Recent Hadronic Cross Section Measurements from *BABAR*

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on behalf of the *BABAR* Collaboration

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International Workshop on e^+e^- Collisions from Phi to Psi, June 2017

Outline

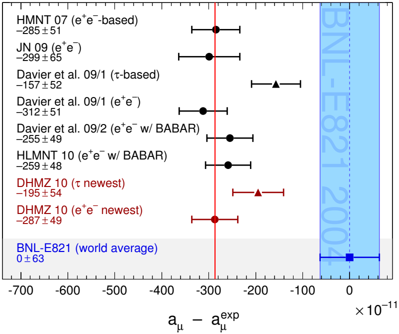
1. Introduction
2. Cross section $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$
3. Cross section $e^+e^- \to \pi^+\pi^-\eta$
4. Cross sections $e^+e^- \to K_S K_L \pi^0, K_S K_L \pi^0\pi^0, K_S K_L \eta$

The contributions to a_μ and its uncertainty

$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$
$$(g_\mu - 2)/2 =: a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{weak}} + a_\mu^{\mathrm{hadronic}}$$

Interaction	Contribution $[\cdot 10^{-11}]$	Uncertainty $[\cdot 10^{-11}]$
QED [1]	116 584 718.951	0.080
EW [9]	153.6	1
hadronic VP [6, 12]	6837	43
hadronic LbL [11, 2]	119	41
total theory	116 591 828	60
E821 experiment [15]	116 592 089	63
deviation exp-theo	261	87

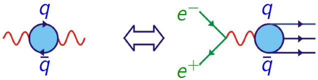
Discrepancy between SM prediction and direct measurement from Eur.Phys.J., C71:1515, 2011 [6].



Just a fluctuation?

3σ effect, thus reduction of uncertainties necessary!

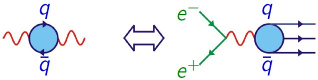
Connection between a_μ and $\sigma_{\rm had}$



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

Kernel function — cross section

Connection between a_μ and $\sigma_{\rm had}$



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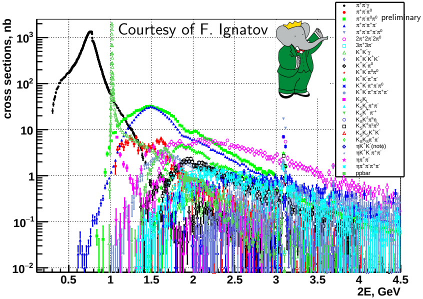
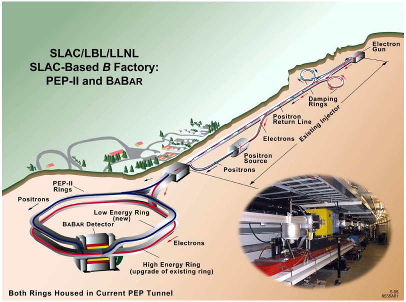


The *BABAR* Experiment



Experimental specifications

Energy: $\sqrt{s} \approx 10.58\,\mathrm{GeV}$ $\quad (E_{e^-} \approx 9.0\,\mathrm{GeV}, E_{e^+} \approx 3.1\,\mathrm{GeV})$,
Luminosity: $\mathcal{L} \approx 500\,\mathrm{fb}^{-1}$ $\quad (\Upsilon(4S))$

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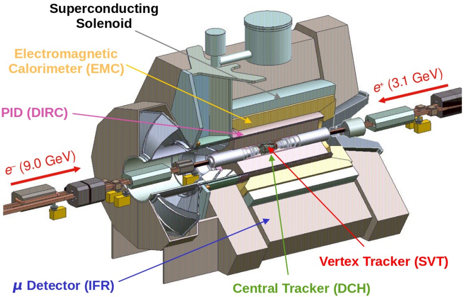

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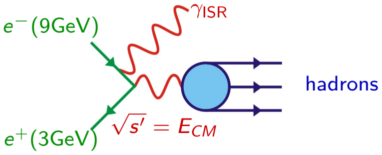
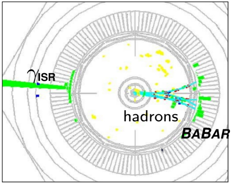
Initial State Radiation (ISR) events at *BABAR*





ISR selection

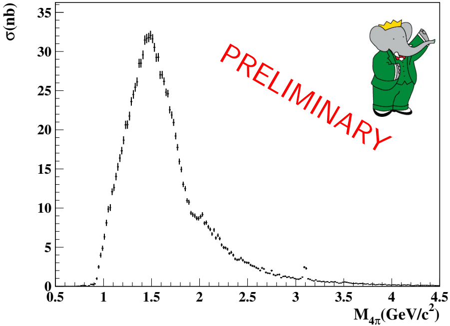
- Detected high energy photon: $E_\gamma > 3\text{GeV}$
  $\rightarrow$ defines E_{CM} & provides strong background rejection
- Event topology: γ_{ISR} back-to-back to hadrons
  $\rightarrow$ high acceptance
- Kinematic fit including γ_{ISR}
  $\rightarrow$ very good energy resolution $(4 - 15\text{MeV})$
- Continuous measurement from threshold to $\sim$5GeV
  $\rightarrow$ provides common, consistent systematic uncertainties

