BABAR

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SLAC

Hadronic Final States in e^+e^- Annihilation at *BABAR*

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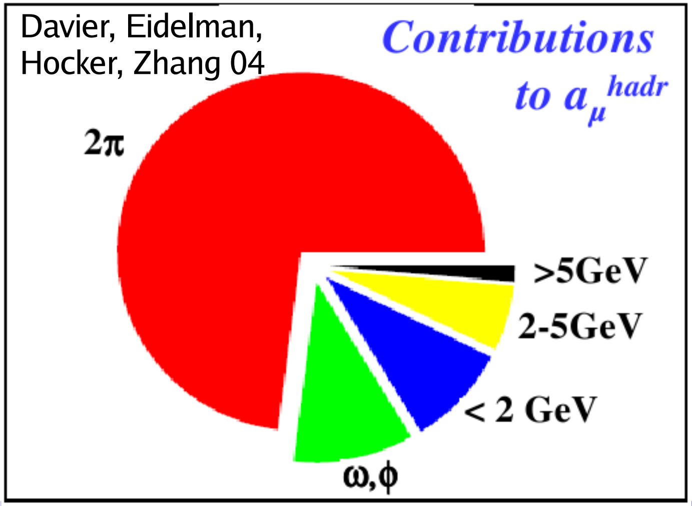
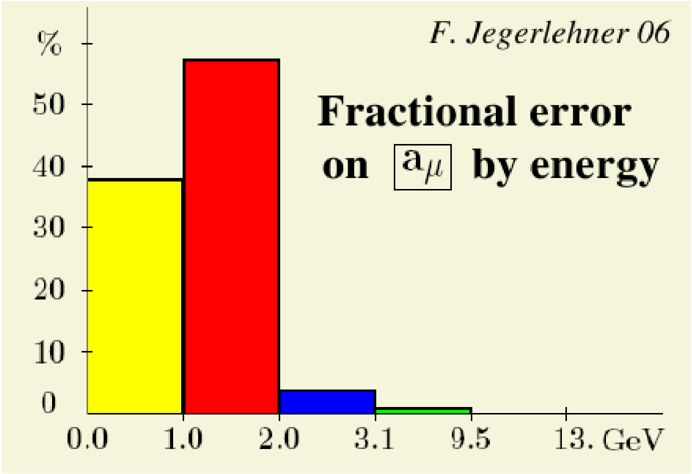
Outline

- e^+e^- $\longrightarrow$ exclusive hadronic final states at low $\sqrt{s}$ using initial state radiation
  - $e^+e^- \to K^+K^-\pi^+\pi^-\gamma, K^+K^-\pi^0\pi^0\gamma, 4K\gamma$
  - $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$
- e^+e^- $\longrightarrow$ exclusive hadronic final states at $\sqrt{s} = 10.58\,\mathrm{GeV}$
  - $e^+e^- \to \rho^0\rho^0, \phi\rho^0$
- Observation of a long-range baryon number correlation in $e^+e^- \to c\bar{c}$

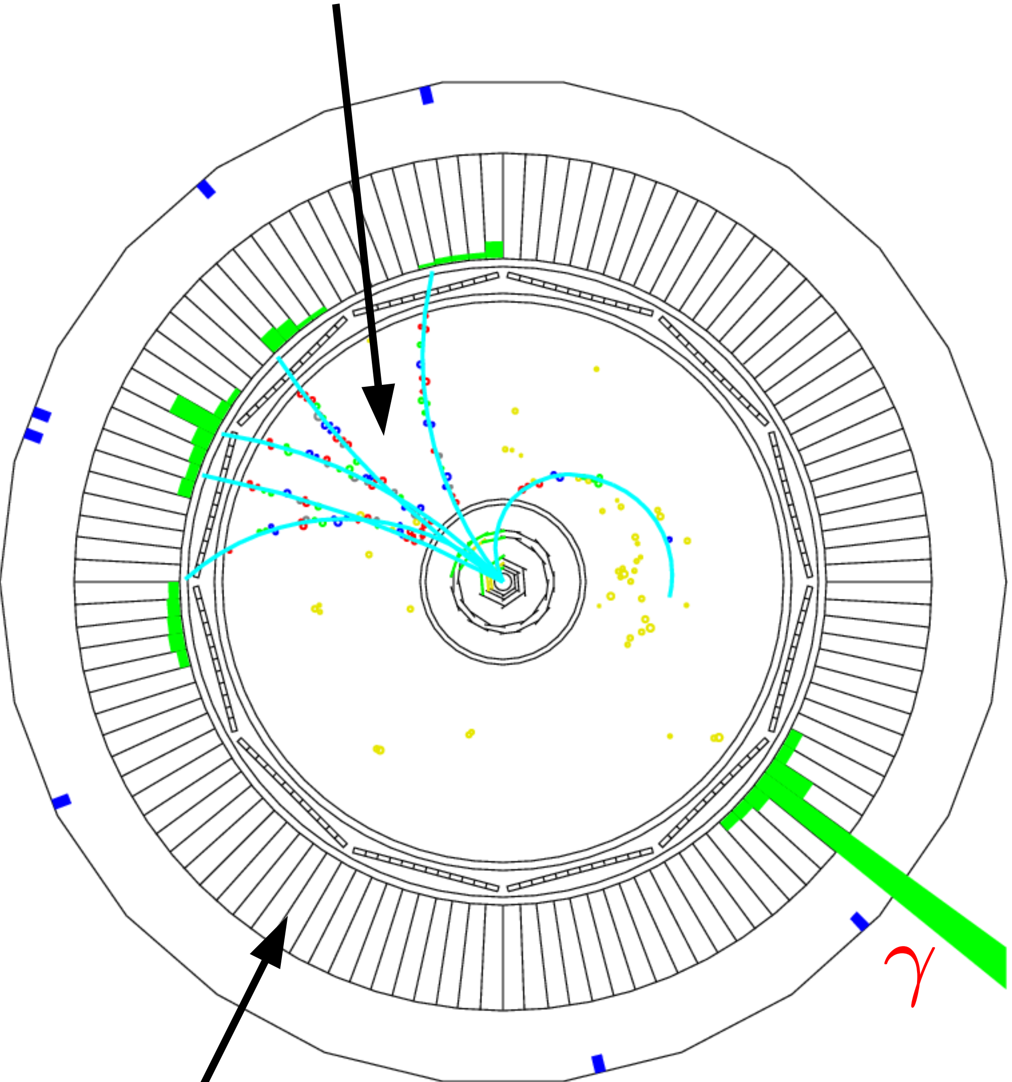
Motivation for Studies at low $\sqrt{s}$

- Hadronic contributions to a_μ and $\alpha_{\rm QED}$ are calculated from hadronic cross sections
- Knowledge of a_μ^{had} and $\Delta\alpha^5_{\rm had}$ can be improved with better precision on cross sections at low $\sqrt{s}$
- a_μ^{had} very sensitive to contributions from $\sqrt{s} < 2\,\mathrm{GeV}$
- $1-2\,\mathrm{GeV}$ region dominated by 4π state
  - Improved measurement of $\pi^+\pi^-\pi^+\pi^-$ from *BABAR* PRD 71, 052001 (2005)
  - New focus on $\pi^+\pi^-\pi^0\pi^0$





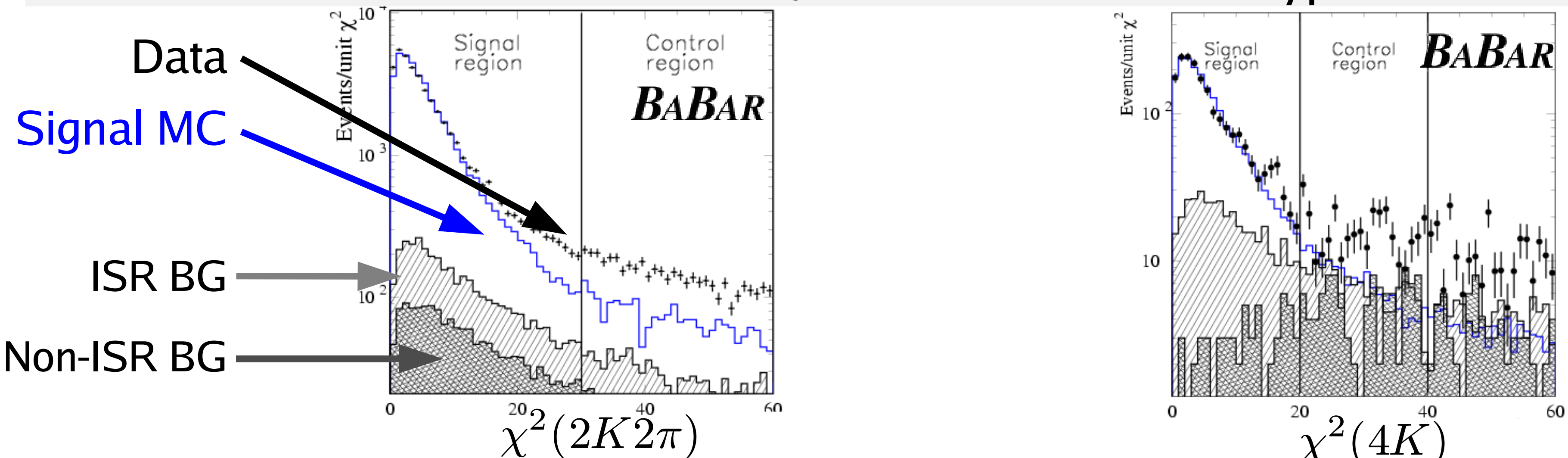
ISR Events



- *BABAR*: e^+e^- $\sqrt{s} = 10.58\,\mathrm{GeV}$
- Radiative return to low $\sqrt{s}$
- ISR photon γ is detected
  - Isolated photon $E_{\mathrm{CM}} > 3\,\mathrm{GeV}$
- Advantages over direct e^+e^-
  - High transverse momentum of remaining hadronic event
  - High acceptance
  - Wide accessible energy range
  - No point-to-point systematic uncertainties

Exclusive ISR Analysis Methods

- Require set of particles with specific ID recoiling against high energy photon
- Kinematic fit for each final state hypothesis
  - Reject ISR/non-ISR backgrounds based on χ^2
  - Select final state based on χ^2 of fits with different hypothesis



- Backgrounds estimated from combination of MC, χ^2 control regions,PID control samples
- Measure cross sections and substructures in decays

