Probing Physics beyond the Standard Model via Precision Particle Physics

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Lots of ways to search for (more) fundamental theory of elementary particles:

- String/M theory
- Cosmology
- Model building
- Physics at colliders, e.g. LHC, ILC, ...
- Precision particle physics
- ⋮

Precision particle physics

- Assuming a well-established theory (e.g. the Standard Model), calculate physical observables at low energies as precisely as possible. Compare them with experiments.
- If there is a significant deviation between theory and exp., it may be a hint for new physics.
- If the precision is high enough, we can infer physics at higher enegies without using high energy experiments like LHC & ILC.
- Typical observables: the anomalous magnetic moment of the muon (the muon $g-2$), flavor violation ($b \to s\gamma, \mu \to e\gamma, \cdots$)

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Muon $g-2$: introduction

Lepton magnetic moment $\vec{\mu}$:

$$\boxed{\vec{\mu} = -g\frac{e}{2m}\vec{s}}, \qquad \left(\vec{s} = \frac{1}{2}\vec{\sigma} \ \text{(spin)}, \qquad g = 2 + 2F_2(0)\right)$$

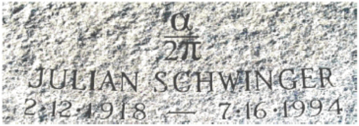
where

$$\overline{u}(p+q)\Gamma^\mu u(p) = \overline{u}(p+q)\left(\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right)u(p)$$

Anomalous magnetic moment: $a \equiv (g-2)/2$ $(= F_2(0))$

Historically,

- ★ $g = 2$ (tree level, Dirac)
- ★ $a = \alpha/(2\pi)$ (1-loop QED, Schwinger)



Today, still important, since...

★ One of the **most precisely measured** quantities:

$$\boxed{a_\mu^{\text{exp}} = 11\ 659\ 208.9(6.3) \times 10^{-10}} \quad [0.5\text{ppm}] \qquad \text{(Bennett } et\ al\text{)}$$

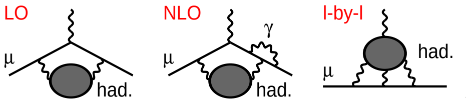
★ **Extremely useful** in **probing/constraining physics beyond the SM**

Introduction: Standard Model prediction for muon $g-2$

QED contribution	11 658 471.808 (0.015)	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2)	Czarnecki et al
Hadronic contributions		
LO hadronic	**694.9 (4.3)**	HLMNT11
NLO hadronic	−9.8 (0.1)	HLMNT11
light-by-light	10.5 (2.6)	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)**	
Experiment	**11 659 208.9 (6.3)**	world avg
Exp − Theory	**26.1 (8.0)**	**3.3 σ discrepancy**

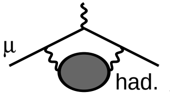
(in units of 10^{-10}. Numbers taken from HLMNT11, arXiv:1105.3149)

n.b.: hadronic contributions:

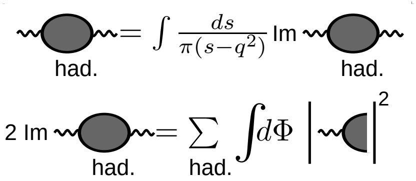


Introduction for $a_\mu^{\mathrm{had,LO}}$

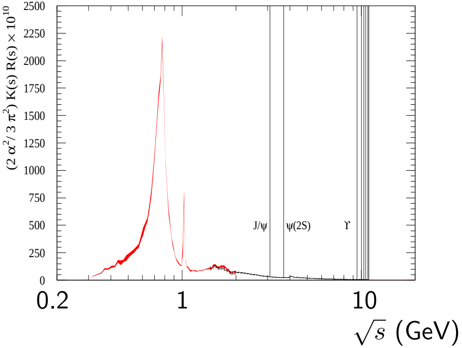
The diagram to be evaluated:



pQCD not useful. Use the dispersion relation and the optical theorem.



