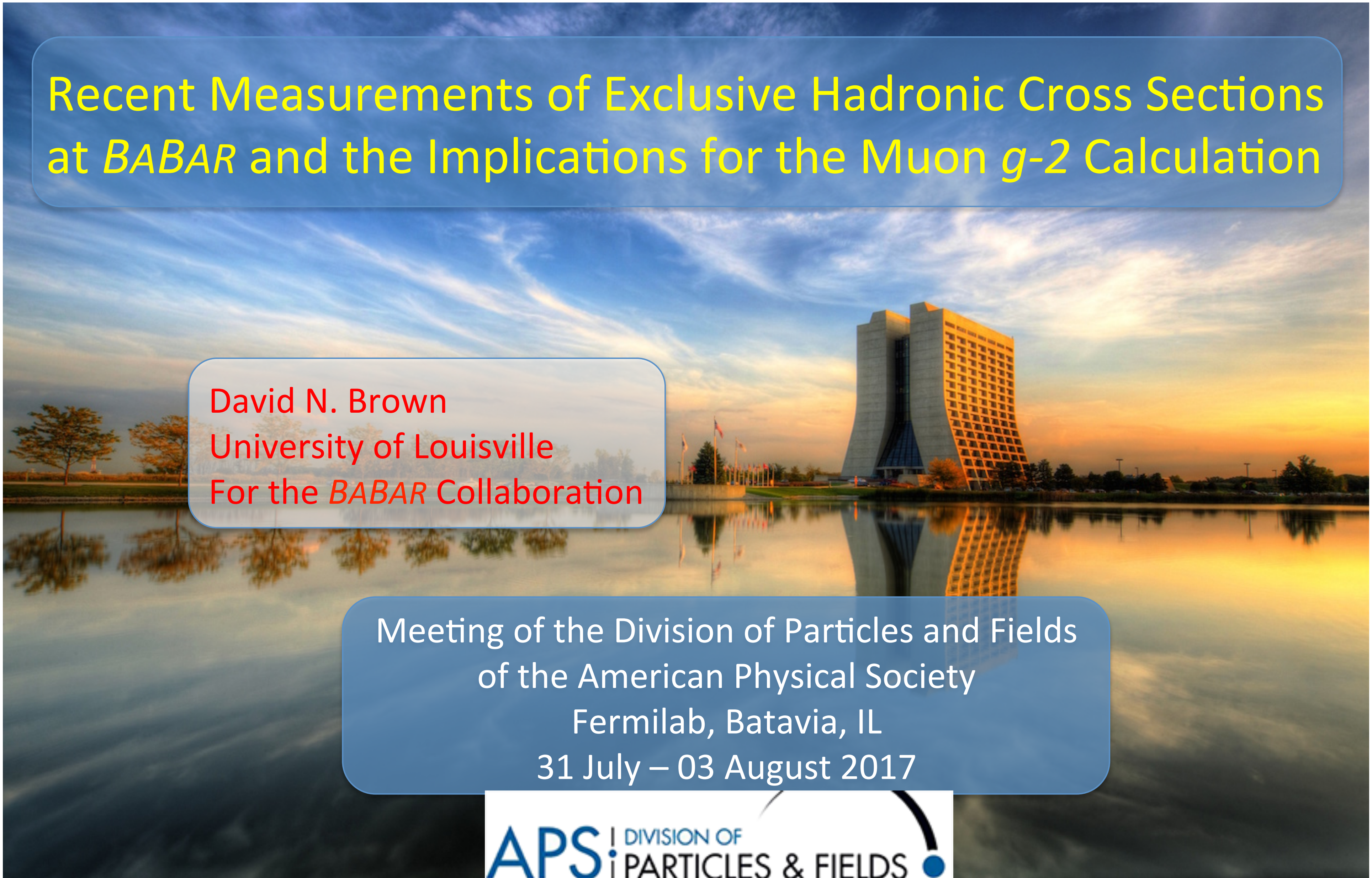

Recent Measurements of Exclusive Hadronic Cross Sections at *BABAR* and the Implications for the Muon *g-2* Calculation

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University of Louisville
For the *BABAR* Collaboration

Meeting of the Division of Particles and Fields
of the American Physical Society
Fermilab, Batavia, IL
31 July – 03 August 2017

BABAR

APS | DIVISION OF PARTICLES & FIELDS
DPF 2017

UNIVERSITY OF LOUISVILLE

Outline

- The muon g-2 puzzle
- *BABAR* and ISR studies
- Recent hadronic cross section measurements

$e^+e^- \to \pi^+\pi^-\pi^0\pi^0, \quad \pi^+\pi^-\eta$ To Be Submitted

$e^+e^- \to K_S^0 K_L^0 \pi^0, \quad K_S^0 K_L^0 \eta, \quad K_S^0 K_L^0 \pi^0 \pi^0$ Phys. Rev. **D95** (2017) 052001.

$e^+e^- \to K_S^0 K^\pm \pi^\mp \pi^0, \quad K_S^0 K^\pm \pi^\mp \eta$ Phys. Rev. **D95** (2017) 092005.

- Implications for muon g-2

The muon g-2 puzzle

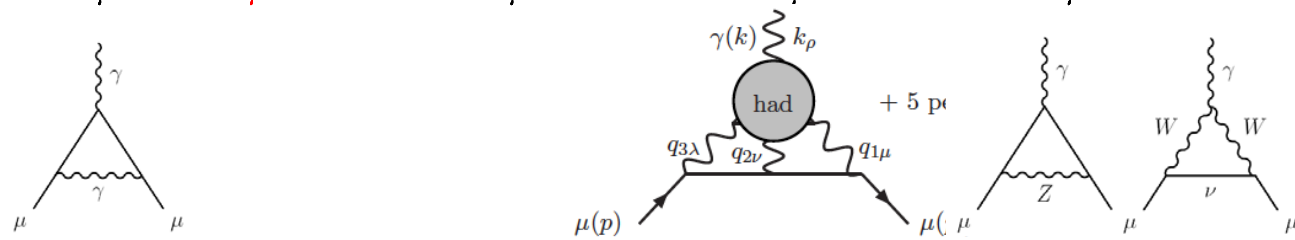
- The magnetic dipole moment for Dirac particles can be written $\vec{\mu} = g\frac{e\hbar}{2mc}\vec{S}$
  - Dirac equation predicts g = 2 exactly
- Corrections from higher order processes cause g to differ from 2 by a small amount. Characterize with anomalous magnetic moment:

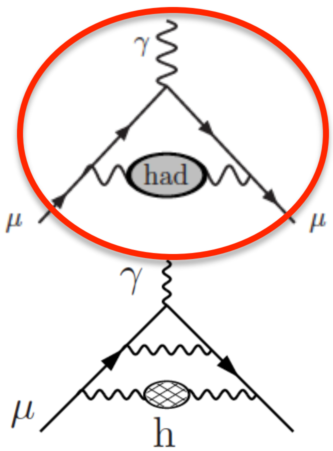
$$a_l = \frac{1}{2}(g_l - 2)$$

- For the electron, theory and experiment agree to great precision
- For the muon, they are in tension, which is the puzzle

Status of a_μ - "before"

$$a_\mu^{theory} = a_\mu^{QED} + a_\mu^{Hadronic\ LO} + a_\mu^{Hadronic\ NLO} + a_\mu^{Hadronic\ LBL} + a_\mu^{Weak}$$



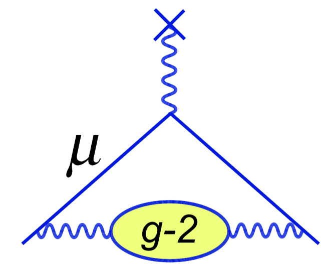


From Quantum Electrodynamics (QED)	11 658 471.895	±0.008
Leading Order Hadronic Vacuum Polarization	692.3	±4.2
NLO Hadronic Vacuum Polarization	-9.8	±0.1
Hadronic Light by Light	10.5	±2.6
Weak Interactions	15.4	±0.1
a_μ^{theory}	11 659 180.2	±4.9
$a_\mu^{experiment}$ J.P. Miller *et al.*, Ann Rev Nucl Part Sci 2012 62:237-64	11 659 208.9	±6.3
$\Delta a_\mu = a_\mu^{experiment} - a_\mu^{theory}$ 3.6σ	28.7	±8.0

