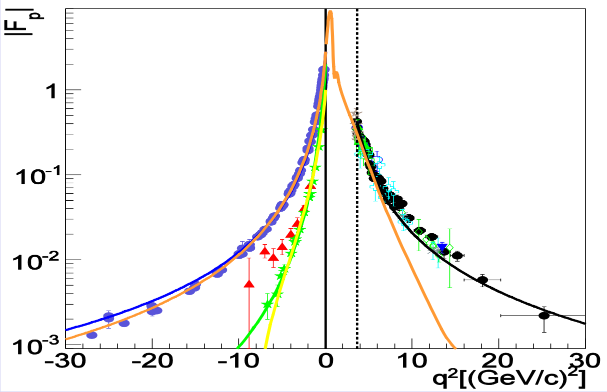
# Hadron Form factors in space-like and time-like regions



*Egle Tomasi-Gustafsson*
*IRFU, SPhN-Saclay,*
*and*
*IN2P3 - IPN Orsay France*

**ICNFP, July 28 - August 6, 2014**

*On behalf of the* $\bar{p}$anda *Collaboration*

# *Plan*

- Introduction
  - formalism

- The Experimental Status
  - The space-like region
    - Unpolarized experiments
    - Polarized experiments
    - Issues and open questions
  - The time-like region: the PANDA Contribution
    - 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.

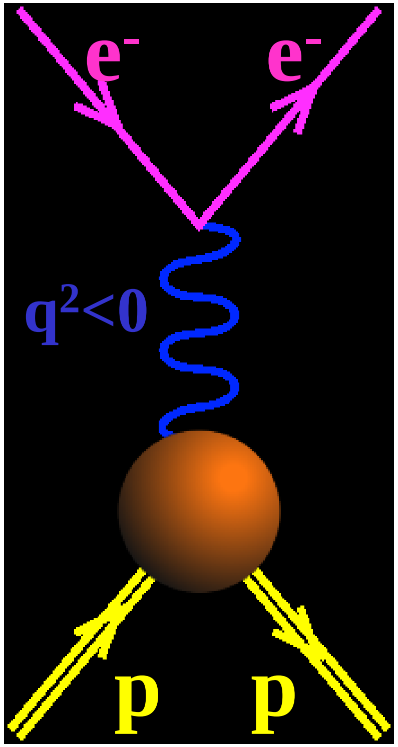
Neutron and proton form factors are different.

