

Hadronic Cross Section and Implications to the Muon g-2

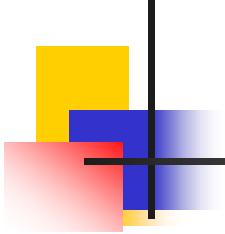


Vladimir Golubev

Budker Institute of Nuclear Physics,
Novosibirsk, Russia

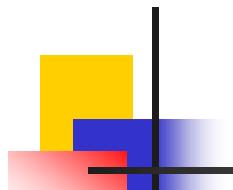
(for the BaBar Collaboration)

XXX-th International Workshop on High Energy Physics
“Particle and Astroparticle Physics, Gravitation and Cosmology
Predictions, Observations, and New Projects”
at IHEP Protvino, June 23–27, 2014

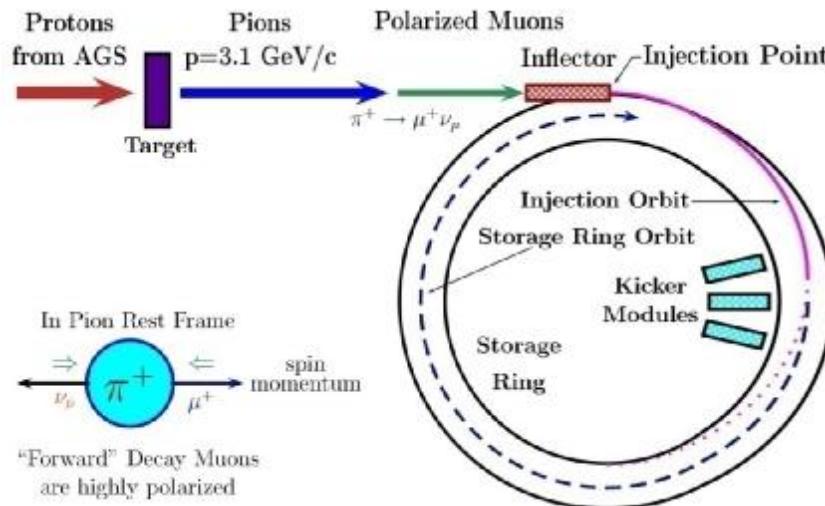


Outline

- Introduction
- BNL $(g-2)_\mu$ experiment
- Theory of $(g-2)_\mu$
- $e^+e^- \rightarrow \text{hadrons}$ impact to $(g-2)_\mu$
- Babar ISR measurements
- Channel $e^+e^- \rightarrow \pi^+\pi^-$
- Channel $e^+e^- \rightarrow K^+K^-$
- Channel $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$
- Channels $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$, $e^+e^- \rightarrow K^+K^-\pi^0\pi^0$
- Perspectives, conclusions

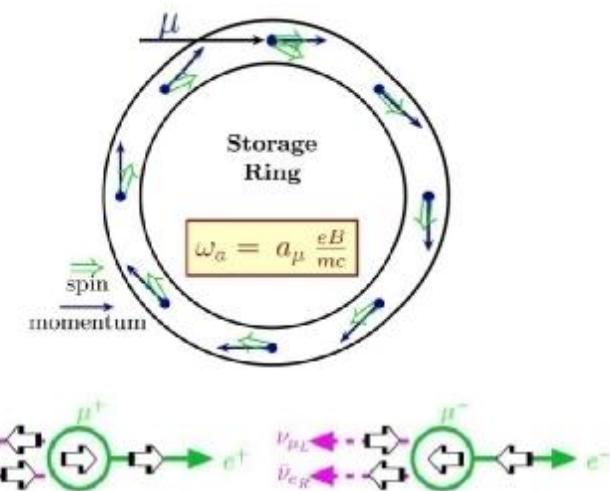


Brookhaven ($g-2$) experiment (E821)



$$\mu \rightarrow e \bar{\nu}_e \nu_\mu$$

$$\begin{aligned} B &= 1.45 \text{ T} \\ \Delta B/B &= 10^{-6} \\ R &= 7.11 \text{ m} \\ \mu/\text{fill} &= 10^4 \end{aligned}$$



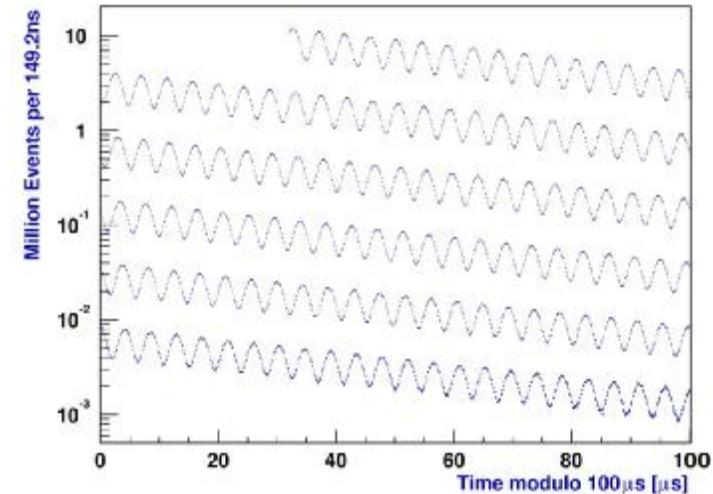
$$\Omega_{\text{spin}} \sim B (g-2)/2$$

$$a_\mu = 11659209(6) \times 10^{-10} \quad 0.54 \text{ ppm}$$

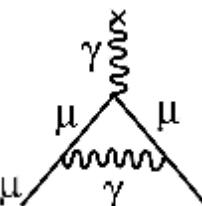
Systematic error:

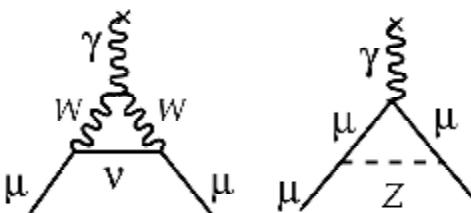
$$0.18 \text{ ppm (B)} \oplus 0.21 \text{ ppm } (\omega_a) = 0.28 \text{ ppm}$$