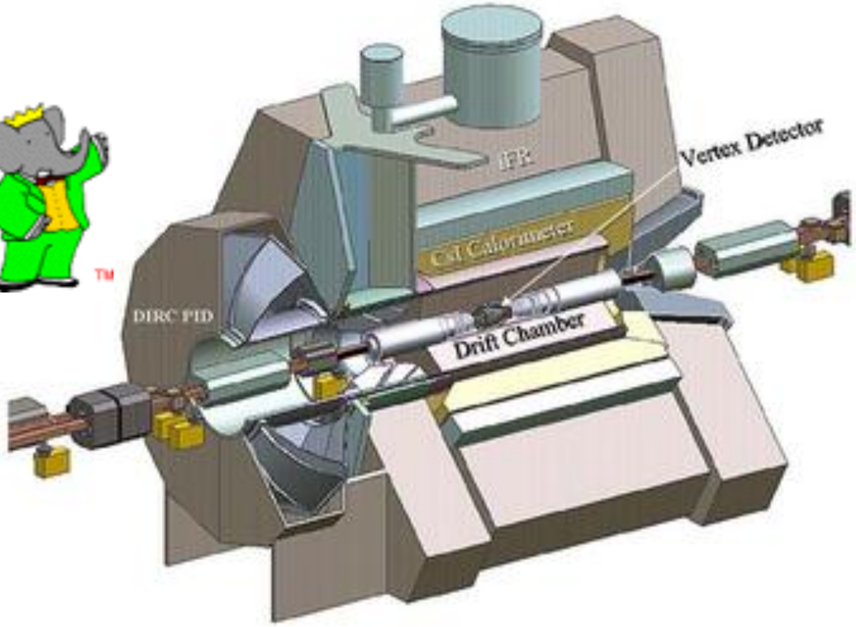
DHMZ: Eur. Phys. J. **C** (2011) **71**:1515 **units of 10^{-10}**

The allure of a_μ

- Longstanding tension between experiment and theory could be a hint at New Physics (NP).
- Rich muon program here at Fermilab and at J-PARC addressing the experimental side.
- Other experiments, including *BABAR*, provide inputs for the theoretical calculations, particularly at low energies where perturbative QCD runs into difficulty.



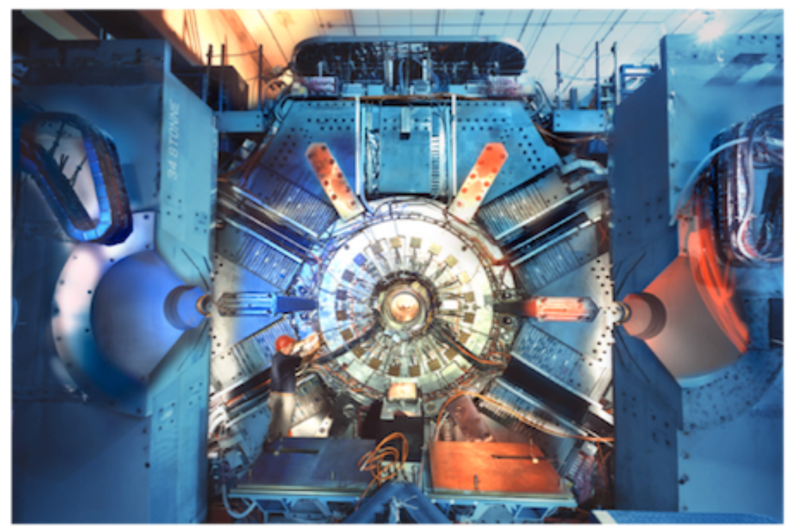
The *BaBar* Experiment at SLAC



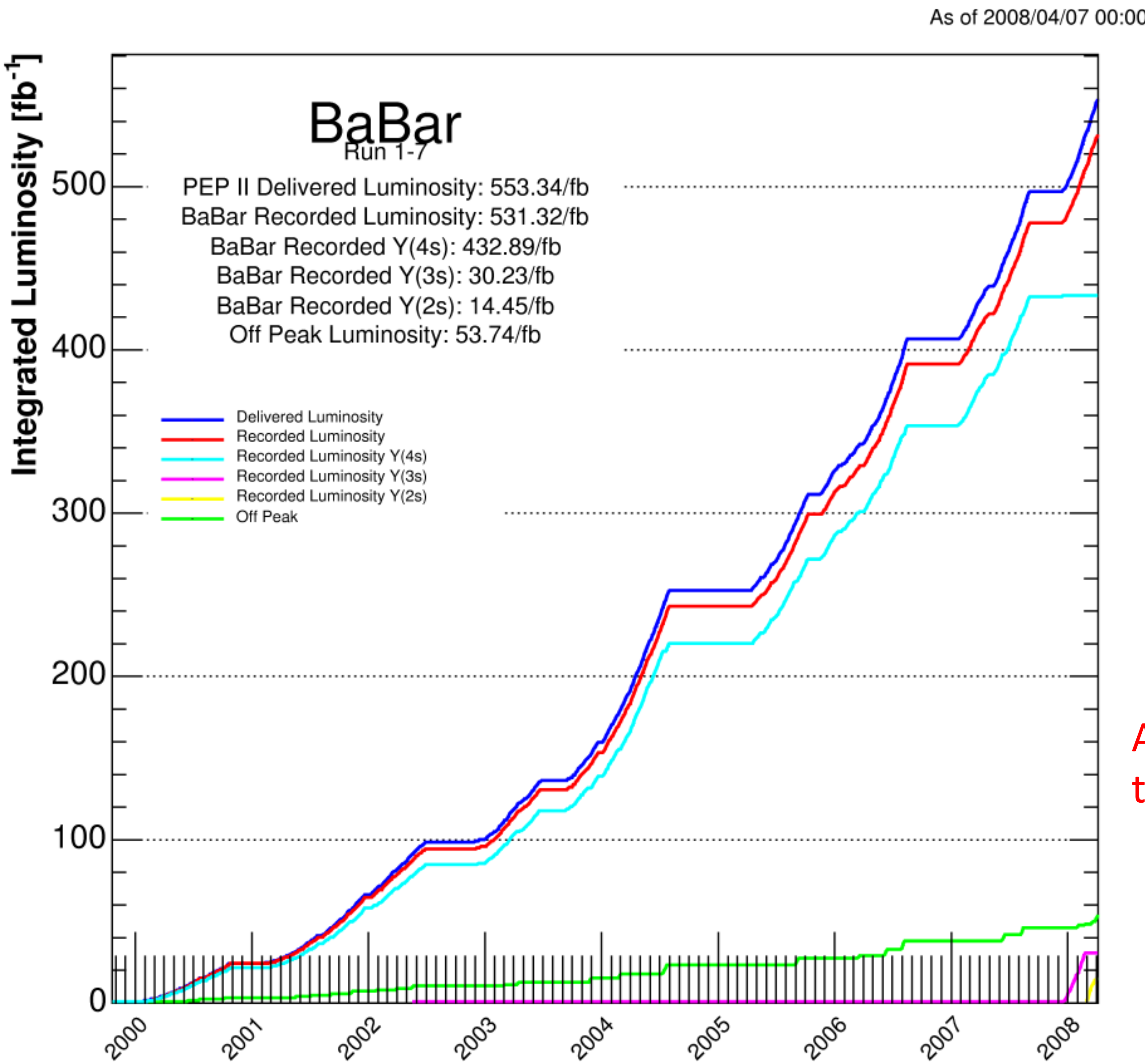
- Asymmetric-energy beams for boost
- Modern/state of the art detector
- 5 cylindrical subdetectors with a 40-layer drift chamber
- Excellent electromagnetic calorimetry
- Multiple measurements for particle identification
- Excellent momentum resolution

