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

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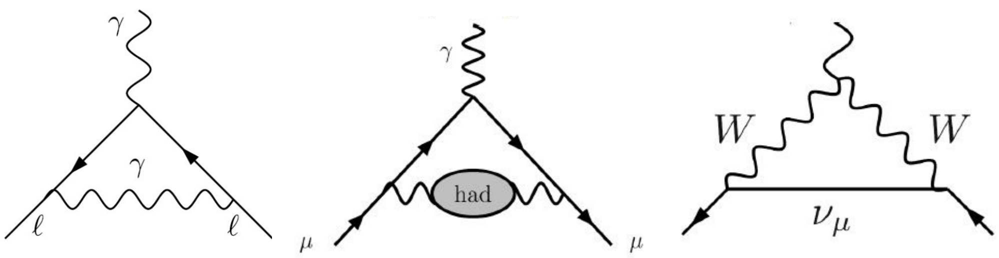
$(g\text{-}2)_\mu/2$ of muon (experiment)

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

$$a=(g-2)/2$$



✓ a_μ is sensitive to New Physics contributions

E821@BNL (1997-2001):
G.W. Bennett *et al*.,
Phys. Rev. D **77**, 072003 (2006)
a_μ = (11 659 209.1±6.3)×10^{-10} (0.54 ppm)

E989 @ FNAL (2017-…):
F. Gray *et al*., arXiv: 1510.003
a_μ = … (0.14 ppm)

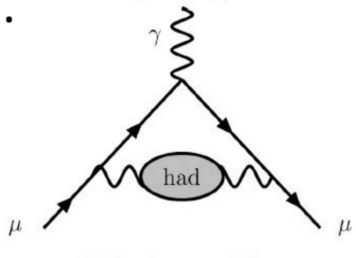
E34 @ J-PARC (????-…):
T. Mibe *et al.,*
Chin. Phys. C **34** (2010) 745
a_μ = … (0.1 ppm)

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

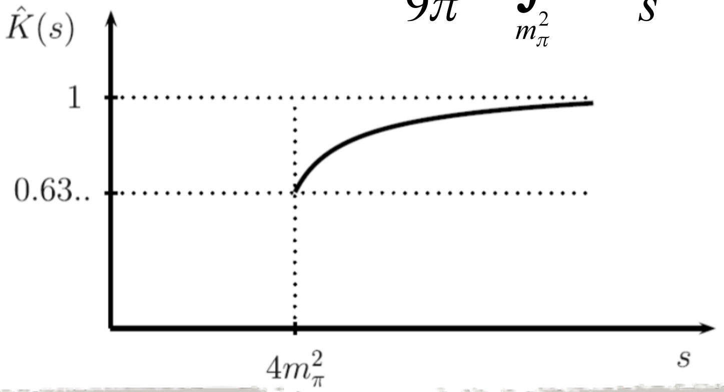
❑ The leading order hadronic contribution is calculated using dispersion relations from experimental data on the total cross section of the e^+e^- annihilation into hadrons

❑ Low energies (E < 2 GeV) give dominant contribution into $a_\mu^{had,LO\text{-}VP}$ (92%).

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



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



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

DHMZ , TAU 2016, arXiv:1612.02743

Individual SM contributions × 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
$a_\mu^{had,LbLs}$	10.5 ± 2.6

Comparison with measurement

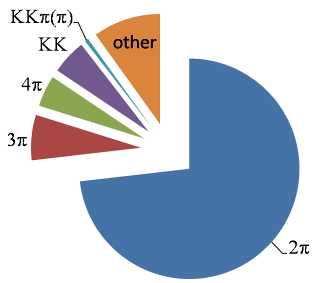
$a_\mu^{total\text{-}SM}$	11659181.7 ± 4.2
$a_\mu^{BNL\text{-}E821}$	11659209.1 ± 6.3
Data - SM	27.4 ± 7.6 (3.6σ)

F.Jegerlehner, arXiv:1705.00263

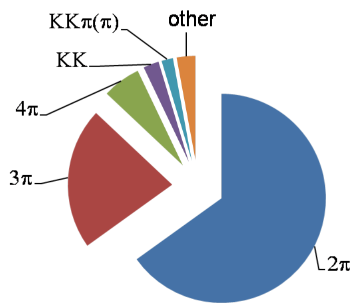
Data-SM 31.3 ± 7.7 (4.1σ)

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

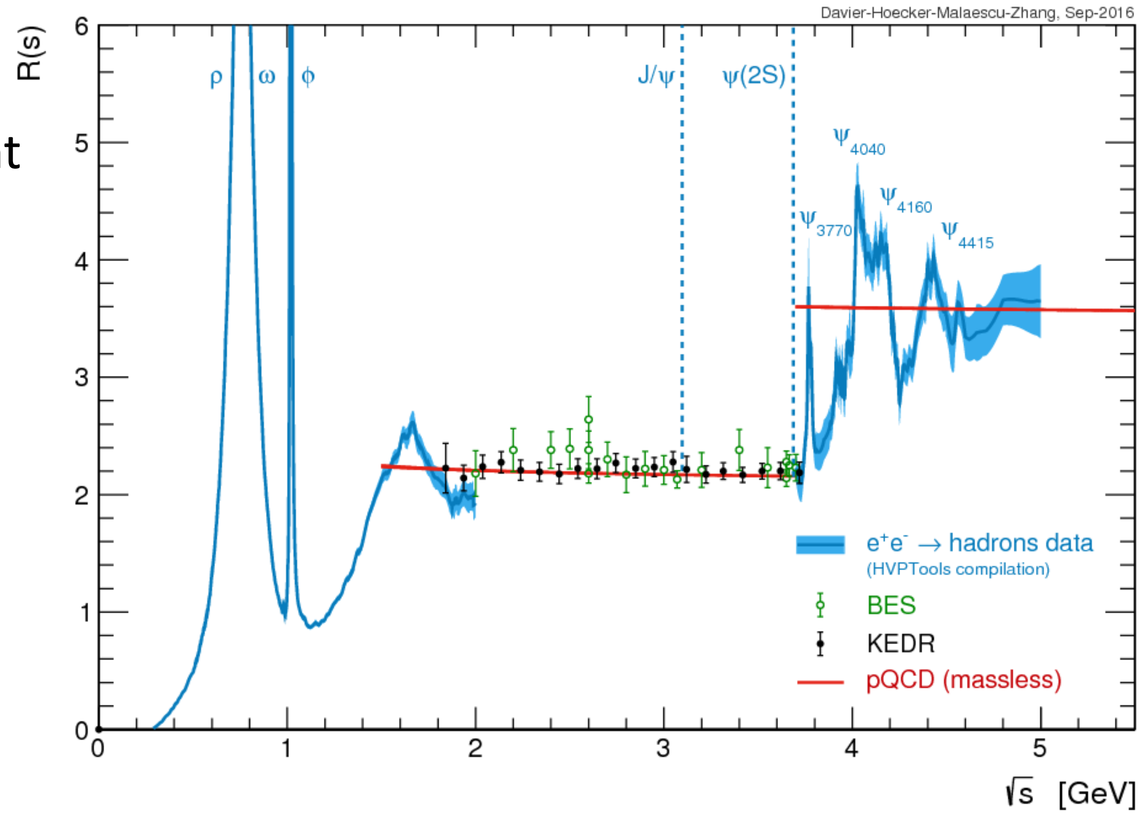
- Below 2 (1.8) GeV the total cross section is calculated as a sum of exclusive channels.
- The contributions of different hadronic channels into $a_\mu^{had,LO-VP}$



