Current Status of the Muon g-2

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1 Motivation

2 Electron g-2 and fine structure constant

3 Muon g-2 : Experiment vs Standard Model

4 Hadronic contributions to the Muon g-2

Introduction

Cosmology tell us that 95% of matter is not described in text-books yet.
Dark Matter surrounds us! Where it is ?

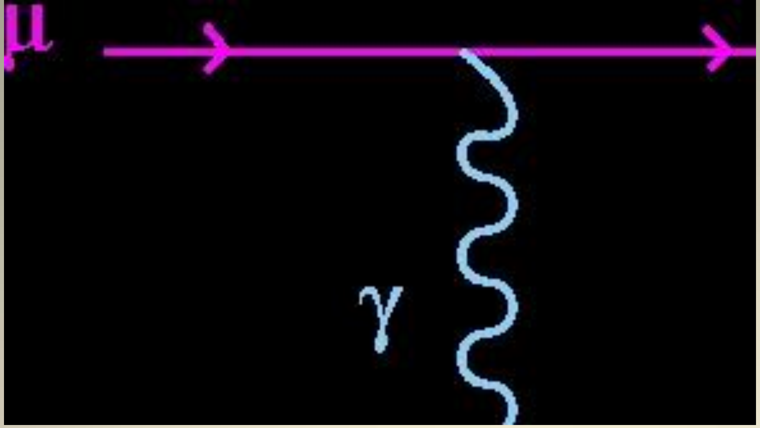
Two search strategies:
1) High energy physics to excite heavy degrees of freedom.
No any evidence till now. We live in LHC era!

2) Low energy physics to produce Rare processes in view of huge statistics.

There are some rough edges of SM.

Anomalous Magnetic Moment of the Muon $(g-2)_\mu$
is most famous and stable (for many years) example

That's intriguing



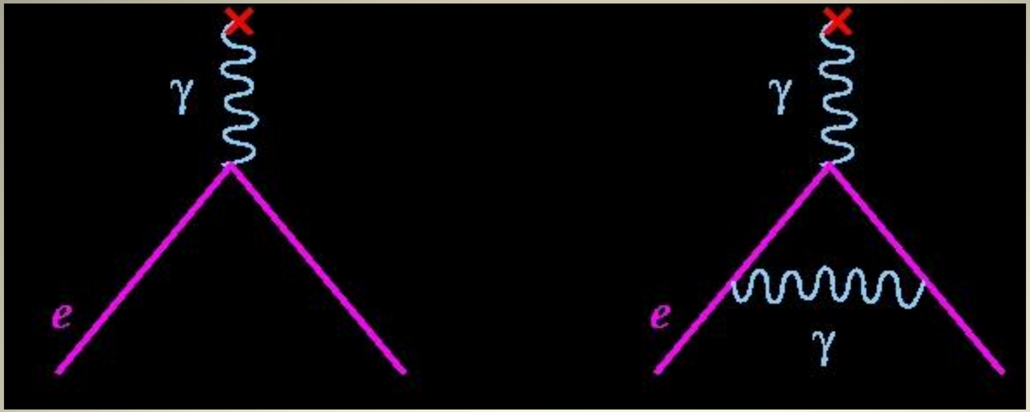
*Dirac Equation Predicts for **free** point-like spin ½ charged particle:*

$$i\hbar\frac{\partial\psi}{\partial t} = [\frac{p^2}{2m} - \frac{e}{2m}(\vec{L}+2\vec{S})\cdot\vec{B}]\psi$$

g=2,   a=(g-2)/2=0 (no anomaly)

a becomes nonzero due to interactions resulting in fermion **substructure**

The lowest order radiative correction (QED)



$$\Gamma_\mu = e\gamma_\mu + a_\ell \frac{ie}{2m}\sigma_{\mu\nu}q_\nu$$

$a_l=(g_l-2)/2$

$$a = \frac{\alpha}{2\pi} = 0.001161$$

Schwinger, 1948

$$a_\mu^{exp} = 0.00119 \pm 0.00005$$

Kush, Foley, 1948

Electron AMM

To measurable level a_e arises entirely from virtual electrons and photons

$$a_e^{exp} = 1\,159\,652\,180.73(0.28) \cdot 10^{-12} \text{ [0.24 ppb] Harvard 2008}$$

$$a_e^{SM} = a_e(\text{QED}) + a_e(\text{hadron}) + a_e(\text{weak}),$$

$$a_e(\text{QED}) = \sum_{n=1}^{5} C_{2n}\left(\frac{\alpha}{\pi}\right)^n + \ldots$$

The theoretical error is dominated by the uncertainty in the input value of the QED coupling $\alpha \equiv e^2/(4\pi)$

$$\alpha^{-1} = 137.035\,999\,1727(341) \text{ [0.25 ppb]}$$

QED is at the level of the best theory ever built to describe nature

Muon AMM: BNL result vs SM

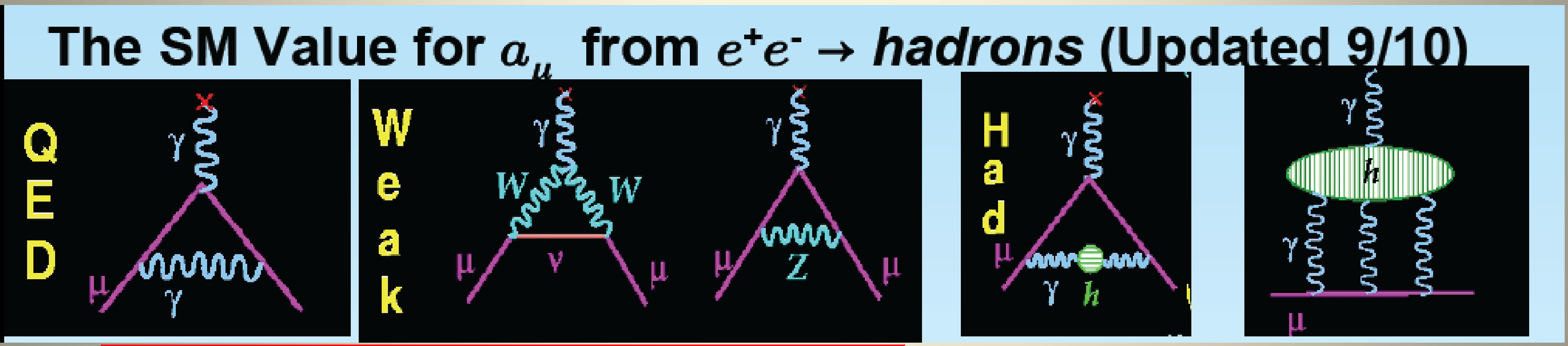
From BNL E821 g-2 experiment (1999-2006)

$$a_\mu^{\text{BNL}} = 11\,659\,208.0(6.3)\bullet 10^{-10} \quad (0.54 \text{ ppm})$$

