Proton Form Factors and related processes in *BABAR* by ISR

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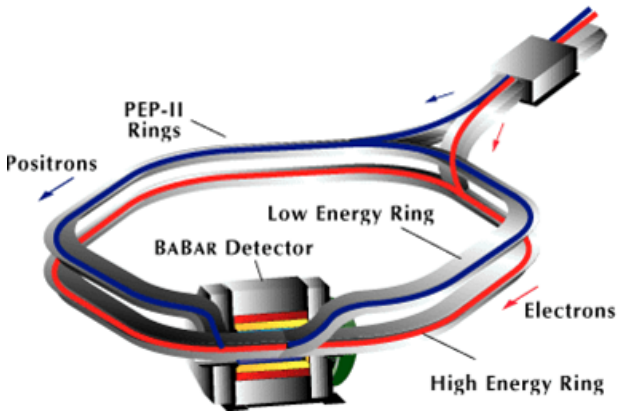
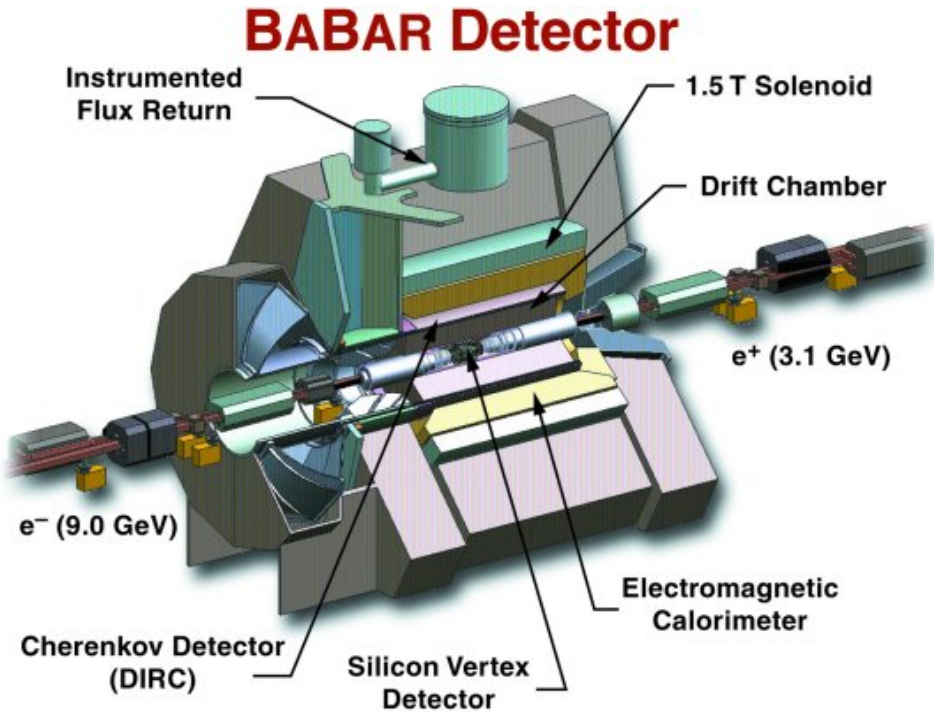
Outline

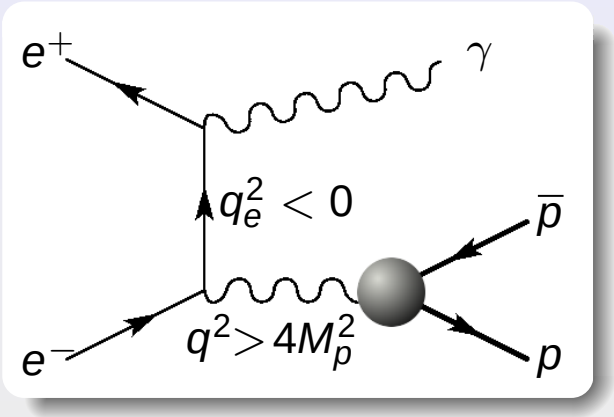
- *BABAR* measurement of $e^+e^- \to p\bar{p}$ by ISR
- Definitions and main properties of Nucleon FF
- Nucleon FF revival: space-like G_E/G_M
- Time-like G_E/G_M
- Sharp drops in $\sigma(e^+e^- \to p\bar{p})$
  and in the FF at the $p\bar{p}$ threshold
- Drops and dips at $p\bar{p}$ threshold in related processes
- Coulomb corrections
  and the $e^+e^- \to n\bar{n}$, $e^+e^- \to \Lambda\bar{\Lambda}$ puzzle
- Conclusions and perspectives

B-factory PEPII@SLAC





I.S.R. main features



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

$w = p\bar{p}$ invariant mass $= q\sqrt{1-x}$, $x = 2E^*_\gamma/q$

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

$\theta^*_\gamma \gg \frac{m_e}{q}$ in e^+e^- c.m.

for $\theta^*_\gamma > 20^o$ I.S.R. Angular Acceptance $\approx 15\%$

ISR γ detected $\Longrightarrow$ $\gamma\gamma$ interactions killed

I.S.R. versus c.m.

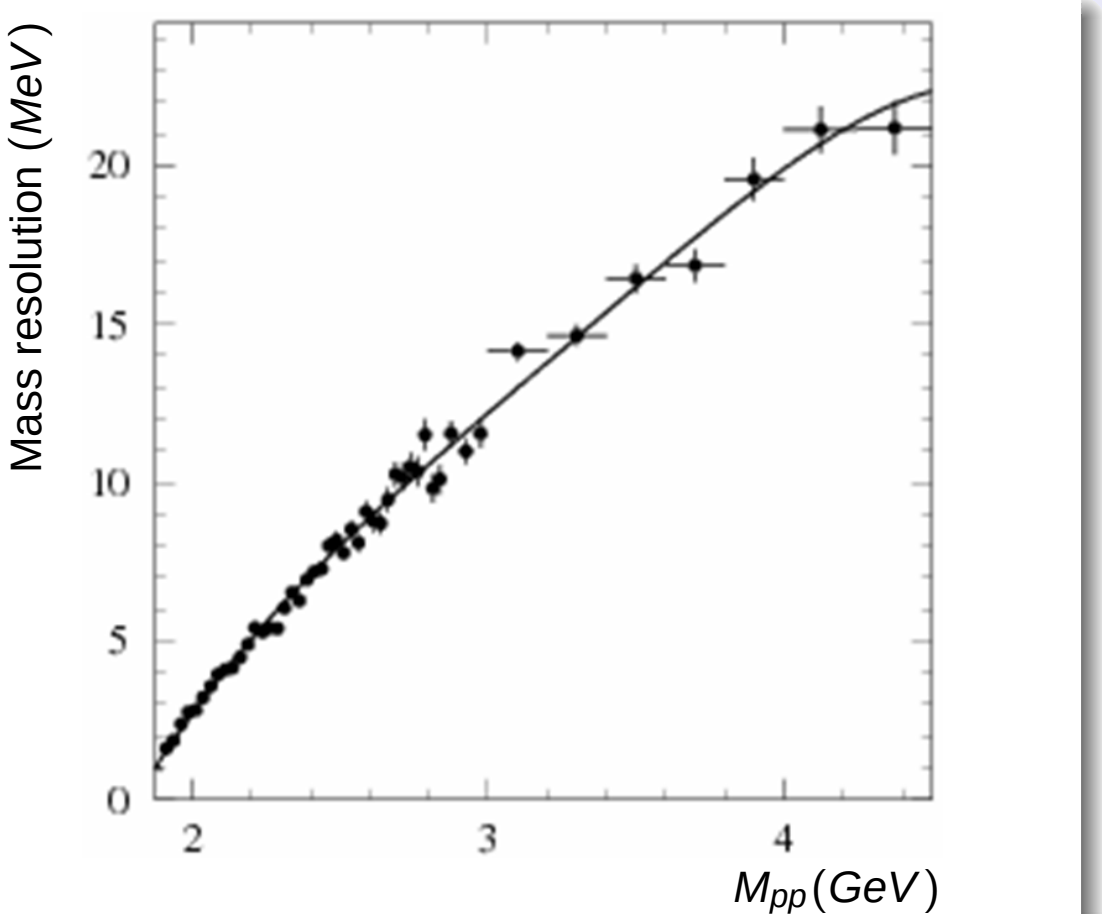
Advantages

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

Drawbacks

- $\mathcal{L} \propto$ invariant mass bin Δw
- More background

Mass resolution



Incredibly good at threshold ($\sim 1\ MeV$), as e^+e^- c.m.

