Recent measurements of low-energy hadronic cross sections at BABAR & implications for g-2 of the muon

J. William Gary
U. California, Riverside

on behalf of the BABAR Collaboration

XLVII International Symposium on Multiparticle Dynamics, Tlaxcala Mexico, September 11-15, 2017

UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

Outline

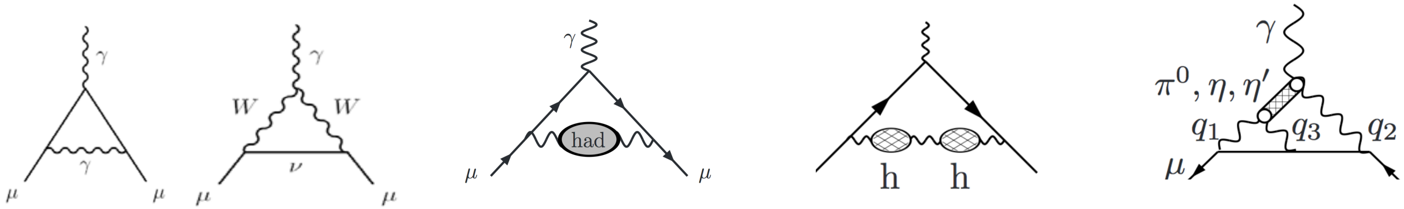
- g - 2 of the muon
- BABAR and the initial-state radiation (ISR) method
- Recent exclusive hadronic cross section measurements
  - $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ arXiv:1709.01171 (05-Sept-2017)
  - $e^+e^- \rightarrow \pi^+\pi^-\eta$ Preliminary
  - $e^+e^- \rightarrow K_SK_L\pi^0,\ K_SK_L\eta,\ K_SK_L\pi^0\pi^0$ PRD 95 (2017) 052001
  - $e^+e^- \rightarrow K_SK^+\pi^-\pi^0,\ K_SK^+\pi^-\eta$ PRD 95 (2017) 092005
- Implications for the muon g - 2
- Summary

The muon g-2 discrepancy

- Magnetic moment of a spin ½ particle: $\vec{\mu} = g\,\frac{e}{2mc}\,\vec{s}$
- Dirac equation predicts $g = 2$ exactly
- Radiative corrections alter the prediction, introducing sensitivity to new physics through loops: $g = 2(1 + a)$
- The "anomalous" moment: $a = \frac{g-2}{2}$
- Theory and experiment agree to high precision for the electron anomalous moment
- For the muon, there is a tension on the order of 3.5 standard deviations → <u>the muon g-2 discrepancy</u>

g_μ - 2 in the standard model

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{hadronic,LO} + a_\mu^{hadronic,HO} + a_\mu^{hadronic,LBLs}$$



Diagrams from Jegerlehner and Nyffeler, Phys. Rept. 477 (2009) 1

Hadronic light-by-light scattering

a_μ^{QED}	116584718.95 ± 0.08
a_μ^{EW}	153.6 ± 1.0
$a_\mu^{had,LO}$	6923 ± **42**
$a_\mu^{had,HO}$	-98.4 ± 0.6
$a_\mu^{had,LbLs}$	105 ± 26
$a_\mu^{total\text{-}SM}$	116591802 ± **49**

M. Davier et al., EPJC 71 (2011) 1515 **units of 10^{-11}**
& PDG (2016)

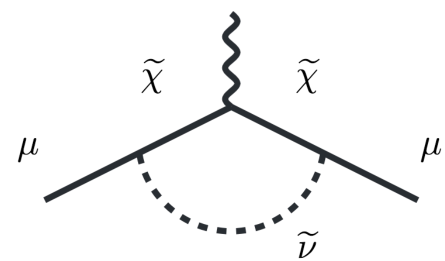
$a_\mu^{BNL\text{-}E821*}$	116592091 ± 63
Data - SM	288 ± 80

*PRD 73 (2006) 072003

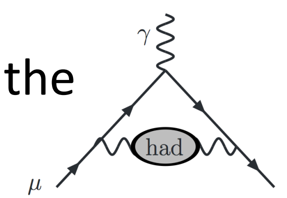
- Discrepancy between data and calculation of 3.6σ
- Uncertainty in SM prediction dominated by LO hadronic term

g_μ- 2 in the standard model

- The longstanding tension between theory and data for the muon g-2 could be an indication of new physics



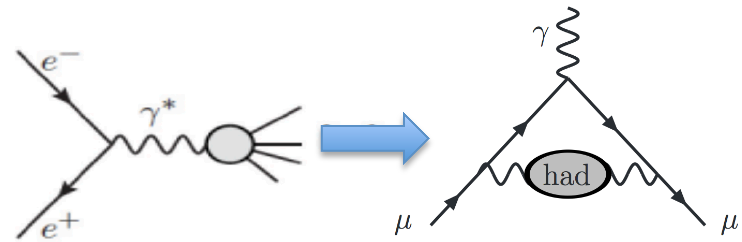
- The Muon g-2 experiment at Fermilab, with data collection starting in Fall 2017, hopes to reduce the experimental uncertainty by a factor of 4 by around 2019
- Similar goal on a somewhat longer time scale (2022 ??) by the J-PARC E34 experiment
- The limiting factor in the theoretical prediction for g - 2 is the uncertainty In the <u>leading-order hadronic term</u>

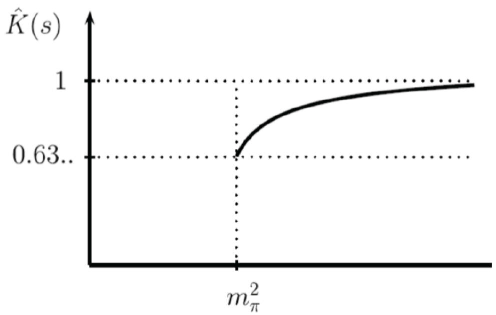


LO hadronic contribution to $a_\mu^{had,}$

The most precise prediction for $a_\mu^{had,LO}$ is from low-energy
e⁺e⁻ → hadrons data and dispersion relations

$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3}\int_{m_\pi^2}^{\infty}\frac{\hat{K}(s)}{s}\sigma_{e^+e^-\to hadrons}(s)\,ds$$





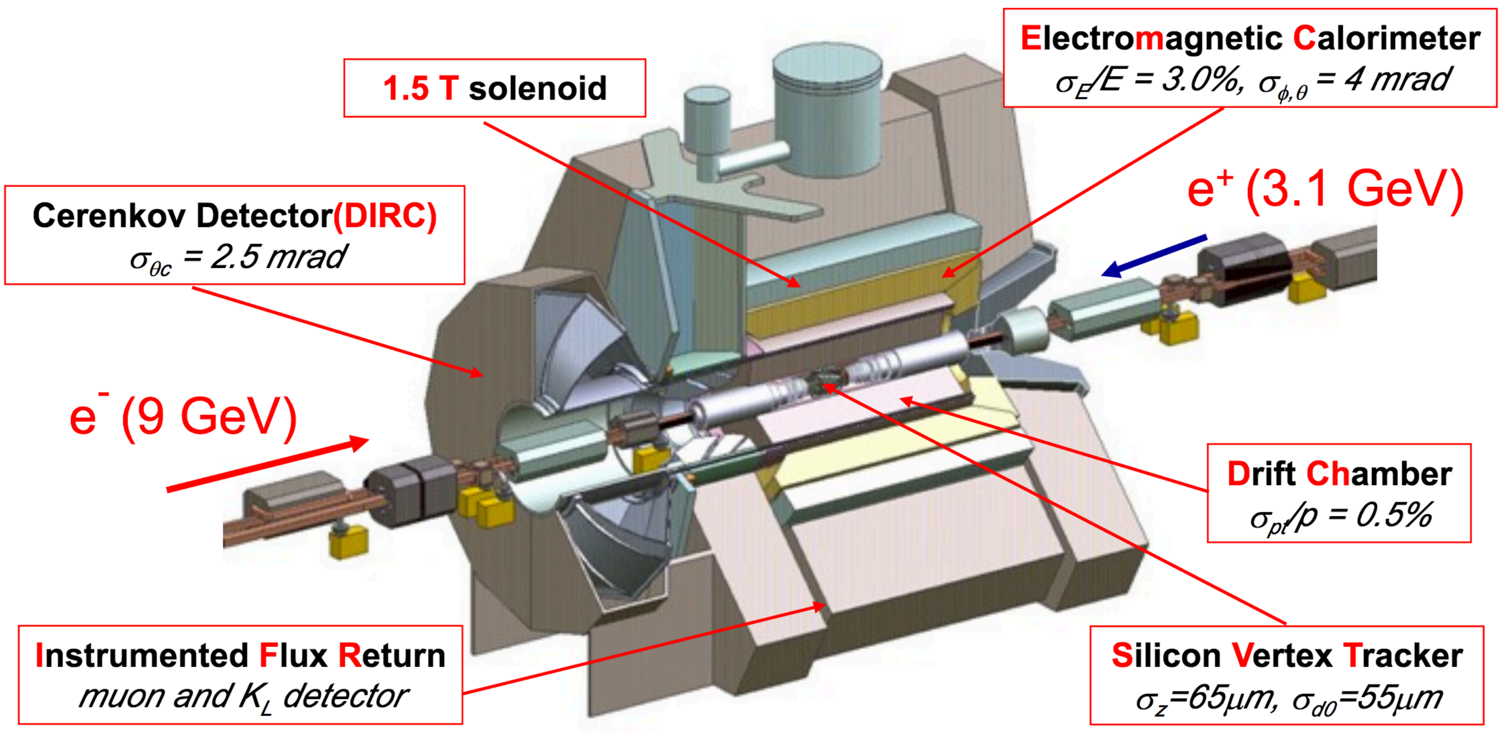
$\hat{K}(s)$ = kinematic factor

$\frac{\hat{K}(s)}{s} \sim \frac{1}{s}$ → low-energy (< 2 GeV) cross sections dominate

