Measurements of low energy e^+e^- hadronic cross sections and implications for the muon g-2

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Outline

- The BABAR ISR (Initial State Radiation) $\pi\pi$ analysis
- Test of the method: $e^+e^- \to \mu^+\mu^-(\gamma)$
- Results on $e^+e^- \to \pi^+\pi^-(\gamma)$

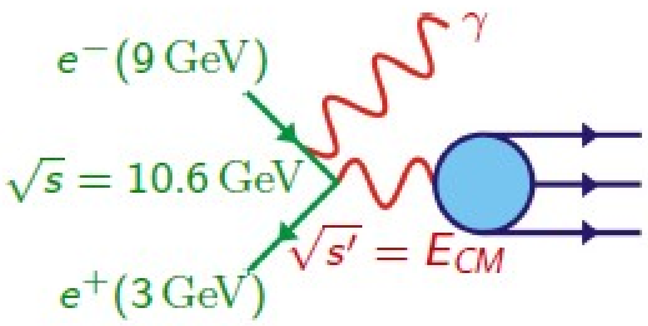
PRL 103, 231801 (2009)
PRD 86, 032013 (2012)

- Results on $K^+K^-(\gamma)$

PRD 88, 032013 (2013)

- Conclusions

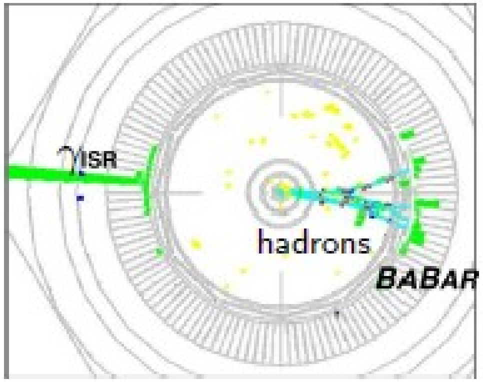
The ISR method at BABAR



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

hadrons

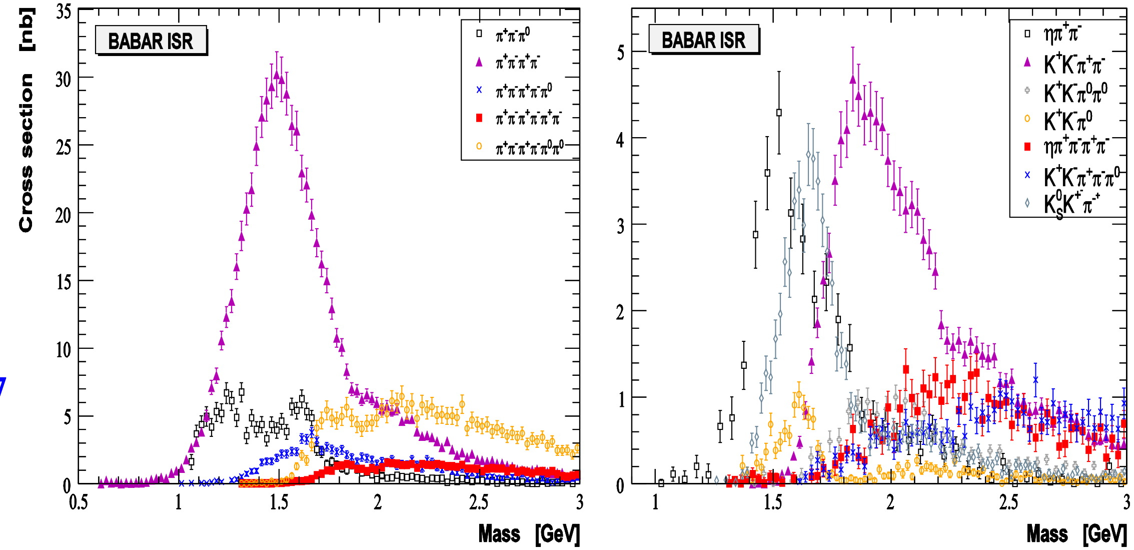
$$s' = s(1-x) = M^2_{\text{hadrons}}$$



- 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, large boost to hadrons (measurements from threshold and easier PID)
- Final state can be hadronic or leptonic (QED)
  → $\mu^+\mu^-\gamma(\gamma)$ 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
  → reduced systematic uncertainties compared to multiple data sets with different colliders and detectors

The BABAR ISR program

- cover an almost complete set of significant exclusive e^+e^- annihilation channels up to 2 GeV



- published:

  $K^+ K^-$ PRD 2013

  $\pi^+\pi^-$ PRL 2009; PRD 2012

  $\pi^+\pi^-\pi^0$ PRD 2004

  $\Phi\ f^0(980)$ PRD 2006; PRD 2007

  $p\ \bar{p}$ PRD 2006; PRD 2013

  $\Lambda\,\Lambda$, $\Lambda\,\Sigma^0$, $\Sigma^0\,\Sigma^0$ PRD 2007

  $2(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$, $K^+K^-\,2\pi^0$, $2(K^+K^-)$ PRD 2007; 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

- in progress:

  $\pi^+\pi^-2\pi^0$, $K^0_S\,K^0_L$, $K^0_S\,K^0_L\,\pi^+\pi^-$, $K^0_S\,K^{+-}\pi^{-+}\pi^0$, $K^0_S\,K^{+-}\pi^{-+}\eta$

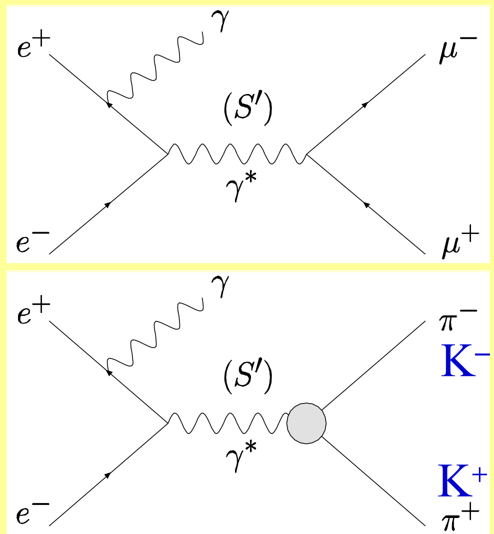
The relevant processes for the $\pi\pi$ and KK measurements

$e^+e^- \to \mu^+\mu^-\gamma_{ISR}$ ($\gamma_{add.}$), $\pi^+\pi^-\gamma_{ISR}$ ($\gamma_{add.}$) and $K^+K^-\gamma_{ISR}$ ($\gamma_{add.}$) measured simultaneously