ISR channels at *BABAR*

- J/ψ in $\mu^+\mu^-\gamma$ PRD-RC 69, 011103 (2004)
- $\pi^+\pi^-\pi^0\gamma$ PRD 70, 072004 (2004)
- $\pi^+\pi^-\pi^+\pi^-\gamma, K^+K^-\pi^+\pi^-\gamma, K^+K^-K^+K^-\gamma$ PRD 71, 052001 (2005)
- $p\bar{p}\gamma$ PRD 73, 012005 (2006)
- $3(\pi^+\pi^-)\gamma, K^+K^-2(\pi^+\pi^-)\gamma, 2\pi^0 2(\pi^+\pi^-)\gamma$ PRD 73, 052003 (2006)
- $\phi\rho\gamma$ PRD-RC 74, 091103 (2006)
- $J/\psi\pi^+\pi^-\gamma, J/\psi K^+K^-\gamma, J/\psi\gamma\gamma\gamma$ arXiv:hep-ex/0608004v1
- Many more in progress

This talk:

- $K^+K^-\pi^+\pi^-\gamma, K^+K^-\pi^0\pi^0\gamma, K^+K^-K^+K^-\gamma$ To appear in PRD, arXiv:0704.0630
- $\pi^+\pi^-\pi^0\pi^0\gamma$ *BaBar* preliminary

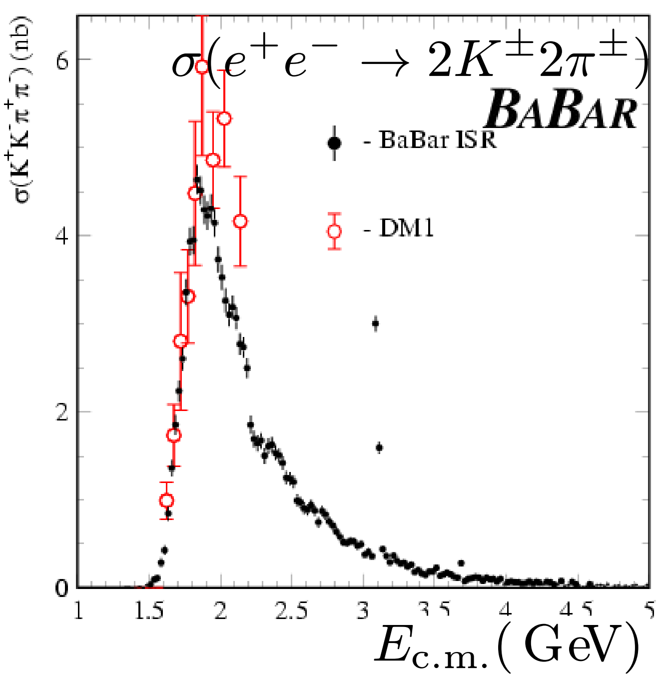
$e^+e^- \rightarrow K^+K^-\pi^+\pi^-\gamma, K^+K^-\pi^0\pi^0\gamma, 4K\gamma$

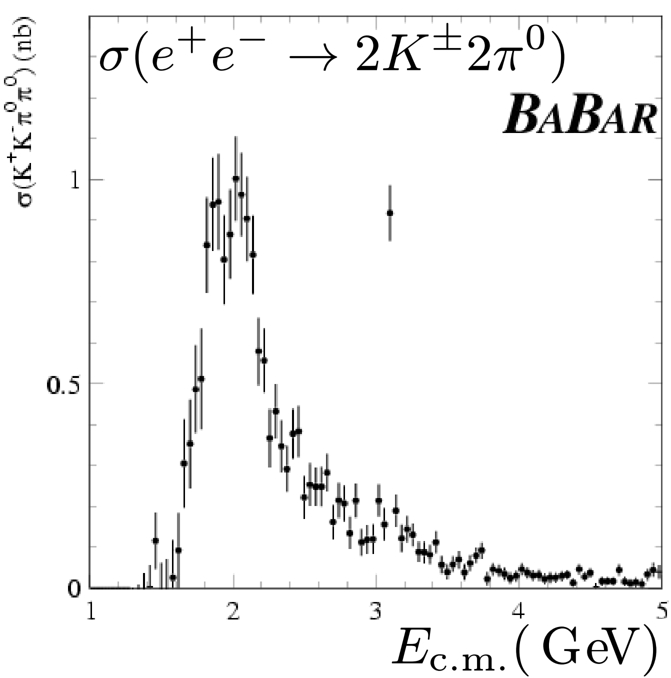
To appear in PRD
arXiv:0704.0630

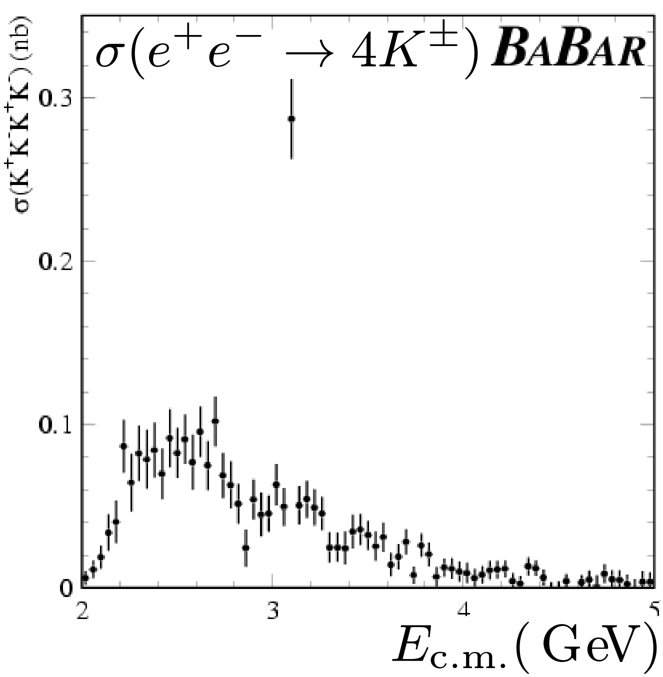
- Identified intermediate states
  - $K^+K^-\pi^+\pi^-$: $K^{*0}K\pi$ $\phi(1020)\pi^+\pi^-$ $\phi(1020)f_0(980)$
  - $K^+K^-\pi^0\pi^0$: $K^{*\pm}K\pi^0$ $\phi(1020)\pi^0\pi^0$ $\phi(1020)f_0(980)$
  - $K^+K^-K^+K^-$: $\phi(1020)K^+K^-$

Cross section measured

- $\mathcal{B}(Y(4260) \rightarrow \phi\pi\pi)$ large in some models
  - Y discovered in ISR $J/\psi\pi\pi$
- Study branching fractions in Charmonium region







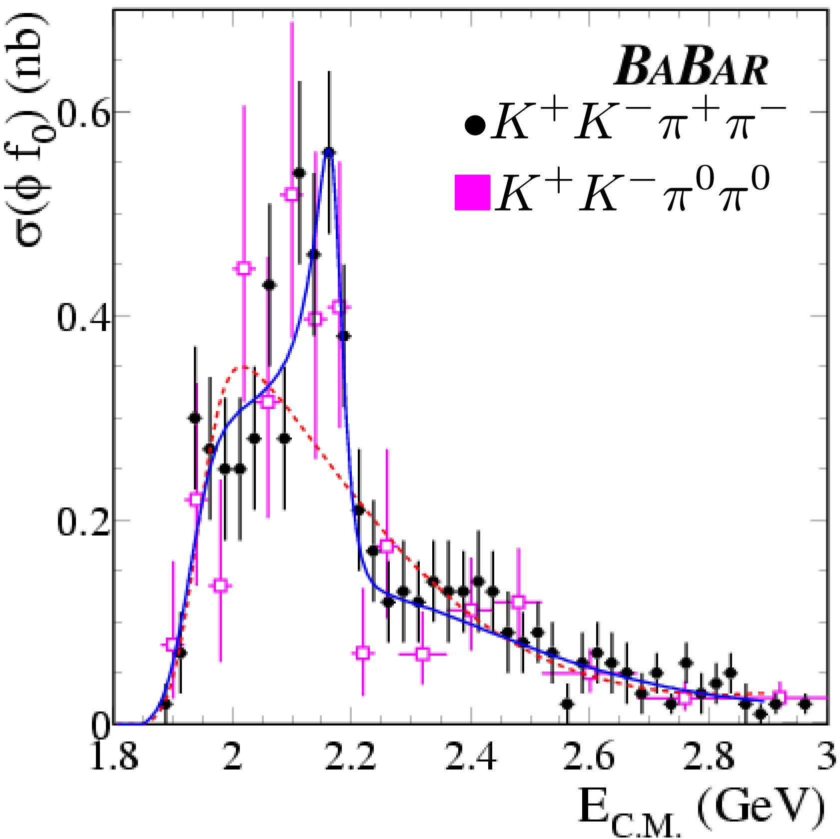
Intermediate States

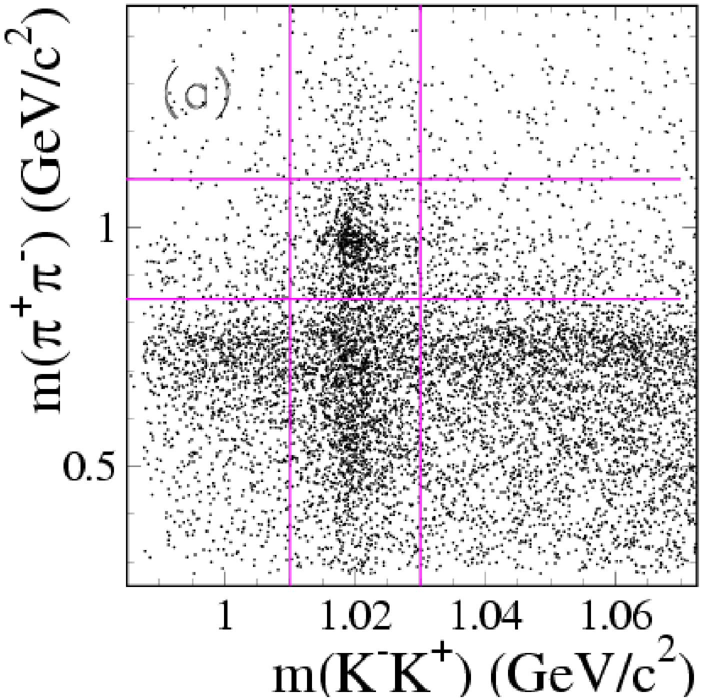
PRD-RC 74, 091103 (2006)

