Strongly Interacting Gauge Theory and Physics Beyond Standard Model

Mass Anomalous Dimension γ

Kohtaroh Miura (CPT, Aix-Marseille Univ. (KMI, Nagoya Univ.))

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Motivation

- The Higgs boson with $M_{\mathrm{H}} \simeq 125$ GeV is discovered (2012, LHC-CERN)!
- The LHC second-run has started!

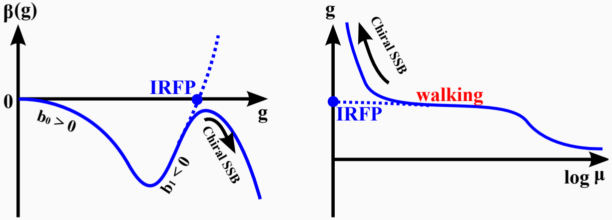
Why Not Investigate The Origin of EWSB?

Strong Dynamics: Origin of EWSB

Questions/Answers: New Strong Dynamics

1. Physical Contents of Higgs?
   Composite Higgs(c.f. σ, Cooper-Pair).
2. Physics of Electroweak (EW) Symmetry Breaking?
   Chiral Symmetry Breaking.
3. Fine-Tuning Problem for $M_{\rm H} = 125$ GeV?
   Log (partly Power-Low) corrections for $M_{\rm H} = 125$ GeV.

Many Flavor QCD and Walking



- Beta function of N_f flavor in SU($N_c = 3$) gauge theory: $\beta(g) = dg(\mu)/d\mu = -b_0(N_f, N_c)g^3 - b_1(N_f, N_c)g^5 + \cdots$.
- In $8 \lesssim N_f \lesssim 12$, Walking Dynamics (Schwinger Dyson Analyses, Yamawaki et.al.('86), Holdom ('85)).
- Stable (light) Higgs: Techni-Dilaton (PNGB for Scale Sym Breaking).
- SM-lepton/quark masses: Enhancement by Factor $(\Lambda_{\rm ETC}/\Lambda_{\rm EW})^{\gamma}$

Subject: Mass Anomalous Dimension

We investigate the mass anomalous dimension γ in many flavor QCD by using

- Lattice Gauge Theory with Monte Carlo Simulations
  (Latest 8-Flavor Results in LatKMI Collaboration).
- Schwinger-Dyson (SD) Equations
  (Miura-Nagai-Shibata, UV/IR Cutoff Effects).

Table of Contents

LatKMI Collaboration

Y. Aoki	(KMI, Nagoya Univ)
T. Aoyama	(KMI, Nagoya Univ)
E. Bennett	(Swansea Univ (UK))
M. Kurachi	(KEK)
T. Maskawa	(KMI, Nagoya Univ)
K. Miura	(CPT, Aix-Marseille Univ (RF) / KMI, Nagoya-Univ)
K-i. Nagai	(KMI, Nagoya Univ)
H. Ohki	(RIKEN)
T. Yamazaki	(Tsukuba Univ)
K. Yamawaki	(KMI, Nagoya Univ)
E. Rinaldi	(LLNL (US))
A. Shibata	(KEK)

Setups I

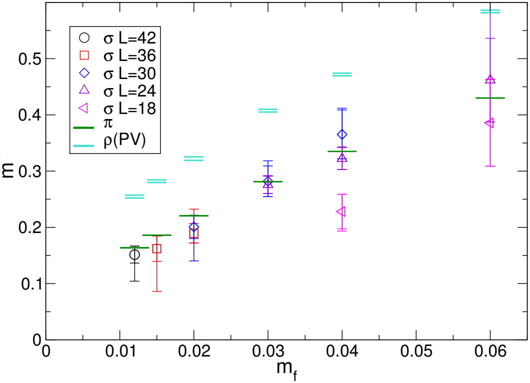
Lattice Action:	$N_f = 8$ HISQ Action
	$+$ Tree-level Symanzik Gauge Action with $\beta = 3.8$.
Argolithm:	HMC with Hasenbush pre-conditioning.
Observables:	$F_\pi,\ M_\pi,\ M_\rho,\ M_{a1},\ M_N$, VPF, $\cdots$.
Code etc:	MILC ver.7.6.3 with some modifications, SciDac Libraly.
Computer:	KMI HPC Cluster φ,
	Nagoya-Univ-ITC CX400,
	Kyushu-Univ-RIIT CX400/HA8000.

