Initial State Radiation Physics at BaBar

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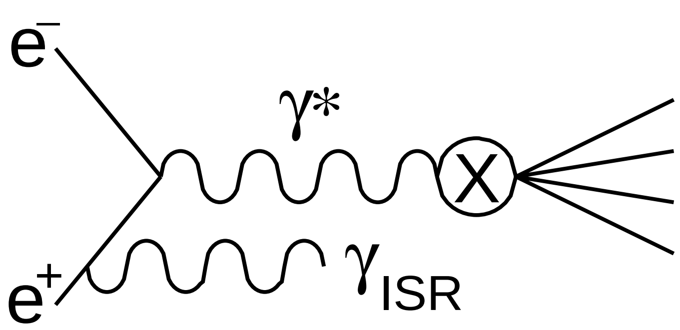
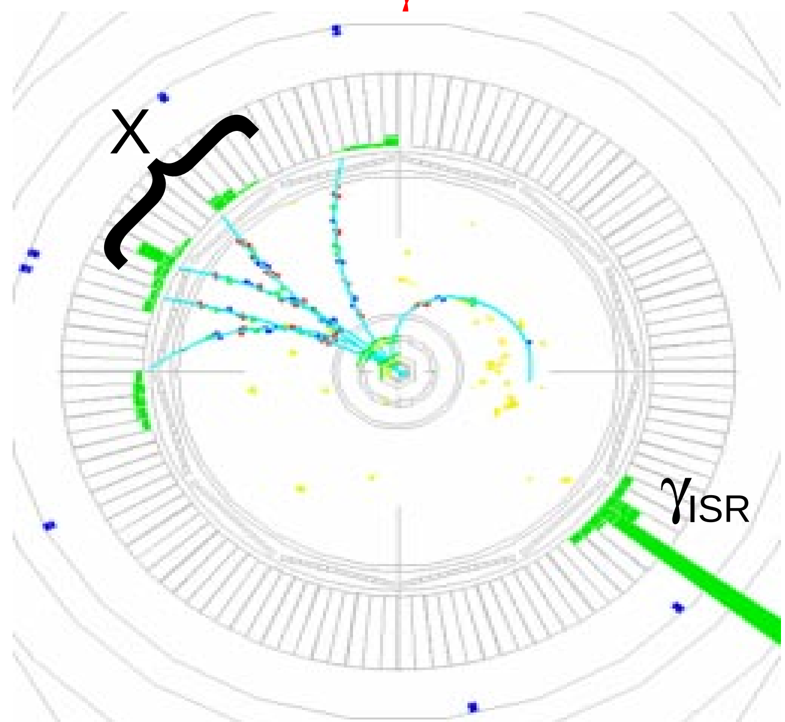
Representing the BaBar Collaboration

- **ISR and BaBar**
- **Energy Dependence, Structure of**
  - $e^+e^- \to p\bar{p}$ — proton form factors
  - $e^+e^- \to \pi^+\pi^-\pi^0$ — ω spectroscopy
  - $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ — contribution to $g_\mu - 2$
  - $e^+e^- \to K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$ — structure in $\phi f_0(980)$
  - $e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$ — resonance in $\omega\eta$
  - $e^+e^- \to K^+K^-K^+K^-$, $K^+K^-\pi^+\pi^-\pi^+\pi^-$ — 1^{st} measurements
  - $e^+e^- \to J/\psi\pi^+\pi^-$, $J/\psi\gamma\gamma$, $D\bar{D}$ — structure at 4260 MeV
  - $e^+e^- \to \psi(2S)\pi^+\pi^-$ — structure at 4320 MeV
- **Summary**

Initial State Radiation in e^+e^- Annihilations



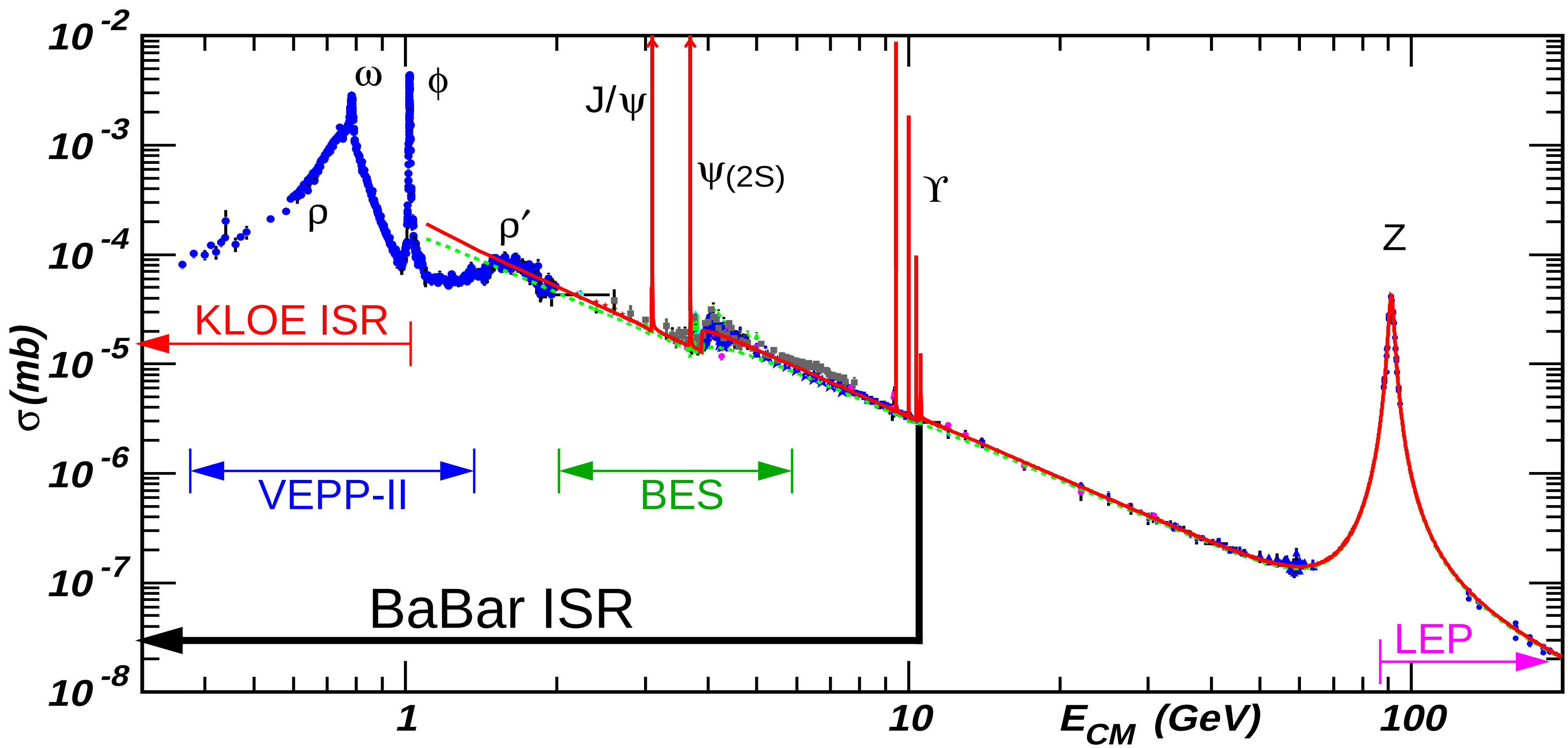
- $e^+e^- \rightarrow \gamma_{ISR} e^+e^- \rightarrow \gamma_{ISR}\gamma^* \rightarrow \gamma_{ISR}X$
- X is any allowed hadronic system, e.g. a resonance with $J^{PC}=1^{--}$
- cross section: $\frac{d\sigma(s,s',\theta_\gamma)}{ds' d\cos\theta_\gamma} = W(s,s',\theta_\gamma)\cdot\sigma(s')$



- The radiator function W is known to <1%
- Measure $\sigma(e^+e^- \rightarrow X)$ as a fcn. of $m_{\gamma*}=m_X=E_{CM}=\sqrt{s'}$
- Features:
  - → access to wide s′ range
  - → very small point-to-point systematic errors
  - → γ_{ISR} detected ↔ hadron system contained
  - → measure all the way down to threshold
- Disadvantages:
  - → mass resolution >beam-E spread
  - → requires very high luminosity

$e^+e^- \rightarrow$ hadrons Cross Section:

- Has been measured over a rather broad range



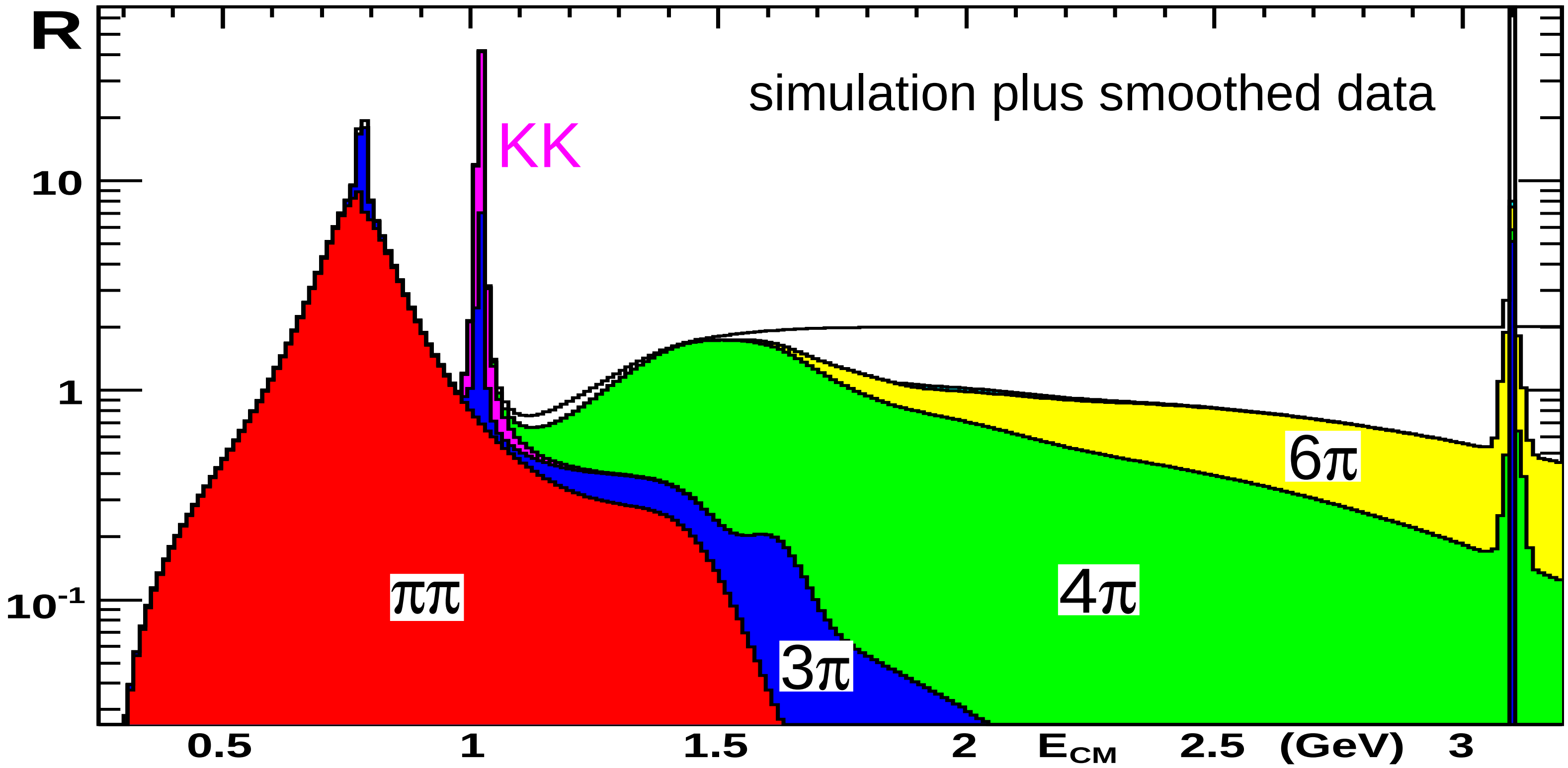
- Recent, precise measurements from KLOE, VEPP-II, BES, LEP
- Perturbative QCD works at high E_{CM}; lots of structure at lower E_{CM}
- Regions around 2, 4 GeV especially interesting
- Theoretical $g_\mu - 2$, $\alpha(M_Z)$ need integral, better data for E_{CM}<10 GeV

What do we measure?

- First, pick a specific final state X and isolate it
- Then measure the cross section, σ(m)
  - $\rightarrow$ ...and $R_X = \sigma_X(m)/\sigma^0_{\mu\mu}(m)$ $\leftrightarrow$ $g_\mu - 2$, $\alpha(m_Z)$
  - $\rightarrow$ spectroscopy, BFs of 1^{--} states
  - $\rightarrow$ discover new 1^{--} states
  - $\rightarrow$ extract form factors if $X = h\bar{h}$
  - $\rightarrow$ tests of QCD in m-dependence see K.Yi's talk to follow
- Then study the resonant substructure
  - $\rightarrow$ some quantum #s through correlations, angular distributions
  - $\rightarrow$ extract cross sections, form factors for “exclusive” submodes
  - $\rightarrow$ discover new resonances
- Then more general substructure
  - $\rightarrow$ general features might expose interesting dynamics
  - $\rightarrow$ at what E_{CM} do the events become “jetty”
  - $\rightarrow$ ....

