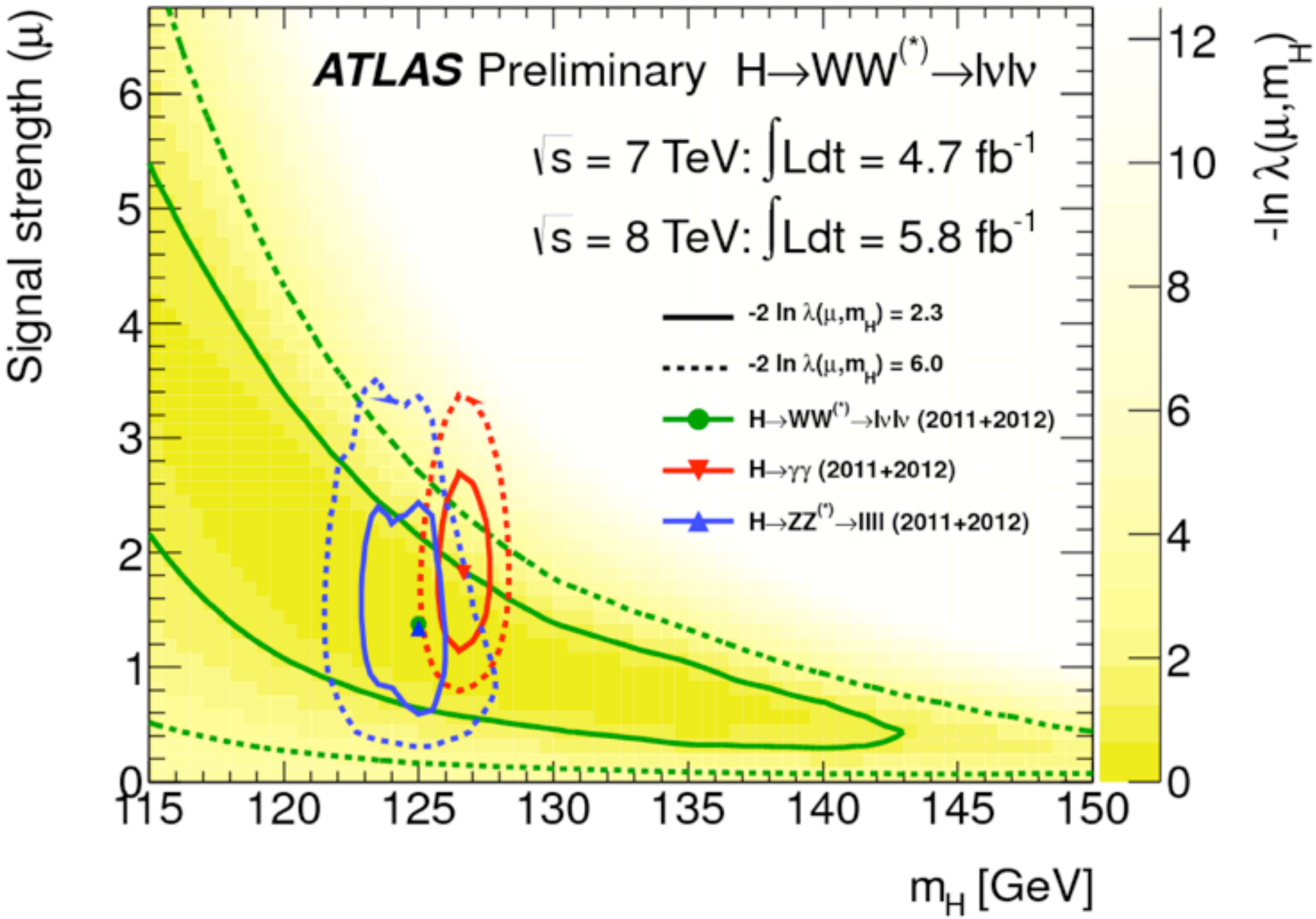
Higgs Mass and Muon g-2 in SUSY Models

Motoi Endo (Tokyo)

ME, Hamaguchi, Iwamoto, Yokozaki, arXiv: 1112.5653,1108.3071,1202.2751

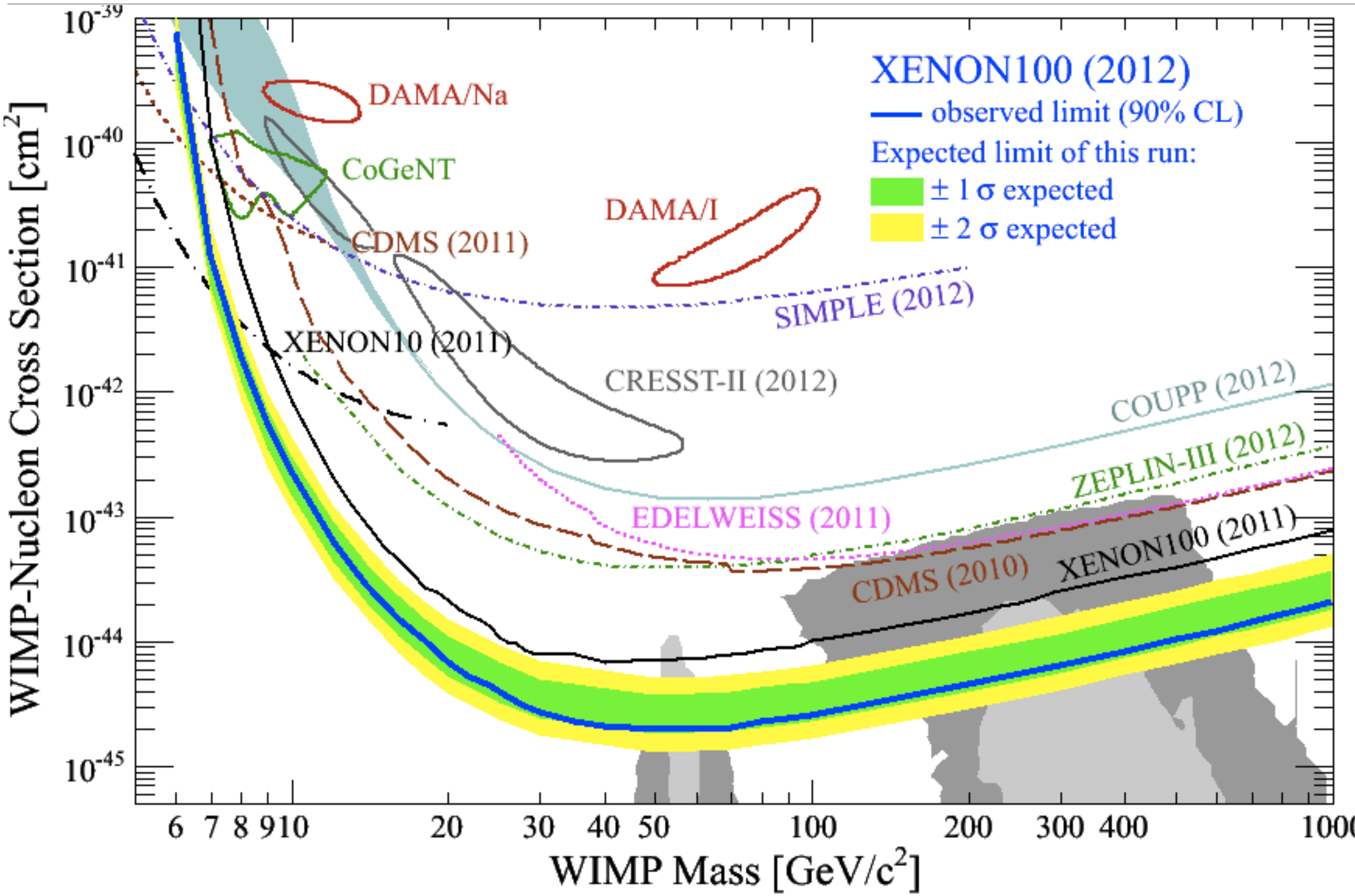
PPP 2012, YITP, 2012.7.20

Latest News: $H_{SM} \rightarrow WW$



signal strength = 1.4 ± 0.5 at $m_h = 125$ GeV

Latest News: XENON100



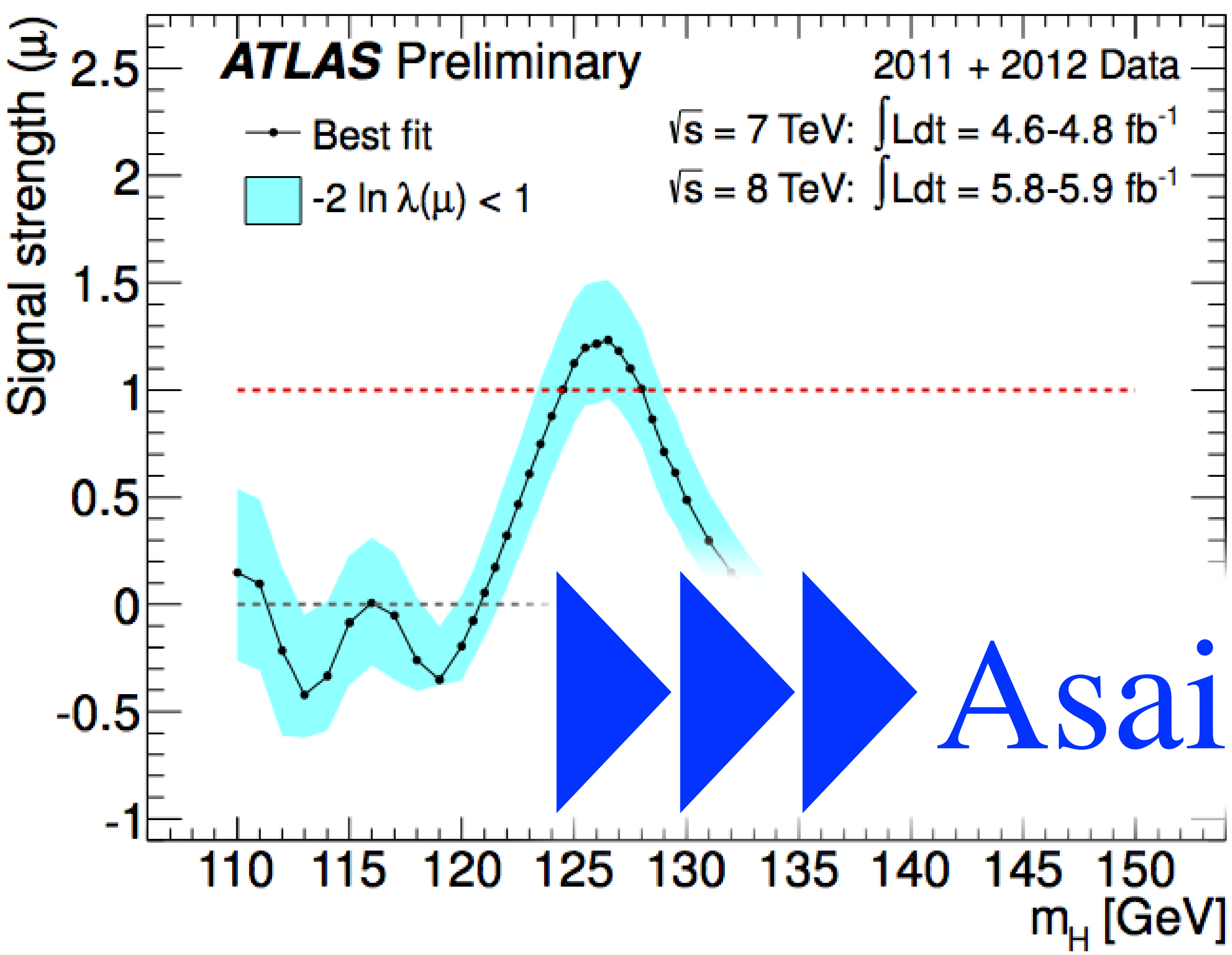
Upper Limit (90% C.L.) is 2 x 10^{-45} cm^2 for 55 GeV/c^2 WIMP

