Double-Aligned 2HDM at the LHC

Michihisa Takeuchi (Sun Yat-sen Univ. [中山大学])
In collaboration with S. Kanemura and K. Yagyu

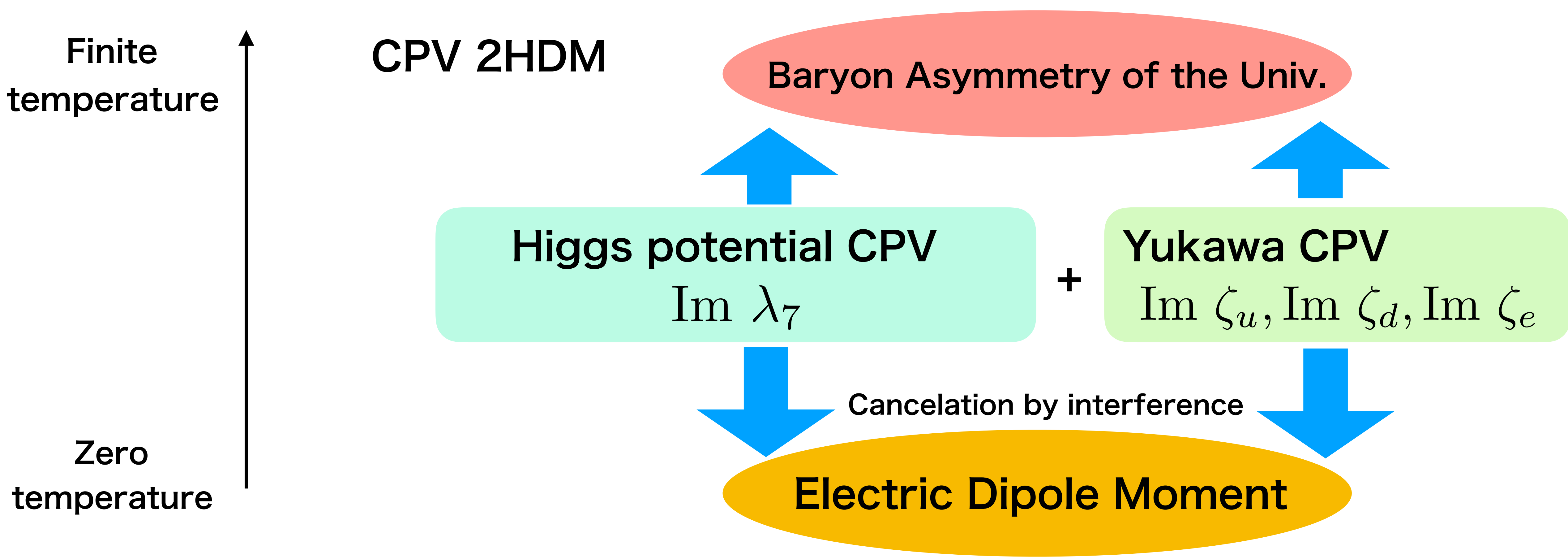
Phys.Rev.D 105 (2022) 11, 115001

CP violation beyond the SM required

- Baryon Asymmetry of the Universe by EWBG : too small CPV in the SM

  → **CPV source of BSM required**

- Consider the possibility: new CPV phases exist in an extended Higgs sector



Aligned CPV 2HDM and EDM

Higgs potential (without Z2 sym.)

(Higgs basis)
[Davidson, Haber, PRD72, 035004 (2005)]

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

Yukawa couplings

$$\mathcal{L}_{\rm yukawa} = -\bar{Q}_L\frac{\sqrt{2}M_u}{v}(\tilde{\Phi}_1 + \zeta_u\tilde{\Phi}_2)u_R$$
$$-\bar{Q}_L\frac{\sqrt{2}M_d}{v}(\Phi_1 + \zeta_d\Phi_2)d_R$$
$$-\bar{L}_L\frac{\sqrt{2}M_e}{v}(\Phi_1 + \zeta_e\Phi_2)e_R$$
$$+h.c.$$

Higgs basis

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

Mass Matrix

$$\mathcal{M}^2 = v^2\begin{pmatrix} \lambda_1 & \mathrm{Re}[\lambda_6] & -\mathrm{Im}[\lambda_6] \\ \mathrm{Re}[\lambda_6] & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3+\lambda_4+\mathrm{Re}[\lambda_5]) & -\frac{1}{2}\mathrm{Im}[\lambda_5] \\ -\mathrm{Im}[\lambda_6] & -\frac{1}{2}\mathrm{Im}[\lambda_5] & \frac{M^2}{v^2}+\frac{1}{2}(\lambda_3+\lambda_4-\mathrm{Re}[\lambda_5])\end{pmatrix}.$$

Pheno-motivated 2 types of alignments assumed:

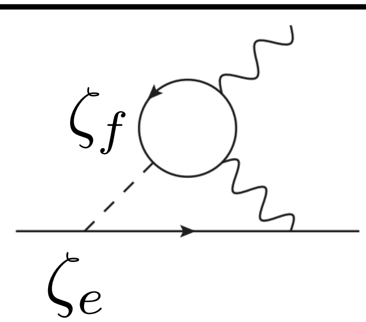
Higgs alignment λ6=0(=μ3) ⇄ No mixing among Higgses 125GeV
Higgs measurements indicate SM like

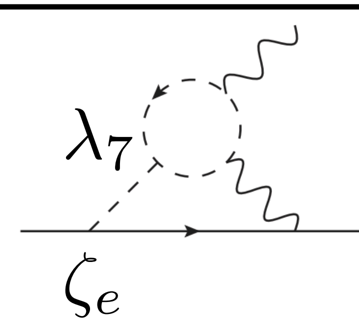
Yukawa alignment to avoid FCNC at tree level

→ 4 complex parameters remain $\zeta_e, \zeta_d, \zeta_u, \lambda_7$

EDM constraint :

$$-i\frac{d_e}{2}\bar{\psi}_e\sigma^{\mu\nu}\gamma^5\psi_e F^{\mu\nu}$$

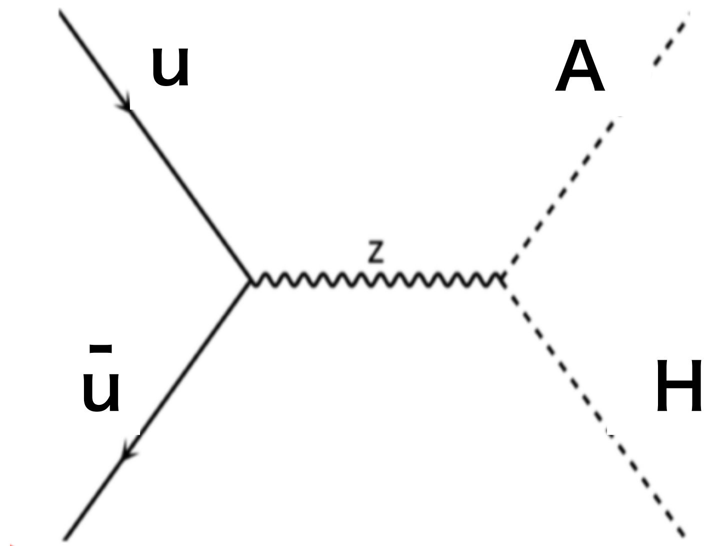
$$d_e = \sum_f^{t,b,\tau}$$


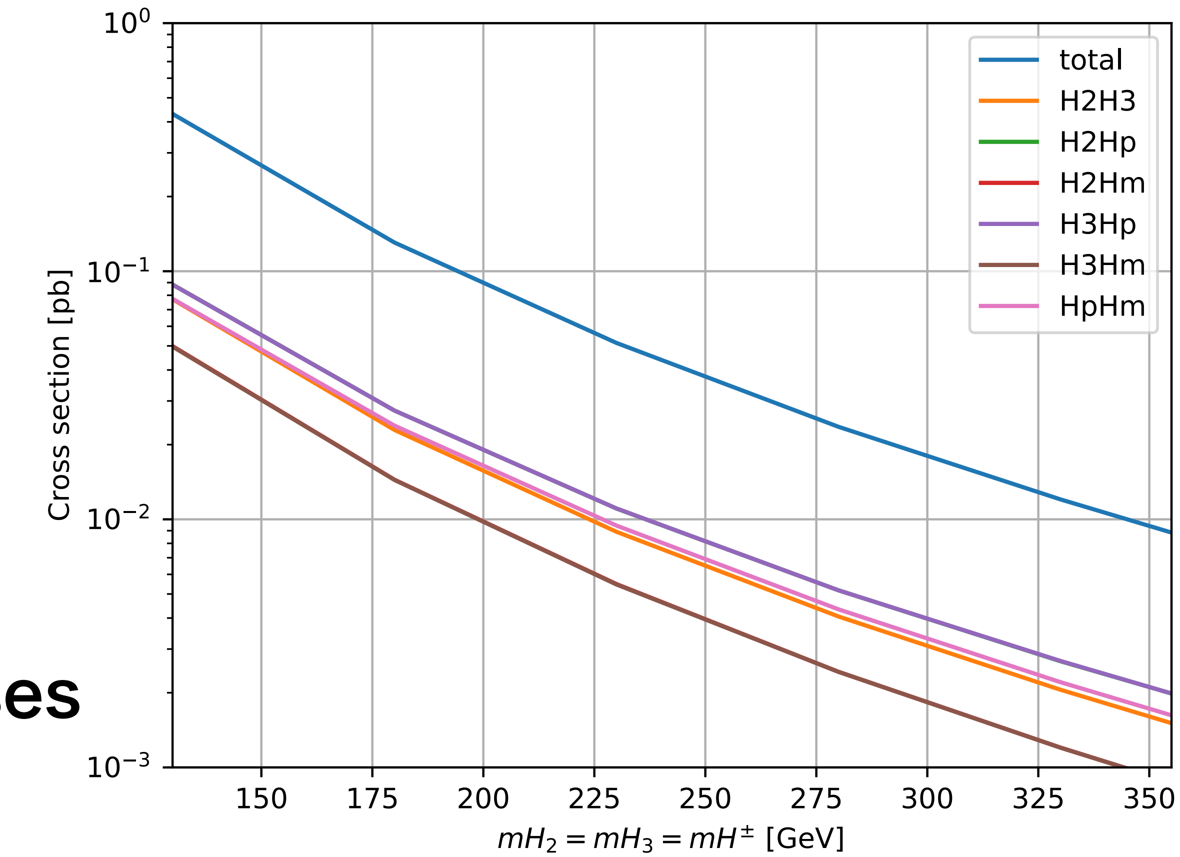
$+$


$< 1.1\times10^{-29} e$ cm

EW production at LHC

- In 2HDM, always we have the EW productions





Cross section fixed only by the masses

→ No dependence on Yukawa param.

For 6 modes (HA, HH±, AH±, H+H-)

~ 10-500 fb at 13 TeV LHC

(mH ~ 300GeV)

10^3 -10^5 Events at 139fb-1

Neutral $H \to \tau\tau, bb$

Charged $H^+ \to \tau\nu, tb$

Heavy higgs also decay via

$$H_2 \to Z^* H_3, H_2 \to W^{*\pm} H^{\mp}$$

→ 4τ lepton events expected

(BR depends on Yukawa param.)

