Recent studies of e^+e^- annihilation into hadrons at low energies via ISR at *BABAR*

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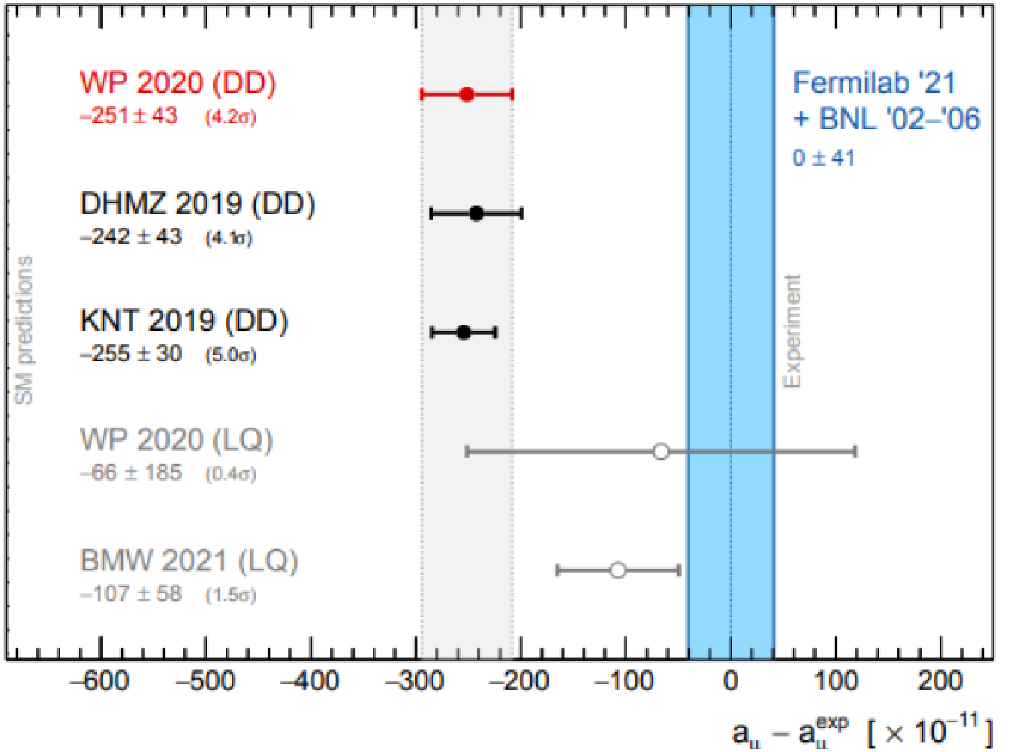
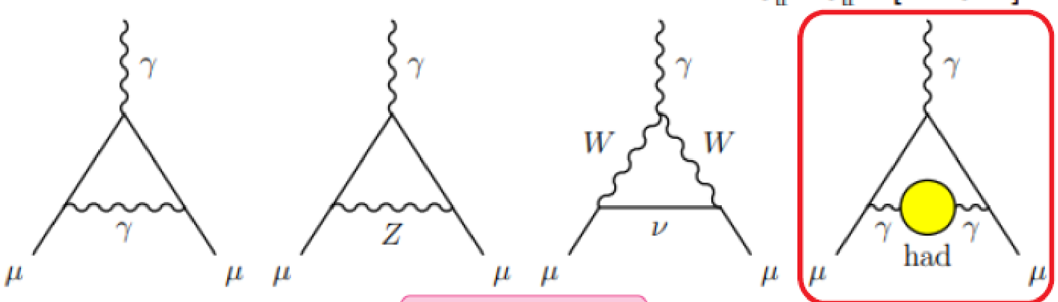
on behalf of the BABAR Collaboration

Meson 2023, June 23th, 2023

Motivation: $(g-2)_\mu$





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- Muon anomalous magnetic moment
$$a_\mu = \frac{g_\mu - 2}{2}$$
- Precise test of the Standard Model
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$
- Long-standing discrepancy (4.2σ) between theory and experiment
- New tensions between dispersive and Lattice QCD
- Main uncertainty of rising from hadronic loop contribution

source	contribution ($\times 10^{-11}$)	
	value	error
a_μ^{QED}	116 584 718.93	±0.10
a_μ^{EW}	53.6	±1.0
a_μ^{Had}[LO]	**6931**	**±40**
a_μ^{Had}[NLO]	-98.3	±0.7
a_μ^{LBL}[NLO]	92	±18
a_μ^{SM}	116 591 810.1	±43.9
a_μ^{exp}	116 592 061	±41
a_μ^{exp} - a_μ^{SM}	4.2σ 251	±59