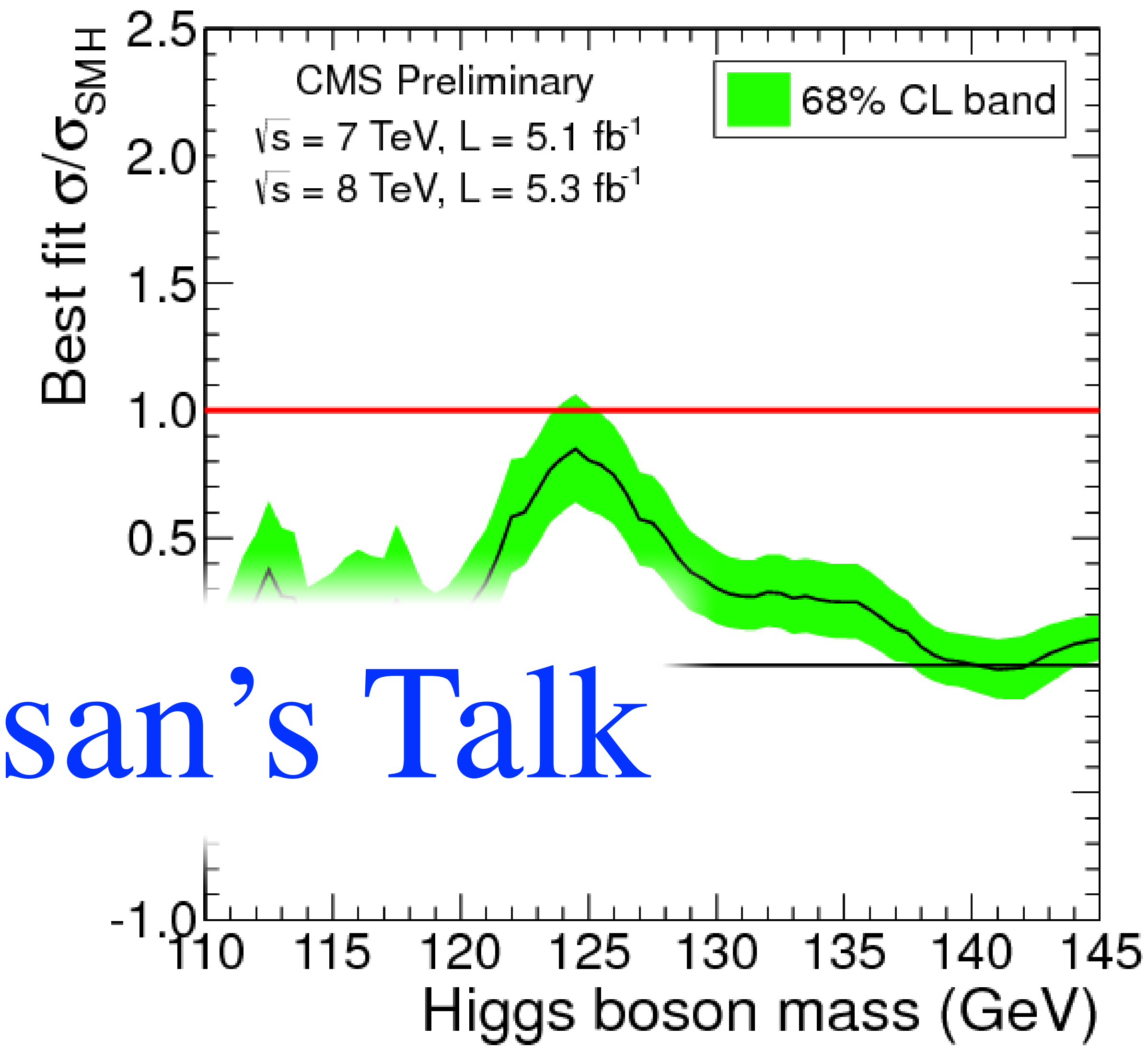
Figure from slide by Aprile at DarkAttack, Ascona, July 18, 2012

Higgs Discovery

2012.7.4@CERN

Higgs Searches at LHC





Asai-san's Talk

- ~5σ signal of Higgs at mass ~125-126GeV
- Is there physics beyond SM in TeV? Why do we believe?

Contents

- Higgs result: Higgs mass ~ 125GeV
- Hints of physics beyond SM
  - some details on muon g-2
- SUSY models: Higgs mass and muon g-2
  - GMSB extensions w/. vector-like matter
- Summary

Hints of New Physics

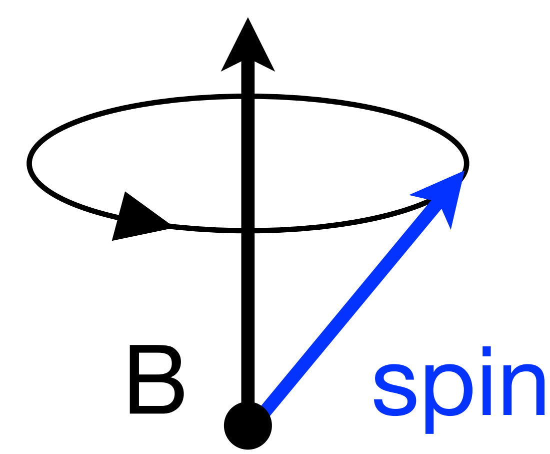
	Signal	Energy Scale
proof	neutrino oscillation	RH neutrino
	– early universe –	
	inflation	very high
	baryogenesis	models
	dark matter	thermal history
	dark energy	10^{-3}eV
implication	GUT	$10^{(13\text{-}16)}$GeV
	– fine-tuning problems –	
	strong CP problem	PQ
	hierarchy problem	TeV
	experimental anomalies	TeV
	cosmology (e.g. dark rad., cosmic ray)	

Anomalies from Experiments

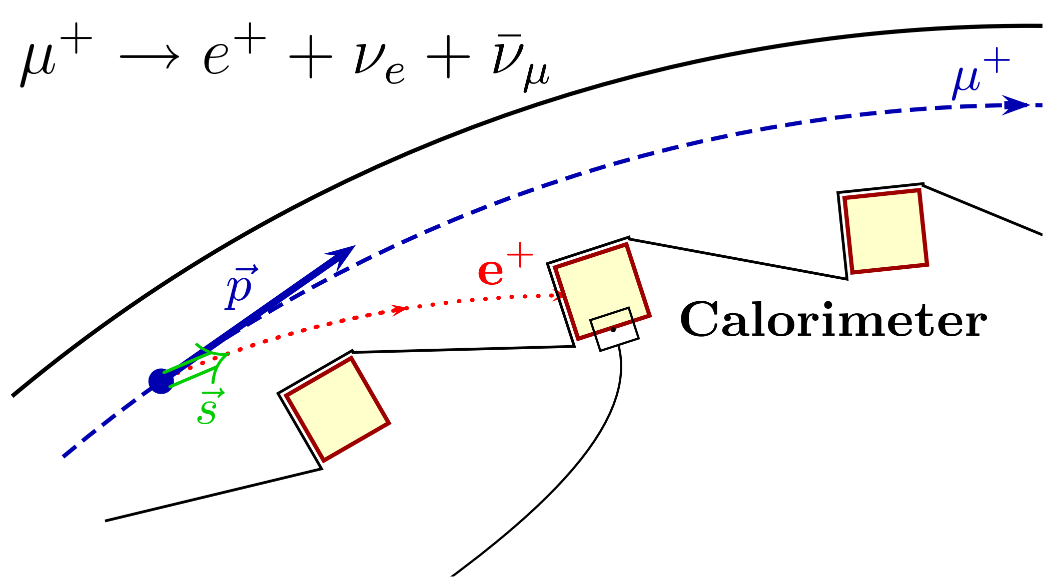
mode	significance
muon anomalous magnetic moment (muon g-2)	>3σ
Br($B \to D^*\tau\nu$)/Br($B \to D^* l\nu$) [cf. ≲2σ for Br($B \to D\tau\nu$)]	2.8σ
~~inclusive and exclusive sin($2\phi_1$) and Br($B \to \tau\nu$)~~ ICHEP2012	~~>2σ~~
Direct CP violation of $B \to K^+\pi^-$ and $B^+ \to K^+\pi^0$	[5σ from 0]
inclusive and exclusive determinations of V_{ub}	2-3σ
Direct CP violation of $D \to K^+K^-$ and $D \to \pi^+\pi^-$	[4σ from 0]
like-sign dimuon charge asymmetry [D0] tight bound on B_s	3.9σ
top forward-backward asymmetry [CDF, D0]	>3σ
electroweak precision [bottom FB asymmetry, NuTeV, SLD]	>2σ
proton charge radius	>5σ
neutrino anomalies [LSND, MiniBooNe, reactor, Gallium]	>2σ
Br($W \to \tau\nu$)/Br($W \to l\nu$) [LEP]	2.8σ

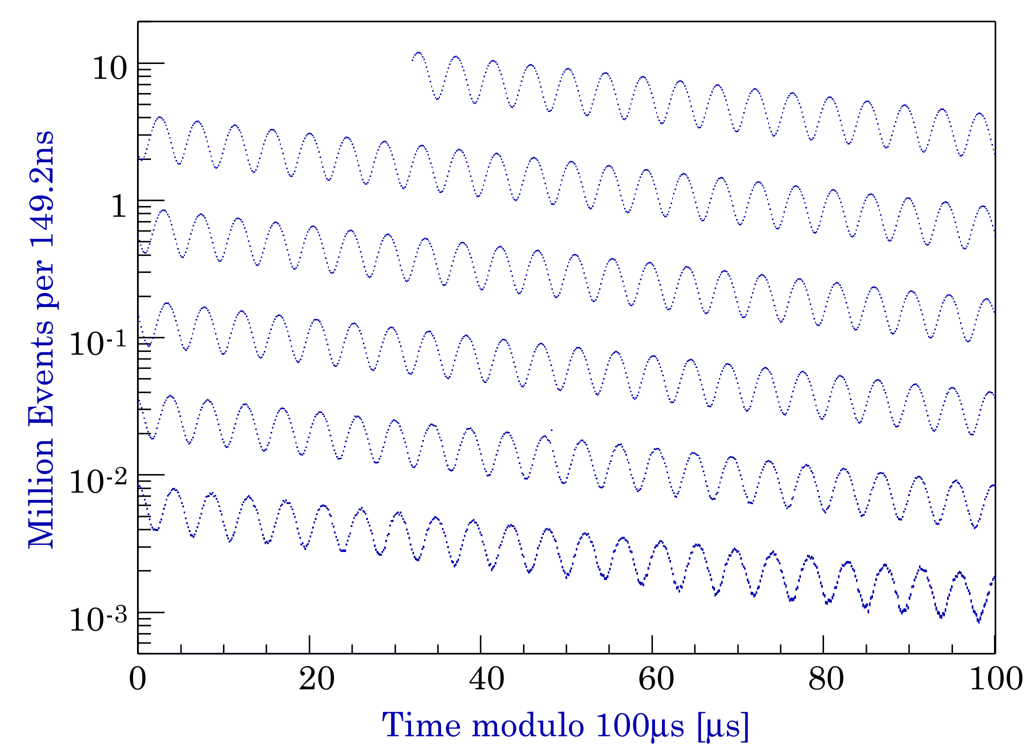
Magnetic Moment of Muon

- spin - magnetic field interaction: g-factor
  - tree level: g = 2
  - radiative correction: $a_\mu = (g-2)/2$
- Experiment: Brookhaven E821



$$a_\mu = 116\,592\,089(63) \times 10^{-11}$$





Standard Model Prediction

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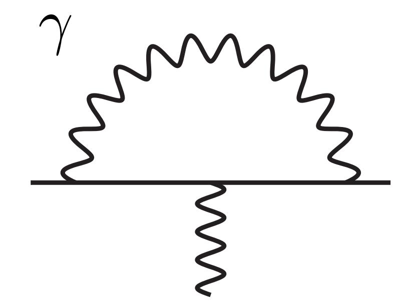
QED (α^5)		116 584 718.962	(0.08)	
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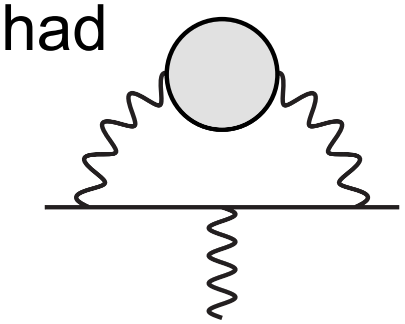
Hadronic (leading)	[HLMNT]	6 949.1	(43)*	
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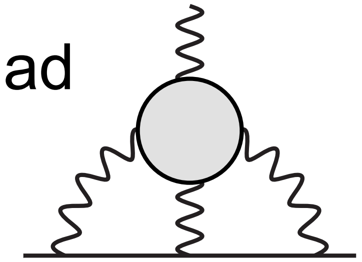
Hadronic (LbL)	[RdRV]	105	(26)*	
	[NJN]	116	(39)	

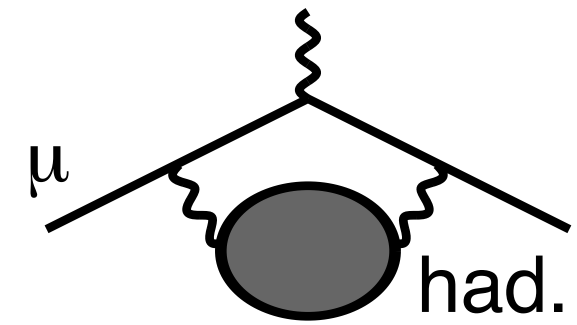
$$a_\mu^{\exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \cdot 10^{-10}$$

