Electroweak Baryogenesis with Flavor Violation

Eibun Senaha (National Taiwan U)

March 4, 2017@HPNP2017

based on

C.-W. Chiang (Natl Taiwan U), K. Fuyuto (UMass-Amherst), E.S., 1607.07316 [PLB]

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Lepton

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Outline

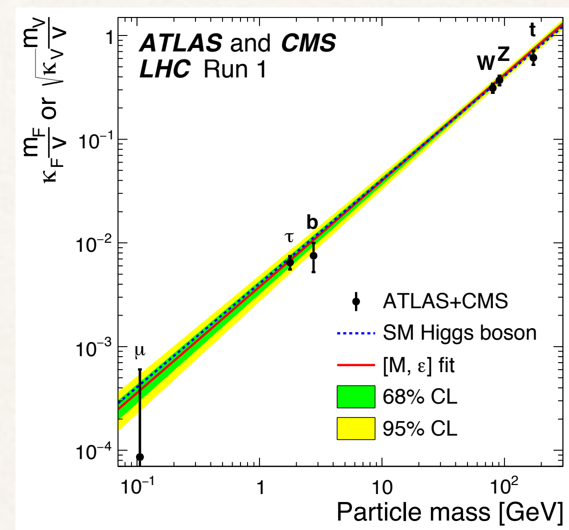
- Introduction
- muon g-2 and h-> $\mu\tau$ in a 2 Higgs doublet model
- Electroweak baryogenesis (EWBG)
    - Electroweak phase transition (EWPT) and sphaleron
    - Baryon asymmetry
- Summary

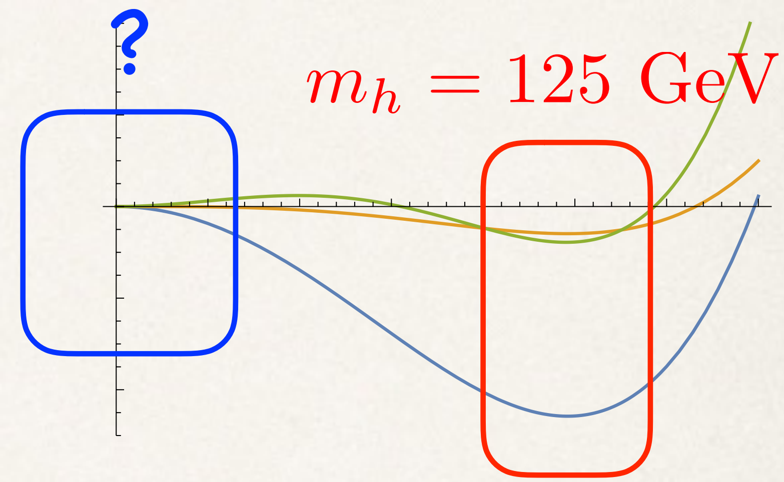
Introduction

problems after the Higgs discovery

Does the 125 GeV boson alone do the following jobs?

- mass generation
- EW symmetry breaking





Experiments will answer those grand questions in the near future.

Most importantly, those experiments may also shed light on unsolved problems.

If

Multi-Higgs → dark matter

Multi-Higgs → baryogenesis

Higgs is a window to new physics.

Let us open the window!!

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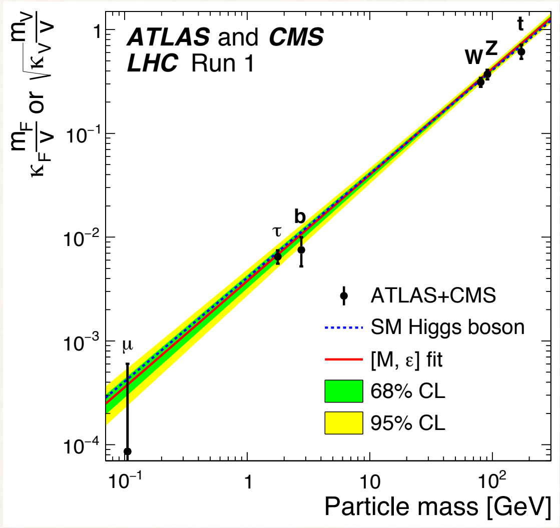

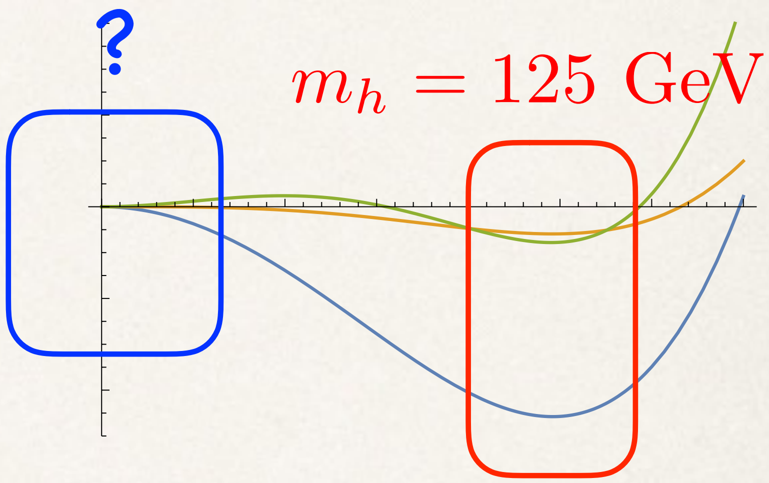

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Hints for new physics?

muon g-2

$$\delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$$

3.3σ excess

Hagiwara et al, 1105.3149.

h-> μτ

CMS: $\mathrm{Br}(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$ 1502.07400 [PLB] 2.4σ excess

Atlas: $\mathrm{Br}(h \to \mu\tau) = (0.53 \pm 0.51)\%$ 1604.07730

We discuss baryogenesis, g-2, h->μτ in a 2 Higgs doublets model (2HDM) with lepton flavor violation (LFV).

2 Higgs doublet model (2HDM)

Higgs potential:

$$
\begin{aligned}
V_0(\Phi_1,\Phi_2) = {} & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\
& + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
& + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \left\{\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right\}(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right],
\end{aligned}
$$

$$m_3^2, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C}$$

Higgs fields: $\Phi_i(x) = \begin{pmatrix} \phi_i^+(x) \\ \frac{1}{\sqrt{2}}\Big(v_i + h_i(x) + i a_i(x)\Big) \end{pmatrix}, \quad i = 1, 2.$

Assumption: CP is NOT violated by the Higgs potential and VEVs.

inputs: $\sin(\beta-\alpha),\ \tan\beta,\ m_H,\ m_A,\ m_{H^\pm},\ M^2 = \frac{m_3^2}{\sin\beta\cos\beta},\ \lambda_{6,7}$

2 Higgs doublet model (2HDM)

Lepton Yukawa couplings (Higgs basis):

$$\begin{aligned}
-\mathcal{L}_Y &= \bar{l}_{iL}(Y_1\Phi_1 + Y_2\Phi_2)_{ij} e_{jR} + \text{h.c.} \\
&\ni \bar{e}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}s_{\beta-\alpha} + \frac{1}{\sqrt{2}}\rho_{ij}c_{\beta-\alpha}\right] e_{jR}h \\
&\quad + \bar{e}_{iL}\left[\frac{y_i}{\sqrt{2}}\delta_{ij}c_{\beta-\alpha} - \frac{1}{\sqrt{2}}\rho_{ij}s_{\beta-\alpha}\right] e_{jR}H + \frac{i}{\sqrt{2}}\bar{e}_{iL}\rho_{ij}e_{jR}A + \text{h.c.}\ ,
\end{aligned}$$

- LFV comes from the off-diagonal entries of ρ_{ij}.

- ρ_{ij} are generally complex. $\rho_{ij} \in \mathbb{C} \Rightarrow$ CPV

  $\Rightarrow$ Baryogenesis!!

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h->μτ and muon g-2

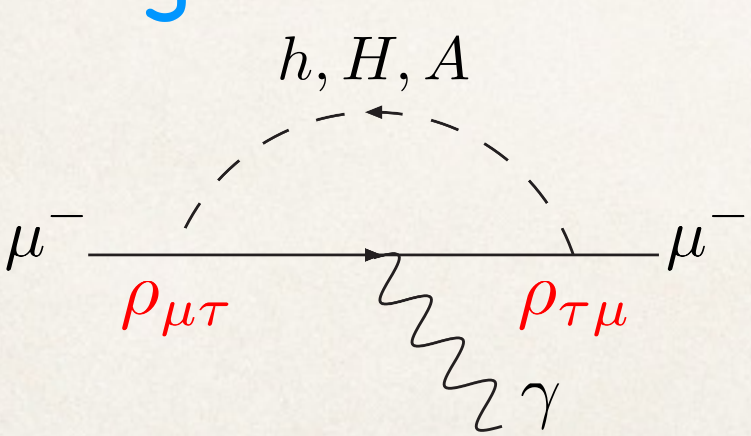
In 2HDM, it is easy to accommodate both h->μτ and muon g-2. [Y. Omura, E.S., K.Tobe, JHEP052015028, PRD94,055019(2016)]

h-> μτ

$$\mathrm{Br}(h \to \mu\tau) = \frac{m_h(|\rho_{\mu\tau}|^2 + |\rho_{\tau\mu}|^2)c^2_{\beta-\alpha}}{16\pi\Gamma_h}, \quad \Gamma_h = 4.1 \text{ MeV}$$

$$\sqrt{\frac{|\rho_{\mu\tau}|^2 + |\rho_{\tau\mu}|^2}{2}} \simeq 0.26 \left(\frac{0.01}{|c_{\beta-\alpha}|}\right) \sqrt{\frac{\mathrm{Br}(h \to \mu\tau)}{0.84 \times 10^{-2}}}$$

muon g-2 $\delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = (26.1 \pm 8.0) \times 10^{-10}$



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Needs: $\rho_{\mu\tau} = \rho_{\tau\mu} \neq 0$ and nonzero mass differences in (m_h,m_H,m_A)

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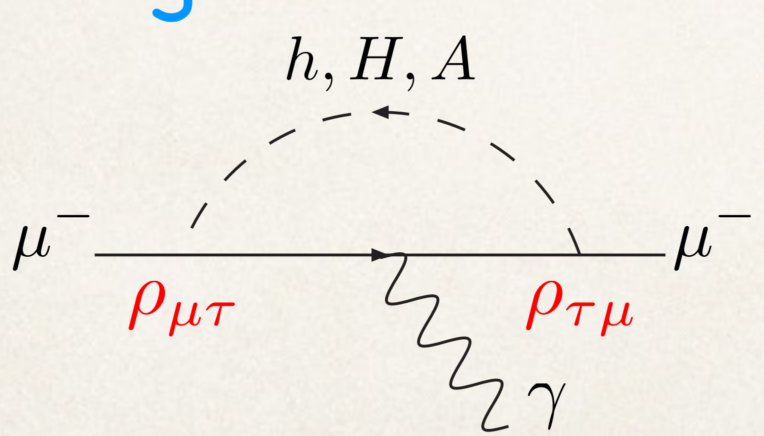

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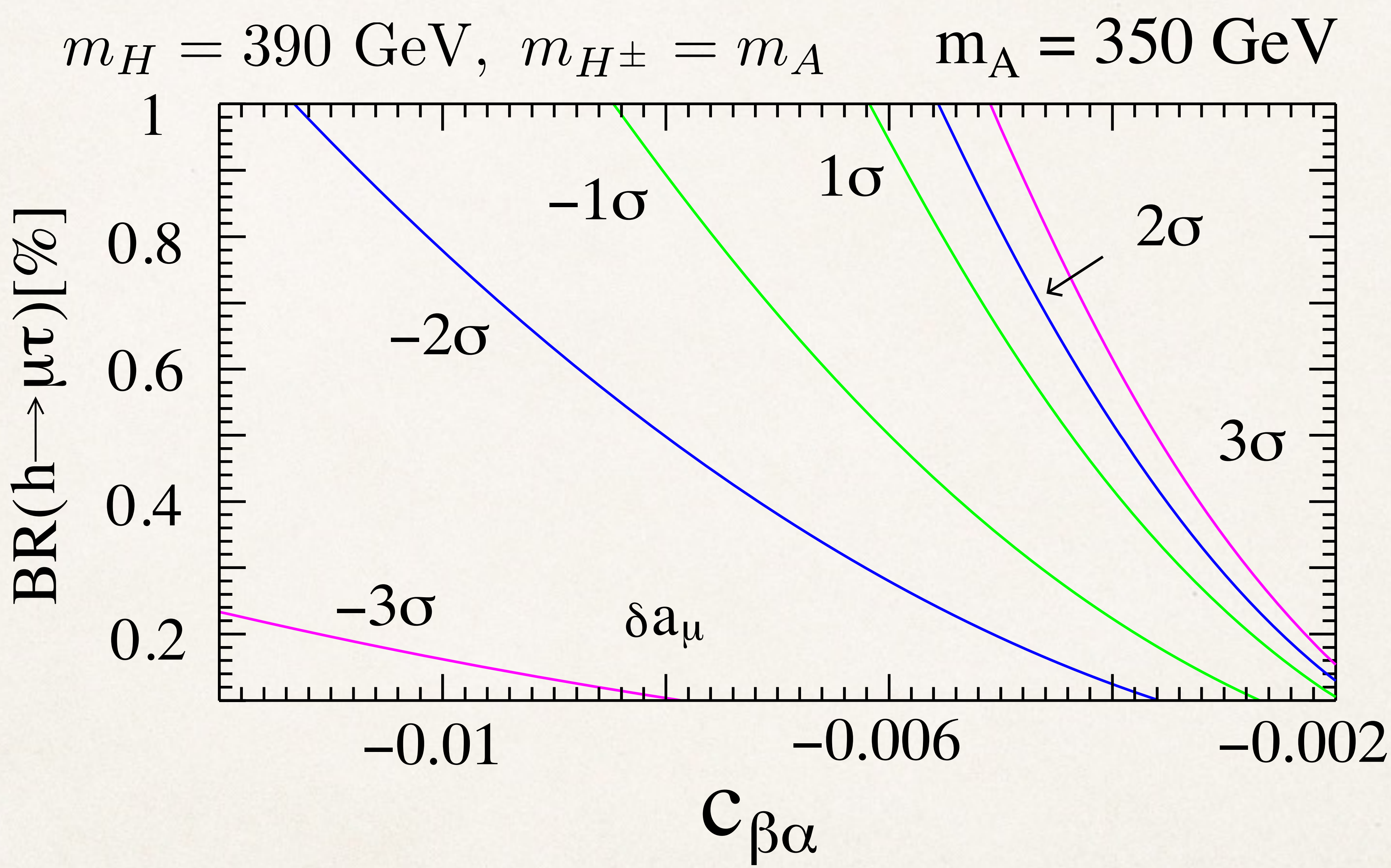


- μ-τ flavor violation can explain both h->μτ and g-2.

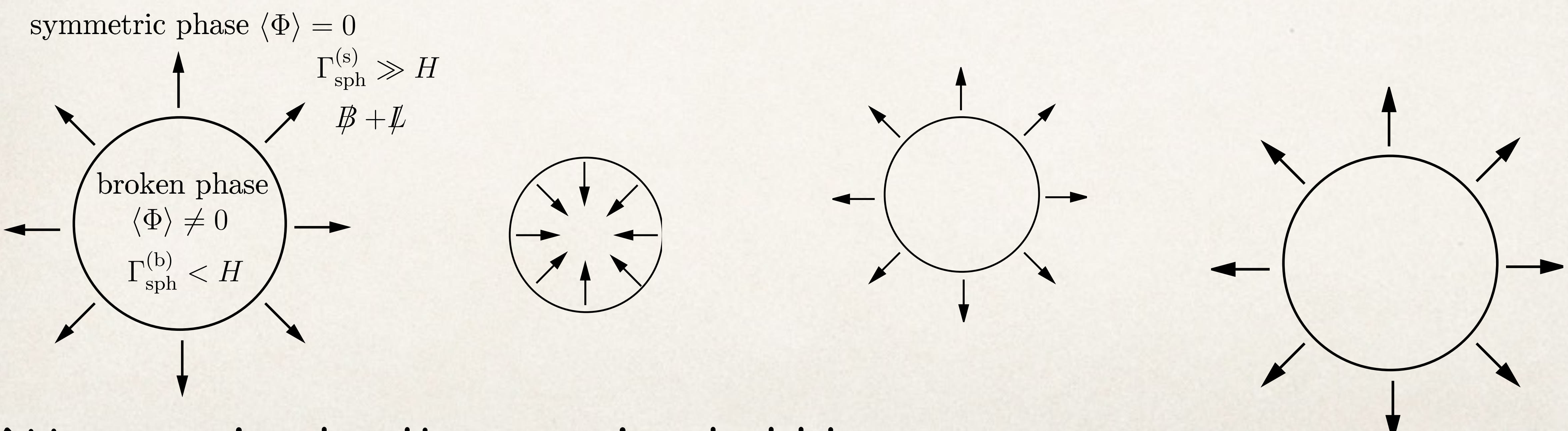
Baryogenesis

Electroweak baryogenesis

[Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]

Sakharov's conditions

- B violation: anomalous (sphaleron) process $0 \leftrightarrow \sum_{i=1,2,3} (3q_L^i + l_L^i)$ (LH fermions)
- C violation: chiral gauge interaction
- CP violation: KM phase and/or other sources in beyond the SM
- Out of equilibrium: 1st order EW phase transition (EWPT) with expanding bubble walls

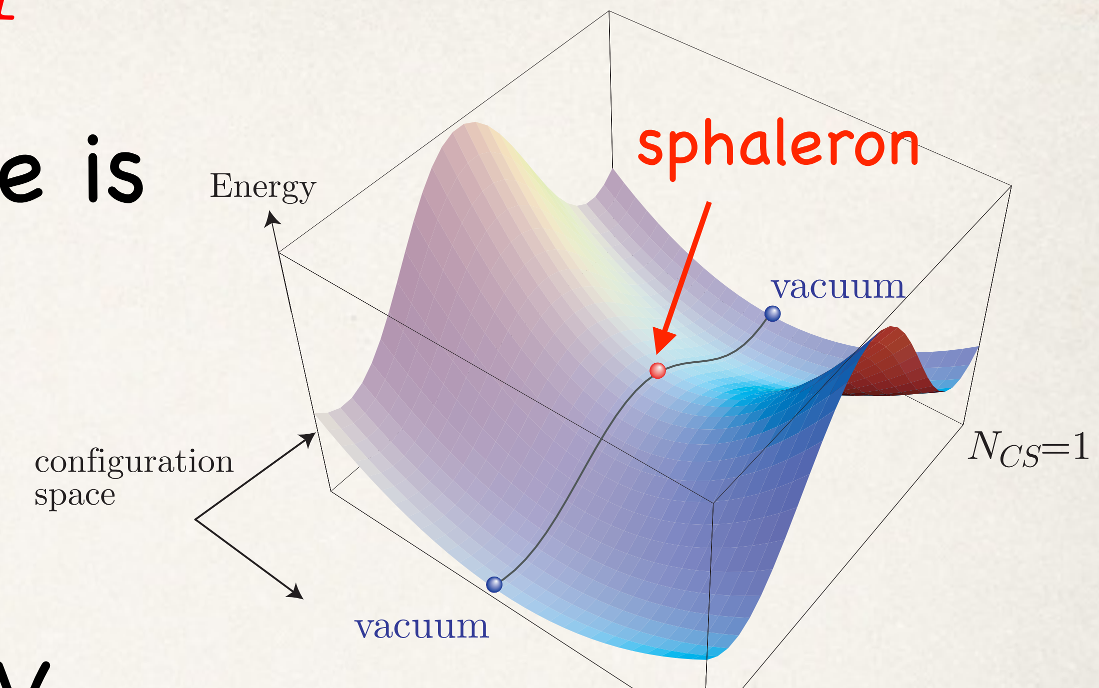


BAU can arise by the growing bubbles.

