BaBar Measurement of Baryon Form Factors Connecting Time and Space Regions

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Exclusive Reactions at High Momentum Transfer

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Outline

- ISR main features, advantages and drawbacks
- *BABAR* $p\bar{p}$ candidates, selection and background

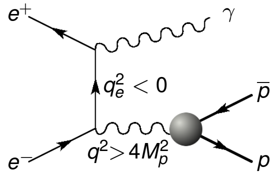
- *BABAR* stepwise $\sigma(e^+e^- \to p\bar{p})$
- $|G_E^p/G_M^p|$ time-like from $e^+e^- \to p\bar{p}$ angular distribution

- Space and time $|G_E^p/G_M^p|$ via dispersion relations
- Asymptotic predictions on G_E^p/G_M^p
- *BABAR* results on G_E^p and G_M^p, F_1^p and F_2^p, B_S^p and B_D^p

- "Baryonium" and dips in $e^+e^- \to$ hadronic channels ?

- Λ and neutron time-like form factors

I.S.R. main features



$$\frac{d\sigma_{e^+e^- \to p\bar{p}\gamma}}{d\cos\theta^*_\gamma}(w) = \frac{dE^*_\gamma}{E^*_\gamma} A(s, E^*_\gamma, \theta^*_\gamma)\sigma_0(w)$$

$w = p\bar{p}$ invariant mass

for $\theta^*_\gamma > 20^o$ I.S.R. Angular Acceptance $\approx 15\%$
ISR γ detected $\Longrightarrow$ no $\gamma\gamma$ interactions background

Advantages

- All $\boldsymbol{q}$ at the same time $\Longrightarrow$ Better control on systematics
- c.m. boost $\Longrightarrow$ at threshold $\epsilon \neq \mathbf{0} + \sigma_W \sim \mathbf{1}$ ***MeV***
- Detected ISR $\gamma \Longrightarrow$ full $\boldsymbol{p\bar{p}}$ angular coverage

Drawbacks

- $\mathcal{L} \propto$ invariant mass bin $\boldsymbol{\Delta w}$
- More background

Events selection and background

- **Analyzed 232 fb^{-1}**
- **Event selection:**
  - Tracks within Tracking and Particle ID acceptance
  - Very tight proton selector $\sim$ 30% good events loss
  - $p\bar{p}\gamma$ kinematical fit

    E_γ resolution not reproduced $\Longrightarrow$ $3C$ fit

    $\epsilon \sim$ **18 $\pm$ 1 %**
- **4025 selected events**

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

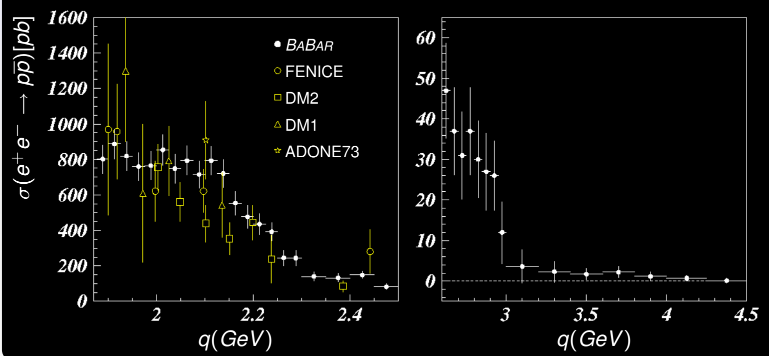
229 $\pm$ 32 estimated

$M_{pp} > 4$ GeV
$p\bar{p}$ signal overwhelmed

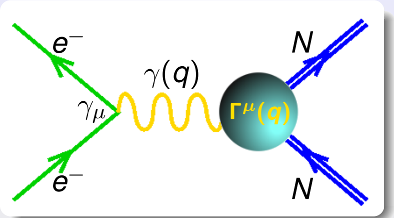
Background Summary

	$\pi^+\pi^-\gamma$	$K^+K^-\gamma$	$p\bar{p}\pi^0$	$p\bar{p}\pi^0\gamma$	*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

BABAR stepwise behaviour cross section [PRD73 (2006) 012005]



Nucleon form factors and cross sections



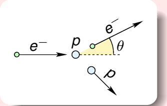
Nucleon current operator (Dirac & Pauli)

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

Electric and Magnetic Form Factors

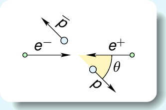
$$G_E(q^2) = F_1(q^2) + \tau F_2(q^2) \qquad \tau = \frac{q^2}{4M_N^2}$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$



