A Variant Two-Higgs Doublet Model with A New Abelian Gauge Symmetry

Chuan-Ren Chen
(NTNU)

12/13/2019 @ NCTS Annual Theory Meeting 2019

CRC, Cheng-Wei Chiang, Kuo-Yen Lin, PLB795 (2019), 22

Outline

Motivation

muon g-2 & dark matter

Benchmark Model

4^{th} generation lepton, singlet scalar and U(1) extension

Constraints

charged lepton decays, Z-boson flavor-changing decay

Dark Matter Phenomenology

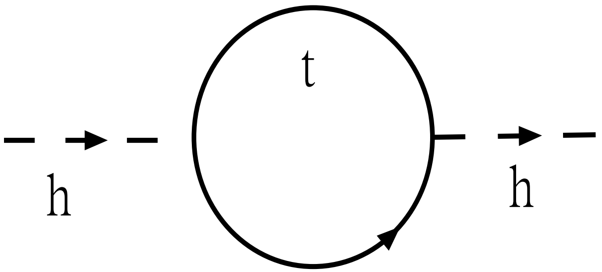
relic density, elastic scattering w/ nucleon

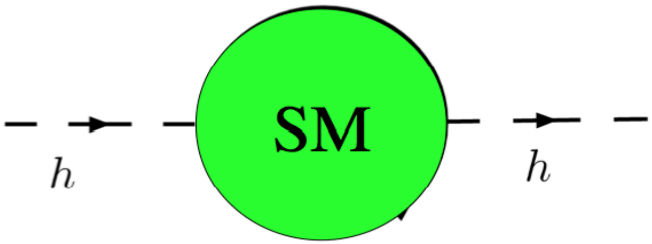
Summary

BSM?

Naturalness "Problem"

$$m_h^2 = m_{h0}^2 + \delta m_h^2$$





Λ^2 terms are canceled !!

BSM → new particles

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 [illegible]	–	[illegible]	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	[illegible]	[illegible]	[illegible]	Λ 40.0 TeV	η_{LL}^-	1707.02424
	CI $tttt$	≥ 1 e, μ	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3} T_{5/3} \lvert T_{5/3} \to Wt + X$	2(SS)/≥ 3 e, μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e, μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

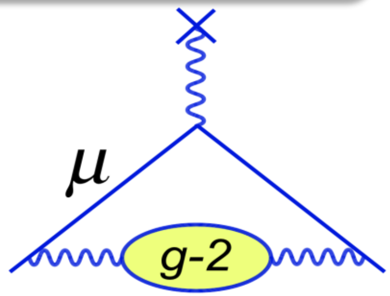
10^{-1} 1 10 Mass scale [TeV]

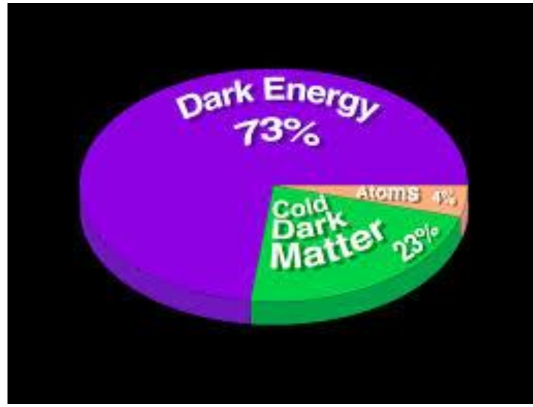
Where is BSM ??

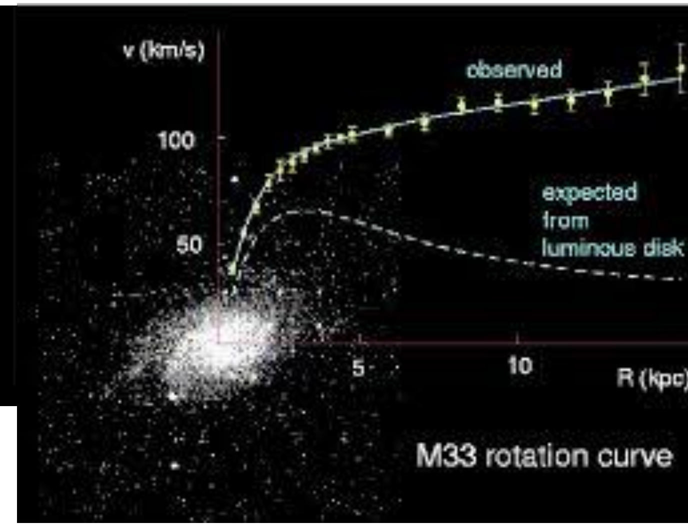
*Only a selection of the available mass limits on new states or phenomena is shown.

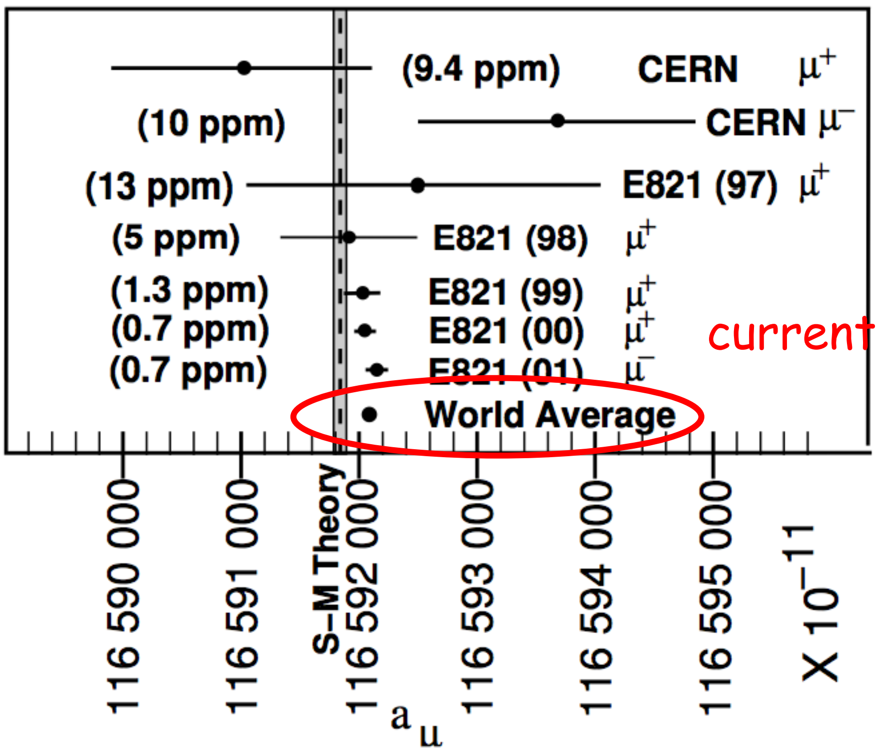
†Small-radius (large-radius) jets are denoted by the letter j (J).

BSM Here(?)

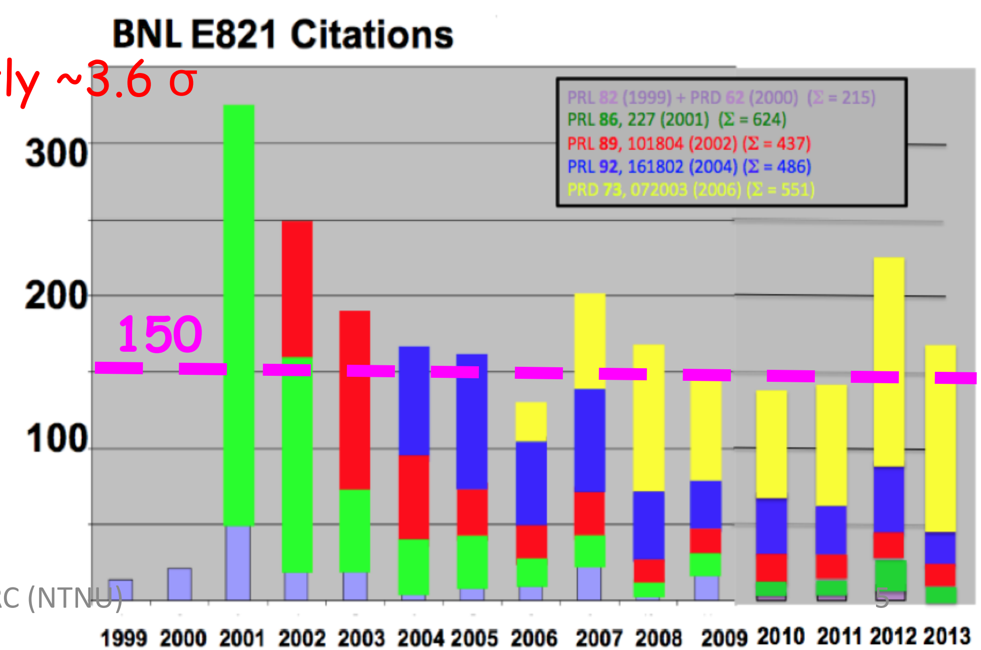








currently ~3.6 σ

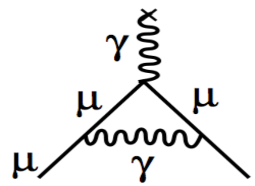


projected > 7 σ ,
if central values of both TH and EXP remain

muon g-2

$$\vec{\mu}_\ell = g_\ell \frac{Qe}{2m_\ell}\vec{s}, \qquad \underbrace{g_\ell = 2}_{\text{Dirac}}(1 + a_\ell), \qquad a_\ell = \frac{g_\ell - 2}{2}$$

