Hadronic Cross Section Measurements with ISR and the Implications on $g_\mu - 2$

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on behalf of the *BABAR* Collaboration

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Determination of Fundamental QCD Parameters,
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Outline

1. Introduction
   - Theoretical relation $a_\mu \leftrightarrow \sigma_{\mathrm{had}}$
   - Experimental setup at *BABAR*
2. Recent Results
   - $e^+e^- \to K^+K^-$
   - $e^+e^- \to K^0_{\mathrm{S}}K^0_{\mathrm{L}}$
   - $e^+e^- \to K^0K^0\pi^+\pi^-$ and $e^+e^- \to K^0_{\mathrm{S}}K^0_{\mathrm{S}}K^+K^-$
3. Summary

The contributions to a_μ and its uncertainty

$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

$$(g_\mu - 2)/2 =: a_\mu = 0 \qquad \text{(Dirac)}$$

The contributions to a_μ and its uncertainty

$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

$$(g_\mu - 2)/2 =: a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{weak}} + a_\mu^{\mathrm{hadronic}}$$

The contributions to a_μ and its uncertainty

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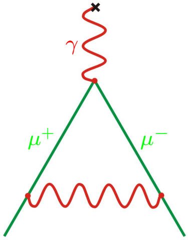

The contributions to a_μ and its uncertainty

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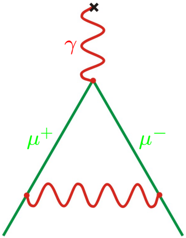
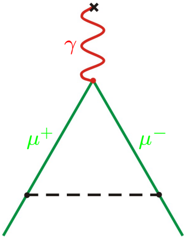


QED



weak

The contributions to a_μ and its uncertainty

$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

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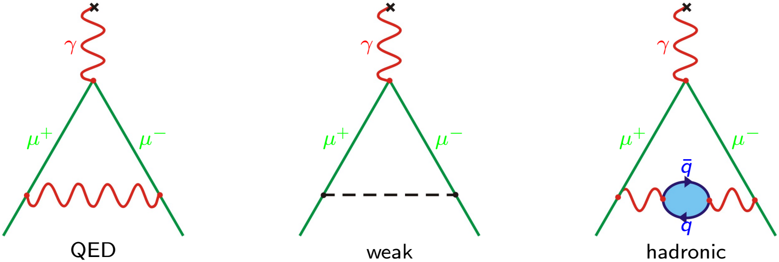
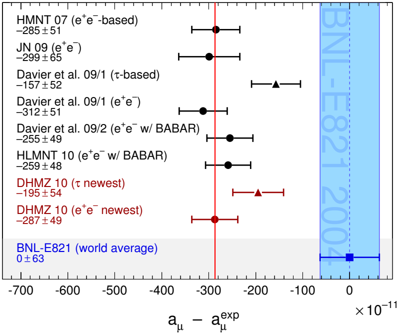


The contributions to a_μ and its uncertainty

$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$
$$(g_\mu - 2)/2 =: a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm weak} + a_\mu^{\rm hadronic}$$

Interaction	Contribution $[\cdot 10^{-11}]$	Uncertainty $[\cdot 10^{-11}]$
QED [1]	116 584 718.951	0.080
EW [5]	153.6	1
hadronic VP [4, 9]	6837	43
hadronic LbL [8, 3]	119	41
total theory	116 591 828	60
E821 experiment [13]	116 592 089	63
deviation exp-theo	261	87

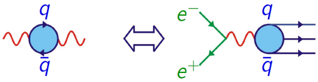
Discrepancy between SM prediction and direct measurement from Eur.Phys.J., C71:1515, 2011 [4].



Just a fluctuation?

3σ effect, thus reduction of uncertainties necessary!

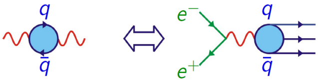
Connection between a_μ and σ_{had}



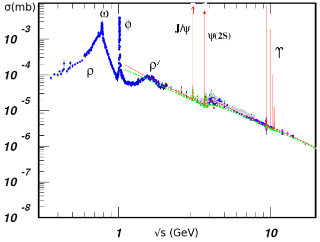
$$a_\mu^{\mathrm{had}} \approx \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} K_\mu(s)\cdot\sigma_{e^+e^-\to\mathrm{had}}(s)\,\mathrm{d}s$$

