Testing the 2HDM explanation of the muon g-2 anomaly at the LHC

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Based on

JHEP 1911 (2019) 130 1907.09845

with Y. Omura(Kindai), M. Takeuchi(KMI)

Key words: Collider, muon g-2, Lepton flavor violation

KEK-PH 2020

Menu

- Introduction of the muon g-2 anomaly
- Our model
- Collider signal
- Summary

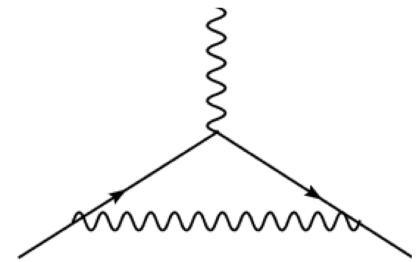
muon g-2 anomaly

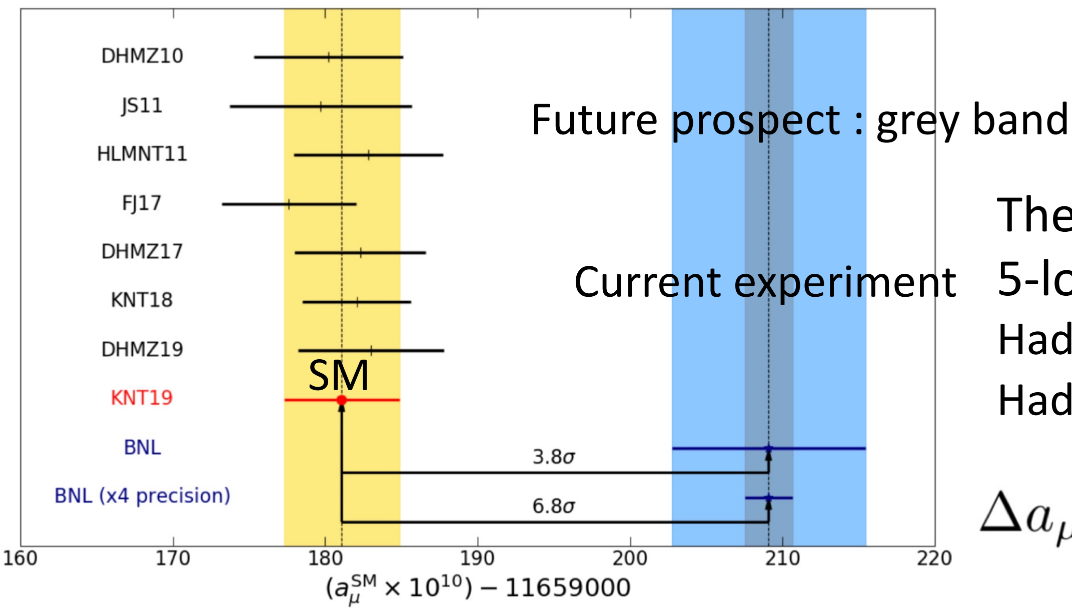
$$\vec{\mu} = -g\frac{e}{2m}\vec{S}$$

$\vec{\mu}$: Magnetic moment of the muon

g=2: tree level corresponds to 2 freedoms (spin up and down)

Anomalous magnetic moment: $a_\mu = (g-2)/2$





Theoretical calculation:
5-loop QED, lattice calculation,
Hadronic Light-by-Light,
Hadronic Vacuum Polarization,,,

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

Alexander, Nomura.... : 1911.00367

Hint for BSM?

The new data will come soon!

Current status

Slide by D. Nomura @CLFV2019

In 10^{-10}

	2011		2018	
QED	11658471.81 (0.02)	$\longrightarrow$	11658471.90 (0.01)	[arXiv:1712.06060]
EW	15.40 (0.20)	$\longrightarrow$	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	$\longrightarrow$	9.80 **(2.60)**	[EPJ Web Conf. 118 (2016) 01016]
NLO HLbL				
LO HVP	)			
NLO HVP	)	$\longrightarrow$	-9.82 (0.04)	this work
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144]
Theory total	11659182.80 (4.94)	$\longrightarrow$	11659182.05 (3.56)	this work
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	$\longrightarrow$	27.1 (7.3)	this work
Δa_μ	3.3σ	$\longrightarrow$	3.7σ	this work

hadronic light-by-light scattering (HLbL)

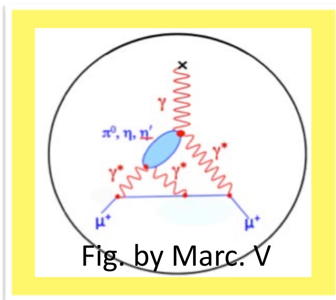


Fig. by Marc. V

7.20(4.31) 1911.08123, Lattice result!
all errors systematically controlled

Consistent with previous result.

(HVP: Hadronic Vacuum Polarization)
(HLbL: Hadronic Light-by-Light)

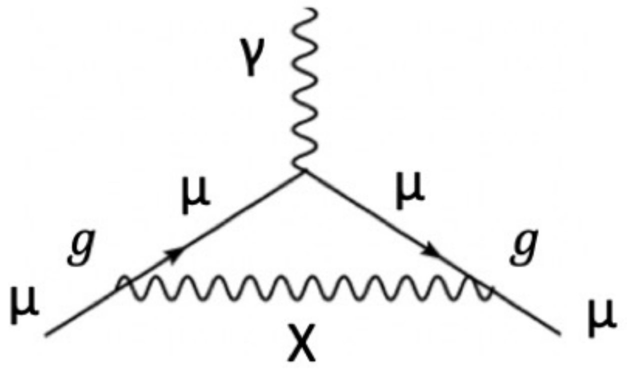
(Numbers taken from KNT18, Phys. Rev. D97 (2018) 114025)

anomaly of muon g-2

If this anomaly is true,
we need some new physics!

What kind of new physics you need?

Naïve new physics scale to explain muon g-2 anomaly.



If new particle X appear at 1-loop with a flavor diagonal coupling

$$\Delta a_\mu \sim \frac{g^2}{16\pi^2}\frac{m_\mu^2}{m_X^2} \sim 3\times10^{-9}\left(\frac{100\mathrm{GeV}}{m_X}\right)^2$$

EW scale！

Various models are tested so far.

No signal so far.

Is there any good mechanism to enhance the contribution of Δa_{μ}?

→ heavier mass or smaller coupling is allowed and it could be relatively difficult to test in current experiments.

$$\Delta a_{\mu} \sim \frac{g^2}{16\pi^2}\frac{m_{\mu}^2}{m_X^2} \sim 3\times10^{-9}\left(\frac{100\mathrm{GeV}}{m_X}\right)^2$$

One solution is

Chirality enhancement

Is there any good mechanism to enhance the contribution of Δa_{μ}?

→ heavier mass or smaller coupling is allowed and it could be relatively difficult to test in current experiments.

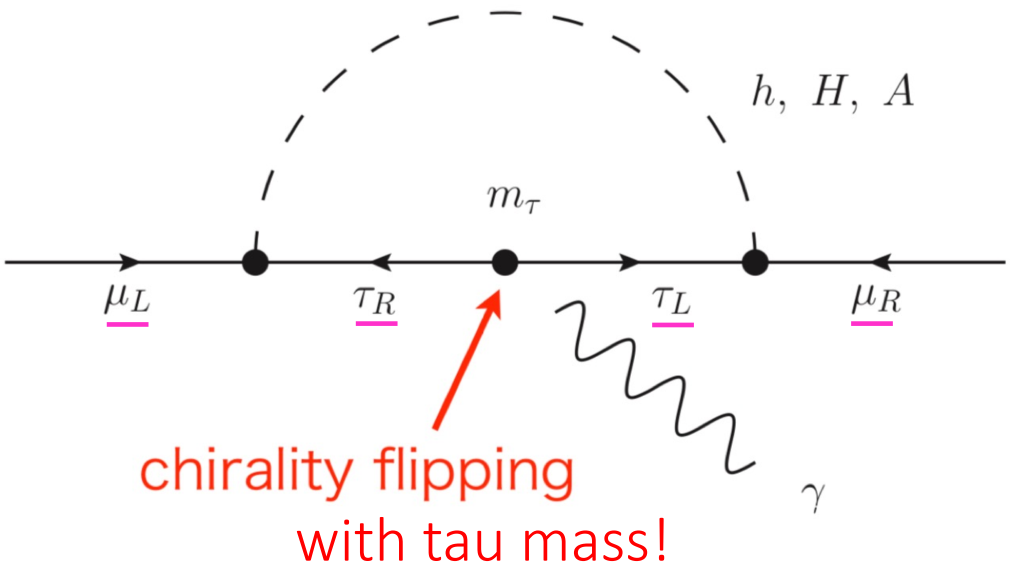
$$\Delta a_{\mu} \sim \frac{g^2}{16\pi^2}\frac{m_{\mu}^2}{m_X^2} \sim 3\times10^{-9}\left(\frac{100\mathrm{GeV}}{m_X}\right)^2$$

Chirality enhancement

Chirality flip with a heavy internal fermion mass(>> m_μ)

e.g. flip with tau mass

Figure by Tobe



$$\frac{m_\tau}{m_\mu} \sim 17$$

When $\Delta a_\mu \propto coupling^2$ coupling can be smaller by $\sqrt{17}$ or mass can be heavy by $\sqrt{17}$.

Model examples

This talk!

