Hunting for New Light Particles in Extended Higgs Sectors: from 0 to 2

International Symposium on Higgs Boson and BSM, 15/8-19/8,2016 Weihai

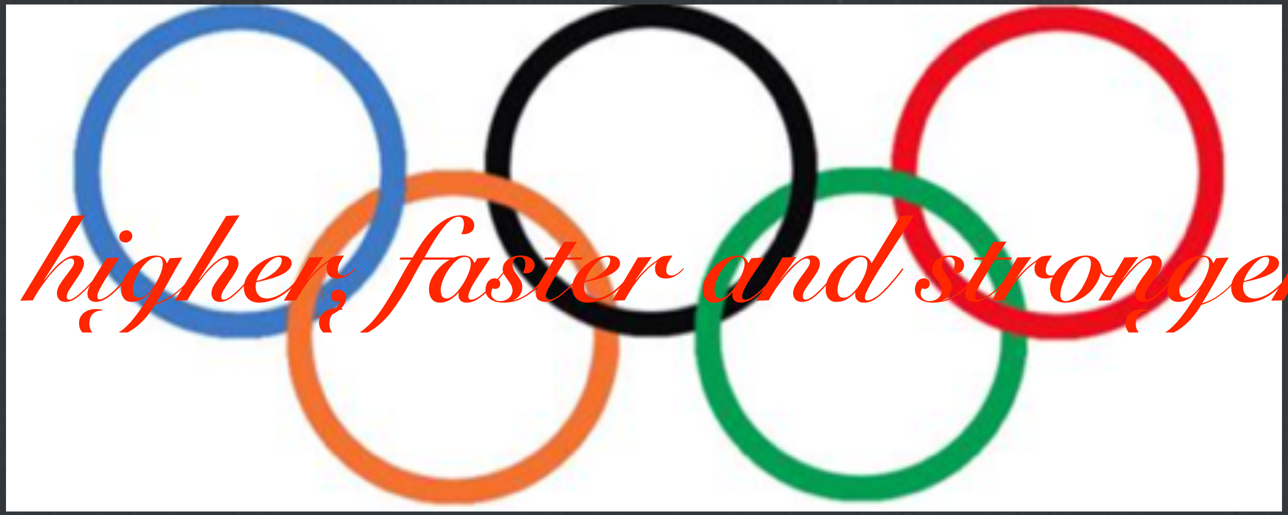
Zhaofeng Kang, KIAS,17/08/2016

outline

- motivation of this talk
- light neutral Higgs
- light doubly charged Higgs
- conclusions

Motivation

- Collider searches just like Olympic games, for



- People are exploring more energetic frontier to look for hints of heavier new states, such as top partners
- However, we also should leave attentions for the weak & light (typically below 125 GeV) particles, who may be submerged in the flooding hadronic backgrounds⚡⚡⚡
- This talk is to give some well motivated examples

0: light h_X(?)

Z.Kang, J.Li,T.Li, D.Liu and J.Shu,Phys.Rev.D88,no.1,015006(2013)[arXiv:1301.0453]

- **A lighter h_X(?) (than h(126)) from NMSSM**

NMSSM is the minimal extension to MSSM aiming at solving the μ-problem $\mu H_u H_d \rightarrow \lambda \langle S \rangle H_u H_d$d

At the same time it provides a non-decoupling F-term $|\lambda H_u H_d|^2$ to lift m_h=126 GeV at tree level. h(126) incurs serious fine-tuning problem in MSSM, but it is evaded in NMSSM 👍

U. Ellwanger, JHEP 1203, 044 (2012)
Z. Kang, J. Li and T. Li, "On Naturalness of the MSSM and NMSSM," JHEP 1211, 024(2012)
J. -J. Cao, Z. -X. Heng, J. M. Yang, Y. -M. Zhang and J. -Y. Zhu, JHEP 1203, 086 (2012)….

the most natural parameter space in the Higgs sector is predictive and looks like

$$\lambda: \ 0.6 - 0.7, \quad \tan\beta: \ 1.3 - 3.0,$$
$$\mu = \lambda v_s: \ 100\,\mathrm{GeV} - 200\,\mathrm{GeV},$$

$v_s = \langle S \rangle = \mu/\lambda$ is also near the weak scale, this has important implication to the Higgs sector

0: light h_X(?)

Z.Kang, J.Li,T.Li, D.Liu and J.Shu,Phys.Rev.D88,no.1,015006(2013)[arXiv:1301.0453]