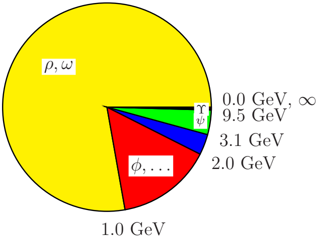
Kernel function — cross section

Connection between a_μ and $\sigma_{\rm had}$



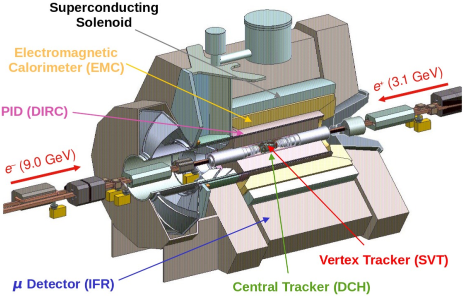
$$a_\mu^{\rm had} \approx \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} K_\mu(s)\cdot \sigma_{e^+e^-\to{\rm had}}(s){\rm d}s$$





$\sigma_{\rm had}$ (left) from Nuovo Cim., C034S1:31-40, 2011 [7] and relative contributions to a_μ^{had} (right).

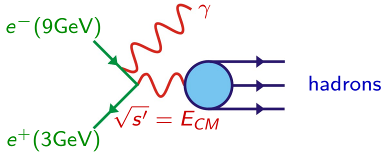
The *BABAR* Experiment

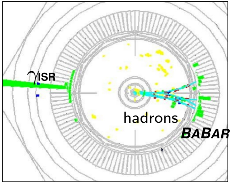


Experimental specifications

Energy: $\sqrt{s} \approx 10.58\,\text{GeV}$ $(E_{e^-} \approx 9.0\,\text{GeV}, E_{e^+} \approx 3.1\,\text{GeV})$,
Luminosity: $\mathcal{L} \approx 454\,\text{fb}^{-1}$ $(\Upsilon(4S))$

Initial State Radiation (ISR) events at *BABAR*

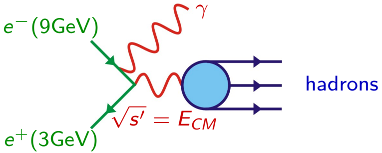


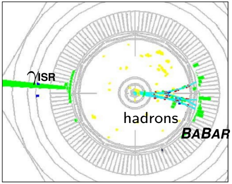


ISR selection: large angle analyses

- Detected high energy photon: $E_\gamma > 3\text{GeV}$
  $\rightarrow$ 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 $(4 - 15\text{MeV})$
- e^+e^--boost into the laboratory reference frame
  $\rightarrow$ high efficiency at production threshold of hadronic system
- Continuous measurement from threshold to $\sim$5GeV
  $\rightarrow$ provides common, consistent systematic uncertainties

Initial State Radiation (ISR) events at *BABAR*

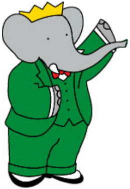


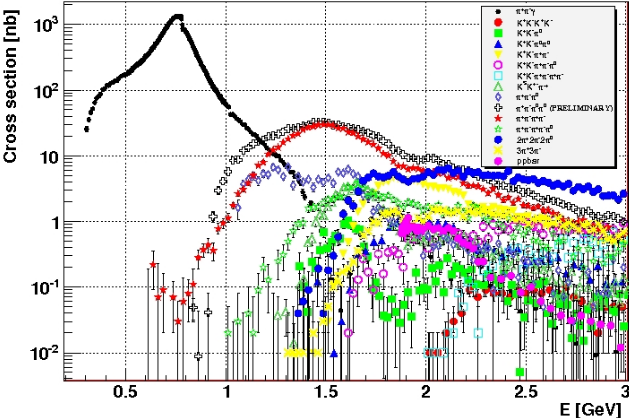


ISR selection: small angle analyses

- ISR photon γ_{ISR} not detected
  $\rightarrow$ more statistics at high energies
- Event topology: γ_{ISR} back-to-back to hadrons
  $\rightarrow$ high acceptance
- Kinematic fit not including γ_{ISR}
  $\rightarrow$ energy resolution $\sim 10 - 15$MeV
- e^+e^--boost into the laboratory reference frame
  $\rightarrow$ high efficiency at production threshold of hadronic system
- Continuous measurement from threshold to $\sim$8GeV
  $\rightarrow$ provides common, consistent systematic uncertainties

