™ and © Nelvana, All Rights Reserved

Hadronic Cross Section Measurements using Initial State Radiation

Lake Louise Winter Institute

Lake Louise, Canada

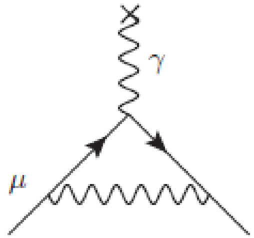
February 24, 2023

Georges Vasseur

georges.vasseur@cea.fr

on behalf of the BABAR Collaboration

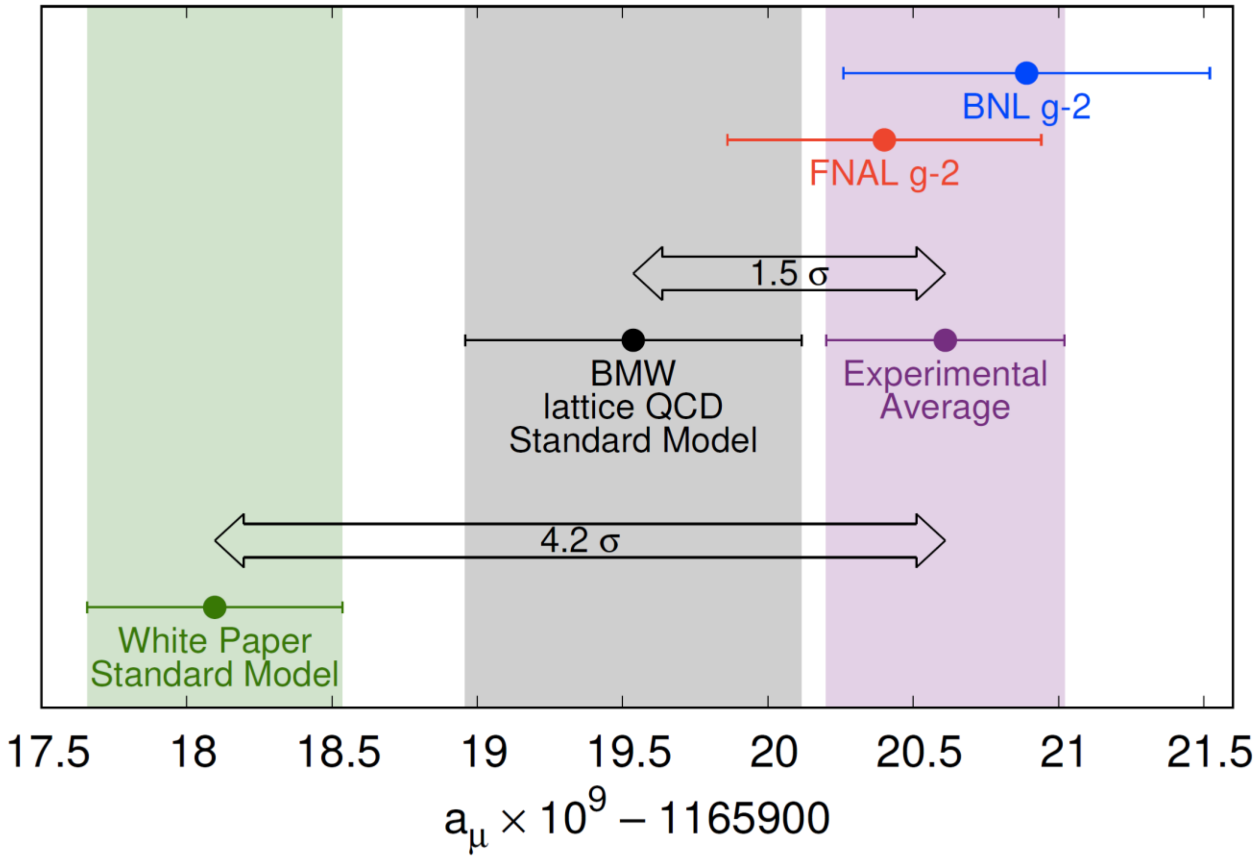
The g-2 puzzle



- Lepton anomalous magnetic moment:

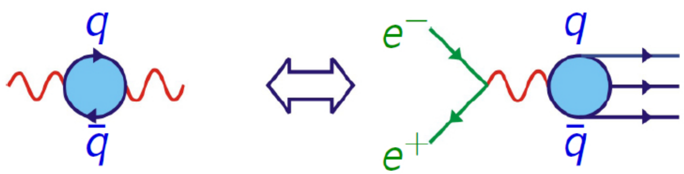
$$a_l = \frac{1}{2}(g-2)_l$$

- Precise test of the Standard Model
- Long-standing discrepancy between theory and experiment for the muon (g-2)



Dispersive approach

- Dominant uncertainty on (g-2) calculation from leading order hadronic vacuum polarization



$$a_\mu^{\mathrm{had}} \approx \frac{1}{4\pi^3} \int_{m_\pi^2}^{\infty} K_\mu(s) \cdot \sigma_{e^+e^- \to \mathrm{had}}(s) \, \mathrm{d}s$$

