Pointlike Baryons?

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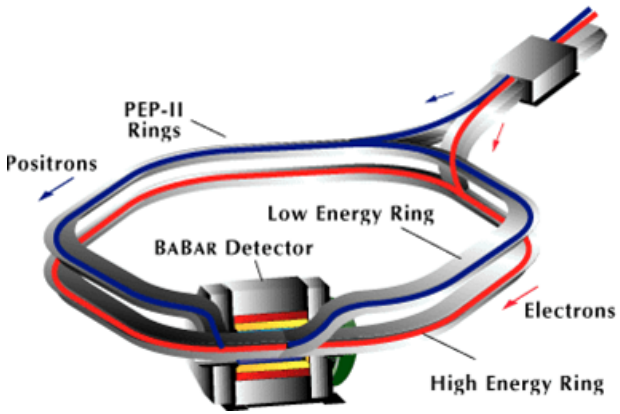
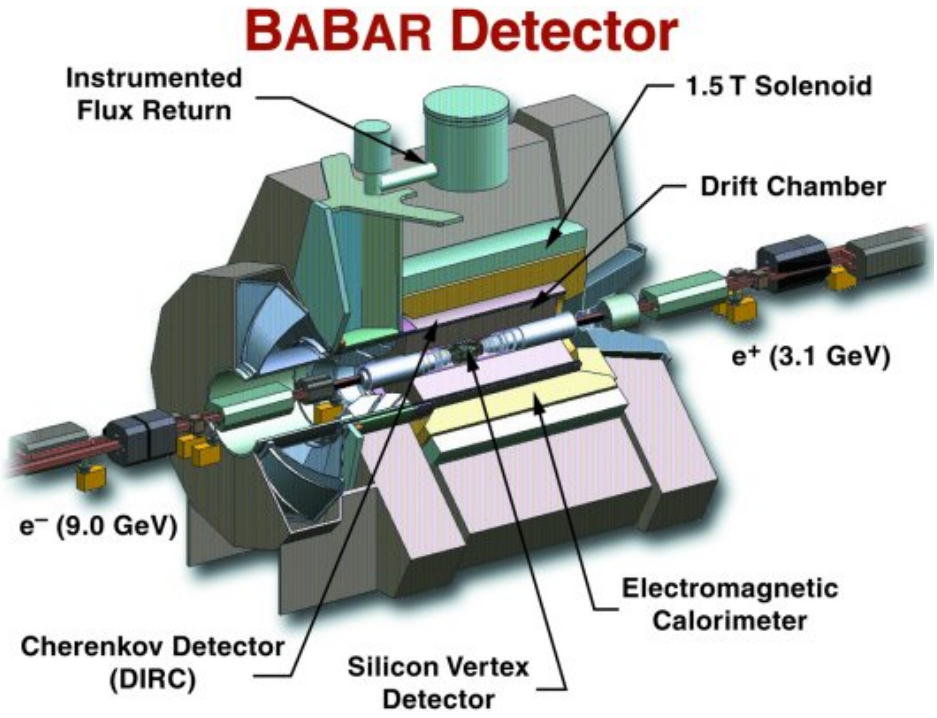
Outline

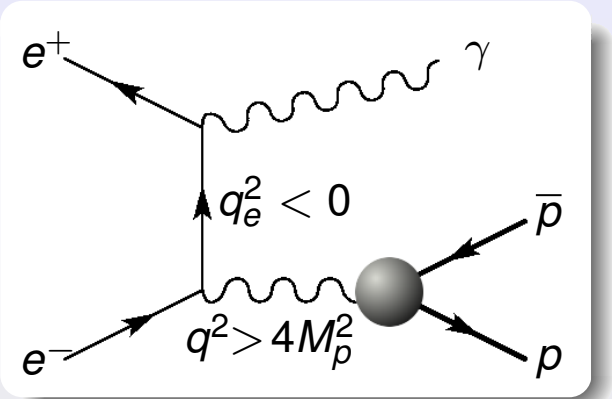
- $e^+e^- \to p\bar{p}$ (*BABAR*)
  - Step behavior at threshold
  - Coulomb dominance
    $G^p(4M_p^2) = 1$ as pointlike fermion pairs
- **DR's applied to space and time-like** G_E^p / G_M^p
  - Asymptotic behavior
  - B_S and B_D extracted
- $e^+e^- \to \Lambda_c^+ \bar{\Lambda}_c^-$
  - $G^{\Lambda_c}(4M_{\Lambda_c}^2) \sim 1$ still as pointlike fermion pairs
- $e^+e^- \to \Lambda\bar{\Lambda}$, $\Sigma^0\bar{\Sigma}^0$, $\Lambda\bar{\Sigma}^0$ **puzzle**
  - step behavior at threshold again
  - Coulomb dominance at quark level?
  - U-spin relations
- **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.

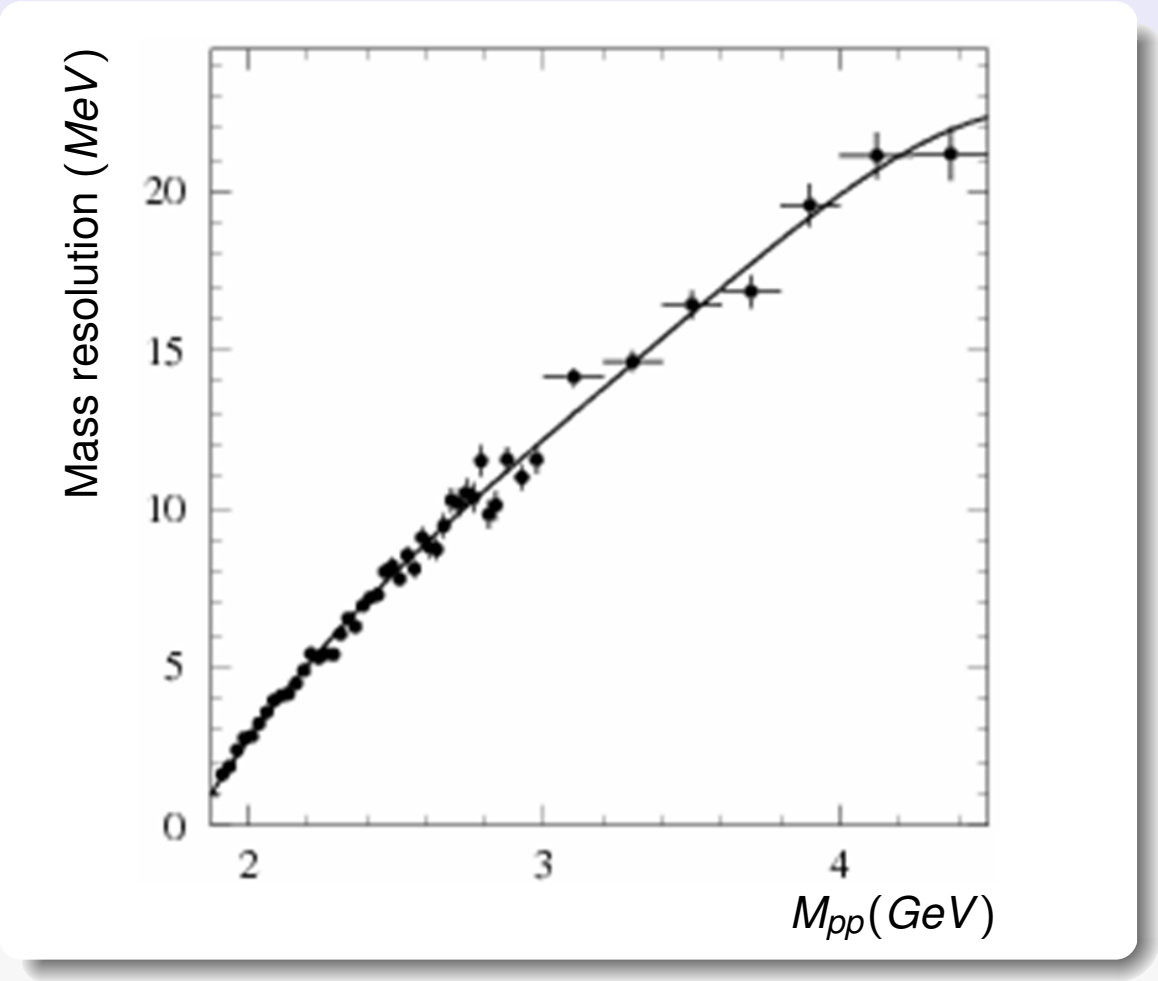
Advantages

- 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

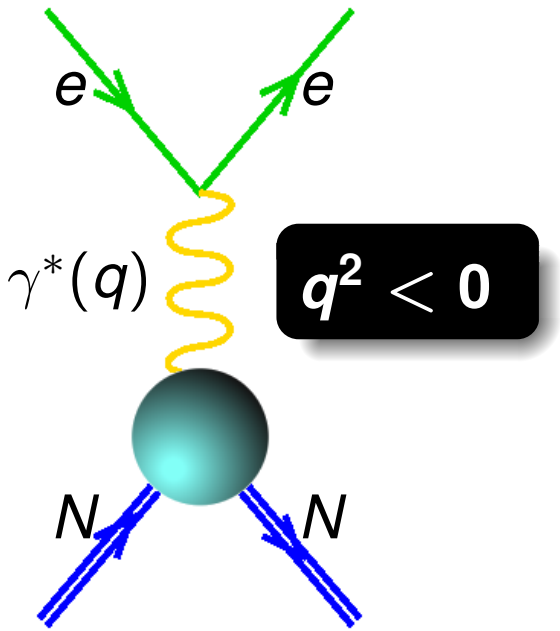


Incredibly good at threshold ($\sim$ 1 *MeV*), as e^+e^- c.m.

Space-like and time-like regions

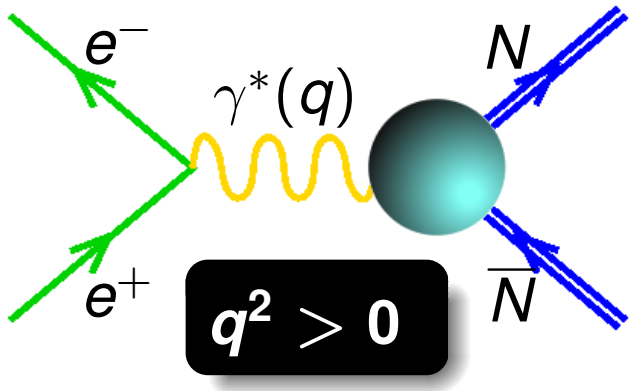
Space-like

$$eN \longrightarrow eN$$

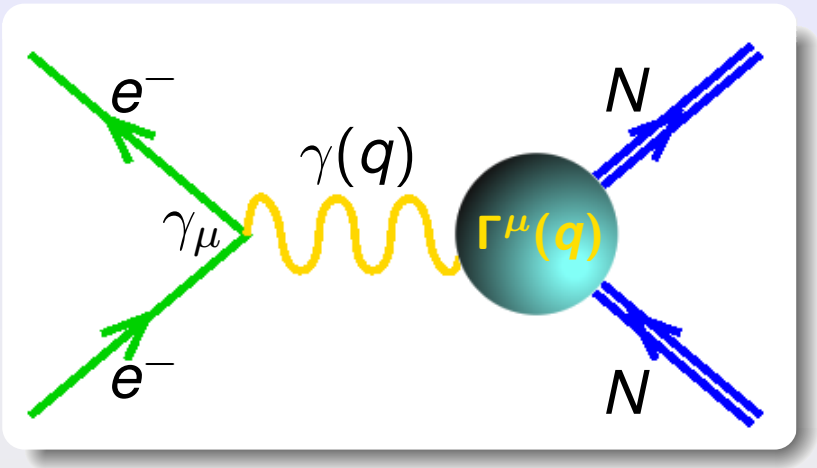


Time-like

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



Nucleon form factors and cross sections

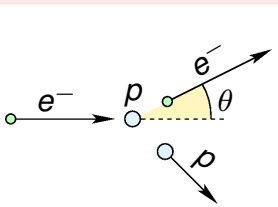


Nucleon current operator (Dirac & Pauli)

