Hadronic Vacuum Polarization: Initial State Radiation results at flavor factories

Andreas Hafner (hafner@kph.uni-mainz.de)

Johannes Gutenberg-University Mainz

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PEP-II and the *BABAR* detector at SLAC

BABAR

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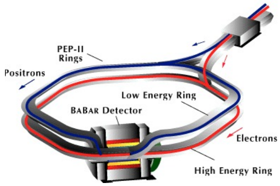
main purpose: B-physics $\rightarrow$ CP violation

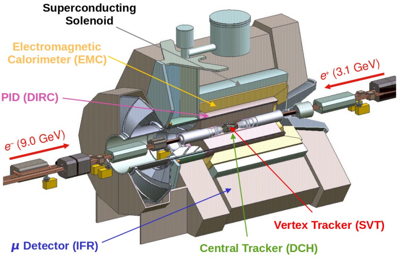
PEP-II

- asymmetric e^+e^--colliders
- $\sqrt{s} = 10.58\,\mathrm{GeV} \Rightarrow \Upsilon(4S)$
  $\Rightarrow$ above $B\bar{B}$-threshold



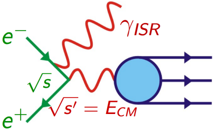
BABAR detector

- multi purpose detector
- data taking: 1999 – 2008:
- $\mathcal{L}_{int} = 531\,\mathrm{fb}^{-1}$
  $\mathcal{L}_{int}(\Upsilon(4S)) = 454\,\mathrm{fb}^{-1}$
  $\approx 4.7 \cdot 10^8$ $B\bar{B}$ pairs



BUT, there is more...

Initial State Radiation (ISR)-Physics



- **high energy** $\gamma_{ISR} \Rightarrow$ lower cms energy
- produce vectors: $J^{PC} = 1^{--}$
- measure σ_{had}

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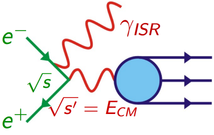
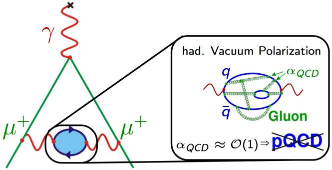
Initial State Radiation (ISR)-Physics



$\Rightarrow a_\mu^{had,VP}$:



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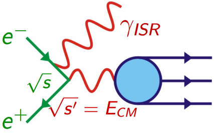

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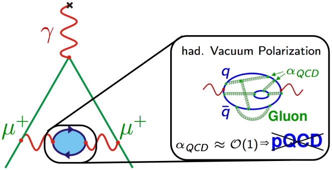
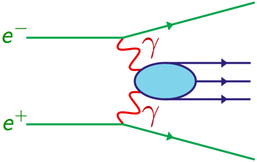


$\gamma\gamma$-Physics

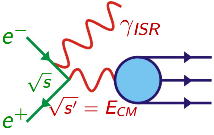


- produce pseudoscalars $J^{PC} = 0^{-+}, \cdots$
- measure **meson photon transition FFs**

$\Rightarrow$ low-energy hadron Physics (u-d-s-quarks) at the B-Factories

BUT, there is more...

Initial State Radiation (ISR)-Physics



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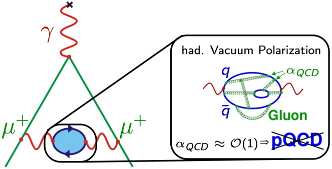
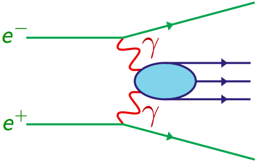
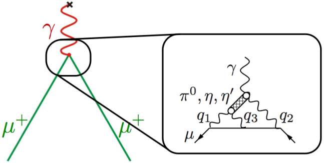


$\gamma\gamma$-Physics

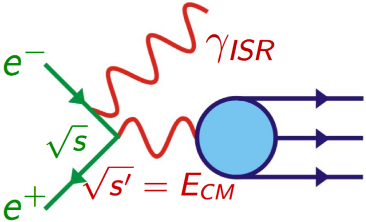


$\Rightarrow a_\mu^{had,LbL}$:



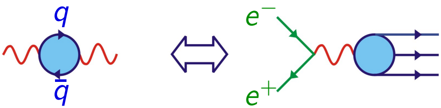
$\Rightarrow$ low-energy hadron Physics (u-d-s-quarks) at the B-Factories

Hadronic cross sections for $a_\mu^{had,VP}$



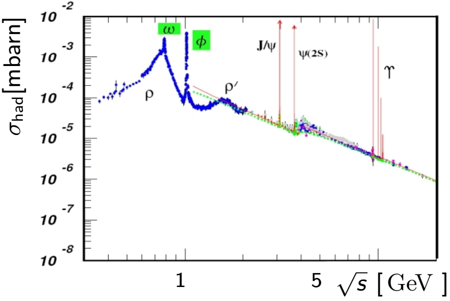
Experimental input for a_μ^{had}

Optical Theorem



Energy scan

- CMD & SND@VEPP-2M & VEPP-2000, Novosibirsk
- BES-I & II, BEPC, Beijing



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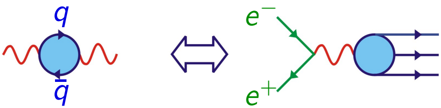
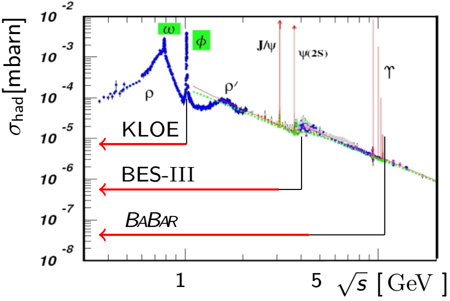
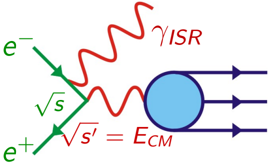