- and its squared error σ^2



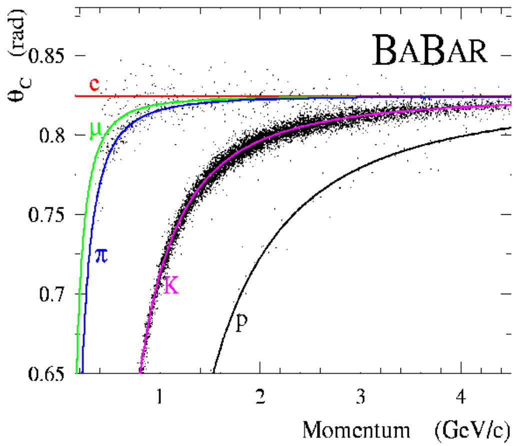
DHMZ , TAU 2016, arXiv:1612.02743

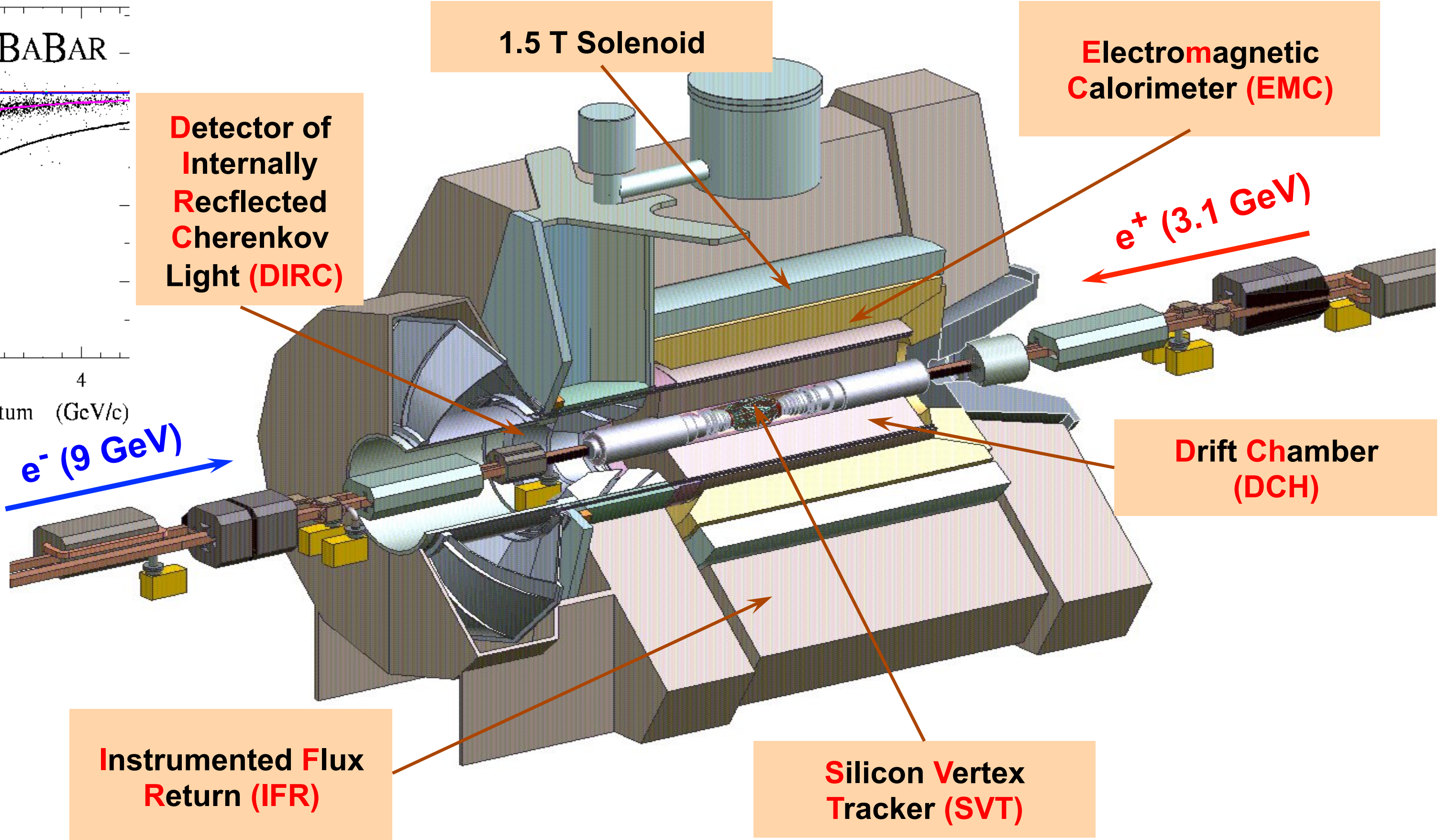


BABAR Experiment

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



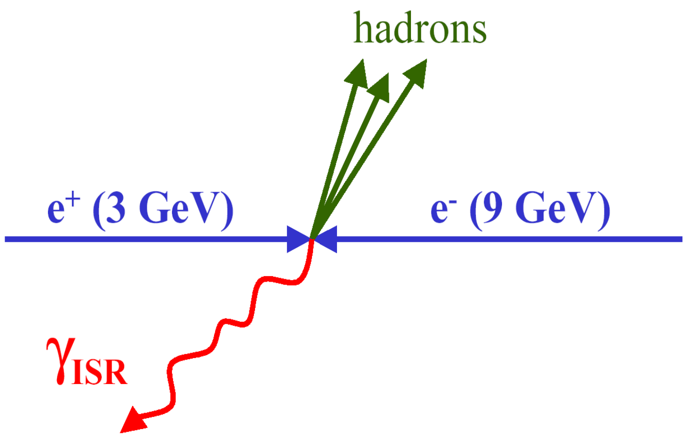


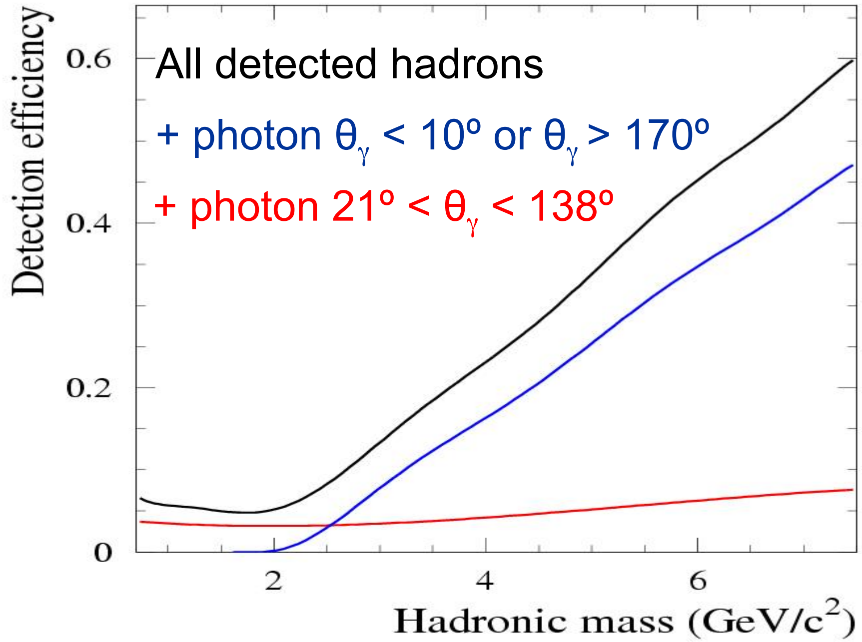
For ISR analyses, a data sample of 469 fb^{-1} collected near or at a c.m. energy of 10.58 GeV (at and near $\Upsilon(4S)$) is used.

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 $e^+e^- \to f$.

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





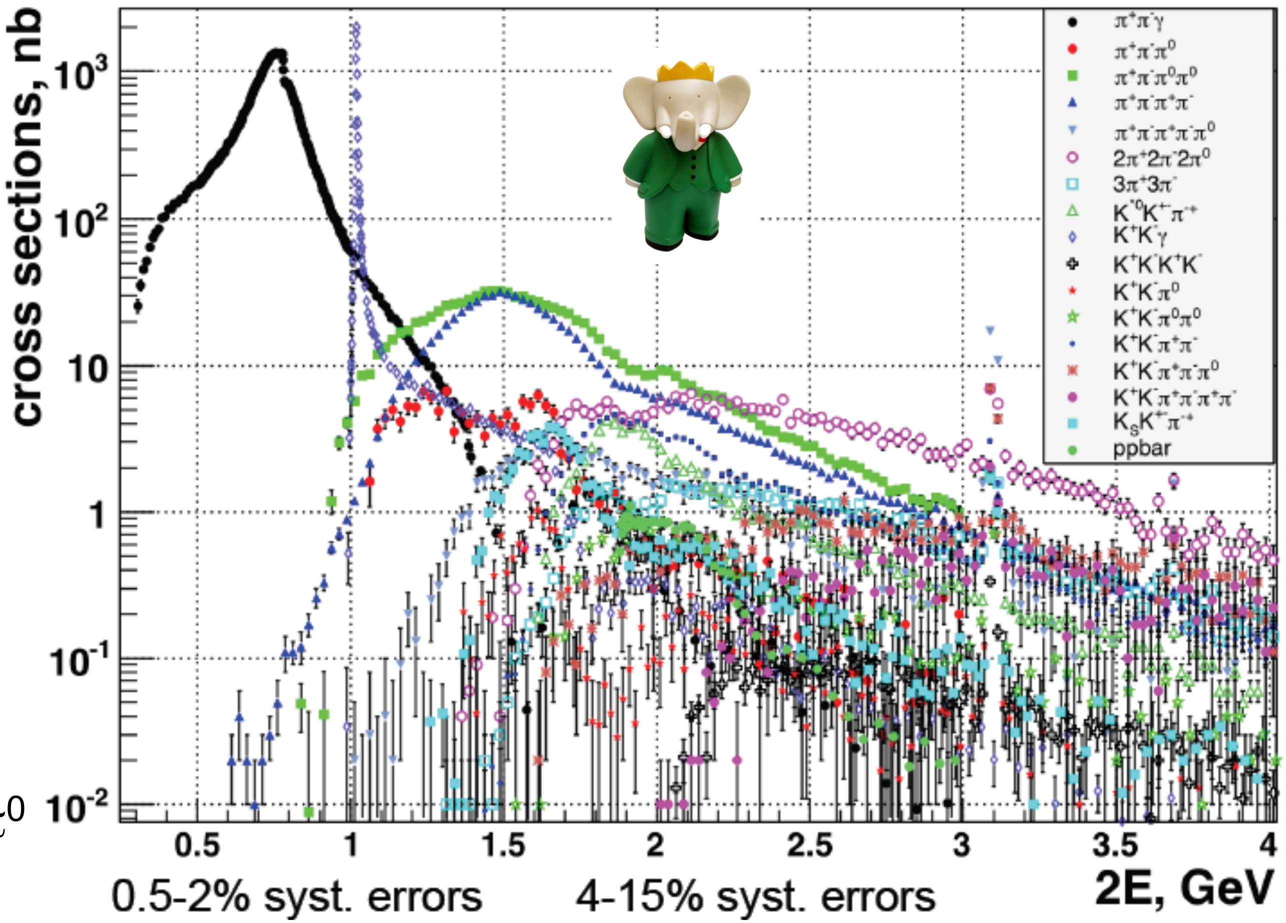
The ISR photon is emitted predominantly along the beam axis. The produced hadronic system is boosted against the ISR photon. Due to limited detector acceptance the mass region below 2 GeV can be studied only with detected photon (about 10% of ISR events).

