Current status of 2HDMs for muon g-2

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PRD108(2023)11,115012 [arXiv:2304.09887]

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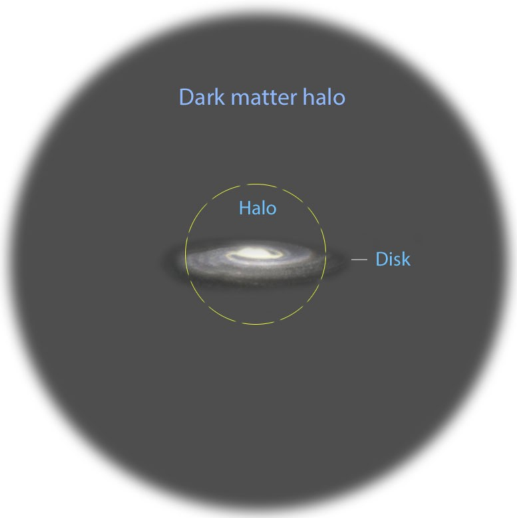
杭州, 2024. 10. 25

Big problem in particle physics : dark matter

Standard Model describes 4% of Universe, but dark matter exits 6 times.



Milky Way model

Neutral in electromagnetism

Gravity interaction

We don't know the identity

Standard Model has to be extended

Weakly Interacting Massive Particle (WIMP) : good candidate for dark matter

Assuming Big Bang we can compute the current abundance of dark matter

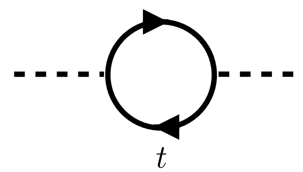
TeV scale particle can explain the current abundance
$\Rightarrow$ We expect new particles accessible to **LHC experiments**

Hierarchy problem : Higgs boson with 125GeV also suggests the TeV new physics

2 big problems in particle physics

Dark Matter

Higgs



TeV scale particles
(reachable at LHC, CEPC)

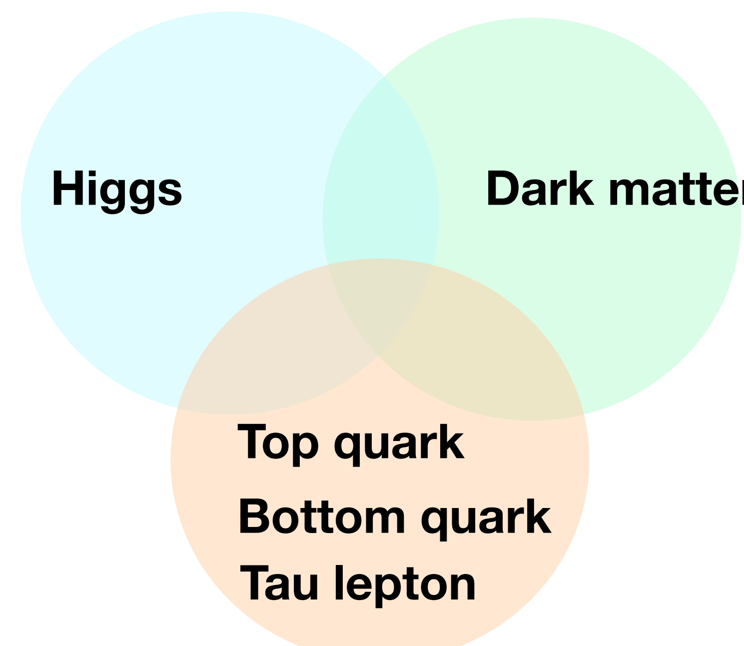
Searching for them at LHC

Higgs：

Top quarks：the heaviest particle in the SM

→ most strongly coupled with Higgs

Third generation fermions: bottom, tau



Various **theory beyond the SM with new particles at TeV scale.**
I especially focus on how to search for them at experiments (collider experiments, LHC)
Fine tuning is welcome

Today, I focus on **two Higgs doublet models (2HDMs).**

2HDMs

The SM contains a SU(2) doublet Higgs. We consider additional doublet.

$$\Phi_1 = \begin{pmatrix} \phi_{11} \\ \phi_{12} \end{pmatrix} : \mathbf{2}_{\frac{1}{2}} \qquad \Phi_2 = \begin{pmatrix} \phi_{21} \\ \phi_{22} \end{pmatrix} : \mathbf{2}_{\frac{1}{2}}$$

Higgs sector:

$$\begin{aligned} V(\Phi) = &- \mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 - \mu_3^2 \left\{\Phi_1^\dagger \Phi_2 + h.c.\right\} \\ &+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ &+ \left\{\left[\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2) + \lambda_6|\Phi_1|^2 + \lambda_7|\Phi_2|^2\right](\Phi_1^\dagger\Phi_2) + h.c.\right\} \end{aligned}$$

Yukawa sector:

$$\begin{aligned} \mathcal{L} = &-\bar{q}_L Y_{1u}\tilde{\Phi}_1 u_R - \bar{q}_L Y_{1d}\Phi_1 d_R - \bar{l}_L Y_{1l}\Phi_1 e_R \\ &-\bar{q}_L Y_{2u}\tilde{\Phi}2 u_R - \bar{q}_L Y_{2d}\Phi_2 d_R - \bar{l}_L Y_{2l}\Phi_2 e_R \end{aligned}$$

$$\tilde{\Phi} = (i\sigma_2)\Phi^*$$

Only 3 additional particles : $H, A, H^{\pm}$

Simplest extension of the SM.

Often appear as an effective theory of well motivated models.

SUSY, Axion models with PQ sym,

FCNC

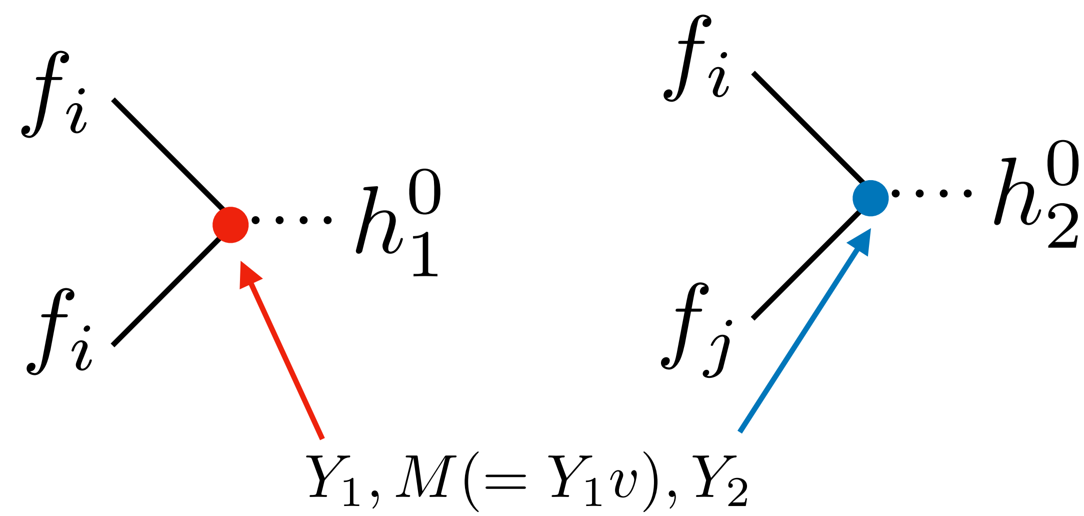
It is known that the SM is free from FCNC at tree level.

$\rightarrow$ Yukawa interaction and mass matrix simultaneously diagonalized $Y_1, M = vY_1$

Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1^0 + iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2^0 + ih_3^0) \end{pmatrix}$$

$$\mathcal{L} = -\bar{q}_L Y_{1u} \tilde{\Phi}_1 u_R - \bar{q}_L Y_{1d} \Phi_1 d_R - \bar{l}_L Y_{1l} \Phi_1 e_R$$
$$-\bar{q}_L Y_{2u} \tilde{\Phi} 2 u_R - \bar{q}_L Y_{2d} \Phi_2 d_R - \bar{l}_L Y_{2l} \Phi_2 e_R$$



In general **not simultaneously diagonalized**

$\rightarrow$ in general Flavor Violation predicted **(Type III)**

To avoid the tree FCNC

$\rightarrow$ **Z2 symmetric 2HDM models**

for each fermion type:

$Y_{1u} = 0 \; or \; Y_{2u} = 0$

$2^3/2 = 4 \; types$

$\Phi_1(+), \Phi_2(-)$

	u_R	d_R	l_R
Type I	$-$	$-$	$-$
Type II	$-$	$+$	$+$
Type X	$-$	$-$	$+$
Type Y	$-$	$+$	$-$

$V(\Phi)$ *also constrained*

$\rightarrow$ **Aligned models (Z2 models included)**

$Y_{1u} \propto Y_{2u}, \quad Y_{1d} \propto Y_{2d}, \quad Y_{1e} \propto Y_{2e}$

(more CP phases : λ_6, λ_7)

Muon g-2 in 2HDMs

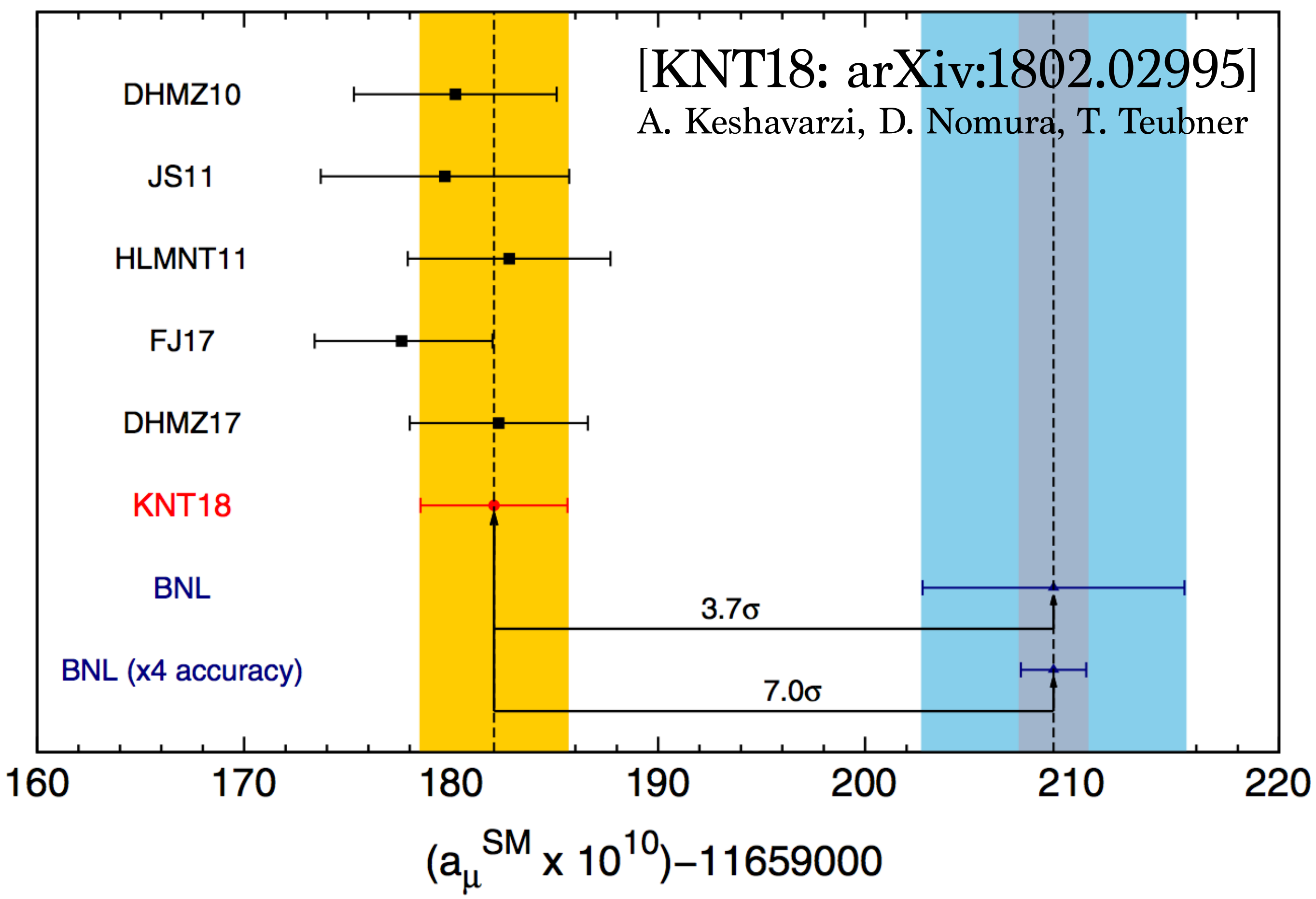
Muon g-2 : signature of BSM?

magnetic moment

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} \qquad \vec{\mu} = -g\frac{e}{2m}\vec{S}$$

anomalous magnetic moment

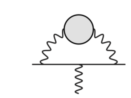
$$a_\mu = (g_\mu - 2)/2 \qquad \mathcal{L} = a_\mu \frac{e}{4m_\mu}\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu}$$



anomaly in anomalous magnetic moment

$g = 2$ tree level, Dirac equation

$g = 2.002\ 331$ QED, $\frac{\alpha}{\pi} = 0.00232\ldots$

$g = 2.002\ 331\ 83$ hadronic 

$$g = 2.\underbrace{002\ 331\ 836\ 6}_{\text{anomalous magnetic moment}} \quad \text{EW}$$

$\times 10^{-10}$

Theory total	11659182.80 (4.94)	$\longrightarrow$	11659182.05 (3.56)
Experiment			11659209.10 (6.33)
Exp - Theory	26.1 (8.0)	$\longrightarrow$	27.1 (7.3)
Δa_μ	3.3σ	$\longrightarrow$	3.7σ

$$\Delta a_\mu = a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} \sim \Delta a_\mu^{\text{EW}} \sim \mathcal{O}(10^{-9})$$

New contribution of the size of the EW-contribution required,

$$\Delta a_\mu^{\text{NP}} \sim \frac{g_{\text{NP}}^2}{16\pi^2}\frac{m_\mu^2}{m_{\text{NP}}^2}$$

New particles at O(100GeV) ?

