Study of e^+e^- annihilation to hadrons at low energies at BABAR

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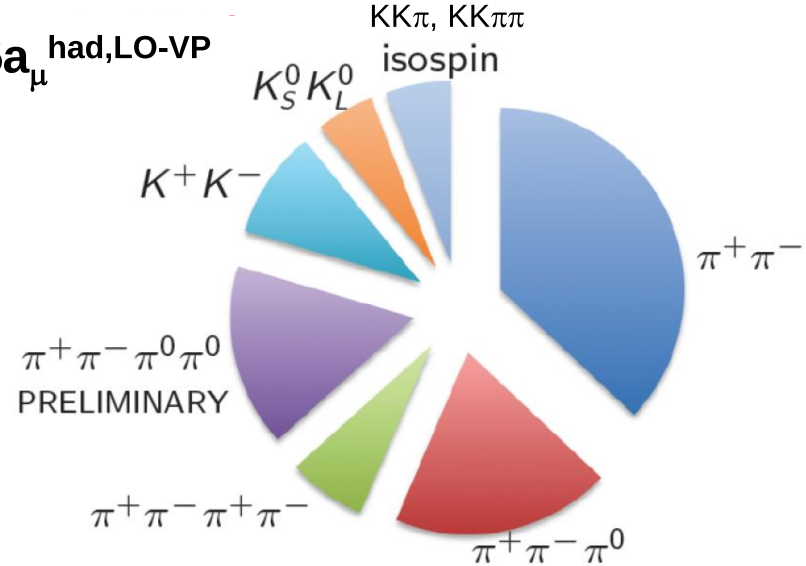
Motivation

- The total cross section of e^+e^- annihilation into hadrons is used in Standard Model (SM) calculation of $(g-2)_\mu$ and α_{QED}.
- Currently, about 3.5 σ difference is observed between experiment and the SM prediction for $(g-2)\mu$. New experiments are planned.
- The low energies (E < 2 GeV) give dominant contribution into $a_\mu^{had,LO-VP}$, where the total cross section is calculated as a sum of exclusive channels.

$\delta a_\mu^{had,LO-VP}$



From Andreas Hafner (Moriond 2015), using M.Davier et al., EPJ C71, 1515 (2011)

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

Individual SM contributions $\times 10^{-11}$

a_μ^{QED}	116584718.951 ± 0.080
a_μ^{EW}	153.6 ± 1.0
$a_\mu^{had,LO-VP}$	6923 ± 42
$a_\mu^{had,HO-VP}$	-98.4 ± 0.7
$a_\mu^{had,LbLs}$	105 ± 26

Comparison with measurement

$a_\mu^{total-SM}$	116591802 ± 49
$a_\mu^{BNL-E821}$	116592089 ± 63
Data - SM	287 ± 80

M. Davier et al., EPJ C71, 1515 (2011)

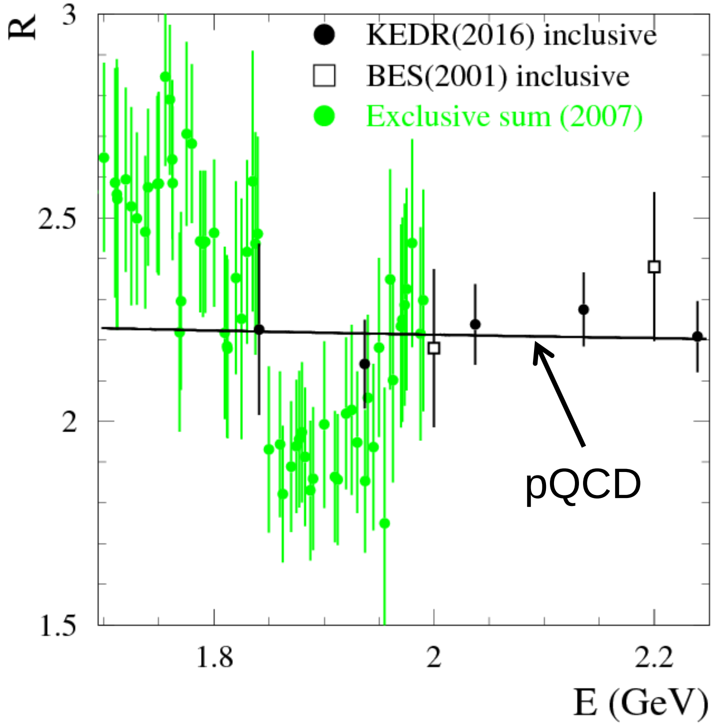
Motivation

❑ 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.
❑ BABAR goal is to measure all significant exclusive channels below 2 GeV, and perform comparison with inclusive measurements and pQCD prediction.

❑ Study of hadronization at low energies (dynamics of exclusive processes).

- Properties of excited vector mesons
- Development of MC events generator for $e^+e^- \to$ hadrons below 2 GeV.

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

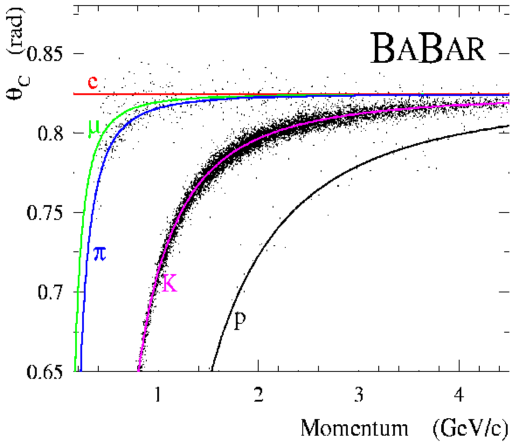


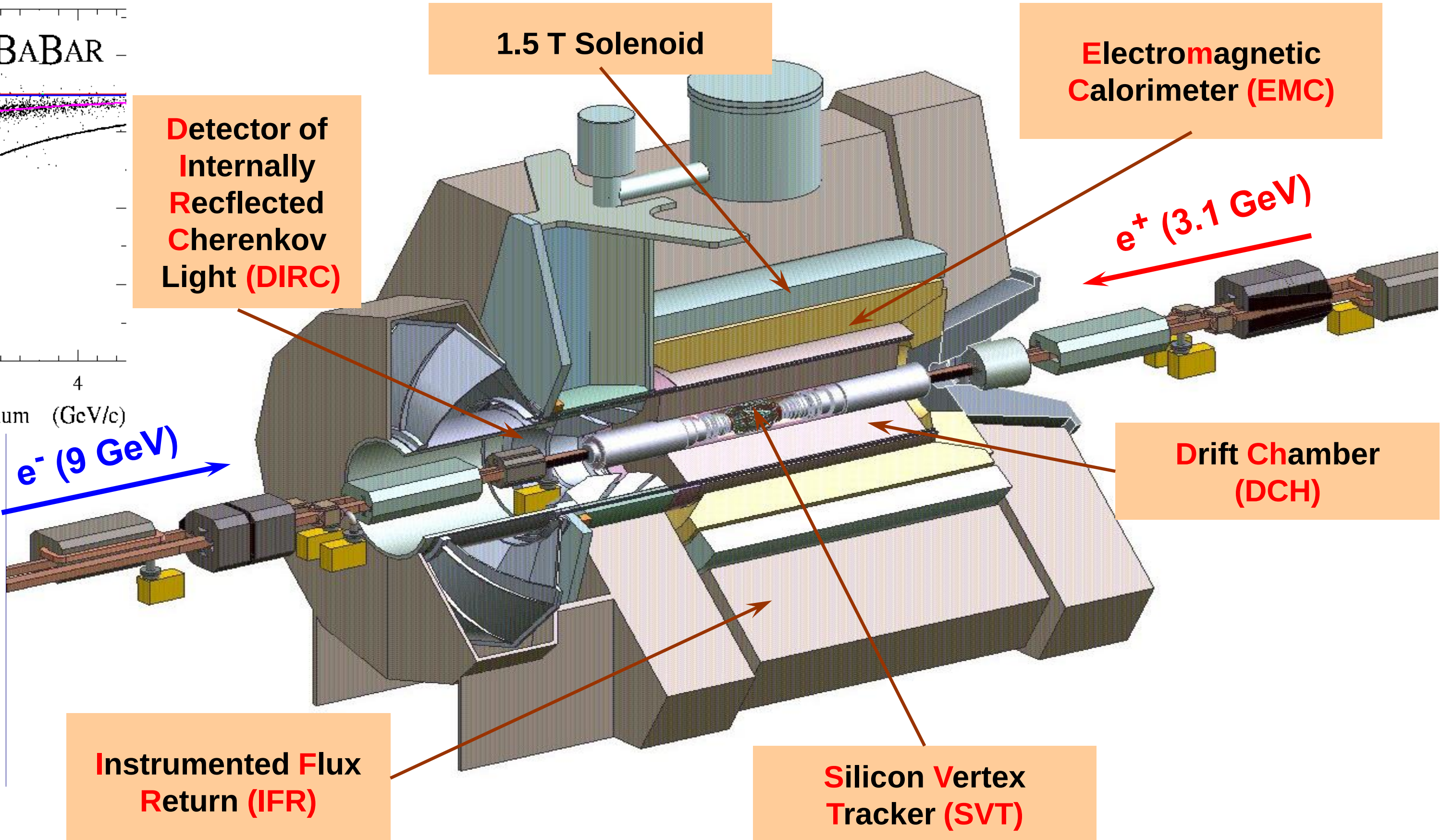
KEDR(2016): arXiv:1610.02827
BES(2001): Phys. Rev. Lett. 88, 101802 (2002)
Exclusive sum (2007): http://pdg.lbl.gov

