Experiments on Form Factors

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Int. Workshop e+e- collisions from Phi to Psi
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Experiments on Form Factors

How ?

What ?

Why ?

Experiments on Form Factors

How ?

What ?

Why ? did I accept to give this talk?

Outline

- Introduction to Baryon Form Factors
- Measurements of Space-like Form Factors
  – Proton
  – Neutron
- Measurements of Time-like Form Factors
  – Proton
  – Neutron
  – Hyperons
- Outlook

- Electromagnetic Form Factors (EMFF) of hadrons are among the most basic quantities containing information about hadron internal structure.

- The electromagnetic structure of a hadron with spin S is given by $2S+1$ Form Factors.

- Elastic Form Factors contain information the hadron ground state.

Electromagnetic Form Factors provide the most direct access to the spatial charge and magnetisation distributions.

EMFF of baryons are studied in:

- elastic $e^- B \rightarrow e^- B$ scattering; Space-Like FF
- baryon-antibaryon production/annihilation, $e^+ e^- \leftrightarrow B\bar{B}$; Time-Like FF

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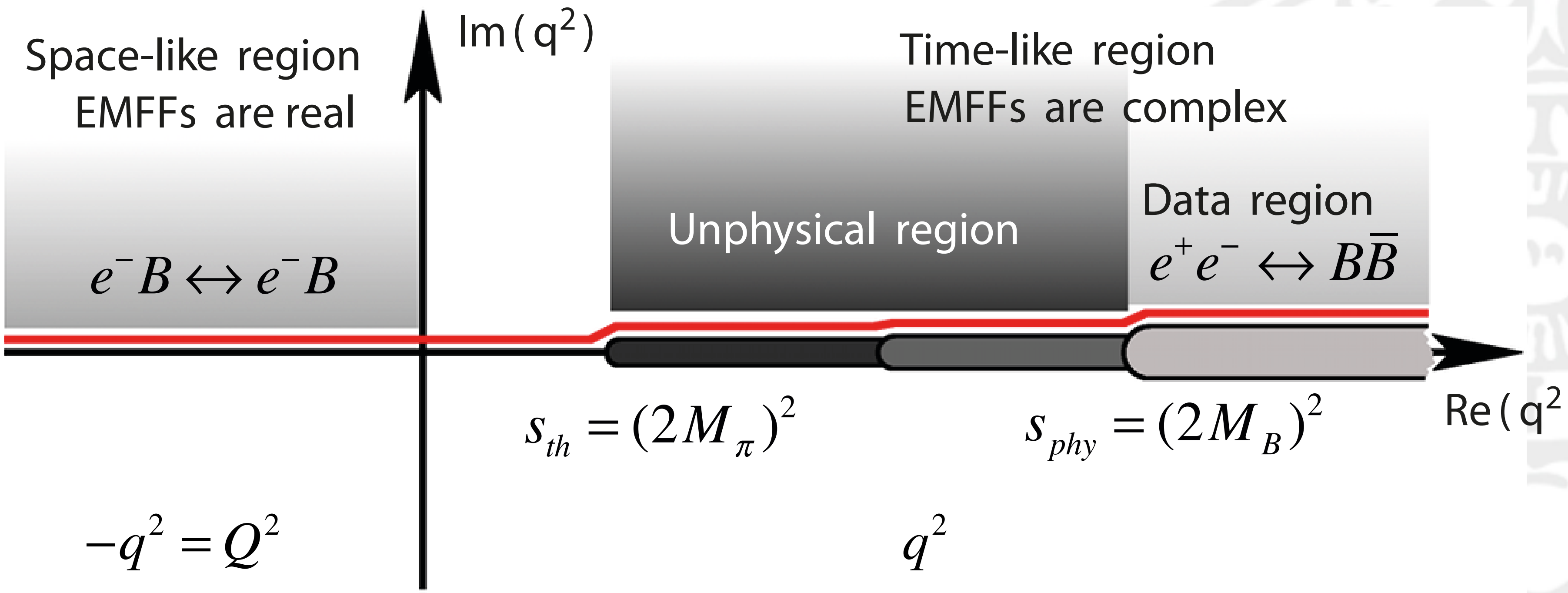
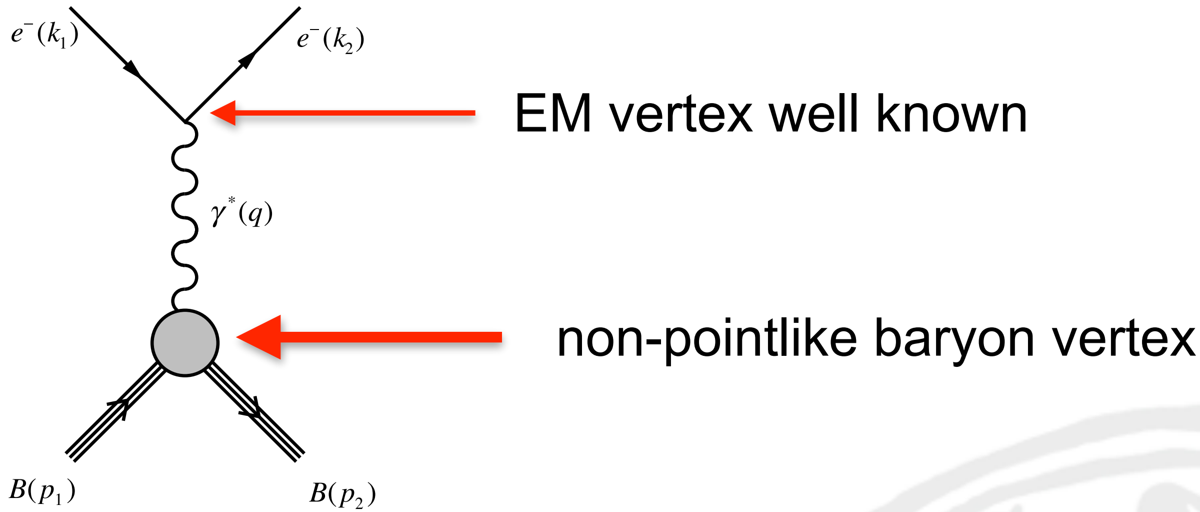


Space-Like FF's

Born term:



Baryon vertex matrix element: $$\Gamma^\mu = F_1^B(Q^2)\gamma^\mu + \frac{\kappa}{2M_B} F_2^B(Q^2) i\sigma^{\mu\nu} q_\nu$$

$F_1(Q^2)$ and $F_2(Q^2)$ are related to non-helicity-flip and helicity-flip part of the hadronic current and are the Dirac and Pauli EMFF's, respectively.

Normalisation: $F_1(0) = Z$ = baryon charge

$F_2(0) = 1$

It is convenient to rewrite the Dirac and Pauli EEMFF's as

$$G_E = F_1 - \tau F_2 \quad ; \quad \tau = \frac{Q^2}{4M_B^2}$$

$$G_M = F_1 + F_2$$

These are the Sachs Form Factors with normalisation
$G_E(0) = Z$ and $G_M(0) = 1 + \boldsymbol{\kappa} = \mu_B$ = baryon magnetic moment.

The Sachs FF´s correspond to the Fourier transformations of the charge and magnetic spatial distributions in the Breit frame ($q = (0, \vec{q})$).
(The situation is more complicated in reality.)

The Space-Like EEMFF is obtained from elastic electron scattering in terms of G_E^2 and G_M^2 (**Rosenbluth separation**) as:

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

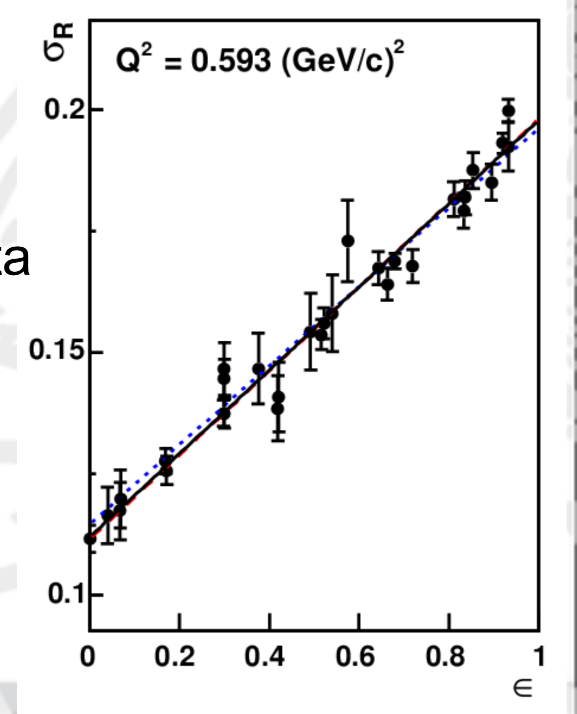
$$\varepsilon = \frac{1}{1 + 2(1+\tau)\tan^2\theta_e / 2}$$ = virtual photon polarisation

The linear dependence on τ in ε makes it possible to define a reduced cross section as

$$\sigma_{red} = \frac{\varepsilon(1+\tau)}{\tau} \frac{E_e}{E_{beam}} \frac{d\sigma}{d\Omega} / \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = G_M^2 + \frac{\varepsilon}{\tau} G_E^2$$

=> σ_{red} is expected to have linear dependence on ε at a given Q^2 with a slope proportional to G_E^2 and with the intercept G_M^2.

G_E^2 and G_M^2 are extracted from fits to experimental data by measuring the cross section at a given Q^2 at different energies (ε).



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G_E^2 difficult to measure at high Q^2

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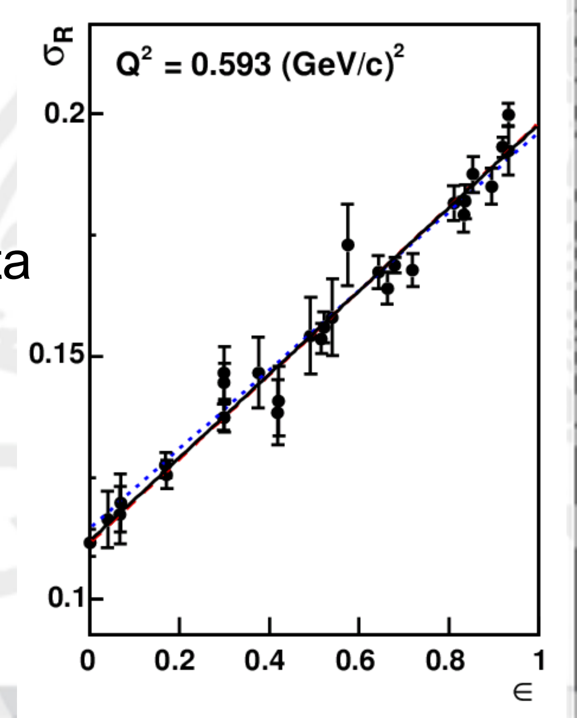
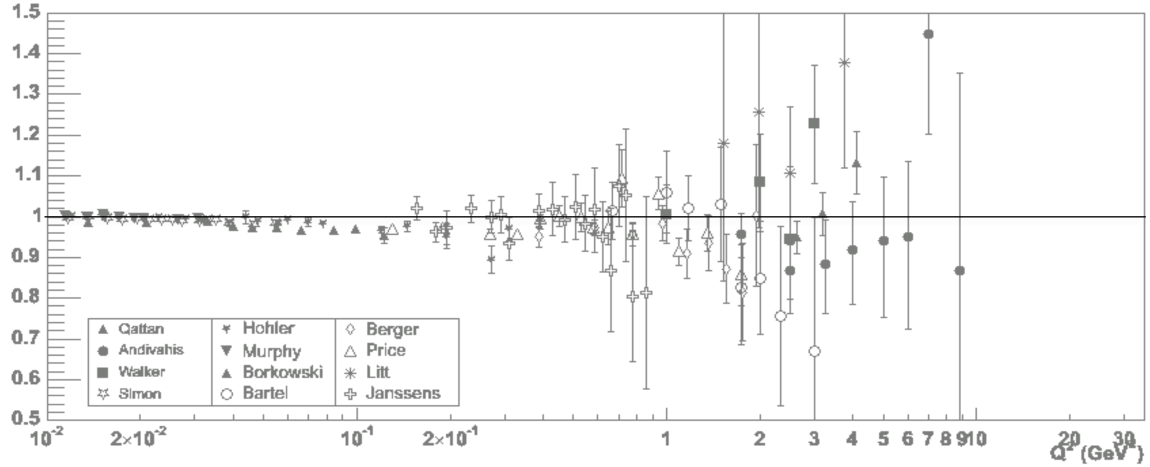
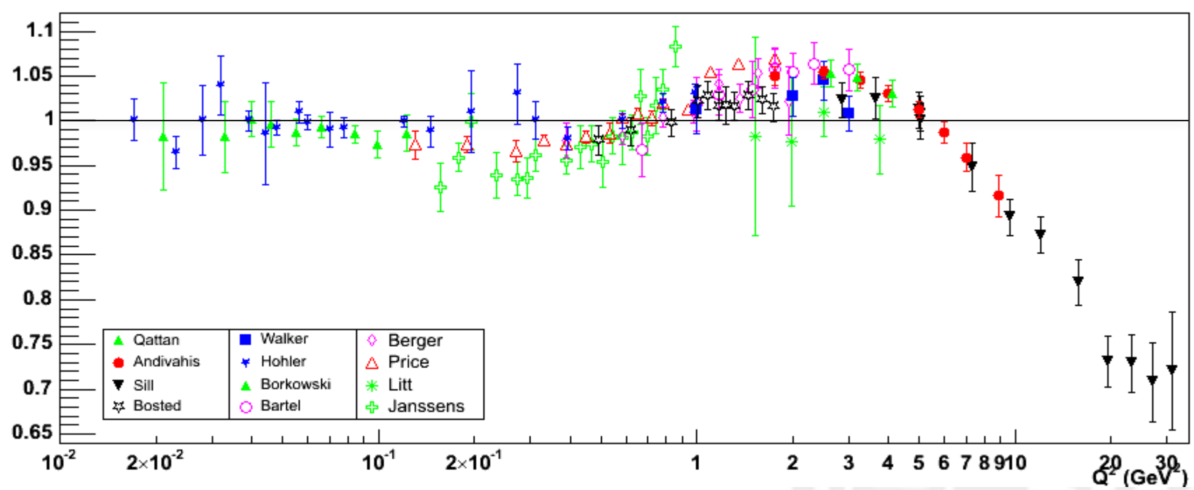


In the static limit is $G_{M_p} = \mu_p G_{E_p}$, and this is roughly consistent with data. Rosenbluth separation:

$$\frac{G_{E_p}}{G_D}$$



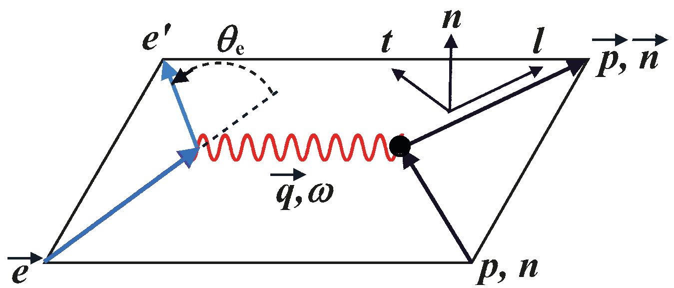
$$\frac{G_{M_p}}{\mu G_D}$$



The q^2 dependence of the proton EMFF is well characterised by a dipole behaviour: $G_D = \left(1 + \frac{Q^2}{.71}\right)^{-2}$

An alternative to extract EEMFF is offered by polarisation measurements.