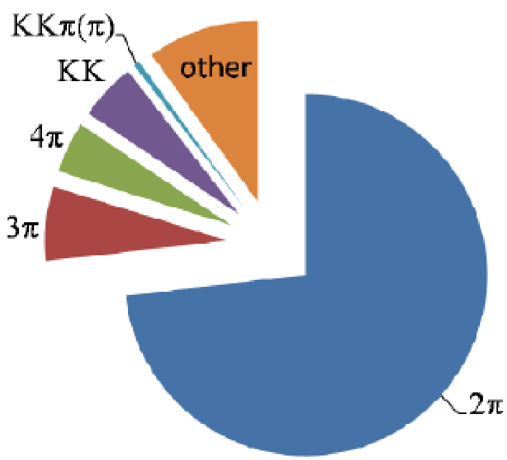
Kernel function   cross section

- Calculation needs experimental inputs

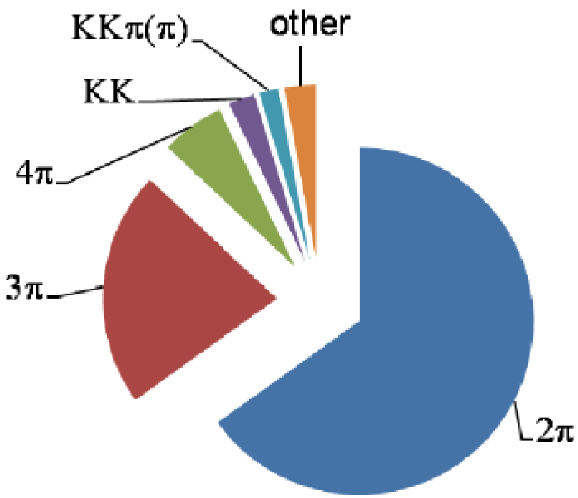
Hadronic cross sections and g-2

- At low energy total hadronic cross section determined from finite sum of exclusive modes
- The $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ mode contributes 7% to a_μ^{had} and 19% to its uncertainty (the second largest).

