Proton Form Factors measurements in the Time-like Region

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On behalf of the *BABAR* Collaboration

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Outline:

- BABAR measurement of $e^+e^- \to$ *pÅ* by means of ISR events
    - analysis strategy
    - cross section and BF of charmonium states

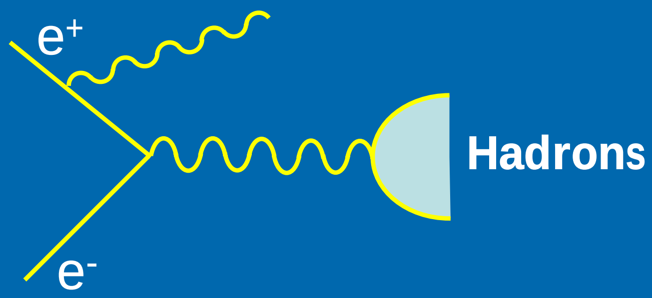
- Form Factors:
    - definitions and main properties
    - measurement of the ratio $|G_E/G_M|$
    - review of $|G_M|$ measurements
    - asymptotic behavior $\to$ fit to pQCD predictions
    - puzzling behavior at *pÅ* threshold

    - Λ and neutron time-like form factors

- Conclusions and perspectives

Initial State Radiation: motivations

ISR studies at the $\Upsilon(4S)$ can yield the same observables as the low energy e^+e^- experiments



- precise measurements of e^+e^- cross sections at low c.m. energy
- hadron spectroscopy for $1 < \sqrt{s} < 5$ GeV
- form factors (this talk)
- new states discovery (e.g. Y(4260))
- measurement of the ratio $$R(s) = \frac{\sigma_{e^+e^- \to hadrons}(s)}{\sigma_{e^+e^- \to \mu^+\mu^-}(s)}$$

ISR cross section

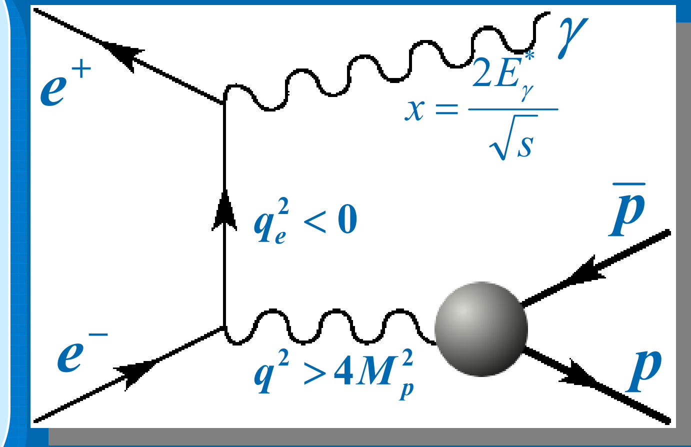
Born approximation

$$\frac{d\sigma_{e^+e^-\to p\bar{p}\gamma}(s, m_{p\bar{p}})}{dm\, d\cos\theta^*_\gamma} = \frac{2m}{s} W(s, x, \theta^*_\gamma) \cdot \sigma_{e^+e^-\to p\bar{p}}(m_{p\bar{p}})$$

$$x = \frac{2E^*_\gamma}{\sqrt{s}} \qquad m^2_{p\bar{p}} = q^2 = s(1-x)$$

θ_γ^*: ISR angle in e^+e^- c.m.

Radiator function: $$W(s, x, \theta^*_\gamma) = \frac{\alpha}{\pi \cdot x} \cdot \left(\frac{2 - 2x + x^2}{\sin^2\theta^*_\gamma} - \frac{x^2}{2} \right)$$



$e^+e^- \rightarrow$ pÅ cross section

$$\sigma_{p\bar{p}}(m) = \frac{(dN/dm)}{\varepsilon\,(1+\delta_{rad})\,(dM/dm)}$$

reconstruction efficiency

radiative corrections

ISR differential luminosity $$\frac{dM}{dM} = \frac{2m}{s}\frac{\alpha}{\pi \cdot x} \cdot \left((2-2x+x^2) \log\frac{1+C}{1-C} - x^2 C \right) L_{ee}$$

Machine integrated luminosity

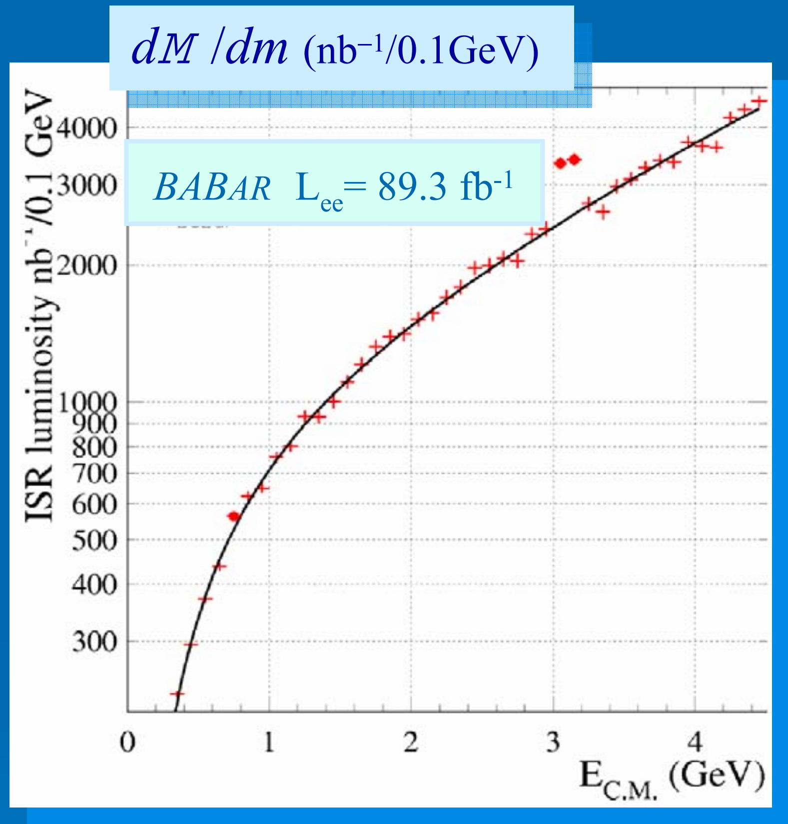
$\cos\theta^*_{\min}$

- obtained from integration of the radiator function over θ_γ^*
- known at 1% level (from MC simulation)
- $20^o < \theta_\gamma^* < 160^o$ ==> **acceptance for ISR photon ~15% in *BABAR***

ISR in *BABAR*

- uniform data quality all-over the energy range
  no systematics from point-to-point normalization
- statistically very competitive sample
  - largest sample of $e^+e^- \rightarrow p\bar{p}$ events collected up to now
- c.m. boost
  - at threshold $\varepsilon \neq 0$
- hard photon detected:
  - event tagging ==> loose hadron selection
  - hadronic system at wide angle (in LAB ref)

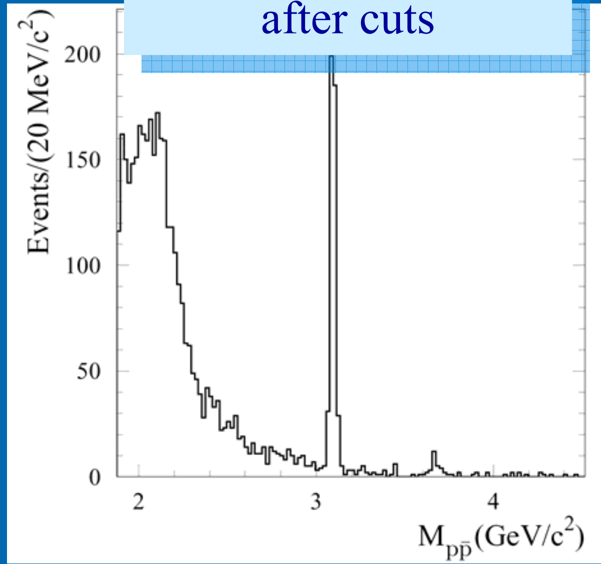
  - large geometric acceptance
  - full $p\bar{p}$ angular coverage (in $p\bar{p}$ c.m.)
- higher background



Analysis strategy

- Events selection:
  - require "hard" γ + 2 tracks of opposite charge identified as protons
  - $\pi/K/p$ discrimination using dE/dx and Cherenkov angle
  - kinematic fit requiring p and E conservation ,
  - select signal according to fit χ^2

mass of *pÅ* system after cuts



- Monte Carlo simulations used for detector acceptances, selection efficiencies and estimates of different background sources:
  - ISR generators based on:

    H.Czyz et al, Eur. Phys. J. C 35(2004)527
  - multiple ISR soft photons:

    M.Caffo et al, N. C. 110A(1997)515
  - final state radiation: (PHOTOS)

    E. Barberio et al, Comp. Phys Comm. 66(1991)115

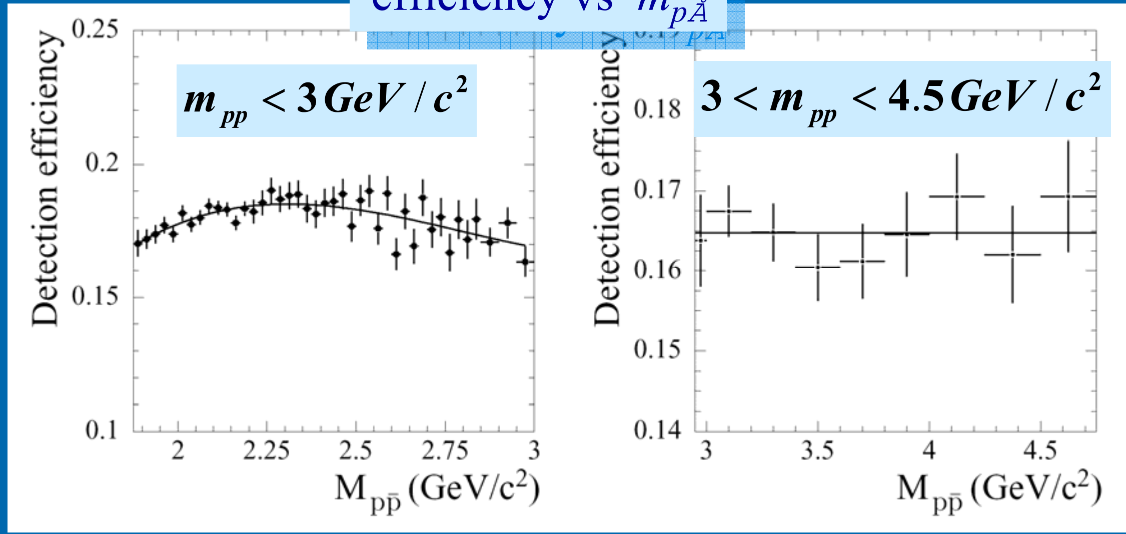
- **4025 events selected in 232 fb^{-1} of data**
- ~6% residual background, dominated by non ISR $e^+e^- \longrightarrow$ *pÅ* π^0

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

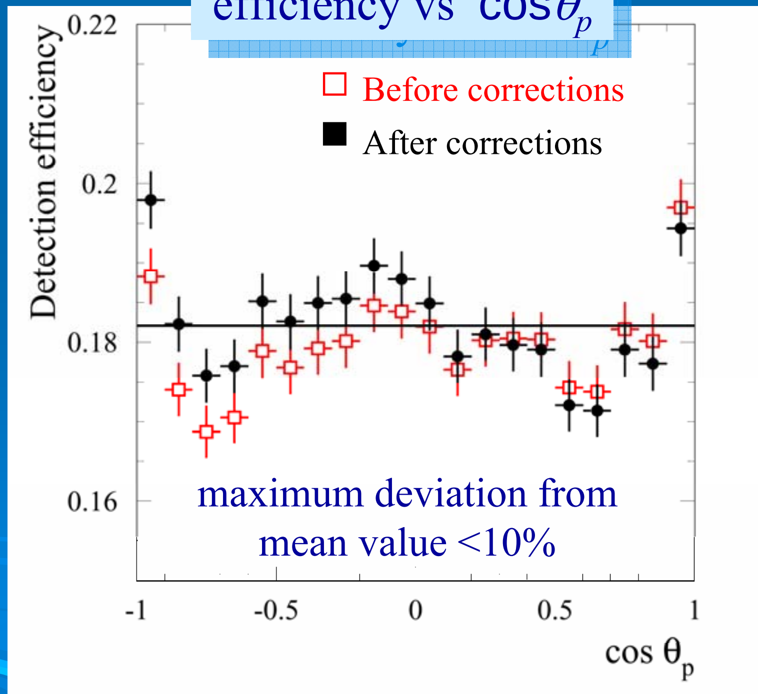
- Determined by MC simulation and corrected by Data/MC differences

