Baryon em Form Factors from Initial State Radiation processes

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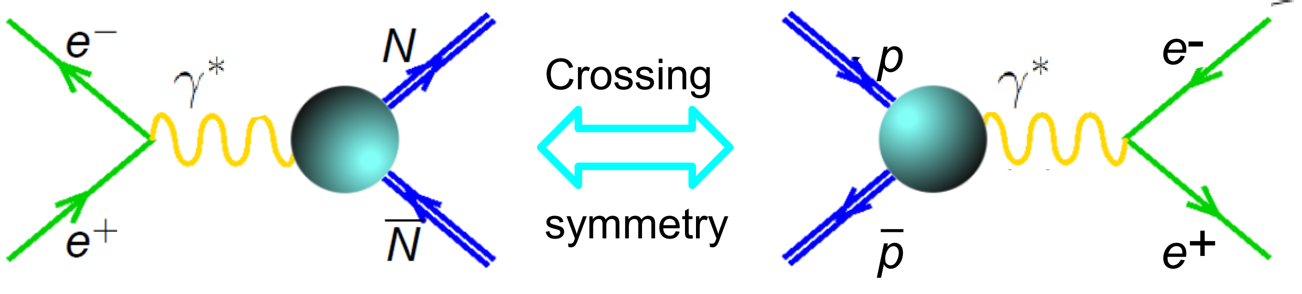
- Motivation
- Initial State Radiation
- Existing experiments
- Measurements and expectations
- Conclusions

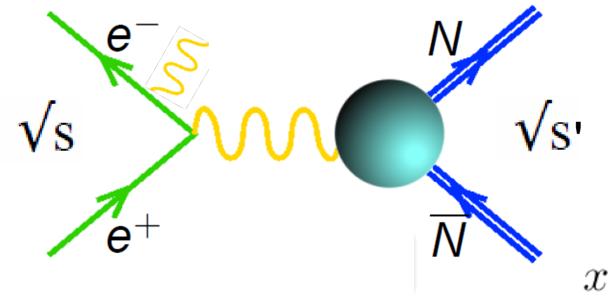
Motivation



- EM form factors (FFs) account for **non point-like structure of hadrons**, contain information on **dynamics and charge and magnetization distributions**
- FFs are **analytic functions of q^2** and need to be determined in the **space-like $q^2<0$** (real functions, scattering experiments) and **time-like region $q^2>0$** (complex functions,annihilation experiments)
- Data from e^+e^- colliders running around baryon threshold energies cover reduced q^2 regions and collected small statistics at each $q^2 = \sqrt{s}$
- **High luminosity, wide energy scan experiments (panda) and initial state radiation processes from b, c- factories are provide high statistics**
- **HIM EMP is analyzing BESIII ISR $N\bar{N}$ production**. We will later on use this konwledge in PANDA's crossing symmetry related processes

Initial State Radiation

In **Initial State Radiation** channels a photon is emitted from e^+e^--beams



Continous coverage from $N\bar{N}$ production threshold to $\sqrt{s}$ in one single experiment!!

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

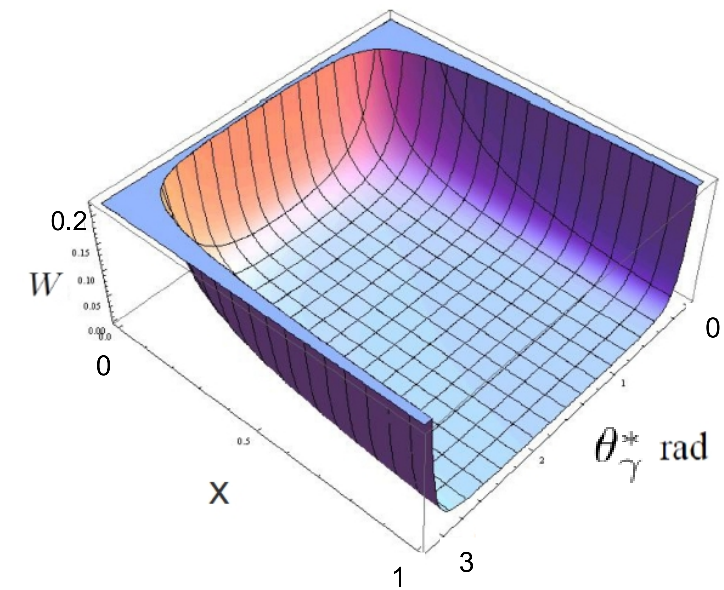
$$q^2 = m^2_{p\bar{p}} = s(1-x)$$

$$\frac{d^2\sigma(e^+e^- \to \gamma X_{\mathrm{had}})}{dx\,d\theta_\gamma} = W(x,\theta_\gamma)\,\sigma_{e^+e^- \to X_{\mathrm{had}}}(s)$$

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

$$\boxed{\frac{d\sigma}{d(\cos\theta)} = \frac{\pi\alpha_e^2 C}{8M^2\tau\sqrt{\tau(\tau-1)}}\left[\tau\boxed{|G_M|^2}(1+\cos^2\theta_N) + \boxed{|G_E|^2}\sin^2\theta_N\right]}$$

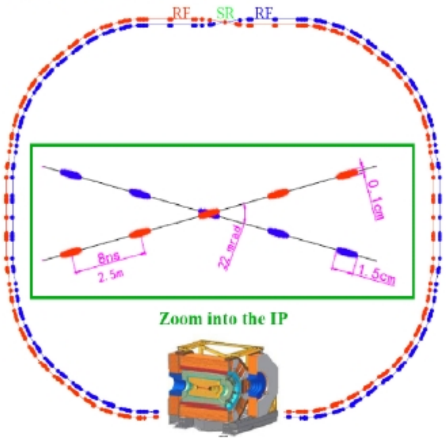
C: Coulomb interaction correction at threshold



Low $\boldsymbol{\sigma}_{\mathbf{ISR}}$ **compensated by high luminosity** in b,c factories!!

BABAR / BESIII

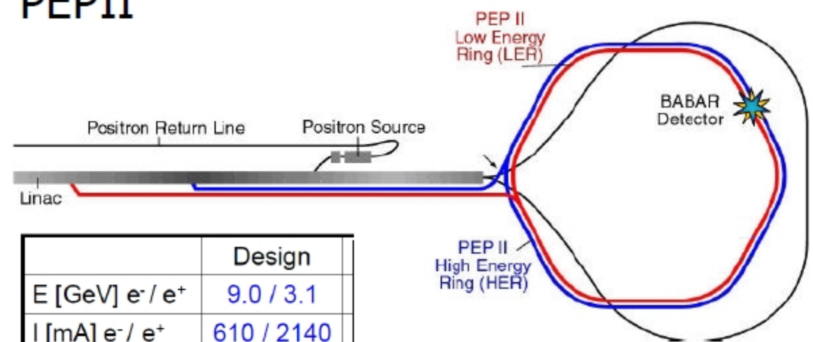
BEPCII



Beam energy: 1.0 – 2.3 GeV
Peak Luminosity:
Design: 1×10^{33} cm^{-2}s^{-1}

L = 10 fb^{-1} at ψ'' aimed
L = 2.9 fb^{-1} at ψ'' available

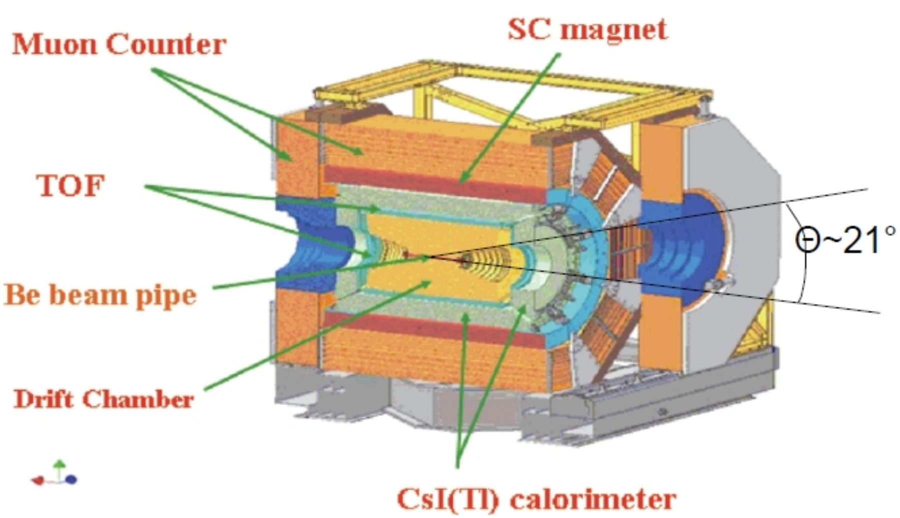
PEPII



	Design
E [GeV] e$^-$ / e$^+$	9.0 / 3.1
I [mA] e$^-$ / e$^+$	610 / 2140
L [cm^{-2} s^{-1}]	3 x 10^{33}
L_{int} [pb^{-1}/day]	135

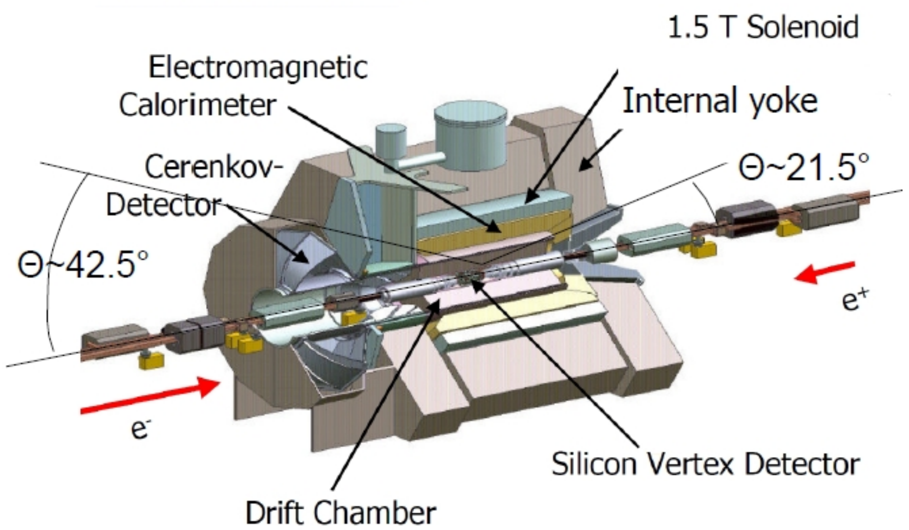
L = 232 fb^{-1} at ϒ(4S) analyzed

BESIII Detector



Typical resolutions: **σ(J/ψ) = 9 MeV , σ(π^0) = 5 MeV**

BABAR Detector



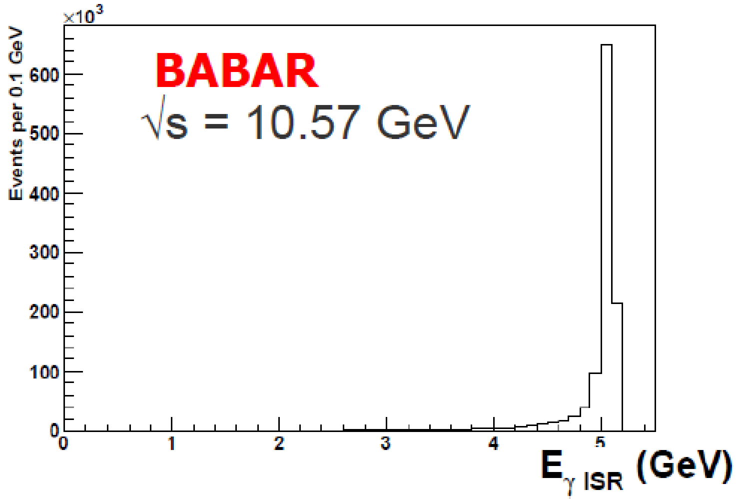
Typical resolutions: **σ(J/ψ) = 12 MeV, σ(π^0) = 6.5 MeV**

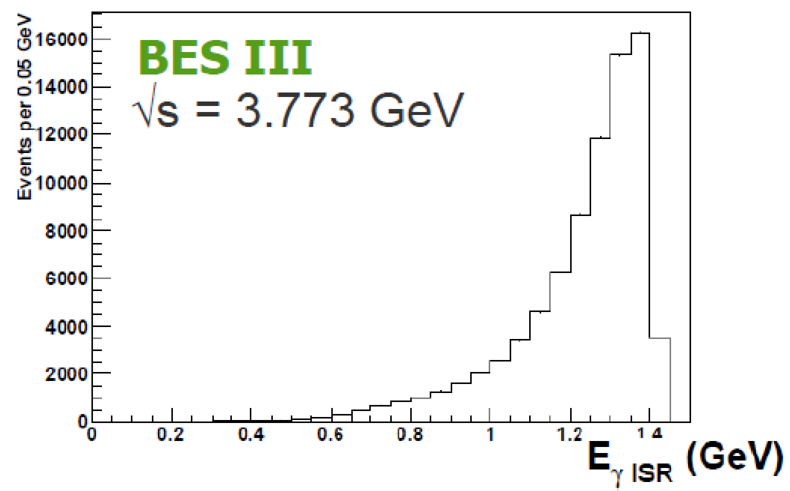
ISR @ BABAR / BESIII

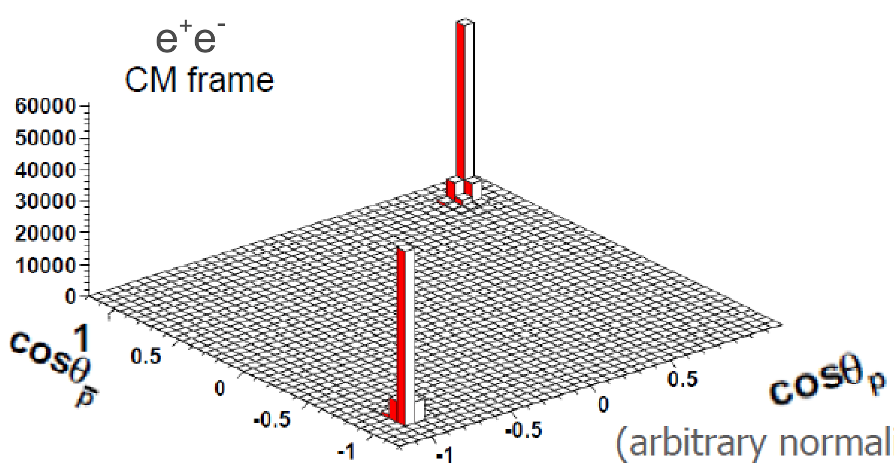
Geometrical acceptance:

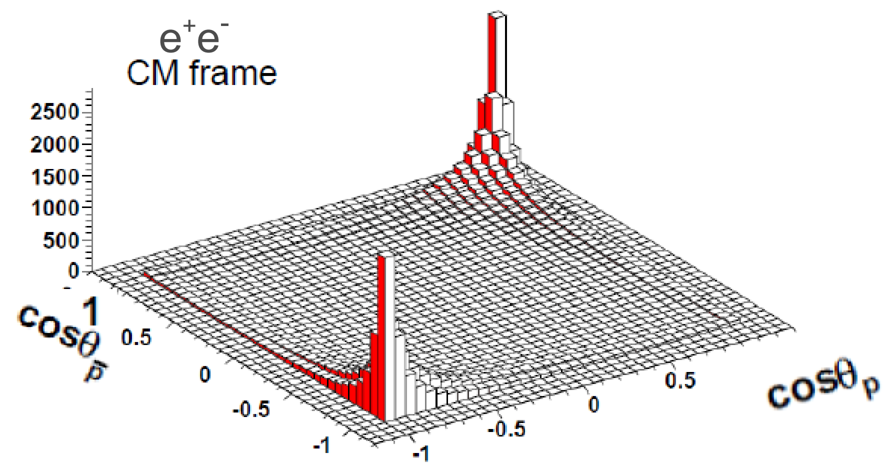
$M_{hadr} << \sqrt{s} \rightarrow$ need high luminosities
Photon tagging unavoidable

M_{hadr} < but close to $\sqrt{s}$
untagged measurement possible









(arbitrary normalization)

$e^+e \to N\,\bar{N}\,\gamma_{ISR}$

$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]

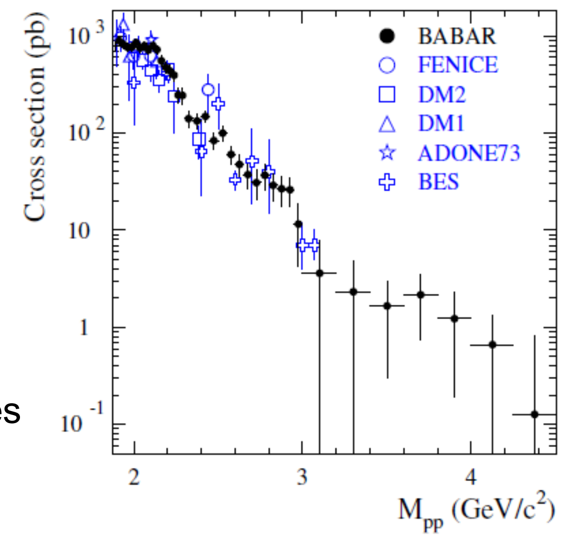
Publication based on 232 fb^{-1}at $\sqrt{s}$=10.57 GeV. 4025 selected ISR signal events with 6% $e^+e^- \to p\bar{p}\pi^0$

$$\sigma(m_{p\bar{p}}) = \frac{dN/dm_{p\bar{p}}}{\varepsilon R\, dL/dm_{p\bar{p}}} = \frac{4\pi\alpha^2\beta C}{3\,q^2}\left[\underbrace{\left|G_M(q^2)\right|^2 + \frac{1}{2\tau}\left|G_E(q^2)\right|^2}_{\text{Effective proton FF}}\right]$$

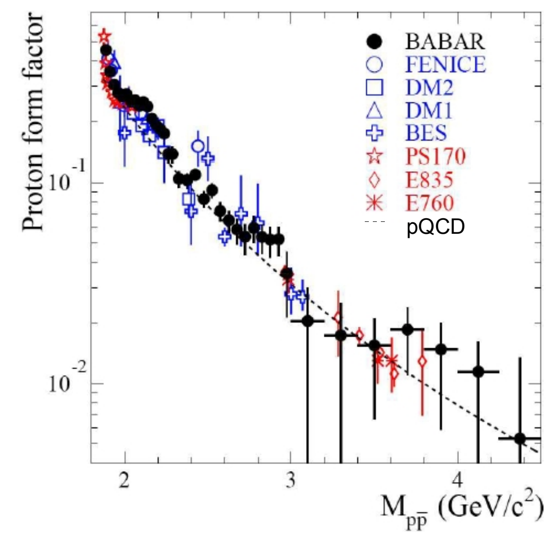
- peak at threshold (baryonium resonance?,
  pion dominance in FSI?,
  Coulomb factor underestimated?)

