e^+e^- results from BABAR and implications for the muon g-2

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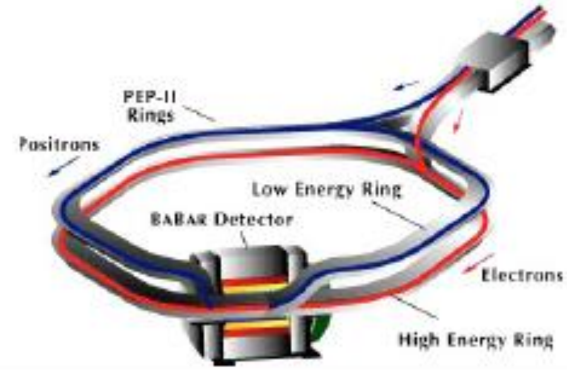
- the BABAR ISR program and the muon g-2
- the dominant $\pi^+\pi^-(\gamma)$ channel
- results on $K^+K^-(\gamma)$
- recent results: toward a complete exclusive measurement up to 1.8 GeV
- BABAR data impact on the g-2 prediction
- ongoing work

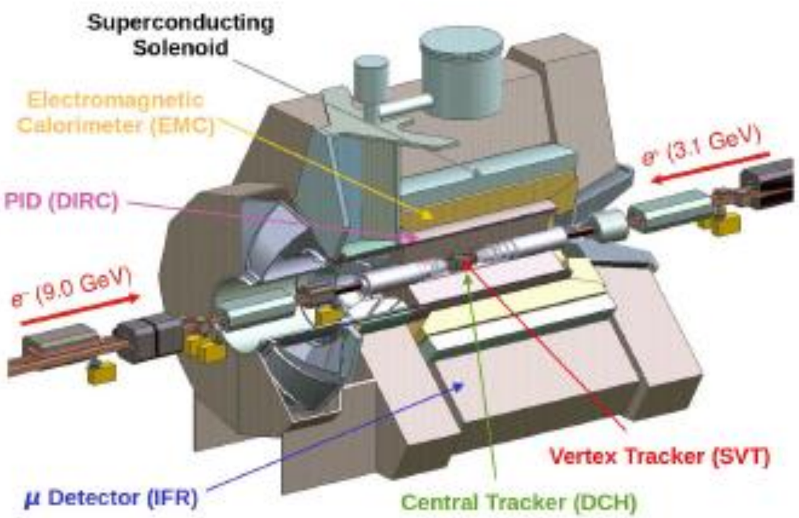
g-2 Theory Initiative
FermiLab, 3-6 June 2017

PEP-II and the *BABAR* detector at SLAC

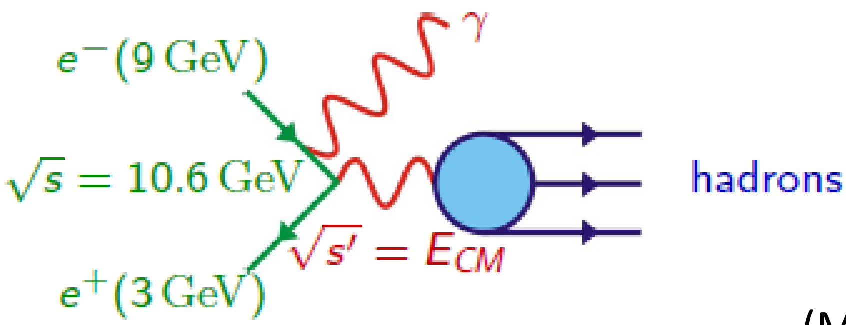
- asymmetric e^+e^--collider: $9\,\mathrm{GeV}$ (e^-) and $3.1\,\mathrm{GeV}$ (e^+)
- $\sqrt{s} = 10.58\,\mathrm{GeV} \Rightarrow \Upsilon(4S)$ $\Rightarrow$ above $B\overline{B}$-threshold



- main purpose: B-physics
- multi purpose detector
- data taken from 1999 – 2008
- integrated luminosity: $531\,\mathrm{fb}^{-1}$ on $\Upsilon(4S)$: $454\,\mathrm{fb}^{-1}$ $\approx 600 \cdot 10^6$ $B\overline{B}$-pairs



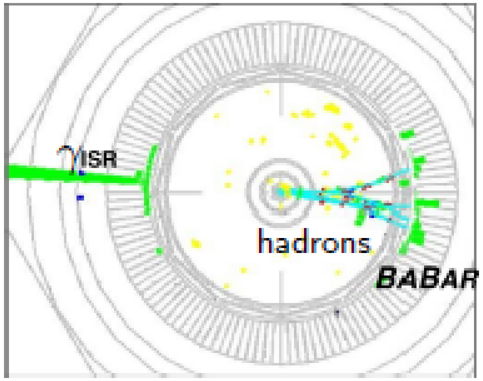
The ISR method at BABAR



$$x = 2E^*_\gamma/\sqrt{s}$$

$$s' = s(1-x)$$

($M^2_{hadrons}$)



- High energy (E^*_γ >3 GeV) detected at large angle
  → defines $\sqrt{s'} = E_{CM}$ and provides strong background rejection
- Event topology: ISR photon back-to-back to hadrons
- → high acceptance, strong boost to hadrons (measurements from threshold and easier PID)
- Final state can be hadronic or leptonic (QED)
  → $\mu^+\mu^-\gamma(\gamma)$ or Bhabha events used to get ISR luminosity
- Kinematic fit including ISR photon
  → removes multihadronic background; improves mass resolution (a few MeV)
- Continuous measurement from threshold to 3-5 GeV
  →reduces systematic uncertainties compared to multiple data sets with different colliders and detectors

The BaBar ISR program

- almost complete set of exclusive hadronic e^+e^- annihilation channels up to 2 GeV
- published:

$\pi^+\pi^-$	PRL 2009; PRD 2012
$K^+ K^-$	PRD 2013
$\pi^+\pi^-\pi^0$	PRD 2004
$2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^- 2\pi^0$, $2(K^+K^-)$	PRD 2007; PRD 2012; PRD 2012
$K^0_S K^{+-}\pi^{-+}$, $K^+K^-\pi^0$, $K^+K^-\eta$	PRD 2005; PRD 2008
$2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-)\eta$, $K^+K^-\pi^+\pi^-\pi^0$, $K^+K^-\pi^+\pi^-\eta$	PRD 2007
$3(\pi^+\pi^-)$, $2(\pi^+\pi^-\pi^0)$, $2(\pi^+\pi^-)K^+K^-$	PRD 2006
$\Phi\ f^0(980)$	PRD 2006; PRD 2007
p p	PRD 2006, PRD 2012
$\Lambda\bar{\Lambda}$, $\Lambda\Sigma^0$, $\Sigma^0\Sigma^0$	PRD 2007
$K^0_S \bar{K}^0_L$, $\bar{K}^0_S K^{\bar{0}}_L \pi^+\pi^-$, $K^0_S K^0_S \pi^+\pi^-$	PRD 2014
K^+K^- large Q^2	PRD 2015
$K^0_S K^{+-}\pi^{-+}\pi^0$, $K^0_S K^{+-}\pi^{-+}\eta$	PRD 2017
$K^0_S K^0_L \pi^0$, $K^0_S K^0_L \pi^0\pi^0$	PRD 2017

- to be published soon: $\pi^+\pi^- 2\pi^0$, $\eta\pi^+\pi^-$
- in progress: $\pi^+\pi^-$ new method + full data sample
- not covered: $\pi^+\pi^- 4\pi^0$, $\pi^+\pi^- 4\pi^0$, $\pi^+\pi^-\pi^0$ below 1.05 GeV, $\geq$7 hadrons

The BaBar ISR method for $\mu\mu\gamma(\gamma)$, $\pi\pi\gamma(\gamma)$, $KK\gamma(\gamma)$

$e^+e^- \rightarrow \mu^+\mu^-\gamma\,(\gamma)$ and $\pi^+\pi^-\gamma\,(\gamma)$, $K^+K^-\gamma(\gamma)$ measured simultaneously