- **3 Higg bosons: well mixed and fairly light**

The mass squared matrix in the Higgs basis

$$(M_S^2)_{11} = M_A^2 + (m_Z^2 - \lambda^2 v^2)\sin^2 2\beta, \qquad M_A^2 = 2\lambda v_s(A_\lambda + \kappa v_s)/\sin 2\beta$$

$$(M_S^2)_{12} = -\frac{1}{2}(m_Z^2 - \lambda^2 v^2)\sin 4\beta,$$

$$(M_S^2)_{13} = -(M_A^2 \sin 2\beta + 2\lambda\kappa v_s^2)\cos 2\beta \frac{v}{v_s},$$

$$(M_S^2)_{22} = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta,$$

$$(M_S^2)_{23} = \frac{1}{2}(4\lambda^2 v_s^2 - M_A^2 \sin^2 2\beta - 2\lambda\kappa v_s^2 \sin 2\beta)\frac{v}{v_s},$$

$$(M_S^2)_{33} = \frac{1}{4}M_A^2 \sin^2 2\beta \left(\frac{v}{v_s}\right)^2 + 4\kappa^2 v_s^2 + \kappa A_\kappa v_s - \frac{1}{2}\lambda\kappa v^2 \sin 2\beta\ ,$$

the well-known tree level m_h, requiring λ~1 and tanβ~1 to maximize the F-term effect

the 3 CP-even Higgs spectra is favored to be ranked as H_3~R(H_d), H_2~h, H_1=h_X(?)~ Re(S), in order to push-up h(126)

Moreover, mixings among these states are sizable, because of large off-diagonal elements & light elements. The heaviest one has mass

$$m_{H_3}^2 \approx M_A^2 \simeq \left(\frac{2\mu}{\sin 2\beta}\right)^2 \left(1 - \frac{\kappa}{\lambda}\frac{\sin 2\beta}{2}\right)$$

0: light h_X(?)

Z.Kang, J.Li,T.Li, D.Liu and J.Shu,Phys.Rev.D88,no.1,015006(2013)[arXiv:1301.0453]

- **Probing $H_3 \to H_2 H_1$: one stone with two birds**

The heaviest Higgs is crucial in producing and boosting H1

$$\mathcal{L}_{\rm tree} \supset r_{i,Z}\frac{\sqrt{2}M_Z^2}{v}H_iZZ + r_{i,W}\frac{M_W^2}{\sqrt{2}v}H_iW^+W^- - r_{i,f}\frac{m_f}{\sqrt{2}v}H_i\bar{f}f + \mu_{ijk}H_iH_jH_k,$$

H_3 has sizable coupling to top quarks due to a smaller tanβ $C_{3,t} = O_{11}\cot\beta + O_{12} \approx O_{11}\cot\beta.$

$H_3H_2H_1$ has sizable coupling $\mu_{123} \sim \lambda A_\lambda$, thus a sizable Br($H_3 \to H_2H_1$)

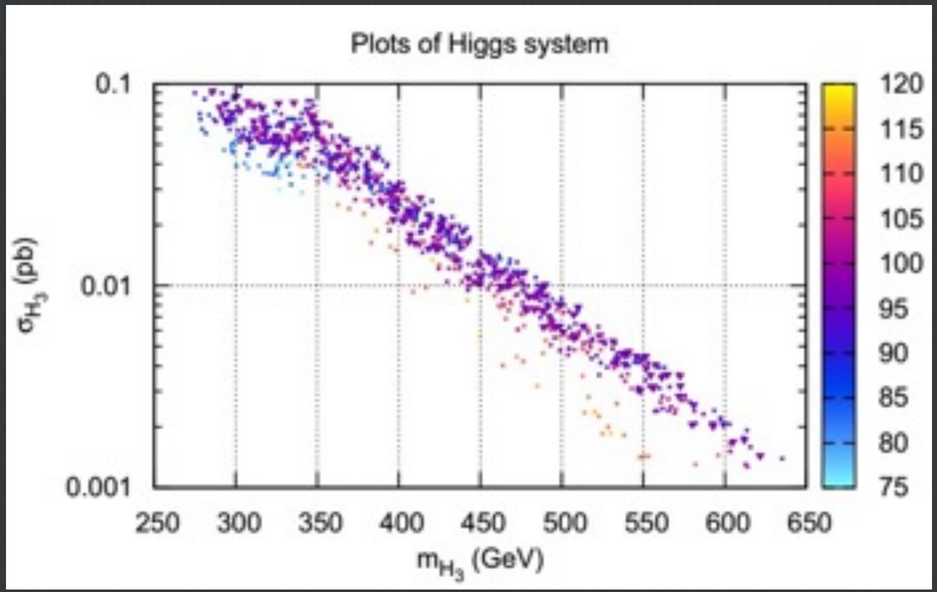
H_3 boosts the light H_1 which is assumed to have benchmark mass 98GeV. This helps to discover signature $gg \to H_3 \to H_2H_1 \to (W_hW_l)(bb)$

$H_1 = h_X(98)$ is hinted by LEP long time ago.

But our analysis is not restricted to this case.

Signature rate estimation

$$\sigma_{H_3} = 0.2\left(\frac{C_{3,g}}{0.4}\right)^2 \frac{{\rm Br}(H_3\to H_1H_2)}{20\%}\frac{{\rm Br}(H_1\to b\bar{b})}{90\%}\frac{{\rm Br}(H_2\to W_\ell W_h)}{28\%}\frac{\sigma_{\rm GF}(h_{\rm SM})}{10\,{\rm pb}}\,{\rm pb},$$



0: light h_X(?)