Energy scan

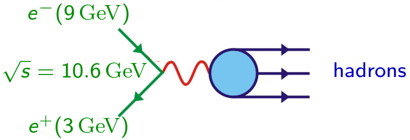
- CMD & SND@VEPP-2M & VEPP-2000 in Novosibirsk
- BES-III@BEPC-II in Beijing

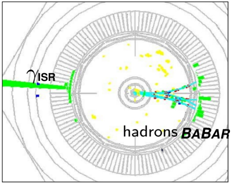
Initial State Radiation



- KLOE@DAϕNE in Frascati
- *BaBar*@PEP-II in Stanford
- BES-III@BEPC-II in Beijing

Initial State Radiation (ISR) events at *BABAR*





ISR selection

- Detected high energy photon: $E_\gamma > 3\,\mathrm{GeV}$
  $\rightarrow$ defines E_{CM} & provides strong background rejection
- Event topology: γ_{ISR} back-to-back to hadrons
  $\rightarrow$ high acceptance
- Kinematic fit including γ_{ISR}
  $\rightarrow$ very good energy resolution ($4 - 15\,\mathrm{MeV}$)
- Continuous measurement from threshold to $\sim 4.5\,\mathrm{GeV}$
  $\rightarrow$ provides common, consistent systematic uncertainties

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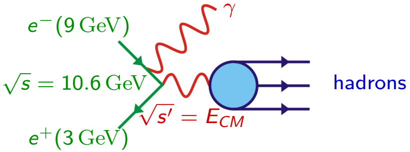

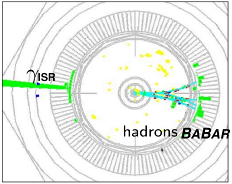

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ISR analyses at *BABAR*

published

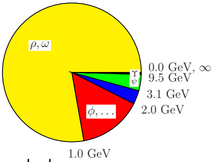
$e^+e^- \to \pi^+\pi^-$	PR D 86 (2012) 032013, PR L 103 (2009) 231801
$e^+e^- \to K^+K^-$	PR D 88, (2013) 032013
$e^+e^- \to \phi f_0(980)$	PR D 74 (2006) 091103, PR D 76 (2007) 012008
$e^+e^- \to \pi^+\pi^-\pi^0$	PR D 70 (2004) 072004
$e^+e^- \to K^+K^-\eta, K^+K^-\pi^0, K_S^0K^\pm\pi^\mp$	PR D 77 (2008) 092002, PR D 71 (2005) 052001
$e^+e^- \to 2(\pi^+\pi^-)$	PR D 85 (2012) 112009, PR D 76 (2007) 012008
$e^+e^- \to K^+K^-\pi^0\pi^0, K^+K^-\pi^+\pi^-, 2(K^+K^-)$	PR D 86 (2012) 012008, PR D 76 (2007) 012008
$e^+e^- \to 2(\pi^+\pi^-)\pi^0, 2(\pi^+\pi^-)\eta, K^+K^-\pi^+\pi^-\pi^0, K^+K^-\pi^+\pi^-\eta$	PR D 76 (2007) 092005
$e^+e^- \to 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0), 2(\pi^+\pi^-)K^+K^-$	PR D 73 (2006) 052003
$e^+e^- \to p\bar{p}$ (small $\sqrt{s}$)	PR D 87 (2013) 092005, PR D 73 (2006) 012005
$e^+e^- \to p\bar{p}$ (large $\sqrt{s}$)	PR D 88 (2013) 072009
$e^+e^- \to \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$	PR D 76 (2007) 092006
$e^+e^- \to c\bar{c} \to \ldots$	... ...

ongoing analyses

$e^+e^- \to K_S^0K_L^0, K_S^0K_L^0\pi^+\pi^-, K_S^0K_S^0\pi^+\pi^-, K_S^0K_S^0K^+K^-, \pi^+\pi^-\pi^0\pi^0, K_S^0K^\pm\pi^\mp\pi^0/\eta$