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

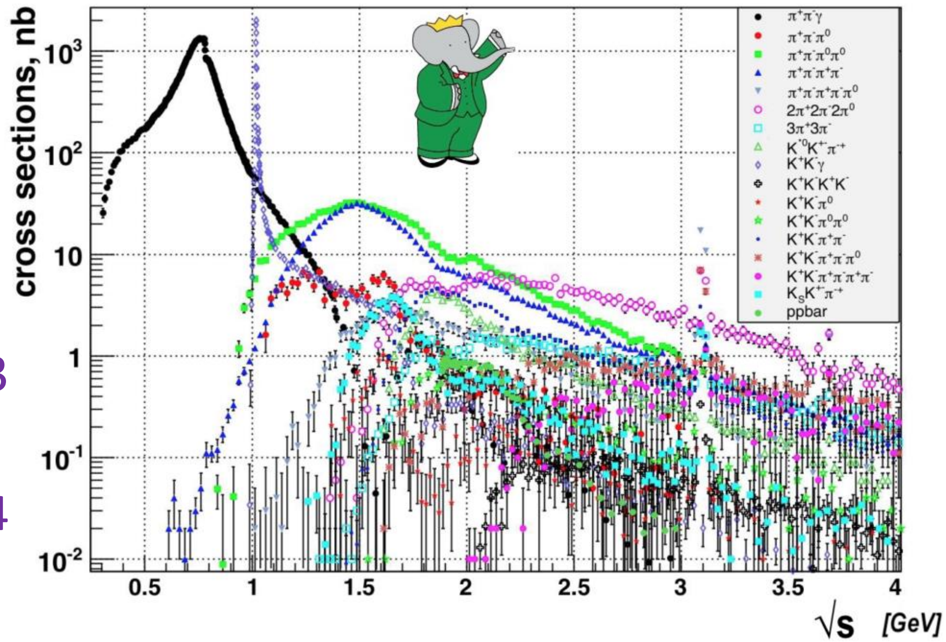


$a_\mu^{had,LO-VP}$ error squared

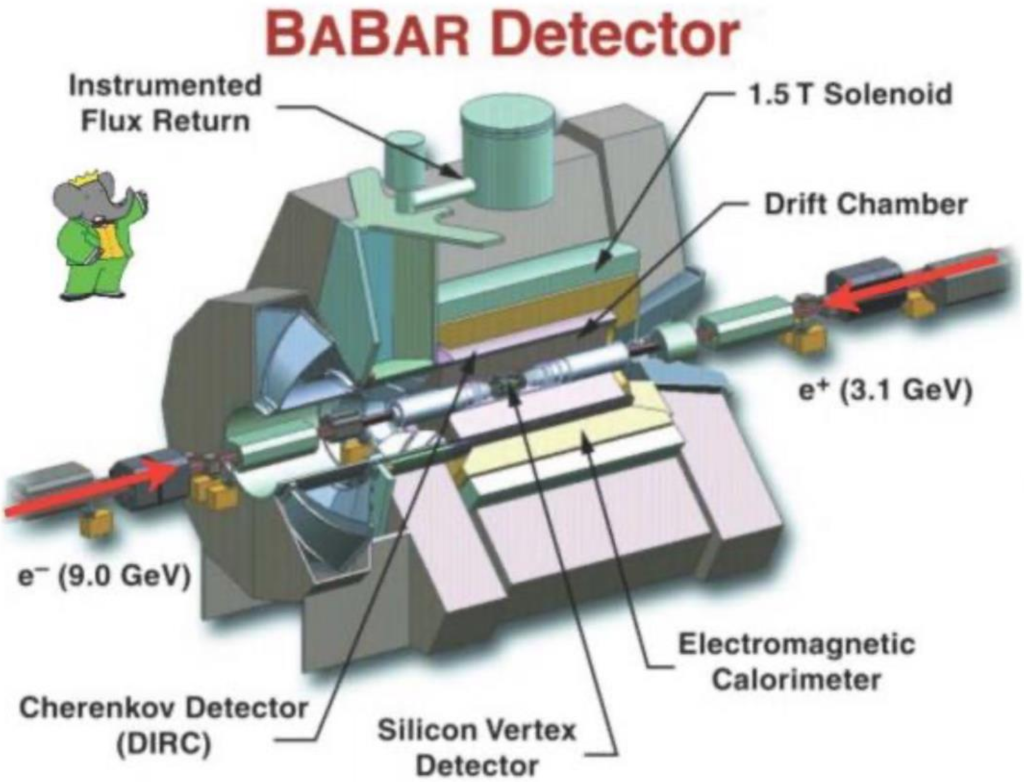


Cross sections from BABAR

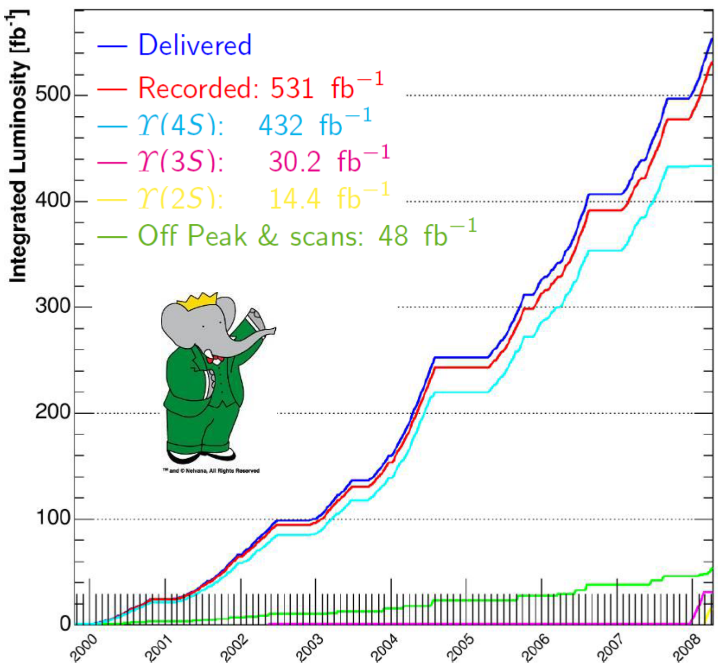
- Comprehensive program of cross section measurements in BABAR
- Most recent results
  - $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$
    - Phys. Rev. D 104 (2021), 112003
  - $e^+ e^- \rightarrow \pi^+ \pi^- 4\pi^0$
    - Phys. Rev. D 104 (2021), 112004
  - $e^+ e^- \rightarrow 2(\pi^+ \pi^-) 3\pi^0$
    - Phys. Rev. D 103 (2021), 092001
  - $e^+ e^- \rightarrow K\, K\, \pi\, \pi\, \pi$
    - arXiv:2207,10340 (2022)