> 3σ deviation

Hadronic Vacuum Polarization

- experimental data with dispersion relation and optical theorem

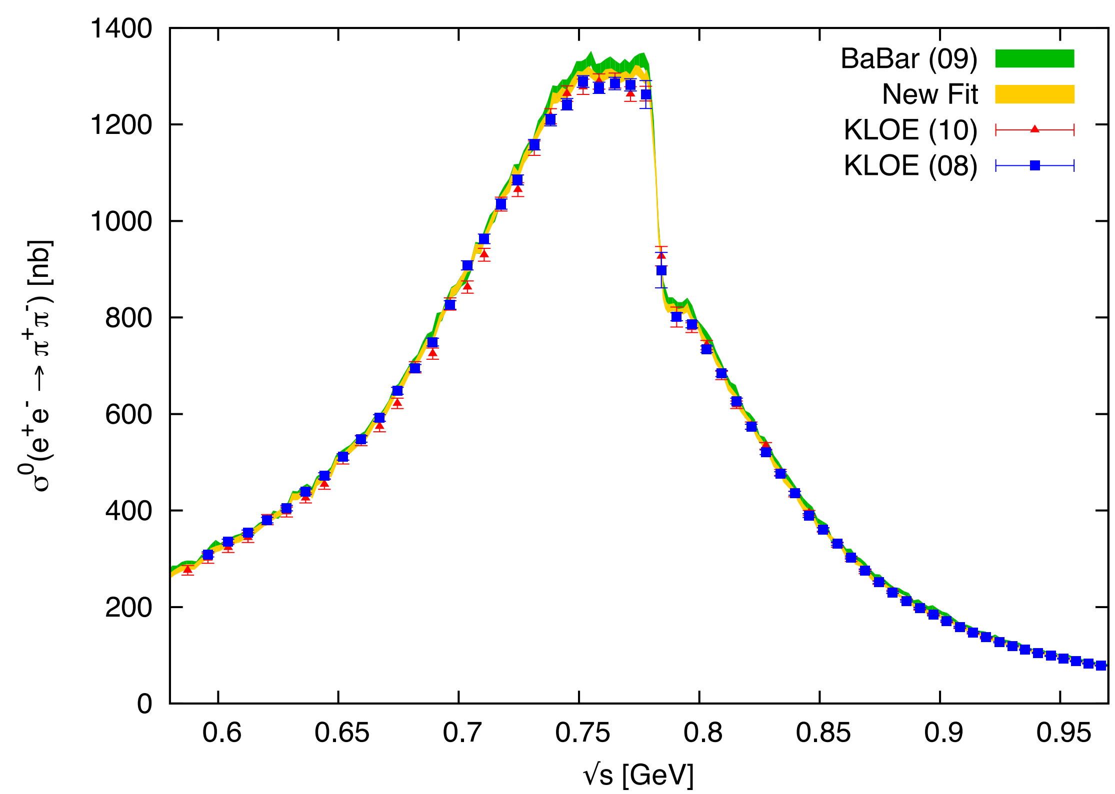
[Hagiwara,Liao,Martin,Nomura,Teubner ;Davier,Hoecker,Malaescu,Zhang]



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

$\sigma_{\mathrm{had}}(s)$: $e^+e^- \to \gamma \to$ hadrons

- K(s)/s is larger in lower energy

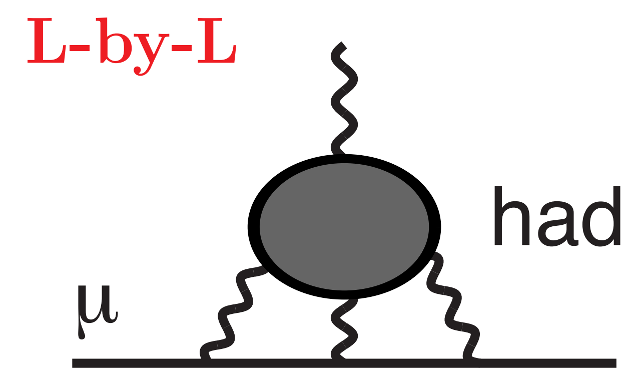


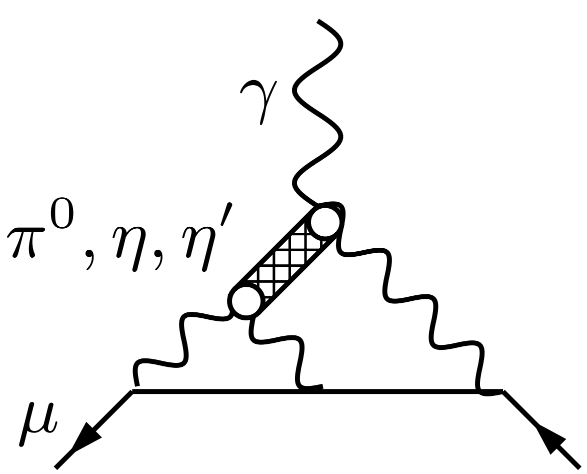
- inconsistency with τ decay data can be resolved by ρ-γ mixing [Jegerlehner,Szafron]

a_μ^{Had}: ~70% from ($e^+e^- \to$) $\gamma \to \pi^+\pi^-$

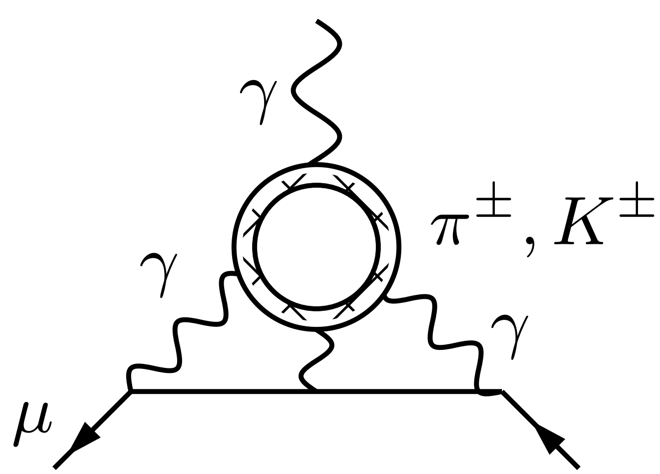
Hadronic Light-by-Light

- hadronic models/lattice required (→ Yamada-san)
- common features of models:
  - pseudo-scalar meson exchange dominates
    [π^0 gives largest contribution]
  - axial vector, scalar; $\pi^{\pm}/K^{\pm}$ loop are small
  - quark loop is small (except for Dyson-Schwinger approach)





(a) [L.D.].



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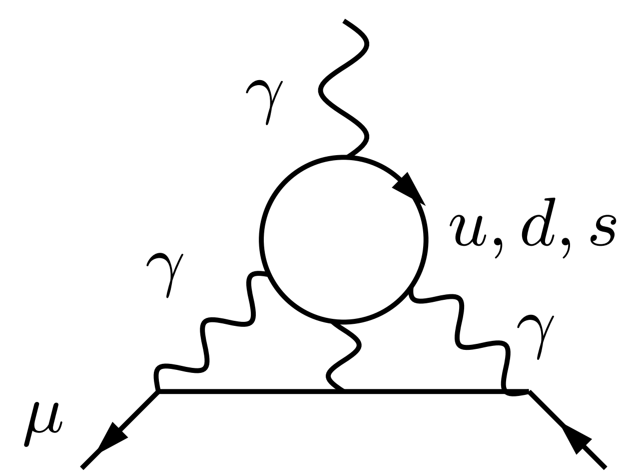
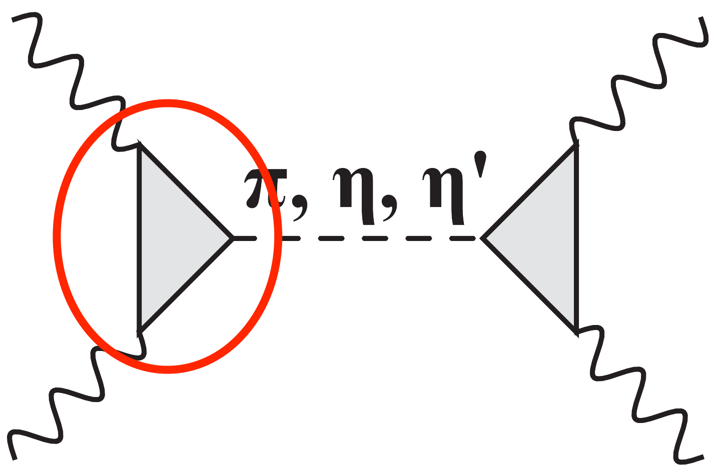


(c) [S.D.]. : p > Λ~1-2GeV

π^0 exchange

- on-/off-shell $\pi\gamma\gamma$ form factor is crucial
  - modeled with parameters in effective field approaches
  - matched to satisfy limit behaviors
  - less constrained parameters give leading uncertainty [see e.g., Nyffeler]
- lattice calculations expected [c.f. Rakow]



c.f. part of 'disconnected' contributions may be included in η' exchange, which is estimated to be sub-leading

Hadronic light-by-light scattering in the muon $g-2$: Summary

Some results for the various contributions to $a_\mu^{\mathrm{LbyL;had}} \times 10^{11}$:

Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN	FGW
π^0, η, η'	85 ± 13	82.7 ± 6.4	83 ± 12	114 ± 10	–	114 ± 13	99 ± 16	84 ± 13
axial vectors	2.5 ± 1.0	1.7 ± 1.7	–	22 ± 5	–	15 ± 10	22 ± 5	–
scalars	-6.8 ± 2.0	–	–	–	–	-7 ± 7	-7 ± 2	–
π, K loops	-19 ± 13	-4.5 ± 8.1	–	–	–	-19 ± 19	-19 ± 13	–
π, K loops $+$subl. N_C	–	–	–	0 ± 10	–	–	–	–
other	–	–	–	–	–	–	–	0 ± 20
quark loops	21 ± 3	9.7 ± 11.1	–	–	–	2.3	21 ± 3	107 ± 48
Total	83 ± 32	89.6 ± 15.4	80 ± 40	136 ± 25	110 ± 40	105 ± 26	116 ± 39	191 ± 81

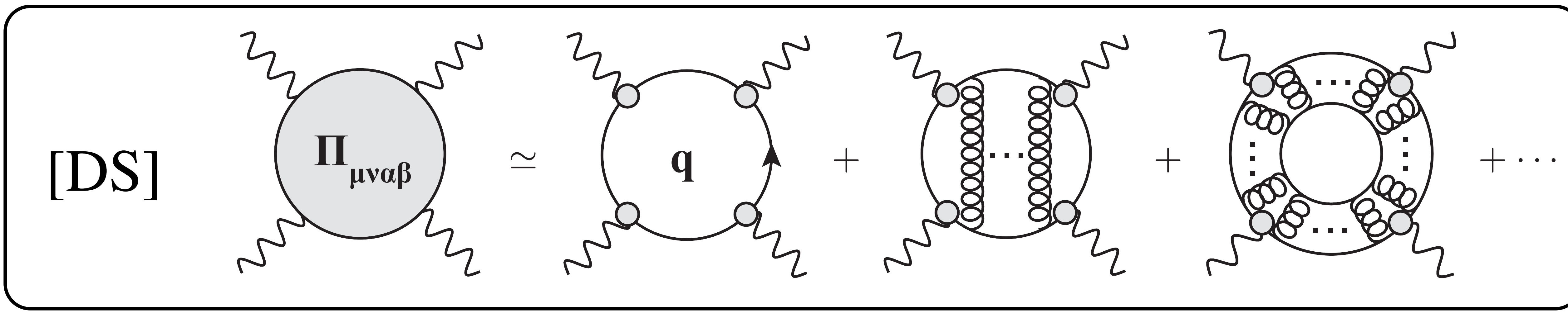
BPP = Bijnens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '98, '02; KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; BP = Bijnens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = Nyffeler '09, JN = Jegerlehner, Nyffeler '09; FGW = Fischer, Goecke, Williams '10, '11 (used values from arXiv:1009.5297v2 [hep-ph], 4 Feb 2011)

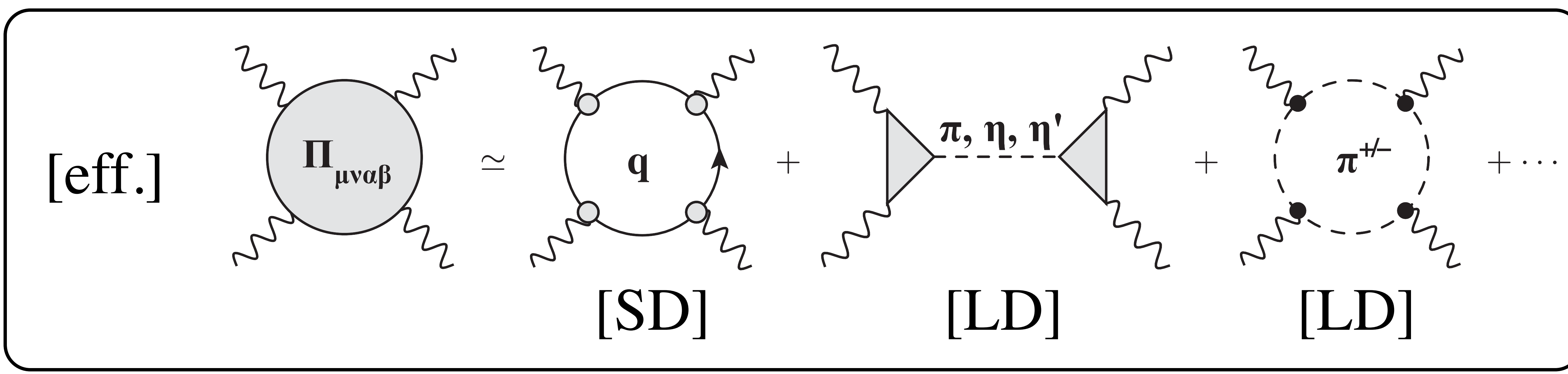
- Pseudoscalar-exchange contribution dominates numerically (except in FGW). But other contributions are not negligible. Note cancellation between π, K-loops and quark loops !
- PdRV: Do not consider dressed light quark loops as separate contribution ! Assume it is already taken into account by using short-distance constraint of MV '04 on pseudoscalar-pole contribution. Added all errors in quadrature ! Like HK(S). Too optimistic ?
- N, JN: New evaluation of pseudoscalars. Took over most values from BPP, except axial vectors from MV. Added all errors linearly. Like BPP, MV, BP, MdRR. Too pessimistic ?
- FGW: new approach with Dyson-Schwinger equations. Is there some double-counting ? Between their dressed quark loop (largely enhanced !) and the pseudoscalar exchanges.