New Prop.
E989 at Fermilab
0.14 ppm
KEK/JParc

In Theory

$$a_\mu = \left\{ a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{Strong}} \right\}^{\text{SM}} + ???$$



$$a_\mu^{\text{SM}} = 11\,659\,180.2(4.9)\bullet 10^{-10}$$

From Standard Model

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{\text{SM}} = 27.8(8.0)\bullet 10^{-10} \quad (3.6\sigma!)$$

$$a_\mu^{QED} = 11\,658\,471.8951(0.0080) \bullet 10^{-10}$$

Kinoshita&Nio 2014

plus

$$a_\mu^{EW} = 15.36(0.10) \bullet 10^{-10}$$

Czarnetski&Marciano&Vainshtein 2003
Gnendiger, Stockinger 2014

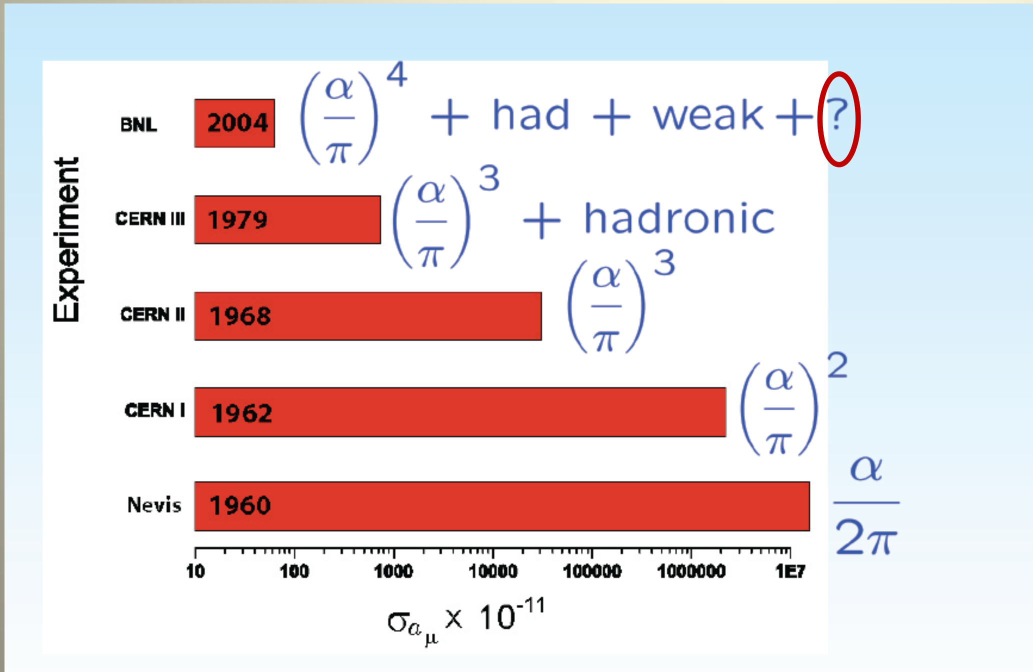
plus

the Hadronic Contribution estimated as

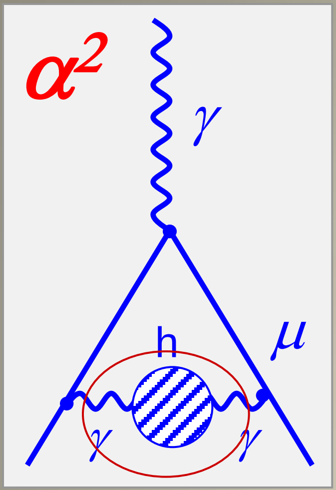
$$a_\mu^{Strong} = 693.0(4.9) \bullet 10^{-10} \quad (<1\% \text{ accuracy!})$$

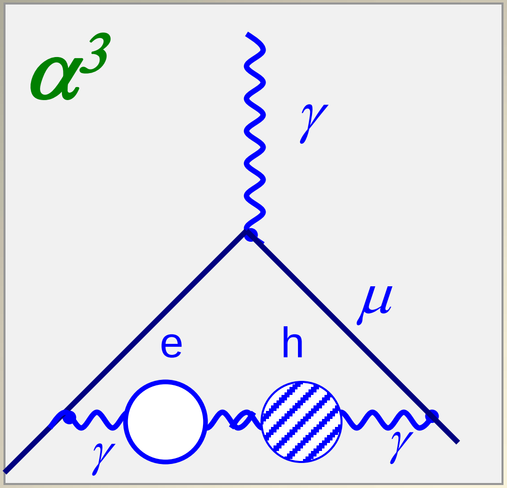
M. Davier, A. Hoecker, B. Malaescu, Z. Zhang 2010;
F. Jegerlehner, R. Szafron 2011

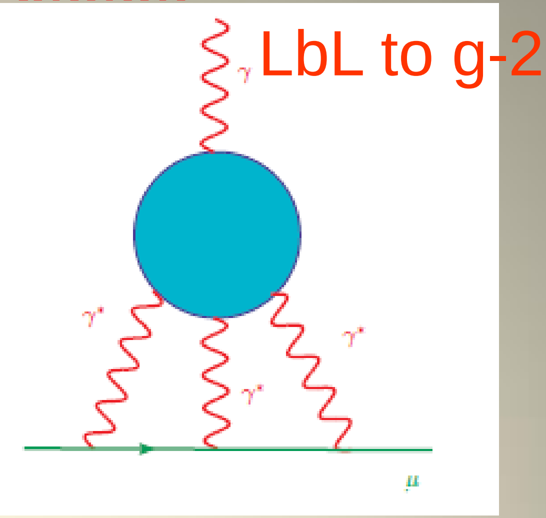
The main question how to get such accuracy from theory.



Strong contributions to Muon AMMM







$$a_\mu^{\text{HVP}} = (692.3 \pm 4.2) \bullet 10^{-10}$$

Hadronic Vacuum polarization

(Davier, Hoecker, Malaescu,Zhang 2011; Hagiwara, Martin, Teubner 2011)

$$a_\mu^{\text{LbL}} = (10.5 \pm 2.6) \bullet 10^{-10}$$

Hadronic Light-by-Light Scattering

(AED, A.Radzhabov, A.Zhevlakov 11-14; C.Fischer, T. Goecke, R.Williams 11-13)

Hadronic Vacuum Polarization contributes 99% and half of error

Fixed by Experiment

$$a_\mu^{(2)\text{hvp}} = \frac{\alpha^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R^{(0)}(s)$$

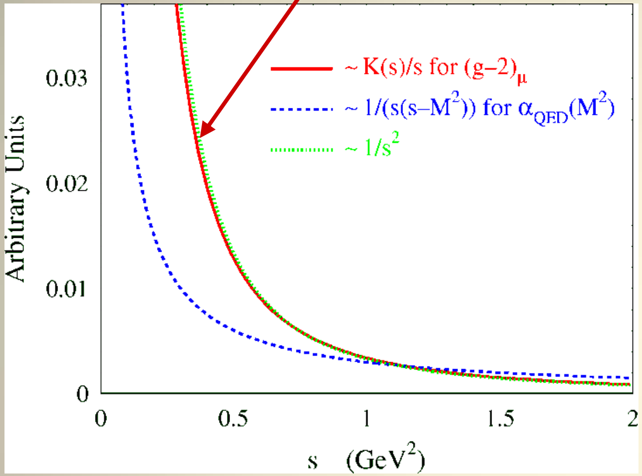
Light-by-light process contributes 1% and half of error