The ISR program at BaBar:

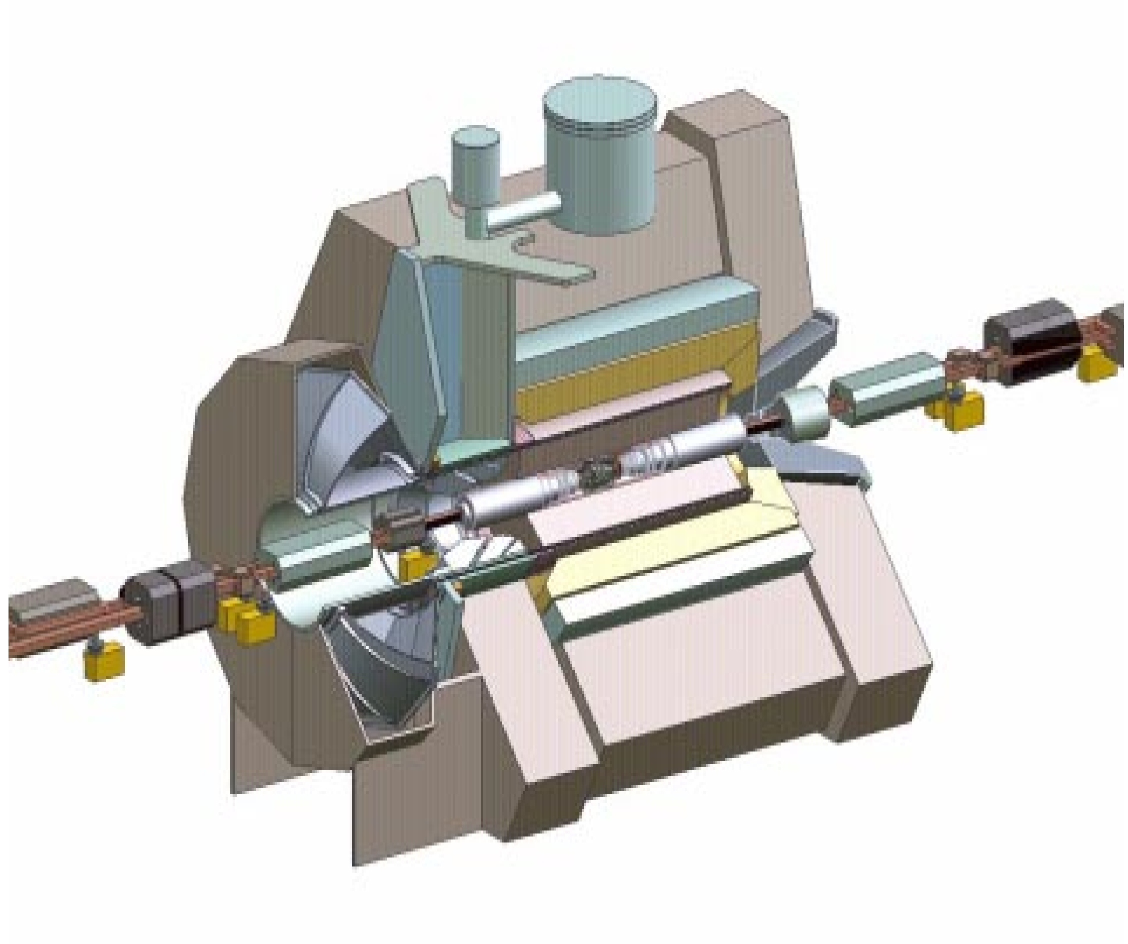
- Measure exclusive final states up to ~4.5 GeV, inclusive to ~7 GeV



- Published: $\mu^+\mu^-$, $p\bar{p}$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$, $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$, $K^+K^-\pi^+\pi^-\pi^+\pi^-$, $J/\psi\pi^+\pi^-$
- Today: these plus $K^+K^-\pi^0\pi^0$, $\phi f_0(980)$, $J/\psi\gamma\gamma$, $D\bar{D}$, $\psi(2S)\pi^+\pi^-$
- In progress: $\pi^+\pi^-$, K^+K^-, $K^+K^-\pi^0$, $K^+K^0\pi^-$, $K^0K^-\pi^+$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^-\pi^+\pi^-\pi^0$, ψK^+K^-, $\Lambda\bar{\Lambda}$, inclusive, ...

The BaBar Experiment

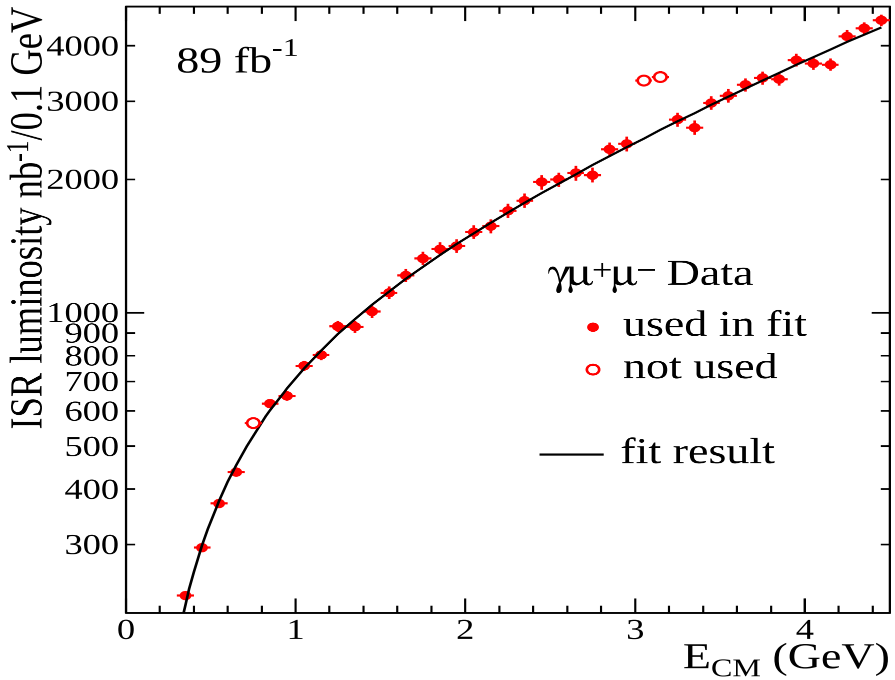
- e^+e^- collisions, ~10.6 GeV
- Different beam energies:
  - → E_{e^-} = 9.0 GeV
  - → E_{e^+} = 3.1 GeV
  - → c.m.-lab boost, $\gamma\beta$=0.55
- Asymmetric detector
  - → c.m. frame acceptance
    –0.9 ~ cosθ* ~ 0.85
    wrt e^- beam
  - → detects ~15% of ISR γ
  - → contains ~50% of evts with fwd/bwd γ_{ISR}

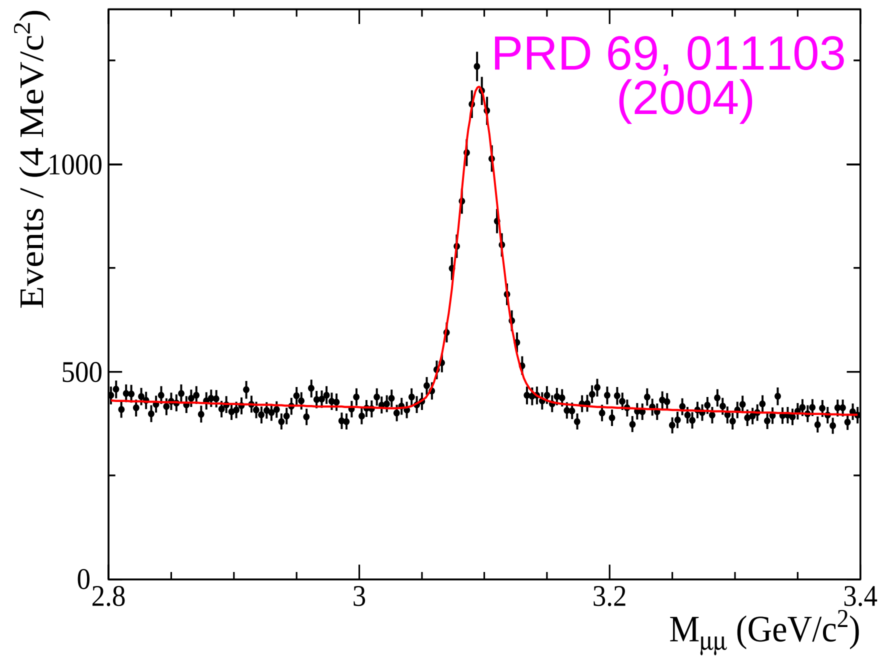


- with excellent performance
  - → Good tracking, mass resolution
  - → Good γ, π^0 recon.
  - → Full e,μ,π,K,p ID
- High luminosity:
  - → ~ 390 fb^{-1} accumulated
  - → 89–298 fb^{-1} used here
    - ↔ 0.3–1.1 billion $e^+e^- \to q\bar{q}$ evts.
    - ↔ 3–10 million $e^+e^- \to \gamma_{ISR} J/\psi$
    - ↔ 2– 7 million $e^+e^- \to \gamma_{ISR}\rho^0$

The equivalent ISR Luminosity:

- Can be calculated from the measured luminosity or derived for our γ_{ISR} acceptance using $e^+e^- \to \gamma_{ISR}\mu^+\mu^-$ events





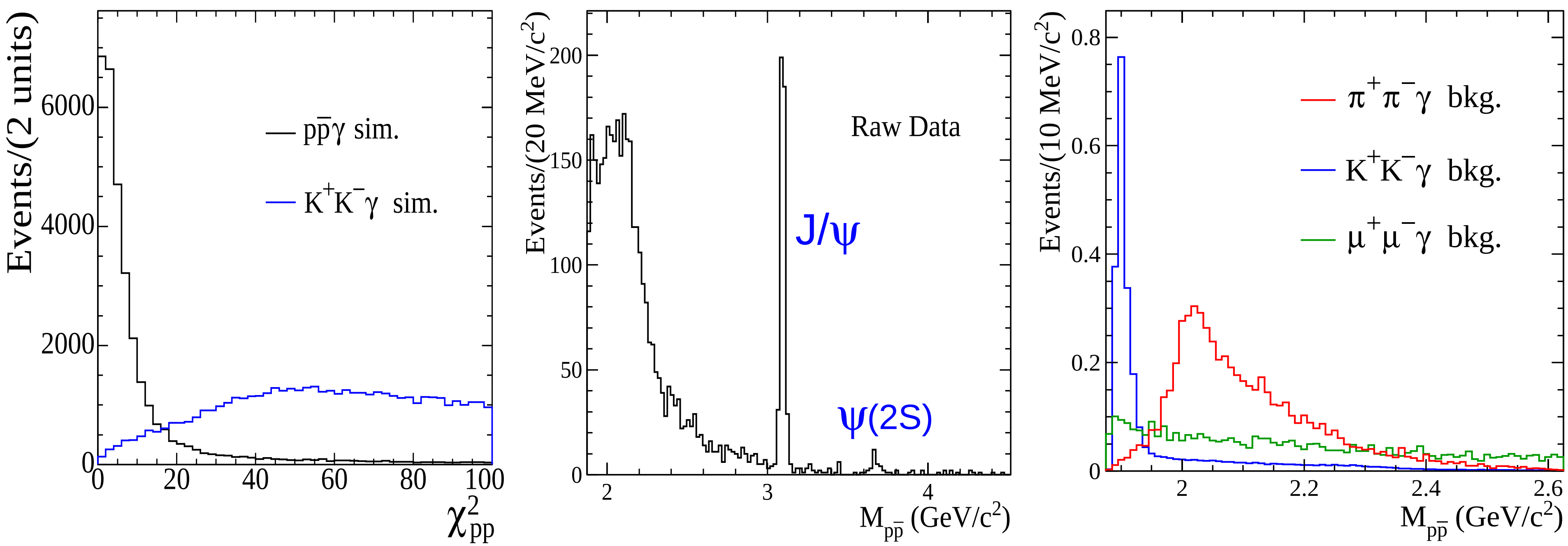
- In each 100 MeV window near
  1 GeV, we expect to accumulate ~ 8 pb^{-1}
  3 GeV ~26

- This mode also gives a nice constraint on the J/ψ width:
  89 fb^{-1}, PDG B_{ee}, $B_{\mu\mu} \to \Gamma_{J/\psi}$ = 93.7±3.5 keV;
  with CLEO 96.1±3.2 keV, dominate world avg.