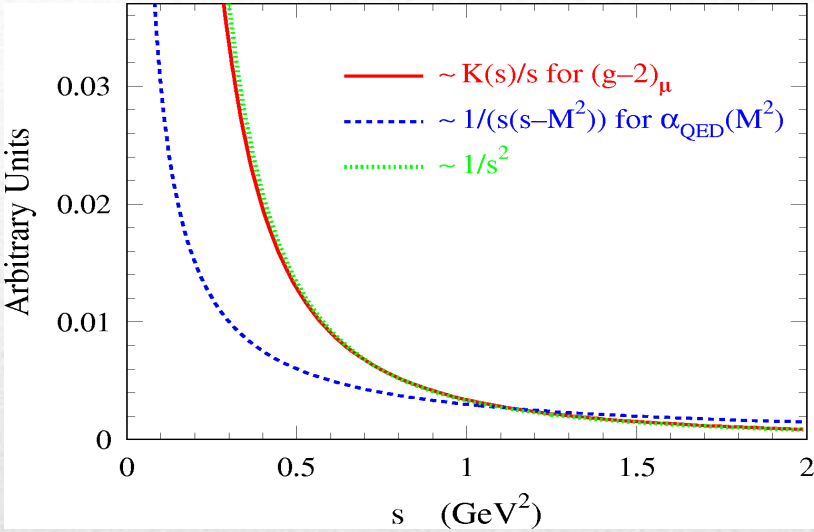
Hadronic Vacuum Polarization

Dominated by the Hadronic Vacuum Polarization LO

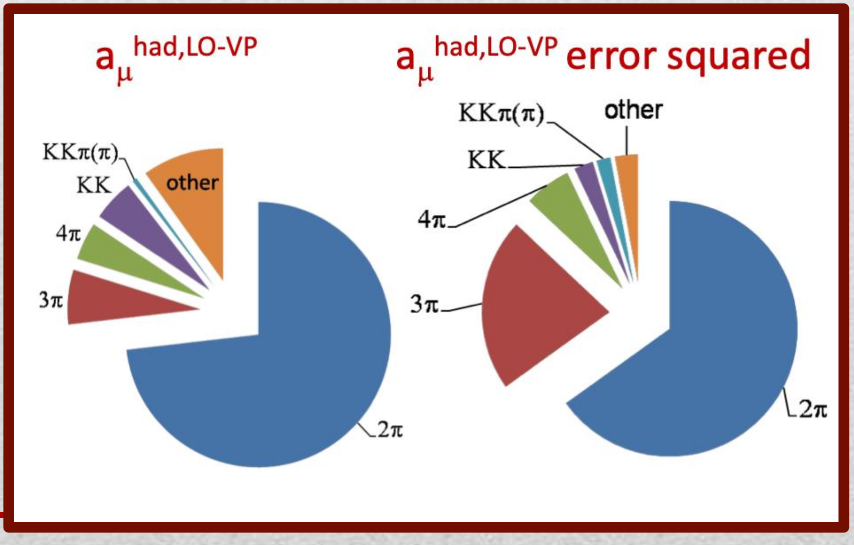
Can be calculated by using dispersion relations

$$a_\mu^{Had} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma^0 [e^+e^- \to \text{hadrons}]}{\sigma^0 [e^+e^- \to \mu^+\mu^-]}$$



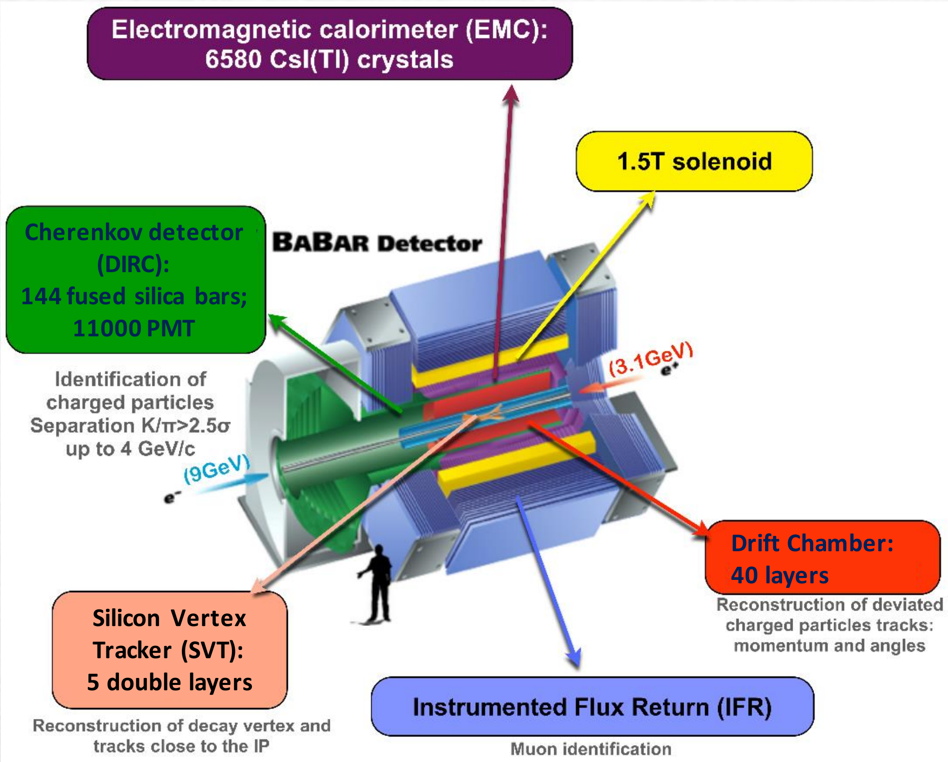
$\sigma^0 [e^+e^- \to \text{hadrons}]$ can be measured experimentally as a sum over exclusive channels

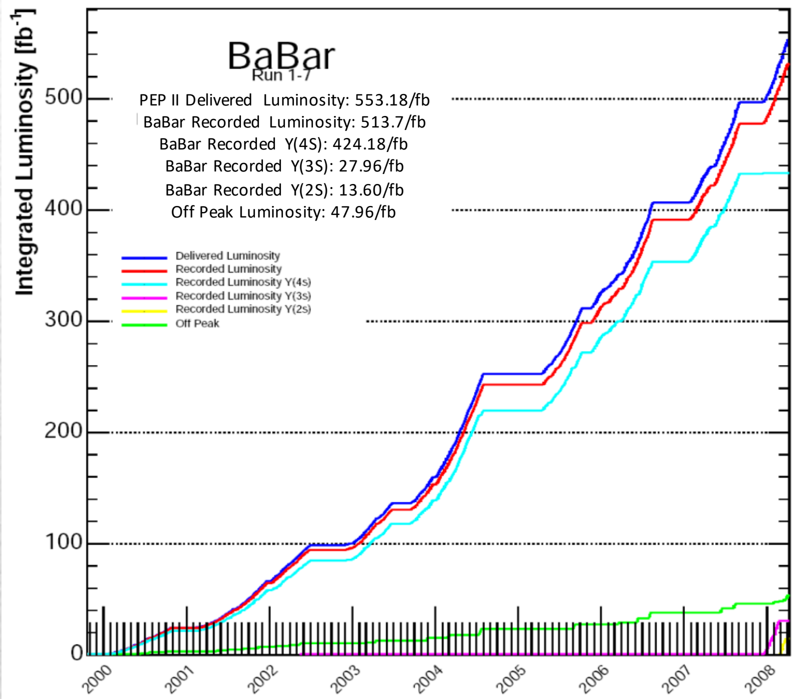


The *BaBar* experiment

The *BaBar* detector was located at the interaction point of PEP II at SLAC

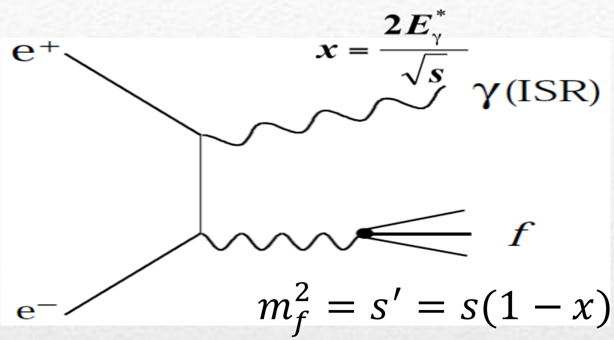
Asymmetric e^+e^- collider, mostly at $\sqrt{s} \sim 10.58\ \mathrm{GeV}$