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

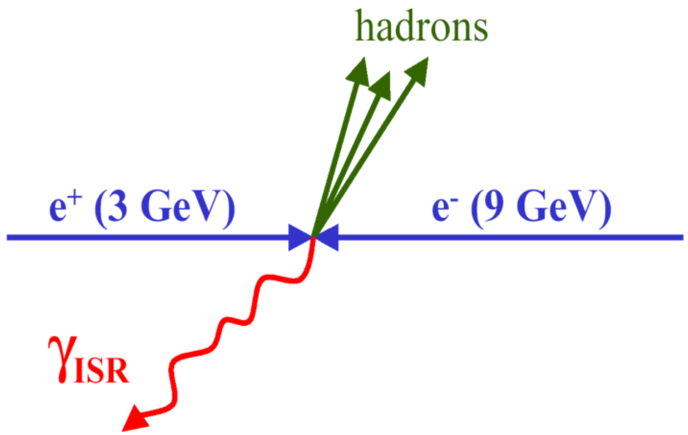




For ISR analyses, a data sample of 469 fb^{-1} collected near or at a c.m. energy of 10.58 GeV (at and near $\Upsilon(4S)$) is used.

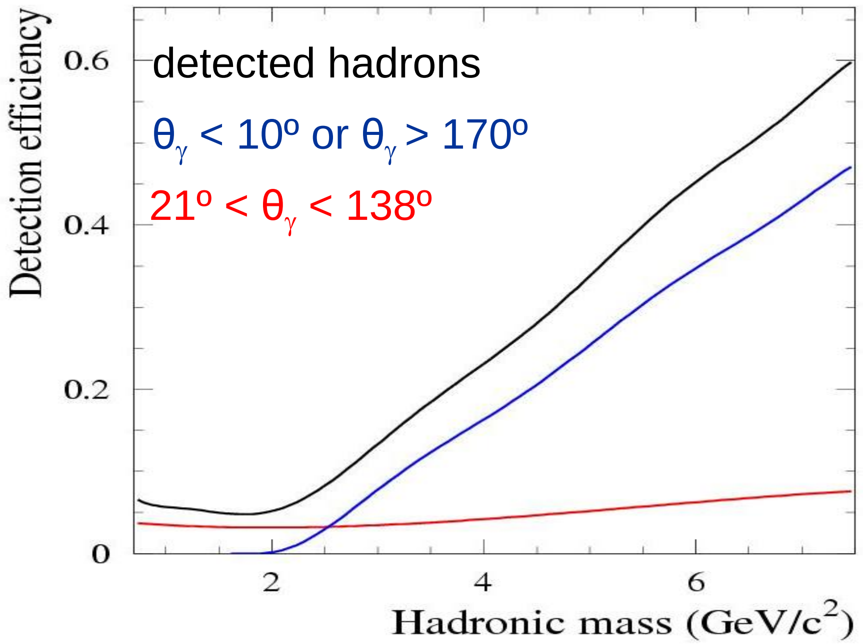
ISR method

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



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

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



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

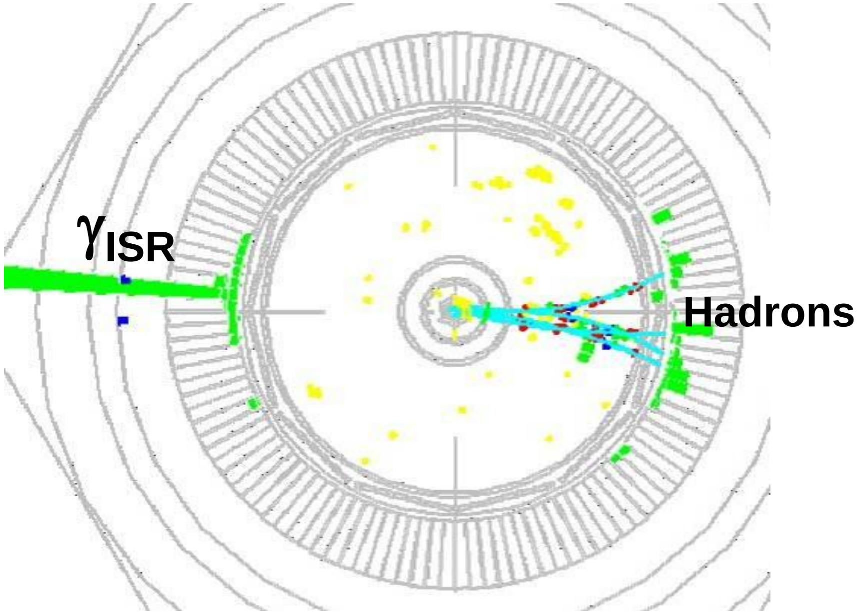
Large-angle ISR forces the hadronic system into the detector fiducial region

- ✓A weak dependence of the detection efficiency on dynamics of the hadronic system (angular and momentum distributions in the hadron rest frame) $\Rightarrow$ smaller model uncertainty
- ✓A weak dependence of the detection efficiency on hadron invariant mass $\Rightarrow$ 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



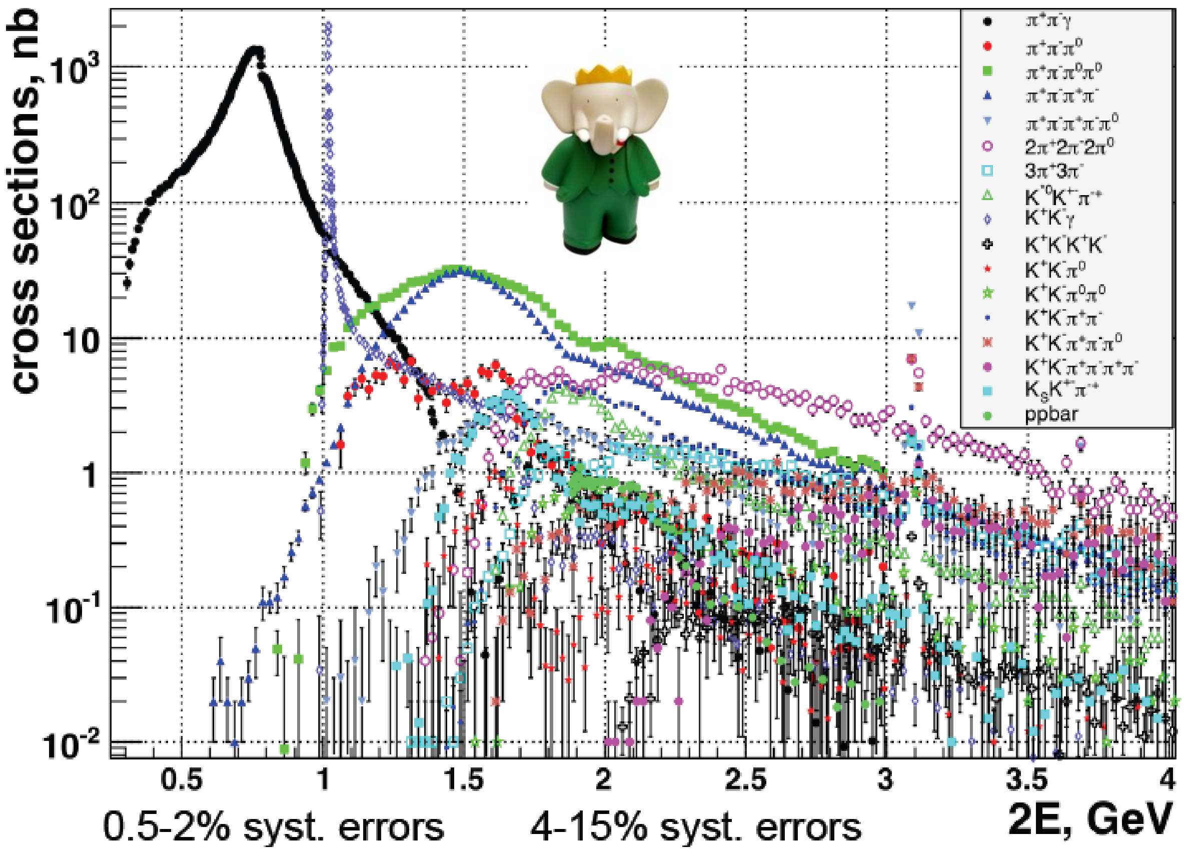
Can access a wide range of energy in a single experiment: from threshold to ~5 GeV

