Study of low-energy e^+e^- annihilation into hadrons at *BABAR*

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DIS2023: XXX International Workshop on Deep Inelastic Scattering and Related Subjects

Outline of the Talk

- Motivation
- The *BABAR* Experiment
- Study of $e^+e^- \to \pi^+\pi^-\pi^0$ using ISR — PRD **104** 112003 (2021)
- Studies of $e^+e^- \to KK\pi\pi\pi$ modes using ISR — arXiv:2207.10340(2022) accepted for publication, PRD

Charge conjugation implied throughout

Motivation: The muon $g - 2$ puzzle

The magnetic dipole moment for Dirac particles can be written $\vec{\mu} = g\frac{e\hbar}{2mc}\vec{S}$

The 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:

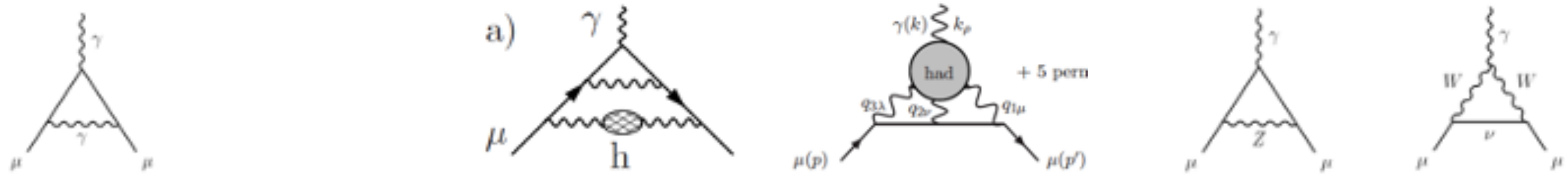
$$a_l = \frac{1}{2}(g_l - 2)$$

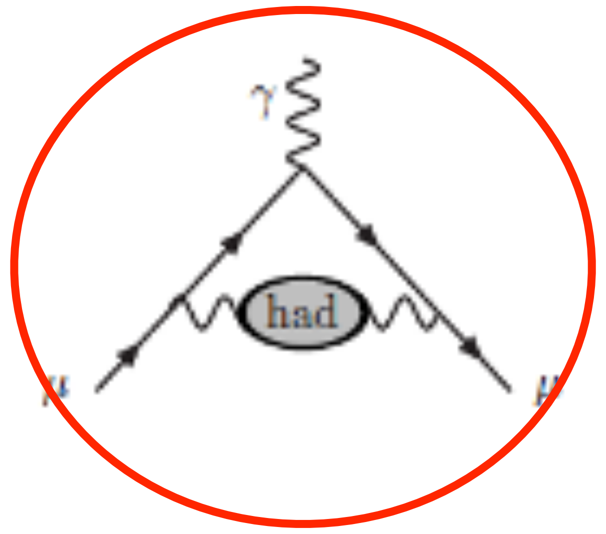
For the electron, theory and experiment agree to great precision

For the muon, they are in tension, which is the puzzle

Motivation: Status of a_μ - "before"

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



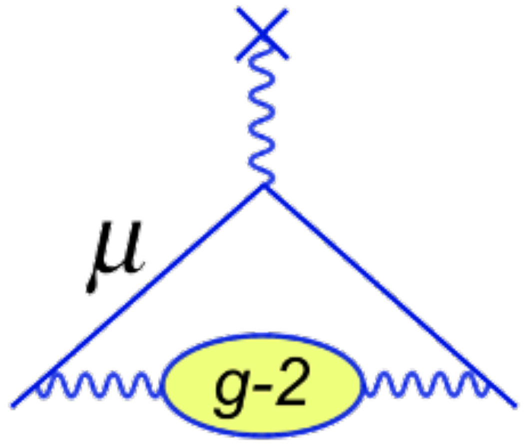


From Quantum Electrodynamics (QED)	11 658 471.895	±0.008
Leading Order Hadronic Vacuum Polarization	694.0	±4.0
NLO Hadronic Vacuum Polarization	-9.9	±0.1
Hadronic Light by Light	10.5	±2.6
Weak Interactions	15.4	±0.1
a_μ^{theory}	11 659 183.1	±4.8
$a_\mu^{experiment}$ J.P. Miller et al., Ann Rev Nucl Part Sci 2012 62:237-64	11 659 209.1	±6.3
$\Delta a_\mu = a_\mu^{experiment} - a_\mu^{theory}$	3.3 σ 26.000	±7.900

DHMZ: Eur. Phys. J. C(2020) **80**:241 units of 10^{-10}

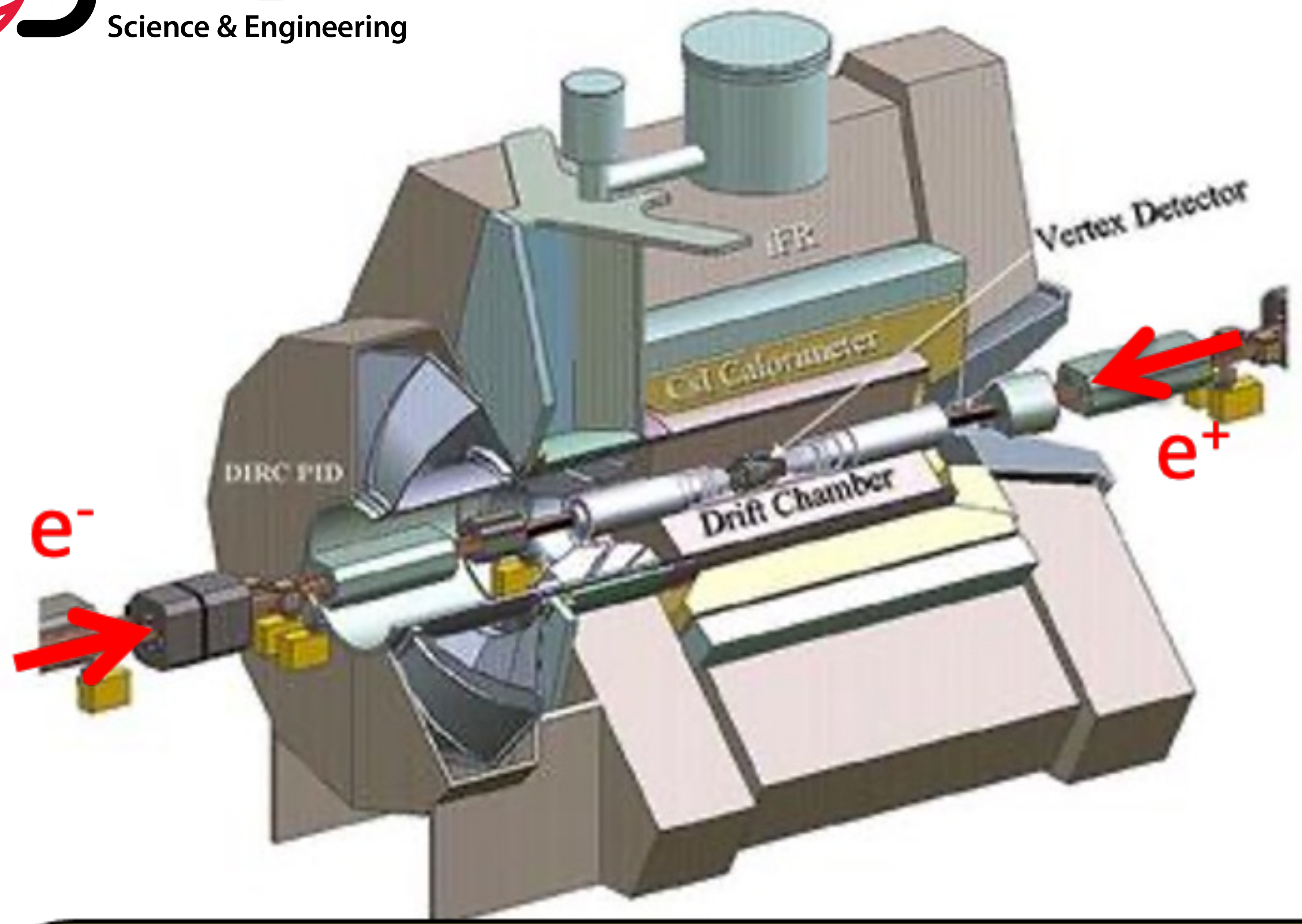
Motivation: The *allure* of a_μ

- Longstanding tension between experiment and theory could be a hint at New Physics (NP)
- Rich muon program at Fermilab and 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

