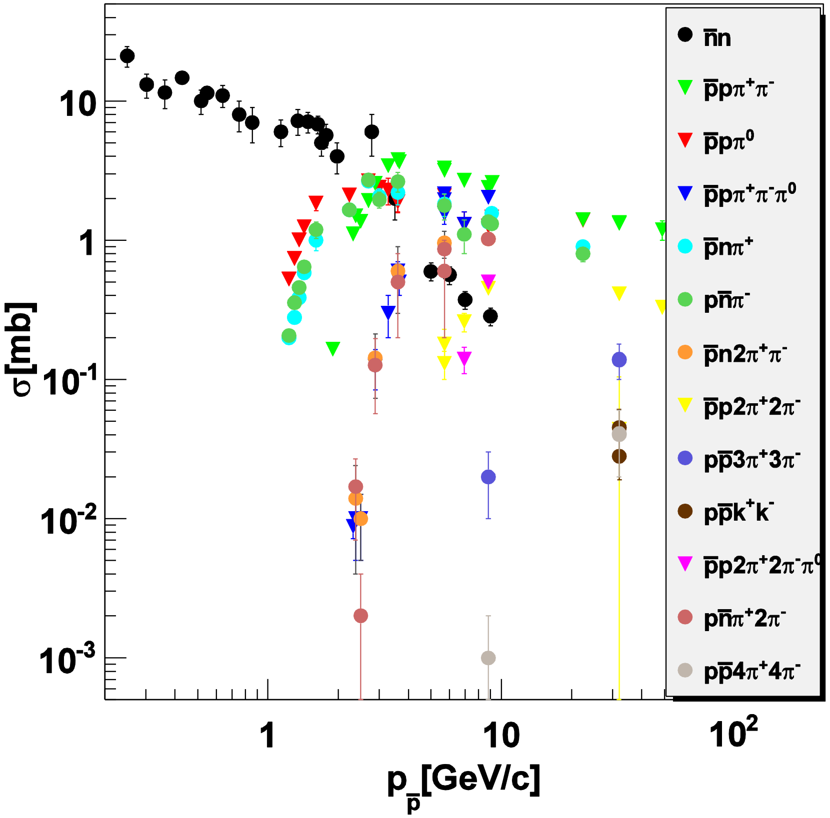
$$\frac{dN}{d\cos\theta_p} = A\left[\boxed{H_M(\cos\theta, M_{p\bar{p}})} + \boxed{\left|\frac{G_E}{G_M}\right|^2 H_E(\cos\theta, M_{p\bar{p}})}\right]$$

BABAR

About cross sections…

A.Dbeyssi amd E.T.-G, Prob Atomic Sci. Technol. 2012N1, 79 (2012).

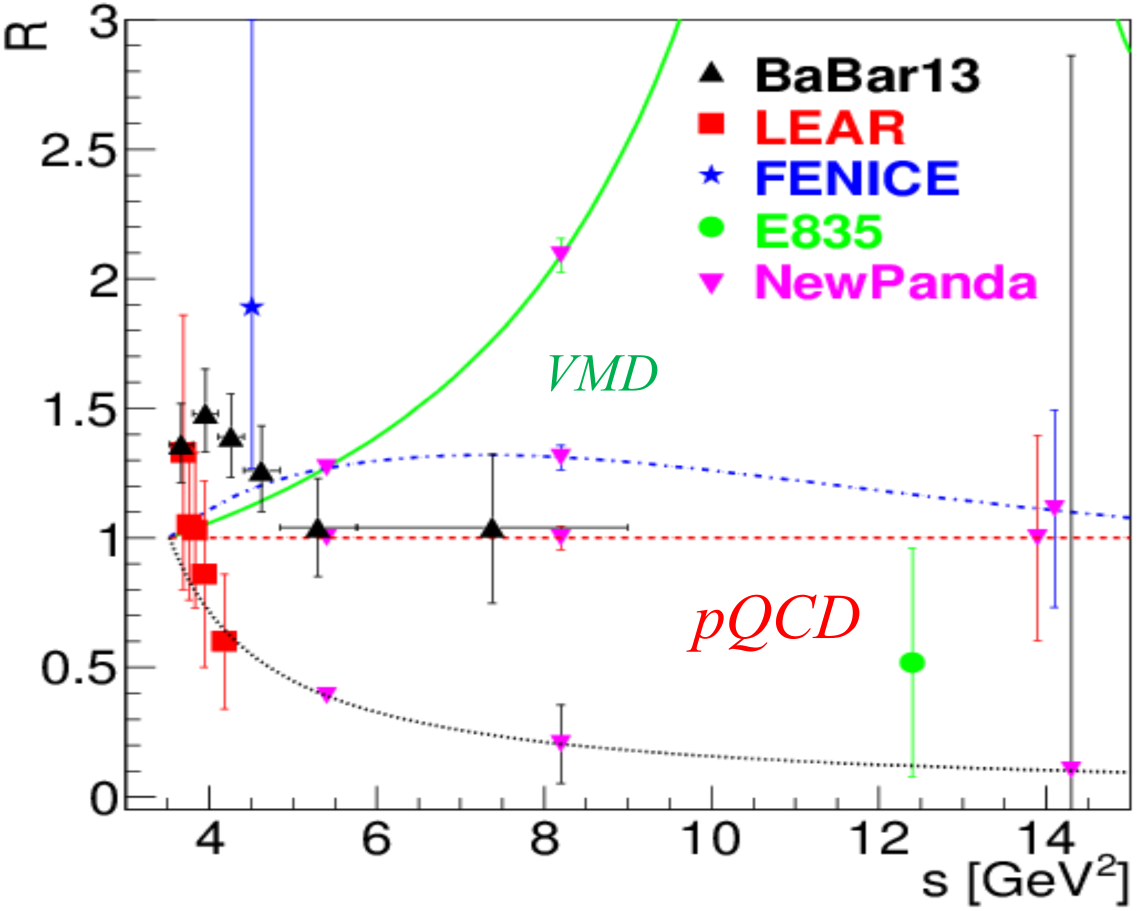




Most probable in the mb region :

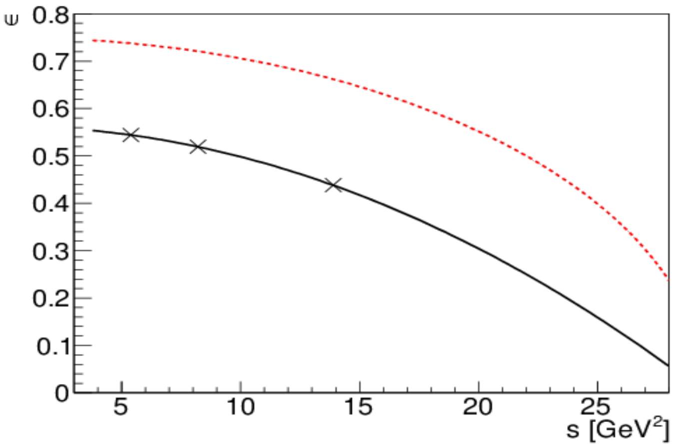
- *Five pion production*
- *Charge exchange*