Kinematic fits with additional small-angle ISR or detected (ISR or FSR) photon

$$x = 2E^*_\gamma/\sqrt{s}$$

$$s' = s(1-x)$$

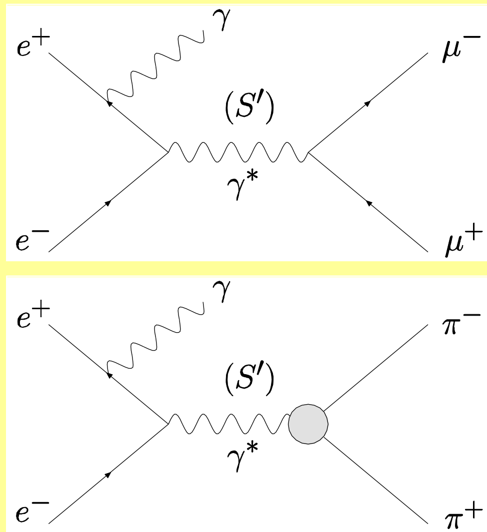
measure ratios

$\pi\pi/\mu\mu$ KK/$\mu\mu$

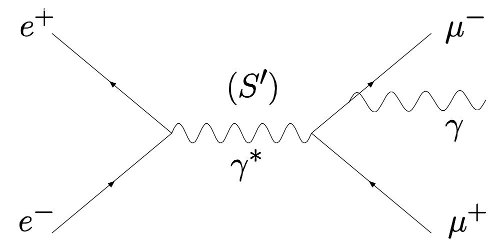
ISR lumi drops out

$\pi\pi/\mu\mu$/KK separated by particle ID

ISR

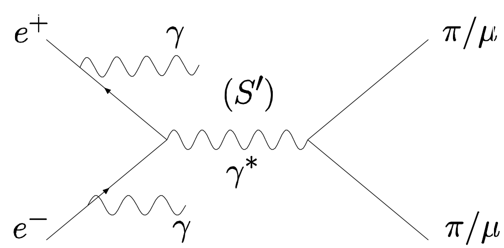


FSR

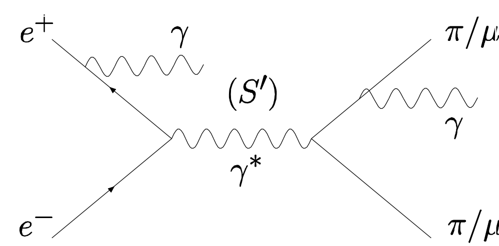


LO FSR negligible for $\pi\pi$ at s~(10.6 GeV)^2, but checked by measuring ISR-FSR interference (charge asymmetry, PRD 2014)

ISR + add. ISR



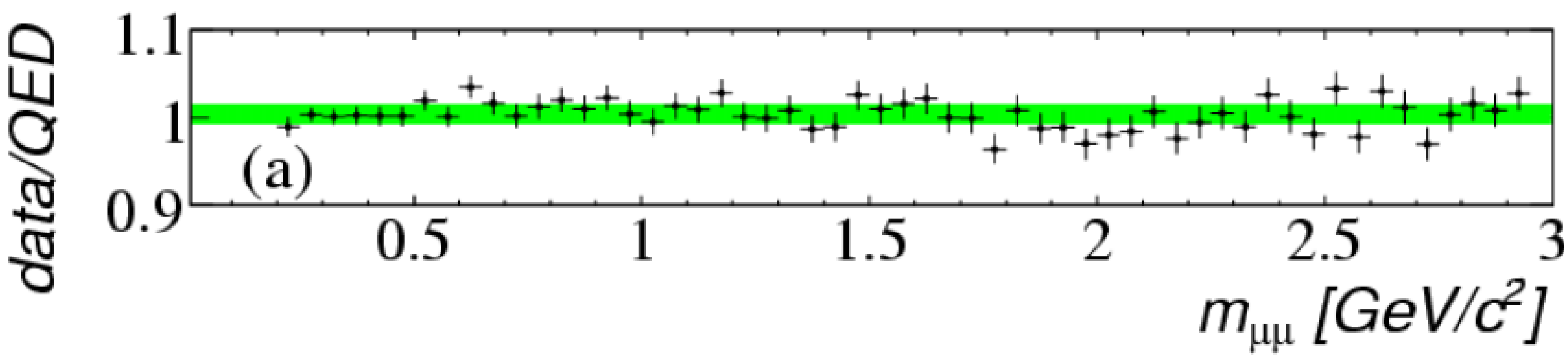
ISR + add. FSR



QED Test with μμγ sample

- absolute comparison of μμ mass spectra in data and in simulation (AfkQed based on EVA)
- simulation corrected for data/MC efficiencies
- AfkQed corrected for incomplete NLO using Phokhara
- strong test (ISR probability drops out for ππ/μμ)

BaBar



$$\frac{\sigma^{data}_{\mu\mu\gamma(\gamma)}}{\sigma^{NLO\ QED}_{\mu\mu\gamma(\gamma)}} = 1 + (4.0 \pm 1.9 \pm 5.5 \pm 9.4)\ 10^{-3}$$

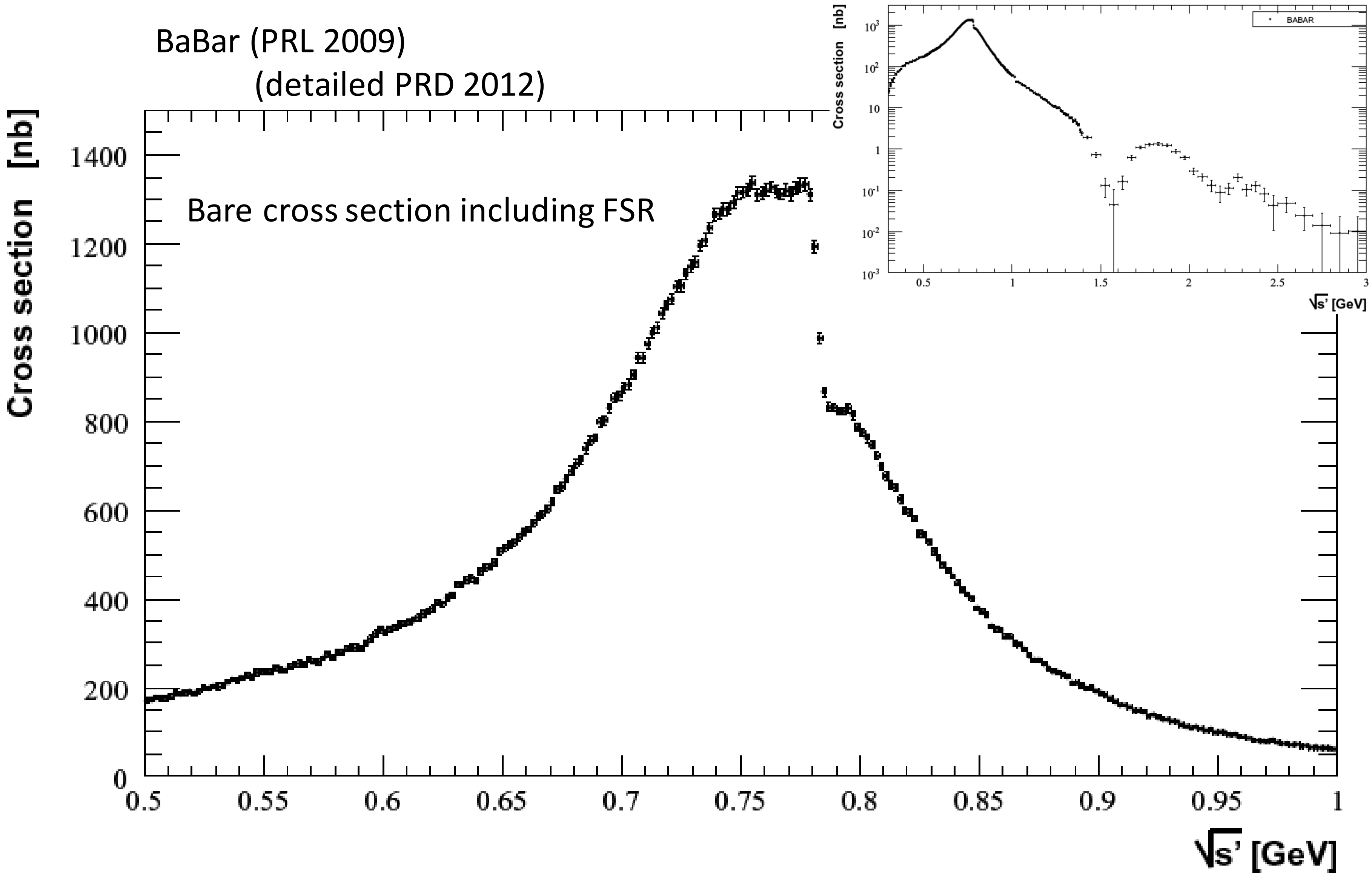
(0.2 – 3 GeV)

