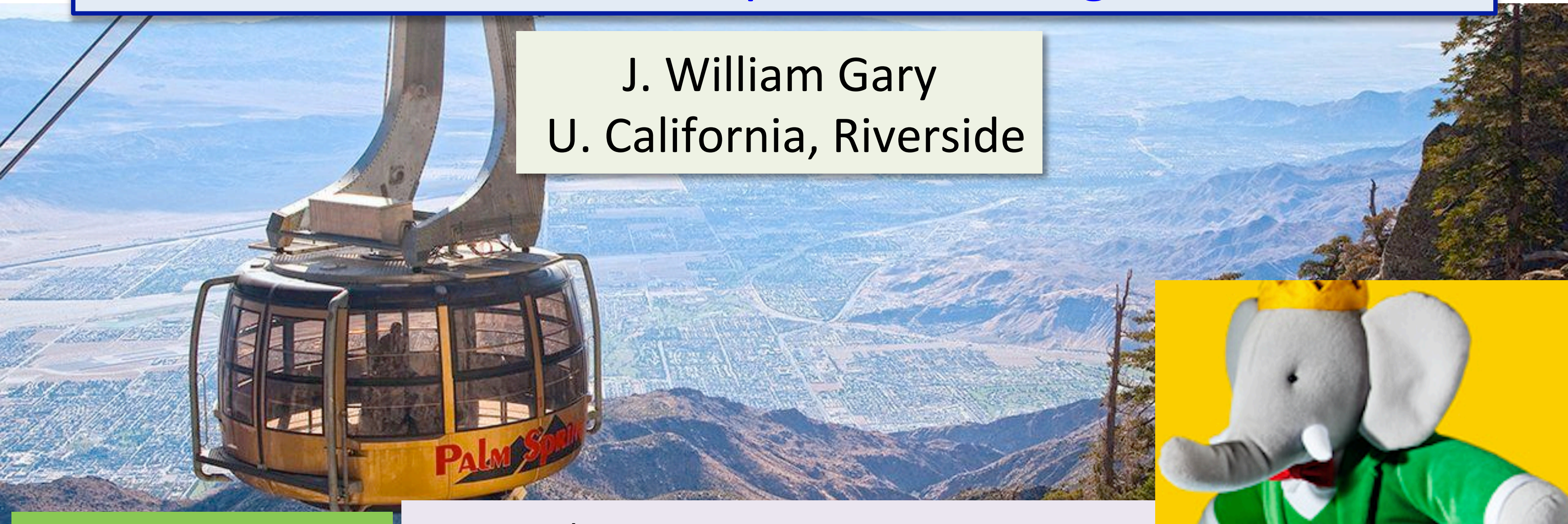
New results on low-energy exclusive hadronic cross sections from BABAR & implications for g-2 of the muon



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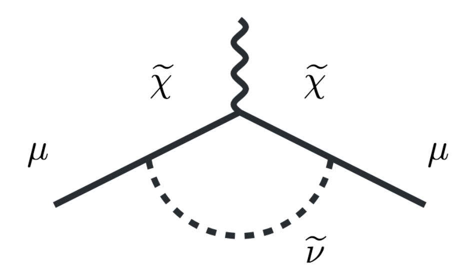
Outline

- g - 2 of the muon
- BABAR and the initial-state radiation (ISR) method
- Recent exclusive hadronic cross section measurements
  - $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ PRD 96 (2017) 092009
  - $e^+e^- \rightarrow \pi^+\pi^-\eta$ PRD 97 (2018) 052007
  - $e^+e^- \rightarrow K_SK_L\pi^0,\ K_SK_L\eta,\ K_SK_L\pi^0\pi^0$ 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

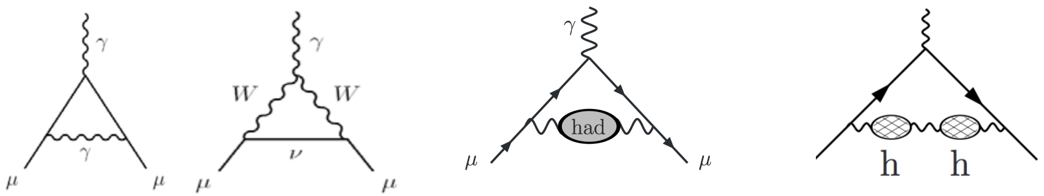
- Magnetic moment of a spin ½ particle: $\vec{\mu} = g \frac{e}{2mc} \vec{s}$
- Dirac equation predicts $g = 2$ exactly
- Radiative corrections alter the prediction, introducing sensitivity to new physics through loops: $g = 2(1 + a)$
- The "anomalous" moment: $a = \frac{g-2}{2}$
- Theory and experiment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

  → the muon g-2 discrepancy

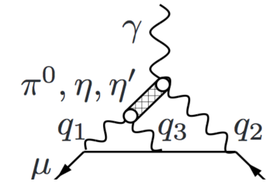


g_μ - 2 in the standard model

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



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
$a_\mu^{total-SM}$	116591802 ± **49**

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

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

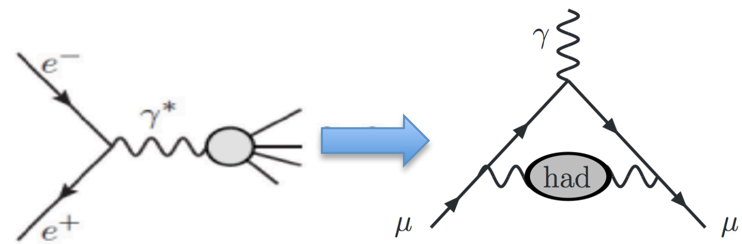
*PRD 73 (2006) 072003

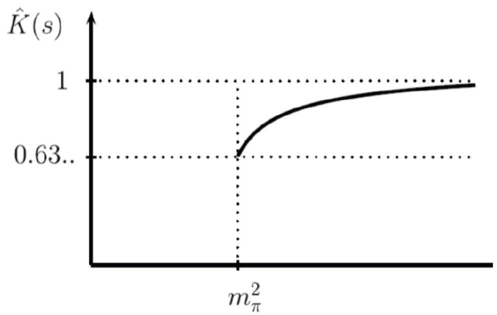
- Discrepancy between data and calculation of about 3.5 σ
- A potential indication of new physics
- Uncertainty in SM prediction dominated by LO hadronic term

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

The most precise prediction for $a_\mu^{had,LO}$ is from low-energy
<u>*$e^+e^- \rightarrow$ hadrons*</u> data and dispersion relations