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, $\gamma_\mu$

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

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

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

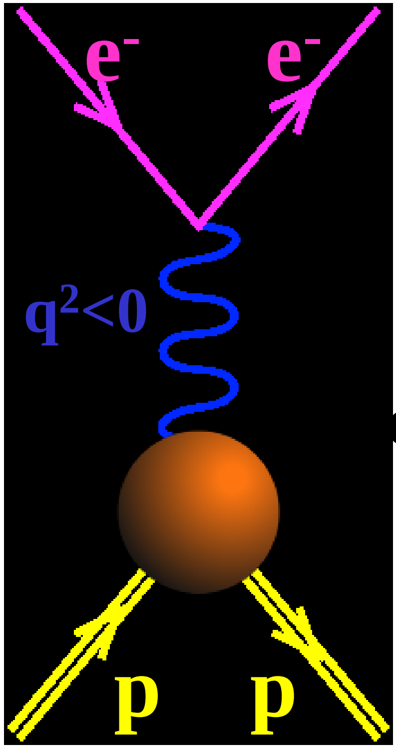
*or in terms of Sachs FFs:*

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

*What about high order radiative corrections?*

# *Hadron Electromagnetic Form factors*

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



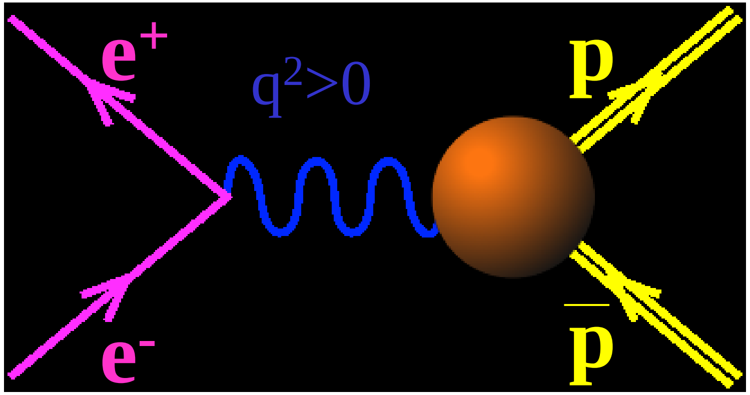
**GE(0)=1**

**GM(0)=$\mu_p$**

*Unphysical region*

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

*Asymptotics*
- *QCD*
- *analyticity*



*Space-like*
*FFs are real*

*Time-Like*
*FFs are complex*

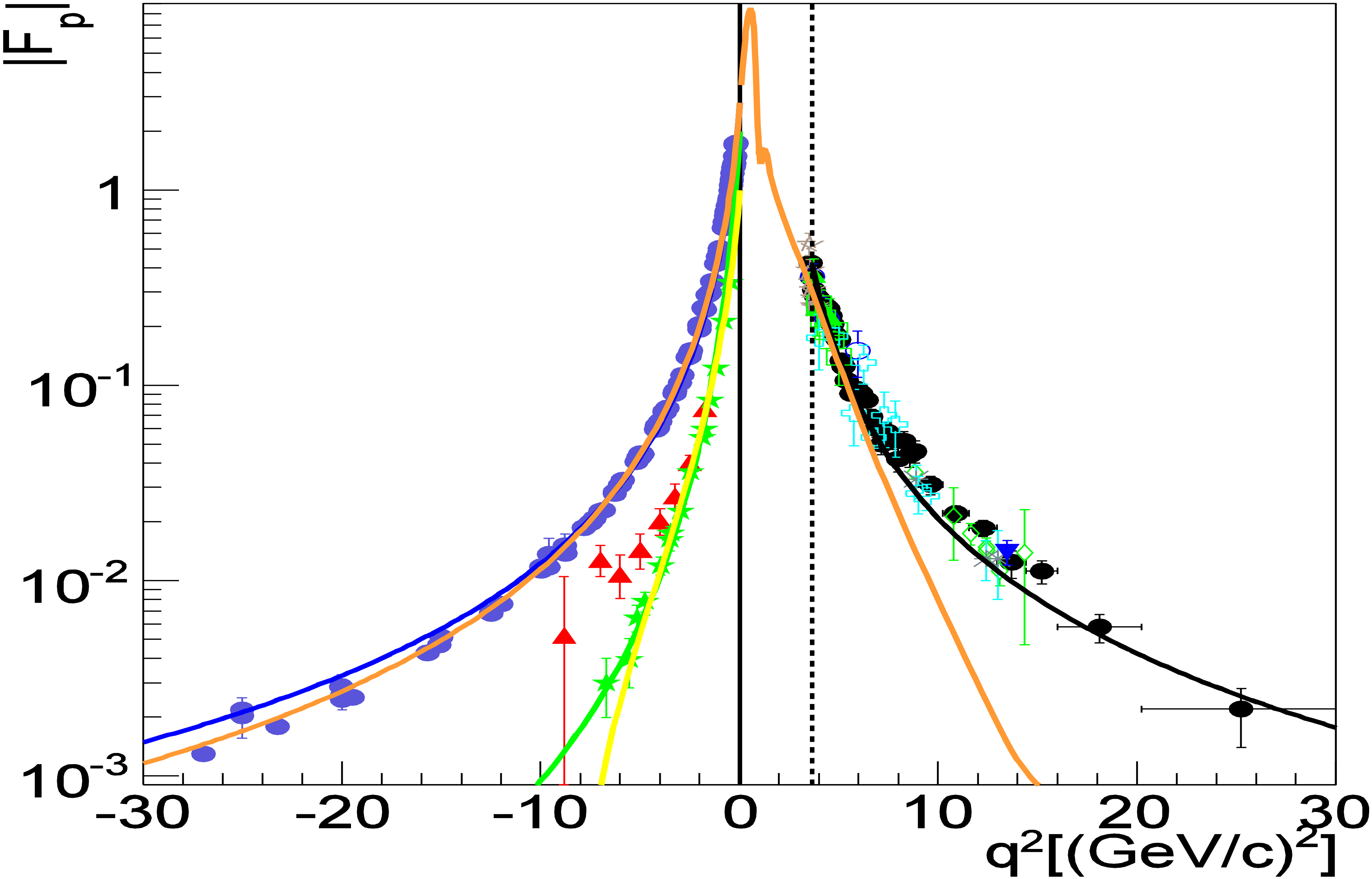
$q^2$

$e+p \rightarrow e+p$

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

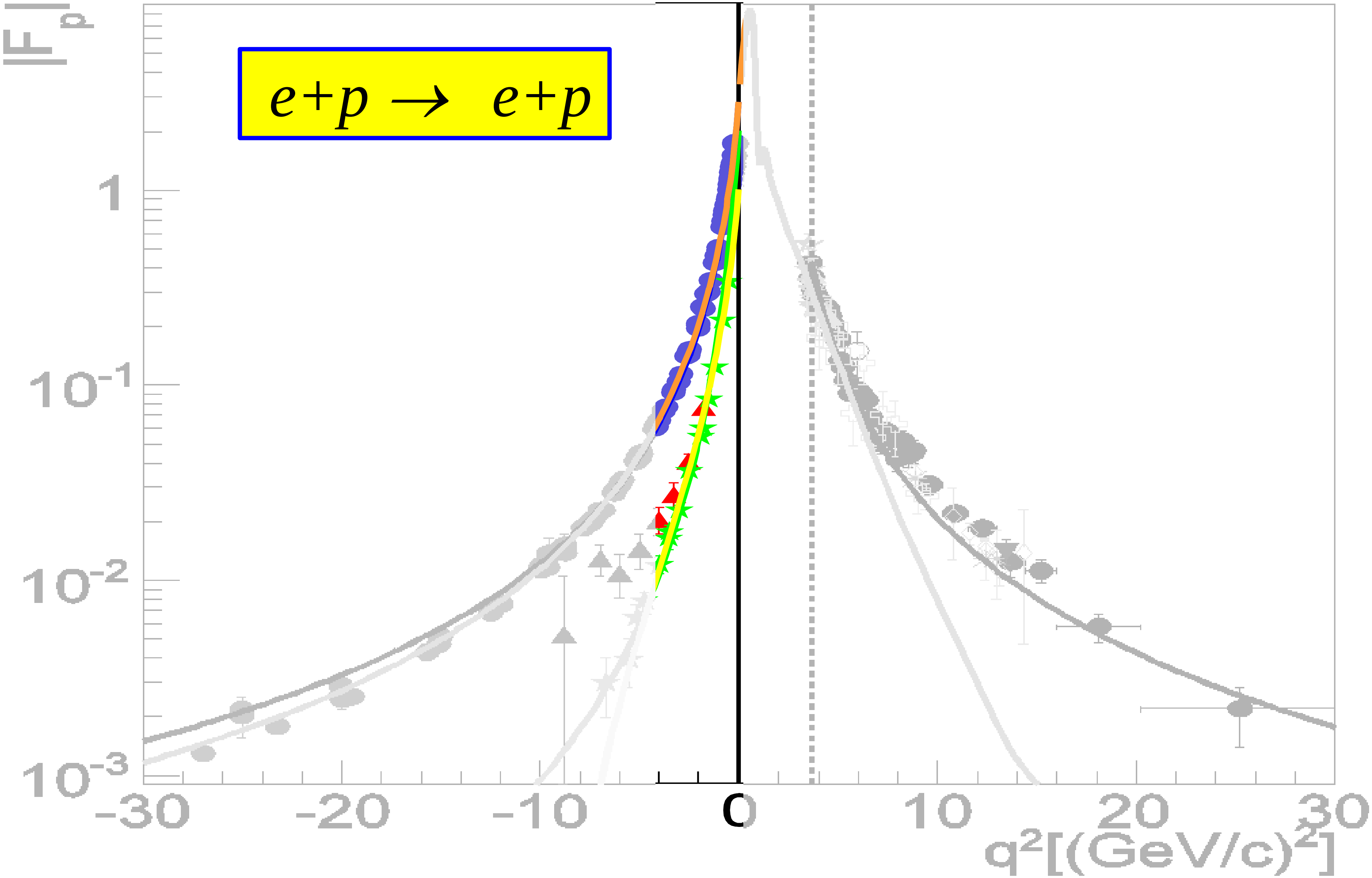
$p+\bar{p} \leftrightarrow e^+ + e^-$

# Hadron Electromagnetic Form factors



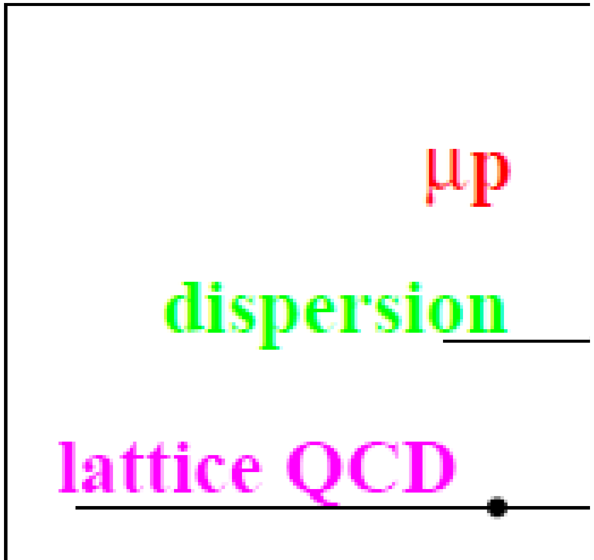
# The Space-Like region: low $Q^2$

$e+p \rightarrow e+p$



# The Proton Radius

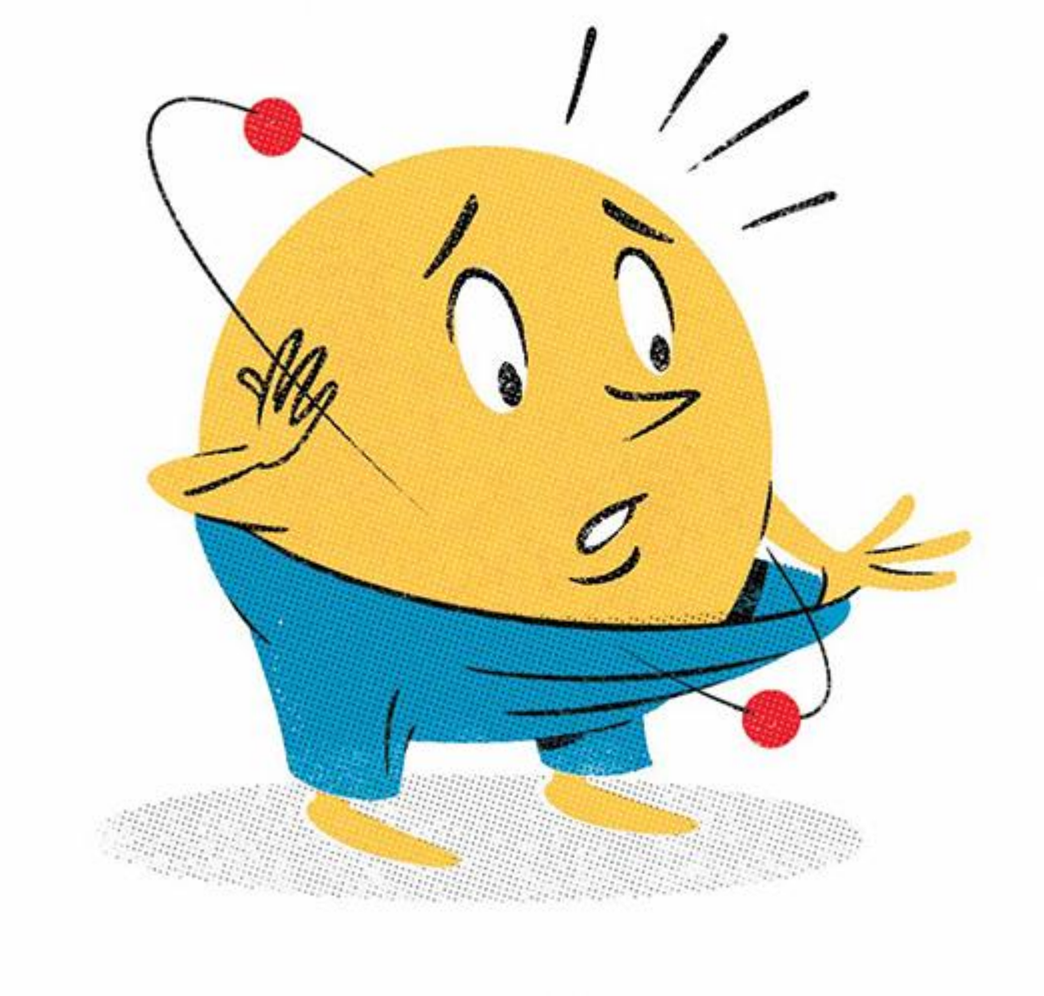
*Rp*=0.84184(67) fm (muonic atom)



n

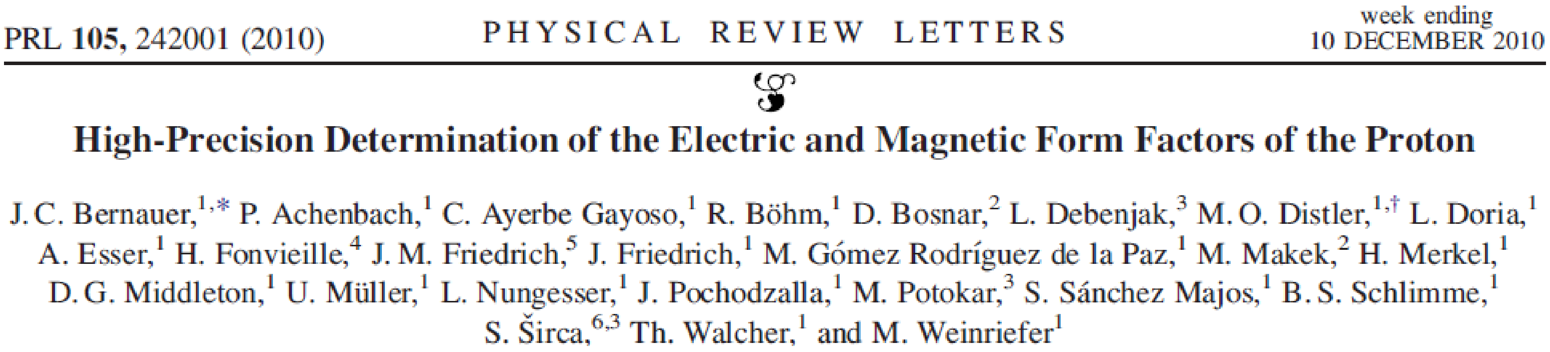
9) fm

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



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


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**

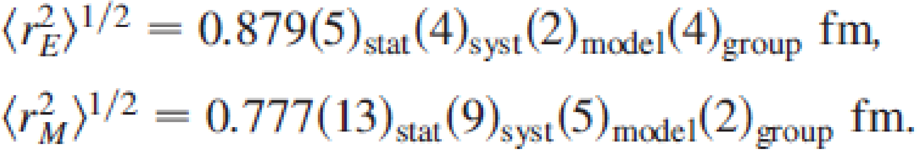
J. C. Bernauer,[1,*] P. Achenbach,[1] C. Ayerbe Gayoso,[1] R. Böhm,[1] D. Bosnar,[2] L. Debenjak,[3] M. O. Distler,[1,†] L. Doria,[1] A. Esser,[1] H. Fonvieille,[4] J. M. Friedrich,[5] J. Friedrich,[1] M. Gómez Rodríguez de la Paz,[1] M. Makek,[2] H. Merkel,[1] D. G. Middleton,[1] U. Müller,[1] L. Nungesser,[1] 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$^2$

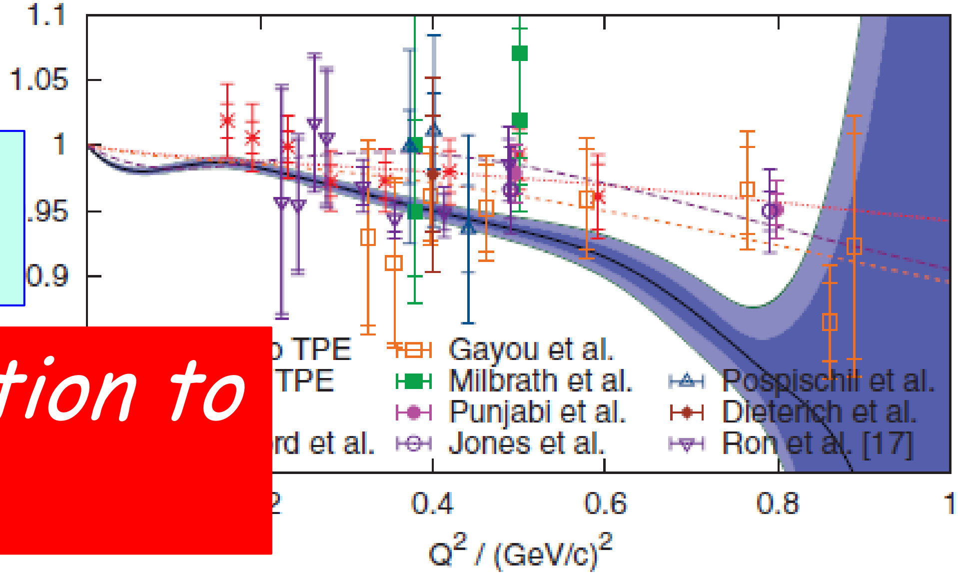
- Radiative corrections
- Two photon exchange
- Coulomb corrections

.....*comments*



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

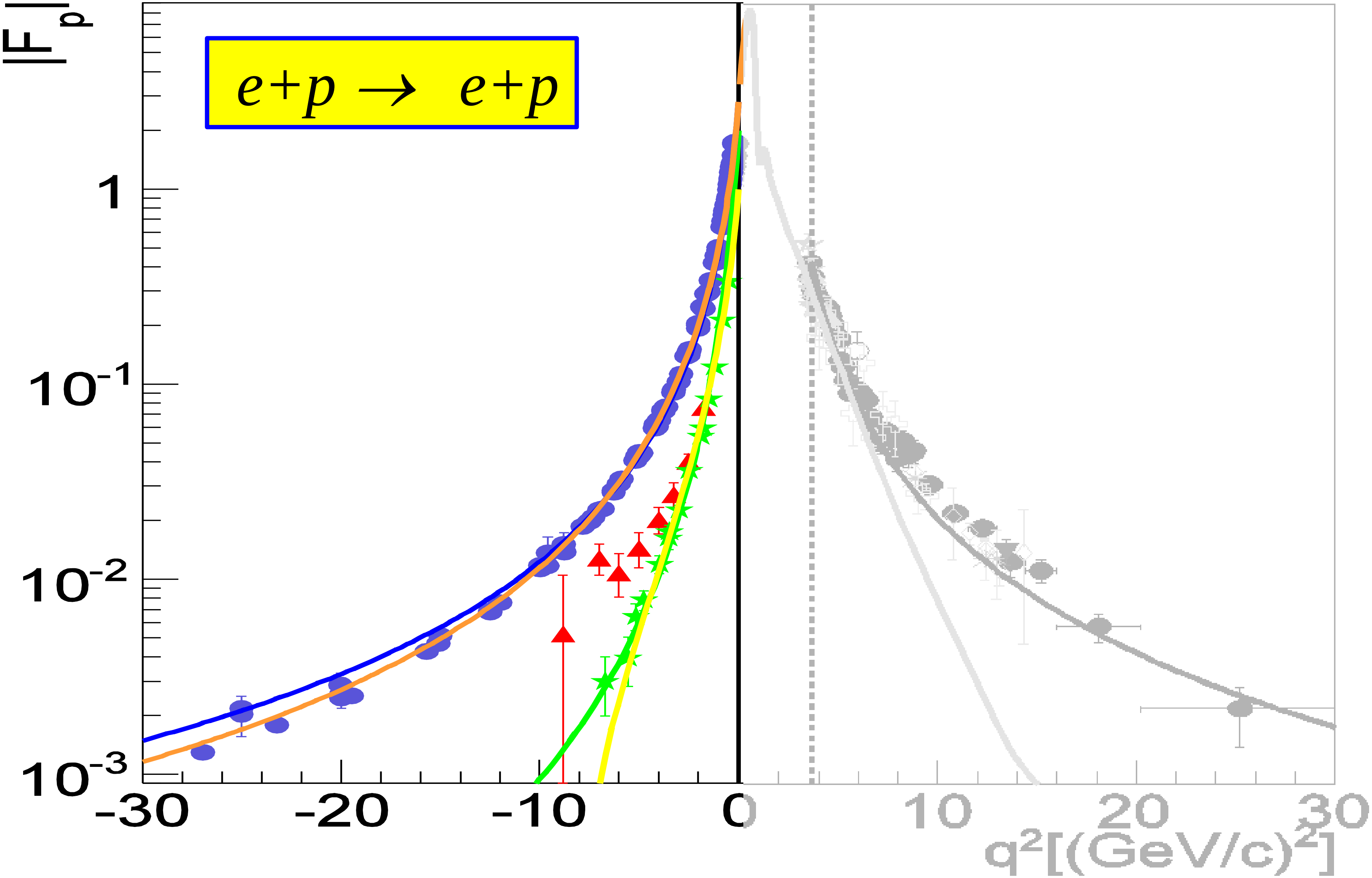
$$\langle r_M^2\rangle^{1/2} = 0.777(13)_{\rm stat}(9)_{\rm syst}(5)_{\rm model}(2)_{\rm group}\ {\rm fm}.$$



- MUSE Experiment
- Jlab CLAS

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

# The Space-Like region

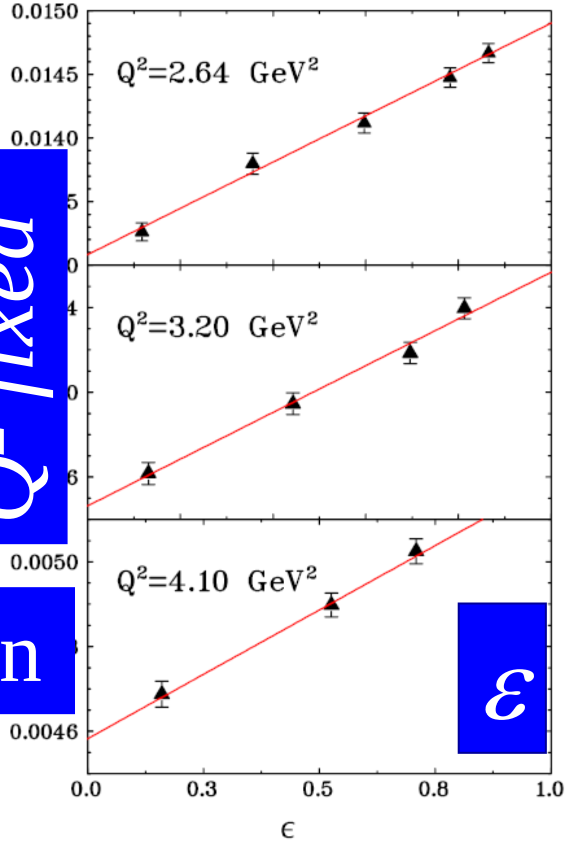


# The Rosenbluth separation

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

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

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



$Q^2$ fixed

$\varepsilon$

PRL 94, 142301 (2005)