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

PRELIMINARY

Resulting cross section

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

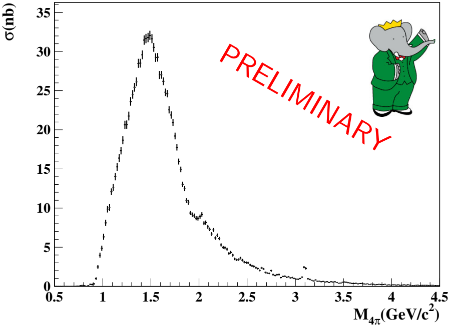


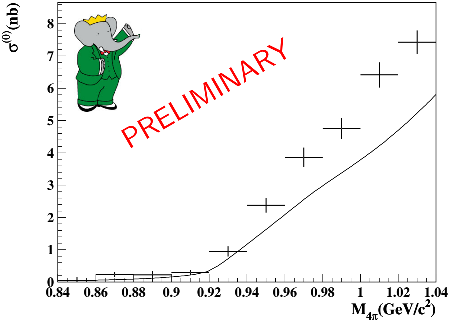
E_{CM}(GeV)	Syst. unc.
1.2 – 2.7	3.1%
2.7 – 3.2	6.7%
> 3.2	7.1%

- dominant ISR-bkg $\pi^+\pi^-3\pi^0$ removed using data
- most precise measurement to date
- widest energy range $0.85 < E_{\mathrm{CM}} < 4.5$ GeV

Resulting cross section

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





E_{CM}(GeV)	Syst. unc.
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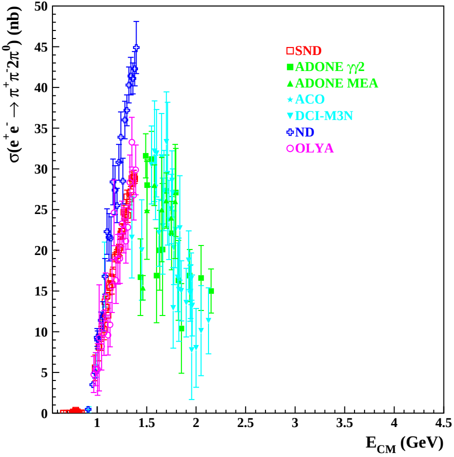
Comparison to Chiral Pert. Theo.

(Eur.Phys.J., C24:535–545, 2002 [8])

Contribution of $\pi^+\pi^-2\pi^0$ to $g_\mu - 2$

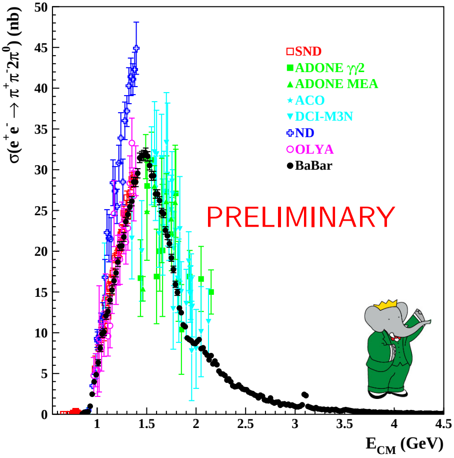


$$a_\mu^{\rm had} = \frac{1}{4\pi^3}\int_{m^2_{\pi^0}}^{\infty} \frac{\sqrt{1-\frac{4m_e^2}{s}}}{1+\frac{2m_e^2}{s}} K_\mu(s)\sigma(s)\mathrm{d}s$$

Before *BABAR* (Eur.Phys.J.,C31:503,2003) [5]

$$a_\mu(1.02 < \sqrt{s} < 1.8\,\text{GeV}) = (16.76 \pm 1.31 \pm 0.20_{\rm rad}) \times 10^{-10}$$

Contribution of $\pi^+\pi^-2\pi^0$ to $g_\mu - 2$



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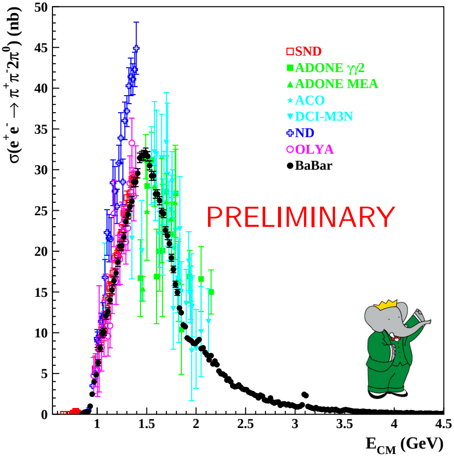
$a_\mu(1.02 < \sqrt{s} < 1.8\,\text{GeV}) =$
$(16.76 \pm 1.31 \pm 0.20_{\text{rad}}) \times 10^{-10}$