- Use sum of measured exclusive channels: 2π, 3π, 4π, KK, $KK\pi$, $KK\pi\pi$, $\eta\pi$, …
- Use isospin relations for missing channels
- Above ~1.8 GeV can start to use pQCD or inclusive $\sigma(e^+e^- \to$ *hadrons)* data
- BABAR has a long-standing program to measure exclusive cross sections below 2 GeV for all possible hadronic final states

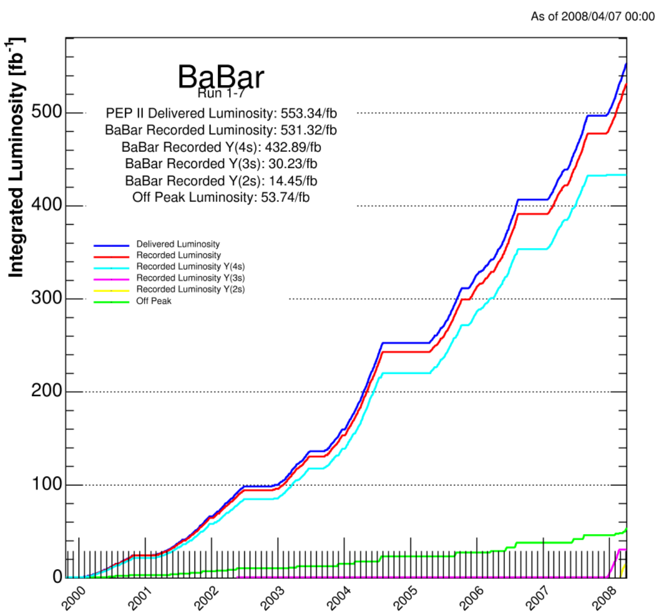
The BABAR experiment at SLAC

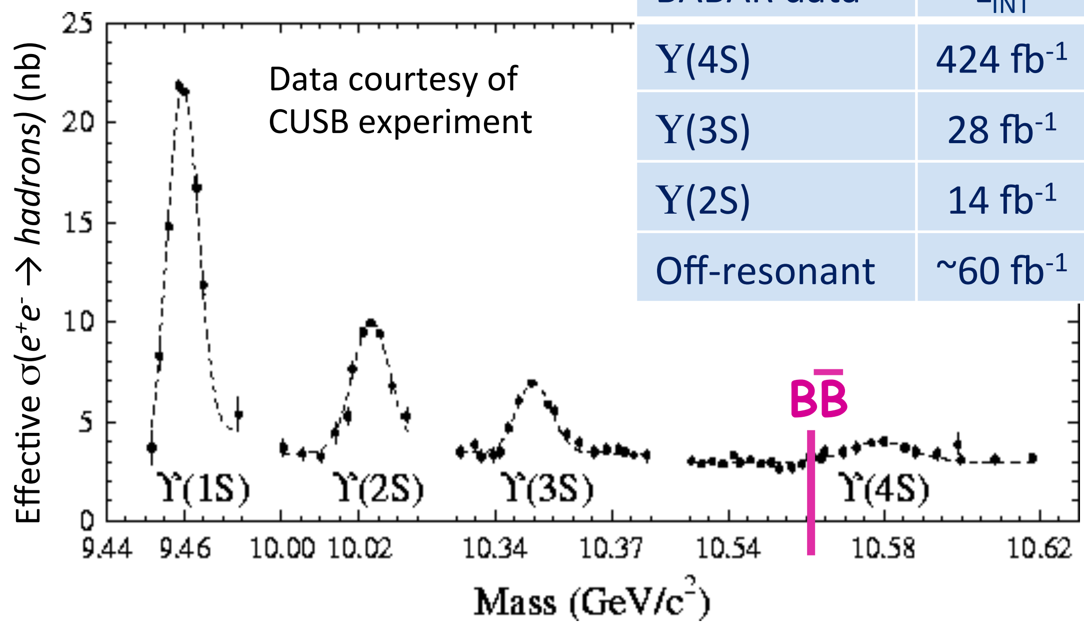
- PEP-II rings: asymmetric e^+e^- collider @ SLAC 9 GeV e^- and 3.1 GeV e^+
- Collected data 1999-2008
- Data analysis still active (6 papers submitted so far in 2017)



The BABAR experiment at SLAC

- Primarily designed for studies of CP violation in B meson decays
- Its general purpose design makes it suitable for a wide variety of other studies

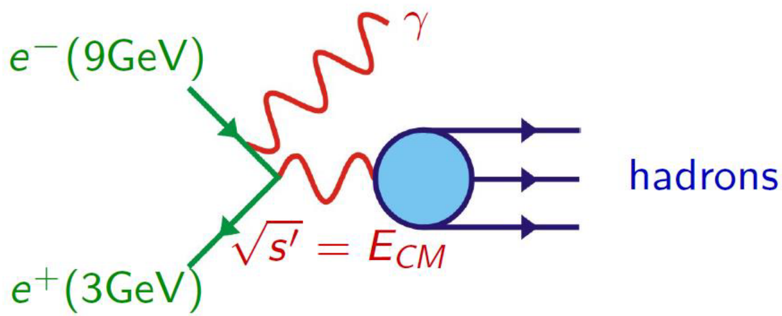


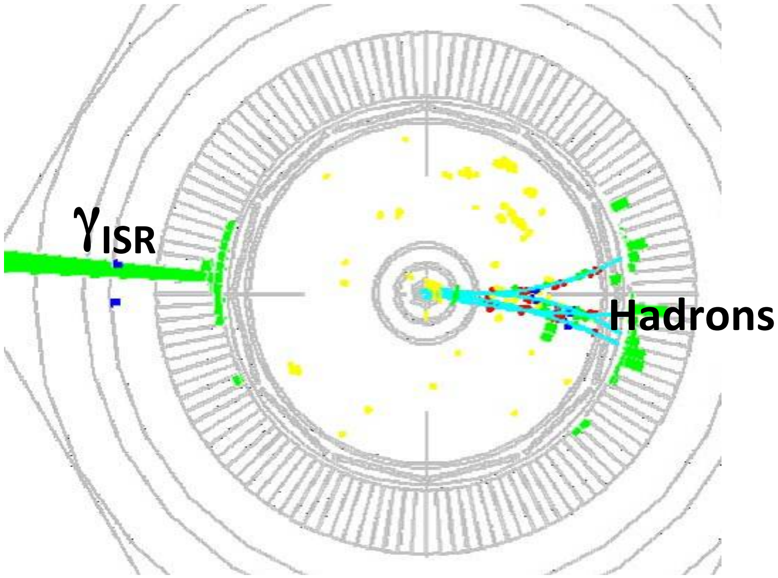


BABAR data	L_{INT}
ϒ(4S)	424 fb^{-1}
ϒ(3S)	28 fb^{-1}
ϒ(2S)	14 fb^{-1}
Off-resonant	~60 fb^{-1}

The analyses presented here use ~470 fb^{-1} of data collected at √s ≈ 10.6 GeV

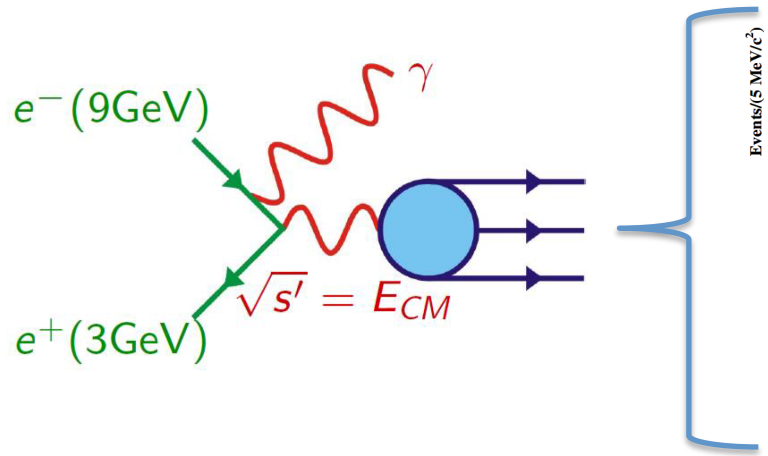
ISR method to measure low energy cross sections

