Hadron Production in e^+e^- Annihilations at BaBar:
implications for the muon anomalous magnetic moment

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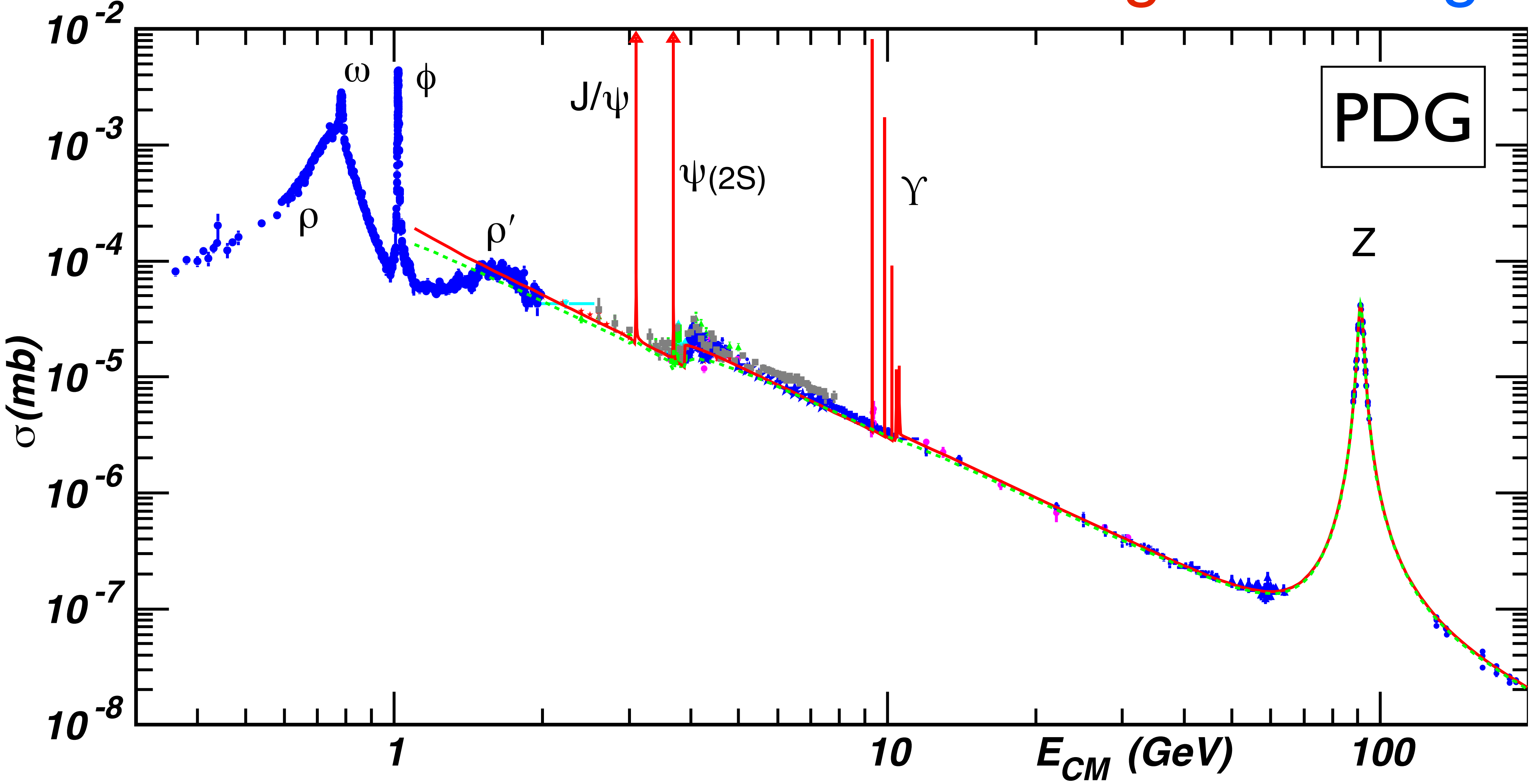
- **Introduction**
- **The $K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$ final states and the Y(2175)** — final, full data sample
- **The $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^0\pi^0$ final states** — final, full data sample; soon to be final
- **The K^+K^- final state** — new result
- **Effect on g_μ–2**
- **Summary**

also, $e^+e^-\rightarrow p\bar{p}$; talk on Wed. afternoon

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

- has been measured over a broad range of energies



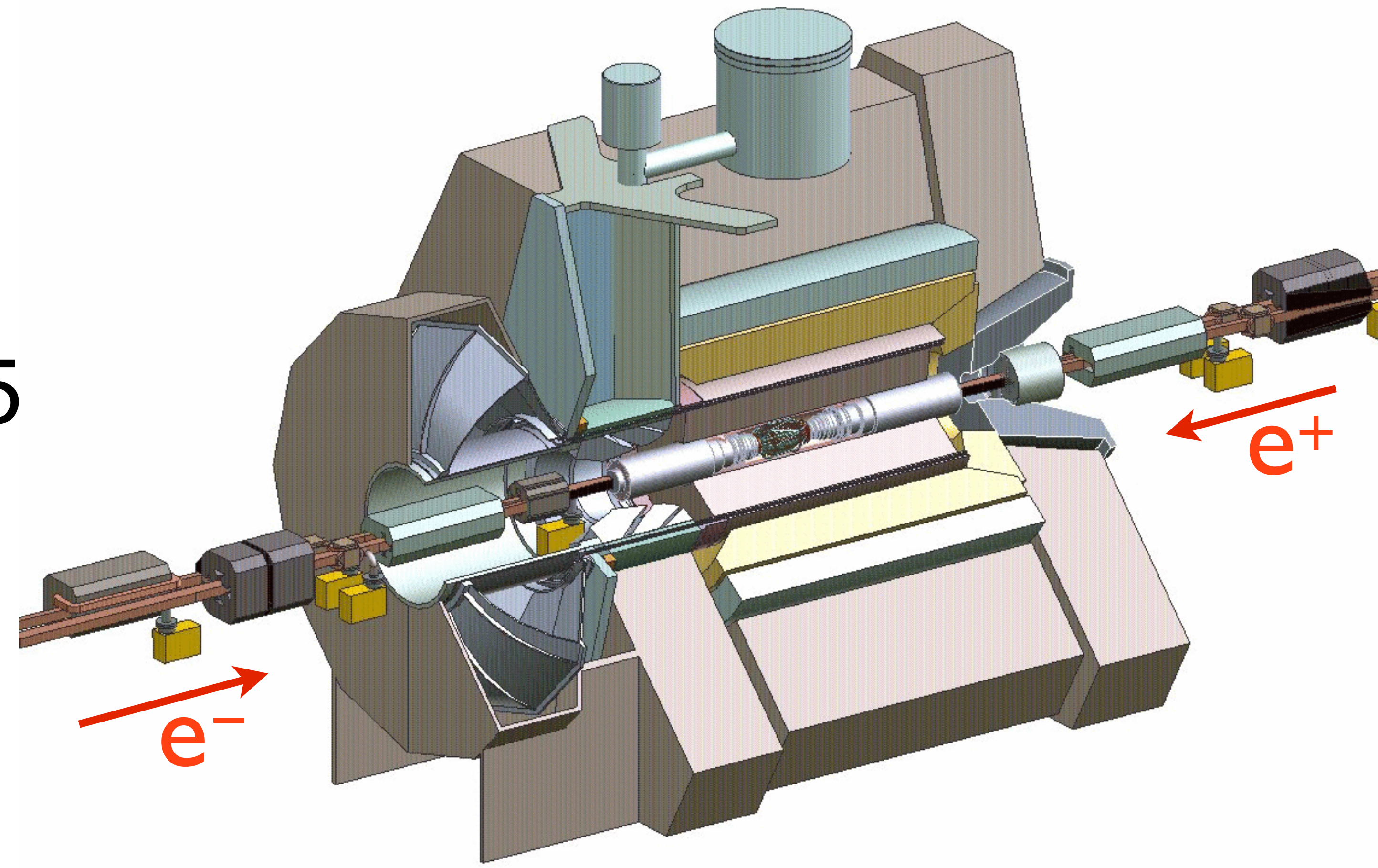
- mostly at fixed energy, highly variable precision
- perturbative QCD works at high E_{CM} $e^+e^- \rightarrow q\bar{q}(g) \rightarrow$ jets
- much structure at very low E_{CM}, near 4, 10 GeV
- theoretical predictions for $g_\mu - 2$, $\alpha(M_Z)$ need better input data for $E_{CM} \lesssim 12$ GeV

The BaBar Experiment

- e^+e^- collisions at E_{CM}=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, $\beta\gamma$=0.55

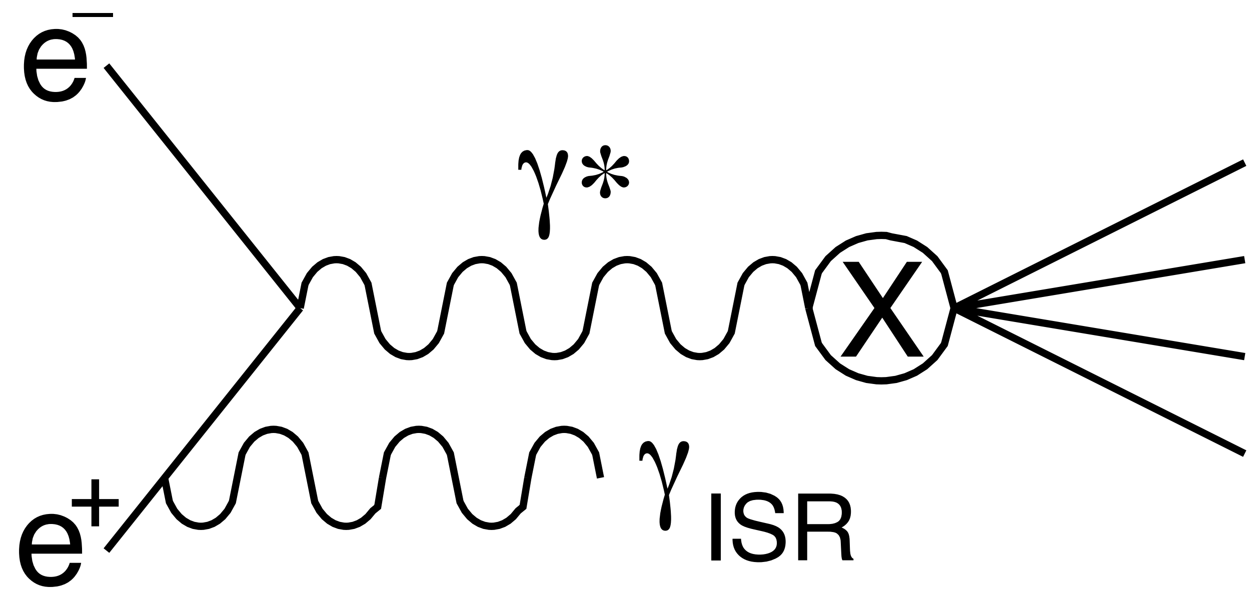
- asymmetric detector
  - → c.m. frame acceptance $-0.9 \sim \cos\theta^* \sim 0.85$ wrt e^- beam