Z.Kang, J.Li,T.Li, D.Liu and J.Shu,Phys.Rev.D88,no.1,015006(2013)[arXiv:1301.0453]

- **Backgrounds and cuts**

Semi-leptonic tt* (dominant) & W_ℓ+bb*+jets (subdominant)

Cut flow: 1) $p_{T,bb^*} > 150$ GeV $p_{T,jjlv} >$120GeV and $|p_{T,bb^*} - p_{T,jj\ell v}|$<20GeV
2) 95 GeV<m_{H1} <100GeV, $m_{jjlv} <$ 150 GeV, and $m_{bb^*jj\ell v} <$ 440 GeV
3) $|\Delta\phi_{\ell j}|$ <1.5, H2 is a scalar and W couples to left-handed fermions
4) $\Delta R_{H1,\bar{b}b} <$ 0.01, and 2.6 < $\Delta R_{H1W_h} <$ 3.4…

- **Results**

	$t\bar{t}$	$W(\to l\nu jj)b\bar{b} + jets$	Signal
Total	1.2×10^8	1.91×10^7	1.25×10^4
Trigged	4.95×10^6	1.45×10^6	1456.75
Cut1	3.77×10^5	1.61×10^5	639.5
Cut2	1932	203	119.75
Cut3	1512	155.2	105.5
Cut4	108	47.75	56.25
Cut5	84	47.75	55

TABLE I: Number of events after each cut for background and signal (normalized to 500 fb^{-1}). The signal significance $S/\sqrt{S+B}$ has reached to 4.02 and with the precise 4.42 σ excess for the LEP-LHC benchmark point.

	m_{H_1}(GeV)	m_{H_3}(GeV)	σ (fb)	$\frac{S}{\sqrt{S+B}}$
B1	100	300	70	0.81
B2	65	300	50	3.84
B3	98	400	25	4.73
B4	65	400	20	7.68
B5	100	600	2	2.79
B6	65	600	2	4.99

TABLE II: Discovery signal significances for 6 representative points at 14 TeV 500 fb^{-1}. We design 25 kinematic variables for BDT analysis [30]: $\not{E}_T$, $p_{T,W}$, m_W, n_{jet}, p_{T,b_1}, p_{T,b_2}, $p_{T,\ell}$, $m_{T,\ell\nu}$, $p_{T,wj\ell}$, p_{T,wj_2}, $p_{T,jj\ell\nu}$, $\Delta R_{\ell j}$, $\Delta\phi_{lw}$, p_{T,H_3}, $m_{\ell\nu}$, $E_{l\nu}$, and m_{H_3}.

0: light A_X(?)

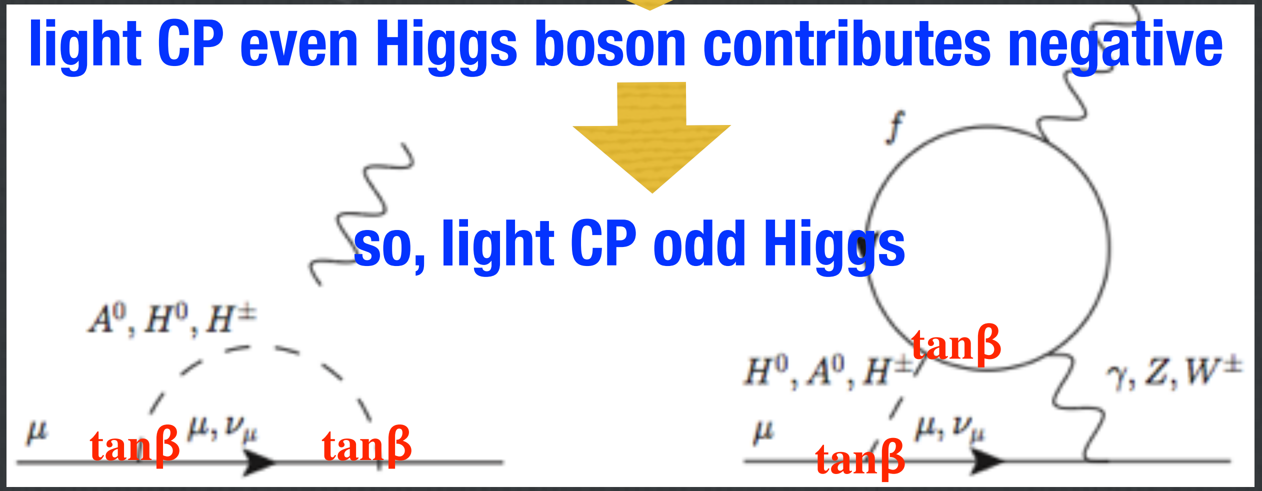
E. J. Chun, Z. Kang, M. Takeuchi and Y. L. S. Tsai, "LHC τ-rich Tests of Lepton-specific 2HDM for (g − 2)μ," arXiv:1507.08067