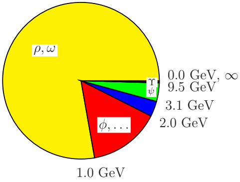
Most important channels

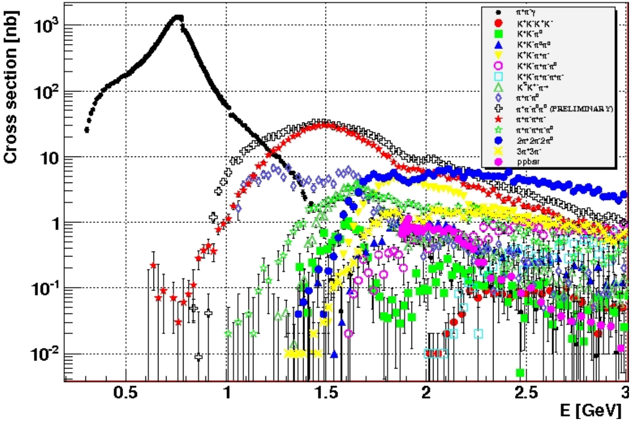




Cross Sections of the single channels measured at *BABAR* (from Nucl.Phys.Proc.Suppl., 207-208:133-136, 2010 [6]).

Most important channels

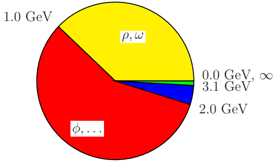


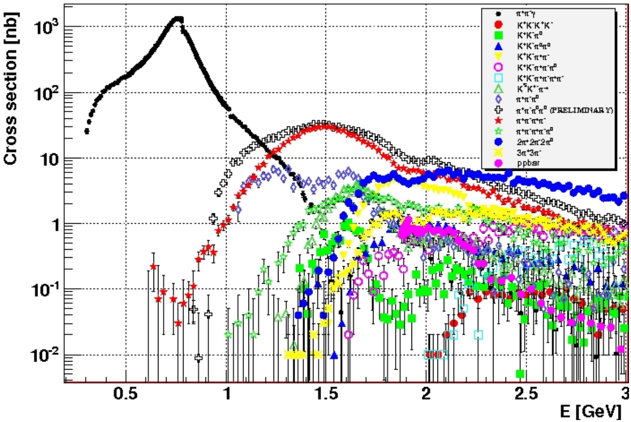


Right panel: Cross Sect. of single channels (from Nucl.Phys.Proc.Suppl., 207-208:133-136, 2010 [6]).

Left panel: Relative contributions to a_μ^{had} (from Nuovo Cim., C034S1:31-40, 2011 [7]).

Most important channels





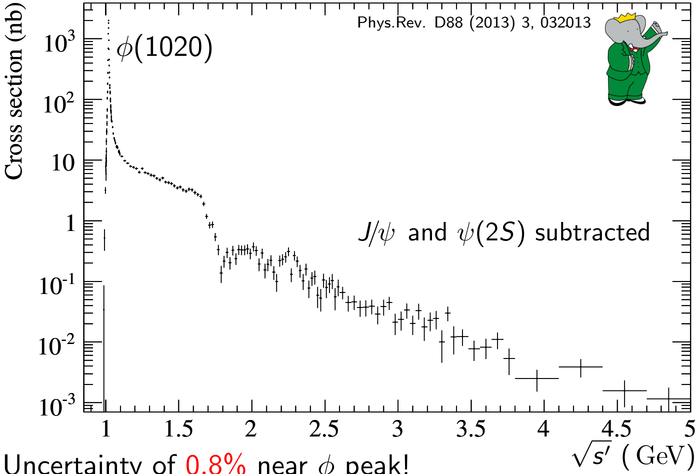
Right panel: Cross Sect. of single channels (from Nucl.Phys.Proc.Suppl., 207-208:133-136, 2010 [6]).

Left panel: Relative contributions to δa_μ^{had} (from Nuovo Cim., C034S1:31-40, 2011 [7]).

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

Phys.Rev. D88 (2013) 3, 032013 [10]
Phys.Rev. D92 (2015) 7, 072008 [12]

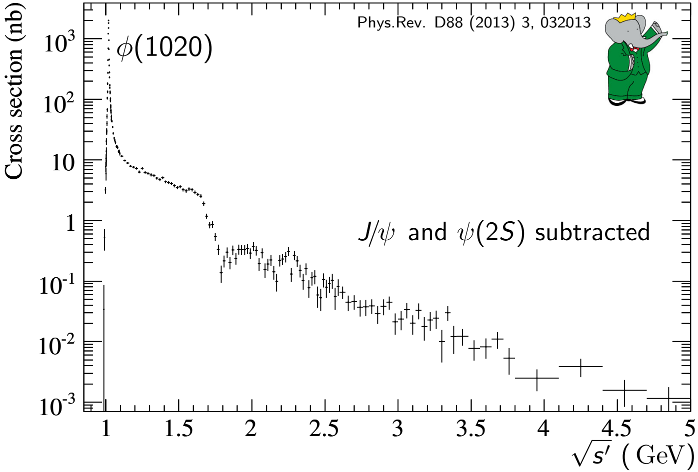
Cross section $\sigma(e^+e^- \to K^+K^-)$



Uncertainty of 0.8% near ϕ peak!