New result in the same energy range

$a_\mu(1.02 < \sqrt{s} < 1.8\,\text{GeV}) =$
$(17.4 \pm 0.1_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-10}$

Contribution of $\pi^+\pi^-2\pi^0$ to $g_\mu - 2$



$$a_\mu^{\rm had} = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} \frac{\sqrt{1-\frac{4m_e^2}{s}}}{1+\frac{2m_e^2}{s}} K_\mu(s)\sigma(s)\mathrm{d}s$$

New result starting at lower limit

$a_\mu(0.85 < \sqrt{s} < 1.8\,\text{GeV}) = (17.9 \pm 0.1_{\rm stat} \pm 0.6_{\rm syst}) \times 10^{-10}$

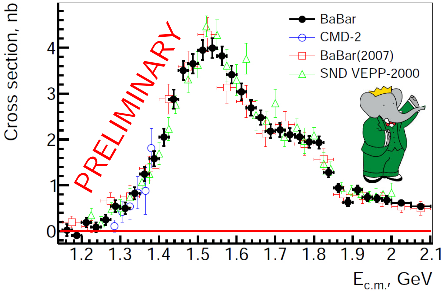
New result in a wider energy range

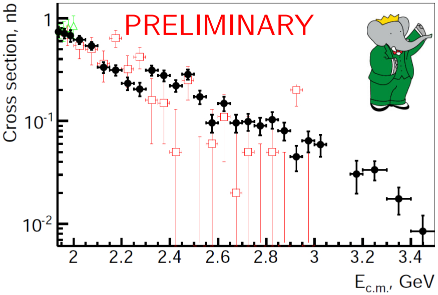
$a_\mu(0.85 < \sqrt{s} < 3.0\,\text{GeV}) = (21.8 \pm 0.1_{\rm stat} \pm 0.7_{\rm syst}) \times 10^{-10}$

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

PRELIMINARY

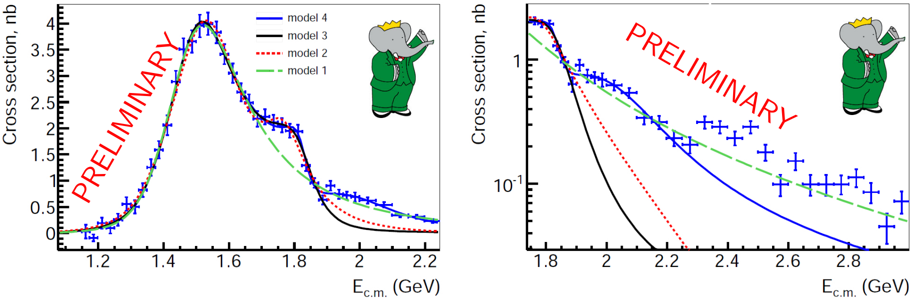
Cross section $e^+e^- \to \pi^+\pi^-\eta$





- Most accurate $\sigma(e^+e^- \to \pi^+\pi^-\eta)$ measurement to date
- First measurement up to 3.5 GeV
- Especially above 1.6 GeV more precise than previous data

Fits to the cross section $e^+e^- \to \pi^+\pi^-\eta$

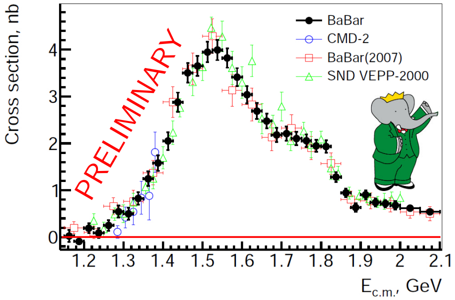


- Model 1: $\rho(770) - \rho(1450)$, fit: $E_{\rm CM} < 1.7$ GeV
- Model 2: $\rho(770) - \rho(1450) - \rho(1700)$, fit: $E_{\rm CM} < 1.9$ GeV
- Model 3: $\rho(770) - \rho(1450) + \rho(1700)$, fit: $E_{\rm CM} < 1.9$ GeV
- Model 4: $\rho(770) - \rho(1450) + \rho(1700) + \rho(2150)$, fit: $E_{\rm CM} < 2.2$ GeV