Elastic scattering

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 E_e' \cos^2\frac{\theta}{2}}{4E_e^3 \sin^4\frac{\theta}{2}} \left[G_E^2 + \tau \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2} \right) G_M^2 \right] \frac{1}{1+\tau}$$



Annihilation

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

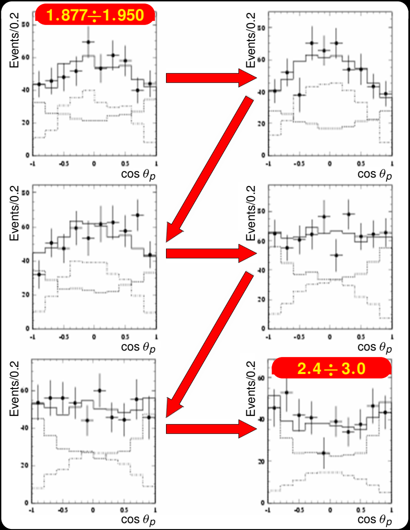
Coulomb correction: $C \approx \frac{y}{1-e^y} \qquad y = \frac{\pi\alpha M_p}{\beta q}$

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

$\cos\theta_p$ distributions
from threshold up to 3 GeV

Histograms show contribution
from: G_E (dashed)
G_M (dash-dotted)

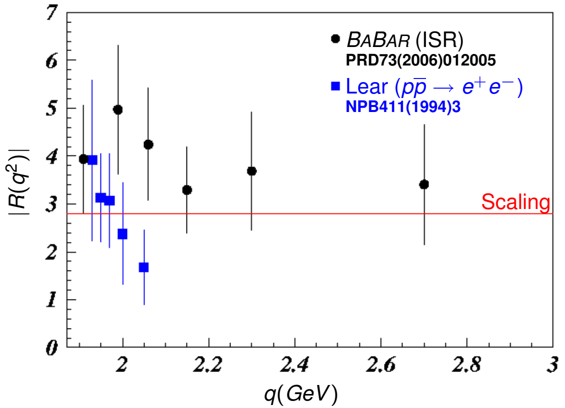
Transition
from: $\sin^2\theta$ (G_E dominant)
to: $1+\cos^2\theta$ (G_M dominant)



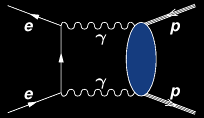
Time-like $|G_E^p/G_M^p|$ measurements

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}|G_M^p|^2\left[(1+\cos^2\theta)+\frac{4M_p^2}{q^2\mu_p}\sin^2\theta|R|^2\right]$$

$$R(q^2) = \mu_p\frac{G_E^p(q^2)}{G_M^p(q^2)}$$



$\gamma\gamma$ exchange

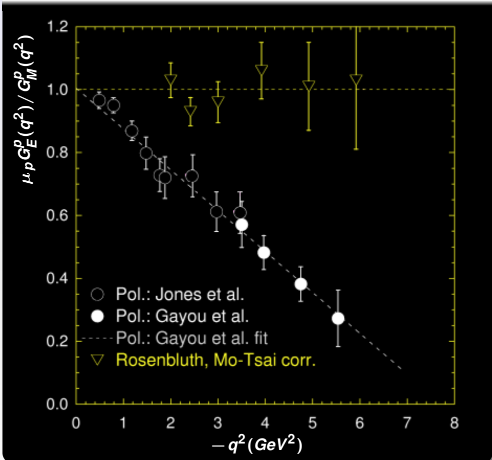


$\gamma\gamma$ exchange interferes with the Born term

Asymmetry in angular distributions

Space-like G_E^p / G_M^p measurements

Space-like data



Space like

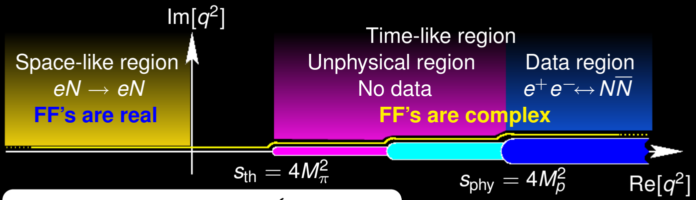
F_1 **and** $\frac{Q^2}{4M^2} F_2$ **cancellation:** $R(Q^2) < 1$

Time like (*BaBar*)

F_1 **and** $\frac{Q^2}{4M^2} F_2$ **enhancement:** $R(Q^2) > 1$

Analyticity constraints on the nucleon form factors

q^2-complex plane



Crossing: tot. helicity $= \begin{cases} 1 \Rightarrow G_E \\ 0 \Rightarrow G_M \end{cases}$