$$\Gamma_B^{(b)} < H$$

B-changing rate in the broken phase is

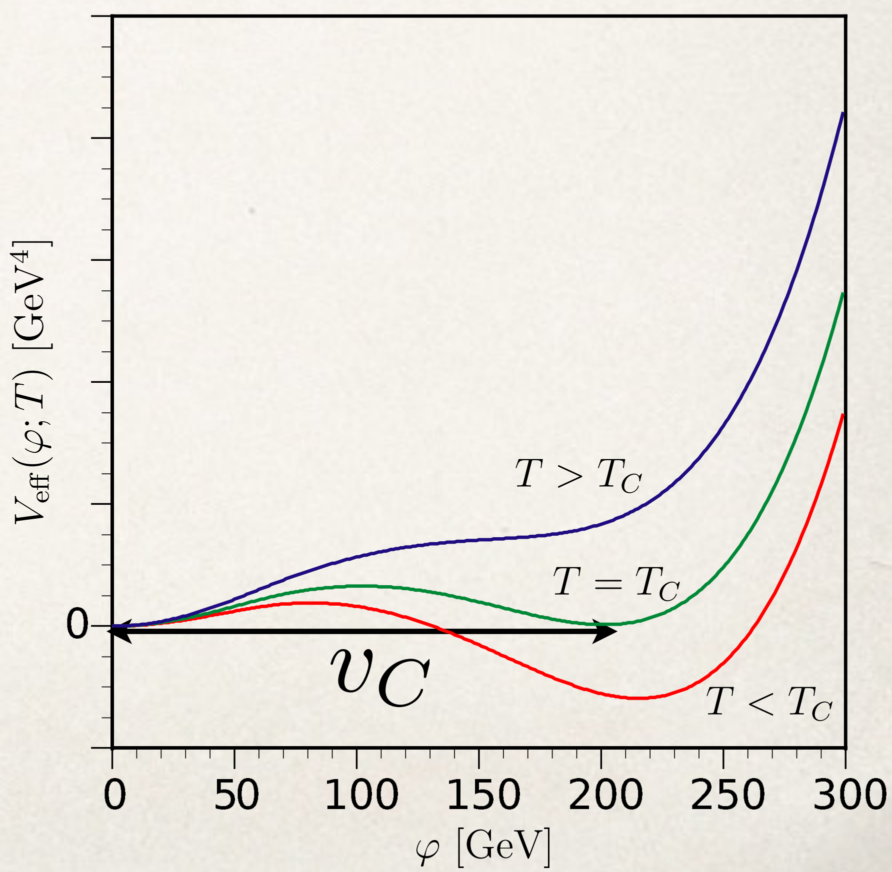
$$\boxed{\Gamma_B^{(b)} \simeq (\text{prefactor})e^{-E_{\rm sph}/T}}$$



$$\Delta B = 3\Delta N_{\rm CS}$$

E_{sph} is proportional to the Higgs VEV

$$\boxed{E_{\rm sph} \propto v(T)}$$



what we need is

large Higgs VEV after the EWPT

→ EWPT has to be "**strong**" 1st order!!

$$\Gamma_B^{(b)} < H$$

$$\boxed{\Gamma_B^{(b)}(T) \simeq (\text{prefactor}) e^{-E_{\rm sph}(T)/T} < H(T) \simeq 1.66\sqrt{g_*}T^2/m_{\rm P}}$$

$E_{\rm sph}(T) = 4\pi v(T)\mathcal{E}/g_2$ (g_2: SU(2) gauge coupling),

$$\rightarrow \boxed{\frac{v(T)}{T} > \frac{g_2}{4\pi\mathcal{E}}\left[42.97 + \log \text{ corrections}\right] = \zeta_{\rm sph}}$$

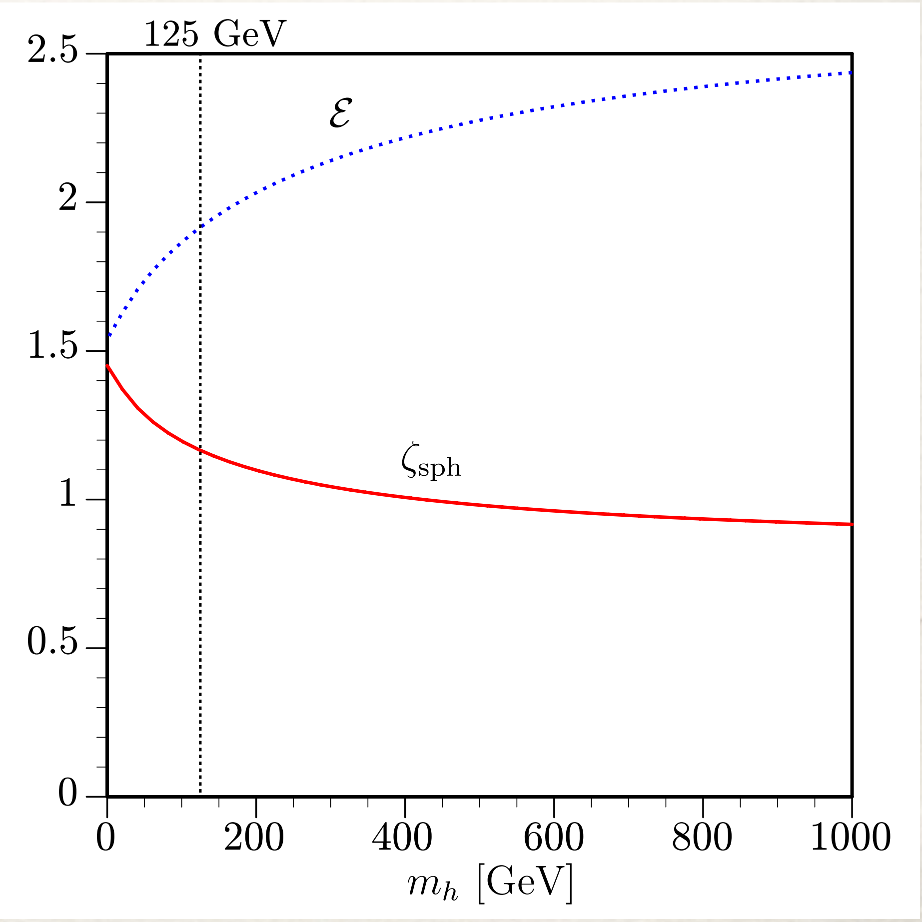
- dominant effect: sphaleron energy.

For 2HDM with alignment limit:

$$\mathcal{E} \to \mathcal{E}_{\rm SM} = 1.92$$

@tree level

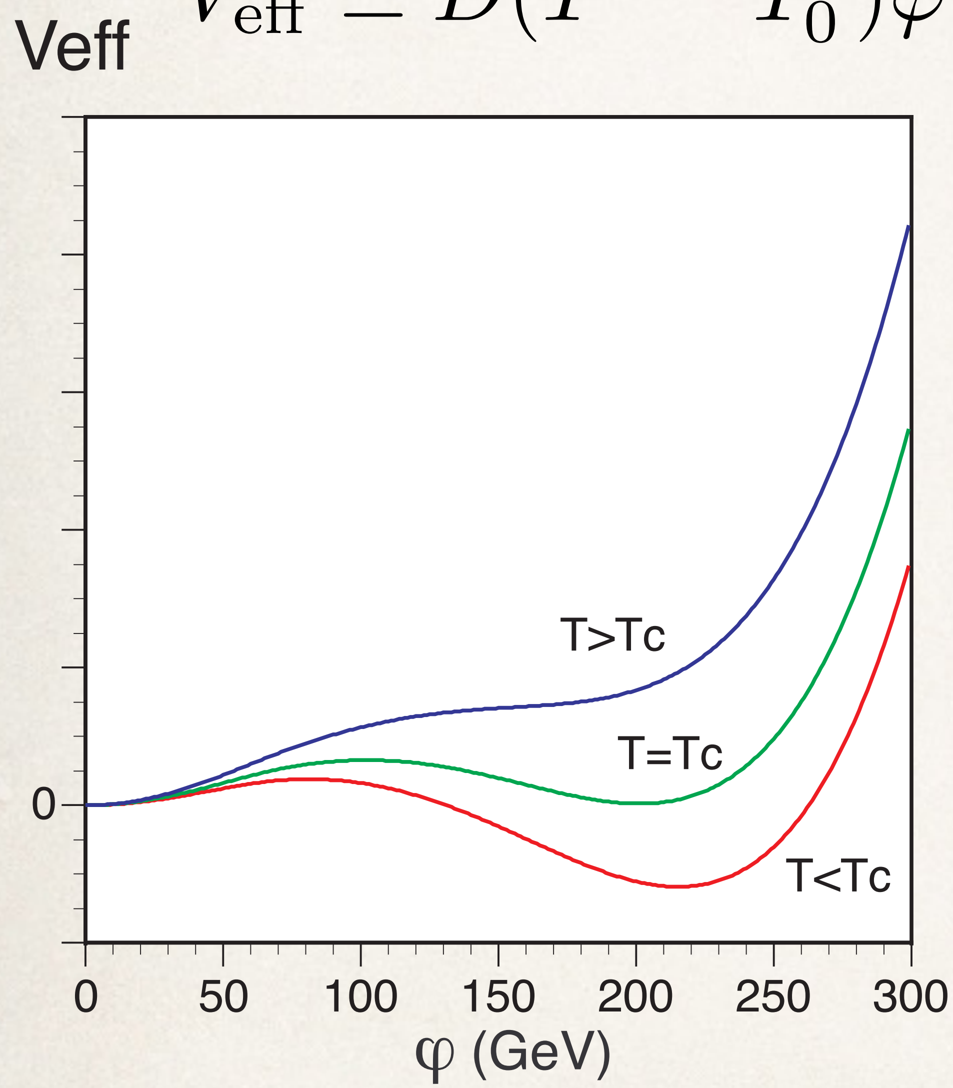
$$\boxed{\frac{v(T)}{T} > 1.17}$$



For a band structure effect on Γ_B,
see [K.Funakubo, K.Fuyuto, E.S., arXiv:1612.05431]

1st-order phase transition

$$V_{\text{eff}} \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 \underset{T=T_C}{\longrightarrow} \frac{\lambda_{T_C}}{4}\varphi^2(\varphi - v_C)^2$$



$$v_C = \frac{2ET_C}{\lambda_{T_C}} \quad \Rightarrow \quad \frac{v_C}{T_C} = \frac{2E}{\lambda_{T_C}}$$

- Heavy Higgs loops can enhance E.

$$m^2_{i=H,A,H^\pm} = M^2 + \tilde{\lambda}_i \varphi^2$$

$$V_{\text{eff}} \ni \begin{cases} -\tilde{\lambda}^{3/2} T \varphi^3 \left(1 + \frac{M^2}{\tilde{\lambda}\varphi^2}\right)^{3/2}, & \text{for } M^2 \ll \tilde{\lambda}\varphi^2, \\ -|M|^3 T \left(1 + \frac{\tilde{\lambda}\varphi^2}{M^2}\right)^{3/2}, & \text{for } M^2 \gtrsim \tilde{\lambda}\varphi^2. \end{cases}$$

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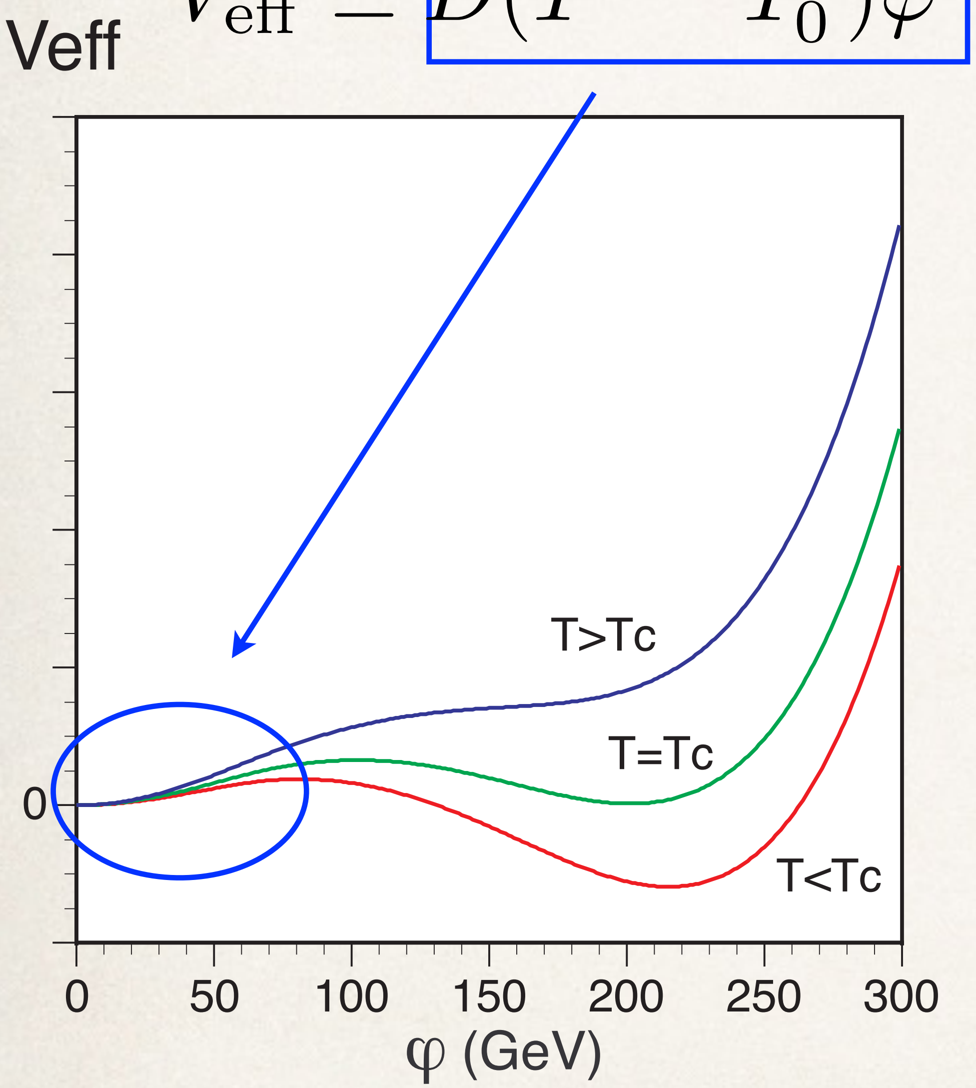

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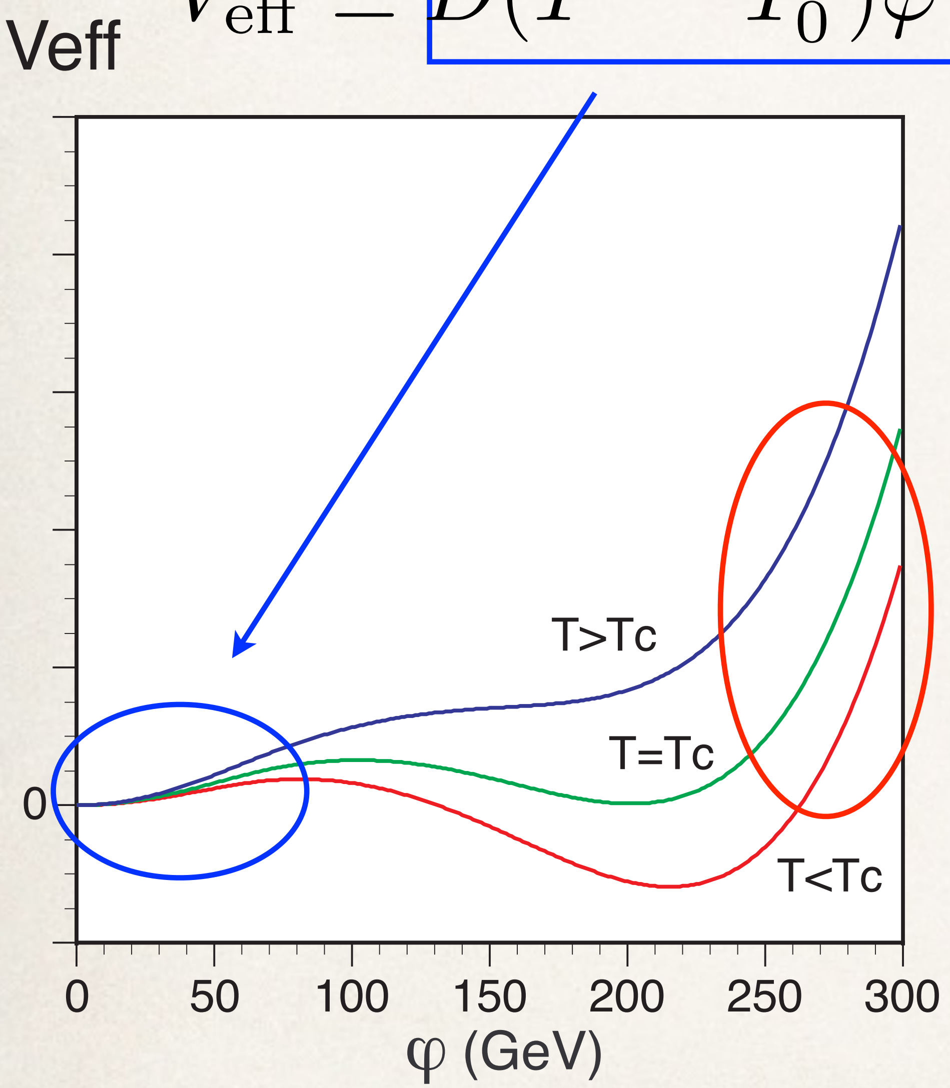

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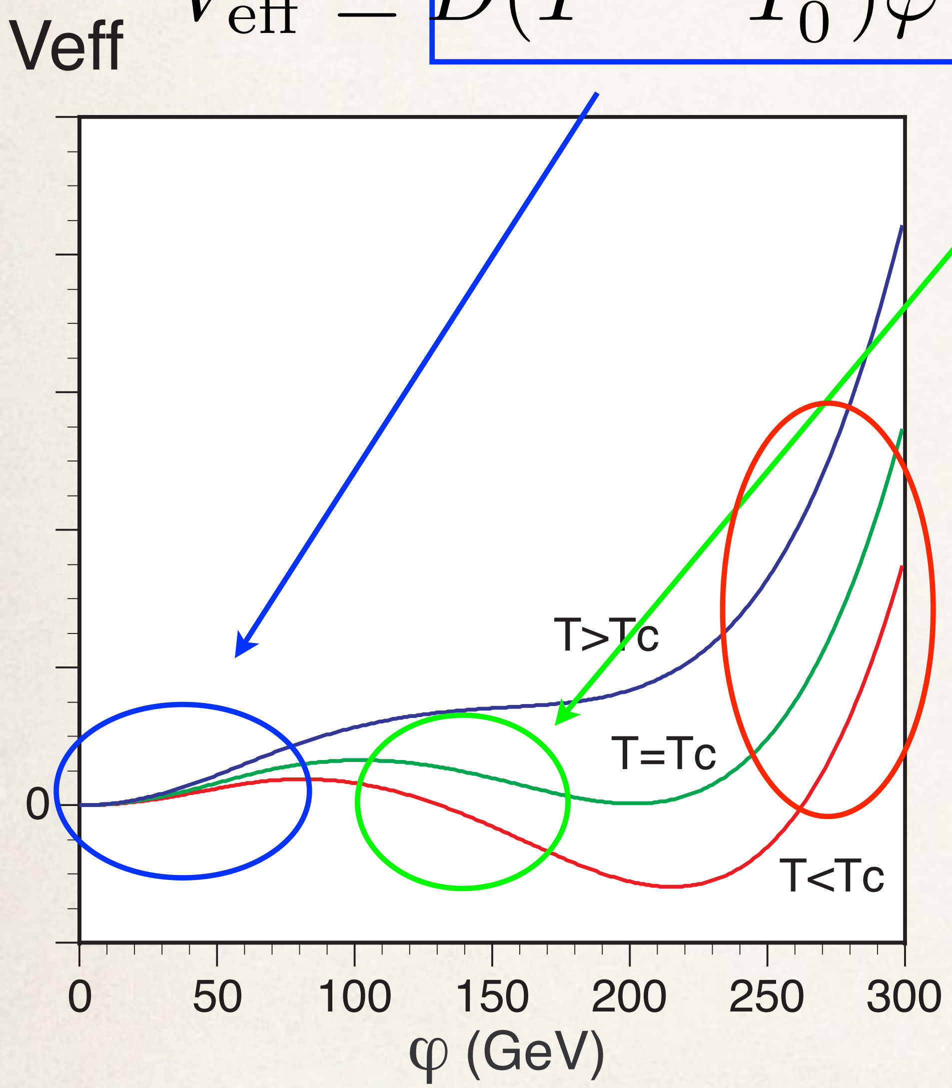