Contributions of exclusive final states to $g_\mu - 2$

Contributions of different energy regions to the dispersion integral

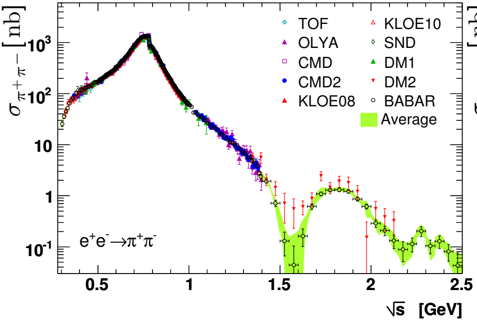


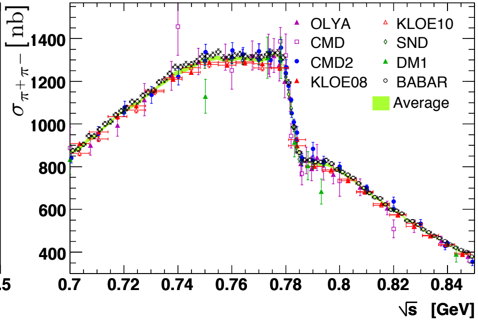
a_μ^{had} Integral

$\rightarrow E < 1\,\mathrm{GeV}$ region dominates
$\rightarrow \pi^+\pi^-$ channel needed!

(F. Jegerlehner, A. Nyfeller, 2009)

$\pi^+\pi^-$ cross section



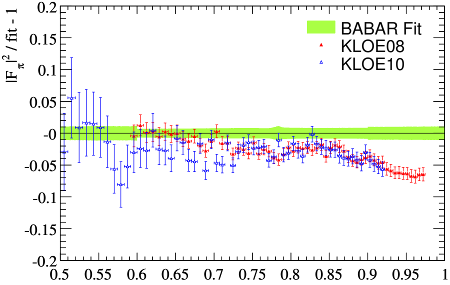


- ρ peak
- $\rho - \omega$ interference
- Dip at 1.6 GeV: excited ρ states
- Dip at 2.2 GeV
- Contribution to a_μ^{had}: 75%!

Systematic Uncertainties

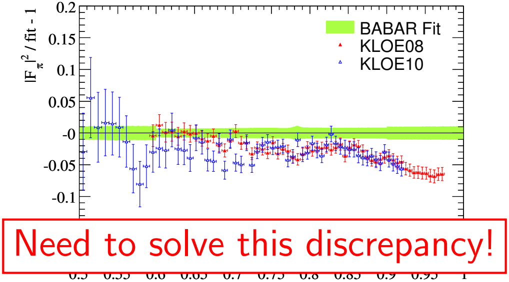
BABAR:	0.5%
CMD2:	0.8%
SND:	1.5%
KLOE:	0.8%

$\pi^+\pi^-$ cross section



- KLOE and *BABAR* dominate the world average
- Uncertainty of both measurements smaller than 1%
- Systematic difference, especially above ρ peak
- Difference $\rightarrow$ relatively large uncertainty for a_μ^{had}

$\pi^+\pi^-$ cross section



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Contributions of exclusive final states

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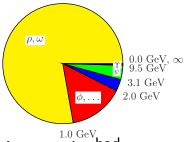
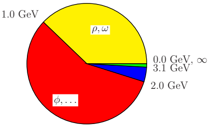
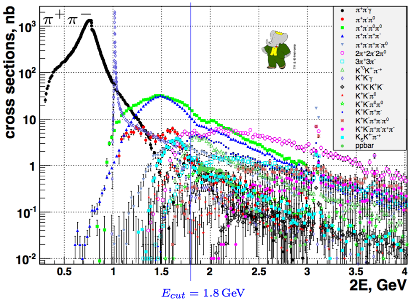


Integral a_μ^{had}



Uncertainty^2 $\delta a_\mu^{\text{had}}$

$\Rightarrow$ Precise measurements $1\,\text{GeV} < E < 2\,\text{GeV}$ needed!

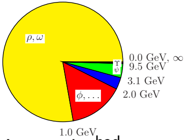


$\Rightarrow$ Other channels important!

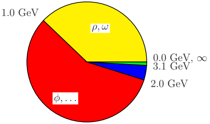
- K^+K^-
- $K_S^0 K_L^0$
- $\pi^+\pi^-\pi^+\pi^-$
- $\pi^+\pi^-\pi^0$
- $\pi^+\pi^-\pi^0\pi^0$

Contributions of exclusive final states

Contributions of different energy regions to the dispersion integral



Integral a_μ^{had}



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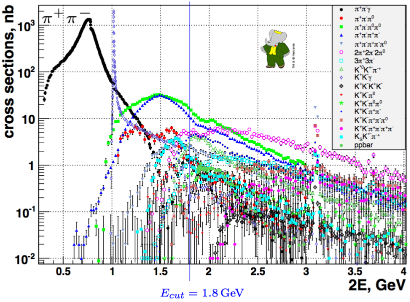