$e^+e^- \to p\bar{p}$

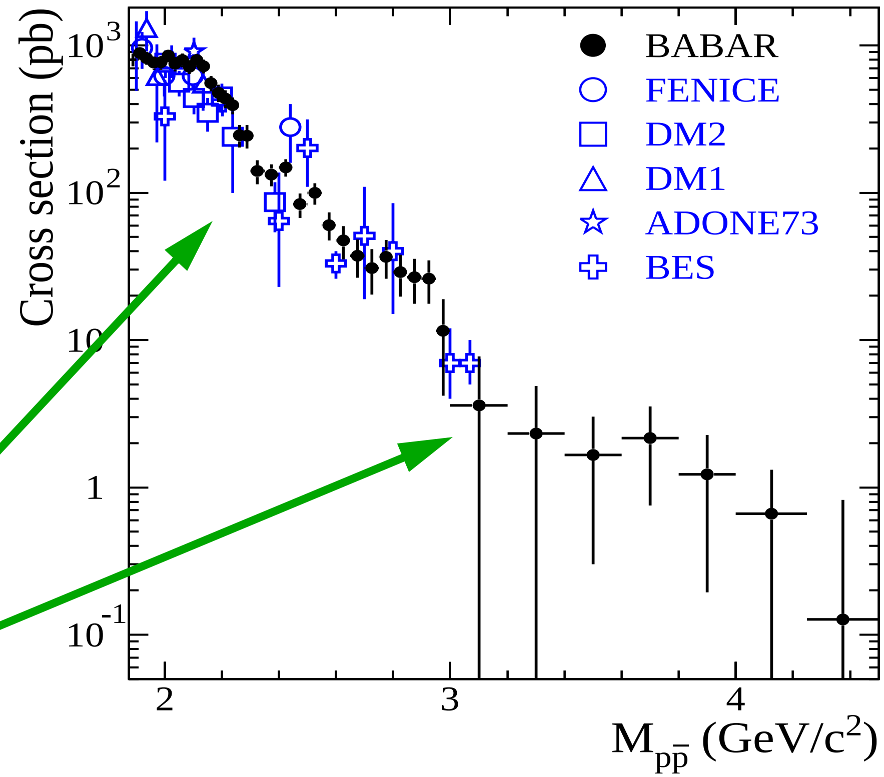
240 fb^{-1} PRD 73, 012005 (06)

- Selection:
  - $\to$ events with exactly two tracks, ID'd as p and $\bar{p}$, and a hard γ
  - $\to$ kinematic fits, imposing 4-momentum conservation
  - $\to$ select events with good $\chi^2_{p\bar{p}\gamma}$



- Evaluate and subtract backgrounds from
  - $\to$ $\pi^+\pi^-\gamma$, $K^+K^-\gamma$, using: measured cross sections, events with ID'd π,K, and $\chi^2_{KK\gamma}$, $\chi^2_{\pi\pi\gamma}$, ...
  - $\to$ $e^+e^- \to p\bar{p}\pi^0$ from MC normalized to π^0 peak in data (~6%)

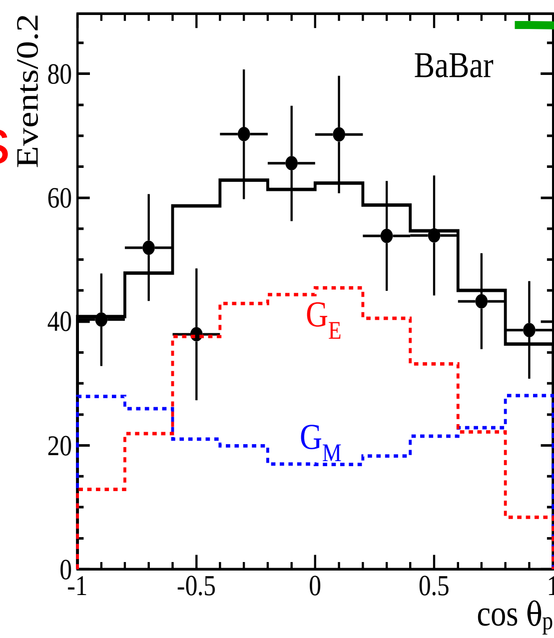
- calculate the cross section
  - → threshold to 4.5 GeV in one experiment
  - → 5→10% systematic, not shown
  - → consistent with previous results
  - → easier to see structure
  - → ...e.g. sharp drops at 2.25, 3 GeV

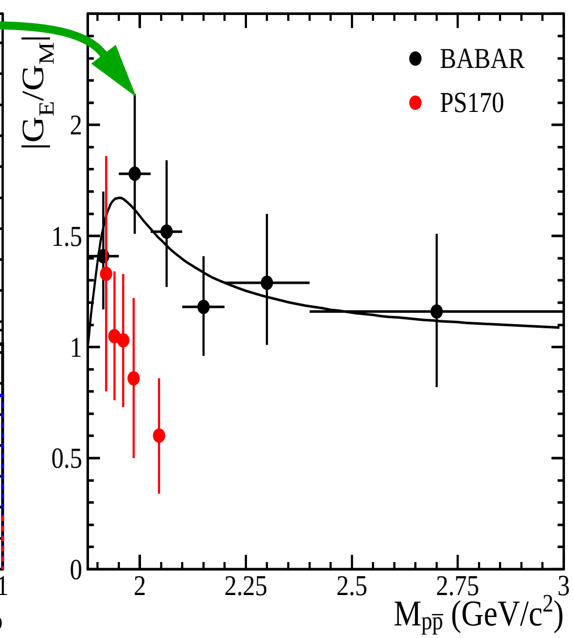


- described in terms of electric, magnetic form factors

  $\sigma(s) \propto |G_M(s)|^2 + 2m_p^2|G_E(s)|^2/s$

  - → full coverage allows separation via production angle distribution
  - → $G_E > G_M$ at low E_{CM}
  - → but consistent at high E_{CM}
  - → inconsistent with PS170





- define the effective form factor, F

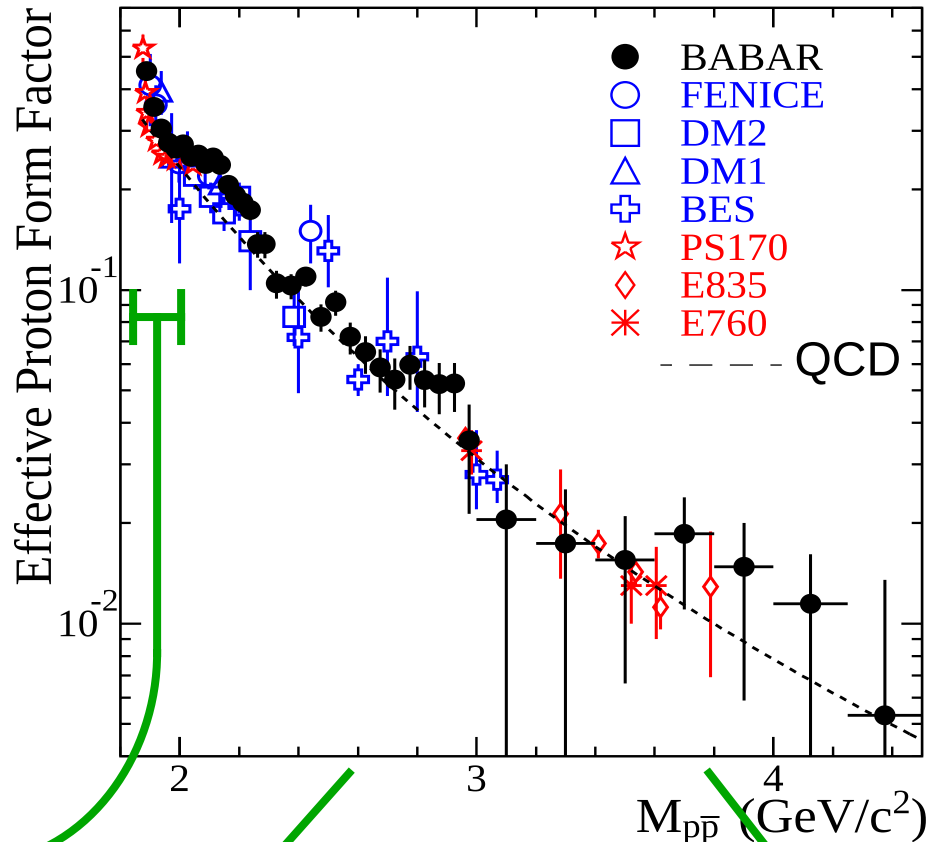
$$\sigma(s) \propto (1 + 2m_p^2/s)\,|F|^2$$