- Primarily designed for study of *CP*-violation in *B* meson decays
- Quality and general-purpose design make it suitable for a large variety of studies

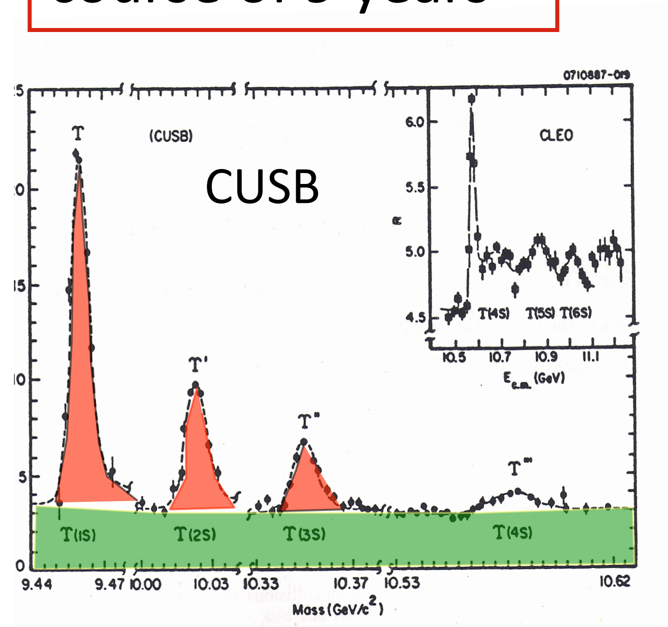
NIM A479,1 (2002),
update: NIM A729, 615 (2013)



The *BABAR* Running Era



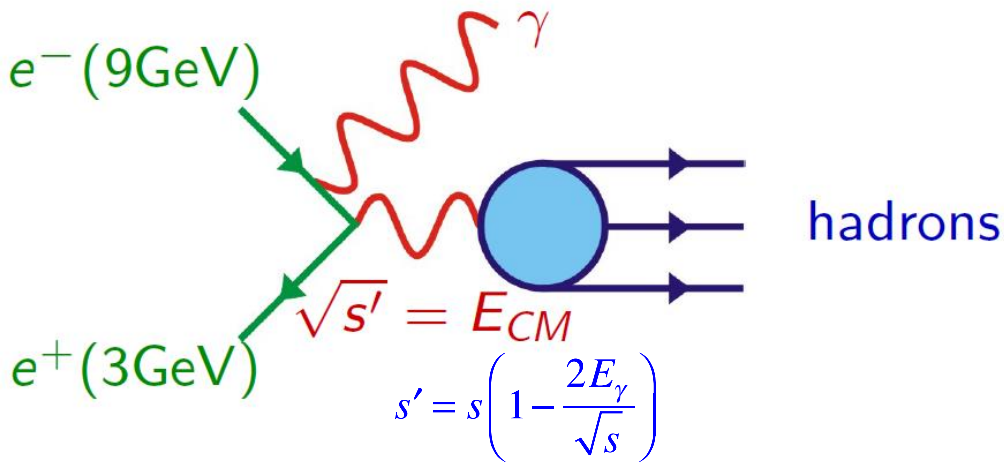
7 Runs over the course of 9 years

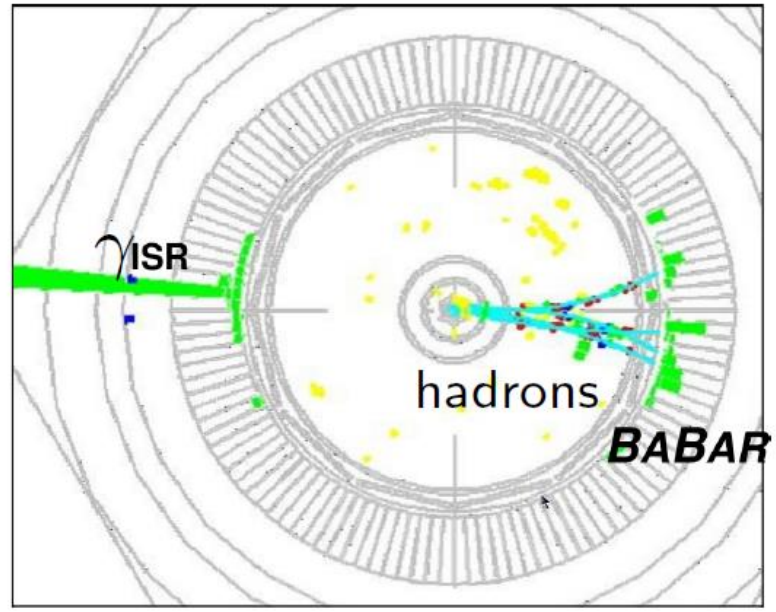


Analyses here use ~470 fb^{-1} of data taken near 4S

- First collisions with BaBar May 26, 1999
- Final data taken 12:43 p.m., April 7, 2008

ISR Method





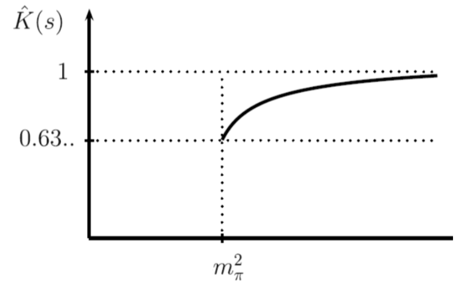
- Photon emitted by electron or positron – Initial State Radiation (ISR)
  - Carries away energy - allows “scan” of energies for remaining system
  - Easily identified back-to-back topology
  - High acceptance, even at threshold
  - Exploited heavily at *BABAR* for large number of hadronic cross sections

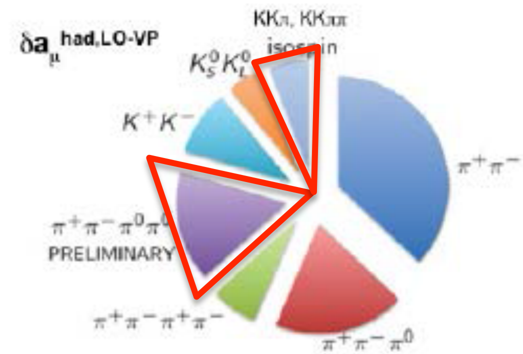
BABAR ISR Contributions

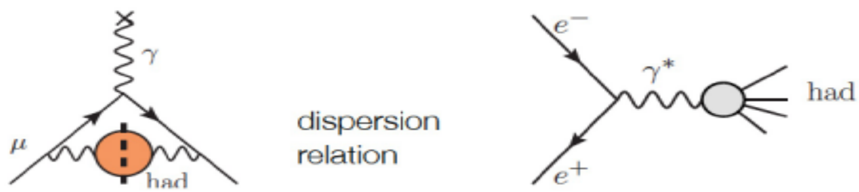
Calculate via dispersion relation integral.
Lowest CM energies contribute most

$$a_\mu^{Hadronic\ LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{\hat{K}(s)}{s^2} R_{HAD}(s)\,ds$$