$\rightarrow$ luminosity from $\mu\mu\gamma$ and K-ID

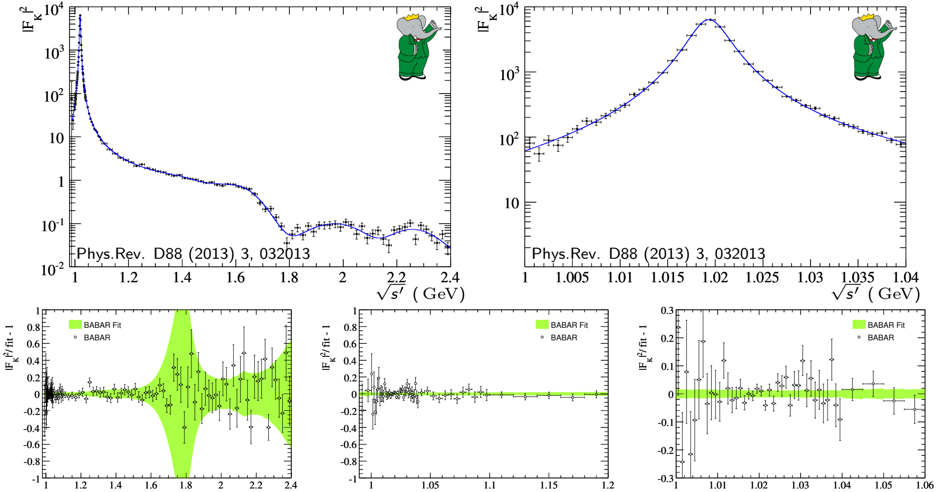
Cross section $\sigma(e^+e^- \to K^+K^-)$



$\Rightarrow a_\mu^{had}(K^+K^-) = (229.5 \pm 1.4 \pm 2.2) \times 10^{-11}$

$\rightarrow$ improvement by factor 2.8 over previous world data

A phenomenological fit to the form factor



The Φ parameters

m_Φ and Γ_Φ obtained from the fit of the form factor

BABAR

$m_\Phi = 1019.51 \pm 0.02(\pm 0.11)\,\mathrm{MeV}$
$\Gamma_\Phi = 4.29 \pm 0.04(\pm 0.07)\,\mathrm{MeV}$

PDG

$m_\Phi = 1019.455 \pm 0.020\,\mathrm{MeV}$
$\Gamma_\Phi = 4.26 \pm 0.04\,\mathrm{MeV}$

$\rightarrow$ good agreement

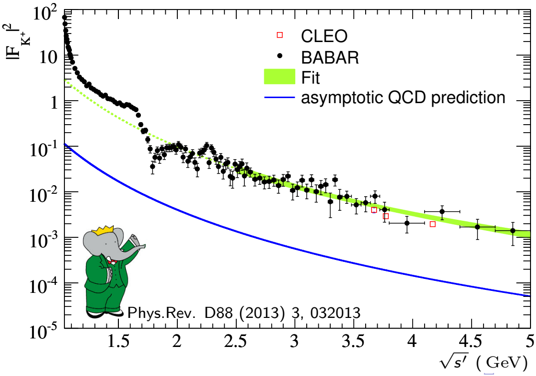
From integrated Φ peak: $\Gamma_\Phi^{ee} \times \mathcal{B}(\Phi \to K^+K^-) = \frac{\alpha^2\beta^3(s,m_K)}{324}\frac{m_\Phi^2}{\Gamma_\Phi}a_\Phi^2 C_{FS}$

BABAR:
$\Gamma_\Phi^{ee} \times \mathcal{B}(\Phi \to K^+K^-) = 0.6344 \pm 0.0059_{exp} \pm 0.0028_{fit} \pm 0.0015_{cal}\,\mathrm{keV}(1.1\%)$
CMD2:
$\Gamma_\Phi^{ee} \times \mathcal{B}(\Phi \to K^+K^-) = 0.605 \pm 0.002 \pm 0.013\,\mathrm{keV}(2.1\%)$

