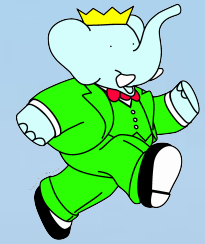
Measurement of hadronic cross sections with the *BABAR* detector



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

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

Phys. Rev. D **98**,112015

University of Victoria

Flavor Physics & CP Violation

Victoria, May 06-10 2019

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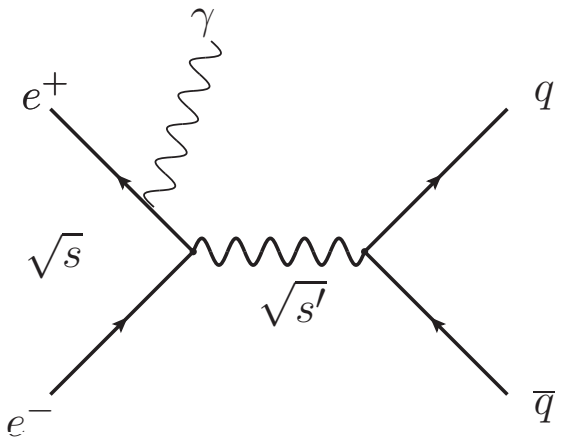
University of Victoria
on behalf of the *BABAR* collaboration

Motivation

- calculation of $(g_\mu - 2)$ in Standard Model depends on input from experiments
  - e^+e^- hadronic cross section data needed to account for hadronic vacuum polarization
  - most sensitive to low-energy region

- about 3.5 standard deviation difference between the Standard Model value and the measured value of $(g_\mu - 2)$ [PDG]
  - not all accessible states have been measured so far
  - new measurements will improve the calculation of the Standard Model value
  - initial-state radiation (ISR) process can be used to obtain results for different $\sqrt{s'}$ in a single experiment

Motivation



- in addition: ISR events allow to study resonance spectroscopy
  - energy regions from threshold up to charmonium region can be studied
- also possible to look for new physics
  - dark photon to hadrons, ...

Previous ISR results by BABAR

- $e^+e^- \to \mu^+\mu^-\gamma$ Phys. Rev. D **69**,011103 (2004)

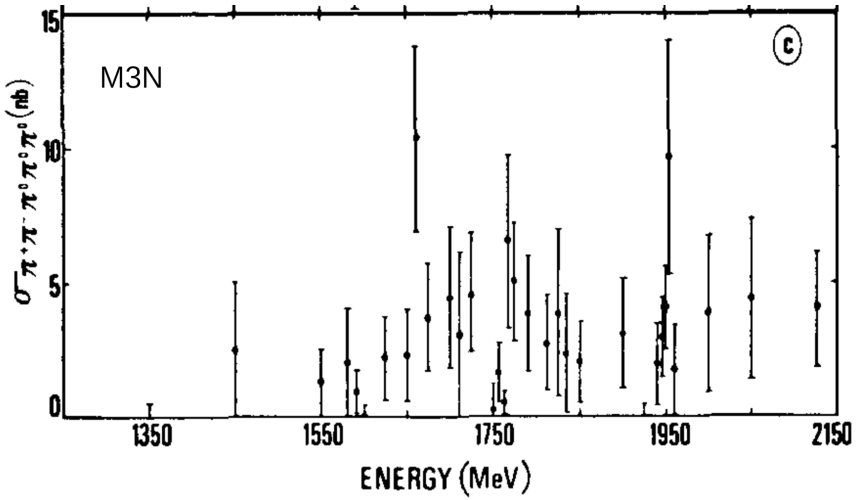
- $e^+e^- \to X_h\gamma$ where X_h is:
  - $\pi^+\,\pi^-$ Phys. Rev. D **86**,032013 (2012), Phys. Rev. Lett. **103**, 231801 (2009)
  - $K^+\,K^-$ Phys. Rev. D **88**,032013 (2013)
  - $p\,\bar{p}$ Phys. Rev. D **88**,072009 (2013)
  - $\pi^+\,\pi^-\,\pi^+\,\pi^-,\ \pi^+\,\pi^-\,K^+\,K^-,\ K^+\,K^-\,K^+\,K^-$ Phys. Rev. D **71**,052001 (2005)
  - $K^+\,K^-\,\pi^0\,\pi^0$ Phys. Rev. D **86**,012008 (2012)
  - $3(\pi^+\pi^-)$, $2(\pi^+\pi^-\pi^0)$, $2(\pi^+\pi^-)K^+K^-$ Phys. Rev. D **73**,052003 (2006)

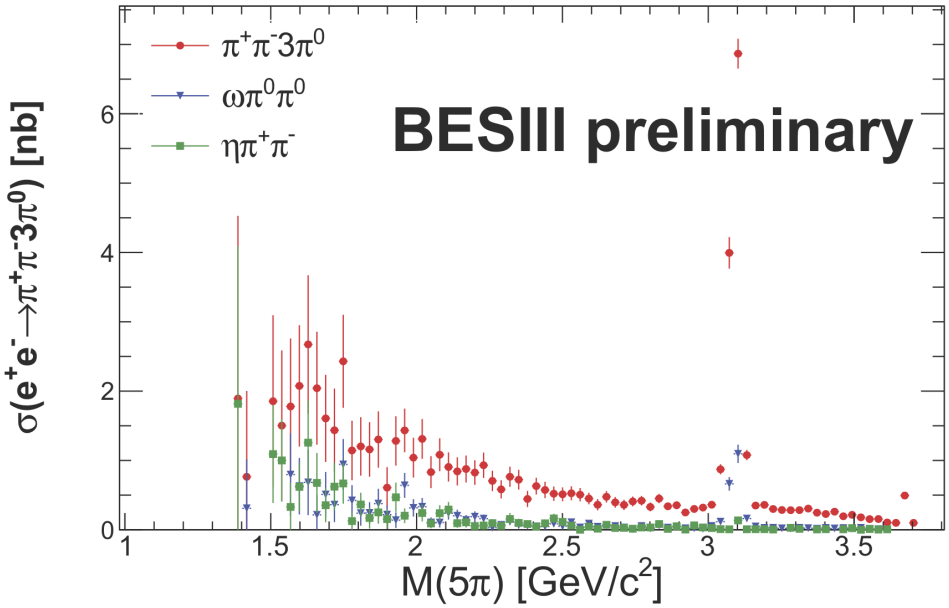
- states with K^0_S, K^0_L, π^0,.... (2004-2018)

