

Studies of $e^+e^- \rightarrow$ Quasi-2-Body processes at 10.6 GeV at BaBar

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Representing the BaBar Collaboration

- Introduction

- $e^+e^- \rightarrow \eta\gamma, \eta'\gamma$

Transition Form Factors

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

Two-Virtual-Photon Annihilation

- $e^+e^- \rightarrow \rho^+\rho^-$

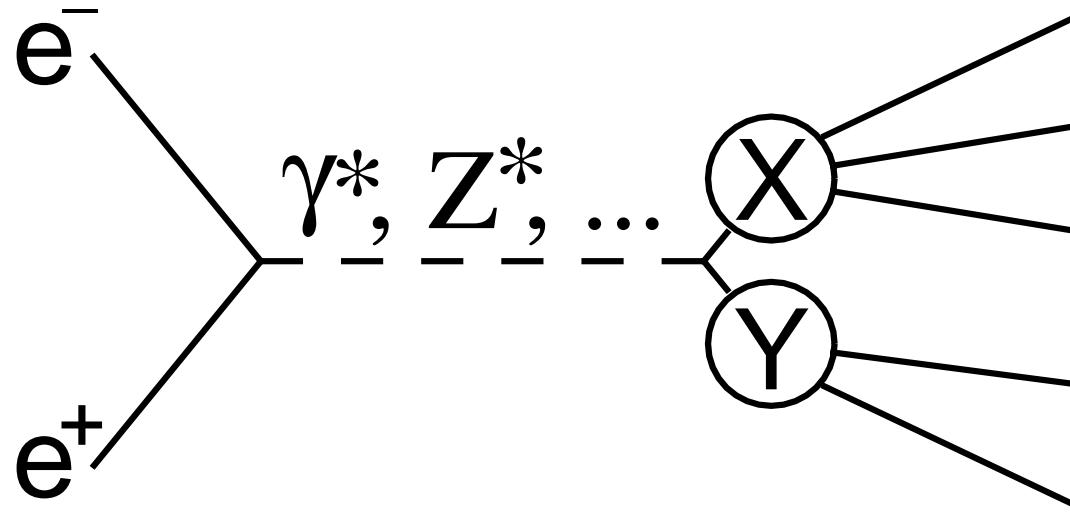
Test of QCD in helicity structure

- $e^+e^- \rightarrow \eta\phi$

Test of QCD in E_{CM} Dependence

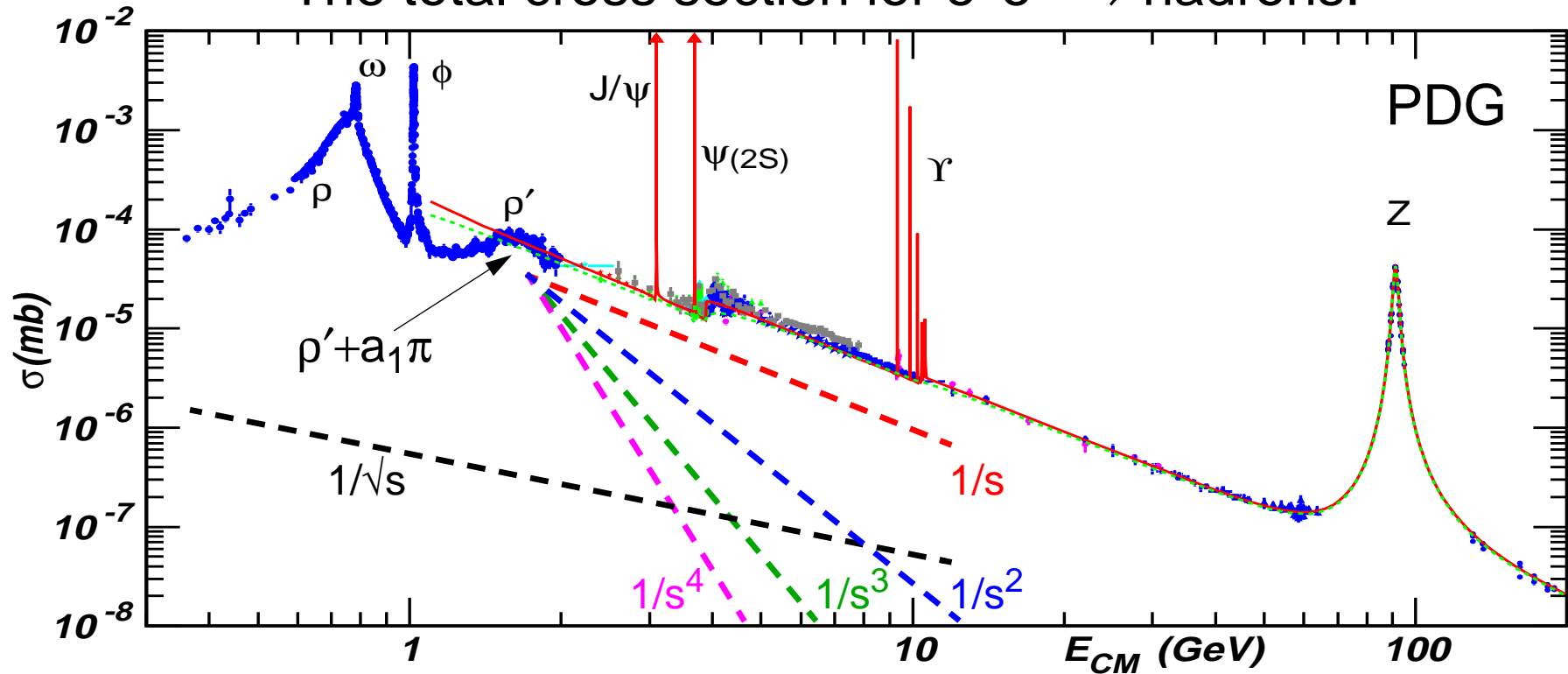
- Summary

Quasi-2-Body Final States in e^+e^- Annihilations:



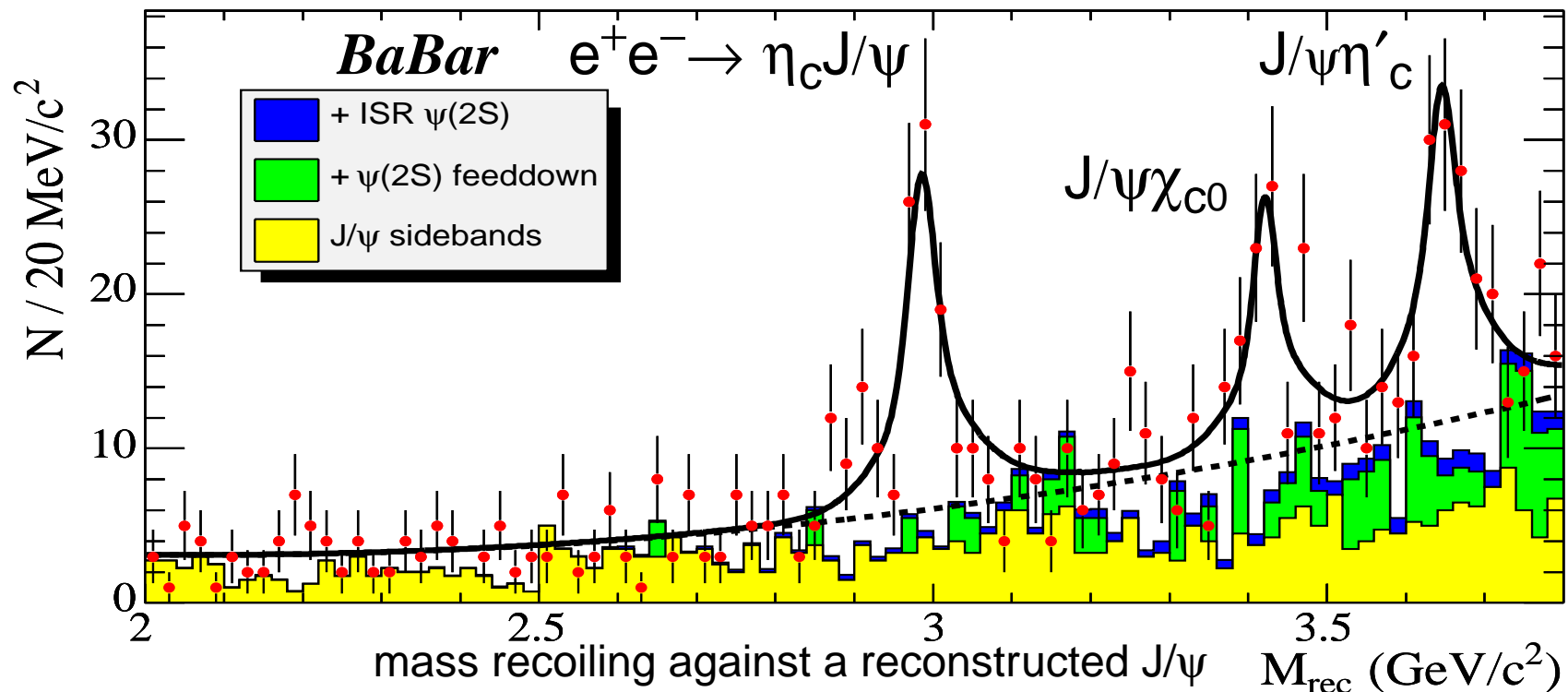
- Only some Quantum #, helicity combinations allowed
- Rich testing ground for QCD
 - cross sections/amplitudes
 - helicity structure
 - E_{CM} dependence
- If $Y=\bar{X}$ then parametrize in terms of a form factor
- If $Y=\gamma$, vector meson then it's a transition form factor
- Potential sensitivity to higher order/new propagators