- **Light *A* from lepton-specific 2HDM (L2HDM) for g_μ-2**

g_μ-2 is a long standing puzzle fails, and L2HDM offers one of the simplest solution via a light CP-odd Higgs *A* with large tanβ

$$-\mathcal{L}_Y = Y^u \overline{Q_L} \widetilde{\Phi}_2 u_R + Y^d \overline{Q_L} \Phi_2 d_R + Y^e \overline{l_L} \Phi_1 e_R + c.c.,$$

the extra Higgs doublet only couples to leptons, and thus a lot of constraints on the ordinary 2HDM with light Higgs bosons but large tanβ go



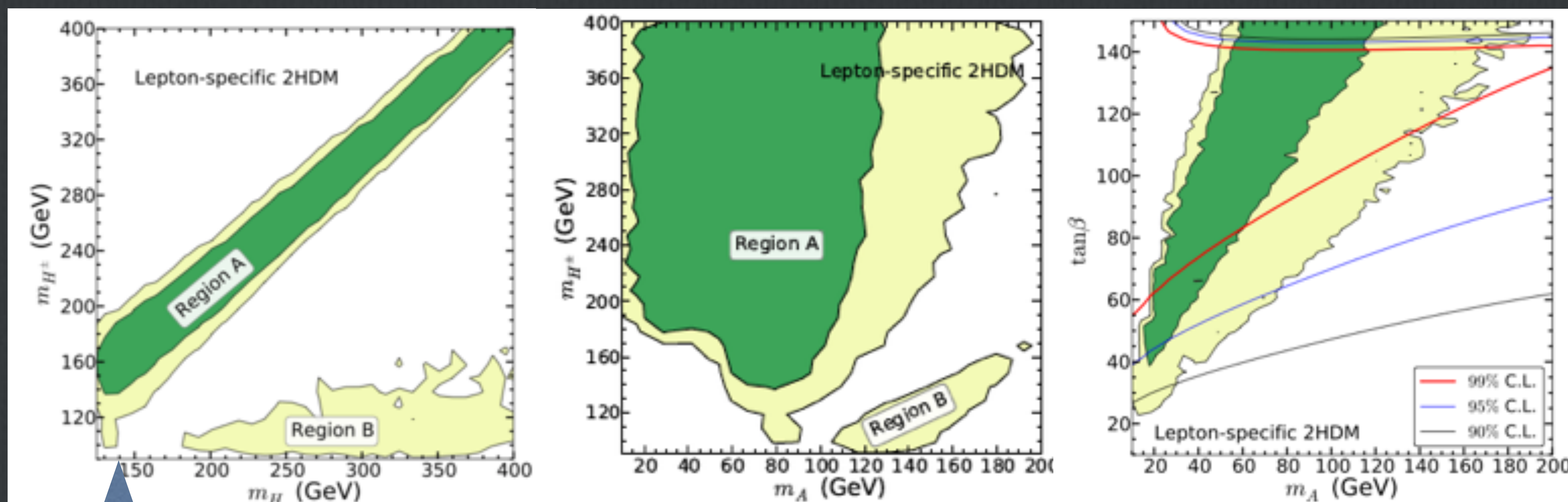
A. Broggio, E. J. Chun, M. Passera, K. M. Patel and S. K. Vempati, JHEP 1411 (2014) 058
L. Wang and X. F. Han, arXiv:1412.4874
T. Abe, R. Sato and K. Yagyu, arXiv:1504.07059
J. Cao, P. Wan, L. Wu and J. M. Yang, Phys. Rev. D 80 (2009) 071701

0: light A_X(?)

E. J. Chun, Z. Kang, M. Takeuchi and Y. L. S. Tsai, "LHC τ-rich Tests of Lepton-specific 2HDM for (g − 2)μ," arXiv:1507.08067

- **Light A from lepton-specific 2HDM (L2HDM) for g_μ-2**

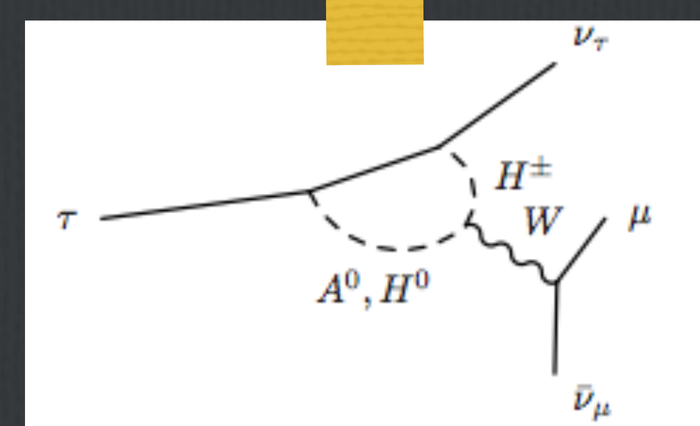
g_μ-2 solution: confronting lepton flavor university & h exotic decays



two regions survive, two ways to satisfy EWPT

for region A, $m_A < m_h/2$ is subtle because one has to carefully tune the parameters to suppress hAA coupling⚡:

$$\xi_h^l s_{\beta-\alpha} \approx -\frac{s^2_{\beta-\alpha} m_H^2 - 2m_A^2 - v\lambda_{hAA}/s_{\beta-\alpha}}{m_H^2 - m_h^2}$$



0: light A_X(?)