Previous results

- cross-section for $e^+e^- \to \pi^+\pi^- 3\pi^0$ reported by M3N Nucl. Phys. B **152**,215 (1979) and MEA Lett. Nuovo Cim. **25**, 5 (1979)

- also by BES-III Nucl.Part.Phys.Proc. **294-296**,158-163





- *BABAR* measured before $e^+e^- \to \eta\pi^+\pi^-$ with $\eta \to \pi^+\pi^-\pi^0$ Phys. Rev. D **76**,092005 (2007) and $\eta \to \gamma\gamma$ Phys. Rev. D **97**,052007 (2018)
  - here we present $e^+e^- \to \eta\pi^+\pi^-$ with $\eta \to 3\pi^0$

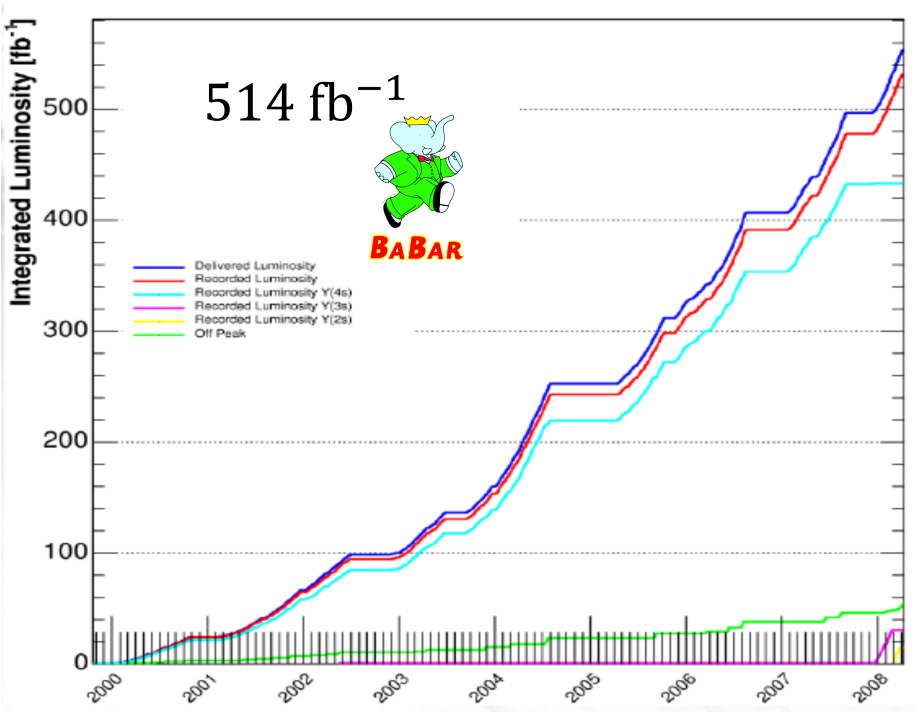
- no measurement for $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\eta$ so far
  - SND reported cross-sections for resonant sub-modes

The BABAR experiment

- e^+e^- experiment at SLAC National Accelerator Center in California
- built to study CP violation in the B-meson system
- $>$580 papers published so far
  - 10 submitted in 2018

Data taking period: 1999-2008

$\Upsilon(4S)$:	$424\,\text{fb}^{-1}$
$\Upsilon(3S)$:	$28\,\text{fb}^{-1}$
$\Upsilon(2S)$:	$14\,\text{fb}^{-1}$
between $b\bar{b}$ resonances:	$48\,\text{fb}^{-1}$
total:	$\mathbf{514\,fb^{-1}}$



ISR study of

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

and

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

Selection criteria

- 2 well reconstructed tracks fitted to common vertex close to collision point
  - inconsistent with kaon or muon

- photon with highest energy considered ISR photon, $E(\gamma_{ISR}) > 3\,\text{GeV}$

- 6 additional photons required, combined into 3 pairs (15 combinations)
  - at least for 2 pairs $\|m_{\pi^0_{\text{cand}}} - m_{\pi^0}\| < 35\,\text{MeV}/c^2$
  - no constraints on 3rd pair $\rightarrow$ allows π^0 and η reconstruction

- kinematic fit for $e^+e^- \rightarrow \pi^+\pi^- 2\pi^0\gamma\gamma\gamma_{ISR}$
  - $m_{\pi^0_{\text{cand}}}$ constrained to m^0_π
  - combination with smallest χ^2 used
  - signal region: $\chi^2_{\pi^+\pi^-\pi^0\pi^0\gamma\gamma} < 60$
  - control region: $60 < \chi^2_{\pi^+\pi^-\pi^0\pi^0\gamma\gamma} < 120$

Background reduction

- no charged track close to ISR photon
  - suppresses background from $\tau^+\tau^-$ decays
- fit candidates for $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma_{ISR}$
  - larger cross-section than the studied decay mode
  - together with 2 background photons it can look like signal
  - reject if $\chi^2 < 30$
- study non-ISR uds background
  - dominated by $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$ with one very high energetic photon from a π^0 decay

