$e^+e^- \rightarrow$ hadrons Cross Sections at BaBar

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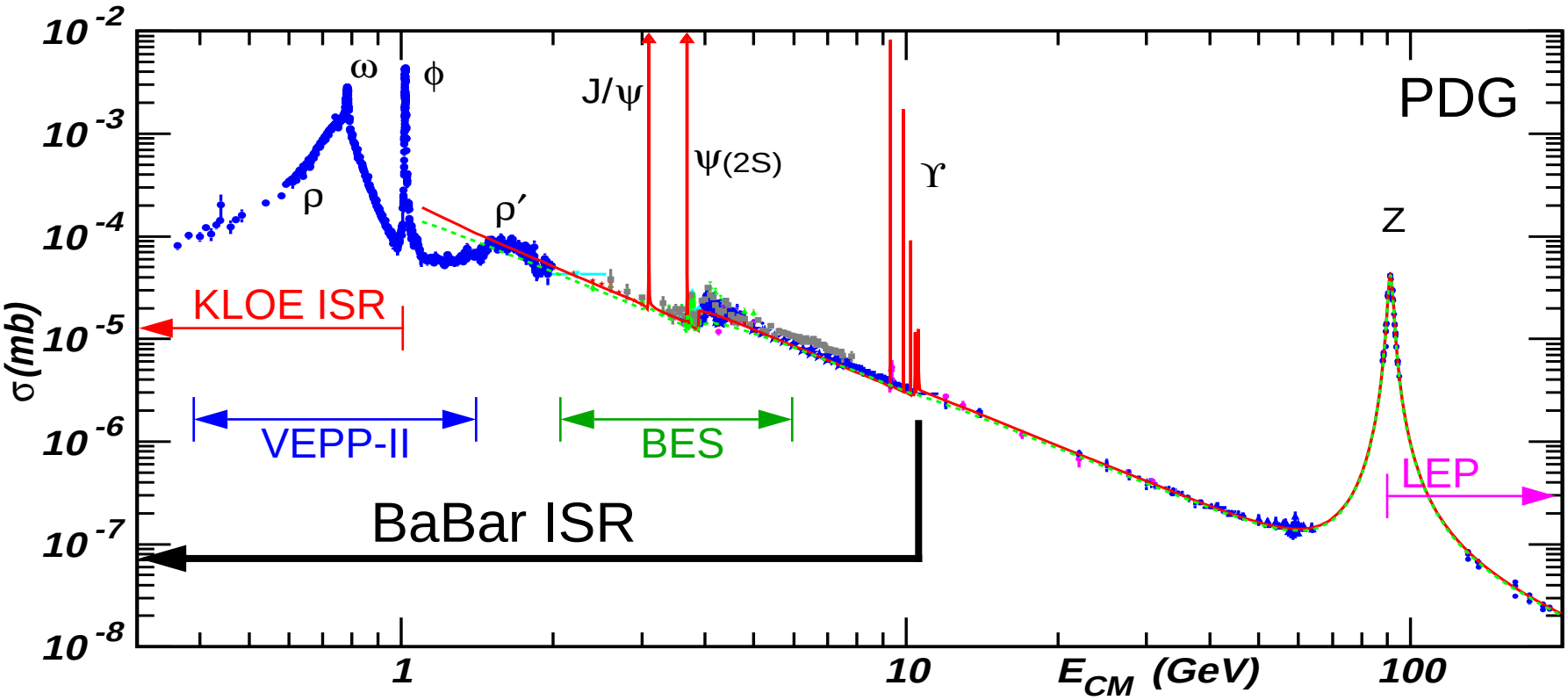
Representing the BaBar Collaboration

- **Introduction**
- **Exclusive Reactions at E_{CM} = 10.6 GeV**
- **Exclusive Reactions at Low E_{CM} via Radiative Return (ISR)**
- **Inclusive ISR Measurement at Low/Medium E_{CM}**
- **Summary**

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



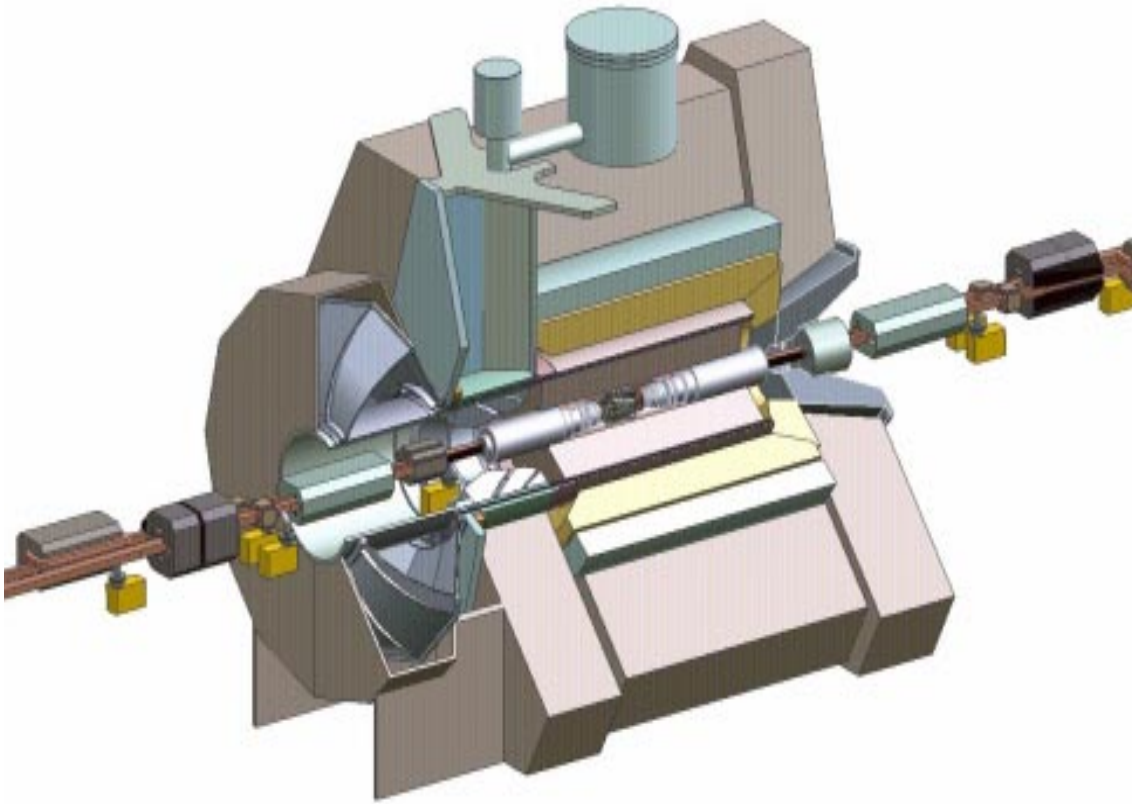
- Low E_{CM}: resonances, quasi-2-,3-body reactions, ...
  $\rightarrow$ lots of physics: spectroscopy, form factors, QCD tests, ...
- Also near $c\bar{c}$, $b\bar{b}$ thresholds (and the Z^0)
- High E_{CM}: perturbative QCD; $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}(g) \rightarrow$ jets
  $\rightarrow$ QCD predicts E_{CM} dependence of "rare" few-body processes
- Theoretical $g_\mu - 2$, $\alpha(M_Z)$ need integral, better data for E_{CM}<10 GeV

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



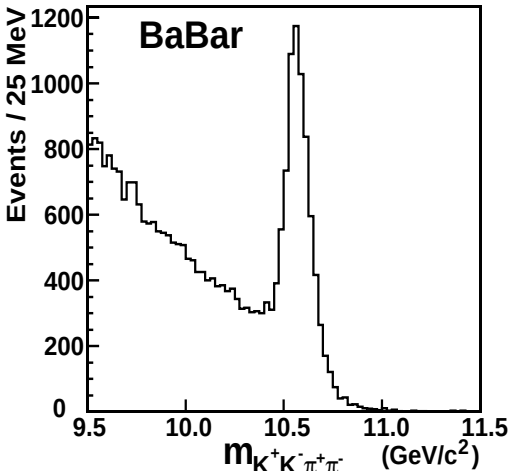
- with excellent performance
  - → Good tracking, mass resolution
  - → Good γ, π^0 recon.
  - → Full e,μ,π,K,p ID

- High luminosity:
  - → ~ 460 fb^{-1} accumulated
    - ↔ 1.6 billion $e^+e^- \to q\bar{q}$ evts
    - ↔ 15 million $e^+e^- \to \gamma_{ISR}J/\psi$
    - ↔ 11 million $e^+e^- \to \gamma_{ISR}\rho^0$
  - → 89–379 fb^{-1} used here

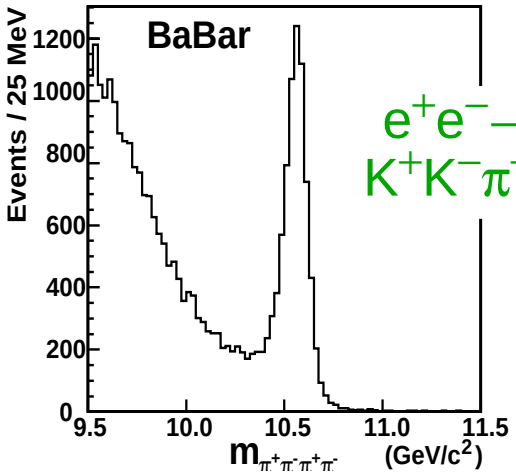
Exclusive reactions at 10.6 GeV

- Select events with a specific set of
  → identified charged tracks → well measured photons
  → reconstructed π^0
- Look at their combined invariant mass, momentum, etc.

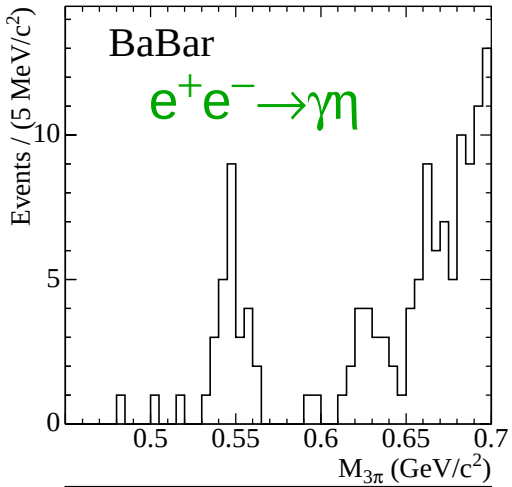
$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$



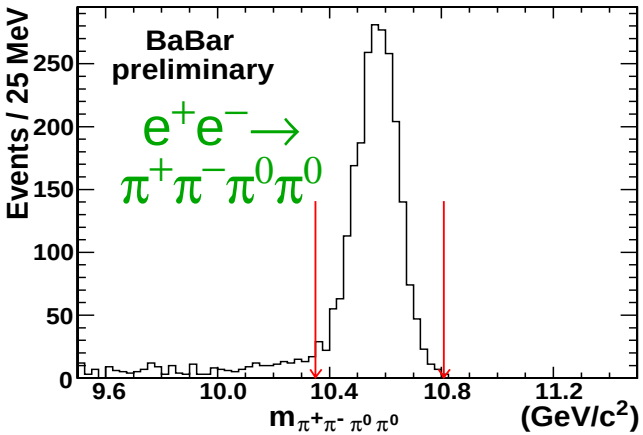
$e^+e^- \to K^+K^-\pi^+\pi^-$



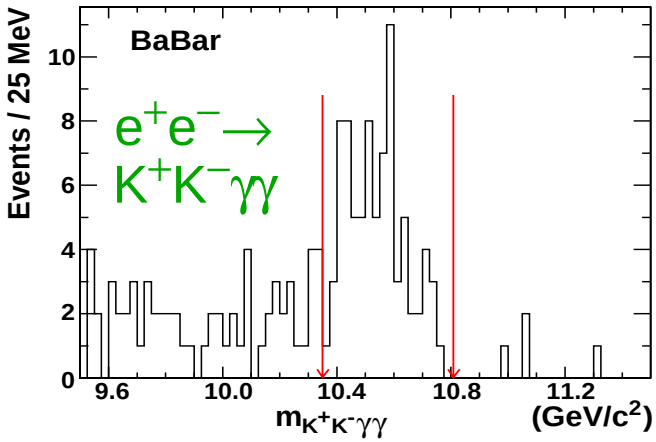
$e^+e^- \to \gamma\eta$



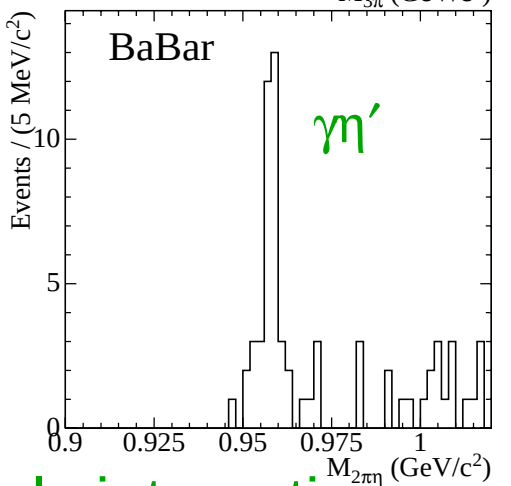
$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$



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



η'



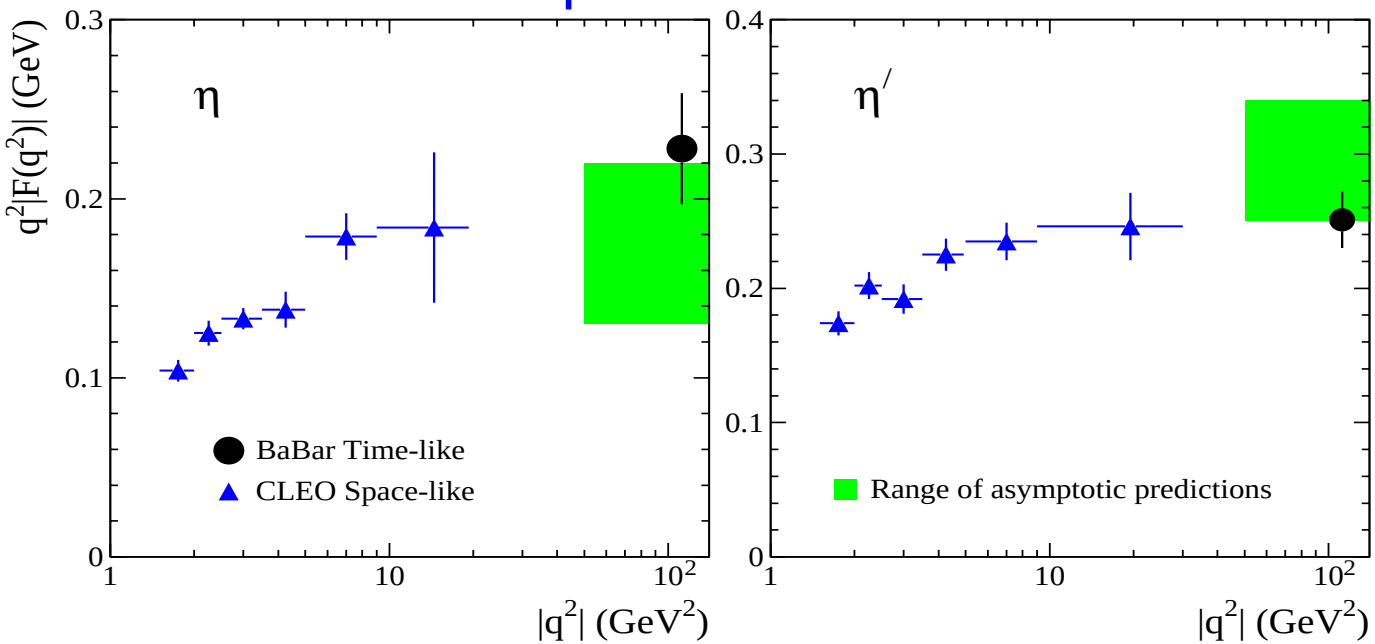
→ clean signals for several modes ... each uniquely interesting ...