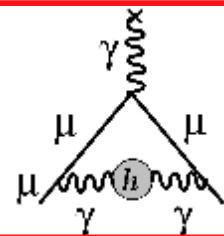
Statistical error: 0.46 ppm



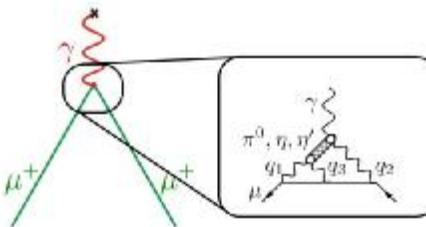
(g-2) _{μ} theory

1. QED:  + graphs up to α^5 = $(116\ 584\ 71.81 \pm 0.02) \times 10^{-10}$
(99.995%)

2. WEAK:  = $(15.32 \pm 0.18) \times 10^{-10}$

3. HADRON (LO):  = $(690.30 \pm 5.26) \times 10^{-10}$ ($6\ 10^{-5}$)

4. HADRON (HO): = $-(10.03 \pm 0.1) \times 10^{-10}$

5. HADRON (LBL):  = $(10.5 \pm 2.6) \times 10^{-10}$

Jegerlehner, Nyffeler / Phys Rept 477 (2009) 1110

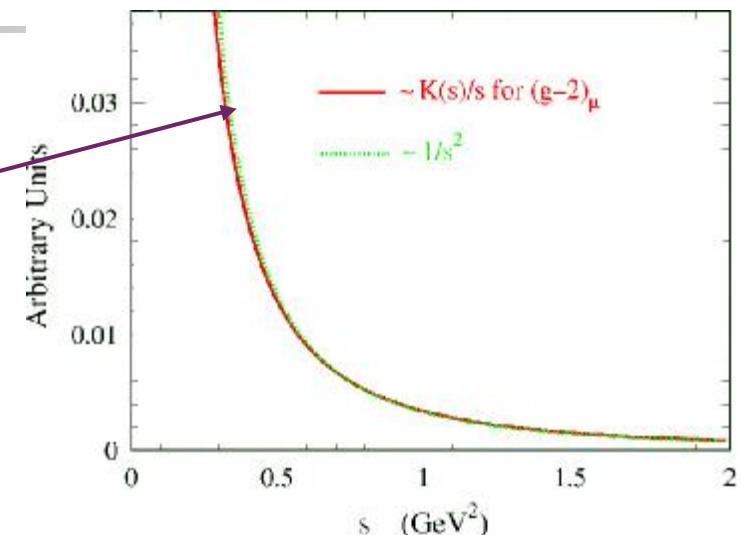
uses e^+e^- input only for VP

(g-2) _{μ} theory

From dispersion relations

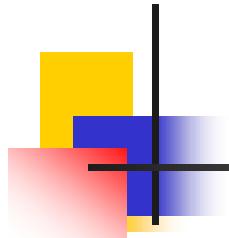
$$a_{\mu}^{\text{had}} = \frac{\alpha^2}{3\pi^2} \int_{4m_e^2}^{\infty} ds$$

$$\frac{K(s)}{s} R(s)$$



For hadron LO contribution

$$R(s) = \frac{\sigma^{(0)}(e^+ e^- \rightarrow \gamma^* \rightarrow \text{hadrons})}{\sigma^{(0)}(e^+ e^- \rightarrow \mu^+ \mu^-)}$$



(g-2)_μ status

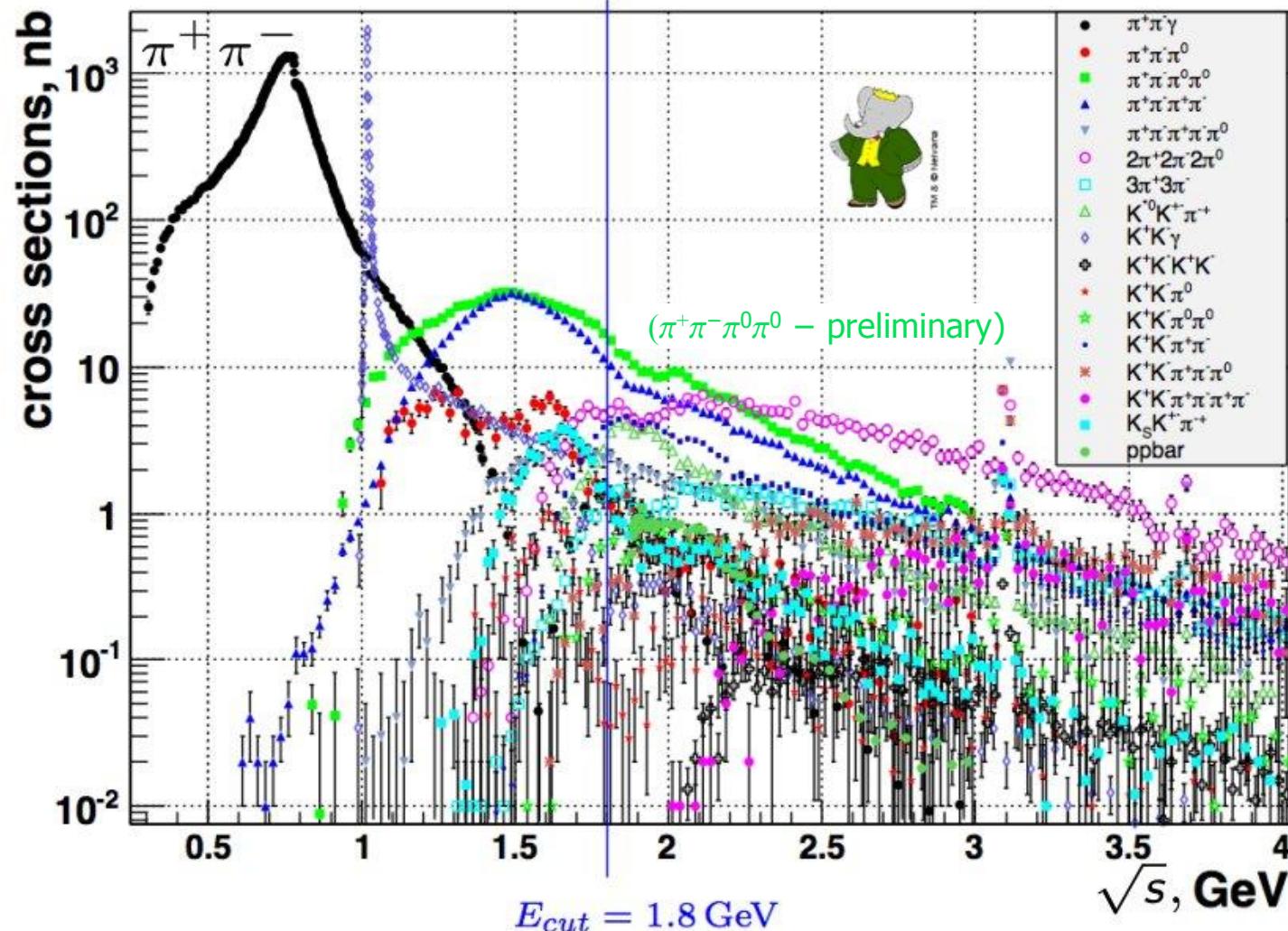
Experiment: $11659208.9(6.3) \times 10^{-10}$ 0.54 ppm