$\int L\,dt \sim 469\ \mathrm{fb}^{-1}$ close to the $\Upsilon(4S)$ peak

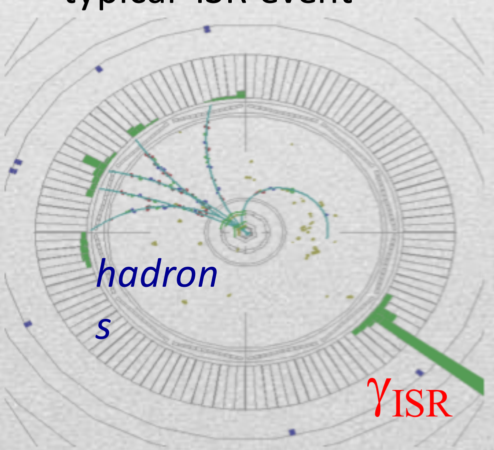
Initial State Radiation



$$\frac{d\sigma_{e^+e^-\to f\gamma}(s,m_f)}{dm_f\, d\cos\theta_\gamma^*} = \frac{2m_f}{s} W(s,x,\theta_\gamma^*)\cdot\sigma_{e^+e^-\to f}(m_f)$$

- The hadronic cross section $e^+e^- \to f$ can be extracted from the ISR cross section $e^+e^- \to \gamma f$.
- The radiator function *W(s,x)* is calculated in QED with accuracy better than 1% level

BABAR display of a typical ISR event

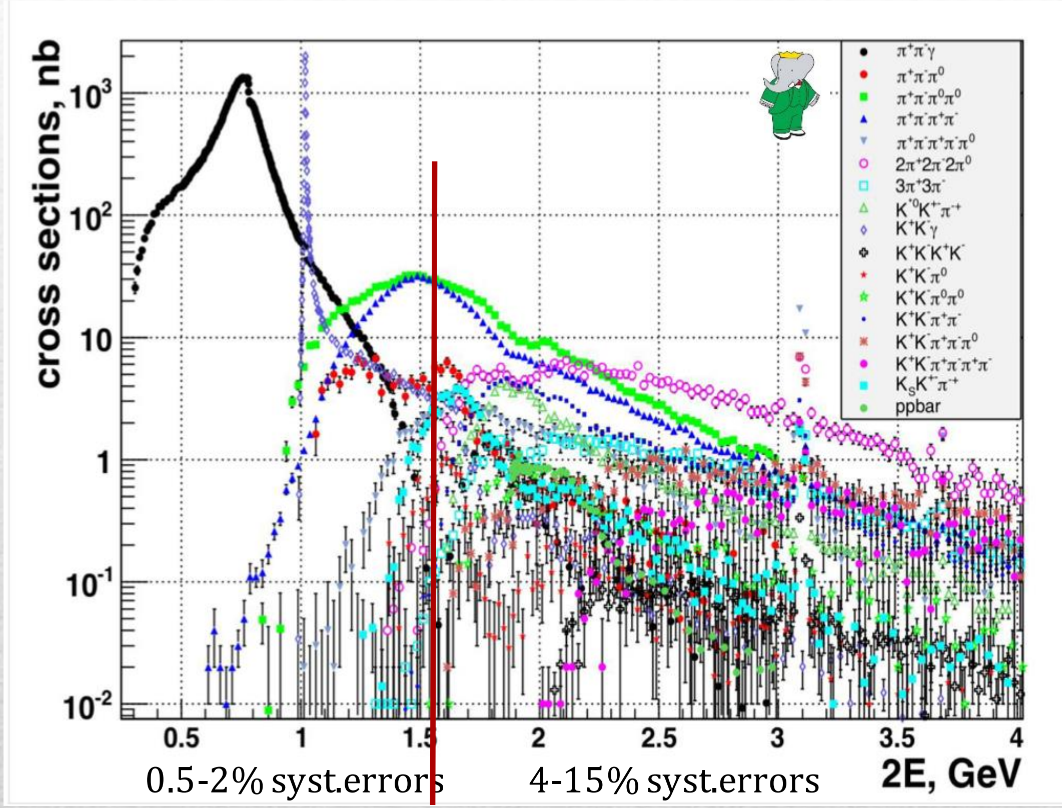


Common ISR analysis strategy

- Tagged analysis (E_γ^*>3 GeV)
- Back-to-back topology btw ISR γ and the rest of the event
- $\pi/K/p$ discrimination based on dE/dx e Cherenkov angle
- Kinematic fit for 4-momentum conservation
- Fitted χ^2 used for signal selection and background subtraction
- Detector acceptances and selection efficiencies estimated with MC simulation

The BaBar ISR program for light hadrons

- 30 publications for more than 40 final states studied
- Almost any channel from 2 to 7 light hadrons in the final state
- Many first measurements and significant precision improvement in most cases
- Discoveries (*e.g.* $\phi(2170)$ in $e^+e^- \to \phi(1020) f_0(980)$)
- Most precise measurement of $e^+e^- \to \pi^+\pi^-$