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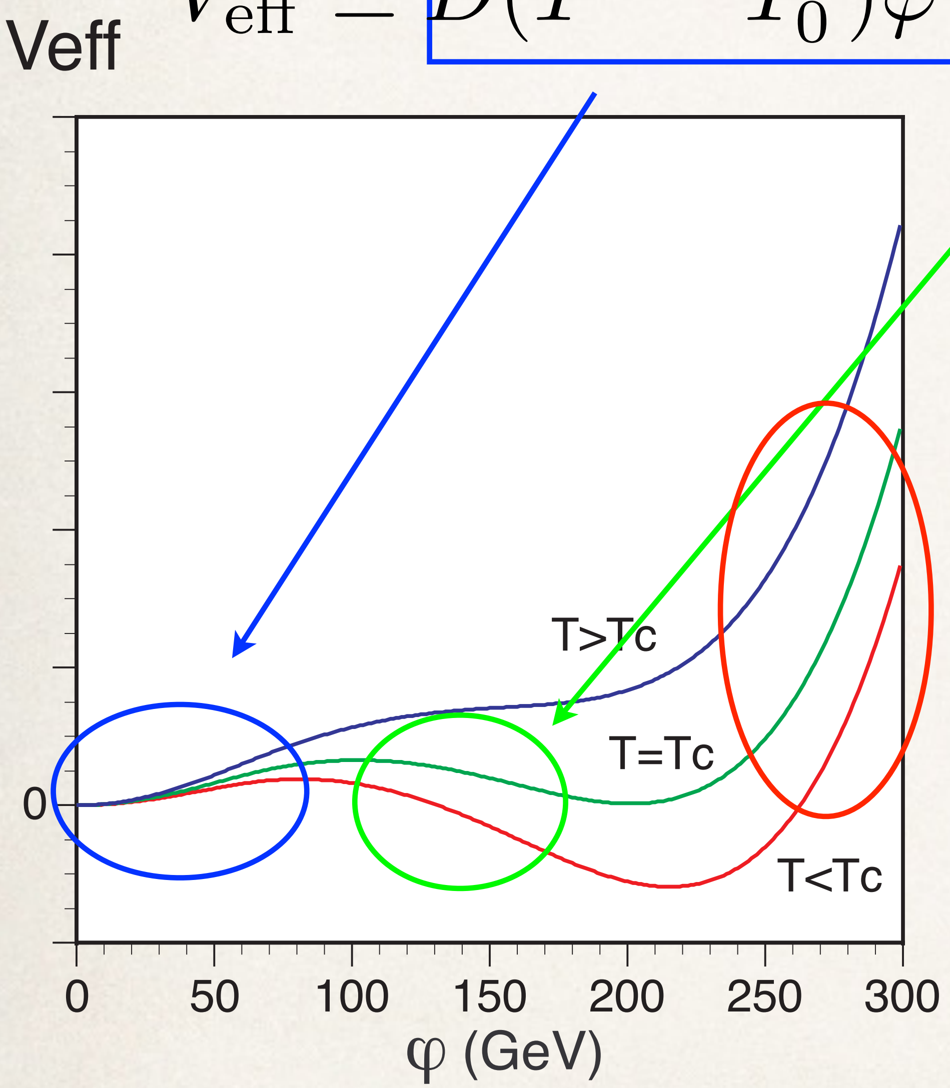

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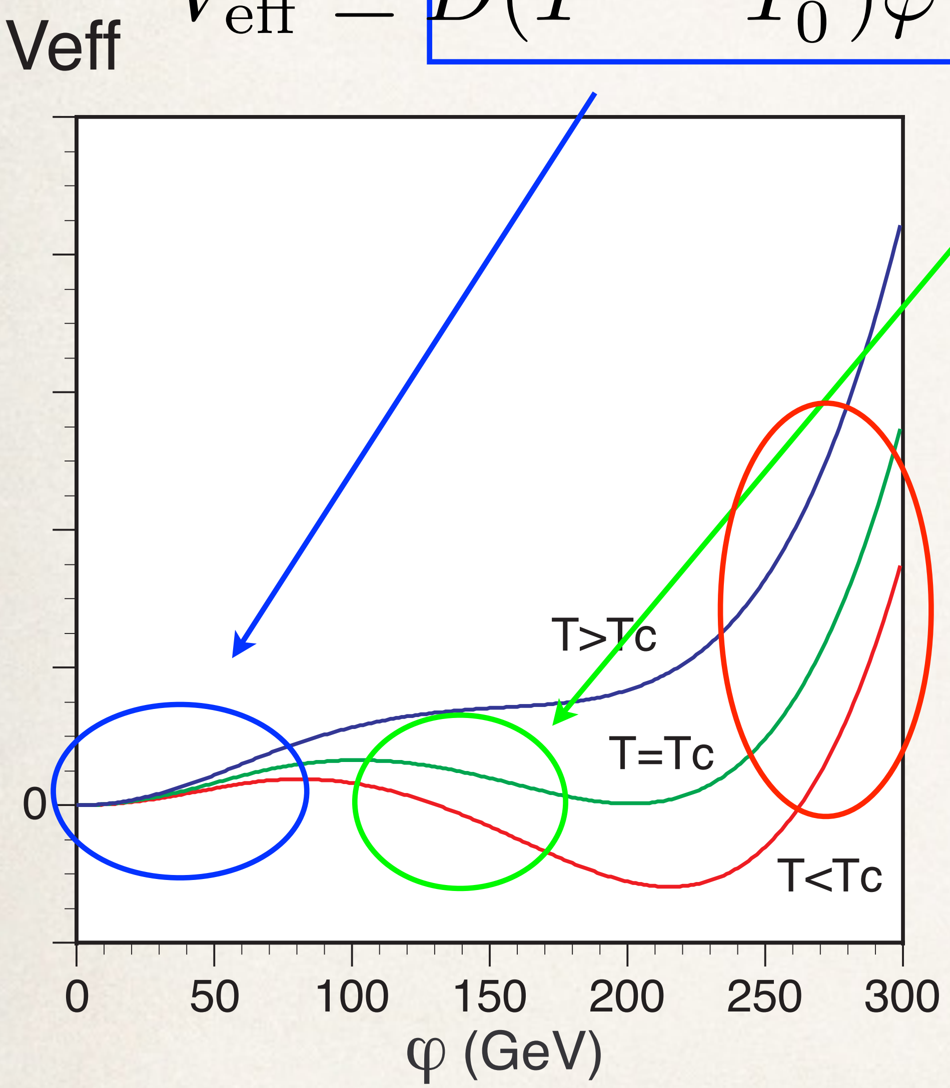

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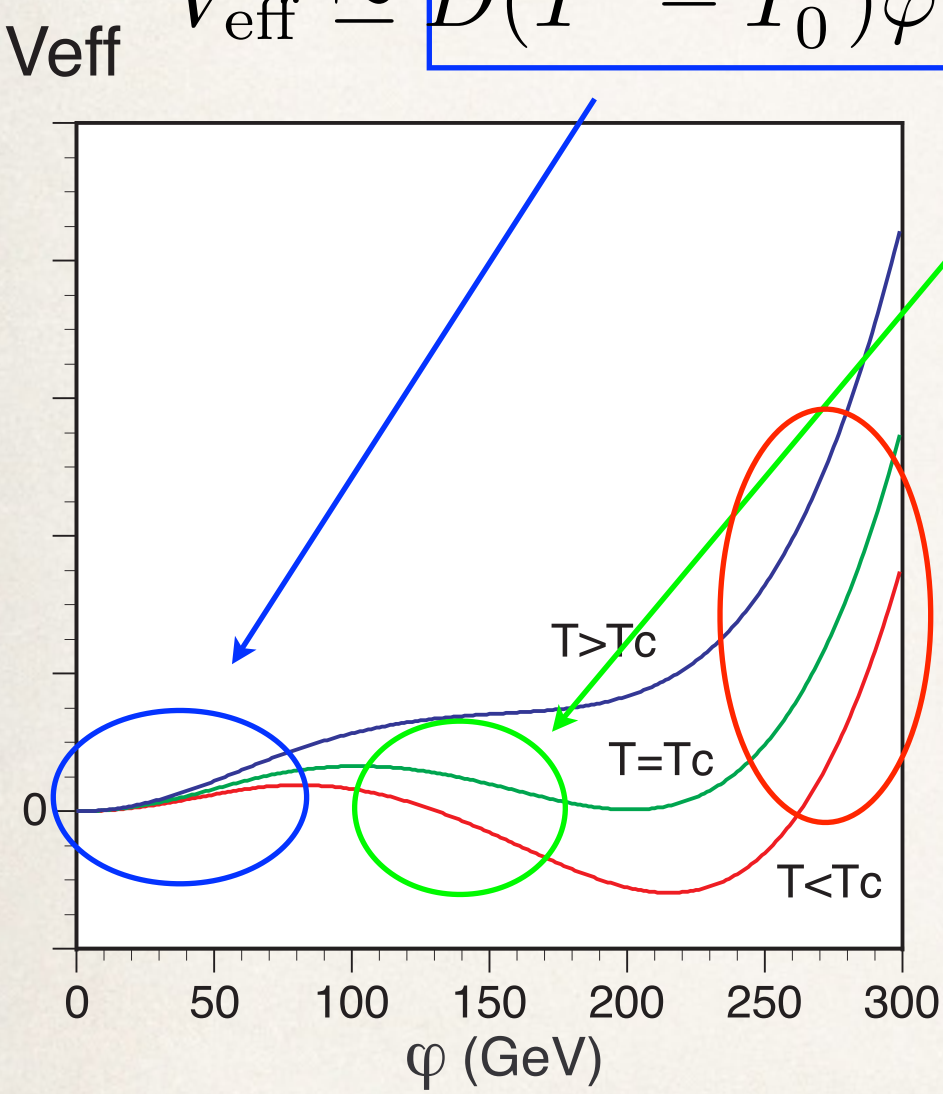

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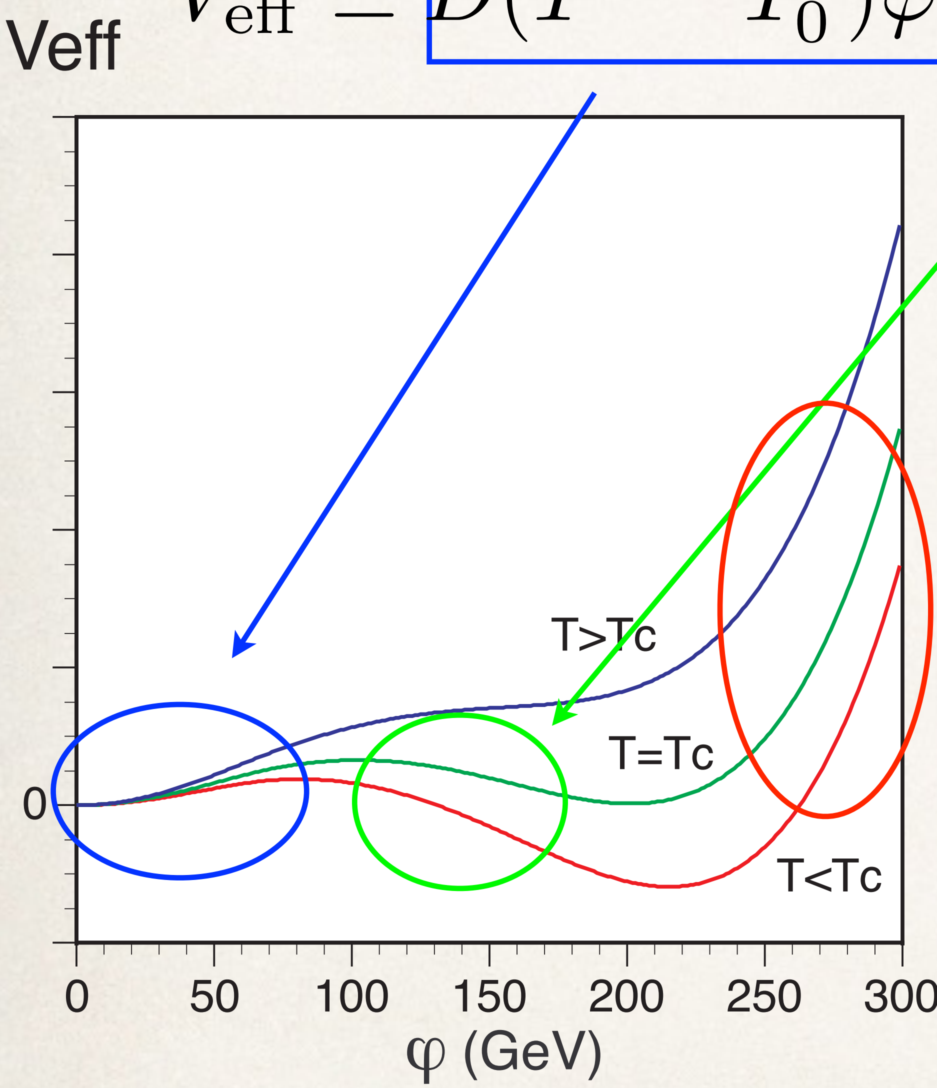

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decoupling

Non-decoupling heavy Higgs bosons play a central role in enhancing E.

EWBG and LFV

[C-W. Chiang, K.Fuyuto, E.S., arXiv:1607.07316 (PLB)]

benchmark point:

$m_A = m_{H^\pm}$, $M = 100$ GeV, $\tan\beta = 1$, $c_{\beta-\alpha} = 0.006$
$|\rho_{\tau\mu}| = |\rho_{\mu\tau}|$, $\phi_{\tau\mu} + \phi_{\mu\tau} = \pi/4$, $\lambda_{6,7} = 0$ $\mathrm{Br}(h \to \mu\tau) = 0.84$ %

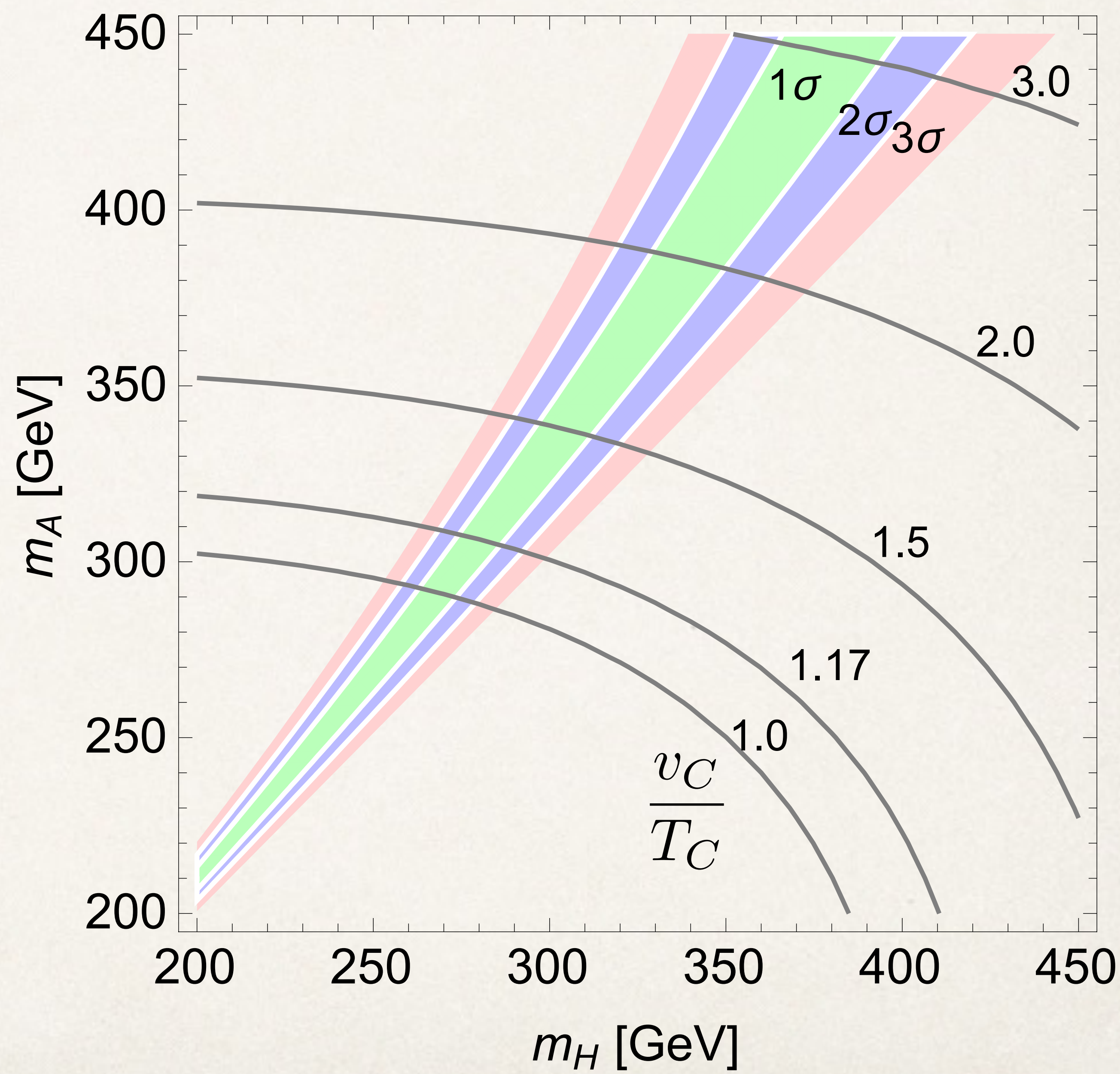
- Br(h->μτ)=0.84%
- g-2 favored region

$$m_A \gtrsim m_H$$

for $\mathrm{Re}(\rho_{\tau\mu}\rho_{\mu\tau})>0$.

- EWBG-viable region

$$v_C/T_C > 1.17$$



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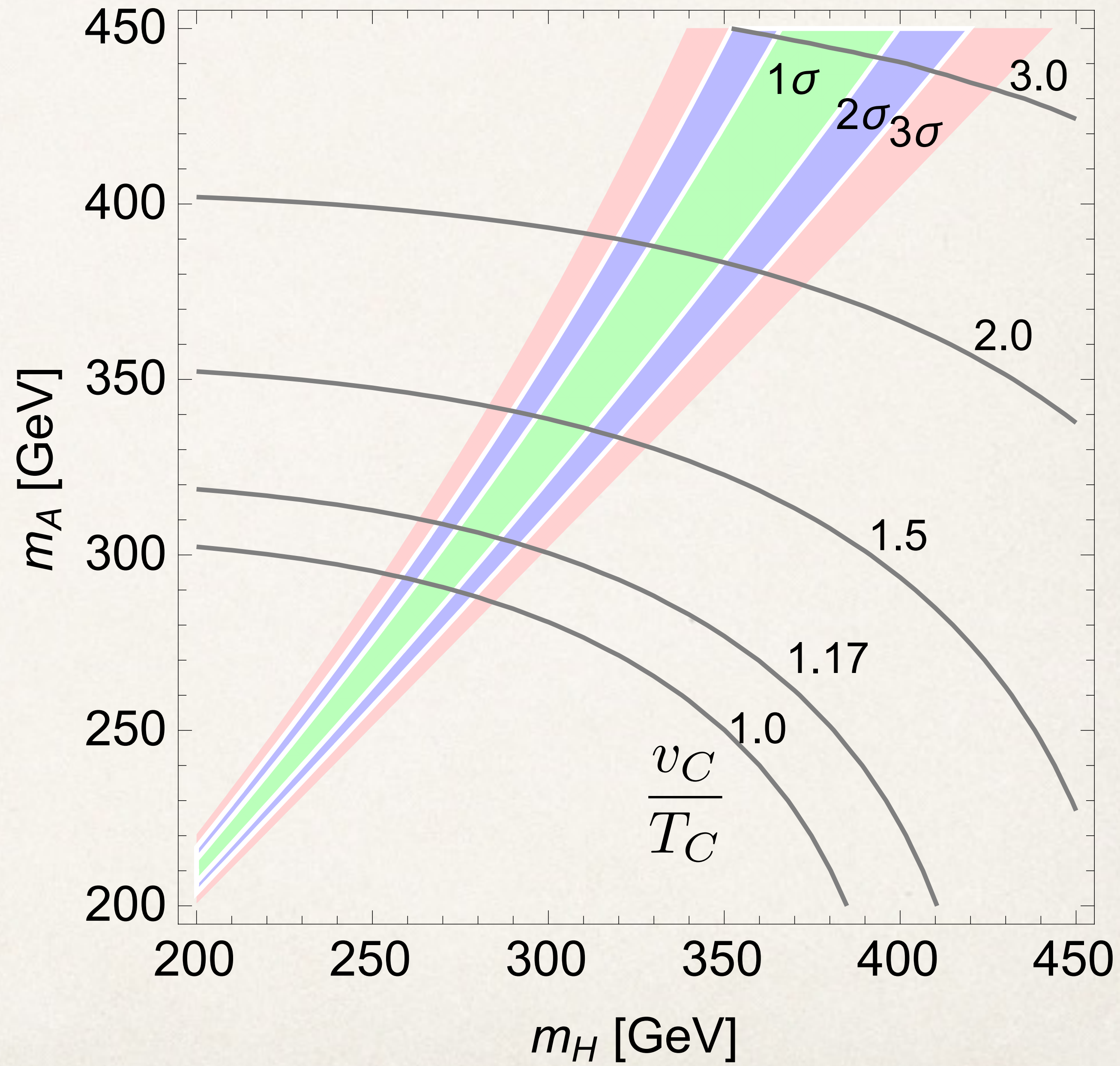

