Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

An experimental overview of time like e.m. Baryon form factors

Monica Bertani
INFN, Laboratori Nazionali di Frascati

Wilhelm und Else Heraeus Stiftung

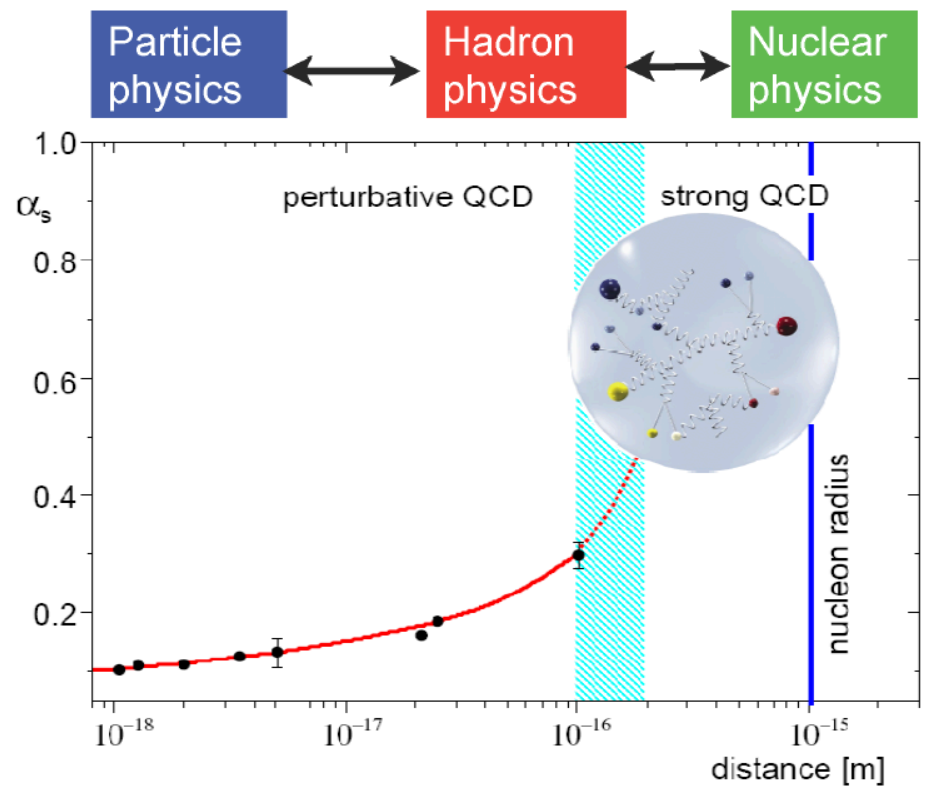
Physikzentrum Bad Honnef

668 WE-Heraeus-Seminar on Baryon Form Factors: Where do we stand?
23-27 April 2018

BARYON FORM FACTORS

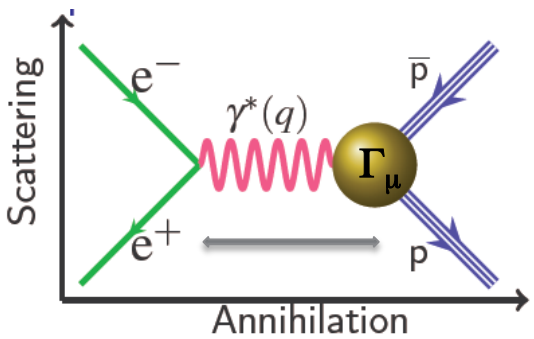
- Fundamental properties of Baryons
  - Characterize the internal structure
  - Connected to charge and magnetization distributions
  - Playground for **theory** and **experiment:**
    - at low q^2 probe the size of the hadron
    - at high q^2 test QCD scaling

By a global analysis of scattering and annihilation experiments Form Factors can be extracted



ELECTROMAGNETIC FORM FACTORS (FF)

- Spin ½ Baryons: two e.m. FFs

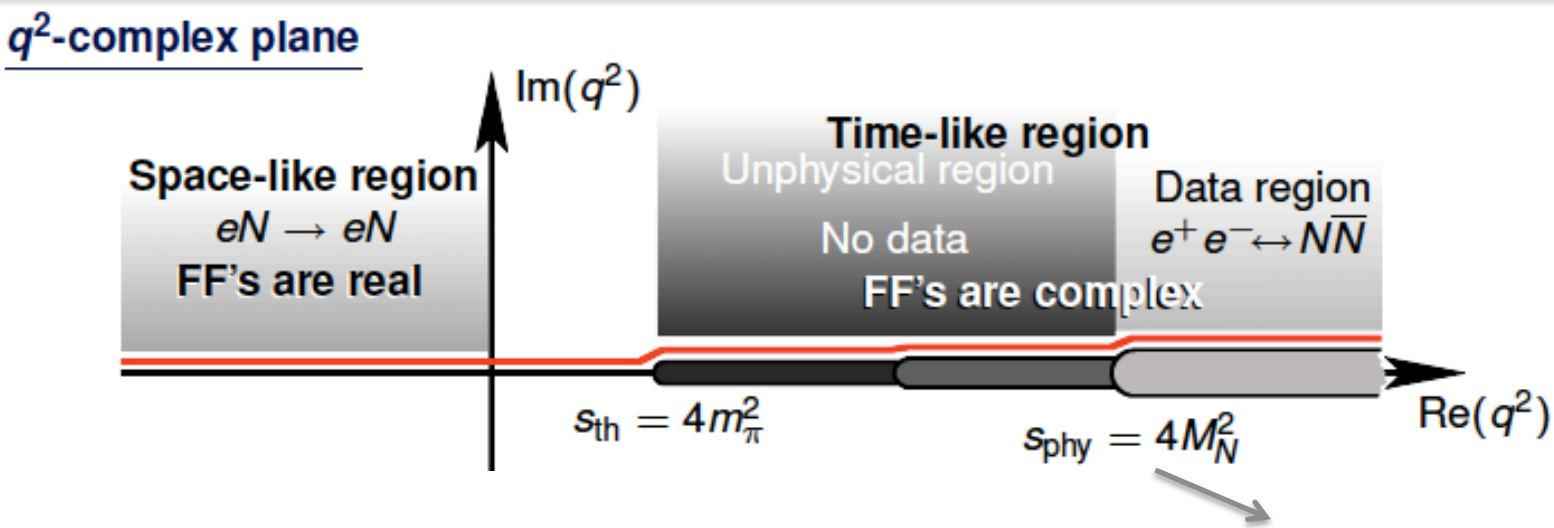


- The vertex Γ_μ contains the unknown structure, parametrized by F1 and F2:

$$\Gamma_\mu = \gamma F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_2(q^2)$$

- Sachs FFs:

$$\begin{cases} G_M(q^2) = F_1(q^2) + F_2(q^2) \\ G_E(q^2) = F_1(q^2) + \dfrac{q^2}{4M} F_2(q^2) \end{cases} \qquad \begin{cases} F_1(0) = Q, F_2(0) = k \\ G_M(0) = \mu, G_E(0) = Q \end{cases}$$

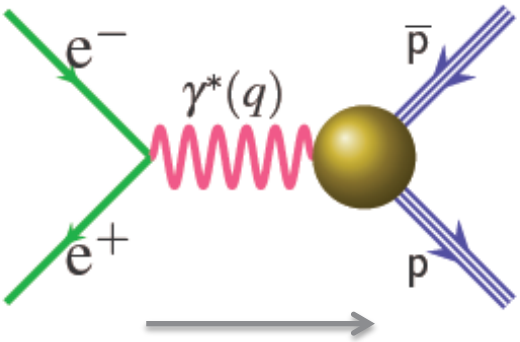


- Analitycity: $G_{E,M}(-\infty) = G_{E,M}(+\infty) \approx (q^2)^{-2}$ real FFs

$$G_E(4M^2) = G_M(4M^2)$$

EXPERIMENTAL ACCESS IN TIME-LIKE REGION

- Energy scan (direct annihilation): fixed q^2



$$\frac{d\sigma^{Born,1\gamma}}{d\Omega} = \frac{\alpha^2\beta C}{4q^2}[(1+\cos^2\theta)\boxed{|G_M|^2} + \frac{4M^2}{q^2}\sin^2\theta\boxed{|G_E|^2}]$$

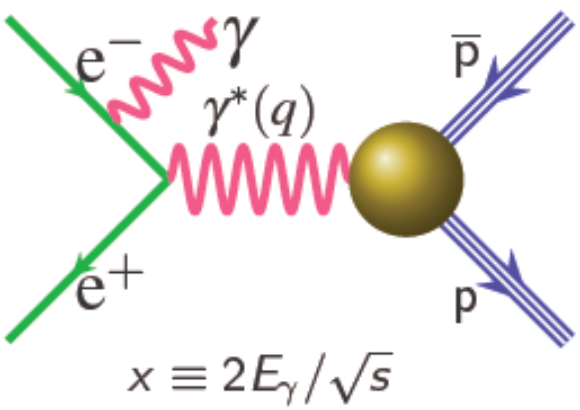
$$\sigma^{Born}(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2}[|G_M(q^2)|^2 + \frac{2M^2}{q^2}|G_E(q^2)|^2]$$

$$C = \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(\pi\alpha/\beta)}$$ charged point-like B

$$C = 1$$ neutral point-like B

$$k = \frac{g-2}{2}, g = \frac{\mu}{J}$$

- Initial State Radiation:



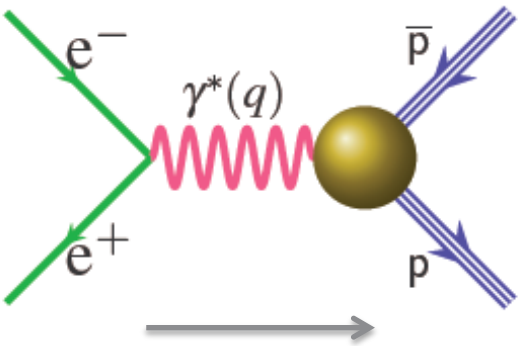
$$\frac{d^2\sigma^{ISR}}{dx\,d\theta_\gamma} = -W(s,x,\theta_\gamma)\sigma^{Born}(q^2)$$

$$W^{LO}(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2}\right)$$

$$x = 1 - q^2/s = 2E_\gamma/\sqrt{s}$$

EXPERIMENTAL ACCESS IN TIME-LIKE REGION

- Energy scan (direct annihilation): fixed q^2

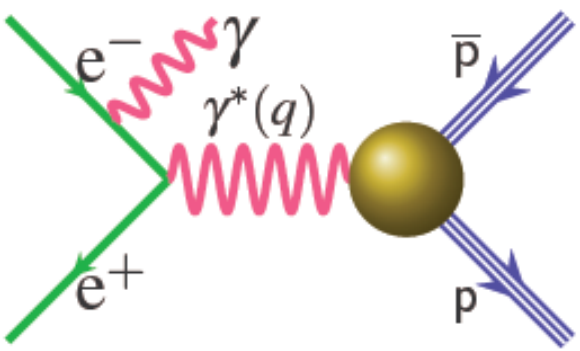


$$\frac{d\sigma^{Born,1\gamma}}{d\Omega} = \frac{\alpha^2\beta C}{4q^2}[(1+\cos^2\theta)\boxed{|G_M|^2} + \frac{4M^2}{q^2}\sin^2\theta\boxed{|G_E|^2}]$$

$$\sigma^{Born}(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2}[|G_M(q^2)|^2 + \frac{2M^2}{q^2}|G_E(q^2)|^2]$$