- Latest LHC 4+ lepton (including taus) searches set very strong constraints

BR in aligned 2HDM

BR is determined by the ζ parameters

(For T parameter constraints, Charged Higgs and one of Neutral Higgses degenerated)

Easy to understand the BR behavior by separating fermion/gauge boson modes.

$$R = \frac{\sum_f \Gamma_f}{\sum_f \Gamma_f + \sum_V \Gamma_V} = \frac{1}{1 + r/\zeta^2} \simeq \sum_f BR_f$$

Fermion modes' ratio

$$R_\tau = \frac{\Gamma_\tau}{\sum_f \Gamma_f} = \zeta_e^2/\zeta^2 \simeq BR_\tau/R$$

τ-mode in fermion modes ratio

$$\zeta^2 \simeq \sum_f \frac{m_f^2}{m_\tau^2} N_f^c |\zeta_f|^2$$

The corresponding parameters $R^\pm, R_\tau^\pm$ also defined for $H^\pm$

Neutral Higgs

$\mathcal{B}(H \to \tau\tau) = RR_\tau$

$\mathcal{B}(H \to bb) = R(1 - R_\tau)$

$\mathcal{B}(H \to Z^{(*)}\tau\tau) = R_Z R_\tau$

$\mathcal{B}(H \to Z^{(*)}bb) = R_Z(1 - R_\tau)$

$\mathcal{B}(H \to W^{(*)}\tau\nu) = R_W R_\tau^\pm$

$\mathcal{B}(H \to W^{(*)}bt) = R_W(1 - R_\tau^\pm)$

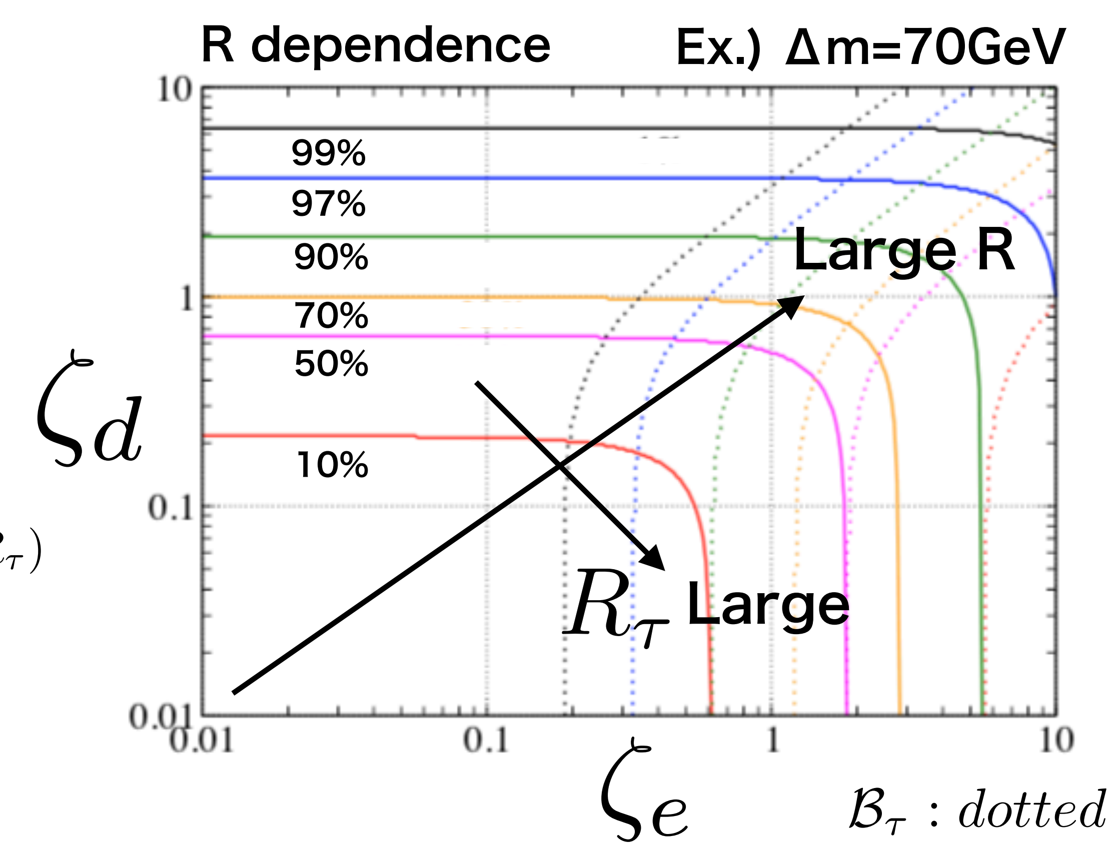
Charged Higgs

$\mathcal{B}(H^\pm \to \tau\nu) = R^\pm R_\tau^\pm$

$\mathcal{B}(H^\pm \to bt) = R^\pm(1 - R_\tau^\pm)$

$\mathcal{B}(H^\pm \to W^{(*)}\tau\tau) = (1 - R^\pm)R_\tau$

$\mathcal{B}(H^\pm \to W^{(*)}bb) = (1 - R^\pm)(1 - R_\tau)$

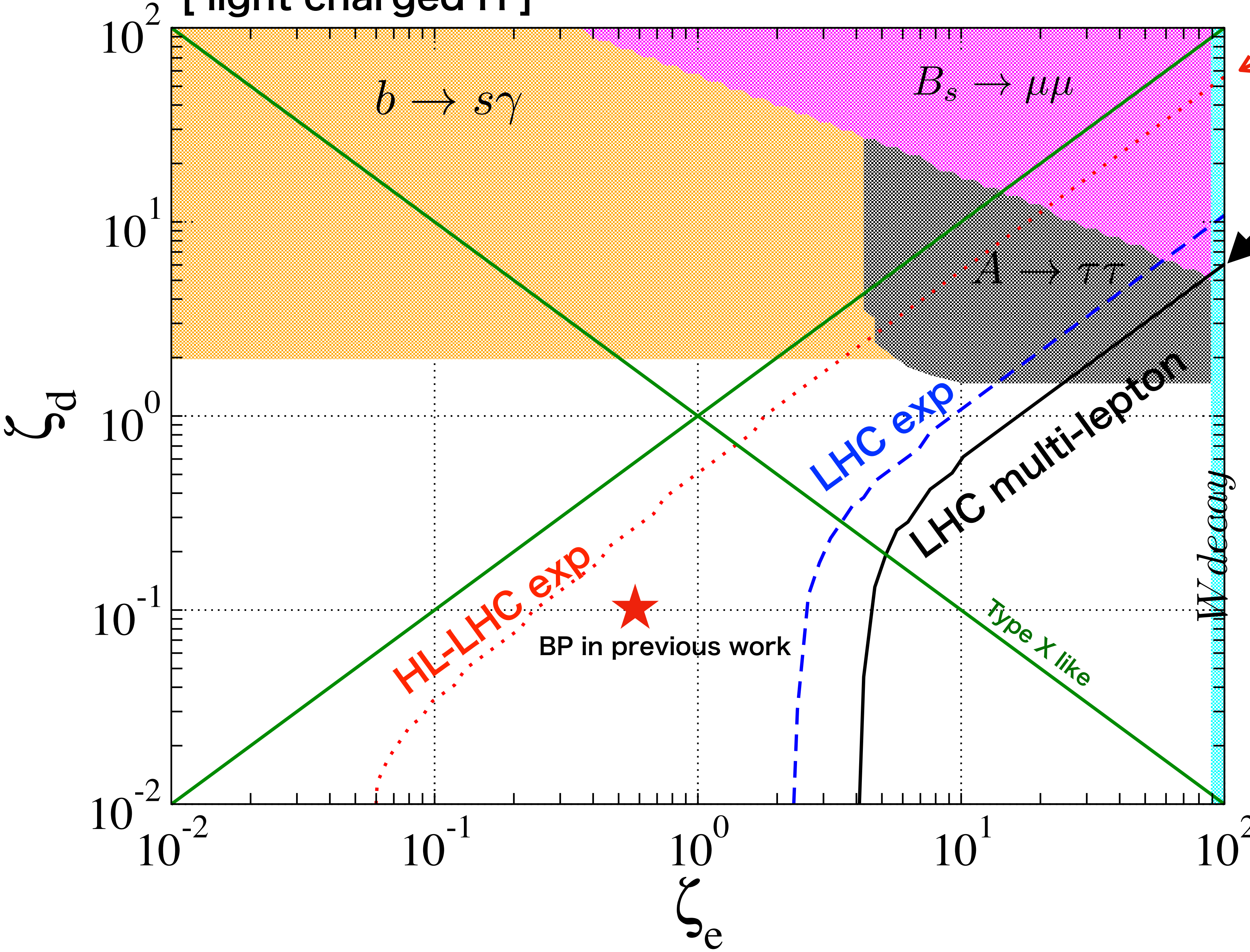


Current LHC bounds

Various flavor constraints make the parameter space finite

$m_{H_3} = m_{H^\pm} = 230$ GeV, $m_{H_2} = 280$ GeV, $|\zeta_u| = 0.1$

[light charged H]



At HL-LHC multilepton $BR_\tau \sim 0.2$ reachable

Large $\tau\tau$ BR constrained by LHC multi lepton searches

Type X interpretation:

$(\zeta_e = \zeta_d^{-1} = \zeta_u^{-1})$

Currently,

$\zeta_e = \tan\beta \gtrsim 5$ **excluded**

At HL-LHC, up to

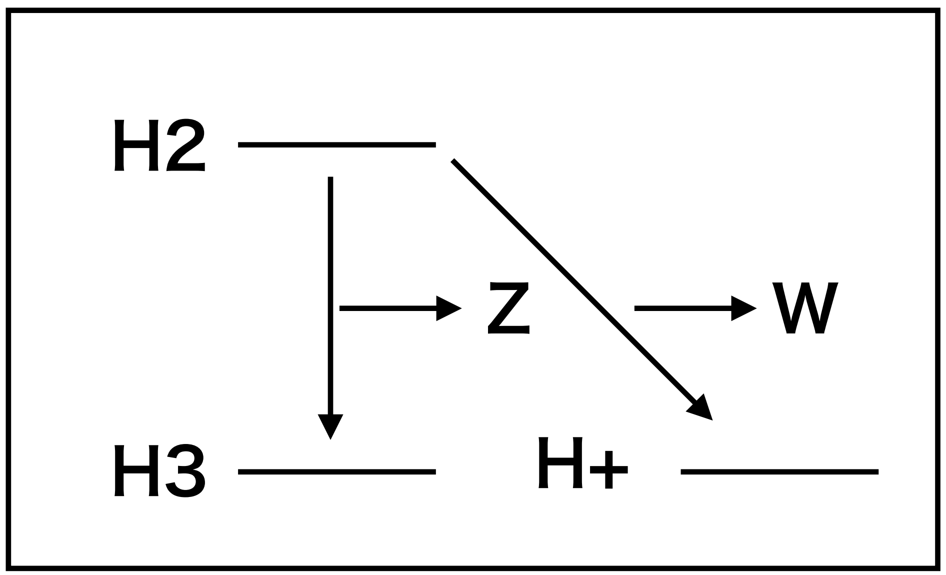
$\zeta_e = \tan\beta \gtrsim 1.5$

would be sensitive

Effects of Charged Higgs spectrum

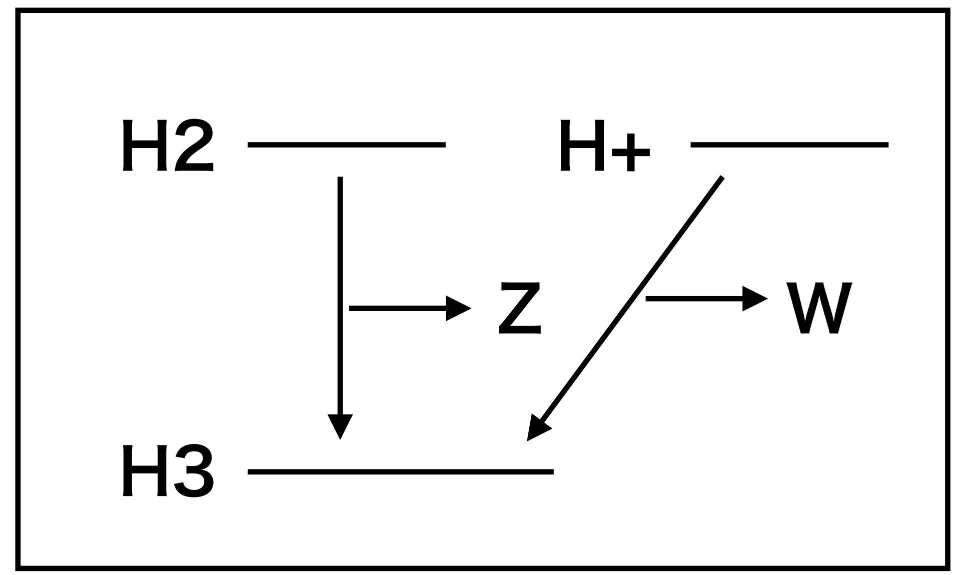
$$m_{H_3} = m_{H^\pm} \leq m_{H_2}$$

[light charged H]



$$m_{H_3} \leq m_{H_2} = m_{H^\pm}$$

[heavy charged H]