BABAR tagged ISR analyses

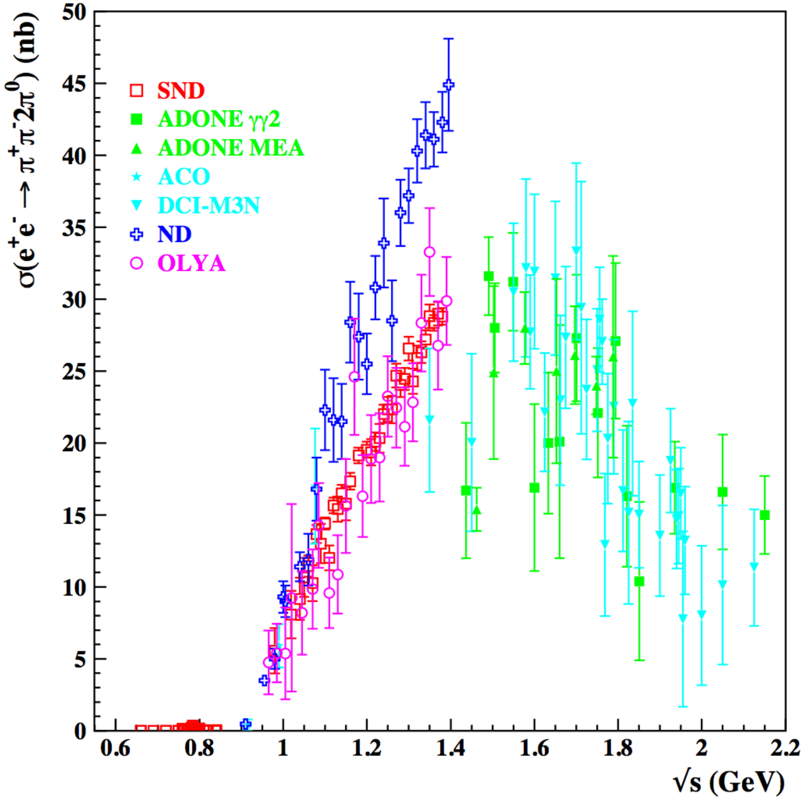
22 final states were studied, 20 papers on low energy ISR studies were published

Four new analyses are discussed in this talk

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



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



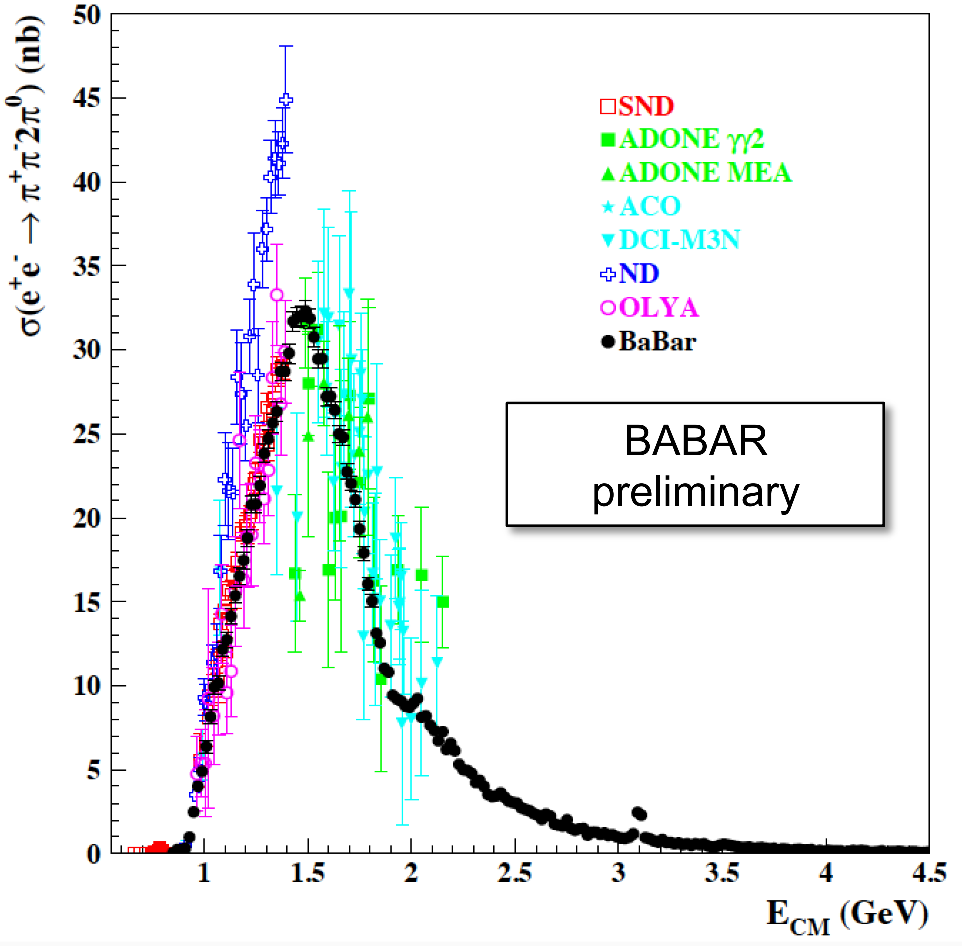
Before the BaBar measurement:

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

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

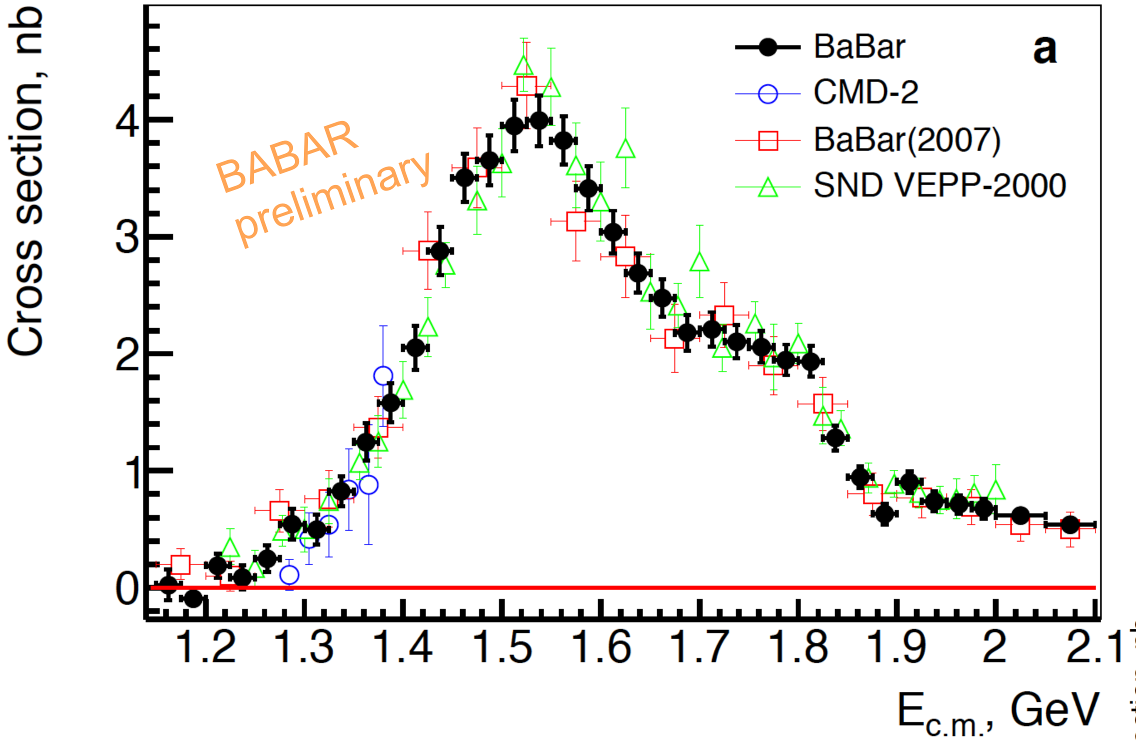
Channel	$a_\mu^{\rm had,LO}$ $[10^{-10}]$
$\pi^0\gamma$	$4.42 \pm 0.08 \pm 0.13 \pm 0.12$
$\eta\gamma$	$0.64 \pm 0.02 \pm 0.01 \pm 0.01$
$\pi^+\pi^-$	$507.80 \pm 1.22 \pm 2.50 \pm 0.56$
$\pi^+\pi^-\pi^0$	$46.00 \pm 0.42 \pm 1.03 \pm 0.98$
$2\pi^+2\pi^-$	$13.35 \pm 0.10 \pm 0.43 \pm 0.29$
$\pi^+\pi^-2\pi^0$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