$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\mathrm{th}}}^{\infty} ds\ \frac{1}{s} \hat{K}(s) \sigma_{\mathrm{had}}(s)$$



- Weight function $\hat{K}(s)/s = \mathcal{O}(1)/s$

$\Longrightarrow$ Lower energies more important

$\Longrightarrow$ $\pi^+\pi^-$ channel: 73% of total $a_\mu^{\mathrm{had,LO}}$

Included Hadronic Final States

Channel	Experiments with References
$\pi^+\pi^-$	OLYA [16, 17, 18], OLYA-TOF [19], NA7 [20], OLYA and CMD [21, 22], DM1 [23], DM2 [24], BCF [25, 26], MEA [27, 28], ORSAY-ACO [29], CMD-2 [10, 11, 30]
$\pi^0\gamma$	SND [31, 32]
$\eta\gamma$	SND [32, 33], CMD-2 [34, 35, 36]
$\pi^+\pi^-\pi^0$	ND [22], DM1 [37], DM2 [38], CMD-2 [10, 13, 34, 39], SND [40, 41], CMD [42]
K^+K^-	MEA [27], OLYA [43], BCF [26], DM1 [44], DM2 [45, 46], CMD [22], CMD-2 [34], SND [47]
$K_S^0K_L^0$	DM1 [48], CMD-2 [10, 14, 49], SND [47]
$\pi^+\pi^-\pi^0\pi^0$	M3N [50], DM2 [51], OLYA [52], CMD-2 [53], SND [54], ORSAY-ACO [55], $\gamma\gamma2$ [56], MEA [57]
$\omega(\to\pi^0\gamma)\pi^0$	ND and ARGUS [22], DM2 [51], CMD-2 [53, 58], SND [59, 60], ND [61]
$\pi^+\pi^-\pi^+\pi^-$	ND [22], M3N [50], CMD [62], DM1 [63, 64], DM2 [51], OLYA [65], $\gamma\gamma2$ [66], CMD-2 [53, 67, 68], SND [54], ORSAY-ACO [55]
$\pi^+\pi^-\pi^+\pi^-\pi^0$	MEA [57], M3N [50], CMD [22, 62], $\gamma\gamma2$ [56]
$\pi^+\pi^-\pi^0\pi^0\pi^0$	M3N [50]
$\omega(\to\pi^0\gamma)\pi^+\pi^-$	DM2 [38], CMD-2 [69], DM1 [70]
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	M3N [50], CMD [62], DM1 [71], DM2 [72]
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	M3N [50], CMD [62], DM2 [72], $\gamma\gamma2$ [56], MEA [57]
$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	isospin-related
$\eta\pi^+\pi^-$	DM2 [73], CMD-2 [69]
$K^+K^-\pi^0$	DM2 [74, 75]
$K_S^0\pi K$	DM1 [76], DM2 [74, 75]
K_S^0X	DM1 [77]
$\pi^+\pi^-K^+K^-$	DM2 [74]
$p\bar{p}$	FENICE [78, 79], DM2 [80, 81], DM1 [82]
$n\bar{n}$	FENICE [78, 83]
incl. (< 2 GeV)	$\gamma\gamma2$ [84], MEA [85], M3N [86], BARYON-ANTIBARYON [87]
incl. (> 2 GeV)	BES [88, 89], Crystal Ball [90, 91, 92], LENA [93], MD-1 [94], DASP [95], CLEO [96], CUSB [97], DHHM [98]

Table 1: Experiments and references for the e^+e^- data sets for the different exclusive and the inclusive channels as used in this analysis. The recent re-analysis from CMD-2 [10] supersedes