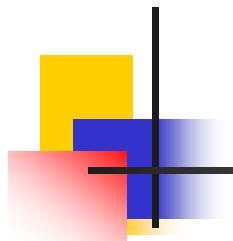
Theory: $11659180.2(4.9) \times 10^{-10}$ (DHMZ-2011) 0.42 ppm
 $D = (28.7 \pm 8.0) \times 10^{-10}$

3.6σ deviation from Standard model !

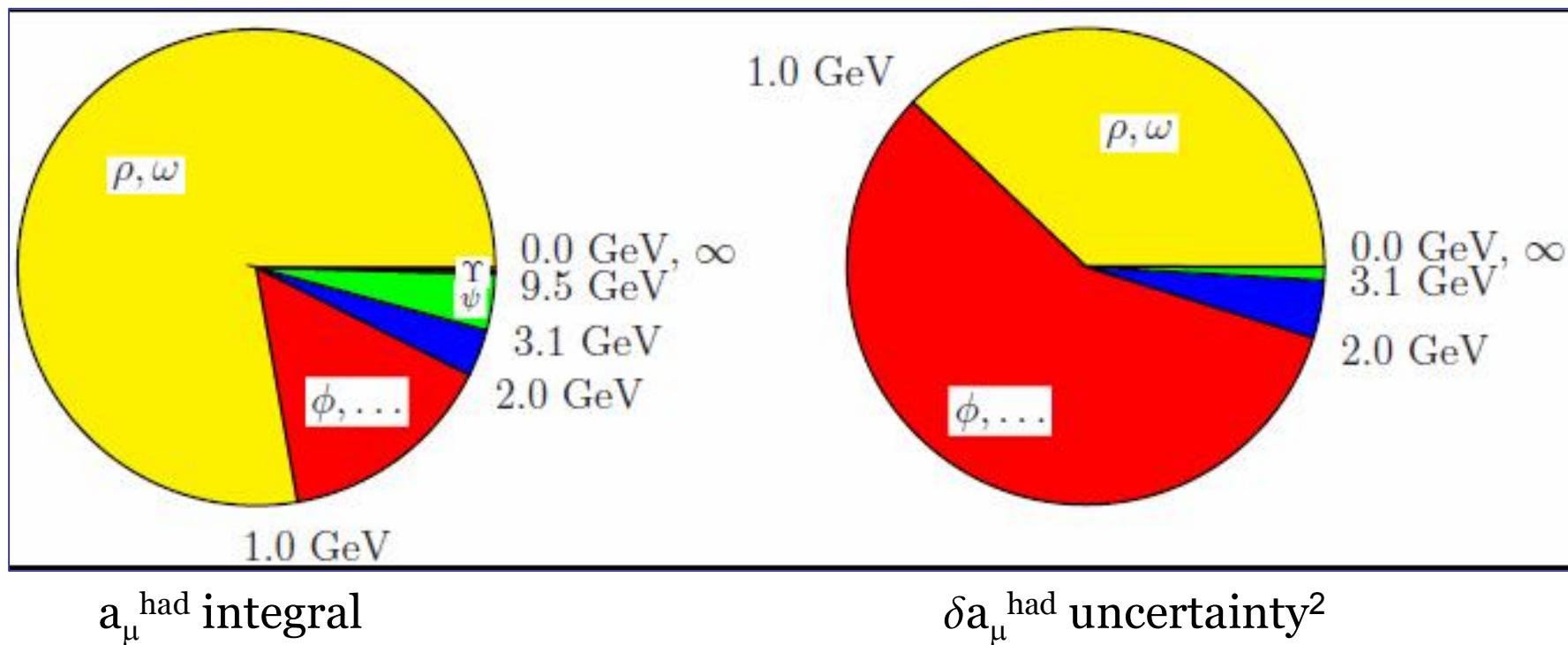
This is the longstanding muon anomaly problem.

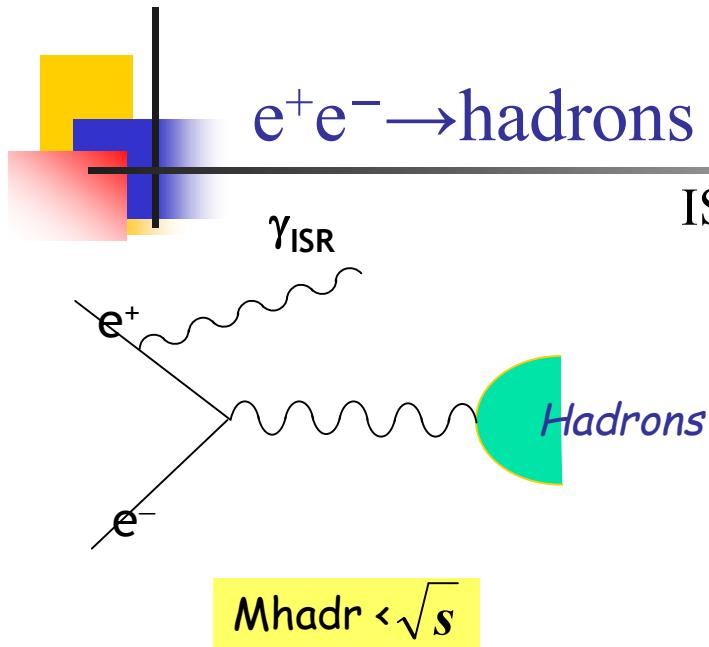
$e^+e^- \rightarrow \text{hadrons}$ at $E < 4$ GeV