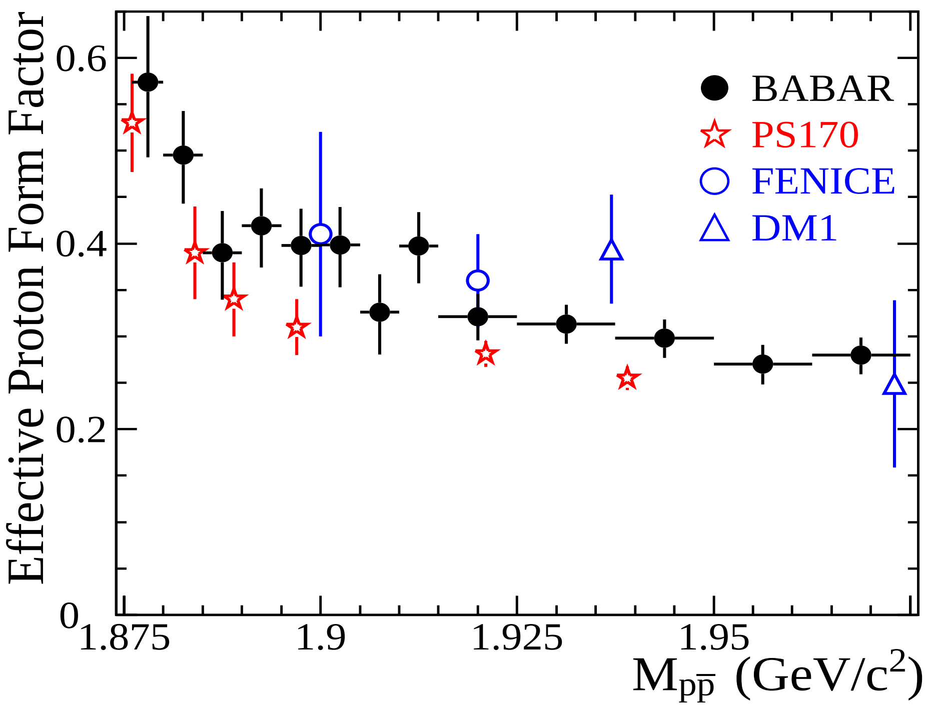
→ compare with $p\bar{p} \to e^+e^-$

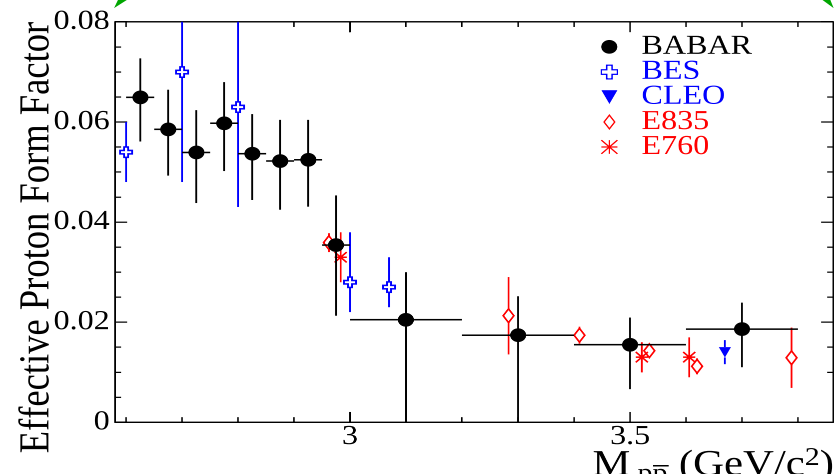
→ consistent with pQCD at high s

→ steep rise near threshold

→ ...similar to features seen in B, J/ψ decays; all need to be understood



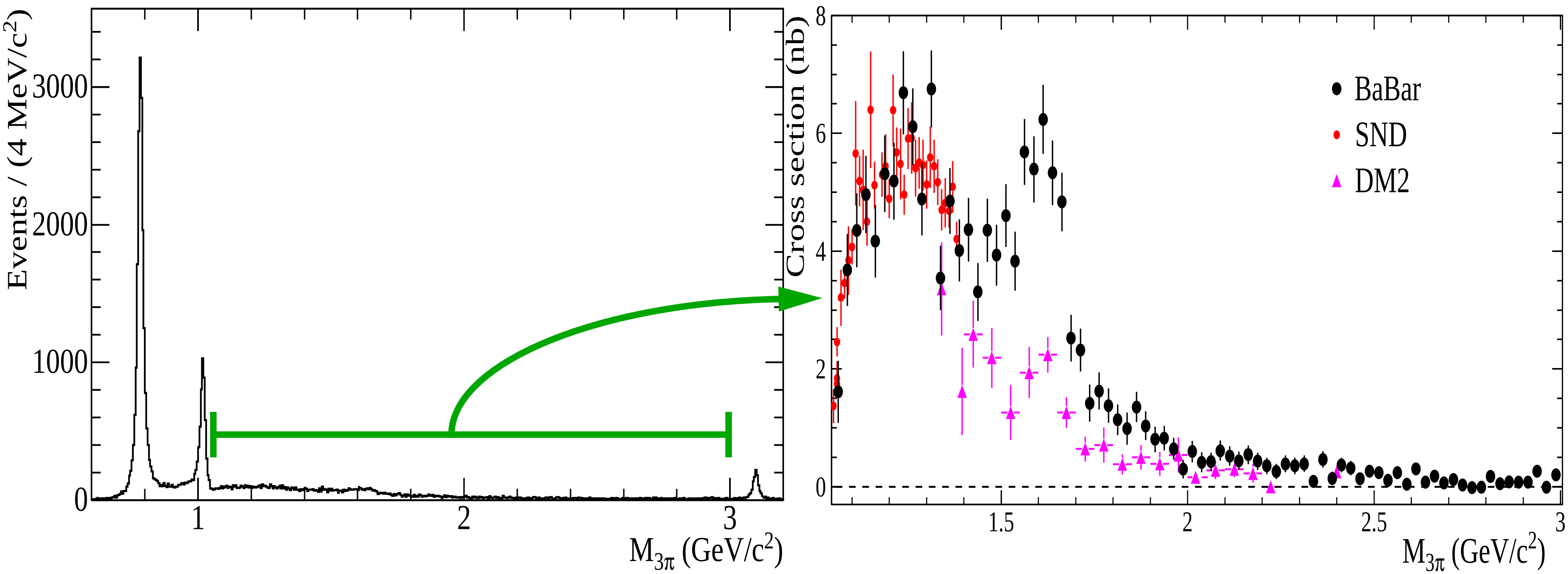




$e^+e^- \to \pi^+\pi^-\pi^0$

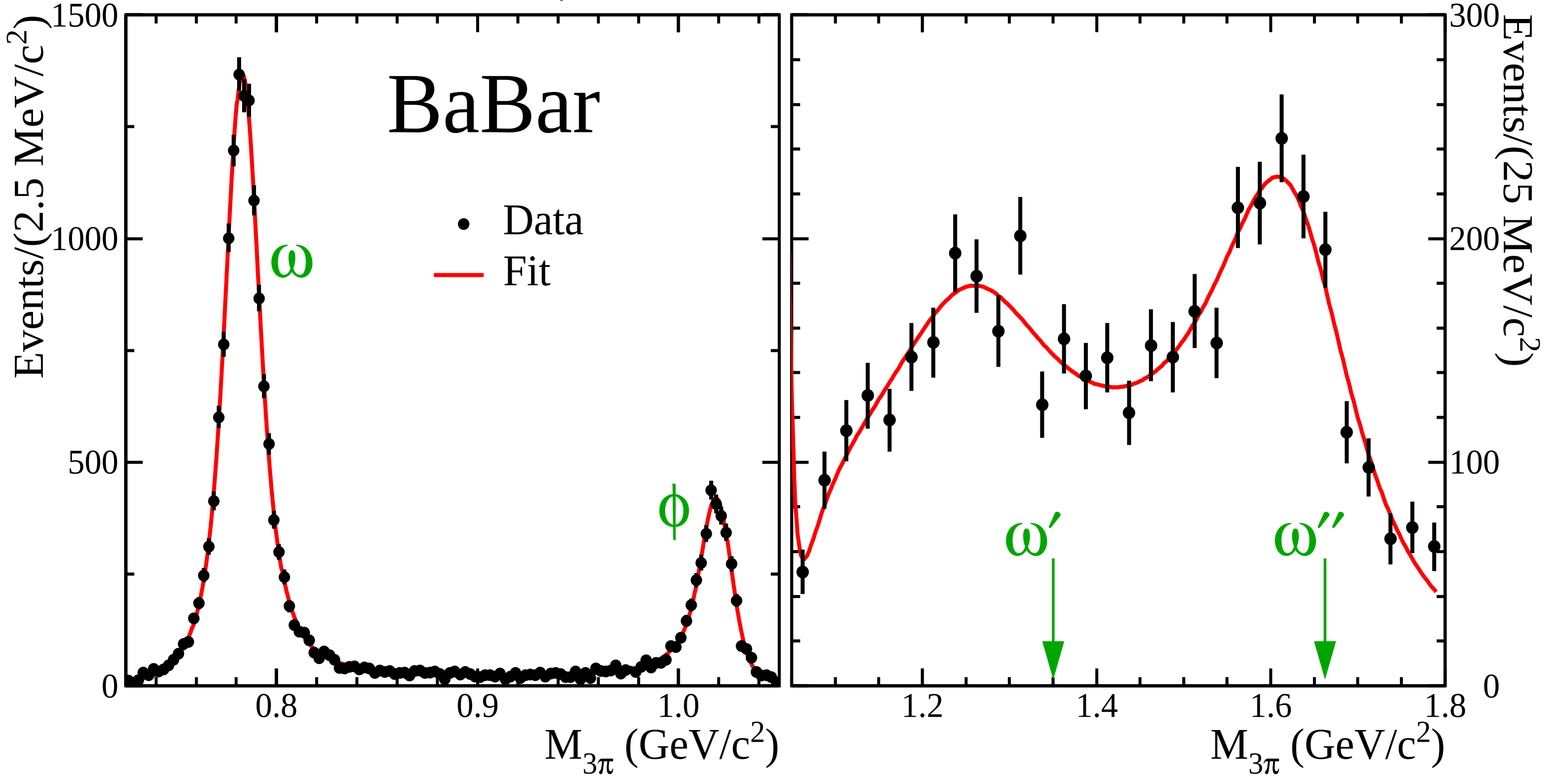
89 fb^{-1} PRD 70, 072004 (04)

- Selection:
  - → events with exactly two tracks, a hard γ, at least 2 more γ
  - → kinematic fits, including π^0 mass constraint
- Cross section



- → dominated by resonances: ω, ϕ, J/ψ, ...plus excited ω?
- → consistent with previous, precise data in ω/ϕ region
- → inconsistent with DM2 data at 1.35–2 GeV

- fit to cross section with ϕ, ω, ω′, ω″ resonances



→ "best" measurements of ω′, ω″

→ ...though relative phases must be assumed

	Mass (MeV/c²)	Γ (MeV)	$B_{ee} \times B_{3\pi}$ ($\times 10^{-6}$)	$\phi - \phi_\omega$
ω	782	8.7	67.0 ±2.8	–
ϕ	1019	4.3	43.0 ±2.2	163°
ω′	1350±28	450±98	0.82±0.08	180°
ω″	1660±10	230±36	1.30±0.14	0°

fixed to world average values

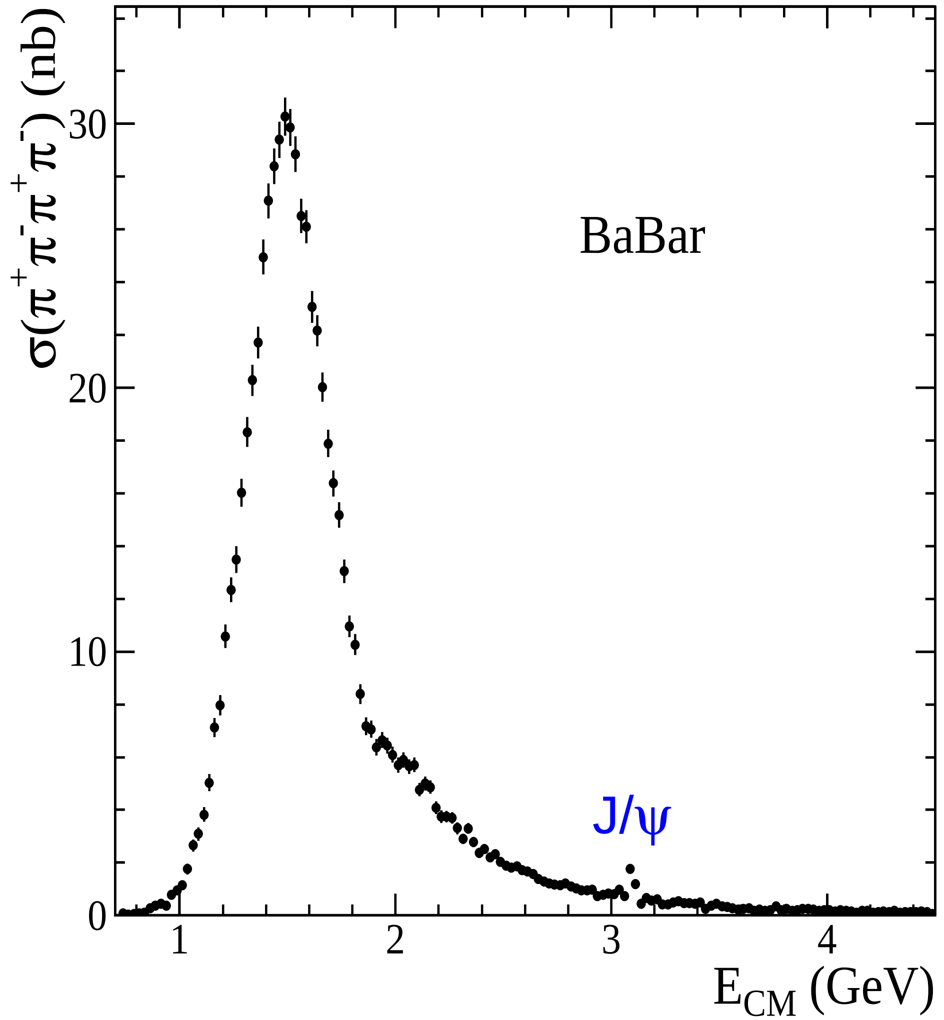
fitted

fixed to assumed values

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

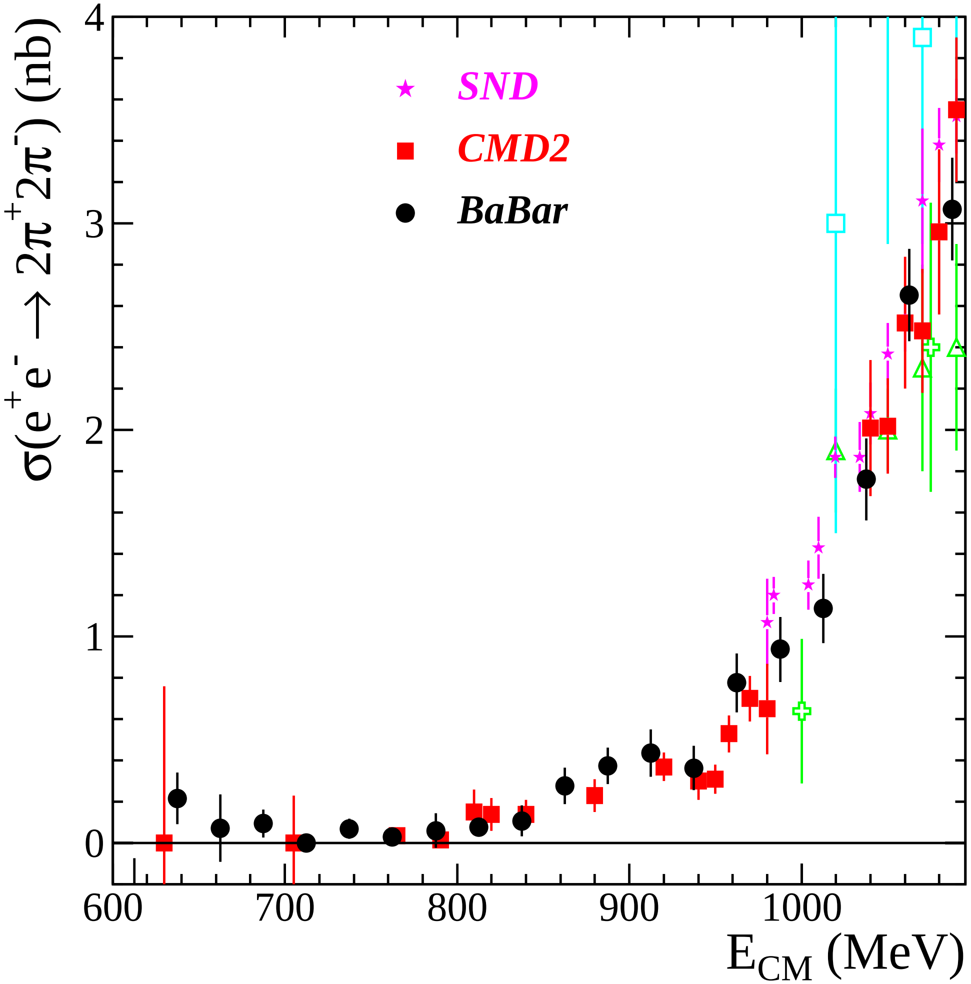
89 fb^{-1} PRD 71, 052001 (05)

- Selection: → four good tracks, a hard γ, kinematic fits
- Cross section
  - → threshold–4.5 GeV in one experiment
  - → interesting structure
  - → this represents ~half the total hadronic σ at 1.5 GeV
  - → 5% systematic over most of range improves the error on $g_\mu-2$
- Substructure
  - → main peak mostly $a_1(1260)\pi$
  - → $f_0(1370)\rho^0$ seen, could ↔ structure at ~2 GeV
  - ⇒ with more data, can study substructure in E_{CM} bins