Events selection

- **Analyzed 232 fb^{-1}**
- **I.S.R. simulation:**
  - $20^o < \theta^*_\gamma < 160^o$ (H. Czyz *et al.*, Eur. Phys. J. C35 (2004) 527)
  - Soft photons (M. Caffo *et al.*, N. C. 110A (1997) 515)
- **Event selection:**
  - Tracks within DHC and DIRC acceptance
  - Very tight proton selector $\sim$ 30% good events loss
  - $p\bar{p}\gamma$ kinematical fit

    E_γ resolution not reproduced $\Longrightarrow$ 3C fit

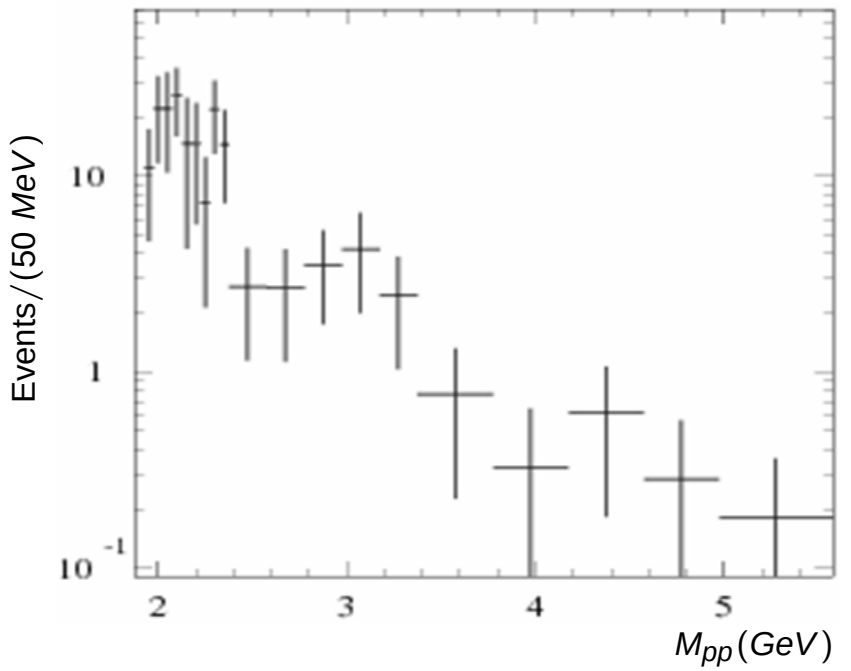
    $\epsilon \sim 18 \pm 1$ %
- **4025 selected events**

$p\bar{p}$ events background

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

229 ± 32 estimated

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



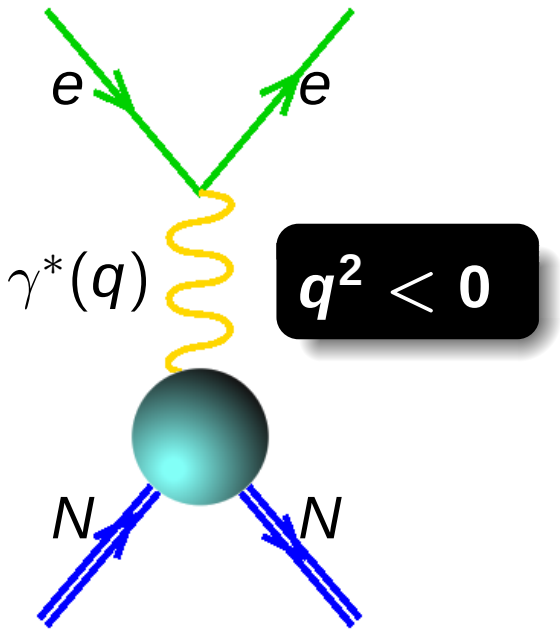
Background Summary

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

Space-like and time-like regions

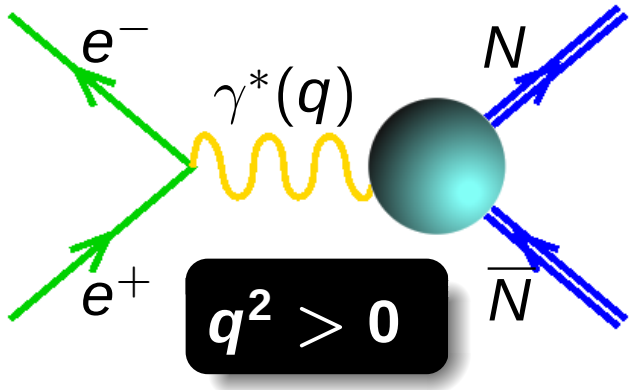
Space-like

$$eN \longrightarrow eN$$

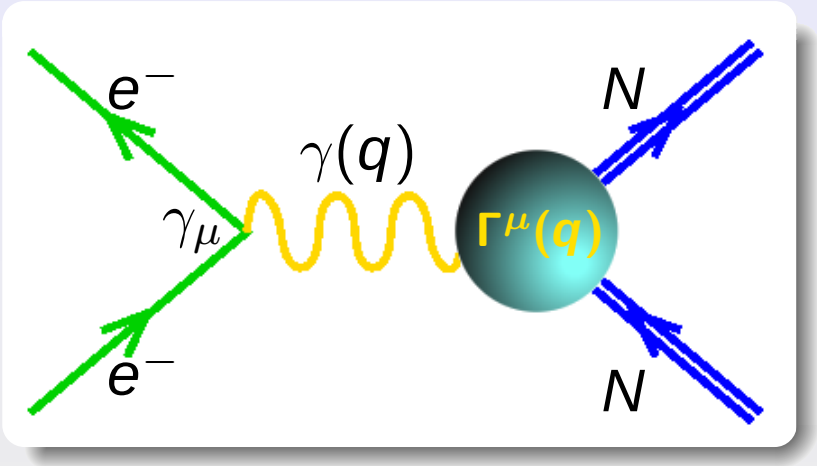


Time-like

$$e^+e^- \leftrightarrow N\overline{N}$$



Nucleon form factors and cross sections

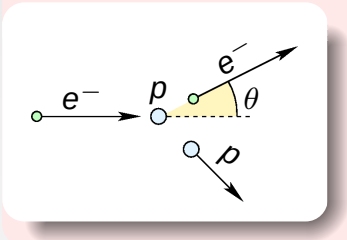


Nucleon current operator (Dirac & Pauli)