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

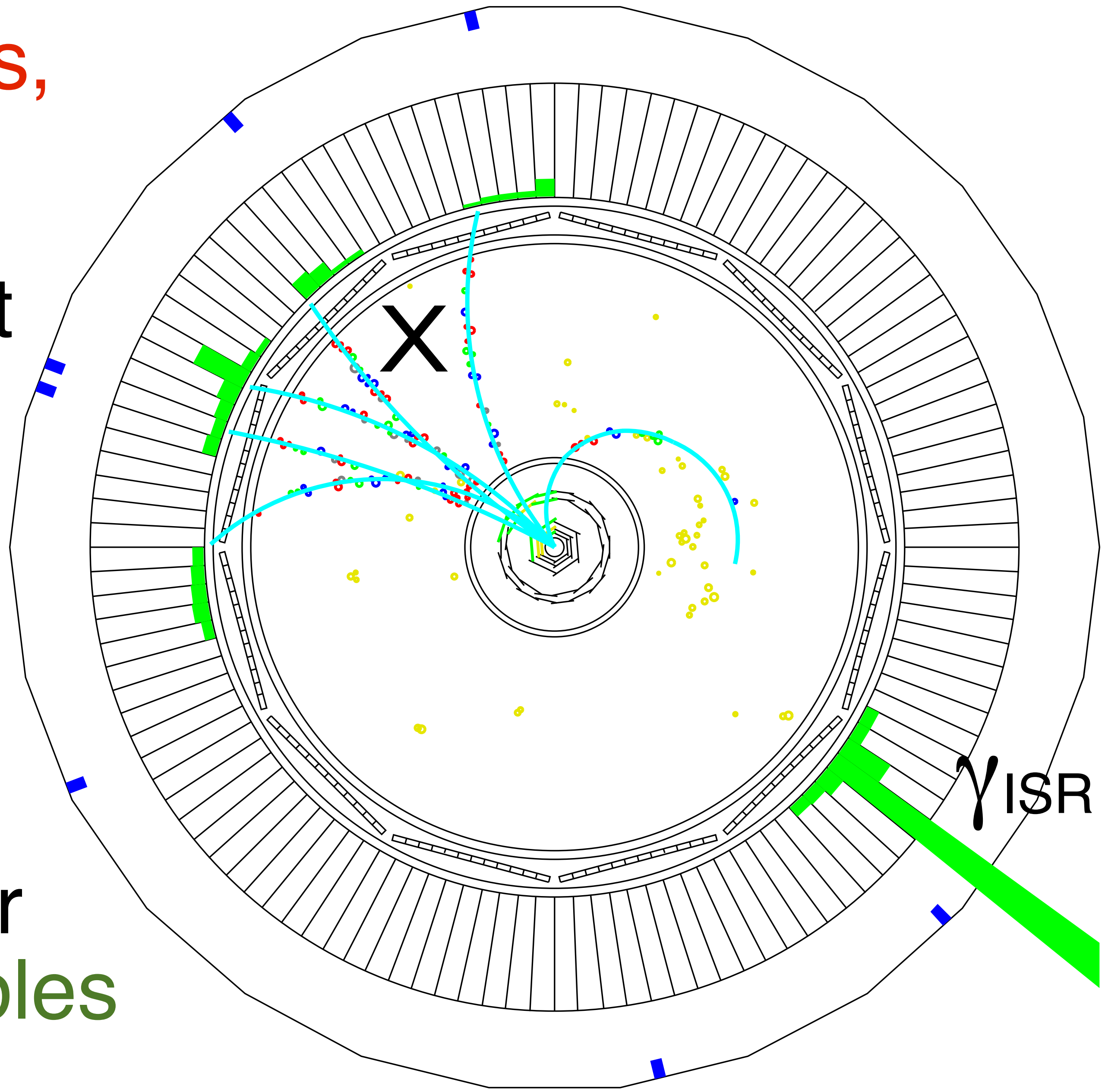
- high luminosity
  - → ~520 fb^{-1} accumulated
  - ↔ 1.7 billion $e^+e^-\to q\bar{q}$ events
  - ↔ 12 million $e^+e^-\to\gamma_{ISR}\rho^0$
  - ↔ 1 million $e^+e^-\to\gamma_{ISR}\phi$

Initial State Radiation in e^+e^- Annihilations



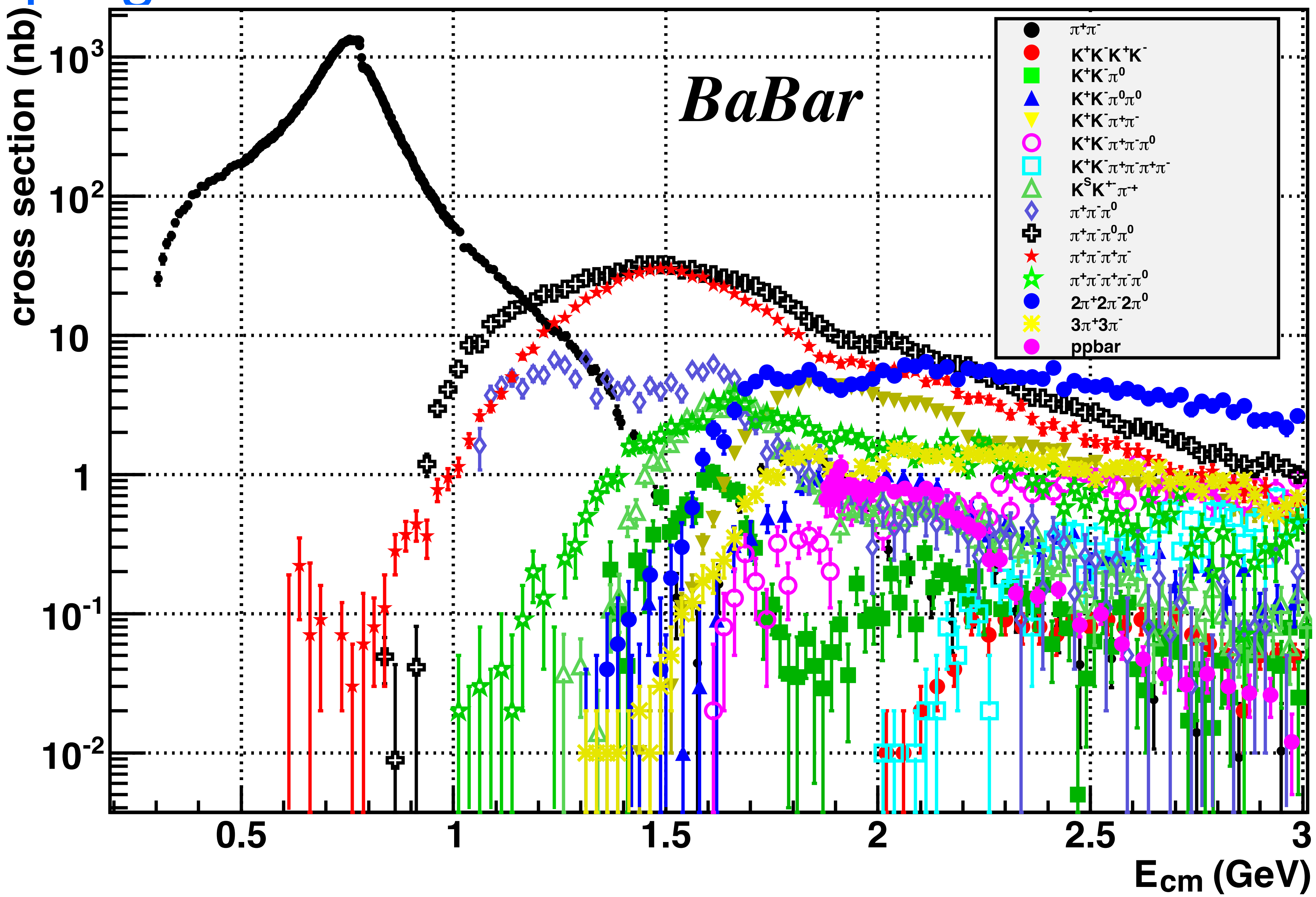
- $e^+e^- \rightarrow \gamma_{ISR} e^+e^- \rightarrow \gamma_{ISR}\gamma^* \rightarrow \gamma_{ISR} X$
- X is any allowed (hadronic) system, e.g.,
  - → a resonance with $J^{PC}=1^{--}$
  - → a particle-antiparticle pair
  - → 3, 4, ... particles
  - → 2 or more jets
- the cross section: $d\sigma(s,s',\theta_\gamma)/ds'd\cos\theta_\gamma = W(s,s',\theta_\gamma)\sigma(s')$
- the radiator function W is known to ~1%
- measure $\sigma(e^+e^-\rightarrow X)$ vs. $m = m_{\gamma^*} = m_X = E_{CM} = \sqrt{s'}$

- ISR accesses a continuous, wide s′ range in a single experiment
  - → very small point-to-point systematic errors
- if the γ_{ISR} is detected then the system X is also well contained in the detector
  - → ~full acceptance
  - → measure the full angular distribution, other variables



- the hadronic system X is boosted
  - → good efficiency and resolution all the way down to threshold
- also
  - → mass resolution worse than collider E_{CM} spread
  - → need very high luminosity at the nominal E_{CM}

- BaBar has a program to measure all individual modes
  - → status in late 2011 (see refs. in backup)

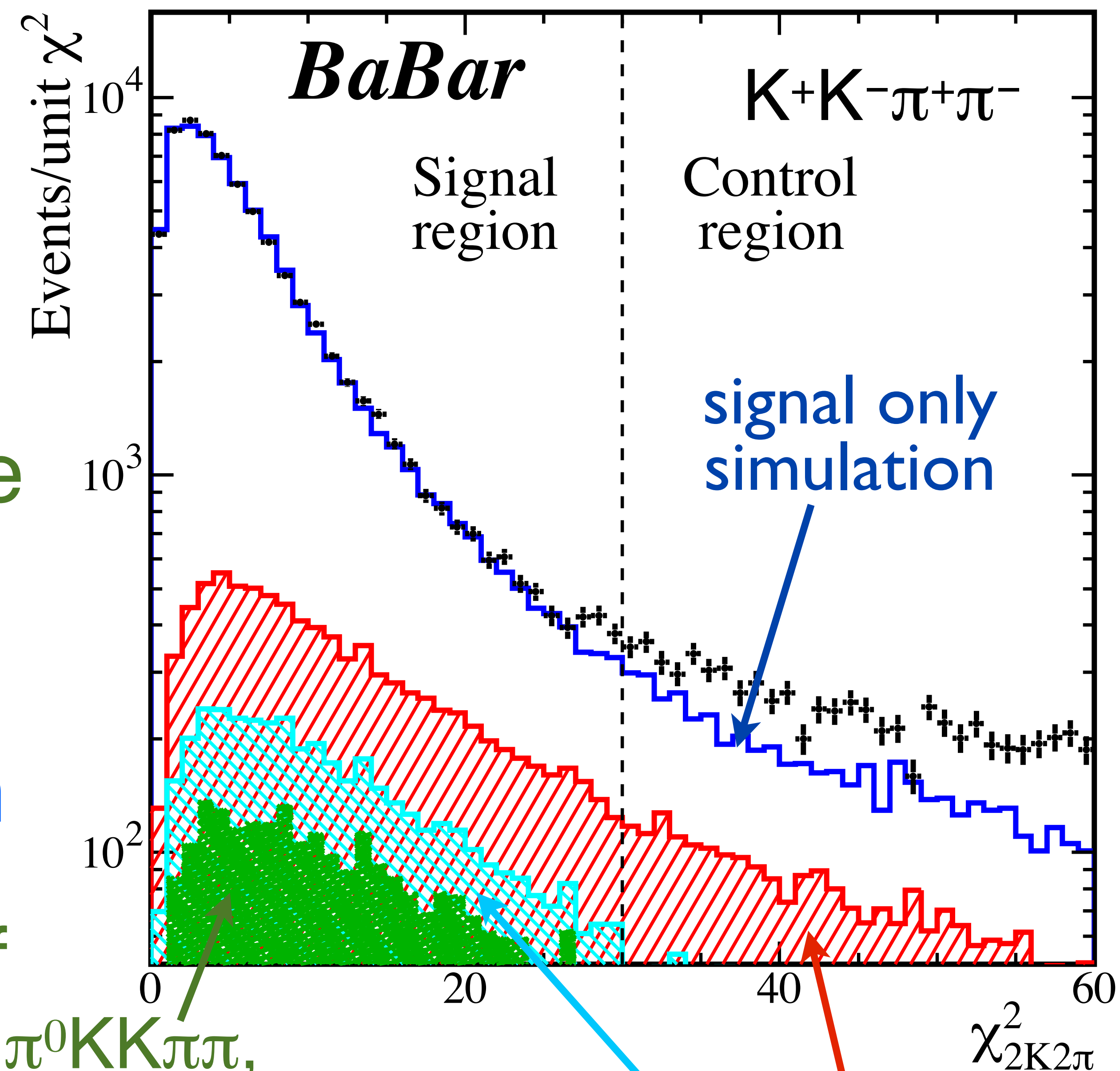


- → sub-% precision on $\pi^+\pi^-$; 1-2% per hadron on others
- → need K^+K^-, K_SK_L, $K_SK_L\pi\pi$, $K_SK^+\pi^-\pi^0$, $\pi^+\pi^-3\pi^0$, $\pi^+\pi^-4\pi^0$
- → could use improved $K^+K^-\pi\pi$, $\pi^+\pi^-\pi^0$, 4π, 5π, ...
- → 1-2 GeV region is critical for $g_\mu-2$, $\alpha(M_Z)$ calculations