- τμ flavor violating G2HDM Tobe, et al 1502.07824
- τμ flavor violating gauge boson,
  Soni,et al 1607.06832

τ mass enhancement
$m_\tau/m_\mu \sim 17$

- Leptoquark(LQ) is also discussed,
  Bauer,Neubert 1511.01900

Top mass enhancement
$m_t/m_\mu \sim 1600$

- Mixing with Heavy vector like leptons
  0102122, 1305.3522

Heavy lepton mass enhancement
$m_L/m_\mu \sim 10 \times m_L$[GeV]

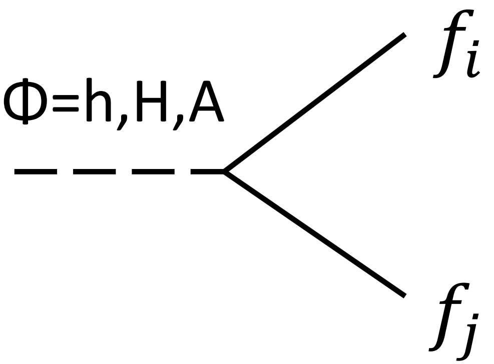
Model: G2HDM

We do not assume Z_2 symmetry

Mass relation $m_H^2 = m_A^2 + \lambda_5 v^2, m_{H^-}^2 = m_A^2 - \frac{\lambda_4 - \lambda_5}{2} v^2$

λ:quadratic coupling in a potencial

Yukawa couplings between a neutral scalar and fermions



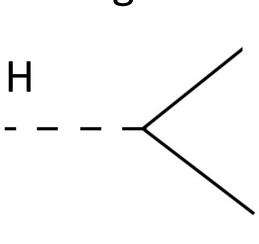
$$\approx i(y^f_{\Phi ij} P_R + y^{f*}_{\Phi ji} P_L)$$

$$y^f_{hij} = \frac{m^i_f}{v}, \quad y^f_{Hij} = -\frac{\rho^{ij}_f}{\sqrt{2}},$$

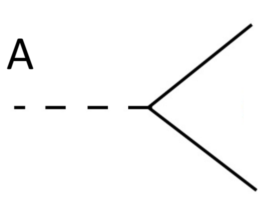
$$y^f_{Aij} = \begin{cases} -\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = u \\ +\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = d, e, \end{cases}$$

Yukawa interactions relevant to muon g-2

In the alignment limit

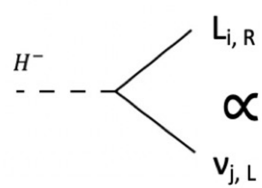


$$\propto (\rho^{\mu\tau}_e P_R + \rho^{\tau\mu *}_e P_L)$$

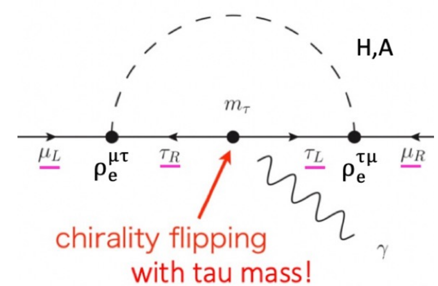


$$\propto (\rho^{\mu\tau}_e P_R - \rho^{\tau\mu *}_e P_L)$$

Both $\rho^{\mu\tau}_e$ and $\rho^{\tau\mu}_e$ should be sizable



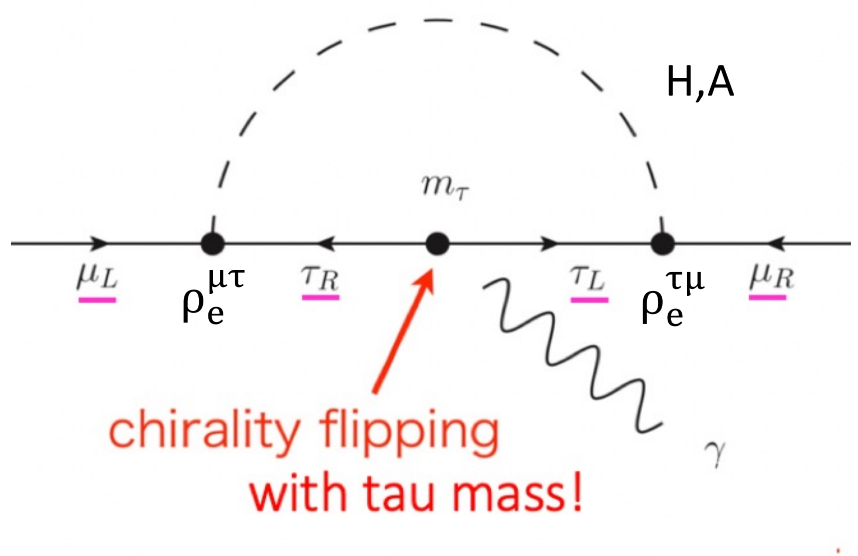
$$\propto \rho^{ij}_e P_L$$



Z_4 symmetry can realize the situation that only $\rho^{\mu\tau}_e$ and $\rho^{\tau\mu}_e$ are sizable.

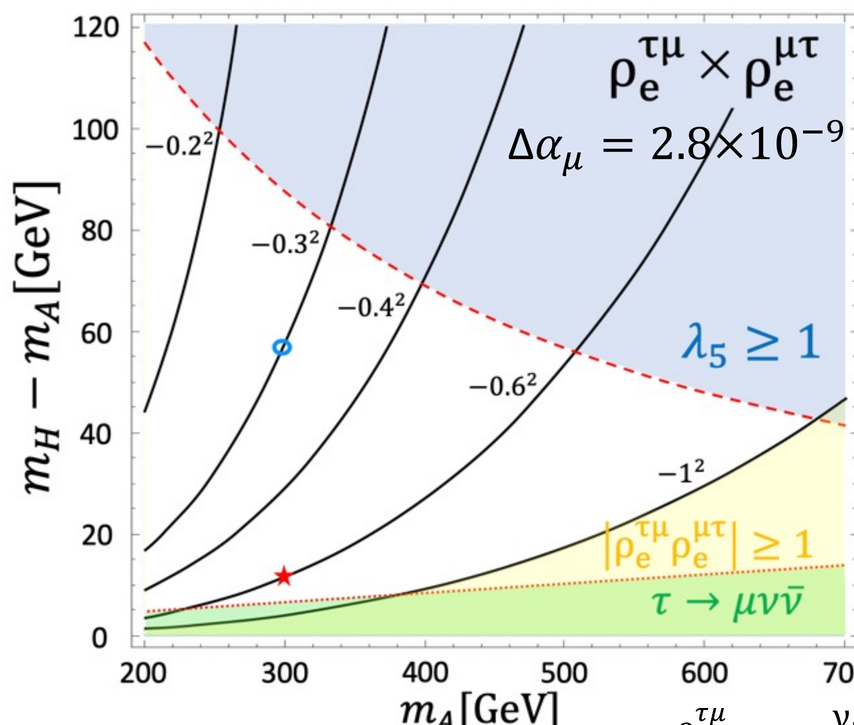
Tsumura, Abe,Toma 1904.10908

If $\rho_e^{\mu\tau}$ and $\rho_e^{\tau\mu}$ are only sizable entries, this model can explain the anomaly.



We assume Yukawas to be real

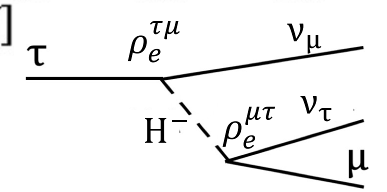
1907.09845 Syuhei Iguro, Y. Omura, M. Takeuchi.



1502.07824, Tobe et al

$$\Delta\alpha_\mu \approx \frac{m_\mu m_\tau \rho_e^{\mu\tau}\rho_e^{\tau\mu}}{16\pi^2}\left(\frac{\log\frac{m_H^2}{m_\tau^2}-\frac{3}{2}}{m_H^2}-\frac{\log\frac{m_A^2}{m_\tau^2}-\frac{3}{2}}{m_A^2}\right)$$

- $m_A - m_H \neq 0$
- $\rho_e^{\mu\tau}\rho_e^{\tau\mu} \neq 0$

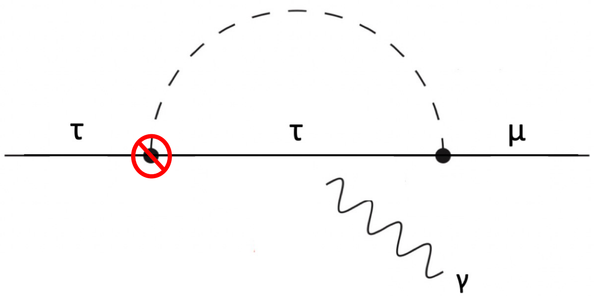


$|\rho_e^{\mu\tau}|, |\rho_e^{\tau\mu}| < 1,$
$0 < \lambda_5 < 1$

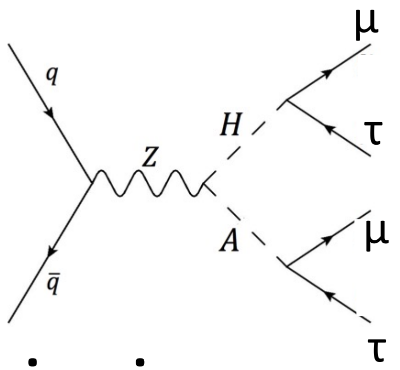
The larger mass gap in H and A, the smaller coupling product to explain the anomaly

If only $\rho_e^{\tau\mu}$ and $\rho_e^{\mu\tau}$ are sizable

It is difficult to test in flavor physics.
Additional scalars do not talk to quark.

