

# **Hadronic Cross Section and Implications to the Muon g-2**

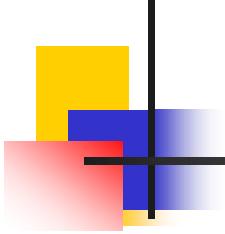


**Vladimir Golubev**

Budker Institute of Nuclear Physics,  
Novosibirsk, Russia

(for the BaBar Collaboration)

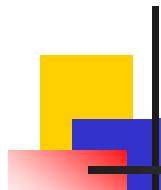
XXX-th International Workshop on High Energy Physics  
“Particle and Astroparticle Physics, Gravitation and Cosmology  
Predictions, Observations, and New Projects”  
at IHEP Protvino, June 23–27, 2014



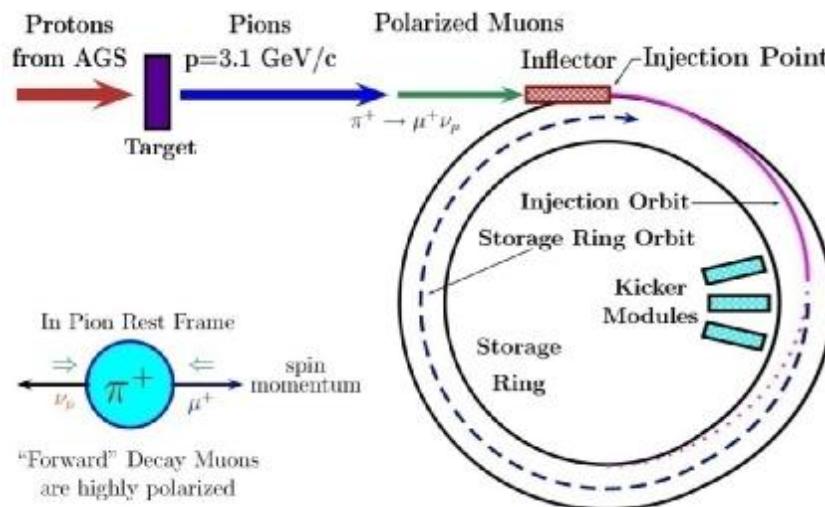
# Outline

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- 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

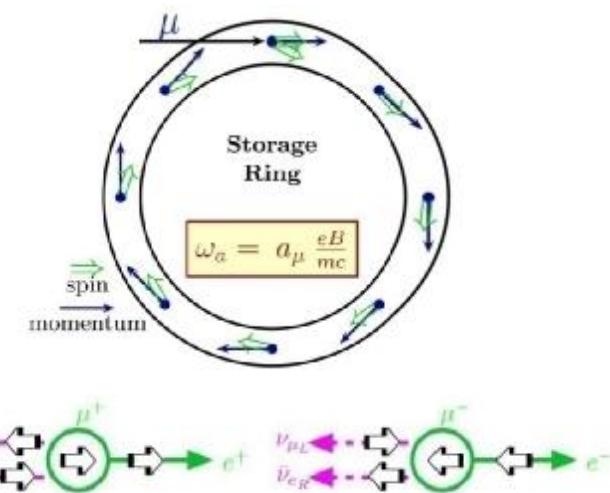


# Brookhaven ( $g-2$ ) experiment (E821)



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

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



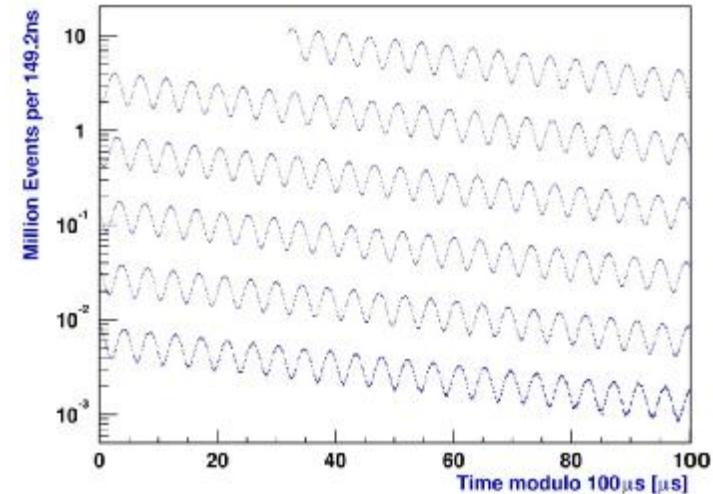
$$\Omega_{\text{spin}} \sim B (g-2)/2$$

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

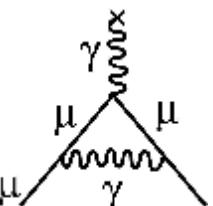
Systematic error:

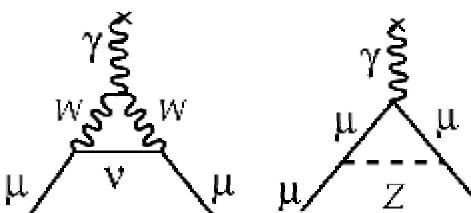
$$0.18 \text{ ppm (B)} \oplus 0.21 \text{ ppm } (\omega_a) = 0.28 \text{ ppm}$$

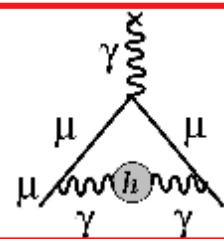
Statistical error: 0.46 ppm



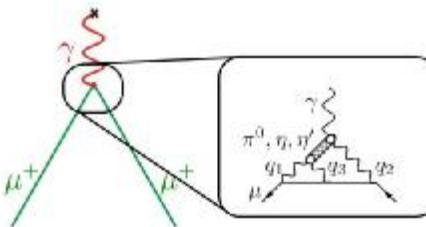
# (g-2) <sub>$\mu$</sub> theory

1. QED:  +  $\sim 1000$  graphs up to  $\alpha^5$  =  $(116\ 584\ 71.81 \pm 0.02) \times 10^{-10}$   
(99.995%)

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

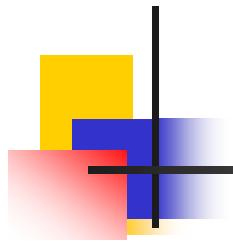
3. HADRON (LO):  =  $(690.30 \pm 5.26) \times 10^{-10}$  ( $6\ 10^{-5}$ )