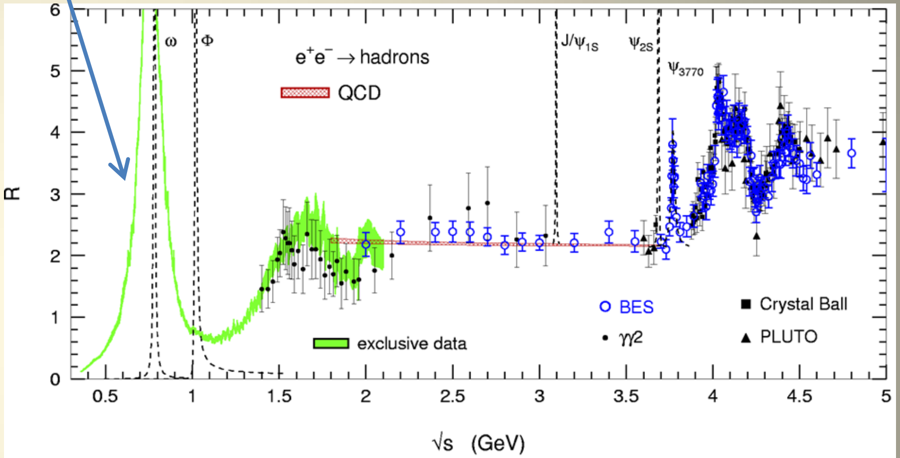
Model Dependent

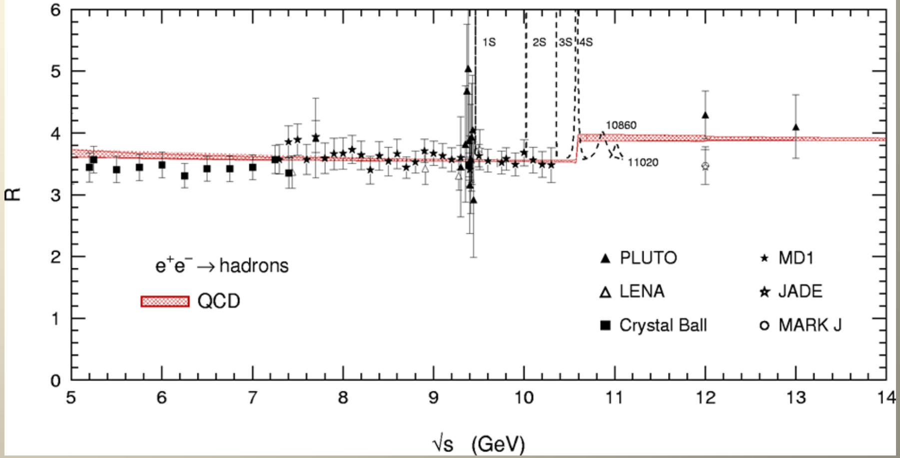
II. Leading Order Hadronic contributions

$$a_\mu^{had} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R^{(0)}(s)$$

Dispersion relation, uses unitarity (optical theorem) and analyticity (Bouchiat and Michel, 1961)

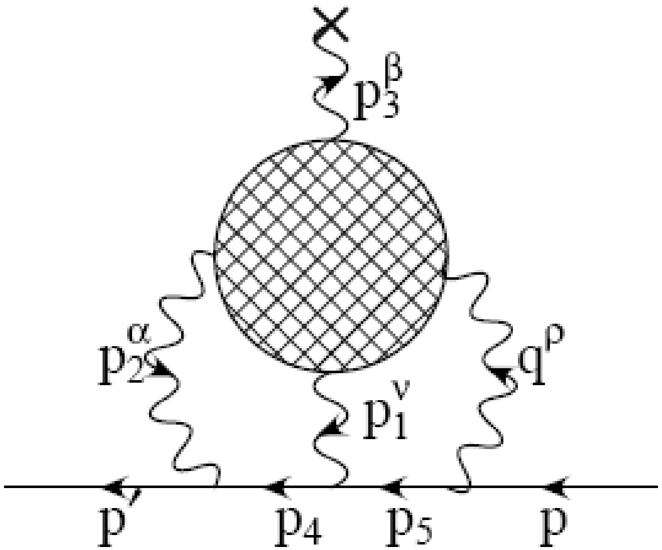






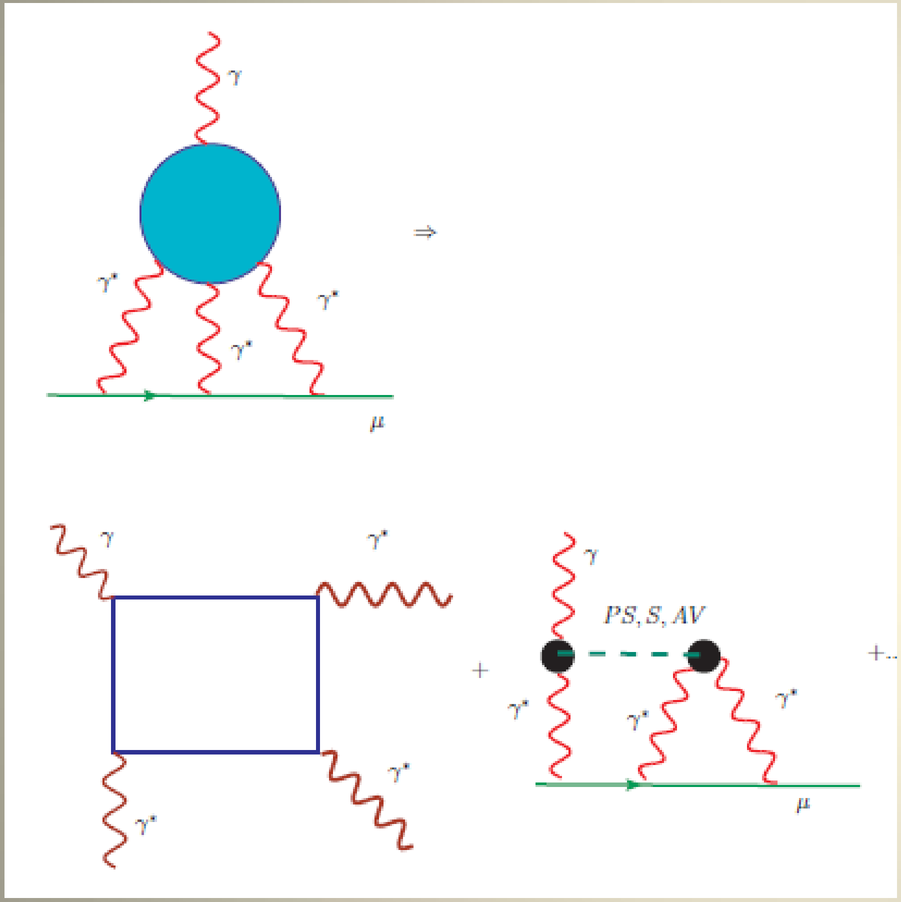
$$R(s) = \frac{\sigma\left[e^+e^- \to \text{hadrons}\right]}{\sigma\left[e^+e^- \to \mu^+\mu^-\right]}$$

Hadronic light-by-light contribution to muon $g-2$

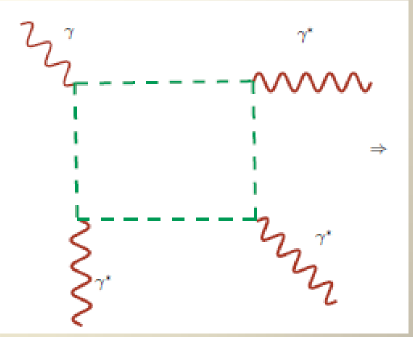


$$\mathcal{M} = |e|^7 A_\beta \int \frac{d^4p_1}{(2\pi)^4} \int \frac{d^4p_2}{(2\pi)^4} \frac{1}{q^2\, p_1^2\, p_2^2 (p_4^2 - m^2)\,(p_5^2 - m^2)}$$
$$\times \underline{\Pi^{\rho\nu\alpha\beta}(p_1, p_2, p_3)}\, \bar{u}(p')\gamma_\alpha(\not{p}_4 + m)\gamma_\nu(\not{p}_5 + m)\gamma_\rho u(p)$$