Effective FF: $|G| = \sqrt{\frac{\sigma^{Born}(q^2)}{(1+\frac{2M^2}{q^2})(\frac{4\pi\alpha^2\beta C}{3q^2})}}$

- Initial State Radiation:



$x \equiv 2E_\gamma/\sqrt{s}$

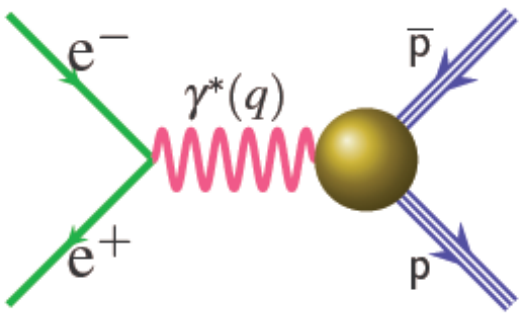
$$\frac{d^2\sigma^{ISR}}{dx\,d\theta_\gamma} = -W(s,x,\theta_\gamma)\sigma^{Born}(q^2)$$

$$W^{LO}(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2}\right)$$

$$x = 1 - q^2/s = 2E_\gamma/\sqrt{s}$$

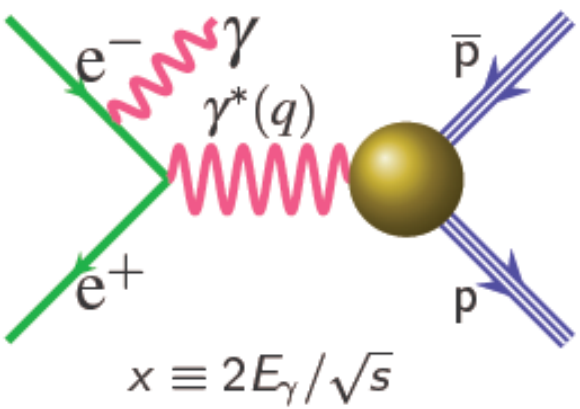
EXPERIMENTAL ACCESS IN TIME-LIKE REGION

- Energy scan (direct annihilation): fixed q^2



- High σ x low luminosity = high statistics
- High q^2 precision (ideal for $G_{E,M}$, thresholds, structure studies…)
- High geometrical acceptance of NNbar pair
- Low background
- Detection efficiencies decrease with q^2

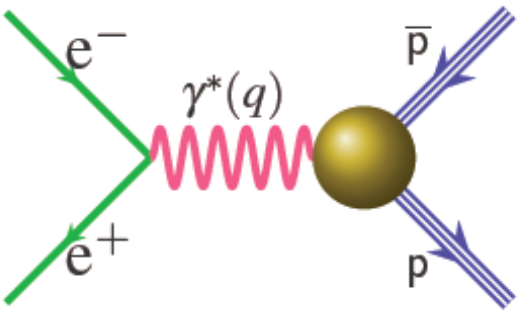
- Initial State Radiation:

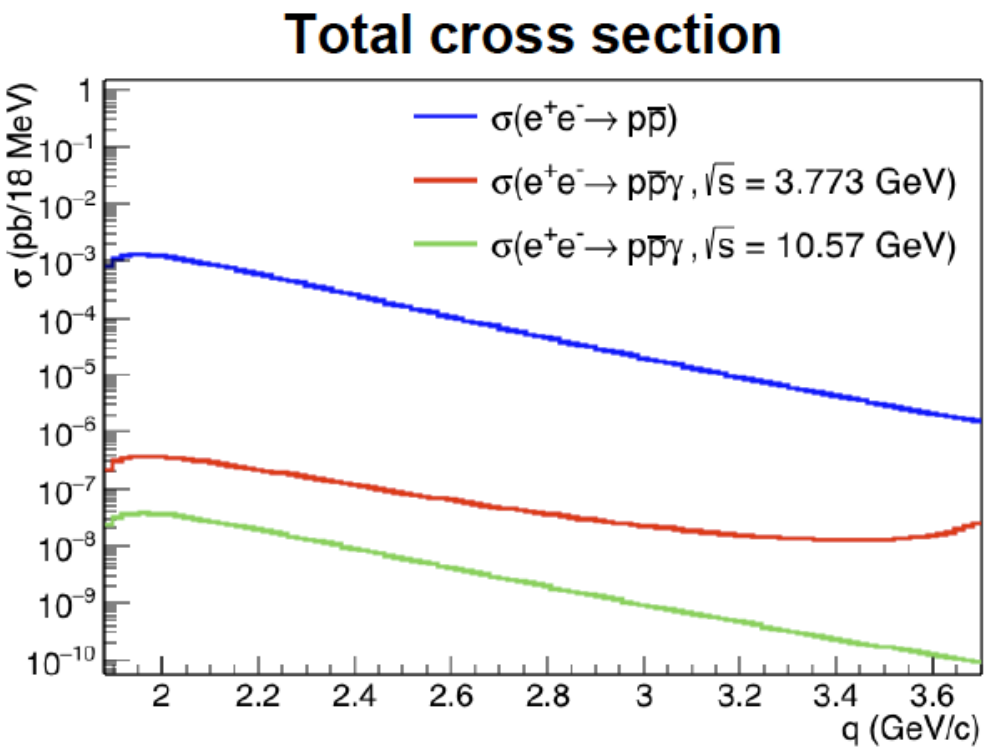


- Low σ x high luminosity = high statistics
- Continuous q2 range available: $m^2_{th}<q^2<s$ in one experiment
- Luminosity at threshold and acceptance $\neq 0$
- Full baryon angular distribution in hadronic center of mass

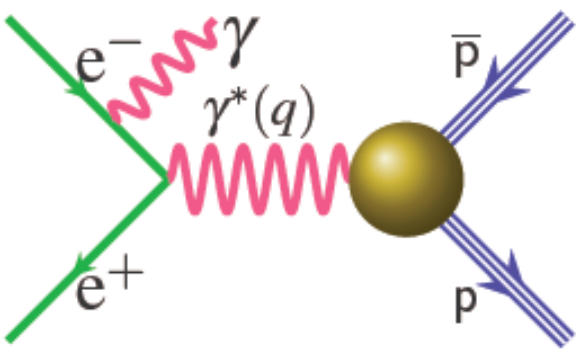
EXPERIMENTAL ACCESS IN TIME-LIKE REGION

- Energy scan (direct annihilation): fixed q^2





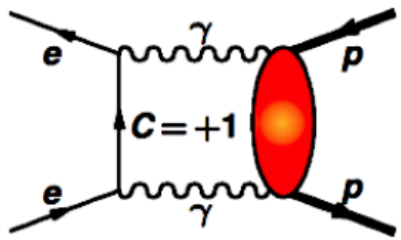
- Initial State Radiation:



$x \equiv 2E_\gamma/\sqrt{s}$

EXPERIMENTAL ACCESS: ANGULAR DISTRIBUTION

γγ exchange



γγ exchange interfere with the Born term

Asymmetry in angular distributions

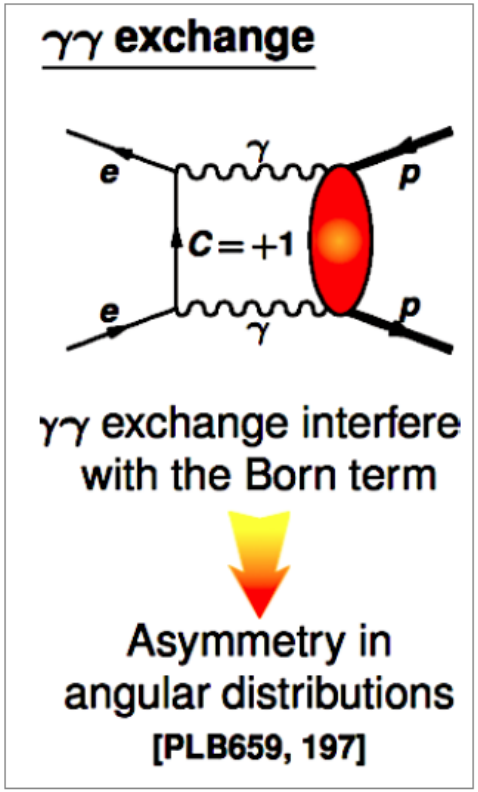
[PLB659, 197]

$$\frac{d\sigma^{Born,1\gamma}}{d\Omega} = \frac{\alpha^2\beta C}{4q^2}[(1+\cos^2\theta)|G_M|^2 + \frac{4M^2}{q^2}\sin^2\theta|G_E|^2]$$

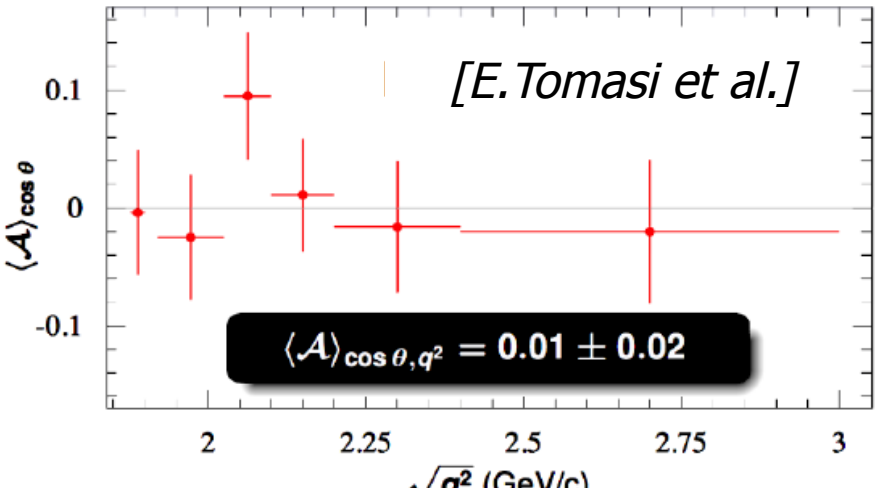
$$\frac{d\sigma^{1\gamma\otimes 2\gamma}}{d\Omega} = \cos\theta[c_0(M^2_{p\bar{p}}) + c_1(M^2_{p\bar{p}})\cos^2\theta + c_2(M^2_{p\bar{p}})\cos^4\theta + ...]$$

$$\mathcal{A}(\cos\theta, M_{p\bar{p}}) = \frac{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) - \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) + \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}$$