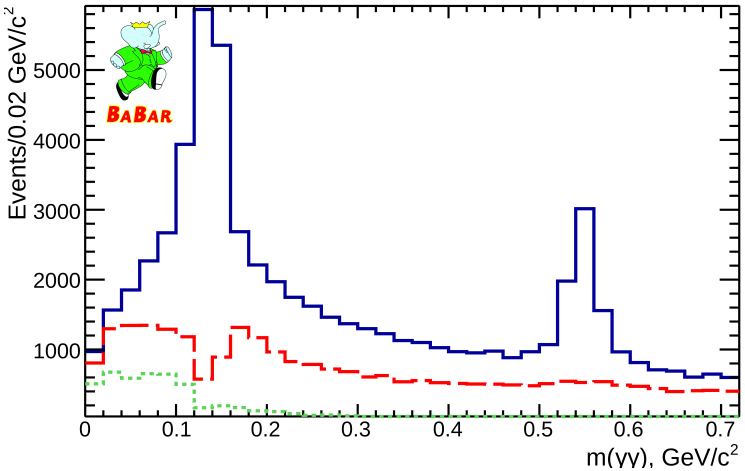
Signal extraction

- signal extraction: $\sqrt{s'}$ scanned in 0.05 GeV/c^2 intervals

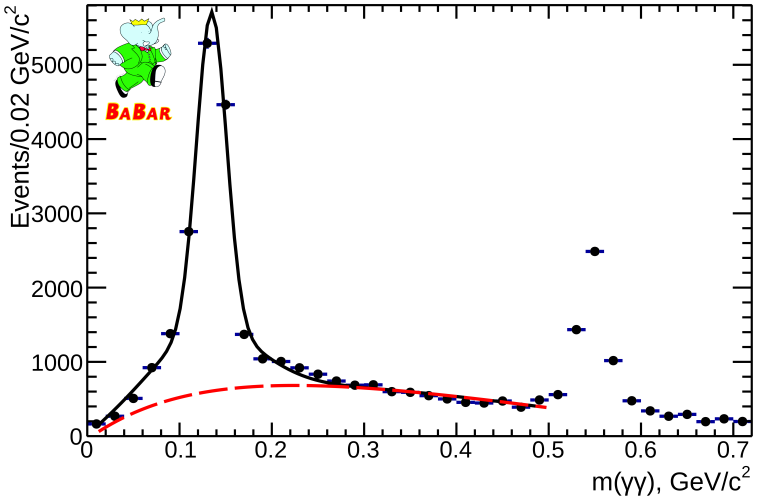
- distribution for control region subtracted from signal distribution
  - $m(\gamma\gamma)$ fitted and $N(\pi^0)$ or $N(\eta)$ used as signal yield for each interval
  - signal shape fixed to the shape obtained from signal MC
  - efficiency nearly independent of $\sqrt{s'}$, $\sim 4\%$

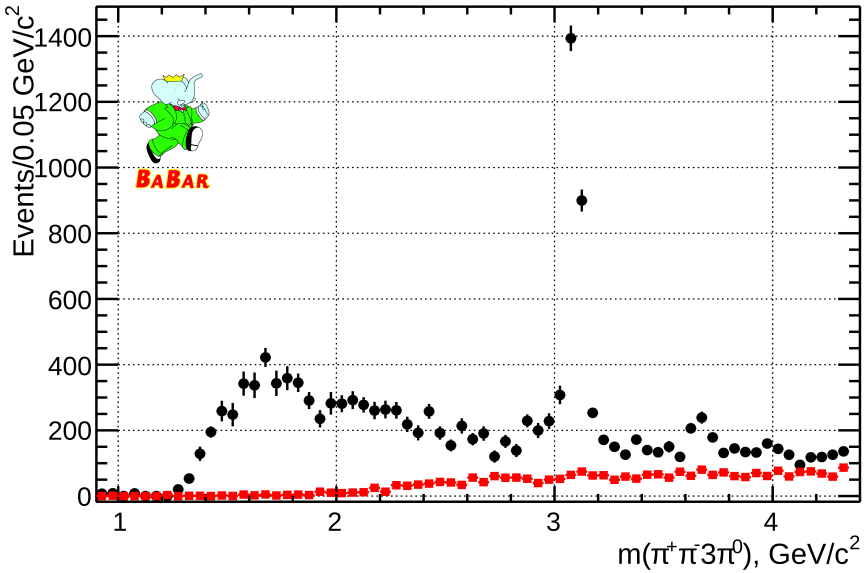
- signal extraction for resonant sub-modes similar:
  - for $\eta\pi^+\pi^-$ events: signal extraction in $m(\pi^0\pi^0\pi^0)$
  - for $\omega\pi^0\pi^0$ events: signal extraction in $m(\pi^+\pi^-\pi^0)$
  - for $\rho^\pm\pi^\mp\pi^0\pi^0$ events: signal extraction in $m(\pi^\pm\pi^0)$