Structure of hadronic LbL contribution



Hierarchy in
a) 1/Nc
b) $M_\mu / (4 \pi f_\pi)$



Effective Model Approach

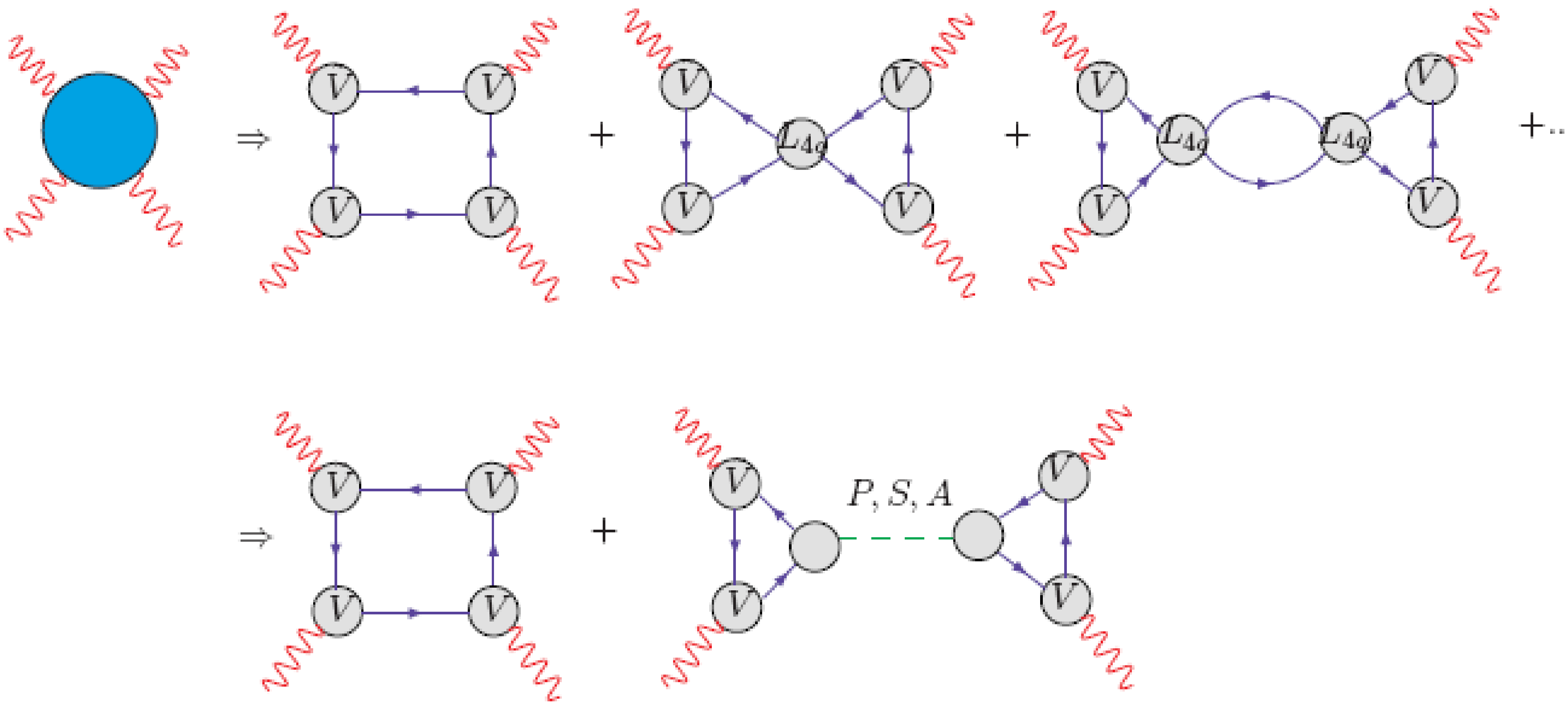
AED, W. Broniowski PRD (08'),
AED, A. Radzhabov, A. Zhevlakov (11'—14')

$$\mathcal{L} = \bar{q}(x)(i\hat{\partial} - m_c)q(x) + \frac{G}{2}[J_S^a(x)J_S^a(x) + J_P^a(x)J_P^a(x)] - \frac{H}{4}T_{abc}[J_S^a(x)J_S^b(x)J_S^c(x) - 3J_S^a(x)J_P^b(x)J_P^c(x)], \quad (1)$$

$$J_M^a(x) = \int d^4x_1 d^4x_2\, f(x_1)f(x_2) \times \times \overline{Q}(x - x_1, x)\,\Gamma_M^a Q(x, x + x_2),$$

$$Q(x, y) = \mathcal{P}\exp\left\{i\int_x^y dz^\mu V_\mu^a(z)\,T^a\right\} q(y)$$

Leading 1/Nc contribution



Nonperturbative QCD is simulated by Nonlocal Chiral Quark model

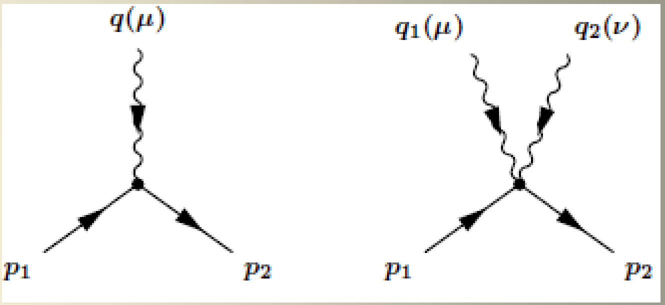
Quark Propagator

$$\frac{\not k}{k^2} \Rightarrow S(k) = \frac{\not k + m(k^2)}{D(k^2)} \xrightarrow{k^2 \to \infty} \frac{\not k}{k^2}$$

Quark-Photon Vertex

$$\gamma_\mu \Rightarrow \Gamma_\mu = \gamma_\mu + \Delta\Gamma_\mu(k,k') \xrightarrow{k^2 \to \infty} \gamma_\mu, \text{ where } \Delta\Gamma_\mu(k,k')$$

guarantes WTI $(k' = k + q)$: $q_\mu \Gamma_\mu = S^{-1}(k') - S^{-1}(k)$



Quark-Pion vertex

$$\frac{1}{f_\pi}\gamma_5 \Rightarrow \Gamma_\pi = \frac{1}{f_\pi}\gamma_5 F(k,k') \underset{k^2 \to \infty}{\overset{k'^2 \to \infty}{=}} 0$$

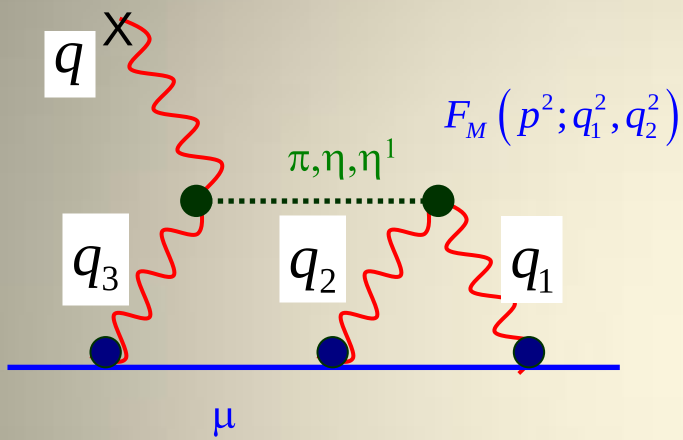
The vertex F is equivalent of the light-cone pion WF

$m(k^2)$ is related to nonlocal quark condensate and thus $m(k^2) \approx M_q e^{-C(k^2)^a}$

We use for the Dynamical Quark Mass

$$m(k^2) = M_q \exp(-2\Lambda k^2)$$

A) Meson exchange LbL contribution – "Goat" diagram



$$a_\mu^{\mathrm{LbL,PS}} = -\frac{2\alpha^3}{3\pi^2}\int_0^\infty dq_1^2 \int_0^\infty dq_2^2 \int_{-1}^{1} dt\sqrt{1-t^2}\,\frac{1}{q_3^2}\times$$