  Similar behavior in m_{pp} seen in processes with different dynamics
  PRL 88,181803('02), PRL 89,151802('02), PRD 72,051101('05), see backup slides
- plateau from 1.8 to 2.1 GeV/c^2
- decrease with drops at 2.25 (ρ(2150)?) and 3 GeV/c^2
  (baryon thresholds? S-wave states open up quickly?)

- **Separation between $G_E(q^2)$ and $G_M(q^2)$ not possible: Effective FF**



pQCD holds well for all $m_{p\bar{p}}$
At high m_{pp} **a factor 2 greater than in space like region !!**



$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

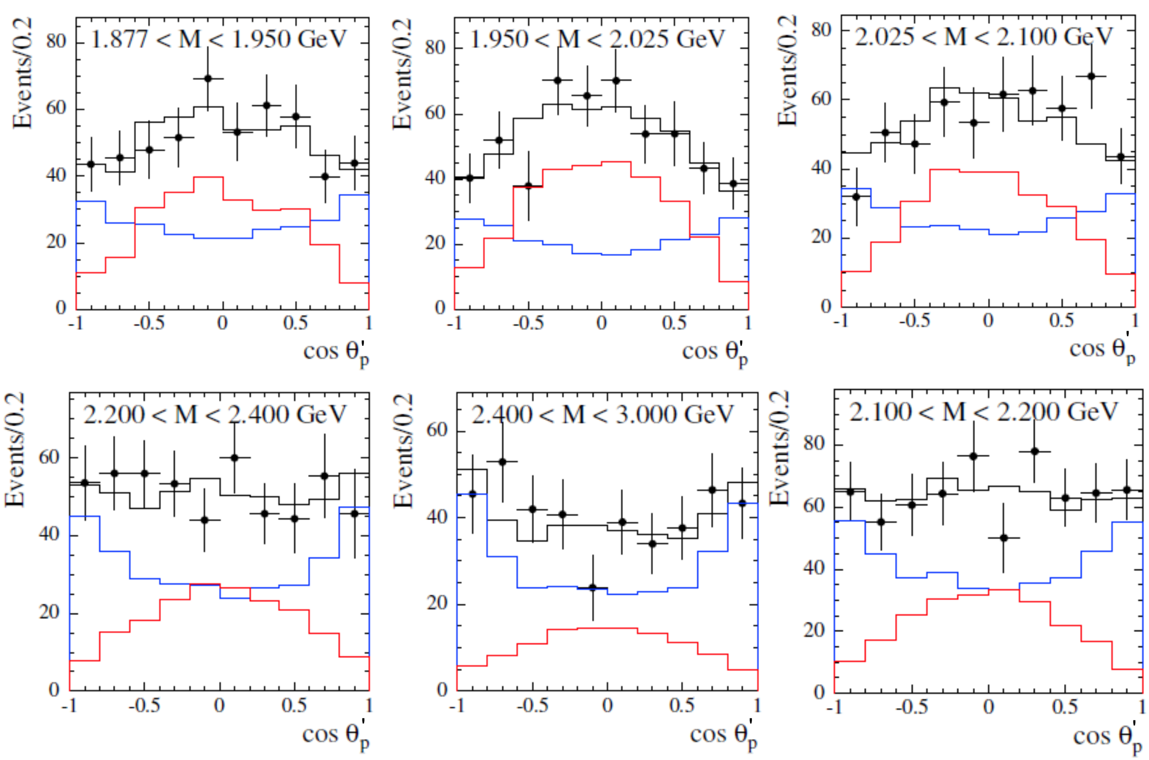
[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]

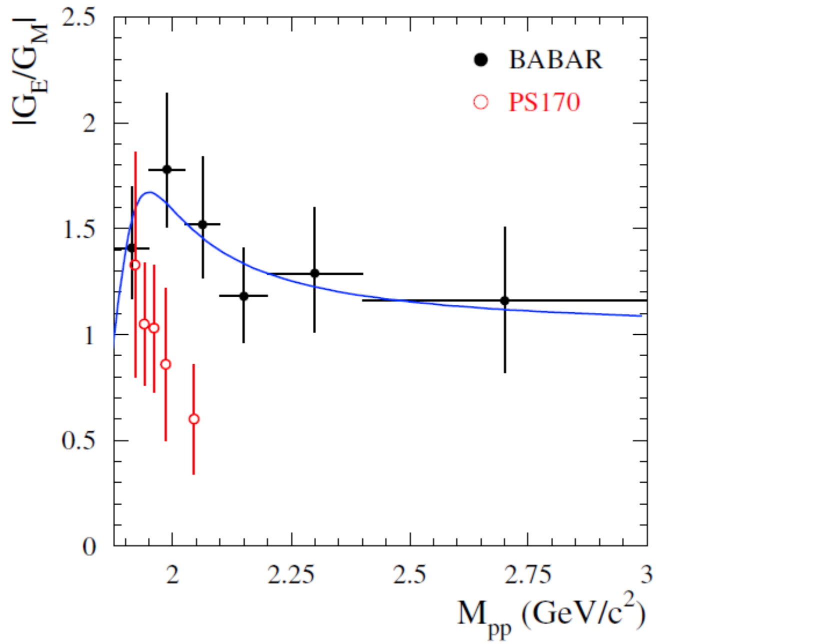
- **Ratio $|G_E(q^2)/G_M(q^2)|$ extracted from analysis of proton helicity angle in the $p\bar{p}$ rest frame**

$$\frac{dN}{d\cos\theta'} = A\left(\boxed{H_M(\cos\theta'_p, m_{pp})} + \left|\frac{G_E}{G_M}\right|\boxed{H_E(\cos\theta'_p, m_{pp})}\right)$$

Not analytic. Extracted from MC ISR generator
Phokhara with $G_E = 0$ and $G_M = 0$

[H.Czyz,J.H.Kühn,E.Nowak,G.Rodrigo,Eur.Phys.J C35,527 (2004)]



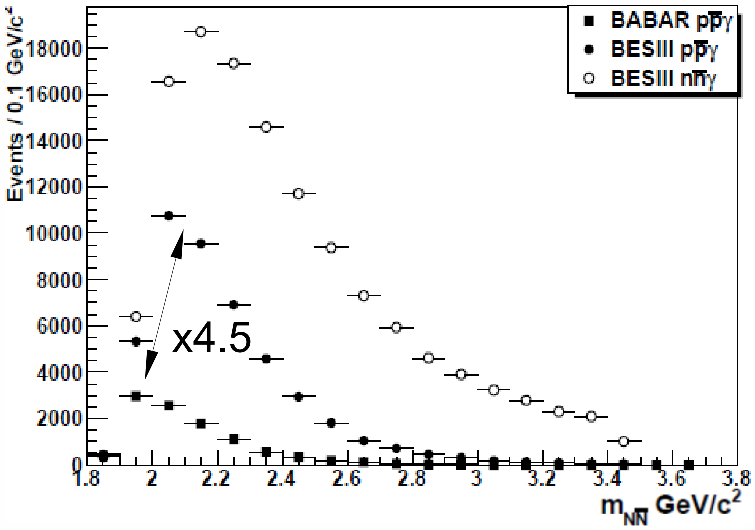


- Maximum at 2 GeV/c^2
- $G_E > G_M$ for all $M_{p\bar{p}}$ (≠ space-like)
  Inconsistent with PS170
  Agreement at threshold
- Consistent with $|G_E/G_M| = 1$ at large M_{pp}

$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

What could BES-III do for this channel? **Which resolution in $|G_E/G_M|$ can BESIII achieve?**

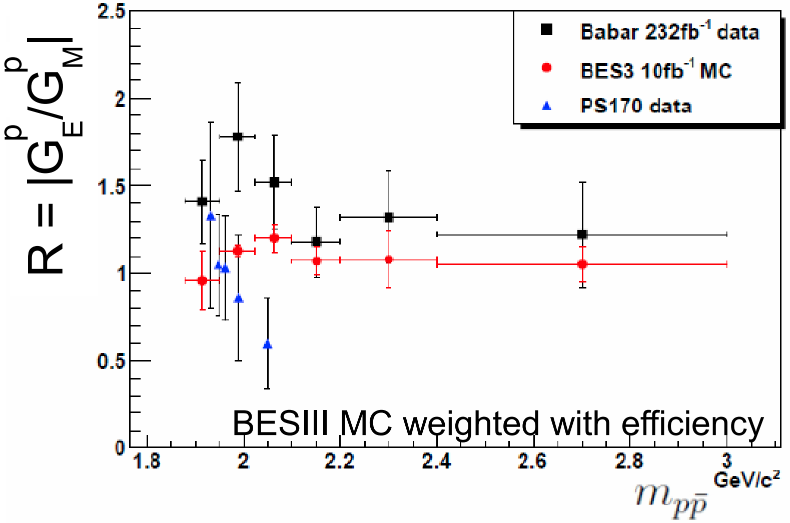
	BES-III	BABAR
$\sqrt{s}$(GeV))	3.77	10.57
$\sigma_{ISR,NLO}$(nb)	8.12×10^{-3}	0.7×10^{-3}
$L(\mathrm{fb}^{-1})$	10	232
$N_{gen} = L \times \sigma$	81261	176856
measurement	"untagged + tagged"	"tagged"
geometry cuts (degrees)	$21.6 < \theta_{p,\bar{p}} < 158.7$	$25.8 < \theta^{lab}_{p,\bar{p}} < 137.7$
	$0 < \theta_{\gamma ISR} < 180$	$21.5 < \theta^{lab}_{\gamma ISR} < 137.5$
$N_{expected}$	45623 (34070 + 11553)	10183



- Expected #data simulated with R=1 MC signal and weighted with selection efficiencies (30% for untagged analysis, 6% for tagged analysis)
- Fit simulated data with:

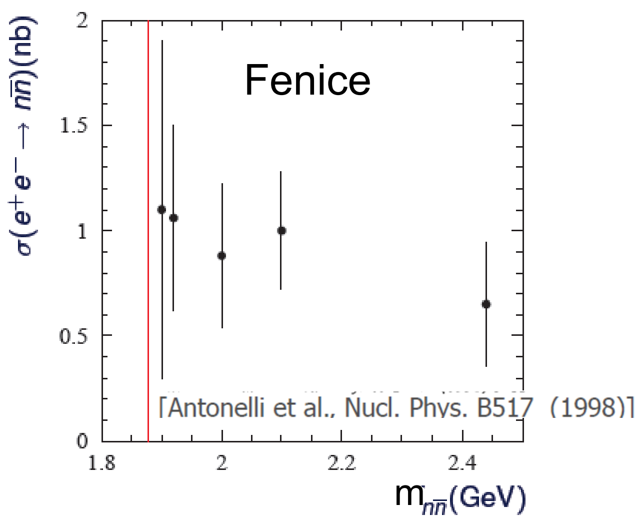
$$F((cos\hat{\theta}, m)) = F_0 \boxed{\frac{\sigma_0}{\sigma_1}} \cdot \underbrace{|G_M|^2 \cdot H_M(cos\hat{\theta}, m)}_{\text{Normalized true MC with GE = 0}} + F_1 \cdot \underbrace{|G_E|^2 \cdot H_E(cos\hat{\theta}, m)}_{\text{Normalized true MC with GM = 0}}$$

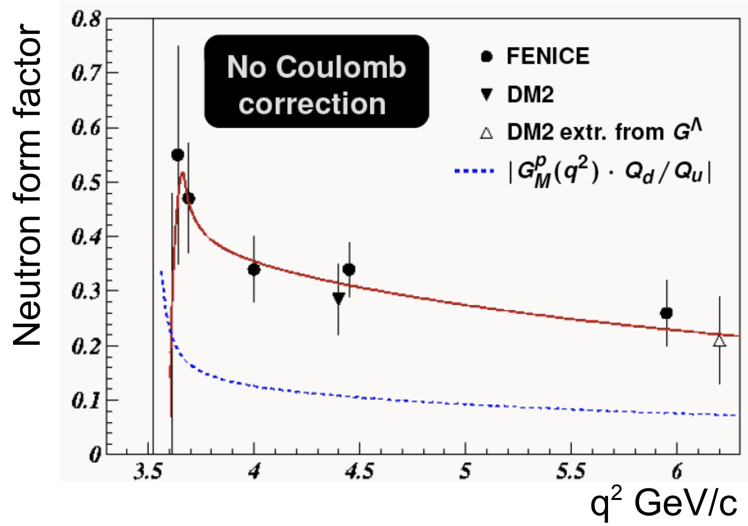
$$\boxed{R = \frac{|G_E|}{|G_M|} = \sqrt{\frac{F_1}{F_0}}}$$

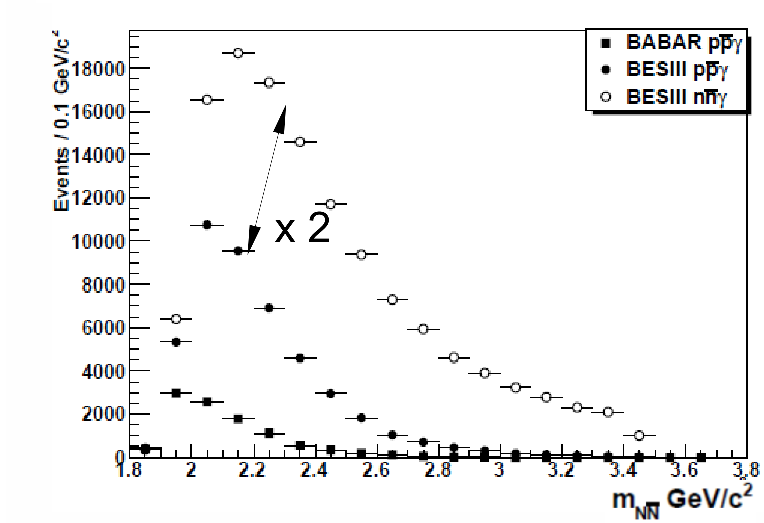


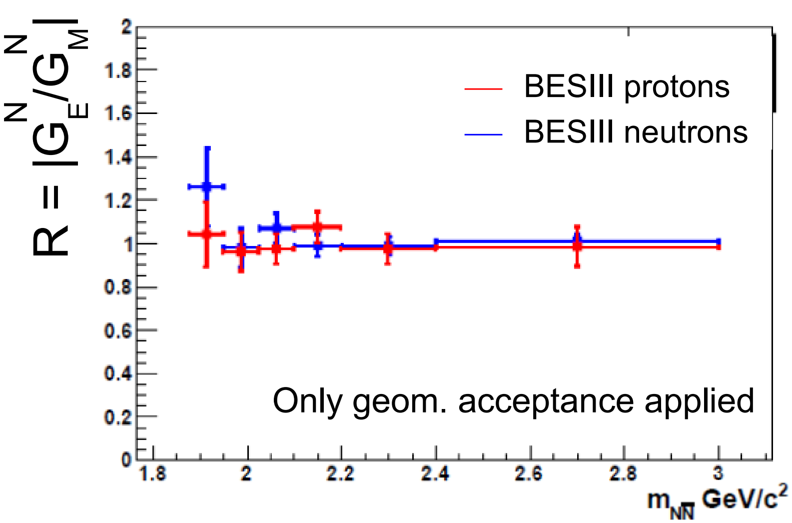
$e^+e^- \rightarrow n\,\bar{n}\,\gamma_{ISR}$

- **Only one measurement from Fenice with 74 signal events** (0.4 pb^{-1}around $\sqrt{s}=2m_n$) using $e^+e^- \rightarrow n\bar{n}$
- **BESIII expects x2 more statistics than for the proton channel (10fb^{-1}@ $\sqrt{s}$=3.770 GeV)**
- ✯ **30% Efficiency in the $\bar{n}$ identification** in $J/\psi \rightarrow n\bar{n}$ publication by BESIII







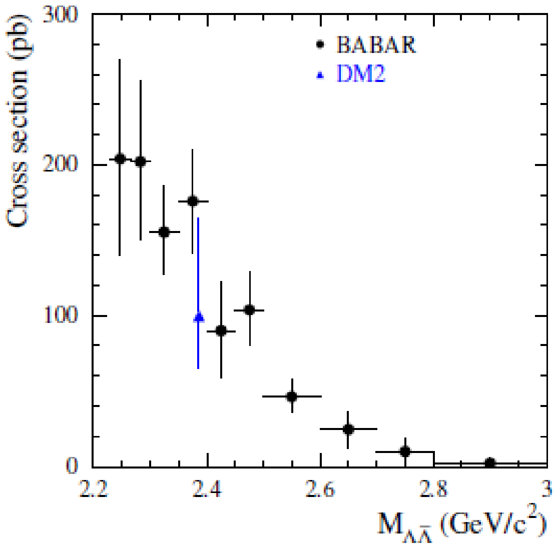


$$e^+e \rightarrow \Lambda\,\bar{\Lambda}\,\gamma_{ISR}\ ,\ \Lambda\,\bar{\Sigma}\,\gamma_{ISR}\ ,\ \Sigma\,\bar{\Sigma}\,\gamma_{ISR}$$

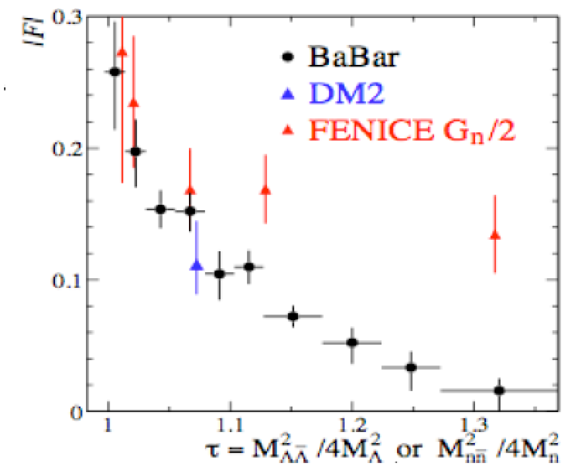
$e^+e^- \to \Lambda\bar{\Lambda}\gamma_{ISR}$

[B. Aubert et al., Phys. Rev. D 76, 092006 (2007)]

