Measurement of exclusive hadronic cross sections with the BaBar detector and implications on the g-2 of the muon

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On behalf of the BaBar collaboration

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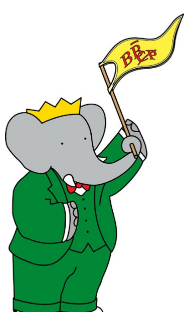


Outline

- g-2 of the muon
- ISR analysis at BaBar
- Recent results:
  - $\pi^+\pi^-\pi^0\pi^0$
  - $\pi^+\pi^-\eta$
  - $K_SK_L\pi^0$, $K_SK_L\eta$, $K_SK_L\pi^0\pi^0$
  - $K_SK^+\pi^-\pi^0$, $K_SK^+\pi^-\eta$
- Conclusions

a_μ of the Muon (1)

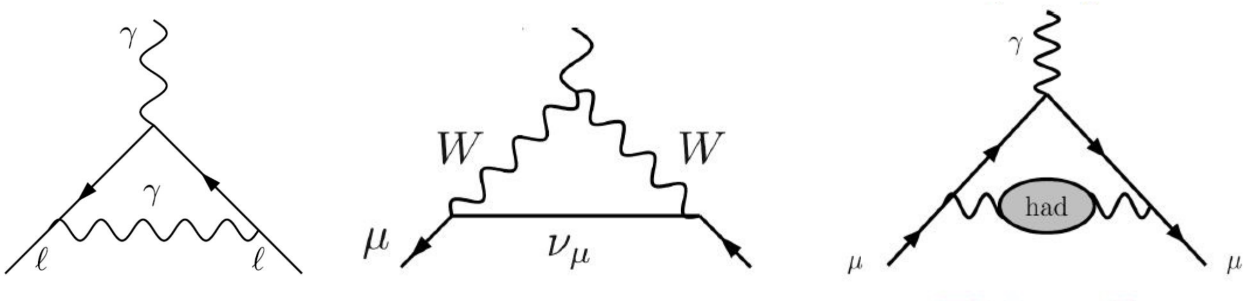
$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

Dirac equation predicts g=2 for point like fermions

$$a_\mu = \frac{g_\mu - 2}{2}$$

Higher orders contributions lead to non zero a_μ

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{hadronic}$$



a_μ is sensitive to New Physics

$$a_\mu = a_\mu^{SM} + a_\mu^{NP}$$

a_μ of the Muon (2)

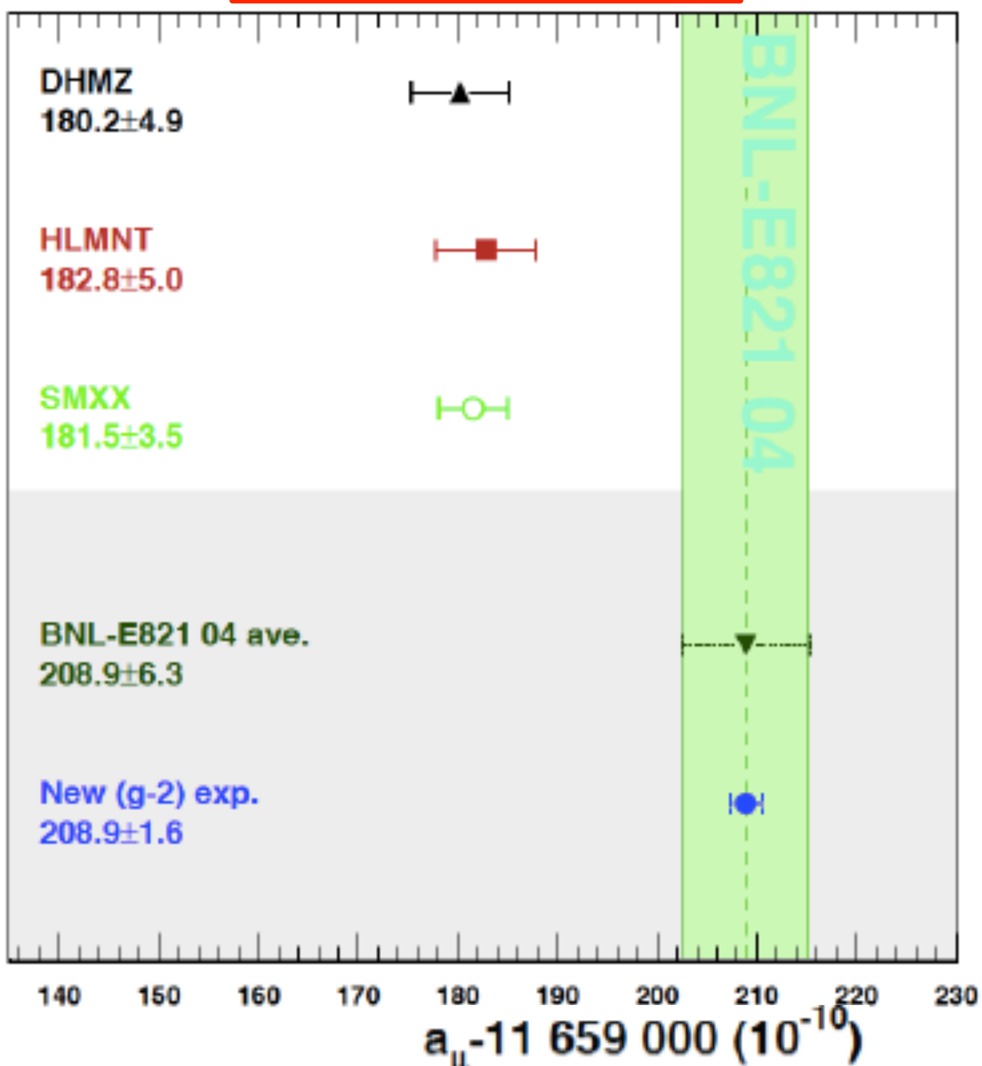
Experiments have achieved an amazing precision and are still improving

E821@BNL (1997-2001):
G.W. Bennett *et al.*,
Phys. Rev. D **77**, 072003 (2006)
$a_\mu = (11\ 659\ 209.1 \pm 6.3) \times 10^{-10}$ (0.54 ppm)

E989 @ FNAL (2017-…):
F. Gray *et al.*, arXiv: 1510.003
$a_\mu = \ldots$ (0.14 ppm)

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

T. Teubner, PhiPsi 2017



DHMZ , TAU 2016, arXiv:1612.02743

a_μ of the Muon (3)

Comparison with measurement ($\times 10^{-10}$)

$a_\mu^{\text{total-SM}}$	11659181.7 ± 4.2
$a_\mu^{\text{BNL-E821}}$	11659209.1 ± 6.3
Data - SM	27.4 ± 7.6 (3.6σ)

1. Need more precise measurements of a_μ
2. Need to improve accuracy of SM prediction

Individual SM contributions ($\times 10^{-10}$)

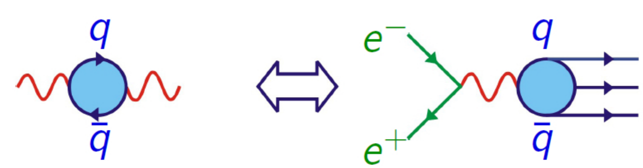
a_μ^{QED}	11658471.895 ± 0.008
a_μ^{EW}	15.4 ± 0.1
$a_\mu^{\text{had,LO-VP}}$	692.6 ± 3.3
$a_\mu^{\text{had,HO-VP}}$	-8.63 ± 0.09
$a_\mu^{\text{had,LbLs}}$	10.5 ± 2.6

Uncertainties from hadronic contributions dominate

a_μ of the Muon (4)

The hadronic leading order vacuum polarization contribution is calculated using dispersion relations from experimental data on the total cross section of the e^+e^- annihilation into hadrons

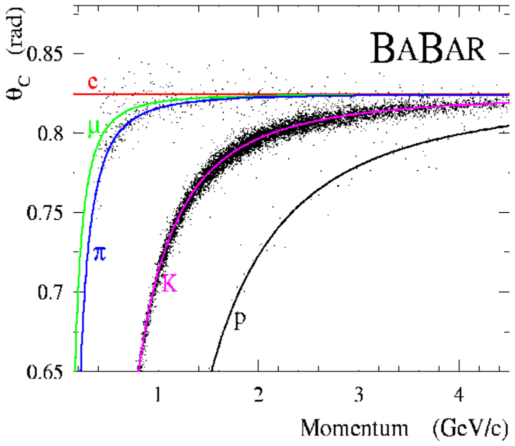
$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\ \frac{1}{s}\hat{K}(s)\sigma_{\mathrm{had}}(s)$$