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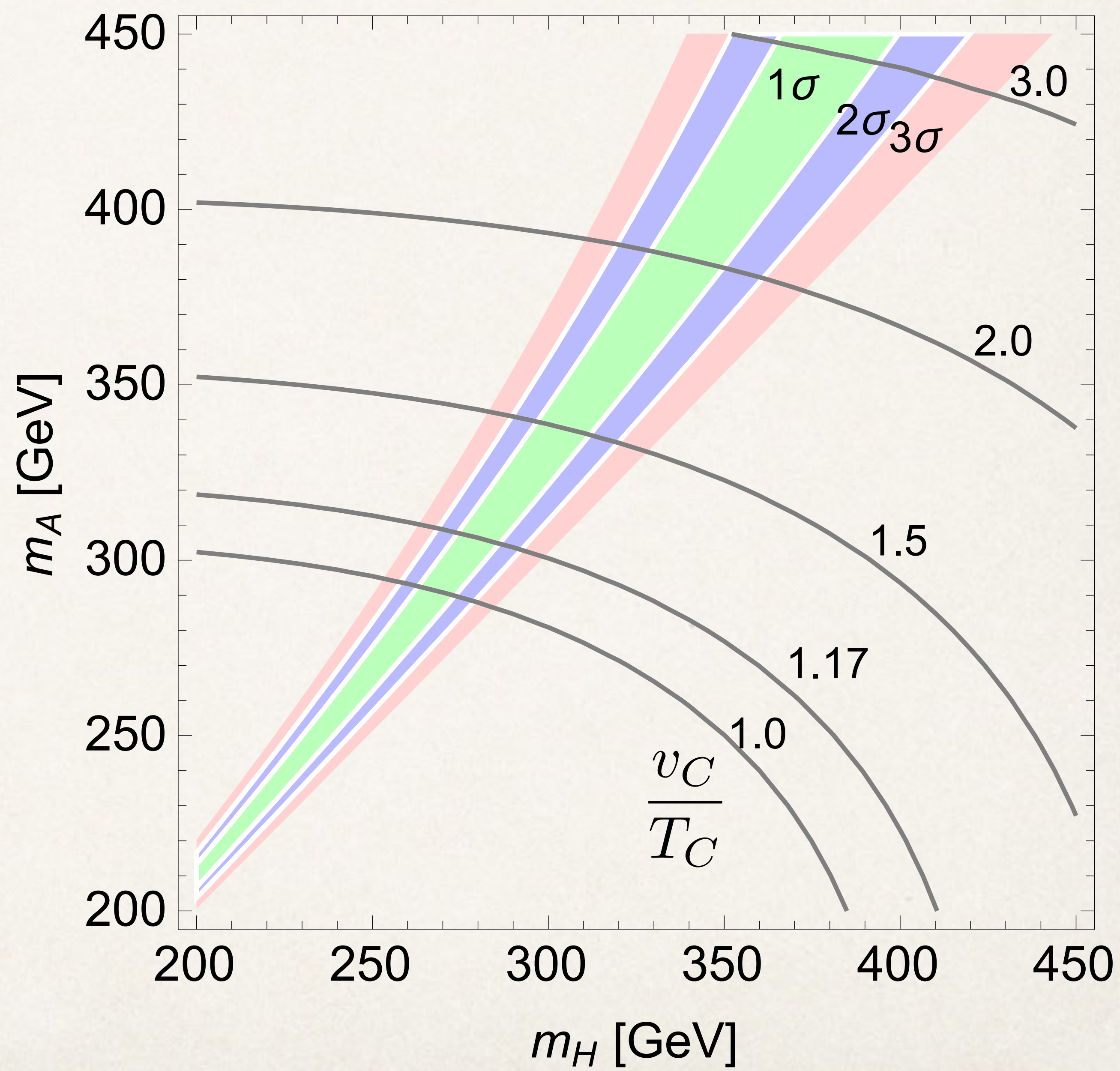

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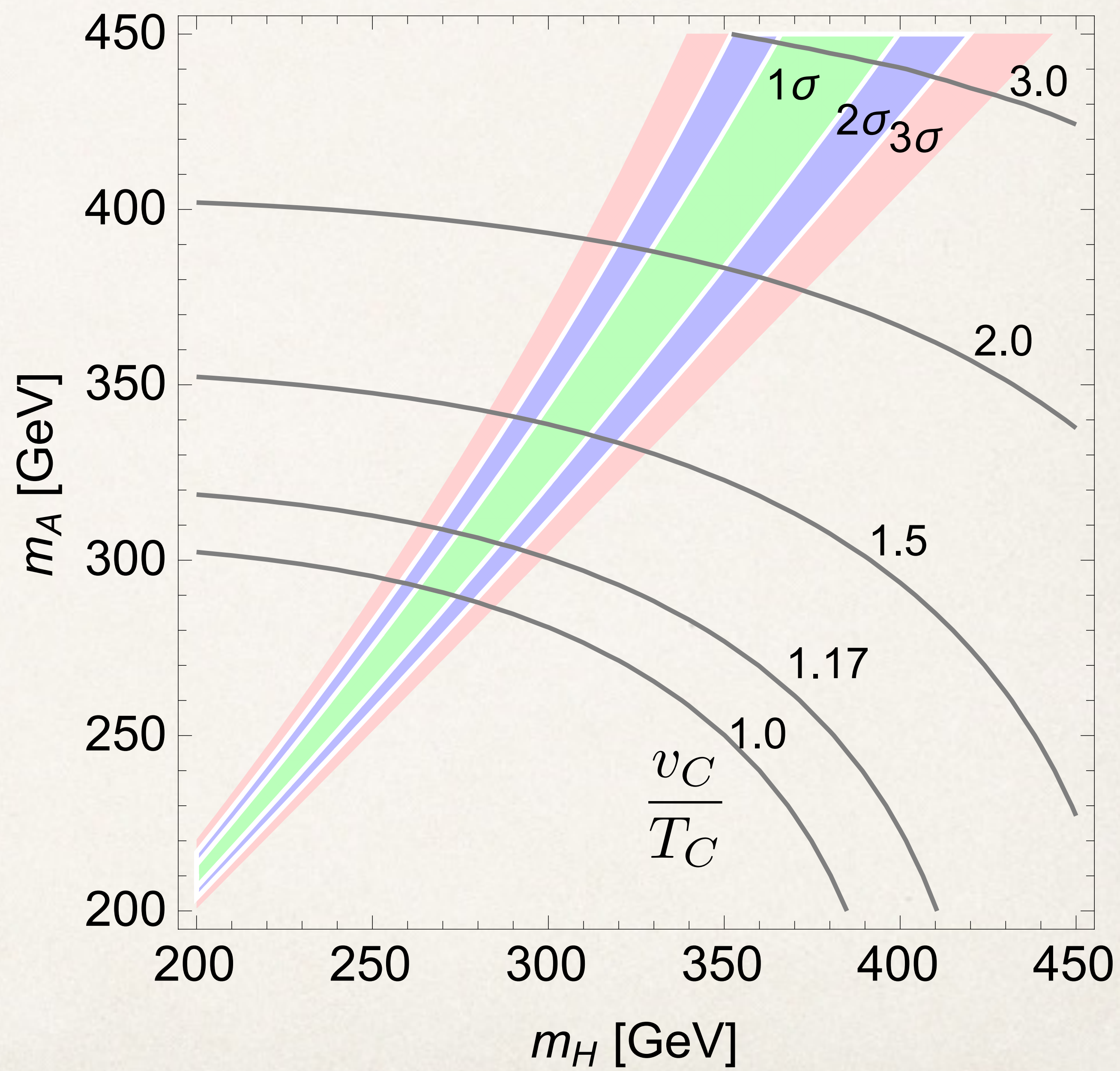

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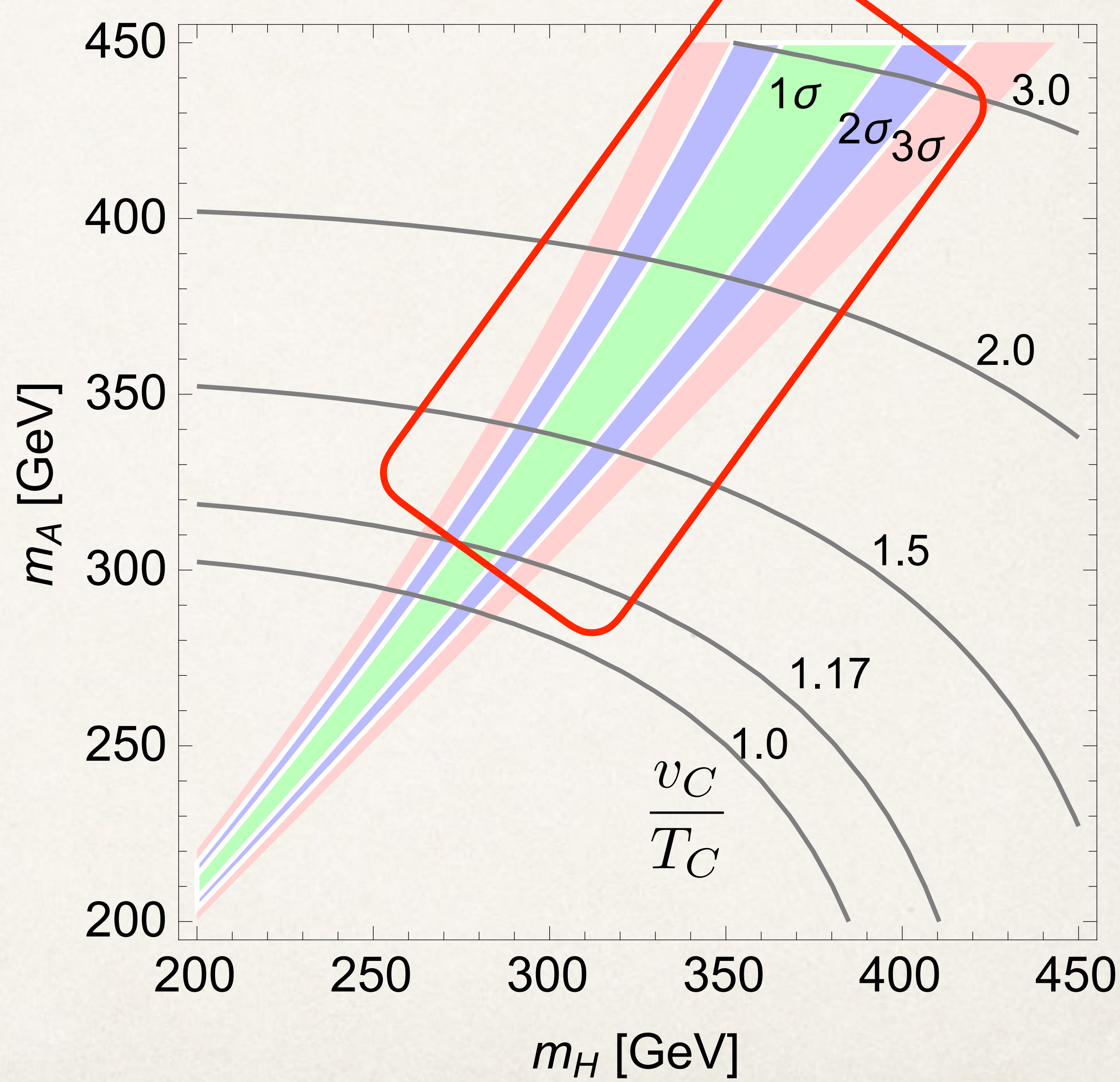
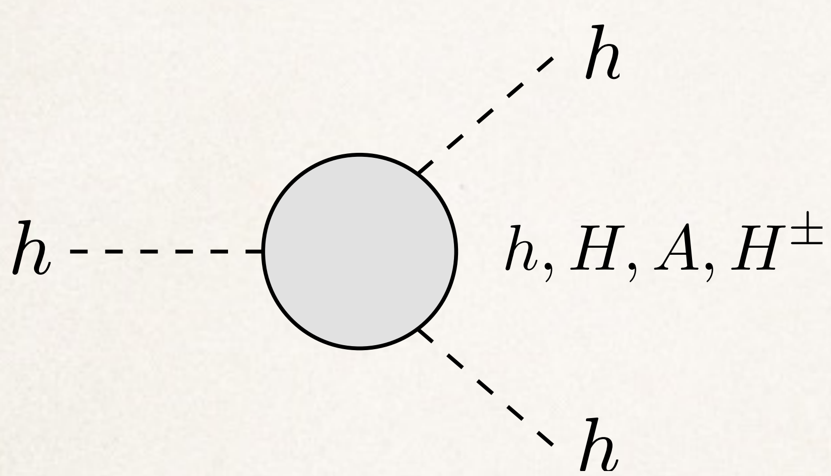
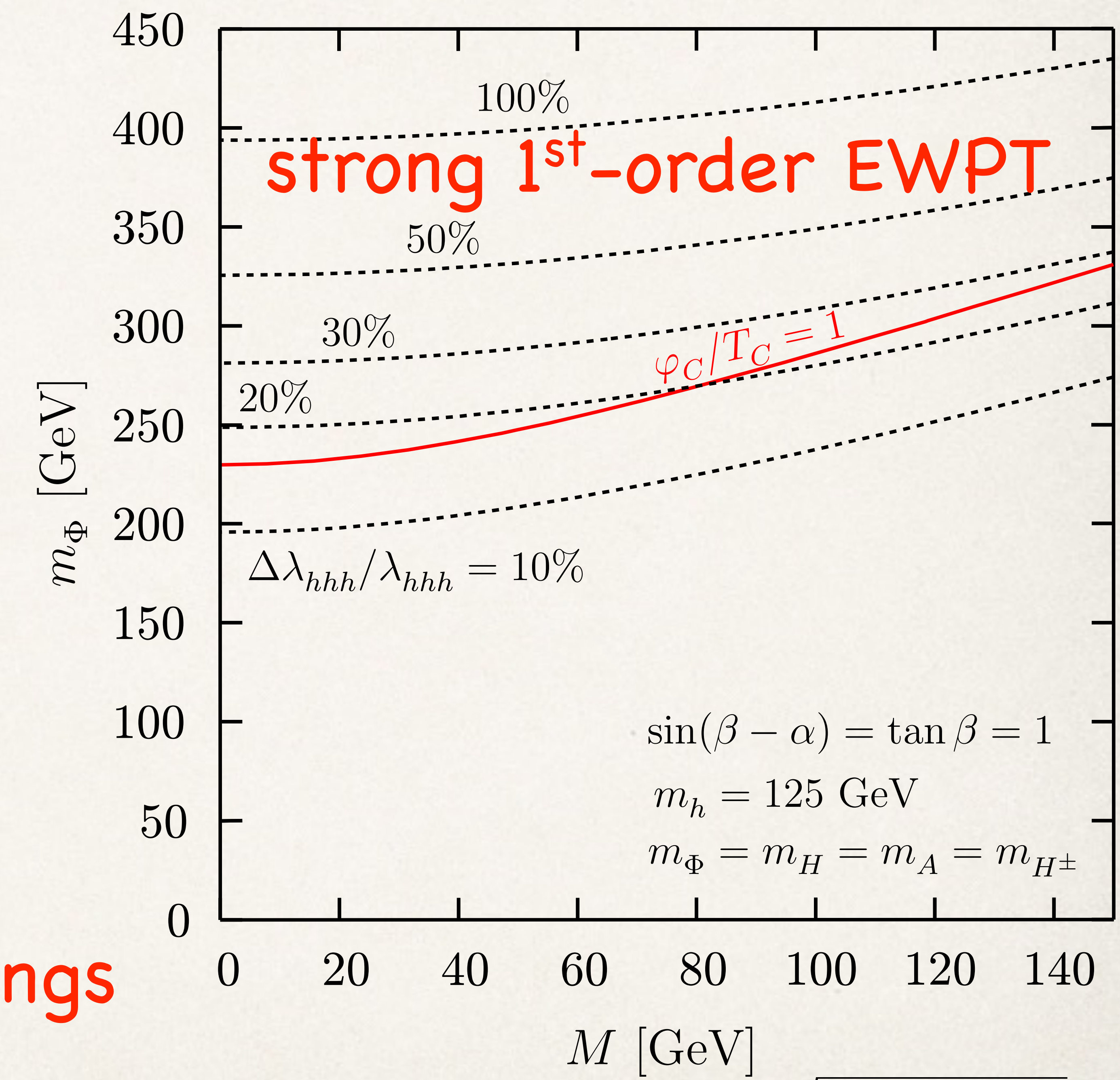


Combined: 300 GeV $\lesssim m_H \lesssim m_A \lesssim$ 450 GeV

λ_{hhh} in the 2HDM

[update of Kanemura, Okada, E.S., PLB606,(2005)361]





$$M = \sqrt{\frac{m_3^2}{\sin\beta\cos\beta}}$$

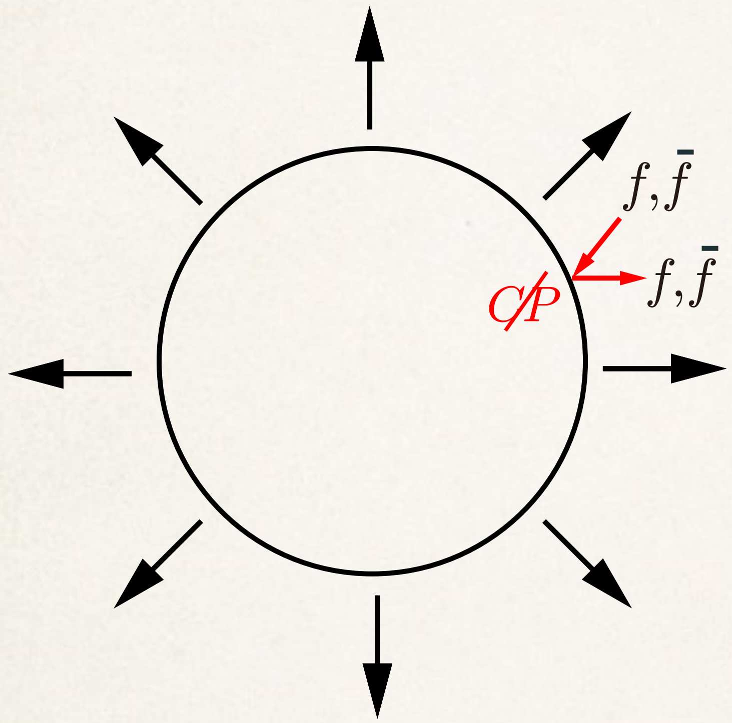
- Non-decoupling heavy Higgs loop can modify λ_{hhh}.