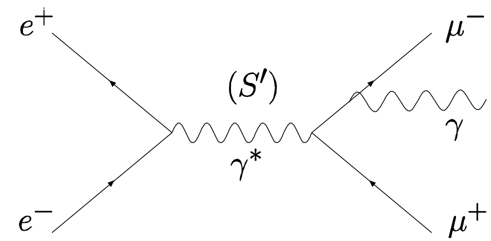
ISR

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

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

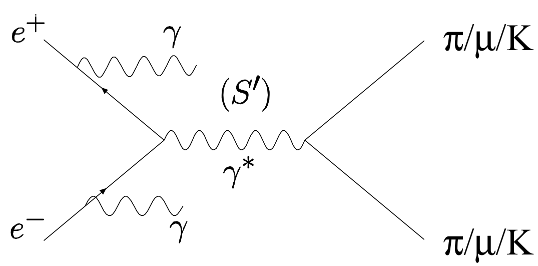


FSR

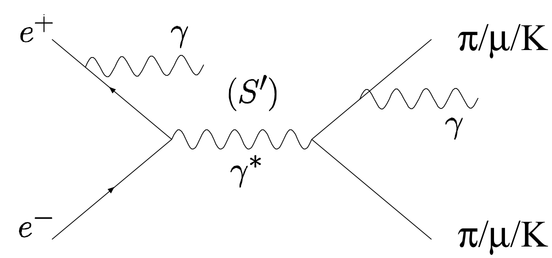


LO FSR negligible for ππ and KK at s~(10.6 GeV)^2

ISR + additional ISR

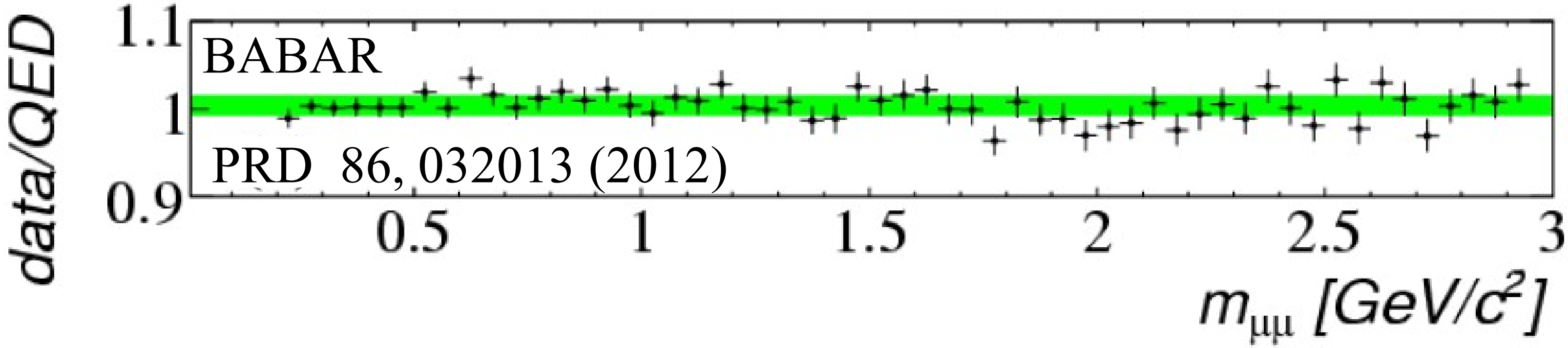


ISR + additional FSR



QED test with μμγ sample

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



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

(0.2 – 3 GeV)

ISR γ efficiency 3.4 syst.
trig/track/PID 4.0

BABAR e^+e^- luminosity

Obtaining the $\pi\pi(\gamma_{FSR})$ cross section

$$\frac{dN_{\pi\pi\gamma(\gamma)}}{d\sqrt{s'}} = \frac{dL_{ISR}^{eff}}{d\sqrt{s'}}\, \varepsilon_{\pi\pi\gamma(\gamma)}(\sqrt{s'})\ \sigma^0_{\pi\pi(\gamma)}(\sqrt{s'})$$

Unfolded spectrum

Acceptance from MC + data/MC corrections

Effective ISR luminosity from $\mu\mu\gamma(\gamma)$ analysis (similar equation + QED)

$\pi\pi$ mass spectrum unfolded (B. M. arXiv:0907.3791) for detector response

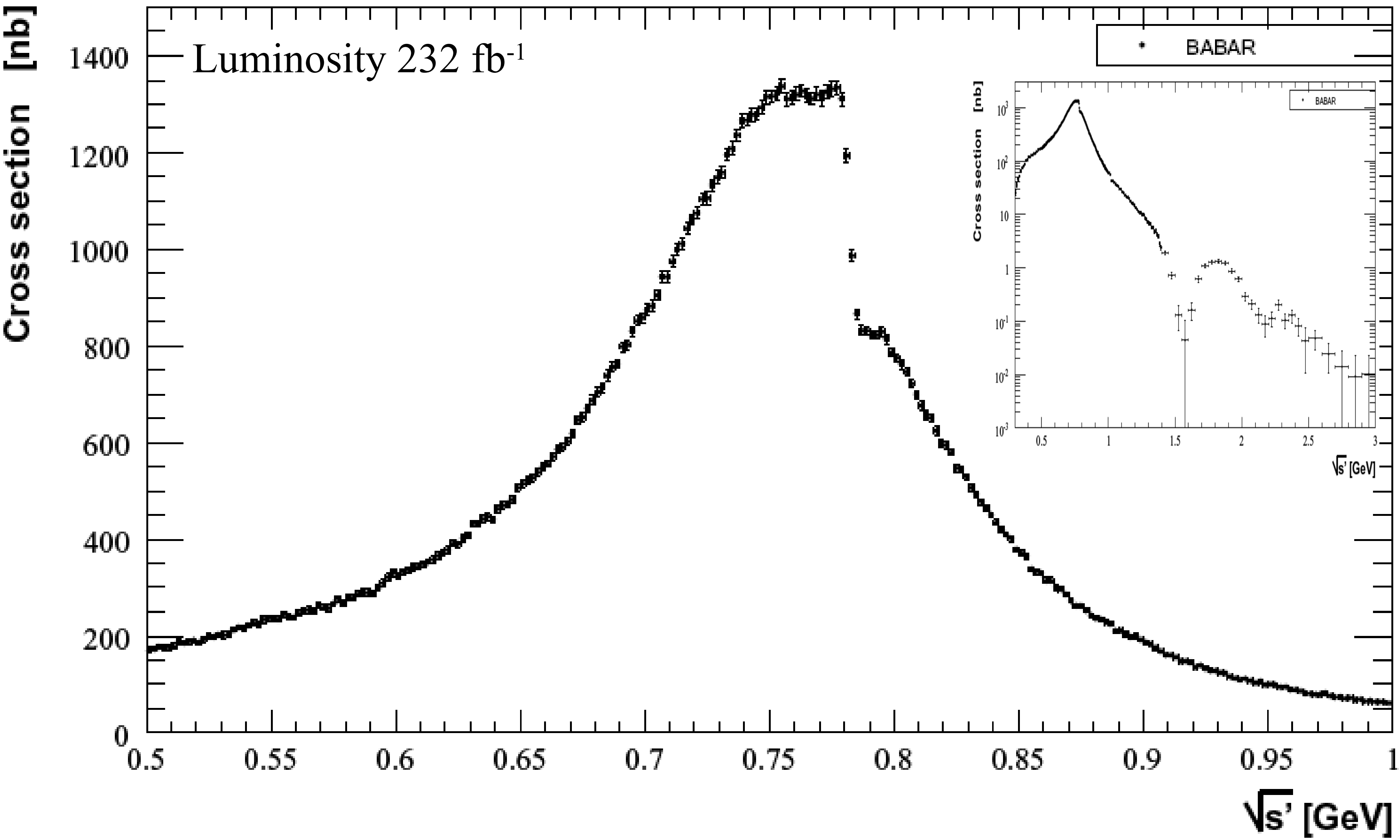
Additional ISR almost cancels in the procedure ($\pi\pi\gamma(\gamma)$ / $\mu\mu\gamma(\gamma)$ spectra ratio)
Correction $(2.5 \pm 1.0) \times 10^{-3}$ $\Rightarrow$ **$\pi\pi$ cross section does not rely on accurate description of NLO in the MC generator**

ISR luminosity from $\mu\mu\gamma(\gamma)$ in 50-MeV energy intervals
(small compared to variation of efficiency corrections)