BABAR tagged ISR analyses

17 final states were studied, 18 papers on low energy ISR studies were published

Four analyses are discussed in this talk

- ✓$\pi^+\pi^-\pi^0\pi^0$
- ✓$\pi^+\pi^-\eta$
- ✓$K_S K_L \pi^0$, $K_S K_L \eta$, $K_S K_L \pi^0\pi^0$
- ✓$K_S K^+\pi^-\pi^0$, $K_S K^+\pi^-\eta$

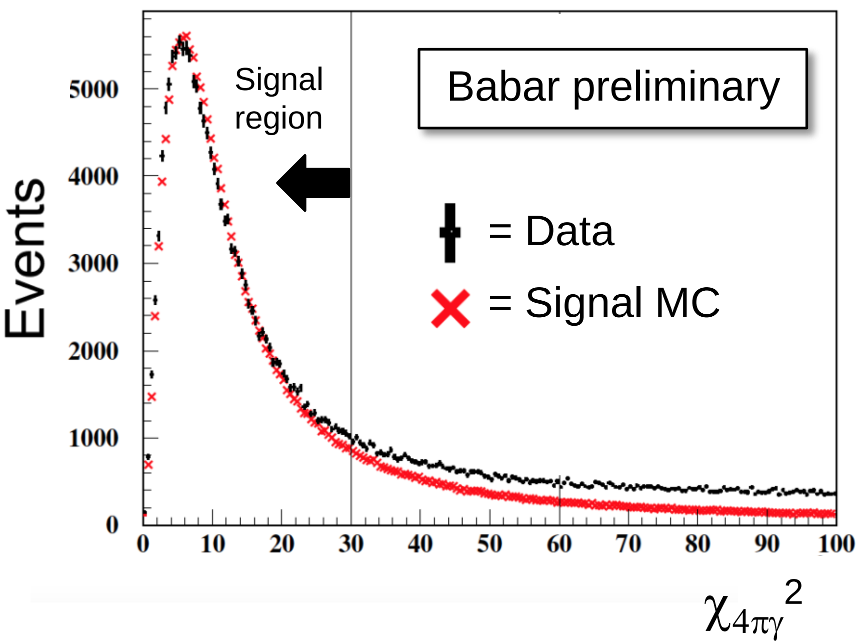


0.5-2% syst. errors 4-15% syst. errors

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

One of the least known cross sections important for $(g\text{-}2)_\mu$

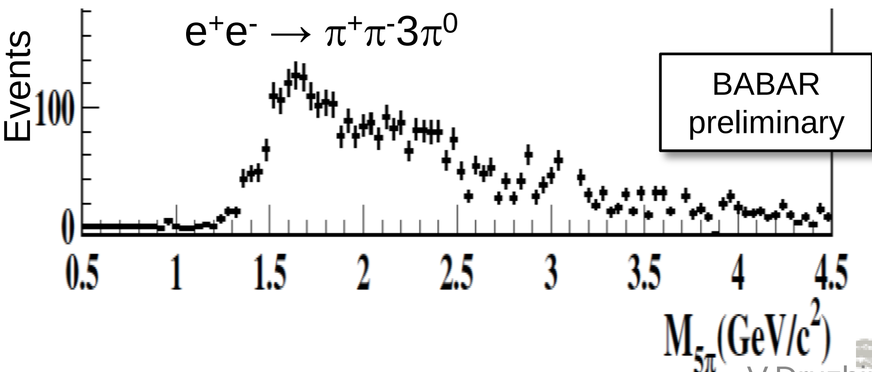
- Exactly 2 opposite-charge tracks with p > 100 MeV originating from the interaction region
- ISR photon candidate: highest energy photon with E_{CM} > 3 GeV
- At least 4 other photons with E > 50 MeV
- Perform a kinematic fit to the $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$ hypothesis with requirements of energy and momentum balance and two π^0-mass constraints
- Select a four-photon combination with the smallest $\chi^2_{4\pi\gamma}$, requiring $\chi^2_{4\pi\gamma} < 30$
- Difference between the $\chi^2_{4\pi\gamma}$ distributions in data and signal MC is due to background

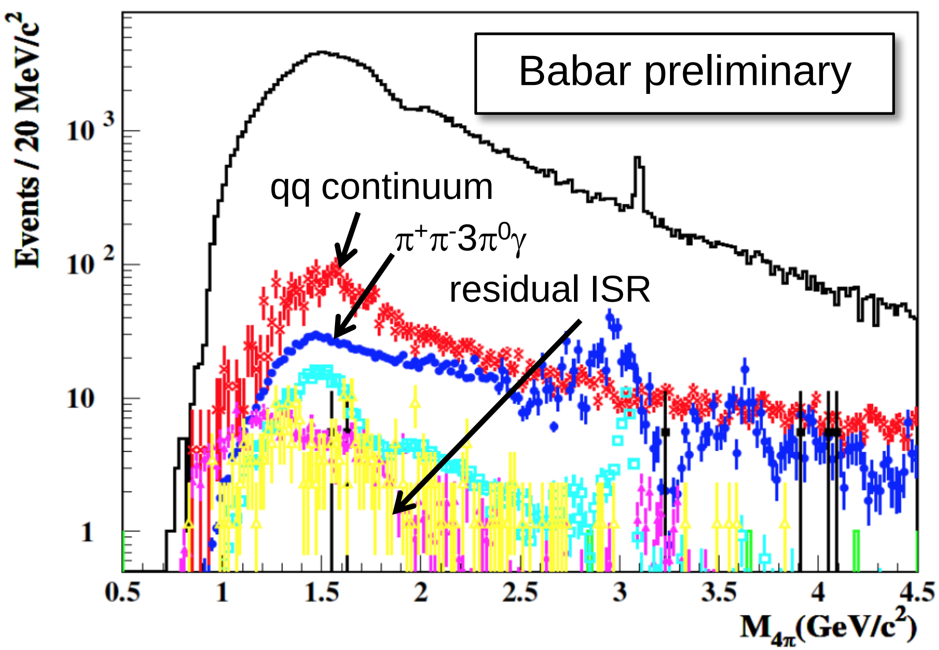


$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

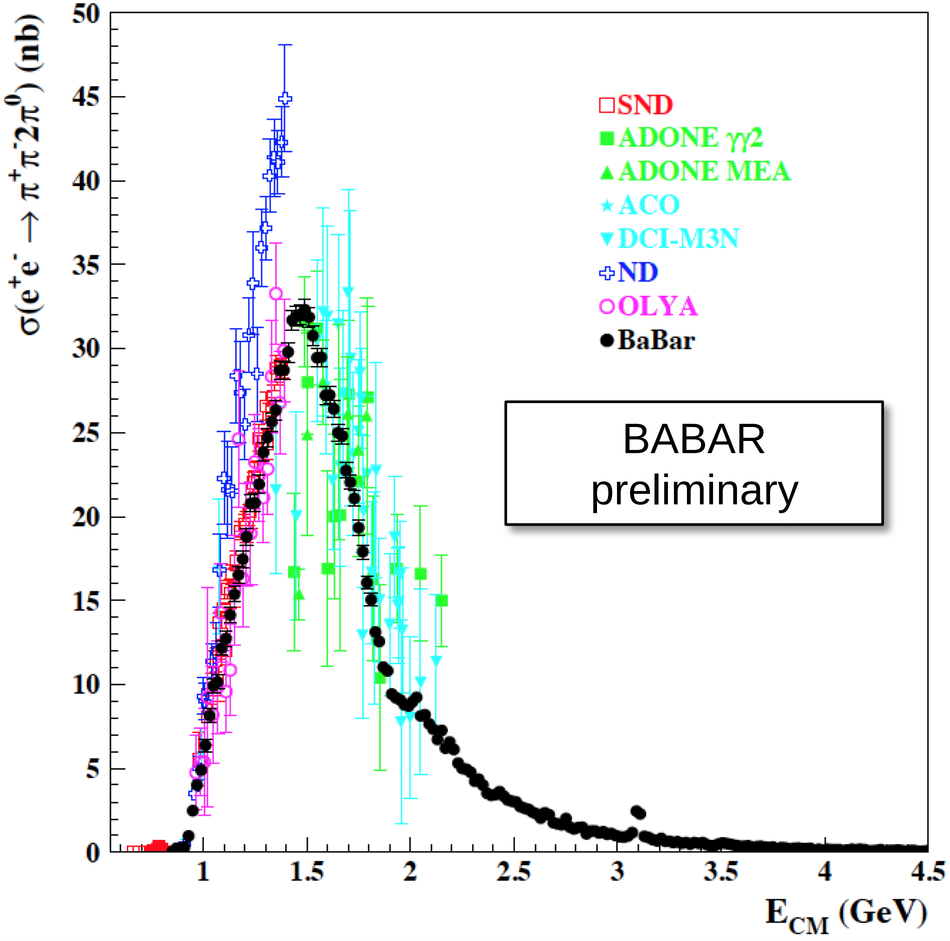
- ISR background from $\pi^+\pi^-\pi^0\gamma$, $\pi^+\pi^-\pi^0\eta\gamma$, $\pi^+\pi^-2\eta\gamma$ is suppressed by rejecting events with kinematic fits consistent with those hypotheses; e.g., require $\chi_{3\pi\gamma}^2 > 25$
- The process with kaons ($K^+K^-\eta\gamma$, $K^+K^-\pi^0\eta\gamma$, ...) are suppressed by requiring none of the charged particles to be identified as a kaon
- Largest remaining background is from non-ISR $q\bar{q}$ continuum events, arising from the misidentification of a photon from π^0 decay as an ISR photon. It is subtracted using MC simulation normalized to the π^0 peak in $\gamma_{ISR}\gamma$ combinations.
- Residual ISR background is subtracted using MC simulation normalized to the existing measurements (rate and shape).