The total cross section for $e^+e^- \rightarrow \text{hadrons}$:



- At low $\sqrt{s}=E_{CM}$: dominated by resonances, few-body reactions
 \rightarrow lots of physics here! We are studying several channels via radiative return – see talks by W. Wang and S. Serednyakov
- High E_{CM} : perturbative regime, $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}(g) \rightarrow \text{jets}$; $\sigma \propto 1/s$
- QCD: few-body cross sections fall faster than $1/s$
 \rightarrow but accessible at high E_{CM} with high statistics
- Some other processes fall more slowly, may be visible at high E_{CM}

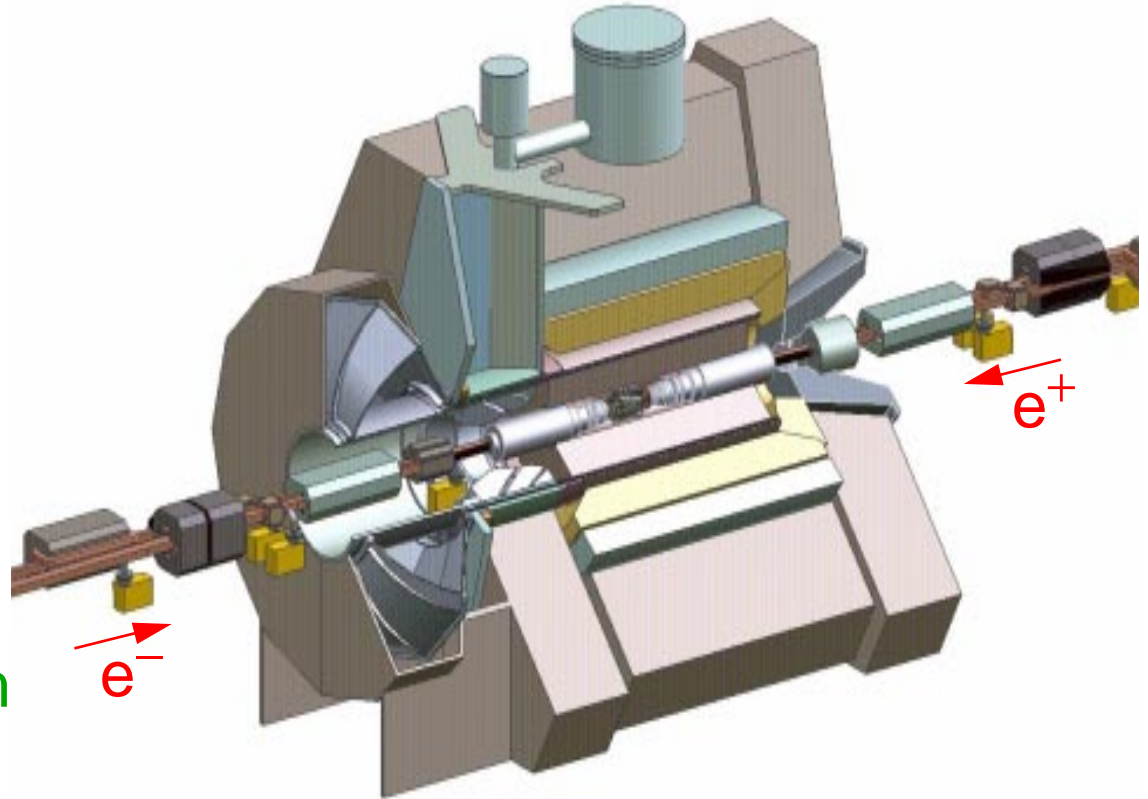
Double charmonium at 10.6 GeV: **seen by BELLE** PRL 89, 151802 (02)
confirmed by BaBar PRD 72, 031101 (05)



- Observed cross sections **higher** than expected
 - spurred considerable theoretical work; ongoing
 - BELLE update includes a new state, $X(3940)$ hep-ex/0507019
- We are studying several **fully reconstructed** low-mult processes
 - just starting to scratch the surface of this physics
 - several interesting results already in quasi-2-body channels

The BaBar Experiment

- e^+e^- collisions at 10.6 GeV, designed for CP violation in B decays
- Different beam energies:
 - $E_{e^-} = 9.0$ GeV
 - $E_{e^+} = 3.1$ GeV
 - c.m.-lab boost, $\gamma\beta=0.55$
- Asymmetric detector
 - c.m. frame acceptance
 $-0.9 \sim \cos\theta^* \sim 0.85$
wrt e^- beam
- with excellent performance
 - Good tracking, mass resolution
 - Good γ , π^0 recon.
 - Full e, μ, π, K, p ID
- High luminosity:
 - $\sim 475 \text{ fb}^{-1}$ accumulated
 - $\Leftrightarrow 1.6$ billion $e^+e^- \rightarrow q\bar{q}$ evts
 - $\Leftrightarrow 0.5$ billion $e^+e^- \rightarrow B\bar{B}$ evts
 - 224–379 fb^{-1} used here

