Measurement of hadronic cross sections with the BABAR detector

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on behalf of the BABAR Collaboration

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(g-2)$_\mu$/2 of muon

Magnetic moment

$$\vec{\mu} = g \frac{e\hbar}{2mc} \vec{S}$$

- ✓ **The Dirac equation predicts g=2 for point-like fermions.**
- ✓ **Higher order QFT contributions lead to nonzero**

$$a_\mu = (g-2)_\mu / 2$$

- ✓ **a_μ is sensitive to New Physics contributions**

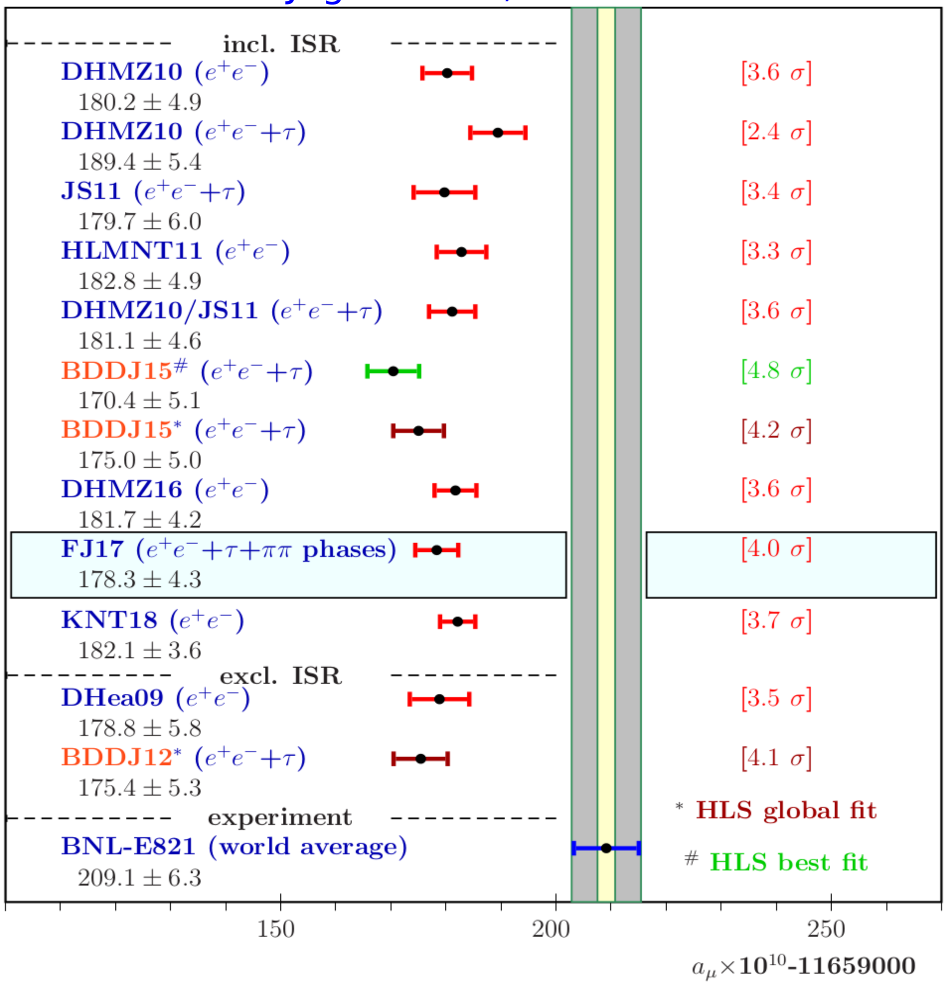
E821@BNL (1997-2001): G.W. Bennett *et al*., Phys. Rev. D **73**, 072003 (2006)

a_μ = (11 659 209.1±6.3)×10^{-10} (0.54 ppm)

E989 @ FNAL (2017-…): F. Gray *et al.*, arXiv: 1510.00346 **a_μ = … (0.14 ppm)**

E34 @ J-PARC (????-…): T. Mibe *et al.*, Chin. Phys. C **34** (2010) 745 **a_μ = … (0.1 ppm)**

F.Jegerlehner, **arXiv:1804.07409**



Data - SM discrepancy is more than 3σ

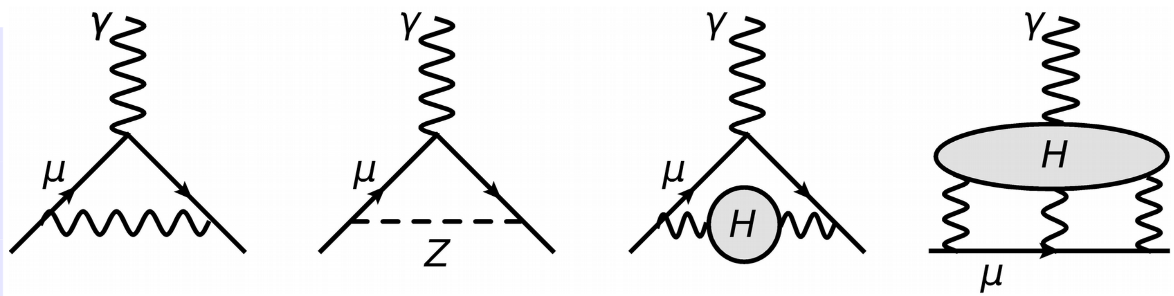
$(g\text{-}2)_\mu/2$ of muon

- The leading order hadronic contribution is calculated using dispersion relations from experimental data on the total cross section of the e^+e^- annihilation into hadrons.
- Low energies (E < 2 GeV) give dominant contribution into $a_\mu^{had,LO\text{-}VP}$ (92%).

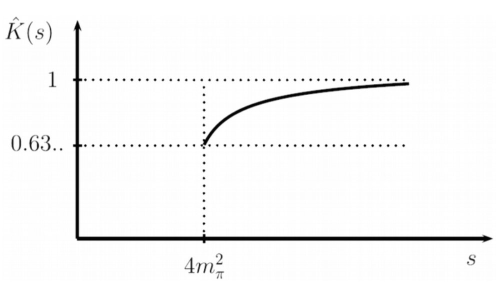
Individual SM contributions $\times 10^{-10}$

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

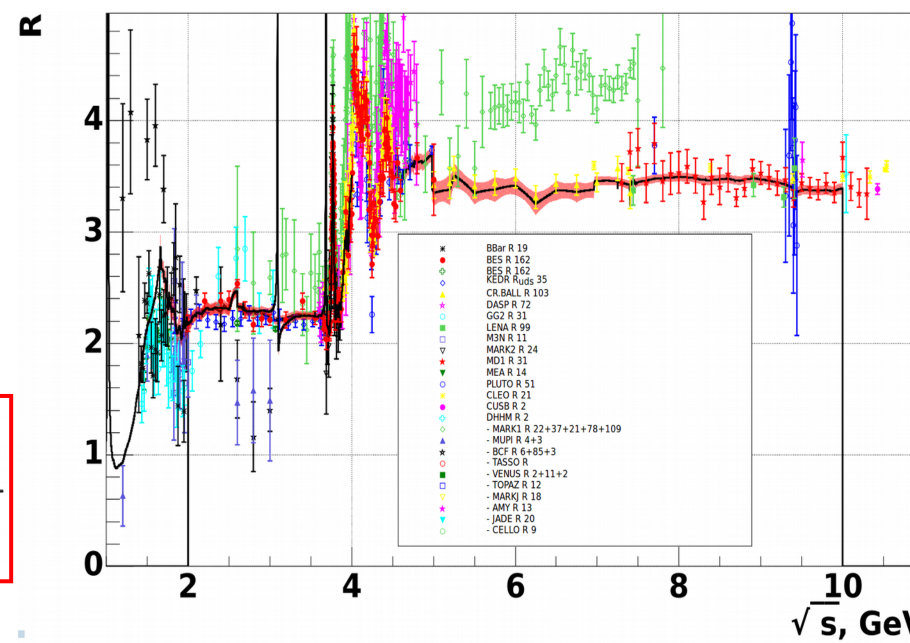
DHMZ , TAU 2016, arXiv:1612.02743



$$a_\mu^{had,LO\text{-}VP} = \frac{\alpha^2 m_\mu^2}{9\pi^2} \int_{m_\pi^2}^{\infty} ds \frac{\hat{K}(s)}{s^2} R(s)$$



$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



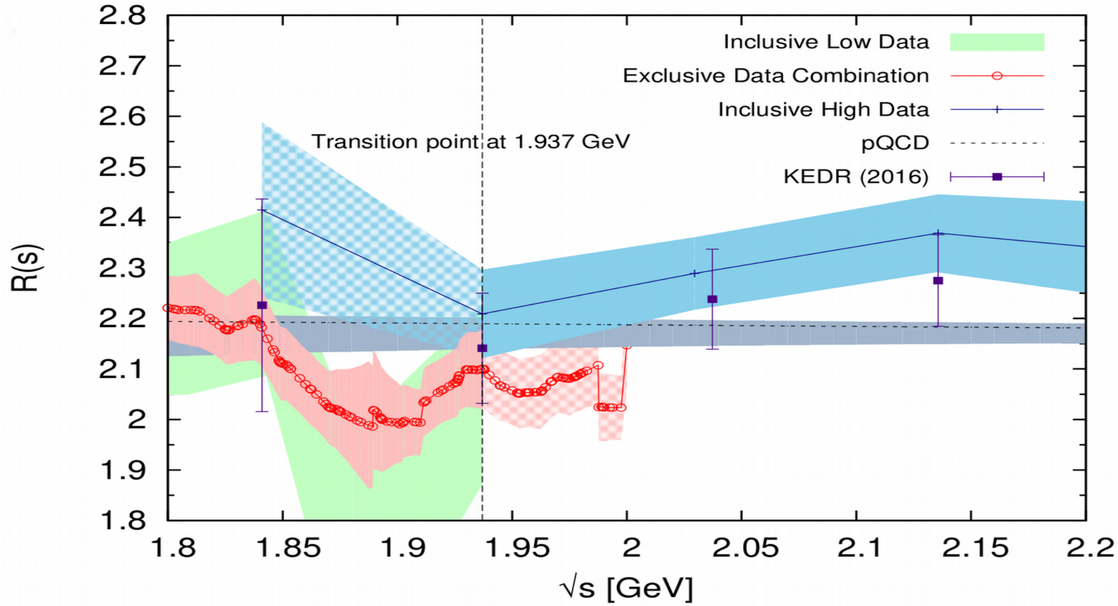
(g-2)$_\mu$/2 of muon

- **Below 1.9(1.8) GeV the total cross section is calculated as a sum of exclusive channels.**