The $K^+K^-\pi^+\pi^-$ and $K^+K^-\pi^0\pi^0$ Final States

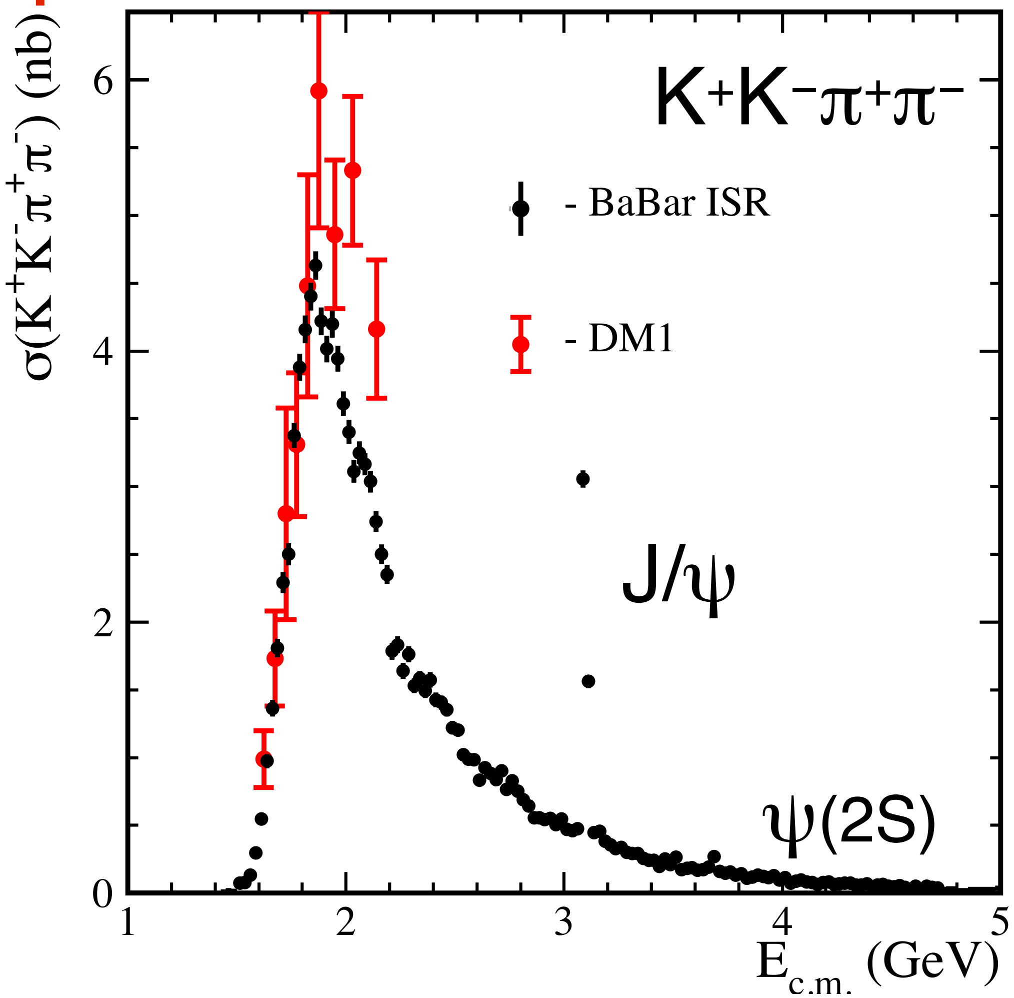
232 fb^{-1}, PRD-RC 74, 091103 (06)
454 fb^{-1}, PRD 86, 012008 (12)

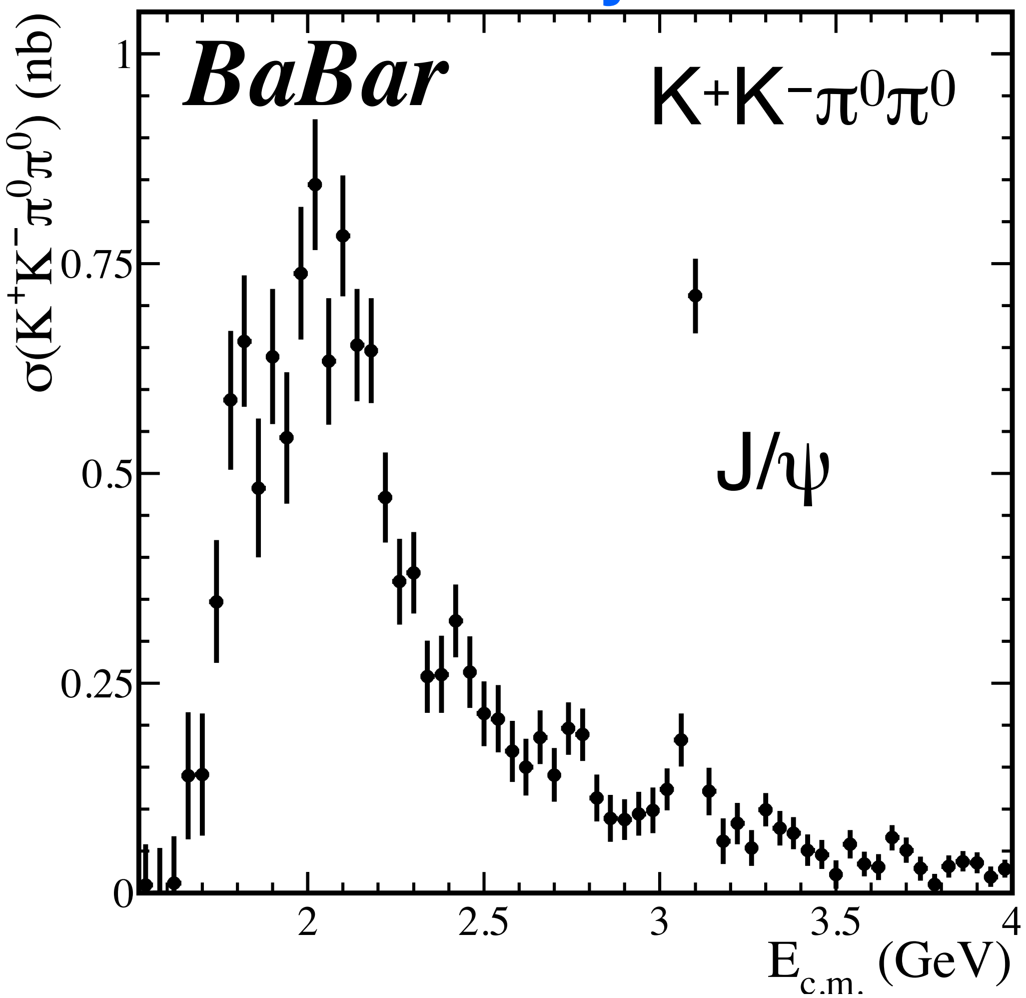
- event selection:
  - → require: a hard γ;
    identified K^+ and K^-;
    identified π^+, π^- or 2 π^0
  - → perform kinematic fits to various hypotheses
  - → select if $\chi^2_{KK\pi\pi\gamma}$ <30 for the signal hypothesis, other χ^2 are poor



- measure backgrounds from the data and subtract
  - → previous/quick msmts. of many, e.g. $e^+e^-\to q\bar{q}\to\pi^0 KK\pi\pi$, $e^+e^-\to\gamma_{ISR}K_S K\pi$, $\gamma_{ISR}4\pi$
  - → others from χ^2 control regions
- measure efficiencies from the data
  - → events with missing particles

• updated cross sections: 5%, 7% overall systematic





→ improved world best $K^+K^-\pi^+\pi^-$, only $K^+K^-\pi^0\pi^0$ msmt.

→ hints of structure in the 2-3 GeV range

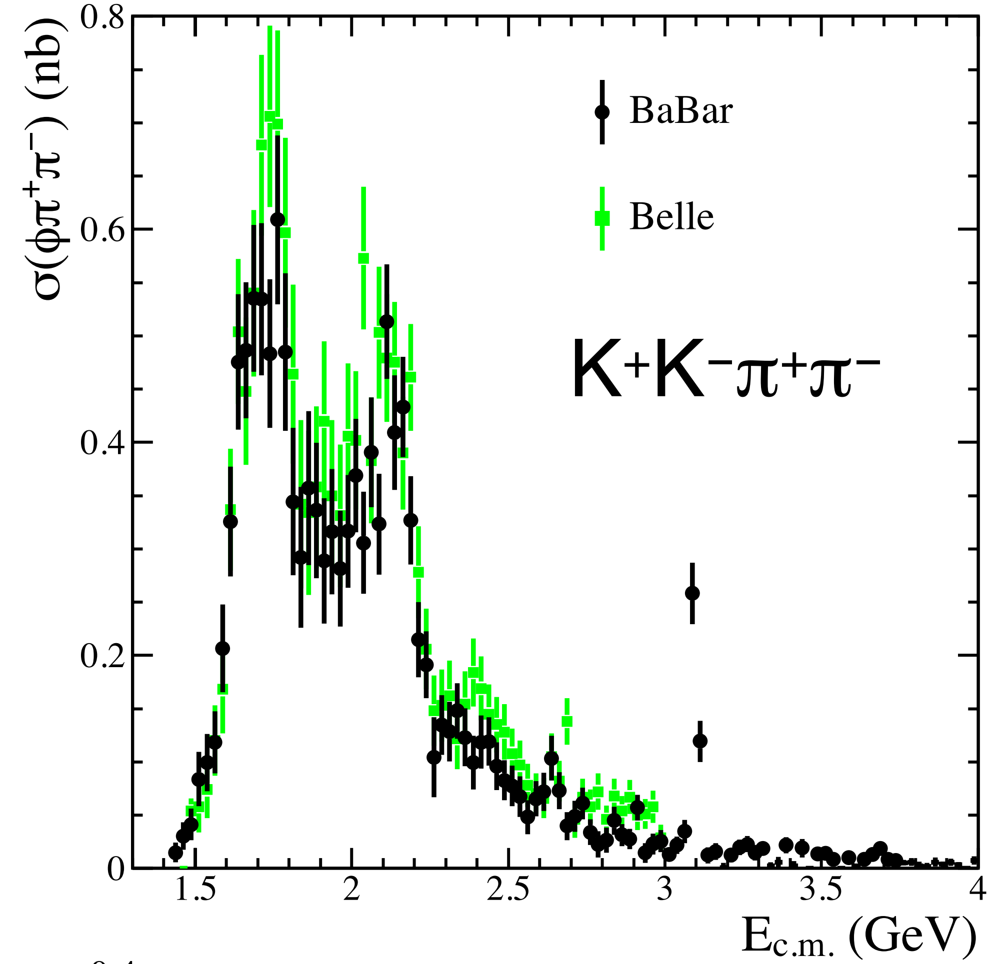
→ signals for J/ψ, $\psi(2S)$ ↔ branching ratios

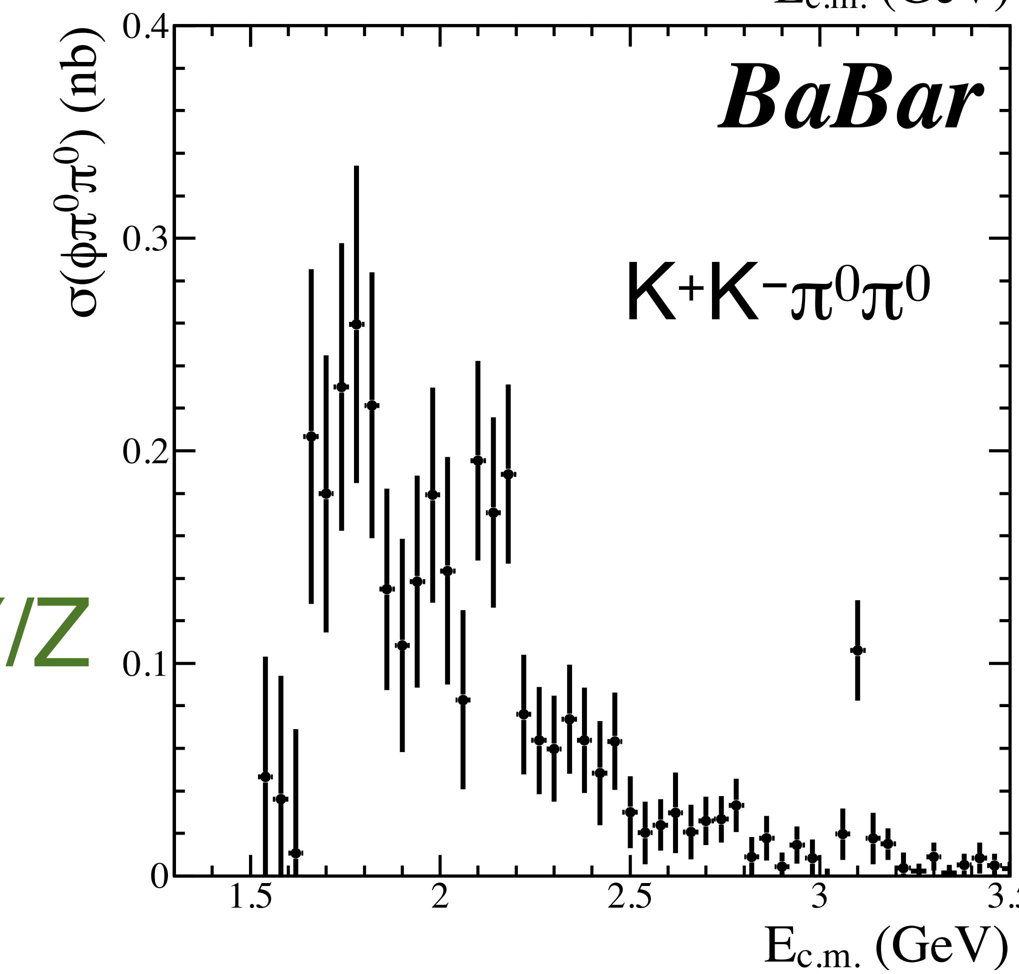
• we observe considerable substructure

→ measure cross sections for $e^+e^-\to K^{*0}(890)K\pi$, $K_2^*(1430)^0K\pi$, $K^+K^-\rho^0(770)$, ...

