# Measurement of $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ at BABAR and calculation of $(g\text{-}2)_\mu$

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**Georges Vasseur**

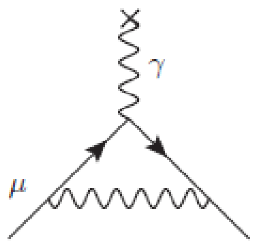
georges.vasseur@cea.fr

*on behalf of the BABAR Collaboration*

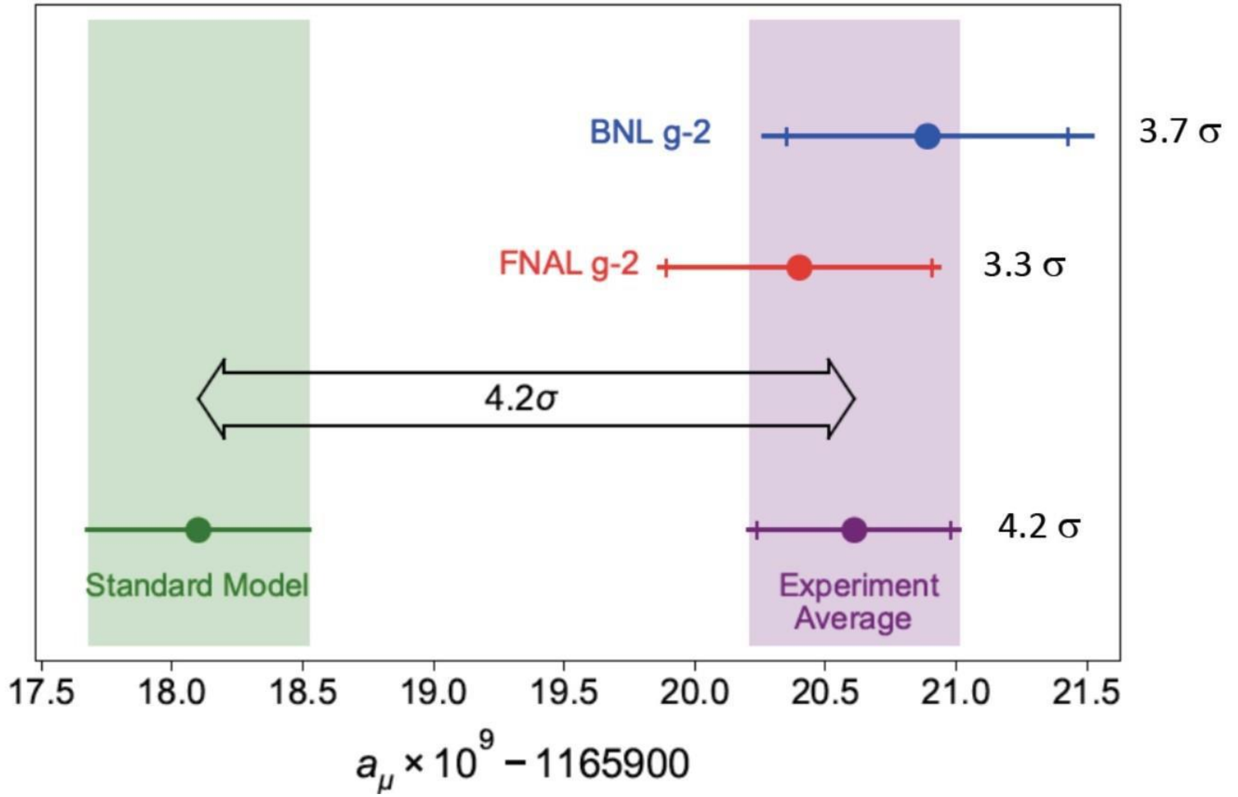
# Outline

- Physics motivation : calculation of (g-2)
- The BABAR experiment
- New result on $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$
  - Published in Phys. Rev. D 104 (2021) 11203
- Status on (g-2)

# The g-2 Puzzle



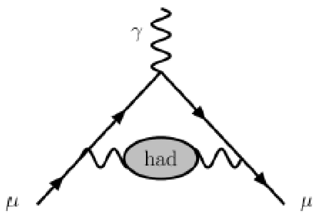

- Lepton anomalous magnetic moment:
  $$a_l = \frac{1}{2}(g-2)_l$$
- Precise test of the Standard Model
- Long-standing discrepancy between theory and experiment for the muon (g-2)



# g-2 Calculation

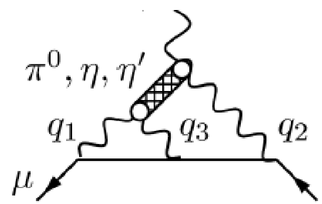
$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{hadronic}} + a_\mu^{\mathrm{NP?}}$$

Hadronic Vacuum Polarisation (VP)

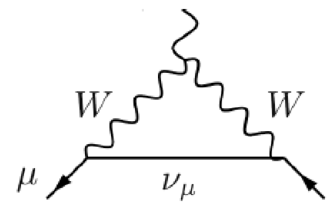



This talk

Hadronic light-by-light Scattering




Weak Interactions

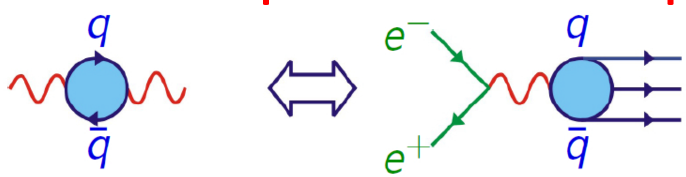



| | | |
|---|---|---|
| **QED** | 11 658 471.89 | ± 0.01 |
| Leading hadronic vacuum polarization | 693.1 | ± 4.0 |
| Sub-leading hadronic vacuum polarization | -8.59 | ± 0.07 |
| Hadronic light-by-light | 9.2 | ± 1.7 |
| Electroweak | 15.36 | ± 0.10 |
| Prediction Phys. Rep. 887 (2020) | 11 659 181.0 | ± 4.3 |

units of $10^{-10}$

# Dispersive approach

- Dominant correction and uncertainty on (g-2) calculation come from hadronic vacuum polarization
- Calculation needs experimental inputs