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





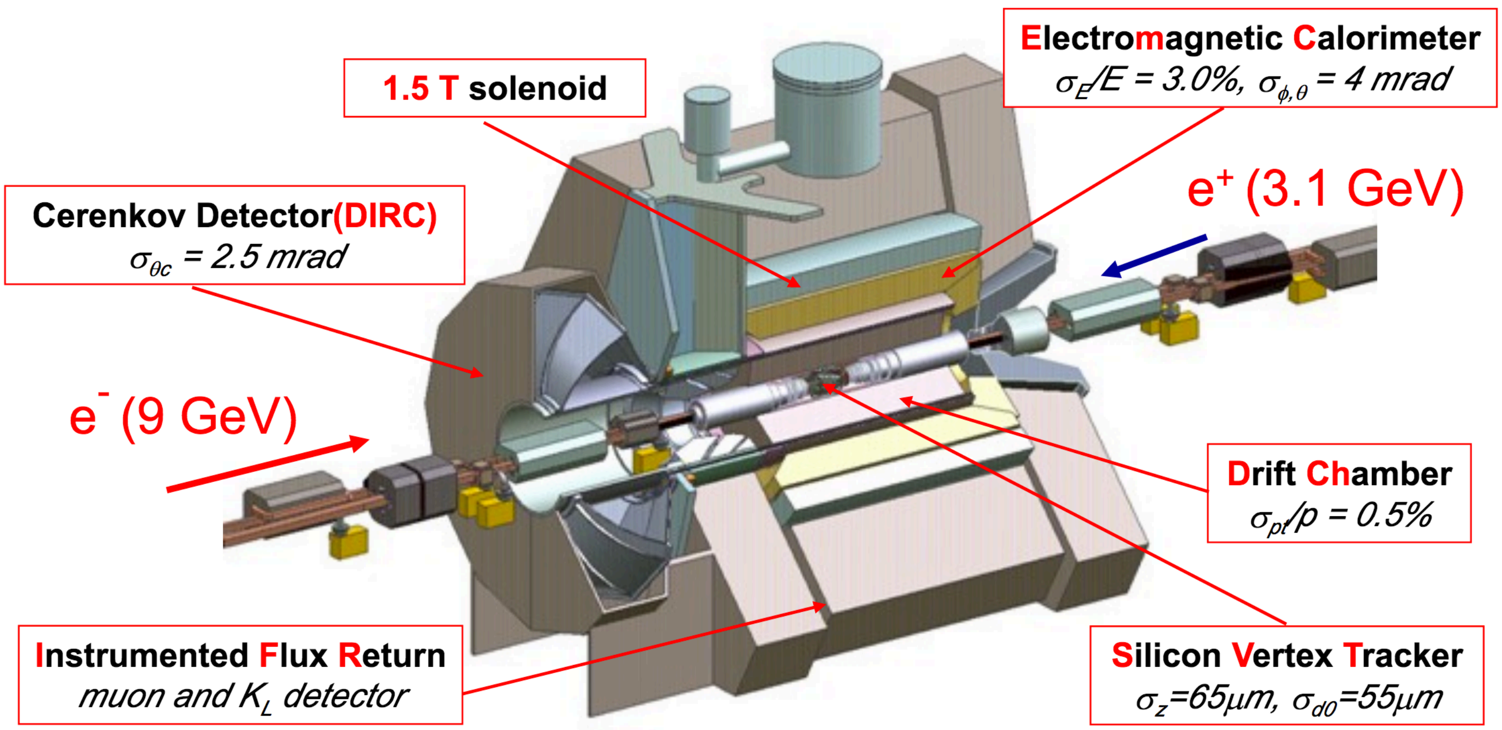
$\hat{K}(s)$ = kinematic factor

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

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

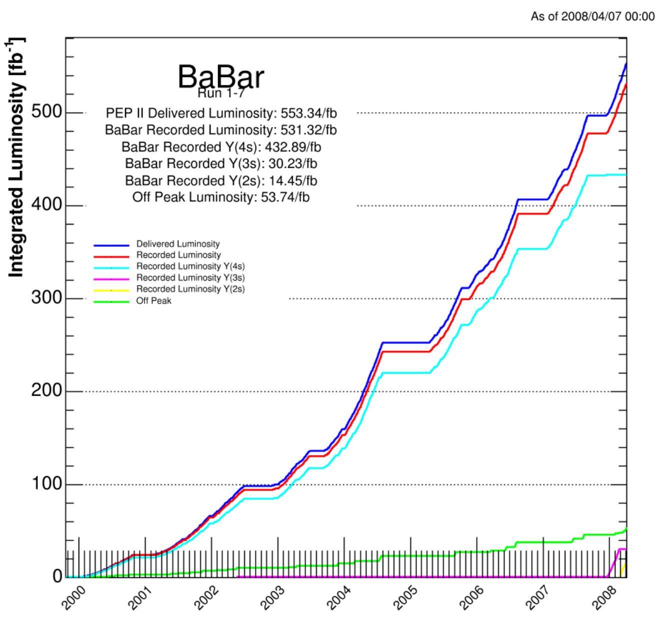
The BABAR experiment at SLAC

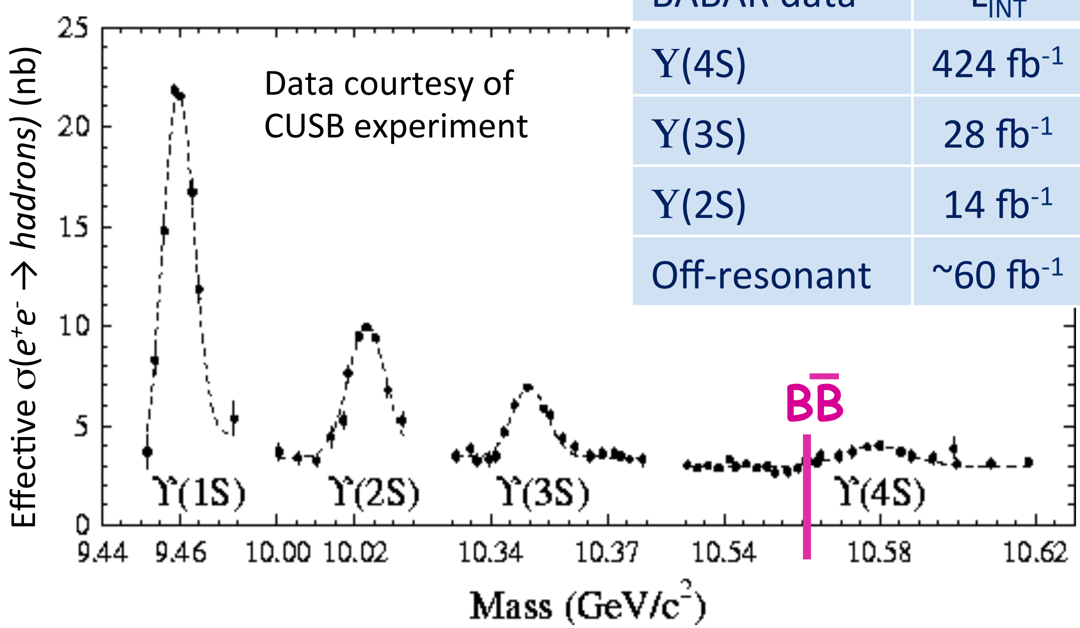
- PEP-II rings: asymmetric e^+e^- collider @ SLAC 9 GeV e^- and 3.1 GeV e^+
- Collected data 1999-2008
- Data analysis still active (5 papers submitted so far in 2018; 6 in 2017)



The BABAR experiment at SLAC

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

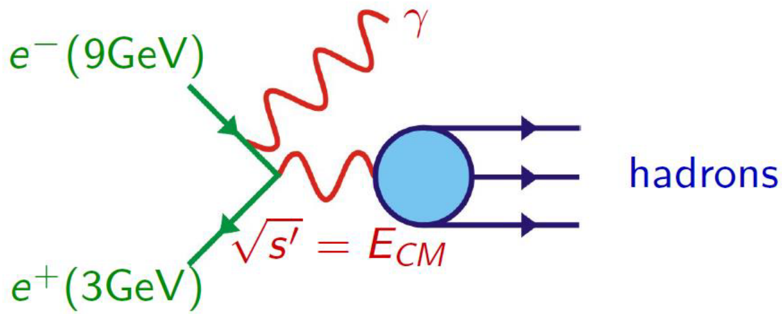


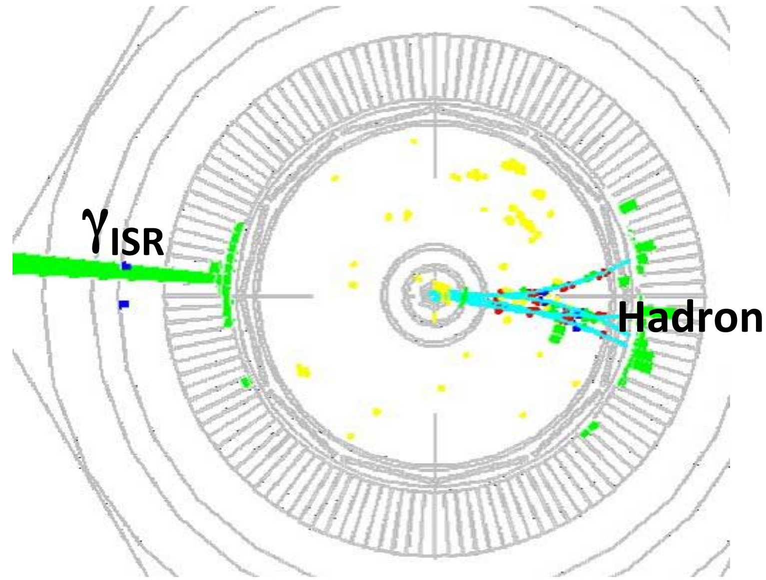


BABAR data	L_{INT}
Υ(4S)	424 fb^{-1}
Υ(3S)	28 fb^{-1}
Υ(2S)	14 fb^{-1}
Off-resonant	~60 fb^{-1}

The analyses presented here use ~470 fb^{-1} of data collected at $\sqrt{s} \approx 10.6$ GeV