→ see $K^{*0}(890)K^{*0}(890)$, $K^{*0}(890)K_2^*(1430)^0$, $K_1(1270)K$, ...

- notably the $\phi\pi\pi$ cross sections:
  - ➞ show 2-peak structure
  - ➞ the lower-mass peak is expected from the $\phi(1680)$
- the second peak is a new resonance, the Y(2175)
  - ➞ now seen by BaBar, BES, Belle; and here at 9.3σ
- What is this new state?
  - ➞ so far, we know $J^{PC}=1^{--}$
  - ➞ decays predominantly to ϕf_0
- mass is just below $\Lambda\bar{\Lambda}$ threshold
  - ➞ is it an $s\bar{s}s\bar{s}$ state?
  - ➞ or an analog of one of the X/Y/Z charmonium-like states?
  - ➞ e.g. Y(4260), which is just below $\Lambda_c\bar{\Lambda}_c$ threshold?

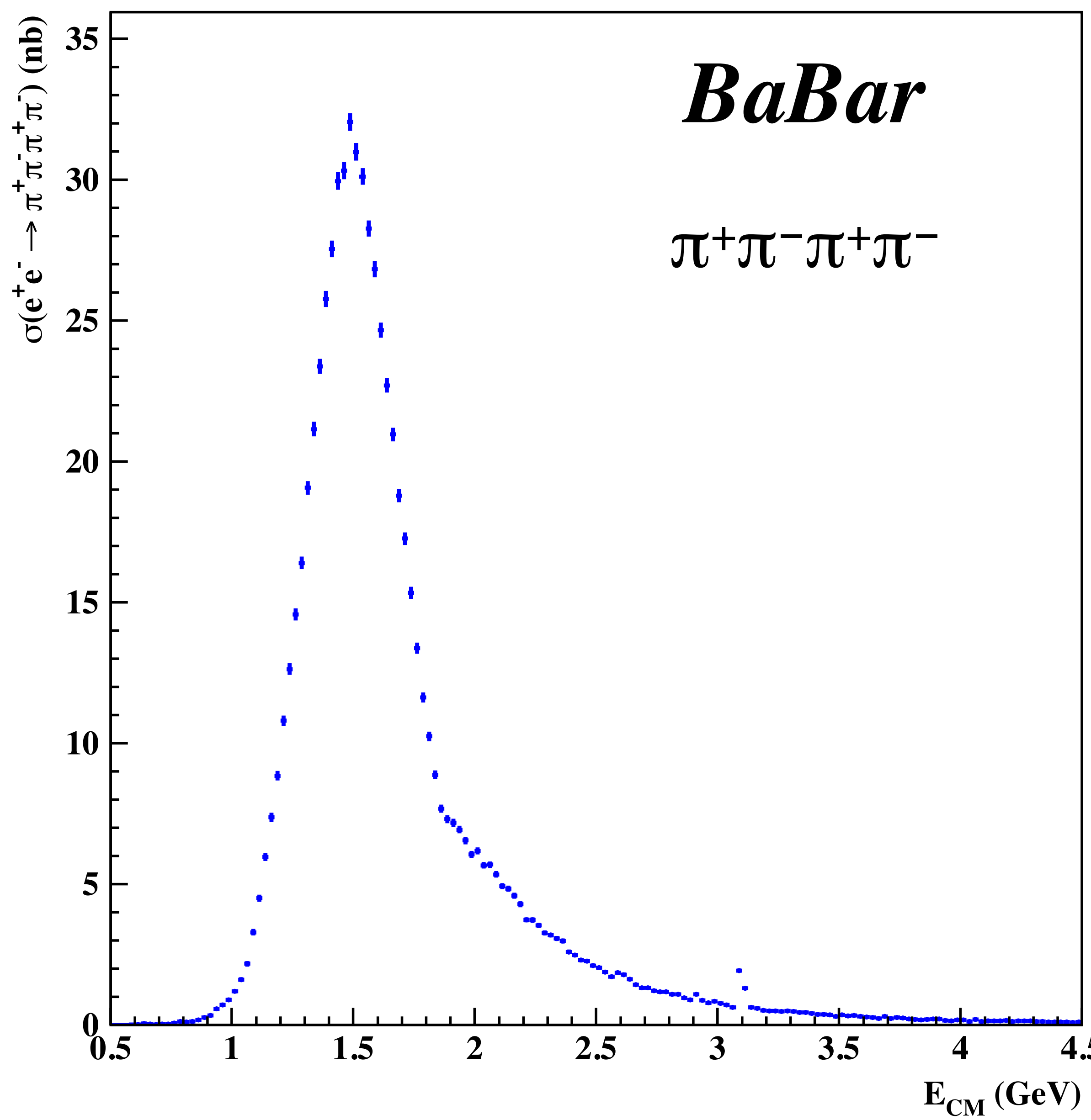




The $\pi^+\pi^-\pi^+\pi^-$ Final State

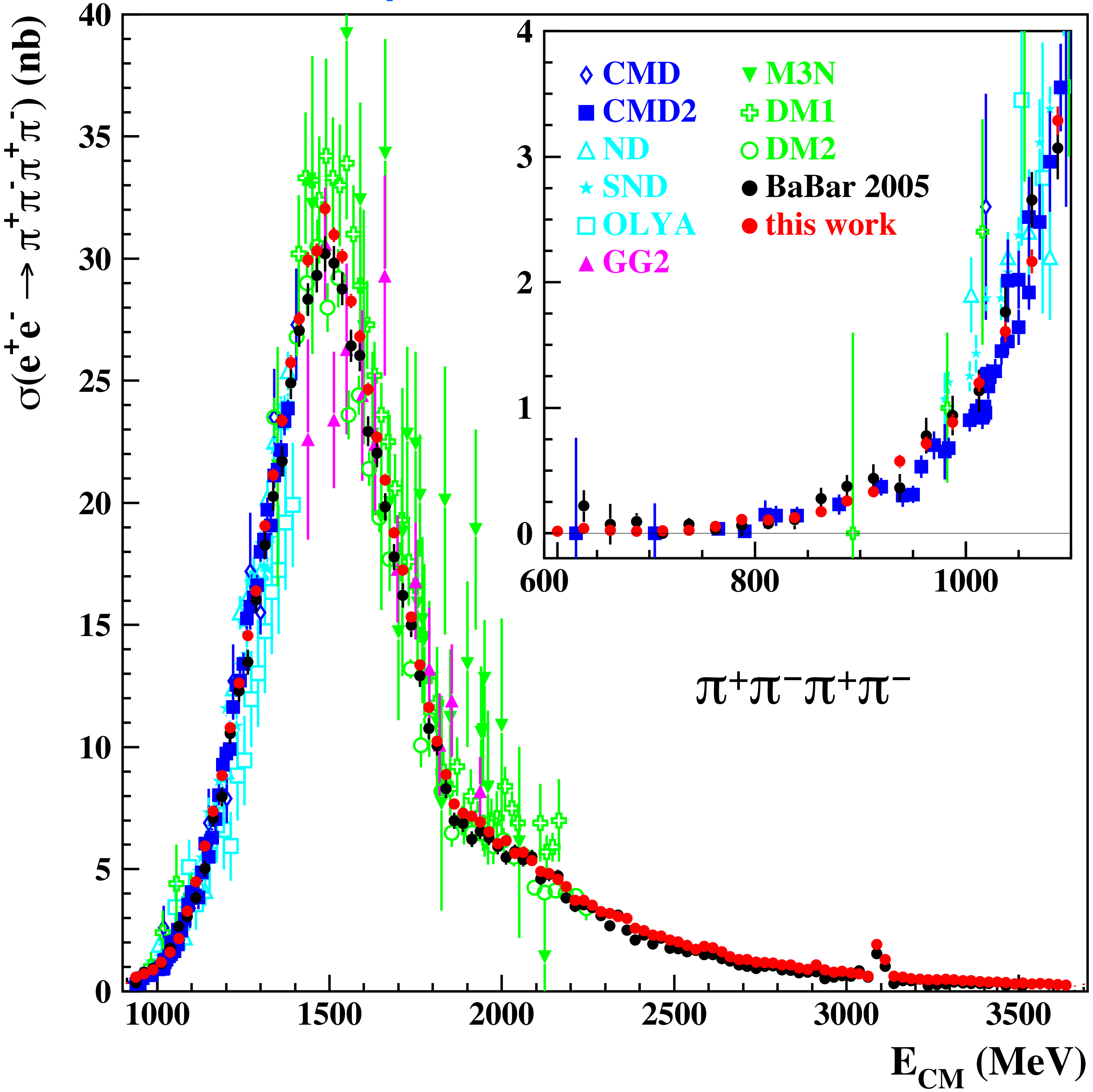
89 fb^{-1}, PRD 71, 052001 (05)
454 fb^{-1}, PRD 85, 112009 (12)

- event selection:
  - → require a hard γ, four loosely id'd $\pi^\pm$
  - → perform kinematic fits to various hypotheses
  - → select if $\chi^2_{\pi\pi\pi\pi\gamma}$ <30 for the signal hypothesis, other χ^2 are poor



- measure backgrounds and efficiencies from the data
  - → cross section measured nicely over a wide range
- (sub)structure:
  - → large contribution from $a_1(1260)\pi$
  - → other modes present, e.g. $f_0(1370)\rho^0$, …
  - → need a partial wave analysis to disentangle

- substantial improvement over our previous result
  - → now 2.4% error in peak region
  - → dominated by tracking efficiency, and background
  - → threshold region understood well



- now better than all previous results

- contribution to g_μ
  - → "standard" integral up to 1.8 GeV

$(13.64 \pm 0.03\,(\text{stat.}) \pm 0.36\,(\text{syst})) \times 10^{-10}$ this result

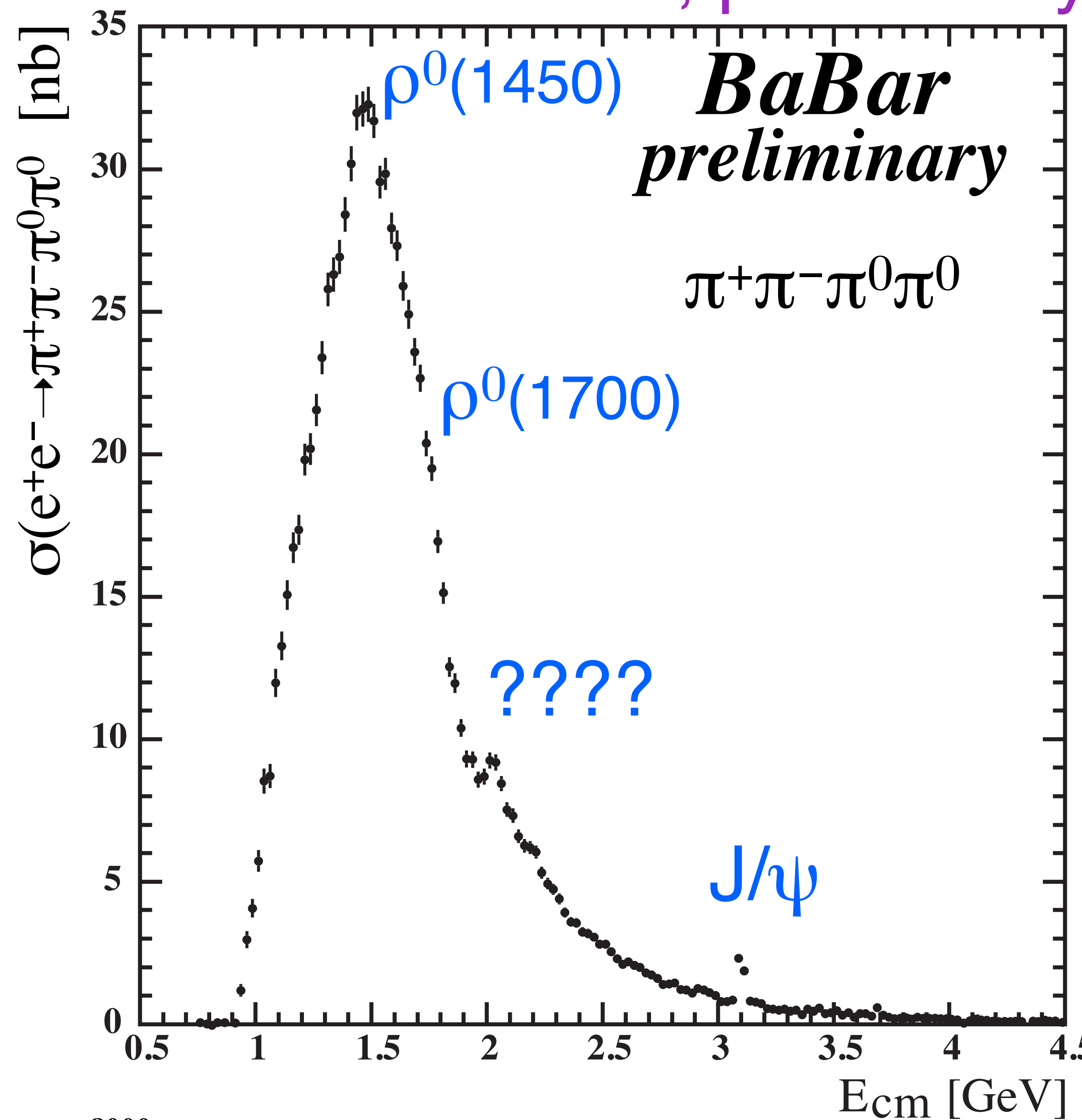
$(13.35 \pm 0.10\,(\text{stat.}) \pm 0.52\,(\text{syst})) \times 10^{-10}$ current avg.