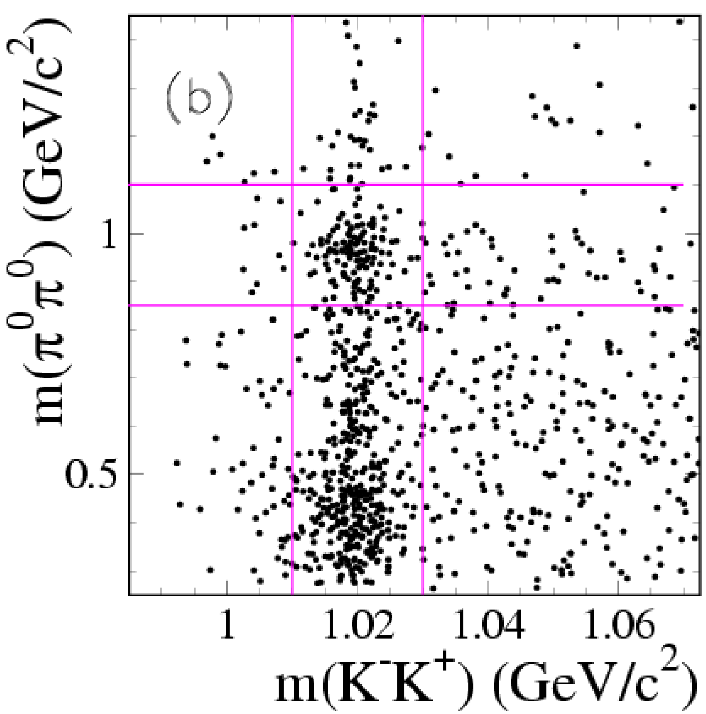
- Clear $e^+e^- \to \phi f_0$ in both $K^+K^-\pi^+\pi^-$ and $K^+K^-\pi^0\pi^0$
- Structure in cross section consistent with new state

$$m = 2.175 \pm 0.010 \pm 0.015\,\mathrm{GeV}/c^2$$

$$\Gamma = 0.058 \pm 0.016 \pm 0.020\,\mathrm{GeV}/c^2$$



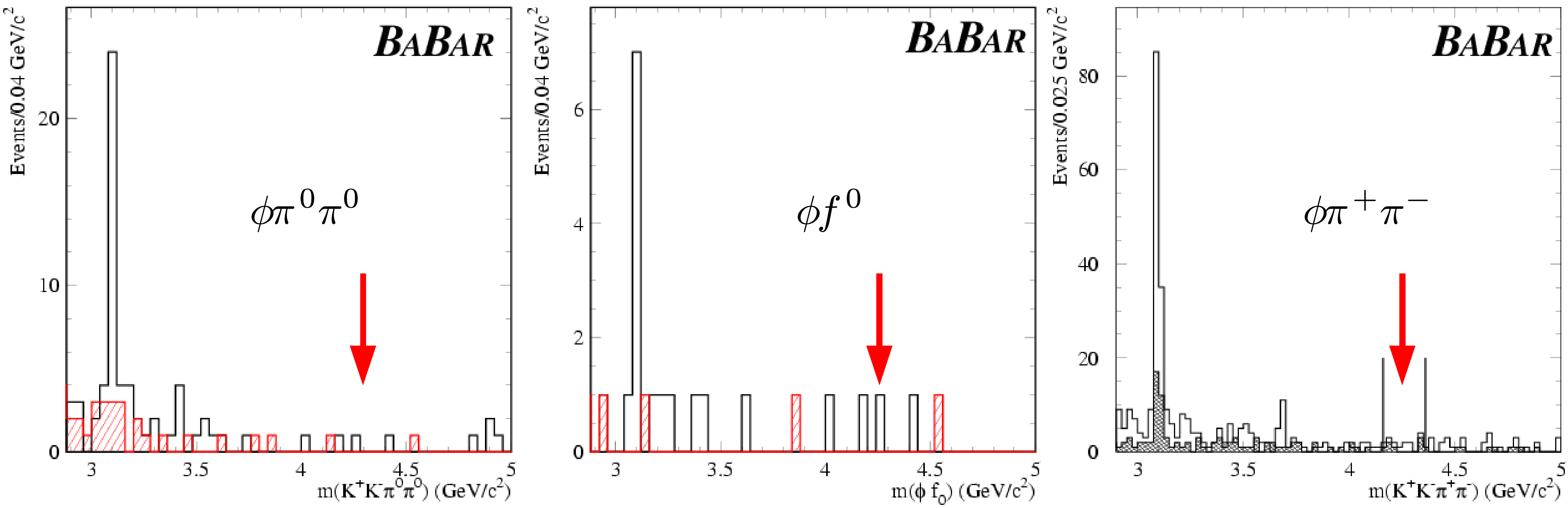




$Y(4260) \to \phi\pi\pi$?

- Glue ball model predicts large branching fraction Phys.Lett.B625:212,2005
- No $Y(4260)$ signal found in any decay mode
- Upper Limit for $\phi\pi^+\pi^-$ decay
  - $\mathcal{B}_{Y\to\phi\pi^+\pi^-} \cdot \Gamma_{ee}^{Y} < 0.4\,\mathrm{eV}$

  Compare to
  - $\mathcal{B}_{Y\to J/\psi\,\pi^+\pi^-} \cdot \Gamma_{ee}^{Y} = (5.5 \pm 1.0 \pm 0.8)\,\mathrm{eV}$ PRL 95, 142001 (2005)



Charmonium Region

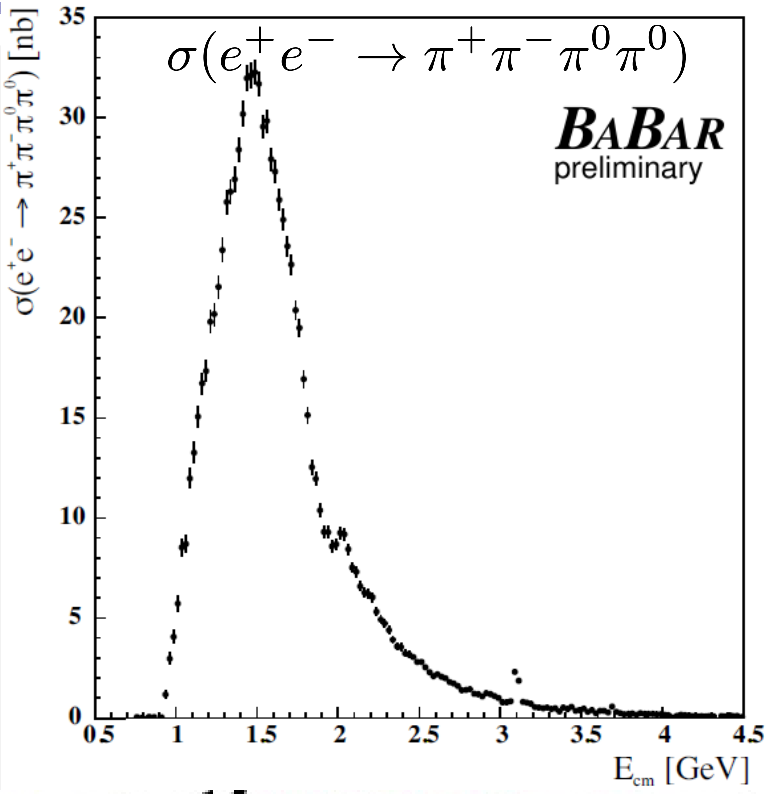
- Branching fractions for 12 decay modes of $J/\psi, \psi(2S)$

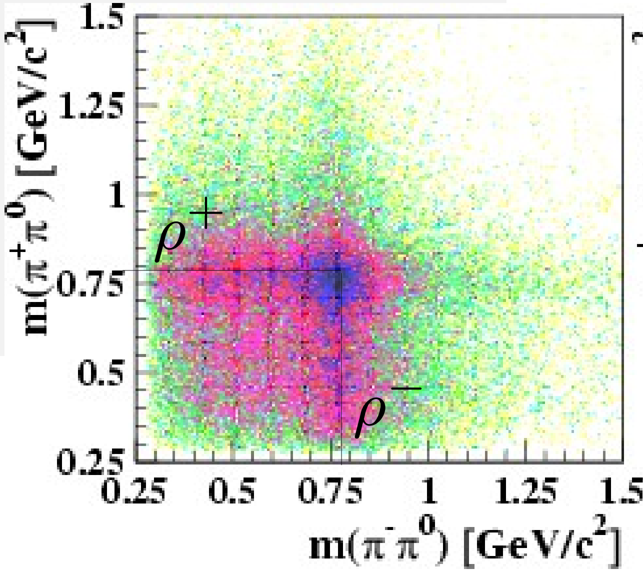
	J/ψ or $\psi(2S)$ Branching Fraction (10^{-3}) Calculated, this work	PDG2006	
$\mathcal{B}_{J/\psi\to K^+K^-\pi^+\pi^-}$	$6.72\pm0.24\pm0.40$	$6.2\ \pm0.7$	
$\mathcal{B}_{J/\psi\to K^+K^-\pi^0\pi^0}$	$2.52\pm0.20\pm0.25$	no entry	new
$\mathcal{B}_{J/\psi\to K^+K^-K^+K^-}$	$0.76\pm0.07\pm0.06$	$0.78\ \pm0.14$	
$\mathcal{B}_{J/\psi\to K^{*0}\bar{K}_2^{*0}}$	$2.7\ \pm0.2\ \pm0.2$	$6.7\ \pm2.6$	
$\mathcal{B}_{J/\psi\to K^{*0}\bar{K}^{*0}}$	$0.11\pm0.04\pm0.01$	< 0.5 at 90% C.L.	new
$\mathcal{B}_{J/\psi\to\phi\pi^+\pi^-}$	$0.98\pm0.11\pm0.07$	$0.94\ \pm0.15$	
$\mathcal{B}_{J/\psi\to\phi\pi^0\pi^0}$	$0.58\pm0.15\pm0.06$	no entry	new
$\mathcal{B}_{J/\psi\to\phi f_0}$	$0.54\pm0.21\pm0.05$	$0.32\ \pm0.09$ (s=1.9)	
$\mathcal{B}_{J/\psi\to\phi f_2}$	$0.50\pm0.08\pm0.04$	< 0.37 at 90% C.L.	new
$\mathcal{B}_{\psi(2S)\to K^+K^-\pi^+\pi^-}$	$1.2\ \pm0.2\ \pm0.08$	$0.72\ \pm0.05$	
$\mathcal{B}_{\psi(2S)\to\phi\pi^+\pi^-}$	$0.27\pm0.11\pm0.02$	0.113 ± 0.029	
$\mathcal{B}_{\psi(2S)\to\phi f_0}$	$0.26\pm0.12\pm0.03$	0.090 ± 0.033	