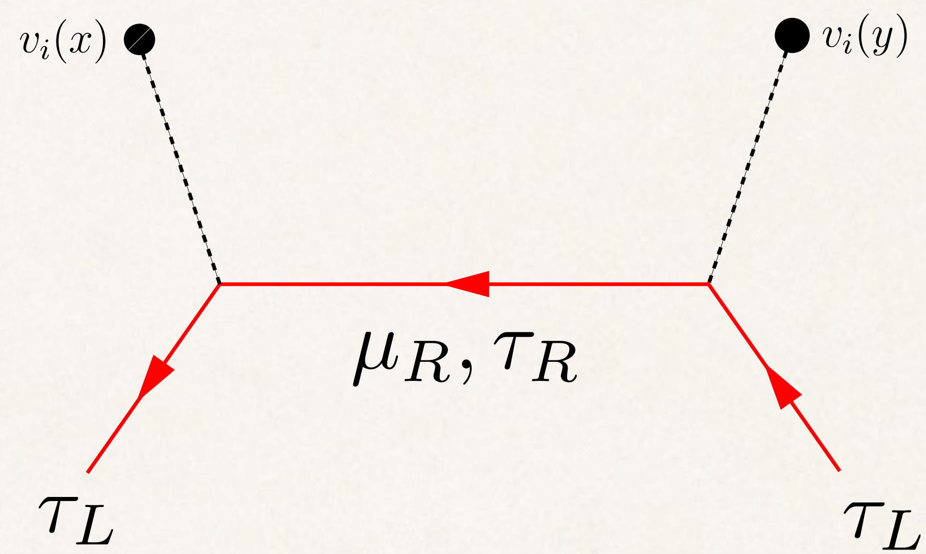
- Even if hVV and hff couplings are SM-like, $\Delta\lambda_{hhh}$>(15-20)%

Baryon number density

We evaluate BAU using closed-time-path formalism.

$$-\mathcal{L}_Y = \bar{l}_{iL}(Y_1\Phi_1 + Y_2\Phi_2)_{ij}e_{jR} + \mathrm{h.c.}$$





Im $\rightarrow$ $S^{\mathrm{CPV}}_{\tau_L}$

Re $\rightarrow$ $\Gamma^{\mathrm{CPC}}_{\tau_L}$

VEV insertion method

$$S^{\mathrm{CPV}}_{\tau_L}(X) = \mathrm{Im}\Big[(Y_1)_{\tau j}(Y_2)^*_{\tau j}\Big] v^2(X)\partial_{t_X}\beta(X), \quad j = \mu, \tau$$

After solving coupled diffusion equations,

$$n_B \simeq \kappa_B \frac{S^{\mathrm{CPV}}}{\sqrt{\Gamma^{\mathrm{CPC}}}}$$

κ_B : coefficient

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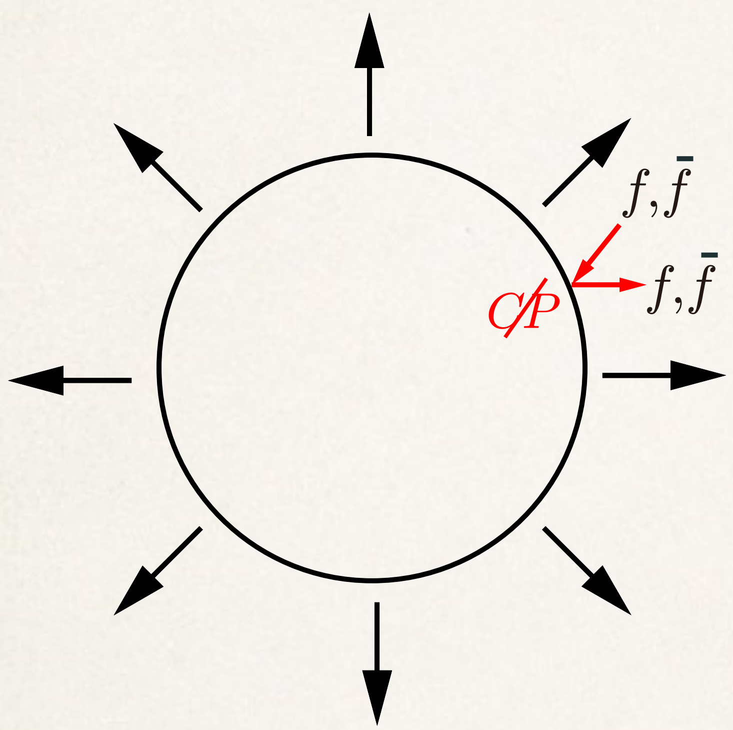

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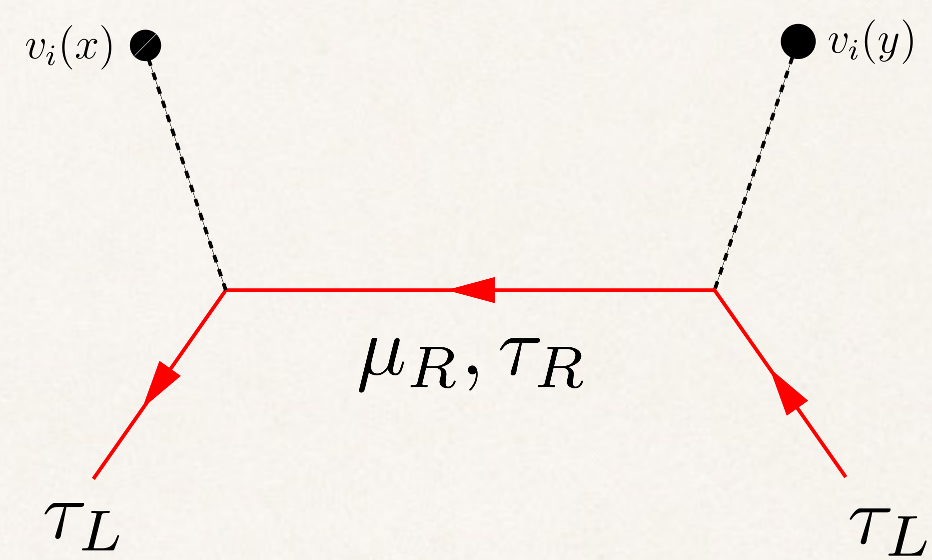

Im $\rightarrow$ $S_{\tau_L}^{\mathrm{CPV}}$

Re $\rightarrow$ $\Gamma_{\tau_L}^{\mathrm{CPC}}$

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BAU-related CPV in the broken phase

$$V_L^{e\dagger}(Y_1 c_\beta + Y_2 s_\beta)V_R^e = Y_D = \mathrm{diag}(y_e, y_\mu, y_\tau),$$
$$V_L^{e\dagger}(-Y_1 s_\beta + Y_2 c_\beta)V_R^e = \rho$$

τ-μ case

$$\longrightarrow \quad \mathrm{Im}\Big[(Y_1)_{\tau\mu}(Y_2)^*_{\tau\mu}\Big] = \mathrm{Im}\Big[(V_L^e Y_D V_R^{e\dagger})_{32}(V_L^e \rho V_R^{e\dagger})^*_{32}\Big]$$

Simplified case: Guo et al, 1609.09849.

$$Y_{i=1,2} = \begin{pmatrix} (Y_i)_{ee} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & (Y_i)_{\tau\mu} & (Y_i)_{\tau\tau} \end{pmatrix}, \quad \tan\beta = 1, \quad (Y_1)_{\tau\tau} = (Y_2)_{\tau\tau}$$

$$\longrightarrow \quad \mathrm{Im}\Big[(Y_1)_{\tau\mu}(Y_2)^*_{\tau\mu}\Big] = -y_\tau \mathrm{Im}(\rho_{\tau\tau}), \quad \rho_{\mu\tau} = 0.$$

To explain muon g-2, both $\rho_{\tau\mu}$ and $\rho_{\mu\tau}$ must be nonzero.

BAU-related CPV in the broken phase

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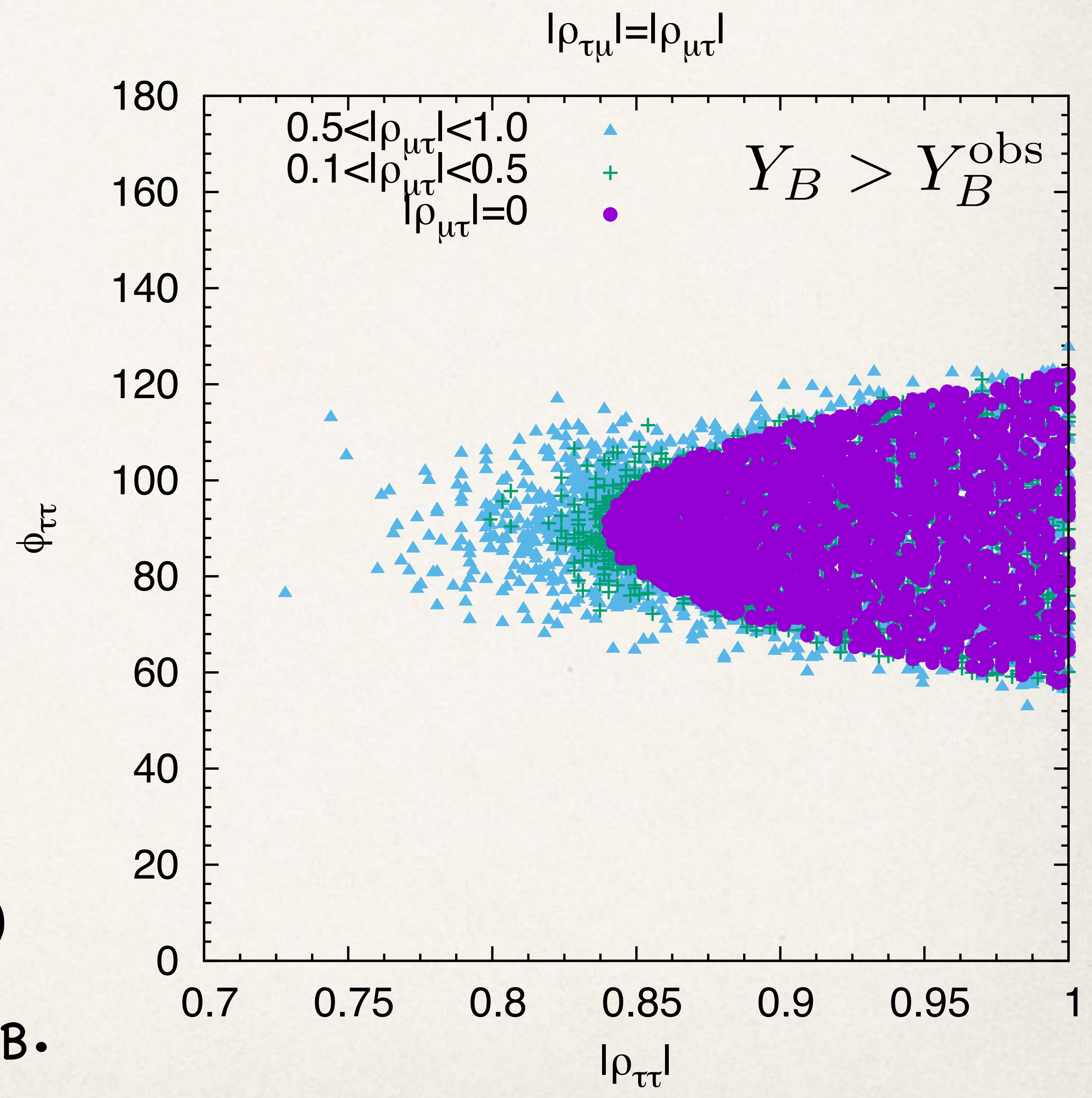
To explain muon g-2, both $\rho_{\tau\mu}$ and $\rho_{\mu\tau}$ must be nonzero.

Ramdom scan

- Yukawa couplings ($Y_{1,2}$) are randomly scanned.
- Leading effect on Y_B: $\rho_{\tau\tau}$
- Subleading effect: $\rho_{\tau\mu}$ and $\rho_{\mu\tau}$.
- Yukawa textures with $\rho_{\mu\tau}\neq 0$ can give visible effects on Y_B.

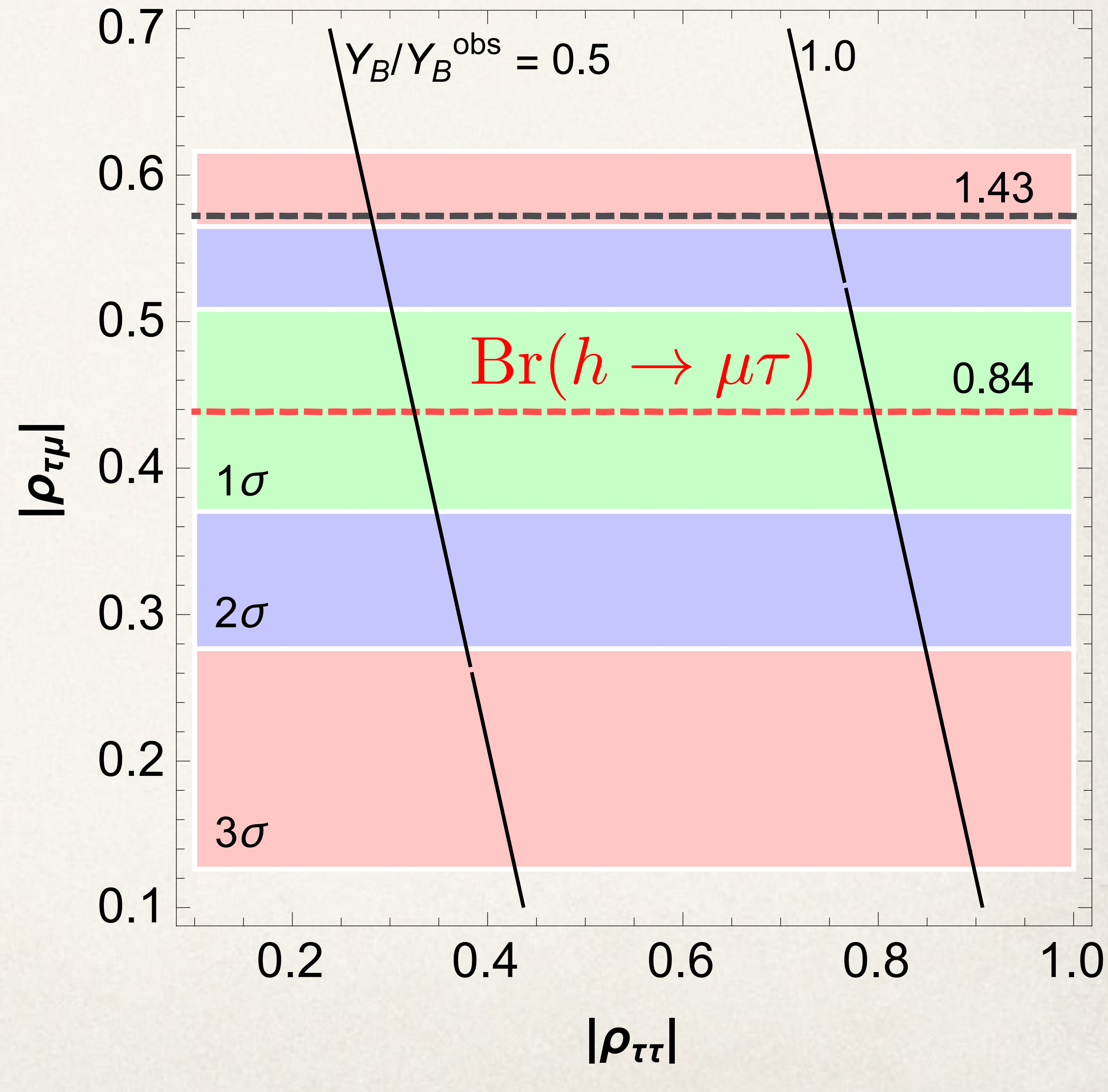


Benchmark

$$m_H = 350 \text{ GeV},\ m_A = m_{H^\pm} = 400 \text{ GeV},\ c_{\beta-\alpha} = 0.006,\ |\rho_{\mu\tau}| = |\rho_{\tau\mu}|$$
$$\phi_{\tau\mu} + \phi_{\mu\tau} = \pi/4,\ \phi_{\tau\tau} = \pi/2$$

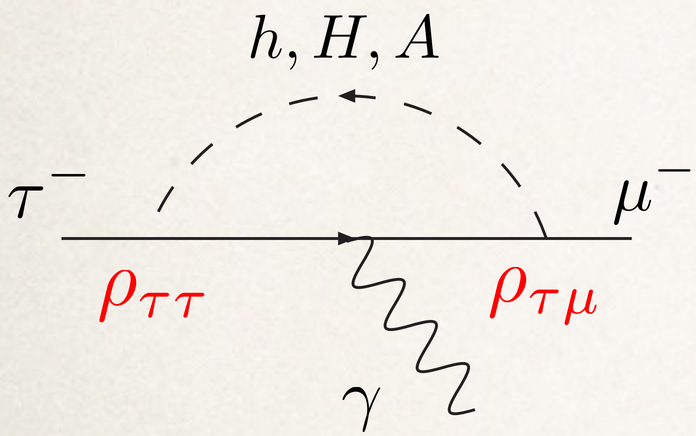
$$\begin{aligned} Y^{\rm SM} &= Y_1 c_\beta + Y_2 s_\beta \\ &= \begin{pmatrix} \sqrt{2}m_e/v & 0 & 0 \\ 0 & 3.31\times 10^{-3} & -6.81i\times 10^{-4} \\ 0 & 8.91i\times 10^{-3} & 3.70\times 10^{-3} \end{pmatrix}, \end{aligned}$$

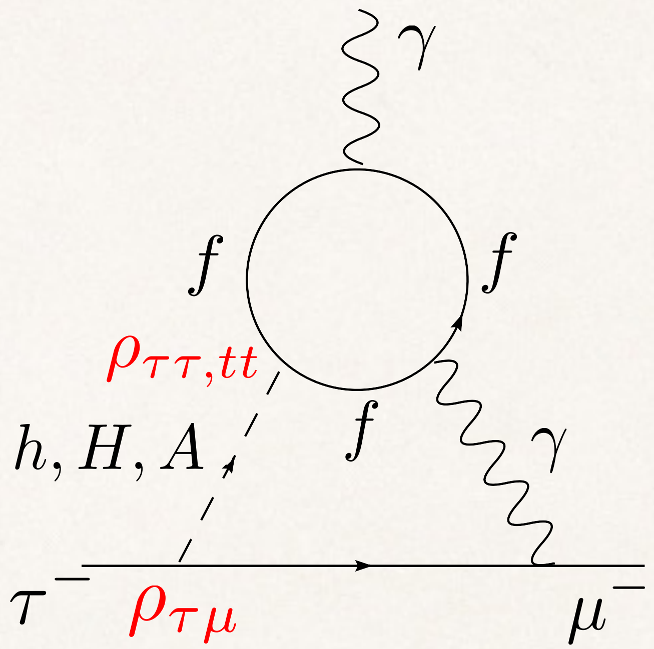
$$V_R^e = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -0.365i & -0.931i \\ 0 & -0.931 & 0.365 \end{pmatrix},\quad V_L^e = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -0.945i & -0.327i \\ 0 & -0.327 & 0.945 \end{pmatrix}$$

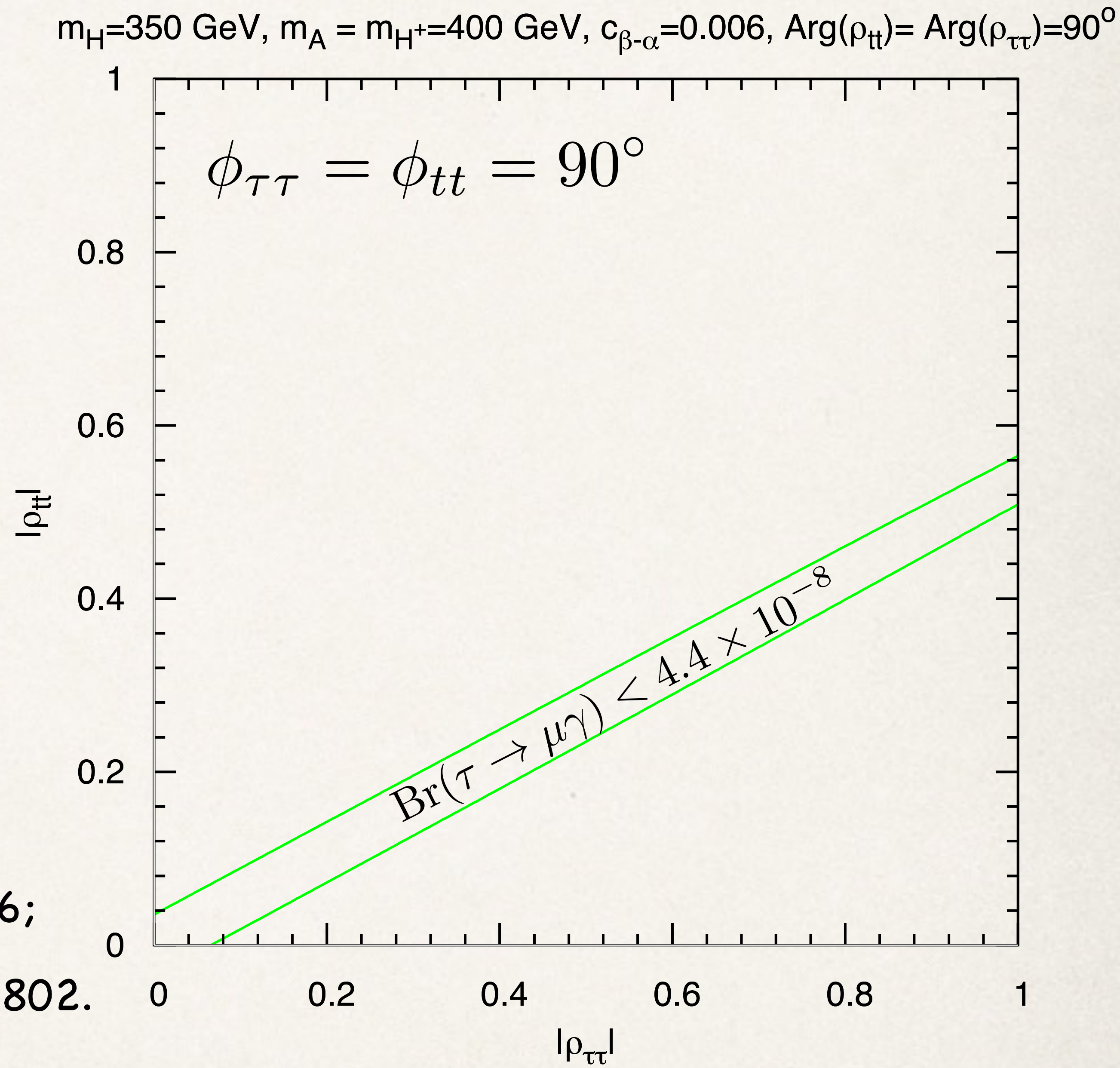


2HDM with LFV explains $h \to \mu\tau$, muon g-2, and BAU.