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

Perturbative QCD constrains the asymptotic behaviour

pQCD: $q^2 \to -\infty$

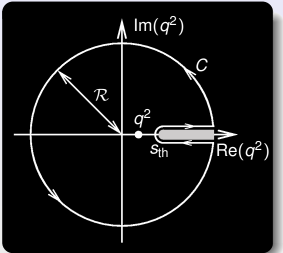
$$F_i(q^2) \to (-q^2)^{-(i+1)} \left[\ln\left(\frac{-q^2}{\Lambda^2_{\rm QCD}} \right) \right]^{-2.173_5}$$

Analyticity: $q^2 \to \pm\infty$

$$|G_{E,M}(-\infty)| = |G_{E,M}(+\infty)|$$

Dispersion relations connecting time and space regions

$R(q^2)$ is analytic on the q^2 plane with a cut $[s_{th} = 4M_\pi^2, \infty[$, if G_M has no zeros



Subtraction at $q^2 = 0$ because of a non-vanishing asymptotic limit of the ratio

For $q^2 \leq s_{th}$ R is real

$$R(q^2) = R(0) + \frac{q^2}{\pi} \int_{s_{th}}^{\infty} \frac{\mathrm{Im}R(s)ds}{s(s-q^2)}$$

For $q^2 > s_{th}$ R is complex

$$\mathrm{Re}R(q^2) = R(0) + \frac{q^2}{\pi} \mathrm{Pr} \int_{s_{th}}^{\infty} \frac{\mathrm{Im}R(s)ds}{s(s-q^2)}$$

$R(q^2)$ parametrization and constraints

The imaginary part of R is parametrized by two series of orthogonal polynomials $T_i(x)$

$$\mathrm{Im}R(q^2) \equiv I(q^2) = \begin{cases} \sum_i C_i T_i(x) & x = \dfrac{2q^2 - s_{phy} - s_{th}}{s_{phy} - s - 0} \quad s_{th} \leq q^2 \leq s_{phy} \\ \sum_j D_j T_j(x') & x' = \dfrac{2 s_{phy}}{q^2} - 1 \quad q^2 > s_{phy} \end{cases}$$

$$s_{th} = 4M_\pi^2 \qquad s_{phy} = 4M_N^2$$

Theoretical constraints on $ImR(q^2)$

- $R(4M_\pi^2)$ is real $\Longrightarrow I(4M_\pi^2) = 0$
- $R(4M_N^2)$ is real $\Longrightarrow I(4M_N^2) = 0$
- $R(\infty)$ is real $\Longrightarrow I(\infty) = 0$

Theoretical constraints on $R(q^2)$

- Continuity at $q^2 = 4M_\pi^2$
- $R(4M_N^2)$ is real and Re$R(4M_N^2) = 1$

Experimental constraints on $R(q^2)$ and $|R(q^2)|$

- Space-like region ($q^2 < 0$) data for R from TJNAF and MIT-Bates
- Time-like region ($q^2 \geq 4M_N^2$) data for $|R|$ from FENICE+DM2, **BABAR** , E835 and Lear

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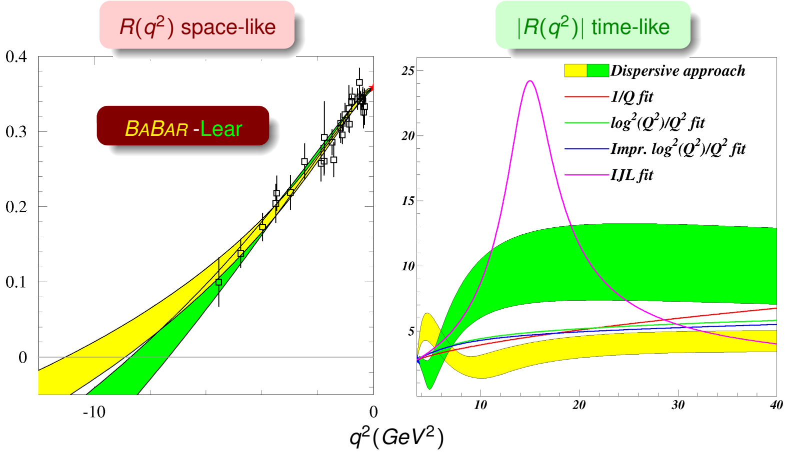
Reconstructed *R* in space and time regions



