# BABAR measurement of baryon time-like form factors via ISR


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On behalf of the BABAR Collaboration

International Workshop on $e^+e^-$ collisions from $\phi$ to $\Psi$

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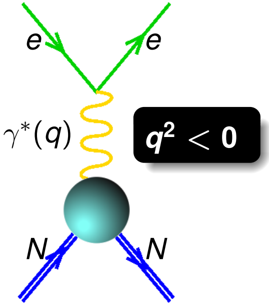
# Outline

- **Form factor definitions and properties**
- **Initial State Radiation technique in *BABAR***
- **$p\overline{p}$ events selection and background**
- **$p\overline{p}$ data: pointlike fermions at threshold**
- **$G_E^p / G_M^p$**
- **Neutral Baryons puzzle**
- **Conclusions and Perspectives**

# Space-like and time-like regions

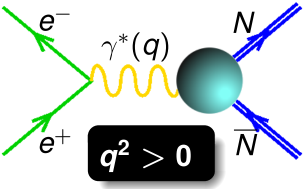
## Space-like

$eN \longrightarrow eN$

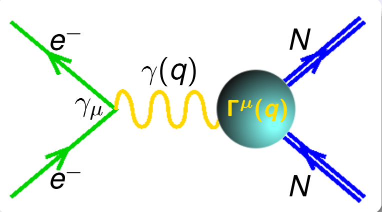



## Time-like

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



# Nucleon form factors and cross sections

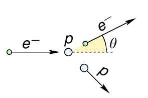



**Nucleon current operator (Dirac & Pauli)**

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

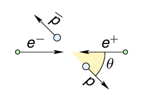
**Electric and Magnetic Form Factors**

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




**Elastic scattering**

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



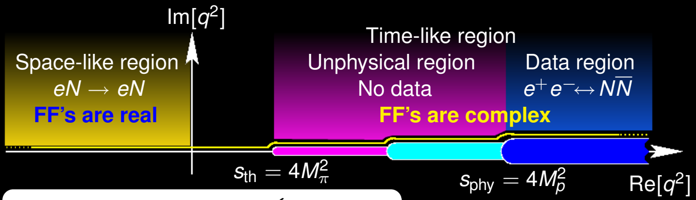

**Annihilation**

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

$$B_S = (2\sqrt{\tau}G_M + G_E)/3 \qquad B_D = (\sqrt{\tau}G_M - G_E)/3$$

# 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: $q^2 \to \pm\infty$**

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

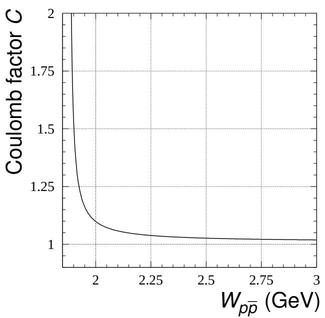
# Crucial at threshold: Coulomb Factor

- **$p\bar{p}$ Coulomb interaction as FSI**
  **(Sommerfeld, Sakharov, Schwinger, Fadin and Khoze)**
- **Distorted wave approx.: $C = |\Psi_{\text{Coul}}(0)|^2$**

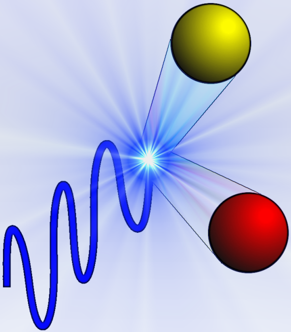
**S-wave:** $$C = \frac{\pi\alpha/\beta_p}{1 - \exp(-\pi\alpha/\beta_p)} \qquad (\beta \to 0,\ C \to \frac{\pi\alpha}{\beta})$$

**D-wave:** $$C = 1$$

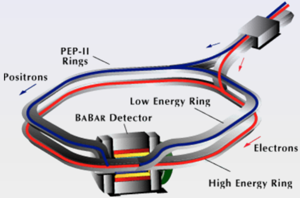
- **Negligible spin dependence**
- **Relativistic extension $\frac{1}{\beta_p} \longrightarrow \frac{1}{\beta_p} - 1$**
  **(Y. Srivastava et al.)**
- **No Coulomb factor for boson pairs (P-wave)**