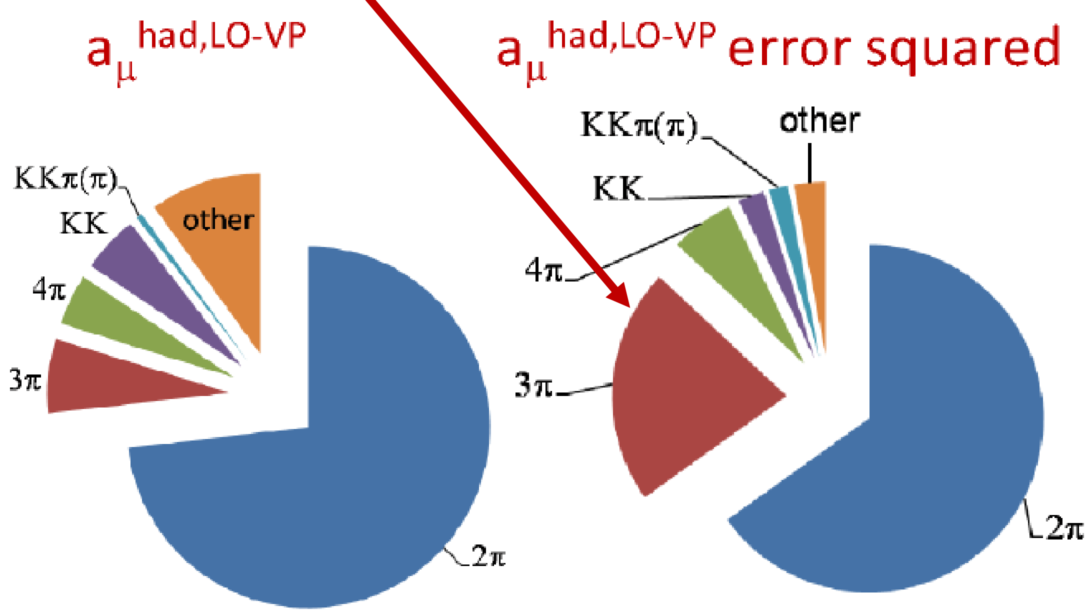



$$a_\mu^{\text{had}} \approx \frac{1}{4\pi^3} \int_{m_\pi^2}^{\infty} K_\mu(s) \cdot \sigma_{e^+e^- \to \text{had}}(s) \, \mathrm{d}s$$

Kernel function        cross section

# Hadronic cross sections

- At low energies total hadronic cross section determined from finite sum of exclusive modes.
- The $e^+ e^- \to \pi^+ \pi^- \pi^0$ mode is one of the main contributor to the uncertainty.

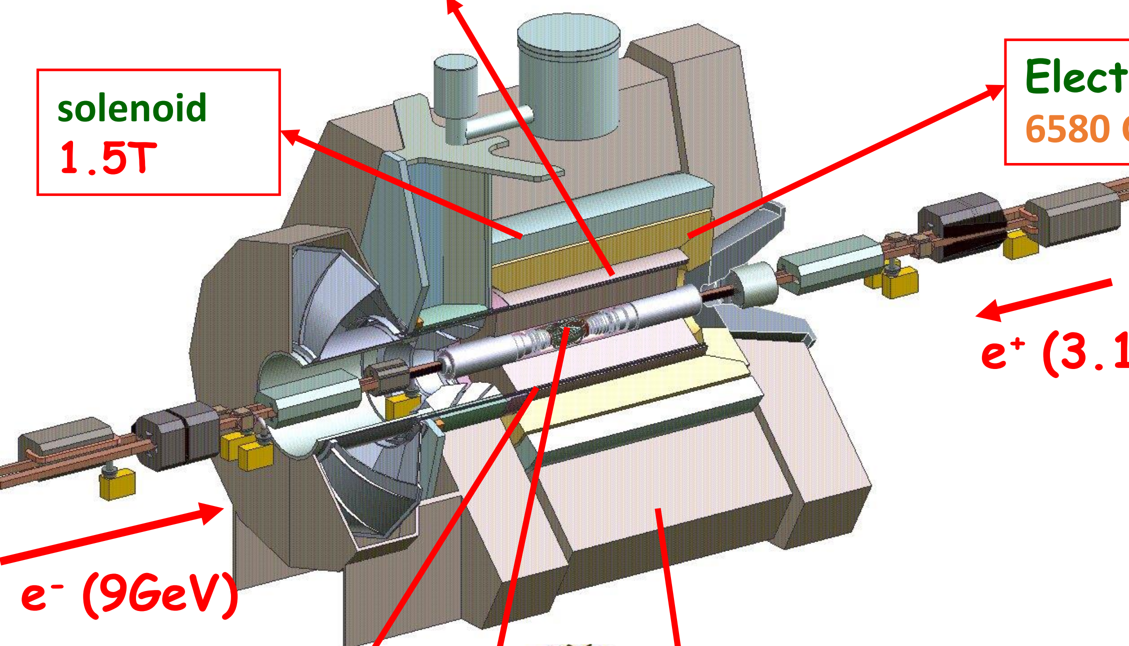


# Detector and Data Sample

**Cherenkov detector (DIRC)**
144 quartz bars and 11000 PMTs

**solenoid**
1.5T

**Electromagnetic calorimeter**
6580 CsI(Tl) crystals



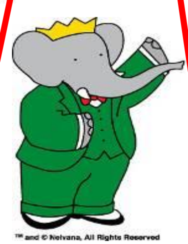
$e^+$ (3.1GeV)