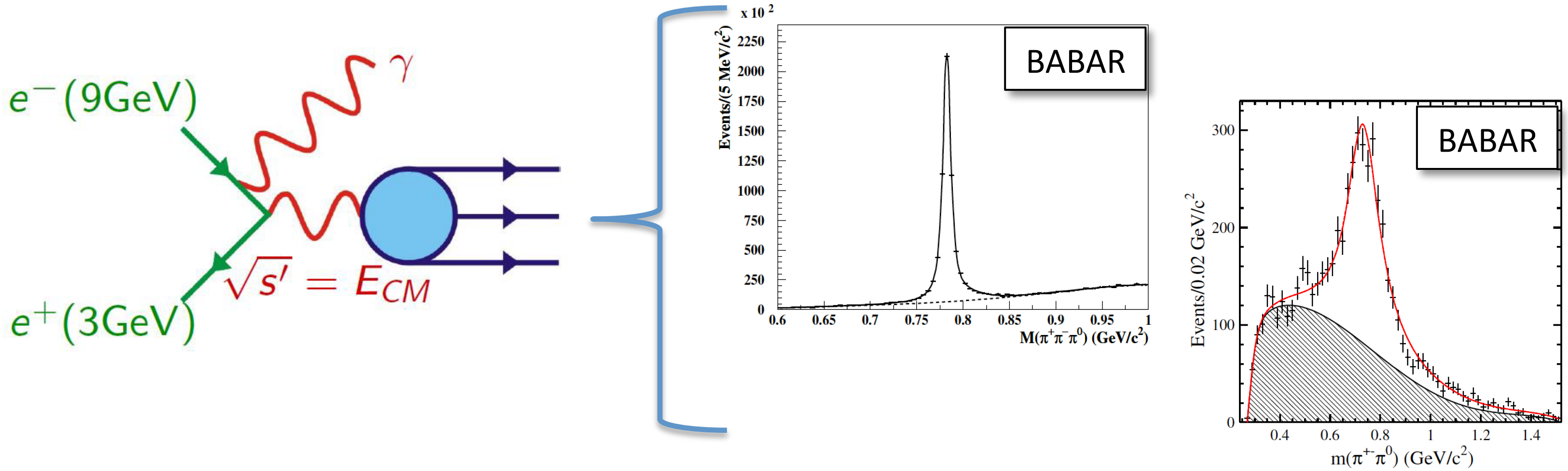
ISR method to measure low energy cross sections





- 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
- Final-state photon radiation rate is negligible
- High event acceptance (the hadrons are strongly boosted), easily recognizable
- Can access a wide range of energies √s' in a single experiment: from threshold to ~5 GeV; eliminate point-to-point systematic uncertainties arising in a √s scan

ISR method to measure low energy cross sections



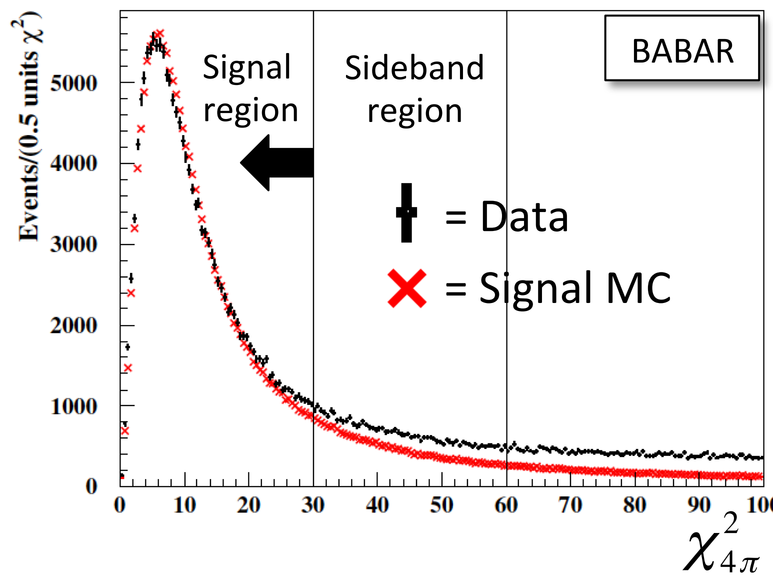
- Study of the intermediate resonance structure in low-energy *$e^+e^- \rightarrow$ hadrons* data is also interesting
- Sheds light on the production process of hadrons
- Can be used to test models of hadron production
- Knowledge of the resonance structure significantly reduces systematic uncertainties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

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

PRD 96 (2017) 092009

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

- Require exactly 2 charged tracks, an ISR photon candidate, ≥ 4 other photons
- Perform kinematic fit to the $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$ 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) $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

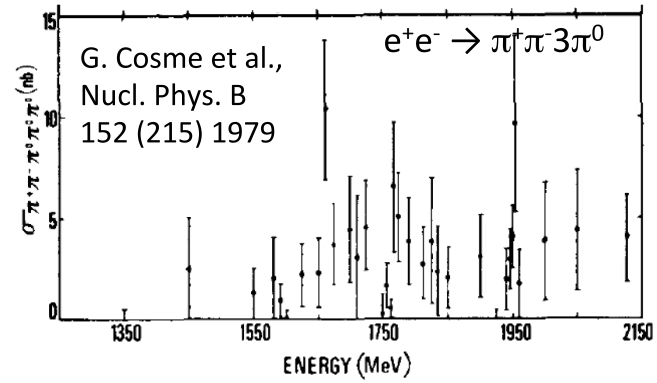
PRD 96 (2017) 092009

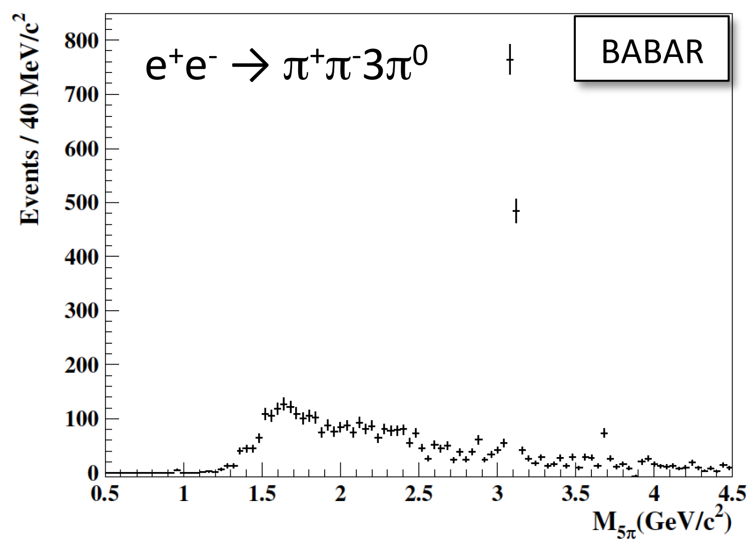
Background subtracted using simulation normalized to data

Cross check using a data sideband method

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 those 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

