Study of e^+e^- annihilation into hadrons at low energies with ISR at BABAR

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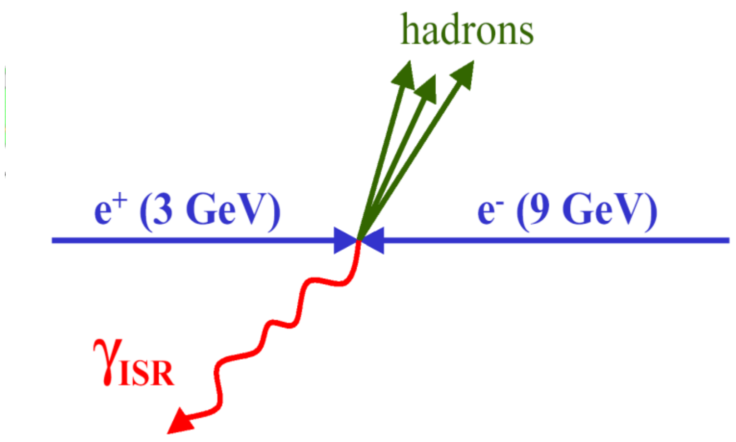
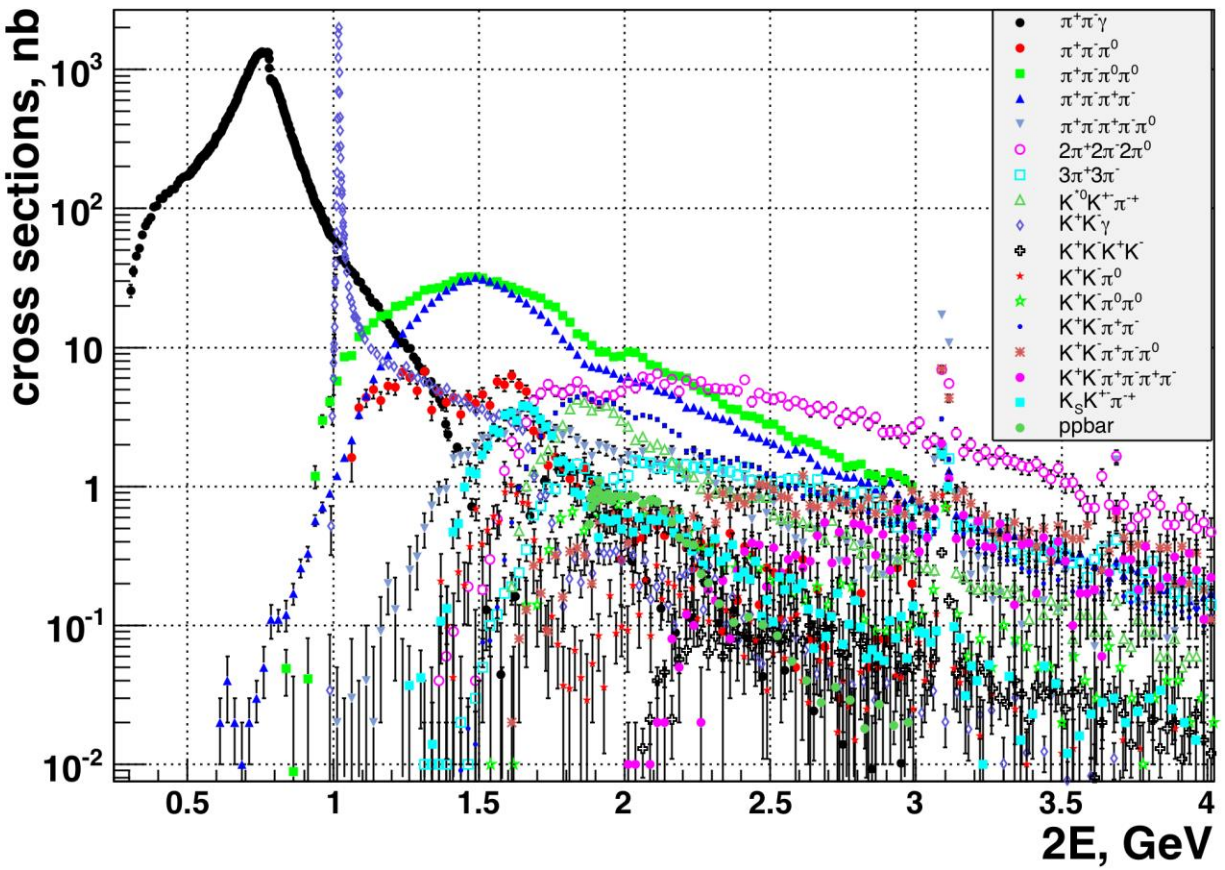
BABAR low-energy hadron cross sections

BABAR performs intensive study of e^+e^- annihilation at low energies using the ISR technique.





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

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

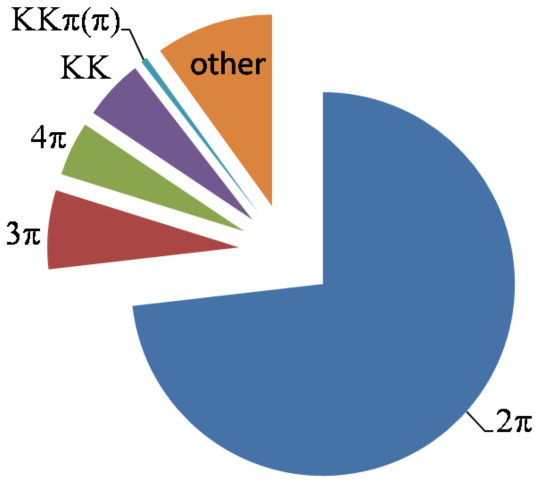
We present

- $e^+e^- \to \pi^+\pi^-\pi^0$. Update with full BABAR data set. 5-fold increase in statistics. Preliminary result.
- $e^+e^- \to 2(\pi^+\pi^-)\pi^0\pi^0\pi^0$, $e^+e^- \to 2(\pi^+\pi^-)\pi^0\pi^0\eta$. First measurement. Phys. Rev. D 103, 092001 (2021).
- $e^+e^- \to \pi^+\pi^-4\pi^0$, $e^+e^- \to \pi^+\pi^-3\pi^0\eta$. First measurement. Preliminary results.