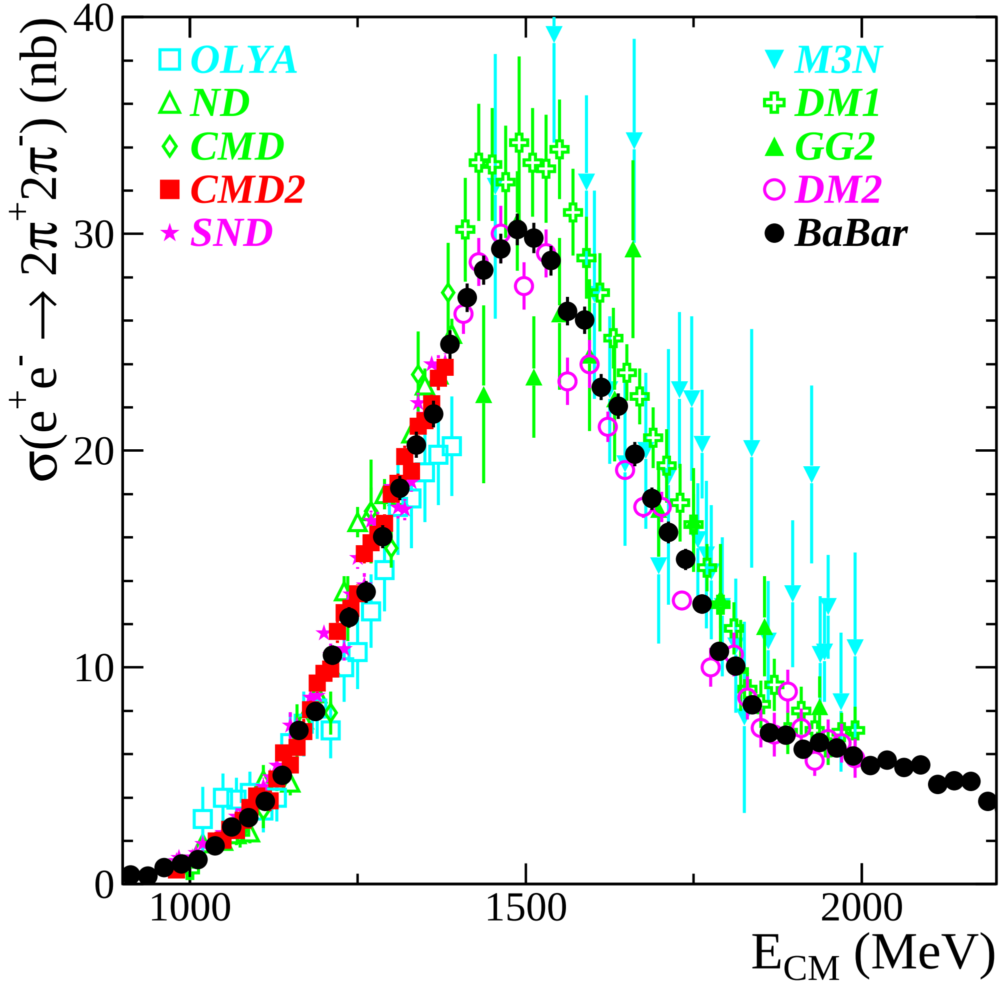


• Comparison with previous results:

near threshold



main peak



→ consistent with prev. results

→ the best measurement for E_{CM} < 0.75 GeV, 12% relative systematic error

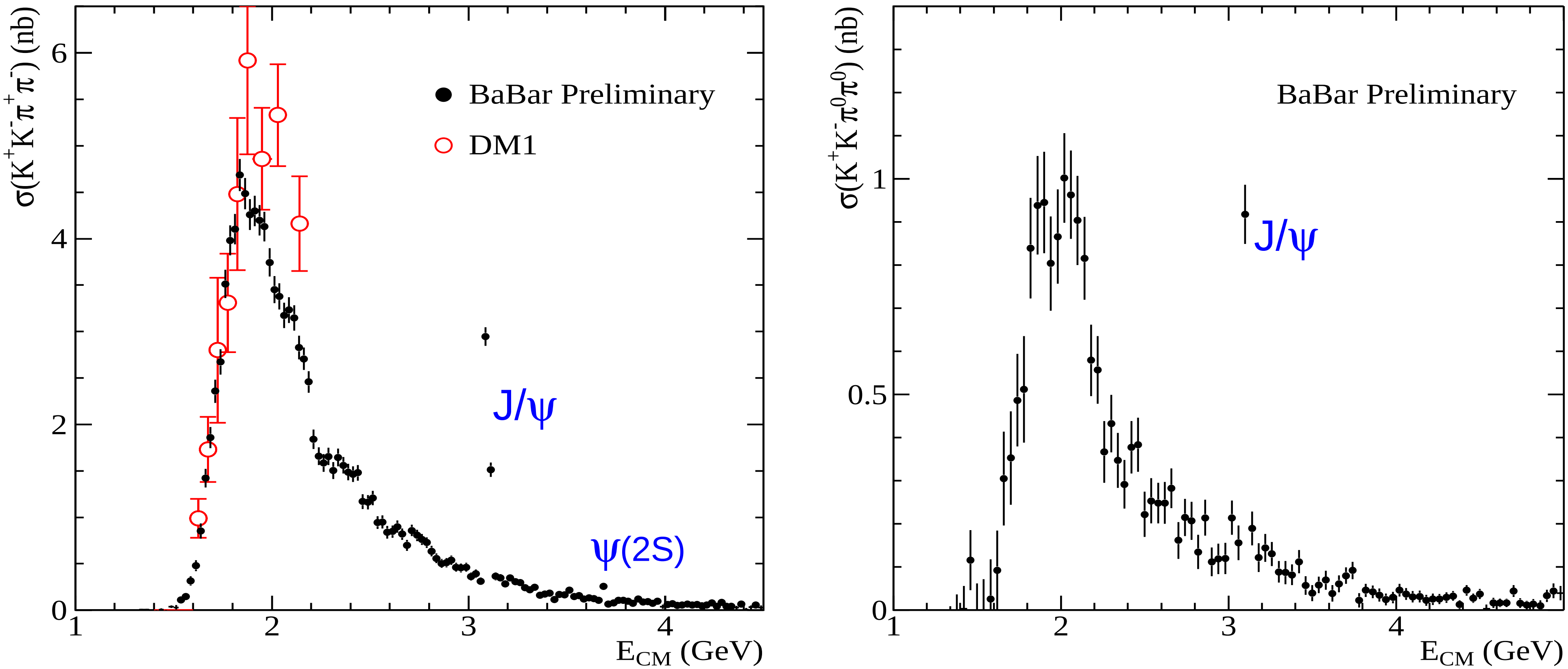
→ the best/first measurement for E_{CM} >1.4 / 2 GeV

⇒ a study of the $\pi^+\pi^-\pi^0\pi^0$ final state is in progress

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

232 fb^{-1} hep-ex/0610018, sub. to PRD-RC

- Cross sections



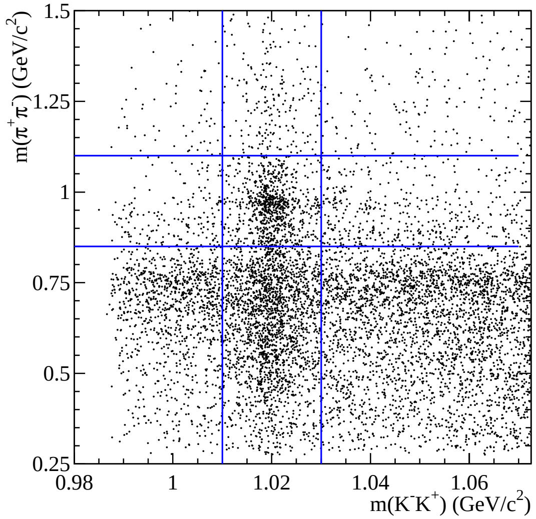
→ huge improvement for $K^+K^-\pi^+\pi^-$, first for $K^+K^-\pi^0\pi^0$

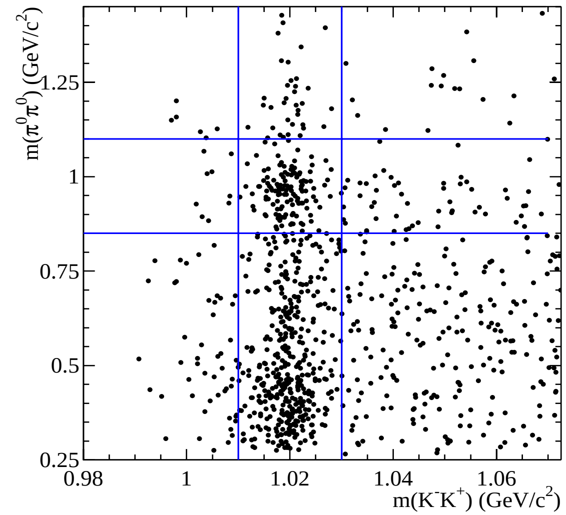
→ rich substructure dominated by $K^*(892)K\pi$, with substantial $K_1(1270)^+K^-$, $K_1(1400)^+K^-$, $\phi\pi^+\pi^-$, $\rho^0K^+K^-$, and more

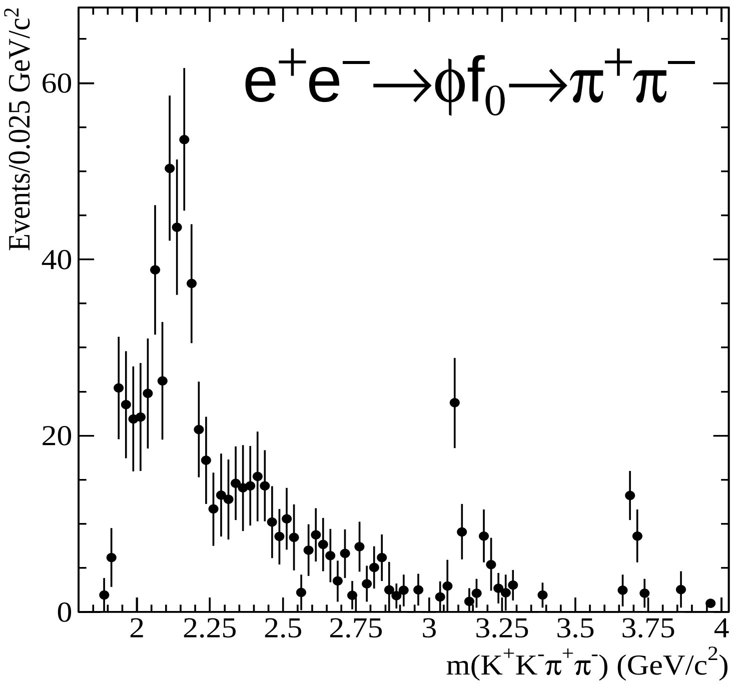
→ several hints of structure, e.g. at ~2 GeV ↔ $\phi f_0(980)$ threshold

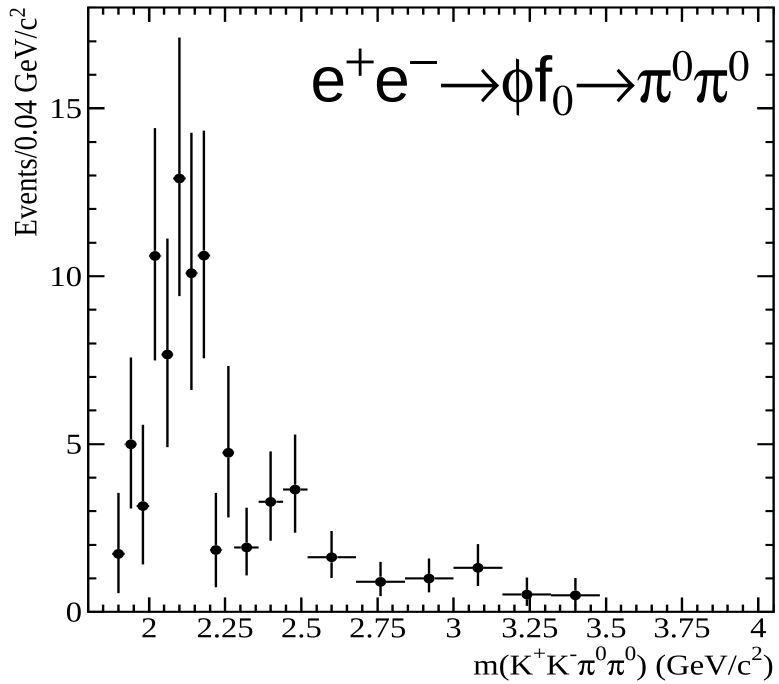
→ since ϕ, $f_0(980)$ are both narrow, this submode can be studied...