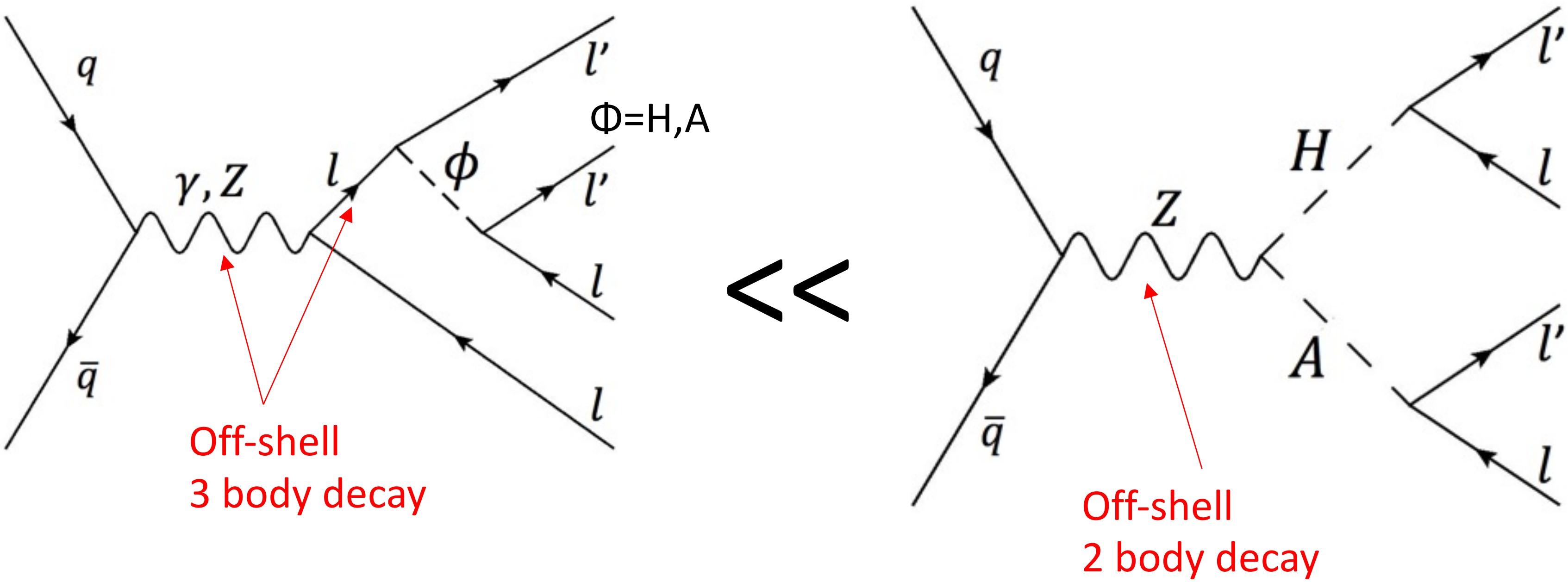


How we test the scenario?



H,A have $SU(2)_L$ charge!
Additional scalars are generated in pair via so-called an electroweak production.
H, A decay into $\mu\tau$(LFV heavy resonance).

$\mu\mu\bar{\tau}\bar{\tau}$ final state in LHC



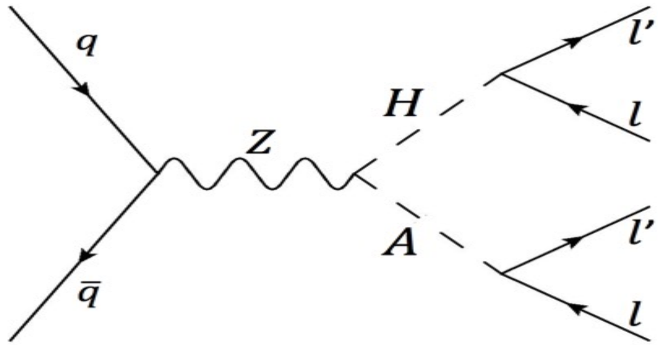
Distinctive features of our signal

- 2 μτ LFV heavy resonances
- same sign lepton pairs

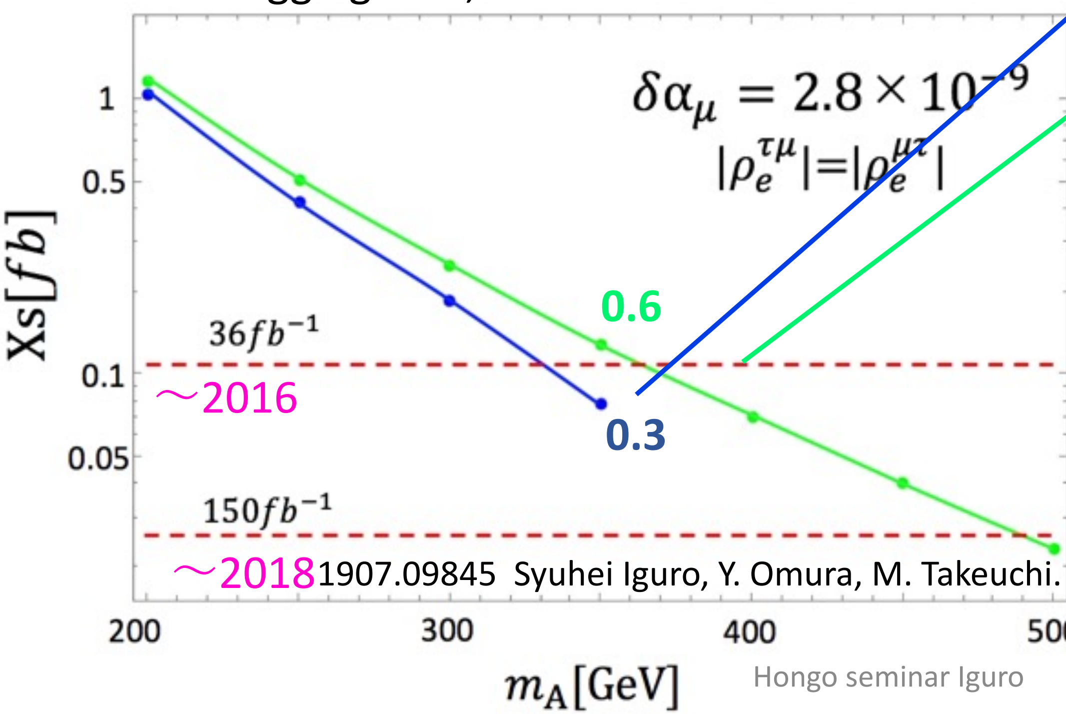
Assume BG free

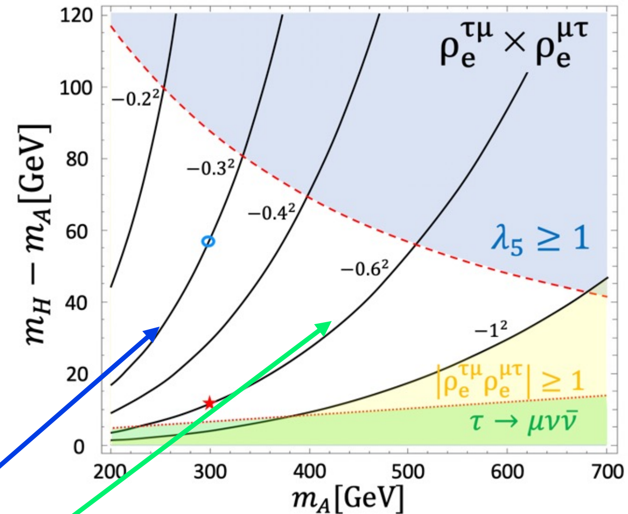
Impact of $\mu\mu\bar{\tau}\bar{\tau}$ search

production mode



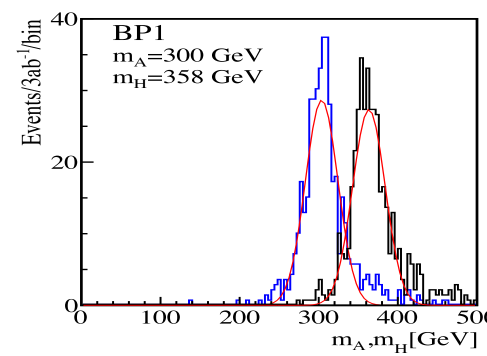
τ tagging 70%, τ hadronic mode: 65%





We can explore the large parameter region with $\mu\mu\bar{\tau}\bar{\tau}$.

Mass reconstruction is also possible with Δm～20GeV (3ab^{-1})



Summary

Testing the 2HDM explanation of the muon g-2 anomaly at the LHC

Chirality enhancement is a very useful mechanism to explain the muon g-2 anomaly.

G2HDM with μτ flavor violation can explain the anomaly due to the τ mass enhancement.

We showed that the scenario is already testable with $\mu\mu\bar{\tau}\bar{\tau}$ signal. Please measure the mode!

Even if the deviation become smaller,
this signal is powerful as long as BR(H->μτ) is dominant.

Thank you so much for listening!

More realistic model

Tsumura, Abe, Toma 1904.10908

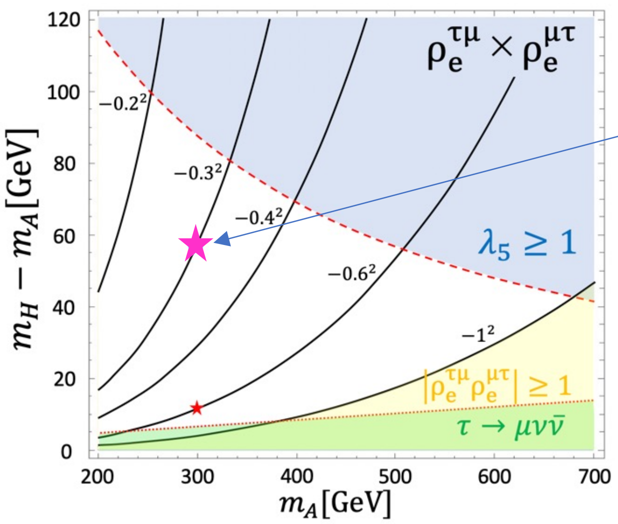
$(SU(3)_c, SU(2)_L)_{U(1)_Y}$

Particle	SM	Z_4
(L_e, L_μ, L_τ)	$(1,2)_{-1/2}$	$(1, i, -i)$
(e_R, μ_R, τ_R)	$(1,1)_{-1}$	$(1, i, -i)$
H	$(1,2)_{1/2}$	1
Φ	$(1,2)_{1/2}$	-1

$$-\mathcal{L}_{Z_4}^{\text{yukawa}} = \overline{\ell_R} \begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & \underline{y_{\mu\tau}\Phi^\dagger} \\ & \underline{y_{\tau\mu}\Phi^\dagger} & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

Additional scalars can only couple to μτ

How much we can reduce our signal by turning other Yukawas on



$m_A = 300, m_H = m_{H^-} = 358$[GeV], $|\rho_e^{\tau\mu}|=|\rho_e^{\mu\tau}| = 0.3$

Which yukawa can be large to dilute BR?