Results for $\pi^+\pi^-3\pi^0$

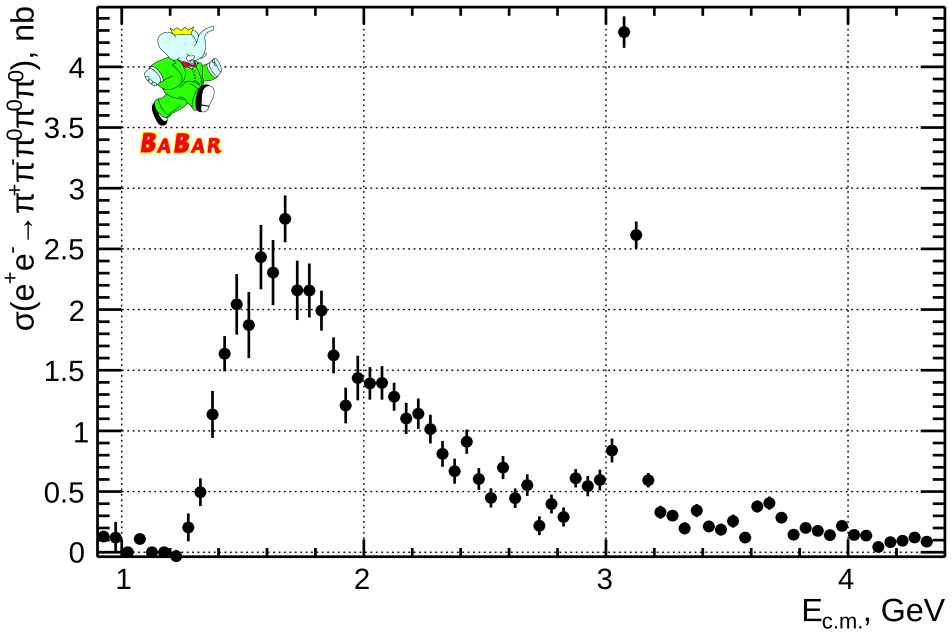


red dashed: bg from χ^2 control region
green dotted: bg from $\pi^+\pi^-\pi^0\pi^0$



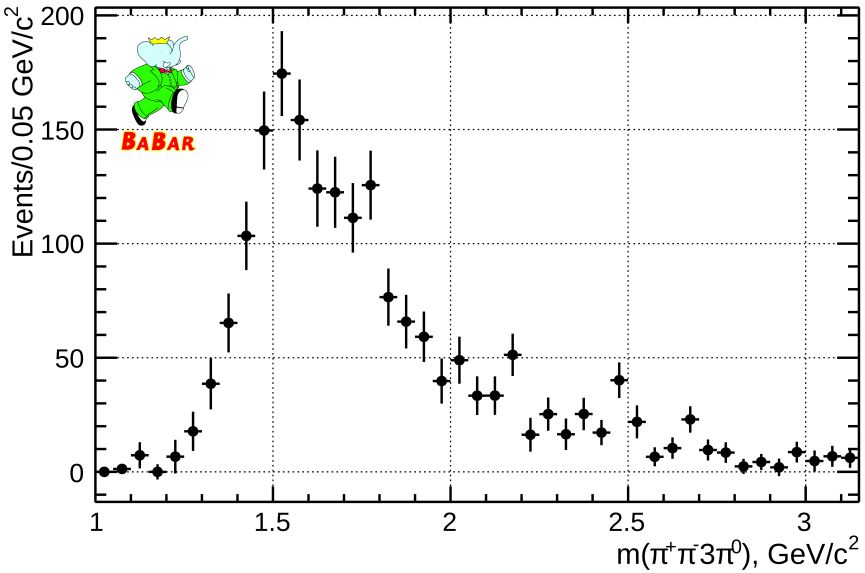


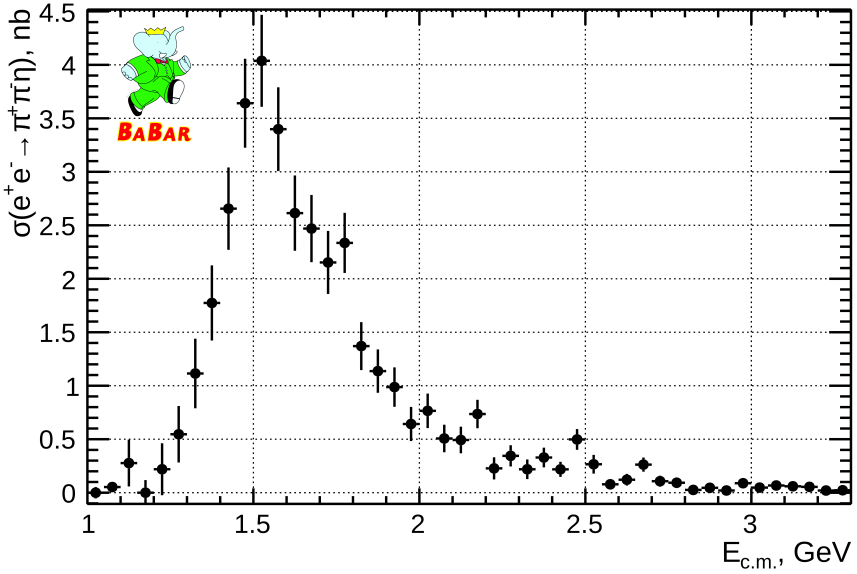
red dotted: background from non-ISR uds events