- **The exclusive data are incomplete in the region 1.6<E<2.0 GeV.**

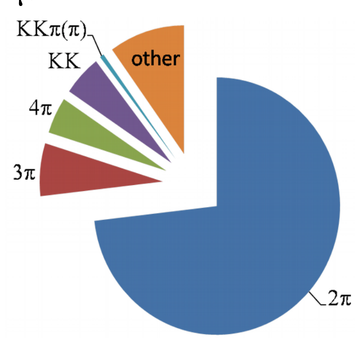
- **There is no experimental information on the final states $\pi^+\pi^-\pi^0\eta$, $\pi^+\pi^-\eta\eta$, $\pi^+\pi^-\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0\pi^0\eta$, 7π ...**

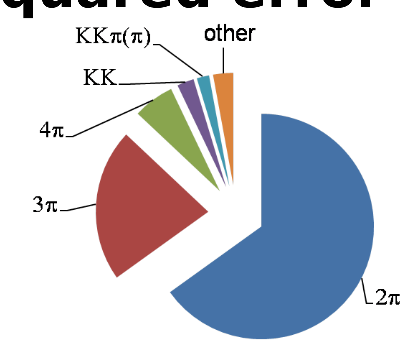
- **The important experimental task is to measure all significant exclusive channels below 2 GeV, and perform comparison with inclusive measurements and pQCD prediction.**



A.Keshavarzi, D.Nomura, T. Teubner **arXiv:1802.02995**

The contributions of different hadronic channels into $a_\mu^{had,LO-VP}$ and its squared error σ^2

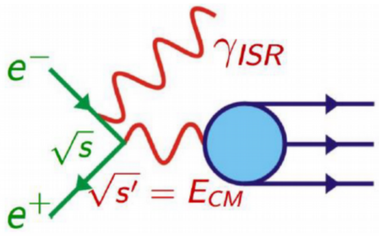


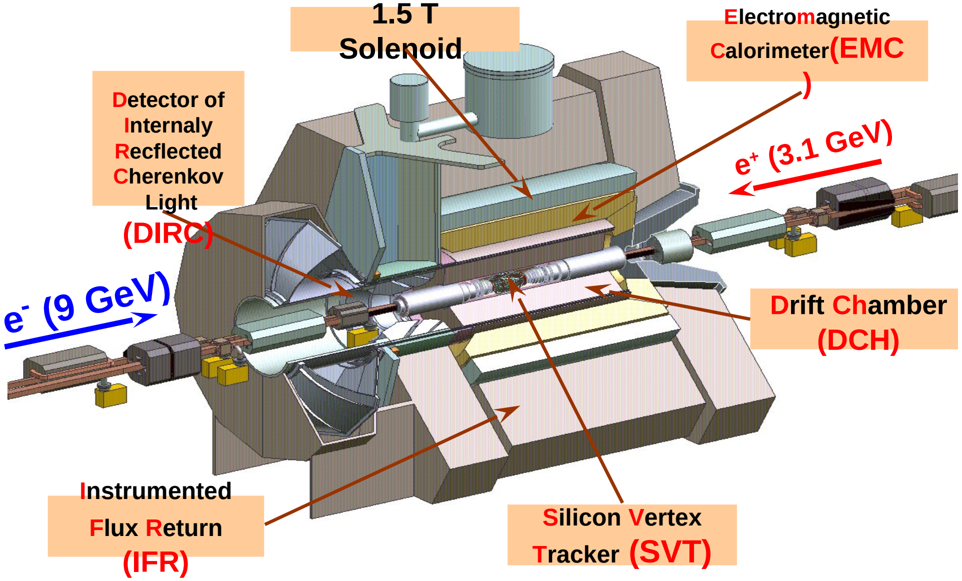


BABAR @ ISR method

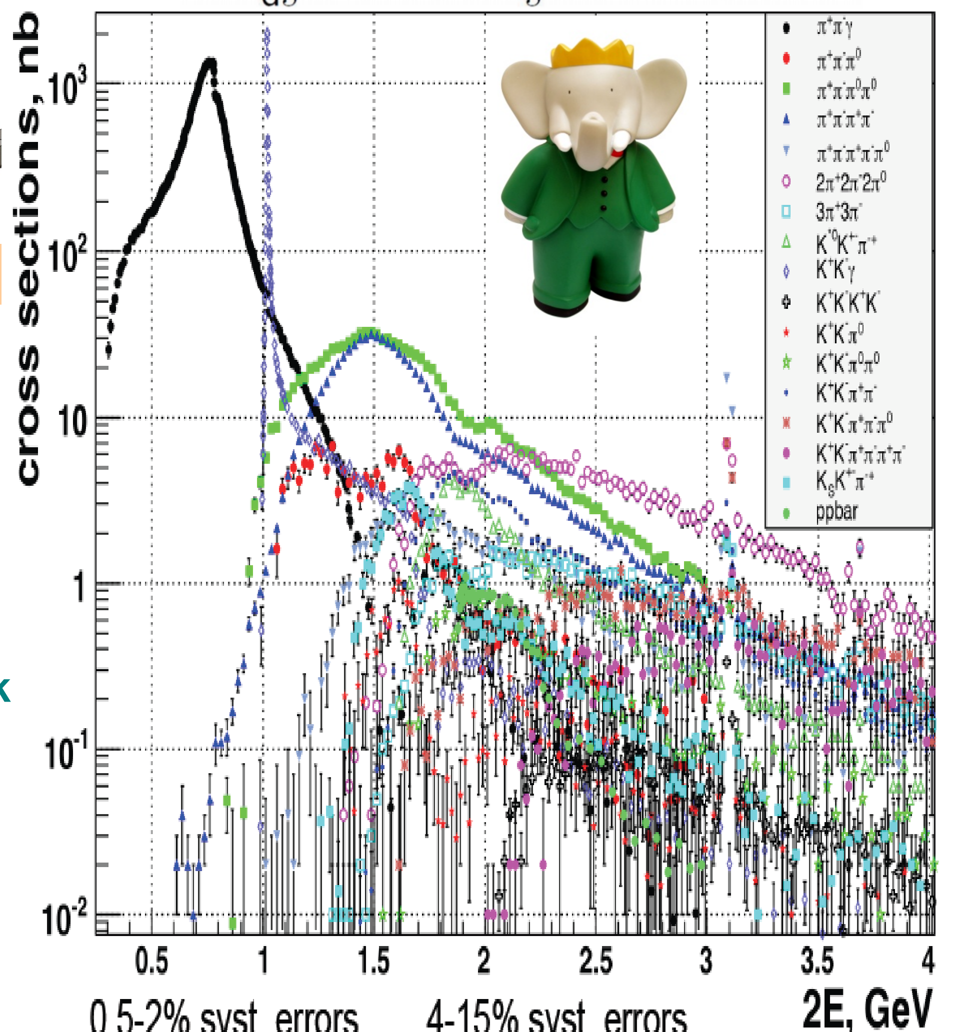
PEP-II asymmetric e^+e^- collider at SLAC
(9 GeV e^- and 3.1 GeV e^+)

Data, about 500 fb^{-1}, were collected in 1999-2008





$$\frac{d\sigma_{[e^+e^-\to f\gamma]}}{ds'}(s') = \frac{2m}{s}W(s,x)\sigma_{[e^+e^-\to f]}$$



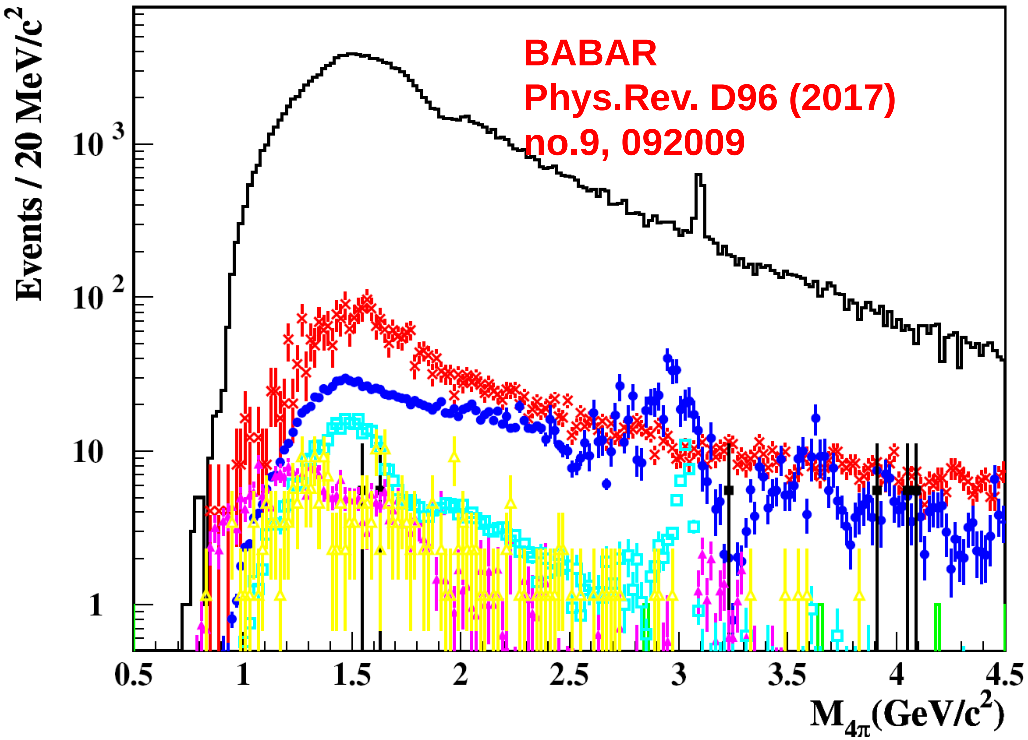
For ISR analyses, a data sample of 469 fb^{-1} collected near or at a c.m. energy of 10.58 GeV (at and near $\Upsilon(4S)$) is used.