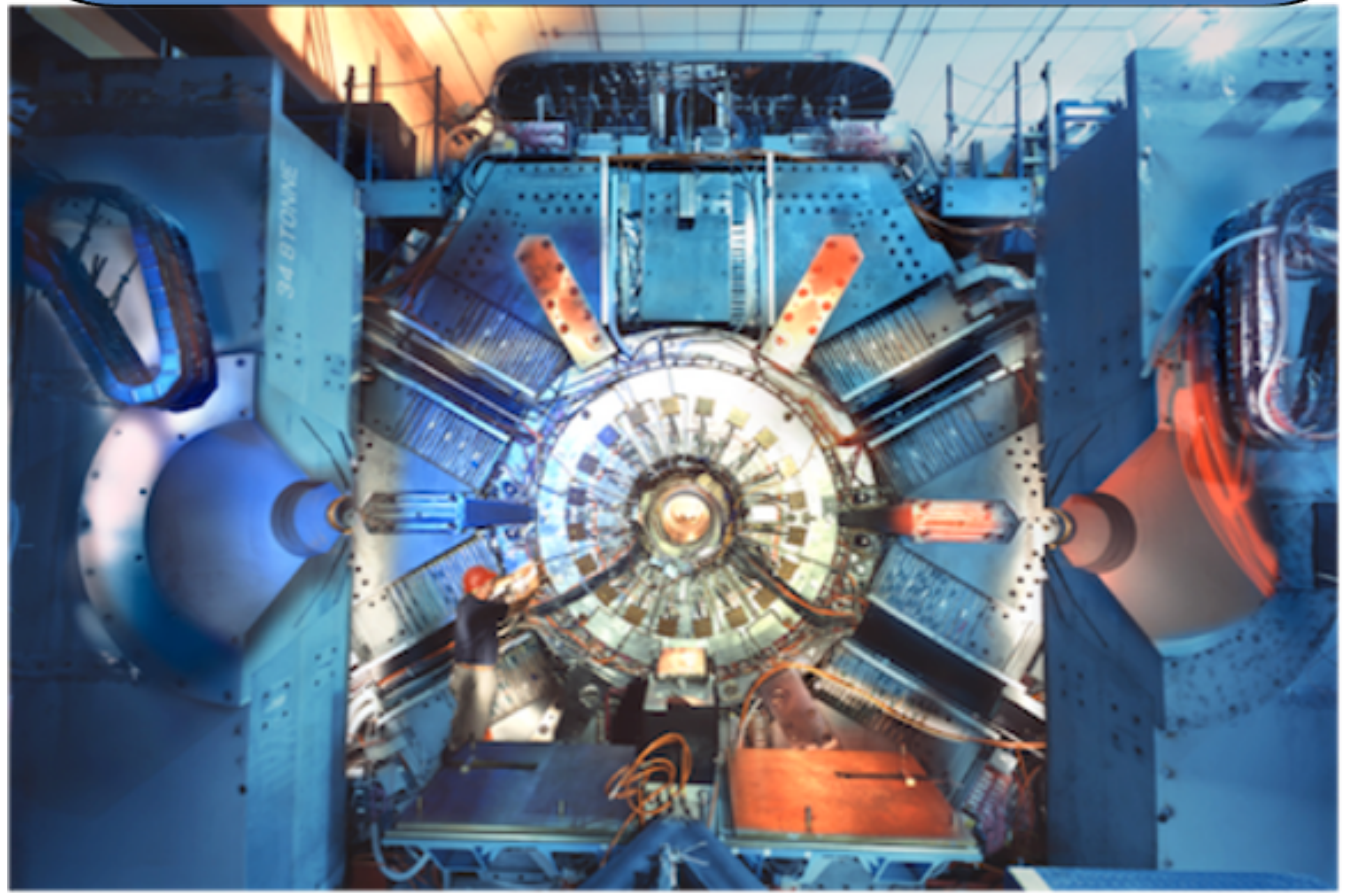
The *B*A*B*AR Detector



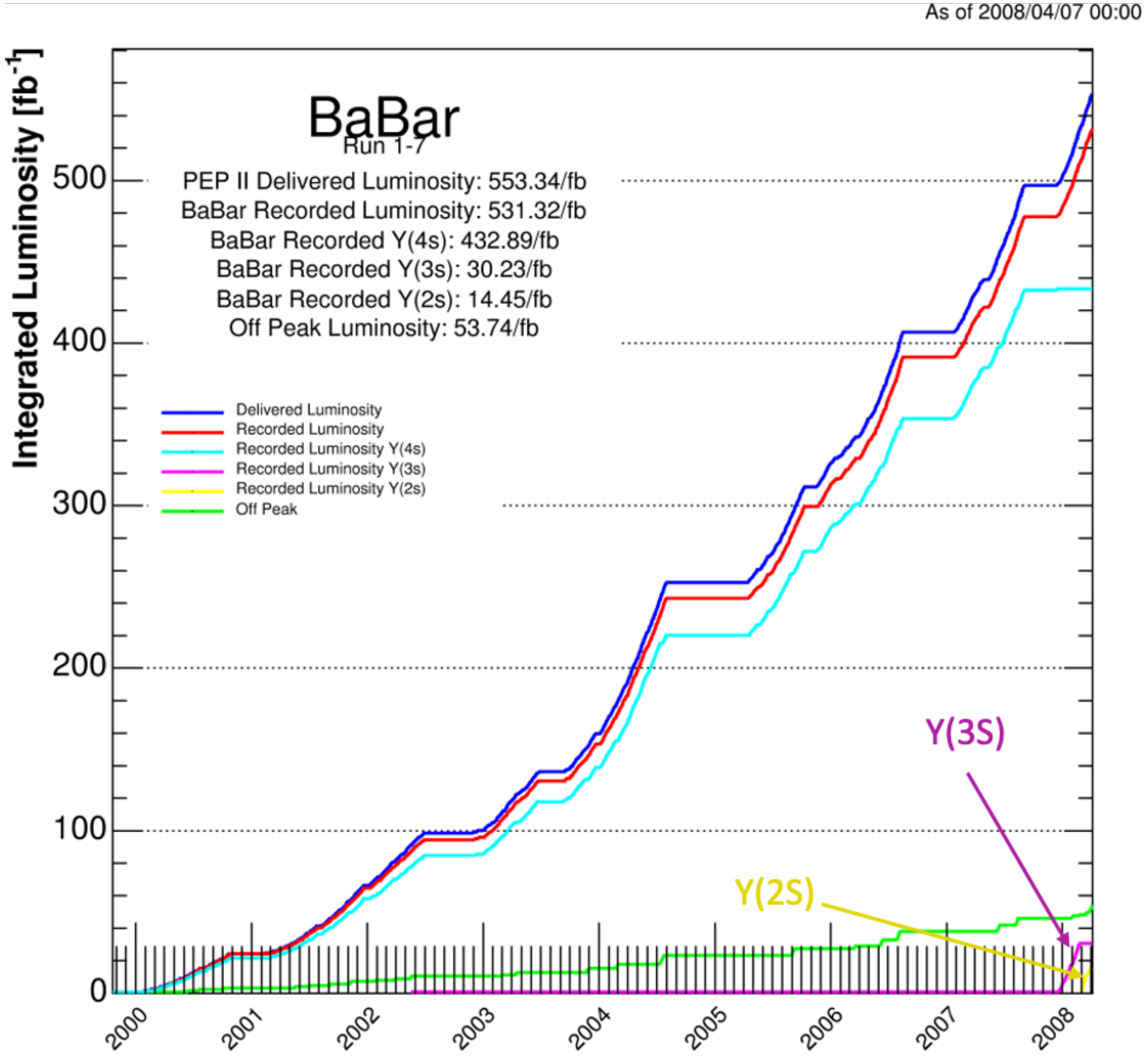
- Asymmetric-energy beams for boost
- Modern/state of the art detector
- 5 cylindrical subdetector systems with a 40-layer drift chamber + 5-layer vertex detector
- Excellent electromagnetic calorimetry
- Multiple measurements for particle identification
- Excellent momentum resolution

- 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

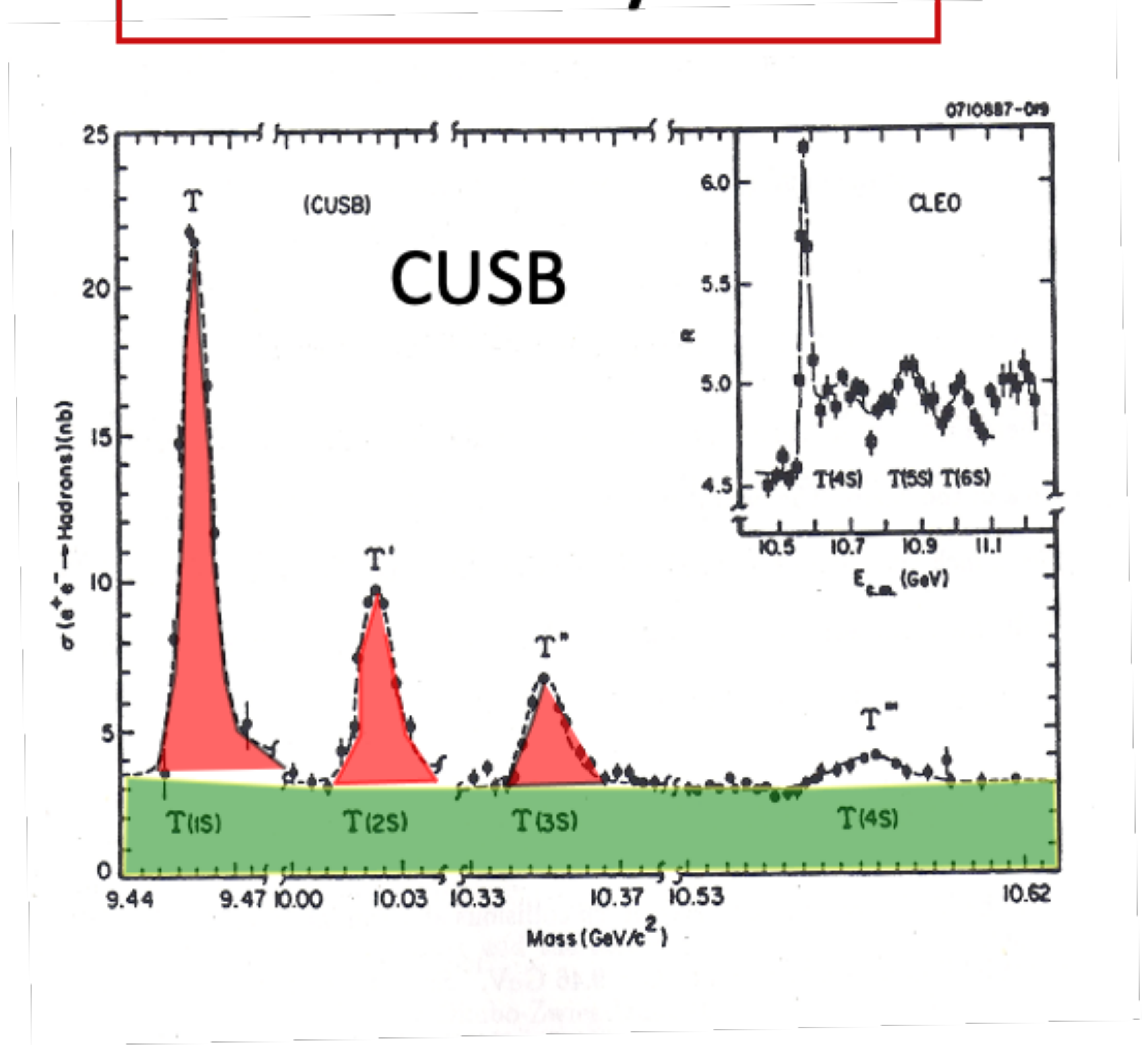
NIM A479,1 (2002),
update: NIM A729, 615 (2013)



