MEASUREMENT OF THE PROTON FORM FACTOR IN e^+e^- ANNIHILATION AT BABAR

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On Behalf of the *BABAR* Collaboration

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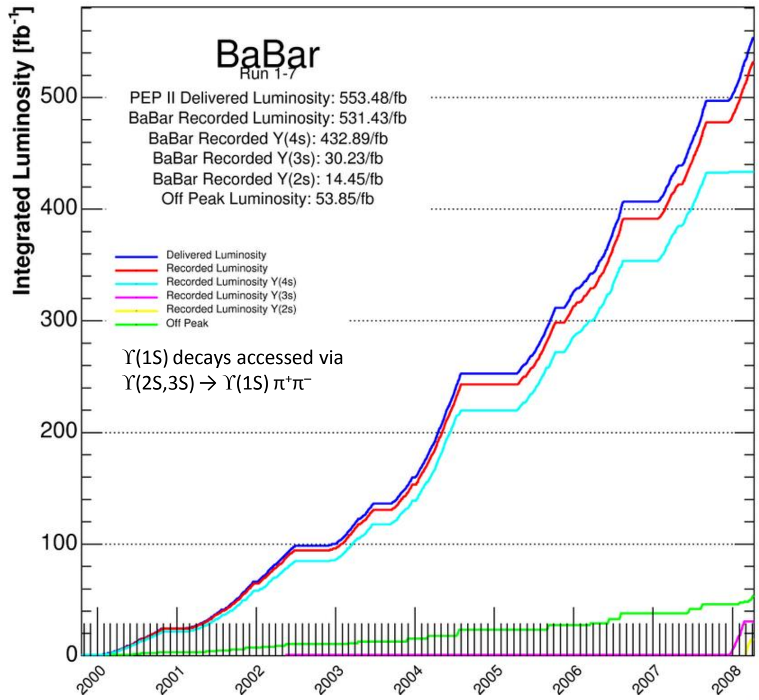
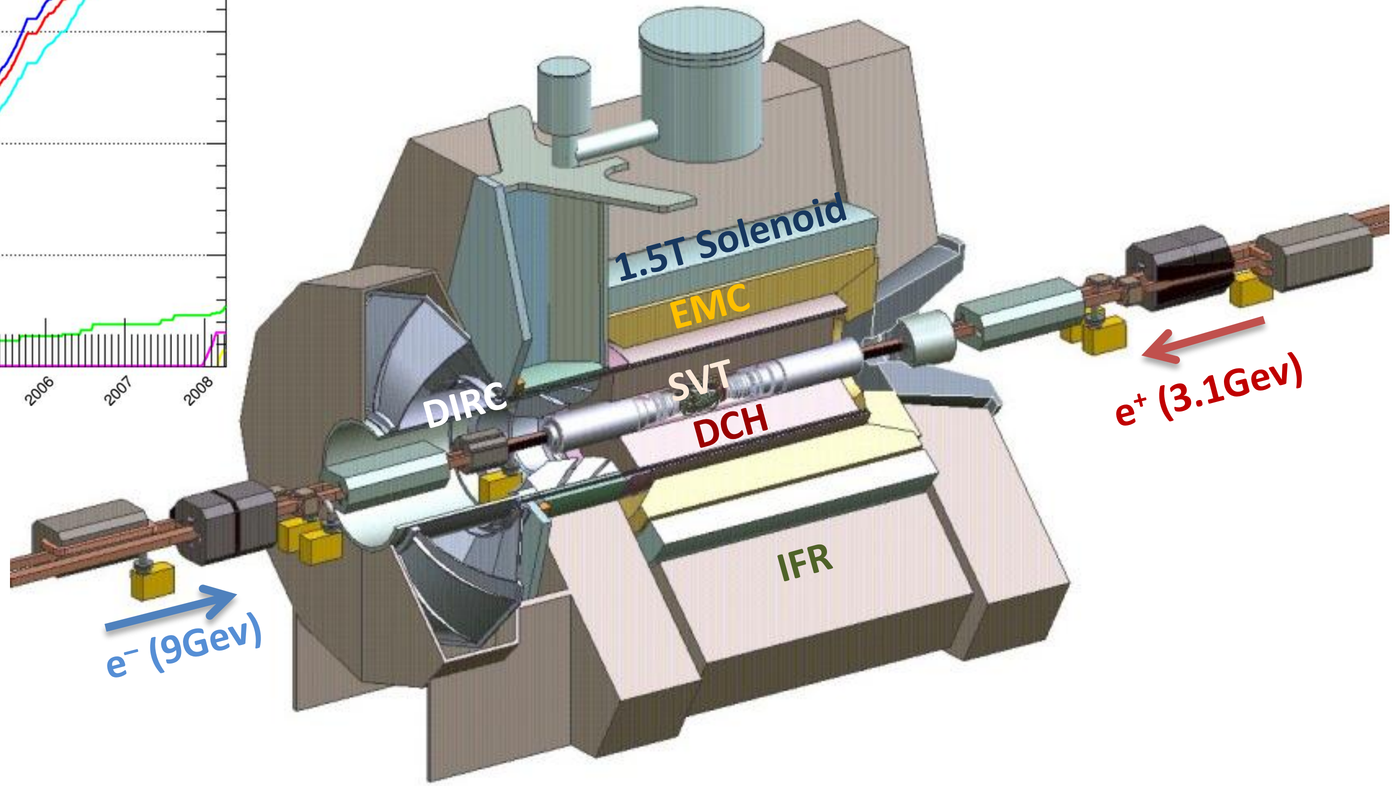
BaBar Dataset



Data used for the analyses presented:

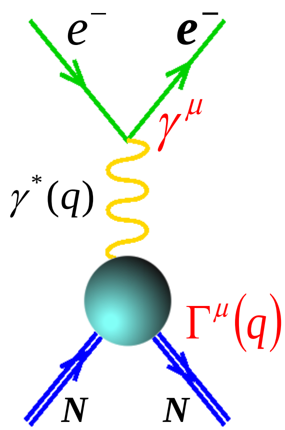
On $\Upsilon(4S)$ resonance (10.58Gev): 424 fb^{-1}

Off $\Upsilon(4S)$ resonance (10.54GeV): 45 fb^{-1}



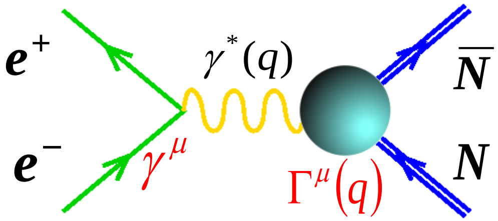
NUCLEONS FORM FACTORS

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) FF

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

k_N=nucleon anomalous magnetic moment

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

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

- Notable points:

$$G_E(0) = 1 \ ; \quad G_M(0) = 2.79$$
$$|G_E(4m_p^2)| = |G_M(4m_p^2)|$$ (p$\bar{p}$ production threshold)

$e^+e^- \to p\bar{p}$ Cross Section

- Cross section of the annihilation process:

$$\sigma(s) = \frac{4\pi\alpha^2 \beta C(s)}{3s}\left(|G_M(s)|^2 + \frac{2m_p^2}{s}|G_E(s)|^2 \right) \qquad \sqrt{s} = 2E^*_{beam}$$

C is the Coulomb factor → The cross section is non-zero at the threshold

- The ratio $|G_E/G_M|$ can be determined from the analysis of the polar angle distribution of the proton:

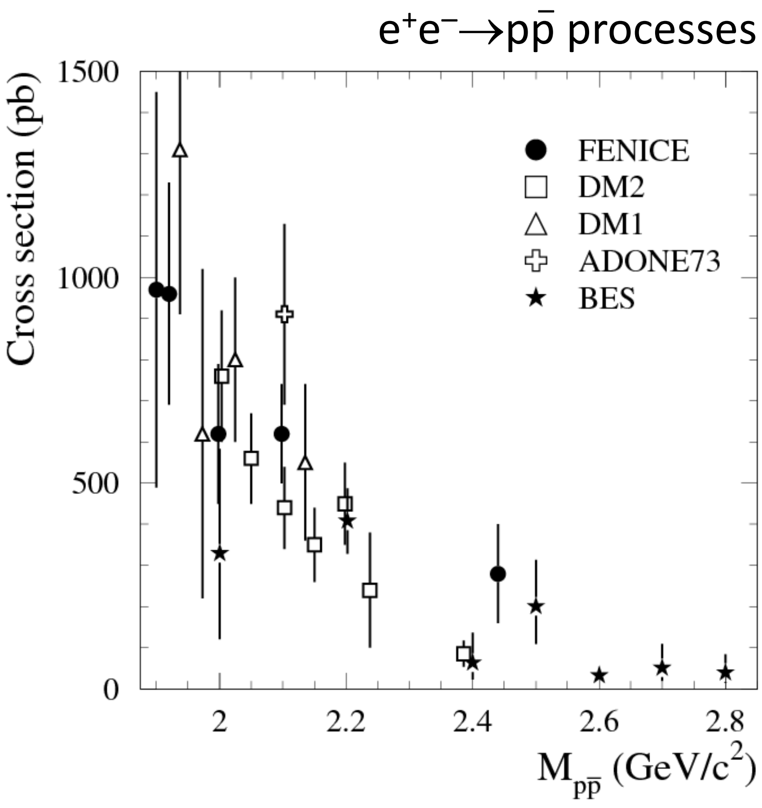
$$\frac{d\sigma}{d\Omega}(s,\theta) = \frac{\alpha^2 \beta C(s)}{4s}\left(|G_M(s)|^2 (1+\cos^2\theta) + \frac{4m_p^2}{s}|G_E(s)|^2 \sin^2\theta \right)$$

- From the measured cross section we define an effective form factor:

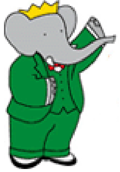
$$|F_p(s)| = \sqrt{\frac{|G_M(s)|^2 + (2m_p^2/s)|G_E(s)|^2}{1+2m_p^2/s}}$$

  - At high energies G_E is suppressed as $1/E^2$ and $|F_p| \sim |G_M|$.

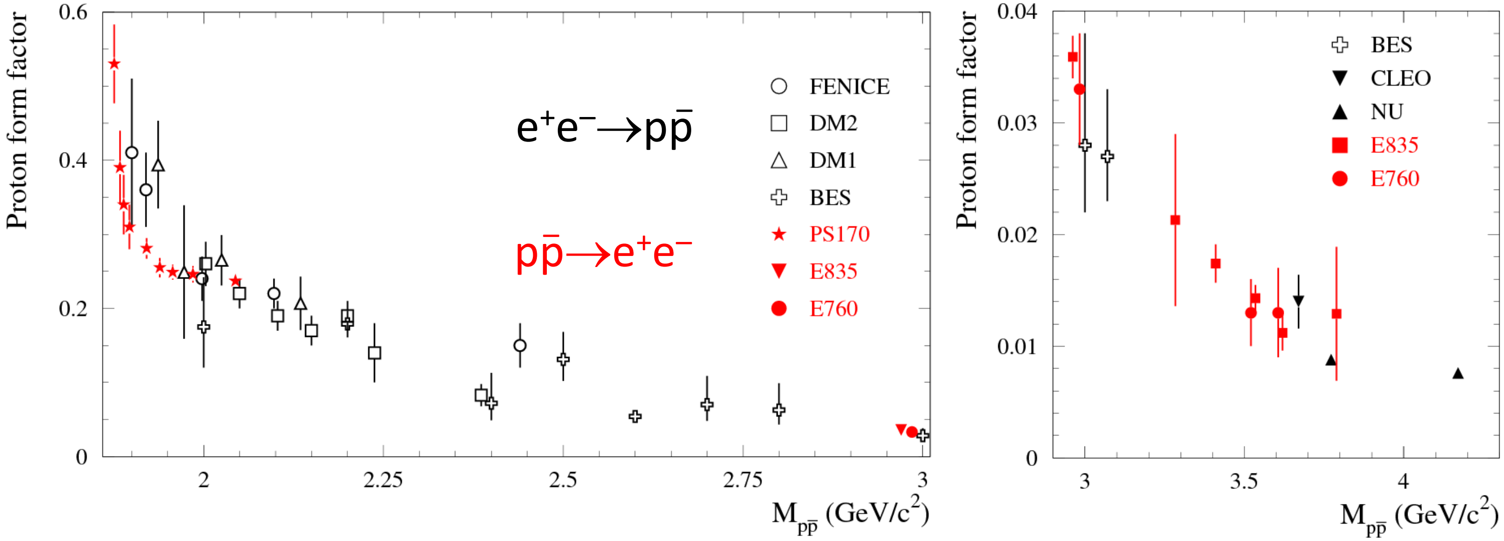
PREVIOUS MEASUREMENTS (1/2)



- Below 3.2 GeV:
  - ADONE73 (1973), DM1(1979), DM2(1983,1990), FENICE(1994), BES(2005).
  - Statistical accuracy of these measurements is (20-30)%.
  - Limited statistics does not allow to extract the G_E/G_M ratio from the analysis of the angular distribution.



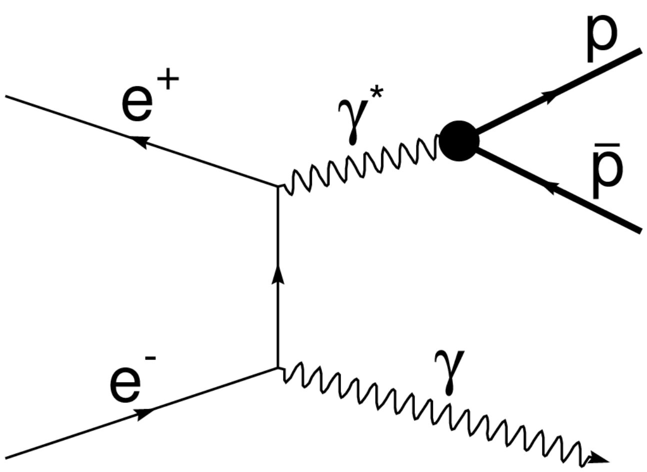
PREVIOUS MEASUREMENTS (2/2)



The statistics of these experiments are usually not enough to study angular distributions. All data were obtained under the assumption that $|G_E|=|G_M|$.