channel	inclusive (1.43,2 GeV)		exclusive (1.43,2 GeV)	
	$a_\mu^{\rm had,LO}$	$\Delta\alpha_{\rm had}(M_Z^2)$	$a_\mu^{\rm had,LO}$	$\Delta\alpha_{\rm had}(M_Z^2)$
$\pi^0\gamma$ (ChPT)	0.13 ± 0.01	0.00 ± 0.00	0.13 ± 0.01	0.00 ± 0.00
$\pi^0\gamma$ (data)	4.50 ± 0.15	0.36 ± 0.01	4.50 ± 0.15	0.36 ± 0.01
$\pi^+\pi^-$ (ChPT)	2.36 ± 0.05	0.04 ± 0.00	2.36 ± 0.05	0.04 ± 0.00
$\pi^+\pi^-$ (data)	502.78 ± 5.02	34.39 ± 0.29	503.38 ± 5.02	34.59 ± 0.29
$\pi^+\pi^-\pi^0$ (ChPT)	0.01 ± 0.00	0.00 ± 0.00	0.01 ± 0.00	0.00 ± 0.00
$\pi^+\pi^-\pi^0$ (data)	46.43 ± 0.90	4.33 ± 0.08	47.04 ± 0.90	4.52 ± 0.08
$\eta\gamma$ (ChPT)	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
$\eta\gamma$ (data)	0.73 ± 0.03	0.09 ± 0.00	0.73 ± 0.03	0.09 ± 0.00
K^+K^-	21.62 ± 0.76	3.01 ± 0.11	22.35 ± 0.77	3.23 ± 0.11
$K_S^0K_L^0$	13.16 ± 0.31	1.76 ± 0.04	13.30 ± 0.32	1.80 ± 0.04
$2\pi^+2\pi^-$	6.16 ± 0.32	1.27 ± 0.07	14.77 ± 0.76	4.04 ± 0.21
$\pi^+\pi^-2\pi^0$	9.71 ± 0.63	1.86 ± 0.12	20.55 ± 1.22	5.51 ± 0.35
$2\pi^+2\pi^-\pi^0$	0.26 ± 0.04	0.06 ± 0.01	2.85 ± 0.25	0.99 ± 0.09
$\pi^+\pi^-3\pi^0$	0.09 ± 0.09	0.02 ± 0.02	1.19 ± 0.33	0.41 ± 0.10
$3\pi^+3\pi^-$	0.00 ± 0.00	0.00 ± 0.00	0.22 ± 0.02	0.09 ± 0.01
$2\pi^+2\pi^-2\pi^0$	0.12 ± 0.03	0.03 ± 0.01	3.32 ± 0.29	1.22 ± 0.11
$\pi^+\pi^-4\pi^0$ (isospin)	0.00 ± 0.00	0.00 ± 0.00	0.12 ± 0.12	0.05 ± 0.05
$K^+K^-\pi^0$	0.00 ± 0.00	0.00 ± 0.00	0.29 ± 0.07	0.10 ± 0.03
$K_S^0K_L^0\pi^0$ (isospin)	0.00 ± 0.00	0.00 ± 0.00	0.29 ± 0.07	0.10 ± 0.03
$K_S^0\pi^\mp K^\pm$	0.05 ± 0.02	0.01 ± 0.00	1.00 ± 0.11	0.33 ± 0.04
$K_L^0\pi^\mp K^\pm$ (isospin)	0.05 ± 0.02	0.01 ± 0.00	1.00 ± 0.11	0.33 ± 0.04
$K\bar{K}\pi\pi$ (isospin)	0.00 ± 0.00	0.00 ± 0.00	3.63 ± 1.34	1.33 ± 0.48
$\omega(\to\pi^0\gamma)\pi^0$	0.64 ± 0.02	0.12 ± 0.00	0.83 ± 0.03	0.17 ± 0.01
$\omega(\to\pi^0\gamma)\pi^+\pi^-$	0.01 ± 0.00	0.00 ± 0.00	0.07 ± 0.01	0.02 ± 0.00
$\eta(\to\pi^0\gamma)\pi^+\pi^-$	0.07 ± 0.01	0.02 ± 0.00	0.49 ± 0.07	0.15 ± 0.02
$\phi(\to$ unaccounted)	0.06 ± 0.06	0.01 ± 0.01	0.06 ± 0.06	0.01 ± 0.01
$p\bar{p}$	0.00 ± 0.00	0.00 ± 0.00	0.04 ± 0.01	0.02 ± 0.00
$n\bar{n}$	0.00 ± 0.00	0.00 ± 0.00	0.07 ± 0.02	0.03 ± 0.01
$J/\psi,\psi'$	7.30 ± 0.43	8.90 ± 0.51	7.30 ± 0.43	8.90 ± 0.51
$\Upsilon(1S-6S)$	0.10 ± 0.00	1.16 ± 0.04	0.10 ± 0.00	1.16 ± 0.04
inclusive R	73.96 ± 2.68	92.75 ± 1.74	42.05 ± 1.14	81.97 ± 1.53
pQCD	2.11 ± 0.00	125.32 ± 0.15	2.11 ± 0.00	125.32 ± 0.15
sum	692.38 ± 5.88	275.52 ± 1.85	696.15 ± 5.68	276.90 ± 1.77