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



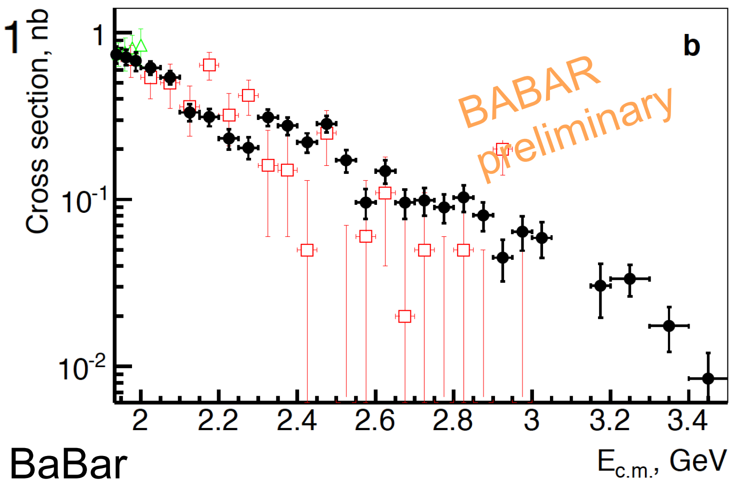
- BABAR results are most precise and covers wider energy range
- Systematic uncertainty is 3.1% in the 1.2-2.7 GeV energy range.
- Contribution to a_μ for the range $1.02<E_{CM}<1.8$ GeV is measured to be $[17.5 \pm 0.6$ (stat+syst)$] \times 10^{-10}$ (3.4% precision)
- Previous result including the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

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



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

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



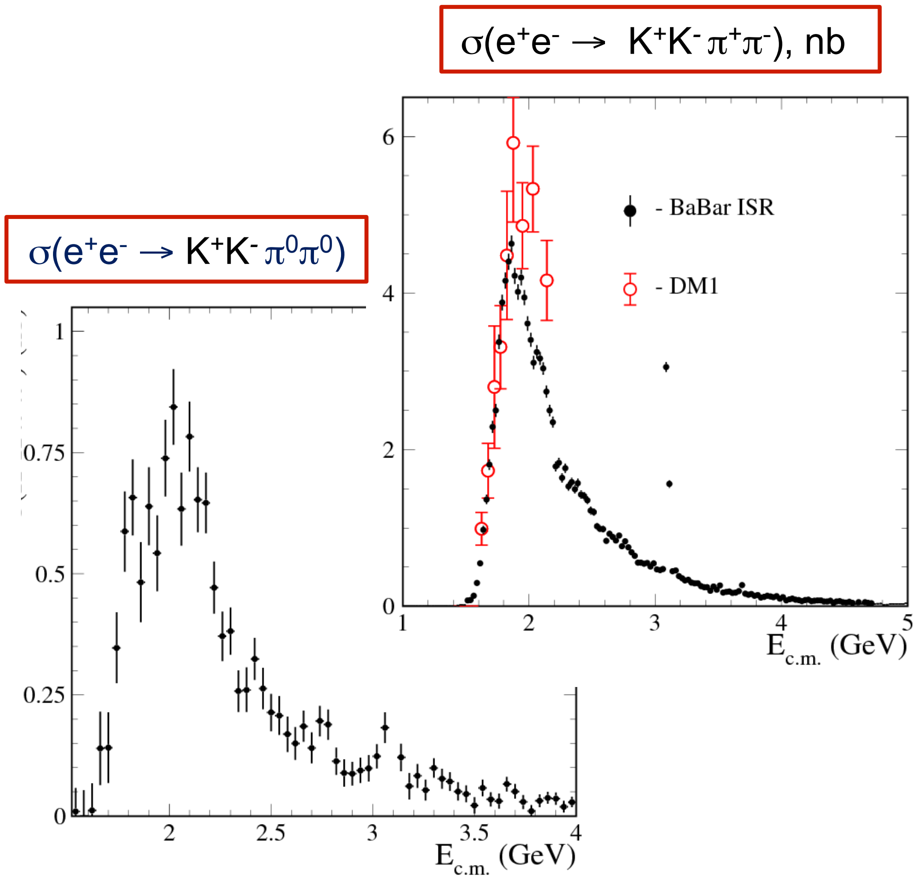
$a_\mu^{had\ LO}(\sqrt{s} < 1.8\ \text{GeV}) = (1.18 \pm 0.06) \cdot 10^{-10}$

1.15 ± 0.10 – All before BaBar

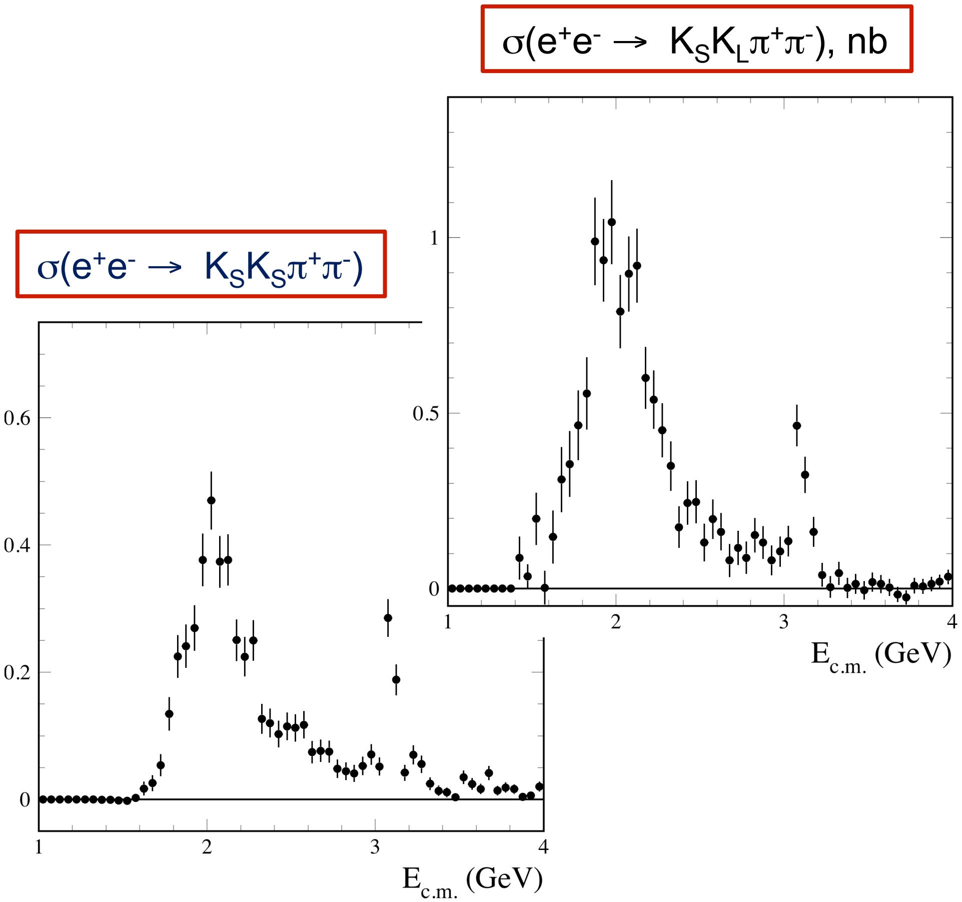
$e^+e^- \to K\bar{K}\pi\pi$

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)