$e^-$ (9GeV)

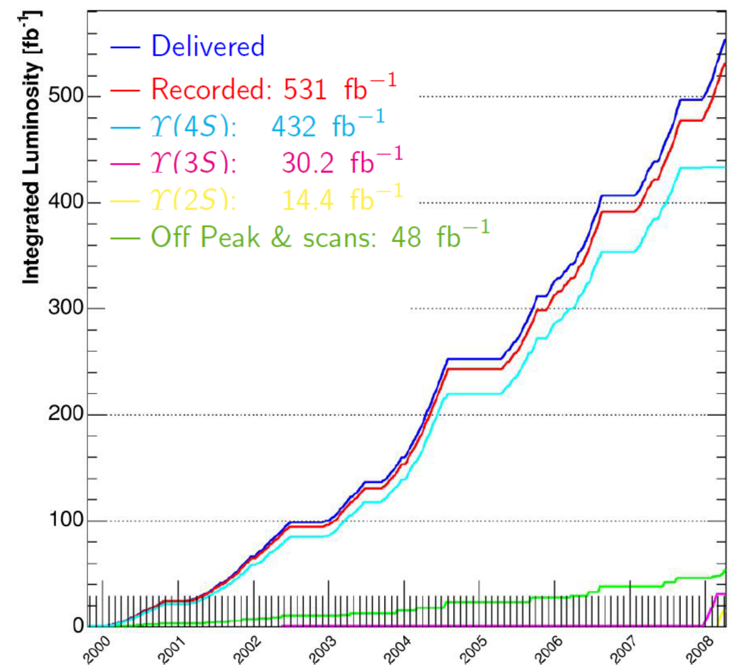
**Drift chamber**
40 layers

**Si vertex tracker**
5 layers

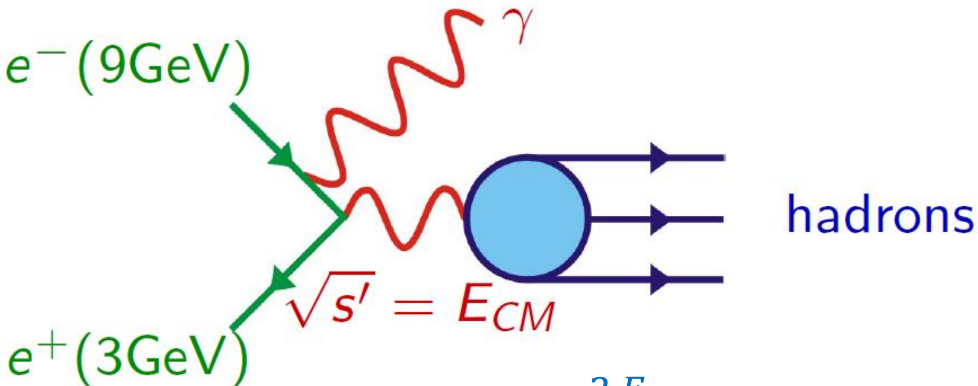
**μ chambers**
RPC / LST

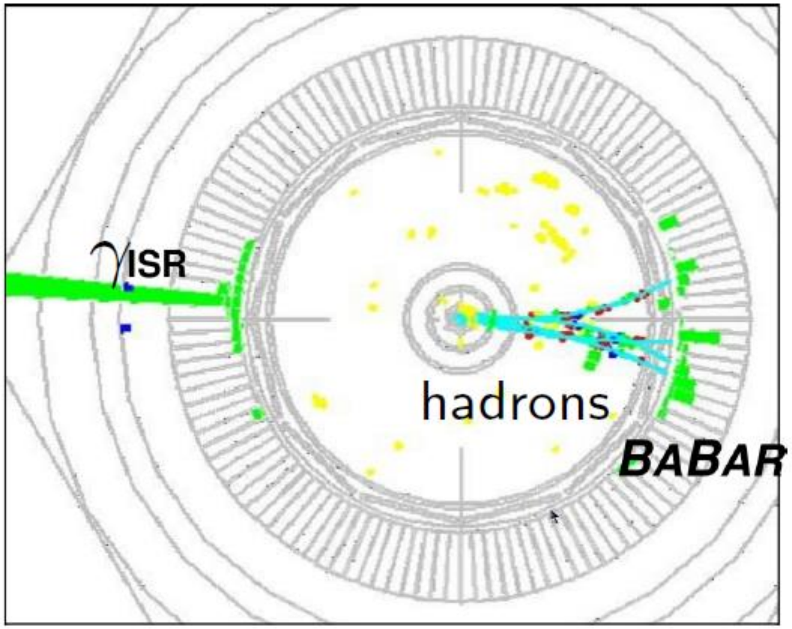



0.5 $ab^{-1}$ over 10 years



# ISR Method



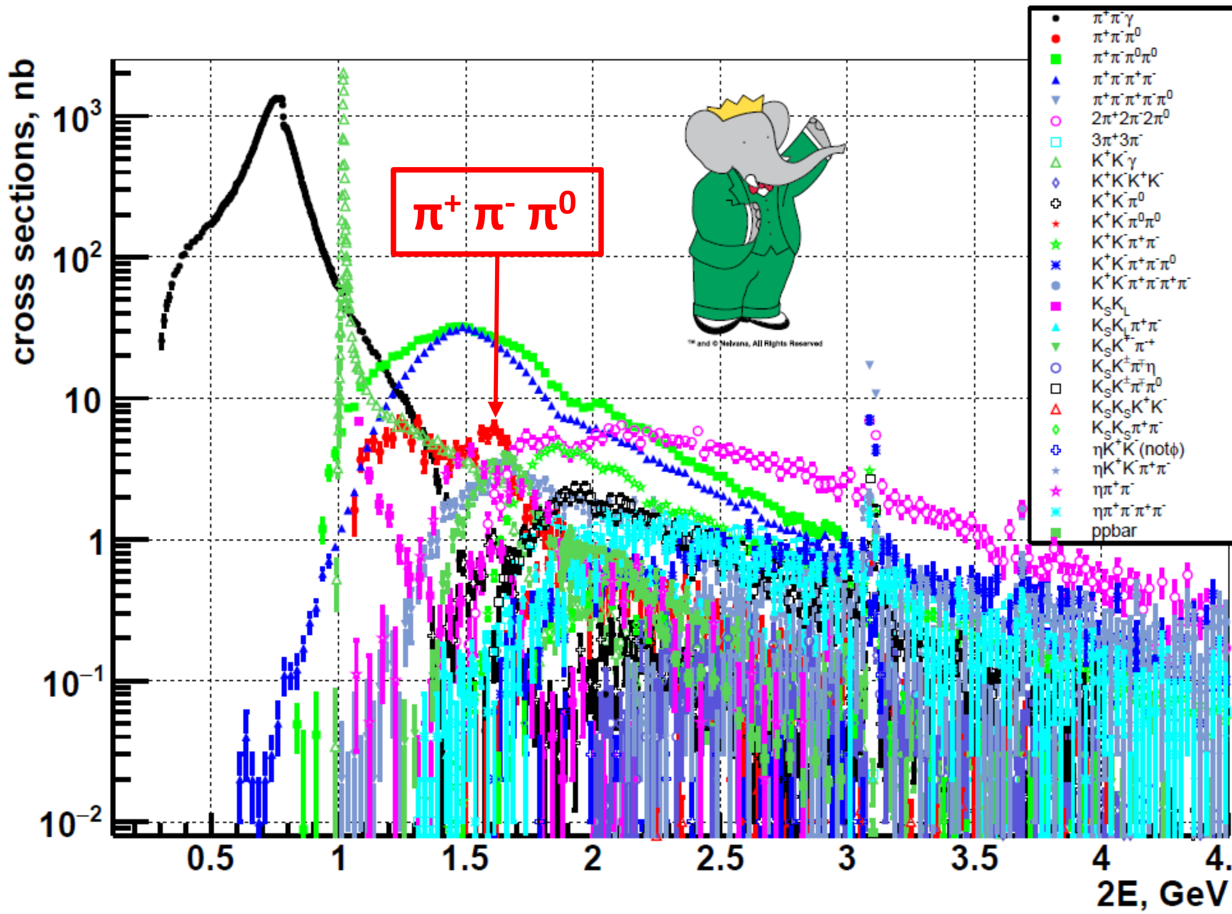




$$s' = s\left(1 - \frac{2\,E_\gamma}{\sqrt{s}}\right)$$

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

# Cross Sections Measurements

- Comprehensive study of many modes in BABAR.
- Coverage of the low energy range thanks to the ISR method.



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

- Second largest contributor to the uncertainty on hadronic correction to (g-2).