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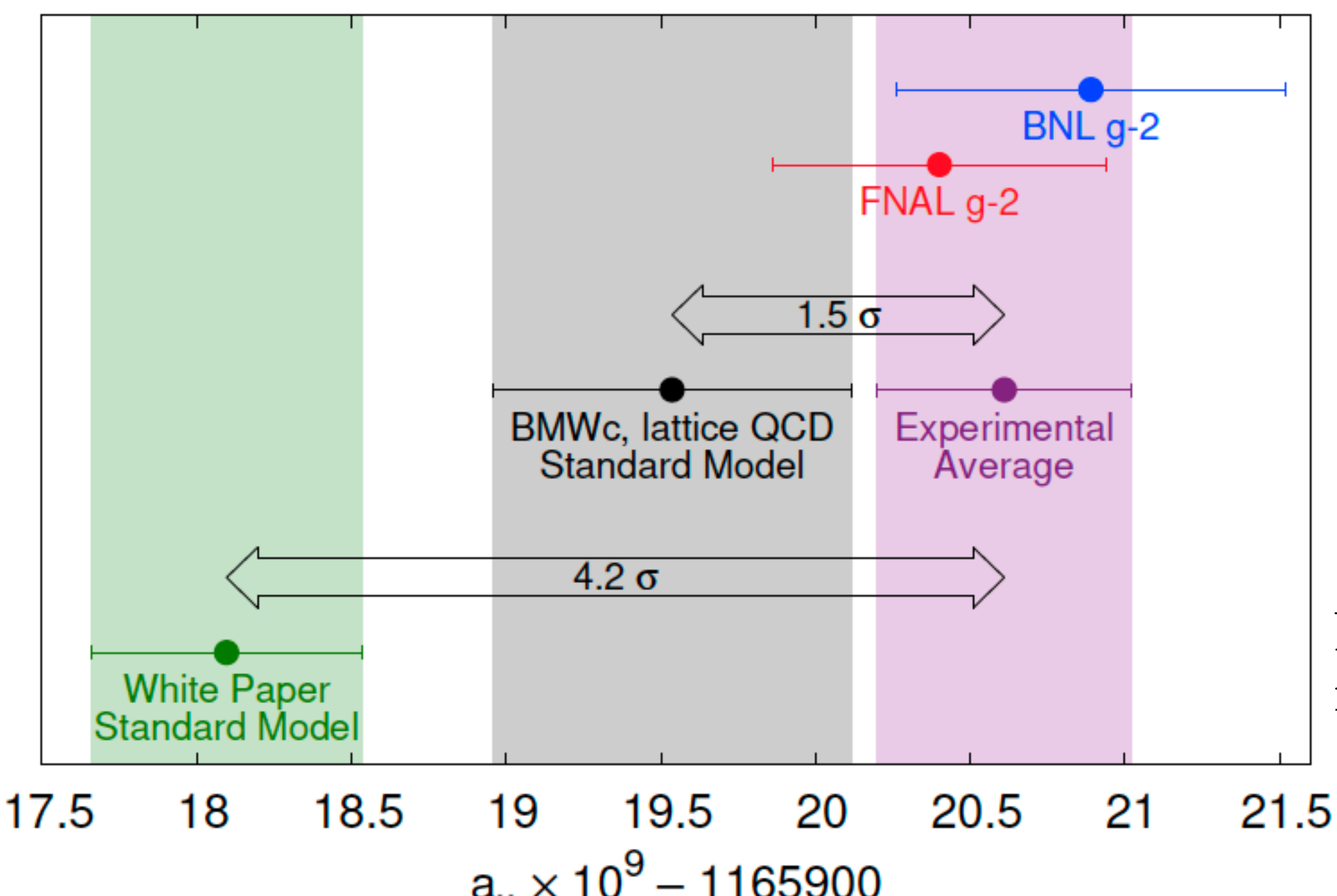

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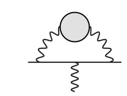
$g = 2.002\ 331\ 83$ hadronic 

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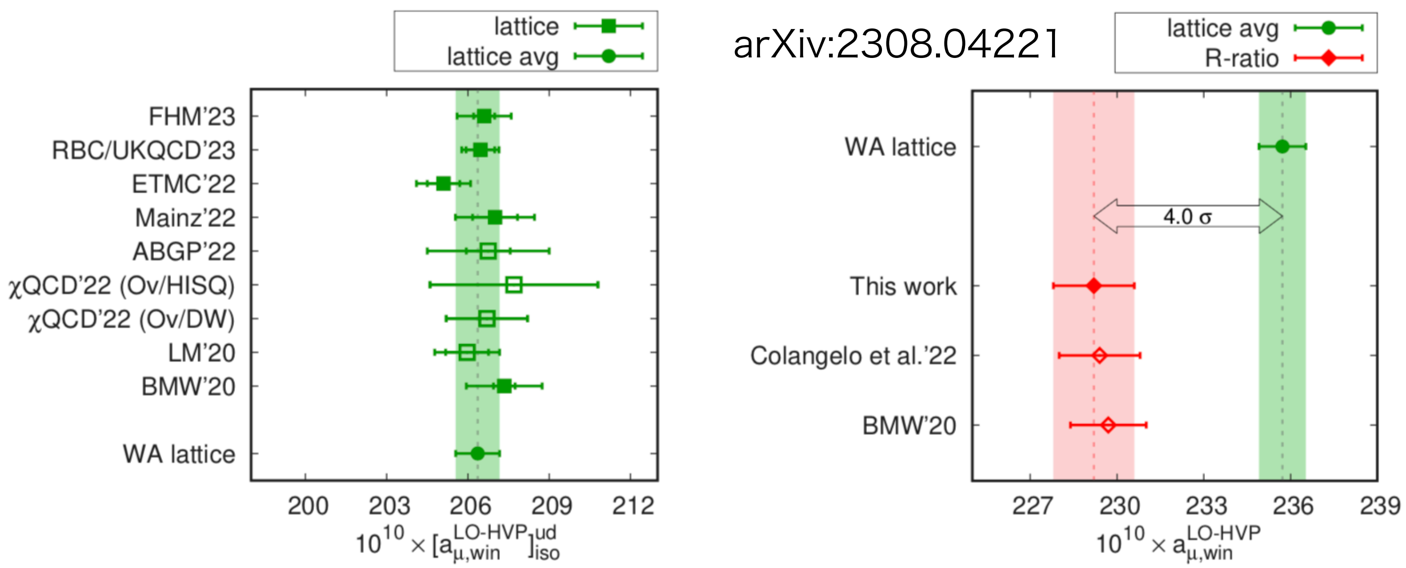
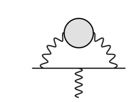


$$g = 2 \qquad \text{tree level, Dirac equation}$$

$$g = 2.002\ 331 \qquad \text{QED}, \quad \frac{\alpha}{\pi} = 0.00232\ldots$$

$$g = 2.002\ 331\ 83 \qquad \text{hadronic}$$



$$g = \underbrace{2.002\ 331\ 836\ 6}_{\text{anomalous magnetic moment}} \qquad \text{EW}$$

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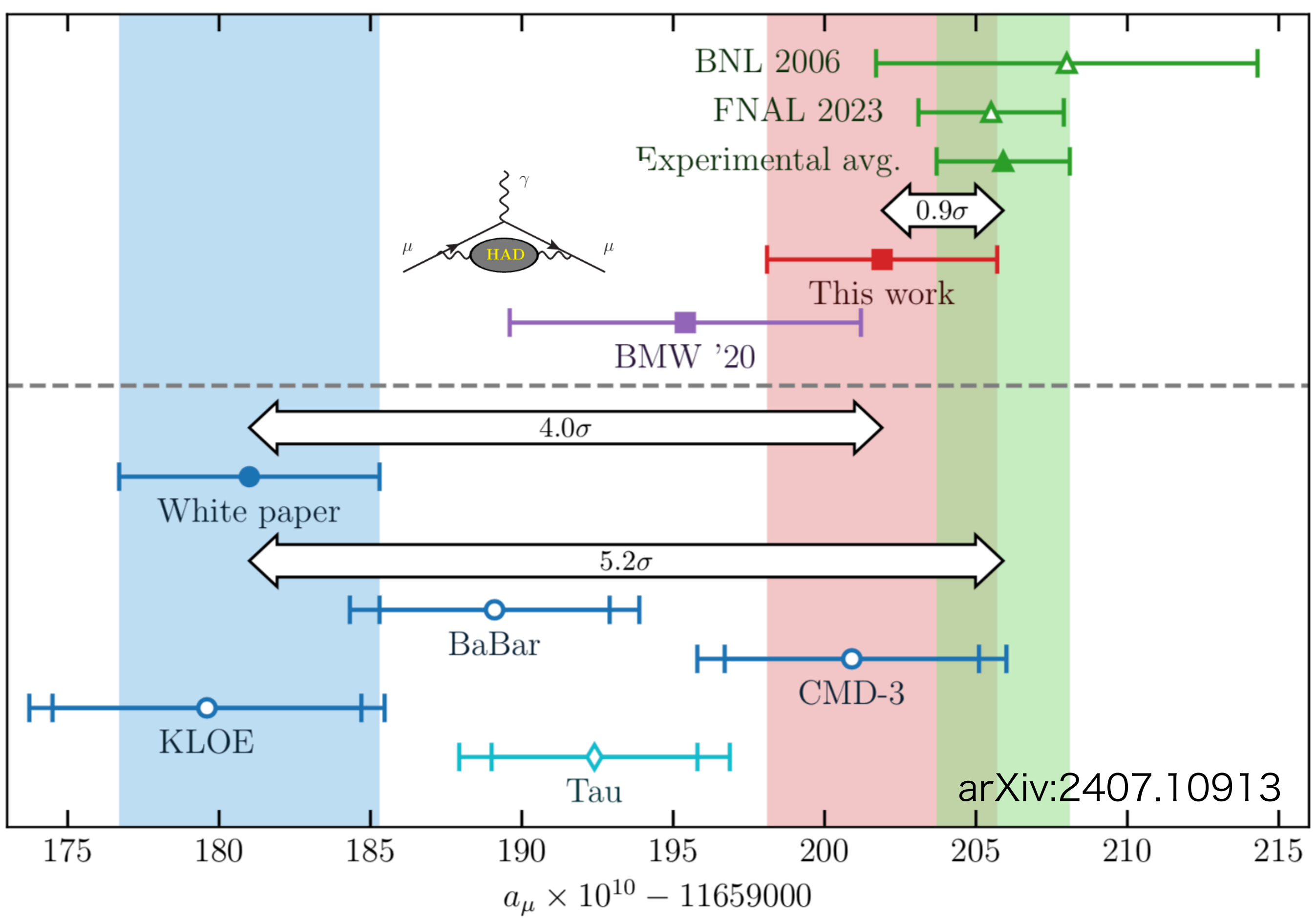

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New particles at O(100GeV) ?

New WP2 for Jan 2025

Two Higgs Doublet Models (2HDM)

appear as a low energy EFT in many well-motivated models (MSSM, Axion Models (PQ sym))

$$\Phi_1 = \begin{pmatrix} H_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + ia_1) \end{pmatrix}, \Phi_2 = \begin{pmatrix} H_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + ia_2) \end{pmatrix}$$

$$v_1^2 + v_2^2 = v_{\rm SM}^2 = (246{\rm GeV})^2$$

$$\tan\beta = v_2/v_1$$

new 4 d.o.f. $\Rightarrow$ new states $H, A, H^\pm$, in addition to h + 3 NG-bosons (*W, Z* longitudinal modes)

Yukawa interactions

$$\mathcal{L} = -\bar{Q}_L^i H_1 y_d^i d_R^i - \bar{Q}_L^i H_2 \rho_d^{ij} d_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \tilde{H}_1 y_u^j u_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \tilde{H}_2 \rho_u^{jk} u_R^k$$
$$-\bar{L}_L^i H_1 y_e^i e_R^i - \bar{L}_L^i H_2 \rho_e^{ij} e_R^j + \text{h.c.}.$$

$$\tilde{H} = (i\sigma_2)H^*$$

To avoid tree-level FCNC by Yukawa interactions, certain parity structure is often introduced

model	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type I	Φ_2	Φ_2	Φ_2	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II (MSSM-like)	Φ_2	Φ_1	Φ_1	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type X (Lepton-specific)	Φ_2	Φ_2	Φ_1	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y (Flipped)	Φ_2	Φ_1	Φ_2	$\cot\beta$	$-\tan\beta$	$\cot\beta$
Aligned				ζ_u	ζ_d	ζ_e

$$\xi_f^h = s_{\beta-\alpha} + c_{\beta-\alpha}\zeta_f$$
$$\xi_f^H = c_{\beta-\alpha} - s_{\beta-\alpha}\zeta_f$$
$$\xi_f^A = (2T_f^3)\zeta_f$$

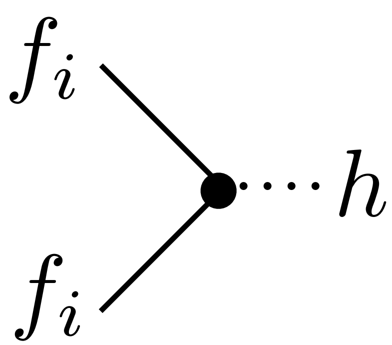
Higgs-gauge couplings identical to the SM in the limit $c_{\beta-\alpha} = 0$ (aligned limit)

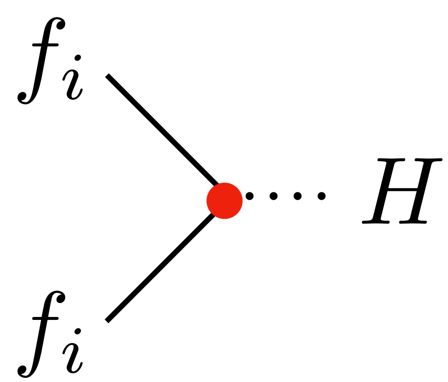
Yukawa interactions to heavy higgses simplified in the limit

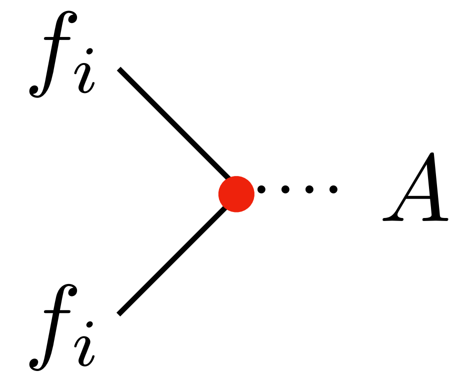
* tan beta enhancement always with the minus sign, the pseudo-scaler couplings depends on isospin