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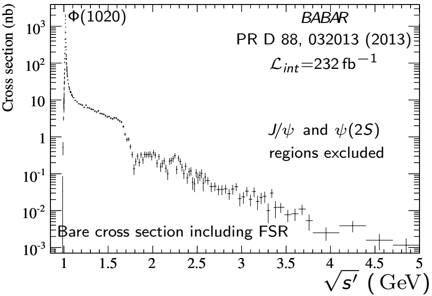
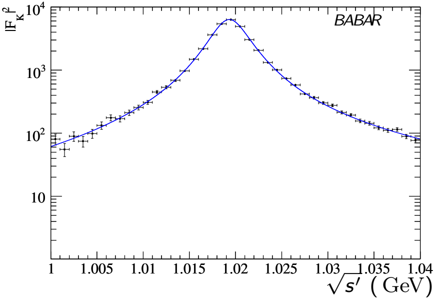
- K^+K^-
- $K^0_S K^0_L$
- $\pi^+\pi^-\pi^+\pi^-$
- $\pi^+\pi^-\pi^0$
- $\pi^+\pi^-\pi^0\pi^0$

will be presented

no recent results

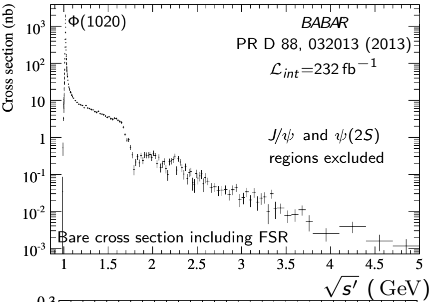
Cross section $\sigma(e^+e^- \to K^+K^-)$

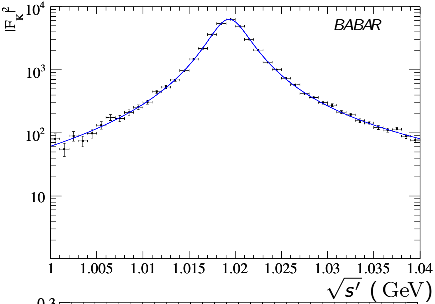


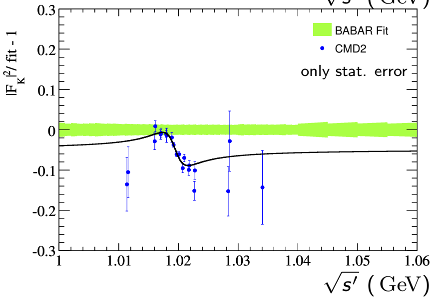


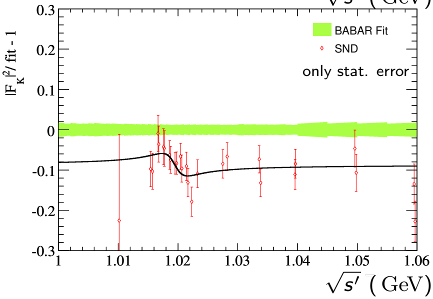
- uncertainty: 0.8% near ϕ peak!
- efficiency obtained from simulation [Kühn *et al.*, EPJC 18 (2001),497]
  $\rightarrow$ data/MC corrections of utmost importance:
  trigger, tracking, particle-ID
- ISR effective luminosity from $\mu\mu\gamma(\gamma)$ as in $\pi^+\pi^-$ study: KK/$\mu\mu$ ratio

