Recent results on exclusive hadronic cross sections measurements with the *BABAR* detector

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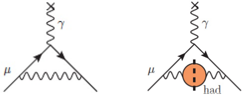
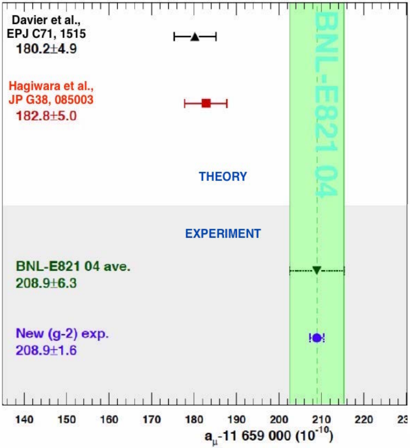
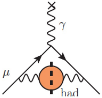
$a_\ell = \frac{1}{2}(g-2)_\ell$ precision test of QED

- OK for electrons
- long-standing $\approx 3\,\sigma$ discrepancy for muons

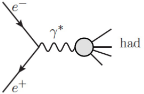




need experimental input for hadronic vacuum polarization



dispersion relation



$K(s)$: analytically known kernel function

$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2(0)}{3\pi^2}\int_{4m_\pi^2}^{\infty} \mathrm{d}s\, \frac{K(s)}{s}\, R(s)$$

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

Low energy hadronic cross sections and a_μ

The dominant correction and error from hadronic vacuum polarization

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

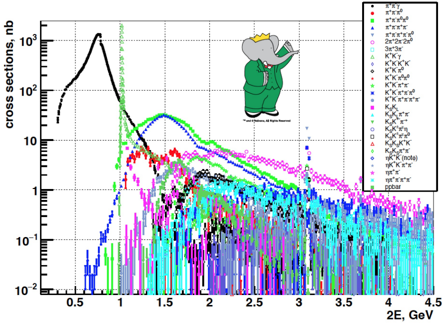
Individual SM contributions $\times 10^{-11}$

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

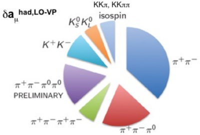
Comparison with measurement

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

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



at low energies total hadronic cross section determined from (finite) sum of exclusive modes

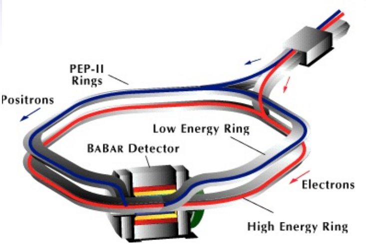


Many exclusive modes measured by *BABAR*

New preliminary measurements for

- $\pi^+\pi^-\pi^0\pi^0$
- $\pi^+\pi^-\eta$
- $K_S^0 K_L^0 \pi^0$; $K_S^0 K_L^0 \eta$; $K_S^0 K_L^0 \pi^0\pi^0$
- $K_S^0 K^+ \pi^+ \pi^0$; $K_S^0 K^+ \pi^+ \eta$

The *BABAR* experiment



PEP-II asymmetric e^+e^- collider operating at center of mass energies near the $\Upsilon(4S)$ (for most of the time)

$$\sqrt{s} = 10.58\,\mathrm{GeV}/c^2$$

Asymmetric:

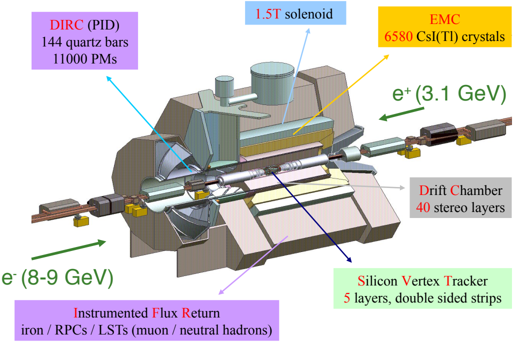
$$-0.9 < \cos\theta^* < 0.85$$

wrt electron beam

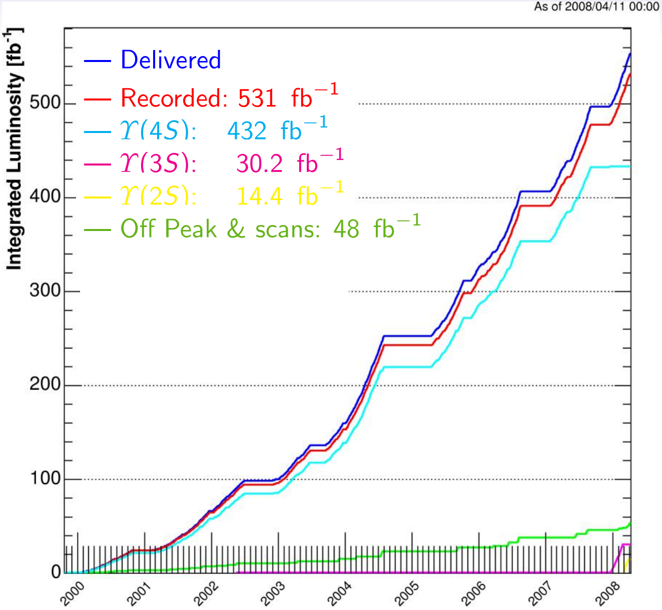
excellent performance:

- vertexing
- tracking
- PID
- calorimeter

General-purpose detector



Data samples

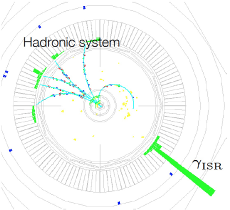


The ISR method at the $\Upsilon(4S)$

Initial State Radiation from e^+e^- allows to measure cross sections at all center-of-mass energies $\sqrt{s'}$ below the nominal $\sqrt{s}$ of the beams

$$\frac{\mathrm{d}\sigma(s;s';\theta_\gamma)}{\mathrm{d}s'\mathrm{d}\theta_\gamma} = W(s;s';\theta_\gamma) \cdot \sigma_x(s')$$

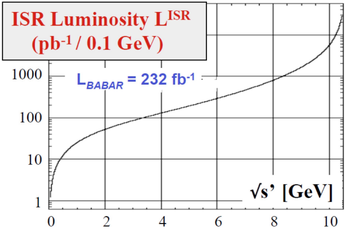
tag photon to identify ISR events



- hadrons in fiducial detector region
- fully reconstruct the final state
- kinematic fit: energy resolution

boost $\Longrightarrow$ harder momentum spectrum for daughter particles

- cross sections down to threshold
- measure σ at all $\sqrt{s}$ simultaneously
- large "effective" luminosity



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

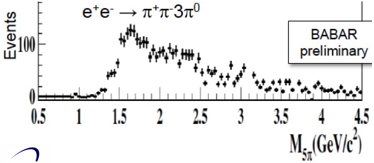
One of the least known cross sections among those relevant to $(g-2)_\mu$

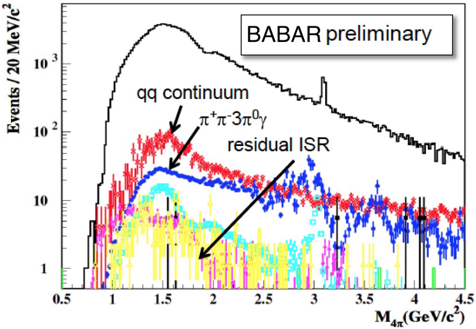
- ISR photon: highest energy photon with $E_\gamma^{CM} > 3\ \mathrm{GeV}$
- exacty two oppositely charged tracks of $p > 100\ \mathrm{MeV}$
- at least 4 additional photons $E > 50\ \mathrm{MeV}$
- kinematic fit $e^+e^- \to \gamma_{ISR}4\pi$: require $\chi^2_{4\pi\gamma} < 30$