A longitudinally polarised electron transfers its polarisation in elastic scattering with non-zero P_l and P_t components:



$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_{beam}+E_e)}{2M_B}\tan\frac{\theta_e}{2}$$

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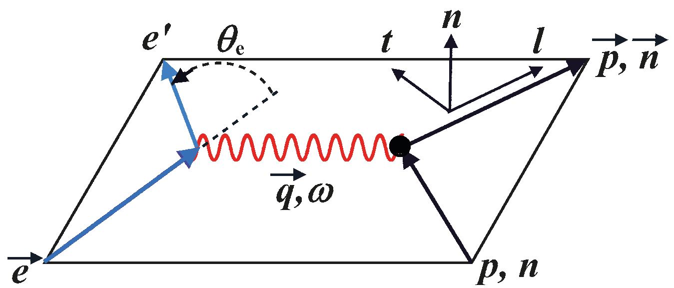

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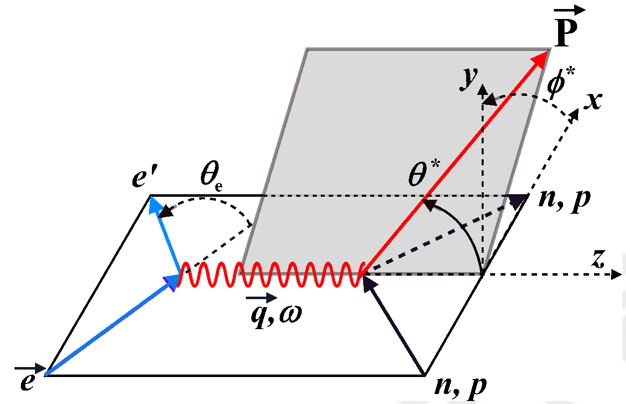
Polarised target:



Asymmetry: $A_{\exp} = hP_eP_{target}A$

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} =$$

$$-\frac{2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}}{G_E^2 + \frac{\tau}{\varepsilon}G_M^2}\left(\sin\theta^*\cos\phi^* G_E G_M + \sqrt{\tau\left(1+(1+\tau)\right)\tan^2\frac{\theta_e}{2}}\cos\theta^* G_M^2\right)$$

$$\theta^* = \pi/2, \phi^* = 0{,}180 \Rightarrow A_y = -\frac{2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}\frac{G_E}{G_M}}{\left(\frac{G_E}{G_M}\right)^2 + \frac{\tau}{\varepsilon}}$$

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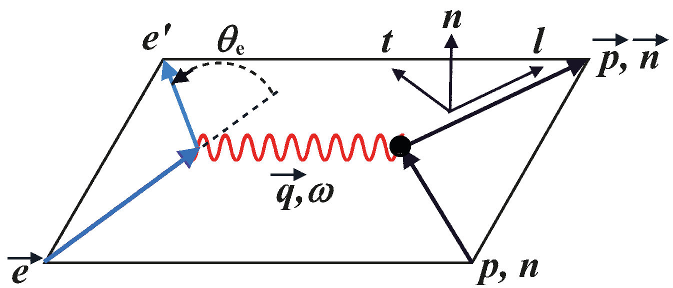
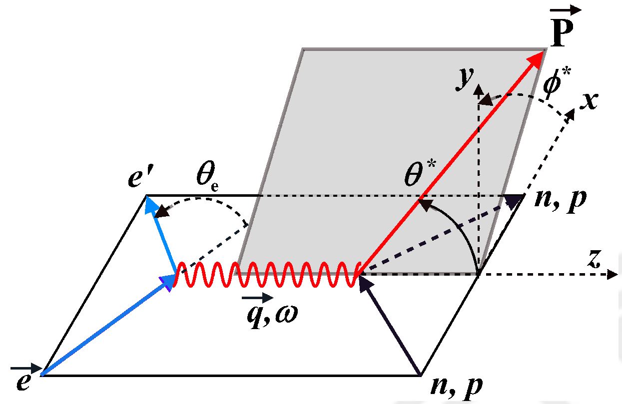


$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_{beam}+E_e)}{2M_B}\tan\frac{\theta_e}{2}$$

- Many systematical effects cancel when taking ratios😊.
- Higher sensitivity to G_E😊.

Polarised target:



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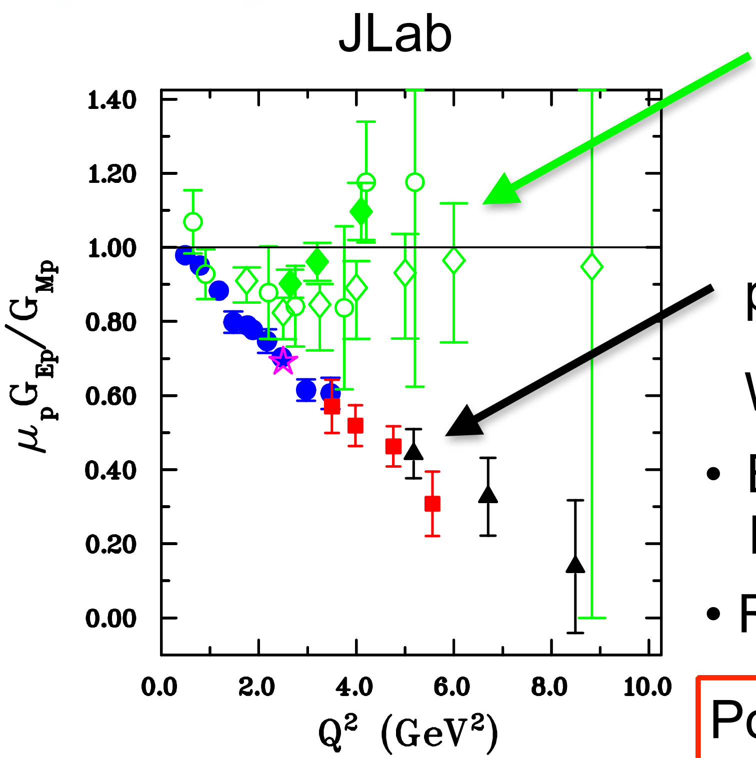
Proton EEMFF features



Why this difference?

- Effect from two-photon exchange? Polarisation expt's much less sensitive
- Radiation effects?

Points to a difference between charge and magnetisation distributions at short distances.

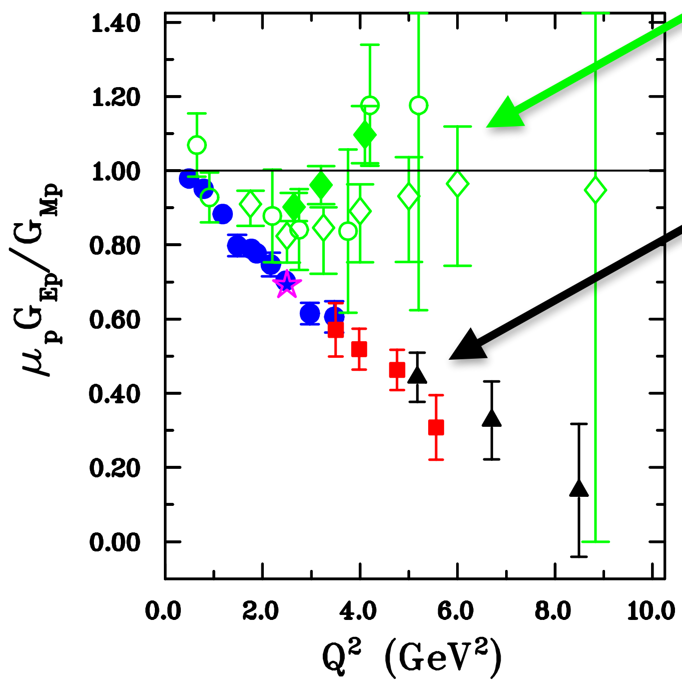
Measurement of the the elastic cross section ratio:

$$R = \frac{\sigma(e^+ p)}{\sigma(e^- p)}$$

may sort out the two-photon effect.

Proton EEMFF features

JLab



Rosenbluth separation

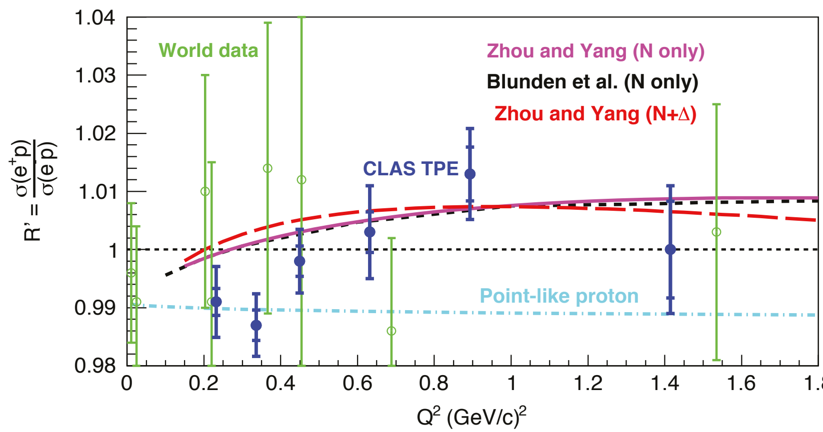
polarisation measurements

Why this difference?

- … e
- …

F … and
r … ances.

$$R' \approx 1 - \frac{2\delta_{2\gamma}}{(1+\delta_{even})}$$



PRL 114 (2015)

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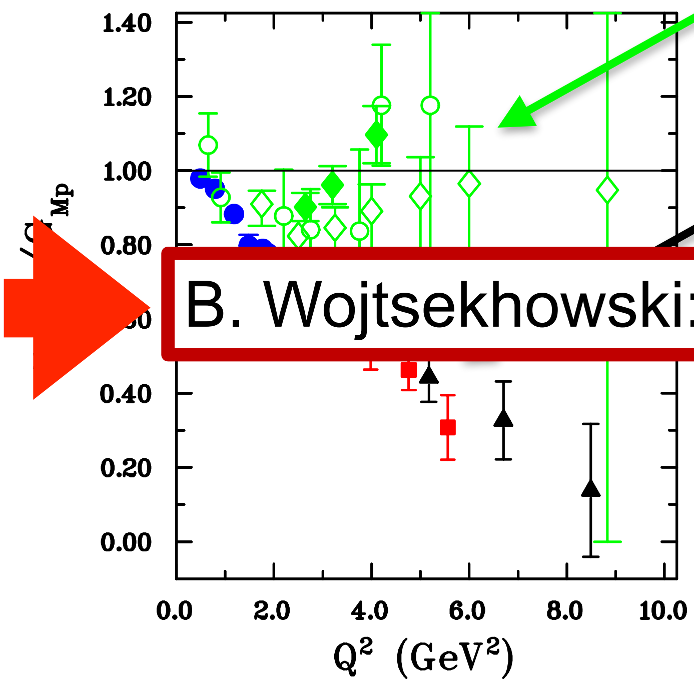
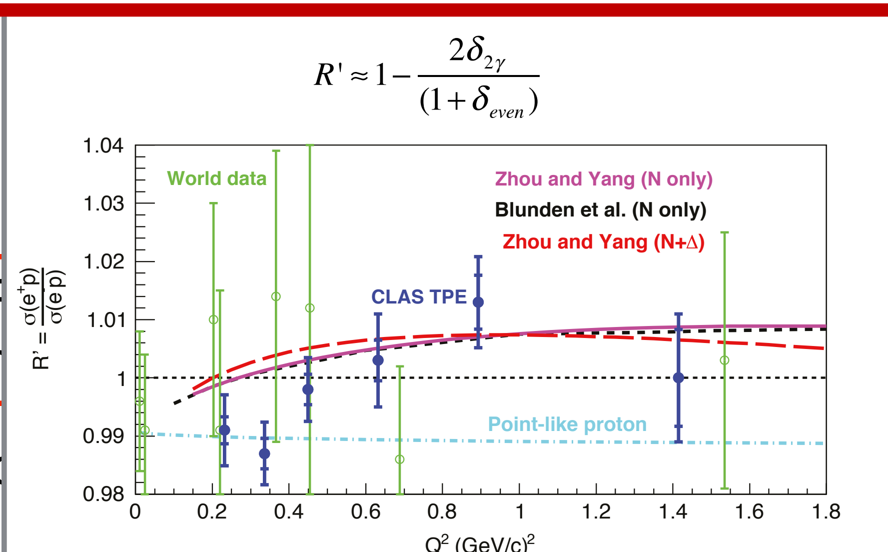


Rosenbluth separation

polarisation measurements

B. Wojtsekhowski: Form Factor measurements at JLab



PRL 114 (2015)

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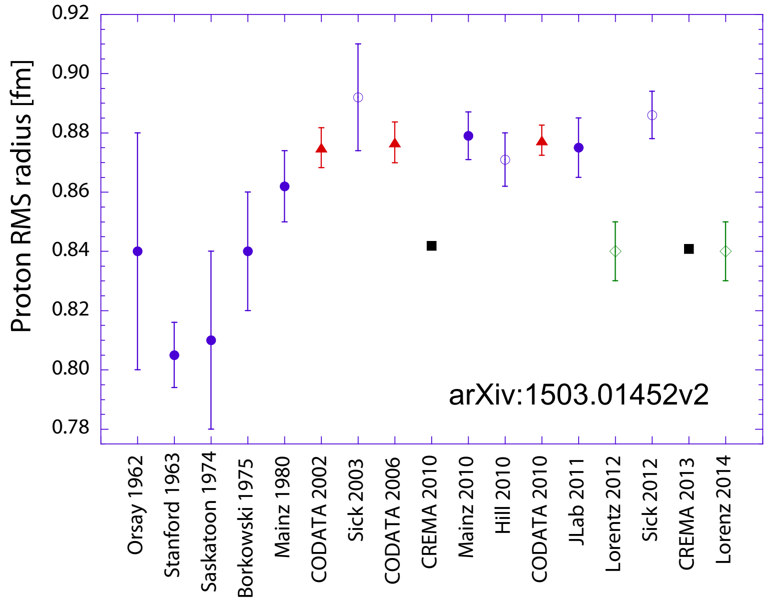
Proton EEMFF features