$e^+e^- \rightarrow \text{hadrons}$ contributions to $(g-2)_\mu$





ISR – Initial State Radiation or Radiative Return

$$\frac{d\sigma(s, x)}{dx d(\cos\theta)} = H(s, x, \theta) \cdot \sigma_0(s(1-x))$$

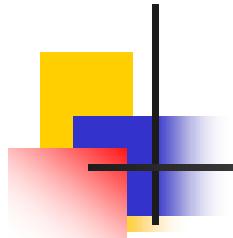
H – radiation function

$$H(s, x, \theta) = \frac{\alpha}{\pi x} \left(\frac{2 - 2x + x^2}{\sin^2 \theta} - \frac{x^2}{2} \right), \quad x = \frac{2E_\gamma}{\sqrt{s}}$$

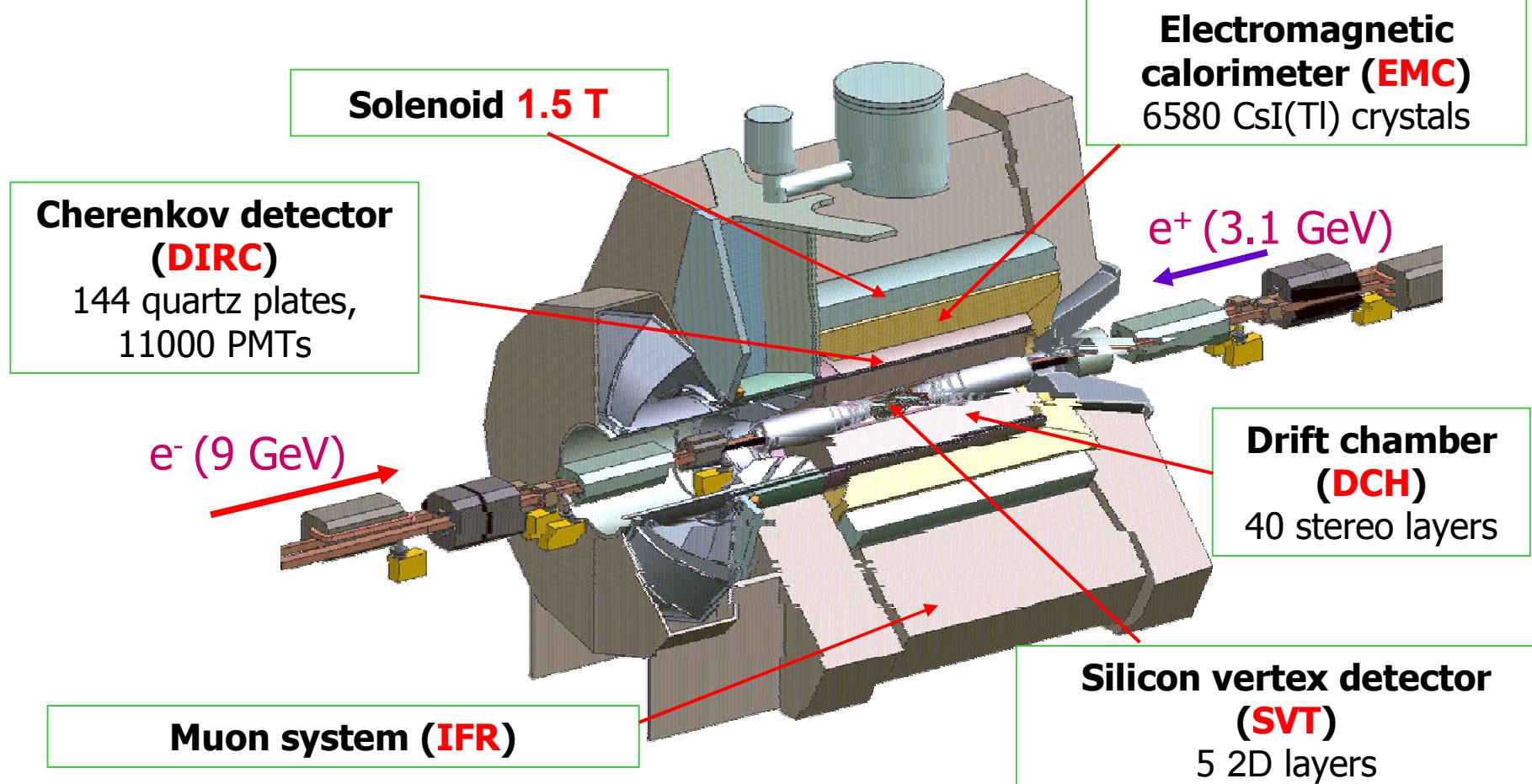
$L_{\text{ISR}} \sim 0.3\% L_0$,
with $L_0 \sim 0.5 \text{ ab}^{-1} \rightarrow L_{\text{ISR}} \sim 1.5 \text{ fb}^{-1}$!