"+": relative phase 0°, "-": relative phase 180°

Contribution of $\pi^+\pi^-\eta$ to $g_\mu - 2$

$$a_\mu^{\rm had} = \frac{1}{4\pi^3}\int_{m^2_{\pi^0}}^{\infty} \frac{\sqrt{1-\frac{4m_e^2}{s}}}{1+\frac{2m_e^2}{s}} K_\mu(s)\sigma(s)\mathrm{d}s$$



HLMNT 2011 [10]

$a_\mu(\sqrt{s} < 1.8\,\text{GeV}) = (0.88 \pm 0.10) \times 10^{-10}$

DHMZ 2011 [6]

$a_\mu(\sqrt{s} < 1.8\,\text{GeV}) = (1.15 \pm 0.06_{\rm stat} \pm 0.08_{\rm syst}) \times 10^{-10}$

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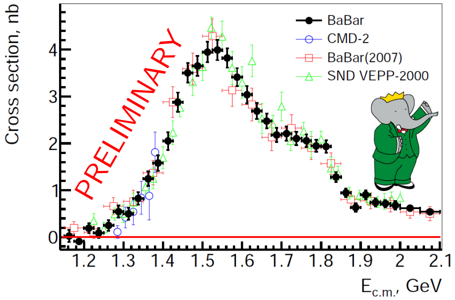
$$a_\mu^{\mathrm{had}} = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} \frac{\sqrt{1-\frac{4m_e^2}{s}}}{1+\frac{2m_e^2}{s}} K_\mu(s)\sigma(s)\mathrm{d}s$$



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$a_\mu(\sqrt{s} < 1.8\,\mathrm{GeV}) =$
$(1.15 \pm 0.06_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}}) \times 10^{-10}$

New result

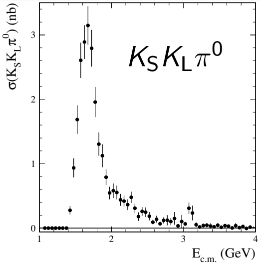
$a_\mu(\sqrt{s} < 1.8\,\mathrm{GeV}) =$
$(1.19 \pm 0.02_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}}) \times 10^{-10}$

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

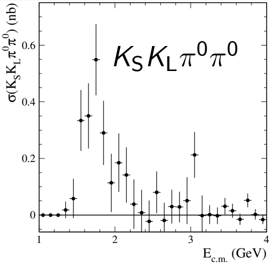
$$e^+e^- \to K_S K^\pm \pi^\mp \pi^0, K_S K^\pm \pi^\mp \eta$$

PRD 95 (2017), 052001
PRD 95 (2017), 092005

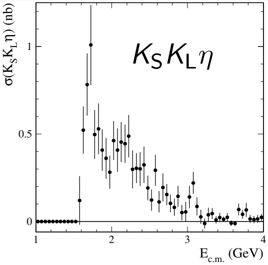
$e^+e^- \to K_S K_L \pi^0, K_S K_L \pi^0\pi^0, K_S K_L \eta$