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

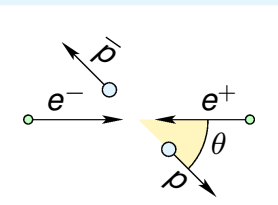
Electric and Magnetic Form Factors

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



Elastic scattering

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



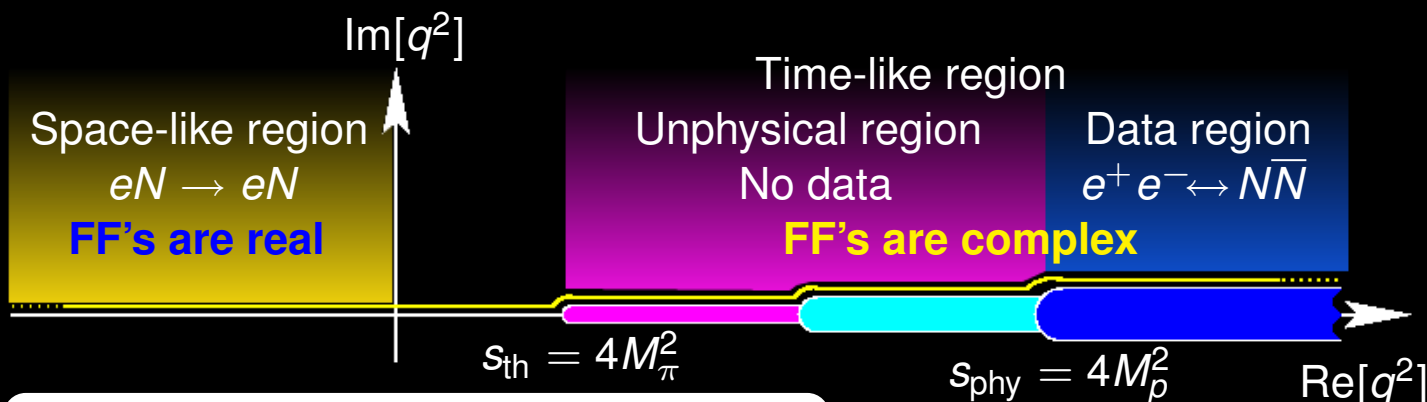
Annihilation

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

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

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

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

Coulomb Factor

- $p\bar{p}$ **Coulomb interaction as FSI**
  (Sommerfeld, Sakharov, Schwinger, Fadin and Khoze)

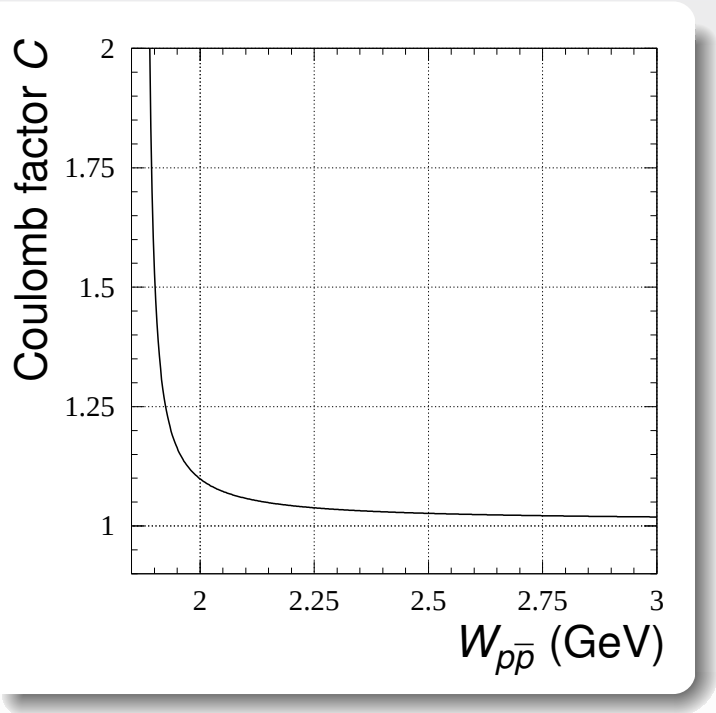
- **Distorted wave approx.:** $C = |\Psi_{\mathrm{Coul}}(0)|^2$

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

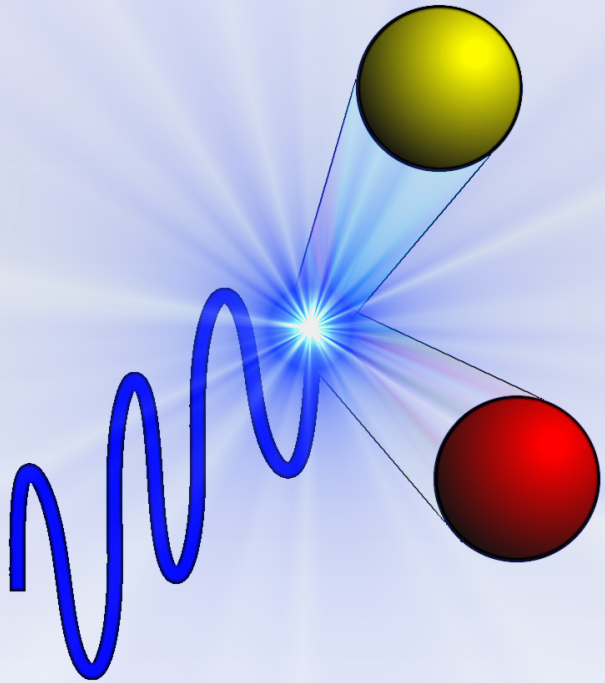
- **Negligible spin dependence**

- **Relativistic extension** $\dfrac{1}{\beta_p} \to \dfrac{1}{\beta_p} - 1$
  (Y. Srivastava et al.)

- **No Coulomb factor for boson pairs (P-wave)**

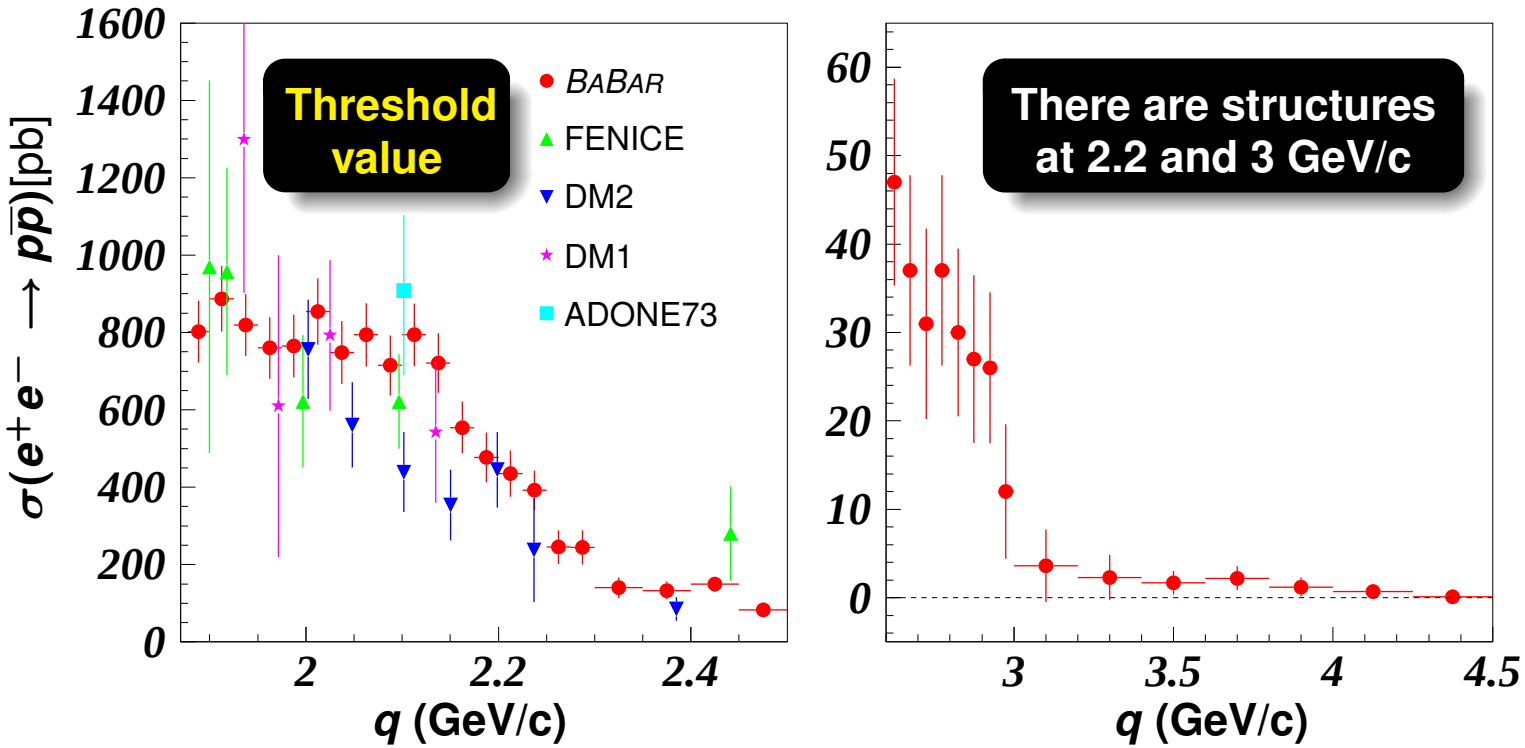


$e^+e^- \rightarrow p\bar{p}$ at BABAR



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

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



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

$$\sigma(e^+e^- \to p\bar{p})(4M_p^2) = 0.80 \pm 0.05 \text{ nb}$$

BABAR

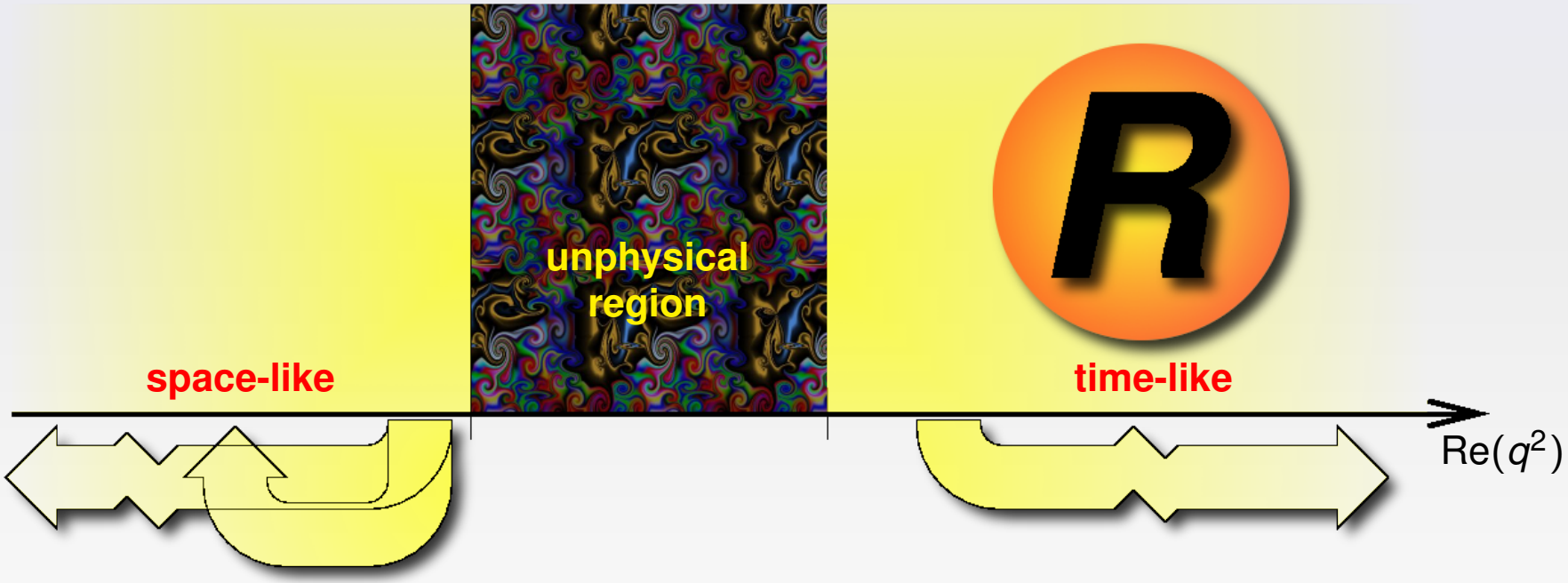
$$\sigma(e^+e^- \to p\bar{p})(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\frac{\beta_p}{\beta_p}|G^p(4M_p^2)|^2 = 0.85\,|G^p(4M_p^2)|^2 \text{ nb}$$

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

as pointlike fermion pairs!

