Measurement of hadronic cross sections with the BABAR detector

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Magnetic moment
\[ \tilde{\mu} = g \frac{e \hbar}{2mc} \]

✓ The Dirac equation predicts \( g=2 \) for point-like fermions.
✓ Higher order QFT contributions lead to nonzero
\[ a_{\mu} = (g-2)_{\mu} / 2 \]
✓ \( a_{\mu} \) is sensitive to New Physics contributions

**E821@BNL (1997-2001):** G.W. Bennett et al.,

\[ a_{\mu} = (11,659,209.1 \pm 6.3) \times 10^{-10} \text{ (0.54 ppm)} \]

**E989 @ FNAL (2017-...):** F. Gray et al.,
arXiv: 1510.00346 \( a_{\mu} = \ldots \text{ (0.14 ppm)} \)

**E34 @ J-PARC (????-...):** T. Mibe et al.,
Chin. Phys. C 34 (2010) 745 \( a_{\mu} = \ldots \text{ (0.1 ppm)} \)

Data - SM discrepancy is more than 3\( \sigma \)
(g-2)$_\mu$/2 of muon

- The leading order hadronic contribution is calculated using dispersion relations from experimental data on the total cross section of the e$^+$e$^-$ annihilation into hadrons.
- Low energies (E < 2 GeV) give dominant contribution into $a_\mu^{\text{had,LO-VP}}$ (92%).

### Individual SM contributions $\times 10^{-10}$

- $a_\mu^{\text{QED}}$  · $11658471.895 \pm 0.008$
- $a_\mu^{\text{EW}}$  · $15.4 \pm 0.1$
- $a_\mu^{\text{had,LO-VP}}$  · $692.6 \pm 3.3$
- $a_\mu^{\text{had,H0-VP}}$  · $-8.63 \pm 0.09$
- $a_\mu^{\text{had,LBL}}$  · $10.5 \pm 2.6$

DHMZ, TAU 2016, arXiv:1612.02743

\[ a_\mu^{\text{had,LO-VP}} = \frac{\alpha^2 m_\mu^2}{9\pi^2 m_\pi^2} \int_0^\infty ds \frac{\hat{K}(s)}{s^2} R(s) \]

\[ \hat{K}(s) \]

\[ R(s) = \frac{\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \]
Below 1.9(1.8) GeV the total cross section is calculated as a sum of exclusive channels.

The exclusive data are incomplete in the region 1.6<E<2.0 GeV.

There is no experimental information on the final states $\pi^+\pi^0\eta$, $\pi^+\pi\eta\eta$, $\pi^+\pi\pi^0\pi^0\pi^0\pi^0\eta$, $7\pi$ ...

The important experimental task is to measure all significant exclusive channels below 2 GeV, and perform comparison with inclusive measurements and pQCD prediction.

The contributions of different hadronic channels into $a_{\mu}^{\text{had,LO-VP}}$ and its squared error $\sigma^2$
PEP-II asymmetric $e^+e^-$ collider at SLAC
(9 GeV $e^-$ and 3.1 GeV $e^+$)

Data, about 500 fb$^{-1}$, were collected in 1999-2008

For ISR analyses, a data sample of 469 fb$^{-1}$
collected near or at a c.m. energy of 10.58 GeV
(at and near $\Upsilon(4S)$) is used.

Four recent analyses are discussed in this talk
✓ $\pi^+\pi^-\pi^0\pi^0$
✓ $\pi^+\pi^-\eta$
✓ $K_S K_L \pi^0$, $K_S K_L \eta$, $K_S K_L \pi^0\pi^0$
✓ $K_S K^+\pi^-\pi^0$, $K_S K^+\pi^-\eta$

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

- Full reconstruction $\pi^+\pi^-\pi^0\pi^0\gamma$
- MC simulated background
- normalized to data and
- subtracted
- Cross-checked with
- 6C-fit $(E, \vec{p}, 2 \times m_{\pi^0})$
- ratio $\chi^2$ region 1/2

- Data
- signal MC (AfkQED)

$q\bar{q}, \tau\tau, \gamma\pi^+\pi^- 3\pi^0,$
$\gamma K_S K\pi, \gamma K^+ K^- 2\pi^0,$
$\gamma 3\pi, \gamma 4\pi^\pm 2\pi^0,$

BABAR
no.9, 092009
\[ e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0 \] @ BABAR