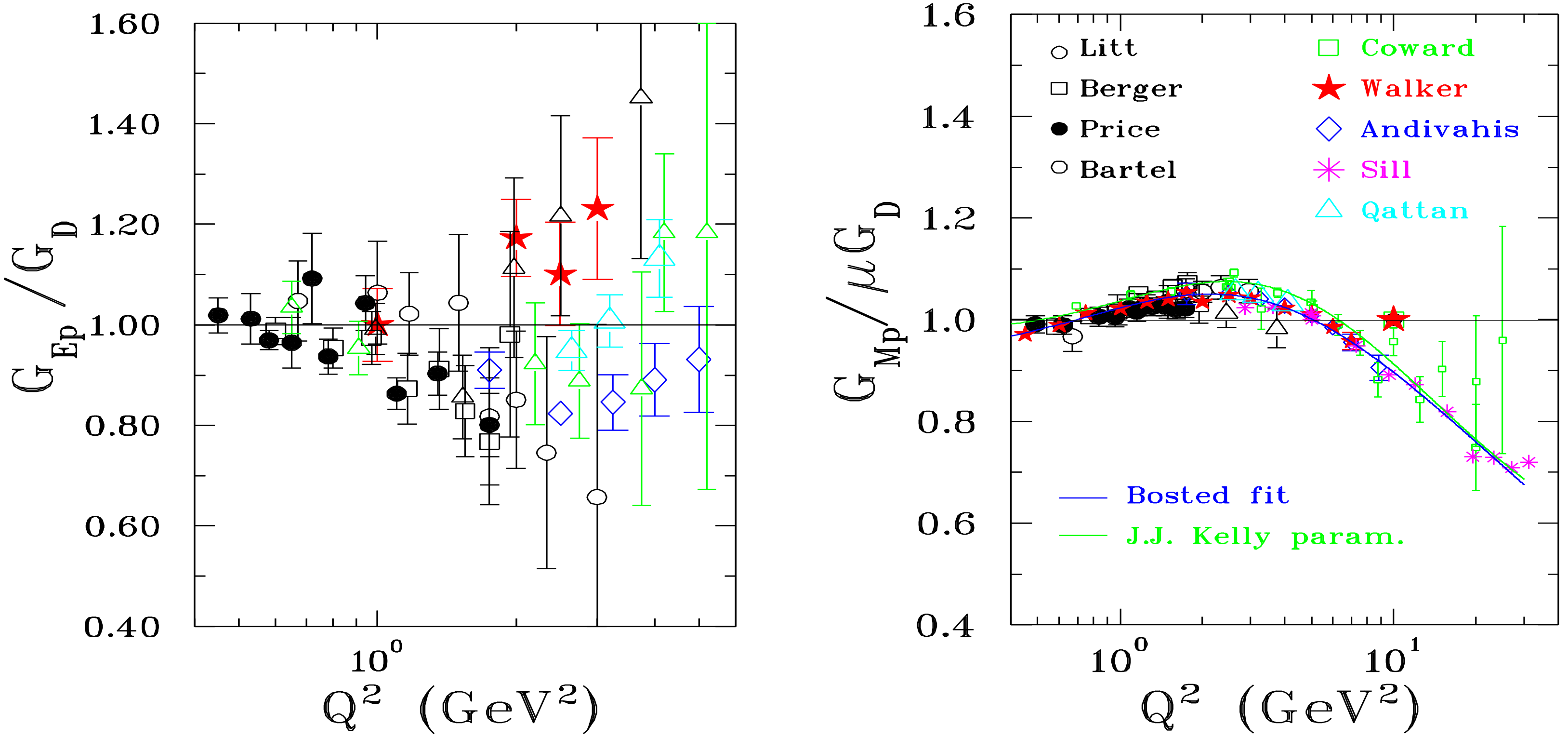
## Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

→ Holds for $1\gamma$ exchange only

# *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*

# The polarization method (theory:1967)

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

PHYSICS

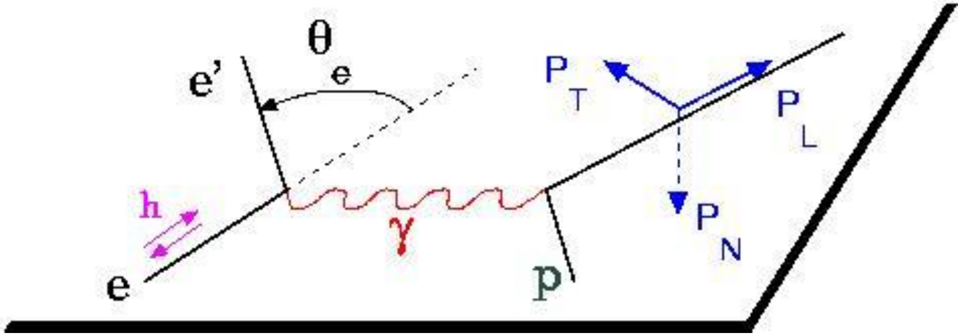
## POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

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,

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



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

Polarized beam and target or

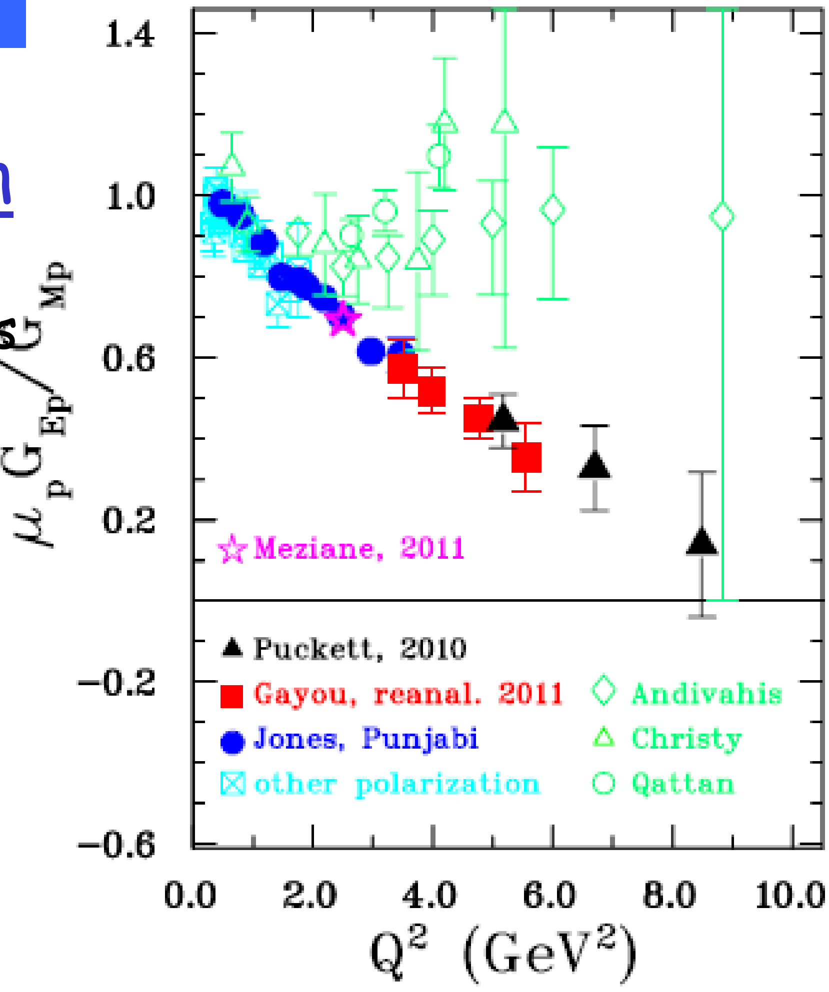
polarized beam and recoil proton polarization

# Polarization experiments

*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***



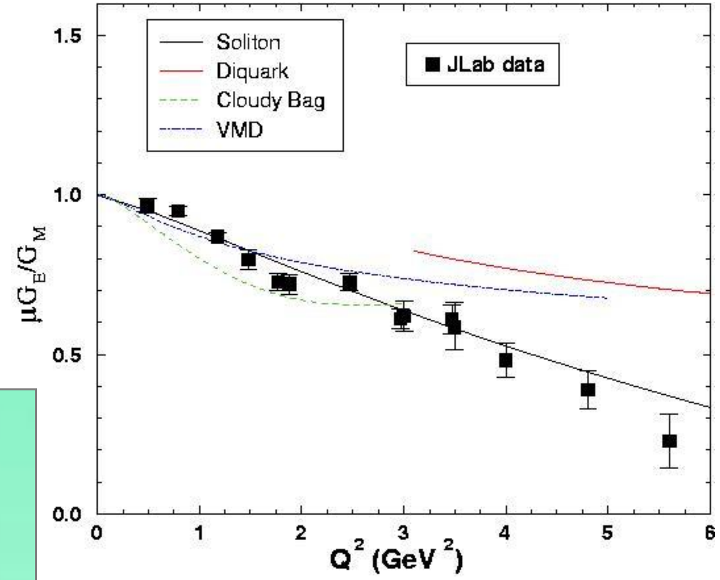
*A.J.R. Puckett et al, PRL (2010), PRC (2012)*

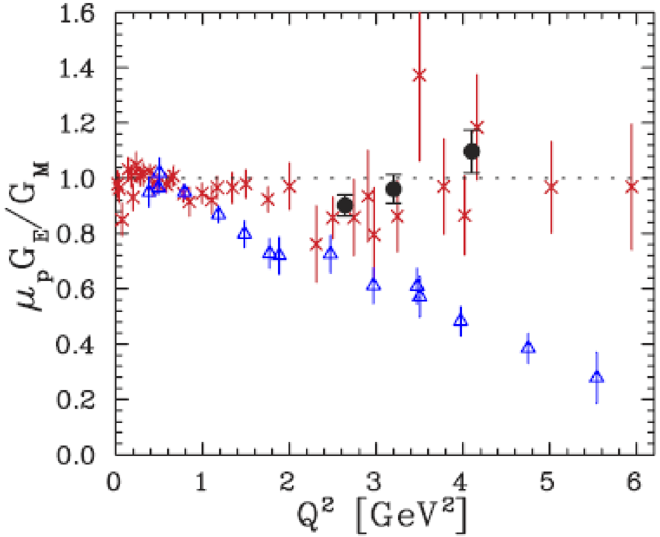
# Issues

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

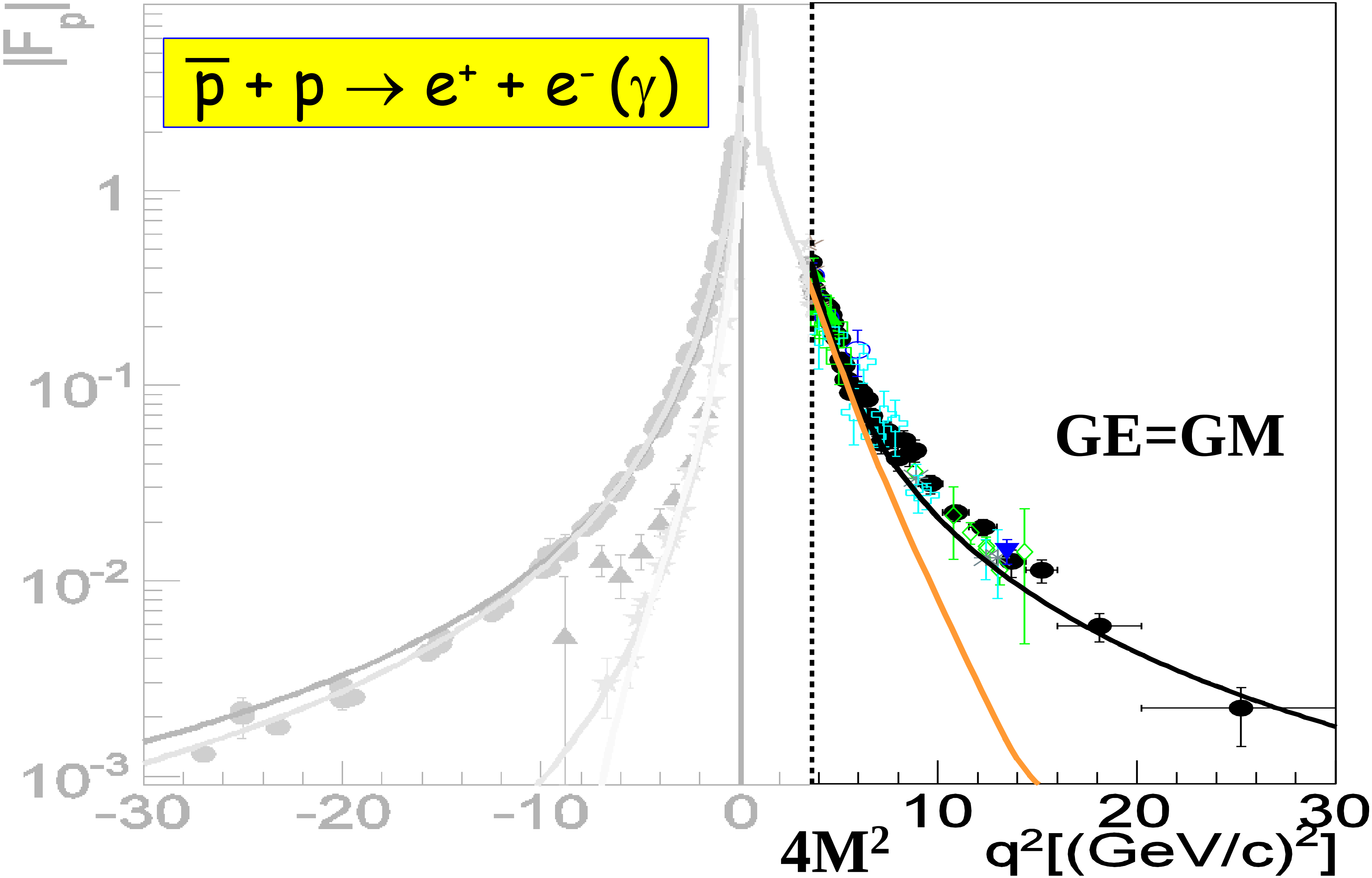
**BUT**

- 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*



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

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

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

$\theta$: 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 $\cos^2\theta$ (1$\gamma$ exchange)
- No dependence on sign of FFs
- Enhancement of magnetic term

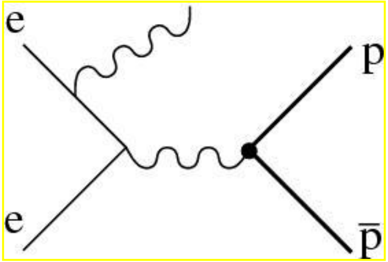
but TL form factors are complex!