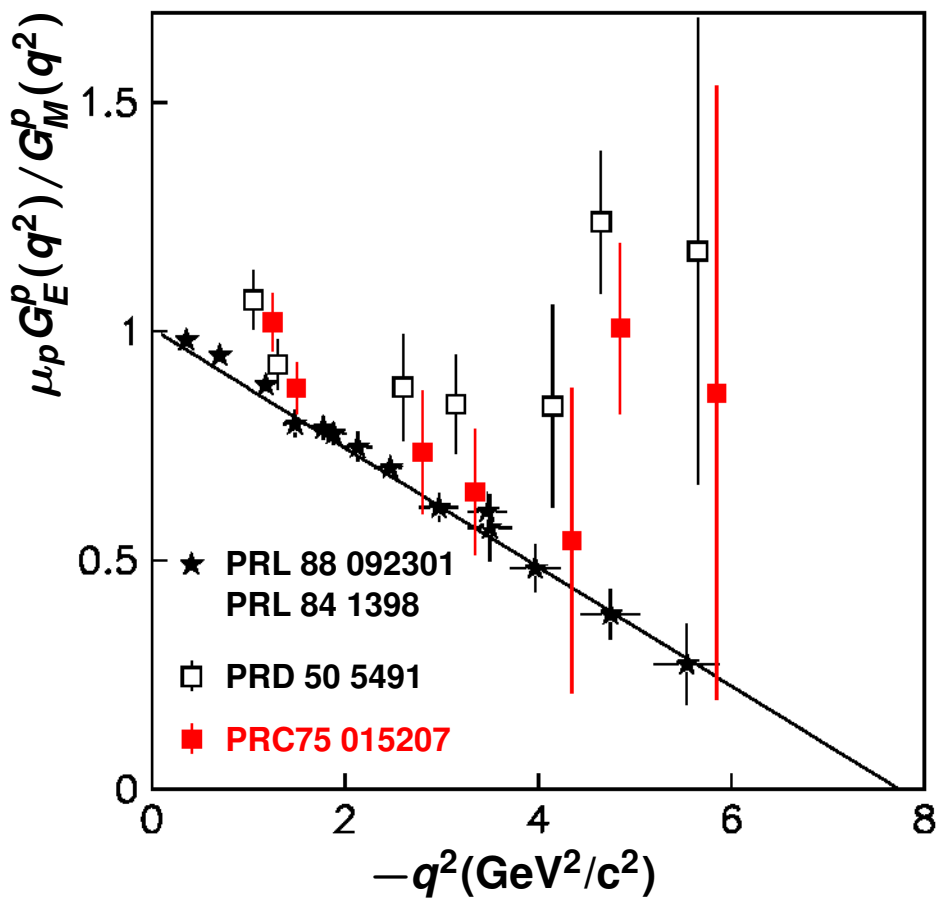
$$|G^p(4M_p^2)| = 0.97 \pm 0.04(\text{stat}) \pm 0.03(\text{syst})$$

Dispersive analysis of the ratio $R = \mu_p \frac{G_E^p}{G_M^p}$



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

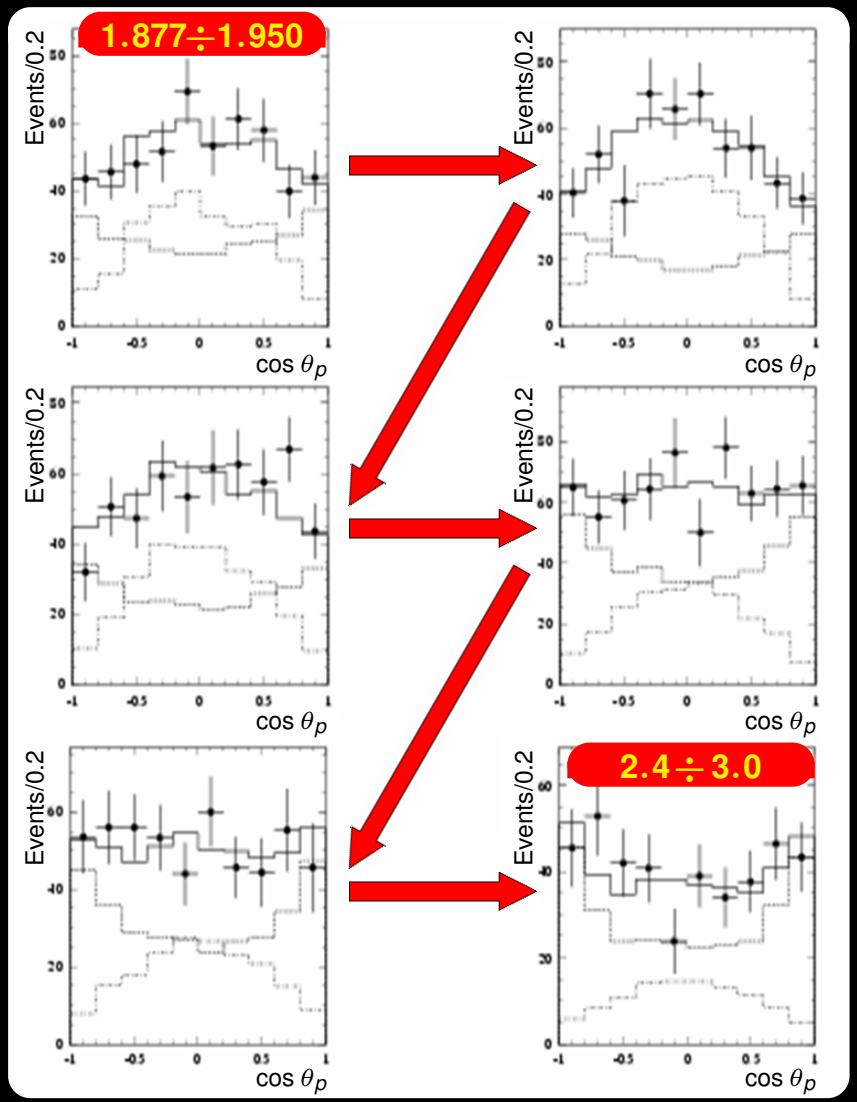
$$\left| \frac{G_E^p(q^2)}{G_M^p(q^2)} \right| > 1$$

Time-like angular distributions (*BABAR*)

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

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

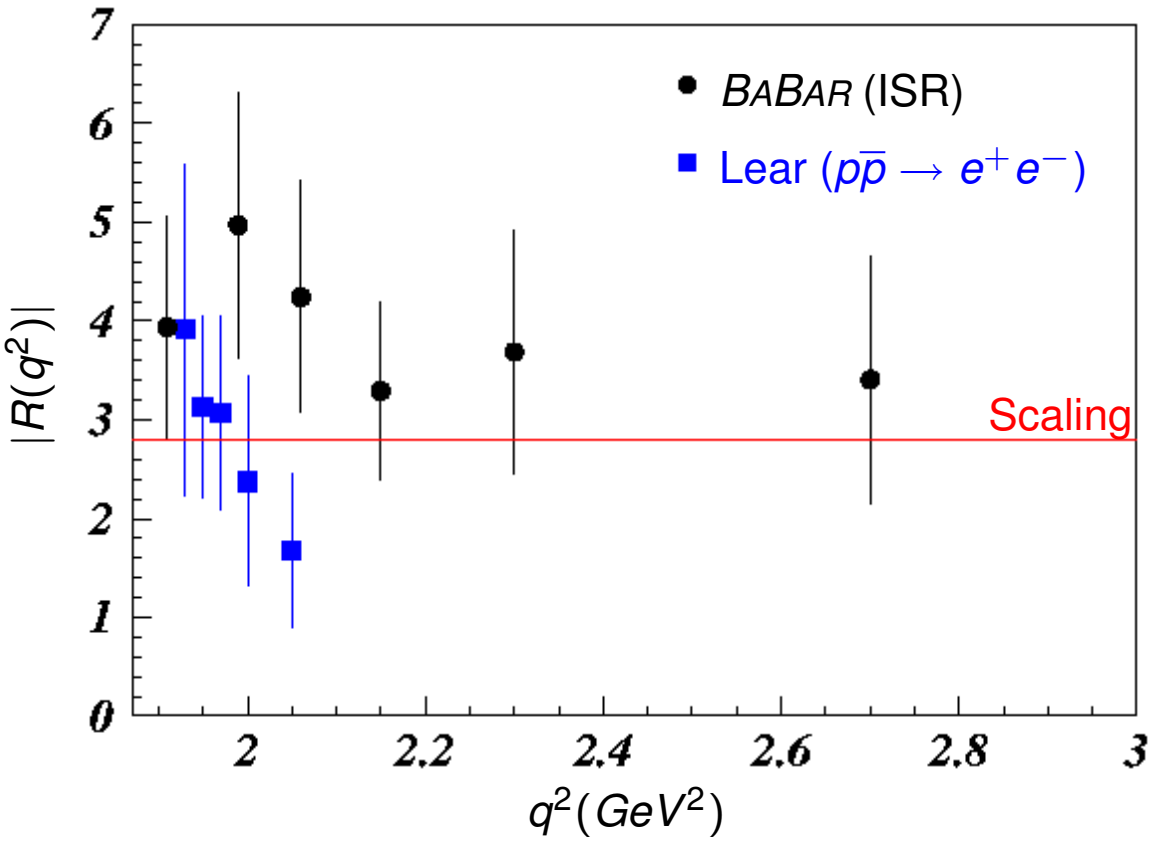
Transition
from: $\sin^2\theta$ (G_E dominant)
to: $1+\cos^2\theta$ (G_M dominant)



