Recent Measurements of Exclusive Hadronic Cross Sections at \textit{BABAR} and the Implications for the Muon $g-2$ Calculation

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Outline

• The muon g-2 puzzle
• BABAR and ISR studies
• Recent hadronic cross section measurements
  \[ e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0, \quad \pi^+\pi^-\eta \]  
  \[ e^+e^- \rightarrow K_S^0K_L^0\pi^0, \quad K_S^0K_L^0\eta, \quad K_S^0K_L^0\pi^0\pi^0 \]  
  \[ e^+e^- \rightarrow K_S^0K^\pm\pi^0\pi^0, \quad K_S^0K^\pm\pi^+\eta \]  
  \[ \text{Phys. Rev. D95 (2017) 052001.} \]
  \[ \text{Phys. Rev. D95 (2017) 092005.} \]

• Implications for muon g-2
The muon $g-2$ puzzle

- The magnetic dipole moment for Dirac particles can be written $\vec{\mu} = g \frac{e\hbar}{2mc} \vec{S}$
  - Dirac equation predicts $g = 2$ exactly
- Corrections from higher order processes cause $g$ to differ from 2 by a small amount. Characterize with anomalous magnetic moment:
  $$a_i = \frac{1}{2}(g_i - 2)$$
- For the electron, theory and experiment agree to great precision
- For the muon, they are in tension, which is the puzzle
Status of $a_\mu$ - “before”

$$a_\mu^{\text{theory}} = a_\mu^{\text{QED}} + a_\mu^{\text{Hadronic LO}} + a_\mu^{\text{Hadronic NLO}} + a_\mu^{\text{Hadronic LBL}} + a_\mu^{\text{Weak}}$$

From Quantum Electrodynamics (QED)  

11 658 471.895 ±0.008

Leading Order Hadronic Vacuum Polarization  

692.3 ±4.2

NLO Hadronic Vacuum Polarization  

-9.8 ±0.1

Hadronc Light by Light  

10.5 ±2.6

Weak Interactions  

15.4 ±0.1

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<td>$\Delta a_\mu = a_\mu^{\text{experiment}} - a_\mu^{\text{theory}}$</td>
<td>3.6σ</td>
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units of $10^{-10}$
The allure of $a_\mu$

- Longstanding tension between experiment and theory could be a hint at New Physics (NP).
- Rich muon program here at Fermilab and at J-PARC addressing the experimental side.
- Other experiments, including BABAR, provide inputs for the theoretical calculations, particularly at low energies where perturbative QCD runs into difficulty.
The $\textit{BABAR}$ Experiment at SLAC

- Asymmetric-energy beams for boost
- Modern/state of the art detector
- 5 cylindrical subdetectors with a 40-layer drift chamber
- Excellent electromagnetic calorimetry
- Multiple measurements for particle identification
- Excellent momentum resolution

- Primarily designed for study of $CP$-violation in $B$ meson decays
- Quality and general-purpose design make it suitable for a large variety of studies

The BABAR Running Era

7 Runs over the course of 9 years

CUSB

Analyses here use ~470 fb⁻¹ of data taken near 4S

- First collisions with BaBar May 26, 1999
- Final data taken 12:43 p.m., April 7, 2008

BaBar
Run 1-7

PEP II Delivered Luminosity: 553.34/fb
BaBar Recorded Luminosity: 531.32/fb
BaBar Recorded Y(4s): 432.89/fb
BaBar Recorded Y(3s): 30.23/fb
BaBar Recorded Y(2s): 14.45/fb
Off Peak Luminosity: 53.74/fb
ISR Method

\[ e^-(9\text{GeV}) \quad \gamma \quad \frac{\sqrt{s'}}{E_{CM}} \quad s' = s \left( 1 - \frac{2E_{\gamma}}{\sqrt{s}} \right) \]

- Photon emitted by electron or positron – Initial State Radiation (ISR)
  - Carries away energy - allows “scan” of energies for remaining system
  - Easily identified back-to-back topology
  - High acceptance, even at threshold
  - Exploited heavily at BABAR for large number of hadronic cross sections
BABAR ISR Contributions

