Measurements of hadronic cross sections with the *BABAR* detector

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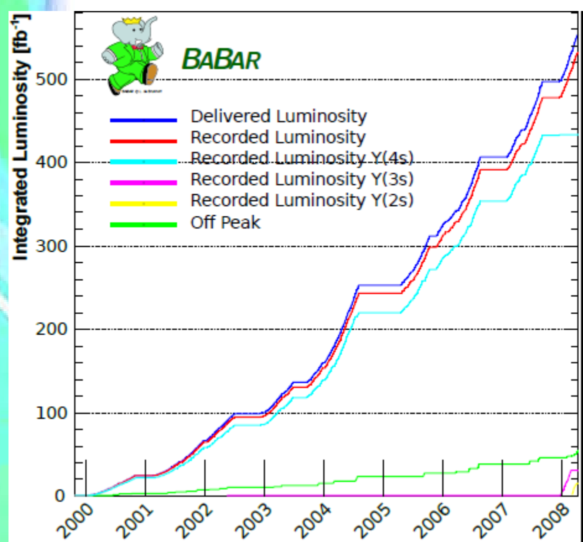
Outline

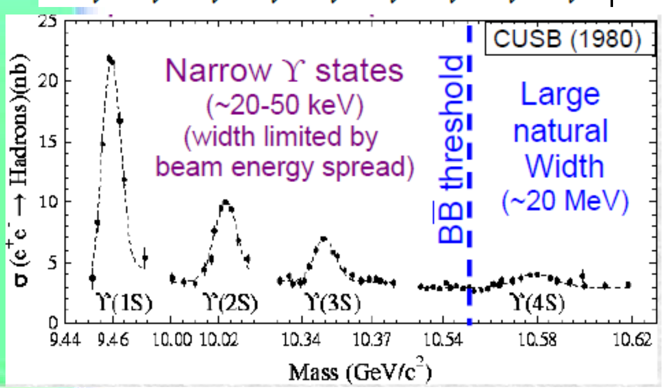
- Introduction and motivations
  - Evaluation of $(g\text{-}2)_\mu$ and $\alpha_{em}(\sqrt{s} = m_Z)$
  - Study of light quark and charm spectroscopy: vector meson excitations, K* resonances, charmonium decay modes and branching fractions

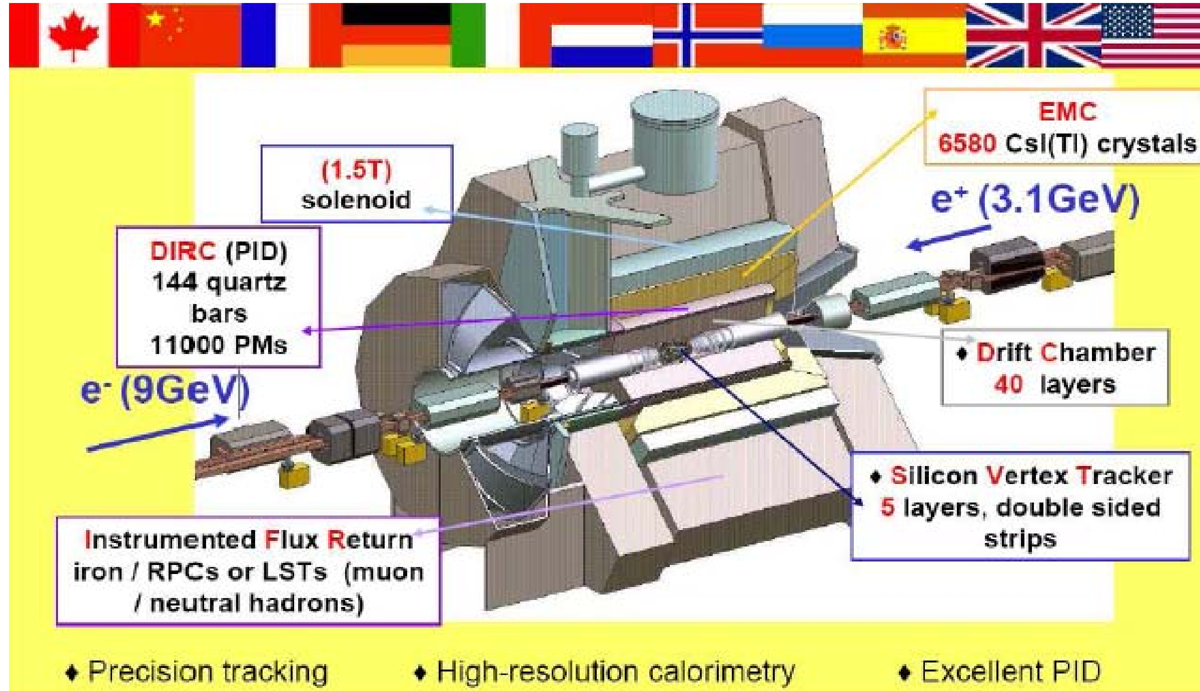
- The *BABAR* cross sections database via ISR technique in e^+e^- collisions
  - Channels with kaons & pions: cross sections and study of resonant substructures
    - $e^+e^- \to K^+K^-\pi^0$
    - $e^+e^- \to K_S K^\pm \pi^\mp$
    - $e^+e^- \to K_S K_L \pi^0$ **NEW (2017)**
    - $e^+e^- \to K_S K_L \pi^+\pi^-$
    - $e^+e^- \to K_S K_S \pi^+\pi^-$
    - $e^+e^- \to K^+K^-\pi^+\pi^-$
    - $e^+e^- \to K^+K^-\pi^0\pi^0$
    - $e^+e^- \to K_S K_L \pi^0\pi^0$ **NEW (2017)**
    - $e^+e^- \to K_S K^\pm \pi^\mp \pi^0$ **NEW (2017)**

- Conclusions

The *BABAR* experiment at PEP-II, SLAC







NIM **A479**, 1 (2002); NIM **A729**, 615 (2013)

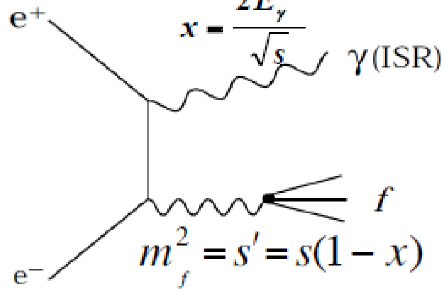
PEP-II and *BABAR* operated from Oct 1999 to Apr 2008

~ 500 fb^{-1}
integrated
luminosity

- ~470 ×10^6 Υ(4S)
- ~120 ×10^6 Υ(3S) (10x BELLE)
- ~100 ×10^6 Υ(2S) (10x CLEO)
- ~18 ×10^6 Υ(1S) from $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$

Initial State Radiation (ISR) at e^+e^- colliders

ISR photon: emitted from the colliding e^+ or e^-

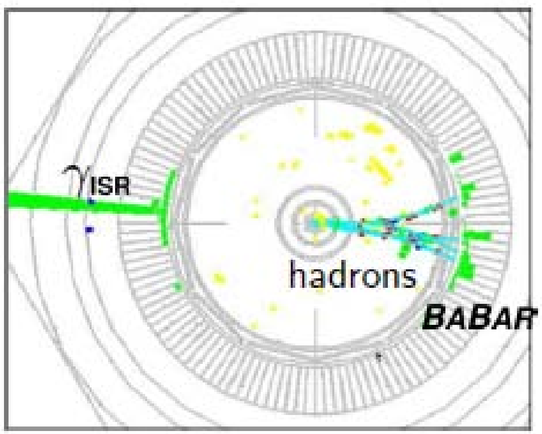


$$x = \frac{2E^*_\gamma}{\sqrt{s}}$$

$$m_f^2 = s' = s(1 - x)$$

$\sigma(e^+e^- \to f)$ extracted from $\sigma(e^+e^- \to \gamma f)$ through a QED radiation function W known at ~ 1% level

$$\frac{d\sigma_{e^+e^- \to f\gamma}(s, m_f)}{dm_f \, d\cos\theta^*_\gamma} = \frac{2m_f}{s} W(s, x, \theta^*_\gamma) \cdot \sigma_{e^+e^- \to f}(m_f)$$



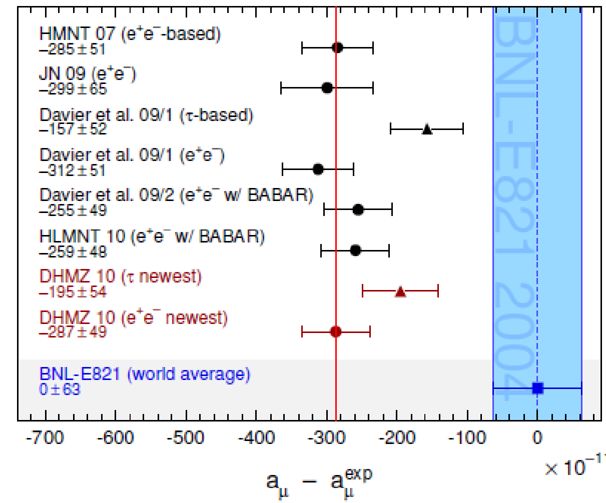
- $J^{PC} = 1^{--}$ at production vertex
- continuous ISR spectrum: from threshold up to √s ~ 8 GeV
- comparable or better sensitivity compared to energy scans
- larger ISR luminosity

- γ_{ISR} selection: $E^*_\gamma > 3$ GeV
- Reduced acceptance issues
- Kinematic fit for final state: good resolution

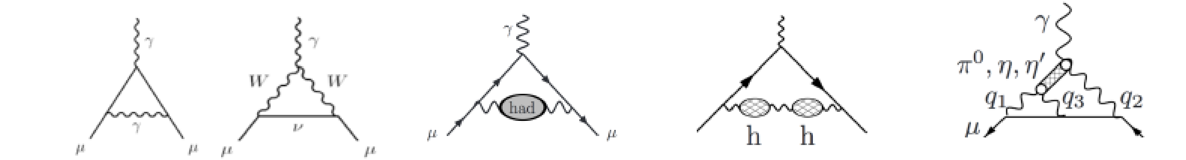
How to solve the $(g\text{-}2)_\mu$ discrepancy