Two Higgs Doublet Models (2HDM)

For Z2 and Aligned models, Yukawa coupling is diagonal at tree level (no Flavor Violation), in Higgs aligned limit,







$$\frac{m_f}{v} \qquad \zeta_f \frac{m_f}{v} \qquad (\pm)\zeta_f \frac{m_f}{v}$$

model	u_R	d_R	e_R	ζ_u	ζ_d	ζ_e
Type I	Φ_2	Φ_2	Φ_2	$\cot\beta$	$\cot\beta$	$\cot\beta$
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Muon g-2 in 2HDM via 1loop

Flavor dependent contribution required
$\Rightarrow$ good candidate : yukawa type coupling

$\Delta a_\mu \sim 2.6 \times 10^{-9}$

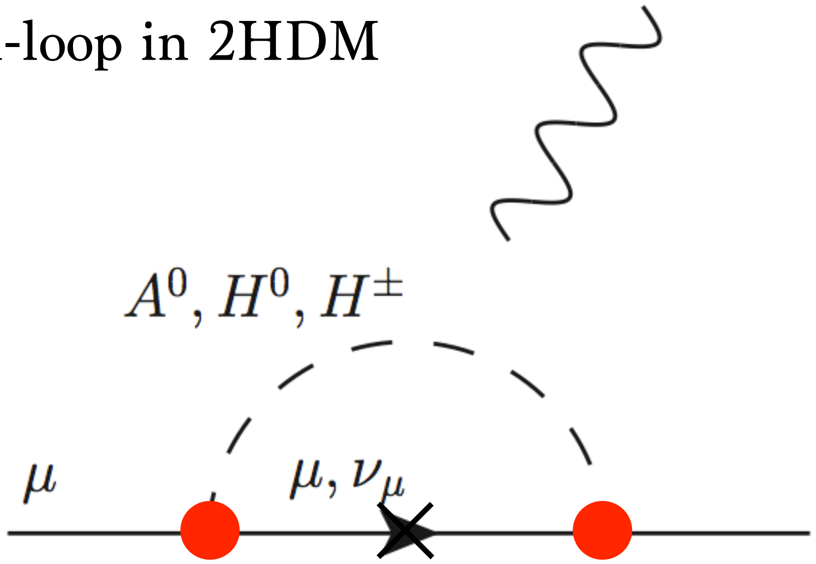
$$r_f^i = m_f^2/m_i^2$$

$$f_{h,H}(r) = \int_0^1 dx \frac{x^2(2-x)}{1-x+rx^2}, \quad f_A(r) = \int_0^1 dx \frac{-x^3}{1-x+rx^2}$$
$$f_{H^\pm}(r) = \int_0^1 dx \frac{-x(1-x)}{1-r(1-x)}.$$

$$g_{h,H}(r) = \int_0^1 dx \frac{2x(1-x)-1}{x(1-x)-r} \ln \frac{x(1-x)}{r},$$
$$g_A(r) = \int_0^1 dx \frac{1}{x(1-x)-r} \ln \frac{x(1-x)}{r}.$$

$\mathcal{O}(10^{-9})$ positive contribution required

1-loop in 2HDM



$$\Delta a_\mu^{\mathrm{VAM,1-loop}} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2} \sum_i^{h,H,A,H^\pm} (\xi^i_{\mu\mu})^2 r^i_\mu f_i(r^i_\mu)$$

$\sim 10^{-9}$ $\quad$ $\sim 10^{-7}$ $\quad m_H = 1\mathrm{TeV}$

$\xi_\mu \sim 3000$ required

Bs $\to$ μμ gives strong constraint: Type II not available
Purturbativity: Type X not available $\zeta_e \lesssim 100$

muon-specific 2HDM
[T. Abe, R. Sato, K. Yagyu, arXiv:1705.01469]

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chirality flip required $\quad \mathcal{L} = a_\mu \frac{e}{4m_\mu} \bar{\psi} \sigma_{\mu\nu} \psi F^{\mu\nu}$

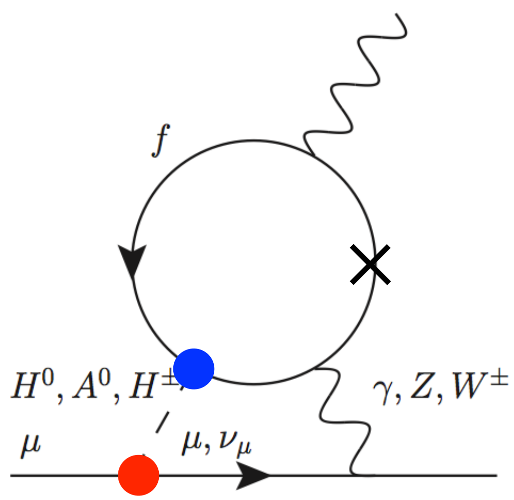
$\propto m_\mu^3/m_H^2$ → LFV enhance with $m_\tau^3/m_\mu^3 \sim 5000$, $\xi_{\mu\tau}^2$ $\quad \xi_{\mu\tau}\xi_{\tau\mu}/m_H^2[\mathrm{TeV}] \sim 10^4$ required

Muon g-2 in 2HDM via 2-loop

2-loop (Barr-Zee) in 2HDM

enhanced by the large yukawa coupling for heavy fermions at 2-loop

$$\Delta a_\mu^{\rm VAM,BZ} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2}\frac{\alpha_{\rm em}}{\pi}\sum_i^{h,H,A}\sum_f^{t,b,c,\tau} N_f^c Q_f^2 \xi_{\mu\mu}^i \xi_{ff}^i r_f^i g_i(r_f^i)$$



$$\propto m_\mu m_f^2/m_H^2$$

	Fermion	(g_f^H, g_f^A)	$(r_f^H g_f^H, r_f^A g_f^A)$	$\times \alpha N_f^c Q_f^2/\pi$	Sign of (δ_H, δ_A)
One loop	μ	$(17, -16)$	$(1.9, -1.8)\times 10^{-7}$	$(1.9, -1.8)\times 10^{-7}$	$(+, -)$
	t	$(-12, 15.9)$	$(-3.6, 4.7)\times 10^{-1}$	$(-1.1, 1.5)\times 10^{-3}$	$(-, -)$
	c	$(-118, 140)$	$(-1.9, 2.3)\times 10^{-4}$	$(-5.9, 7.1)\times 10^{-7}$	$(-, -)$
Two loop	u	$(-282, 330)$	$(-1.5, 1.7)\times 10^{-9}$	$(-4.6, 5.4)\times 10^{-12}$	$(-, -)$
$m_H = m_A = 1{\rm TeV}$	b	$(-87, 105)$	$(-1.5, 1.8)\times 10^{-3}$	$(-1.1, 1.4)\times 10^{-6}$	$(-, +)$
	τ	$(-109, 130)$	$(-3.4, 4.1)\times 10^{-4}$	$(-8.0, 9.6)\times 10^{-7}$	$(-, +)$

the sign depends on the fermion isospin ⇒ tau is only the possibility

2.6×10^{-9} positive contribution required

$\xi_\mu \xi_\tau / m_H^2[{\rm TeV}] \sim 10^6$ required

bottom (type II) disfavored by bbA at LHC and Bs→μμ

In lepton-specific 2HDM model (type X), tau-loop enhanced by tanβ

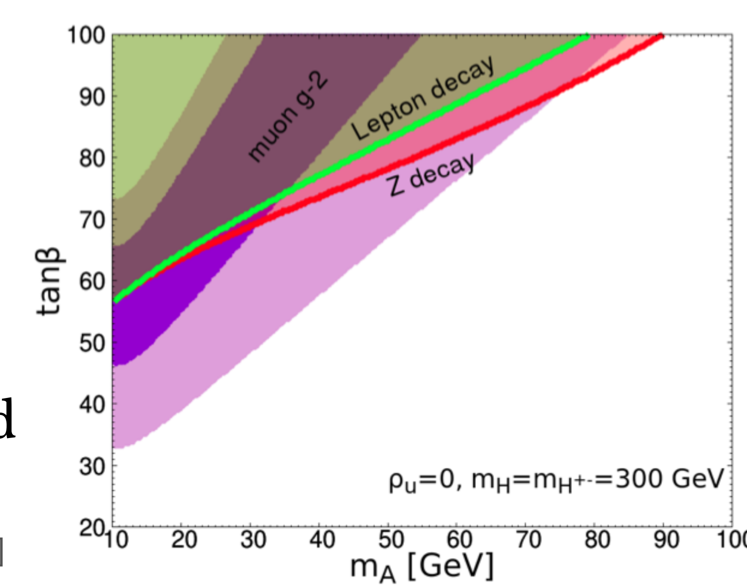
mA ~ 30GeV and tanβ ~ 40 will give a enough contribution

tension : Lepton Universality measurements

As A is light, constraints from Z -> tau tau A (LEP) also exist

LHC constraints weak since all quark couplings to heavier bosons suppressed

Drell-Yan productions ⇒ multi-taus (4 tau, 3tau, 2tau) events sensitive



E.J. Chun, Z.Kang, M.Takeuchi and Y.L.S. Tsai, JHEP11(2015)099, 1507.08067 [hep-ph]

c.f) extension to well motivated model (Variant Axion Model) C-W. Chiang, M. Takeuchi, P-Y. Tseng, T. T. Yanagida Phys. Rev. D **98**, 095020

Muon g-2 at 2HDMs

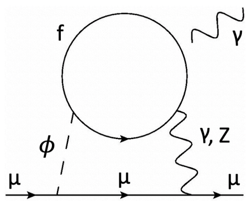
S. Iguro, T. Kitahara, M. Lang, M.T. [PRD108 (11),115012 [arXiv:2304.09887]

In the framework of 2HDMs, available models to explain muon g-2

	Δa_μ	Mass range	Precision	LHC	Lifetime
Type-X 2HDM	2 loop	$m_A = \mathcal{O}(10)$ GeV $\ll m_H = m_{H^\pm}$	$h \to AA$, Z, τ decays	multi-τ	Run 2
FA2HDM	2 loop	$m_A = \mathcal{O}(10)$ GeV $\ll m_H = m_{H^\pm}$	$B_s \to \mu^+\mu^-$, $h \to AA$	multi-τ	Run 2
μ2HDM	1 loop	900 GeV $\le m_{A,H} \le$ 1000 GeV	Z decay	multi-μ	Run 3
$\mu\tau$2HDM	1 loop	500 GeV $\le m_{A,H} \le$ 1600 GeV	$\tau \to \mu\nu\bar{\nu}$	$\mu^\pm\mu^\pm\tau^\mp\tau^\mp$	HE-LHC

Among popular Z2 models, Type X is the only possibility with light A O(30)GeV

Tuning for $h \to AA$ is required. $|\lambda_{hAA}| \lesssim 0.03 - 0.01$ $\lambda_{hAA} = \lambda_3 + \lambda_4 - \lambda_5$



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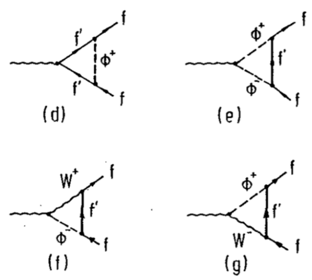
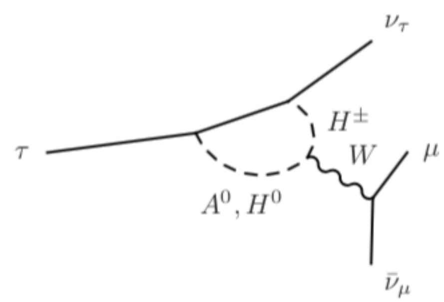
Z decay

