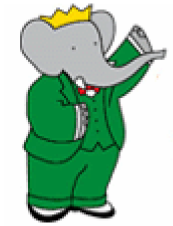
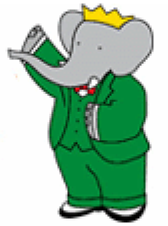
Proton Form Factor Measurements in the Time-like Region from *BABAR*

Bill Dunwoodie [SLAC]

Representing the *BABAR* Collaboration





JLab Users' Meeting, June 14, 2006

Outline

(1) Status of PEP II and *BABAR*

(2) Initial State Radiation (ISR) studies ; towards improved precision on R below ~ 3 GeV c.m.energy

(3) ISR distributed luminosity { i.e. sampling, or radiator, function } for c.m. energy below 4.5 GeV

(4) $e^+ e^- \rightarrow p \bar{p}$ from threshold to 4.5 GeV ; cross section , extraction of $| G_E | / | G_M |$

(5) c. m. energy dependence of effective FF; comparison to mass dependence of $p \bar{p}$ invariant amplitude squared for selected $B \rightarrow p \bar{p} X$ decays

(6) Summary and status of ongoing analyses

Status of PEP II & *BABAR*

As of June 5th :

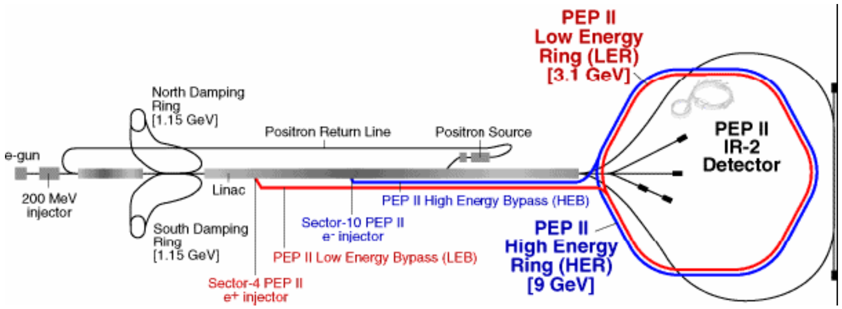
Peak L   1.088 x 10^{34} cm^{-2} sec^{-1} (5/25/06)

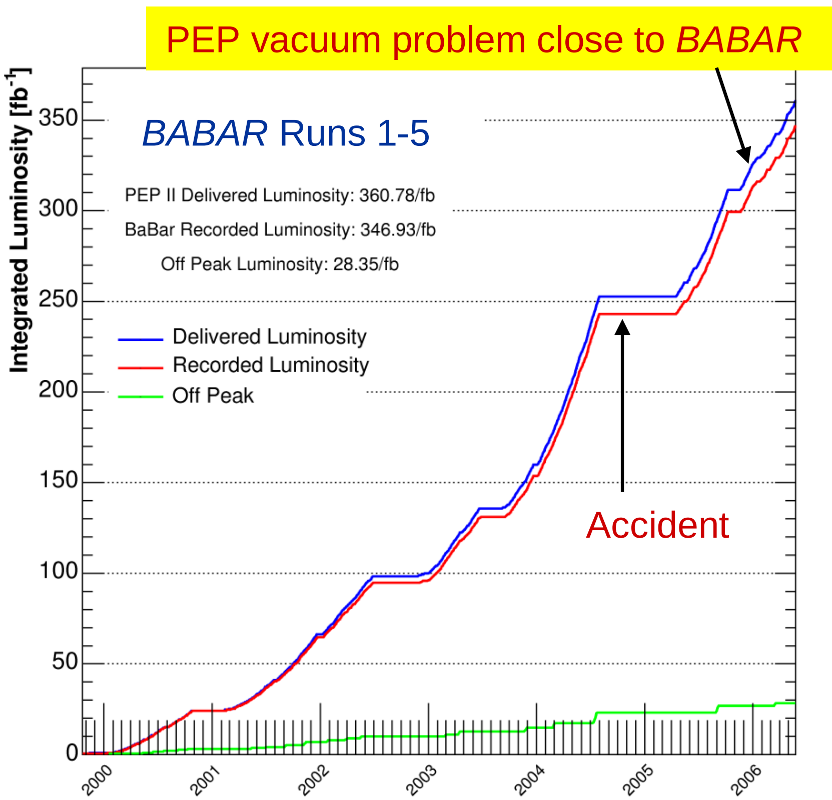
{ 2.7 A (LER) , 1.775 A (HER) ,1722 bunches}

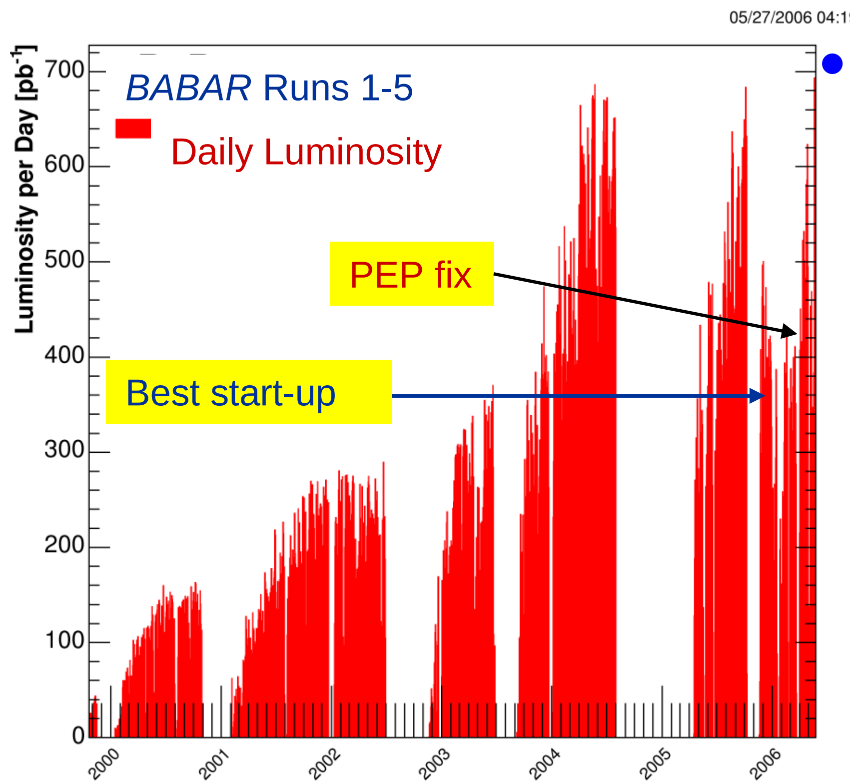
Best Day   713.5 pb^{-1} ●   (5/22/06)

Delivered   369 fb^{-1} { ~ 410 fb^{-1} by Run 5 end ;