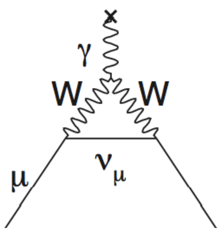
$$a^{SM} = a^{QED} + a^{Had} + a^{Weak}$$

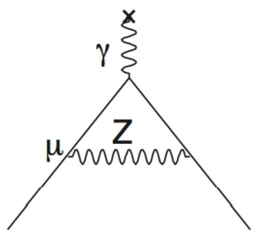


$+ \cdots$

$$a_\mu^{\rm QED} = 116\ 584\ 718.951\ (0.009)(0.019)(0.007)(.077) \times 10^{-11}$$

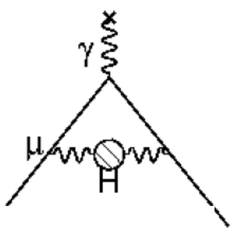
Aoyama, Hayakawa, Kinoshita and Nio, PRL109(2012),111808





$$a_\mu^{\rm EW} = (153.6 \pm 1.0) \times 10^{-11}$$

Miller, de



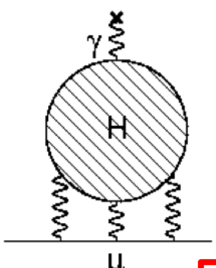
$+ \cdots$

$a_\mu^{\rm had;LO}$

$a_\mu^{\rm had;NL}$

Hagiwara, Li

	$\text{Value } (\times 10^{-11}) \text{ units}$
QED	$116\,584\,718.95 \pm 0.08$
HVP	$6\,850.6 \pm 43$
HLbL	105 ± 26
EW	153.6 ± 1.0
Total SM	$116\,591\,828 \pm 49$



$$a_\mu^{\rm HLbL} = (105 \pm 26) \times 1($$

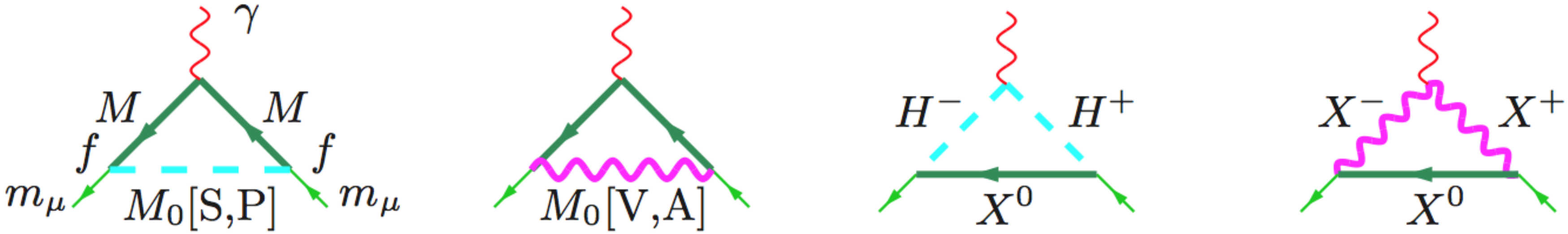
3.6σ

$$\boxed{a_\mu^{\rm E821} = (116\,592\,089 \pm 63) \times 10^{-11}}$$

$$\boxed{\Delta a_\mu({\rm E821} - {\rm SM}) = (287 \pm 80) \times 10^{-11}}$$

NP & g_μ-2

Lautrup, Peterman, de Rafael, Phys. Reports 3C(1972), 193
Leveille, NPB137(1978), 63



$$\Delta a_\mu^{\rm NP} = \frac{f^2}{4\pi^2}\,\frac{m_\mu^2}{M_0^2}\,L,$$

$$L = \frac{1}{2}\int_0^1 \mathrm{d}x\,\frac{Q(x)}{(1-x)\,(1-\lambda^2\,x)+(\epsilon\lambda)^2\,x},$$

neutral boson

$$Q_{\rm V} = 2x\,(1-x)\,(x-2\,(1-\epsilon))\;+\lambda^2\,(1-\epsilon)^2\,Q_{\rm S}$$
$$Q_{\rm A} = 2x\,(1-x)\,(x-2\,(1+\epsilon))\;+\lambda^2\,(1+\epsilon)^2\,Q_{\rm P}$$
$$Q_{\rm S} = x^2\,(1+\epsilon-x)$$
$$Q_{\rm P} = x^2\,(1-\epsilon-x)$$

$$L = \frac{1}{2}\int_0^1 \mathrm{d}x\,\frac{Q(x)}{(\epsilon\lambda)^2\,(1-x)\,(1-\epsilon^{-2}\,x)+x}$$

charged boson

$$Q_{\rm S} = -\,x\,(1-x)\,(x+\epsilon)$$
$$Q_{\rm P} = -\,x\,(1-x)\,(x-\epsilon)$$
$$Q_{\rm V} = 2\,x^2\,(1+x-2\epsilon)-\lambda^2\,(1-\epsilon)^2\,Q_{\rm S}$$
$$Q_{\rm A} = 2\,x^2\,(1+x+2\epsilon)-\lambda^2\,(1+\epsilon)^2\,Q_{\rm P}$$

$$\epsilon = M/m_\mu$$
$$\lambda = m_\mu/M_0$$

Heavy Fermions

Sequential 4th generation --- chiral fermions

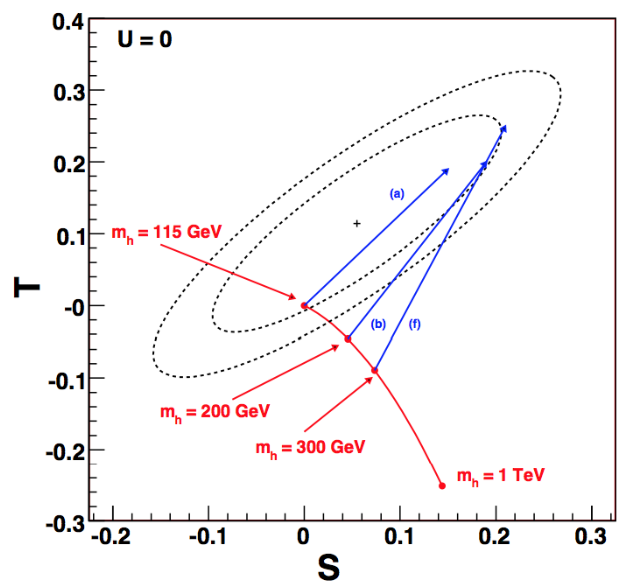
b' , t' , ℓ_4 , ν_4

✔ why not !?

✔ new CP phases → BAU(?) Hou, Chin. J. Phys 47 (2009) 134

✔ accommodate to a heavy Higgs boson He, Polonsky, Su, PRD64(2001) 053004
Kribs,Plehn, Spannowsky, Tait, PRD76(2007) 075016