ISR γ efficiency 3.4 syst.
trigger/tracking/PID 4.0

BaBar ee luminosity

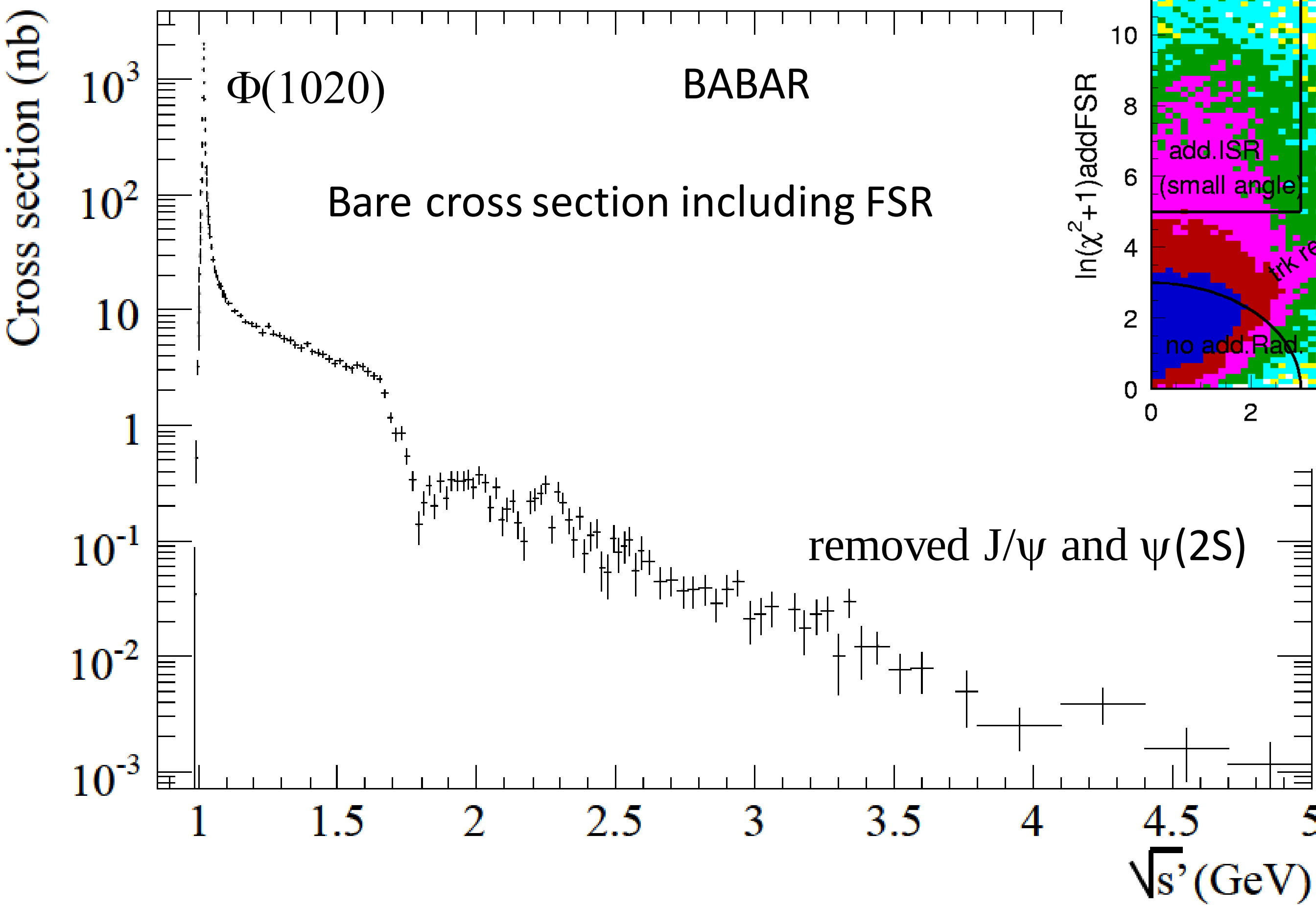
Results on $e^+e^- \to \pi^+\pi^-(\gamma)$

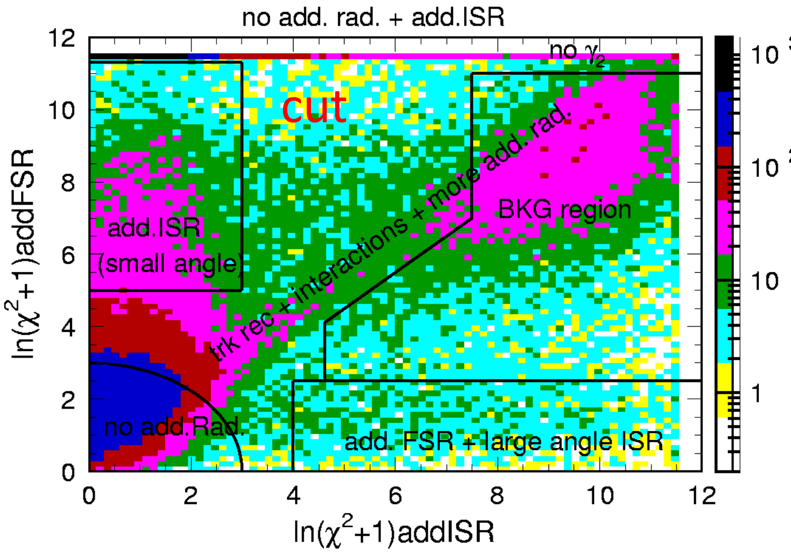
BaBar (PRL 2009)
(detailed PRD 2012)



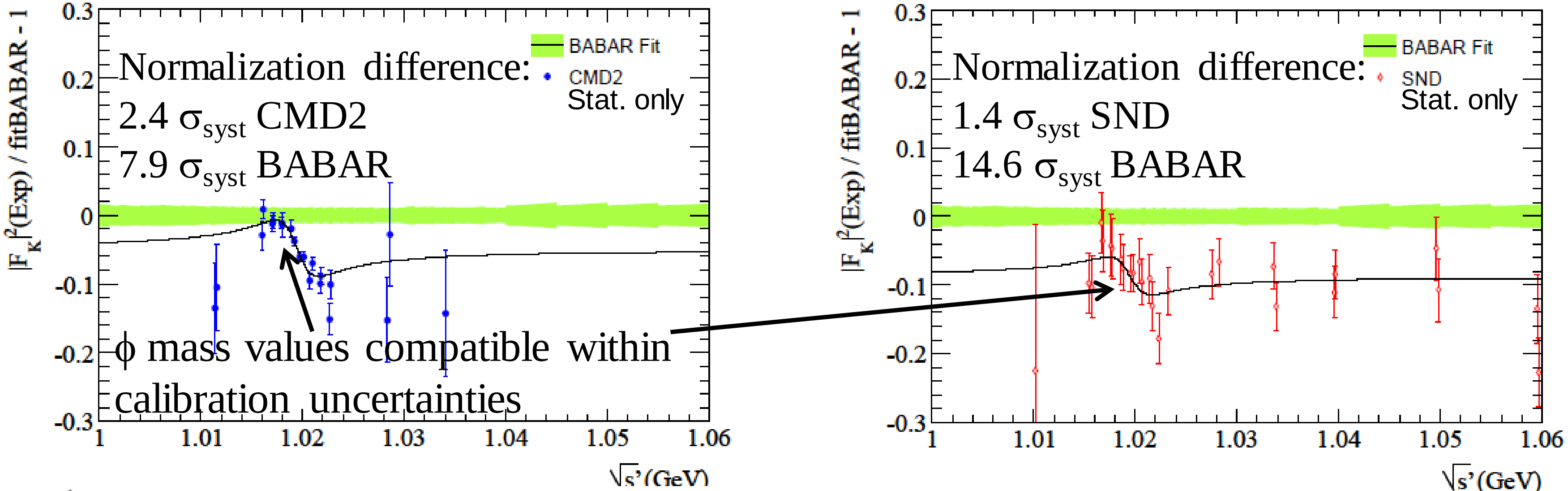
Results on the $e^+e^- \rightarrow K^+K^-(\gamma)$ bare cross section