~ 4 x 10^8 B $\overline{B}$ pairs }

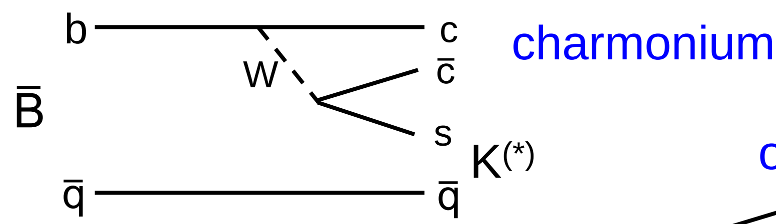


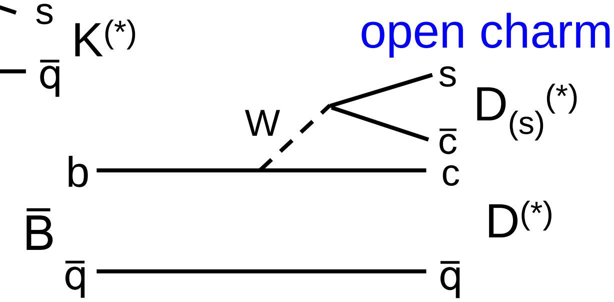




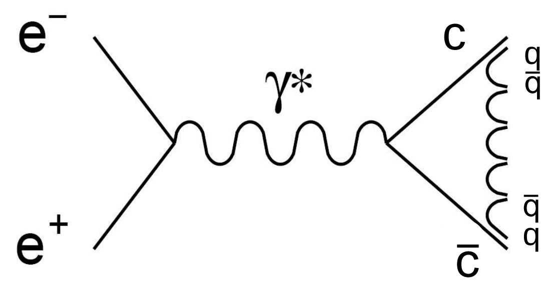
Production of hidden- and open-charm states

- Production in B decays
  - provides access to inclusive measurements of absolute branching fractions
  - also copious charm baryon production

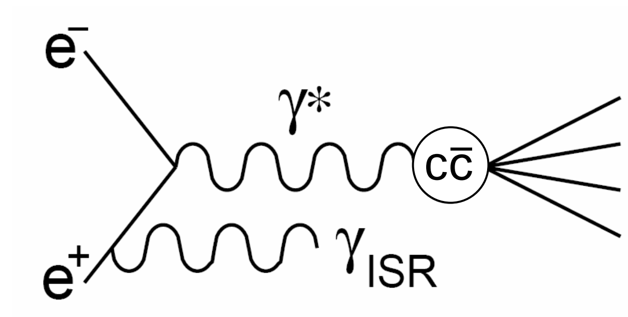




- $e^+e^- \rightarrow c\bar{c}$ fragmentation
  - cross section at 10.58 GeV $\sigma(c\bar{c})$~1.3 nb → ~ 10^9 charm particles
  - spectroscopy of open charm states with high precision



- Initial state radiation (ISR) $e^+e^- \rightarrow \gamma_{ISR}(c\bar{c})$
  - $J^{PC} = 1^{--}$ spectroscopy at energies << 10.58 GeV e.g. have produced ~ 1.5×10^7 J/ψ



BABAR offers excellent options for charm / charmonium spectroscopy

Initial State Radiation (ISR) Studies at *BABAR*

- **Objective :**

  Precise cross section measurements for all significant processes,
  $e^+ e^- \rightarrow f$, from threshold to c.m. energy ~ 4.5 GeV

- **Purpose :**

  Significantly improve understanding of the spectroscopy of $J^{PC} = 1^{--}$ states, and of their resonant substructure

  Combine the cross section measurements to obtain improved precision on the c.m. energy dependence of R in this region

- **Reactions for which results have been published :**

  $e^+e^- \rightarrow p\bar{p}$ ← This Talk

  $e^+e^- \rightarrow \pi^+\pi^-\pi^0$

  $e^+e^- \rightarrow 2\pi^+2\pi^-, K^+K^-\pi^+\pi^-, 2K^+2K^-$

  $e^+e^- \rightarrow 3\pi^+3\pi^-, 2\pi^+2\pi^-\pi^0\pi^0, K^+K^-2\pi^+2\pi^-$

- **Work in progress on :**

  $\pi^+\pi^-$, $K\bar{K}$, $K\bar{K}\pi^0$, $K\bar{K}\eta$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^- 3(\pi^0)$, $\Lambda\bar{\Lambda}$, $\Lambda\bar{\Sigma}$, $\Sigma\bar{\Sigma}$, $d\bar{d}$,.....

  Brief comments on these states at end of Talk

Relevance of Precision R Measurements

- **R(s) is defined as**

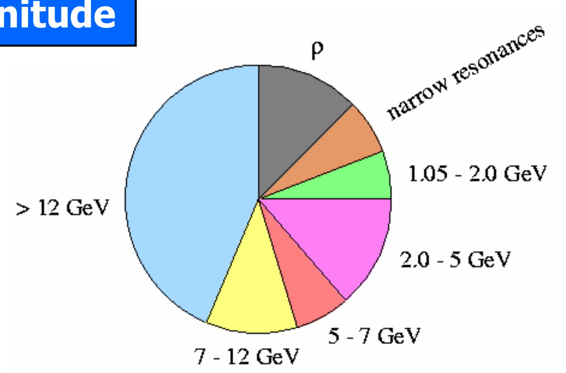
$$R(s) = \frac{\sigma(e^+e^- \to \text{Hadrons})}{\sigma_0(e^+e^- \to \mu^+\mu^-)}$$

- **Crucial input for hadronic contributions to**
  - **Muon anomalous magnetic moment (a_μ)**
  - **Running of α_{QED} (for SM fits, $\Rightarrow$ Higgs Mass).**