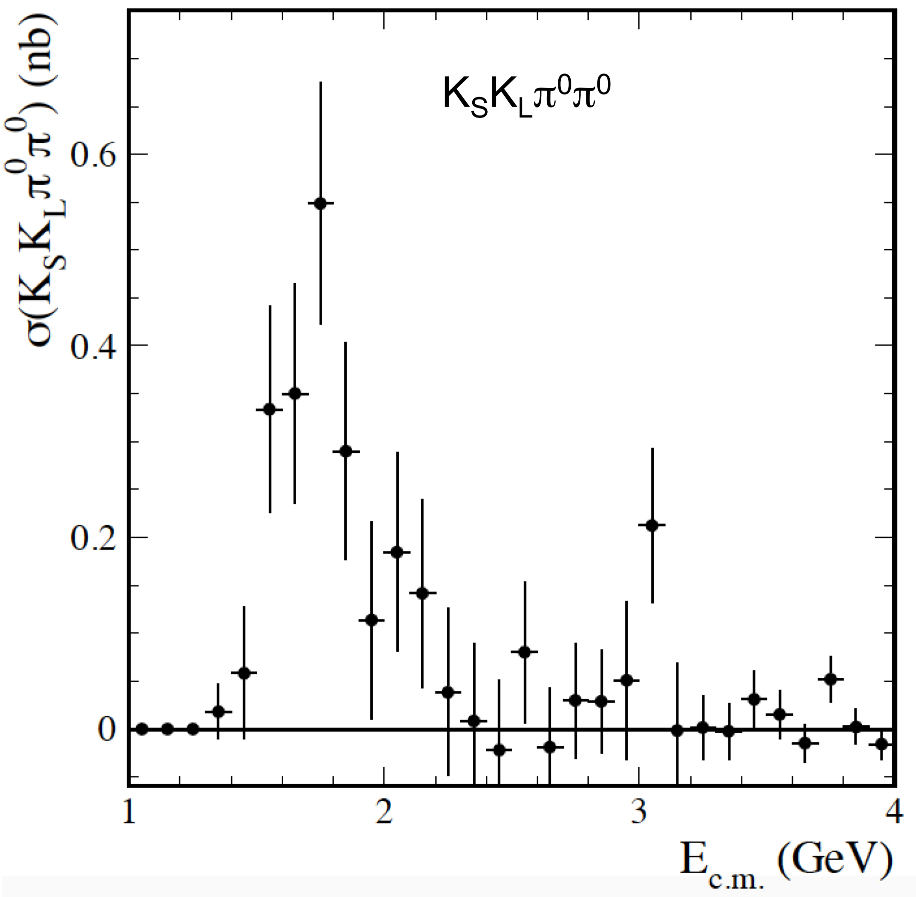


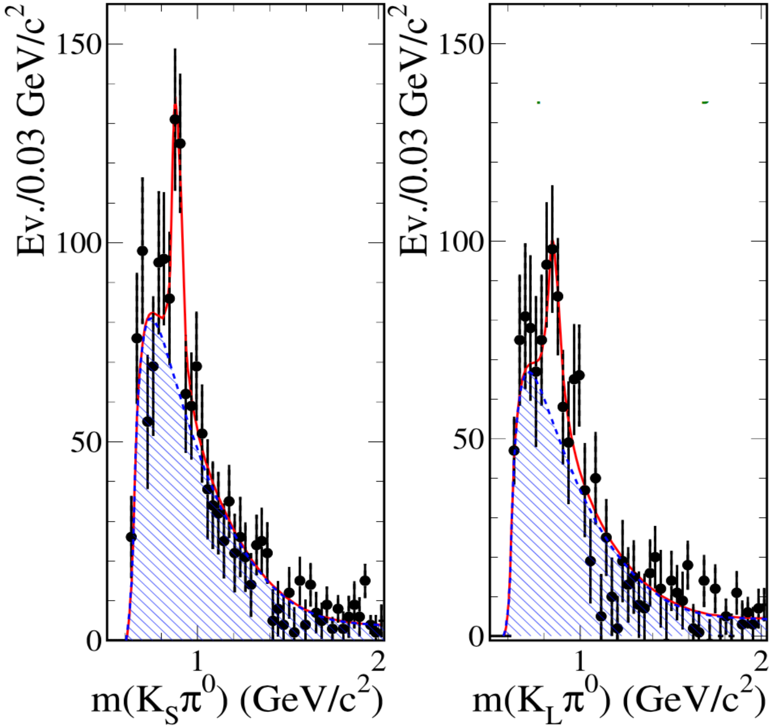
Phys. Rev. D 89, 092002 (2014)



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

Phys. Rev. D 95, 052001 (2017)

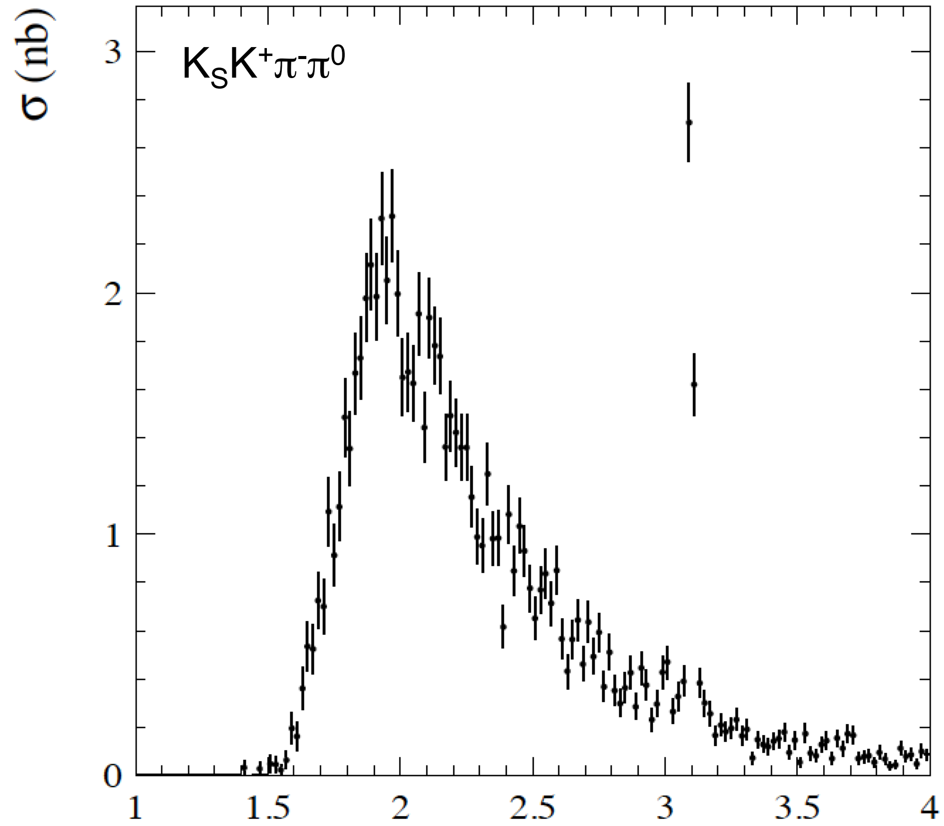




- First measurement
- Systematic uncertainty is 25% at the peak, grows to 60% at 2 GeV
- Dominant $K^*(892)\bar{K}\pi$ intermediate state.

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

Phys. Rev. D 95, 092005 (2017)



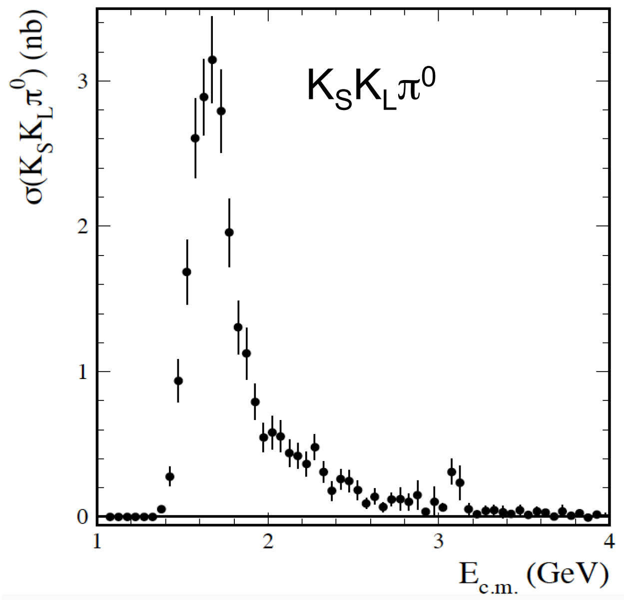
Intermediate state
$K^{*0} K^0_S \pi^0$
$K^{*0} K^\pm \pi^\mp$
$K^*_2(1430)^0 K^0_S \pi^0$
$K^*_2(1430)^0 K^\pm \pi^\mp$
$K^*(892)^\pm K^0_S \pi^\mp$
$K^*(892)^\pm K^\mp \pi^0$
$K^*_2(1430)^\pm K^0_S \pi^\mp$
$K^*_2(1430)^\pm K^\mp \pi^0$
$K^{*0} \overline{K}^{*0}$
$K^*(892)^+ K^*(892)^-$
$K^0_S K^\pm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

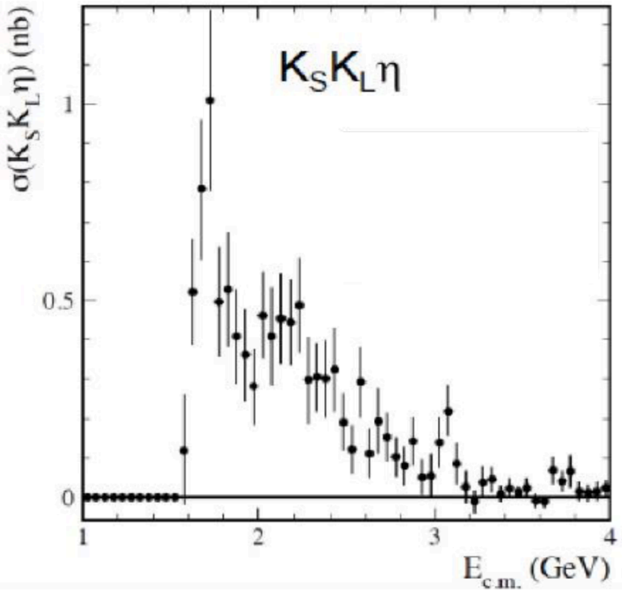
- First measurement
- Systematic uncertainty is 6-7% below 3 GeV
- More than 10 intermediate states – dominant are $K^*(892)\overline{K}\pi$, $K_S K^+\rho^-(770)$