- 3.5σ long-standing discrepancy of theory vs experiment for the muon anomalous magnetic moment: $a_\mu = (g_\mu - 2)/2$

M. Davier et al, EPJC71, 1515 (2011)



$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{hadronic,LO} + a_\mu^{hadronic,HO} + a_\mu^{hadronic,LBLs}$$



Diagrams from Jegerlehner and Nyffeler, Phys. Rept. 477 (2009) 1

Hadronic light-by-light scattering

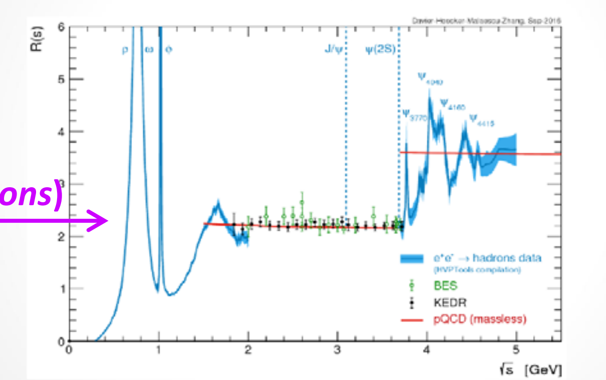
- Dominant correction and error from the LO hadronic term
  - Most precise predictions from low-energy *$e^+e^- \longrightarrow$ hadrons* exclusive cross sections and dispersion relations
  - Wide program of measurements at *BABAR*

$$a_\mu^{had,LO} = \frac{\alpha^2(0)}{3\pi^2}\int_{m_\pi^2}^{\infty} ds \boxed{\frac{K(s)}{s}} \cdot \boxed{R(s)}$$

≈ σ($e^+e^- \to$*hadrons*)

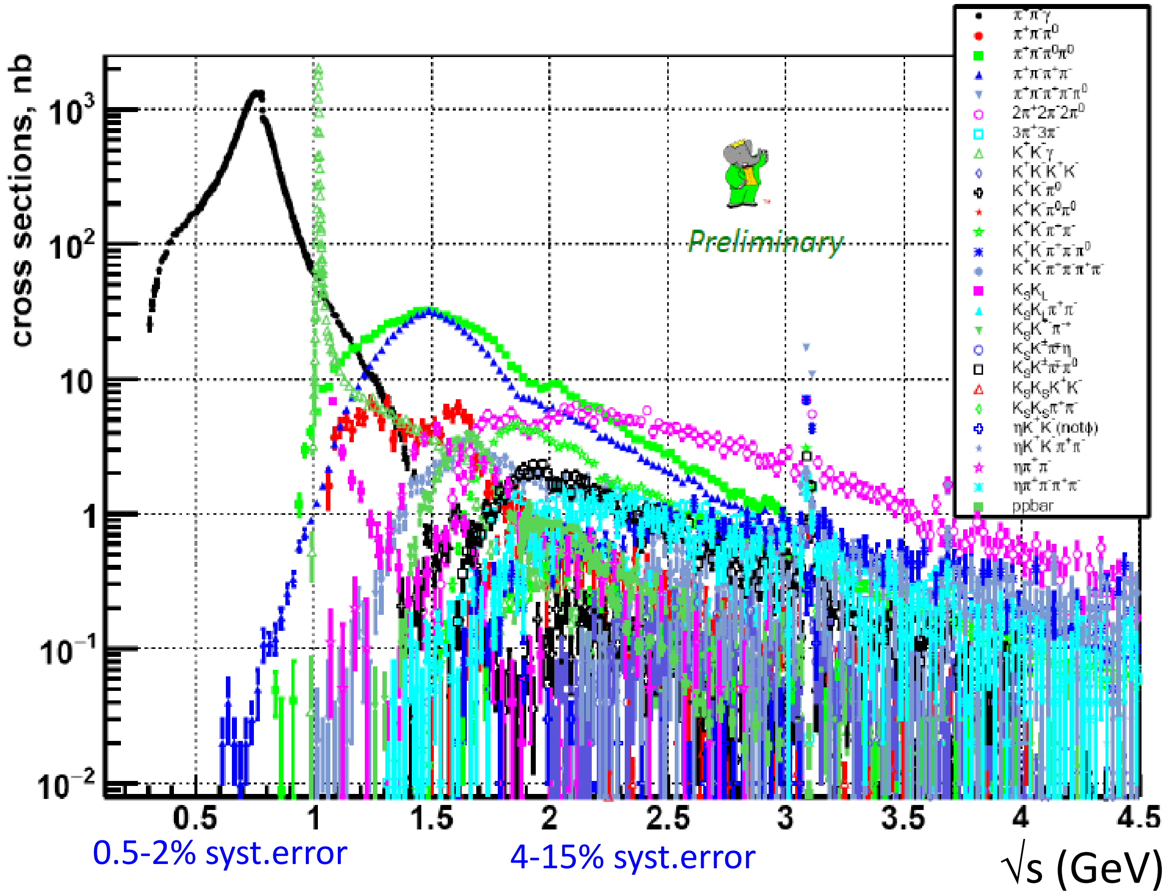
low energy dominance

DHMZ , TAU 2016, 1612.02743



BABAR exclusive σ_{had} measurements

- 2π dominates for √s < 1 GeV
- 4π dominates for 1 < √s < 2 GeV
- 6π dominates for √s > 2 GeV



Courtesy Fedor V. Ignatov, via J. Chauveau

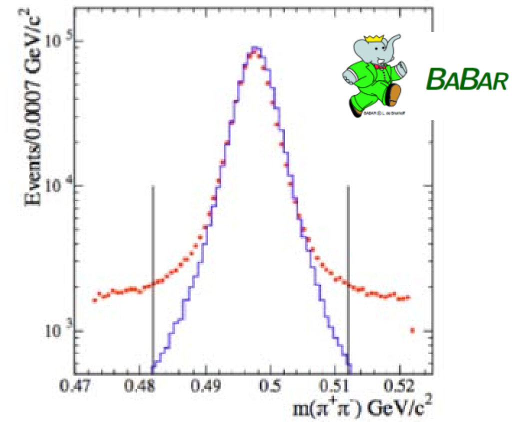
- Extended covered energy range
- Larger precision
- One experiment for all measurements

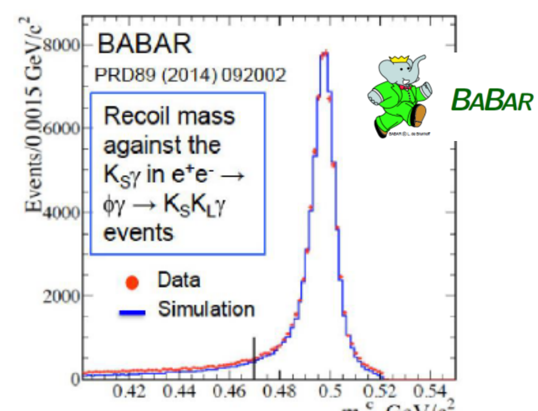
- Long list of published papers, > 20 studied channels
- Last channels with kaons recently published (2017)

Kaon identification in *BABAR*

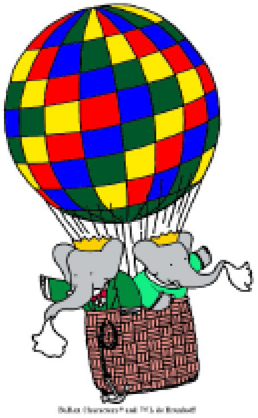
- $K^{\pm}$
  - standard charged particle pid using specific energy loss, time of flight, Cherenkov radiation
  - 80% efficiency, 2% misidentification rate
- K_S^0
  - reconstructed through pairs of opposite charged tracks with common displaced vertex: $K_S^0 \to \pi^+\pi^-$
- K_L^0
  - Identified via an isolated energy cluster in the calorimeter with cluster shape not consistent with a photon
  - Validated via