- The $\phi f_0(980)$ submode:
  - → visible in m_{KK} vs. $m_{\pi\pi}$ scatter plots
  - → extract yield by fitting the m_{KK} distribution in each E_{CM} bin in a $m_{\pi\pi}$ slice around the f_0 mass









  - → background from $\phi\pi\pi$ <10%
  - → threshold behavior inconsistent with a typical, smooth function

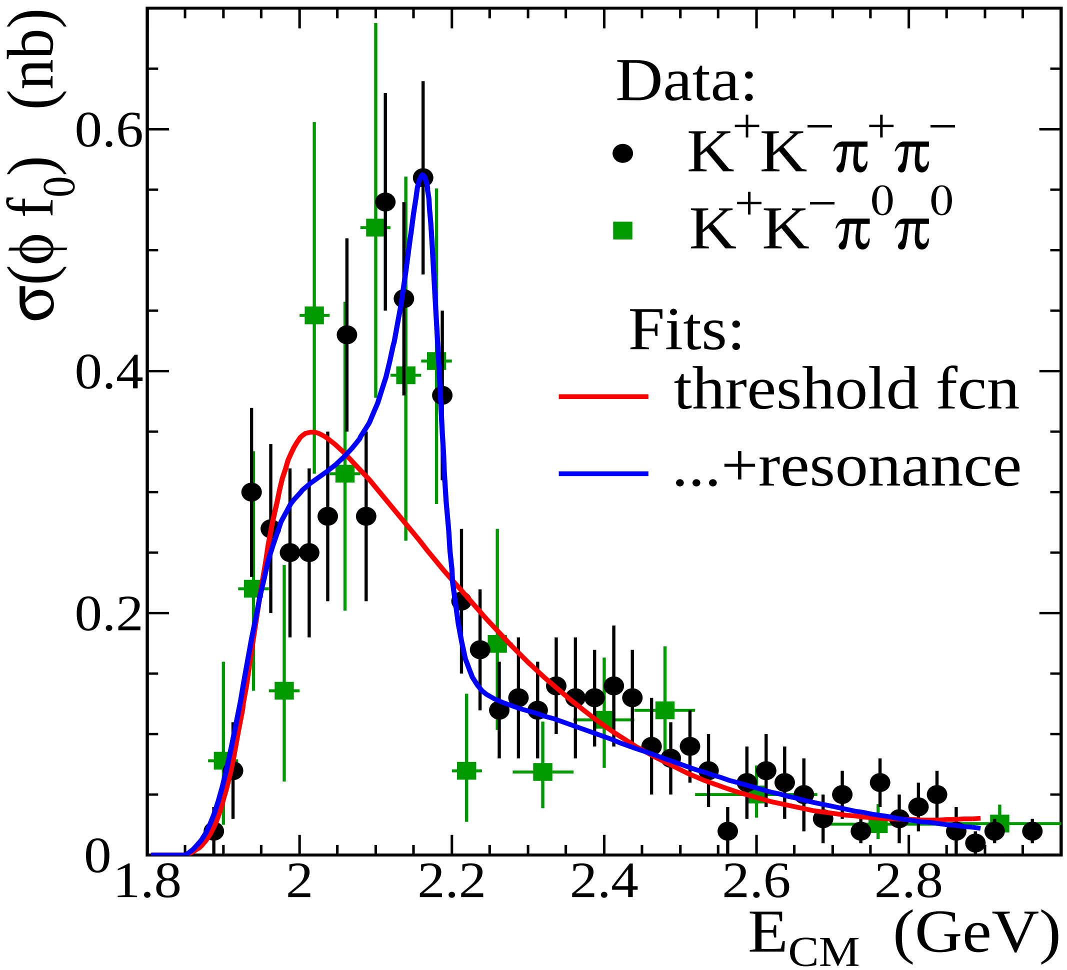
- Convert to cross sections
  - → behavior near threshold unchanged
  - → $\pi^+\pi^-$ and $\pi^0\pi^0$ modes give consistent results
  - → can be described by adding a resonance; a fit yields:

    m = 2175±18 MeV/c^2

    Γ = 58±26 MeV

    φ = –36±56° wrt non-res

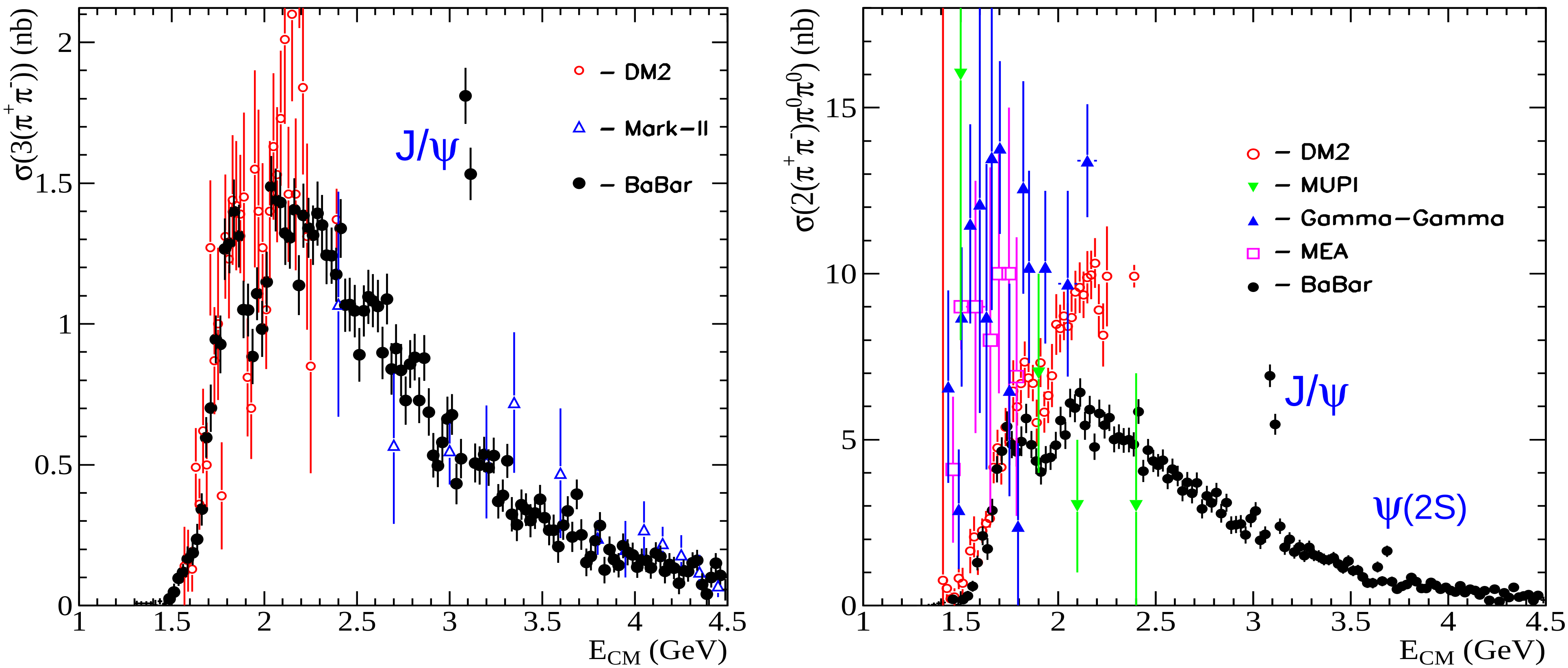
    5.6σ significance



- → very interesting mass region, just below $\Lambda\bar{\Lambda}$ threshold
- → is this a new state?
- → is it analogous to the Y(4260)?
- → need more data, other modes to understand structure in detail

$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-,\ \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$ 232 fb^{-1} PRD 73, 052003 (06)

- Cross sections



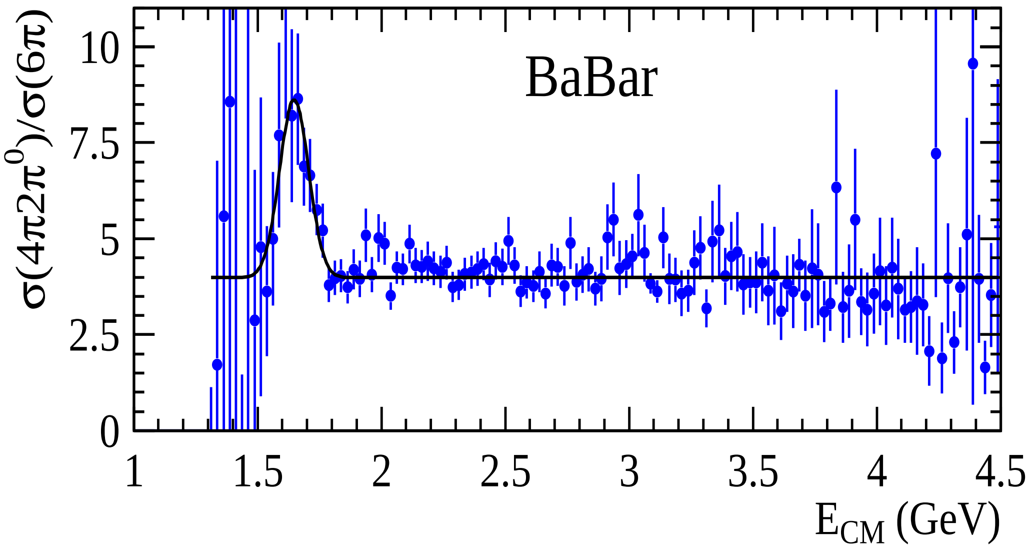
→ large improvements in both measurements

→ dips at ~1950 MeV confirmed; also seen by FOCUS

→ the 6-charged mode has very little substructure, ~1ρ^0 per event

→ ...but the 4-charged mode has a rich substructure, including $\omega\eta$, $\omega\pi^+\pi^-\pi^0$, $\eta\pi^+\pi^-\pi^0$ submodes, signals for $\rho^\pm$, ρ^0, $f_0(980)$, ...

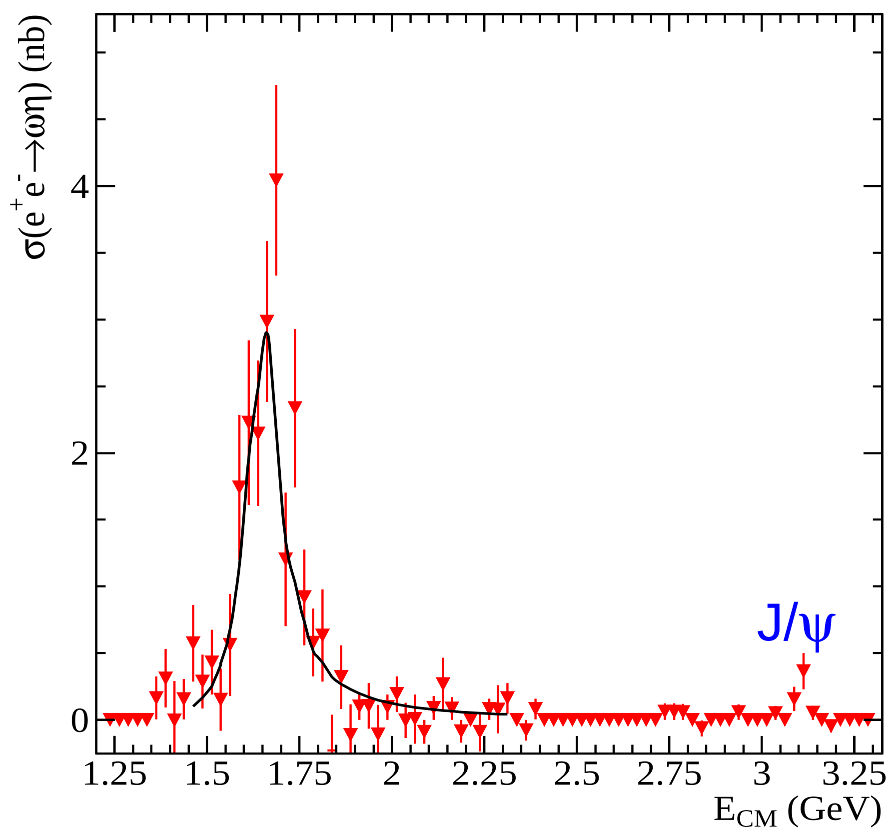
- The $2(\pi^+\pi^-)\pi^0\pi^0:3(\pi^+\pi^-)$ ratio
  - → is flat and ...
  - → =4 except where the ωη submode contributes
  - → a challenge to understand
  - → will keep studying, do a coupled-channel analysis



- The ωη submode
  - → is easy to isolate, use sidebands to subtract background
  - → the cross section is dominated by two resonances, J/ψ and something with