$$\begin{pmatrix} \rho_e^{ee} & \rho_e^{e\mu} & \rho_e^{e\tau} \\ \rho_e^{\mu e} & \rho_e^{\mu\mu} & \rho_e^{\mu\tau} \\ \rho_e^{\tau e} & \rho_e^{\tau\mu} & \rho_e^{\tau\tau} \end{pmatrix}$$

Lepton Yukawa

$$\begin{pmatrix} \rho_u^{uu} & \rho_u^{uc} & \rho_u^{ut} \\ \rho_u^{cu} & \rho_u^{cc} & \rho_u^{ct} \\ \rho_u^{tu} & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

Up type quark

$$\begin{pmatrix} \rho_d^{dd} & \rho_d^{ds} & \rho_d^{db} \\ \rho_d^{sd} & \rho_d^{ss} & \rho_d^{sb} \\ \rho_d^{bd} & \rho_d^{bs} & \rho_d^{bb} \end{pmatrix}$$

Down type quark

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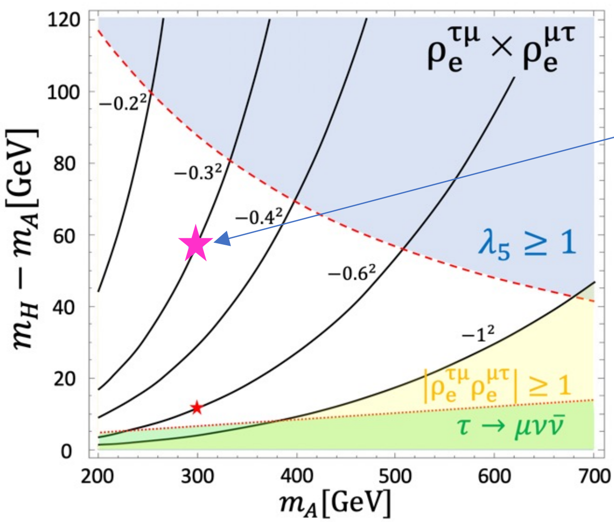


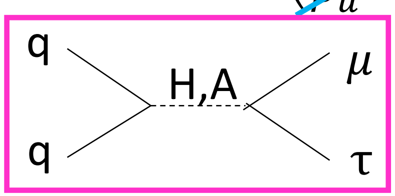
$m_A = 300, m_H = m_{H^-} = 358$[GeV], $|\rho_e^{\tau\mu}|=|\rho_e^{\mu\tau}| = 0.3$

$$\begin{pmatrix} \rho_e^{ee} & \rho_e^{e\mu} & \rho_e^{e\tau} \\ \rho_e^{\mu e} & \rho_e^{\mu\mu} & \rho_e^{\mu\tau} \\ \rho_e^{\tau e} & \rho_e^{\tau\mu} & \rho_e^{\tau\tau} \end{pmatrix}$$

Couplings to the light quark are dangerous for collider physics.

$$\begin{pmatrix} \rho_u^{uu} & \rho_u^{uc} & \rho_u^{ut} \\ \rho_u^{cu} & \rho_u^{cc} & \rho_u^{ct} \\ \rho_u^{tu} & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

$$\begin{pmatrix} \rho_d^{dd} & \rho_d^{ds} & \rho_d^{db} \\ \rho_d^{sd} & \rho_d^{ss} & \rho_d^{sb} \\ \rho_d^{bd} & \rho_d^{bs} & \rho_d^{bb} \end{pmatrix}$$



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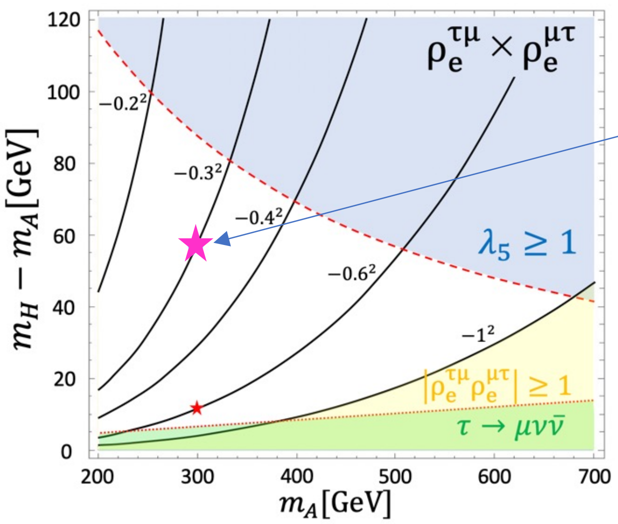

$m_A = 300, m_H = m_{H^-} = 358$[GeV], $|\rho_e^{\tau\mu}| = |\rho_e^{\mu\tau}| = 0.3$

$$\begin{pmatrix} \rho_e^{ee} & \rho_e^{e\mu} & \rho_e^{e\tau} \\ \rho_e^{\mu e} & \rho_e^{\mu\mu} & \rho_e^{\mu\tau} \\ \rho_e^{\tau e} & \rho_e^{\tau\mu} & \rho_e^{\tau\tau} \end{pmatrix}$$

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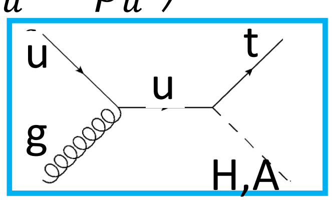

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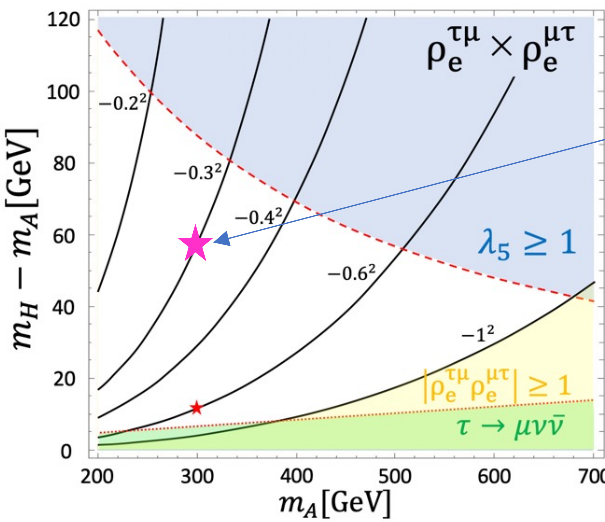


$m_A = 300, m_H = m_{H^-} = 358$[GeV], $|\rho_e^{\tau\mu}|=|\rho_e^{\mu\tau}| = 0.3$

τ->μee:tree

τ->eγ :1-loop, τ->μee:tree

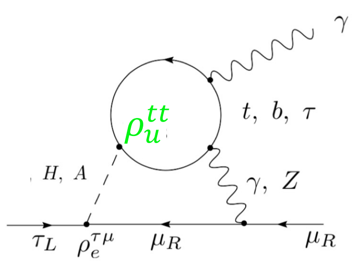
$$\begin{pmatrix} \rho_e^{ee} & \rho_e^{e\mu} & \rho_e^{e\tau} \\ \rho_e^{\mu e} & \rho_e^{\mu\mu} & \rho_e^{\mu\tau} \\ \rho_e^{\tau e} & \rho_e^{\tau\mu} & \rho_e^{\tau\tau} \end{pmatrix}$$

τ->μμμ:tree

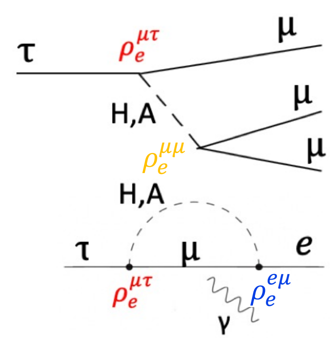
τ->μγ:1-loop

μ->eγ :1-loop

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_u^{ct} \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

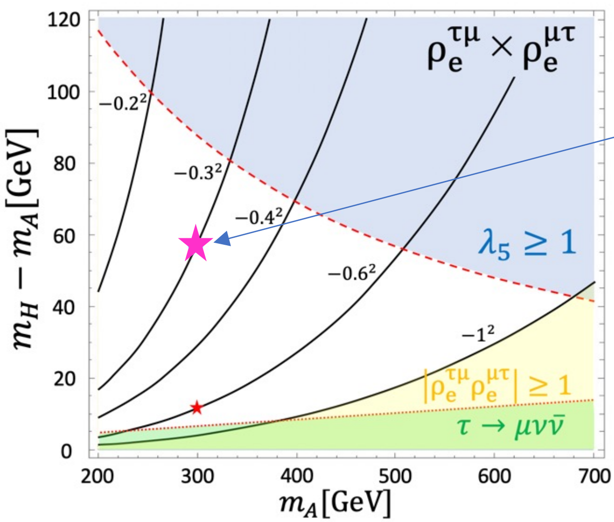


$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_d^{sb} \\ 0 & \rho_d^{bs} & \rho_d^{bb} \end{pmatrix}$$



τ->μγ:2-loop Barr-Zee

How much we can reduce our signal by turning other Yukawas on



$m_A = 300, m_H = m_{H^-} = 358$[GeV], $|\rho_e^{\tau\mu}| = |\rho_e^{\mu\tau}| = 0.3$

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_e^{\mu\tau} \\ 0 & \rho_e^{\tau\mu} & 0.06 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_u^{ct} \\ 0 & \rho_u^{tc} & 0.05 \end{pmatrix}$$

ε_K: H^- loop

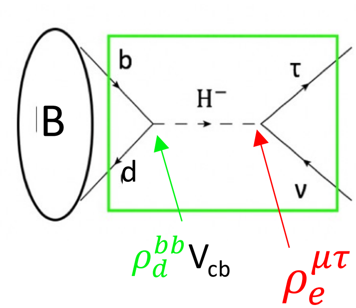
$\frac{B(B\to D^*\mu\nu)}{B(B\to D^* e\nu)}$: H^- tree,