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





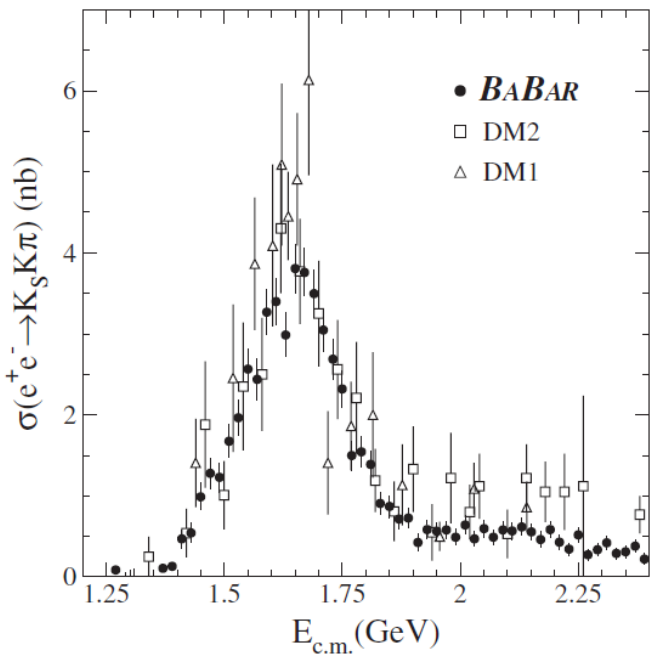
$K\bar{K}\pi$ final states

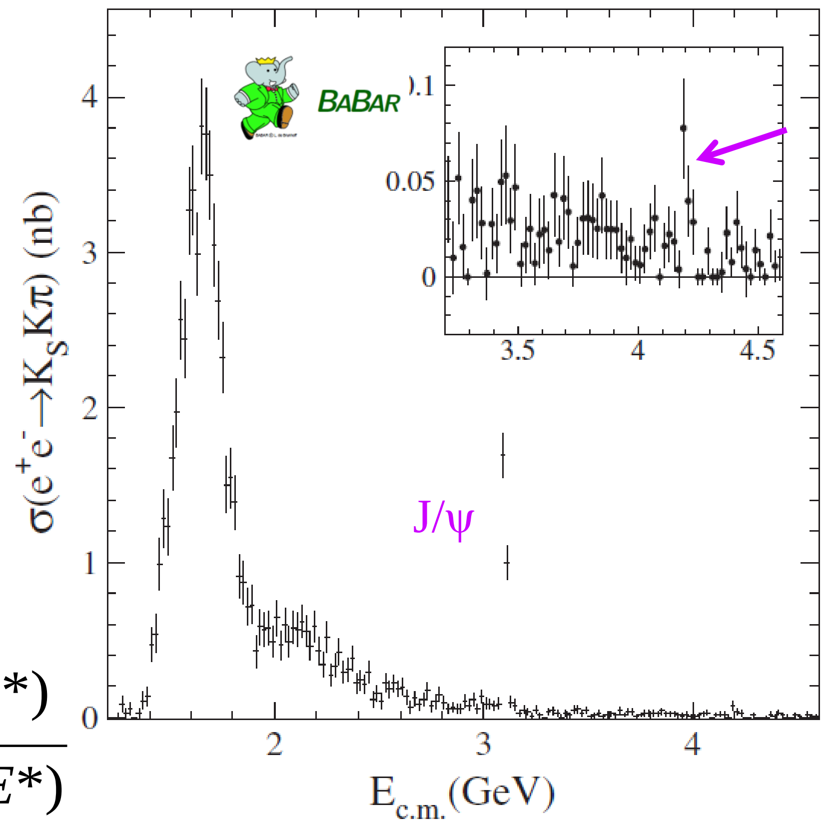


BABAR Coll., PRD77(2008), 092002

$e^+e^- \rightarrow K_S K^{\pm}\pi^{\mp}$: cross section

- Event reconstruction: γ_{ISR}, K_S^0
- Clear observation of J/ψ
- No evidence for Y(4260), upper limit at 90% C.L. $\Gamma_{ee}^{Y(4260)} \cdot \mathcal{B}_{K_S^0 K^{\pm}\pi^{\mp}}^{Y(4260)} = 0.5\,\text{eV}$
- Excess of events observed at ~ 4.2 GeV: 3.5σ fluctuation



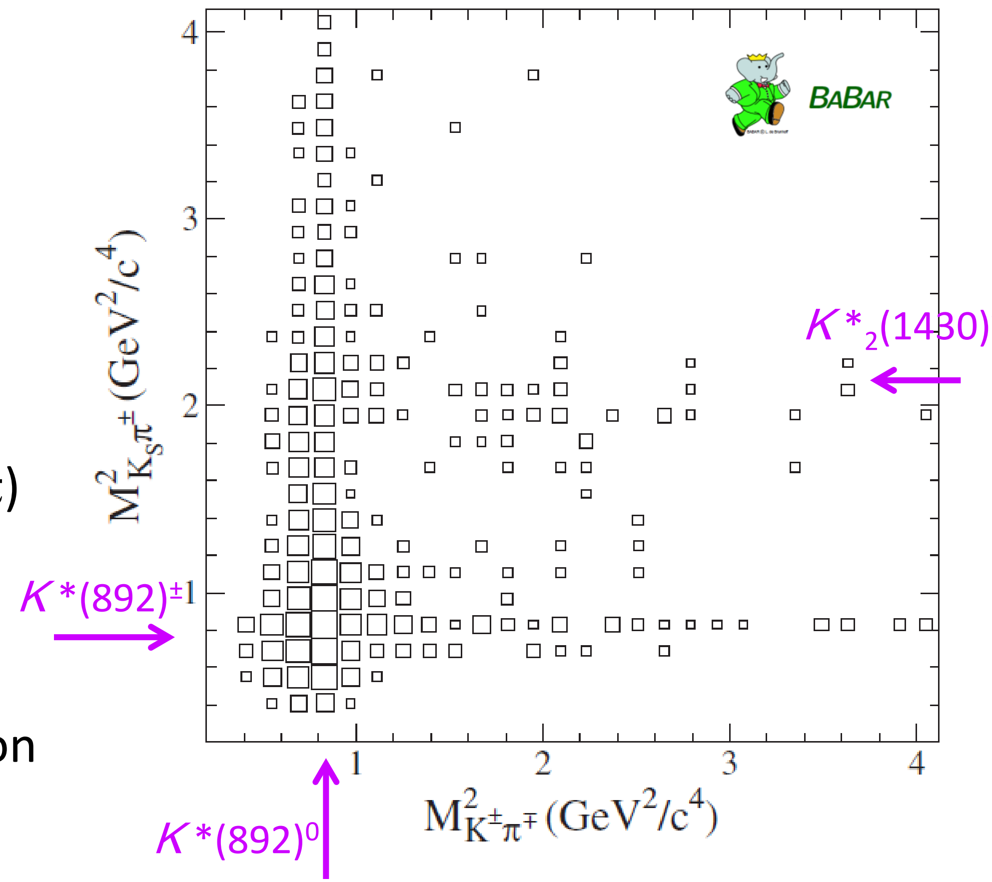


$$\sigma(e^+e^- \rightarrow K_S^0 K^{\pm}\pi^{\mp})(E^*) = \frac{dN_{K_S^0 K^{\pm}\pi^{\mp}}(E^*)}{d\mathcal{L}(E^*) \cdot \varepsilon(E^*)}$$

BABAR Coll., PRD77(2008), 092002

$e^+e^- \rightarrow K_S K^{\pm}\pi^{\mp}$: Dalitz analysis

- Main contribution given by $K^*(892)^{\pm}K^{\mp}$ and $K^*(892)^0 K_s$ or $K^*_2(1430)^{\pm}K^{\mp}$ and $K^*_2(1430)^0 K_s$
  - Both charged and neutral K^*
  - Asymmetric Dalitz plot
- Small contribution from $KK_1(1410)$ (small width in $K\bar{K}\pi$)
- From Dalitz plot analysis the isovector and isoscalar components of the cross section can be extracted
  - Charged/neutral K* modeled differently by interference effects
  - Dominant isoscalar component with clear resonant behavior (*ϕ (1680)*)
  - Isovector component: one broad resonance only (*ρ(1450)*)

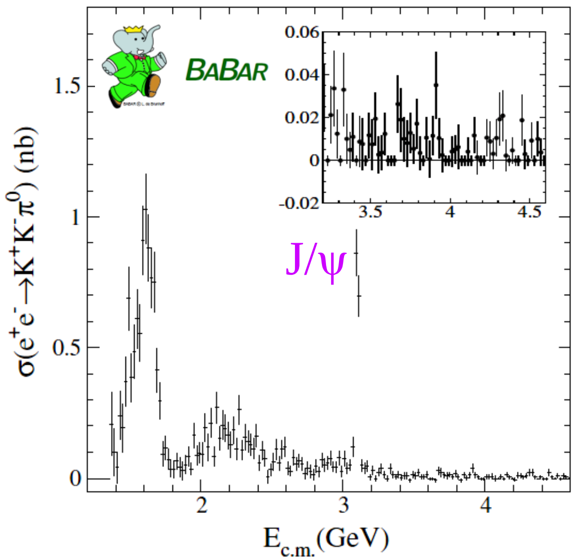


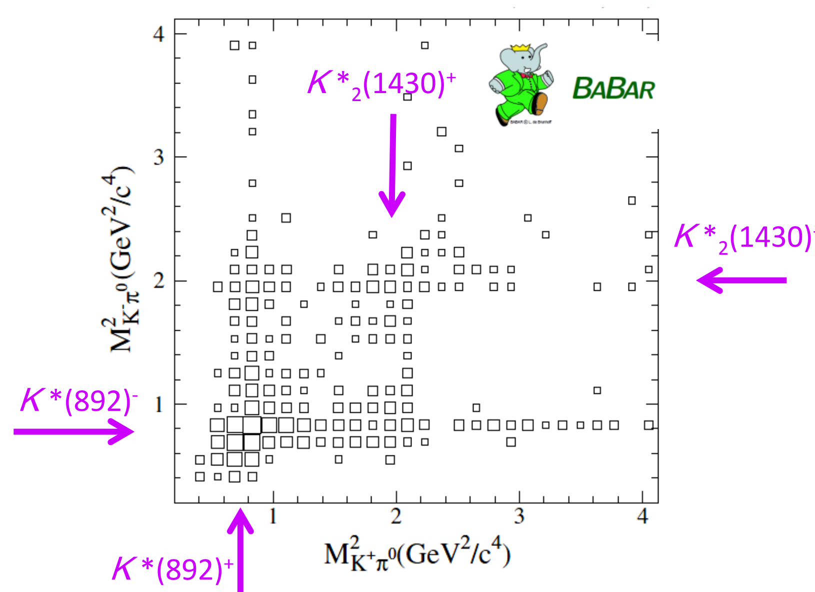
- Main contribution to $K_s\pi^{\mp}$ above 2 GeV given by $K^*_2(1430)^{\pm}$

BABAR Coll., PRD77(2008), 092002

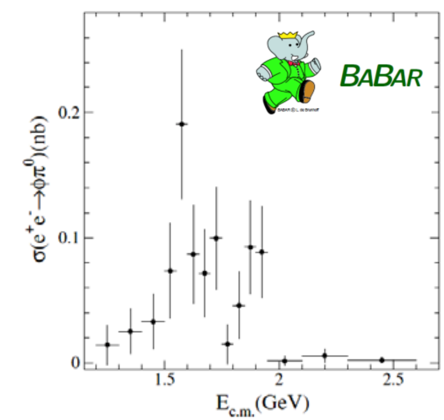
$e^+e^- \rightarrow K^+K^-\pi^0$

- Clear observation of J/ψ
- No evidence for *Y(4260)*, upper limit of decay BR at 90% C.L.: 0.6 eV