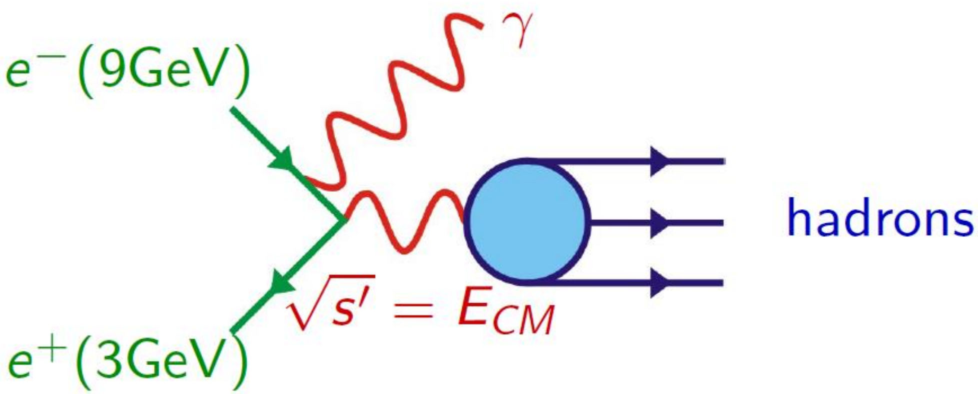
Detector and data sample

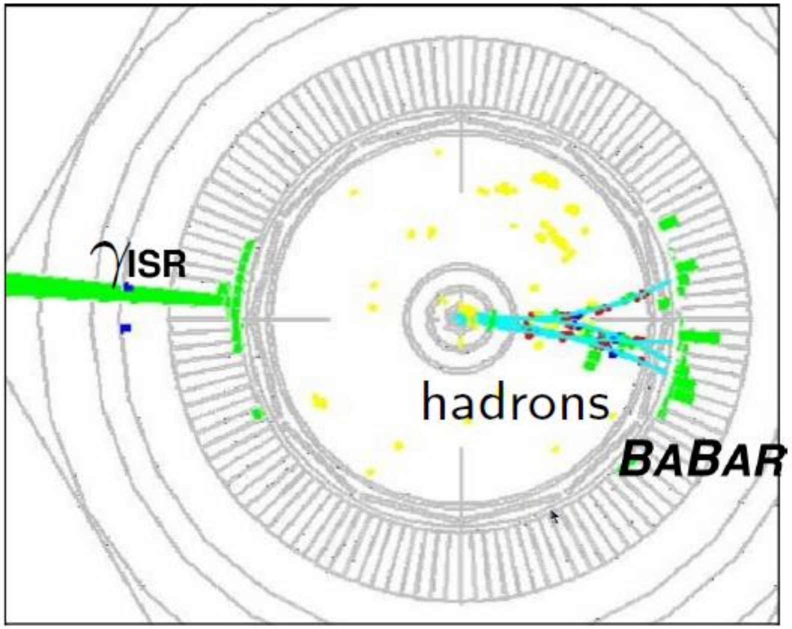


0.5 ab^{-1} over 10 years



ISR method

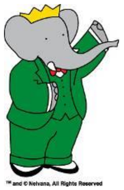


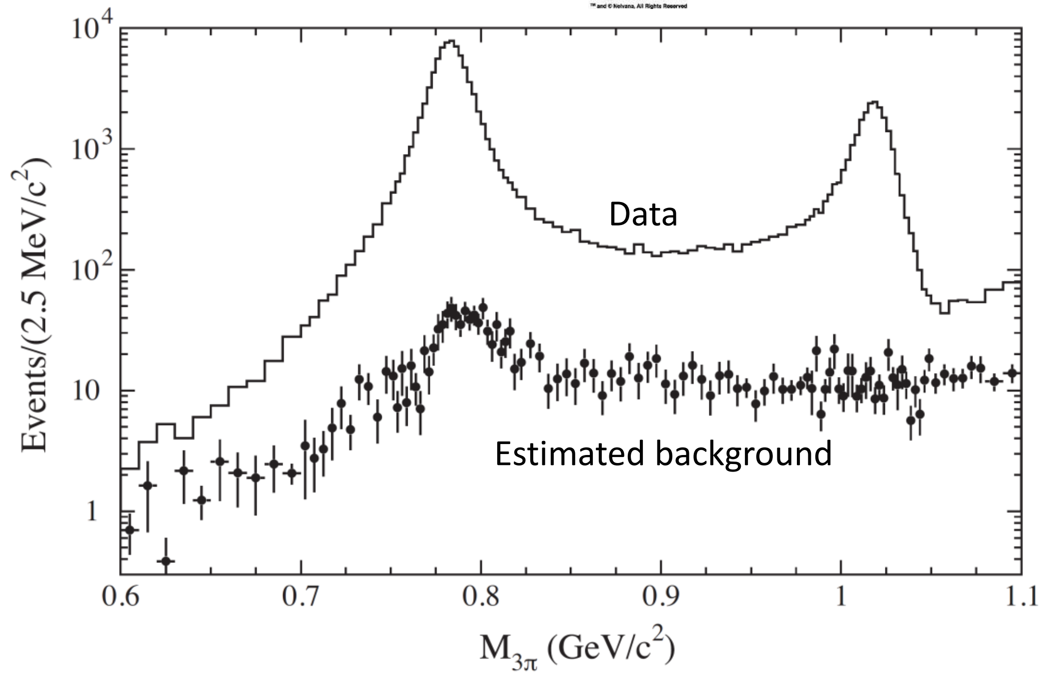


- Photon emitted from e^+ or e^- as Initial State Radiation (ISR).
  - allows to measure cross sections at low energy.
- Hadronic system boosted and back to back with photon.
  - Good detection even at threshold.
  - In detector acceptance: fully reconstructed.

$e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ selection

- Analysis on the full BABAR dataset (469 fb^{-1}).
- ISR γ : γ with highest energy over 3 GeV.
- Exactly 2 “good” tracks (opposite sign).
- At least 2 additional photons.
- $0.10 < m_{\gamma\gamma} < 0.17$ GeV
- Kinematic fit.
- Further cuts to reduce backgrounds.

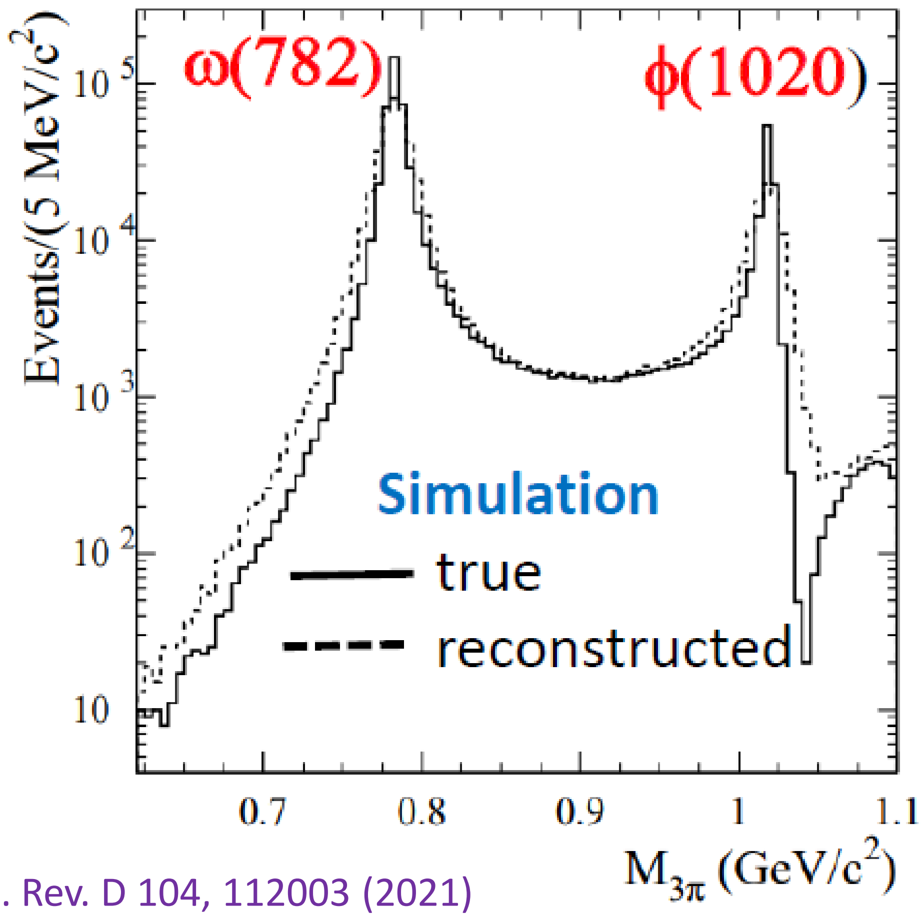




Phys. Rev. D 104, 112003 (2021)