Four recent analyses are discussed in this talk

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

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

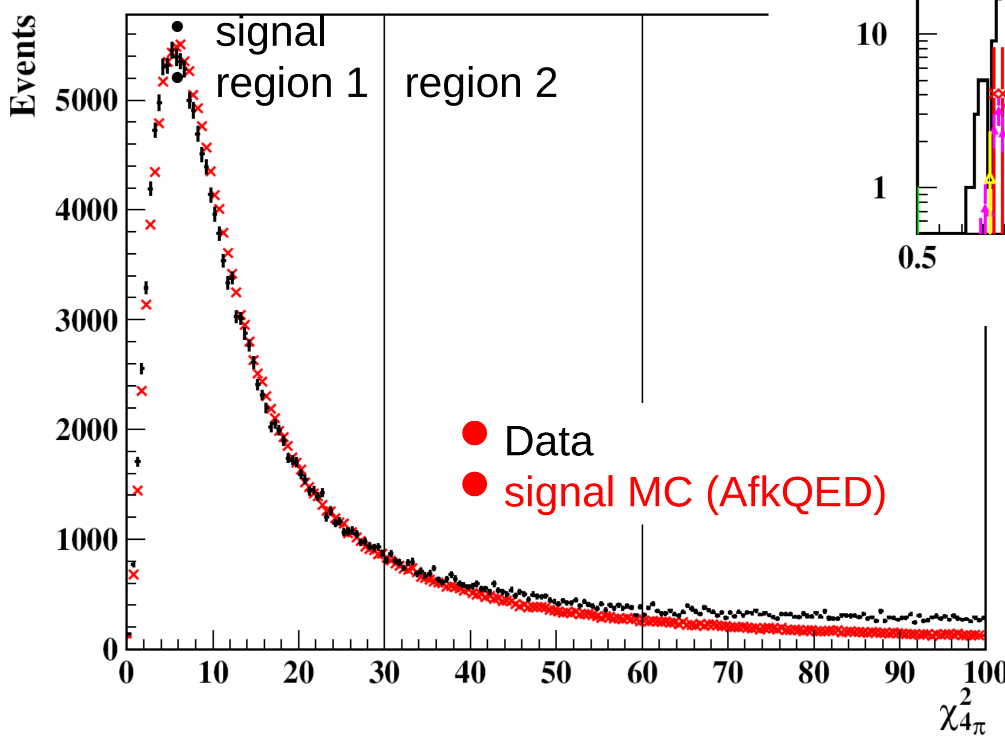
- Full reconstruction $\pi^+\pi^-\pi^0\pi^0\gamma$
- MC simulated background
- normalized to data and
- subtracted
- Cross-checked with
- 6C-fit $(E, \vec{p}, 2\times m_{\pi^0})$
- ratio χ^2 region 1/2



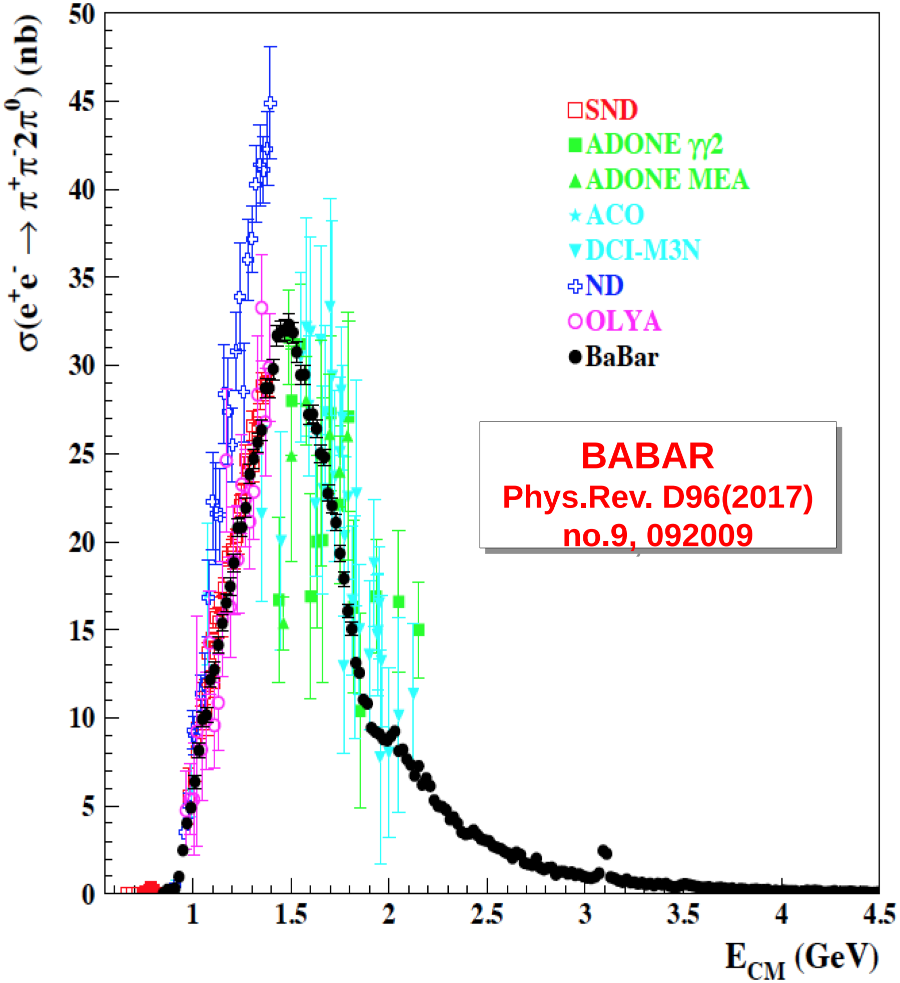
$q\bar{q}$, $\tau\tau$, $\gamma\pi^+\pi^-3\pi^0$,

$\gamma K_S K\pi$, $\gamma K^+K^-2\pi^0$,

$\gamma 3\pi$, $\gamma 4\pi^\pm 2\pi^0$,



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

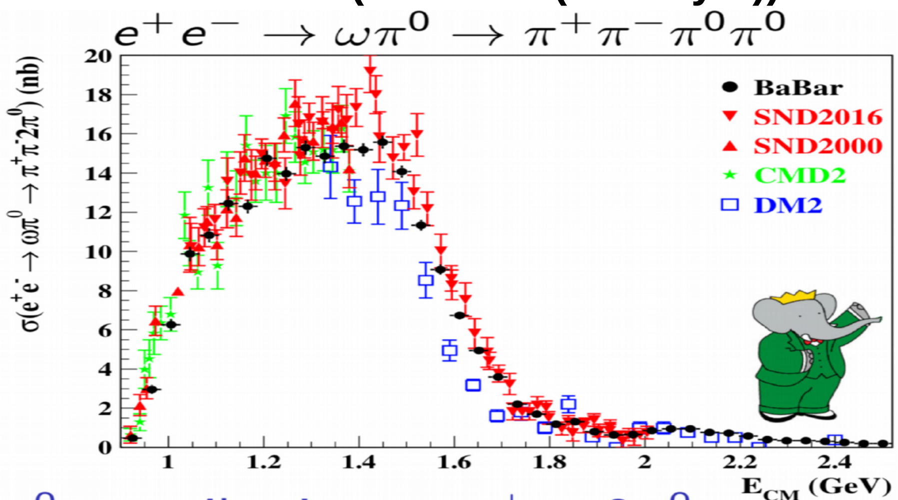


- **BABAR results are most precise and cover wider energy range.**
- **Systematic uncertainty is 3.1% in the 1.2-2.7 GeV energy range.**
- **Contribution to a_μ for the range $1.02<E_{CM}<1.8$ GeV is measured to be**

$$a_\mu^{\text{had LO}}(\sqrt{s} < 1.8\text{ GeV}) = (17.9 \pm 0.1 \pm 0.6)\cdot 10^{-10}$$