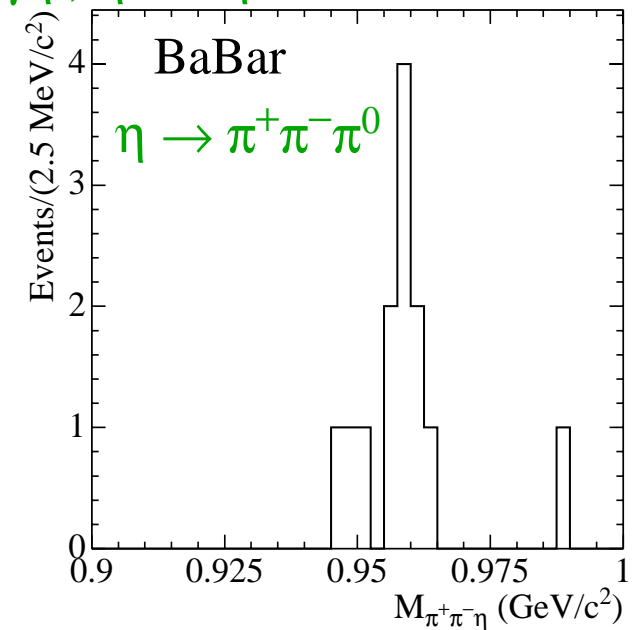
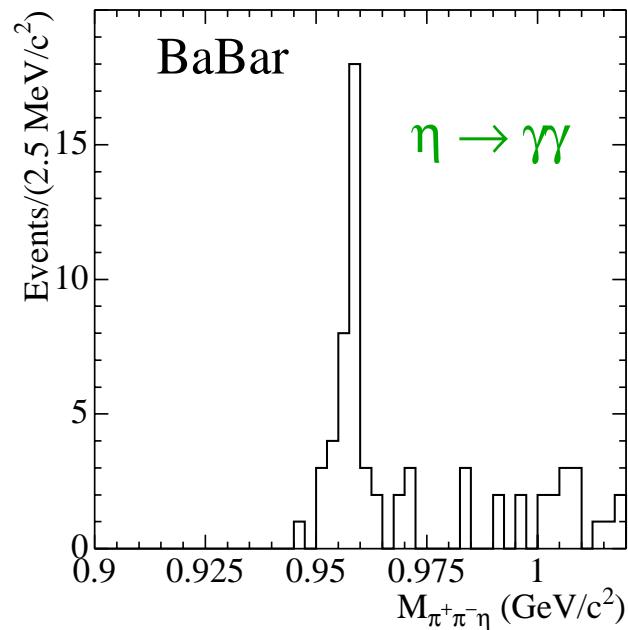
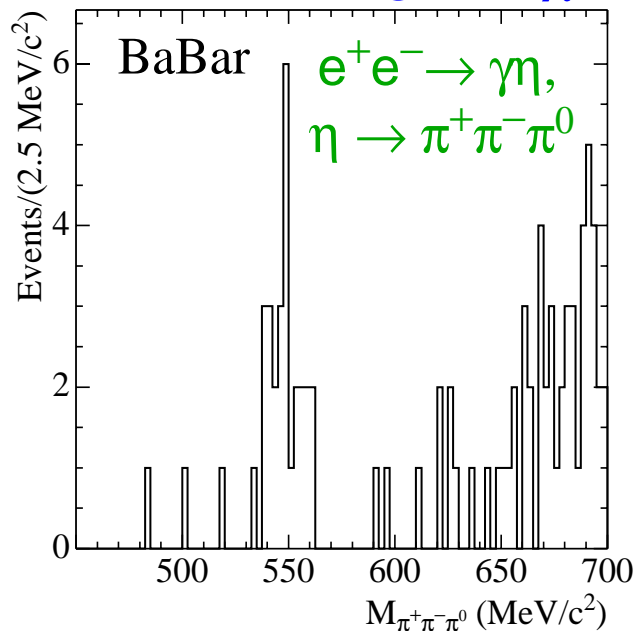


$e^+e^- \rightarrow \gamma\eta$ and $\gamma\eta'$

232 fb⁻¹, PRD 74, 012002 (06)

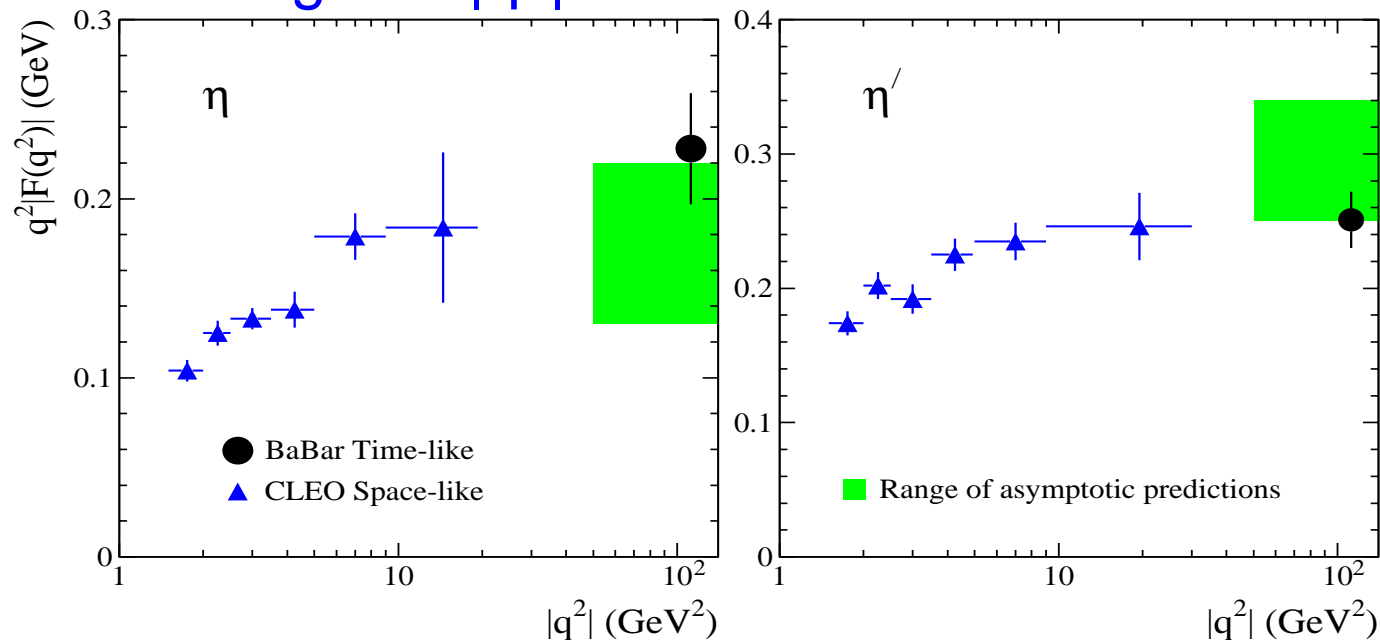
- **Vector-pseudoscalar** states with a distinctive topology:
 - one high-energy photon recoiling against ...
 - a set of 2-4 charged tracks and two photons
- **Reconstruct:**
 - $\eta \rightarrow \pi^+\pi^-\pi^0$, $\pi^0 \rightarrow \gamma\gamma$
 - $\eta' \rightarrow \pi^+\pi^-\eta$, $\eta \rightarrow \gamma\gamma$ or $\pi^+\pi^-\pi^0$
- **Constrain total 4-momentum, $\gamma\gamma$ mass** in a kinematic fit, select events with good χ^2

$e^+e^- \rightarrow \gamma\eta', \eta' \rightarrow \eta\pi^+\pi^-$



→ nice clean signals, fit to extract yield

- The corresponding cross sections $\sigma(e^+e^- \rightarrow \gamma\eta) = 4.5 \pm 1.2 \pm 0.3 \text{ fb}$
 $\gamma\eta' = 5.4 \pm 0.8 \pm 0.3 \text{ fb}$
- can be related to Transition Form Factors
 - QCD predicts asymptotic values
 - models predict s dependence at low $s=|q^2|$
- We have the highest- $|q^2|$ measurements to date