About 350 $\Lambda\bar{\Lambda}\gamma_{ISR}$ events with $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ found in 232 fb^{-1} at $\sqrt{s}$ = 10.57 GeV by BaBar



- Only one measurement before by DM2
- **Cross section roughly flat at threshold** and **possibly not vanishing** even thogh no Coulomb correction for neutral baryons production
- However, large error bars do not exclude $\sigma_{threshold} = 0$



- **Rise of FFs close to threshold** observed also in this case
- Fit with $f = K/q^n$ gives n= 9.2 ±0.3
  - pQCD asymptotic prediction (q^4) reached at 3GeV first
- F_Λ in agreement with DM2 and with F_n by Fenice

$e^+e^- \to \Lambda\bar{\Lambda}\gamma_{ISR}$

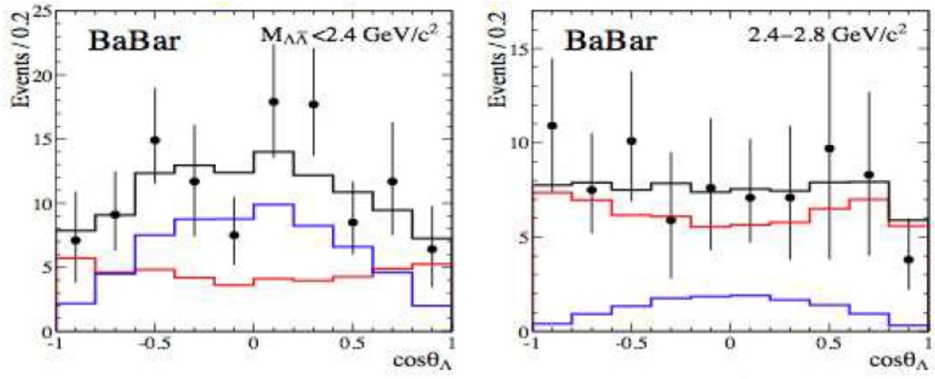
[B. Aubert et al., Phys. Rev. D 76, 092006 (2007)]

- **Ratio of form factors extracted from analysis of angular distribution of lambda helicity angle**

  Two $m_{\Lambda\Lambda}$ bins analyzed

  $(2.23\text{–}2.40\ \mathrm{GeV})/c^2 \qquad |G_E^\Lambda/G_M^\Lambda| < 1.73^{+0.99}_{-0.57}$

  $(2.40\text{–}2.80\ \mathrm{GeV})/c^2 \qquad |G_E^\Lambda/G_M^\Lambda| < 0.71^{+0.66}_{-0.71}$

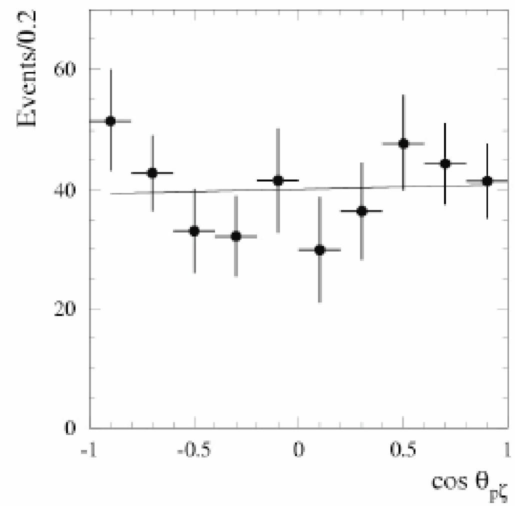


  - Results compatible with $|G_E^\Lambda/G_M^\Lambda| = 1$, but with large uncertainties

- **Polarization** tested by fitting slope of angle between lambda polarization axis and proton momentum in Λ rest frame

$$\frac{dN}{d\cos\theta_{p\zeta}} = A(1 + \alpha_\Lambda \zeta_f \cos\theta_{p\zeta})$$

$$\Longrightarrow -0.22 < \zeta_f < 0.28 \quad (90\%\ \mathrm{CL})$$



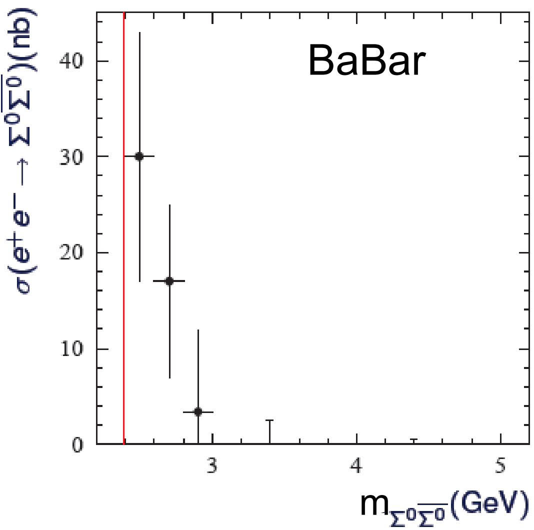
Under $|G_E^\Lambda| = |G_M^\Lambda|$ assumption, tests a **non-zero relative phase** between G_E^Λ and G_M^Λ:

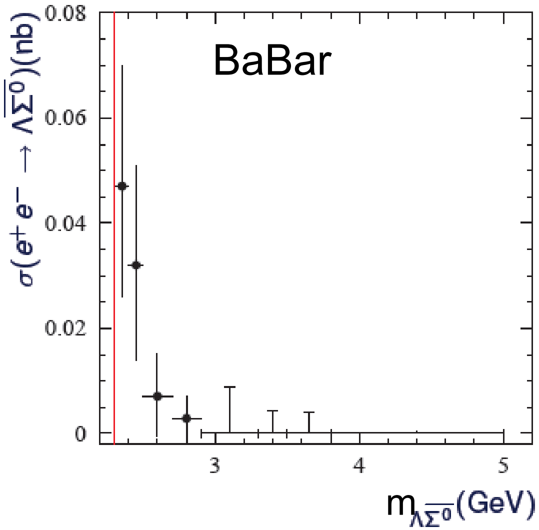
$$-0.76 < \sin\phi < 0.98$$

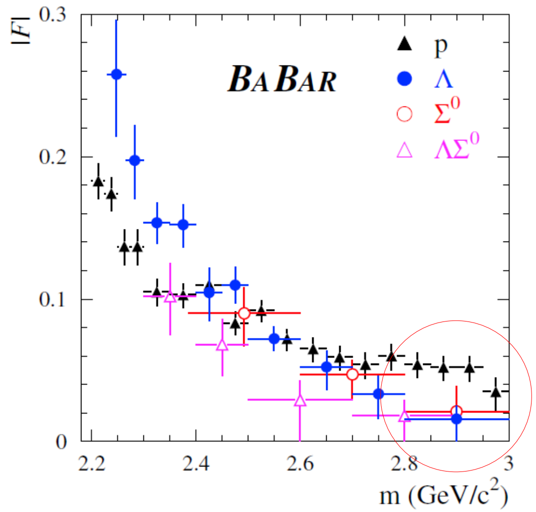
[B. Aubert et al., Phys. Rev. D 76, 092006 (2007)]

BaBar performed first measurement ever for these channels

Reconstructed Σ baryon in decay channels $\Sigma \to \Lambda\gamma$ and $\Lambda \to p\pi$: few tens of signal events in 232fb^{-1} at $\sqrt{s}$=10.57 GeV







- $\sigma(e^+e^- \to \Sigma^0\overline{\Sigma^0})$ is different from zero at threshold, being 0.030 ± 0.013 nb
- $\sigma(e^+e^- \to \Lambda\overline{\Sigma^0})$ is different from zero at threshold, being 0.047 ± 0.022 nb

QCD predictions:

$$F_\Lambda/F_p = 0.24$$
$$F_\Sigma/F_\Lambda = -1.18$$
$$F_{\Sigma\Lambda}/F_\Lambda = -2.34$$

- Effective |F| shows same rising behavior
- Data seem to agree with theory only for F_Σ/F_Λ (by accident?)
- F_Λ/F_p decrease with energy, similar to prediction close to 3 GeV

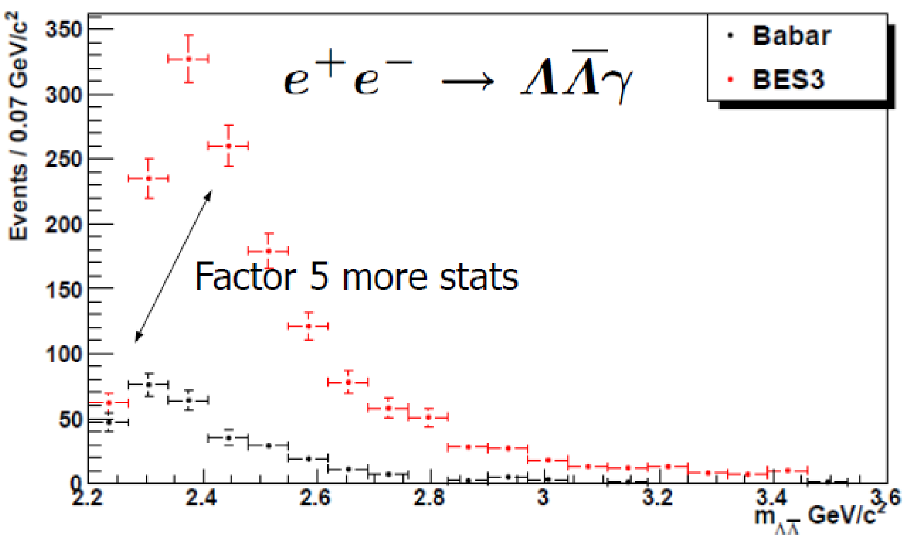
[Chernyak et al. Z. Phys. C 42, 569 (1989)]

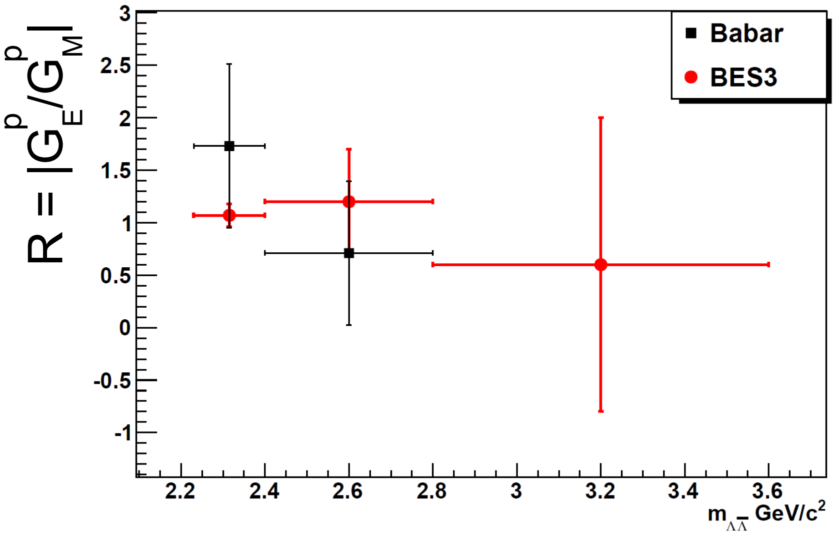
$e^+e^- \to \Lambda\bar{\Lambda}\gamma_{ISR}, \Lambda\bar{\Sigma}\gamma_{ISR}, \Sigma\bar{\Sigma}\gamma_{ISR}$

What could BES-III do for this channel?

[H.Czyz,A.Grzelinska,J.H.Kühn,Phys.Rev. D75:074026 (2007)]

- BES-III (10fb-1 @ 3.770 GeV) expects about 5 times more stats in e+e- → $\Lambda\bar{\Lambda}\gamma$ than BaBar (232 fb-1 @ 10.57 GeV)





- The resolution of $|G_E^\Lambda/G_M^\Lambda|$ in the first two bins could be improved by a factor 4 and 2 correspondingly and also the measurement of the phase difference

- Assuming statisics in $e^+e \to \Lambda\bar{\Sigma}\gamma_{ISR}, \Sigma\bar{\Sigma}\gamma_{ISR}$ also increase by a factor 5, BESIII could provide a similar improvement in |F| resolution than for the case of Λ

Conclusions

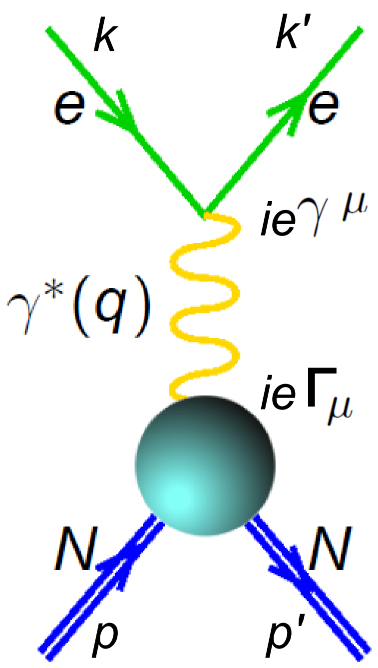
- BaBar and BESIII show the power of ISR method for measuring baryon FFs
- **Precise results from BaBar obtained via ISR** but several effects remain to be understood
- BESIII will bring some light on these issues with higher statistics using ISR and a dedicated energy scan near baryon thresholds
- **No dedicated experiments planned**. Nucleon structure can be studied in several operating or planned facilities (VEPP-2000, BELLE, super B-factories...)
- Feasibility studies on the measurement of proton FFs in $p\bar{p} \rightarrow e^+e^-$ in **PANDA** predict a **factor 10 improvement** in the current resolution of ratio of em FFs and $\sigma(p\bar{p} \rightarrow e^+e^-)$ will be measured up to $q^2 = 28\ (\mathrm{GeV}/c)^2$ + great statistics at theshold!!

Eur. Phys. J. A **44**, 373–384 (2010)

Thank you for your attention

Electromagnetic Form Factors

- Account for the non point-like structure of hadrons
- Are **fundamental hadron structure observables**:
  - **At low Q^2**: **charge distribution** and **magnetization**
  - **At higher Q^2**: **dynamics, quark distribution**



N = spin ½ baryon

Vector current, **two form factors** (F_1 and F_2)

$$\Gamma_{\mu} = e\bar{u}(p')[F_1(q^2)\gamma_{\mu} + \frac{\kappa}{2M_N}F_2(q^2)i\sigma_{\mu\nu}q^{\nu}]u(p)e^{iqx}$$

Dirac	**Pauli**
$F_1^p(q^2=0)=1$	$F_2^p(q^2)=1$
$F_1^n(q^2=0)=0$	$F_2^n(q^2)=1$

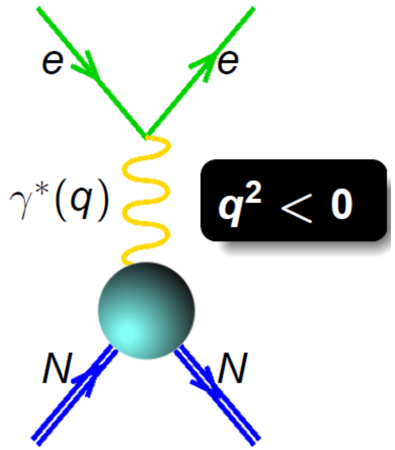
Sachs

$$G_E = F_1 + \frac{\kappa q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2$$

Electromagnetic Form Factors

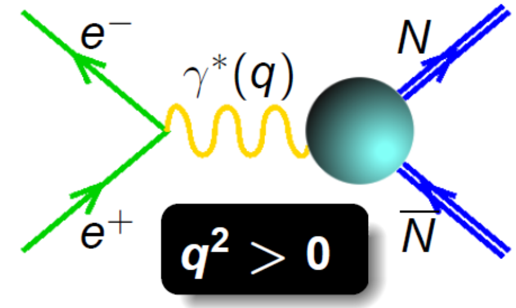
Space-like

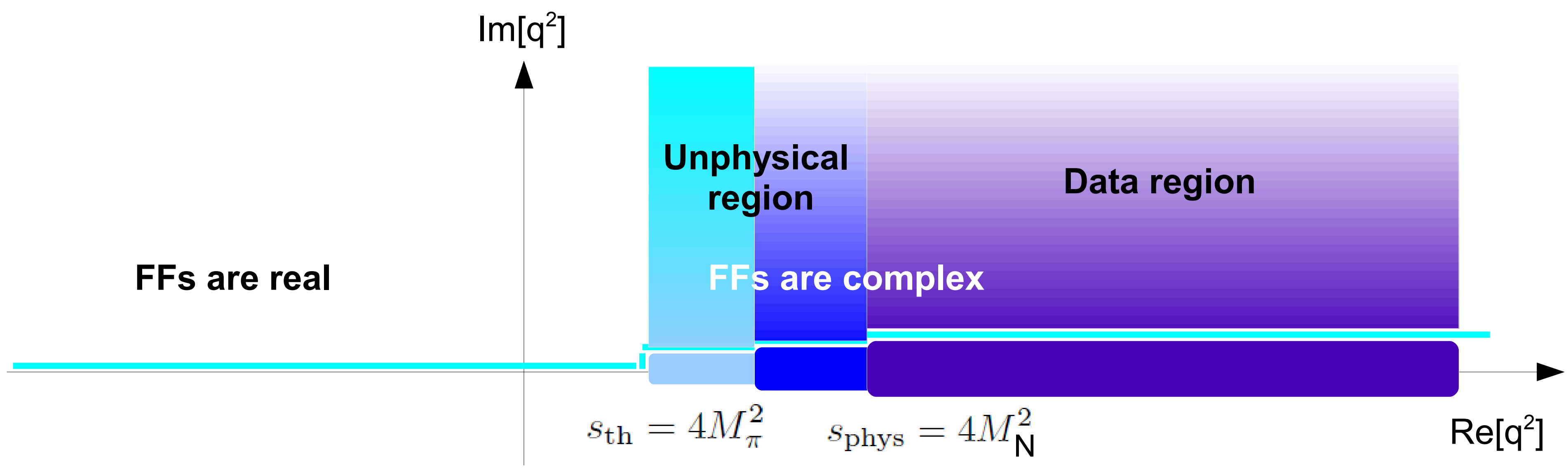
$eN \longrightarrow eN$



Time-like

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





$$G_E(4M_N^2) = G_M(4M_N^2)$$

Electromagnetic Form Factors

- **Dispersion relations connect space and time-like regions**
- **Perturbative QCD constrains the asymptotic behaviour** [Matveev,Muradyan,Tevkheldize,Farrar, Brodsky-Lepage,...]