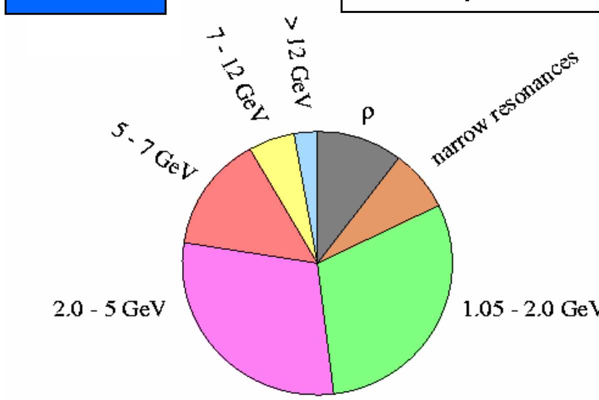
Contributions to $\Delta\alpha^{had}$

Burkhardt & Pietrzyk 2001

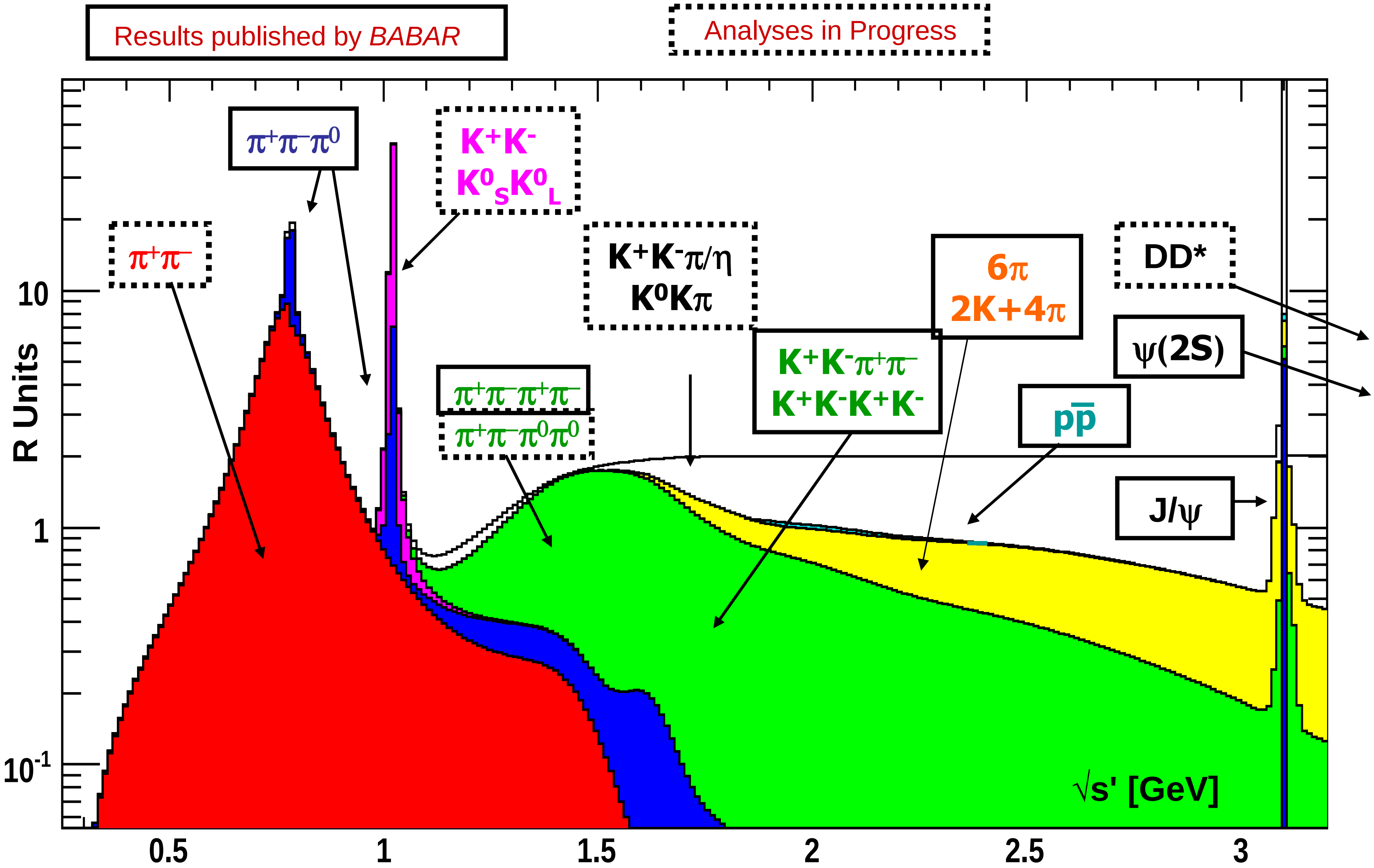
magnitude



errors



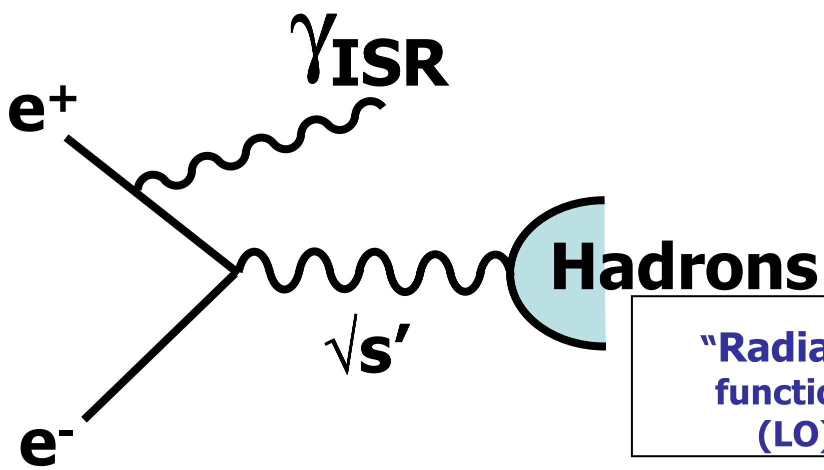
Build R from Sum Over Exclusive Final States (MC)



ISR at $\Upsilon(4S)$ Energies

- rely on tagged photon for identification, loose hadronic selection
- Photon gives s'.
- High fiducial efficiency :
  - wide-angle ISR forces hadronic system into the detector fiducial region
  - Collimated hadronic system due to boost.
  - Weak dependence on details of fragmentation
- Harder momentum spectrum due to boost,
  - **fewer problems with soft particles.**

- **whole √s' spectrum from threshold to ~4-5 GeV**
- **Greatly reduced point-to- point uncertainty**
- **Already used at KLOE, can be used at BaBar over a wider energy range and with tagged photons**
- **excellent resolution from kinematic fits**



Born cross-section:

$$\frac{d\sigma}{dx}(s') = W(s',s).\sigma_0(s')$$

"Radiator function" (LO)

$$W(s,x) \cong \frac{\alpha}{\pi}\frac{1+x^2}{x(1-x)}\left(\log\frac{1-\cos\theta_{\min}}{1+\cos\theta_{\min}} - (1-x)\cos\theta_{\min}\right)$$