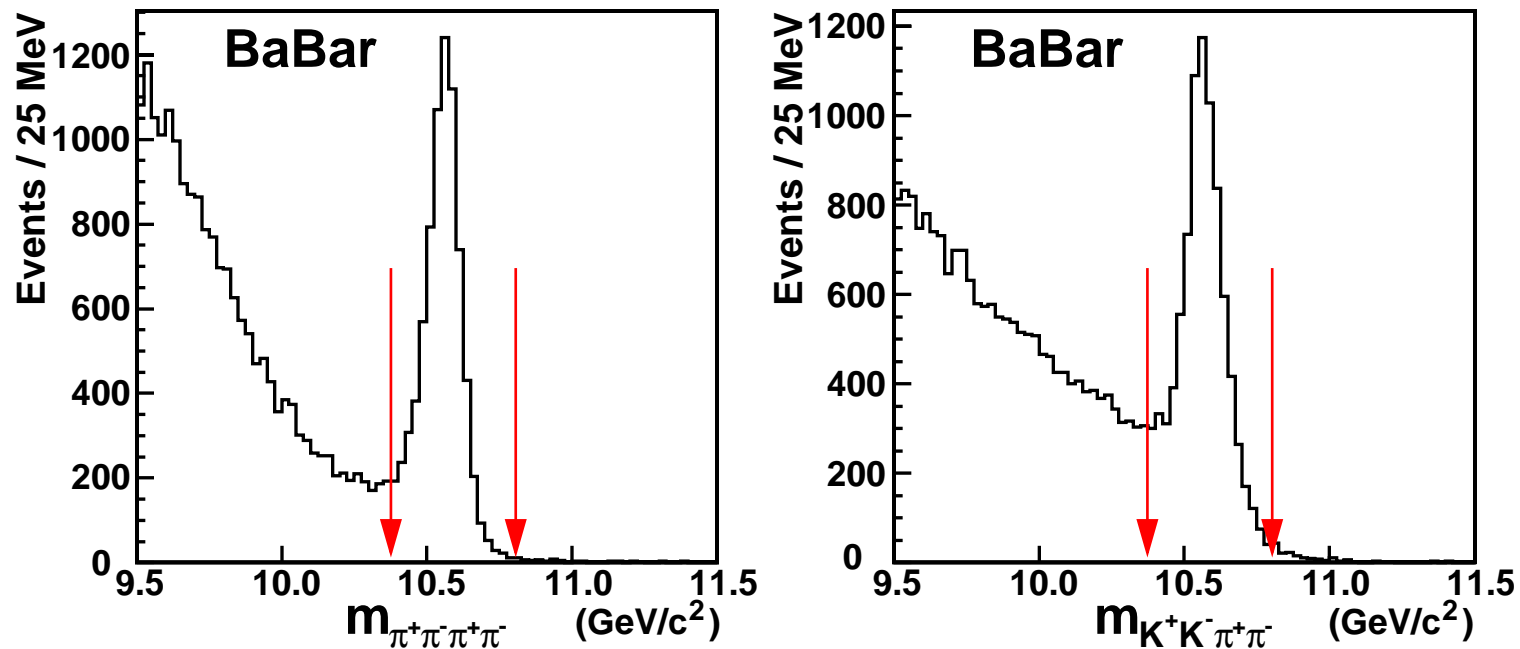


- consistent with approach to asymptotic regime
- and with QCD predictions ... which depend on η - η' mixing ...
- ...but the ratio, 1.10 ± 0.17 is outside the theory range, 1.6–2.3
- ⇒ more theoretical, experimental input needed

$$e^+e^- \rightarrow \rho^0\rho^0 \text{ and } \rho^0\phi$$

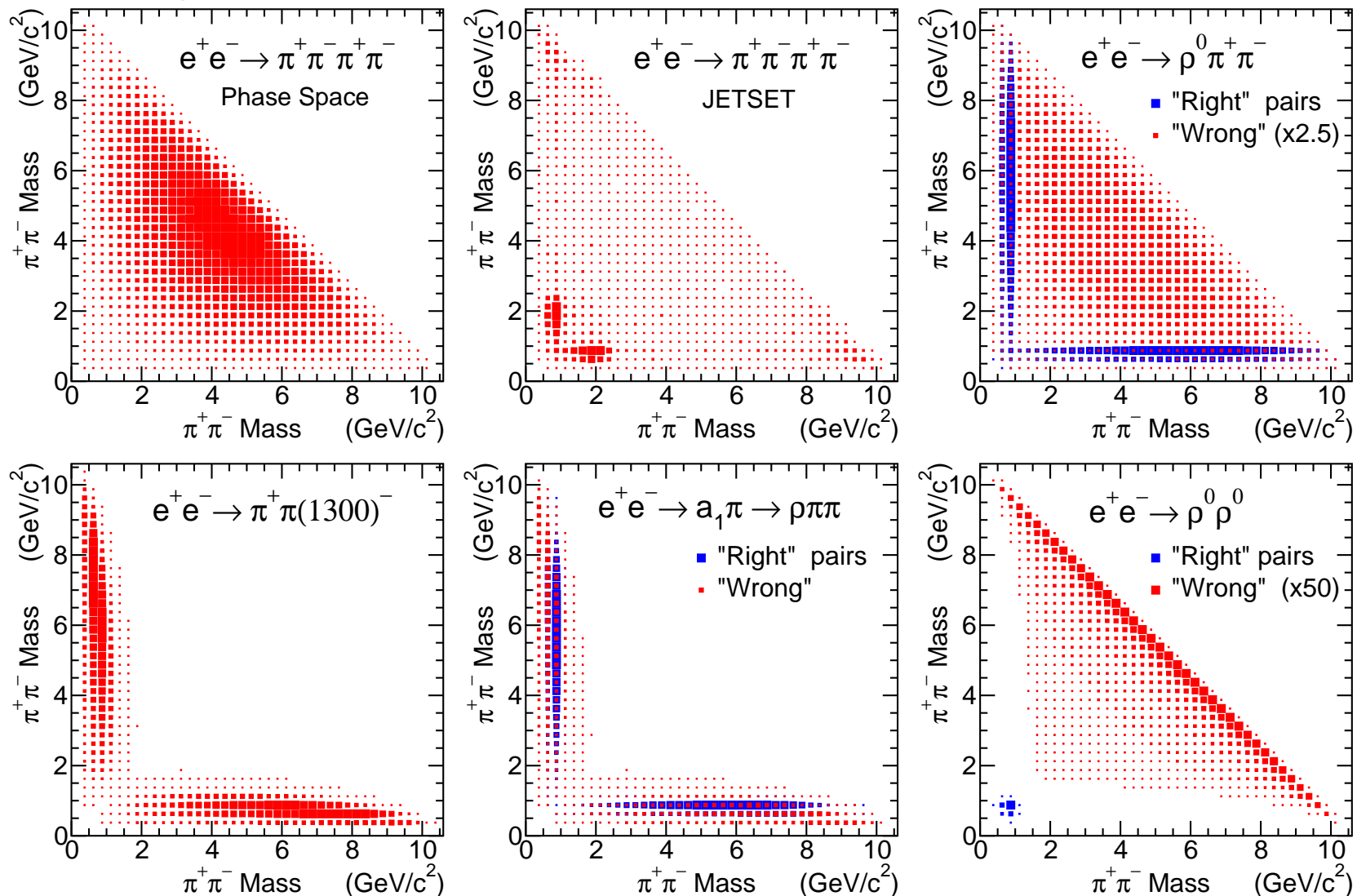
225 fb⁻¹, PRL 97, 112002 (06)

- Study of the $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ and $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$ reactions
→ expect several intermediate states to contribute
- Require:
→ exactly four good charged tracks with zero total charge
→ identified as π^\pm or K^\pm



- Nice signals at total invariant mass \leftrightarrow the e^+e^- c.m. energy
→ backgrounds are small, but interesting; still under study
→ select events within 170 MeV of the nominal E_{CM}

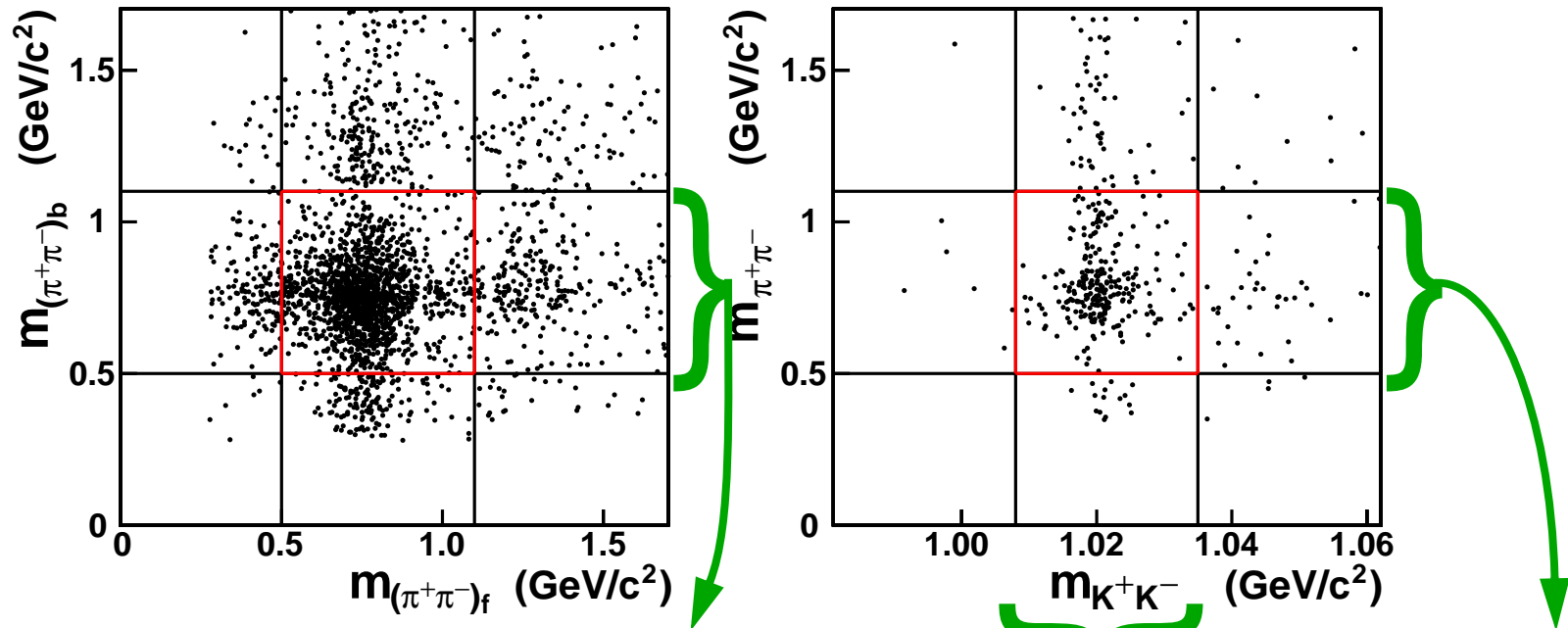
- Now study the internal structure of these events
 → some generator level simulations for $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$