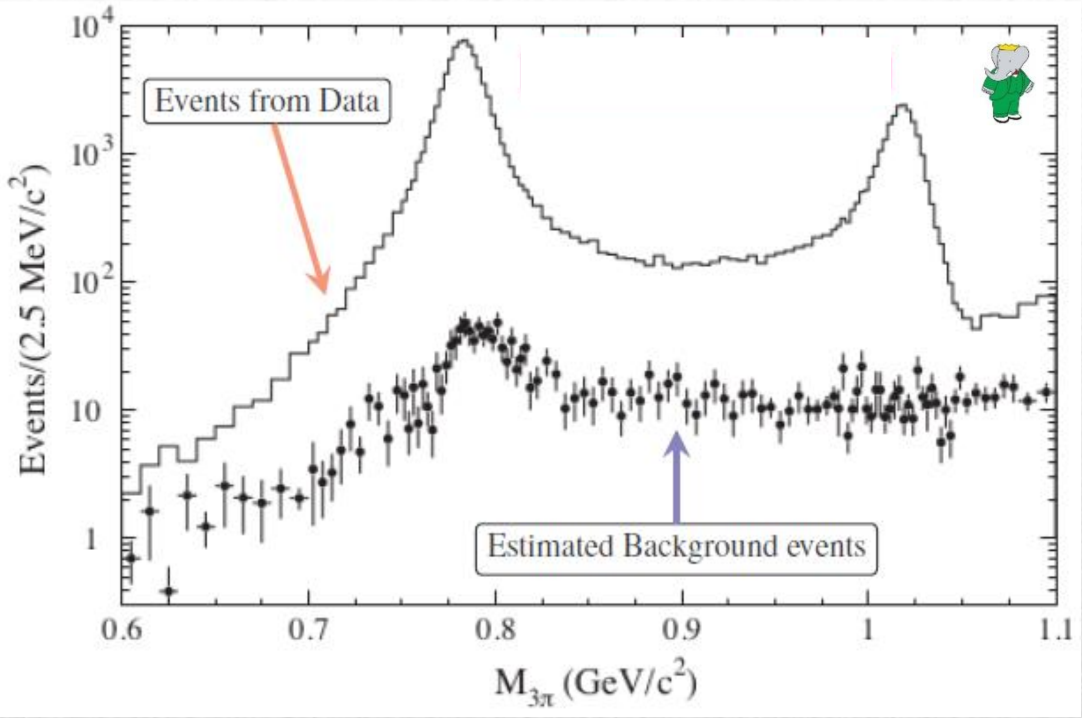
Study of the process $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ using initial state radiation with BaBar

BaBar coll., PRD104, 112003 (2021)

The process $e^+e^- \to \pi^+\pi^-\pi^0$ at BaBar

The 2nd largest contribution mode, $e^+e^- \to 3\pi$, ~7% to a_μ^{Had} but ~19% to its uncertainty

The relative uncertainty on the 3π channel is over 3%, almost 5 times larger than the 2π channel



The 3π channel was analyzed with the full BaBar dataset, 469 fb^{-1},

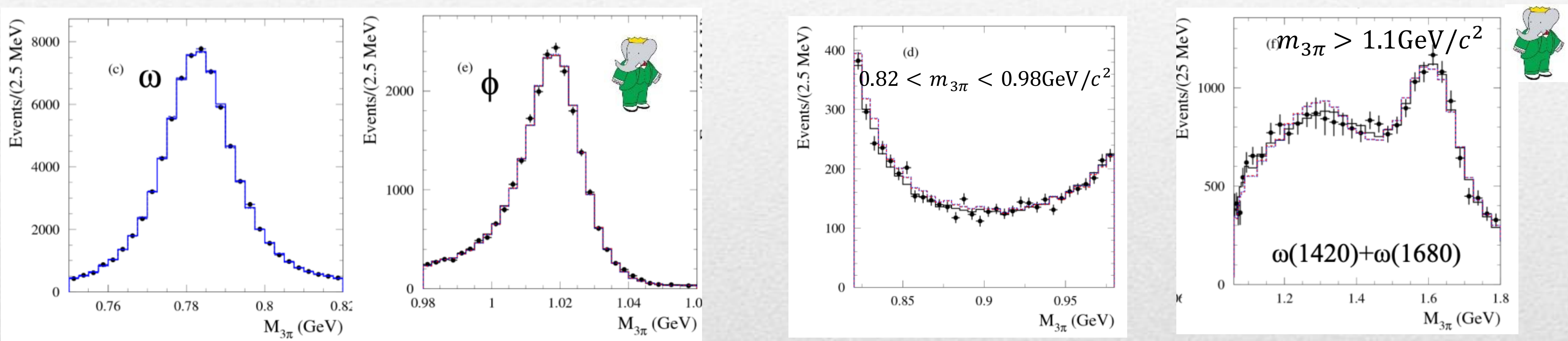
- ISR photon: with highest energy over 3 GeV,
- Require only 2 "good" tracks with opposite charge,
- At least 2 additional good photons, with $m_{\gamma\gamma} \in (0.10, 0.17)$ GeV
- Kinematic fit, and further cuts to suppress backgrounds

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

The fit to the measured mass spectrum is based on the VMD model with

$$\omega(782) + \omega(1420) + \omega(1680) + \phi(1020) + \rho(770)$$

The true spectrum is smeared to account for data-MC difference in the mass resolution, and then multiplied by the transfer matrix obtained from simulation for the unfolding



- Parameters fitted for ω and ϕ in good agreement with world average

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

PDG: $\Gamma_\omega \times \mathcal{B} = 0.557 \pm 0.011$ keV
$\Gamma_\phi \times \mathcal{B} = 0.1925 \pm 0.0043$ keV

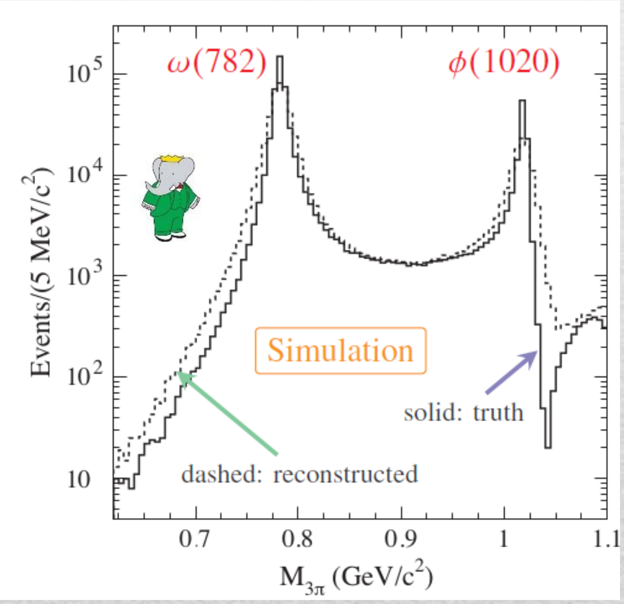
- The ρ → 3π decay needed to describe the data
- The significance of ρ → 3π is greater than 6σ
- In agreement with SND PRD68, 052006 (2003)