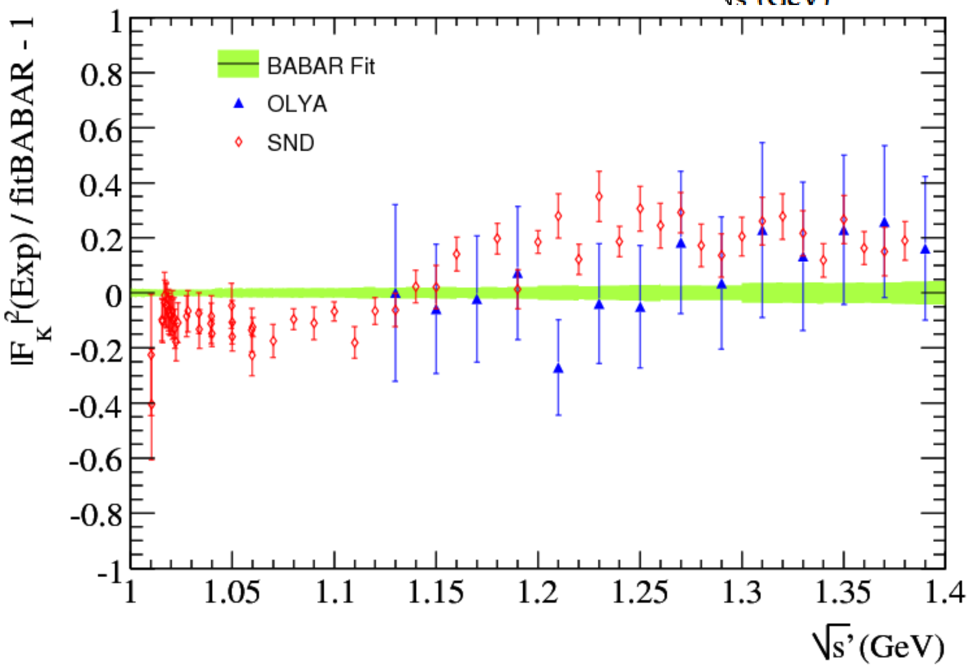
- effective ISR luminosity obtained with μμ sample as for ππ cross section
- FSR measured and included





K^+K^- : Comparison to previous experiments





New developments:

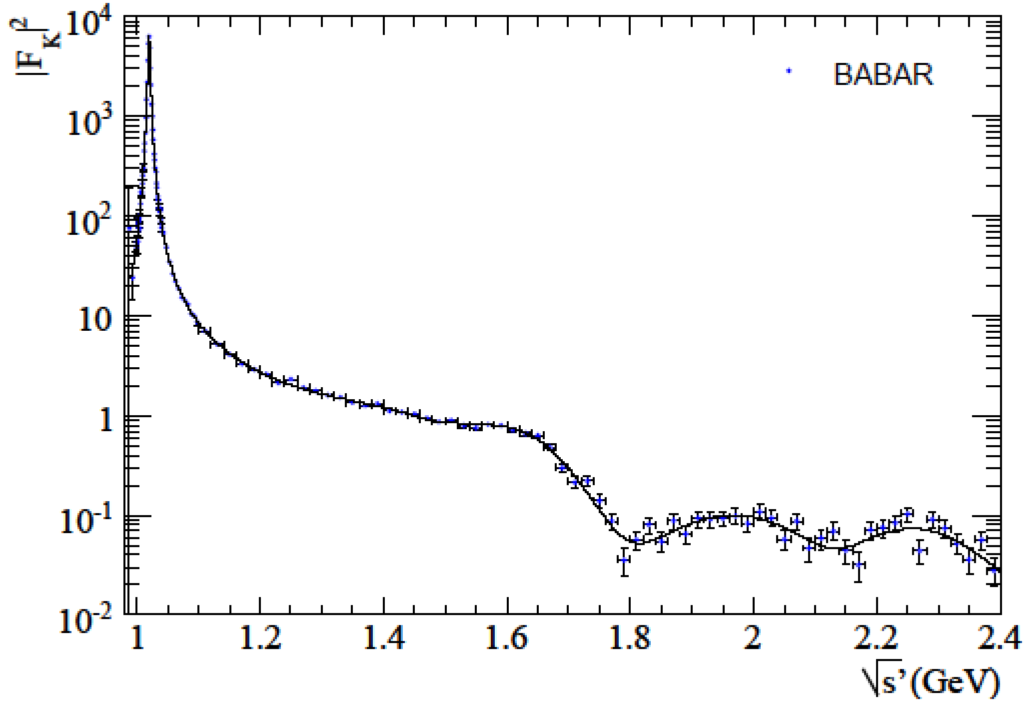
- recent SND measurement at VEPP-2000 disagrees with older VEPP-2M results in 1.15-1.4 GeV and agrees with BABAR
- preliminary results from CMD3 (2016) on the $\Phi(1020)$ strongly disagree with older published: +11%, 5% above BABAR ! to be clarified

The ϕ parameters

m_ϕ, Γ_ϕ, and ϕ cross section obtained from a VDM fit of the form factor (Kuehn et al.)

$m_\phi = (1019.51 \pm 0.02 \pm 0.05)$ MeV
$\Gamma_\phi = (4.29 \pm 0.04 \pm 0.07)$ MeV

Good agreement with PDG:
$m_\phi = 1019.455 \pm 0.020$ MeV
$\Gamma_\phi = 4.26 \pm 0.04$ MeV



From integrated ϕ peak:

$\Gamma^\phi_{ee} \times B(\phi \to K^+K^-) = (0.6344 \pm 0.0059_{exp} \pm 0.0033_{fit} \pm 0.0015_{cal})$ keV (1.1%)

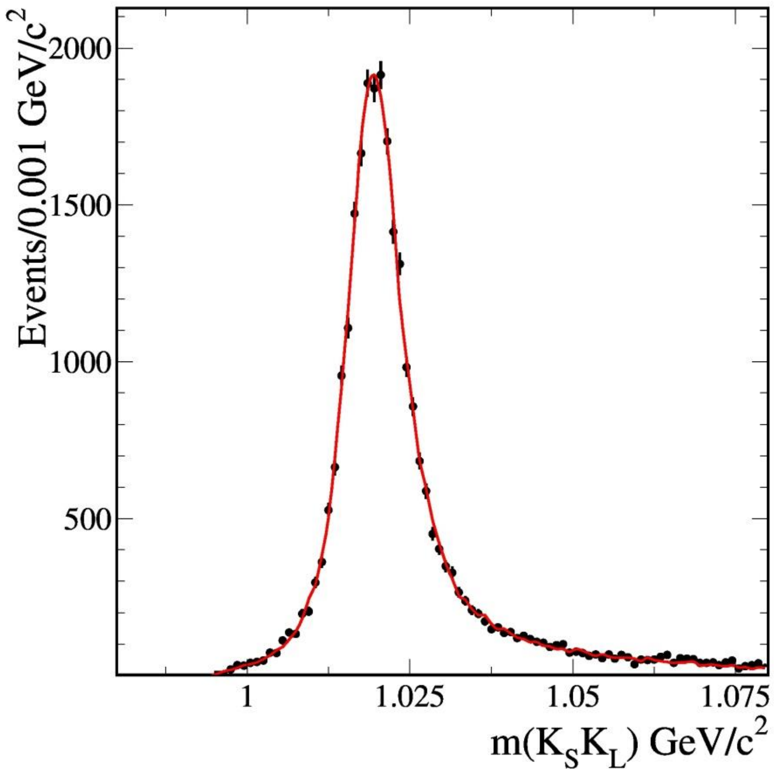
[CMD2: $(0.605 \pm 0.021 \pm 0.013)$ keV (4.1%) published, new result?]