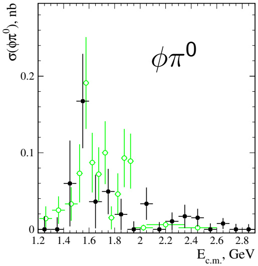
syst.: 10–30 %

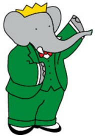


syst.: 25–60 %

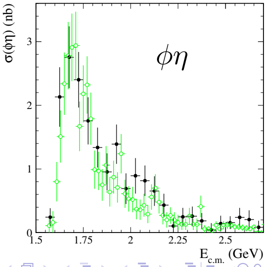


syst.: 15–30 %

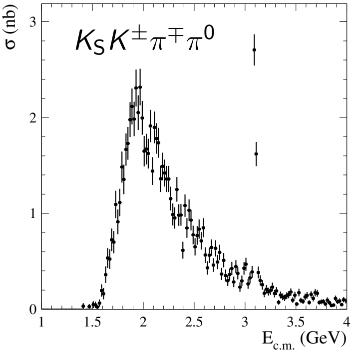




Published in
PRD 95 (2017), 052001

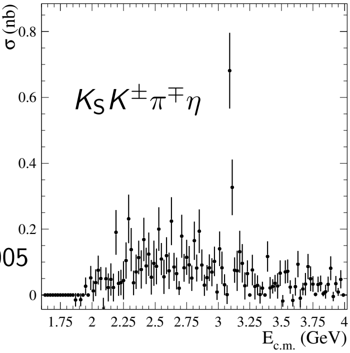


$e^+e^- \to K_S K^\pm \pi^\mp \pi^0$, $K_S K^\pm \pi^\mp \eta$



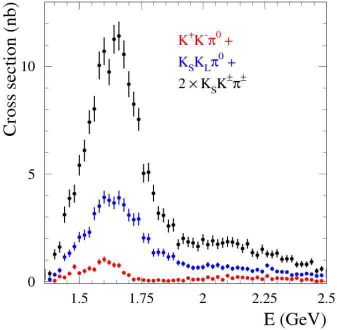
total unc.: 6–12 %

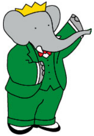
Published in
PRD 95 (2017), 092005



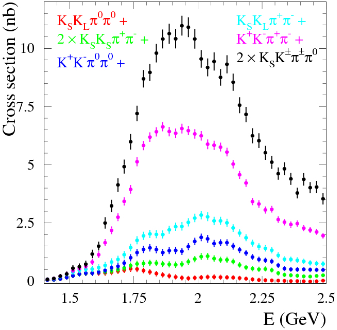
total unc.: 13–19 %

Total $e^+e^- \to KK\pi(\pi)$ cross sections





Courtesy of
V. Druzhinin [7]



- all $KK\pi(\pi)$ channels now measured by *BABAR*
  $\Rightarrow$ isospin relations not necessary any more
- new contributions to $g_\mu - 2$:
  - ⋆ $a_\mu(KK\pi) = (2.45 \pm 0.15) \times 10^{-10}$ [4]
  - ⋆ $a_\mu(KK\pi\pi) = (0.85 \pm 0.05) \times 10^{-10}$

Summary

- ISR physics has proven to be a very productive field even years after the end of data taking at the B-factories
- Precision measurements of hadronic cross sections have greatly improved a_μ^{SM} & more hadronic final states in preparation
- New results from *BABAR*:
  - ⋆ $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$
  - ⋆ $e^+e^- \to \pi^+\pi^-\eta$
  - ⋆ first measurement of $e^+e^- \to K_S K_L \pi^0, K_S K_L \pi^0\pi^0, K_S K_L \eta, K_S K^\pm \pi^\mp \pi^0, K_S K^\pm \pi^\mp \eta$

Thank you!

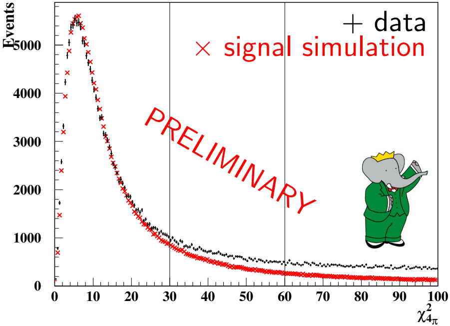
Any questions?

Backup

$\pi^+\pi^-2\pi^0\gamma$ Event Selection

Full $\Upsilon(4S)$ on peak data set of 454.4 fb^{-1}

$$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma_{\rm ISR}$$



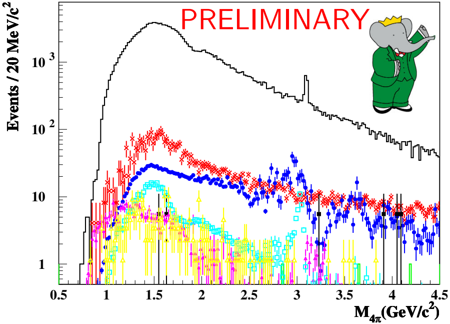
Main Selection Requirements

- exactly 2 charged tracks
- ≥ 5 photons
- $E_\gamma^{\rm lab} > 0.05$ GeV
- $|M_{\pi^0}^{\rm reco} - M_{\pi^0}^{\rm PDG}| < 0.03$ GeV
- $E_{\gamma_{\rm ISR}} > 3$ GeV
- 6C kinematic fit: $\chi^2_{2\pi 2\pi^0\gamma} < 30$
- reject other hypotheses
- Muon and Kaon PID

Background subtraction

$$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma_{\rm ISR}$$

Simulated background channels:



$q\bar{q}$, 3π, $4\pi 2\pi^0$, $K_s K\pi$, $K^+K^-2\pi^0$, $\tau\tau$, $\pi^+\pi^-3\pi^0$

Background subtraction

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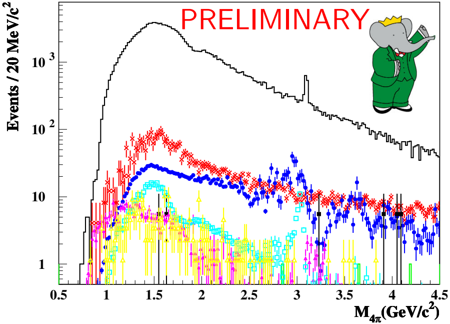
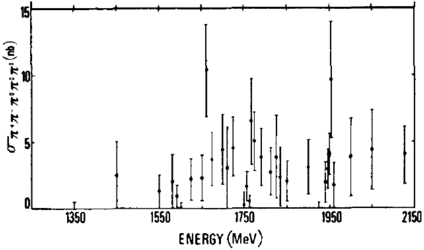