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

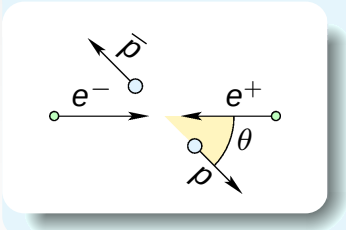
Electric and Magnetic Form Factors

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



Elastic scattering

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

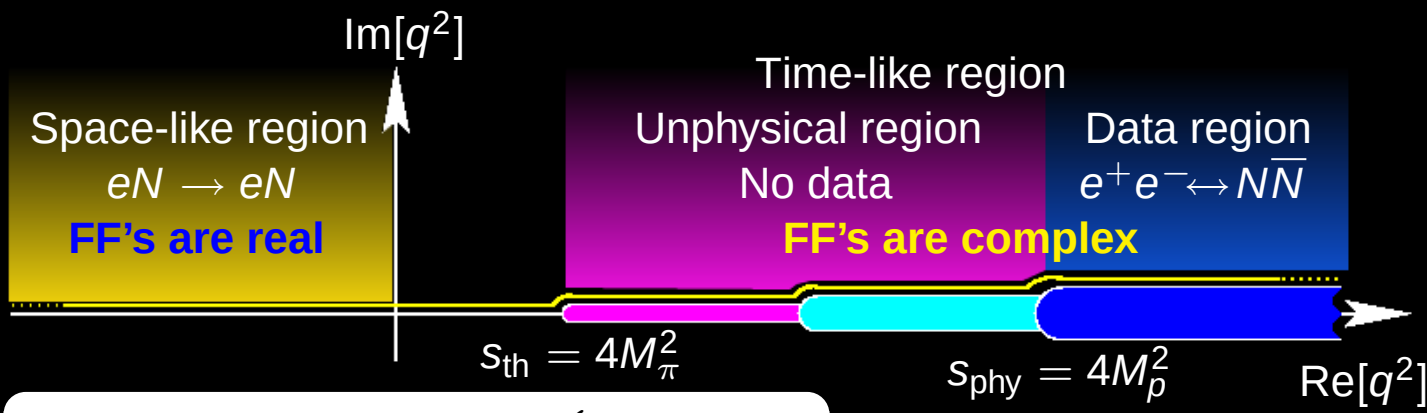


Annihilation

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

Analyticity of 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: $q^2 \to -\infty$

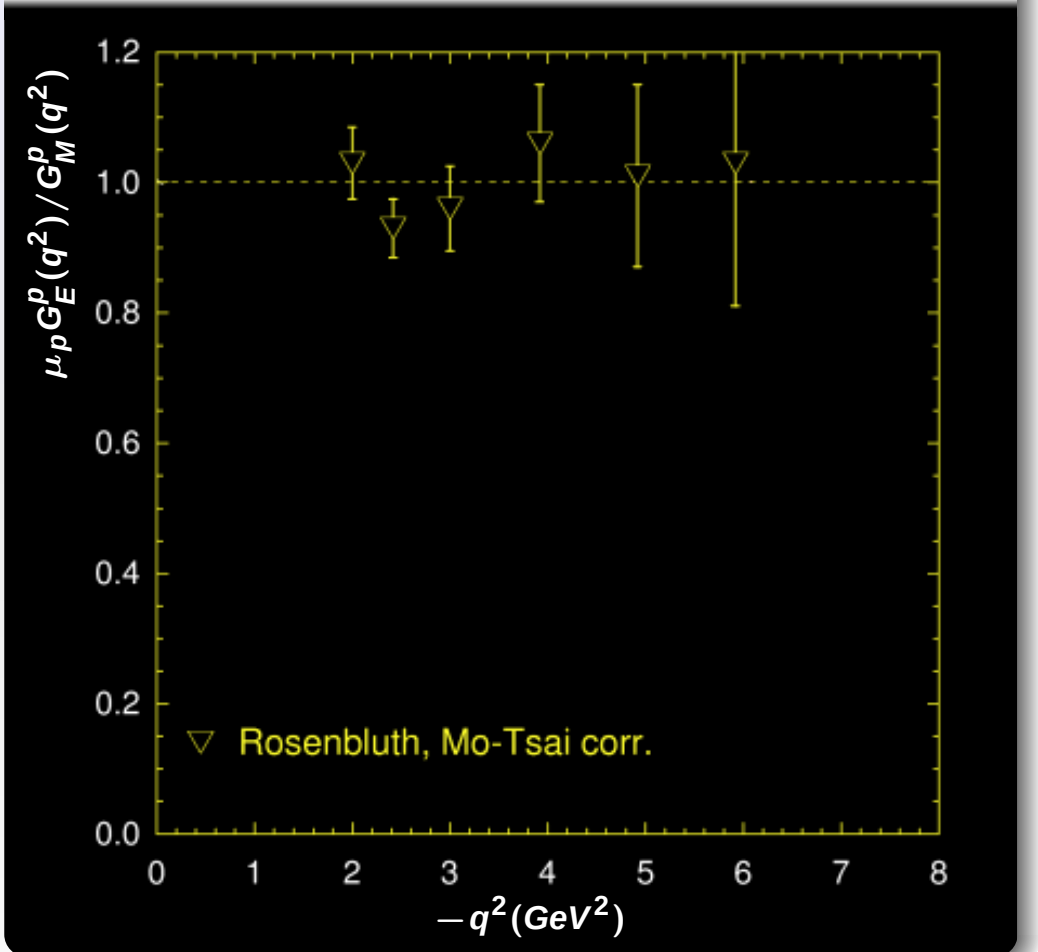
$$F_i(q^2) \to (-q^2)^{-(i+1)} \left[\ln\left(\frac{-q^2}{\Lambda^2_{QCD}} \right) \right]^{-2.173_5}$$

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

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

Space-like G_E^p / G_M^p measurements

Space-like data



"Scaling" law

$$G_E^p \simeq G_M^p / \mu_p$$

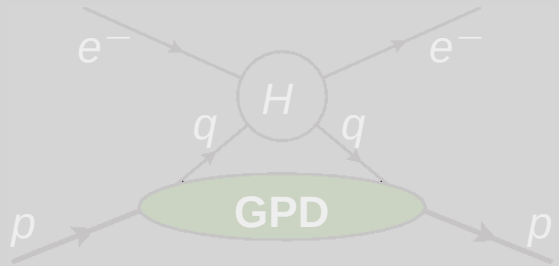
Jlab measurement

Polarization method

$$\frac{G_E^p(q^2)}{G_M^p(q^2)} = -\sqrt{\frac{-2\epsilon}{\tau(1+\epsilon)}}\frac{\mathcal{P}_\parallel}{\mathcal{P}_\perp}$$

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

2γ+GPD correction



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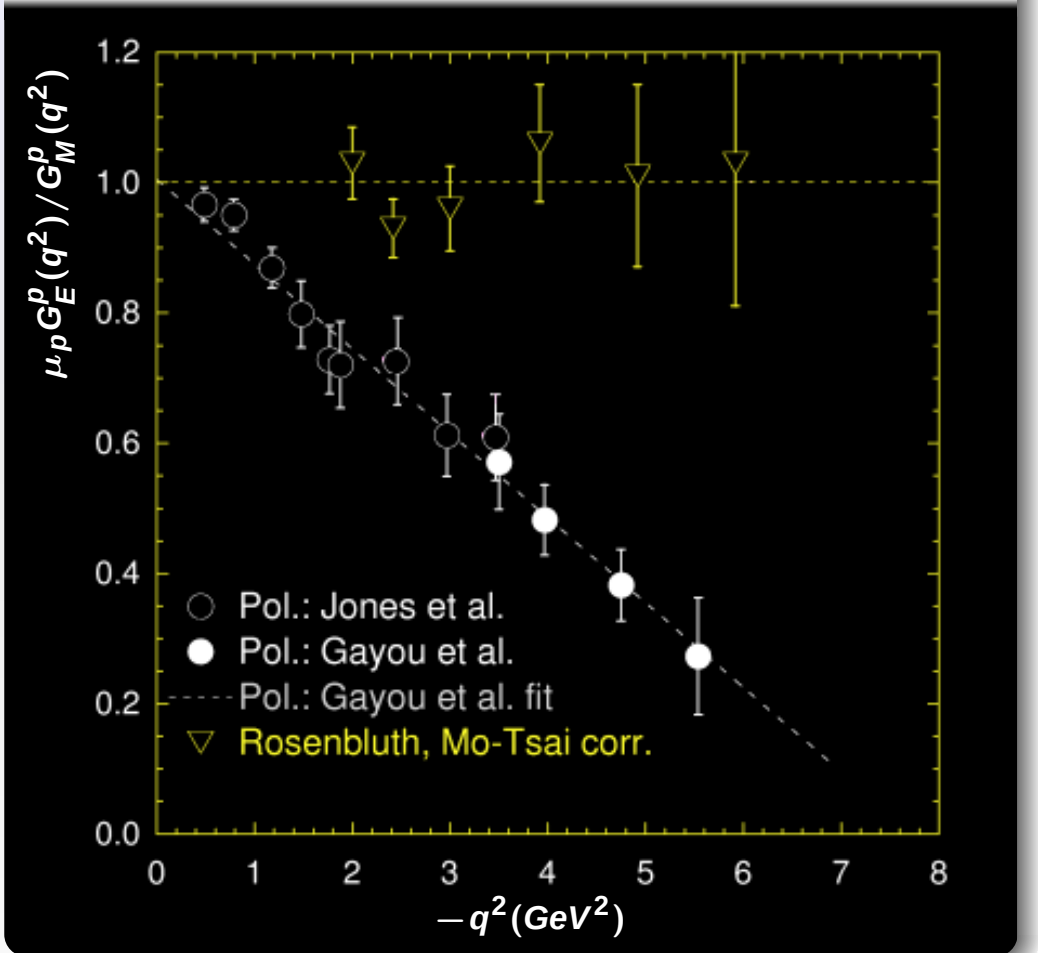