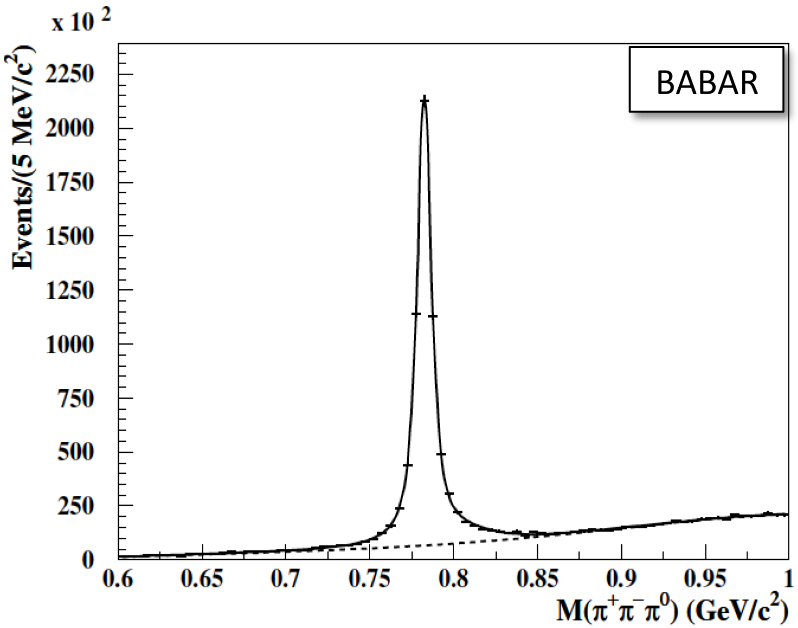


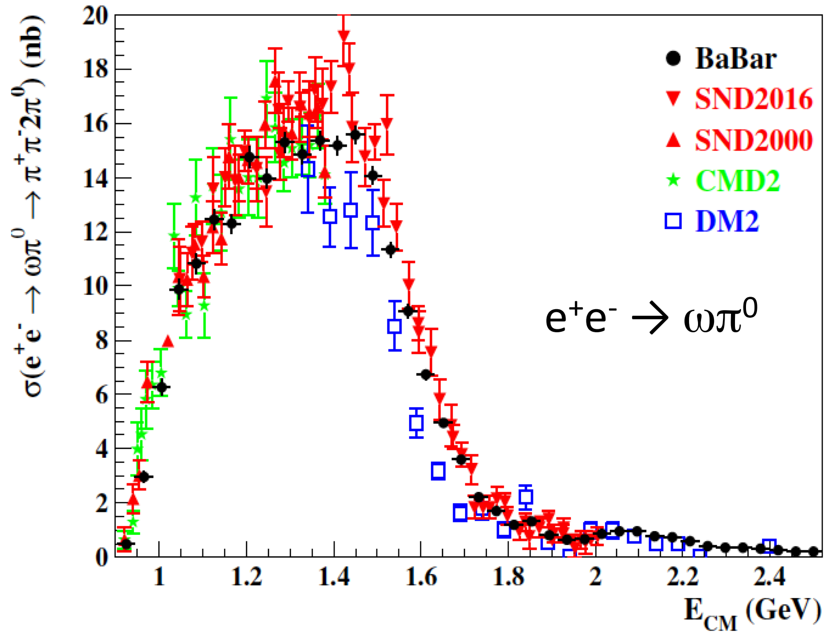


(I) $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

PRD 96 (2017) 092009

Intermediate resonances: a large fraction of $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ proceeds through $e^+e^- \rightarrow \omega\pi^0$ with $\omega \rightarrow \pi^+\pi^-\pi^0$

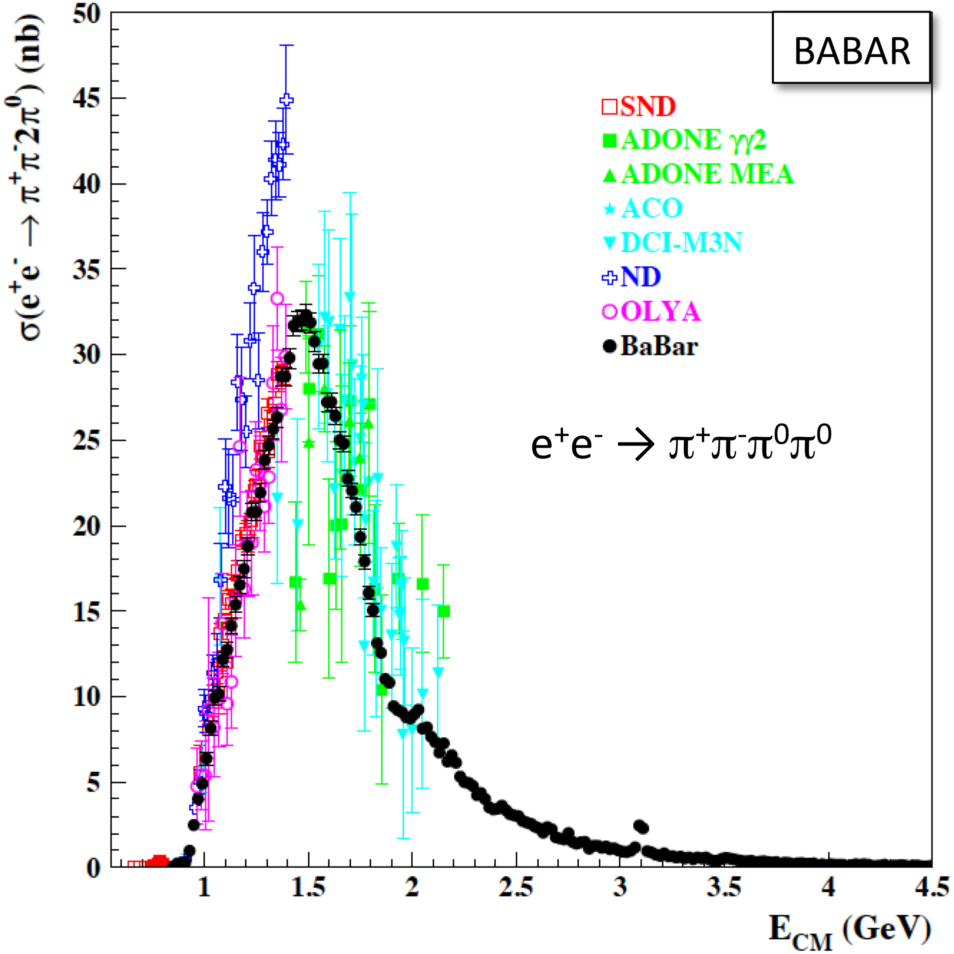




BABAR results more precise than those from previous experiments; cover wider energy range; resolve some discrepancies

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

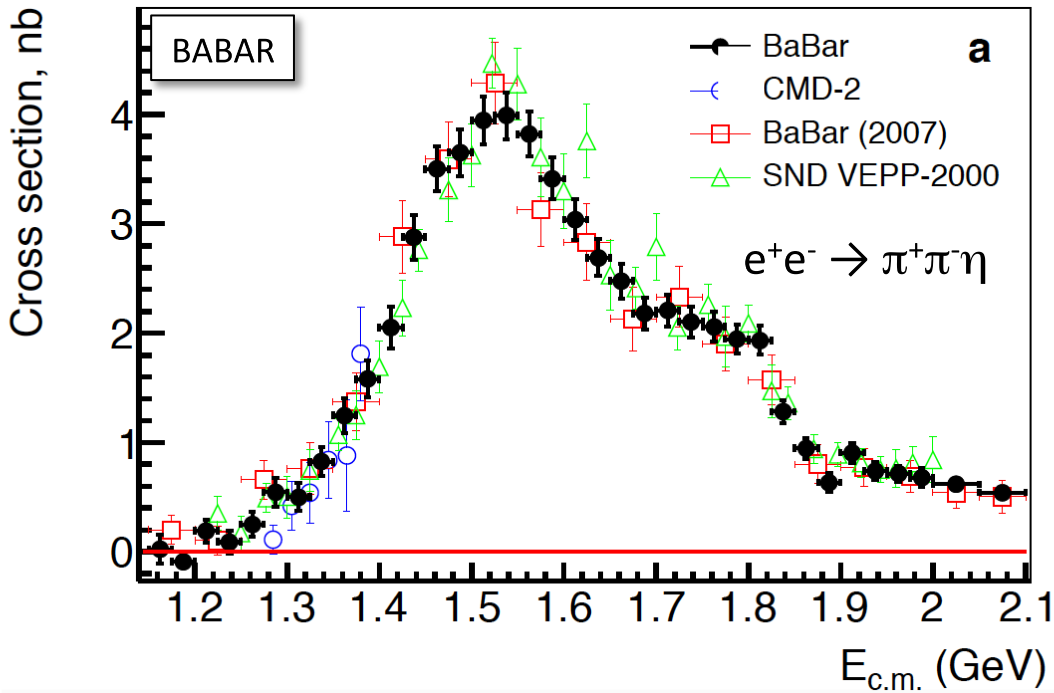
PRD 96 (2017) 092009



- 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 ± 1(stat) ± 6(syst) x 10^{-11} (3.2% precision)
- World average without BABAR: 167 ± 13 (stat+syst) x 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 $\eta \rightarrow \gamma\gamma$