Setups II

★ (blue): New Configs. ★ (red): Updates, $\mathcal{O}(10^4)$ Configs.

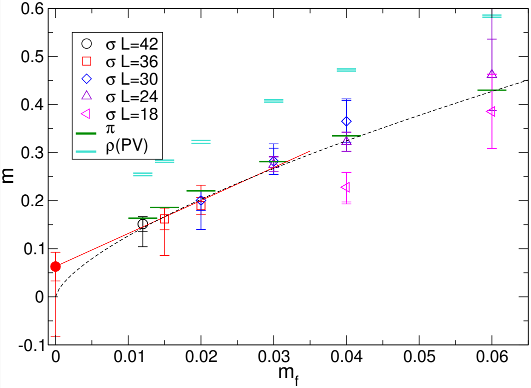
$m_f \diagdown L$	42	36	30	24	18	12
0.012	★ (blue)					
0.015	★ (blue)	★ (red)				
0.02		★ (red)	★ (red)	★		
0.03		★ (blue)	★ (red)	★ (red)		
0.04			★ (red)	★ (red)	★ (red)	
0.05			★	★	★	★
0.06			★	★ (red)	★ (red)	
0.07			★	★	★	★
0.08				★ (red)	★ (red)	★
0.09						★
0.10				★	★	★
0.12						★
0.14						★
0.16						★

$N_f = 8$ Flavor Singlet Scalar σ I (Update from LatKMI PRD 2014)



Light $\sigma \sim$ Dilaton (PNGB for Broken Scale Symm.)

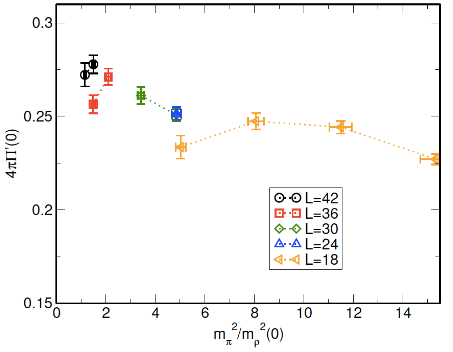
$N_f = 8$ Flavor Singlet Scalar σ II (Update from LatKMI PRD 2014)



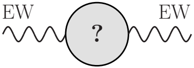
Light $\sigma \sim$ SM Higgs (125 GeV)?

(c.f. LatHC Collab. ('14), Hietanen et.al. ('14), Athenodorou et.al. ('15)).

$N_f = 8$ S-Parameter

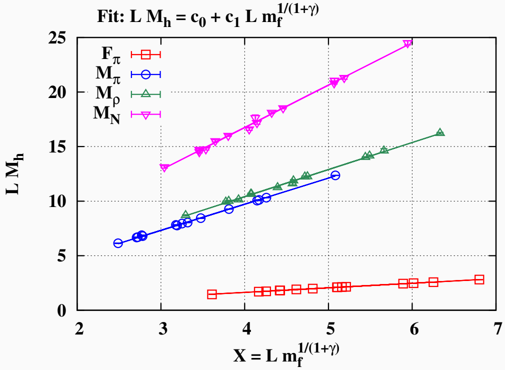


$S \equiv 4\pi\Pi'_{V-A}(Q^2 \to 0)$

$\Pi_{V-A} \sim$ 

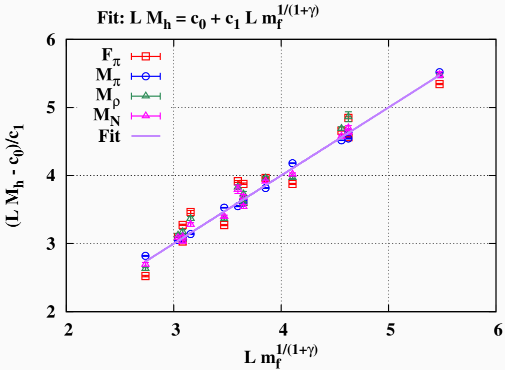
- The result $S \sim 0.25 - 0.275$ is smaller than that $S_{\mathrm{QCD},N_f=2} \sim 0.43$.
- Walking $\sim$ Weaker Chiral SSB $\sim$ V-A Doubling (c.f. LSD-Collab. ('14), Knecht et.al. (Large N_c '98)).
- Still much larger than $S_{\mathrm{exp}} = 0.03(10)$.