Expected mass spectrum

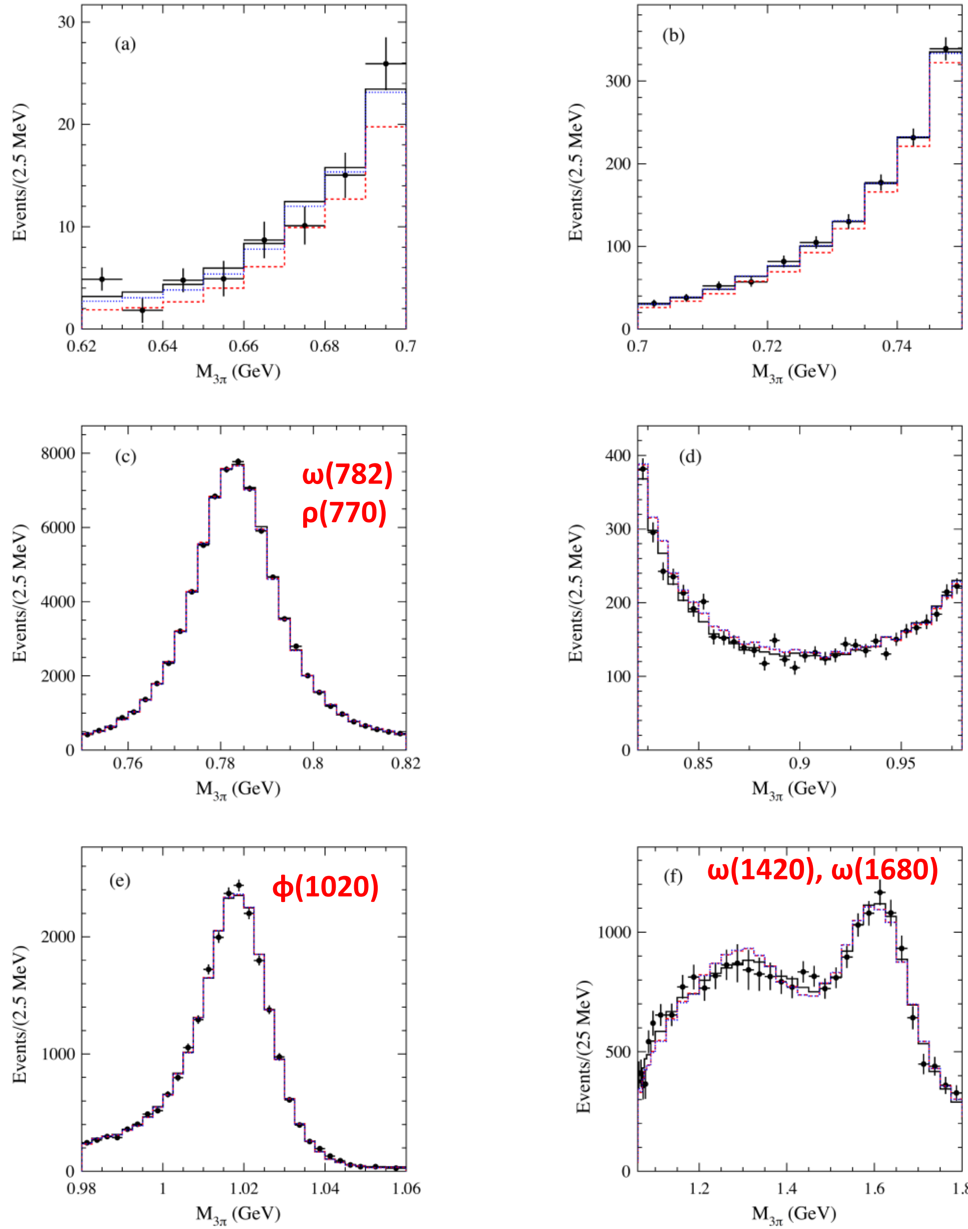
- Sharp structure of the mass spectrum below 1.1 GeV.
  - over 4 orders of magnitude.
- Unfolding the detector resolution effects is essential.



Phys. Rev. D 104, 112003 (2021)

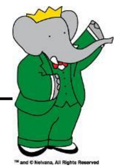
Measured mass spectrum

- Fit using Vector Dominance Model
  - including ρ(770)+ω(782)+ϕ(1020)+ω(1420)+ω(1680)
  - overall fit shown in different mass ranges
- Best fit (in black) including ρ(770)
- Alternate fit (in red) with no ρ(770)



Phys. Rev. D 104, 112003 (2021)