All 6 modes produced similar in size

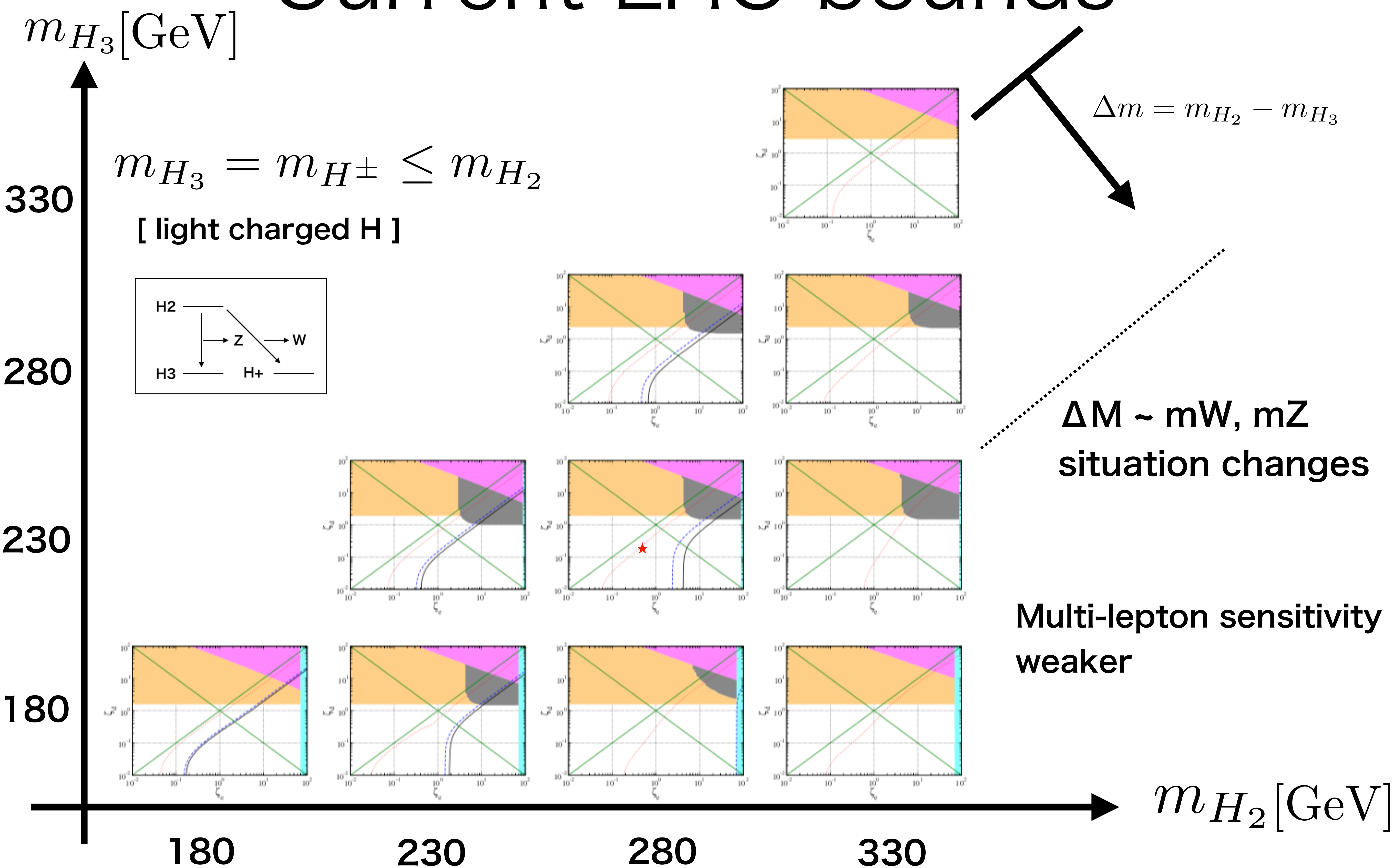
If H+ exists below, H2 decay into H+ → $\tau\nu$: fewer leptons

→ heavier H+ provides stronger constraints (H→$\tau\tau$, bb, H+→ $\tau\nu$, tb)

At ΔM ~ mW, mZ the situation changes :

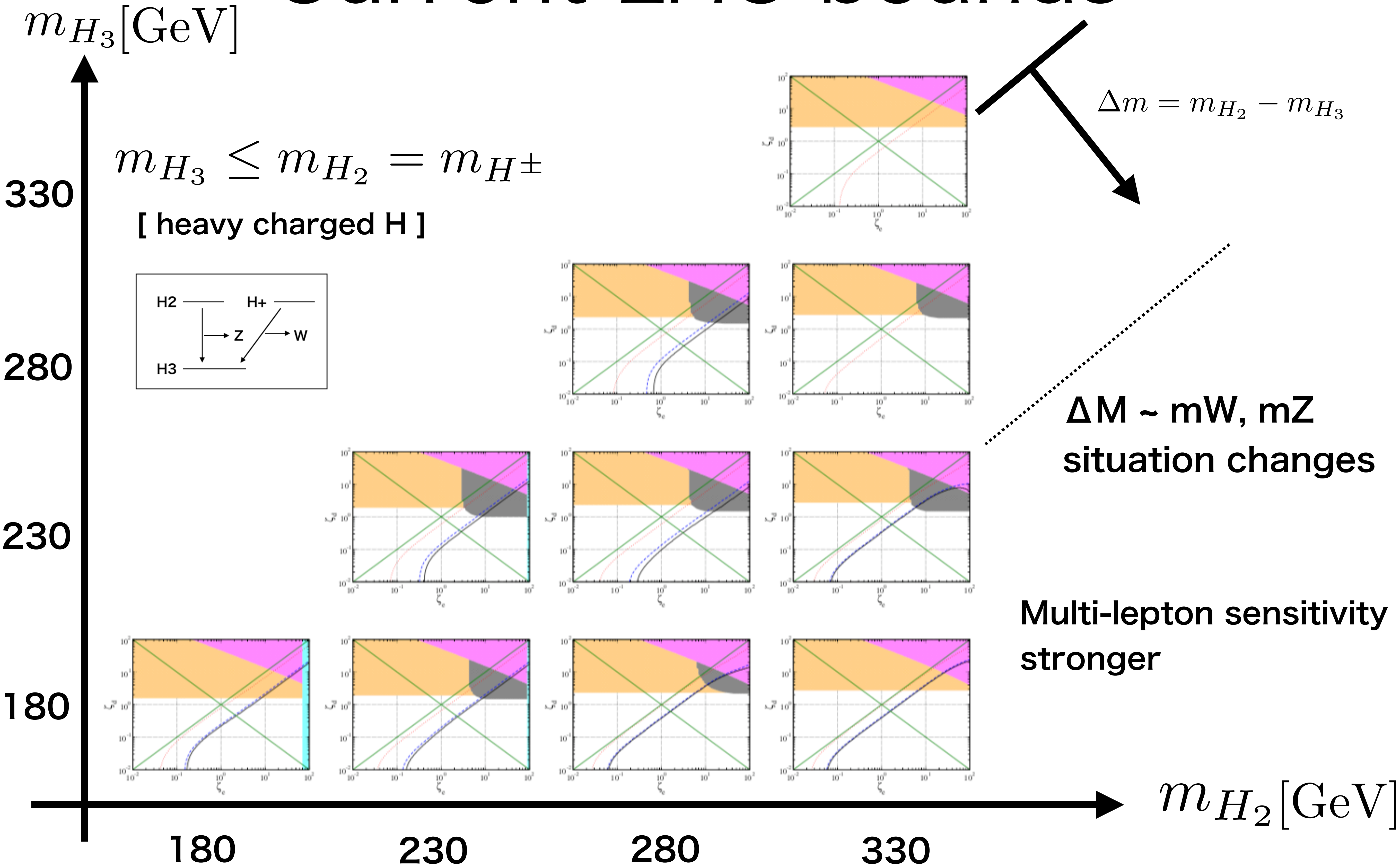
difference between light/heavy H± more significant when open

Current LHC bounds



Type X interpretation: $\zeta_e = \tan\beta \gtrsim 2$ excluded at HL-LHC

Current LHC bounds



$m_{H_3} \leq m_{H_2} = m_{H^\pm}$

[heavy charged H]

ΔM ~ mW, mZ situation changes

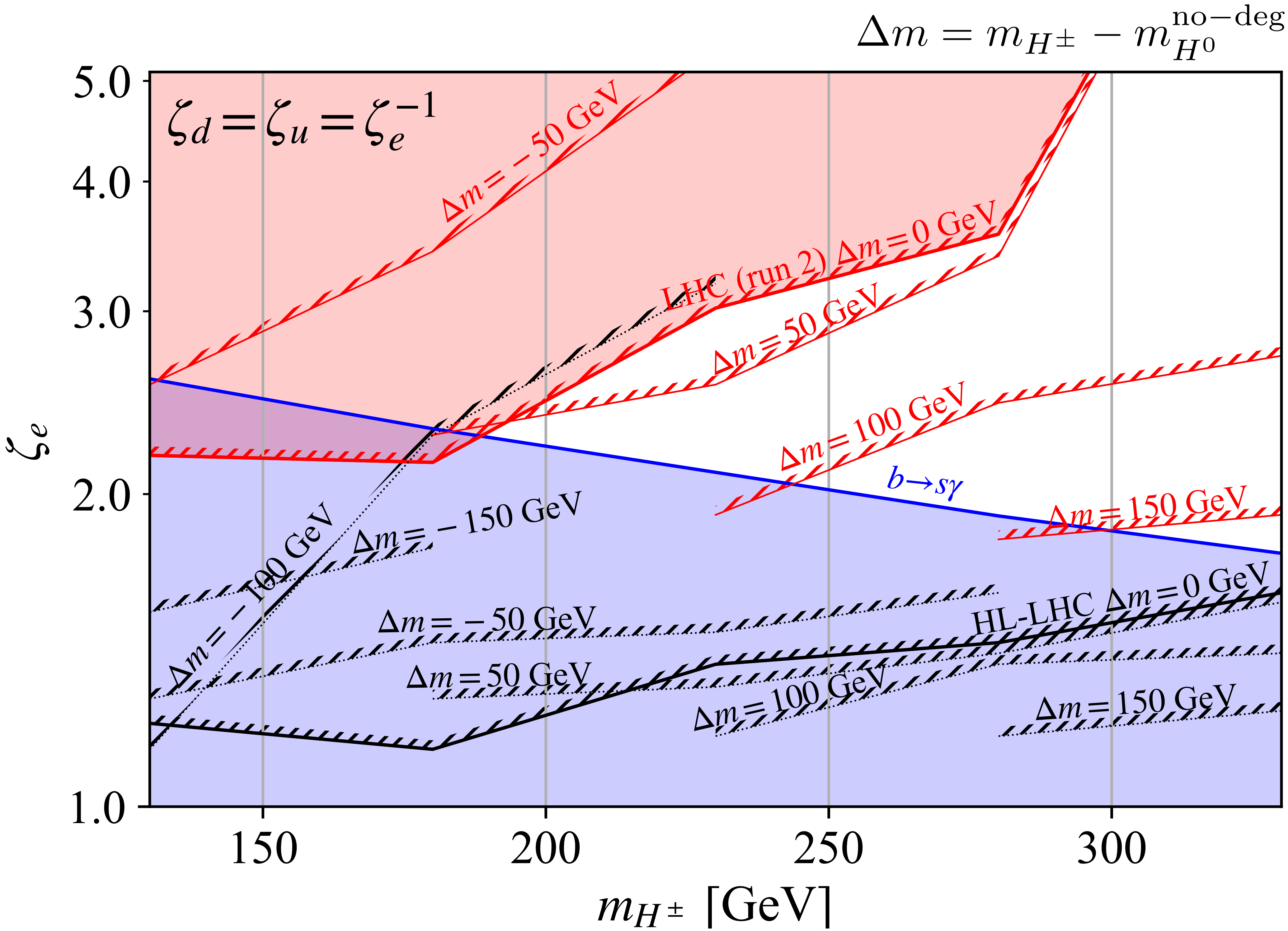
Multi-lepton sensitivity stronger

Heavier H+ set stronger constraints (H→ $\tau\tau$, bb, H+→ $\tau\nu$, tb)

Type X interpretation: $\zeta_e = \tan\beta \gtrsim 1$ **excluded at HL-LHC**

Current/future reaches in type X-like case

S. Kanemura, M.T., K. Yagyu [Phys.Rev.D 105 (2022) 11, 115001]



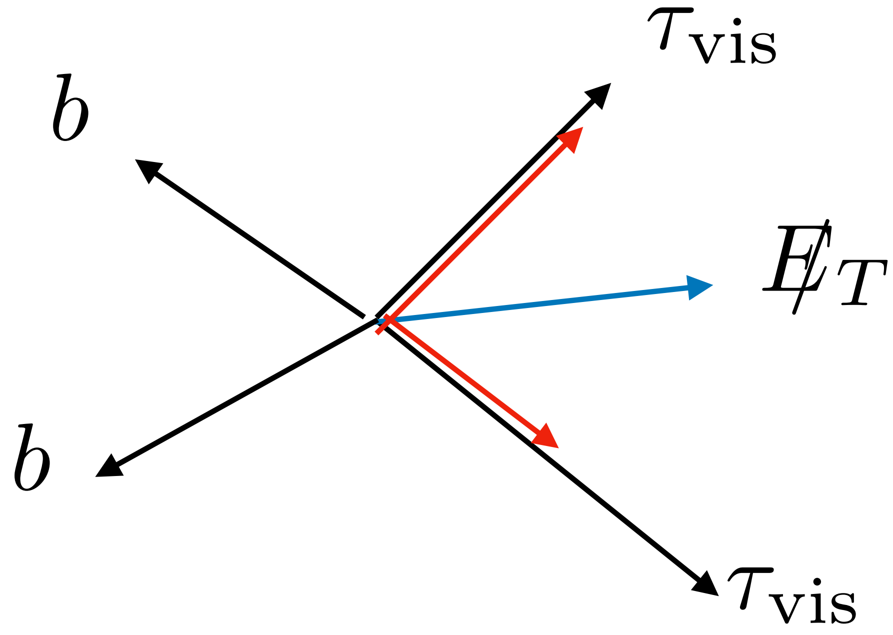
Type X-like case, lighter charged Higgs case($\Delta m < 0$) constrained weaker.
At HL-LHC almost all parameter space reachable below 2mt.