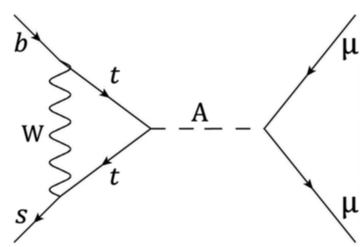


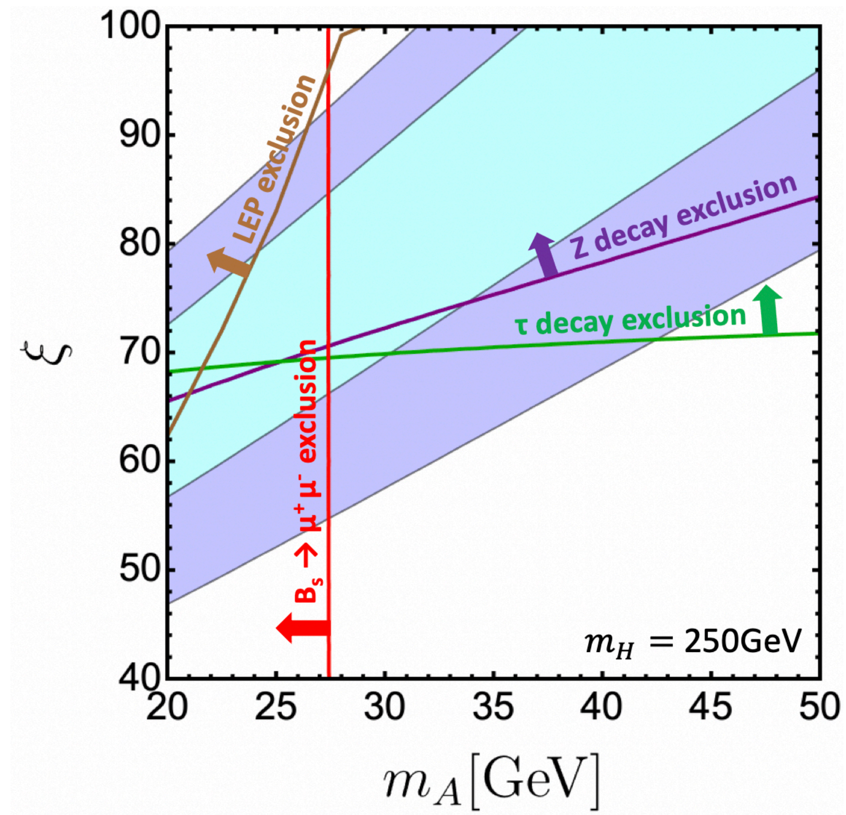
τ decay

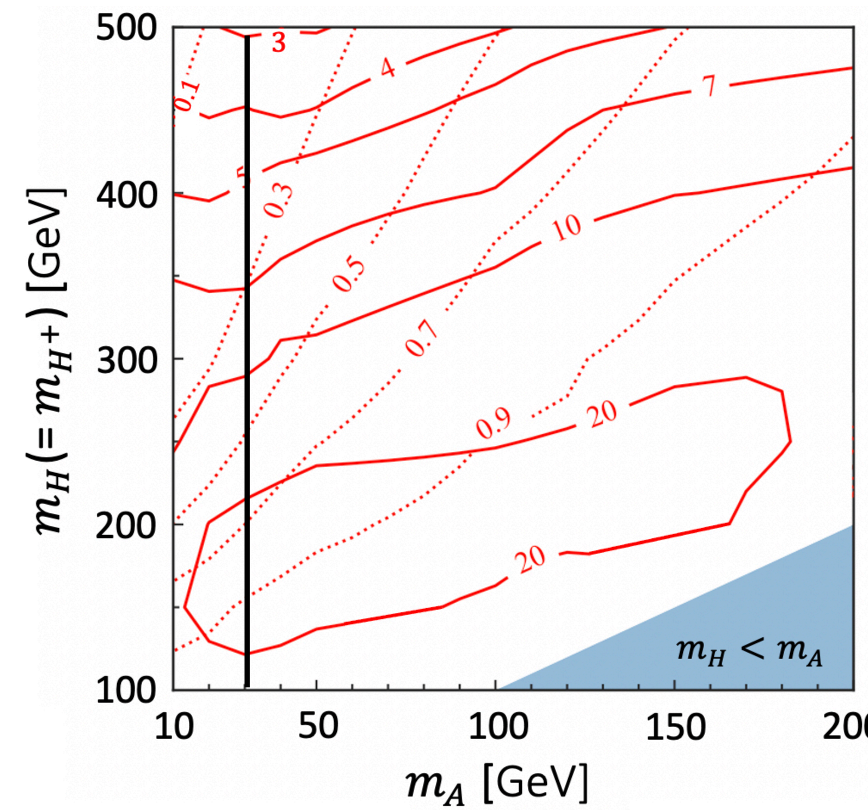


LEP $e^+e^- \to \tau^+\tau^-(A \to \tau^+\tau^-)$

$B_s \to \mu^+\mu^-$





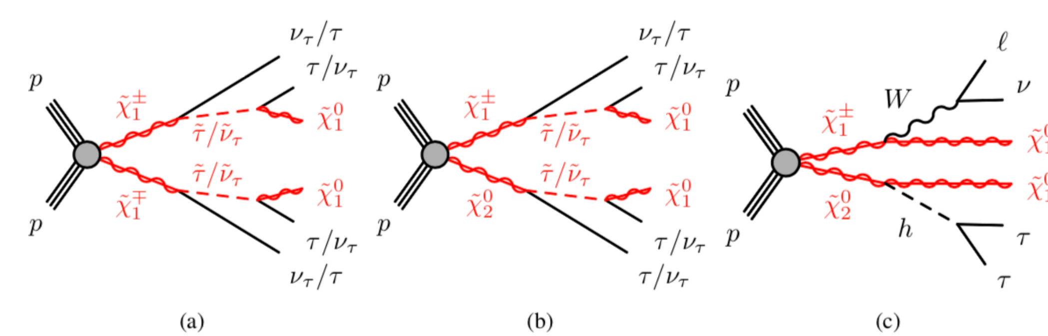


Chargino-neutralino, Chargino-chargino searches at LHC in multi-tau SRs already exclude the type-X and aligned 2HDMs to explain muon g-2.

[ATLAS-CONF-2022-042] OS taus, SS taus etc. 139 ifb

$$pp \to HA, H^\pm A, H^\pm H, H^+H^- \to \text{multi}-\tau$$

$$BR(H \to \tau\tau) + BR(H \to ZA) = 1 \quad BR(A \to \tau\tau) \simeq 1$$



Muon g-2 at 2HDMs

S. Iguro, T. Kitahara, M. Lang, M.T. [PRD108 (11),115012 [arXiv:2304.09887]

In the framework of 2HDMs, available models to explain muon g-2

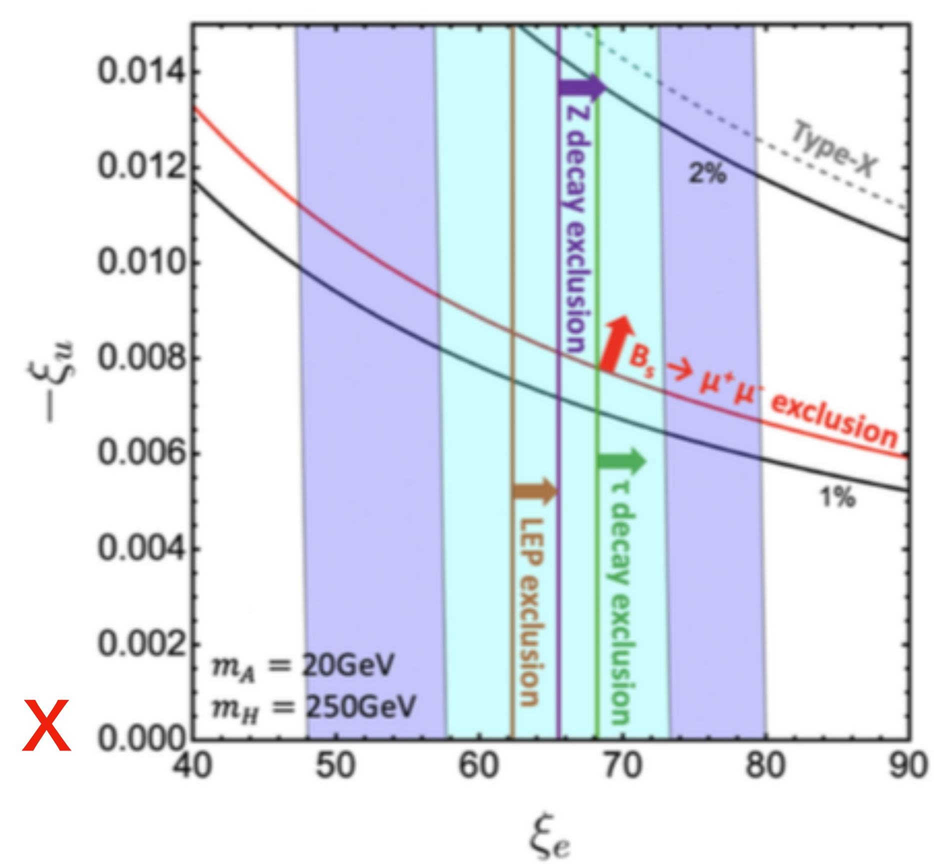
	Δa_μ	Mass range	Precision	LHC	Lifetime
~~Type-X 2HDM~~	~~2 loop~~	~~$m_A = \mathcal{O}(10)$ GeV $\ll m_H = m_{H^\pm}$~~	~~$h \to AA$, Z, τ decays~~	~~multi-τ~~	~~Run 2~~
~~FA2HDM~~	~~2 loop~~	~~$m_A = \mathcal{O}(10)$ GeV $\ll m_H = m_{H^\pm}$~~	~~$B_s \to \mu^+\mu^-$, $h \to AA$~~	~~multi-τ~~	~~Run 2~~
μ2HDM	1 loop	900 GeV $\leq m_{A,H} \leq$ 1000 GeV	Z decay	multi-μ	Run 3
$\mu\tau$2HDM	1 loop	500 GeV $\leq m_{A,H} \leq$ 1600 GeV	$\tau \to \mu\nu\bar{\nu}$	$\mu^\pm\mu^\pm\tau^\mp\tau^\mp$	HE-LHC

Flavor-Aligned 2HDM: Available parameter space in is only the vicinity of the above Type X solution (we don't consider a very fine tuned cancelation among $\zeta_e, \zeta_u, \zeta_d$)

$B_s \to \mu^+\mu^-$ constrain $\zeta_u \lesssim 0.01$,
where BZ contribution is at most O(1)%

→ Phenomenology is essentially identical to Type X

→ Excluded



Muon g-2 at mu2HDM

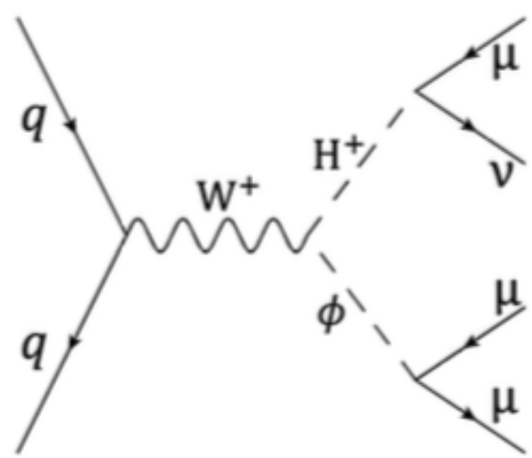
S. Iguro, T. Kitahara, M. Lang, M.T. [PRD108 (11),115012 [arXiv:2304.09887]

$m_H < m_A$ to have correct sign of $\Delta a_\mu^{\rm NP} \propto -\xi_\mu^2 \Delta m_{H-A}$ $m_H \simeq m_H^\pm$ favored

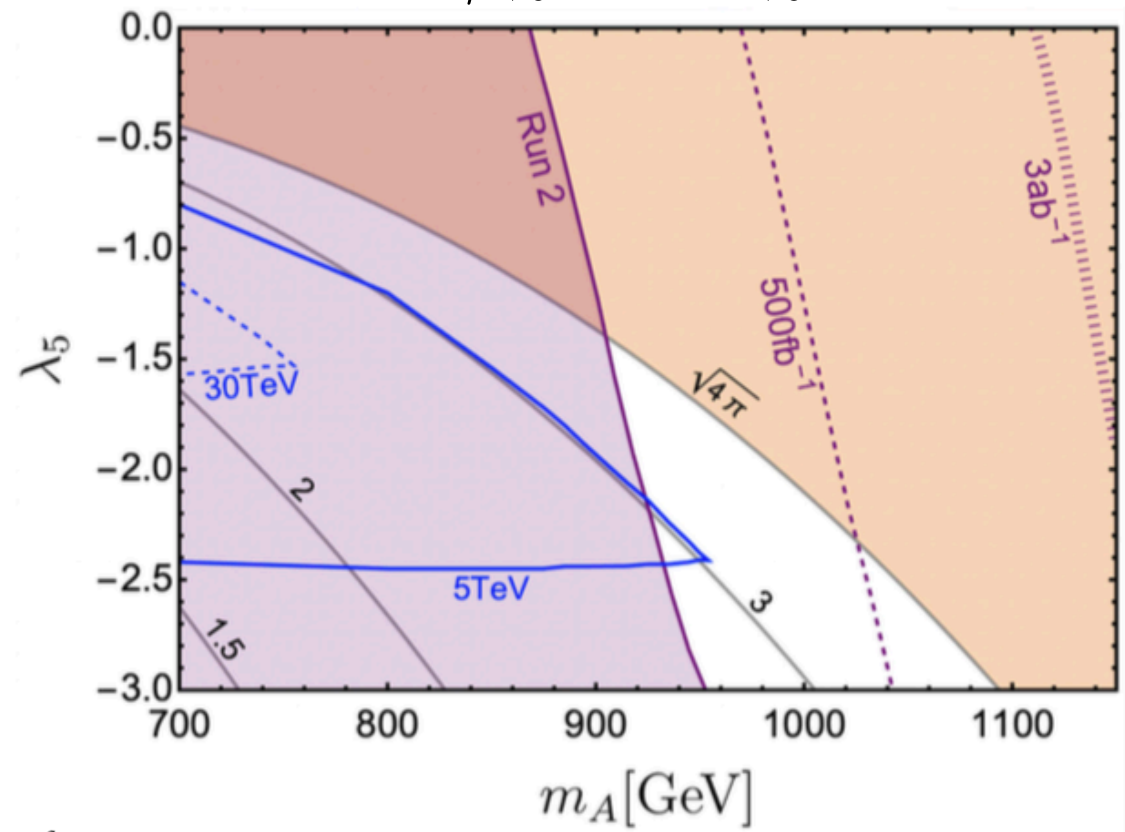
$$m_H^2 = m_A^2 + \lambda_5 v^2$$

Multi-mu signature constrain the scenario

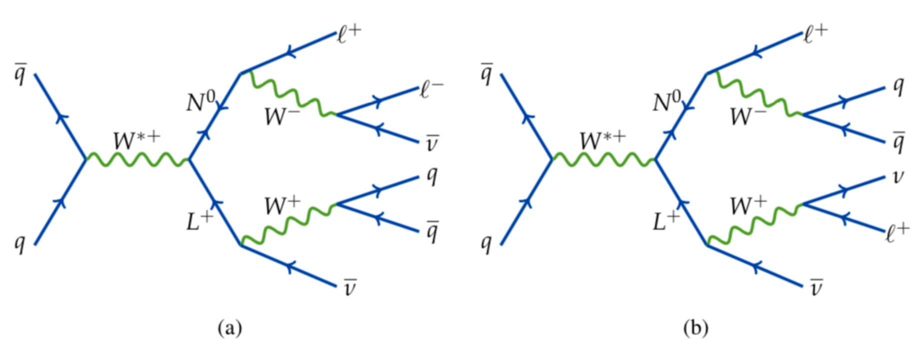
$$pp \to \phi H^\pm \to 3\mu + \nu_\mu$$



$\xi_\mu \lesssim 5900, \lambda_5 \lesssim \sqrt{4\pi}$



Recasting
arXiv:2008.07949
[ATLAS]
type 3 see saw search



Currently, $m_A \lesssim 900$ GeV is excluded. Run 3 (500 fb^{-1}) will cover the whole region.

g-2 in 2HDM via 1loop

Flavor dependent contribution required
$\Rightarrow$ good candidate : yukawa type coupling