- Corrections for:
  - χ^2 shape
  - nuclear interactions with detector material
  - particle-ID
  - photon detection (use $e^+e^- \to \mu^+\mu^-\gamma$ data)
  - dependence on G_E and G_M
  - Triggering

efficiency vs $m_{p\bar{p}}$



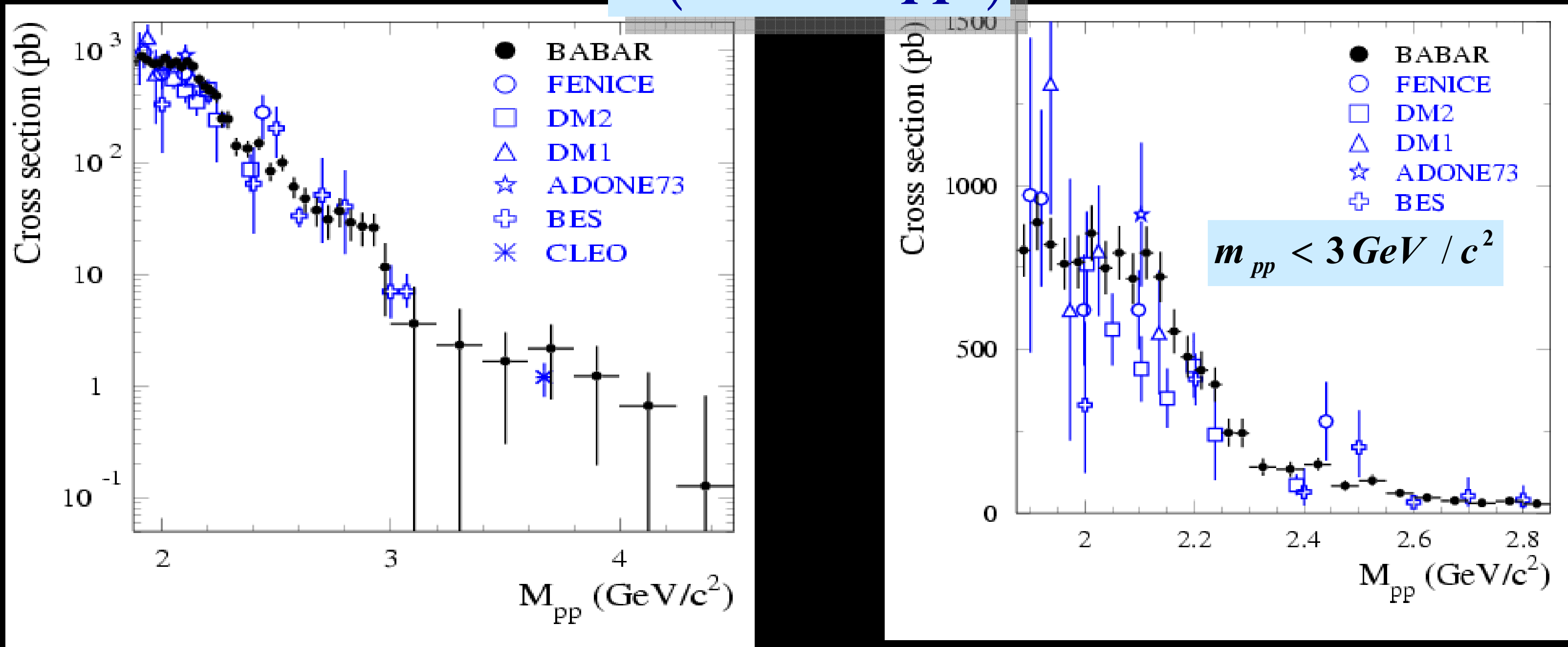
efficiency vs $\cos\theta_p$



$e^+e^- \to pÅ\gamma$: cross section

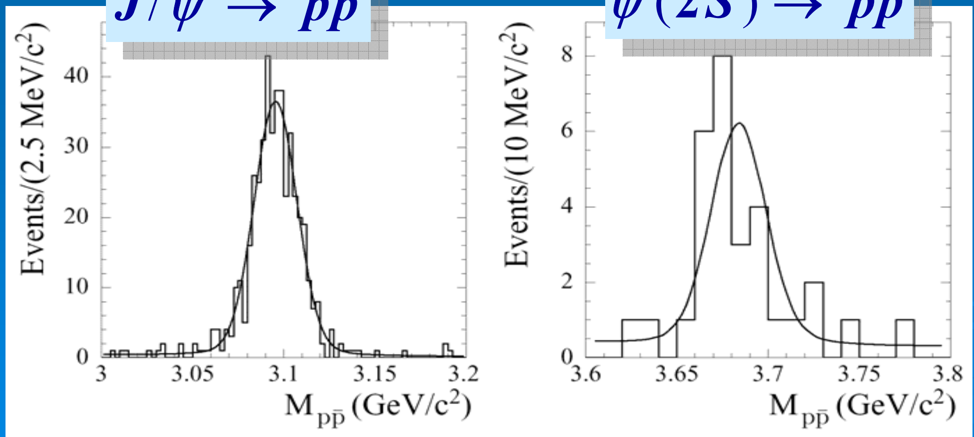
PRD 73, 012005 (2006)

$\sigma\left(e^+e^- \to p\bar{p}\right)$



$J/\psi \to p\bar{p}$

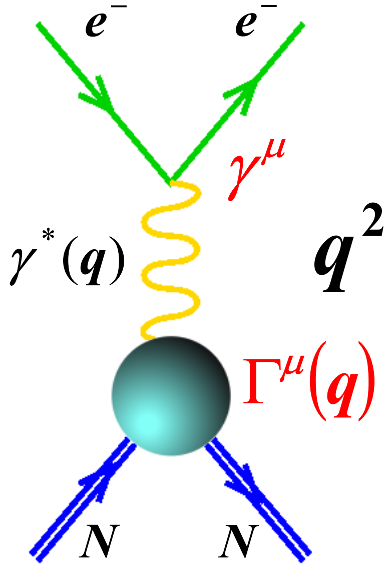
$\psi(2S) \to p\bar{p}$



Mode	BaBar BF	PDG 06
J/ψ → pÅ!	**(2.22 ± 0.16)·10⁻³**	**(2.17 ± 0.08)·10⁻³**
ψ(2S) → pÅ!	**(3.3 ± 0.9)·10⁻⁴**	**(2.65 ± 0.22)·10⁻⁴**

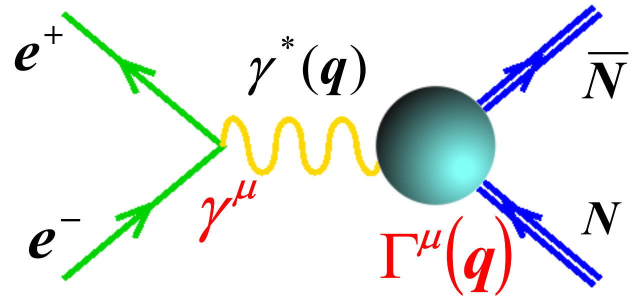
FF: Space-like and Time-like region

Space-like



$$q^2 < 0$$

Time-like



$$q^2 = s > 0$$

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

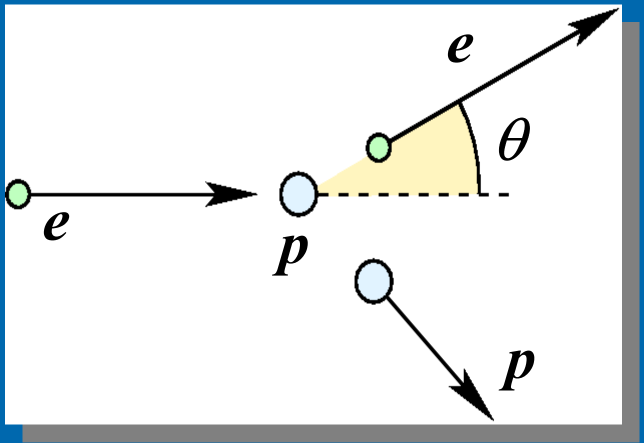
- Dirac (F_1) and Pauli (F_2) F.F.

$$F_1^p(0) = 1 \quad F_2^p(0) = 1$$
$$F_1^n(0) = 0 \quad F_2^n(0) = 1$$

- Sachs FF: Electric (G_E), Magnetic (G_M)

$$G_E(q^2) \equiv F_1(q^2) + \frac{q^2}{4M^2} F_2(q^2)$$
$$G_M(q^2) \equiv F_1(q^2) + F_2(q^2)$$

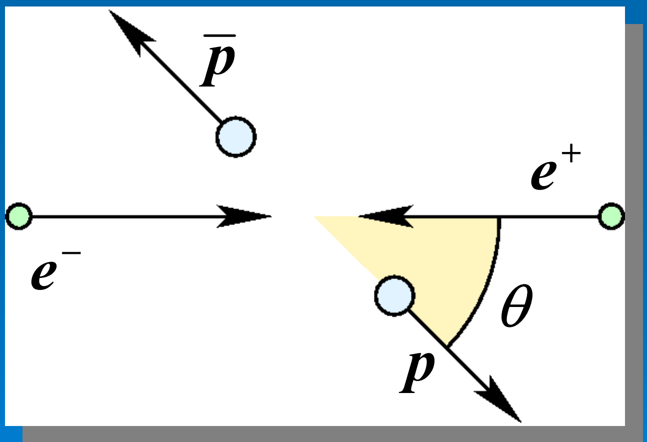
FF: Space-like and Time-like region



- **Elastic scattering**

$$\frac{d\sigma}{d\Omega}\left(q^2,\theta\right)=\frac{\sigma_M}{1-\tau}\left[G_E^2-\tau\left(1+2(1-\tau)\tan^2\frac{\theta}{2}\right)G_M^2\right]$$

$$\sigma_M=\frac{\alpha^2 E'\cos^2(\theta/2)}{4E^3\sin^4(\theta/2)} \qquad \tau\equiv\frac{q^2}{4M^2}$$



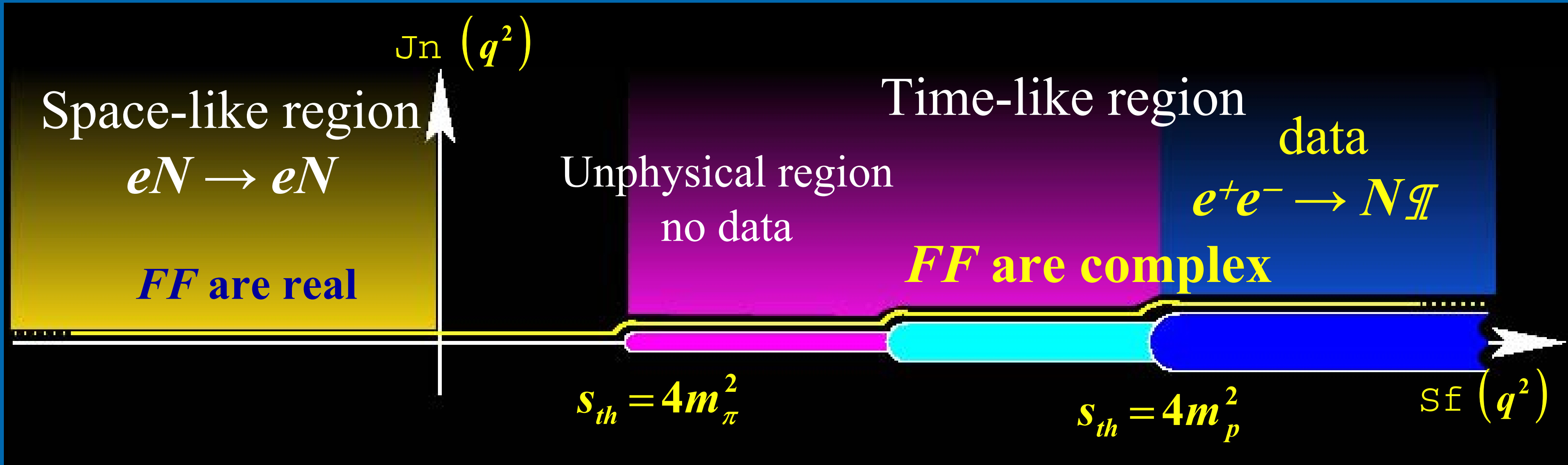
- **Annihilation**

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

$$\beta=\sqrt{1-\frac{1}{\tau}} \qquad C=\frac{y}{1-e^{-y}}; \quad y=\frac{\pi\alpha M_p}{\beta q}$$

C: correction for Coulomb interaction at threshold.
Not present in $e^+e^-\to n\bar{n},\ \Lambda\bar{\Lambda}$

FF properties: analyticity and asymptotic behavior



- by definition, at threshold: $G_E(4m_p^2) = G_M(4m_p^2)$

- perturbative QCD constrains the FF asymptotic behavior

$$q^2 \rightarrow -\infty \quad \Rightarrow \quad G_{E,M} \rightarrow \frac{\text{constant}}{q^4 \ln\left(q^2/\Lambda^2_{QCD}\right)^2}$$

- pQCD + analyticity

$$q^2 \rightarrow \pm\infty \quad \Rightarrow \quad G_{E,M}(q^2) = G_{E,M}(-q^2)$$

Measurement of the proton FF

- The moduli of the FF in the time-like region can be derived from measurements of the cross sections of $e^+e^- \leftrightarrow p\mathring{A}$ processes
- Many measurements both from $e^+e^- \rightarrow p\mathring{A}$ and $p\mathring{A} \rightarrow e^+e^-$ experiments
- Most experiments collected very low statistics ==> impossible to disentangle $|G_E|$ and $|G_M|$

Extract $|G_M|$ from the total cross section under the arbitrary assumption $|G_M| = |G_E|$

$$\sigma = \frac{4\pi\alpha^2 \beta C}{3 m_{p\bar{p}}^2} |F|^2, \qquad |F| = \sqrt{|G_M|^2 + \frac{1}{2\tau}|G_E|^2}$$