η and η′ Transition Form Factors

232 fb^{-1}, PRD 74, 012002 (06)

- The cross section for $e^+e^- \to \gamma^* \to \eta^{(\prime)}\gamma$ is related to a TFF
  - → QCD prediction for asymptotic value
  - → model predictions for s dependence at low s

- Our time-like vs. CLEO space-like measurements

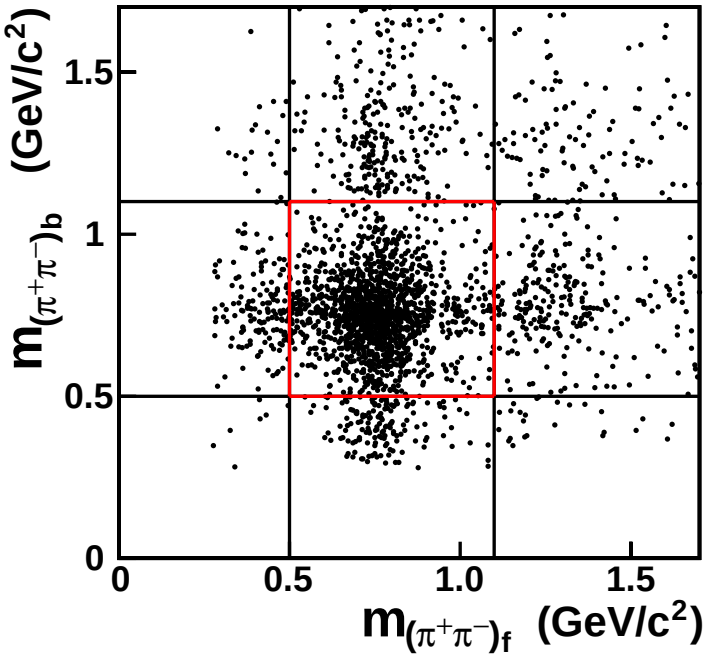


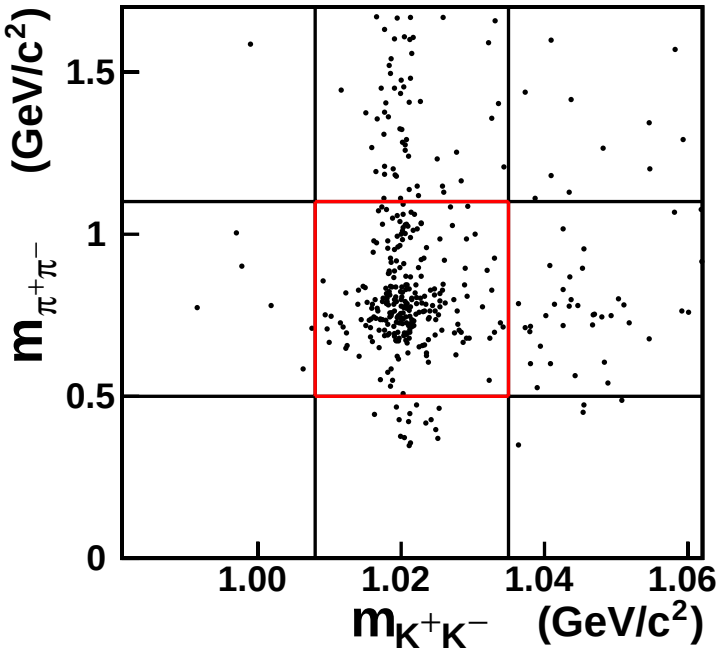
  - → consistent with approach to asymptotic regime
  - → and with model predictions ... which depend on η-η′ mixing ...
  - → ...but ratio is not (very) consistent ...
  - ⇒ more theoretical, experimental input needed

Two-Virtual-Photon Annihilation

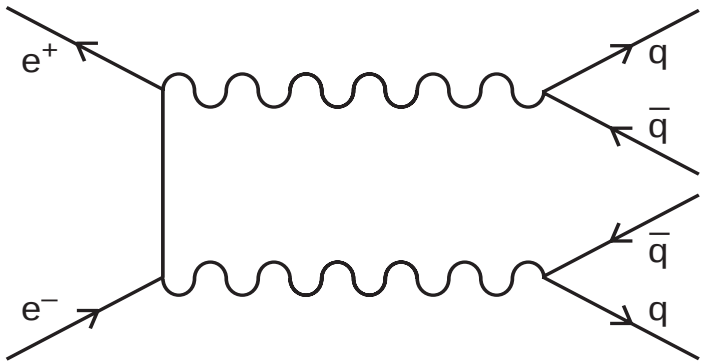
225 fb^{-1}, PRL 97, 112002 (06)

- The $\pi^+\pi^-\pi^+\pi^-$ and $K^+K^-\pi^+\pi^-$ modes show clear signals for $e^+e^- \to \rho^0\rho^0$ and $e^+e^- \to \rho^0\phi$, respectively





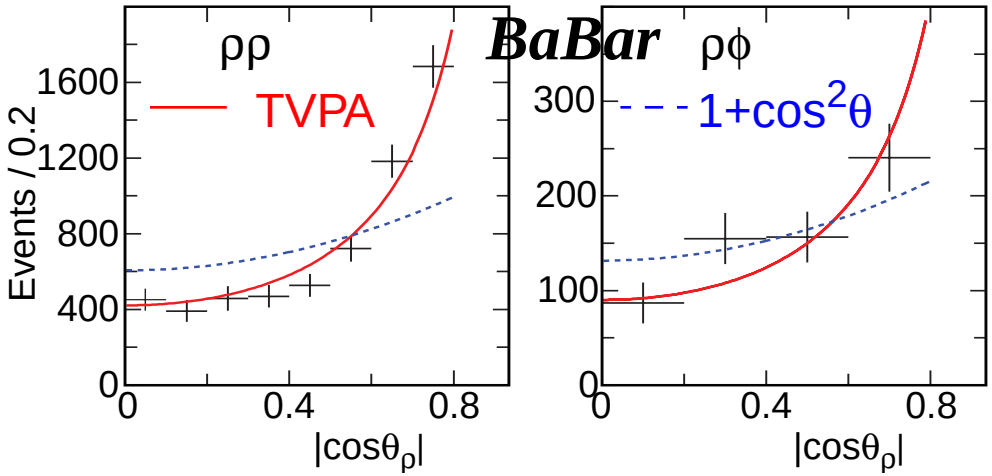
- These have C = +1
  - → forbidden in single γ^* annihilation
  - → allowed (and expected at ~this level) in 2-γ^* annihilation (TVPA)
  - → can check angular distributions...



- TVPA predicts strongly forward-peaked production angles

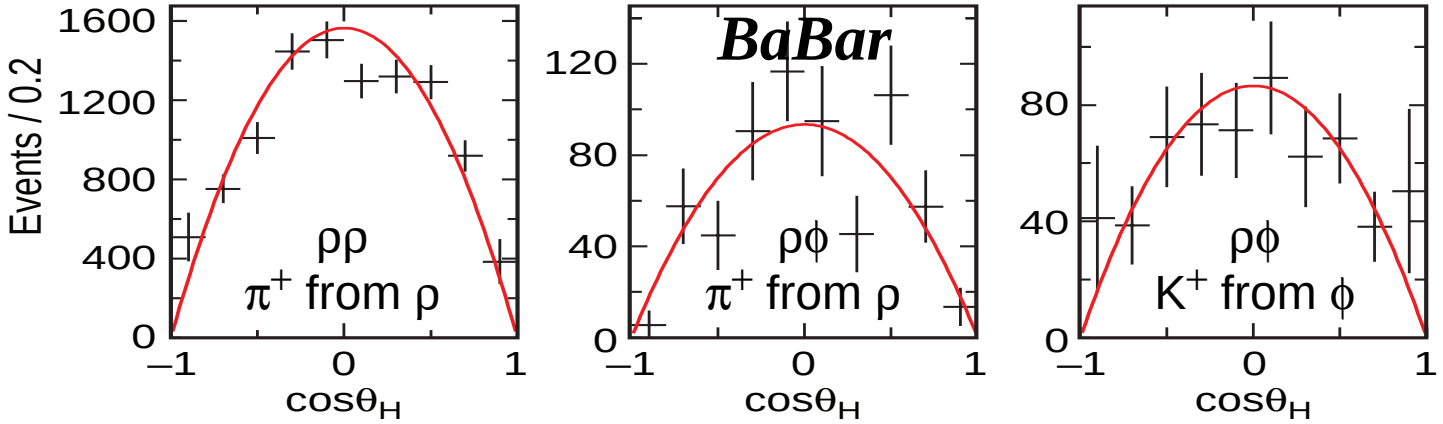
  → distributed as
  $\sim (1+\cos^2\theta_\rho) / (1-\cos^2\theta_\rho)$

  → other processes might give
  $\sin^2\theta_\rho$, flat, $1+\cos^2\theta_\rho$, ...



- and transverse ρ,φ polarization

  → i.e. $\sin^2\theta_H$ distributions for decay/helicity angles



  ⇒ First observation of TVPA

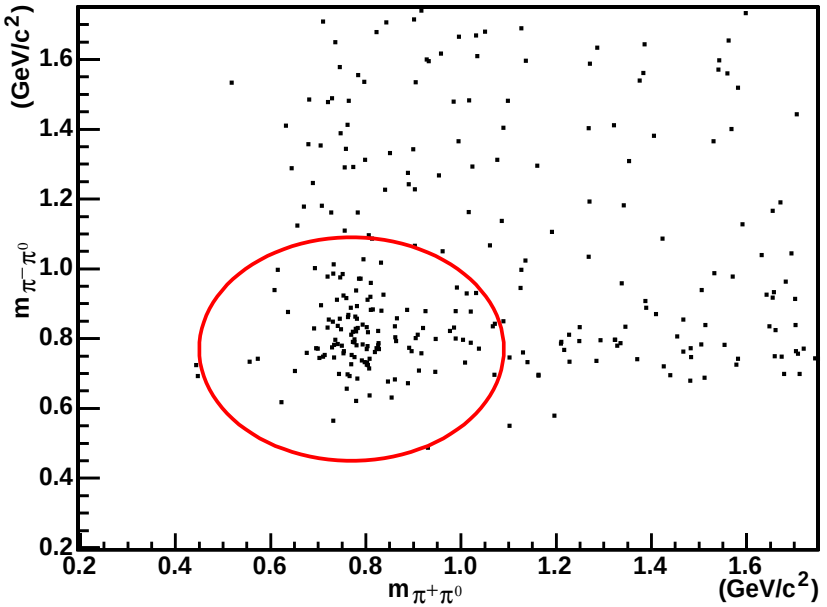
  ⇒ (Fiducial) cross sections of 20.7±0.7±2.7 fb for ρρ
  5.7±0.5±0.8 fb ρφ
  consistent with vector-dominance prediction

hep-ph/0606155

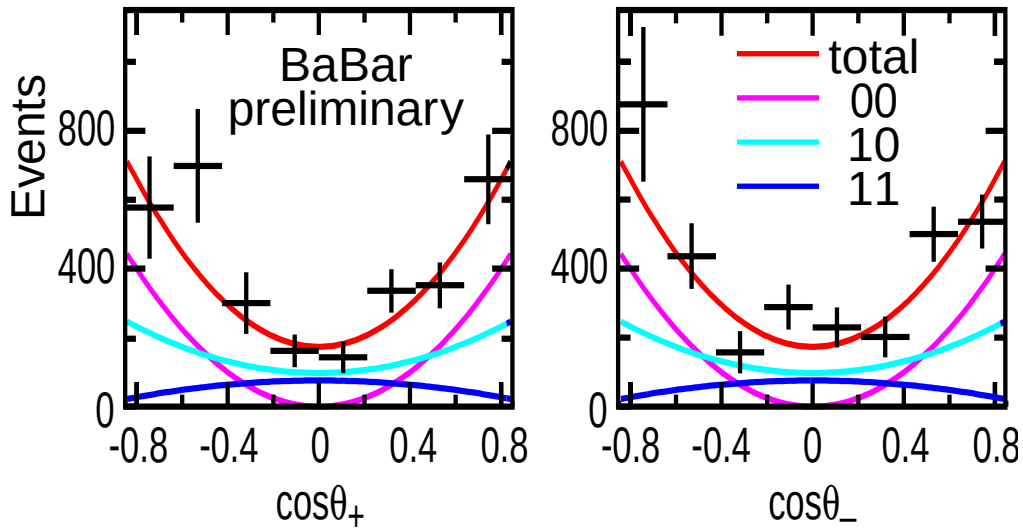
One- (and Two?)-VPA in $e^+e^- \to \rho^+\rho^-$

379 fb^{-1}, Prelimnary

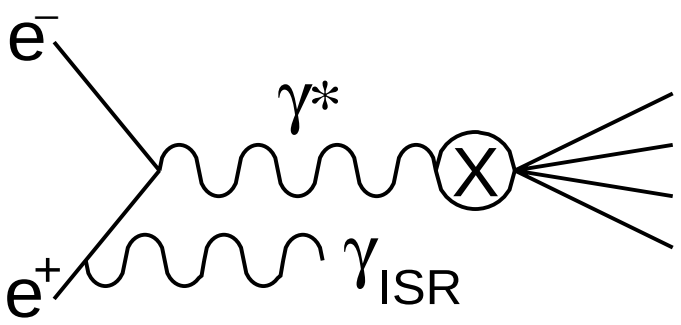
- The $\pi^+\pi^-\pi^0\pi^0$ mode shows a clear signal for $e^+e^- \to \rho^+\rho^-$
  - → allowed via a single γ^*
  - → TVPA could also contribute via final state rescattering, ...
  - → (fiducial) cross section of
    8.5±0.7±1.5 fb
    oddly(?) similar to that for $\rho^0\rho^0$



- Angular distribution study
  - → shows contributions from at least 2 of the 3 allowed helicity states, 00, 01, 11
  - → inconsistent with a QCD prediction of 00 dominance PRD 24, 2848 (81)