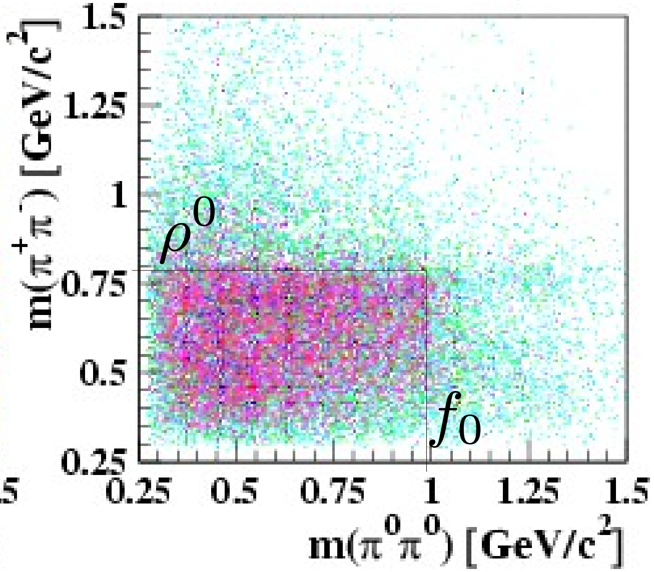
$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma$

BaBar preliminary

- Very important channel for $a_\mu, \alpha_{\rm QED}$
- Preliminary precision:
  - 8% in peak - hope to achieve 5%
- Cross section
  - Structures: $\rho(1450), \rho(1700), J/\psi, \psi(2S)$
  - Peak at $2.050\,\mathrm{GeV}$ under study
- Intermediate states in $\pi^+\pi^-\pi^0\pi^0$
  - $\omega\pi^0 \quad a_1(1260)\pi$
  - Previously unknown contributions from $\rho^+\rho^-$ and $f_0(980)\rho^0$



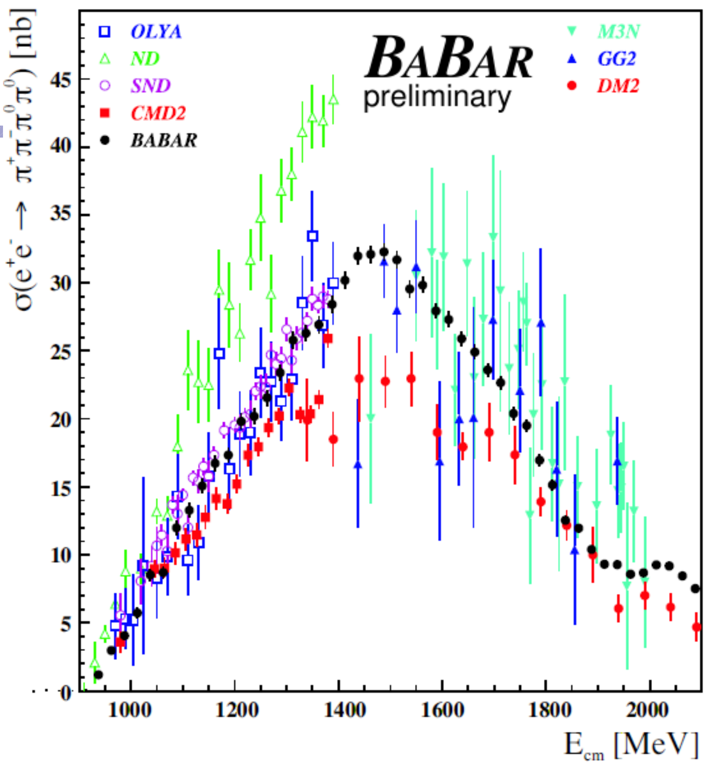


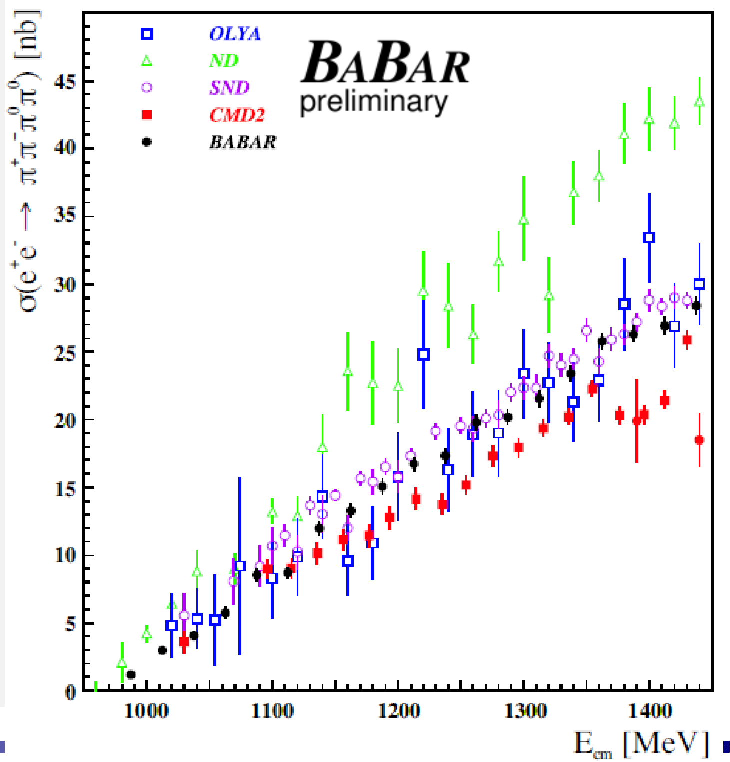


MC Generator:
H. Czyz, H. Kuehn,
Eur.Phys.J. C18 (2001) 497

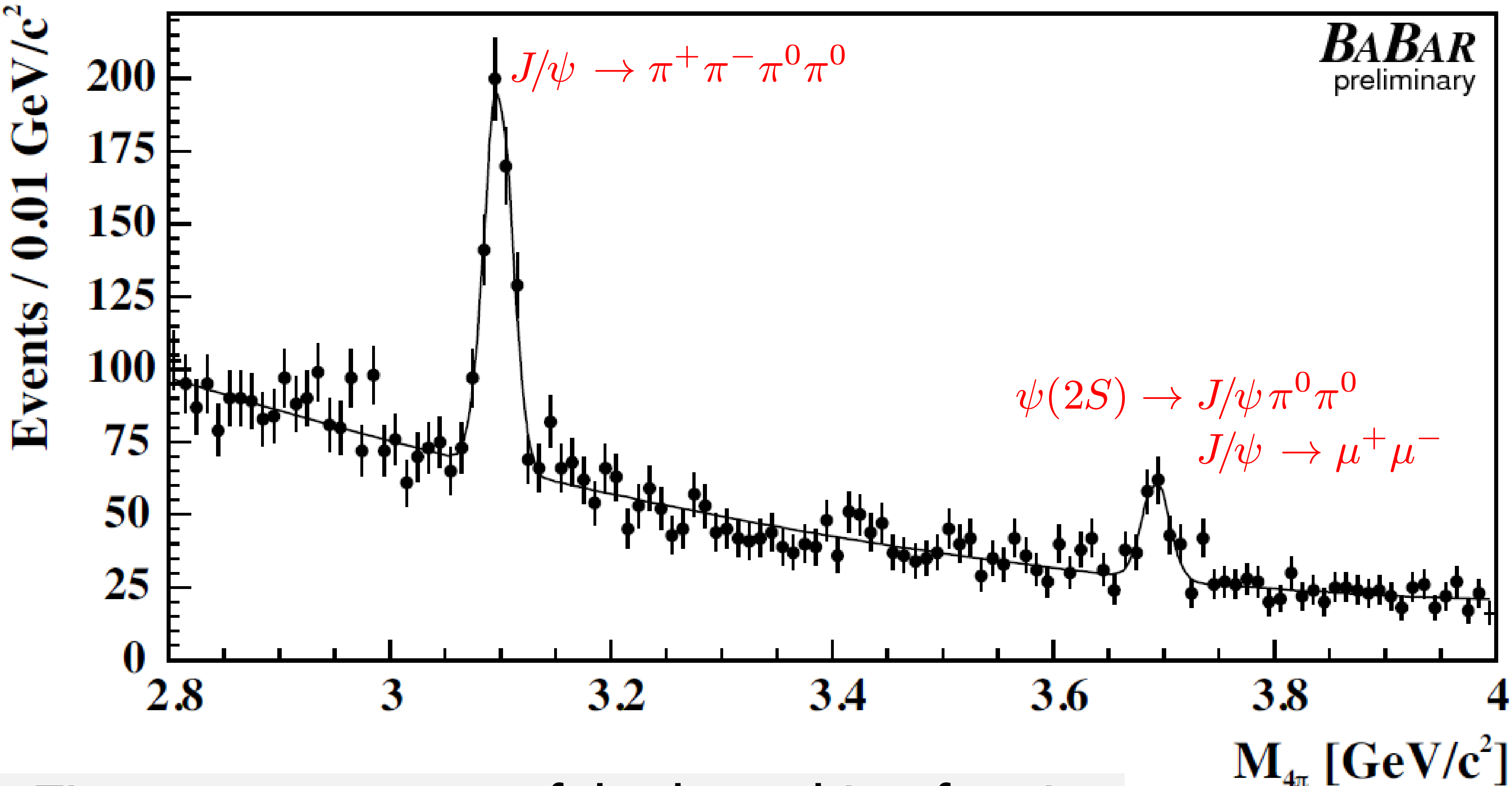
Cross Section and a_μ

- Below $1.4\,\mathrm{GeV}$
  - Good agreement with SND
  - Improved accuracy
- Above $1.4\,\mathrm{GeV}$
  - Huge improvement in precision with small point-to-point uncertainties
  - Allows to fix scale below $1.4\,\mathrm{GeV}$
  - 1st measurement above $2.4\,\mathrm{GeV}$
- Implication for a_μ
  - Final BABAR result will improve the error of the $\pi^+\pi^-\pi^0\pi^0$ contribution
  - Discrepancy between experiment and theory will remain