τ->μγ







current bound:

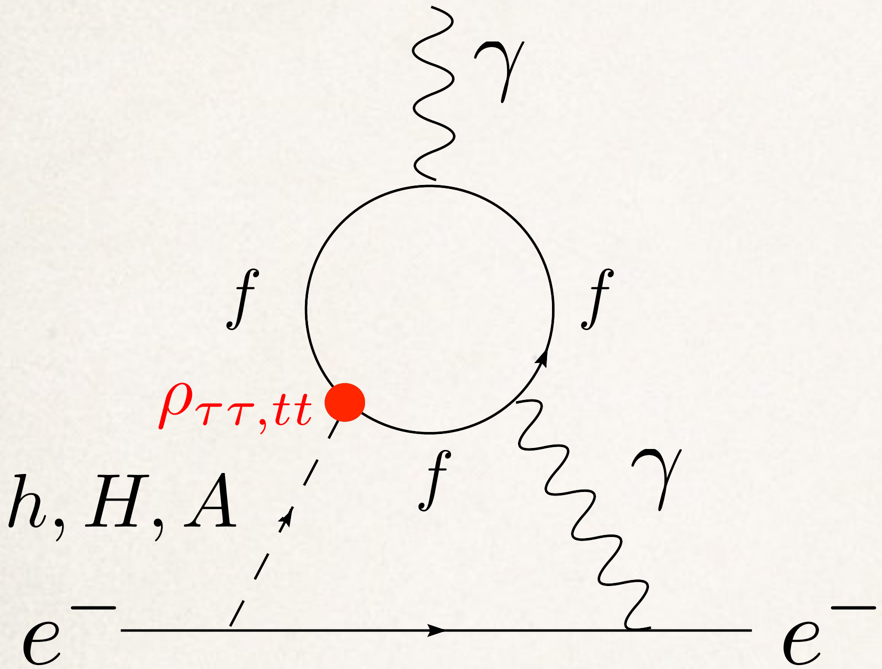
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

K. Hayasaka et al. [Belle Collaboration], PLB666 (2008) 16;

B. Aubert et al. [BaBar Collaboration], PRL104 (2010) 021802.

Cancellation between 1- and 2-loop diagrams can happen.

electron EDM

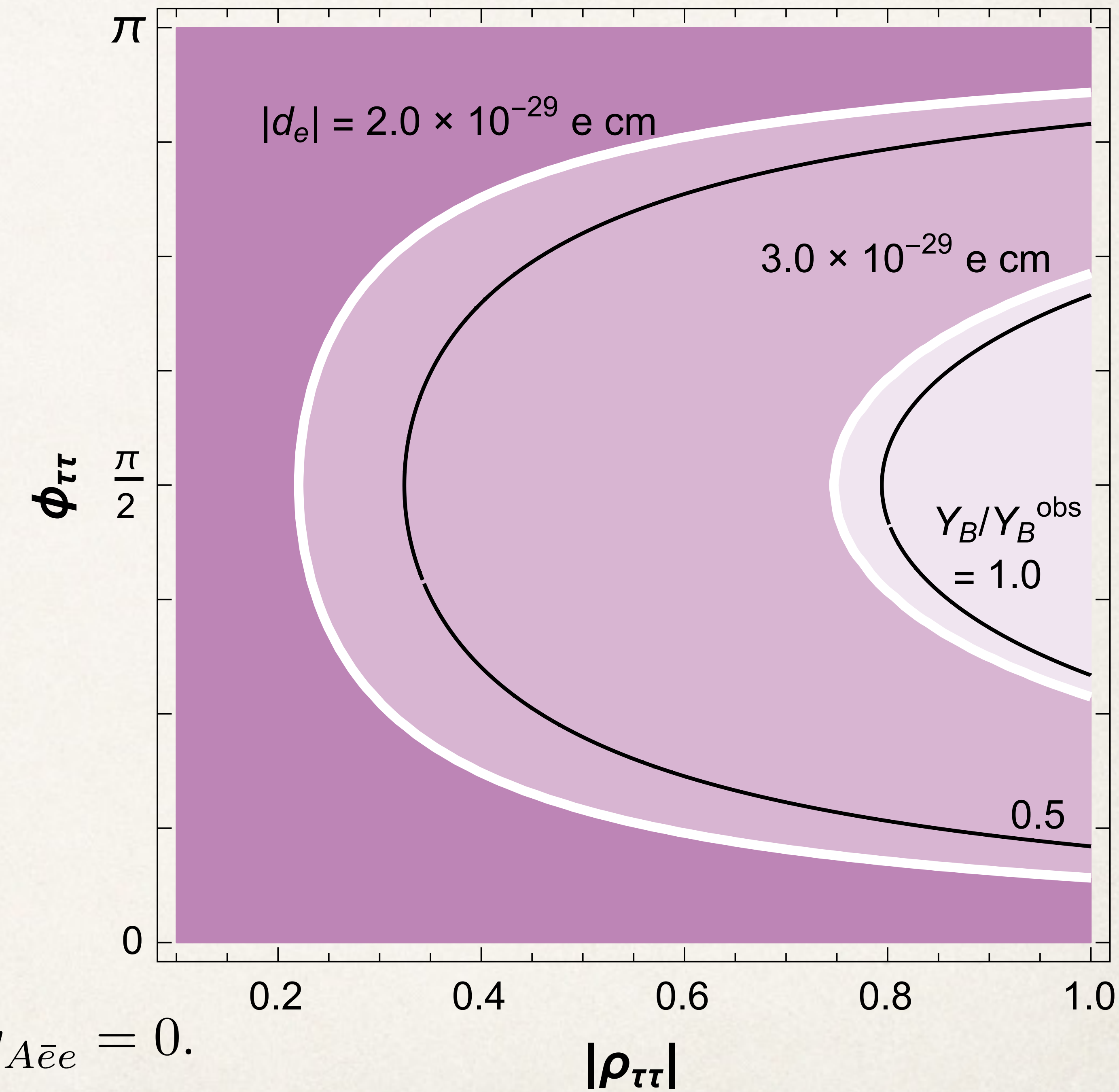


current eEDM bound:

$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$$

We take $\rho_{ee} = 0$

$$g_{h\bar{e}e} = \frac{m_e}{v} s_{\beta-\alpha}, \quad g_{H\bar{e}e} = \frac{m_e}{v} c_{\beta-\alpha}, \quad g_{A\bar{e}e} = 0.$$



Future eEDM experiment can probe the EWBG-viable region.

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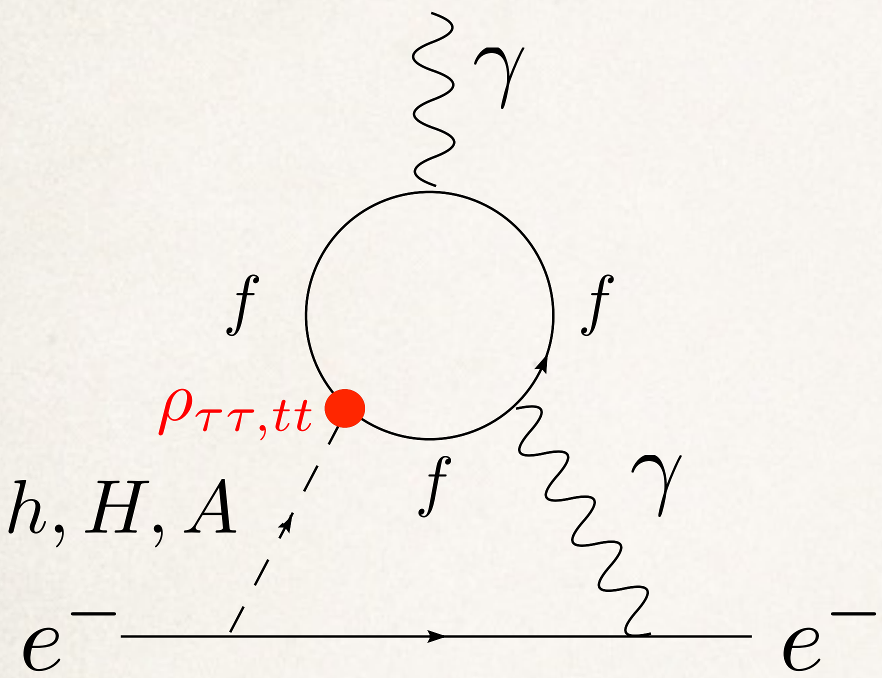

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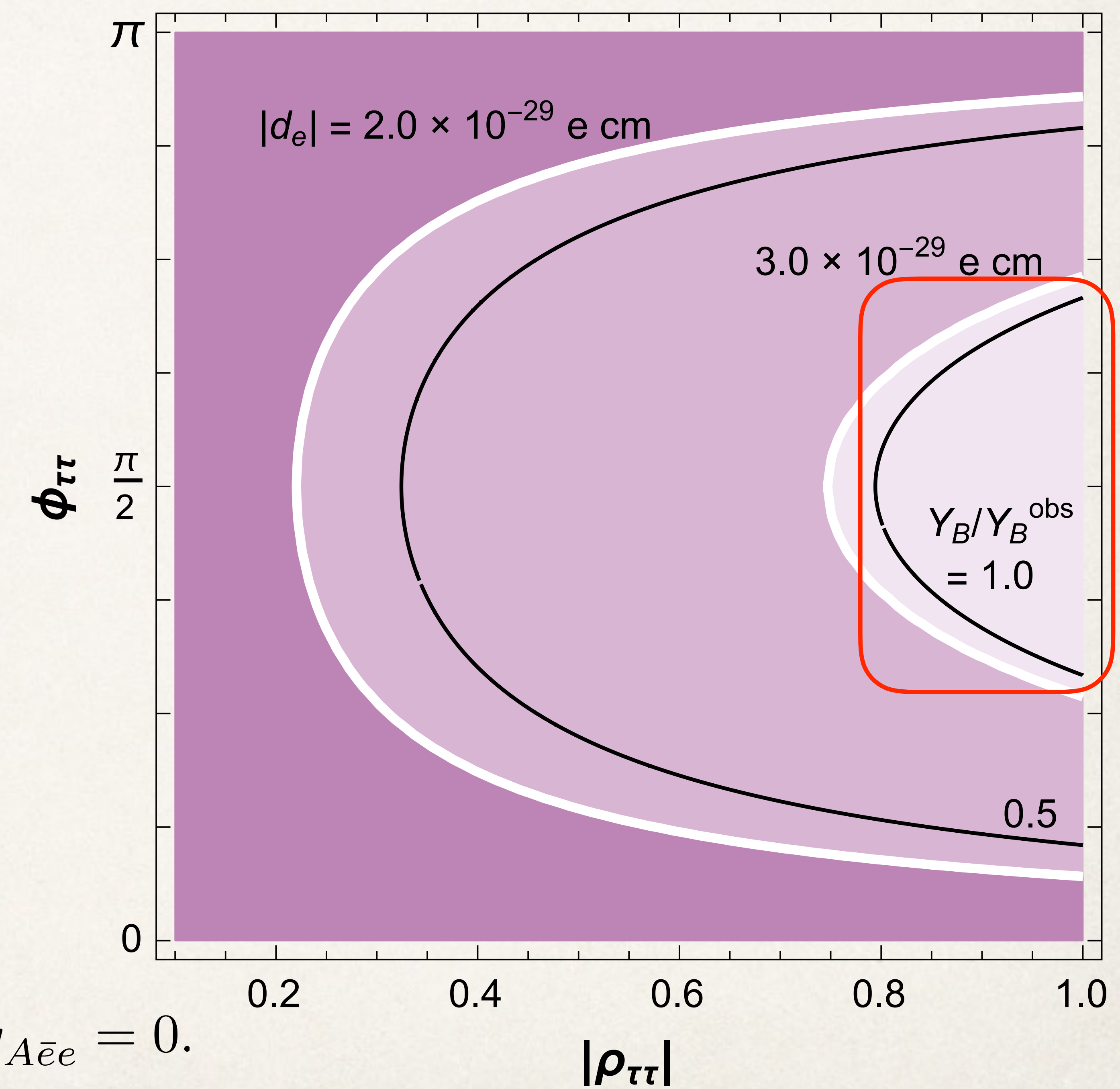

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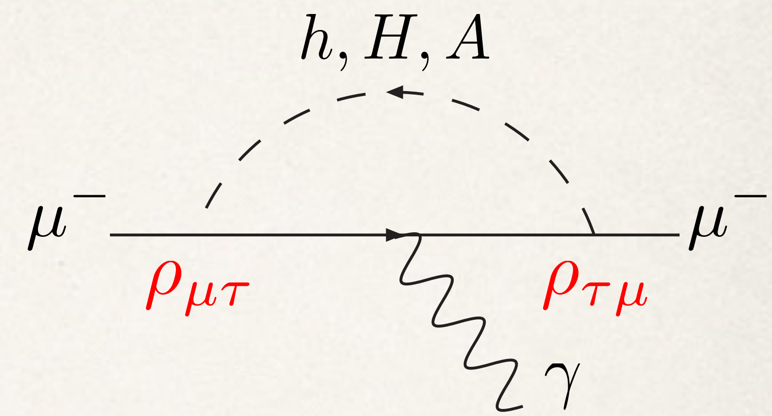
muon EDM



muon EDM is induced by 1-loop diagram.

$$\frac{d_\mu}{|e|} = -\frac{m_\tau}{32\pi^2}\mathrm{Im}(\rho_{\mu\tau}\rho_{\tau\mu})\left[\frac{c^2_{\beta-\alpha}f(r_h)}{m_h^2} + \frac{s^2_{\beta-\alpha}f(r_H)}{m_H^2} - \frac{f(r_A)}{m_A^2}\right]$$
$$= -\frac{1}{2m_\mu}\mathrm{Arg}(\rho_{\mu\tau}\rho_{\tau\mu})\delta a_\mu, \qquad r_\phi = m_\tau^2/m_\phi^2, \quad f(r) \simeq \ln\frac{1}{r} - \frac{3}{2}.$$

$$\rightarrow \quad d_\mu \simeq -3\times 10^{-22}\ e\ \mathrm{cm} \times \left(\frac{\mathrm{Arg}(\rho_{\mu\tau}\rho_{\tau\mu})}{1}\right) \times \left(\frac{\delta a_\mu}{3\times 10^{-9}}\right)$$

current muon EDM bound: $|d_\mu| < 1.9\times 10^{-19}\ e\ \mathrm{cm}$

G. W. Bennett et al. PRD80,052008 (2009).

A -> ττ

ATLAS-CONF-2016-085

In our EWBG scenario,

- $|\rho_{\tau\mu}|=|\rho_{\mu\tau}|=0.1-0.6$,
- $|\rho_{\tau\tau}|=0.8-0.9$.
- $|\rho_{tt}|=0.5$.

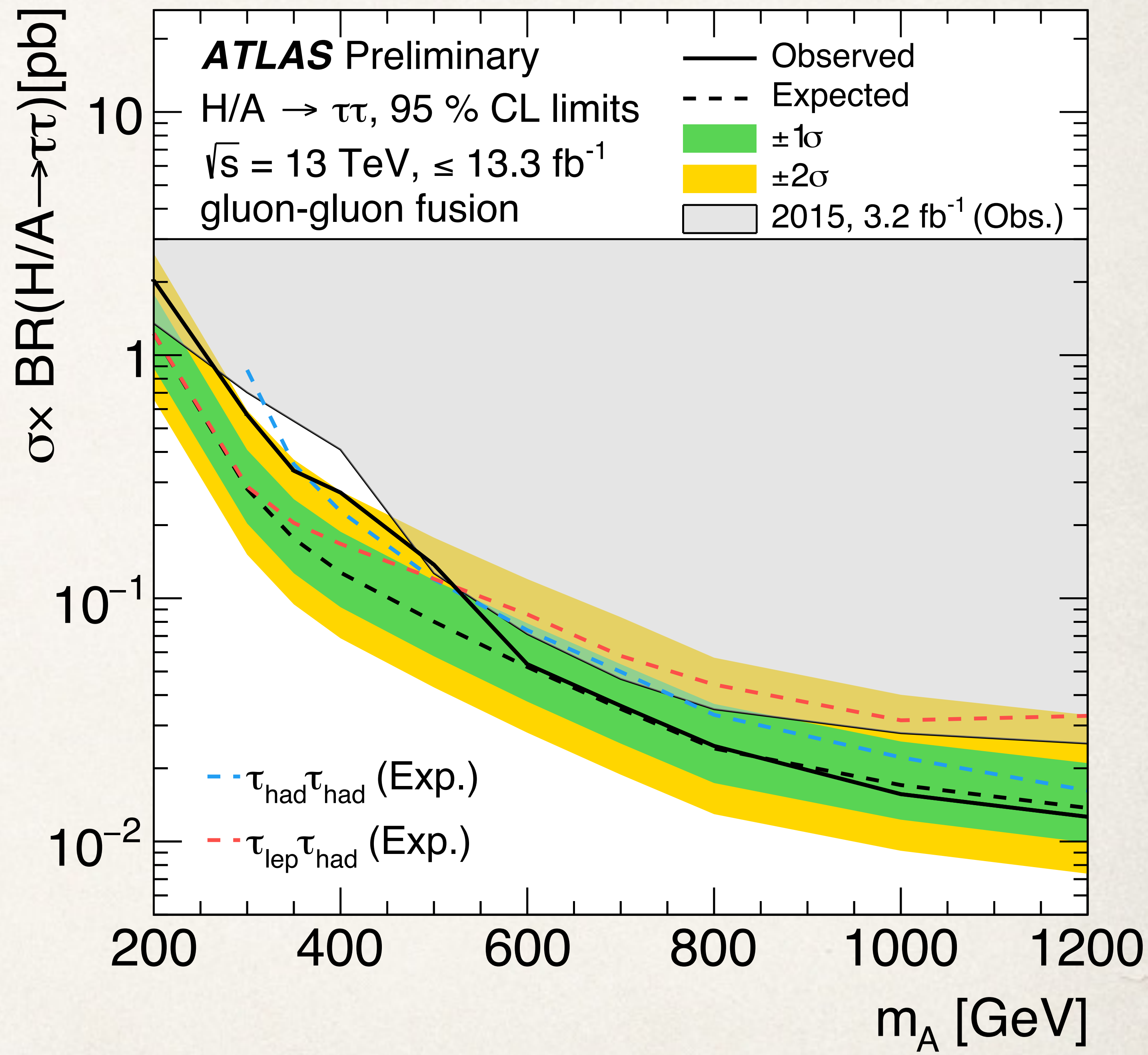
-> sizable Br(A->ττ)

e.g.

$$\sigma_{gg\to A}\times \mathrm{BR}(A\to\tau\tau)\simeq 0.82\ \mathrm{pb}$$

~70%

-> tension with data!