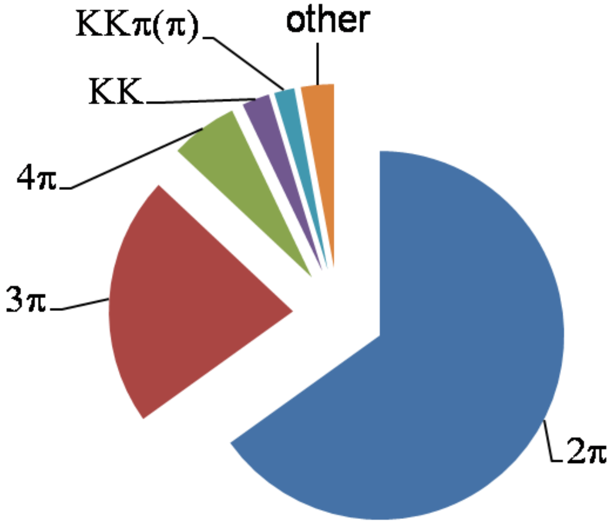
$e^+e^- \to \pi^+\pi^-\pi^0$

The process $e^+e^- \to \pi^+\pi^-\pi^0$ gives the second largest contribution into $a_\mu^{had,LO-VP}$ and its error.

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



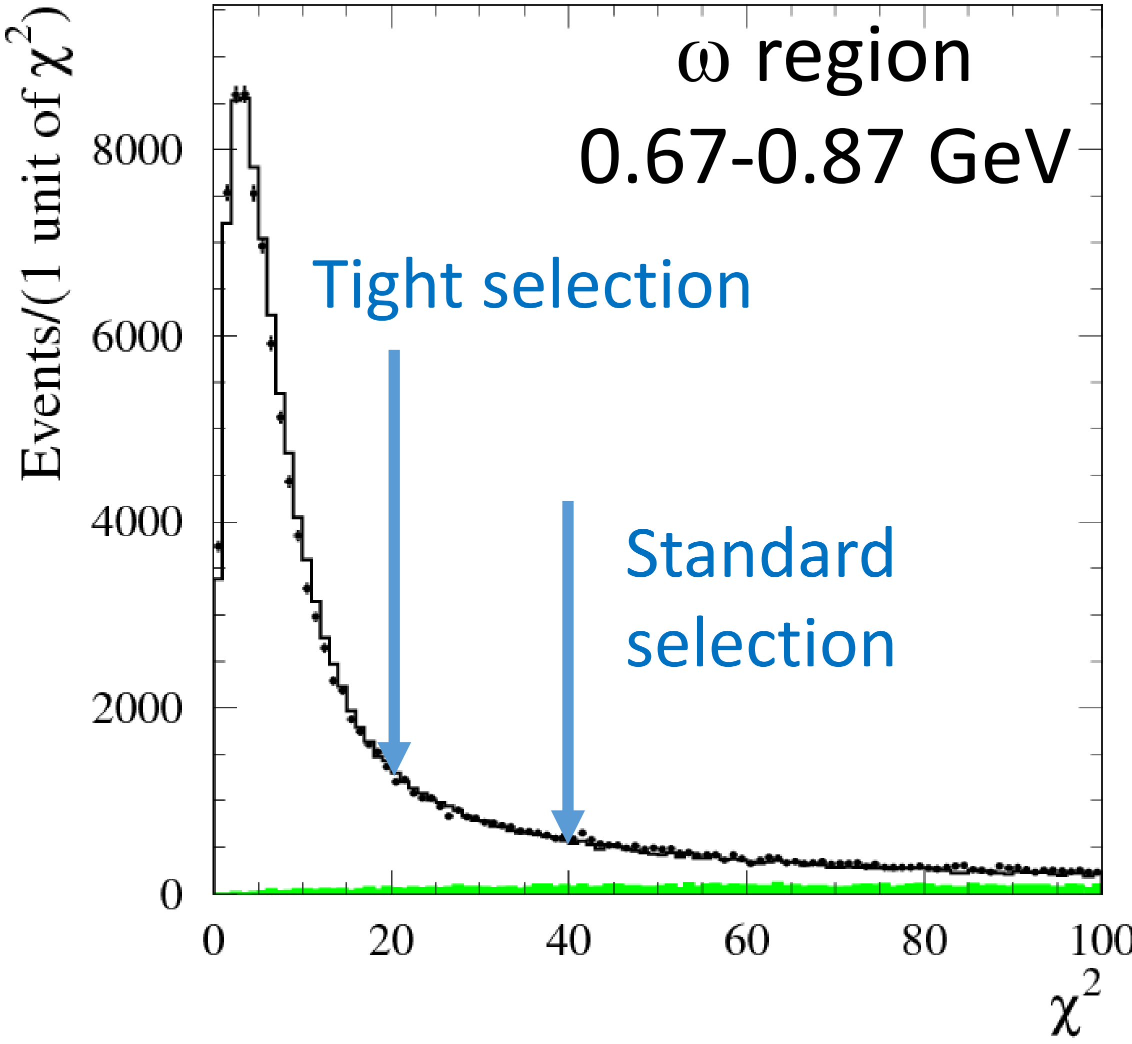
$a_\mu^{had,LO-VP}$ error squared



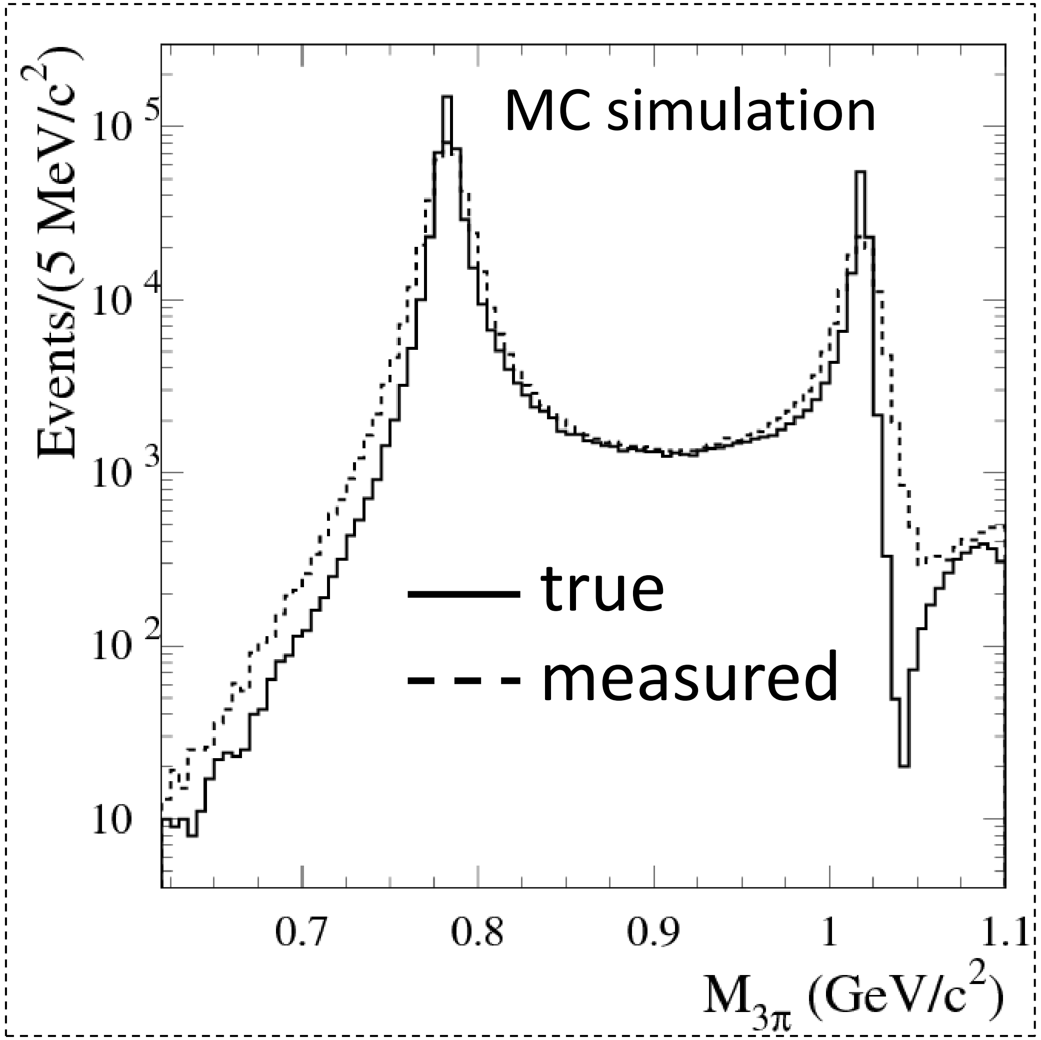
- ✓ Previous BABAR measurement (Phys. Rev. D 70 (2004) 072004) was based on 1/5 of the existing data set. The $e^+e^- \to \pi^+\pi^-\pi^0$ cross section was measured in the range 1.05-3 GeV.
- ✓ In the new analysis we measure the cross section also below 1.05 GeV, in the region of the ρ, ω, and ϕ resonances.
- ✓ Currently the $e^+e^- \to \pi^+\pi^-\pi^0$ contribution to $a_\mu^{had,LO-VP}$ is known with about 3% accuracy. We improve the accuracy to about 1.5%.

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

- All final particles are detected.