- at 10.6 GeV, large kinematic separation between modes
- ...and between "correct" and "incorrect" pairings

- We see several such modes in the data
- The most striking (and easy to analyze) are the clear signals for

$$e^+e^- \rightarrow \rho^0 \rho^0 \quad \text{and} \quad e^+e^- \rightarrow \rho^0 \phi$$



- 2D fit projections:

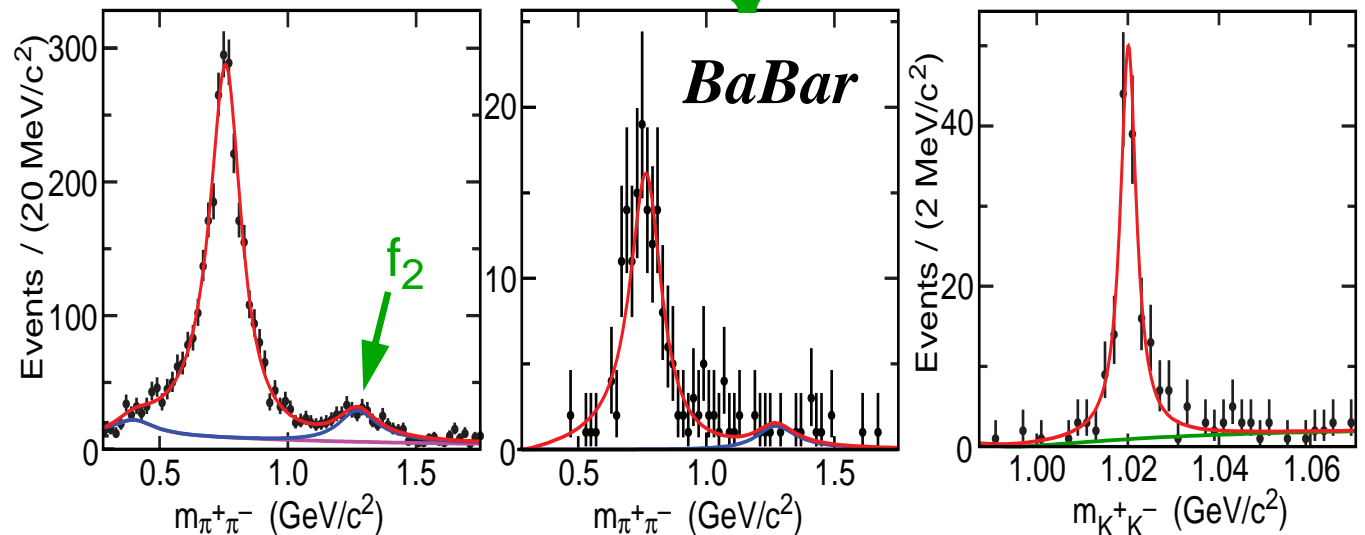
→ including:

$\rho\pi\pi/\rho KK/\phi\pi\pi$ —

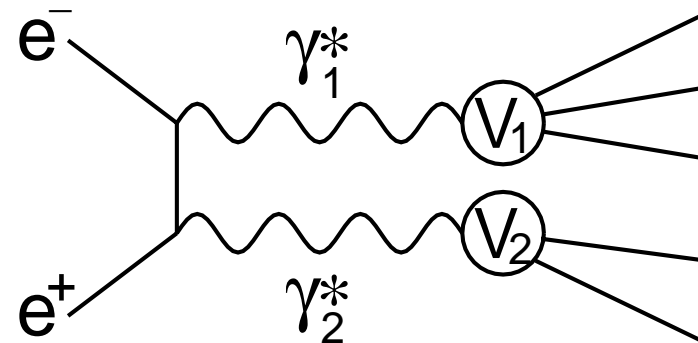
...+ $\rho\mu\mu$ —

...+ $\rho/\phi f_2(1270)$ —

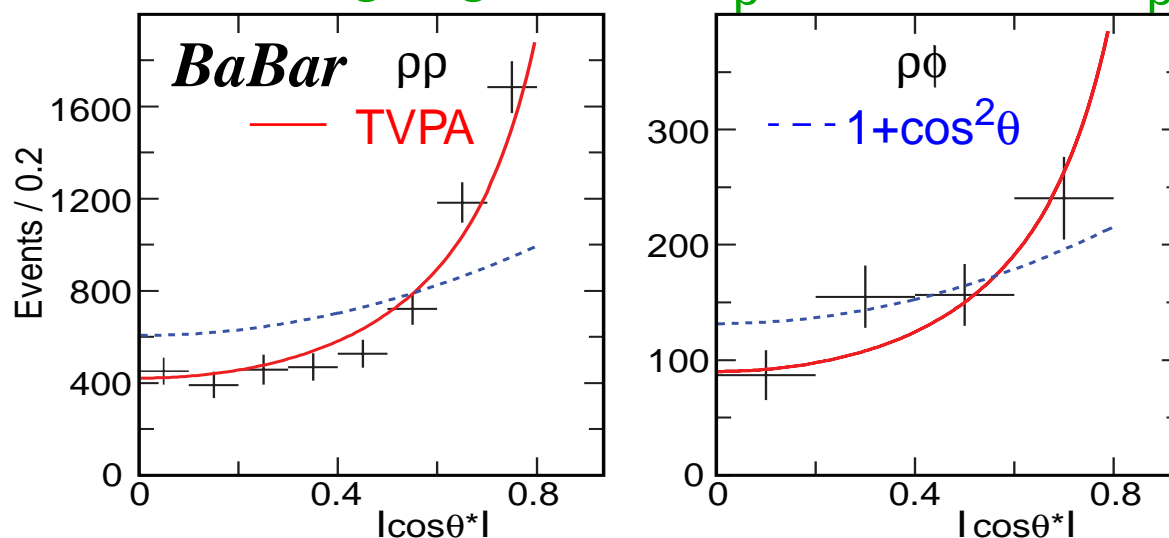
...+ $\rho\rho/\phi\rho$ —



- $\rho^0\rho^0$ and $\rho^0\phi$ are neutral vector-vector states with $C = +1$
 - forbidden in single γ^* annihilation
 - allowed in 2- γ^* annihilation (TVPA)
 - ...and expected at ~this level
 - ⇒ Are we observing this process?