Cross section $\sigma(e^+e^- \to K^+K^-)$

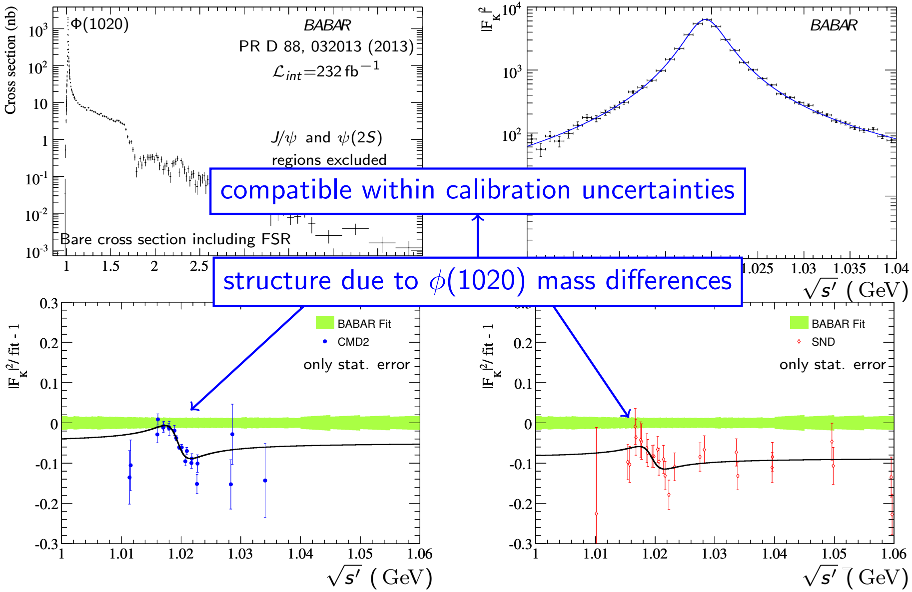








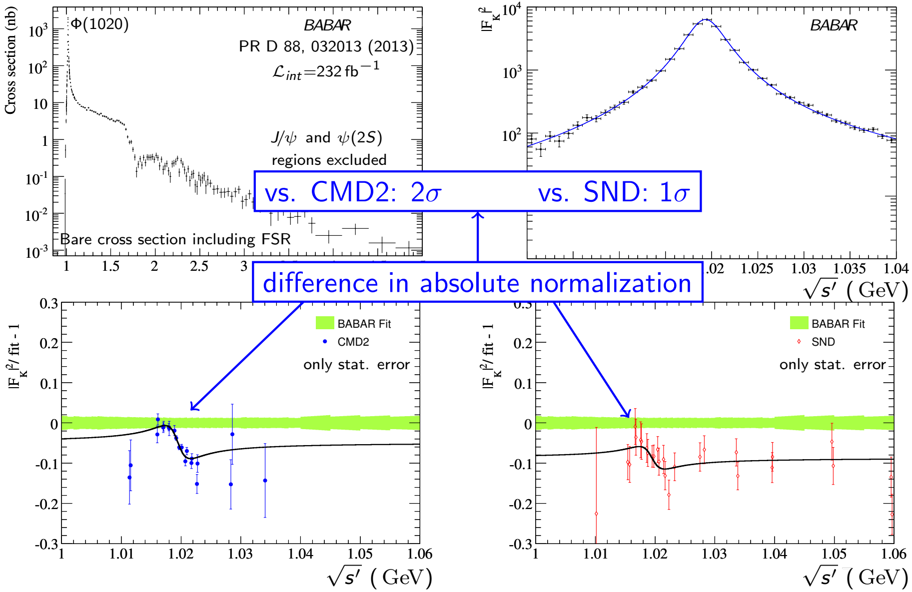
Cross section $\sigma(e^+e^- \to K^+K^-)$



compatible within calibration uncertainties

structure due to $\phi(1020)$ mass differences

Cross section $\sigma(e^+e^- \to K^+K^-)$



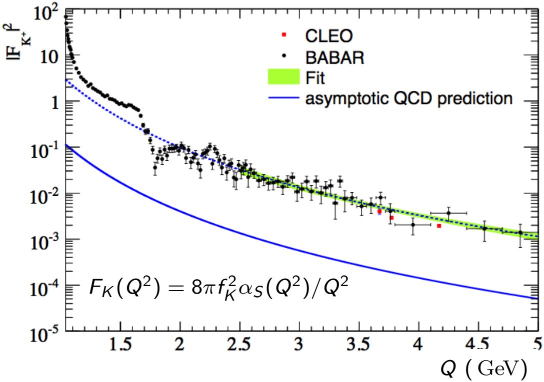
vs. CMD2: 2σ vs. SND: 1σ

difference in absolute normalization

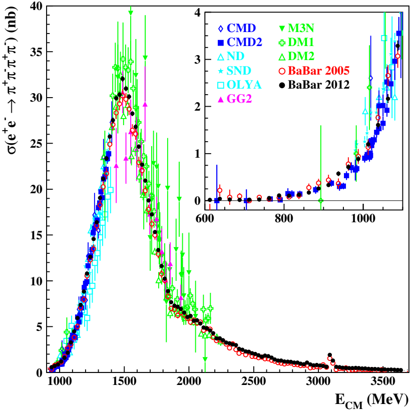
Charged kaon form factor at large Q^2

Predictions based on QCD in asymptotic regime (Chernyak, Brodsky-Lepage, Farrar-Jackson)

- Power law: $F_K \propto \alpha_S(Q^2)Q^{-n}$ with $n = 2$
  $\rightarrow$in good agreement with the data (2.5-5 GeV $n = 2.10 \pm 0.23$)
- HOWEVER: data on $|F_K|^2$ factor ≈ 20 above prediction!
- No trend in data up to 25 GeV^2 for approaching the asymp. QCD prediction



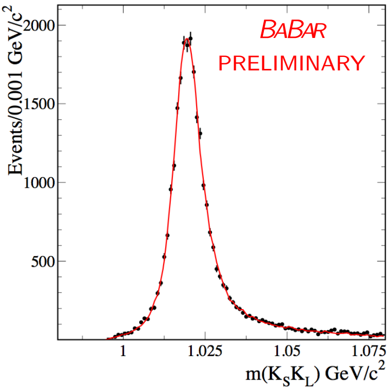
Cross section $\sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^-)$

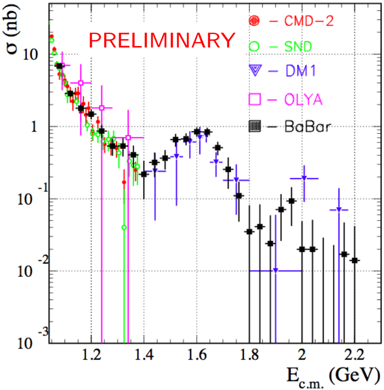


- *BABAR* 12: 2.4% uncertainty in peak region
- various experiments agree

Cross section $\sigma(e^+e^- \to K_S^0 K_L^0)$

arxiv: 1403.7593





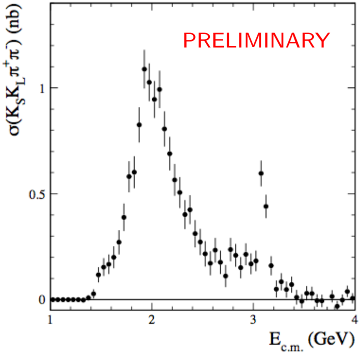
σ extracted from fit

- consistent with CMD2
- syst uncertainty: 2.9%
- dominated by trigger

systematic uncertainty:

- $\sim 10\%$ for $\sigma > 0.5\,\mathrm{nb}$
- $\sim 30\%$ for $\sigma < 0.5\,\mathrm{nb}$
- dominated by bkg-subtraction

Cross Section of $e^+e^- \to K_S^0 K_L^0 \pi^+\pi^-$



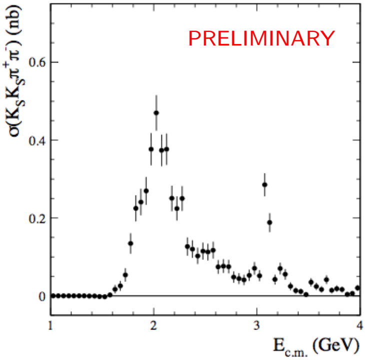
$$\mathcal{B}_{J/\psi \to K_S^0 K_L^0 \pi^+\pi^-} = (3.7 \pm 0.6 \pm 0.4) \cdot 10^{-3}$$

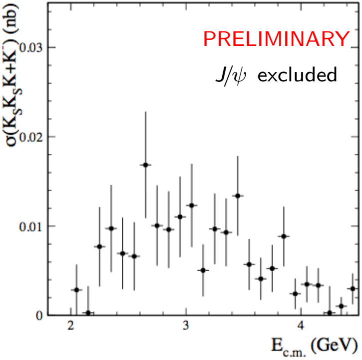
1$^{\text{st}}$ measurement

Systematic uncertainty dominated by background-subtraction procedure:

- $\sim 10\%$ in peak region
- Increases to $\sim 30\%$ at 1.5 and 3 GeV
- $\sim 100\%$ above 3 GeV

Cross Section of $K_s^0K_s^0\pi^+\pi^-$ and $K_s^0K_s^0K^+K^-$





$\mathcal{B}_{J/\psi \to K_S^0K_S^0\pi^+\pi^-} = (1.68 \pm 0.16 \pm 0.08) \cdot 10^{-3}$ $\mathcal{B}_{J/\psi \to K_S^0K_S^0K^+K^-} = (0.42 \pm 0.08 \pm 0.02) \cdot 10^{-3}$

1^{st} measurement

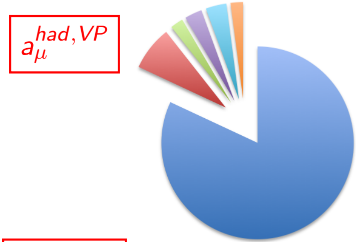
Systematic uncertainties:

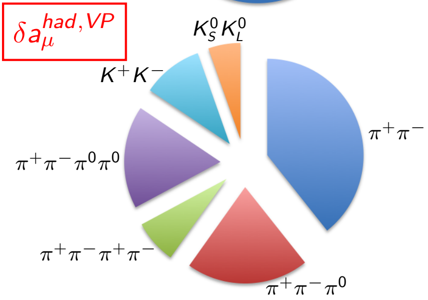
- $\sim 5\%$ in peak region
- Increases to $\sim 20\%$ at $1.5/3\,\mathrm{GeV}$
- $\sim 50 - 70\%$ above $3\,\mathrm{GeV}$

- $\sim 5\%$
- stat. error dominates

Impact on $g_\mu - 2$: had. VP

$a_\mu^{\mathrm{VP,LO}} = (692.3 \pm 4.2) \cdot 10^{-10}$





[data from Davier, EPJ **C** 71, 1515 (2011)]

$K_S^0 K_L^0$

BABAR not evaluated, yet

K^+K^-

BABAR reduces $\delta a_\mu^{had}(K^+K^-)$ by factor ≈ 3

$\pi^+\pi^-\pi^0\pi^0$

wait for *BABAR*, BESIII and CMD3 results

$\pi^+\pi^-\pi^+\pi^-$

BABAR reduces $\delta a_\mu^{had}(\pi^+\pi^-\pi^+\pi^-)$ by 40%

$\pi^+\pi^-$ & $\pi^+\pi^-\pi^0$

wait for BESIII and CMD3 results

Summary & outlook

hadronic cross sections for $a_\mu^{had,VP}$

- still dominate the uncertainty of a_μ^{had} and thus a_μ^{theory}
- $e^+e^- \to \pi^+\pi^-\pi^+\pi^-, K^+K^-, K_S^0 K_L^0$: well under controll

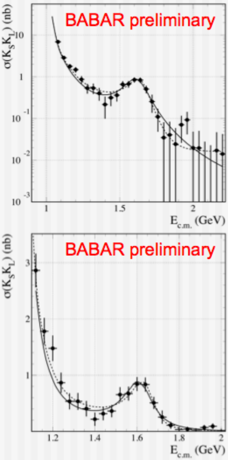
challenge between ISR and scan experiments continues

- $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ $\Rightarrow$ *BABAR*, CMD3, BESIII
- $e^+e^- \to \pi^+\pi^-\pi^0, \pi^+\pi^-$ $\Rightarrow$ CMD3, BESIII, (*BABAR* ???)
  $\Rightarrow$ validation is essentiel!

backup slides

$\phi(1680) \to K_S^0 K_L^0$

Is it $\phi(1680)$?