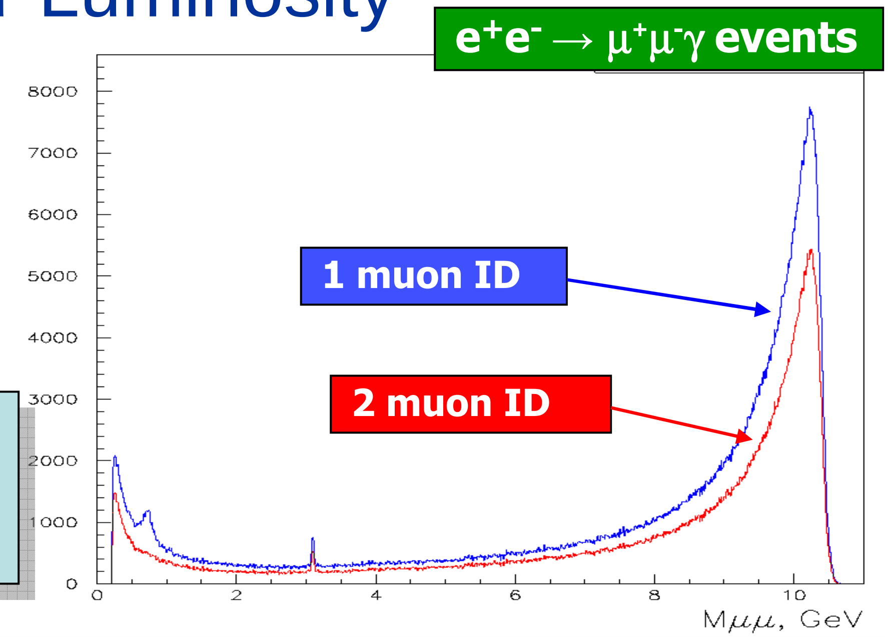
ISR Distributed Luminosity

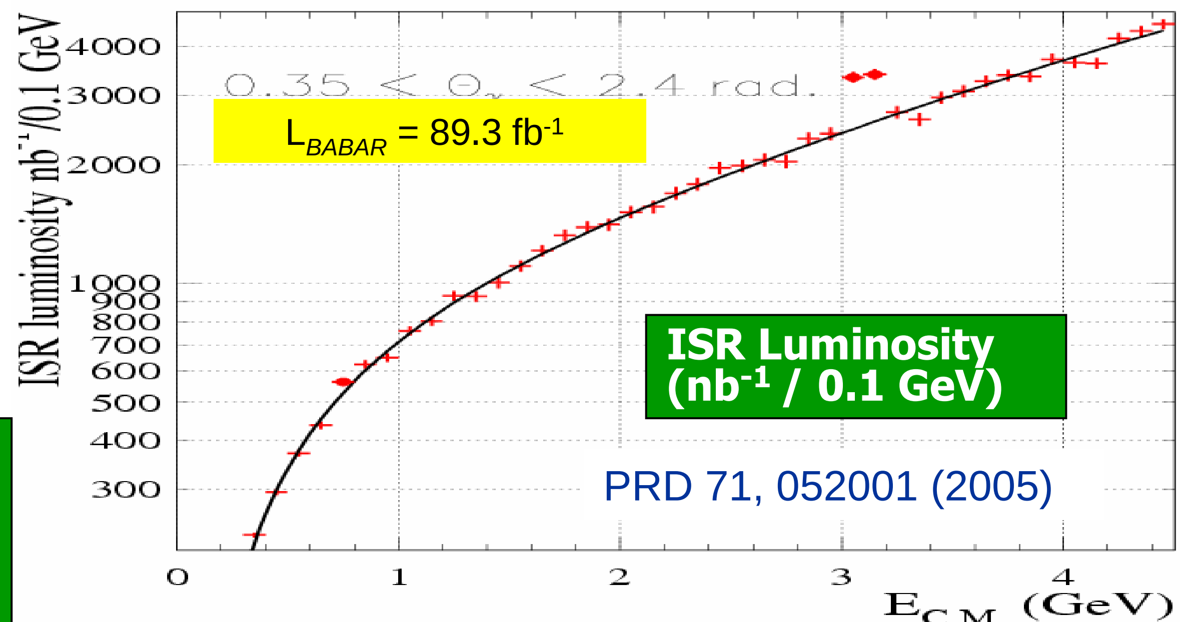
- Use $e^+e^- \to \mu^+\mu^-\gamma$ events for normalization
- Efficiency ~ 15% ; Binned in $m_{\mu\mu}$, p_μ and hit position in muon detector.

$$dL(m) = \frac{dN_{obs}(m)}{\varepsilon_{\mu\mu}(m)(1+\delta_{FSR}(m))\sigma^0_{\mu\mu}(m)}$$

$$\sigma^0_{\mu\mu}(m) = \frac{4\pi\alpha^2}{3m^2}\sqrt{1-\frac{4m_\mu^2}{m^2}}\left(1+\frac{2m_\mu^2}{m^2}\right)$$

MC simulation (AFKQED) uses Born-level ISR + FSR + Interference, + Structure functions for soft photons; precision ~1%





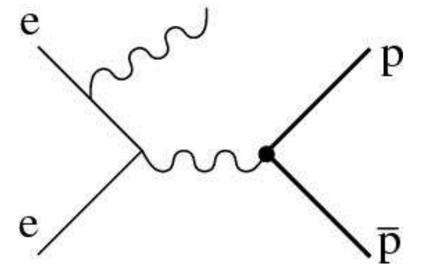
$e^+e^- \to p\bar{p}$

($240\ fb^{-1}$)

Phys. Rev. D 73, 012005 (2006)

Event Selection for $e^+e^- \to p\bar{p}$

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



$$\sigma(e^+e^- \to p\bar{p}) = \frac{4\pi\alpha^2\beta C}{3m^2}\left(|G_M|^2 + \frac{2m_p^2}{m^2}|G_E|^2\right)$$

- Cross section parametrized by Electric and Magnetic form factors
- Can be separated using proton helicity angle distributions

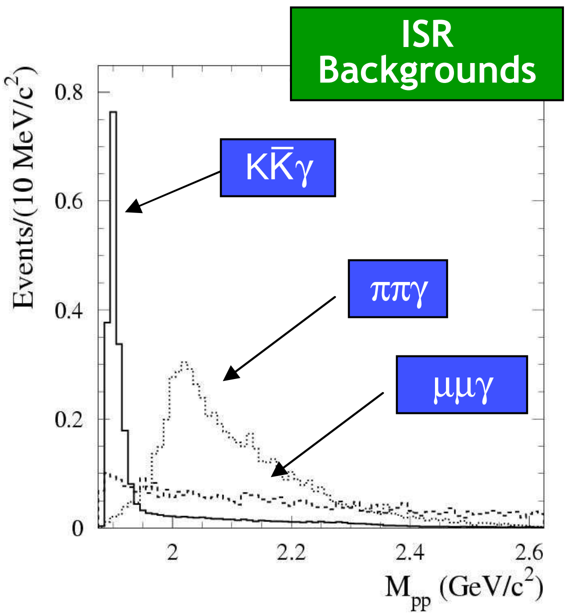
Correction for Coulomb FSI, (cancels β at threshold)

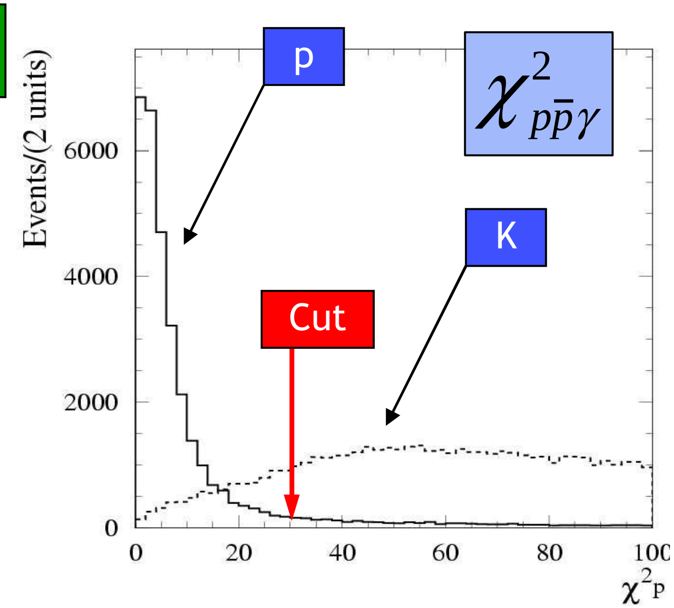
$$C = y/(1-e^{-y})$$

$$y = \pi\alpha m_p / \beta m$$

$$\beta = \sqrt{1 - \frac{4m_p^2}{m^2}}.$$

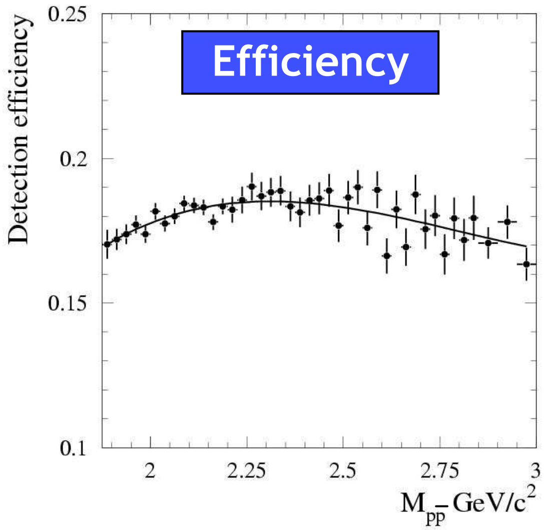
- Experimental challenge: KK, ππ, μμ ~ 10-100 more events
- Require 2 good proton tracks (dE/dx, DIRC)
- Perform 3C kinematic fit to Beam 4-momentum with p, K and π masses, require $\chi^2_{pp\gamma} < 30$