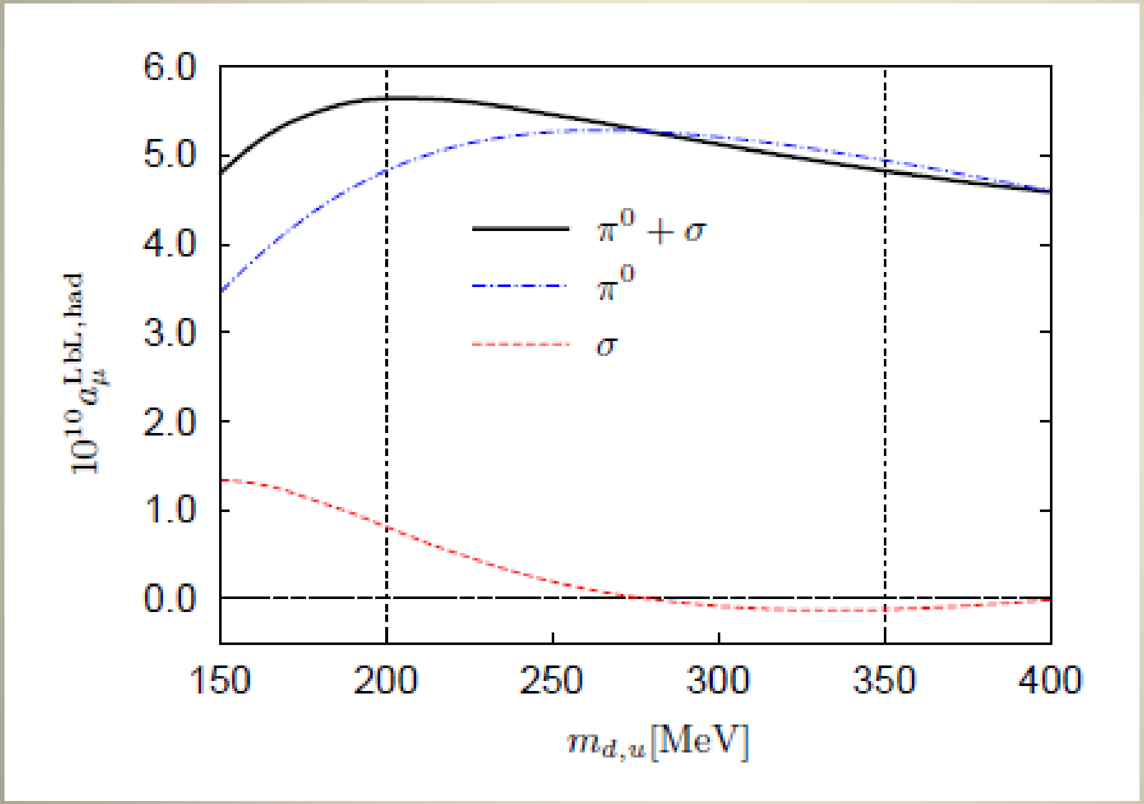
$$\times \sum_{a=\pi^0,\eta,\eta'}\left[2\frac{\mathrm{F}_{a^*\gamma^*\gamma^*}\left(q_2^2;q_1^2,q_3^2\right)\mathrm{F}_{a^*\gamma^*\gamma}\left(q_2^2;q_2^2,0\right)}{q_2^2+M_a^2} I\right.$$

$$\left.+\frac{\mathrm{F}_{a^*\gamma^*\gamma^*}\left(q_3^2;q_1^2,q_2^2\right)\mathrm{F}_{a^*\gamma^*\gamma}\left(q_3^2;q_3^2,0\right)}{q_3^2+M_a^2} I_2\right],$$

Phenomenological and QCD Constraints are used to reduce Model Dependence

Sum of PS(π,η,η’) and S(σ,a0(980),f0(980)) exchange contributions to a $_{\mu}$

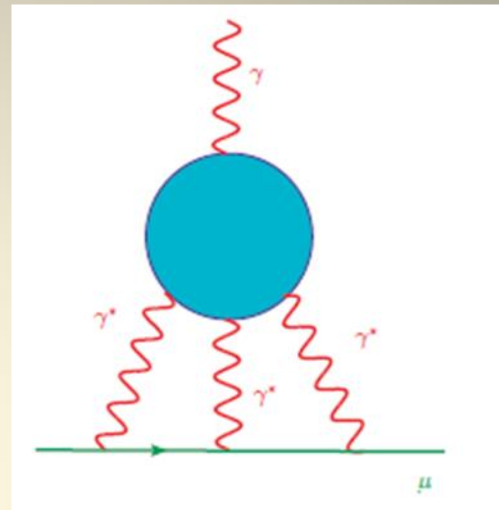
AED, AE Radzhabov, AS Zhevlakov (11’—14’)



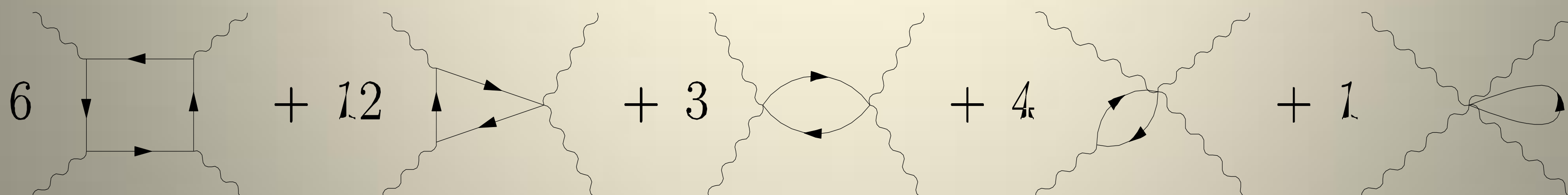
$$a_\mu^{\mathrm{LbL,PS}+S} = (6.19 \pm 0.95) \cdot 10^{-10}$$

B) Contribution of Dynamical Quark Box to a $_\mu$

$$a_\mu^{\mathrm{HLbL}} = \frac{1}{48 m_\mu} \mathrm{Tr}[(\hat{p} + m_\mu)[\gamma^\rho, \gamma^\sigma](\hat{p} + m_\mu)\Pi_{\rho\sigma}(p, p)]$$



$$\Pi_{\rho\sigma}(p', p) = -ie^6 \int \frac{d^4 q_1}{(2\pi)^4} \int \frac{d^4 q_2}{(2\pi)^4} \frac{1}{q_1^2 q_2^2 (q_1 + q_2 - k)^2} \times \gamma^\mu \frac{\hat{p}' - \hat{q}_1 + m_\mu}{(p' - q_1)^2 - m_\mu^2} \gamma^\nu \frac{\hat{p} - \hat{q}_1 - \hat{q}_2 + m_\mu}{(p - q_1 - q_2)^2 - m_\mu^2} \gamma^\lambda \times \frac{\partial}{\partial k^\rho} \Pi_{\mu\nu\lambda\sigma}(q_1, q_2, k - q_1 - q_2),$$