- Events are selected using a kinematic fit
- Several additional cuts decrease background by a factor of 2.
- Remaining ISR and $q\bar{q}$ background is subtracted using simulation normalized to data.
- Above 1.1 GeV there is a sizable FSR background from the $e^+e^- \to a_1\gamma, a_2\gamma$ processes. This background is estimated using pQCD with 100% uncertainty. Near 1.3 GeV it reaches about 8%.



$\pi^+\pi^-\pi^0$ mass spectrum below 1.1 GeV

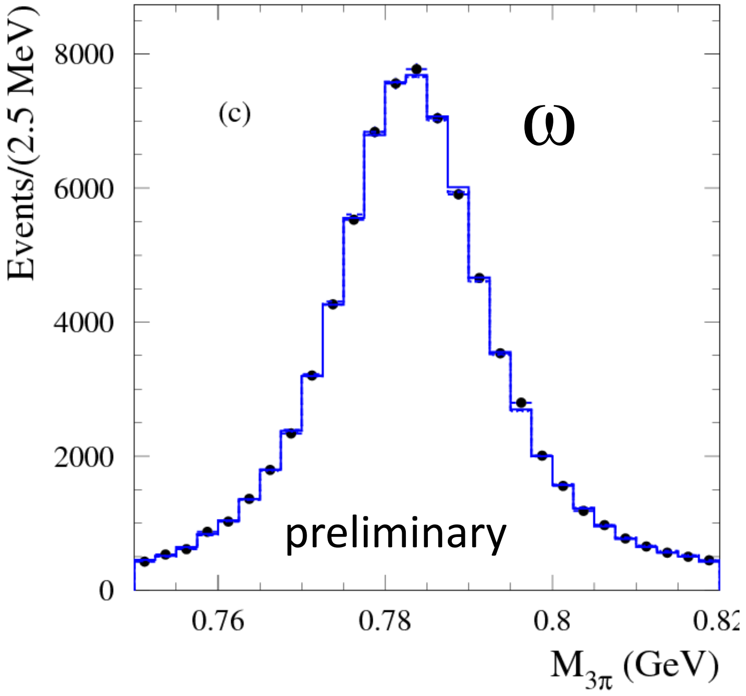


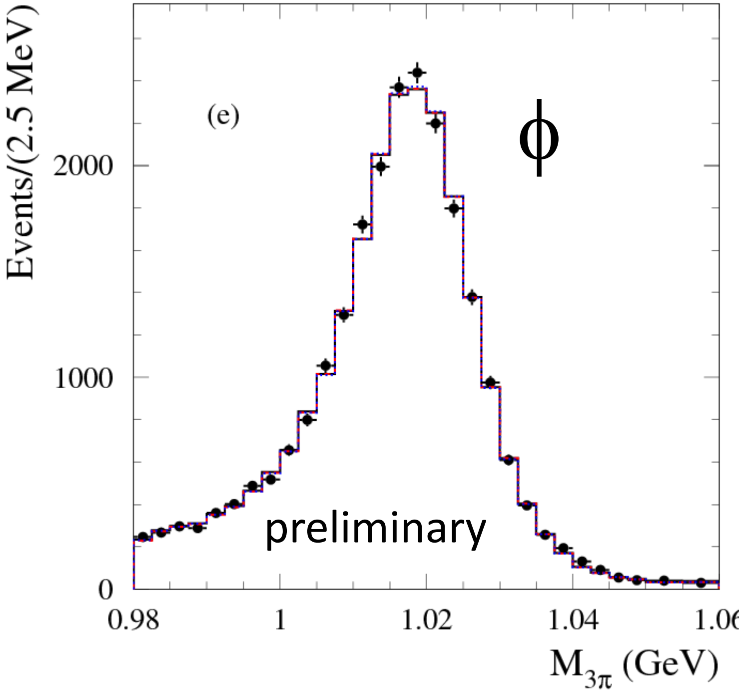
- Below 1.1 GeV, the mass spectrum has sharp structure; unfolding is required to obtain the true spectrum.
- The result depends strongly on the assumed mass resolution.
- The ω and ϕ widths are well known: use the data to correct the simulated resolution function.
- The tails of the resolution depend on χ^2 of the kinematic fit used for event selection: try more than one cut value.