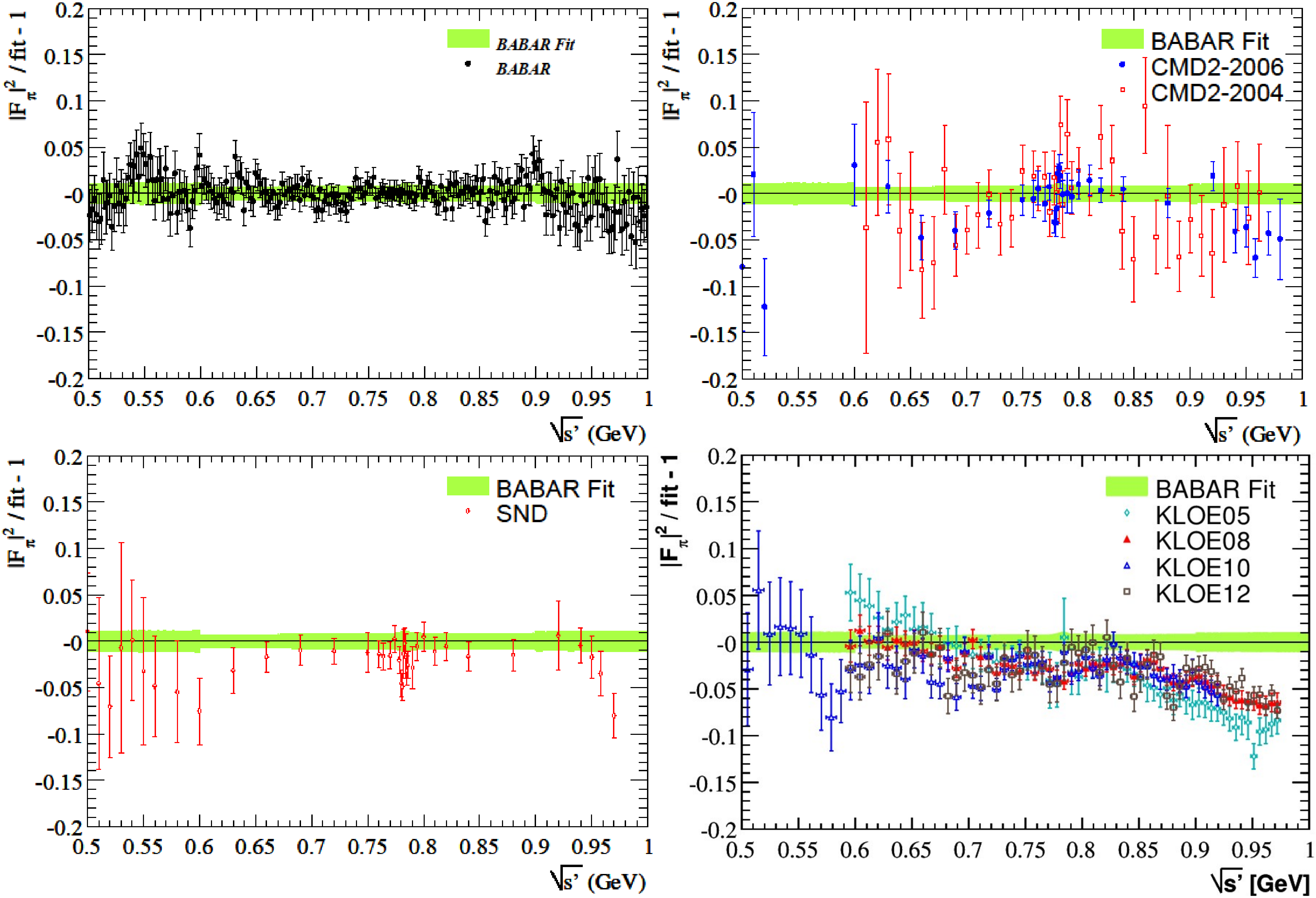
Total systematic uncertainty of 0.5% in the ρ region (dominant for a_μ)

BABAR results (PRL 103, 231801 (2009); PRD 86, 032013 (2012))

$e^+ e^- \to \pi^+ \pi^- (\gamma_{FSR})$ bare (no VP) cross section stat+syst uncertainties shown

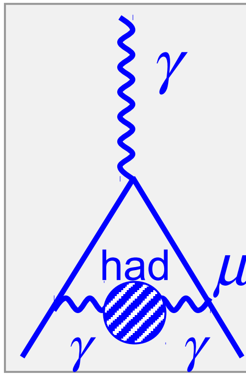


BABAR fit vs. e^+e^- data (stat + syst errors included)



Computing $a_\mu^{\pi\pi}$

$$a_\mu^{\pi\pi(\gamma),LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^0_{\pi\pi(\gamma)}(s) \ ,$$



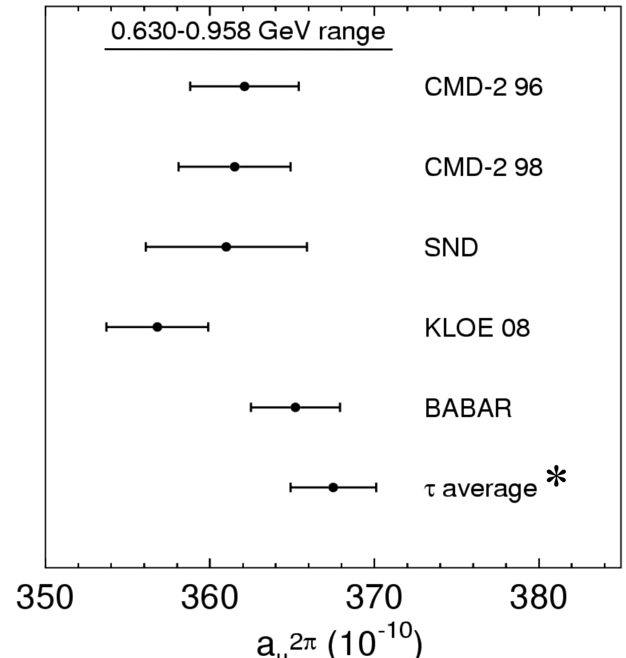
where $K(s)$ is the QED kernel,

$$K(s) = x^2\left(1-\frac{x^2}{2}\right) + (1+x)^2\left(1+\frac{1}{x^2}\right)\left[\ln(1+x) - x + \frac{x^2}{2}\right] + x^2\frac{1+x}{1-x}\ln x$$

with $x = (1-\beta_\mu)/(1+\beta_\mu)$ and $\beta_\mu = (1-4m_\mu^2/s)^{1/2}$.

<u>0.28–1.8 (GeV)</u>

BABAR	$(514.1 \pm 3.8) \times 10^{-10}$
previous e^+e^- combined	$(503.5 \pm 3.5) \times 10^{-10}$ *
+ BABAR	$(508.4 \pm 2.9) \times 10^{-10}$ *
+ KLOE 10	$(507.8 \pm 2.7) \times 10^{-10}$ *
τ combined	$(515.2 \pm 3.5) \times 10^{-10}$ *



Deviation between BNL measurement and theory prediction reduced using BABAR $\pi^+\pi^-$ data

a_μ [exp] – a_μ [SM] =**(19.8 ± 8.4)**$\times 10^{-10}$ (2.4σ)

$\pi^+\pi^-$ from BABAR only

* arXiv:0906.5443; 0908.4300; 1010.4180 M. Davier et al.

Analysis of $e^+e^- \to K^+K^-(\gamma)$ (PRD 88, 032013 (2013))