- Current accuracy on this mode at 3%.
- Previous measurements:
  - SND and CMD-2 at VEPP.
    SND: PRD 63, 72002 (2001), PRD 68, 52006 (2003), EPJ C80, 993 (2020)
    CMD-2: PLB 578, 285 (2004), PLB 642, 203 (2006)
  - BABAR on 89 $fb^{-1}$. Phys. Rev. D 70, 72004 (2004)
  - Some disagreements: BABAR and SND 8% larger than CMD-2 at the ω.
- New analysis on the full BABAR dataset (469 $fb^{-1}$).

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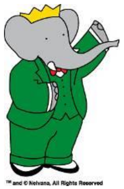
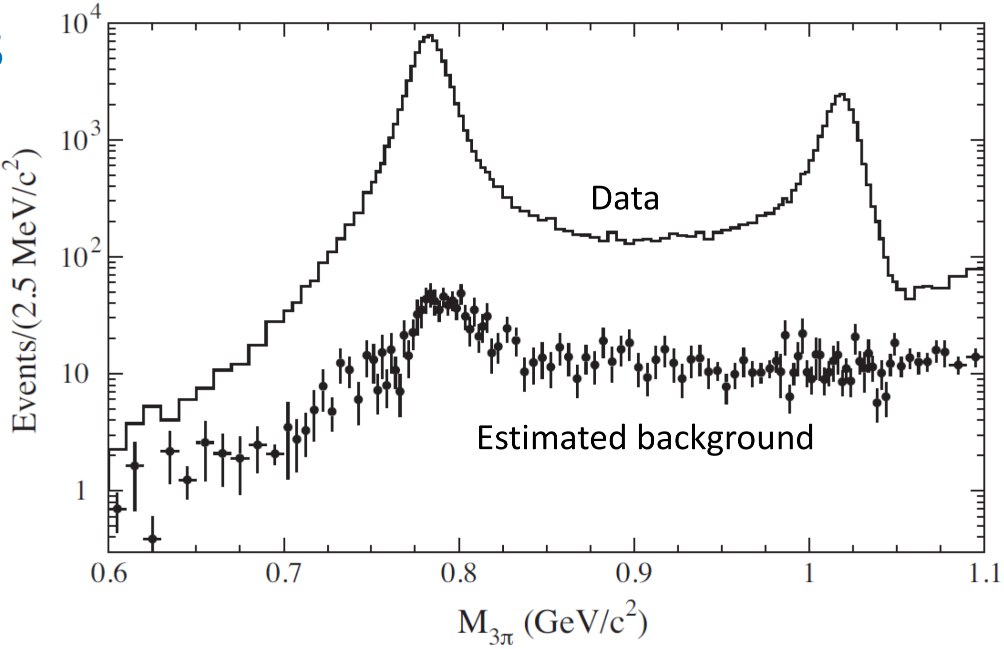
# $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ Selection

- 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.