FSHS: Individual Fits



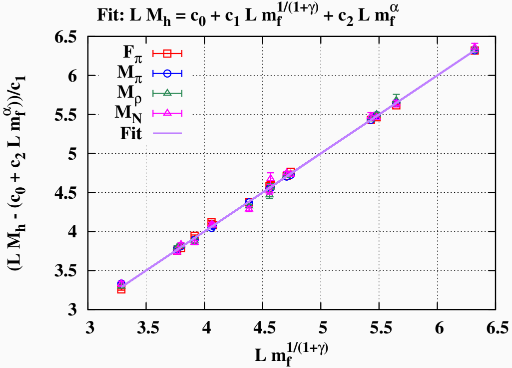
	F_π	M_π	M_ρ	M_N
γ	1.003(5)	0.627(2)	0.896(11)	0.810(11)
χ^2/dof	2.34	15.26	1.41	2.58

FSHS: Simultaneous Fits



$$(\gamma, \chi^2/\mathrm{dof}) = (0.709(2), 124.96).$$

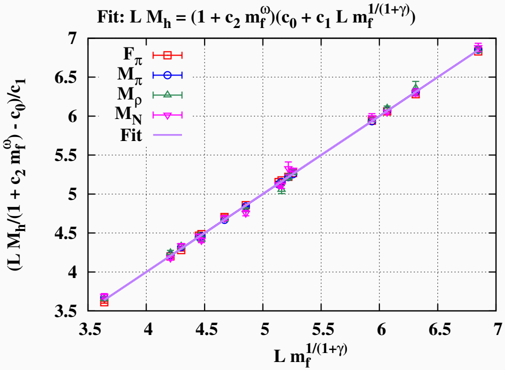
FSHS: Simultaneous Fits with Mass Collection



$$(\gamma, \chi^2/\mathrm{dof}) = (0.893(15), 3.26) \text{ for } \alpha = 1.$$

FSHS: Simultaneous Fits with A-Hasenfratz Type Collection

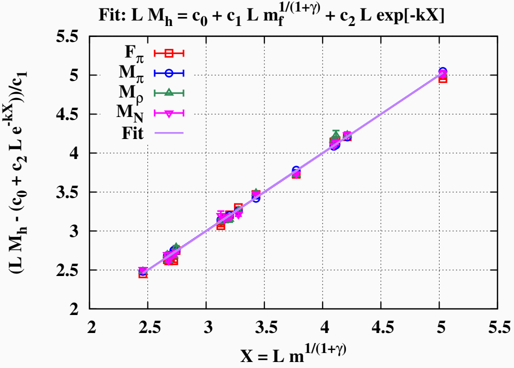
Fit Ansatz: Cheng-Hasenfratz-Liu ('14).



$$(\gamma, \chi^2/\mathrm{dof}) = (1.014(35), 2.46) \text{ for } \omega = 0.35.$$

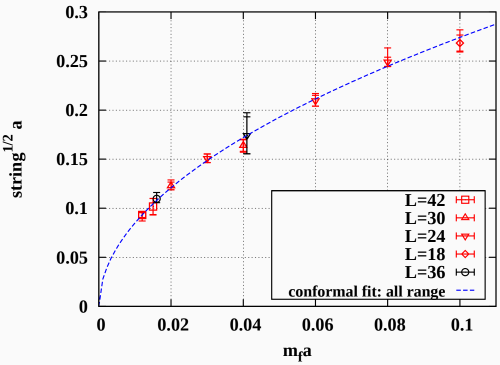
FSHS: Simultaneous Fits with Frascati-Groningen Type Collection

Fit Ansatz: Lombardo-Miura-Silva-Pallante ('14).



$$(\gamma, \chi^2/\mathrm{dof}) = (0.617(2), 12.80) \text{ for } k = 0.1.$$

$N_f = 8$ String Tension



$$\sqrt{\mathrm{string}} \cdot a = C(m_f a)^{1/(1+\gamma)},$$
$$(\gamma, \chi^2/\mathrm{dof}) = (0.97(4), 0.68).$$