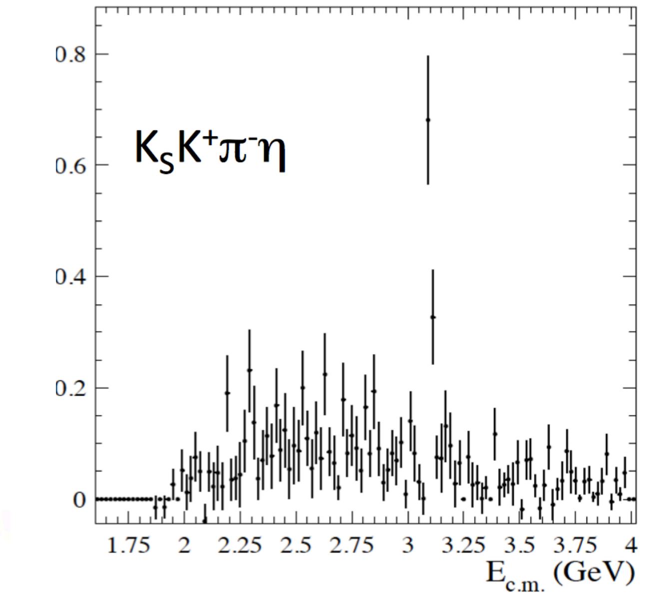
$e^+e^- \rightarrow K_S K_L \pi^0$, $K_S K_L \eta$, $K_S K^+ \pi^- \eta$ @ BABAR

Phys. Rev. D 95, 052001 (2017)

Phys. Rev. D 95, 092005 (2017)





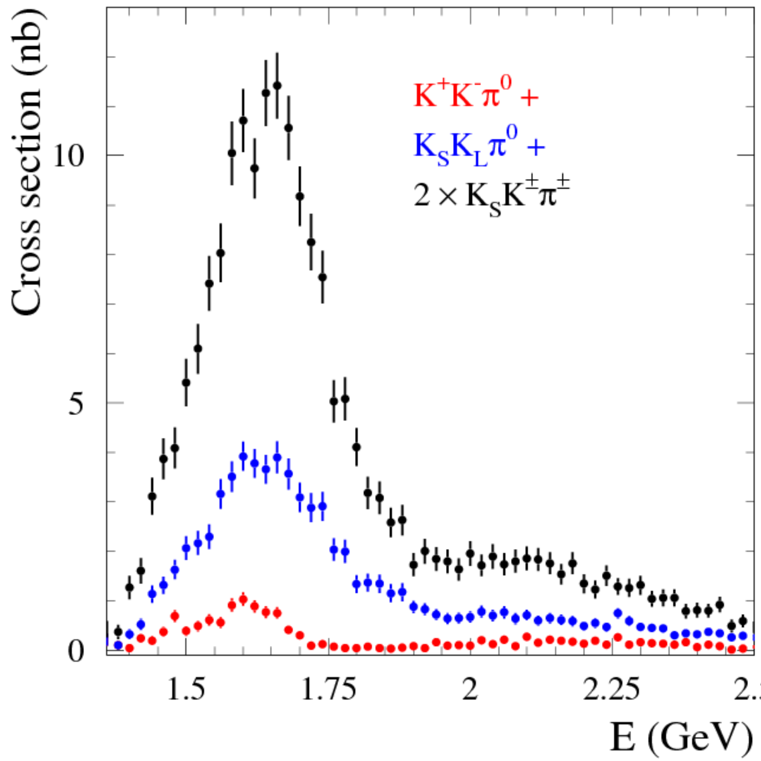


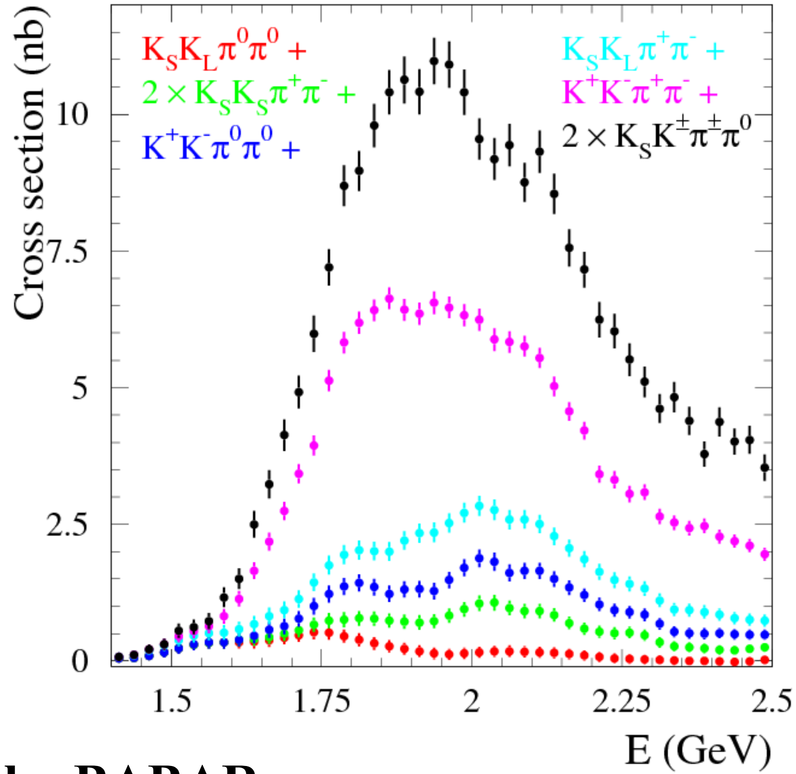
- First measurement
- Systematic uncertainty is 10% near the peak, grows to 30% at 3.0 GeV
- Dominant $K^*(892)\bar{K}$ intermediate state

- 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

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

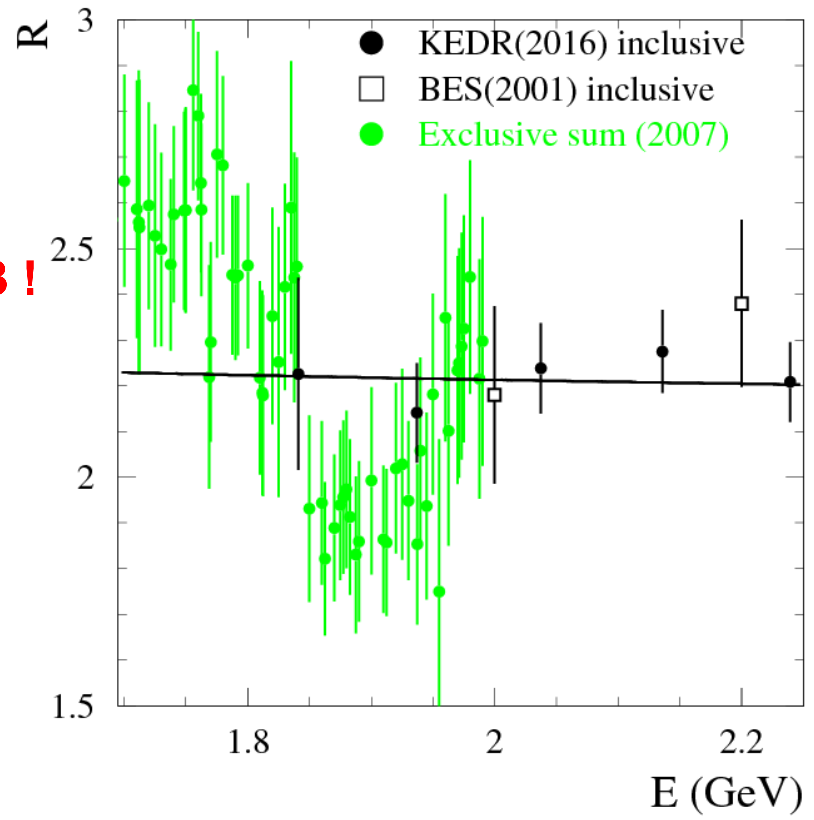
1.35 ± 0.39

Energy region near 2 GeV

- At E < 2 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.

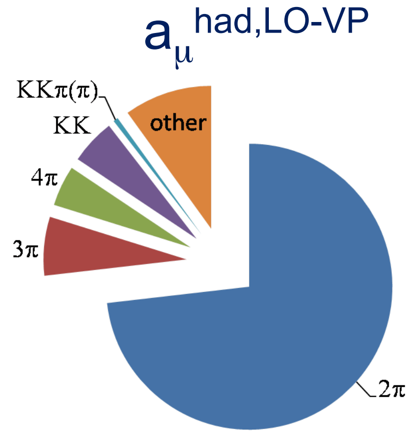
CMD-3 !