$$\sigma(s) = \frac{P(s)}{s^{5/2}} \left| \frac{A_{\phi(1020)}}{\sqrt{P(m_\phi)}} + \frac{A_X}{\sqrt{P(m_X)}} \cdot e^{i\varphi} + A_{bkg} \right|^2$$

$$P(s) = \left((s/2)^2 - m_{K^0}^2 \right)^{3/2}$$

$$A(s) = \frac{\Gamma(m^2) \cdot m^3 \sqrt{\sigma_0 \cdot m}}{s - m^2 + i\sqrt{s}\Gamma(s)}$$

$$\Gamma(s) = \Gamma \cdot \sum_f B_f \cdot \frac{P_f(s)}{P_f(m_f^2)}$$

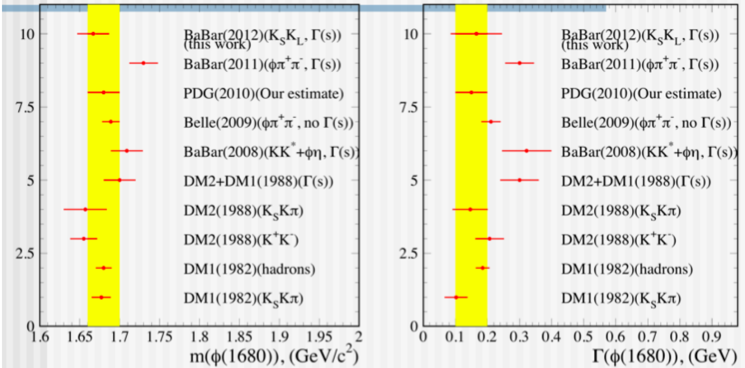
$$A_{\phi(1020)} = A_\phi + A_\omega - A_\rho, \qquad f = K^* K, \phi\eta, \phi\pi\pi, K_S K_L$$

$\sigma_0 = 0.46 \pm 0.10 \pm 0.04$ nb
m = $1674 \pm 12 \pm 6$ MeV/c^2
$\Gamma_0 = 165 \pm 38 \pm 70$ MeV
$\varphi = 3.01 \pm 0.38$ – fixed to π
$\sigma_{bkg} = 0.36 \pm 0.18$ nb
$\Gamma_{ee} \bullet B_{KSKL} = 14.3 \pm 2.4 \pm 1.5 \pm 6.0$ eV

Simultaneous K_SK_L and K^+K^- (and $\pi\pi$) fit is needed to separate I=0,1 states and $\omega(1420, 1650)$, $\rho(1450,1700)$ contribution ...

$\phi(1680)$ observations in other channels

What we know about φ(1680)



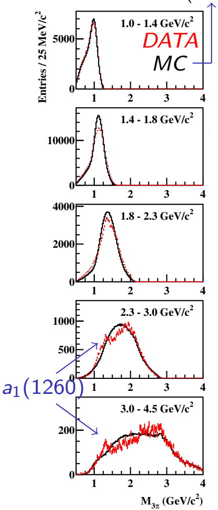
Energy dependence significantly increase width.

BaBar has measured φ(1680) parameters in major decay modes:

$\phi(1680) \rightarrow K_S K\pi$, $KK\pi^0$ (K^*K), $\phi\eta$, $\phi\pi\pi$, $K_S K_L$ (preliminary) - still no info in PDG

Internal structure in various E_{CM} energy slices

(EPJ C18, 497 (2001))

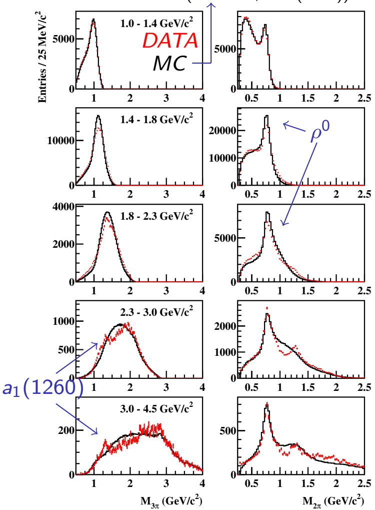


First column (4 entries/event):

$a_1(1260)$

Internal structure in various E_{CM} energy slices

(EPJ C18, 497 (2001))



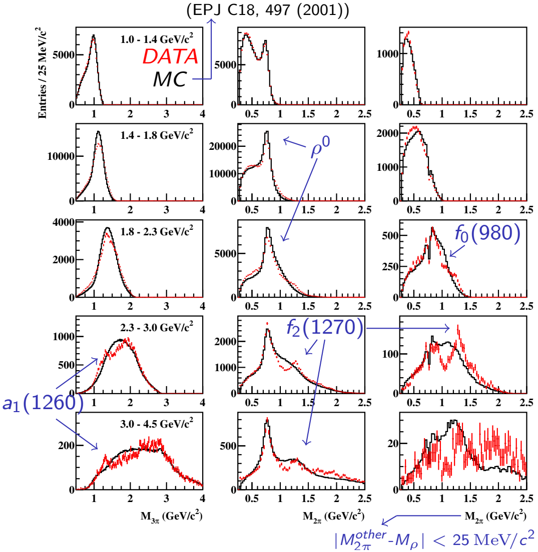
First column (4 entries/event):

$a_1(1260)$

Second column (4 entries/event):

strong ρ^0 contribution
e.g. for $M_{4\pi} > 1.4\,\mathrm{GeV}/c^2$:
$1/4th$ of entries in ρ^0 peak
$\rho^0\rho^0$ is forbidden
$\rightarrow \rho^0$ in each event!