Dyson-Schwinger

[Goecke,Fischer,Williams]

- estimation by DS and BS equations
- classified by "topology" (not by scale)





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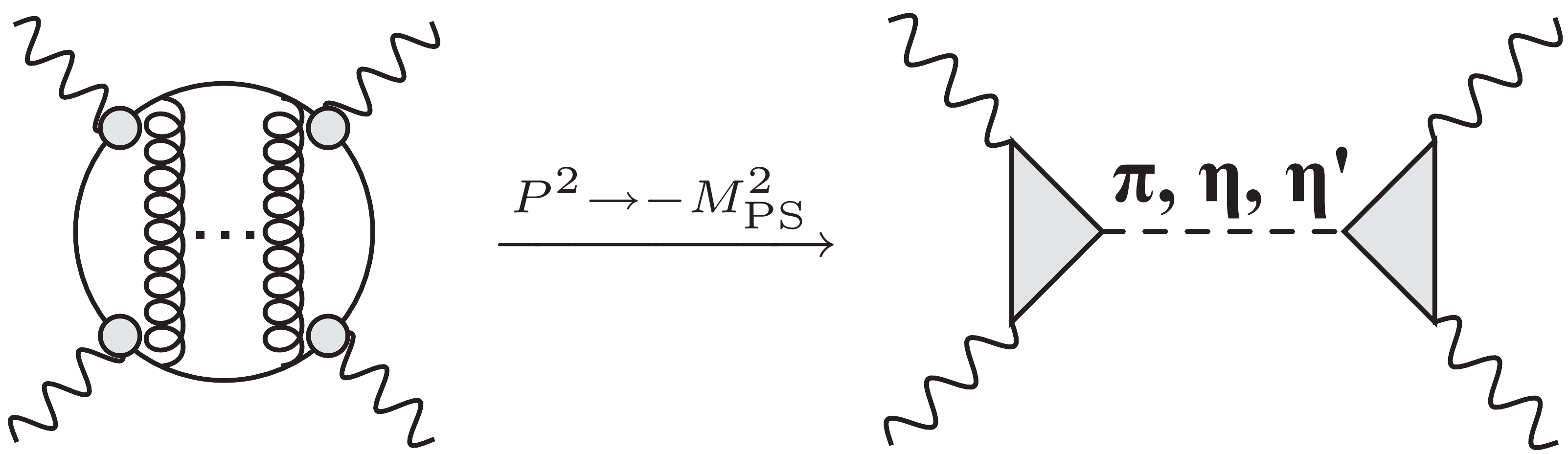

$a_\mu(\pi,\eta,\eta') = 81(12)$ $[10^{-11}]$ 99(16) [Jegerlehner,Nyffeler]

Dyson-Schwinger

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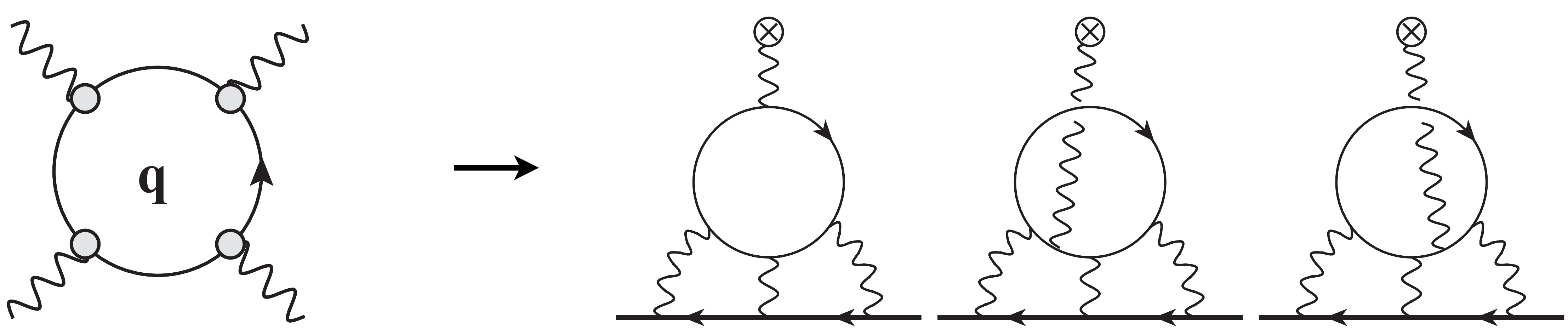
- difference stems from quark-loop contribution



a_μ(quark-loop) = 136(59) [10^{-11}] ↔ 21(3) [p > Λ=1-2GeV]

[Bijnens,Pallante,Prades]

Dyson-Schwinger

[Goecke,Fischer,Williams]

- estimation by DS and BS equations
- classified by "topology" (not by scale)
- pseudo-scalar exchange result is consistent
- difference stems from quark-loop contribution
- still under debate ($\rightarrow$ lattice):

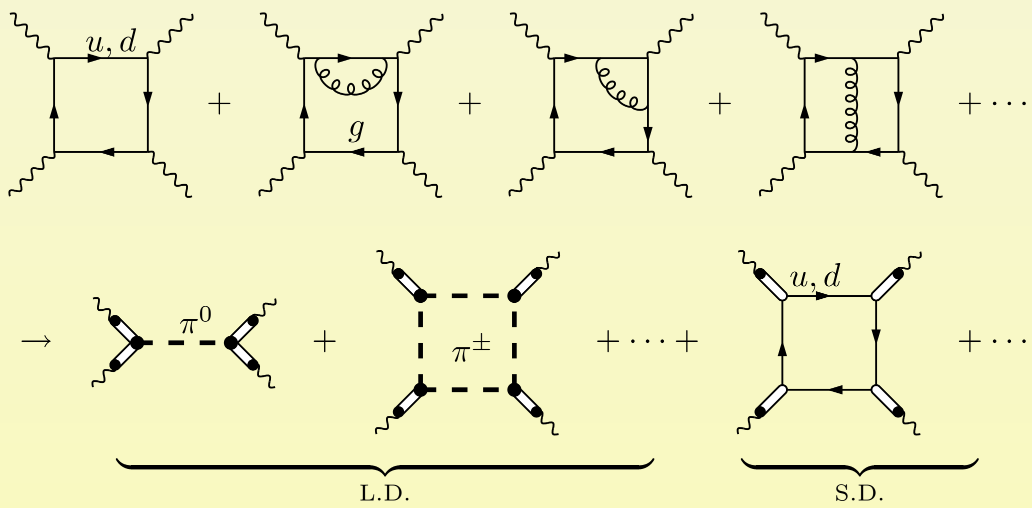
✓consistency check with vacuum polarization contribution

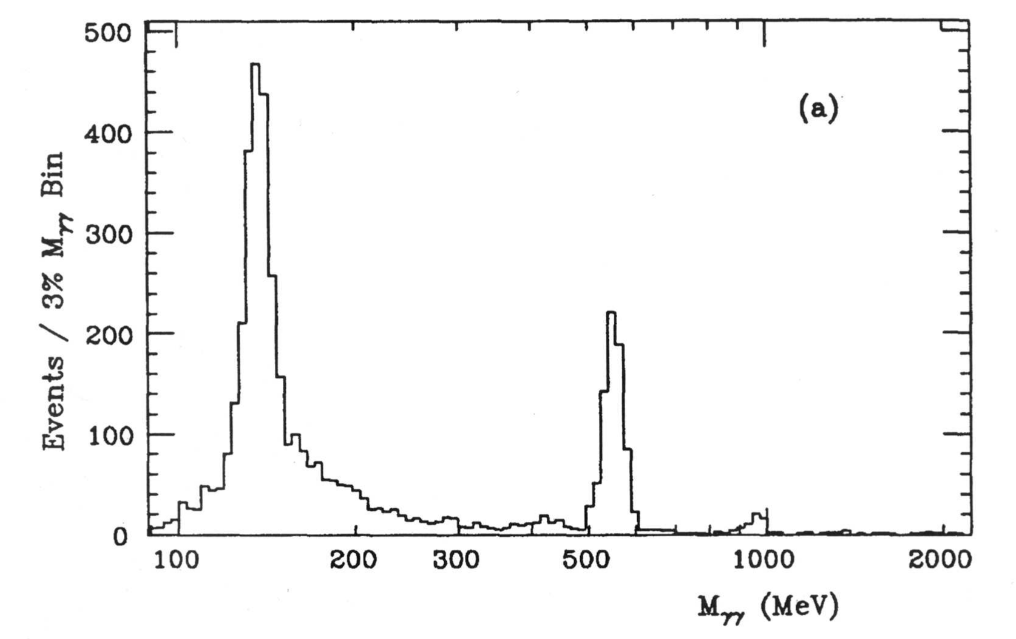
- dominated by vector-meson exchange (consistent w/ eff.)

✓inconsistencies with other constituent quark loop evals.

- quark loop at perturbative level [Boughezal,Melnikov]
- constituent chiral quark model [Greynat,Rafael]
- Crystal Ball experiment of $\gamma\gamma \rightarrow$ pseudo-scalar $\rightarrow \gamma\gamma$

Crystal Ball 1988





Data show almost background free spikes of the PS mesons! Substantial background form quark loop is absent (seems to contradict large quark-loop contribution as obtained in SDA). Clear message from data: fully non-perturbative, evidence for PS dominance. However, no information about axial mesons (Landau-Yang theorem). Illustrates how data can tell us where we are.

Low energy expansion in terms of hadronic components: theoretical models vs experimental data

➠ KLOE, KEDR, BES, BaBar, Belle, ?

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$\gtrsim 3\sigma$!

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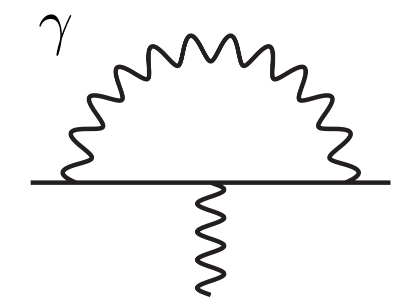
QED (α^5)		116 584 718.962	(0.08)		
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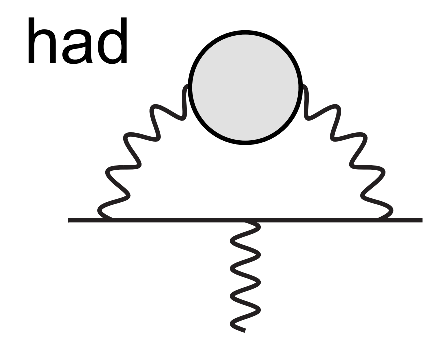
Hadronic (leading)	[HLMNT]	6 949.1	(43)*		
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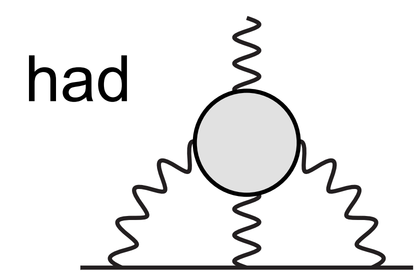
Hadronic (LbL)	[RdRV]	105	(26)*		
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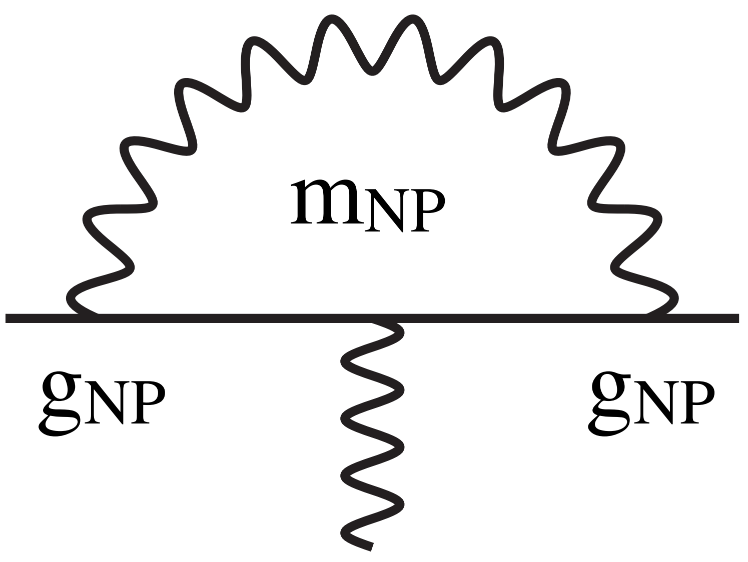
$$a_\mu^{\exp} - a_\mu^{SM} = (26.1 \pm 8.0) \cdot 10^{-10}$$

> 3σ deviation

New Physics

- challenging to explain the deviation
  - it is as large as EW contribution of SM prediction
- light new particle or large coupling
  - large coupling required for physics beyond SM in TeV scale

new particle



$$a_\mu(\mathrm{NP}) \sim \frac{\alpha_{\mathrm{NP}}}{4\pi}\frac{m_\mu^2}{m_{\mathrm{NP}}^2} \longleftrightarrow a_\mu(\mathrm{EW}) \sim \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{m_W^2}$$

note: muon mass dependence due to chirality flip

Large coupling: SUSY

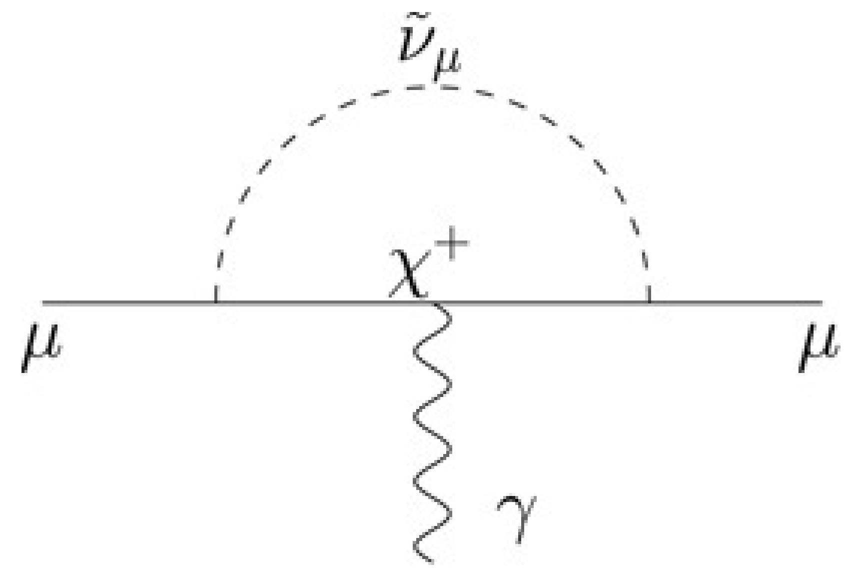
- muon g-2 is enhanced
  - small soft mass
  - large tanβ

$$\Delta a_\mu \sim \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{m_{\rm soft}^2}\tan\beta$$