◆unitary bound: $m \lesssim 600\ \mathrm{GeV}$

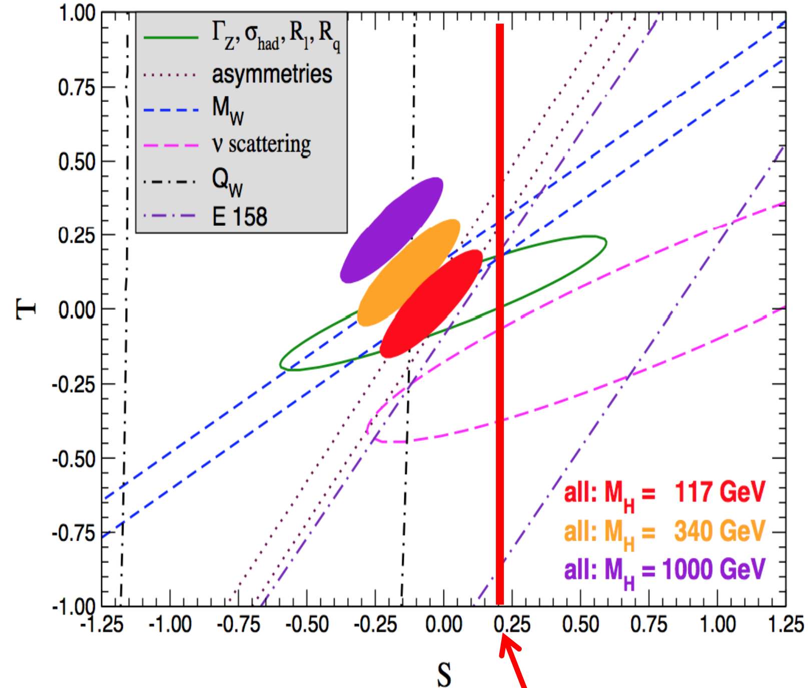


EWPO & SM4

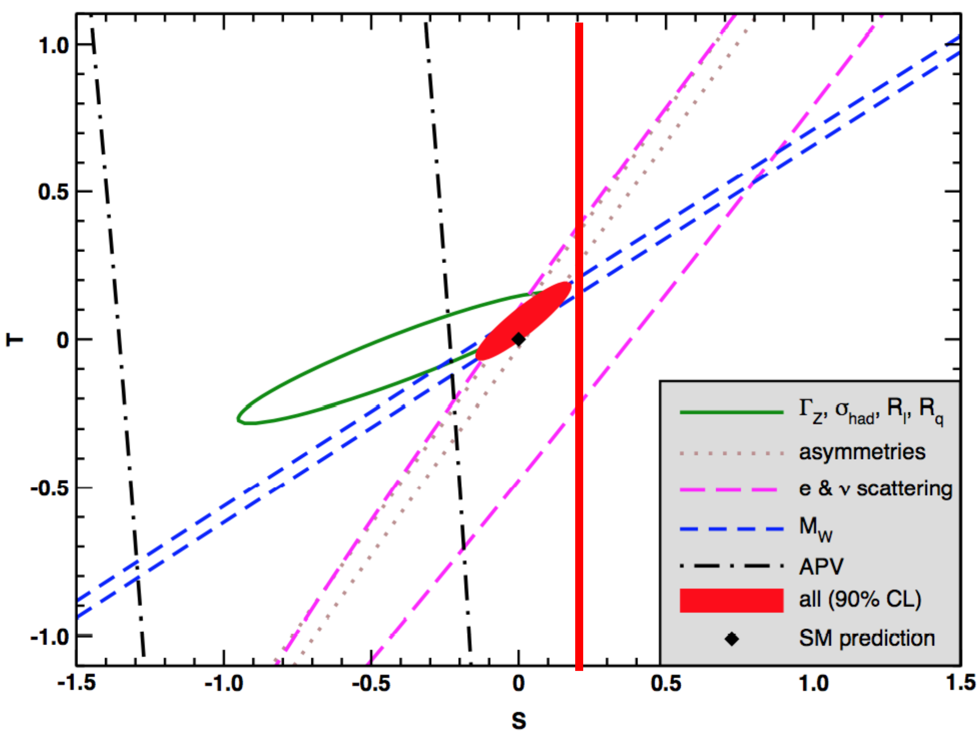
✗ "An extra generation of ordinary fermions is excluded at the 6σ level on the basis of S parameter alone, ⋯"

PDG 2008

$$S = -0.04 \pm 0.09$$
$$T = \quad 0.02 \pm 0.09$$



$$\frac{2\pi}{3} \simeq 0.21$$



PDG 2018

$$S = 0.02 \pm 0.07$$

$$T = 0.06 \pm 0.06$$

LHC search

b' (4^{th} Generation) Quark, Searches PDG 2018

$b'(-1/3)$-q[...] > 880 GeV [...]s in $p\bar{p}$ and pp collisions

VALUE (GeV)	CL%	[...]MENT ID		TECN	COMMENT
>730	95	[1] SIRUNYAN	17AU	CMS	

t' (4^{th} Generation) Quark, Searches for

$t'(2/3)$-quark/hadron mass limits in $p\bar{p}$ and pp collisions

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT	
>1160 (CL = 95%) OU						
>1160	95	> 1169 GeV	17L	ATLS	$B(t' \to Z t) = 1$	$t' \to Z t$
> 350	95	> 350 GeV	12BC	ATLS	$B(t' \to W q)=1$ ($q=d,s,b$)	$t' \to W q$
> 420	95	> 420 GeV	12C	ATLS	$t' \to X t$ ($m_X < 140$ GeV)	$t' \to X t$

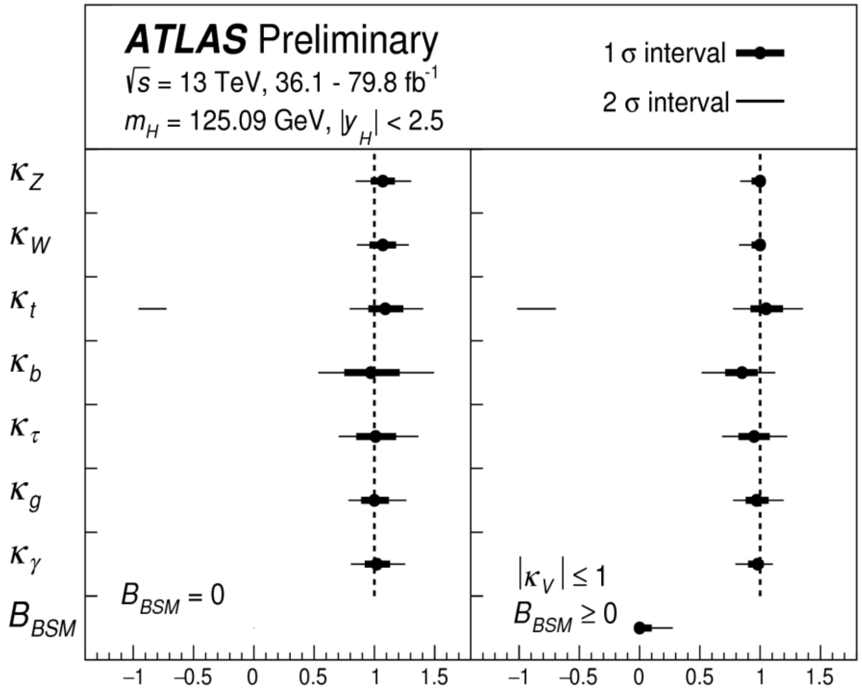
Heavy Charged Lepton Searches

Charged Heavy Lepton MASS LIMITS

Sequential Charged Heavy Lepton ($L^{\pm}$) MASS LIMITS

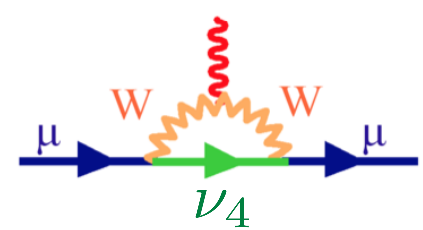
VALUE (GeV)	CL%			TECN	COMMENT
>100.8	95	> 100.8 GeV	LB	L3	Decay to νW

SM4 & Other Data



$$R_{gg} = \frac{\left|\kappa_t F_{1/2}(\tau_t) + \sum_{f=t',b'} \kappa_f F_{1/2}(\tau_f)\right|^2}{\left|F_{1/2}(\tau_t)\right|^2} = 9$$

$$a_\mu^{\rm SM}(W^+W^-N) \sim 233 \times 10^{-11}\, |V_{N\mu}|^2\, F(x), \quad x = m_N^2/M_W^2$$