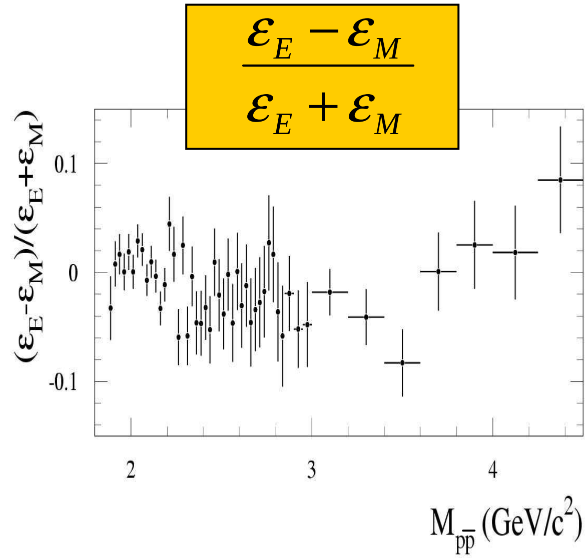


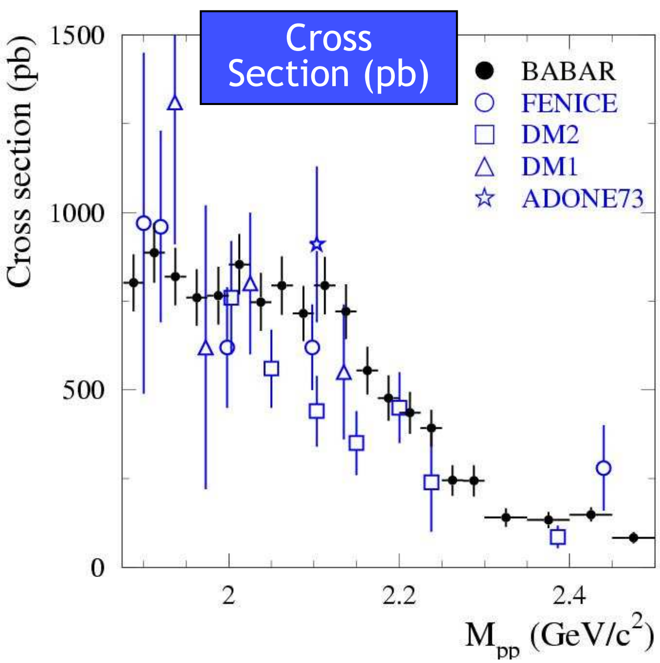


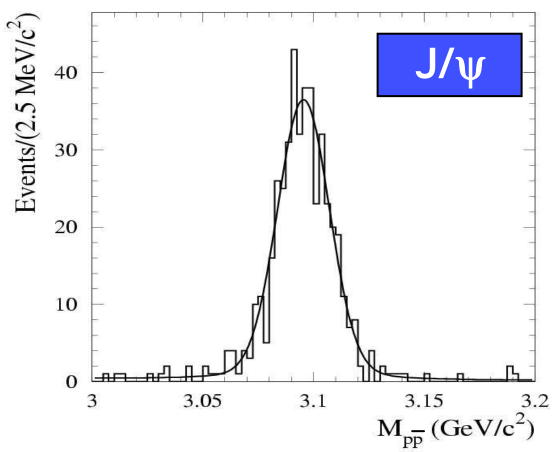
$p\bar{p}$: Efficiency, Cross Section, ψ's

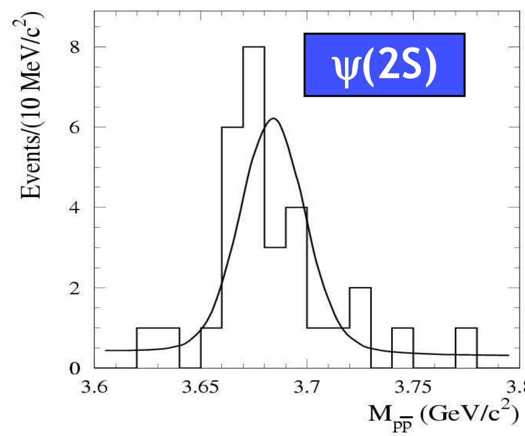
- Efficiency Corrections
  - Dependence on $|G_E/G_M|$
  - χ^2 shape
  - Nuclear interactions with detector material
  - PID
  - photon detection
  - Triggering
- Cross Section:
  - No dip at threshold
  - Sharp dips at 2.25 GeV, 3 GeV
- J/ψ, $\psi(2S)$ signals.
- Normalize to $e^+e^- \to \mu^+\mu^-\gamma$











$$B(J/\psi \to p\bar{p}) = (2.22 \pm 0.16) \times 10^{-3}$$
$$B(\psi(2S) \to p\bar{p}) = (3.3 \pm 0.9) \times 10^{-4}$$

PDG

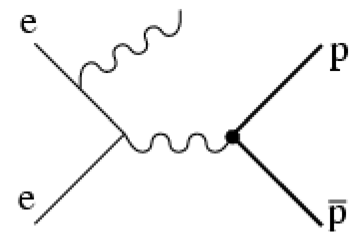
$(2.17\pm0.08)\cdot 10^{-3}$

$(2.36\pm0.24)\cdot 10^{-4}$

ISR production of $p\bar{p}$

- The cross section for $e^+e^- \rightarrow p\bar{p}$ is parametrized by Electric (G_E) and Magnetic (G_M) form factors:

$$\sigma(m) = \frac{2\pi\alpha^2 \beta C}{3m^2}\left(2|G_M(m)|^2 + \tau |G_E(m)|^2\right) \qquad \tau = \frac{4m_p^2}{m^2}$$