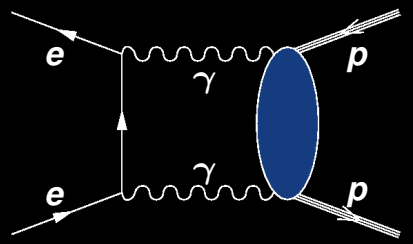
Time-like $|G_E^p/G_M^p|$ measurements

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

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



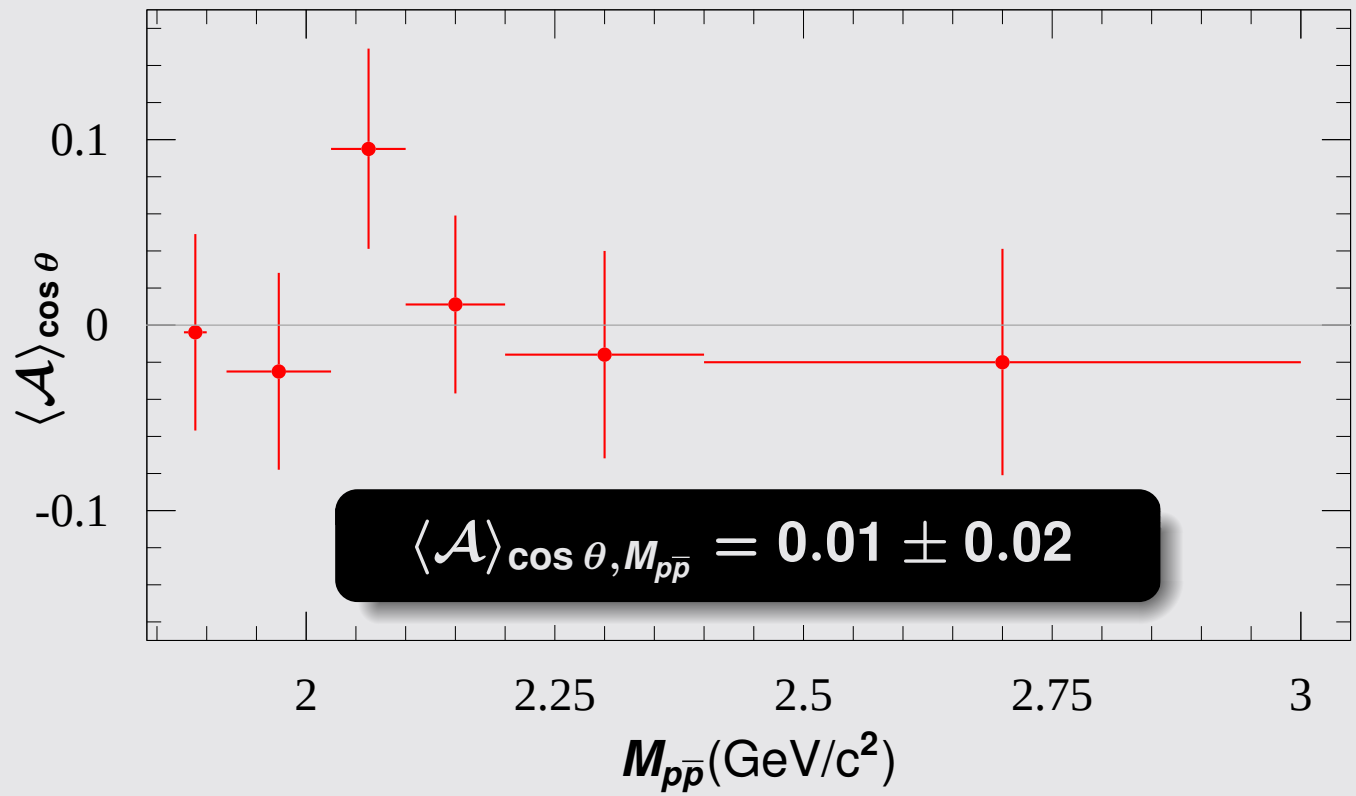
$\gamma\gamma$ exchange



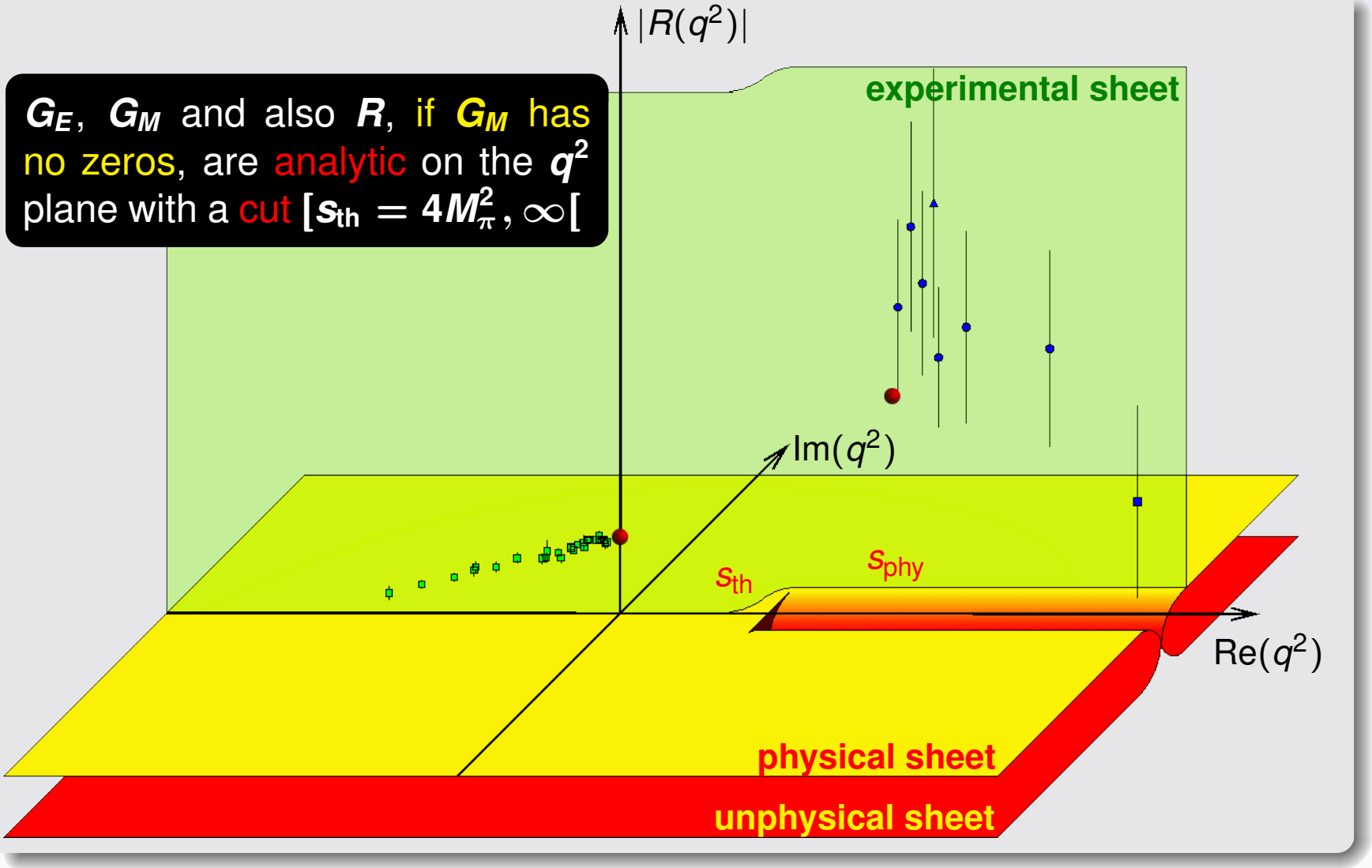
$\gamma\gamma$ exchange interferes with the Born term

Asymmetry in angular distributions

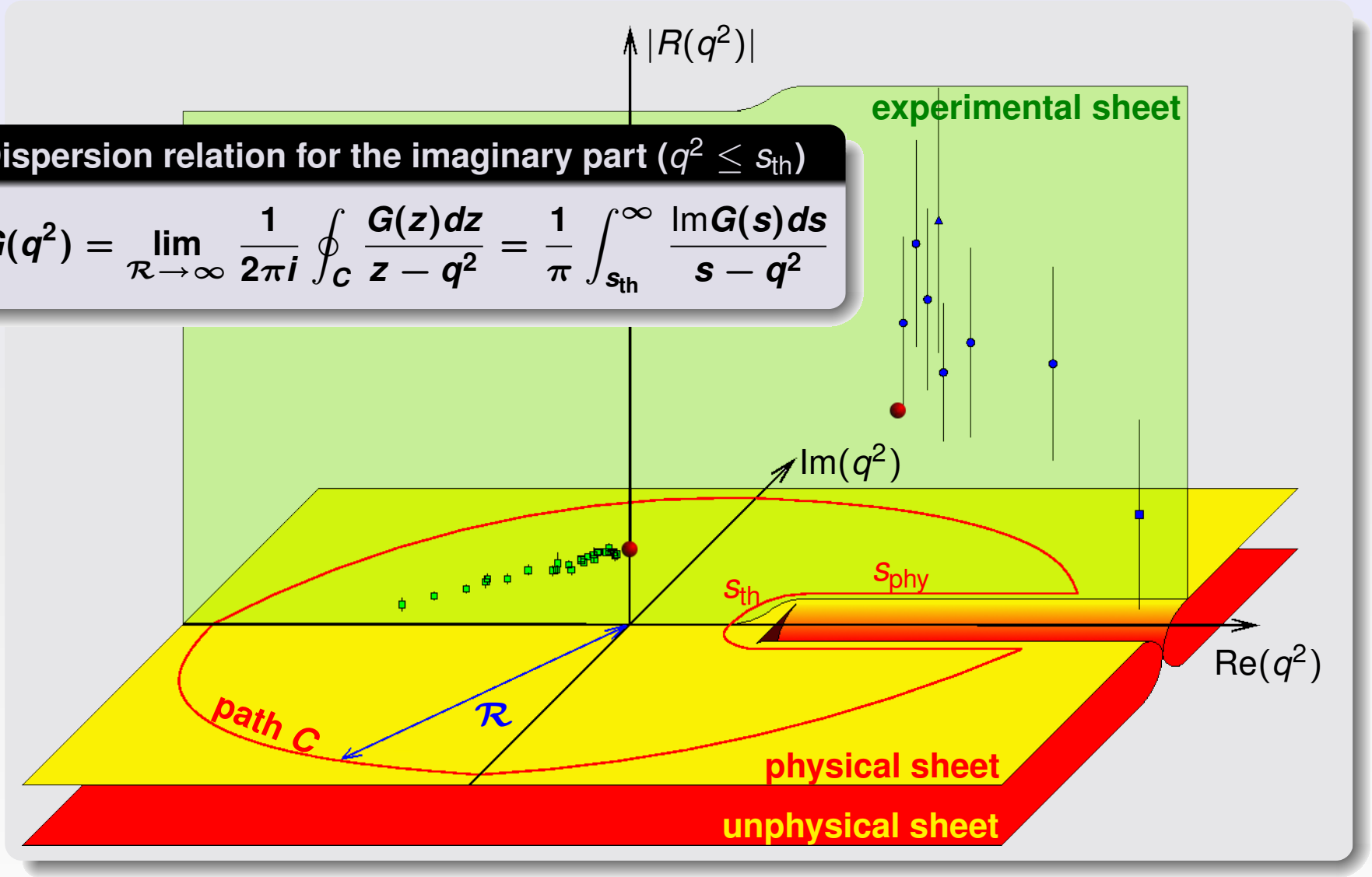
$$\mathcal{A}(\cos\theta, M_{p\bar{p}}) = \frac{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) - \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}{\frac{d\sigma}{d\Omega}(\cos\theta, M_{p\bar{p}}) + \frac{d\sigma}{d\Omega}(-\cos\theta, M_{p\bar{p}})}$$



$R(q^2)$ in the complex plane



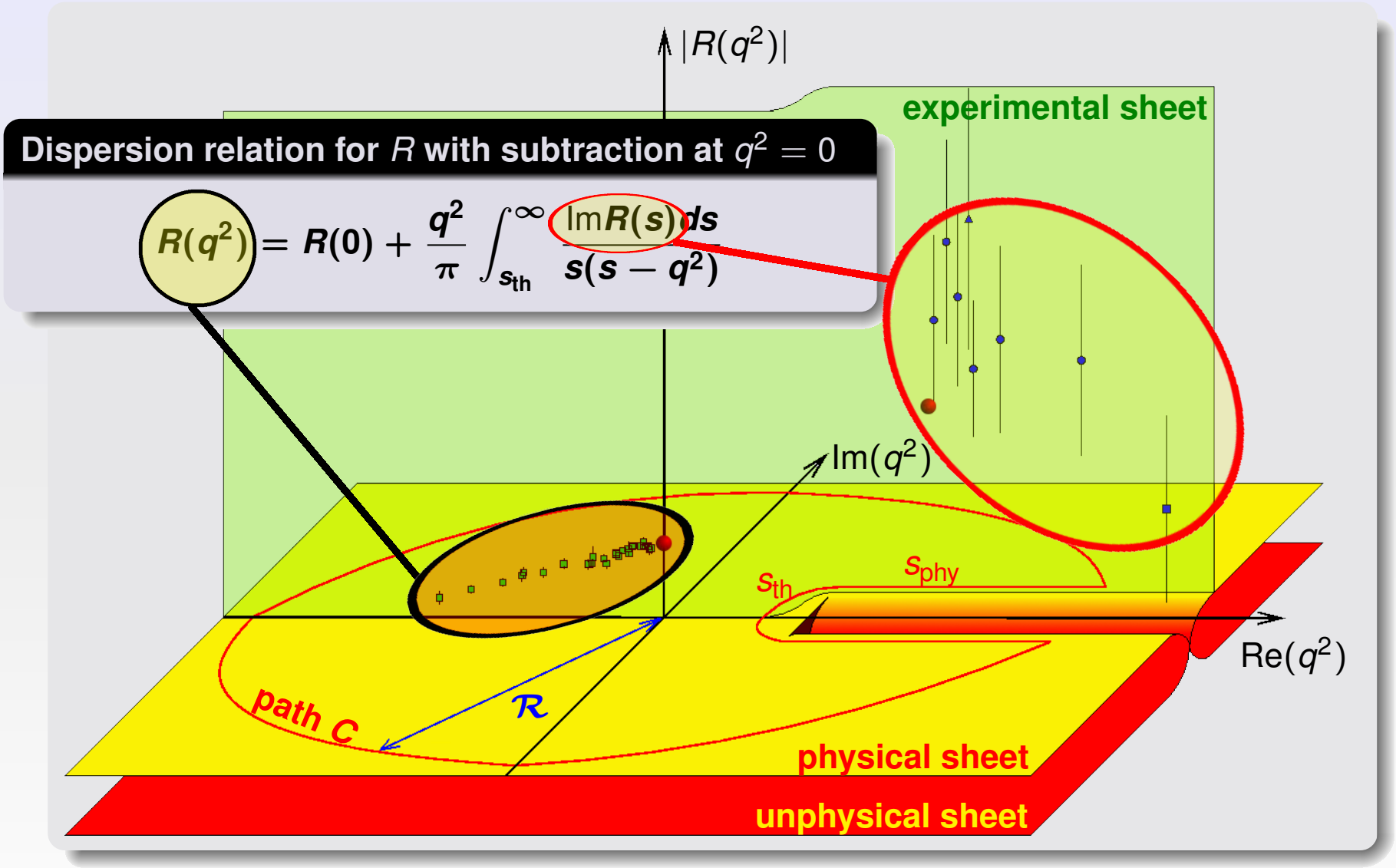
$R(q^2)$ in the complex plane



Dispersion relation for the imaginary part ($q^2 \leq s_{th}$)

$$G(q^2) = \lim_{\mathcal{R}\to\infty} \frac{1}{2\pi i} \oint_C \frac{G(z)dz}{z - q^2} = \frac{1}{\pi} \int_{s_{th}}^{\infty} \frac{\mathrm{Im}G(s)ds}{s - q^2}$$