- Near threshold data were obtained at the PS170 experiment at the antiproton storage ring LEAR (CERN) :
  - Steep growth of the form factor near threshold.
  - The ratio $|G_E/G_M|$, measured with 30% accuracy in five energy points, agrees with unity
- Measurements above 3GeV were performed at FNAL (E835 and E760)
- The very precise points marked “NU” (Phys. Rev. Lett. 110 (2013) 022002) were obtained using CLEO data(~1/fb) collected at 3.77 and 4.17 GeV

THE ISR METHOD (1/2)



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

$$x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{m^2}{s}$$

- The $p\bar{p}$ mass spectrum in $e^+e^-\to \gamma p\bar{p}$ is related to the cross section for the non radiative process $e^+e^-\to p\bar{p}$
- $W(s,x,\theta)$ is calculated from QED and describes angular ($1/\sin^2\theta$ at $\theta >> m_e/\sqrt{s}$) and energy ($1/x$) distributions of the ISR photon.

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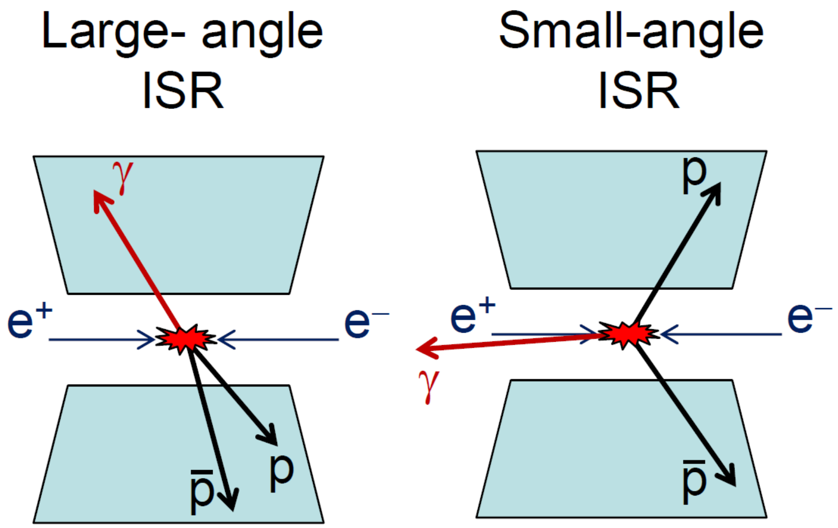
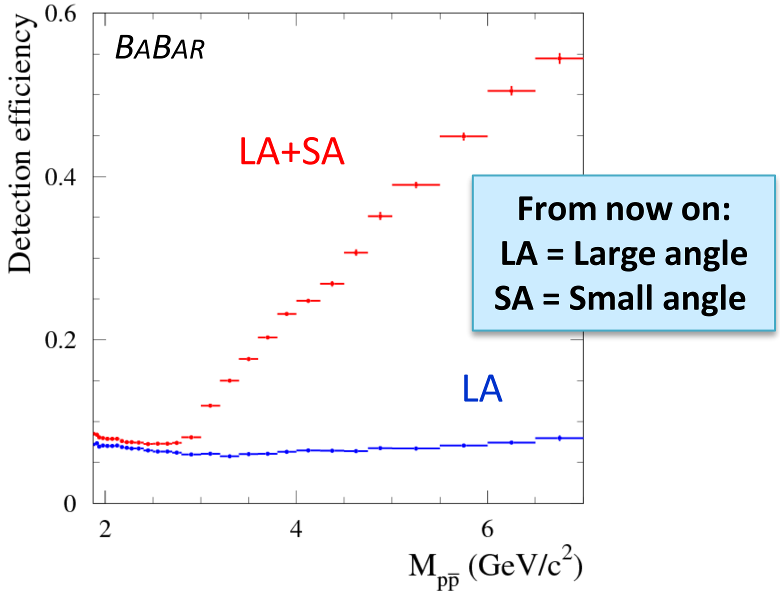
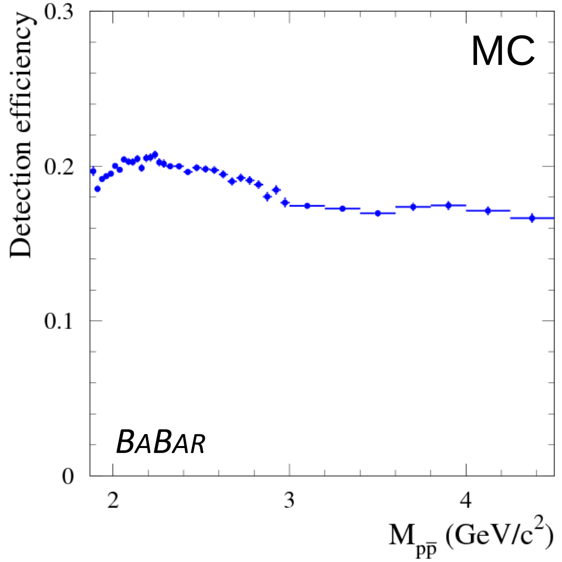
THE ISR METHOD (2/2)

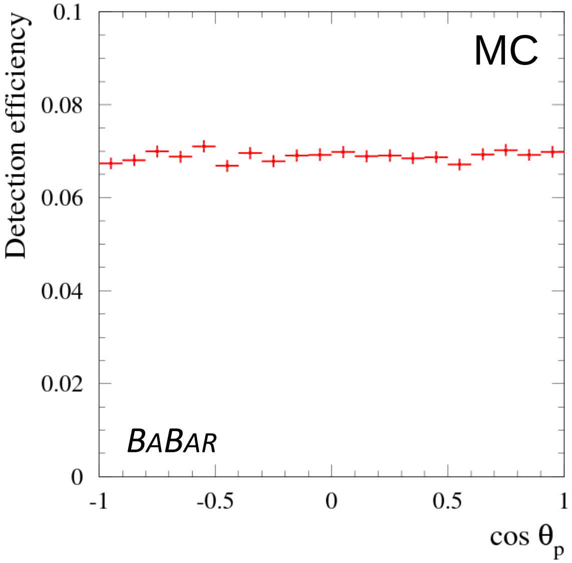




- The ISR photon is emitted predominantly along the beam axis. The produced hadronic system is boosted against the ISR photon. Due to limited detector acceptance the mass region below 3 GeV can only be studied with detected photons (about 10% of ISR events).
- The statistics can be significantly increased above 3 GeV by using small-angle ISR.

ADVANTAGES OF THE ISR METHOD

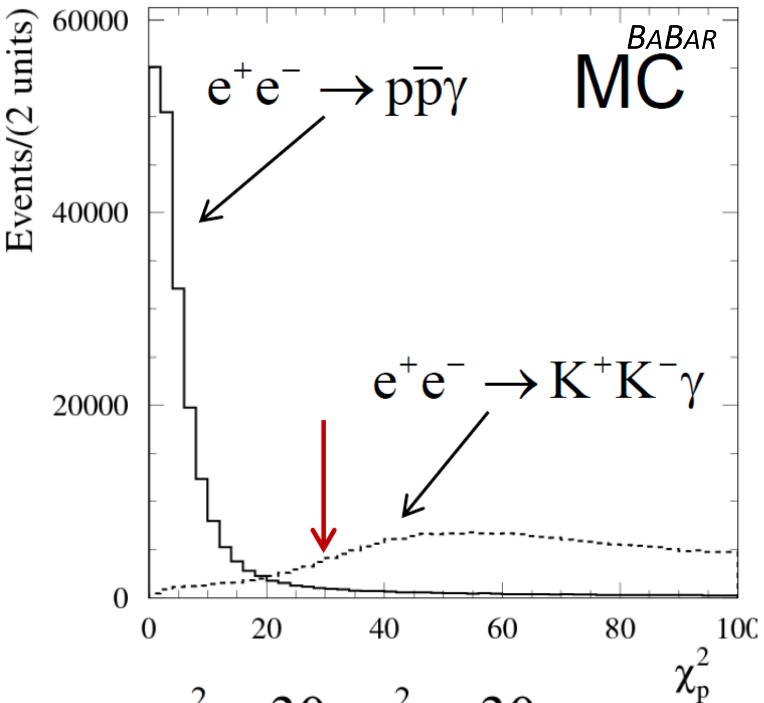




- A wide energy region is studied in a single experiment.
  - The effective ISR luminosity (pb^{-1}/GeV) increases with mass, partly compensating a decrease of the measured cross section.
- Low dependence of the detection efficiency on the hadronic invariant mass.
  - Measurement near and above threshold with the same selection criteria.
- Low dependence of the detection efficiency on hadron angular distributions (in the hadron rest frame).
  - For protons this significantly increases sensitivity for measurements of the G_E/G_M ratio.