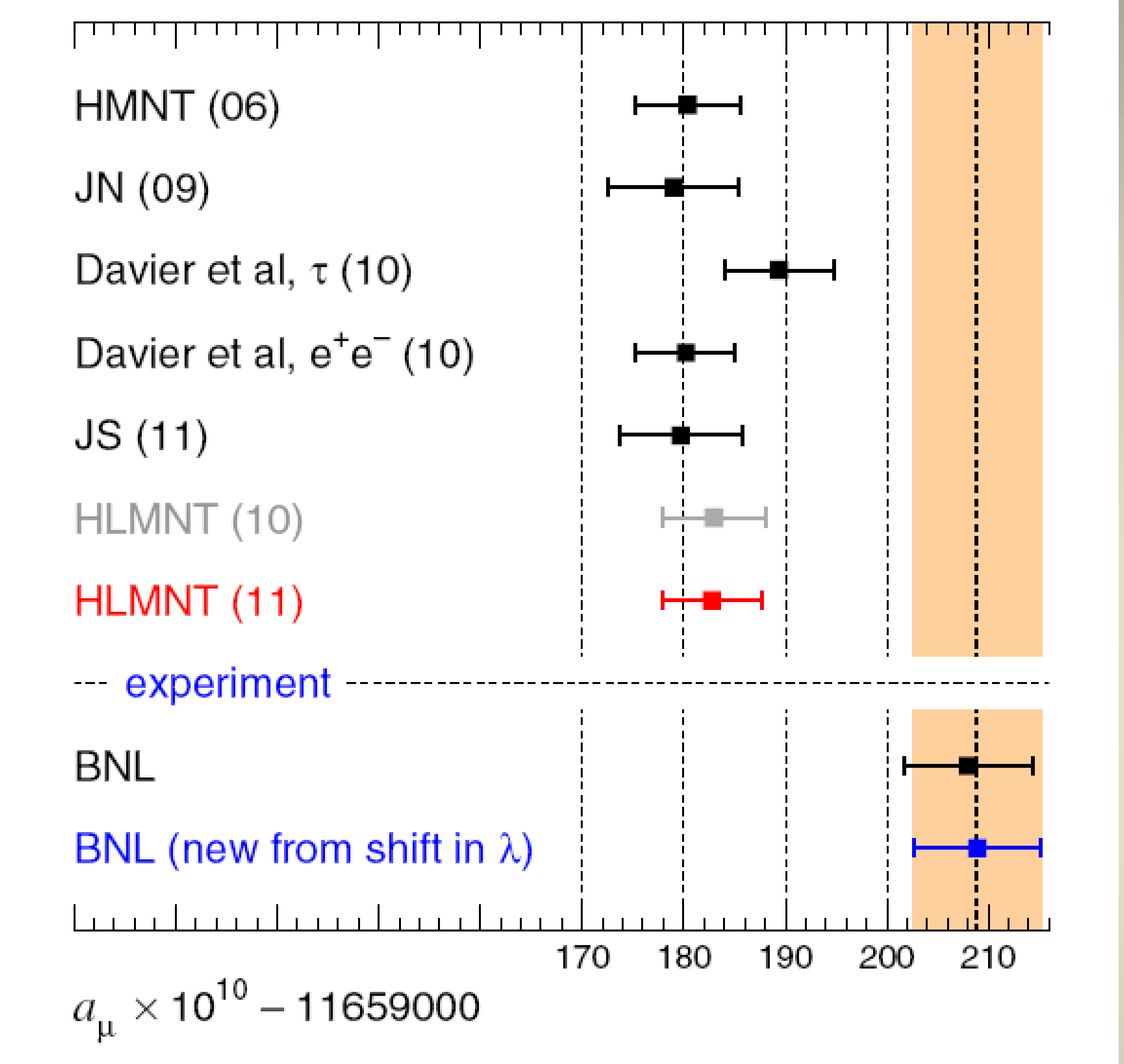
$$a^{Box} = \iint_0^\infty dQ_1 dQ_2 \rho(Q_1, Q_2)$$

$Q_4 \to 0,$

Q3= – Q2 –Q1

Estimates of Hadronic Contributions in different Approaches

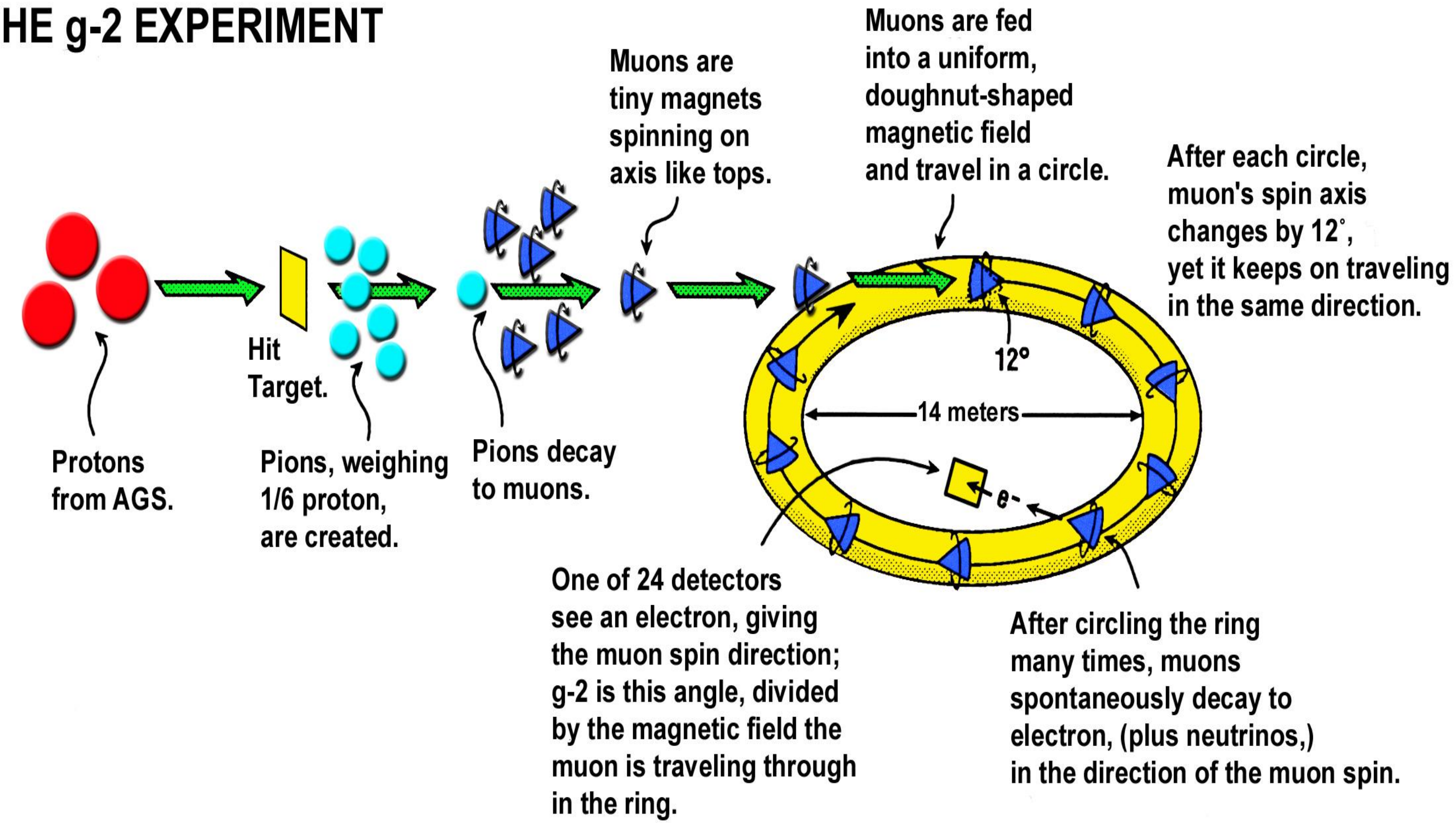
Model	π^0	PS (π^0, η, η')	S (σ, f_0, a_0)	AV	Quark loop	$\pi, K-$ loops	Total
VMD (Hayakawa [24])	5.74(0.36)	8.27(0.64)		0.17(0.10)	0.97(1.11)	−0.45(0.81)	8.96(1.54)
ENJL (Bijnens [25])	5.58(0.05)	8.5(1.3)	−0.68(0.2)	0.25(0.1)	2.1(0.3)	−1.9(1.3)	8.3(3.2)
LMD+V (Knecht [26])	5.8(1.0)	8.3(1.2)					8.0(4.0)
Q-box (Pivovarov [32])					14.05		14.05
LENJL (Bartos [31])	8.18(1.65)	9.55(1.7)	1.23(0.24)				10.77(1.68)
(LMD+V)′(Melnikov [27])	7.65(1.0)	11.4(1.0)		2.2(0.5)		0(10)	13.6(0.25)
NχQM (Dorokhov [36–38])	5.01(0.37)	5.85(0.87)	0.34(0.48)		11.0(0.9)		16.8(1.25)
oLMDV (Nyffeler [28])	7.2(1.2)	9.9(1.6)	−0.7(0.2)	2.2(0.5)	2.1(0.3)	−1.9(1.3)	11.6(0.4)
DS (Goecke [39])	5.75(0.69)	8.07(1.2)			10.7(0.2)		18.8(0.4)
CχQM (Greynat [35])	6.8(0.3)	6.8(0.3)			8.2(0.6)		15.0(0.3)