$R(q^2)$ in the complex plane



Parameterization and constraints

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

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

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

Theoretical conditions 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 conditions on $R(q^2)$

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

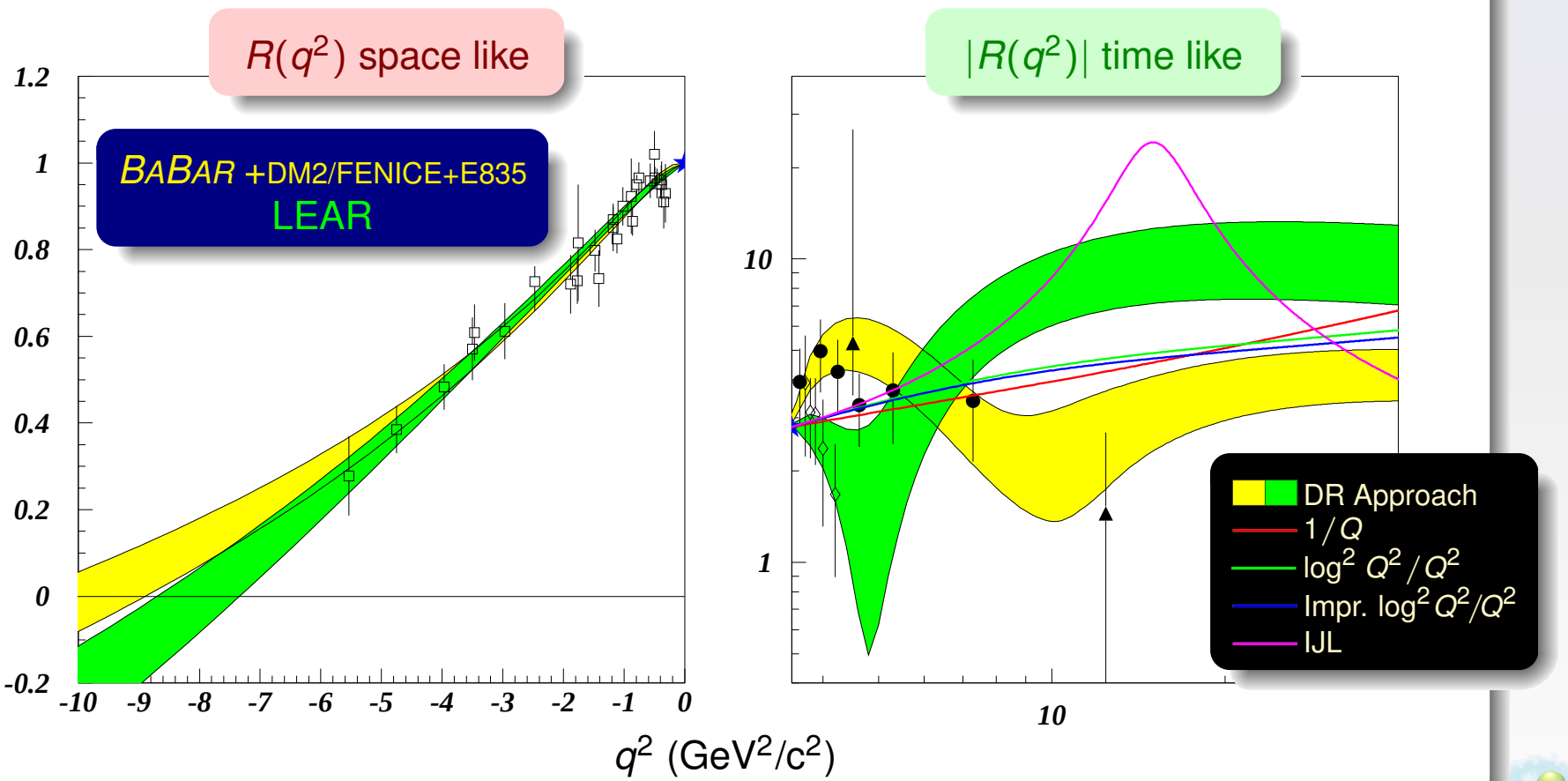
Experimental conditions on $R(q^2)$ and $|R(q^2)|$

- 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

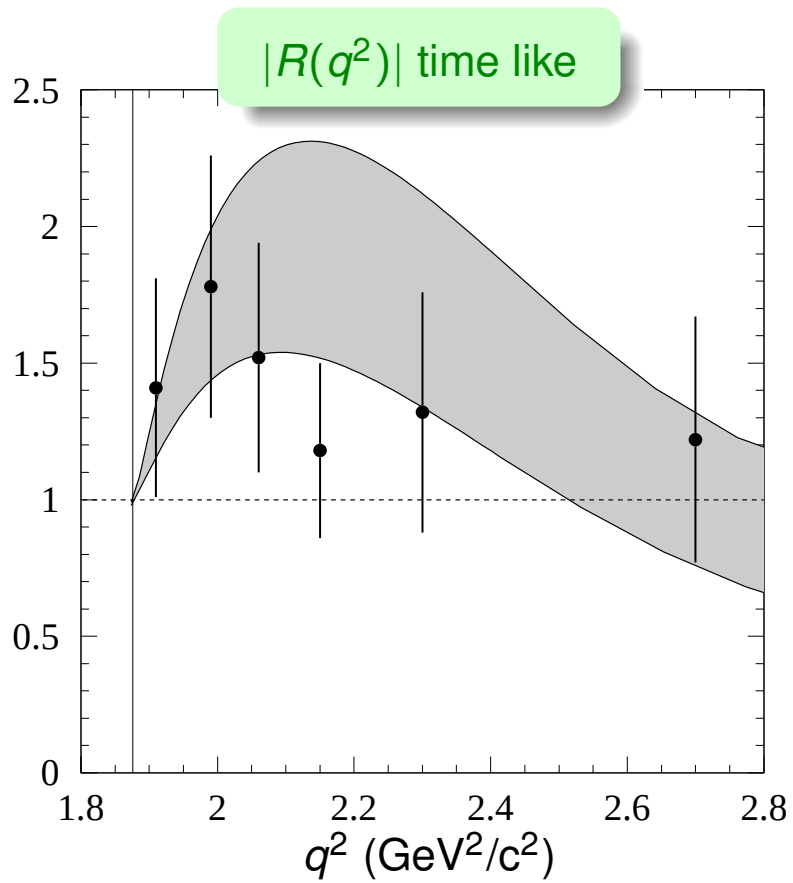
NPB(Proc.Supp.)162(2006)46

Using a Dispersion Relation (DR) formalism, we fit data in the time- and space-like regions and extrapolate into the whole q^2-complex plane

Reconstructed R in space and time regions

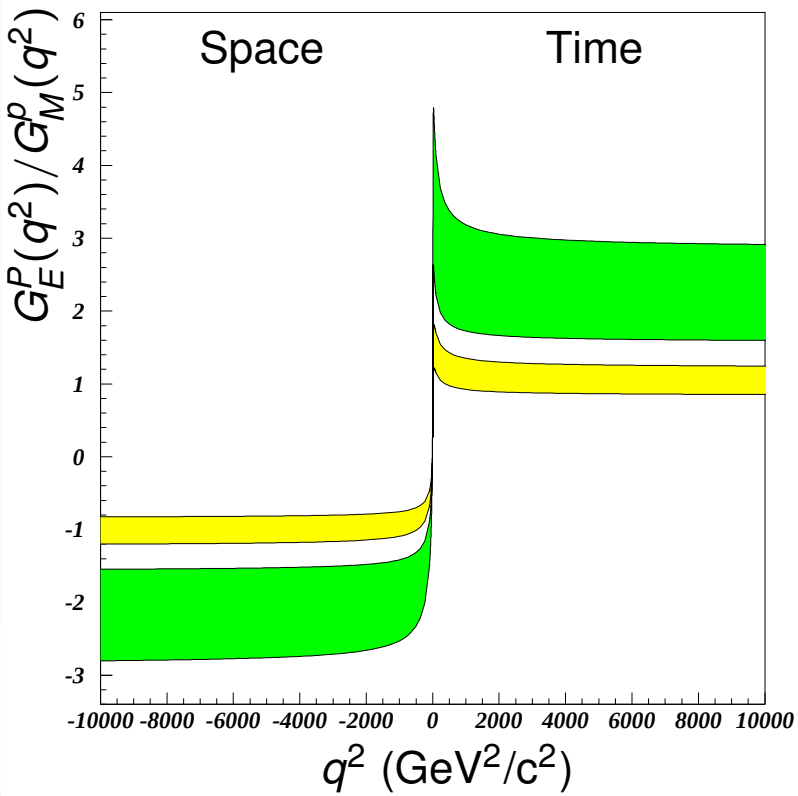


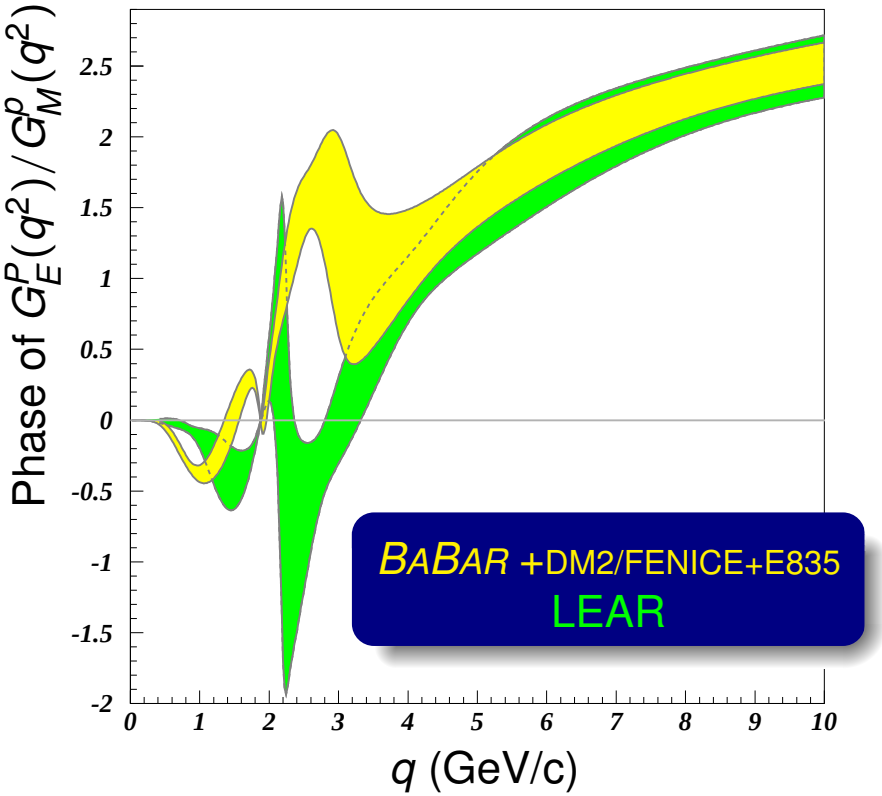
Reconstructed time-like R (*BABAR* only)