LA EVENT SELECTION

- The LA analysis is published in:
  - **Phys. Rev. D 87, (2013) 092005 (469 fb^{-1}).**
  - **Phys. Rev. D 73, (2006) 012005 (232 fb^{-1}).**

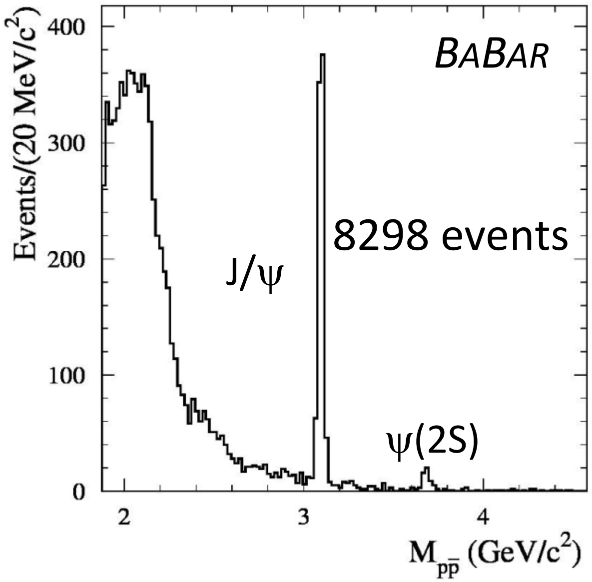


$\chi^2_p < 30, \chi^2_K > 30$

- 2 tracks of opposite charge originating from the IP and identified as protons ($25.8° < \theta < 137.5°$) .
- A photon with $E_{CM} > 3$ GeV ($20.0° < \theta < 137.5°$).
- Kinematic fit to $e^+e^- \to \gamma h^+h^-$ (h=p,K) requiring *p* and E conservation.
- $e^+e^- \to \gamma\pi^+\pi^-$, $\gamma\mu^+\mu^-$, γK^+K^- backgrounds suppressed by PID requirements and χ^2 cuts.

BACKGROUNDS FOR LA SELECTION

Reconstructed $p\bar{p}$ mass spectrum



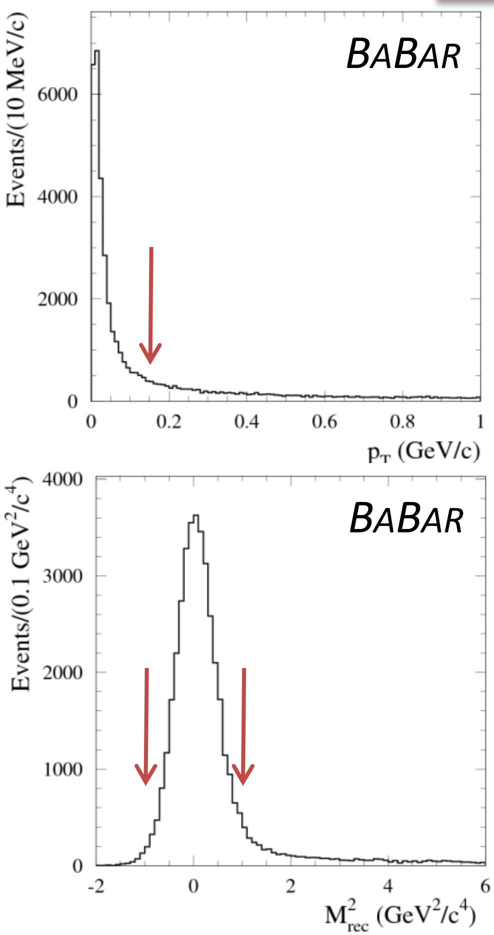
Data	ppγ	ppπ⁰	ISR and e⁺e⁻
8298	7741±113	448±42	109±30

- Main background from $e^+e^- \to p\bar{p}\pi^0$
  - Undetected low-energy photon or merged photons from the π^0 decay.
  - Estimated from data using a control sample of $e^+e^- \to p\bar{p}\pi^0$ events.
    - Increases from 5% at M_{pp}< 2.5 GeV to 50% at 4 GeV.
  - All data events observed above 4.5 GeV are explained by this background.

SA EVENT SELECTION

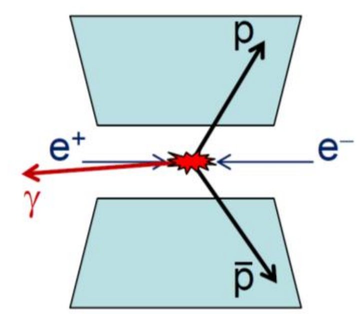
- SA analysis is a preliminary result:
  - **http://arxiv.org/abs/1308.1795**

$e^+e^- \to \gamma p\bar{p}$ (MC)



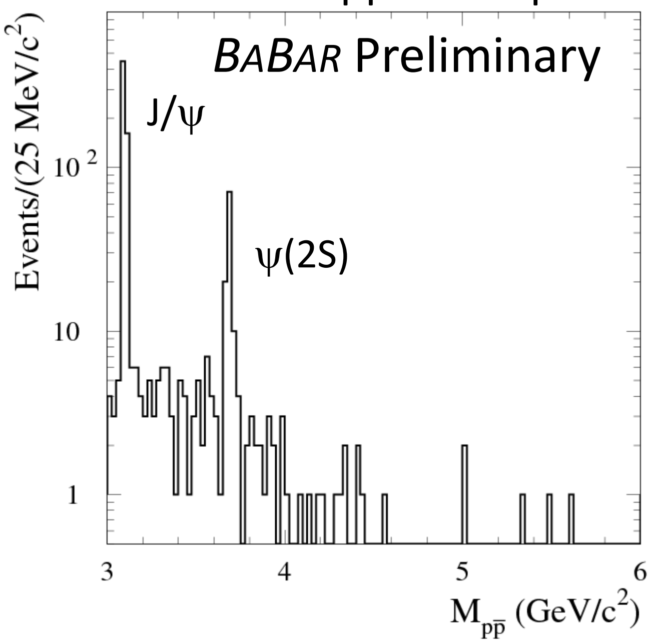
- 2 tracks of opposite charge originating from the IP and identified as protons (25.8°<θ< 137.5°)
- P_T< 0.15 GeV/c
- $|M^2_{rec}|$< 1GeV^2/c^4

No requirement on the ISR photon!