- Only BABAR has measurements in the entire range 1.875-4.5 GeV/c^2

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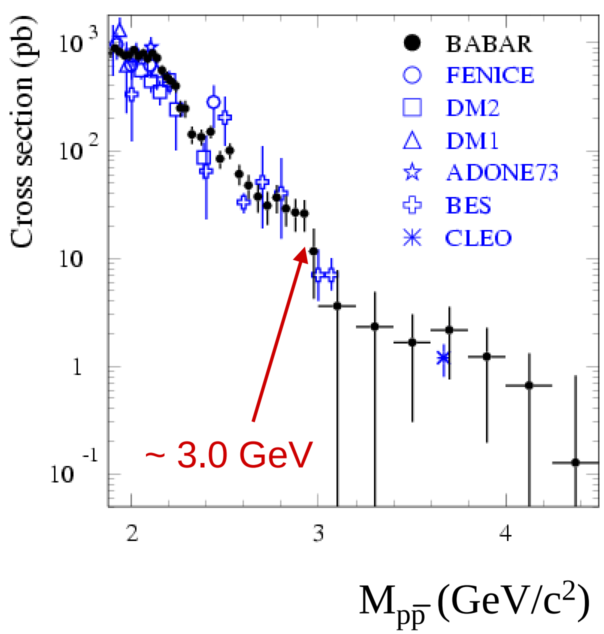
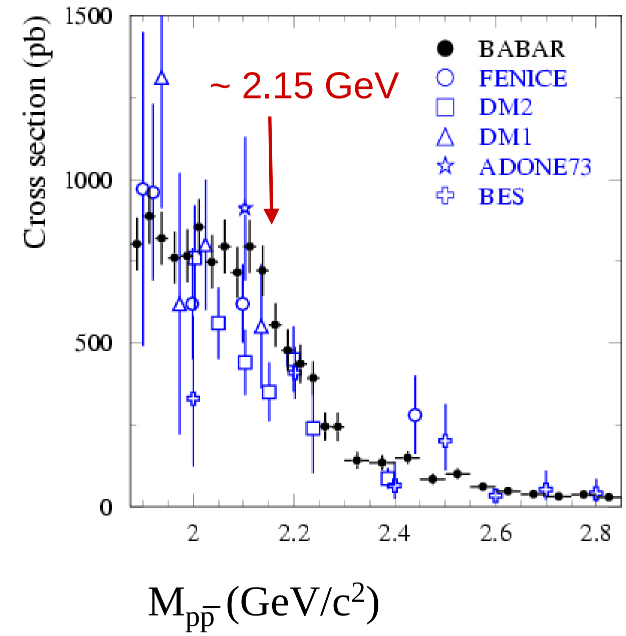
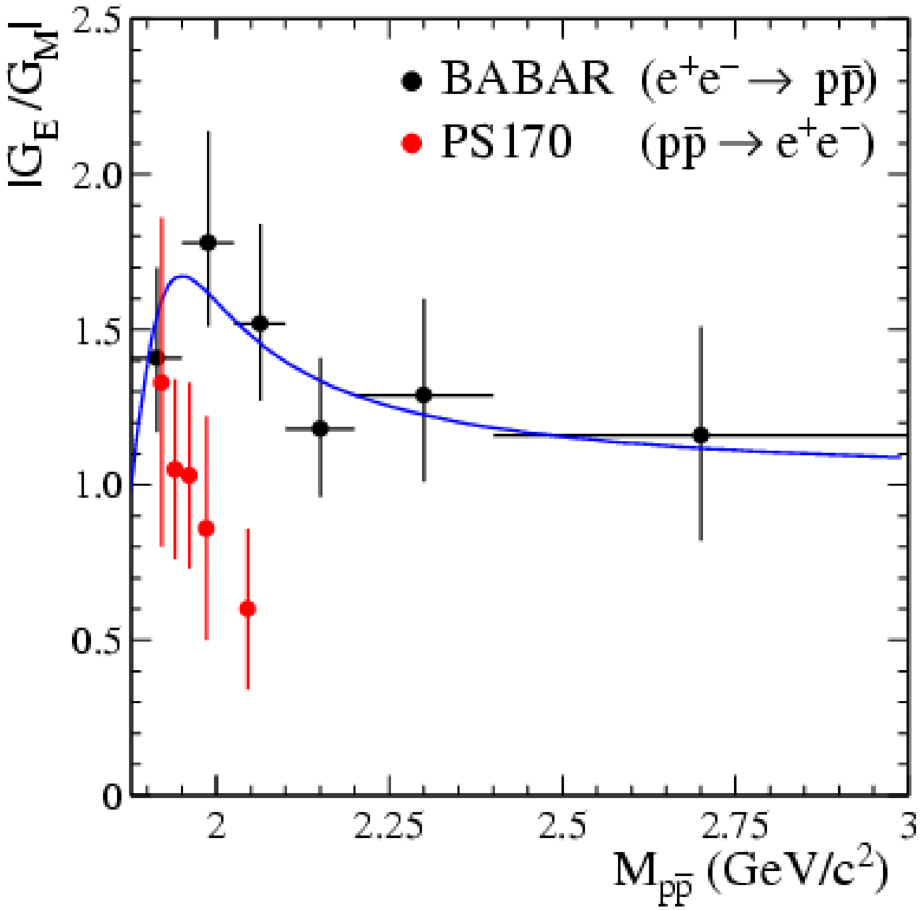


There is no simple theoretical interpretation of the sharp drops at ~2.15 and ~3.0 GeV/c^2



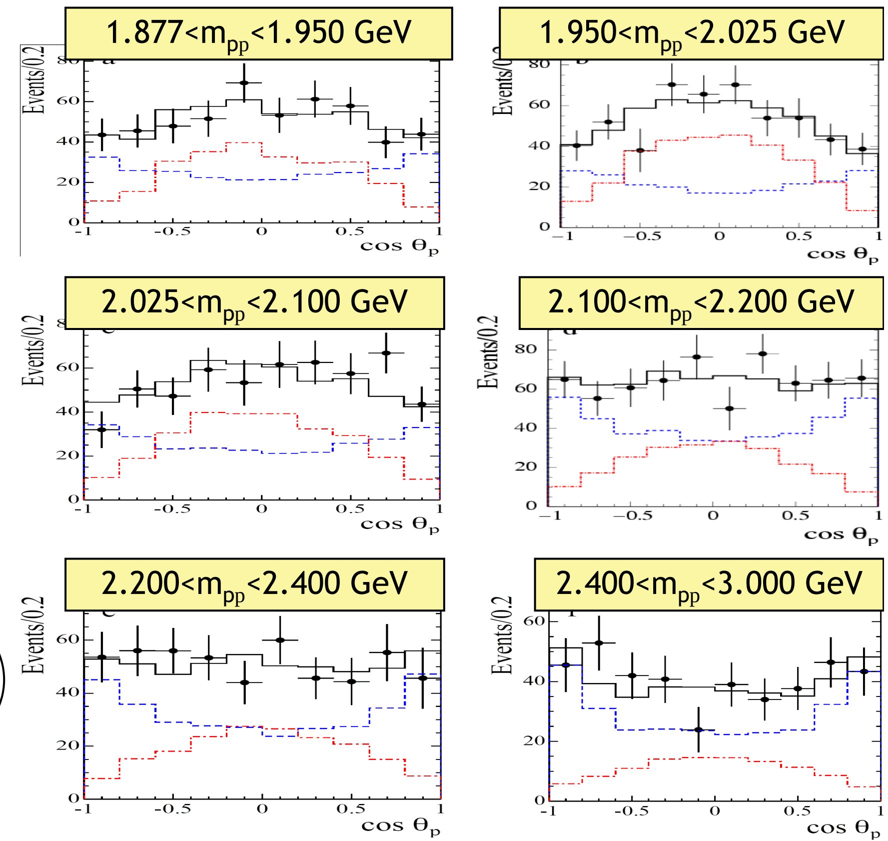
ISR production of $p\bar{p}$



- angular distributions associated with G_E and G_M are:

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

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

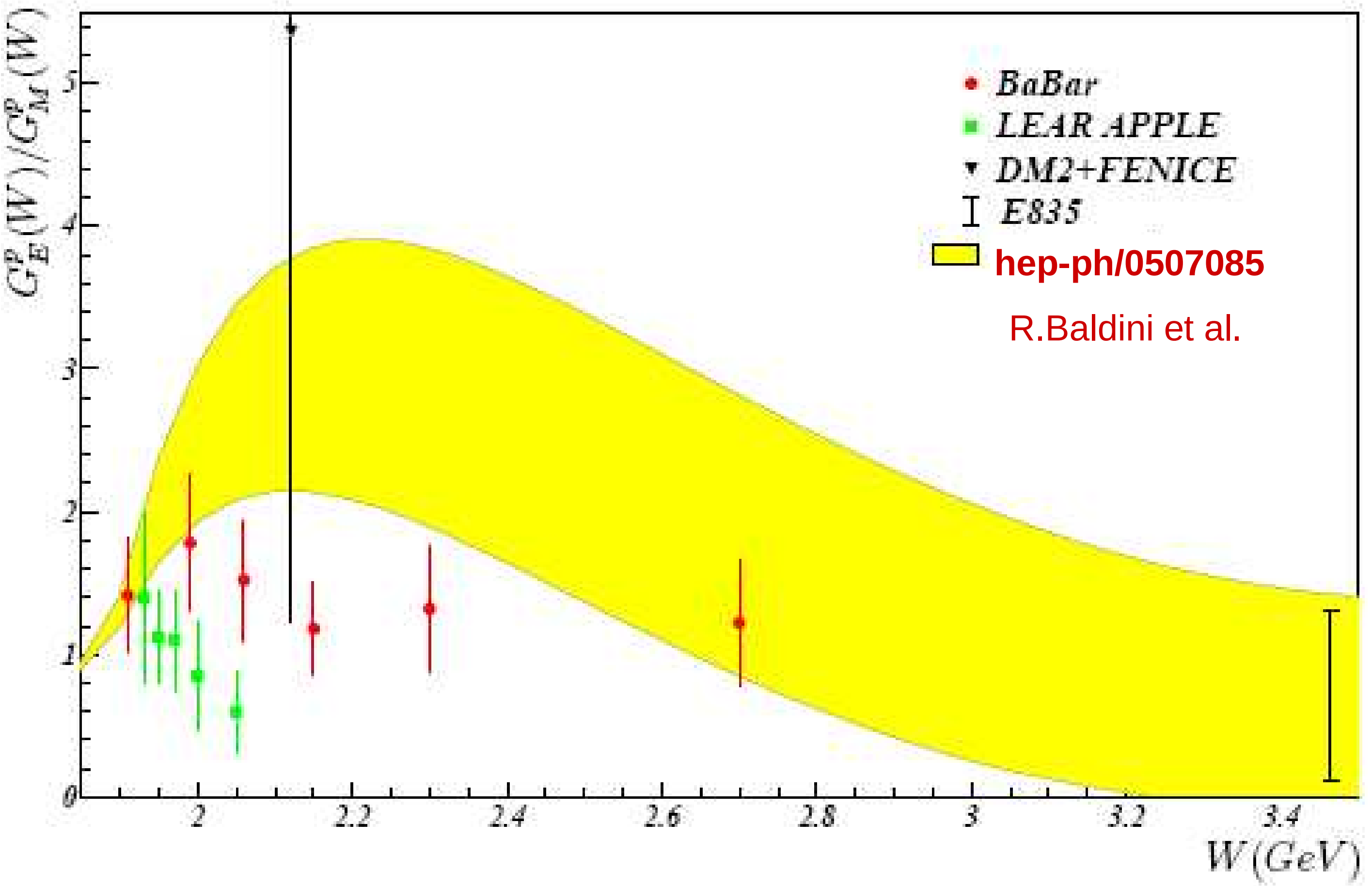


G_E dominates near m≈2 GeV/c^2

Inconsistent with PS170 measurements

G_M in Blue
G_E in Red

Proton Form Factor Ratio From Dispersion Relations



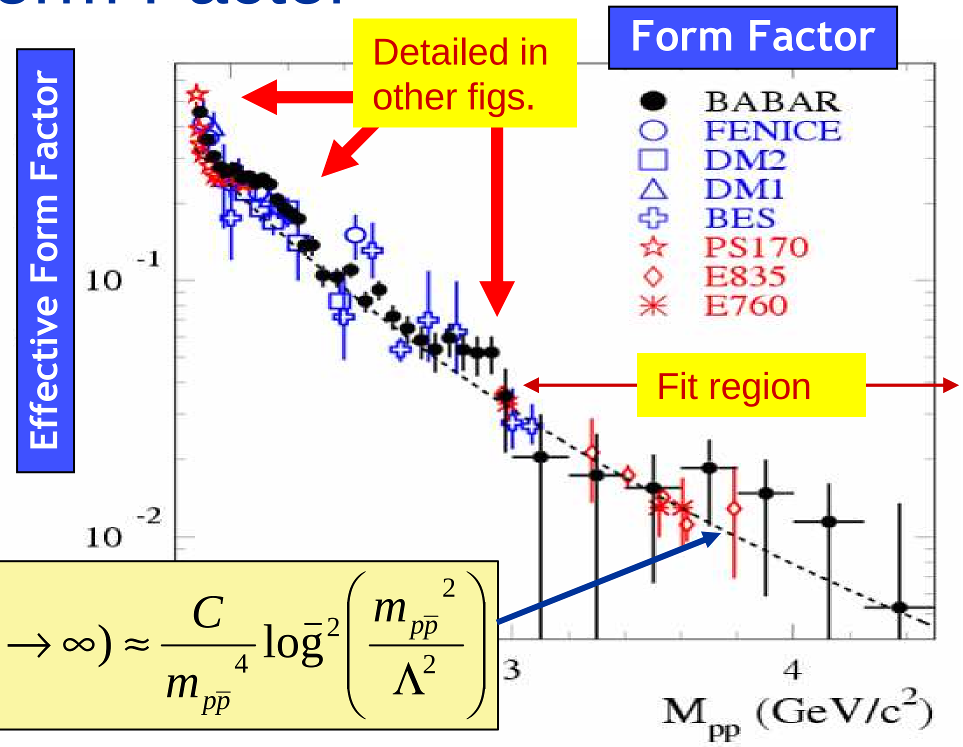
$p\bar{p}$ Effective Form Factor

- Define "Effective" form factor, |F|, by

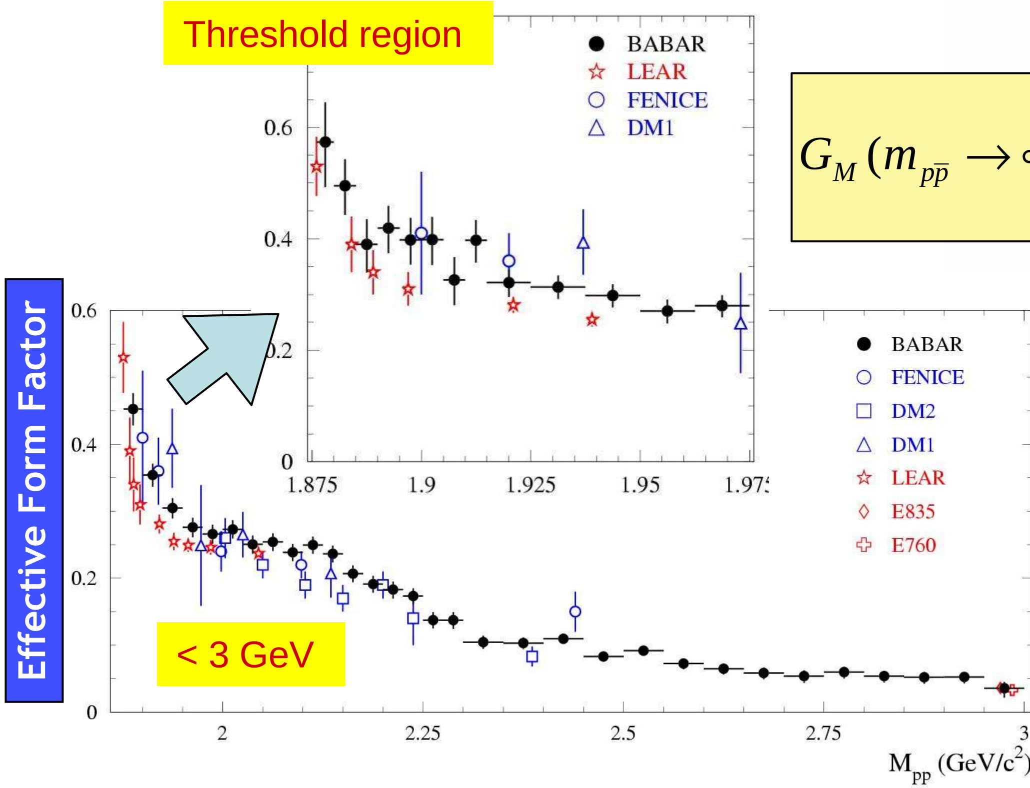
$$\sigma = \frac{4\pi\alpha^2 \beta C}{3 m_{p\bar{p}}^2} |F|^2$$