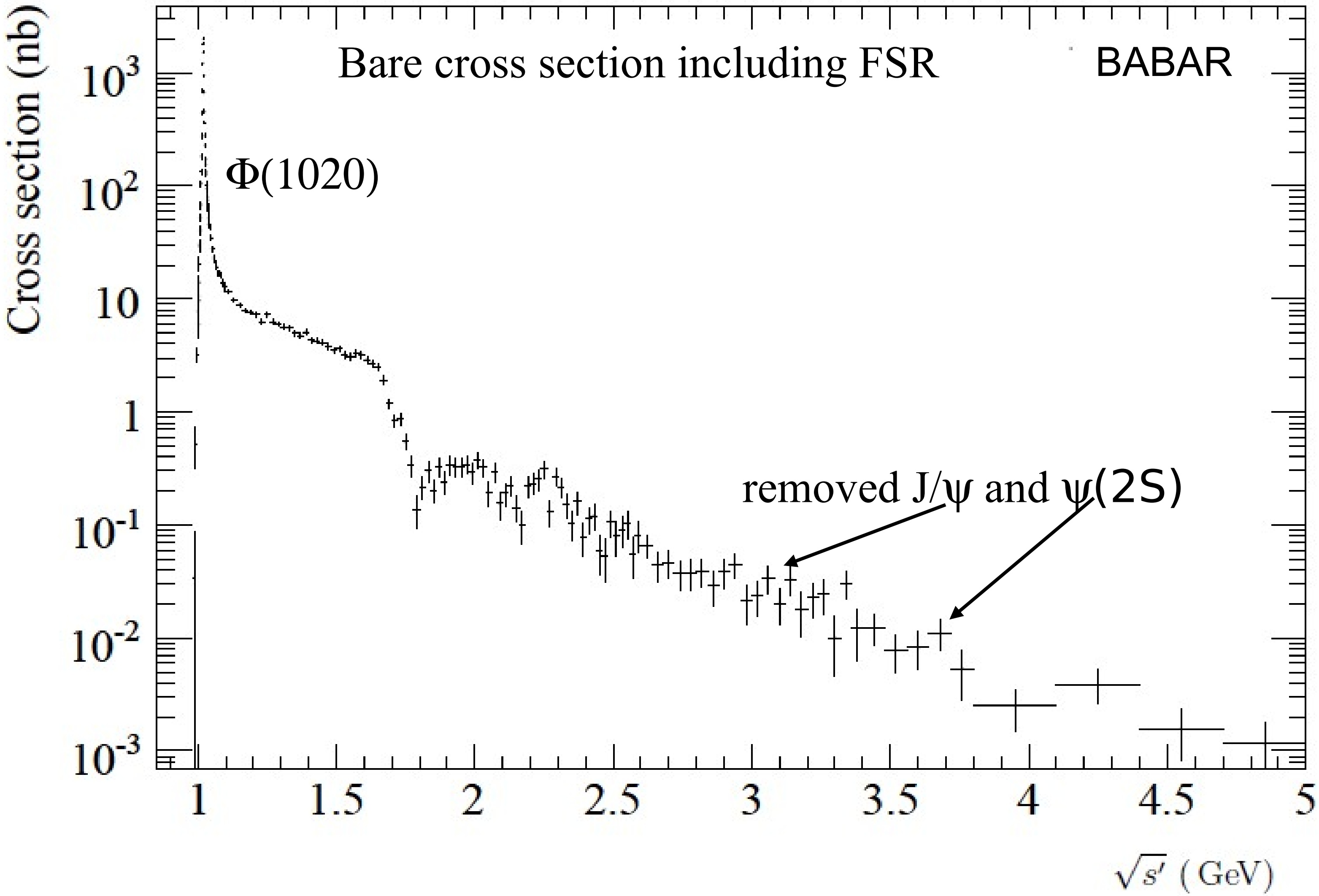
- procedures similar to $\pi\pi$ analysis
- luminosity 232 fb^{-1}

- efficiencies obtained from full simulation (AfkQed) and data/MC corrections
  - trigger, tracking , K-ID and mis-ID efficiencies
- background studies, normalization using data, subtraction
- efficiency of the kinematic fit χ^2 cut
  - → additional radiation ISR/FSR
    - → studies with muons
  - → differences between kaons and muons: secondary interactions, FSR
- unfolding background-subtracted and data/MC corrected mass spectra
- geometrical acceptance and second-order corrections using Phokhara
- ISR effective luminosity from $\mu\mu\gamma(\gamma)$: $KK/\mu\mu$ ratio
- mass-dependent systematic uncertainties, best in ϕ region (0.7%)

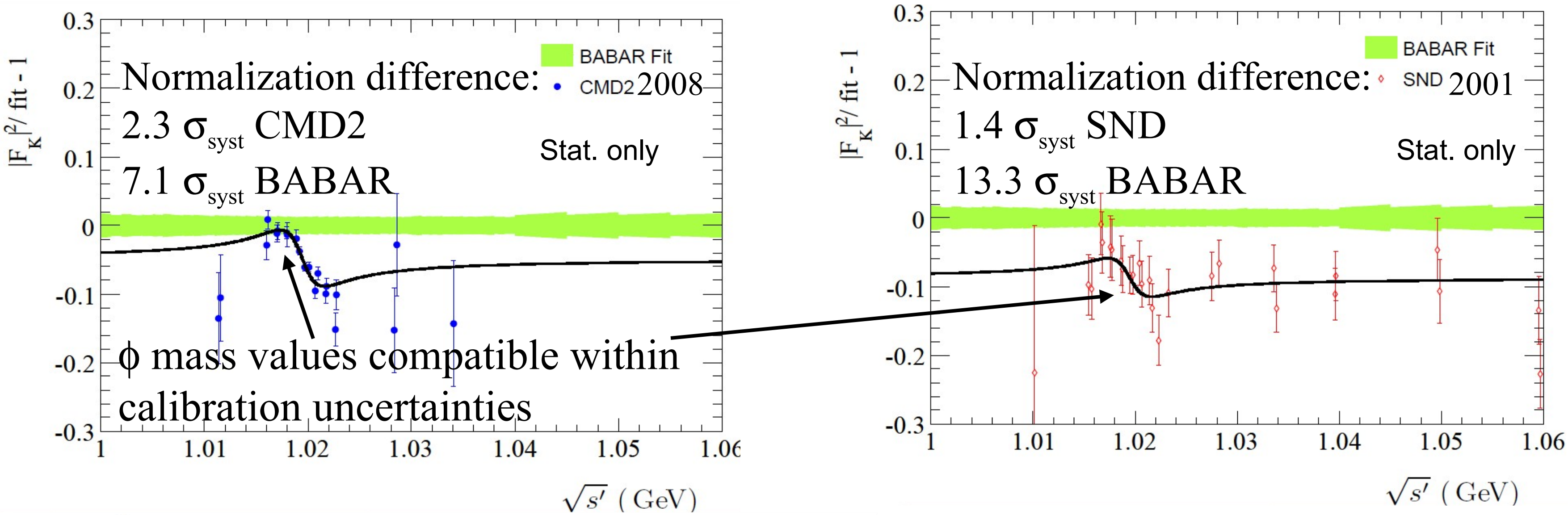
- cross section
- form factor phenomenological fits
- contribution to a_μ

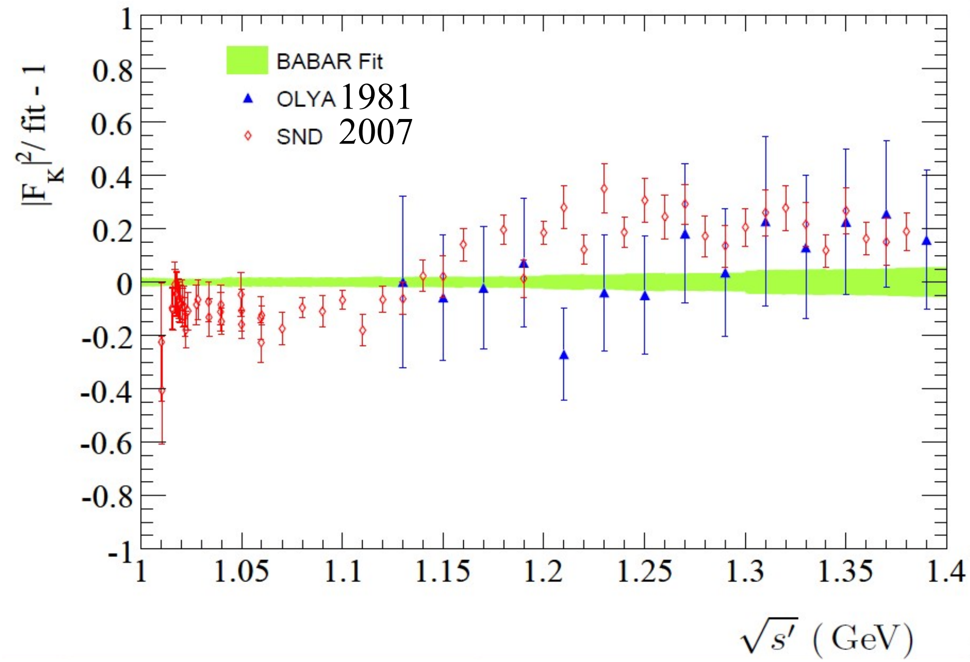
Results on the $e^+e^- \rightarrow K^+K^-(\gamma)$ bare cross section with FSR included (small)

→ Use effective ISR luminosity obtained with μμ sample.