# The Experimental facilities

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

VEPP-Novosibirsk

IHEP

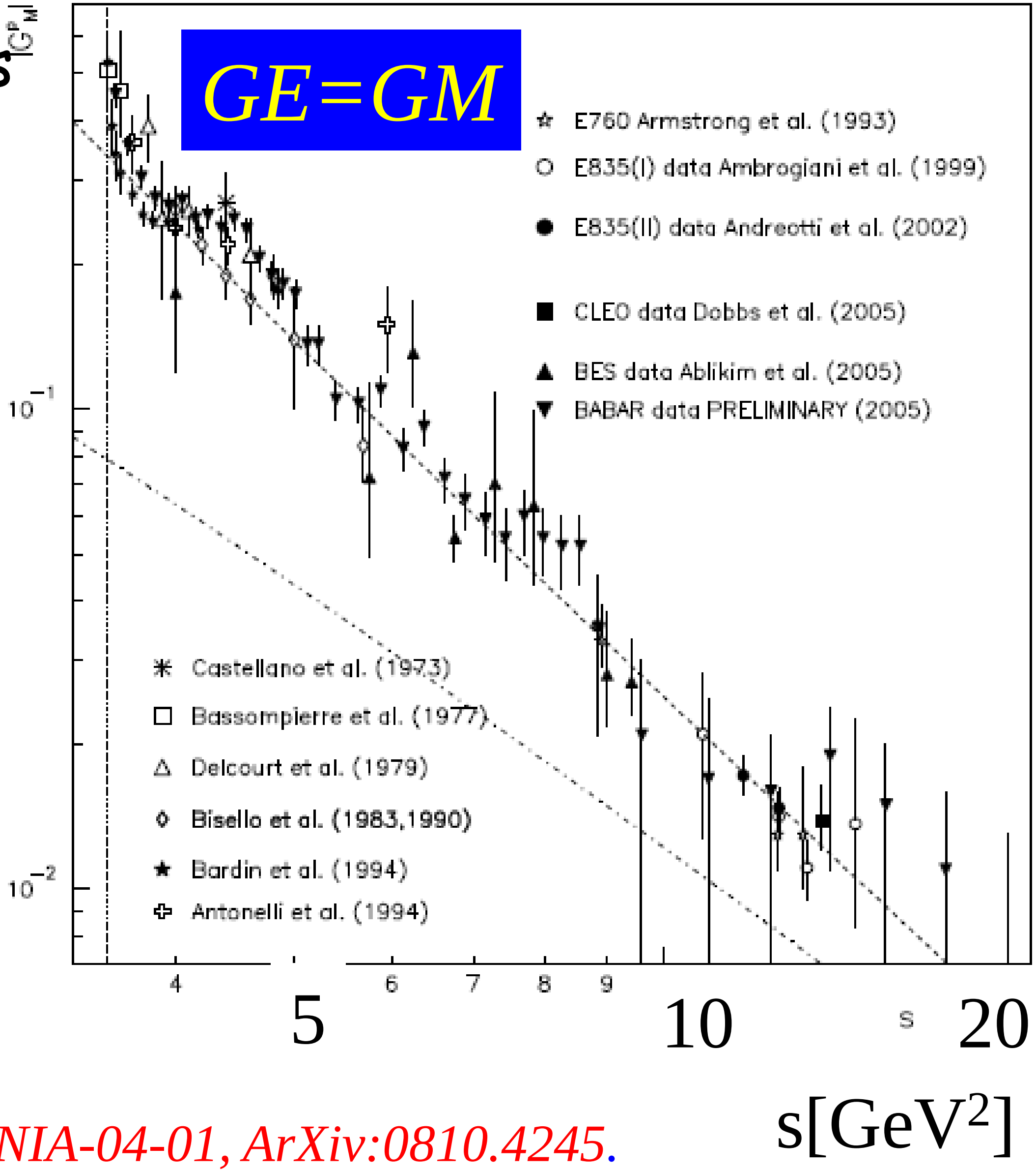


# The Time-like region

- 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.*

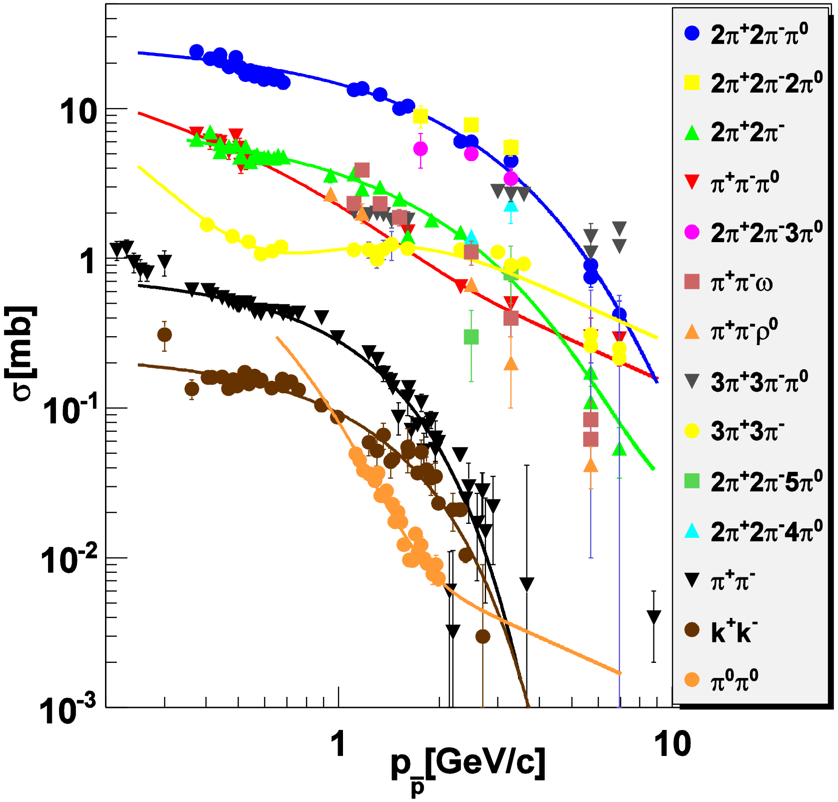
# Antiproton facilities

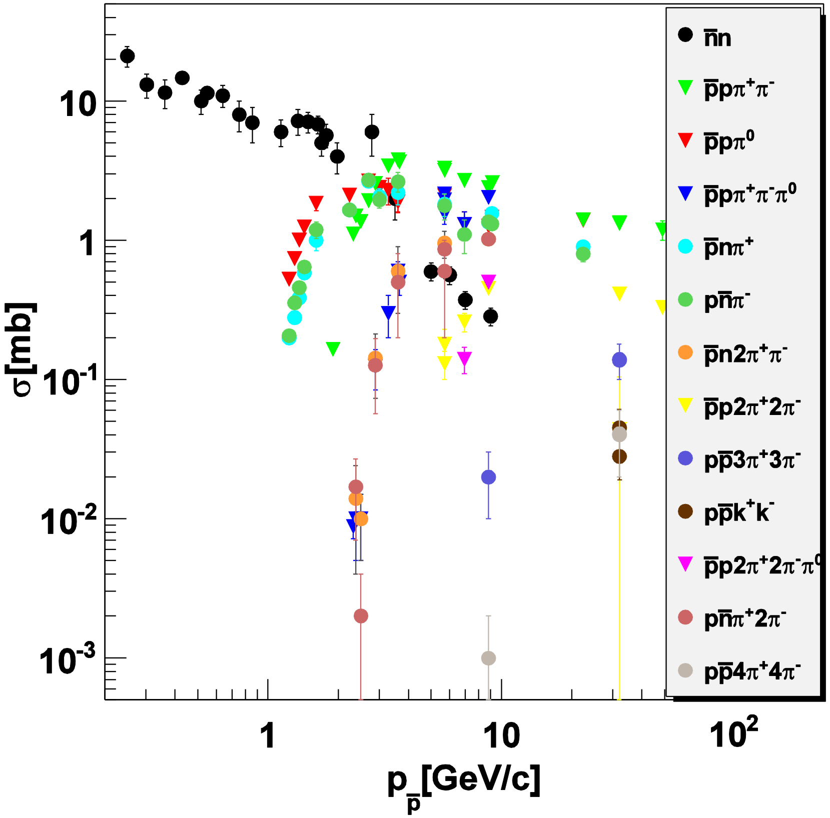
| Experiment | Years | Intensity $\bar{p}/s$ | Momentum range [GeV/c] | $\Delta p/p$ |
|---|---|---|---|---|
| CERN -LEAR | 1983-1996 | $2 \cdot 10^6$ | 0.06-1.94 | $10^{-3}$ |
| FermiLab<br>45% polarized $\bar{p}$ | 1985-2011 | $2 \cdot 10^6$<br>$10^4$ | <8.9<br>(Low energy beams) | $10^{-4}$ |
| PANDA | | $2 \cdot 10^7$ | 1.5-15 | $10^{-5}$ |

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

# *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*

The following slides concerning ongoing PANDA simulations :

- are extracted/derived from:

A. Dbeyssi, PhD thesis
Université Paris XI, 27-IX-2013

- they are considered
'PANDA unofficial results'