Results on $e^+e^- \to K_S K_L$: ϕ

published in 2014 based on the full BABAR statistics (454 fb^{-1})

- K_S reconstructed $\pi^+\pi^-$
- K_L direction measured in EM calorimeter (original method)
- K_L efficiencies measured using kinematically constrained $\phi \to K_S$ (K_L)

$$\Gamma^{\phi}_{ee} \times B(\phi \to K_S K_L) = (0.4200 \pm 0.0033_{stat} \pm 0.0122_{syst} \pm 0.0019_{fit})\ \text{keV} \quad (3.0\%)$$



$$m_\phi = (1019.46 \pm 0.04 \pm 0.06)\ \text{MeV}$$
$$\Gamma_\phi = (4.21 \pm 0.10 \pm 0.07)\ \text{MeV}$$

$$\frac{B(\phi \to K_S K_L)}{B(\phi \to K^+K^-)} = 0.662 \pm 0.021 \quad \text{BABAR}$$

[0.68 ± 0.03 CMD-2]

[0.671 ± 0.023 PDG BR av]

Impact of BABAR data for g-2: K^+K^- and 4-pion

$a_\mu^{KK, LO}$ [0.98;1.80] GeV = $(22.95 \pm 0.14$ (stat) ± 0.22 (syst) $)\ 10^{-10}$ (1.1%)

DHMZ 2011: update of all results before BABAR:

$a_\mu^{KK, LO}$[0.98;1.8]GeV = $(21.63 \pm 0.27$ (stat) ± 0.68 (syst) $)10^{-10}$ (3.4%)

BABAR more precise than previous world average by a factor of 3

$a_\mu^{4\pi, LO}$ [0.9;1.80] GeV = $(13.64 \pm 0.03$ (stat) ± 0.36 (syst) $)\ 10^{-10}$ (2.6%)

DEHZ 2003: all results but BABAR:

$a_\mu^{4\pi, LO}$[0.9;1.8]GeV = $(13.95 \pm 0.90$ (exp) ± 0.23(rad) $)10^{-10}$ (6.7%)

BABAR more precise than previous world average by a factor of 2.6

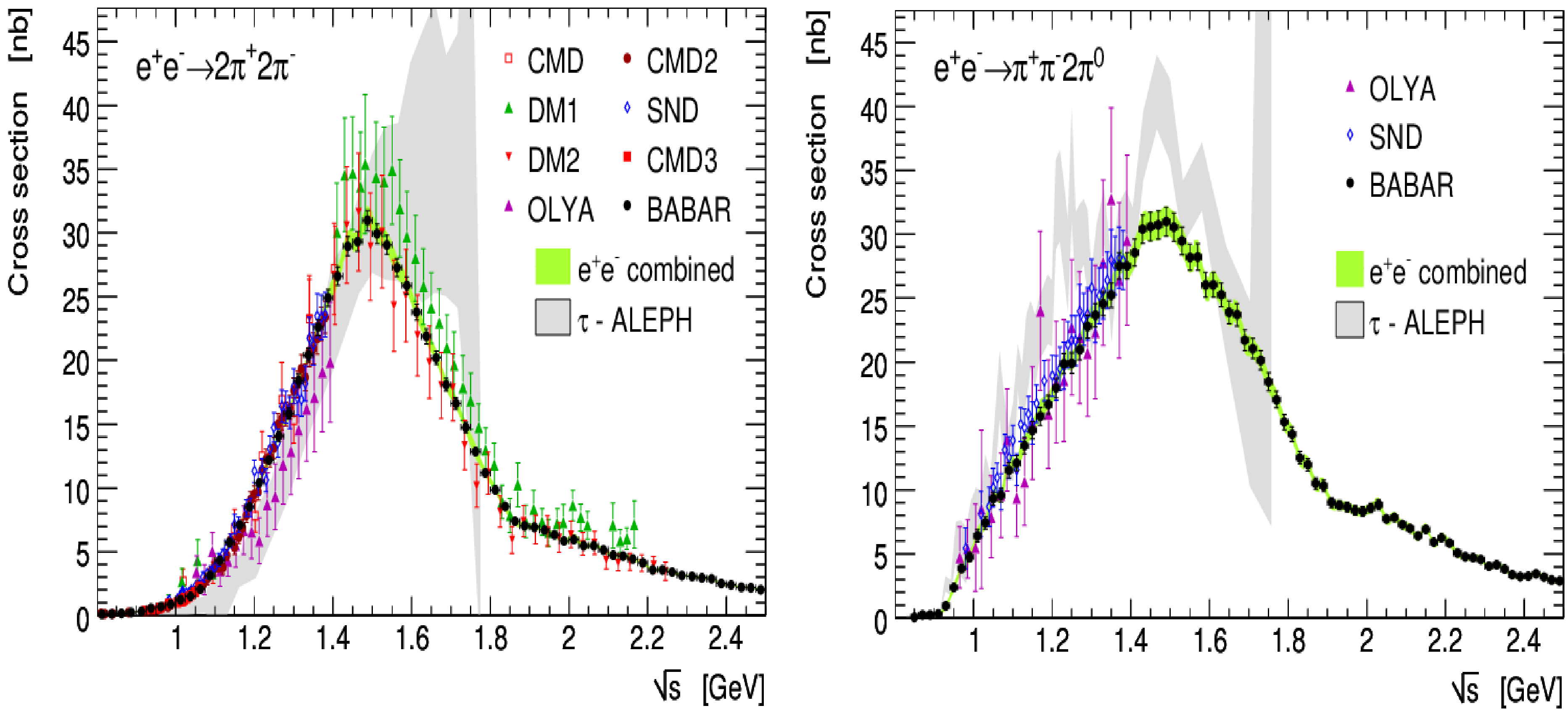
$a_\mu^{2\pi 2\pi 0, LO}$ [0.9;1.80] GeV = $(18.03 \pm 0.03$ (stat) ± 0.55 (syst) $)\ 10^{-10}$ (3.0%)

DEHZ 2003: all results but BABAR:

$a_\mu^{4\pi, LO}$[0.9;1.8]GeV = $(16.76 \pm 1.31$ (exp) ± 0.20(rad) $)10^{-10}$ (7.9%)

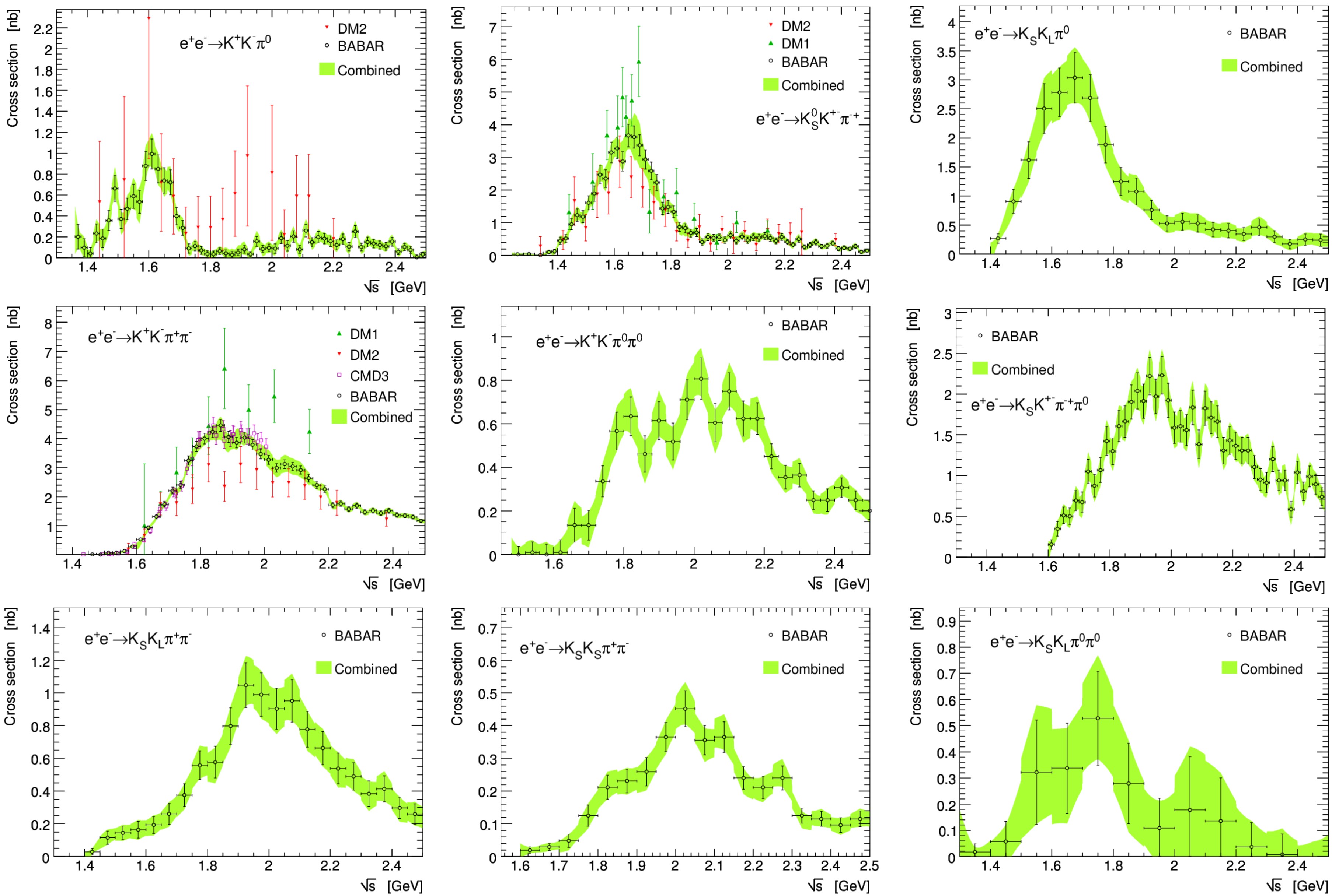
BABAR more precise than previous world average by a factor of 2.6