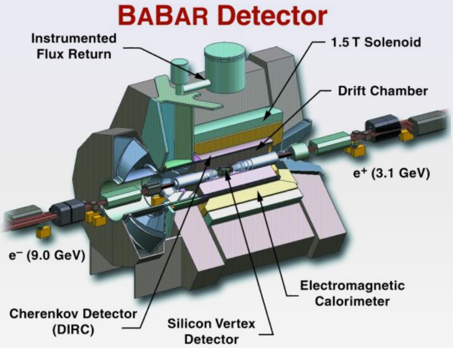
# $e^+e^- \to p\bar{p}$ at BABAR



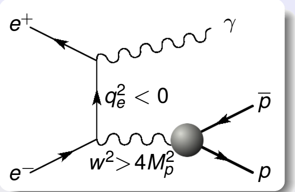
# B-factory PEPII@SLAC




- Asymmetric *B*-factory at $\Upsilon(4S)$
- $\Delta p_T/p_T \sim 0.5\%$ ...... at 1 GeV
- $(\Delta E/E)_{\rm Cal} \sim 3\%$ ..... at 1 GeV



# 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 $= \sqrt{s(1-x)}$, $x = 2E^*_\gamma/\sqrt{s}$

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

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

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

ISR $\gamma$ 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 efficiency $\neq 0 + \sigma_W \sim 1$ *MeV*
- Detected ISR $\gamma \Longrightarrow$ full $p\bar{p}$ angular coverage

## Drawbacks

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

# Events selection

- **Results, quoted in the following, concern 232 $fb^{-1}$ (out of $\sim$ 500 $fb^{-1}$)**

- **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 DCH and DIRC acceptance
  - Very tight proton selector $\sim$ 30% good events loss
  - $p\bar{p}\gamma$ kinematical fit

    $E_\gamma$ resolution not reproduced $\Longrightarrow$ $3C$ fit

  efficiency $\sim$ **18 $\pm$ 1 %**

- **4025 selected events**

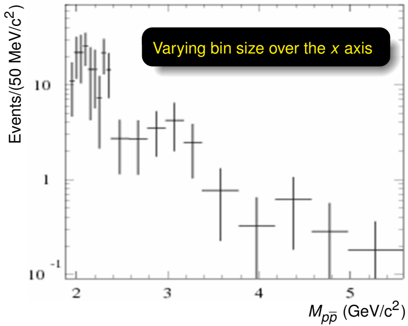
# $p\bar{p}$ events background

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

229 ± 32 estimated

$M_{pp} > 4\ GeV$

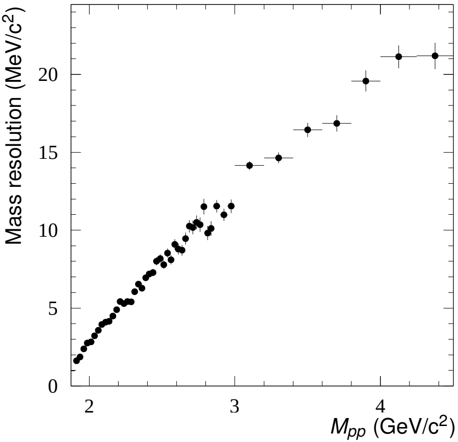
$p\bar{p}$ signal is overwhelmed




## 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 |

# Mass resolution




Incredibly good at threshold ($\sim$ 1 MeV/c$^2$), as $e^+e^-$ c.m.

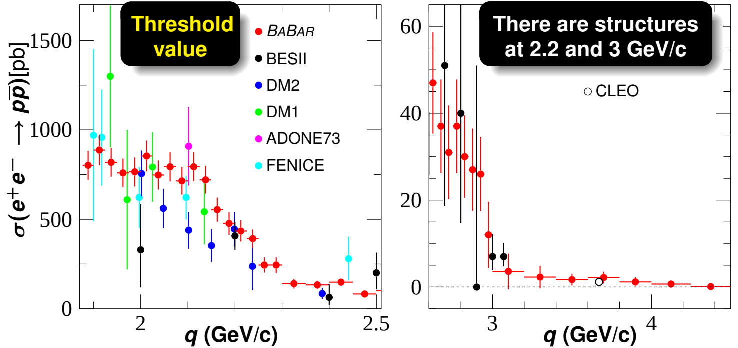
$\Delta p_T / p_T \sim 0.5\%$ at 1 GeV

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



$$\sigma(e^+e^- \longrightarrow p\bar{p}) = \frac{4\pi\alpha^2\beta C}{3q^2}\left[|G_M|^2 + \frac{2M_p^2}{q^2}|G_E|^2\right]$$