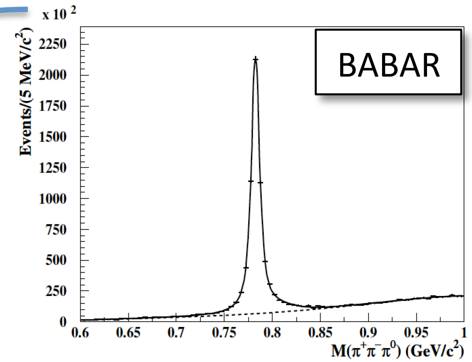


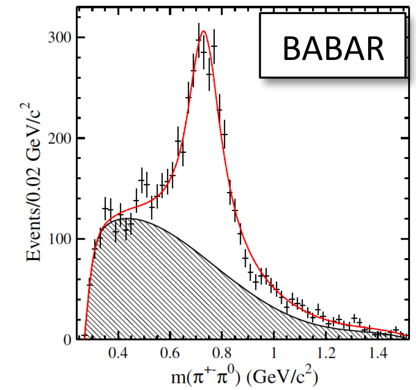


- Photon emitted by the incoming e^+ or e^-: initial-state radiation (ISR)
- γ_{ISR} is γ with highest E_{CM} & with $E_{CM} > 3$ GeV
- High event acceptance, easily recognizable
- Final-state photon radiation rate negligible
- Can access a wide range of energy in a single experiment: from threshold to ~5 GeV; eliminate point-to-point systematic uncertainties

ISR method to measure low energy cross sections







- Study of the intermediate resonance structure in low-energy ***$e^+e^- \rightarrow$ hadrons*** data is also interesting
- Sheds light on the production process of hadrons
- Can be used to test theoretical models
- Knowledge of the resonance structure significantly reduces systematic uncertainties in the acceptance since the acceptance differs for different intermediate states → incorporate information into the MC simulations

(I) $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

arXiv:1709.01171 (submitted to PRD)

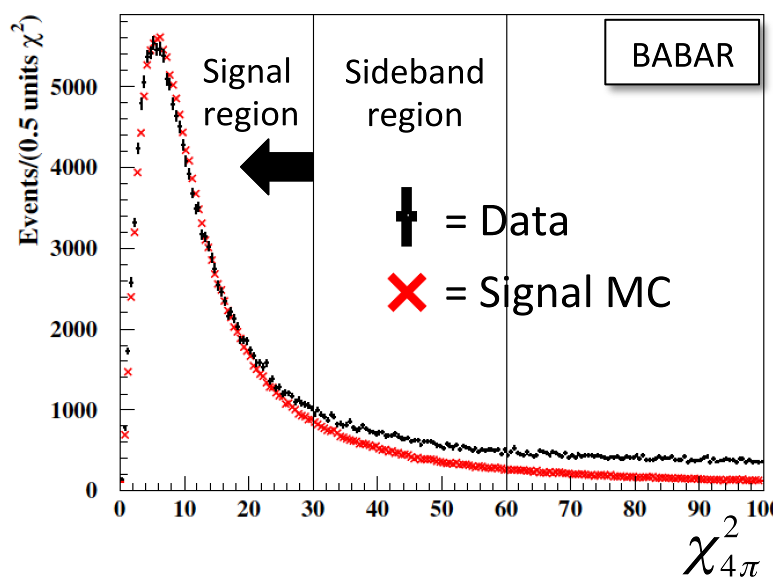
- One of the least known cross sections important for $a_\mu^{had,LO}$
- The new results supersede preliminary BABAR results from 2007 based on around half the final data set

• Require exactly 2 charged tracks, an ISR photon candidate, ≥ 4 other photons

• Perform kinematic fit to the $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\gamma$ hypothesis, constraining two 2γ combinations to the π^0 mass

• Select the overall combination of four photons yielding the smallest $\chi_{4\pi\gamma}^2$, requiring $\chi_{4\pi\gamma}^2 < 30$

• Difference between the $\chi_{4\pi\gamma}^2$ distributions of data and signal MC due to background in the former



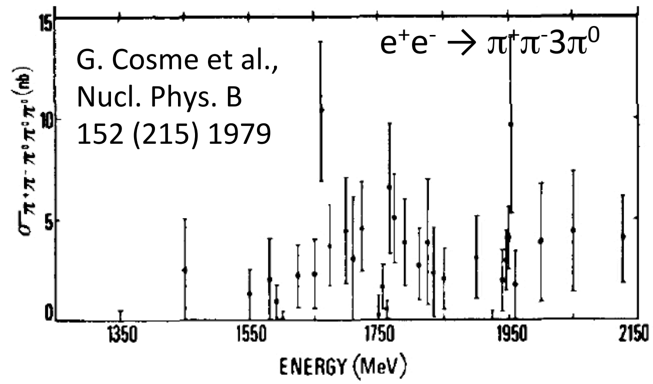
(I) $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

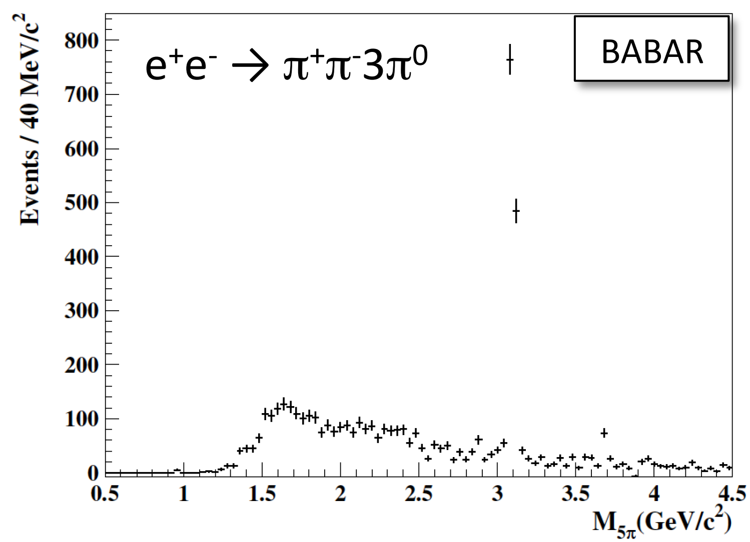
arXiv:1709.01171 (submitted to PRD)

Background subtracted using simulation normalized to data or using the data sideband

Largest ISR background: $\pi^+\pi^-3\pi^0\gamma_{ISR}$

- Cross section not well measured; only previous measurement is from 1979
- Perform new measurement using similar techniques to that used for the $\pi^+\pi^-\pi^0\pi^0$ cross section
- Obtain reliable background estimate, adjusting the shape and normalization of $e^+e^- \to \pi^+\pi^-3\pi^0$ in the simulation