Previous result including the preliminary BABAR data from 2007 is

$(18.0 \pm 1.2(\text{stat+syst}))\cdot 10^{-10}$

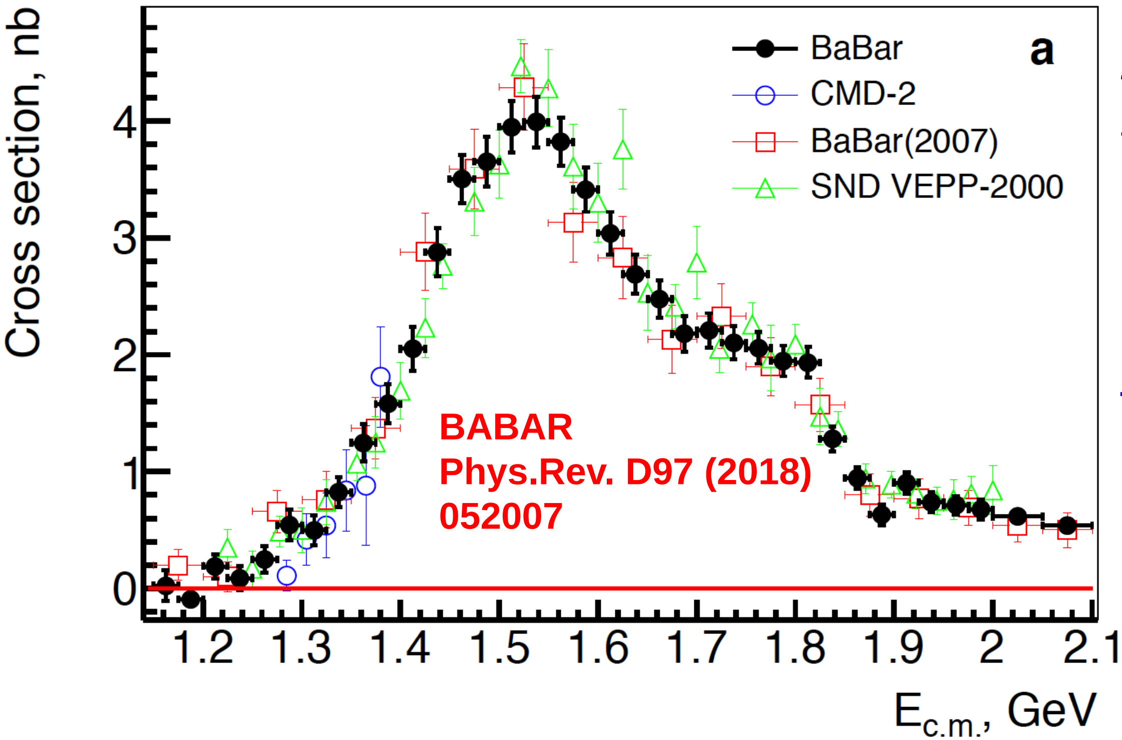


$\omega\pi^0$ contribution to $\pi^+\pi^-2\pi^0$

$(32.1 \pm 0.2_{stat} \pm 2.6_{syst})$ %

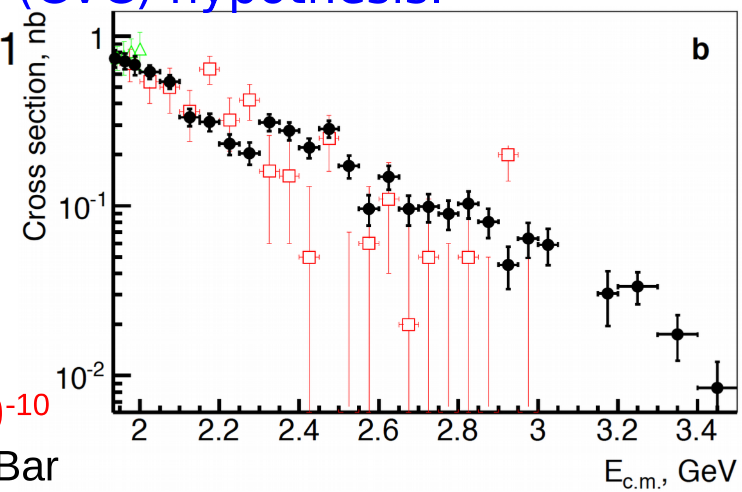
Intermediate states $a_1\pi$, $\omega\pi^0$, $\rho^+\rho^-$, $f_0\rho^0$

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



The BABAR results in the $\eta\to\gamma\gamma$ mode agrees well with the previous measurements, but is more precise and extending energy range up to 3.5 GeV.

The $e^+e^- \to \pi^+\pi^-\eta$ cross section is used to test conserved vector current (CVC) hypothesis.



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

$a_\mu^{\text{had LO}}(\sqrt{s} < 1.8\text{ GeV}) = (1.19 \pm 0.02 \pm 0.06)\cdot 10^{-10}$

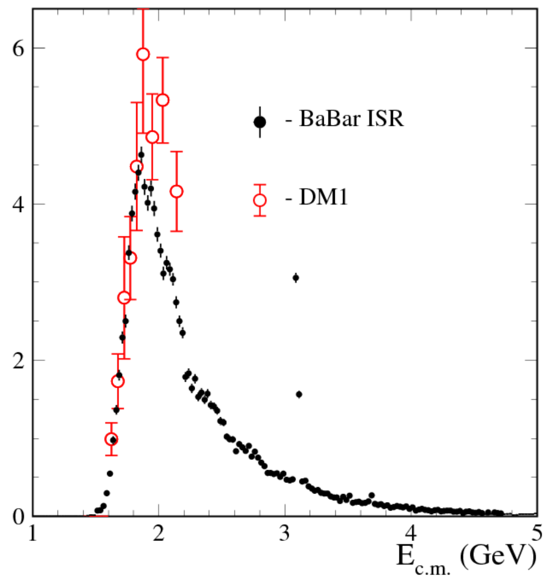
1.15 ± 0.10 – All before BaBar

$e^+e^- \to K\bar{K}\pi\pi$

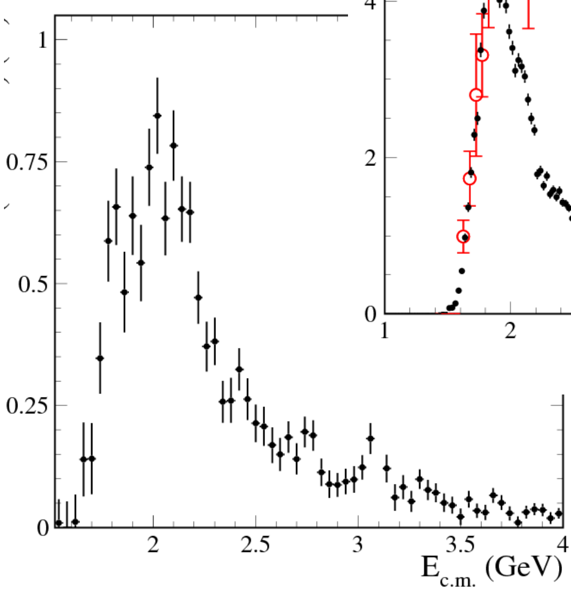
There are six combinations in the $e^+e^- \to K\bar{K}\pi\pi$ process. Four were measured previously.

Phys. Rev. D 86, 012008 (2012)

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

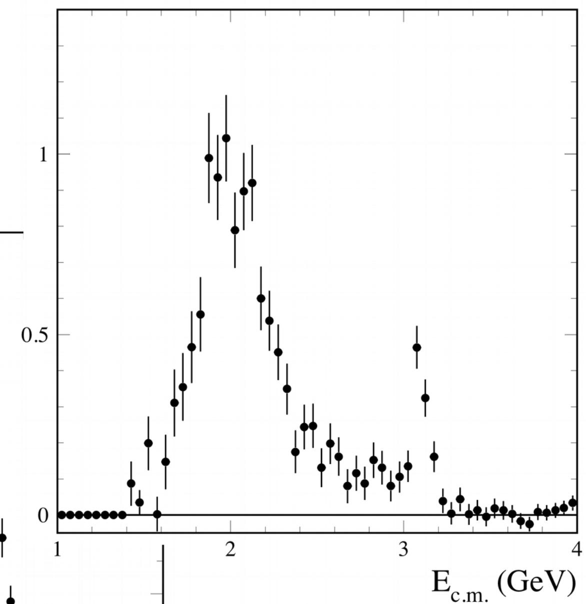


$\sigma(e^+e^- \to K^+K^-\pi^0\pi^0)$

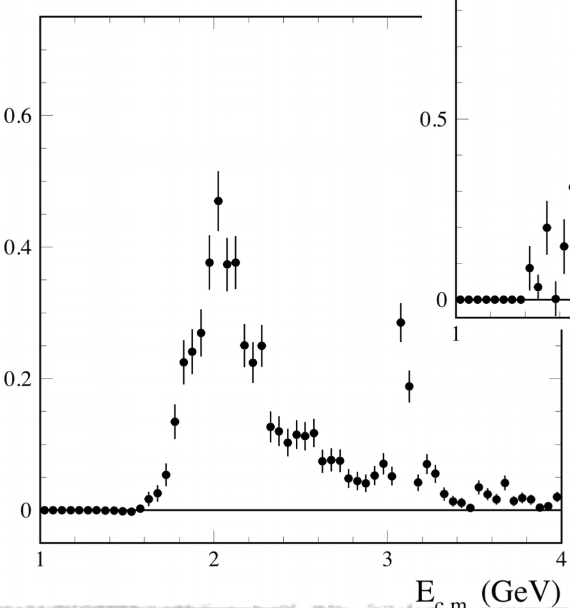


Phys. Rev. D 89, 092002 (2014)