EXPERIMENTAL ACCESS: ANGULAR DISTRIBUTION

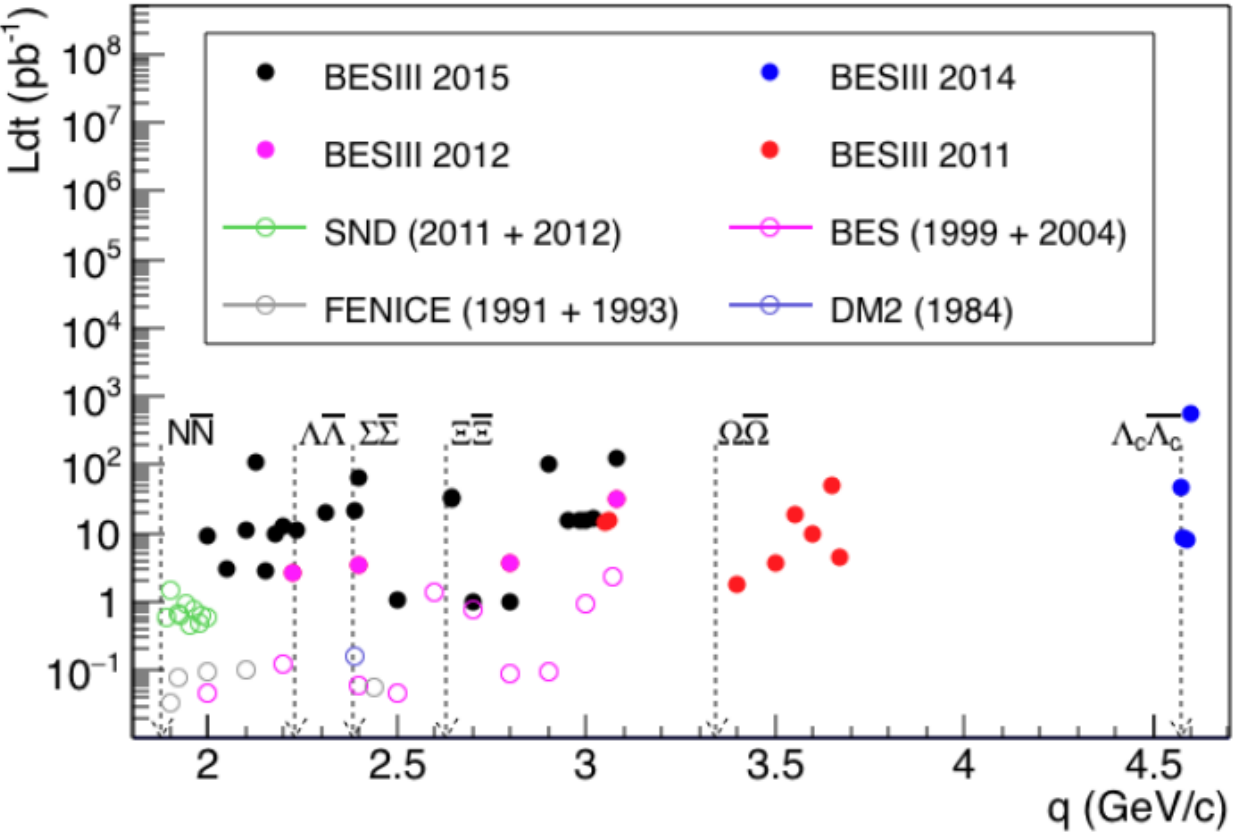


- No hints of Asymmetry from BaBar data within an error of 2%



$$A_{\cos\theta_p} = \frac{\sigma(\cos\theta_p > 0) - \sigma(\cos\theta_p < 0)}{\sigma(\cos\theta_p > 0) + \sigma(\cos\theta_p < 0)} = -0.025 \pm 0.014 \pm 003$$

SCAN DATA SETS



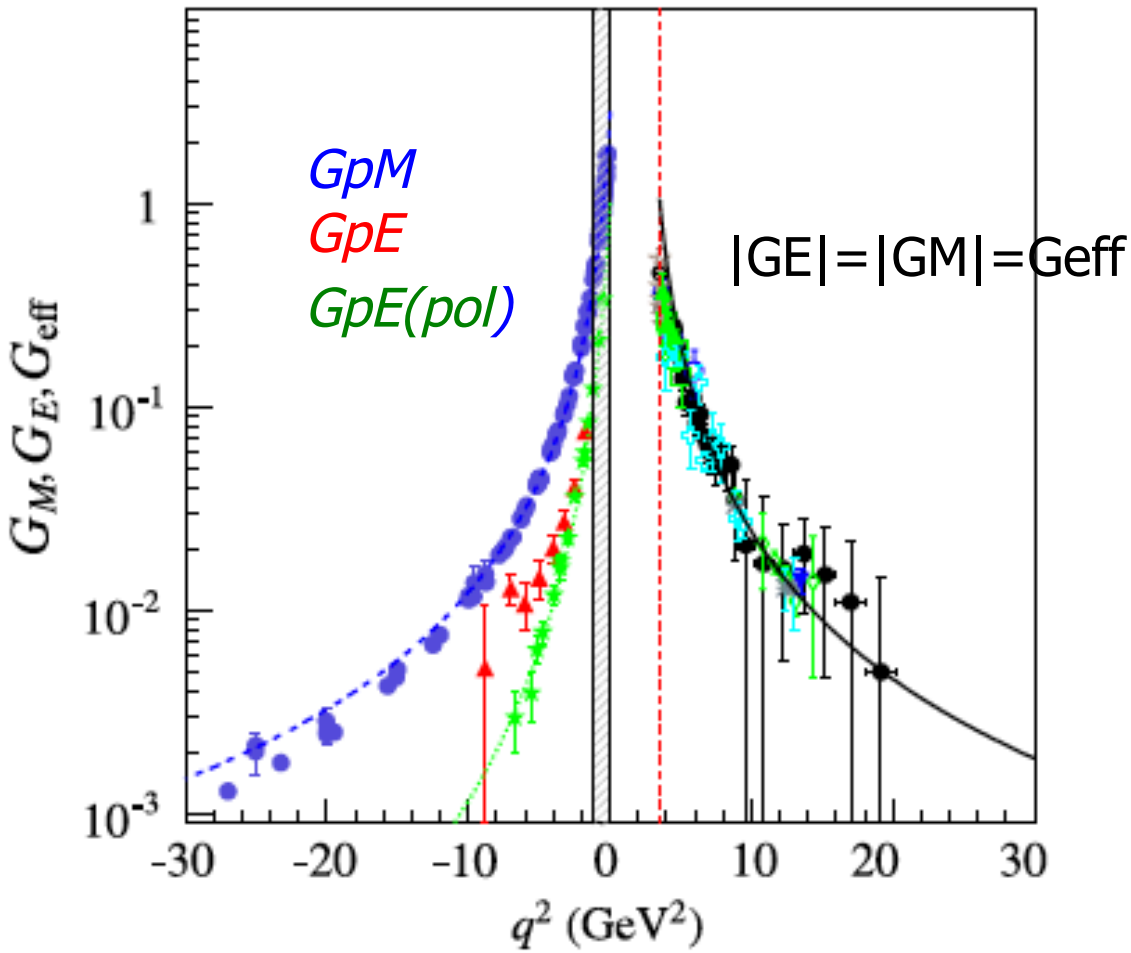
See Talks/Postes:

- proton ff (C.Rosner)
- neutron (E.P. Solodov, S.Amhed)
- Λ (X.Zhou)
- Λ_c (W.Wen)
- Hyperons (K.Shoenning)

PROTON FORM FACTORS

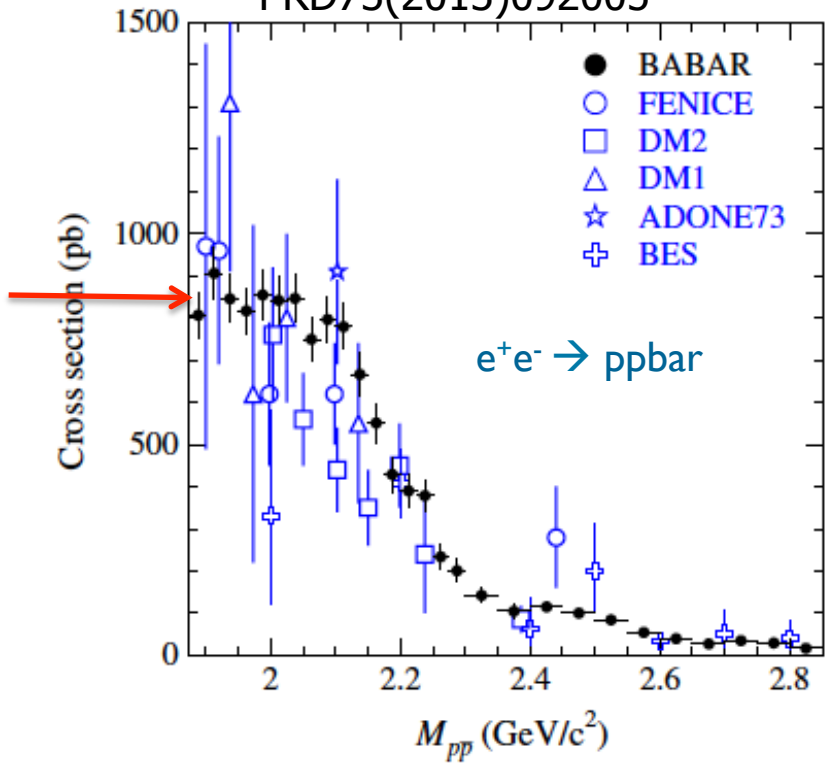
PROTON SPACE-LIKE AND TIME-LIKE FF

S. Pacetti et al. / Physics Reports 550–551 (2015) 1–103

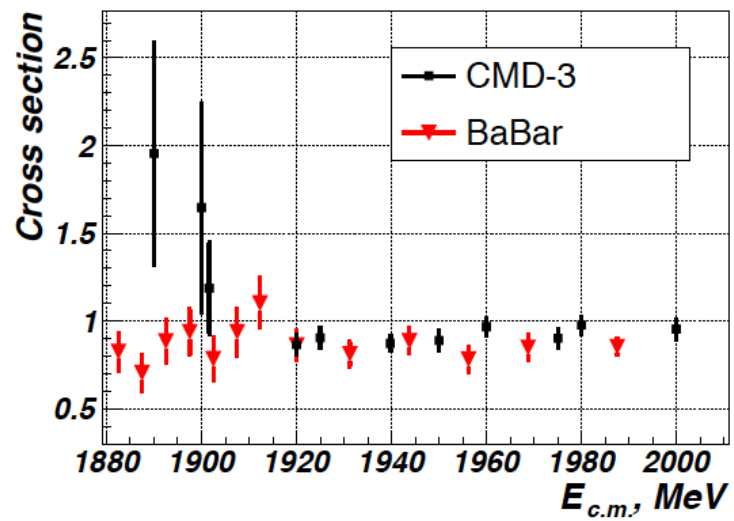


THRESHOLD ENERGY DEPENDENCE

PRD73(2013)092005



PLB759(2016)634



- Flat cross section near threshold followed by a step

$$\sigma_{p\bar{p}}(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\frac{\beta_p}{\beta_p}|G^p(4M_p^2)|^2 = 850\,|G^p(4M_p^2)|^2 \Longrightarrow \boxed{G^p(4M_p^2)| = 1}$$