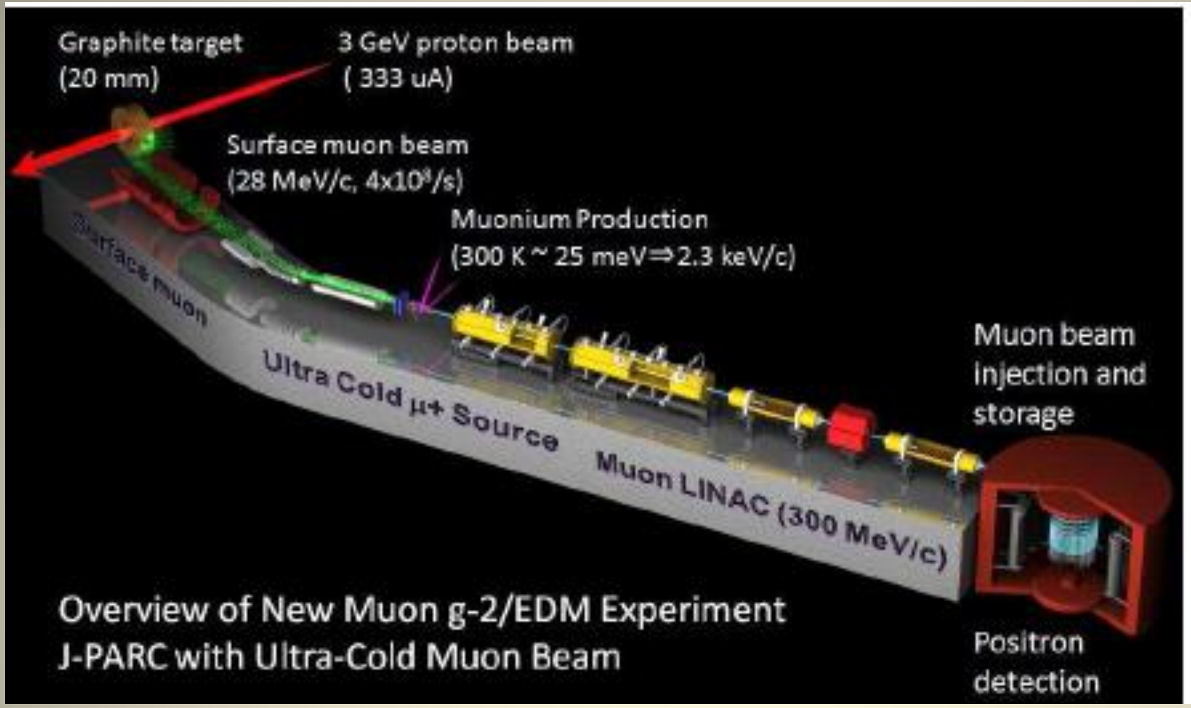
Our results indicate that the LbL is underestimated
And discrepancy may be less than 3 sigma

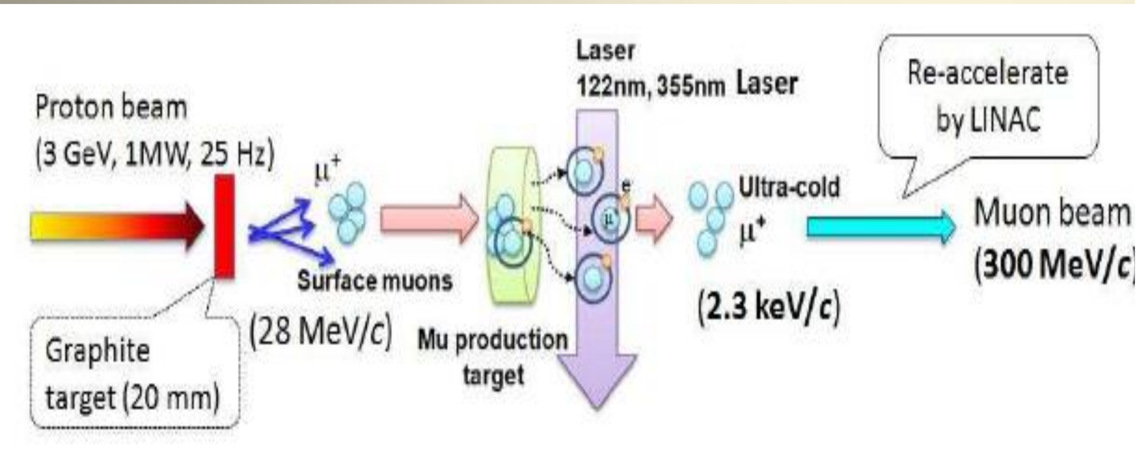
$$\Delta a_\mu \bullet 10^{+10} = a_\mu^{\exp} - a_\mu^{SM} = 27.8(8.0) \Rightarrow \approx 23$$