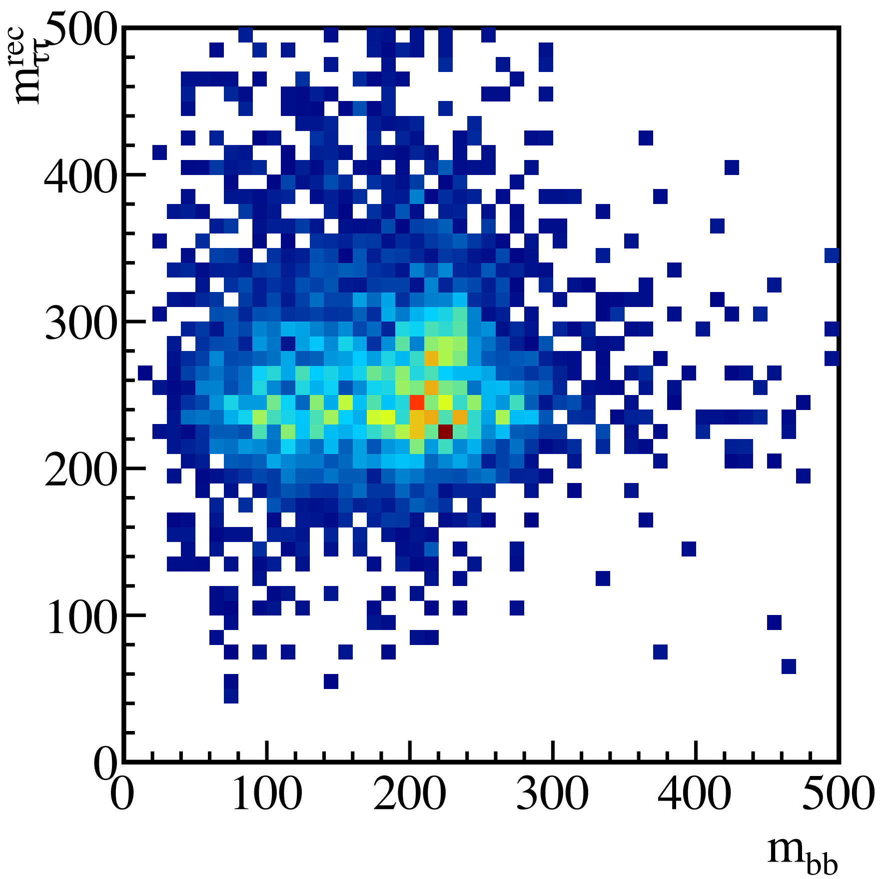
Mass measurements at LHC

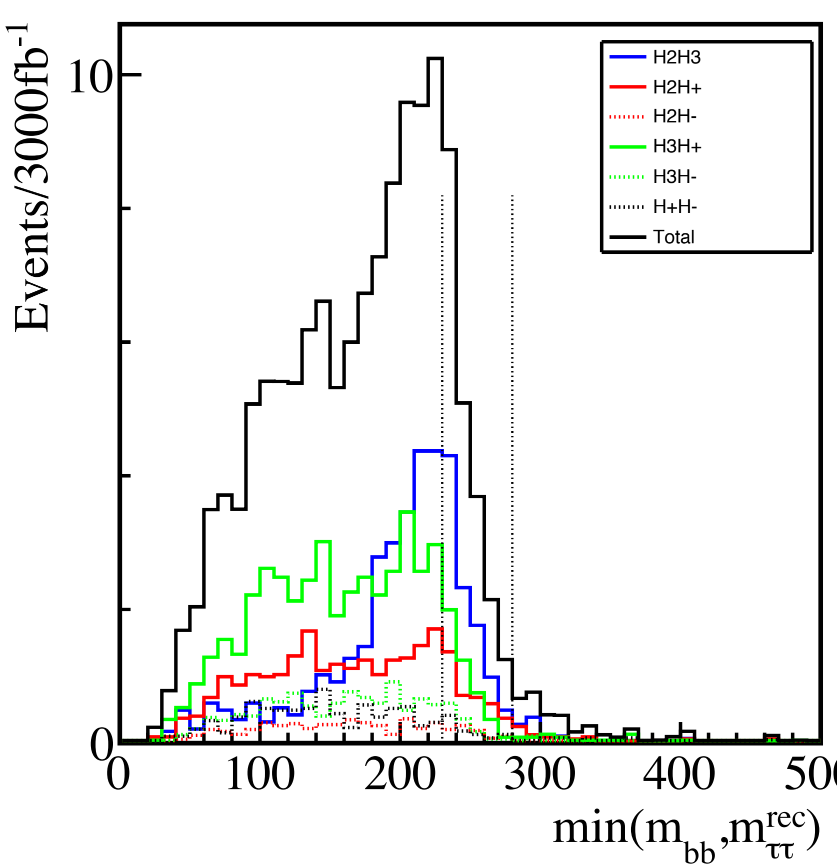
BR($\tau\tau$) ~1 already constrained
Can we use bb$\tau\tau$ mode?

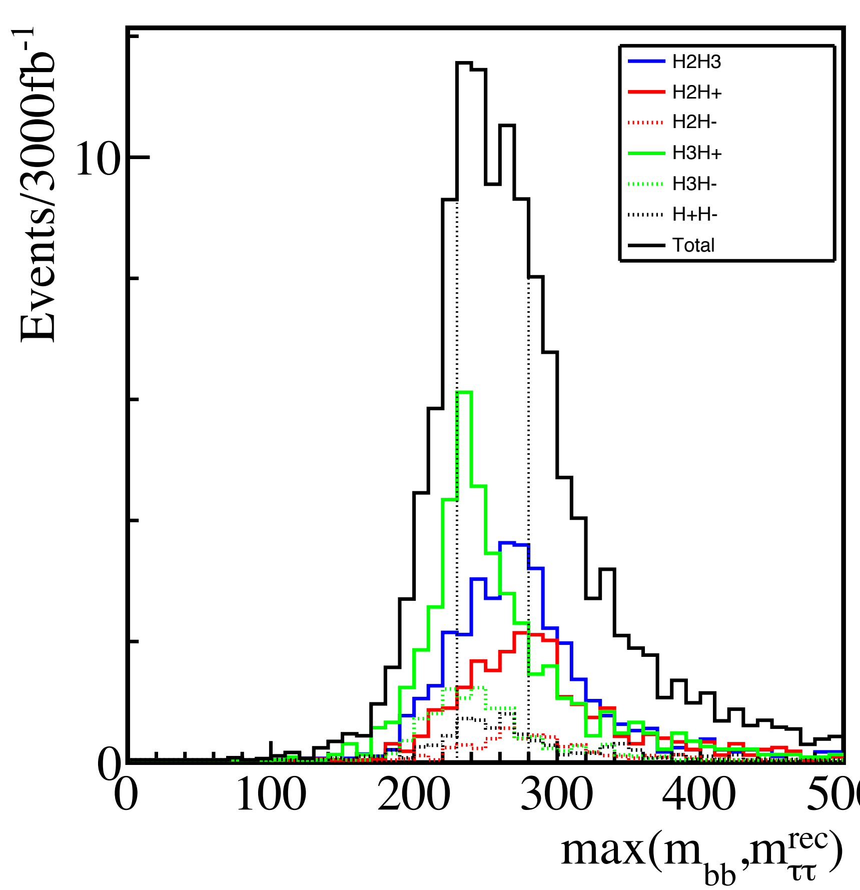
H is heavy enough, collinear approx. valid

$$\vec{p}_{\nu_1} = \alpha_1 \vec{p}_{\tau_{\rm vis1}}$$
$$\vec{p}_{\nu_2} = \alpha_2 \vec{p}_{\tau_{\rm vis2}}$$







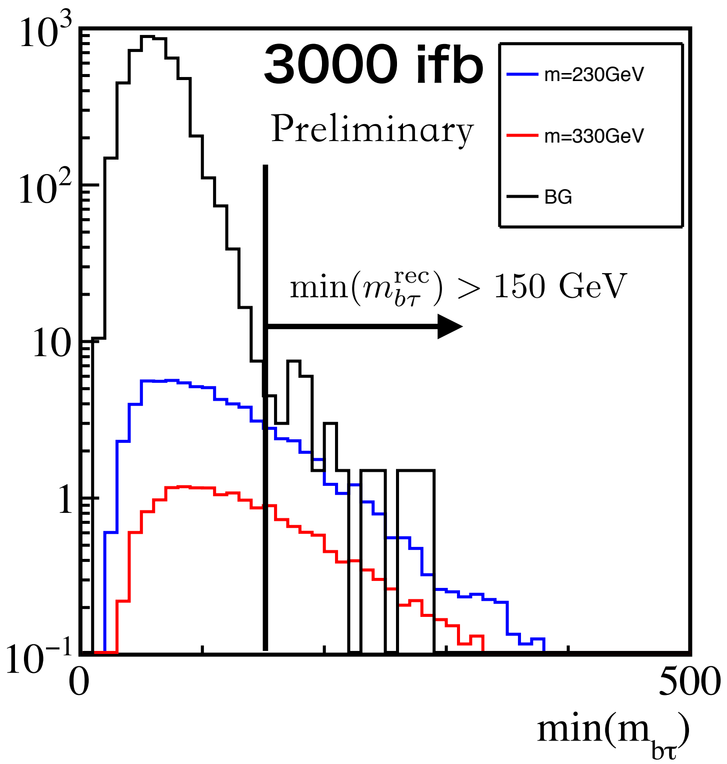


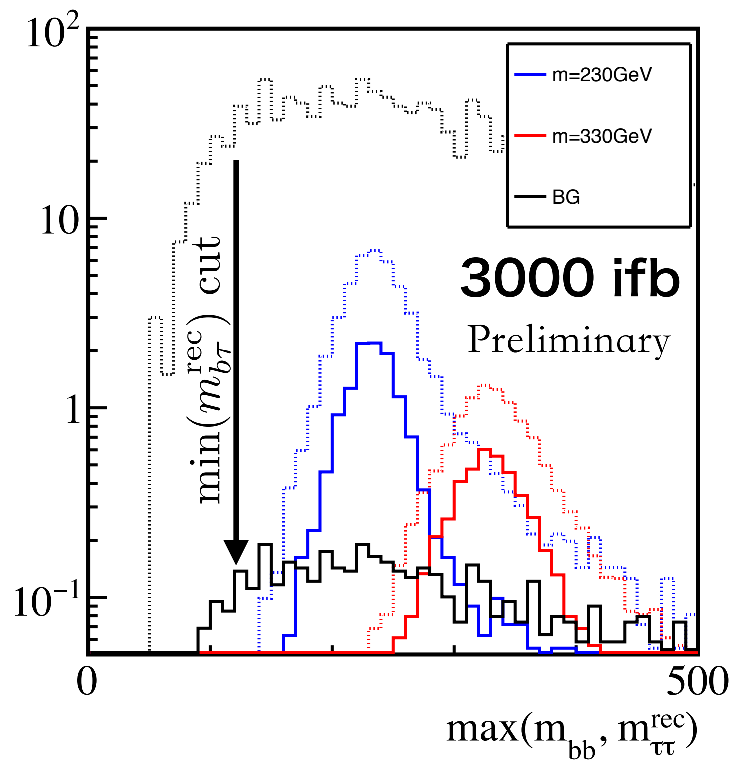
example) $m_{H2}, m_{H3}, m_{H^\pm}$ = 280, 230, 280 GeV

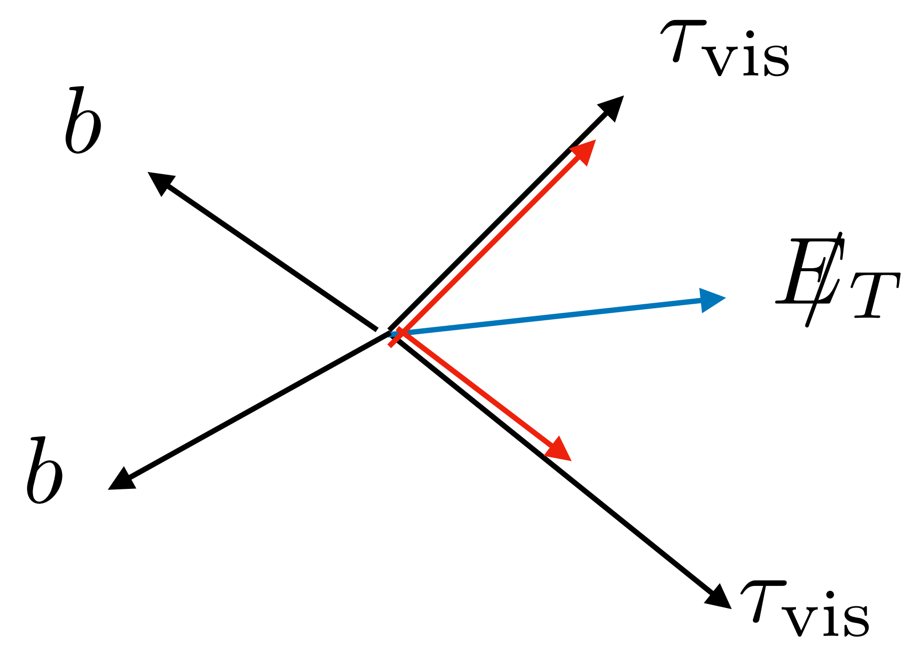
Mass measurements at LHC

Can we use bb$\tau\tau$? Large ttbar BG ~ 900pb

For the masses 230 GeV, 330GeV (signal xs ~ 10 - 50 fb)