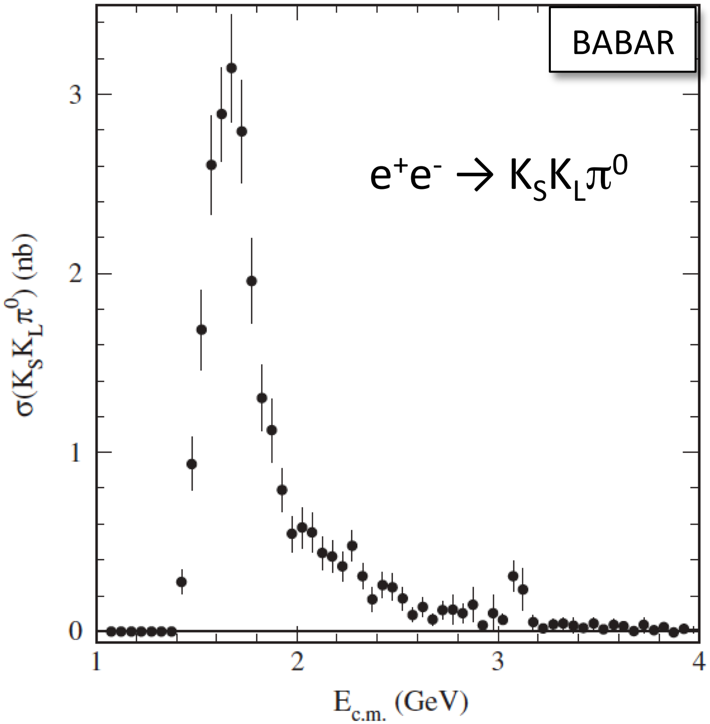
PRD 97 (2018) 052007

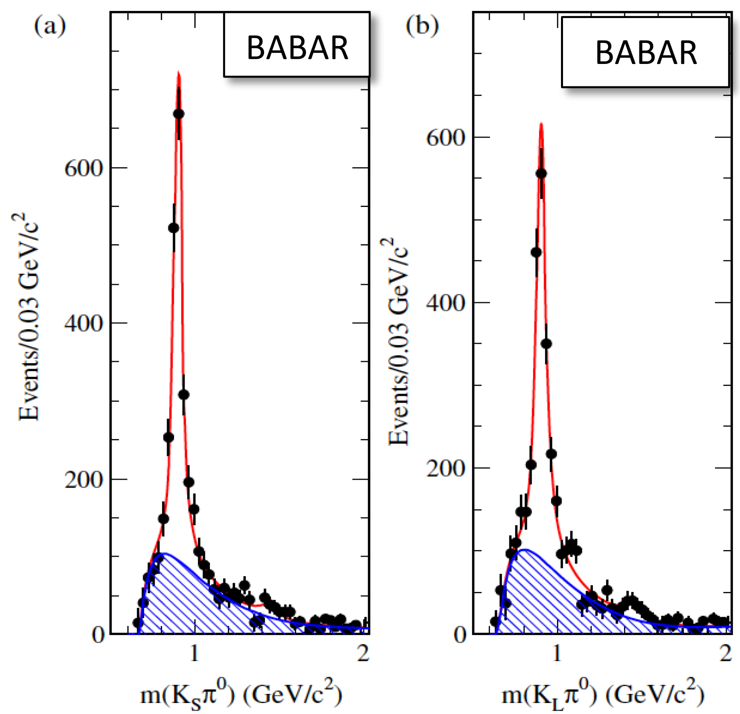


- Similar analysis techniques to $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$; 8000 signal events
- Complements and improves the precision of the BABAR result from 2007 [PRD 76 (2007) 092005], based on 232 fb^{-1} and the $\eta \rightarrow \pi^+\pi^-\pi^0$ decay mode
- Reaction dominated $\rho(770)\eta$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

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

Phys. Rev. D 95 (2017) 052001





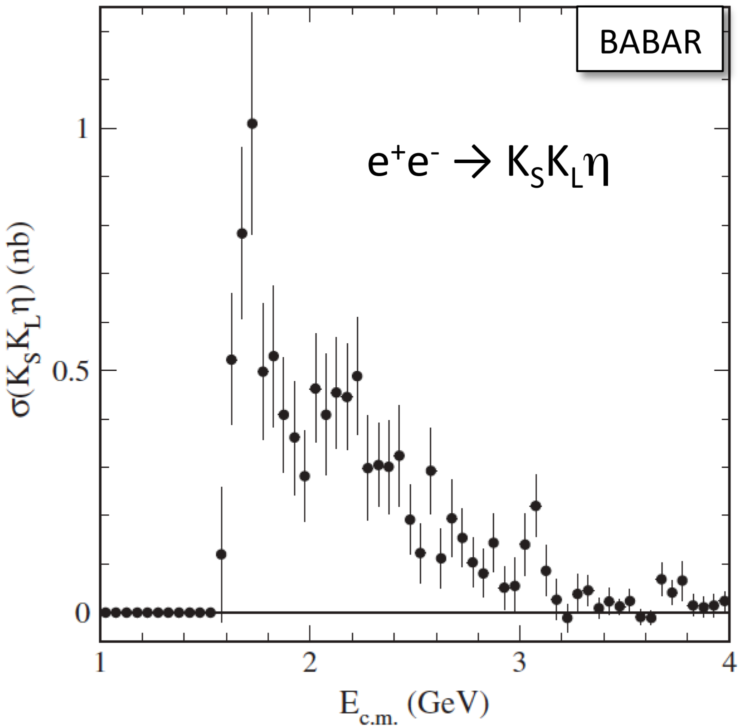
hatched areas = nonresonant components

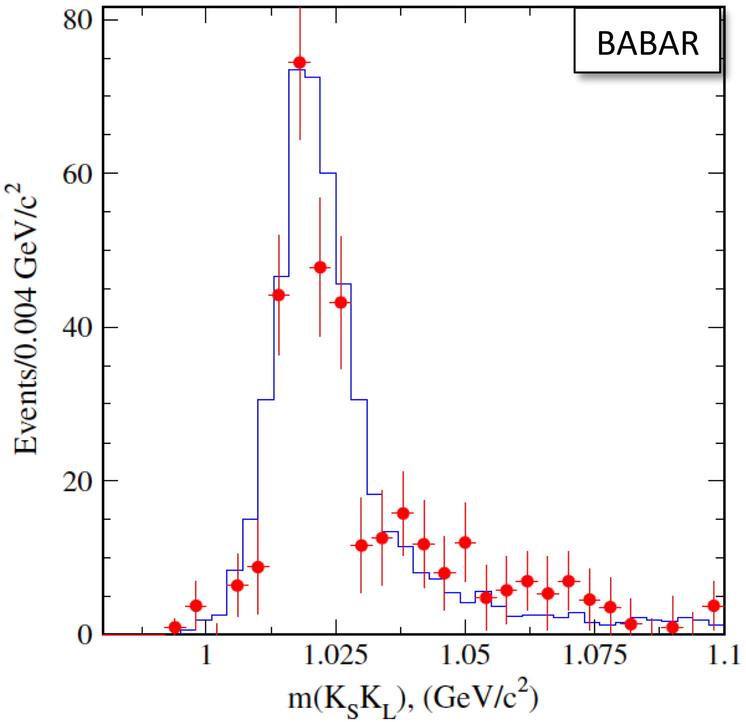
- 3700 signal events
- First measurement of this process
- First observation of $J/\psi \to K_S K_L \pi^0$