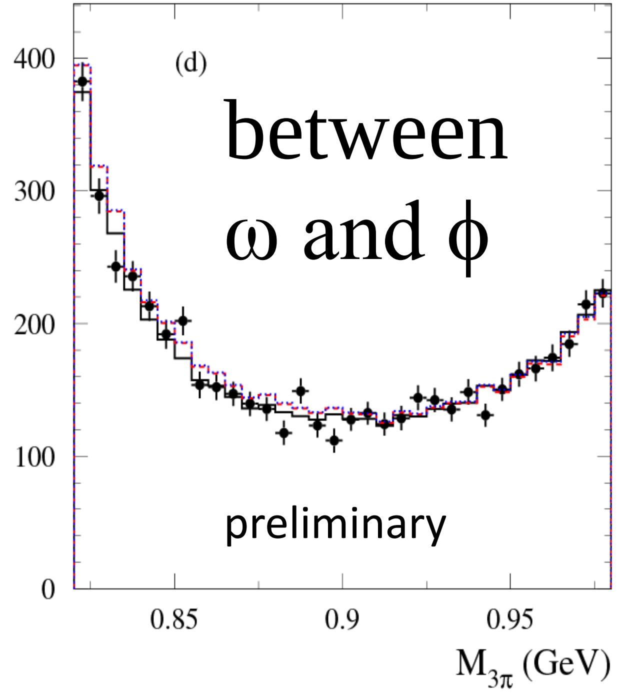
Fit to the 3π mass spectrum

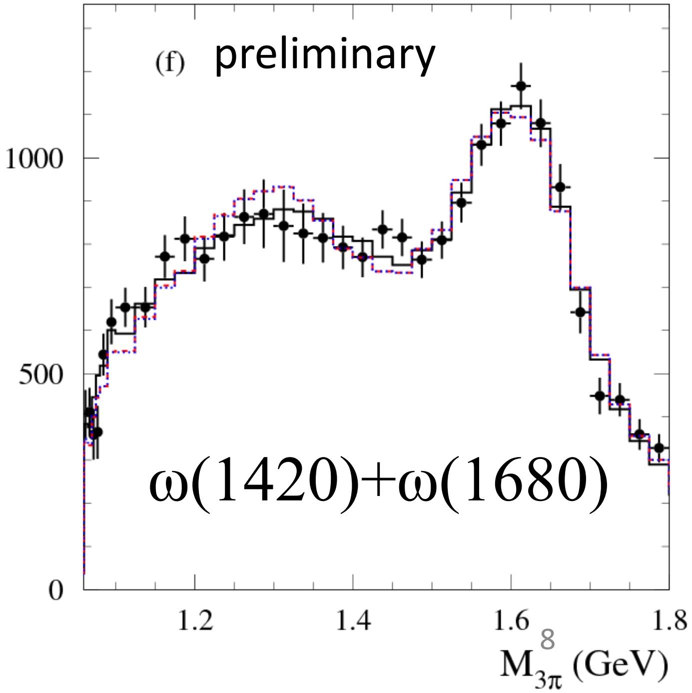
- The measured mass spectrum is fitted by the VMD model with $\omega(782)+\omega(1420)+\omega(1680)+\phi(1020)$ resonances and the rare $\rho(770)\to3\pi$ decay. The $\omega(782)$ and ϕ widths are fixed to PDG values.
- For $\chi^2 < 20$ (nominal result), we obtain a good fit with additional Gaussian smearing: $\sigma_s = 1.5\pm0.2$ MeV, $m_\omega - m_{PDG} = 0.042\pm0.055$ MeV, $m_\phi - m_{PDG} = 0.095 \pm 0.084$ MeV.
- For $\chi^2 < 40$ (cross check), we also need a Lorentzian smearing to describe the tails (its fraction is $(0.7\pm0.2)\%$, $\gamma=63\pm35$ GeV). The fit gives consistent results for other parameters.
- The data cannot be described without the $\rho(770)$.

Fit to the 3π mass spectrum ($\chi^2 < 40$)









———	Lorentzian smearing and $\rho \to 3\pi$,	χ^2/ν=136/127
– – – –	No Lorentzian smearing and no $\rho \to 3\pi$,	χ^2/ν=201/131
....	Lorentzian smearing and no $\rho \to 3\pi$,	χ^2/ν=180/129

Physical fit parameters

$$\Gamma(\omega \to e^+e^-)\mathcal{B}(\omega \to \pi^+\pi^-\pi^0) = (0.5698 \pm 0.0031 \pm 0.0082)\ \text{keV}$$
$$\Gamma(\phi \to e^+e^-)\mathcal{B}(\phi \to \pi^+\pi^-\pi^0) = (0.1841 \pm 0.0021 \pm 0.0080)\ \text{keV}$$

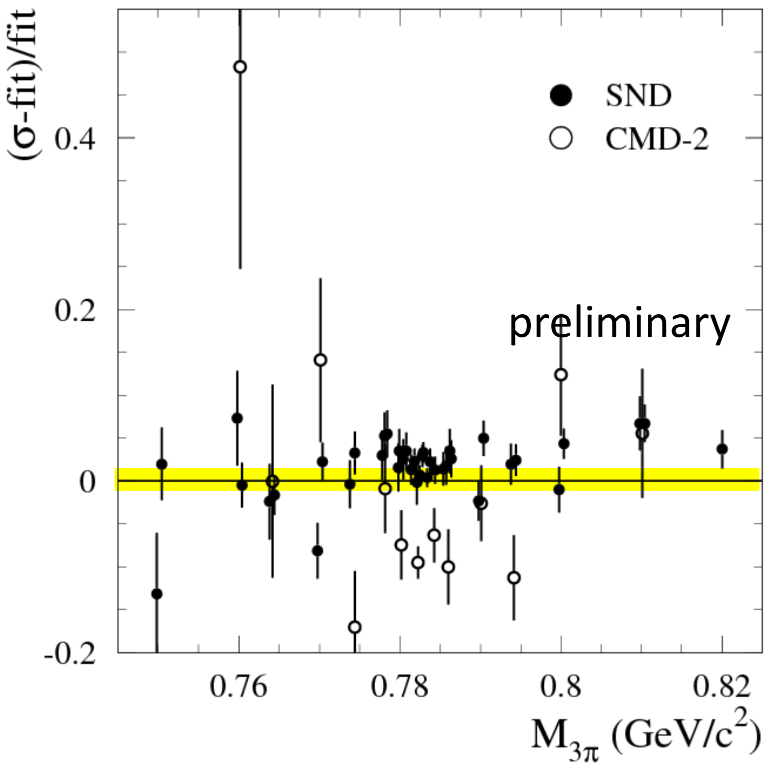
- The fitted parameters for ω and ϕ are in reasonable agreement with the world average values: 0.557±0.011 keV and 0.1925±0.0043 keV.

$$\mathcal{B}(\rho \to 3\pi) = (0.88 \pm 0.23 \pm 0.30) \times 10^{-4}$$
$$\phi_\rho = -(99 \pm 9 \pm 15)^\circ.$$