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



Simulations
A. Dbeyssi PhD

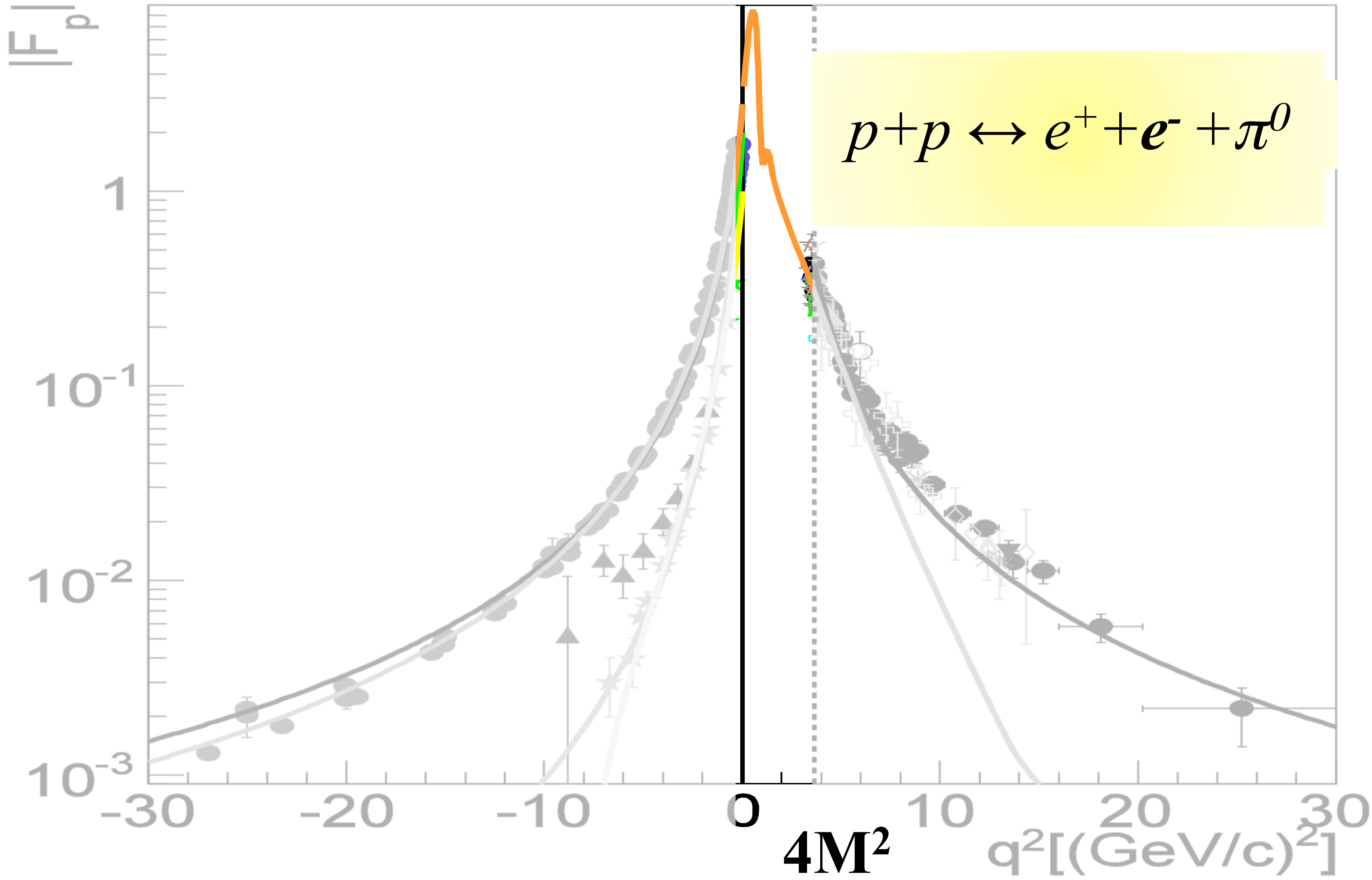
$\varepsilon<50\%$



F. Iachello et al., Phys. Rev. C 69 (2004) 055204
E. L. Lomon, Phys. Rev. C 66 (2002) 045501

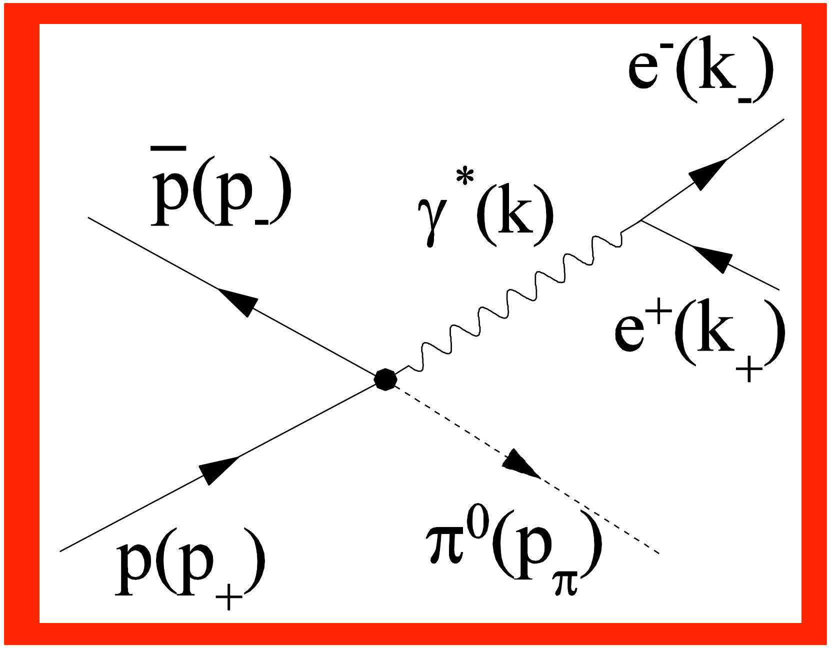
E. A. Kuraev et al., Phys. Lett. B 712, (2012)
V. A. Matveev, S. J. Brodsky , D. V. Shirkov….

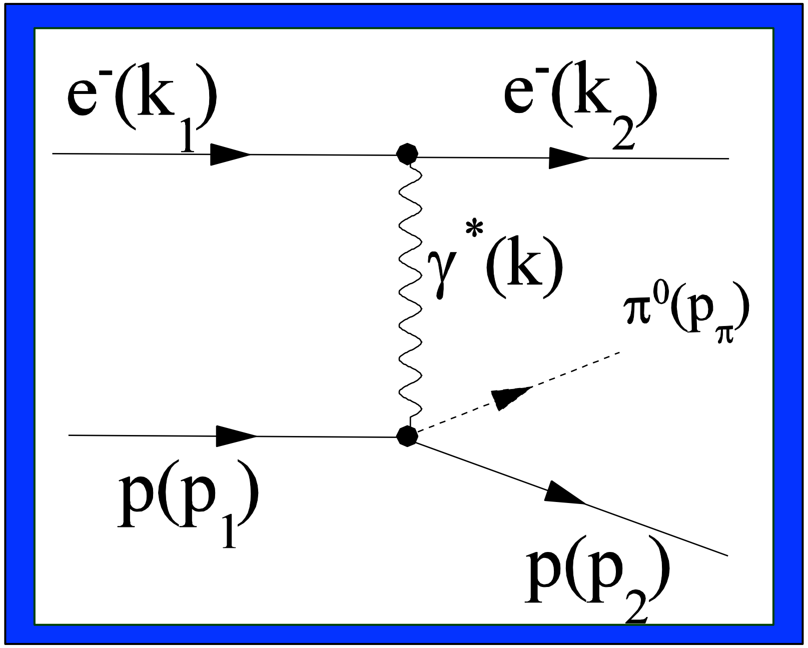
The "unphysical region"



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

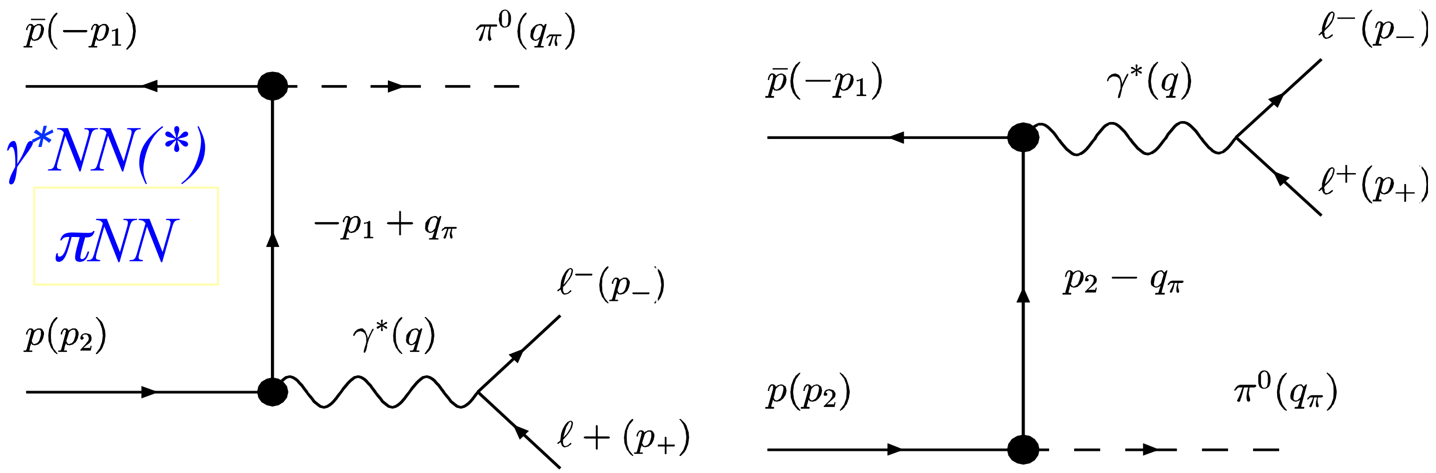
$p + \bar{p} \rightarrow e^+ + e^- + \pi^0$ and $e^- + p \rightarrow e^- + p + \pi^0$