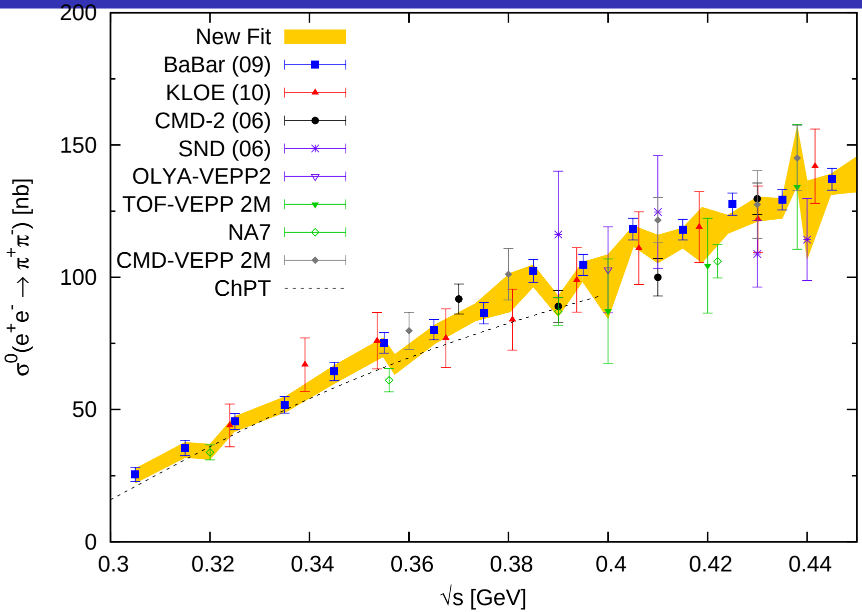
Important Channels

Contributions for $\sqrt{s} < 1.8$GeV:

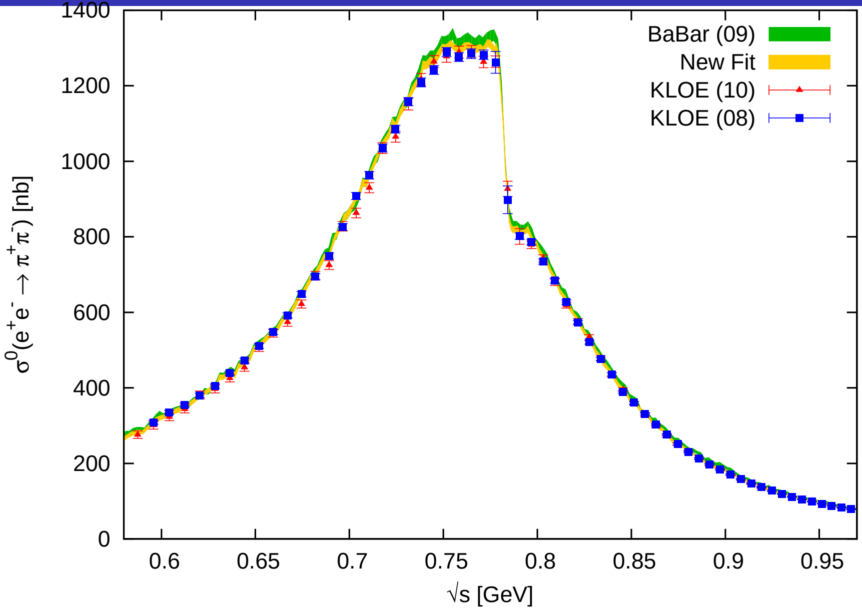
channel	HLMNT11	Davier et al '10	diff
$\pi^+\pi^-$	505.65 ± 3.09	507.80 ± 2.84	-2.15
$\pi^+\pi^-\pi^0$	47.38 ± 0.99	46.00 ± 1.48	1.38
K^+K^-	22.09 ± 0.46	21.63 ± 0.73	0.46
$\pi^+\pi^-2\pi^0$	18.62 ± 1.15	18.01 ± 1.24	0.61
$2\pi^+2\pi^-$	13.50 ± 0.44	13.35 ± 0.53	0.15
$K^0_S K^0_L$	13.32 ± 0.16	12.96 ± 0.39	0.36
$\pi^0\gamma$	4.54 ± 0.14	4.42 ± 0.19	0.12
$\vdots$	$\vdots$	$\vdots$	$\vdots$
Sum	634.28 ± 3.53	633.93 ± 3.61	0.35