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

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

(analiticty)

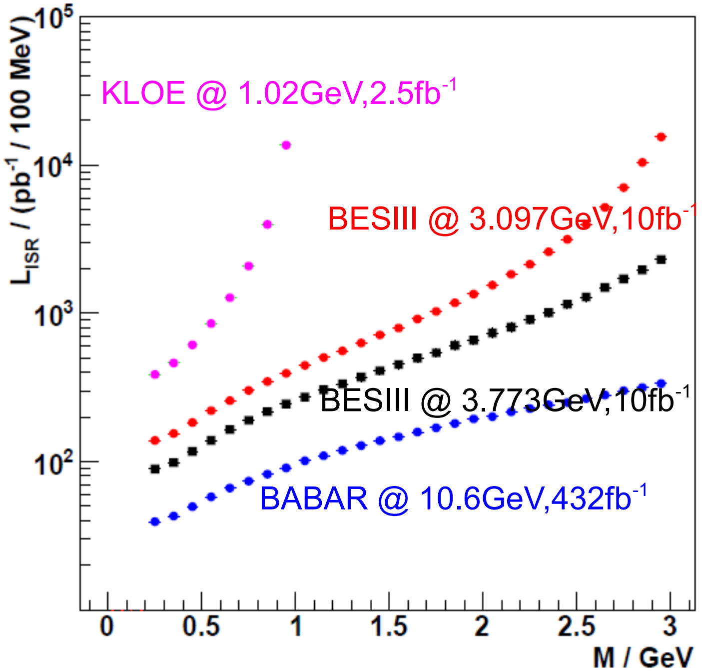
Why time-like (TL) form factors (FFs)?

- **To test theory relations beween space-like and time-like processes**
- **Precise knowledge of FFs needed** by many experiments and phenomenological models
- **To test pQCD** expanding the Q^2 kinematical domain up to soft-hard transition region (10 – 15 $(\mathrm{GeV}/c)^2$)

ISR pros and cons

Advantages

- Low σ_{ISR} **compensated by high luminosity** of b,c factories!!
- Same observables as dedicated experiments at low energies and within higher ranges
- Comes for free, no need for a dedicated experiment
- All q at the same time: **better control of point to point sytematics**
- High luminosity also at threshold
- **Acceptance at threshold ≠ 0**
- Detection efficiency almost independent of q^2 and angular distribution



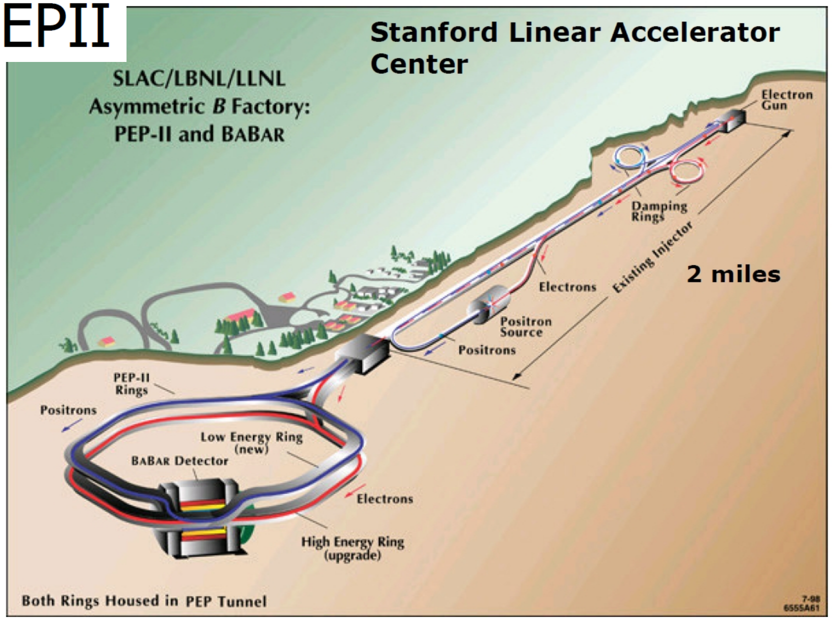
[Ch. Zimmermann, Diplomarbeit. Mainz 2011]

Drawbacks

- Luminosity proportional to bin width
- More backgrounds

PEPII / BEPCII

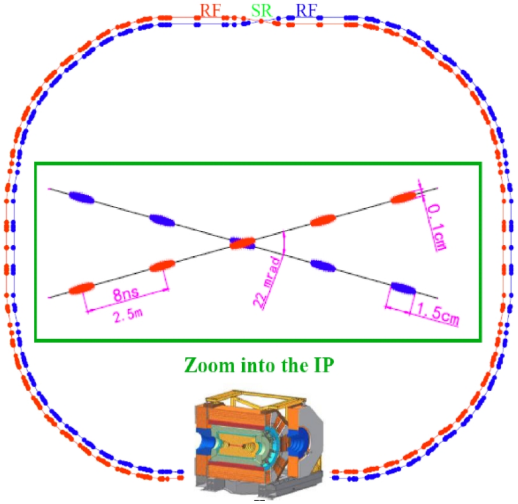
PEPII



	Design
E [GeV] e^- / e^+	9.0 / 3.1
I [mA] e^- / e^+	610 / 2140
L [$cm^{-2}\,s^{-1}$]	3×10^{33}
L_{int} [pb^{-1}/day]	135

- Asymmetric energy collider: $\beta\gamma = 0.56$ (for time dependent CP studies)
- Luminosity collected (1999-2008): 530 fb^{-1}
- Luminosity used for ISR publications: 232 fb^{-1} at $\sqrt{s}$ = 10.57 GeV

BEPCII



Beam energy: 1.0 – 2.3 GeV

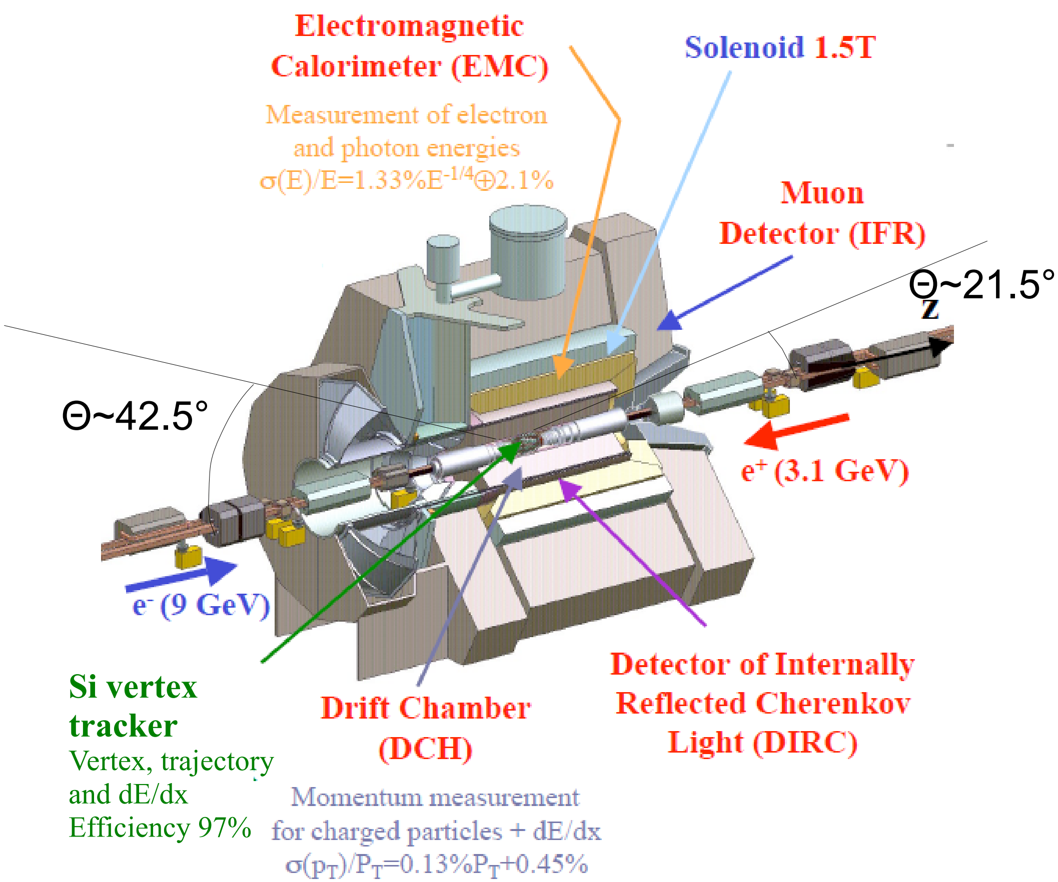
Peak Luminosity:

Design: 1×10^{33} $cm^{-2}s^{-1}$

- Luminosity collected at ψ''(3770) = 2.9 fb^{-1}
- Luminosity aimed at ψ''(3770) = 10 fb^{-1}
- Data at other energies can also be used
- Data from newly started R-Scan 2-3GeV

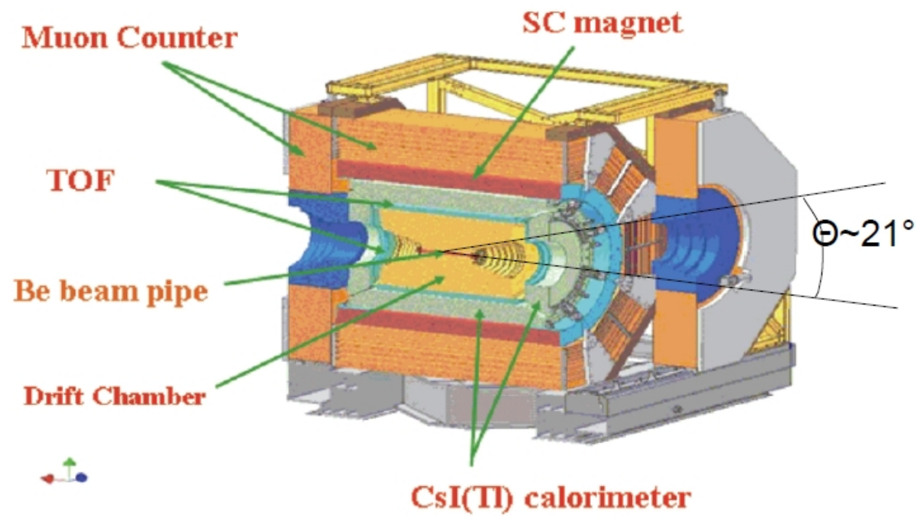
BABAR / BESIII

BaBar Collaboration Home Page



Typical resolutions: **$\sigma(J/\psi)$ = 12 MeV, $\sigma(\pi^0)$ = 6.5 MeV**

BES-III



MDC: main drift chamber (He 60% + propane 40%):
$\sigma(p)/p < 0.5\%$ for 1GeV tracks, $\sigma(xy)$ = 130 μm
$\sigma(dE/dx)/(dE/dx) < 6\%$

TOF: time of flight (two layers plastic scintillator):
$\sigma(t) < 90$ ps

EMC: Cs I(Tl), barrel+2 end caps:
$\sigma(E)/E < 2.5$ %, $\sigma(x) < 6$mm for 1 GeV e-

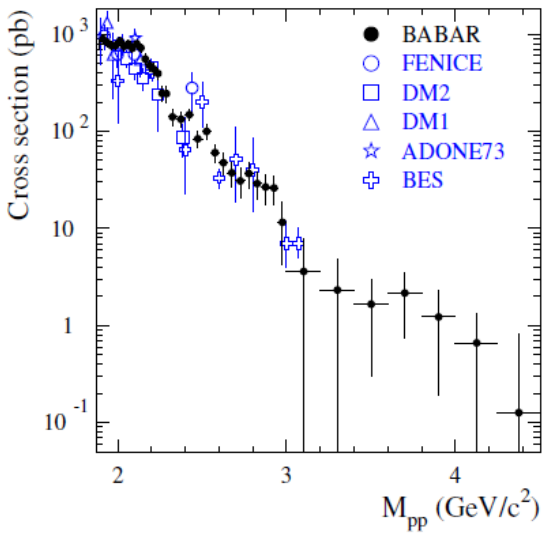
MUC: time of flight (RPC): $\sigma(xy) < 2$ cm

Typical resolutions: **$\sigma(J/\psi)$ = 9 MeV , $\sigma(\pi^0)$ = 5 MeV**

$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]

Publication based on 232 fb^{-1} at $\sqrt{s}$=10.57 GeV. 4025 selected ISR signal events with 6% $e^+e^- \to p\bar{p}\pi^0$

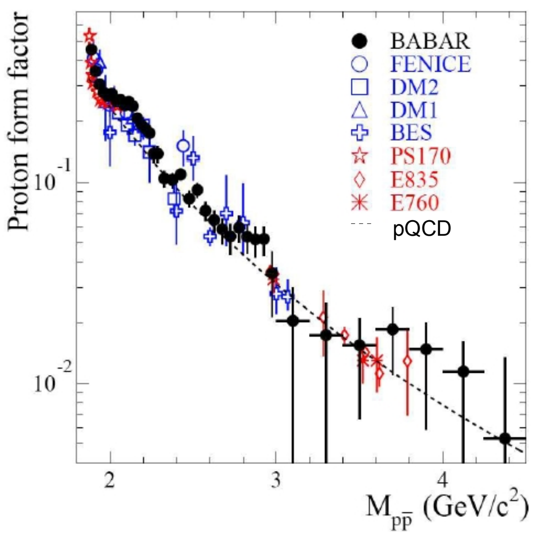


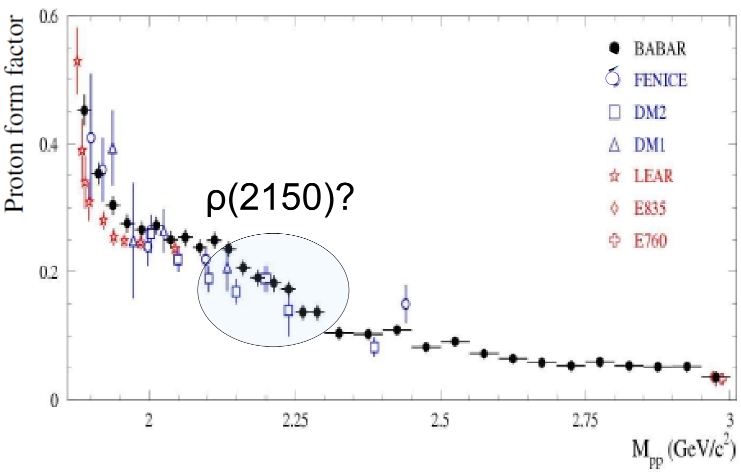
$$\sigma(m_{p\bar{p}}) = \frac{dN/dm_{p\bar{p}}}{\varepsilon R\, dL/dm_{p\bar{p}}} = \frac{4\pi\alpha^2\beta C}{3q^2}\left[\underbrace{|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2}_{\text{Effective proton FF}}\right]$$

- peak at threshold
- plateau from 1.8 to 2.1 GeV/c^2
- decrease with drops at 2.25 (ρ(2150)?) and 3 GeV/c^2 (baryon thresholds? S-wave states open up quickly?)

- **Separation between $G_E(q^2)$ and $G_M(q^2)$ not possible !!**

- **Effective form factor extracted from cross section measurement**



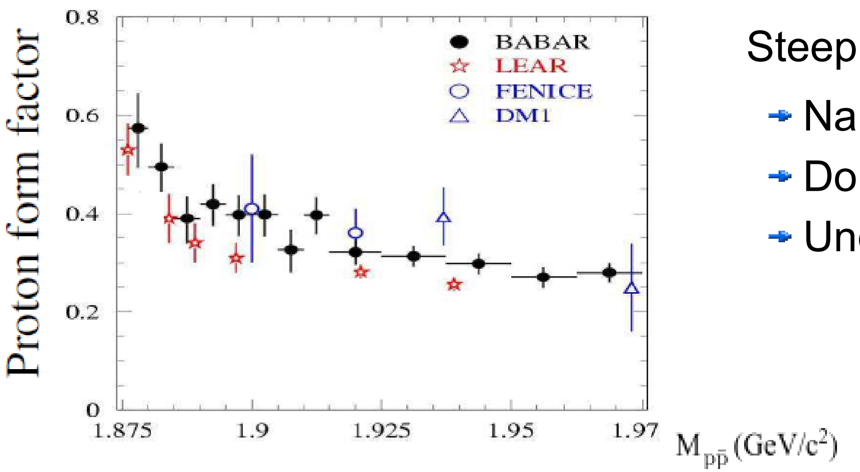


pQCD holds well for all $m_{p\bar{p}}$ but at high $m_{p\bar{p}}$ **is a factor 2 greater than in space like region !!**

$e^+e^- \rightarrow p\,\bar{p}\,\gamma_{ISR}$

What happens at threshold?

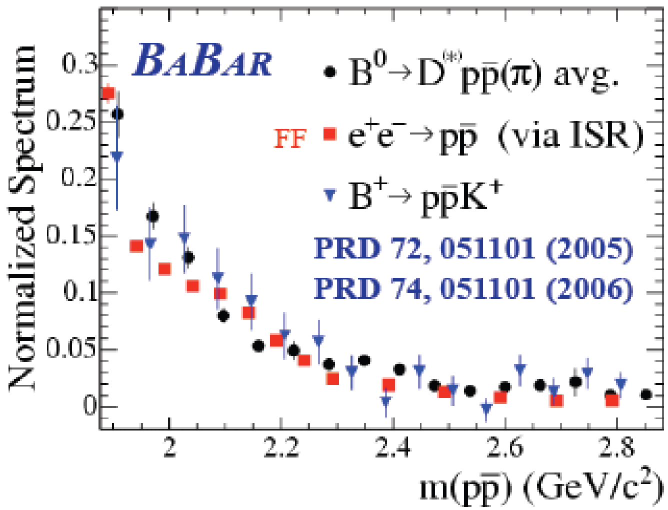
[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]



Steep rise at threshold seen by both PS170 and BaBar

- Narrow **resonance** below threshold? → Baryonium
- Dominance of pion exchange in **Final State Interaction**?
- Underestimation of **Coulomb factor**?