Described in general by 6 amplitudes which depend on 3 kinematical variables

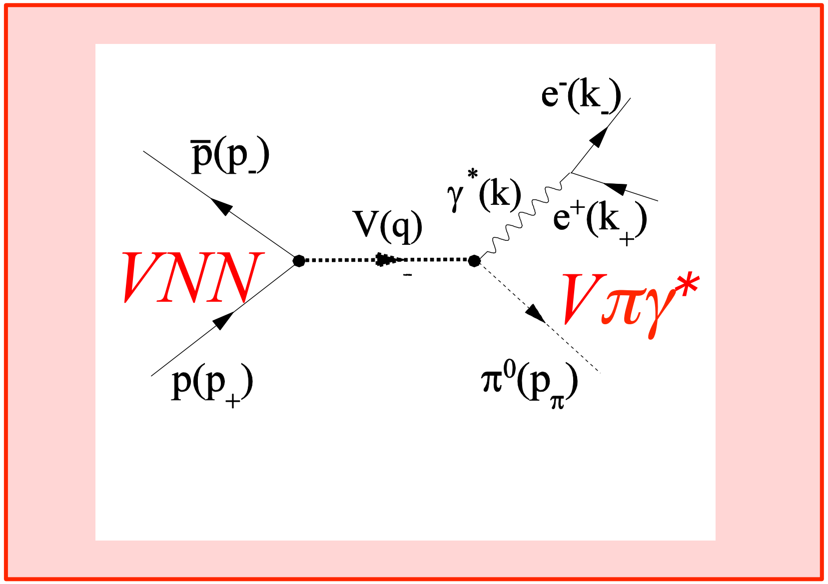
The reaction $p + \bar{p} \rightarrow e^+ + e^- + \pi^0$



$\gamma^*NN(^*)$

πNN

M. P. Rekalo, 1967

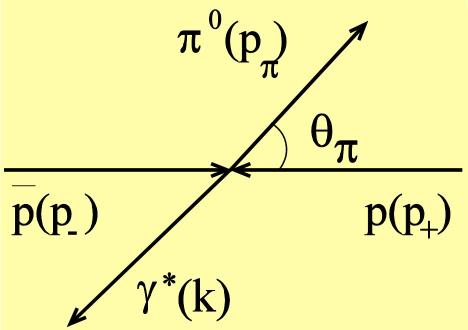


VNN

$V\pi\gamma^*$

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

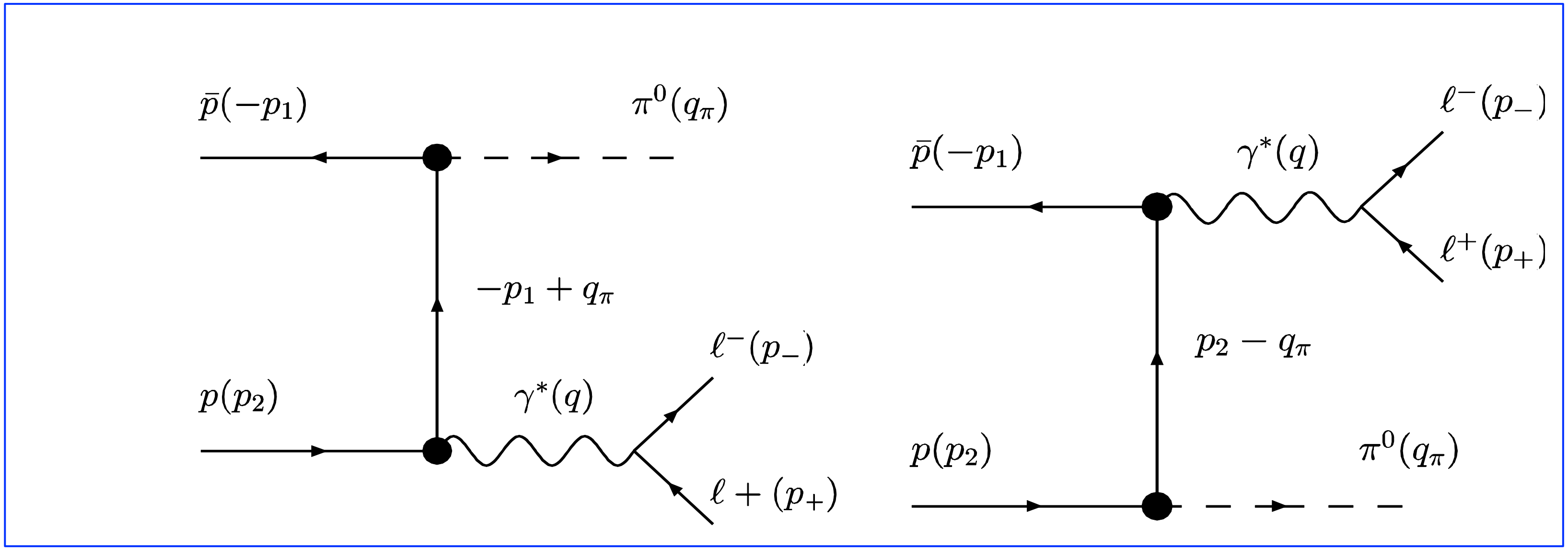
CMS system



A model: 'scattering' channel

E.A. Kuraev

C. Adamuscin et al, Phys. Rev. C. 75, 045205 (2007).



The hadronic current

$$J_\mu = \varphi_\pi^+(q_\pi)\bar{u}(-p_1)O_\mu u(p_2).$$

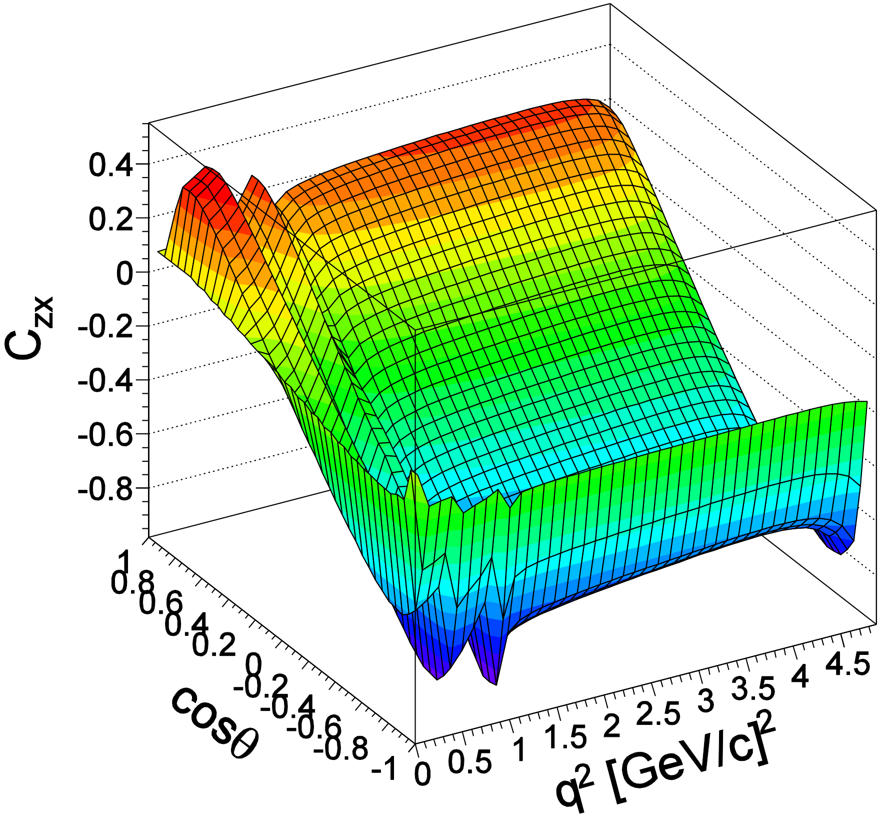
$$O_\mu = \frac{g}{d_1}\Gamma_\mu(q)(\hat{q} - \hat{p}_1 + M)\gamma_5 + \frac{g}{d_2}\gamma_5(\hat{p}_2 - \hat{q} + M)\Gamma_\mu(q),$$