The largest ISR background process $e^+e^- \to \pi^+\pi^-3\pi^0\gamma$ is not well measured; the $\pi^+\pi^-3\pi^0$ mass spectrum used to reweight simulation is extracted from BABAR data.



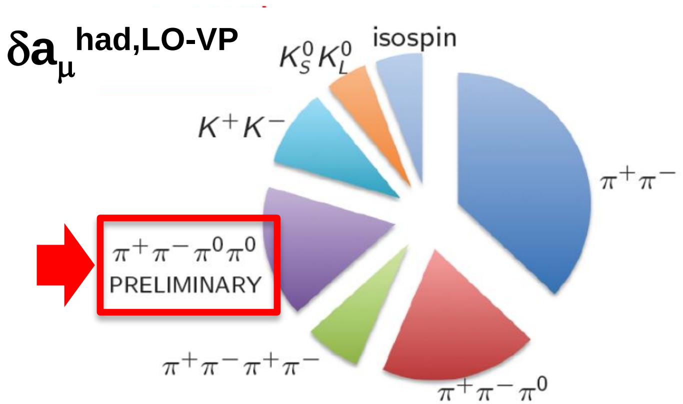


$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ cross section



Systematic uncertainty is 3.1% in the 1.2-2.7 GeV energy range.

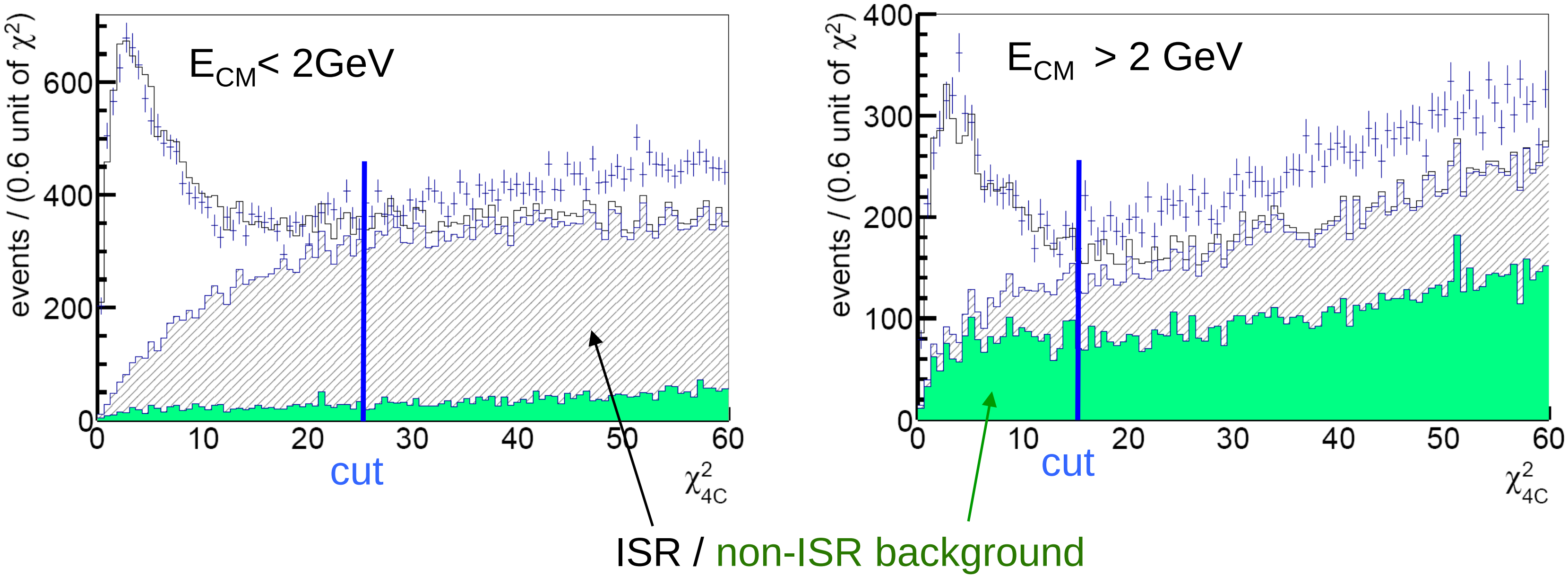
- BABAR results are most precise and covers wider energy range
- Contribution to a_μ for the range $1.02<E_{CM}<1.8$ GeV is measured to be $[175 \pm 6$ (stat+syst)$] \times 10^{-11}$ (3.4% precision)
- Previous result including the preliminary BABAR data from 2007 is $[180 \pm 12$ (stat+syst)$] \times 10^{-11}$ (6.7% precision)



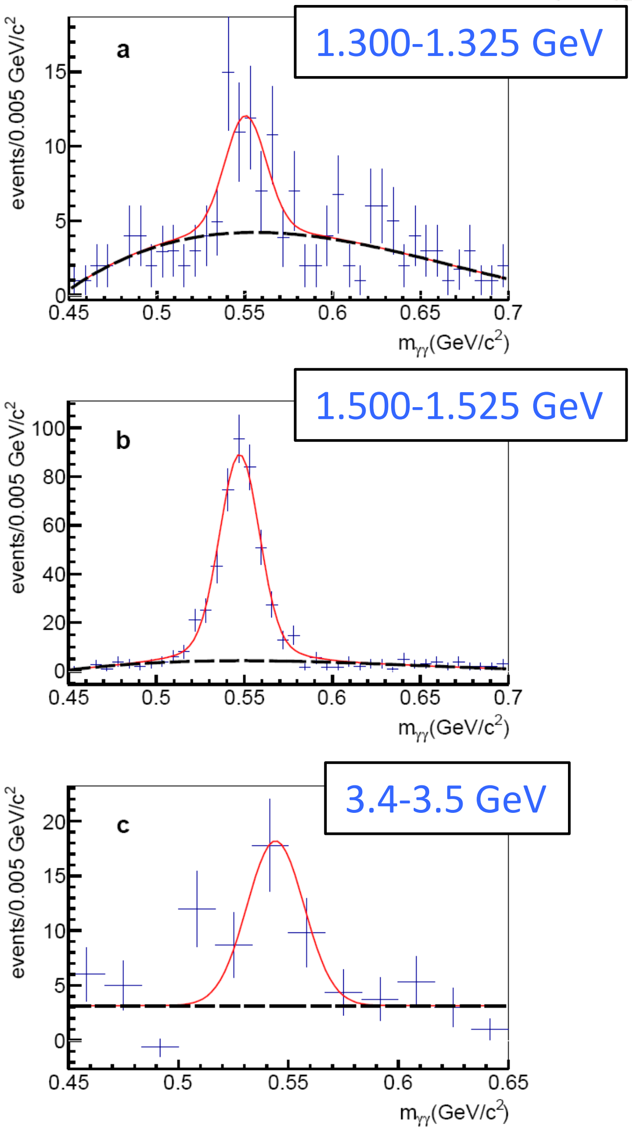
$e^+e^- \to \pi^+\pi^-\eta$

This reaction is expected to proceed via the $\rho\eta$ intermediate state. It is important for spectroscopy of excited ρ-like states.

- The $e^+e^- \to \pi^+\pi^-\eta$ process is studied in the $\eta\to\gamma\gamma$ decay mode.
- Event selection is based on χ^2 of the kinematic fit using requirements of energy and momentum balance.