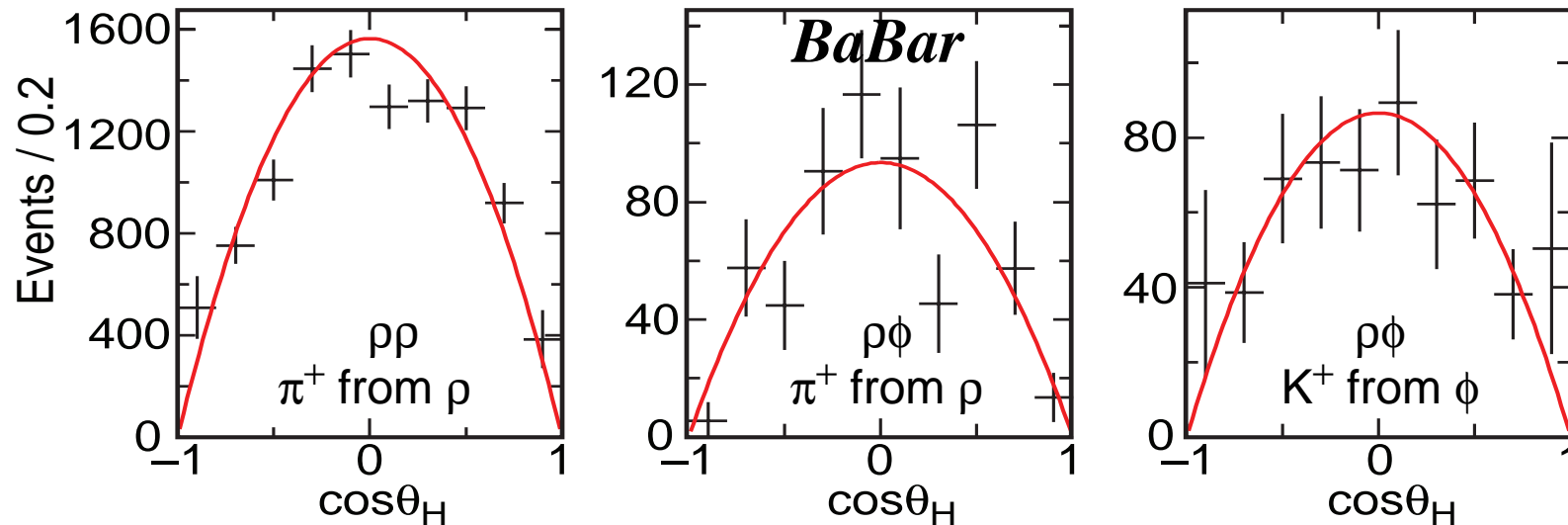


- TVPA predicts strongly forward-peaked production angles
 - distributed as $\sim (1 + \cos^2\theta_\rho) / (1 - \cos^2\theta_\rho)$
 - other processes might give $\sin^2\theta_\rho$, flat, $1 + \cos^2\theta_\rho$, ...



→ The data are consistent with TVPA, “nothing” else

- also, ρ, ϕ light enough that polarization \sim transverse



→ Helicity angles are consistent with $\sin^2\theta_H$ distributions

- and slow energy dependence, $\sim 1/s$

→ Not seen in ISR data at 1-4.5 GeV

PRD 71, 052001 (05)

⇒ First observation of $e^+e^- \rightarrow$ hadrons via TVPA ⇐

- Extract cross sections within the ranges $\cos\theta^* \in [-0.8-0.8]$
 $m_\rho \in [500-1100] \text{ MeV}/c^2$
 $m_\phi \in [1008-1035] \text{ MeV}/c^2$

⇒ $20.7 \pm 0.7 \pm 2.7 \text{ fb}$ for $e^+e^- \rightarrow \rho\rho$
 $5.7 \pm 0.5 \pm 0.8 \text{ fb}$ for $\rho\phi$

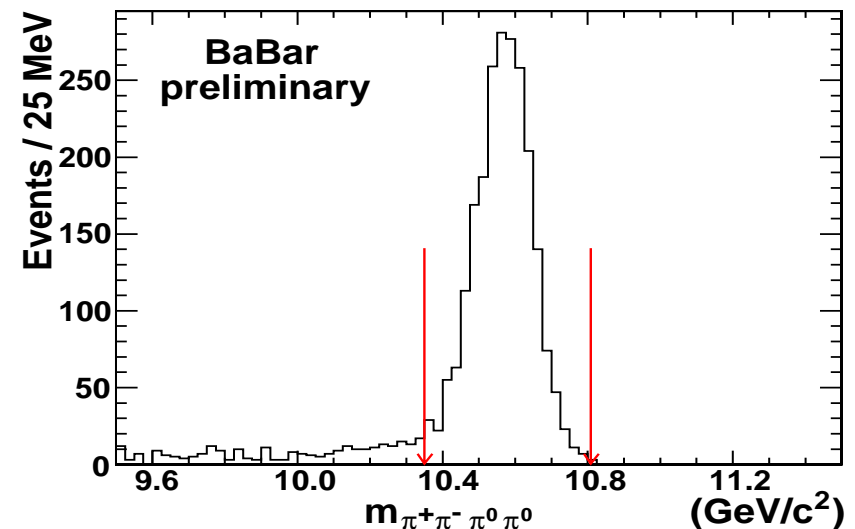
⇒ a vector-dominance prediction is consistent

hep-ph/0606155

$$e^+e^- \rightarrow \rho^+\rho^-$$

379 fb⁻¹, BaBar Preliminary

- Study of the $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ reaction
 - expect several intermediate states to contribute
- The $\rho^+\rho^-$ channel is especially interesting:
 - allowed via single γ^* annihilation, in some helicity states
 - amplitude level QCD test in helicity structure
 - TVPA could also contribute via a final state interaction
 - ...and interference could give an observable(?) asymmetry
- Require:
 - exactly two tracks, identified as π^+ and π^-
 - two good $\pi^0 \rightarrow \gamma\gamma$ candidates
 - momentum $|\mathbf{p}_{\pi^+\pi^-\pi^0\pi^0}| < 0.2$ GeV/c in the c.m. frame
 - a pairing with both $m_{\pi^+\pi^0}$ and $m_{\pi^-\pi^0} < 1.6$ GeV/c²
 - select events within 280 MeV of the nominal E_{CM}



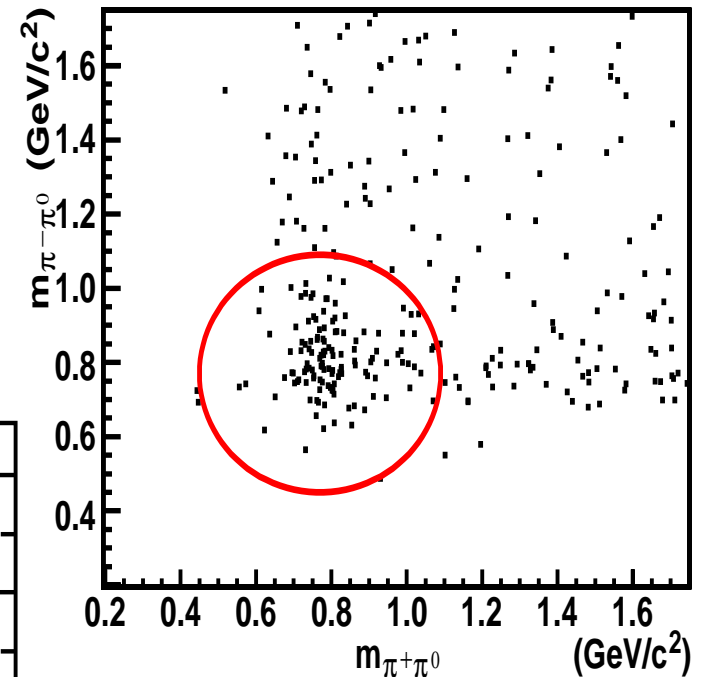
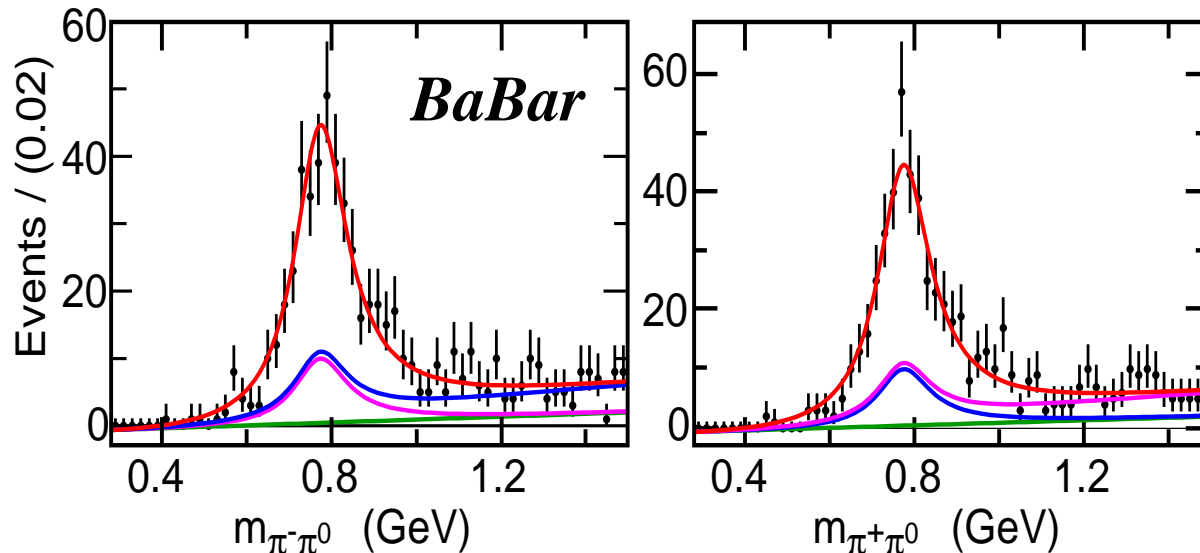
- There is a clear signal for $e^+e^- \rightarrow \rho^+\rho^-$