$|V_{N\mu}| > 0.7$ excluded by $Br(\mu \to e\gamma)$

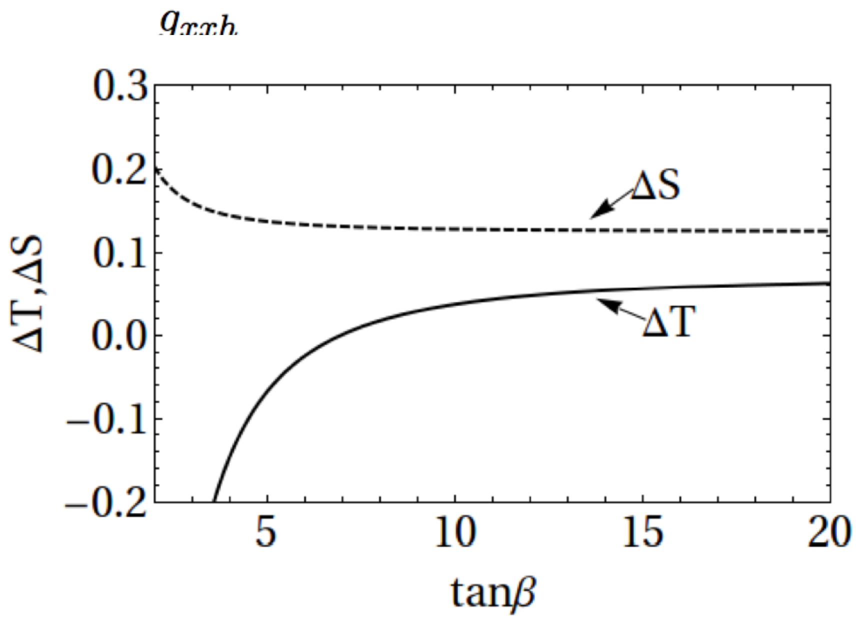
Huo, Feng, hep-ph/0301153

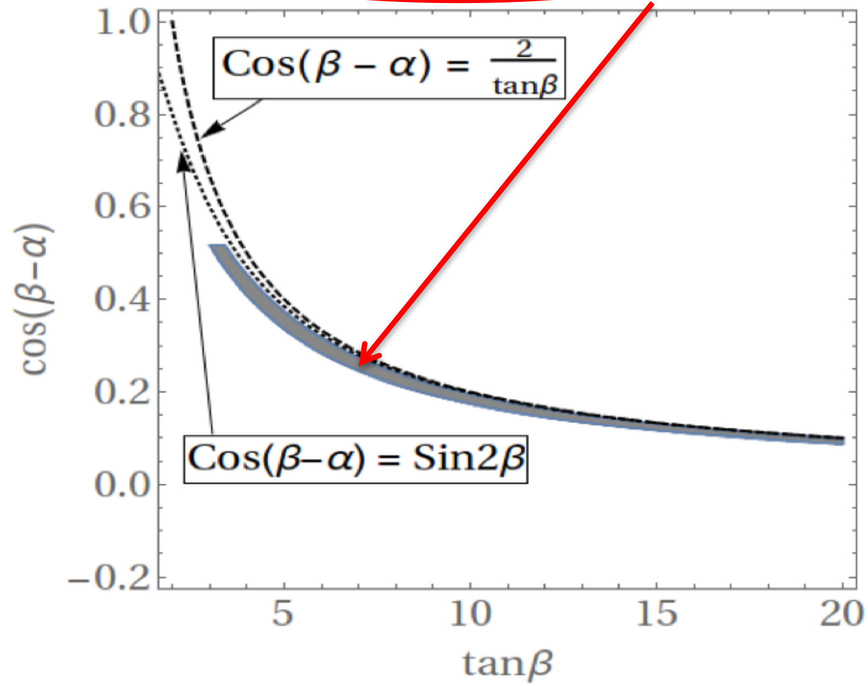
Hou et al., ICHEP2008 Proceedings

4^{th} + 2HDM

Das, Kundu, Saha, 1707.03000,
Wang, Shi, Han, 1708.0688

agree w/ LHC data



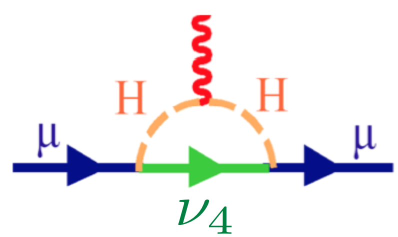


$$a_\mu^{\rm 2HDM-II}(H^+H^-N) \sim -233 \times 10^{-11}\,|V_{N\mu}|^2\,[f_{H^+}(x) + g_{H^+}(x)\cot^2\beta + x_\mu\, q_{H^+}(x)\tan^2\beta],$$

goes to wrong direction

Huo, Feng, hep-ph/0301153

Hou et al., ICHEP2008 Proceedings



Non-canonical 4th Generation

Langacker and London, PRD 38 (1988), 886

Sequential fermions

$$\begin{pmatrix} N \\ E^- \end{pmatrix}_L \quad E_R^- \,, \quad \begin{pmatrix} U \\ D \end{pmatrix}_L \quad \begin{matrix} U_R \\ D_R \end{matrix}$$

Noncanonical SU(2)×U(1) assignments

(a) Mirror fermions

$$\boxed{E_L^- \quad \begin{pmatrix} N \\ E^- \end{pmatrix}_R \,, \quad \begin{matrix} U_L \\ D_L \end{matrix} \quad \begin{pmatrix} U \\ D \end{pmatrix}_R}$$

(b) Vector doublets

$$\begin{pmatrix} N \\ E^- \end{pmatrix}_L \quad \begin{pmatrix} N \\ E^- \end{pmatrix}_R \,, \quad \begin{pmatrix} U \\ D \end{pmatrix}_L \quad \begin{pmatrix} U \\ D \end{pmatrix}_R$$

(c) Vector singlets

$$E_L^- \quad E_R^- \,, \quad U_L \quad U_R \,, \quad D_L \quad D_R$$

Non-canonical L4 + 2HD + U(1)

non-canonical
4^{th} generation leptons
w/ dark matter
+ $U(1)_X$
2HDM

CRC, Chiang, Lin, to appear

	SM fermions						Higgs	
	$Q_L \equiv \binom{u}{d}_L$	u_R	d_R	$L_L \equiv \binom{\nu}{e}_L$	e_R	ν_R	Φ_1	Φ_2
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**2**	**2**
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$-1/2$	-1	0	$1/2$	$1/2$
$U(1)_X$	x_q	x_q	x_q	0	0	0	0	0
Z_2	$+$	$+$	$-$	$+$	$-$	$+$	$+$	$-$

	Fourth generation fermions						Scalar
	$Q_4 \equiv \binom{u}{d}_{L4}$	u_{R4}	d_{R4}	$L_4 \equiv \binom{\nu}{e}_{R4}$	e_{L4}	ν_{L4}	ϕ
$SU(3)_C$	**3**	**3**	**3**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**1**
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$-1/2$	-1	0	0
$U(1)_X$	x_{q4}	x_{q4}	x_{q4}	x_{L4}	x_{L4}	x_{L4}	x_ϕ
Z_2	$+$	$+$	$-$	$+$	$-$	$+$	$+$

CRC (NTNU)

dark matter

additional decay mode of 4^{th} generation fermions:

e.g. $q_4 \to Z' + q_{SM}$ or $\phi + q_{SM}$

$L_4 \to \phi + L_{SM}$

Benchmark point

$$m_{u4} = 550 \text{ GeV} \quad m_H = 400 \text{ GeV} \quad m_{e4} = m_{\nu 4} = 400 \text{ GeV}$$
$$m_{d4} = 500 \text{ GeV} \quad m_A = 810 \text{ GeV} \quad m_{H^+} = 600 \text{ GeV}$$

Non-canonical L4

$$\mathcal{L}_{\rm Yukawa} = -\left[f^L_{4i}\bar{L}_{R4}L_{Li} + f^e_{4i}\bar{e}_{L4}e_{Ri} + f_{4i}\bar{\nu}_{L4}\nu_{Ri}\right]\phi + h.c.$$

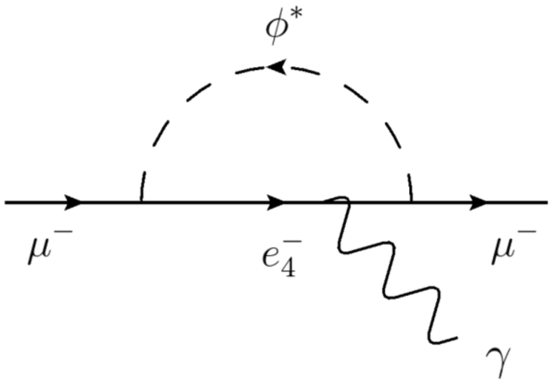
$$V_{\rm 2HDM} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_1\Phi_2^\dagger) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$
$$+ \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_1\Phi_2^\dagger)^2]$$

$$V_\phi = m_0^2|\phi|^2 + \mu_\phi|\phi|^4 + \kappa_1|\phi|^2|\Phi_1|^2 + \kappa_2|\phi|^2|\Phi_2|^2$$

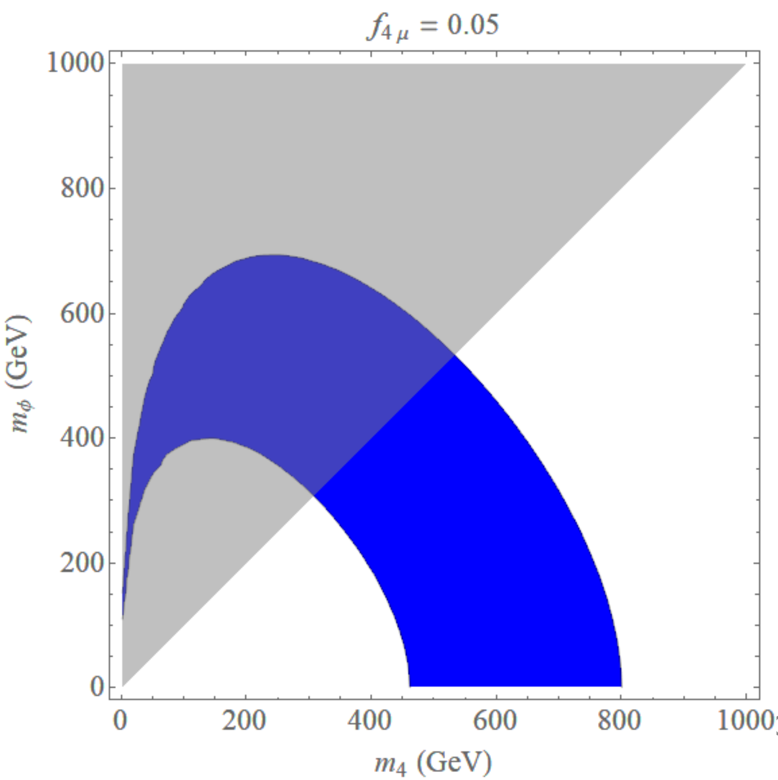
$$m_\phi = m_0^2 + \frac{1}{2}\kappa_1 v^2\cos^2\beta + \frac{1}{2}\kappa_2 v^2\sin^2\beta$$
$$\lambda_h = v(-\kappa_1\sin\alpha\cos\beta + \kappa_2\cos\alpha\sin\beta)$$
$$\lambda_H = v(\kappa_1\cos\alpha\cos\beta + \kappa_2\sin\alpha\sin\beta).$$