Explicitly veto backgrounds based on particle ID (kaons) and kinematic fit to any competing mode

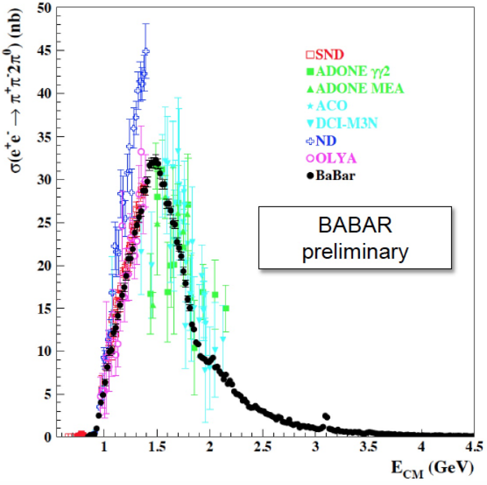
non-ISR $q\bar{q}$ events where photons from π^0 misidentified as γ_{ISR} subtracted based on simulation and π^0 yield in $\gamma_{ISR}\gamma$ combinations

poorly known $\pi^+\pi^-3\pi^0$ cross section: use data





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



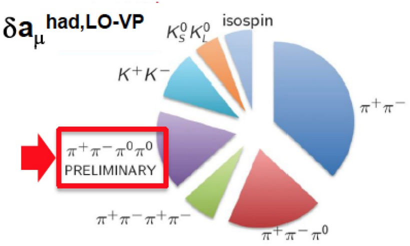
Contribution to a_μ in $1.02 < E_{CM} < 1.8$ GeV reduced from

$(180 \pm 12_{(stat+sys)}) \times 10^{-11}$ (6.7% *precision*)

(incl. 2007 BABAR preliminary result)

to

$(175 \pm 6_{(stat+sys)}) \times 10^{-11}$ (3.4% *precision*)

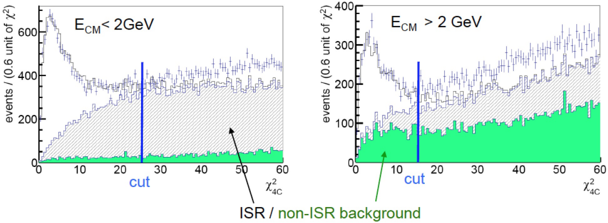


$e^+e^- \to \pi^+\pi^-\eta$

Expected to proceed via $\rho\eta$: important to understand higher ρ excitations

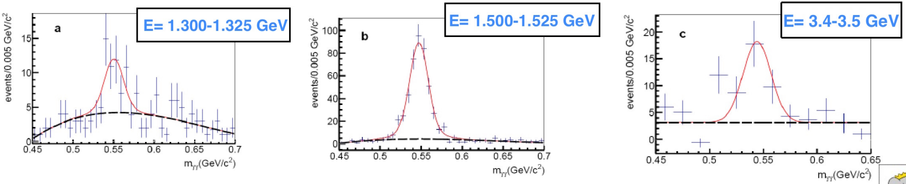
Reconstruct $\gamma_{ISR}\pi^+\pi^-\gamma\gamma$; kinematic fit.

Background modelled on MC extrapolating yields from data

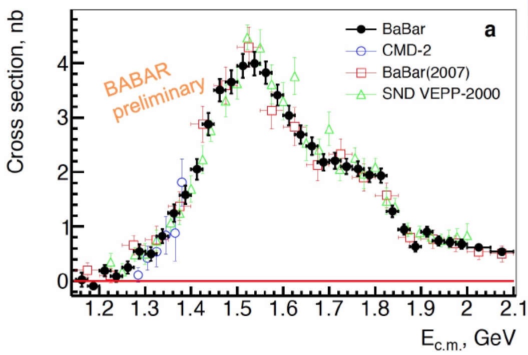


Extract signal yield in each energy bin fitting the $\gamma\gamma$ inv. mass

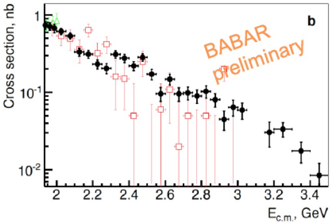
residual background from processes with η subtracted using MC