Asymptotic $G_E^p(q^2)/G_M^p(q^2)$ and phase

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





pQCD prediction

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

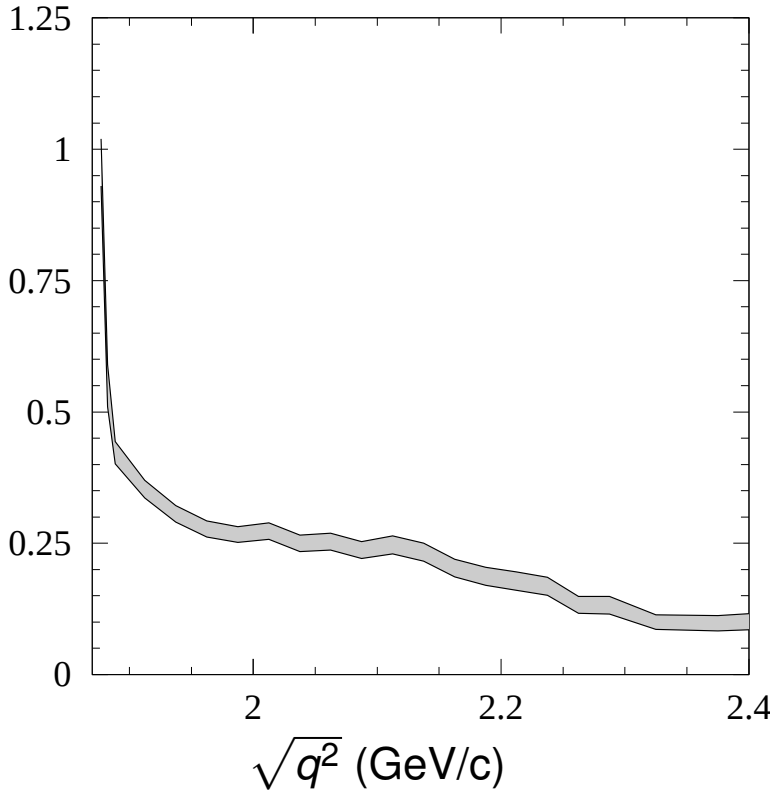
Real part from subtracted DR $\Rightarrow$ phase

$$\mathrm{Re}R(q^2) = \underbrace{R(0)}_{=1} + \frac{q^2}{\pi}\,\mathrm{Pr}\int_{s_{th}}^{\infty}\frac{\mathrm{Im}R(s)ds}{s(s-q^2)}$$

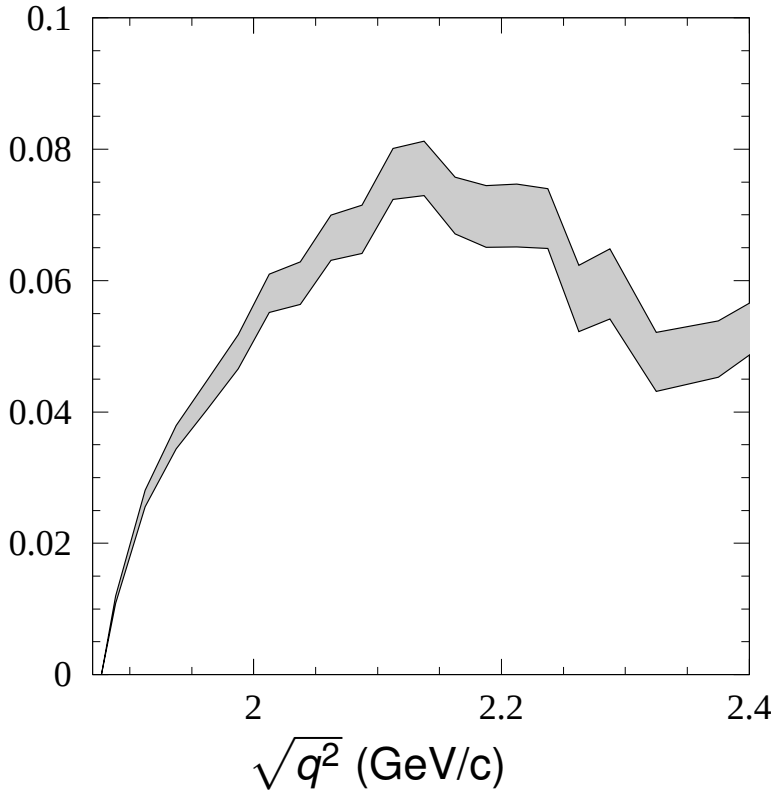
Phases from DR: $|B^p_S(q^2)|$ and $|B^p_D(q^2)|$

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

$|B^p_S(q^2)| = |2\sqrt{\tau}G^p_M + G^p_E|$

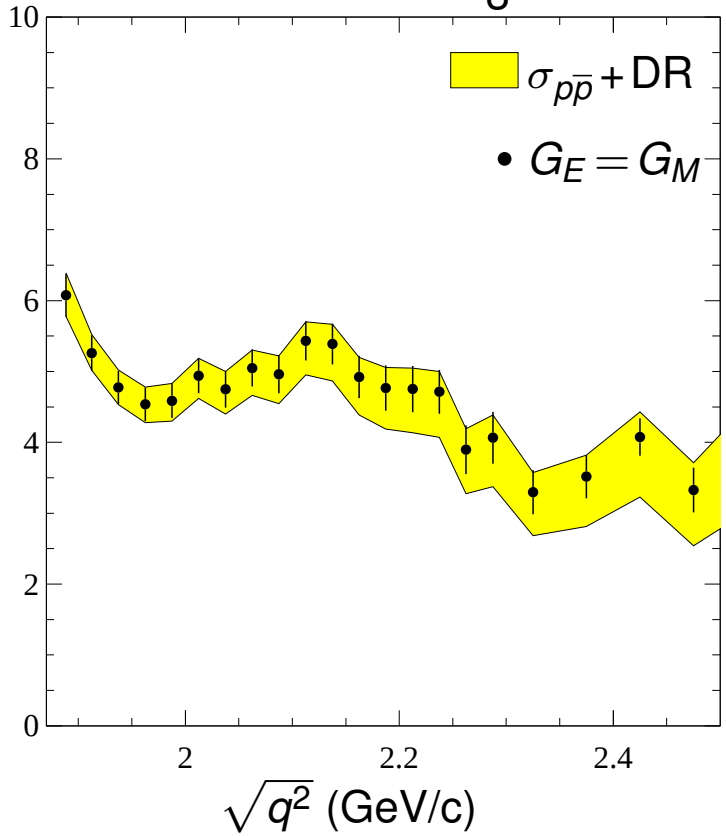


$|B^p_D(q^2)| = |\sqrt{\tau}G^p_M - G^p_E|$

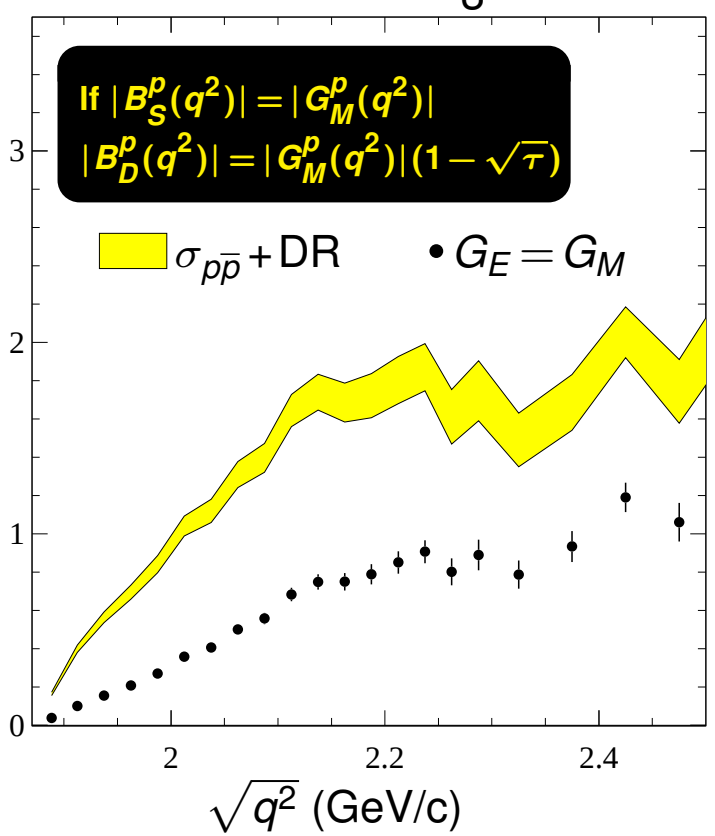


BABAR $\sigma(e^+e^- \to p\bar{p})$ + DR

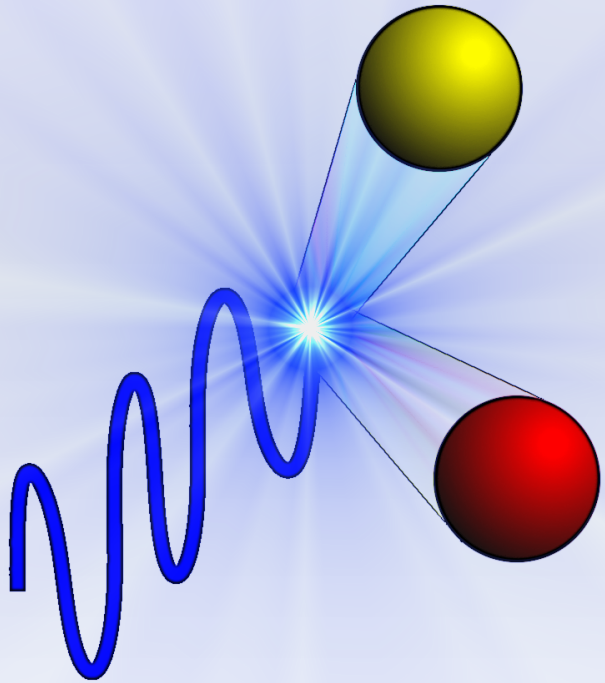
$$|B_S^p(q^2)|q^4 = \frac{|2\sqrt{\tau}G_M^p + G_E^p|}{3}q^4$$



$$|B_D^p(q^2)|q^4 = \frac{|\sqrt{\tau}G_M^p - G_E^p|}{3}q^4$$

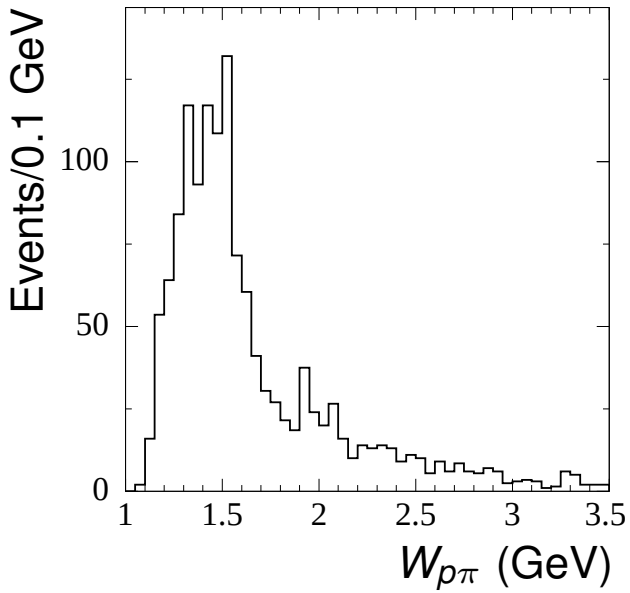


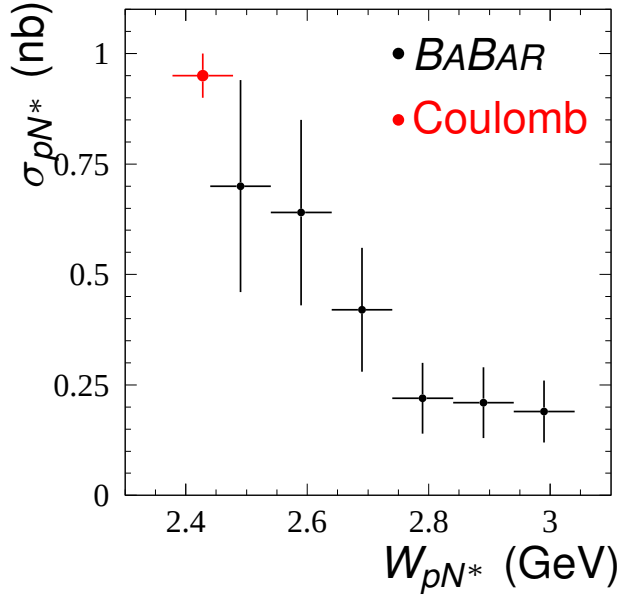
Other charged baryon FF's at threshold



$e^+e^- \to N\overline{N}^* + \overline{N}N^*$

- $e^+e^- \to p\bar{p}\pi^0\gamma$ (*BABAR*)
- "Unfolding N^* width"
- Systematic error: $\frac{\Delta\epsilon}{\epsilon} + \frac{\Delta B}{B}(N^* \to N\pi) + \frac{\Delta N}{N}(\text{unfold})$
- $\sigma^{\text{Coulomb}} = 0.85 \times \left(\frac{2M_p}{M_p + M_{N^*}}\right)^2 \times \frac{16M_p^2 M_{N^*}^2}{(M_p + M_{N^*})^4} \times 2 = 0.95 \pm 0.05$ nb