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

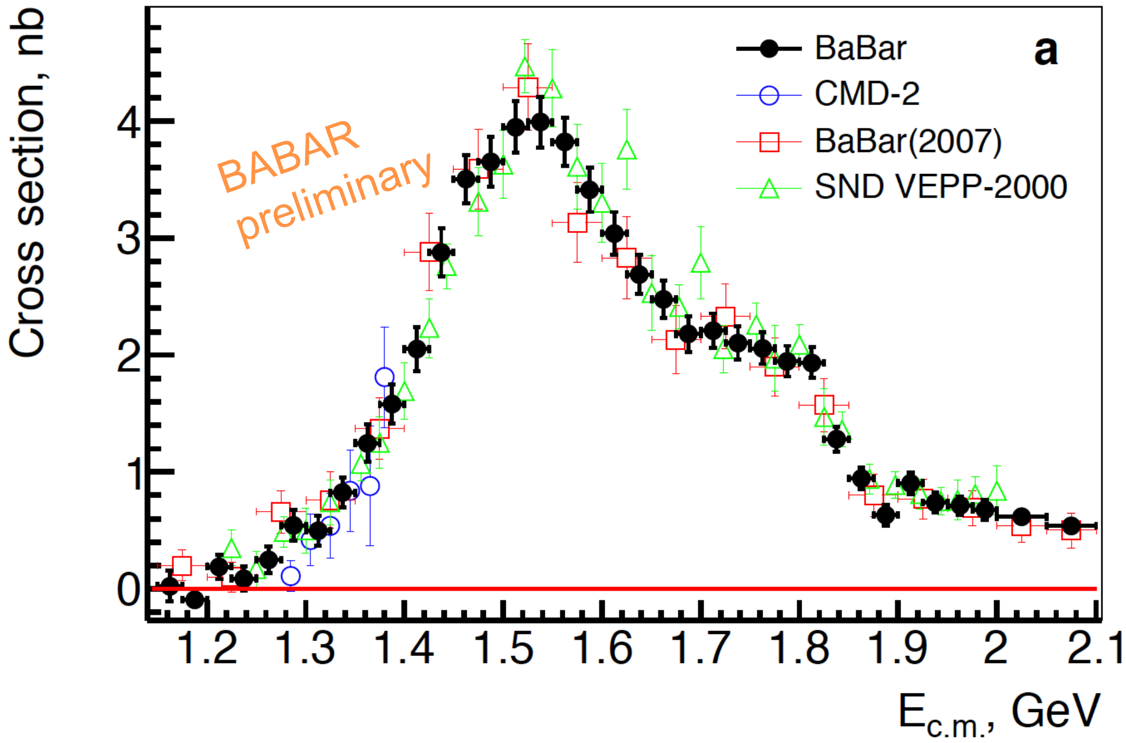


- The number of signal events is determined from the fit to the two-photon mass distribution for the η-candidate.

- The fit removes background from the processes not containing η.

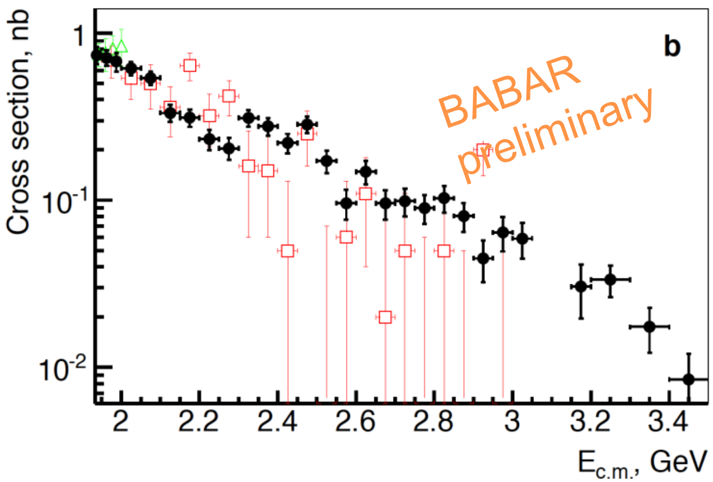
- Peaked background from ISR ($e^+e^-\to K^+K^-\eta\gamma$, $\pi^+\pi^-\pi^0\eta\gamma$) and non-ISR processes ($e^+e^-\to\pi^+\pi^-\pi^0\eta$) is subtracted using corrected MC simulation.

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

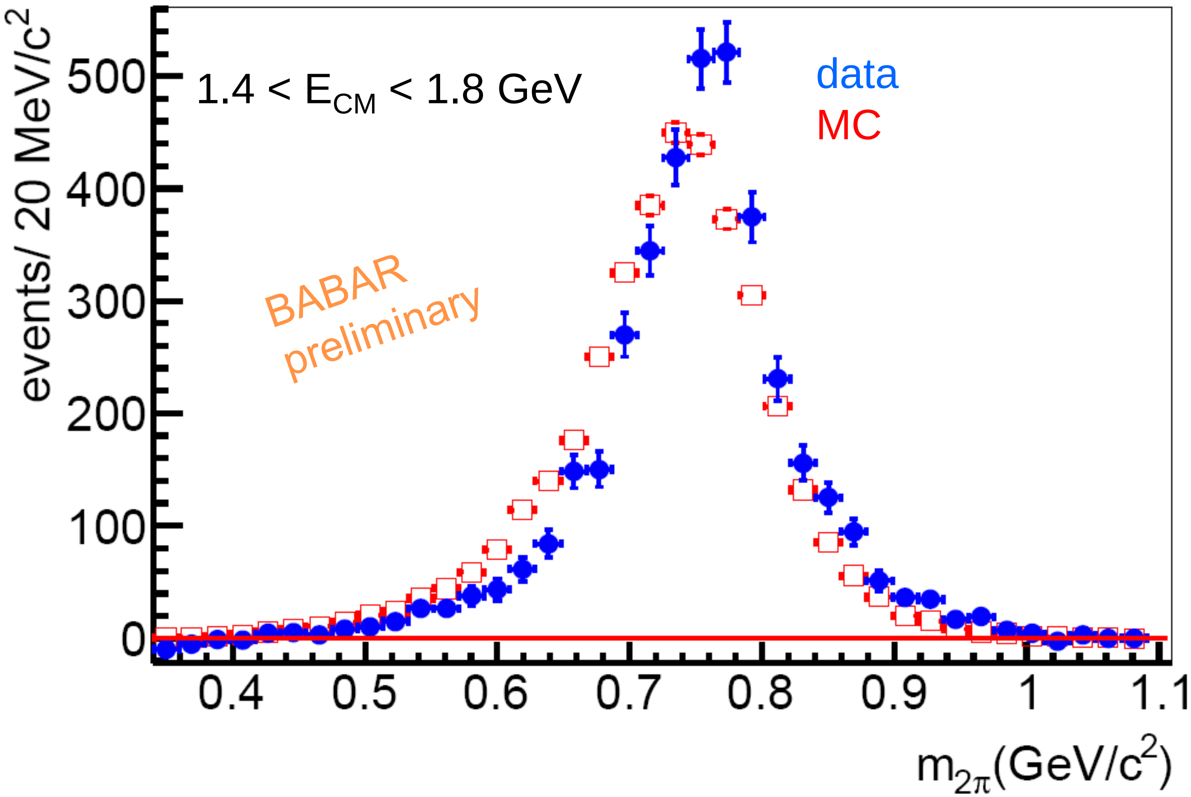


The BABAR results in the $\eta\to\gamma\gamma$ mode agrees well with the previous measurements, but is more precise and covers wider energy range.