J/ψ region in $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

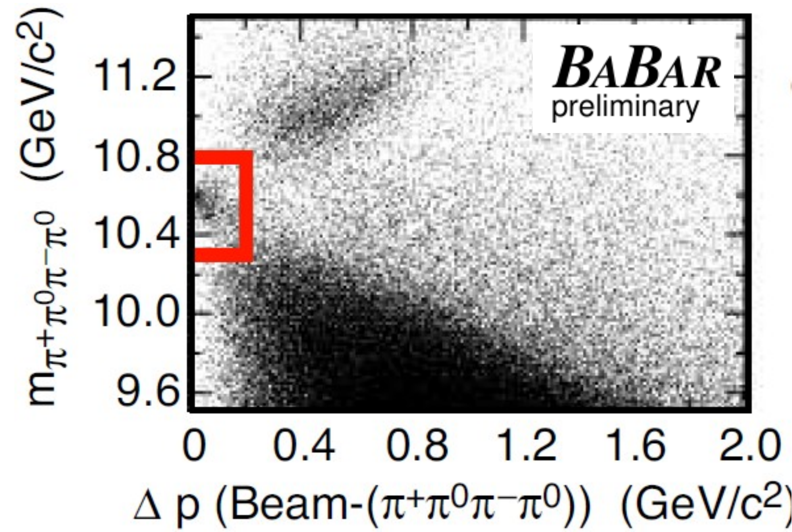


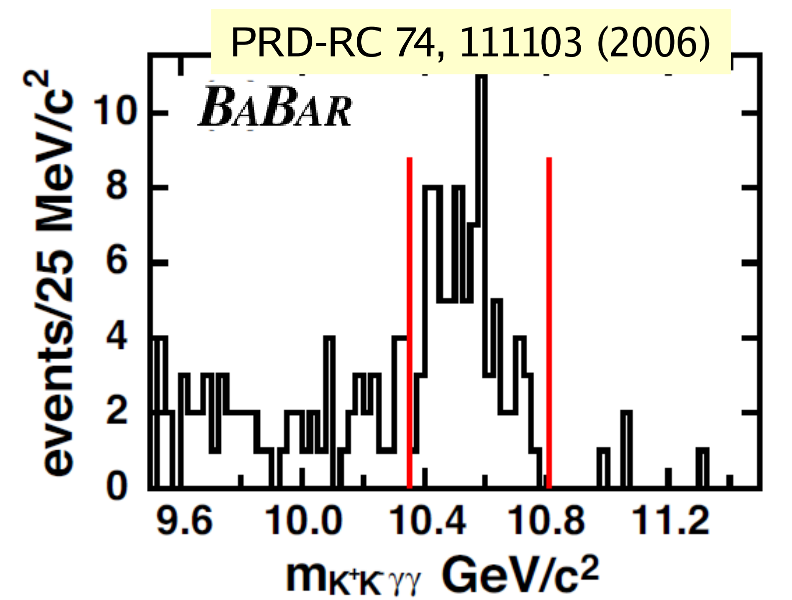
- First measurement of the branching fraction
  - $\mathcal{B}_{J/\psi \to 4\pi} = (5.74 \pm 0.74) \times 10^{-3}$
- $\psi(2S)$ signal due to $\mu^\pm$ misidentified as $\pi^\pm$

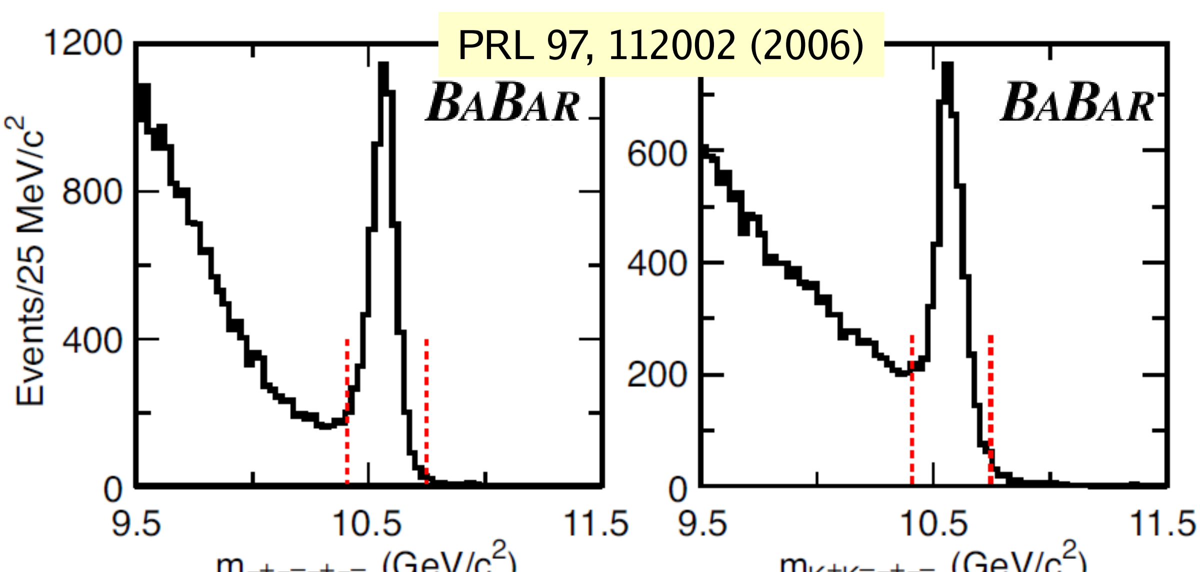
Exclusive Final States at 10.58GeV

- $\rho^+\rho^-$ seen in $\pi^+\pi^-\pi^0\pi^0$
  - Provides new, stringent test of QCD
- $\phi\eta$ seen in $K^+K^-\gamma\gamma$
  - Relates to puzzle of the large double charmonium rates
- $\rho^0\rho^0$ observed in $\pi^+\pi^-\pi^+\pi^-$
  $\phi\rho^0$ observed in $K^+K^-\pi^+\pi^-$

This talk



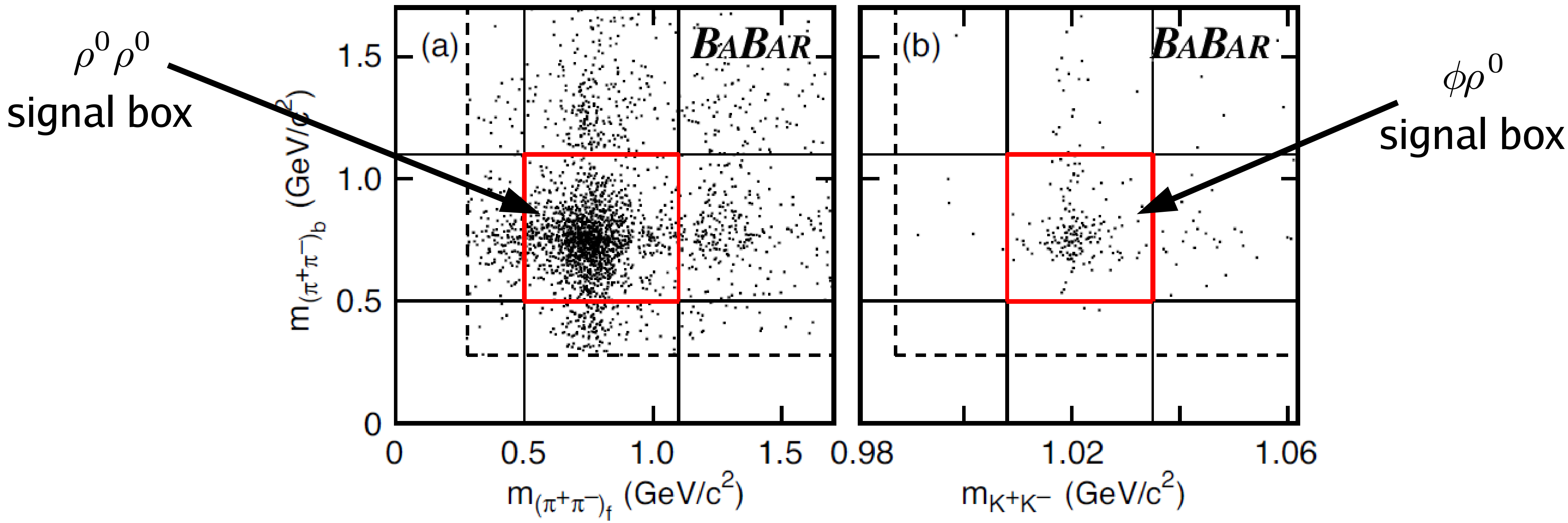




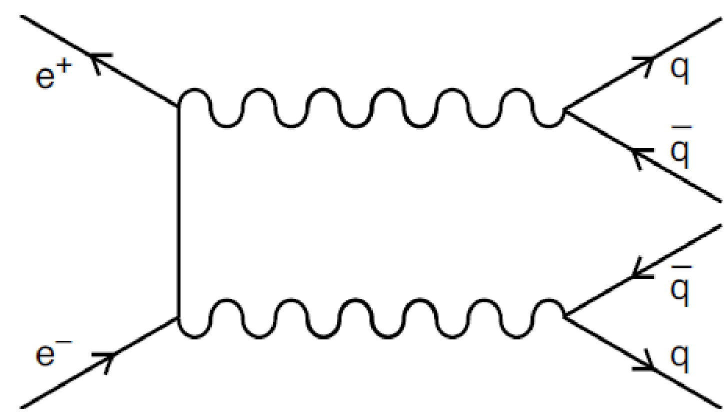
$e^+e^- \to \rho^0\rho^0, \phi\rho^0$

PRL 97, 112002 (2006)

- Clear signal of $\rho^0\rho^0, \phi\rho^0$ in $\pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-$



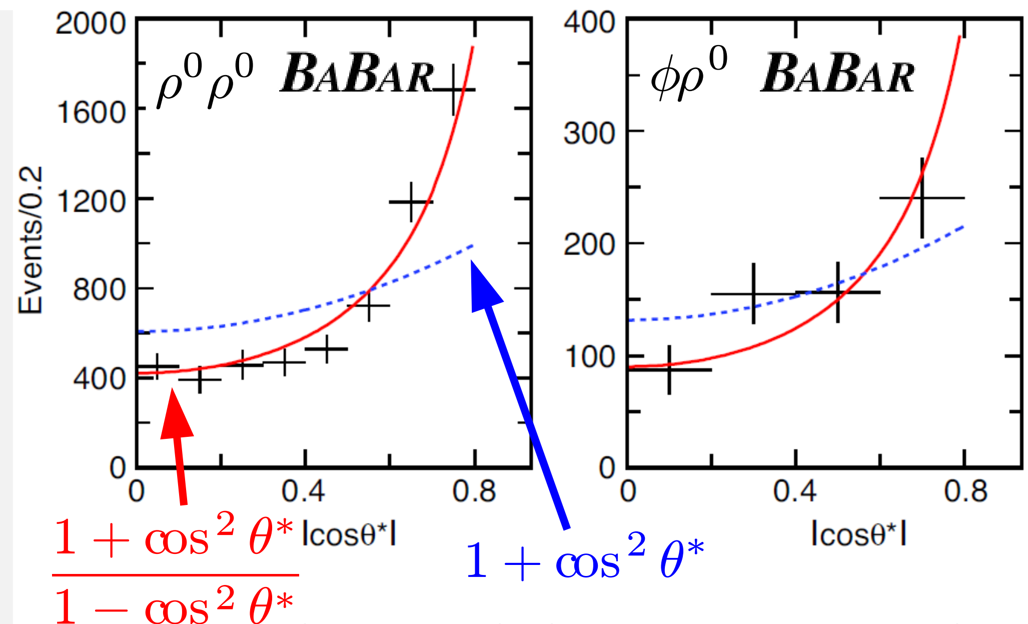
- $\rho^0\rho^0, \phi\rho^0$ are $C = +1$ states
  - Forbidden in single-virtual-photon annihilation (SVPA)
  - Can two-virtual-photon annihilation (TVPA) be confirmed?