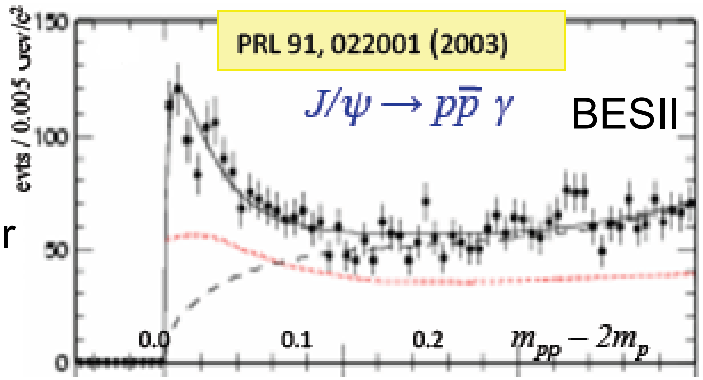
- **Similar behavior observed in $m_{p\bar{p}}$ in processes with different dynamics**:



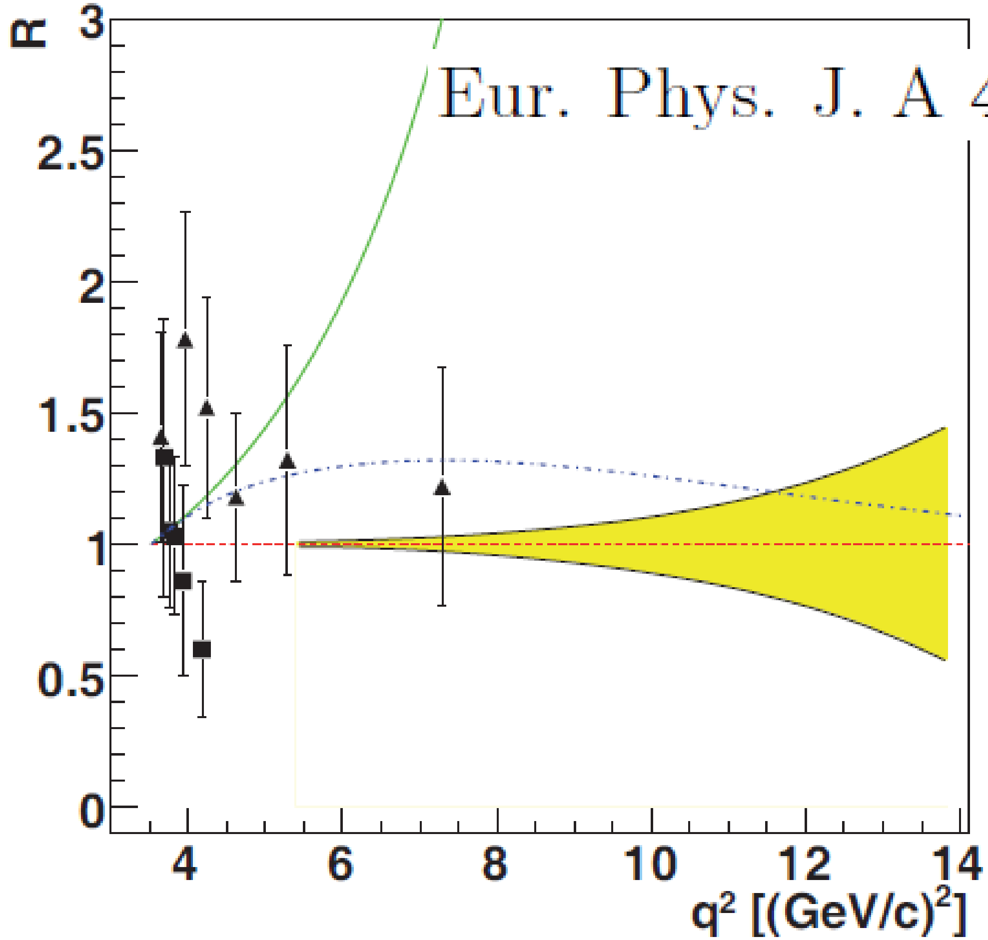
BELLE

PRL 88, 181803 (2002)
PRL 89, 151802 (2002)

BESIII confirms behavior in radiative ψ'



R @ PANDA

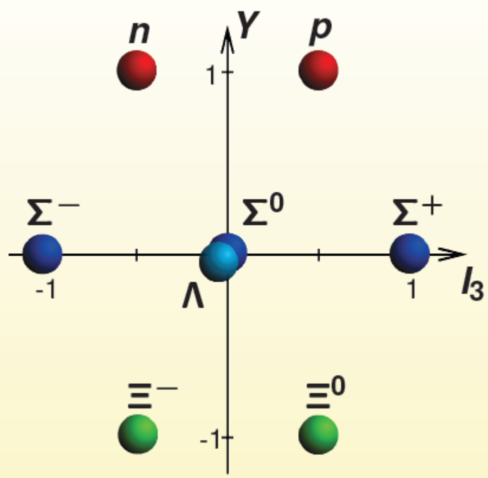


Eur. Phys. J. A **44**, 373–384 (2010)

Fig. 7. (Color online) Expected statistical precision on the determination of the ratio $\mathcal{R}$, (yellow band) for $\mathcal{R} = 1$, as a function of q^2, compared with the existing data from refs. [24] (triangles) and [23] (squares). Curves are theoretical predictions (see text).

Baryon octet and U-spin

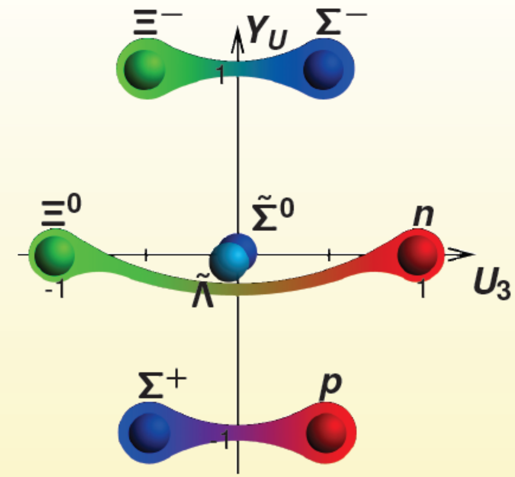
Baryon octet and U-spin



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

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

$$Y_U = -Q$$



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

U-spin direct relations

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

Tow U-spin indirect relations

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

S. Pacetti

Baryon octet and U-spin

Data and *U*-spin predictions

Theory: *U*-spin indirect relations

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

Data+Coulomb correction at threshold

- $(2.0 \pm 0.7) - 2 \cdot (1.01 \pm 0.16) = \boxed{0.0 \pm 0.7}$
- $(0.41 \pm 0.09) - (1.01 \pm 0.16) + \frac{2}{\sqrt{3}} \cdot (0.50 \pm 0.16) = \boxed{0.0 \pm 0.3}$

Perfect agreement at threshold where the breaking of $SU(3)$ flavor symmetry is partially cancelled

Baryon octet and FFs at threshold

A simple procedure to extract FF's at threshold

- The Coulomb correction for $e^+e^- \longrightarrow \mathcal{B}\overline{\mathcal{B}}$ cross sections is assumed
- The cross sections are finite and non-zero at threshold
- The first data point may be extrapolated down to the threshold

$$\sigma(e^+e^-\!\longrightarrow\mathcal{B}\overline{\mathcal{B}}')\left[(M_{\mathcal{B}}+M_{\mathcal{B}'})^2\right] = \frac{2\pi^2\alpha^3 C_{\mathcal{B}}}{(M_{\mathcal{B}}+M_{\mathcal{B}'})^2}\left|G^{\mathcal{B}\mathcal{B}'}\left[(M_{\mathcal{B}}+M_{\mathcal{B}'})^2\right]\right|^2$$

Coulomb factor: $C_{\mathcal{B}} = \begin{cases} 1 & \text{for charged baryons} \\ 1/2 & \text{for neutral baryons} \end{cases}$

FF's for three neutral channels (BABAR)

$$\left|G^{\Lambda}(4M_{\Lambda}^2)\right| = 1.01 \pm 0.16$$

$$\left|G^{\Sigma^0}(4M_{\Sigma^0}^2)\right| = 0.41 \pm 0.09$$

$$\left|G^{\Lambda\overline{\Sigma^0}}\left[(M_{\Lambda}+M_{\Sigma^0})^2\right]\right| = 0.50^{+0.16}_{-0.12}$$

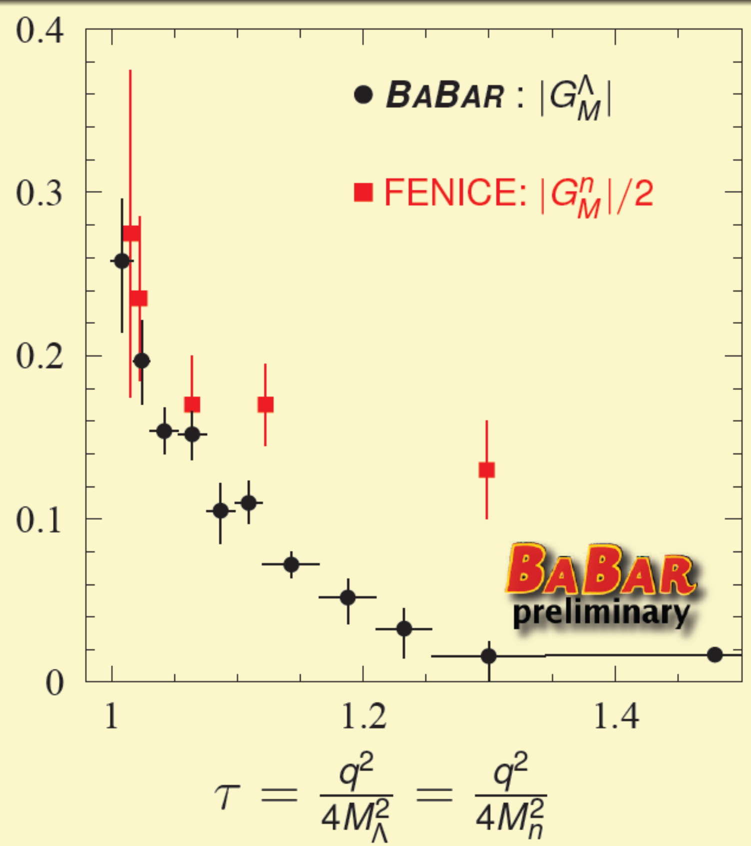
FENICE: $e^+e^- \longrightarrow n\bar{n}$

$$\left|G^{n}(4M_{n}^2)\right| = 2.0 \pm 0.7$$

Baryon octet and FFs at threshold

$|G_M^\Lambda|$ and $|G_M^n|$ comparison through U-spin

U-spin $\Longrightarrow G_M^\Lambda = G_M^n/2$



Additional corrections are needed to account for the $SU(3)$ flavor symmetry breaking

Extraction of FFs

Two approaches:

- From cross section

1) **Select $e^+e^- \rightarrow X_{had}\, \gamma_{ISR}$** events and **measure $\sigma(e^+e^- \rightarrow X_{had})$**:

\# signal in mass bin
(after acceptance and resoution)

center value of $p\bar{p}$ mass bin

$$\sigma(m_{had}) = \frac{dN/dm_{had}}{\varepsilon\, R\; dL/dm_{had}} = \frac{4\pi\alpha^2\beta C}{3\,q^2}\left[\left|G_M(q^2)\right|^2 + \frac{1}{2\tau}\left|G_E(q^2)\right|^2\right]$$

efficiency of reconstruction
and radiative corrections in mass bin

ISR differential luminosity
From: 1) L_{int} * W(x)
2) $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$

$|F(q^2)|^2$

2) **Extract** effective form factor **$F(q^2)$**

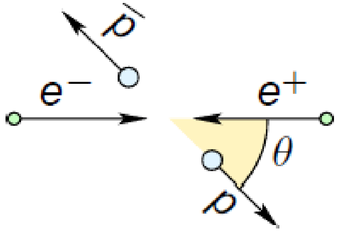
3) **Assume $\mu \cdot |G_E| = |G_M|$** and identify **$F = G_M(q^2)$**

- Used in e+e- colliders at low energies and if low stats available
- **Separation between $G_E(q^2)$ and $G_M(q^2)$ not possible !!**

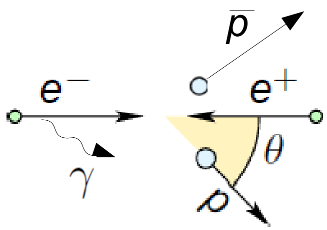
Extraction of FFs

- From angular analysis: $|G_E/G_M|$

  1) **Analyze** distribution of **proton helicity angle** in $p\bar{p}$ rest frame



$$\boxed{\frac{d\sigma}{d(\cos\theta)} = \frac{\pi\alpha_e^2 C}{8M^2\tau\sqrt{\tau(\tau-1)}}\left[\tau|G_M|^2(1+\cos^2\theta) + |G_E|^2\sin^2\theta\right]}$$



$$\frac{dN}{d\cos\theta'_p} = A\left(H_M(\cos\theta'_p, m_{pp}) + \left|\frac{G_E}{G_M}\right| H_E(\cos\theta'_p, m_{pp})\right)$$

No analytic form: extracted from MC

  2) Angular distribution analized **in bins of $q^2 = m^2_{pp}$ and fitted** with previous equation with two free parameters: **A and $|G_E/G_M|$**

→ **Separation between $G_E(q^2)$ and $G_M(q^2)$ without any assumption possible** if high stats and precise luminosity measurement

$e^+e^- \to p\,\bar{p}\,\gamma_{ISR}$

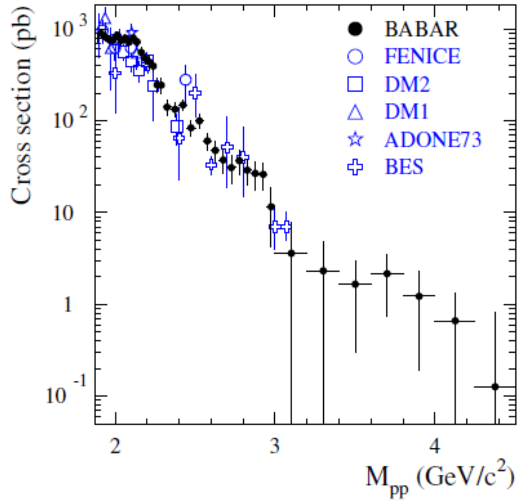
[BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D 73, 012005 (2006)]

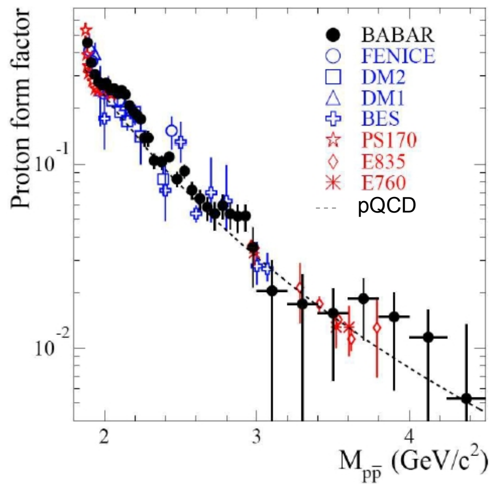
Publication based on 232 fb-1

4025 selected signal events with 6% $e^+e^- \to pp\pi^0$

- **Effective form factor** **extracted from cross section measurement**

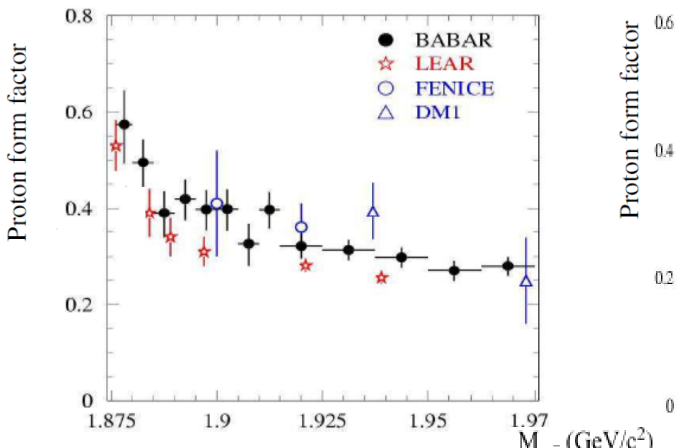
$$\sigma = \frac{4\pi\alpha^2\beta C}{3m_{p\bar{p}}^{\;2}}|F|^2$$

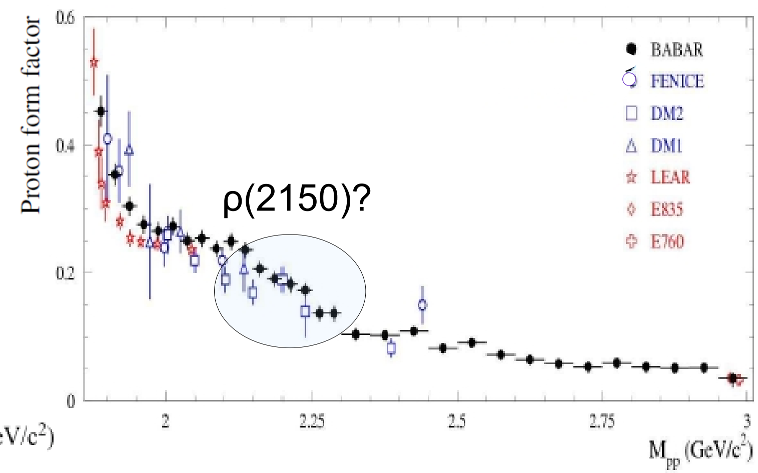




High statistics unveils:

- peak at threshold
- plateau from 1.8 to 2.1 GeV/c^2
- decrease with drops at 2.25 (ρ(2150)?) and 3 GeV/c^2 (baryon thresholds? S-wave states open up quickly?)