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



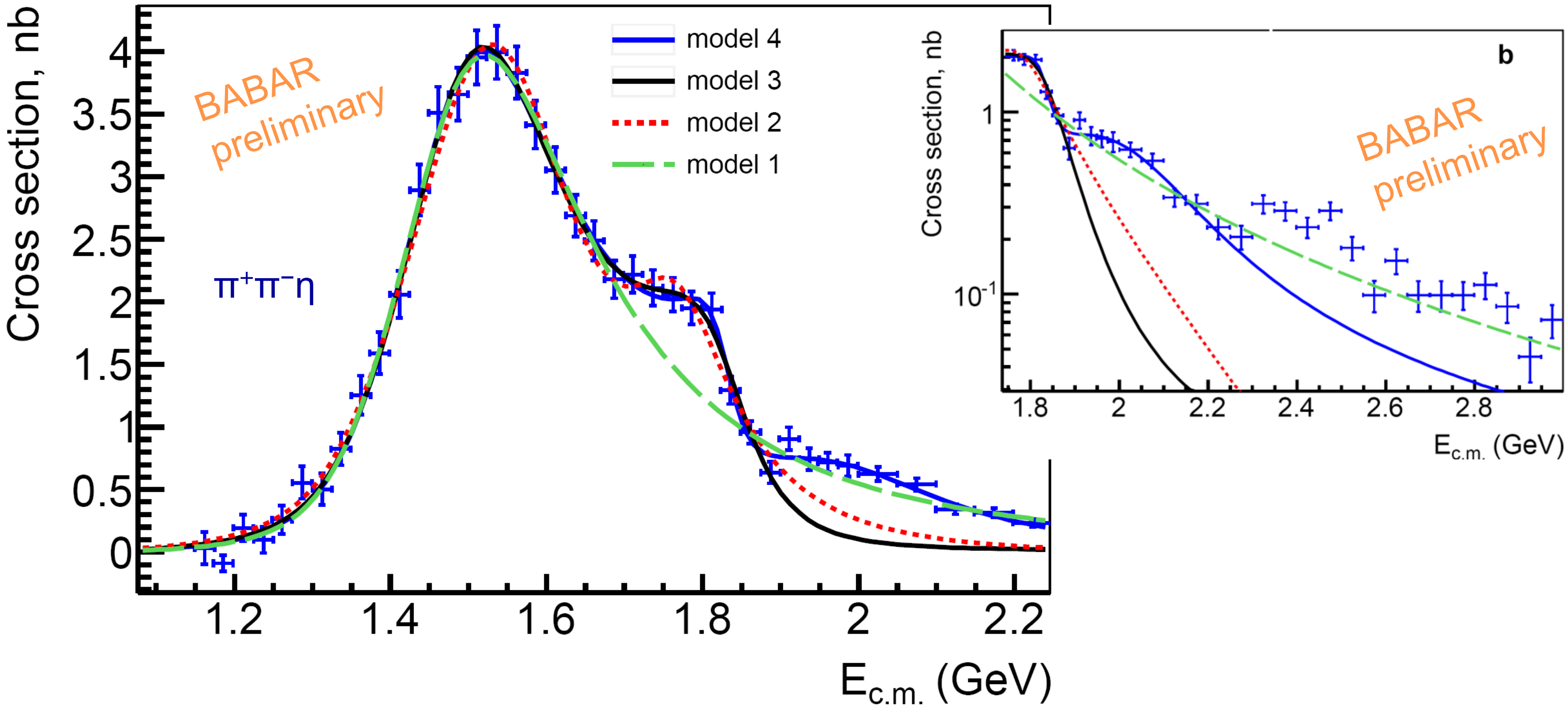
$\pi^+\pi^-$ mass spectrum



- 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.

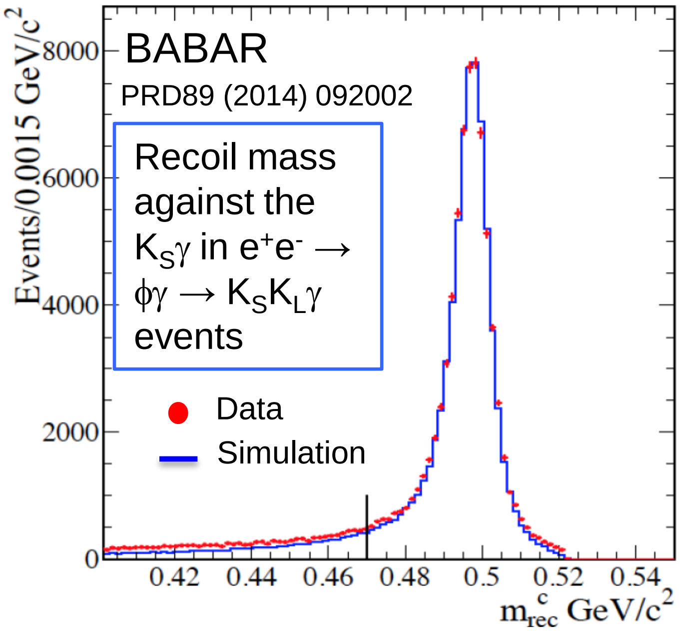
PDG14 value:
$B(\tau^- \to \pi^-\pi^0\eta\nu_\tau) = (0.139 \pm 0.010)\%$
CVC-experiment difference is 1.8σ.

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.

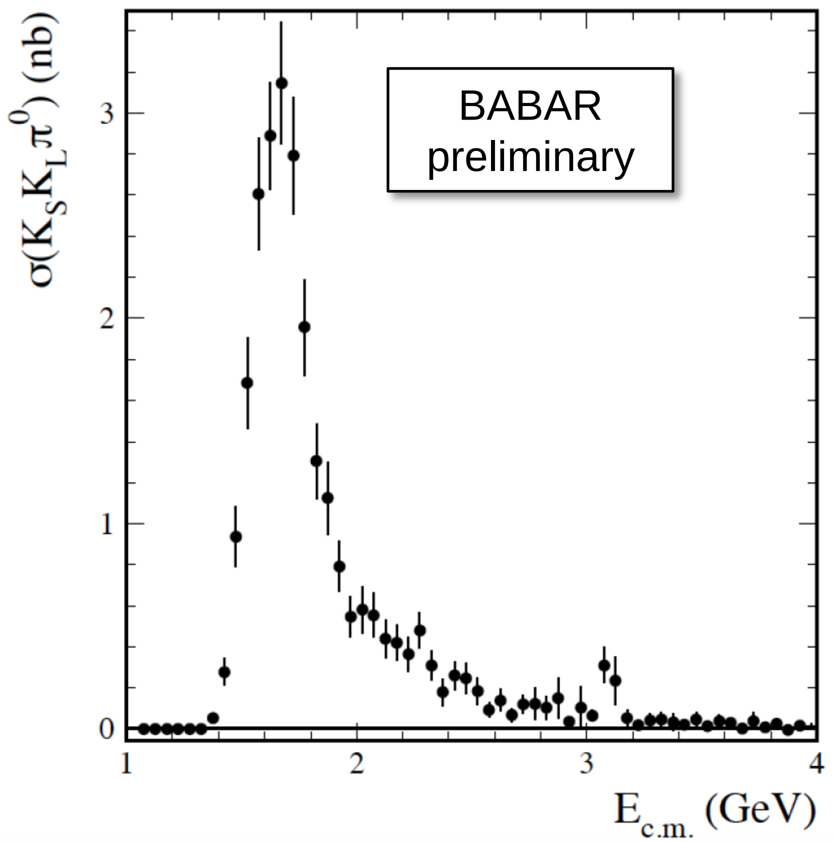
$e^+e^- \to K_S K_L \pi^0$

- ISR photon = highest energy g with $E_{CM} > 3$ GeV
- At least one $K_S \to \pi^+\pi^-$ candidate consistent with the interaction point
- At least two additional photons, with $m_{\gamma\gamma}$ consistent with m_{π^0}

- K_L candidates identified as an isolated calorimeter clusters with E > 0.2 GeV; the detection efficiency as a function of the K_L energy and direction was measured in data from $e^+e^- \to \phi\gamma \to K_S K_L \gamma$ events
- Perform the kinematic fit to fit the $K_S K_L \pi^0 \gamma$ hypothesis; combination with the lowest respective χ^2 is chosen.

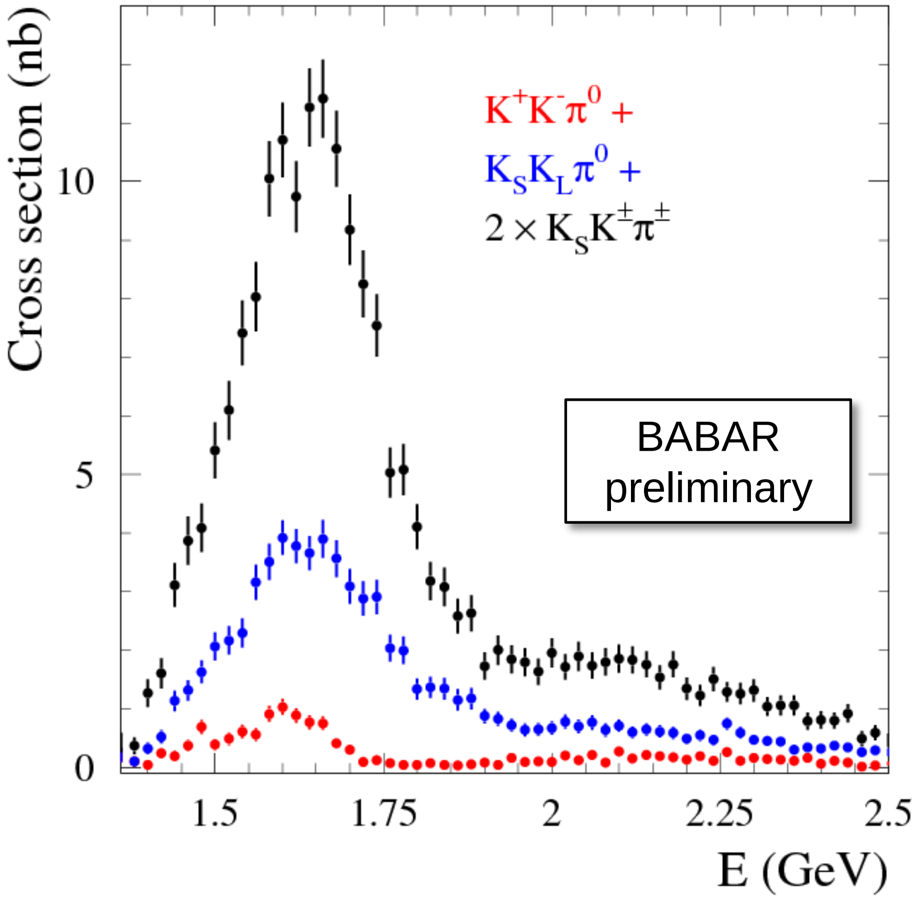


$e^+e^- \to K_S K_L \pi^0$



- ✓ First measurement of this process
- ✓ Systematic uncertainty is 10% near the peak, increase up to 30% at 3.0 GeV
- ✓ The dominant intermediate state (>95%) is $K^*(892)\bar{K}$. The $K_2^*(1430)\bar{K}$ and $\phi\pi^0$ are seen.