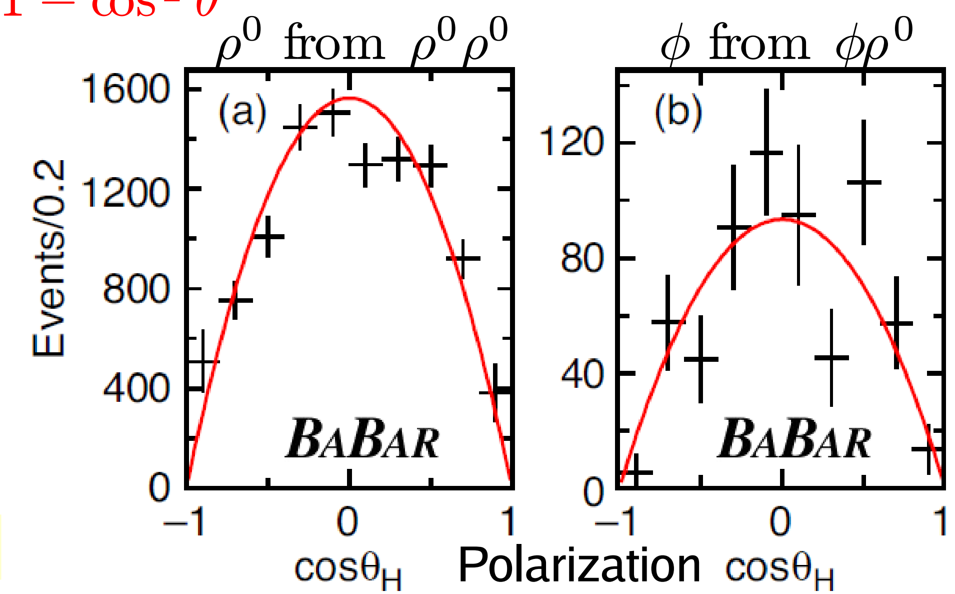


Angular Distribution Study

- ρ^0, ϕ production angle θ^*
  - TVPA prediction of $\dfrac{1+\cos^2\theta^*}{1-\cos^2\theta^*}$ consistent with data
  - SVPA: flat, $\sin^2\theta^*, 1+\cos^2\theta^*$, ...
- Decay helicity angles
  - TVPA predicts transverse polarization, $\sin^2\theta_{\mathrm{H}}$ distribution, consistent with data
- Fiducial cross sections
  - $\sigma_{\mathrm{fis}}(e^+e^- \to \rho^0\rho^0) = 20.7 \pm 0.7 \pm 2.7\,\mathrm{fb}$
  - $\sigma_{\mathrm{fis}}(e^+e^- \to \phi\rho^0) = 5.7 \pm 0.5 \pm 0.8\,\mathrm{fb}$
  - Agree with vector-dominance two-photon exchange

arXiv:hep-ph/0606155v1





- 1st observation of non-SVPA processes in e^+e^-

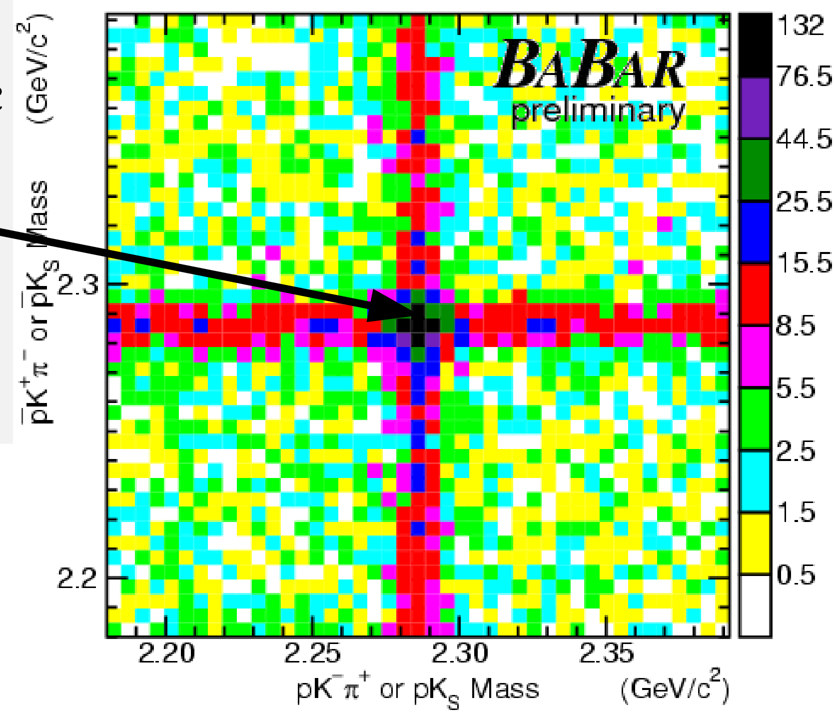
$e^+e^- \to c\bar{c}$ at *BABAR*

- *BABAR*/PEP-II is a charm factory
- New charm states
  - $Y(4260)$ $X(3872)$ $Y(3940)$ See talk by G. Cibinetto
- Charmed baryons
  - Precision measurement of Λ_c mass PRD 72, 052006 (2005)
  - Λ_c spectrum inconsistent with models PRD 75, 012003 (2007)
  - New Ξ_c baryons See talk by T. Schroeder
  - Study events with $\Lambda_c\bar{\Lambda}_c$ pairs *BABAR* preliminary This talk

$e^+e^- \to c\bar{c} \to \Lambda_c^+ \bar{\Lambda}_c^- X$

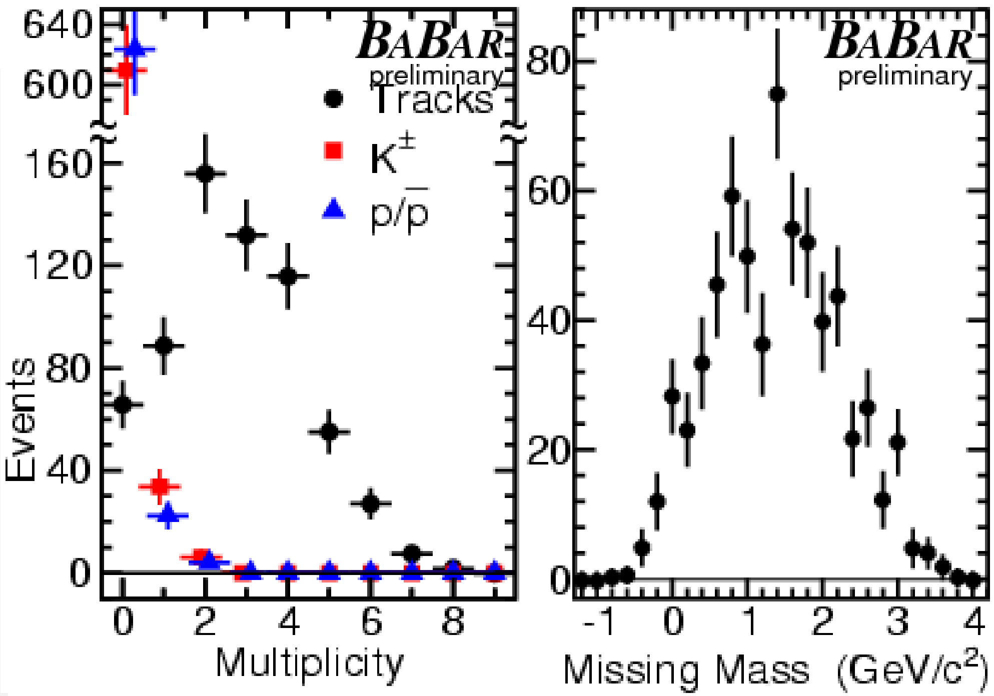
BaBar preliminary

- Local baryon number conservation observed in $p\bar{p}, \Lambda\bar{\Lambda}$
- CLEO reports excess of events with $\Lambda_c^+ \bar{\Lambda}_c^-$ pairs PRD 63, 112003 (2001)
  - $\Lambda_c^+ \bar{\Lambda}_c^-$ are leading particles – new model required?
- Analysis strategy
  - Reconstruct Λ_c^+ in $pK^-\pi^+, pK_S^0$
  - Reject $\Upsilon(4S)$ decays by $p^*_\Lambda > 2.3\,\mathrm{GeV}/c$
- Observe 649 ± 31 $\Lambda_c^+ \bar{\Lambda}_c^-$ events
  - Expect ≈ 150 events
  - Ratio of 4.2 consistent with CLEO



$e^+e^- \to c\bar{c} \to \Lambda_c^+ \bar{\Lambda}_c^- X$

- *X* system contains few baryons
  - No large amounts of undetected $n\bar{n}$
- Only 13 ± 8 4-baryon events
  - Expect ≈ 150
- Data inconsistent with pair production of known states or new/exotic states