- 2D fit to extract the signal yield

→ including linear background

→ ...+ $\rho^+\pi^-\pi^0$ / $\rho^-\pi^+\pi^0$

→ ...+ $\rho^+\rho^-$



⇒ (fiducial) cross section is $8.5 \pm 0.7 \pm 1.5$ fb
cf. $20.7 \pm 0.7 \pm 2.7$ fb for $\rho^0\rho^0$

→ is this similarity interesting?

⇒ ...but this channel **is** seen in ISR data at 2-4 GeV

→ we will study the energy dependence

- Angular distributions

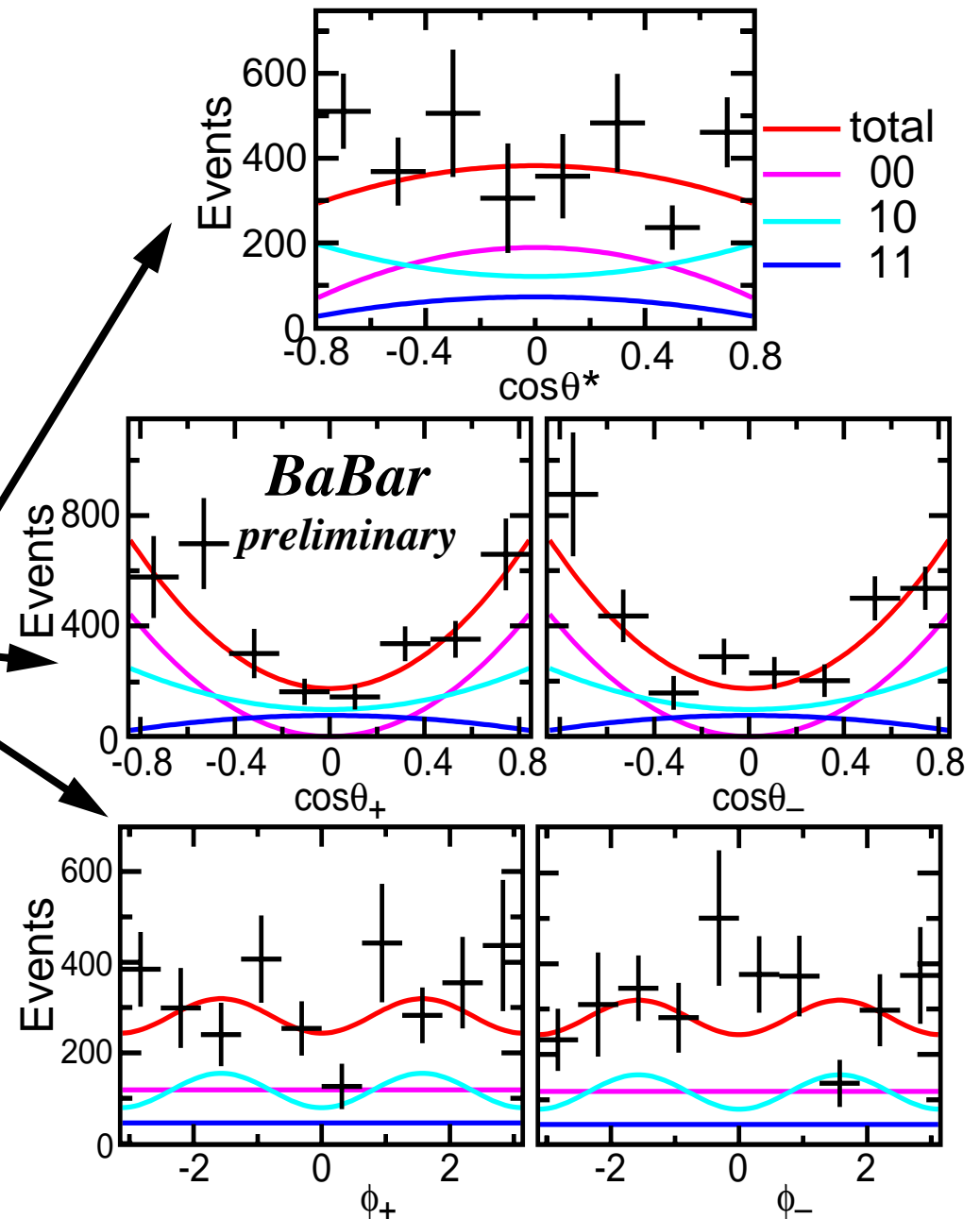
- single- γ^* annihilation allows 3 nonzero helicity amplitudes: 00, 10, 11

- QCD predicts that the 00 state should dominate at high E_{CM} PRD 24, 2848 (81)

- Fit the production decay helicity and decay azimuthal angles simultaneously

- limited statistics, but...
- the 00 contribution is largest, but not dominant
- ~40% needed from 01 and/or 11

- insufficient stats to look at dihedral angle/presence of TVPA



$$e^+e^- \rightarrow \eta\phi$$

224 fb⁻¹, PRD 97, 111103 (06)

- Study of the $e^+e^- \rightarrow K^+K^-\gamma\gamma$ reaction

→ expect only a few intermediate states to contribute

→ can this be related to $e^+e^- \rightarrow \eta_c J/\psi$?

→ theoretical E_{CM} dependence: $1/s^3$
...or $1/s^4$

PLB 425, 365 (98)

PRD 24, 2848 (81)

PRpt 112, 173 (84)

- Require:

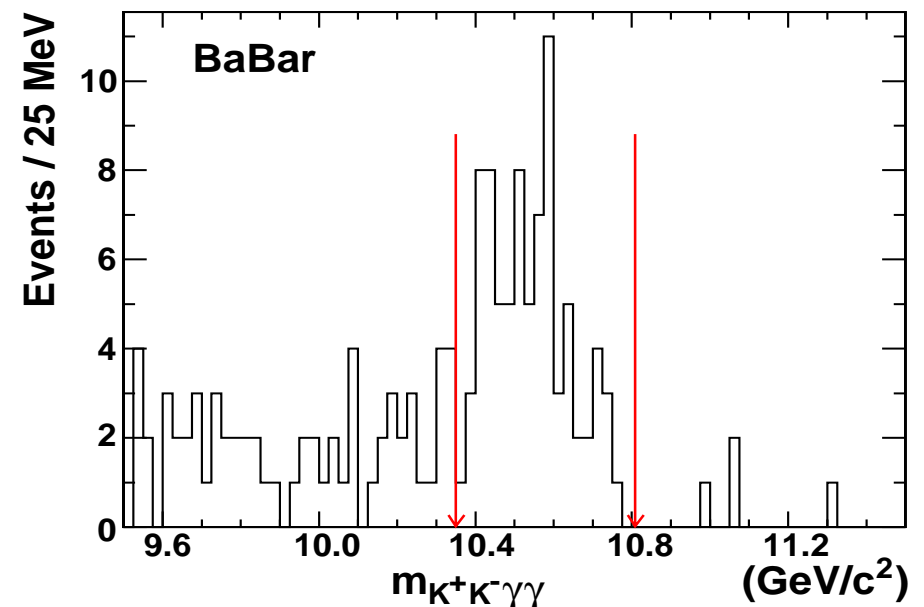
→ exactly two good charged tracks, identified as K^+ and K^-