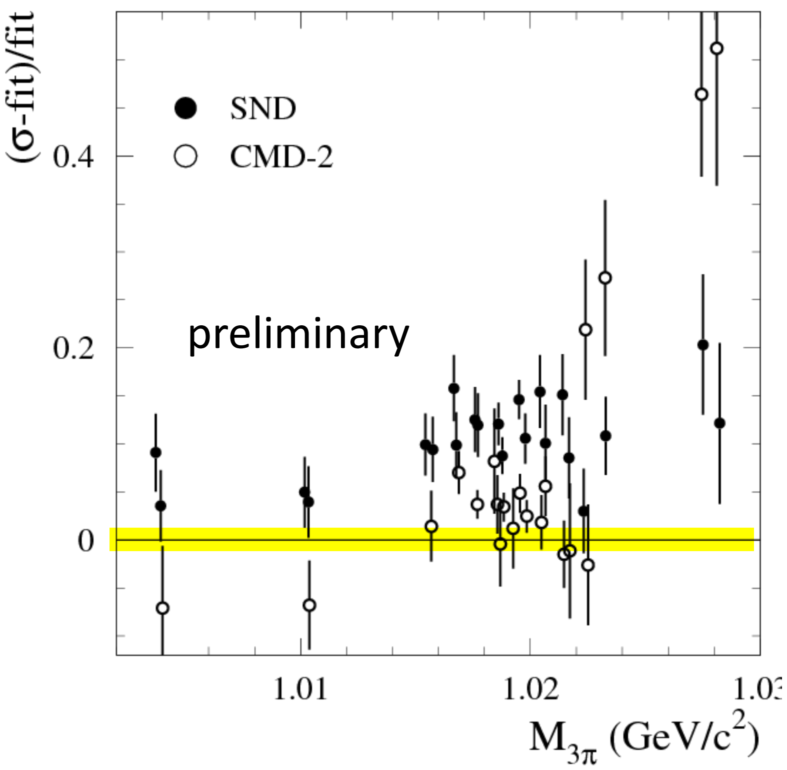
- The significance of ρ → 3π is greater than 6σ
- The BABAR results for B(ρ → 3π) and ϕ_ρ agree with the SND measurement: $B(\rho \to 3\pi) = (1.01^{+0.54}_{-0.36} \pm 0.34) \times 10^{-4}$ and $-(135^{+17}_{-13} \pm 9)^\circ$.

SND: Phys.Rev.D 68, 052006 (2003)

Comparison with existing cross section data



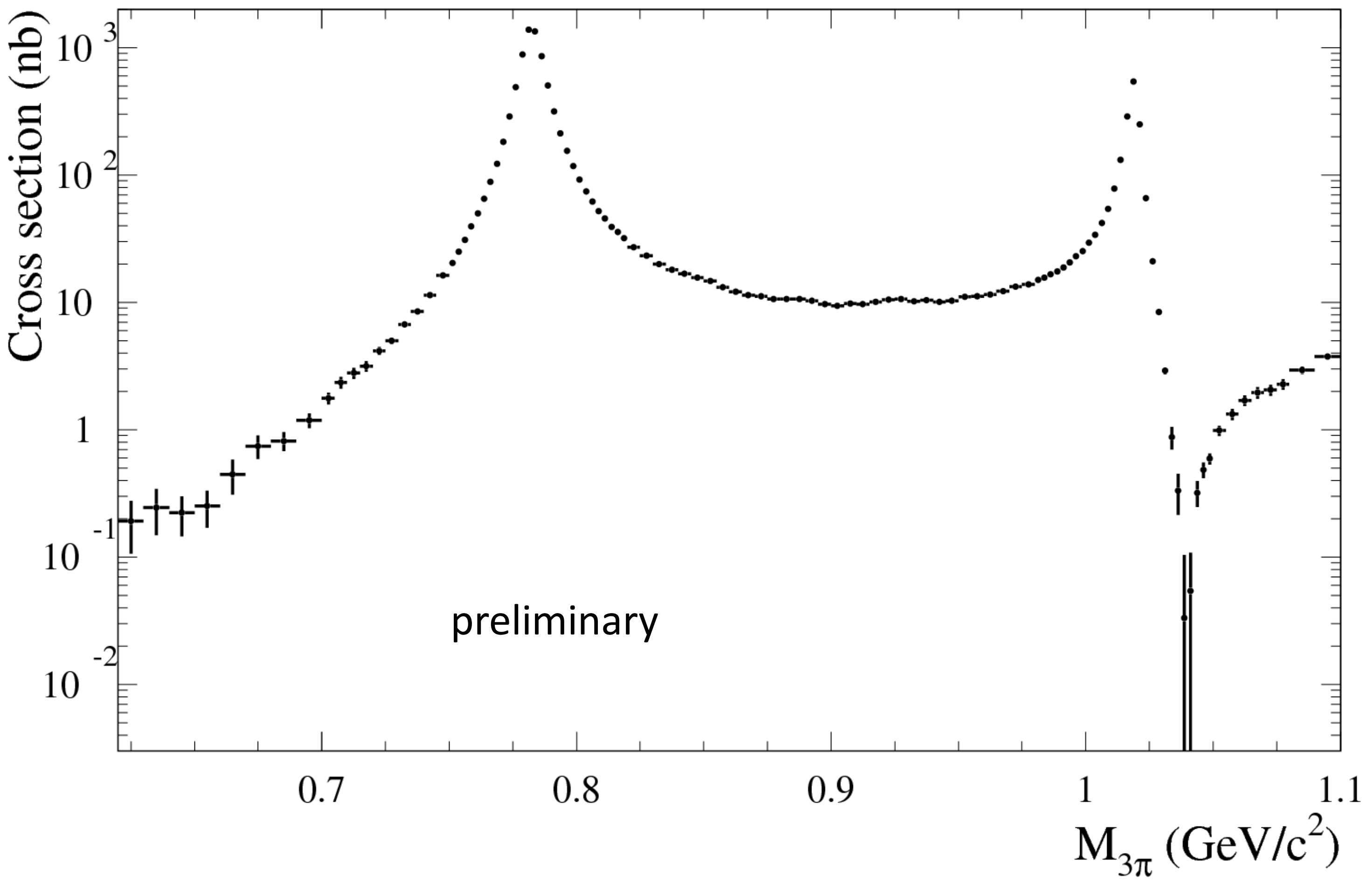
SND: Phys.Rev.D
68, 052006 (2003)
CMD-2: Phys.Lett.B
578, 285 (2004)



SND: Phys.Rev.D
63, 072002 (2001)
CMD-2: Phys.Lett.B
642, 203 (2006)

- ✓ At the ω the difference between the SND and BABAR is about 2%, well below the systematic uncertainty (3.4% for SND and 1.4% for BABAR). The CMD-2 points lie about 7% below zero. The CMD-2 statistical and systematic uncertainties are 1.8% and 1.3%, respectively. So, the difference between CMD-2 and BABAR is about 2.7σ.
- ✓ At the ϕ the CMD-2 and SND data with systematic uncertainties of 2.5% and 5%, respectively, lie about 3% and 11% higher than the fit to the BABAR data.