*Past its prime PANDA simulations are published in:*

- *M.C. Mora Espi, PhD Mainz 2013*
- *M. Sudol et al., EPJA A44(2010)373*

# *MC spectra…*

*A.Dbeyssi, PhD 2013*

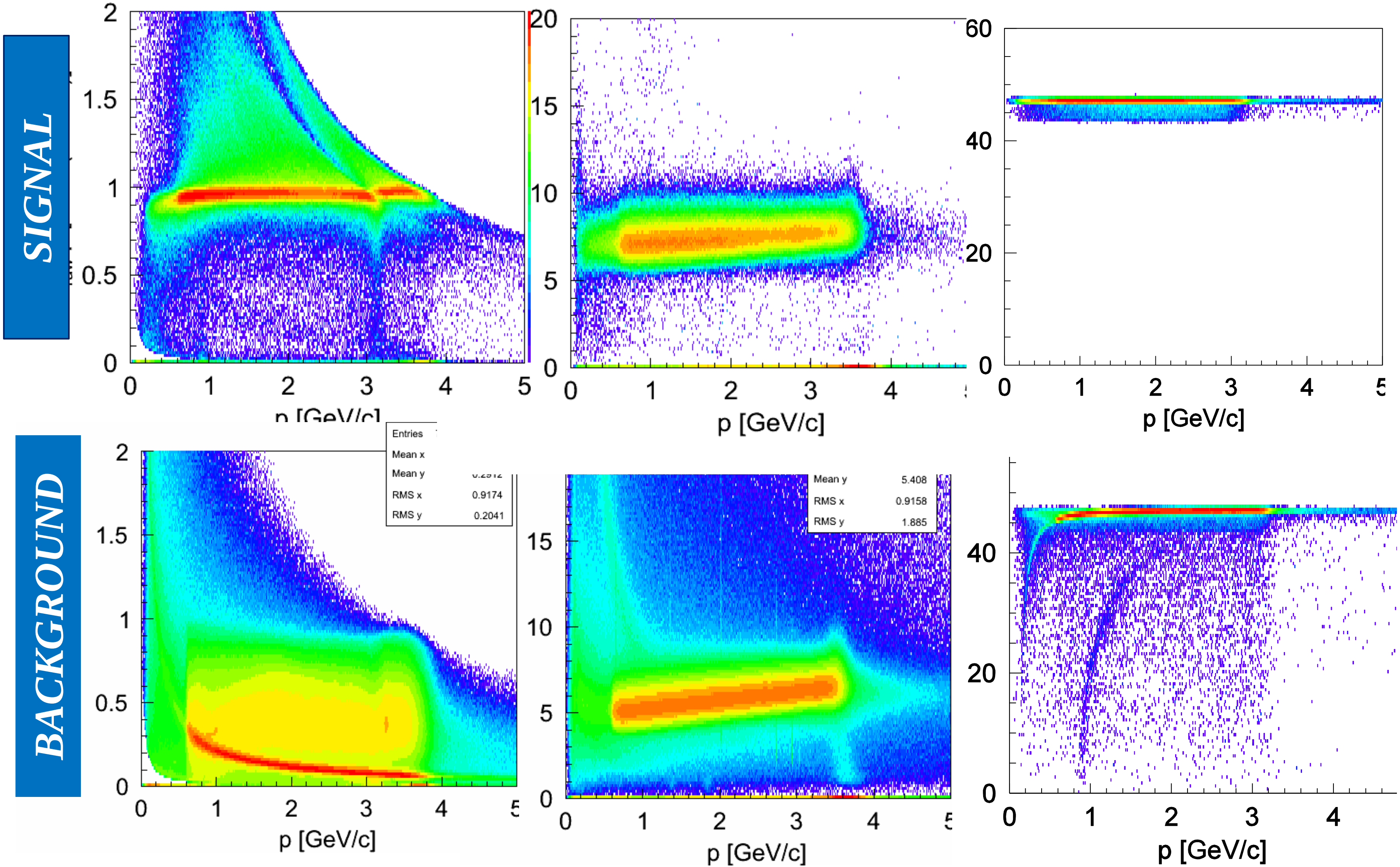
*EMC*$E_{raw}/p$ vs. p

*STT dE/dx vs p*

*Barrel DIRC Θ Cherenkov*

**SIGNAL**

**BACKGROUND**



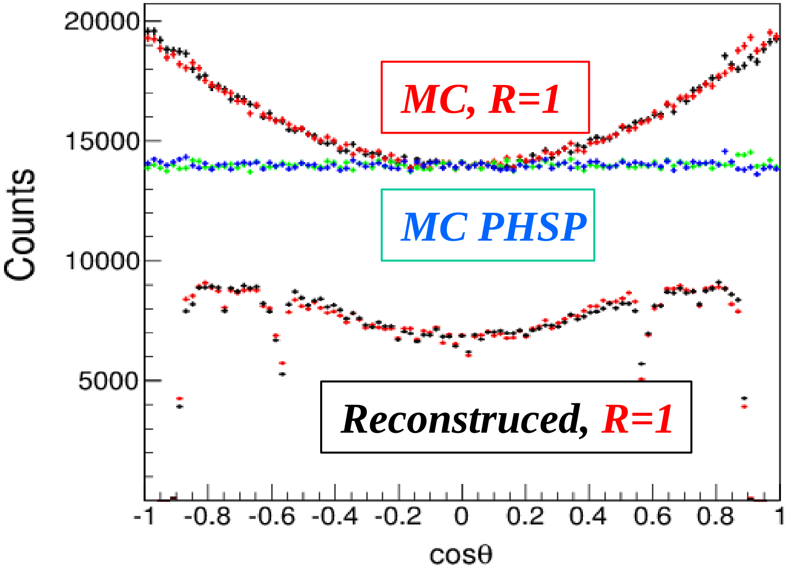
# From PHSP to physical angular distributions

A.DBEYSSI
PhD-2013

The differential cross section in the CM for $\bar{p}p \rightarrow e^+e^-$ is:

$$\frac{d\sigma}{d\cos\theta} = \sigma_0(1 + \mathcal{A}\cos^2\theta) \quad \begin{cases} \sigma_0 = \dfrac{d\sigma}{d\cos\theta}\left(\theta = \dfrac{\pi}{2}\right) \\ \mathcal{A} = \dfrac{\tau - R^2}{\tau + R^2}, R = |G_E|/|G_M|, \tau = \dfrac{s}{4M^2} \end{cases}$$

*A. Zichichi et al., Nuovo Cim. 24 (1962) 170*
*E. Tomasi-Gustafsson and M.P. Rekalo, Phys.Lett. B504 (2001) 291-295*