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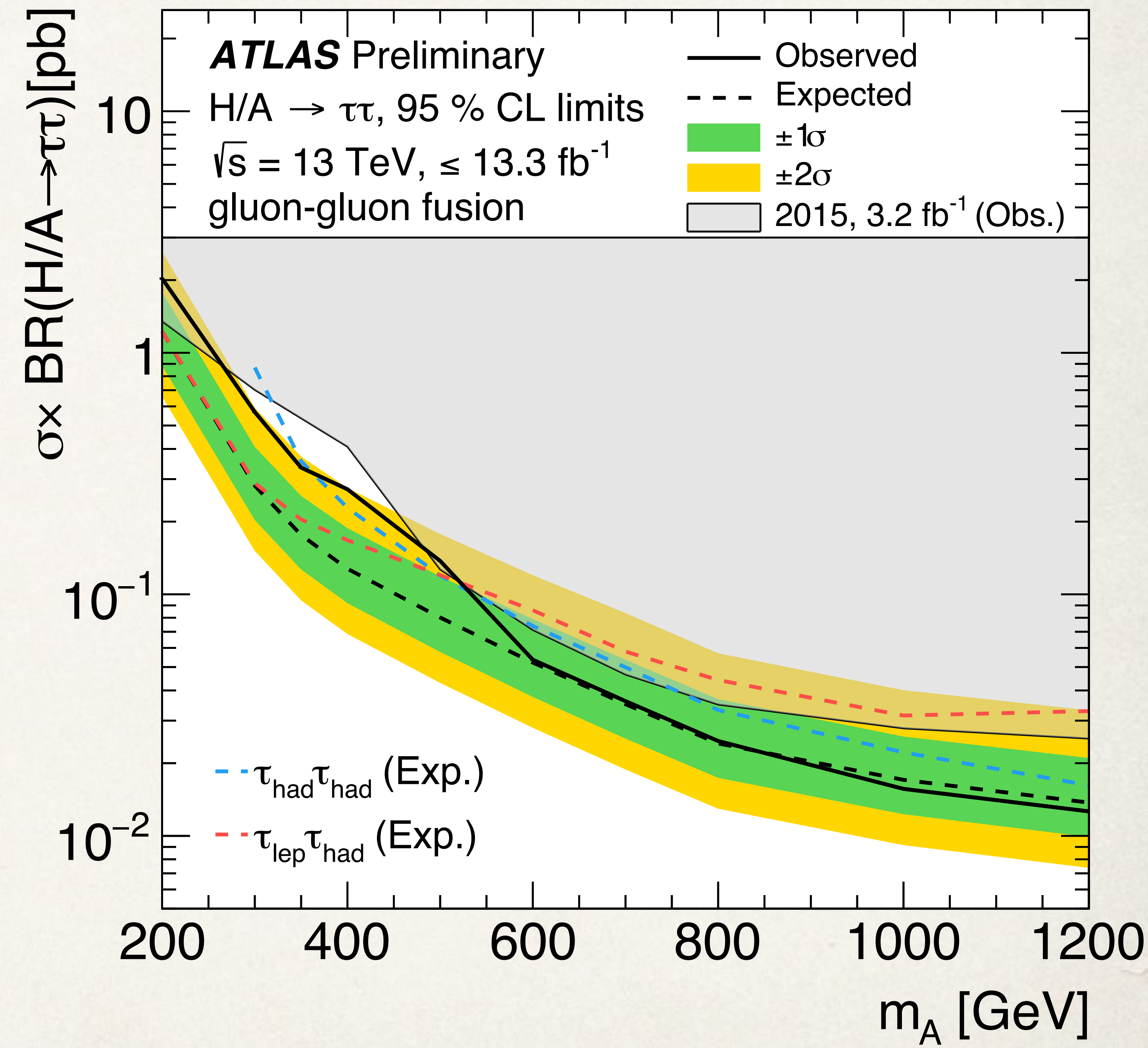

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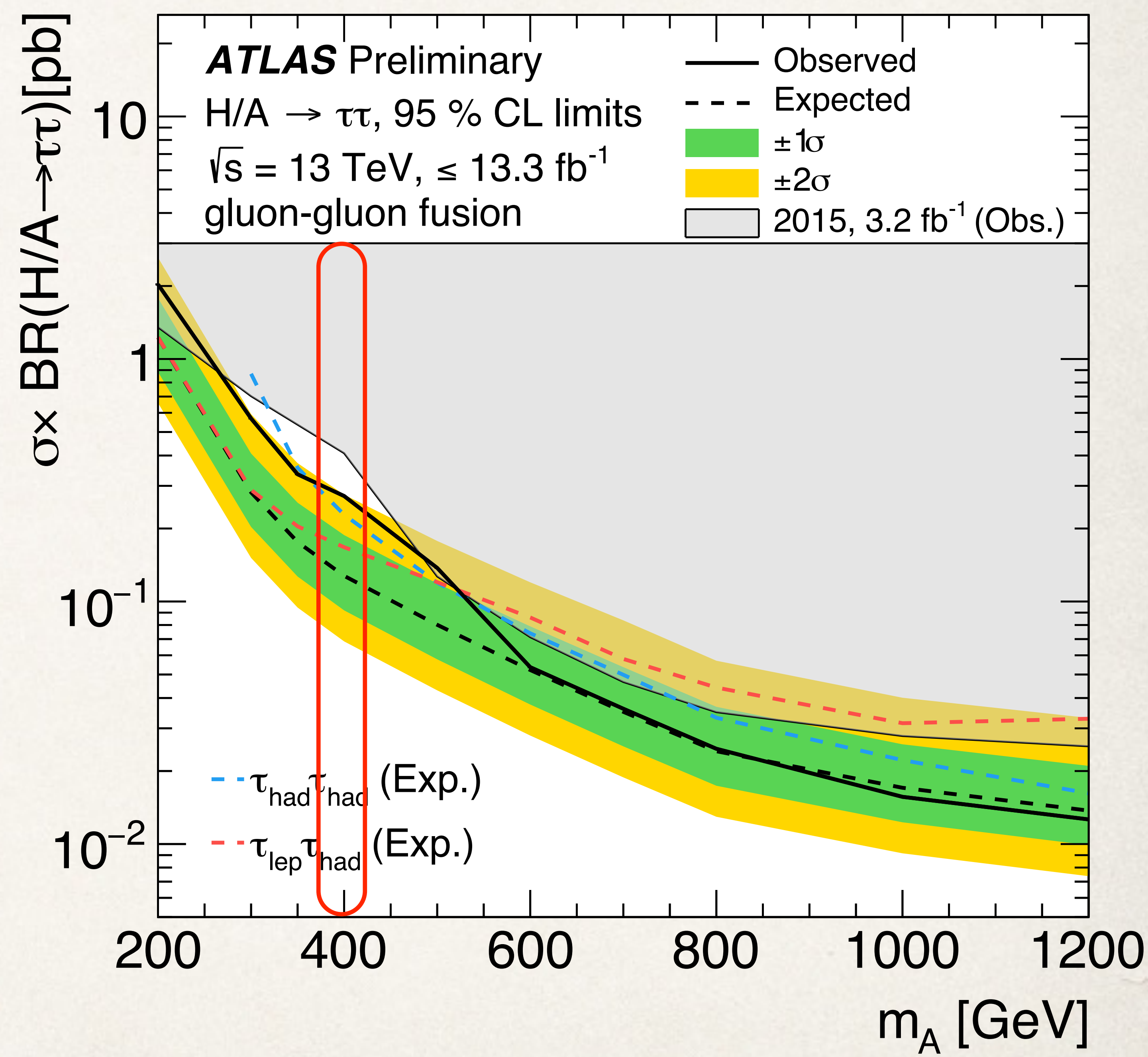

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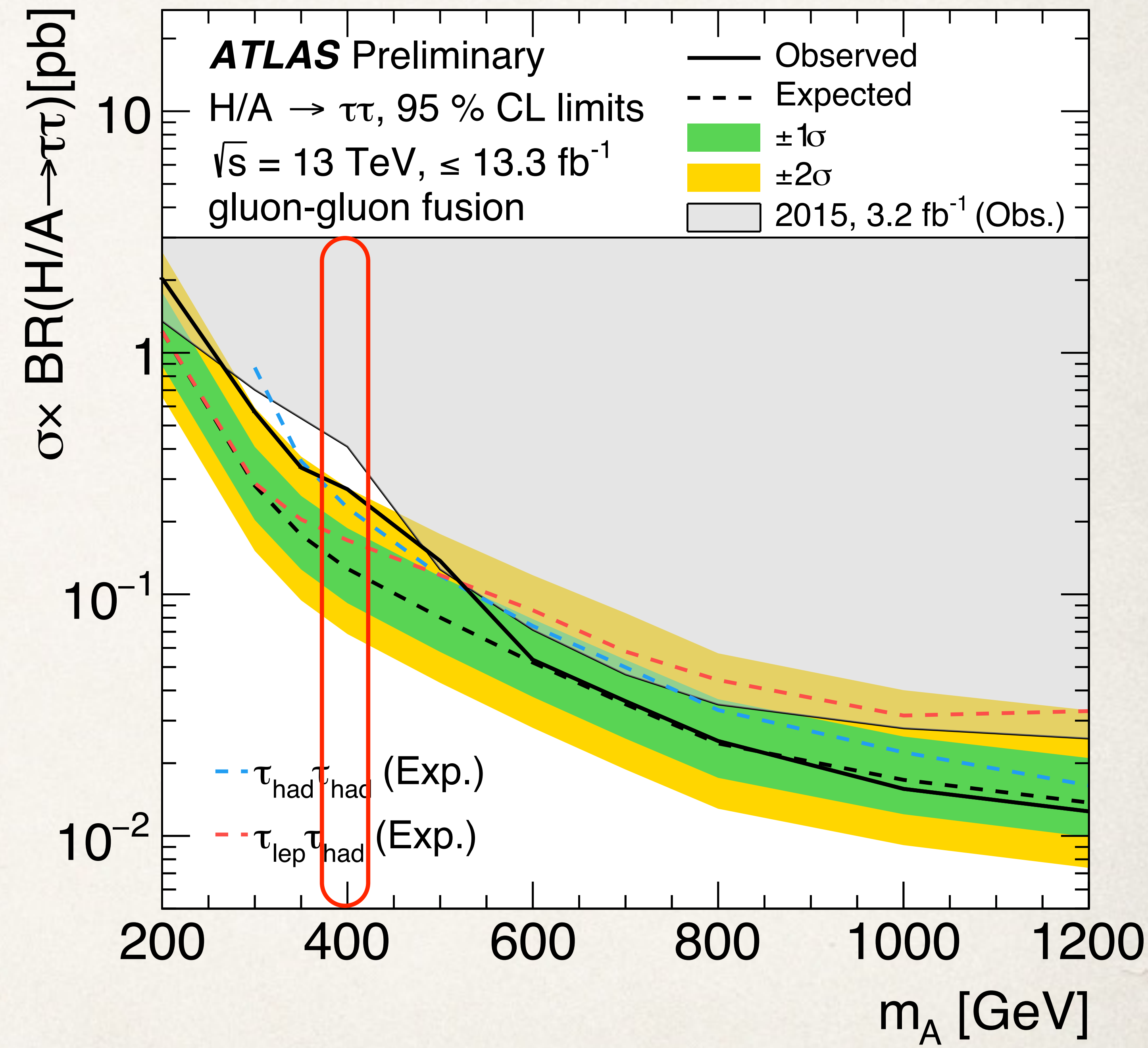


way-out: Br(A->ττ) can be reduced if other ρ couplings are nonzero.

$\rho_{tc}<1.5,\ \rho_{ct}<0.1$ [Altunkaynak, Hou, Kao, Kohda, MacKoy, 1506.00651 [PLB]]

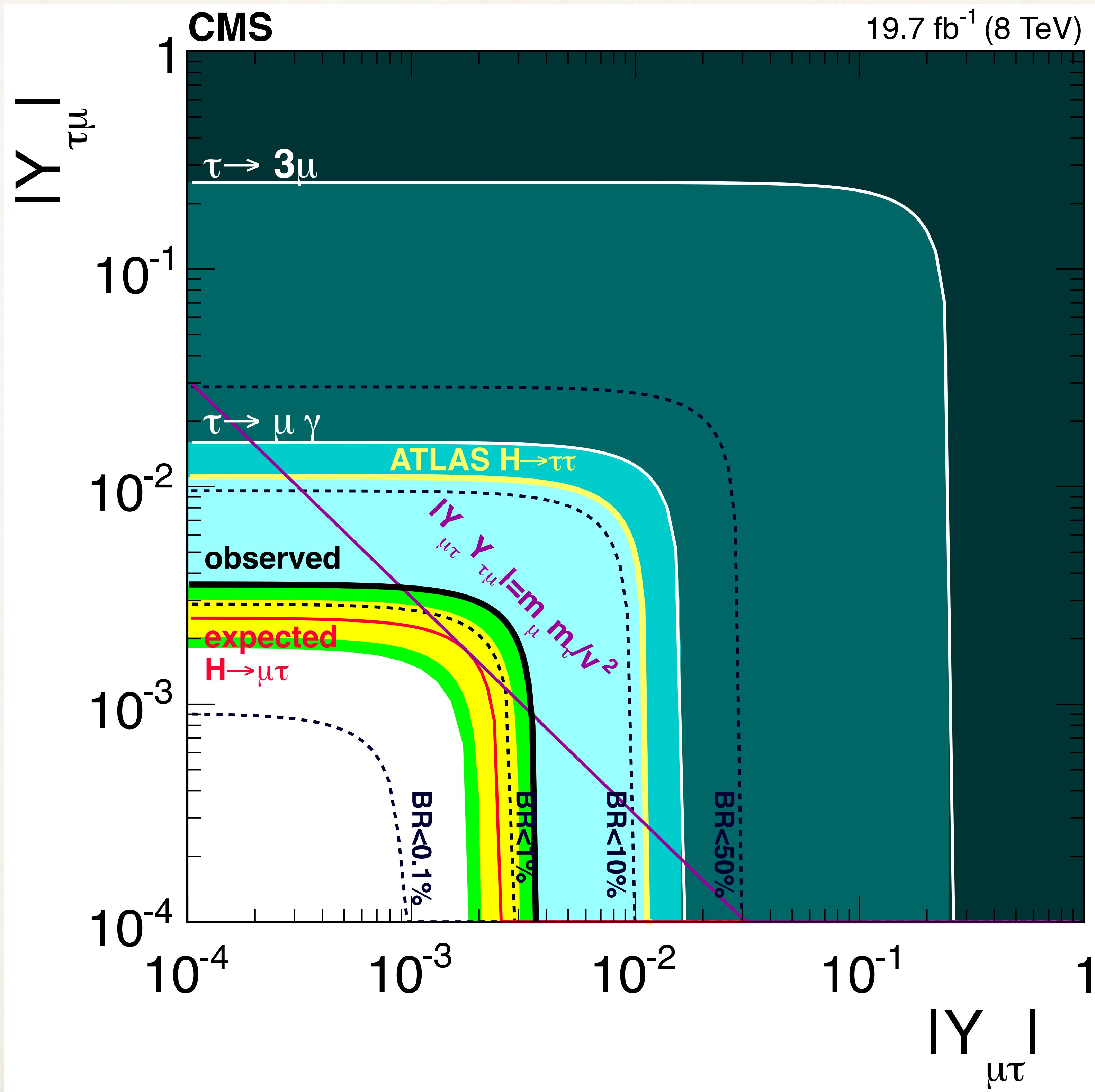
Summary

- We have discussed EWBG with LFV in the general 2HDM.
- Strong 1st-order EWPT and muon g-2 favored region: 300 GeV $\lesssim m_H \lesssim m_A$ for $\mathrm{Re}(\rho_{\tau\mu}\rho_{\mu\tau})>0$.
- BAU can be explained if $|\rho_{\tau\tau}|=0.8$-0.9, $|\rho_{\tau\mu}|=|\rho_{\mu\tau}|=0.1$-$0.6$, $|\rho_{tt}|=0.5$.
- gg->A->ττ is now in tension with the LHC data -> $\rho_{tc}=O(1)$.