The *BaBar* Running Era



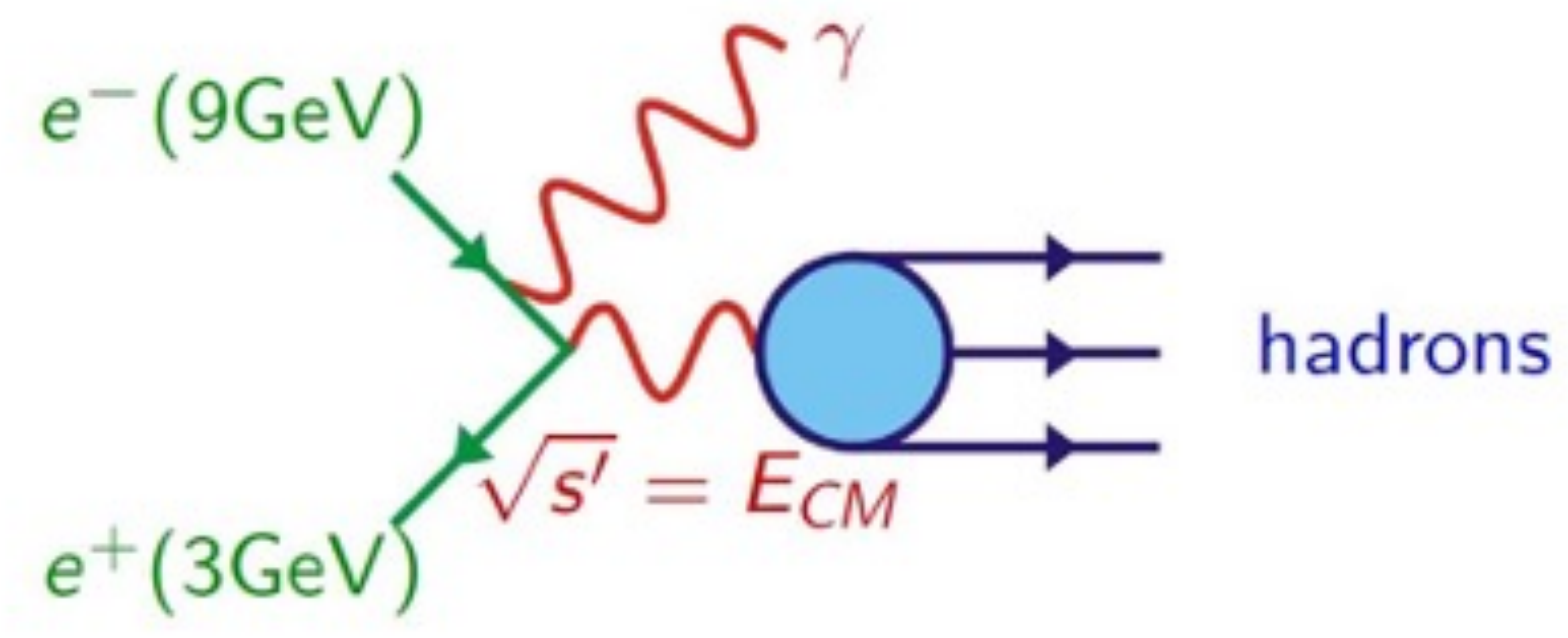
7 Runs over the course of 9 years

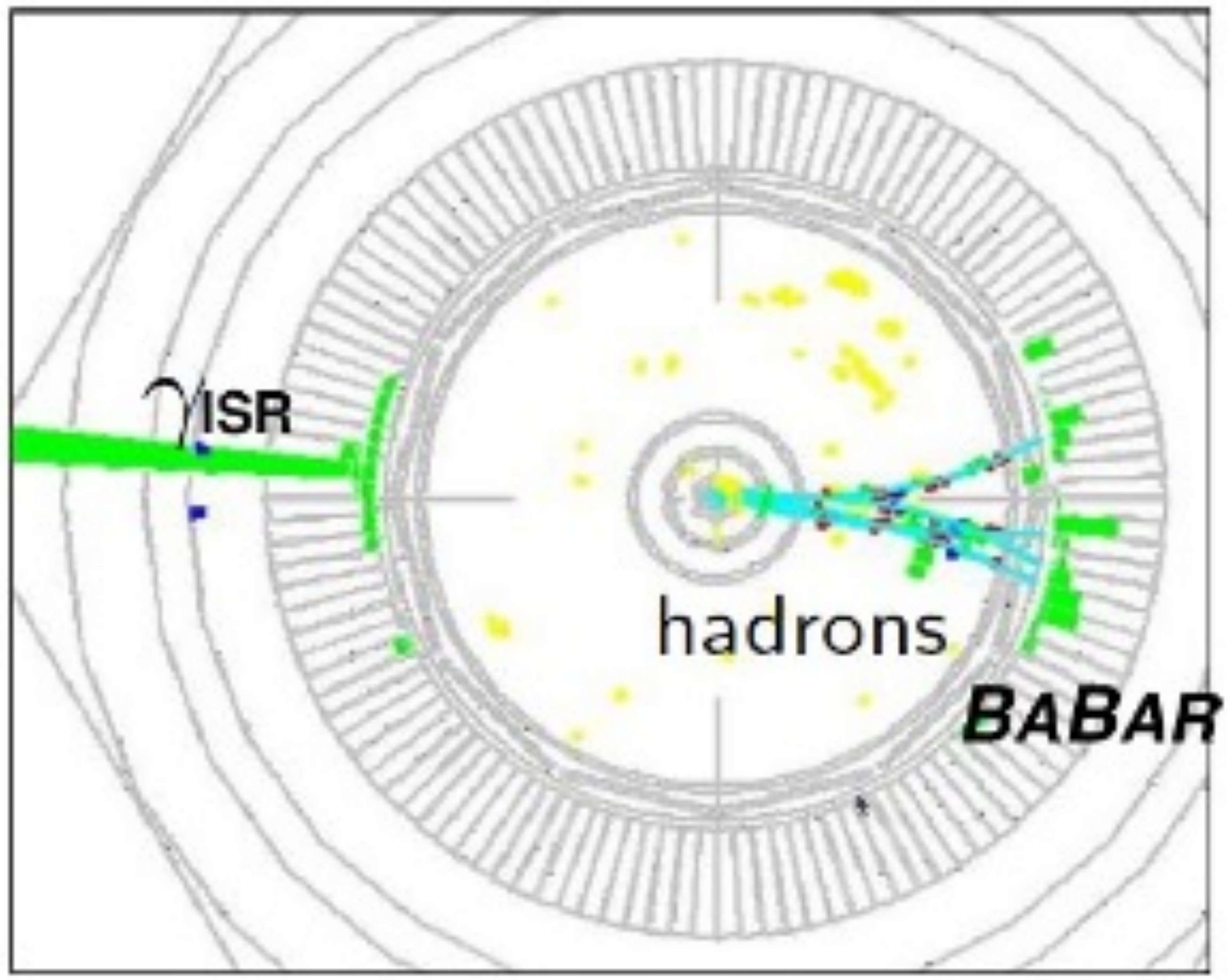


This analysis uses 468 fb^{-1} of data

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

ISR Method



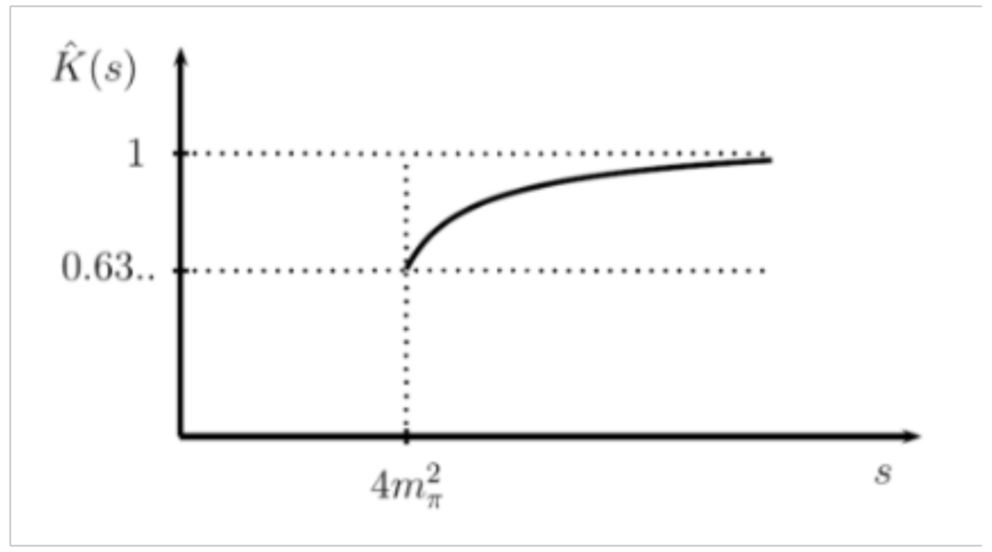


- Photon emitted by electron or positron - Initial State Radiation (ISR)
  - Carries away energy - allows “scan” of energies for remaining system
  - Easily identified back-to-back topology
  - High acceptance, even at threshold
  - Exploited heavily at *BABAR* for large number of hadronic cross sections

BABAR ISR Contributions

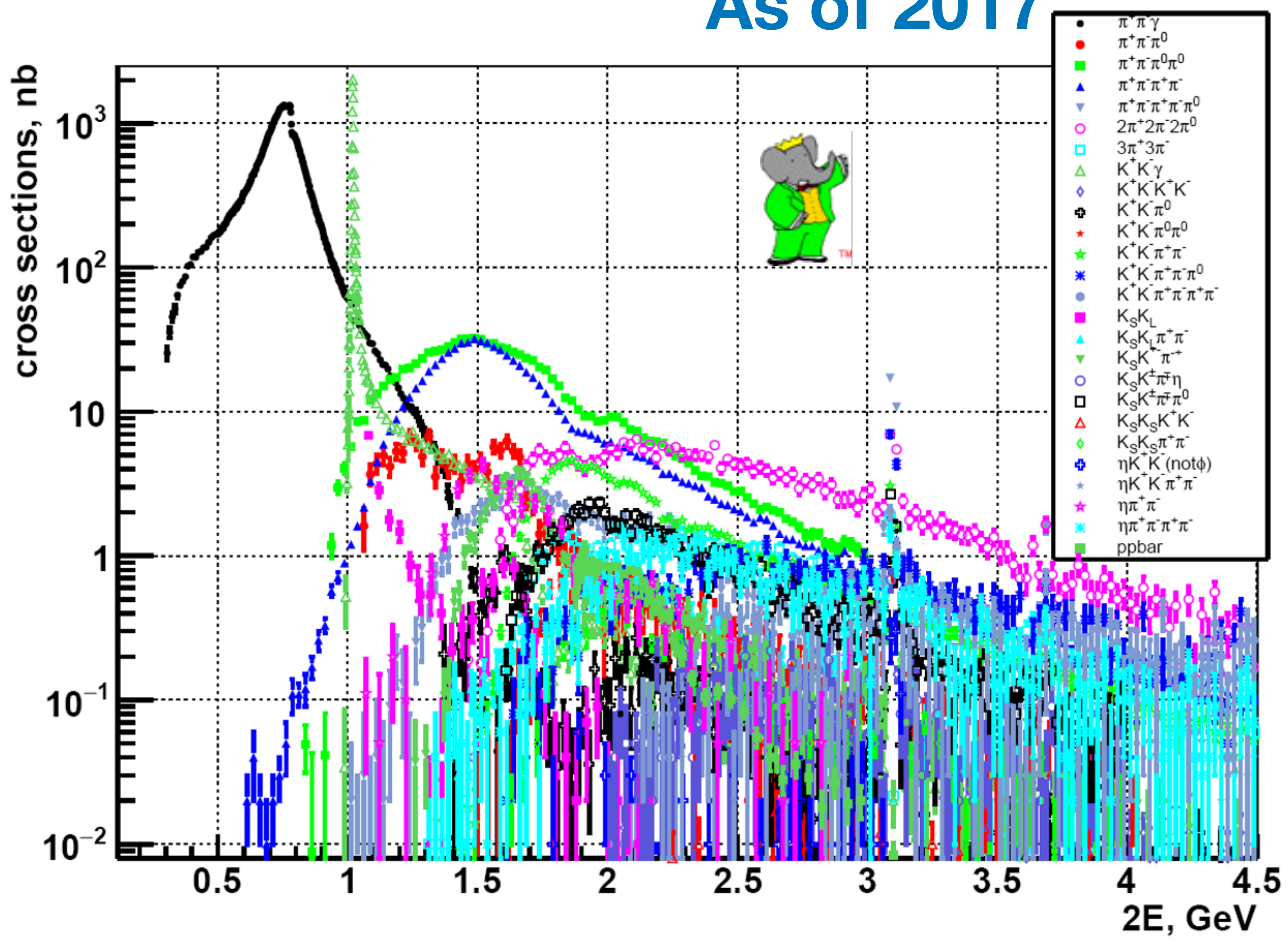
Calculate via dispersion relation integral.
Lowest CM energies contribute most