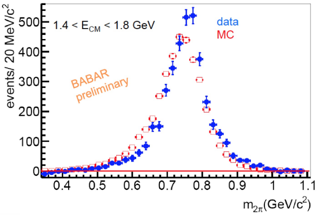


$e^+e^- \to \pi^+\pi^-\eta$ cross section



BABAR measurement compatible with previous measurements, but more precise and on a broader energy range

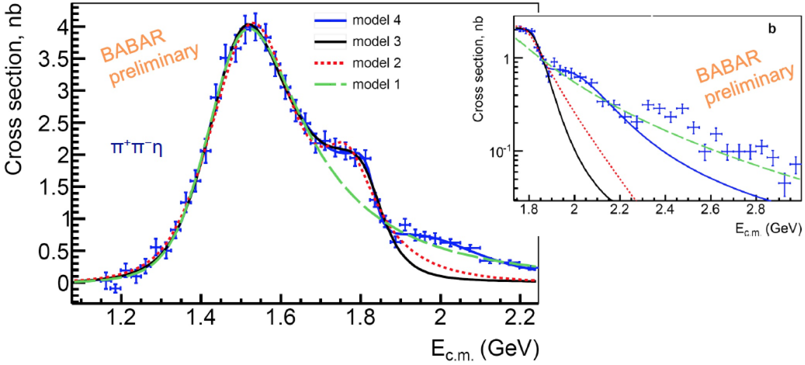




the $\pi^+\pi^-$ mass spectrum is not well described by the $\rho(770)\eta$ model (already noticed by SND)

interference with $\rho(1450)\eta$?

VDM fits to the $e^+e^- \to \pi^+\pi^-\eta$ cross section



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° (−)

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

arXiv:1701.08297

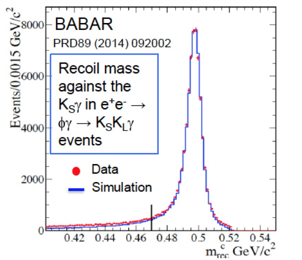
NEW

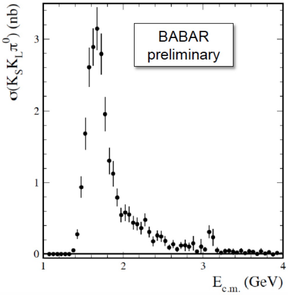
Reconstruct γ_{ISR}, $K_S^0 \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$

K_L^0 detected as isolated energy cluster in the calorimeter $E > 0.2\ \mathrm{GeV}$

validated on $e^+e^- \to \gamma\phi \to \gamma K_S^0 K_L^0$

Inv. mass resolution of hadronic system (after kin.fit): $\approx 25\ \mathrm{MeV}$





First measurement of this cross section

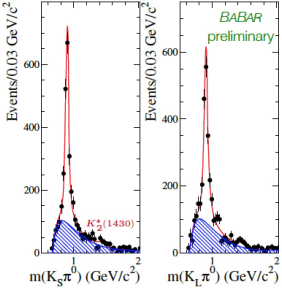
syst. uncertainty $\approx 10\%$ at peak, $\approx 30\%$ at $3.0\ \mathrm{GeV}$