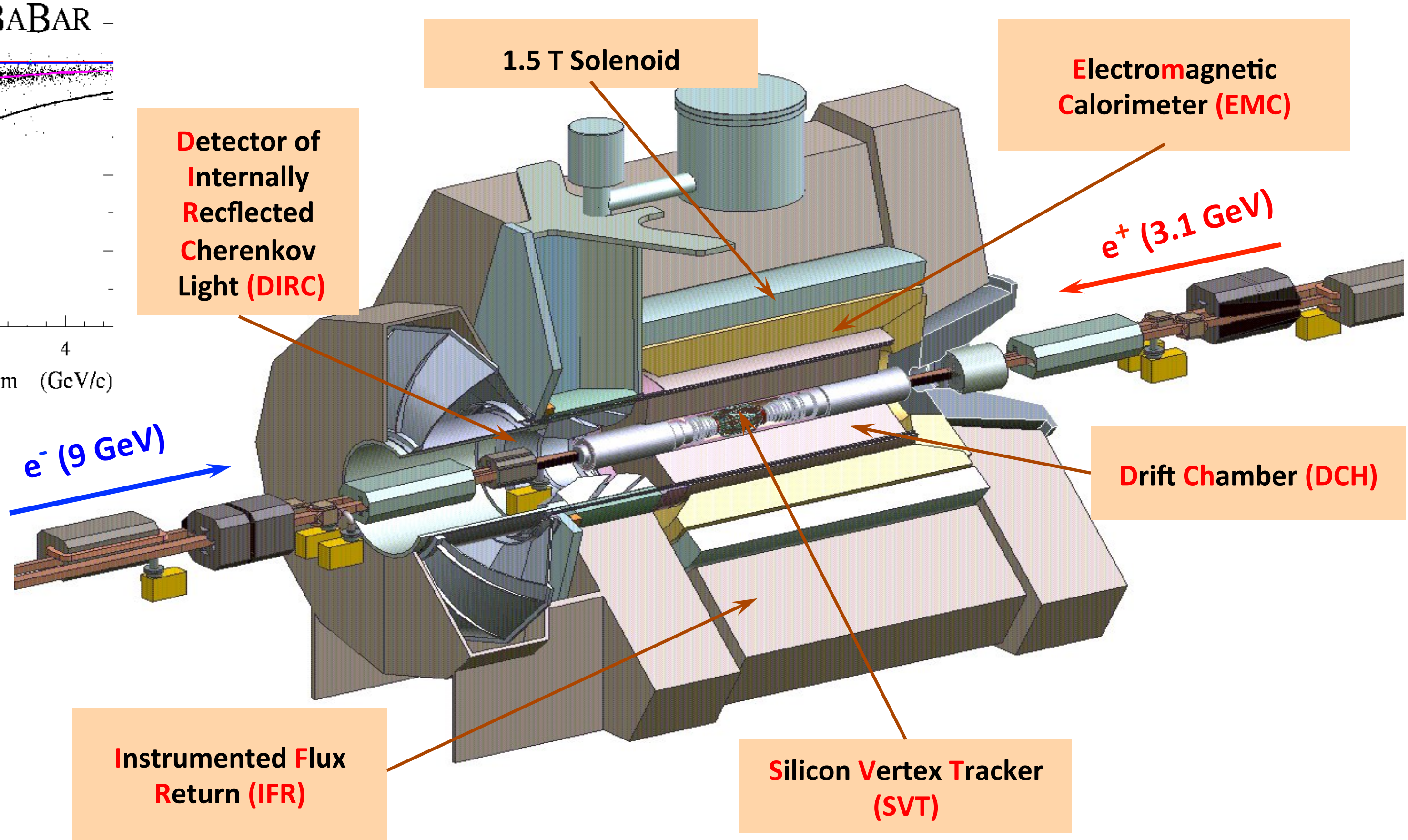


Lower energies (E < 2 GeV) give dominant contribution

- To get σ^0_{had} sum cross sections of measured exclusive channels and use isospin relations for missing channels
- Experimental options are:
  - perform a direct scan (require tunable beam energy)
  - take advantage of radiative return (ISR events)

The BaBar Detector

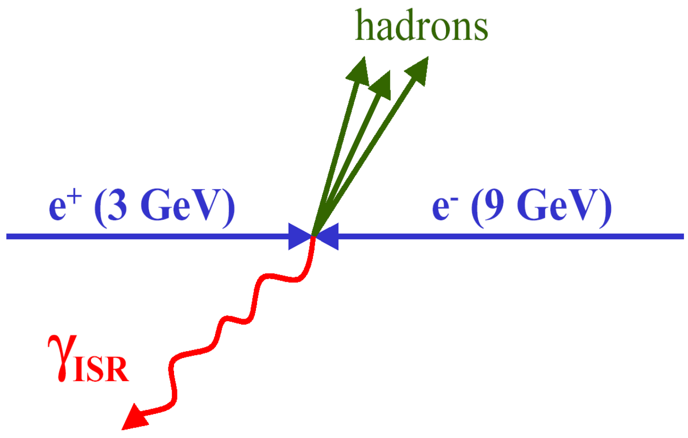




BaBar collected data at the PEP-II asymmetric collider at SLAC between 1999 and 2008.

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

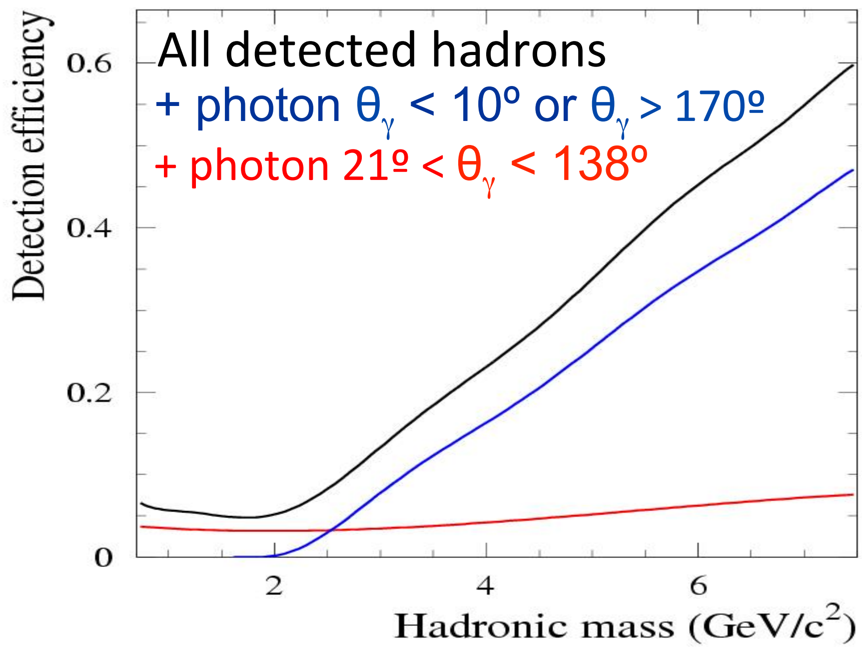
ISR Method at BaBar



The mass spectrum of the hadronic system in the reaction $e^+e^- \to f\,\gamma$ is related to the cross section of the reaction $e^+e^- \to f$.

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

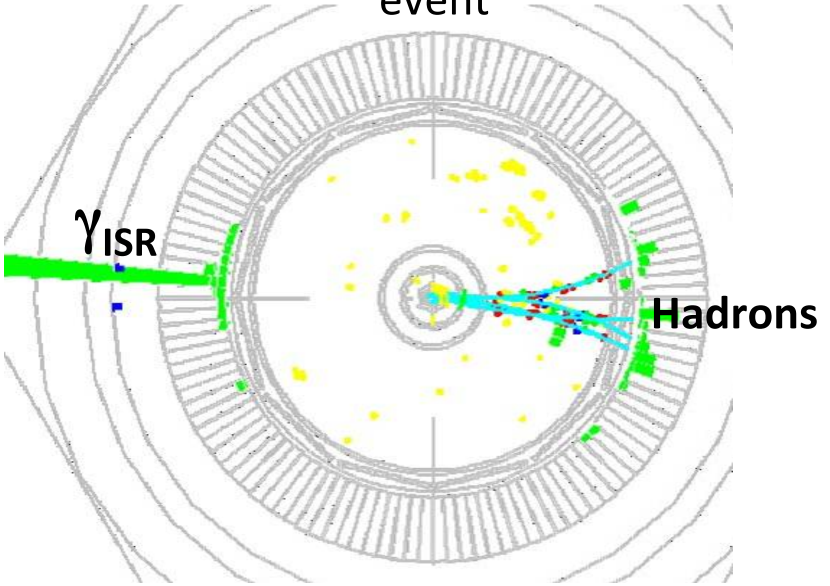
The ISR photon is emitted predominantly along the beam axis. The produced hadronic system is boosted against the ISR photon. Due to limited detector acceptance the mass region below 2 GeV can be studied only with detected photon.