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



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

As of 2017



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

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

PRD **104** 112003 (2021)

From previous measurements, we know this mode contributes approximately 7% to $a_\mu^{HAD\ LO}$, second only to $e^+e^- \to \pi^+\pi^-$

The relative uncertainty on the three pion mode is over 3%, which is almost five times the relative uncertainty on the two pion mode

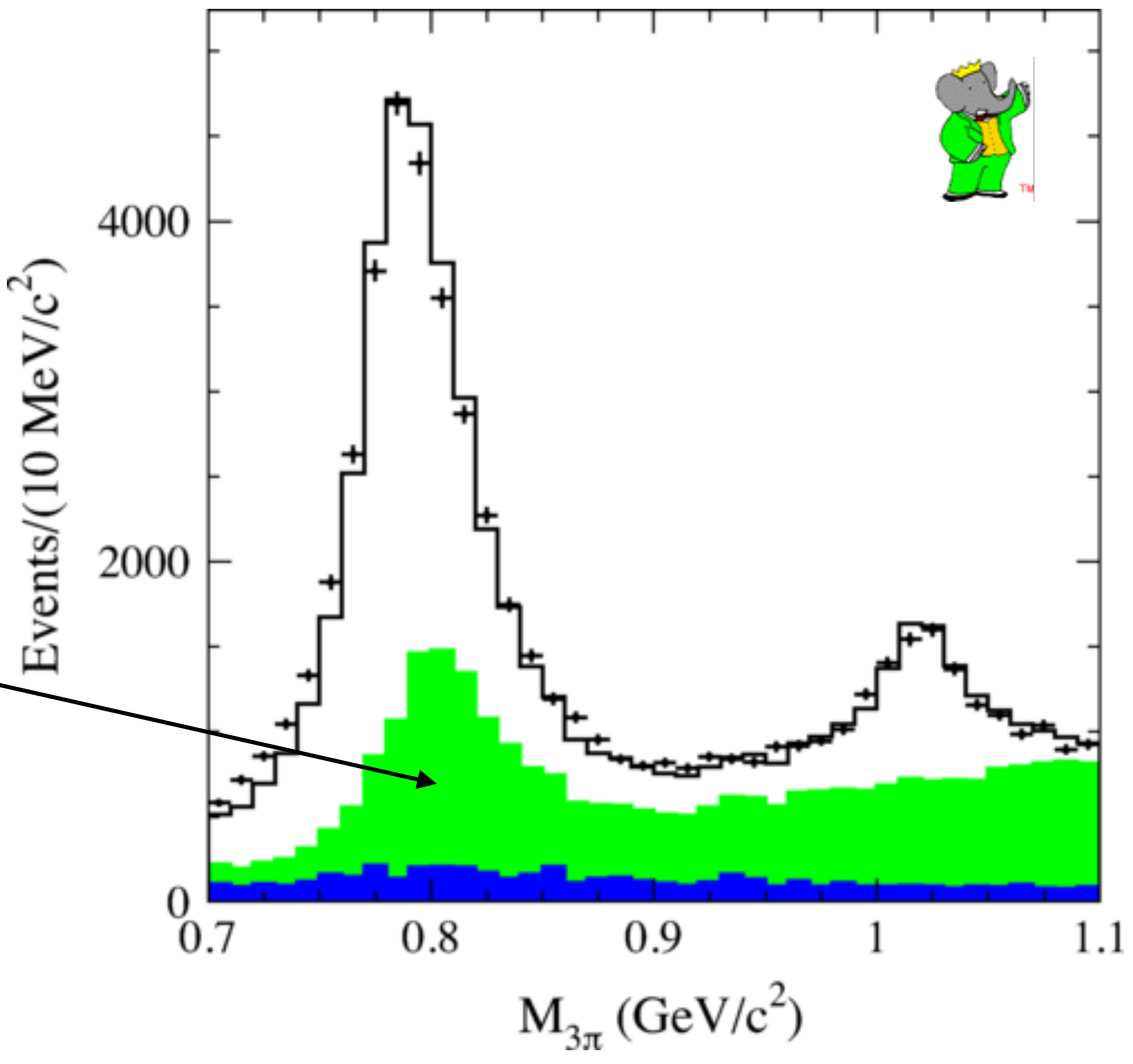
Important to improve the measurement of $a_\mu^{e^+e^-\to\pi^+\pi^-\pi^0}$.

Measure resonant substructure both for QCD knowledge and as cross-experiment check

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

PRD **104** 112003 (2021)

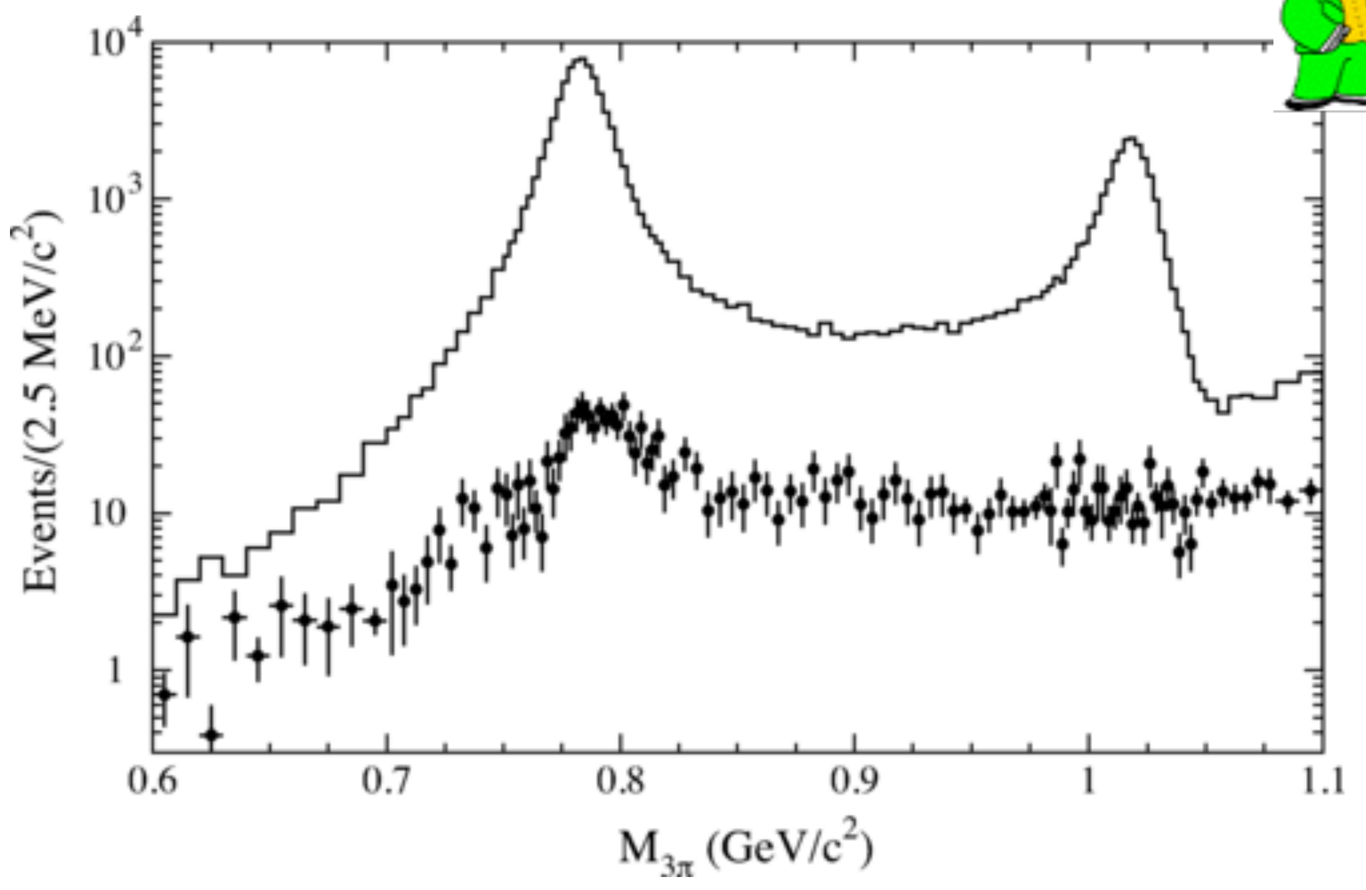
- Require two quality opposite-charge tracks not identified as kaons
- Require one photon with energy above 3 GeV, assign as γ_{ISR}
- Require a pair of photons to have invariant mass consistent with π^0 mass
  - Reject event if γ_{ISR} meets this criterion (suppress background from $e^+e^- \to q\bar{q}$)
- Reject event if $M_{\pi\gamma_{ISR}} > 1.5\ \mathrm{GeV/c^2}$ (suppress background from $e^+e^- \to \tau^+\tau^-$)
- Major remaining backgrounds studied in detail with special selection criteria for scaling and subtraction. Most significant is $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma_{ISR}$



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

PRD **104** 112003 (2021)

We unfold detector efficiency effects and use four models to study the 3π spectrum. Extract $P_V = \Gamma(V \rightarrow e^+e^-)\,\mathcal{B}(V \rightarrow \pi^+\pi^-\pi^0)$