table taken from HLMNT11

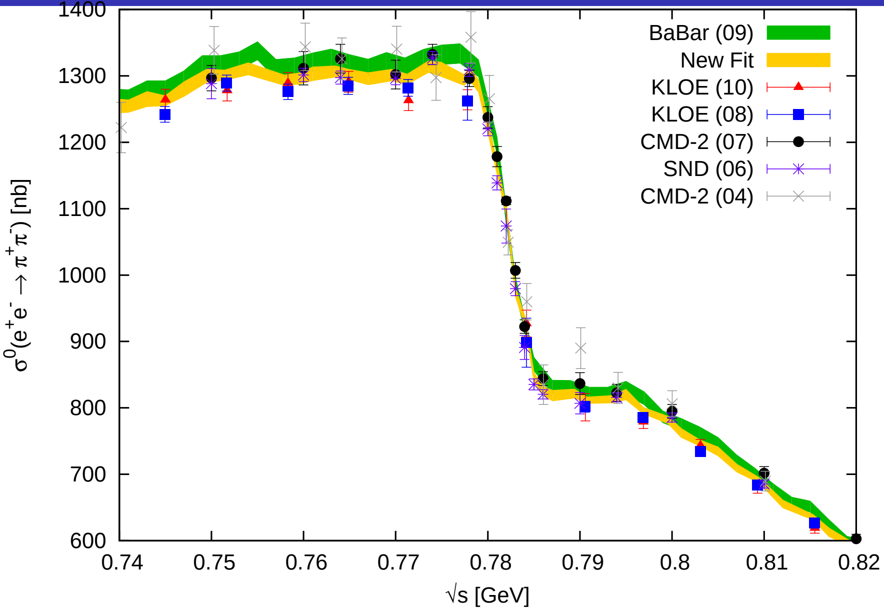
$\pi^+\pi^-$ channel: Low Energy Tail



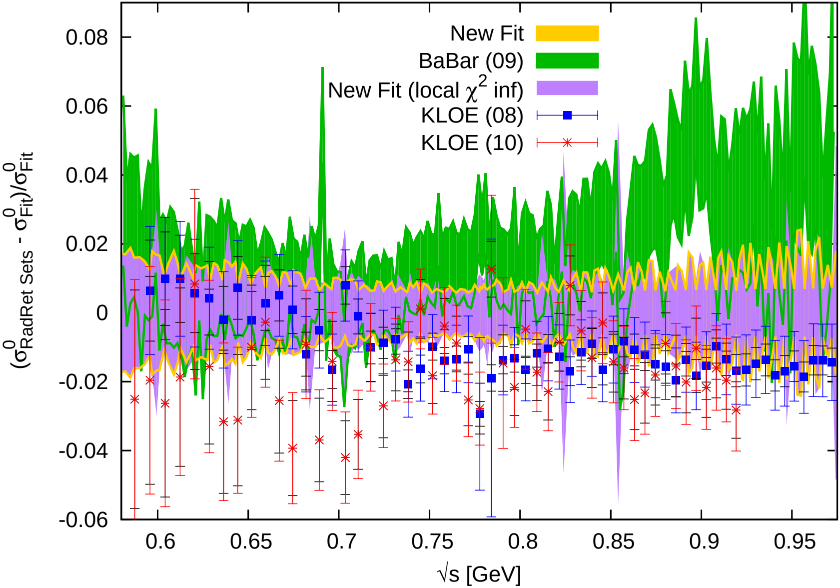
$\pi^+\pi^-$ channel: New Radiative Return Data



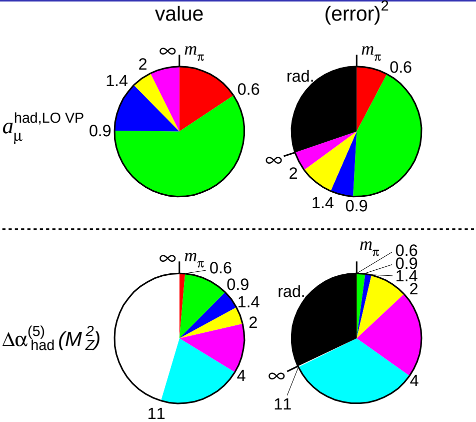
$\pi^+\pi^-$ channel: Zoom-In at ρ-ω Region



Rad. Rtn. Data (for $\pi^+\pi^-$) and Our Combined Result



Results: $a_\mu^{\rm had,LO}$, $a_\mu^{\rm had,NLO}$ and $\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$