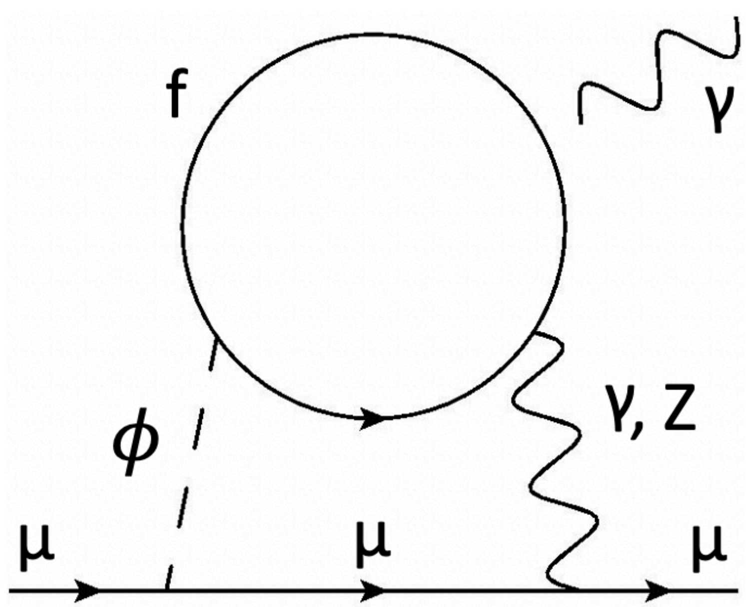
Only 1prong pi+ contributions $\tau^{\pm} \to \pi^{\pm}\nu$(BR~10%) plotted, other modes also usable

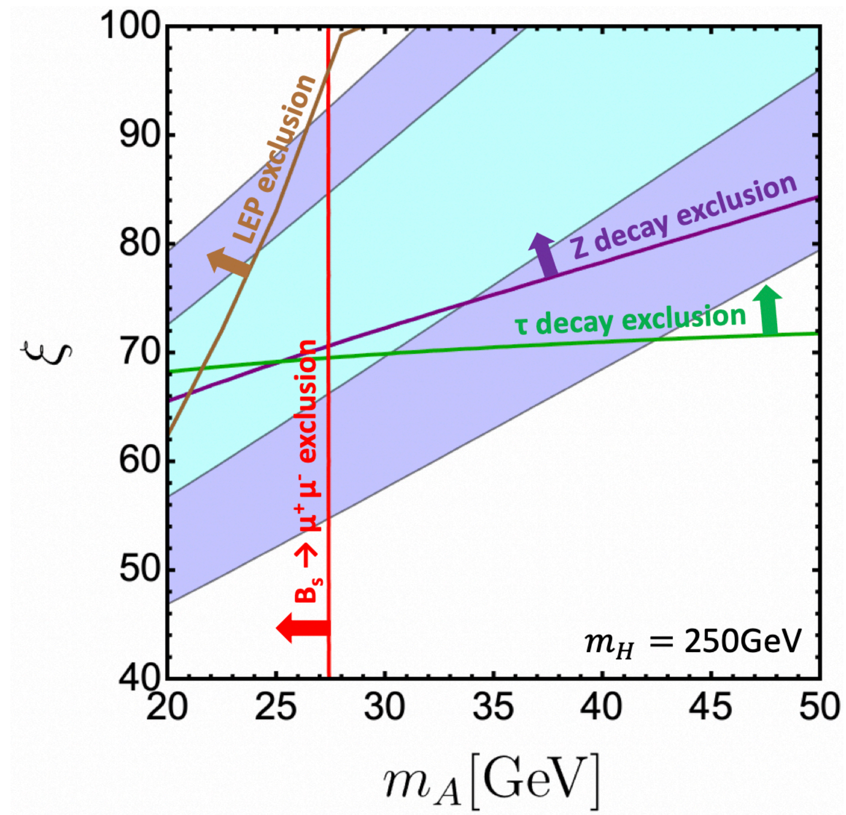
top BG reduced by $\min(m_{b\tau}^{\rm rec}) > 150\ {\rm GeV}$: efficiency ~ 0.04 vs. 10^-4

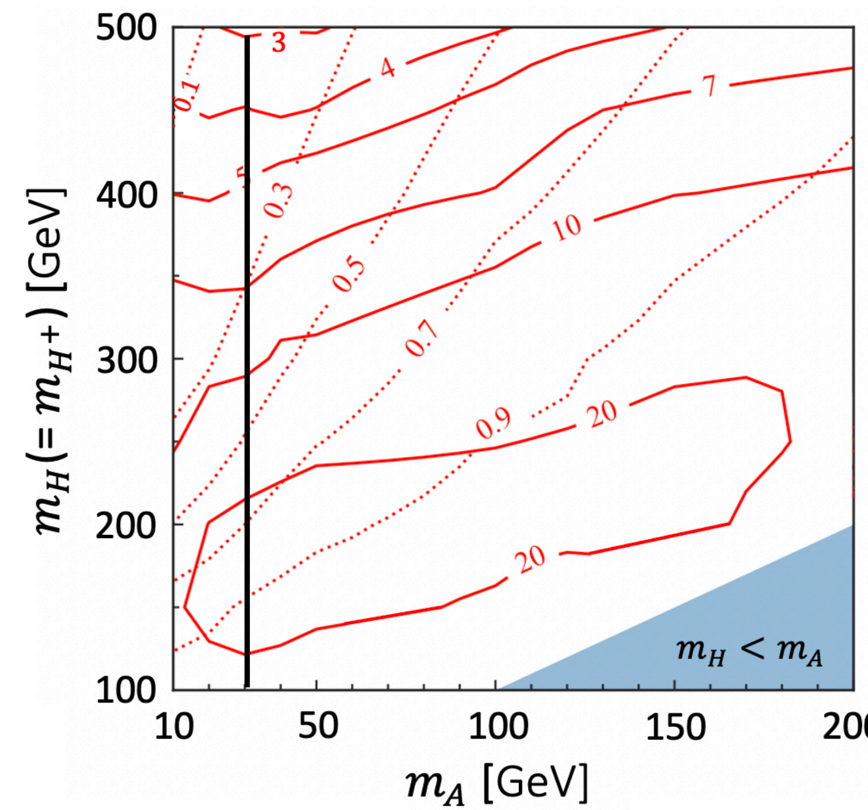
We expect top BG controllable using further 2D cut

Muon g-2 at 2HDMs

S. Iguro, T. Kitahara, M. Lang, M.T. [arXiv:2304.09887 [hep-ph]]







Light A (mA~ 30GeV) is known as a possible solution to explain muon g-2

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

Summary

- Baryon Asymmetry of the Unv. — too small CPV phase in the SM, thus CP violation beyond the SM required
- 125GeV Higgs is SM like → Aligned CPV 2HDM
- discussed Heavy Higgs discovery, measurements of mass, phases at LHC
- As the first step, we identify the current/future available region by multi-lepton searches at LHC

  → (counter-intuitively) heavier H+ cases stronger constrained

  S. Kanemura, M.T., K. Yagyu [Phys.Rev.D 105 (2022) 11, 115001]

At LHC, heavy Higgs mass measurable?

→ possible if they are light.

CPV phases at HL-LHC challenging [requires future ILC?]

- Correlation with 1st order phase transition, EW Baryon number generation

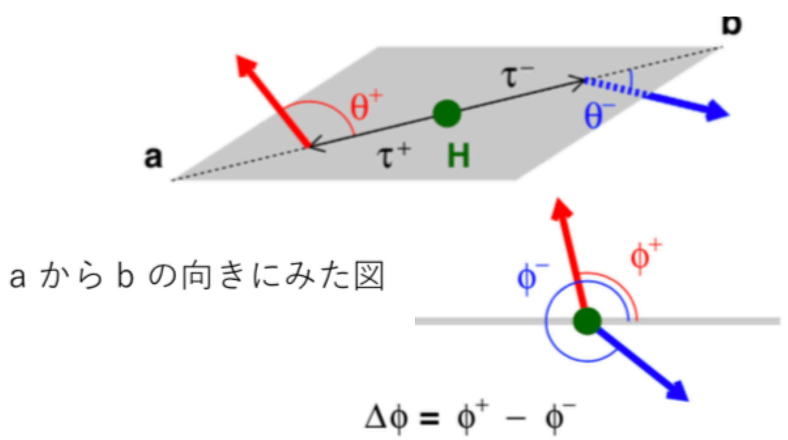
Backup

CPV phase measurement

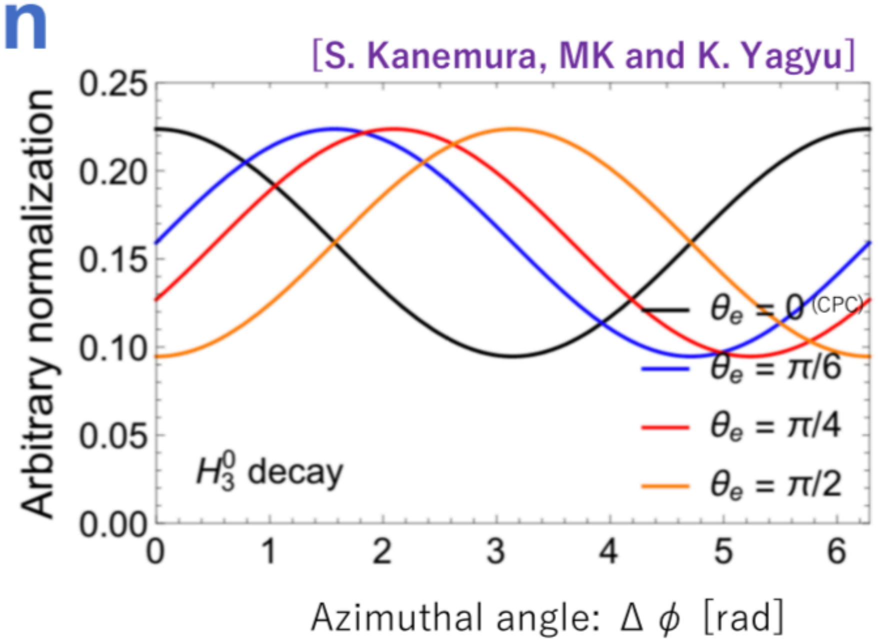
The former study : O(1) phases compatible to EDM constraints with heavy Higgses ~ 300GeV

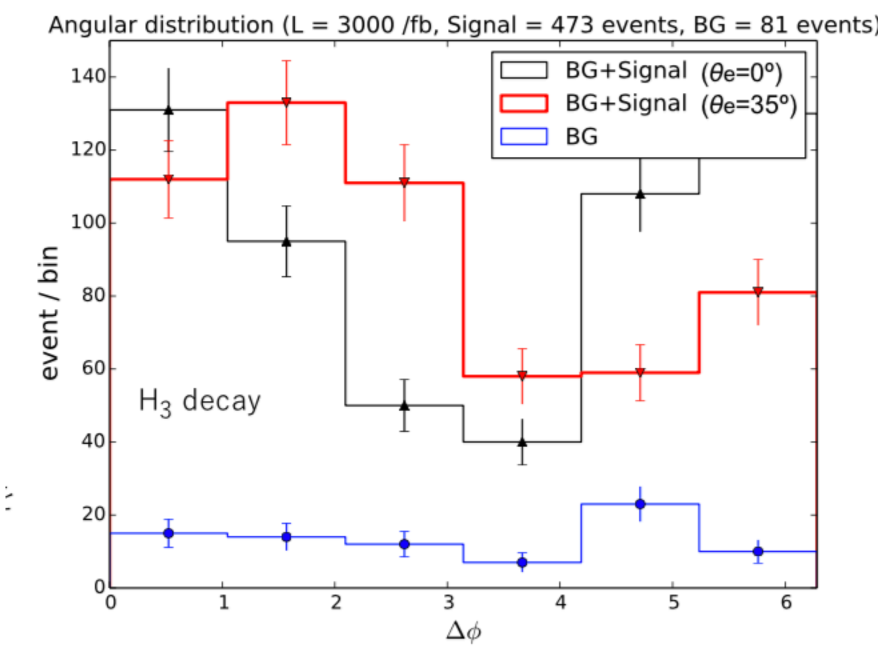
S. Kanemura, M. Kubota, K. Yagyu [J*HEP* 08 (2020) 026]