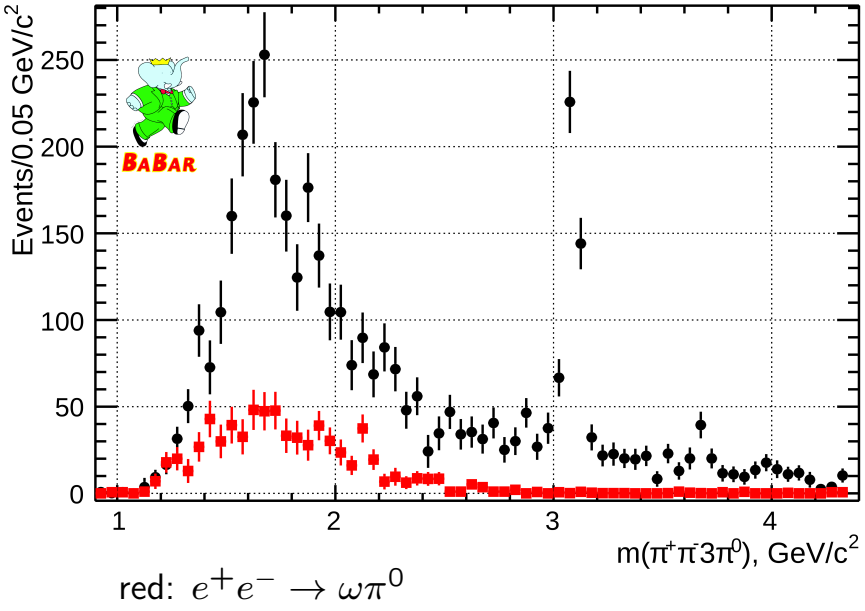


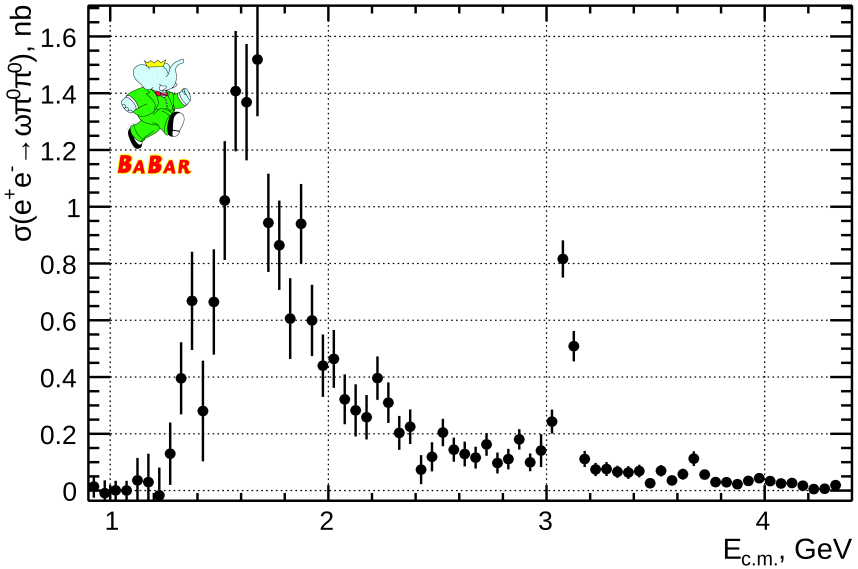
$$m(\pi^+\pi^-3\pi^0) = E_{\mathrm{c.m.}'} = \sqrt{s'}$$