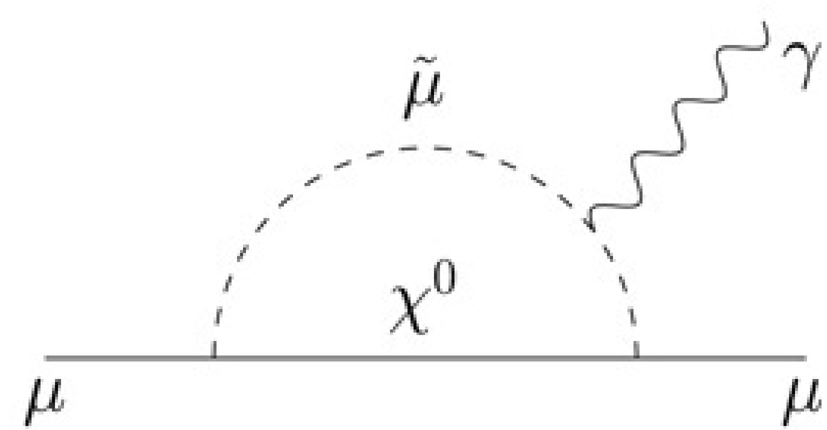
$\tan\beta = v_u/v_d = O(1\text{-}10)$

- tension against Higgs mass

⟶ Today's Topic



chargino-sneutrino



neutralino-smuon

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- Higgs result: Higgs mass ~ 125GeV
- Hints of physics beyond SM
  - muon g-2 has ≳3σ deviation
- SUSY models: Higgs mass and muon g-2
  - GMSB extensions w/. vector-like matter
- Summary

SUSY is natural

- Hints of New Physics

SUSY

- neutrino oscillation		
- early universe (e.g. DM)	→	LSP (χ_1^0 or $\psi_{3/2}$) scalars
- hierarchy problem	→	solved
- GUT	→	unification
- muon g-2	→	natural

$$\Delta a_\mu(\chi^\pm) \simeq \frac{\alpha_2 m_\mu^2}{8\pi m_{\rm soft}^2} {\rm sgn}(M_2\mu) \boxed{\tan\beta}$$

SUSY is natural

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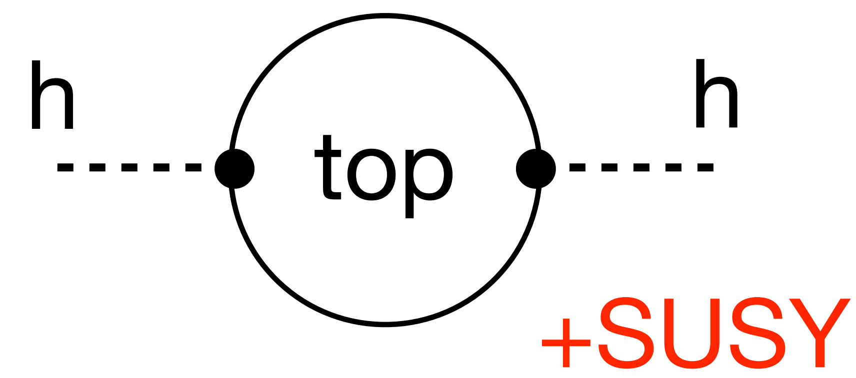
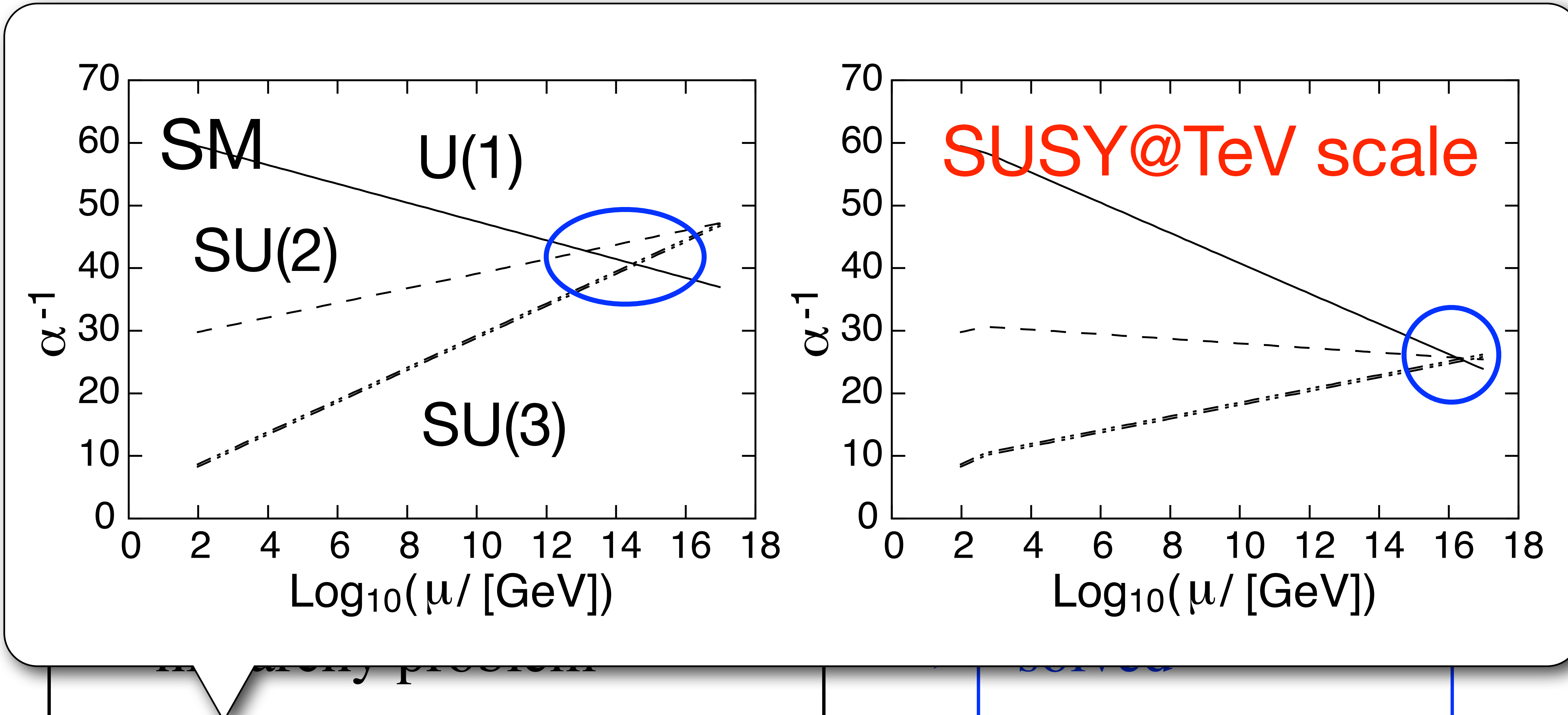


$$m_H^2 = m_H^2(\text{tree}) + \Delta m_H^2$$

$$\Delta m_H^2 \sim \frac{Y_t^2}{16\pi^2}\Lambda_{\text{cut}}^2$$

$$\Delta a_\mu(\chi^\pm) \simeq \frac{\alpha_2 m_\mu^2}{8\pi m_{\text{soft}}^2}\text{sgn}(M_2\mu)\boxed{\tan\beta}$$



- GUT → unification
- muon g-2 → natural

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SUSY

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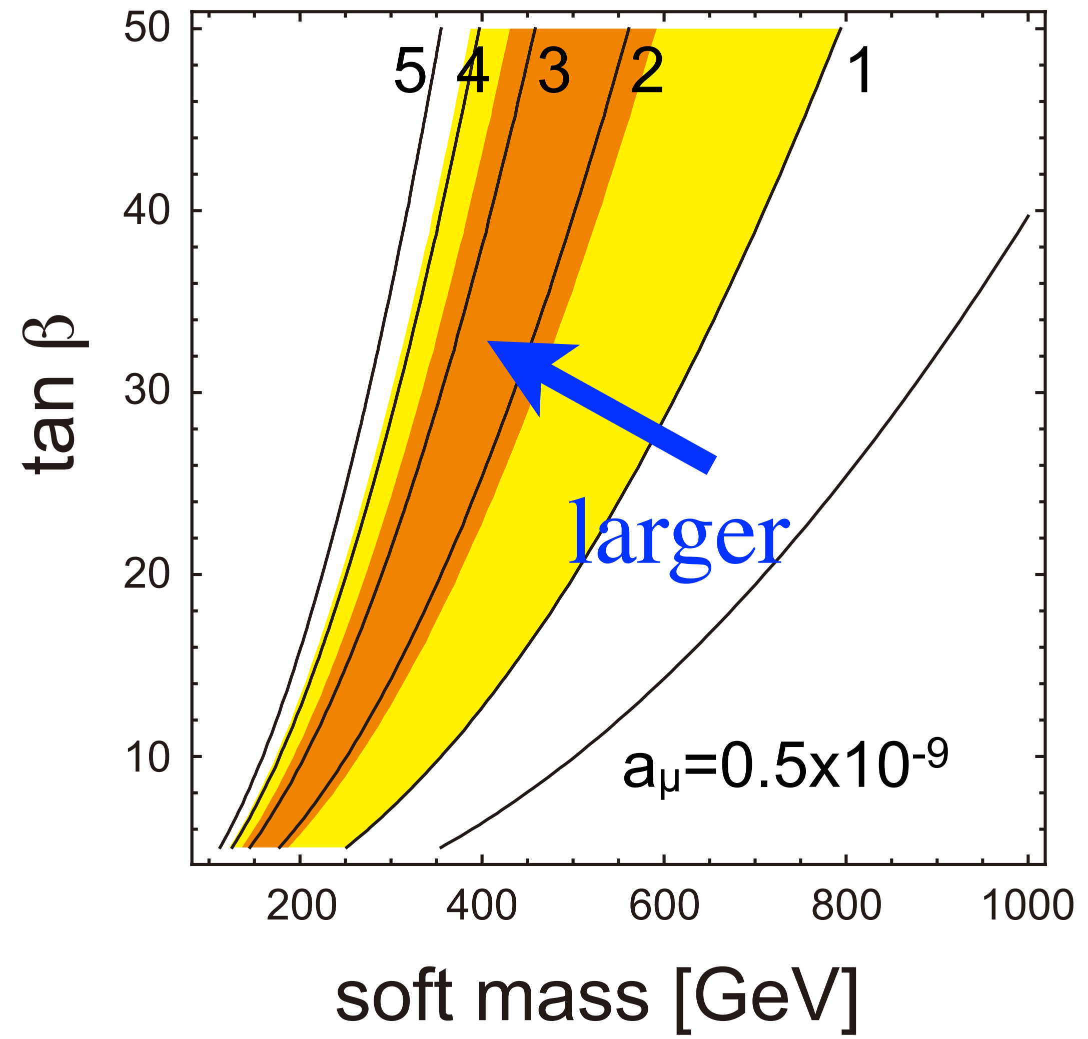
What is unnatural?