Asymptotic $G_E^P(q^2)/G_M^p(q^2)$

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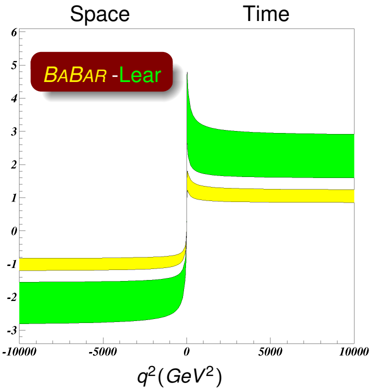
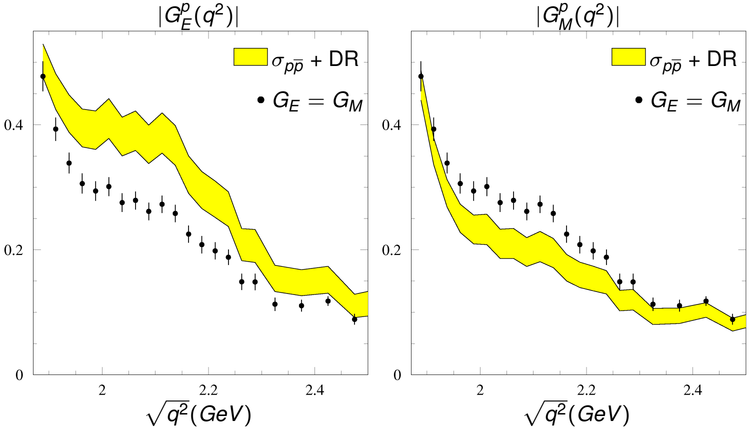
Asymptotic behaviour of $G_E^P(q^2)/G_M^p(q^2)$



pQCD prediction

$$\left|\frac{G_E^p(q^2)}{G_M^p(q^2)}\right| \xrightarrow[|q^2|\to\infty]{} 1$$

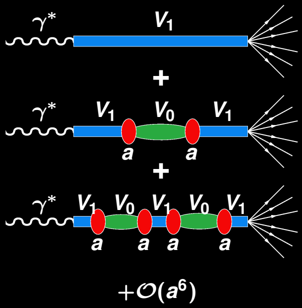
BABAR



G_M^p very steep at threshold $\Longrightarrow$ vector "Baryonium" ?

"Baryonium" → dip in multihadronic processes

P.J. Franzini and F.J. Gilman, 1985



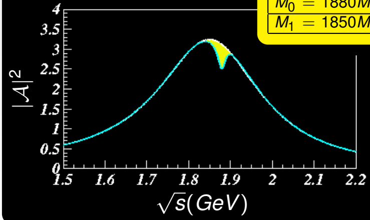
A vector meson V_0 ($J^{PC} = 1^{--}$), with vanishing e^+e^- coupling, which decays through an intermediate broad vector meson V_1

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

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

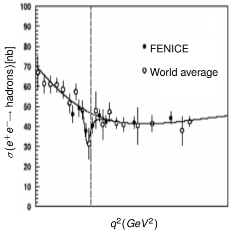
For instance...

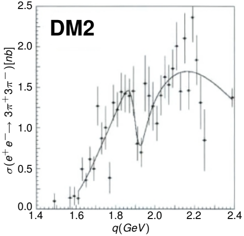
$M_0 = 1880 MeV$	$\Gamma_0 = 20 MeV$
$M_1 = 1850 MeV$	$\Gamma_1 = 300 MeV$



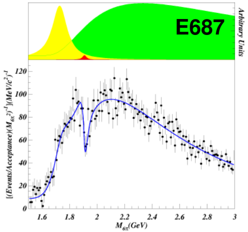
Dips in multihadronic reactions

e^+e^- annihilation processes

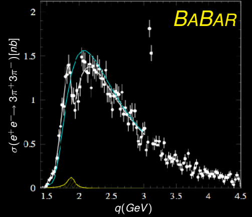


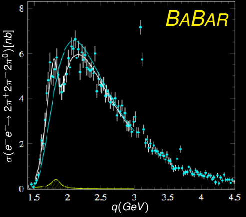


Diffractive photoproduction



e^+e^- annihilation processes with ISR





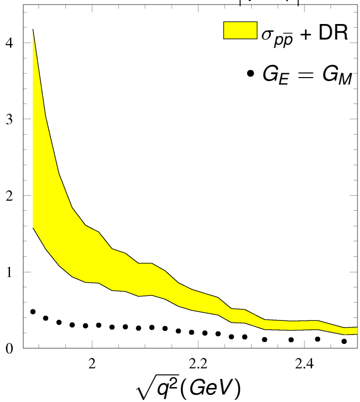
V_0	$M(MeV)$	$\Gamma(MeV)$
hadrons	$\sim$1870	10÷20
DM2	1930(30)	35(20)
E687	1910(10)	37(13)
BABAR	1880(50)	130(30)
BABAR(π^0)	1860(20)	160(20)