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

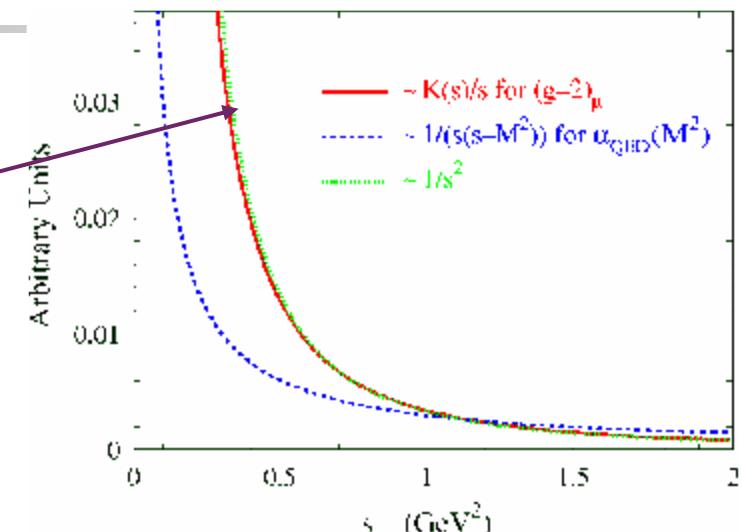


## $(g-2)_\mu$ theory

From dispersion relations

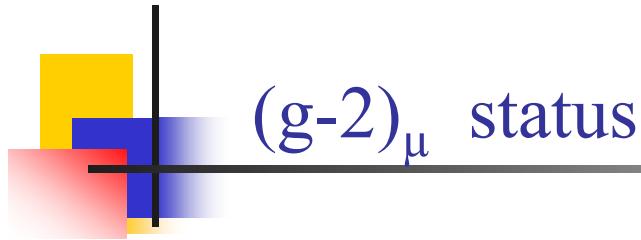
$$a_\mu^{\text{had}} = \frac{\alpha^2}{3\pi^2} \int_{4m_\pi^2}^\infty ds$$

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



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)<sub>μ</sub> status

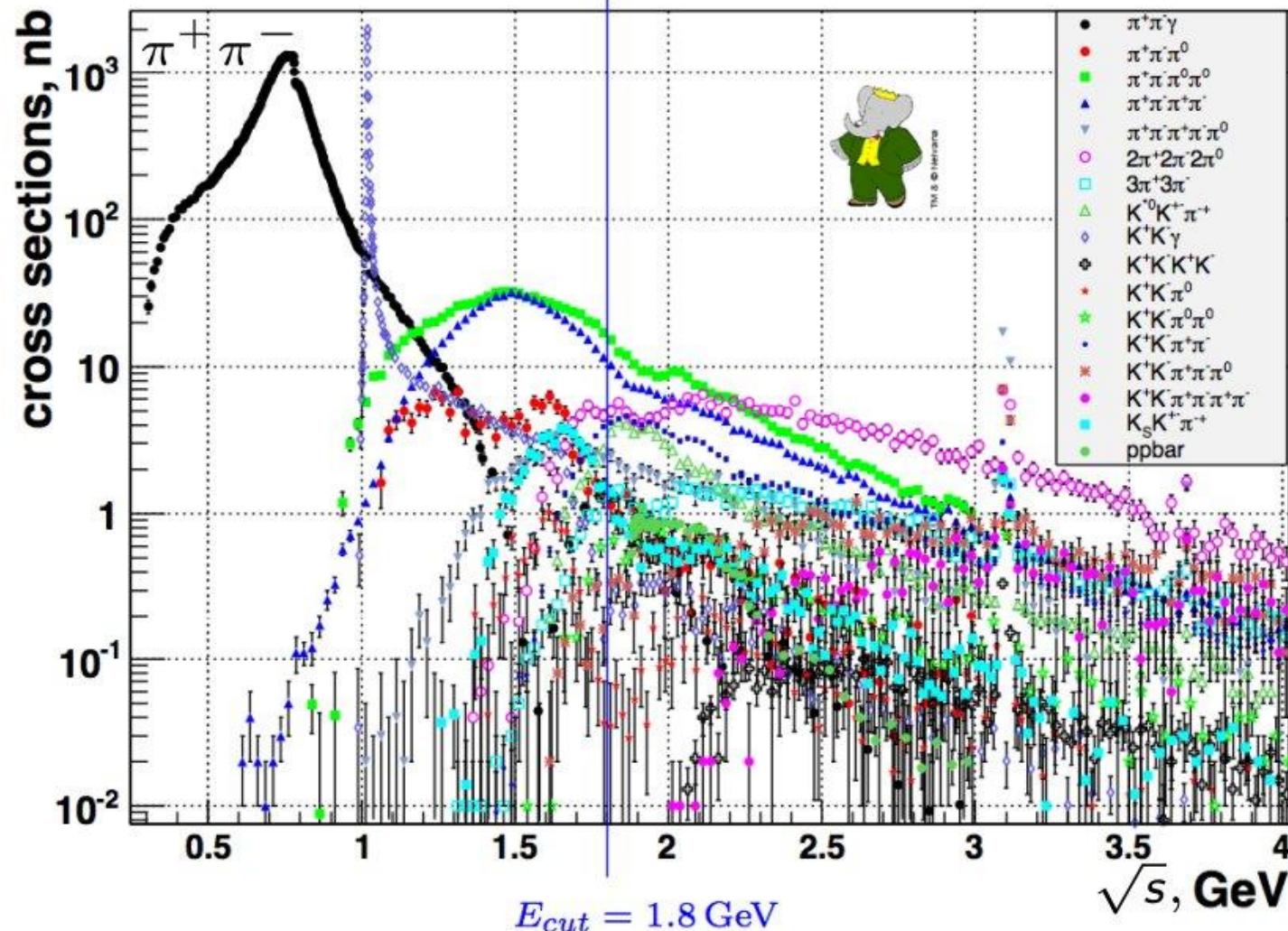
Experiment:  $11659208.9(6.3) \times 10^{-10}$  0.54 ppm

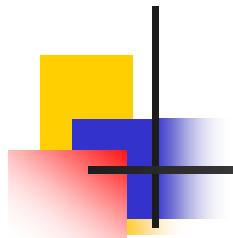
Theory:  $11659180.2(4.9) \times 10^{-10}$  (DHMZ-2011) 0.42 ppm  
 $D = (28.7 \pm 8.0) \times 10^{-10}$

$3.6\sigma$  deviation from Standard model !