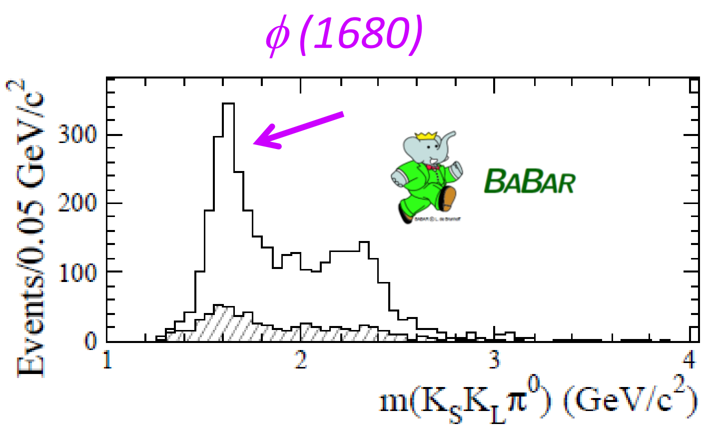
- Resonant substructures:
  - Final state produced through $K^*(892)^\pm K^\mp$ or $K^*_2(1430)^\pm K^\mp$
  - neutral K* only, symmetric Dalitz plot
  - $\phi\pi^0$ final state: observation of *C(1480)*? Of ρ *(1700)*? Of ρ *(1900)* as a dip?

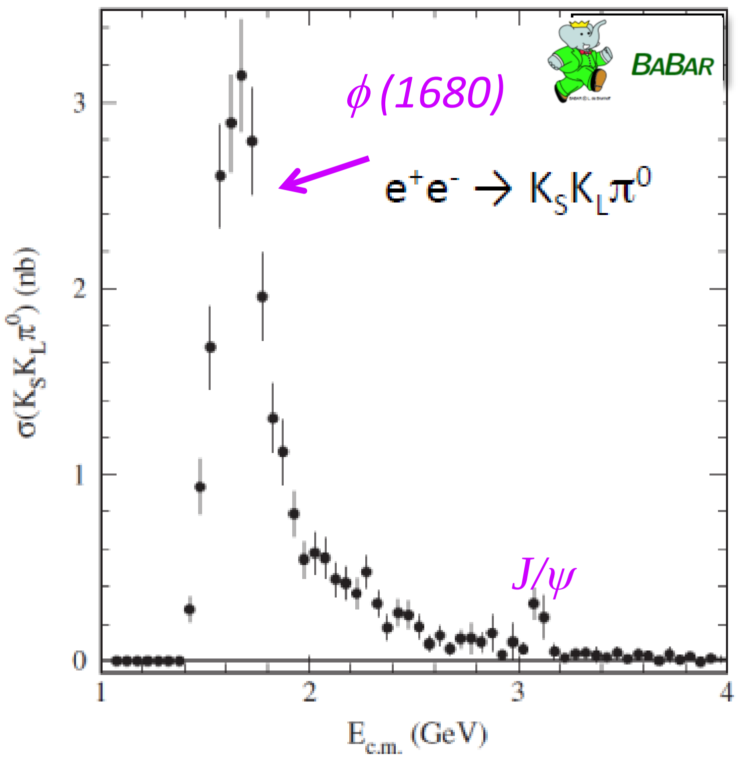


BABAR Coll., PRD95(2017), 052001

$e^+e^- \rightarrow K_S K_L \pi^0$: cross section

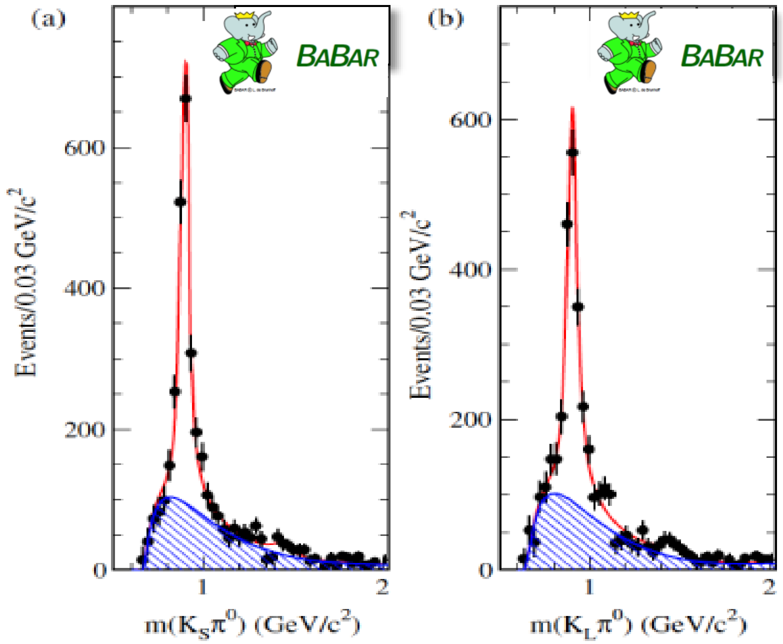
- Event reconstruction: γ_{ISR}, $\pi^0 \rightarrow \gamma\gamma$, K_S^0
- Invariant mass resolution of the final state: 25 MeV
- First measurement of this process: 3700 events
- First observation of $J/\psi \rightarrow K_S K_L \pi^0$
- Systematic uncertainty: ~10% at peak, ~ 30% at 3 GeV



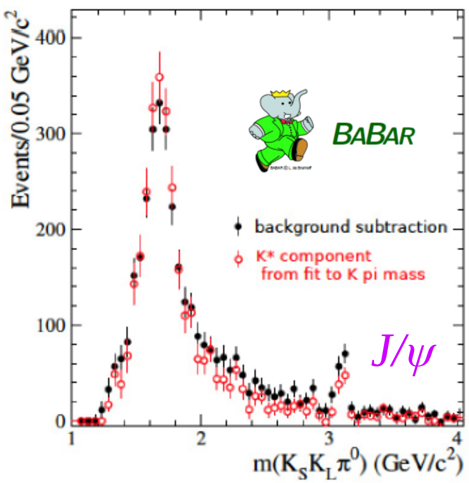


$e^+e^- \rightarrow K_S K_L \pi^0$: resonant substructures

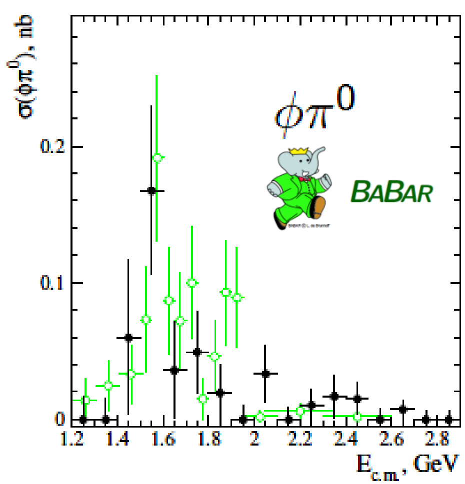
- Fit of background subtracted ($K_S \pi^0$) and ($K_L \pi^0$) invariant mass spectra with coherent resonant+non-resonant contributions
  - Dominant $K^{*0}\overline{K}^0$ + c.c.
    - mostly $K^*(892)^0\overline{K}^0$ + small $K^*(1430)^0\overline{K}^0$



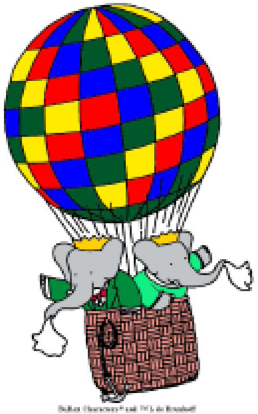
hatched areas = nonresonant components



- Cross section saturated by $K^*(892)^0\overline{K}^0$ + c.c.
- Small contribution from $\phi\pi^0$
  - Possible resonant structure I=1 @ 1.6 GeV?

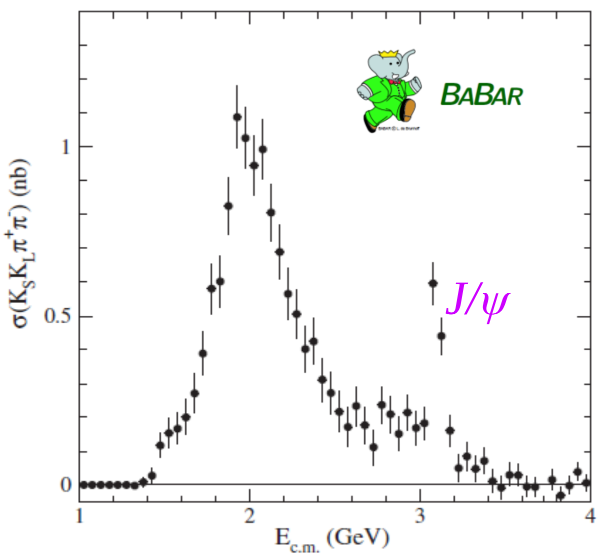


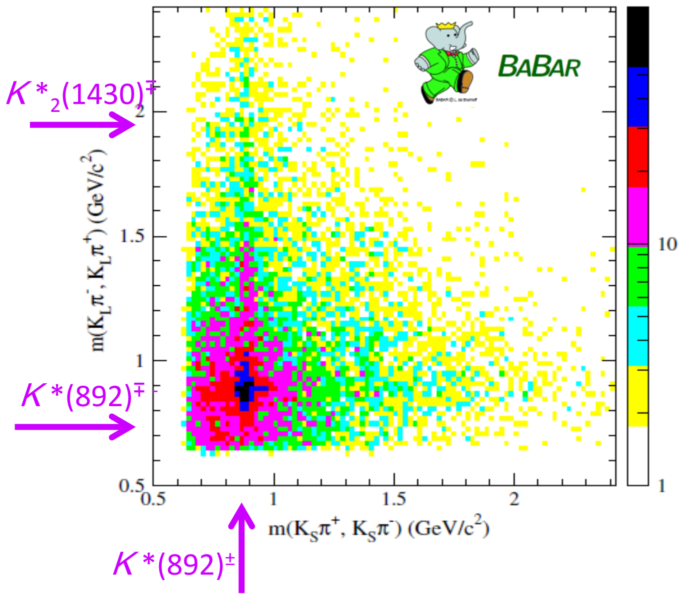
$K\bar{K}\pi\pi$ final states



$e^+e^- \rightarrow K_S K_L \pi^+\pi^-$

- Events with two tracks (not kaons) not coming from K_S but consistent with the same decay vertex
- Large background from ISR and non-ISR multihadron events
- Systematic uncertainty: ~10% for E*<2 GeV, ~ 30% at 2.5-3 GeV, 100% above 3.4 GeV
- Resonant substructure:
  - Clear bands of $K^*(892)^{\pm}$ and indications of $K^*_2(1430)^{\pm}$
  - Correlated production of $K^*(892)^+K^*(892)^-$ and $K^*(892)^{\pm} K^*_2(1430)^{\mp}$