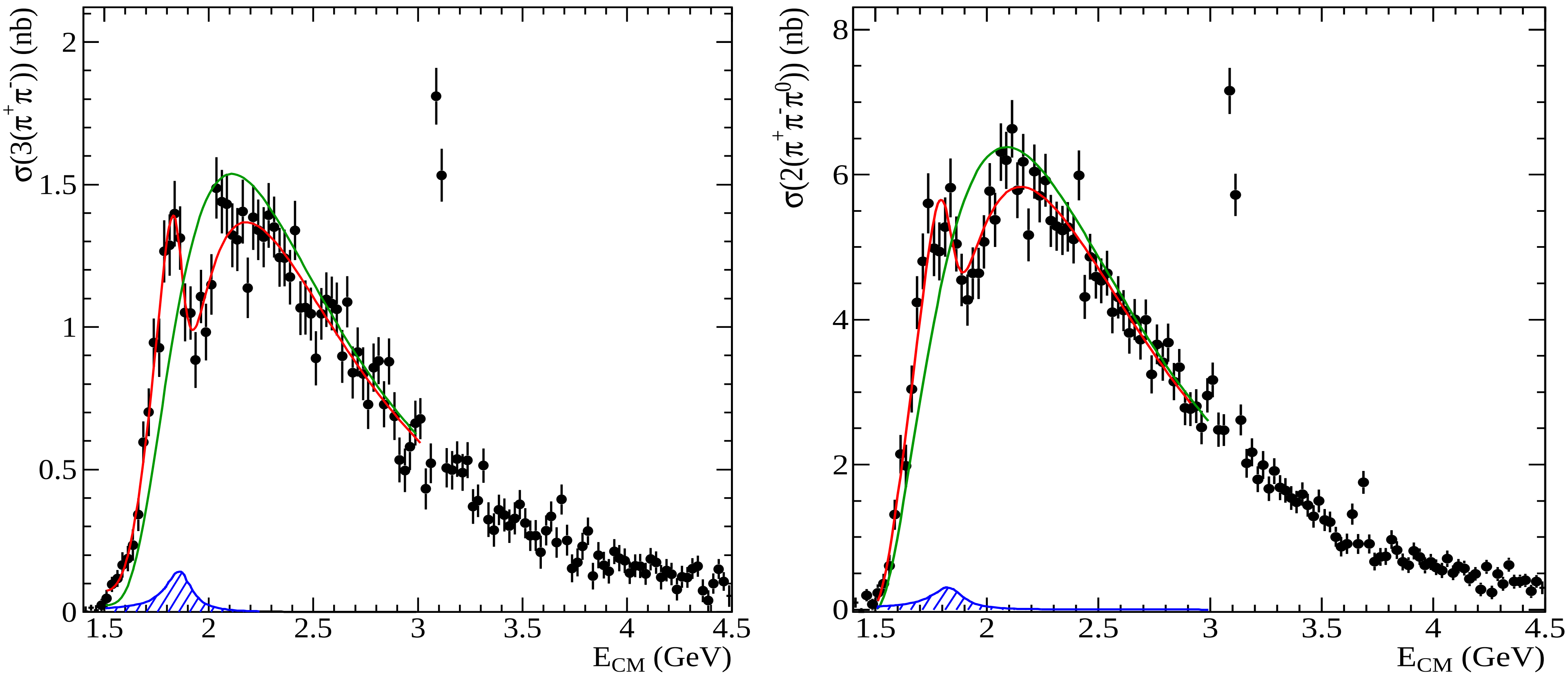
    $m = 1645 \pm 8\ \mathrm{MeV}/c^2$

    $\Gamma = 114 \pm 14\ \mathrm{MeV}$
  - ⇒ is it the ω(1650)? (Γ=315) ...or the φ(1680)? ...or something new...?



- What is causing the dip at 1950 MeV?

  → we don't know, so let's fit a resonance



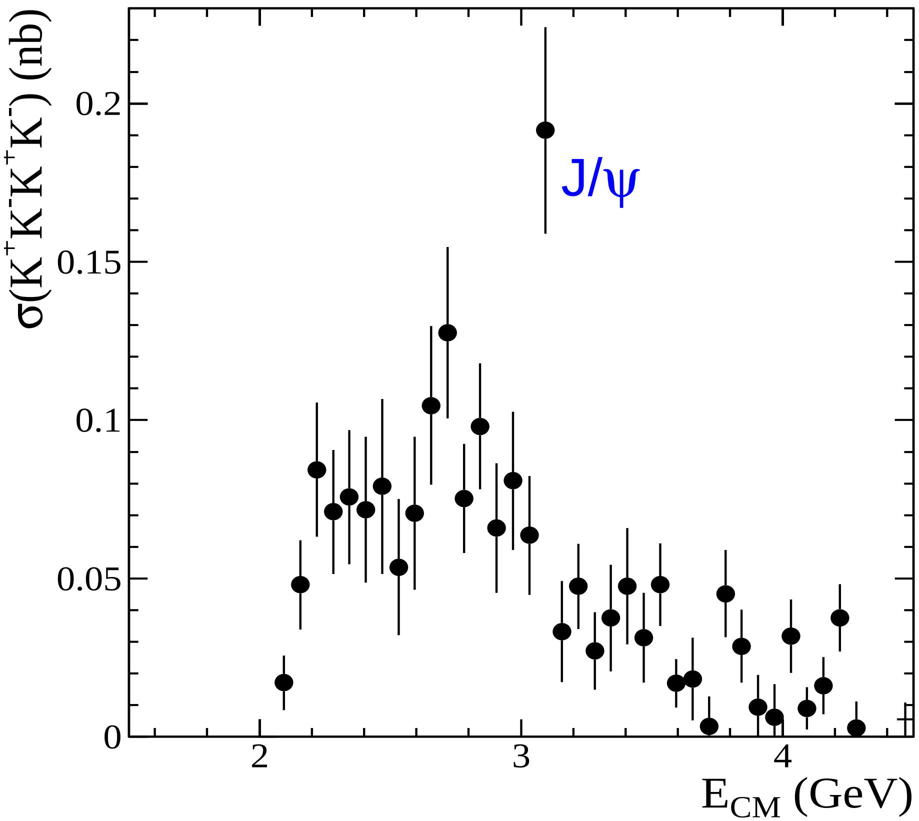
→ fitted parameter values for our two modes are consistent

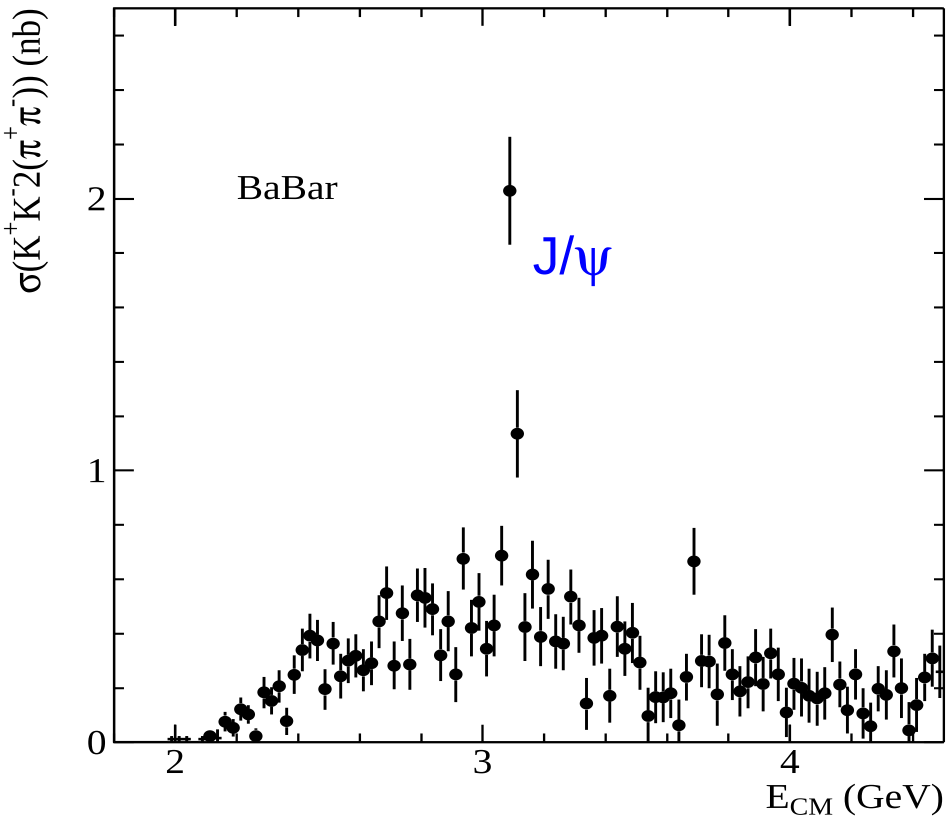
→ combined:
$m = 1870 \pm 20$ MeV/c^2, $\Gamma = 150 \pm 20$ MeV, $\delta\phi = 9 \pm 15°$

→ the width is significantly larger than seen by FOCUS,
$m = 1910 \pm 10$ MeV/c^2, $\Gamma = 37 \pm 13$ MeV

$e^+e^- \to K^+K^-K^+K^-$ 89 fb^{-1} PRD 71, 052001 (05)
$e^+e^- \to K^+K^-\pi^+\pi^-\pi^+\pi^-$ 232 fb^{-1} PRD 73, 052003 (06)

- Cross sections





→ first measurements

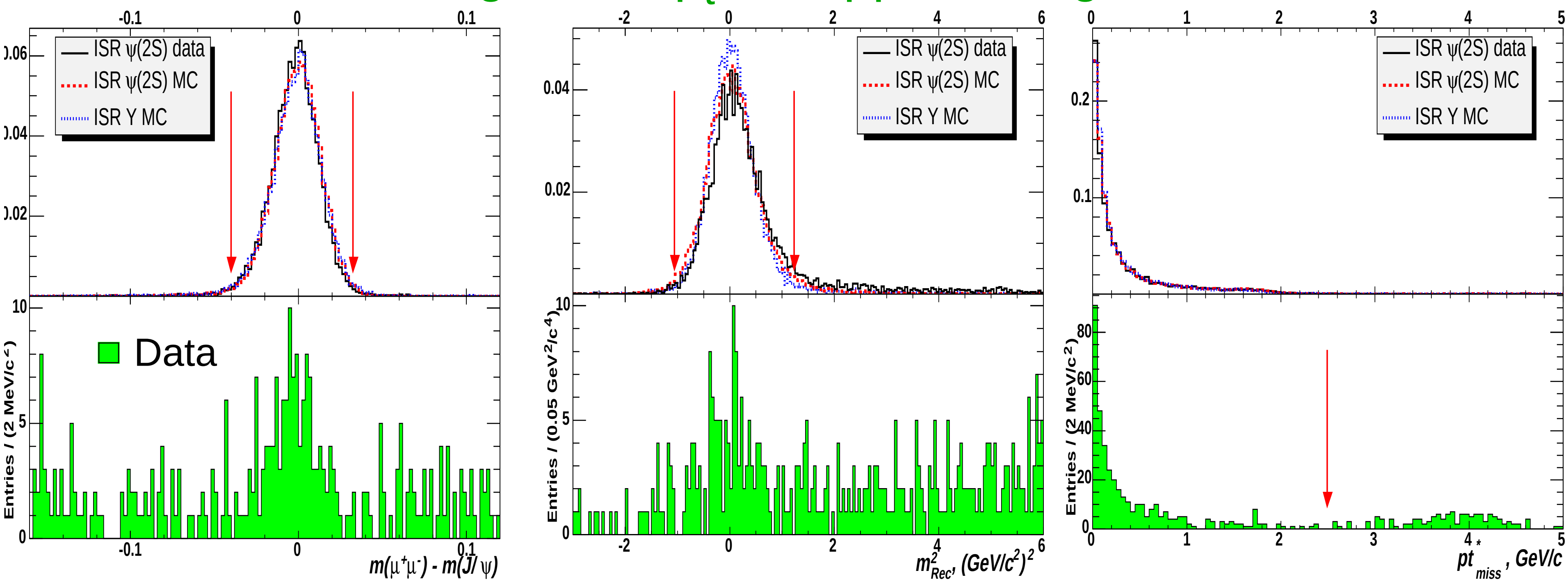
→ the $K^+K^-K^+K^-$ mode has a strong ϕ, but no other substructure

→ the $K^+K^-\pi^+\pi^-\pi^+\pi^-$ mode has a complex substructure with a strong K*(890), but a weak ϕ

$e^+e^- \to J/\psi\pi^+\pi^-$

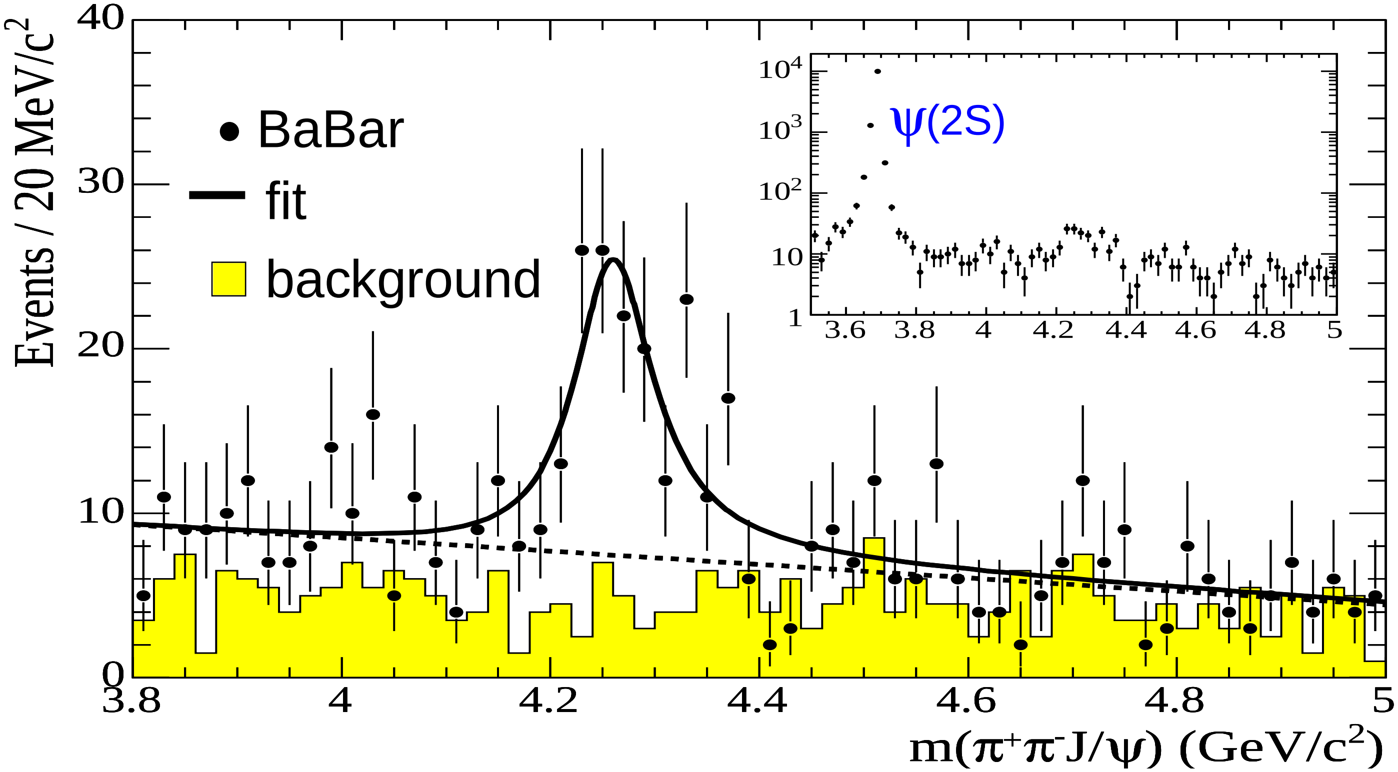
233 fb^{-1} PRL 95, 142001 (05)