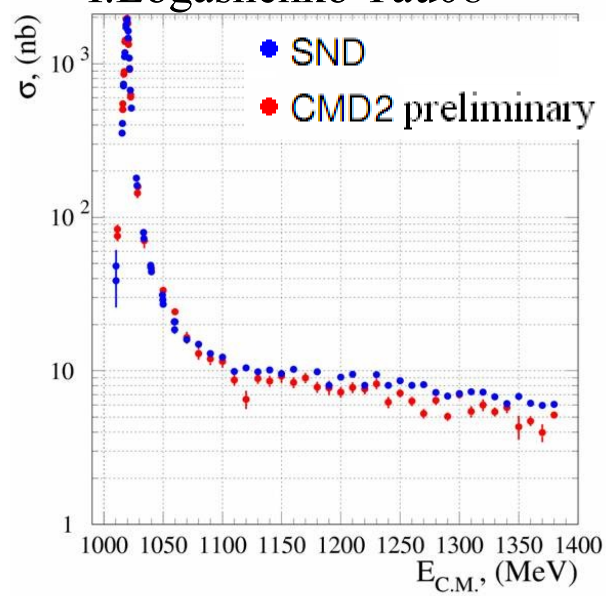


Comparison to previous experiments





I.Logashenko Tau08



The ϕ parameters

m_ϕ, Γ_ϕ, and a_ϕ obtained from the VDM fit (ϕ + other vector mesons) of the form factor

BABAR:
$m_\phi = 1019.51 \pm 0.02\ (\pm 0.05)$ 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:

$$\Gamma^{\phi}_{\mathrm{ee}} \times B(\phi \to K^+K^-) = \frac{\alpha^2 \beta^3(s, m_K)}{324} \frac{m_\phi^2}{\Gamma_\phi} a_\phi^2 C_{FS}$$ Final-state correction (Coulomb)

$$\Gamma_\phi^{ee} \times \mathcal{B}(\phi \to K^+K^-) = (0.6340 \pm 0.0070_{\mathrm{exp}} \pm 0.0037_{\mathrm{fit}} \pm 0.0013_{\mathrm{cal}})\ \mathrm{keV}$$ (1.3%)

CMD2 2010: $0.605 \pm 0.004 \pm 0.013$ keV (2.2%)

Charged kaon form factor at large Q^2

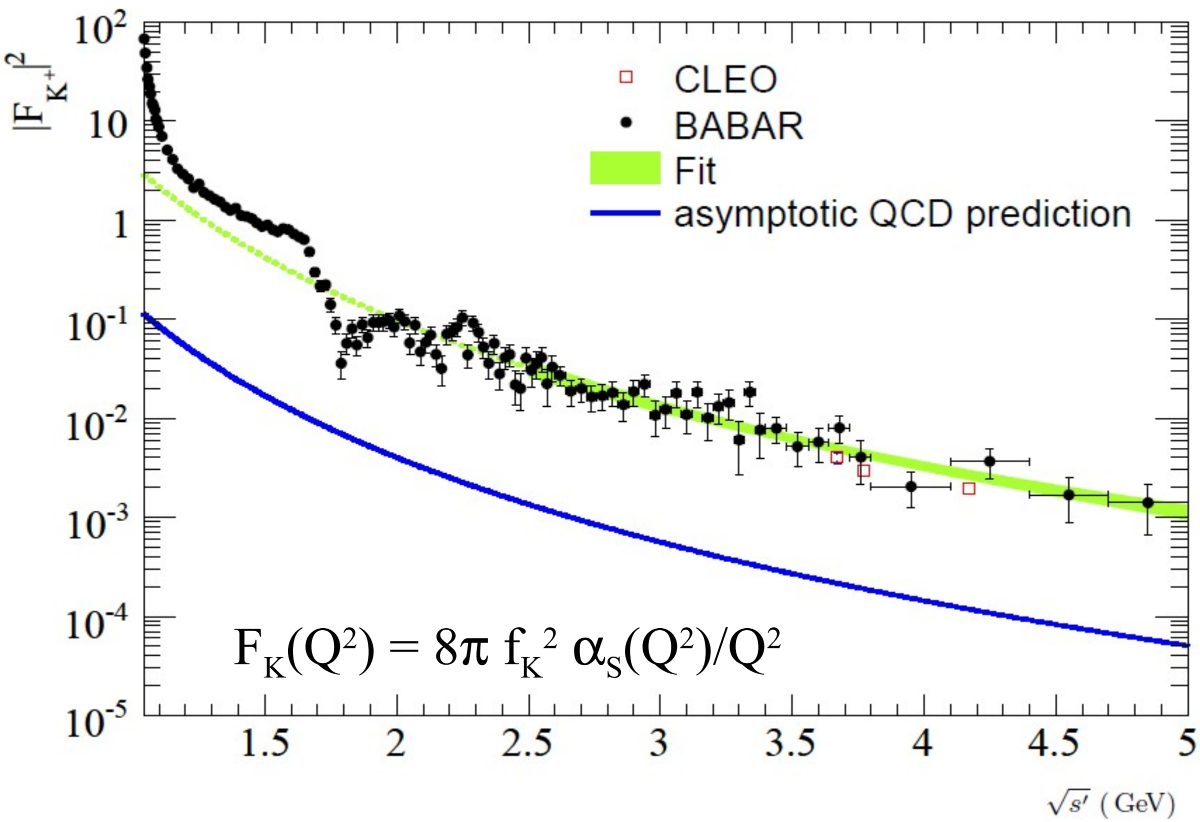
Predictions based on QCD in asymptotic regime
(Chernyak-Zhitnitsky JETP Lett. 1977; Brodsky-Lepage Phys. Lett. B 1979)

→ power law $F_K \sim \alpha_S(Q^2)\, Q^{-n}$ with n=2 in good agreement with data
(2.5-5 GeV n=2.04 ± 0.22)

→ but data on $|F_K|^2$ a factor ~20 above prediction !

→ no trend in data up to 25 GeV² for approaching the asymptotic QCD prediction

→ similar trend observed with F_π



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

BABAR:

$a_\mu^{KK,\,LO}$ [0.98-1.8] GeV = (22.93 ± 0.18 (stat) ± 0.22 (syst)) 10^{-10} (1.3%)

DHMZ arXiv:1010.4180 : update of all results before BABAR

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

BABAR more precise than previous world average by a factor of ~2.7

Conclusions

- Through the ISR method BABAR carried out a complete and consistent program to measure precise cross sections for the dominant channels of $e^+e^- \rightarrow$ hadrons from threshold to ~2 GeV.
- Just a few more channels still in progress.
- BABAR results have a large impact on the knowledge of hadronic vacuum polarization (HVP) contribution to the muon g-2.
- In addition to HVP there are other applications of these data for QCD tests with finite energy sum rules, complementing similar studies done with hadronic τ decays.
- Also (not covered in this talk) BABAR ISR results provide input into hadron spectroscopy, resonance dynamics and measurements of baryon form factors.