Non rel. : $$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left| \int_V \rho(\mathbf{r}) e^{i\mathbf{qr}}\, d\mathbf{r} \right|$$

$$G_{E_p} = 1 - \frac{Q^2}{6}\left\langle r_{E_p}^2 \right\rangle + \frac{Q^4}{120}\left\langle r_{E_p}^4 \right\rangle \cdots$$

Low Q^2: $$\frac{dG_{E_p}}{dQ^2} \cong -\frac{1^2}{6}\left\langle r_{E_p}^2 \right\rangle\Big|_{Q^2=0}$$

=> The proton RMS radius is obtained from the slope



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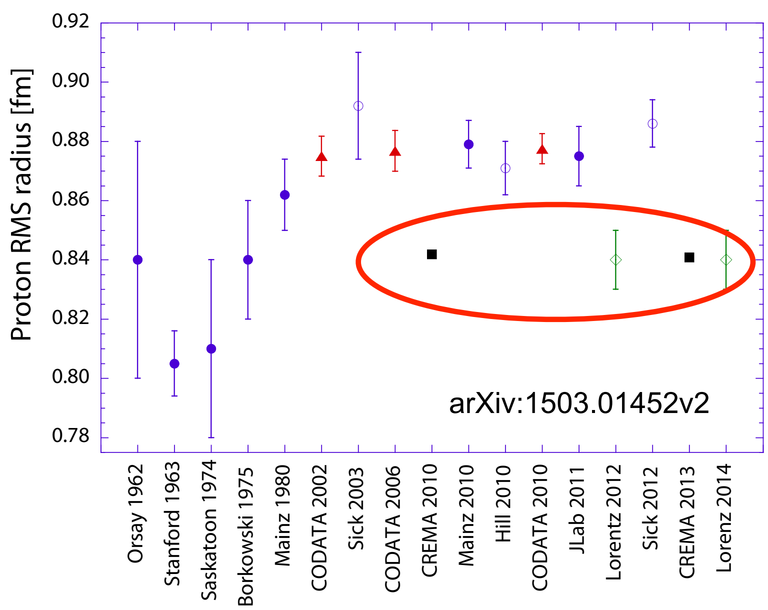

=>=> muonic hydrogen measurements at PSI give a 4% (7σ) smaller proton RMS radius.

!!??

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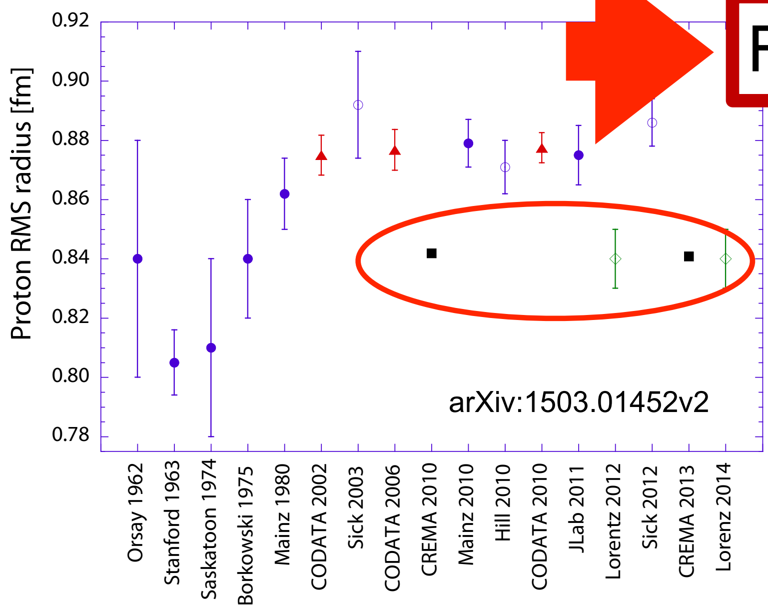


Friday morning session

=>=> muonic hydrogen measurements at PSI give a 4% (7σ) smaller proton RMS radius.

!!??

Neutron SL EEMFF

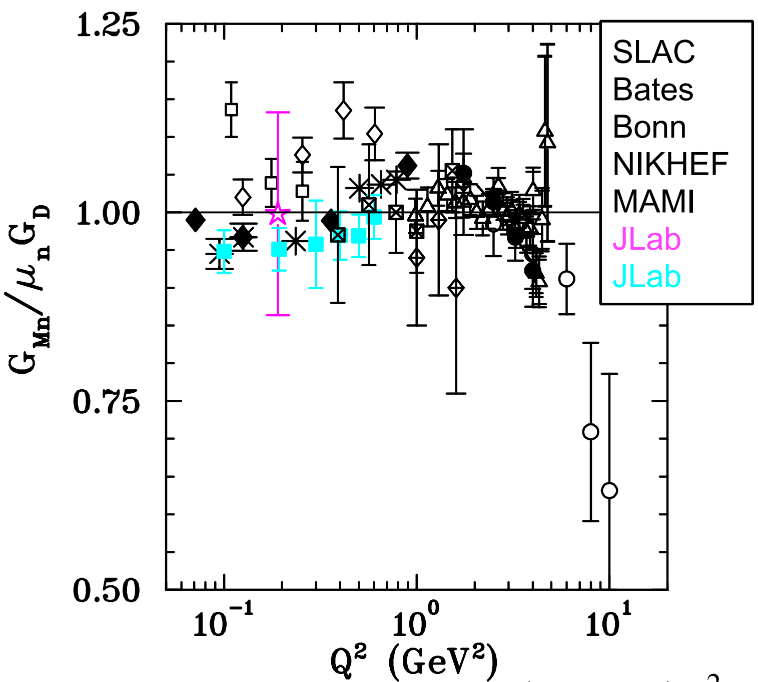
G_{En}: Earlier extracted from elastic (e^-,*d*) scattering.
Now polarisation measurements.

The slope as $Q^2 \rightarrow 0$ determines, in principle, $\langle r_{E_n}^2 \rangle$
(n,e^-), however, more precise (-.1161±.0022 fm^2) (PDG)

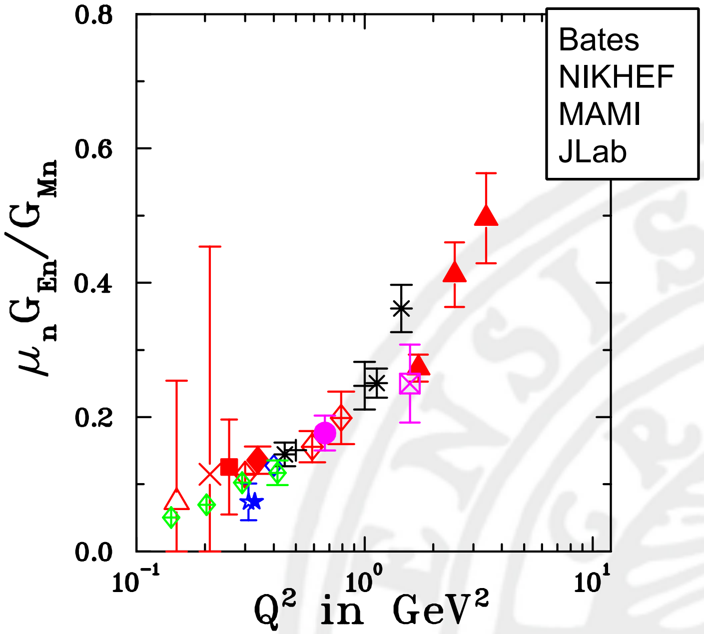
G_{Mn}: Earlier Rosenbluth separation from quasi-free (e^-,*n*) scattering on deuterons. Requires large corrections.
Now polarisation measurements.

Polarisation measurements use recoil polarisation and double polarisation measurements deuteron and ^{3}He targets.

Neutron SL EEMFF



Polarisation expt's



Agrees with $G_D = \left(1 + \frac{Q^2}{.71}\right)^{-2}$

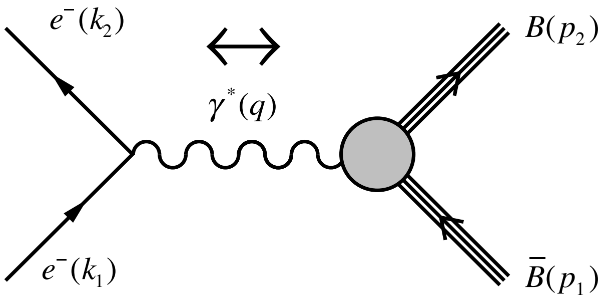
=> similarity between G_{Mn} and G_{Mp}

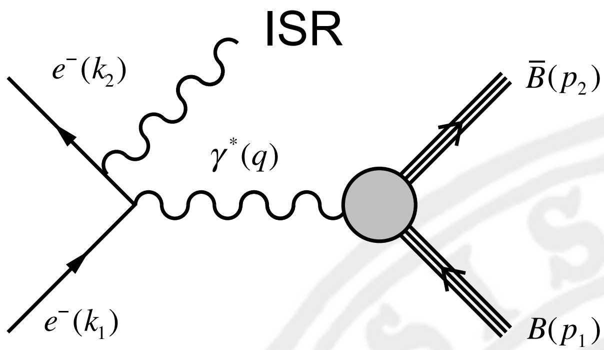
$G_{En} \neq G_{Ep}$

arXiv:1503.01452v2

Time-Like FF's

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





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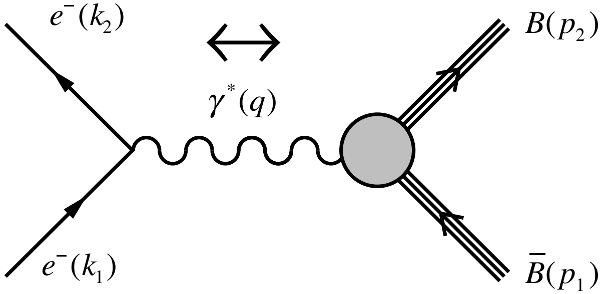
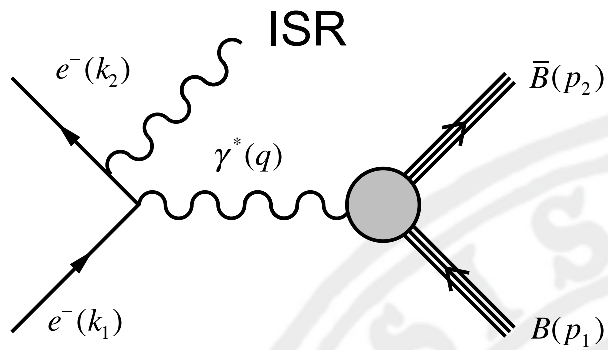
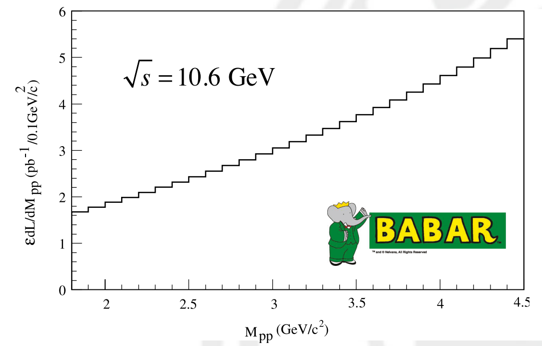






Non-zero momentum of final state particles at threshold.

Time-Like Form Factors

- Time-like FF's are complex:

$$\mathrm{Re}\left[G_E(q^2)G_M^*(q^2)\right] = \left|G_E(q^2)\right|\left|G_M(q^2)\right|\cos\Delta\phi$$

$$\mathrm{Im}\left[G_E(q^2)G_M^*(q^2)\right] = \left|G_E(q^2)\right|\left|G_M(q^2)\right|\sin\Delta\phi$$

$\Delta\phi$ = the relative phase between G_E and G_M.

=> Three observables determine the Time-Like Form Factors.

- The relative phase between G_E and G_M gives polarisation effects on the final state even when the initial state is unpolarised.

Time-Like Elastic FF can be extracted from the differential cross sections in analogy with the Rosenbluth technique.

$$\frac{d\sigma}{d\cos\theta} = \frac{\alpha^2 \beta C}{4q^2}\left(|G_M|^2\left(1+\cos^2\theta\right)+\frac{1}{\tau}|G_E|^2\sin^2\theta\right);$$

$$\tau = \frac{q^2}{4m_B^2},\ \beta = \sqrt{1-1/\tau},\ C = \text{Coulomb factor} = \text{y/(1-e}^{-y}\text{)}, y = \pi\alpha/\beta$$

A measurement of the differential cross section at one energy is sufficient to extract the modulii of $|G_E|$ and $|G_M|$ 😊.