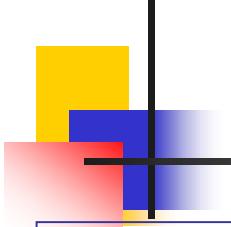
Advantages of ISR

1. Full energy range from $2m_\pi$ up to \sqrt{s} is available
2. Detection efficiency is flat over reaction mechanism
3. No large radiative corrections



Babar Detector





$e^+e^- \rightarrow$ hadrons reactions studied at Babar via ISR

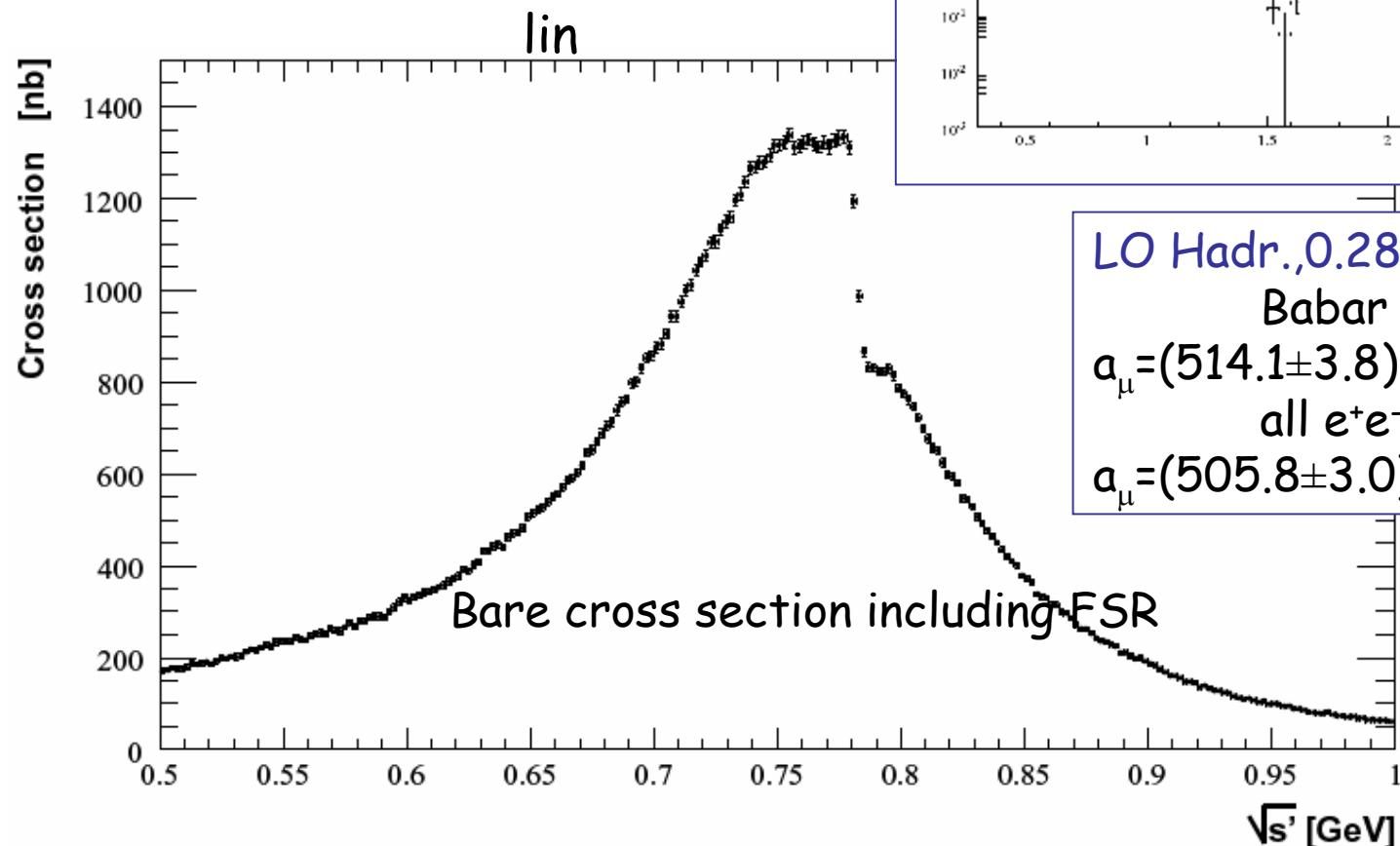
$e^+e^- \rightarrow \pi^+\pi^-$	PR D 86 (2012) 032013
$e^+e^- \rightarrow K^+K^-$	PD D 88 (2013) 032013
$e^+e^- \rightarrow \phi f_0(980)$	PR D 76 (2007) 012008
$e^+e^- \rightarrow \pi^+\pi^-\pi^0$	PR D 70 (2004) 072004
$e^+e^- \rightarrow K^+K^-\eta, K^+K^-\pi^0, K_S K^\pm \pi^\mp$	PR D 77 (2008) 092002
$e^+e^- \rightarrow 2(\pi^+\pi^-)$	PR D 85 (2012) 112009
$e^+e^- \rightarrow K^+K^-\pi^0\pi^0, K^+K^-\pi^+\pi^-, 2(K^+K^-)$	PR D 86 (2012) 012008
$e^+e^- \rightarrow K_S K_L, K_S K_L \pi^+\pi^-, K_S K_S \pi^+\pi^-, K_S K_S K^+K^-$	PR D 89 (2014) 092002
$e^+e^- \rightarrow 2(\pi^+\pi^-)\pi^0, 2(\pi^+\pi^-)\eta, K^+K^-\pi^+\pi^-\pi^0, K^+K^-\pi^+\pi^-\eta$	PR D 76 (2007) 092005
$e^+e^- \rightarrow 3(\pi^+\pi^-), 2(\pi^+\pi^-\pi^0), 2(\pi^+\pi^-)K^+K^-$	PR D 73 (2006) 052003
$e^+e^- \rightarrow p\bar{p}$ (small \sqrt{s})	PR D 87 (2013) 092005
$e^+e^- \rightarrow p\bar{p}$ (large \sqrt{s})	PR D 88 (2013) 072009
$e^+e^- \rightarrow \Lambda\bar{\Lambda}, \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0$	PR D 76 (2007) 092006
$e^+e^- \rightarrow c\bar{c} \rightarrow \dots$	

Most recent : $e^+e^- \rightarrow K_S K_L, K_S K_L \pi^+\pi^-, K_S K_S \pi^+\pi^-, K_S K_S K^+K^-$

Ongoing analyses: $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0\pi^0\pi^0, K_S K^\pm \pi^\mp \pi^0/\eta$