E. J. Chun, Z. Kang, M. Takeuchi and Y. L. S. Tsai, "LHC τ-rich Tests of Lepton-specific 2HDM for (g – 2)μ," arXiv:1507.08067

- **Searches for the light A via τ-rich signature**

All new particles tend to overwhelmingly decay into τ-flavor, so we can search this states using τ-rich (≥ 3) **signature:**

$$pp \to W^{\pm *} \to H^{\pm}A \to (\tau^{\pm}\nu)(\tau^{+}\tau^{-}),$$
$$pp \to Z^{*}/\gamma^{*} \to HA \to (\tau^{+}\tau^{-})(\tau^{+}\tau^{-}),$$
$$pp \to W^{\pm *} \to H^{\pm}H \to (\tau^{\pm}\nu)(\tau^{+}\tau^{-}),$$
$$pp \to Z^{*}/\gamma^{*} \to H^{+}H^{-} \to (\tau^{+}\nu)(\tau^{-}\bar{\nu}).$$

S. Su and B. Thomas, Phys. Rev. D 79, 095014 (2009);
S. Kanemura, K. Tsumura and H. Yokoya, Phys. Rev. D 85, 095001 (2012);
S. Kanemura, K. Tsumura, K. Yagyu and H. Yokoya, Phys. Rev. D 90, 075001 (2014)

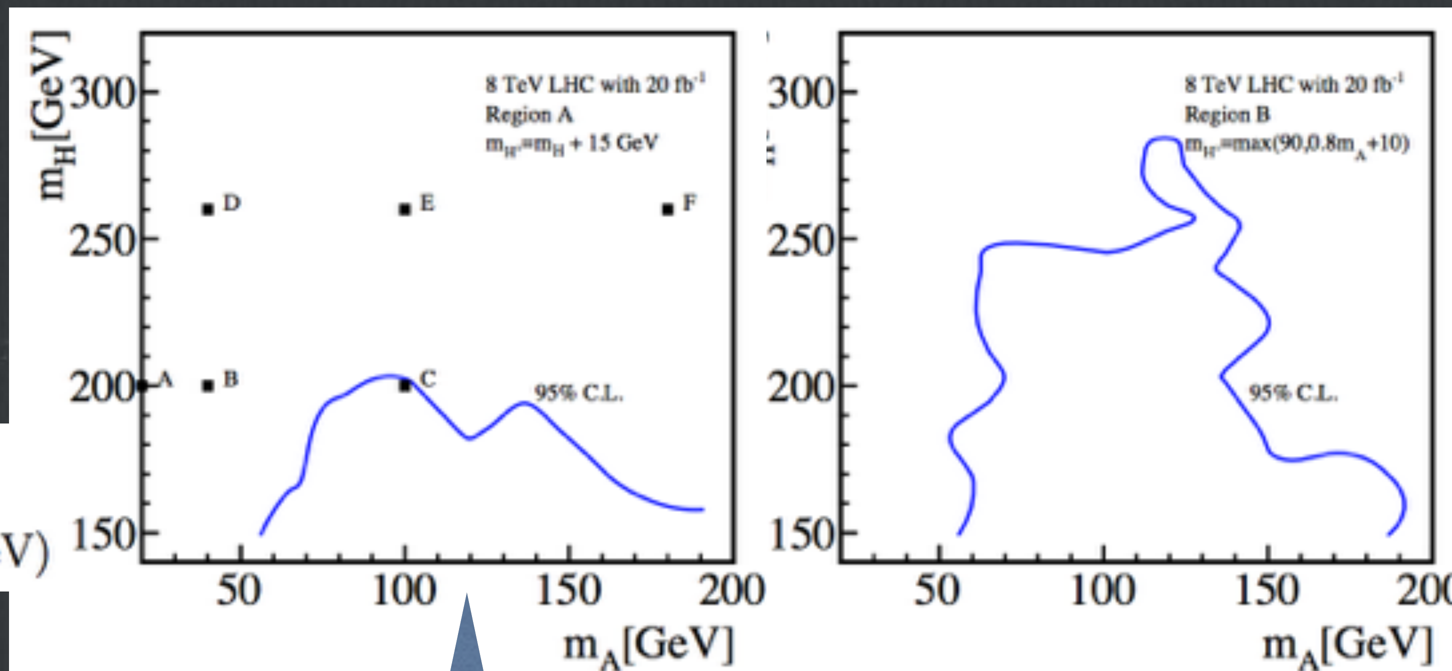
Recent sensitivity to the lepton-specific Higgs doublet for g_μ-2