BABAR: 4-pion channels

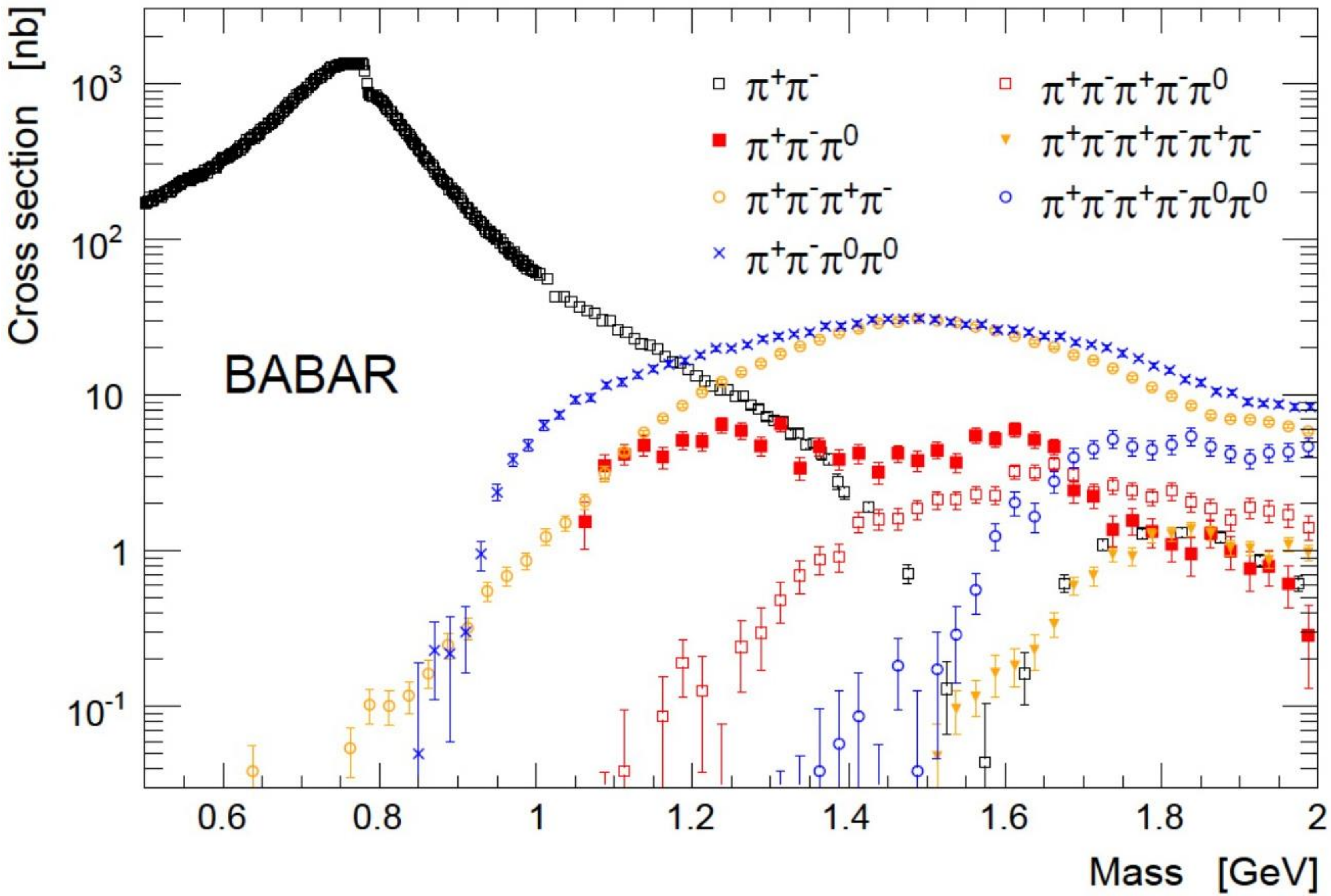


Large acceptance provided by large-angle ISR: essential to identify final-state dynamics $\Rightarrow$ model MC simulation to get detection efficiency under control