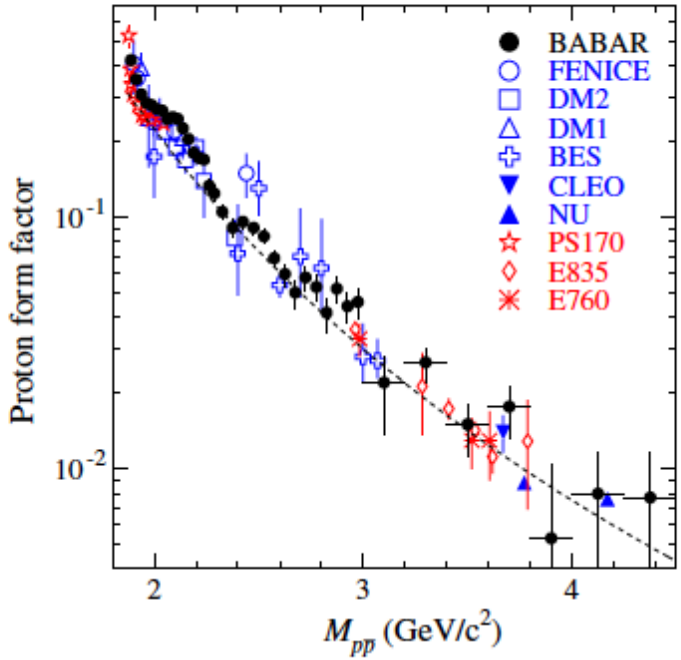
as point-like fermion pairs! [EPJA39,315]

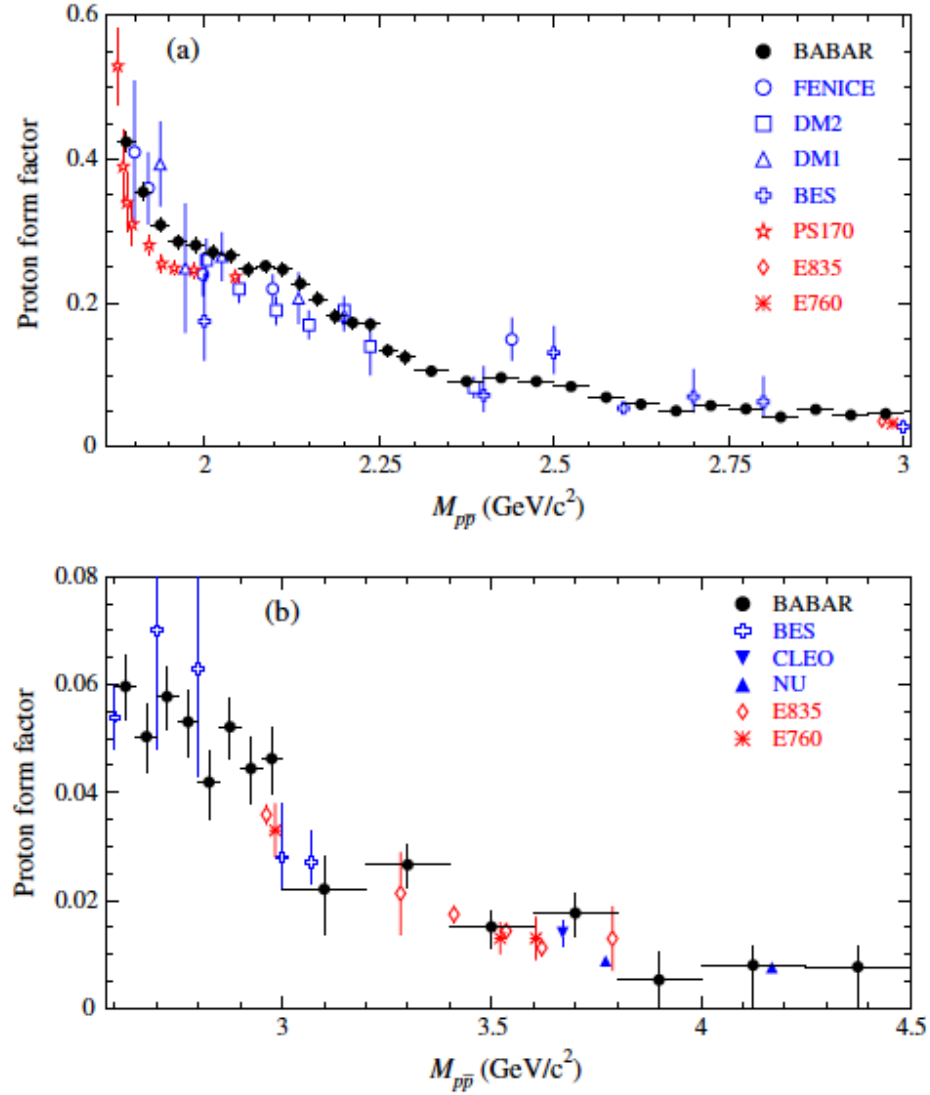
- Structures in BABAR data

see Rinaldo's talk

PROTON FORM FACTOR

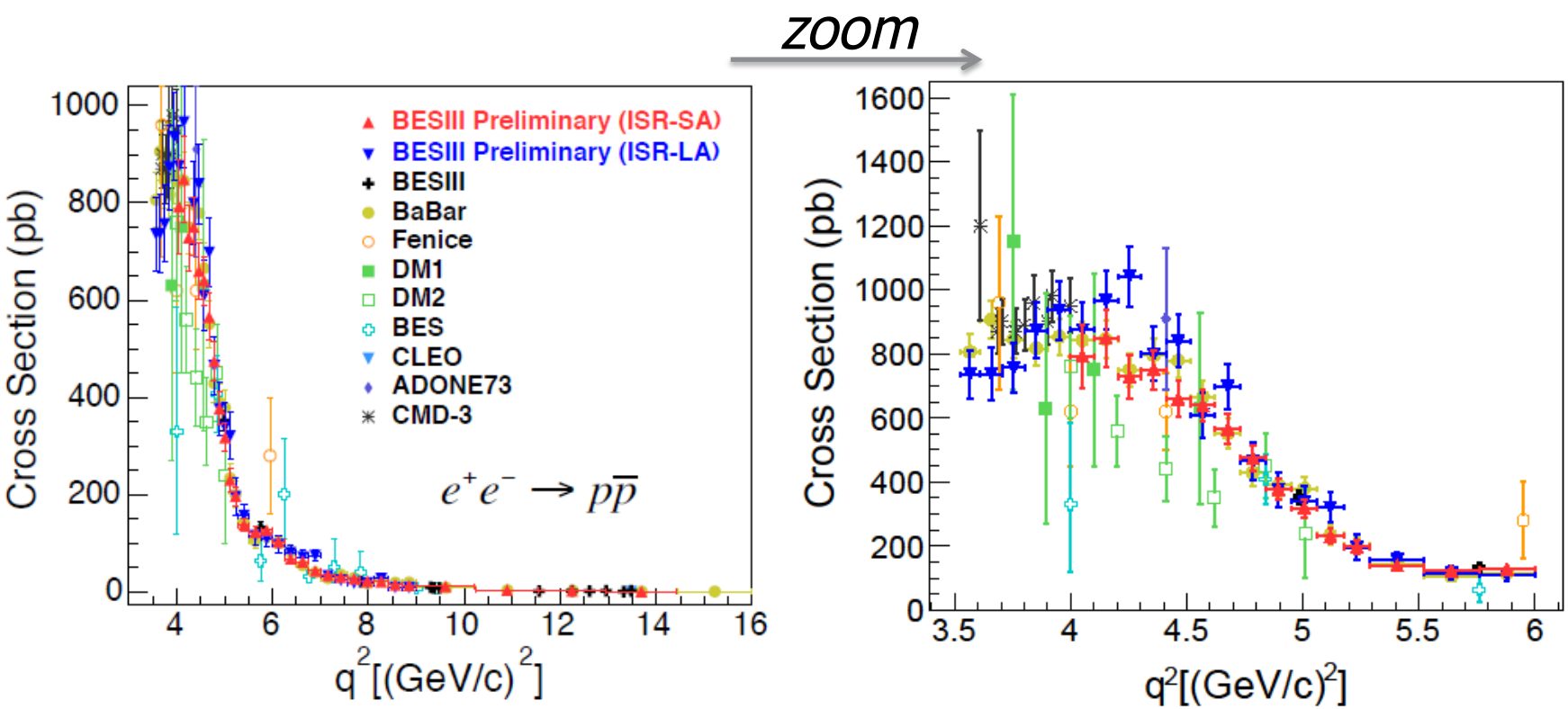
PHYSICAL REVIEW D 87, 092005 (2013)





- Steep behaviour of G_{eff} at threshold
- no individual determination of G_E or G_M
- Structures in BaBar data:
  - Resonances [(PRD92 (2015) 034018]
  - Rescattering processes in final state [(PRL114 (2015) 232301]

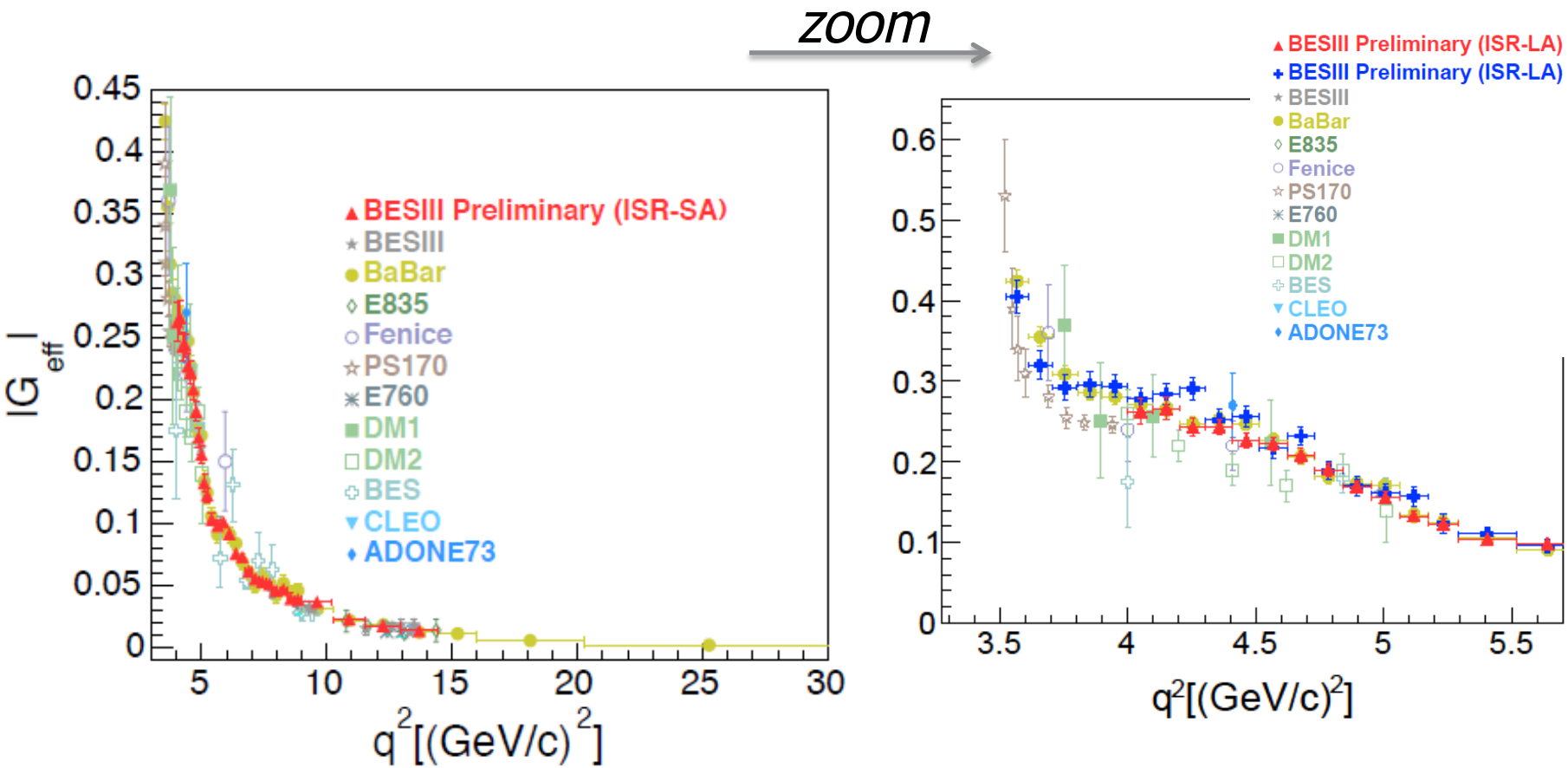
CROSS SECTION $e^+e^- \rightarrow p\bar{p}$