(includes our prev. msmt.)

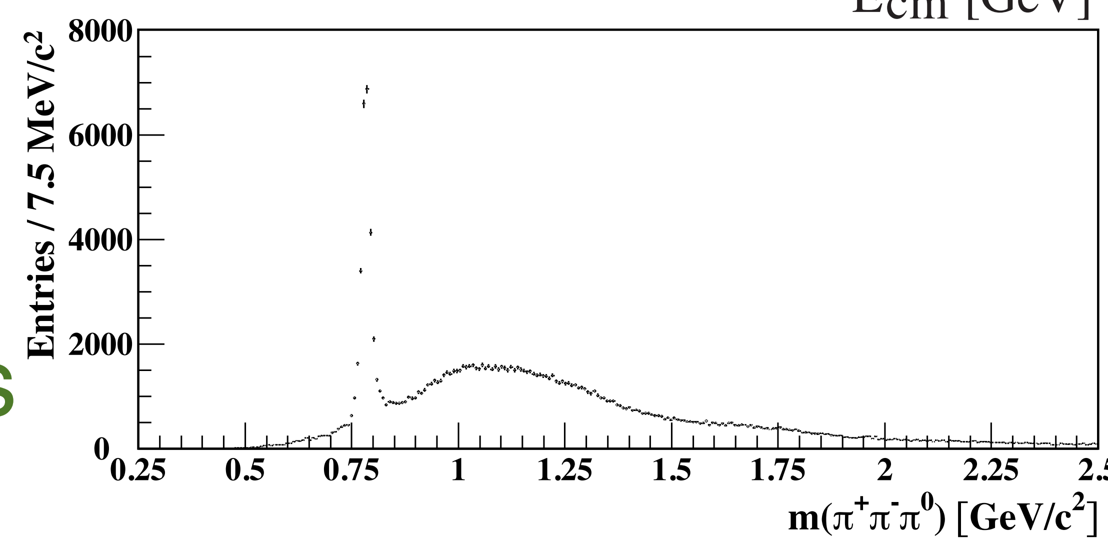
The $\pi^+\pi^-\pi^0\pi^0$ Final State

239 fb^{-1}, preliminary

- event selection:
  - → require: a hard γ;
    loosely identified π^+, π^-
    2 good π^0 candidates
  - → perform kinematic fits to various hypotheses
  - → select if $\chi^2_{\pi\pi\pi\pi\gamma}$ <30 for the signal hypothesis, other χ^2 are poor

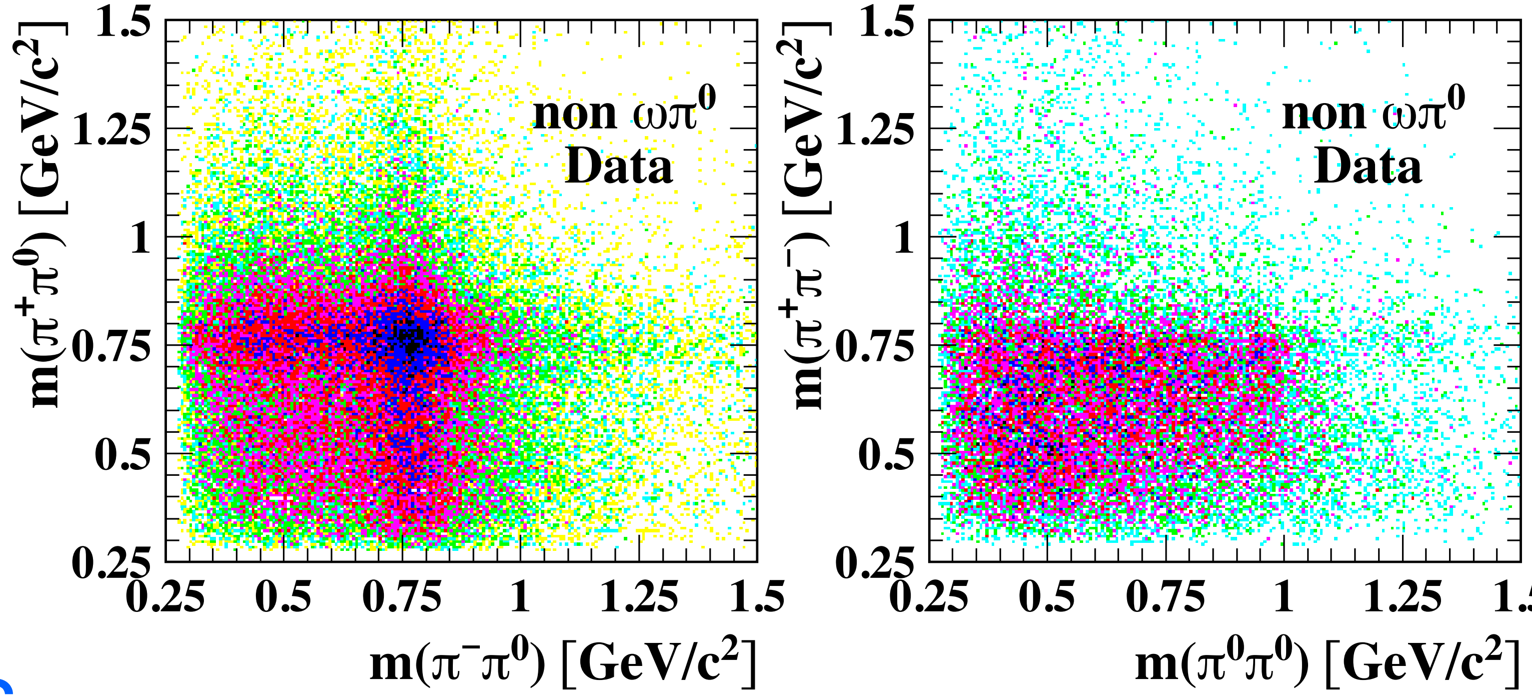


- measure backgrounds and efficiencies from the data
  - → cross section measured nicely over a wide range



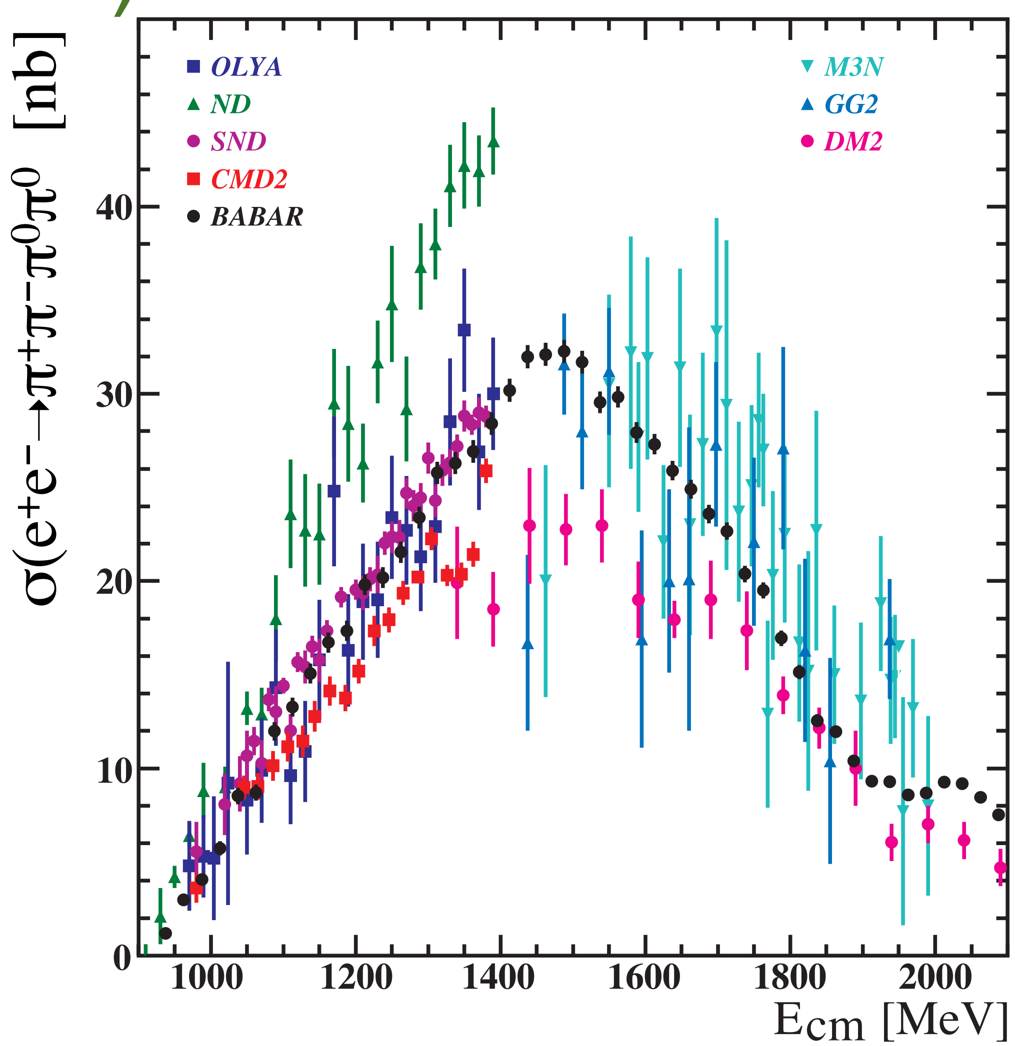
- (sub)structure:
  - → several identifiable features
  - → $\omega\pi^0$ and $a_1(1260)\pi$ dominate

- we also see quite strong $\rho^+\rho^-$ and $\rho^0 f_0$
  → unexpected?
  → looking into E_{CM} dependence



- again, really need partial wave analysis
  → coupled with $\pi^+\pi^-\pi^+\pi^-$ (and other) modes