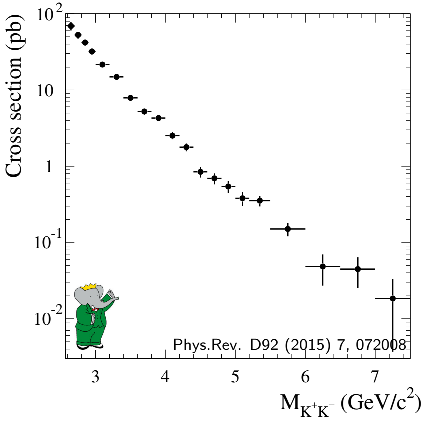
Charged kaon form factor at large Q^2

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

- Power law: $F_K \sim \alpha_S(Q^2)Q^{-n}$ with n=2
  →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 5 GeV for approaching the asymp. QCD prediction

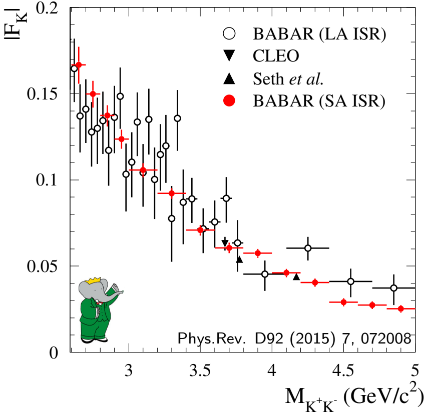


Small angle analysis → even larger Q^2



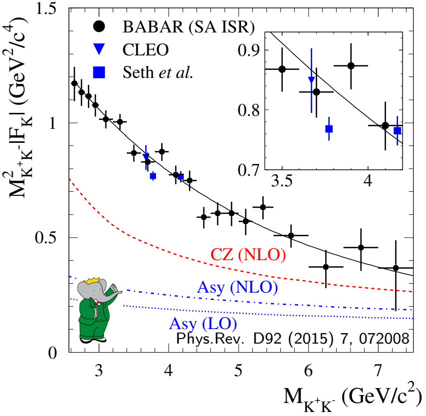
- Small angle measurement reaches energies above 5 GeV
- Smooth decrease over full energy range

Comparison between small and large angle analysis



Good agreement between measurements in overlapping region

Asymptotic behavior of the form factor at largest Q^2?



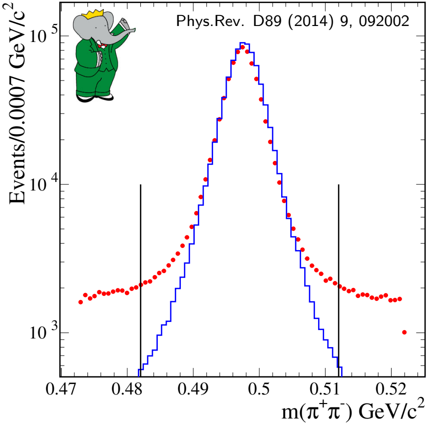
At large energies, data tends to agree better with predictions

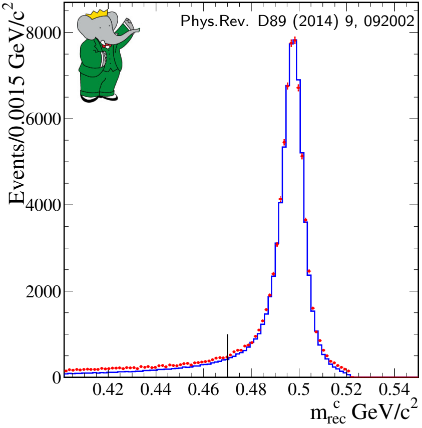
$e^+e^- \to K^0_{\mathrm{S}} K^0_{\mathrm{L}}$

Phys.Rev. D89 (2014) 9, 092002 [11]