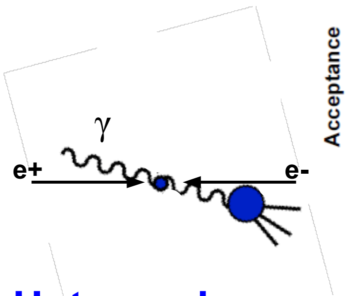
pQCD holds well for all m_{pp} but at high m_{pp} **is a factor 2 greater than in space like region !!**

ISR @ BABAR / BESIII

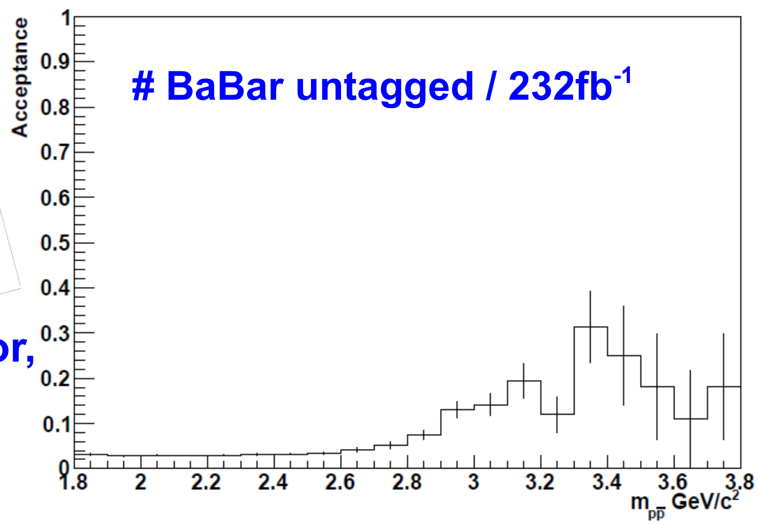
Geometrical acceptance:

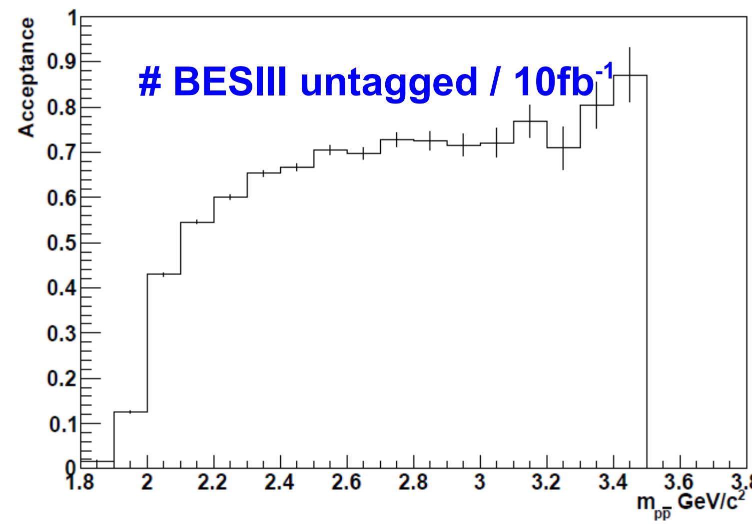
$M_{hadr} << \sqrt{s} \rightarrow$ need high luminosities
Photon tagging unavoidable

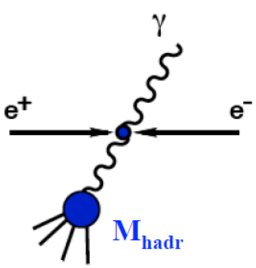
M_{hadr} < but close to $\sqrt{s}$
untagged measurement possible



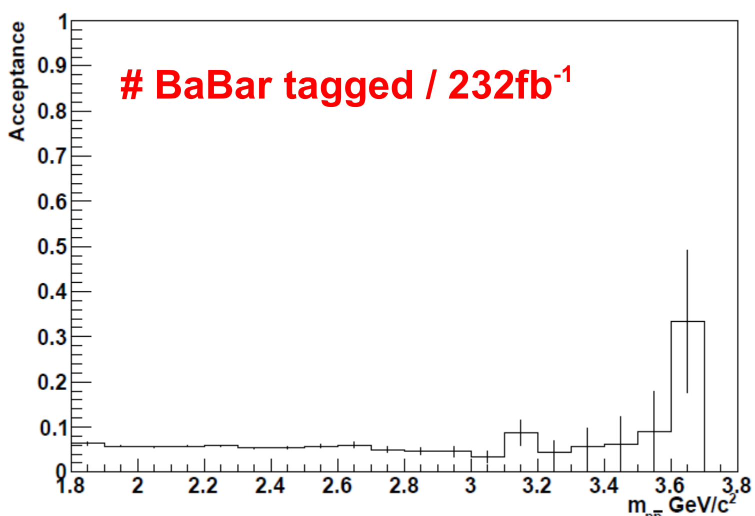
Untagged γ:
γ not in detector, hadrons in detector

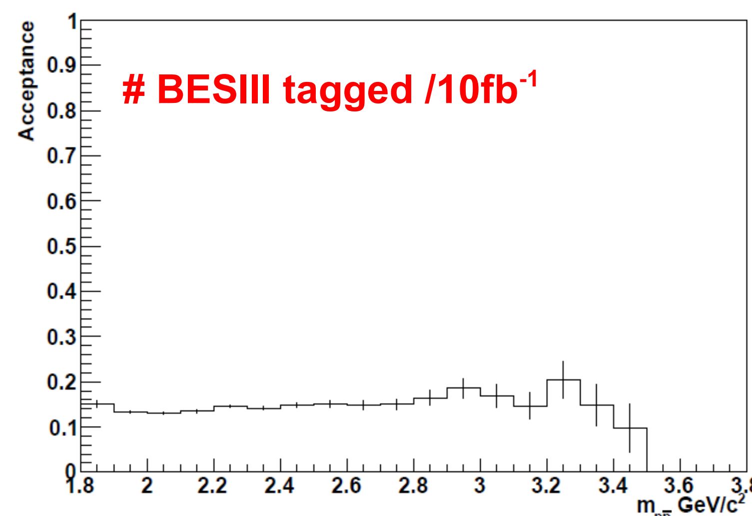




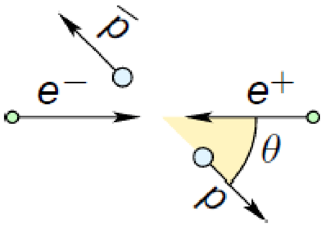


Tagged γ:
γ and hadrons in detector





Time-like em Form Factors

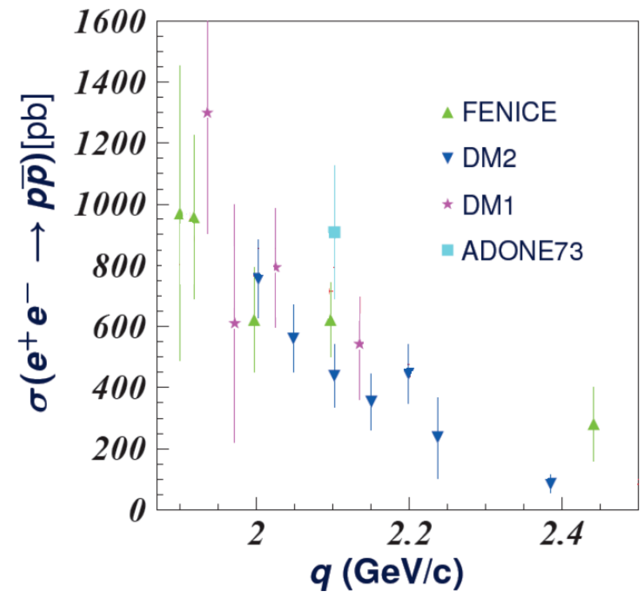


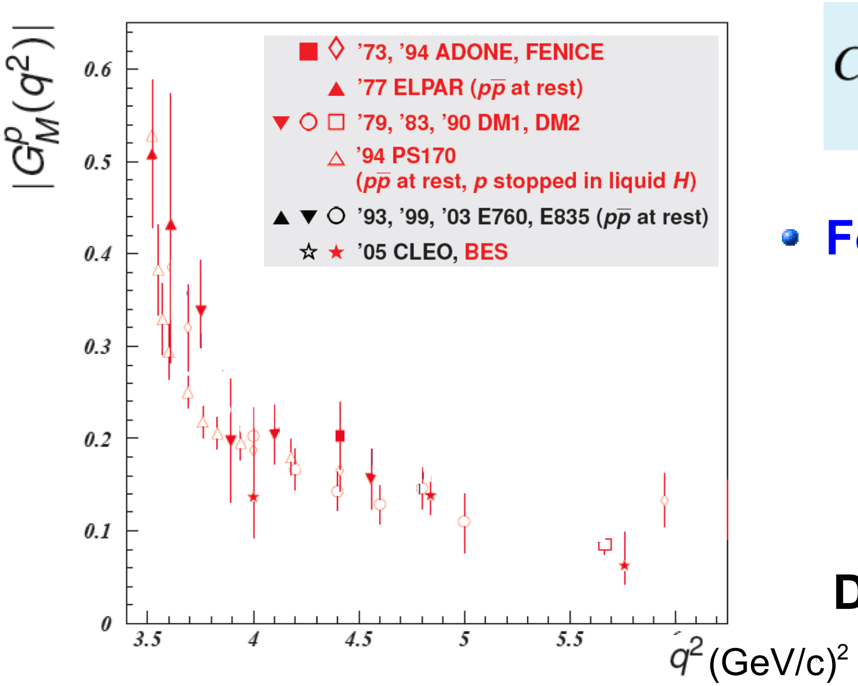
- Only **measurements of cross sections** available

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

C: Coulomb interaction correction at threshold

$$C = \frac{y}{1-e^{-y}}; \quad y = \frac{\pi\alpha M}{\beta q}$$





- **Form factors** extracted under **assumption**:

$$\mu_p \cdot |G_E| = |G_M| = |G^p|$$

$$|G^p|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\frac{16\pi\alpha^2 C}{3}\frac{\sqrt{1-1/\tau}}{4q^2}(1+1/2\tau)}$$

Due to low statistics: no true separation of G_E and G_M

BABAR / BESIII Data

Status:

BaBar publications on ISR in baryons:

- 2 baryons $e^+e^- \to p\bar{p}$ PRD 73 (2006) 012005
- 2 hyperons $e^+e^- \to \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$ PRD 76 (2007) 092006

based on 232 fb^{-1}. Analysis of remaining statistics (x2) ongoing.

BESIII available data which could be used for Baryon FFs analysis:

- 1225M J/Ψ
- 106M + 8pb^{-1} $\Psi(3686)$
- 2.9 fb^{-1} $\Psi(3770)$
- 0.5 fb^{-1} $\Psi(4040)$
- R-scan 2–3GeV in 100 MeV bins with 10^5 hadrons/bin planned

- For this presentation BaBar's published 232 fb^{-1} at Y(4S) will be shown and compared with BESIII simulations for 10fb^{-1} at Ψ''
- Generator used for all ISR channels: PHOKHARA 7.0

[H.Czyz,A.Grzelinska,J.H.Kühn,Phys.Rev. D75:074026 (2007)]
[H.Czyz,J.H.Kühn,E.Nowak,G.Rodrigo,Eur.Phys.J C35,527 (2004)]

Coulomb correction for quarks

Coulomb correction at quark level

$p\overline{p}$ case

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

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

Cross section data		Form factors
$\sigma(e^+e^- \to p\overline{p})(4M_p^2) = (0.85 \pm 0.05)\ nb$	$\Rightarrow$	$\|G^p(4M_p^2)\| \sim 1$

$\Lambda\overline{\Lambda}$ case

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

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

Cross section data		Form factors
$\sigma(e^+e^- \to \Lambda\overline{\Lambda})(4M_\Lambda^2) = (0.20 \pm 0.05)\ nb$	$\Rightarrow$	$\|G^\Lambda(4M_\Lambda^2)\| \sim 1$

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FFs at threshold

A simple procedure to extract FF's at threshold

- The Coulomb correction for $e^+e^- \longrightarrow \mathcal{B}\overline{\mathcal{B}}$ cross sections is assumed
- The cross sections are finite and non-zero at threshold
- The first data point may be extrapolated down to the threshold

$$\sigma(e^+e^-\rightarrow\mathcal{B}\overline{\mathcal{B}}')\left[(M_{\mathcal{B}}+M_{\mathcal{B}'})^2\right] = \frac{2\pi^2\alpha^3 C_{\mathcal{B}}}{(M_{\mathcal{B}}+M_{\mathcal{B}'})^2}\left|G^{\mathcal{B}\mathcal{B}'}\left[(M_{\mathcal{B}}+M_{\mathcal{B}'})^2\right]\right|^2$$

Coulomb factor: $C_{\mathcal{B}} = \begin{cases} 1 & \text{for charged baryons} \\ 1/2 & \text{for neutral baryons} \end{cases}$

FF's for three neutral channels (BABAR)

$$\left|G^{\Lambda}(4M_{\Lambda}^2)\right| = 1.01 \pm 0.16$$

$$\left|G^{\Sigma^0}(4M_{\Sigma^0}^2)\right| = 0.41 \pm 0.09$$

$$\left|G^{\Lambda\overline{\Sigma^0}}\left[(M_{\Lambda}+M_{\Sigma^0})^2\right]\right| = 0.50^{+0.16}_{-0.12}$$

FENICE: $e^+e^- \longrightarrow n\bar{n}$

$$\left|G^{n}(4M_{n}^2)\right| = 2.0 \pm 0.7$$

S. Pacetti

Coulomb correction

Coulomb correction in $p\bar{p}$ at threshold

Coulomb correction at threshold

$$C = \frac{\frac{\pi\alpha}{\beta}}{1 - \exp\left(-\frac{\pi\alpha}{\beta}\right)} \xrightarrow[\beta\to 0]{} \frac{\pi\alpha}{\beta}$$

This factor compensates for phase space and gives a constant value at threshold

Cross section at threshold $(\beta \to 0,\ \tau \to 1,\ s \to 4M_p^2)$

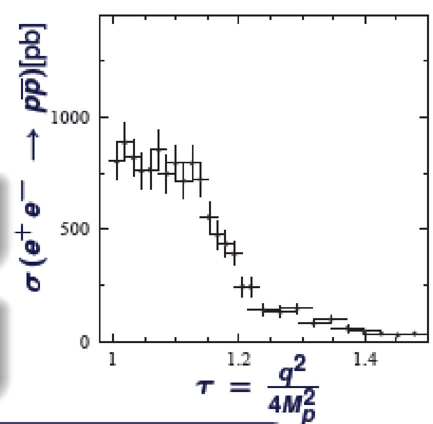
$$\lim_{\text{threshold}} \sigma(s) = \frac{4\pi^2\alpha^3}{3 \cdot 4M_p^2}\,\frac{3}{2}\,|G^p(4M_p^2)|^2 \approx 850\ \text{pb}\ |G^p(4M_p^2)|^2$$

Coulomb correction

$\Downarrow$

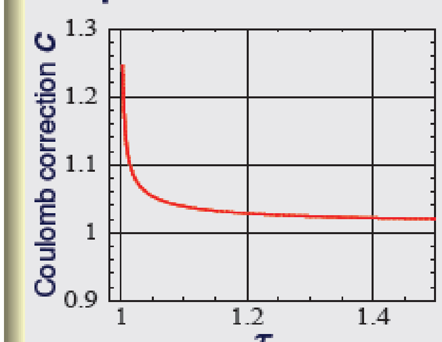
Non-zero value for $\tau = 1$

Data show unexplained plateau



$$|G_E^p(4M_p^2)| \equiv |G_M^p(4M_p^2)| \approx 1$$

The Coulomb correction does not explain the plateau for $\tau > 1$



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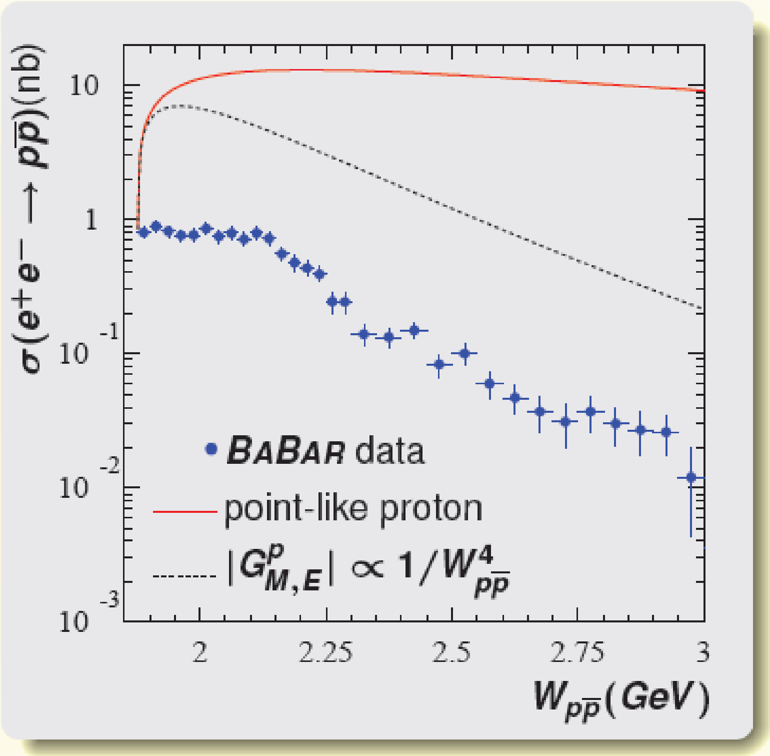
7

ECT* - Trento, May 22, 2008 | Unexpected threshold behavior in $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$

Simple FFs models

Structured form factors



Simple models for FF's

- point-like proton (red curve)

$$G_E^p = G_M^p \equiv 1$$

- pQCD behavior (dashed curve)

$$|G^p_{M,E}| \propto 1/W^4_{p\bar{p}}$$
$$\Downarrow$$
$$\sigma(e^+e^- \to p\bar{p}) \propto 1/W^{10}_{p\bar{p}}$$

Additional factors related to β and non-trivially structured electric and magnetic FF's must be included to reproduce the flat behavior of the data

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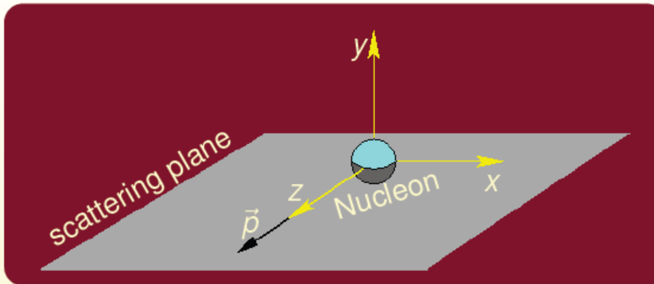
Polarization in TL region

Polarization formulae in the time-like region

The ratio $R(q^2)$ is complex for $q^2 \geq s_{\rm th}$

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

The polarization depends on the phase ρ



Polarization components and single spin asymmetry

$$\mathcal{P}_y = -\frac{\sin(2\theta)|R|\sin(\rho)}{\mu_p D\sqrt{\tau}} = \left\{ \text{Does not depend on } P_e \text{ in } p^{\uparrow}\overline{p} \longrightarrow e^+e^- \right\} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \equiv \mathcal{A}_y$$

$$\mathcal{P}_x = -P_e \frac{2\sin(2\theta)|R|\cos(\rho)}{\mu_p D\sqrt{\tau}}$$

$$\mathcal{P}_z = P_e \frac{2\cos(\theta)}{D} = \left\{ \text{Does not depend on the phase } \rho \right.$$

$$D = 1 + \cos^2\theta + \frac{1}{\tau\mu_p^2}|R|^2\sin^2\theta \qquad \tau = \frac{q^2}{4M_N^2} \qquad P_e = \text{electron polarization}$$