BACKGROUND FOR SA ISR

Reconstructed $p\bar{p}$ mass spectrum

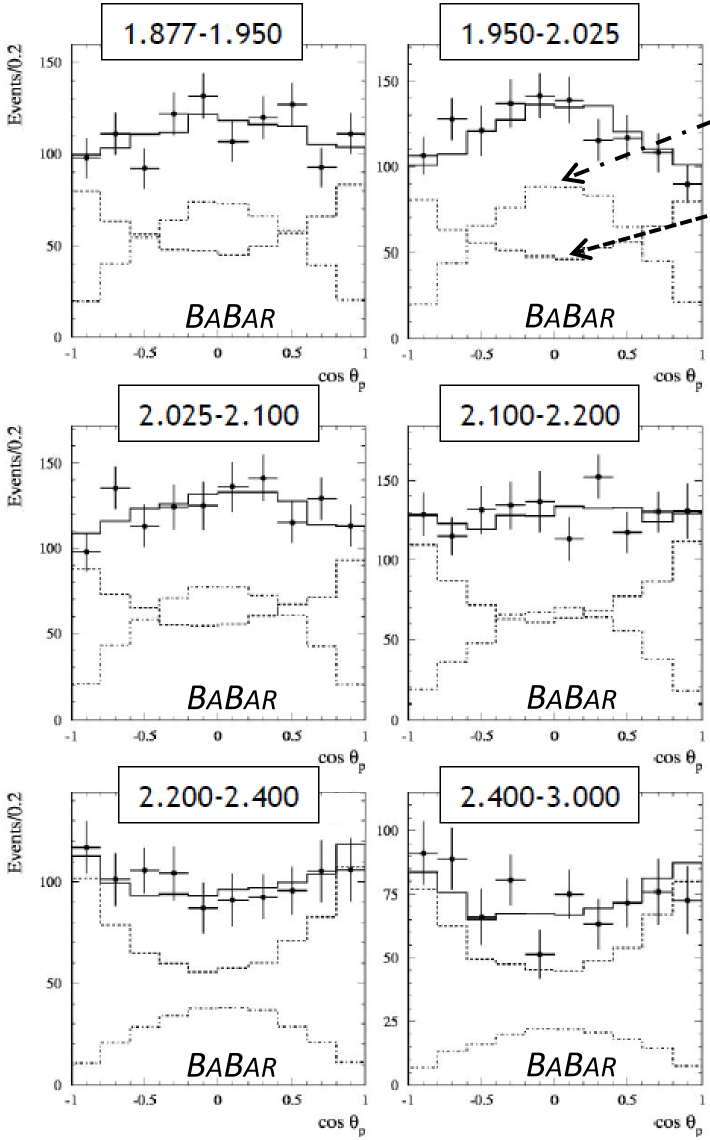


Data	$\mu\mu\gamma$	2-photons	ISR
149±12	<1.2	1.6±0.9	6.3±3.5

- The dominant background process is $e^+e^- \rightarrow \gamma p\bar{p}\pi^0$
- The main background in our large-angle ISR analysis from $e^+e^- \rightarrow p\bar{p}\pi^0$ is found to be negligible.
- Selected events: 845.
- Non resonant events: 149.
- No events are observed with mass above 6 GeV/c^2.

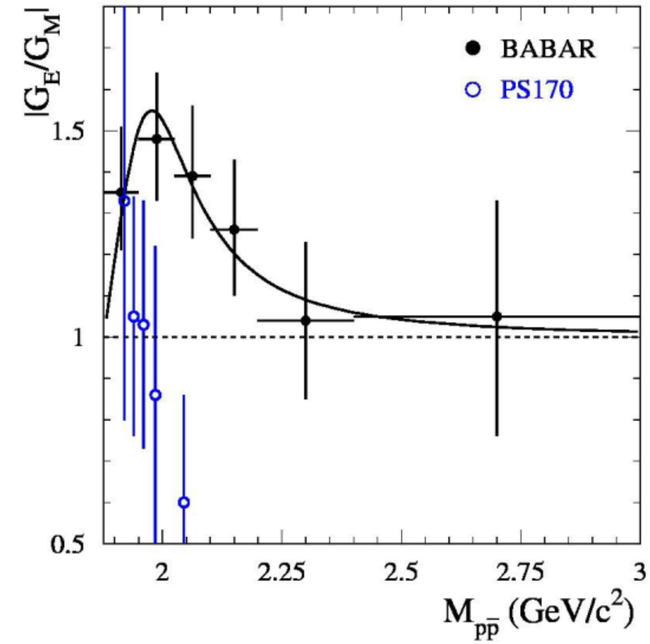
Phys. Rev. D 87, (2013) 092005

LA ANGULAR DISTRIBUTION



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

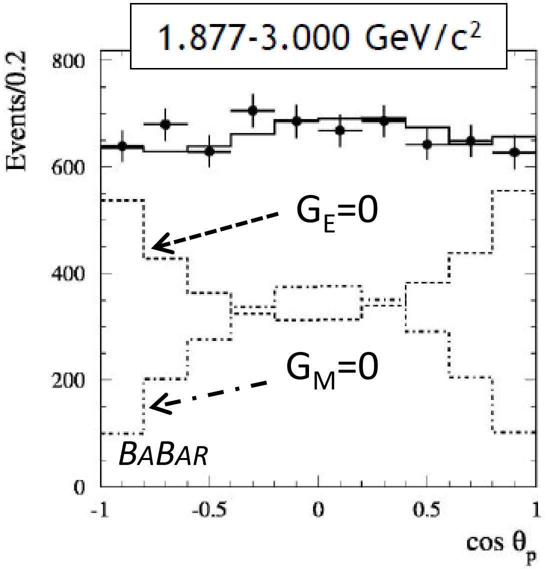
$$\frac{d\sigma(G_M)}{d\cos\theta} \sim 1+\cos^2\theta_p$$

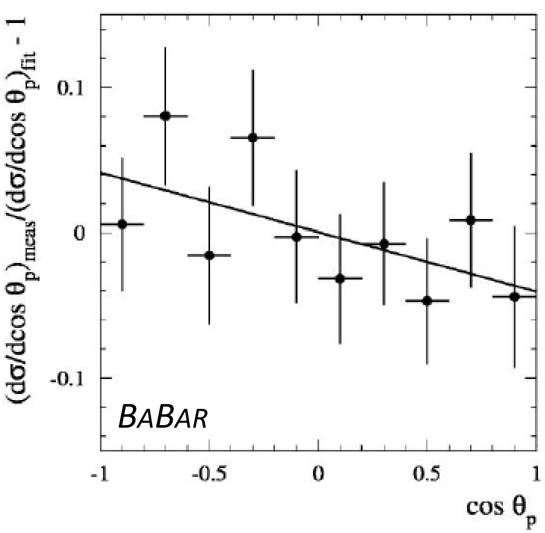


- θ_p is the angle between the proton momentum in the $p\bar{p}$ rest frame and the momentum of $p\bar{p}$ system in the e^+e^- c.m. frame.
- The distribution is fitted by a sum of histograms from two simulated samples, one with $G_E=0$ (dashed) and other with $G_M=0$ (dot-dashed) .