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



The $e^+e^- \to K_SK^+\pi^-$ and $K^+K^-\pi^0$ cross sections were measured previously [Phys. Rev. D 77, 092002 (2008)].

Summing the cross sections for three charge configurations we obtain the total $e^+e^- \to K\bar{K}\pi$ cross section.

The $e^+e^- \to K\bar{K}\pi$ cross section is about 12% of the total hadronic cross section at 1.65 GeV.

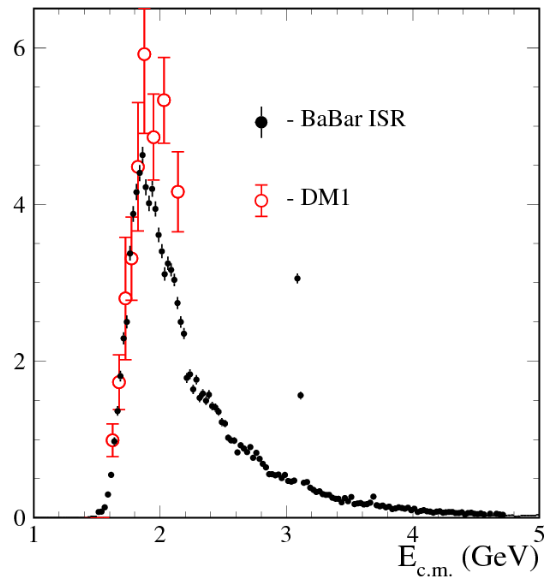
$e^+e^- \to K\bar{K}\pi\pi$

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

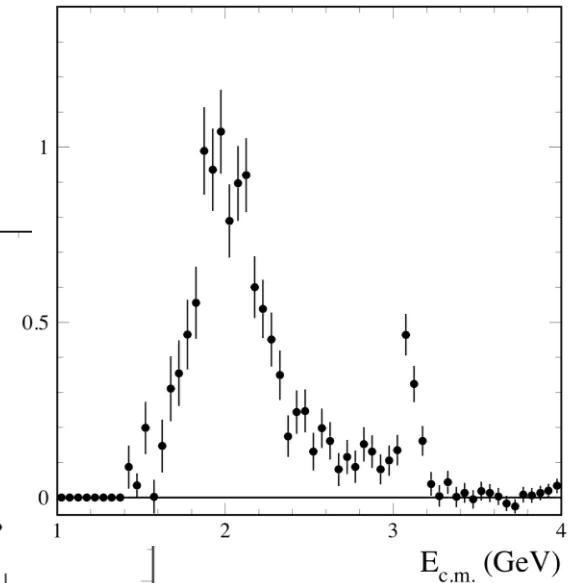
Phys. Rev. D 86, 012008 (2012)

Phys. Rev. D 89, 092002 (2014)

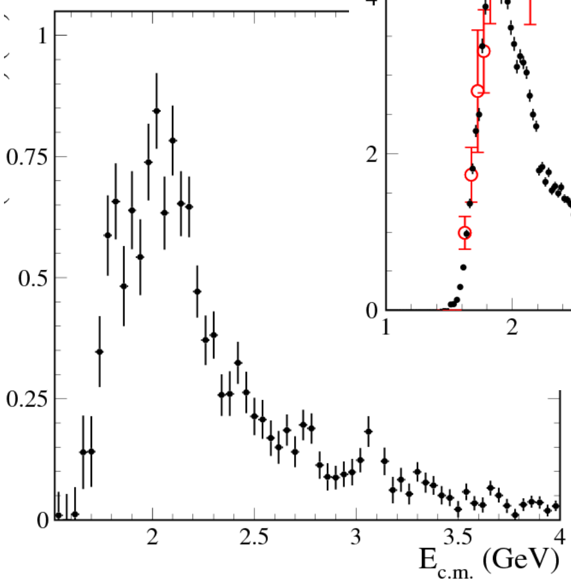
$\sigma(e^+e^- \to K^+K^-\pi^+\pi^-)$, nb



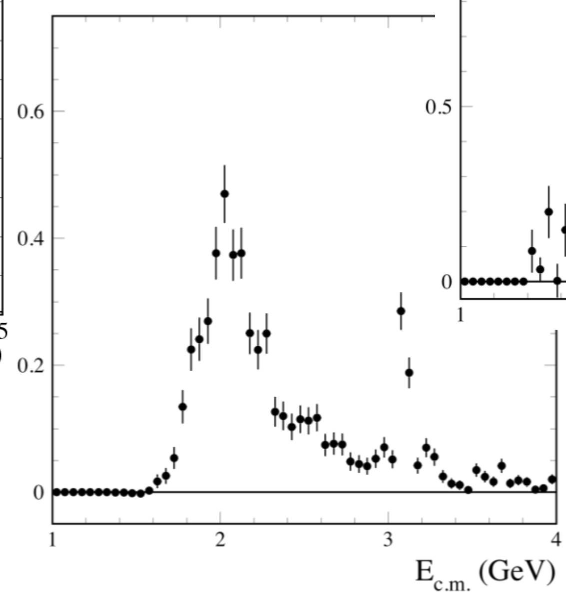
$\sigma(e^+e^- \to K_SK_L\pi^+\pi^-)$, nb