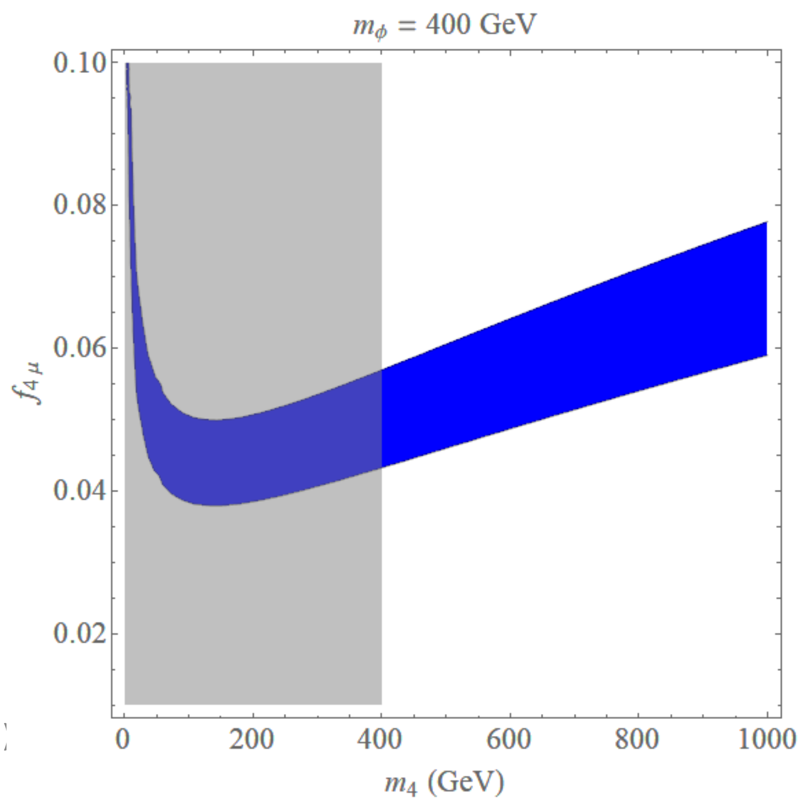
$$y_u^h = \frac{\cos\alpha}{\sin\beta} = \cos(\beta-\alpha)\cot\beta + \sin(\beta-\alpha)$$
$$y_d^h = -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta.$$

Muon g-2

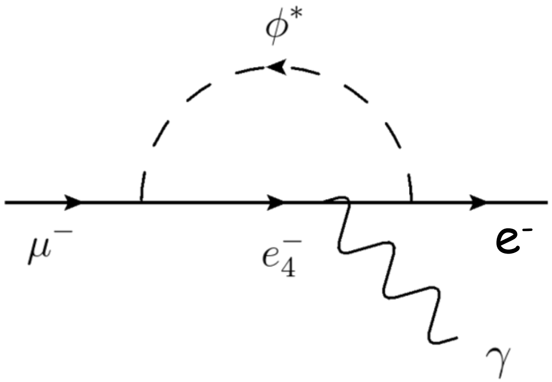


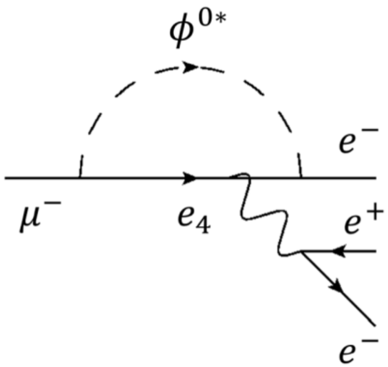
$$\Delta a_\mu = \frac{|f_{4\mu}|^2}{8\pi^2}\int_0^1 dx\,\frac{x^2(m_\mu^2(1-x)+m_\mu m_4)}{(1-x)(m_\phi^2-m_\mu^2 x)+m_4^2 x}$$





Lepton rare decay





$$\mathrm{BR}(\mu^- \to e^-\gamma) < 4.2 \times 10^{-13} \qquad (f_{4e}f_{4\mu})^2$$

$$\mathrm{BR}(\tau^- \to e^-\gamma) < 3.3 \times 10^{-8} \qquad (f_{4e}f_{4\tau})^2$$

$$\propto$$

$$\mathrm{BR}(\tau^- \to \mu^-\gamma) < 4.4 \times 10^{-8} \qquad (f_{4\mu}f_{4\tau})^2$$

$$\mathrm{BR}(\mu^- \to e^-e^-e^+) < 1 \times 10^{-12} \qquad (f_{4e}f_{4\mu})^2$$

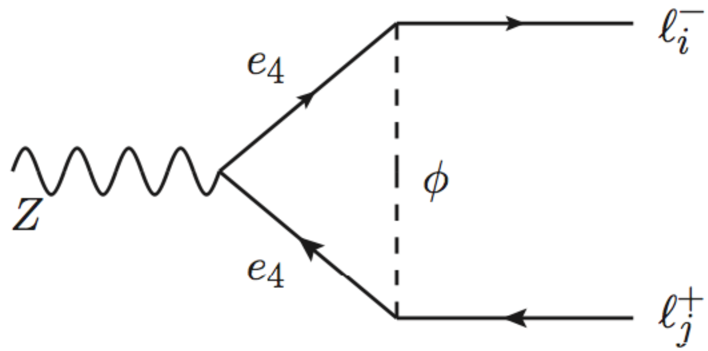
take $f_{4\mu} \simeq 0.05$

$$f_{4e} \lesssim 5 \times 10^{-7}$$

$$f_{4\tau} \lesssim 5 \times 10^{-5}$$

A.M. Baldini, et al., MEG Collaboration, Eur. Phys. J. C 76 (8) (2016) 434, https://doi.org/10.1140/epjc/s10052-016-4271-x, arXiv:1605.05081 [hep-ex].
C. Patrignani, et al., Particle Data Group, Chin. Phys. C 40 (10) (2016) 100001, https://doi.org/10.1088/1674-1137/40/10/100001.
G.M. Pruna, EPJ Web Conf. 179 (2018) 01019, https://doi.org/10.1051/epjconf/201817901019, arXiv:1801.04709 [hep-ph].

Z rare decay



$$\mathrm{BR}(Z \to e_i^{\pm} e_j^{\mp}) = \frac{m_Z}{12\pi\Gamma_Z}[2(f_V^2 + f_A^2) + (f_M^2 + f_E^2)m_Z^2]$$

$$\mathrm{BR}(Z \to e^{\pm}\mu^{\mp}) < 1.7 \times 10^{-6}$$

$$\mathrm{BR}(Z \to e^{\pm}\tau^{\mp}) < 9.8 \times 10^{-6}$$

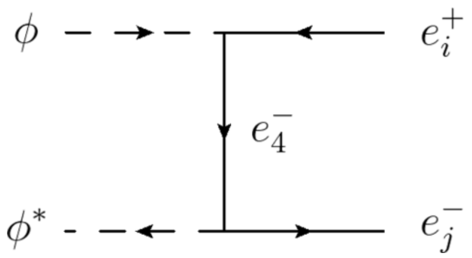
$$\mathrm{BR}(Z \to \mu^{\pm}\tau^{\mp}) < 1.2 \times 10^{-5}$$

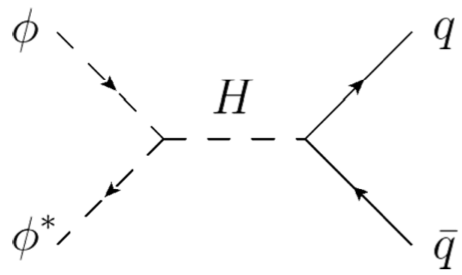
J.I. Illana, T. Riemann, Phys. Rev. D 63 (2001) 053004, https://doi.org/10.1103/PhysRevD.63.053004, arXiv:hep-ph/0010193.

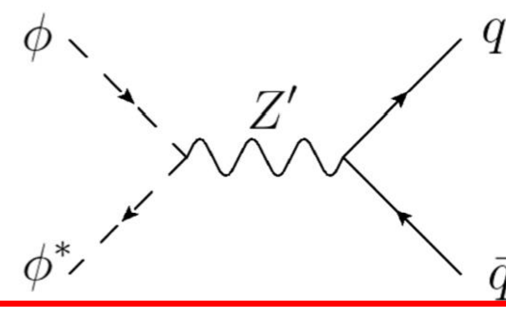
the constraints on f_{4e} and $f_{4\tau}$ are NOT as stringent as the limits from charged lepton rare decays.