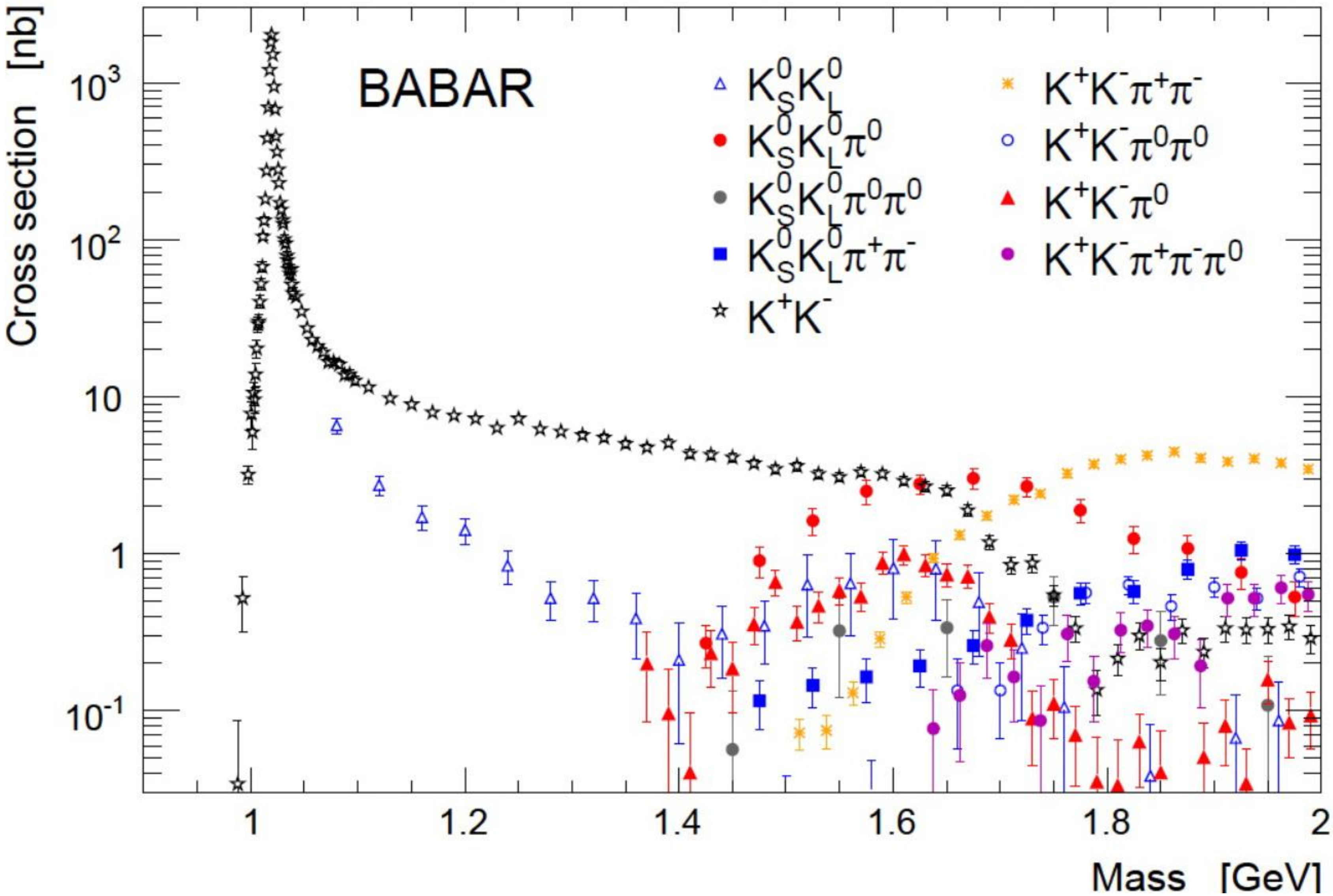
BABAR: K K π and K K π π channels



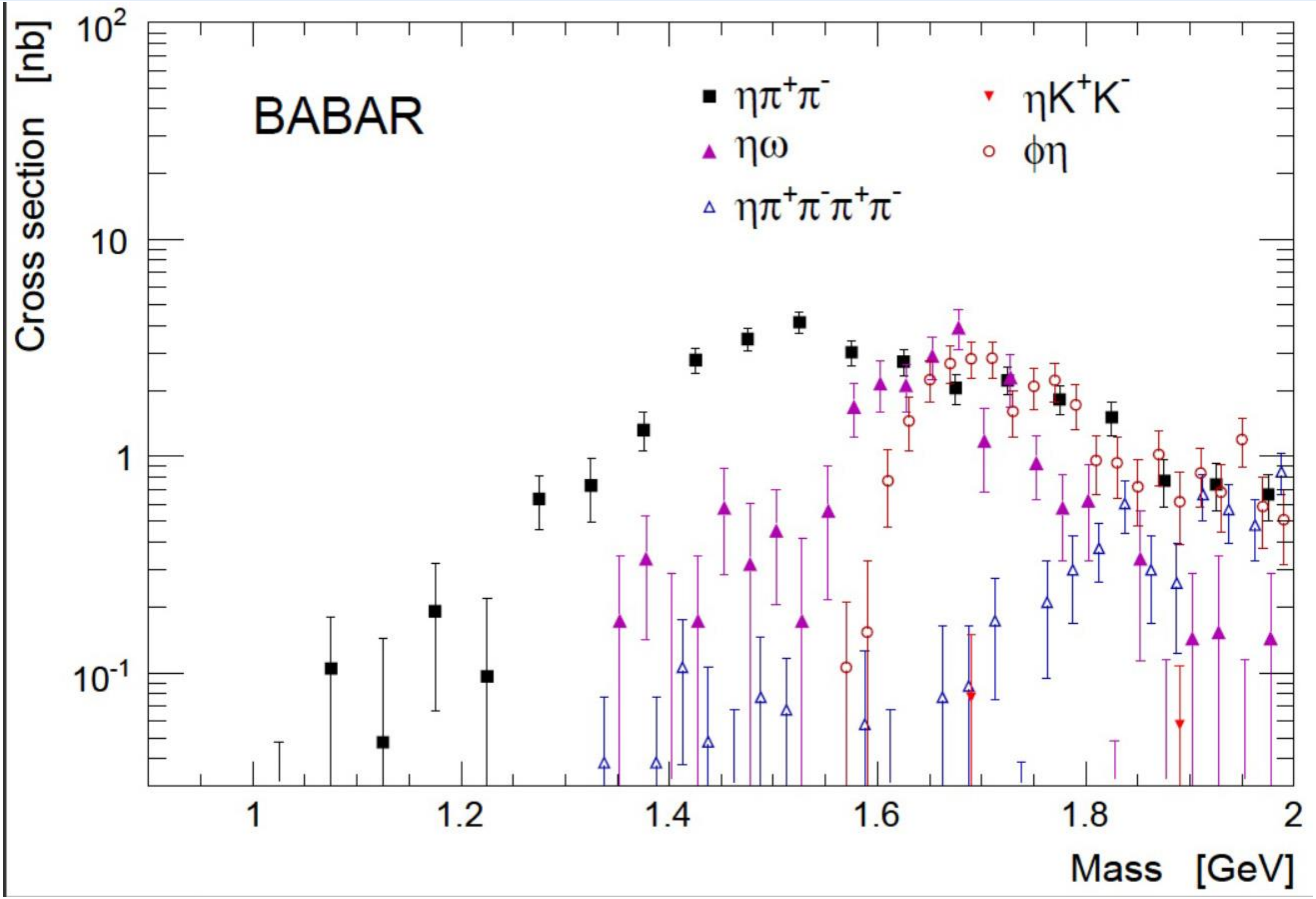
BABAR: multi-pion channels



BABAR: channels with K pair

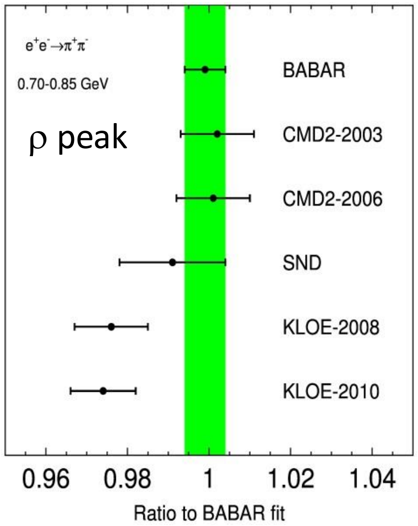


BABAR: channels with η



New BABAR $\pi\pi\gamma(\gamma)$ / $\mu\mu\gamma(\gamma)$ analysis

Cross section ratio to BaBar



- BaBar measurement most precise to date
- discrepancy with KLOE results to be resolved
- consequence: accuracy of combined results degraded
- BaBar has almost complete measurements of other hadronic contributions (27%)
- New direct measurement at Fermilab in sight
- imperative to improve accuracy of prediction
- Other efforts at VEPP-2000
- Design a new BABAR analysis for further improvement

Systematic uncertainties in published analysis

($\times 10^{-3}$)

mass (GeV)

sources	0.3-0.4	0.4-0.5	0.5-0.6	0.6-0.9	0.9-1.2	1.2-1.4	1.4-2.0	2.0-3.0
trigger/ filter	5.3	2.7	1.9	1.0	0.7	0.6	0.4	0.4
tracking	3.8	2.1	2.1	1.1	1.7	3.1	3.1	3.1
π-ID	10.1	2.5	6.2	2.4	4.2	10.1	10.1	10.1
background	3.5	4.3	5.2	1.0	3.0	7.0	12.0	50.0
acceptance	1.6	1.6	1.0	1.0	1.6	1.6	1.6	1.6
kinematic fit (χ^2)	0.9	0.9	0.3	0.3	0.9	0.9	0.9	0.9
correl $\mu\mu$ ID loss	3.0	2.0	3.0	1.3	2.0	3.0	10.0	10.0
$\pi\pi/\mu\mu$ non-cancel.	2.7	1.4	1.6	1.1	1.3	2.7	5.1	5.1
unfolding	1.0	2.7	2.7	1.0	1.3	1.0	1.0	1.0
ISR luminosity	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
sum (cross section)	13.8	8.1	10.2	5.0	6.5	13.9	19.8	52.4

$\pi\pi\mu\mu$

μ ID 3.3

- systematic uncertainty dominated by π/μ ID
- ρ region (0.6-0.9 GeV) 0.50% of which 0.43% comes from ID

  $(0.26 \oplus 0.43)\%$
- statistical and systematic uncertainties comparable
- PID systematics mostly from non-ideal performance of muon system

- Challenge: separate $\pi\pi$ and $\mu\mu$ without PID

The new analysis method

- increase statistics by using the full BaBar data set (x2)

- Use a method not relying on π/μ separation in calorimeters

  $\pi\ \pi$, $\mu\ \mu$ and K K have different angular distributions (θ^*) in the pair center-of-mass
  the distributions are fixed by first principles (spins)