Phys. Rev. D 87, (2013) 092005

LA Angular Distribution Asymmetry

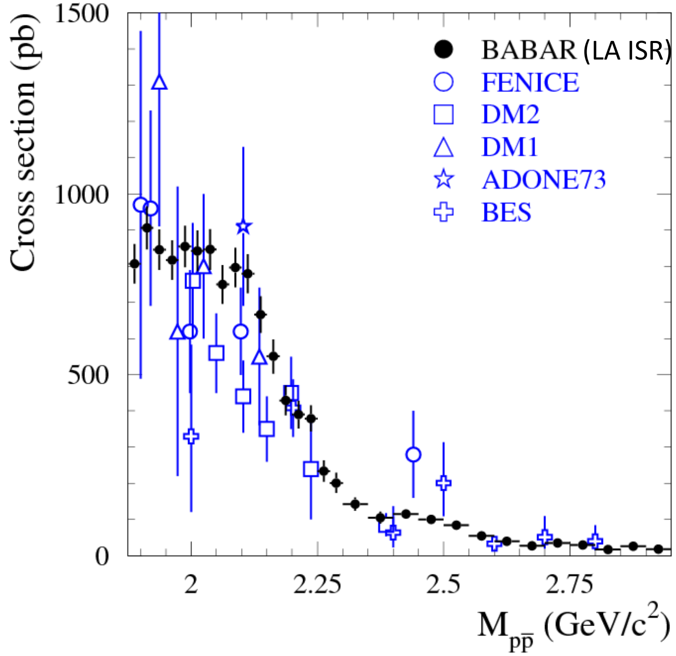


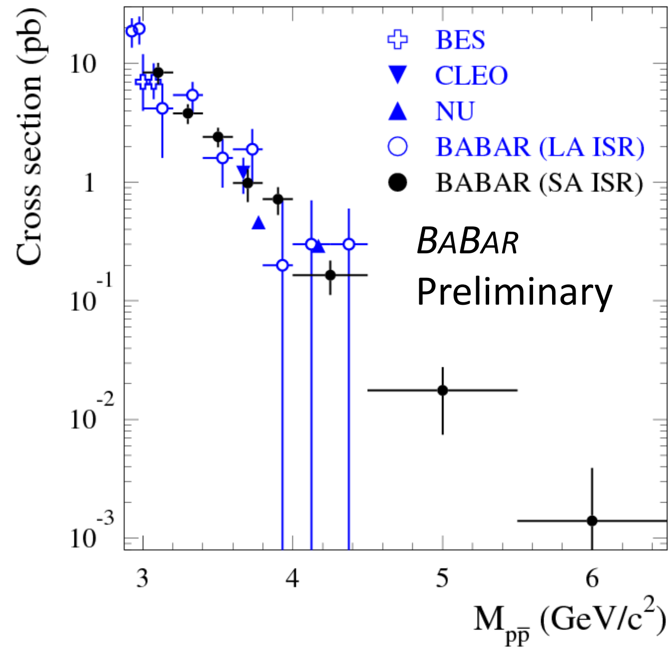


- The asymmetry is absent in lowest order ($\gamma^* \to p\bar{p}$). It arises from higher-order contributions (soft extra ISR and FSR interference, two-photon exchange). By measuring the asymmetry we control the higher-order contributions.
- We analyze the difference between the measured and fitted distributions.
  - The slope is – 0.041±0.026±0.005
  - The integral asymmetry :

$$A = \frac{\sigma(\cos\theta_p > 0) - \sigma(\cos\theta_p < 0)}{\sigma(\cos\theta_p > 0) + \sigma(\cos\theta_p < 0)} = -0.025 \pm 0.014 \pm 0.003$$

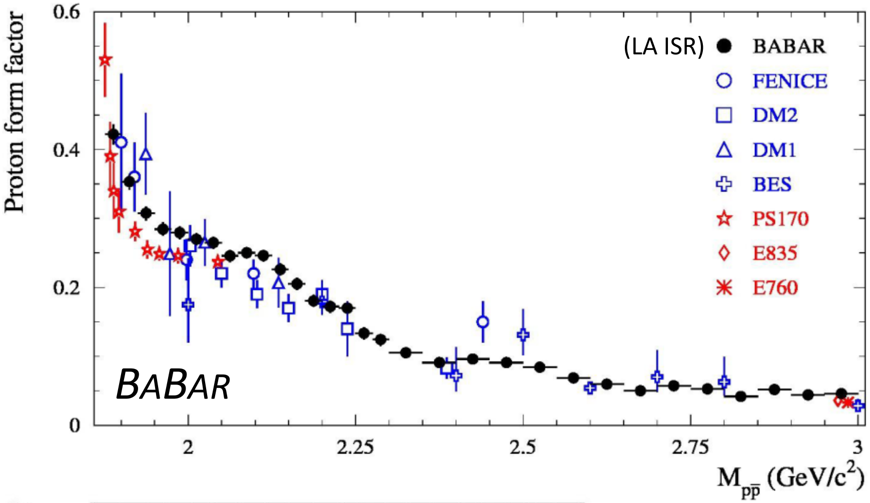
MEASURED CROSS SECTION $\sigma_{ee \to p\bar{p}}(m) = \frac{dN/dm}{\varepsilon R dL/dm}$

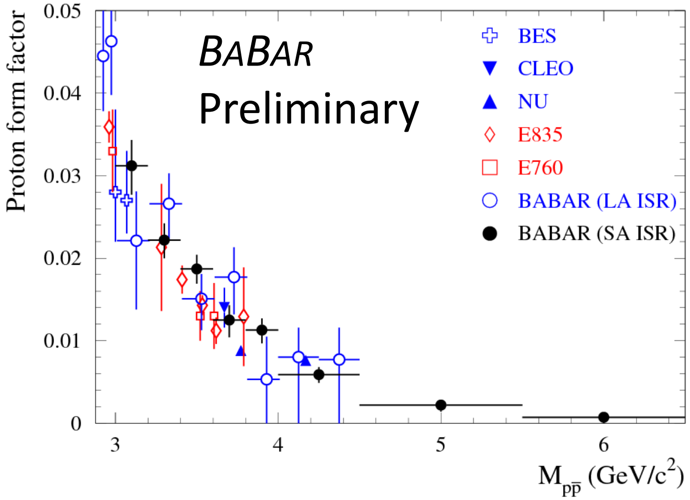


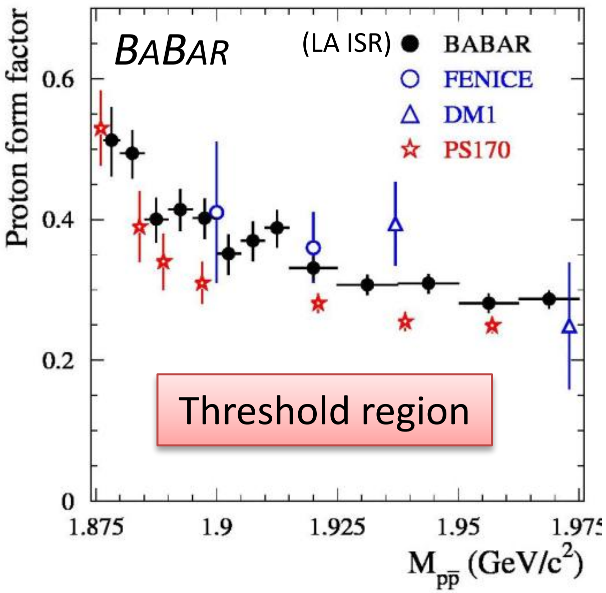


- Mass-independent systematic uncertainty is 4-5% for LA ISR. For SA ISR it decreases from 16% at 3 GeV to 6% at 4.5 GeV.
- In the mass region under study the cross section changes by about six orders of magnitude.
- Our data are in reasonable agreement with previous measurements.
- We improve accuracy and extend the mass region of measurements.