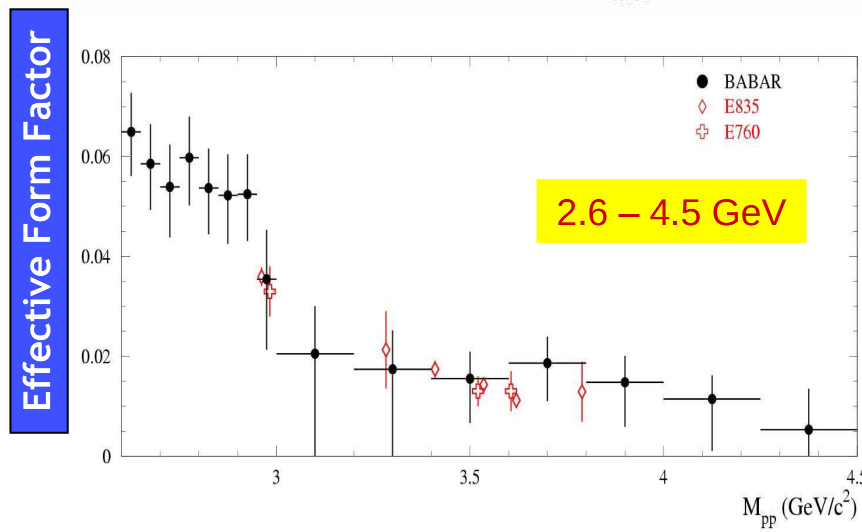
$\{|G_M|^2 + (2m_p^2/m_{\bar{p}p}^2)\,|G_E|^2\}$ with $|G_M| = |G_E| = 1$

- Peak at threshold, sharp dips at 2.15 GeV, 3.0 GeV.
- Good fit to pQCD prediction for high $m_{p\bar{p}}$

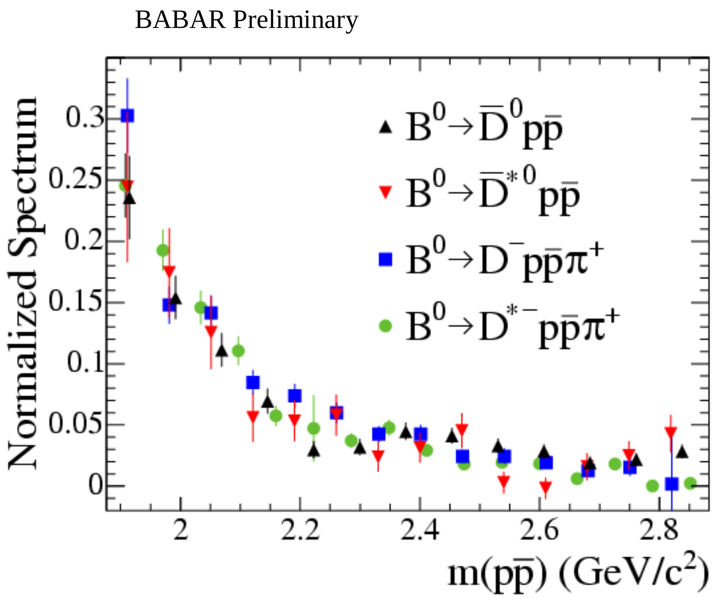


$$G_M(m_{p\bar{p}} \to \infty) \approx \frac{C}{m_{p\bar{p}}^4} \log^{-2}\left(\frac{m_{p\bar{p}}^2}{\Lambda^2}\right)$$



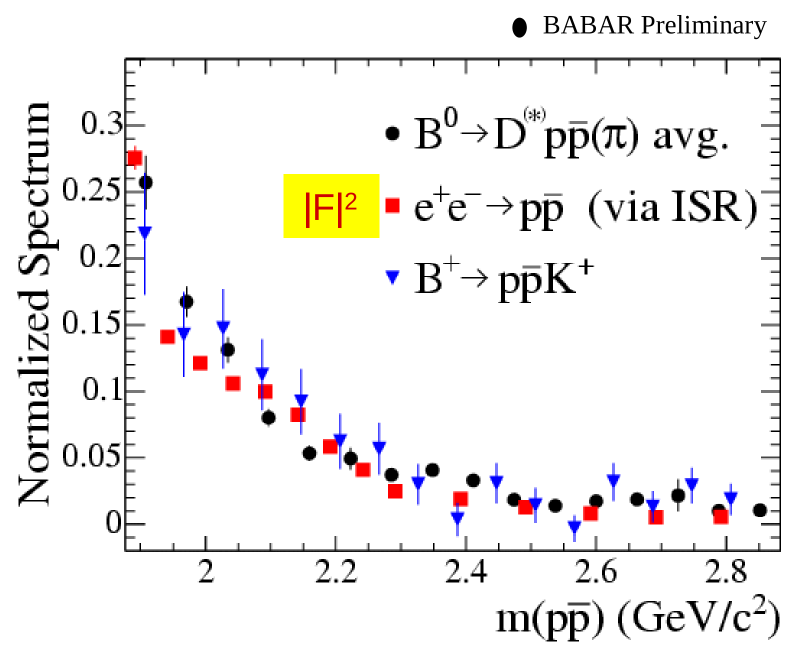


B decay to final states containing $p\bar{p}$



The phase-space-corrected $p\bar{p}$ invariant mass for $B^0 \to \bar{D}^0 p\bar{p}$, $B^0 \to \bar{D}^{*0} p\bar{p}$, $B^0 \to D\, p\bar{p}\pi^+$ and $B^0 \to D^*\, p\bar{p}\pi^+$

Comparing the average of the four decay modes with $e^+e^- \to p\,\bar{p}$ and $B^+ \to p\,\bar{p}\,K^+$



Question : Why should these distributions be so similar ?

The BES analysis of $J/\psi \to \gamma\, p\, \bar{p}$ { PRL 91, 022001 2003) } shows a very sharp rise at $p\,\bar{p}$ threshold also, but the C parity is +1

Summary of $p\,\bar{p}$ ISR Analysis at *BABAR*

- Studied $e^+ e^- \rightarrow p\,\bar{p}$ from threshold to 4.5 GeV ; measured cross section and extracted $|G_E| / |G_M|$

- Measured the c. m. energy dependence of the effective FF

Compared to mass dependence of $p\,\bar{p}$ invariant amplitude squared for selected $B \rightarrow p\,\bar{p}\,X$ decays ; behaviour very similar ; why ?

Work in progress :

$\pi^+\pi^-$, $K\,\bar{K}$: Michel Davier et al. [Orsay] ; trying to reduce systematic uncertainty to ~ 1% { for g – 2 } ; very tough

$\Lambda\,\bar{\Lambda}$, $\Lambda\,\bar{\Sigma}$, $\Sigma\,\bar{\Sigma}$: Vladimir Druzhinin [Novosibirsk] ; low statistics, difficult

$d\,\bar{d}$: Sergey Serednyakov [Novosibirsk] ; no events seen so far, but upper limit just above threshold may be getting interesting