Results for $\pi^+\pi^-\eta/\omega 2\pi^0$

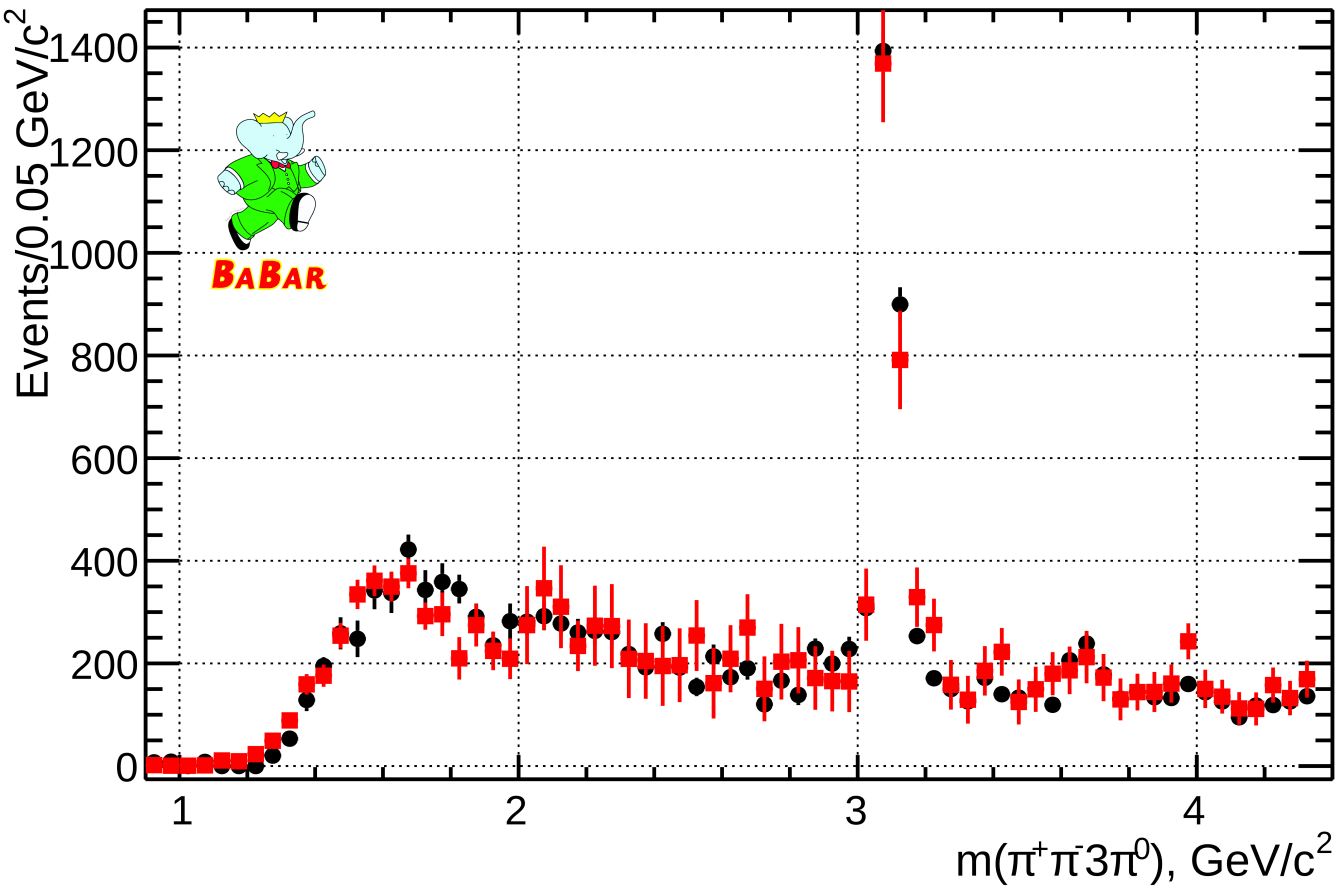








Sum of intermediate states

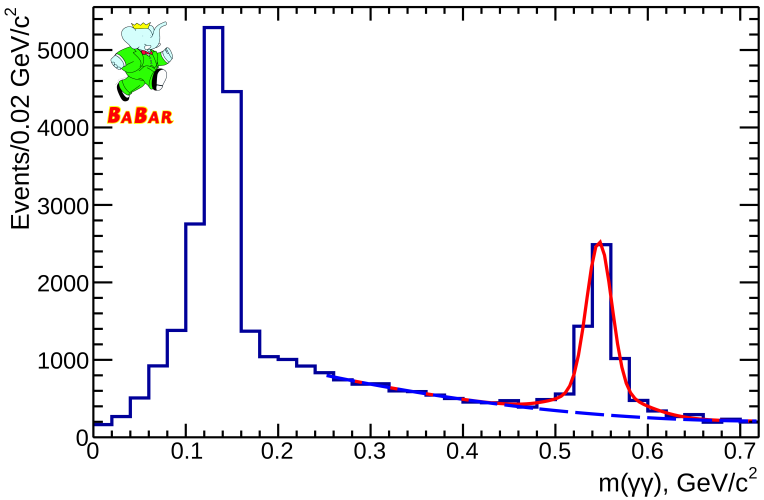


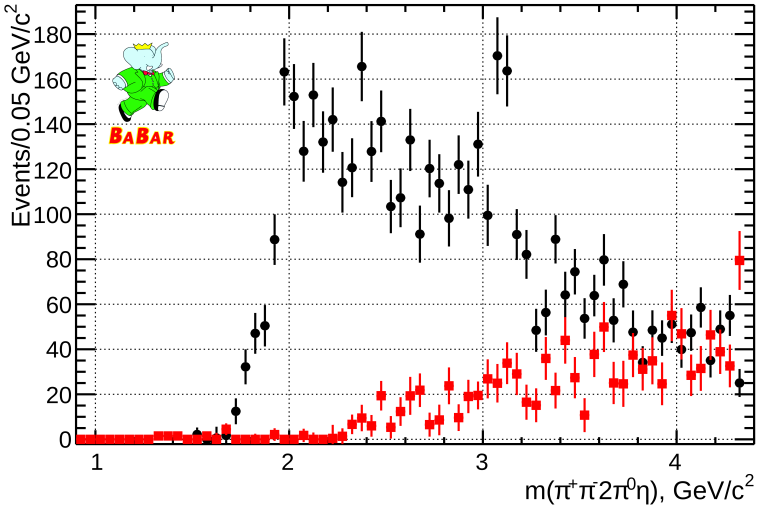
black: total number of events for $\pi^+\pi^-3\pi^0$ final state

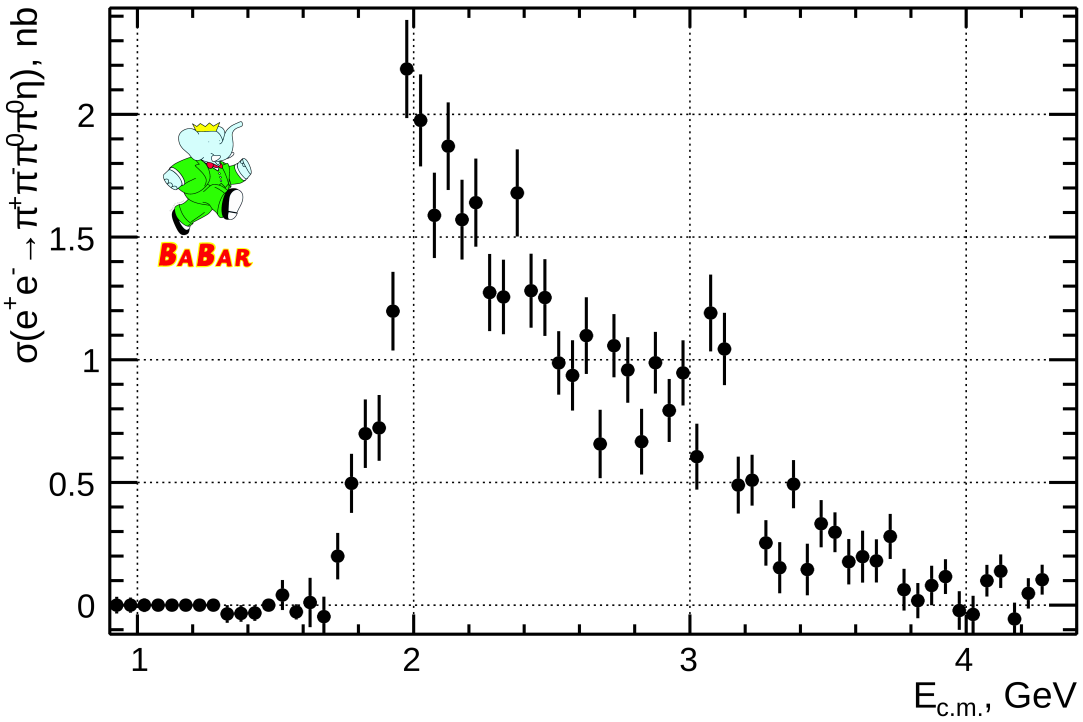
red: number of events for resonant sub-modes ($\pi^+\pi^-\eta, \omega 2\pi^0, \rho^\pm\pi^\mp 2\pi^0, \rho^+\rho^-\pi^0$)