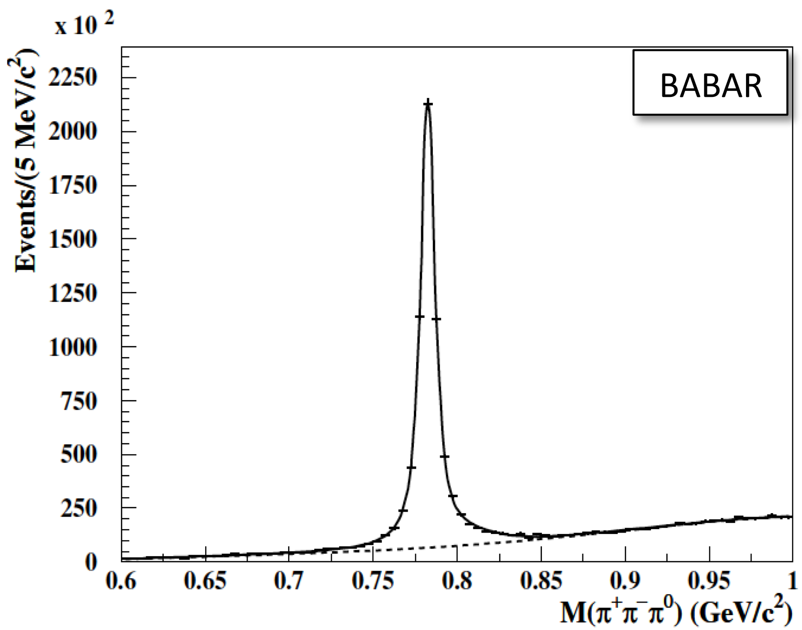


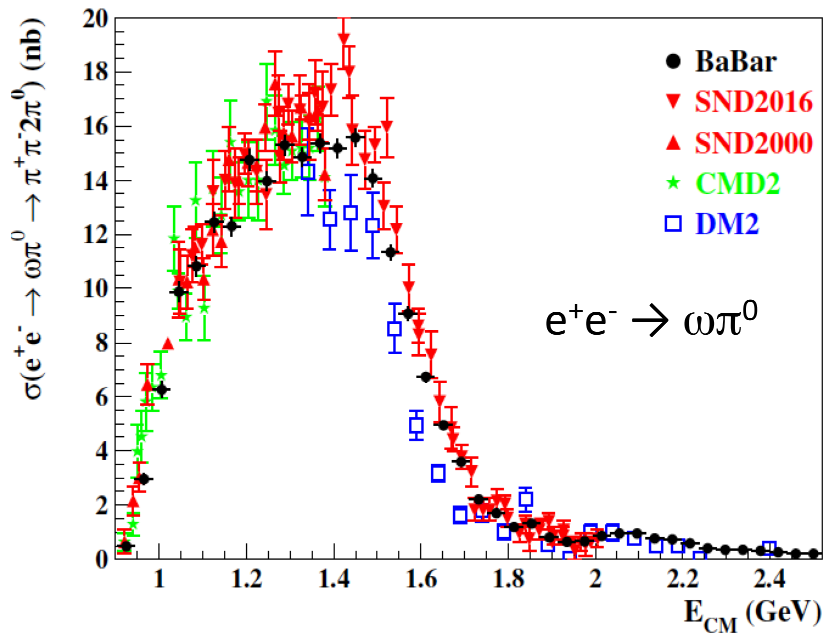
(I) $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

arXiv:1709.01171 (submitted to PRD)

Intermediate resonances:

a large fraction of $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ comes from $e^+e^- \to \omega\pi^0$ with $\omega \to \pi^+\pi^-\pi^0$

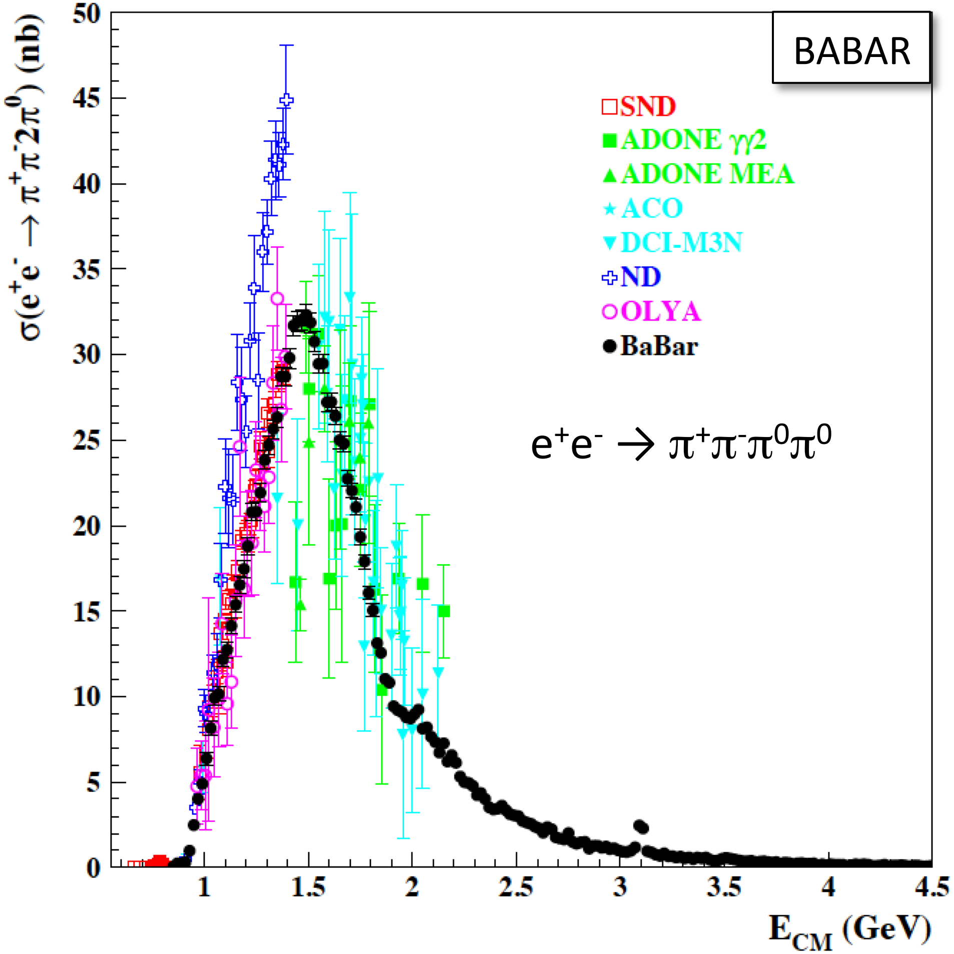




BABAR more precise than previous experiments; cover wider energy range; resolve some discrepancies

(I) $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

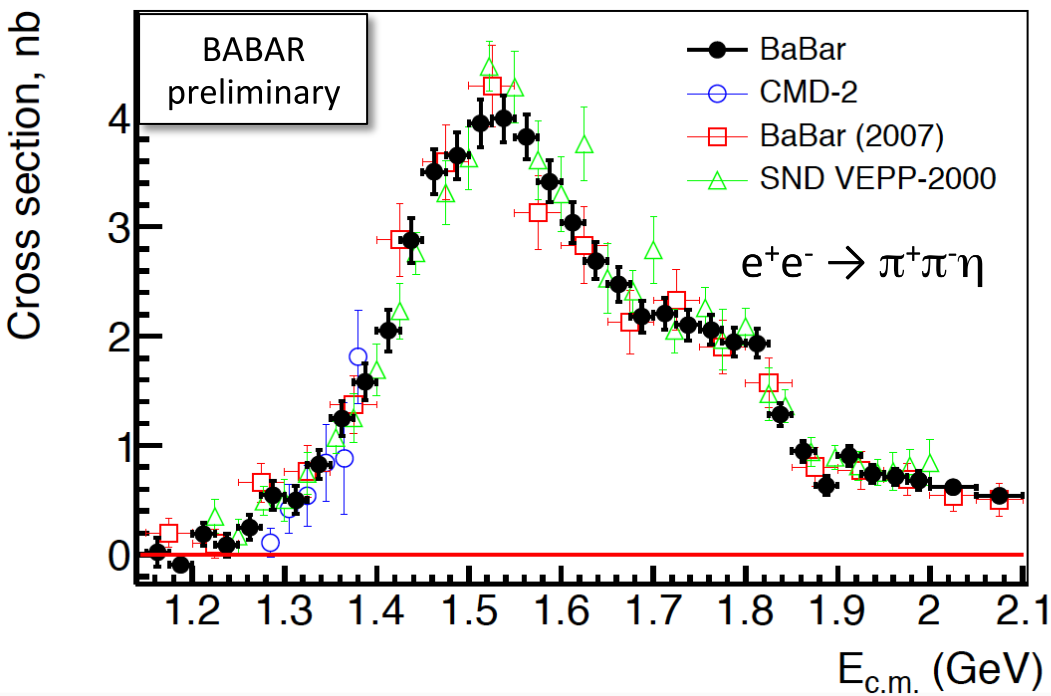
arXiv:1709.01171 (submitted to PRD)

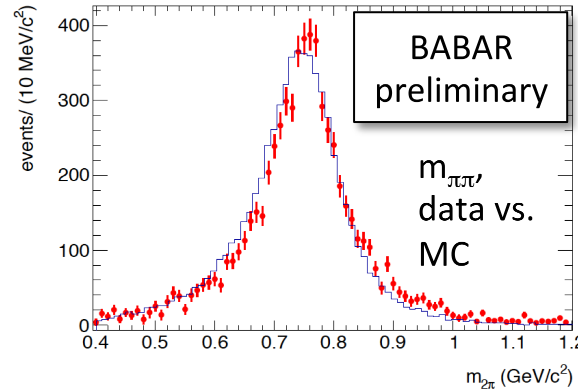


- BABAR results (150,000 signal events)
  - far more precise
  - cover far wider energy range
- Result for $a_\mu^{\pi+\pi-\pi0\pi0}$ ($E_{CM} < 1.8$ GeV):
  $179 \pm 1(\text{stat}) \pm 6(\text{syst}) \times 10^{-11}$
  (3.2% precision)
- World average without BABAR:
  $167 \pm 13\,(\text{stat+syst}) \times 10^{-11}$
  (7.9% precision)
- The BABAR data reduce uncertainty in $a_\mu^{\pi+\pi-\pi0\pi0}$ by a factor of 2.5