$$d_i = q^2 - 2q \cdot p_i, i = 1, 2,$$

$$< N(p')|\Gamma_\mu(q^2)|N(p) >= \bar{u}(p')\left[F_1(q^2)\gamma_\mu + \frac{1}{4M}F_2(q^2)(\hat{q}\gamma_\mu - \gamma_\mu\hat{q})\right]u(p),$$

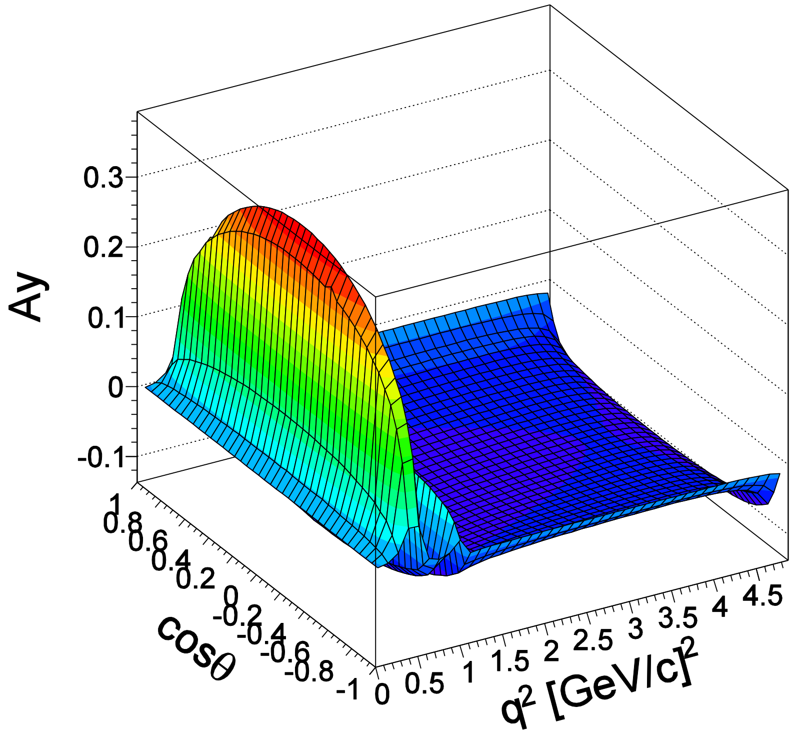
Results with IJL FFs

Czx: large at small angles



2E=5.4 GeV

Ay: small except on resonances



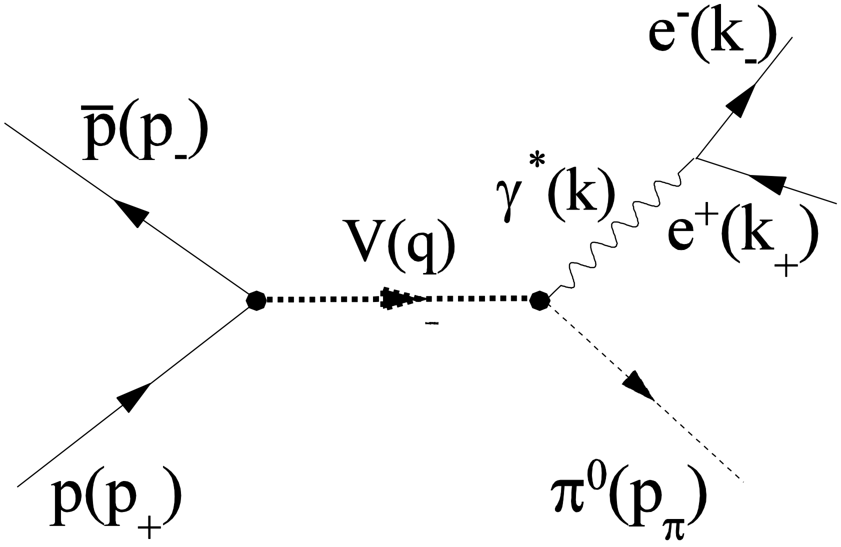
Polarization phenomena help to distinguish the reaction mechanism!

G.I. Gakh, J. Boucher, E.T-G., Phys.Rev. C83 (2011)

Cross section for $p + \bar{p} \to e^+ + e^- + \pi^0$

The cross section:

$$d\sigma = \frac{1}{4I}\int \sum_{spin} |\mathcal{M}|^2 \, d\Phi_3$$



Generalization to $\omega+\rho$ mesons
relative phase ϕ =101°

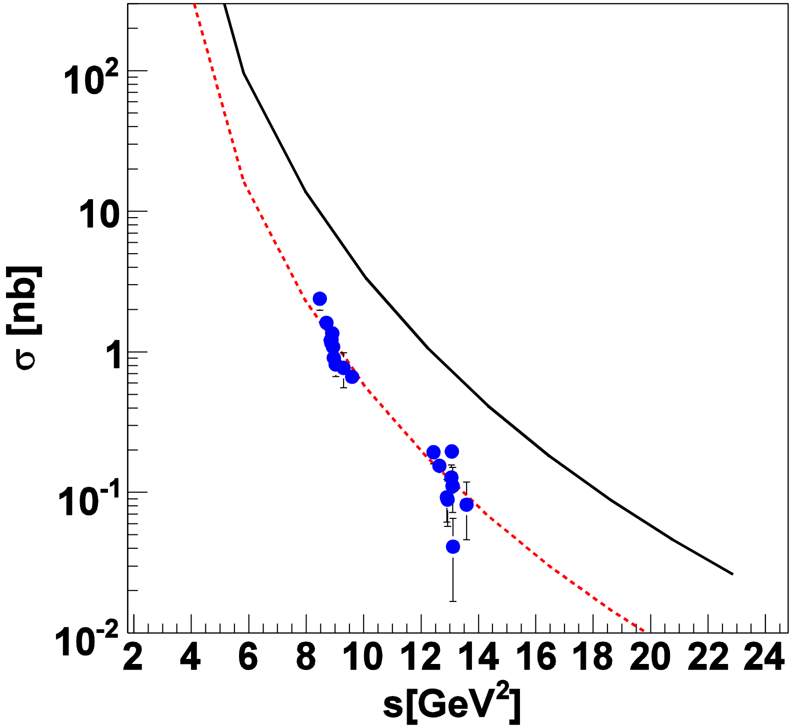
$$|\mathcal{M}_V|^2 \to |\mathcal{M}_\omega + \mathcal{M}_\rho e^{i\phi}|^2$$