- BESIII has a lot of new, preliminary points (ISR technique), compatible with BaBar

[see talk by C.Rosner for BESIII results]

PROTON FORM FACTOR



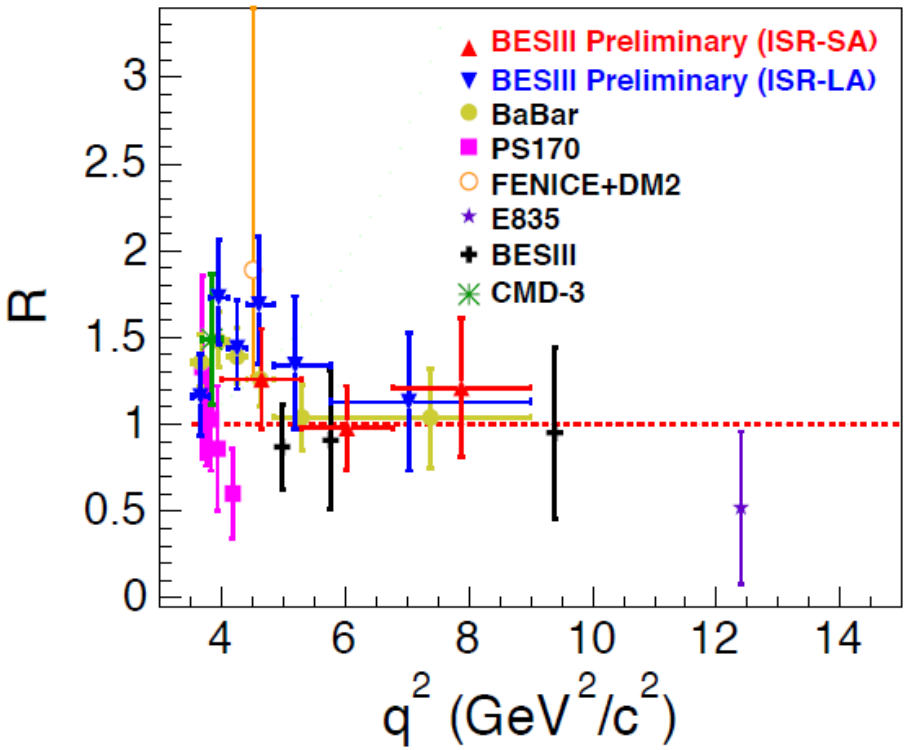
- Asymptotic behaviour is S.L. and T.L. region differ: $|G_M^{TL}$ (10GeV^2)>$|G_M^{SL}$ (10GeV^2)
- BESIII has a lot of new, preliminary points (ISR technique), compatible with BaBar

[see talk by C.Rosner for BESIII results]

G_E AND G_M RATIO

Extraction of the electromagnetic R=|GE|/|GM| ratio from proton angular distribution

$$\frac{d\sigma}{\mathcal{L}\cdot d\cos\theta_p} = \frac{\pi\alpha^2\beta C}{2q^2}|G_M|^2[(1+\cos^2\theta) + \frac{|G_E|^2}{|G_M|^2}\cdot\frac{4M^2}{q^2}\sin^2\theta]$$



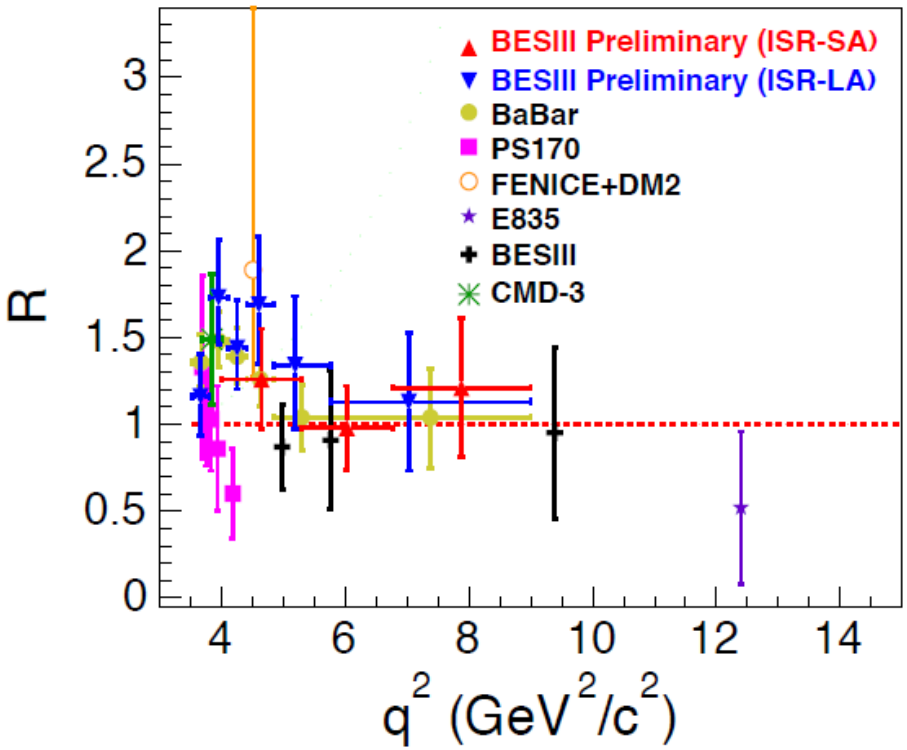
- **R=|G_E|/G_M| consistent with 1**
  - precision 11%-43%
  - Discrepancy between BaBar and PS170

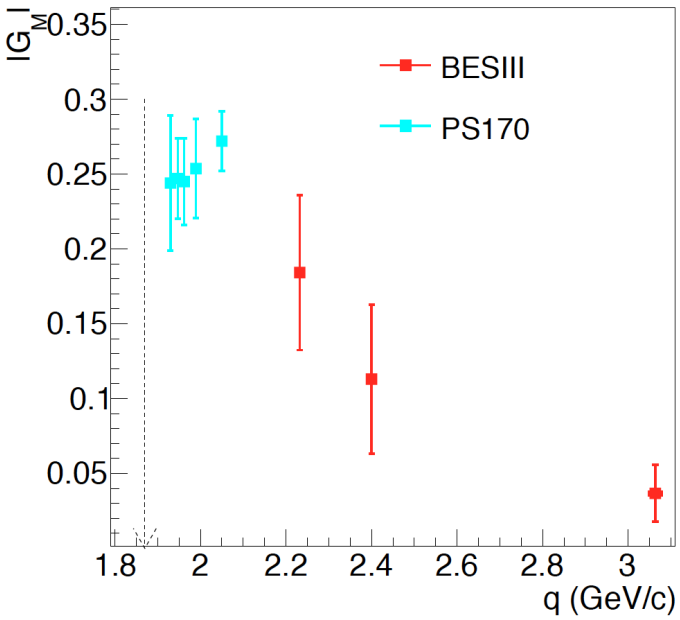
[see talk by C.Rosner for BESIII results]

G_E AND G_M RATIO

Extraction of the electromagnetic R=|GE|/|GM| ratio from proton angular distribution

$$\frac{d\sigma}{\mathcal{L}\cdot d\cos\theta_p} = \frac{\pi\alpha^2\beta C}{2q^2}|G_M|^2[(1+\cos^2\theta) + \frac{|G_E|^2}{|G_M|^2}\cdot\frac{4M^2}{q^2}\sin^2\theta]$$



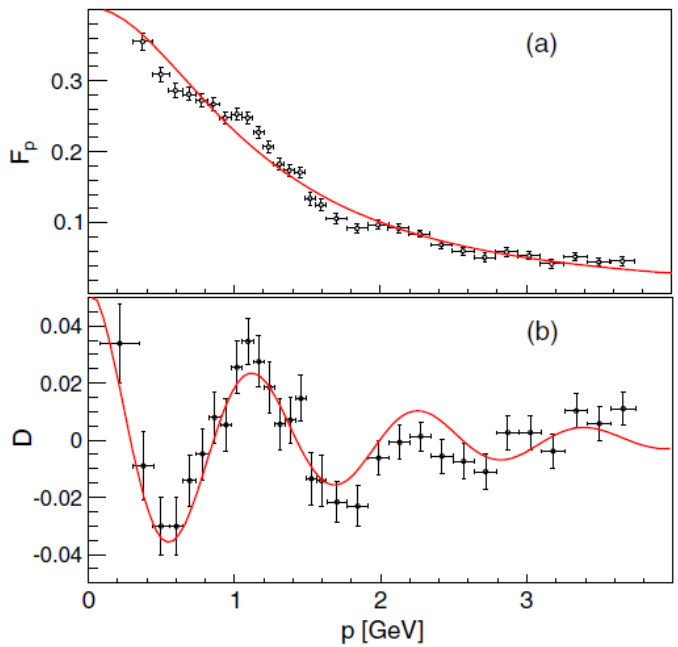


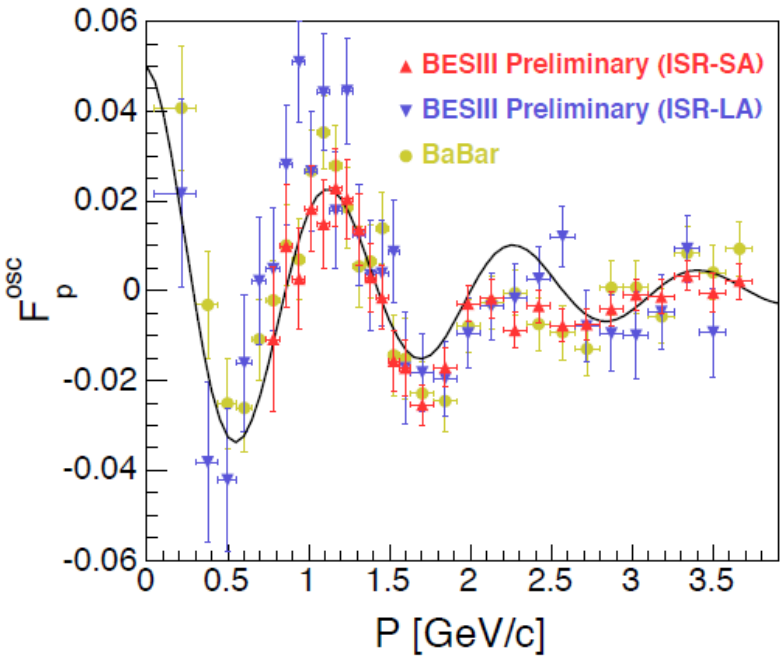
- few separate determinations of $|G_M|$

[see talk by C.Rosner for BESIII results]

OSCILLATIONS IN PROTON FF

[A. Bianconi, E. Tomasi-Gustafsson PRL114 (2015)232301, PRC93(2016)035201]





Periodic interference in F_p ($e^+e^- \to p\bar{p}$) first seen in BaBar data, confirmed in BESIII !