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

(IV) $e^+e^- \to K_SK_L\eta$

Phys. Rev. D 95 (2017) 052001



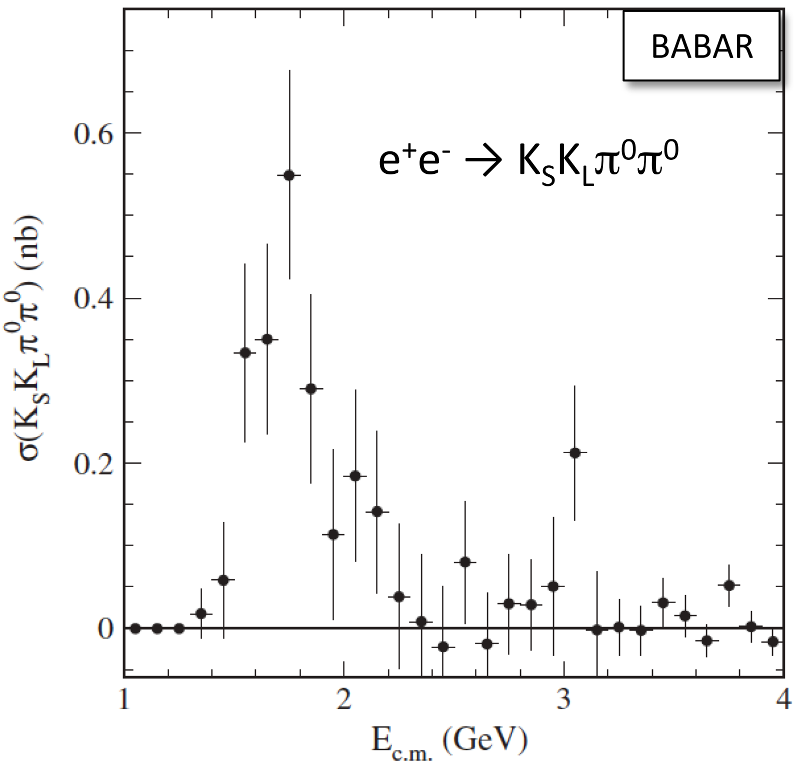


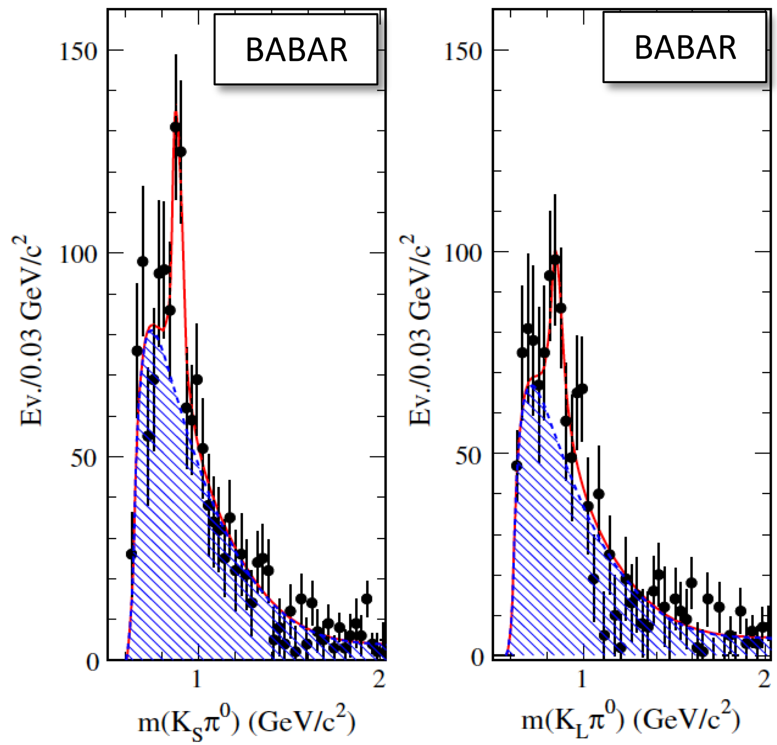
- 864 signal events
- First measurement of this process

- Dominated by $e^+e^- \to \phi\eta$

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

Phys. Rev. D 95 (2017) 052001





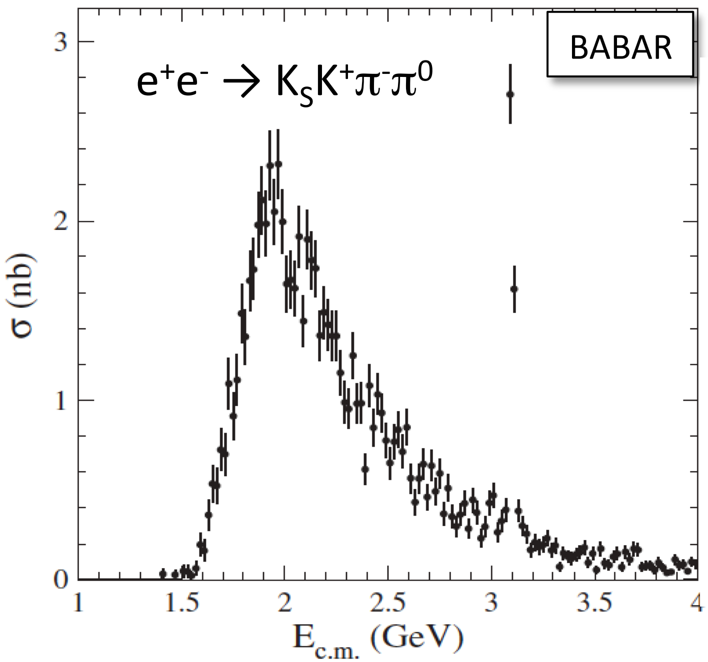
hatched areas = nonresonant components

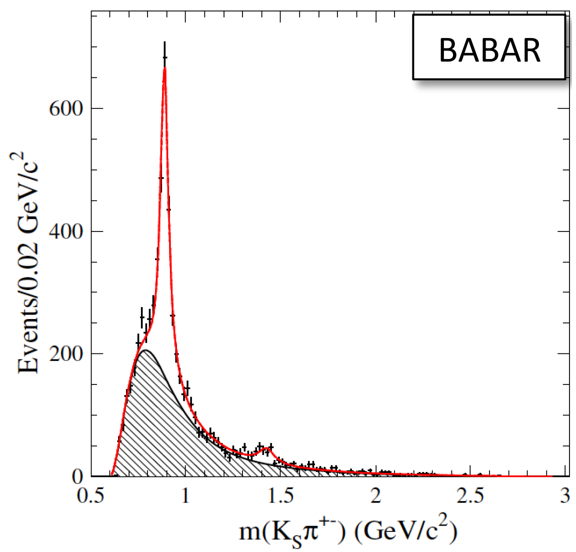
- 392 signal events
- First measurement of this process

- Clear $e^+e^- \to K^*(892)K\pi$ signals

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

Phys. Rev. D 95 (2017) 092005





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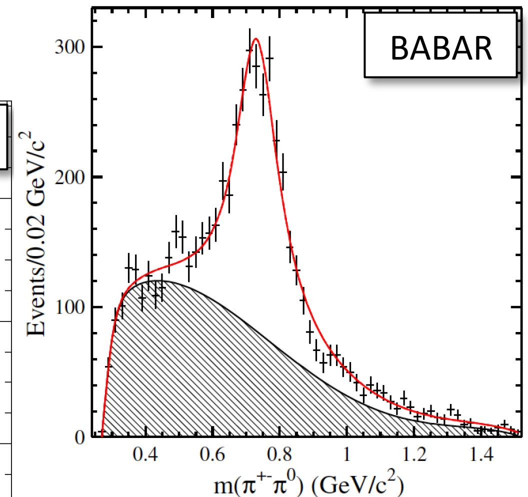
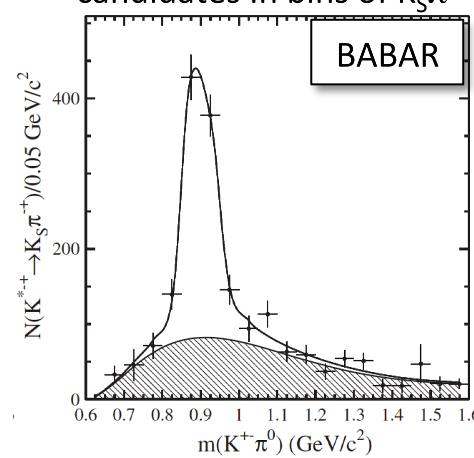


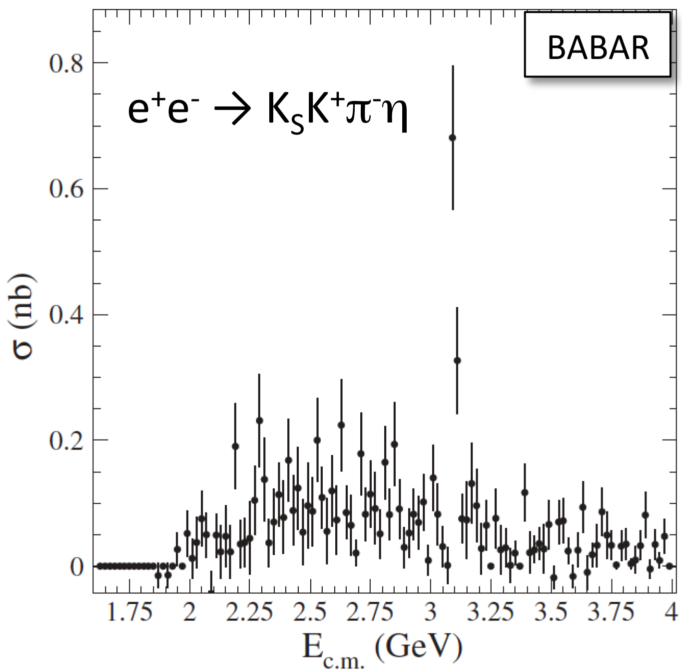
Number of fitted $K^* \to K^+\pi^-$ candidates In bins of $K_S\pi^0$

