Hadron Production in e^+e^- Annihilation at *BaBar* and Implications for the Muon Anomalous Magnetic Moment

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$e^+e^- \to$ hadrons and $g_\mu - 2$ in BaBar
Outline

- Introduction
- Muon anomalous magnetic moment
- ISR measurement of $e^+e^- \to$ hadrons
- Analysis
- Results
- Conclusions

Introduction

BaBar is a high luminosity (10^{34} cm^{-2}s^{-1}) e^+e^- experiment.

In processes involving initial state radiation, this enables precise measurement of $\sigma(e^+e^- \rightarrow \text{hadrons})$ as a function of CM energy from threshhold to several GeV.

- Hadron form factors (π, K, p)
- Light hadron spectroscopy
- Hadronic vacuum polarization (HVP) contribution to $(g-2)_\mu$

Muon $g-2$

Lepton magnetic moment anomaly, sensitivity to new physics $\sim m_\ell^2$

$$\vec{\mu}_\ell = -\frac{g_\ell e}{2m_\ell}\vec{S}; \quad a_\ell \equiv \frac{(g-2)_\ell}{2}$$

$$a_\mu(\text{measured}) = 116592089 \pm 63 \times 10^{-11}$$

(BNL E821 – Bennett 2006 PRD 73, 072003; RPP 2013)

$$a_\mu(\text{SM}) = 116591802 \pm 49 \times 10^{-11}$$

Measured value is 3.6σ larger than SM prediction!

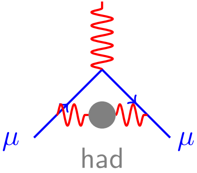
Standard Model calculation:

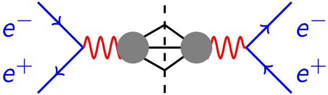
$$\begin{aligned}
a_\mu(\text{SM}) &= a_\mu(\text{QED}) + a_\mu(\text{weak}) + a_\mu(\text{had}) \\
a_\mu(\text{QED}) &= 116584718.10 \pm 0.15 \times 10^{-11} \\
a_\mu(\text{weak}) &= 154 \pm 2 \times 10^{-11} \\
a_\mu(\text{had}) &= 6930 \pm 49 \times 10^{-11}
\end{aligned}$$

See Engel, Patel, Ramsey-Musolf, PR D **86** (2012) 037502; Davier, Hoecker, Malaescu, Zhang, EP J C **71** (2011) 1515

$a_\mu(\text{had})$

- $a_\mu(\text{had})$ is largest term after $a_\mu(\text{QED})$
- Contributions from hadronic vacuum polarization and hadronic light-by-light scattering
- Largest contribution to uncertainty ($\pm 42 \times 10^{-11}$) is hadronic vacuum polarization, $a_\mu(\text{HVP})$
- Not possible to compute $a_\mu(\text{HVP})$ perturbatively
- Instead, measure $\sigma(e^+e^- \to \text{hadrons})$ as a function of CM energy and use dispersion relation





Use of dispersion relation for a_μ(had)

Dispersion relation

$$a_\mu(\text{had}) = \frac{\alpha^2}{3\pi^2}\int_{\text{threshold}}^{\infty} R(s)\frac{K(s)}{s}ds$$

where

$$R(s) = \frac{\sigma^0(e^+e^- \to \text{hadrons}(\gamma))}{\sigma_{\text{pt}}}$$

and

$$K(s) \sim 1/s$$

Hence, emphasis is from the low-energy portion of hadron spectrum
Dominant contribution is from $\pi^+\pi^-$ (but other channels can not be neglected)

We need to measure σ^0, the bare cross section including FSR, as a function of s.

The ISR method

- *BaBar*: e^+e^- collisions at $\sqrt{s} = 10.6$ GeV
- With ISR, effective $e^+e^- \to \gamma^*$ energy is $\sqrt{s'} = \sqrt{s(1-x)}$, where $x = 2E^*_\gamma/\sqrt{s}$ in CM frame
- Select events with a high energy ISR photon ($E^*_\gamma > 3$ GeV) at large angle
- ISR photon is opposite hadrons in CM. High acceptance for boosted hadrons even from threshhold
- ISR luminosity determined with $e^+e^- \to \gamma_{\rm ISR}\mu^+\mu^-$ $(\pi\pi, KK)$
- Additional ISR and FSR accounted for
- Measurement from threshold to 3–5 GeV in single dataset, reduces systematics

BaBar's ISR measurements

BaBar has extensive program to measure $e^+e^- \to$ hadrons as a function of energy using ISR method (channels include possible additional FSR photon)