Backup

$\pi^+\pi^-$ systematic uncertainties

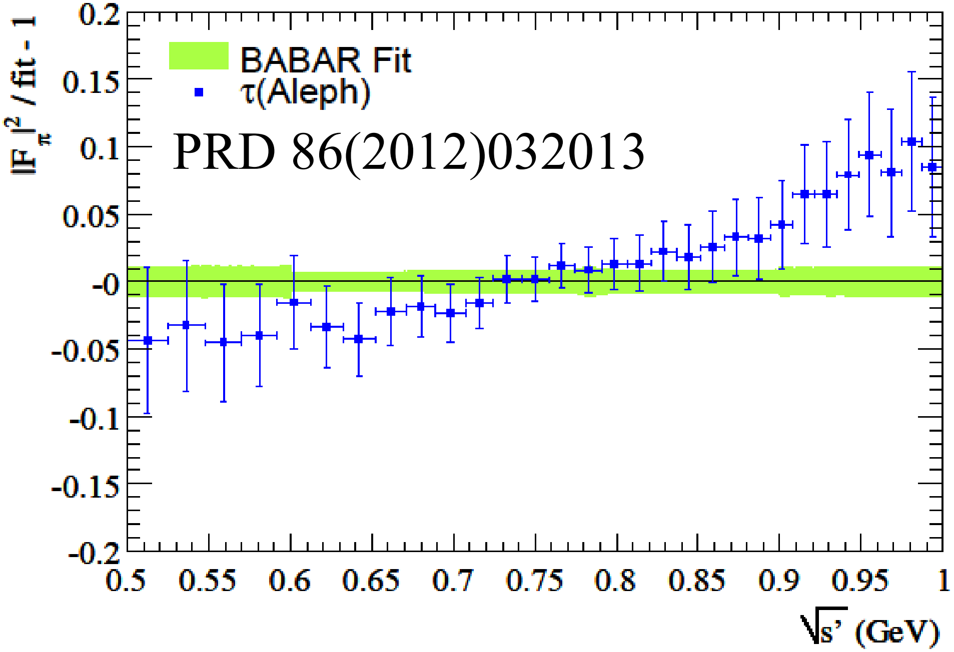
$\sqrt{s'}$ intervals (GeV) relative uncertainties in 10^{-3}

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	0.5	0.4	0.3	0.3
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
$\pi\pi/\mu\mu$ 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

ρ

Dominated by particle ID (π-ID, correlated μμ→'ππ', μ-ID in ISR luminosity)

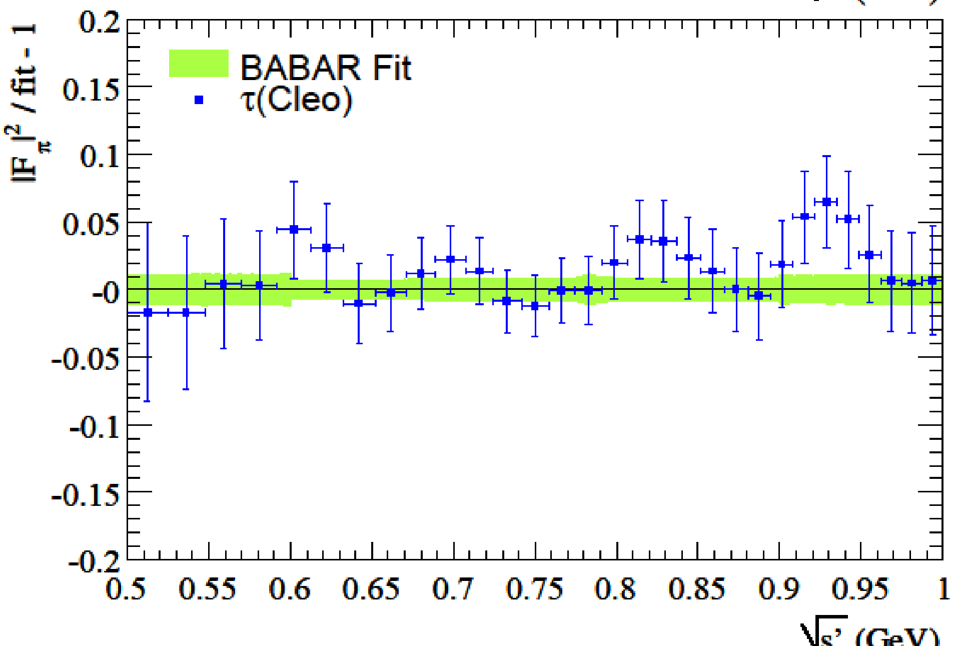
BABAR vs. IB-corrected τ data (0.5-1.0 GeV)

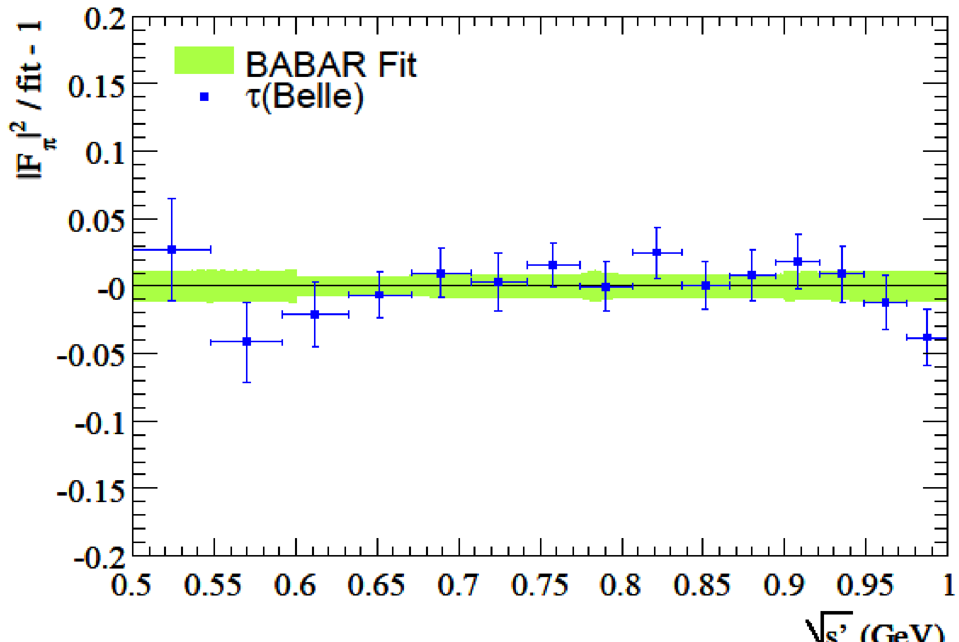


Relative comparison w.r.t. BABAR of τ spectral functions corrected for isospin-breaking(IB)

IB corrections: radiative corr., π masses, ρ-ω interference, ρ masses/widths

Each τ data normalized to its own BR





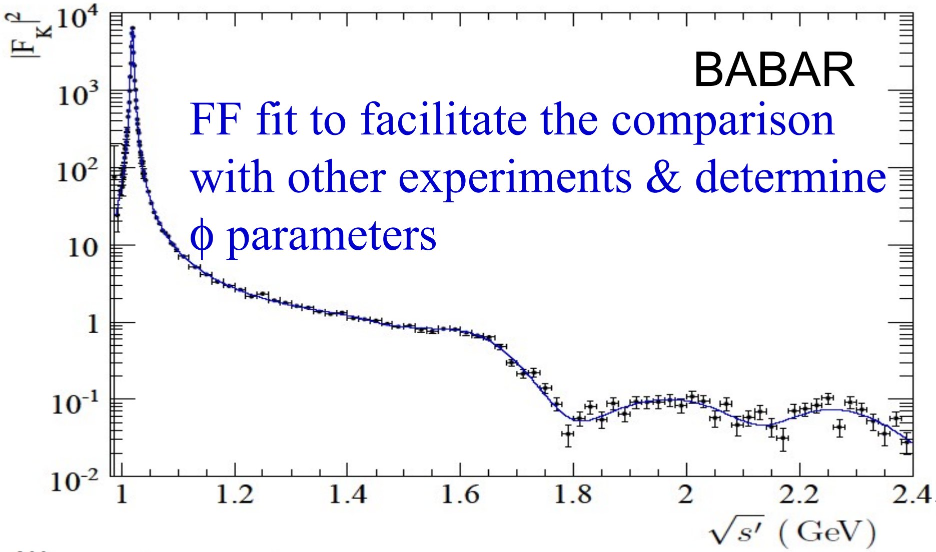
A phenomenological fit to the K form factor