Oscillations due to rescattering of and pbar at ~1fm distance→large Imaginary part close to threshold

p=proton momentum in p rest frame

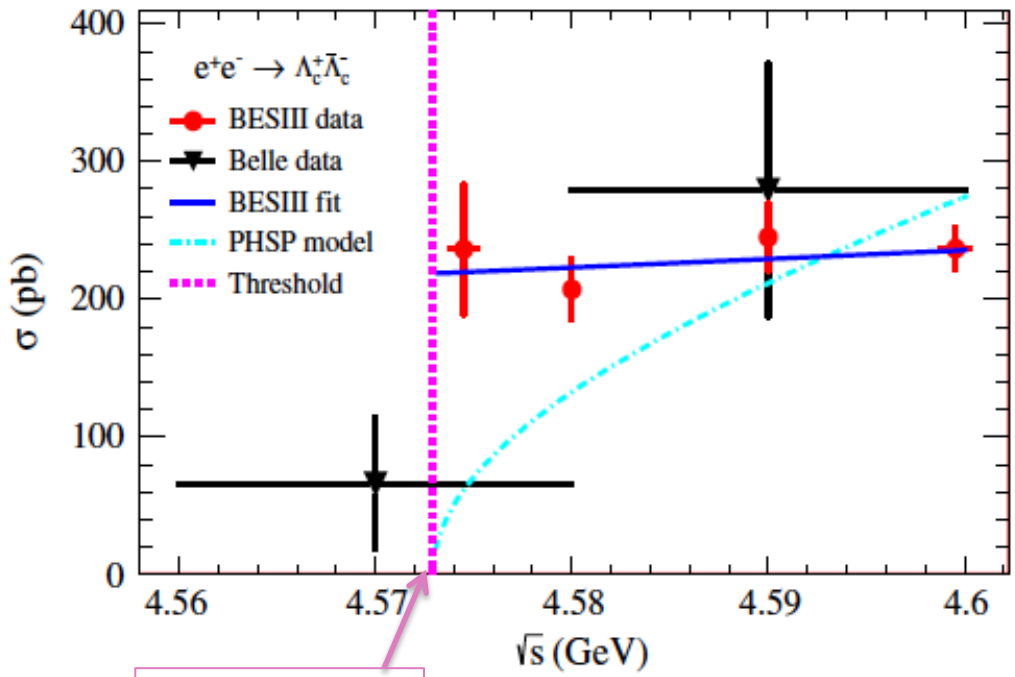
$D=F_{osc}$=Osc-Reg.

see Egle's talk !

Λ_c CROSS SECTION

CROSS SECTION OF $e^+e^- \rightarrow \Lambda\bar{\Lambda}_c$

Jump of cross section at threshold !



4.5729GeV

$$|G_E/G_M|^2(1-\beta^2) = (1-\alpha_{\Lambda_c})/(1+\alpha_{\Lambda_c})$$

first measurement of $|G_E/G_M|$ by BESIII

Energy (GeV)	$\lvert G_E/G_M \rvert$
4.5745	$1.14 \pm 0.14 \pm 0.07$
4.5995	$1.23 \pm 0.05 \pm 0.03$

[(PRL120 (2018) 132001]

see poster by Weiping Wen !

NEUTRAL BARYONS FORM FACTORS

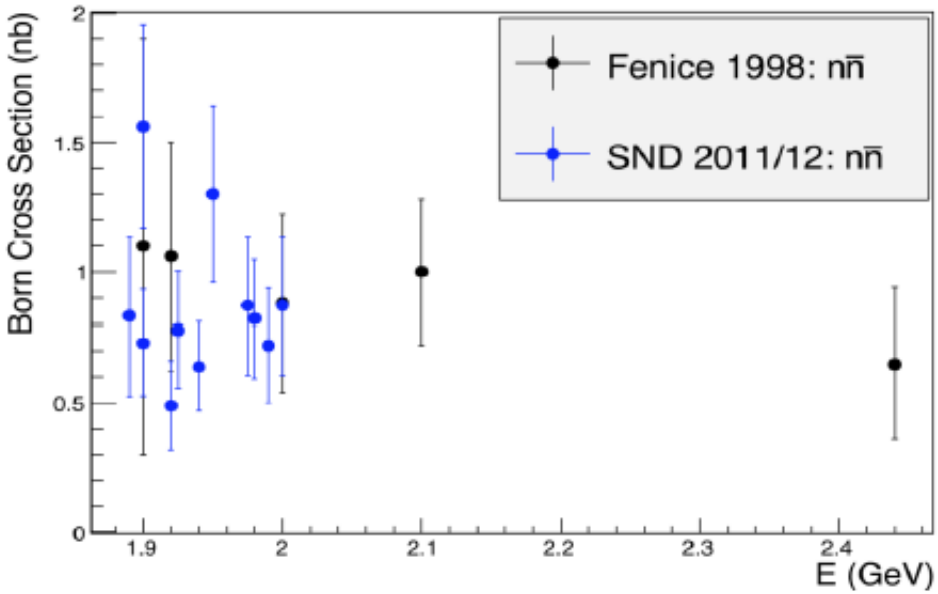
NEUTRAL BARYONS ENERGY BEHAVIOUR AT THRESHOLD

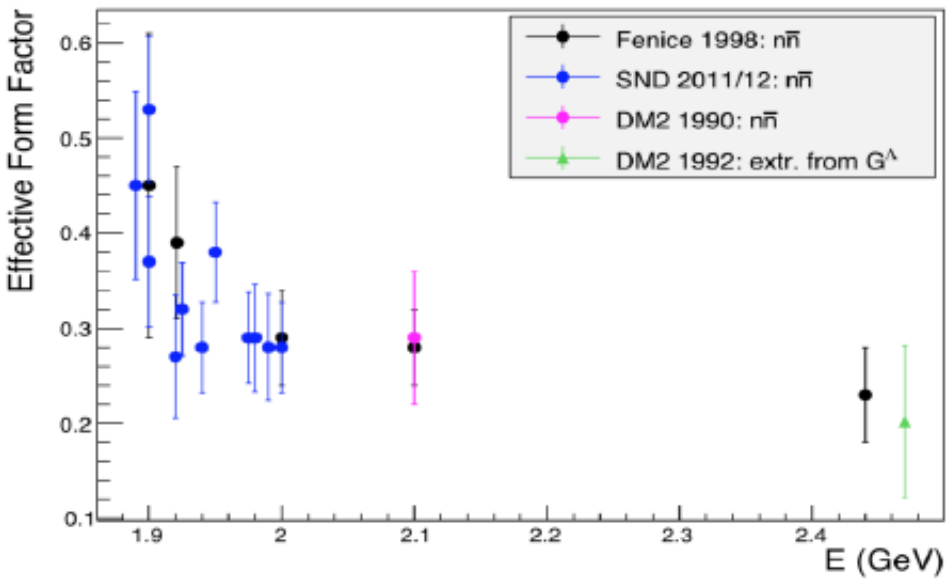
$$\sigma_{B^0\overline{B^0}}(q^2) = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M(q^2)|^2 + \frac{2M^2}{q^2}|G_E(q^2)|^2\right] \xrightarrow[q^2\to 4M^2]{} \frac{\pi\alpha^2\beta}{3q^2}|G|^2 \to 0$$

o NO Coulomb correction at hadron level: C=1, yet experimentally non zero cross are found

NEUTRON F.F.

- Only two direct measurements of σ (e+e- → $n\bar{n}$) and neutron Effective f.f.
- Large errors (30%)



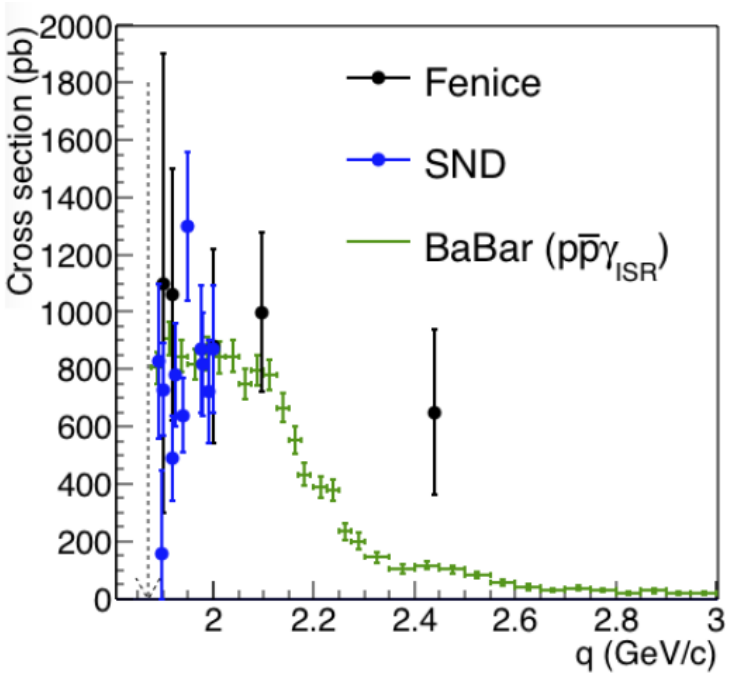


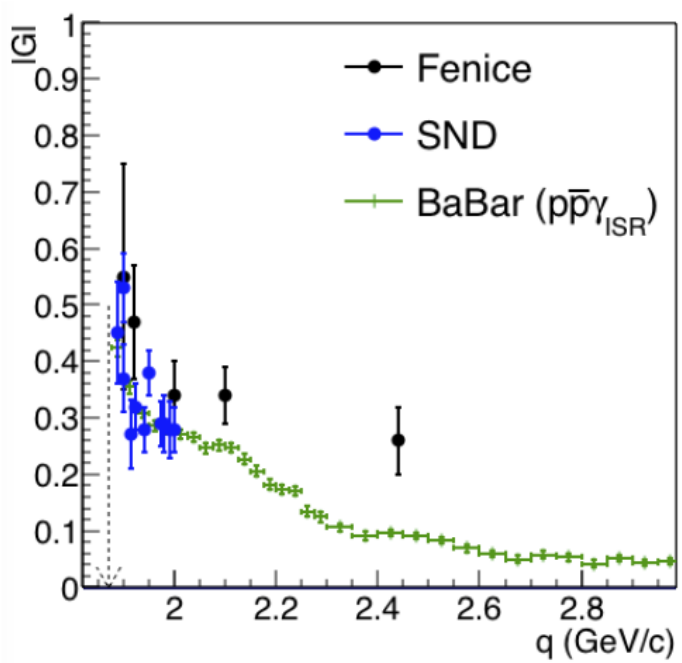
- No measurement of $R=|G_E/G_M|$ or $|G_E|$ and $|G_M|$
- q<2GeV σ (e+e- → nnbar) ≈σ (e+e- → ppbar)
- |Gn| > |Gp| as q increases (pQCD: |Gp|≈: |Gn|)
- Non vanishing cross section at threshold ?