Summary on $N_f = 8$ QCD

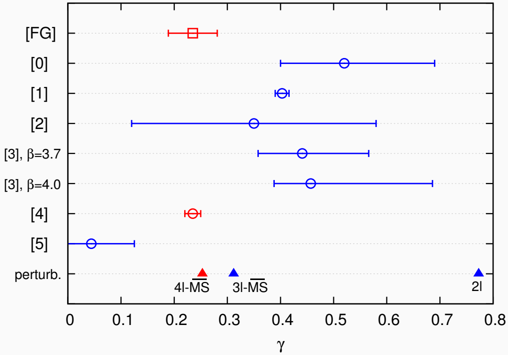
FSHS Individual	F_π	M_π	M_ρ	M_{N}
γ	1.003(5)	0.627(2)	0.896(11)	0.810(11)
χ^2/dof	2.34	15.26	1.41	2.58

FSHS Simultaneous	γ	χ^2/dof
$LM_h = c_0 + c_1 X,\ X = Lm_f^{1/(1+\gamma)}$	0.709(2)	124.96
$LM_h = c_0 + c_1 X + c_2 Lm_f^{\alpha=1}$	0.893(15)	3.26
$LM_h = c_0 + c_1 X + c_2 Lm_f^{\alpha=2}$	0.772(5)	19.38
$LM_h = (1 + c_2 m_f^{\omega=0.35})(c_0 + c_1 X)$	1.014(35)	2.46
$LM_h = c_0 + c_1 X + c_2 L \exp(-kX)\vert_{k=0.1}$	0.617(2)	12.80

- For $m_f \in [0.012, 0.03]$, the quadratic fit (motivated by ChPT) works for all measured operators. However, $N_f(M_\pi/(4\pi F/\sqrt{2}))^2 \gtrsim 6$ and $FL \lesssim 0.85$.
- For the same m_f range, the naive hyper-scaling fit also works except few cases with somewhat larger χ^2/dof. The γ is operator dependent.

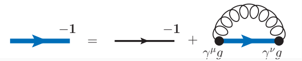
$N_f = 8$ QCD: Having Light σ, Showing Quasi-Conformal Nature with $\gamma \sim 1$.

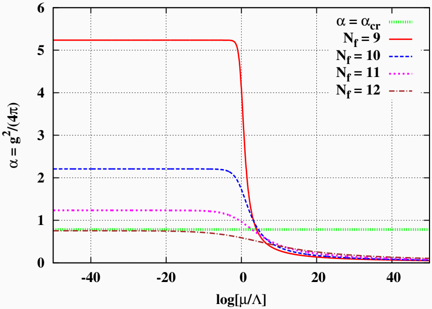
Motivation: Lattice Results on γ in Color $SU(N_c = 3)$ with $N_f = 12$



[FG] Nunes et.al. ('14), [0] Deuzemann et.al. ('09), [1] LSD-Collab ('11), (using data provided in [7]), [2] DeGrand ('11), (using data provided in [7]), [3] LatKMI ('12), [4] Cheng et.al. ('13), [5] Itou ('13), [6] Shrock ('13) [7] Fodor et.al. ('11).

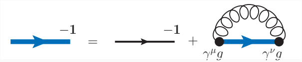
SD with Too-Loop Improved Ladder Approx.





- $N_f \geq 8.05$: Banks-Zaks (BZ) Infra-Red Fixed Point (IRFP, α_*).
- $N_f \gtrsim 12$: Conformal Window with $\alpha_* \leq \alpha_{\rm cr} = \pi/(3C_2[F])$.

SD with $\Lambda_{\mathrm{UV/IR}}$

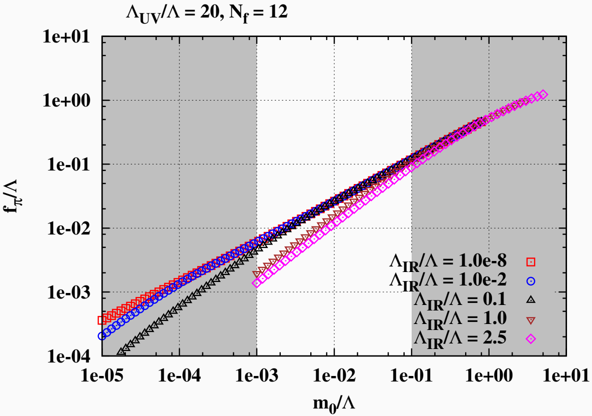


$$
\begin{aligned}
iS_{\mathrm{F}}^{-1}(q) &= \left[A(p^2)\not{p} - \Sigma(p^2)\right] \text{ (Fermion Invers-Prop.)} ,\\
m_p(m_0, \Lambda_{\mathrm{UV/IR}}) &= \Sigma(p^2 = m_p; m_0, \Lambda_{\mathrm{UV/IR}}) \text{ , (Pole Mass, SD-Output)} ,\\
f_\pi^2(m_0, \Lambda_{\mathrm{UV/IR}}) &= \frac{N_c}{4\pi^2} \int dz\, z\, \frac{\left(1 - \frac{1}{4} z \frac{d}{dz}\right)\Sigma^2(z)}{\left(z + \Sigma^2(z)\right)^2} \text{ , (Pagels-Stoker)} .
\end{aligned}
$$