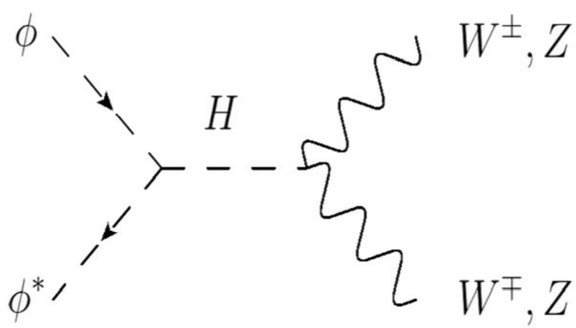
Dark Matter

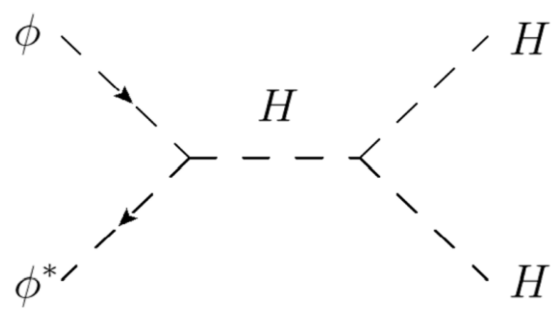
dark matter annihilation

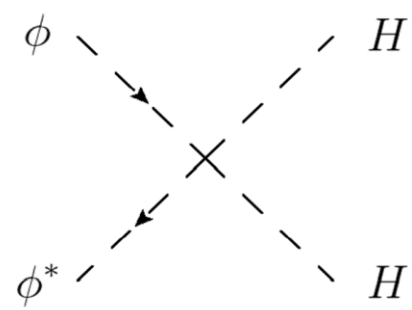




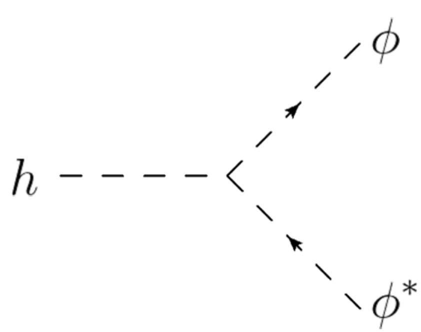








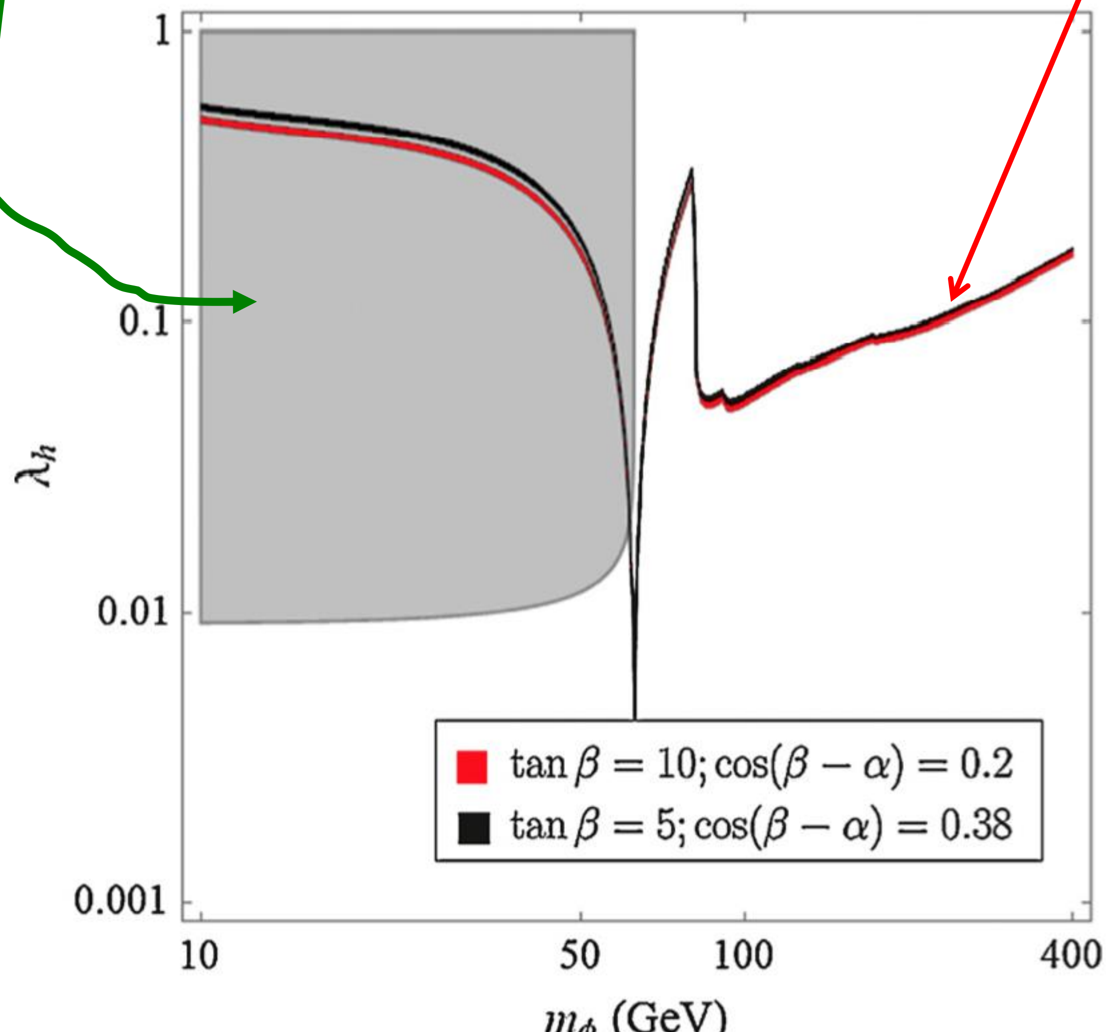
Higgs invisible decay



Dark Matter

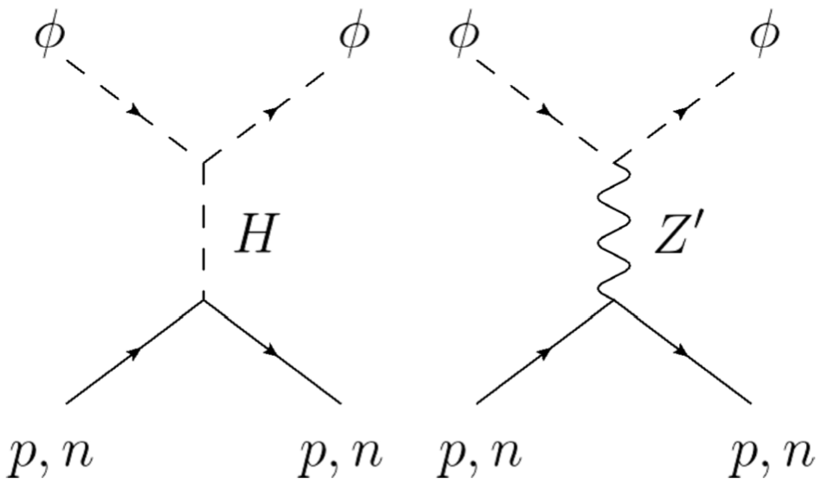
invisible Higgs decay

$\Omega\, h^2$=0.12±0.0012



Dark Matter

dark matter nucleon elastic scattering



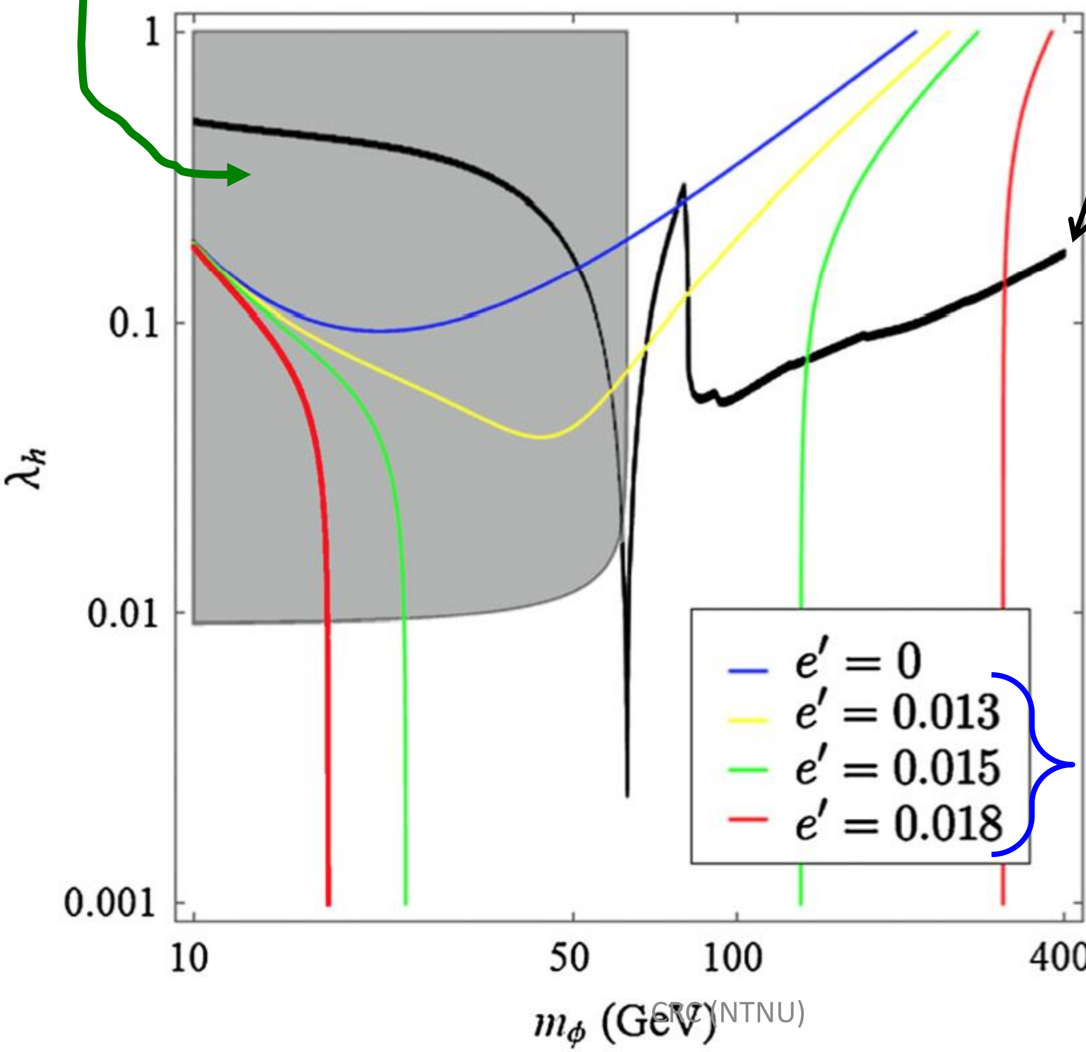
$$\sigma^{SI-h}_{\phi p(n)} = \frac{m^2_{p(n)}}{4\pi(m_\phi + m_{p(n)})^2} f_S^{p(n)2}$$