- BABAR results are most precise and cover wider energy range.
- Systematic uncertainty is 3.1% in the 1.2-2.7 GeV energy range.
- Contribution to \( a_\mu \) for the range \( 1.02 < E_{cm} < 1.8 \) GeV is measured to be
  \[ a_\mu^{\text{had LO}}(\sqrt{s} < 1.8 \text{ GeV}) = (17.9 \pm 0.1 \pm 0.6) \cdot 10^{-10} \]

Previous result including the preliminary BABAR data from 2007 is
  \[ (18.0 \pm 1.2\text{(stat+syst)}) \cdot 10^{-10} \]

Intermediate states \( a_1 \pi, \omega\pi^0, \rho^+\rho^-, f_0\rho^0 \)

\( \omega\pi^0 \) contribution to \( \pi^+\pi^-2\pi^0 \)
  \[ (32.1 \pm 0.2_{\text{stat}} \pm 2.6_{\text{syst}}) \% \]
The BABAR results in the \( \eta \rightarrow \gamma \gamma \) mode agrees well with the previous measurements, but is more precise and extending energy range up to 3.5 GeV.

The \( e^+e^- \rightarrow \pi^+\pi^-\eta \) cross section is used to test conserved vector current (CVC) hypothesis.

Systematic uncertainty near the cross section maximum, 1.35-1.80 GeV, is 4.5%.

\[
a^\text{had LO} (\sqrt{s} < 1.8 \text{ GeV}) = (1.19 \pm 0.02 \pm 0.06) \times 10^{-10}
\]

\[
1.15 \pm 0.10 \text{ – All before BaBar}
\]
There are six combinations in the $e^+e^- \rightarrow K\bar{K}\pi\pi$ process. Four were measured previously.

$\sigma(e^+e^- \rightarrow K^+K^-\pi^+\pi^0), \text{ nb}$

$\sigma(e^+e^- \rightarrow K_S K_L \pi^+\pi^0), \text{ nb}$
\[ e^+e^- \rightarrow K_S K_L \pi^0 \pi^0 \] @ BABAR


- First measurement
- Systematic uncertainty is 25% at the peak, grows to 60% at 2 GeV
- Dominant \( K^*(892)K \pi \) intermediate state. No evidence \( K^*0K^*0 \)
\[ e^+e^- \rightarrow K_S K^+ \pi^- \pi^0 @ \text{BABAR} \]

- First measurement of largest KK\(\pi\pi\) mode
- Systematic uncertainty is 6-7% below 3 GeV
- More than 10 intermediate states – dominant are \(K^*(892)K\pi\), \(K_S K^+ \rho^- (770)\)

Intermediate states:
- \(K^*0 K_S^0 \pi^0\)
- \(K^*0 K^\mp \pi^\mp\)
- \(K_2^* (1430)^0 K_S^0 \pi^0\)
- \(K_2^* (1430)^0 K^\mp \pi^\mp\)
- \(K^* (892)^\pm K_S^0 \pi^\mp\)
- \(K^* (892)^\pm K^\mp \pi^0\)
- \(K_2^* (1430)^\pm K_S^0 \pi^\mp\)
- \(K_2^* (1430)^\pm K^\mp \pi^0\)
- \(K^*0 \overline{K}^*0\)
- \(K^* (892)^+ K^* (892)^-\)
- \(K_S^0 K^\pm \rho^- (770)^\mp\)
$e^+e^- \rightarrow K_S K_L \pi^0$, $K_S K_L \eta$, $K_S K^+ \pi^- \eta$ @ BABAR


- First measurement
- Systematic uncertainty is 10% near the peak, grows to 30% at 3.0 GeV
- Dominant $K^*(892)K$ intermediate state

- First measurement
- Systematic uncertainty is 25% at the peak, grows to 60% at 2 GeV

- First measurement
- Systematic uncertainty is 12-19% below 3 GeV
- Dominant $K^*(892)\bar{K}\eta$ intermediate state.
Total $e^+e^- \rightarrow K\bar{K}\pi$ and $K\bar{K}\pi\pi$ cross sections

- All modes have now been measured by BABAR
- $KK\pi$ is about 12% of the total cross section for $E_{cm} = 1.65$ GeV
- $KK\pi\pi$ is about 25% of the total cross section for $E_{cm} = 2.0$ GeV
- Precision on $(g-2)/2$ improved (no reliance on isospin)

$$a_\mu(KK\pi) = (2.45 \pm 0.15) \times 10^{-10} \quad 2.39 \pm 0.16$$

$$a_\mu(KK\pi\pi) = (0.85 \pm 0.05) \times 10^{-10} \quad 1.35 \pm 0.39$$
✓ Precise low-energy $e^+e^-$ hadronic cross section data are needed to obtain an accurate SM prediction for $a_\mu^{\text{had, LO-VP}}$