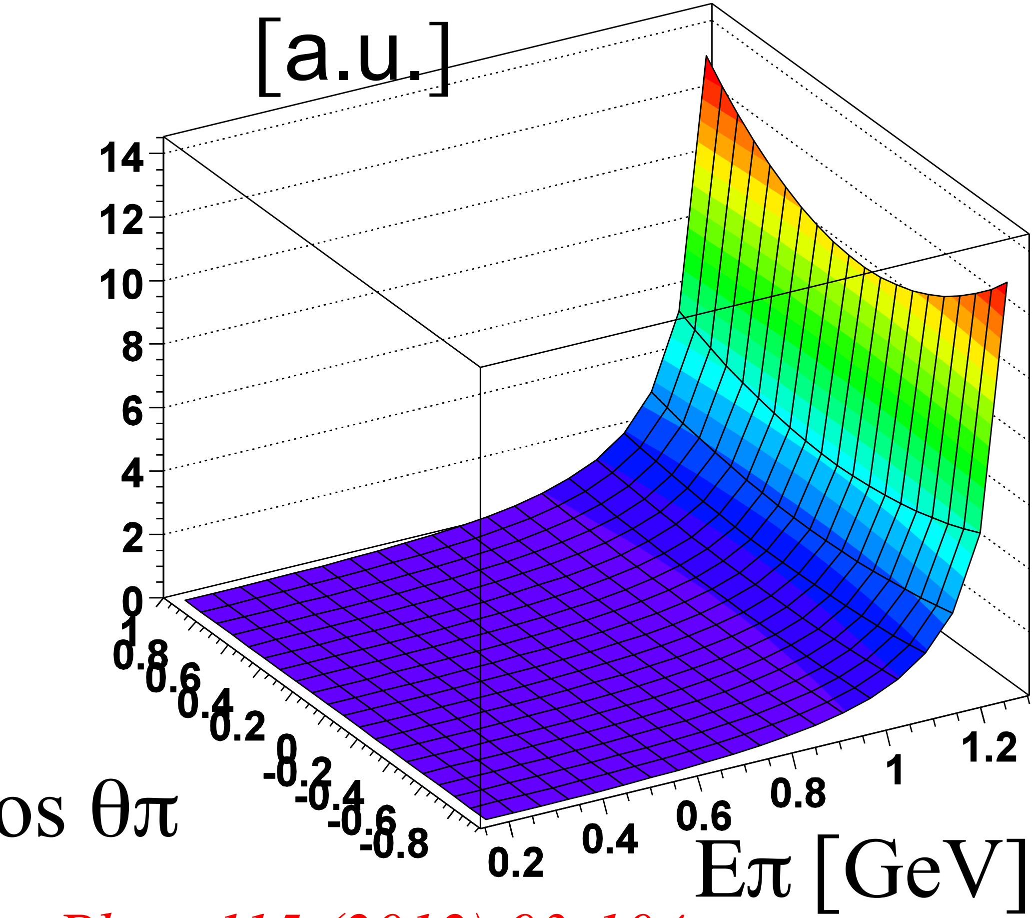
$$\sigma_0 \to \tilde{\sigma}_0 = \frac{\alpha s^2}{2^3 \pi^3 3 \beta} \left| \frac{g_{\omega\pi\gamma^*} \left|F_1^\omega(s)\right|}{s - M_\omega^2 + i M_\omega \Gamma_\omega} + \frac{g_{\rho\pi\gamma^*} \left|F_1^\rho(s) + F_2^\rho(s)\right|}{s - M_\rho^2 + i M_\rho^2 \Gamma_\rho^2} e^{i\phi_\rho} \right|^2$$

E.A. Kuraev et al., J.Exp.Theor.Phys. 115 (2012) 93-104

Cross section for $p + \bar{p} \rightarrow e^+ + e^- + \pi^0$

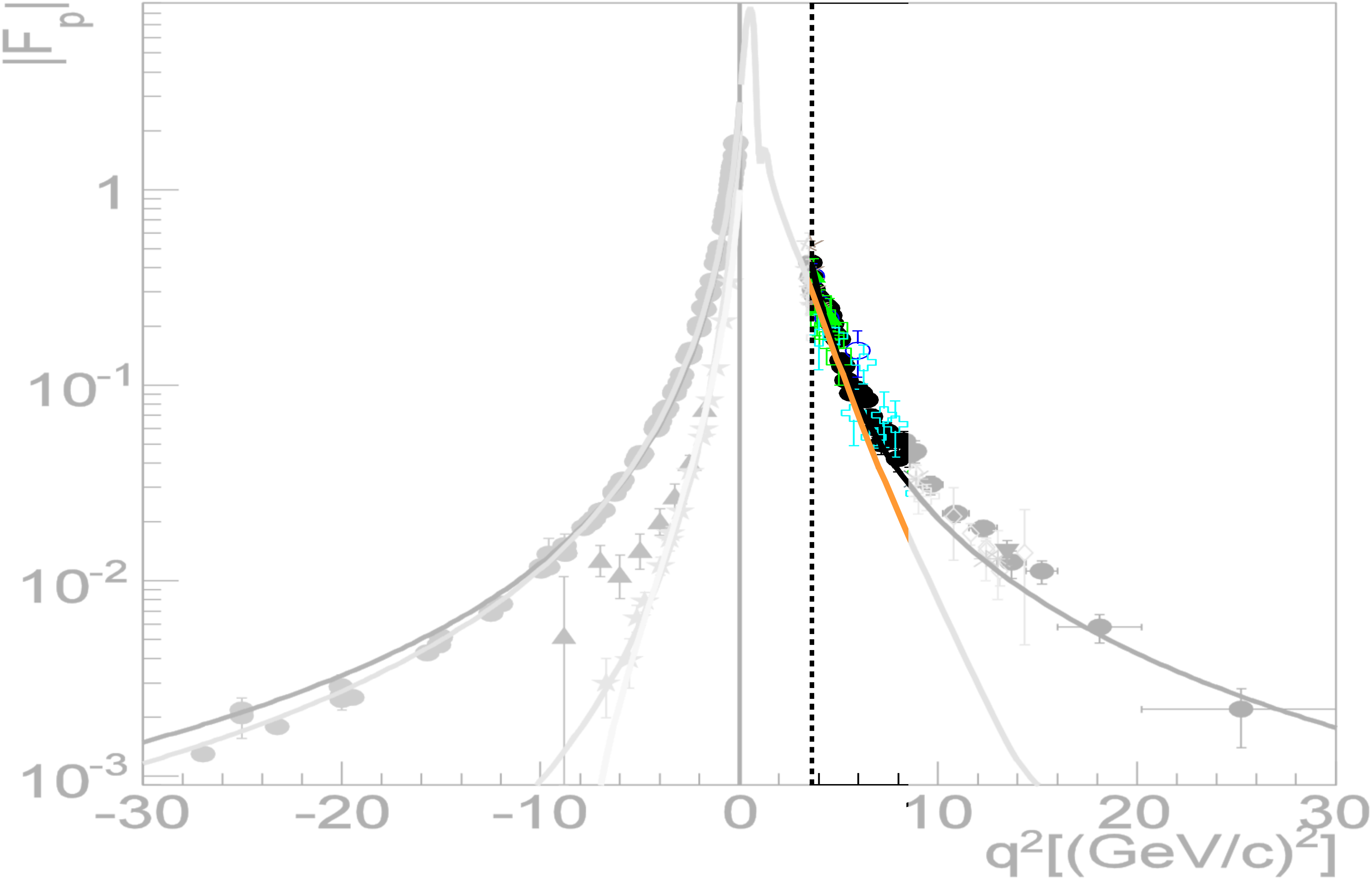
$$\frac{d^2\sigma}{dE_\pi dc_\pi} = \sigma_0 \frac{E_\pi^3 \left(2 - \beta^2 \sin^2\theta_\pi\right)}{s\left(s + M_\pi^2 - 2E_\pi\sqrt{s}\right)},$$