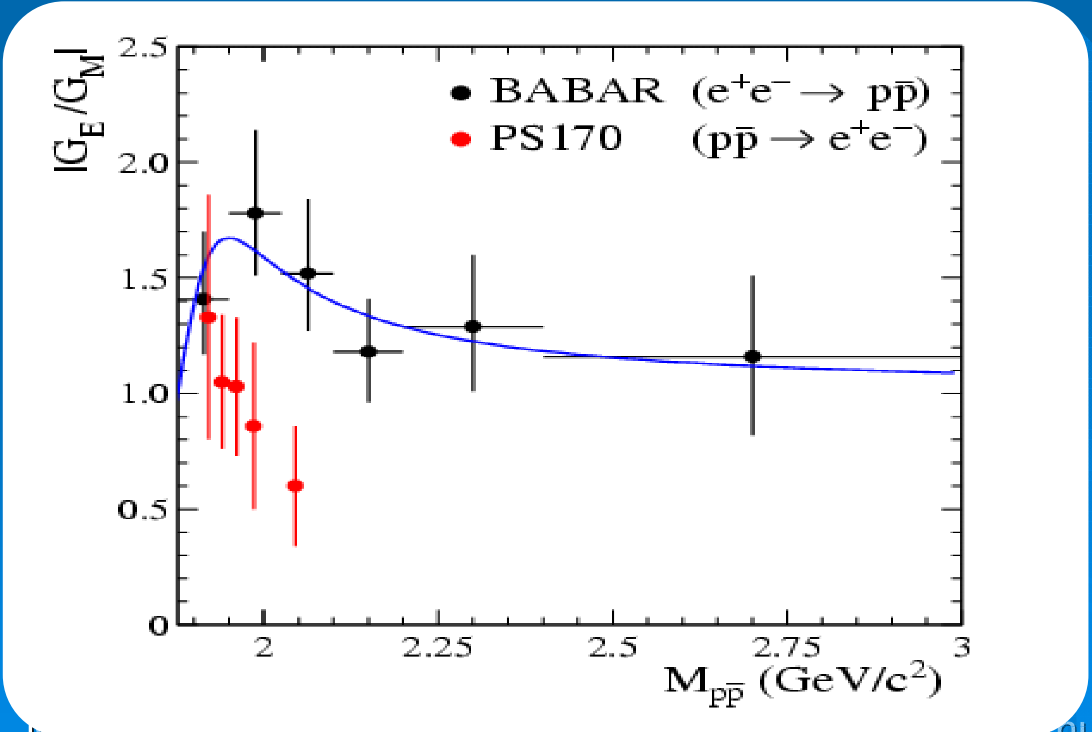
Quantitative information on $|G_E|$ only by PS170 and *BABAR* (by measuring the ratio $|G_E/G_M|$ from angular distributions)

$$\frac{d\sigma}{d\cos\theta} \propto \left(1 + \cos^2\theta\right) + \tau \left|\frac{G_E}{G_M}\right|^2 \sin^2\theta$$

Time-like $|G_E/G_M|$ measurements

- ***BABAR*** measured angular distribution from threshold up to $\sim$3 GeV/c^2
- Observed maximum at m ≅ 2 GeV/*c*2 (G_E dominance after threshold)

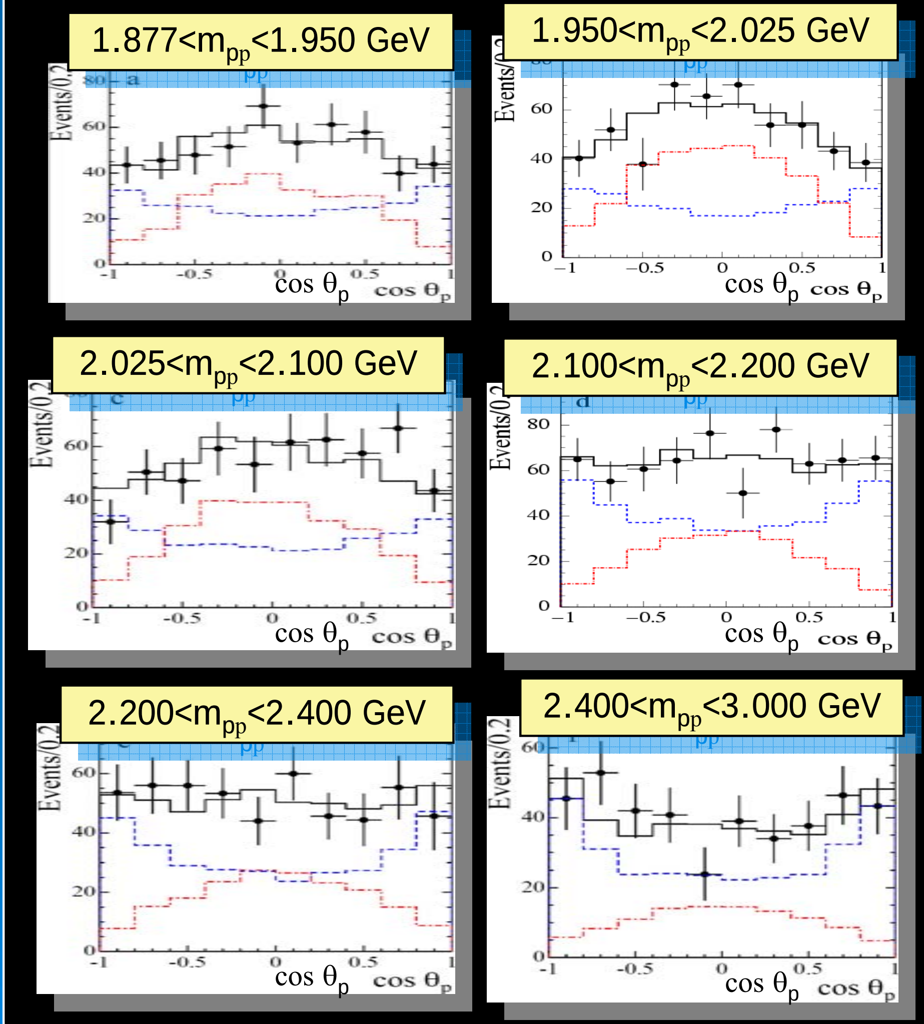
- Inconsistent with PS170 measurements at LEAR
- strong point in favour of ISR method: very weak angular dependence of detection efficiency



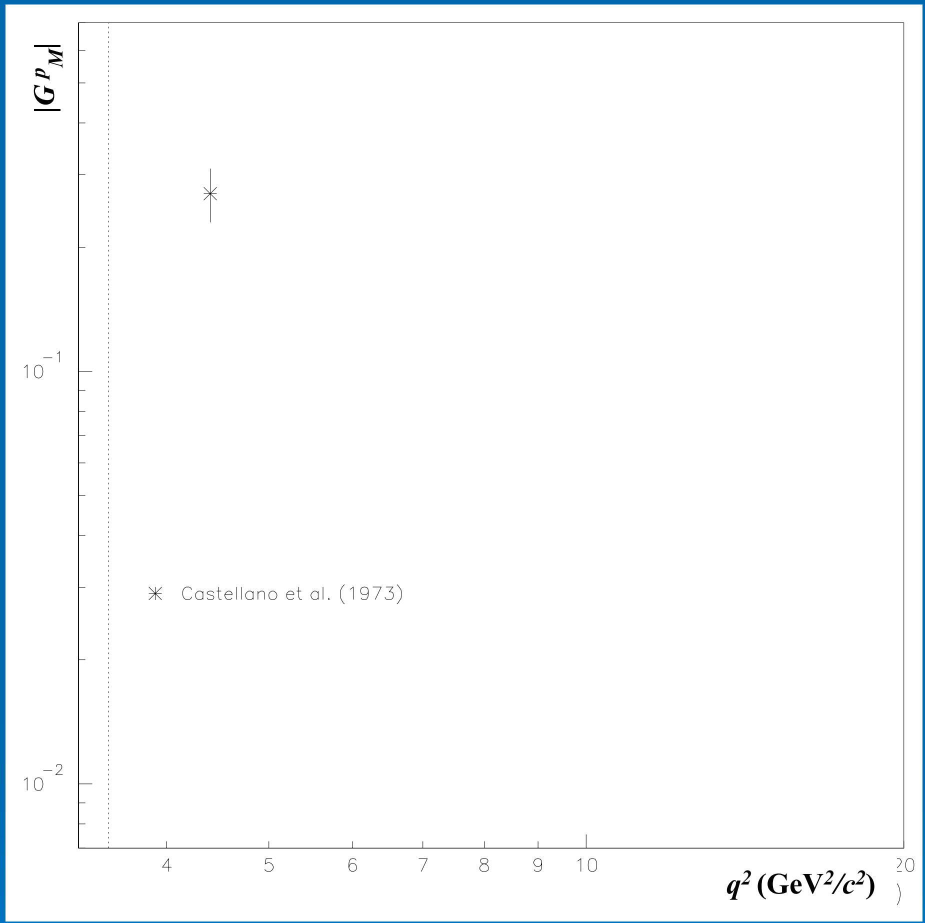
BABAR

$$\frac{d\sigma(G_M)}{d\cos\theta} \sim 1+\cos^2\theta_p$$

$$\frac{d\sigma(G_E)}{d\cos\theta} \sim \sin^2\theta_p$$



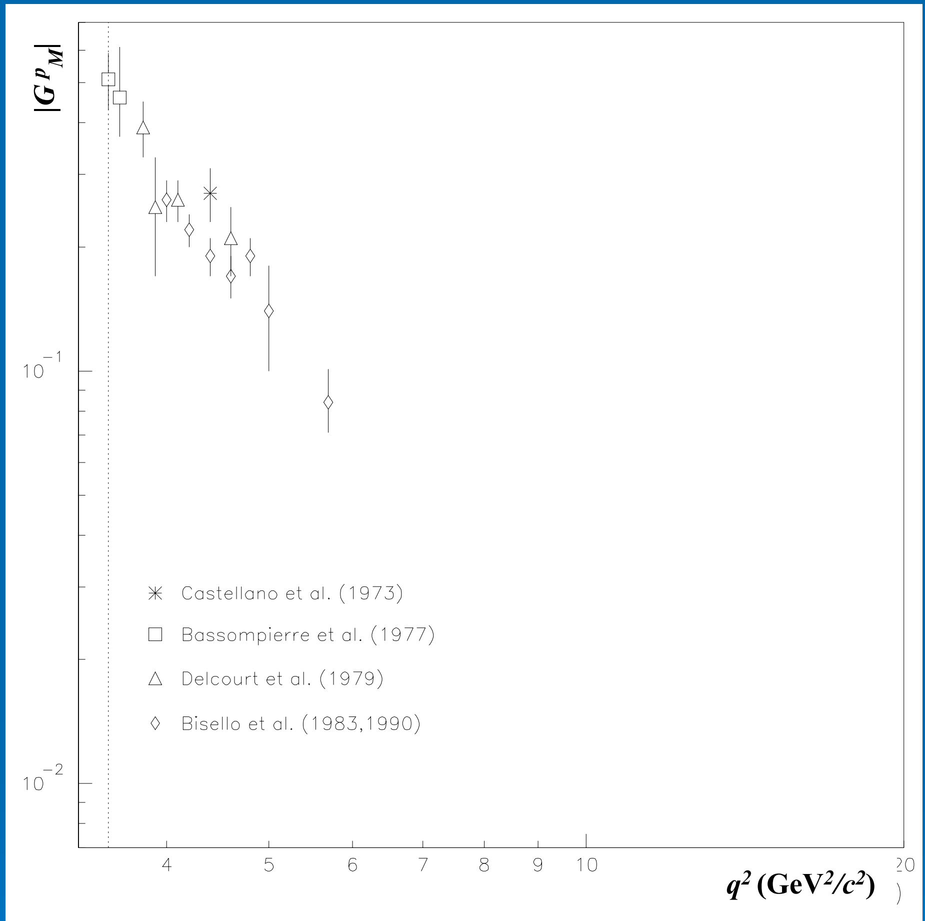
History of $|G_M|$ measurements



First successful measurements:

- **1973 ppbar @ ADONE** (Frascati)
  - $e^+e^- \to p\bar{p}$
  - 25 events in 0.2 pb^{-1} of data at 4.4 GeV^2

History of $|G_M|$ measurements



First successful measurements:

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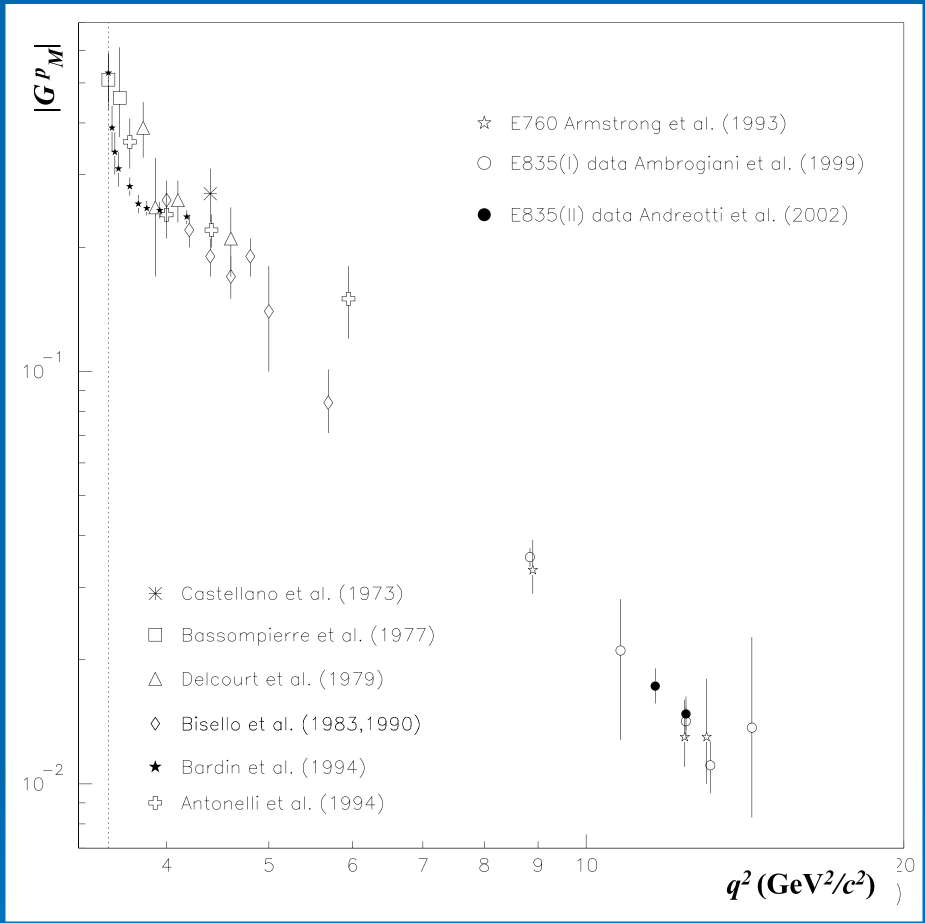
70's and 80's:

- ELPAR exp. (CERN)
  - $p\bar{p}$ annihilations at rest
- **DM1, DM2 @ DCI (Orsay)**
  - $e^+e^- \rightarrow p\bar{p}$
  - 0.7 pb^{-1} of data collected
  - first attempts to measure angular distributions

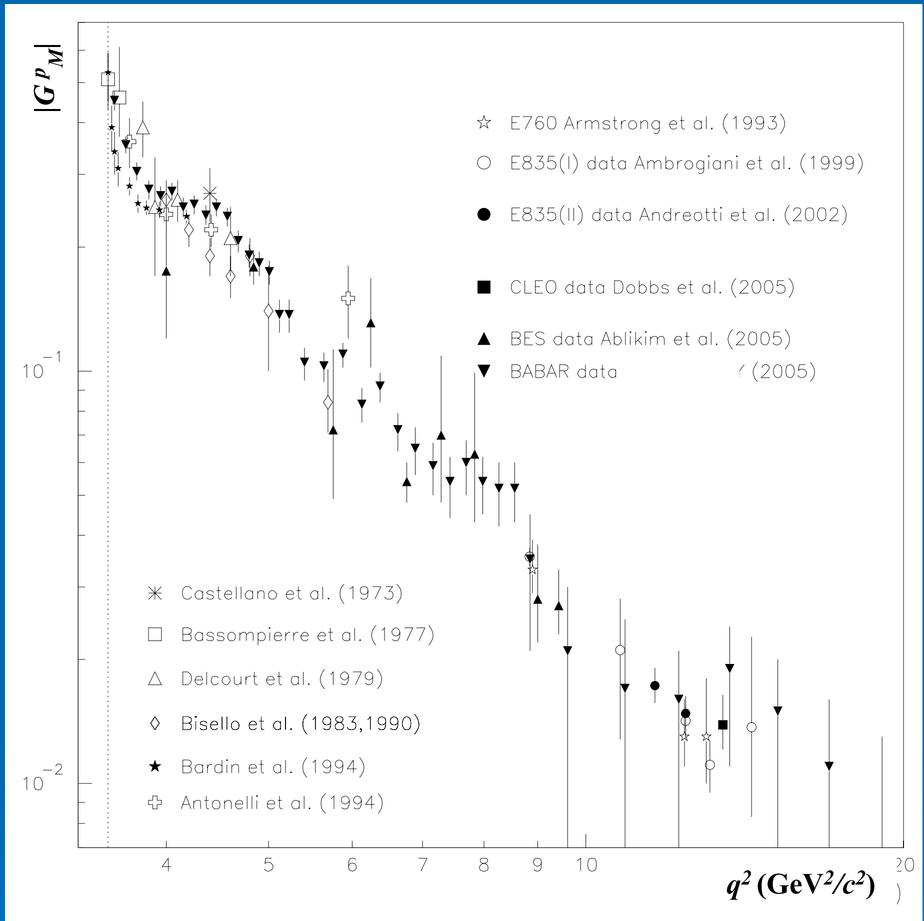
History of $|G_M|$ measurements



Experiments in the 90's :

- **FENICE @ ADONE**
  - Mainly devoted to neutron FF measurement
  - 69 $e^+e^- \to p\bar{p}$ events in 4 q^2 bins
- **PS170 @ LEAR (CERN)**
  - First high statistics experiments
  - $\bar{p}$ beam stopped in a liquid H target
  - 3667 $p\bar{p} \to e^+e^-$ events in 9 q^2 bins
  - Angular distribution measured compatible with $|GE| = |GM|$
- **E760 and E835 (FNAL)**
  - $p\bar{p} \to e^+e^-$ (fixed target)
  - First measurements of FF at high q^2

History of $|G_M|$ measurements

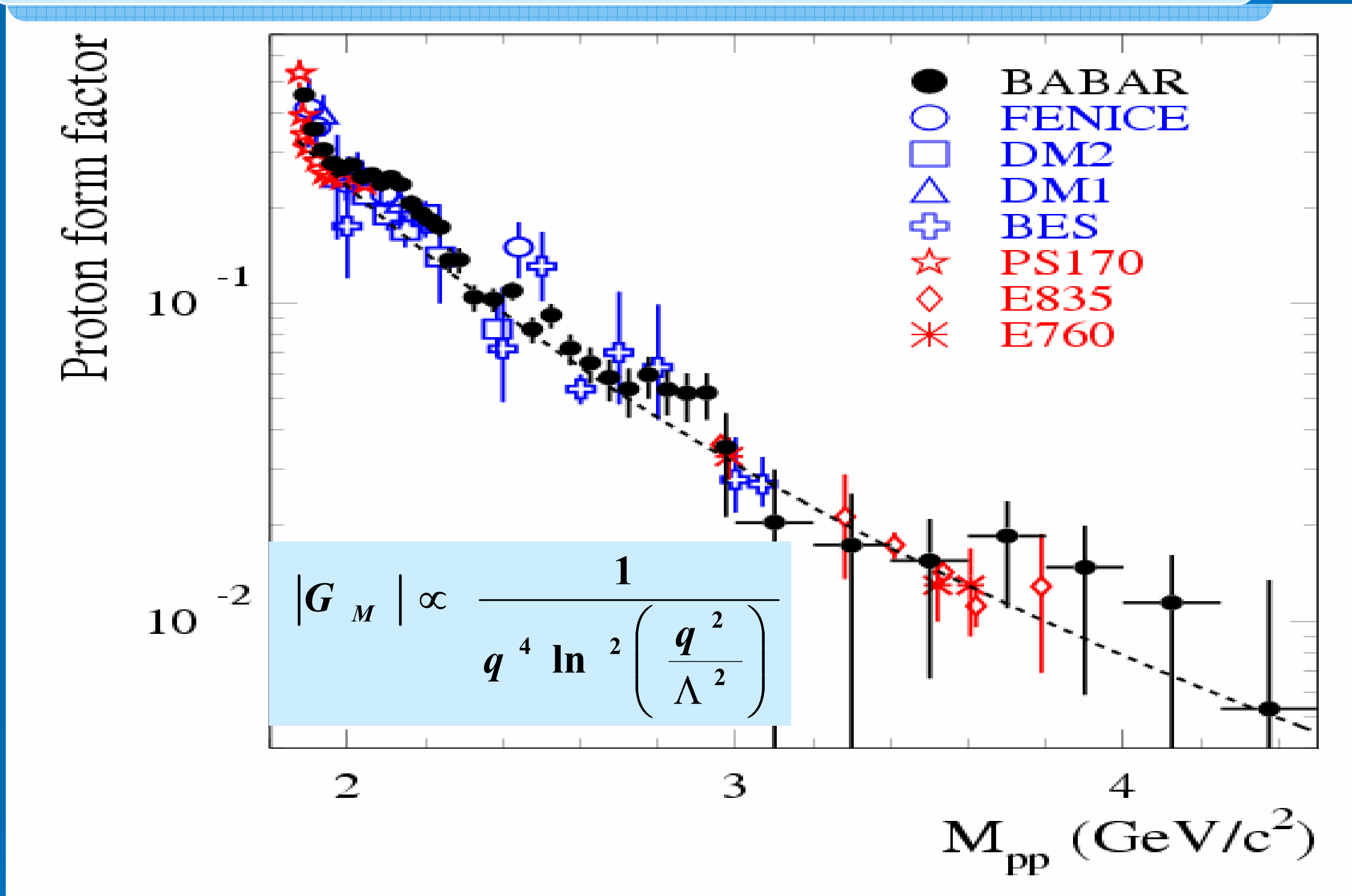


New e^+e^- colliders

- **CLEO @ CESR (2005)**
  - Only 14 events
- **BES @ BEPC (2005)**
  - 9 q^2 bins from 4 GeV^2 up to 9 GeV^2 (~200 events total)
  - No angular measurements
  - Assume $|G_E| = |G_M|$
- ***BaBar* @ PEP-II (2006)**
  - ISR events
  - ~4000 events divided in ~40 q^2 bins
  - Results presented assuming $|G_E| = |G_M|$

Closer look at the results:

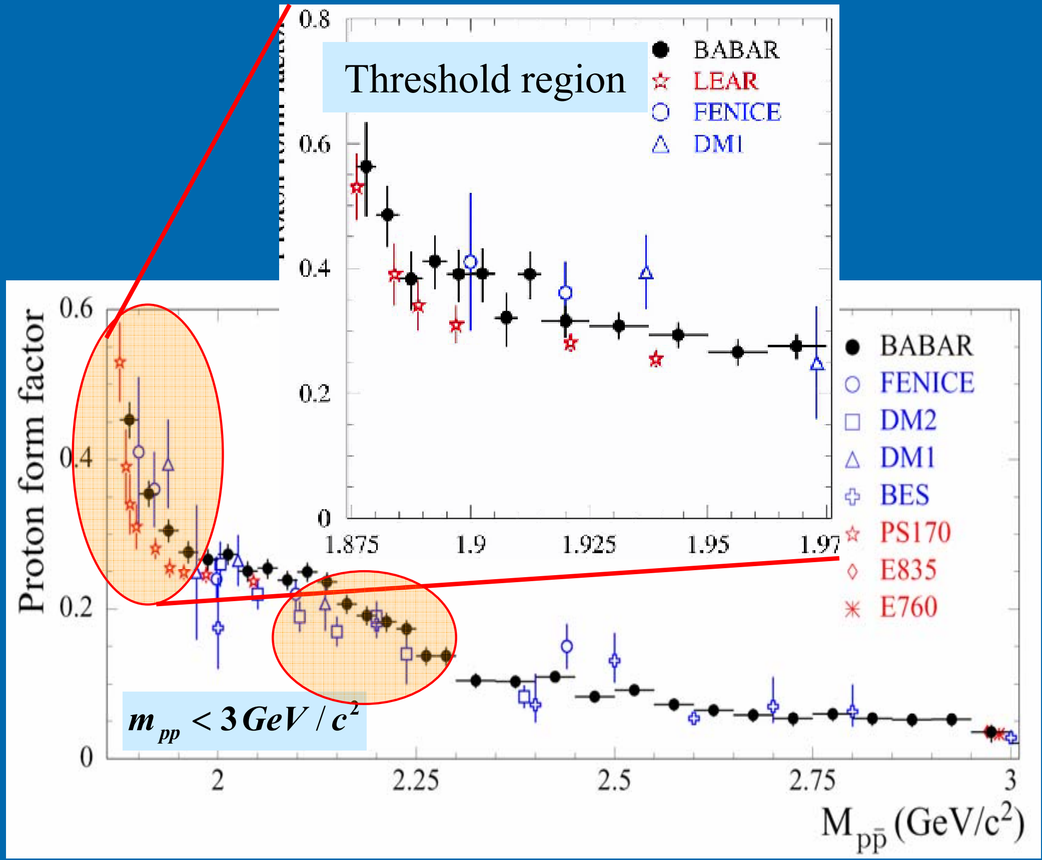
Fit to the pQCD prediction (assuming $\Lambda = 0.3$ GeV):