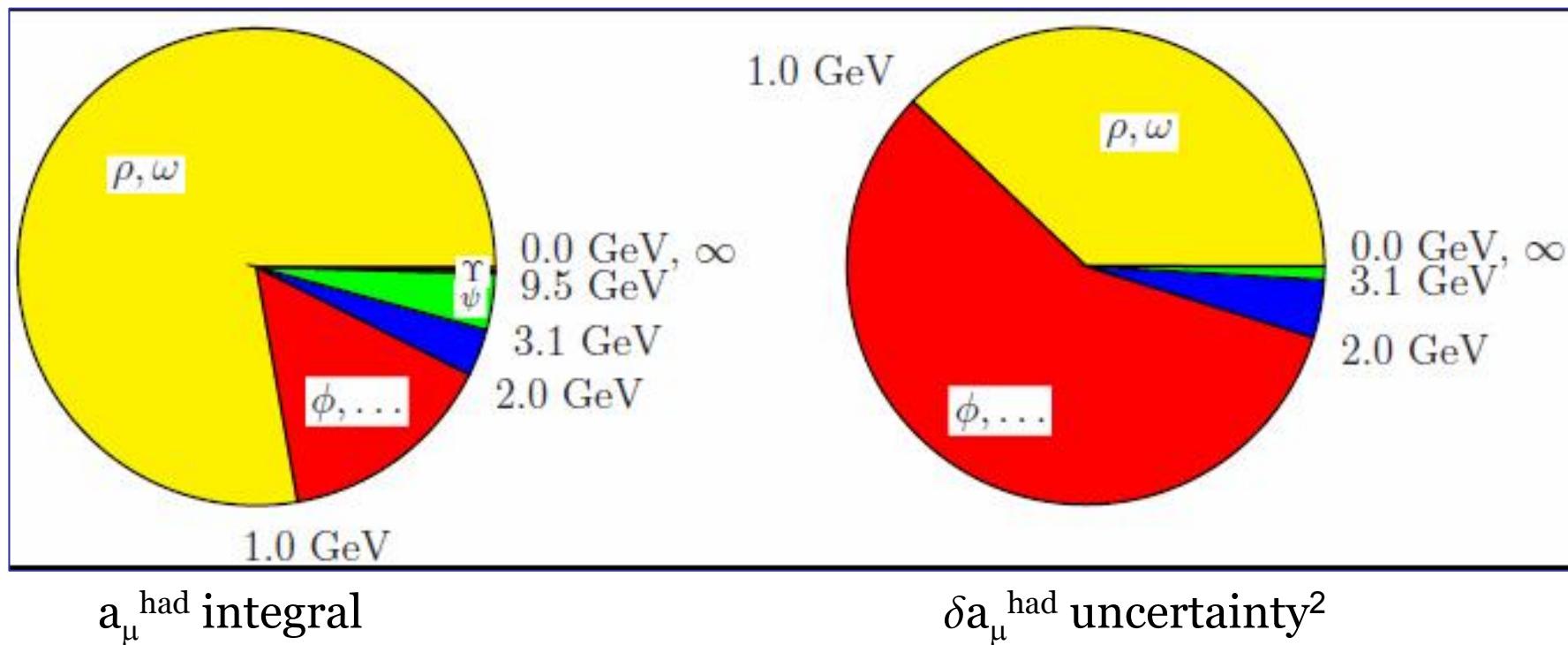
This is the longstanding muon anomaly problem.

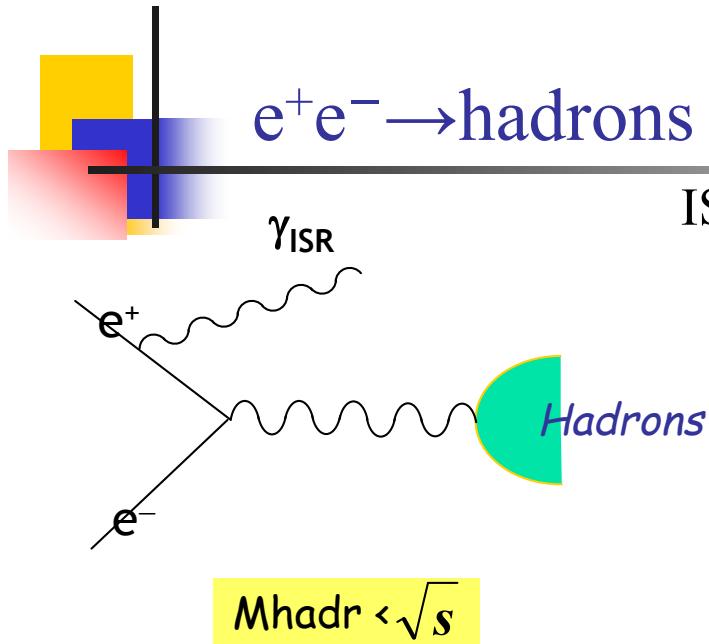
# $e^+e^- \rightarrow \text{hadrons at } E < 4 \text{ GeV}$