$e^+e^- \rightarrow \pi^+\pi^-$, Babar,
PRL 2009, PRD 2012

Babar most significant $(g-2)_\mu$ result

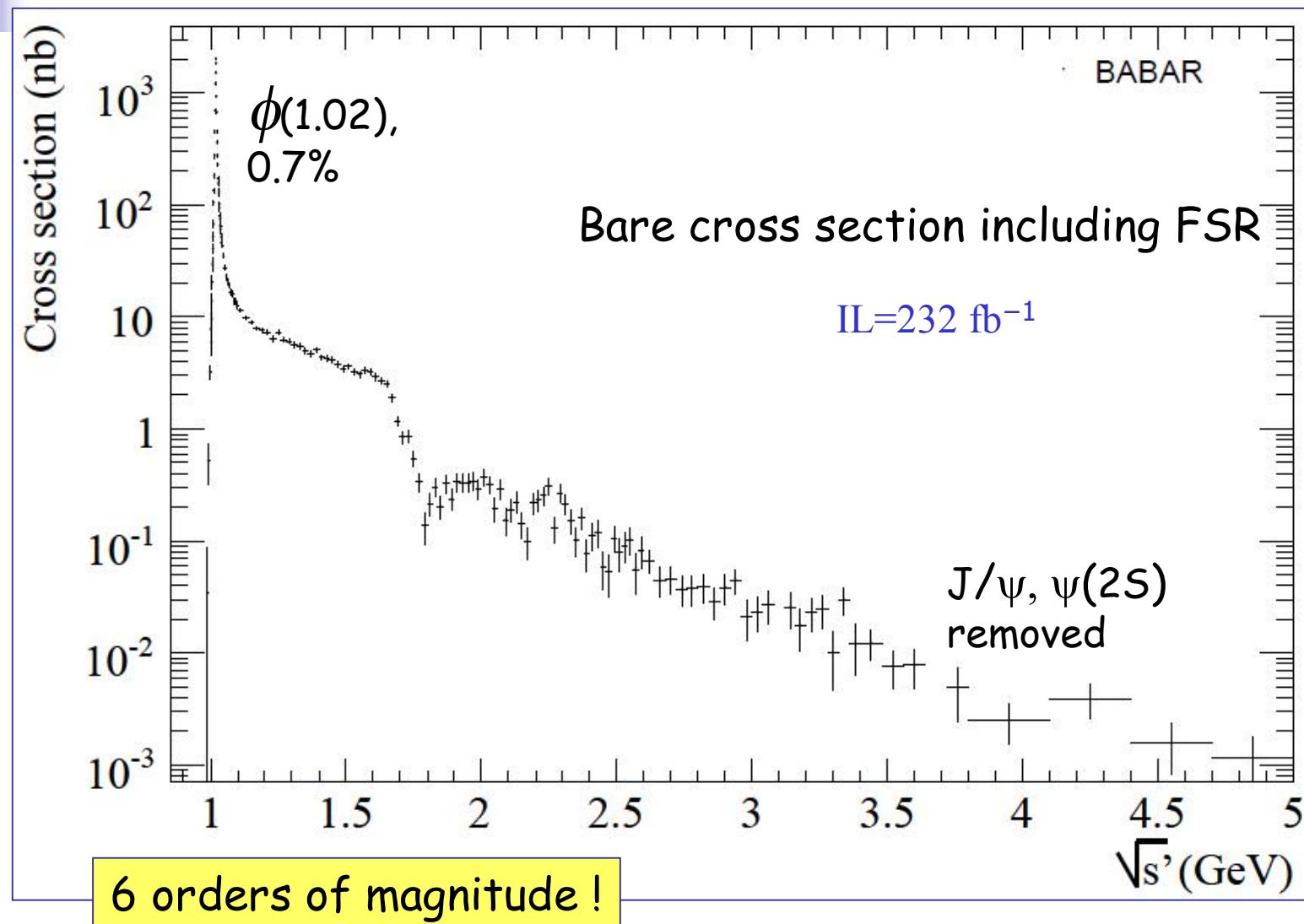


5 orders of magnitude in one experiment !

Phys Rev D 86 (2012) 032013

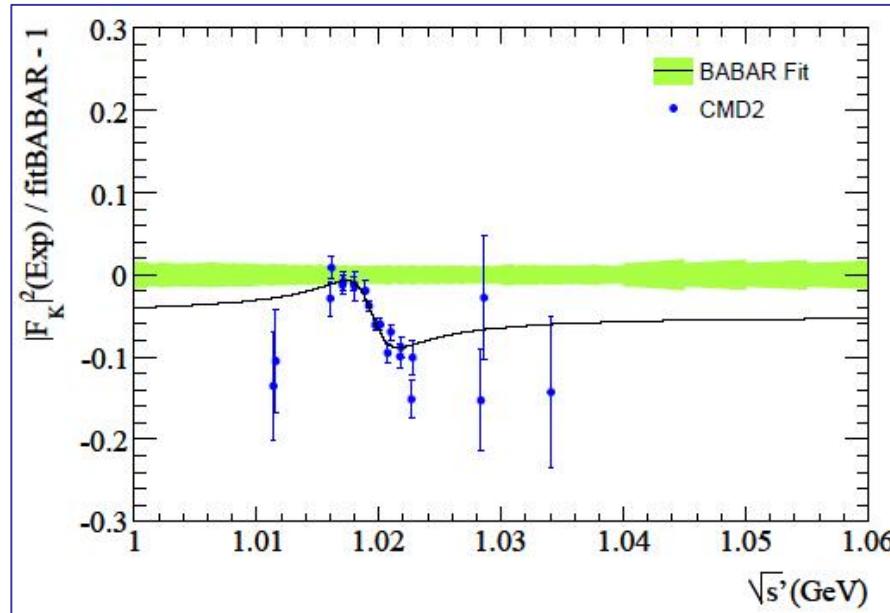
$IL=232 \text{ fb}^{-1}$

$e^+e^- \rightarrow K^+K^-$, Babar, (arxiv:1306.3600)