Resonant substructures in $K^0_S K^0_L \pi^0$

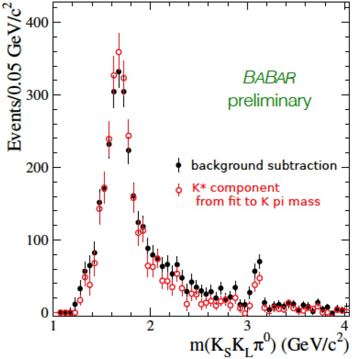
arXiv:1701.08297

NEW

Fit the (background-subtracted) $K^0_S\pi^0$ and $K^0_L\pi^0$ invariant mass distributions with coherent resonant/non resonant



Dominant $K^*(892)^0\bar{K}^0$ with small $K_2^*(1430)^0\bar{K}^0$

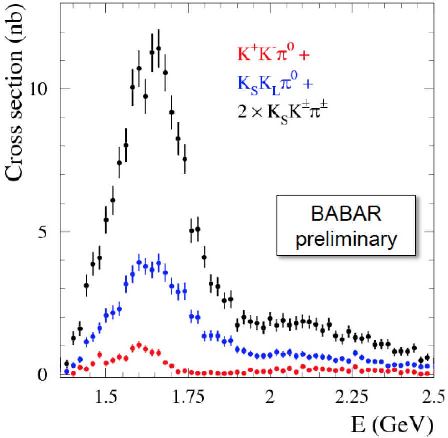


The $K^*(892)^0\bar{K}^0$ nearly saturates the $K^0_S K^0_L\pi^0$ cross section

small $K_2^*(1430)^0\bar{K}^0$ and $\phi\pi^0$

Total $K\bar{K}\pi$ cross section

Summing the $K_S^0 K_L^0 \pi^0$ cross section and the other two charge configurations measured previously by *BABAR* PRD 77, 092002 (2008)



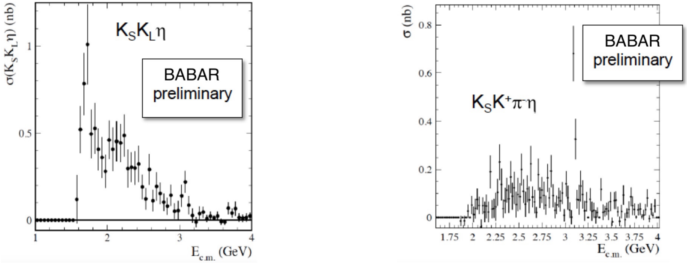
The $K\bar{K}\pi$ is $\approx 12\%$ of the total cross section for $E \approx 1.65$ GeV

Cross sections to final states with K and η

arXiv:1701.08297

NEW

Both measured for the first time!

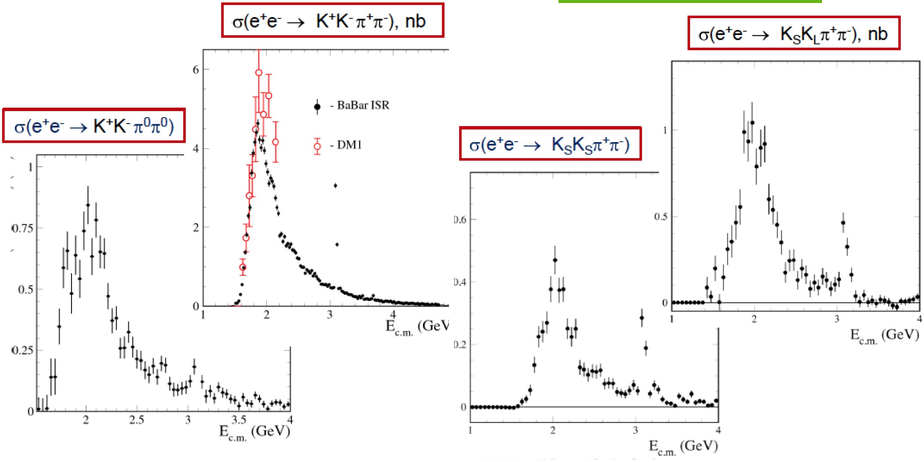


$KK\pi\pi$ cross sections

Of the 6 possible charge combinations, 4 were already measured by *BABAR*

PRD 86, 012008 (2012)