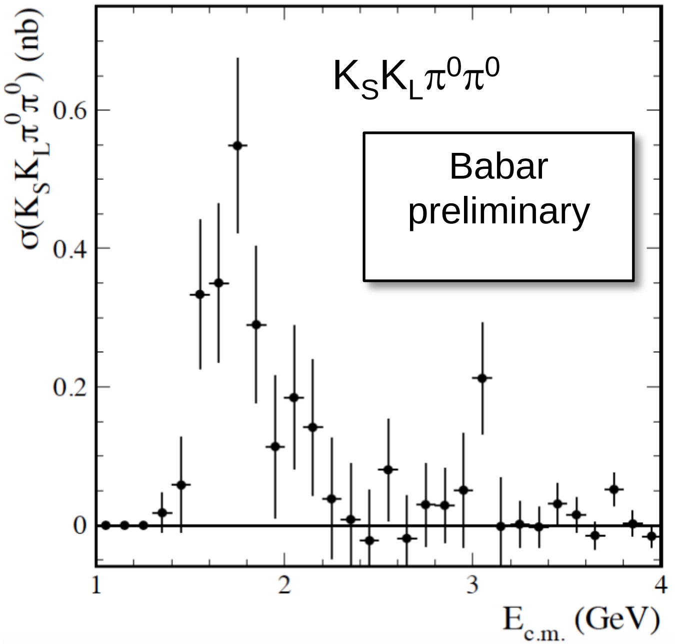
$\sigma(e^+e^- \to K^+K^-\pi^0\pi^0)$

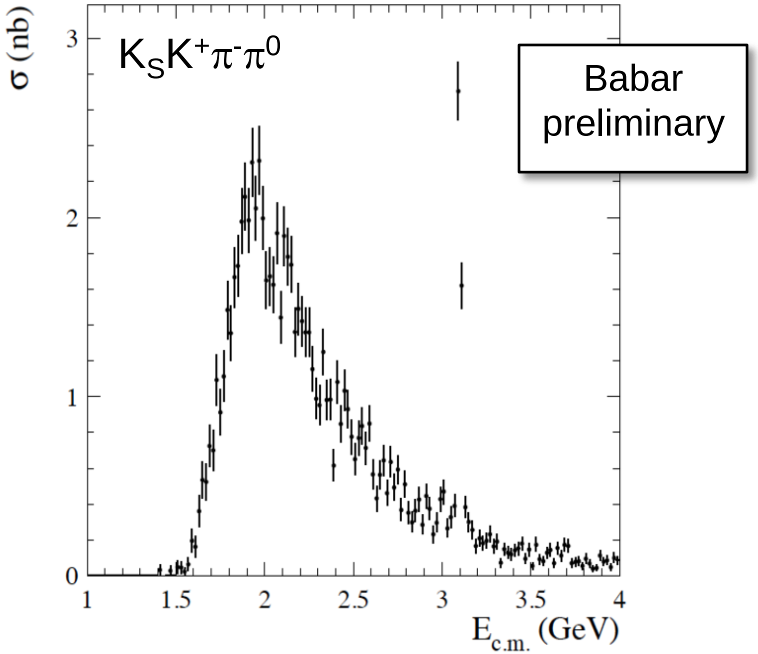


$\sigma(e^+e^- \to K_SK_S\pi^+\pi^-)$



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

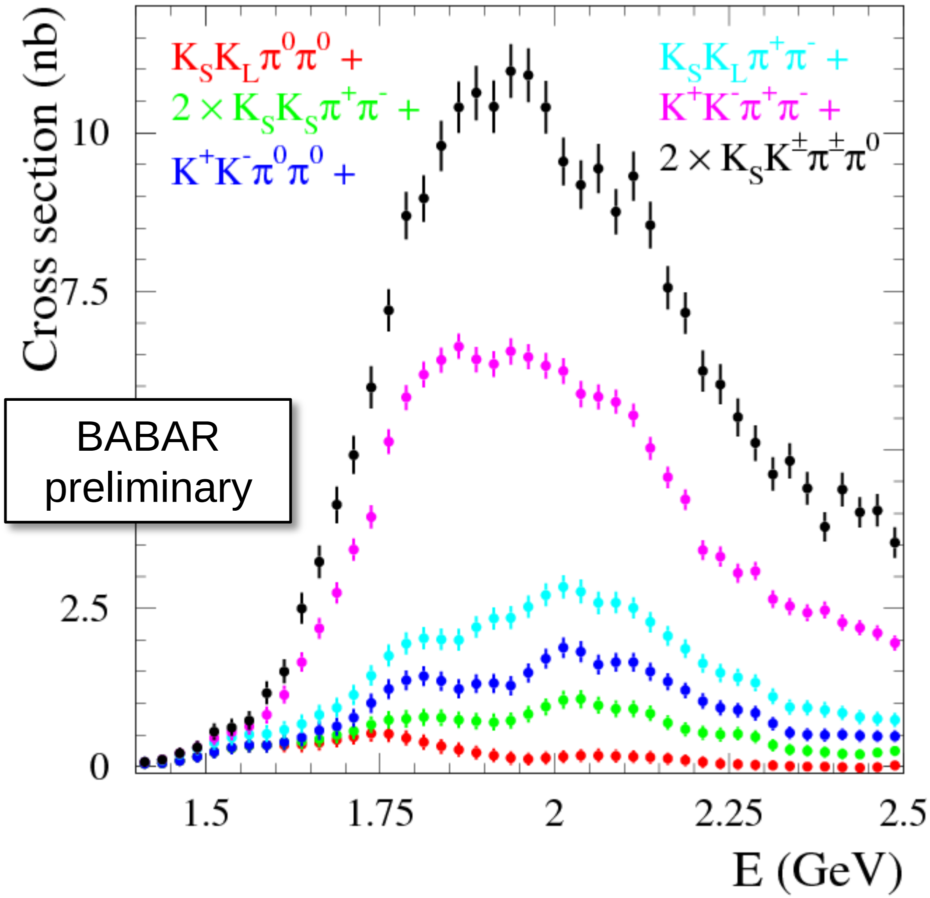




- First measurement
- Systematic uncertainty is 25% at the peak, grows to 60% at 2 GeV
- Dominant $K^*(892)\bar{K}\pi$ intermediate state.
- Correlated $K^*(892)\bar{K}^*(892)$ production is small.

- First measurement
- Systematic uncertainty is 6-7% below 3 GeV
- Dominant $K^*(892)\bar{K}\pi$, $K_SK^+\rho^-(770)$ intermediate state.
- A correlated $K^*(892)\bar{K}^*(892)$ production is small (< 15%), and dominated by $K^{*+}\bar{K}^{*-}$.

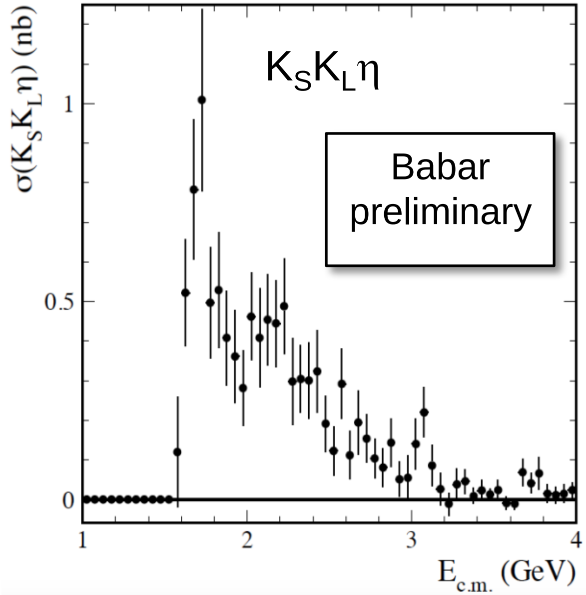
Total $e^+e^- \rightarrow K\bar{K}\pi\pi$ cross section

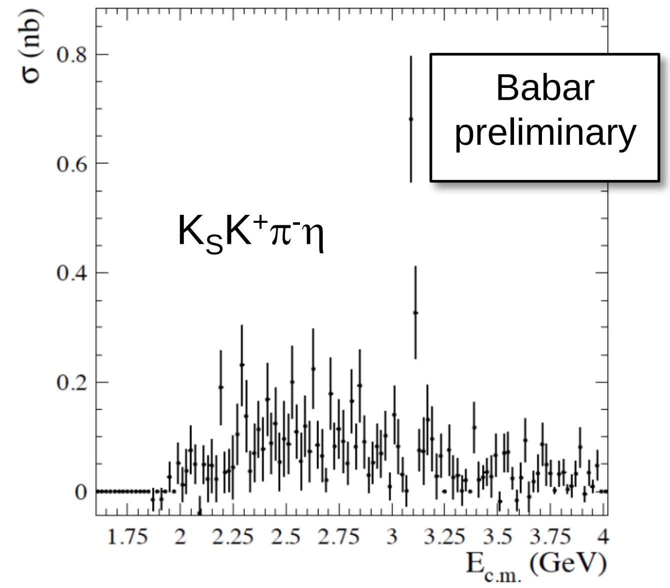


The cross section is calculated without any model assumptions.

The $e^+e^- \rightarrow K\bar{K}\pi\pi$ cross section is about 25% of the total hadronic cross section at 2 GeV.

Processes with kaons and η

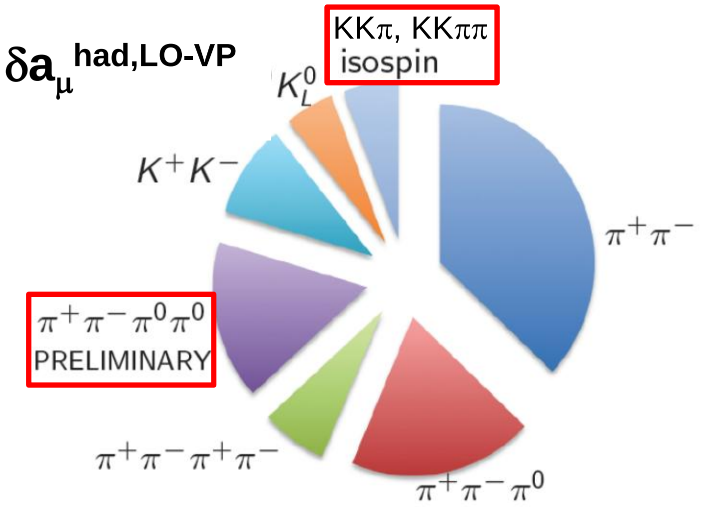




- First measurement
- Dominant intermediate state is $\phi(1020)\eta$.
- The cross section agrees with previous BABAR measurements in the $K^+K^-\eta$ mode with $\eta\to\gamma\gamma$ and $\eta\to\pi^+\pi^-\pi^0$

- First measurement
- Dominant intermediate state is $K^*(892)\bar{K}\eta$.

Summary



- ✓ Precise low-energy e^+e^- hadronic cross section data are needed to obtain an accurate SM prediction for $a_\mu^{had,LO\text{-}VP}$
- ✓ New results on from BABAR reduce the respective uncertainty in $a_\mu^{had,LO\text{-}Vp}$ due to
  - $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$
  - $e^+e^- \to K\bar{K}\pi$, $K\bar{K}\pi\pi$
- ✓ Several previously unmeasured processes contributed to the total hadronic cross section below 2 GeV have been observed
- ✓ Besides the implications for $a_\mu^{had,LO\text{-}VP}$, the BABAR ISR program has provided new information about hadronization at low energies and properties of low-mass resonances.

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)