**BABAR cross section from threshold to 4.5 GeV/c [PRD73 (2006) 012005]**



# Proton form factor at $q^2 = 4M_p^2$

$$\sigma(e^+e^- \to p\overline{p})(4M_p^2) = 0.83 \pm 0.05 \text{ nb}$$

BaBar

$$\sigma(e^+e^- \to p\overline{p})(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\frac{\beta_p}{\beta_p}|G^p(4M_p^2)|^2 = 0.85\,|G^p(4M_p^2)|^2 \text{ nb}$$

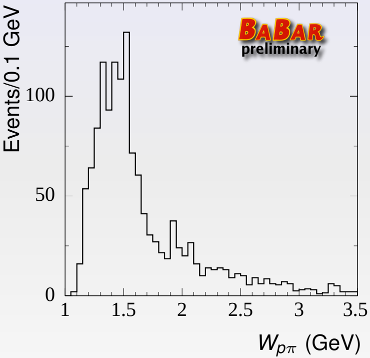
$$|G^p(4M_p^2)| \equiv 1$$

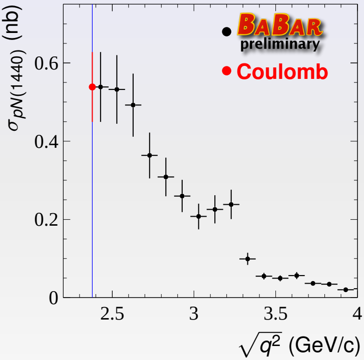
**as pointlike fermion pairs!**

$$|G^p(4M_p^2)| = 0.99 \pm 0.04(\text{stat}) \pm 0.03(\text{syst})$$

# $e^+e^- \to p\bar{N}(1440) + \bar{p}N(1440)$

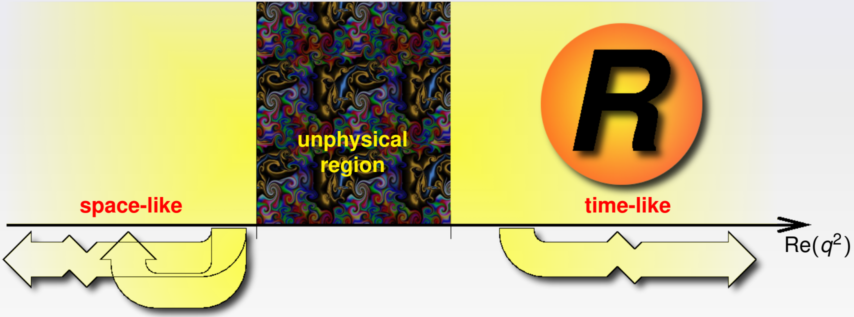
$$\sigma^{\text{Coulomb}} = \frac{16\pi^2\alpha^3 M_p^{3/2} M_{N(1440)}^{3/2}}{(M_p + M_{N(1440)})^5} \left|G^{pN(1440)}\right|^2 = \left|G^{pN(1440)}\right|^2 \times 0.49\ \text{nb}$$