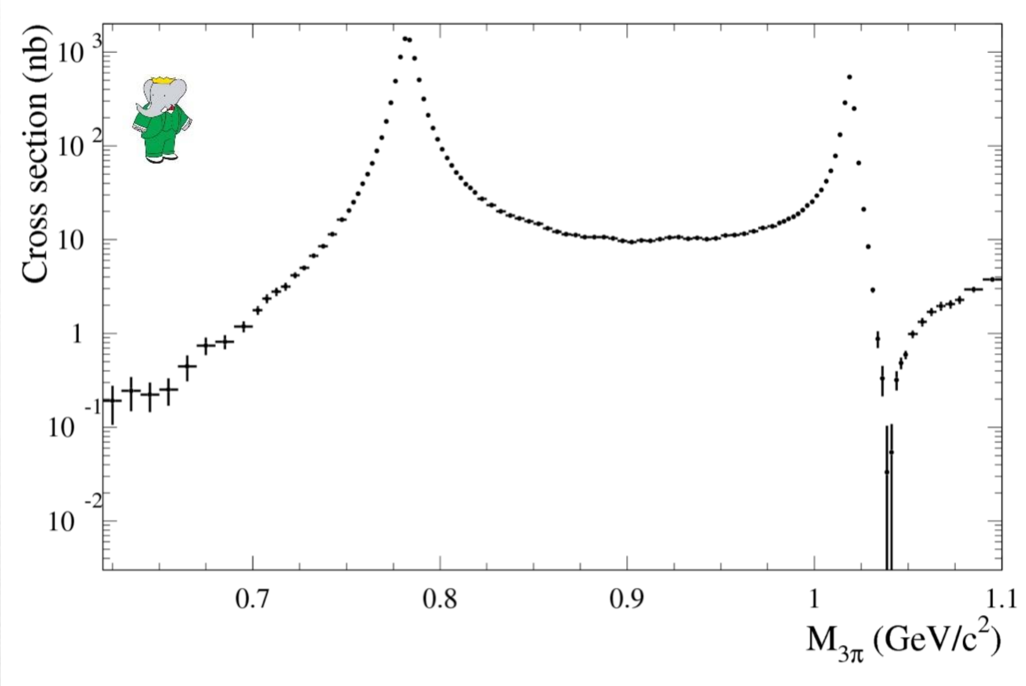
	$BF(\rho\to 3\pi)\times 10^4$	ϕ (∘)
BABAR	$0.88 \pm 0.23 \pm 0.30$	$-(99 \pm 9 \pm 15)$
SND	$1.01^{+0.54}_{-0.36} \pm 0.34$	$-(135^{+17}_{-13} \pm 9)$

Cross section below 1.1 GeV

Sharp structure of mass spectrum from resonances, over 4 orders of magnitude below 1.1 GeV. It is essential to unfold the detect efficiency effects with the (iterative, dynamically stabilized) method B. Malaescu, arXiv:0907.3791

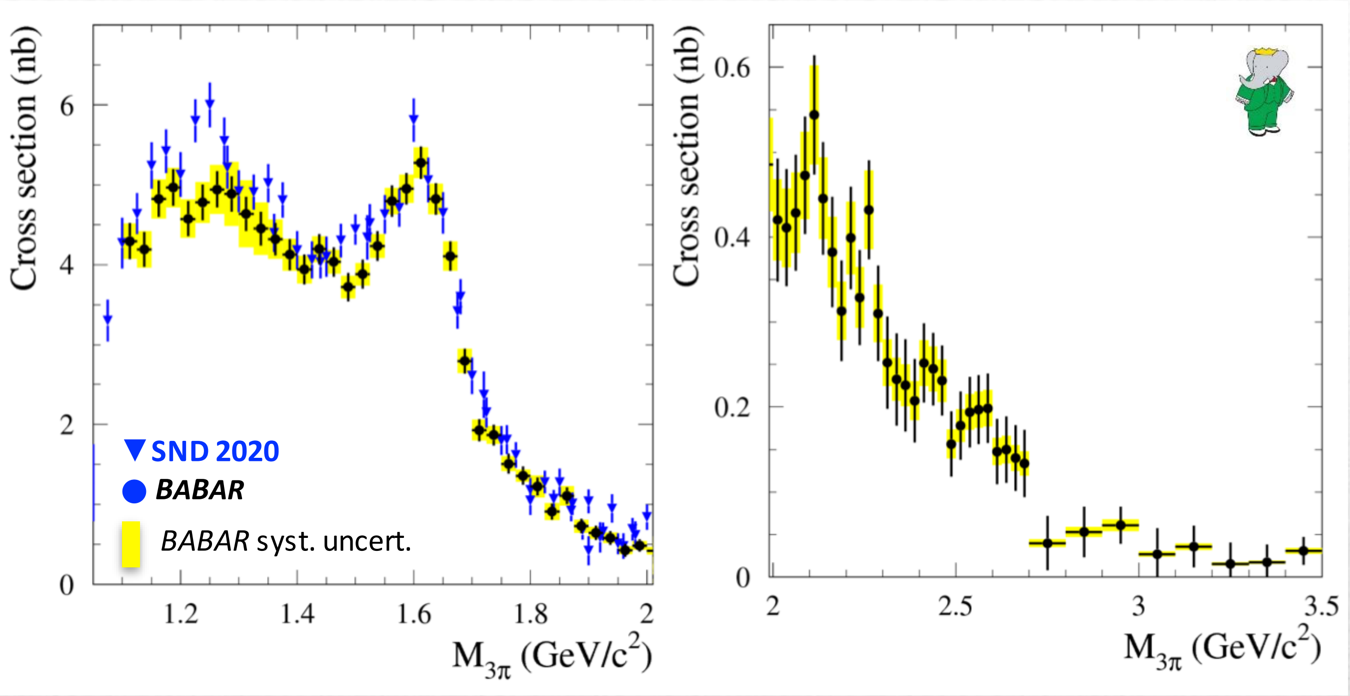
$$\frac{dN}{dm} = \sigma_{3\pi}(m)\frac{d\mathcal{L}}{dm}R\,\varepsilon$$





- Bin-width in the peaks regions: 2.5 MeV
- Systematic uncertainties at resonance peaks amount to about 1.3 % (most precise results)

Cross section above 1.1 GeV



No narrow structures
Bin size 25 MeV (100 MeV for $m_{3\pi} > 2.7$ GeV)
=> no need for unfolding

Systematic uncertainties (4-15%) dominated by background subtraction

- SND 2020: EPJC80, 993 (2020)
- Sizable difference between SND and BABAR data near 1.25 and 1.5 GeV, general agreement elsewhere
- SND systematic uncertainties are 4.4%

Result for $a_\mu^{3\pi}$

TABLE VI. Values of $a_\mu^{3\pi}$ for different mass intervals. The first three rows represent the *BABAR* result, while the last three are the calculations [1,49–51] based on previous $e^+e^- \to \pi^+\pi^-\pi^0$ measurements.