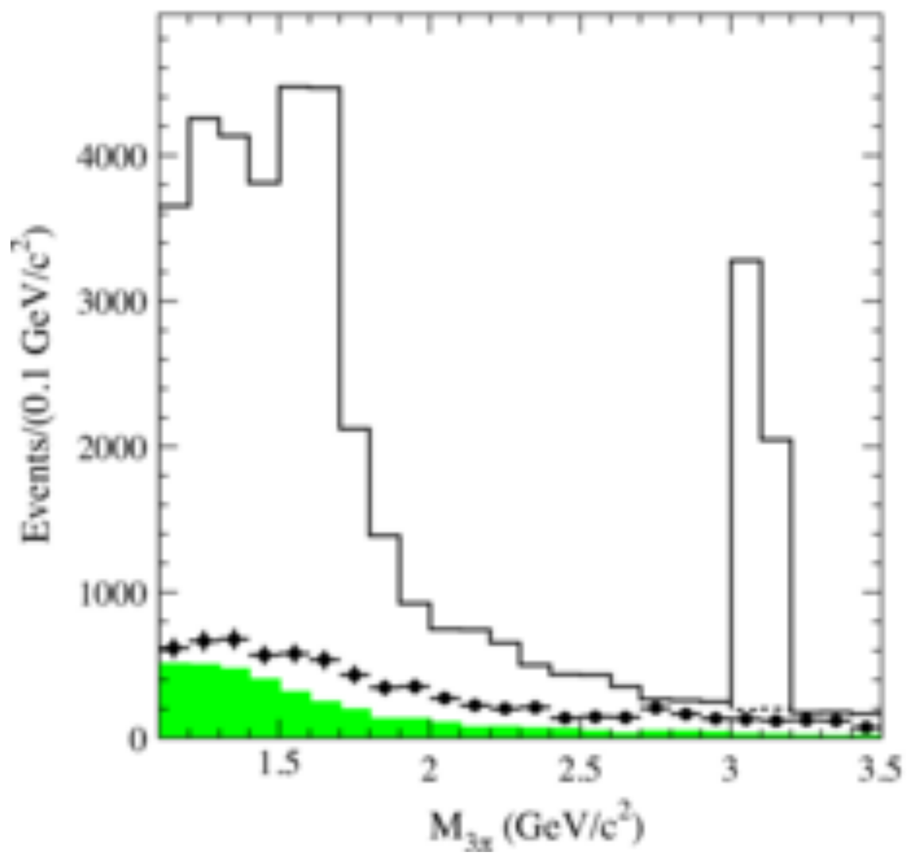
$$P_\omega = (0.5698 \pm 0.0031 \pm 0.0082)\ \mathrm{keV}$$

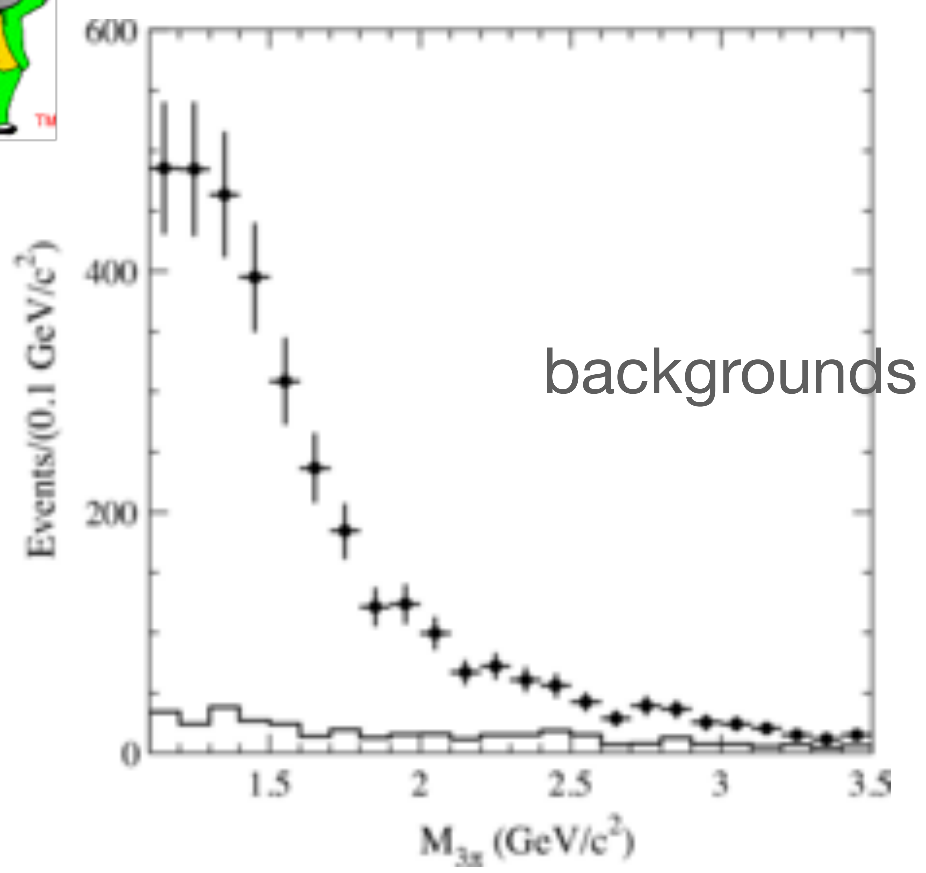
$$P_\phi = (0.1841 \pm 0.0021 \pm 0.0080)\ \mathrm{keV}$$

$$\mathcal{B}(\rho \rightarrow 3\pi) = (0.88 \pm 0.23 \pm 0.30) \times 10^{-4}$$

$$\varphi_\rho = -(99 \pm 9 \pm 15)^\circ$$

$$P_{J/\psi} = (0.1248 \pm 0.0019 \pm 0.0026)\ \mathrm{keV}$$





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

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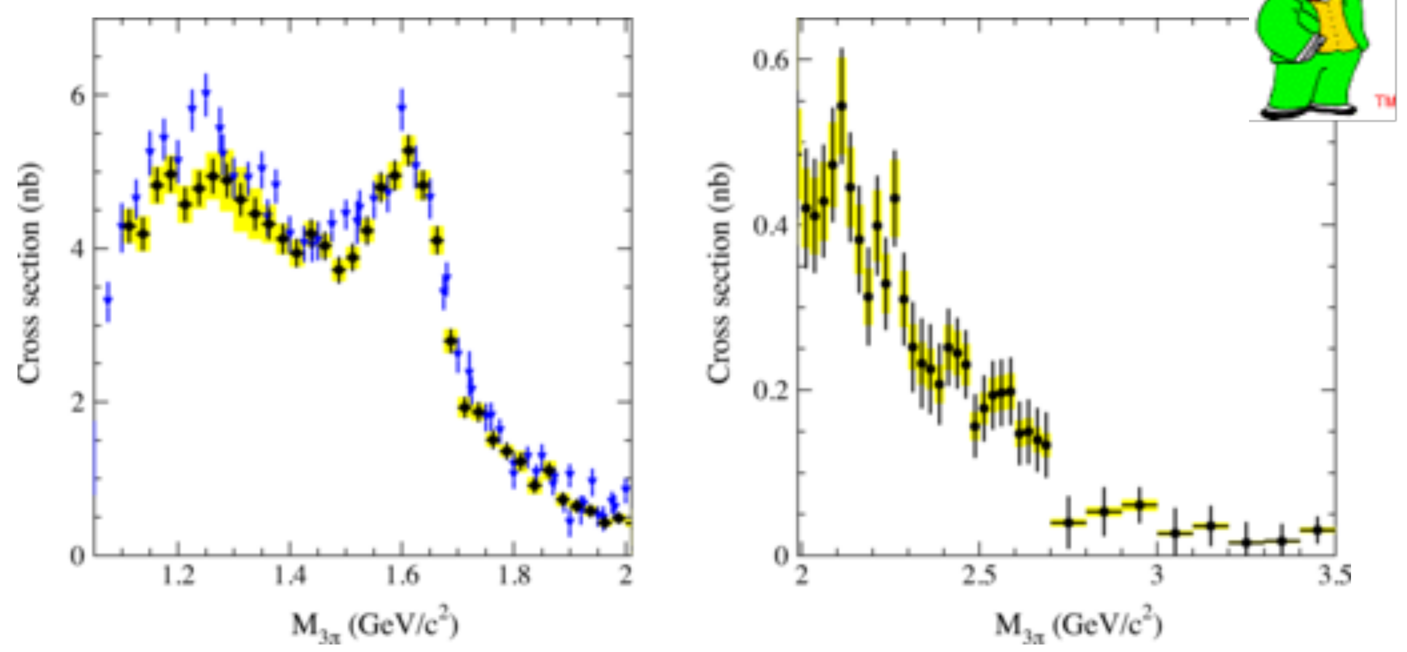


Using measured cross section from threshold to 2.0 GeV

$$a_\mu^{e^+e^-\to\pi^+\pi^-\pi^0} = (45.86 \pm 0.14 \pm 0.58) \times 10^{-10}$$

Comparable to previous measurements but with higher precision

$M_{3\pi}$ 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]	$46.2 \pm 0.6 \pm 0.6$