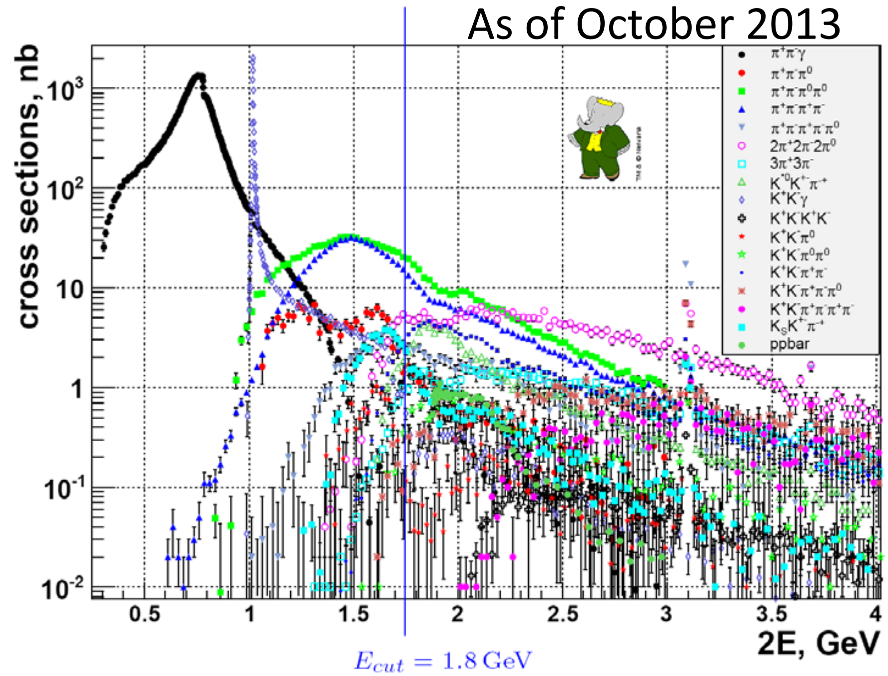
$$R_{HAD}(s) = \frac{\sigma(e^+e^- \to HAD)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$







As of October 2013



Above ~2 GeV, theory can use perturbative QCD.
Below that, rely on experimental input. *BABAR* providing significant inputs

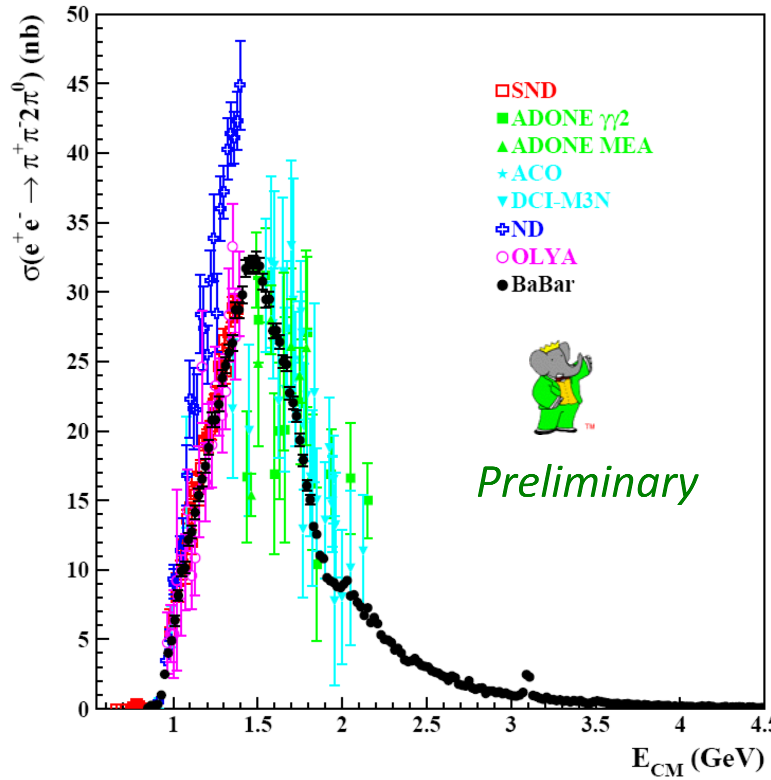
Study of $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

To Be Submitted

- Resolves tensions among previous results
- Large signal (over 150,000 events)
- Larger energy range than previous results
- Biggest background from $e^+e^- \to \pi^+\pi^- 3\pi^0$
  - Background measured from data

Impact:

Greatly improved uncertainties. ~3.3% for energies less than 1.8 GeV



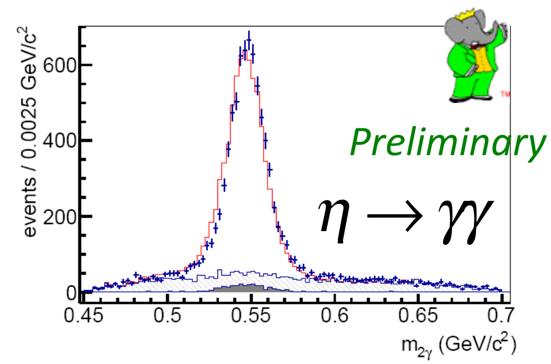
$$a_\mu^{\pi^+\pi^-\pi^0\pi^0} = (17.9 \pm 0.1 \pm 0.6) \times 10^{-10}$$

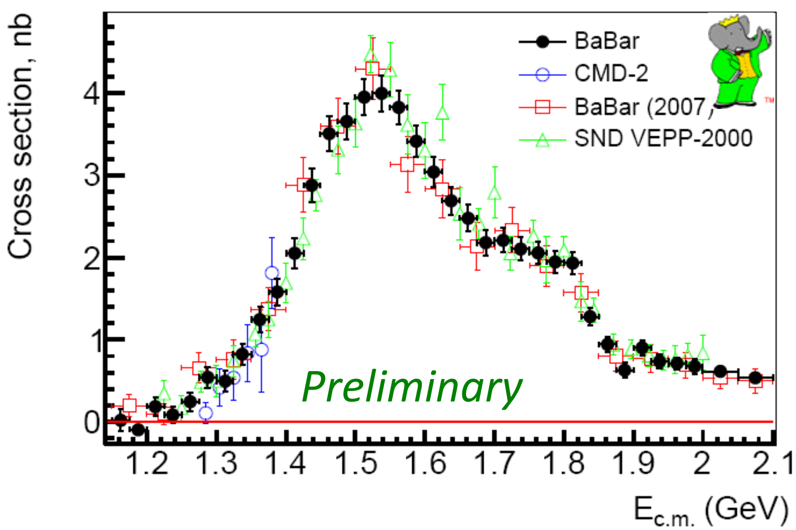
BABAR Preliminary

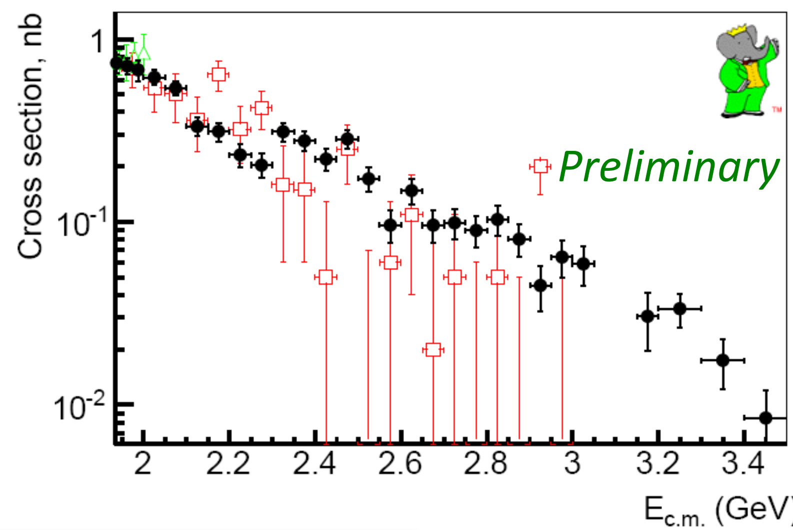
Study of $e^+e^- \to \pi^+\pi^-\eta$

To Be Submitted

- Reconstruct via $\eta \to \gamma\gamma$ decay
- Highest energy range for this mode
- Most precise measurement
- ~8,000 signal events