Fit results

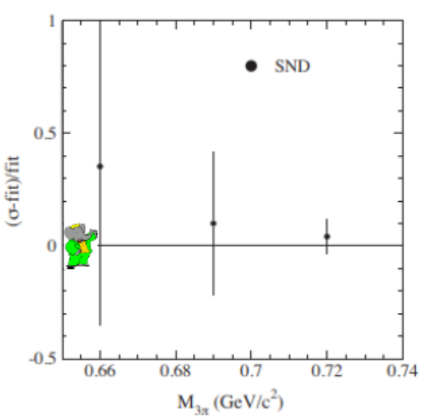


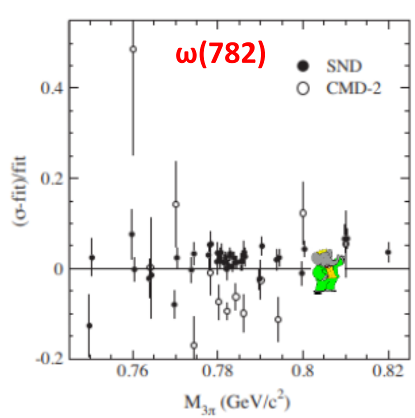
	BABAR	Previous measurement
$\Gamma(\omega\to e^+e^-) \times B(\omega\to\pi^+\pi^-\pi^0)$	0.5698 ± 0.0031 ± 0.0082 keV	0.557 ± 0.011 keV (PDG)
$\Gamma(\phi\to e^+e^-) \times B(\phi\to\pi^+\pi^-\pi^0)$	0.1841 ± 0.0021 ± 0.0080 keV	0.1925 ± 0.0043 keV (PDG)
$B(\rho\to\pi^+\pi^-\pi^0)$	$(0.88 \pm 0.23 \pm 0.30)\ 10^{-4}$	$(1.01\ ^{+0.54}_{-0.34} \pm 0.34)\ 10^{-4}$ (SND)
$(\phi_\rho-\phi_\omega)$	$-(99 \pm 9 \pm 15)°$	$-(135\ ^{+17}_{-13} \pm 9)°$ (SND)

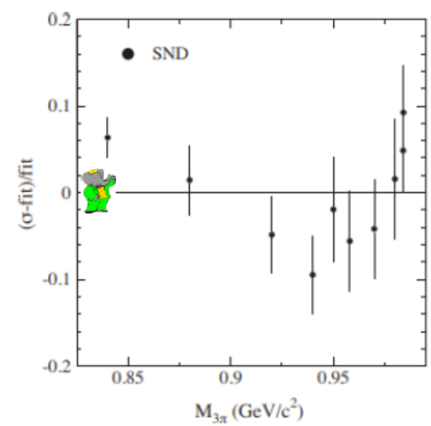
Phys. Rev. D 104, 11203 (2021)

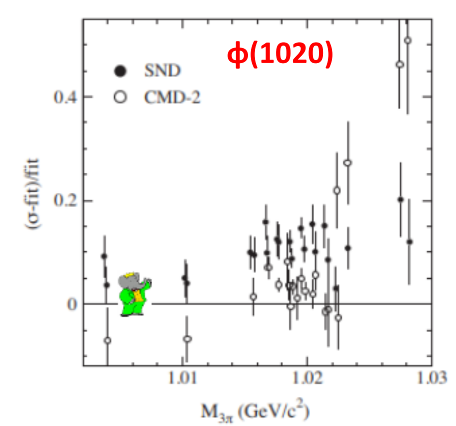
- BABAR results in agreement with previous values.
- Rare decay $\rho\to\pi^+\pi^-\pi^0$ observed with significance greater than 6 σ.

Relative cross section differences of $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ below 1.1 GeV