We parameterize the two regions as

Region A: $m_{H^\pm} = m_H + 15$ GeV

Region B: $m_{H^\pm} = \max(90 \text{ GeV}, 0.8 m_A + 10 \text{ GeV})$

$\tan\beta = 1.25(m_A/\text{GeV}) + 25$



the strongest constraint comes from chargino-neutralino search in ATLAS

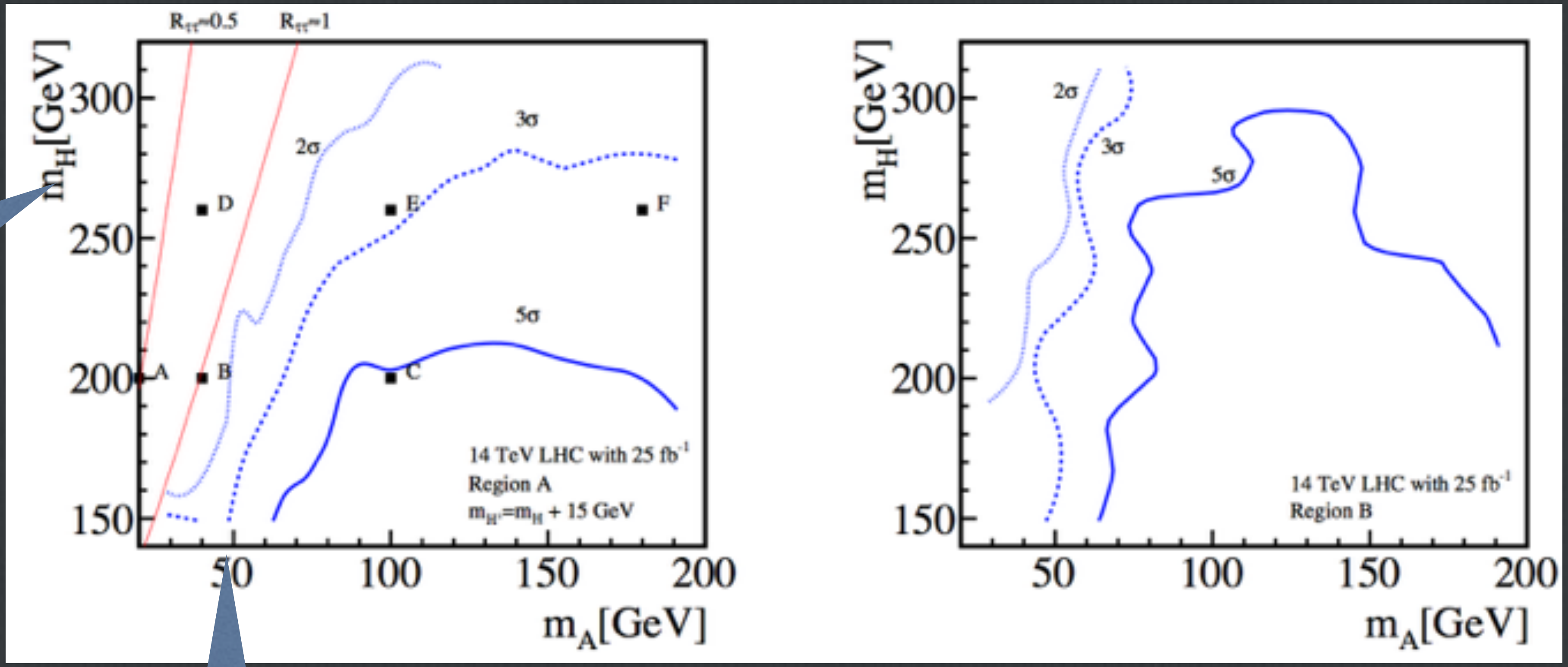
0: light A_X(?)

E. J. Chun, Z. Kang, M. Takeuchi and Y. L. S. Tsai, "LHC τ-rich Tests of Lepton-specific 2HDM for (g – 2)μ," arXiv:1507.08067

- **Searches for the light A via τ-rich signature**

Prospect in the near future, 14 TeV LHC with 25/fb

SM backgrounds including tt*, *V*+jets and *VV*; cuts, asides from at least 3τ, include MET>100 GeV (kill *V*+jets) & *b*-veto for p_{bT}>50 GeV (kill tt*)



τ-tagging efficiency is taken to be 59%

there is still a corner for a lighter *A*, for two reasons: 1) smaller acceptance for the softer τ; 2) *A* from decay is boosted and thus the ττ pair become collimated and thus hard to tag

2: light $H^{\pm\pm}$

E. J. Chun, Z. Kang, M. Takeuchi and Y. L. S. Tsai, "LHC τ-rich Tests of Lepton-specific 2HDM for (g – 2)μ," arXiv:1507.08067

- **$H^{\pm\pm}$ from Higgs triplet with hypercharge ±1, Δ**

$$\Delta = \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \delta^0 & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix}$$