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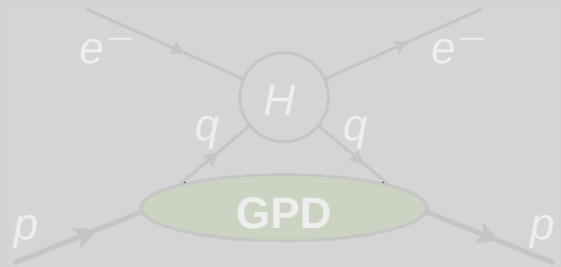

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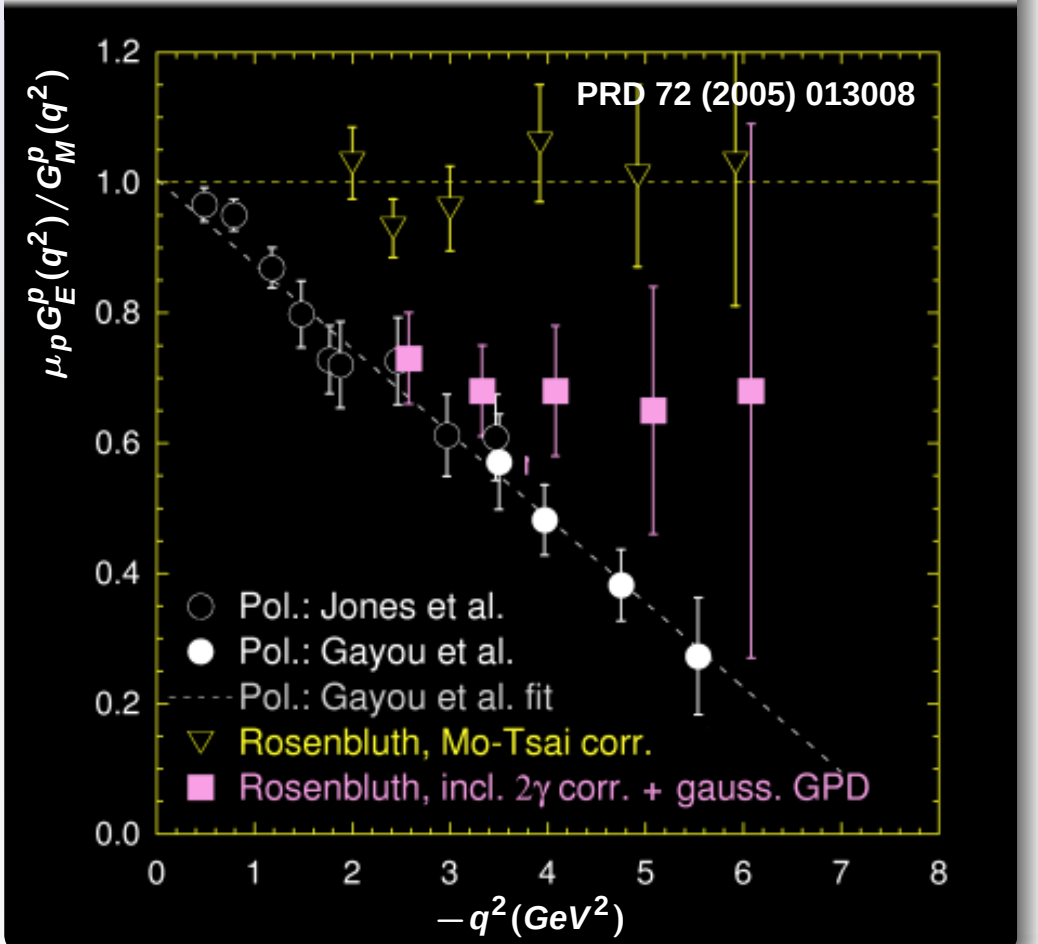

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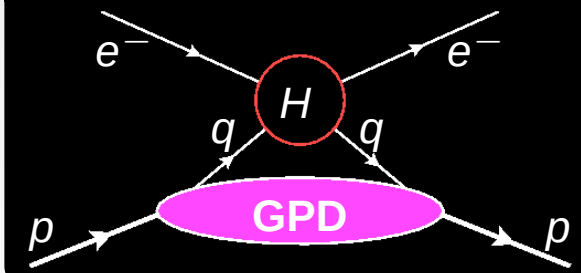