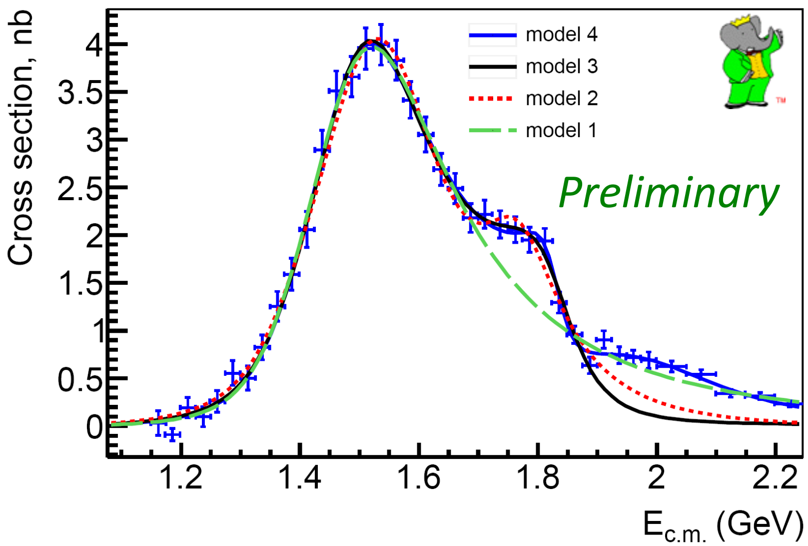


$$a_\mu^{\pi^+\pi^-\eta} = (1.19 \pm 0.02 \pm 0.06) \times 10^{-10}$$

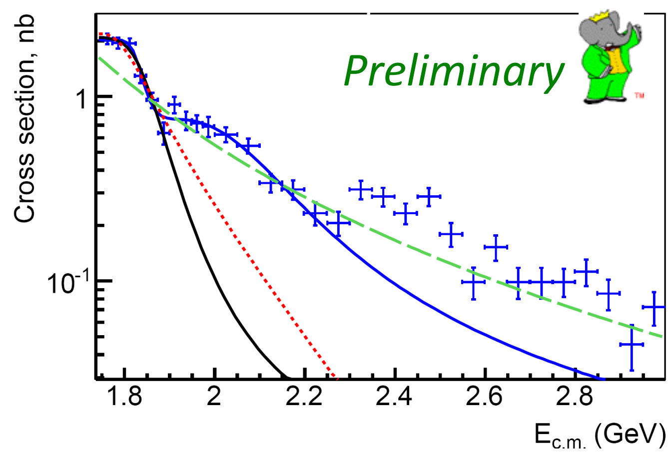
BABAR Preliminary

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

To Be Submitted



Vector Dominance Model fits
- detailed information on dynamics

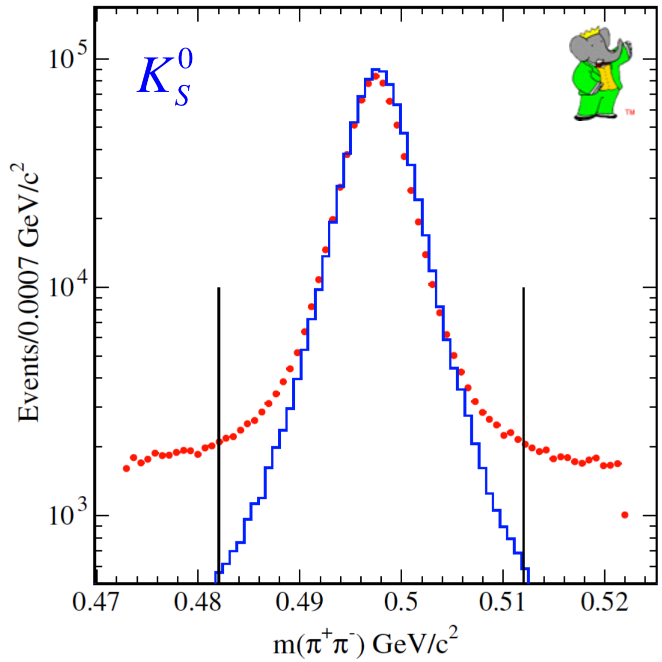


model 1: ρ(770) −ρ(1450) fits ECM < 1.7 GeV
model 2: ρ(770) −ρ(1450) −ρ(1700) fits < 1.9 GeV
model 3: ρ(770) −ρ(1450) +ρ(1700) fits < 1.9 GeV
model 4: ρ(770) −ρ(1450) +ρ(1700) +ρ(2150) fits < 2.2 GeV
relative phases 0 (+) and 180° (−)

Implications for both a_μ and hadronic τ decays!

Modes with Kaons

K_S^0 reconstructed as a pair of opposite charge tracks with a displaced vertex via its decay $K_S^0 \to \pi^+\pi^-$

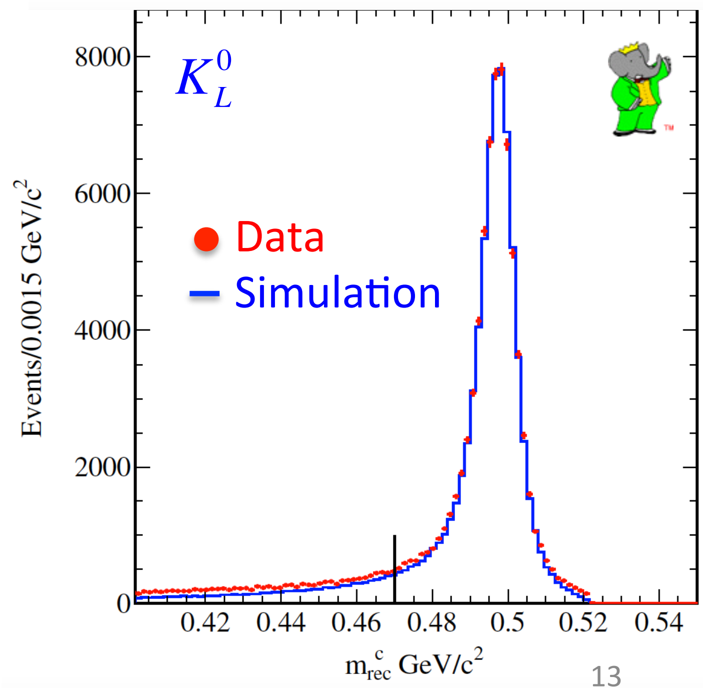


K_L^0 identified as an isolated energy cluster in the calorimeter, cluster shape not consistent with a photon.

- Validated via

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

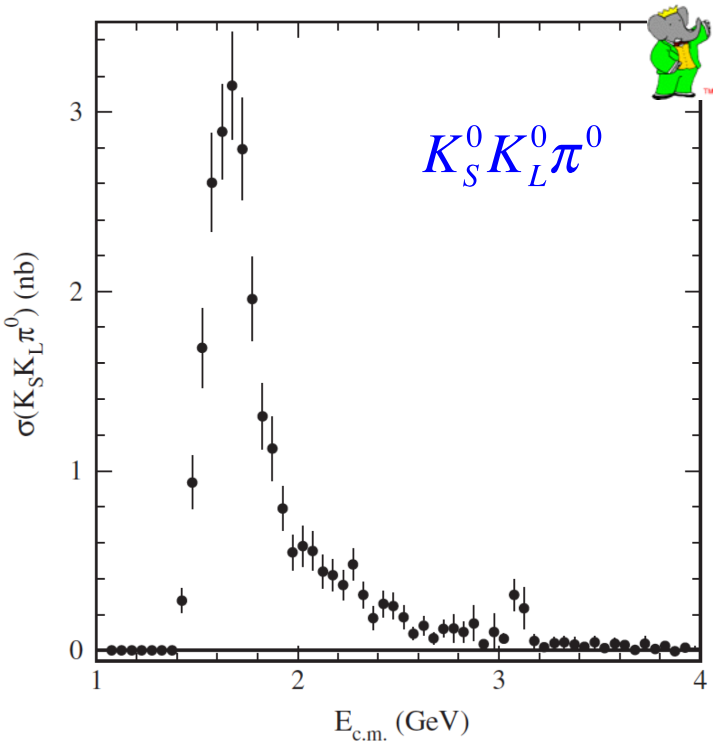
PR**D89** 0092002 (2014)