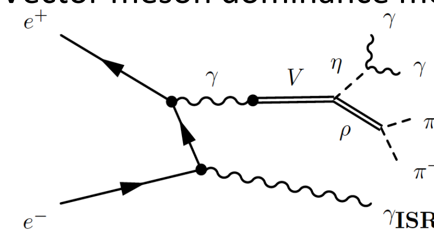
(II) $e^+e^- \rightarrow \pi^+\pi^-\eta$ with $\eta \rightarrow \gamma\gamma$

Preliminary





Vector meson dominance model



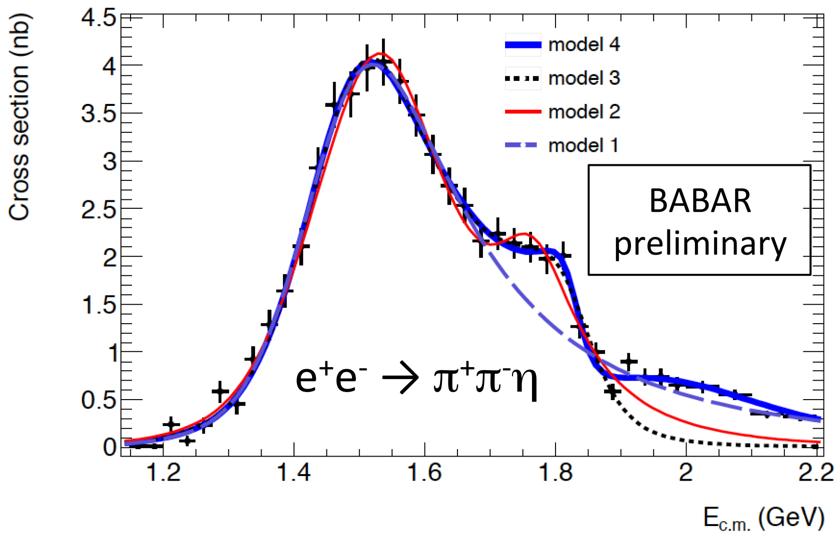
V = $\rho(770)$, $\rho(1450)$, $\rho(1700)$, higher ρ excitations

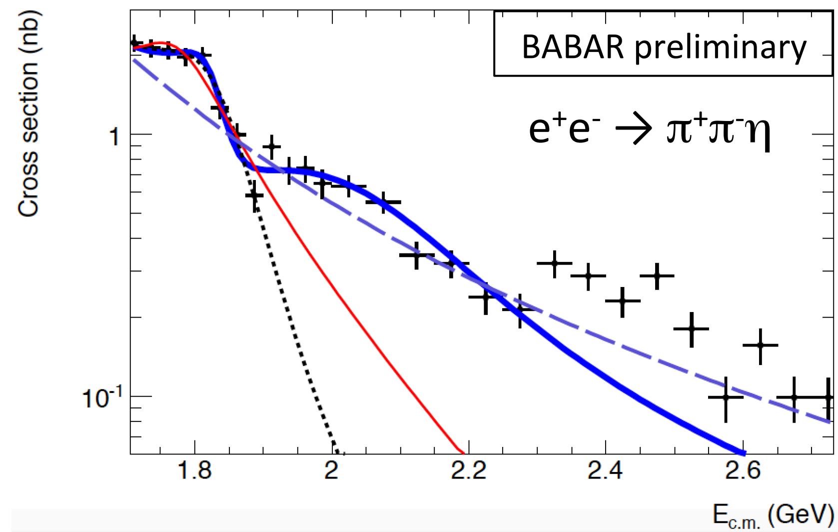
- Similar analysis techniques to $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$; 8000 signal events
- Complements and improves the precision of the BABAR result from 2007 [PRD 76 (2007) 092005], based on 232 fb^{-1} and the $\eta \rightarrow \pi^+\pi^-\pi^0$ decay mode
- Reaction dominated $\rho(770)\eta$ intermediate state, but has complex E_{CM} structure

(II) $e^+e^- \rightarrow \pi^+\pi^-\eta$ with $\eta \rightarrow \gamma\gamma$

Preliminary

Test of vector meson dominance model:



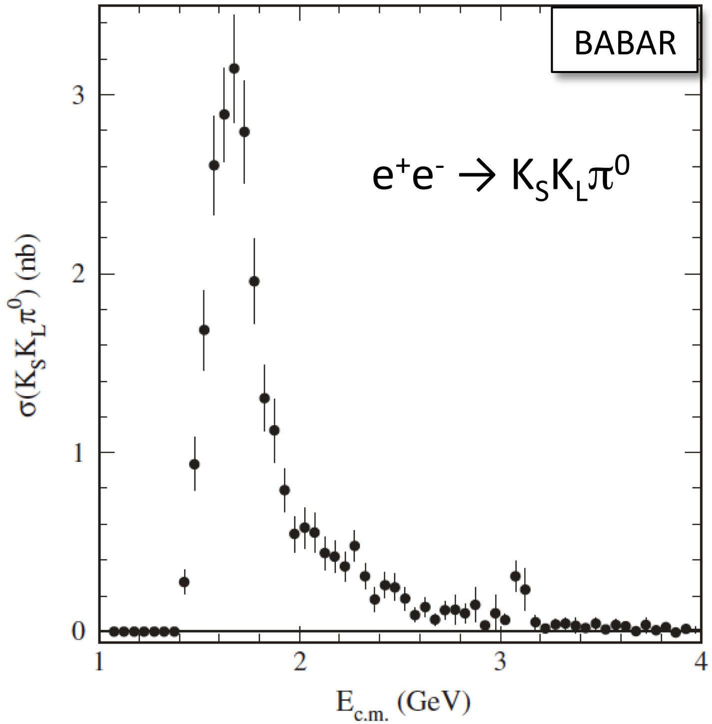


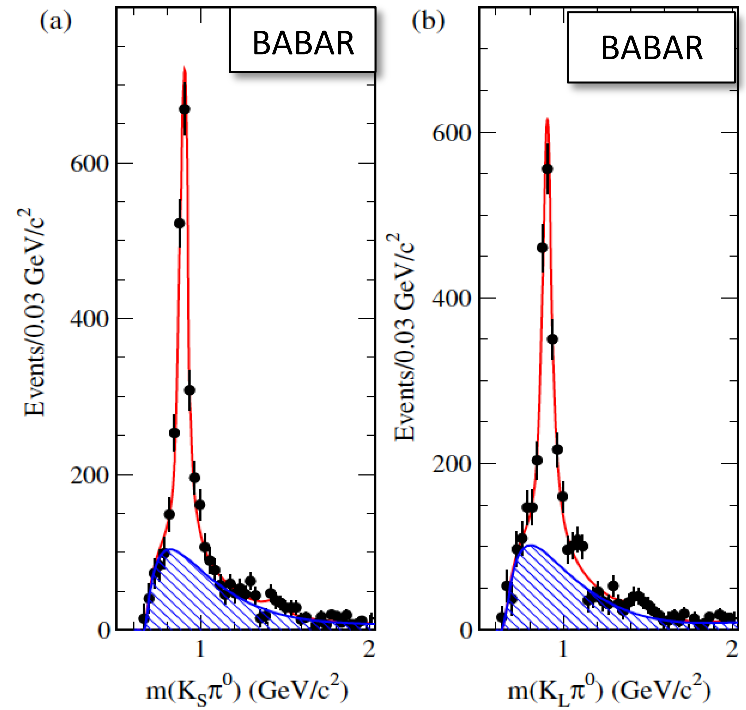
model	Resonance model	Good fit for
0	ρ(770) + ρ(1450)	Doesn't fit
1	ρ(770) − ρ(1450)	E_{cm} < 1.7 GeV
2	ρ(770) − ρ(1450) − ρ(1700)	E_{cm} < 1.9 GeV
3	ρ(770) − ρ(1450) + ρ(1700)	E_{cm} < 1.9 GeV
4	ρ(770) − ρ(1450) + ρ(1700) + ρ(2150)	E_{cm} < 2.2 GeV

- Coupling constants governing the decays ~real: phase differences are 0 or π only
- Need an additional resonance to describe data above E_{cm}= 2.3 GeV