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

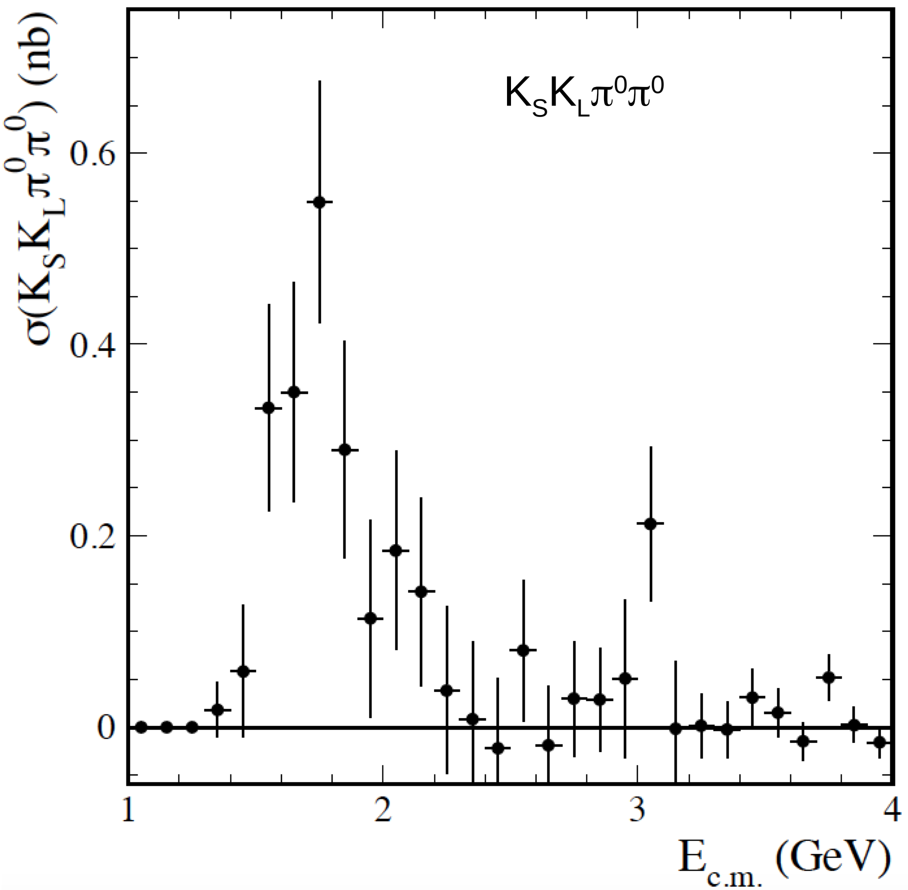


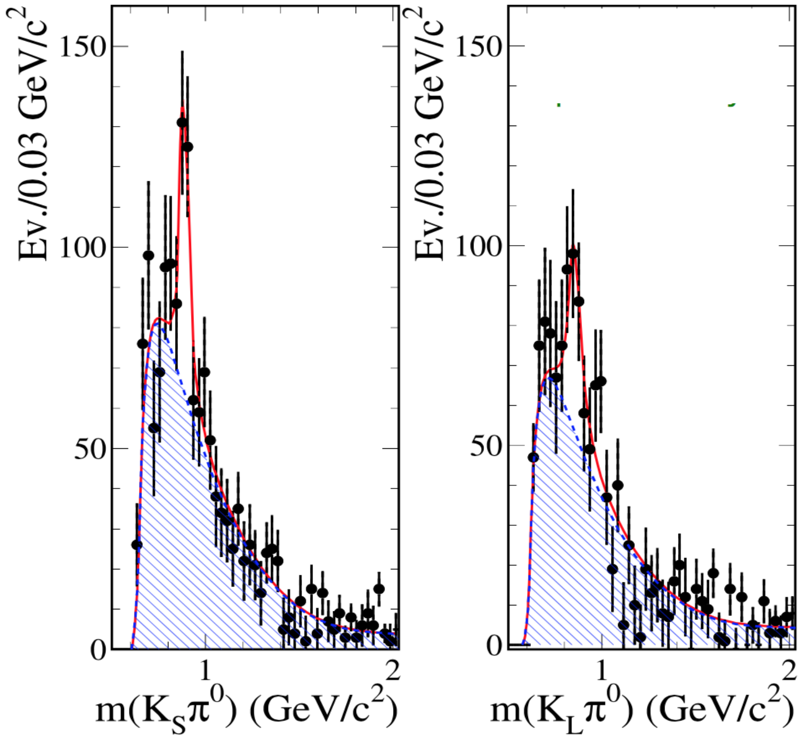
$\sigma(e^+e^- \to K_SK_S\pi^+\pi^-)$



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

Phys. Rev. D 95, 052001 (2017)

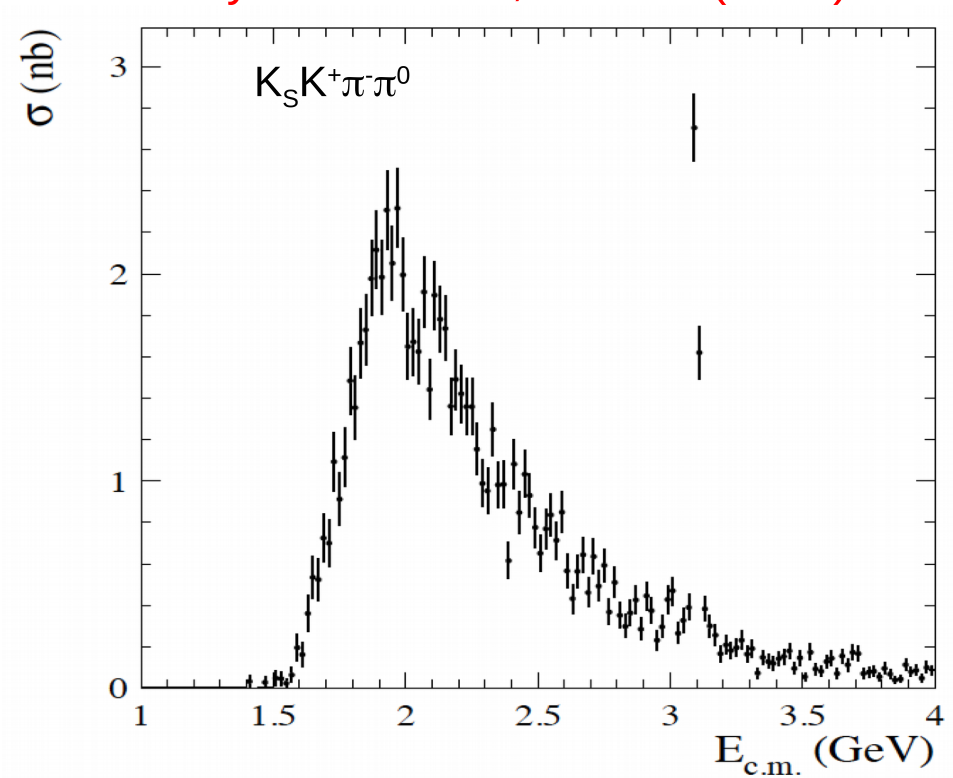




- First measurement
- Systematic uncertainty is 25% at the peak, grows to 60% at 2 GeV
- Dominant K*(892)K π intermediate state. No evidence $K^{*0}\overline{K}^{*0}$

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

Phys. Rev. D 95, 092005 (2017)

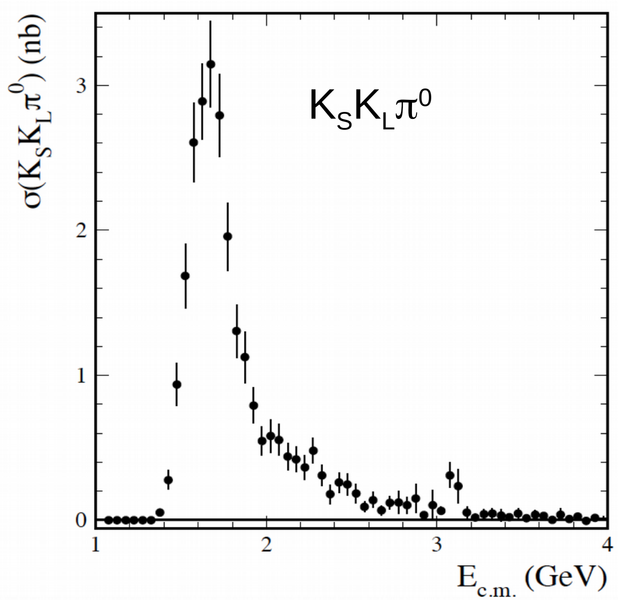


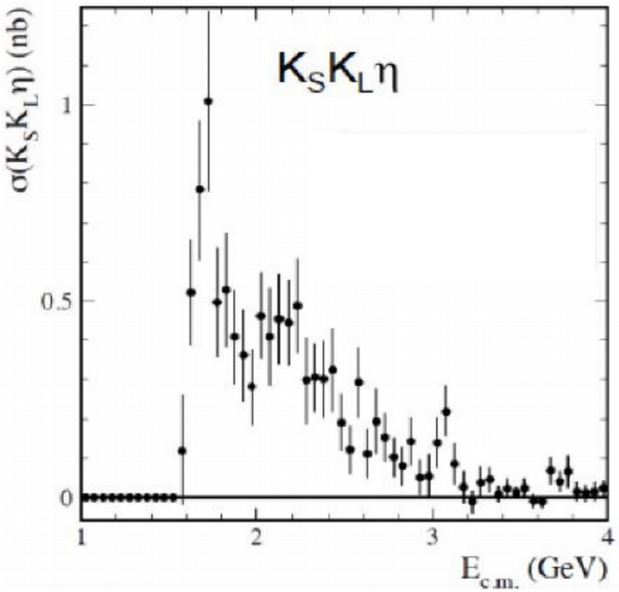
Intermediate state
$K^{*0} K^0_S \pi^0$
$K^{*0} K^\pm \pi^\mp$
$K_2^*(1430)^0 K^0_S \pi^0$
$K_2^*(1430)^0 K^\pm \pi^\mp$
$K^*(892)^\pm K^0_S \pi^\mp$
$K^*(892)^\pm K^\mp \pi^0$
$K_2^*(1430)^\pm K^0_S \pi^\mp$
$K_2^*(1430)^\pm K^\mp \pi^0$
$K^{*0} \overline{K}^{*0}$
$K^*(892)^+ K^*(892)^-$
$K^0_S K^\pm \rho(770)^\mp$