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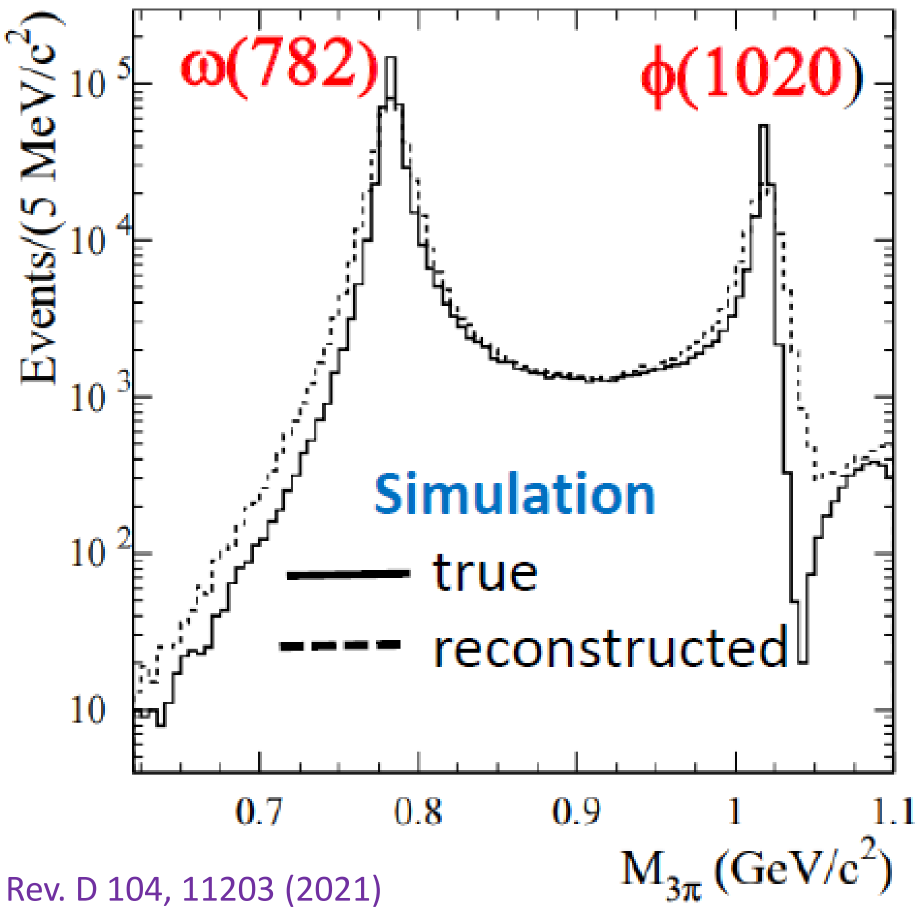
# Expected mass spectrum

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

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# Measured mass spectrum

- Fit using Vector Dominance Model.

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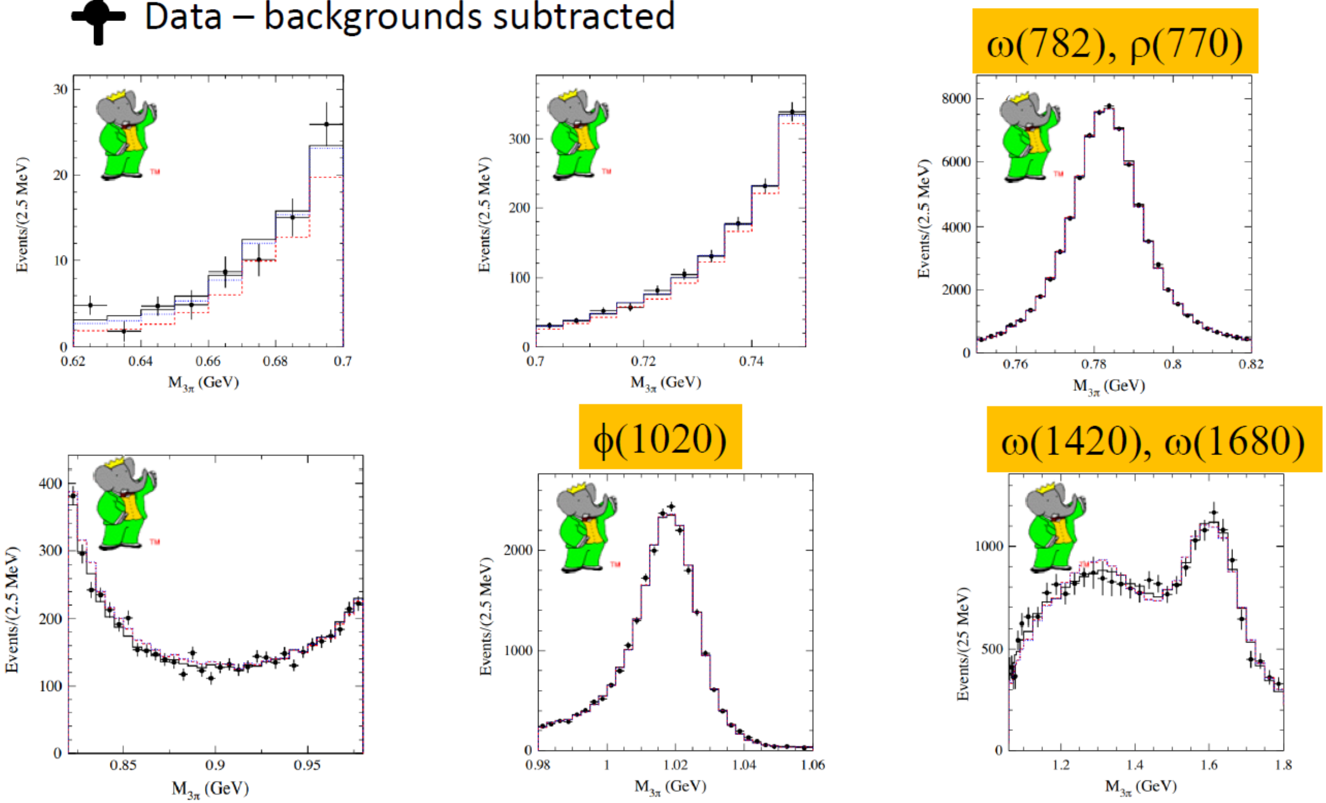
✚ Data – backgrounds subtracted