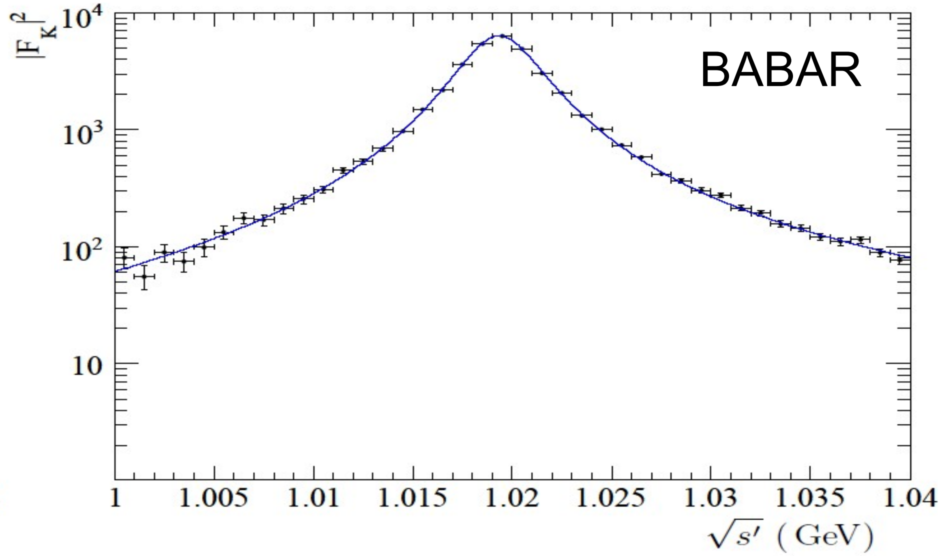
Kuehn et al.

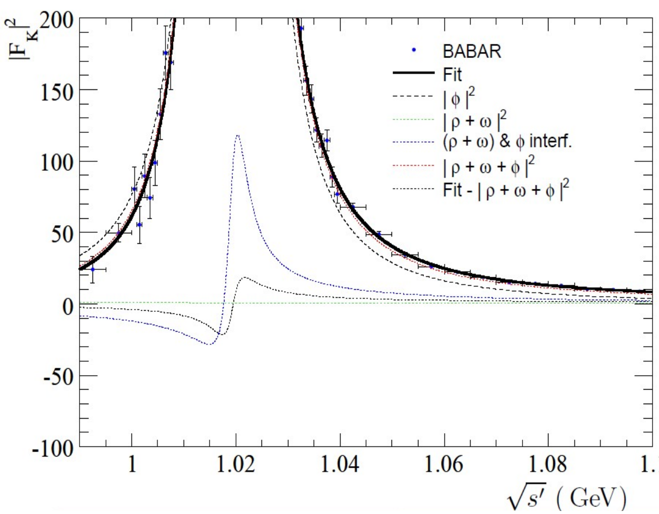
$$F_K(s) = (a_\phi\ BW_\phi + a_{\phi'}\ BW_{\phi'} + a_{\phi''}\ BW_{\phi''})/3$$
$$+ (a_\rho\ BW_\rho + a_{\rho'}\ BW_{\rho'} + a_{\rho''}\ BW_{\rho''} + a_{\rho'''}\ BW_{\rho'''})/2$$
$$+ (a_\omega\ BW_\omega + a_{\omega'}\ BW_{\omega'} + a_{\omega''}\ BW_{\omega''} + a_{\omega'''}\ BW_{\omega'''})/6$$

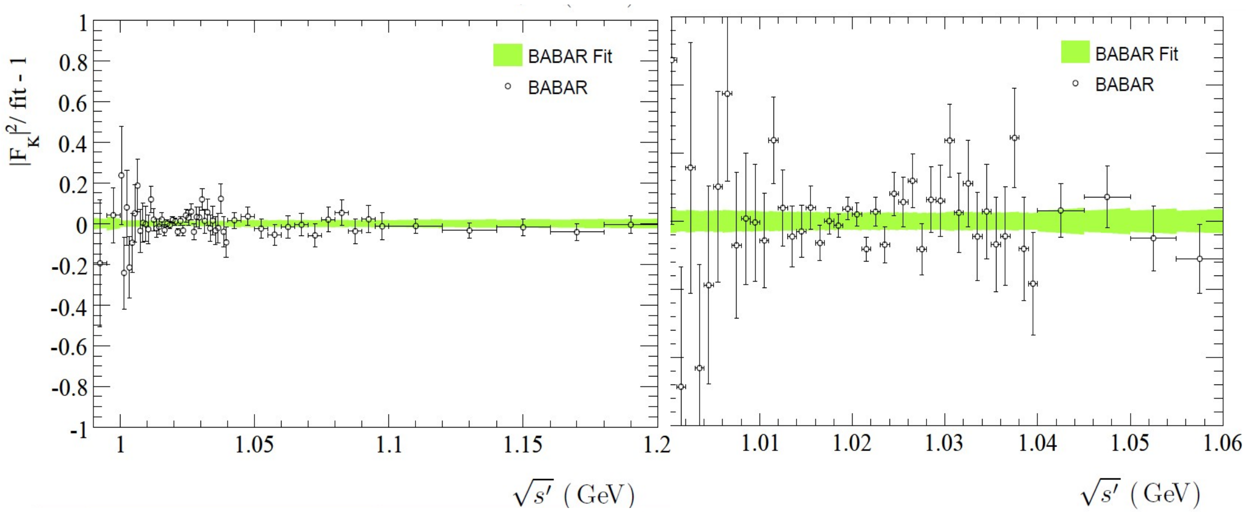
$$a_\phi + a_{\phi'} + a_{\phi''} = 1,$$
$$a_\rho + a_{\rho'} + a_{\rho''} + a_{\rho'''} = 1,$$
$$a_\omega + a_{\omega'} + a_{\omega''} + a_{\omega'''} = 1.$$

FF fit to facilitate the comparison with other experiments & determine ϕ parameters