BESIII will soon have new results, stay tuned !
see S.Ahmed Poster !

NEUTRON F.F.

- Only two direct measurements of σ (e+e- → nnbar) and neutron Effective f.f.
- Large errors (30%)





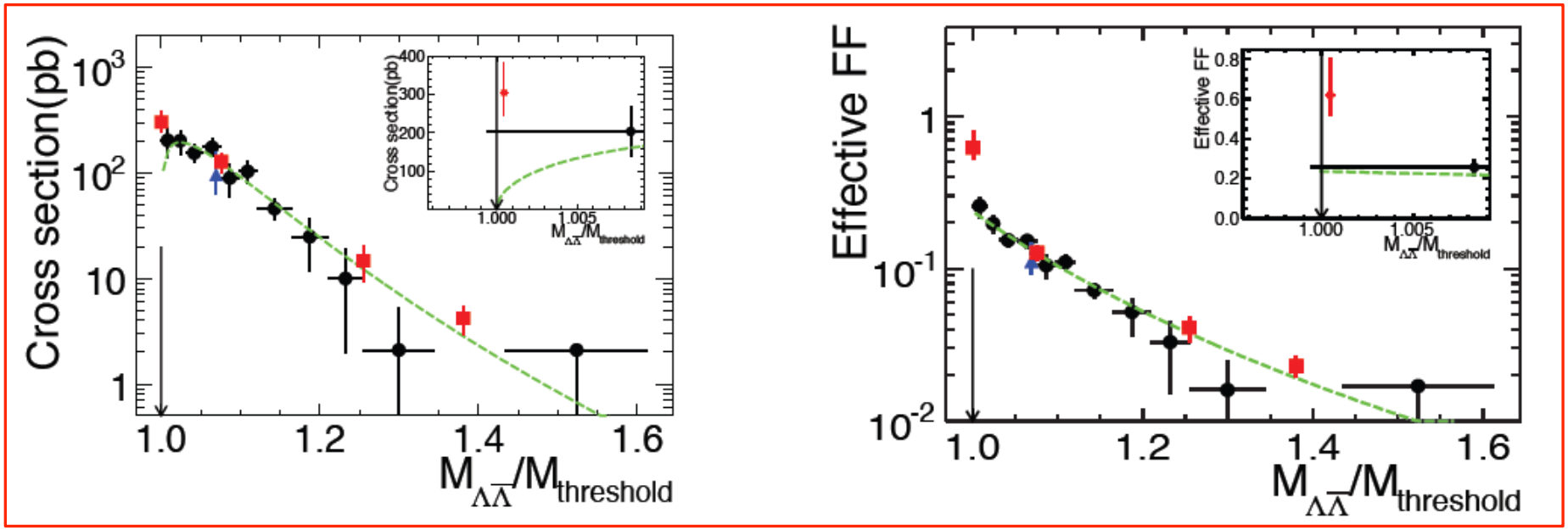
- |Gn| > |Gp| as q increases (pQCD: |Gp|≈: |Gn|)

BESIII will soon have new results, stay tuned !
see S.Amed Poster !
new data from VEPP2000 ? see E.Solodov's talk

LAMBDA FORM FACTOR

- Only few measurements of σ ($e^+e^- \rightarrow \Lambda\bar{\Lambda}$) and Lambda Effective f.f.:
  - BaBar, DM2, very recently BESIII:

[(PRD92 (2015) 034018]



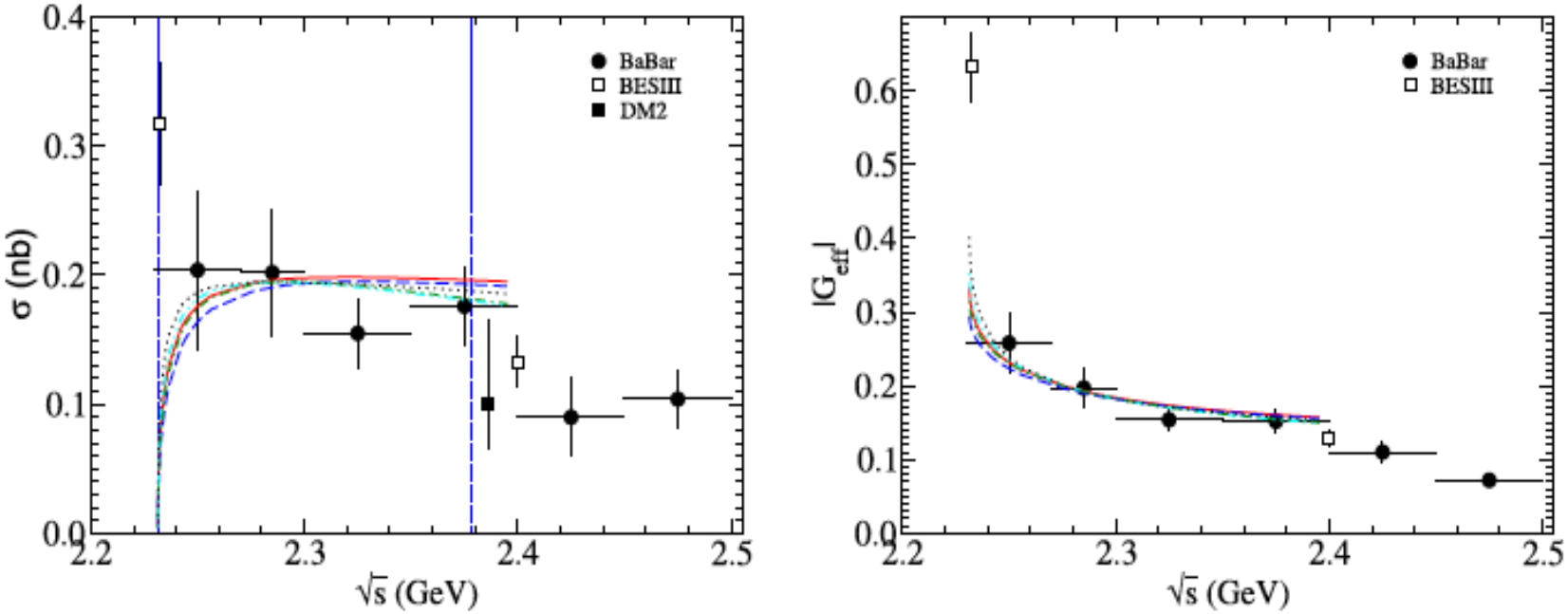
- Threshold enhancement: BESIII point only 1 MeV over threshold q^2=2.2324 GeV: s(e+e-→ΛΛbar)=(305+-45+66-36)pb , not zero !
- Away from threshold agreement between BESIII and BaBar points

see Xiaoron Zhu's talk about BESIII measurement

LAMBDA FORM FACTOR

- Interactions in the final state of $\Lambda\bar{\Lambda}$ well reproduce BaBar data but not the first BESIII point near threshold.

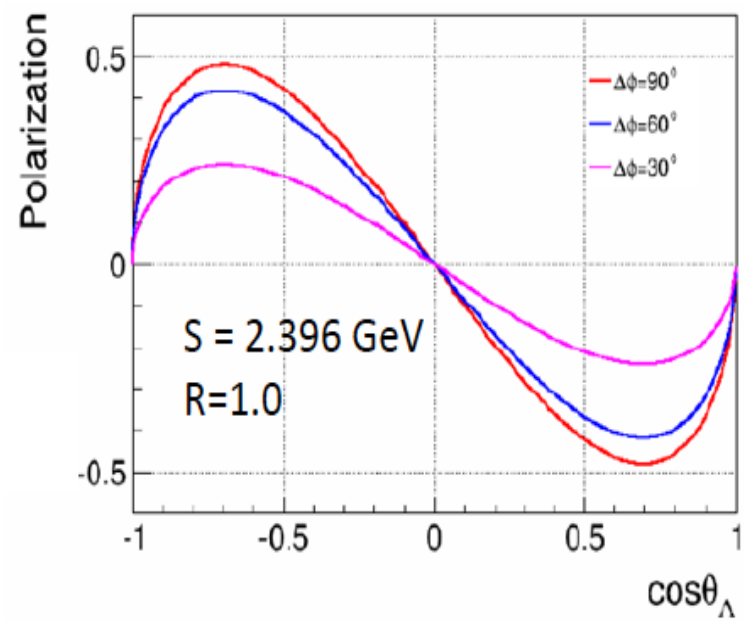
J. Haidenbauer, U.-G. Meißner / Physics Letters B 761 (2016) 456–461



see Xiaoron Zhu's talk !

POLARIZATION OBSERVABLES

- With hyperons, polarization is experimentally observable by their weak Parity violating decay, polarization effects can be observed even if the initial e^+e^- state in unpolarized.
- the phase between G_E and G_M can be obtained from angular distribution
- mathematical formalism developed [PLB772(2017)16]
- New, preliminary results obtained by BESIII for Λ (K.Shoenning's talk)



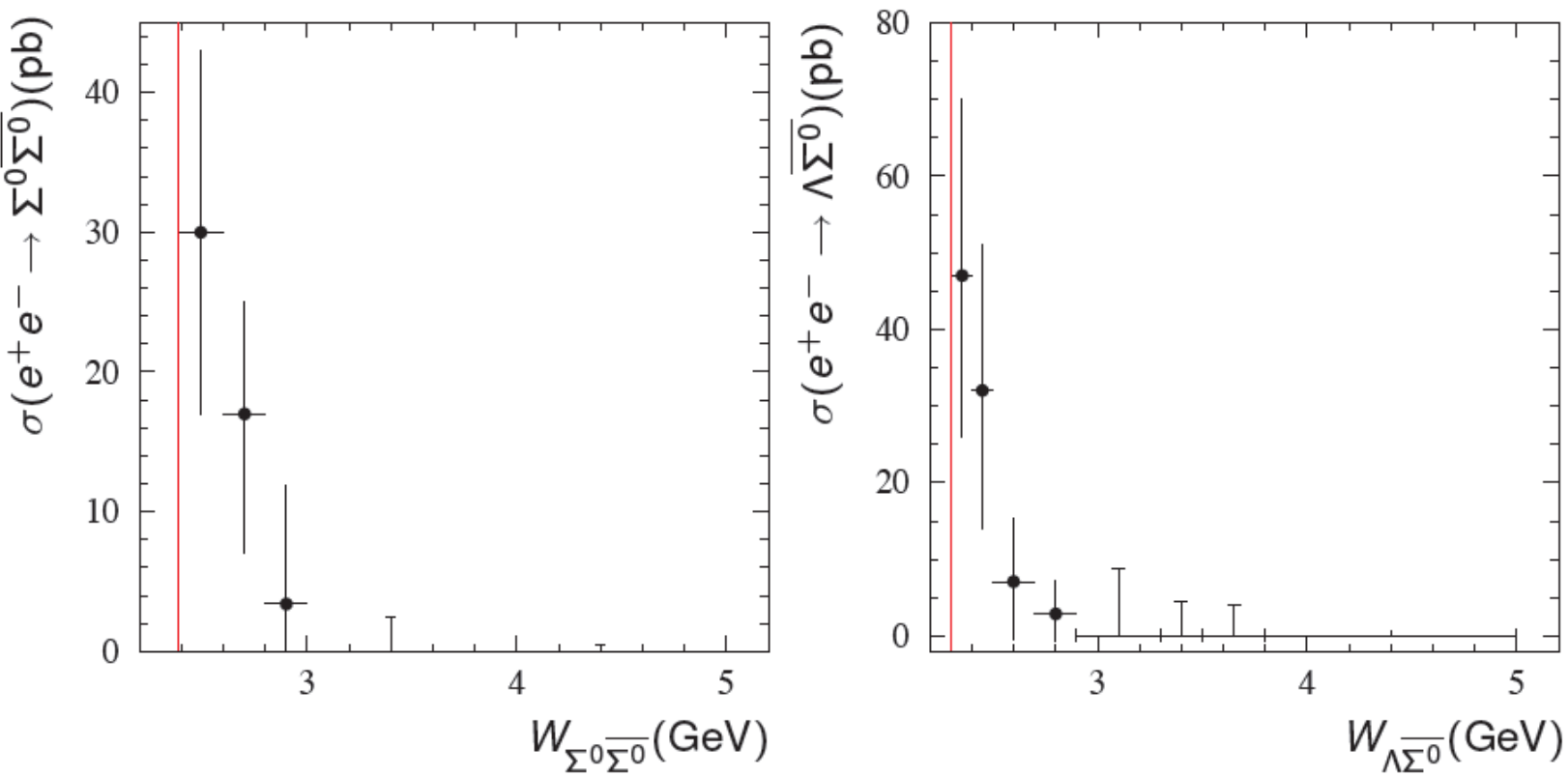
see K.Shoenning's talk!