$e^+e^- \to \pi^+\pi^-\pi^0$ cross section below 1.1 GeV

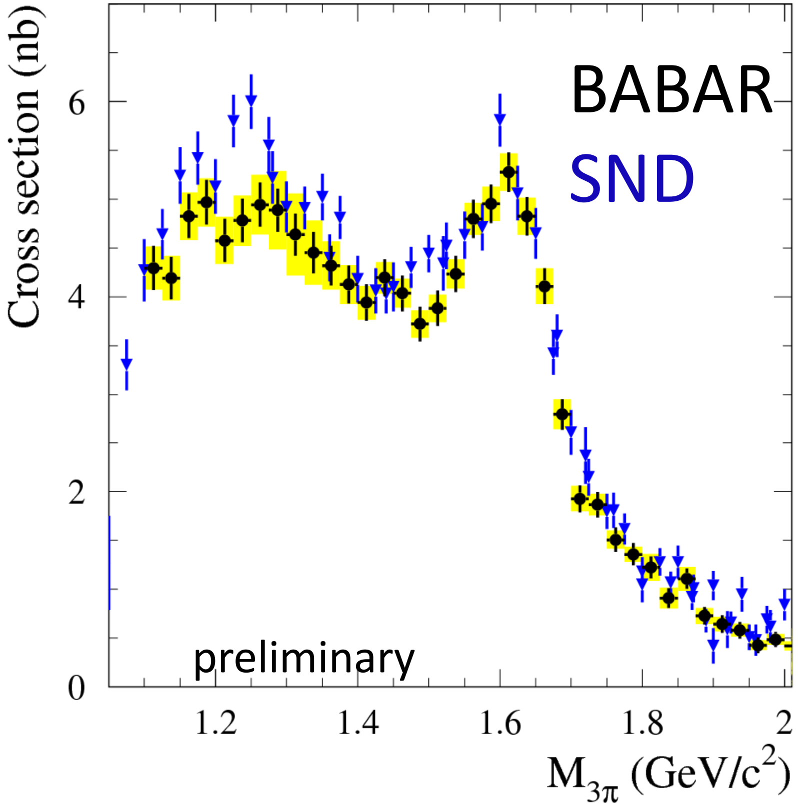


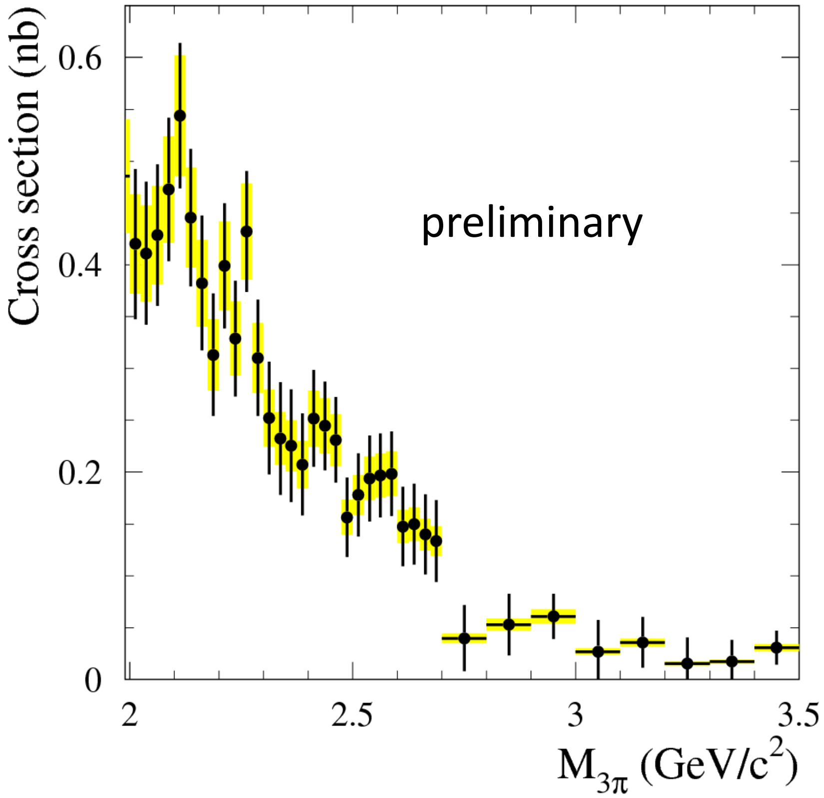
The parameters of the smearing function obtained from the VMD fit are used to correct the simulated resolution function.

The IDS (iterative, dynamically stabilized) method is used to perform unfolding. B.Malaescu, arXiv:0907.3791

The systematic uncertainty at resonance peaks is about 1.3%.

$e^+e^- \to \pi^+\pi^-\pi^0$ cross section above 1.1 GeV





Above 1.1 GeV there is no narrow structure, so no unfolding is performed.

The systematic uncertainty (4-15%) is dominated by the uncertainty of background subtraction.

The sizable difference between the SND *[Eur.Phys.J. C 80. 993 (2020)]* and BABAR measurements is observed near 1.25 GeV and 1.5 GeV. The SND systematic uncertainty is 4.4%.

$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ contribution to a_μ

$M_{3\pi}$ GeV/c^2	$a_\mu^{3\pi} \times 10^{10}$
0.62–1.10	$42.91 \pm 0.14 \pm 0.55 \pm 0.09$
1.10–2.00	$2.95 \pm 0.03 \pm 0.16$
< 2.00	$45.86 \pm 0.14 \pm 0.58$
< 1.80[1] DHMZ	$46.21 \pm 0.40 \pm 1.40$
< 1.97[50] KNT	46.74 ± 0.94
< 2[51] Y	44.32 ± 1.48