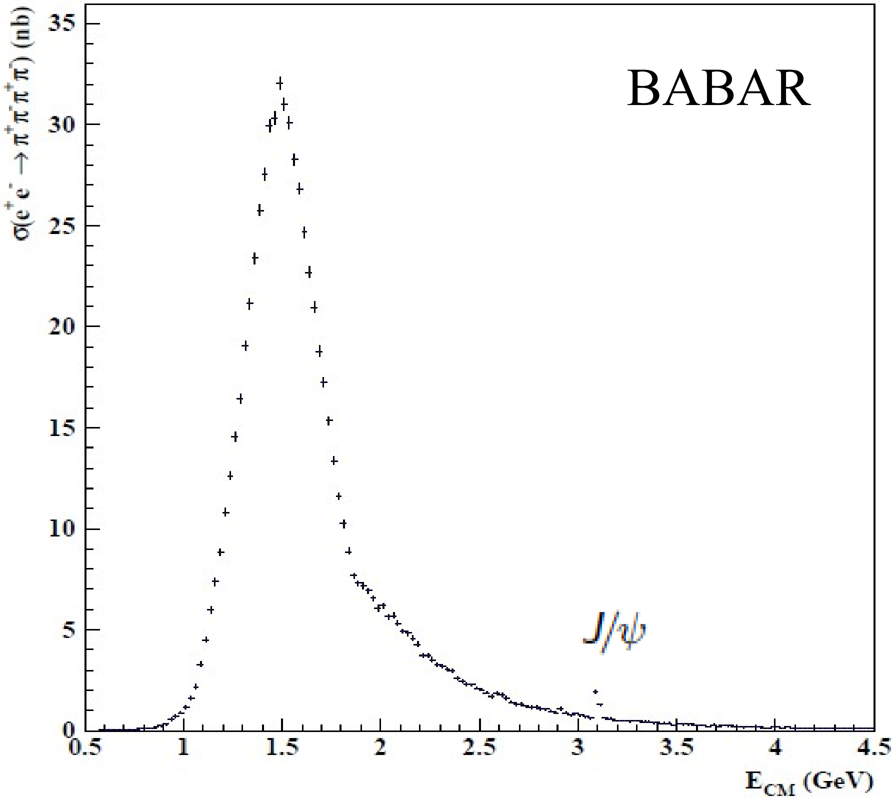


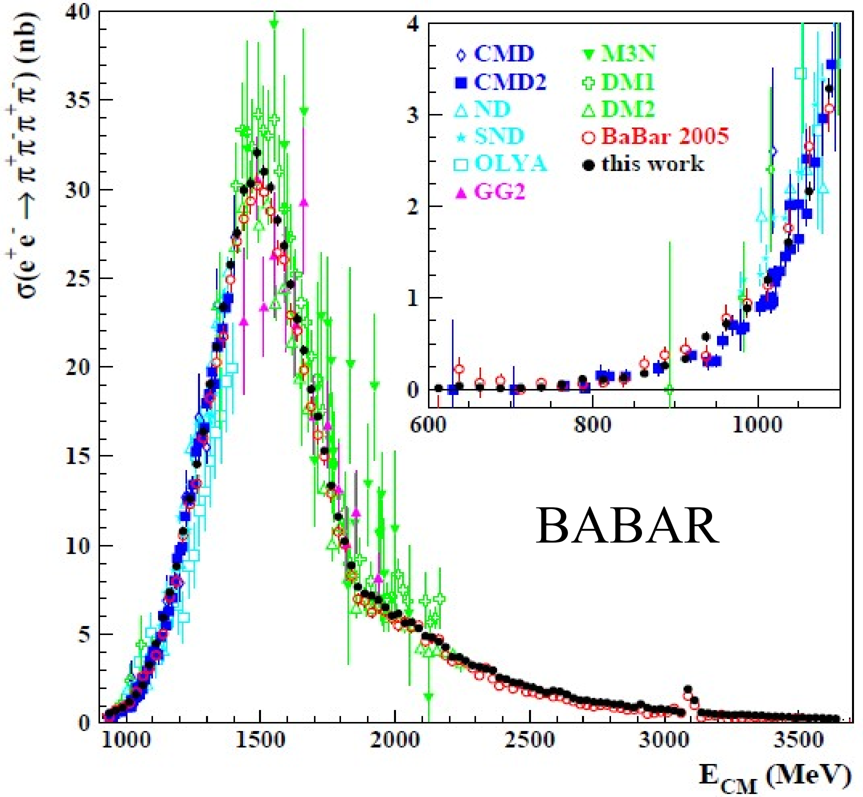




New results: $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$

published in 2012 based on the full BABAR statistics (454 fb^{-1})
previous publication on 89 fb^{-1} only



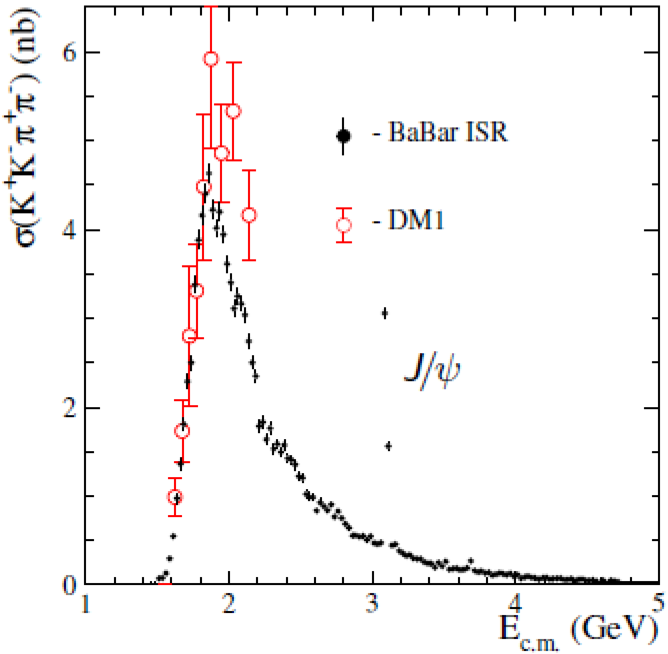


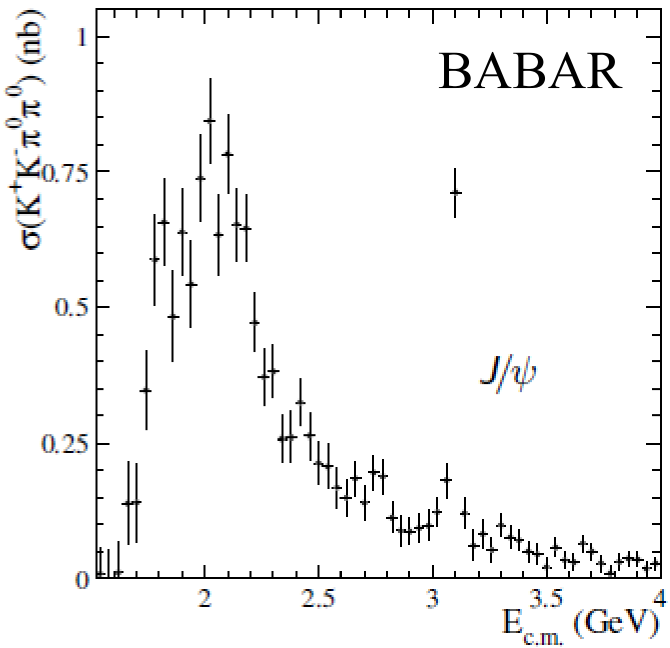
- Systematic uncertainties
  2.4% in peak region (1.1-2.8 GeV)
  11% (0.6-1.1 GeV)
  4% (2.8-4.0 GeV)
- J/ψ visible

- < 1.4 GeV: agreement with previous *BABAR* results, SND and CMD-2 data
- > 1.4 GeV: highest precision (DM2, 20%)

New results: $e^+e^- \rightarrow K^+ K^- \pi^+\pi^-$, $K^+K^- \pi^0\pi^0$

Published in 2012 based on the full BABAR statistics (454 fb^{-1})
→ huge improvement compared to existing data





- syst. uncertainty: 4 - 11%
- resolution: 4.2 - 5.5 MeV
- J/ψ clearly visible

- syst. uncertainty: 7 - 16%
- resolution: 8.8 - 11.2 MeV
- J/ψ clearly visible

Cross sections dominated below 1.8 GeV by $K^*(892)^0 K^{+-} \pi^{-+}$ and $K^*(892)^{+-} \pi^{-+} \pi^0$
important to know resonance dynamics to estimate unmeasured final states for g-2 integral

Impact of BABAR data for g-2: $2(\pi^+ \pi^-)$

BABAR results:

$a_\mu^{4\pi,\,LO}$ [0.6-1.8] GeV = $(13.64 \pm 0.03\ (stat) \pm 0.36\ (syst)\ )\ 10^{-10}$ (2.6%)

DEHZ 2003: all results but BABAR 2007:

$a_\mu^{4\pi,\,LO}$[0.6-1.8]GeV = $(13.95 \pm 0.90\ (exp) \pm 0.23(rad^*)\ )10^{-10}$ (6.7%)

* missing radiative corrections

DHMZ 2011: all results but BABAR 2012:

$a_\mu^{4\pi,\,LO}$[0.6-1.8]GeV = $(13.35 \pm 0.10\ (stat) \pm 0.52(syst)\ )10^{-10}$ (4.0%)

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