Results for $\pi^+\pi^-2\pi^0\eta$

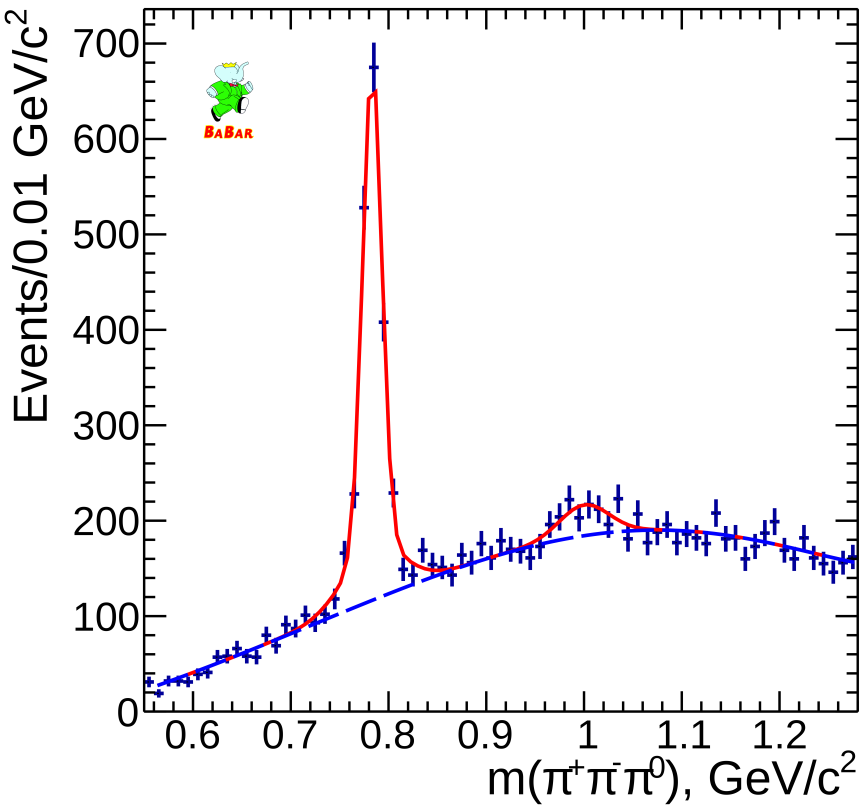
red: background from non-ISR uds events

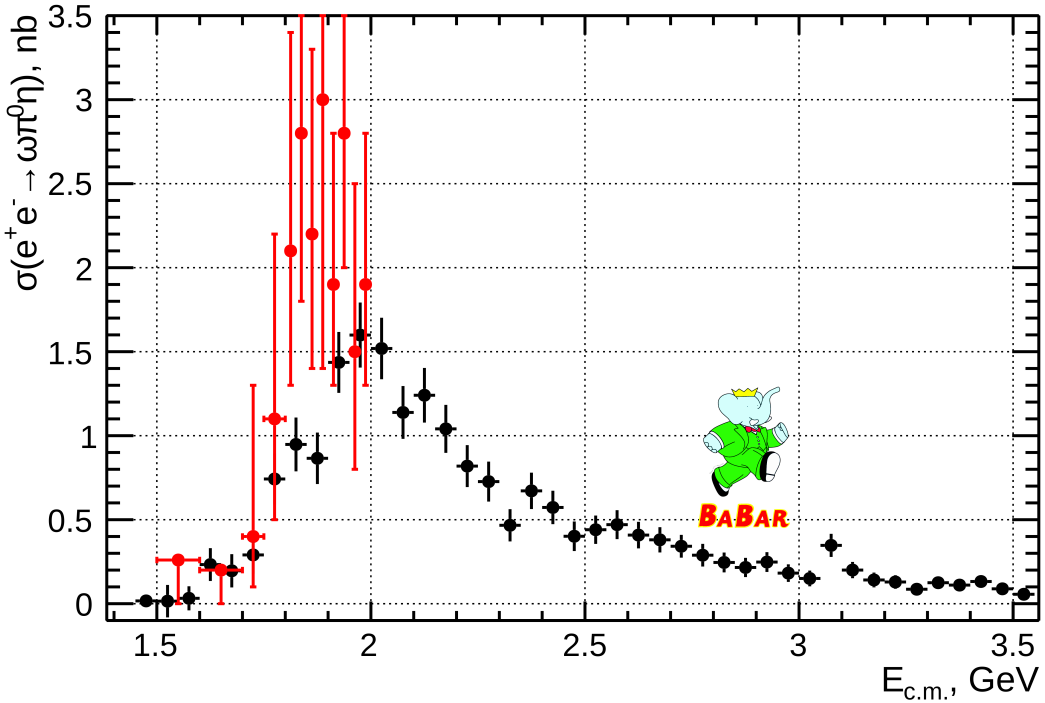






Results for $\omega\pi^0\eta/\phi\pi^0\eta$

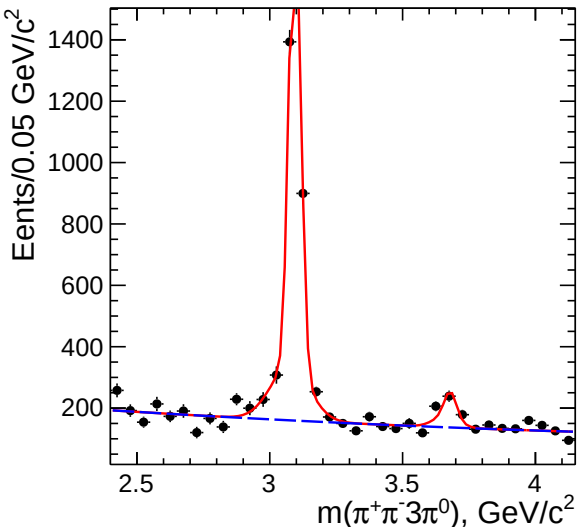


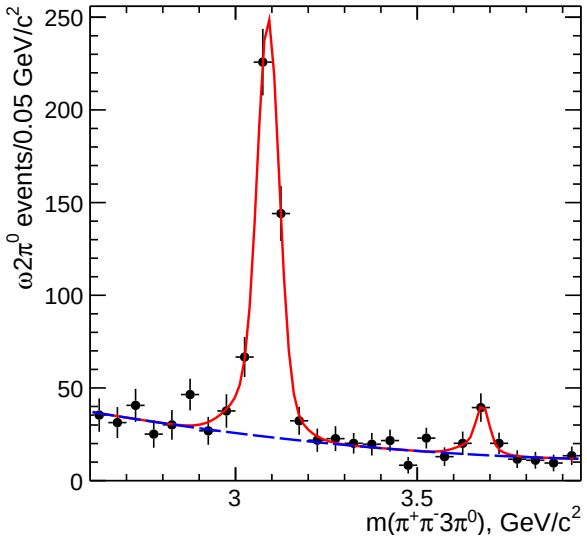


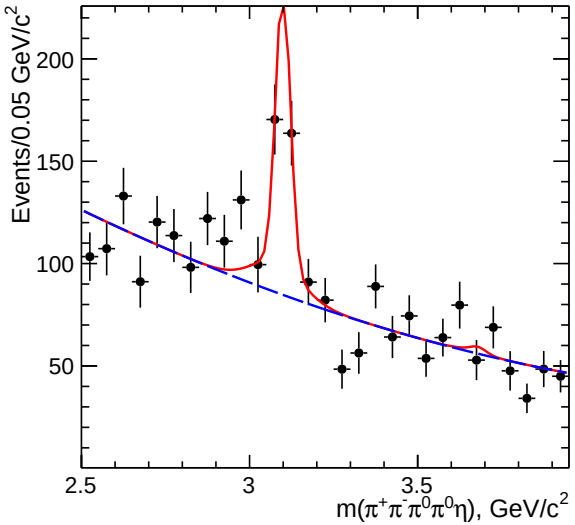
red: results by SND Collaboration

Phys. Rev. D **94**,032010 (2016)

J/ψ and $\psi(2S)$ branching fractions







J/ψ and $\psi(2S)$ branching fractions

Measured Quantity	Measured Value (eV)	J/ψ or $\psi(2S)$ Branching Fraction (10^{-3}) Calculated, this work	PDG
$\Gamma_{ee}^{J/\psi}\cdot\mathcal{B}_{J/\psi\to\pi^+\pi^-\pi^0\pi^0\pi^0}$	150.0±4.0±15.0	27.0 ±0.7 ±2.7	no entry
$\Gamma_{ee}^{J/\psi}\cdot\mathcal{B}_{J/\psi\to\omega\pi^0\pi^0}\cdot\mathcal{B}_{\omega\to 3\pi}$	24.8±1.8±2.5	5.04±0.37±0.50	3.4±0.8
$\Gamma_{ee}^{J/\psi}\cdot\mathcal{B}_{J/\psi\to\rho^\pm\pi^\mp\pi^0\pi^0}$	78.0±9.0±8.0	14.0 ±1.2 ±1.4	no entry
$\Gamma_{ee}^{J/\psi}\cdot\mathcal{B}_{J/\psi\to\rho^+\rho^-\pi^0}$	33.0±5.0±3.3	6.0 ±0.9 ±0.6	no entry
$\Gamma_{ee}^{J/\psi}\cdot\mathcal{B}_{J/\psi\to\pi^+\pi^-\pi^0\pi^0\eta}$	12.8±1.8±2.0	2.30±0.33±0.35	no entry
$\Gamma_{ee}^{J/\psi}\cdot\mathcal{B}_{J/\psi\to\omega\pi^0\eta}\cdot\mathcal{B}_{\omega\to 3\pi}$	1.7±0.8±0.3	0.34±0.16±0.06	no entry
$\Gamma_{ee}^{J/\psi}\cdot\mathcal{B}_{J/\psi\to\rho^\pm\pi^\mp\pi^0\eta}$	10.5±4.1±1.6	1.7 ±0.7 ±0.3	no entry