***Monte Carlo events, PHSP***

× Weight: $1 + \mathcal{A}\cos^2\theta$

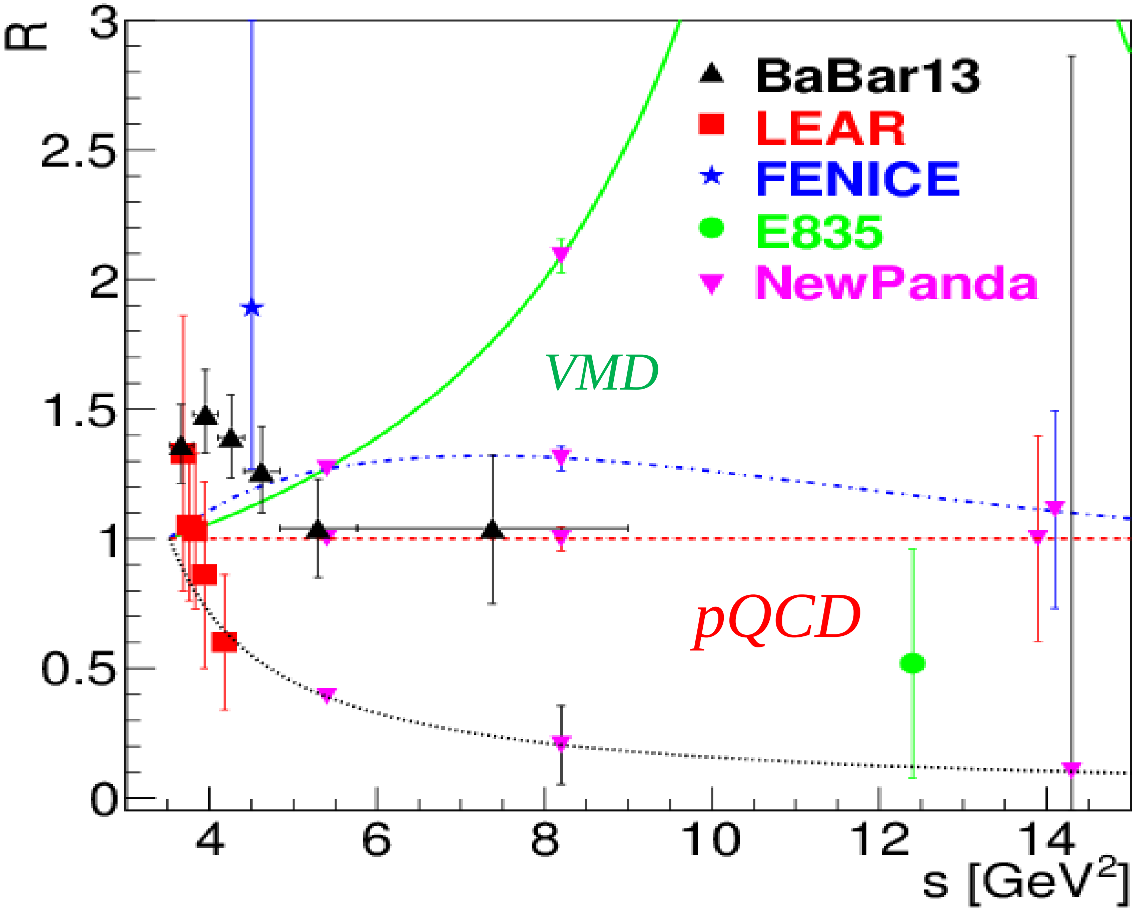
***Physical Monte Carlo events***

× Efficiency $\epsilon(c)$

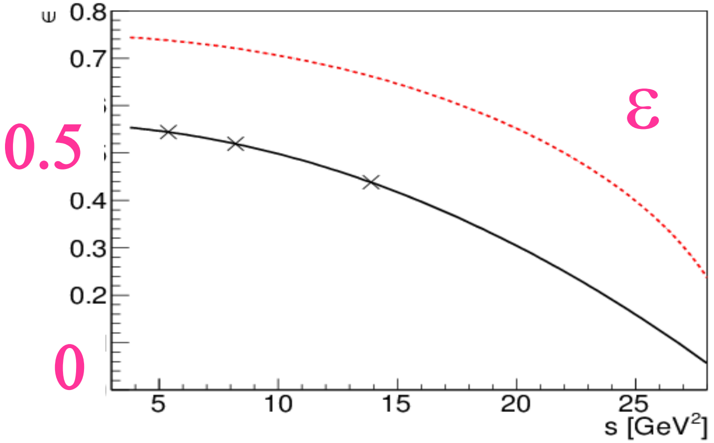
***Physical reconstructed events***

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

**A.Dbeyssi**
**PhD 2013**



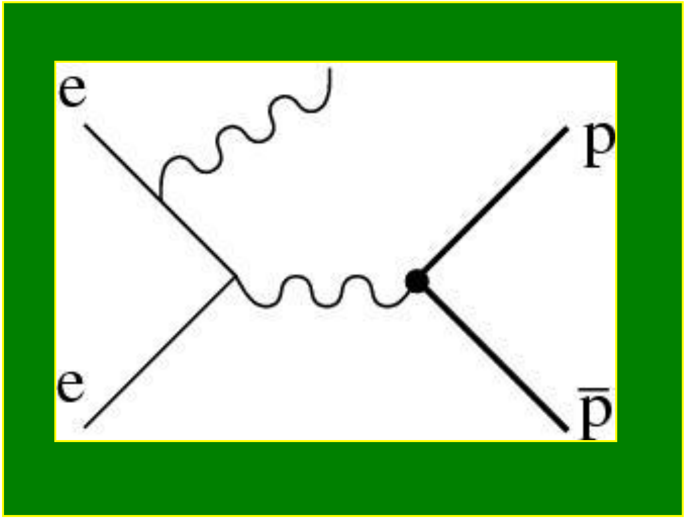
ε≤50%



*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….*

# Radiative return (ISR)



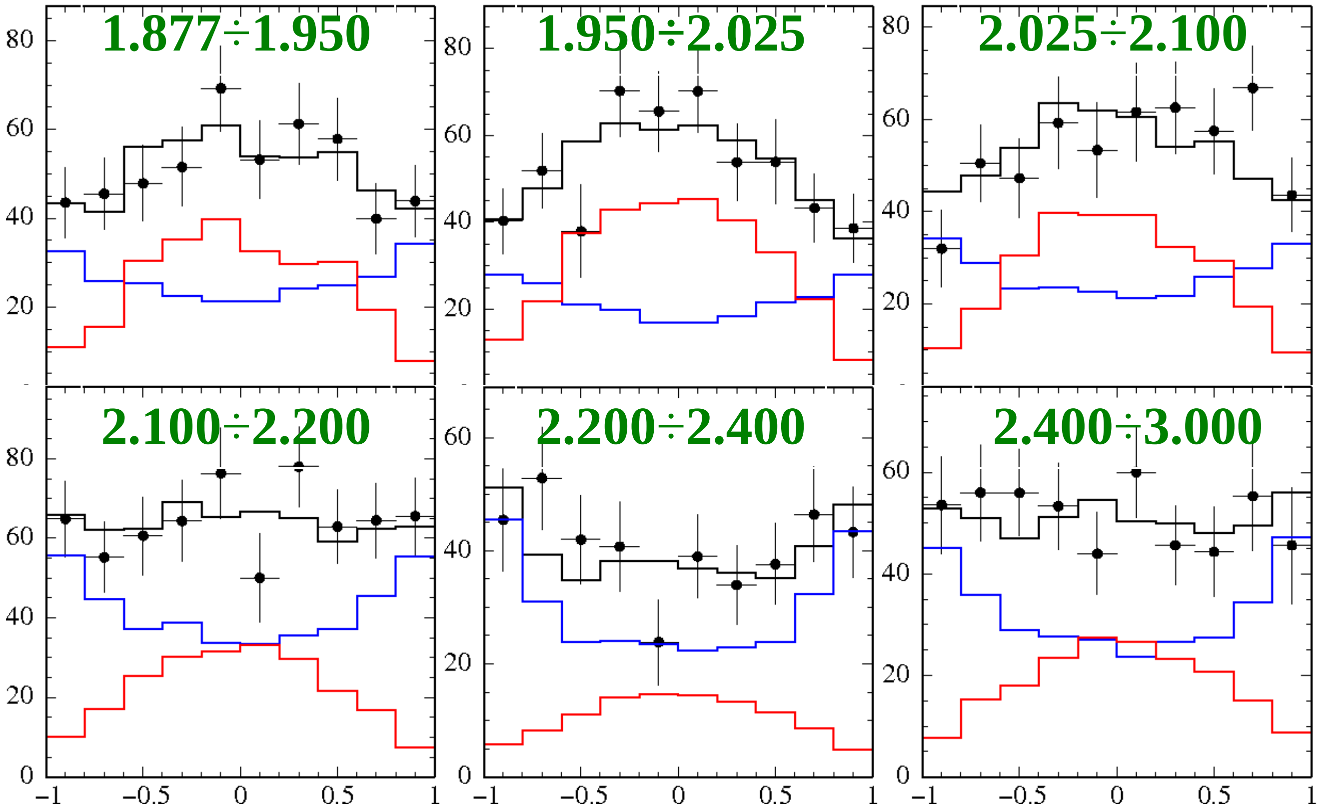
$$e^+ + e^- \to p + \bar{p} + \gamma$$

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

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

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

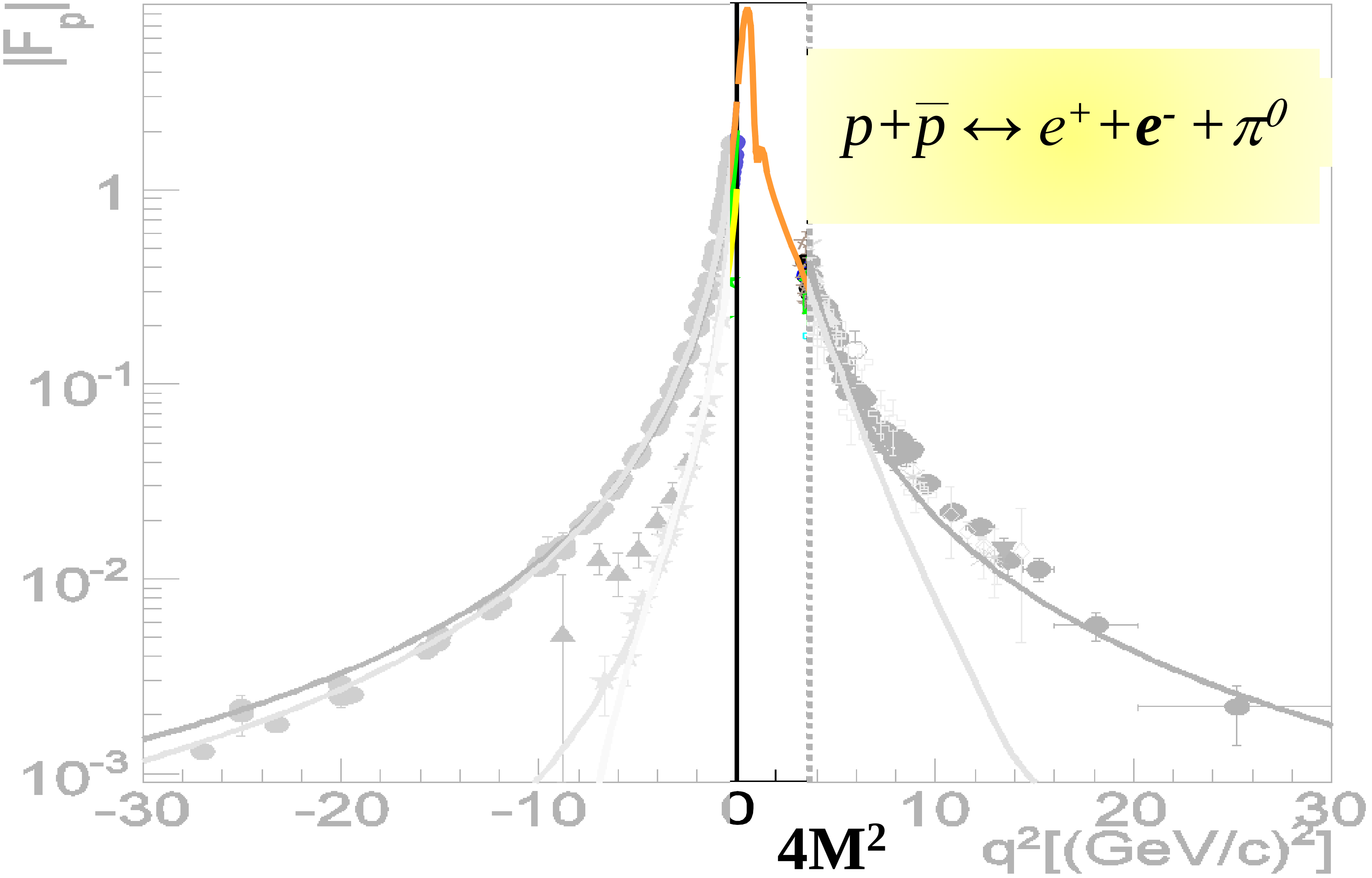
# Angular distribution



Events/0.2 vs. cos θ

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

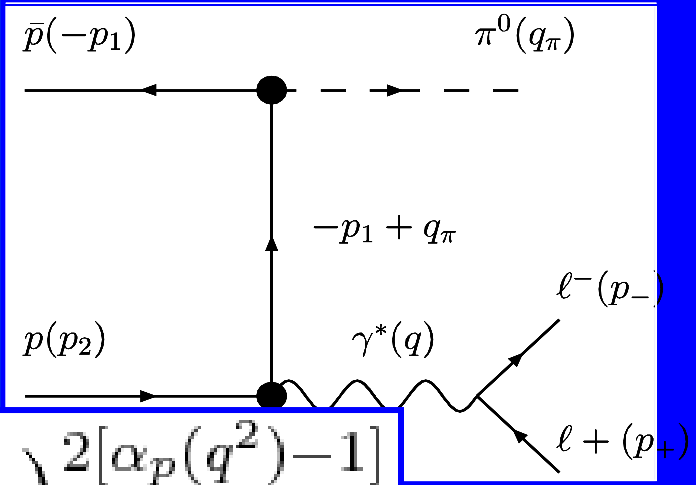
# The "unphysical region"

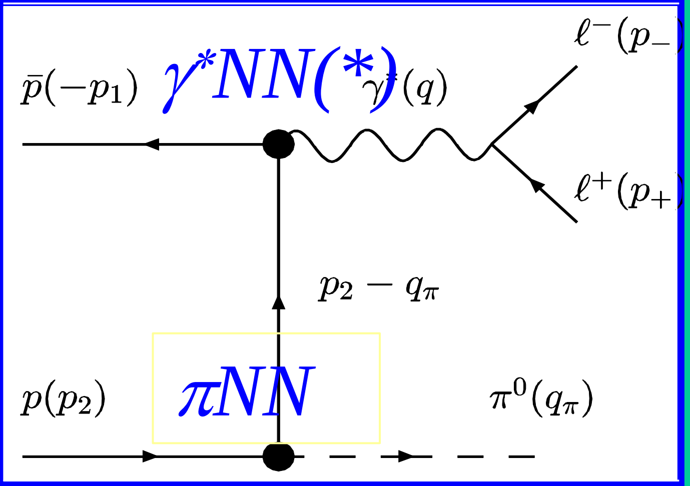


$$p+\overline{p} \leftrightarrow e^{+}+\boldsymbol{e}^{-}+\pi^{0}$$

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

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

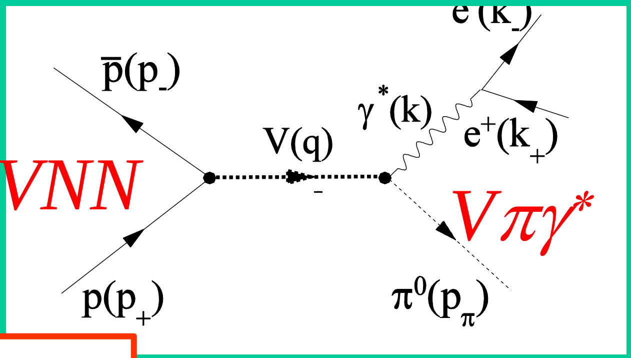




$$d\sigma_s \propto \frac{1}{q^2}\left(\frac{s}{M^2}\right)^{2[\alpha_P(q^2)-1]}$$

*M. P. Rekalo, 1967*

*V=ρ,ω,φ, J/Ψ, ..*



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

*Forward/backward*
*Regge trajectory*
*of the proton*

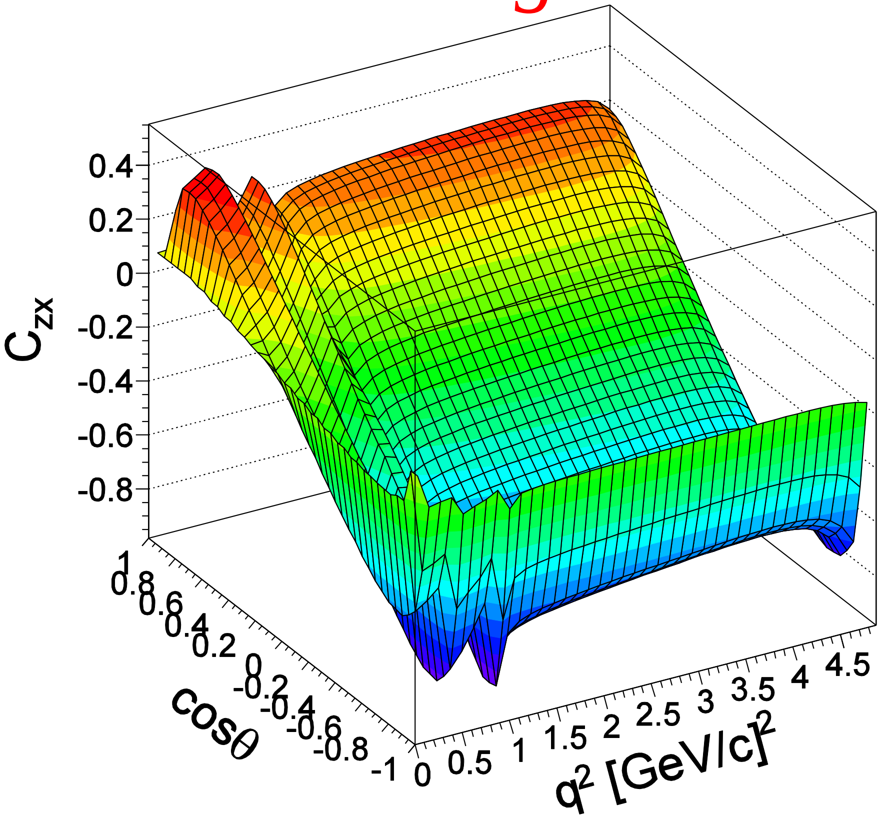
$$\frac{d\sigma_s}{d\sigma_a} \propto \left(\frac{s}{M^2}\right)^{2[\alpha_P(q^2)-1]} \ll 1$$