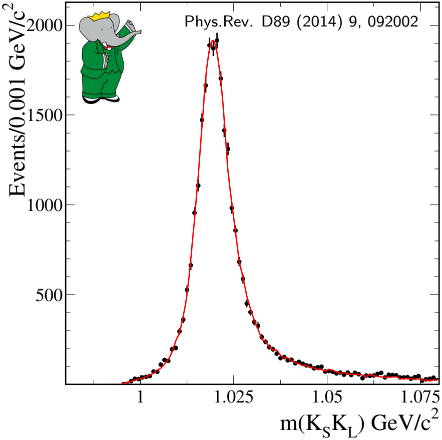
Detection of $K^0_S K^0_L$

$K^0_S \to \pi^+\pi^-$ and K^0_L selected via recoil mass





$K^0_S K^0_L$ mass spectrum

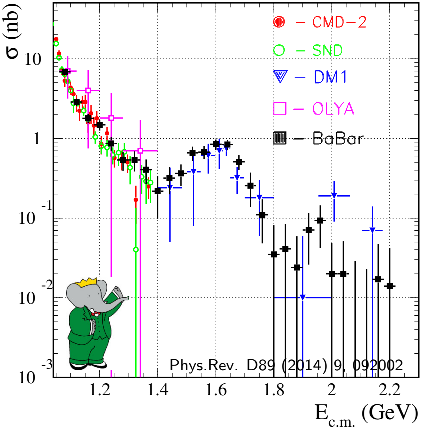


Fit results

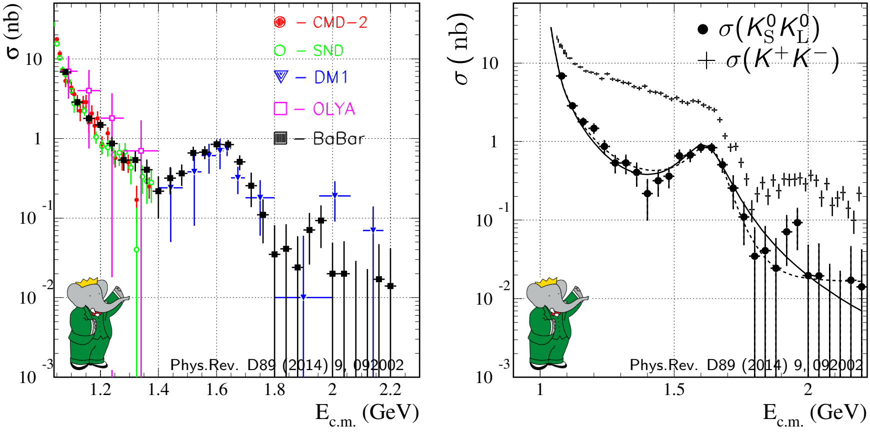
$\sigma_\phi = 1409 \pm 33 \pm 42 \pm 15\,\mathrm{nb}$
$m_\phi = 1019.462 \pm 0.042 \pm 0.050 \pm 0.025\,\mathrm{MeV}/c^2$
$\Gamma_\phi = 4.205 \pm 0.103 \pm 0.050 \pm 0.045\,\mathrm{MeV}$
$\Gamma^{ee}_\Phi \times \mathcal{B}(\Phi \to K^0_S K^0_L) = 0.4200 \pm 0.0033 \pm 0.0122 \pm 0.0013\,\mathrm{keV}$

$\rightarrow$ consistent with world data

Cross section of $e^+e^- \to K^0_S K^0_L$



Cross section of $e^+e^- \to K^0_S K^0_L$



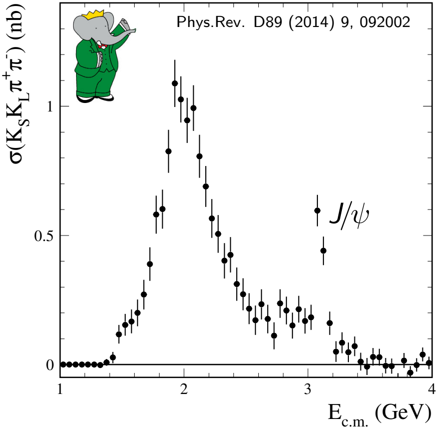
$$e^+e^- \to K^0_S K^0_L \pi^+\pi^-$$

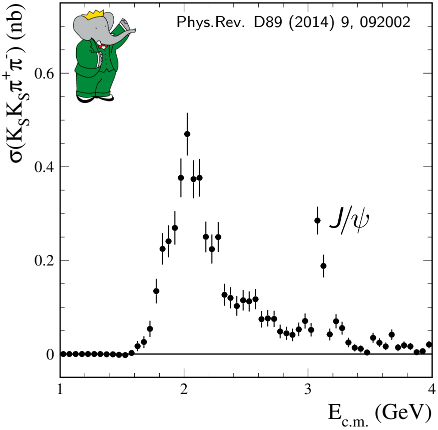
$$e^+e^- \to K^0_S K^0_S \pi^+\pi^-$$

$$e^+e^- \to K^0_S K^0_S K^+K^-$$

Phys.Rev. D89 (2014) 9, 092002 [11]

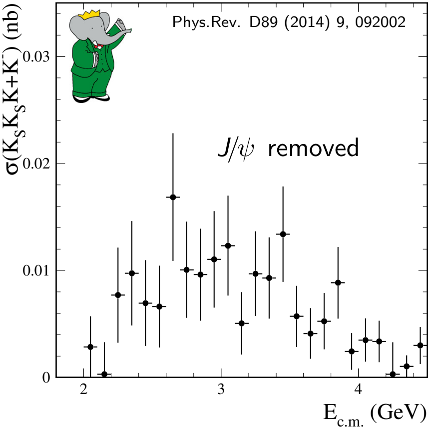
Cross sections of $e^+e^- \to K^0_S K^0_L \pi^+\pi^-$ and $K^0_S K^0_S \pi^+\pi^-$