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

Was over 3% before this study

Modes With Kaons

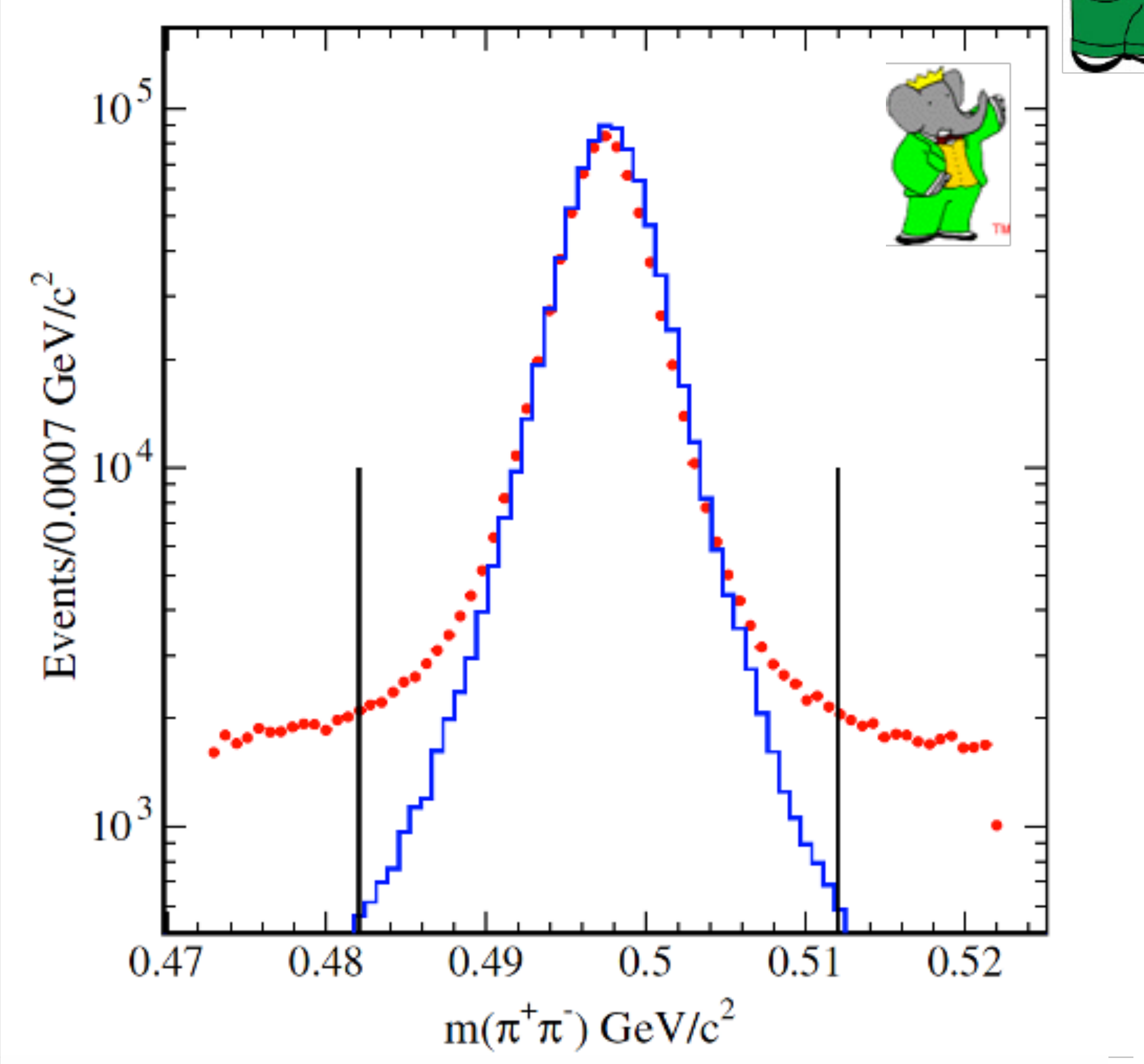
K_S^0 reconstructed as a pair of opposite-charge tracks with a displaced vertex via its decay $K_S^0 \to \pi^+\pi^-$

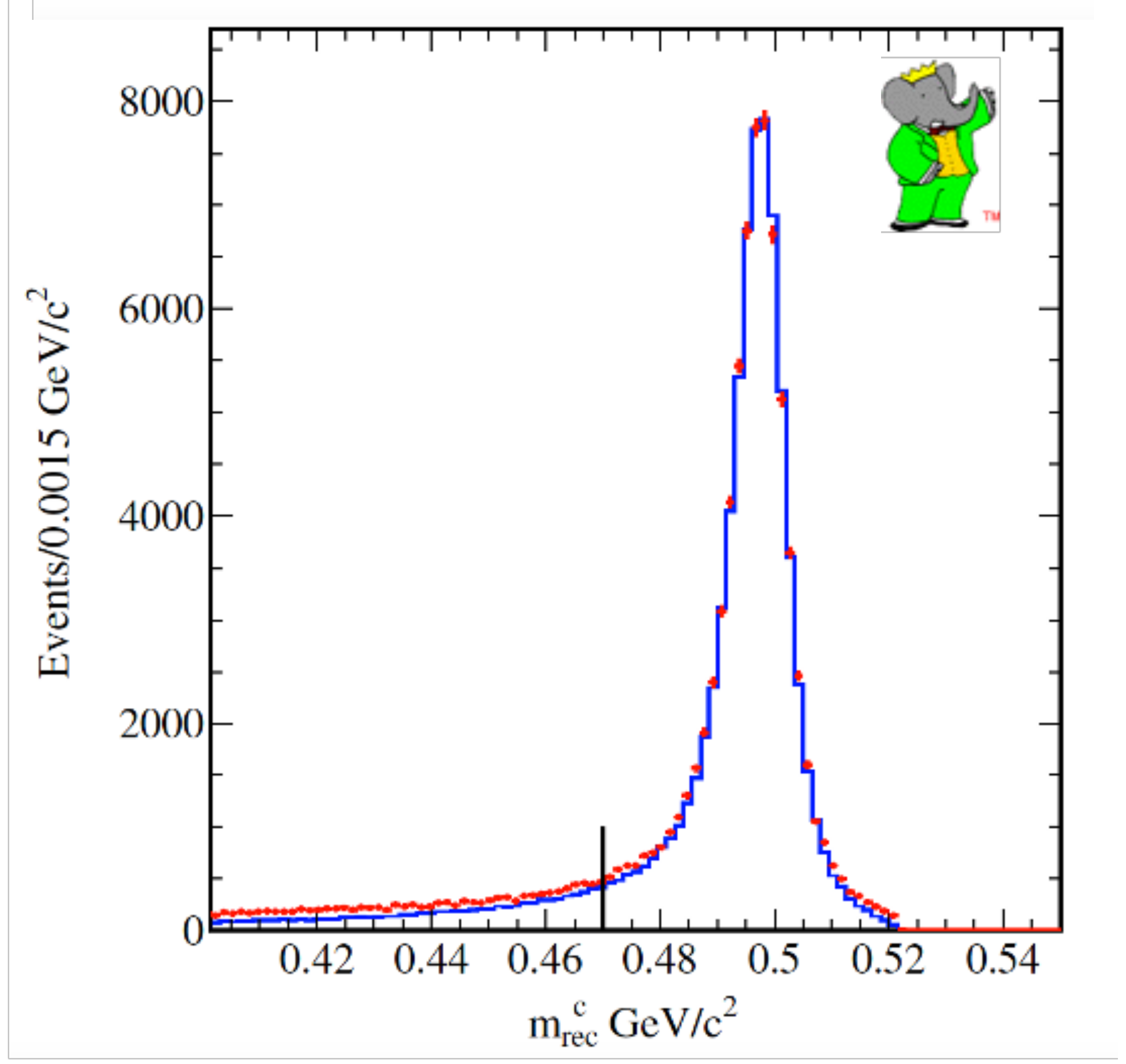
K_L^0 identified as an isolated energy cluster in the calorimeter, shape not consistent with a photon. Validated via:

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

PRD **89** 092002 (2014)

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

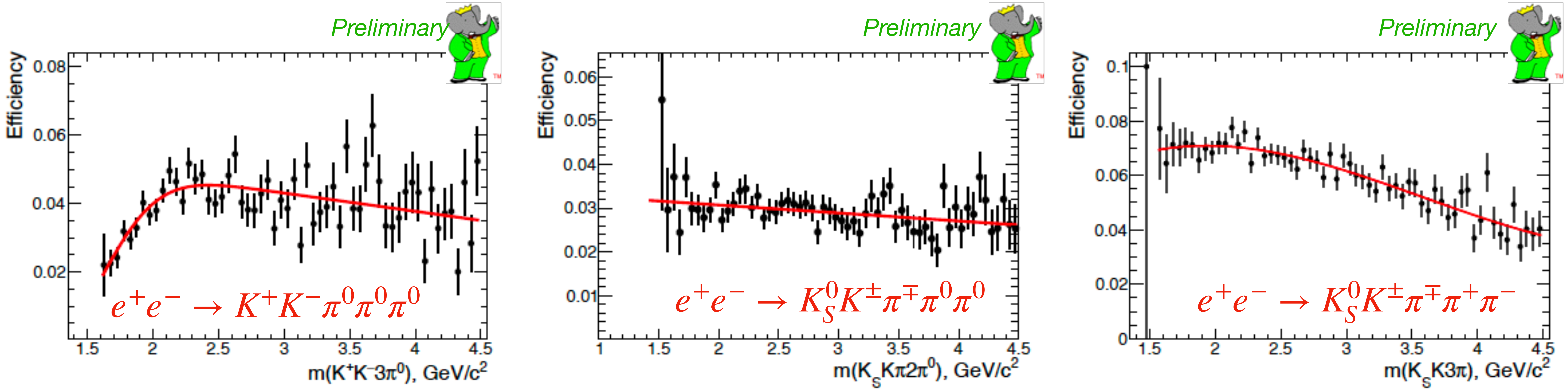




Study of $e^+e^- \to 2K\,3\pi$

arXiv:2207.10340(2022)
accepted, PRD

- Only $e^+e^- \to K^+K^-\pi^+\pi^-\pi^0$ studied previously. Most of these modes not accounted for in $a_\mu^{Had\ LO}$
- Require 2 or 4 good charged tracks from interaction point
- Use constrained fit on each candidate mode. Use tight χ^2 cut to define signal region