Tagged ISR Analysis at BaBar

- Fully exclusive measurement
  - Photon with E_{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) ⇒ small 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

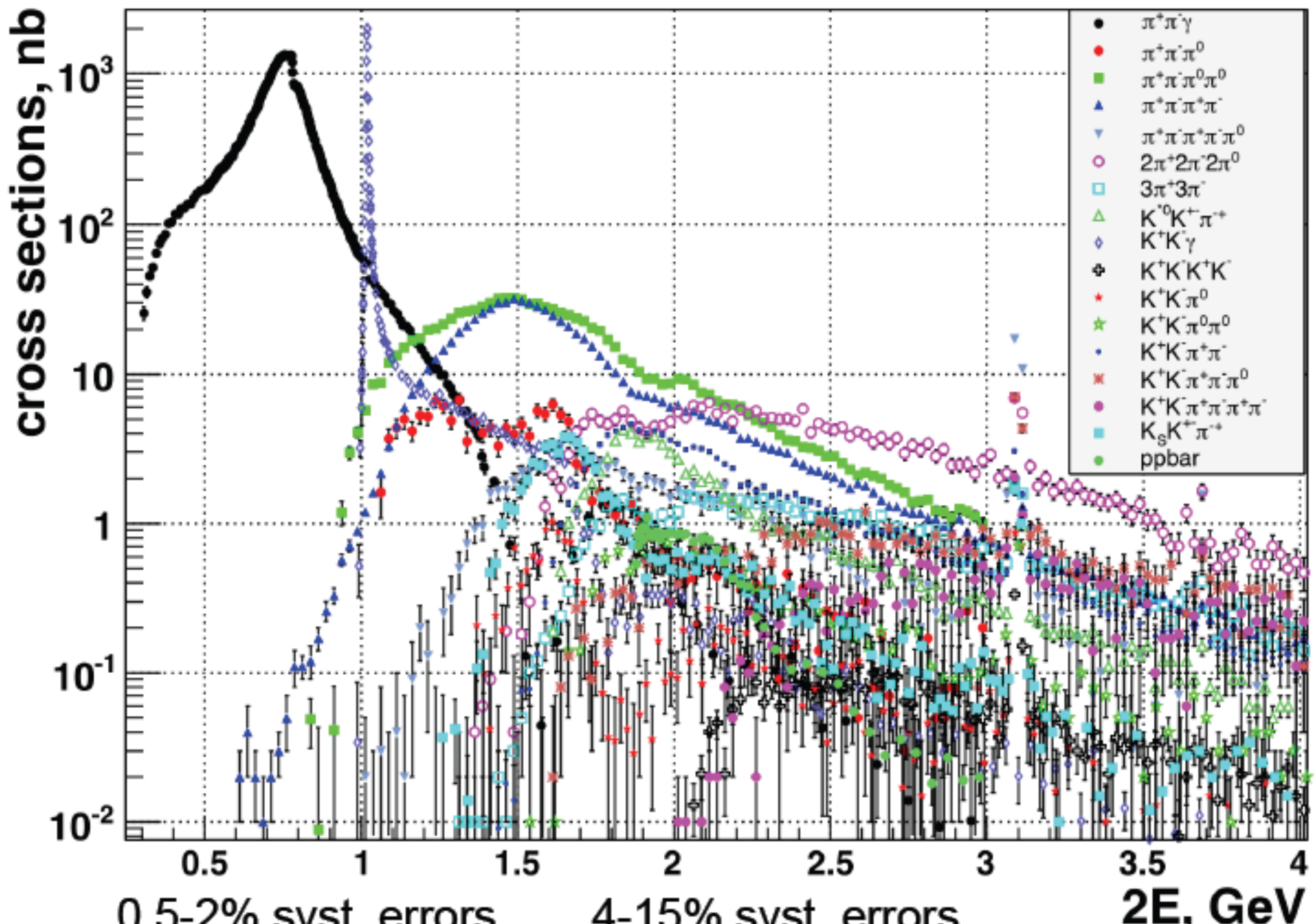
Generic BABAR ISR event



Can access a wide range of energy in a single experiment: from threshold to ~5 GeV

22 final states studied
20 published papers

BaBar Tagged ISR Analysis



0.5-2% syst. errors 4-15% syst. errors

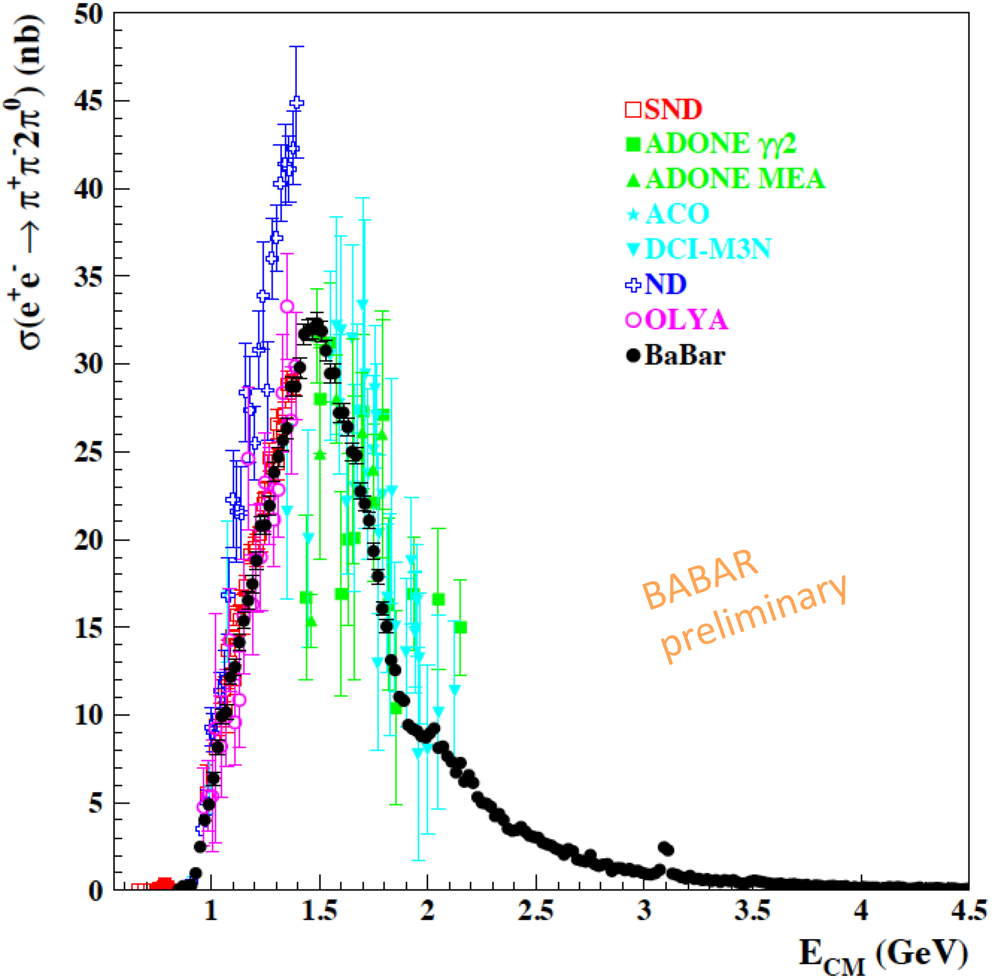
Before the BaBar Measurements (Presented in This Talk)

BaBar measurements presented in this talk:

- $\pi^+\pi^-\pi^0\pi^0$
- $\pi^+\pi^-\eta$
- $K_SK_L\pi^0$, $K_SK_L\eta$, $K_SK_L\pi^0\pi^0$
- $K_SK^+\pi^-\pi^0$, $K_SK^+\pi^-\eta$