(III) $e^+e^- \rightarrow K_S K_L \pi^0$

Phys. Rev. D 95 (2017) 052001





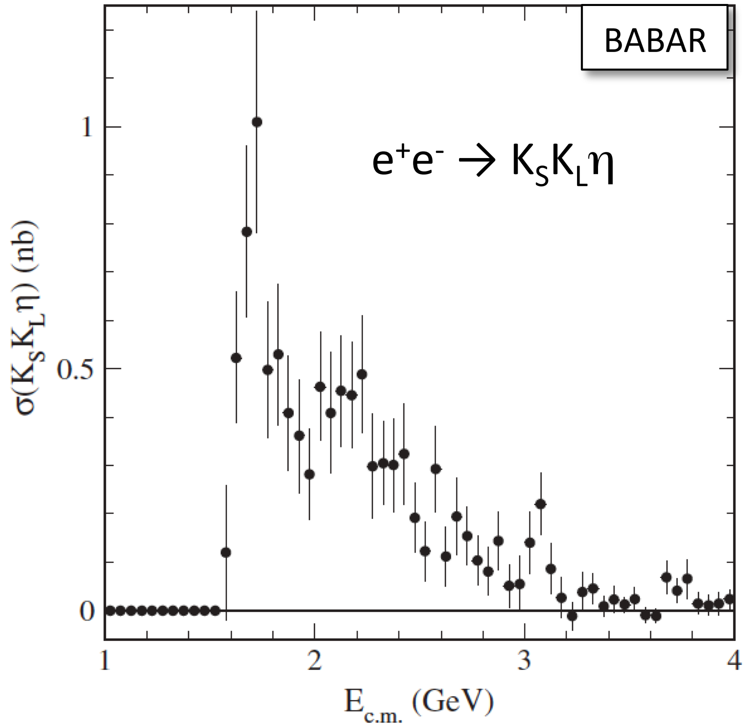
hatched areas = nonresonant components

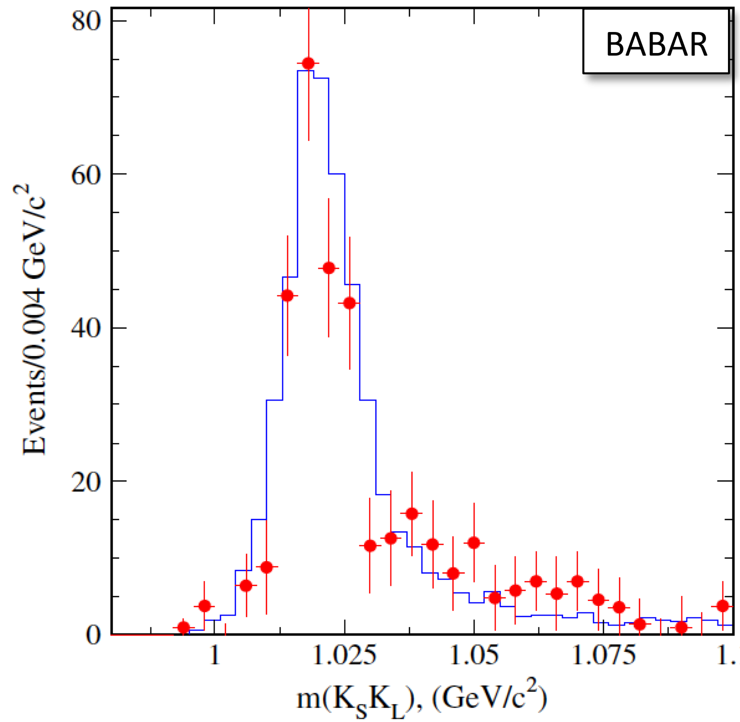
- 3700 signal events
- First measurement of this process
- First observation of $J/\psi \rightarrow K_S K_L \pi^0$

- Dominant intermediate state (95%) is K*(892)K
- K*(1430)K and $\phi(\rightarrow K_S K_L)\pi^0$ also seen

(IV) $e^+e^- \rightarrow K_S K_L \eta$

Phys. Rev. D 95 (2017) 052001

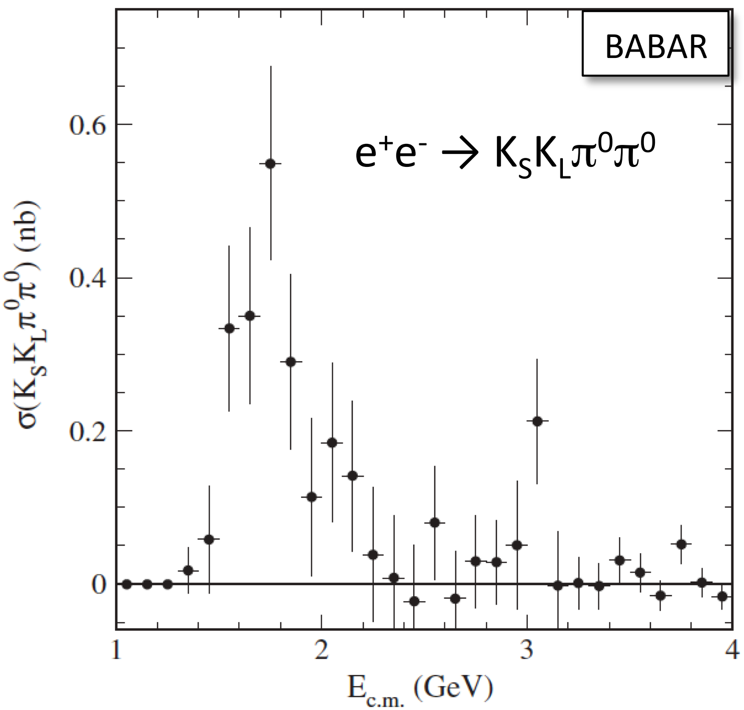


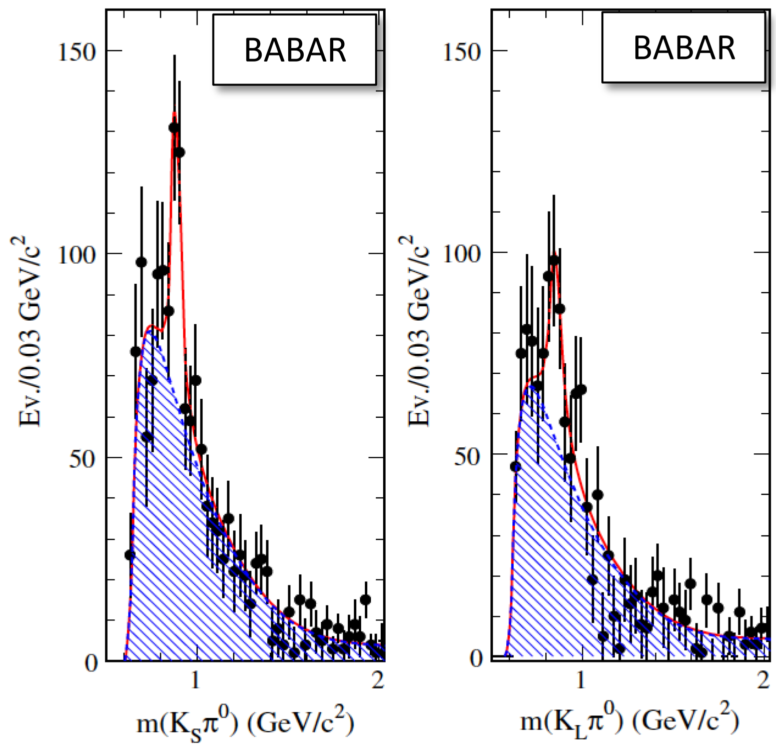


- 864 signal events
- First measurement of this process
- Dominated by $e^+e^- \rightarrow \phi\eta$