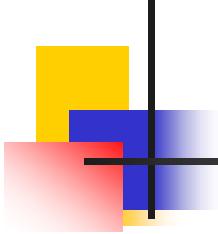
Phys Rev D 88 (2013) 032013

$e^+e^- \rightarrow K^+K^-$, comparison CMD2 and Babar



arxiv:0804.0178

CMD2 data are below
Babar by $\sim 5\%$ (2σ)



Contribution of $e^+e^- \rightarrow K^+K^-$ to $(g-2)_\mu$

Without Babar-2012:

$$a_\mu(K^+K^-) = 21.63 \pm 0.73 \cdot 10^{-10}.$$

Babar:

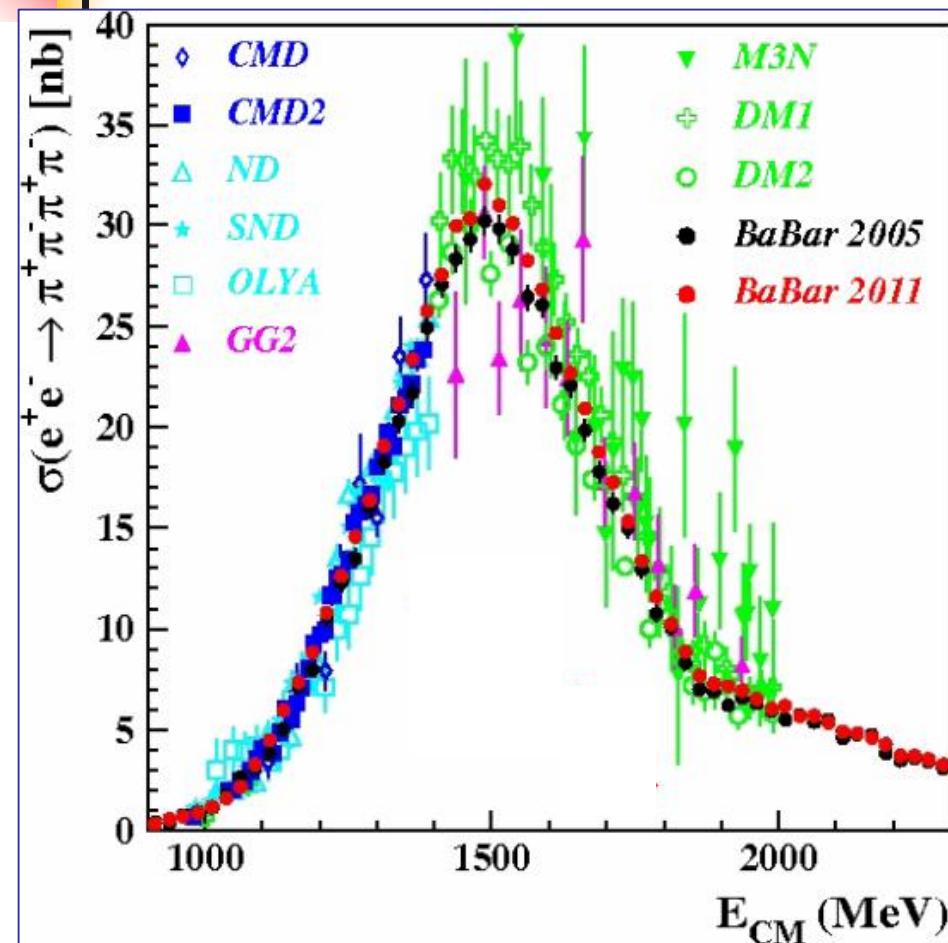
3 times lower error !

$$a_\mu(K^+K^-) = 22.95 \pm 0.26 \cdot 10^{-10}.$$

$$\Delta a_\mu = 1.32 \pm 0.74 \cdot 10^{-10}, \text{ 2}\sigma \text{ shift up !}$$

2 σ difference between CMD2 and Babar !

$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$, Babar, PRD 2012



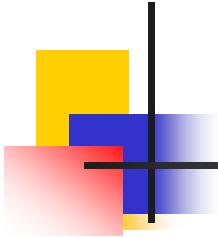
Systematics - 2.4%
in peak 1.1-2.8 GeV

$IL = 454 \text{ fb}^{-1}$

Structure:

$\rho(770) 2\pi$
 $a_1(1260) \pi$
 $f_0(1300) 2\pi$
 $\rho f_0(1300)$
 $\rho f_0(980)$

Phys Rev D 85 (2012) 112009



Contribution of $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ to $(g-2)_\mu$

Without Babar-2012:

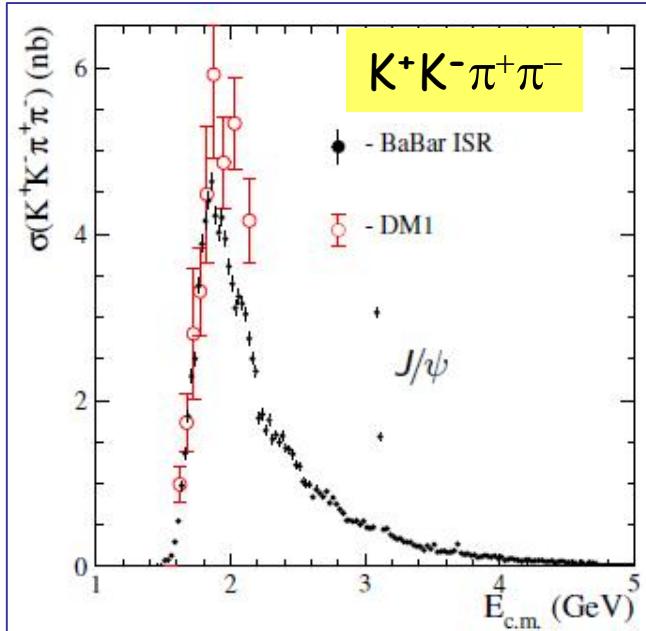
$$a_\mu(4\pi^{+-}) = 13.35 \pm 0.53 \cdot 10^{-10}.$$

Babar 2012:

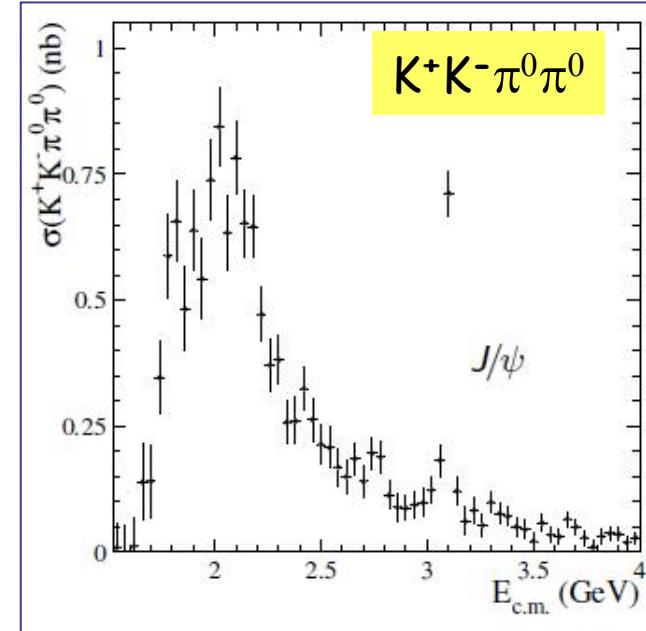
$$a_\mu(4\pi^{+-}) = 13.64 \pm 0.36 \cdot 10^{-10}.$$

Babar agrees with world average
with improved precision

$e^+e^- \rightarrow K^+K^-\pi^+\pi^-$, Babar, PRD 2012



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

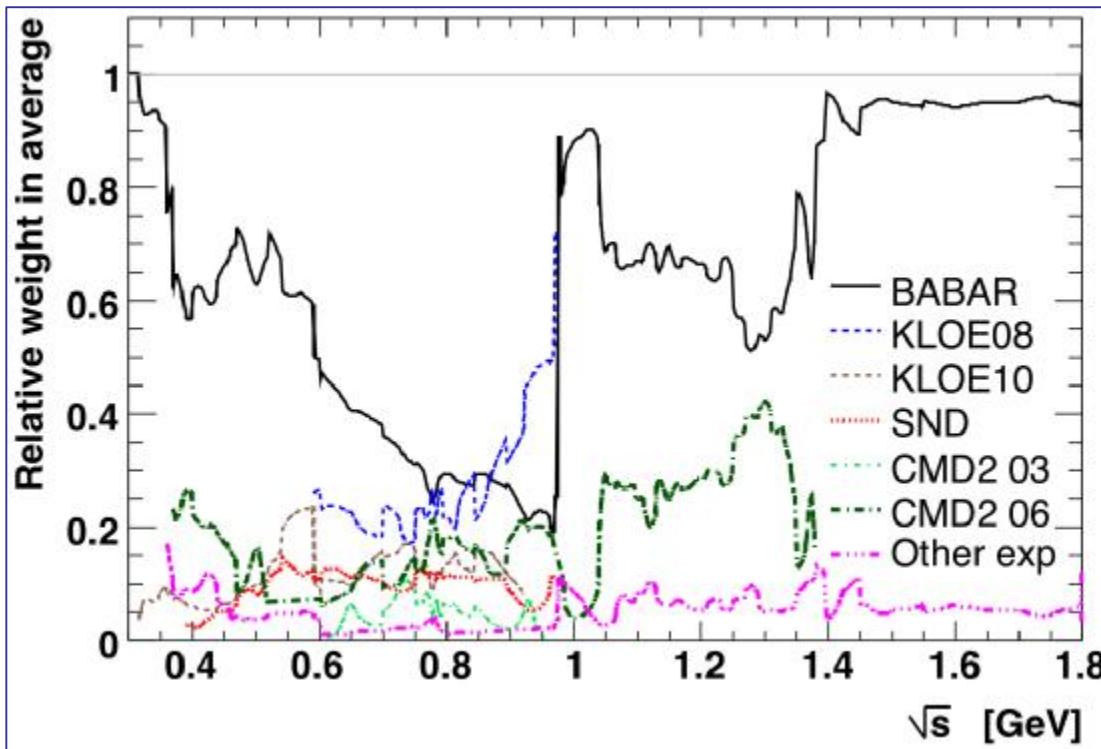


IL=454 fb⁻¹

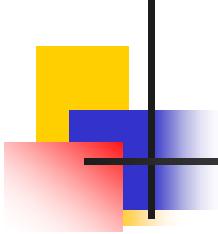
- syst. uncertainty: 7 - 16%
- resolution: 8.8 - 11.2 MeV
- J/ψ clearly visible

Phys Rev D 86 (2012) 012008

Relative weight of different experiments in their contribution to $(g-2)_\mu$



Babar dominates !
(DHMZ)
EPJ C 71, 1515 (2011)

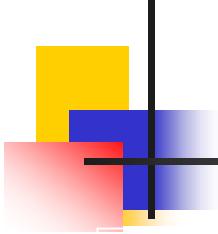


Perspectives

Experiment: **E969** (FNAL) → 0.14 ppm
J-PARC (Japan) → 0.1 ppm

e⁺e⁻→hadrons : e⁺e⁻-SND,CMD (VEPP-2000,Novosibirsk) ~1%
: ISR – Babar, Belle, KLOE , BEPC <1%

Theory : **LBL** (Light By Light) → 0.1 ppm



Conclusions

1. ISR method is used at Babar for study of $e^+e^- \rightarrow$ hadrons annihilation in the range from $2m_\pi$ to $4 \text{ GeV}/c^2$
2. Large number of $e^+e^- \rightarrow$ hadrons processes are measured at Babar, ~ 40 channels
3. Babar results on $e^+e^- \rightarrow$ hadrons cross section give significant improvement of HVP contribution to muon ($g-2$) factor
4. Latest studied channels $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$, K^+K^- , $K^+K^-\pi\pi$ have accuracies ~ 3 times better than in previous data
5. In current analyses are channels $\pi^+\pi^-\pi^0\pi^0$, K_SK_L , $K_SK_L\pi\pi$ etc. promising further accuracy improvements.