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





$e^+e^- \rightarrow \text{hadrons in ISR}$

ISR – Initial State Radiation or Radiative Return

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

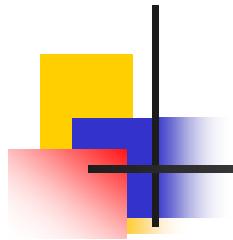
$H$  – radiation function

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

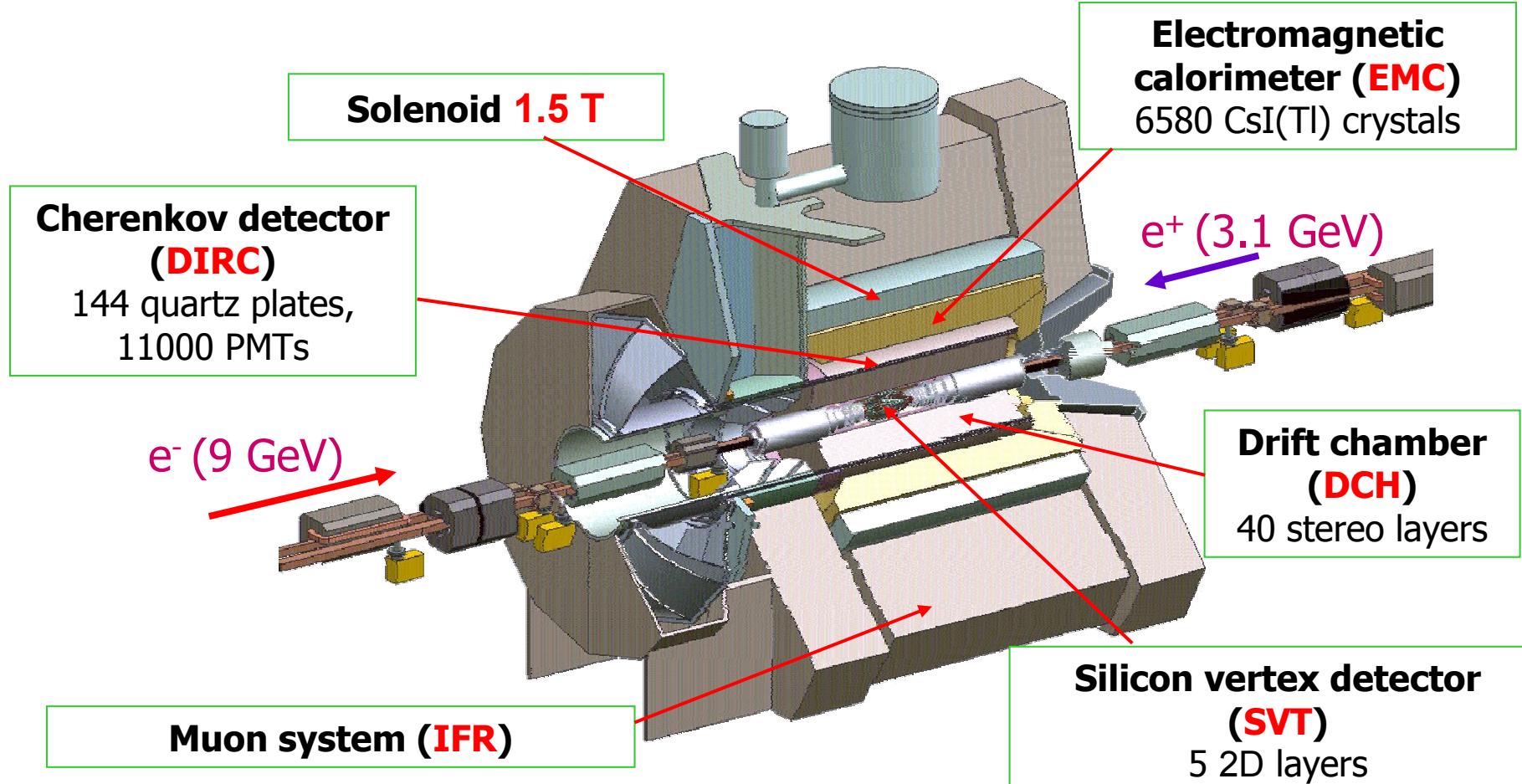
$L_{\text{ISR}} \sim 0.3\% L_0$ ,  
 with  $L_0 \sim 0.5 \text{ ab}^{-1} \rightarrow L_{\text{ISR}} \sim 1.5 \text{ fb}^{-1}$  !