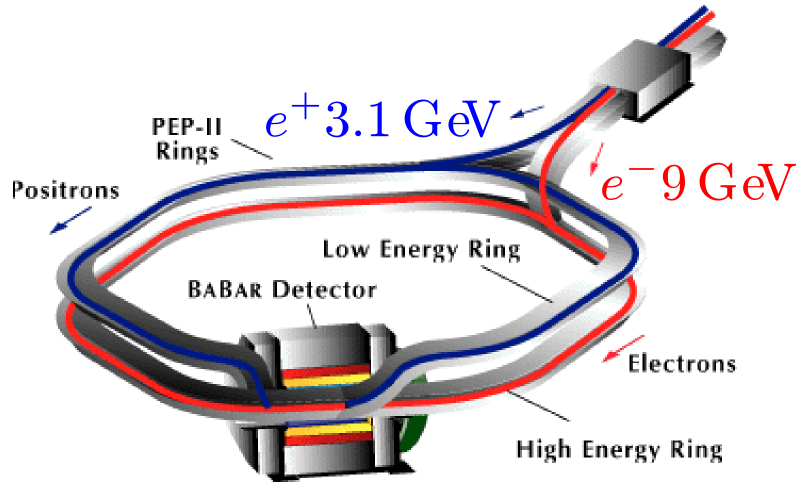
- Inclusive distributions consistent with jet-like events
  - Long-range baryon-antibaryon correlation
  - 2.2 units of rapidity difference on average
  - 2.6 ± 0.2 additional charged mesons per event

Summary

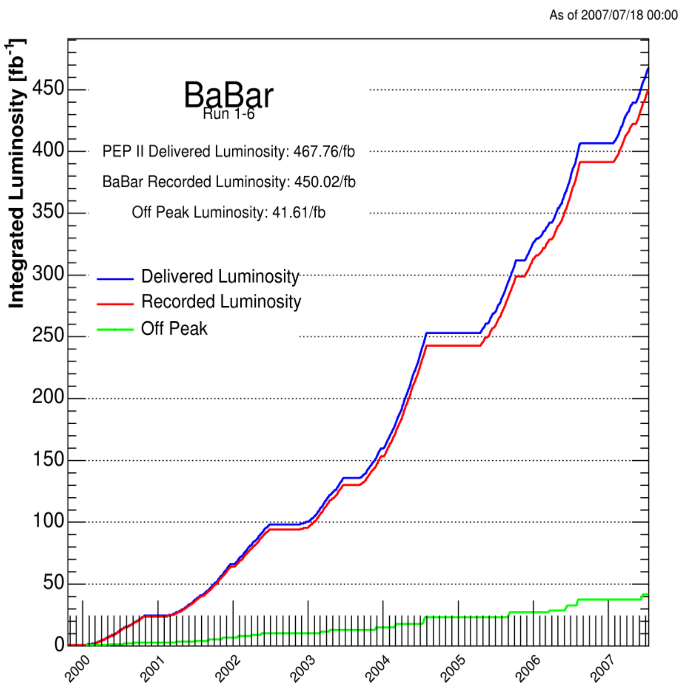
- *BABAR* makes many essential contributions to understanding of hadronic final states
- ISR methods give access to wide energy range
- Cross sections and decay structures of $e^+e^- \to K^+K^-\pi^+\pi^-, K^+K^-\pi^0\pi^0, K^+K^-K^+K^-, \pi^+\pi^-\pi^0\pi^0$ have been measured with high precision
- First observation of $C = +1$ states $\rho^0\rho^0, \phi\rho^0$ consistent with two-virtual-photon annihilation
- Results for $\Lambda_c^+\overline{\Lambda}_c^- X$ compatible with long-range correlation

Backup Slides

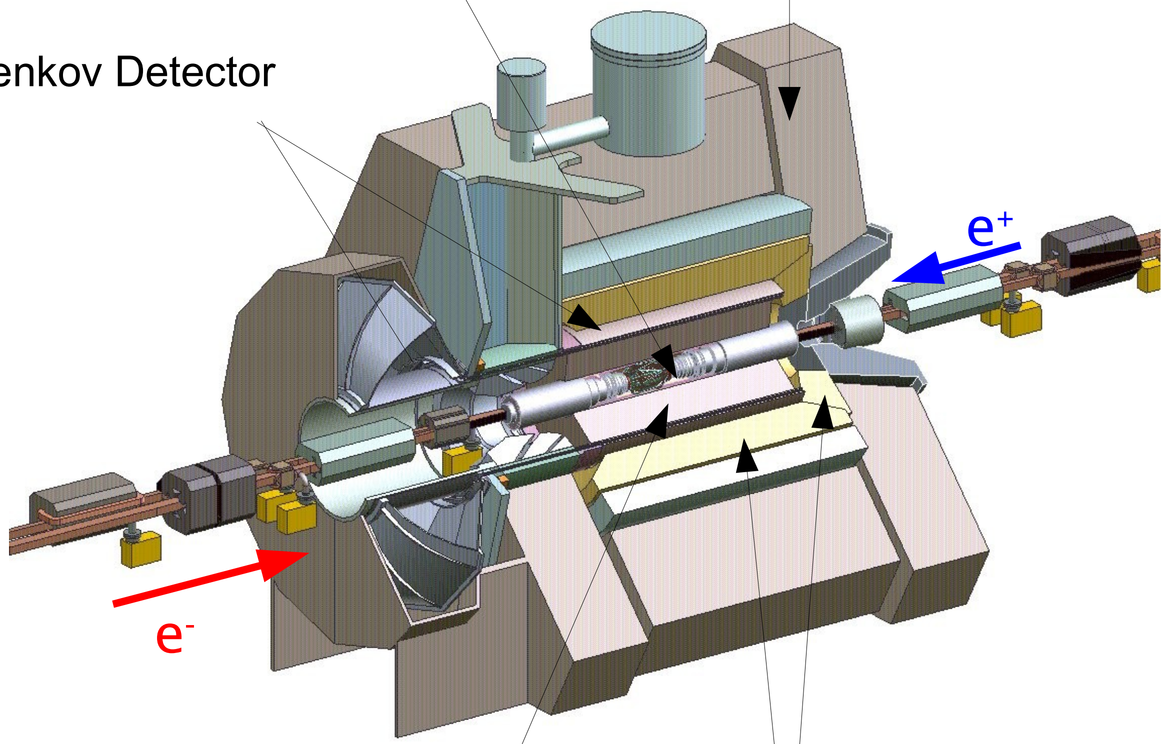
PEP II & *BABAR*



PEP-II Rings
$e^+ 3.1\,\mathrm{GeV}$
$e^- 9\,\mathrm{GeV}$
Positrons
Low Energy Ring
BABAR Detector
Electrons
High Energy Ring



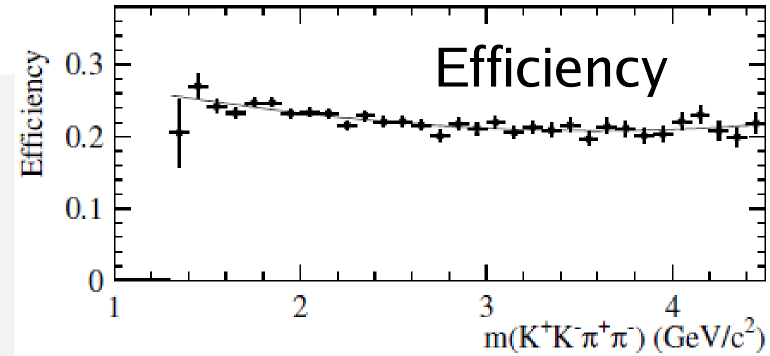
As of 2007/07/18 00:00
BaBar
Run 1-6
PEP II Delivered Luminosity: 467.76/fb
BaBar Recorded Luminosity: 450.02/fb
Off Peak Luminosity: 41.61/fb
Delivered Luminosity
Recorded Luminosity
Off Peak
Integrated Luminosity [fb⁻¹]

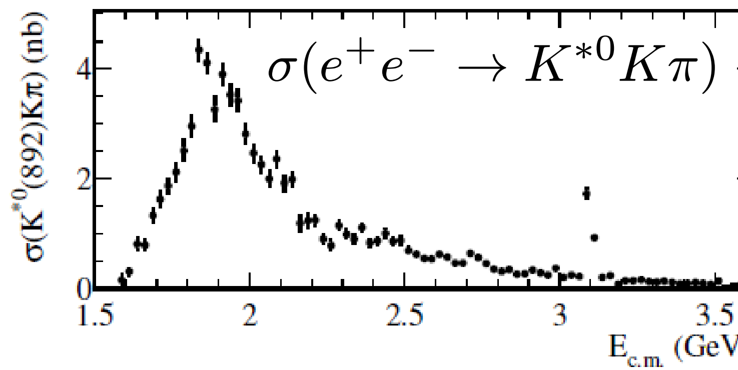


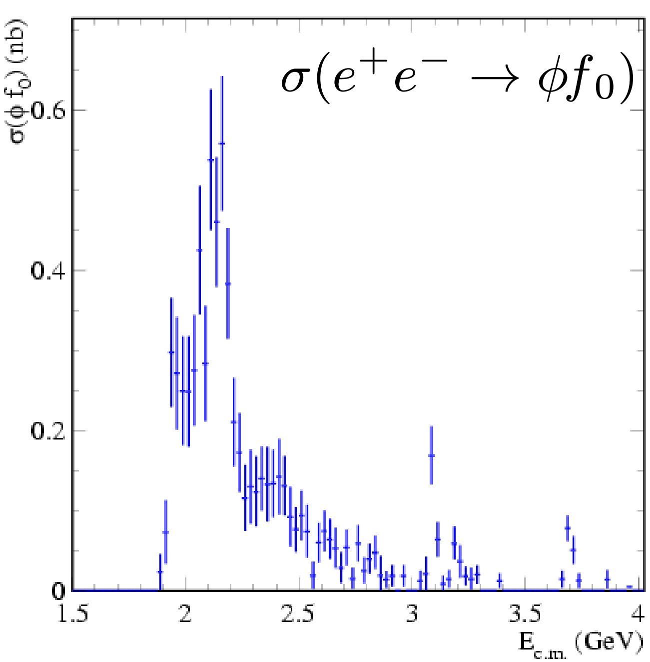
Instrumented Flux Return
Silicon Vertex Tracker
Cherenkov Detector
DIRC
e^+
e^-
Drift Chamber
Electromagnetic Calorimeter