$\Delta a_\mu \sim 2.6 \times 10^{-9}$

$\mathcal{O}(10^{-9})$ positive contribution required

$$r^i_f = m_f^2/m_i^2$$

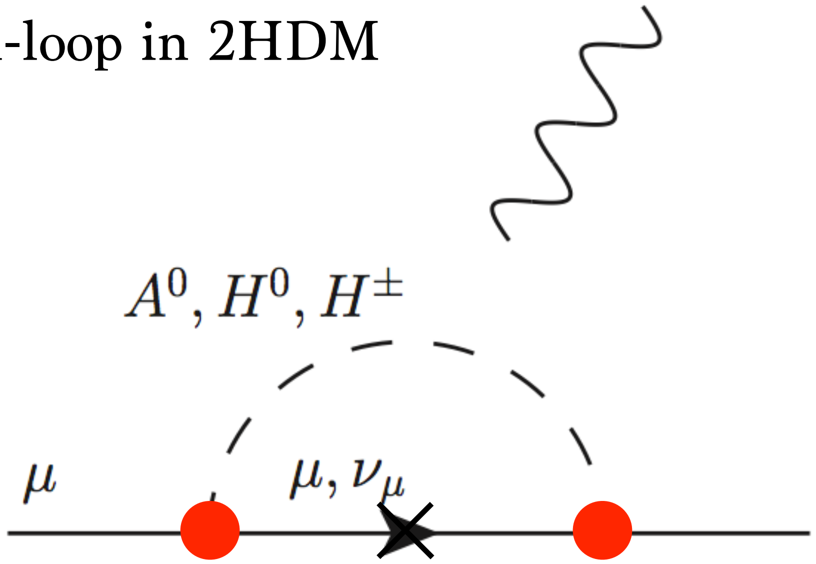
$$f_{h,H}(r) = \int_0^1 dx \frac{x^2(2-x)}{1-x+rx^2}, \quad f_A(r) = \int_0^1 dx \frac{-x^3}{1-x+rx^2}$$

$$f_{H^\pm}(r) = \int_0^1 dx \frac{-x(1-x)}{1-r(1-x)}.$$

$$g_{h,H}(r) = \int_0^1 dx \frac{2x(1-x)-1}{x(1-x)-r} \ln \frac{x(1-x)}{r},$$

$$g_A(r) = \int_0^1 dx \frac{1}{x(1-x)-r} \ln \frac{x(1-x)}{r}.$$

1-loop in 2HDM



$$\Delta a_\mu^{\mathrm{VAM,1-loop}} = \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2} \sum^{h,H,A,H^\pm} (\xi^i_{\mu\mu})^2 r^i_\mu f_i(r^i_\mu)$$

$\sim 10^{-9}$ $\qquad$ $\sim 10^{-7}$ $\quad m_H = 1\mathrm{TeV}$

$\xi_\mu \sim 3000$ **required**

chirality flip required $\quad \mathcal{L} = a_\mu \frac{e}{4m_\mu} \bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu}$

$\propto m_\mu^3/m_H^2$ ➡ **LFV enhance with** $m_\tau^3/m_\mu^3 \sim 5000$, $\xi^2_{\mu\tau}$ $\quad \xi_{\mu\tau}\xi_{\tau\mu}/m_H^2[\mathrm{TeV}] \sim 10^4$ required

g-2 via lepton flavor violation

[S.Iguro, Y. Omura, MT arXiv:1907.09845]

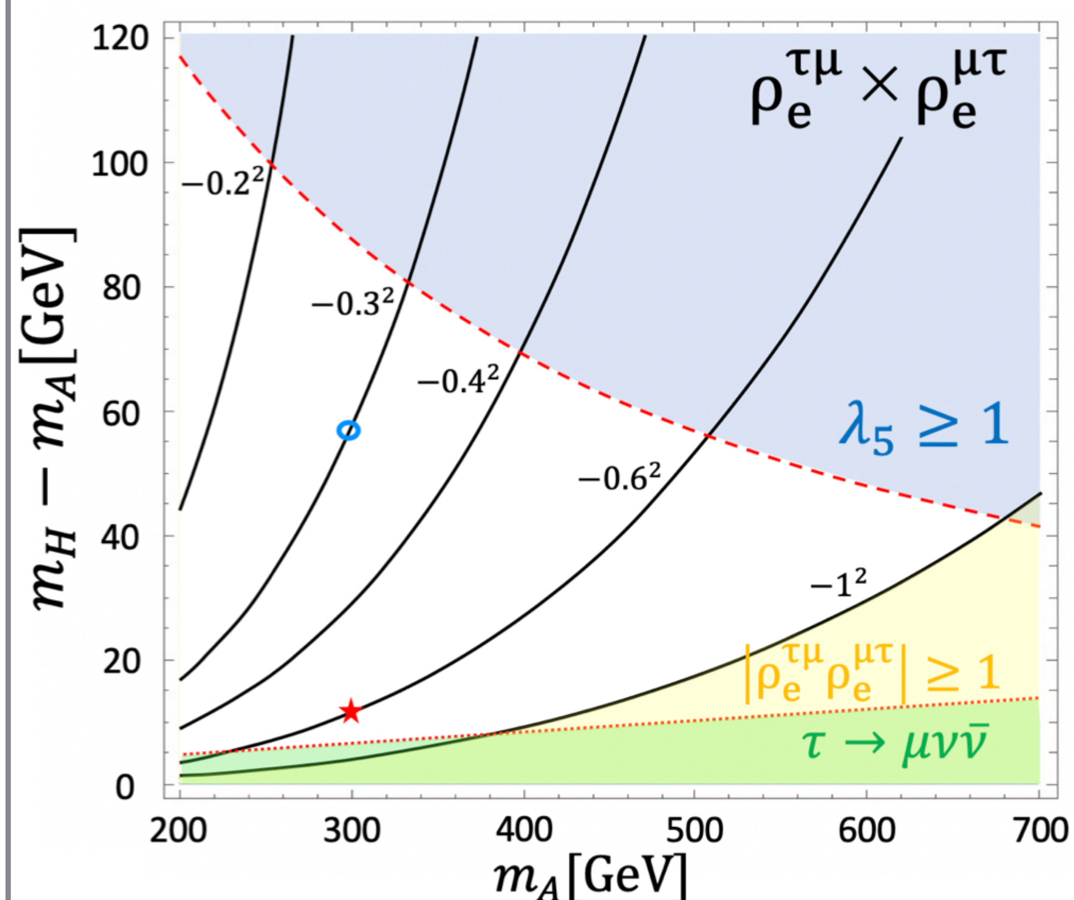
	Φ_1	Φ_2	Q	u_R	d_R	(L_e, L_μ, L_τ)	(e_R, μ_R, τ_R)
Type I	0	1	0	1	1	0	1
Type II	0	1	0	1	0	0	0
Type X	0	1	0	1	1	0	0
Type Y	0	1	0	1	0	0	1
μ2HDM	2	0	0	0	0	(0, −1, 0)	(0, 1, 0)
$\mu\tau$2HDM	2	0	0	0	0	(0, 1, −1)	(0, 1, −1)

g2HDM (new Yukawa matrices : free parameters, phenomenological analysis)

we consider only $\rho^{\mu\tau}, \rho^{\tau\mu}$

cf) [Y. Abe, T. Toma and K. Tsumura, arXiv:1904.10908]
J. High Energy Phys. 06 (2019) 142.

$$\mathcal{L} = -\bar{Q}^i_L H_1 y^i_d d^i_R - \bar{Q}^i_L H_2 \rho^{ij}_d d^j_R - \bar{Q}^i_L (V^\dagger)^{ij} \tilde{H}_1 y^j_u u^j_R - \bar{Q}^i_L (V^\dagger)^{ij} \tilde{H}_2 \rho^{jk}_u u^k_R$$
$$-\bar{L}^i_L H_1 y^i_e e^i_R - \bar{L}^i_L H_2 \rho^{ij}_e e^j_R + \text{h.c.}.$$



$$\Delta a_\mu \simeq -\frac{m_\mu m_\tau \rho_e^{\mu\tau}\rho_e^{\tau\mu}}{8\pi^2}\frac{\Delta_{H-A}}{m_A^3}\left(\ln\frac{m_A^2}{m_\tau^2}-\frac{5}{2}\right)$$
$$\simeq -3\times 10^{-9}\left(\frac{\rho_e^{\mu\tau}\rho_e^{\tau\mu}}{0.3^2}\right)\left(\frac{\Delta_{H-A}}{60[\text{GeV}]}\right)\left(\frac{300[\text{GeV}]}{m_A}\right)^3$$

$$\Delta_{H-A} = m_H - m_A$$

$\xi_{\mu\tau}\xi_{\tau\mu}/m_H^2[\text{TeV}] \sim 10^4$ required

in Higgs potential, $V(H_i) = \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \{\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \text{h.c.}\} + \cdots$

$$m_H^2 \simeq m_A^2 + \lambda_5 v^2, \qquad m_{H^\pm}^2 \simeq m_A^2 - \frac{\lambda_4 - \lambda_5}{2} v^2,$$

perturbativity, stability $0 < \lambda_5 < 1 \quad |\rho^{\mu\tau}|, |\rho^{\tau\mu}| < 1$

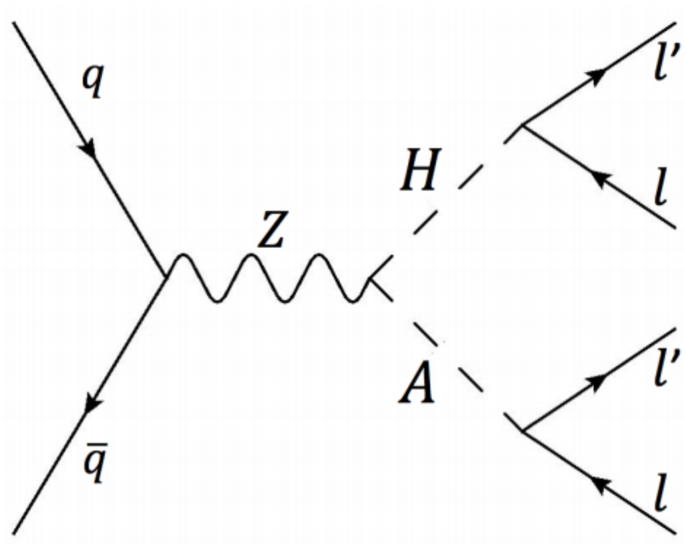
we consider $m_A \leq m_H = m_{H^\pm}$

then the parameter region available is finite $m_A \lesssim 700\text{GeV}$

$10\text{GeV} \lesssim \Delta_{H-A} \lesssim 100\text{GeV}$

	m_A	m_H	$m_{H^\pm}$	$\sigma(HA)$	$\sigma(AH^\pm)$	$\sigma(HH^\pm)$	$\sigma(H^+H^-)$
BP1	300 GeV	358 GeV	358 GeV	2.4 fb	4.6 fb	3.3 fb	1.8 fb
BP2	300 GeV	312 GeV	312 GeV	3.3 fb	6.3 fb	5.7 fb	3.2 fb

g-2 via lepton flavor violation — LHC signatures



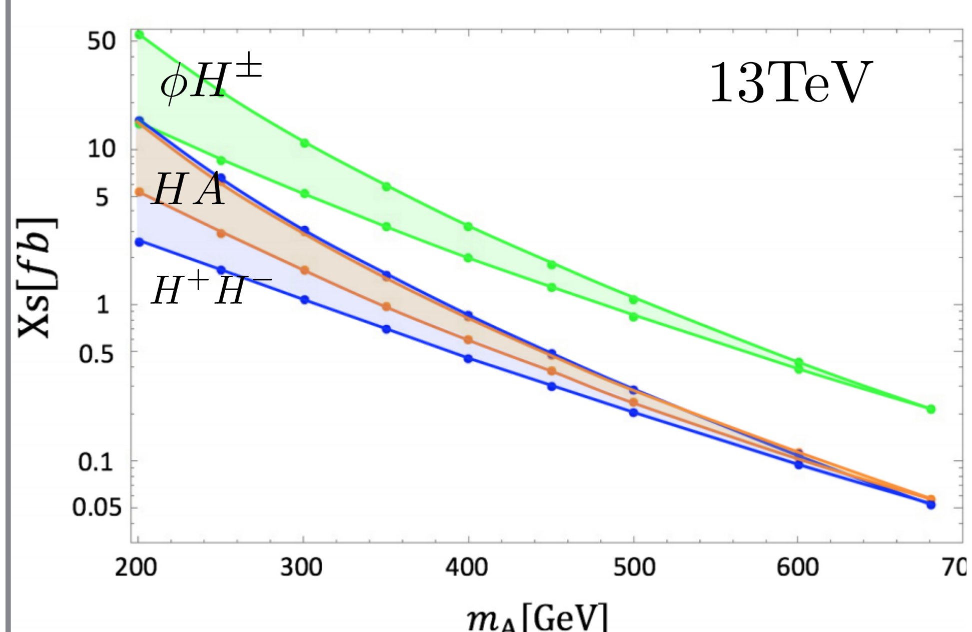
no QCD coupling : small production rate at LHC, still finite rate via SU(2) coupling

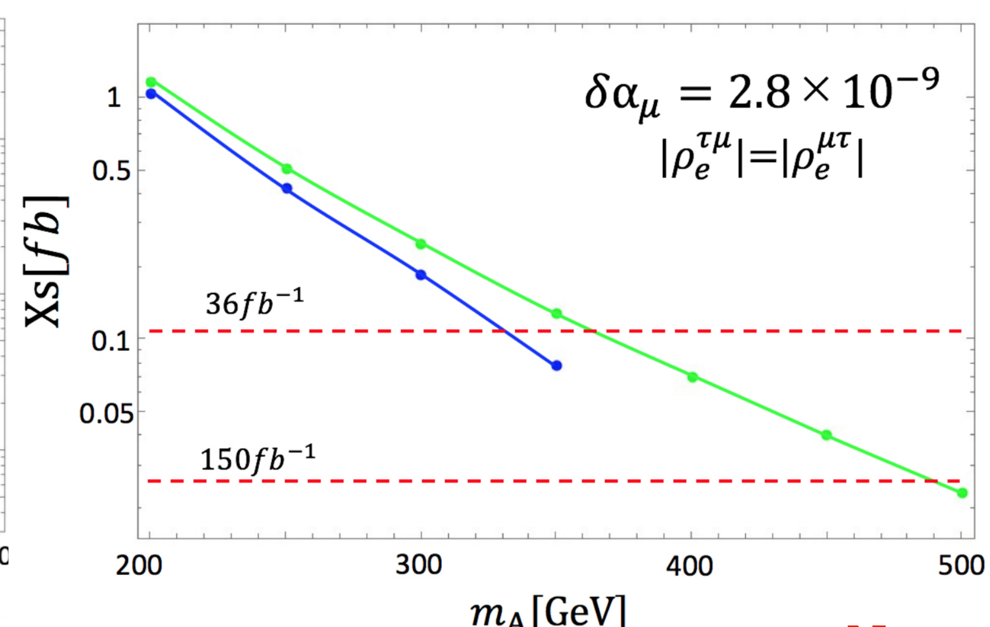
Heavy higgses produced in pair via Drell-Yan,

the three production processes, HA, $\phi H^{\pm}$, and $H^{+}H^{-}$, where $\phi = H, A$.