$q\bar{q}$, 3π, $4\pi2\pi^0$, $K_s K\pi$, $K^+K^-2\pi^0$, $\tau\tau$, $\pi^+\pi^-3\pi^0$

Main issue: background from $e^+e^- \to \pi^+\pi^-3\pi^0$

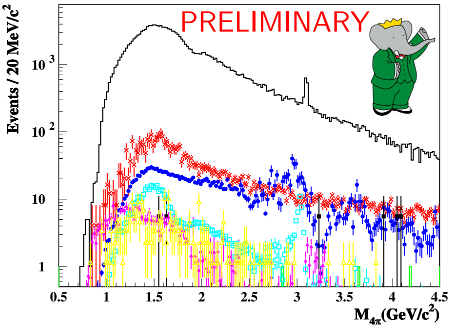


Only little data [3] and no full simulation available

Background subtraction

$$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma_{\rm ISR}$$

Simulated background channels:



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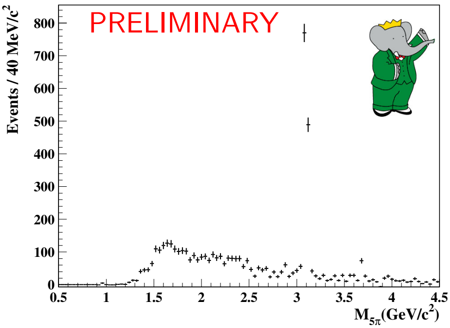
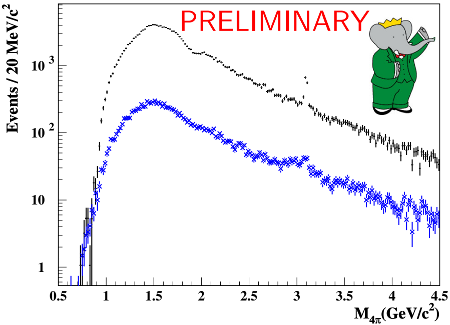


$\Rightarrow$ dedicated *BABAR* measurement

$\Rightarrow$ adjust simulation

Background subtraction: cross check

Sideband bkg subtraction

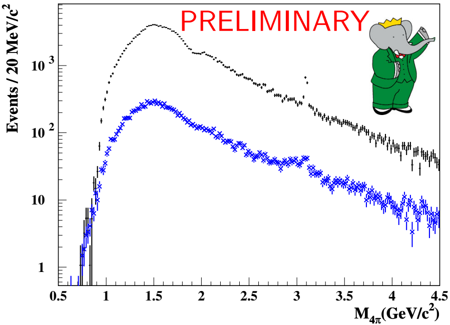


$$N_{1s} = \frac{\beta}{\beta - \alpha} \cdot N_1 - \frac{1}{\beta - \alpha} \cdot N_2$$

$$\alpha := \frac{N_{2s}}{N_{1s}}, \quad \beta := \frac{N_{2b}}{N_{1b}}$$

Background subtraction: cross check

Sideband bkg subtraction



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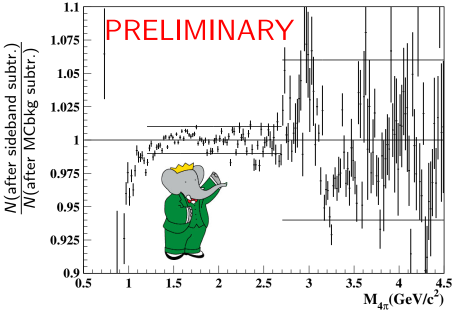
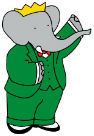
Comparison of both methods

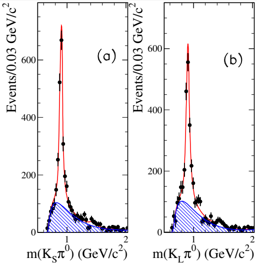


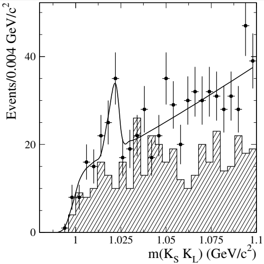
Less than 1 % discrepancy in the peak region around 1.5 GeV/c^2