E.g., in the type-II seesaw mechanism with $<\delta^0>=v_\Delta$,

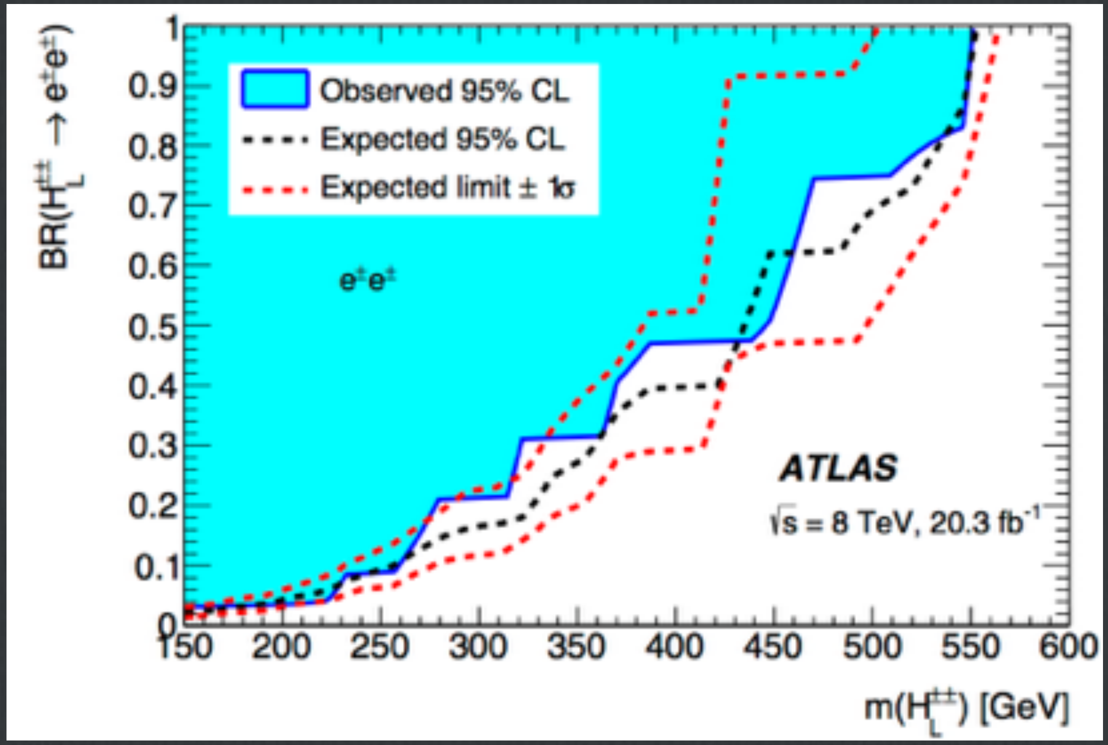
$$y_{ij}\left[\nu_i^T C P_L \nu_j \delta^0 - \frac{1}{\sqrt{2}}(\nu_i^T C P_L \ell_j - \ell_i^T C P_L \nu_i)\delta^+ - \overline{\ell_i^C} P_L \ell_j \delta^{++}\right] + h.c. \quad \Rightarrow \quad (m_\nu)_{ij} = \sqrt{2} y_{ij} v_\Delta$$

In the supersymmetirc version, light $H^{\pm\pm}$ below 100GeV is predicted to enhance the Higgs to diphoton rate～10%

E. J. Chun and P. Sharma, Phys. Lett. B 722 (2013) 86 [arXiv:1301.1437];
Z. Kang, Y. Liu and G. -Z. Ning, JHEP 1309, 091 (2013) [arXiv:1301.2204]

If $H^{\pm\pm}$ dominantly decays into the same sign dilepton (SSDL), the current LHC searches already yield strong upper bound on such $H^{\pm\pm}$, for example the latest exclusion on the $e_L e_L$ mode, ~550 GeV!

G.~Aad {\it et al.} [ATLAS Collaboration], JHEP 1503, 041 (2015)