μν resonance search

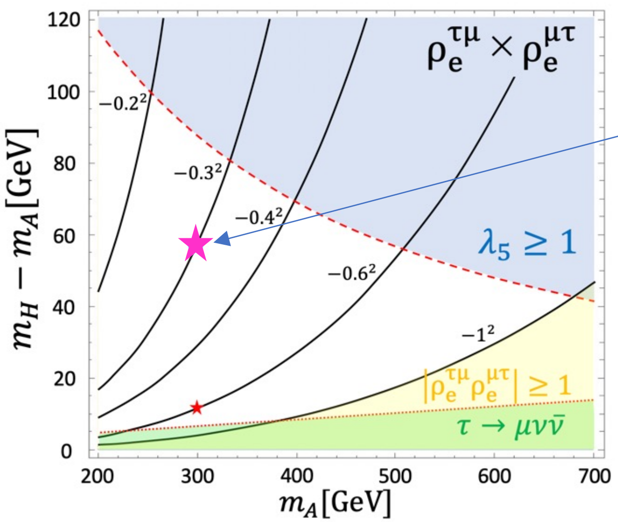
$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_d^{sb} \\ 0 & \rho_d^{bs} & \rho_d^{bb} \end{pmatrix}$$

Bs mixing:tree

$B \to \mu\nu$,
$B \to \tau\nu$



How much we can reduce our signal by turning other Yukawas on



$m_A = 300, m_H = m_{H^-} = 358$[GeV], $|\rho_e^{\tau\mu}| = |\rho_e^{\mu\tau}| = 0.3$

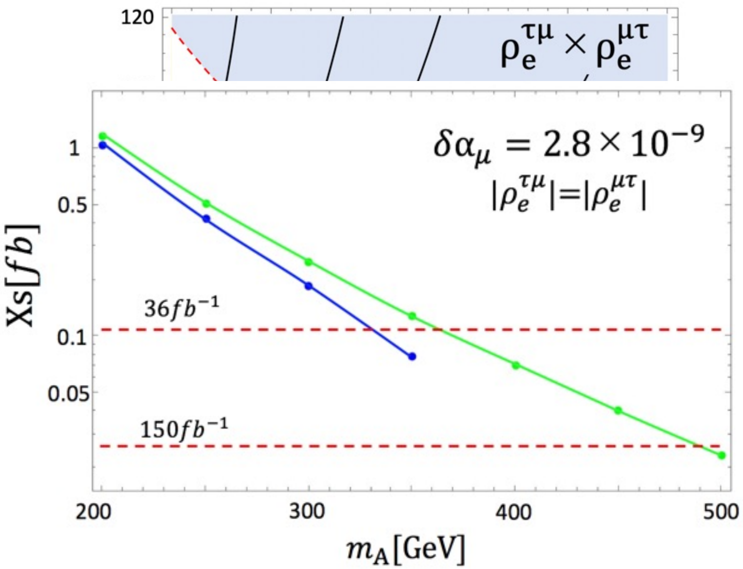
$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_e^{\mu\tau} \\ 0 & \rho_e^{\tau\mu} & 0.06 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0.04 \\ 0 & 0.11 & 0.05 \end{pmatrix}$$

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0.22 \end{pmatrix}$$

ρ_d^{bb}=0.22 can be the largest element.

How much we can reduce our signal by turning other Yukawas on



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$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \rho_e^{\mu\tau} \\ 0 & \rho_e^{\tau\mu} & 0 \end{pmatrix}$$

ρ_d^{bb}=0.22 can be the largest element.

Then signal number can be **30%** of original one.
We need 3 times more luminosity to obtain the original sensitivity at most.

pp->bb->H->μτ is not considered

Current status

Slide by D. Nomura @CLFV2019

In 10^{-10}

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LO HLbL	10.50 (2.60)	$\longrightarrow$	9.80 **(2.60)**	[EPJ Web Conf. 118 (2016) 01016]
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]
	HLMNT11		**KNT18**	
LO HVP	694.91 (4.27)	$\longrightarrow$	693.27 **(2.46)**	this work
NLO HVP	-9.84 (0.07)	$\longrightarrow$	-9.82 (0.04)	this work
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144]
Theory total	11659182.80 (4.94)	$\longrightarrow$	11659182.05 (3.56)	this work
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	$\longrightarrow$	27.1 (7.3)	this work
Δa_μ	3.3σ	$\longrightarrow$	3.7σ	this work

(HVP: Hadronic Vacuum Polarization)
(HLbL: Hadronic Light-by-Light)

(Numbers taken from KNT18, Phys. Rev. D97 (2018) 114025)

anomaly of muon g-2

Current status

Slide by D. Nomura @CLFV2019

In 10^{-10}

	2011		2018	
QED	11658471.81 (0.02)	$\longrightarrow$	11658471.90 (0.01)	[arXiv:1712.06060]
EW	15.40 (0.20)	$\longrightarrow$	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	$\longrightarrow$	9.80 **(2.60)**	[EPJ Web Conf. 118 (2016) 01016]
NLO HLbL				
LO HVP	)			
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hadronic light-by-light scattering (HLbL)

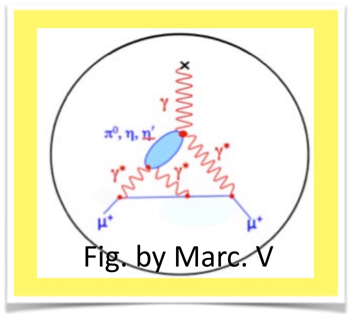


Fig. by Marc. V

7.20(4.31) 1911.08123, Lattice result!
all errors systematically controlled

Consistent with previous result.

(HVP: Hadronic Vacuum Polarization)
(HLbL: Hadronic Light-by-Light)

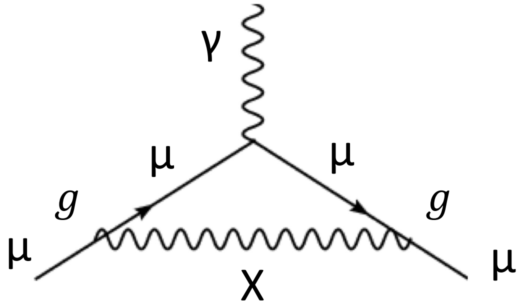
(Numbers taken from KNT18, Phys. Rev. D97 (2018) 114025)

anomaly of muon g-2

What kind of new physics you need?

Naïve new physics scale to explain muon g-2 anomaly.

$$L \sim \frac{e\Delta a_\mu}{m_\mu} \mu_L \sigma^{\mu\nu} \mu_R F_{\mu\nu}$$



If new particle X appear at 1-loop with a flavor diagonal coupling

$$\Delta a_\mu \sim \frac{g^2}{16\pi^2} \frac{m_\mu^2}{m_X^2} \sim 3\times10^{-9} \left(\frac{100\text{GeV}}{m_X}\right)^2$$

EW scale !

No signal in LHC

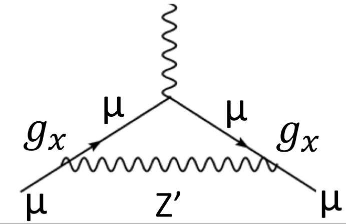
What kind of new physics scenario is still allowed?

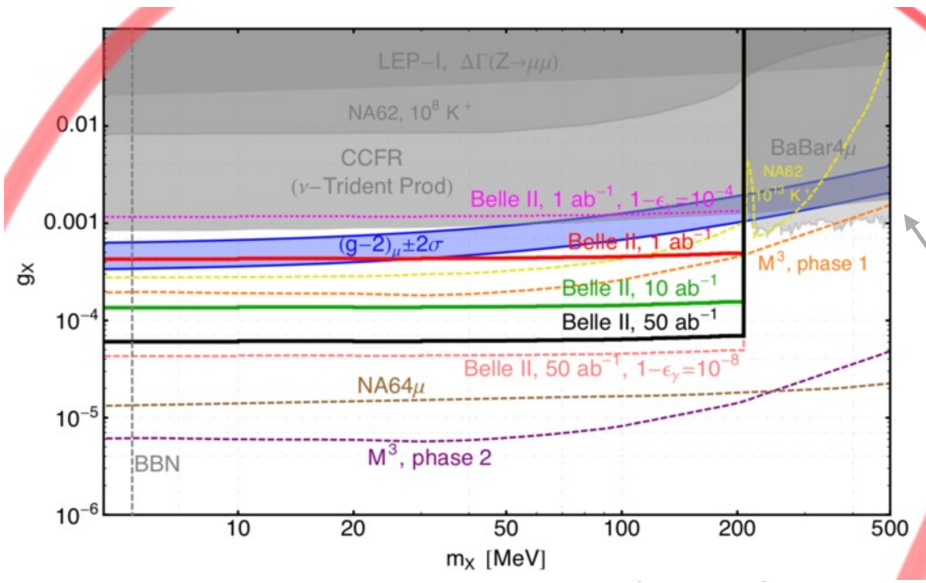
Light particle is available.

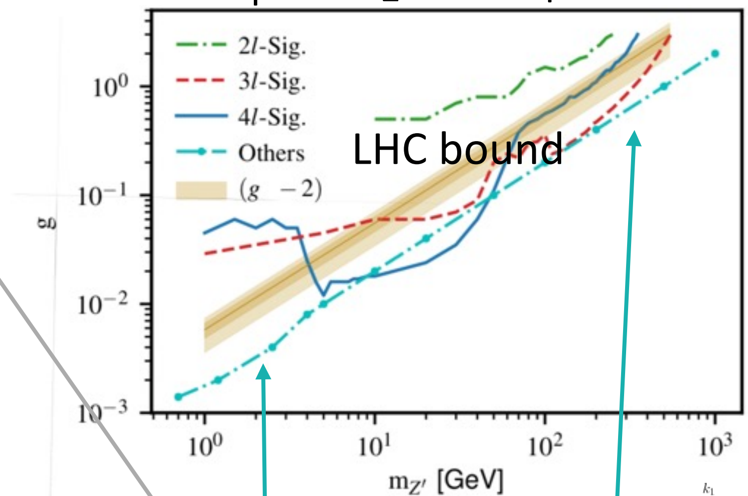
flavor conserving

e.g. Z’: $L_\mu - L_\tau$ (global U(1) symmetry).