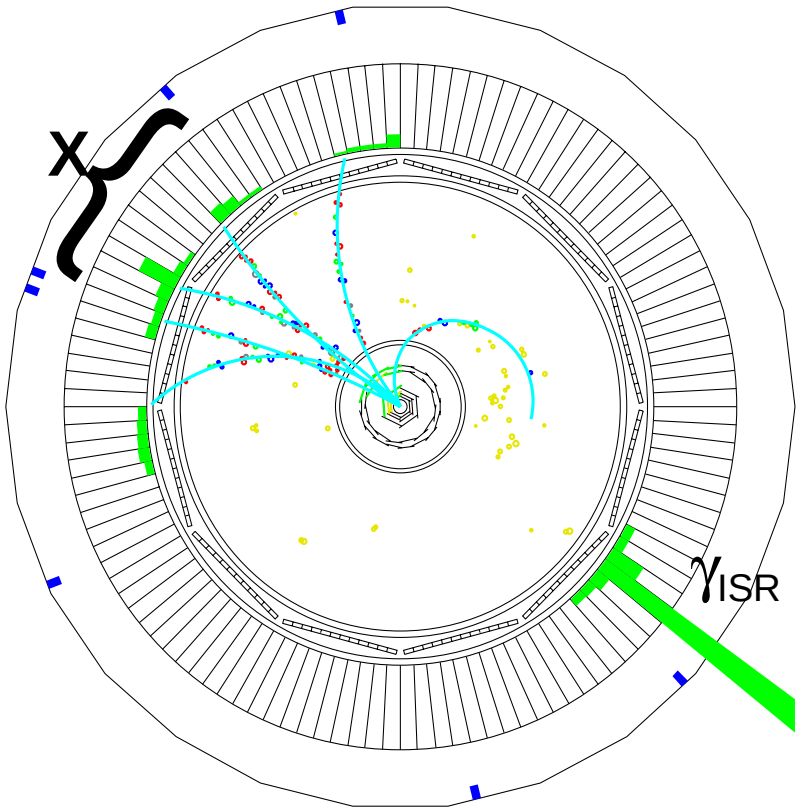


Initial State Radiation in e^+e^- Annihilations



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

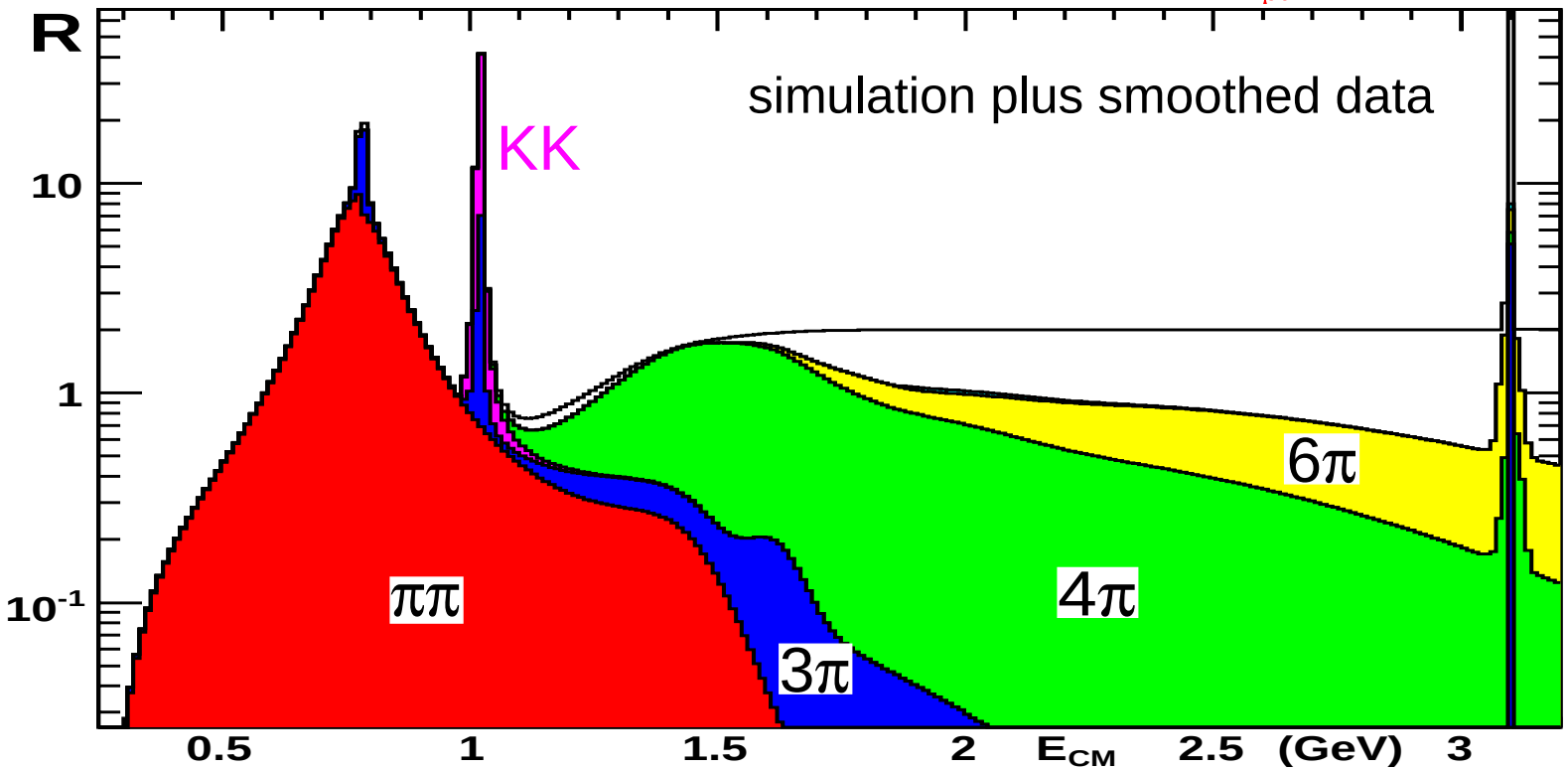
- The radiator function W is known to <1%
- Measure $\sigma(e^+e^- \rightarrow X)$ as a fcn. of $m_{\gamma^*}=m_X=E_{CM}=\sqrt{s'}$
- Features:
  - → access to wide s′ range
  - → very small point-to-point systematic errors
  - → γ_{ISR} detected ↔ hadron system contained
  - → measure all the way down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



- Disadvantages:
  - → mass resolution >beam-E spread
  - → requires very high luminosity

Low-energy ISR at BaBar:

- Exclusive final states up to ~4.5 GeV, sum → $g_\mu - 2$



- Published: $\mu^+\mu^-$, $p\bar{p}$, $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$, $K^+K^-K^+K^-$, $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$, $K^+K^-\pi^+\pi^-\pi^+\pi^-$, $J/\psi\pi^+\pi^-$, $\psi(2S)\pi^+\pi^-$

  This talk

- Preliminary: $\pi^+\pi^-\pi^0\pi^0$, $J/\psi\gamma\gamma$, $D\bar{D}$

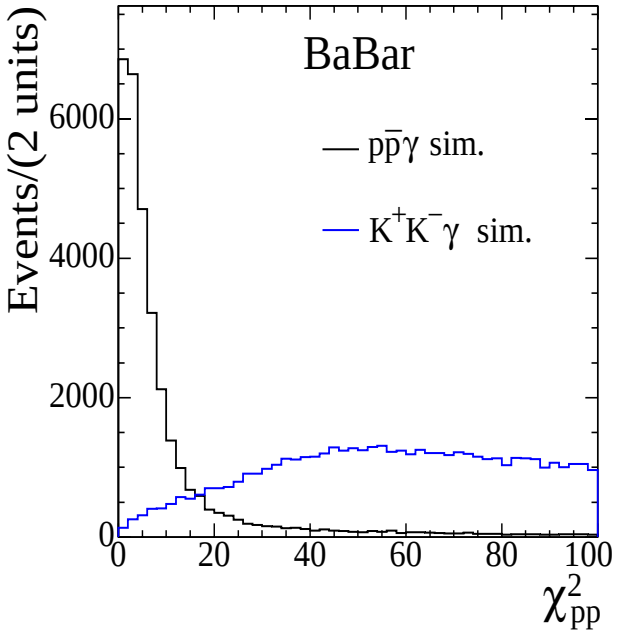
  See talk by B. Fulsom

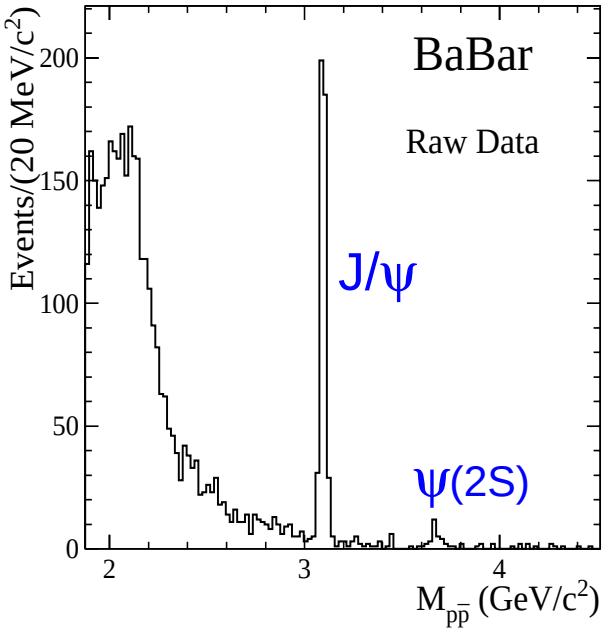
- In progress: $\pi^+\pi^-$, K^+K^-, $K^+K^-\pi^0$, $K^+K^0\pi^-$, $K^0K^-\pi^+$, $K^+K^-\eta$, ψK^+K^-, $\pi^+\pi^-\pi^+\pi^-\pi^0$, $\Lambda\bar{\Lambda}$, inclusive, ...

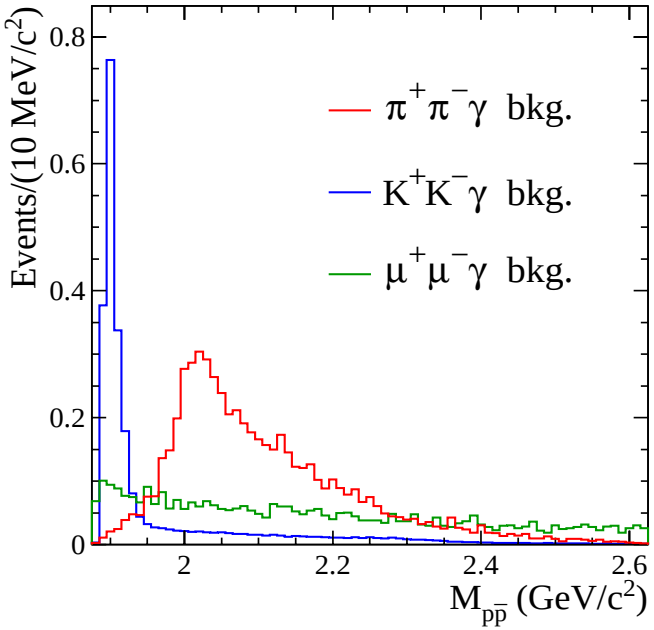
ISR Analysis Method; $e^+e^- \to p\bar{p}$

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

- Event selection:
  - → require exact topology; ID'd p and $\bar{p}$, hard γ
  - → perform kinematic fits, 4-p conservation
  - → select good events; $\chi^2_{p\bar{p}\gamma} < 20$



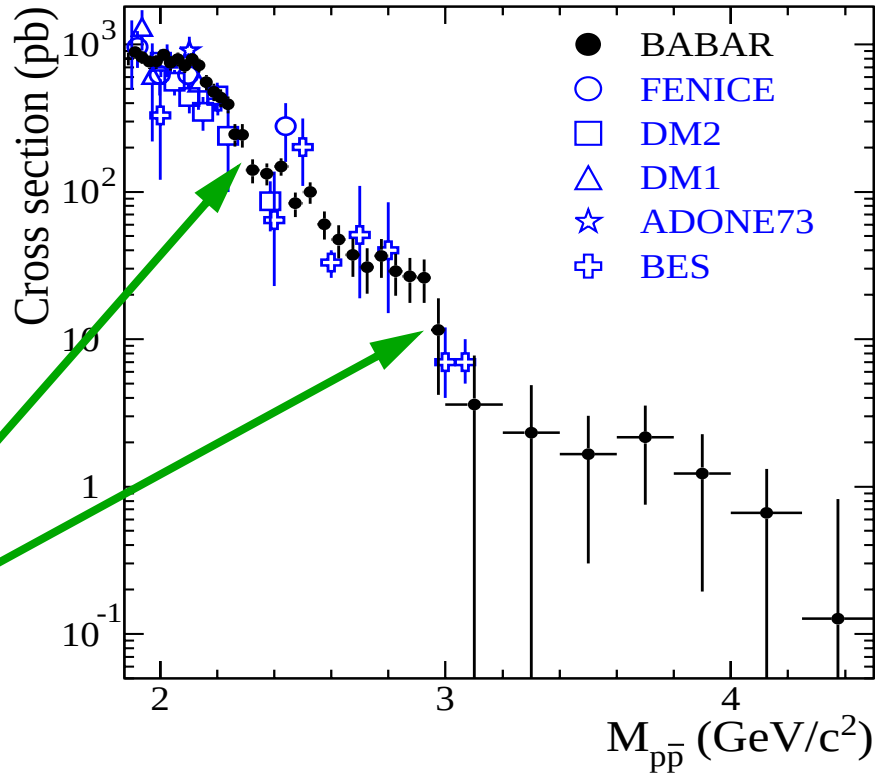




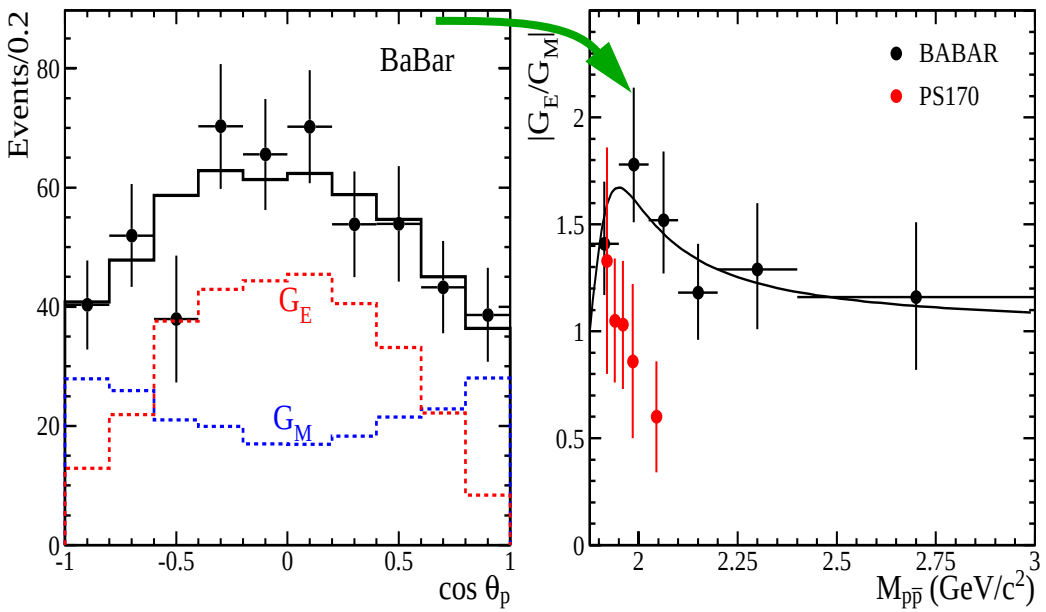
- Evaluate, suppress and subtract backgrounds from
  - → Other ISR processes; $\pi^+\pi^-$, K^+K^-, $\pi^+\pi^-\pi^0$, ...
  - → Feeddown from 10.6 GeV; $e^+e^- \to p\bar{p}\pi^0$, ...

  using measured cross sects, ID'd π,K,
  $\chi^2_{KK\gamma}$, $\chi^2_{\pi\pi\gamma}$, π^0 peak, ... in data

- The cross section
  - → threshold to 4.5 GeV in one experiment
  - → 5→10% overall systematic
  - → consistent with prev. results
  - → easier to see structure
  - → ...e.g. sharp drops at 2.25, 3 GeV



- Electric, magnetic form factors
  - $\sigma(s) \propto |G_M(s)|^2 + 2m_p^2 |G_E(s)|^2/s$
  - → full acceptance allows separation via production angle distribution
  - → $G_E > G_M$ at low E_{CM}
  - → but consistent at high E_{CM}
  - → inconsistent with PS170