EFFECTIVE PROTON FORM FACTOR





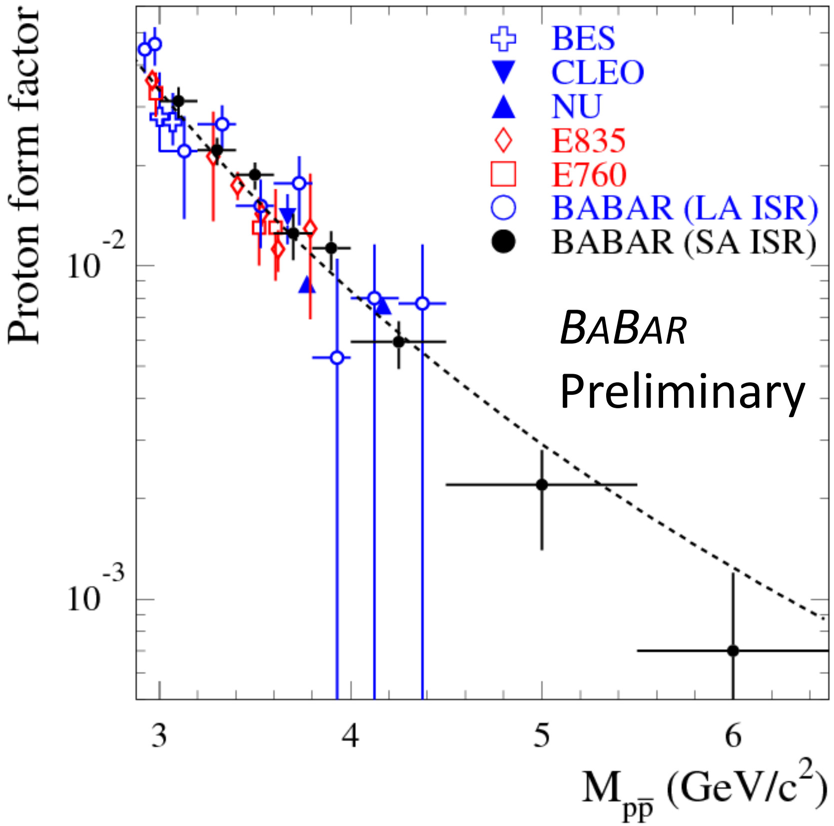


$$|F_p(s)| = \sqrt{\frac{|G_M(s)|^2 + (2m_p^2/s)|G_E(s)|^2}{1+2m_p^2/s}}$$

Effective proton form factor

- A steep fall off and $G_E/G_M \neq 1$ near threshold are explained by nucleons' final state interaction.
- A complex step-like behavior far off threshold (steps at 2.2, 2.55, 3 GeV/c2) is not described by existing models.

QCD MOTIVATED FIT



$$G_M \sim \frac{\alpha_s^2(m^2)}{m^4} \sim \frac{1}{m^4 \ln^2(m^2/\Lambda^2)}$$

- All the data above 3 GeV except the two "NU" points are well described by this function.
- Adding the "NU" points change the fit χ^2/ν from 17/24 to 54/26.
- Our data shows that the form factor decreases in agreement with the asymptotic QCD prediction or even faster above 4.5 GeV.

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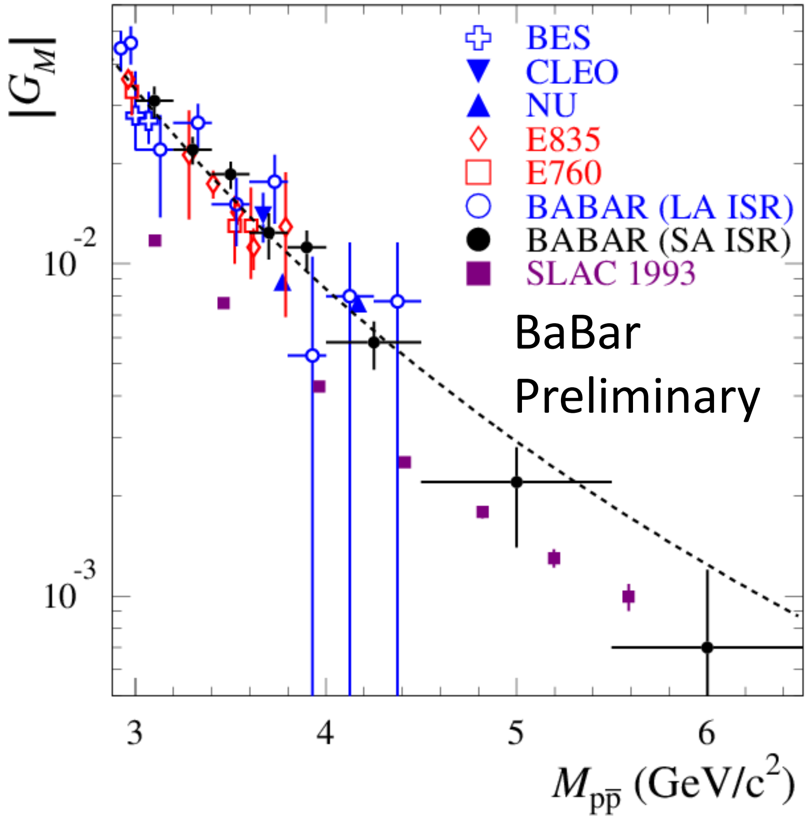
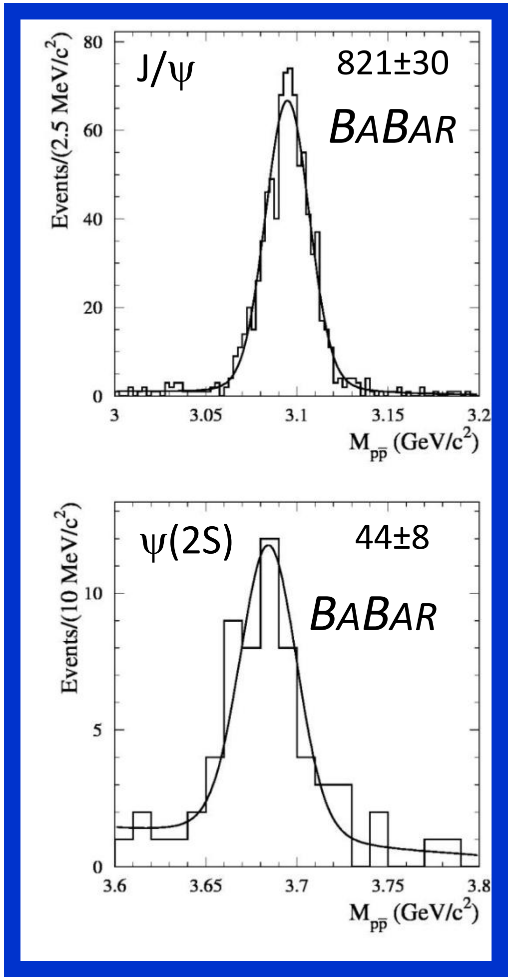
COMPARISON WITH SPACE-LIKE G_M