*Large angle: VM exchange*

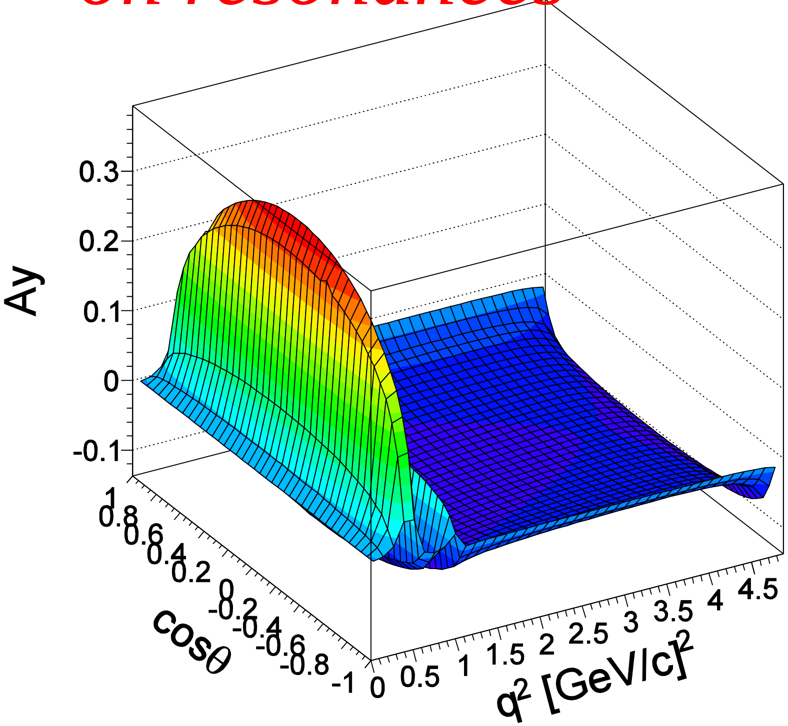
# Results with IJL FFs

Czx: large at small angles

2E=5.4 GeV



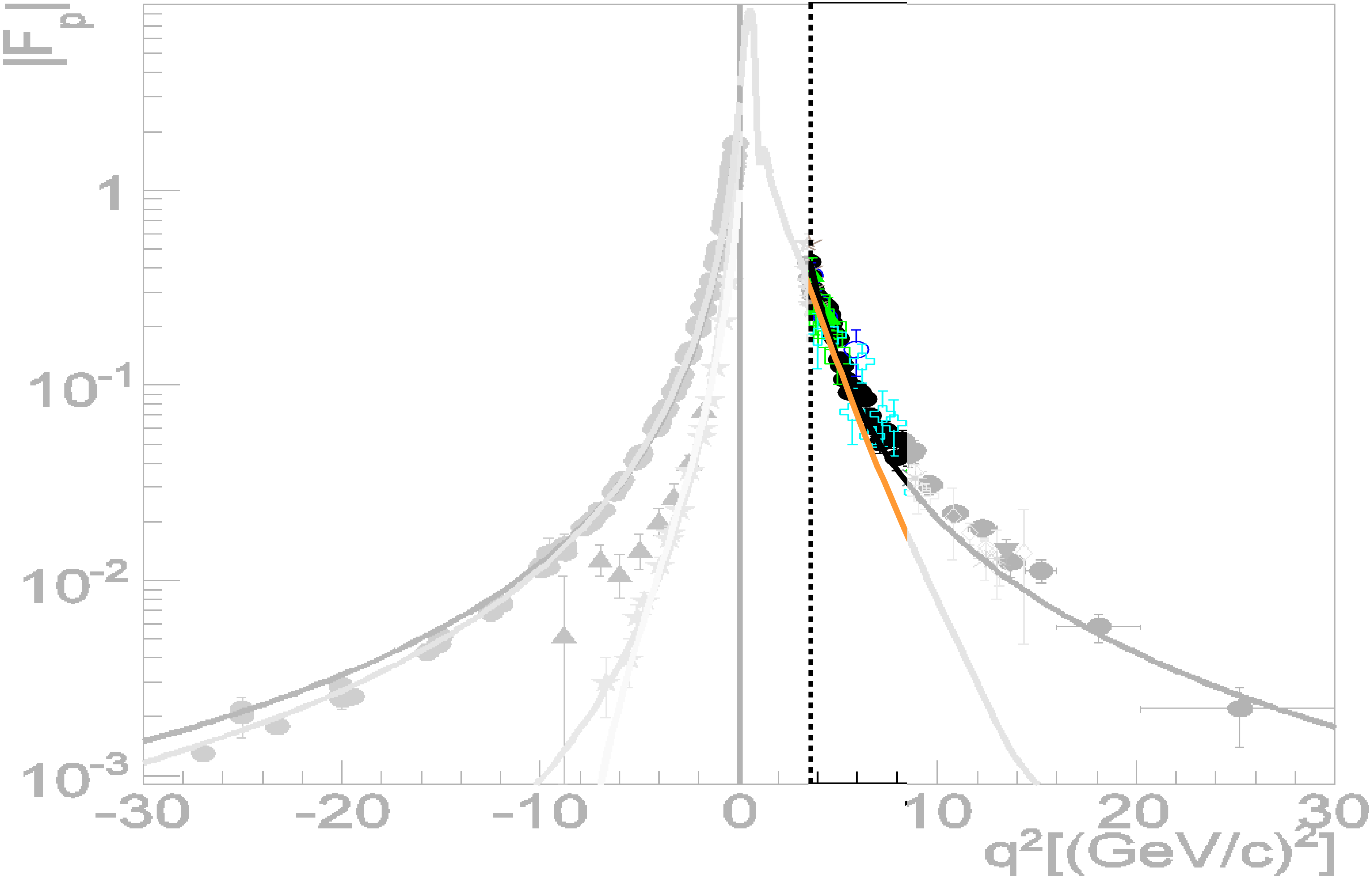
Ay: small except on resonances



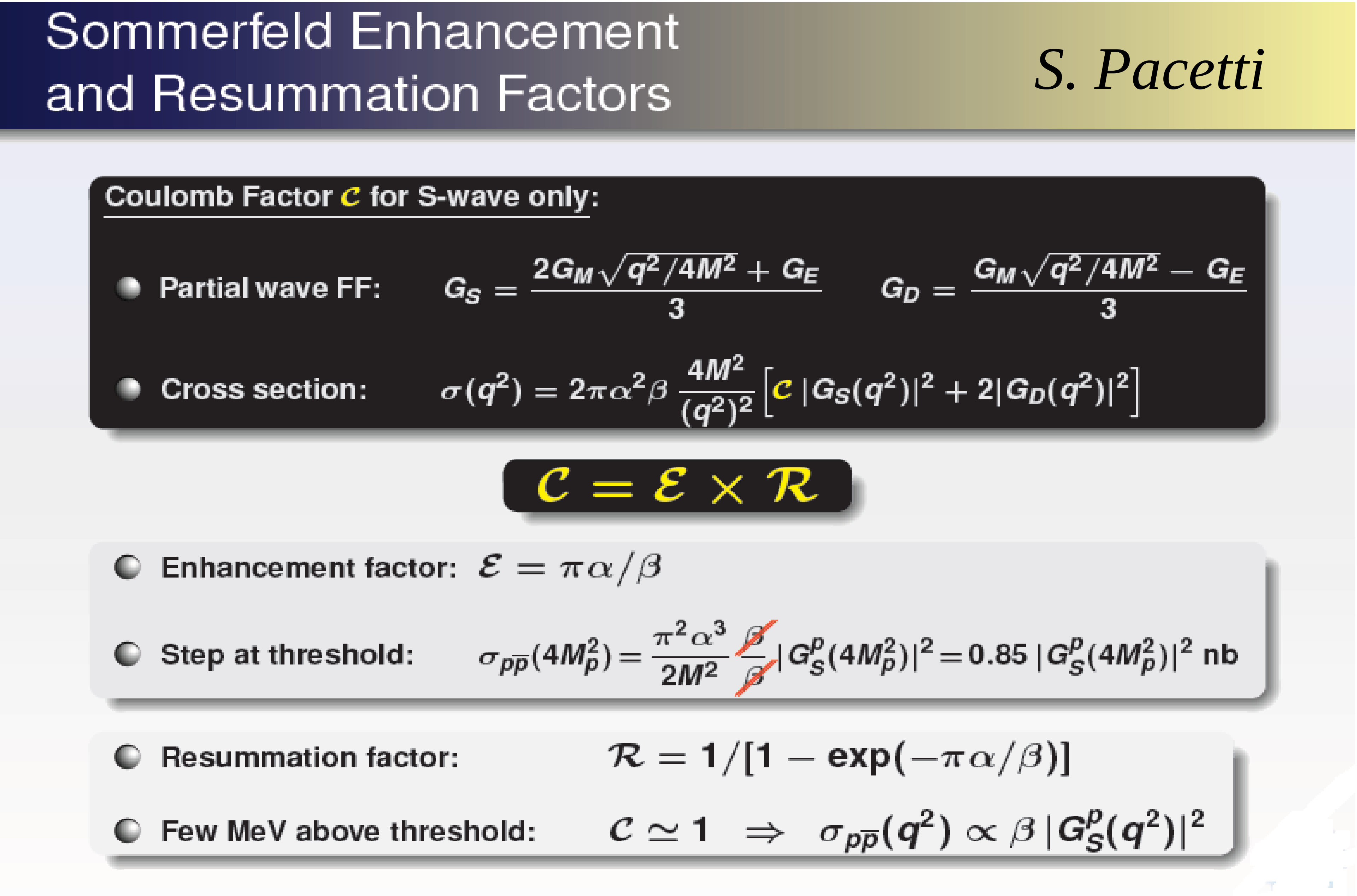
*Polarization phenomena help to distinguish the reaction mechanism!*

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

# *The Time-like region: the threshold*



# *Point-like form factors?*



## Sommerfeld Enhancement and Resummation Factors

*S. Pacetti*

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

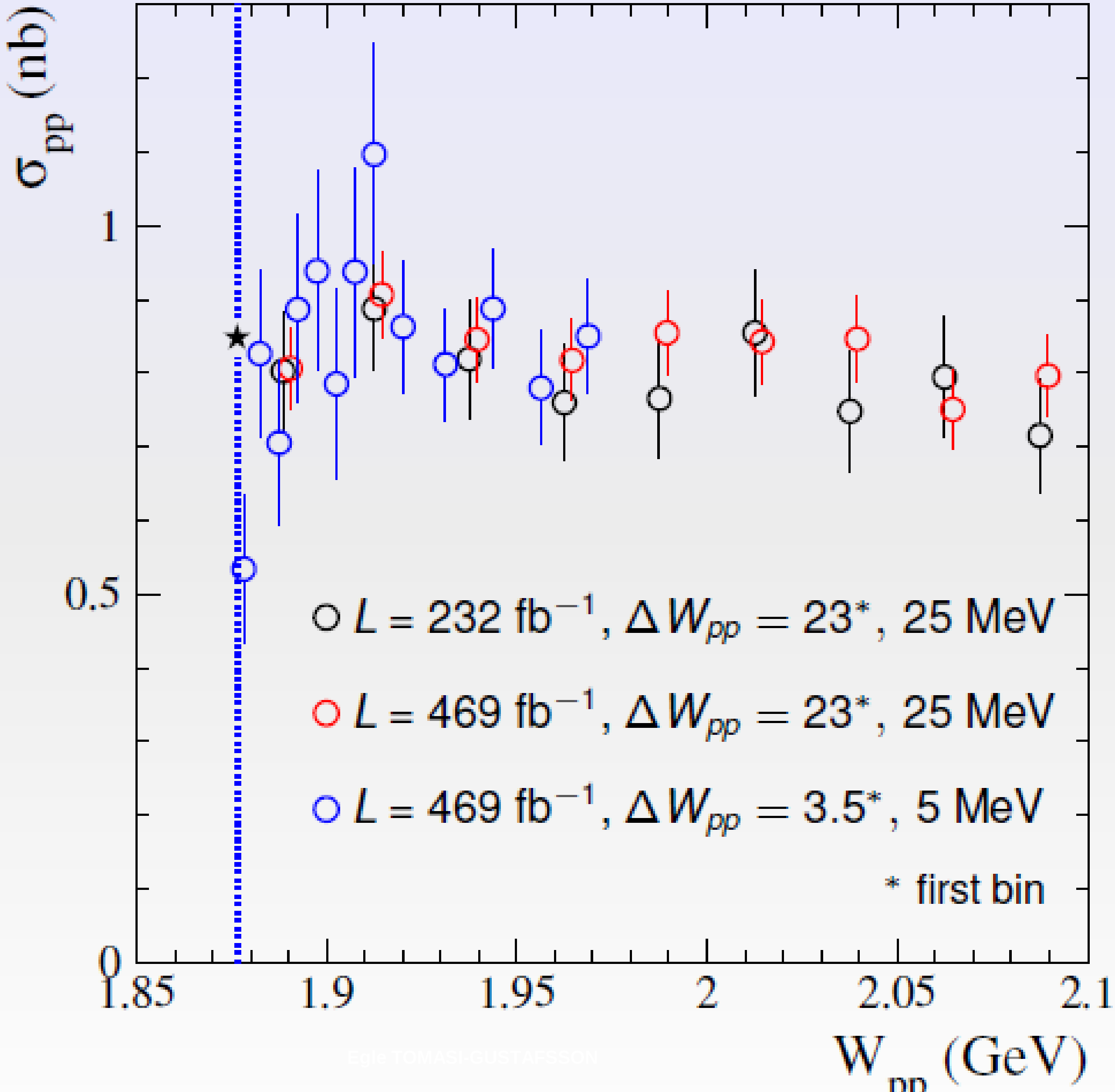
$$\boxed{\mathcal{C} = \mathcal{E} \times \mathcal{R}}$$

- 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

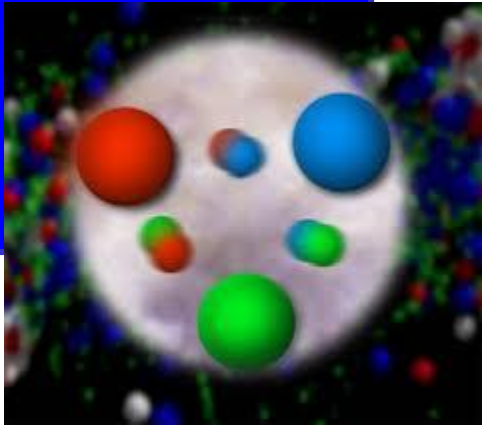
- Resummation factor: $\mathcal{R} = 1/[1-\exp(-\pi\alpha/\beta)]$
- Few MeV above threshold: $\mathcal{C} \simeq 1 \quad \Rightarrow \quad \sigma_{p\bar{p}}(q^2) \propto \beta\,|G_S^p(q^2)|^2$

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

PRD73-012005, arXiv:13



# 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*

# Model: generalized form factors

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

**Definition:**

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

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

*In SL- Breit frame (zero energy transfer):*

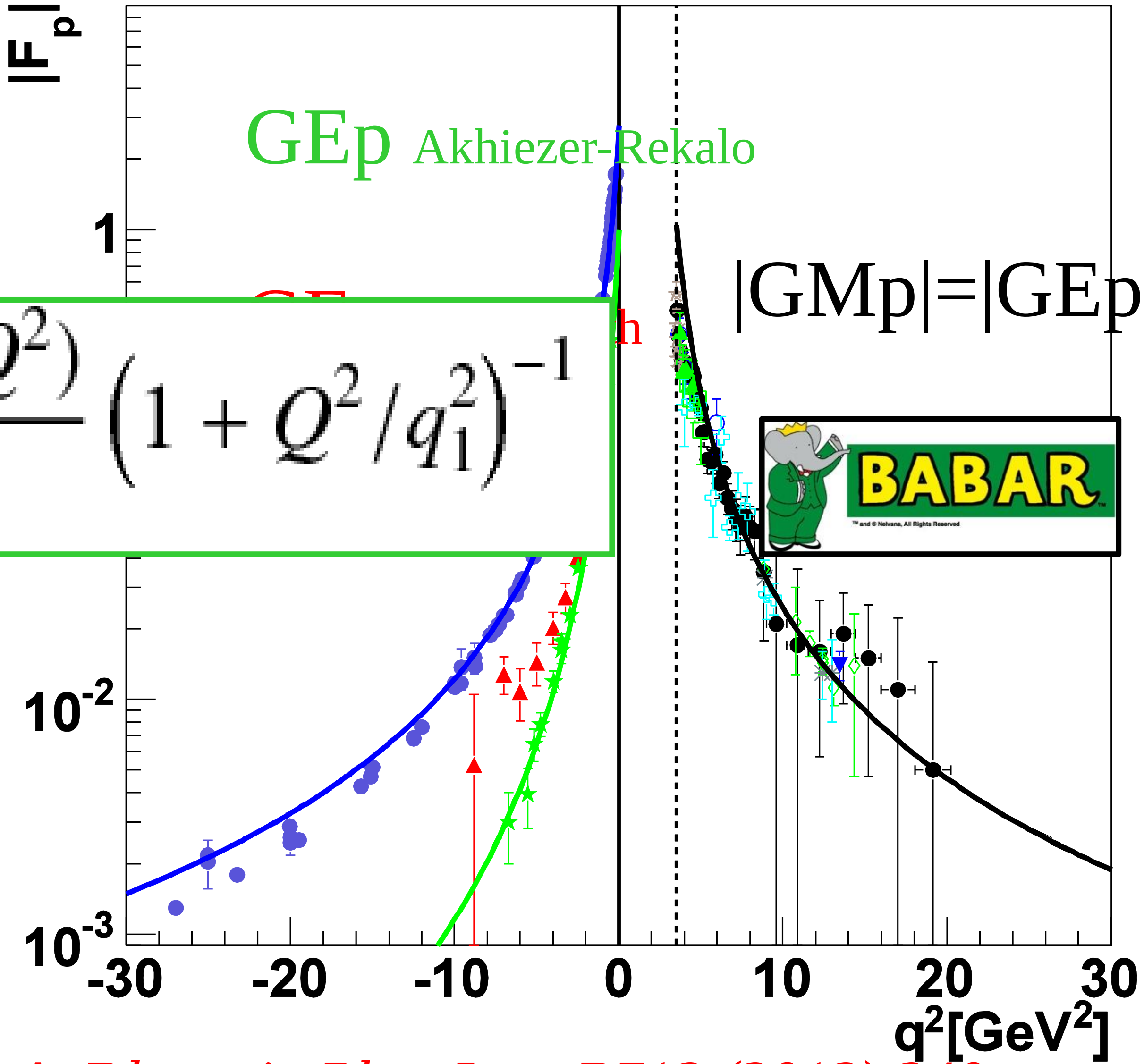
$$F(q^2) = \delta(q_0)F(Q^2),\ Q^2 = -(q_0^2 - \vec{q}^2) > 0.$$