$\Gamma_{ee}^{\psi(2S)}\cdot\mathcal{B}_{\psi(2S)\to\pi^+\pi^-\pi^0\pi^0\pi^0}$	12.4±1.8±1.2	5.2 ±0.8 ±0.5	no entry
$\Gamma_{ee}^{\psi(2S)}\cdot\mathcal{B}_{\psi(2S)\to J/\psi\pi^0\pi^0}\cdot\mathcal{B}_{J/\psi\to 3\pi}$	10.1±1.5±1.1	22.9 ±2.8 ±2.3	21.1±0.7
$\Gamma_{ee}^{\psi(2S)}\cdot\mathcal{B}_{\psi(2S)\to\omega\pi^0\pi^0}\cdot\mathcal{B}_{\omega\to 3\pi}$	2.3±0.7±0.2	1.1 ±0.3 ±0.1	no entry
$\Gamma_{ee}^{\psi(2S)}\cdot\mathcal{B}_{\psi(2S)\to\rho^\pm\pi^\mp\pi^0\pi^0}$	<6. 2 at 90% C.L.	<2. 6 at 90% C.L.	no entry
$\Gamma_{ee}^{\psi(2S)}\cdot\mathcal{B}_{\psi(2S)\to\pi^+\pi^-\pi^0\pi^0\eta}$	<0. 85 at 90% C.L.	<0. 35 at 90% C.L.	no entry

Summary

- determined hadronic cross-sections for different final states and large $\sqrt{s'}$ region
  Phys. Rev. D **98**,112015

- increased precision for $e^+e^- \to \pi^+\pi^- 3\pi^0$ cross-sections and for resonant sub-modes

- cross-sections for $e^+e^- \to \pi^+\pi^- 2\pi^0\eta$ measured for the first time and increased precision for measurements on resonant sub-modes

- both modes are dominated by resonant sub-modes

- 12 different J/ψ and $\psi(2S)$ branching fractions measured
  - for 10 modes first-time measurement

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Analyses based on the BABAR dataset still very fruitful even 11 years after data taking!