Final state(s)	Publication
$\pi^+\pi^-$	PRD **86** 032013 (2012)
K^+K^-	TBP, PRD (2013) arXiv:1306.3600
$\pi^+\pi^-\pi^0$	PRD **70** 072004 (2004)
$K^+K^-\eta$, $K^+K^-\pi^0$, $K^0_S K^\pm\pi^\mp$	PRD **77** 092002 (2008)
$\pi^+\pi^-\pi^+\pi^-$	PRD **85** 112009 (2012)
$K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$, $2(K^+K^-)$	PRD **86** 012008 (2012)
$\Lambda\bar{\Lambda}$, $\Lambda\bar{\Sigma}^0$, $\Sigma\bar{\Sigma}^0$	PRD **76** 092006 (2007)
$2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $K^+K^-\pi^+\pi^-\pi^0$, $K^+K^-\pi^+\pi^-\eta$	PRD **76** 0922005 (2007)
$\phi\eta$	PRD RC **74** 111103 (2006)
$3(\pi^+\pi^-)$, $2(\pi^+\pi^-\pi^0)$, $K^+K^-2(\pi^+\pi^-)$	PRD **73** 052003 (2006)
$p\bar{p}$, see C. Cartaro talk	PRD **87** 092005 (2013)
$K^0_S K^0_L$, $K^0_S K^0_L\pi^+\pi^-$, $K^0_S K^\pm\pi^\mp\pi^0$, $K^0_S K^\pm\pi^\mp\eta$, $\pi^+\pi^-2\pi^0$	in progress

Analysis (e.g., K^+K^-)

- Measured $K^+K^-(\gamma)$ yield in ISR production
- Effective luminosity from measured $\mu^+\mu^-(\gamma)$ rate (for $\pi\pi$, KK)
- Efficiency from data-corrected simulations
- Gives the result for the cross section

$$\frac{dN_{K^+K^-(\gamma)\gamma_{\rm ISR}}}{d\sqrt{s'}} = \frac{dL^{\rm eff}_{\rm ISR}}{d\sqrt{s'}}\ \epsilon_{KK\gamma_{\rm ISR}}(\sqrt{s'})\ \sigma^0_{KK(\gamma)}(\sqrt{s'})$$

"Bare" cross section σ^0 includes Final State Radiation (FSR), but no leptonic or hadronic vacuum polarization effects. These have been removed by using the normalization based on the measured $\mu^+\mu^-(\gamma)$ rate.

Efficiency and Background

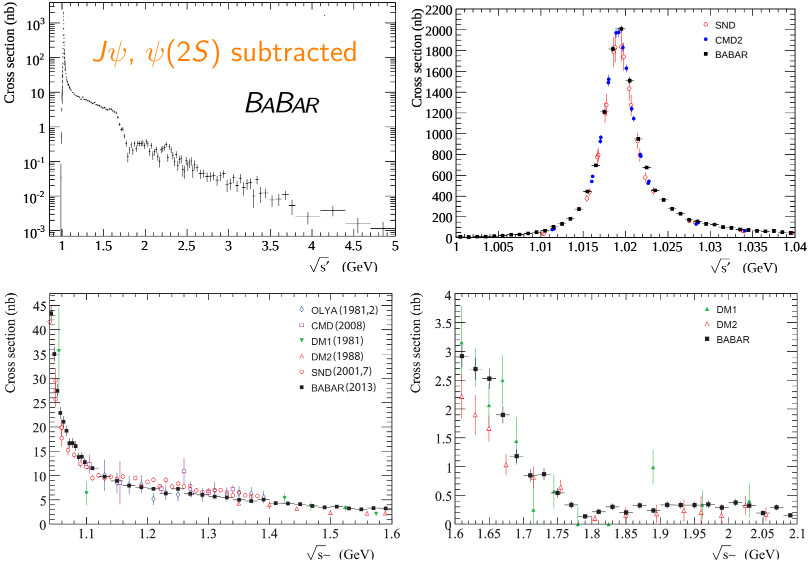
(Many details skipped! See publications)
Monte Carlo efficiency corrected for MC/data differences, using in situ efficiency measurements:

- Trigger: Corrections $\sim$ few $\times 10^{-4}$
- Tracking: Systematic uncertainties $<$ few $\times 10^{-3}$
- Particle identification: Systematic uncertainties typically few $\times 10^{-3}$
- Kinematic fit selection errors from uncertainty in modeling of additional ISR/FSR: Systematic uncertainties $<$ few $\times 10^{-3}$