$e^+e^- \to K_S K_L \pi^0, K_S K_L \eta$ intermediate st.: $K^*(892)$ and ϕ

$e^+e^- \to K_S K_L \pi^0$







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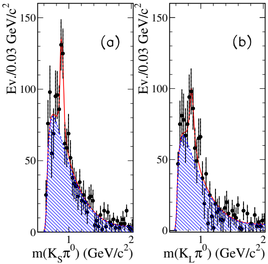
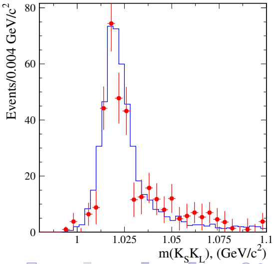
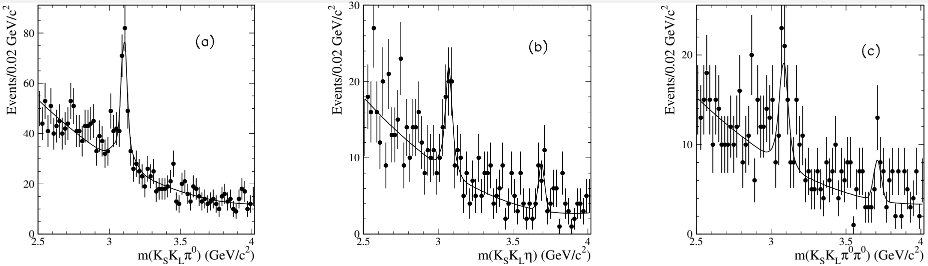
$e^+e^- \to K_S K_L \eta$





$e^+e^- \to K_S K_L \pi^0$, $K_S K_L \eta$, $K_S K_L \pi^0 \pi^0$, int. st.: ψ and K^*



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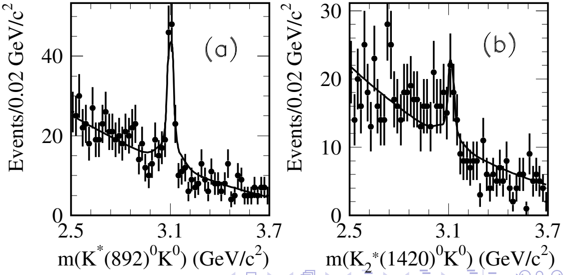
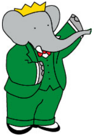


$e^+e^- \to K_S K^\pm \pi^\mp \pi^0$ intermediate states



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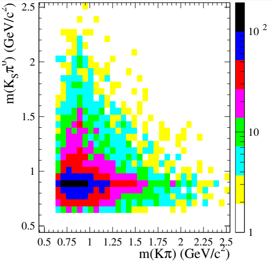
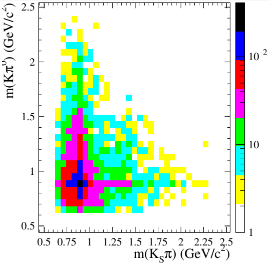
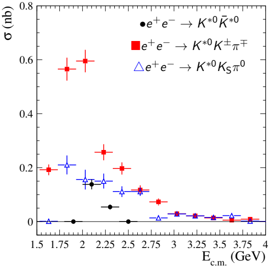
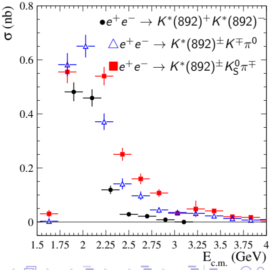
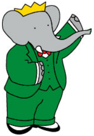








$e^+e^- \to K_S K^\pm \pi^\mp \pi^0$ intermediate states



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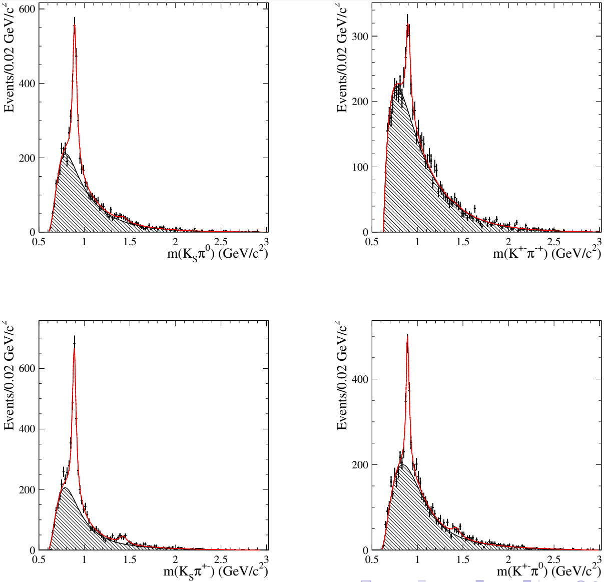
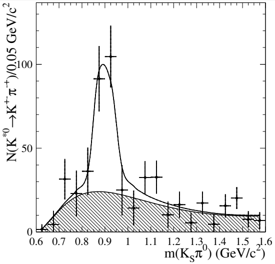
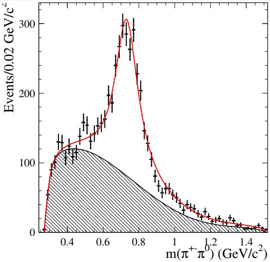
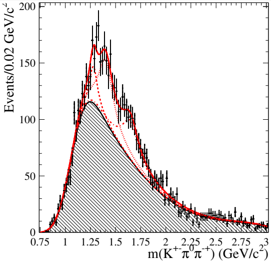