✓ Recent results on the $e^+e^-\rightarrow\pi^+\pi^0\pi^0,\pi^+\pi^-\eta, KK\pi, KK\pi\pi$ modes from BABAR reduce the uncertainty on $a_\mu^{\text{had,LO-VP}}$

✓ New results are expected from BABAR, as well as from BES III, SND, CMD-3
Before the BaBar measurement:

- Limited precision
- Big disagreement between experiments
- Small energy ranges
$e^+e^- \rightarrow \pi^+\pi^-\eta$: VMD fits

**Models:**

- **Model 1:** $\rho(770) - \rho(1450)$ fits $E_{\text{cm}} < 1.7$ GeV
- **Model 2:** $\rho(770) - \rho(1450) - \rho(1700)$ fits $< 1.9$ GeV
- **Model 3:** $\rho(770) - \rho(1450) + \rho(1700)$ fits $< 1.9$ GeV
- **Model 4:** $\rho(770) - \rho(1450) + \rho(1700) + \rho(2150)$ fits $< 2.2$ GeV

Relative phases 0 (+) and 180° (−)

**Graph:**

- BABAR

**Axes:**

- Cross section, nb
- $E_{\text{cm}}$ (GeV)

**Inset:**

- Comparison of cross sections for different models at $E_{\text{cm}}$.

**Notes:**

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The conserved vector current (CVC) hypothesis and isospin symmetry allow to predict the hadronic mass spectrum and branching fraction for the decay $\tau^+ \rightarrow \pi^+ \pi^0 \eta \nu_\tau$ from data on the $e^+e^- \rightarrow \pi^+ \pi^- \eta$ cross section.

**CVC-prediction based on BABAR data:**
$B(\tau^+ \rightarrow \pi^+ \pi^0 \eta \nu_\tau) = (0.162 \pm 0.008)\%$

**PDG14 value:**
$B(\tau^+ \rightarrow \pi^+ \pi^0 \eta \nu_\tau) = (0.139 \pm 0.010)\%$

The difference between the CVC prediction and experimental value, about 15%, is too large to be explained by isospin-breaking corrections.

**CVC-prediction based on the SND data:**
$B(\tau^+ \rightarrow \pi^+ \pi^0 \eta \nu_\tau) = (0.156 \pm 0.011)\%$

**CVC-experiment difference is 1.8\sigma.**

The PDG value is dominated by the Belle measurement:
$B(\tau^+ \rightarrow \pi^+ \pi^0 \eta \nu_\tau) = (0.135 \pm 0.007)\%$

**CVC-experiment difference is 2.4\sigma.**
The mass spectrum of the hadronic system in the reaction $e^+e^- \rightarrow f \gamma$ reaction is related to the cross section of the reaction $e^+e^- \rightarrow f$.

$$\frac{d\sigma(s,x)}{dxd(\cos\theta)} = W(s,x,\theta) \cdot \sigma_0(s(1-x)), \quad x = \frac{2E_\gamma}{\sqrt{s}}$$

The ISR photon is emitted predominantly along the beam axis. The produced hadronic system is boosted against the ISR photon. Due to limited detector acceptance the mass region below 2 GeV can be studied only with detected photon (about 10% of ISR events).
BABAR tagged ISR analyses

Fully exclusive measurement
✓ Photon with $E_{\text{cm}} > 3$ GeV, which is assumed to be the ISR photon
✓ All final hadrons are detected and identified

Large-angle ISR forces the hadronic system into the detector fiducial region
✓ A weak dependence of the detection efficiency on dynamics of the hadronic system (angular and momentum distributions in the hadron rest frame) ⇒ smaller model uncertainty
✓ A weak dependence of the detection efficiency on hadron invariant mass ⇒ measurement near and above threshold with the same selection criteria.

Kinematic fit with requirement of energy and momentum balance
✓ excellent mass resolution
✓ background suppression

Can access a wide range of energy in a single experiment: from threshold to ~5 GeV
Large progress in ISR measurements during the last decade
- CMD-2, KLOE, BABAR, BES-III claim systematic uncertainty at a sub-percent level
- Most recent measurement was performed by BES III using ISR technique
- Analysis is based on the data set with an integrated luminosity of 2.93 fb\(^{-1}\) taken at 3.773 GeV

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

Systematic differences between data from different experiments reach 5% and are significantly larger than the claimed systematic uncertainties (<1%)