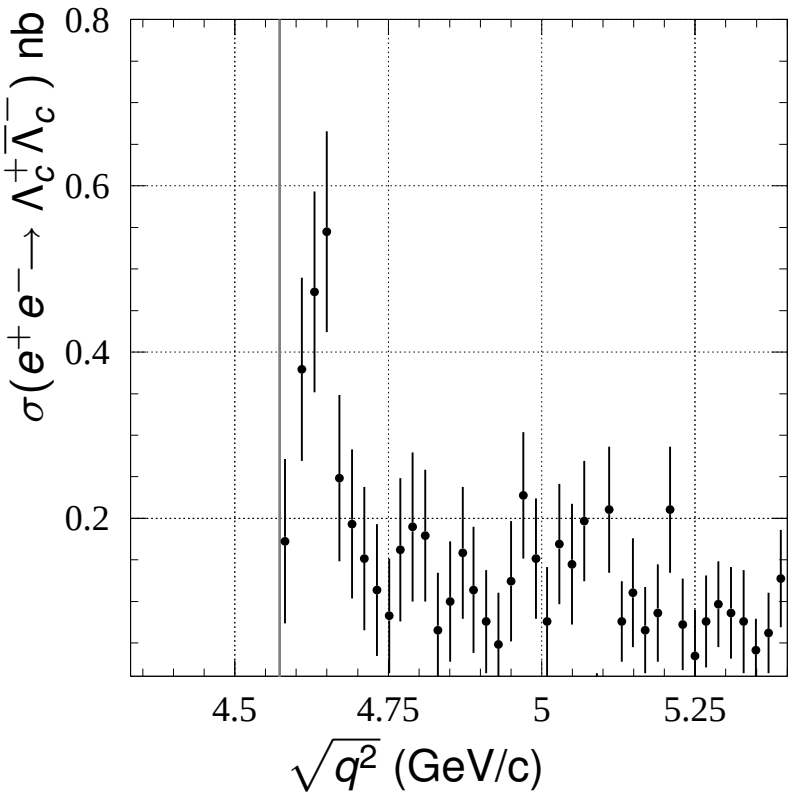


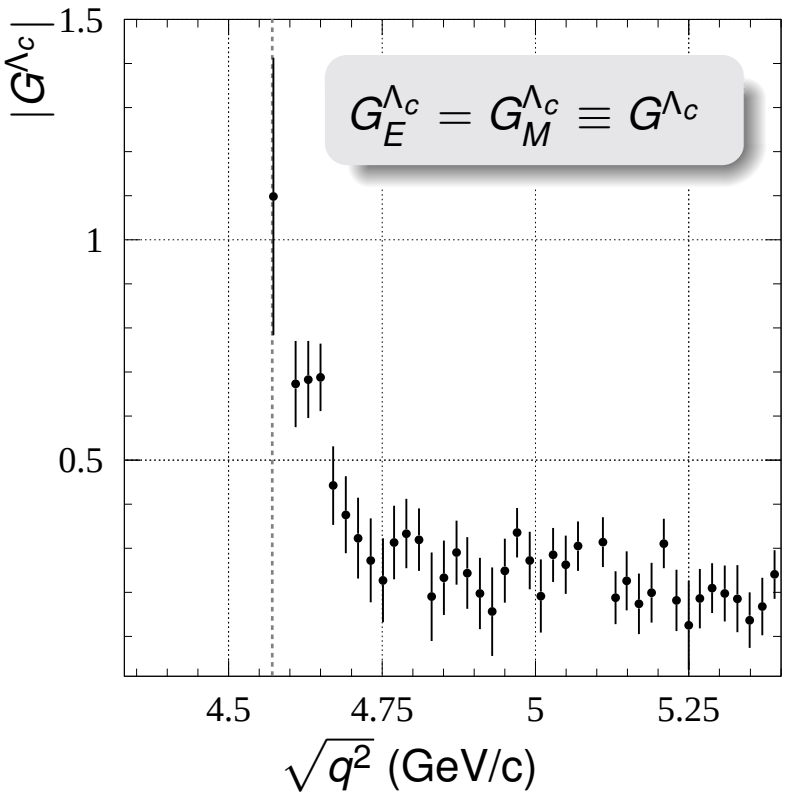


- Much smaller $\Delta(1236)$ excitation cross sections

Λ_c^+ form factor

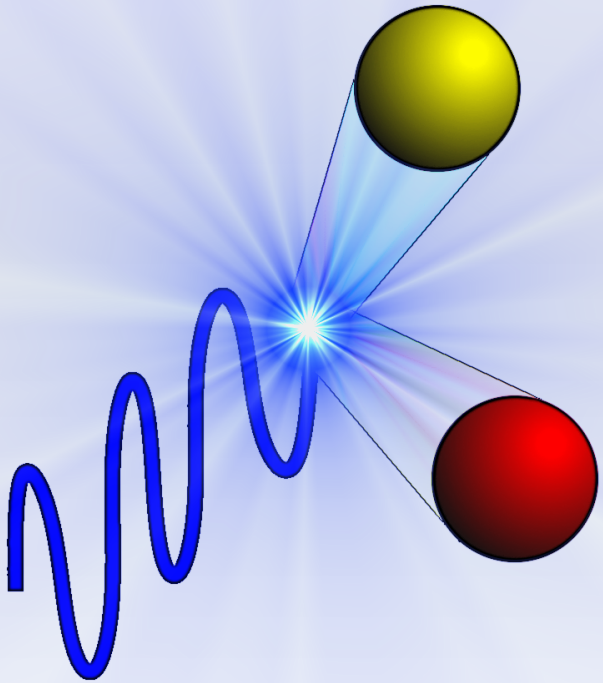
Belle $\sigma(e^+e^- \to \Lambda_c^+ \overline{\Lambda}_c^-)$



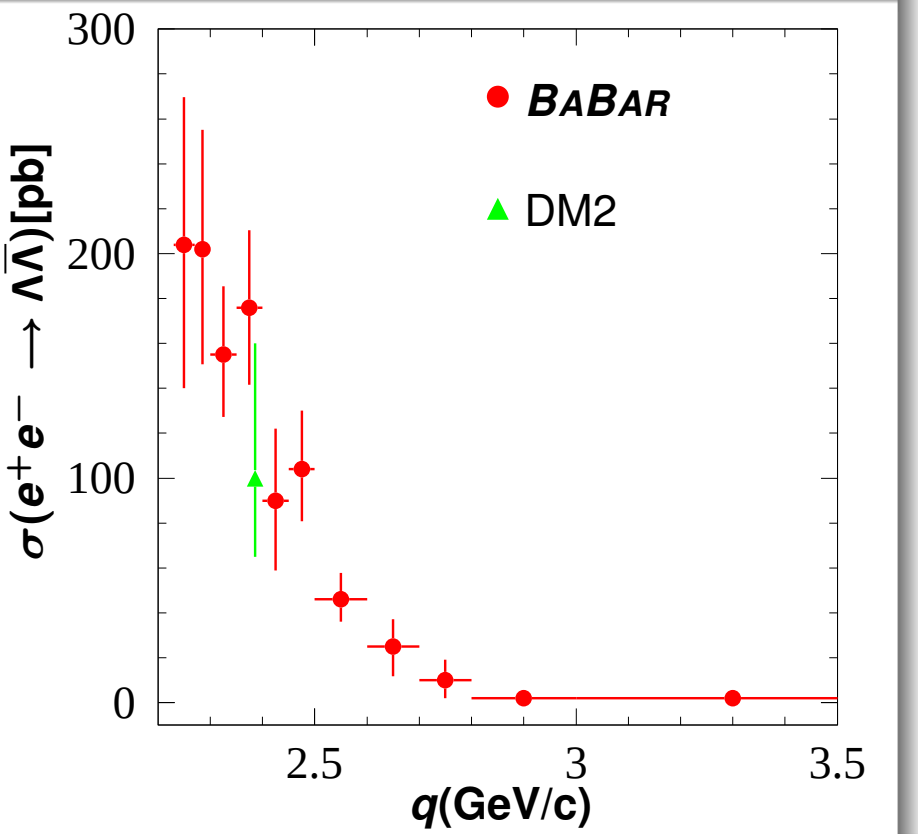


$$|G^{\Lambda_c}(4M_{\Lambda_c}^2)| = 1.1 \pm 0.3(\text{stat}) \pm 0.4(\text{syst})$$

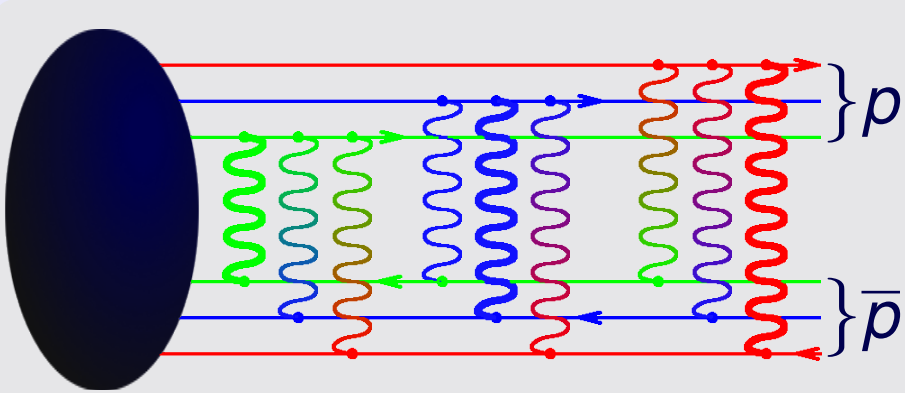
The neutral baryons puzzle



$\Lambda\bar{\Lambda}$ cross section



Coulomb correction at quark level?



For each pair $q\overline{q}$ there is a Coulomb amplitude

$$C(W^2_{p\overline{p}} \to 4M_p^2) \approx \frac{\alpha\pi}{\beta}\left|\sum_{q,\overline{q}} \sqrt{Q_q Q_{\overline{q}}}\; e^{ik_{q\overline{q}}\cdot x_{q\overline{q}}}\right|^2$$

The phase accounts for the quark displacement inside the baryon

- The interference terms have several **suppression factors**
- **Asymmetry** between repulsive and attractive Coulomb interactions

Q_q and $Q_{\overline{q}'}$ same sign: $$C(W_{p\overline{p}}) = \frac{-\pi\alpha|Q_q Q_{\overline{q}'}|/\beta}{1-\exp(+\pi\alpha|Q_q Q_{\overline{q}'}|/\beta)} \xrightarrow[W^2_{p\overline{p}}\to 4M_p^2]{} 0$$

QCD-Coulomb-like effects contribute to the FF?

Coulomb correction at quark level?