Reconstruction efficiency as a function of invariant mass

Study of $e^+e^- \to 2K\,3\pi$

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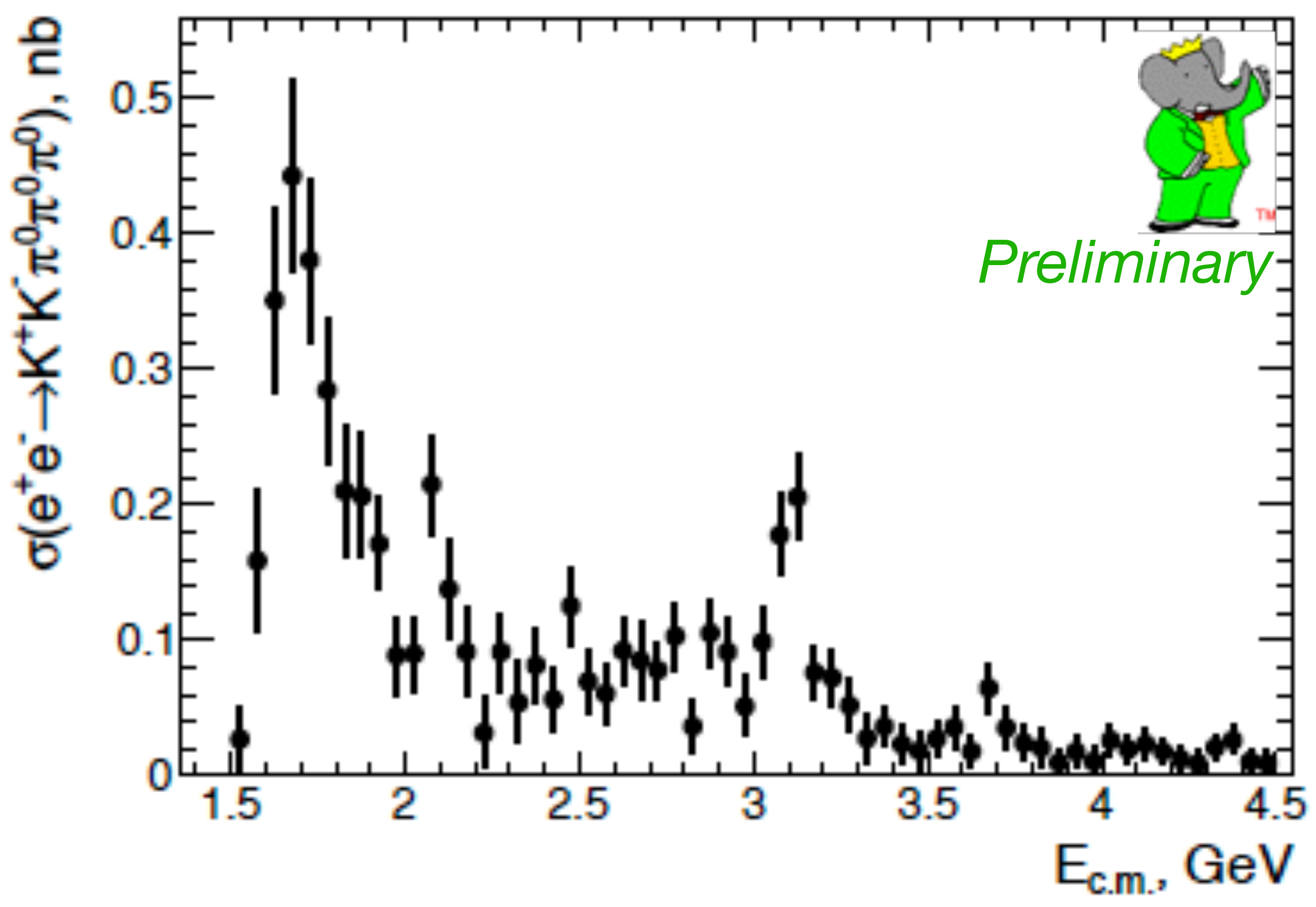
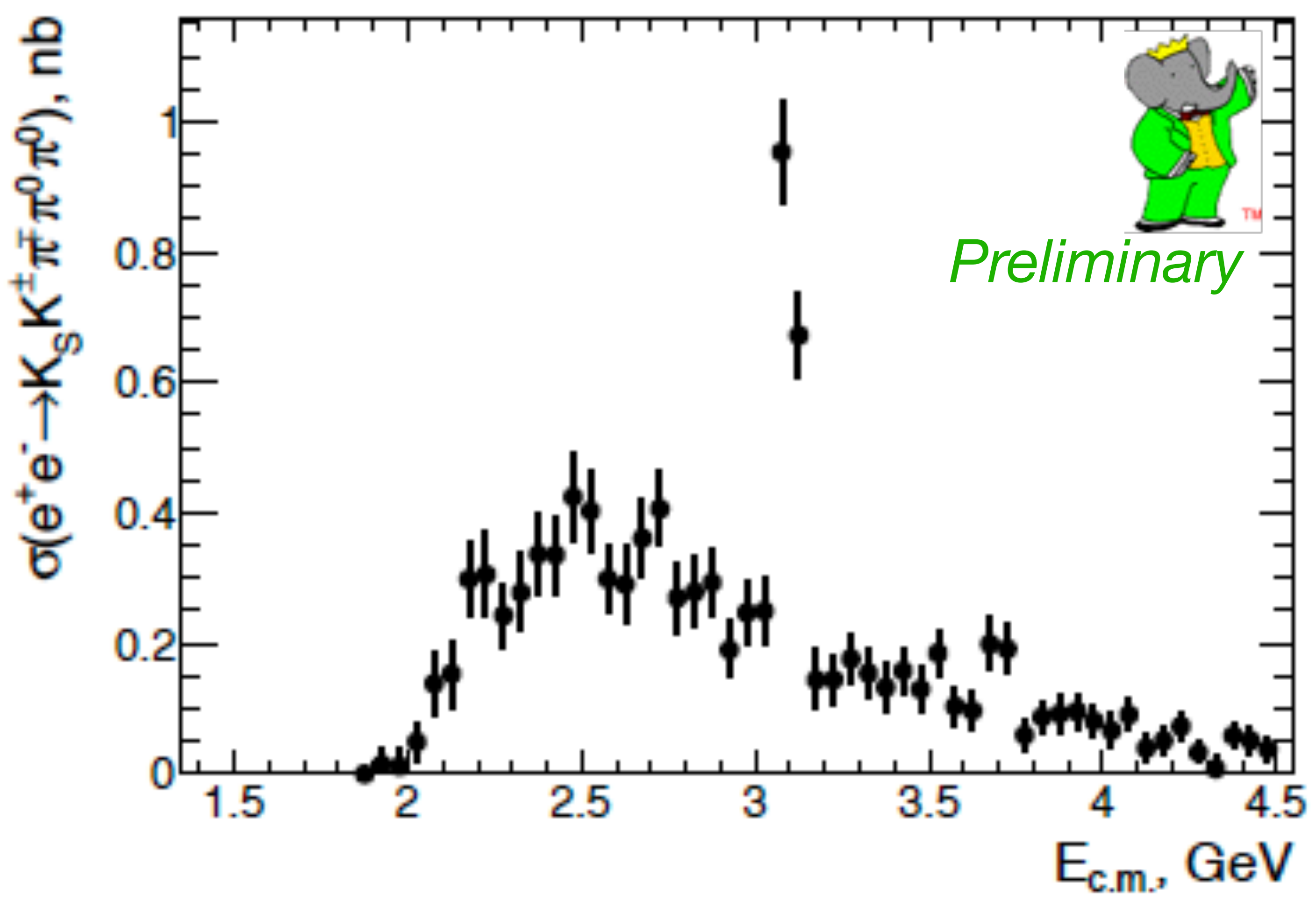
Measured cross-sections for each mode