$$BR(\phi \to \tau^{+}\mu^{-}) = BR(\phi \to \tau^{-}\mu^{+}) = 0.5,$$
$$BR(H^{\pm} \to \tau^{\pm}\nu) = 1 - BR(H^{\pm} \to \mu^{\pm}\nu) = \frac{|\rho_e^{\mu\tau}|^2}{|\rho_e^{\tau\mu}|^2 + |\rho_e^{\mu\tau}|^2} \equiv r.$$

they results in 4 leptons, 3 leptons, 2 leptons (OS, SS)





multi-lepton $2\mu 2\tau$ channels

No SMBG expected.

current data should already be sensitive at LHC up to 500 GeV

No experimental study available yet!

g-2 via lepton flavor violation

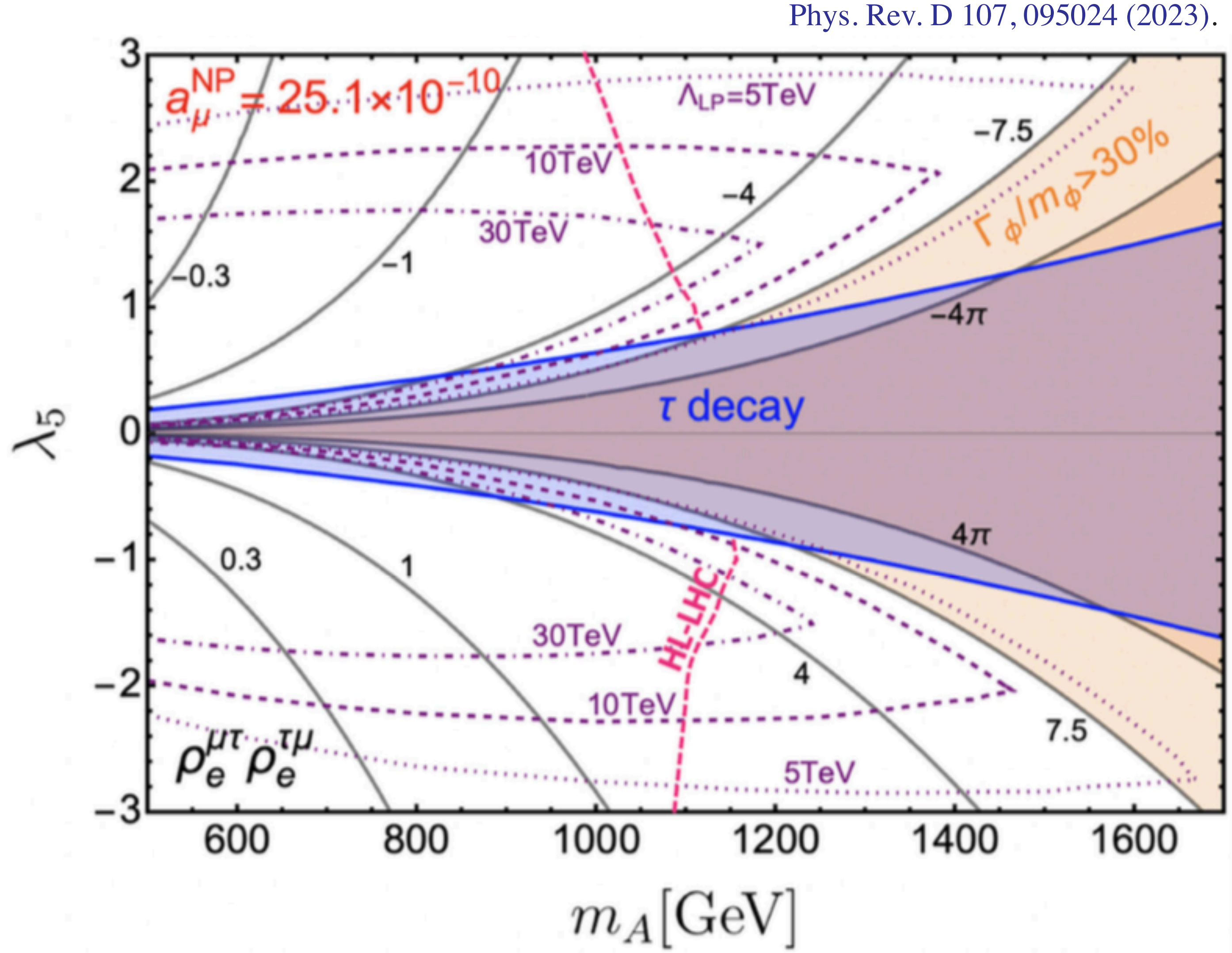
S. Iguro, T. Kitahara, M. Lang, M.T. [PRD108 (11),115012 [arXiv:2304.09887]

g2HDM (new Yukawa matrices : free parameters, phenomenological analysis)

we consider only $\rho^{\mu\tau}, \rho^{\tau\mu}$

cf) [Y. Abe, T. Toma and K. Tsumura, arXiv:1904.10908] J. High Energy Phys. 06 (2019) 142.

Phys. Rev. D 107, 095024 (2023).



Considering RGE effects and purturbativity the parameter space is finite.

$$m_A < 1650(1250)\ \text{GeV}$$

HL-LHC cover $m_A \lesssim 1100\text{GeV}$

Signal: $(\mu^+\tau^-)(\mu^+\tau^-)$ with two resonances

HE-LHC cover the entire region.

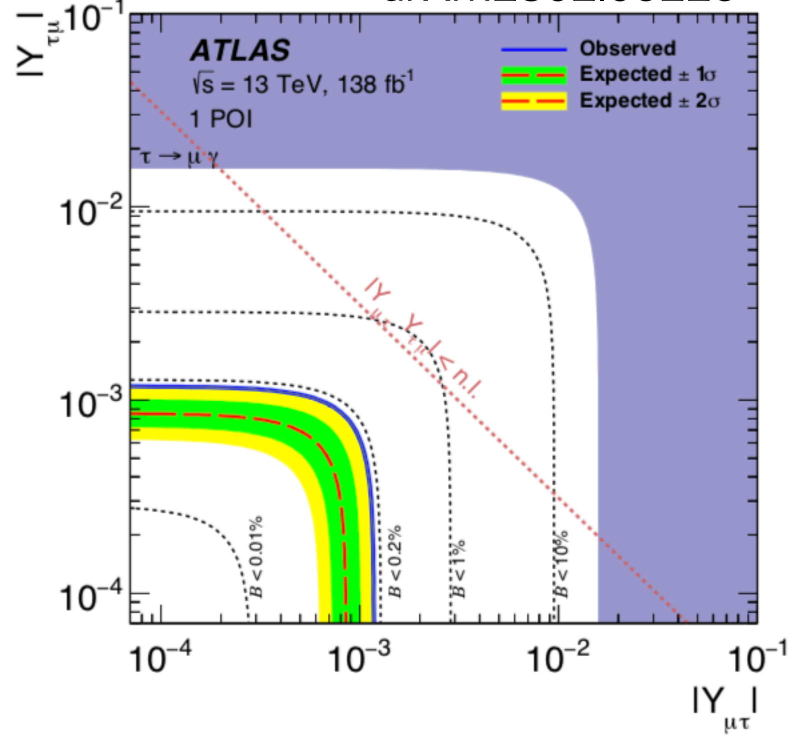
Signal doesn't depend much on $|\rho|$

$R = \rho_{\mu\tau}/\rho_{\tau\mu}$ will affect the $H^\pm$ decays and H/A decay polarizations.

arXiv:2302.05225

hLFV in 2HDM

Some excess in h → $\tau\,\mu$ at LHC

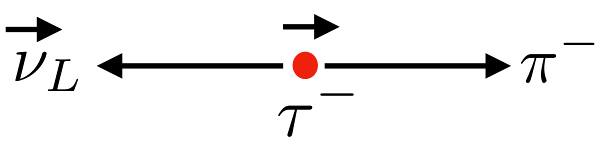


Tau-decays preserve the information on its polarization

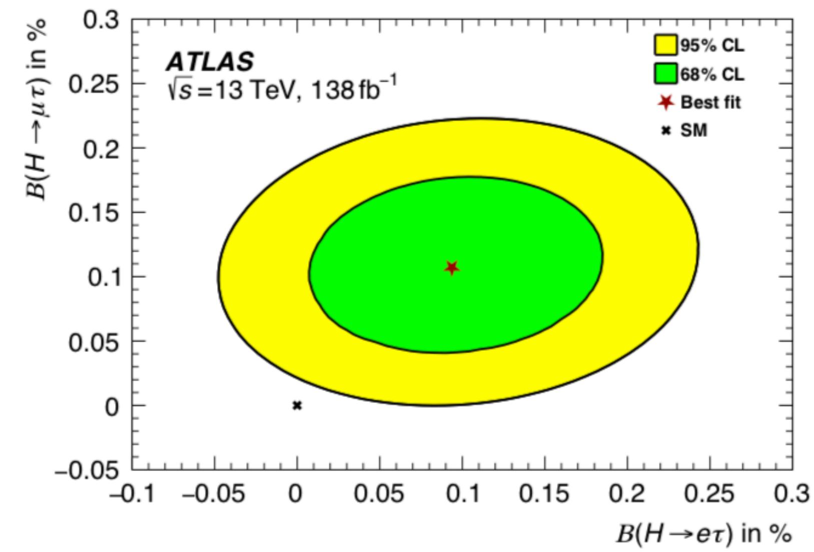
M. Aoki, S. Kanemura, MT, L. Zamakhsyari
[Phys.Rev.D 107 (2023) 5, 055037, arXiv: 2302.08489]

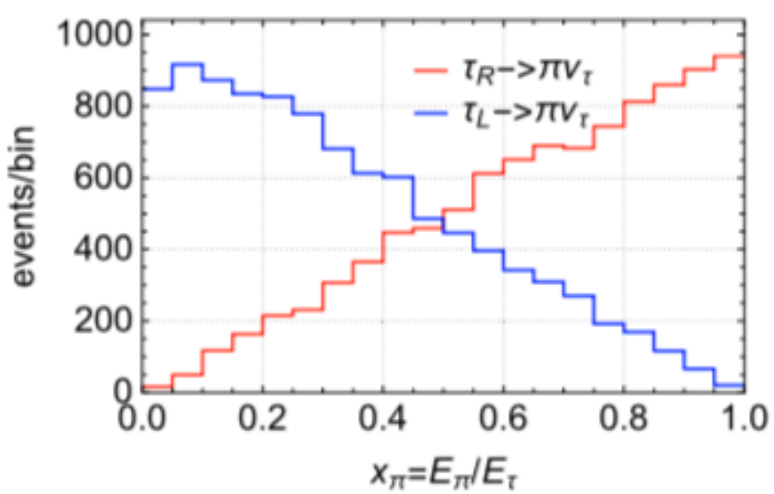
R-handed τ- produce

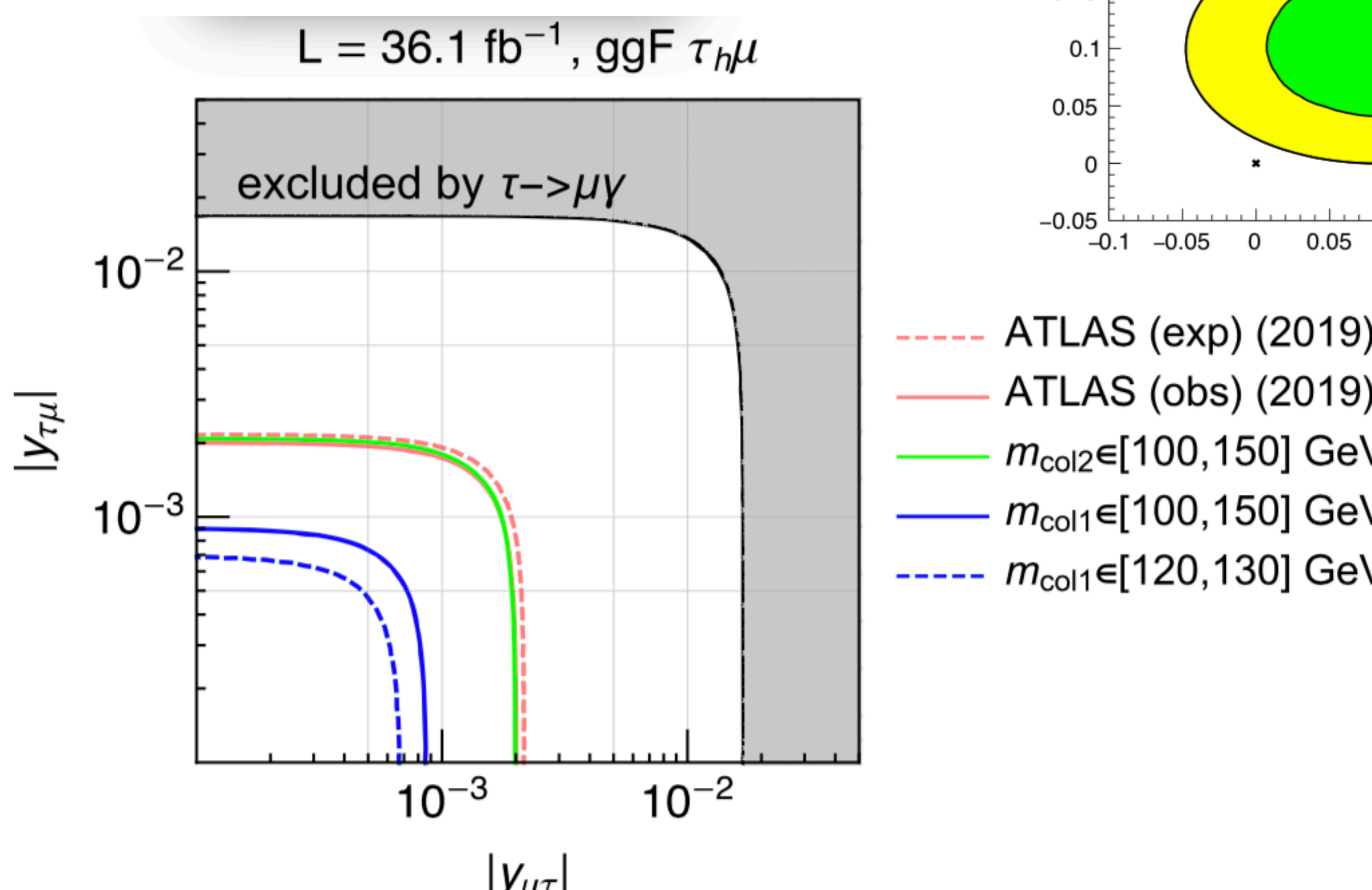
more energetic π-

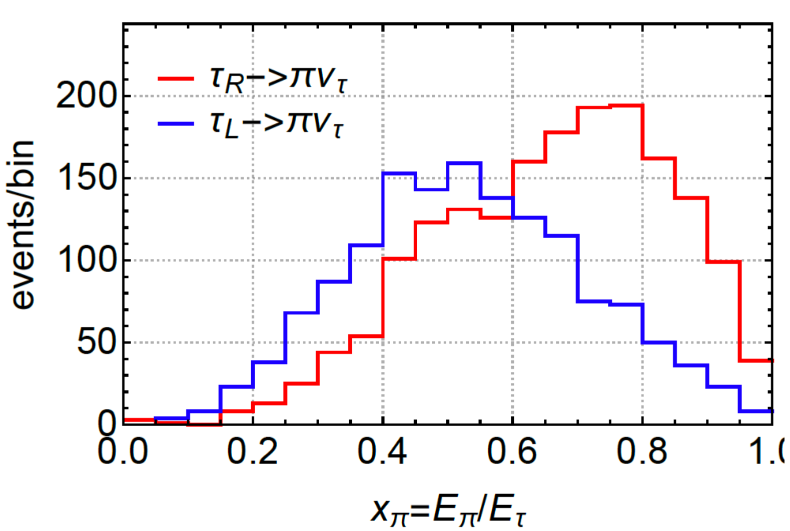


$$-\mathcal{L}_{\rm LFV} = y_{\tau\mu} h \bar{\tau}_L \mu_R + y_{\mu\tau} h \bar{\mu}_L \tau_R + h.c.$$