First cross section measurements
Clear J/ψ peaks

Cross section of $e^+e^- \to K^0_S K^0_S K^+K^-$



First cross section measurement
J/ψ observed in mass distribution

Summary

- ISR physics has proven to be a very productive field even years after the end of data taking at the B-factories
- Precision measurements of hadronic cross sections have greatly improved a_μ^{SM} & more hadronic final states in preparation
- $g_\mu - 2$ puzzle needs to be solved
  - ⋆ Data from new experiments (e.g. BES-III)
  - ⋆ Light-By-Light scattering needs to be studied
  - ⋆ *E989* at Fermilab and J-PARC g-2/EDM
- QCD predictions on form factors are tested experimentally

Thank you!

Any questions?

Backup slides

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Phys. Rev., D92(7):072008, 2015.

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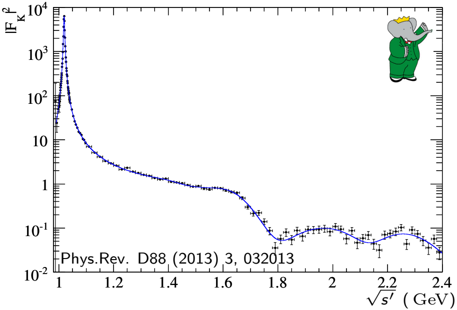
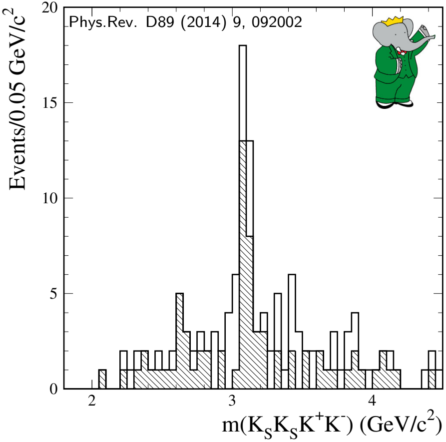
Breit-Wigner fit function



$$
\begin{aligned}
F_K(s) &= (a_\phi \cdot BW_\phi(s) + a_{\phi'} \cdot BW_{\phi'}(s) + a_{\phi''} \cdot BW_{\phi''}(s))/3 \\
&+ (a_\rho \cdot BW_\rho(s) + a_{\rho'} \cdot BW_{\rho'}(s) + a_{\rho''} \cdot BW_{\rho''}(s) + a_{\rho'''} \cdot BW_{\rho'''}(s))/2 \\
&+ (a_\omega \cdot BW_\omega(s) + a_{\omega'} \cdot BW_{\omega'}(s) + a_{\omega''} \cdot BW_{\omega''}(s) + a_{\omega'''} \cdot BW_{\omega'''}(s))/6 \\
\text{with} \quad & a_\phi + a_{\phi'} + a_{\phi''} = 1 \\
& a_\rho + a_{\rho'} + a_{\rho''} + a_{\rho'''} = 1 \\
& a_\omega + a_{\omega'} + a_{\omega''} + a_{\omega'''} = 1
\end{aligned}
$$

$K_S K_S K^+ K^-$ mass spectrum



Basic method

Definition of g:

$$\vec{\mu} = g\frac{e}{2m}\vec{s}\,.$$

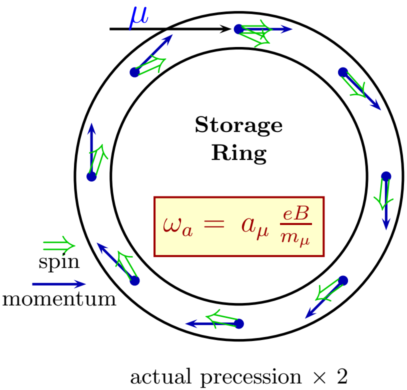
Motion in magnetic field:

$$\vec{\omega}_c = \frac{e\vec{B}}{m\gamma}\,,$$

$$\vec{\omega}_l = \frac{e\vec{B}}{m\gamma} + a\frac{e\vec{B}}{m}\,,$$

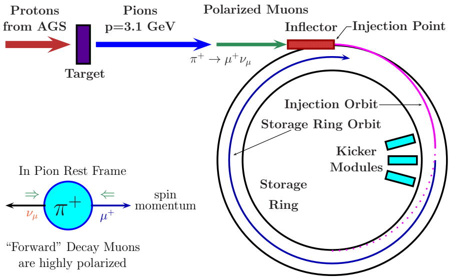
$$\Rightarrow \vec{\omega}_a = a\frac{e\vec{B}}{m}\,.$$

$$(a = (g-2)/2)$$



Spin precession. [7]