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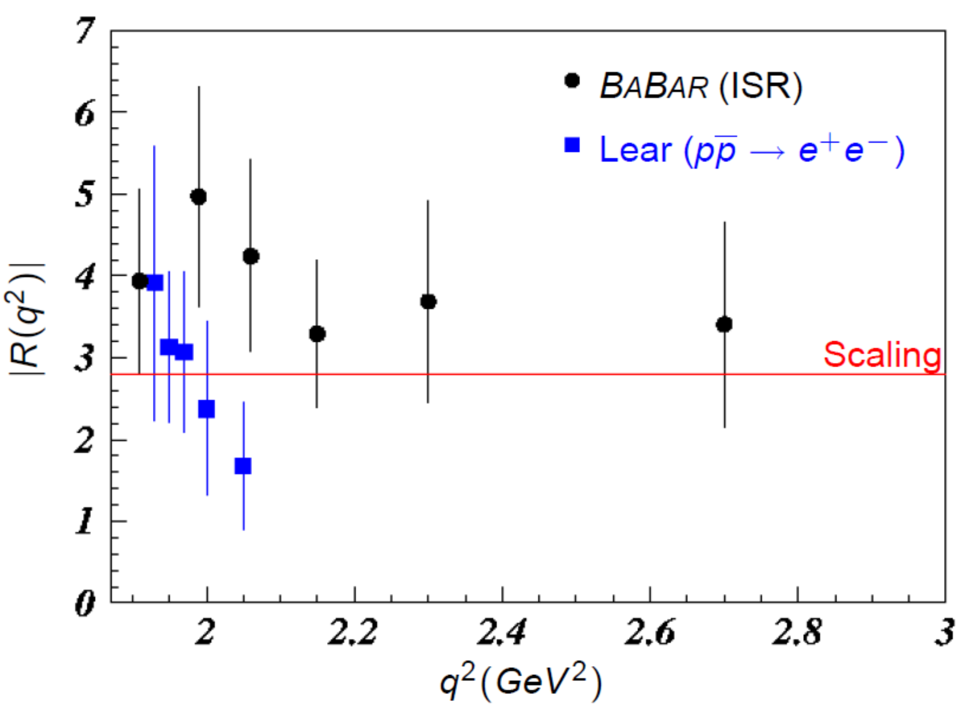
TL region measurements

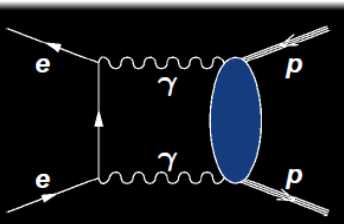
Time-like $|G_E^p/G_M^p|$ measurements

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

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



$\gamma\gamma$ exchange



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

Asymmetry in angular distributions

R. Baldini

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$e^+e^- \to \Lambda\,\bar{\Lambda}\,\gamma_{ISR}$

[H.Czyz,A.Grzelinska,J.H.Kühn,Phys.Rev. D75:074026 (2007)]

$$R_\Lambda = 1 - \alpha_\Lambda\ \bar{S}_\Lambda \cdot \bar{n}_{\pi^-}$$

$$\begin{aligned} d\sigma\left(e^+e^- \to \bar{\Lambda}(\to \pi^+\bar{p})\Lambda(\to \pi^-p)\right) = \\ d\sigma\left(e^+e^- \to \bar{\Lambda}\Lambda\right)\left(S_{\Lambda,\bar{\Lambda}} \to \mp\alpha_\Lambda n_{\pi^\mp}\right) \\ \times\ d\bar{\Phi}_2(q_1;p_{\pi^+},p_{\bar{p}})d\bar{\Phi}_2(q_2;p_{\pi^-},p_p) \\ \times\ \mathrm{Br}(\bar{\Lambda} \to \pi^+\bar{p})\mathrm{Br}(\Lambda \to \pi^-p)\ , \end{aligned}$$

$$\begin{aligned} L^{ij}H_{ij} \simeq \frac{(4\pi\alpha)^3}{4Q^2y_1y_2}\left(1+\cos^2\theta_\gamma\right)\Bigg\{ & |G_M|^2\left(1+\cos^2\theta_{\bar{\Lambda}}\right) + \frac{1}{\tau}|G_E|^2\sin^2\theta_{\bar{\Lambda}} - \alpha_\Lambda\frac{Im(G_MG_E^*)}{\sqrt{\tau}}\sin(2\theta_{\bar{\Lambda}})\left(n^y_{\pi^-} - n^y_{\pi^+}\right) \\ & +\alpha_\Lambda^2\frac{Re(G_MG_E^*)}{\sqrt{\tau}}\sin(2\theta_{\bar{\Lambda}})\left(n^z_{\pi^-}n^x_{\pi^+} + n^z_{\pi^+}n^x_{\pi^-}\right) - \alpha_\Lambda^2\left(\frac{1}{\tau}|G_E|^2 + |G_M|^2\right)\sin^2\theta_{\bar{\Lambda}}\ \ n^x_{\pi^+}n^x_{\pi^-} \\ & -\alpha_\Lambda^2\left(\frac{1}{\tau}|G_E|^2 - |G_M|^2\right)\sin^2\theta_{\bar{\Lambda}}\ \ n^y_{\pi^+}n^y_{\pi^-} + \alpha_\Lambda^2\left(\frac{1}{\tau}|G_E|^2\sin^2\theta_{\bar{\Lambda}} - |G_M|^2\left(1+\cos^2\theta_{\bar{\Lambda}}\right)\right)\ \ n^z_{\pi^+}n^z_{\pi^-}\Bigg\} \end{aligned}$$

APPENDIX: ANGULAR DISTRIBUTIONS AND Λ POLARIZATION IN THE $e^+e^- \to \Lambda\Lambda\gamma$ REACTION

The formulae given in this section are taken from Ref. [3]. The process $e^+e^- \to \Lambda\bar{\Lambda}\gamma$ is considered in the e^+e^- center-of-mass frame, where the electron has momentum $\boldsymbol{p}$ and energy ε, and the photon has momentum $\boldsymbol{k}$ and energy ω. The Λ momentum $\boldsymbol{P}$ is given in the $\Lambda\bar{\Lambda}$ rest frame. The differential cross section summed over the polarization of one of the final particles is given by

$$\mathrm{d}\sigma = \frac{\alpha^3 P \mathrm{d}^3k\mathrm{d}\Omega_\Lambda}{16\pi^2\omega\varepsilon^2Q^3[1-(\mathbf{n}\cdot\boldsymbol{\nu})^2]}\mathcal{A}(1+\boldsymbol{\zeta_f}\cdot\mathbf{s}),\ \ \mathcal{A} = 2|G_M|^2(1+N^2) + \left(\frac{4m_\Lambda^2}{Q^2}|G_E|^2 - |G_M|^2\right)([\mathbf{n}\times\mathbf{f}]^2 + [\mathbf{N}\times\mathbf{f}]^2),$$

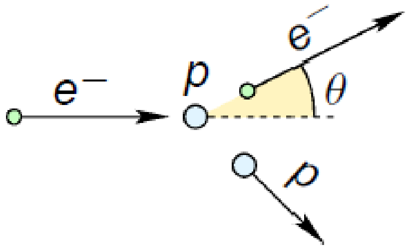
$$\boldsymbol{\zeta_f} = \frac{4m_\Lambda}{Q\mathcal{A}}\mathrm{Im}(G_E^*G_M)\left((\mathbf{n}\cdot\mathbf{f})[\mathbf{n}\times\mathbf{f}] + (\mathbf{N}\cdot\mathbf{f})[\mathbf{N}\times\mathbf{f}]\right);\quad \mathbf{n} = \frac{\mathbf{k}}{\omega},\ \boldsymbol{\nu} = \frac{\mathbf{p}}{\varepsilon},\ \mathbf{N} = \frac{\boldsymbol{\nu} + (\gamma-1)(\mathbf{n}\cdot\boldsymbol{\nu})\mathbf{n}}{\sqrt{\gamma^2-1}},$$

$$N^2 = (\mathbf{n}\cdot\boldsymbol{\nu})^2 + \frac{1}{\gamma^2-1},\ \gamma = \frac{2\varepsilon-\omega}{Q},\ Q = \sqrt{\varepsilon(\varepsilon-\omega)},\ P = |\mathbf{P}| = \sqrt{Q^2/4 - m_\Lambda^2},\ \mathbf{f} = \frac{\mathbf{P}}{P}.$$

Here s and $\boldsymbol{\zeta_f}$ are the spin and polarization vectors of the Λ in its rest frame.

[3] L. V. Kardapoltzev, Bachelor's thesis, Novosibirsk State University, 2007 (unpublished).

Space-like em Form Factors

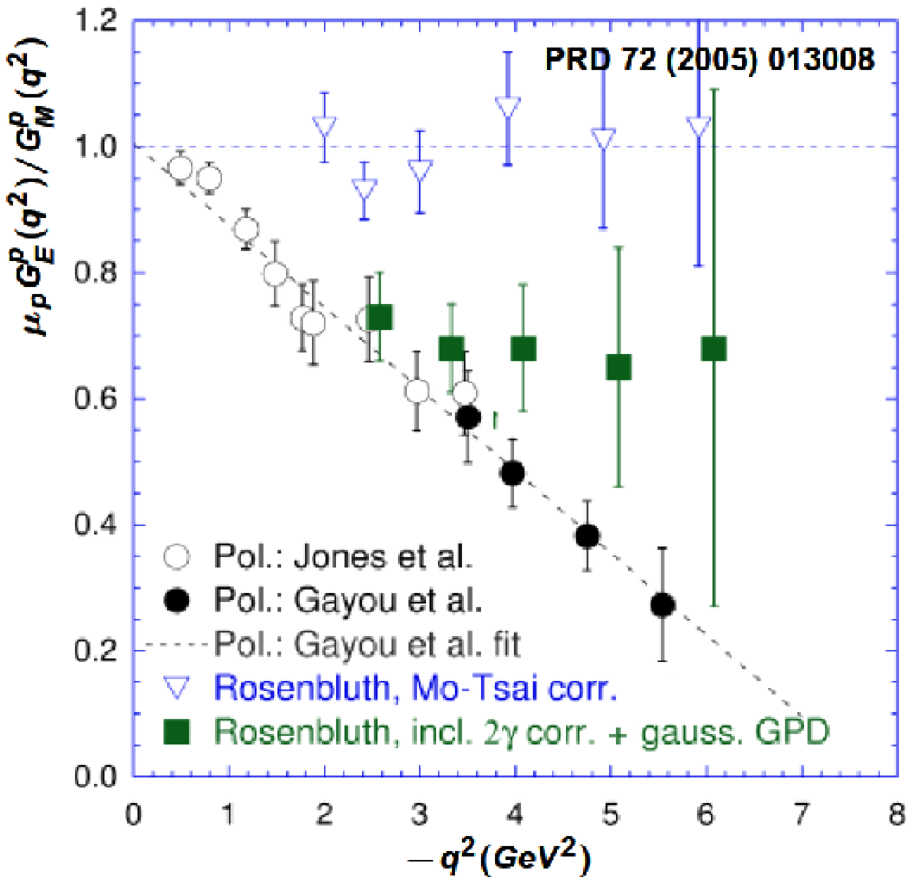


Rosenbluth

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

$$\sigma_R = d\sigma/d\Omega\,[\varepsilon(1+\tau)/\sigma_{Mott}] = \boxed{\tau G_M^2 + \varepsilon G_E^2}$$

$$\tau = \frac{q^2}{4M_N^2}$$



Scaling:

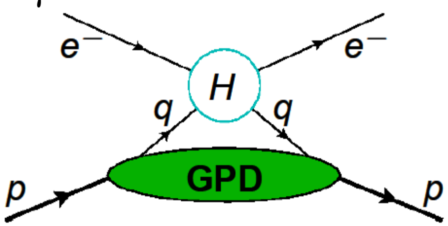
$$G_E^p \simeq G_M^p/\mu_p$$

Polarization method:

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

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

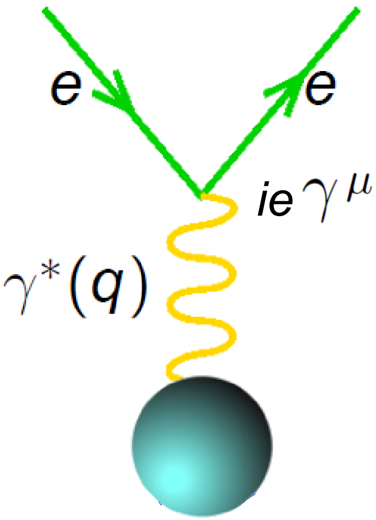
GPD + 2γ



Electromagnetic Form Factors

Suppose we want to determine the **charge distribution** of an object

→ **Elastic scattering**



$$j_\mu^{fi} = -e\bar{u}_f\gamma_\mu u_i\, e^{iq\cdot x} = -\frac{e}{2m}\bar{u}^f \underbrace{((p_f+p_i)_\mu}_{\text{charge}} \underbrace{-i\sigma_{\mu\nu}q^\nu)}_{\text{magnetic moment}} u^i\, e^{iq\cdot x}$$

$$T^{fi} = -i\int j_\mu{}^{fi} A^\mu d^4x$$

$$\boldsymbol{\mu} = -\frac{e}{2m}\boldsymbol{\sigma}$$

Static, spinless object:

$$\boxed{\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{(Z\alpha)^2E^2}{4p^4\sin^4\frac{\theta}{2}}(1-v^2\sin^2\frac{\theta}{2})\cdot|\mathrm{F}(\mathbf{q})|^{\mathbf{2}} \\ F(\mathbf{q}) &= \int\rho(\mathrm{x})\mathrm{e}^{\mathbf{iq\cdot x}}\mathrm{d}^3\mathrm{x} \end{aligned}}$$

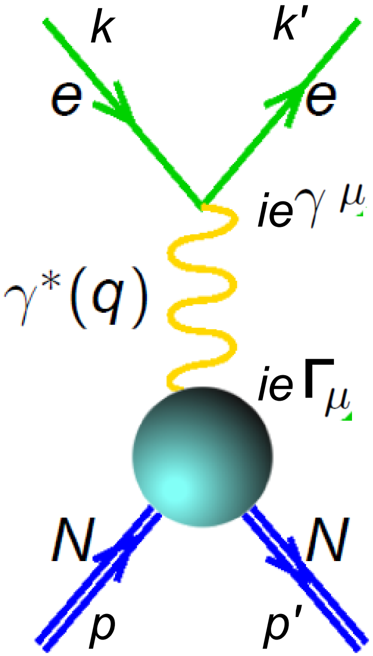
$|p_f| = |p_i| = |p|$

θ: scattering angle

and measure **angular distribution** of scattered electron

Electromagnetic Form Factors

Elastic scattering on nucleon: non static, spin 1/2 object



Spin ½ : two FFs (Pauli, Dirac)

$$\Gamma_\mu = e\bar{u}(p')[F_1(q^2)\gamma_\mu + \frac{\kappa}{2M}F_2(q^2)i\sigma_{\mu\nu}q^\nu]u(p)e^{iqx}$$

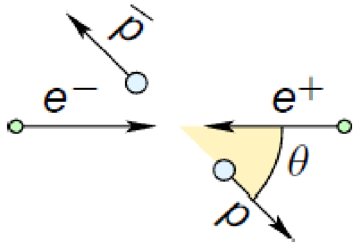
Rosenbluth formula

$$\boxed{\left[\frac{d\sigma}{d\Omega}\right]_{lab} = \frac{(\alpha)^2}{4E^2\sin^4\frac{\theta}{2}}\frac{E'}{E}\left[(F_1^2 - \frac{\kappa^2 q^2}{4M^2}F_2^2)\cos^2\frac{\theta}{2}\right] - \frac{q^2}{2M^2}(F_1+\kappa F_2)^2\sin^2\frac{\theta}{2}}$$

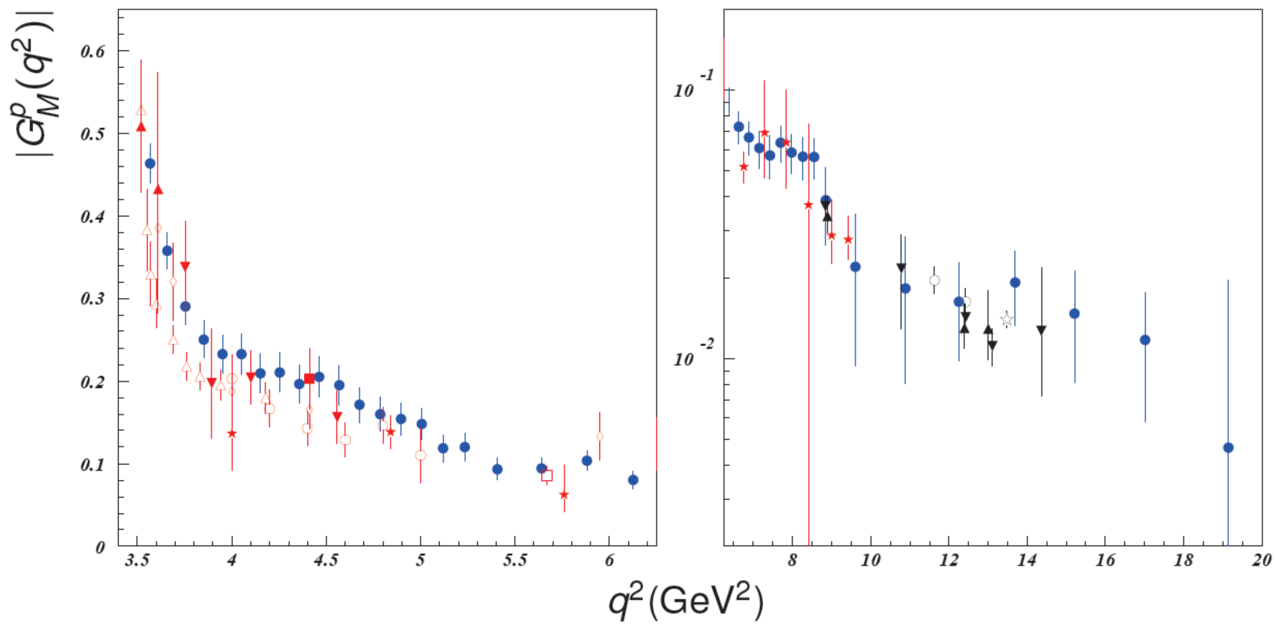
$$G_E = F_1 + \frac{\kappa q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2$$