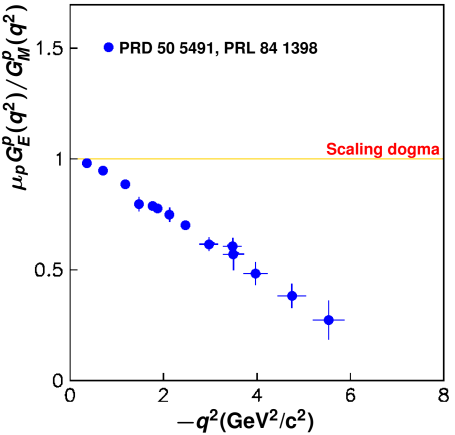

$$\left|G^{pN(1440)}\right| = 1.04 \pm 0.09$$

# The ratio $R = \mu_p \frac{G_E^p}{G_M^p}$



# JLab: Space-like $G_E^p/G_M^p$ measurements

## Space-like data




$$G_E^p = F_1^p + \frac{q^2}{4M_p^2} F_2^p$$

$$G_M^p = F_1^p + F_2^p$$

### Space-like

$F_1$ and $\frac{q^2}{4M_p^2} F_2$ cancellation

$$\frac{G_E^p(q^2)}{G_M^p(q^2)} < 1$$

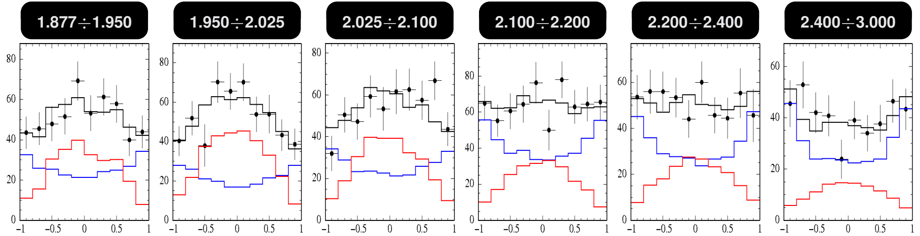
### Time-like

$F_1$ and $\frac{q^2}{4M_p^2} F_2$ enhancement

$$\left|\frac{G_E^p(q^2)}{G_M^p(q^2)}\right| > 1$$

# $e^+e^- \longrightarrow p\bar{p}$ angular distribution (BaBar)

## $\cos\theta_p$ distributions form threshold up to 3 GeV [intervals in $E_{CM} \equiv q$ (GeV)]

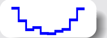



Events/0.2 vs. $\cos\theta_p$

$$\frac{d\sigma}{d\cos\theta_p} = A\left[H_E(\cos\theta_p, q^2)\left|\frac{G_E^p(q^2)}{G_M^p(q^2)}\right|^2 + H_M(\cos\theta_p, q^2)\right]$$

$H_E$ and $H_M$ from MC

**Histograms show contributions from**

- $G_E$ 
- $G_M$ 

**At low $q$**

$\sin^2\theta_p > 1 + \cos^2\theta_p$

$\Rightarrow$

**First observation!**

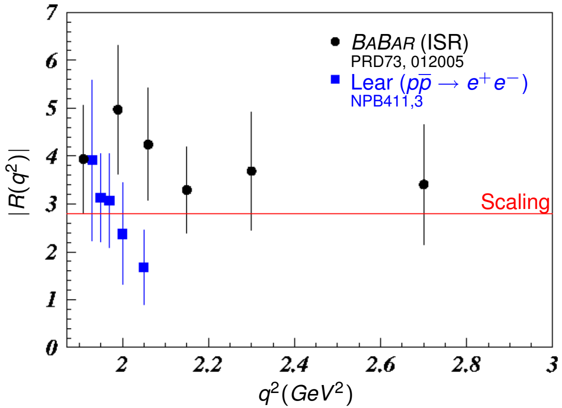
$|G_E^p| > |G_M^p|$

**At higher $q$, $|G_E^p| \longrightarrow |G_M^p|$**

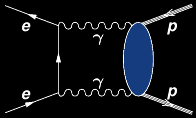
# Time-like $|G_E^p/G_M^p|$ measurements

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

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




## $\gamma\gamma$ exchange



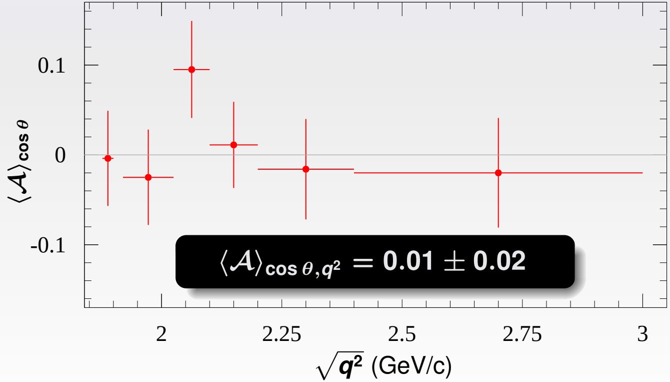

$\gamma\gamma$ exchange interferes with the Born term

Asymmetry in angular distributions

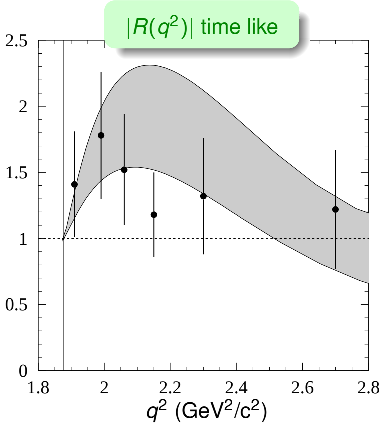
# $\gamma\gamma$ exchange from $e^+e^- \to p\bar{p}\gamma$ BABAR data