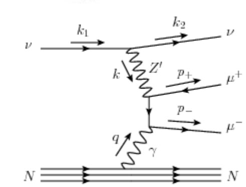
particle	$L_2 = (\nu_{\mu L}, \mu_L)$	$L_3 = (\nu_{\tau L}, \tau_L)$	$(\mu_R)^c$	$(\tau_R)^c$	$(\nu_{\mu R})^c$	$(\nu_{\tau R})^c$	others
charge	$+1$	-1	-1	$+1$	-1	$+1$	0



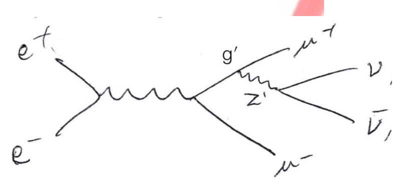




1811.12446



1904.13053:2μ+missing



“Others” corresponds to the ν trident and BaBar 4μ final state with 500fb^-1

The scenario will be explored soon in Belle II!

Muon specific 2HDM is available.

flavor conserving

1705.01469, Abe et al.

Table I: Particle contents and the charge assignment.

	q_L^j	u_R^j	d_R^j	ℓ_L^e	ℓ_L^τ	ℓ_L^μ	e_R	τ_R	μ_R	H_1	H_2
$SU(3)_c$	3	3	3	1	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	2	2	1	1	1	2	2
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1/2	−1/2	−1	−1	−1	1/2	1/2
Z_4	1	1	1	1	1	i	1	1	i	−1	1

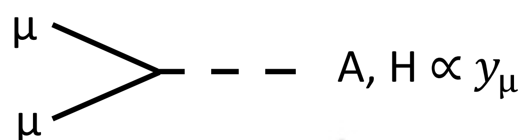
$$i = e^{i\frac{\pi}{2}}$$

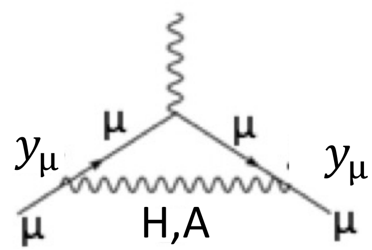
H_1 only couples to μμ

$$\mathcal{L}^{\text{Yukawa}} = -\bar{q}_L \tilde{H}_2 Y_u u_R - \bar{q}_L H_2 Y_d d_R - \bar{L}_L H_1 Y_{\ell 1} E_R - \bar{L}_L H_2 Y_{\ell 2} E_R + (h.c),$$

$$Y_{\ell 1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\mu \end{pmatrix}$$

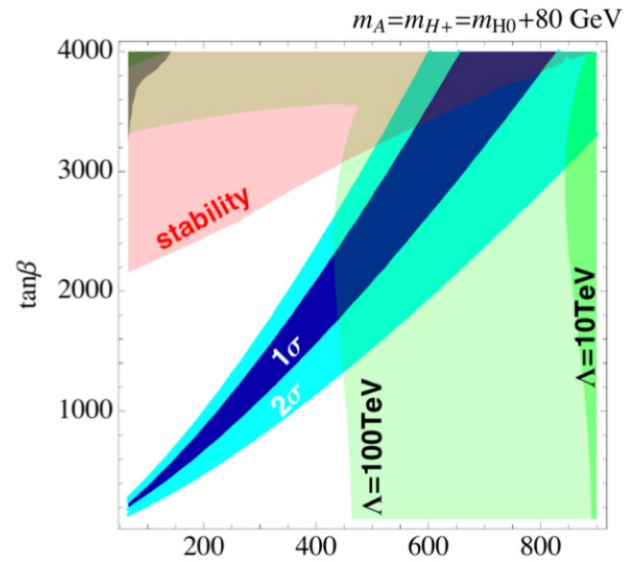
$$y_\mu = \frac{\sqrt{2} m_\mu}{v}\sqrt{1+t_\beta^2} \simeq 0.6\left(\frac{t_\beta}{1000}\right)$$





$$H_1 = \begin{pmatrix} H^+ \\ \frac{H + iA + v'}{\sqrt{2}} \end{pmatrix} \quad H_2 = \begin{pmatrix} G^+ \\ \frac{v'' + h + iG}{\sqrt{2}} \end{pmatrix}$$

tanβ=v''/v' $\quad v = \sqrt{v'^2 + v''^2}$



$$m_\mu = \frac{v}{\sqrt{2}}\frac{y_\mu}{\sqrt{1+t_\beta^2}}, \quad m_f = \frac{v}{\sqrt{2}}\frac{y_f t_\beta}{\sqrt{1+t_\beta^2}}$$ others

Muon specific 2HDM is available.

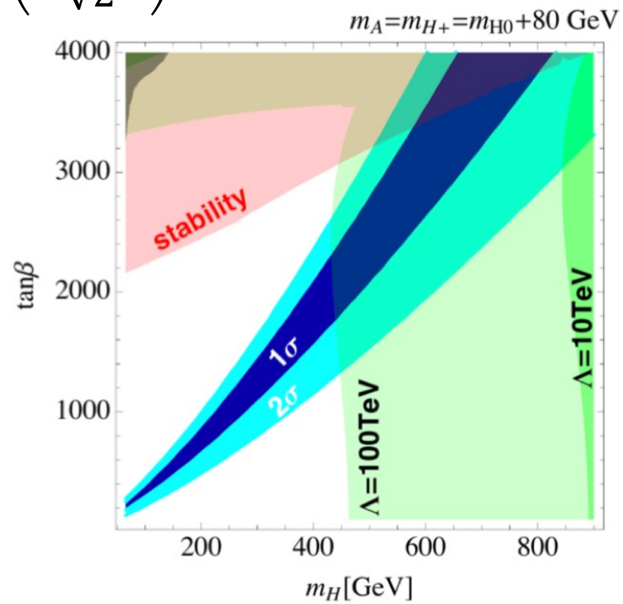
flavor conserving

1705.01469

Table I: Particle contents and the charge assignment.

	q_L^j	u_R^j	d_R^j	ℓ_L^e	ℓ_L^τ	ℓ_L^μ	e_R	τ_R	μ_R	H_1	H_2
$SU(3)_c$	3	3	3	1	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	2	2	1	1	1	2	2
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1/2	−1/2	−1	−1	−1	1/2	1/2
Z_4	1	1	1	1	1	i	1	1	i	−1	1

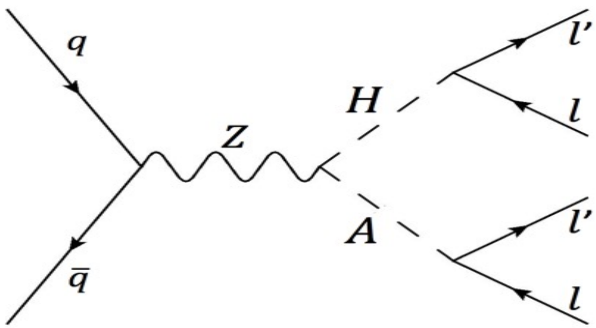
$$H_1 = \begin{pmatrix} H^+ \\ \frac{H + iA}{\sqrt{2}} \end{pmatrix}$$ in large tanβ limit



H_1 only couples to μμ

$$\mathcal{L}^{\rm Yukawa} = -\bar{q}_L \tilde{H}_2 Y_u u_R - \bar{q}_L H_2 Y_d d_R - \bar{L}_L H_1 Y_{\ell 1} E_R - \bar{L}_L H_2 Y_{\ell 2} E_R + (h.c),$$

$$Y_{\ell 1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\mu \end{pmatrix}$$



Multi lepton search in LHC(36fb^-1)

$m_H \lesssim 640$ GeV is excluded at 95% CL

The scenario will be explored in LHC!

Light pseudo scalar scenario in 2HDM is also available (Barr-Zee) …many models…….

General Two Higgs Doublet Model (G2HDM)

We take so called Higgs base : a doublet acquires VEV

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h+iG}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

G^+,G: N-G boson, H^+ :charged Higgs, A : CP odd Higgs

h: SM Higgs, H: heavy CP even Higgs (Alignment limit).

Yukawa terms

$$\mathcal{L}_{CC} = -\sum_{f=u,d,e} \sum_{\Phi=h,H,A} y^f_{\Phi ij} \overline{f_{Li}} \Phi f_{Rj} + \text{h.c.}$$
$$- \overline{\nu_{Li}} (V^\dagger_{MNS} \rho_e)^{ij} H^+ e_{Rj} + \text{h.c.}$$
$$- \bar{u}_i (V_{CKM} \rho_d P_R - \rho^\dagger_u V_{CKM} P_L)^{ij} H^+ d_j + \text{h.c.},$$

$$y^f_{hij} = \frac{m^i_f}{v} \delta_{ij}, \quad y^f_{Aij} = \begin{cases} -\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = u \\ +\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = d, e, \end{cases} \quad y^f_{Hij} = -\frac{\rho^{ij}_f}{\sqrt{2}}$$

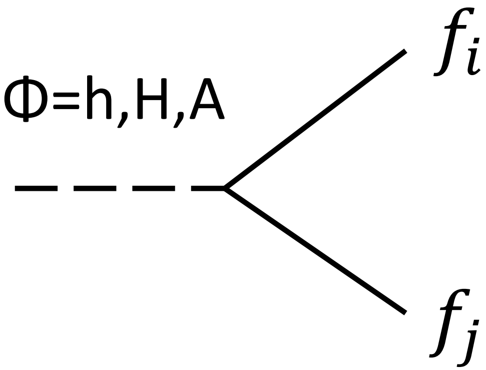
Model: G2HDM

Mass relation

$$m_H^2 = m_A^2 + \lambda_5 v^2,\; m_{H^-}^2 = m_A^2 - \frac{\lambda_4 - \lambda_5}{2} v^2$$