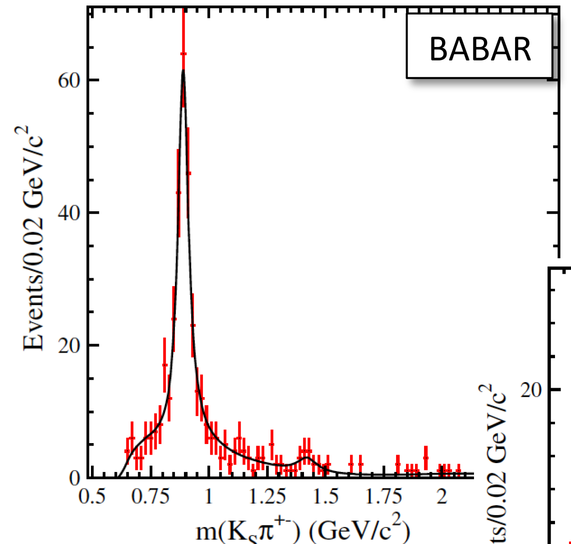


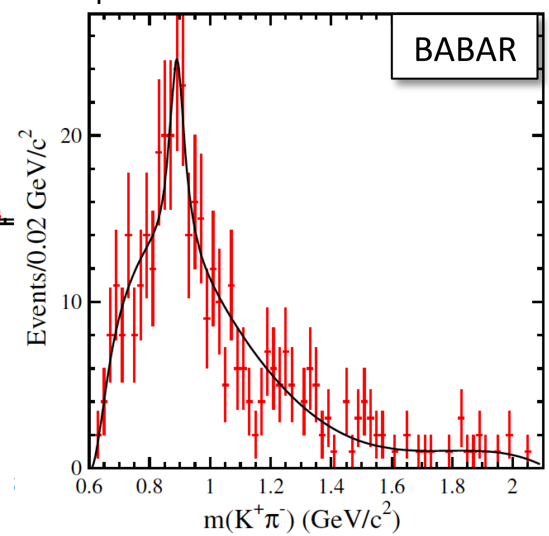
- 6400 signal events, first measurement of this process
- Large $J/\psi \to K_S K^+ \pi^- \pi^0$ peak (first observation of this decay)
- $K^*(892)K\pi$ and $K_S K^+ \rho(770)^-$ are dominant
- $K^*(892)K^*(892)$ ~ 15%; small $K^*(1430)K\pi$ component

(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)Kη peak, primarily in $K^*(892)^{\pm} \rightarrow K_S \pi^{\pm}$

Implications for the muon g - 2

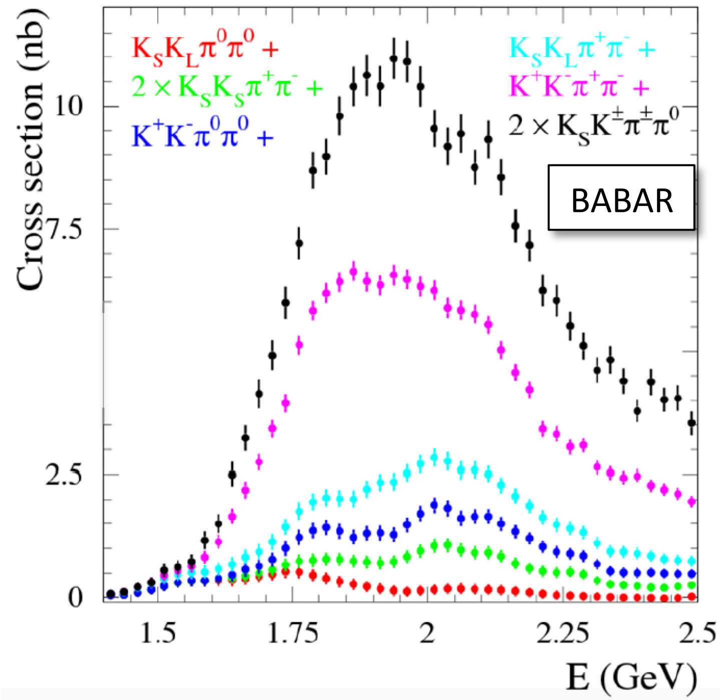
- With the new results for
  - $e^+e^- \rightarrow K_S K_L \pi^0$ PRD95 (2017) 052001
  - $e^+e^- \rightarrow K_S K^+ \pi^- \pi^0$ PRD95 (2017) 092005
  - $e^+e^- \rightarrow K_S K_L \pi^0 \pi^0$ PRD95 (2017) 052001

  in combination with previous BABAR results, BABAR has now measured <u>all</u>
  - $e^+e^- \rightarrow KK\pi$
  - $e^+e^- \rightarrow KK\pi\pi$

  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 $e^+e^- \rightarrow KK\pi\pi$ states from BABAR



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

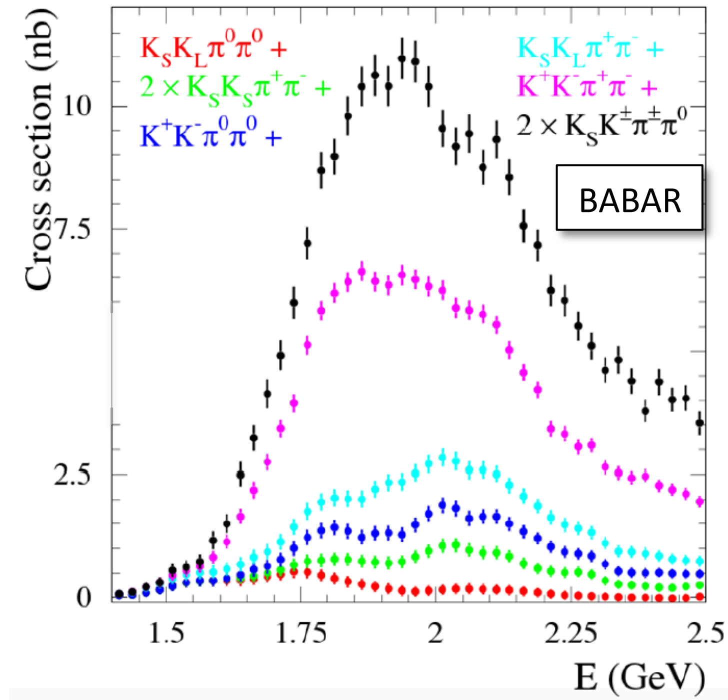
Implications for the muon g - 2

- KKππ 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
  $e^+e^- \rightarrow$ 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 $e^+e^- \rightarrow KK\pi\pi$ states from BABAR



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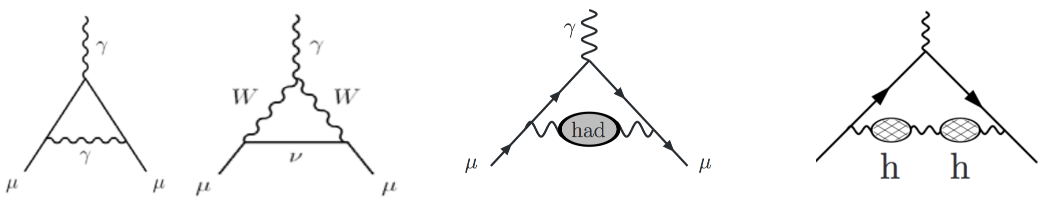

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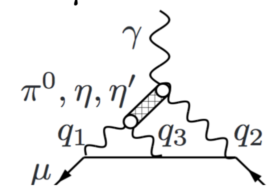

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M. Davier et al., EPJC 71 (2011) 1515 **units of 10^{-11}**
& PDG (2016)