$M_{3\pi}$ 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	$45.86 \pm 0.14 \pm 0.58$
<1.8 [1]	$46.21 \pm 0.40 \pm 1.40$
<1.97 [49]	46.74 ± 0.94
<2 [50]	44.32 ± 1.48
<1.8 [51]	$46.2 \pm 0.6 \pm 0.6$

TABLE VII. Contributions to the systematic uncertainty in $a_\mu^{3\pi}(0.62 < M_{3\pi} < 1.1\ \mathrm{GeV}/c^2)$ from different effects.

Effect	Uncertainty (%)
Luminosity	0.4
Radiative correction	0.5
Detection efficiency	1.1
MC statistics	0.15
Background subtraction	0.073
Gaussian smearing	0.0007
Lorentzian smearing	0.003
Unfolding procedure	0.045
Total	1.3

$$a_\mu^{3\pi} = (45.86 \pm 0.14 \pm 0.58) \times 10^{-10}$$

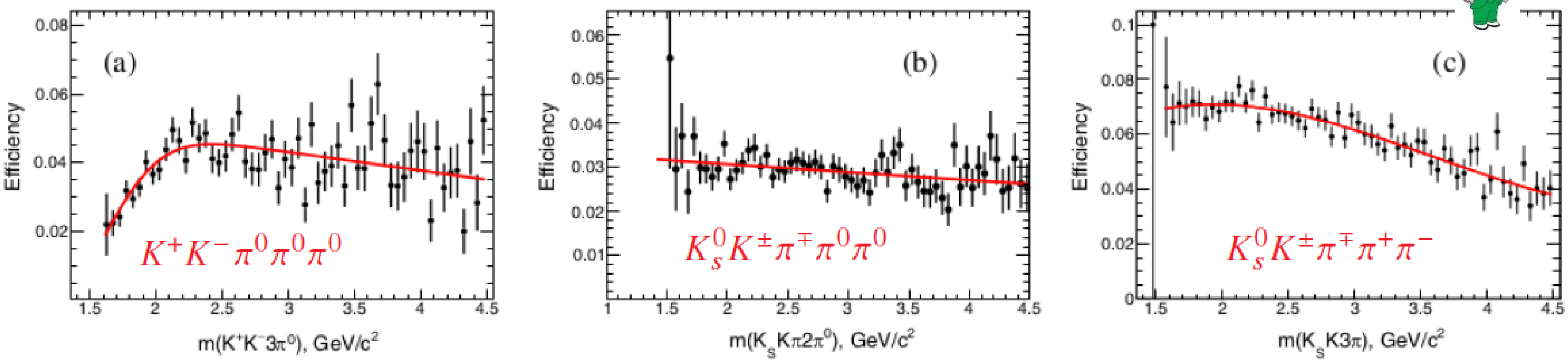
- LO hadronic contribution to muon anomaly magnetic moment is calculated with the measured cross section below 2.0 GeV
- Agreement with calculation based on previous measurements, more precise by a factor of ~2
- Previous relative uncertainty on the 3π mode is over 3%.

Study of the reactions $e^+e^- \rightarrow K^+K^-\pi^0\pi^0\pi^0$, $e^+e^- \rightarrow K_S^0K^\pm\pi^\mp\pi^0\pi^0$, and $e^+e^- \rightarrow K_S^0K^\pm\pi^\mp\pi^+\pi^-$ at center-of-mass energies from threshold to 4.5 GeV using initial-state radiation

BaBar coll., PRD107, 072001 (2023)

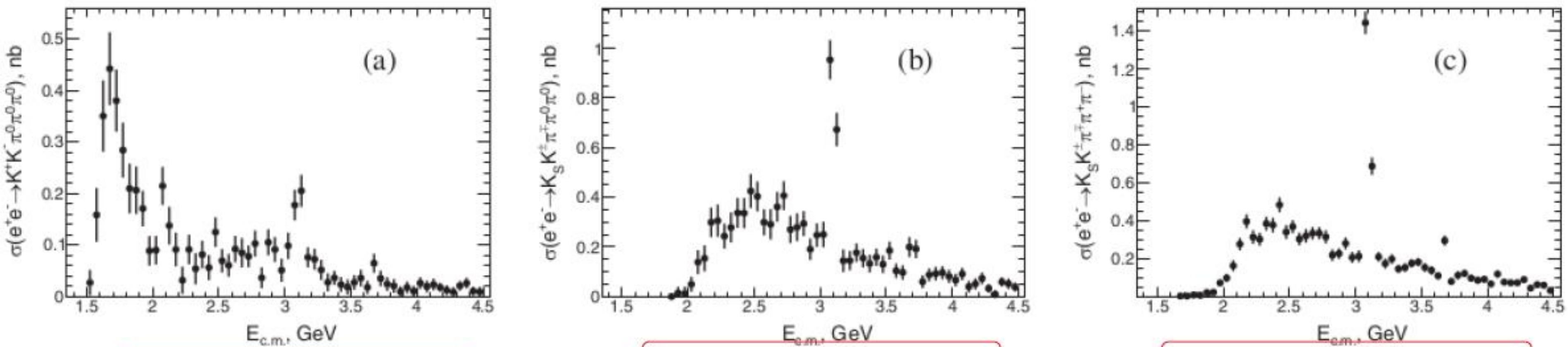
The process $e^+e^- \to 2K3\pi$ at BaBar

invariant-mass-dependent reconstruction efficiency



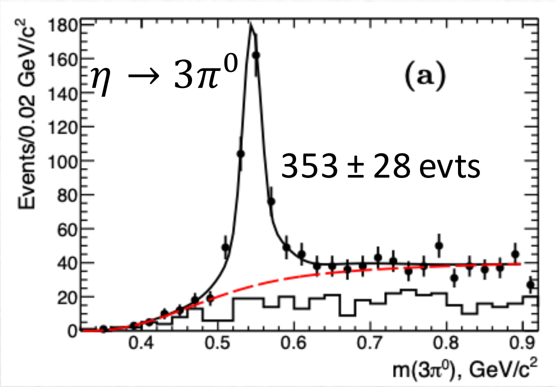
- Three channels for the $2K3\pi$ mode measured at BaBar for the first time: $K^+ K^- \pi^0 \pi^0 \pi^0$, $K_S^0 K^\pm \pi^\mp \pi^0 \pi^0$, and $K_S^0 K^\pm \pi^\mp \pi^+$
- Main motivations:
  - systematic deviation seen exclusive cross sections near 2 GeV and pQCD
  - direct measurement of the final states reduces the need of isospin relations for a_μ
  - study of intermediate states, look for new states or decay modes
- Only $K^+ K^- \pi^+ \pi^- \pi^0$ has been studied previously (PRD76 (2007) 092005),
- Similar technique used as above