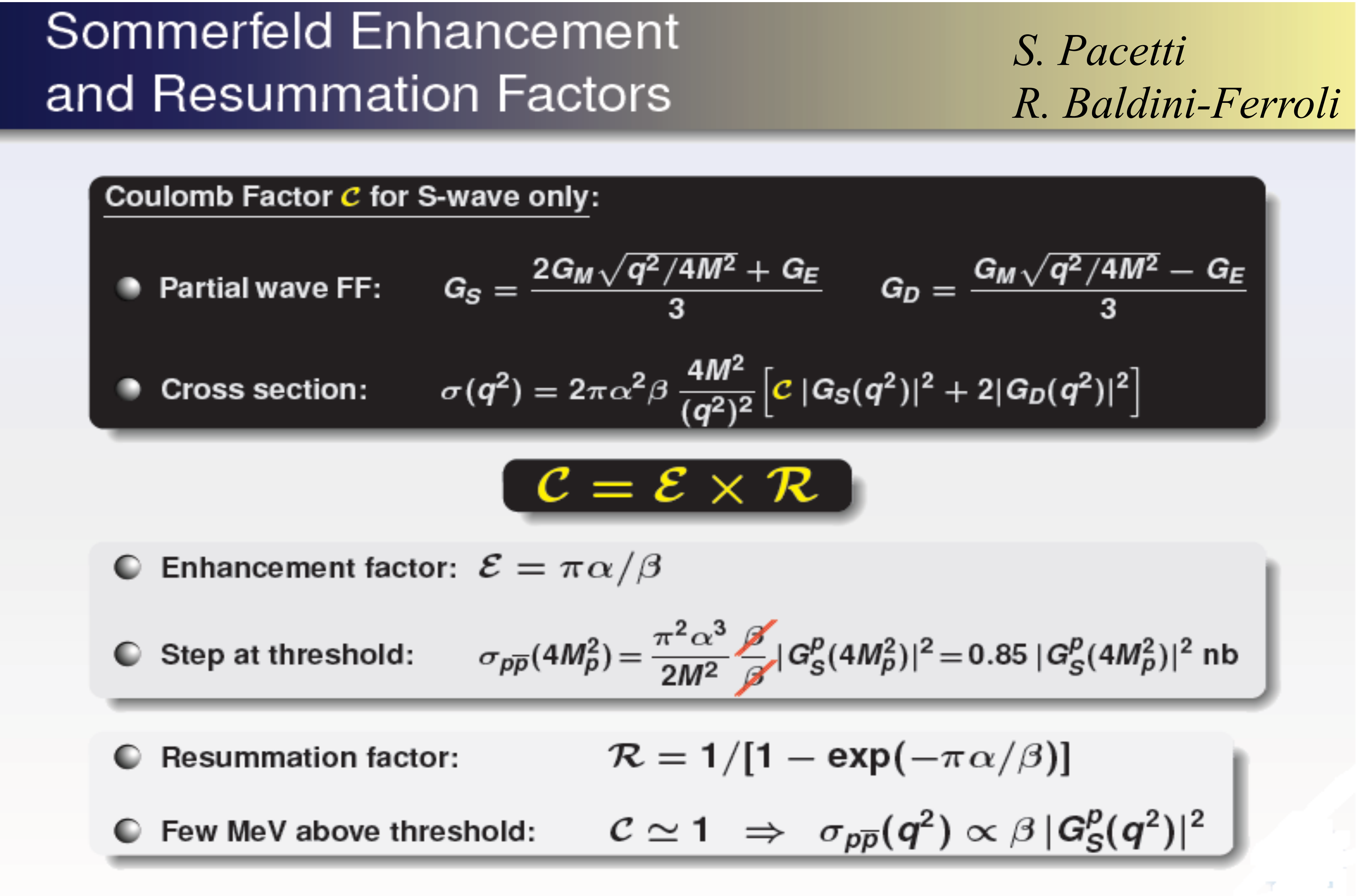


E.A. Kuraev et al., J.Exp.Theor.Phys. 115 (2012) 93-104

The Time-like region: the threshold



Point-like form factors?



Sommerfeld Enhancement and Resummation Factors

S. Pacetti
R. Baldini-Ferroli

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: $\sigma(q^2) = 2\pi\alpha^2\beta\,\dfrac{4M^2}{(q^2)^2}\left[\mathcal{C}\,|G_S(q^2)|^2 + 2|G_D(q^2)|^2\right]$

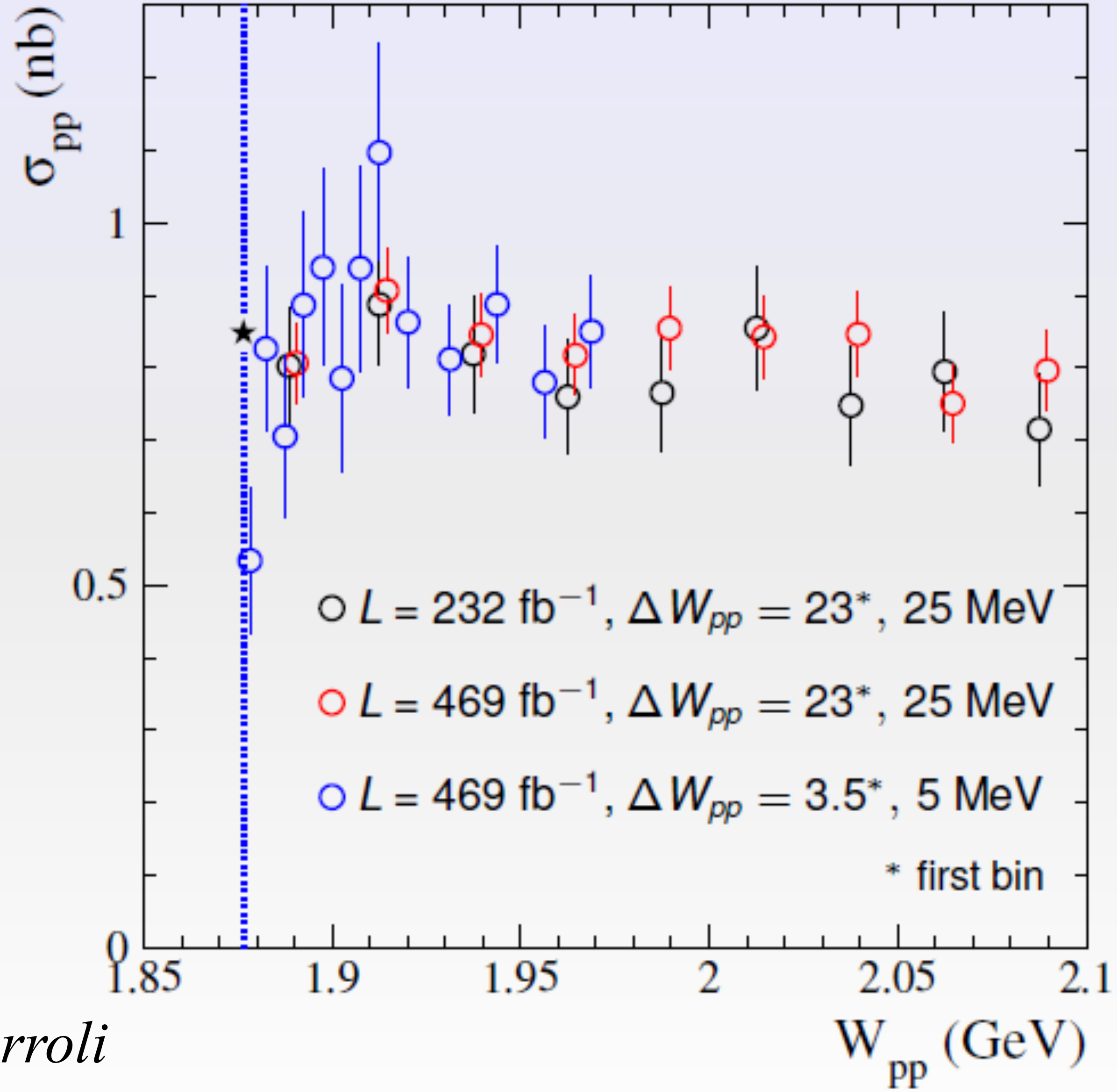
$$\mathcal{C} = \mathcal{E} \times \mathcal{R}$$

- 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: $\mathcal{C} \simeq 1 \quad\Rightarrow\quad \sigma_{p\bar{p}}(q^2) \propto \beta\,|G_S^p(q^2)|^2$