$\Sigma^0\Sigma^0$ and $\Lambda\Sigma^0$ channels

PRD76, 092006

Phys.Rev. D76 (2007) 092006

Cross sections of $e^+e^- \to \Sigma^0\overline{\Sigma^0}$, $\Lambda\overline{\Sigma^0}$ via ISR (*BABAR*)



$\sigma(e^+e^- \to \Sigma^0\overline{\Sigma^0})_{th} = 30 \pm 13$ pb

$\sigma(e^+e^- \to \Lambda\overline{\Sigma^0})_{th} = 47 \pm 22$ pb

Other neutral baryon: large errors but hints of a non zero cross section

CONCLUSIONS

- ✓ **New results on Baryon FFs, both SL and TL, from theoretical and experimental side have brought to light many issues, yet they opened new questions !**

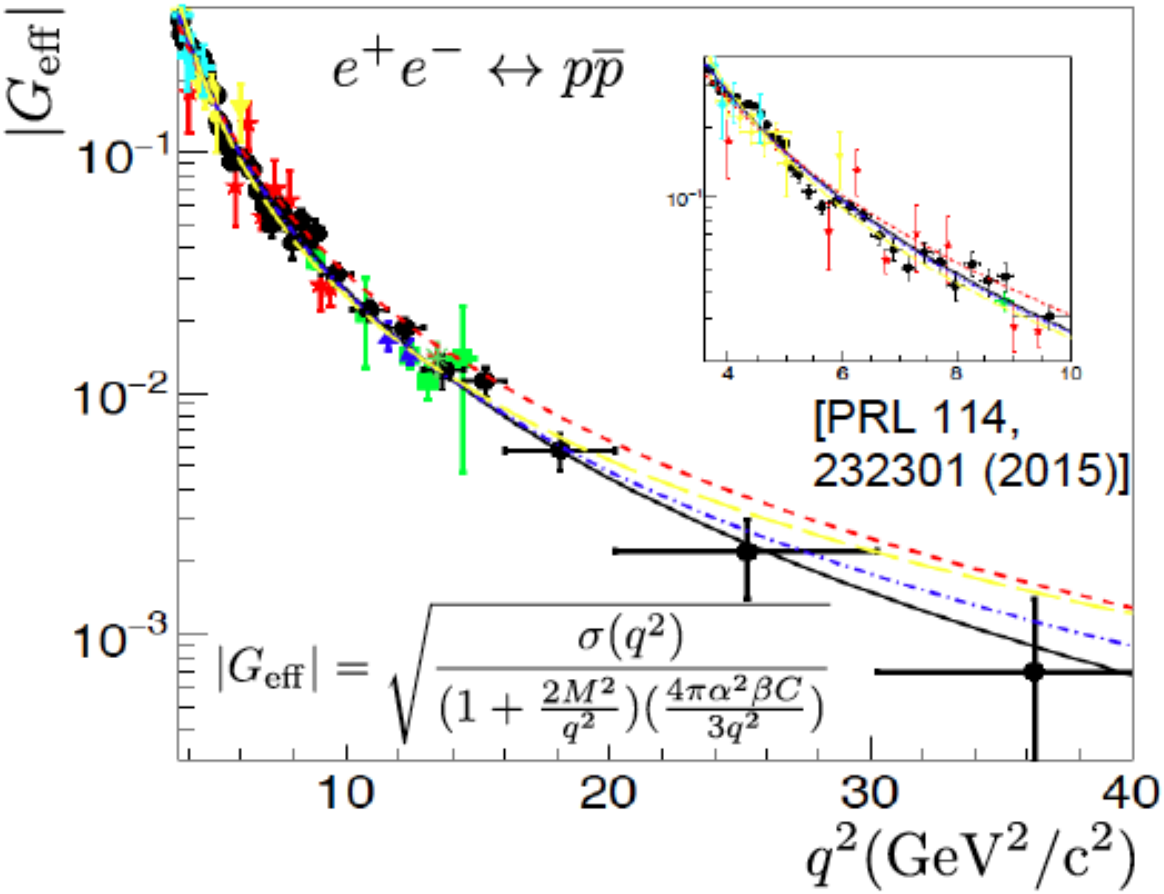
- ✓ **Experimental measurements are getting more precise, higher luminosity, more data to come from existing and future experiments**

- ✓ **Stay tuned and let's follow the talks in these days**

THANK YOU!

SPARES

Effective form factor



PROTON FORM FACTOR

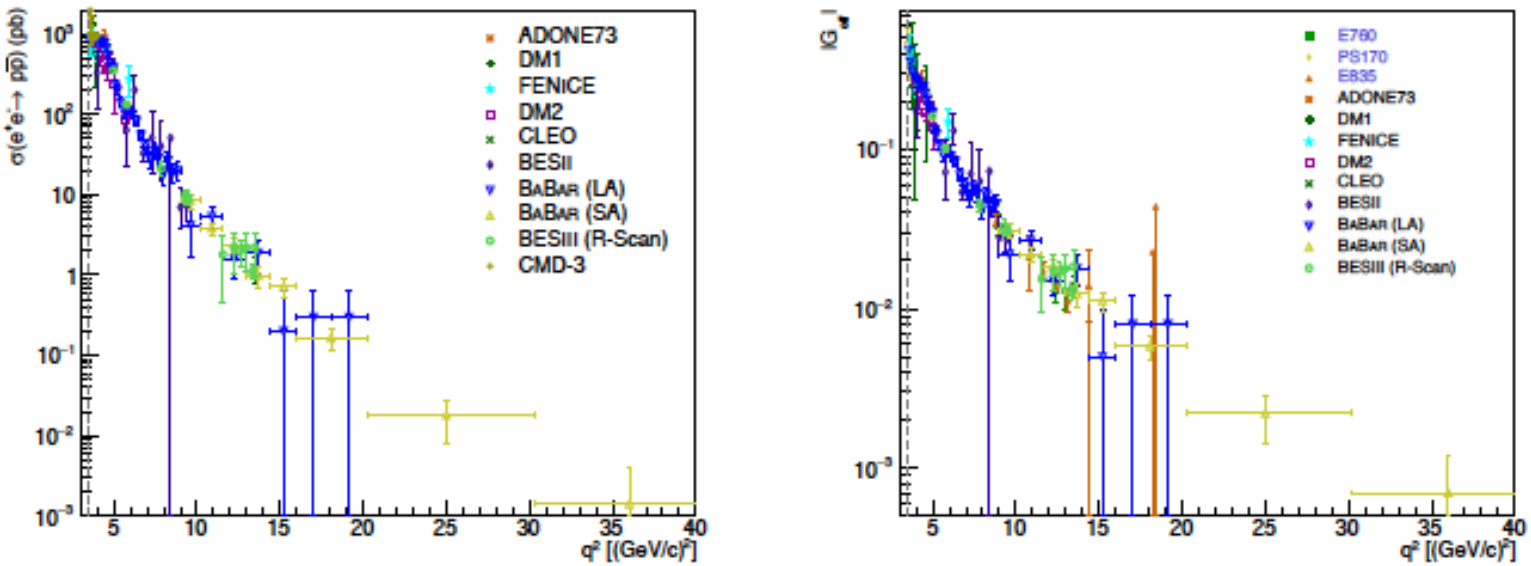


Figure 5: World data on the cross section of $e^+e^- \to p\overline{p}$ and the effective FF of the proton, as the function of q^2: (a) The cross section measured by $e^+e^- \to p\overline{p}$, (b) The effective FF of the proton including $p\overline{p} \to e^+e^-$ experiments.

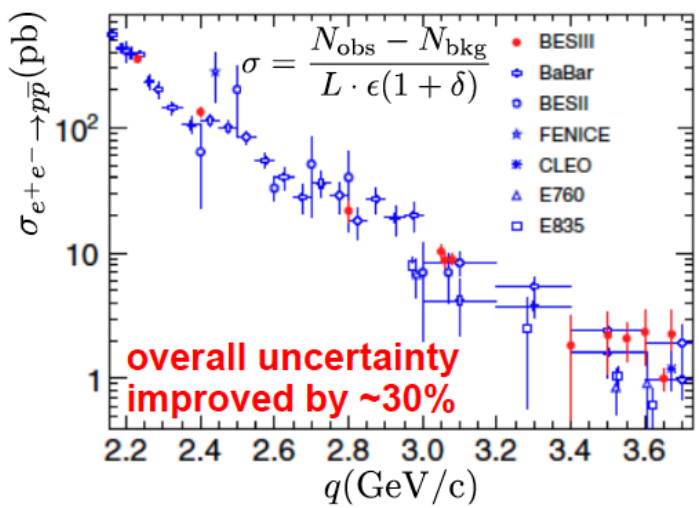
$e^+e^- \to p\bar{p}$ at BESIII Phys. Rev. D91, 112004 (2015)

Based on **157 pb^{-1}** collected in 12 scan points with $\sqrt{s}$= **2.23 – 3.71 GeV** in 2011/2012

- p and $\bar{p}$ from vertex, in time, back to back, $E_{p,\bar{p}} = E_{CM}/2$
- Background negligible or subtracted
- Efficiencies around 60%
- Radiative corrections up to LO in ISR (ConExc)
- Normalization to $e^+e^- \to \gamma\gamma$ (Babayaga 3.5)

E_{CM} (GeV)	Ldt (pb^{-1})
2.23	2.6
2.40	3.4
2.80	3.8
3.05,3.06,3.08	60.7
3.40,3.50,3.54,3.56	23.3
3.60,3.65,3.67	63.0

Cross section



Effective form factor