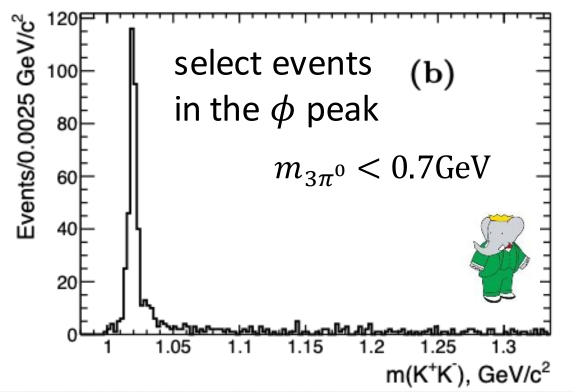
Cross sections



	$K^+K^-\pi^0\pi^0\pi^0$	$K_S^0K^\pm\pi^\mp\pi^0\pi^0$	$K_S^0K^\pm\pi^\mp\pi^+\pi^-$
signal events:	1230	2658	6582
uncertainty:	~10%	~10%	~8%

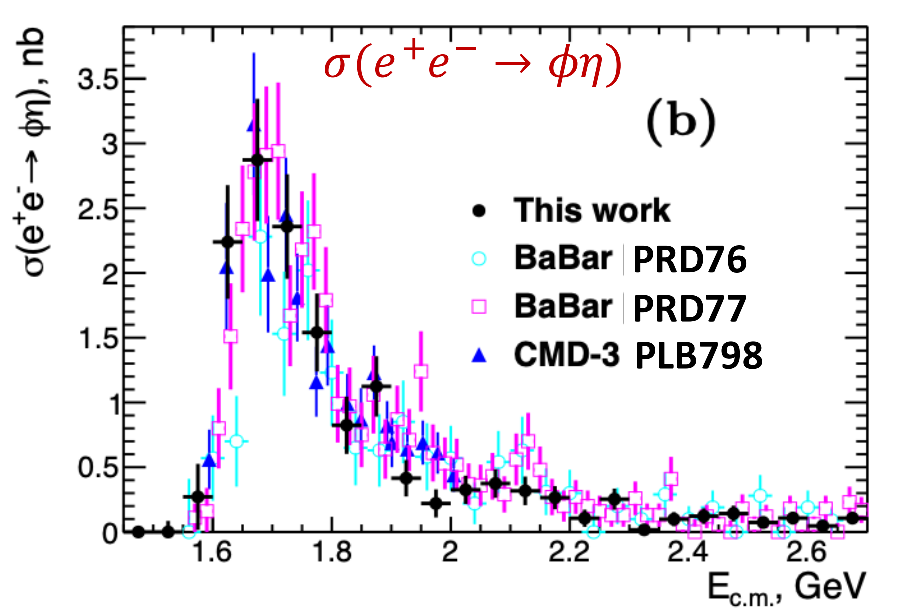
Intermediate resonances in $\phi\eta \to K^+K^-3\pi^0$