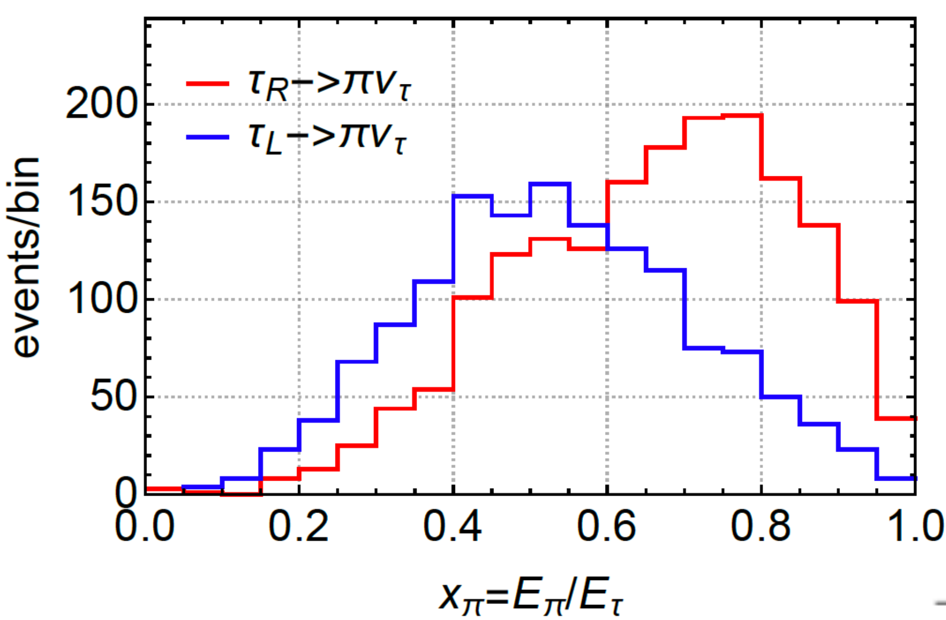




Use of Tau-polarization in hLFV

M. Aoki, S. Kanemura, MT, L. Zamakhsyari [Phys.Rev.D 107 (2023) 5, 055037, arXiv: 2302.08489]

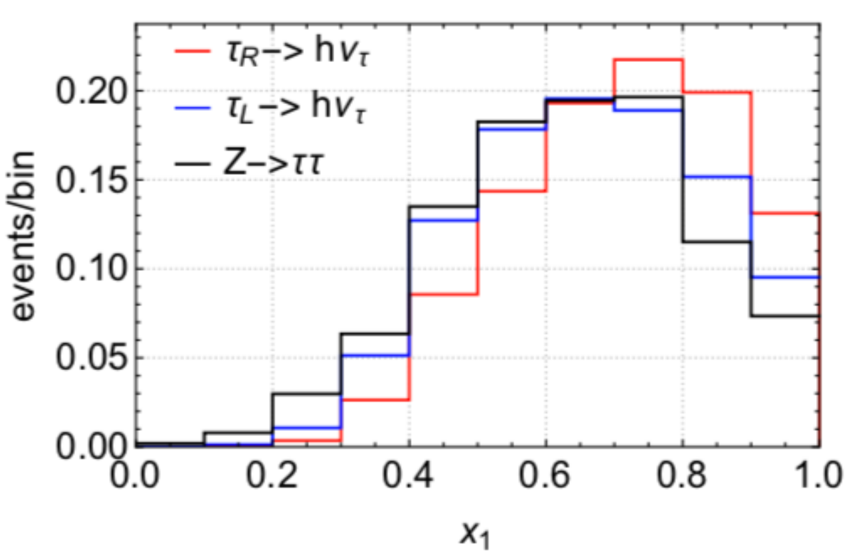
Tau-decays preserve the information on its polarization



$$-\mathcal{L}_{\rm LFV} = y_{\tau\mu} h \bar{\tau}_L \mu_R + y_{\mu\tau} h \bar{\mu}_L \tau_R + h.c.$$

ATLAS reports an excess on h → τμ (BR~ 0.1%)
[arXiv:2302.05225 [hep-ex]]

Sensitivity for the chirality, which would help to discriminate the UV models

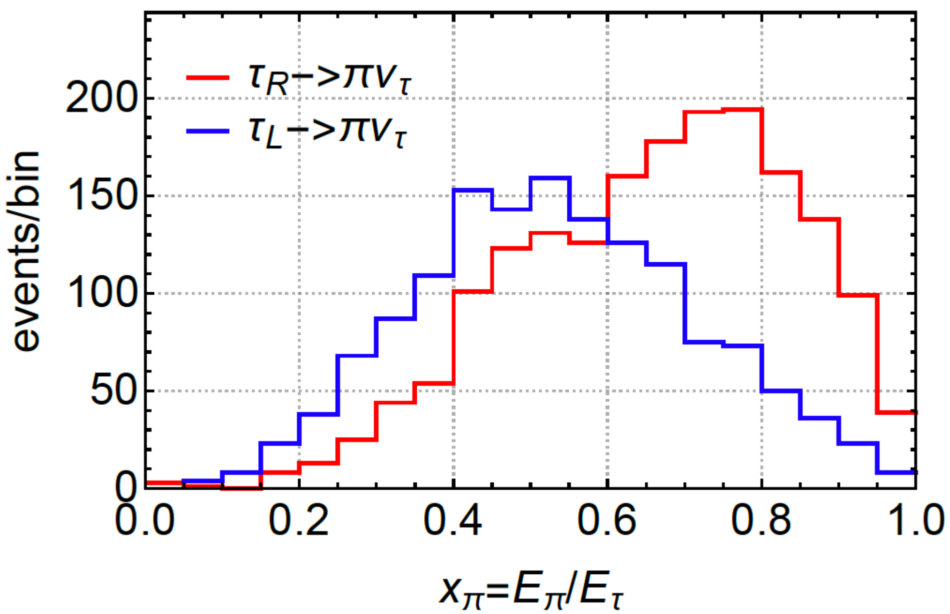


$\Delta m^{\rm th}_{\rm col1}$	SR	$N_{i,BR=0.12\%}$			N_i/N			$N_{i,\rm obs}$ for each scenario		
		τ_R	τ_L	$Z\to\tau\tau$	τ_R	τ_L	$Z\to\tau\tau$	τ_R	τ_0	τ_L
25 GeV	SR_1	50.6	66.1	1692	0.26	0.37	0.42	3436	3443	3451
	SR_2	144.5	113.1	2331	0.74	0.63	0.58	4807	4791	4776
	total	195.1	179.2	4023	1	1	1	8243	8234	8227
5 GeV	SR_1	17.8	25.6	136	0.24	0.37	0.37	289.8	293.7	297.6
	SR_2	56.2	43.6	80	0.76	0.63	0.63	216.2	209.9	203.6
	total	74.0	69.2	216.0	1	1	1	506	503.6	501.2

Use of Tau-polarization in hLFV

M. Aoki, S. Kanemura, MT, L. Zamakhsyari [Phys.Rev.D 107 (2023) 5, 055037, arXiv: 2302.08489]

Tau-decays preserve the information on its polarization



$$-\mathcal{L}_{\rm LFV} = y_{\tau\mu} h \bar{\tau}_L \mu_R + y_{\mu\tau} h \bar{\mu}_L \tau_R + h.c.$$

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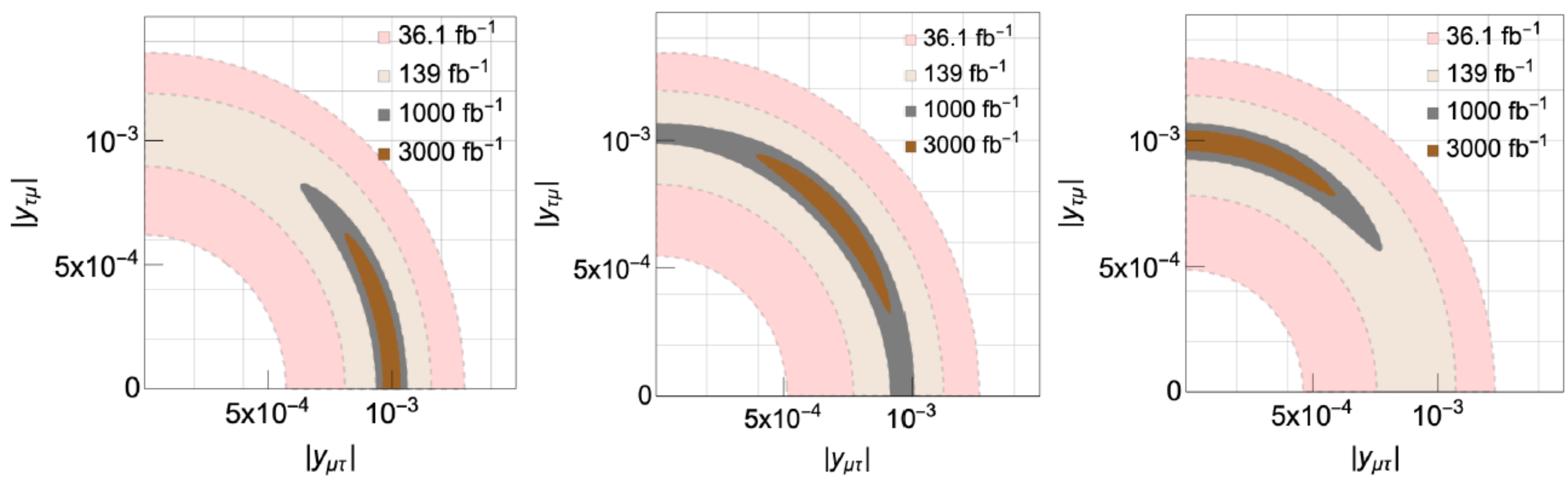
Sensitivity for the chirality, which would help to discriminate the UV models



Use of Tau-polarization in hLFV

M. Aoki, S. Kanemura, MT, L. Zamakhsyari [Phys.Rev.D 107 (2023) 5, 055037, arXiv: 2302.08489]

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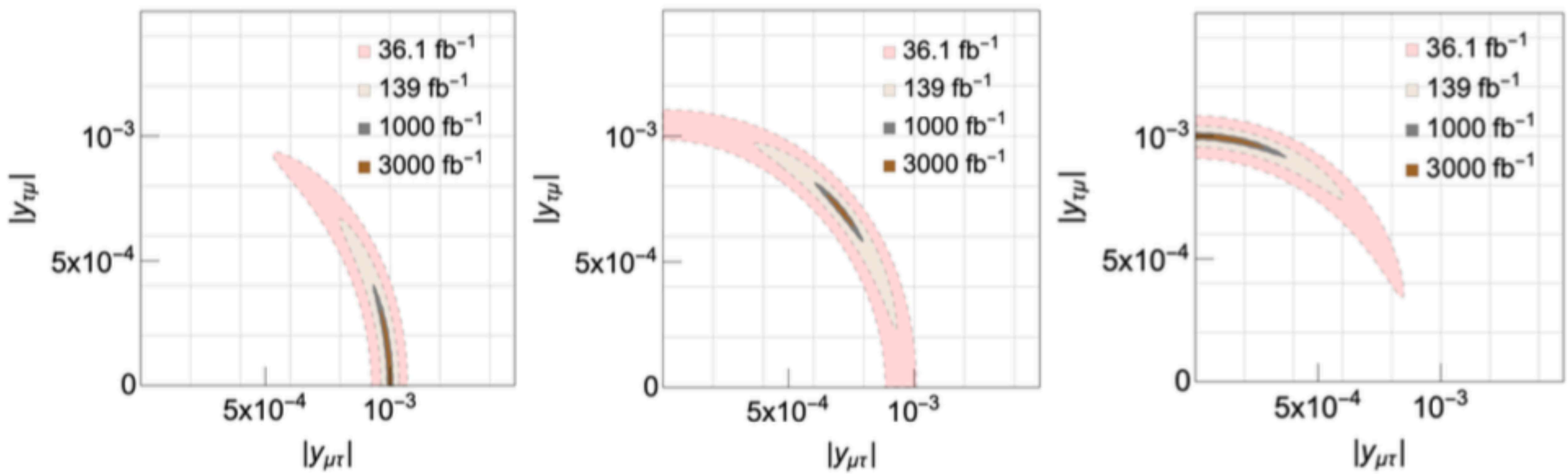


FIG. 8. Estimated sensitivity for the chirality structure in $h \to \tau\mu$ process using the signal region with $\Delta m^{\rm th}_{\rm col1} = 5$ GeV. The results for the three types of benchmark points predicting BR$(h \to \tau\mu) = 0.12$ %, τ_R scenario (left), τ_0 scenario (center), and τ_L scenario (right) are shown. The 1σ contours for the integrated luminosity at 36.1, 139, 1000, and 3000 fb^{-1} are shown.