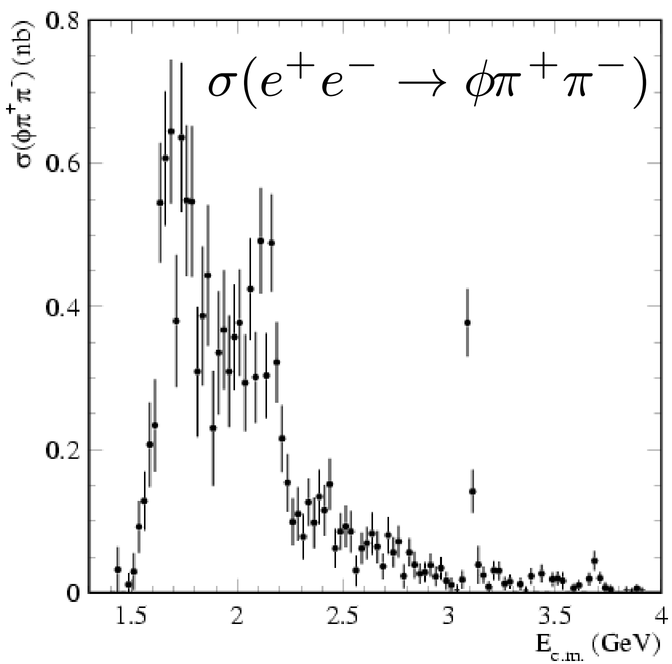
$e^+e^- \rightarrow K^+K^-\pi^+\pi^-\gamma$

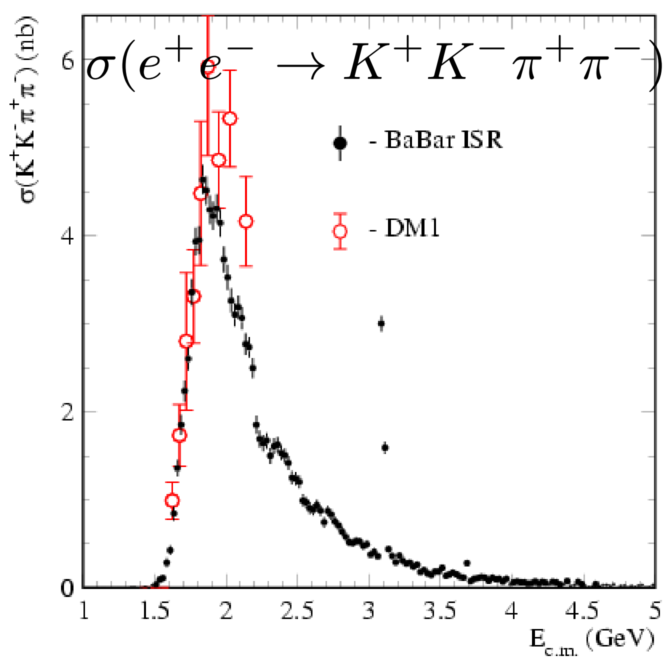
- Reconstruction efficiency ~25%
- Inclusive cross section
  - Consistent with direct measurement but better precision
- Substructure
  - $K^{*0}K\pi$ $\phi(1020)\pi^+\pi^-$ $\phi(1020)f_0(980)$





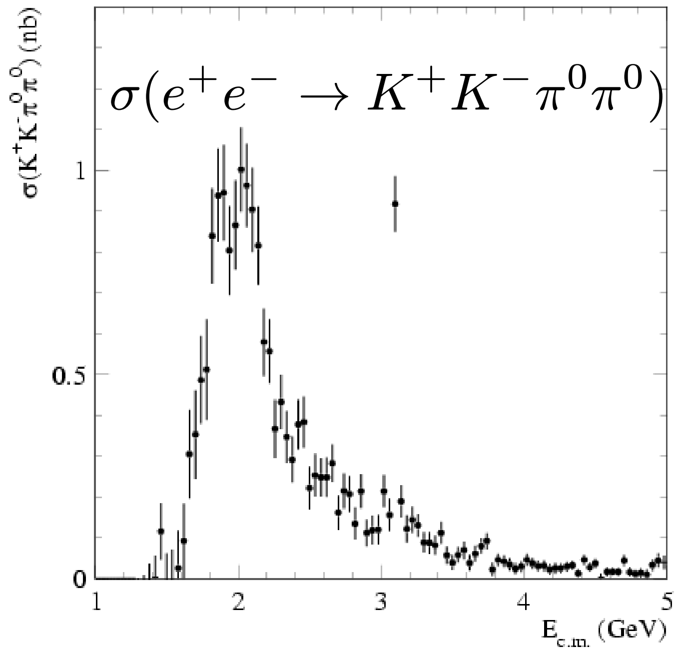


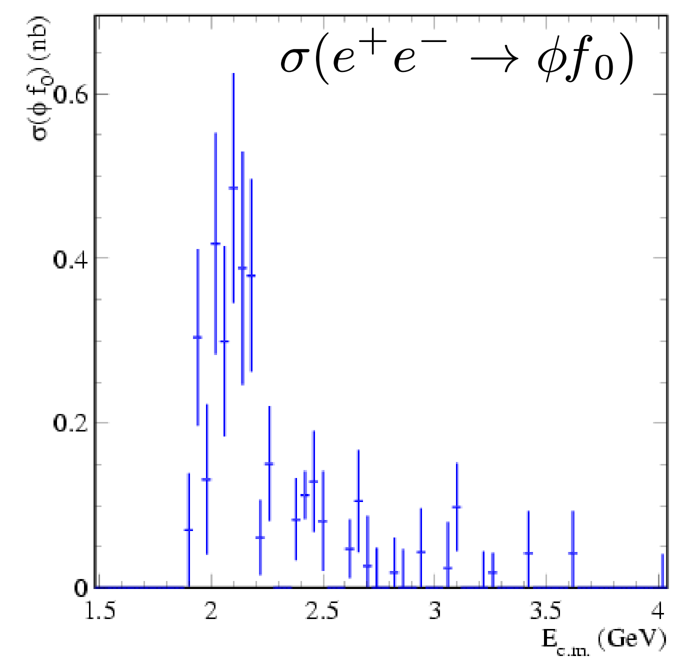




$e^+e^- \rightarrow K^+K^-\pi^0\pi^0\gamma$

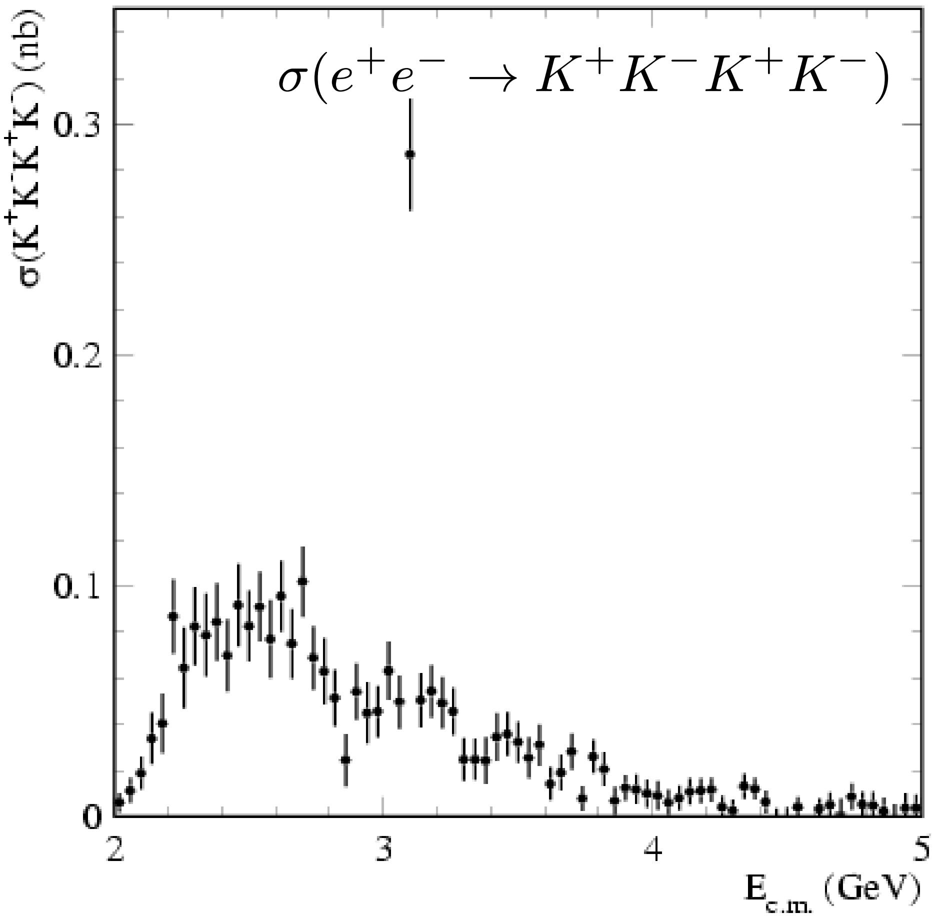
- Reconstruction efficiency ~5-9%
- Dominant uncertainties
  - Background model 5-10%
  - $\chi^2_{KK\pi^0\pi^0}$ Distribution 6%
- Total systematic uncertainty
  - $10\% (m_{KK\pi^0\pi^0} < 3\,\mathrm{GeV}/c^2)$
  - $14\% (m_{KK\pi^0\pi^0} > 3\,\mathrm{GeV}/c^2)$
- Substructure
  - $K^{*\pm}K\pi^0$ dominant, no sign of $K^{*+}K^{*-}$
  - $\phi(1020)\pi^0\pi^0$
    No cross section due to high backgrounds
  - $\phi(1020)f_0(980)$





$e^+e^- \rightarrow K^+K^-K^+K^-\gamma$

- Reconstruction efficiency ~20%
- Dominant uncertainty
  - Backgrounds 5-10%
- Total systematic uncertainty
  - $9\%(m_{4K} < 3\,\mathrm{GeV}/c^2)$
  - $13\%(m_{4K} > 3\,\mathrm{GeV}/c^2)$
- Substructure
  - $\phi(1020)K^+K^-$



$e^+e^- \to c\bar{c} \to \Lambda_c^+ \bar{\Lambda}_c^- X$

- 649 ± 31 signal events
  - $\times 4.2$ more than MC prediction (PYTHIA, HERWIG, UCLA)
- 13 ± 8 true 4-baryon events
  - Expect 155
  - 4-Baryon process strongly suppressed
- Heavier c-baryons
  - $\Sigma_c^{++/0}$, excited Λ_c^+
- Conclusions:
  - Not consistent with uncorrelated production of leading baryons
  - Baryon number conserved by leading baryon antibaryon pair