- Effective form factor, F

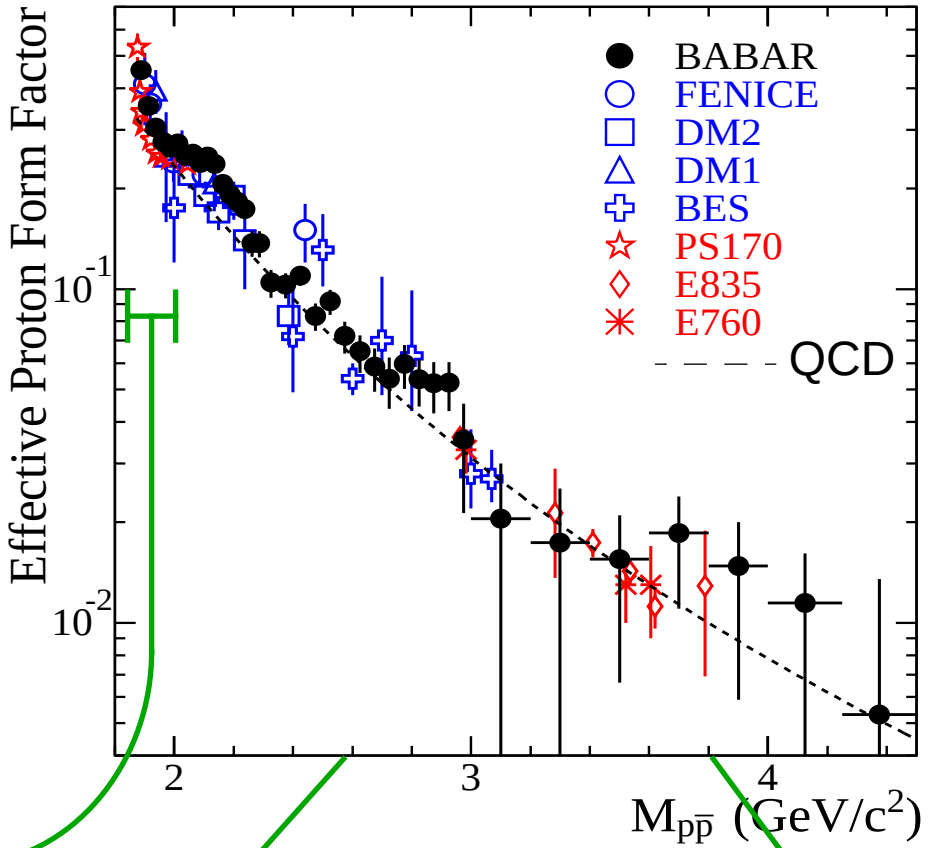
$$\sigma(s) \propto (1 + 2m_p^2/s)\,|F|^2$$

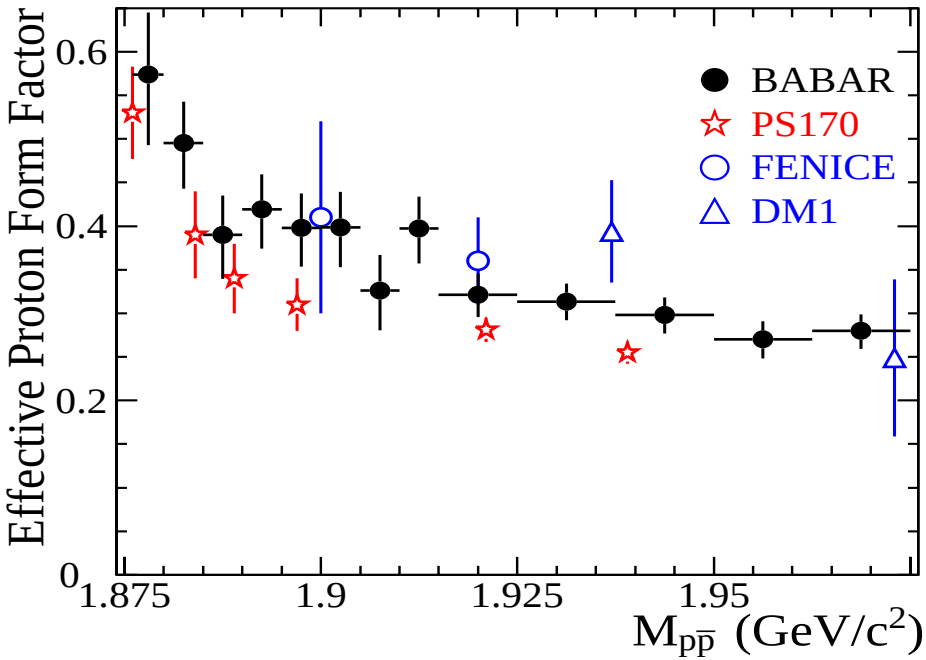
→ compare with $p\bar{p} \rightarrow e^+e^-$

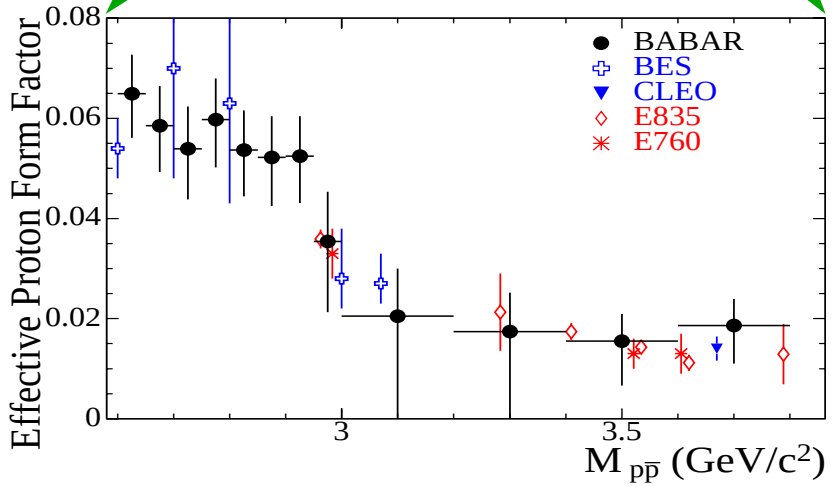
→ consistent with pQCD at high s

→ steep rise near threshold

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



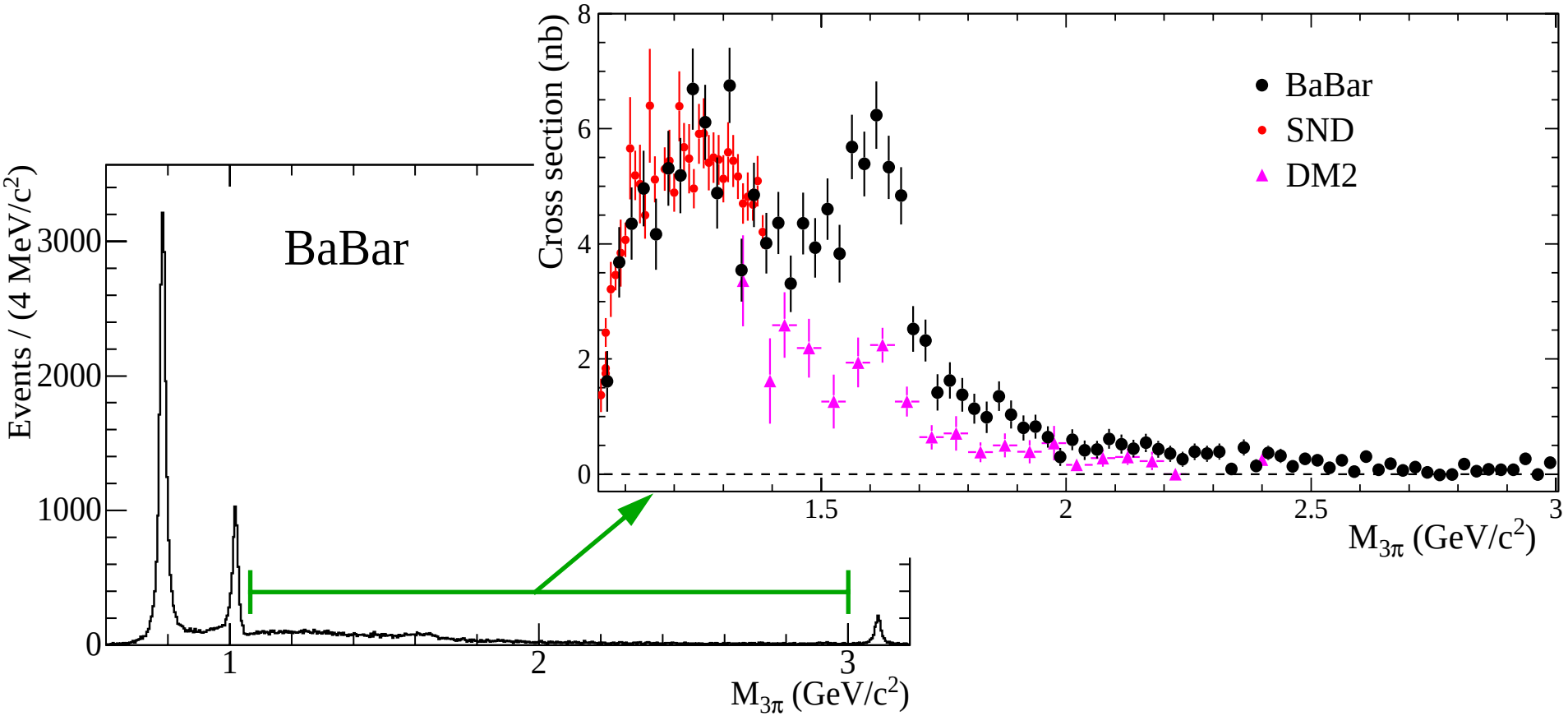




$e^+e^- \to \pi^+\pi^-\pi^0$

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

- Cross section



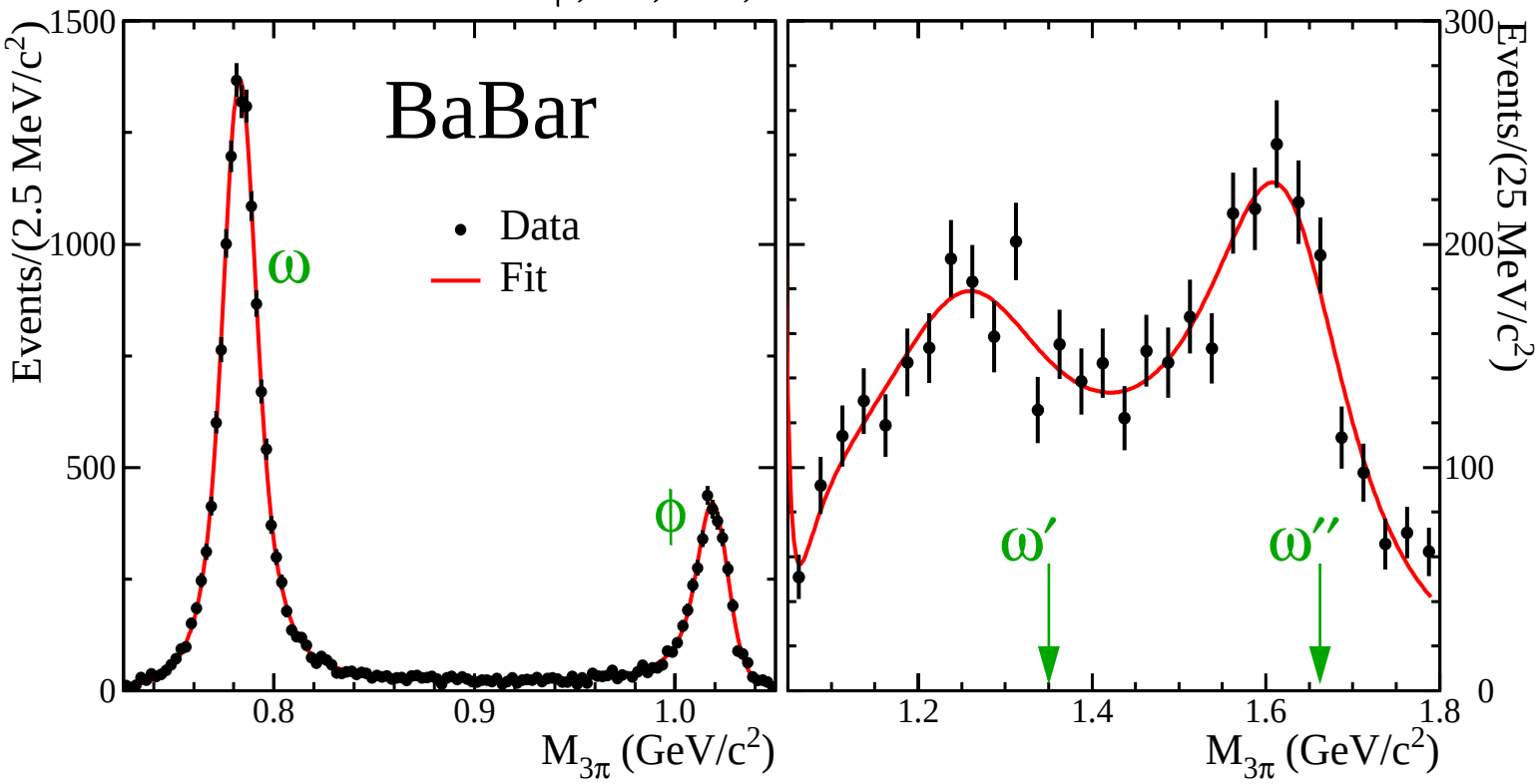
→ dominated by resonances: ω, ϕ, J/ψ, ...plus excited ω?