PRD 89, 092002 (2014)

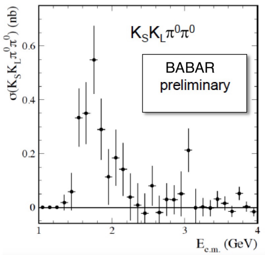


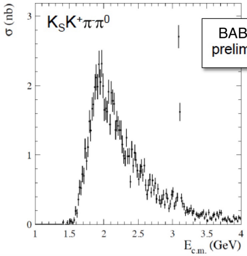
$KK\pi\pi$ cross sections

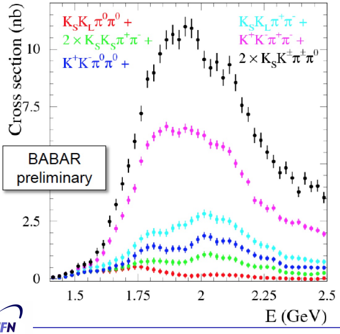
arXiv:1701.08297

NEW

First (preliminary) measurement of the missing charge combinations:







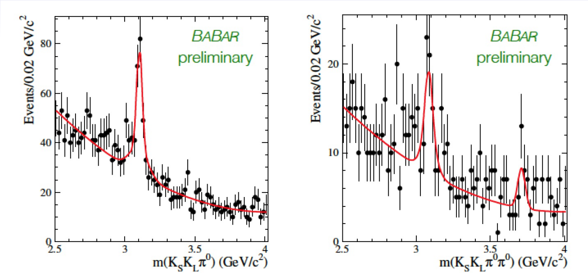
The total $KK\pi\pi$ cross section is $\approx 25\%$ of the total at $E \approx 2$ GeV

now measured without any model assumption

$K_S^0 K_L^0 \pi^0 (\pi^0)$ in the charmonium region

arXiv:1701.08297

NEW



$$\sigma(e^+e^- \to (c\bar{c}) \to X) \propto \Gamma((c\bar{c}) \to e^+e^-) \times \mathcal{B}((c\bar{c}) \to X)$$

from which the $\mathcal{B}$ can be determined without I-spin assumptions

Measured Quantity	Measured Value (eV)	Calculated Branching Fractions (10^{-3}) This work	Previous
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K_S^0 K_L^0 \pi^0}$	$11.4 \pm 1.3 \pm 0.6$	$2.06 \pm 0.24 \pm 0.10$	–
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K_S^0 K_L^0 \eta}$	$8.0 \pm 1.8 \pm 0.4$	$1.45 \pm 0.32 \pm 0.08$	–
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K_S^0 K_L^0 \pi^0 \pi^0}$	$10.3 \pm 2.3 \pm 0.5$	$1.86 \pm 0.43 \pm 0.10$	–
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K^*(892)^0 \overline{K}^0 + c.c.} \cdot \mathcal{B}_{K^*(892)^0 \to K^0 \pi^0}$	$6.7 \pm 0.9 \pm 0.4$	$1.20 \pm 0.15 \pm 0.06$	–
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K_2^*(1430)^0 \overline{K}^0 + c.c.} \cdot \mathcal{B}_{K_2^*(1430) \to K^0 \pi^0}$	$2.4 \pm 0.7 \pm 0.1$	$0.43 \pm 0.12 \pm 0.02$	< 4 [26]
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S) \to K_S^0 K_L^0 \pi^0}$	< 0.7	< 0.3	–
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S) \to K_S^0 K_L^0 \eta}$	$3.14 \pm 1.08 \pm 0.16$	$1.33 \pm 0.46 \pm 0.07$	–
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S) \to K_S^0 K_L^0 \pi^0 \pi^0}$	$2.92 \pm 1.27 \pm 0.15$	$1.24 \pm 0.54 \pm 0.06$	–

Published cross sections measured by *BABAR* via ISR

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