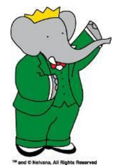



(solid): Lorentzian smearing and $\rho \to 3\pi$ $\chi^2/\nu = 136/127$

(dash): No Lorentzian smearing and no $\rho \to 3\pi$ $\chi^2/\nu = 201/131$

(dot): Lorentzian smearing and no $\rho \to 3\pi$ $\chi^2/\nu = 180/129$

# Fit results



| | BABAR | Previous measurement |
|---|---|---|
| $\Gamma(\omega\to e^+e^-).\mathcal{B}(\omega\to\pi^+\pi^-\pi^0)$ | 0.5698 ± 0.0031 ± 0.0082 keV | 0.557 ± 0.011 keV (WA) |
| $\Gamma(\phi\to e^+e^-).\mathcal{B}(\phi\to\pi^+\pi^-\pi^0)$ | 0.1841 ± 0.0021 ± 0.0080 keV | 0.1925 ± 0.0043 keV (WA) |

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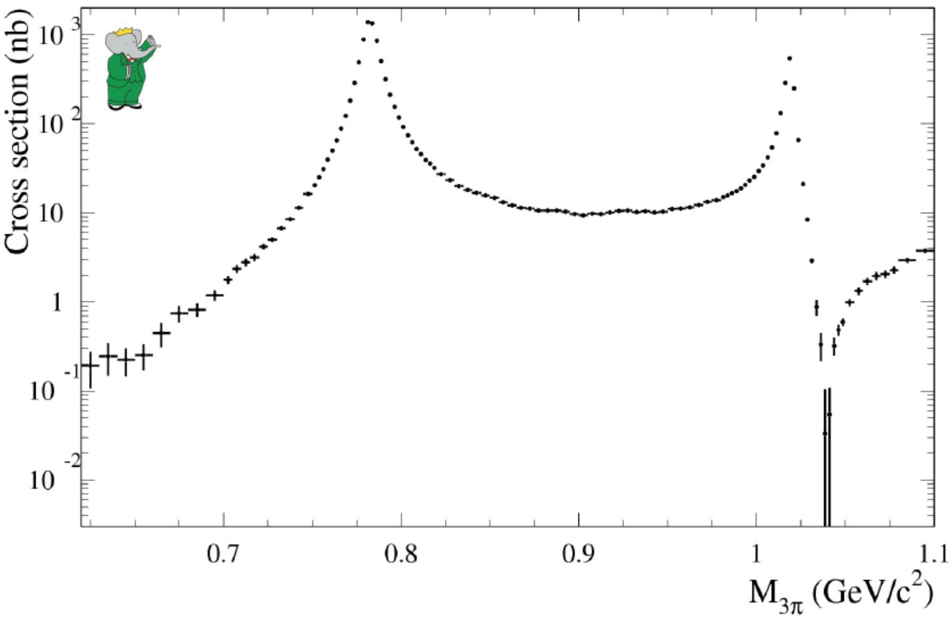
| | | |
|---|---|---|
| $\mathcal{B}(\rho\to\pi^+\pi^-\pi^0)$ | $(0.88 \pm 0.23 \pm 0.30)\ 10^{-4}$ | $(1.01\ ^{+0.54}_{-0.34} \pm 0.34)\ 10^{-4}$ (SND) |
| $(\phi_\rho-\phi_\omega)$ | $-(99 \pm 9 \pm 15)°$ | $-(135\ ^{+17}_{-13} \pm 9)°$ (SND) |

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

# $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ Cross Section below 1.1 GeV

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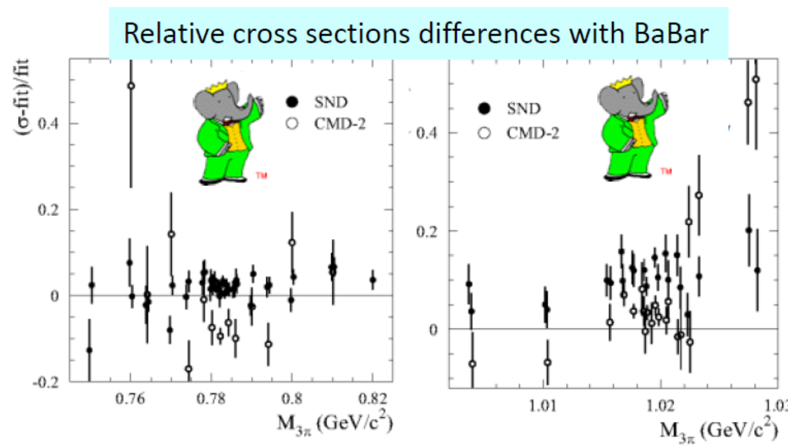


