Proton and kaon timelike form factors from Babar

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OUTLINE

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$p\bar{p}$ quantum numbers

$$J^{PC} = 1^{--}, \quad J = L+S,$$

$$P = (-1)^{L+1} = -1, \quad L = 0, 2,$$

$$C = (-1)^{L+S} = -1, \quad S = 1,$$

$S, D$ – waves,

two form factors

e.g. $G_E, G_M$
$e^+e^- \rightarrow N\bar{N}$ cross section

Differential cross section ($N=p,n$):

$$\sigma(e^+e^- \rightarrow N\bar{N}) = \frac{\alpha^2\beta C^2}{4m^2} \left( |G_M|^2 (1 + \cos^2 \theta) + \frac{4m_B^2}{m^2} |G_E|^2 (1 - \cos^2 \theta) \right)$$

Total cross section:

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

Effective form factor

$$|F|^2 = \frac{|G_M|^2 + |G_E|^2}{1+1/2\tau}, \quad \tau = \frac{m^2}{4m_B^2}$$

Two measurable values:

1. effective FF
2. $|G_E/G_M|$ for protons:

$$C = y/(1-e^{-y}), \quad y = \pi\alpha/\beta, \quad \alpha = 1/137, \quad \beta = v/c$$

Function C (Coulomb factor) is significant at ~ 1 MeV above threshold
Expectations for the nucleon form factors

- $|G_E| = |G_M|$ at threshold, S-wave only
- $\sigma \rightarrow \text{const at threshold, } C \sim 1/v$
- Proton polarization $\sim \phi(G_E - G_M)$

perturbative QCD constrains the FF asymptotic behavior

\[ q^2 \rightarrow -\infty \quad \Rightarrow \quad G_{E,M} \rightarrow \text{constant} \]
\[ q^4 \ln \left( \frac{q^2}{\Lambda_{QCD}^2} \right)^2 \]

pQCD + analyticity

\[ q^2 \rightarrow \pm \infty \quad \Rightarrow \quad G_{E,M}(q^2) = G_{E,M}(-q^2) \]
Reactions to study e.m. TL form factors

1. $e^+e^- \text{ annihilation, e}^+\text{e}^- \text{ colliders - Adone, DCI, CLEO, BES, VEPP-2000}$

2. Antiproton annihilation, proton-antiproton colliders – CERN, FNAL

3. ISR – Initial State Radiation, e$^+$e$^-$ colliders - Babar
Two latest BABAR works:

1 - PhysRevD.87.092005(2013), m < 4 GeV - LA ISR
2 - PhysRevD.88.072009(2013), m = 3 – 6 GeV - SA ISR
**PEP-II $e^+e^-$ collider, Babar detector**

$E_+ = 3.1$ GeV, $E_- = 9$ GeV

$E_{CM} = M(Y(4S)) = 10.6$ GeV

2000 - 2008 yrs

$L_{ins} = 10$ nb$^{-1}$/sec

$IL = 500$ fb$^{-1}$

$N(B) = 10^9$

**BaBar IFR:** resistive plate chambers

**BaBar EMC:**
6580 CsI(Tl) crystals,
E resolution $\sim 1-2$ % at high E.

**BaBar DIRC**
Particle ID up to 4-5 GeV/c

**BaBar SVT and DCH**
precision tracking

30.06.2015 QFTHEP2015
e+e→hadrons in ISR

ISR – Initial State Radiation or Radiative Return

\[
\frac{d\sigma(s, x)}{dxd(\cos \theta)} = H(s, x, \theta) \cdot \sigma_0(s(1 - x))
\]

\(H\) - radiation function

\[
H(s, x, \theta) = \frac{\alpha}{\pi x} \left( 2 - 2x + \frac{x^2}{\sin^2 \theta} - \frac{x^2}{2} \right), \quad x = \frac{2E_\gamma}{\sqrt{s}}
\]

\(L_{\text{ISR}} \sim 0.3\% L_0\),
\(\text{with } L_0 \sim 0.5 \text{ ab}^{-1} \implies L_{\text{ISR}} \sim 1.5 \text{ fb}^{-1}\)!

Advantages of ISR
1. Full energy range from \(2m_\pi\) up to \(\sqrt{s}\) is available
2. Detection efficiency is independent on the reaction mechanism
3. No large radiative corrections

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Large/small angles kinematic in ISR

~10% ISR events, $M_h < 3$ GeV

~90% ISR events, because of ISR boost $M_h > 3$ GeV
$e^+e^- \rightarrow p\bar{p}$ analysis, SA ISR kinematics

**Main selection criteria, SA case**

1. Two tracks: $p, \bar{p}$
2. $M_{\text{miss}}^2 < 1\text{ GeV}/c^2$
3. $P_{\text{trans.}} < 0.15\text{ GeV}/c$
4. $P_p < 5\text{ GeV}/c$

**Backgrounds**

1. Two photon + $e^+e^- \rightarrow e^+e^- p\bar{p}$, ~3%
2. ISR with $\pi^0 + e^+e^- \rightarrow \gamma p\bar{p} \pi^0$, ~5%