The total cross section gives access to effective form factor:

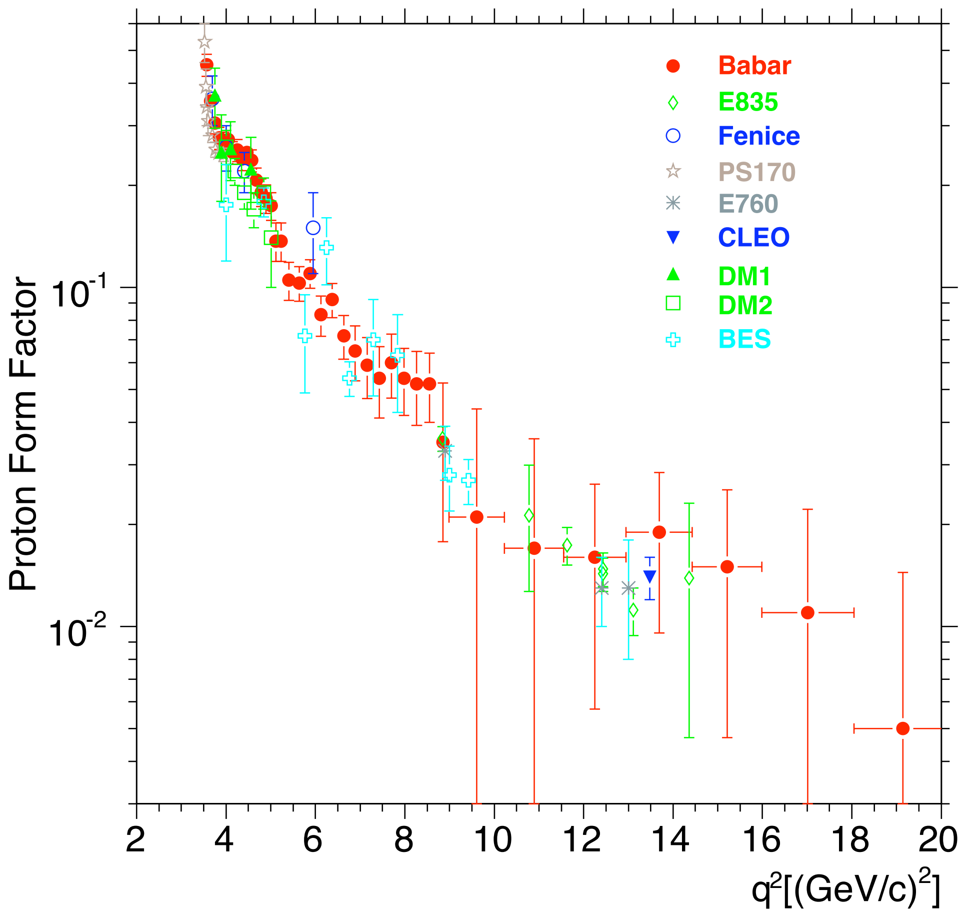
$$\sigma_{tot} = \frac{4\pi\alpha^2\beta C}{3q^2}\left[|G_M|^2 + \frac{|G_E|^2}{2\tau}\right] \Leftrightarrow |G_{eff}| = \left(\frac{\sigma_{tot}}{4\pi\alpha^2\beta C/3q^2}\right)^{\frac{1}{2}}$$

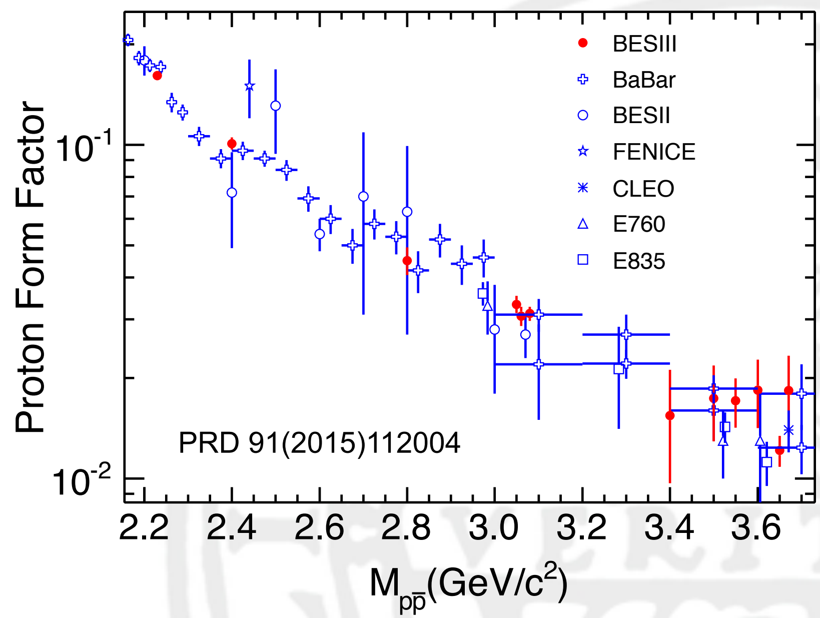
At threshold: τ = 1 and $|G_E| = |G_M|$,

The Coulomb factor leads to a non-zero cross section for a charged final state.

• Most experiments in the TL region only provide G_{eff}.

• The q^2 dependence is obtained from energy scan or by using initial state radiation (ISR):





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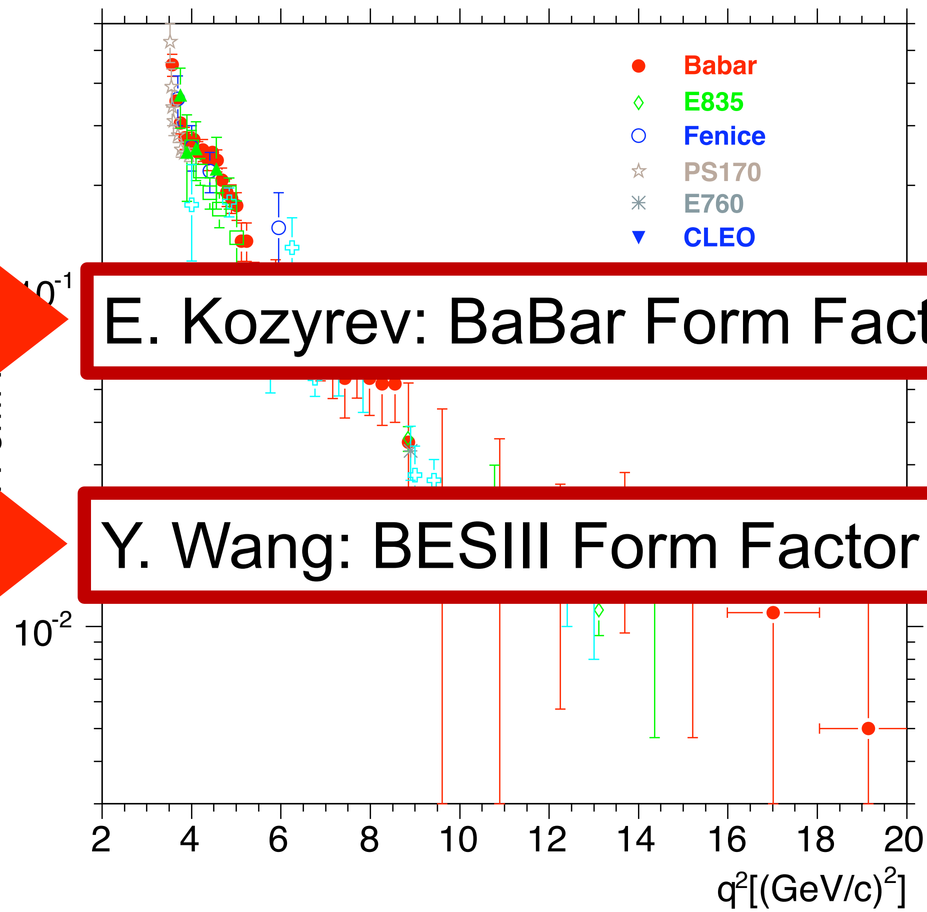
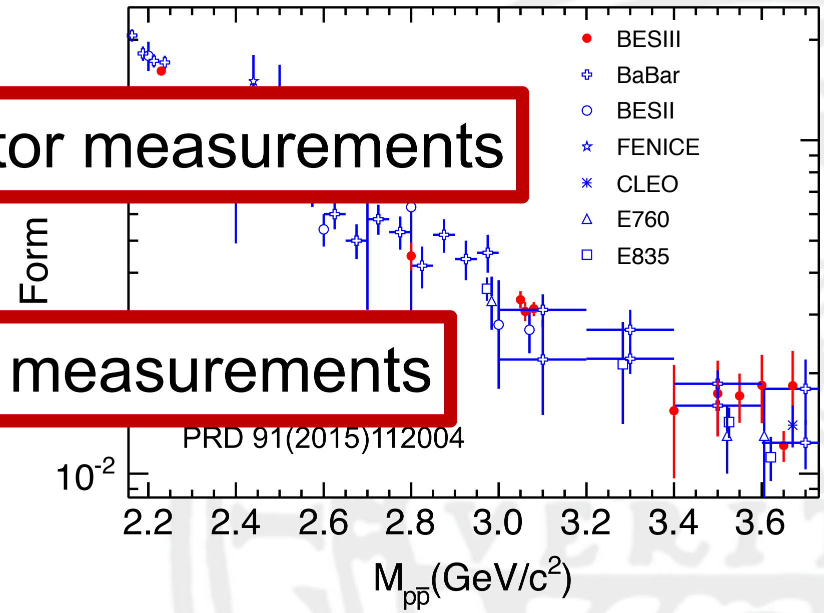


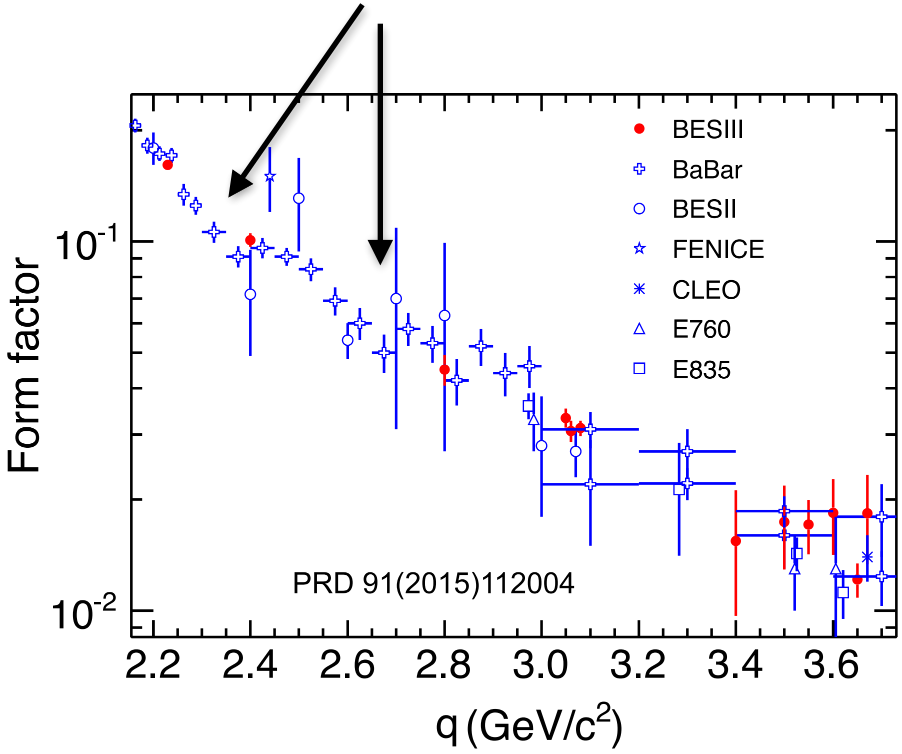


E. Kozyrev: BaBar Form Factor measurements

Y. Wang: BESIII Form Factor measurements

Proton TL EMFF features

Different slopes. Structure?



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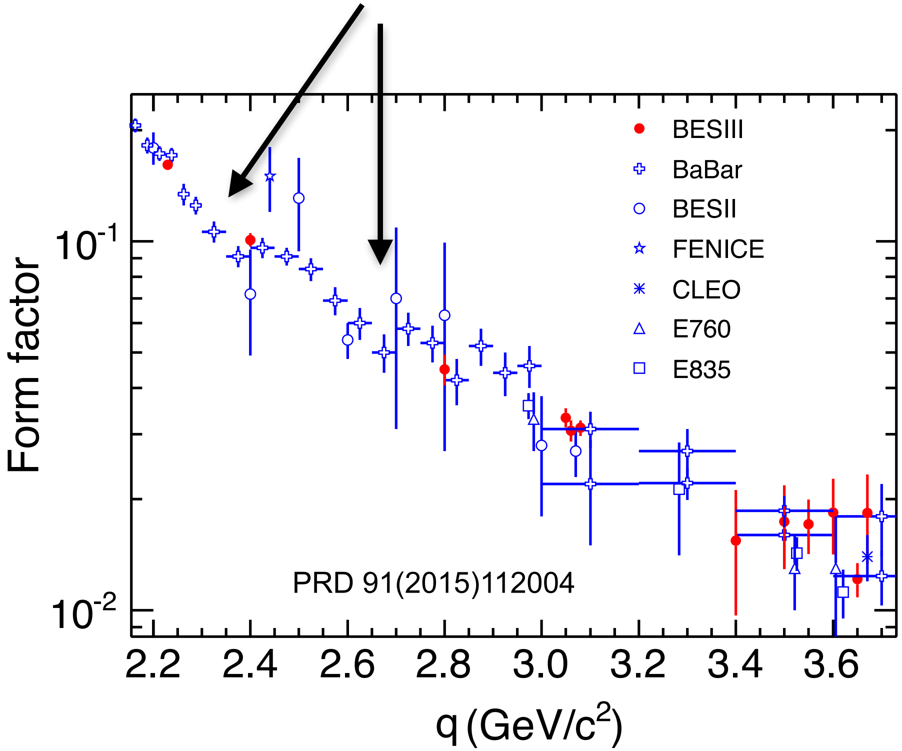