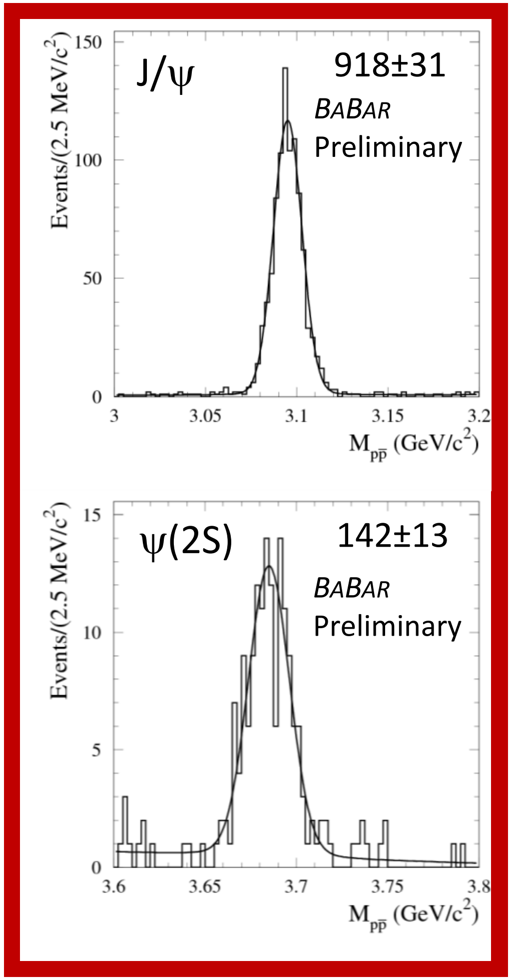
Our two points above 4.5 GeV may give an indication that the difference between the time-and space-like form factors begins to decrease.

- The points “SLAC 1993” represent data on the space-like magnetic form factor measured in *ep* scattering as a function of $\sqrt{-q^2}$.
- The asymptotic values of the space-and time-like form factors are expected to be the same.
- In the mass region from 3 to 4.5 GeV the time-like form factor is about two times larger than the space-like one.

J/ψ AND *ψ(2S)* DECAYS



- LA ISR



- SA ISR

- $B(J/\psi \to p\bar{p}) \times 10^{-3}$
  - SA: 2.33±0.08±0.09
  - LA: 2.04±0.07±0.07
  - PDG: 2.17±0.07
- $B(\psi(2S) \to p\bar{p}) \times 10^{-4}$
  - SA: 3.14±0.28±0.18
  - LA: 2.86±0.51±0.09
  - PDG: 2.76±0.12

SUMMARY

- The $e^+e^- \to p\bar{p}$ cross section and the proton effective form factor have been measured from threshold up to 6.5 GeV using the full BaBar data sample.
- The form factor shows a complex mass dependence. There are a near-threshold steep fall off and a step-like behavior at higher masses.
- The $|G_E/G_M|$ ratio has been measured from threshold up to 3 GeV/c^2. A large deviation of this ratio from unity is observed below 2.2 GeV/c^2.
- Asymmetry in the proton angular distribution has been measured.
- At masses above 3 GeV the observed decrease of the form factor agrees with the asymptotic dependence $\alpha_s^2(m)/m^4$ predicted by QCD.
- New measurements expected : VEPP2000, BES, FAIR,…

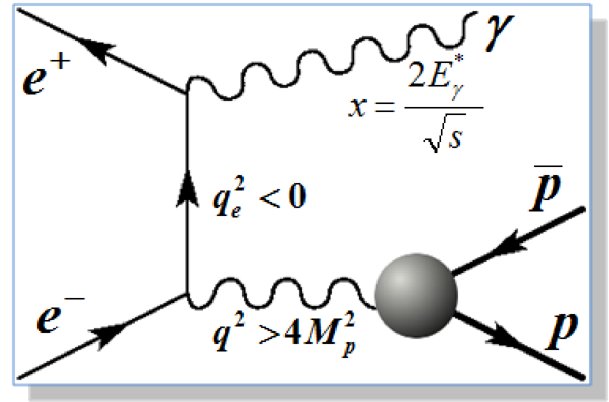
ISR CROSS SECTION

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:

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

$e^+e^- \to p\bar{p}$ cross section

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

reconstruction efficiency

radiative corrections

ISR differential luminosity

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

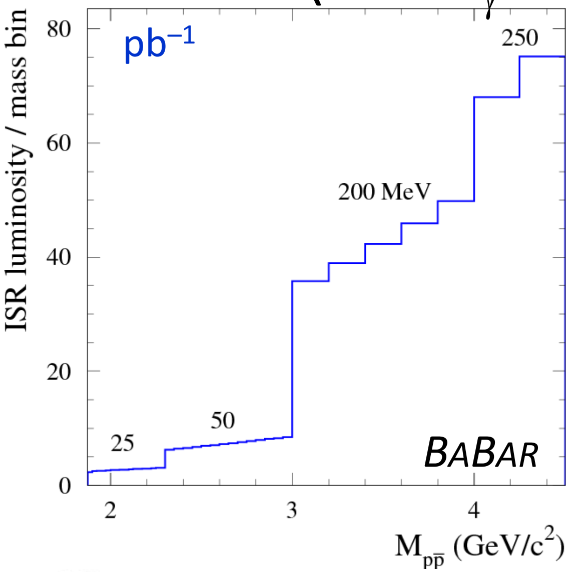
Machine integrated luminosity

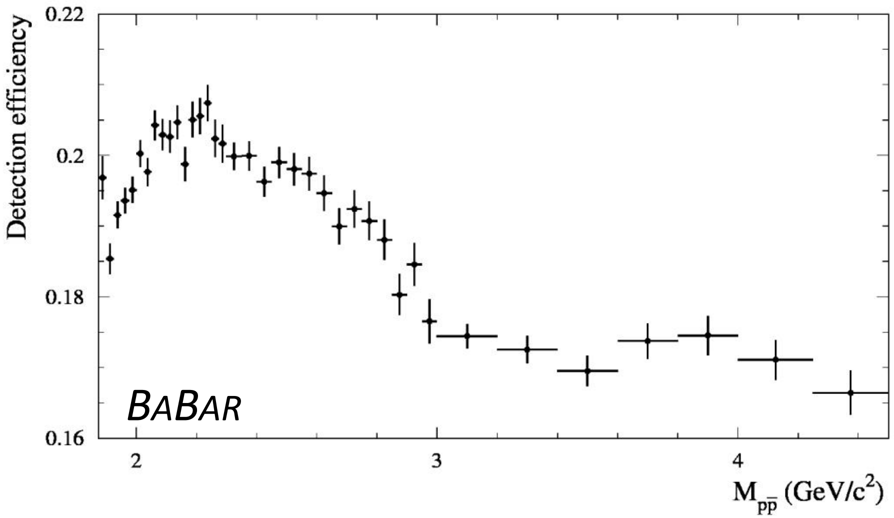
$\cos\theta^*_{\min}$

- Obtained from integration of the radiator function over θ_γ^*
- Known at 1% level (from MC simulation)
- $20^\circ < \theta_\gamma^* < 160^\circ$ → acceptance for ISR photon ~10-15% in BABAR

CROSS SECTION

- LA ISR ($20° < \theta_\gamma^* < 160°$)





$$\sigma_{ee\to p\bar{p}}(m) = \frac{dN/dm}{\varepsilon R dL/dm}$$

- SA ISR (Preliminary)