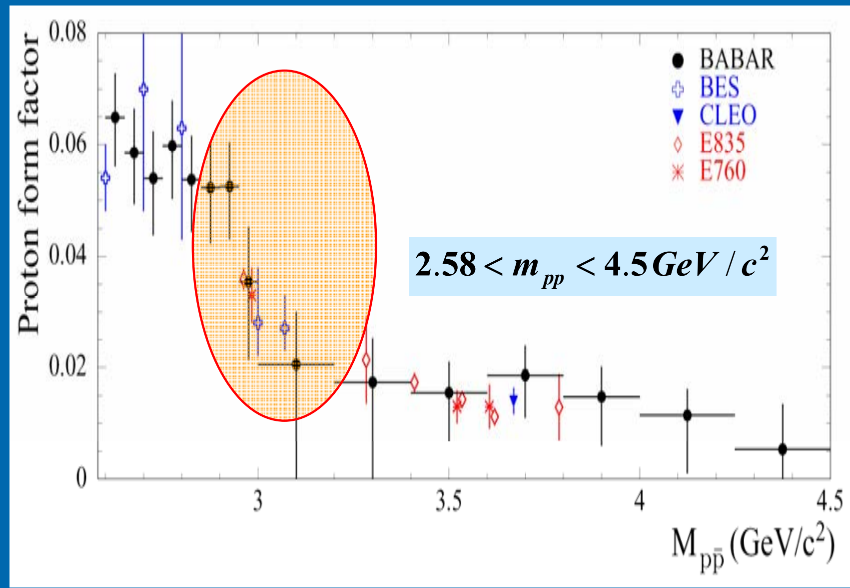


$$|G_M| \propto \frac{1}{q^4 \ln^2\left(\frac{q^2}{\Lambda^2}\right)}$$

➢ Asymptotic behavior holds already for $m_{p\bar{p}} > 3$ GeV/c^2

Closer look at the results:





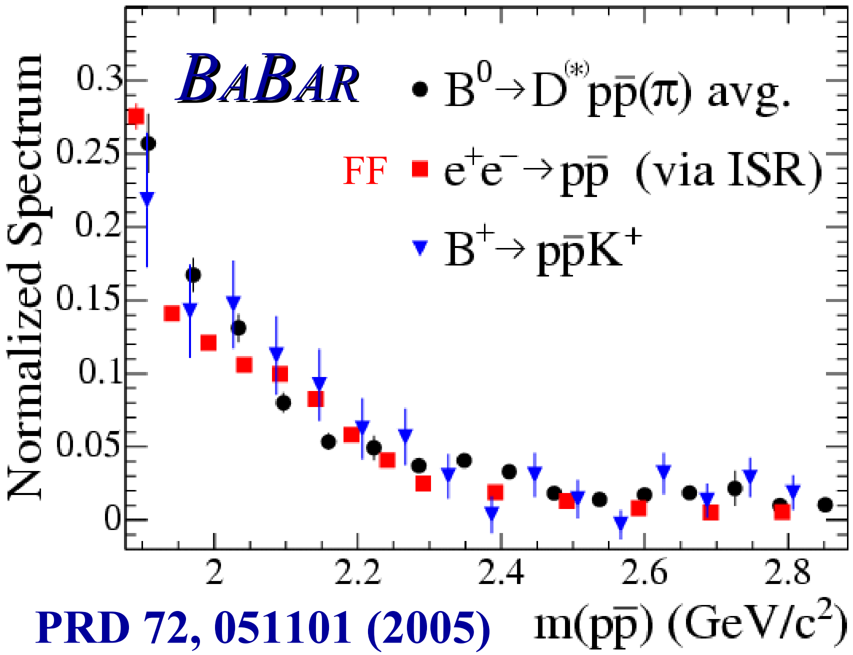
Sharp drops at $m_{p\bar{p}}$~2.2 and 3.0 GeV,
- no interpretations yet
- seen also in cross section distribution

Steep rise of the FF at threshold seen by PS170 and *BABAR*

Why the rise of FF at threshold?

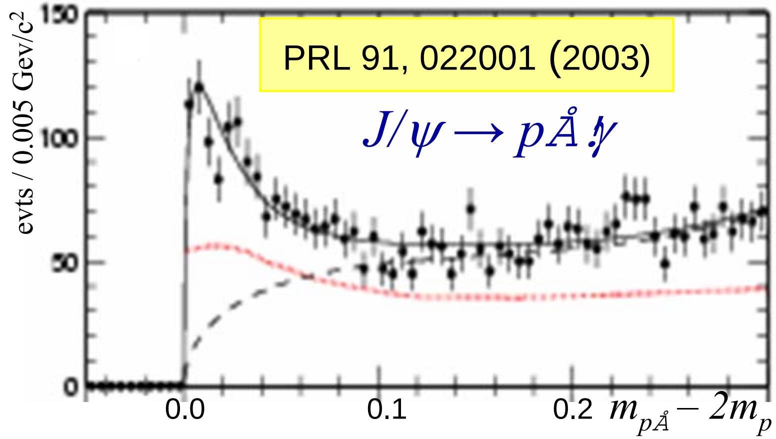
- Similar behavior observed in the *pÅ* mass spectrum in processes with different dynamics:

Mass spectrum of the *pÅ* system in several *B* decays compared to *FF* distribution



PRD 72, 051101 (2005)
PRD 74, 051101 (2006)

BES measurement of $J/\psi \to p$Å γ
Sharp peak of $m_{pÅ}$ at threshold
opposite C-parity



Fit consistent with a sub-threshold resonant structure with $J^{PC} = 0^{\pm +}$ (m ~1860 MeV/c^2, $\Gamma < 30$MeV), inconsistent with known states

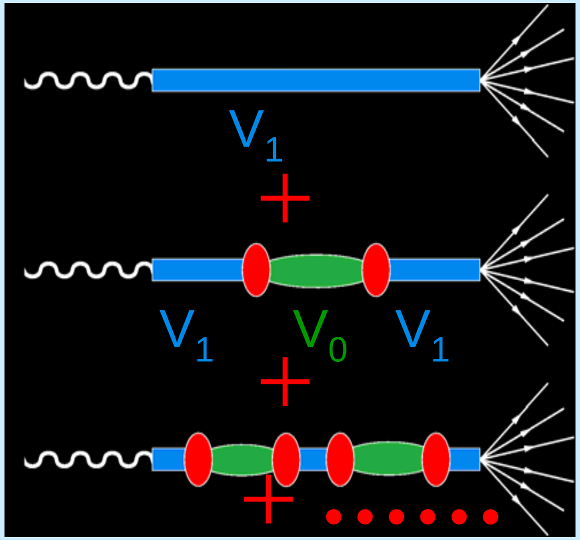
Similar results on B decays published by **Belle:**

PRL 88, 181803 (2002)
PRL 89, 151802 (2002)

A possible explanation

- The rise is the tail of a narrow resonance below threshold ==> Baryonium

- This hypothesis can be tested:
  - A meson V_0, with vanishing coupling to e^+e^-, which decays trough a ρ/ω recurrence (V_1), should show up as a dip in several hadronic cross sections

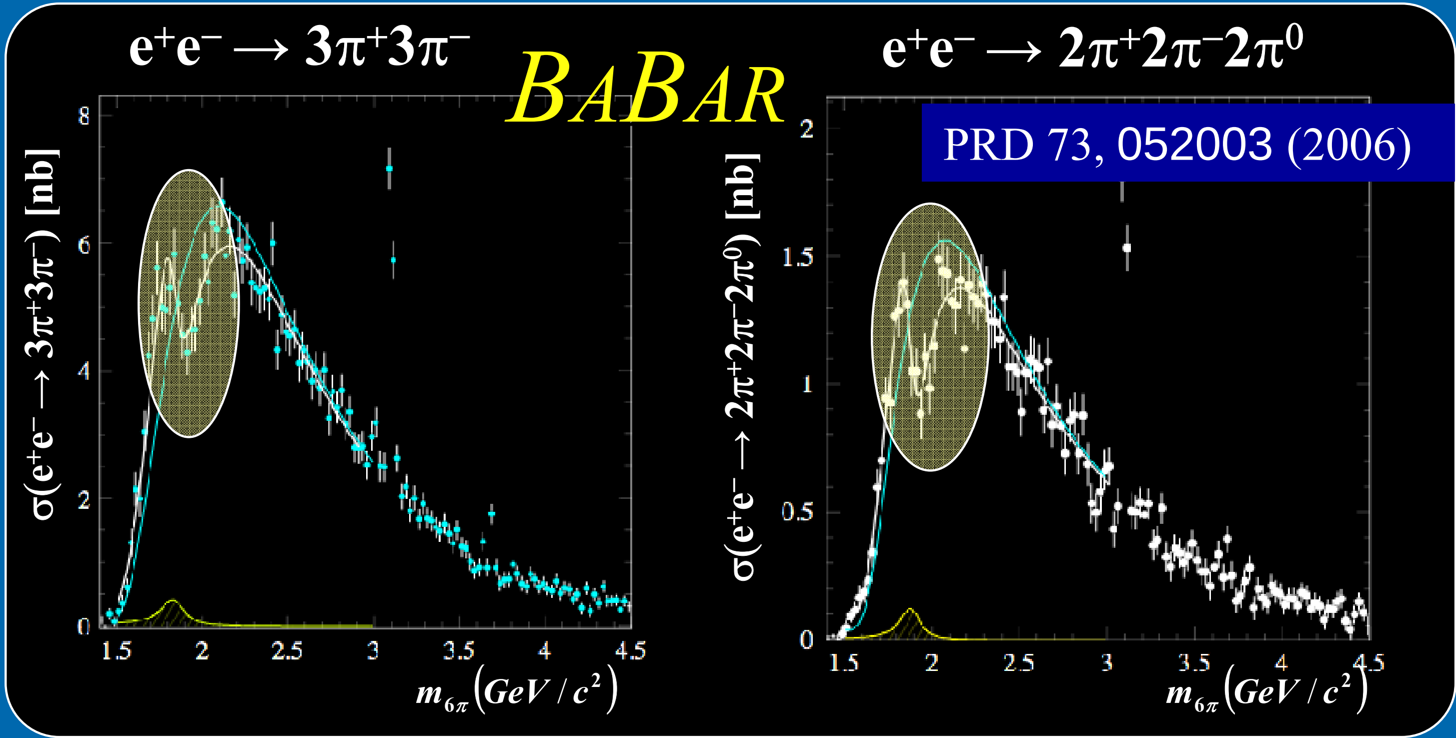


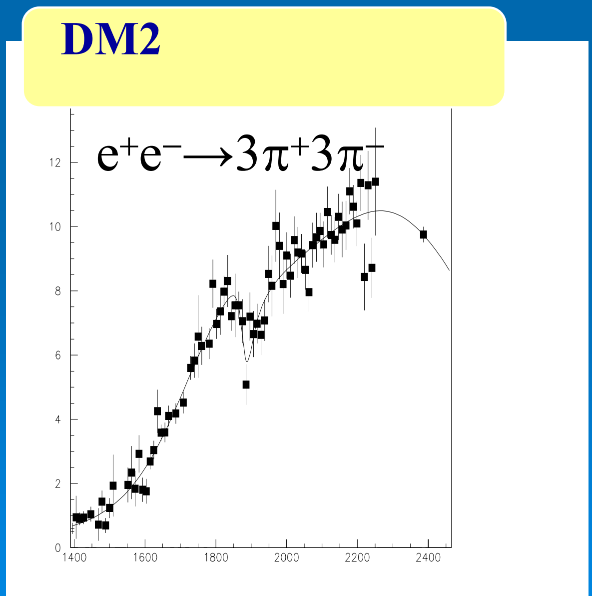
$$A \propto \frac{1}{s-M_1^2}\left(1 + a\frac{1}{s-M_0^2}a\frac{1}{s-M_1^2} + ...\right)$$

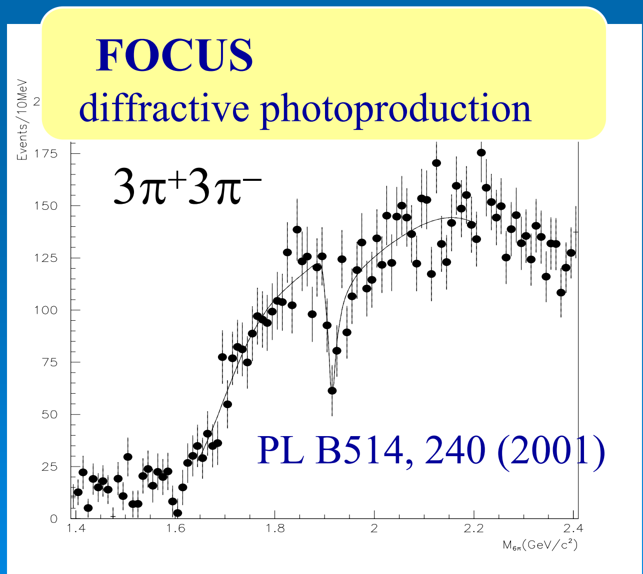
$$A = \frac{s-M_0^2}{\left(s-M_1^2\right)\left(s-M_0^2\right)-a^2}$$

P.J. Franzini and F.J. Gilman (1985)