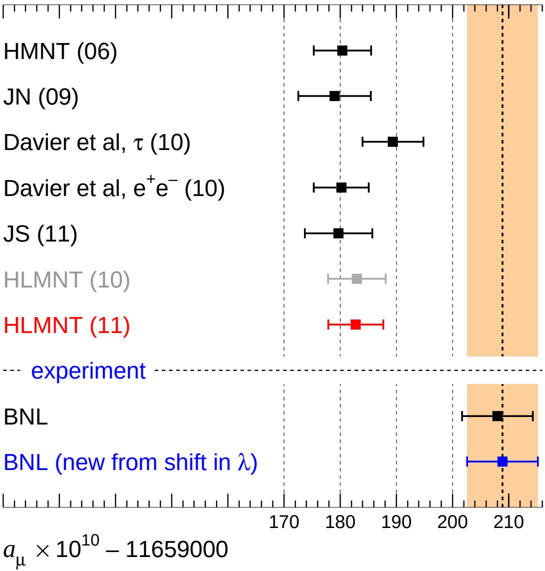


$$a_\mu^{\rm had,LO} = (694.91 \pm 3.72_{\rm exp} \pm 2.10_{\rm rad}) \times 10^{-10}$$

$$a_\mu^{\rm had,NLO} = (-9.84 \pm 0.06_{\rm exp} \pm 0.04_{\rm rad}) \times 10^{-10}$$

$$\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = (276.26 \pm 1.16_{\rm exp} \pm 0.74_{\rm rad}) \times 10^{-4}$$

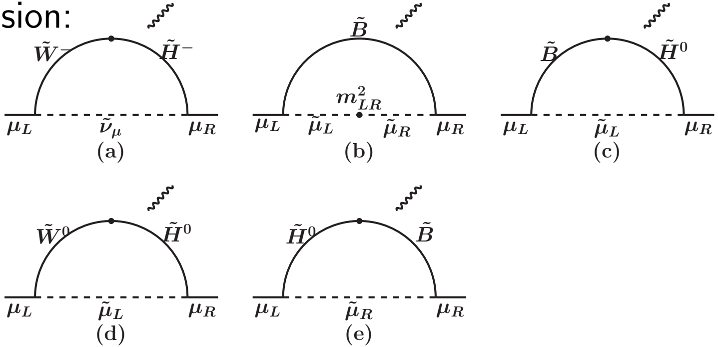
Full SM Result and Comparison with Other Groups



SUSY Contributions to Muon $g-2$

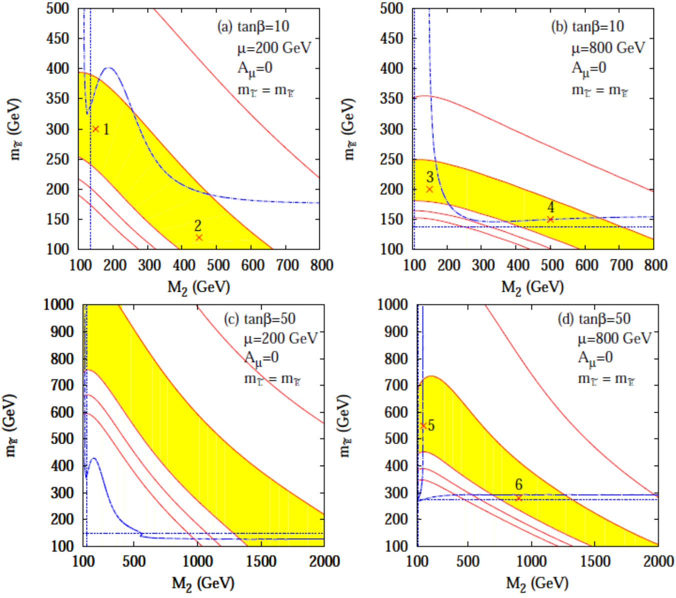
Suppose that the 3.3 σ deviation is due to SUSY...

Leading **SUSY contributions** in the $m_Z/m_{\rm SUSY}$ expansion:



In most cases, the $\tilde{\chi}^{\pm}$-$\tilde{\nu}$ diagram (a) and/or the $\widetilde{B}$-$\widetilde{\mu}_{L/R}$ diagram (b) dominate. (Lopez-Nanopoulos-Wang, Chattopadhyay-Nath, Moroi, $\cdots$)

MSSM Contributions to Muon $g-2$



x-axis: M_2 (gaugino mass)

y-axis: $m_{\tilde{l}}$ (slepton mass)

Figs from Cho, Hagiwara, Matsumoto and DN

Summary

- Precision particle physics: powerful way to approach fundamental theory
- Muon $g-2$: typical example
- Hadronic contrib. to the muon $g-2$: key to improve the Standard Model prediction
- $\gtrsim 3\ \sigma$ discrepancy between experiment and theory
  $\Longrightarrow$ **New Physics?**
  ($\Leftrightarrow$ No new physics seen at the LHC so far. What does this mean?)
- Two new experiments to measure the muon $g-2$ planned at J-PARC and Fermilab.