Angular distribution



Picture by [Jeans, Wilson, PRD98, 013007 (2018)]





At ILC, ζe phase measurements using azumuthal angle dist. in H2H3→(bb)($\tau\,\tau$)

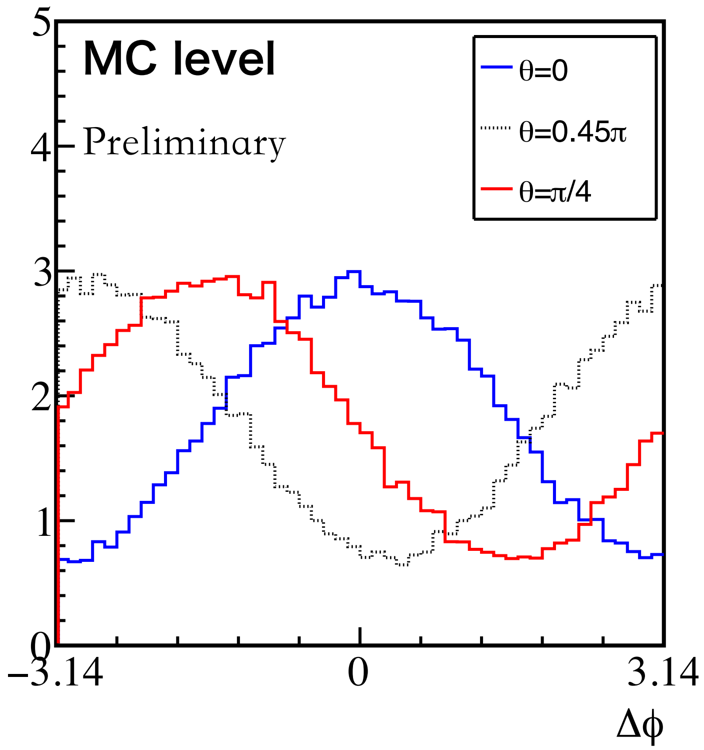
$\mathcal{M} = \mathcal{M}_{h_1 h_2}^{H\to\tau^+\tau^-}\mathcal{M}_{h_1}^{\tau^+}\mathcal{M}_{h_2}^{\tau^-}, \quad \mathcal{M}_h^{\tau^+} \sim e^{ih\phi}$ **assuming the heavy higgs masses measured at LHC**

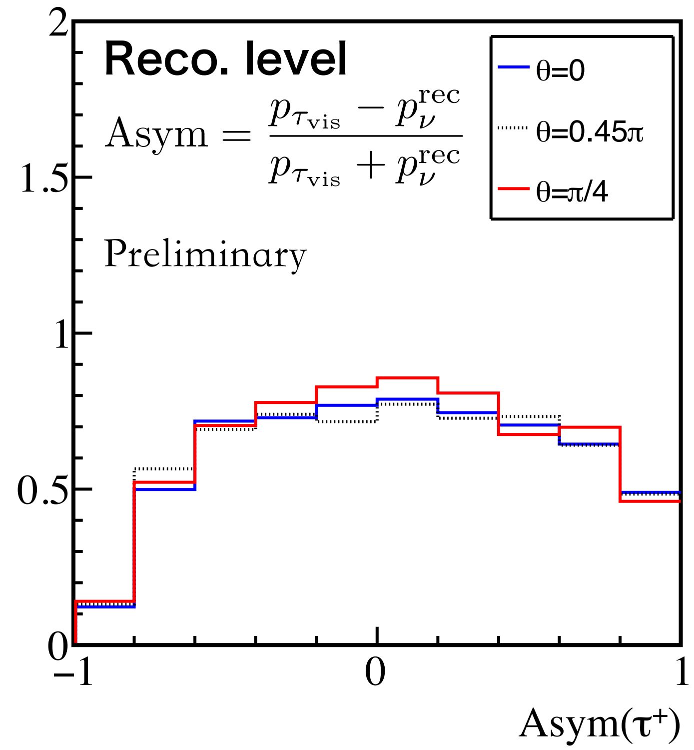
→ At LHC, can we discover the heavy higgses? Current reaches?
Can we measure the masses？

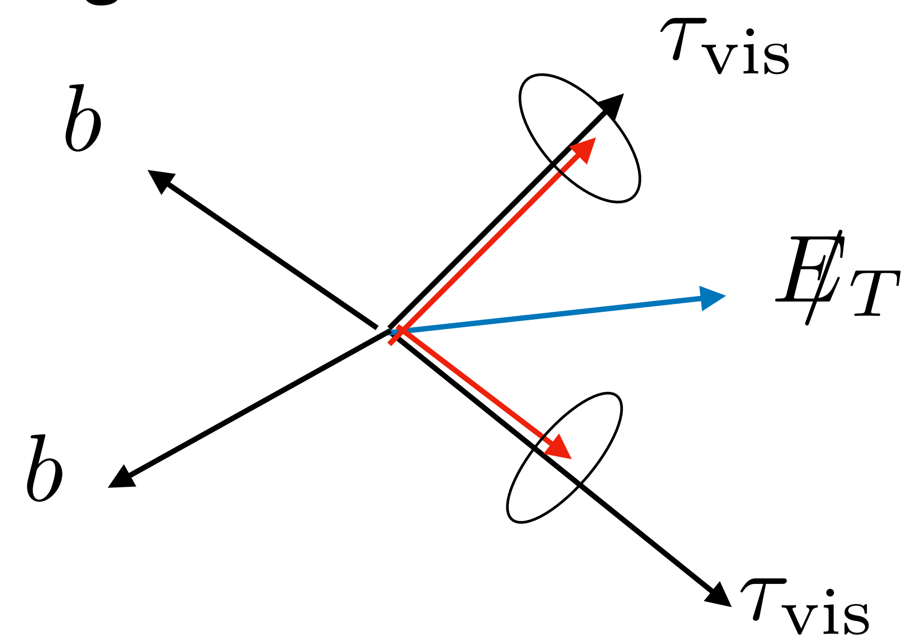
CPV phase measurement at LHC

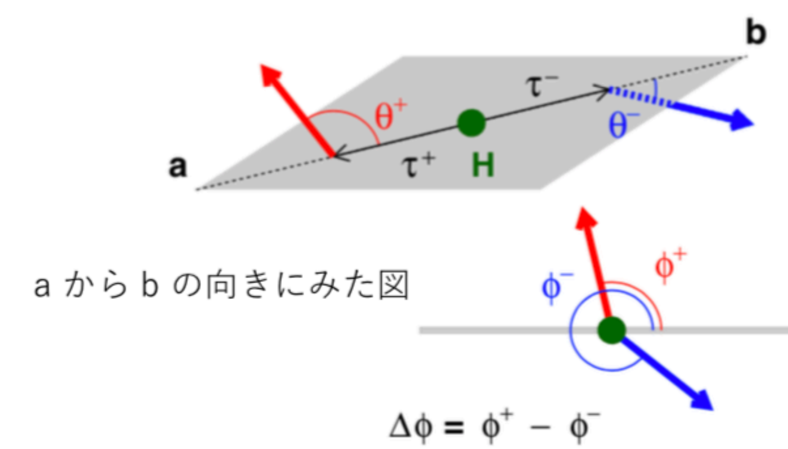
Collinear approx. not accessible to azimuthal angle at τ-rest frame

Small τ-mass makes it difficult









TauDecay [Eur.Phys.J.C 73 (2013) 2489, K.Hagiwara,T. Li,K.Mawatari,J.Nakamura]

Current LHC bounds

Various flavor constraints make the parameter space finite

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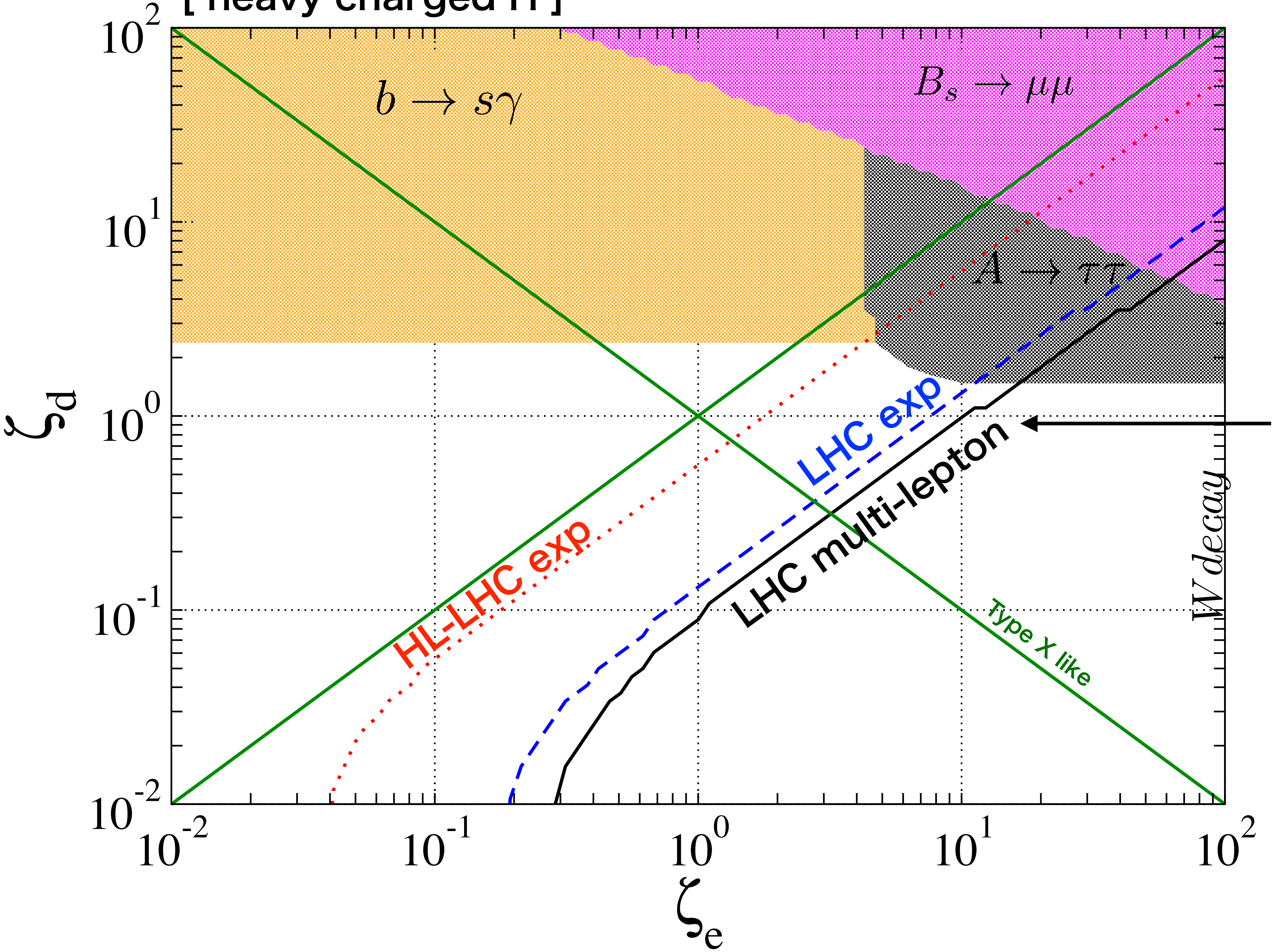
[heavy charged H]



Large $\tau\tau$ BR constrained by LHC multi lepton searches

Type X interpretation:

Currently,

$\zeta_e = \tan\beta \gtrsim 3$ **excluded**

At HL-LHC, up to

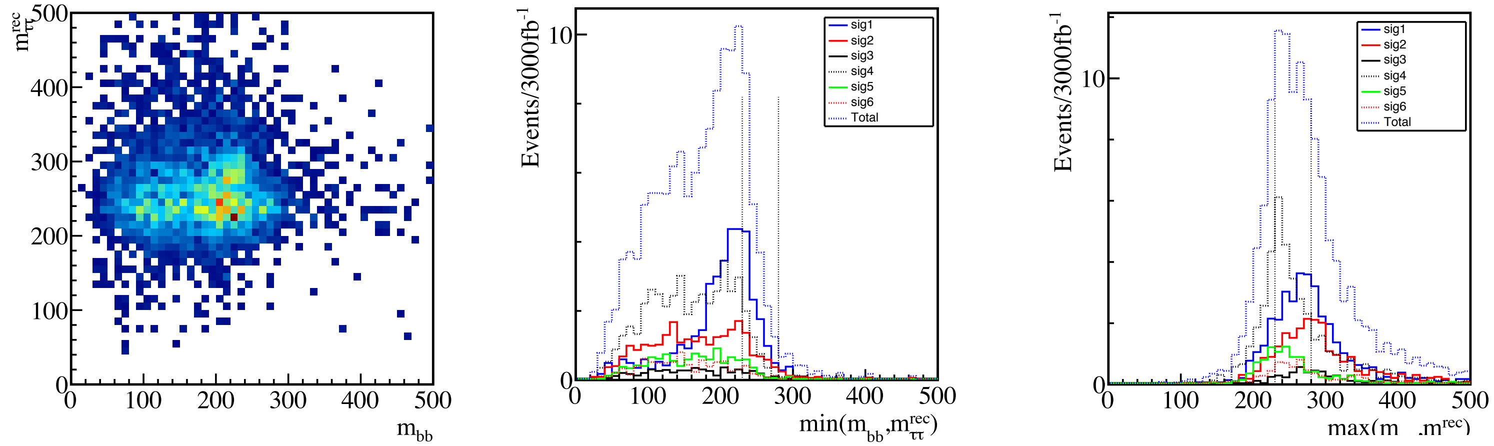
$\zeta_e = \tan\beta \gtrsim 1.5$

would be sensitive

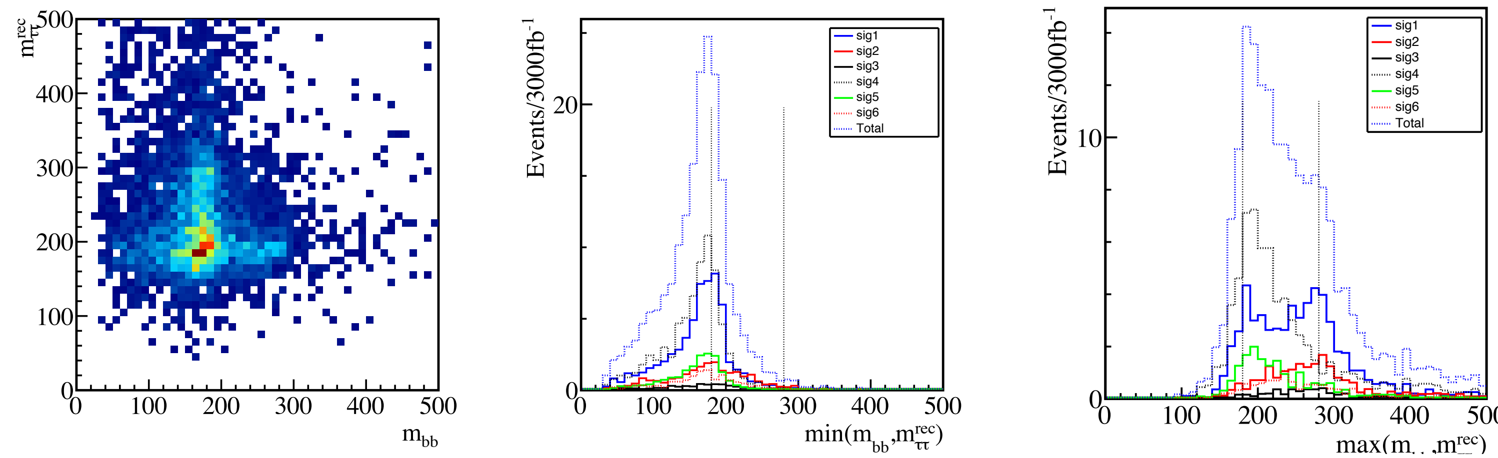
Mass measurements at LHC

$m_{H2}, m_{H3}, m_{H^\pm}$

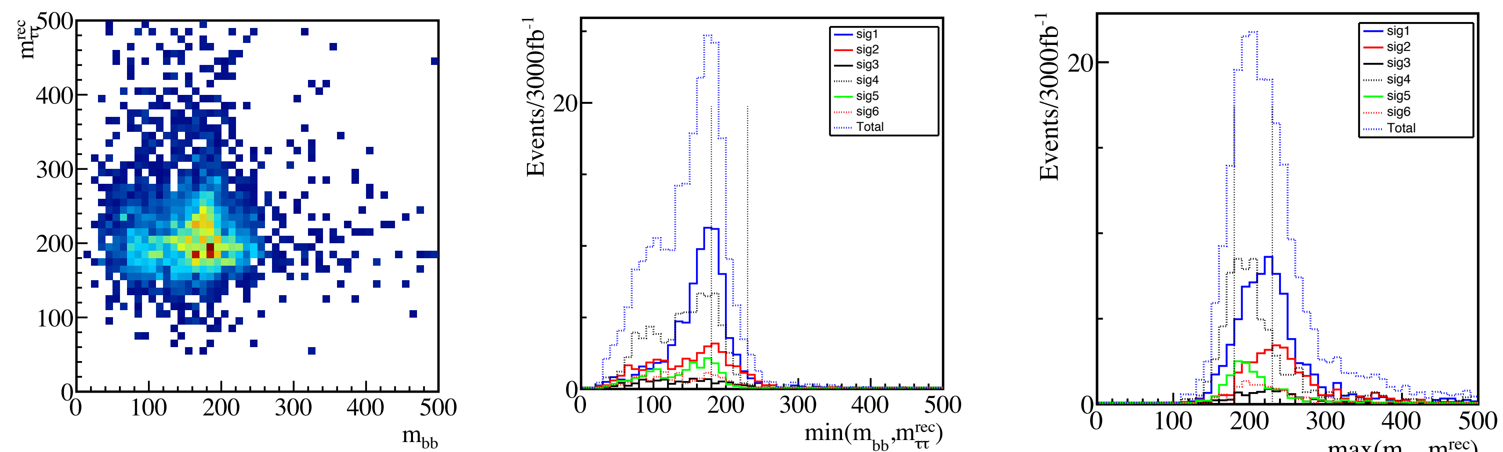
280, 230, 280



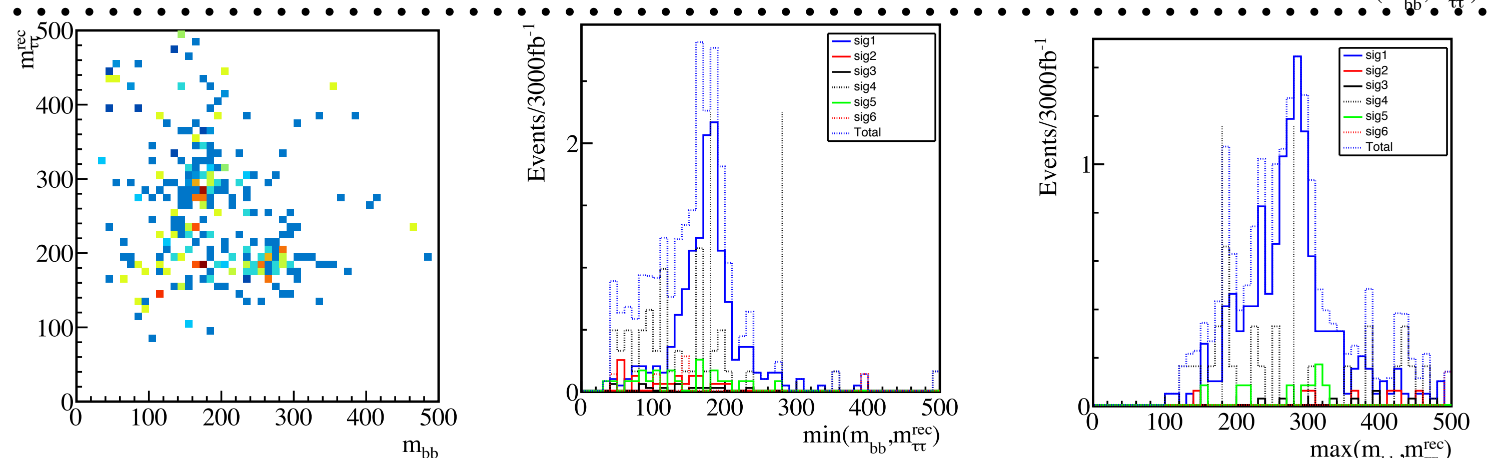
280, 180, 280



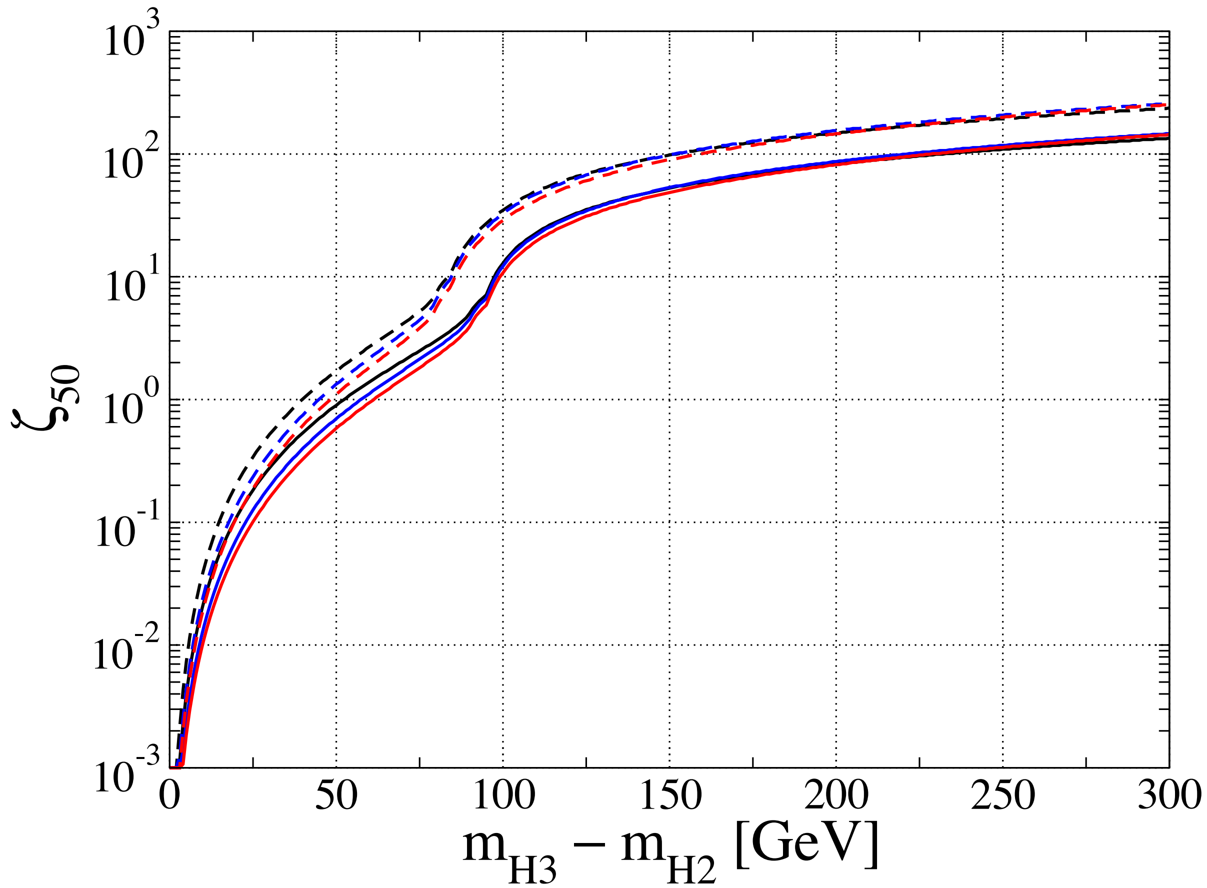
230, 180, 230

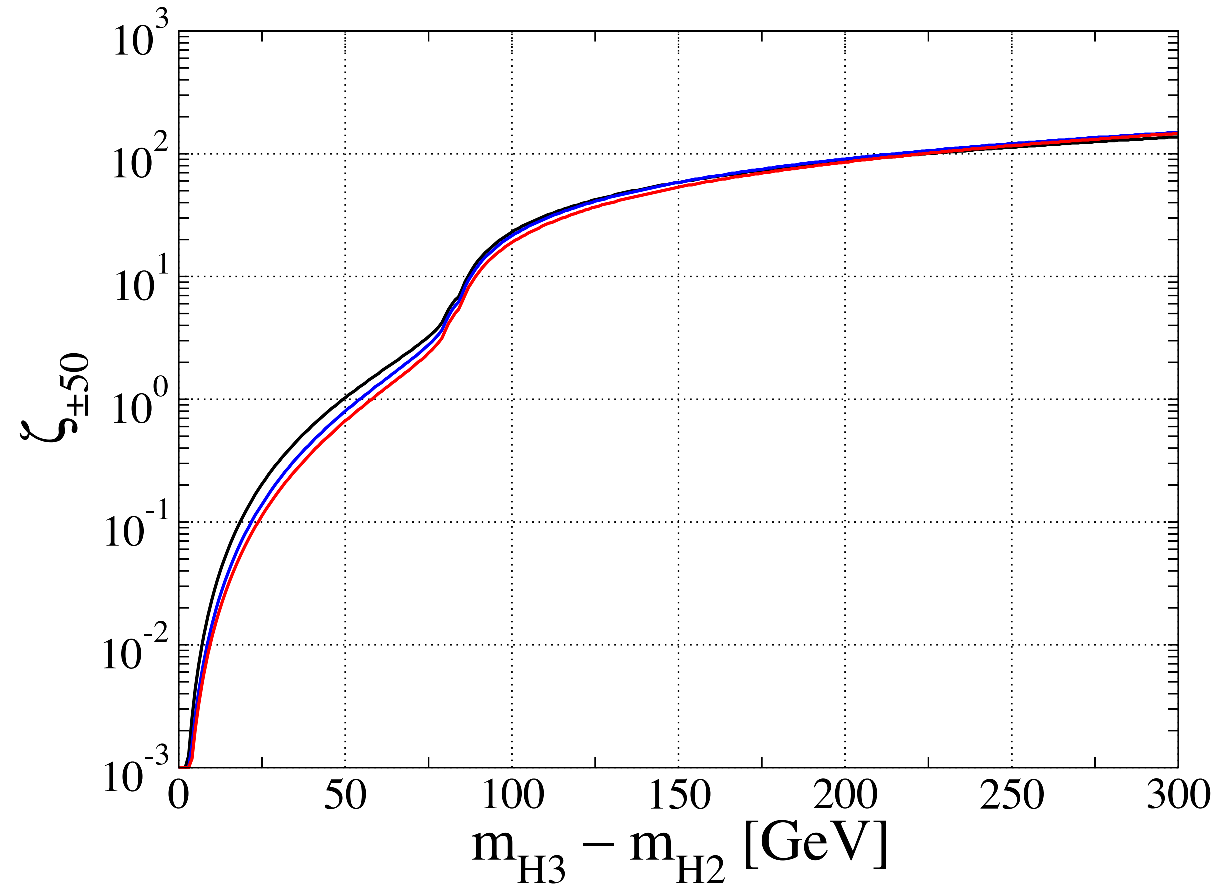


280, 180, 180



Fermion BR





$$R = \frac{1}{1 + r/\zeta^2}, \quad R_\tau = \frac{|\zeta_e|^2}{\zeta^2},$$

$$\zeta^2 = \frac{\sum_f \Gamma(H_3^0 \to f\bar{f})}{\Gamma_0}, \quad \Gamma_0 = \frac{\sqrt{2}G_F}{8\pi} m_{H_3^0} m_\tau^2,$$

$$\zeta_{50}^2 = r = \begin{cases} \frac{m_{H_3^0}^2}{2m_\tau^2} \sum_{V,\phi} \lambda^{3/2}\left(\frac{m_\phi^2}{m_{H_3^0}^2}, \frac{m_V^2}{m_{H_3^0}^2}\right) & (m_{H_3^0} - m_\phi \geq m_V) \\ \frac{9}{2\sqrt{2}\pi^2} \frac{G_F}{m_\tau^2} \sum_{V,\phi} m_V^4 \delta_V G\left(\frac{m_\phi^2}{m_{H_3^0}^2}, \frac{m_V^2}{m_{H_3^0}^2}\right) & (m_{H_3^0} - m_\phi < m_V), \end{cases}$$

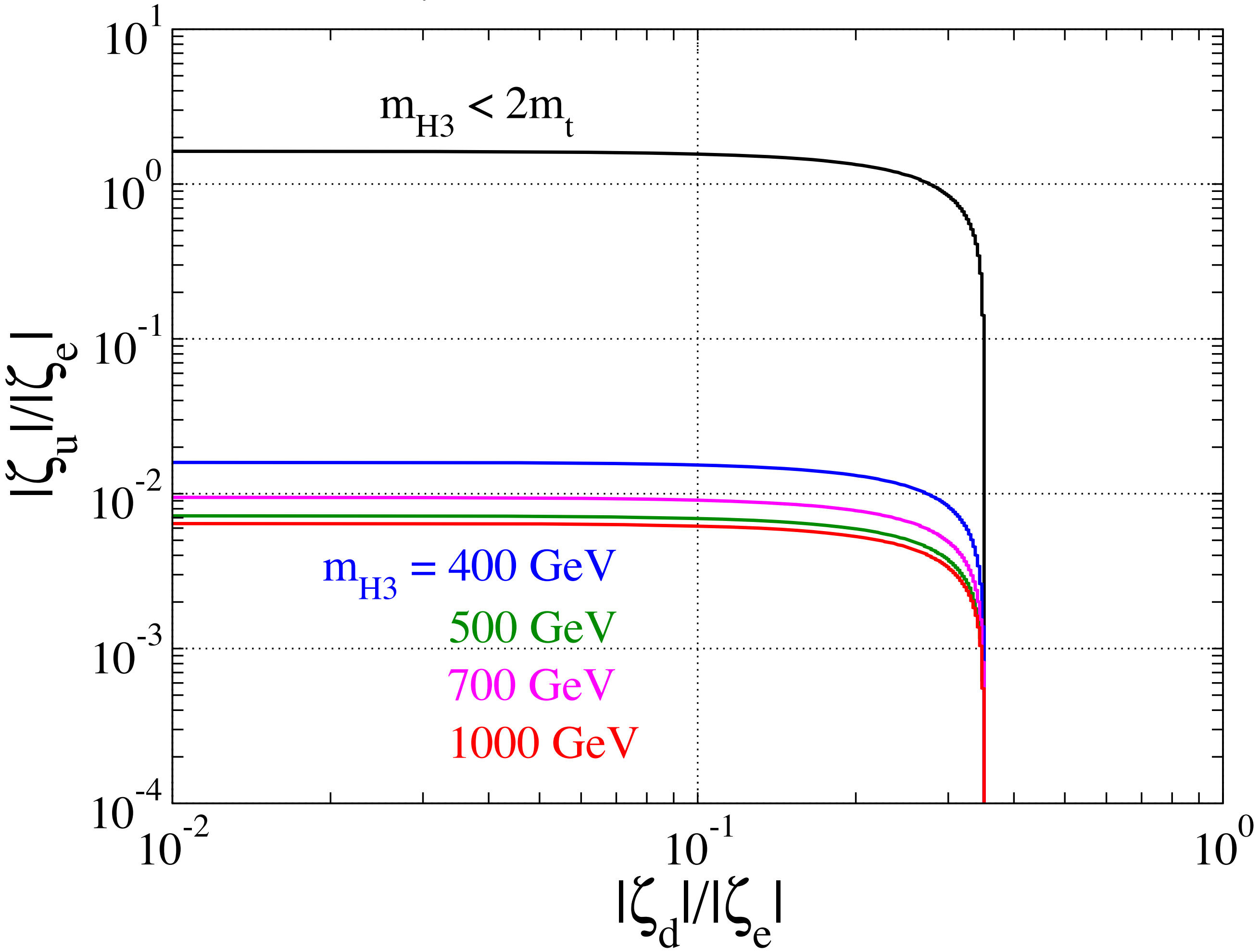
$$R^\pm = \frac{1}{1 + r_\pm/\zeta_\pm^2}, \quad R_\tau^\pm = \frac{|\zeta_e|^2}{\zeta_\pm^2},$$