λ:quadratic coupling in a potencial

Yukawa couplings between a neutral scalar and fermions

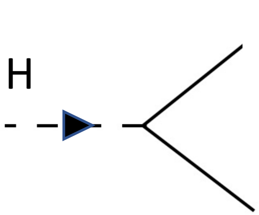


$$\approx i(y^f_{\Phi ij} P_R + y^{f*}_{\Phi ji} P_L)$$

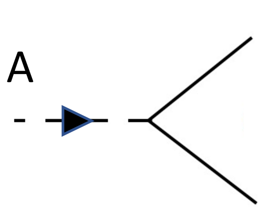
$$y^f_{hij} = \frac{m^i_f}{v},\quad y^f_{Hij} = -\frac{\rho^{ij}_f}{\sqrt{2}},$$

$$y^f_{Aij} = \begin{cases} -\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = u \\ +\frac{i\rho^{ij}_f}{\sqrt{2}} & \text{for } f = d, e, \end{cases}$$

Yukawa interactions relevant to muon g-2

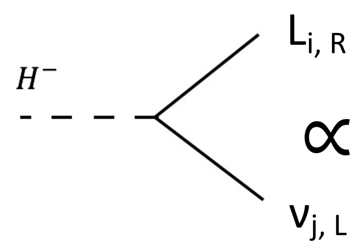


$$\propto (\rho^{\mu\tau}_e P_R + \rho^{\tau\mu *}_e P_L)$$

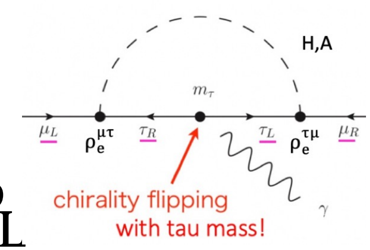


$$\propto (\rho^{\mu\tau}_e P_R - \rho^{\tau\mu *}_e P_L)$$

Both $\rho^{\mu\tau}_e$ and $\rho^{\tau\mu}_e$ are sizable



$$\propto \rho^{ij}_e P_L$$



More realistic model

Tsumura, Abe, Toma 1904.10908

$(SU(3)_c, SU(2)_L)_{U(1)_Y}$

Particle	SM	Z_4
(L_e, L_μ, L_τ)	$(1,2)_{-1/2}$	$(1, i, -i)$
(e_R, μ_R, τ_R)	$(1,1)_{-1}$	$(1, i, -i)$
H	$(1,2)_{1/2}$	1
Φ	$(1,2)_{1/2}$	-1

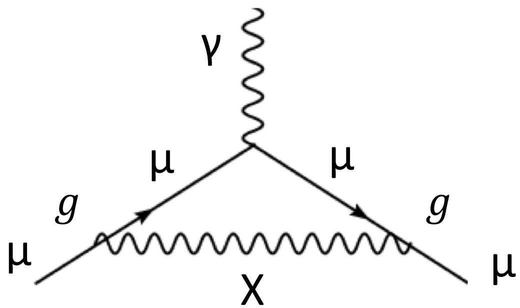
$$-\mathcal{L}^{\text{yukawa}}_{Z_4} = \overline{\ell_R} \begin{pmatrix} y_e H^\dagger & & \\ & y_\mu H^\dagger & \underline{y_{\mu\tau}\Phi^\dagger} \\ & \underline{y_{\tau\mu}\Phi^\dagger} & y_\tau H^\dagger \end{pmatrix} L + \text{H.c.}$$

Additional scalars can only couple to μτ

What kind of new physics you need?

Naïve new physics scale to explain muon g-2 anomaly.

$$L \sim \frac{e\Delta a_\mu}{m_\mu} \mu_L \sigma^{\mu\nu} \mu_R F_{\mu\nu}$$



If new particle X appear at 1-loop with a flavor diagonal coupling

$$\Delta a_\mu \sim \frac{g^2}{16\pi^2}\frac{m_\mu^2}{m_X^2} \sim 3\times10^{-9}\left(\frac{100\mathrm{GeV}}{m_X}\right)^2$$

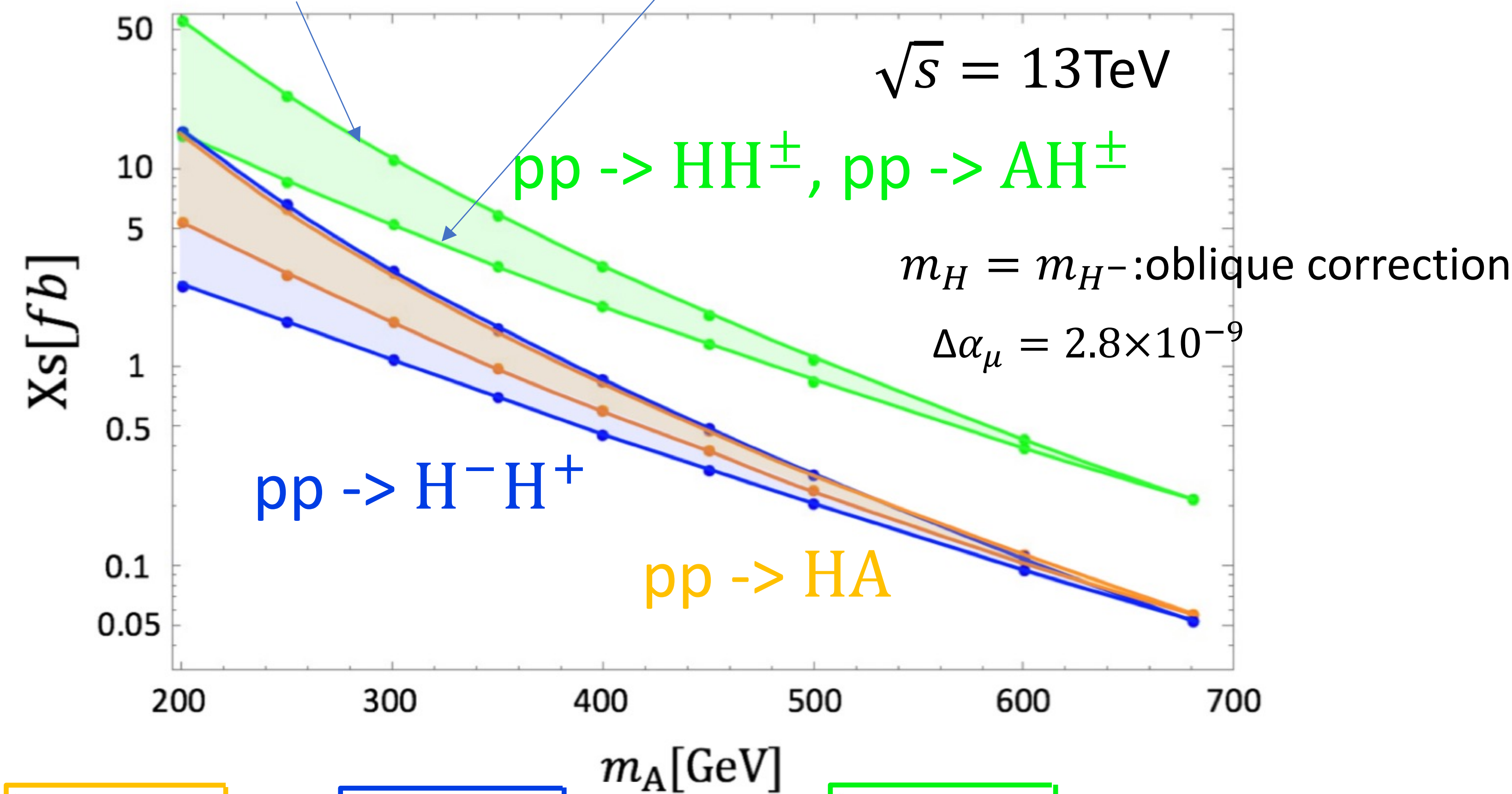
EW scale！

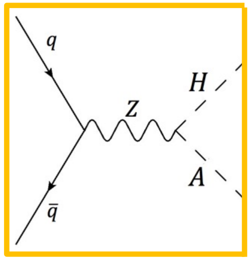
No signal in LHC

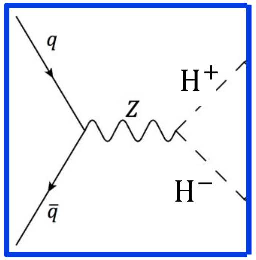
What kind of new physics scenario is still allowed?

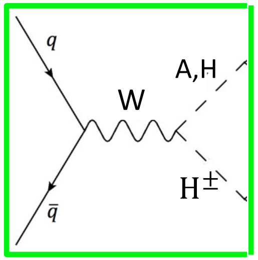
Electroweak production in LHC

- Maximum mass gap in H and A is given as $m_H^2 = m_A^2 + \lambda_5 v^2 = m_A^2 + v^2$ (λ_5=1)
- Minimum mass gap is given by $|\rho_e^{\mu\tau}|, |\rho_e^{\tau\mu}| < 1$.

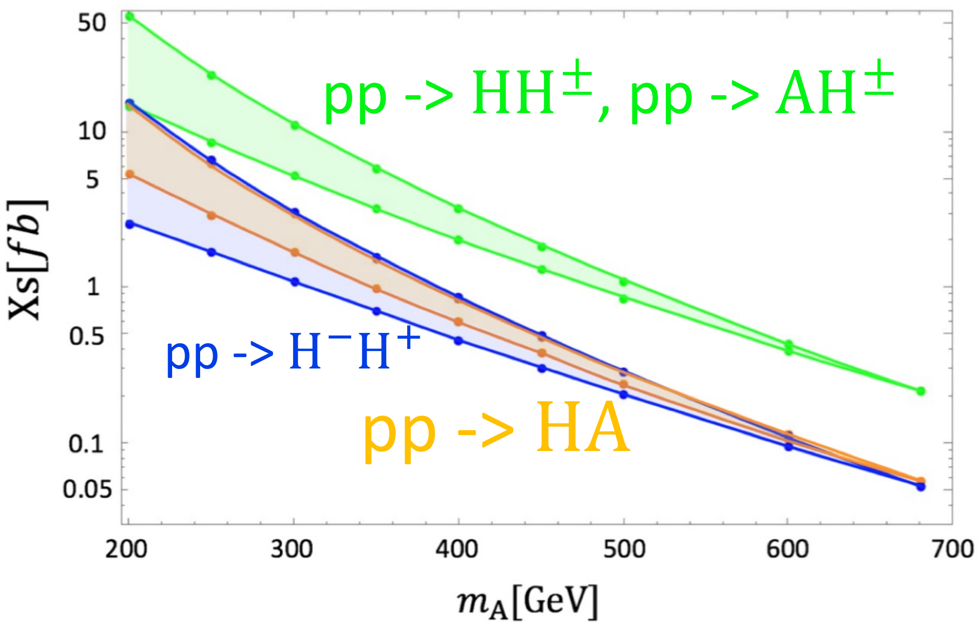








Electroweak production in LHC



$m_A^2 + \lambda_5 v^2 = m_A^2 + v^2$ (λ_5=1)