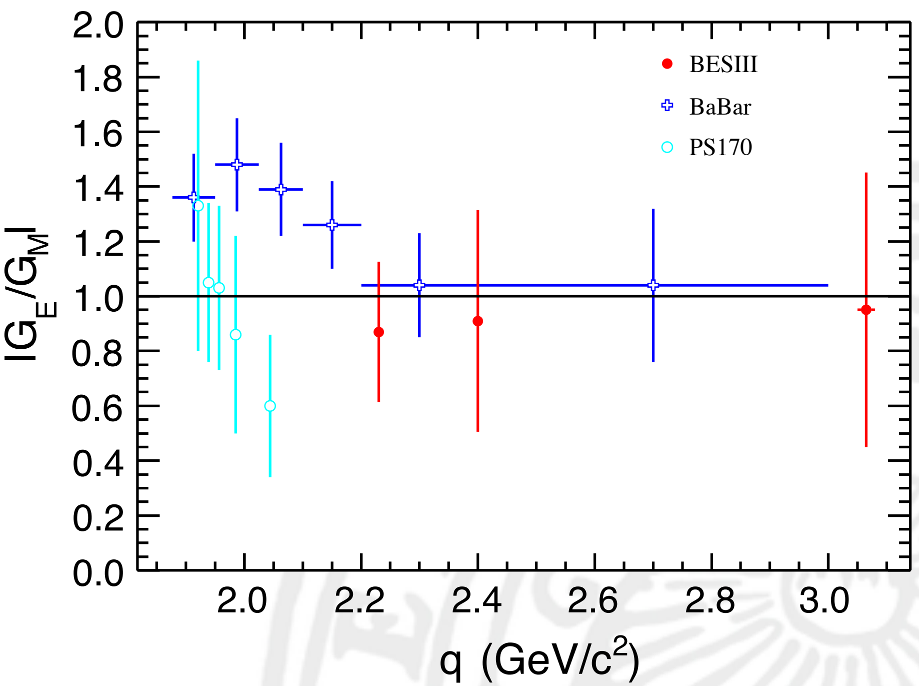

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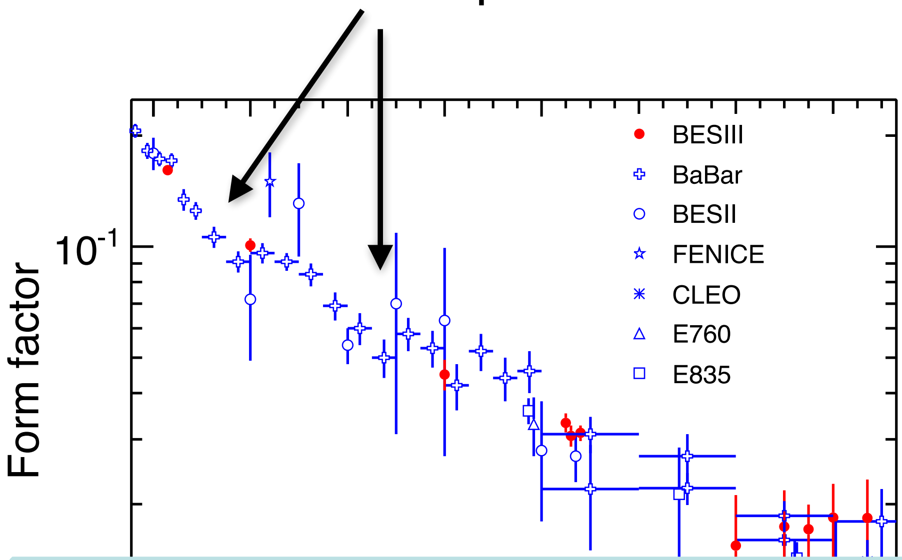

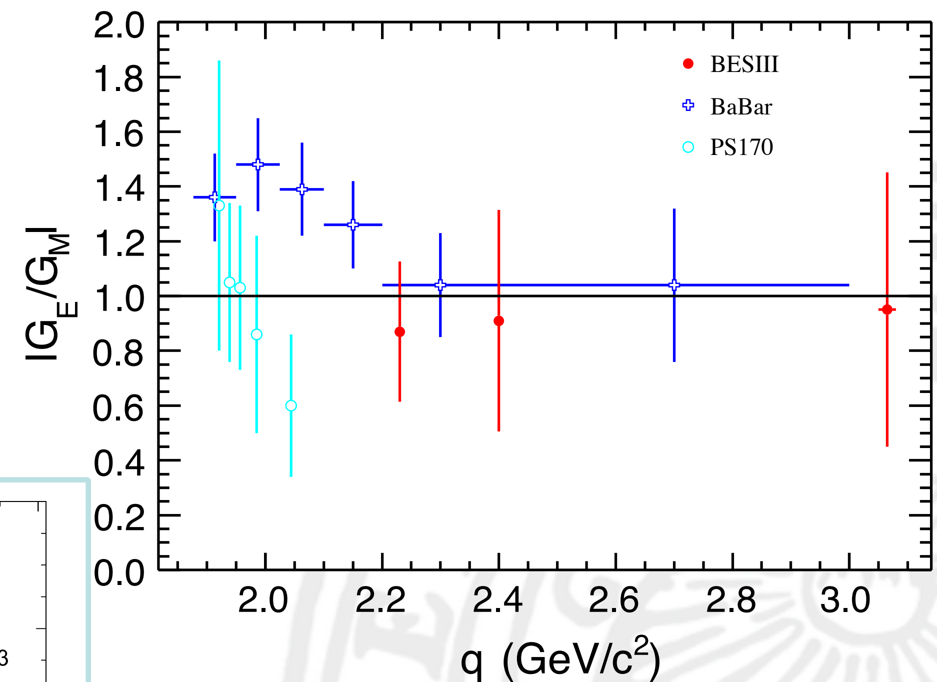

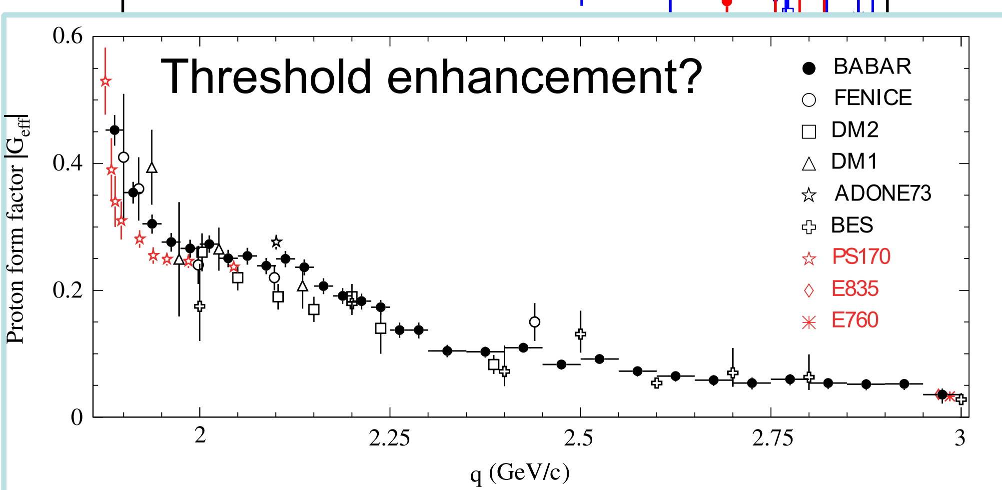

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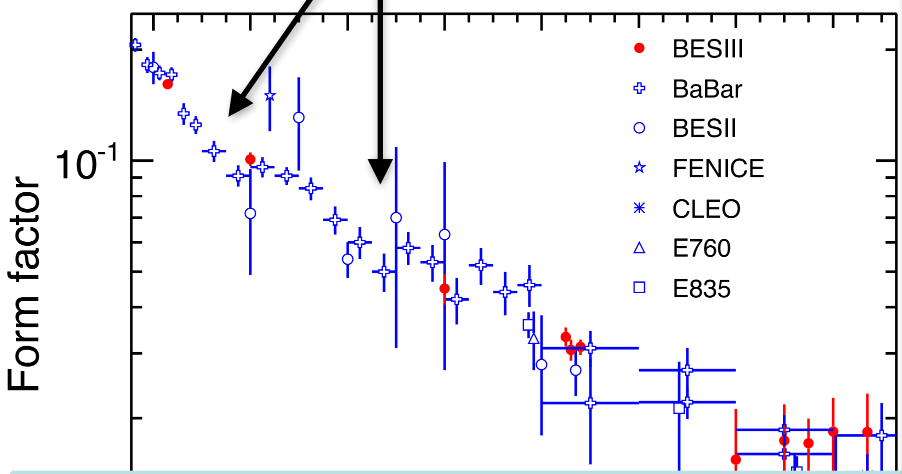
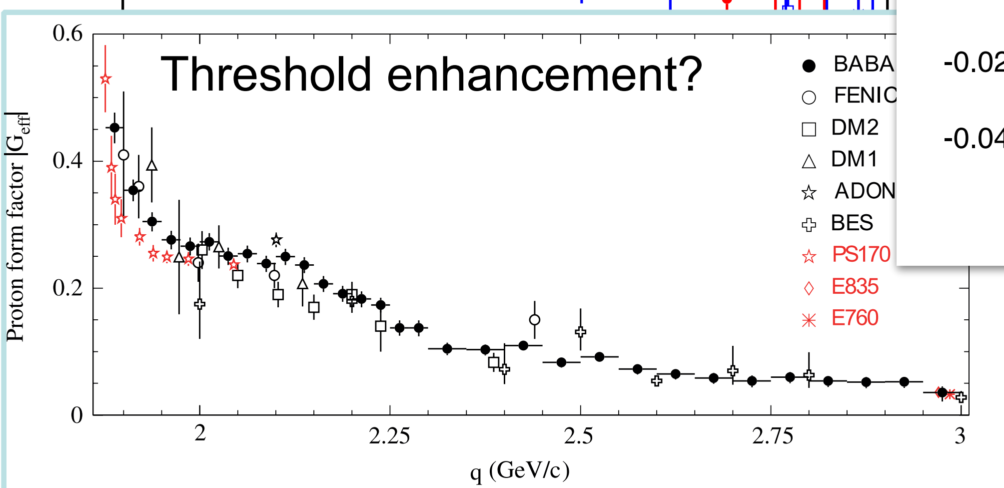
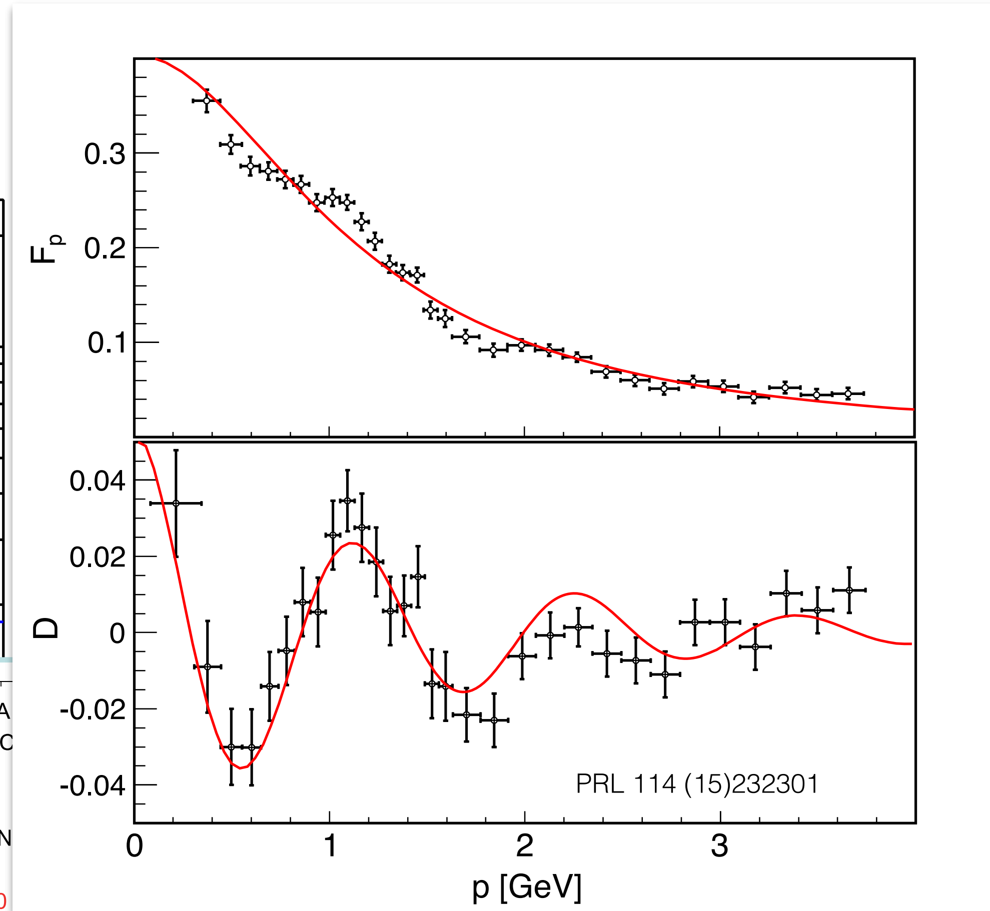


Threshold enhancement?





Proton EMFF features

pQCD predicts that asymptotically

$$F_i^B(q^2) \to \left(\frac{1}{q^2}\right)^{i+1} \left(\ln\left(\frac{q^2}{\Lambda_{qcd}^2}\right)\right)^{\gamma}$$

$$i = 1,2;\ \gamma = 2.148\ (N_f = 2)$$

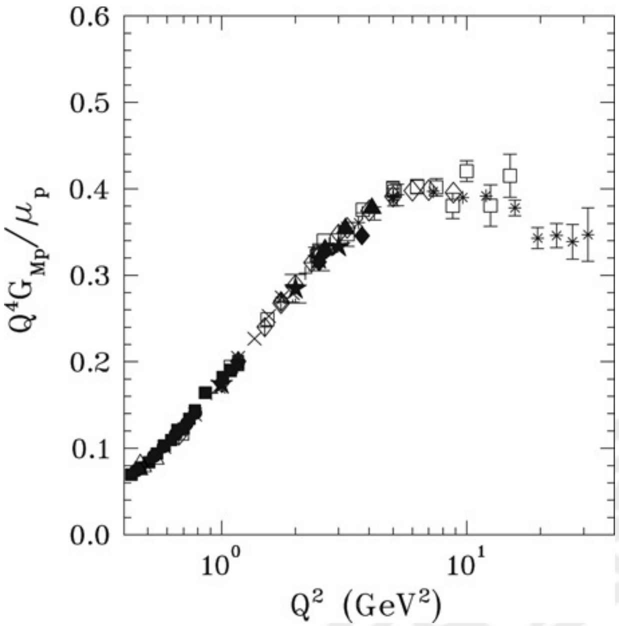
$$\Rightarrow\ G_E, G_M \propto \frac{1}{q^4} \text{ and } \frac{G_E}{G_m} \sim 1$$

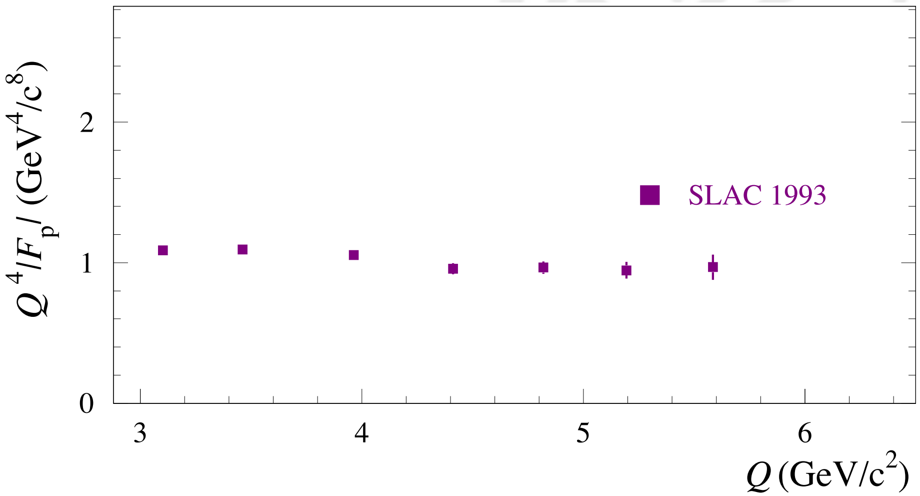
PRL 31(73)1153
Nuov. Cim. L. 7(73)719

Analyticity:

$$G_{E,M}^{SL}\Big|_{q^2 \to -\infty} = G_{E,M}^{TL}\Big|_{q^2 \to \infty}$$

pQCD scaling observed
at Q > 3 GeV/c^2?