Example: observed dip in 6π production



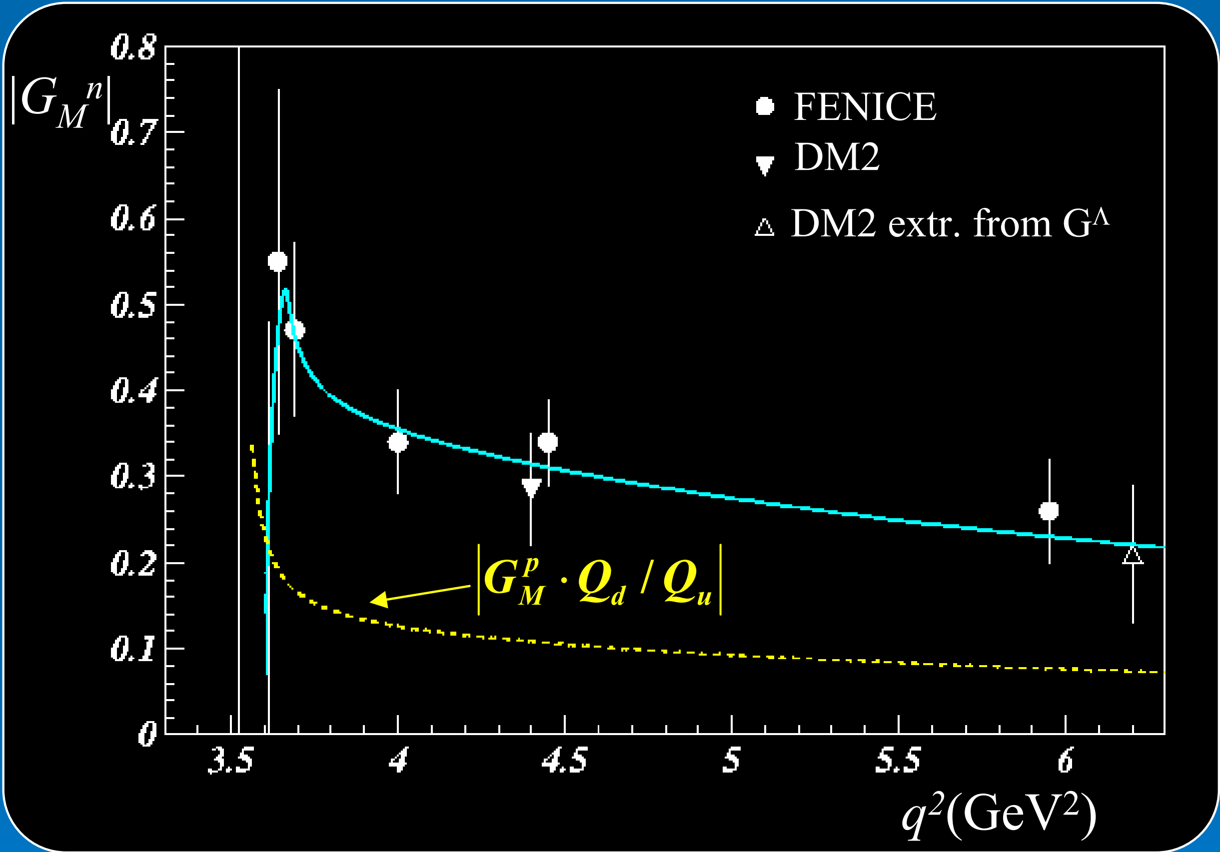




V_0	$M(MeV/c^2)$	$\Gamma(MeV)$
hadrons	~1870	10÷20
DM2	1930(30)	35(20)
FOCUS	1910(10)	37(13)
BABAR	1880(50)	130(30)
BABAR (π^0)	1860(20)	160(20)

Neutron Form Factor

- Measurements only from FENICE and DM2 experiments
- No Coulomb correction at threshold ==> $\sigma(s=4m_n^2) = 0$



data - theoretical prediction comparison

	$\lvert G_M^n / G_M^p \rvert$
data	**~ 1.5**
naively	**~ $\lvert Q_d/Q_u \rvert$ = 0.5**
pQCD	**< 1**

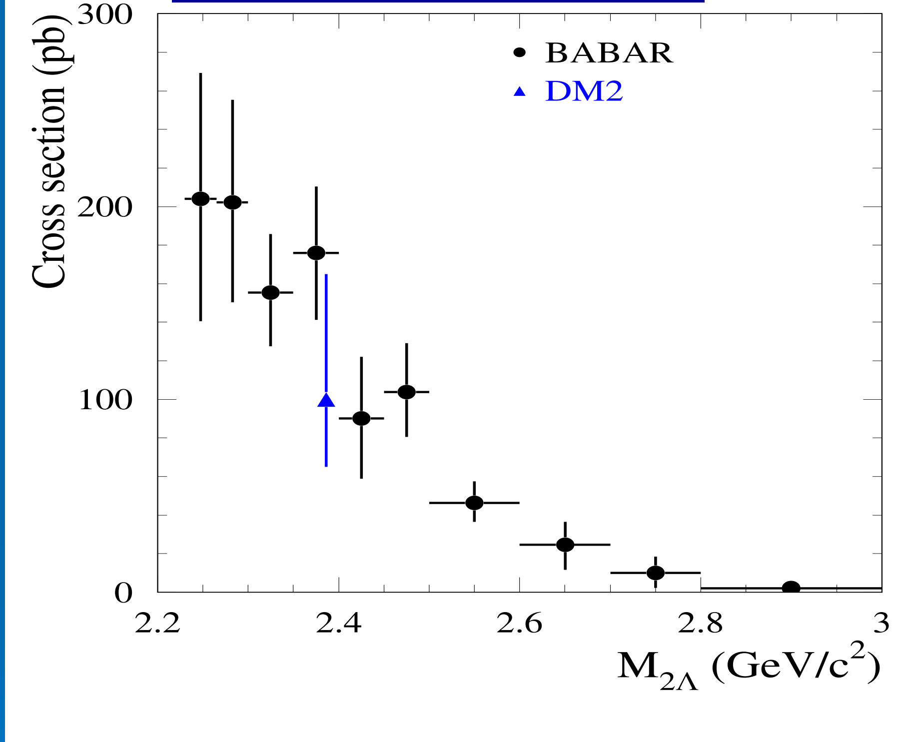
Need to be clarified with new neutron FF measurements

Measurement of $e^+e^- \to \Lambda\bar{\Lambda}$ cross section and Λ FF

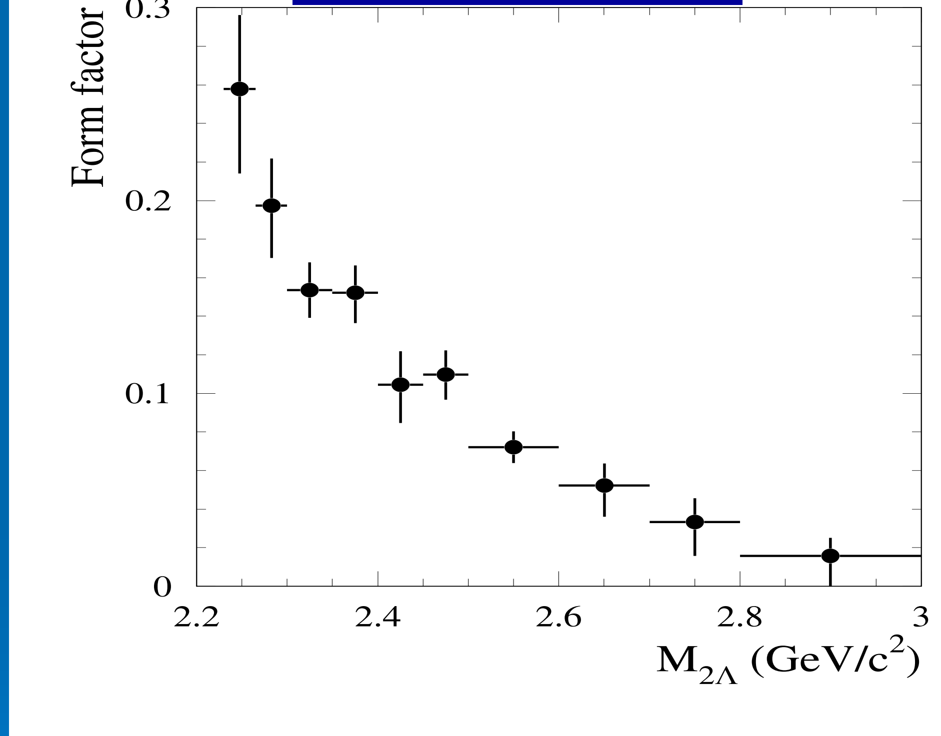
NEW BABAR RESULT!

- $e^+e^- \to \gamma\Lambda\bar{\Lambda}$ recently measured at BABAR (presented at LP2007, submitted to PRD)

$\sigma(e^+e^- \to \Lambda\bar{\Lambda})$

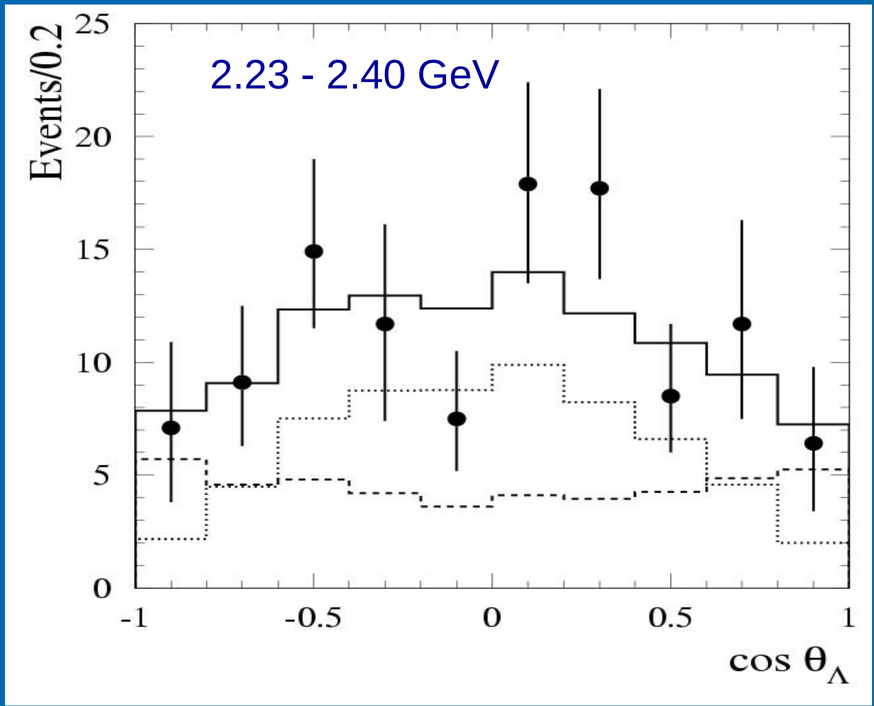


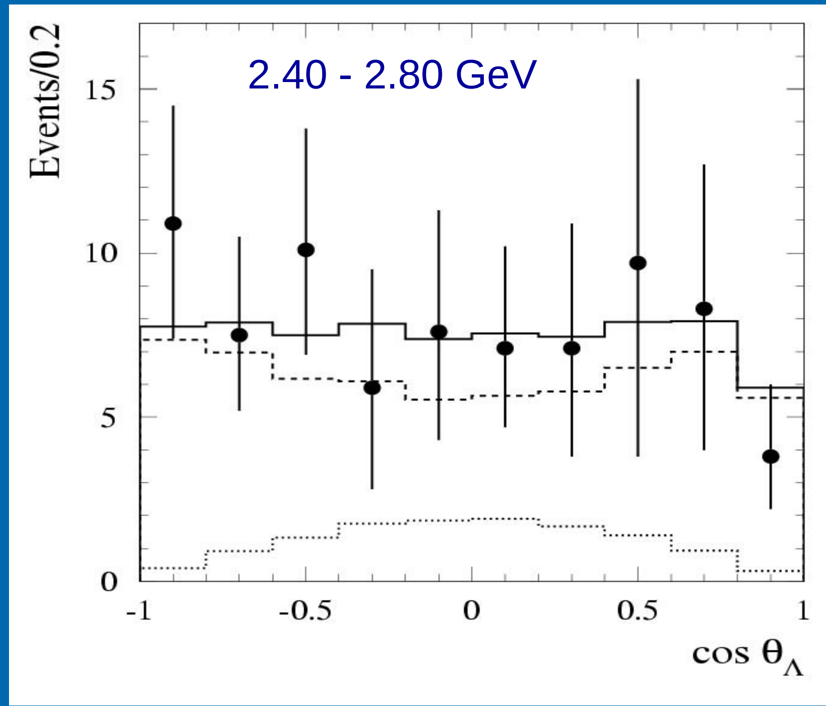
$|G_M^\Lambda|$ vs $m_{\Lambda\Lambda}$



Analyzed 232 fb^{-1}
Signal: 204 ± 19
Background: 15 ± 3

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





- Extract $|G_E/G_M|$ from angular distributions:

$m_{\Lambda\Lambda}$, GeV/c^2	N	N_{bkg}	$\lvert G_E/G_M \rvert$
2.23-2.40	120	3 ± 5	$1.73^{+0.99}_{-0.57}$
2.40-2.80	96	10 ± 6	$0.71^{+0.66}_{-0.71}$