(V) $e^+e^- \to K_S K_L \pi^0 \pi^0$

Phys. Rev. D 95 (2017) 052001





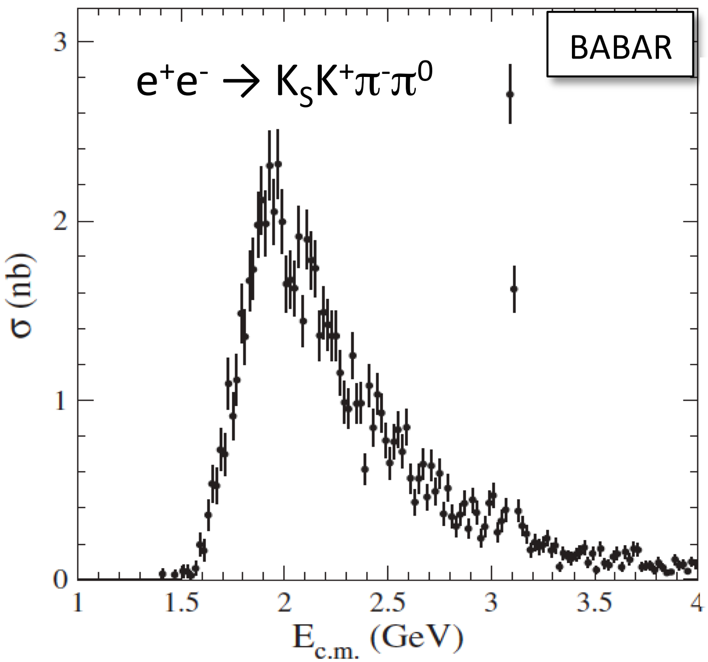
hatched areas = nonresonant components

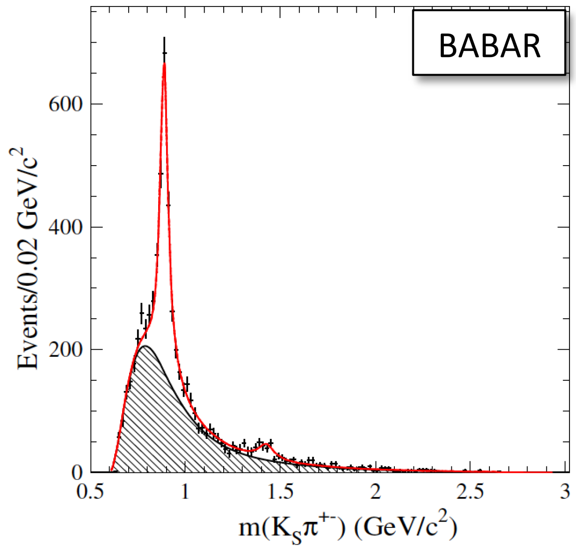
- 392 signal events
- First measurement of this process
- Clear $e^+e^- \to K^*(892)K\pi$ signals

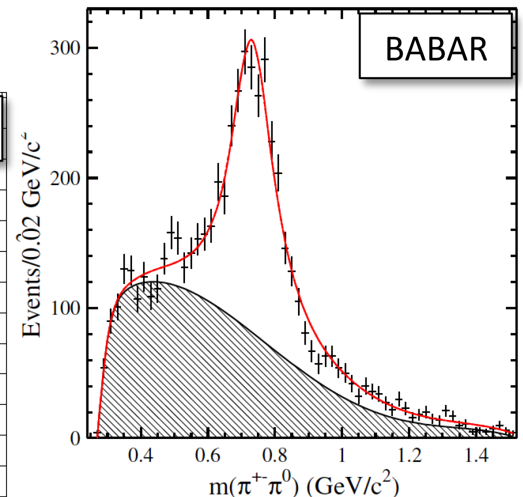
(VI) $e^+e^- \rightarrow K_S K^+ \pi^- \pi^0$

Phys. Rev. D 95 (2017) 092005

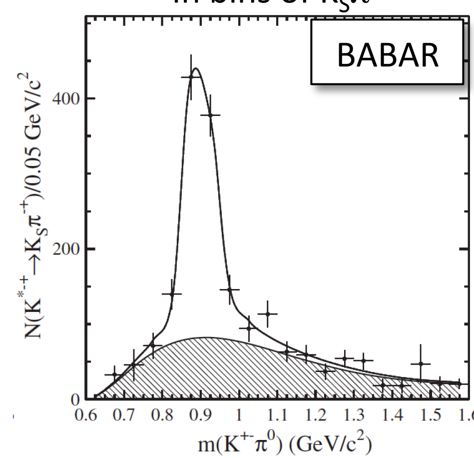
hatched areas = nonresonant components







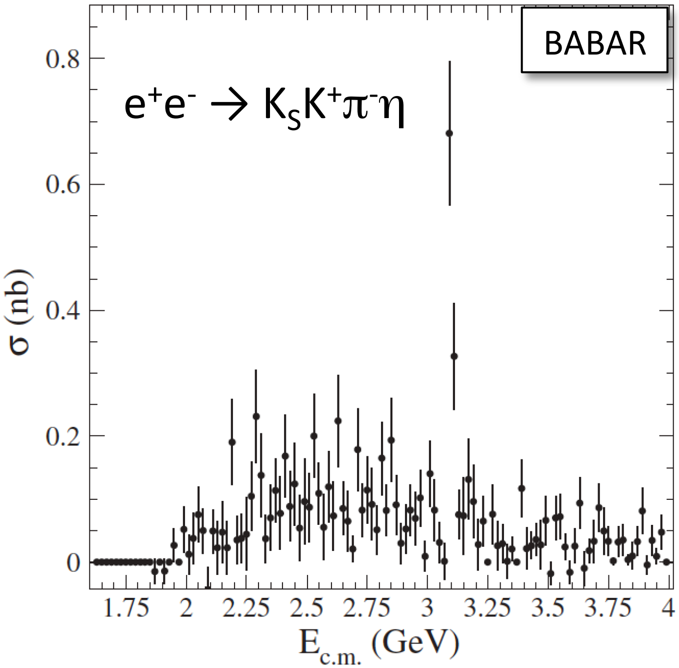
Nr. of fitted $K^* \rightarrow K^+\pi^-$
In bins of $K_S\pi^0$

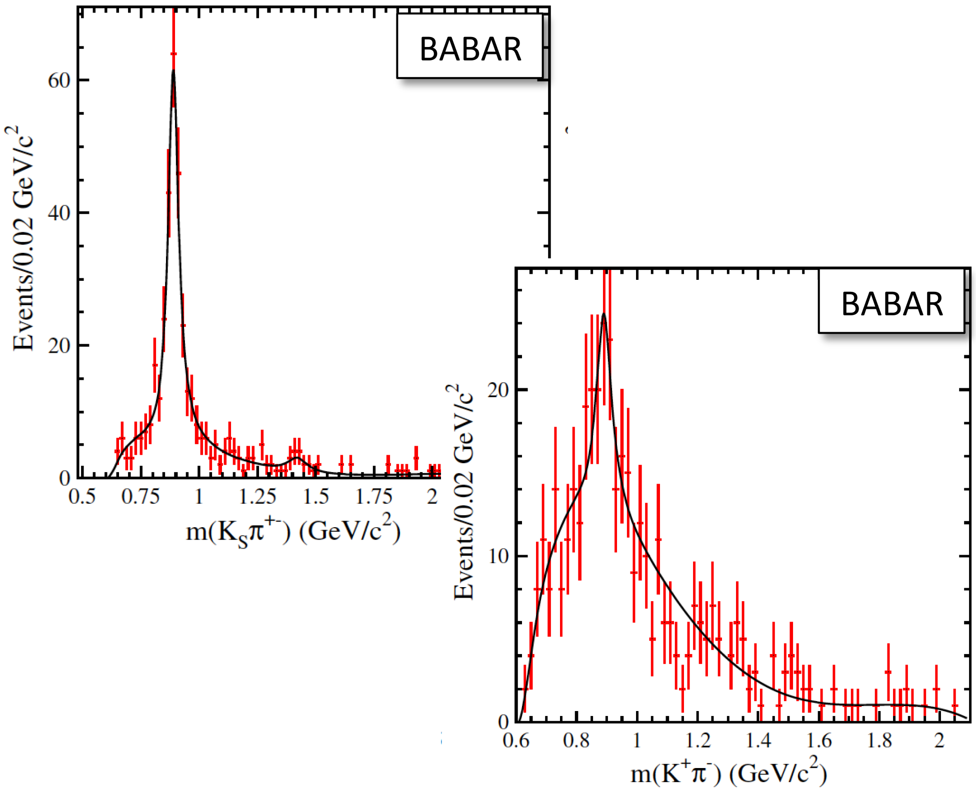


- 6400 signal events, first measurement of this process
- Large $J/\psi \rightarrow K_S K^+ \pi^- \pi^0$ peak (first observation of this decay)
- $K^*(892)K\pi$ and $K_S K^+ \rho(770)^-$ are dominant
- $K^*(892)K^*(892) \sim 15\%$; small $K^*(1430)K\pi$ component

(VII) $e^+e^- \rightarrow K_S K^+ \pi^- \eta$

Phys. Rev. D 95 (2017) 092005





- 358 signal events
- First measurement of this process
- Dominated by $K^*(892)K\eta$ peak, primarily in $K^*(892)^\pm \rightarrow K_S\pi^\pm$

Implications for the muon g - 2

- With the new results for
  - $e^+e^- \to K_S K_L \pi^0$ PRD95 (2017) 052001
  - $e^+e^- \to K_S K^+ \pi^- \pi^0$ PRD95 (2017) 092005
  - $e^+e^- \to K_S K_L \pi^0 \pi^0$ PRD95 (2017) 052001