Backup

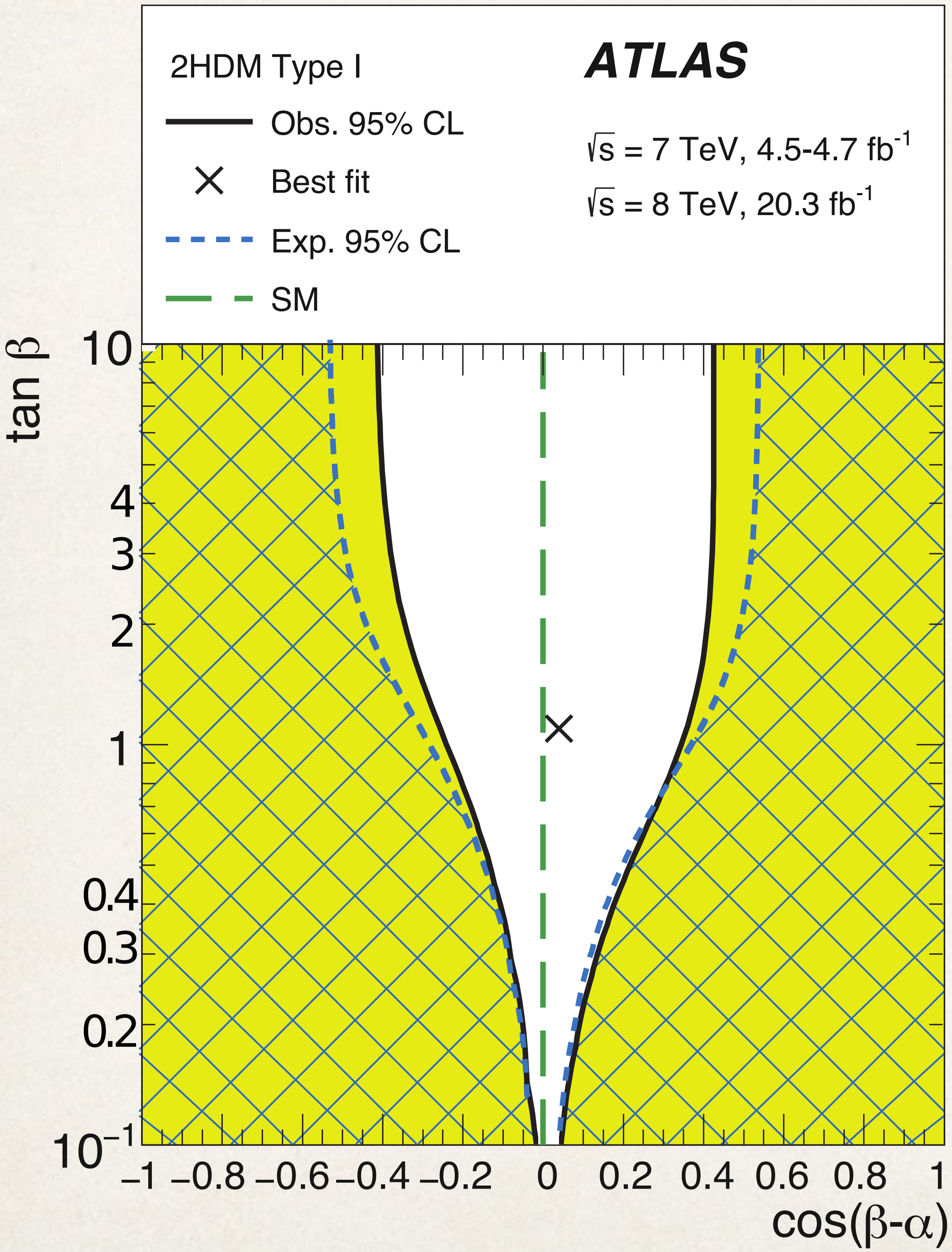
Constraint on μ-τ coupling

1502.07400

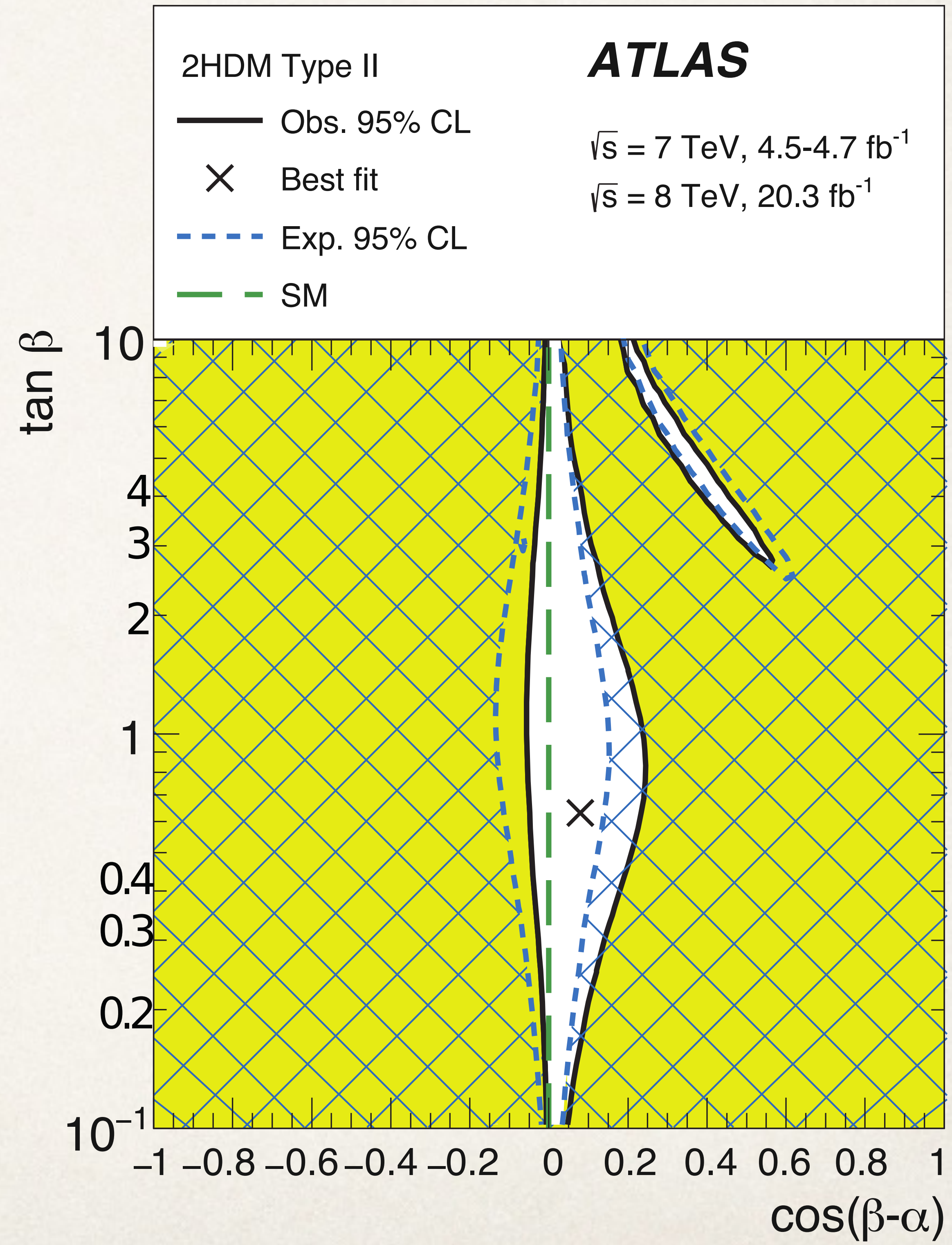


Constraints in ($\cos(\beta-\alpha)$, $\tan\beta$) plane

arXiv:1509.00672

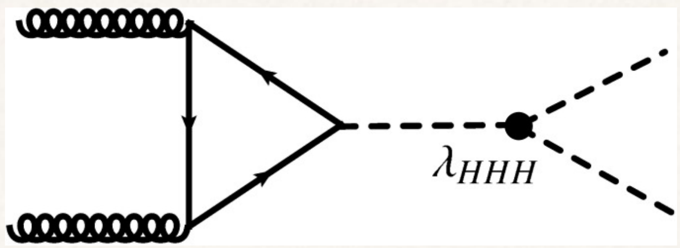


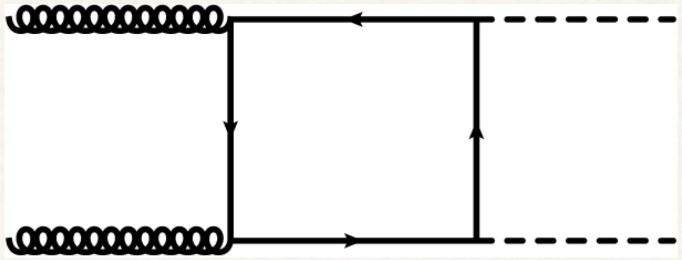
(a) Type I



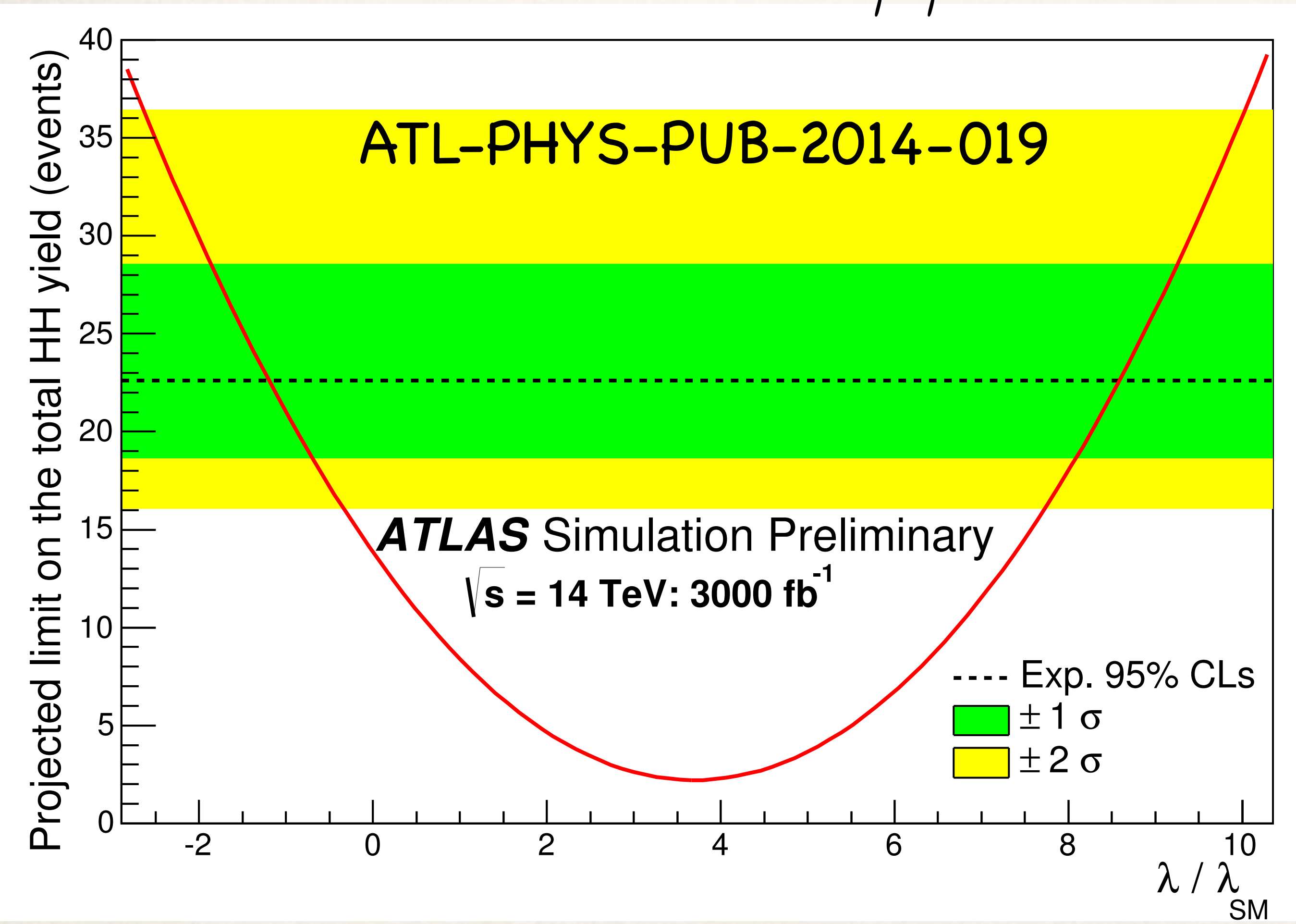
(b) Type II

hhh coupling at LHC





$HH \to bb\gamma\gamma$



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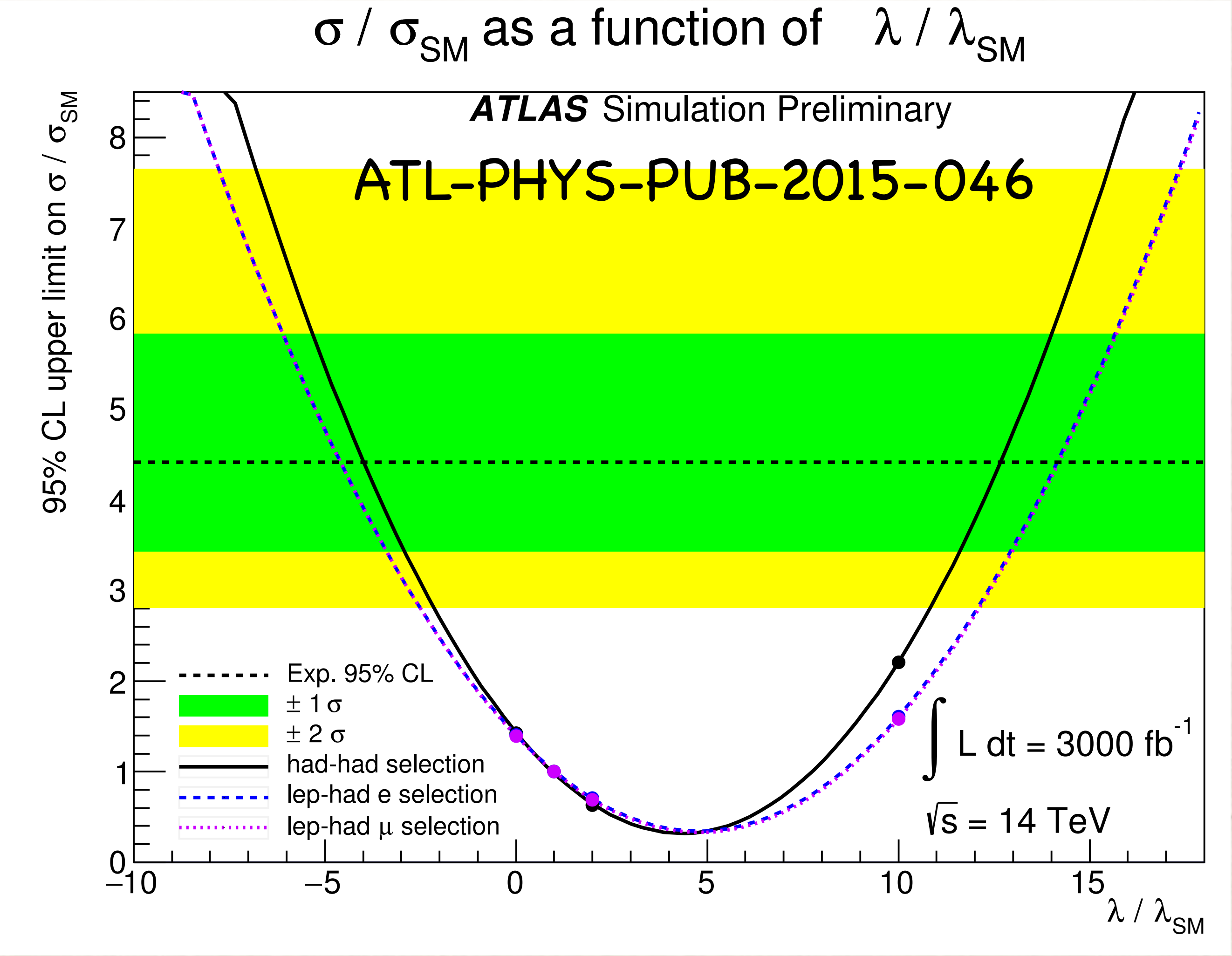
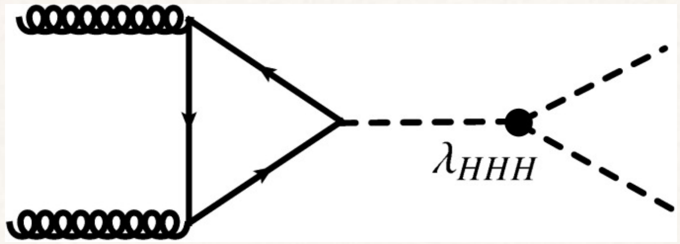
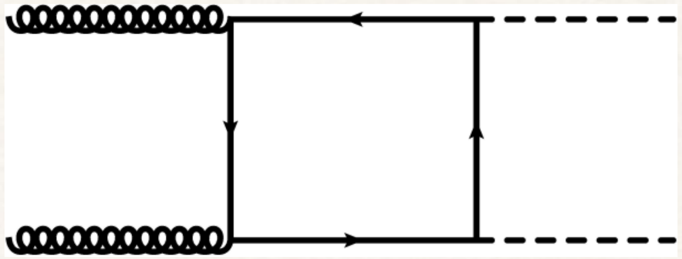


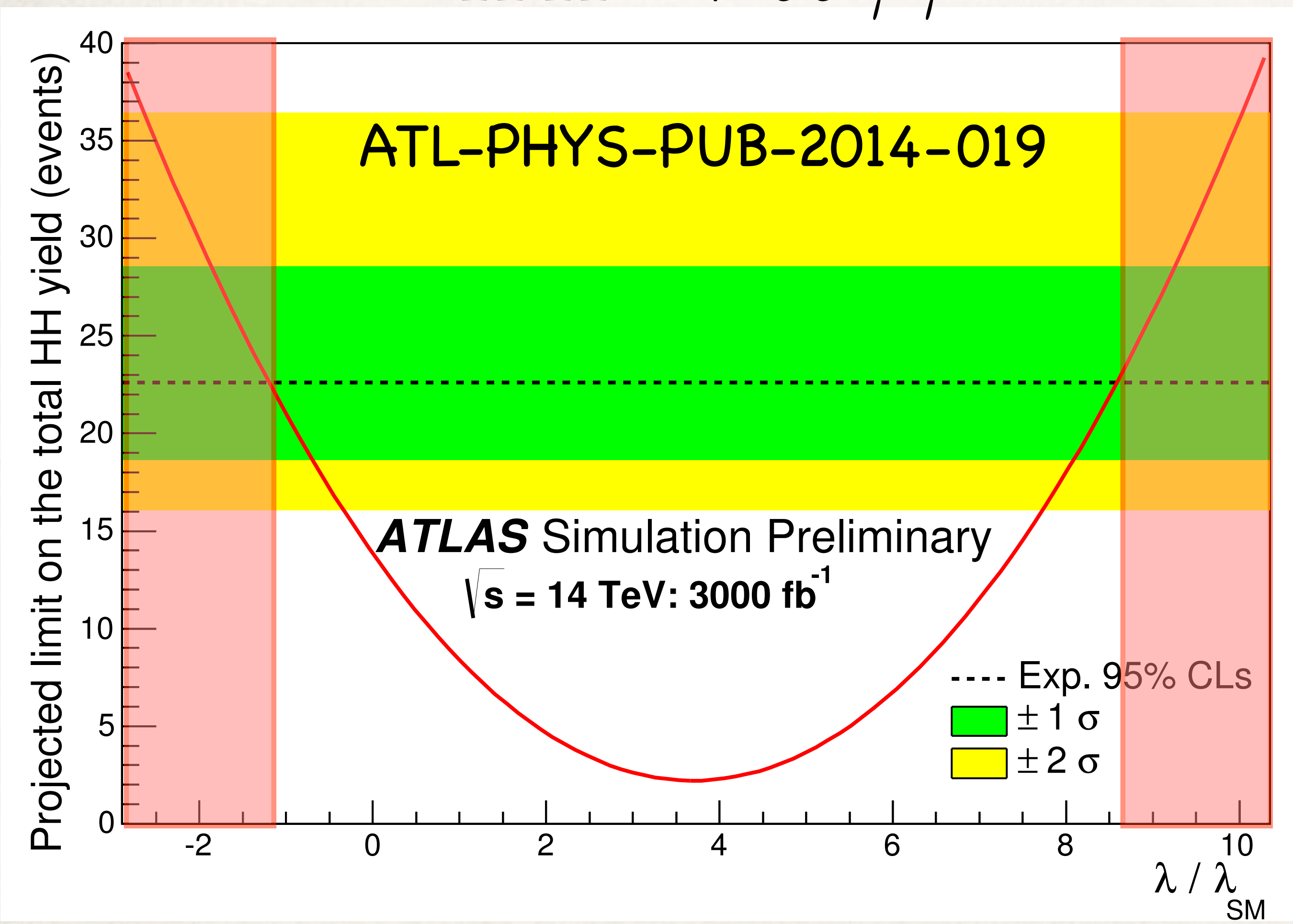
Access to λ_{hhh} of 2HDM at the LHC is challenging.

hhh coupling at LHC

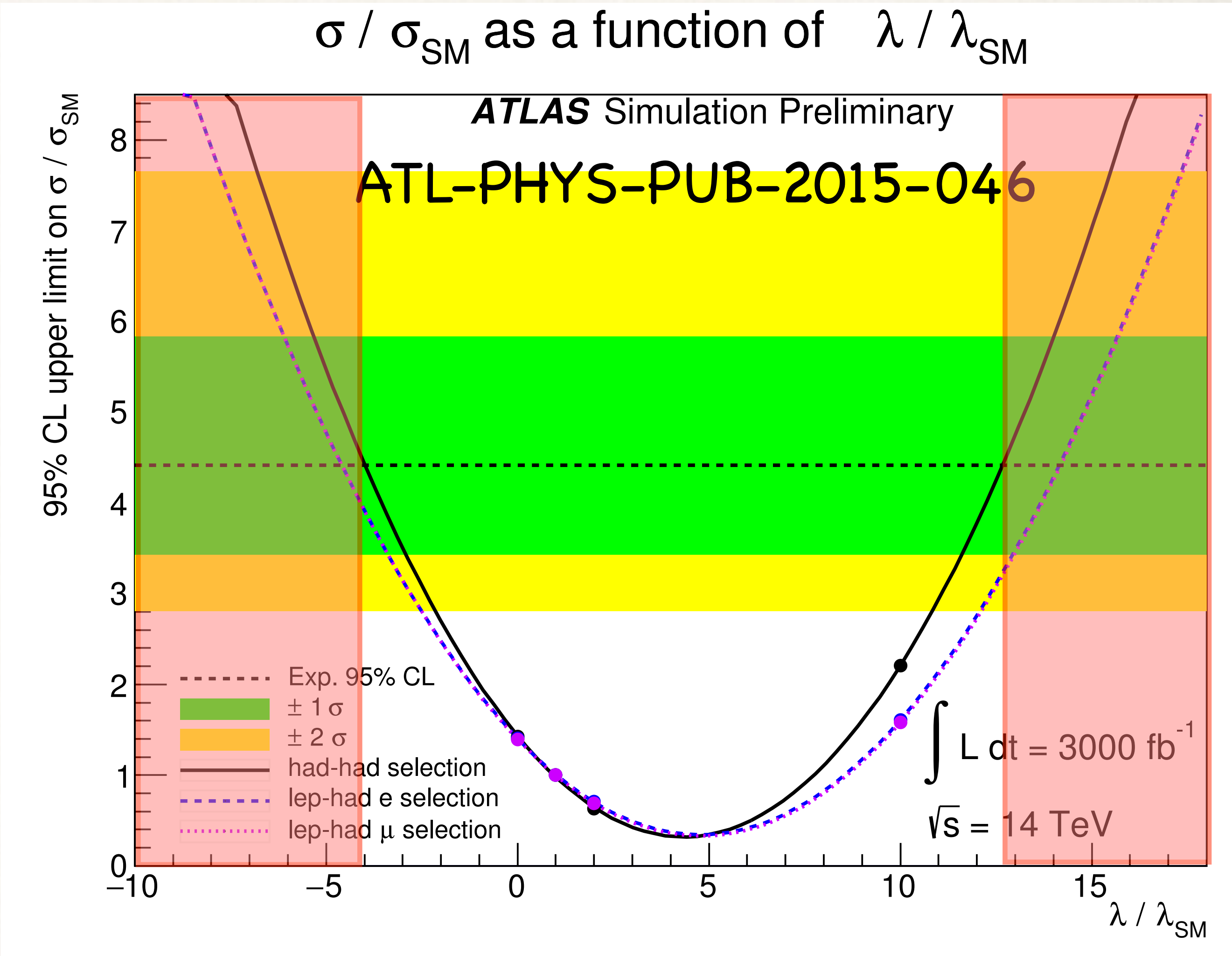




$$HH \to bb\gamma\gamma$$



$$HH \to bb\tau\tau$$



Access to λ_{hhh} of 2HDM at the LHC is challenging.

Higgs couplings measurements@ILC

ILC white paper, 1310.0763

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.8 %	1.1 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.1 %	1.9 %
$b\bar{b}$	5.3 %	1.6 %	1.3 %	0.7 %
$\tau^+\tau^-$	5.7 %	2.3 %	1.6 %	0.9 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.0 %
$\mu^+\mu^-$	91%	91%	16 %	10 %
$\Gamma_T(h)$	12 %	4.9 %	4.5 %	2.3 %
hhh	–	83 %	21 %	13 %
BR(invis.)	$<$ 0.9 %	$<$ 0.9 %	$<$ 0.9 %	$<$ 0.4 %

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BR(invis.)	< 0.9 %	< 0.9 %	< 0.9 %	< 0.4 %