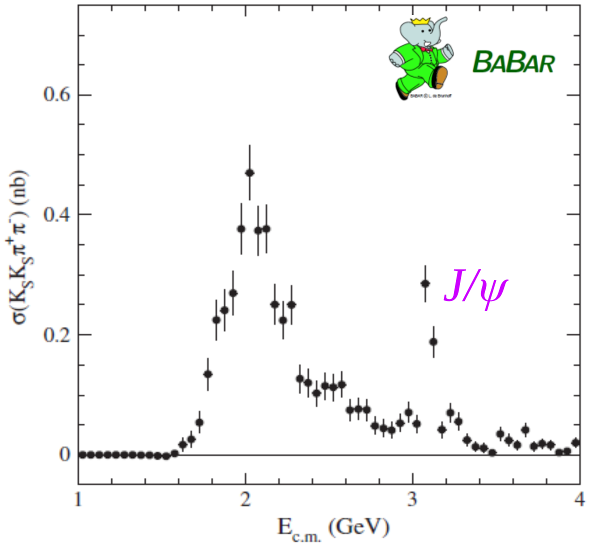


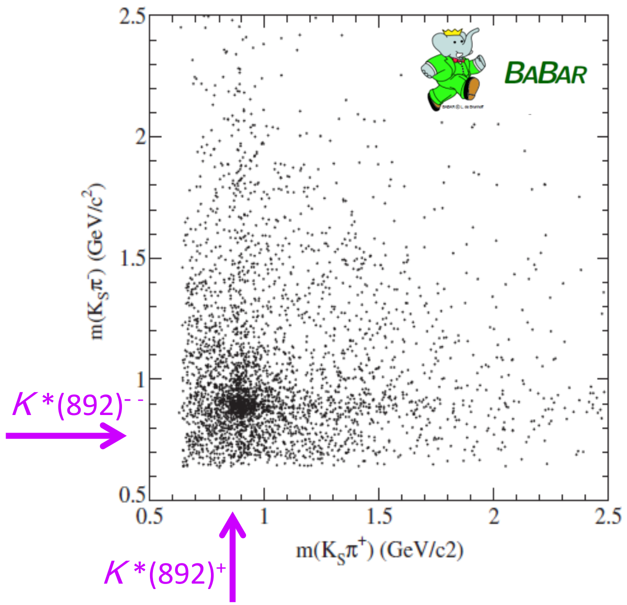


BABAR Coll., PRD89(2014), 092002

$e^+e^- \rightarrow K_S K_S \pi^+\pi^-$

- Only one neutral particle: ISR photon
- Systematic uncertainty dominated by the uncertainty of the background: ~5% at the peak, 50-70% at higher energies
- Resonant substructure:
  - Clear bands of $K^*(892)^\pm$ and indications of $K^*_2(1430)^\pm$
  - Correlated production of $K^*(892)^+K^*(892)^-$, dominant contribution below 2.5 GeV
  - Number of correlated $K^*(892)^+K^*(892)^-$ in $K_SK_S\,\pi^+\pi^-$ vs $K_SK_S\,\pi^+\pi^-$ vs $K^+K^-\pi^0\pi^0$ consistent with 1:2:1
  - no significant signal for $K^*(892)^\pm K^*_2(1430)^\mp$, small for $K^*_2(1430)^\pm K_S\,\pi^\mp$

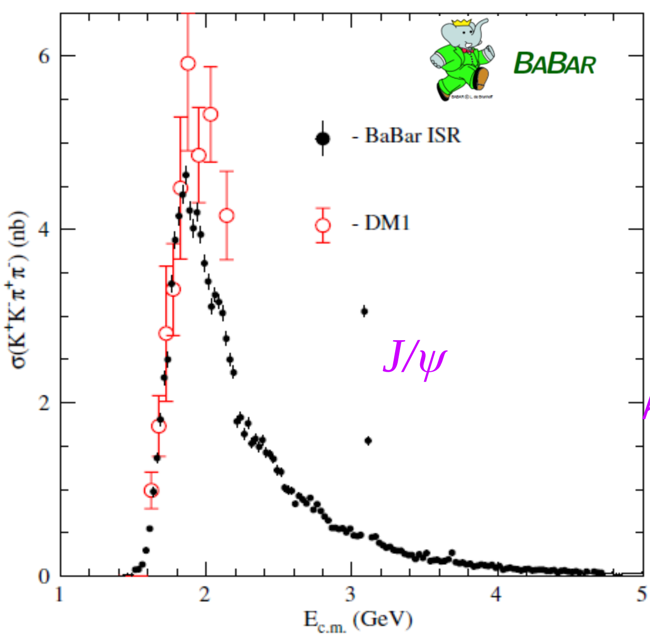


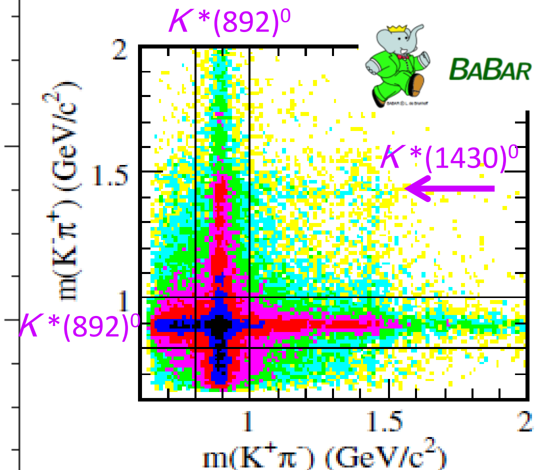


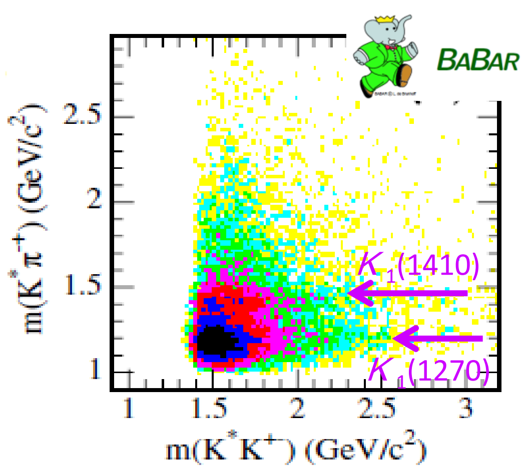
BABAR Coll., PRD86(2012), 012008

$e^+e^- \to K^+K^-\pi^+\pi^-$: cross section

- Systematic uncertainty: ~20% below 1.6 GeV,~2% in the 1.6-3.3 GeV range, ~ 10% in the range 3.3-5 GeV
- Cross section systematically lower than DM1 measurements
- Narrow peaks from *J/ψ*, *ψ(2S)* + possibly other structures (due to thresholds for intermediate states?)
- Mass resolution: 4.2 MeV below 2.5 GeV, 5.5 MeV above
- Resonant substructure: plenty of intermediate states



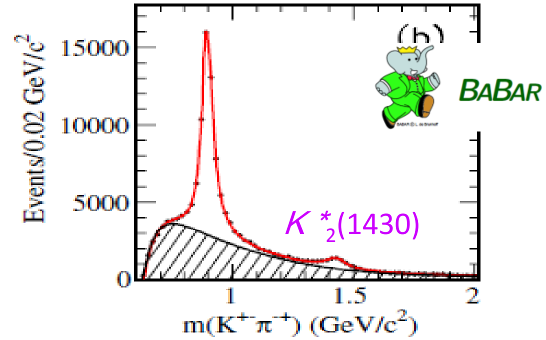




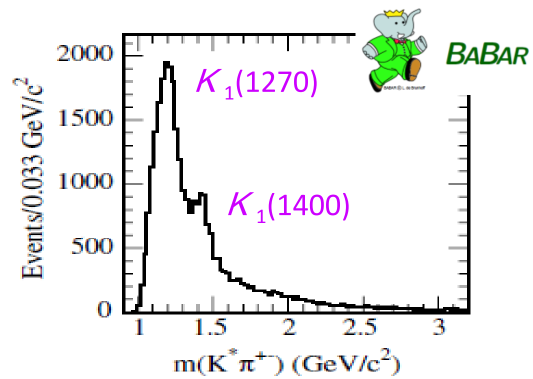
BABAR Coll., PRD86(2012), 012008

$e^+e^- \rightarrow K^+K^-\pi^+\pi^-$: resonant substructure

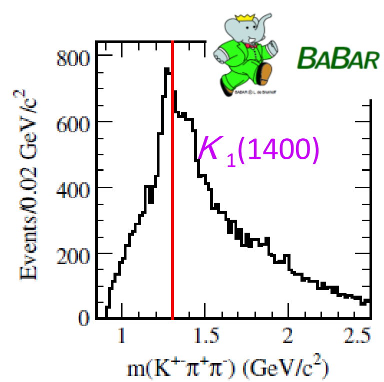
- Clear signal of $K^*(892)^0$ and $K^*_2(1430)^0$
  - Marginal contributions from $K^*(1410)^0$ and/or $K^*_0(1430)^0$ (other $K^\pm\pi^\mp$ decays)