$$\zeta_\pm^2 = \frac{\sum_f \Gamma(H^\pm \to f\bar{f}')}{\Gamma_0|_{H_3^0 \to H^\pm}} \simeq |\zeta_e|^2 + 3\left(1 - \frac{m_t^2}{m_{H^\pm}^2}\right)^2 \left(\frac{m_t^2}{m_\tau^2}|\zeta_u|^2 + \frac{m_b^2}{m_\tau^2}|\zeta_d|^2\right),$$

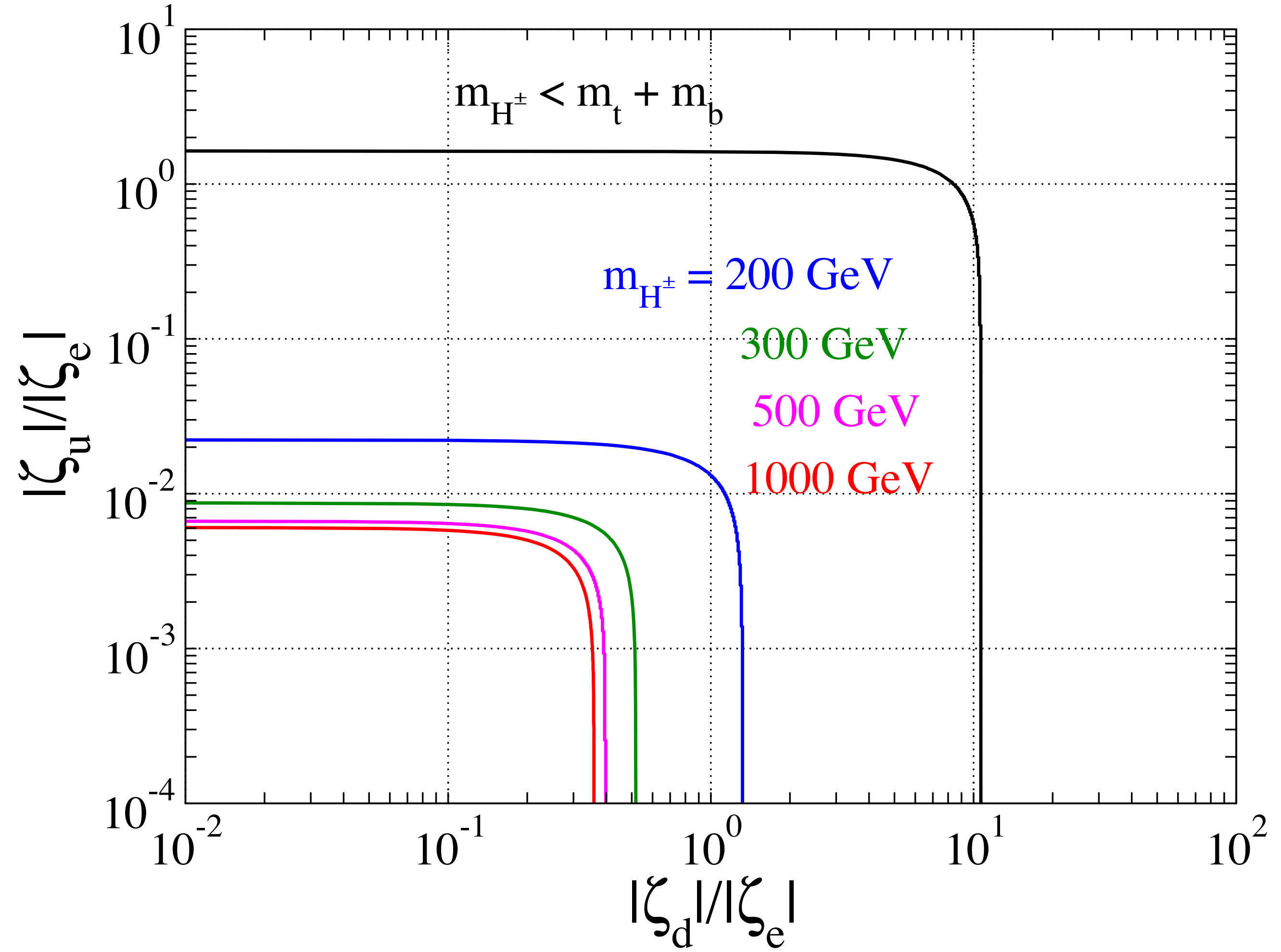
$$r_\pm = \begin{cases} \frac{m_{H^\pm}^2}{2m_\tau^2} \lambda^{3/2}\left(\frac{m_{H_2^0}^2}{m_{H^\pm}^2}, \frac{m_W^2}{m_{H^\pm}^2}\right) & (m_{H^\pm} - m_{H_2^0} \geq m_W) \\ \frac{9}{2\sqrt{2}\pi^2} \frac{G_F}{m_\tau^2} m_W^4 G\left(\frac{m_{H_2^0}^2}{m_{H^\pm}^2}, \frac{m_W^2}{m_{H^\pm}^2}\right) & (m_{H^\pm} - m_{H_2^0} < m_W) \end{cases},$$

Lepton BR

$R_\tau = 50\%$



$R_\tau^\pm = 50\%$



$$R_\tau^{-1} \simeq 1 + \frac{3m_b^2}{m_\tau^2}\frac{|\zeta_d|^2}{|\zeta_e|^2} + \left[\frac{3m_c^2}{m_\tau^2} + \theta_{tt}\frac{3m_t^2}{m_\tau^2}\left(1 - \frac{4m_t^2}{m_{H_3^0}^2}\right)^{3/2}\right]\frac{|\zeta_u|^2}{|\zeta_e|^2},$$

$$(R_\tau^\pm)^{-1} \simeq 1 + \left[\frac{3m_s^2}{m_\tau^2} + \theta_{tb}\frac{3m_b^2}{m_\tau^2}\left(1 - \frac{m_t^2}{m_{H^\pm}^2}\right)^2\right]\frac{|\zeta_d|^2}{|\zeta_e|^2} + \left[\frac{3m_c^2}{m_\tau^2} + \theta_{tb}\frac{3m_t^2}{m_\tau^2}\left(1 - \frac{m_t^2}{m_{H^\pm}^2}\right)^2\right]\frac{|\zeta_u|^2}{|\zeta_e|^2},$$