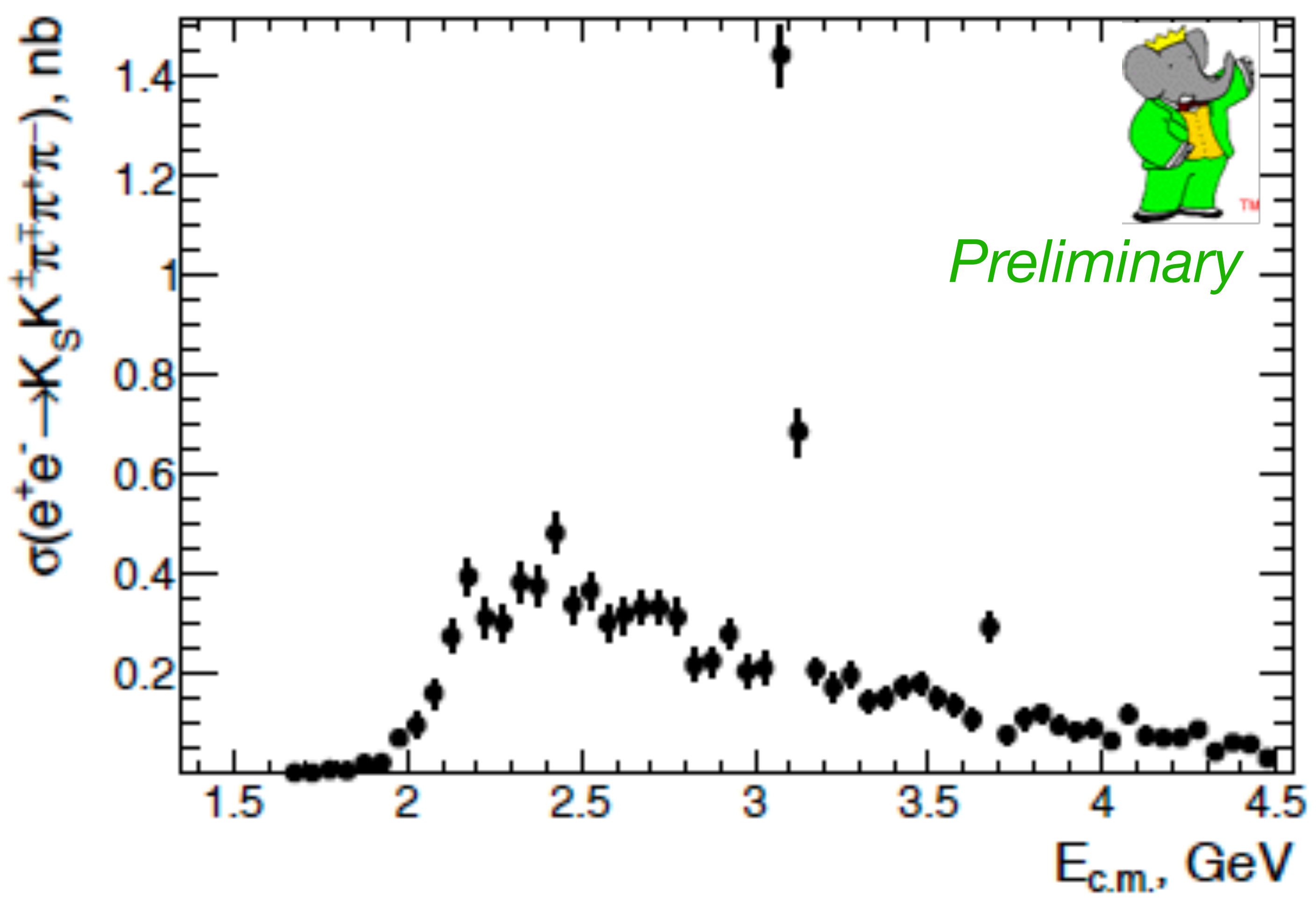
$e^+e^- \to K^+K^-\pi^0\pi^0\pi^0$



$e^+e^- \to K^0_S K^\pm \pi^\mp \pi^0 \pi^0$



$e^+e^- \to K^0_S K^\pm \pi^\mp \pi^+ \pi^-$



Signal events:	1230	2658	6582
Uncertainty	~10%	~10%	~8%

Study of $e^+e^- \to 2K\,3\pi$

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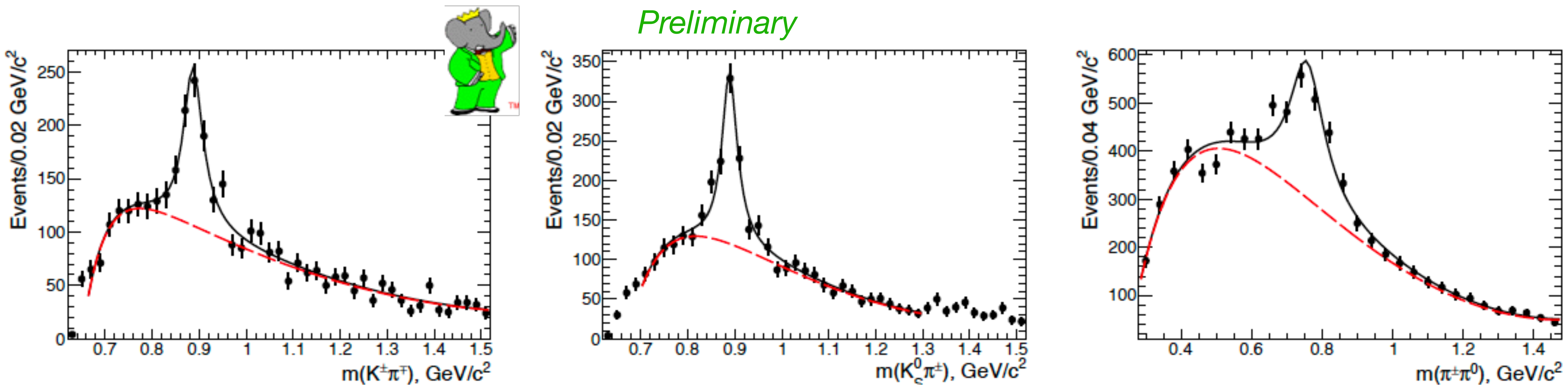
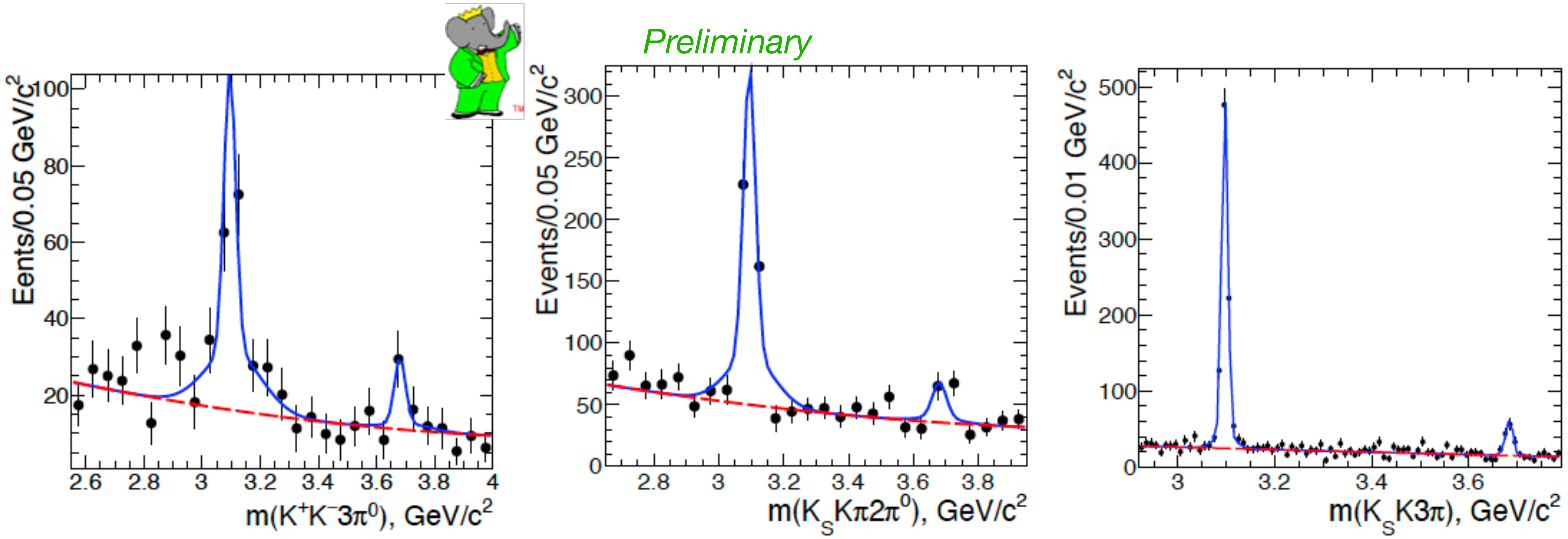
Examined substructure with ϕ, η, K^{*0}, $K^{*\pm}$, ρ^0, J/ψ, $\psi(2S)$



K^* and ρ structure in $e^+e^- \to K_S^0 K^\pm \pi^\mp \pi^0 \pi^0$



$e^+e^- \to K^+K^-\pi^0\pi^0\pi^0$ $e^+e^- \to K_S^0 K^\pm \pi^\mp \pi^0 \pi^0$ $e^+e^- \to K_S^0 K^\pm \pi^\mp \pi^+ \pi^-$

J/ψ and $\psi(2S)$ structure in each mode

Study of $e^+e^- \to 2K3\pi$

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Preliminary

Measured Quantity	Measured Value (eV)	J/ψ or $\psi(2S)$ Branching Fraction (10^{-3}) Derived, this work	PDG [30]
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K^+K^-\pi^0\pi^0\pi^0}$	8.9 ±1.3 ±0.9	1.6 ±0.2 ±0.2	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to \eta K^+K^-} \cdot B_{\eta \to \pi^0\pi^0\pi^0}$	1.55±0.51±0.16	0.85±0.28±0.09	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to \phi\eta} \cdot B_{\phi \to K^+K^-} \cdot B_{\eta \to \pi^0\pi^0\pi^0}$	0.64±0.26±0.06	0.72±0.29±0.07	0.74±0.08
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K^{*+}K^{*-}\pi^0} \cdot B_{K^{*+} \to K^+\pi^0} \cdot B_{K^{*-} \to K^-\pi^0}$	6.9 ±1.2 ±0.7	5.0 ±0.9 ±0.5	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to K^+K^-\pi^0\pi^0\pi^0}$	1.54±0.63±0.15	0.66±0.27±0.07	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to J/\psi\pi^0\pi^0} \cdot B_{J/\psi \to K^+K^-\pi^0}$	1.31±0.35±0.13	3.1 ±0.8 ±0.3	2.88±0.13
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to \eta K^+K^-} \cdot B_{\eta \to \pi^0\pi^0\pi^0}$	<0. 2 at 90% C.L.	<0. 25 at 90% C.L.	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to K^{*+}K^{*-}\pi^0} \cdot B_{K^{*+} \to K^+\pi^0} \cdot B_{K^{*-} \to K^-\pi^0}$	0.94±0.45±0.10	1.6 ±0.8 ±0.2	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K_S^0K^\pm\pi^\mp\pi^0\pi^0}$	29.3 ±2.6 ±2.9	5.3 ±0.5 ±0.5	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K^{*\pm}K^\mp\pi^0\pi^0} \cdot B_{K^{*\pm} \to K^0\pi^\pm} \cdot B_{K^0 \to K_S^0}$	2.89±0.52±0.28	2.0 ±0.4 ±0.2	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K^0K^{*0}\pi^0\pi^0} \cdot B_{K^{*0} \to K^\pm\pi^\mp} \cdot B_{K^0 \to K_S^0}$	3.73±0.53±0.37	2.7 ±0.4 ±0.3	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K_S^0K^\pm\rho^\mp\pi^0}$	16.0 ±4.1 ±1.6	2.9 ±0.7 ±0.3	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to K_S^0K^\pm\pi^\mp\pi^0\pi^0}$	4.0 ±1.4 ±0.4	1.7 ±0.6 ±0.2	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to J/\psi\pi^0\pi^0} \cdot B_{J/\psi \to K_S^0K^\pm\pi^\mp}$	2.36±0.59±0.24	5.5 ±1.4 ±0.6	5.6 ±0.5
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to K^{*\pm}K^\mp\pi^0\pi^0} \cdot B_{K^{*\pm} \to K^0\pi^\pm} \cdot B_{K^0 \to K_S^0}$	0.54±0.22±0.05	0.92±0.37±0.09	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to K^0K^{*0}\pi^0\pi^0} \cdot B_{K^{*0} \to K^\pm\pi^\mp} \cdot B_{K^0 \to K_S^0}$	0.47±0.19±0.05	0.81±0.32±0.08	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to K_S^0K^\pm\rho^\mp\pi^0}$	<1. 6 at 90% C.L.	<0. 6 at 90% C.L.	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K_S^0K^\pm\pi^\mp\pi^+\pi^-}$	34.6 ±1.4 ±1.8	6.2 ±0.2 ±0.4	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K^{*\pm}K^{*0}\pi^\mp} \cdot B_{K^{*\pm} \to K^0\pi^\pm} \cdot B_{K^{*0} \to K^\pm\pi^\mp} \cdot B_{K^0 \to K_S^0}$	5.9 ±1.0 ±0.6	8.5 ±1.5 ±0.9	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K^{*\pm}K^\mp\pi^+\pi^-} \cdot B_{K^{*\pm} \to K^0\pi^\pm} \cdot B_{K^0 \to K_S^0}$	6.2 ±2.1 ±0.6	4.4 ±1.5 ±0.4	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K^0K^{*0}\pi^+\pi^-} \cdot B_{K^{*0} \to K^\pm\pi^\mp} \cdot B_{K^0 \to K_S^0}$	6.3 ±2.1 ±0.6	4.5 ±1.5 ±0.5	no entry
$\Gamma_{ee}^{J/\psi} \cdot B_{J/\psi \to K_S^0K^\pm\pi^\mp\rho^0}$	17.3 ±2.1 ±1.7	3.1 ±0.4 ±0.3	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to K_S^0K^\pm\pi^\mp\pi^+\pi^-}$	5.1 ±0.7 ±0.4	2.2 ±0.3 ±0.2	no entry
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to J/\psi\pi^+\pi^-} \cdot B_{J/\psi \to K_S^0K^\pm\pi^\mp}$	4.14±0.55±0.29	5.1 ±0.7 ±0.1	5.6 ±0.5
$\Gamma_{ee}^{\psi(2S)} \cdot B_{\psi(2S) \to K_S^0K^\pm\pi^\mp\rho^0}$	<1. 6 at 90% C.L.	<0. 6 at 90% C.L.	no entry

Thorough study of substructure in J/ψ region

First measurements for many modes.

Conclusions

- The a_μ puzzle is important to address given the potential for a gateway to New Physics (NP)

- BABAR results provide important inputs to the a_μ calculation that, along with new measurements from CMD-3 and others, may help pin down better knowledge of the muon magnetic moment and the potential for NP

- We have presented a study of $e^+e^- \to \pi^+\pi^-\pi^0$ via ISR and reduced the uncertainty on its contribution to a_μ by greater than a factor of 2 PRD **104** 112003 (2021)

- We presented first measurements of cross sections and substructure associated with select $e^+e^- \to 2K\,3\pi$ modes, which may help improve knowledge of the hadronic contributions to a_μ

arXiv:2207.10340(2022)
accepted for publication, PRD

- 15 years after end of data taking, *BABAR* continues to produce important results 

Thank you!