$BABAR$ $e^+e^- \longrightarrow p\bar{p}$

new results

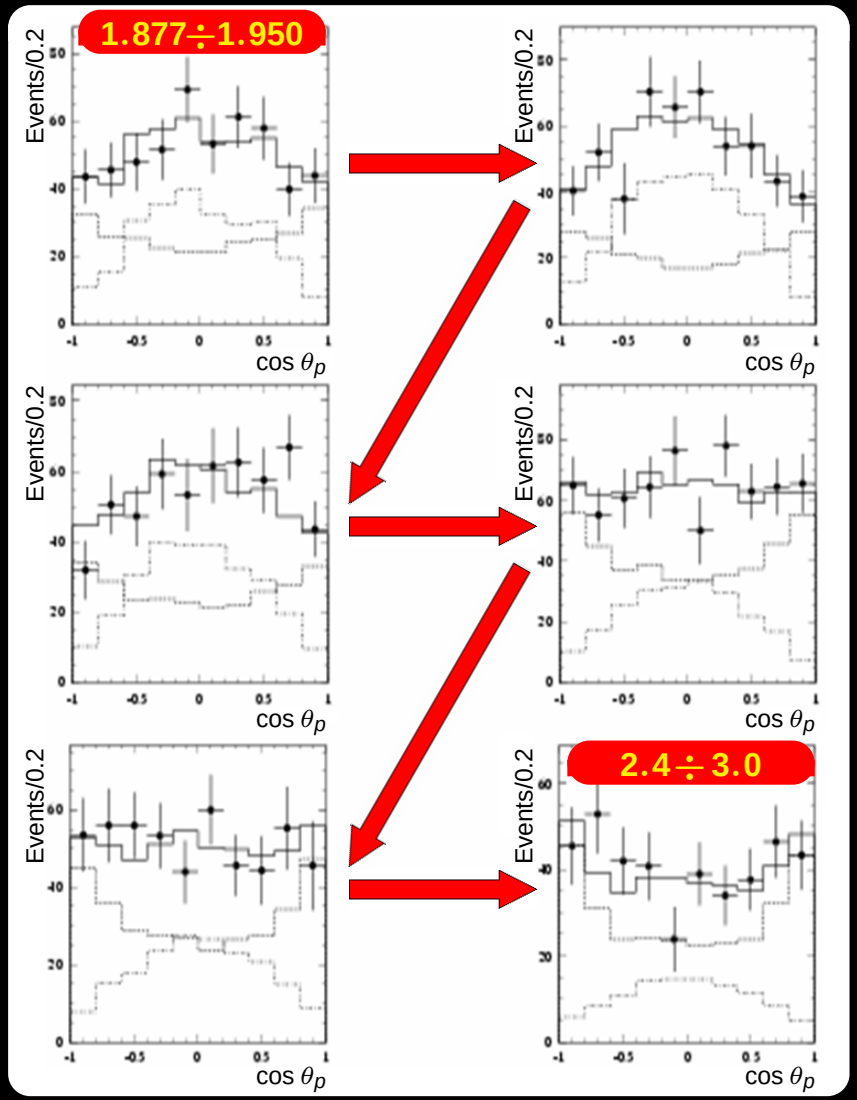
by means of Initial State Radiation

Angular distributions

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

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

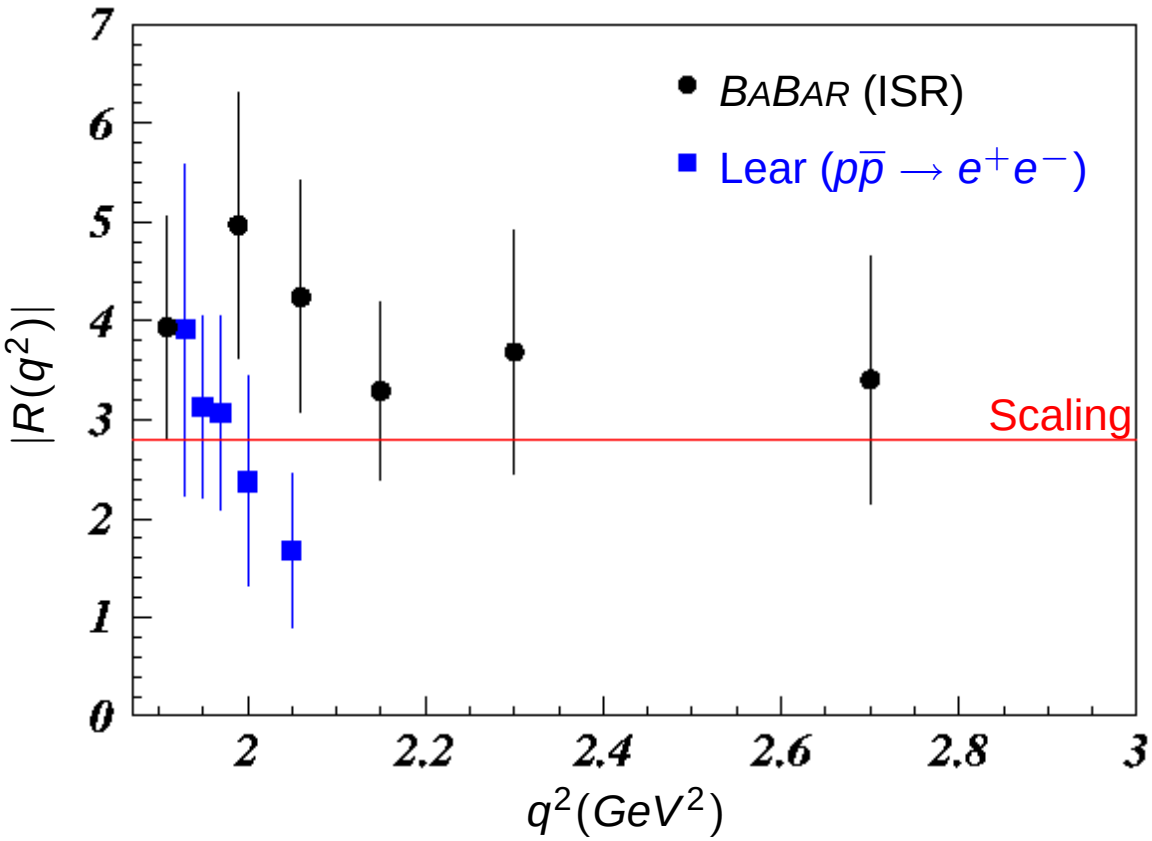
Transition
from: $\sin^2\theta$ (G_E dominant)
to: $1+\cos^2\theta$ (G_M dominant)