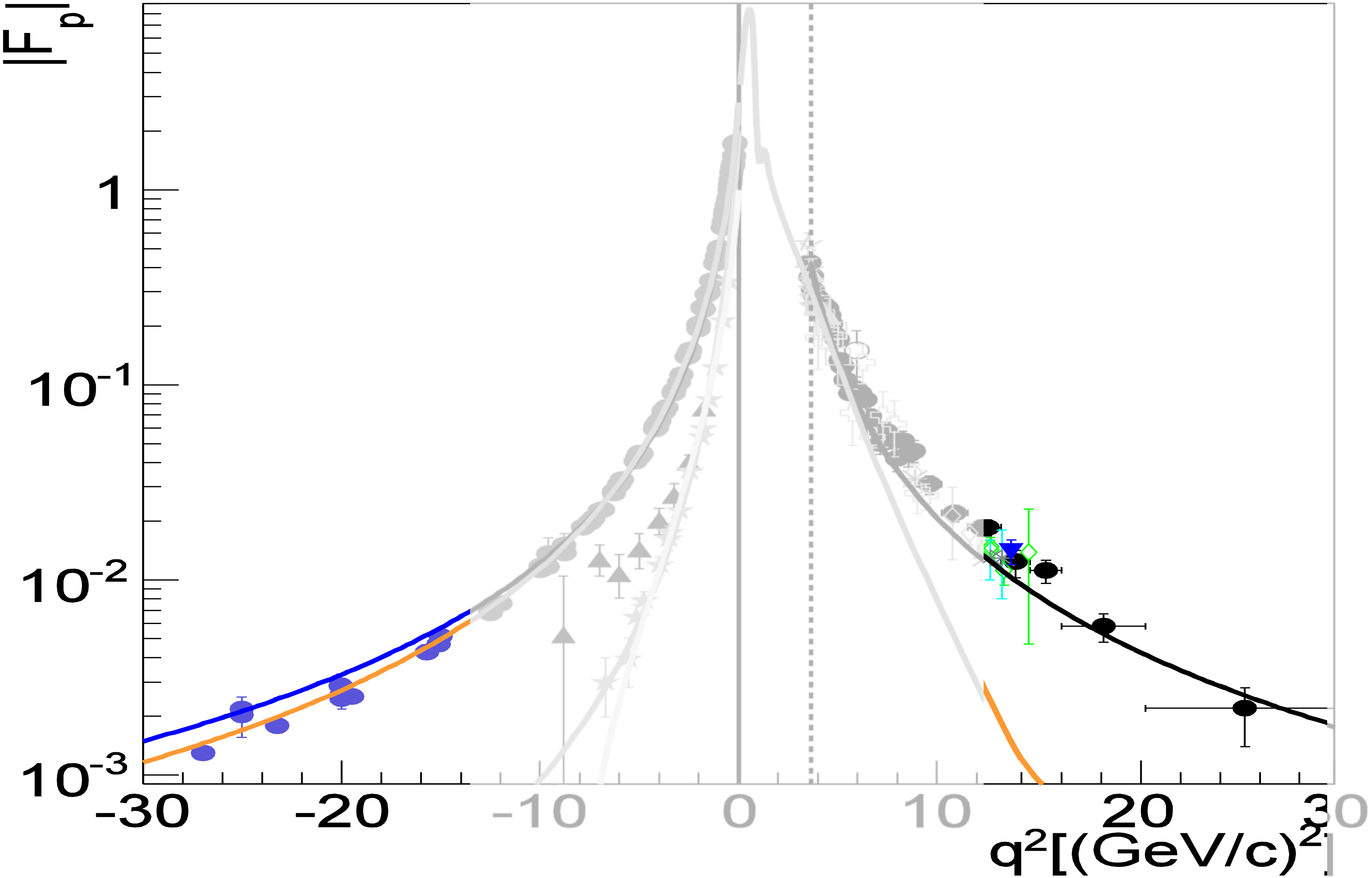
BABAR 2013: $e^+e^- \to p\bar{p}$

PRD73-012005, arXiv:1302.0055



S. Pacetti
R. Baldini-Ferroli

The asymptotic region

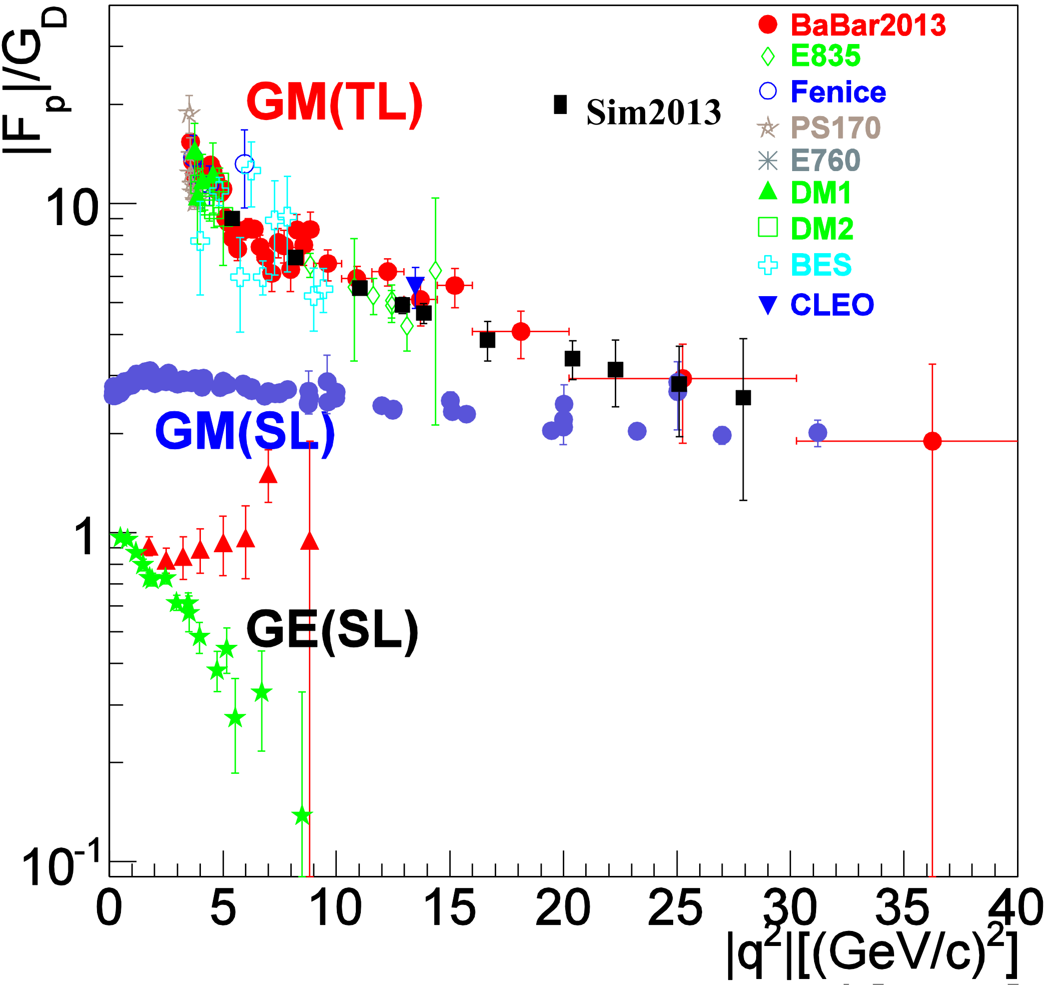


Egle Tomasi-Gustafsson

Proton form factors at large q^2

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

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

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

Applies to NN and $N\bar{N}$ Interaction

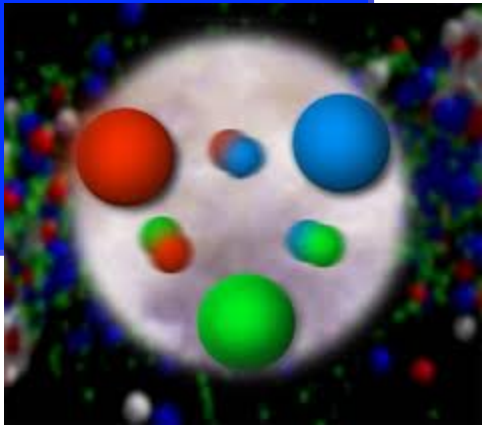
(Pomeranchuk theorem)

t=0 : not a QCD regime!

Analyticity

Connection with QCD asymptotics?