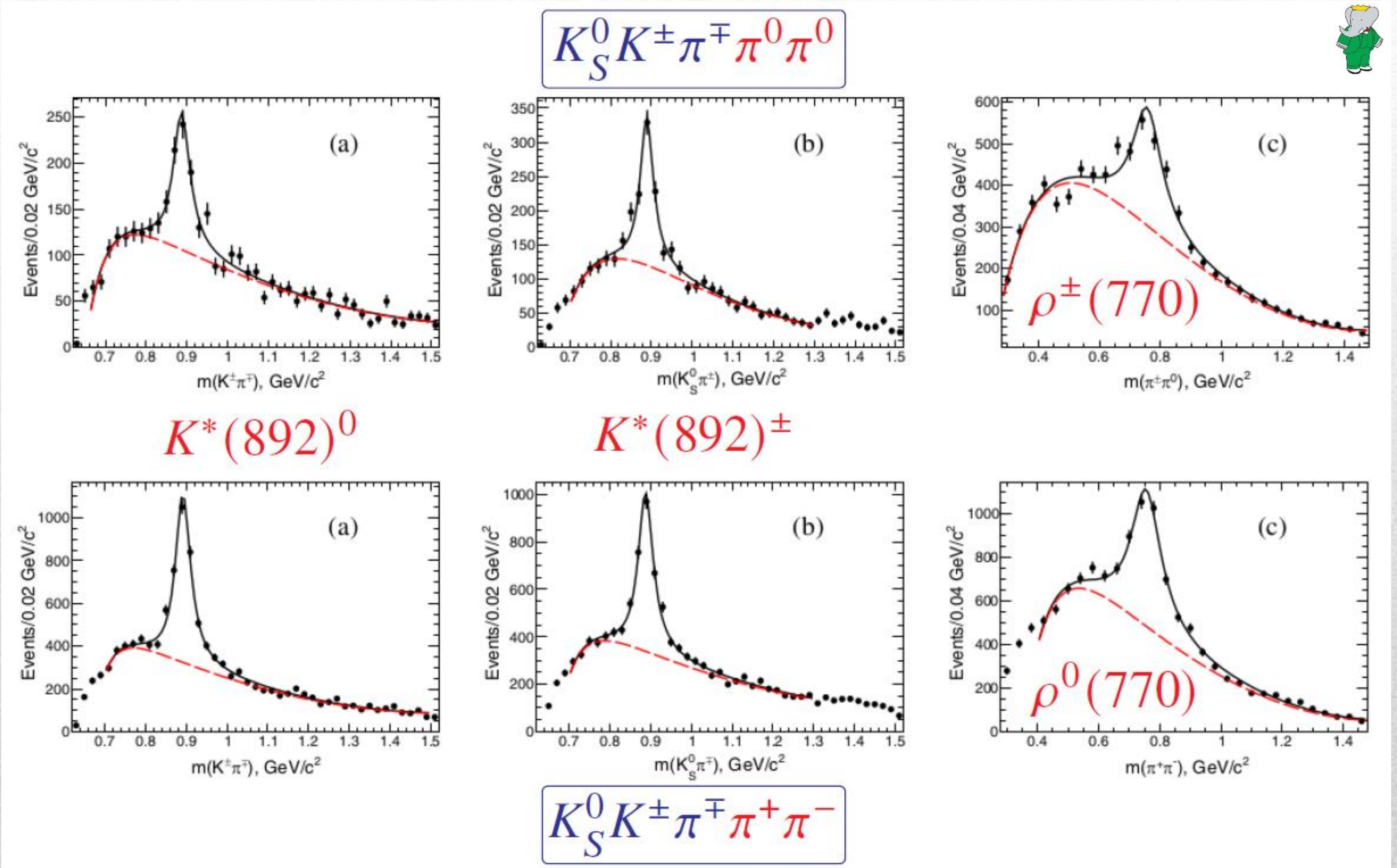


The cross section is dominated by the channel $e^+ e^- \to \phi\eta$. To extract the cross section:

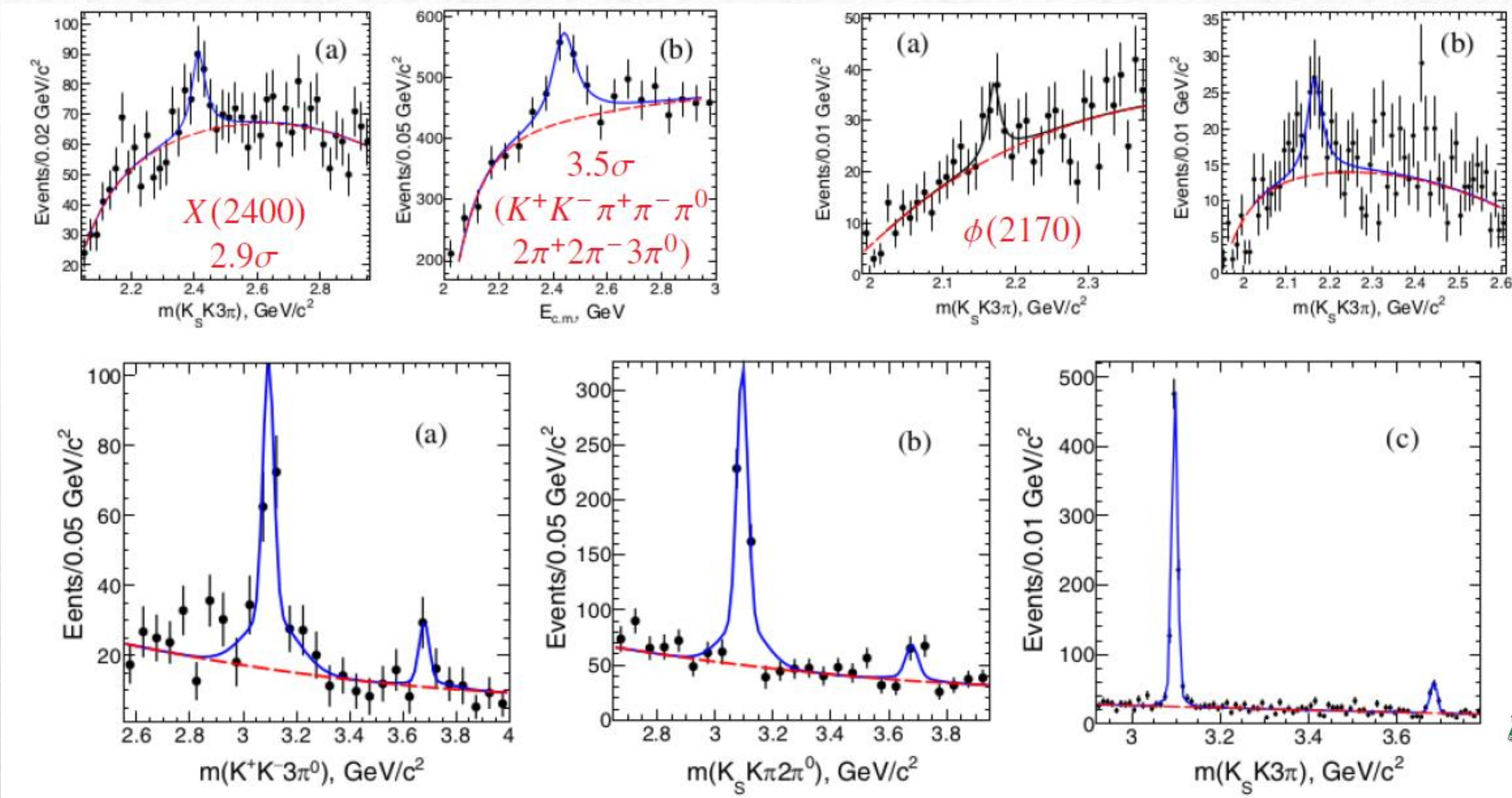
- select events with $m_{KK} < 1.05$ GeV
- divide the $2K3\pi^0$ mass spectrum in 50 MeV wide bins
- fit the $3\pi^0$ mass distribution to get the events in the η peak
- account for $\phi \to K^+K^-$ and $\eta \to 3\pi^0$ branching fractions



Other intermediate resonances



Resonances in $2K3\pi$



- $X(2400)$ and $\phi(2170)$ decay to $\mathrm{K}_S K 3\pi$ final states,
- Clear J/ψ and $\psi(2S)$ peaks in the $2K3\pi$ final states.

Summary

- The muon g-2 puzzle is important for SM precise test, even a potential gateway to New Physics
- Precision studies of e^+e^- annihilation into hadrons in low energy at BaBar with ISR technique, which provide important experimental input for a_μ^{Had} calculation
- The new measurement of $e^+e^- \to \pi^+\pi^-\pi^0$ improved the precision $a_\mu^{3\pi}$ calculation by a factor of $\sim$2

  PRD104, 112003 (2021)

- Measurements of the cross section and substructure associated with $e^+e^- \ \to \ 2K3\pi$ modes help to improve knowledge of the hadronic contributions to a_μ^{Had}

  PRD107, 072001 (2023)

Thank you!

BACKUP