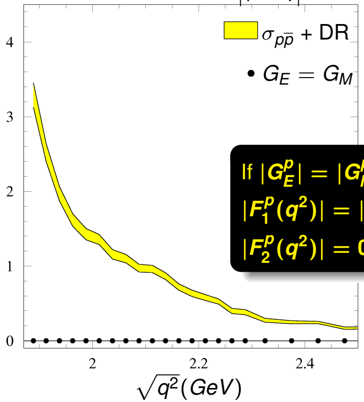
S.Pacetti, PANDA Workshop,Orsay'07

BABAR

$$|F_1^p(q^2)| = |G_M^p| \frac{|G_E^p/G_M^p - \tau|}{|1-\tau|}$$

$$|F_2^p(q^2)| = |G_M^p| \frac{|G_E^p/G_M^p - 1|}{|\tau-1|}$$





If $|G_E^p| = |G_M^p|$

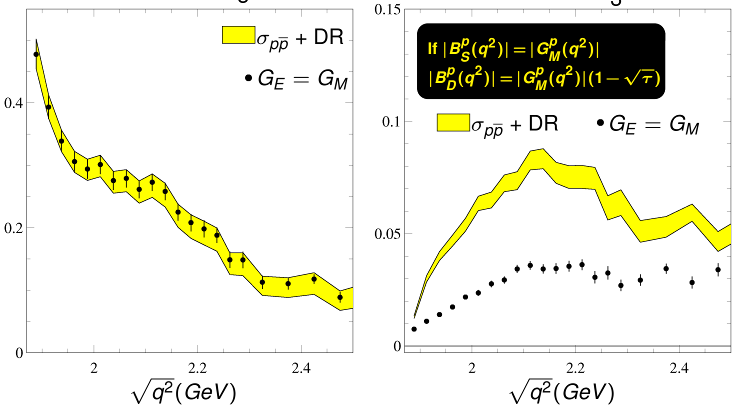
$|F_1^p(q^2)| = |G_M^p(q^2)|$

$|F_2^p(q^2)| = 0$

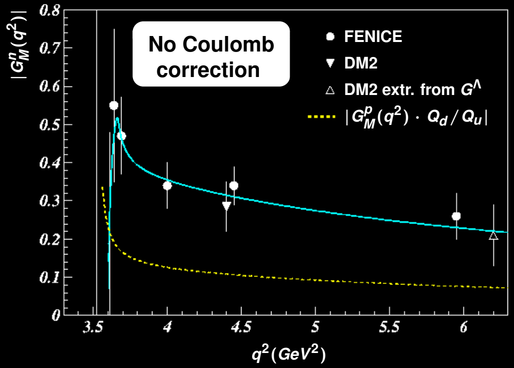
BaBar

$$|B_S^p(q^2)| = \frac{|2\sqrt{\tau}G_M^p + G_E^p|}{3}$$

$$|B_D^p(q^2)| = \frac{|\sqrt{\tau}G_M^p - G_E^p|}{3}$$



Only two measurements by FENICE and DM2



	$\lvert G_M^n / G_M^p \rvert$
Data	~ 1.5
Naively	$\sim \lvert Q_d / Q_u \rvert$
pQCD	< 1
Soliton models	~ 1
VMD	$\gg 1$

Threshold behaviour from angular distribution

$$G_M^n(4M_n^2) = G_E^n(4M_n^2) = 0?$$

Does *BABAR* agree with FENICE ?

Large $G^\Lambda \stackrel{U-spin}{\Longrightarrow}$ large G_M^n

Conclusions

- $B_{A}B_{AR}$: stepwise $\sigma(e^+e^- \to p\bar{p})$
- $B_{A}B_{AR}$: $|G_E^p| \gg |G_M^p|$ above threshold

- Space and time $|G_E^p/G_M^p|$ via dispersion relations
- Asymptotic predictions on G_E^p/G_M^p
- $B_{A}B_{AR}$ results on G_E^p and G_M^p, F_1^p and F_2^p, B_S^p and B_D^p

- "Baryonium" and dips in $e^+e^- \to$ hadronic channels ?

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