Realization in detail



From π^+ production to μ^+ decay. [7]

Electric field necessary for focussing: BMT equation

$$\vec{\omega}_a = \frac{e}{m_\mu}\left(a_\mu \vec{B} - \left[a_\mu - \frac{1}{\gamma^2 - 1}\right]\vec{v} \times \vec{E}\right) .$$

$\vec{\omega}_a$ is independent of $\vec{E}$ for $\gamma = 29.3 \Leftrightarrow E_\mu = \gamma m_\mu = 3.1\,\text{GeV}$.

Direct Measurement of $(g_\mu - 2)$

Experiment E821 at Brookhaven National Laboratory

The result [2]:

$$a_\mu = (116\,592\,089 \pm 54_{stat} \pm 33_{syst}) \cdot 10^{-11}$$

New Direct Measurement of $(g_\mu - 2)$

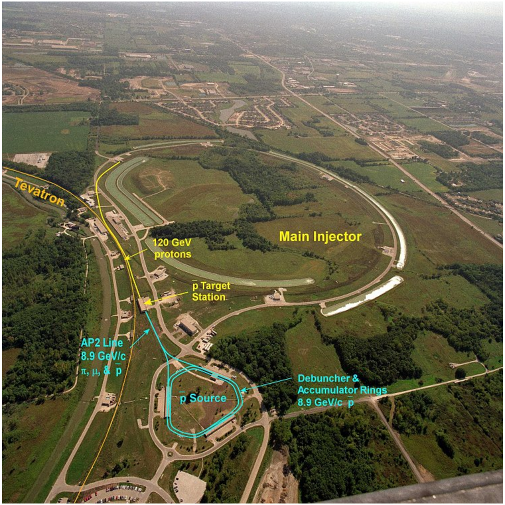
Experiment E989 at Fermilab

The goal:

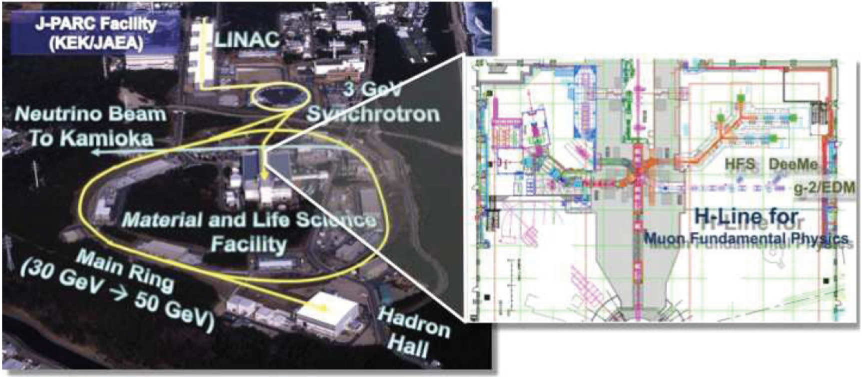
Reduce uncertainty by factor 4 (!)

New Direct Measurement of $(g_\mu - 2)$

Experiment E989 at Fermilab



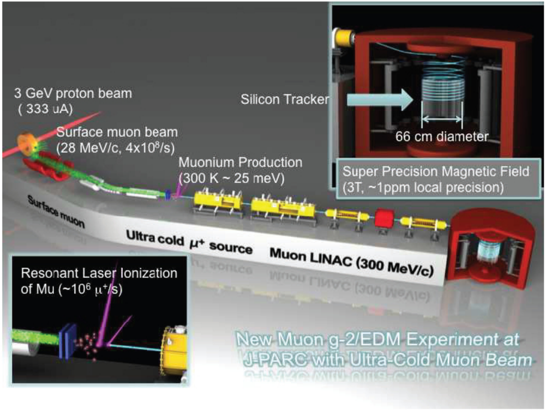
Ultra-cold muon experiment at J-PARC MLF from [14]



The goal:

Uncertainty of $\sim 10 \cdot 10^{-11}$ (!)

Ultra-cold muon experiment at J-PARC MLF from [14]



New Method:

Produce muons from ionization of muonium, store them and track decay.