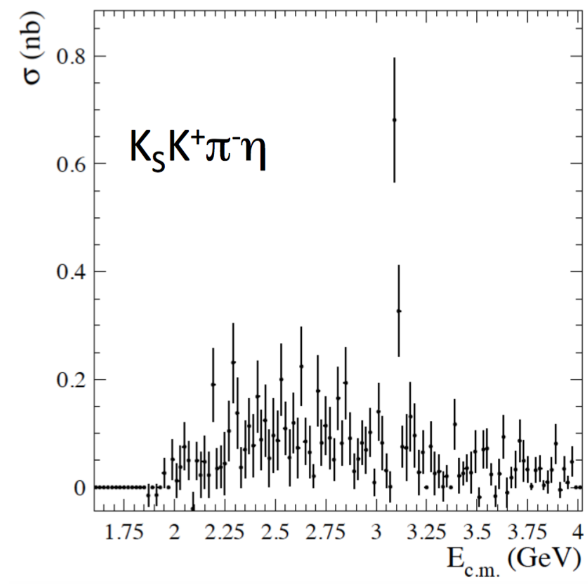
- First measurement of largest KKππ mode
- Systematic uncertainty is 6-7% below 3 GeV
- More than 10 intermediate states – dominant are $K^*(892)K\pi$, $K_S K^+ \rho^-(770)$

$e^+e^- \to K_S K_L \pi^0$, $K_S K_L \eta$, $K_S K^+ \pi^- \eta$ @ BABAR

Phys. Rev. D 95, 052001 (2017)





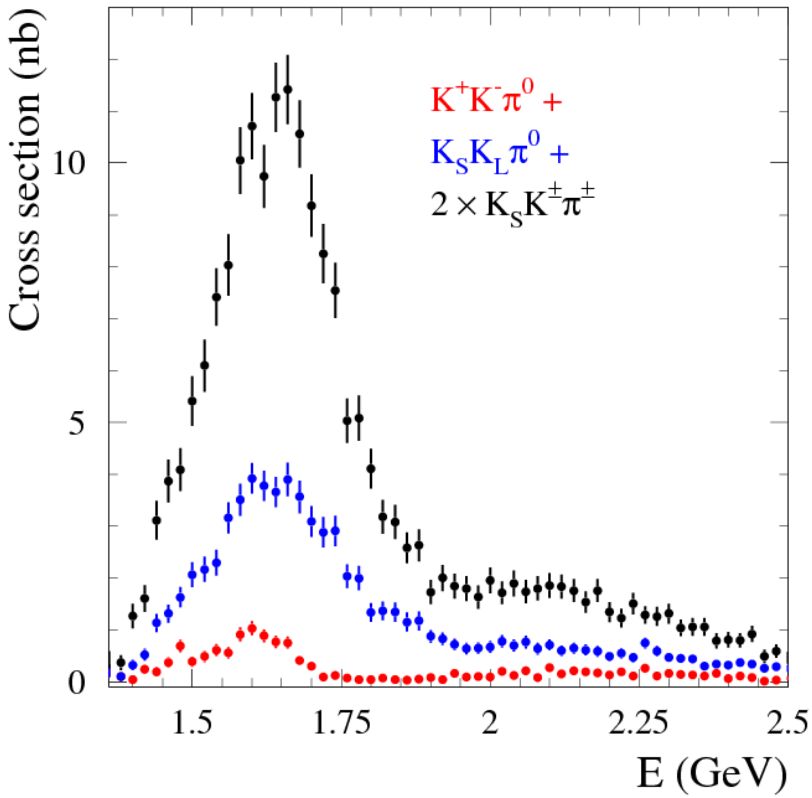


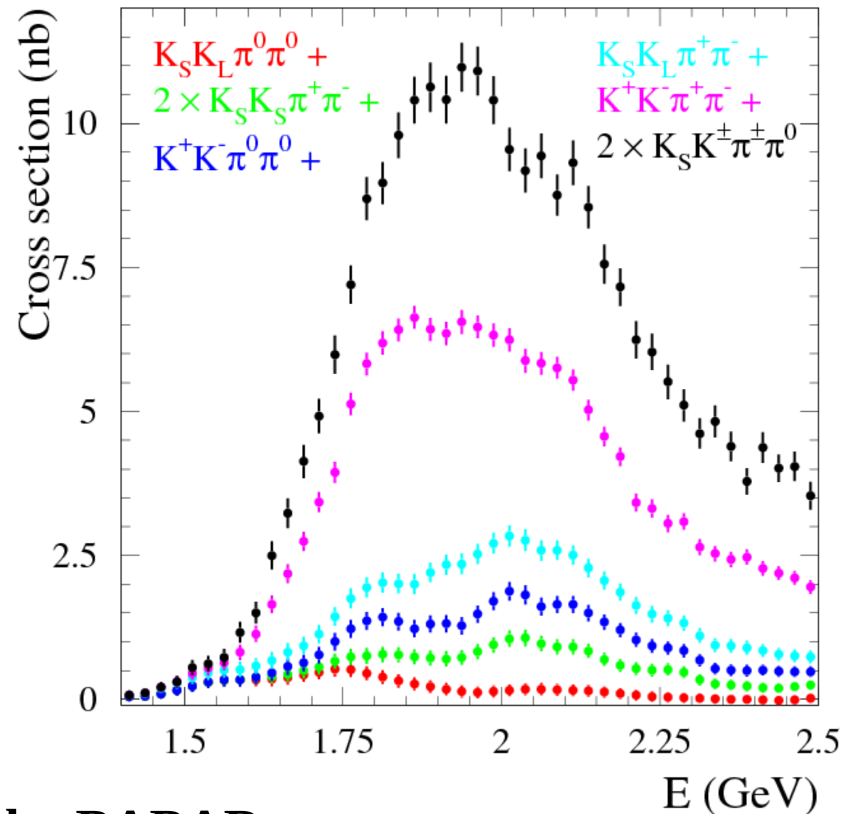
- First measurement
- Systematic uncertainty is 10% near the peak, grows to 30% at 3.0 GeV
- Dominant $\bar{K}^*(892)K$ intermediate state

- First measurement
- Systematic uncertainty is 25% at the peak, grows to 60% at 2 GeV

- First measurement
- Systematic uncertainty is 12-19% below 3 GeV
- Dominant $K^*(892)\bar{K}\eta$ intermediate state.

Total $e^+e^- \to K\bar{K}\pi$ and $K\bar{K}\pi\pi$ cross sections





- **All modes have now been measured by BABAR**
- **KKπ is about 12% of the total cross section for E_{cm} = 1.65 GeV**
- **KKππ 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

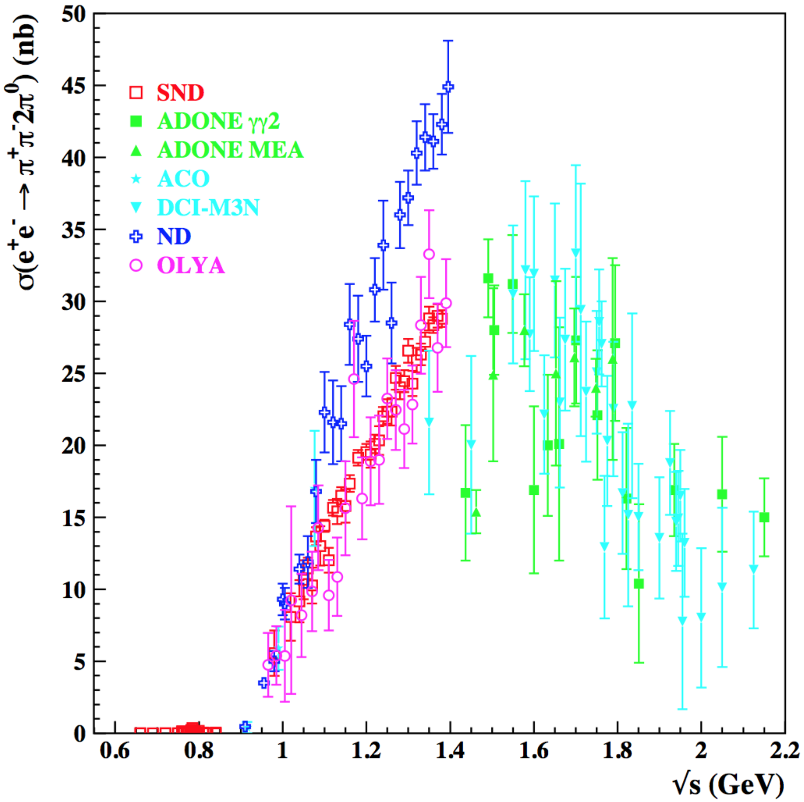
Summary

- ✓ **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 $e^+e^- \to \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\eta$, $KK\pi$, $KK\pi\pi$ modes from BABAR reduce the uncertainty on $a_\mu^{had,LO-VP}$**

- ✓ **New results are expected from BABAR, as well as from BES III, SND, CMD-3**

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ (before BABAR)