- Selection: see talk by S.Ye, Hadron Spectroscopy
  - → ID'd e^+e^- or $\mu^+\mu^-$ pair, ID'd $\pi^+\pi^-$ pair, no more tracks
  - → **NO**, hard γ required as J/ψ signal is fairly clean
  - → use prominent $\psi(2S)$ signal to choose cuts, evaluate efficiency
  - → also use missing mass, p_t to suppress bkgs



- Evaluate backgrounds from
  - → all non-J/ψ sources using events with $m_{ee,\mu\mu}$ in J/ψ sidebands
  - → $J/\psi X$ sources from missing mass, p_t (very small)

- E_{CM} distribution of selected events
  - → is there non-resonant production? → inconclusive
  - → do heavy ψ states decay this way? → inconclusive
  - → are there new (charmonium) state(s) → yes! (maybe)



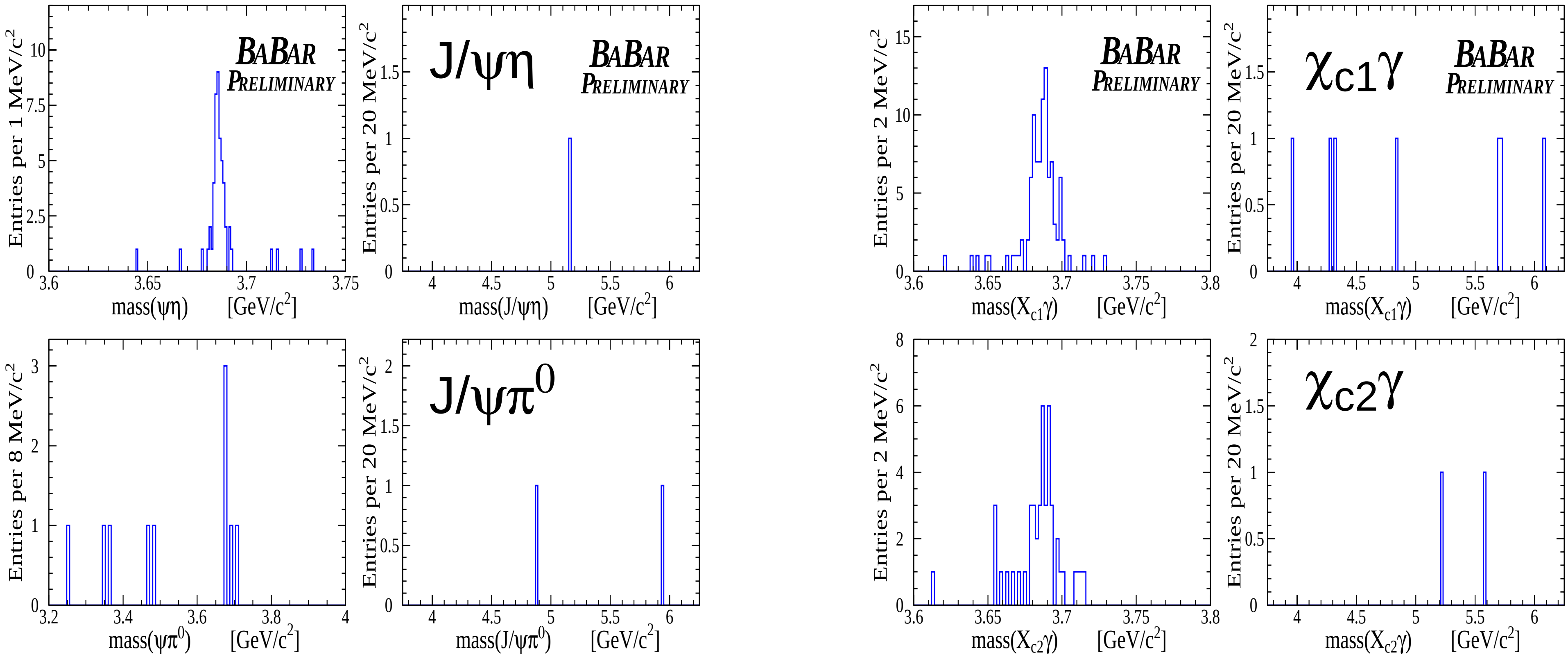
⇒ single resonance: M~4260 MeV/c^2, Γ~90 MeV

⇒ such a wide state above $D\bar{D}$ threshold shouldn't decay to J/ψππ

⇒ there is a dip in R at this energy...

⇒ is there is more than one state? What are they?

- Further studies of the Y(4260)
  - → searches in B decays → inconclusive PRD 73, 011101 (06)
  - → ISR studies of $J/\psi\gamma\gamma$ → no signal hep-ex/0608004

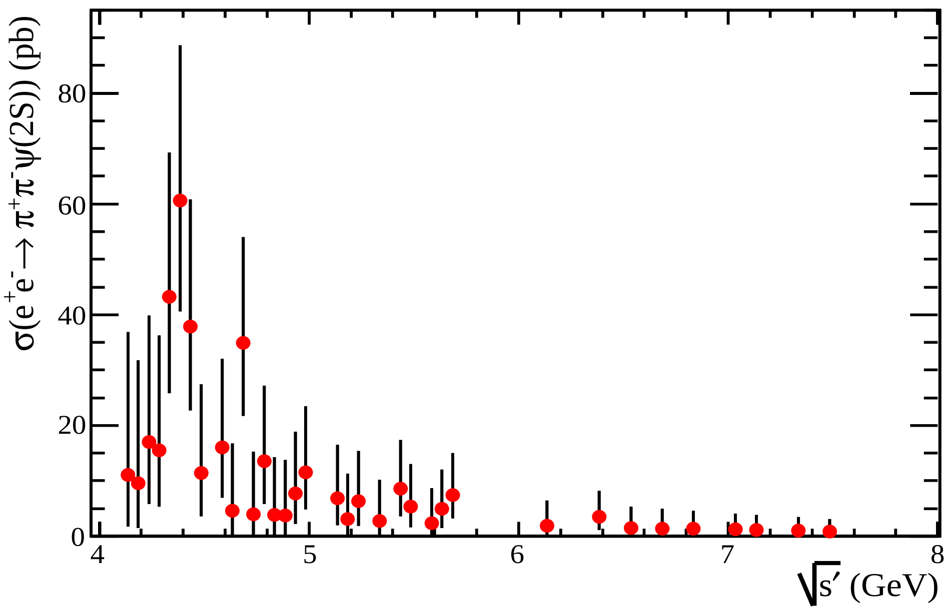


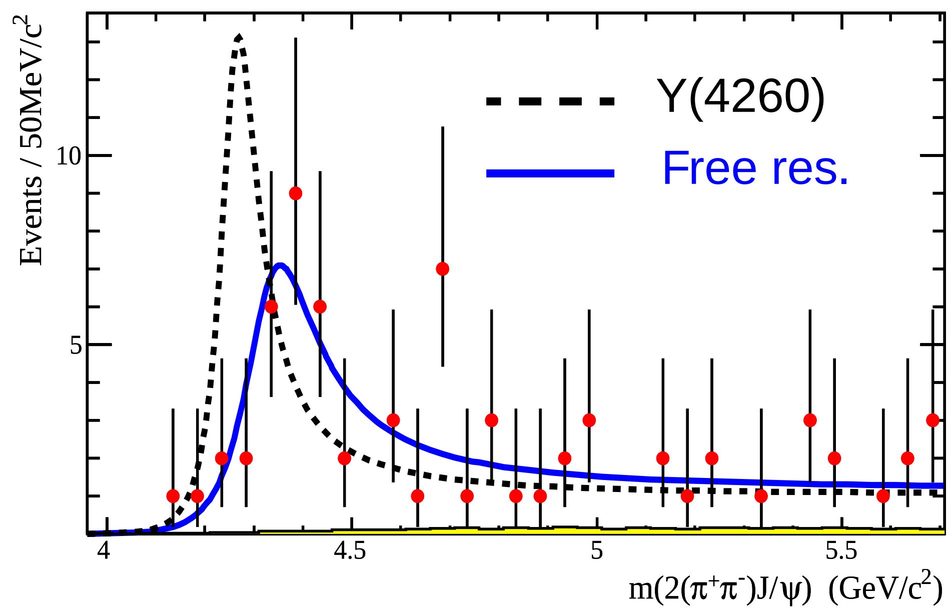
  - → ISR studies of $D\overline{D}$ → no signal hep-ex/0607083
  - → all above ISR modes (e.g. $\phi\pi\pi$, $p\overline{p}$) → no signal
  - → several more studies in progress

$e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$

298 fb^{-1} hep-ex/0610057 submitted to PRL

- Selection:
  - → Rec'd $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ candidate, ID'd $\pi^+\pi^-$ pair, no more tracks, no π^0 or η candidates
  - → **NO**, hard γ required as the $\psi(2S)$ signal is very clean
  - → cuts on missing mass and p_t, lepton helicity angle
- Yield and cross section





→ interesting structure near threshold...

→ ...but it's NOT the Y(4260) M~4325 MeV/c^2, Γ~170 MeV

⇒ this is fun! And there's more fun to come...

J/ψ and ψ(2S) Branching Fractions

- Observed in all/many of the above studies:
  $\rightarrow$ measure BF($\psi \rightarrow f$)$\times\Gamma_{ee}$, use PDG Γ_{ee} to obtain

Mode	BaBar BF (%)	PDG 2004	Other since 2004
$J/\psi \rightarrow p\bar{p}$	0.222±0.016	0.217±0.008	
$J/\psi \rightarrow \pi^+\pi^-\pi^0$	2.18 ±0.19	1.50 ±0.20	2.09 ±0.12 BES
$J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-$	0.361±0.037	0.40 ±0.10	0.353±0.031 BES
$J/\psi \rightarrow K^+K^-\pi^+\pi^-$	0.609±0.073	0.720±0.230	
$\phi\pi^+\pi^-$	0.098±0.013	0.080±0.012	0.109±0.013 BES
$\phi\pi^0\pi^0$	0.585±0.162	–	
$J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	0.440±0.041	0.40 ±0.20	
$J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	1.65 ±0.21	–	
$\omega\pi^+\pi^-\pi^0$	0.40 ±0.07	–	
$\omega\eta$	0.147±0.044	0.158±0.016	0.235±0.027 BES
$J/\psi \rightarrow K^+K^-K^+K^-$	0.67 ±0.14	–	
$J/\psi \rightarrow K^+K^-\pi^+\pi^-\pi^+\pi^-$	0.509±0.055	0.31 ±0.13	
$\phi\pi^+\pi^-\pi^+\pi^-$	0.177±0.037	0.160±0.032	
$\psi(2S) \rightarrow p\bar{p}$	0.033±0.009	0.0236±0.0024	
$\psi(2S) \rightarrow \phi\pi^+\pi^-$	0.027±0.011	0.0150±0.0028	
$\psi(2S) \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	0.53 ±0.17	–	
$\psi(2S) \rightarrow K^+K^-\pi^+\pi^-\pi^+\pi^-$	0.21 ±0.10	–	

useful
competitive
best
dominant

Summary

- The very high luminosity of the B factories has (re)opened several interesting areas of elementary particle physics
- At BaBar we have exploited initial state radiation to
  - $\rightarrow$ study e^+e^- annihilations at E_{CM} from threshold to ~5 GeV
  - $\rightarrow$ improve our knowlege of R, g_μ–2, $\alpha(M_Z)$
  - $\rightarrow$ improve spectroscopy of ω states
  - $\rightarrow$ study proton form factors, find $G_E > G_M$ at low E_{CM}
  - $\rightarrow$ discover new states/structures at m~2175, 4260, 4400 MeV
  - $\rightarrow$ improve measurement of an ω/ϕ state at 1645 MeV
- In the future, many new, improved studies planned
  - $\rightarrow$ update current results with full data set
  - $\rightarrow$ additional exclusive modes under study or consideration
  - $\rightarrow$ in particular, hope to reach 1% uncertainty on $e^+e^- \rightarrow \pi^+\pi^-$
  - $\rightarrow$ inclusive measurements