E. Tomasi-Gustafsson, E. A. Kuraev,
S. Bakmaev, S. Pacetti
PLB659, 197

$$\mathcal{A}(\cos\theta, q^2) = \frac{\frac{d\sigma}{d\Omega}(\cos\theta, q^2) - \frac{d\sigma}{d\Omega}(-\cos\theta, q^2)}{\frac{d\sigma}{d\Omega}(\cos\theta, q^2) + \frac{d\sigma}{d\Omega}(-\cos\theta, q^2)}$$

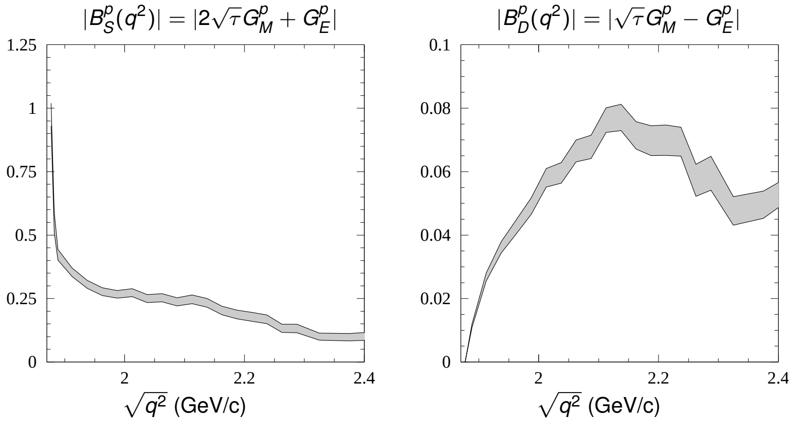


## Reconstructed time-like *R* (*BABAR* only)

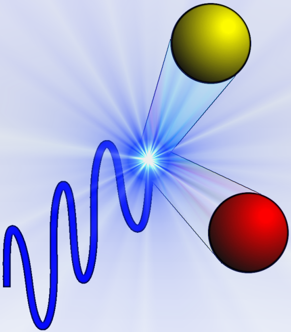


# Phases from DR: $|B_S^p(q^2)|$ and $|B_D^p(q^2)|$

## *BABAR* $\sigma(e^+e^- \to p\bar{p})$ + DR

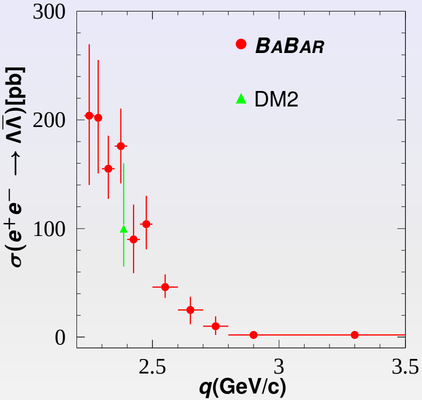


# The neutral baryons puzzle



# $e^+e^- \longrightarrow \Lambda\bar{\Lambda}$





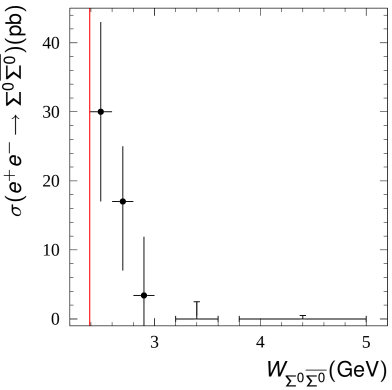

$\sigma(e^+e^- \longrightarrow \Lambda\bar{\Lambda})$ not zero at threshold?

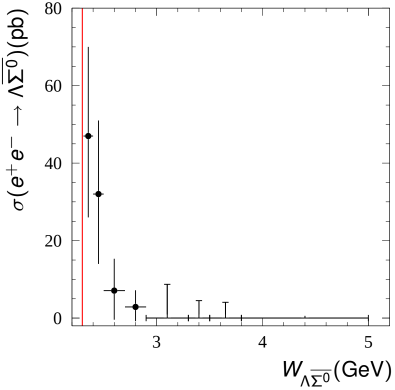
- No Coulomb enhancement
- $G_\Lambda \propto 1/\sqrt{\beta}$? Coulomb enhancement at quark level?