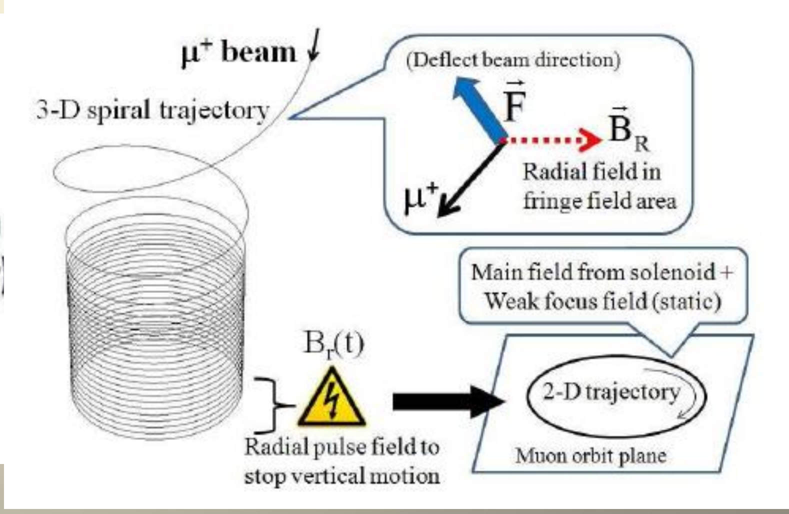
LIFE OF A MUON: THE g-2 EXPERIMENT



Precise measurment of muon g-2/EDM at JPARC







Summary

1) Study of Electron AMM provides very precise value for the QED coupling α

2) Study of Muon AMM is sensitive to effects of SM and NP

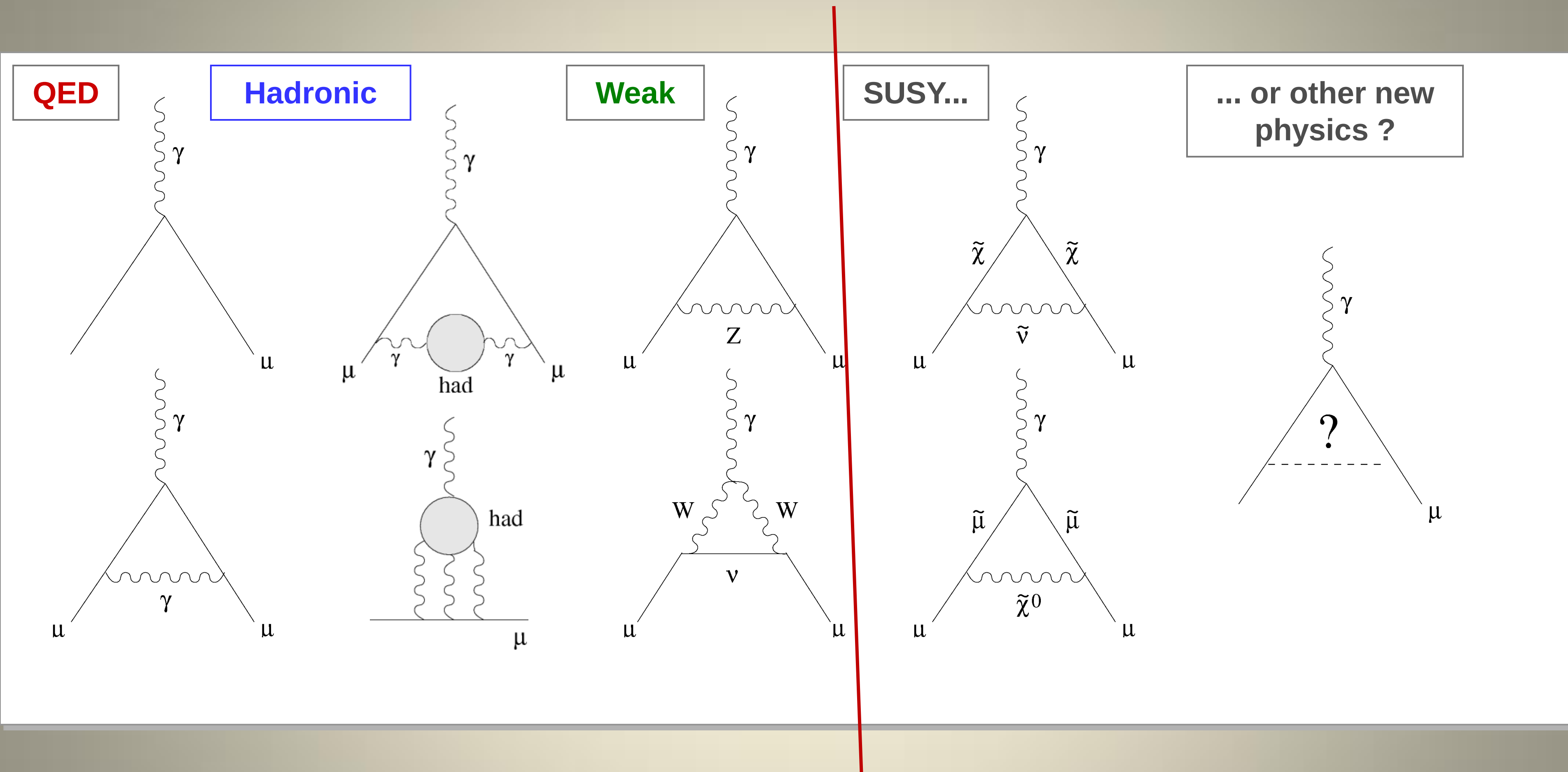
3) At present there is 3.4σ disagreement between SM and BNL experiment. New experiments at FNAL and Jparc are promising

4) New experiments at VEPP2000, KLOE2, BESS III on cross section will further diminish the error for HVP contribution

5) The account of full kinematic dependence of meson-two-photon vertex reduces the value for the meson exchange LbL contribution

6) Dynamical quark box contribution make total result bigger than in previous estimates

Anomalous Magnetic Moment in SM and beyond



Basic of Standard Model

Results on PS meson exchange LbL contribution

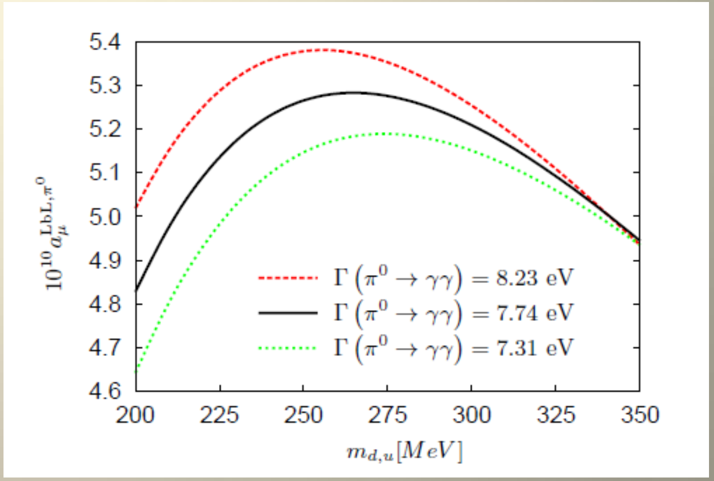
AED, AE Radzhabov, AS Zhevlakov, EPJC (2011)

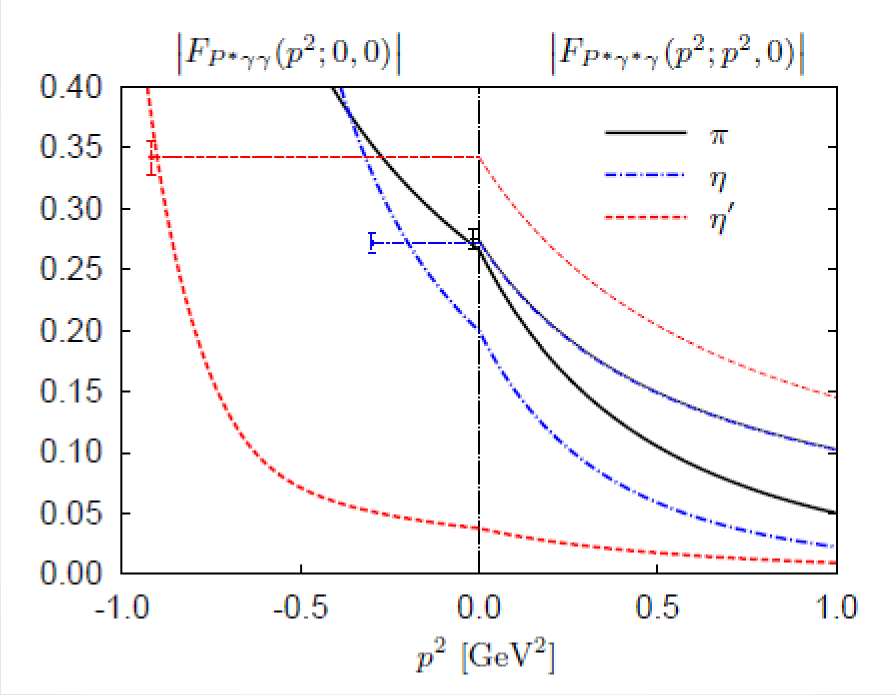
Model	π^0	η	η'	$\pi^0+\eta+\eta'$
VMD [6]	5.74	1.34	1.19	8.27(0.64)
ENJL [11]	5.6			8.5(1.3)
LMD+V, VMD [7]	5.8(1.0)	1.3(0.1)	1.2(0.1)	8.3(1.2)
NJL [12]	8.18(1.65)	0.56(0.13)	0.80(0.17)	9.55(1.66)
(LMD+V)′,VMD[8]	7.97	1.8	1.8	11.6(1.0)
NχQM [13]	6.5(0.2)			
HM [16]	6.9	2.7	1.1	10.7
DIP, VMD [10]	6.54(0.25)			
DSE [15]	5.75(0.69)	1.36(0.30)	0.96(0.21)	8.07(1.20)
This work (NχQM)	5.01(0.37)	0.54	0.30	5.85

Our results are systematically lower!

Why?

Because we use full kinematical
Dependence of the photon-meson vertices!





$|F_{P^*\gamma\gamma}(p^2;0,0)|$
$|F_{P^*\gamma^*\gamma}(p^2;p^2,0)|$
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-1.0
-0.5
0.0
0.5
1.0
p^2 [GeV^2]
π
η
η'