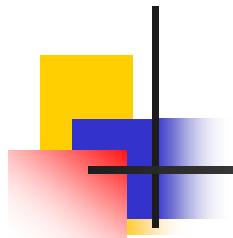
### Advantages of ISR

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

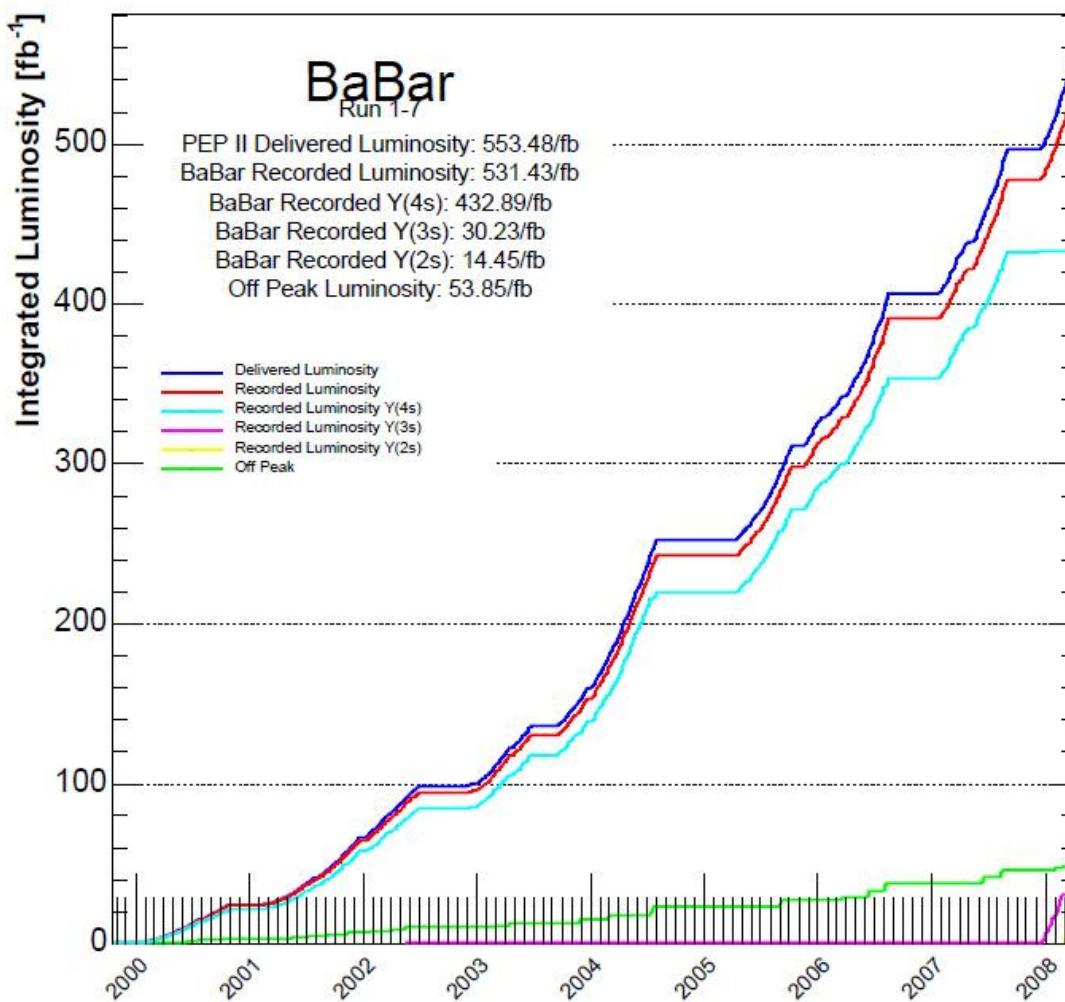


# Babar Detector

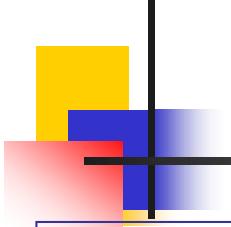




# BaBar



- $IL \approx 430 \text{ fb}^{-1}$   $Y(4S)$   
and  $\approx 45 \text{ fb}^{-1}$  40MeV  
below  $Y(4S)$
- $\approx 470 \text{ M } B\bar{B}$
- total  $IL \approx 550 \text{ fb}^{-1}$



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

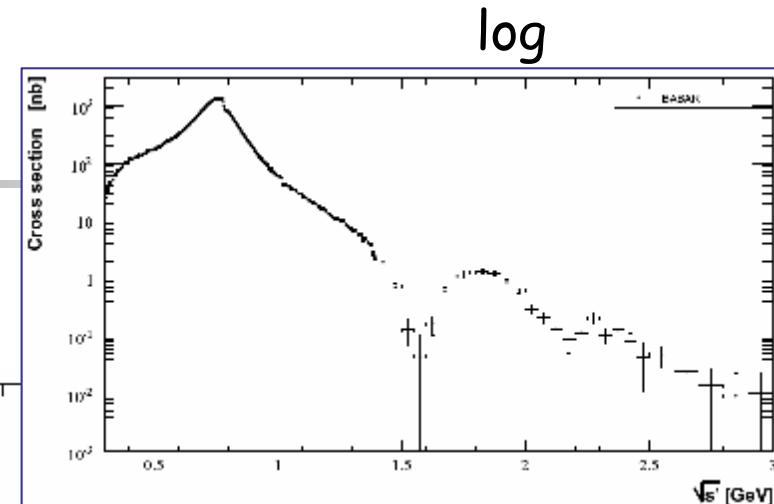
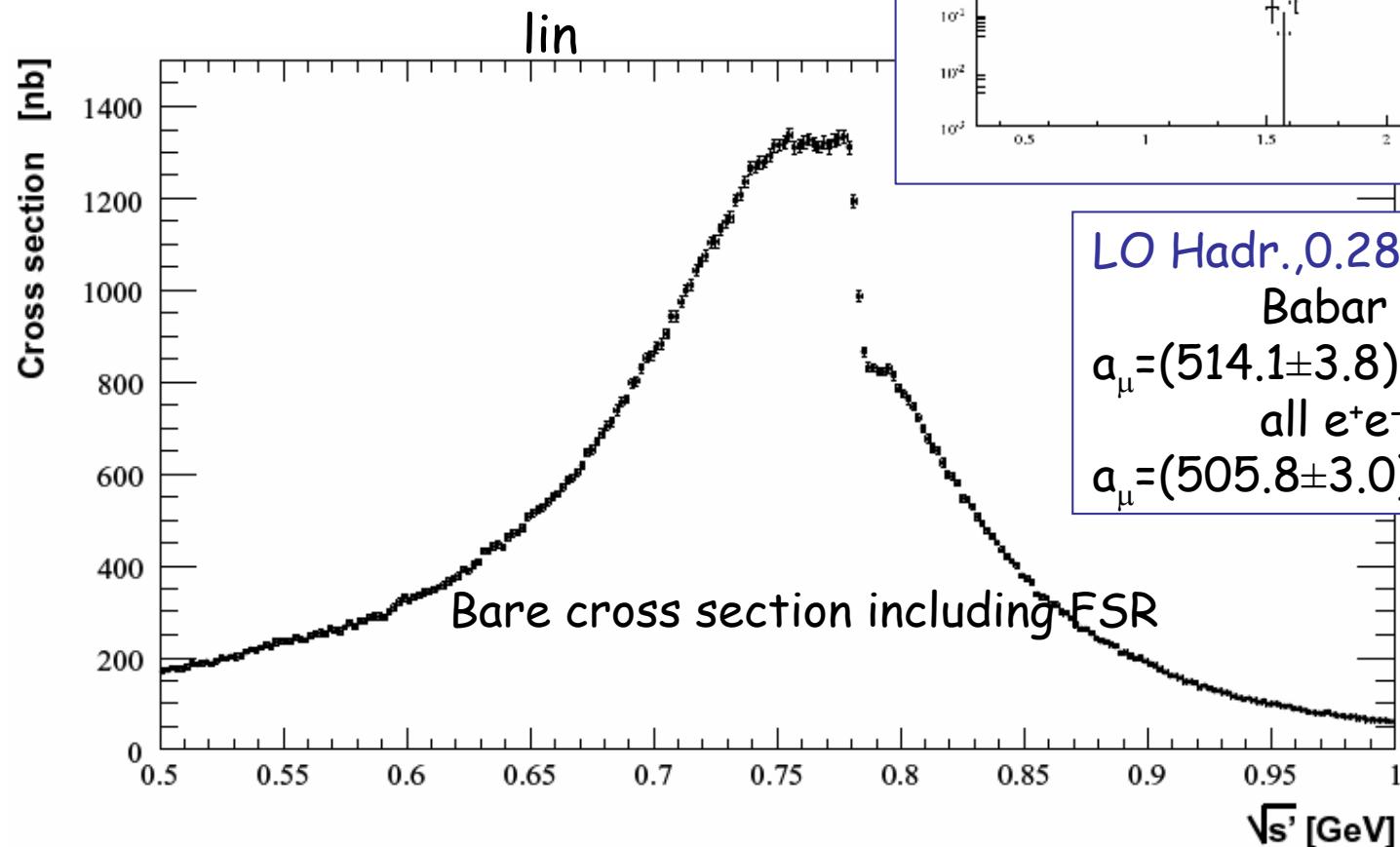
$e^+e^- \rightarrow \pi^+\pi^-$	PR D 86 (2012) 032013
$e^+e^- \rightarrow K^+K^-$	PD D 88 (2013) 032013
$e^+e^- \rightarrow \phi f_0(980)$	PR D 76 (2007) 012008
$e^+e^- \rightarrow \pi^+\pi^-\pi^0$	PR D 70 (2004) 072004
$e^+e^- \rightarrow K^+K^-\eta, K^+K^-\pi^0, K_S K^\pm \pi^\mp$	PR D 77 (2008) 092002
$e^+e^- \rightarrow 2(\pi^+\pi^-)$	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