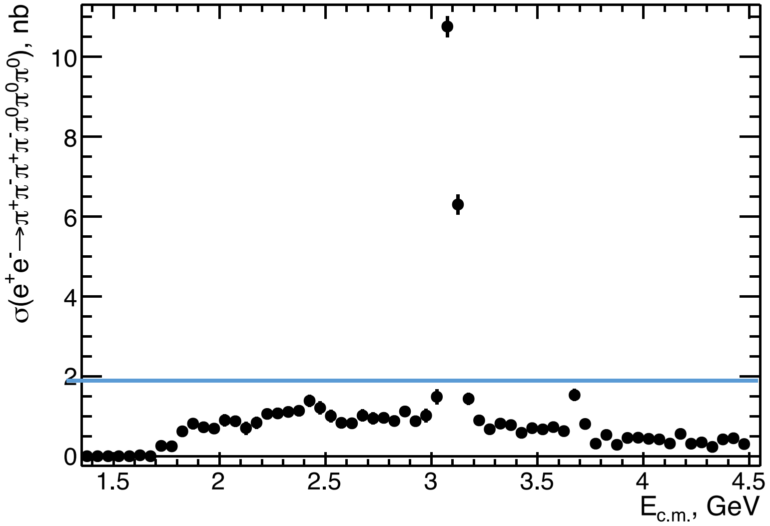
preliminary

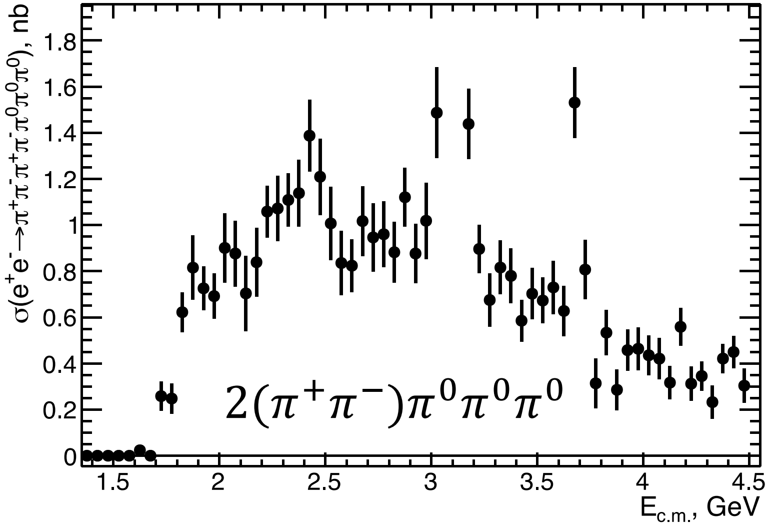
Uncertainty in $a_\mu^{3\pi}$ is improved by a factor of 2.

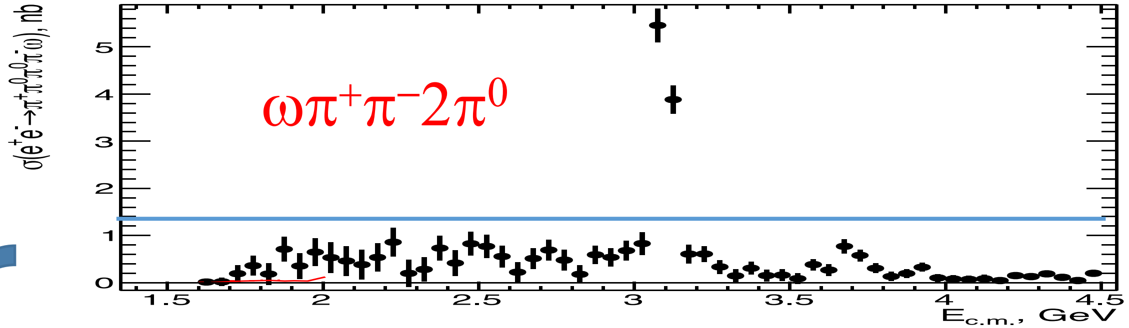
Cross sections for $e^+e^- \to 2(\pi^+\pi^-)\pi^0\pi^0\pi^0$

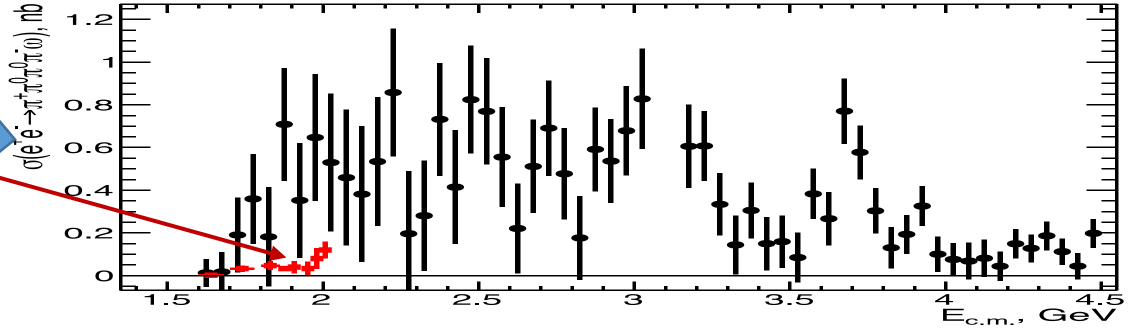
Phys. Rev. D 103, 092001 (2021)

- ✓ First measurement of this cross section.
- ✓ Systematic uncertainty is about 10%.
- ✓ Below 2.5 GeV the cross section is dominated by the previously measured intermediate states with η meson ($\omega\pi^0\eta$, $\pi^+\pi^-2\pi^0\eta$, $2(\pi^+\pi^-)\eta$) and $\omega\pi^+\pi^-2\pi^0$. Above 2.5 GeV, $(\rho\pi)\pi^+\pi^-2\pi^0$ channel is also seen.