Calculate via dispersion relation integral. Lowest CM energies contribute most

$$a_{\mu}^{\text{Hadronic LO}} = \left( \frac{\alpha m_\mu}{3\pi} \right)^2 \int_{m_\pi^2}^{\infty} \frac{\hat{K}(s)}{s^2} R_{\text{HAD}}(s) ds$$

$$R_{\text{HAD}}(s) = \left( \frac{\sigma(e^+e^- \to HAD)}{\sigma(e^+e^- \to \mu^+\mu^-)} \right)$$

Above \(\sim 2\) GeV, theory can use perturbative QCD.
Below that, rely on experimental input. BABAR providing significant inputs.
Study of $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0 \pi^0$

To Be Submitted

- Resolves tensions among previous results
- Large signal (over 150,000 events)
- Larger energy range than previous results
- Biggest background from $e^+ e^- \rightarrow \pi^+ \pi^- 3\pi^0$
  - Background measured from data

**Impact:**

Greatly improved uncertainties. ~3.3% for energies less than 1.8 GeV

$$\alpha^{\pi^+ \pi^- \pi^0 \pi^0}_\mu = (17.9 \pm 0.1 \pm 0.6) \times 10^{-10}$$

08/01/2017

Brown: BABAR and g-2
Study of $e^+ e^- \rightarrow \pi^+ \pi^- \eta$

To Be Submitted

- Reconstruct via $\eta \rightarrow \gamma \gamma$ decay
- Highest energy range for this mode
- Most precise measurement
- $\sim 8,000$ signal events

$$a^\pi^+ \pi^- \eta = (1.19 \pm 0.02 \pm 0.06) \times 10^{-10}$$

08/01/2017  Brown:  BABAR and g-2
Study of $e^+e^- \rightarrow \pi^+\pi^-\eta$

To Be Submitted

Vector Dominance Model fits
- detailed information on dynamics

model 1: $\rho(770) - \rho(1450)$ fits ECM < 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° (−)

Implications for both $a_\mu$ and hadronic $\tau$ decays!
Modes with Kaons

\( K_S^0 \) reconstructed as a pair of opposite charge tracks with a displaced vertex via its decay \( K_S^0 \rightarrow \pi^+ \pi^- \)

\( K_L^0 \) identified as an isolated energy cluster in the calorimeter, cluster shape not consistent with a photon.
- Validated via
  \[
e^+ e^- \rightarrow \gamma \phi \rightarrow \gamma K_S^0 K_L^0
  \]
  \textbf{PRD89 0092002 (2014)}

\( K^\pm \) identified via standard charged-particle PID system utilizing specific ionization, timing, Cerenkov radiation, calorimetry
Study of $e^+e^- \rightarrow K^0_S K^0_L \pi^0$, $K^0_S K^0_L \eta$, $K^0_S K^0_L \pi^0 \pi^0$


Extensive study of resonant substructure.

Improved energy range and cross-section uncertainties.
First observation for $J/\psi$ decays to these states.
Study of $e^+e^- \rightarrow K_S^0 K_L^0 \pi^0, \ K_S^0 K_L^0 \eta, \ K_S^0 K_L^0 \pi^0 \pi^0$

Very significant contribution from $\phi \eta$

No significant contribution from $K^* K^*$
Study of $e^+ e^- \rightarrow K_S^0 K^\pm \pi^\mp \pi^0$, $K_S^0 K^\pm \pi^\mp \eta$


Completing the $KK\pi$ modes

Significant contributions from $J/\psi$ obvious
Total $KK\pi(\pi)$ cross section

- All possible modes now measured by BABAR
- No more need to rely on isospin arguments
- Improves precision on inputs to g-2 calculations

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

$$a_{\mu}^{KK\pi\pi} = (0.85 \pm 0.05) \times 10^{-10}$$

Courtesy V. Druzhinin

EPJ WoC 142, 01013 (2017)
Progress!  
\[ E_{\text{cut}} = 1.8 \text{ GeV} \]

Courtesy Fedor V. Ignatov, via J. Chauveau
Progress!

Now

Courtesy Fedor V. Ignatov, via J. Chauveau

Preliminary.
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Summary and Conclusions

• \textit{BABAR} has made considerable use of the ISR technique to study $e^+e^-$ annihilation across a broad energy range.
  – Including several new hadronic modes reported here.
• Important to improve our knowledge of muon $g$-2
  – the puzzle continues, more input needed!
  – More on the way! Stay Tuned.