# $\Sigma^0\overline{\Sigma^0}$ and $\Lambda\overline{\Sigma^0}$ channels

PRD76, 092006

## Cross sections of $e^+e^- \longrightarrow \Sigma^0\overline{\Sigma^0}$, $\Lambda\overline{\Sigma^0}$ via ISR (*BABAR*)

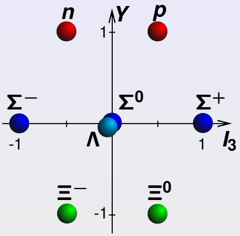



$\sigma(e^+e^- \longrightarrow \Sigma^0\overline{\Sigma^0})_{th} = 30 \pm 13$ pb

$\sigma(e^+e^- \longrightarrow \Lambda\overline{\Sigma^0})_{th} = 47 \pm 22$ pb

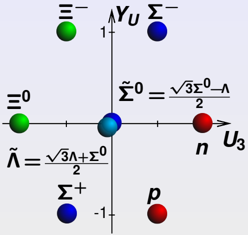
# Baryon octet and *U*-spin




$$(Y, I_3) \longrightarrow (Y_U, U_3)$$

$$U_3 = -\tfrac{1}{2} I_3 + \tfrac{3}{4} Y$$

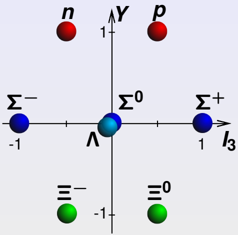
$$Y_U = -Q$$




U-spin relation: $G^{\Sigma^0} - G^{\Lambda} + \frac{2}{\sqrt{3}} G^{\Lambda\Sigma^0} = 0$

$$M_{\Sigma^0}\sqrt{\sigma_{\Sigma^0\overline{\Sigma^0}}} - M_{\Lambda}\sqrt{\sigma_{\Lambda\bar{\Lambda}}} + \frac{2}{\sqrt{3}}\overline{M_{\Lambda\Sigma^0}}\sqrt{\sigma_{\Lambda\overline{\Sigma^0}}} = (-0.06 \pm 6.0) \times 10^{-4}$$

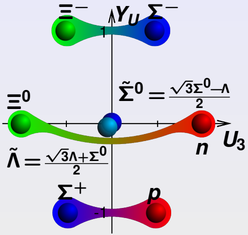
# Baryon octet and $U$-spin




$$(Y, I_3) \longrightarrow (Y_U, U_3)$$

$$U_3 = -\tfrac{1}{2} I_3 + \tfrac{3}{4} Y$$

$$Y_U = -Q$$




U-spin relation: $G^{\Sigma^0} - G^{\Lambda} + \frac{2}{\sqrt{3}} G^{\Lambda\Sigma^0} = 0$

$$M_{\Sigma^0}\sqrt{\sigma_{\Sigma^0\overline{\Sigma^0}}} - M_{\Lambda}\sqrt{\sigma_{\Lambda\bar{\Lambda}}} + \frac{2}{\sqrt{3}}\overline{M_{\Lambda\Sigma^0}}\sqrt{\sigma_{\overline{\Lambda\Sigma^0}}} = (-0.06 \pm 6.0) \times 10^{-4}$$

## Conclusions

- Proton-antiproton
  - $G_p(4M_p^2) = 1$: No strong interaction at threshold
  - More data needed to disentangle $G_E^p$, $G_M^p$
- Neural baryons
  - Puzzling non vanishing cross section at threshold?
  - Much more data are needed

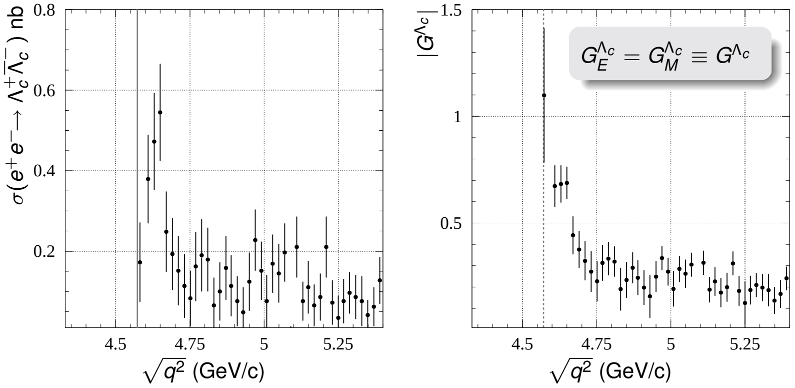
## Perspectives

- *BABAR* ×2, BESIII, VEPP2000
- SuperKEKB, SuperB?

# BACK-UP SLIDES

# $\Lambda_c^+$ form factor

## Belle $\sigma(e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-)$




$$|G^{\Lambda_c}(4M^2_{\Lambda_c})| = 1.1 \pm 0.3(\text{stat}) \pm 0.4(\text{syst})$$