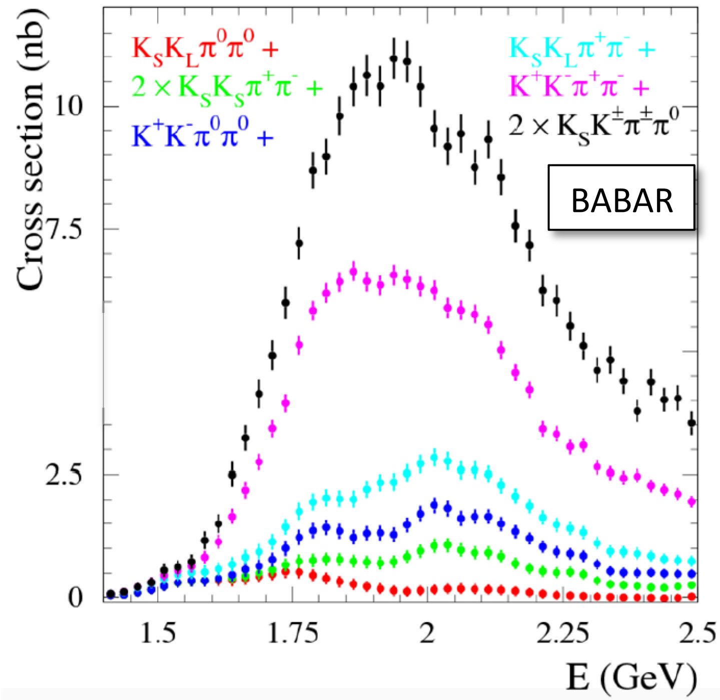
  in combination with previous BABAR results, BABAR has now measured <u>all</u>

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

  cross sections except those with a $K_L K_L$

- $a_\mu^{KK\pi}$ and $a_\mu^{KK\pi\pi}$ can be determined with no assumptions or isospin relations (except assume the $K_L K_L$ rates to be the same as for $K_S K_S$)

Sum of all $e^+e^- \to KK\pi\pi$ states from BABAR



From V.P. Druzhinin, EPJ Web of Conferences 142, 01013 (2017)

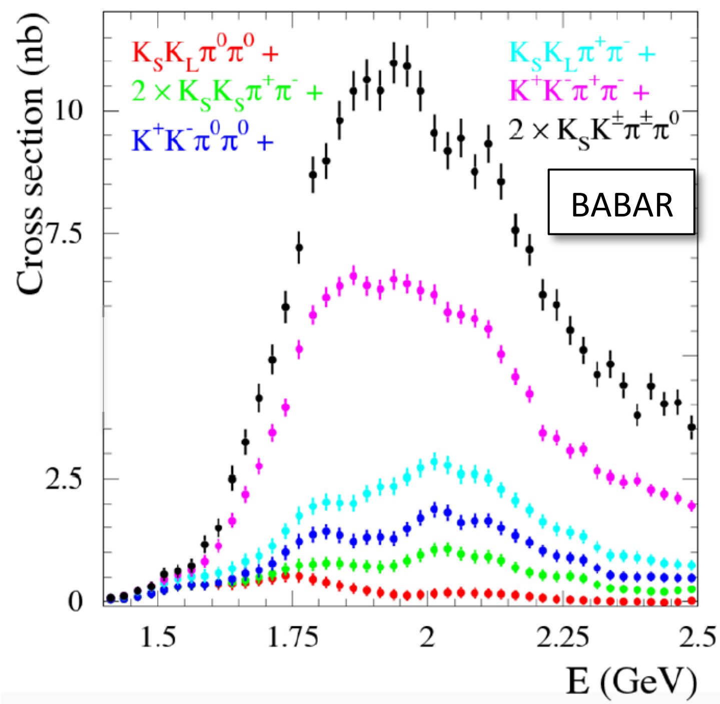
Implications for the muon g - 2

- $K K \pi\pi$ states comprise ~25% of the total hadronic cross section at $E_{CM} \approx 2$ GeV
- Can be used, along with the other BABAR measurements at $E_{CM} \approx 2$ GeV, to test the pQCD prediction for *$e^+e^- \to$ hadrons*
- The BABAR results yield ($E_{CM} < 1.8$ GeV)

  $a_\mu^{KK\pi\pi} = 8.5 \pm 0.5$ (stat+syst) x 10^{-11}

  (6% precision)
- Previous result, based mostly on isospin relations: 30% precision

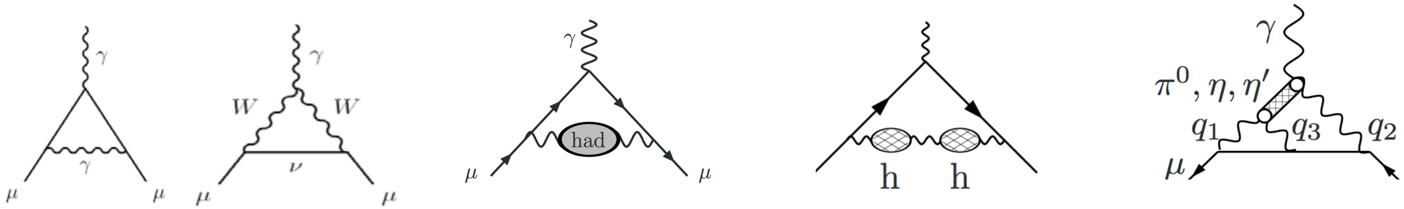
Sum of all $e^+e^- \to KK\pi\pi$ states from BABAR



From V.P. Druzhinin, EPJ Web of Conferences 142, 01013 (2017)

Implications for the muon g - 2

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{hadronic,LO} + a_\mu^{hadronic,HO} + a_\mu^{hadronic,LBLs}$$



Diagrams from Jegerlehner and Nyffeler, Phys. Rept. 477 (2009) 1

Hadronic light-by-light scattering

a_μ^{QED}	116584718.95 ± 0.08
a_μ^{EW}	153.6 ± 1.0
$a_\mu^{had,LO}$	$\boxed{6923 \pm \mathbf{42}}$
$a_\mu^{had,HO}$	-98.4 ± 0.6
$a_\mu^{had,LbLs}$	105 ± 26
$a_\mu^{total\text{-}SM}$	116591802 ± **49**

M. Davier et al., EPJC 71 (2011) 1515 **units of 10^{-11}**
& PDG (2016)

$a_\mu^{BNL\text{-}E821}$	116592091 ± 63
Data - SM	288 ± 80

Updated result from ,M. Davier [arXiv:1612.02743 (Feb. 2017)] using all the newly available (since 2010) data, dominated by BABAR

$a_\mu^{had,LO} = 6926 \pm \mathbf{33}$

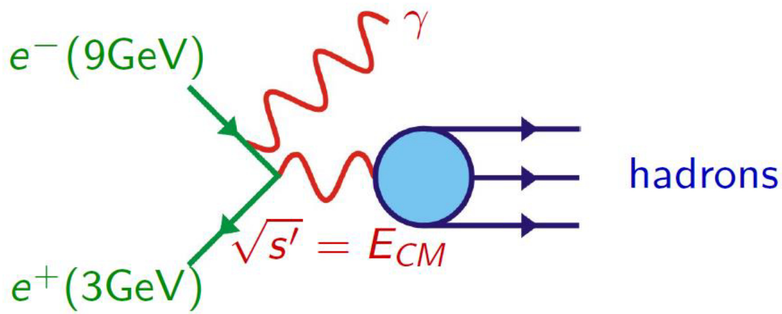
Reduction in $\delta a_\mu^{had,LO}$ by 20%

Summary

- Low-energy *$e^+e^- \rightarrow$ hadrons* cross section data currently provide the most accurate prediction for $a_\mu^{had,LO}$
- The *$e^+e^- \rightarrow$ hadrons* data also
  - yield important information on hadron dynamics
  - allow tests of QCD, including for $\sigma(e^+e^- \rightarrow hadrons)$ at $E_{CM} \approx 2$ GeV
  - provide first observations of cross sections and of (for example) J/ψ and $\psi(2S)$ branching fractions
- New BABAR results reduce the uncertainty in $a_\mu^{had,LO}$
  - $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ from around 7% to around 3%
  - $e^+e^- \rightarrow KK\pi\pi$ from around 30% to around 6%
- Future progress in $a_\mu^{had,LO}$ will come from reduced systematic uncertainties in $e^+e^- \rightarrow \pi^+\pi^-$ (BABAR and CMD3) and perhaps eventually lattice QCD

EXTRA

ISR method to measure low energy cross sections



The measured radiative cross section is then interpreted in terms of nonradiative cross section

$$\frac{d\sigma_{\gamma f}(s,x)}{dx} = W(s,x)\sigma_f(E_{\text{c.m.}})$$

W (s,x) = radiator function

= probability for the initial e^+ or e^- to radiate a photon, lowering the annihilation energy from $\sqrt{s}$ to E_{CM} (calculated in QED to better than 0.5% accuracy)

$E_{CM} = \sqrt{(1-x)s}$ = invariant mass of the hadronic system

$x = 2\,E_\gamma/\sqrt{s}$; E_γ measured in CM frame