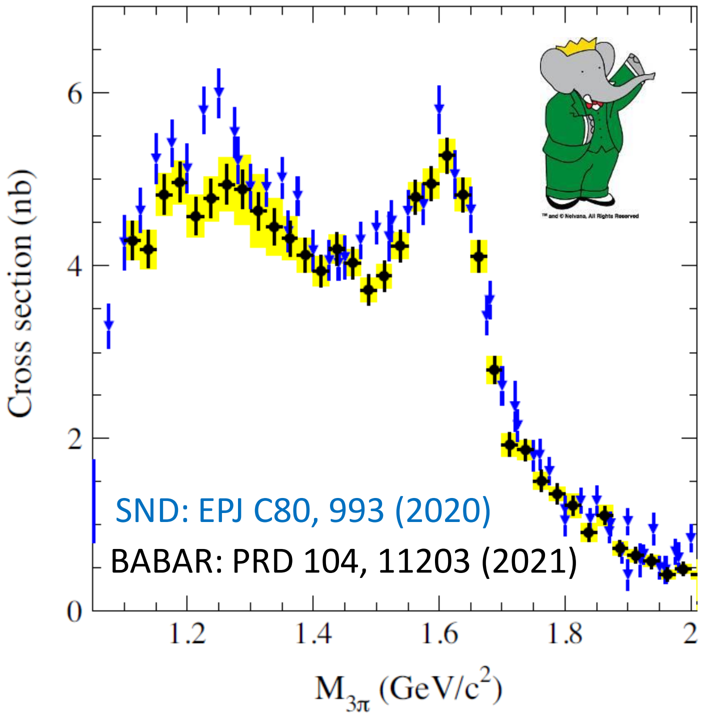

Δ(SND-BaBar) = 2%
Δ(CMD-2-BaBar) = 7%

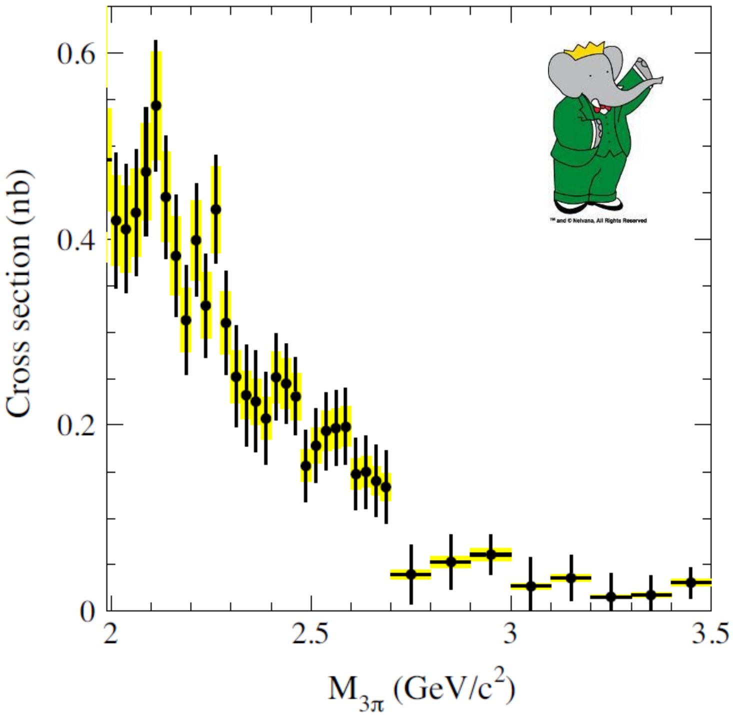
Δ(SND-BaBar) = 11%
Δ(CMD-2-BaBar) = 3%

- Parameters of the smearing function determined in the fit.
- Systematic uncertainty ~ 1.3%

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




- Systematics uncertainty 4-15%, dominated by background.
- Localized differences between SND and BABAR around 1.25 GeV and 1.5 GeV.

# $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ Impact on g-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 | $2.95 \pm 0.03 \pm 0.16$ |
| $< 2.00$ | $45.86 \pm 0.14 \pm 0.58$ |
| $< 1.80$ [A] | $46.21 \pm 0.40 \pm 1.40$ |
| $< 1.97$ [B] | $46.74 \pm 0.94$ |
| $< 2$ [C] | $44.32 \pm 1.48$ |

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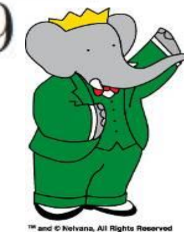
[A] DHMZ19: EPJ C 80, 241 (2020)
[B] KNT19: PRD 101, 14029 (2020)
[C] J17: STMP 274, 1 (2017)

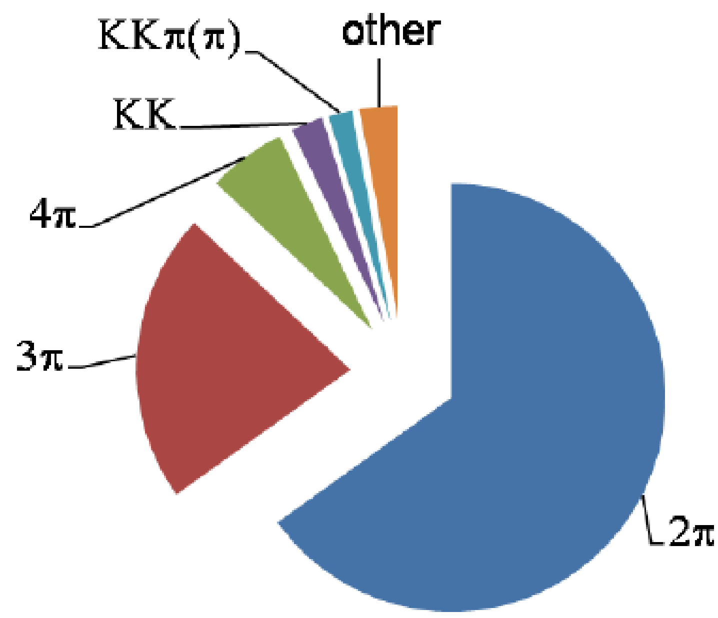


- Uncertainty on (g-2) contribution from 3π mode reduced by a factor 2
  - Dominant systematic on BABAR result from detection efficiency