→ consistent with previous, precise data in ω/ϕ region

→ inconsistent with DM2 data at 1.35–2 GeV

⇒ can interpret in terms of excited ω resonances

- fit to cross section with ϕ, ω, ω', ω'' resonances



→ "best" measurements of ω', ω''

→ ...though relative phases must be assumed

	Mass (MeV/c^2)	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

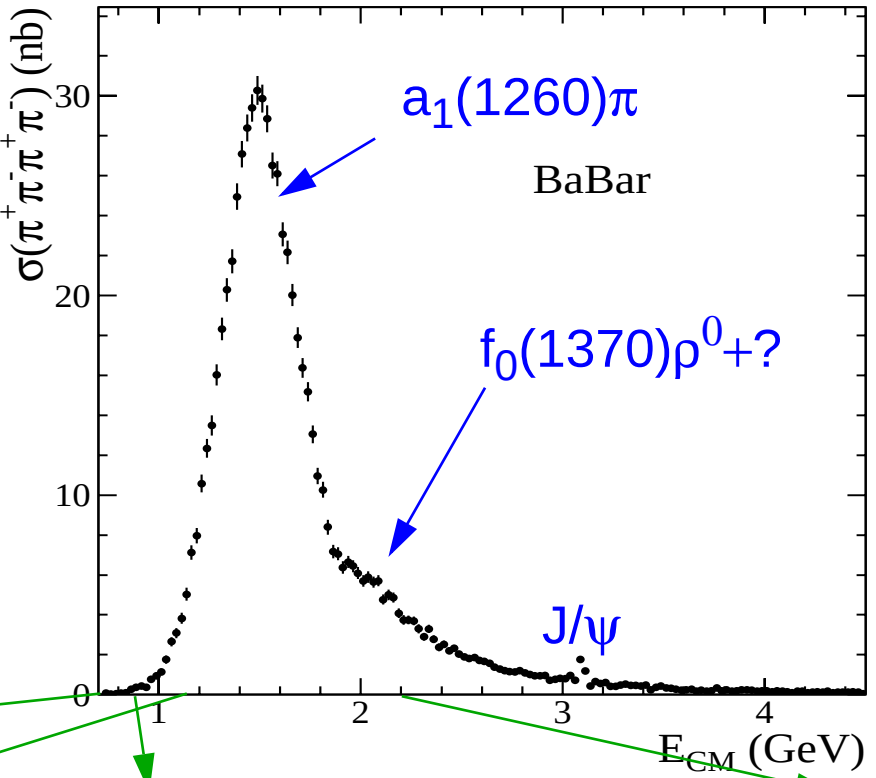
fitted

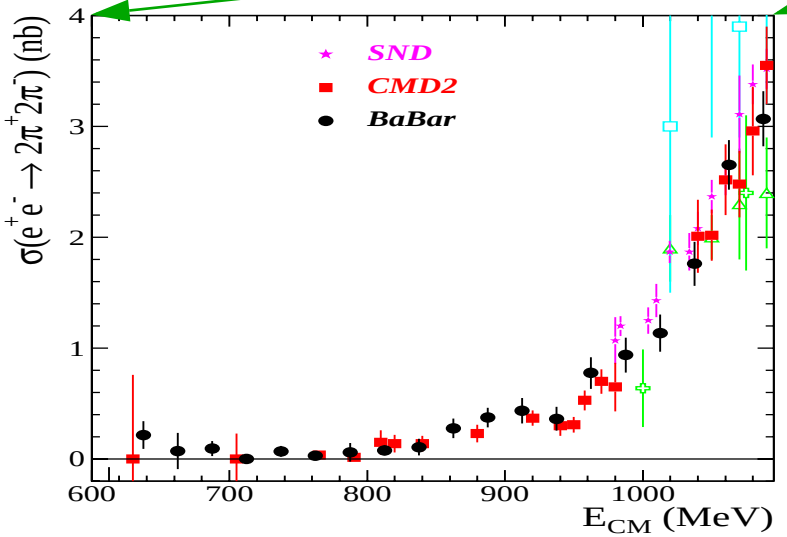
fixed to assumed values

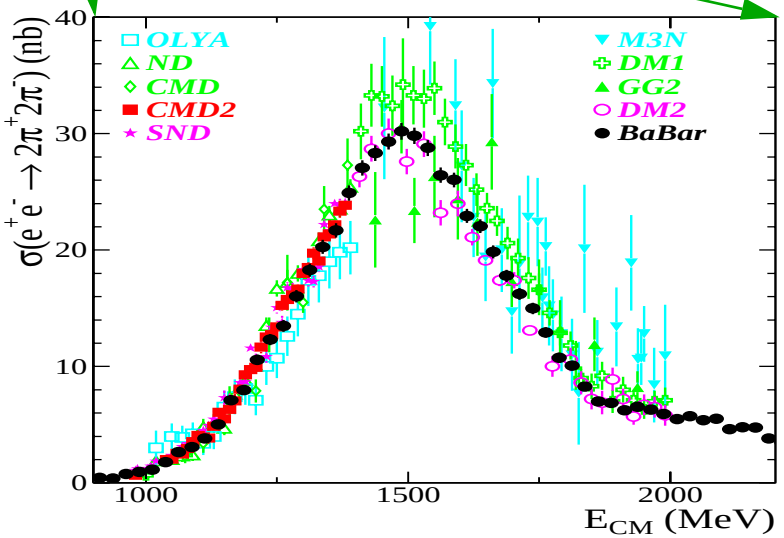
$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$

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

- Cross section
  - → consistent with prev. results
  - → best/first measurement for $E_{CM} < 0.75$, $E_{CM} > 1.4 / 2$ GeV
  - → represents ~half the total hadronic σ at 1.5 GeV
  - → 5% systematic over most of the range improves the error on $g_\mu - 2$



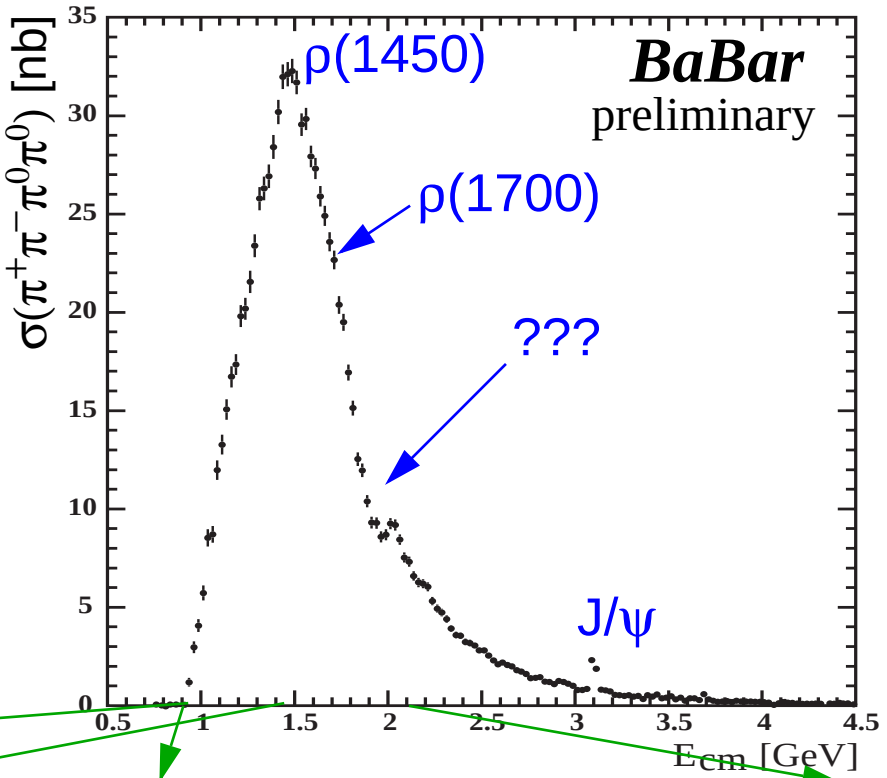


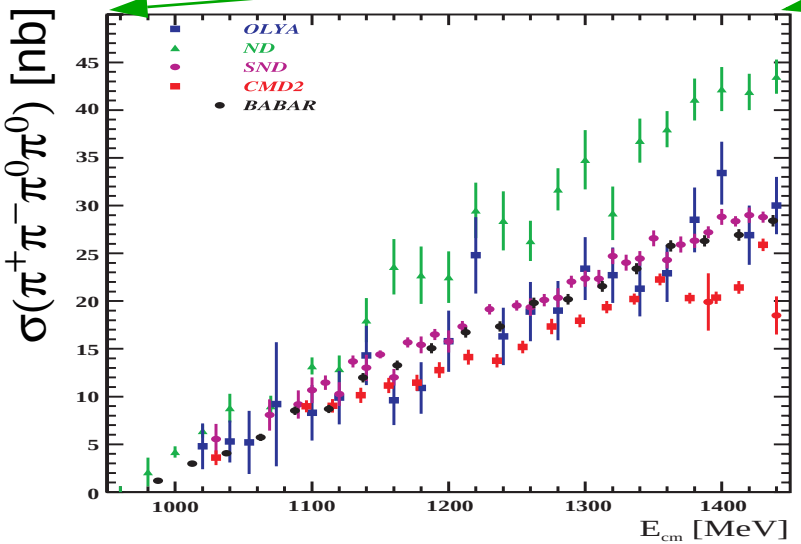


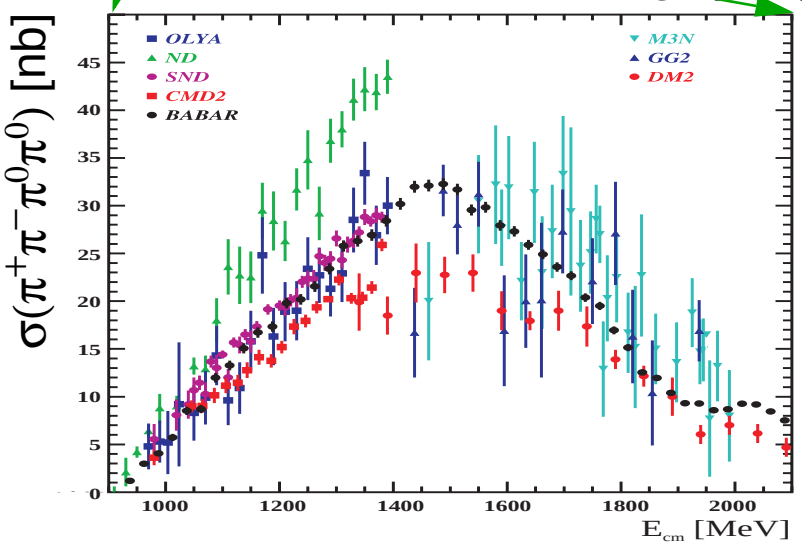
$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

239 fb^{-1} Preliminary

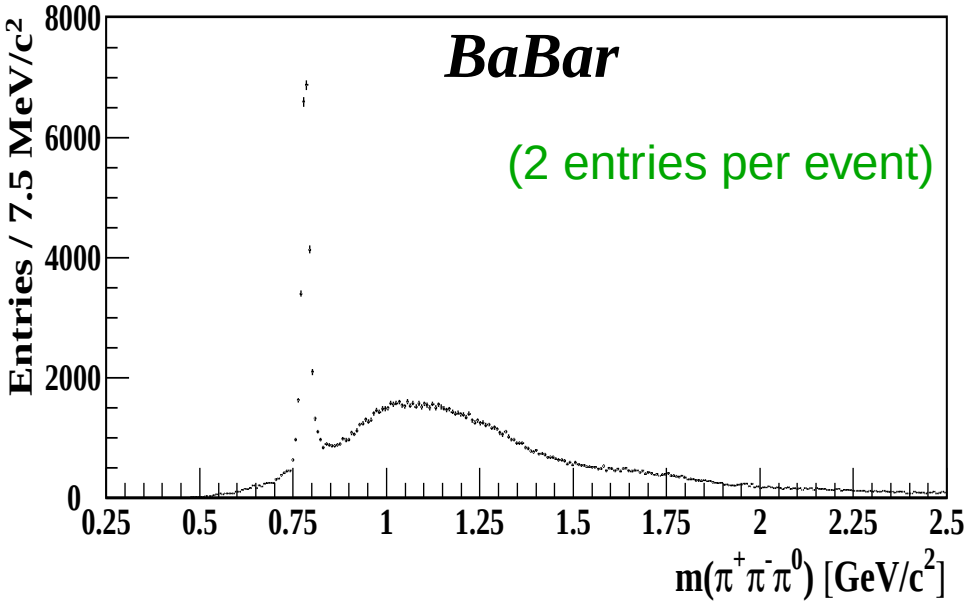
- Cross section
  - → consistent with prev. results
  - → competitive / best / first measurement for E_{CM} < 1.4 / <2.4 / >2.4 GeV
  - → 8% (eventually ~5%) error over peak region helps with the error on $g_\mu - 2$

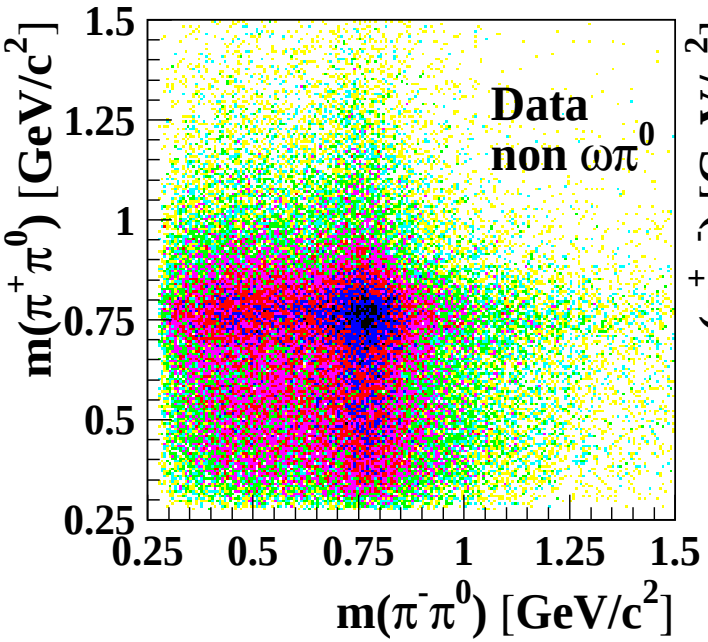


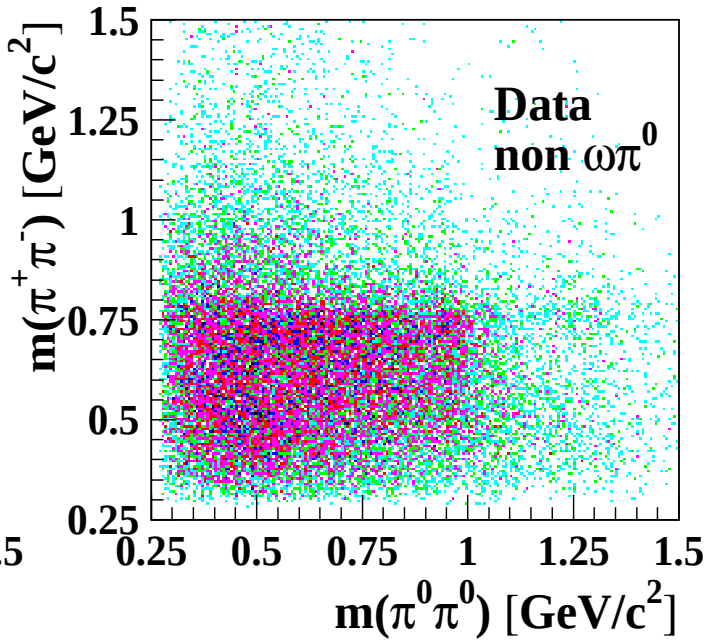




- Dominated by $\omega\pi^0$ and $a_1(1260)\pi$ channels
  → as seen previously
- We also observe $\rho^0 f_0$ and $\rho^+\rho^-$
  → unexpected?
  → working on extracting the $\rho^+\rho^-$ cross section vs. E_{CM}
  → ...further nice tests of QCD, especially when connected with the msmt at 10.6 GeV