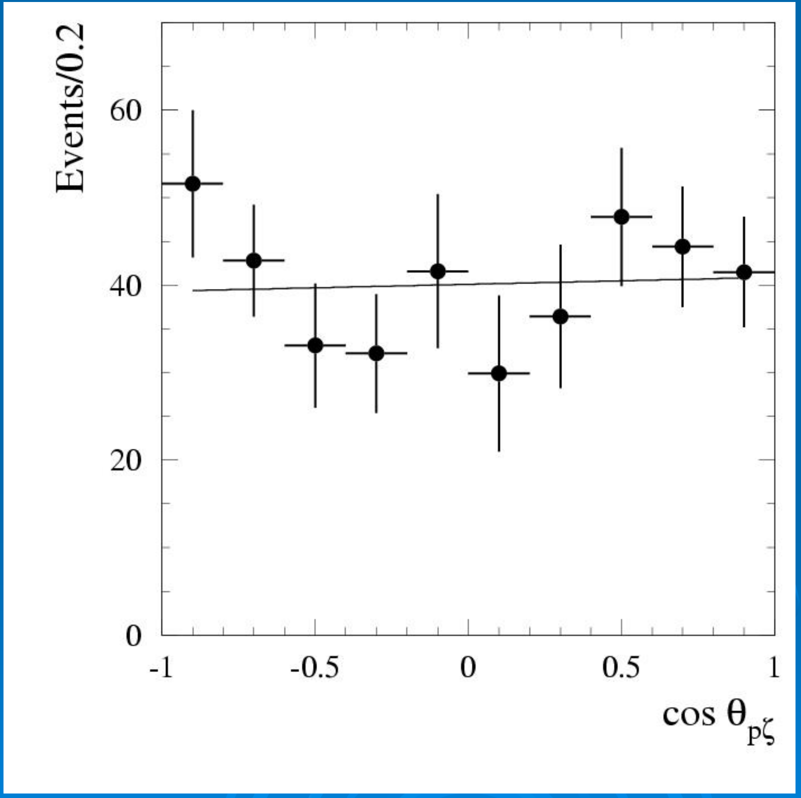
- Compatible with $|G_E/G_M| = 1$, but also with results from proton FF

Λ polarization

- If the relative phase ϕ between G_E and G_M is different from zero, the outgoing baryons are polarized in the direction normal to the scattering plane
  - A.Z. Dubnickova *et al*., Nuovo Cim. A109, 241 (1996), Brodsky *et al*. hep-ph/0310277
- Polarization measured using correlation between the directions of the Λ polarization vector and the momentum of decay proton in Λ rest frame

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta_{p\xi}} = A(1+\alpha_\Lambda \varsigma_f \cos\theta_{p\varsigma}), \quad \alpha_\Lambda = 0.642 \pm 0.013$$

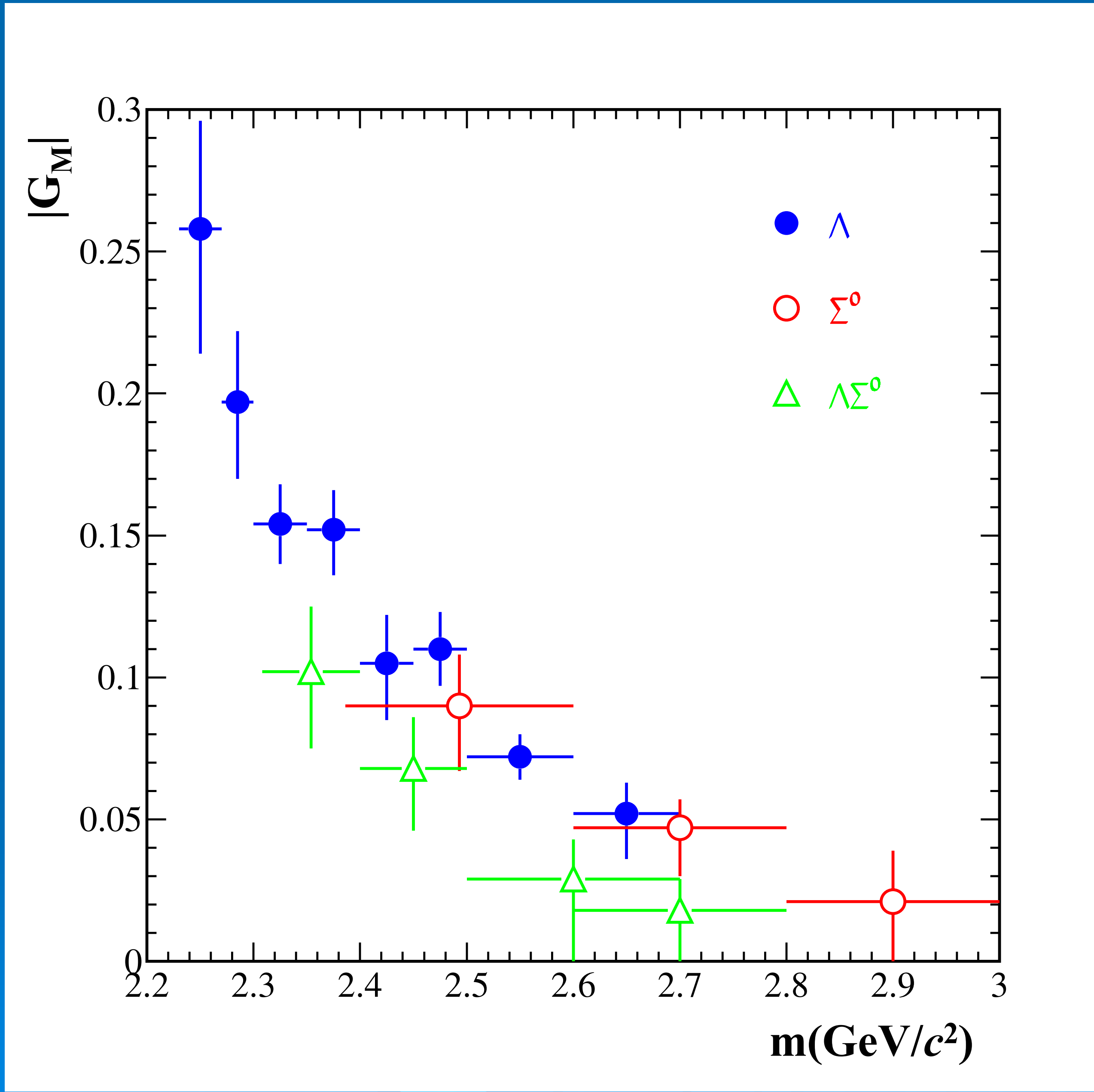
$$\textit{with the polarization } \varsigma_f \propto \sin\phi$$



- Slope in data is 0.020 ± 0.097 for $M_{\Lambda\Lambda} < 2.8$ GeV
  ==> $-0.22 < \varsigma_f < 0.28$ (90% CL)
- Under $|G_E|=|G_M|$ assumption

$$-0.76 < \sin\phi < 0.98$$

Baryons FF measurement in BABAR



Summary

- Time-like Proton FF have been measured at several e^+e^- and *pÅ* facilities for the last ~30 years, most of them statistically limited

Precise results from *BABAR* obtained via ISR:

- most accurate measurements of **σ($e^+e^- \to$ *pÅ*)** and proton FF
- FF measured from threshold up to $q^2 \sim 20$ GeV^2
- drops in the cross section and FF observed at $q^2 \sim 4.4$ and 9 GeV^2
- enhancement at threshold of the FF confirmed
- $|G_E/G_M|$ measured via angular distribution for $q^2 < 9$ GeV^2
  - $|G_E/G_M| > 1$ just above threshold (disagreement with previous results)

- Other open questions in Nucleon FF measurements:
  - $|G_M^n| > |G_M^p|$ contrary to expectations
  - JLab results on space-like proton FF

New results from *BABAR* on Λ Form Factors:

- **σ($e^+e^- \to \Lambda\Lambda$)** and Λ FF measured from threshold up to 3 GeV
- Angular distribution and polarization measurements ==> first attempts to determine $|G_E/G_M|$ and relative phase between G_E and G_M

Perspectives

- *BABAR* :

  - will have 4X data by 2008 ==> increase the precision on $p\mathring{A}$ and $\Lambda\bar{\Lambda}$
- expected new results from Belle in a near future

- τ/charm factory at Beijing can use ISR, too
- VEPP-2000 (BINP) :

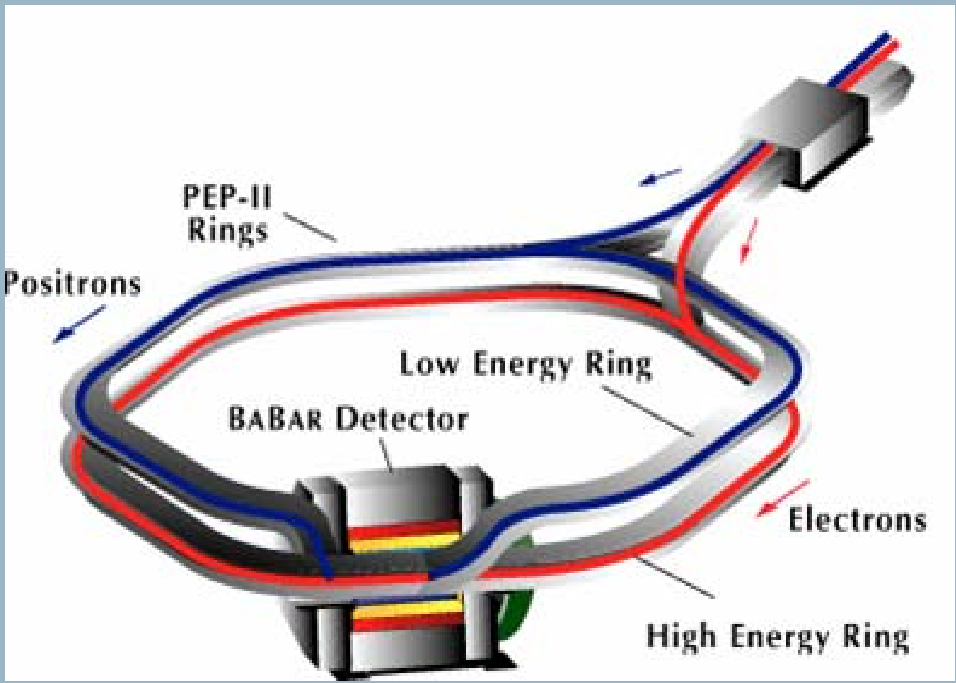
  - near threshold $e^+e^- \to p\mathring{A}$
- PANDA @ GSI:

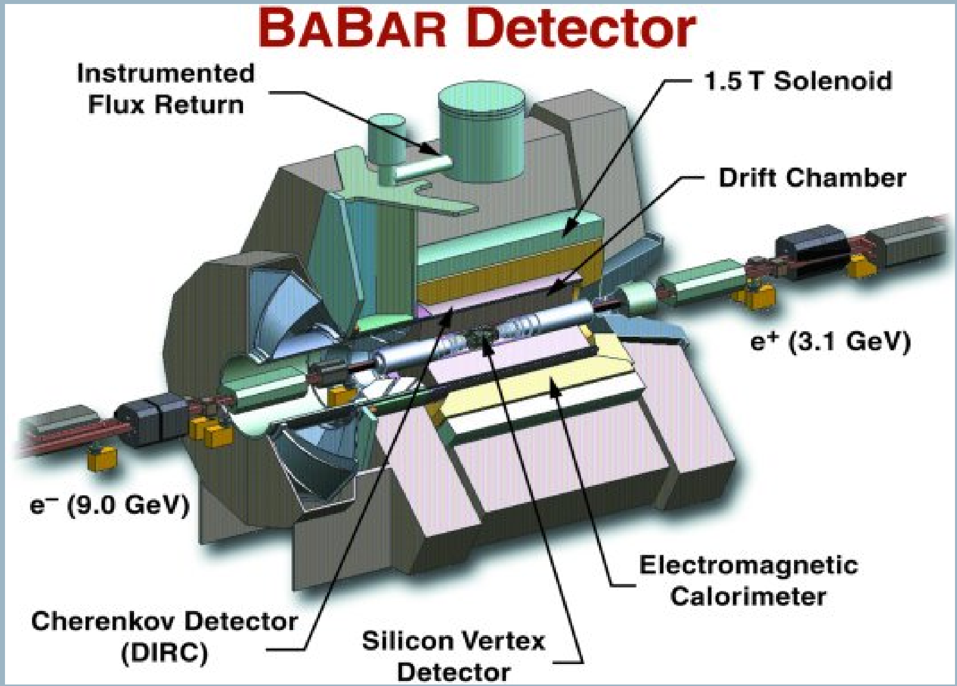
  - $p\mathring{A} \to e^+e^-$ up to 20 GeV^2

- ? DANAE (Frascati) $e^+e^- \to n\ddot{A}$, $e^+e^- \to p\mathring{A}$
- ? Super-B factory