State of The Arts (c.f. Previous Work (LatKMI '09))

- The full momentum dependence of the two-loop running coupling g ($\Lambda_{\mathrm{UV/IR}}$ vs scales encoded in g).
- Wide range probe in the parameter space ($\Lambda_{\mathrm{IR}}/\Lambda \in [10^{-8}, 2.5]$ and $\Lambda_{\mathrm{UV}}/\Lambda \in [1.0, 20]$ including $f_\pi/\Lambda_{\mathrm{IR}} \sim f_\pi L \sim 1$).

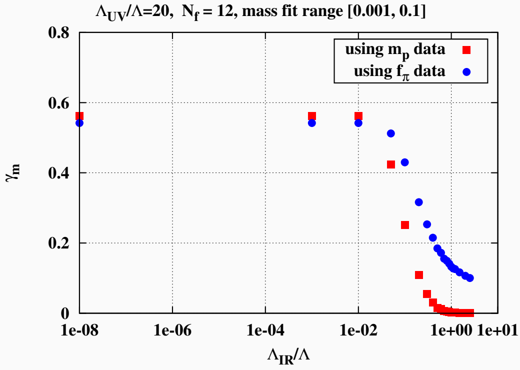
$N_f = 12$ f_π vs m_0



$$M_h = C m_0^{1/(1+\gamma_m)} \ , \quad M_h = m_p \text{ or } f_\pi \ . \qquad (1)$$

$N_f = 12$ γ_m vs Λ_{IR}

$$M_h = C m_0^{1/(1+\gamma_m)} \; , \quad M_h = m_p \text{ or } f_\pi \; . \qquad (2)$$



SD-Based FSHS: Formulation

$$\frac{m_0}{Z_{\rm UV}\, m_p} = \frac{A_{\omega_m}(y_{\rm IR}) D_{\omega_m}(y_\Lambda) \left(\frac{1+y_{\rm IR}}{1+y_\Lambda}\right)^{(1-\omega_m)/2} + (\omega_m \leftrightarrow -\omega_m)}{A_{\omega_m}(y_{\rm IR}) N_{\omega_m}(\max\{1, y_{\rm IR}\}) \left(\frac{1+y_{\rm IR}}{1+\max\{1,y_{\rm IR}\}}\right)^{(1-\omega_m)/2} + (\omega_m \leftrightarrow -\omega_m)} ,$$

$$A_{\omega_m}(y) = \frac{1+\omega_m}{2\omega_m} F\left[\frac{-1+\omega_m}{2}, \frac{-1+\omega_m}{2}, 1+\omega_m; \frac{1}{1+y}\right] ,$$

$$D_{\omega_m}(y) = \frac{1+\omega_m}{2} F\left[\frac{1-\omega_m}{2}, \frac{1-\omega_m}{2}, 1-\omega_m; \frac{1}{1+y}\right] ,$$

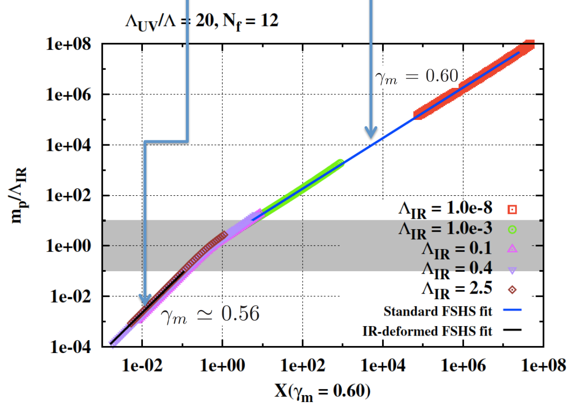
$$N_{\omega_m}(y) = F\left[\frac{1-\omega_m}{2}, \frac{3-\omega_m}{2}, 1-\omega_m; \frac{1}{1+y}\right] , \tag{3}$$