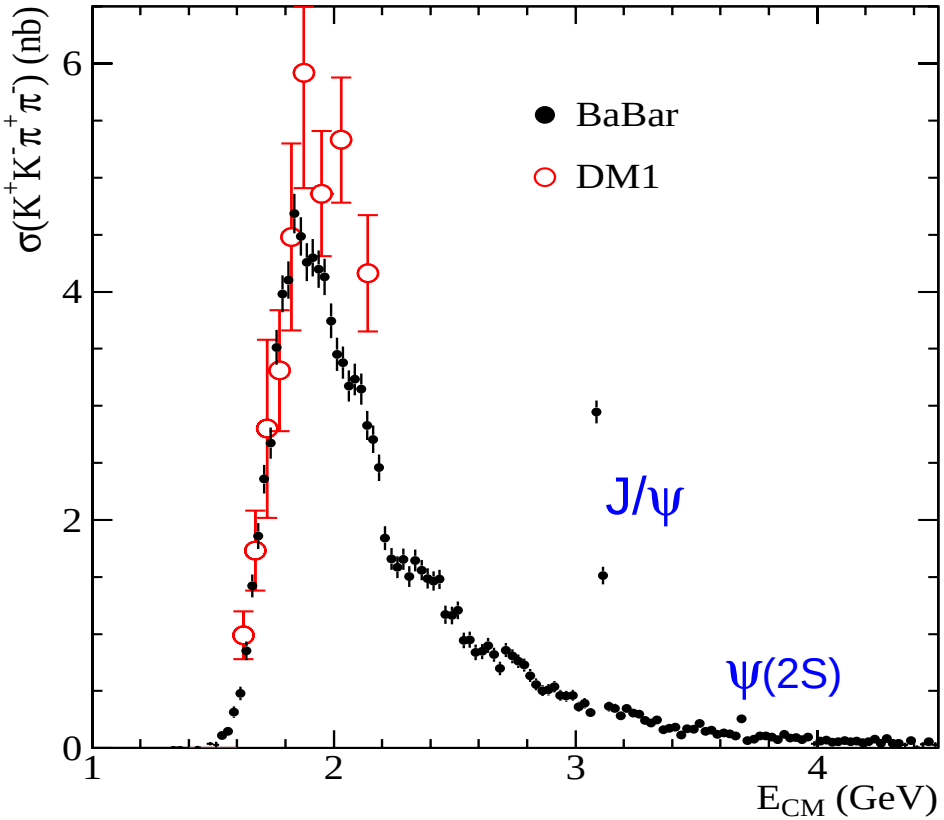


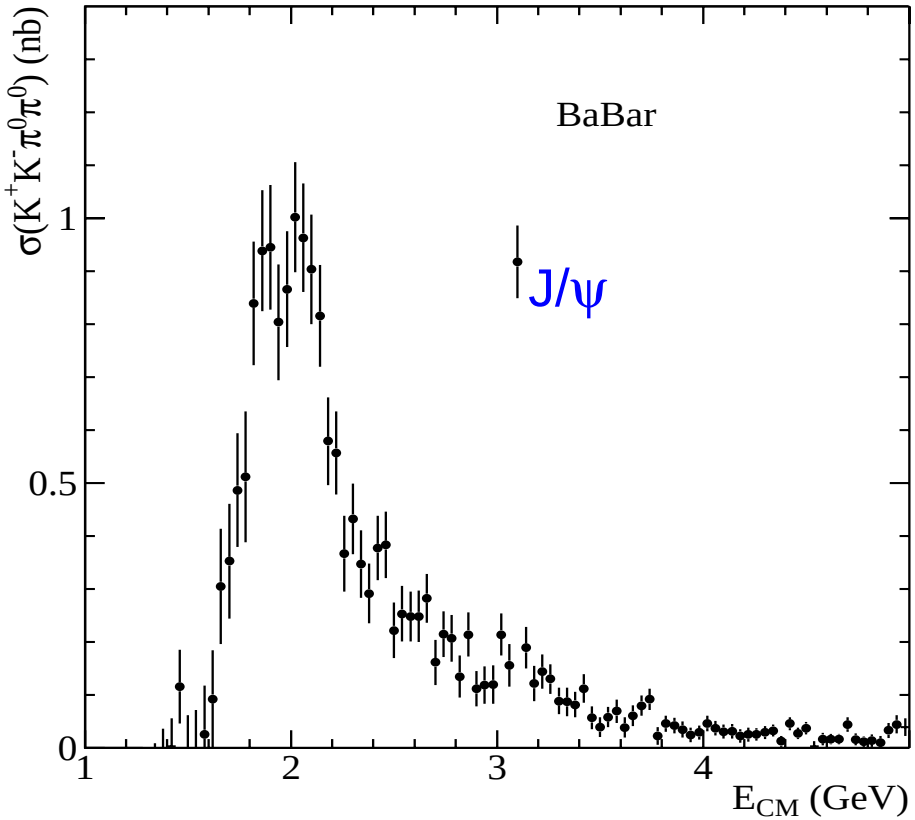


$e^+e^- \to K^+K^-\pi^+\pi^-, K^+K^-\pi^0\pi^0$

232 fb^{-1} PRD-RC 74, 091103 (06)

- Cross sections





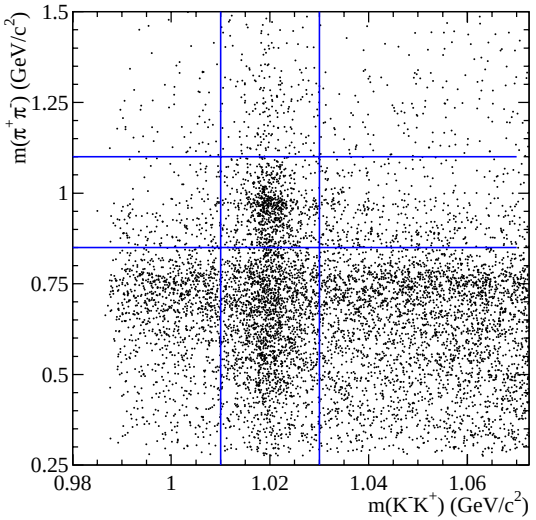
→ huge improvement for $K^+K^-\pi^+\pi^-$, first for $K^+K^-\pi^0\pi^0$

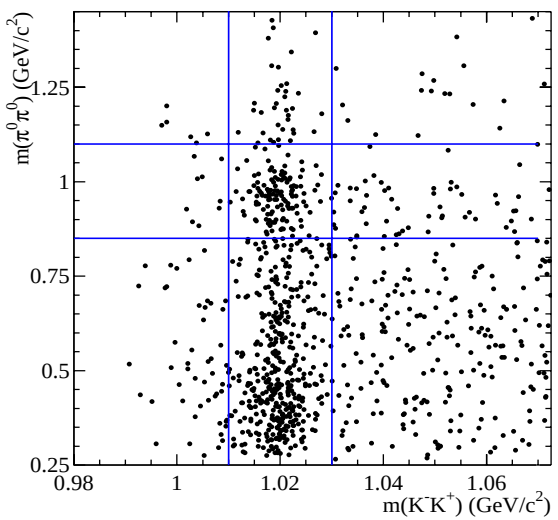
→ rich substructure dominated by $K^*(892)K\pi$, with substantial $K_1(1270)^+K^-$, $K_1(1400)^+K^-$, $\phi\pi^+\pi^-$, $\rho^0K^+K^-$, and more

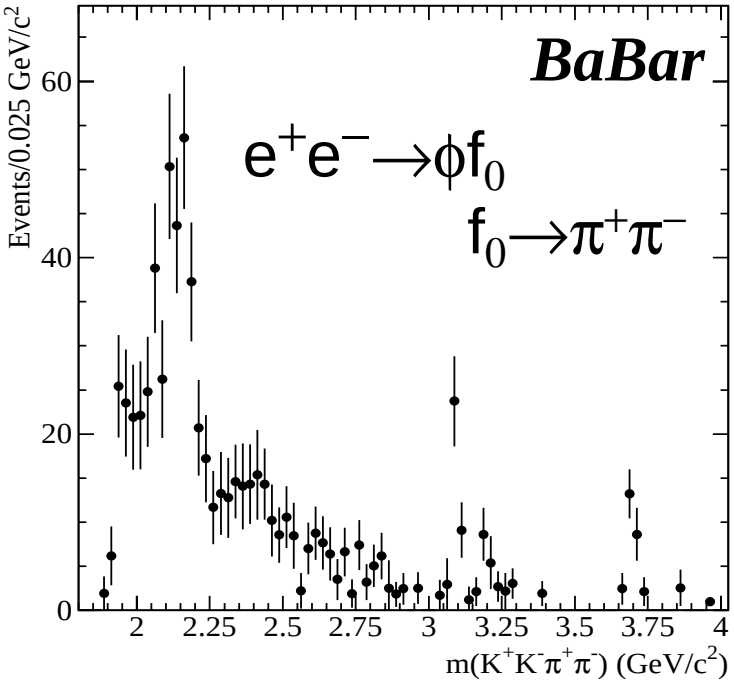
→ several hints of structure, e.g. at ~2 GeV ↔ $\phi f_0(980)$ threshold

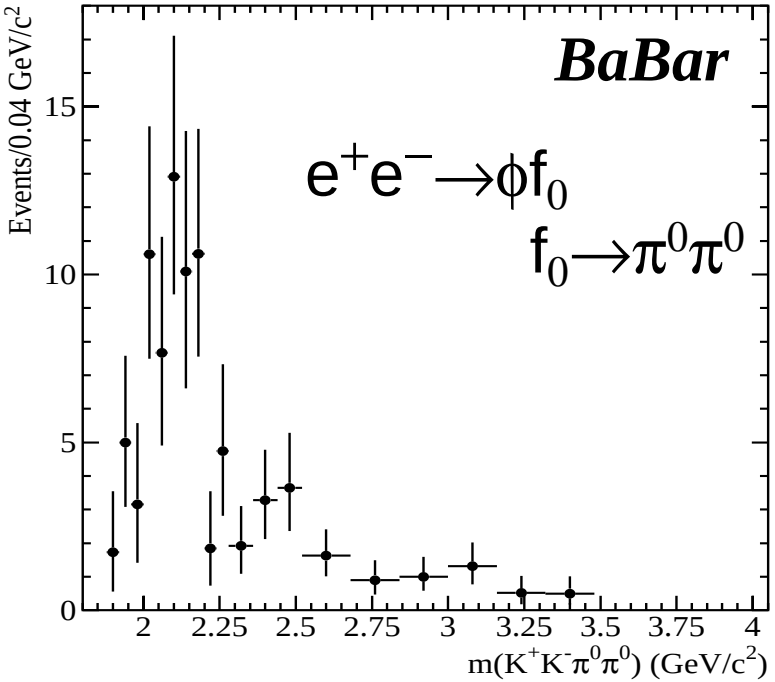
→ since ϕ, $f_0(980)$ are both narrow, this submode can be studied...

- 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 thresh-old unchanged
  - → $\pi^+\pi^-$ and $\pi^0\pi^0$ modes give consistent results
  - → can be described by adding a resonance; a fit yields:

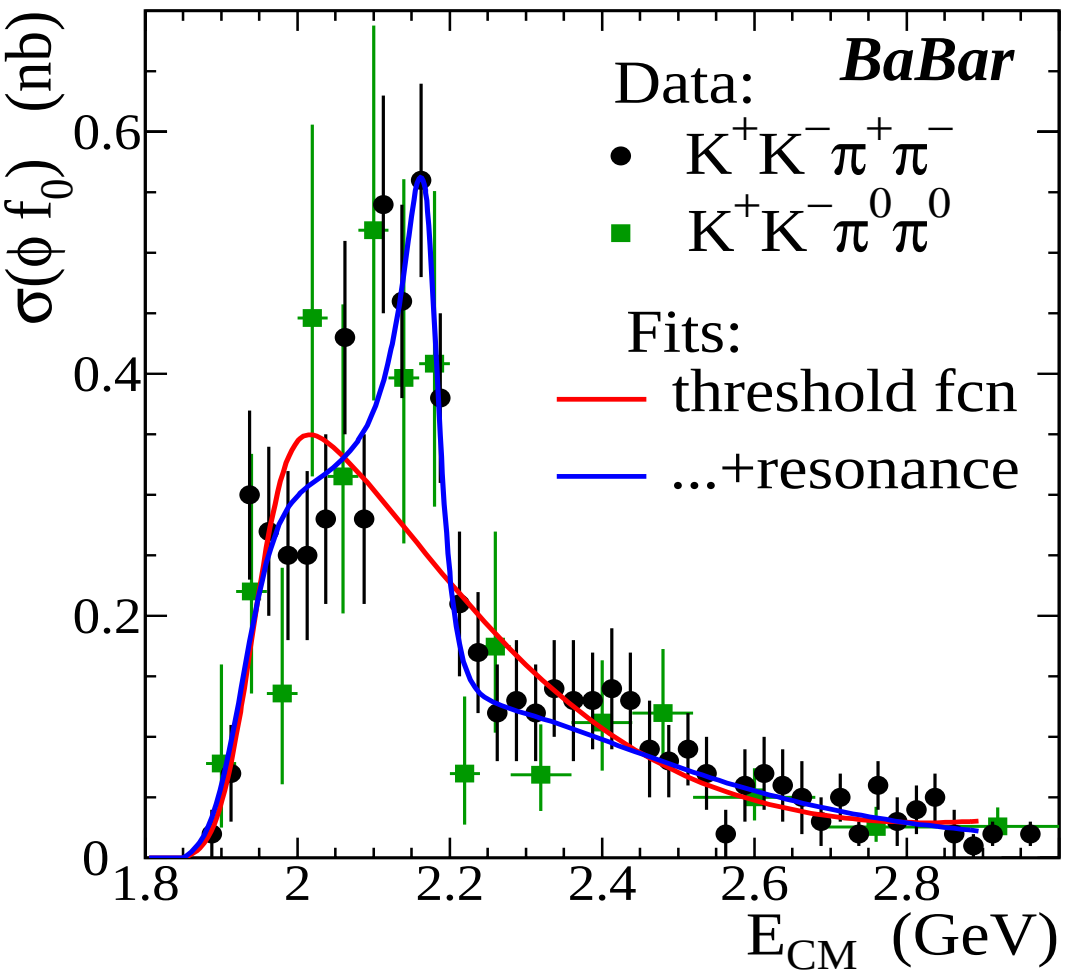
    m = 2175±18 MeV/c^2

    Γ = 58±26 MeV

    ϕ = –36±56°

    wrt non-res

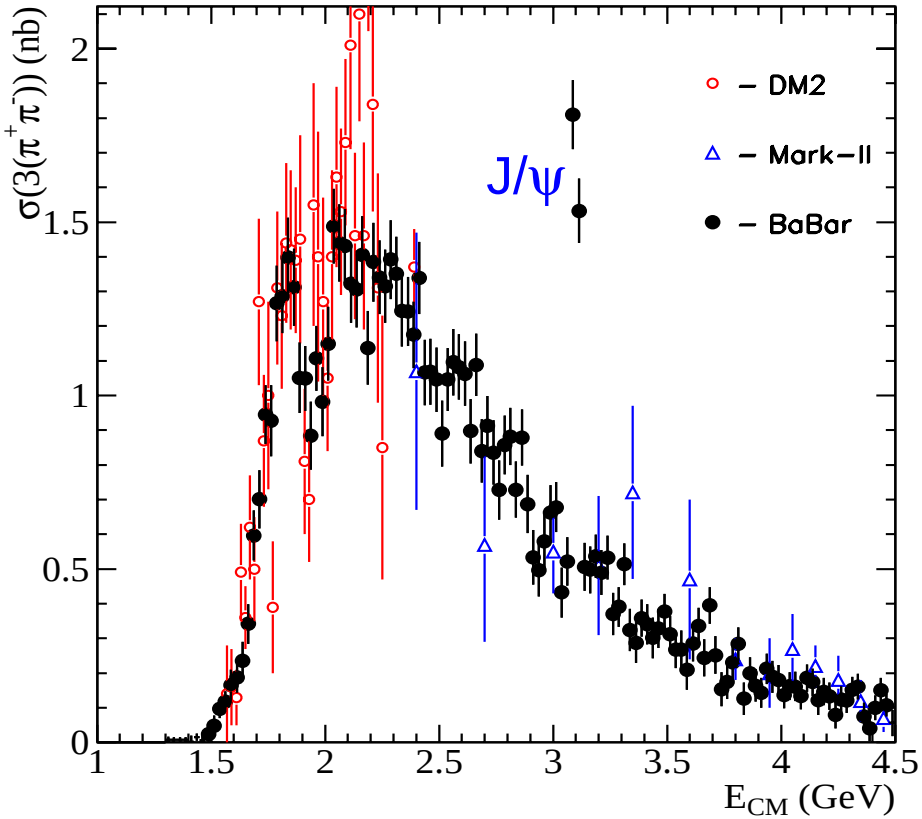
    5.6σ significance

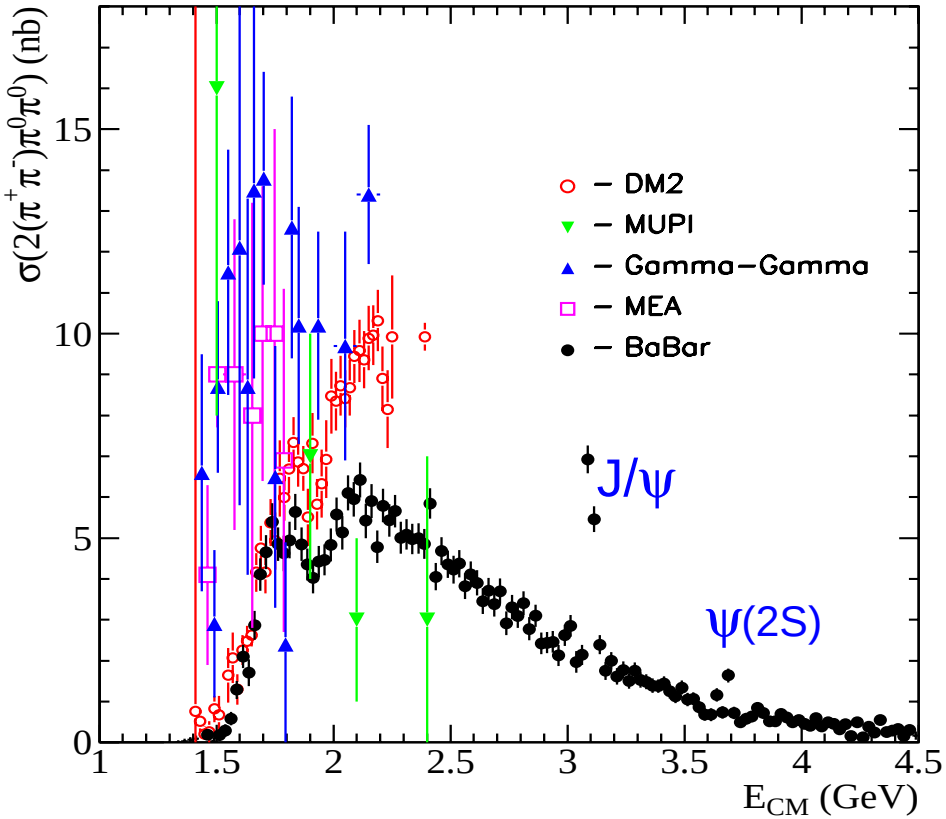


  - → very interesting mass region, just below $\Lambda\bar{\Lambda}$ threshold
  - → is this a new state?
  - → is it analogous to the Y(4260)?
  - → need more data, other modes to understand structure in detail

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

- Cross sections





→ large improvements in both measurements

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

→ ... but resonance fits give inconsistent parameters

⇒ is this the "same" as the dip in the $\pi^+\pi^-\pi^0\pi^0$ modes?

⇒ or is something(s) else going on?

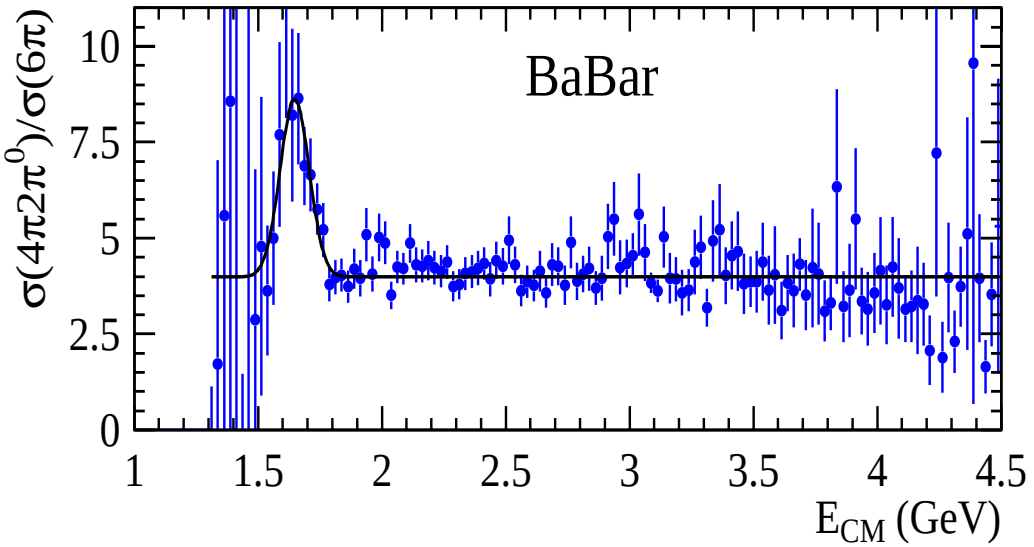
- The $2(\pi^+\pi^-)\pi^0\pi^0$:$3(\pi^+\pi^-)$ ratio
  - → is flat and ...
  - → =4 except where the $\omega\eta$ submode contributes
  - → a challenge since the former/latter has very little/ rich substructure
- The $\omega\eta$ submode
  - → is easy to isolate, use sidebands to subtract background
  - → the cross section is dominated by two resonances, J/ψ and something with

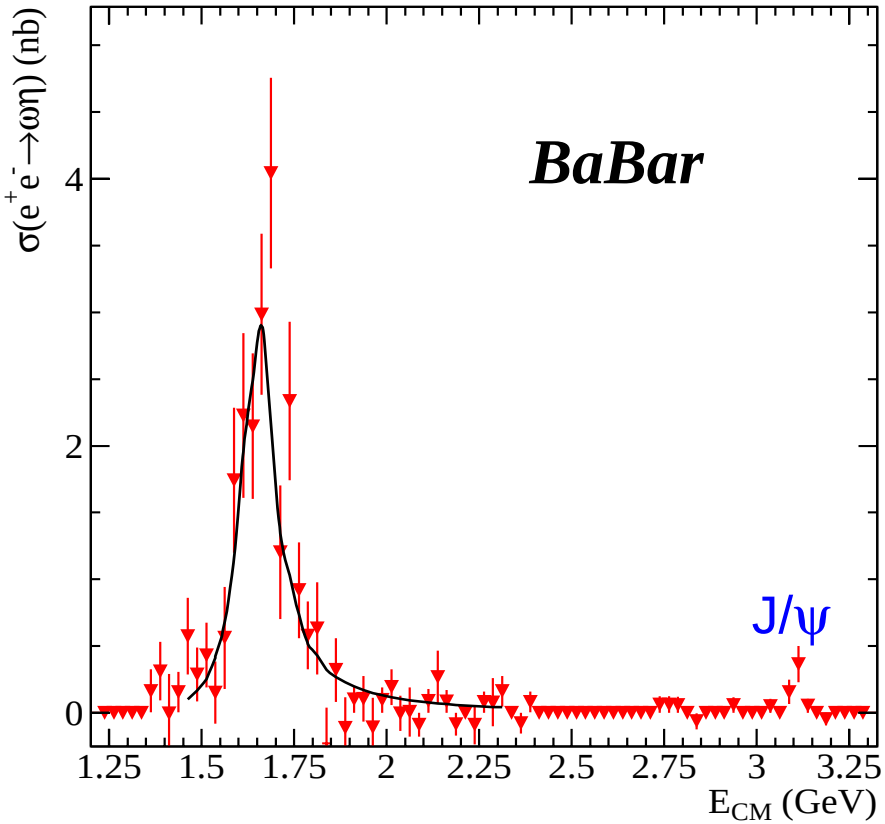
    $m = 1645 \pm 8$ MeV/c^2

    $\Gamma = 114 \pm 14$ MeV
  - ⇒ is it the $\omega(1650)$? (Γ=315)

    ...or the $\phi(1680)$?

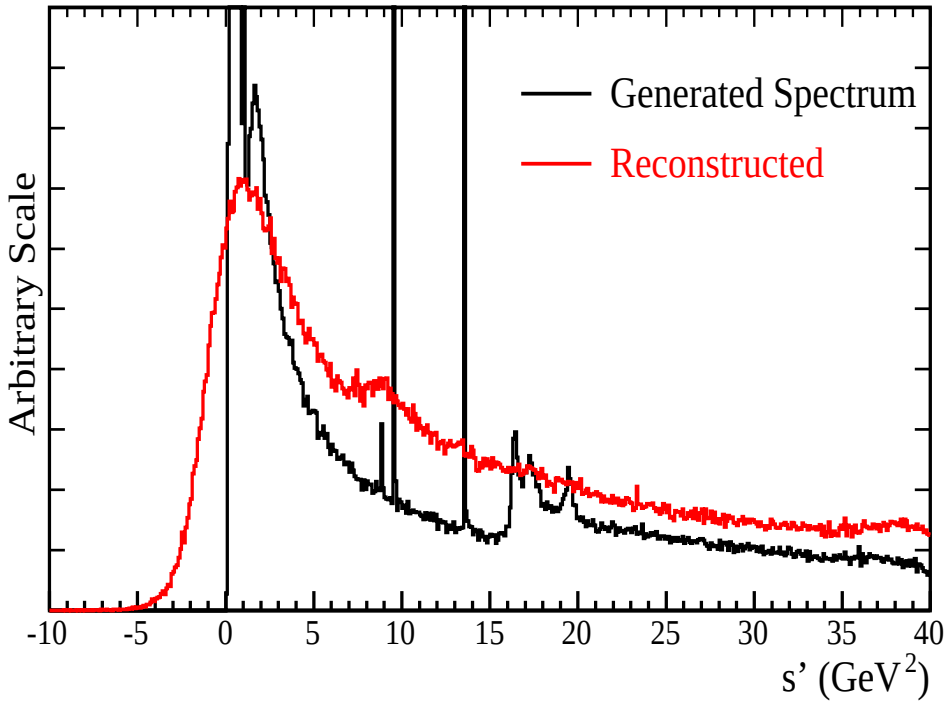
    ...or something new...?

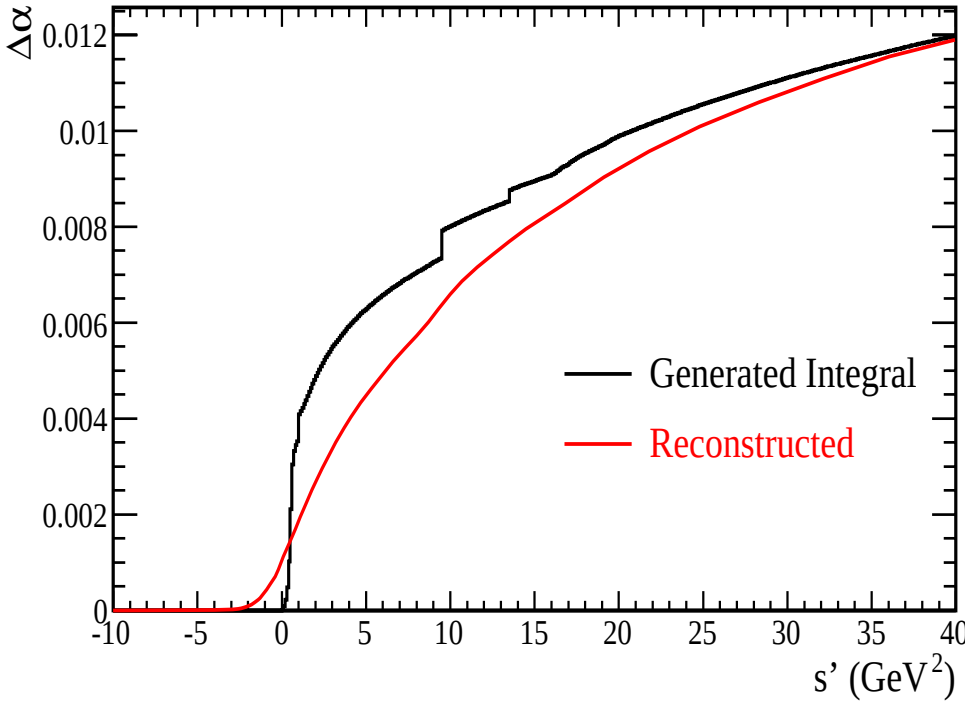




Inclusive Cross Section via ISR

- Can we measure the total $e^+e^- \rightarrow$ hadrons cross section with ISR?
  - → select events with a hard photon recoiling against "stuff"
  - → problem: photon energy resolution is not great

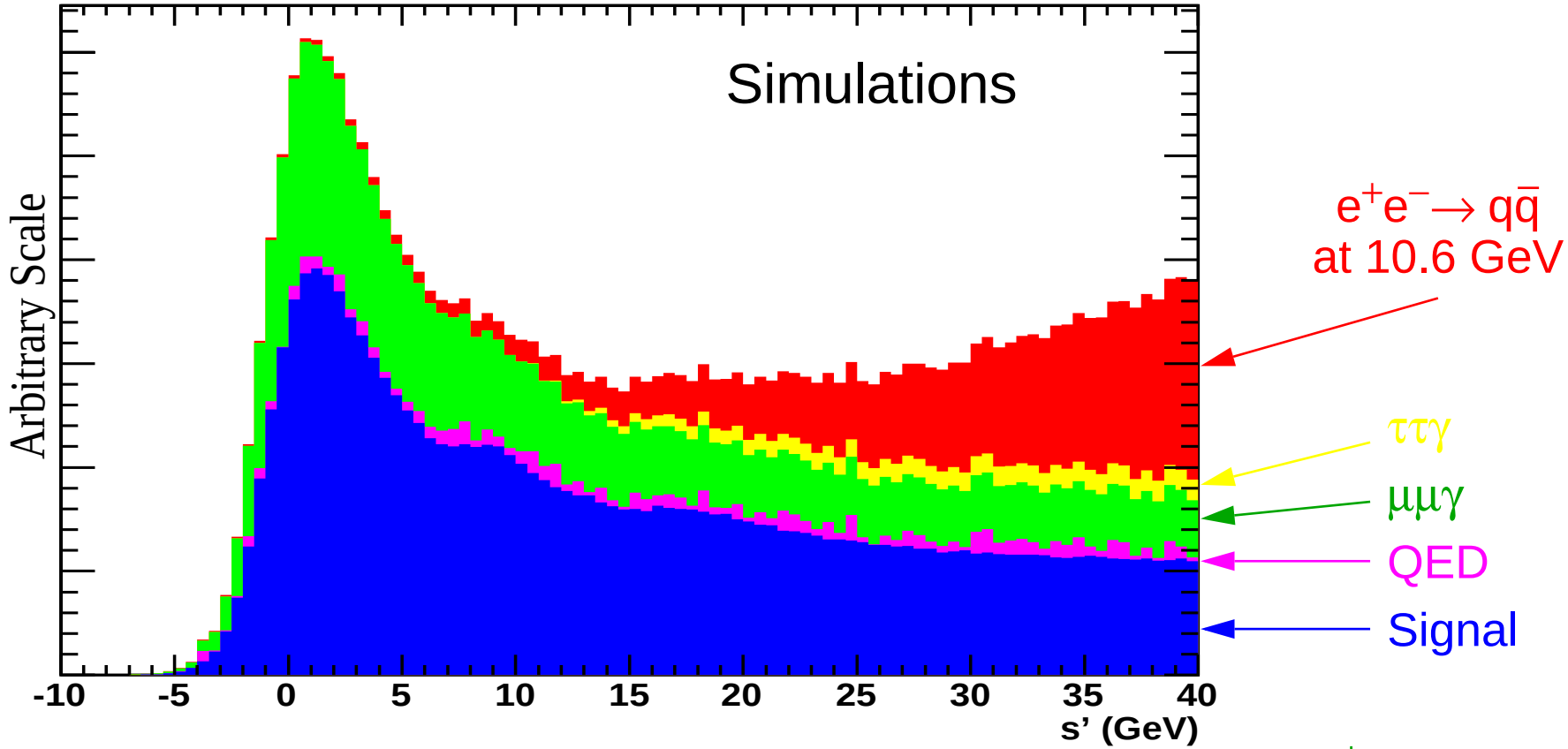




- → but we can measure the integral nicely in the $q\bar{q}$ region
- → ...and the integral convolved with the kernel for $\alpha_{QED}(M_Z^2)$
- → (but the g_μ–2 kernel is too sharply peaked...)