→ two good photons, $E > 0.5$ GeV

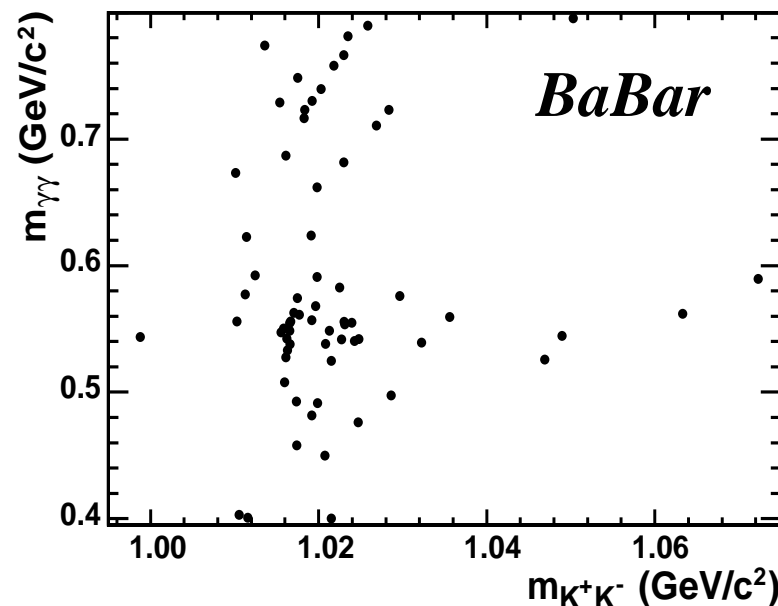
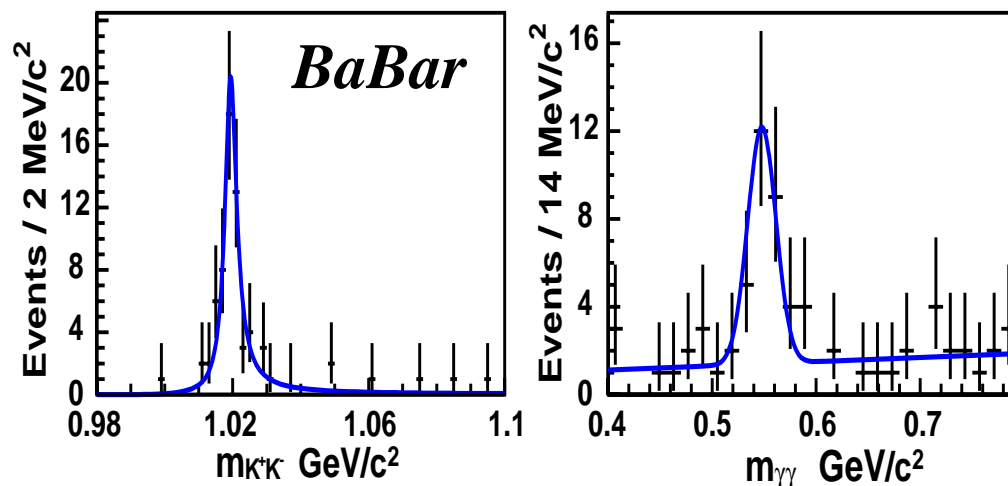
→ $m_{KK} < 1.1$ GeV/c²

→ $0.4 < m_{\gamma\gamma} < 0.8$ GeV/c²

→ select events within 230 MeV
of the nominal E_{CM}



- Very clean signals for $K^+K^-\eta$,
 $\phi\gamma\gamma$,
 $\eta\phi$
- 2D fit to extract the signal yield



⇒ fiducial cross section is $2.1 \pm 0.4 \pm 0.1$ fb

⇒ angular distributions consistent (stat. limited) with expectations for single- γ^* production of a pseudoscalar-vector state

- assuming this, cross section is $2.9 \pm 0.5 \pm 0.1$ fb
cf. $25.6 \pm 2.8 \pm 3.4$ fb for $\eta_c J/\psi$
- comparison depends on the $s\bar{s}$ content of the η
- theoretical input needed

- $e^+e^- \rightarrow \eta\phi$ is seen at lower energies

- in ISR by BaBar in $K^+K^-\pi^+\pi^-\pi^0$
and $K^+K^-\gamma\gamma$

arXiv:0708.2451, subm. to PRD

Preliminary

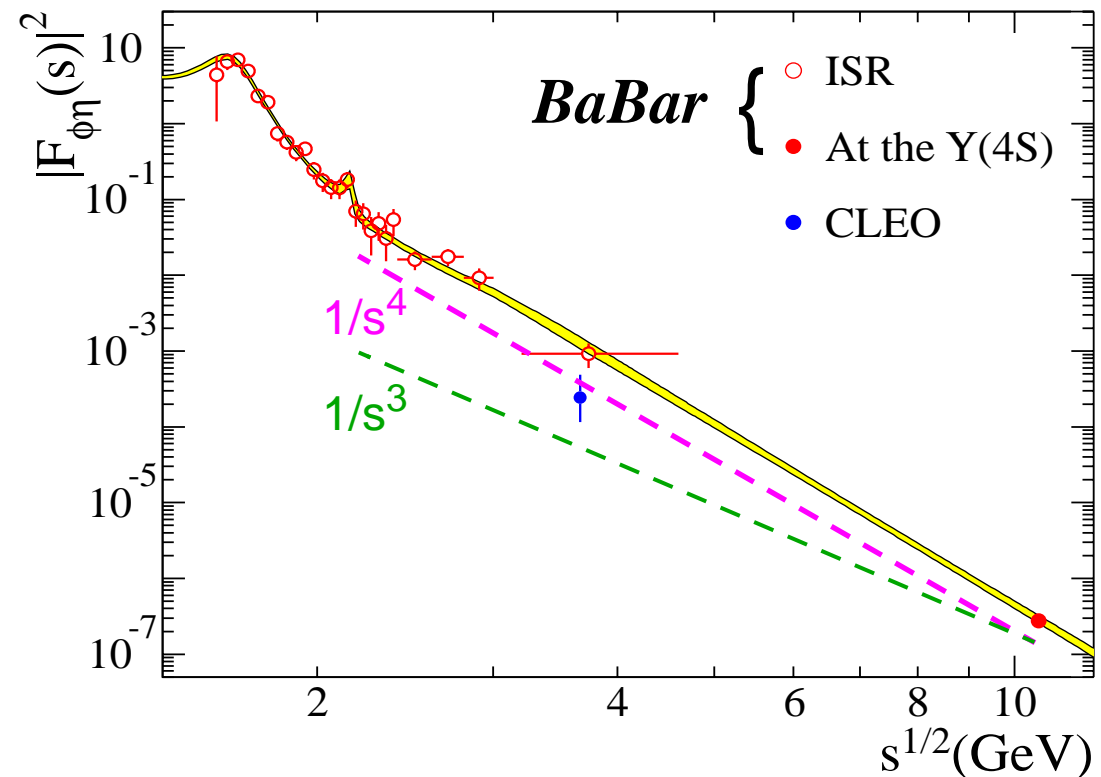
PRD 73, 212002 (06)

- by CLEO at 3.67 GeV

- Can study E_{CM} dependence

- possible structure(s) near threshold, 2.2 GeV

- at “high”- E_{CM} , data are consistent with $1/s^4$ but not with $1/s^3$



- Dispersion relation phenomenology

EPJ A31, 665 (07)

- explains the data nicely in terms of ϕ' and ρ' resonances

- confirms $1/s^4$ asymptotic behavior

Conclusions

- The very high luminosity of the B factories has (re)opened the study of several interesting areas of elementary particle physics
- In particular, exclusive reactions at 10.6 GeV:
 - first observation of e^+e^- annihilations into hadrons via $2\gamma^*$
 - η , η' form factors measured in(?) the asymptotic region
 - $\eta\phi$, $\rho^+\rho^-$ cross sections measured in the asymptotic region
 - new test of QCD in the $\rho^+\rho^-$ helicity structure
- Many new, improved studies planned
 - update results with full data set
 - more (quasi)-2-body modes, form factors, QCD tests
 - “complete” studies of particular final states