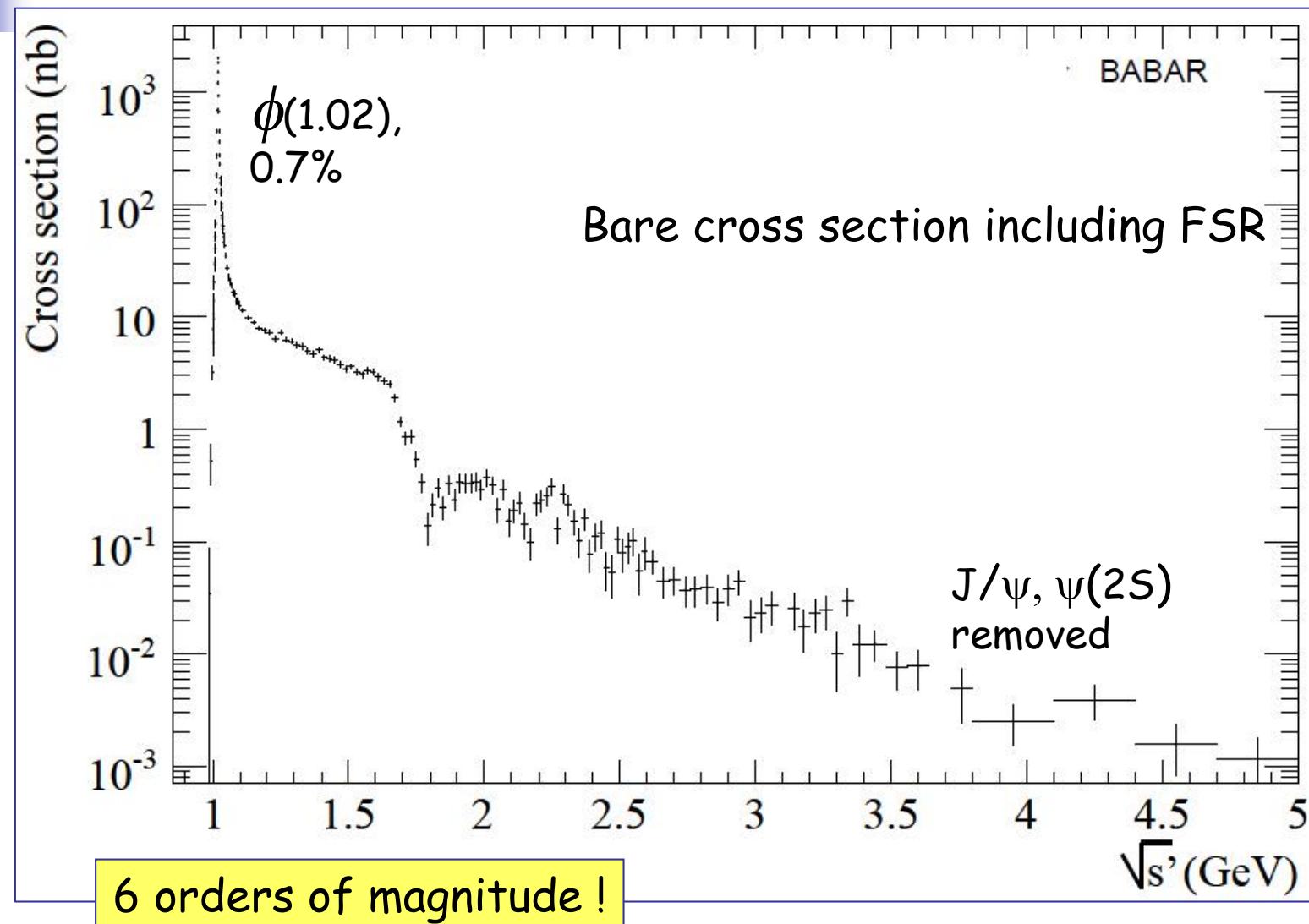
Babar most significant  $(g-2)_\mu$  result