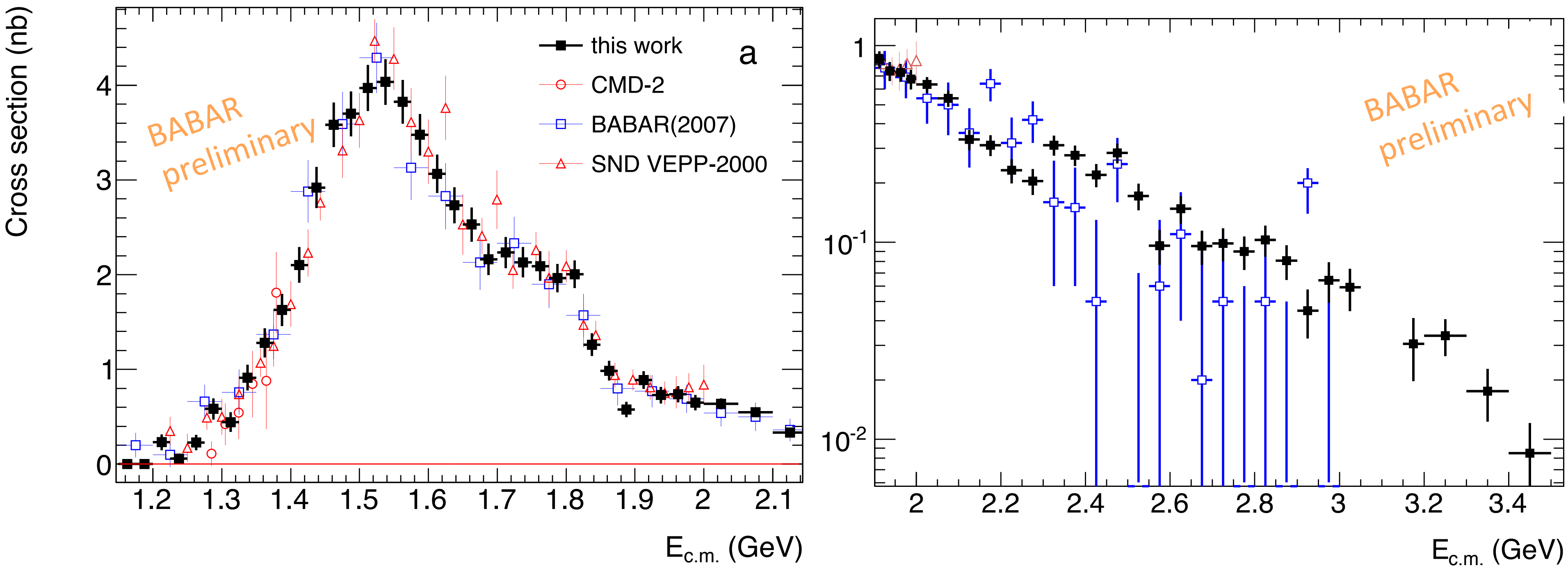
Channel	$a_\mu^{\mathrm{had,LO}}$ $[10^{-10}]$
$\pi^0\gamma$	$4.42 \pm 0.08 \pm 0.13 \pm 0.12$
$\eta\gamma$	$0.64 \pm 0.02 \pm 0.01 \pm 0.01$
$\pi^+\pi^-$	$507.80 \pm 1.22 \pm 2.50 \pm 0.56$
$\pi^+\pi^-\pi^0$	$46.00 \pm 0.42 \pm 1.03 \pm 0.98$
$2\pi^+2\pi^-$	$13.35 \pm 0.10 \pm 0.43 \pm 0.29$
$\pi^+\pi^-2\pi^0$	$18.01 \pm 0.14 \pm 1.17 \pm 0.40$
$2\pi^+2\pi^-\pi^0$ (η excl.)	$0.72 \pm 0.04 \pm 0.07 \pm 0.03$
$\pi^+\pi^-3\pi^0$ (η excl., from isospin)	$0.36 \pm 0.02 \pm 0.03 \pm 0.01$
$3\pi^+3\pi^-$	$0.12 \pm 0.01 \pm 0.01 \pm 0.00$
$2\pi^+2\pi^-2\pi^0$ (η excl.)	$0.70 \pm 0.05 \pm 0.04 \pm 0.09$
$\pi^+\pi^-4\pi^0$ (η excl., from isospin)	$0.11 \pm 0.01 \pm 0.11 \pm 0.00$
$\eta\pi^+\pi^-$	$1.15 \pm 0.06 \pm 0.08 \pm 0.03$
$\eta\omega$	$0.47 \pm 0.04 \pm 0.00 \pm 0.05$
$\eta 2\pi^+2\pi^-$	$0.02 \pm 0.01 \pm 0.00 \pm 0.00$
$\eta\pi^+\pi^-2\pi^0$ (estimated)	$0.02 \pm 0.01 \pm 0.01 \pm 0.00$
$\omega\pi^0$ ($\omega \to \pi^0\gamma$)	$0.89 \pm 0.02 \pm 0.06 \pm 0.02$
$\omega\pi^+\pi^-, \omega 2\pi^0$ ($\omega \to \pi^0\gamma$)	$0.08 \pm 0.00 \pm 0.01 \pm 0.00$
ω (non-$3\pi, \pi\gamma, \eta\gamma$)	$0.36 \pm 0.00 \pm 0.01 \pm 0.00$
K^+K^-	$21.63 \pm 0.27 \pm 0.58 \pm 0.36$
$K_S^0K_L^0$	$12.96 \pm 0.18 \pm 0.25 \pm 0.24$
ϕ (non-$K\overline{K}, 3\pi, \pi\gamma, \eta\gamma$)	$0.05 \pm 0.00 \pm 0.00 \pm 0.00$
$KK\pi$ (partly from isospin)	$2.39 \pm 0.07 \pm 0.12 \pm 0.08$
$K\overline{K}2\pi$ (partly from isospin)	$1.35 \pm 0.09 \pm 0.38 \pm 0.03$
$KK3\pi$ (partly from isospin)	$-0.03 \pm 0.01 \pm 0.02 \pm 0.00$
$\phi\eta$	$0.36 \pm 0.02 \pm 0.02 \pm 0.01$
$\omega K\overline{K}$ ($\omega \to \pi^0\gamma$)	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$

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



- BABAR results are most precise and covers wider energy range
- Systematic uncertainty is 3.1% in the 1.2-2.7 GeV energy range. Dominated by background subtraction.
- Contribution to a_μ for the range $1.02<E_{CM}<1.8$ GeV is measured to be
  - 17.5 ± 0.6 (stat+syst)] × 10^{-10}
  - 3.4% precision
- Previous result including the preliminary BaBar data from 2007 is
  - 18.0 ± 1.2 (stat+syst)] × 10^{-10}
  - 6.7% precision

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



The BaBar results in the $\eta \rightarrow \gamma\gamma$ mode agrees well with the previous measurements, but is more precise and covers wider energy range

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

$a_\mu^{had\ LO}(\sqrt{s} < 1.8\ GeV) = (1.18 \pm 0.06) \cdot 10^{-10}$ (this analysis)

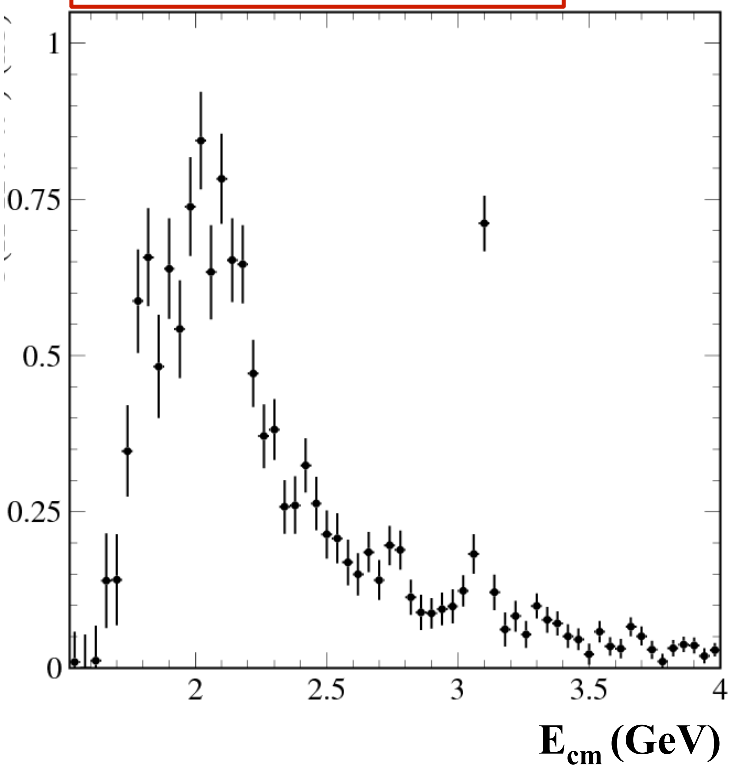
1.15 ± 0.10 – (before this measurement)

$e^+ e^- \to K K \pi\pi$ (1)

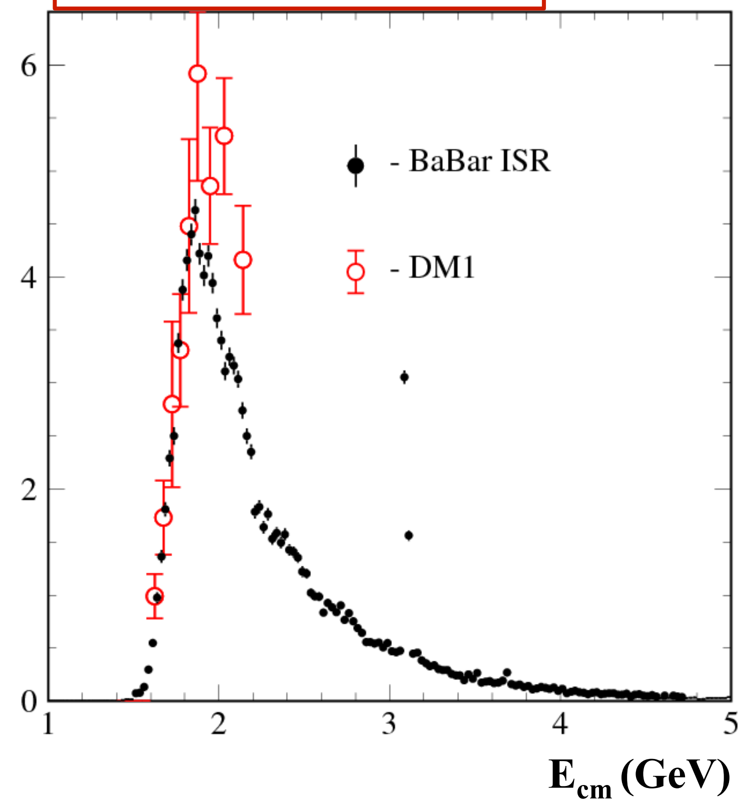
There are six combinations in the $e^+e^- \to K K\pi\pi$ processes . Four were measured previously

Phys. Rev. D 86, 012008 (2012)

$\sigma(e^+e^- \to K^+K^-\pi^0\pi^0)$, nb



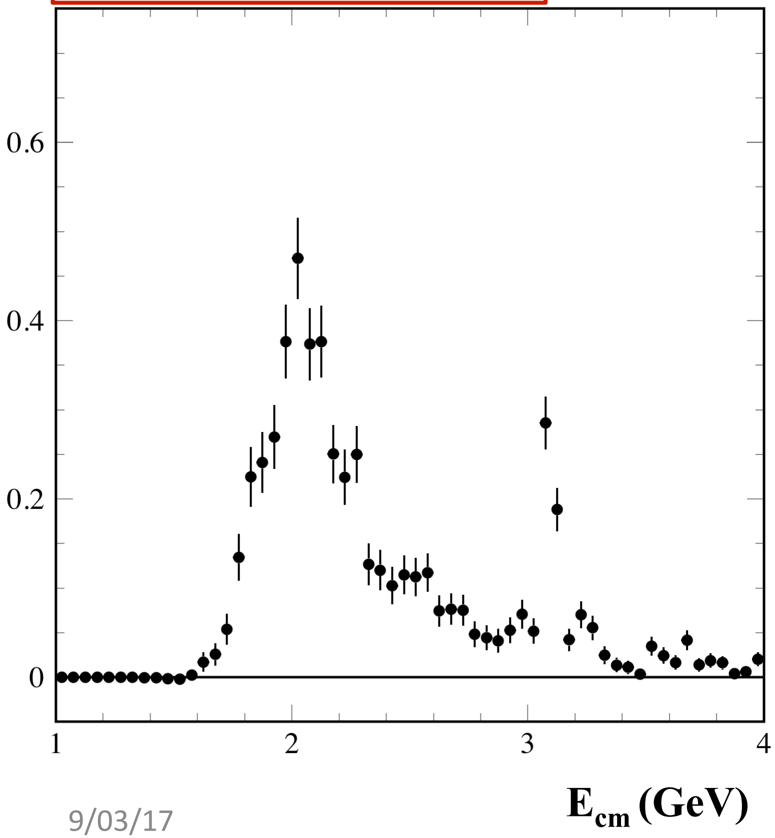
$\sigma(e^+e^- \to K^+K^-\pi^+\pi^-)$, nb