The nucleon



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

antisymmetric state of colored quarks

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

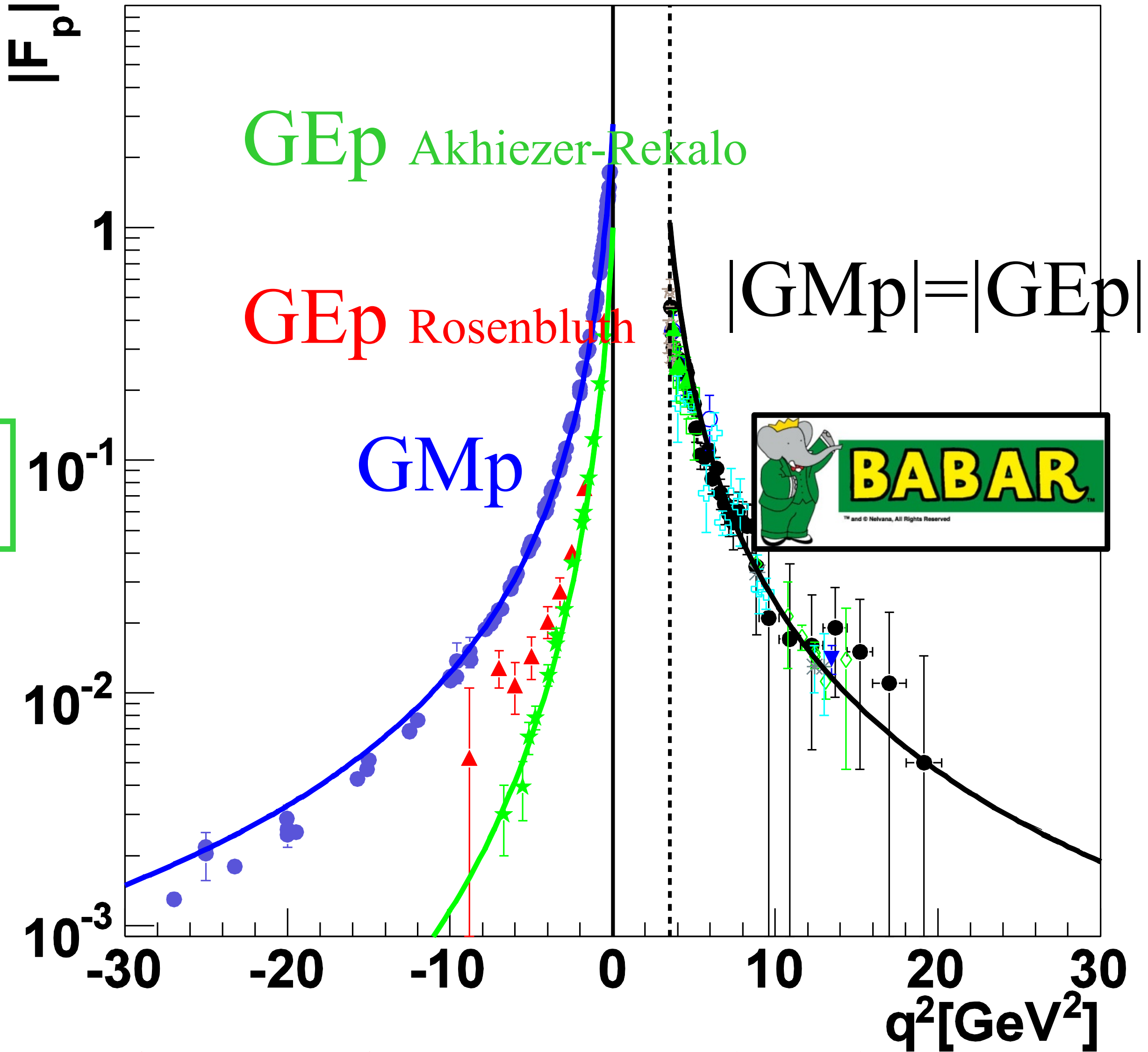
Main assumption

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

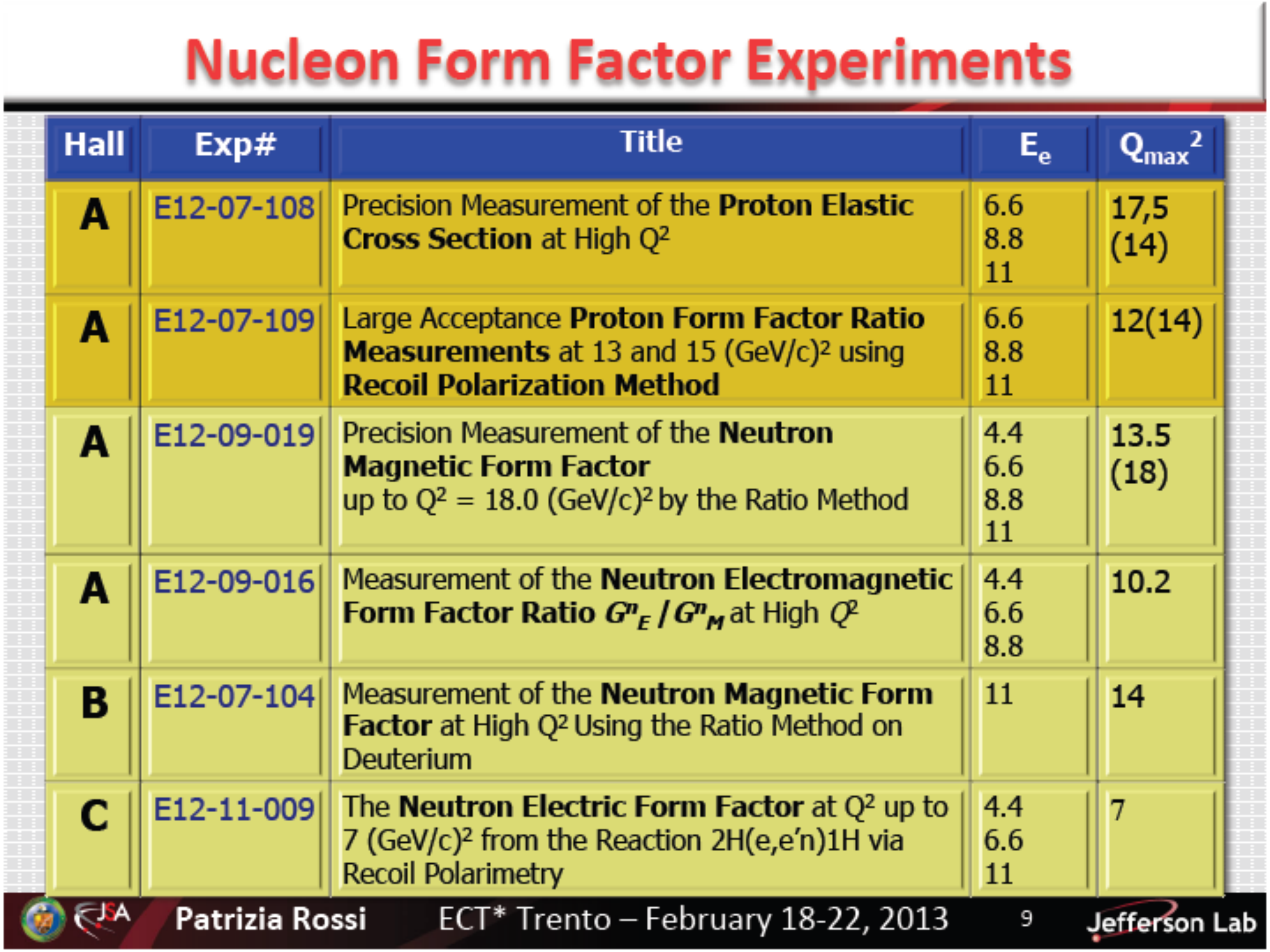
E.A. Kuraev, E. T-G, A. Dbeyssi, Phys.Lett. B712 (2012) 240

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



Nucleon Form Factor Experiments

Hall	Exp#	Title	E_e	Q_{max}^2
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

Conclusions

- Large activity both in Space and Time-like regions

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Novosibirsk

IHEP BES

- Unified models in SL and TL regions:
  - *describe* proton, neutron, electric, magnetic FFs
  - pointlike behavior at threshold?
  - *understand* GE, GM(SL) < GE,GM(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!