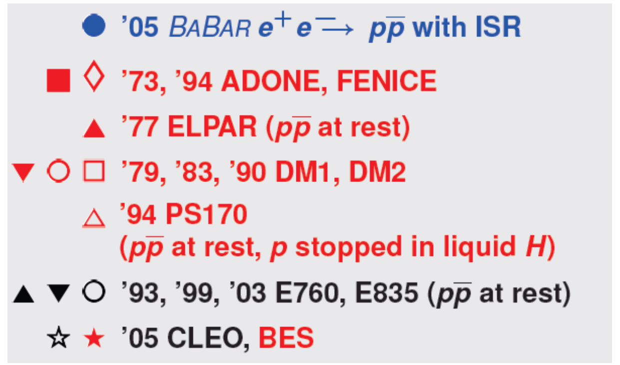
$$\boxed{\left[\frac{d\sigma}{d\Omega}\right]_{lab} = \frac{\alpha^2 E_e'\cos^2\frac{\theta}{2}}{4E_e^3\sin^4\frac{\theta}{2}}\left[G_E^2 + \tau\left(1+2(1+\tau)\tan^2\frac{\theta}{2}\right)G_M^2\right]\frac{1}{1+\tau}}$$

Time-like em Form Factors



- Only **measurements of cross sections** available
- **Form factors** (if) extracted under **assumption**: $G_M^p = \mu_p G_E^p$
- Due to low statistics: **no true separation of G_E and G_M**





All these data have been obtained assuming $|G_M^p| = |G_E^p| \equiv |G^p|$

$$|G^p|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\frac{16\pi\alpha^2 C}{3}\frac{\sqrt{1-1/\tau}}{4q^2}(1+1/2\tau)}$$

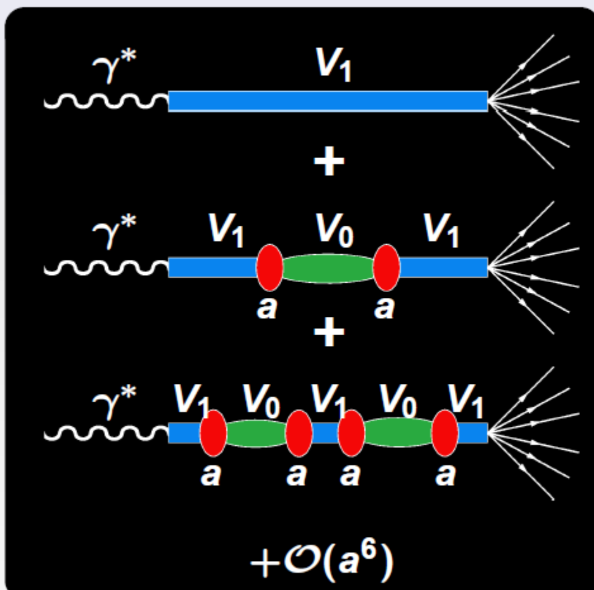
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\sqrt{1-1/\tau}}{4q^2}C\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2\right]$$

<u>Coulomb correction</u>: $C \approx \frac{y}{1-e^{-y}} \qquad y = \frac{\pi\alpha}{\beta}$

'Baryonium'

Baryonium: dip in ppbar processes

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

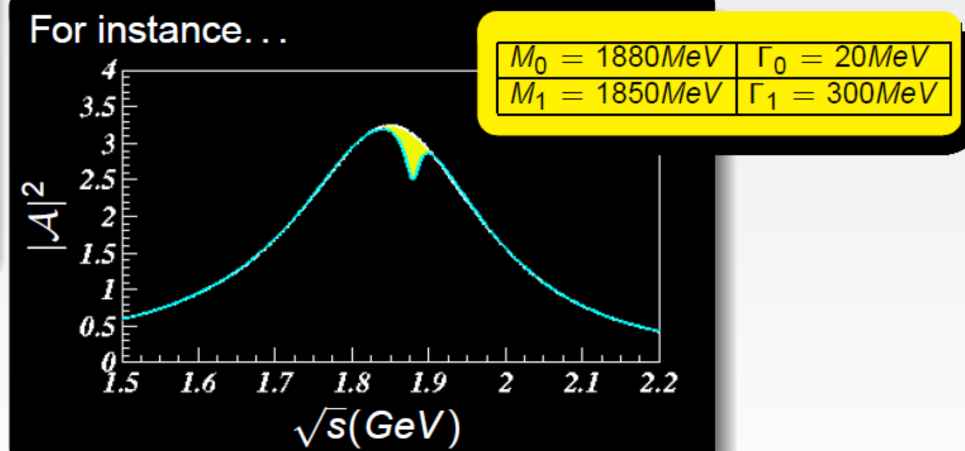


A vector meson V_0 ($J^{PC} = 1^{--}$), with vanishing e^+e^- coupling, which decays through an intermediate broad vector meson V_1

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

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

For instance...



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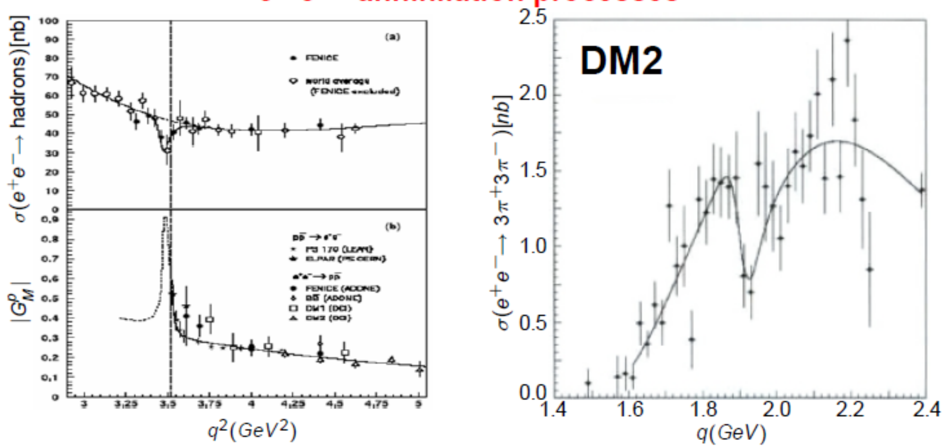
'Baryonium'

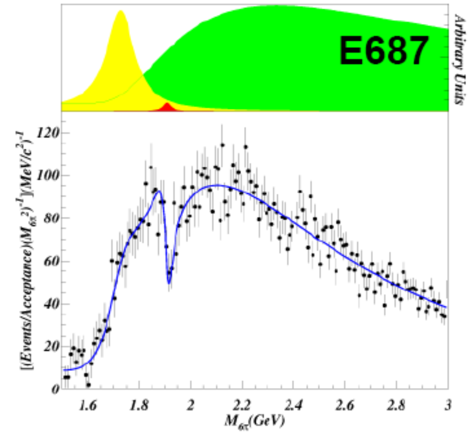
Dips in multi-hadronic processes

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

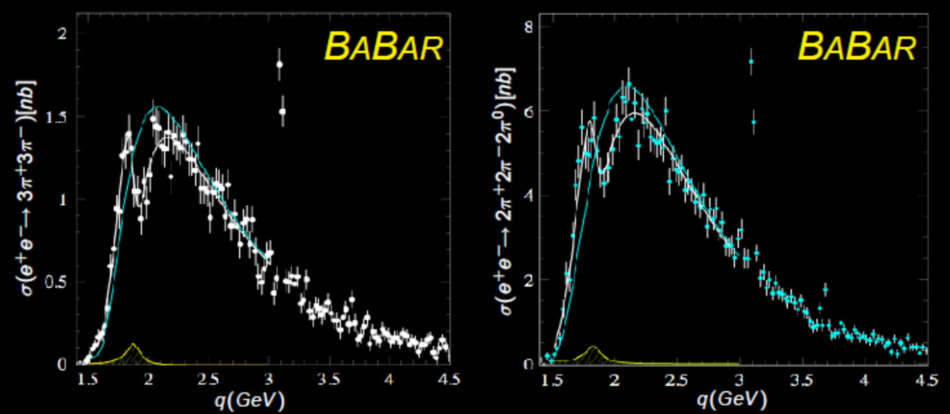
e^+e^- annihilation processes



Diffractive photoproduction



e^+e^- annihilation processes with ISR



V_0	$M(MeV)$	$\Gamma(MeV)$
hadrons	$\sim$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)

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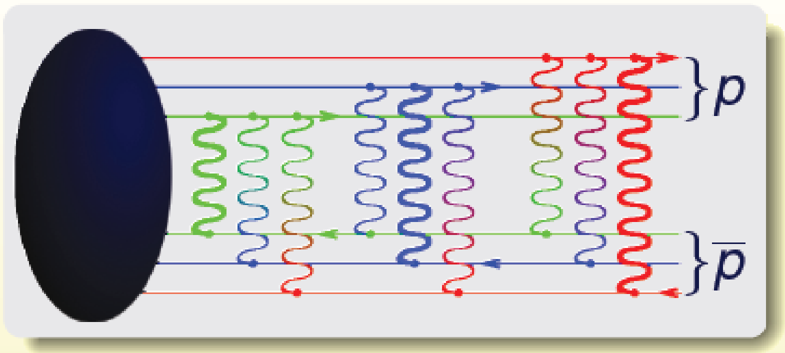
Coulomb term

A simple interpretation



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

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

The phase accounts for the quark displacement inside the baryon

- The interference terms have several suppression factors
- No symmetry between repulsive and attractive Coulomb interactions
- This asymmetry explains the non-vanishing cross section at threshold even for neutral baryon pairs

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

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ECT* - Trento, May 22, 2008 Unexpected threshold behavior in $e^+e^- \to \mathcal{B}\overline{\mathcal{B}}$

Coulomb term

Coulomb correction at threshold

$$C = \frac{\frac{\pi\alpha}{\beta}}{1 - \exp\left(-\frac{\pi\alpha}{\beta}\right)} \xrightarrow[\beta\to 0]{} \frac{\pi\alpha}{\beta}$$

This factor compensates for phase space and gives a constant value at threshold

Cross section at threshold $(\beta \to 0, \tau \to 1, s \to 4M_p^2)$

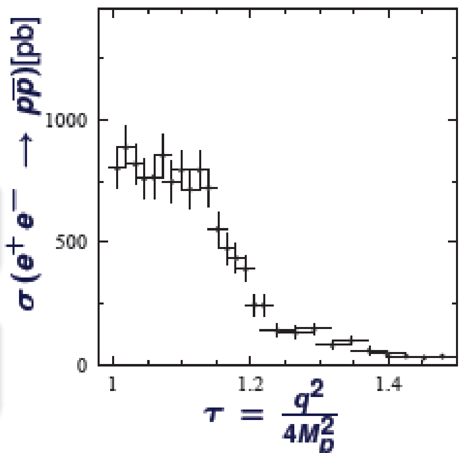
$$\lim_{\text{threshold}} \sigma(s) = \frac{4\pi^2\alpha^3}{3 \cdot 4M_p^2}\frac{3}{2}|G^p(4M_p^2)|^2 \approx 850 \text{ pb } |G^p(4M_p^2)|^2$$

Coulomb correction

$\Downarrow$

Non-zero value for $\tau = 1$

Data show unexplained plateau



$$|G_E^p(4M_p^2)| \equiv |G_M^p(4M_p^2)| \approx 1$$

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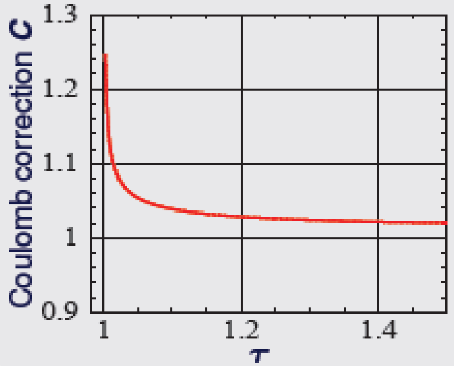
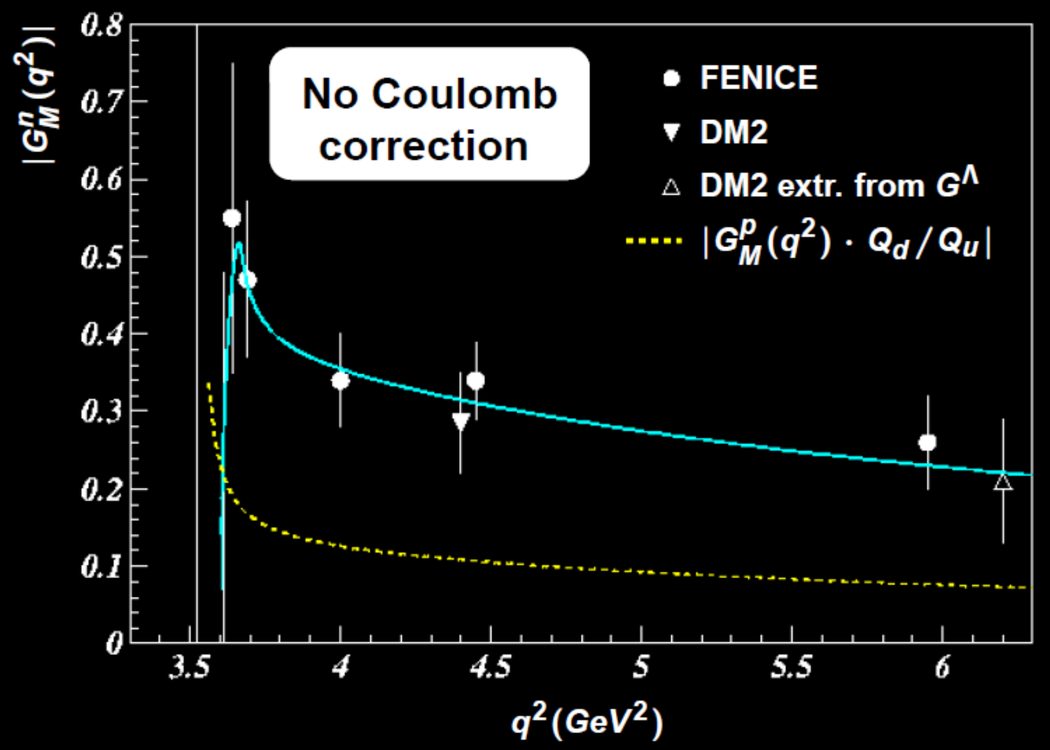
The Coulomb correction does not explain the plateau for $\tau > 1$



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 ?

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

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

R-scan 2-3 GeV

E_{cm}	$N_{had,observed}(10^5)$	L(1/pb)	N_{ppbar} * 50%Eff	$N_{ppbarISR}$($10fb^{-1}$produced)	6% Eff_{tagg} +30%Eff_{untagg}
2.0	1.0	7.1	2288	21417 (1.95 < E'_{cm} <= 2.05 GeV)	1285 + 6425 = 7710
2.1	1.5	10.2	2413	16842	1011 + 5053 = 6063
2.2	2.0	13.5	2147	11474	688 + 3442 = 4131
2.3	3.0	20.9	2170	7450	447 + 2235 = 2682
2.4	3.5	25.1	1685	4573	274 + 1372 = 1646
2.5	4.0	29.4	1275	2763	166 + 829 = 995
2.6	5.0	37.9	1066	1631	98 + 489 = 587
2.7	6.0	48.0	881	1025	62 + 308 = 369
2.8	7.0	60.3	728	612	37 + 184 = 220
2.9	8.0	69.9	559	403	24 + 121 = 145

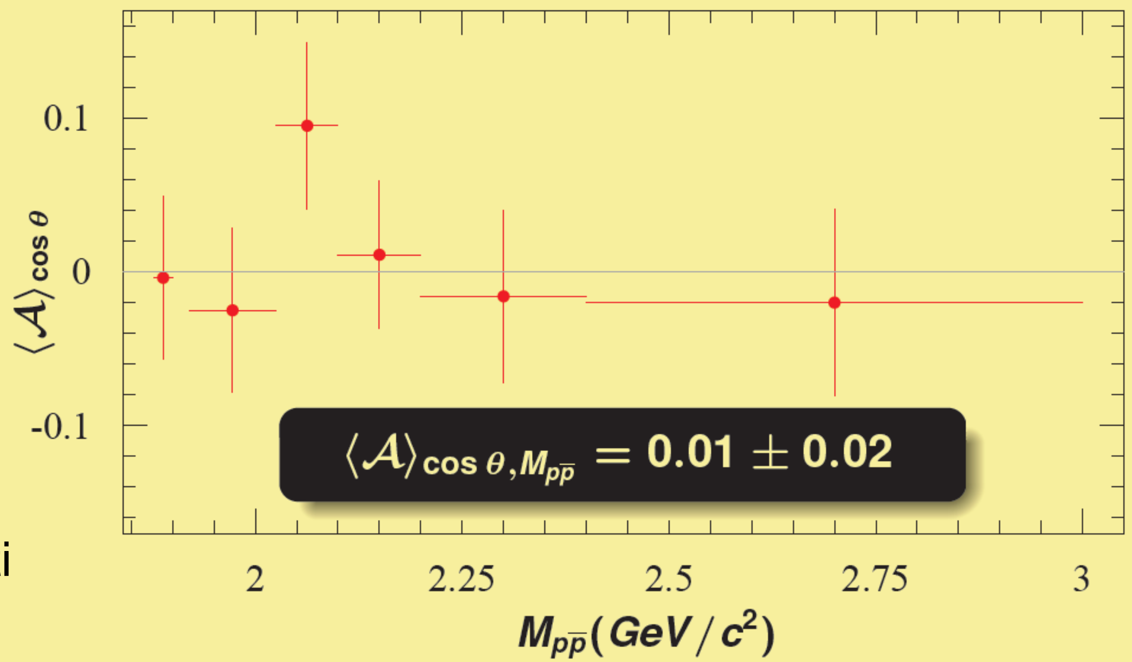
MORE STATISTICS, MUCH FASTER
→ **WE NEED THIS R-SCAN!!**

- Input values provided by Guangshun HUANG
- Observed **ppbar** events after eff of 50%
- **Produced** ISR tagged and untagged at psi(3770) for 10 fb-1
- **Reconstructed** after 6%Eff for tagged events and 30% for untagged events

Gamma gamma exchange

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

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



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