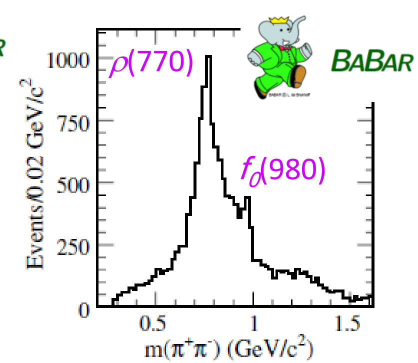


- $K^*(892)^0\,\pi^\pm$ invariant mass:
  - Evidence of contributions from $K_1(1270)$ and $K_1(1400)$



- Events **without** $K^*(892)^0 K\,\pi$:
  - Evidence for $K_1(1270)$ and $K_1(1400)$ decaying into $K\rho(770)$
  - No indications of additional $\pi^+\pi^-$ structures

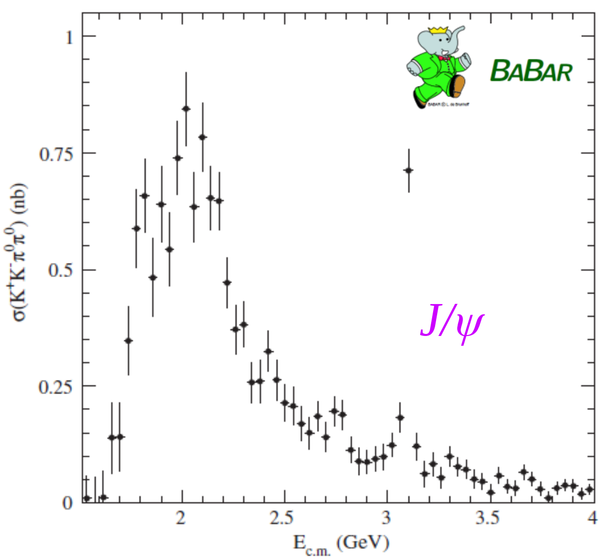


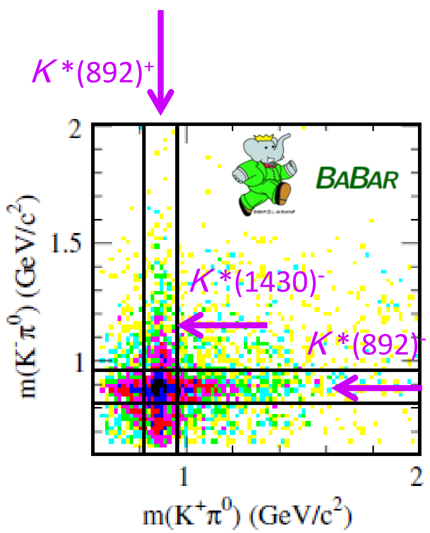


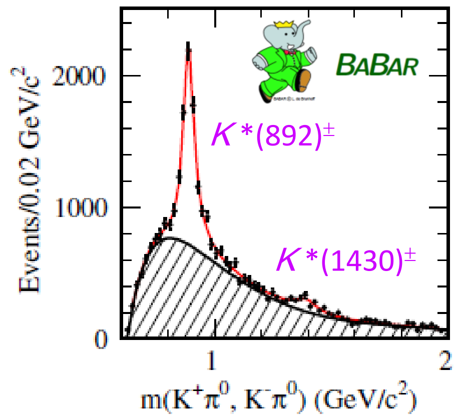
BABAR Coll., PRD86(2012), 012008

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

- Systematic uncertainty: ~7% at low mass, ~16% above 3 GeV
- Mass resolution: 8.8 MeV, increase to 11.2 MeV in the 2.5-3.5 GeV range
- Resonant substructure:
  - Large contributions from *K*(892)*$^{\pm}$
  - K*(1430)$^{\pm}$/K*(892)$^{\pm}$ consistent with the neutral K* production in $K^+K^-\pi^+\pi^-$
  - Clear correlated production observed for K*(892)$^+$K*(892)$^-$ and K*(892)$^+$K*$_2$(1430)$^-$
  - No evidence of resonant production in $K^+K^-\pi^0$ or $K^{\pm}\pi^0\pi^0$



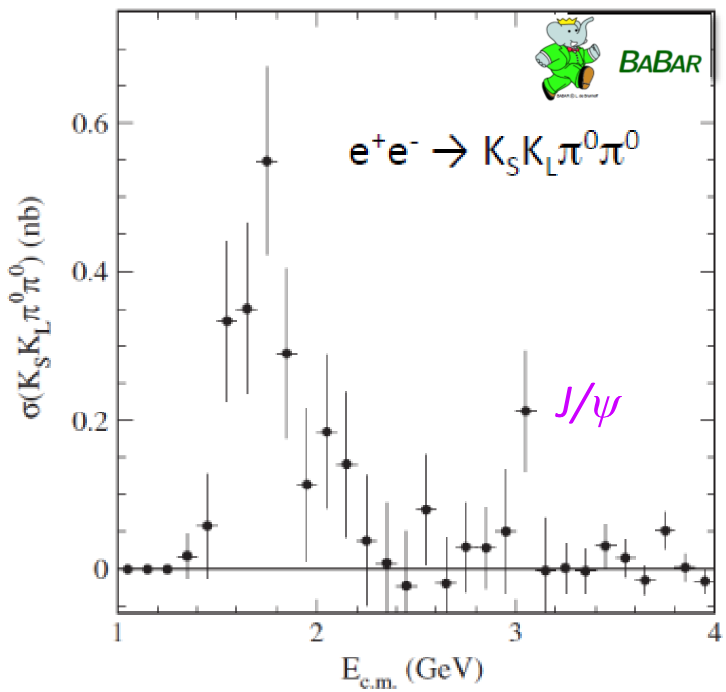


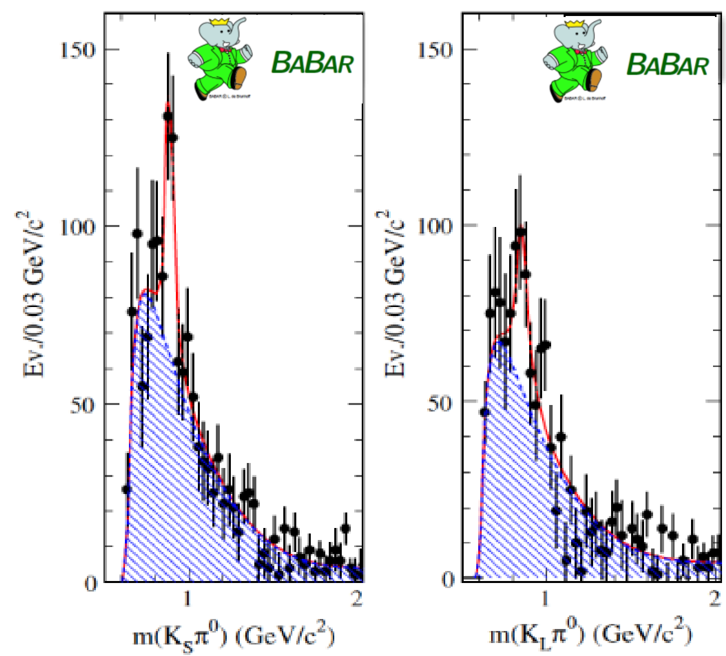


BABAR Coll., PRD95(2017), 052001

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

- First cross section measurement
- First observation of $J/\psi \rightarrow K_S K_L 2\pi^0$ (possibly $\psi(2S)$)
- Systematic uncertainty: ~25% at peak, ~60% at 2 GeV
- Dominant contribution from $K^*(892)K\,\pi$ intermediate state
  - Evident signals from $K^*(892)^0$ (large background)
  - No significant contribution from $K^*(892)^0\,\overline{K}^*(892)^0$



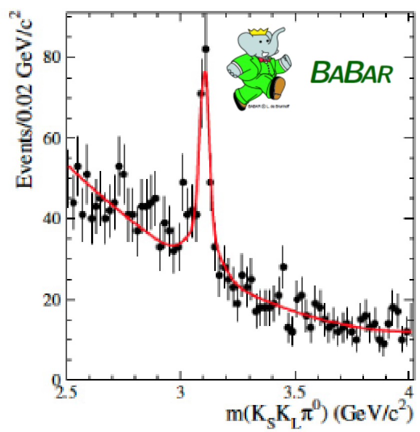


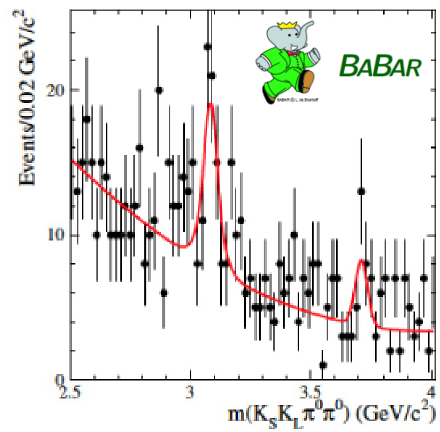
hatched areas = nonresonant components

Charmonium region: decay branching ratios

- Many new J/ψ and $\psi(2S)$ decay channels observed
- Branching ratio determination based on cross sections:

$$\sigma(e^+e^- \to c\bar{c} \to X) \sim \Gamma(c\bar{c} \to e^+e^-) \cdot \mathcal{B}(c\bar{c} \to X)$$