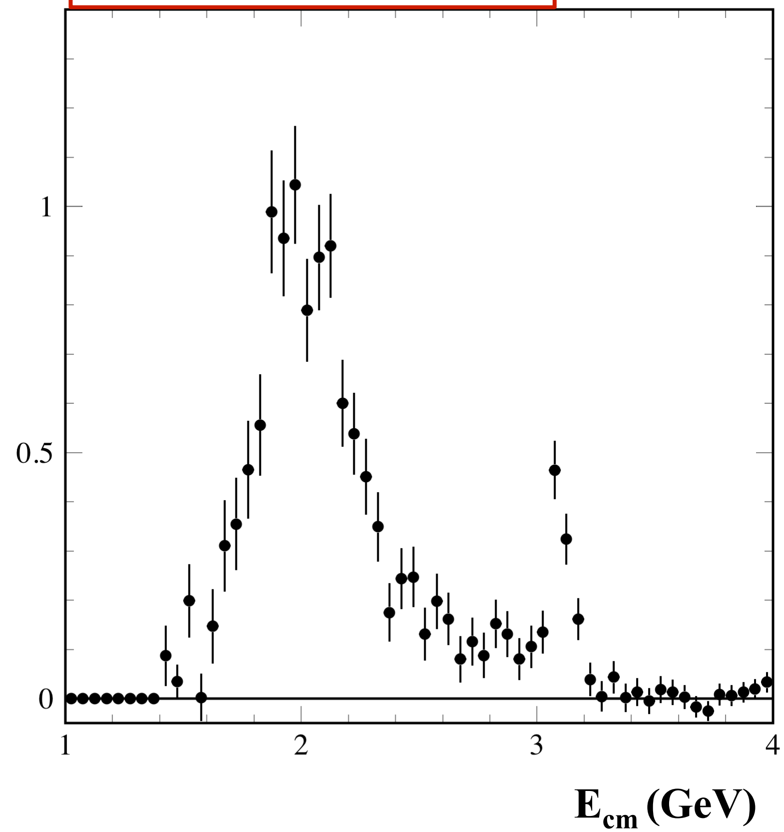
$e^+ e^- \to KK\pi\pi$ (2)

Phys. Rev. D 89, 092002 (2014)

$\sigma(e^+e^- \to K_S K_S \pi^+\pi^-)$

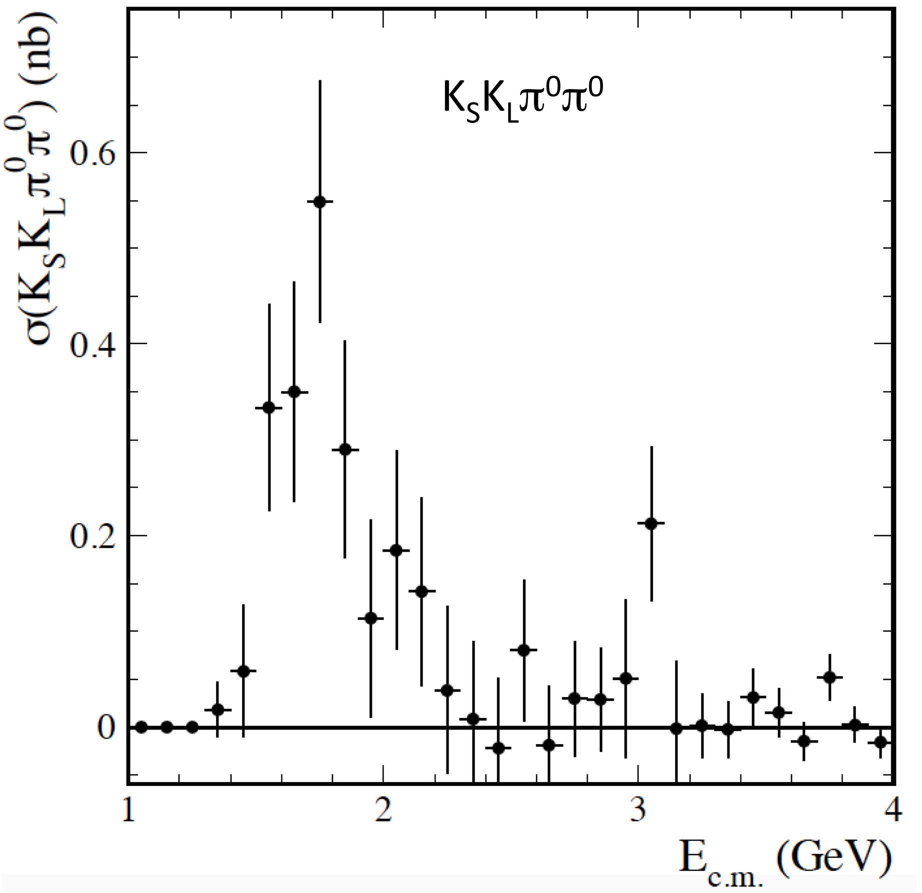


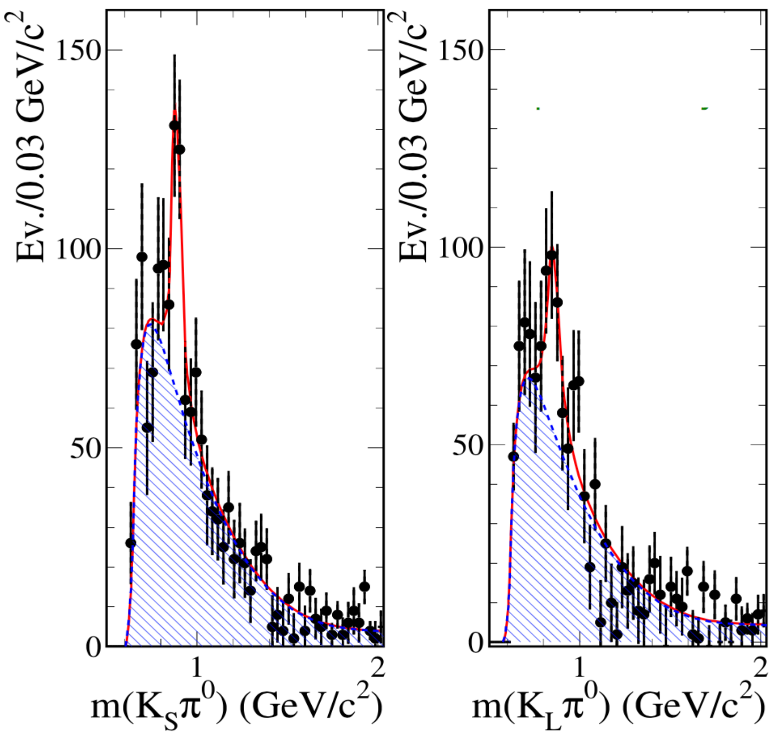
$\sigma(e^+e^- \to K_S K_L \pi^+\pi^-)$, nb



Phys. Rev. D 95, 052001 (2017)

$e^+ e^- \to K_S K_L \pi^0 \pi^0$

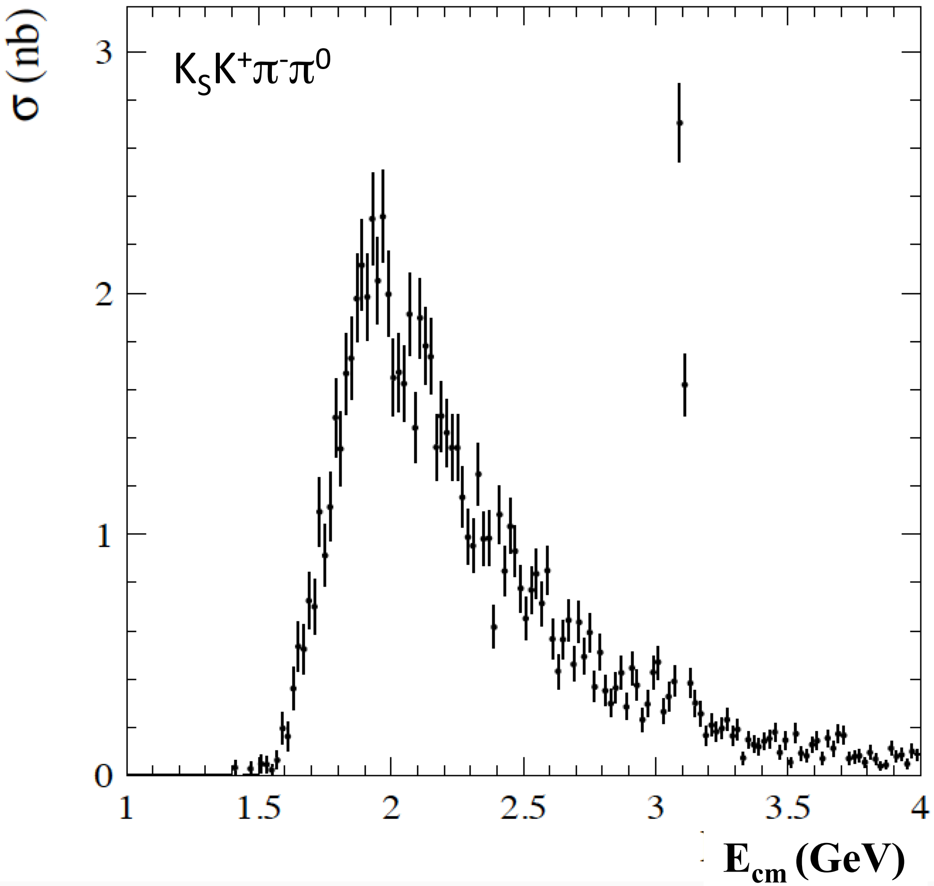




- First measurement
- Systematic uncertainty is 25% at the peak, grows to 60% at 2 GeV. Dominated by background subtraction.
- Dominant K*(892)Kπ intermediate state.