Summary

- 2HDM: good benchmark model, effective theory of well motivated UV models.

- Muon g-2: large deviation, simple models very constrained.

$$\text{~~Type X, Aligned,~~}\ \mu 2\text{HDM},\ \mu\tau 2\text{HDM}$$

S.I, T.K, M.L, MT [PRD108(11),115012, arXiv:2304.09887]

- We found two loop solutions are excluded by LHC multi lepton searches.

- LFV signatures in higgs sector?

g-2 via LFV — mass reconstruction at LHC

in future at 14 TeV, ~2fb (300 GeV) with 3 ab ⇒ ~ 6000 HA pair produced, other modes similarly produced

4 leptons from HA production

$\mu^\pm\mu^\pm\tau^\mp\tau^\mp$ same-sign di-muon di-tau (50%)

$\mu^+\mu^-\tau^+\tau^-$ opposite-sign di-muon di-tau (50%)

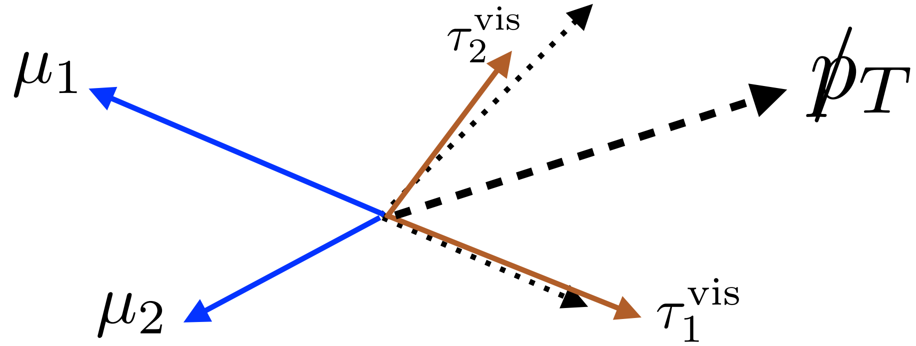
$\mathcal{O}(200-300)$ events for 3 ab^{-1}

OSOF pair gives the resonances (almost BG free)

τ-momentum : collinear approx.

$$\mathbf{p}_{\tau_i} = (1+c_i)\mathbf{p}^{\rm vis}_{\tau_i}$$

$$\not{p}_T = c_1\mathbf{p}^{\rm vis}_{T,\tau_1} + c_2\mathbf{p}^{\rm vis}_{T,\tau_2} \qquad (c_1, c_2 > 0).$$



for $\mu^\pm\mu^\pm\tau^\mp\tau^\mp$

two possible combinations :

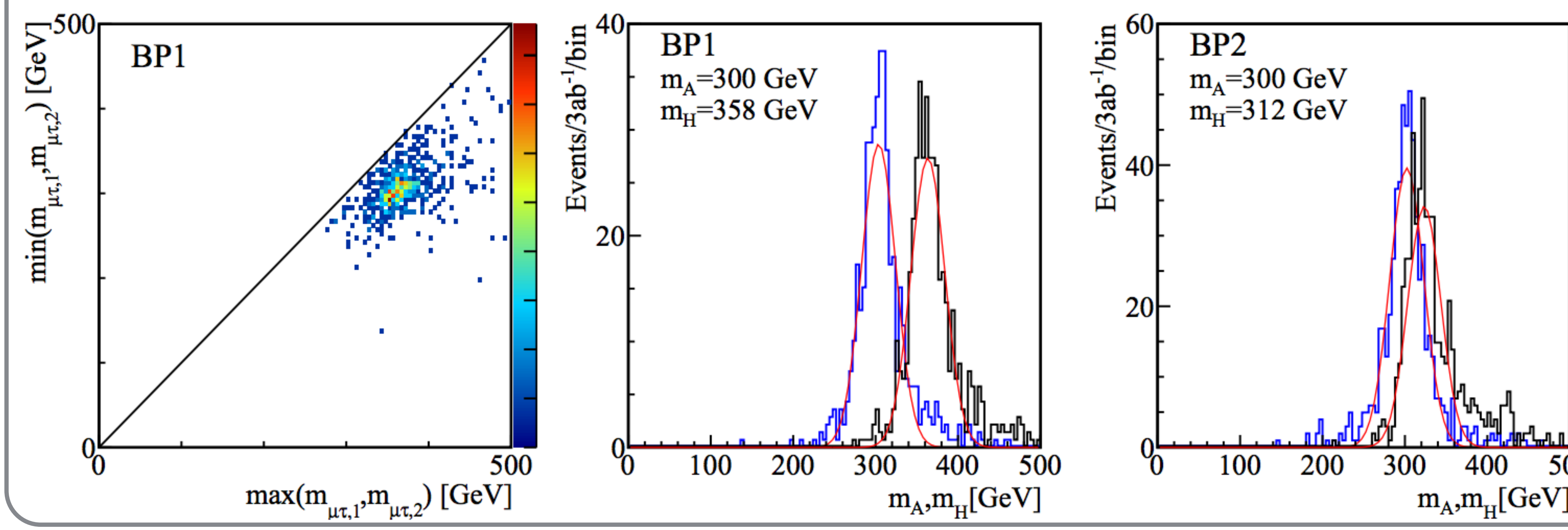
combination 1 : $m_{\mu_1\tau_1}$ and $m_{\mu_2\tau_2}$

combination 2 : $m_{\mu_1\tau_2}$ and $m_{\mu_2\tau_1}$

$\mu_1, \mu_2, \tau_1^{\rm vis}$, and $\tau_2^{\rm vis}$ in p_T-order

select the one minimizing the sum of

$$\chi_i^2(m_A, m_H) = (m^{\rm min}_{\mu\tau,i} - m_A)^2/\sigma^2_{\rm res} + (m^{\rm max}_{\mu\tau,i} - m_H)^2/\sigma^2_{\rm res}$$



can reconstruct two invariant masses mA and mH

$\sigma_{\rm res} \sim 20$GeV

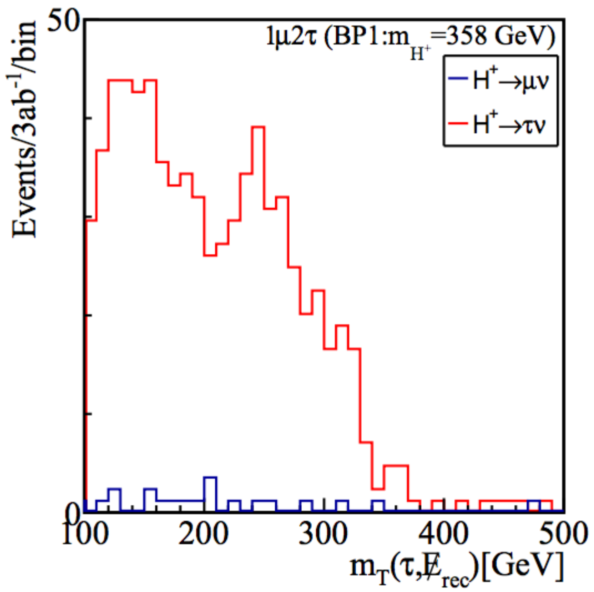
cf.) $10\mathrm{GeV} \lesssim \Delta_{H-A} \lesssim 100\mathrm{GeV}$

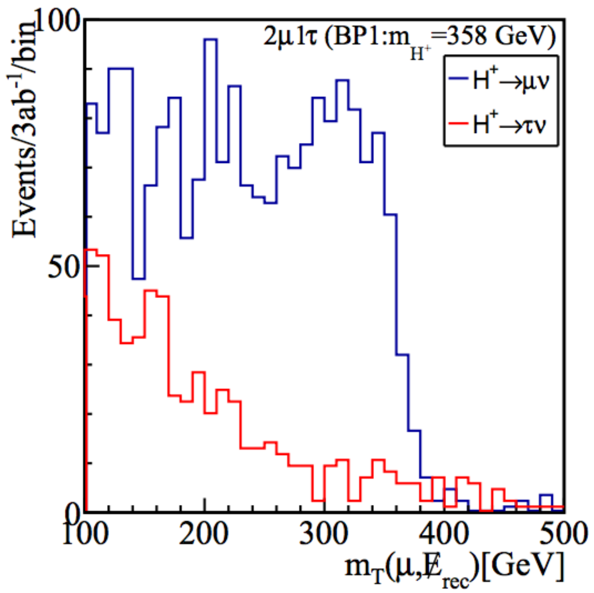
g-2 via LFV — mass reconstruction at LHC

charged Higgs mass can be reconstructed via 3 leptons from $\phi H^{\pm}$ production $\mu^{\pm}\tau^{\mp}\tau\nu$ and $\mu^{\pm}\tau^{\mp}\mu\nu$

ratio controlled by $BR(H^{\pm}\to\tau^{\pm}\nu) = 1 - BR(H^{\pm}\to\mu^{\pm}\nu) = \frac{|\rho_e^{\mu\tau}|^2}{|\rho_e^{\tau\mu}|^2+|\rho_e^{\mu\tau}|^2} \equiv r.$

part of τ-mode contribute to μ-mode





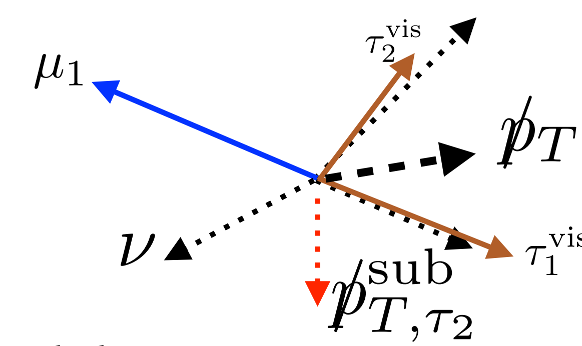
combinatorics : (production Φ=A, H) x (2 τμ combinations)

$$\mathbf{p}^{\rm rec}_{\tau_i} = (1+c_{\tau_i\phi})\mathbf{p}^{\rm vis}_{\tau_i}, \quad (c_{\tau_i\phi}>0).$$

$$m^2_{\mu\tau_i^{\rm rec}} = (p_\mu + p^{\rm rec}_{\tau_i})^2 = m_\phi^2,$$

$$\not{\mathbf{p}}^{\rm sub}_{T,\tau_i\phi} = \not{\mathbf{p}}_T - c_{\tau_i\phi}\mathbf{p}^{\rm vis}_{T,\tau_i}$$

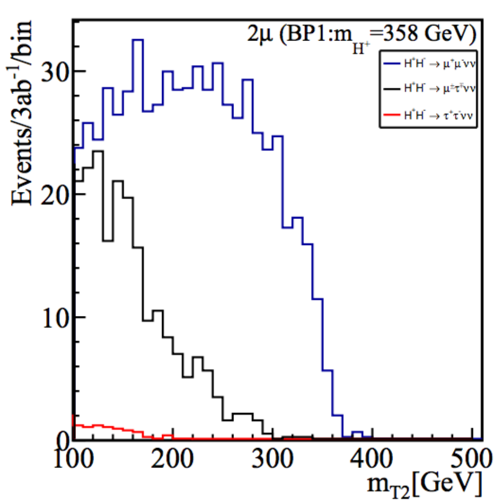
$$m_{T,\tau_i\phi} = m_T(\mathbf{p}^{\rm vis}_{\tau_{i'}}, \not{\mathbf{p}}^{\rm sub}_{T,\tau_i\phi}),$$

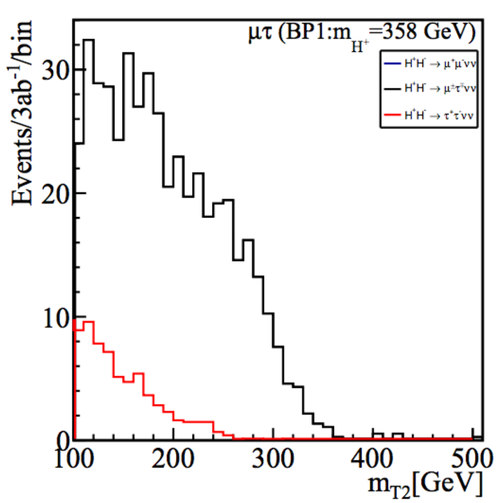


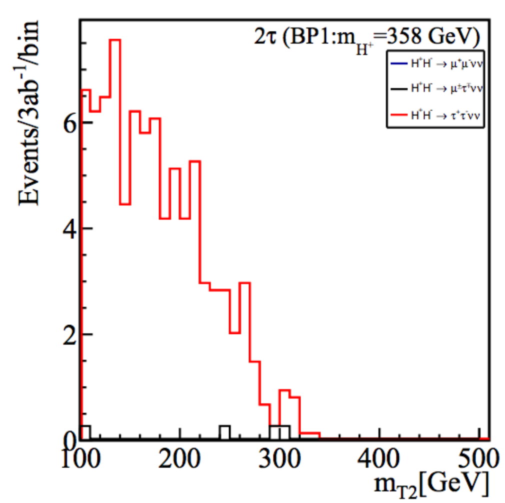
taking the minimum of the 4 possibilities

$$m^{\rm min}_{T,\tau} = \min(m_{T,\tau_1 A}, m_{T,\tau_1 H}, m_{T,\tau_2 A}, m_{T,\tau_2 H})$$

also via 2 leptons from H^+H^- production







mH, mA, mH+ reconstructed by 4,3,2 lepton events

event number ratios among various modes sensitive to the BR

$$m_{T2}(\mathbf{p}_{\ell_1}, \mathbf{p}_{\ell_2}, \not{\mathbf{p}}_T) = \min_{\not{\mathbf{p}}_T = \not{\mathbf{p}}_{T,1}+\not{\mathbf{p}}_{T,2}} \{\max[m_T(\mathbf{p}_{\ell_1}, \not{\mathbf{p}}_{T,1}), m_T(\mathbf{p}_{\ell_2}, \not{\mathbf{p}}_{T,2})]\}$$