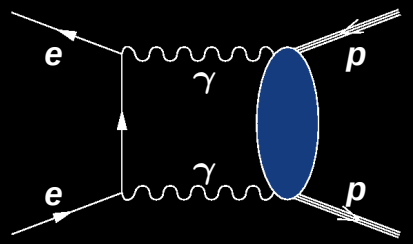
Time-like $|G_E^p/G_M^p|$ measurements

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

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



$\gamma\gamma$ exchange

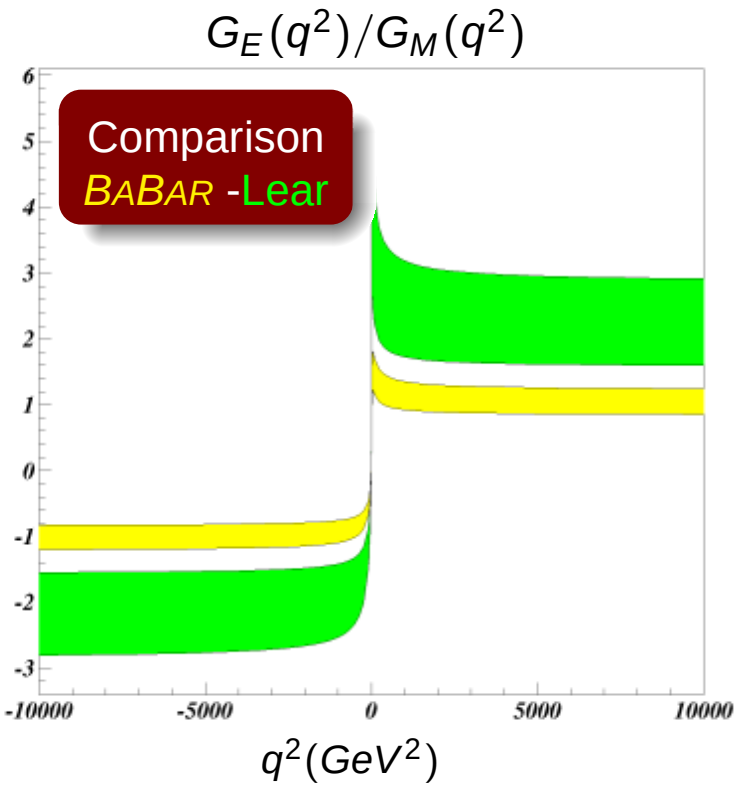


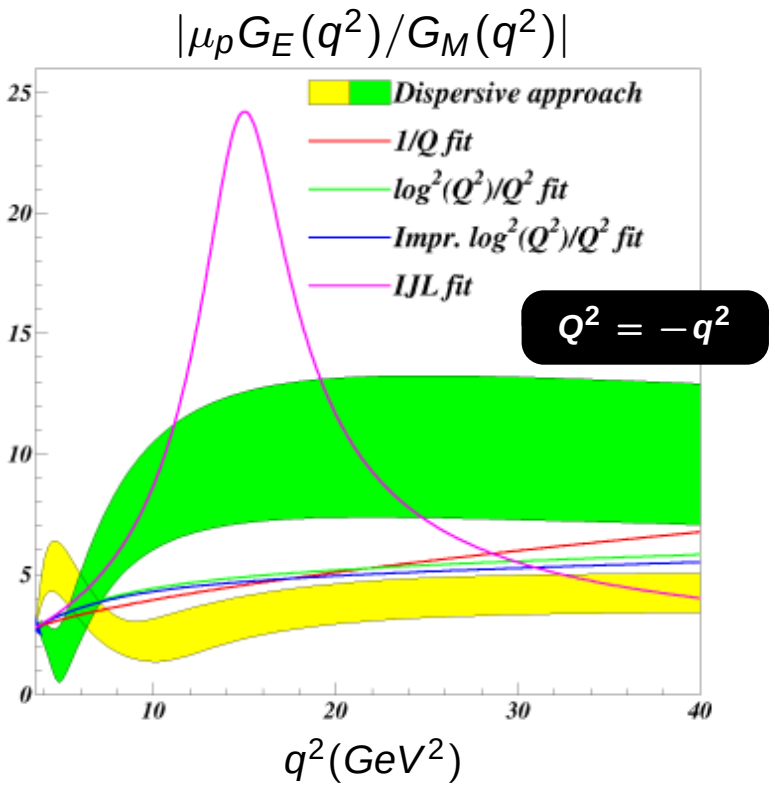
$\gamma\gamma$ exchange interferes with the Born term

Asymmetry in angular distributions

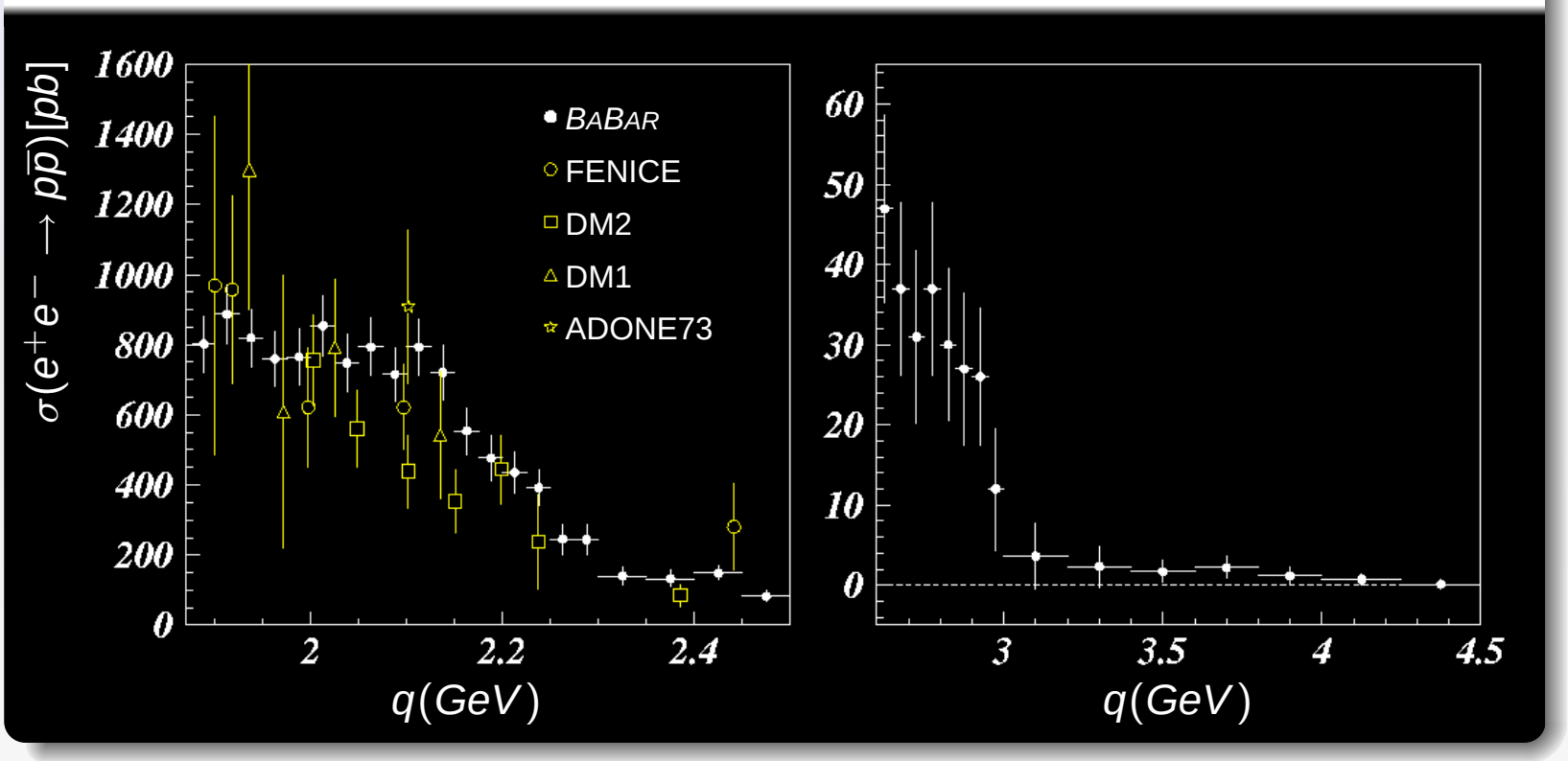
Dispersive analysis of G_E/G_M (Eur. Phys. J. **C46** (2006) 421)

Asymptotic behaviour and comparison with some existing models



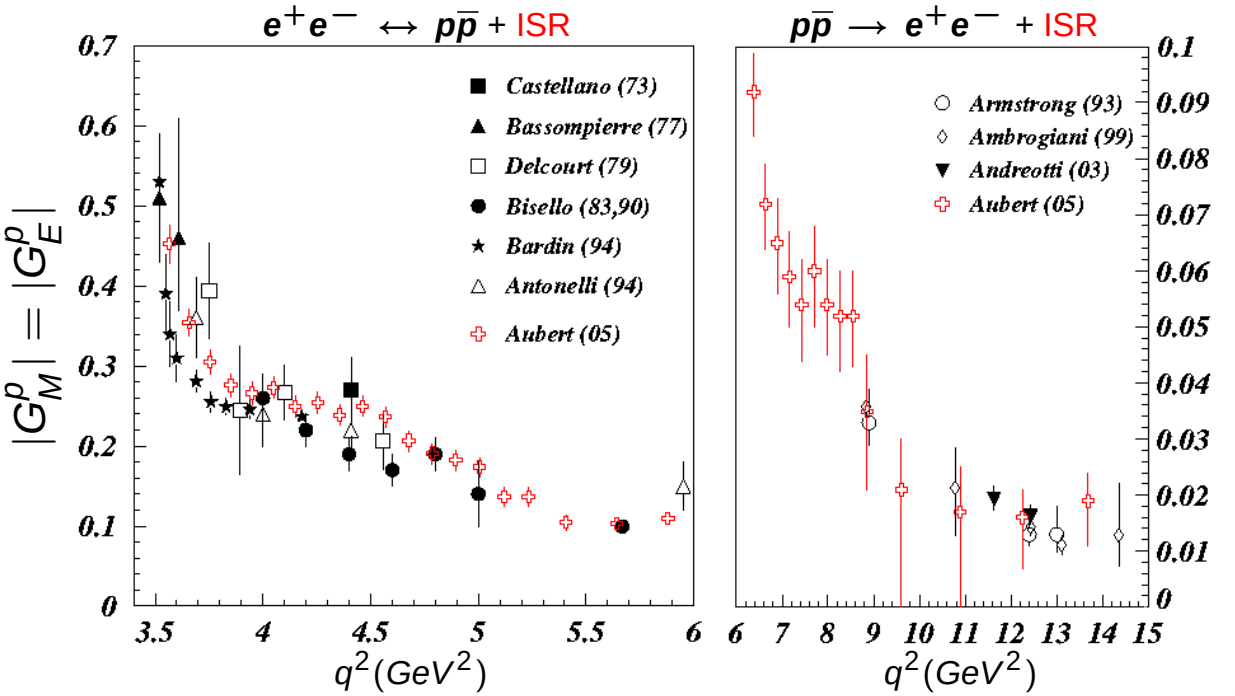


BABAR stepwise behaviour cross section [PRD73 (2006) 012005]