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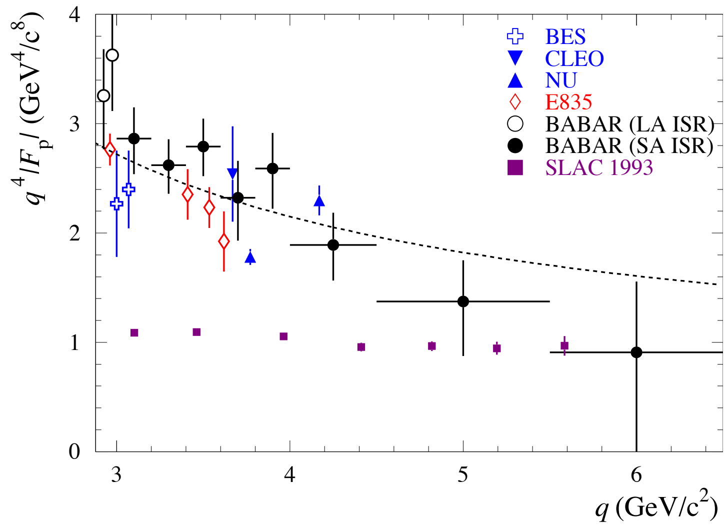
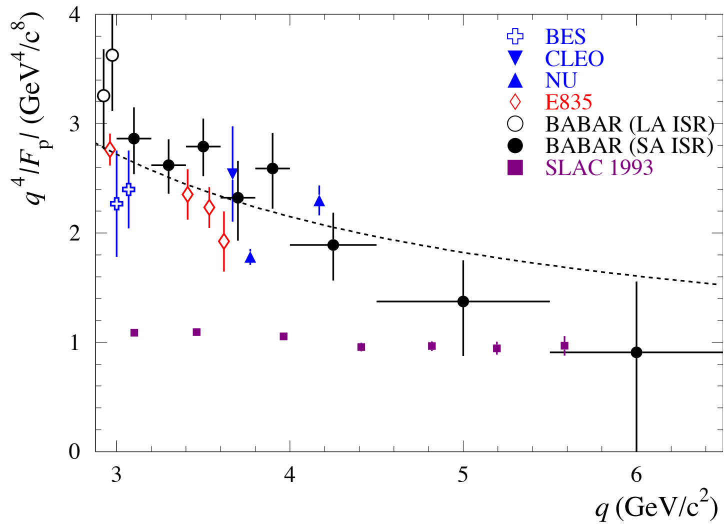


pQCD region reached at $Q \approx 6$ Gev/c^2?

arXiv:1311.751v1

Proton EMFF features



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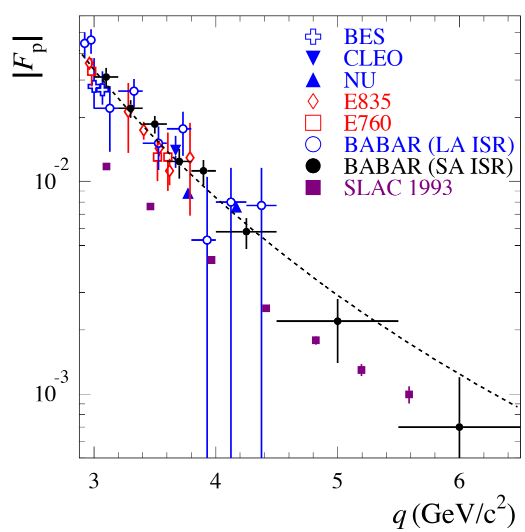
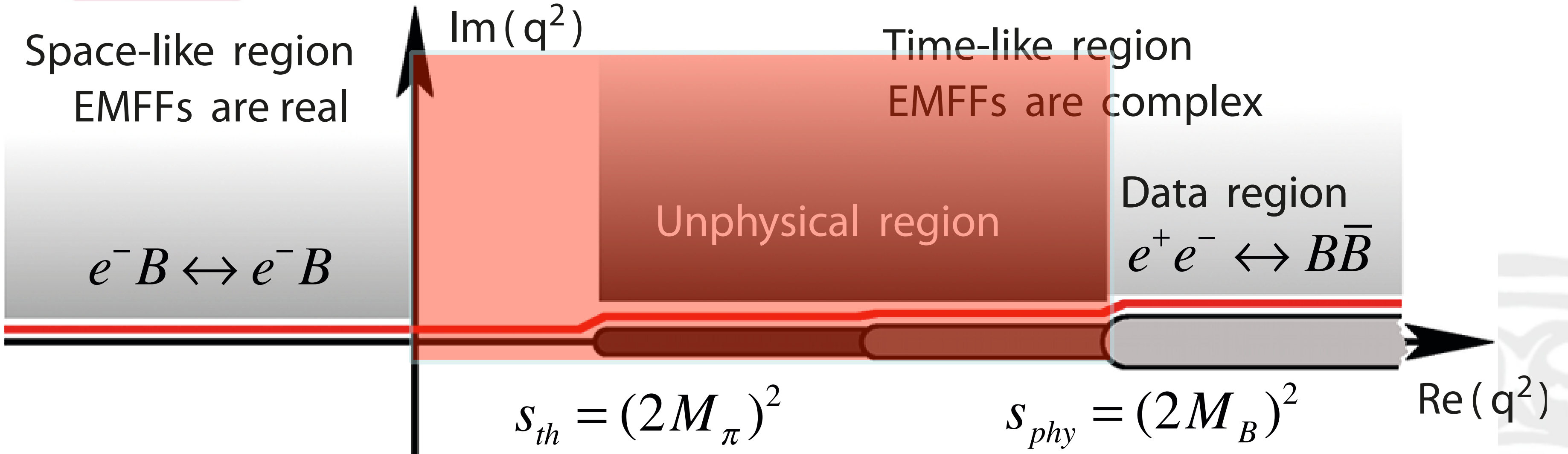


TL $|F_p|$ = 2x SL $|F_p|$!?

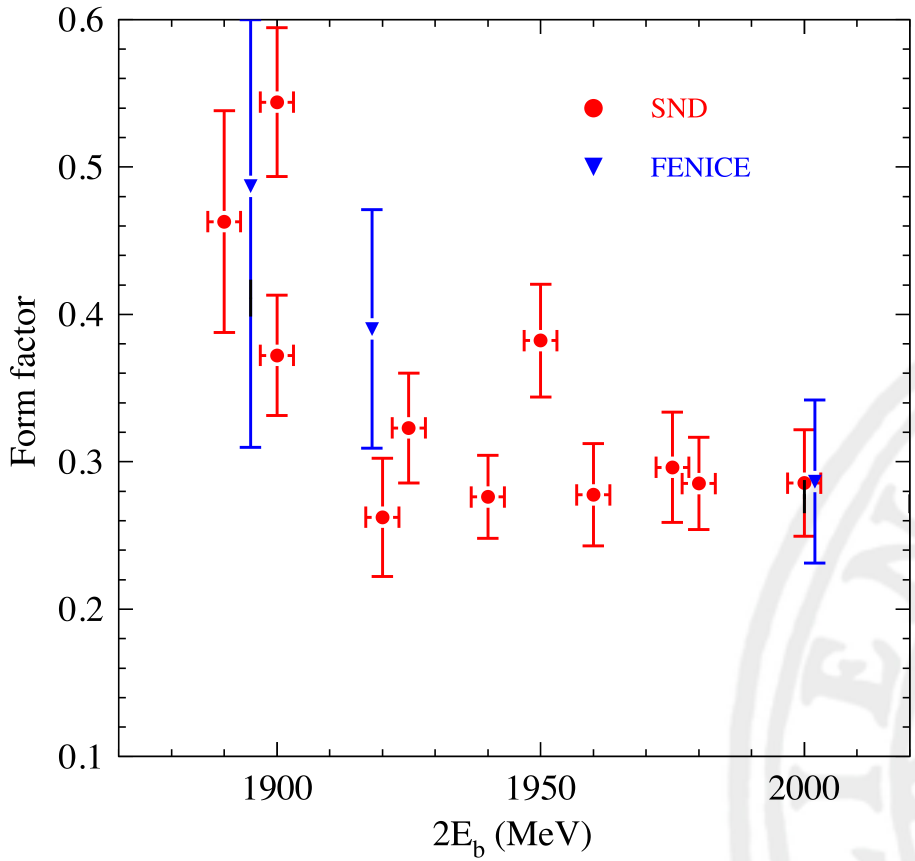
Time-Like FF features



Access to the unphysical region via $\bar{p}p \to e^+ e^- \pi^0$?

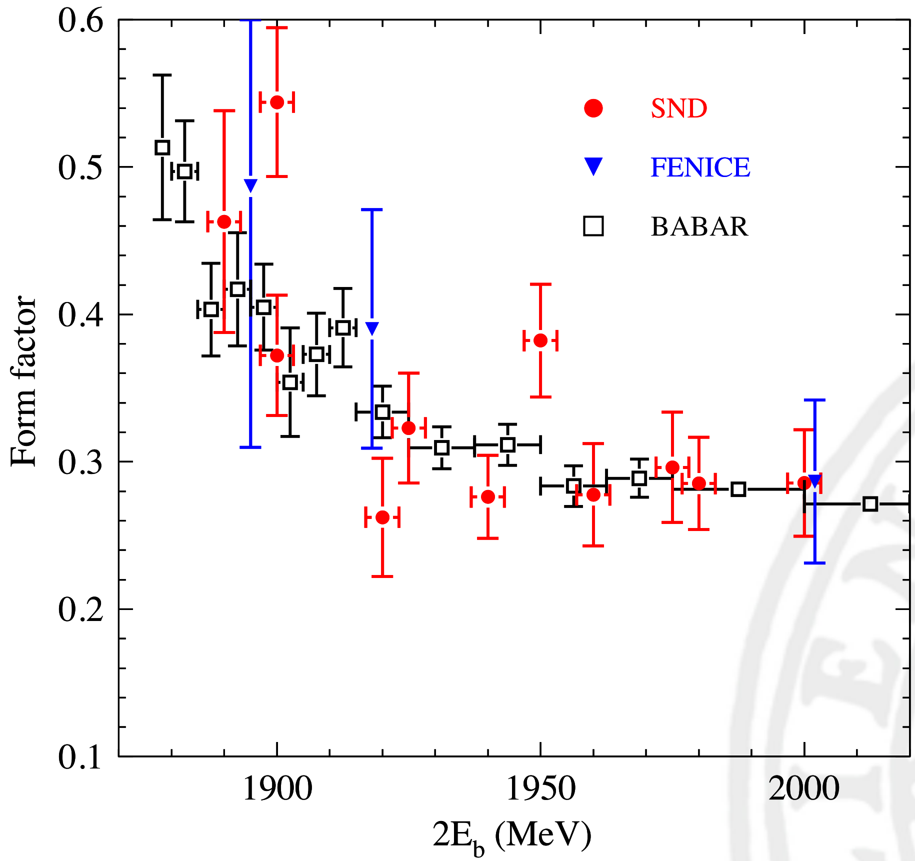
C. Adamuscin et al., PRC 75(07) 045205
E.A. Kuraev er al., PLB 649 (07) 400.

Scarse data on neutron TL FF:



PRD 90 (14) 112007

Scarse data on neutron TL FF:



PRD 90 (14) 112007

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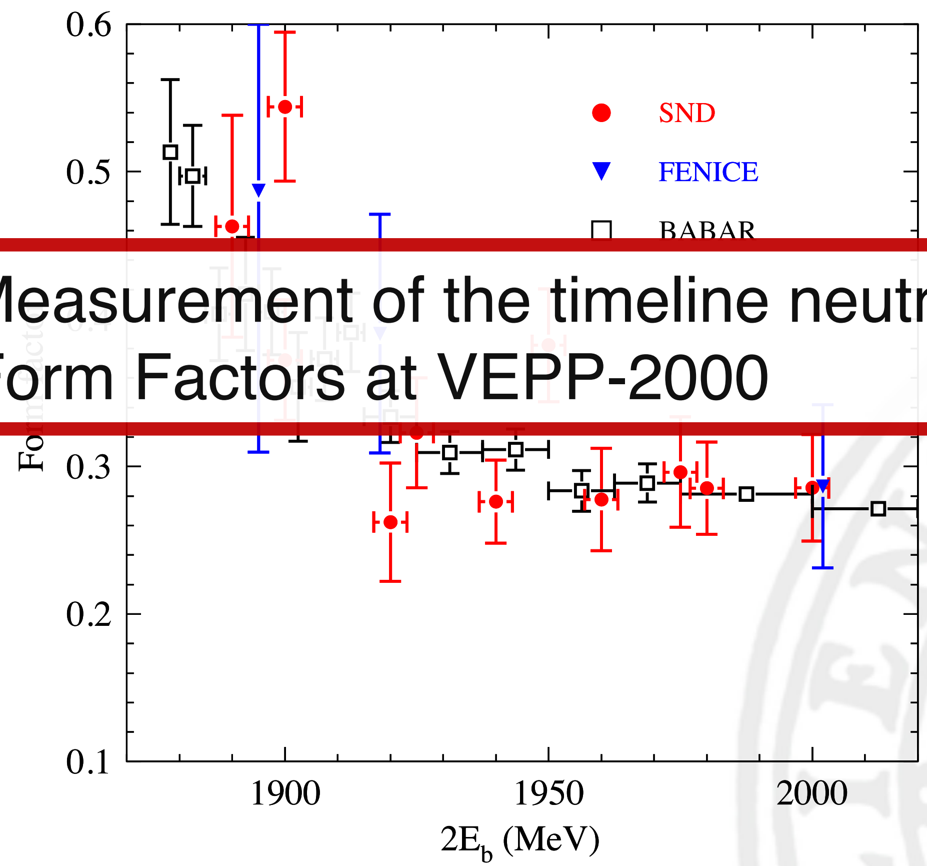