Good Agreement

Δ(SND-BaBar) = 2%
Δ(CMD-2-BaBar) = 7%

Good agreement

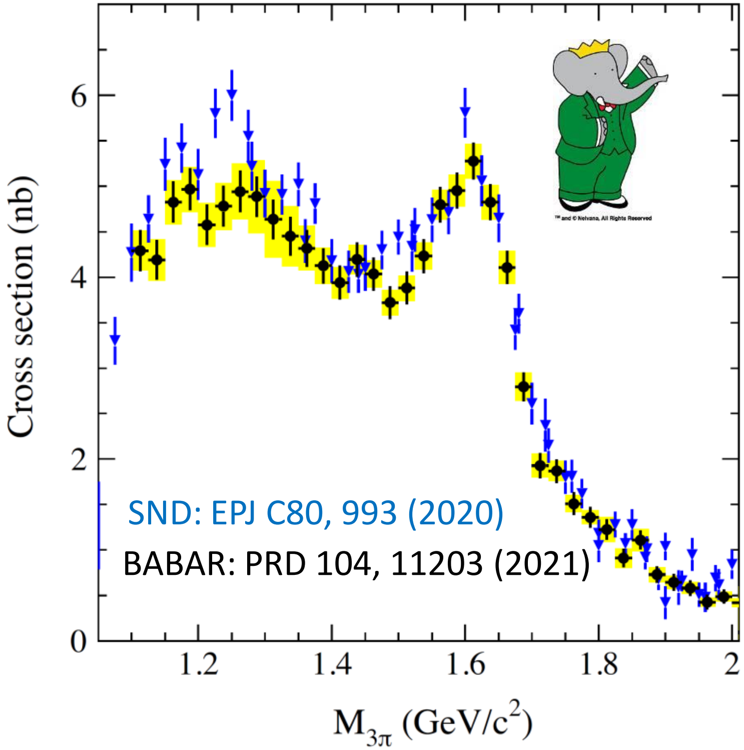
Δ(SND-BaBar) = 11%
Δ(CMD-2-BaBar) = 3%

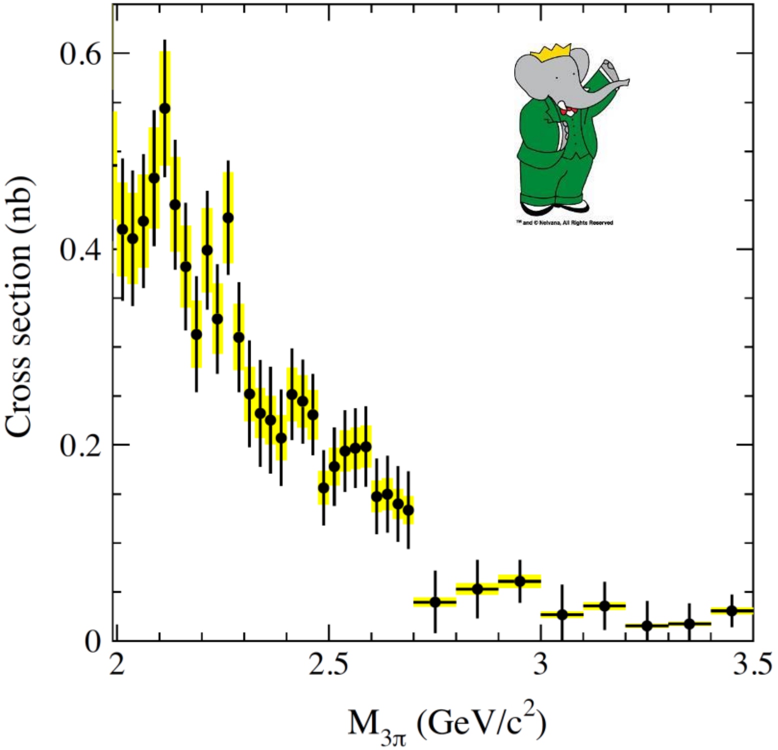
BABAR: Phys. Rev. D 104, 112003 (2021)

Systematic uncertainty ~ 1.3% on ω and ϕ
dominated by detection efficiency

SND: PRD 63, 72002 (2001), PRD 68, 52006 (2003)
CMD-2: PLB 578, 285 (2004), PLB 642, 203 (2006)

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

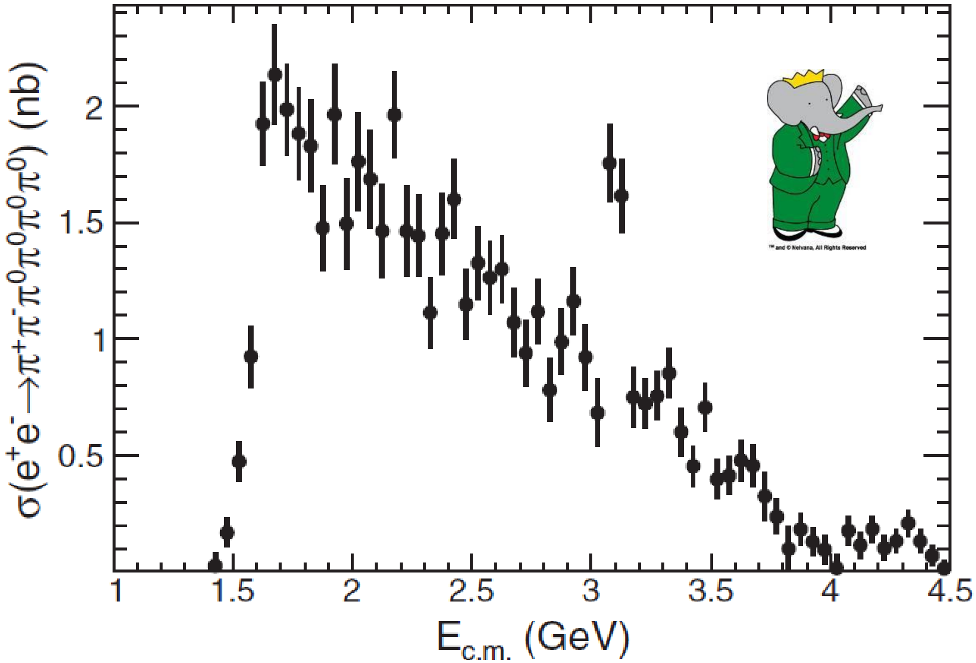




- Systematic uncertainty 4-15%, dominated by background.
- Good agreement between SND and BABAR with localized differences around 1.25 GeV and 1.5 GeV.

$e^+ e^- \to \pi^+ \pi^- 4\pi^0$ cross section

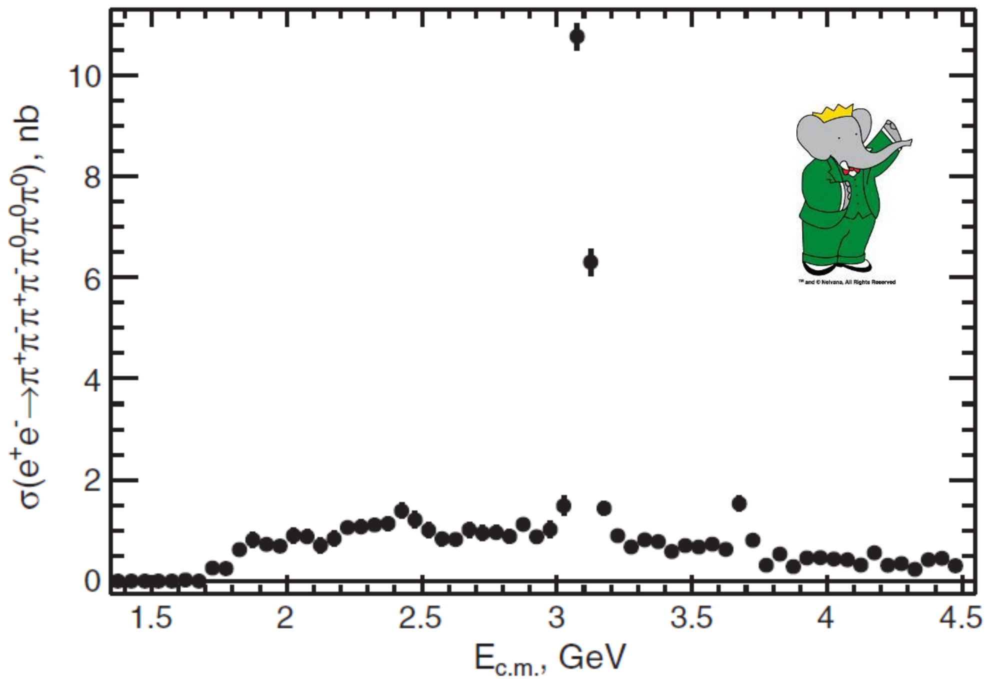
- Measured for the first time
- Similar technique to $\pi^+ \pi^- \pi^0$
- Same integrated luminosity ($469\ fb^{-1}$)
- Also measured
  - Intermediate states:
  - $e^+ e^- \to \pi^+ \pi^- \pi^0 \eta(\to 3\pi^0)$
  - $e^+ e^- \to \omega(\to \pi^+ \pi^- \pi^0)\ 3\pi^0$
  - $e^+ e^- \to \omega(\to \pi^+ \pi^- \pi^0)\ \eta(\to 3\pi^0)$
  - Related state:
  - $e^+ e^- \to \pi^+ \pi^-\ 3\pi^0\ \eta(\to \gamma\gamma)$