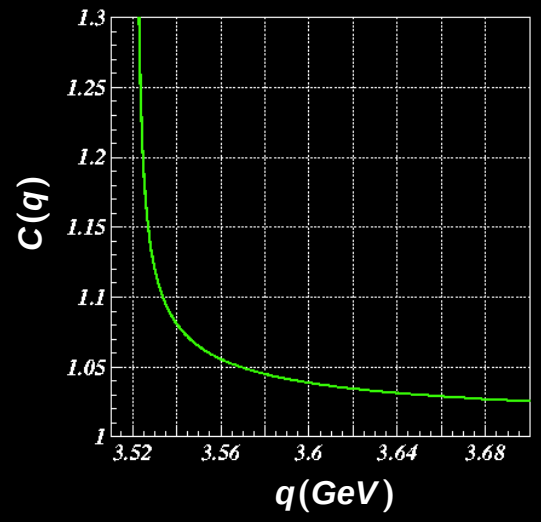
Time-like $|G_M^p|$ measurements

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



Coulomb correction

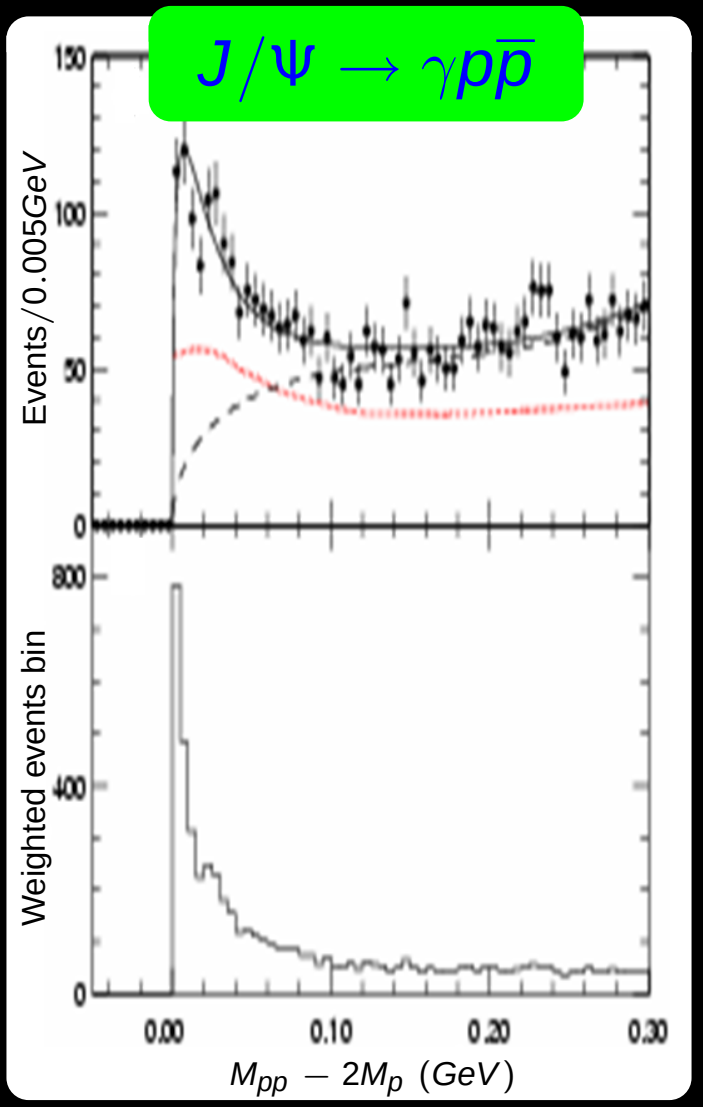
$$C = \frac{y}{1-e^{-y}} \qquad y = \frac{\pi\alpha M_P}{\beta q}$$



$J/\Psi \to \gamma p\bar{p}$ by BES

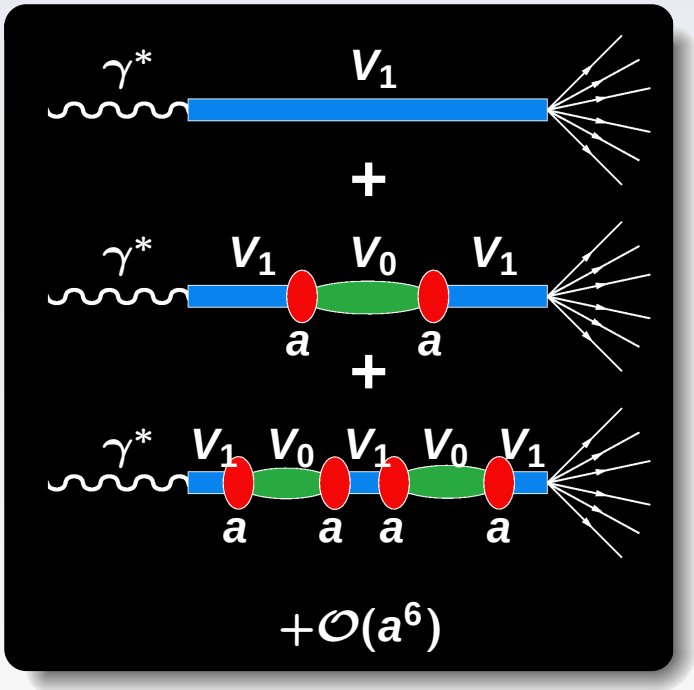
Steep behaviour at threshold
also seen in other processes
with different quantum numbers

BES	$J/\Psi \to \gamma\, p\bar{p}$
BABAR	$B^+ \to K^+\, p\bar{p}$
BABAR	$B^0 \to D^0\, p\bar{p}$



“Baryonium” $\longrightarrow$ dip in multihadronic processes

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



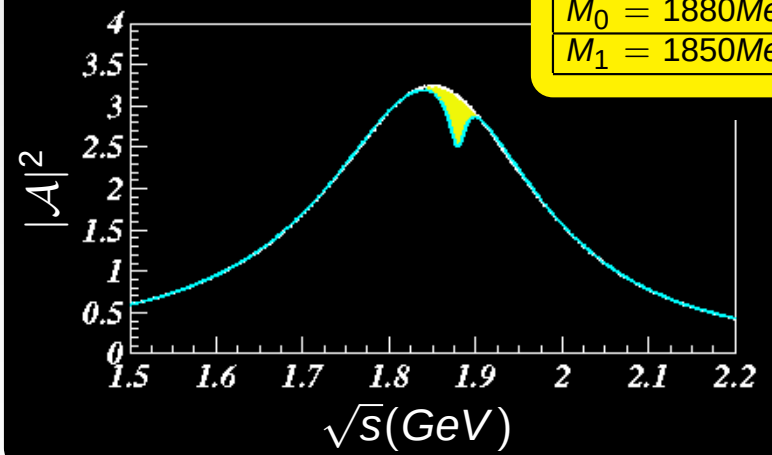
A vector meson V_0 ($J^{PC} = 1^{--}$), with vanishing e^+e^- coupling, which decays through an intermediate broad vector meson V_1

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

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

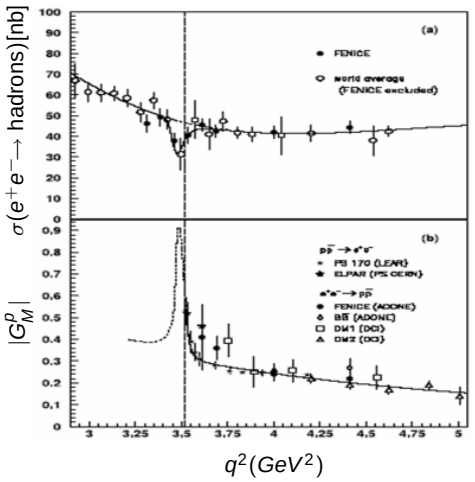
For instance...