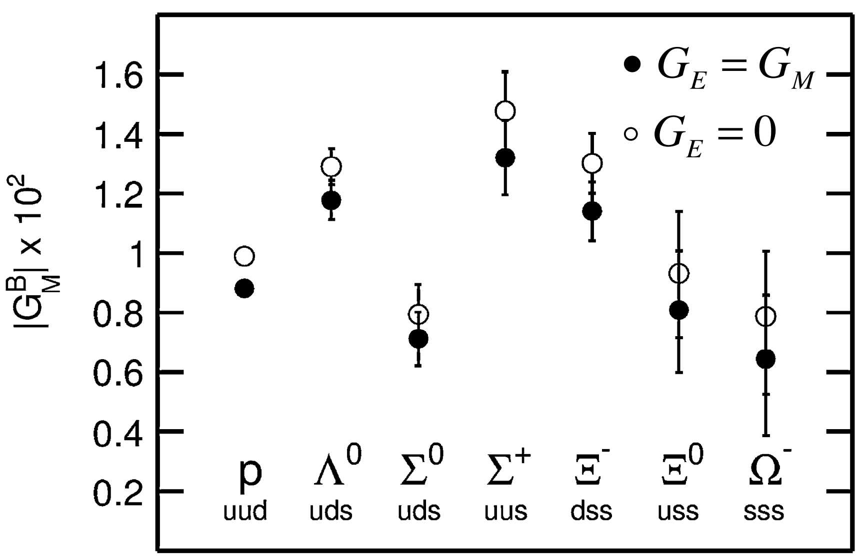
A. Korol: Measurement of the timeline neutron and proton Form Factors at VEPP-2000

PRD 90 (14) 112007

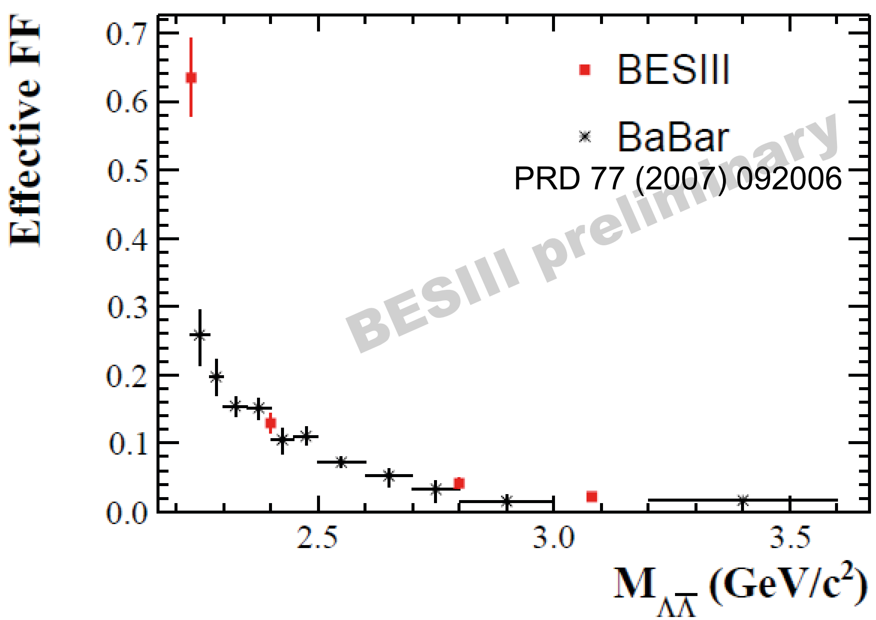
Hyperon Form Factors

- What happens when adding strangeness to the baryons? SU(3) breaking?
- Only Time-Like Form Factors are experimentally accessible.
- e^+e^--collisions are currently the best way to study hyperon structure.

CLEO-C @ 3.77 GeV



PLB 739 (2014) 90



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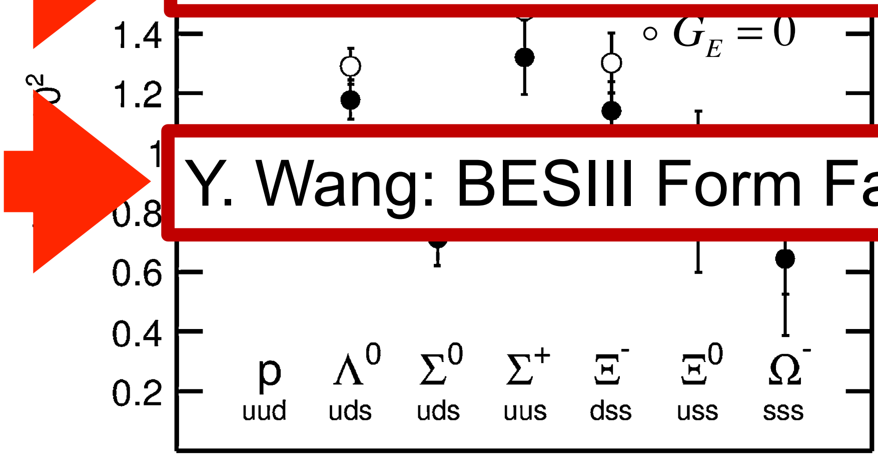
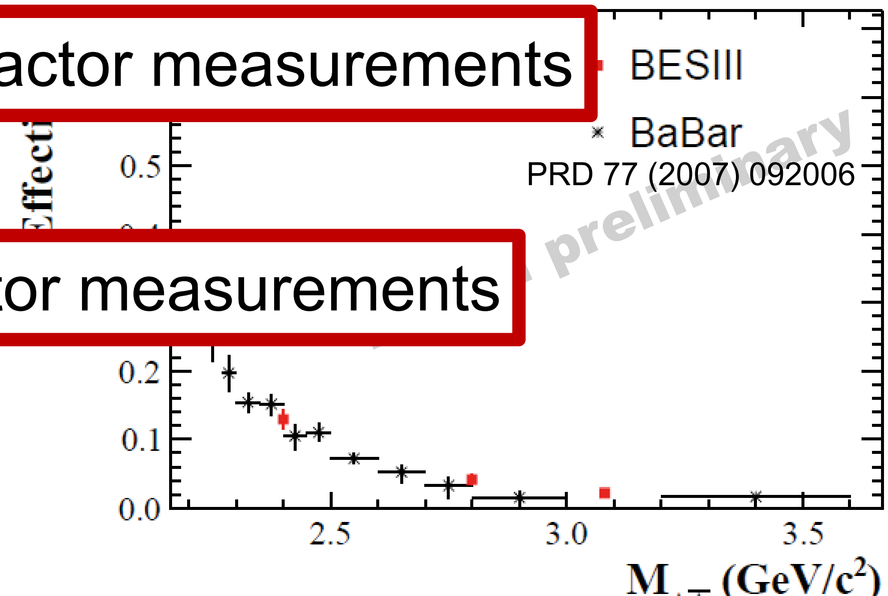
E. Kozyrev: BaBar Form Factor measurements

Y. Wang: BESIII Form Factor measurements

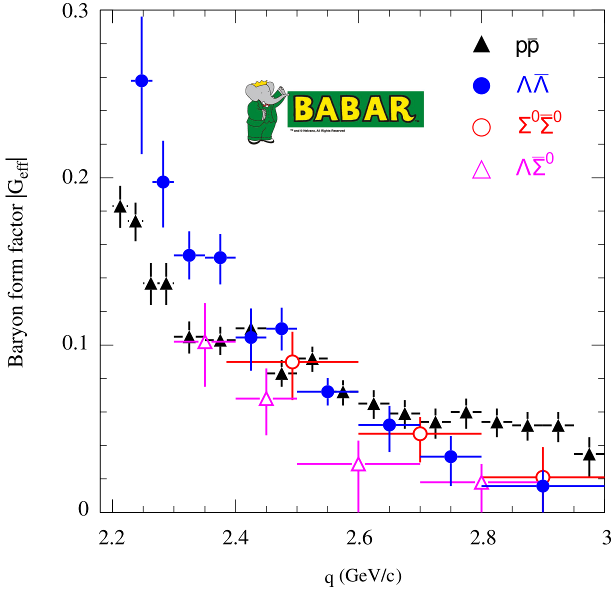


PLB 739 (2014) 90

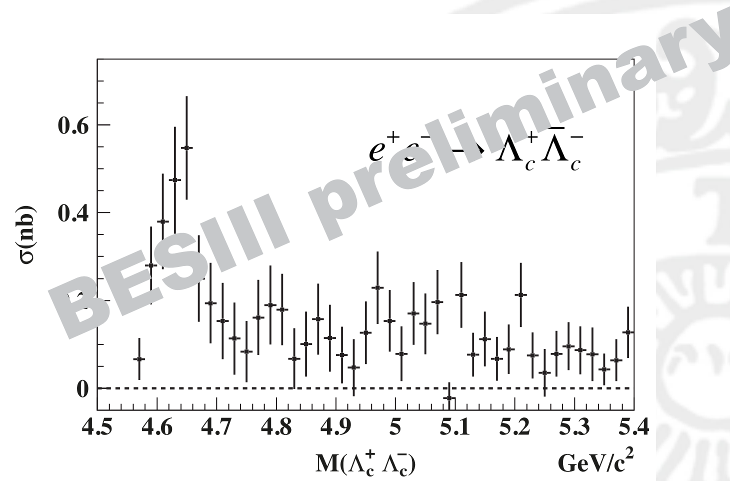


Time-Like FF features

Threshold enhancements?



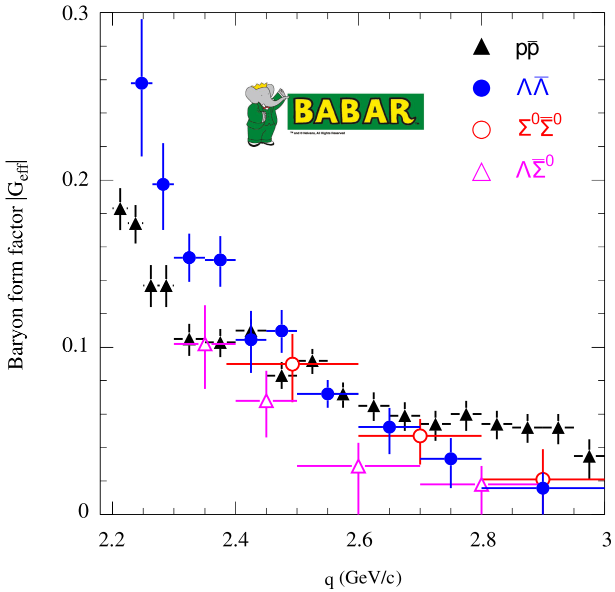
PRD 91(15)112004



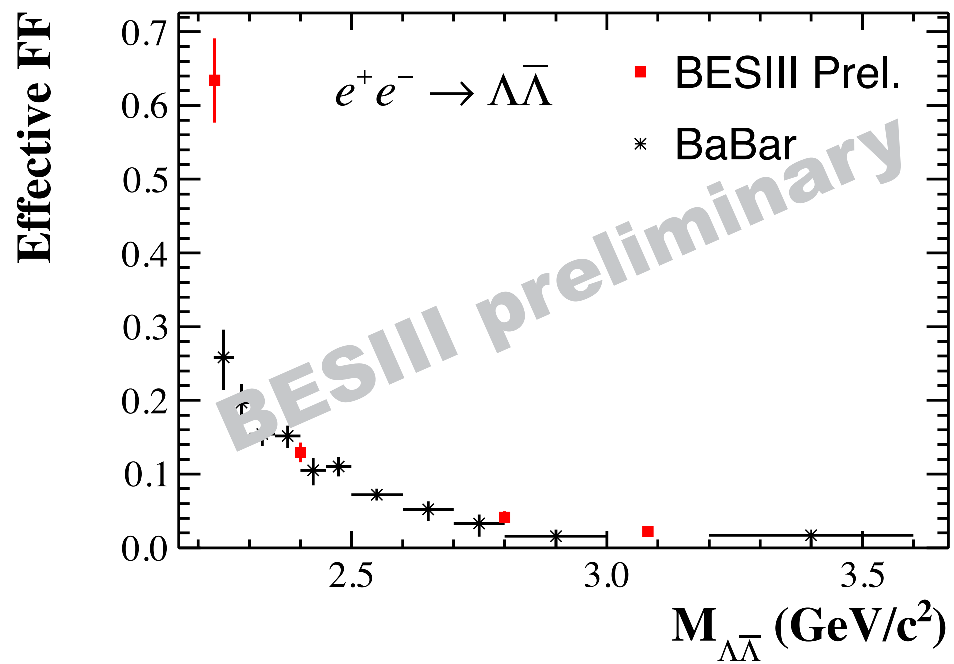
BELLE PRL 101(08)172001

Time-Like FF features

Threshold enhancements?