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Data - SM	288 ± 80

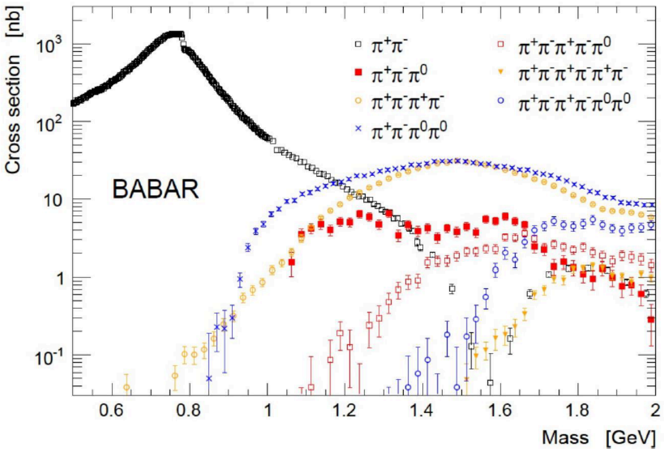
Updated result from ,M. Davier [arXiv:1612.02743 (Feb. 2017)] using all the newly available (since 2010) data, dominated by BABAR

$a_\mu^{had,LO}$ = 6926 ± **33**

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

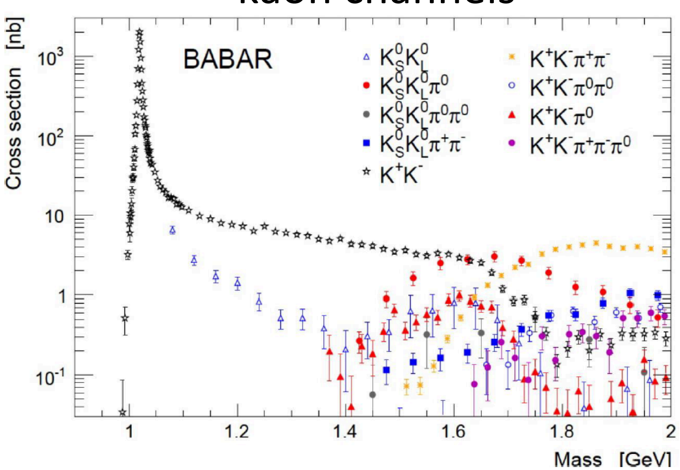
Summary of BABAR ISR results

pion channels

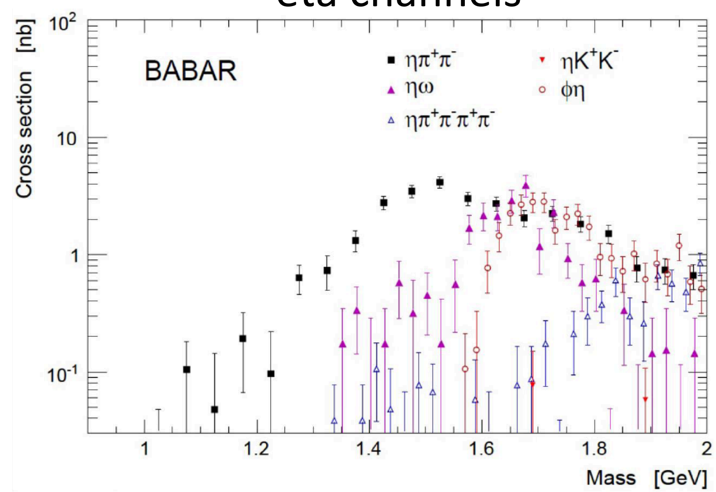


- Plots don't yet contain all the latest results
- Discrepancy of up to 3% between BABAR and KLOE in the all-important $\pi^+\pi^-$ channel
- New BABAR analysis on $\pi^+\pi^-$ with reduced systematics and 8 times more data expected around the end of 2018

kaon channels



eta channels



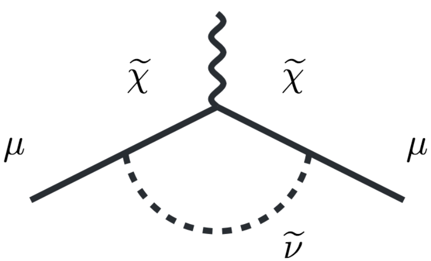
Summary

- 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

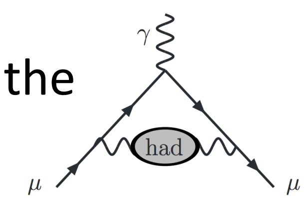
EXTRA

g_μ- 2 in the standard model

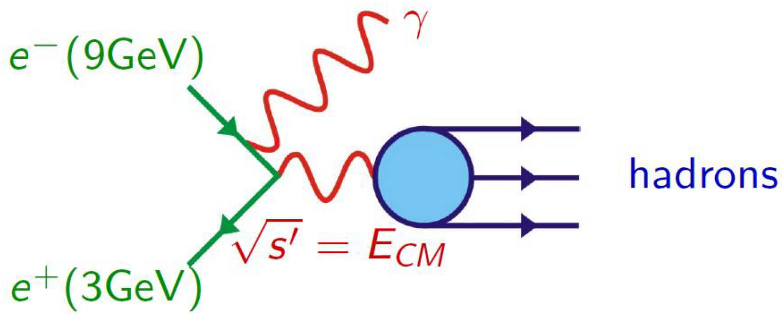
- The longstanding tension between theory and data for the muon g-2 could be an indication of new physics



- 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>



ISR method to measure low energy cross sections



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

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

W (s,x) = radiator function

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

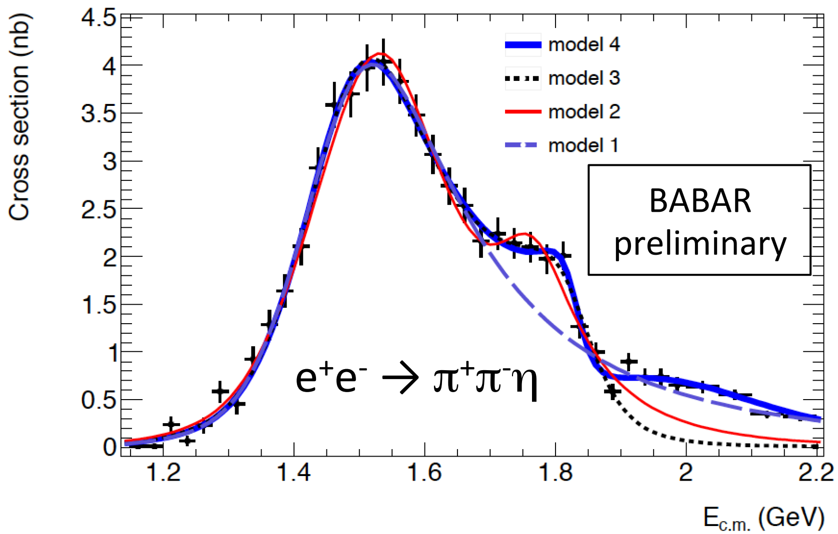
$E_{CM} = \sqrt{(1-x)s}$ = invariant mass of the hadronic system

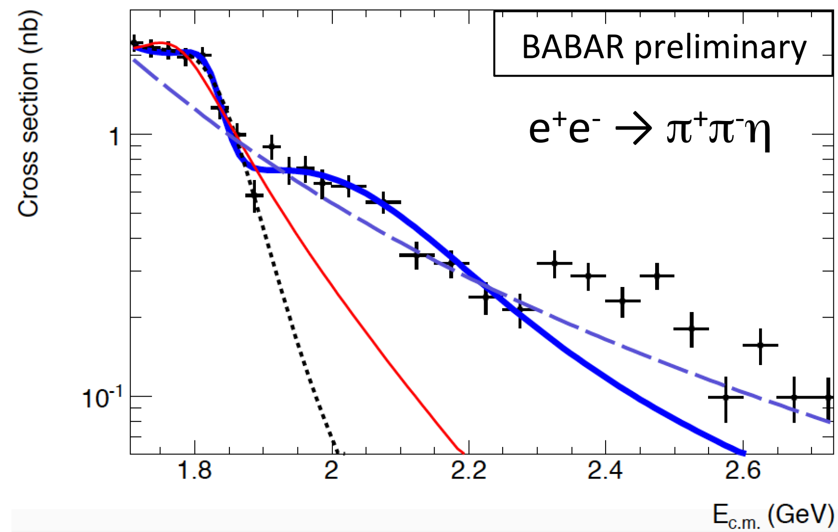
$x = 2\,E_\gamma/\sqrt{s}$; E_γ measured in CM frame

(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