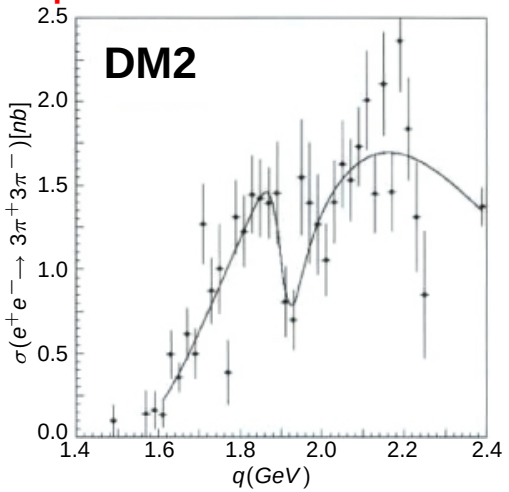
$M_0 = 1880 MeV$	$\Gamma_0 = 20 MeV$
$M_1 = 1850 MeV$	$\Gamma_1 = 300 MeV$



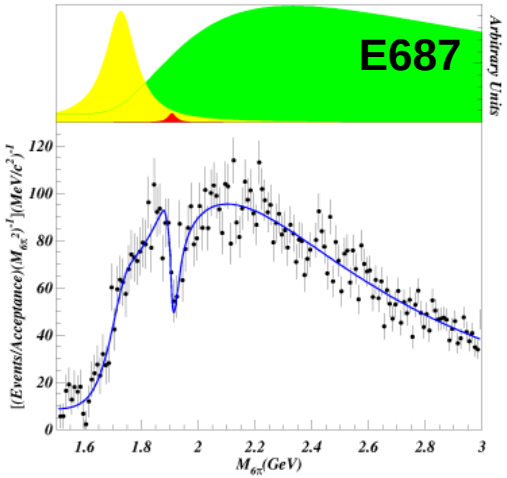
Dips in multihadronic reactions

e^+e^- annihilation processes

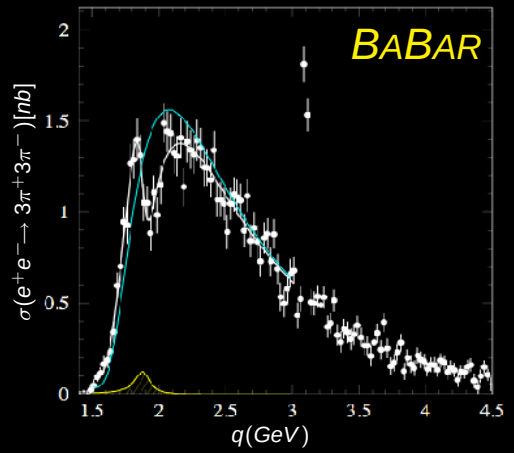


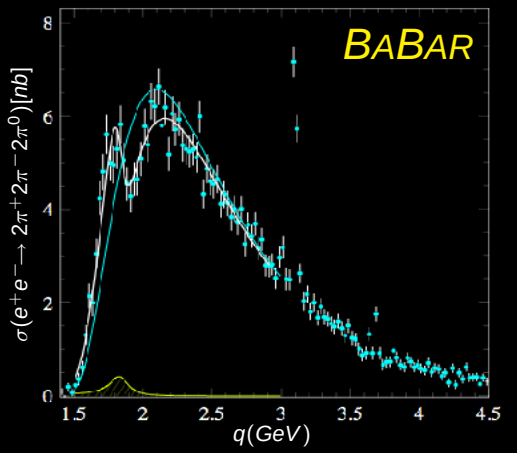


Diffractive photoproduction



e^+e^- annihilation processes with ISR

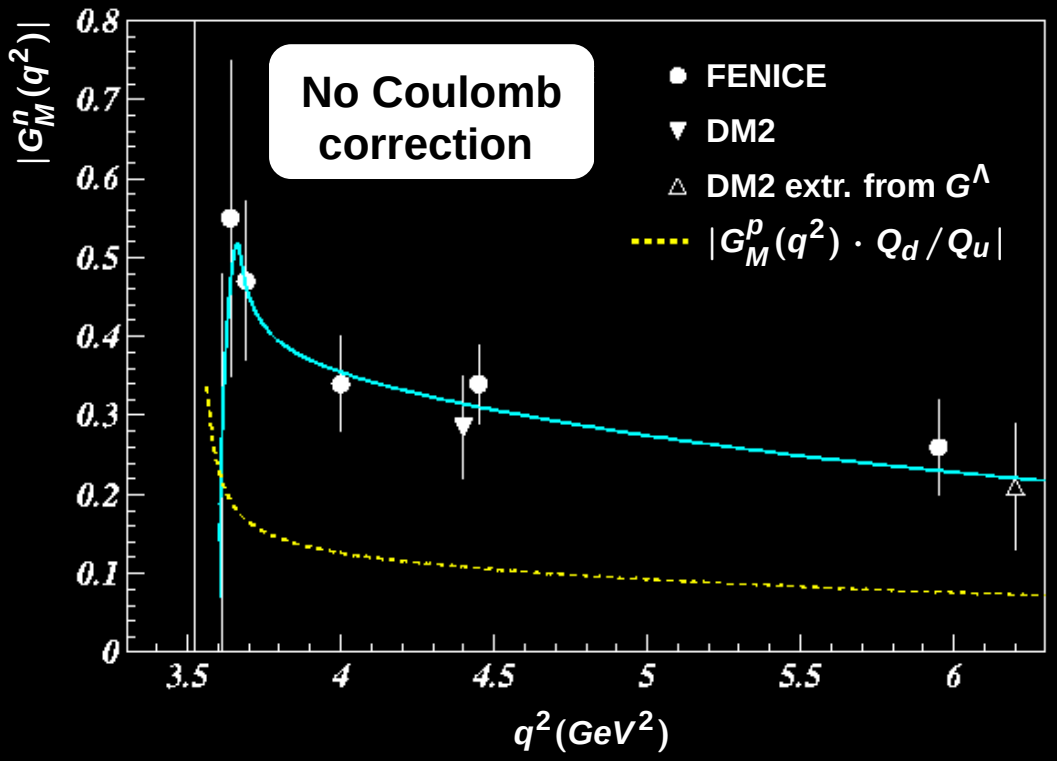




V_0	$M(MeV)$	$\Gamma(MeV)$
hadrons	∼1870	10÷20
DM2	1930(30)	35(20)
E687	1910(10)	37(13)
BABAR	1880(50)	130(30)
BABAR(π^0)	1860(20)	160(20)

Time-like $|G_M^n|$ measurements

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

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

Does *BABAR* agree with FENICE ?

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

Conclusions and perspectives

- Nucleon FF Revival: unexpected space-like G_E/G_M
- *BABAR* :
  - $G_E/G_M > 1$ just above $p\bar{p}$ threshold
  - Cross section drops at $q^2 \sim 5$ and 8 GeV^2
  - Sharp drop at $p\bar{p}$ threshold
  - Dip at $p\bar{p}$ threshold in $e^+e^- \to 6\pi$

- Perspectives:
  - *BABAR* : redoubled statistics
    $e^+e^- \to n\bar{n}$ very difficult, but $e^+e^- \to \Lambda\bar{\Lambda}$ coming soon
  - τ/charm at Beijing
  - Near $N\bar{N}$ threshold: VEPP2000
  - DANAE (?)
  - Super *B*-factory (?)