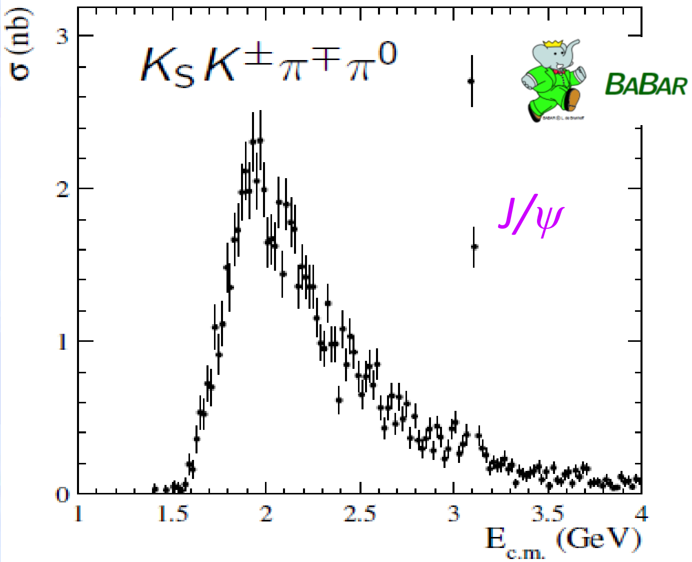




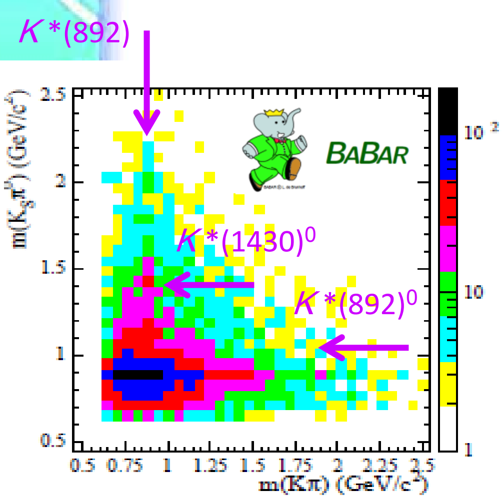
Measured Quantity	Measured Value (eV)	Calculated Branching Fractions (10^{-3}) This work	Previous
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K_S^0 K_L^0 \pi^0}$	$11.4 \pm 1.3 \pm 0.6$	$2.06 \pm 0.24 \pm 0.10$	–
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K_S^0 K_L^0 \eta}$	$8.0 \pm 1.8 \pm 0.4$	$1.45 \pm 0.32 \pm 0.08$	–
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K_S^0 K_L^0 \pi^0 \pi^0}$	$10.3 \pm 2.3 \pm 0.5$	$1.86 \pm 0.43 \pm 0.10$	–
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K^*(892)^0 \overline{K}^0 + c.c.} \cdot \mathcal{B}_{K^*(892)^0 \to K^0 \pi^0}$	$6.7 \pm 0.9 \pm 0.4$	$1.20 \pm 0.15 \pm 0.06$	–
$\Gamma_{ee}^{J/\psi} \cdot \mathcal{B}_{J/\psi \to K_2^*(1430)^0 \overline{K}^0 + c.c.} \cdot \mathcal{B}_{K_2^*(1430) \to K^0 \pi^0}$	$2.4 \pm 0.7 \pm 0.1$	$0.43 \pm 0.12 \pm 0.02$	< 4 [26]
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S) \to K_S^0 K_L^0 \pi^0}$	< 0.7	< 0.3	–
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S) \to K_S^0 K_L^0 \eta}$	$3.14 \pm 1.08 \pm 0.16$	$1.33 \pm 0.46 \pm 0.07$	–
$\Gamma_{ee}^{\psi(2S)} \cdot \mathcal{B}_{\psi(2S) \to K_S^0 K_L^0 \pi^0 \pi^0}$	$2.92 \pm 1.27 \pm 0.15$	$1.24 \pm 0.54 \pm 0.06$	–

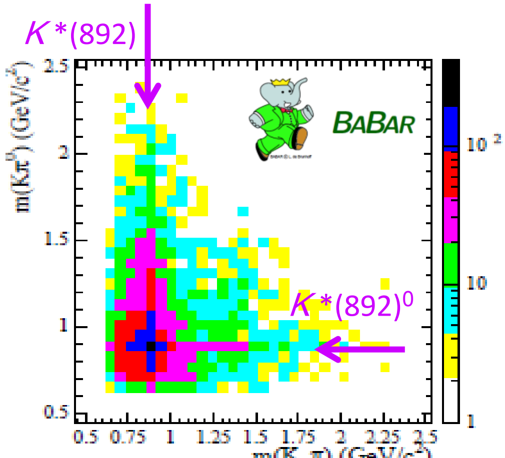
BABAR Coll., PRD95(2017), 092005

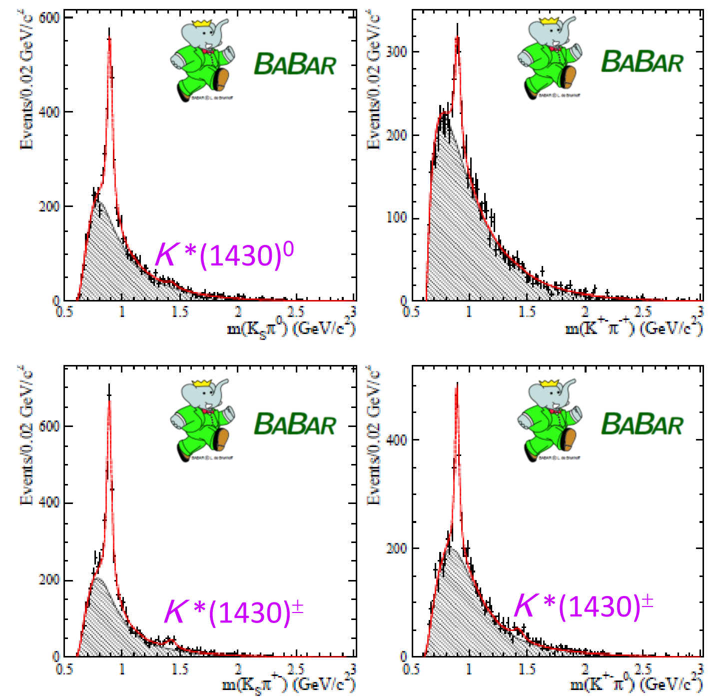
$e^+e^- \rightarrow K_S K^{\pm} \pi^{\mp} \pi^0$



- Systematic uncertainty: ~6% (E*< 2 GeV) - ~12% (E*> 3 GeV)
- Very rich intermediate state composition
  - Single, double K*(892)⁰ production (charged and neutral)
  - $K^*_2(1430)$, $K^*_0(1430)$
  - *ρ(770)* resonance







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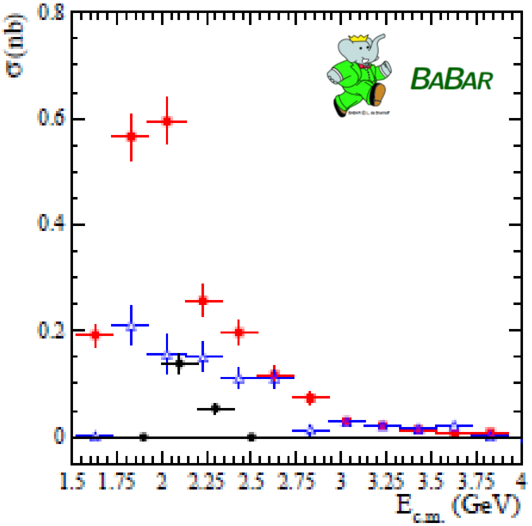
$e^+e^- \to K^*(892)K\pi,\ K_S K\pi$