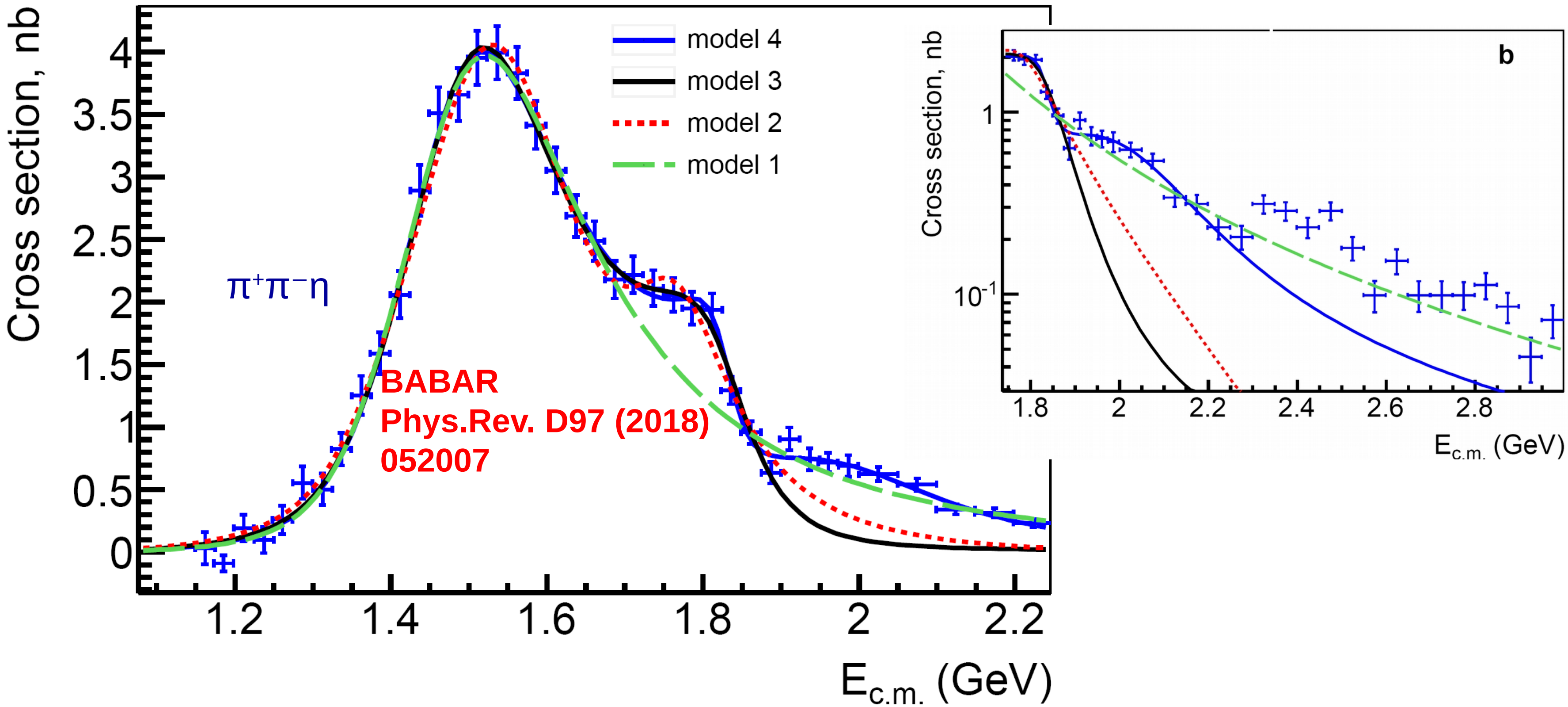
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C71 (2011) 1515, C72 (2012) 1874.

Channel	$a_\mu^{\rm had,LO}$ $[10^{-10}]$
$\pi^0\gamma$	$4.42 \pm 0.08 \pm 0.13 \pm 0.12$
$\eta\gamma$	$0.64 \pm 0.02 \pm 0.01 \pm 0.01$
$\pi^+\pi^-$	$507.80 \pm 1.22 \pm 2.50 \pm 0.56$
$\pi^+\pi^-\pi^0$	$46.00 \pm 0.42 \pm 1.03 \pm 0.98$
$2\pi^+2\pi^-$	$13.35 \pm 0.10 \pm 0.43 \pm 0.29$
$\pi^+\pi^-2\pi^0$	$18.01 \pm 0.14 \pm 1.17 \pm 0.40$
$2\pi^+2\pi^-\pi^0$ (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)	$-0.03 \pm 0.01 \pm 0.02 \pm 0.00$
$\phi\eta$	$0.36 \pm 0.02 \pm 0.02 \pm 0.01$
$\omega K\overline{K}$ ($\omega \to \pi^0\gamma$)	$0.00 \pm 0.00 \pm 0.00 \pm 0.00$

Before the BaBar measurement:

- **Limited precision**
- **Big disagreement between experiments**
- **Small energy ranges**

$e^+e^- \to \pi^+\pi^-\eta$: VMD fits



model 1: ρ(770) −ρ(1450) fits E_{CM} < 1.7 GeV

model 2: ρ(770) −ρ(1450) −ρ(1700) fits < 1.9 GeV

model 3: ρ(770) −ρ(1450) +ρ(1700) fits < 1.9 GeV

model 4: ρ(770) −ρ(1450) +ρ(1700) +ρ(2150) fits < 2.2 GeV

relative phases 0 (+) and 180° (−)

$e^+e^- \to \pi^+\pi^-\eta$: CVC test

$$\frac{\mathcal{B}(\tau^- \to \pi^-\pi^0\eta\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)} = \int_{(2m_\pi+m_\eta)^2}^{m_\tau^2} dq^2$$

$$\sigma^{I=1}_{e^+e^-\to\pi^+\pi^-\eta}(q^2)\frac{3|V_{ud}|^2 S_{EW}}{2\pi\alpha^2}\frac{q^2}{m_\tau^2}(1-\frac{q^2}{m_\tau^2})^2(1+2\frac{q^2}{m_\tau^2})$$

The conserved vector current (CVC) hypothesis and isospin symmetry allow to predict the hadronic mass spectrum and branching fraction for the decay $\tau^- \to \pi^-\pi^0\eta\nu_\tau$ from data on the $e^+e^- \to \pi^+\pi^-\eta$ cross section.

CVC-prediction based on BABAR data:
$B(\tau^- \to \pi^-\pi^0\eta\nu_\tau) = (0.162 \pm 0.008)\%$

CVC-prediction based on the SND data:
$B(\tau^- \to \pi^-\pi^0\eta\nu_\tau) = (0.156 \pm 0.011)\%$

The difference between the CVC prediction and experimental value, about 15%, is too large to be explained by isospin-breaking corrections.

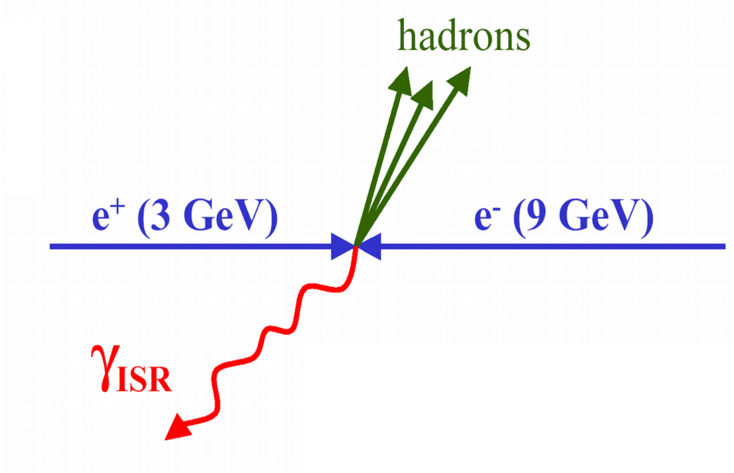
PDG14 value:
$B(\tau^- \to \pi^-\pi^0\eta\nu_\tau) = (0.139 \pm 0.010)\%$
CVC-experiment difference is 1.8σ.

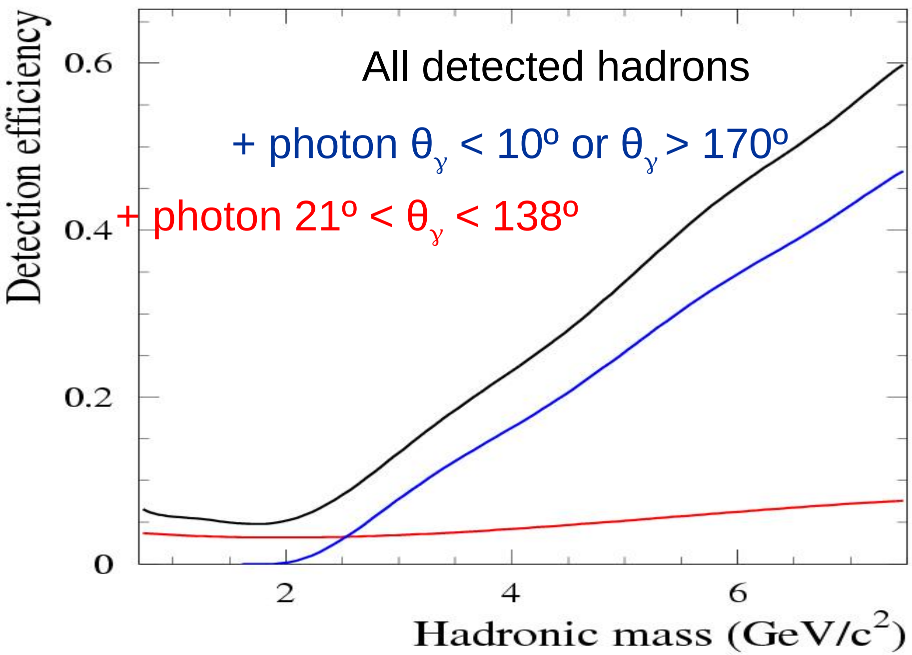
The PDG value is dominated by the Belle measurement:
$B(\tau^- \to \pi^-\pi^0\eta\nu_\tau) = (0.135 \pm 0.007)\%$
CVC-experiment difference is 2.4σ.

ISR method@BABAR

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

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





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 (about 10% of ISR events).