$\sqrt{s}$ = 13TeV

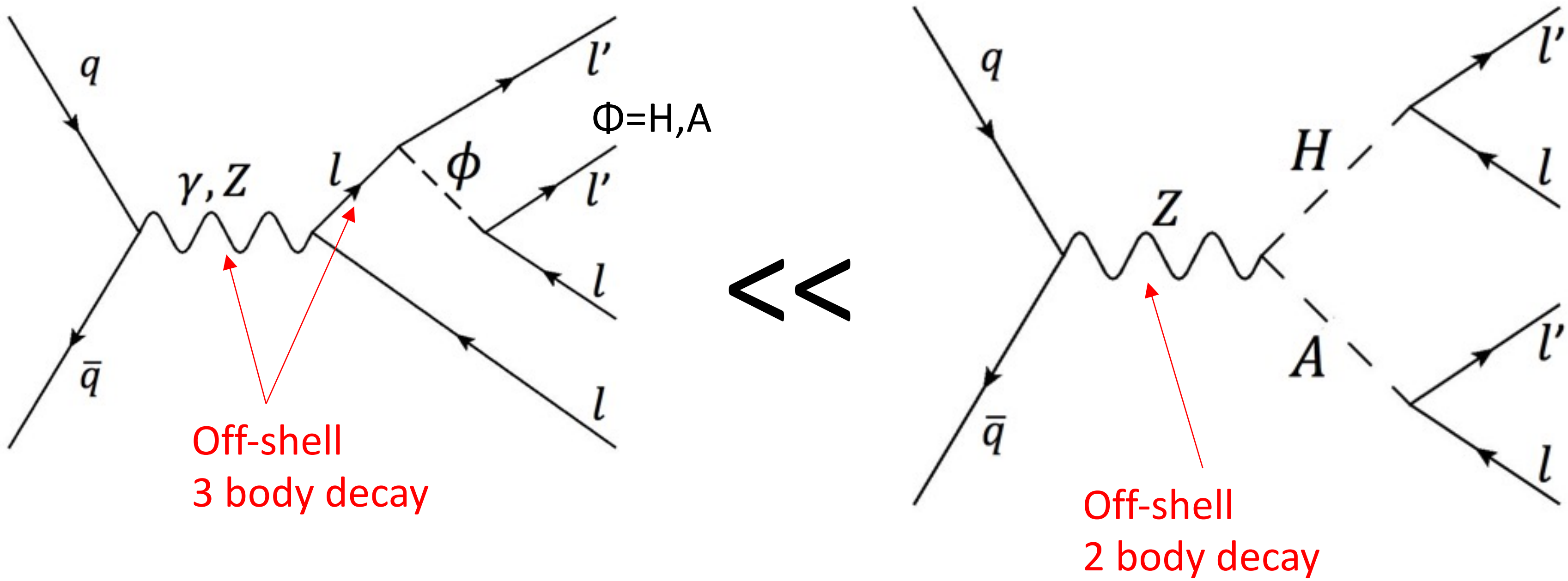
$m_H = m_{H^-}$:oblique correction

Cross section itself is not huge.

What is the most useful process?

pp→HA → $\mu\bar{\tau}\mu\bar{\tau}$

$\mu\mu\bar{\tau}\bar{\tau}$ final state in LHC



Distinctive features of our signal

- 2 $\mu\tau$ LFV heavy resonances
- same sign lepton pairs

Assume BG free

Other Yukawa couplings

$$\rho_e^{ij} = \begin{pmatrix} \rho_e^{ee} & \rho_e^{e\mu} & \rho_e^{e\tau} \\ \rho_e^{\mu e} & \rho_e^{\mu\mu} & \rho_e^{\mu\tau} \\ \rho_e^{\tau e} & \rho_e^{\tau\mu} & \rho_e^{\tau\tau} \end{pmatrix}$$

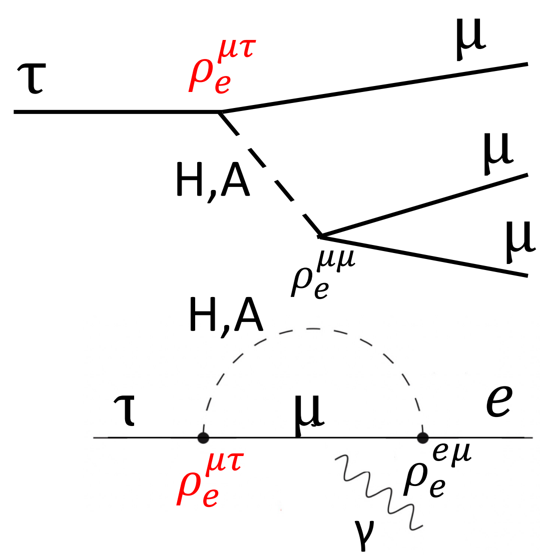
$\rho_e^{\tau\tau}$: $\tau \to \mu\gamma$,

$\rho_e^{\mu\mu}$: $\tau \to 3\mu$,

ρ_e^{ee}: $\tau \to \mu 2e$

$\rho_e^{\tau e}, \rho_e^{e\tau}$: $\mu \to 3e$,

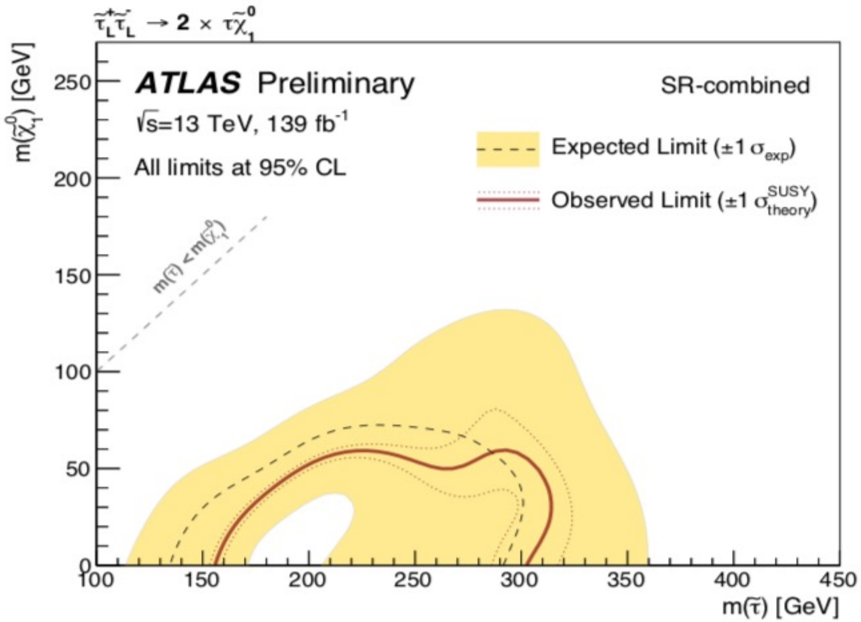
$\rho_e^{\mu e}, \rho_e^{e\mu}$: $\tau \to e\gamma$,



Phenomenologically the other couplings should be small.

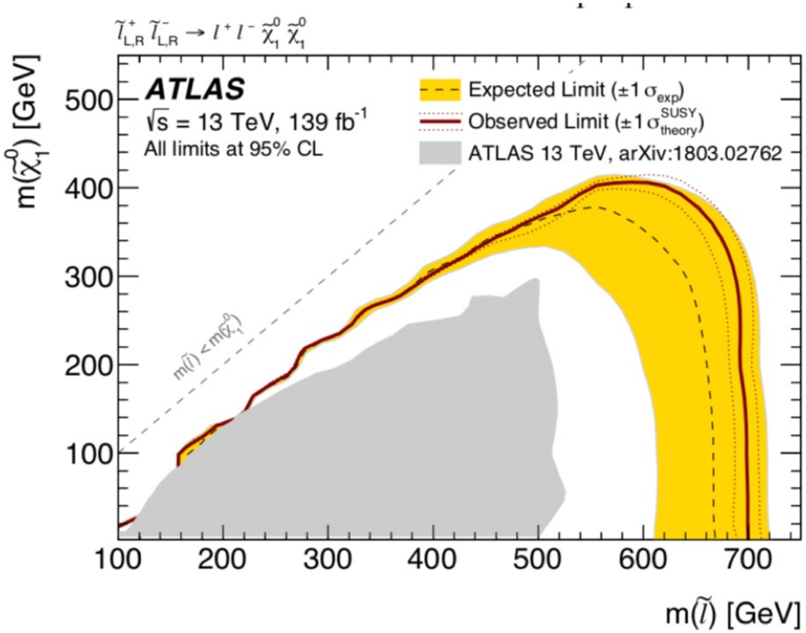
Slepton search

stau



150-300 GeV with BR($H^- \to \tau\nu$)=1
Is excluded

smuon



All $\tilde{e}_L, \tilde{e}_R, \tilde{\mu}_L$ and $\tilde{\mu}_R$ are combined

Higgs potential

$$V = M_{11}^2 H_1^\dagger H_1 + M_{22}^2 H_2^\dagger H_2 - \left(M_{12}^2 H_1^\dagger H_2 + \text{h.c.} \right)$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \left\{ \lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2) \right\} (H_1^\dagger H_2) + \text{h.c.}.$$

Mass relation

$$m_h^2 \simeq \lambda_1 v^2,$$

v=246GeV

$$m_H^2 \simeq m_A^2 + \lambda_5 v^2,$$

$$m_{H^+}^2 = m_A^2 - \frac{\lambda_4 - \lambda_5}{2} v^2,$$