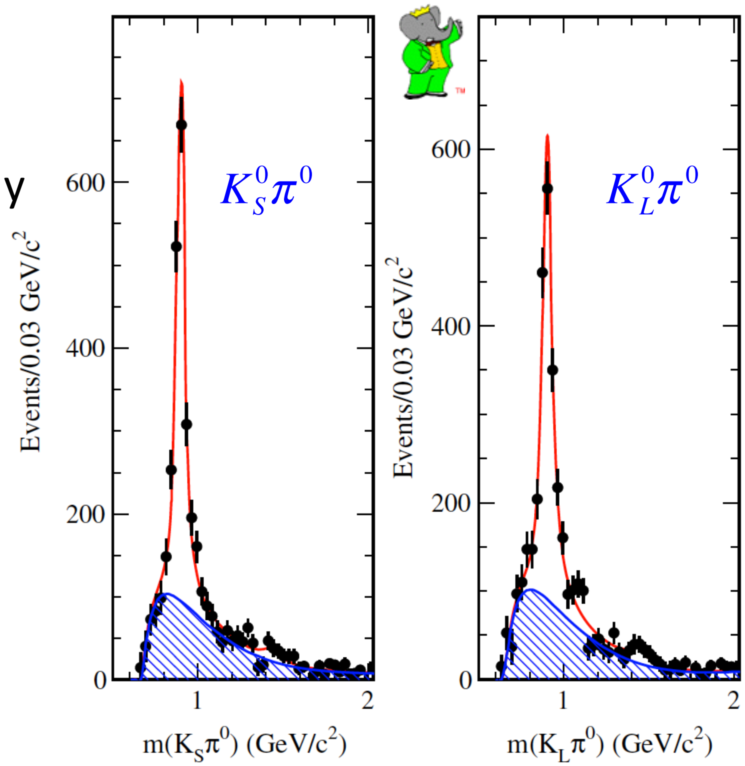
$K^\pm$ identified via standard charged-particle PID system utilizing specific ionization, timing, Cerenkov radiation, calorimetry

Study of $e^+e^- \to K_S^0 K_L^0 \pi^0, \quad K_S^0 K_L^0 \eta, \quad K_S^0 K_L^0 \pi^0 \pi^0$

Phys. Rev. **D95** (2017) 052001.



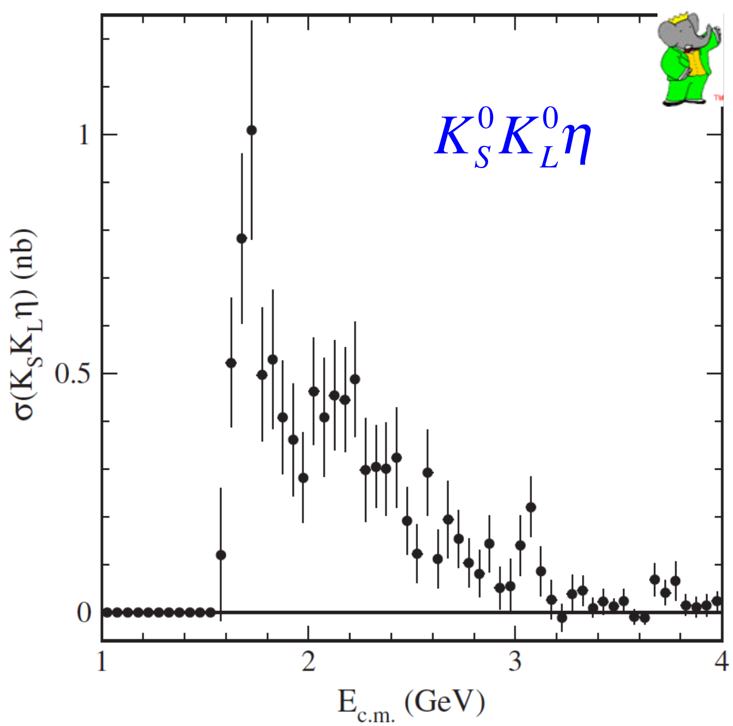
Extensive study of resonant substructure.

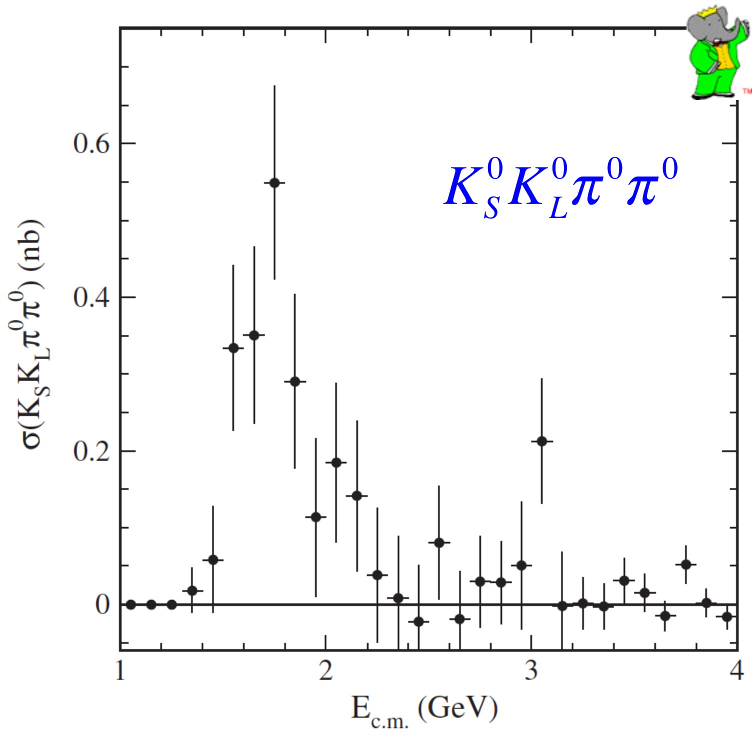


Improved energy range and cross-section uncertainties.
First observation for J/ψ decays to these states

Study of $e^+e^- \rightarrow K_S^0 K_L^0 \pi^0, \quad K_S^0 K_L^0 \eta, \quad K_S^0 K_L^0 \pi^0 \pi^0$

Phys. Rev. **D95** (2017) 052001.