Phys. Rev. D 95, 092005 (2017)

$e^+ e^- \to K_S K^+ \pi^- \pi^0$

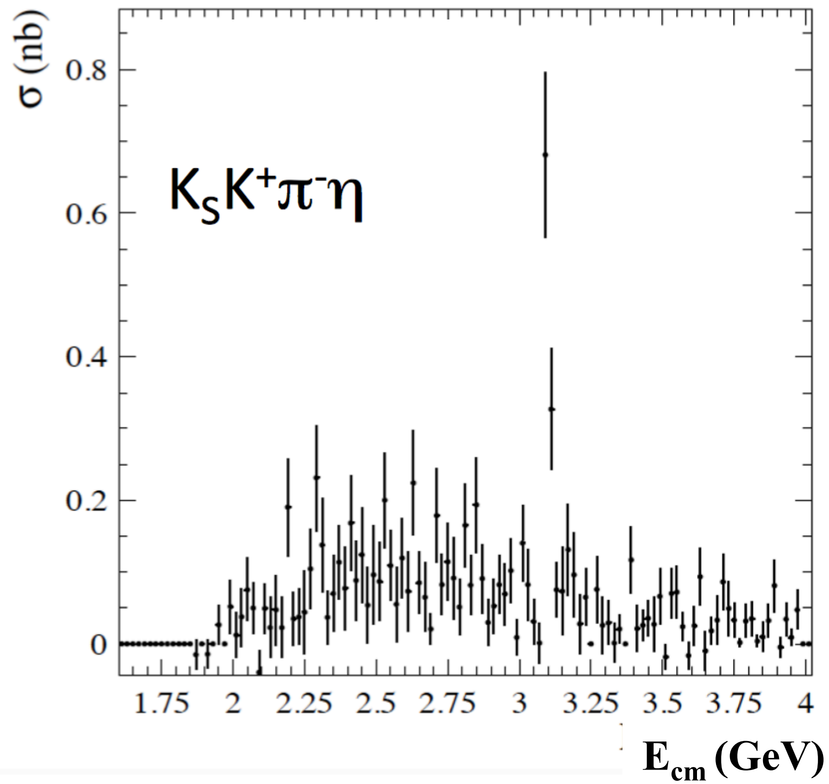


Intermediate state
$K^{*0} K^0_S \pi^0$
$K^{*0} K^{\pm} \pi^{\mp}$
$K^*_2(1430)^0 K^0_S \pi^0$
$K^*_2(1430)^0 K^{\pm} \pi^{\mp}$
$K^*(892)^{\pm} K^0_S \pi^{\mp}$
$K^*(892)^{\pm} K^{\mp} \pi^0$
$K^*_2(1430)^{\pm} K^0_S \pi^{\mp}$
$K^*_2(1430)^{\pm} K^{\mp} \pi^0$
$K^{*0} \overline{K}^{*0}$
$K^*(892)^+ K^*(892)^-$
$K^0_S K^{\pm} \rho(770)^{\mp}$

- First measurement
- Systematic uncertainty is 6-7% below 3 GeV. Dominated by background subtraction.
- 11 intermediate states – dominant are $K^*(892)K\pi$, $K_S K^+ \rho^-(770)$

Phys. Rev. D 95, 092005 (2017)

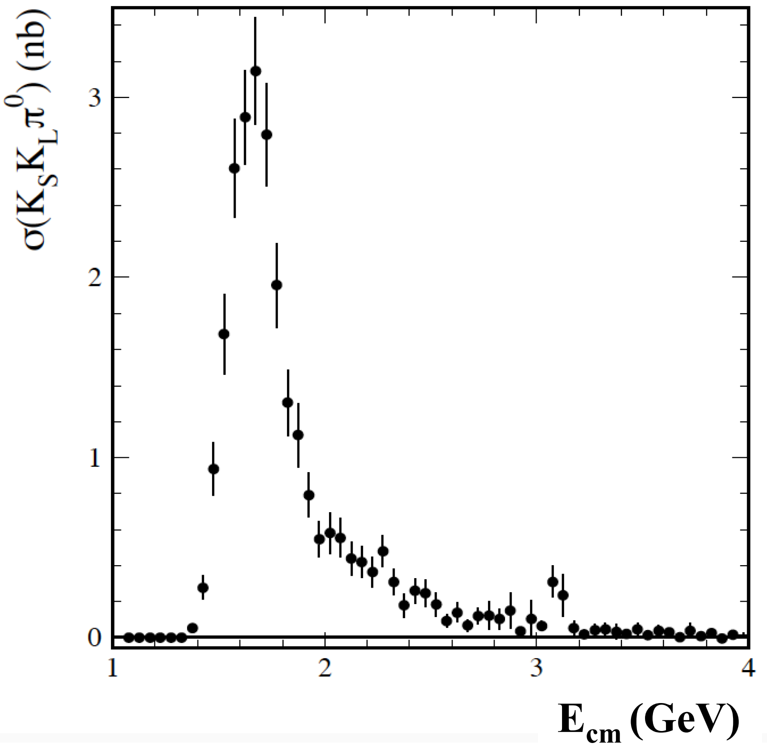
$e^+ e^- \rightarrow K_S K^+ \pi^- \eta$

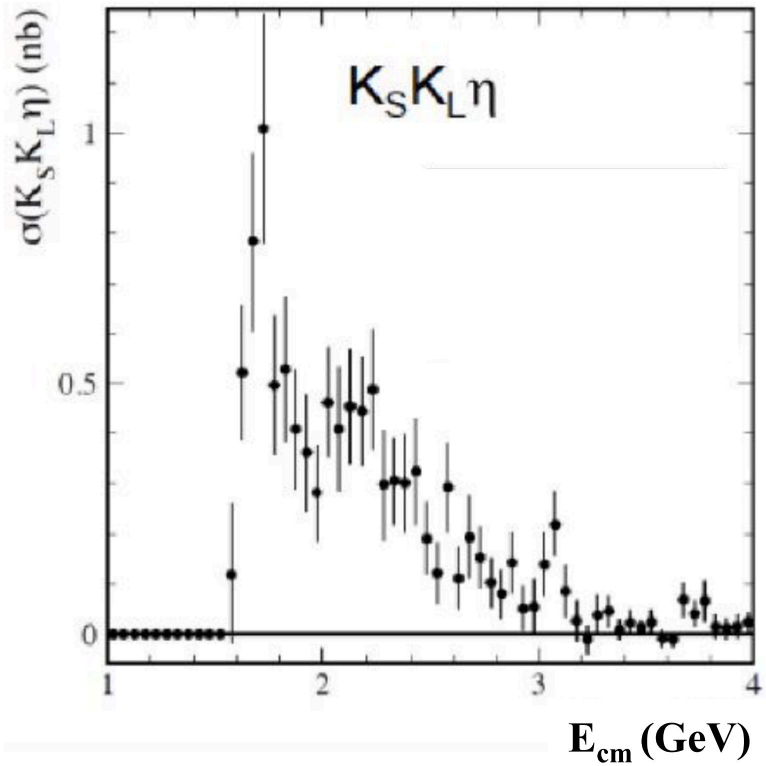


- First measurement
- Systematic uncertainty is 12-19% below 3 GeV. Dominated by background subtraction
- Dominant $K^*(892)K\eta$ intermediate state.