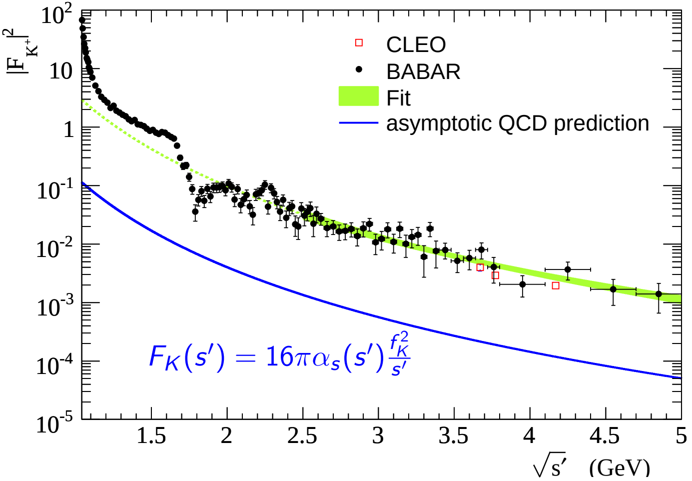
Backgrounds mainly cross-feed from other ISR processes; systematic uncertainty typically few $\times 10^{-3}$ or less depending on channel, but tends higher at extremes of $\sqrt{s'}$

K^+K^- results: Cross section

Based on 232 fb^{-1} dataset



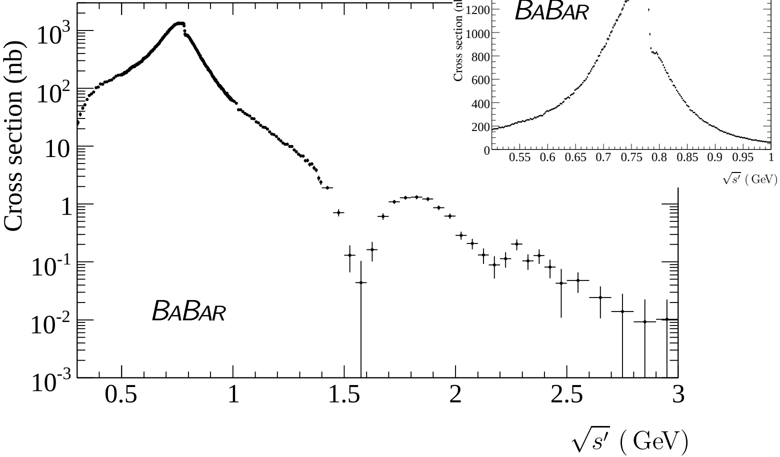
K^+K^- results: Charged kaon form factor



Confirm discrepancy with QCD prediction for normalization ($\sim \times 4$); shape is consistent.

$\pi^+\pi^-$ cross section results

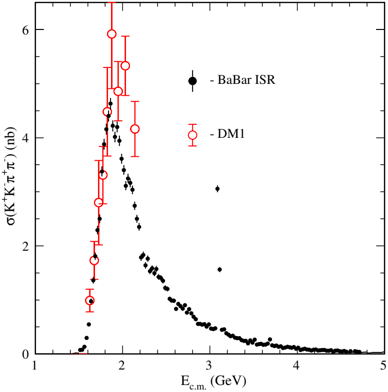
Based on 232 fb^{-1} dataset



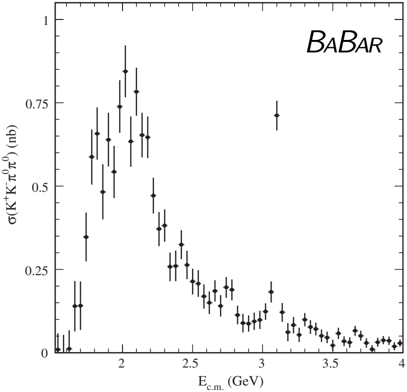
$K^+K^-\pi\pi$ cross section results

Based on 454 fb^{-1} dataset (statistical uncertainties shown)
Dressed cross section, including vacuum polarization