$e^+e^- \to K_S K^\pm \pi^\mp \pi^0$ intermediate states







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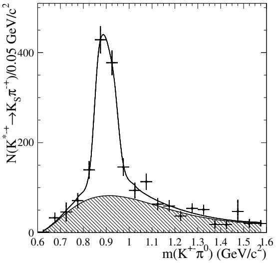
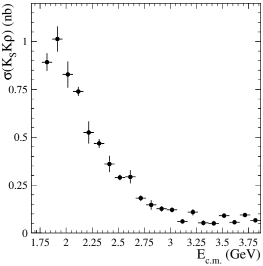
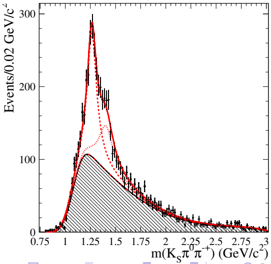
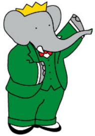






$e^+e^- \to K_S K^\pm \pi^\mp \eta$ intermediate states



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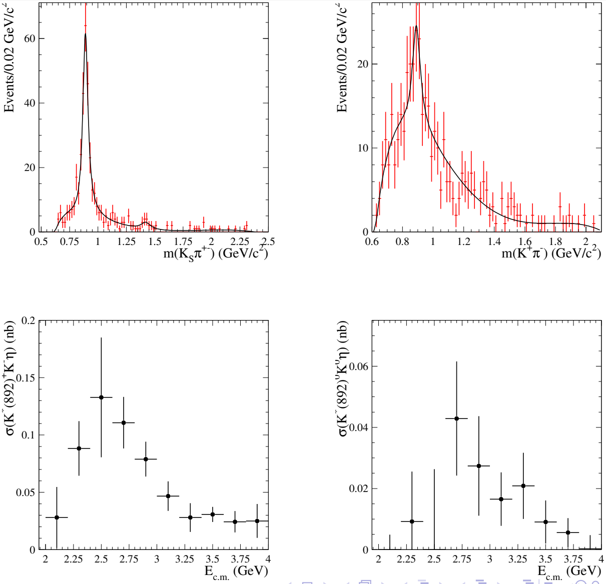
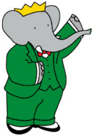


$e^+e^- \to K_S K^{\pm}\pi^{\mp}\pi^0/\eta$ intermediate states: J/ψ



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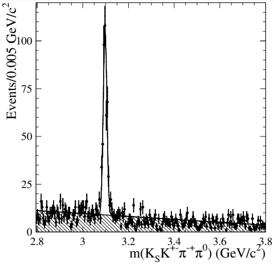
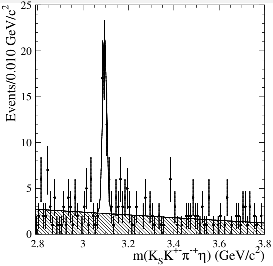
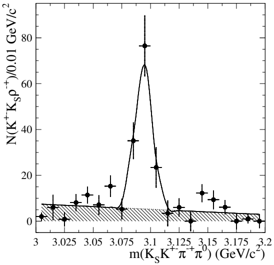
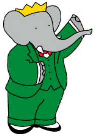






$e^+e^- \to K_S K^\pm \pi^\mp \pi^0$ intermediate states: K^*



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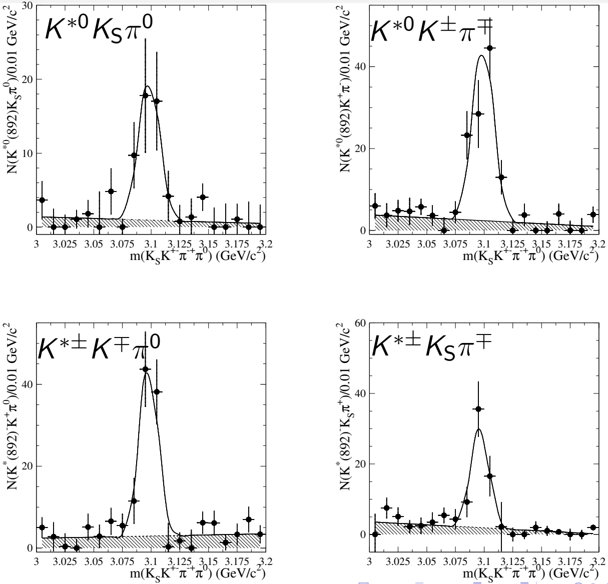

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