- Flavor/CP violations
  - scalar fermion mass, scalar trilinear coupling, μ
  - constraints: K, B, D, μLFV, τLFV, EDM's,...
- Cosmological gravitino problems
  - gravitino production depends on T_R and E_{inf}
  - constraints: BBN, DM abundance
- Tension between Higgs mass ~125GeV & muon g-2

Higgs mass and muon g-2

- enhance muon g-2:
  - small soft mass
  - large tanβ
- enhance Higgs mass:
  - large soft mass
  - large A_t term

$$\Delta a_\mu \sim \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{m_{\rm soft}^2}\tan\beta$$



Higgs mass and muon g-2

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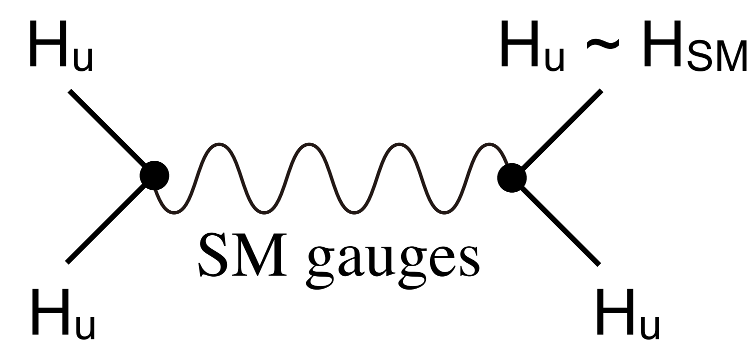
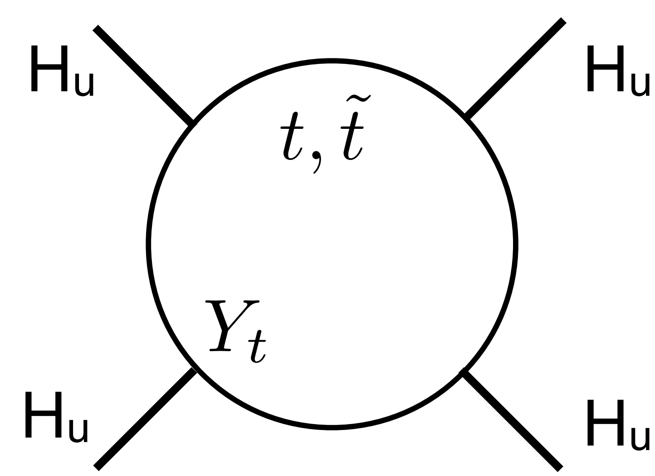
- enhance Higgs mass:
  - large soft mass
  - large A_t term

[tree level]

$$m_h^{(\mathrm{tree})} \leq M_Z \quad (\leftrightarrow 125\mathrm{GeV})$$



[radiative corrections]



$$\Delta m_h \sim \frac{3m_t^4}{2\pi^2 v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \left(\frac{A_t^2}{m_{\tilde{t}}^2} - \frac{1}{12}\frac{A_t^4}{m_{\tilde{t}}^4}\right)\right]$$

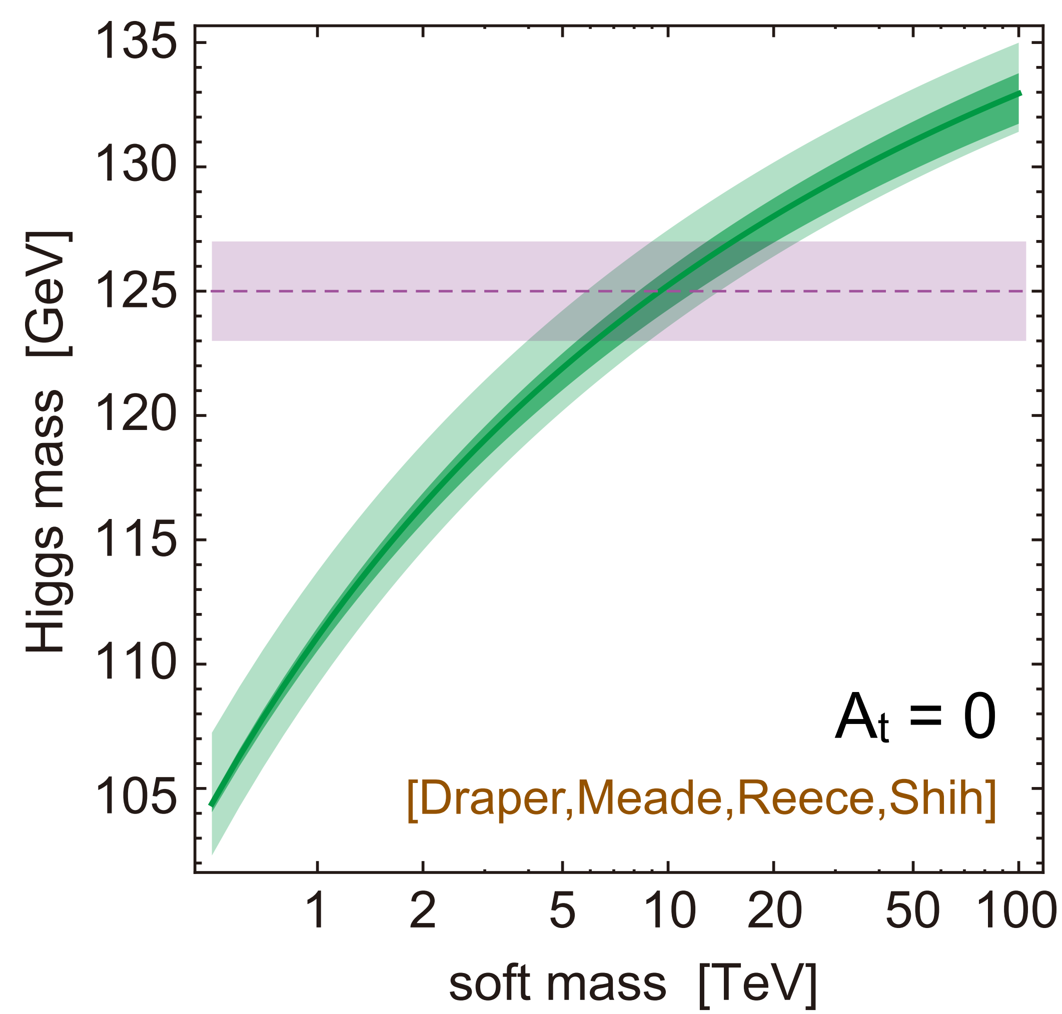
where $\mathcal{L} = -Y_t A_t H_u^0 \tilde{t}_L^* \tilde{t}_R$

Higgs mass and muon g-2

- enhance muon g-2:
  - small soft mass
  - large tanβ
- enhance Higgs mass:
  - large soft mass
  - large A_t term

[large scalar top mass]

$$\Delta m_h \sim \frac{3m_t^4}{2\pi^2 v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \left(\frac{A_t^2}{m_{\tilde{t}}^2} - \frac{1}{12}\frac{A_t^4}{m_{\tilde{t}}^4}\right)\right]$$



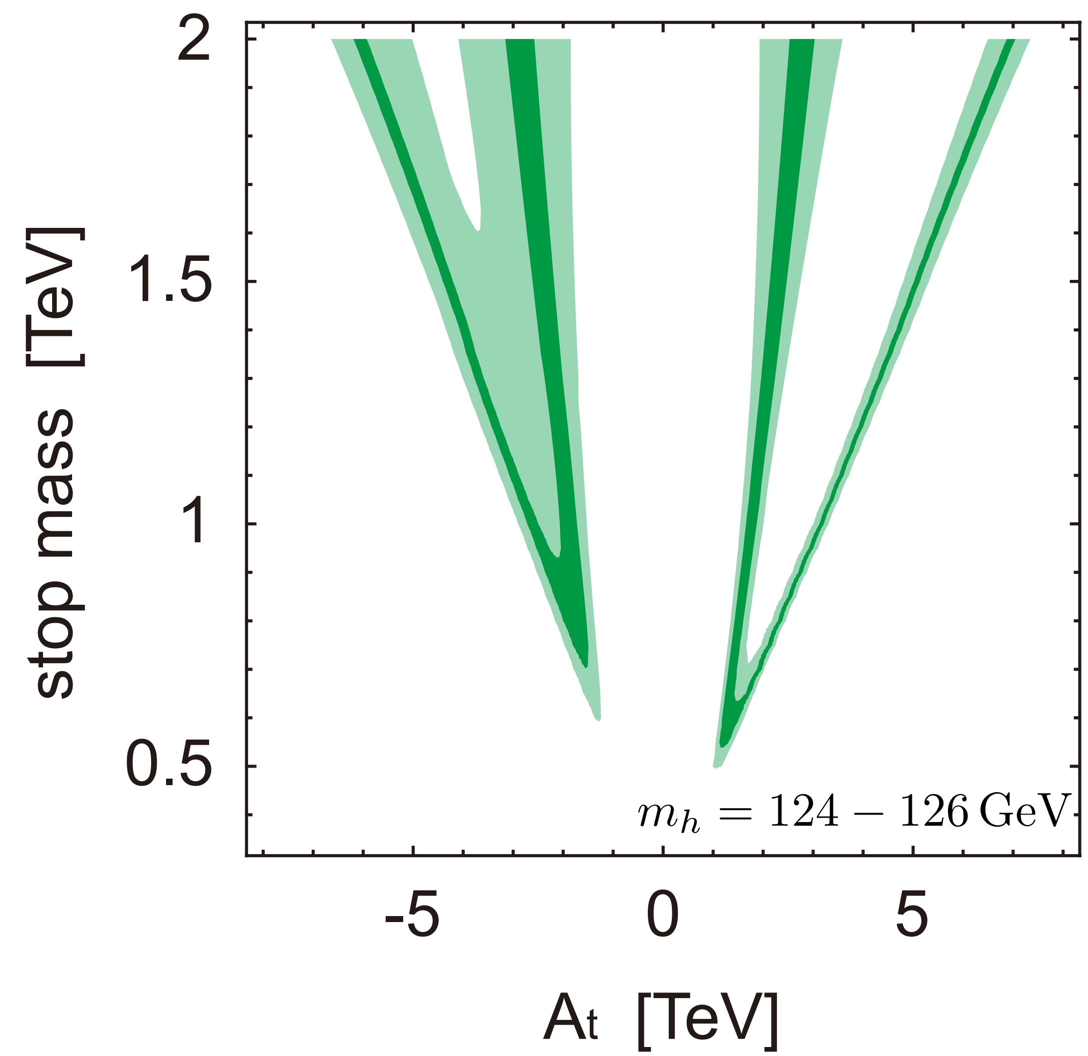
Higgs mass and muon g-2

- enhance muon g-2:
  - small soft mass
  - large tanβ
- enhance Higgs mass:
  - large soft mass
  - large A_t term

focus on soft mass scale
→ tension!!

[large A_t term]

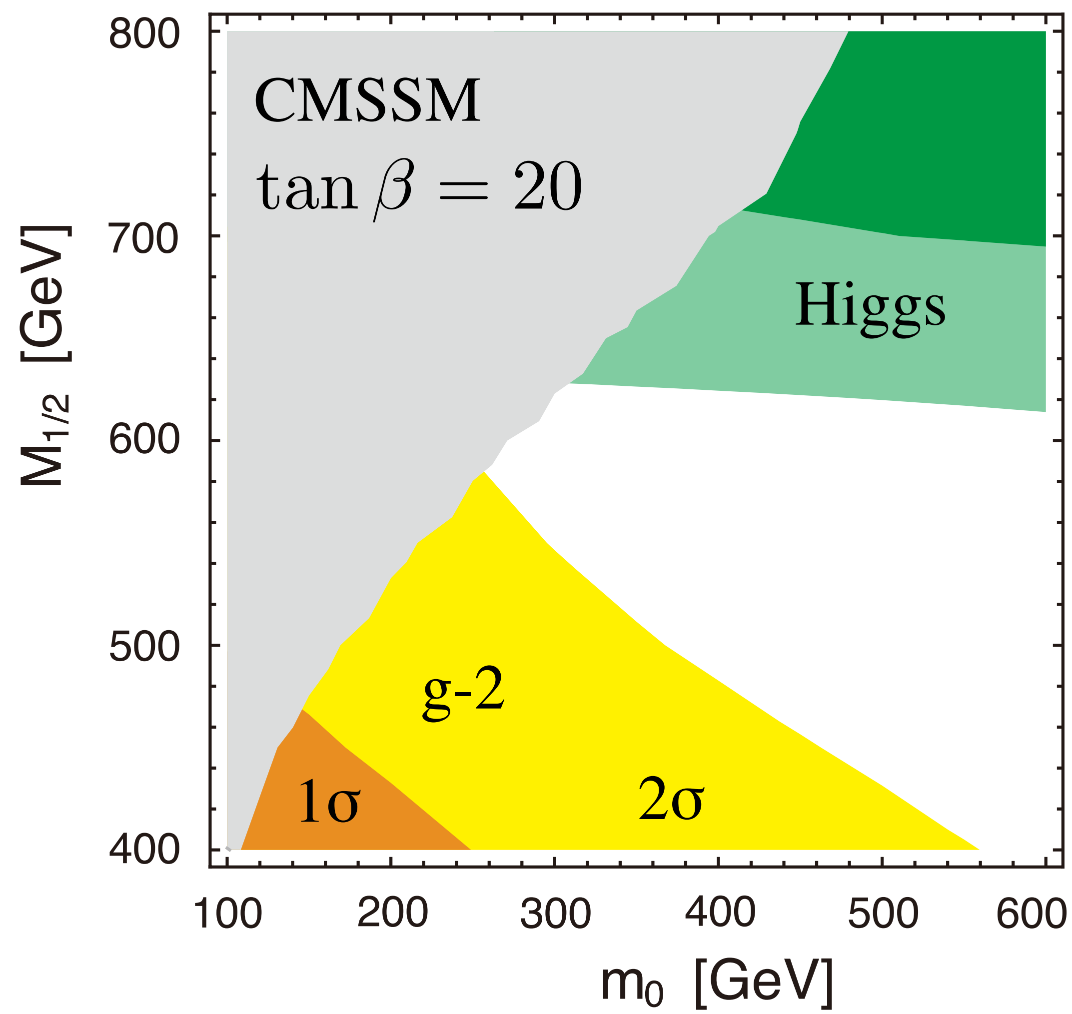
$$\Delta m_h \sim \frac{3m_t^4}{2\pi^2 v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \left(\frac{A_t^2}{m_{\tilde{t}}^2} - \frac{1}{12}\frac{A_t^4}{m_{\tilde{t}}^4}\right)\right]$$



Tension

- enhance muon g-2:
  - small soft mass ←
  - large tanβ
- enhance Higgs mass:
  - large soft mass ←
  - large A_t term

focus on soft mass scale
→ tension!!



m_h >124GeV + error

[Higgs maximized by A_t w/ Br(b → sγ)@2σ]

m_h~125GeV is too large for muon g-2 in mSUGRA

What is unnatural?