$K^+K^-\pi^+\pi^-$

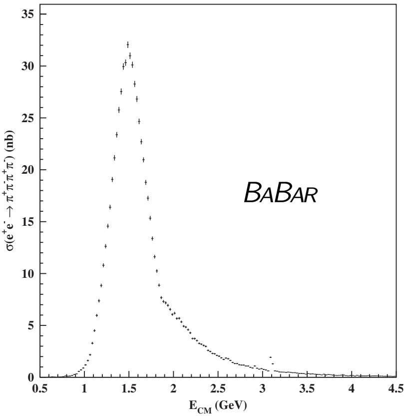


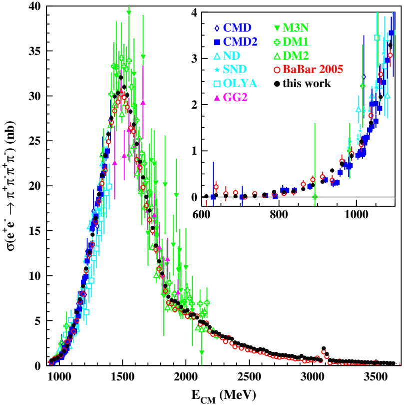
$K^+K^-\pi^0\pi^0$



$\pi^+\pi^-\pi^+\pi^-$ cross section results

Based on 454 fb^{-1} dataset (statistical uncertainties shown)
Dressed cross section, including vacuum polarization





Conclusions

Channel	$a_\mu(\text{had})$ (10^{-11})	
	BaBar	world average w/o *BaBar*
$\pi\pi(\gamma)$	$5141 \pm 22 \pm 31$	5056 ± 30
$\pi^+\pi^-\pi^+\pi^-$	$136.4 \pm 0.3 \pm 3.6$	139.5 ± 9.0
K^+K^-	$229.3 \pm 1.8 \pm 2.2$	$216.3 \pm 2.7 \pm 6.8$

- Precision on $\pi^+\pi^-$ comparable with previous WA
- Precision on 4π factor 2.6 better than previous WA
- Precision on K^+K^- factor 3 better than previous WA

- FNAL E989 goal: reduce error bar on measured a_μ from 63×10^{-11} to 16×10^{-11}
  - Expect lattice calculations to eventually provide most precise SM predictions for HVP, but:
  - "few percent error on timescale of Muon $g-2$ experiment"

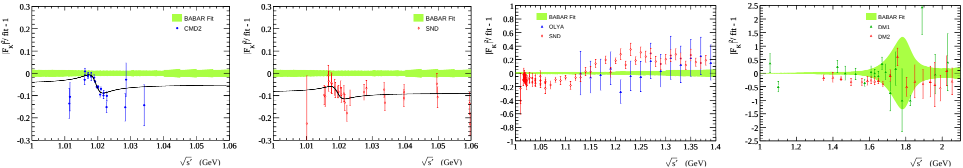
    R. Van de Water, Snowmass 2013
  - Dominant $\pi\pi$ channel result is on half of the *BaBar* dataset. Possibly could use other half as well to help on E989 timescale.
- Analysis of $K_S^0K_L^0$, $K_S^0K_L^0\pi^+\pi^-$, $K_S^0K^\pm\pi^\mp\pi^0$ in progress

BACKUP

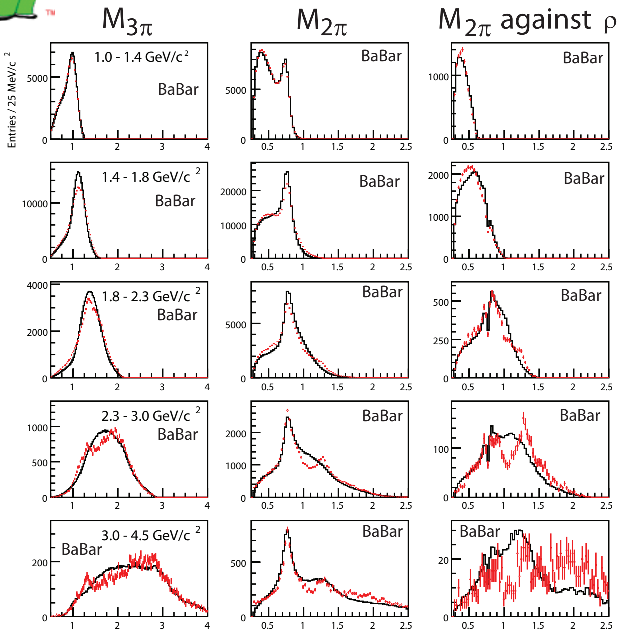
K^+K^- comparison with other experiments

ϕ mass consistent within calibration uncertainties with CMD2 and SND However, normalization is not:

$$\frac{\text{norm}(\textit{BaBar})}{\text{norm}(\text{CMD2, SND})} - 1 = \begin{cases} 0.051 \pm 0.003_{\text{CMD2}} \pm 0.006_{\textit{BaBar}} & \textit{BaBar} \text{ vs CMD2} \\ 0.096 \pm 0.009_{\text{SND}} \pm 0.006_{\textit{BaBar}} & \textit{BaBar} \text{ vs SND} \end{cases}$$



Substructure in $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$



Red: Data
Black: MC
Czyż and Kühn, EP J C**18** 497 (2001)