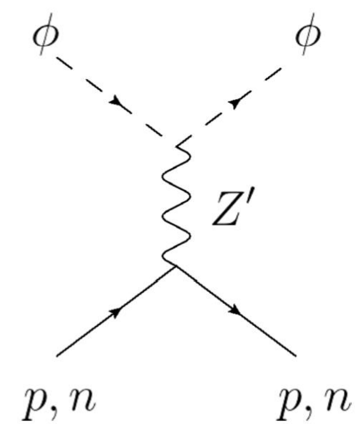
$$\sigma^{SI-Z'}_{\phi p(n)} = \frac{16 e'^4 m^2_\phi m^2_{p(n)}}{\pi(m_\phi + m_{p(n)})^2 m^4_{Z'}}$$

Dark Matter

invisible Higgs decay

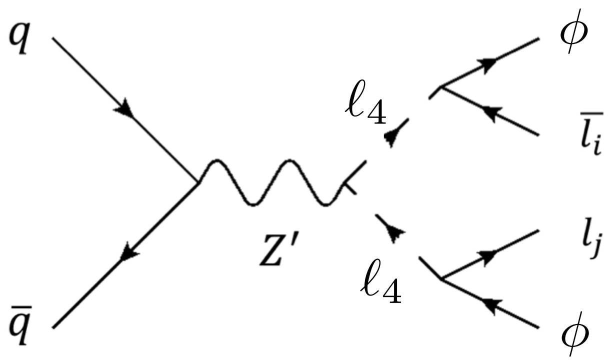
$\Omega\ h^2$=0.12±0.0012

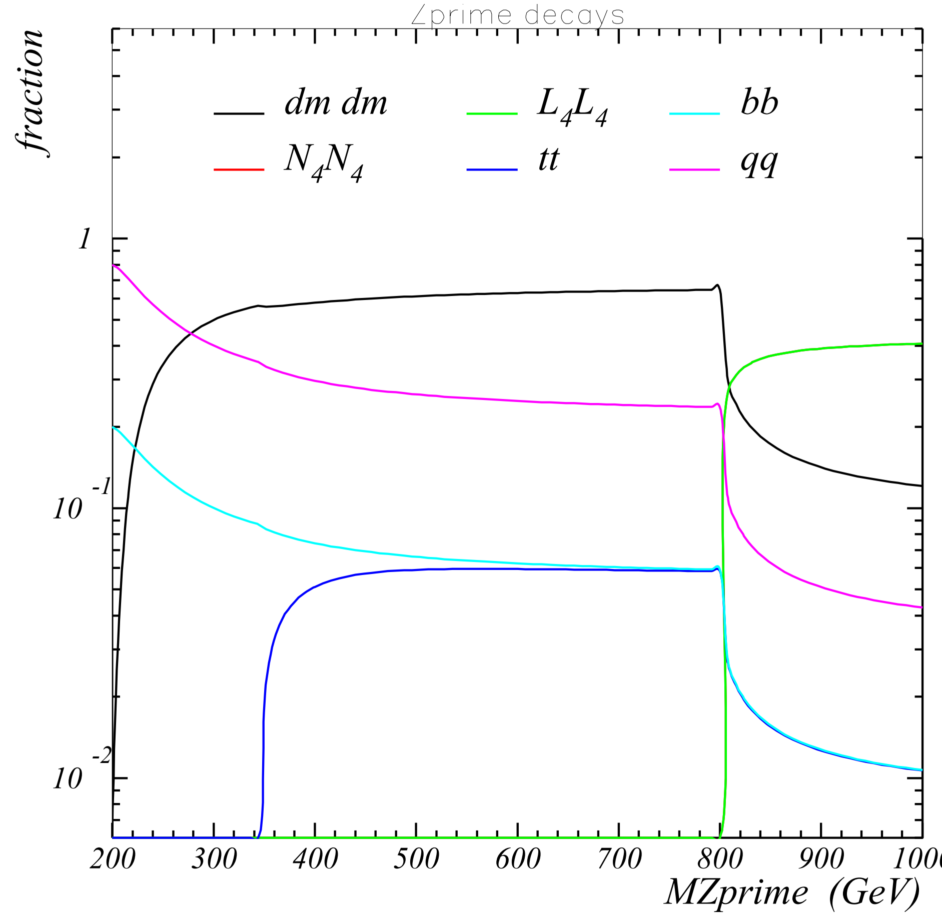




LHC Pheno

Z′ production





Signals:

flavor non-conserving lepton pair + missing ET

monjet+ missing ET

Summary

* The existence of Dark Matter requires BSM

* long-standing discrepancy between TH and EXP in muon g-2 may show the hints of BSM.

* Fourth generation fermions in 2HDM is still possible!

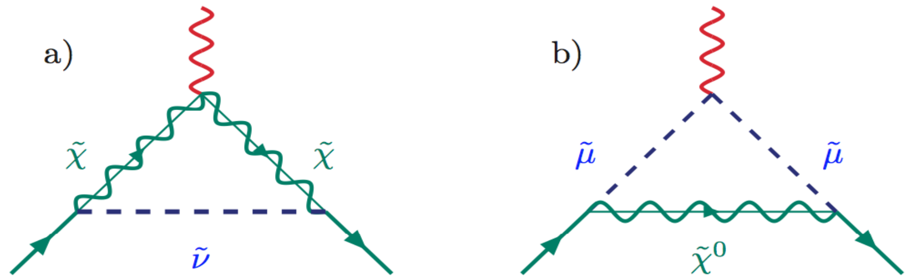
* With non-canonical charge assignment under SM and an additional U(1), 4^{th} generation lepton can provide a possible explanation for muon g-2 anomaly and dark matter.

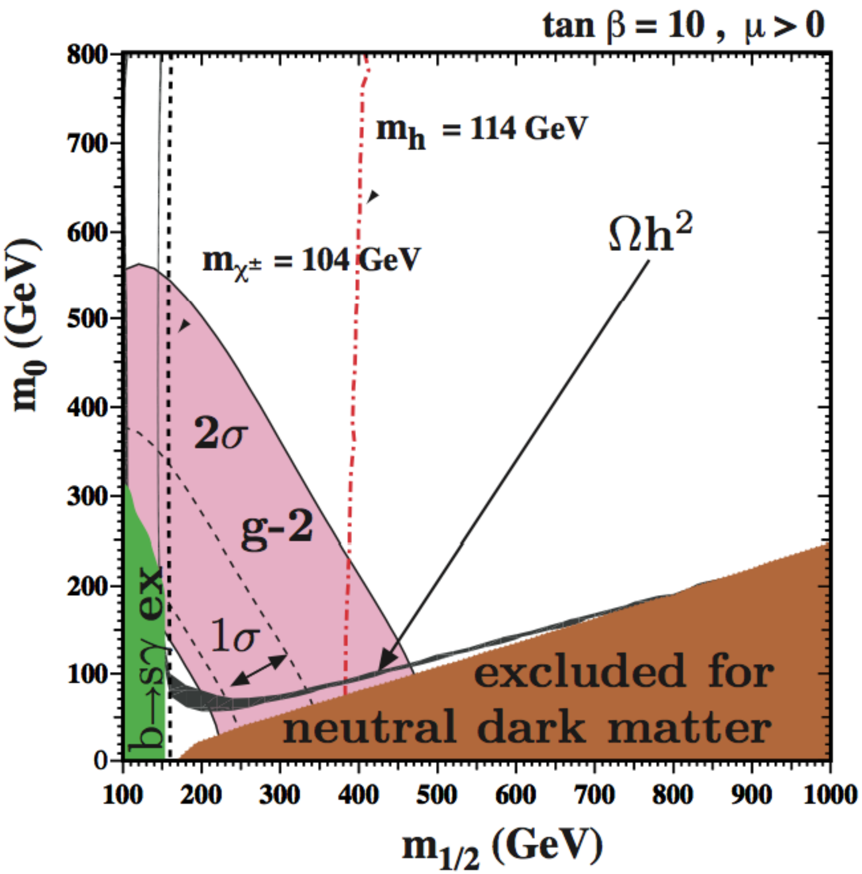
* LHC phenomenology is worth a detailed study!