- substantial improvement over previous results

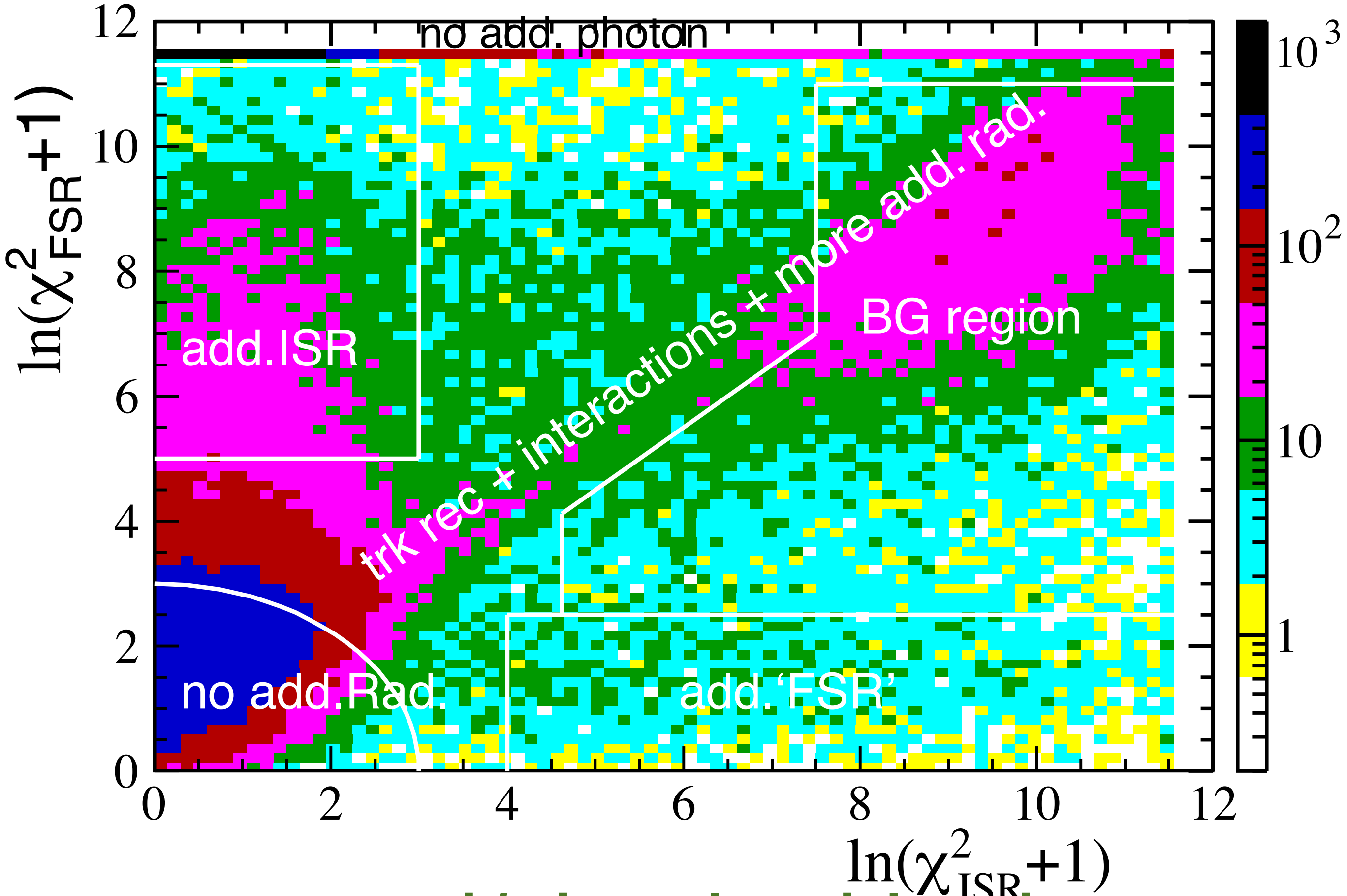


- contribution to g_μ
  → expect contribution slightly larger than from $\pi^+\pi^-\pi^+\pi^-$
  → with ~5% error (currently 8%)

The K^+K^- Final State

232 fb^{-1}, pub. in preparation

- extremely detailed analysis, similar to our $\pi^+\pi^-$ analysis – aim for sub-% precision
  - → require a hard γ, identified K^+ and K^-
  - → effectively, measure $e^+e^- \to \mu^+\mu^-$, $\pi^+\pi^-$ simultaneously
  - → then consider features specific to $e^+e^- \to K^+K^-$
- must worry about higher-order radiation
  - → kinematic fit including each additional γ; choose best ≡ "FSR"
  - → and a fit assuming an undetected γ along the beam ≡ "ISR"
  - → define signal, control regions the 2D χ^2 plane



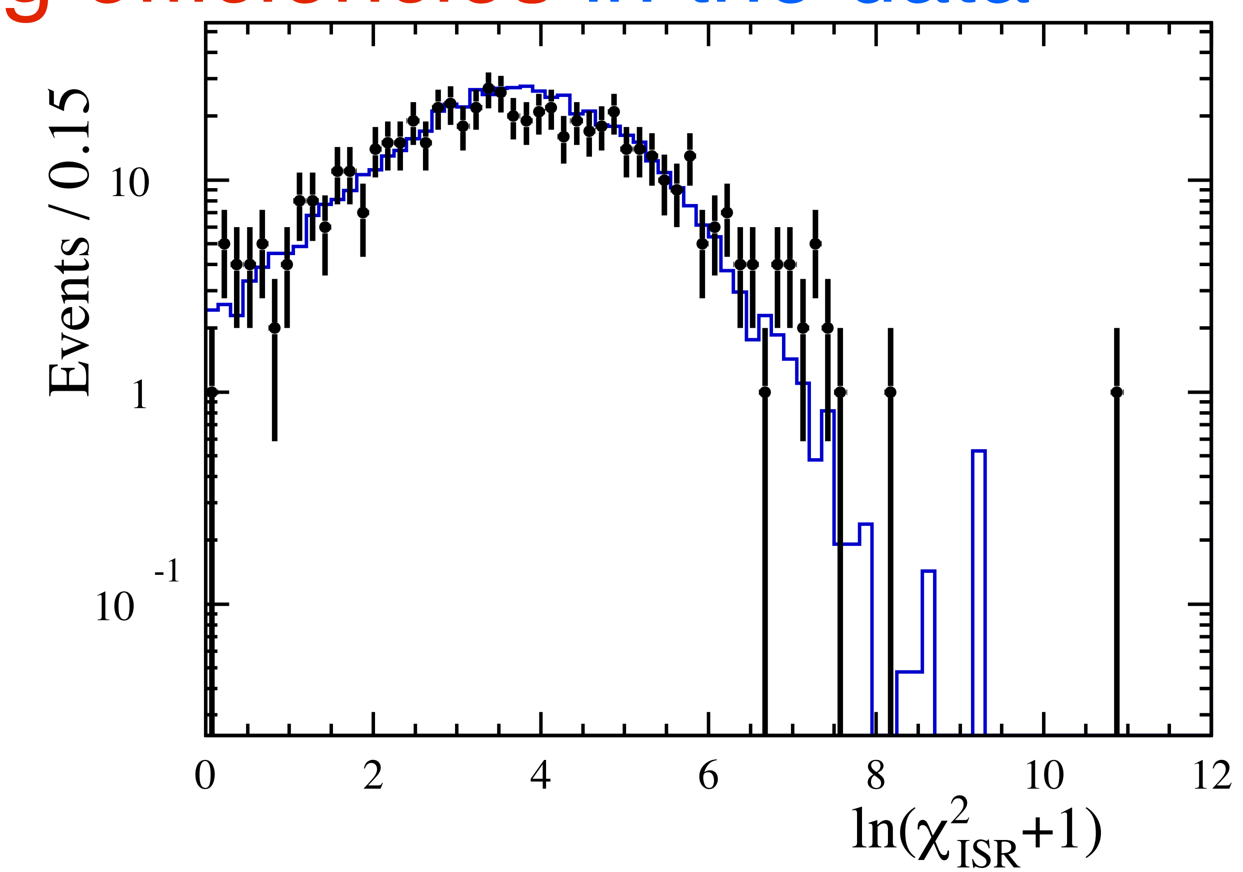
⇒ higher-order corrections measured/checked in data

⇒ also provides many other cross checks

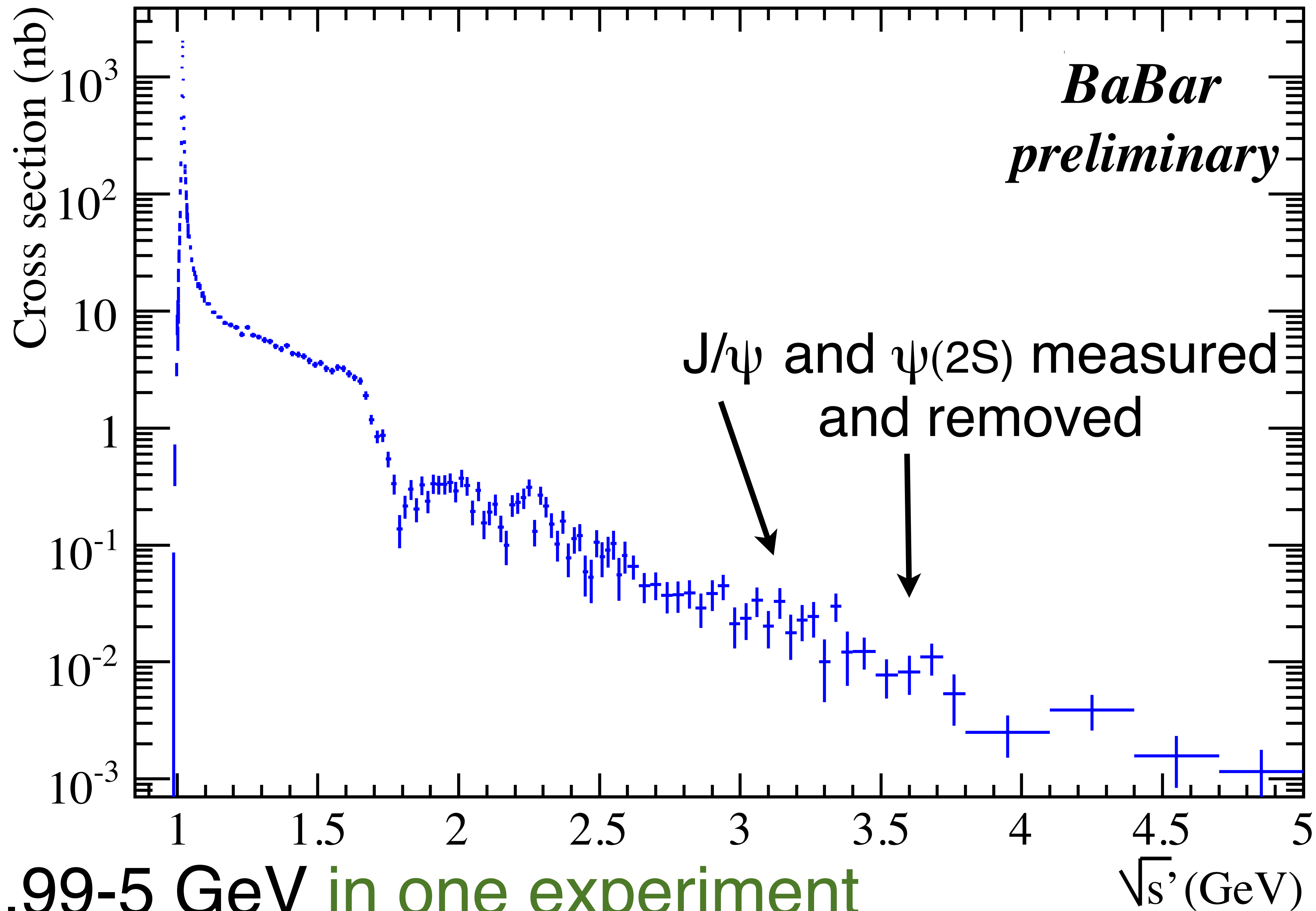
- measure particle identification efficiency from the data
  → using concurrent modes

- measure backgrounds from the data
  → from concurrent modes:
    $\pi^+\pi^-$ small, but spikes to 20% at ρ reflection
    $\mu^+\mu^-$ small at low m_{KK}, limiting above 3 GeV
  → $e^+e^-\to q\bar{q}\to\pi^0\pi^+\pi^-$, $\pi^0K^+K^-$: comb γ_{ISR}, other γ
  → other ISR: previous or dedicated measurements

- measure trigger and tracking efficiencies in the data
  → including correlations, dead regions, etc.
  → many many systematic checks, corrections to the simulation
  → example: χ^2 for events with a track having DOCA 1.5-5 mm from IP