PRD 91(15)112004



Time-Like FF features

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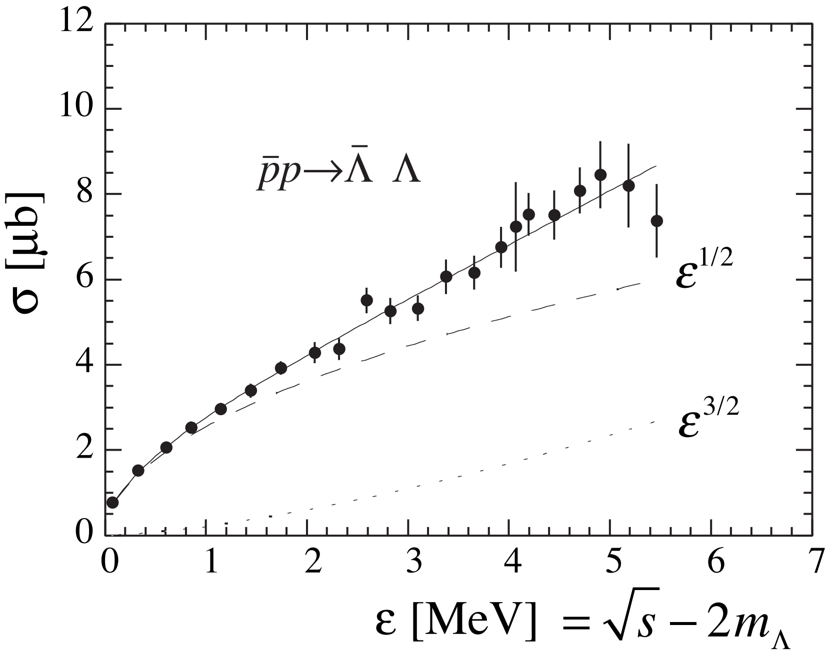
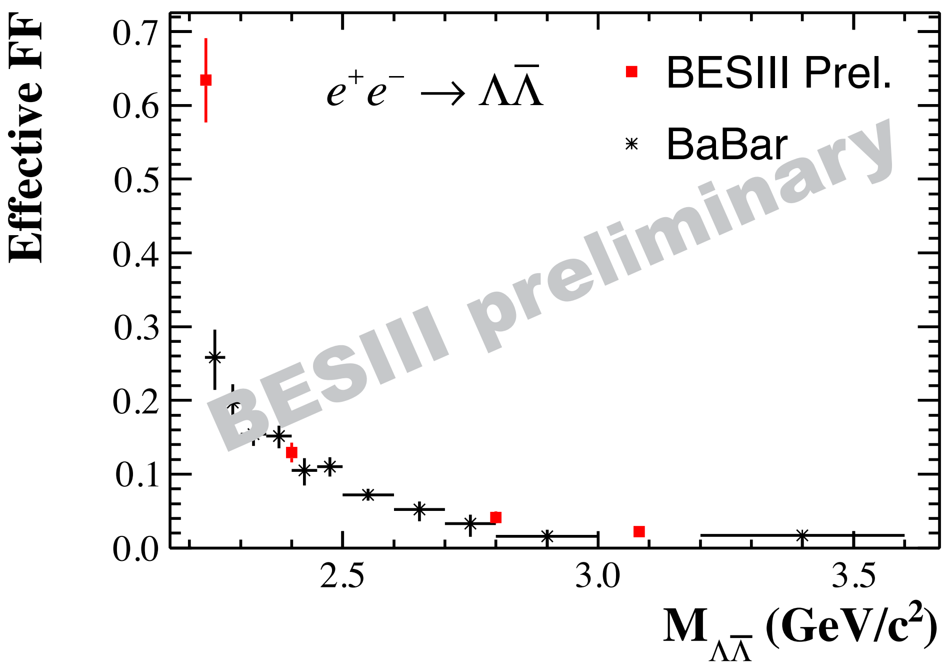


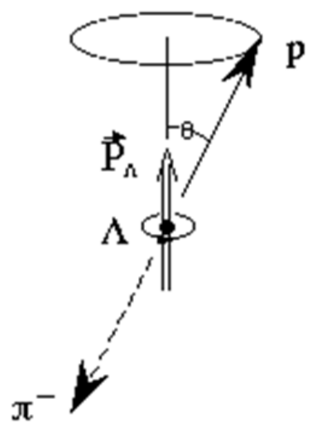
PRD 91(15)112004



Time-Like FF features

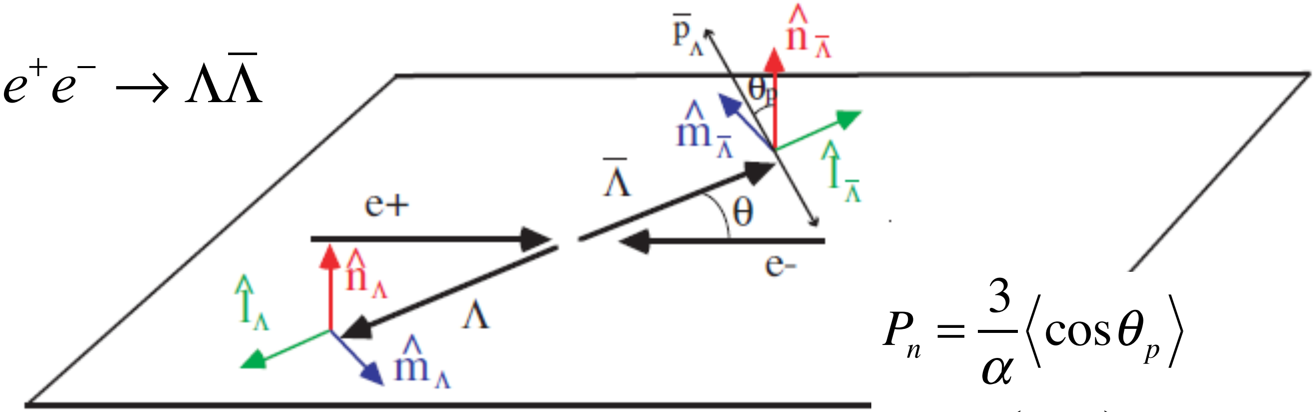
Need to measure polarisation to extract the phase between G_E and G_M.

Polarisation is available "for free" in hyperon TL FF's experiments because of their self-analysing weak decay.



$$\frac{dN}{d\cos\theta_p} \propto 1 + \alpha_\Lambda P_n \cos\theta_p$$

$$e^+e^- \to \Lambda\bar{\Lambda}$$



$$P_n = \frac{3}{\alpha}\left\langle \cos\theta_p \right\rangle$$

$$C_{lm} = \left(\frac{9}{\alpha\bar{\alpha}}\right)\left\langle \cos\theta_{pl} \cos\theta_{\bar{p}m} \right\rangle$$

$$P_n = -\frac{\sin 2\theta \,\mathrm{Im}\left[G_E G_M^*\right]/\sqrt{\tau}}{\left(|G_E|^2 \sin 2\theta\right)/\tau + |G_M|^2\left(1+\cos^2\theta\right)} = -\frac{\sin 2\theta \sin\Delta\phi/\tau}{R\sin^2\theta + \left(1+\cos^2\theta\right)/R}; \quad R = \frac{|G_E|}{|G_M|}$$

=> gives modulus of the phase ϕ

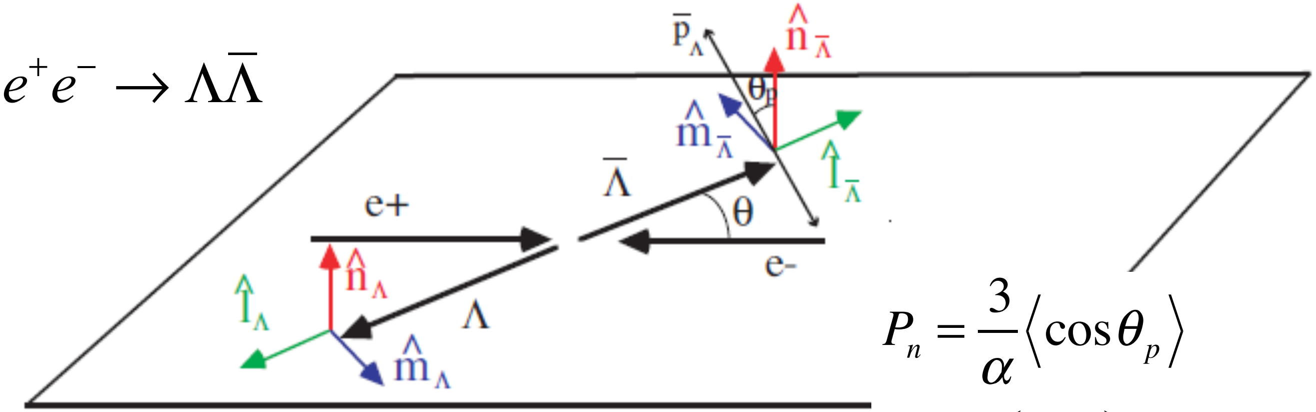
$$C_{lm} = -\frac{\sin 2\theta \,\mathrm{Re}\left[G_E G_M^*\right]/\sqrt{\tau}}{\left(|G_E|^2 \sin 2\theta\right)/\tau + |G_M|^2\left(1+\cos^2\theta\right)} = -\frac{\sin 2\theta \cos\Delta\phi/\tau}{R\sin^2\theta + \left(1+\cos^2\theta\right)/R}$$

Nuov. Cim. A109(96)241

=> gives the sign of the phase ϕ

A complete determination of the Λ Time-Like Form Factor using $e^+e^- \to \Lambda\bar{\Lambda}$ is possible!

$e^+e^- \to \Lambda\bar{\Lambda}$



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=> g m

Y. Wang: BESIII Form Factor measurements

$$C_{lm} = -\frac{\sin 2\theta \, \mathrm{Re}\left[G_E G_M^*\right]/\sqrt{\tau}}{\left(\left|G_E\right|^2 \sin 2\theta\right)/\tau + \left|G_M\right|^2\left(1+\cos^2\theta\right)} = -\frac{\sin 2\theta \cos\Delta\phi/\tau}{R\sin^2\theta + \left(1+\cos^2\theta\right)/R}$$

Nuov. Cim. A109(96)241

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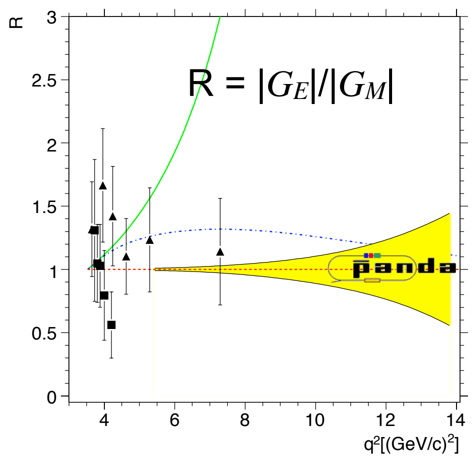
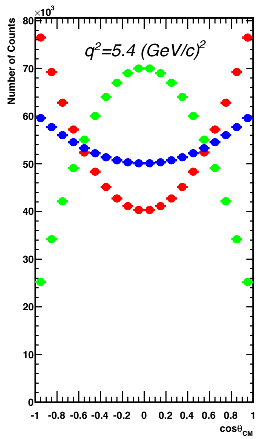
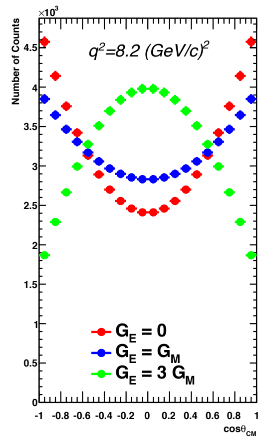
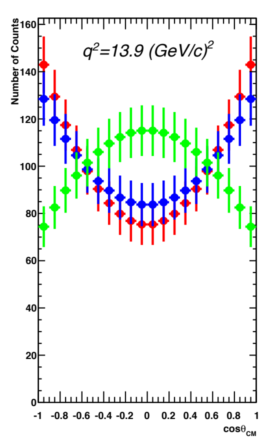
$\bar{p}p \rightarrow e^+e^-$

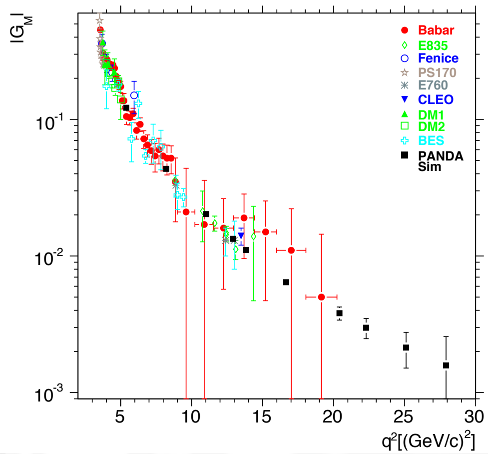
High luminosity mode: $2\text{x}10^{32}$ cm^{-2}s^{-1} → 100 fb^{-1} in ≈ 100 days



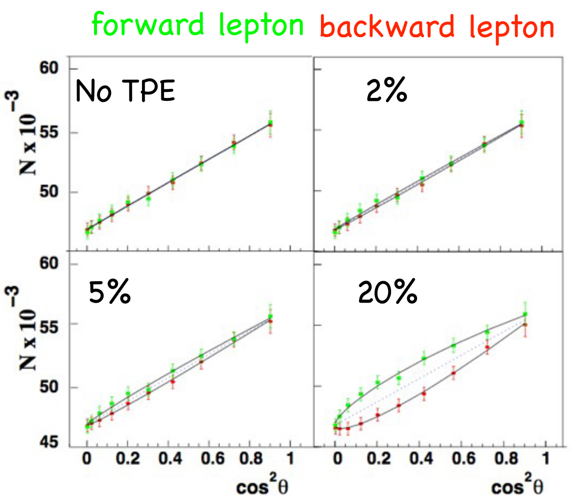








EPJ A44 (10) 373



- Individual determination of |G_E|, |G_M| up to q^2 ≈ 14 (GeV/c)^2
- |G_M| up to q^2 ≈ 28 (GeV/c)^2
- Sensitivity to odd cos-terms down to ≈ 5 %
  => two photon exchange can be investigated.

Long range: Polarised target to measure the phase.

Conclusions and Outlook

(non-exhaustive list)

A lot has been learned on baryon elastic EM Form Factors and there is much more to come.

SL: - Polarisation measurements are superior to Rosenbluth separation in determining Form Factors.

- New precise data at very low Q^2 will shed light on the proton radius puzzle.

- The importance of two-photon contributions will be clarified.

- Neutron FF's at higher q^2 .

TL: - New precise data at very low q^2 will shed light on threshold enhancements.

- First precise determination of $|G_E|$ and $|G_M|$ for the proton and the Λ.

- First measurement of the phase between of $|G_E|$ and $|G_M|$ is within reach via $e^+e^- \rightarrow \Lambda\bar{\Lambda}$.

SL+TL: Measure FF's at higher momentum transfers to investigate analyticity and the onset of pQCD. Flavour decomposition.

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Backup slide

A1

Jefferson Lab

BESIII

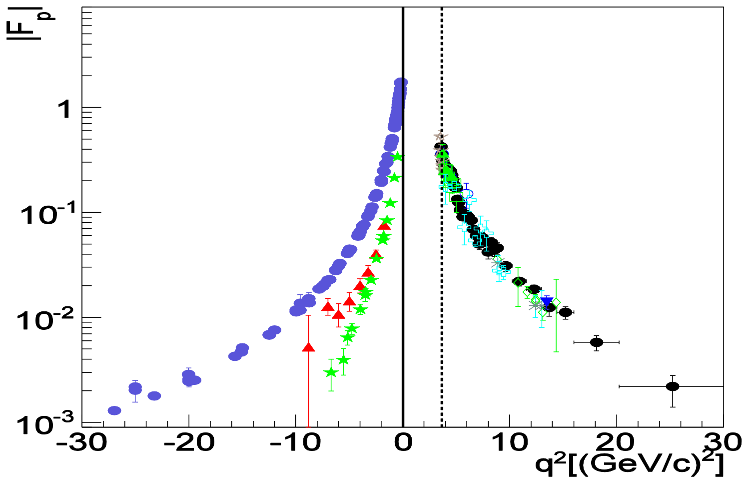
SND

CMD

panda

Wishes

An unified description
of baryon EM Form Factors.



Density distributions.