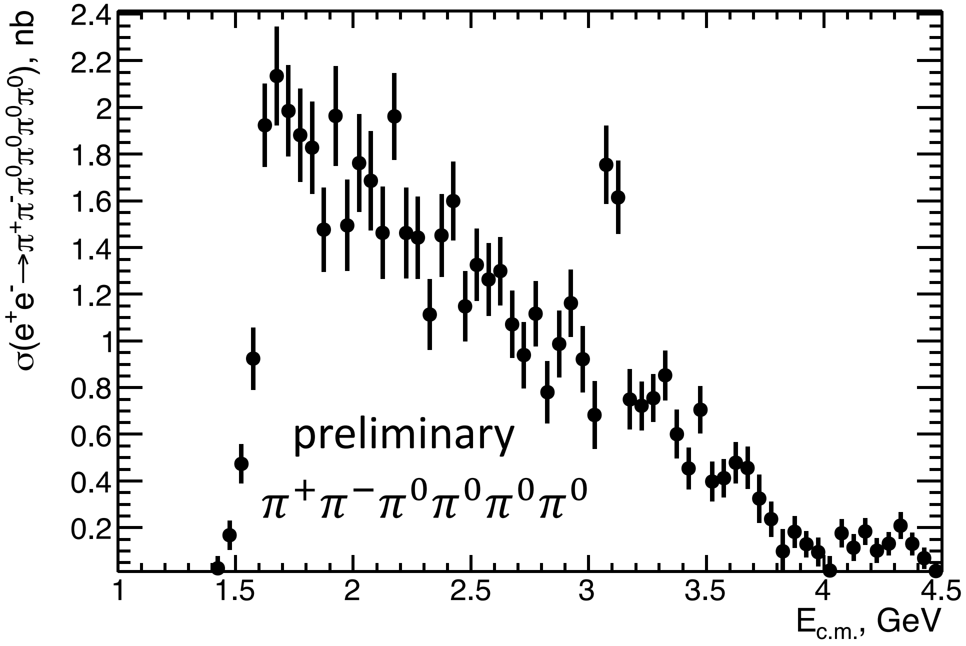




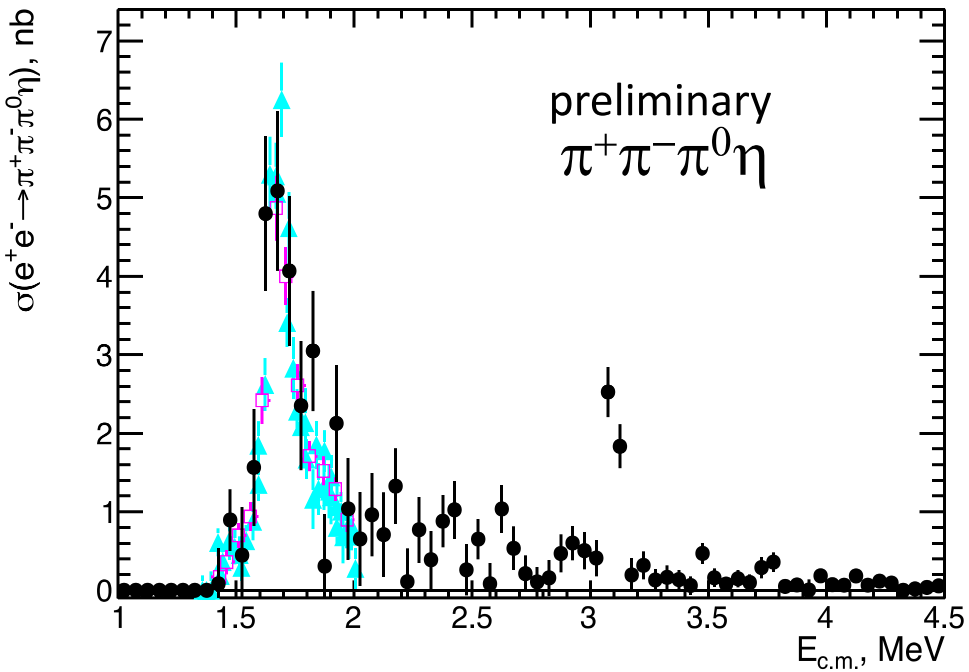


$\omega 2(\pi^+\pi^-)$ by CMD-3

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

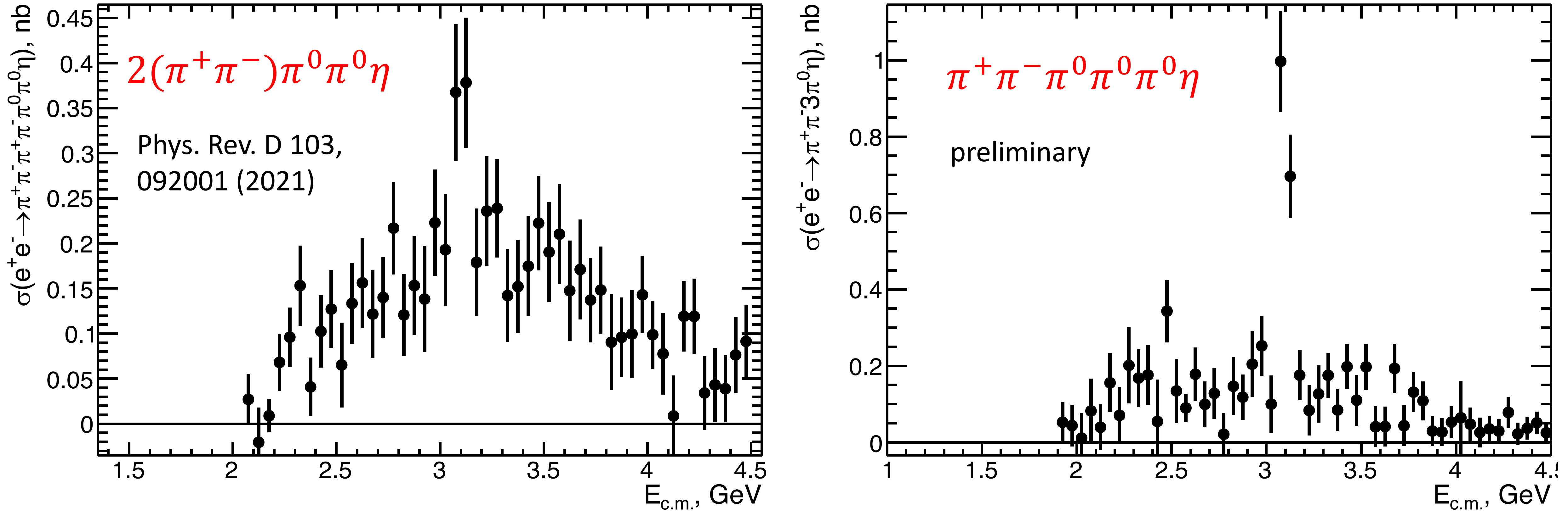


- ✓ The intermediate states $\pi^+\pi^-\pi^0\eta$, $\omega 3\pi^0$, $(\rho\pi)3\pi^0$, and probably $\rho^+\rho^-2\pi^0$ above 2.9 GeV are seen.
- ✓ Below 2 GeV the BABAR result on the $\pi^+\pi^-\pi^0\eta$ cross section agrees with previous SND and CMD-3 measurements.



- ✓ First measurement
- ✓ Systematic uncertainty is about 10%.

$e^+e^- \to 2(\pi^+\pi^-)\pi^0\pi^0\eta$ and $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0\eta$



No previous measurements

Summary

- The cross section for the process $e^+e^- \to \pi^+\pi^-\pi^0$ has been measured from the 0.62 to 3.5 GeV, using the ISR method. Near the maxima of the ω and ϕ resonances, it is measured with a systematic uncertainty of 1.3%.
- The leading-order hadronic contribution to the muon magnetic anomaly $(45.86 \pm 0.14 \pm 0.58) \times 10^{-10}$ from the $e^+e^- \to \pi^+\pi^-\pi^0$ channel (E<2 GeV) has been calculated. Its accuracy has been improved by a factor of about 2.
- The cross sections for the processes of $e^+e^- \to 2(\pi^+\pi^-)\pi^0\pi^0\pi^0$, $\pi^+\pi^-4\pi^0, 2(\pi^+\pi^-)\pi^0\pi^0\eta, \pi^+\pi^-3\pi^0\eta$ have been measured for the first time.