- Neutral/charged K*(892): dominant contribution

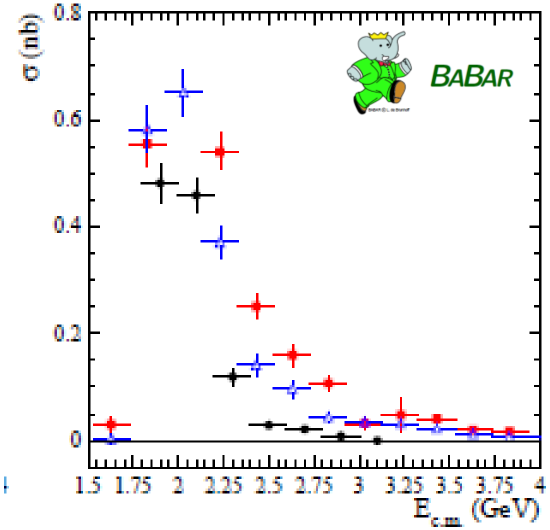


Neutral K^0

$e^+e^- \to K^{*0}K^{\pm}\pi^{\mp}$

$e^+e^- \to K^{*0}K_S\pi^0$

$e^+e^- \to K^{*0}\overline{K}^{*0}$



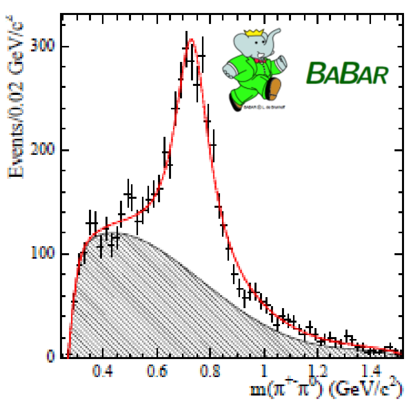
Charged K*

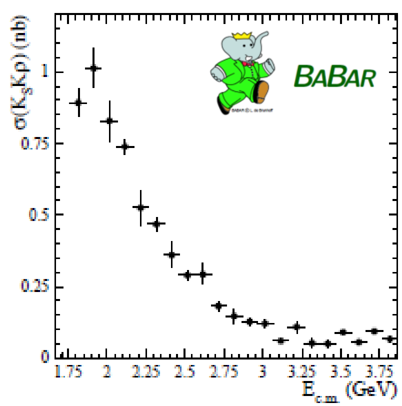
$e^+e^- \to K^{*\pm}K_S\pi^{\mp}$

$e^+e^- \to K^{*\pm}K^{\mp}\pi^0$

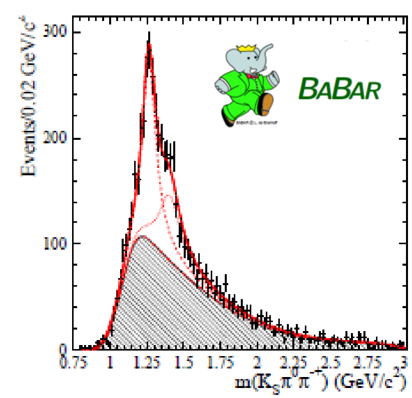
$e^+e^- \to K^{*+}K^{*-}$

- Large $K_S K^{\pm}\rho^{\mp}(770)$ fraction

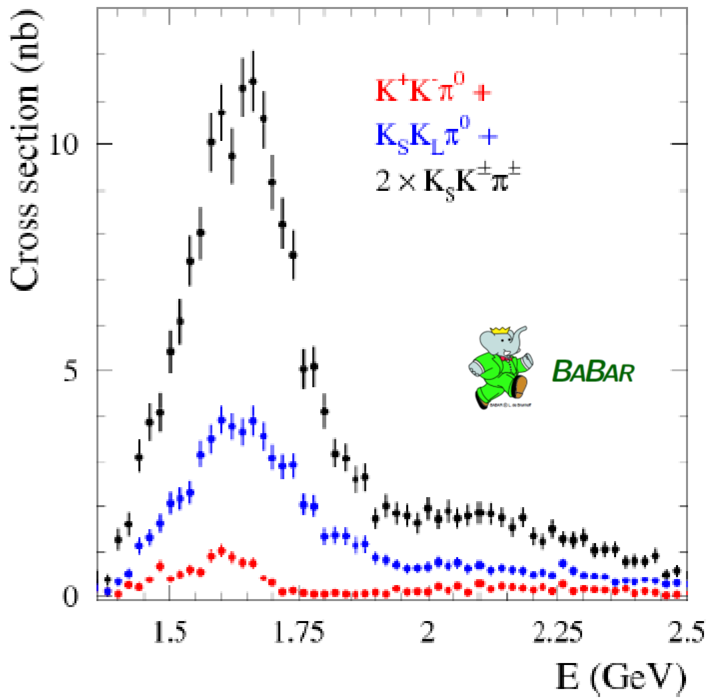


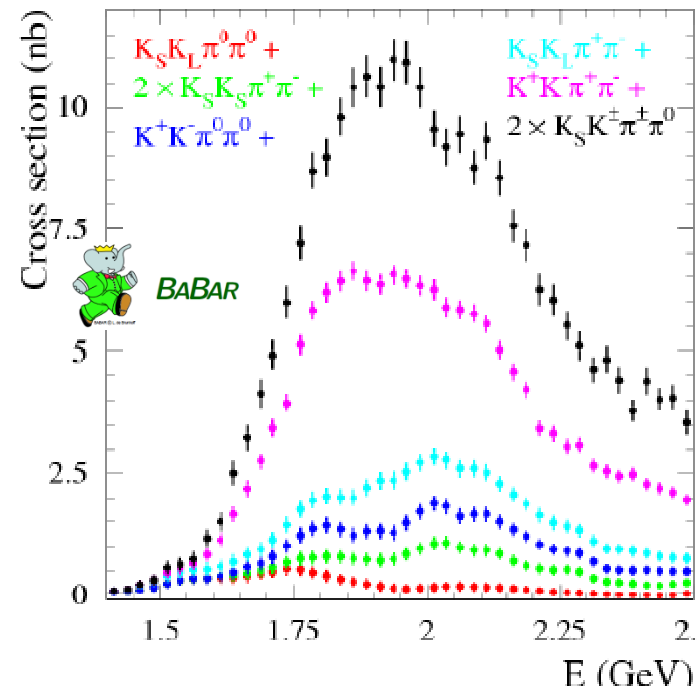


Some events may come from $K_1 \to K\rho^{\mp}$
($K_1(1270)$, $K_1(1400)$, $K_1(1650)$)



Total $e^+e^- \to K\bar{K}\pi$, $K\bar{K}\pi\pi$ cross sections





V. Druzhinin, EPJ Web of Conf., 142, 01013 (2017)

- Cross sections for all channels measured by *BABAR* (except with $2K_L$)
  - $K\bar{K}\pi$: ~12% of total cross section @ E* ~1.6 GeV
  - $K\bar{K}\pi\pi$: ~25% of total cross section @ E* ~2 GeV
- Symmetry relationships no more necessary
- Significant improvement on $(g-2)_\mu$ determination : 30% $\Rightarrow$ 6% precision

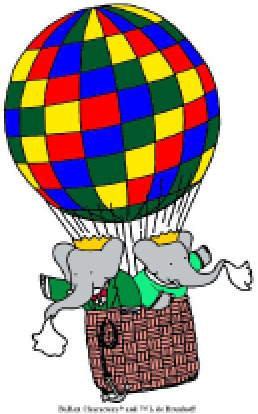
Conclusions

- The use of ISR technique at *B*-factories was pioneered by *BABAR* and led to a wealth of precision measurements of many exclusive hadronic cross sections

- $\sigma(e^+e^- \rightarrow hadrons)$:
  - Most precise determination of the LO hadronic contribution to the muon magnetic momentum anomaly
    - Improvement in precision of $a_\mu^{had,LO}$ ~20%
  - New information on hadron dynamics and light hadron spectrum
  - First measurements of never observed decay channels
  - First observations of charmonium decay modes and branching fractions
  - Study of new resonances and decay modes

- New experimental inputs awaited from new generation of charm and *B*-factories

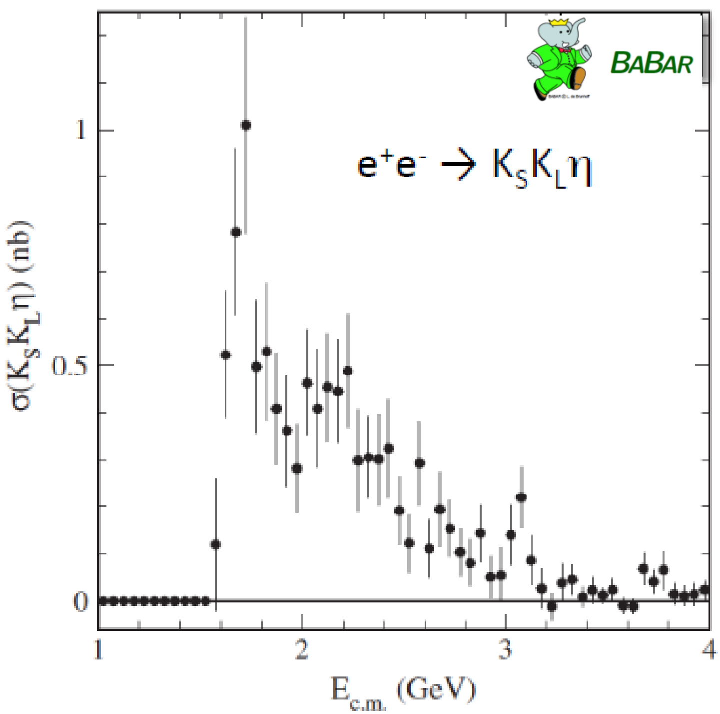
backup slides

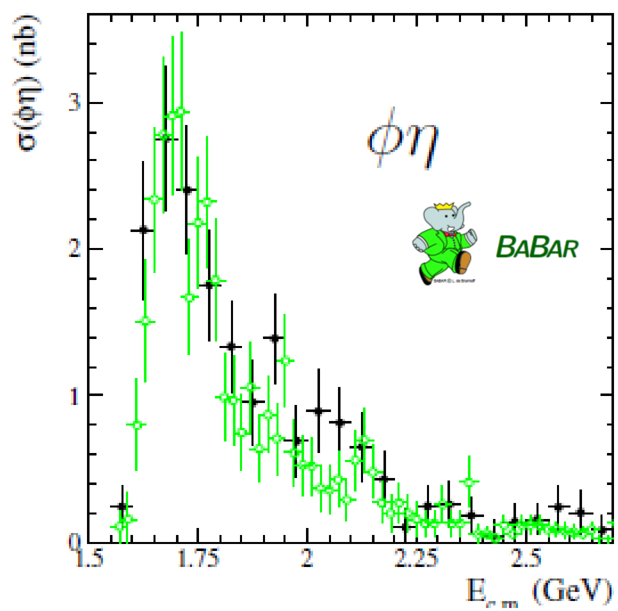


BABAR Coll., PRD95(2017), 052001

$e^+e^- \to K_SK_L\eta$ cross section

- Event reconstruction: γ_{ISR}, $\eta \to \gamma\gamma$ in proper mass window,
- First cross section measurement
- First observation of $J/\psi \to K_SK_L\eta$
- Systematic uncertainty: ~25% at peak, ~ 60% at 2 GeV
- $\varphi\eta$ channel dominating the $K_SK_L\eta$ channel
  - No significant J/ψ signal
  - No significant structures in $K_S\eta$ or $K_L\eta$





BABAR Coll., PRD95(2017), 092005

$e^+e^- \to K_S K^{\pm}\pi^{\mp}\eta$

- First cross section measurement
- First observation of narrow $J/\psi \to K_S K^{\pm}\pi^{\mp}\eta$
- Systematic uncertainty: 12% below 3 GeV, 19% for E*> 3 GeV
- No significant structure observed in $K^{\pm}K_S$, $K^{\pm}\eta$, $K_s\eta$
- Dominant $K^*(892)^{\pm}$ + $K^*_2(1430)^{\pm}$
- Suppression of neutral vs charged $K^*(892)$, no hint of $K^*_2(1430)^0$