**Systematics:** ~3%
$e^+e^- \rightarrow p\bar{p}$  LA ISR kinematics

Babar: PhysRevD.87.092005(2013)

Fit: \[ F_{pp} \sim \frac{\alpha_s^2(m)}{m^4} \sim \frac{C}{m^4 \ln^2(m^2 / \Lambda^2)} \]

FF $\sim 1$ at threshold

Babar results are in agreement with previous data and more precise
$e^+ e^- \rightarrow p\bar{p}$

Cos $\theta$ distribution and $|G_E/G_M|$ ratio (Babar)

Babar: PhysRevD.87.092005(2013)
$e^+ e^- \rightarrow p\bar{p}$  SA ISR kinematics

Babar: PhysRevD.88.072009(2013)

Babar results are in agreement with previous data at $E<4$ GeV, and have a tendency to approach spacelike FF at $E>4$ GeV.
$e^+e^- \rightarrow \text{hadrons}$ cross section near nucleon-antinucleon threshold

$e^+e^- \rightarrow pp + nn$

$e^+e^- \rightarrow 6\pi$

$e^+e^- \rightarrow \text{hadrons}$

arXiv:1402.5225v1 [hep-ph] 21 Feb 2014
Comparison of baryons form factors

Proton: PhysRevD.87.092005(2013) - Babar
Neutron: PhysRevD. 90, 112007 (2014) - SND
$\Lambda$, $\Sigma$: PhysRevD. 76, 092006 (2007) - Babar
pQCD: Z.Ph. C42 569 (1989) – Chernyak,Zhitn.
The charged kaon form factor

Two BABAR works:
1. Phys.Rev.D88 032013 (2013) - $E < 5 \text{ GeV/c}^2$ - LA ISR
2. Preliminary - $E < 7.5 \text{ GeV/c}^2$ - SA ISR
The charged kaon form factor

\[ e^+e^- \rightarrow K^+K^-, \quad J^{PC}=1^{--}, \quad L=J=1 \]

P-wave

\[ F_K = \frac{8\pi\alpha_s f_K}{s} \]

\[ \alpha_s \sim \frac{C}{\ln(m^2/\Lambda^2)} \]

\[ \Gamma(K \rightarrow l\nu) = \frac{G_F^2}{8\pi} f_K^2 M_K^2 (1 - \left( \frac{m_l}{m_K} \right)^2)^2 |V_{qs}|^2 \]

\[ f_K = 156 \text{MeV} \]

\[ \sigma_{K^+K^-}(s) = \frac{\pi\alpha^2 \beta^3}{3s} |F_K|^2, \]
The history of kaon TL form factor above $\phi (1020)$

1. $e^+e^- \rightarrow K^+K^-$
   VEPP-2 (1970), Adone, DCI, VEPP-2M
   $\sigma \sim 5$ nb

2. $e^+e^- \rightarrow K^+K^- \gamma$ (ISR)
   Babar (2013)

in 40 years
$10^6$ times in Lum.!
e^+e^- \rightarrow K^+K^- analysis, SA ISR

Main selection criteria
1 - two tracks : K^+, K^-
2 - M_{\text{miss}}^2 < 1\text{GeV}/c^2
3 - P_{\text{trans.}} < 0.15 \text{GeV}/c
4 - P_K < 5 \text{GeV}/c

Background
1 - Two photon - e^+e^- \rightarrow e^+e^- K^+K^- , \sim 3\%
2 - ISR with \pi^0 : e^+e^- \rightarrow \gamma K^+K^- \pi^0 , \sim 5\%
3 - ISRmisID : e^+e^- \rightarrow \gamma \mu^+\mu^- , \sim 5\%

Systematics \sim 3\%
$e^+e^- \rightarrow K^+K^-$ cross section

Phys.Rev.D88 032013 (2013)

Babar data
Kaon form factor, LA ISR

Data are higher the QCD prediction by 4 times

Phys. Rev. D88 032013 (2013)
CZ: Z. Ph. C42 569 (1989)
The kaon form factor with SA ISR technique agrees with LA ISR data and more precise. At $E > 5$ GeV/c$^2$ the tendency to approach to the QCD limit is seen.
Conclusions on the proton timelike form factor (FF)

1. Using the ISR method in Babar the proton FF has been measured from the threshold up to 6 GeV
2. Near the threshold the proton FF is close to the pointlike value 1.
3. The $e^+e^- \rightarrow p\bar{p}$ cross section is nearly constant from the threshold up to 2.2 GeV.
4. A resonance structure in proton FF is seen in the region 2-3 GeV
5. Beginning from $q=5$ GeV the proton FF reveals the tendency to approach to the QCD prediction $F(q^2)=F(-q^2)$. 
Conclusions on the charged kaon timelike form factor (FF)

1. Using the ISR method in Babar, the charged kaon FF has been measured from the threshold up to 7 GeV.
2. Below 2 GeV in the kaon FF, the resonance structure is seen.
3. At $E<4$ GeV, the kaon FF is $\sim 4$ times higher than the QCD limit.
4. At $E>5$ GeV, the kaon FF approaches to the QCD limit.
Thank you for attention