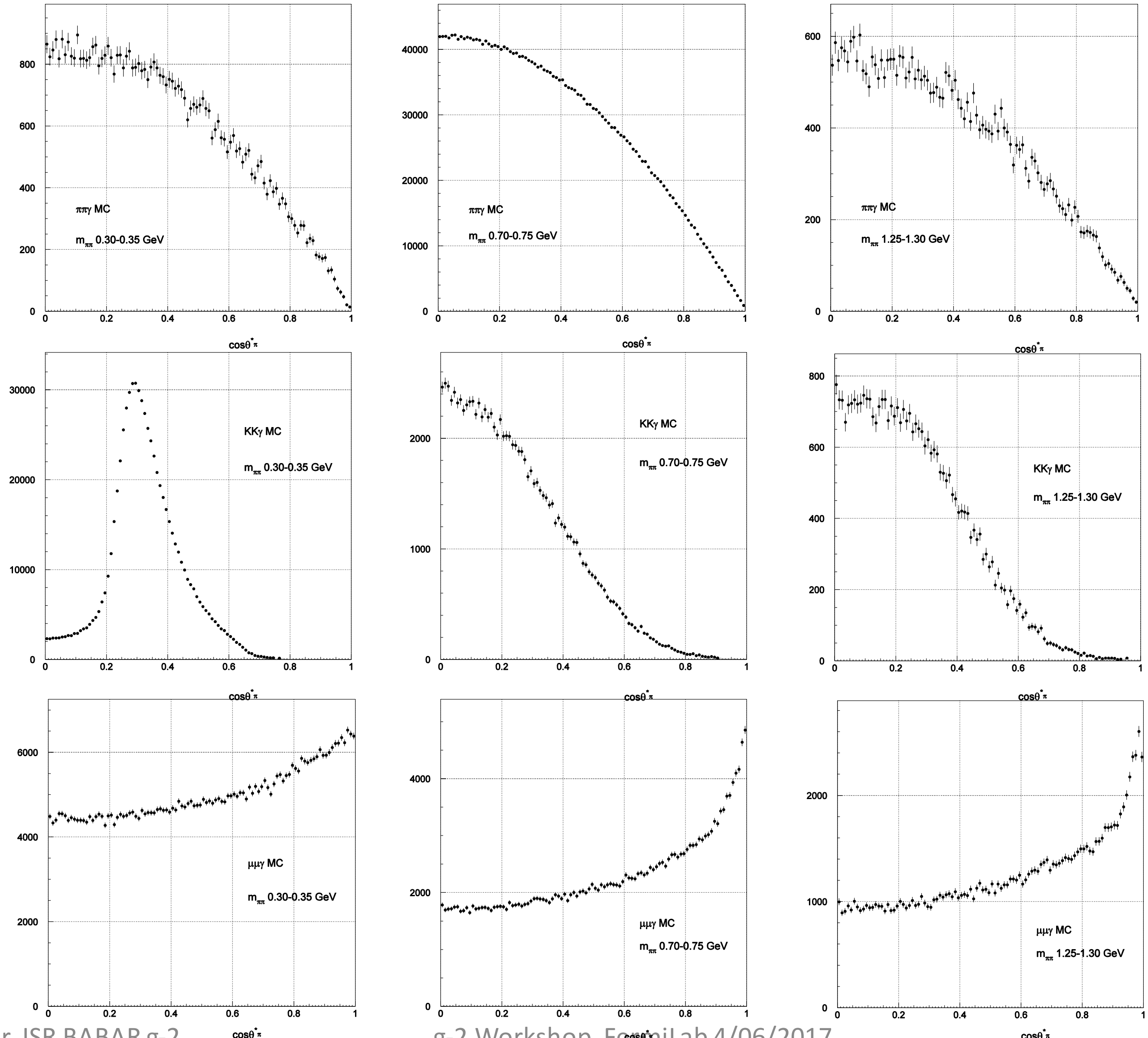
  $\Rightarrow$ require only 2 reconstructed tracks with a kinematic fit to $\pi^+\pi^-\gamma$ (γ) hypothesis
  fit angular distribution in each $\pi\pi$ mass interval with $\pi\pi$ / $\mu\mu$ / KK / bkg components
  unfold the individual mass spectra to correct for resolution and kinematics
  take ratio $\pi\pi$ / $\mu\mu$ to cancel common systematics

advantages: get rid of the largest systematic uncertainty
increase statistics: no reduction of active area
remove 1 GeV momentum cut
use full data set
use full angular distribution (low momenta)
} x8

new needs: understand tracking and trigger efficiencies data/MC <1 GeV

MC angular distributions ($|\cos\theta^*_\pi|$)

$m_{\pi\pi}$ (GeV) 0.30-0.35 0.70-0.75 1.25-1.30

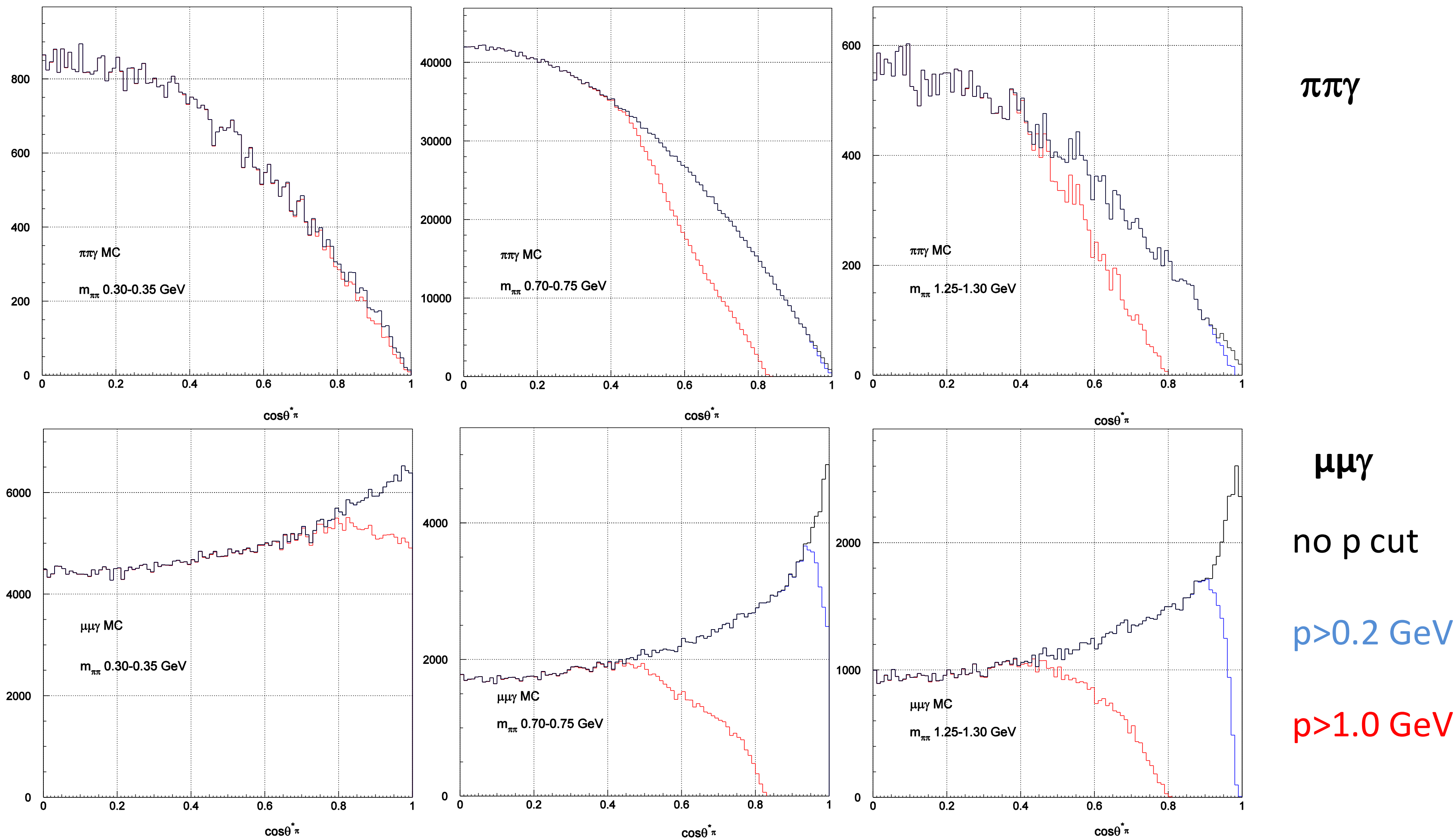


ππγ

KKγ

μμγ

Importance of low-momentum tracking (MC)



Conclusions

- Through the ISR method BABAR could plan a complete and consistent program to measure precise cross sections for the dominant channels of $e^+e^- \rightarrow$ hadrons from threshold to ~2 GeV.
- This program has been carried out.

- Many new results presented.
- BABAR results have a large impact on the hadronic vacuum polarization (HVP) contribution to the muon g-2.
- In addition to HVP there are other applications of these data in progress for QCD tests with finite energy sum rules, complementing similar studies done with hadronic τ decays.

- An analysis of $\pi\pi/\mu\mu$ with a new approach is in progress. It should yield more precise results, both for statistics and systematics.