BACKUP SLIDES

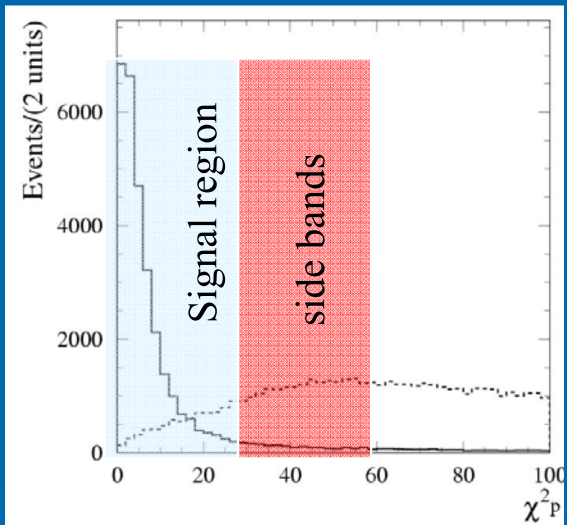
PEP-II and *BABAR*



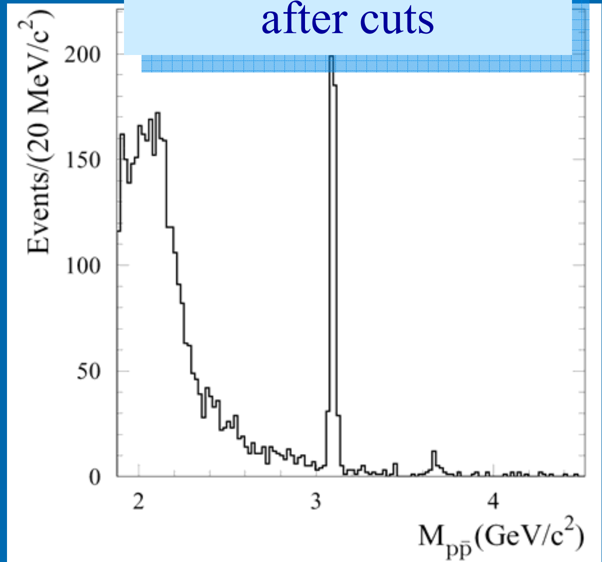


$e^+e^- \to p$Åγ : background

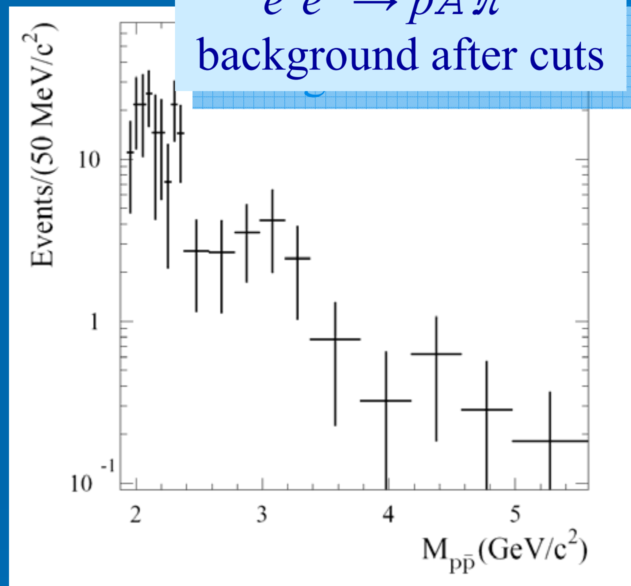
- 4025 events selected in 232 fb^{-1} of data
- ~6% residual background, dominated by non ISR $e^+e^- \to p$Åπ^0



mass of pÅ system after cuts



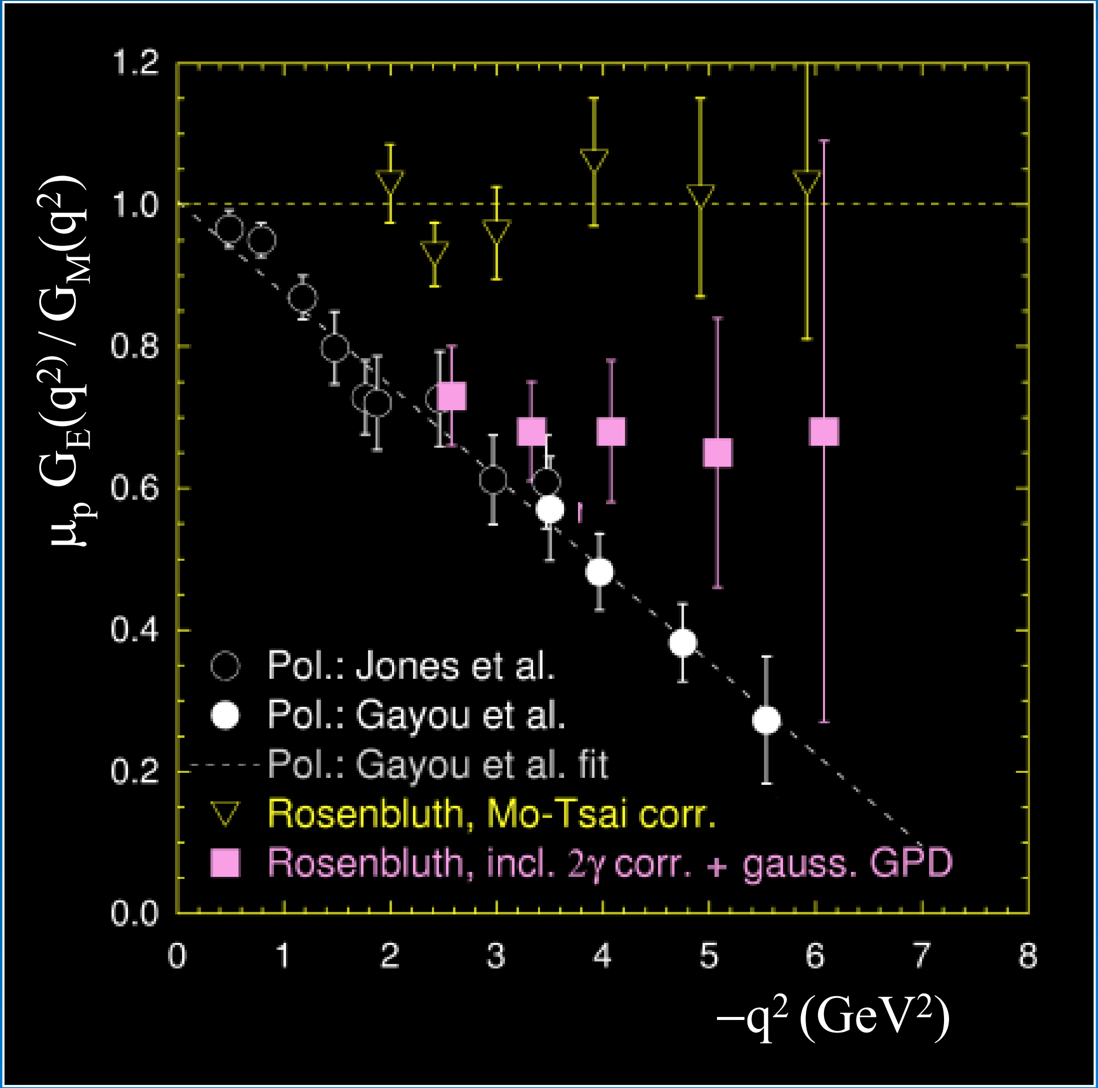
$e^+e^- \to p$Åπ^0 background after cuts



Background Summary

	$\pi^+\pi^-\gamma$	$K^+K^-\gamma$	$p\bar{p}\pi^0$	$p\bar{p}\pi^0\gamma$	*uds*	$p\bar{p}\gamma$	data
N_1	5.9$\pm$2.5	2.5$\pm$1.0	229$\pm$32	13$\pm$3	26$\pm$4	3737$\pm$75	4025

Space-like G_E/G_M measurements



- Scaling law predicts:

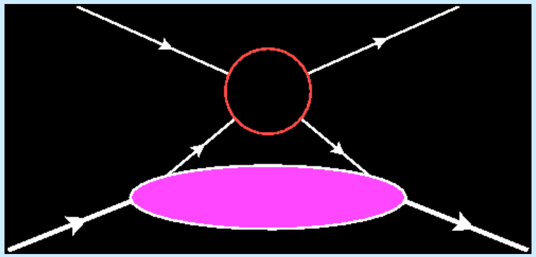
  $G_E(q^2) \approx G_M(q^2)/\mu_p$

Jlab measurement
polarization method

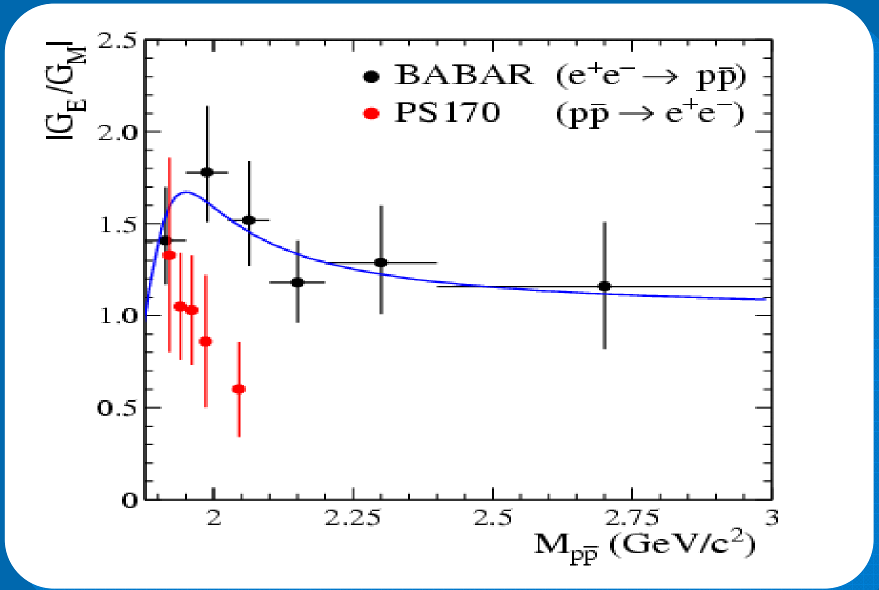
$$\frac{G_E(q^2)}{G_M(q^2)} = -\sqrt{\frac{-2\varepsilon}{\tau(1+\tau)}}\,\frac{\mathcal{P}_{||}}{\mathcal{P}_{\perp}}$$

$$\frac{1}{\varepsilon} = 1 + 2(1-\tau)\tan^2\left(\frac{\theta}{2}\right)$$

2γ + GPD correction



Dispersive analysis of G_E/G_M



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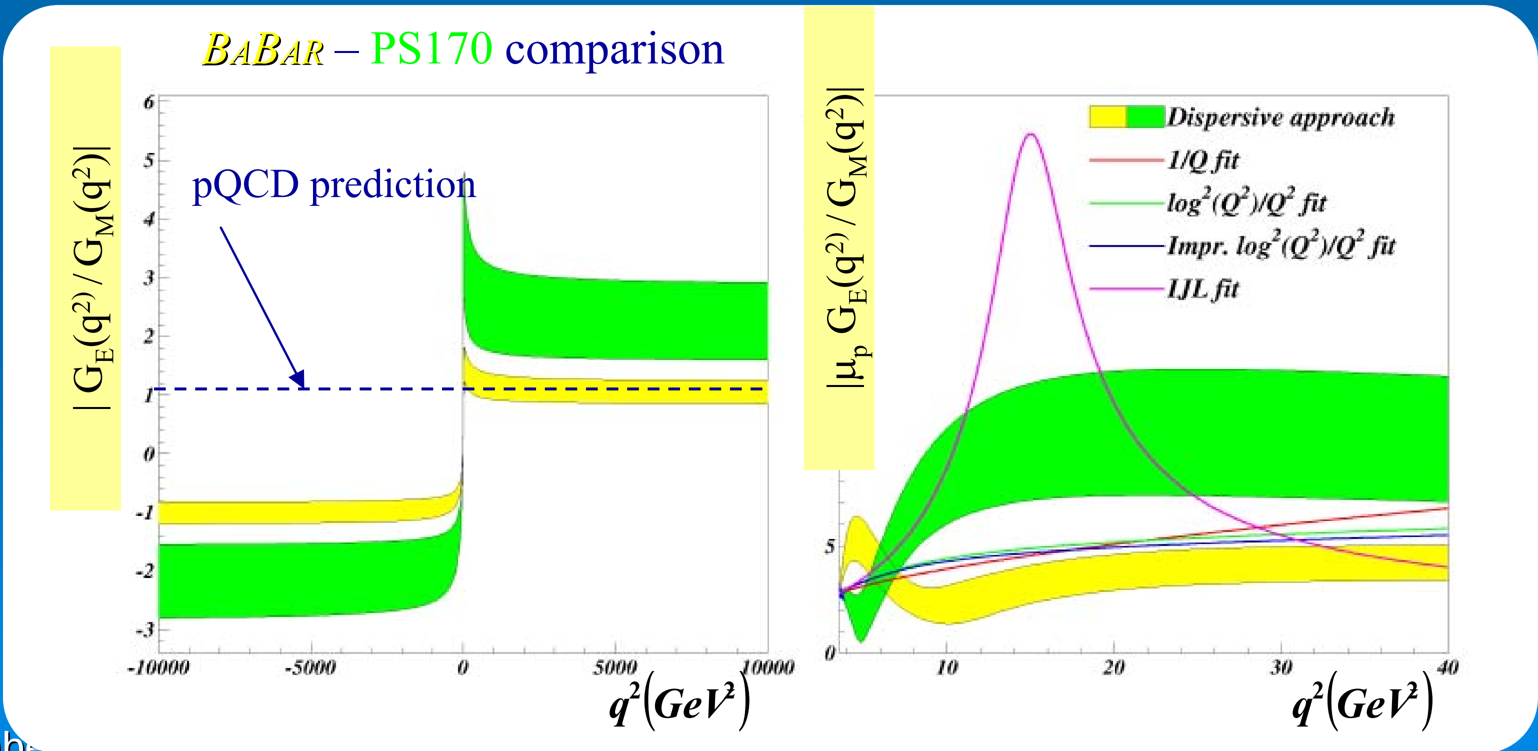

Comparison of baryon FF measured by BABAR