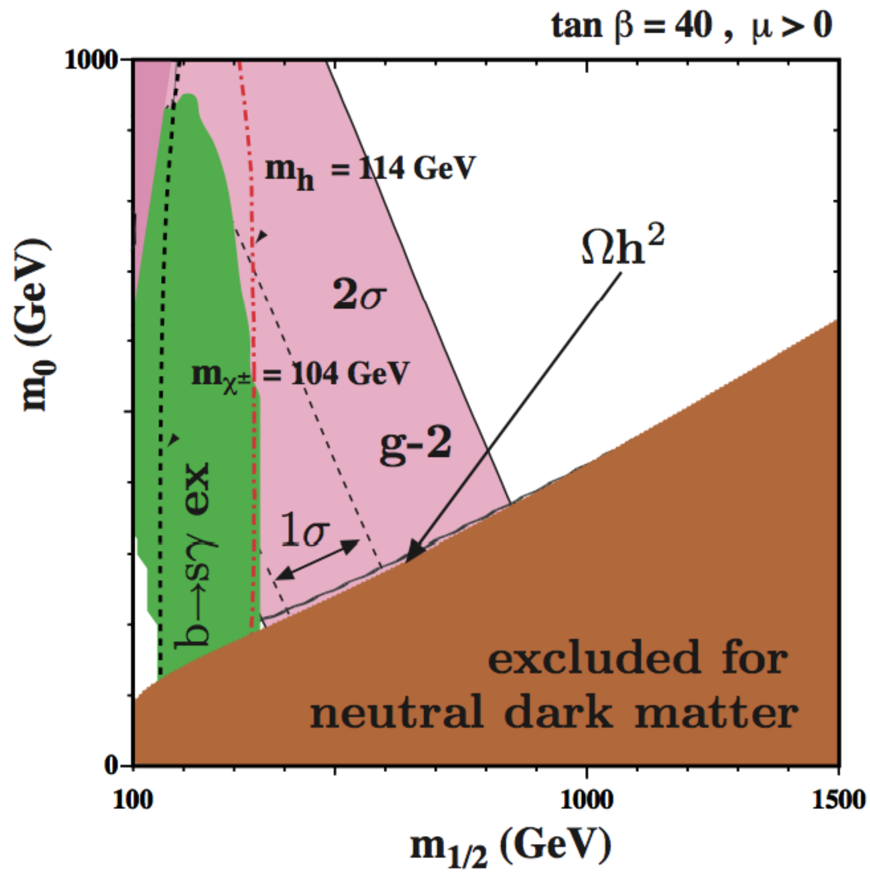
Backup

NP g_μ-2

SUSY (CMSSM)







Ellis, Olive, Santoso, Spanos, PLB 565(2003) 176
Olive, Eur, Phys. J. C 59(2009) 269

General 2HDM

$Hf\bar{f},\ f=b,t$	$-\frac{g}{2}\left(\frac{m_b}{M_W}\frac{\cos\alpha}{\cos\beta},\ \frac{m_t}{M_W}\frac{\sin\alpha}{\sin\beta}\right)$
$hf\bar{f},\ \ f=b,t$	$-\frac{g}{2}\left(-\frac{m_b}{M_W}\frac{\sin\alpha}{\cos\beta},\ \frac{m_t}{M_W}\frac{\cos\alpha}{\sin\beta}\right)$
$Af\bar{f},\ f=b,t$	$-\gamma_5\frac{g}{2}\left(\frac{m_b}{M_W}\tan\beta,\ \frac{m_t}{M_W}\cot\beta\right)$
$H^+b\bar{t}$	$\frac{g}{\sqrt{2}}\left(\frac{m_b}{M_W}\tan\beta\,\frac{1+\gamma_5}{2}+\frac{m_t}{M_W}\cot\beta\,\frac{1-\gamma_5}{2}\right)V_{tb}$

NP g_μ-2

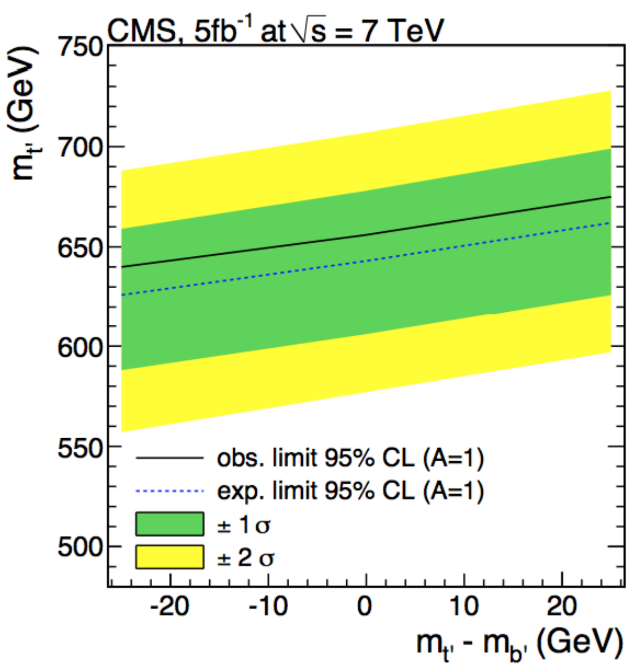
Little Higgs $a_\mu^{\rm LH} \sim 10 \times 10^{-11}$; $a_\mu^{\rm LHT} < 12 \times 10^{-11}$

Park, Song, PRD 69(2004) 115010 Blanke et al., JHEP 0705(2007) 013

Sequential SM4

$$a_\mu^{\rm SM}(W^+W^-N) \sim 233 \times 10^{-11}\, |V_{N\mu}|^2\, F(x), \quad x = m_N^2/M_W^2$$

$|V_{N\mu}| > 0.7$ excluded by $Br(\mu \to e\gamma)$ Huo, Feng, hep-ph/0301153



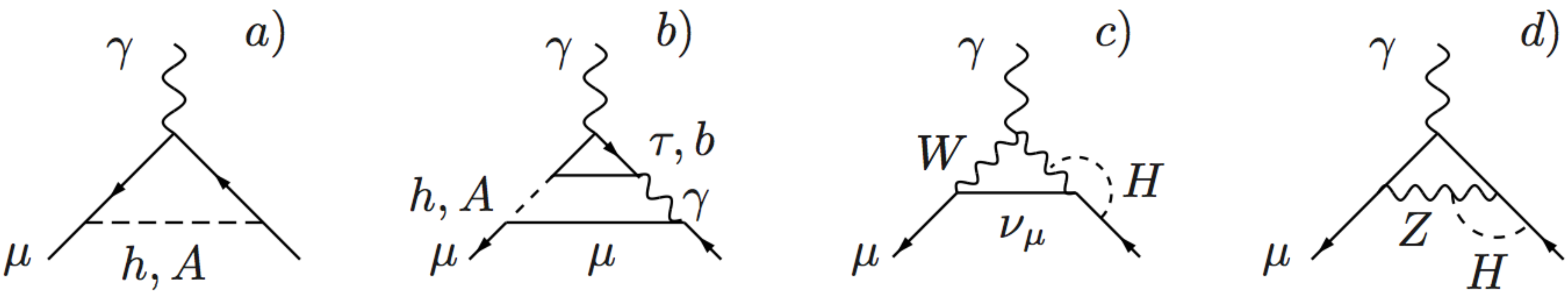
The existence of 4th generation with mass below 685 GeV is excluded @ 95% CL.

CMS-PH-EP/2012-251, 1209.1062[hep-ex]

NP g_μ-2

Krawczyk, hep-ph/0512371
Cheung, Kong, PRD68(2003) 053003
Wahab El Kaffas, Osland, Magne Ogreid, PRD76(2007) 095001
Ellis, Hanh, Heinemeyer, Olive, Weiglein, JHEP 0710(2007) 092

general 2HDM



$(m_h, m_A, \tan\beta)$	$a_\mu^{(2)}(h)$	$a_\mu^{(2)}(A)$	$a_\mu^{(4)}(h)$	$a_\mu^{(4)}(A)$	sum
(100, 100, 10)	0.65	−0.62	−2.31	2.88	0.61
(100, 100, 40)	10.45	−9.89	−36.90	46.09	9.74
(100, 300, 10)	0.65	−0.08	−2.31	0.55	−1.18
(100, 300, 40)	10.45	− 1.30	− 36.90	8.85	− 18.90

NOTE: $\boxed{\Delta a_\mu(\mathrm{E821} - \mathrm{SM}) \ = \ (287 \pm 80) \times 10^{-11}}$