BABAR tagged ISR analyses

Fully exclusive measurement

- ✓ Photon with E_{CM} > 3 GeV, which is assumed to be the ISR photon
- ✓ All final hadrons are detected and identified

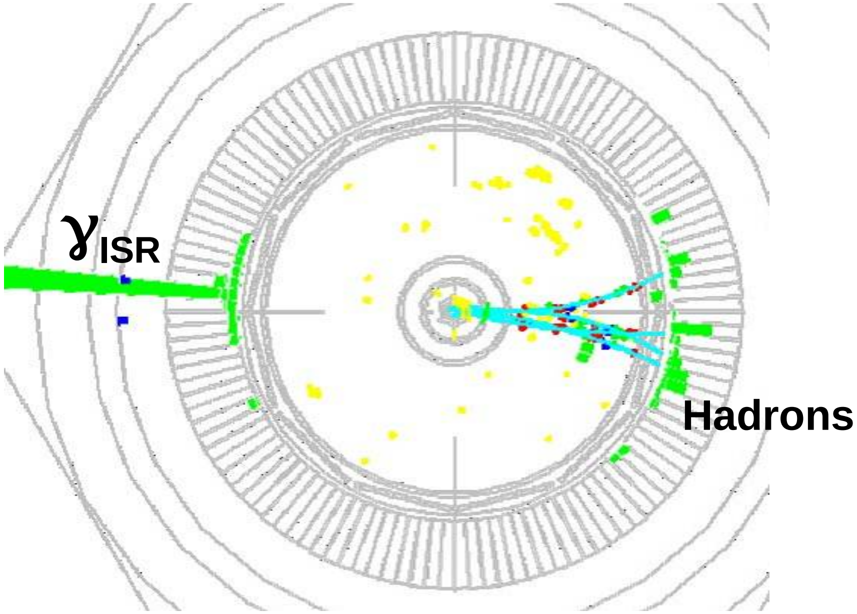
Large-angle ISR forces the hadronic system into the detector fiducial region

- ✓ A weak dependence of the detection efficiency on dynamics of the hadronic system (angular and momentum distributions in the hadron rest frame) ⇒ smaller 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

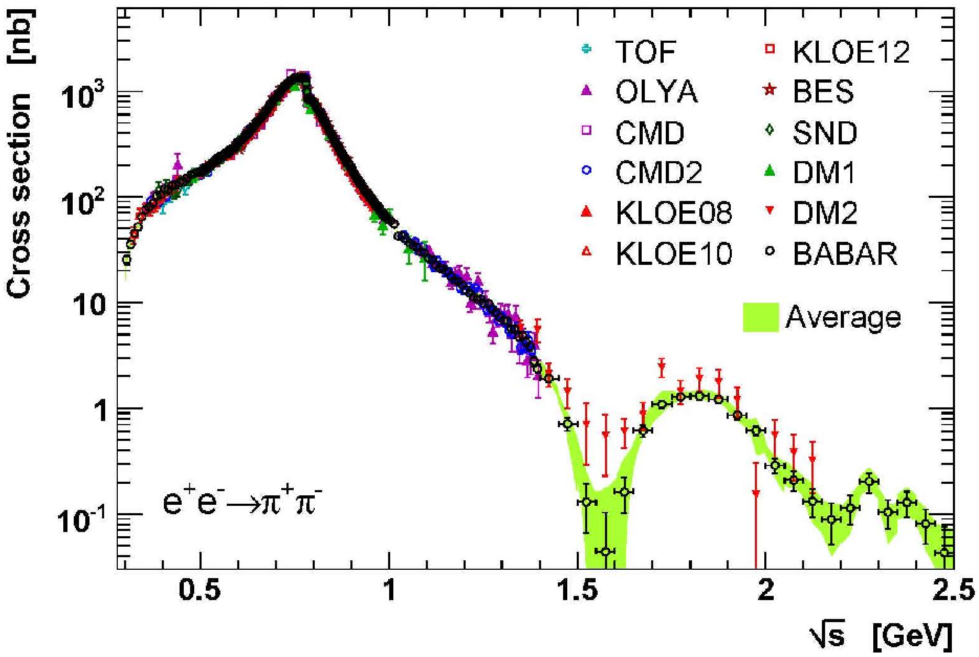
- ✓ excellent mass resolution
- ✓ background suppression

Generic BABAR ISR event

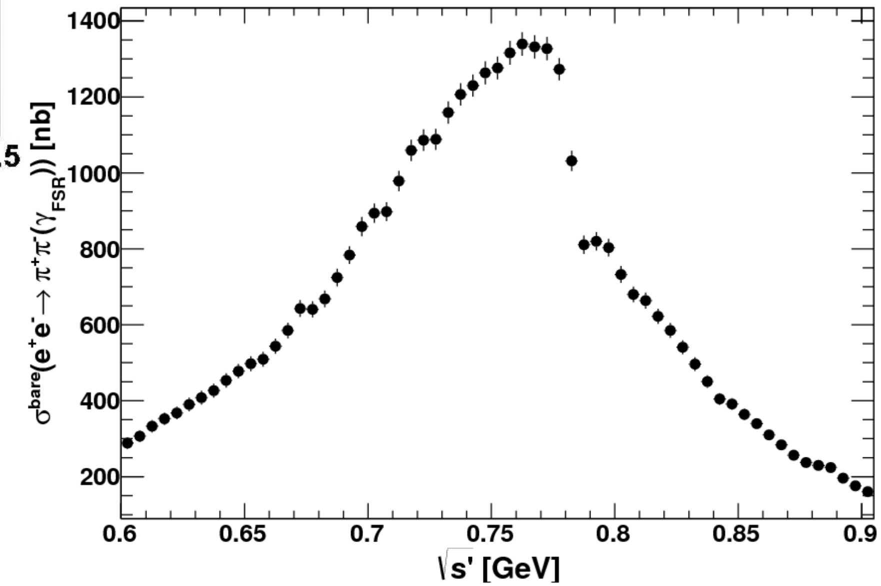


Can access a wide range of energy in a single experiment: from threshold to ~5 GeV

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



- Most recent measurement was performed by BES III using ISR technique
- Analysis is based on the data set with an integrated luminosity of 2.93 fb^{-1} taken at 3.773 GeV



- Large progress in ISR measurements during the last decade
- CMD-2, KLOE, BABAR, BES-III claim systematic uncertainty at a sub-percent level

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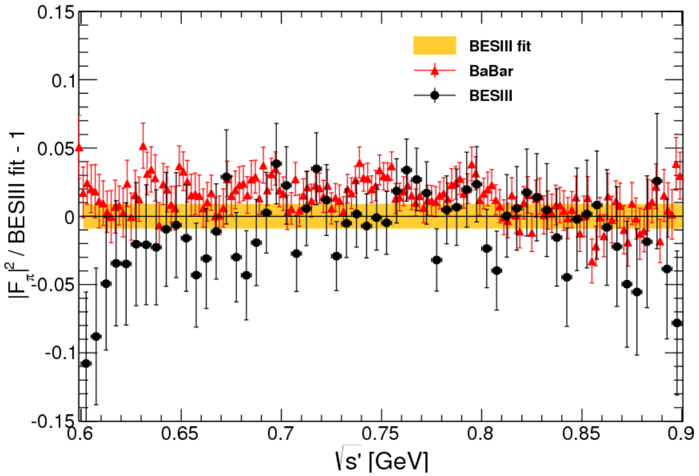
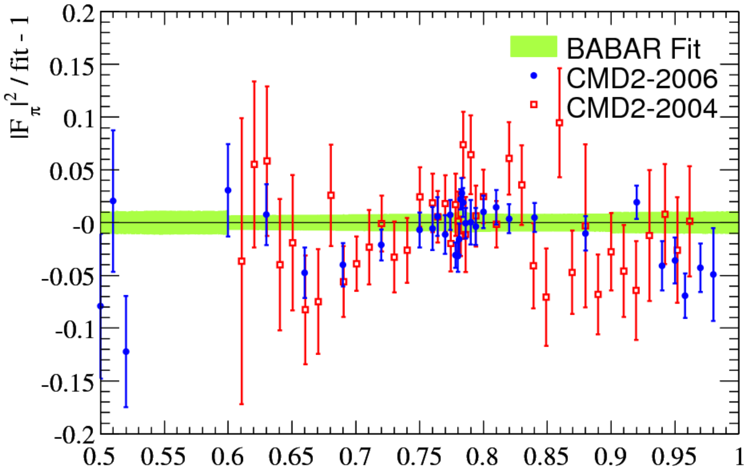
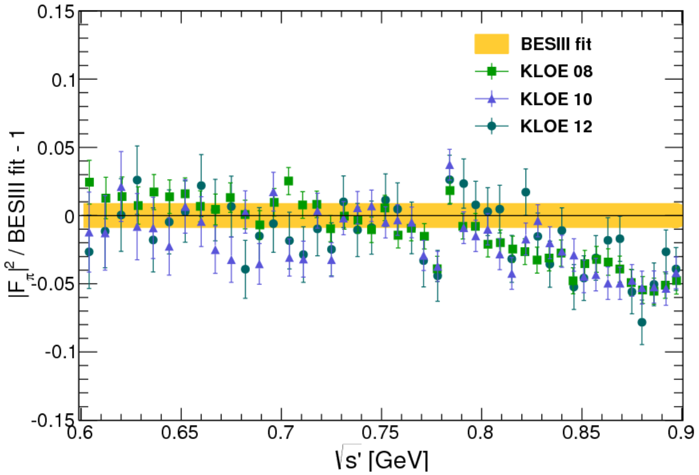
$e^+e^- \to \pi^+\pi^-$







Systematic differences between data from different experiments reach 5% and are significantly larger than the claimed systematic uncertainties (<1%)