Internal structure in various E_{CM} energy slices



First column (4 entries/event):

$a_1(1260)$

Second column (4 entries/event):

strong ρ^0 contribution
e.g. for $M_{4\pi} > 1.4\,\mathrm{GeV}/c^2$:
$1/4th$ of entries in ρ^0 peak
$\rho^0\rho^0$ is forbidden
$\rightarrow \rho^0$ in each event!

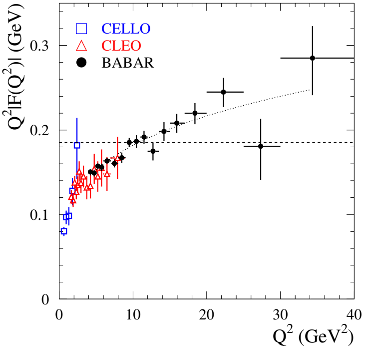
Third column (1 entry/event):

2π lie within ρ^0 mass
$\rightarrow$ other $\pi^+\pi^-$'s mass plotted

$f_2(1270)$, $a_1(1260)$, $f_0(980)\ldots$?

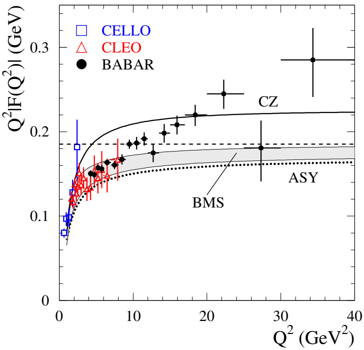
$\rightarrow$ Partial Wave Analysis needed

π^0-photon transition form factors



- systematic uncertainty:
  efficiency (trigger): 2.5%
  bkg ($e^+e^- \to e^+e^-\pi^0\pi^0$): 0.3 – 6.0%
  model uncertainty: 1.5%
- $4\,\mathrm{GeV}^2 < Q^2 < 9\,\mathrm{GeV}^2$:
  reasonable agreement with CLEO
- $Q^2 > 10\,\mathrm{GeV}^2$:
  pQCD: $\lim_{Q^2\to\infty} Q^2 F(Q^2) = \sqrt{2} f_\pi$
  $\Rightarrow$ asymptotic limit exceeded!

π^0-photon transition form factors



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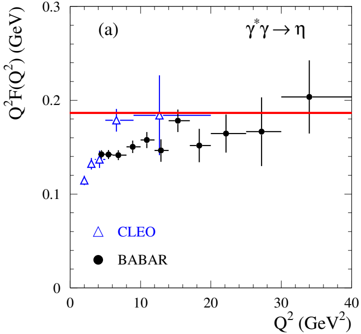
  pQCD: $\lim_{Q^2\to\infty} Q^2F(Q^2) = \sqrt{2}f_\pi$
  $\Rightarrow$ asymptotic limit exceeded!

$\Rightarrow$ triggered a lot of theoretical work & a new measurement at Belle

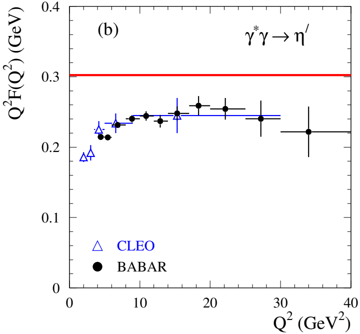
$>$ 200 citations since 2009

η/η'-photon transition form factors

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



$\eta' \to \pi^+\pi^-\eta, \eta \to \gamma\gamma$

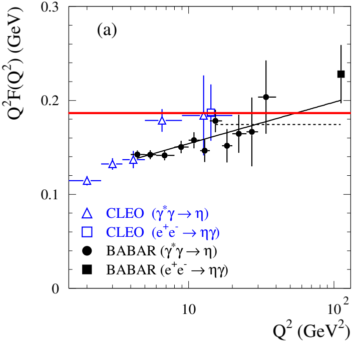


systematic uncertainty: 2.9%
dominated by model unc. & π^0 rec.

systematic uncertainty: 3.5%
dominated by model unc. & η rec.

η/η'-photon transition form factors

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

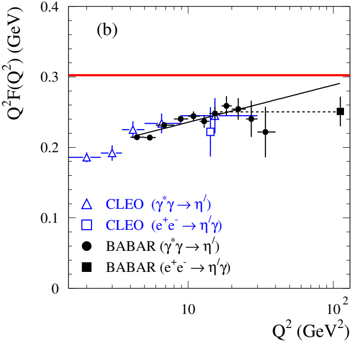


systematic uncertainty: 2.9%

dominated by model unc. & π^0 rec.

η-FF exceeds asymptotic limit

$\eta' \to \pi^+\pi^-\eta, \eta \to \gamma\gamma$



systematic uncertainty: 3.5%

dominated by model unc. & η rec.

η'-FF below asymptotic expectation