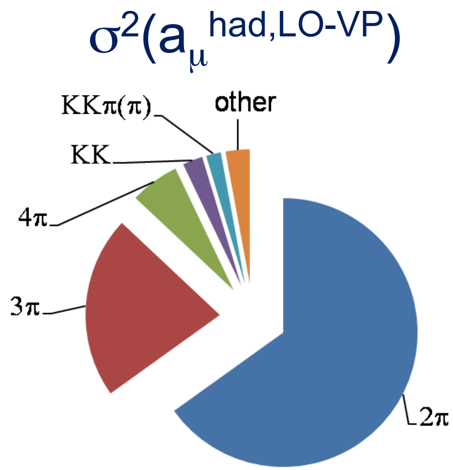
$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



Summary

- ✓ Precise low-energy e^+e^- hadronic cross section data are needed to obtain an accurate SM prediction for $a_\mu^{had,LO\text{-}VP}$
- ✓ Recent results on the $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$, $K\bar{K}\pi$, $K\bar{K}\pi\pi$ cross sections from BABAR reduce the uncertainty on $a_\mu^{had,LO\text{-}VP}$
- ✓ New results are expected from BABAR, as well as from BES III, SND, CMD-3





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)

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

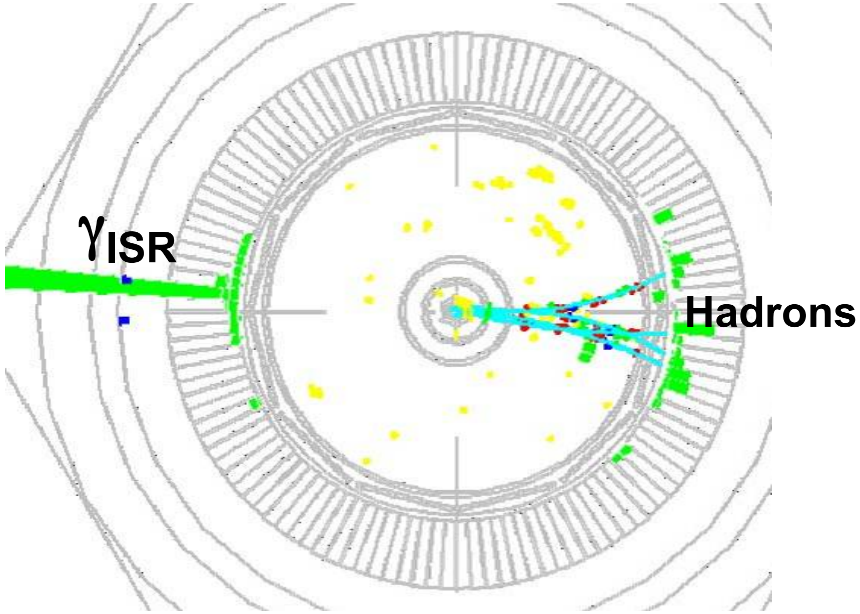
✓A weak dependence of the detection efficiency on hadron invariant mass ⇒ measurement near and above threshold with the same selection criteria.

Kinematic fit with requirement of energy and momentum balance

✓excellent mass resolution

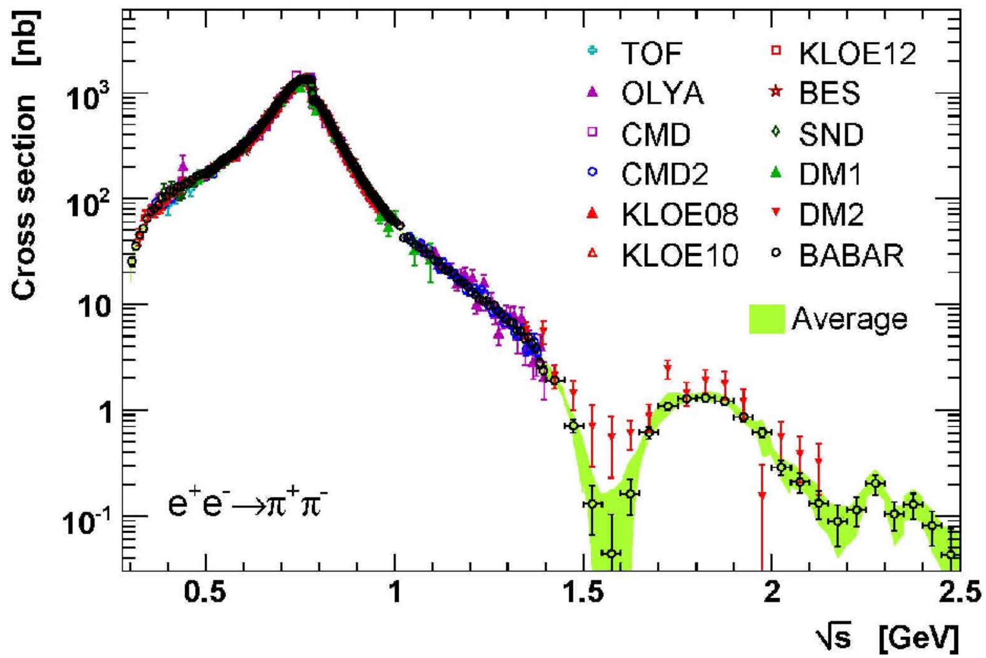
✓background suppression

Generic BABAR ISR event

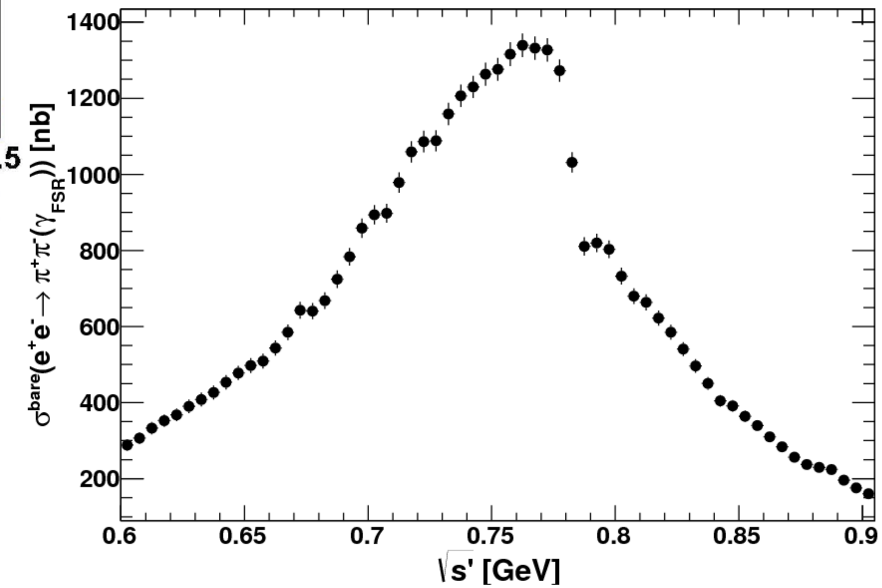


Can access a wide range of energy in a single experiment: from threshold to ~5 GeV

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



- 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



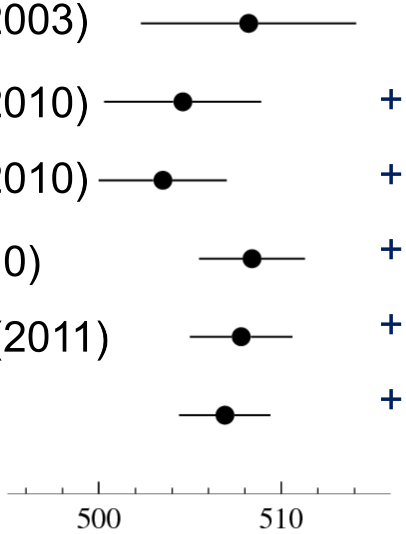
Phys. Lett. B 753, 629 (2016)

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

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

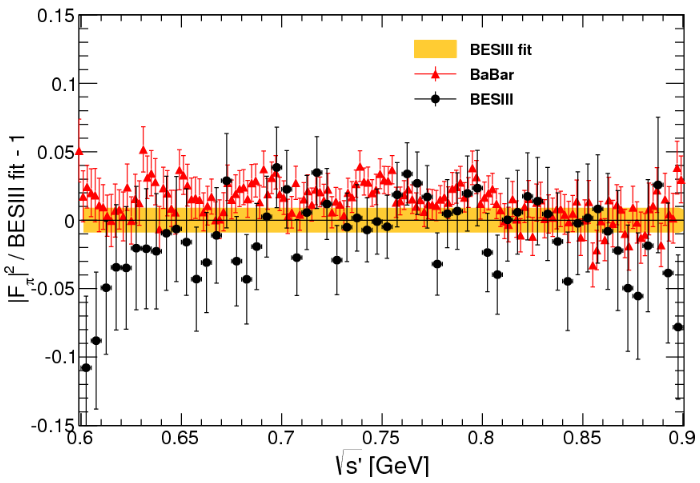
Evolution of the $e^+e^- \to \pi^+\pi^-$ contribution into $a_\mu^{had,LO}$ (DHMZ)

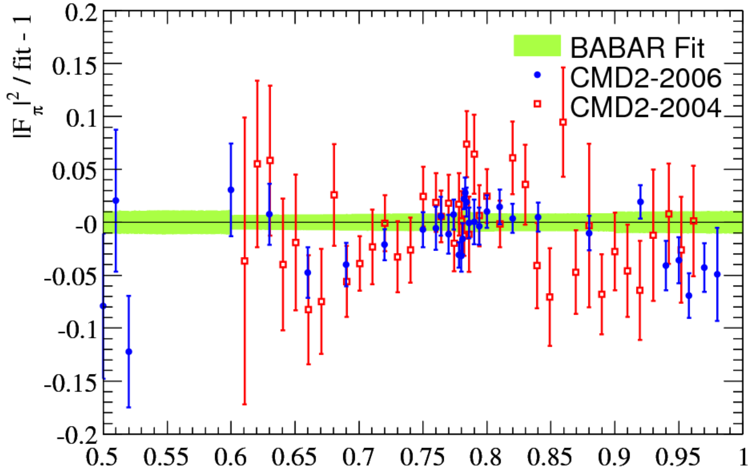
		$\times 10^{-10}$
EPJ C 31,503 (2003)	CMD-2 2003 + other e^+e^-	508.2 ± 5.9
EPJ C 66,127 (2010)	+ CMD-2 2006 + SND 2006	504.6 ± 4.3
EPJ C 66,127 (2010)	+ KLOE 2008	503.5 ± 3.5
EPJ C 66,1 (2010)	+ BABAR 2009	508.4 ± 2.9
EPJ C 71,1515 (2011)	+ KLOE 2010	507.8 ± 2.8
TAU 2016	+ KLOE 2012 + BES III 2016	506.9 ± 2.5