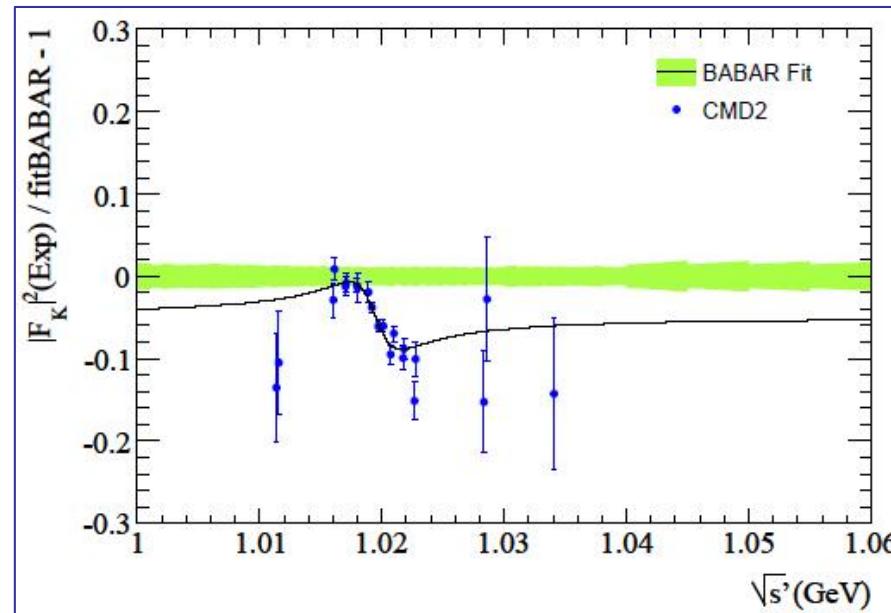
LO Hadr., 0.28-1.8 GeV  
Babar  
 $a_\mu = (514.1 \pm 3.8) 10^{-10}$   
all  $e^+e^-$   
 $a_\mu = (505.8 \pm 3.0) 10^{-10}$

5 orders of magnitude in one experiment !

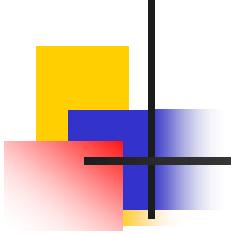
$e^+e^- \rightarrow K^+K^-$ , Babar, (arxiv:1306.3600,  $232 \text{ fb}^{-1}$ )



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



CMD2 data are below  
Babar by ~5% ( $2\sigma$ )



## 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:

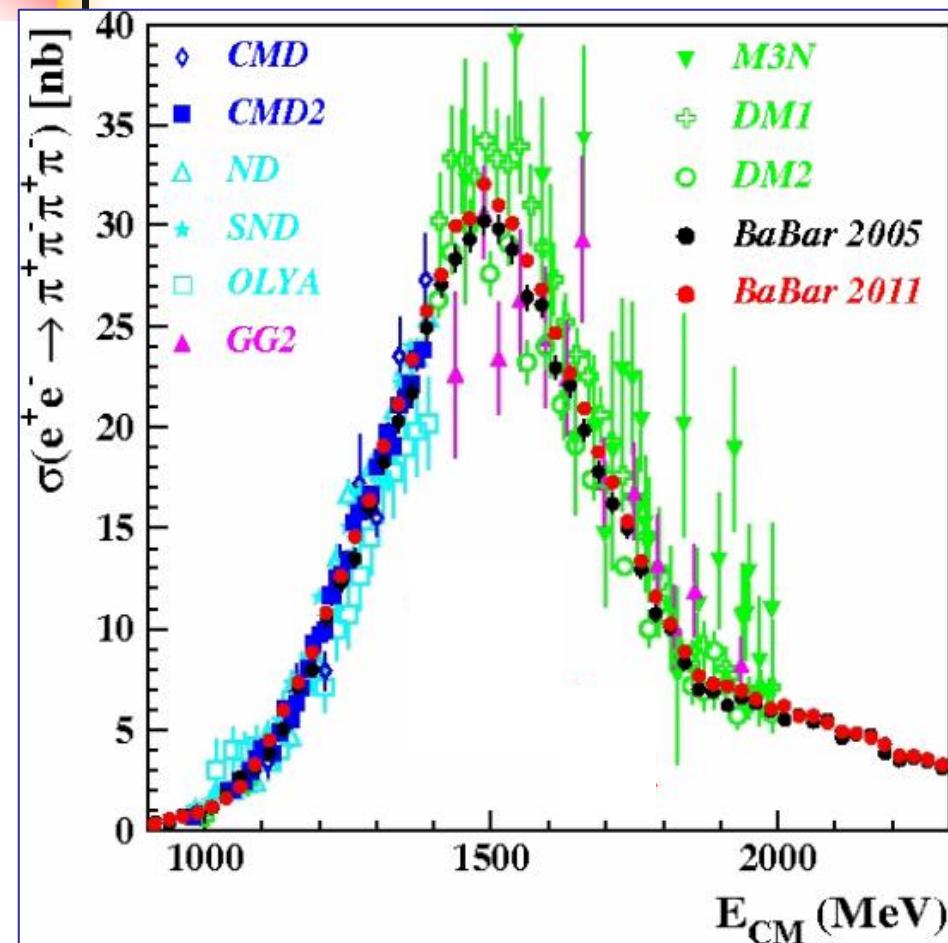
3 times lower error !

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

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

2 $\sigma$  difference between CMD-SND and Babar !

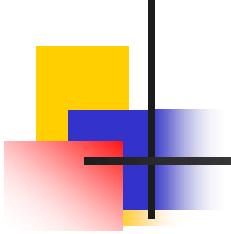
# $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ , Babar, PRD 2012



Systematics - 2.4%  
in peak 1.1-2.8 GeV

Structure:

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



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

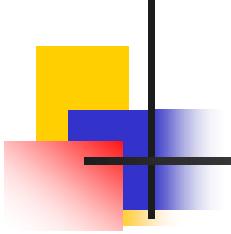
Without Babar-2012:

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

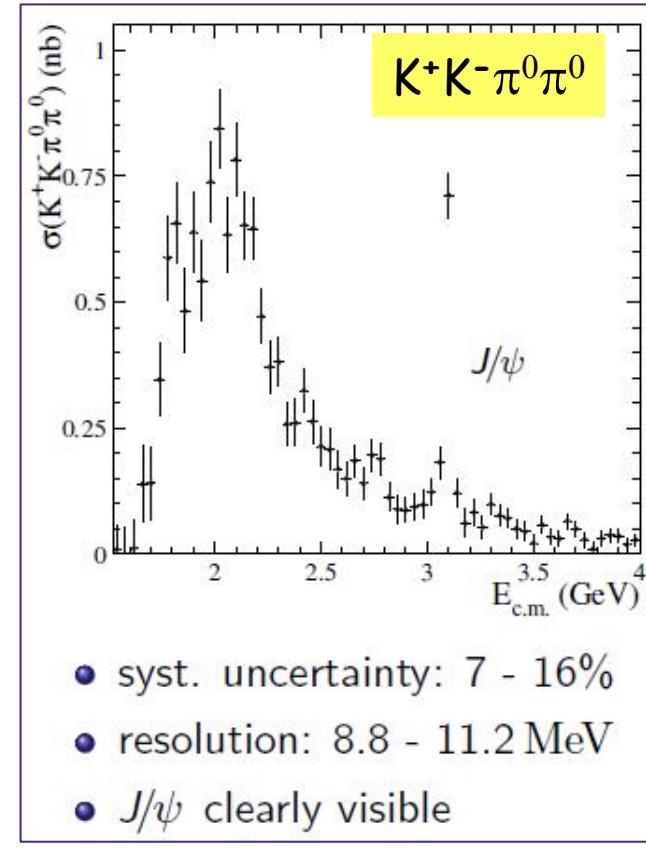
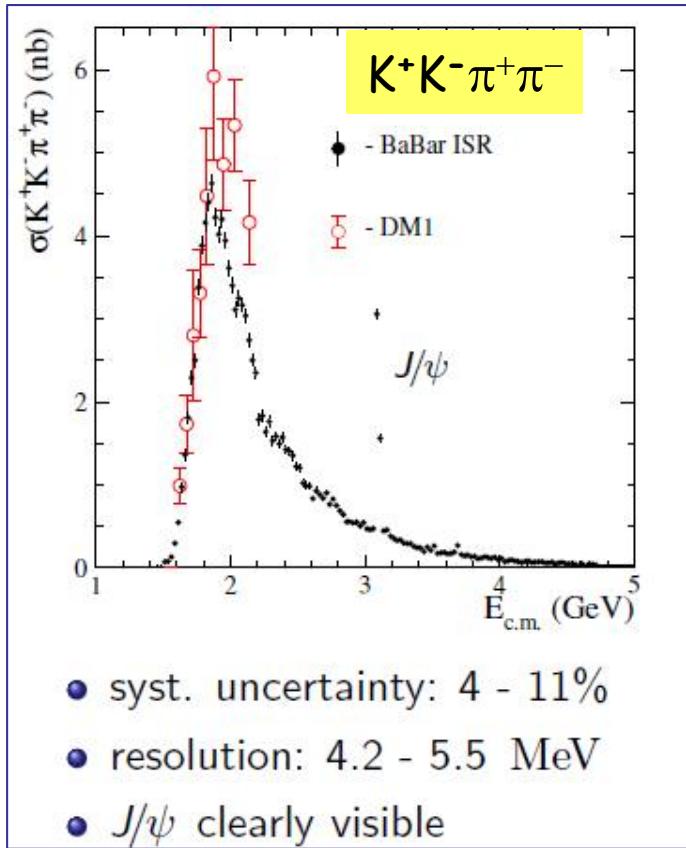
Babar 2012:

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

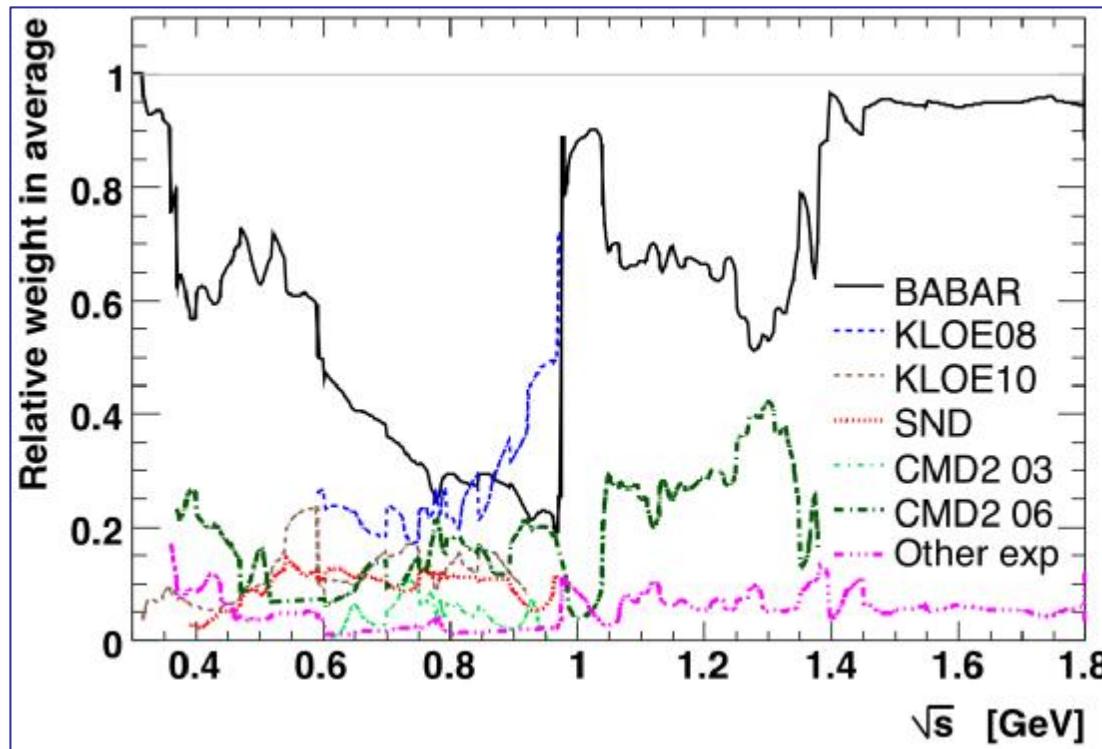
Babar agrees with world average  
with improved precision



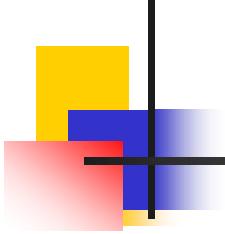
# $e^+e^- \rightarrow K^+K^-\pi^+\pi^-$ , Babar, PRD 2012



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



Babar dominates !  
(DHMZ)

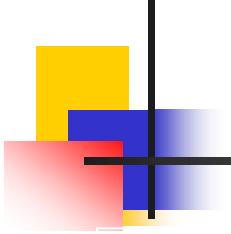


## Perspectives

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

**e<sup>+</sup>e<sup>-</sup>→hadrons** : e<sup>+</sup>e<sup>-</sup>-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,  $\sim 40$  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  $\sim 3$  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.