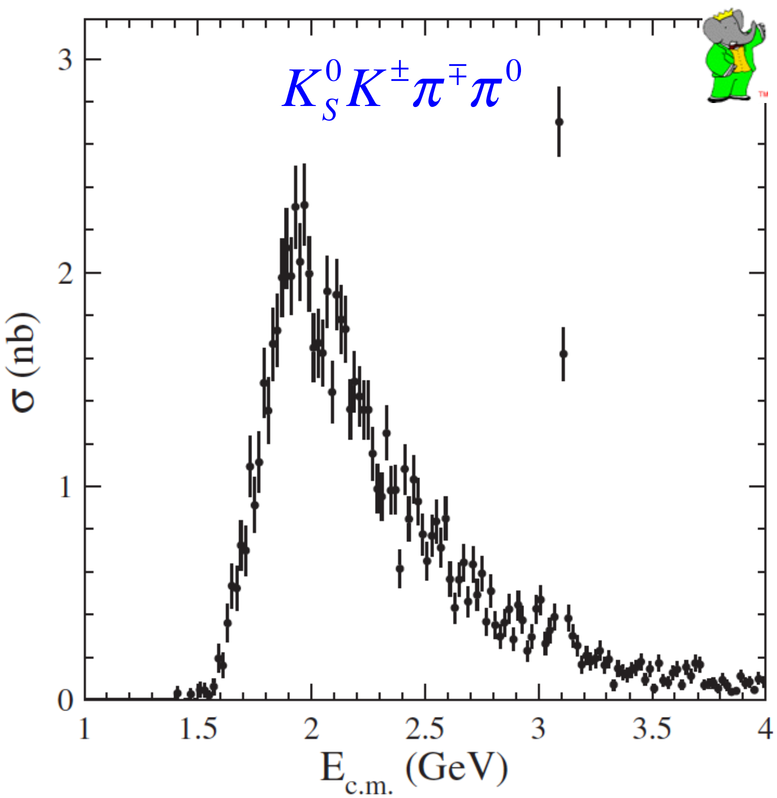


Very significant contribution from $\phi\eta$

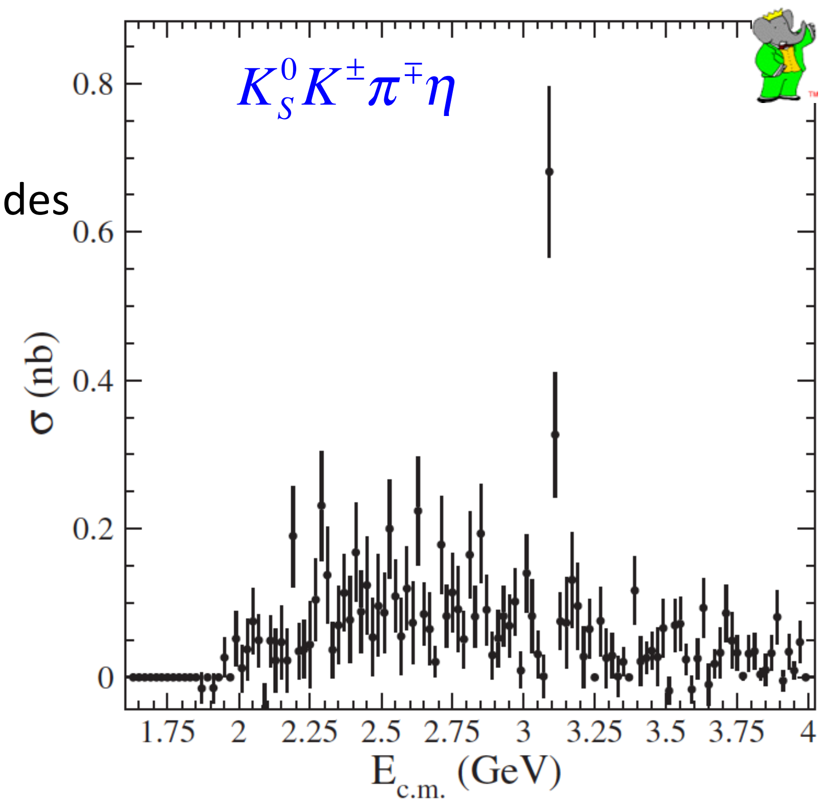
No significant contribution from $K^* K^*$

Study of $e^+e^- \rightarrow K_S^0 K^{\pm}\pi^{\mp}\pi^0, \quad K_S^0 K^{\pm}\pi^{\mp}\eta$

Phys. Rev. **D95** (2017) 092005.

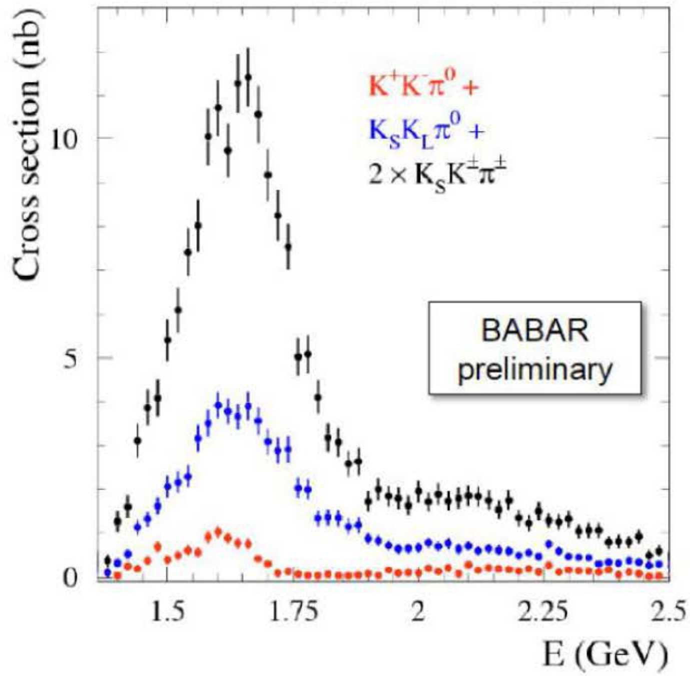


Completing the $KK\pi$ modes



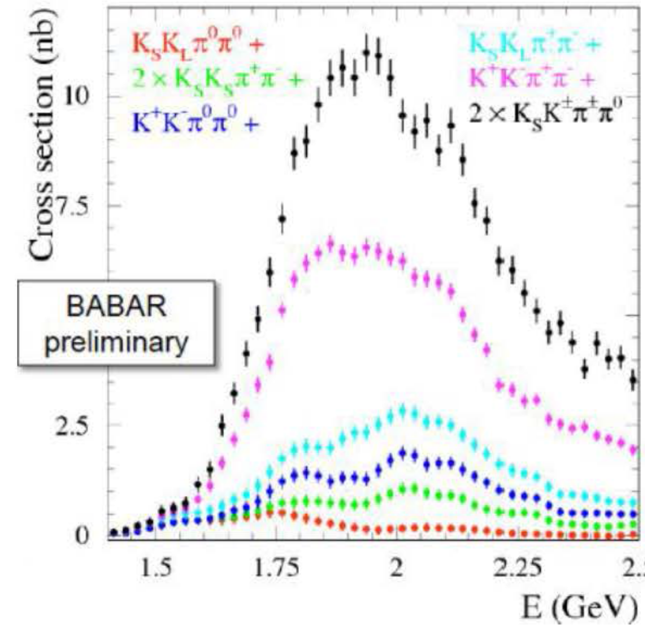
Significant contributions from J/ψ obvious

Total $KK\pi(\pi)$ cross section



Courtesy
V. Druzhinin

EPJ WoC **142,** 01013 (2017)