- Flavor/CP violations
  - scalar fermion mass, scalar trilinear coupling, μ
  - constraints: K, B, D, μLFV, τLFV, EDM's,...
- Cosmological gravitino problems
  - gravitino production depends on T_R and E_{inf}
  - constraints: BBN, DM abundance
- Tension between Higgs mass ~125GeV & muon g-2

soft mass is large

soft mass is small

Simple Approaches

Model	Flavor/CP	gravitino problems	Higgs mass	muon g-2	dark matter
mSUGRA	fine-tuning	severe limit	tension		neutralino
large soft masses	suppressed	OK	OK	hopeless	neutralino
GMSB	suppressed	OK	too small	OK	gravitino

Simple Approaches

Model	Flavor/CP	gravitino problems	Higgs mass	muon g-2	dark matter
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large soft masses	suppressed	OK	OK	hopeless	neutralino
GMSB	suppressed	OK	too small	OK	gravitino
extended GMSB			"OK"	OK	

Extended GMSB

- large A_t term [Evans,Ibe,Yanagida;Evans,Ibe,Shirai,Yanagida ;ME,Hamaguchi,Iwamoto,Yokozaki]
  - messenger-top coupling
- extra vector-like matter [ME,Hamaguchi,Iwamoto,Yokozaki ;Evans,Ibe,Yangida;Martin,Wells]
  - t' coupling with Higgs [Asano,Moroi,Sato,Yanagida;Moroi, Sato,Yanagida;Nakayama,Yokozaki]
- extra gauge symmetry [ME,Hamaguchi,Iwamoto,Nakayama ,Yokozaki]
  - Z' and a charge for Higgs

- singlet Higgs: Higgs mass enhanced when tanβ is small
- triplet Higgs: may spoil perturbative GUT
- ...

Extra Vector-like Matter

[Moroi,Okada]

- introduce 10 + $\overline{10}$ [10:(Q’,U’,E’)]
- extra ‘top’ couples to Higgs

$$W = Y' H_u Q' U' + M'(Q'\bar{Q}' + U'\bar{U}')$$

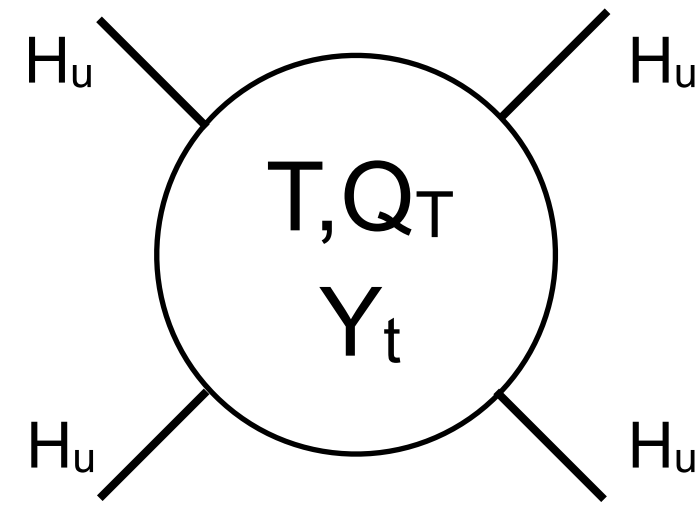
- Higgs mass raised by U’, Q’ loop

$$\Delta m_h \simeq \frac{3v^2}{4\pi^2} Y'^4 \ln \frac{m_S^2}{m_F^2} + \dots$$

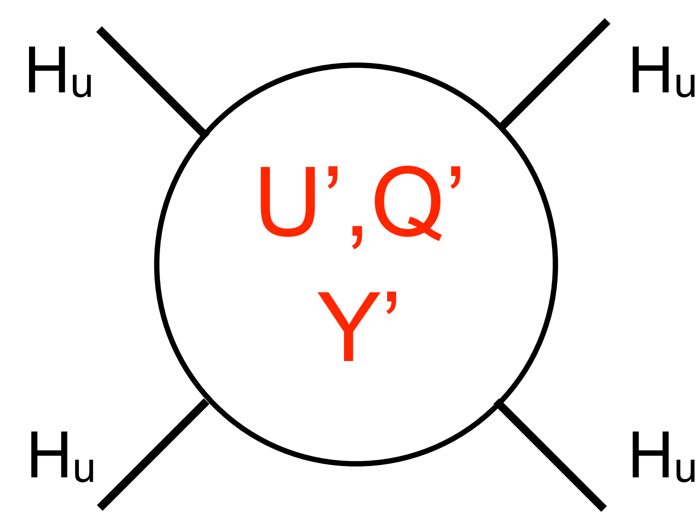
$m_{S(F)}$: vector scalar(fermion) mass

cf. A’ suppressed by RG running and irrelevant for Higgs mass. “mh-max” scenario is not realized

MSSM



vector



Extra Vector-like Matter

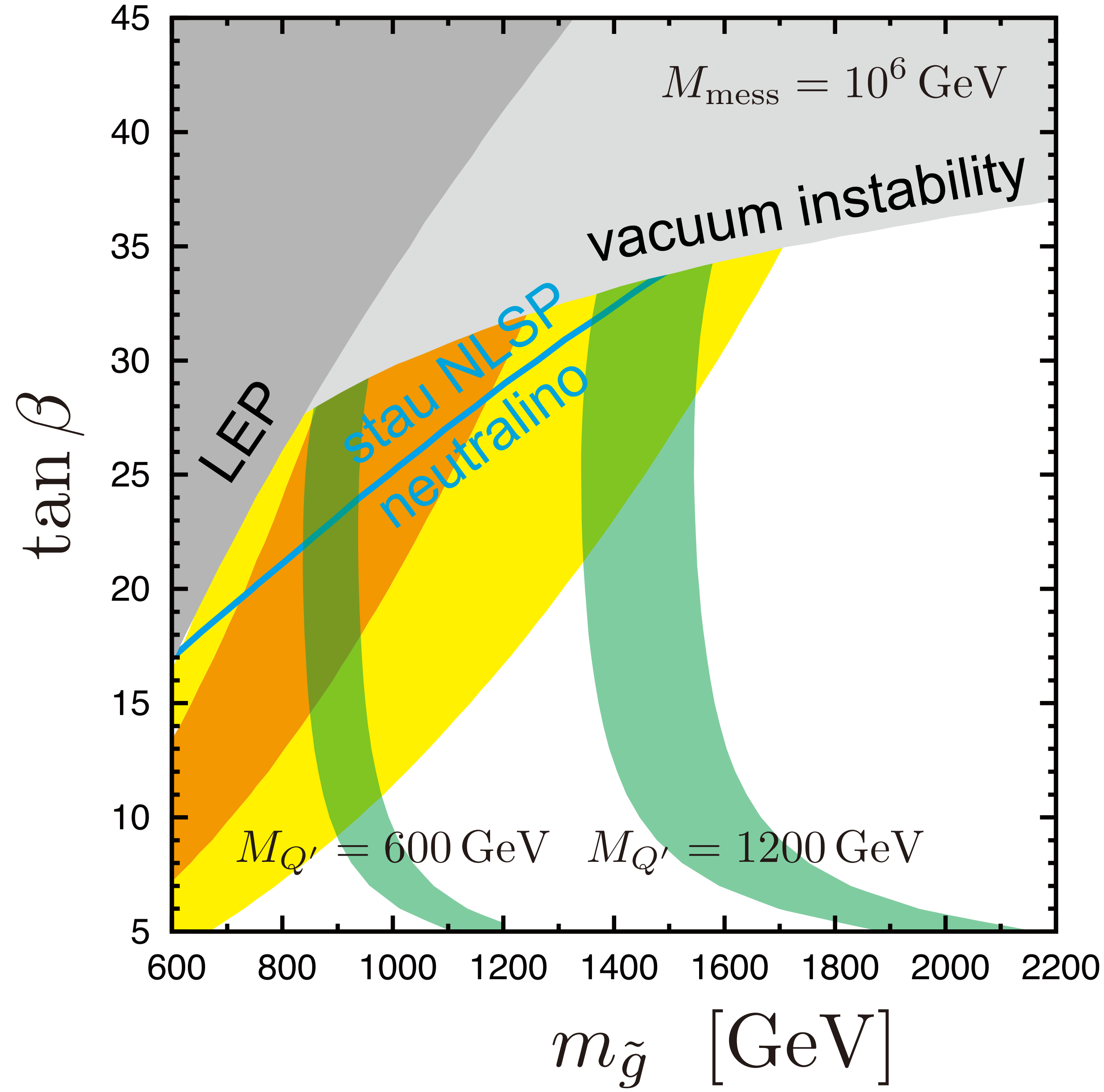
- muon g-2 is accommodated to Higgs mass ~125GeV
- upper bound on gluino mass from muon g-2 and stability

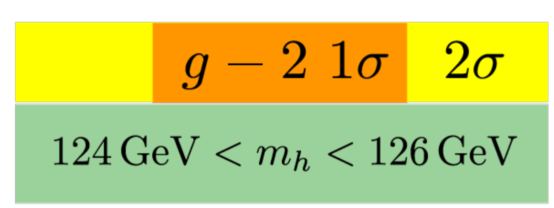
$$m_{\tilde{g}} \lesssim 1.7\,\mathrm{TeV}\ \ (2\sigma; \tilde{\chi}^0)$$

- upper bound on vector mass from Higgs mass

$$M_{U',Q'} \lesssim 1.5\,\mathrm{TeV}$$

$\longrightarrow$ LHC search!





[ME,Hamaguchi,Iwamoto,Yokozaki]

Extra Vector-like Matter

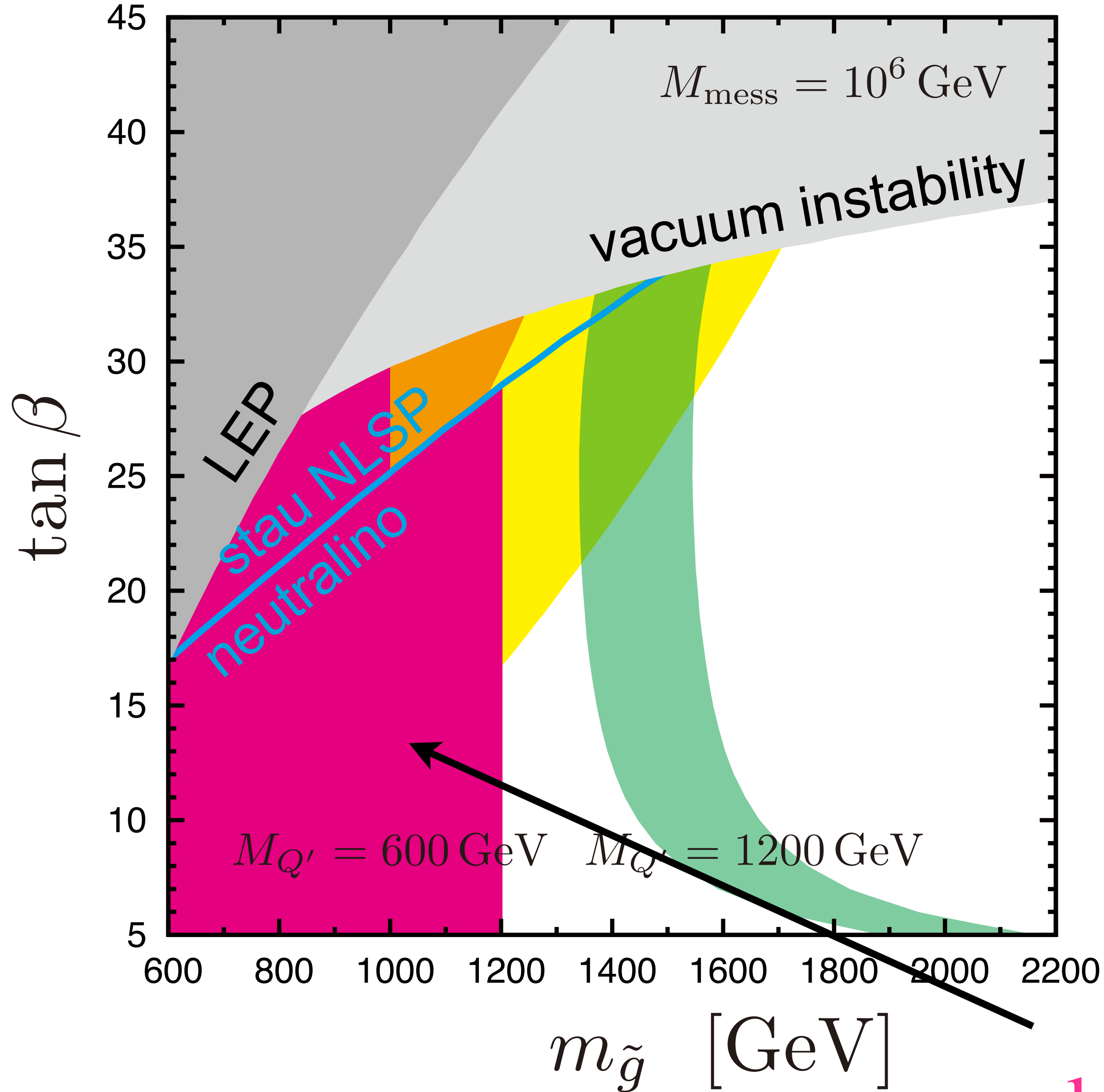
- current LHC bounds
  - blue: low background, easy to detect
  - red: usual SUSY signals

NLSP	prompt decay (low messenger scale)	long-lived (higher messenger scale)
neutralino	$2\gamma + E_{T\text{miss}}$ $m_{\tilde{g}} \gtrsim 1.2\,\text{TeV}$	jets + $E_{T\text{miss}}$ $m_{\tilde{g}} \gtrsim 0.9\,\text{TeV}$
stau	jets + leptons + $E_{T\text{miss}}$ $m_{\tilde{g}} \gtrsim 1.0\,\text{TeV}$	heavy charge track $m_{\tilde{\tau}} \gtrsim 297\,\text{GeV}$