Phys. Rev. D 95, 052001 (2017)

$e^+ e^- \rightarrow K_S K_L \pi^0$, $K_S K_L \eta$

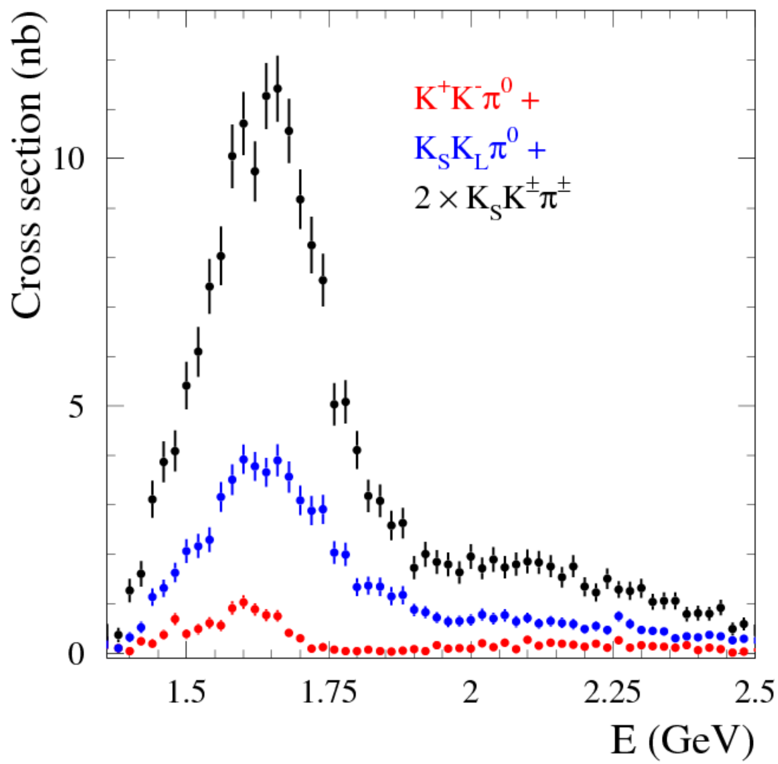


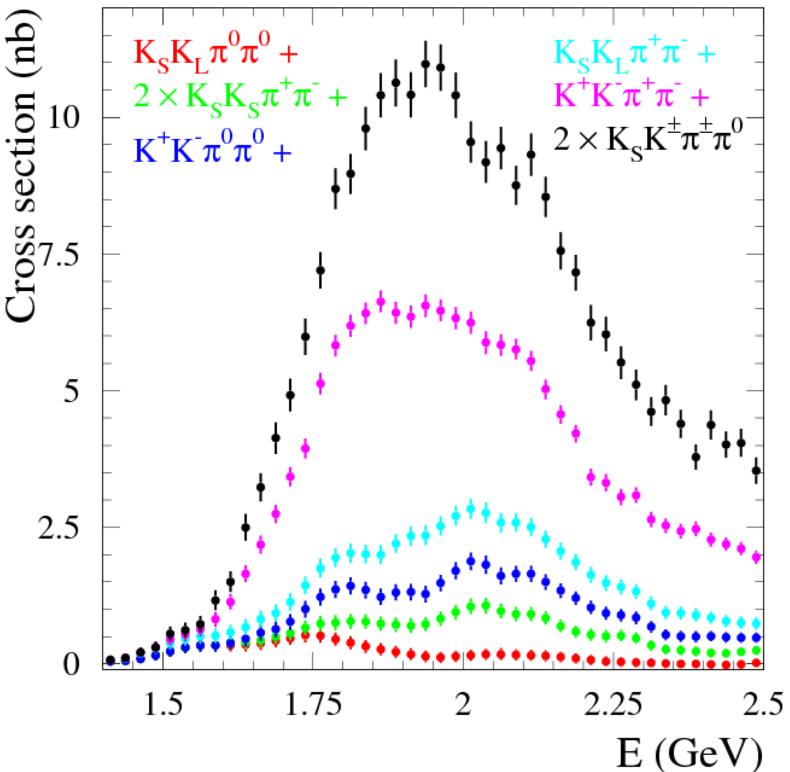


- First measurement
- Systematic uncertainty is 10% near the peak, grows to 30% at 3.0 GeV. Dominated by backgrond subtraction.
- Dominant K*(892)Kπ intermediate state

- First measurement
- Systematic uncertainty is 25% at the peak, grows to 60% at 2 GeV. Dominated by background subtraction

$e^+ e^- \rightarrow KK\pi, KK\pi\pi$: all modes





- **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)**

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

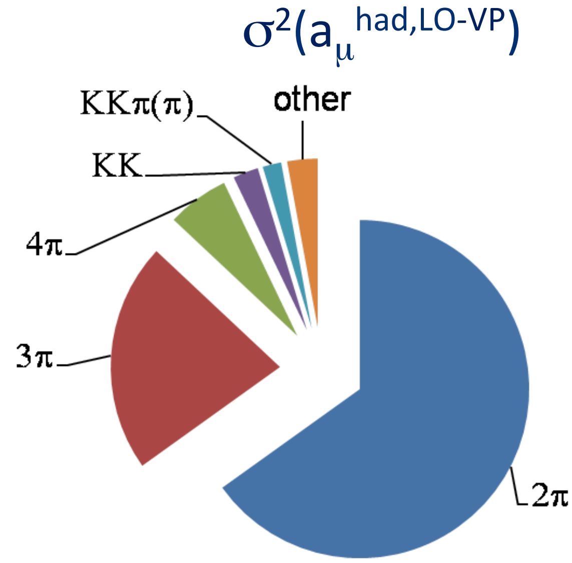
2.39 ± 0.16

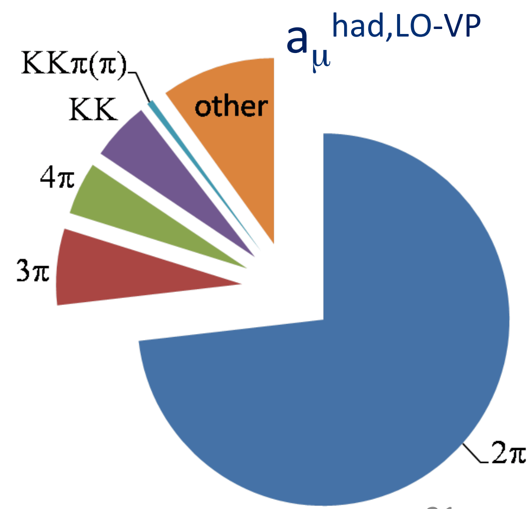
$$a_\mu(KK\pi\pi) = (0.85 \pm 0.05)\, 10^{-10}$$

1.35 ± 0.39

Summary

- Precise low-energy e^+e^- hadronic cross section data are needed to obtain an accurate SM prediction for $a_\mu^{had,LO-VP}$
- Recent results on the $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$, $KK\pi$, $KK\pi\pi$ cross sections from BaBar reduce the uncertainty on $a_\mu^{had,LO-VP}$
- However the exclusive data are incomplete in the region 1.6<E<2.0 GeV.
  - There is still no experimental information on final states like $\pi^+\pi^-\pi^0\eta$, $\pi^+\pi^-\eta\eta$, $\pi^+\pi^-\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0\pi^0\eta$, 7π…
- New results are expected from BaBar, as well as from BES III, SND, CMD-3
  - On a longer term, Belle II can have a significant impact





Backup

BaBar ISR References

$e^+e^- \to \pi^+\pi^-$	Phys. Rev. Lett. 103 231801 (2009)
	Phys. Rev. D 86, 032013 (2012)
$e^+e^- \to K^+K^-$	Phys. Rev. D 88, 032013 (2013)
	Phys. Rev. D 92, 072008 (2015)
$e^+e^- \to K_SK_L$, $K_SK_L\pi^+\pi^-$, $K_SK_S\pi^+\pi^-$, $K_SK_SK^+K^-$	Phys. Rev. D 89, 092002 (2014)
$e^+e^- \to$ p anti-p	Phys. Rev. D 73, 012005 (2006)
	Phys. Rev. D 87, 092005 (2013)
	Phys. Rev. D 88, 072009 (2013)
$e^+e^- \to \Lambda$ anti-Λ, Σ^0 anti-Σ^0, Λ anti-Σ^0	Phys. Rev. D 76, 092006 (2007)
$e^+e^- \to \pi^+\pi^-\pi^0$	Phys. Rev. D 70, 072004 (2004)
$e^+e^- \to K^+K^-\eta$, $K_SK^+\pi^-$ $K^+K^-\pi^0$	Phys. Rev. D 77, 092002 (2008)
$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$	Phys. Rev. D 71, 052001 (2005)
	Phys. Rev. D 85, 112009 (2012)
$e^+e^- \to K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$, $K^+K^-K^+K^-$	Phys. Rev. D 74, 091103 (2006)
	Phys. Rev. D 76, 012008 (2007)
	Phys. Rev. D 86, 012008 (2012)
$e^+e^- \to 2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $K^+K^-\pi^+\pi^-\pi^0$, $K^+K^-\pi^+\pi^-\eta$	Phys. Rev. D 76, 092005 (2007)
$e^+e^- \to 3(\pi^+\pi^-)$, $2(\pi^+\pi^-\pi^0)$, $K^+K^-2(\pi^+\pi^-)$	Phys. Rev. D 73, 052003 (2006)

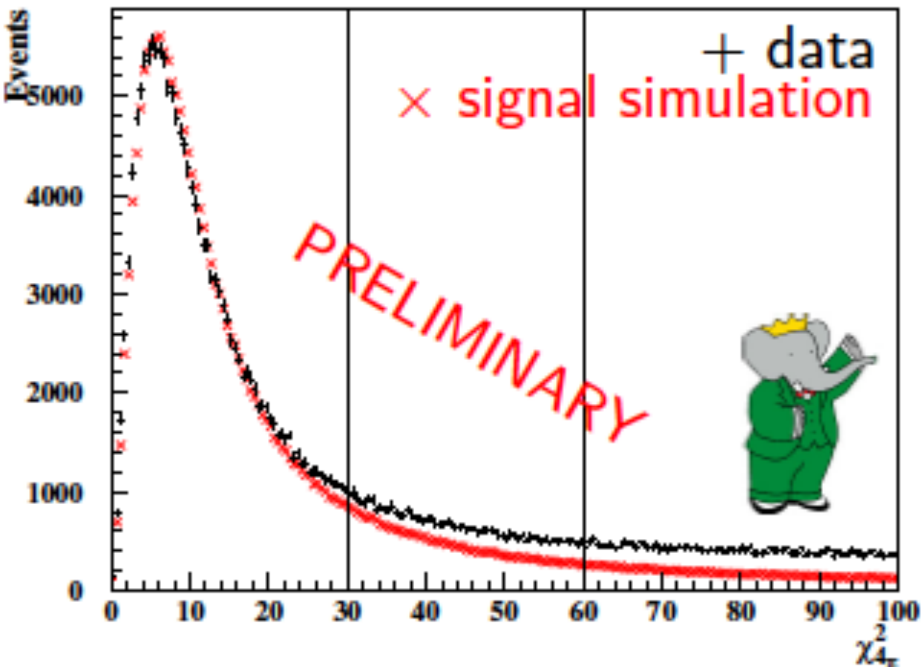
a_μ of the Muon (2)