# Going further: experimental inputs to the calculation

- Square uncertainty reduced by a factor ~4 for $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$
- Analysis currently ongoing in BABAR for the channel giving the largest uncertainty:
  - $e^+ e^- \rightarrow \pi^+ \pi^-$
- Discrepancy between BABAR and KLOE for $e^+ e^- \rightarrow \pi^+ \pi^-$

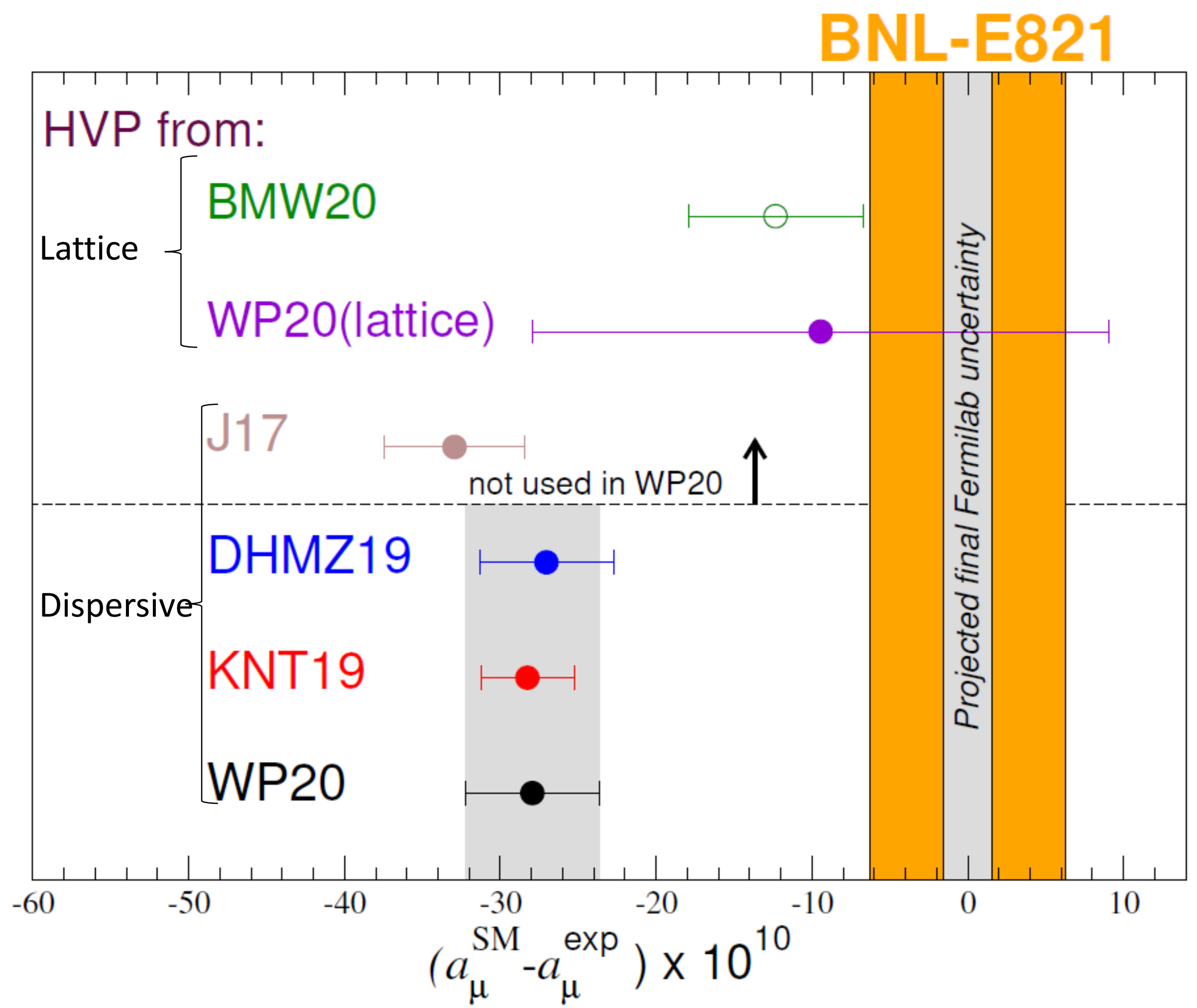
$a_\mu^{had,LO\text{-}VP}$ error squared




$$a_\mu^{had\ LO}(SM) = (693.1 \underbrace{\pm 2.8_{exp} \pm 2.8_{BABAR\text{-}KLOE} \pm 0.7_{QCD}}_{\pm 4.0}) \times 10^{-10}$$

# Future: theory and experiment

- Experiments:
  - Fermilab E989 with full dataset
  - New experiment at J-PARC: E34
- Theory
  - Improving dispersive approach
    - New experimental results
  - Emerging lattice QCD:
    - Ab initio calculation
    - In better agreement with the measurement



# Summary

- Using the ISR technique BABAR does precision studies of low energy $e^+e^-$ annihilations.
- New results from BABAR in $e^+ e^- \to \pi^+ \pi^- \pi^0$ mode.
- Contribute to improve (g-2) prediction.
  - Discrepancy currently at 4.2 $\sigma$.