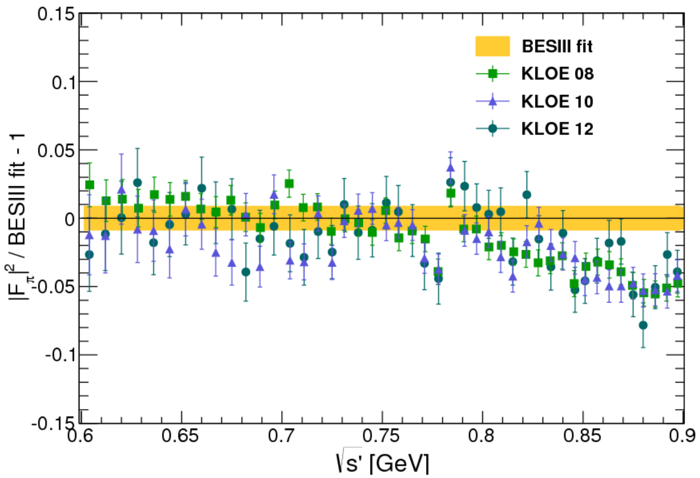


The statistical error decreased from 5.2 to 1.1, while the systematic from 2.7 to 2.3.

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

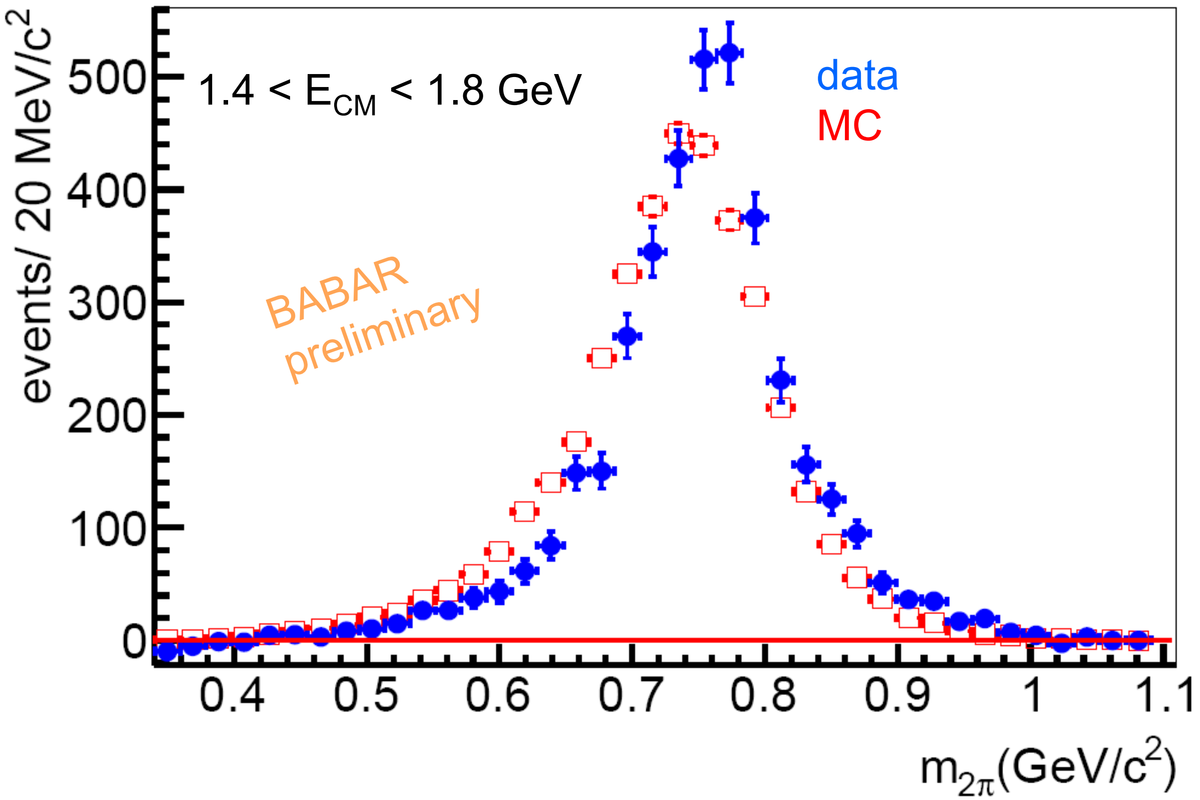






Systematic differences between data from different experiments reach 5% and are significantly larger than the claimed systematic uncertainties (<1%)

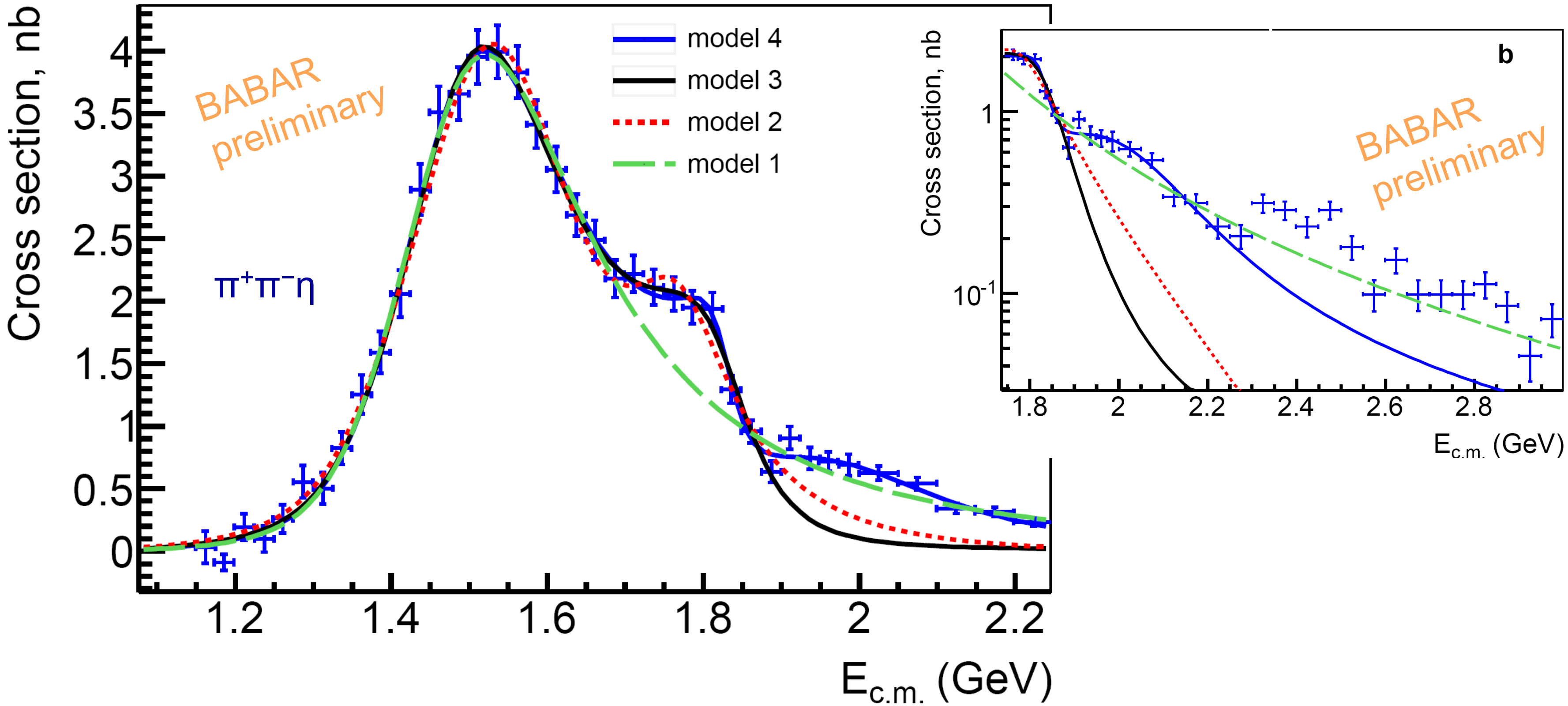
$\pi^+\pi^-$ mass spectrum



- MC uses a model with the $\rho(770)\eta$ intermediate state
- The $\rho(770)\eta$ mechanism is dominant
- We confirm the SND observation that the $\pi^+\pi^-$ mass distribution is not fully described by the $\rho(770)\eta$ model.

The observed shift of the peak may be result of the interference with other mechanism, for example, $\rho(1450)\eta$

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