*In TL-(CMS):*

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

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

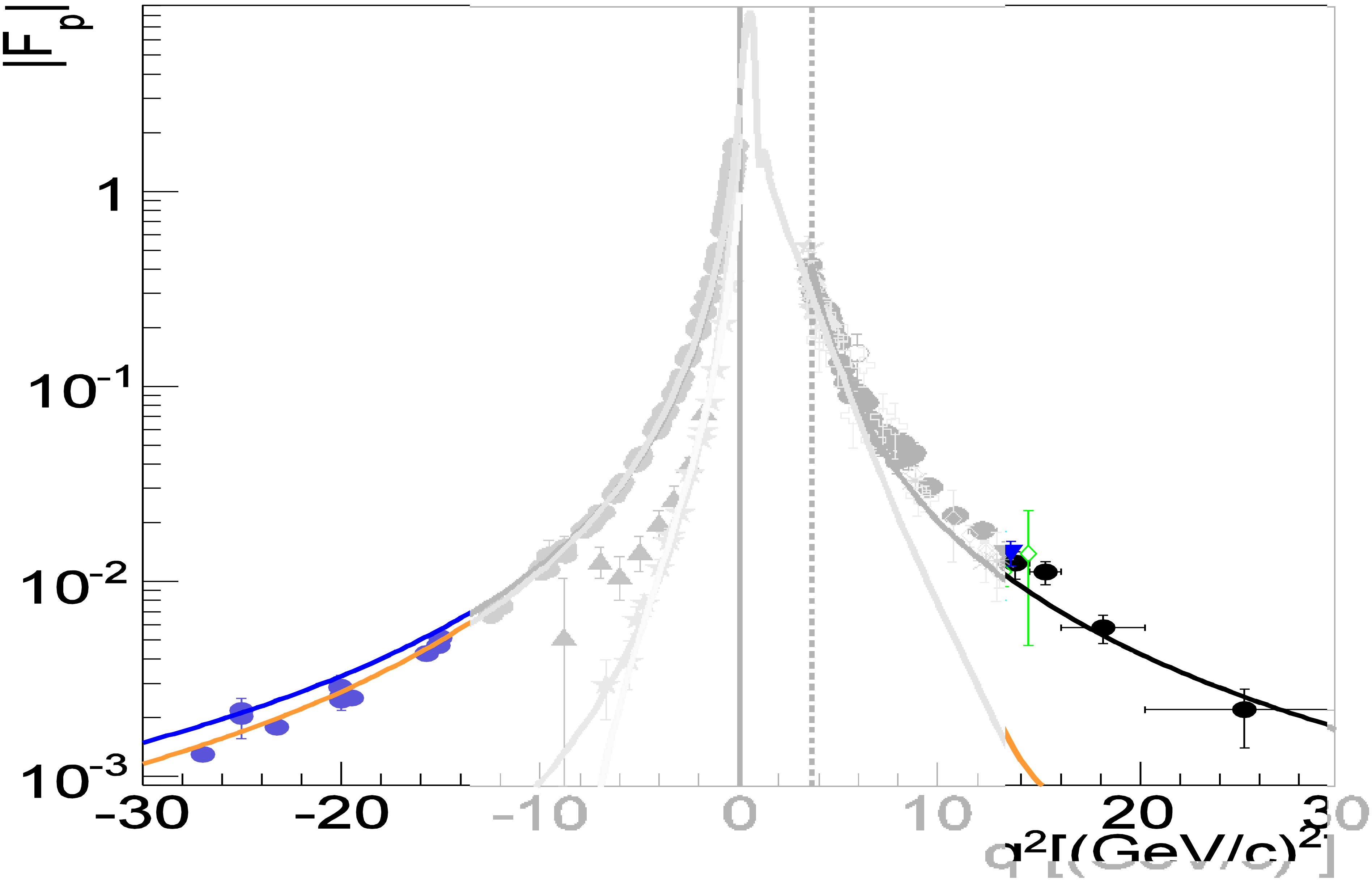
# Proton Form Factors



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

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

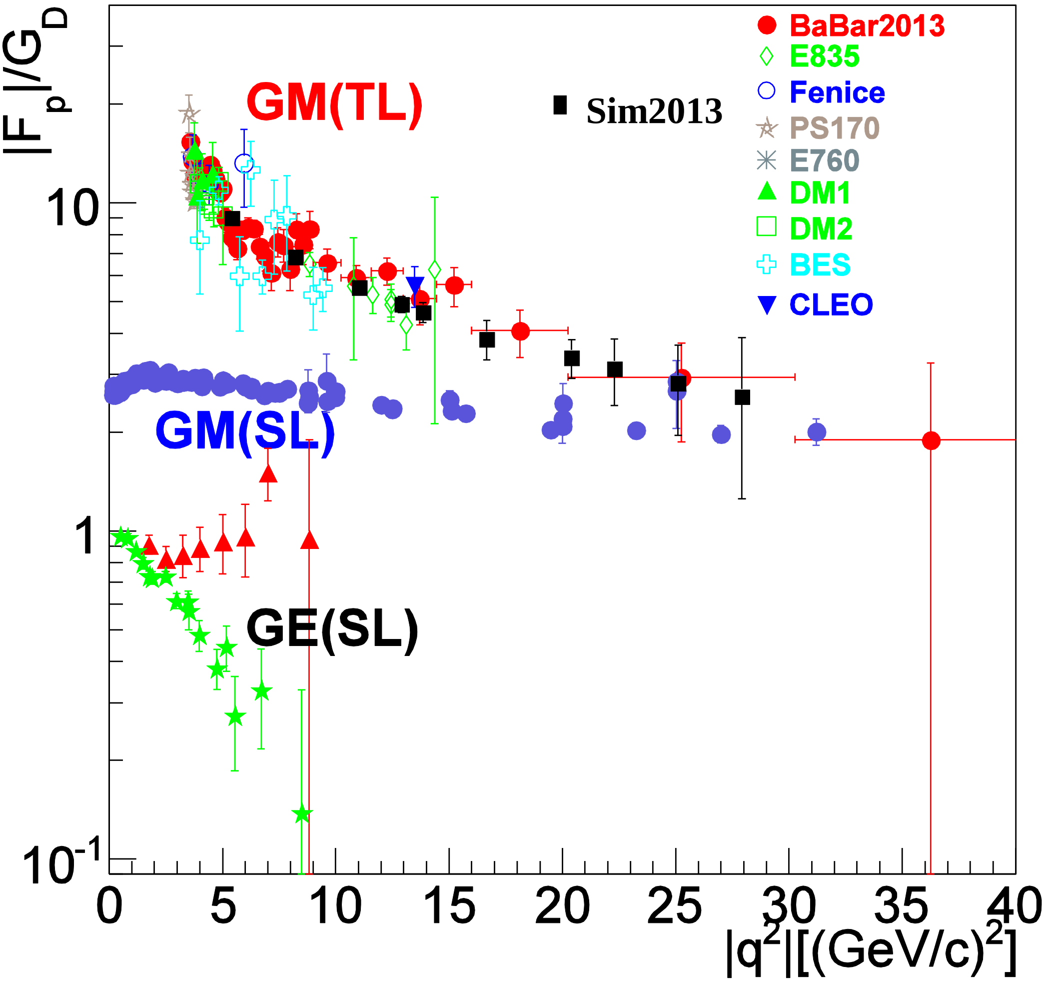
# The asymptotic region



# 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 |
|---|---|
| $(e^- + p \to e^- + p)$ | $(e^+ + e^- \leftrightarrow \bar{p} + p)$ |

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

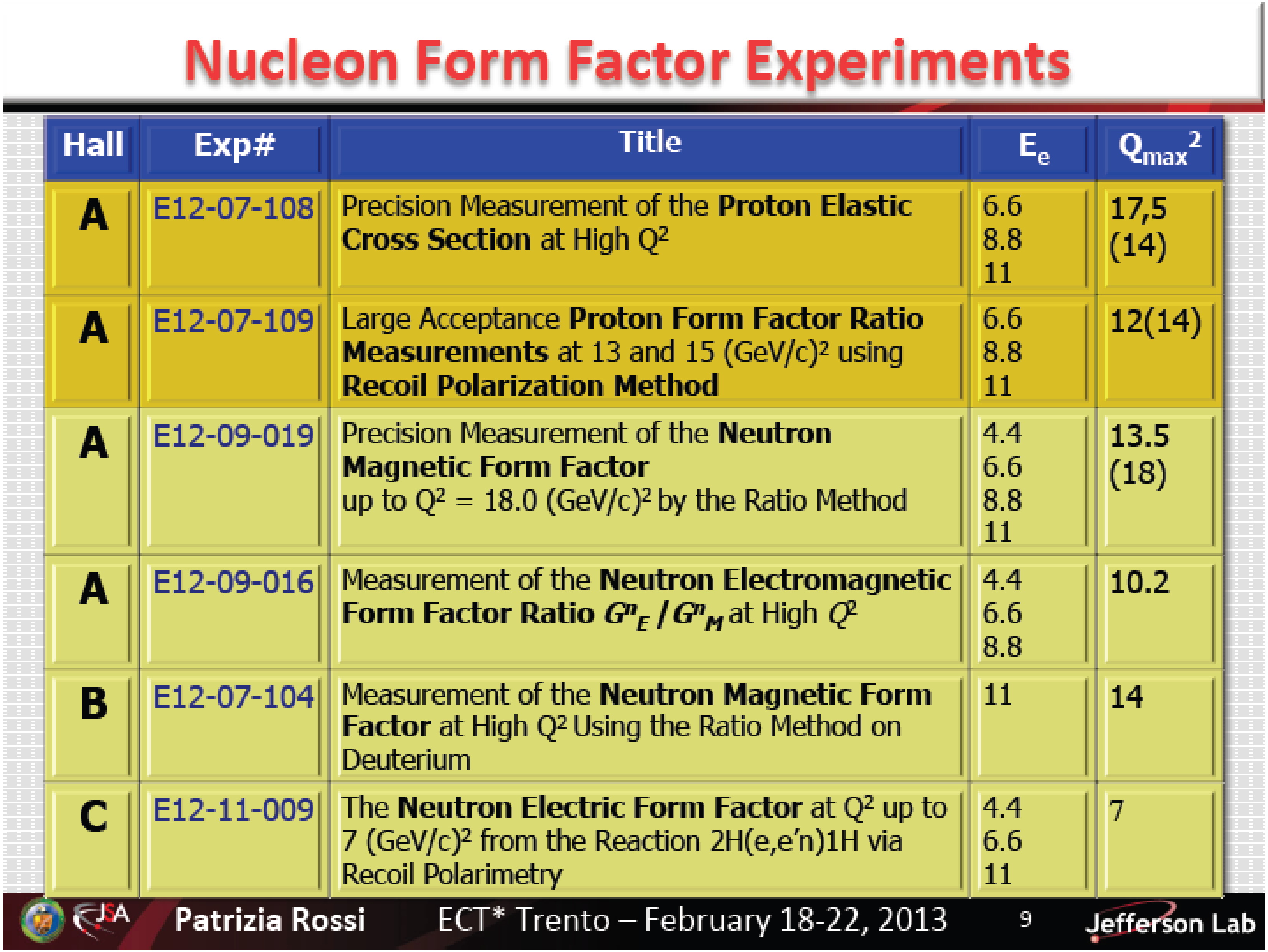
Applies to NN and $N\bar{N}$ Interaction

(Pomeranchuk theorem)

t=0 : not a QCD regime!

Analyticity

Connection with QCD asymptotics?



# 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<br>8.8<br>11 | 17,5<br>(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<br>8.8<br>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<br>6.6<br>8.8<br>11 | 13.5<br>(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<br>6.6<br>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<br>6.6<br>11 | 7 |

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

# Conclusions

- Large activity both in Space and Time-like regions

p̄anda

Jefferson Lab

VEPP-3
Novosibirsk

IHEP B E S

- 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 (PANDA)
- complex FFs in TL region: polarization

*Σας ευχαριστώ*
*για την προσοχή σας*

# 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

# PID and kinematical Cuts

A. DBEYSSI ,PhD 2013

| **s [GeV$^2$]** | **5.4** | **8.2** | **13.9** |
|---|---|---|---|
| Total PID prob. | >99% | >99% | >99.9% |
| Individual PID$_i$ prob. | >5% | >5% | >6% |
| Number of fired crystals | >5 | >5 | >5 |
| $(\theta + \theta')$ [CMS] | [178°-182°] | [178°-182°] | [175°-185°] |
| $\|\phi - \phi'\|$ | [178°-182°] | [178°-182°] | [175°-185°] |
| Invariant mass [GeV] | No cut | > 2.14 GeV | > 2.5 GeV |
| Background [Events] | 0 | 0 | 0 |

- *PID --> probability for the detected particle to be identified as the signal.*
- *PID information are taken from EMC, STT, DIRC and MVD subdetectors.*