Only Coulomb enhancement factors:

$p\bar{p}$ case

$$\sigma(e^+e^- \to p\bar{p})(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}(2Q_u^2 + Q_d^2) = 0.85 \text{ nb}$$

- At hadron level: $\sigma(e^+e^- \to p\bar{p})(4M_p^2) = 0.85$ nb

Cross section data

$$\sigma(e^+e^- \to p\bar{p})(4M_p^2) = (0.80 \pm 0.05) \text{ nb}$$

$\Lambda\bar{\Lambda}$ case

$$\sigma(e^+e^- \to \Lambda\bar{\Lambda})(4M_\Lambda^2) = \frac{\pi^2\alpha^3}{2M_\Lambda^2}(Q_u^2 + Q_d^2 + Q_s^2) = 0.4 \text{ nb}$$

- At hadron level: $\sigma(e^+e^- \to \Lambda\bar{\Lambda})(4M_\Lambda^2) = 0$

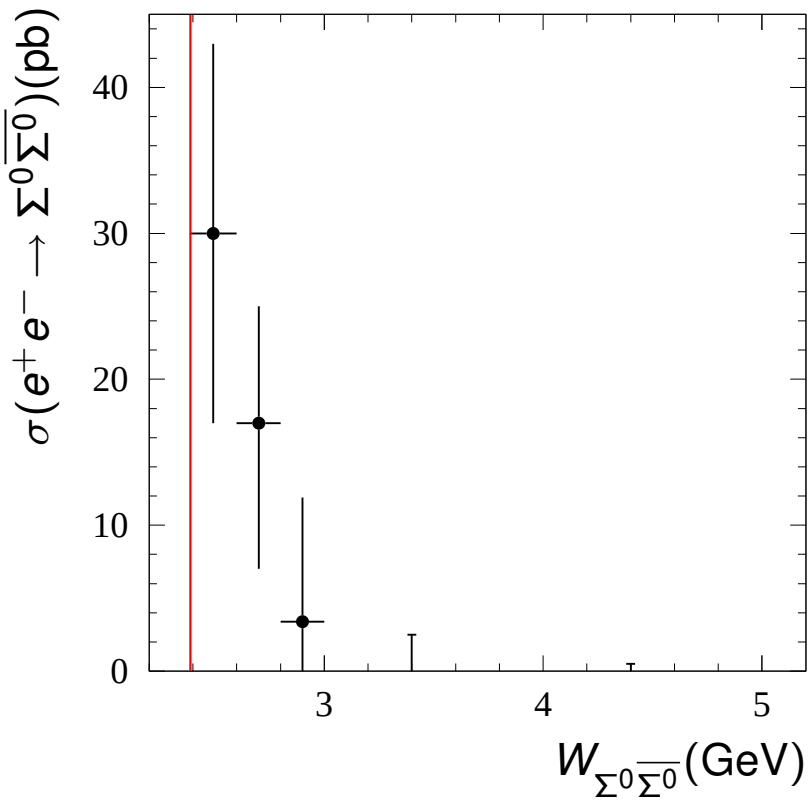
Cross section data

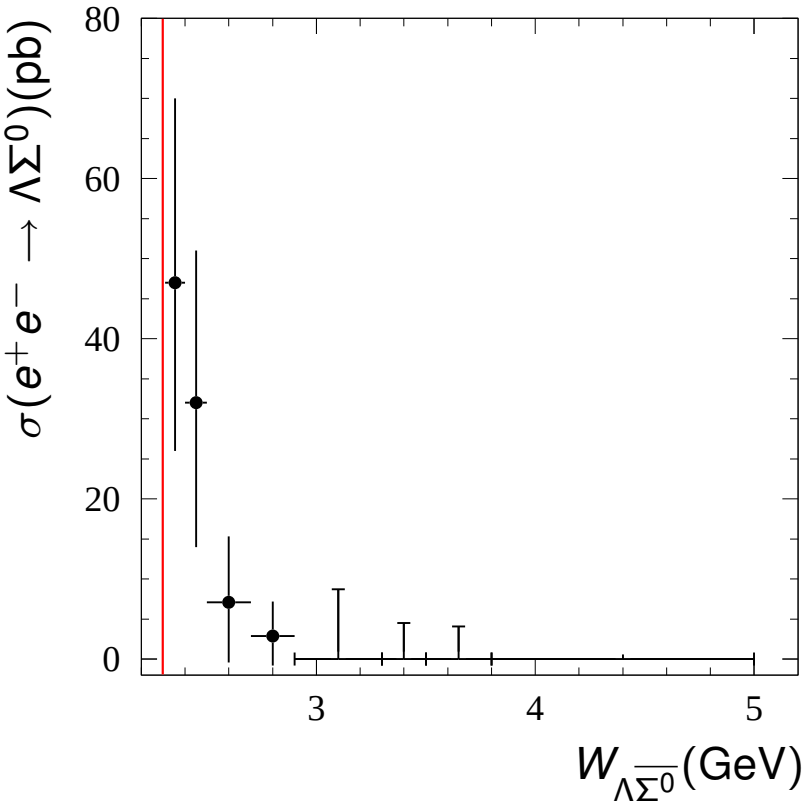
$$\sigma(e^+e^- \to \Lambda\bar{\Lambda})(4M_\Lambda^2) = (0.20 \pm 0.05) \text{ nb}$$

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

PRD76, 092006

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

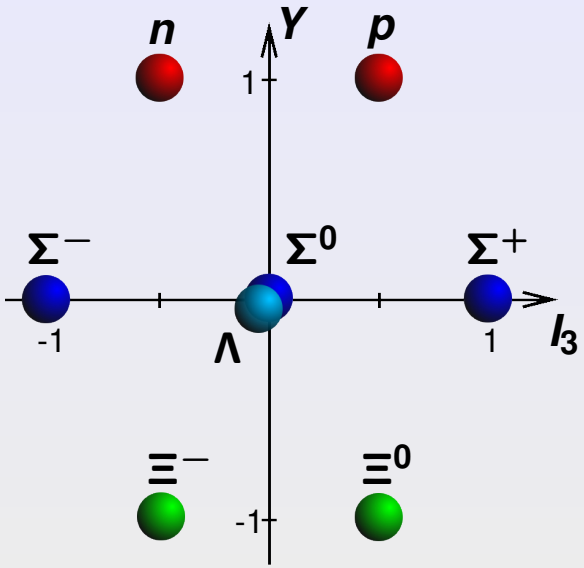




$\sigma(e^+e^- \to \Sigma^0\overline{\Sigma^0})_{\text{th}} = 30 \pm 13$ pb

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

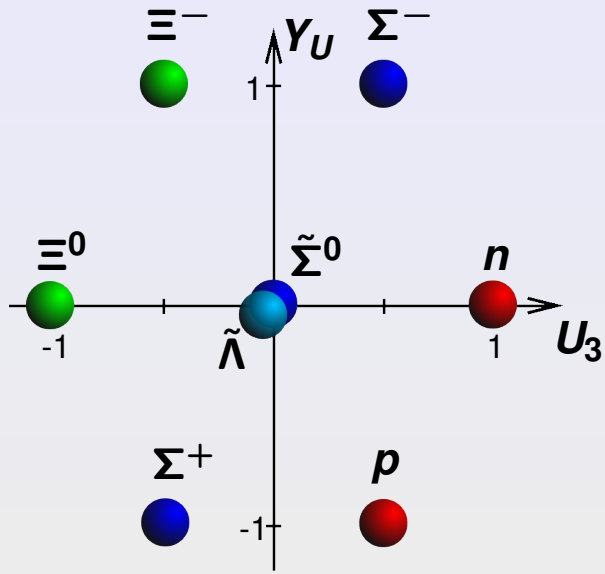
Baryon octet and *U*-spin



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

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

$$Y_U = -Q$$



$$\tilde{\Lambda} = (\sqrt{3}\Lambda + \Sigma^0)/2$$
$$\tilde{\Sigma}^0 = (\sqrt{3}\Sigma^0 - \Lambda)/2$$

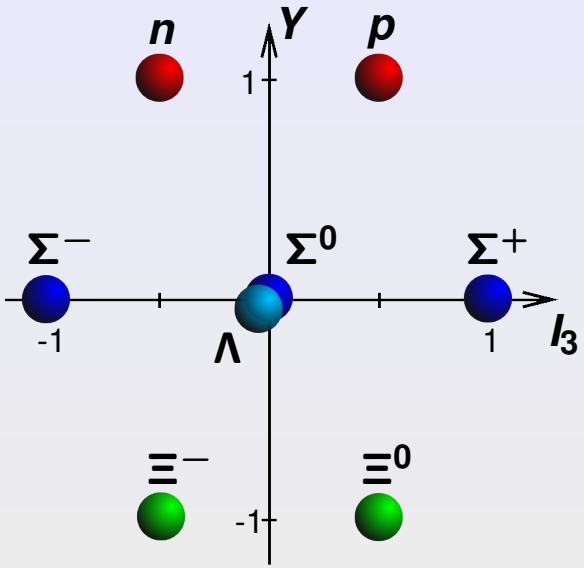
U-spin direct relations

- $G^{\Xi^-} = G^{\Sigma^-}$
- $G^{\Xi^0} = G^n$
- $G^{\Sigma^+} = G^p$

Two U-spin indirect relations

- $G^n - \frac{3}{2} G^\Lambda - \frac{1}{2} G^{\Sigma^0} = 0$
- $G^{\Sigma^0} - G^\Lambda + \frac{2}{\sqrt{3}} G^{\Sigma^0 \Lambda} = 0$

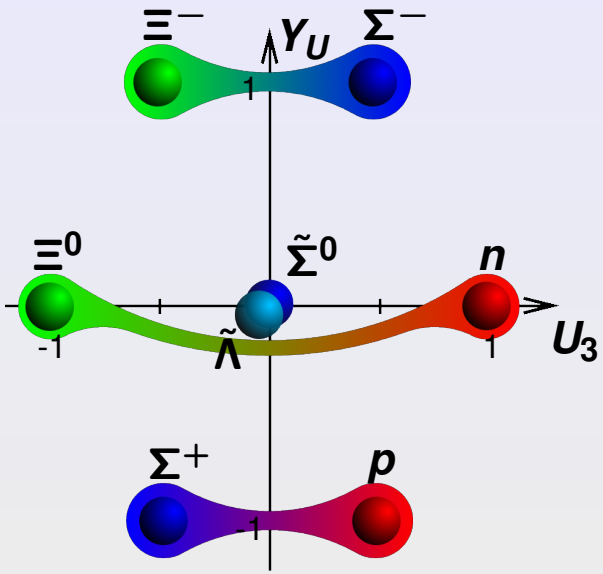
Baryon octet and *U*-spin



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

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

$$Y_U = -Q$$



$$\tilde{\Lambda} = (\sqrt{3}\Lambda + \Sigma^0)/2$$
$$\tilde{\Sigma}^0 = (\sqrt{3}\Sigma^0 - \Lambda)/2$$

U-spin direct relations

- $G^{\Xi^-} = G^{\Sigma^-}$
- $G^{\Xi^0} = G^{n}$
- $G^{\Sigma^+} = G^{p}$

Two U-spin indirect relations

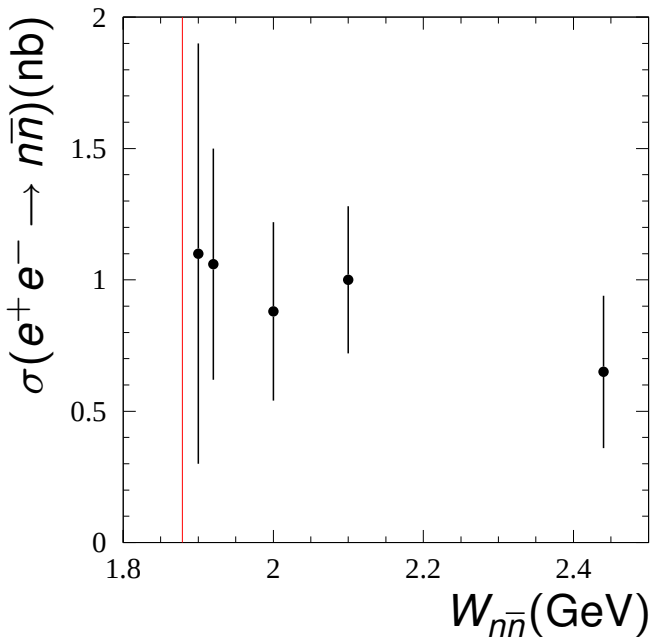
- $G^{n} - \frac{3}{2} G^{\Lambda} - \frac{1}{2} G^{\Sigma^0} = 0$
- $G^{\Sigma^0} - G^{\Lambda} + \frac{2}{\sqrt{3}} G^{\Sigma^0 \Lambda} = 0$

Data and U-spin predictions

Data+Coulomb correction at threshold

- $M_{\Sigma^0}\sqrt{\sigma_{\Sigma^0\overline{\Sigma^0}}} - M_\Lambda\sqrt{\sigma_{\Lambda\overline{\Lambda}}} + \frac{2}{\sqrt{3}}\overline{M_{\Lambda\Sigma^0}}\sqrt{\sigma_{\Lambda\Sigma^0}} = (-0.06 \pm 6.0) \times 10^{-4}$
- $\sigma(e^+e^- \to n\overline{n}) = \frac{1}{4}(3\sqrt{\sigma_{\Lambda\overline{\Lambda}}}M_\Lambda - \sqrt{\sigma_{\Sigma^0\overline{\Sigma^0}}}M_\Sigma)^2\frac{1}{M_n^2} = 0.5 \pm 0.2$ nb

$e^+e^- \to n\overline{n}$ **(FENICE@ADONE)**



Conclusions and Perspectives

- Charged baryon pairs at $Q^2 = 4M_{\mathcal{B}}^2$ as pointlike fermions
- Neutral baryon pairs at $Q^2 = 4M_{\mathcal{B}}^2$ puzzling cross sections (remnant of quark Coulomb interactions?)
- Time-like G_E^p/G_M^p predicts space-like $G_E^p/G_M^p \longrightarrow -1$

- Waiting for:
  - Theoretical interpretations
  - New data from ***BABAR*** , Belle, BESIII and new flavor factories