- Let's see what we can do ...

→ applying some simple selection criteria, backgrounds are high

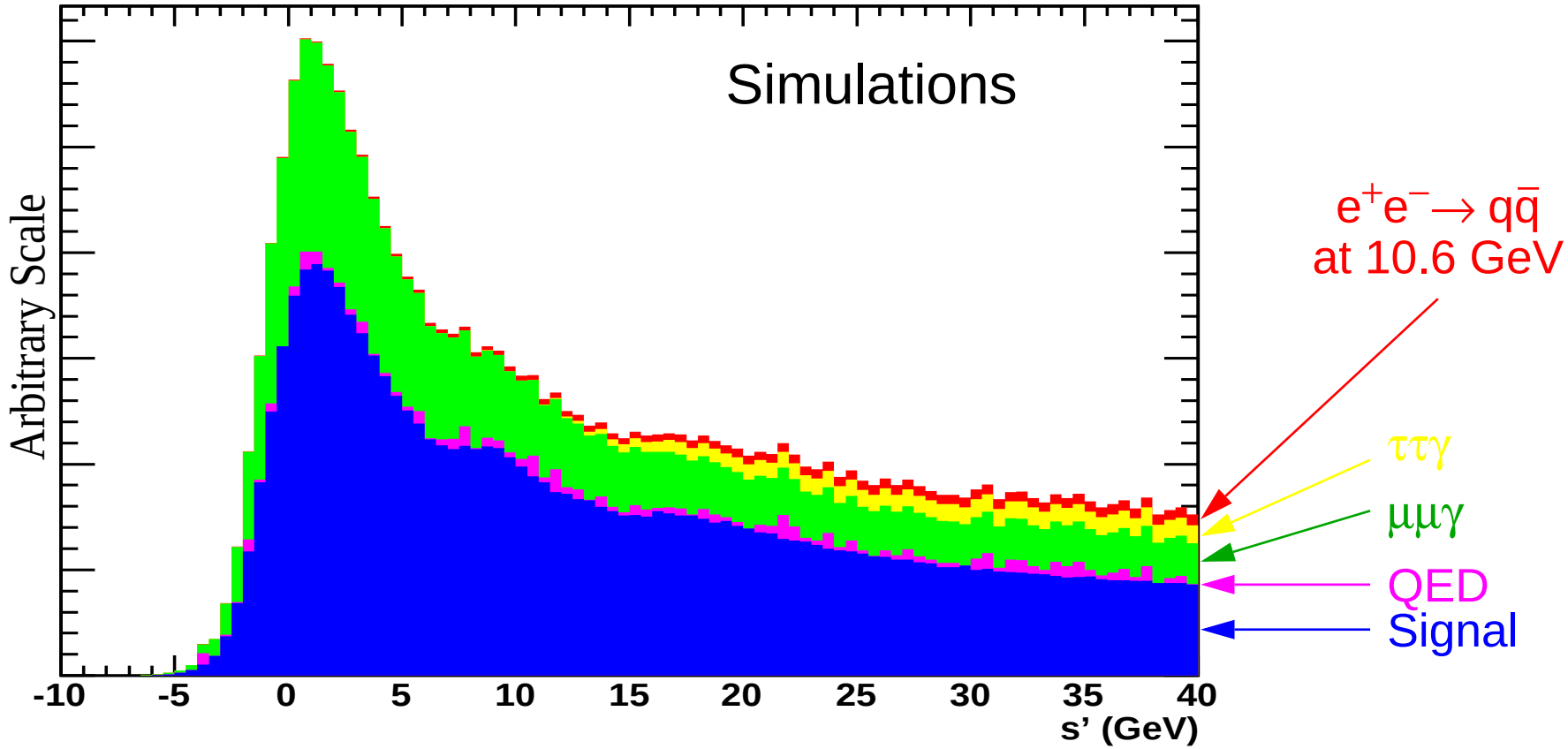


→ strategy: keep well understood radiative $\mu^+\mu^-$ and $\tau^+\tau^-$ events, subtract them later

→ use data to characterize, suppress and measure the remaining background from $q\bar{q}$ events

→ much work on detector response to photons, π^0, η, η', ω, K_L, neutrons, event shapes, other backgrounds, ...

- The current status is ...



→ backgrounds are now manageable, but must be understood very well before subtraction

→ this is in progress; we expect a 3.5-4.5% measurement of the hadronic contribution to $\alpha_{QED}(M_Z^2)$ from $s'<6.5$ GeV

→ current errors are 15 (6)% in the 1-2 (2-5) GeV region, so this measurement should be quite useful

Summary

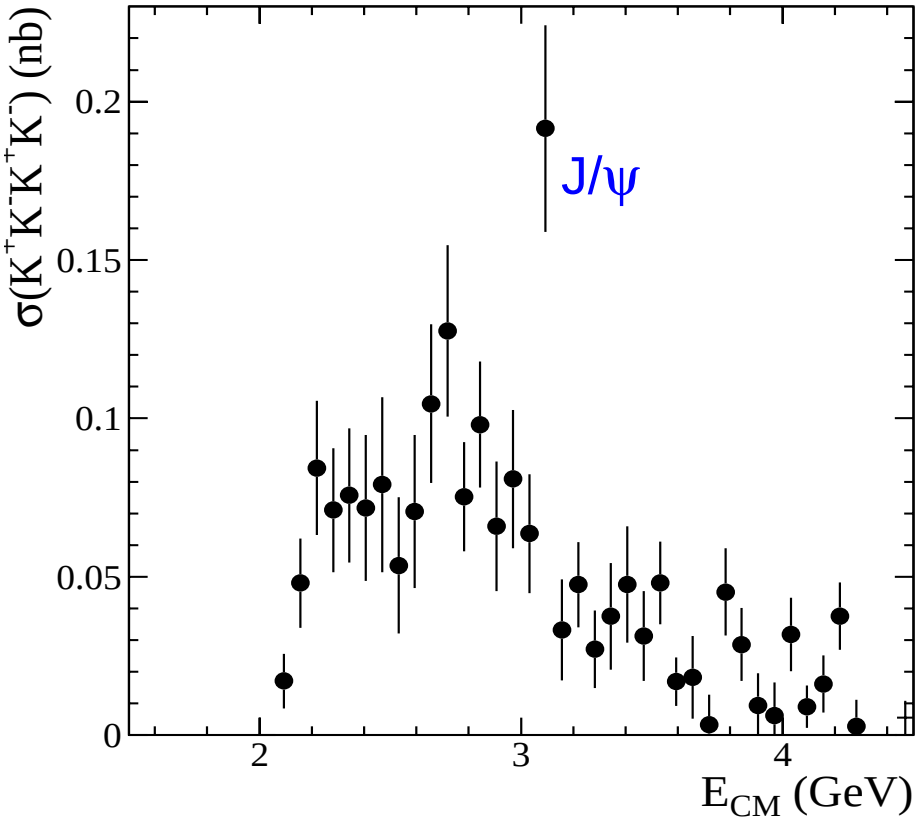
- The very high luminosity of the B factories has (re)opened several interesting areas of elementary particle physics
- Using exclusive reactions at 10.6 GeV:
  - → first observation of e^+e^- annihilations via $2\gamma^*$
  - → η, η' form factors in asymptotic region
  - → new tests of QCD
- Using initial state radiation:
  - → improved knowlege of R, $g_\mu - 2$, $\alpha(M_Z)$
  - → improved spectroscopy of ω, ϕ states
  - → improved proton form factors, find $G_E > G_M$ at low E_{CM}
  - → new/improved spectroscopy at ~1900, 2175, 1650 MeV
- Many new, improved studies planned
  - → update results with full data set
  - → more exclusive modes at low and high E_{CM}

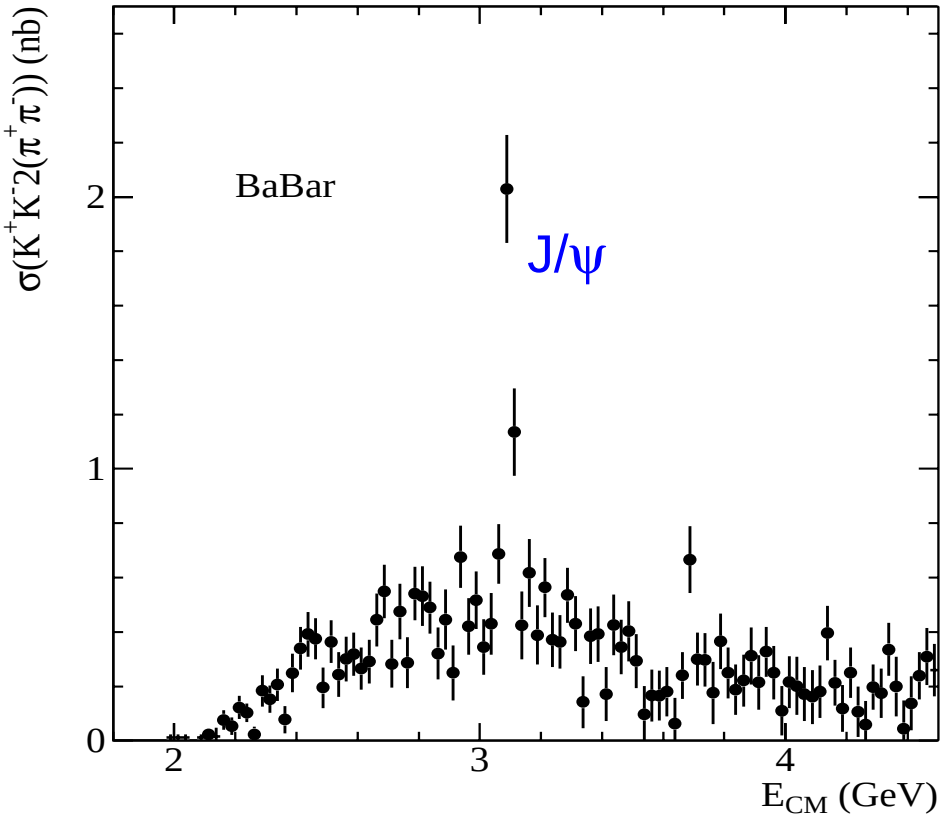
Backup Slides

$e^+e^- \to K^+K^-K^+K^-$ 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





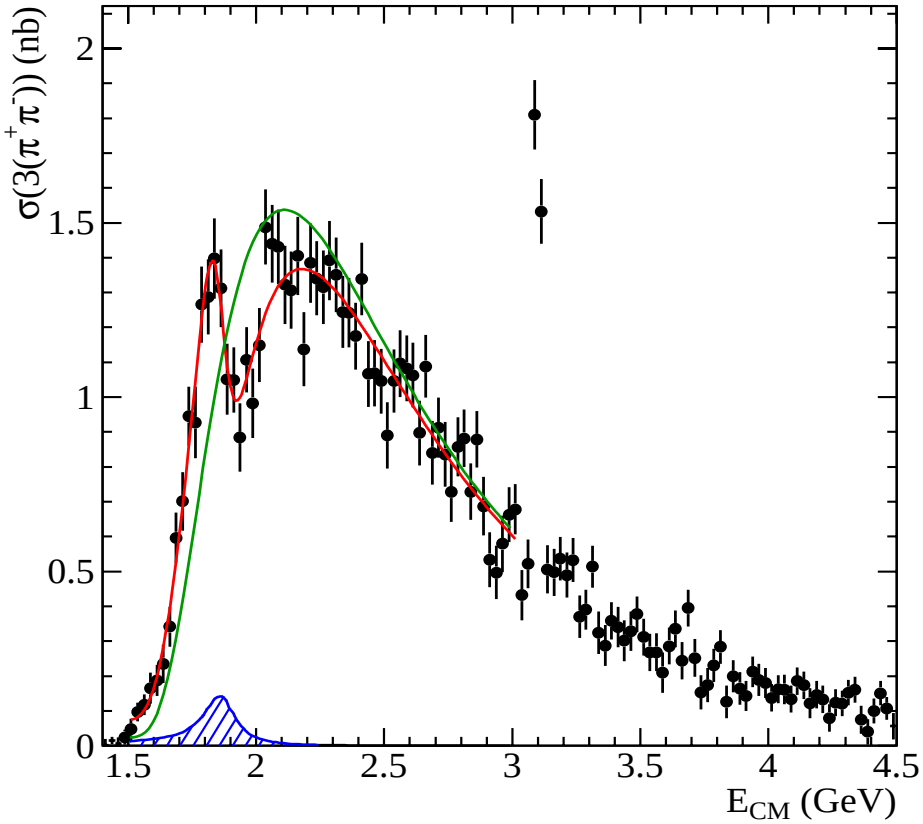
→ first measurements

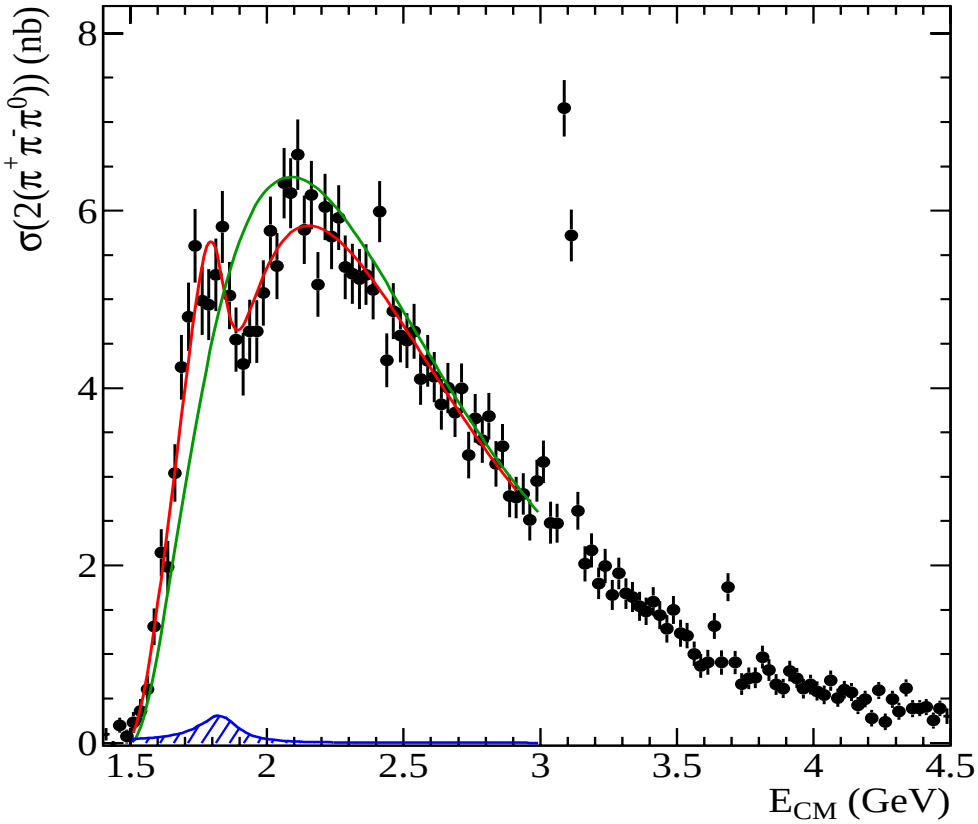
→ the $K^+K^-K^+K^-$ mode has a strong ϕ, but no other substructure

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

- 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