Phys. Rev. D 104, 112004 (2021)

$e^+ e^- \to$ **$2(\pi^+ \pi^-)$** $3\pi^0$ cross section

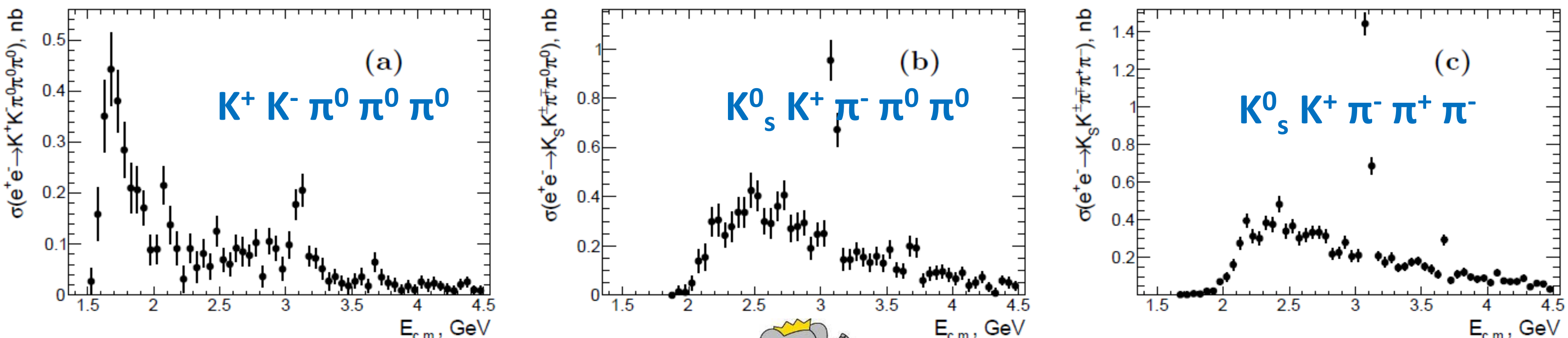
- Measured for the first time
- Similar technique to $\pi^+ \pi^- \pi^0$
- Same integrated luminosity ($469\ fb^{-1}$)
- Also measured
  - Intermediate states:
  - $e^+ e^- \to 2(\pi^+ \pi^-)\ \eta(\to 3\pi^0)$
  - $e^+ e^- \to \eta(\to \pi^+ \pi^- \pi^0)\ \pi^+ \pi^-\ 2\pi^0$
  - $e^+ e^- \to \omega(\to \pi^+ \pi^- \pi^0)\ \pi^+ \pi^-\ 2\pi^0$
  - Related state:
  - $e^+ e^- \to 2(\pi^+ \pi^-)\ 2\pi^0\ \eta(\to \gamma\gamma)$

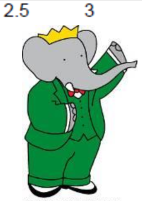


Phys. Rev. D 103, 092001 (2021)

$e^+ e^- \rightarrow K K \pi \pi \pi$ cross sections

- Measured for the first time
- Similar technique to $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$
- Same integrated luminosity (469 fb^{-1})
- Also measured: modes with intermediate resonances η, ρ, K*



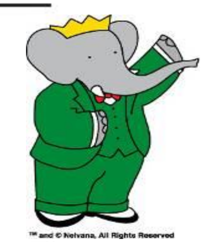


arXiv:220710340 (2022)

Impact on g-2

- $e^+ e^- \to \pi^+ \pi^- 3\pi^0, 2(\pi^+ \pi^-) 3\pi^0, K K \pi \pi \pi$
  - Measured for the first time
  - Contribute < 0.5% to a_μ^{had} to and <1.5% to its uncertainty
- $e^+ e^- \to \pi^+ \pi^- \pi^0$
  - Second largest contributor to uncertainty on a_μ^{had}
  - **Uncertainty on its contribution reduced by a factor 2**

$M_{3\pi}$ 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	Phys. Rev. D 104, 112003 (2021)	$45.86 \pm 0.14 \pm 0.58$
< 1.80 [A]	[A] DHMZ19: EPJ C 80, 241 (2020)	$46.21 \pm 0.40 \pm 1.40$
< 1.97 [B]	[B] KNT19: PRD 101, 14029 (2020)	46.74 ± 0.94
< 2 [C]	[C] J17: STMP 274, 1 (2017)	44.32 ± 1.48



Summary

- Using the ISR technique BABAR does precision studies of low energy e^+e^- annihilations.

- Long history of cross section measurements.

- Most recent results
  - precision measurement in $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ mode,
  - first measurements in several high multiplicity modes.

- Contribute to improve (g-2) calculation.