- correct the data and unfold for mass resolution



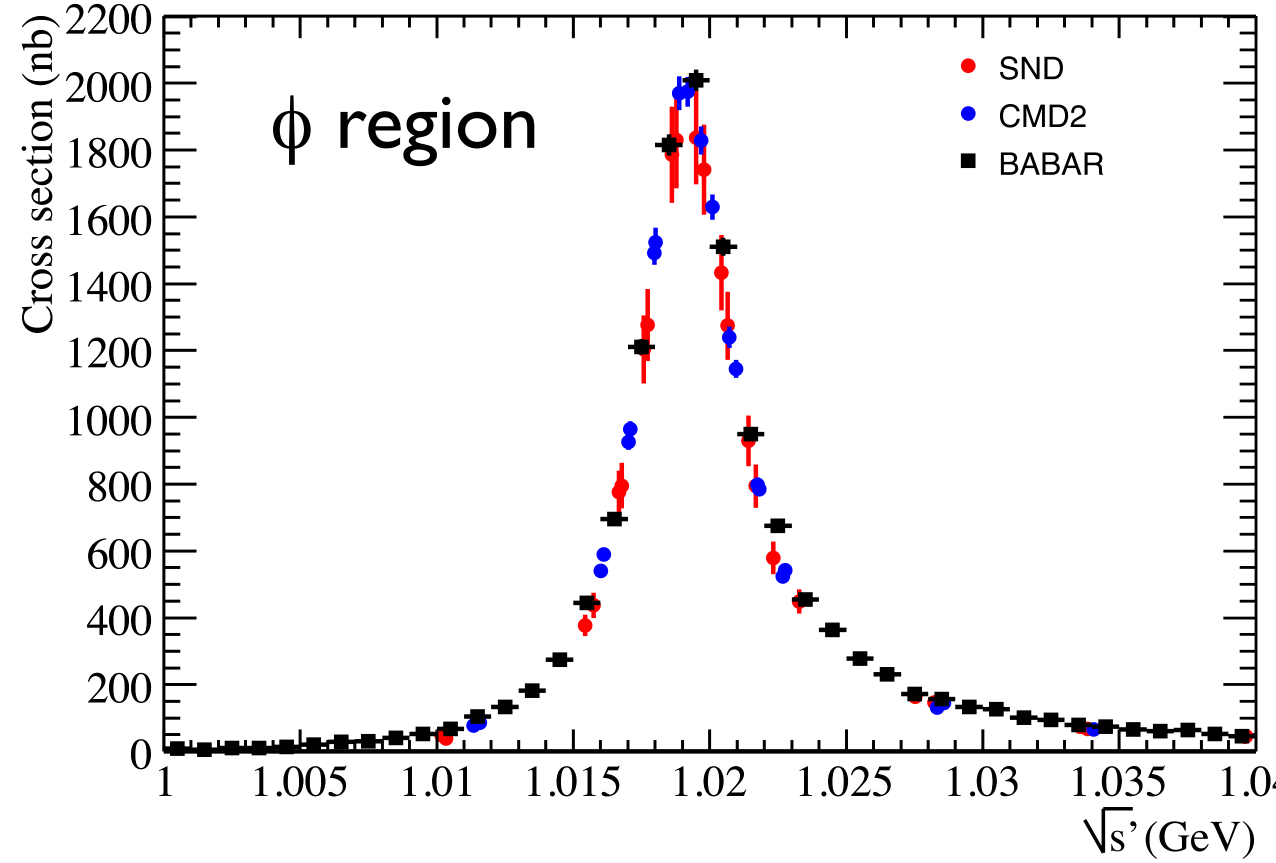
→ 0.99-5 GeV in one experiment

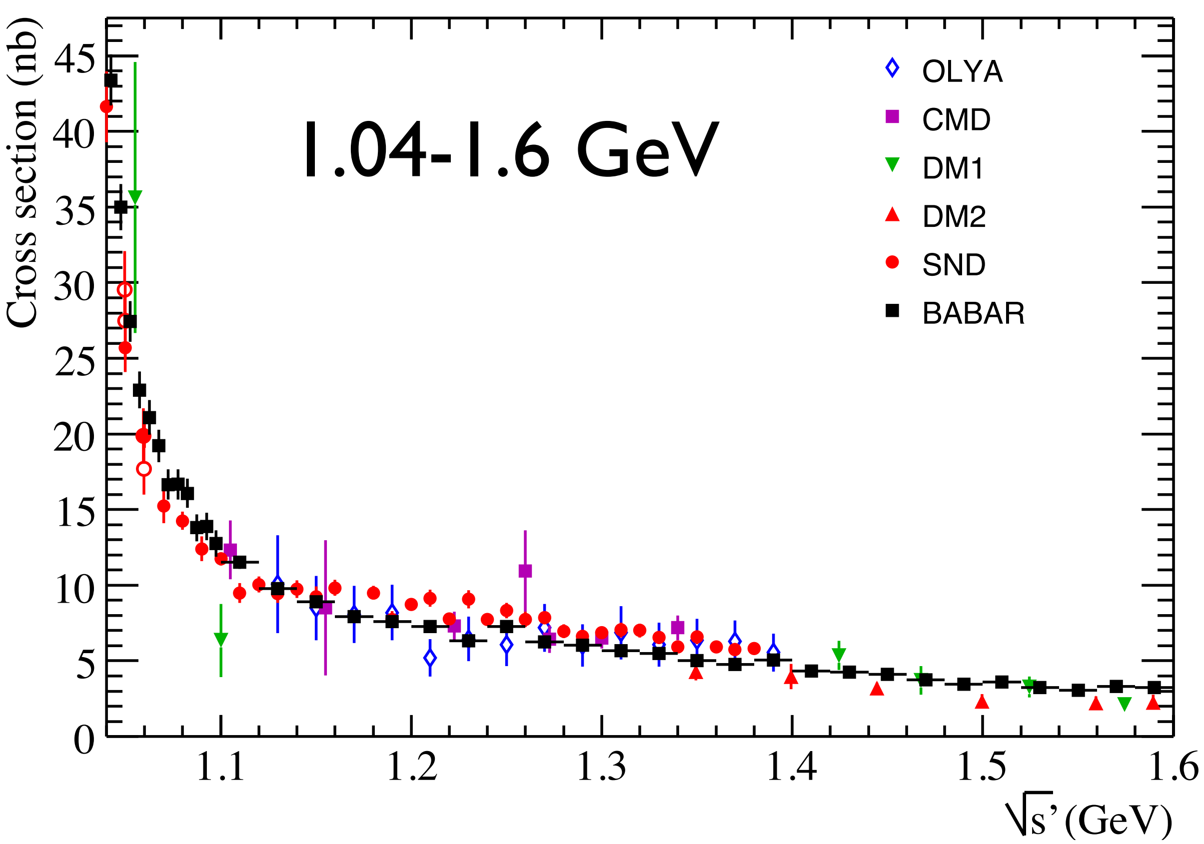
→ 0.7% systematic near φ peak, →3.4% at 1.4 GeV
7 % at 3 GeV

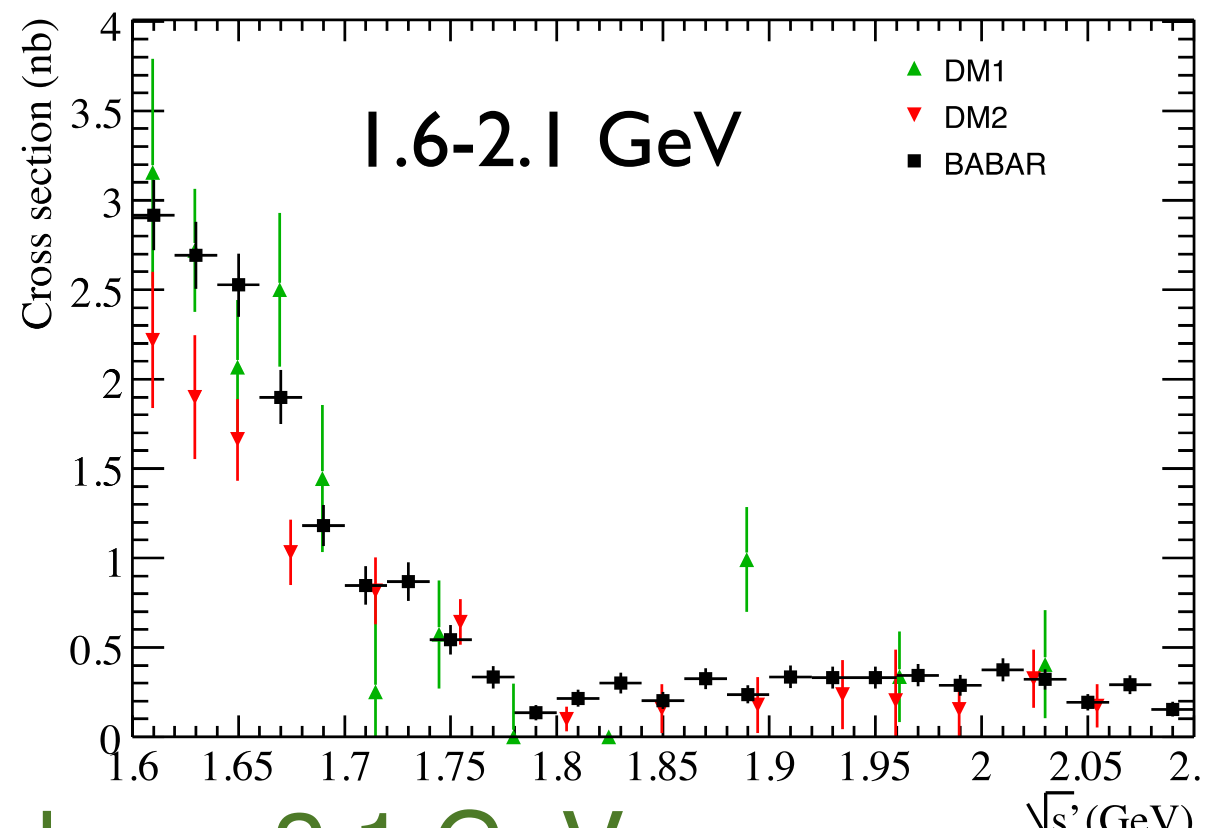
→ quite a bit of structure; needs to be understood...

→ ...but needs a coupled channel analysis

- comparison with previous results
  - → generally consistent:
  - → > SND, E_{CM} > 1.1 GeV
    < SND, E_{CM} < 1.1 GeV
  - → above DM2