$$\omega_m = 1-\gamma_m , \quad (y_{\rm IR}, y_\Lambda) = \left(\frac{\Lambda_{\rm IR}^2}{m_p^2}, \frac{\Lambda^2}{m_p^2}\right) . \tag{4}$$

$$\frac{\hat{m}_p}{\hat{\Lambda}_{\rm IR}} = \begin{cases} C_{\rm X}(\gamma_m, Z_m^{\rm UV}) \cdot X , & X \equiv \hat{m}_0^{1/(1+\gamma_m)}/\hat{\Lambda}_{\rm IR} \quad (\Lambda_{\rm IR} \ll m_p \ll \Lambda) , \\ C_{\rm Y}(\gamma_m, Z_m^{\rm UV}) \cdot Y , & Y \equiv \hat{m}_0/\hat{\Lambda}_{\rm IR}^{-(1+\gamma_m)} \quad (m_p \ll \Lambda_{\rm IR} \ll \Lambda) . \end{cases} \tag{5}$$

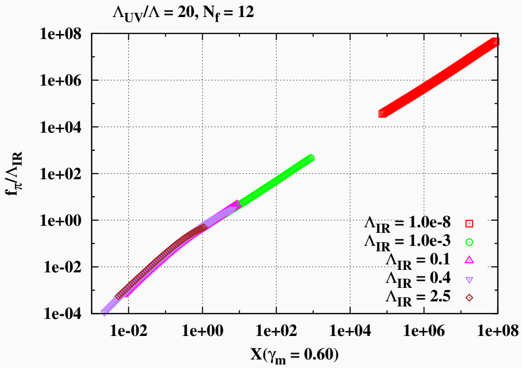
$N_f = 12$ SD-Based FSHS I

$$\frac{\hat{m}_p}{\hat{\Lambda}_{\mathrm{IR}}} = \begin{cases} C_{\mathrm{X}}(\gamma_m, Z_m^{\mathrm{UV}}) \cdot X \\ C_{\mathrm{Y}}(\gamma_m, Z_m^{\mathrm{UV}}) \cdot Y \end{cases}$$



$N_f = 12$ SD-Based FSHS II

$$\frac{\hat{m}_p}{\hat{\Lambda}_{\rm IR}} = \begin{cases} C_{\rm X}(\gamma_m, Z_m^{\rm UV}) \cdot X \ , & X \equiv \hat{m}_0^{1/(1+\gamma_m)}/\hat{\Lambda}_{\rm IR} \quad (\Lambda_{\rm IR} \ll m_p \ll \Lambda) \ , \\ C_{\rm Y}(\gamma_m, Z_m^{\rm UV}) \cdot Y \ , & Y \equiv \hat{m}_0/\hat{\Lambda}_{\rm IR}^{-(1+\gamma_m)} \quad (m_p \ll \Lambda_{\rm IR} \ll \Lambda) \ . \end{cases} \tag{6}$$



c.f. $f_\pi L$ in recent lattice results: [1] Fodor et.al. ('11), [2] Cheng et.al. ('14), [3] DeGrand ('11).

Summary

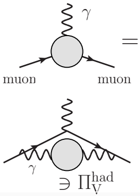
8-flavor QCD (LatKMI)

- Having Light σ, Showing Quasi-Conformal Nature with $\gamma \sim 1$.
- A viable candidate of Walking Technicolor Model (One-Family Model).

SD with $\Lambda_{\mathrm{UV/IR}}$ (Miura-Nagai-Shibata)

- The γ is strongly suppressed when the IR cutoff Λ_{IR} gets comparable to the scale (m_p, f_π).
- The SD-based FSHS allows us to avoid the suppression, explains how two slopes in FSHS result from the IR cutoffs.
- The fomulas applicable for lattice mass spectra are desirable.

LABEX-OCEVU Project in CPT Aix-Marseille Univ: Muon $(g-2)$



$$= -ie[\gamma_\nu F_1(q^2) + \frac{i\sigma^{\nu\rho}q_\rho}{2m_{\mathrm{muon}}} F_2(q^2)]$$

$$a_\mu = (g-2)/2 \to F_2(0)$$

$$S \equiv 4\pi \Pi'_{\mathrm{V-A}}(Q^2 \to 0)$$

$$\Pi_{\mathrm{V-A}} \sim$$

There exists 3.3σ deviation between a_μ^{exp} and a_μ^{SM}.