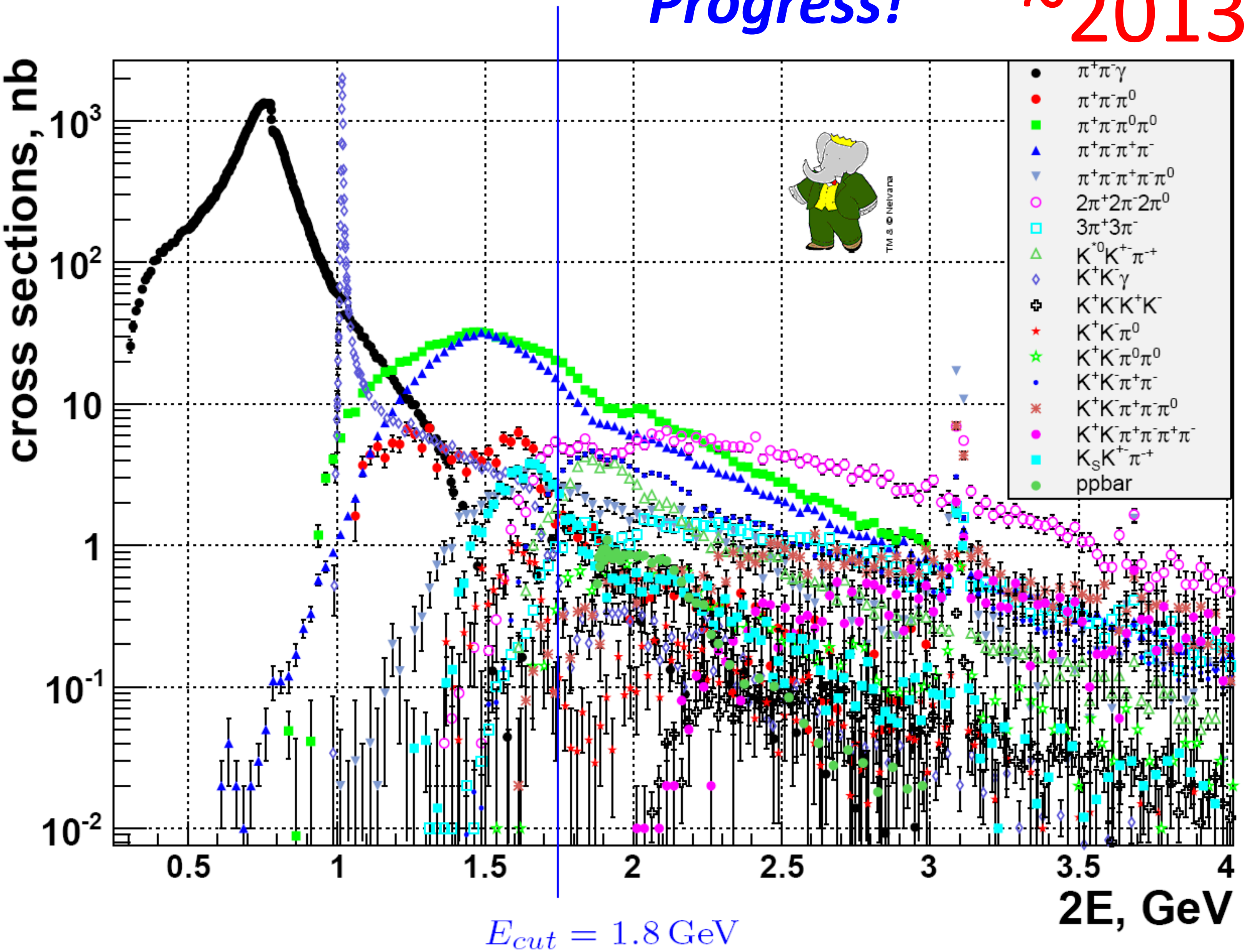


- All possible modes now measured by BABAR
- No more need to rely on isospin arguments
- Improves precision on inputs to g-2 calculations

$$a_\mu^{KK\pi} = (2.45 \pm 0.15)\times 10^{-10}$$
$$a_\mu^{KK\pi\pi} = (0.85 \pm 0.05)\times 10^{-10}$$

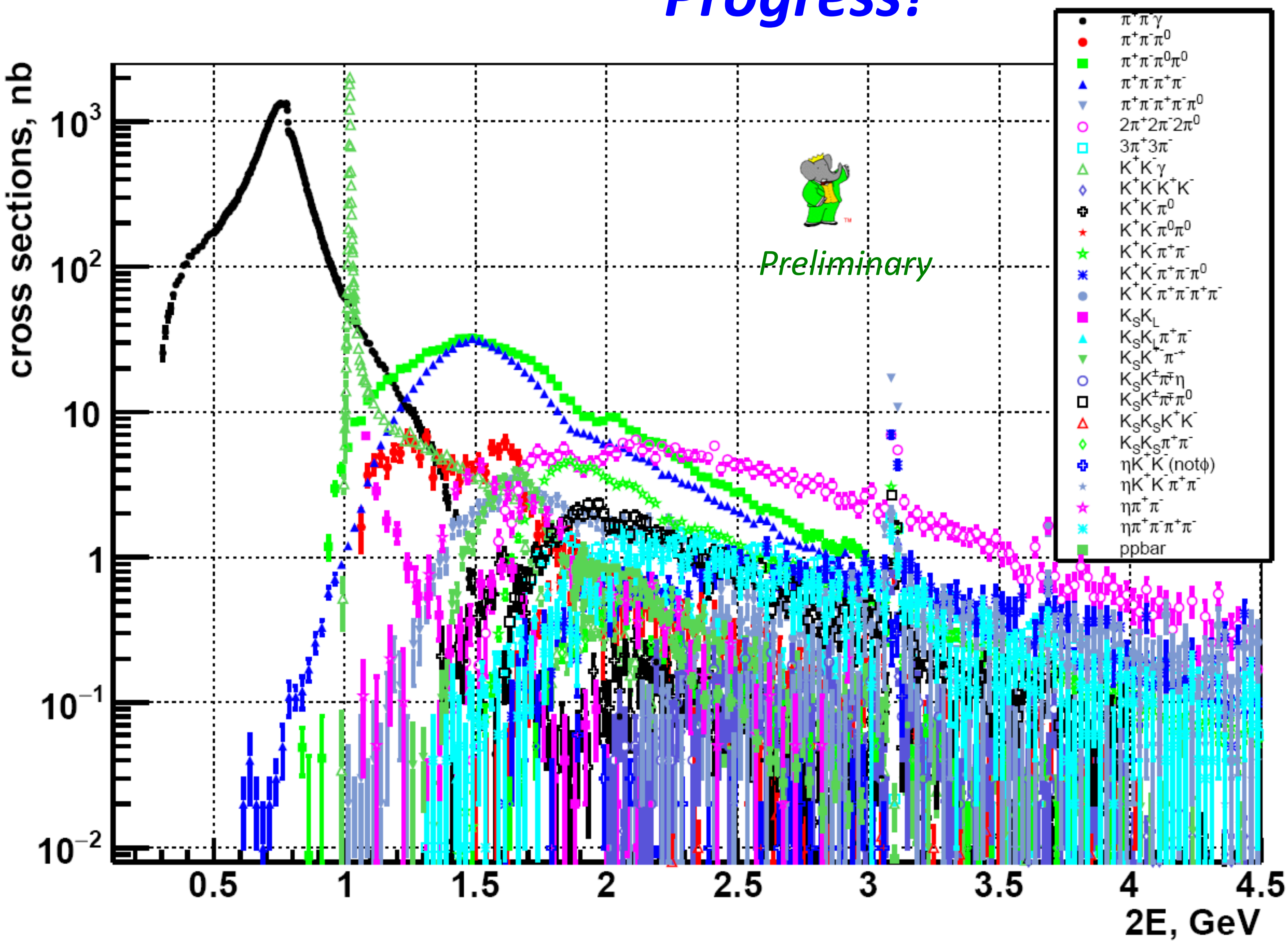
Progress!

~2013



Courtesy Fedor V. Ignatov, via J. Chauveau

Progress!



Now

Courtesy Fedor V. Ignatov, via J. Chauveau

Status of a_μ – "after"

$$a_\mu^{theory} = a_\mu^{QED} + a_\mu^{Hadronic\ LO} + a_\mu^{Hadronic\ NLO} + a_\mu^{Hadronic\ NNLO} + a_\mu^{Hadronic\ LBL} + a_\mu^{Weak}$$

From Quantum Electrodynamics (QED)	11 658 471.885	±0.004
Leading Order Hadronic Vacuum Polarization	692.8	±3.3
Before:	*692.3*	*±4.2*
NLO Hadronic Vacuum Polarization	-9.87	±0.09
NNLO Hadronic Vacuum Polarization	1.24	±0.01
→ Hadronic Light by Light	10.5	±2.6
Weak Interactions	15.4	±0.1
a_μ^{theory}	11 659 181.9	±4.2
$a_\mu^{experiment}$	11 659 208.9	±6.3
$\Delta a_\mu = a_\mu^{experiment} - a_\mu^{theory}$ — 3.6σ	27.0	±7.6

M. Davier, arXiv 1612.02743 (2017). **units of 10^{-10}**

Summary and Conclusions

- *BaBar* has made considerable use of the ISR technique to study e^+e^- annihilation across a broad energy range.
  - Including several new hadronic modes reported here.
- Important to improve our knowledge of muon g-2
  - the puzzle continues, more input needed!
  - More on the way! Stay Tuned.