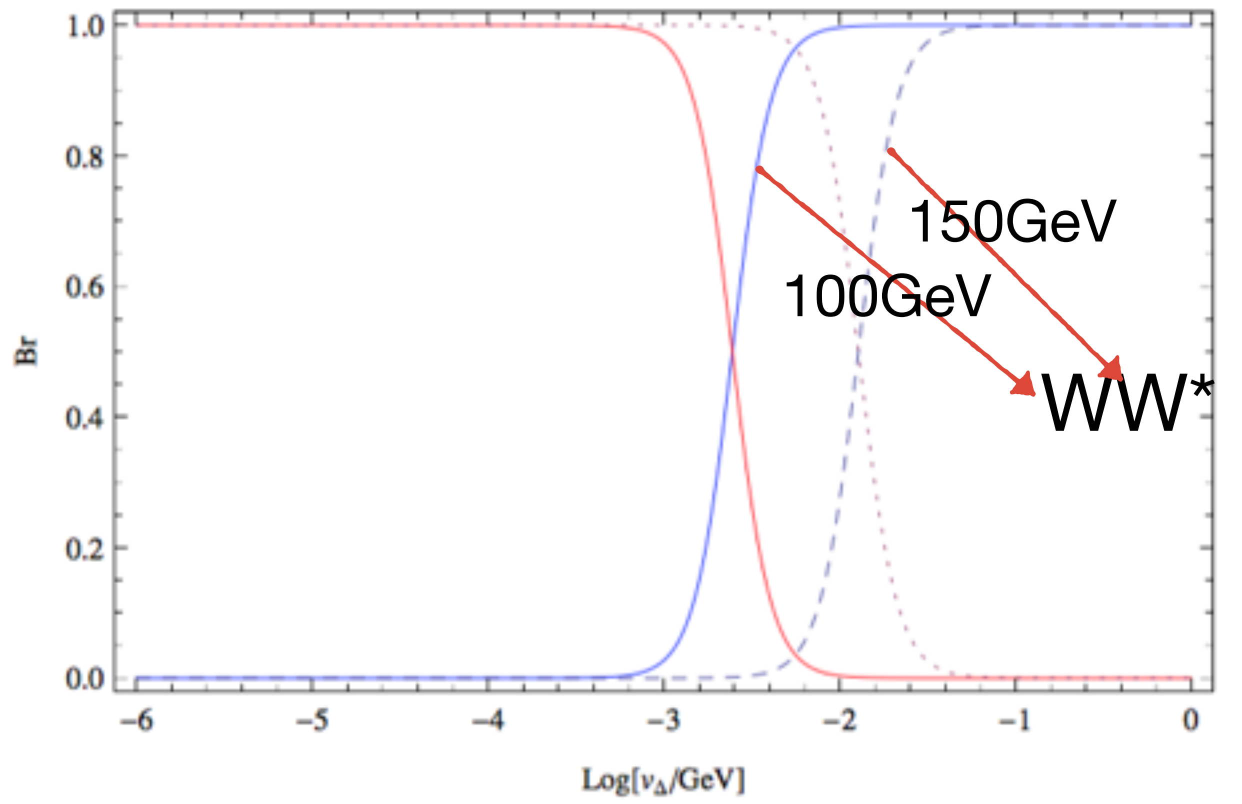
2: light $H^{\pm\pm}$

Z. Kang, J. Li, T. Li, Y. Liu and G. Z. Ning, "Light Doubly Charged Higgs Boson via the Di-W Channel at LHC," arXiv:1404.5207

- **Hiding a light $H^{\pm\pm}$ in the WW^* channel**

However, the SSDL mode has no theoretical priority over the di-W mode $H^{\pm\pm}\rightarrow W^{\pm}W^{\pm}$, which becomes dominant for a larger v_Δ, says around 1GeV (in type-II seesaw)

P. Fileviez Perez, T. Han, G. -y. Huang, T. Li and K. Wang, Phys. Rev. D 78, 015018 (2008); A. Melfo, M. Nemevsek, F. Nesti, G. Senjanovic and Y. Zhang, Phys. Rev. D 85, 055018 (2012) C. -W. Chiang, T. Nomura and K. Tsumura, Phys. Rev. D 85, 095023 (2012); C. Englert, E. Re and M. Spannowsky, Phys. Rev. D 88, 035024 (2013)....



In particular, if $H^{\pm\pm}$ is lighter than $2m_W$, all of the current searches fail to hunt for such a state!

one of the main reasons is, the leptons are soft, easily missed at LHC

2: light $H^{\pm\pm}$

Z. Kang, J. Li, T. Li, Y. Liu and G. Z. Ning, "Light Doubly Charged Higgs Boson via the Di-W Channel at LHC," arXiv:1404.5207

- **Digging out $H^{\pm\pm} \in (m_W, 2m_W)$ at 14 TeV LHC**

We use the signature pp→$H^{\pm\pm}H^{\pm\pm}$→SSDL+jets

The dominant BG for SSDL is non-prompt lepton BG like tt*, mainly out of events with leptons from heavy flavor quark decay

this important BG is omitted before

Cuts: SSDL with $p_{T,1/2}$> 10 GeV, |η| < 2.5➡️at least one jet with p_T>20GeV, |η|<4.5 and b-veto➡️ E_{miss}>20GeV, H_T>100GeV➡️ m_{ll}< 75GeV……

The good prospect with 10/fb

	100	110	120	130	140	150
Ratio required to be excluded	4.5	4.0	4.2	4.3	4.5	4.3
Events Number	2608	1864	1365	1024	786	612
2SSL	126.3	123.3	102.9	84.5	70.2	57.8
$N_j > 0$, N_b=0	114.0	112.9	94.7	78.1	64.6	53.1
$E_T^{miss} > 20$	104.1	103.7	87.5	72.4	60.8	50.4
$H_T > 100$ GeV	95.5	95.0	82.5	69.5	59.2	49.4
m_{ll} <75 GeV	95.5	95.0	81.5	65.8	53.2	41.6
$\Delta R(l,l) < 1.5$	76.4	72.2	59.5	46.5	37.7	30.0
$\Delta\phi(ll, p_T^{miss}) < 1.5$	61.3	56.8	46.5	36.6	29.7	23.4
$N_j > 2$, $m_{jjj} < 150$	11.2	16.3	14.4	13.6	11.3	8.8
σ	3.89	5.64	4.98	4.70	3.91	3.04

Conclusions

- Light extra Higgs bosons are, not everywhere but indeed somewhere
- they are not on the focus of LHC searches
- but they are quite important
- singly charged Higgs? Open…
- Thank you!