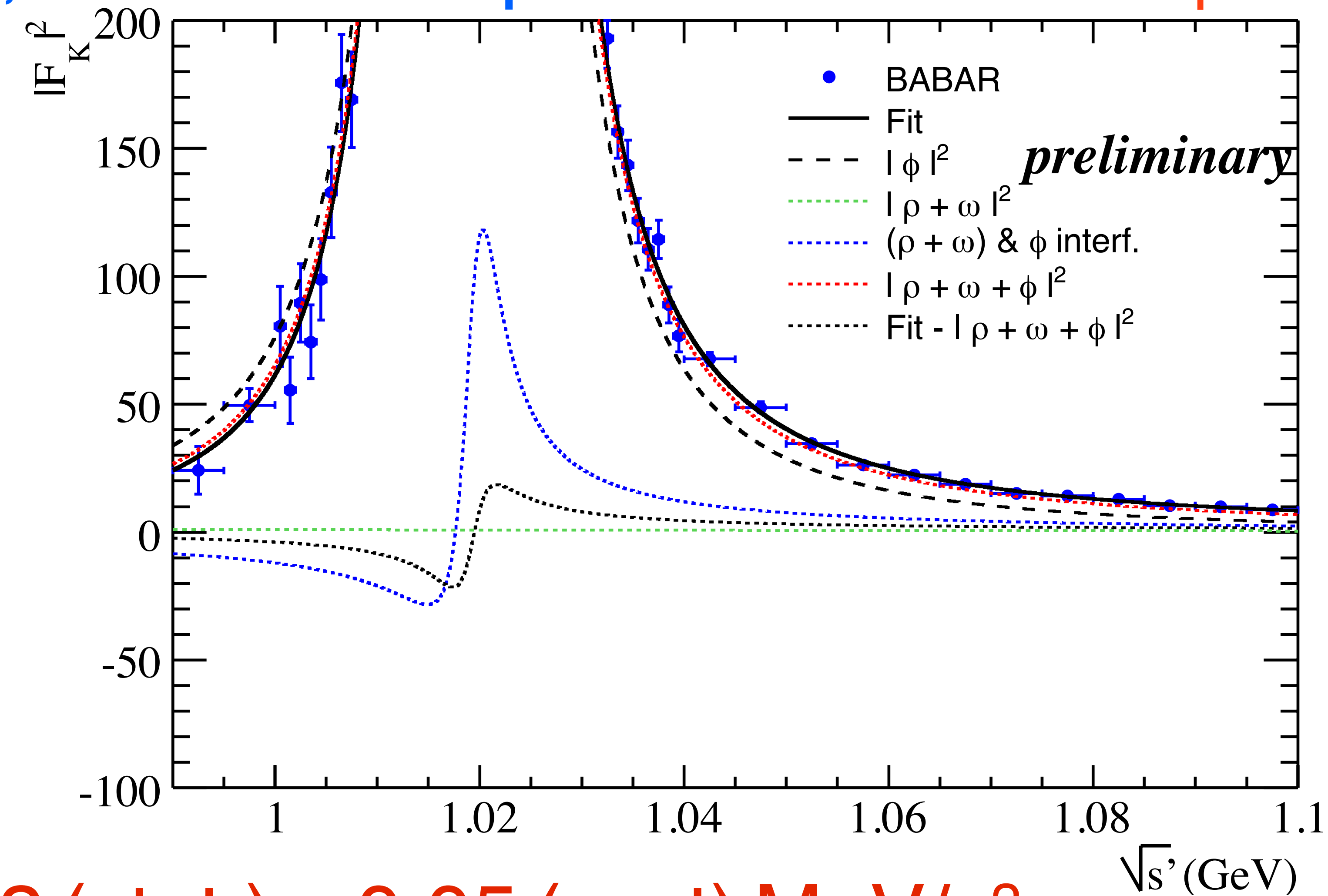




→ no other measurements above 2.1 GeV

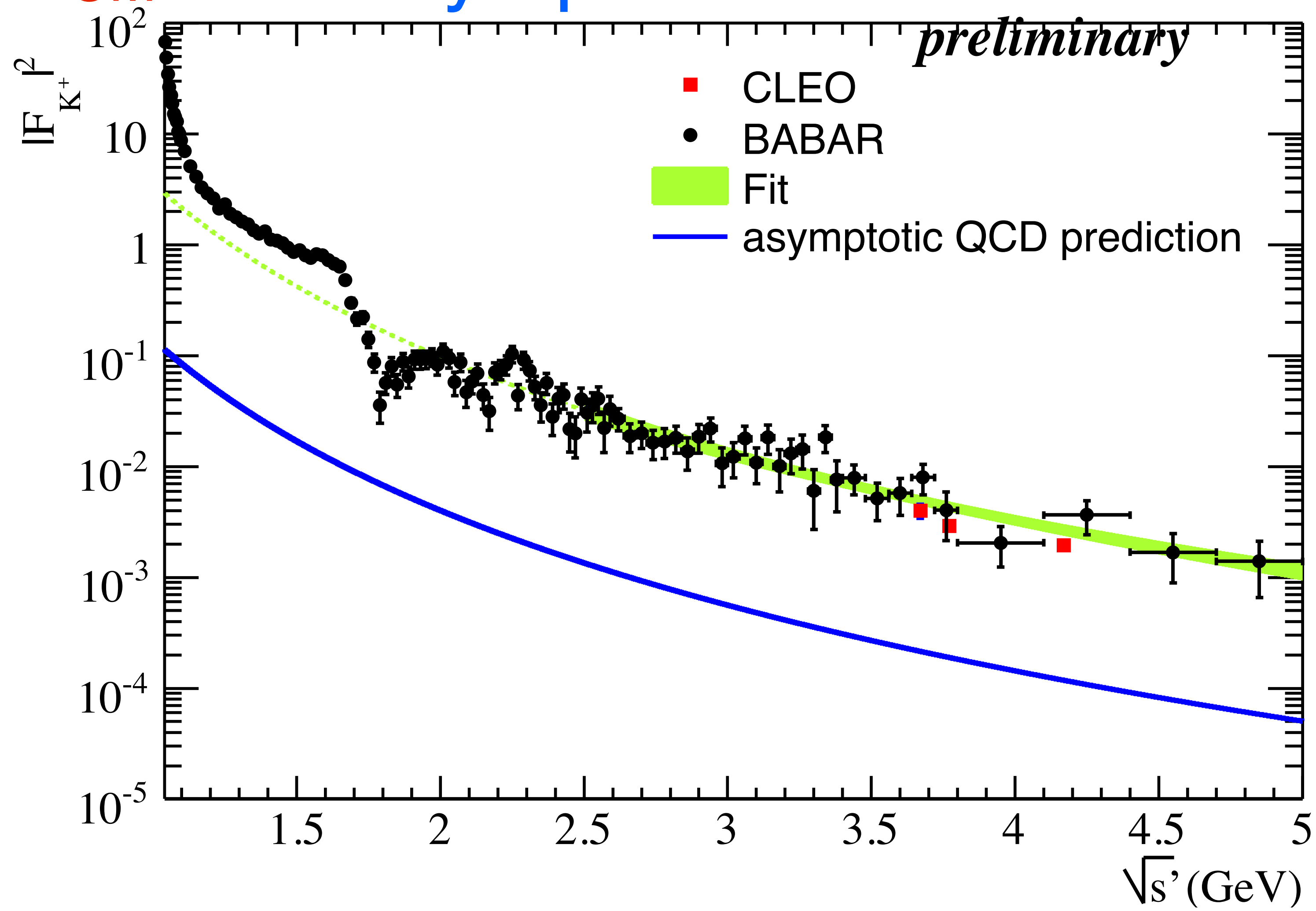
→ most precise measurement above 1.4 GeV

- convert to form factor, fit to extract parameters of the ϕ
  - → use wide m_{KK} range to constrain other resonances
  - → small but important effects from ρ, ω



- mass
  m_ϕ = 1019.51 ± 0.02 (stat.) ± 0.05 (syst) MeV/c^2
  1019.455 ± 0.020 PDG
- width
  Γ_ϕ = 4.29 ± 0.04 (stat.) ± 0.06 (syst) MeV
  4.26 ± 0.04 PDG
- (e^+e^- width)x(K^+K^- Branching Fraction)
  $\Gamma_\phi^{ee} B_{KK}$ = 0.634 ± 0.07 (exp.) ± 0.04 (fit) keV

- fit form factor at high E_{CM} with asymptotic QCD form
  - ➞ consider data above 2.5 GeV
  - ➞ good fit quality
  - ➞ slope consistent with QCD ...
  - ➞ but magnitude is not



- contribution to g_μ
  - ➞ "standard" integral up to 1.8 GeV

$(22.93 \pm 0.18\,(\text{stat.}) \pm 0.22\,(\text{syst}))\ \text{x}\ 10^{-10}$ this result
$(21.63 \pm 0.27\,(\text{stat.}) \pm 0.68\,(\text{syst}))\ \text{x}\ 10^{-10}$ current avg.

The Anomalous Muon Magnetic Moment

- the theoretical calculation of $g_\mu-2$ requires the integral

  $$a_\mu^{had} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} K(s)\sigma_{had}(s)ds, \qquad \text{with } K(s) \sim 1/s$$

- the $e^+e^-\to\pi^+\pi^-$ process contributes most to this integral
  → our measurement was an important contribution
- last year, the theory and experimental values differed by $(28.7\pm8.0)\times10^{-10}$, or 3.6σ M. Davier, et al., EPJC 71, 1515 (11)
- next largest contributions and uncertainties are from the 1-2 GeV region
  → K^+K^-: $21.63 \pm 0.73 \to 22.93 \pm 0.28$
  → $\pi^+\pi^-\pi^+\pi^-$: $13.35 \pm 0.53 \to 13.64 \pm 0.36$
  → $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0$, ... still to come
- overall effect of BaBar measurements so far
  → reduce error on global fits by ~25%
  → move value slightly closer to the SM value

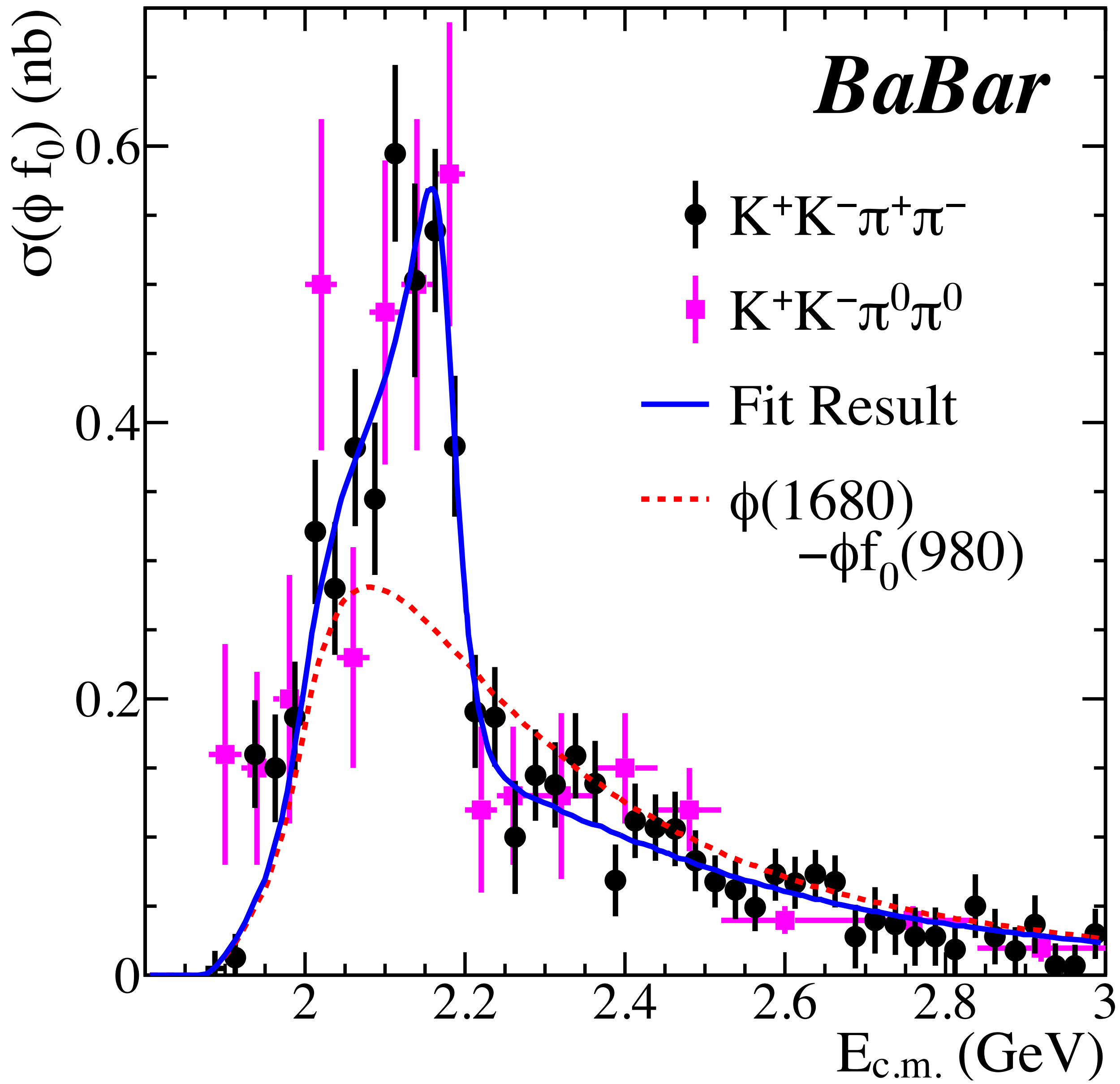
Summary

- BaBar continues to make large contributions to hadron physics via initial state radiation
  - → e^+e^- annihilations at low energy
  - → meson and baryon form factors
  - → discovery of new states and spectroscopy of others
  - → improved understanding of R, $g_\mu-2$, $\alpha(M_Z)$
- recent new/improved measurements
  - → $e^+e^- \to K^+K^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, 1.3-4.5 GeV
  - → $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$, 0.5-4.5 GeV
  - → $e^+e^- \to K^+K^-$, 0.99-5 GeV
- and coming soon
  - → $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$, 0.5-4.5 GeV
- large influence on $g_\mu-2$
  - → error on prediction reduced
  - → still ~3.6σ discrepancy with experiment

Backup Slides

- What is this new state?
  → $J^{PC}=1^{--}$
- simultaneous fit to several mass distributions gives:

m_Y: 2180± 8± 8 MeV/c²
Γ_Y: 77± 15± 15 MeV
σ_Y: 93± 21± 10 pb
ψ_Y: −2.11±0.24±0.12 rad wrt $\phi(1680)$



- decay modes:
  → $\phi f_0(980)$ dominant
  → hint of non-ϕ KKf_0
  → no evidence for $\phi\pi\pi$ or $KK\pi\pi$ outside ϕf_0 region
  ⇒ unlikely to be a ϕ''
- mass is just below $\Lambda\bar{\Lambda}$ threshold → is it an $s\bar{s}s\bar{s}$ state?
  → analog of Y(4260)- $J/\psi\pi\pi$ just below $\Lambda_c\bar{\Lambda}_c$ threshold?
  → ...or some other charmonium-like state?

BaBar cross sections with ISR

$e^+e^- \rightarrow$:

$\pi^+\pi^-$	threshold-3.0 GeV	PRL 103, 231801 (2009) PRD 86, 032013 (2012)
$\pi^+\pi^-\pi^0$	1.05-3.0 GeV	PRD 70, 072004 (2004)
$\pi^+\pi^-\pi^0\pi^0$	threshold-4.5 GeV	Preliminary
$\pi^+\pi^-\pi^+\pi^-$	threshold-4.5 GeV	PRD 85, 112009 (2012)
$\pi^+\pi^-\pi^+\pi^-\pi^0/\eta$, $K^+K^-\pi^+\pi^-\pi^0/\eta$	threshold-4.5 GeV	PRD 76, 092005 (2007)
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$ $K^+K^-\pi^+\pi^-\pi^+\pi^-$	threshold-4.5 GeV	PRD 73, 052003 (2006)
$K^+K^-\pi^0$, $K^+K_S\pi^-$, $K^+K^-\eta$	threshold-2.6 GeV	PRD 77, 092002 (2008)
$K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$, $K^+K^-K^+K^-$	threshold-4.5 GeV	PRD 86, 012008 (2012)
pp	threshold-4.5 GeV	PRD 73, 012005 (2006) update submitted to PRD
$\Lambda^0\Lambda^0$, $\Lambda^0\Sigma^0$, $\Sigma^0\Sigma^0$	threshold-3.0 GeV	PRD 76, 092006 (2007)
$J/\psi\pi^+\pi^-$	threshold-5.5 GeV	PRL 95, 142001 (2005) PRD 86, 051102 (2012)
$D^{(*)}D^{(*)}$	threshold-6.0 GeV	PRD 79, 092001 (2009)
$\psi(2S)\pi^+\pi^-$	threshold-5.5 GeV	PRL 98, 212001 (2007)