T. Teubner, TAU 2016

QED contribution	$11\ 658\ 471.808\ (0.015) \times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	$15.4\ (0.2) \times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	$\mathbf{694.9\ (4.3)} \times 10^{-10}$	HLMNT11
NLO hadronic	$-9.8\ (0.1) \times 10^{-10}$	HLMNT11
light-by-light	$10.5\ (2.6) \times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	$\mathbf{11\ 659\ 182.8\ (4.9)} \times 10^{-10}$	
Experiment	$\mathbf{11\ 659\ 208.9\ (6.3)} \times 10^{-10}$	world avg
Exp − Theory	$\mathbf{26.1\ (8.0)} \times 10^{-10}$	**3.3 σ discrepancy**

(Numbers taken from HLMNT11, arXiv:1105.3149)

$e^+ e^- \to \pi^+\pi^-\pi^0\pi^0$

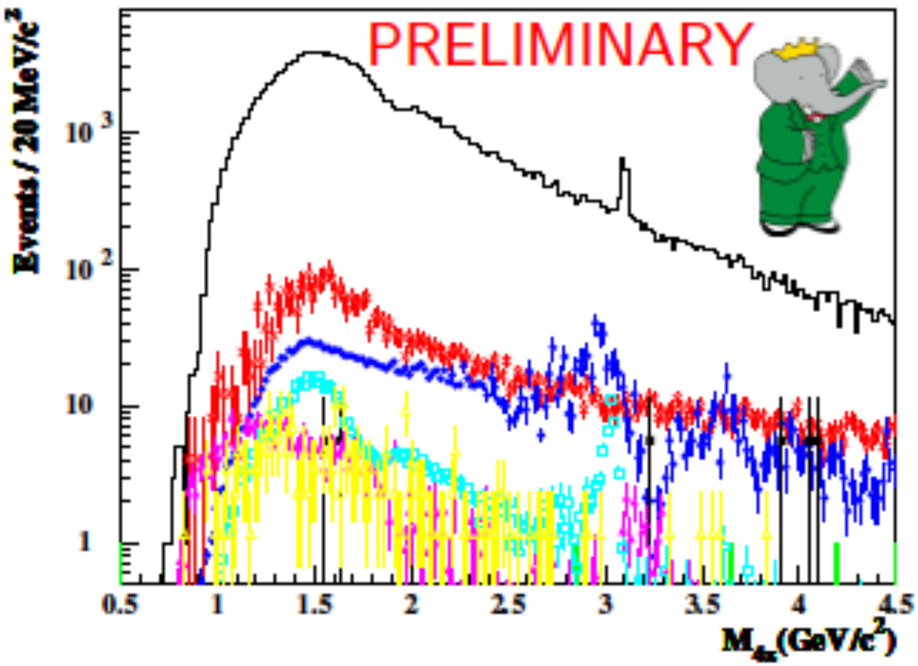


Main Selection Requirements

- exactly 2 charged tracks
- ≥ 5 photons
- $E_\gamma^{\text{lab}} > 0.05$ GeV
- $|M_{\pi^0}^{\text{reco}} - M_{\pi^0}^{\text{PDG}}| < 0.03$ GeV
- $E_{\gamma_{\text{ISR}}} > 3$ GeV
- 6C kinematic fit: $\chi^2_{2\pi 2\pi^0 \gamma} < 30$
- reject other hypotheses
- Muon and Kaon PID

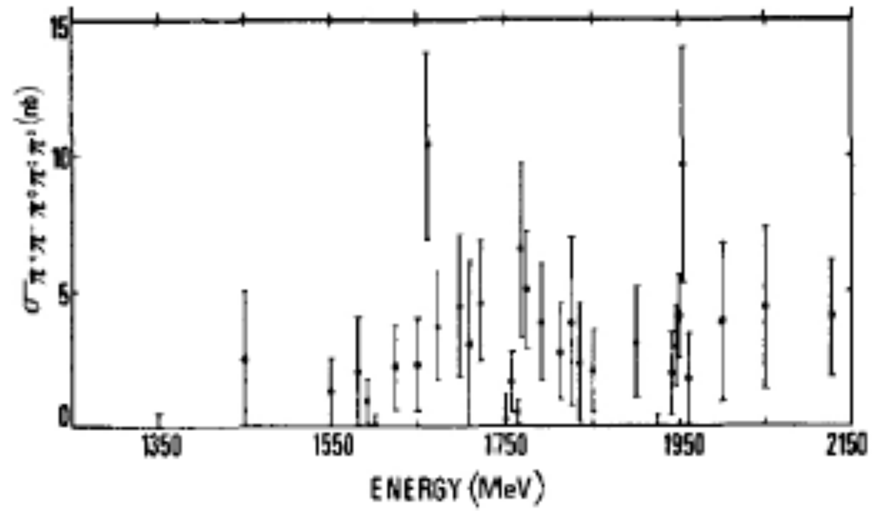
$e^+ e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

Simulated background channels:



$q\bar{q}$, 3π, $4\pi 2\pi^0$, $K_s K\pi$, $K^+K^-2\pi^0$, $\tau\tau$, $\pi^+\pi^-3\pi^0$

Main issue: background from $e^+e^- \rightarrow \pi^+\pi^-3\pi^0$



Only little data [3] and no full simulation available

$e^+ e^- \to \pi^+\pi^-\pi^0\pi^0$

$M(\pi^+\pi^-2\pi^0)(\mathrm{GeV}/c^2)$	< 1.2	$1.2 - 2.7$	$2.7 - 3.2$	> 3.2
Tracking eff.	0.8%	0.8%	0.8%	0.8%
γ eff.	0.4%	0.4%	0.4%	0.4%
$2\pi^0$ eff.	2.0%	2.0%	2.0%	2.0%
$\chi^2_{4\pi\gamma}$ eff.	0.4%	0.4%	0.4%	0.4%
Resonances in AfkQED	0.4%	0.4%	0.4%	0.4%
Mass res.	0.3%	0.3%	0.3%	0.3%
FSR	1.0%	1.0%	1.0%	1.0%
NLO ISR	0.5%	0.5%	0.5%	0.5%
ISR luminosity	1.0%	1.0%	1.0%	1.0%
continuum Bkg	1.0%	1.0%	1.0%	2.0%
ISR Background	$1 - 100\%$	1.0%	6.0%	6.0%
Kaon PID	0.5%	0.5%	0.5%	0.5%
Muon PID	0%	0%	0%	2.0%
total	$3 - 100\%$	3.1%	6.7%	7.2%

$e^+ e^- \to \pi^+\pi^-\eta$

Source	Correction, %	Systematic uncertainty, %
Selection criteria		2.5
Background subtraction		
$m_{\pi^+\pi^-\eta} < 1.35$		9
$1.35 < m_{\pi^+\pi^-\eta} < 1.80$		2
$1.80 < m_{\pi^+\pi^-\eta} < 2.50$		5
$2.50 < m_{\pi^+\pi^-\eta} < 3.10$		10.5
$3.10 < m_{\pi^+\pi^-\eta} < 3.50$		11
Trigger and filters	-1.5	1.6
η reconstruction	-2	1.0
ISR photon efficiency	-1.1	1.0
Track reconstruction	-1.1	1.0
Radiative correction		1.0
Luminosity		1.0
Total		
$m_{\pi^+\pi^-\eta} < 1.35$	-5.7	10
$1.35 < m_{\pi^+\pi^-\eta} < 1.80$	-5.7	4.5
$1.80 < m_{\pi^+\pi^-\eta} < 2.50$	-5.7	6.5
$2.50 < m_{\pi^+\pi^-\eta} < 3.10$	-5.7	11
$3.10 < m_{\pi^+\pi^-\eta} < 3.50$	-5.7	12

$e^+ e^- \to K_S K^+ \pi^- \pi^0$

Source	Correction (%)	Systematic uncertainty (%)
π^0 reconstruction	+2.0	1.0
$K^\pm$, $\pi^\pm$ reconstruction	+1.6	2.0
K^0_S reconstruction	+1.1	1.0
PID efficiency	0.0	2.0
χ^2 selection	+3.7	4.6
Background subtraction	—	2.5, $<$ 2.0 GeV
		4.2, 2.0-3.0 GeV
		10.0, $>$ 3.0 GeV
Model acceptance	—	0.5
Luminosity and Rad.Corr.	—	1.4
Total	+8.6	6.3, $<$ 2.0 GeV
		7.1, 2.0-3.0 GeV
		11.5, $>$ 3.0 GeV