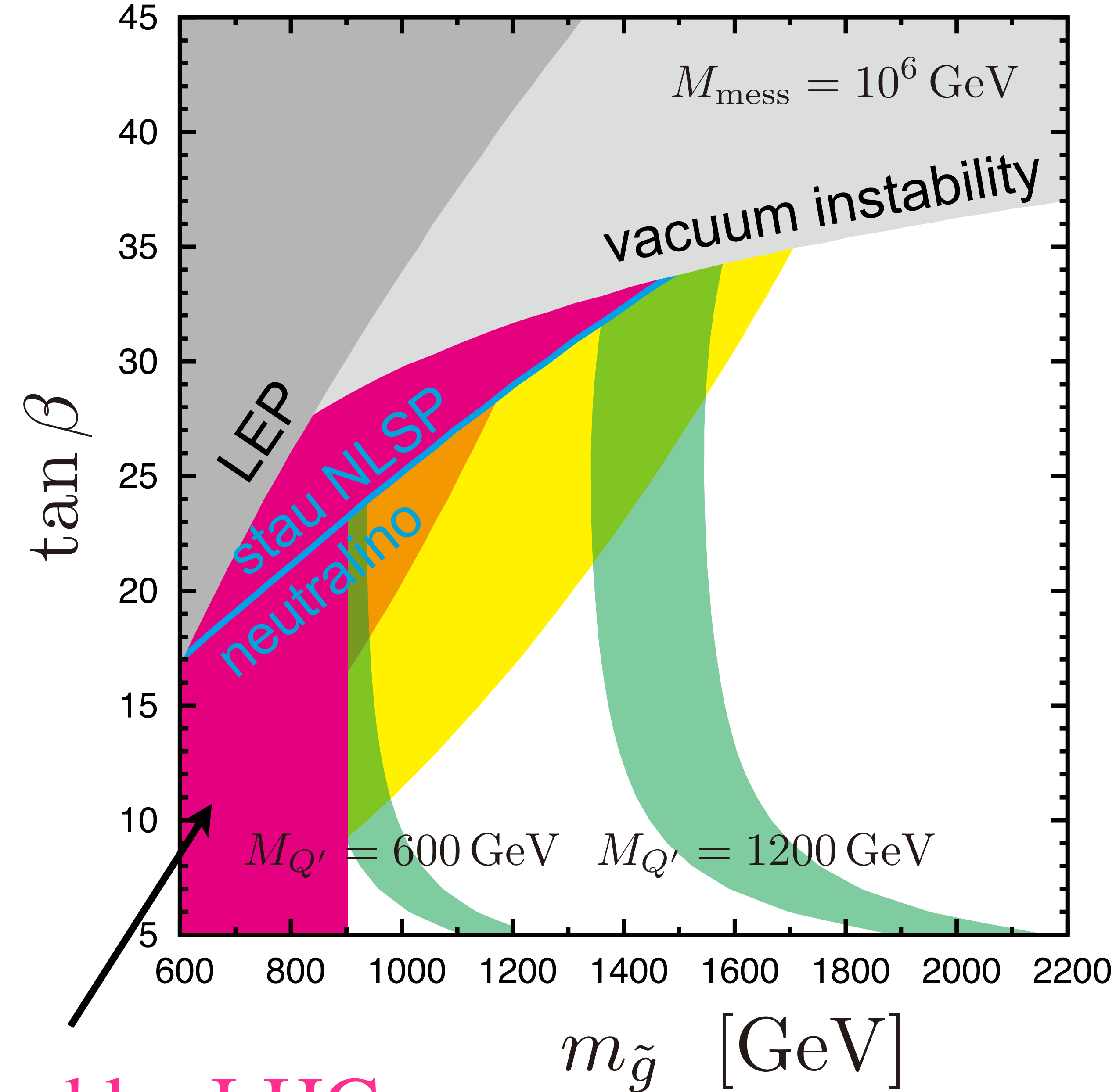
* recent multi-lepton

Extra Vector-like Matter

NLSP: prompt decay



NLSP: long-lived

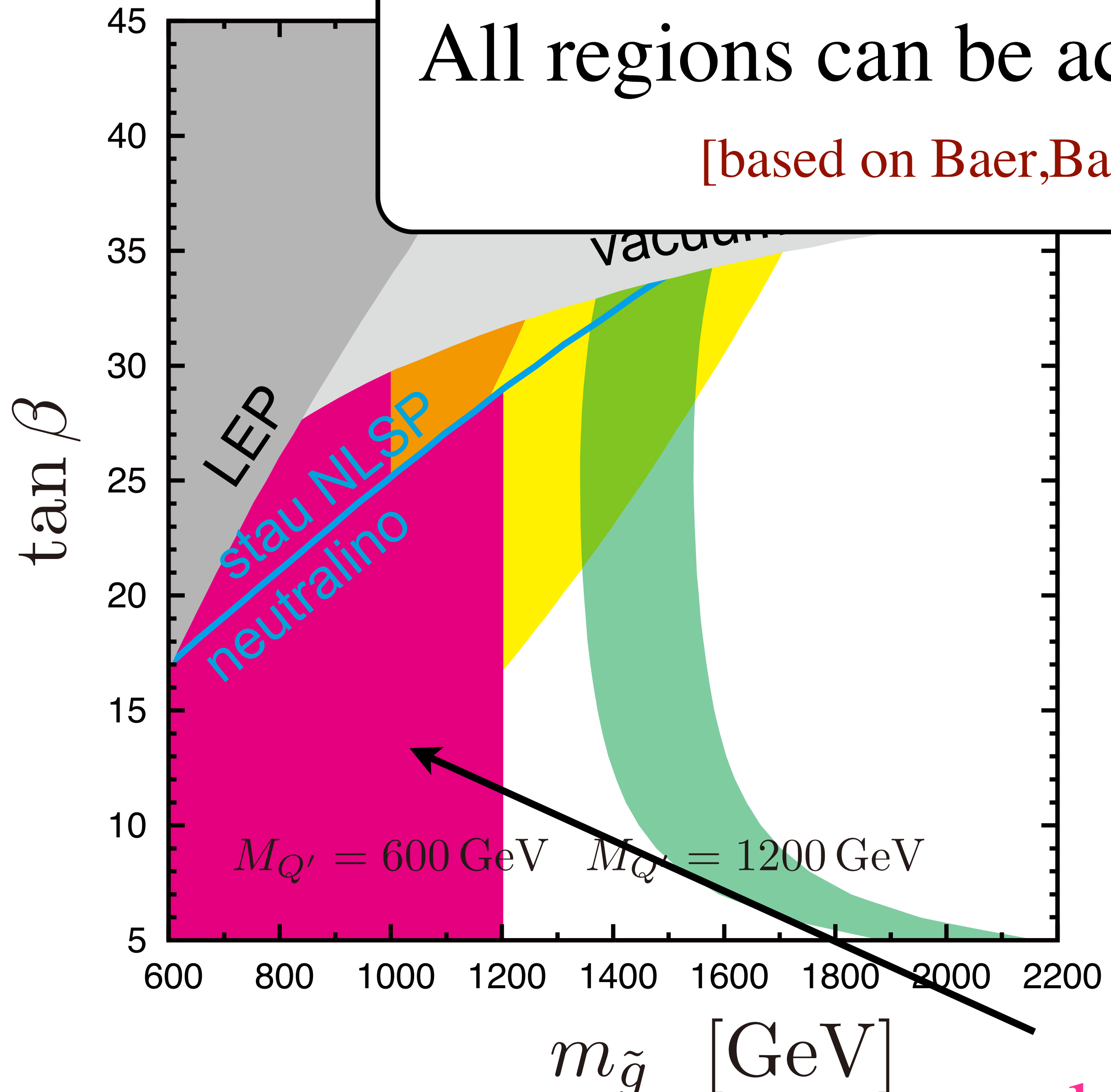


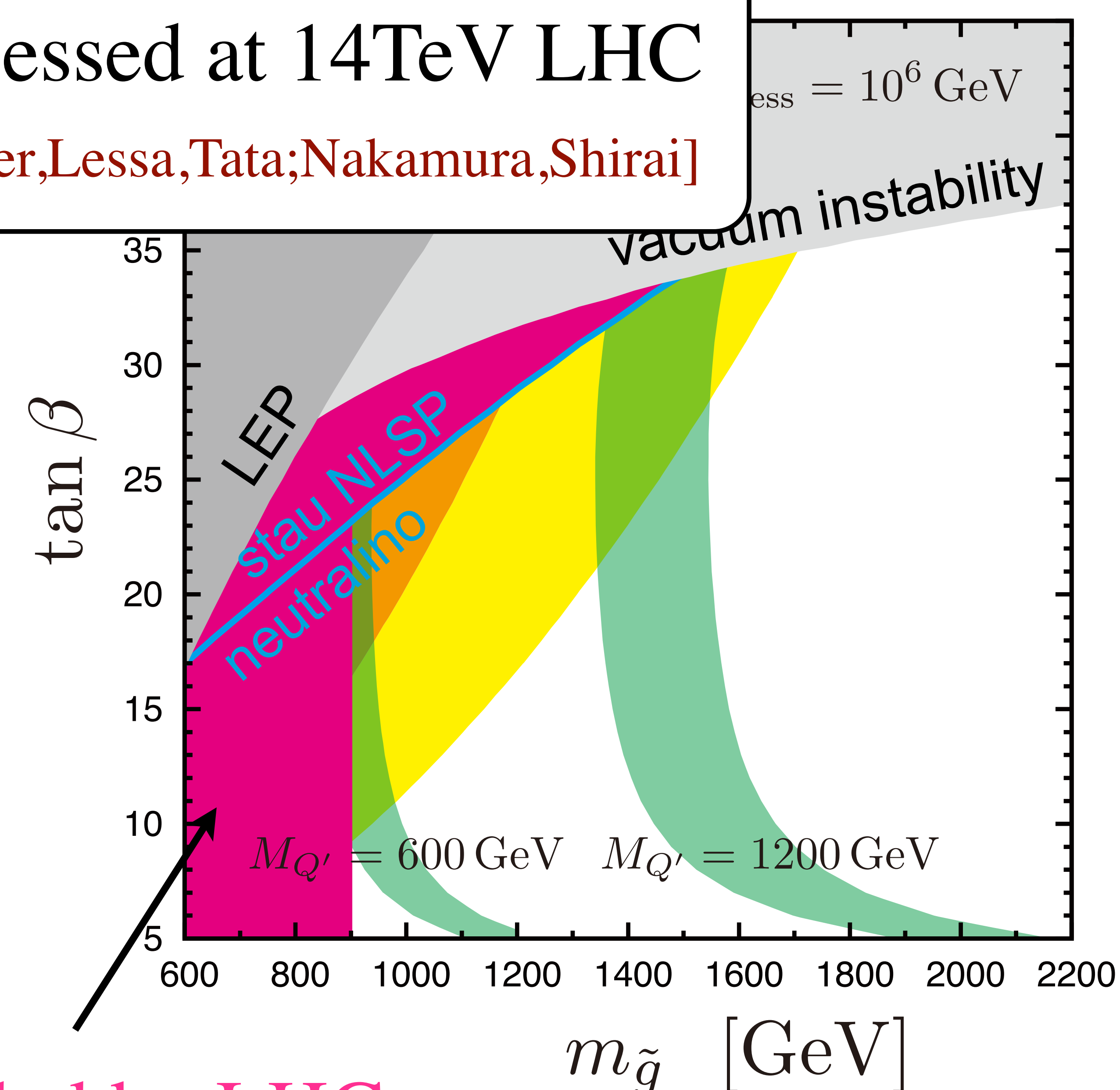
excluded by LHC

Extra Vector-like Matter

NLSP: prompt decay

NLSP: long-lived





All regions can be accessed at 14TeV LHC

[based on Baer,Barger,Lessa,Tata;Nakamura,Shirai]

excluded by LHC

t' mixing with SM matters

- stable extra matters spoil cosmology ("matter" parity can be assigned)
- weak mixing with SM matters
  - extra matter searches
    - LHC, Tevatron
  - Flavor and CP violations
    - similar to 4th generations
    - interesting to see EDM, B decays, ...

current bounds [LHC,TVT]

$$t' \to bW : \; m_{t'} > 557\,\text{GeV}$$
$$t' \to d_i W : \; m_{t'} > 340\,\text{GeV}$$
$$t' \to tZ : \; m_{t'} > 475\,\text{GeV}$$
$$t' \to u_i Z : \; \text{No bound}$$
$$t' \to th : \; \text{No bound}$$
$$t' \to u_i h : \; \text{No bound}$$

* no (detailed) studies on future sensitivity

Comparison of Models

Model	Flavor/CP	gravitino problems	Higgs mass muon g-2	dark matter	GUT (perturbative)
mSUGRA	fine-tuning	severe limit	tension	neutralino	OK
large soft masses	suppressed	OK	too small muon g-2	neutralino	OK
GMSB	suppressed	OK	too small Higgs mass	gravitino	OK
GMSB +vector-like matter	weakly violated	OK	OK	gravitino	OK

LHC searches for SUSY, extra matters

Summary

- Extended GMSB is implied by
  - low energy phenomena and cosmology
  - Higgs mass of ~125GeV & muon g-2
- GMSB + vector-like matters
- SUSY particle masses are in reach of LHC
- relatively light extra matters are expected
- LHC search is interesting!!