Higgs and Z exotic decays

Zhen Liu (刘真)
University of Minnesota

08/15/2023

CEPC味物理-新物理和相关探测技术研讨会

Outline

- General Motivation
- A Global View
- Case Studies
  - Electroweak Phase Transition
  - Many other cases

Outline

- General Motivation
- A Global View
- Case Studies
  - Electroweak Phase Transition
  - Many other cases

Why Exotic Decays?

- There is a whole zoo of light BSM particle to be explored at colliders.

(checking all the possibility; theoretical interests.)

(Higgs Portal: $(H^{+}H)$, HNL, ALPs, Dark Matter ...)

- The precision does not pin-point a scale, the exotic decays are to fully probe the scale below Higgs mass. **

(complementarity)

Why Exotic Decays? (continued)

- Higgs has tiny width ~4 MeV

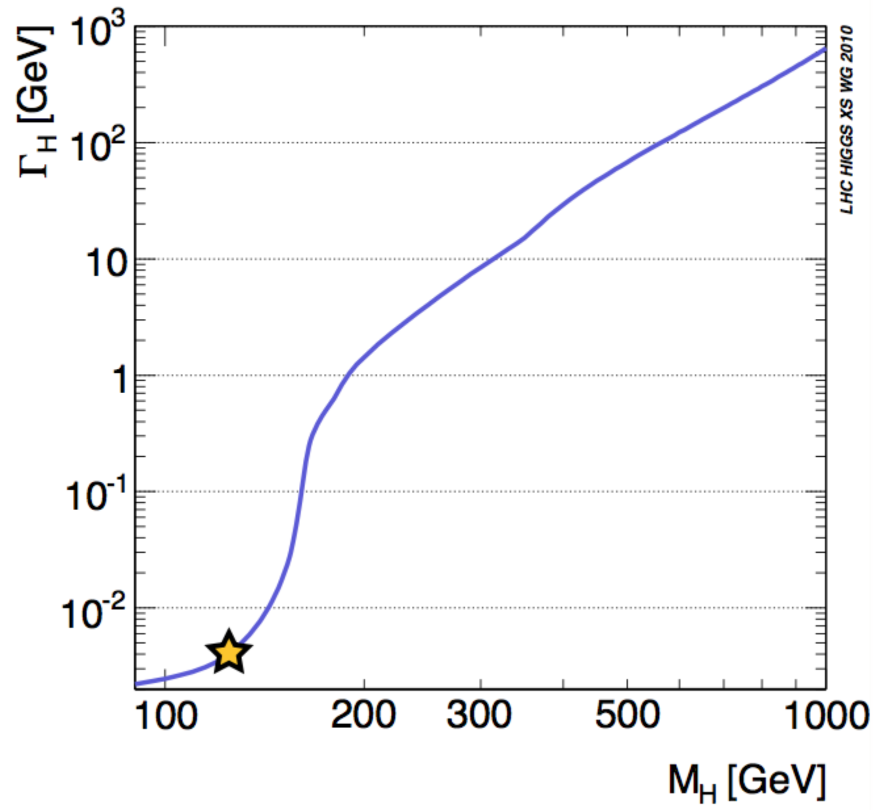
$$\frac{\Gamma}{M} = O(10^{-5})$$

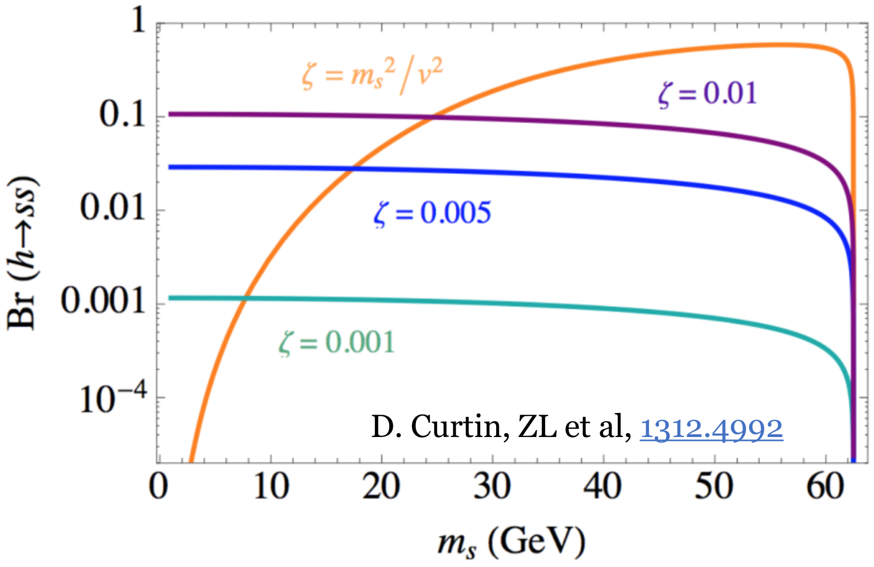
all its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc. Dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$

- small couplings to BSM could have sizable branching, e.g.,

$$L = \frac{\zeta}{2} s^2 |H|^2$$

(common building block in extended Higgs sectors) can give BR(h→ss)~O(10%) for ζ *as small as* 0.01 !



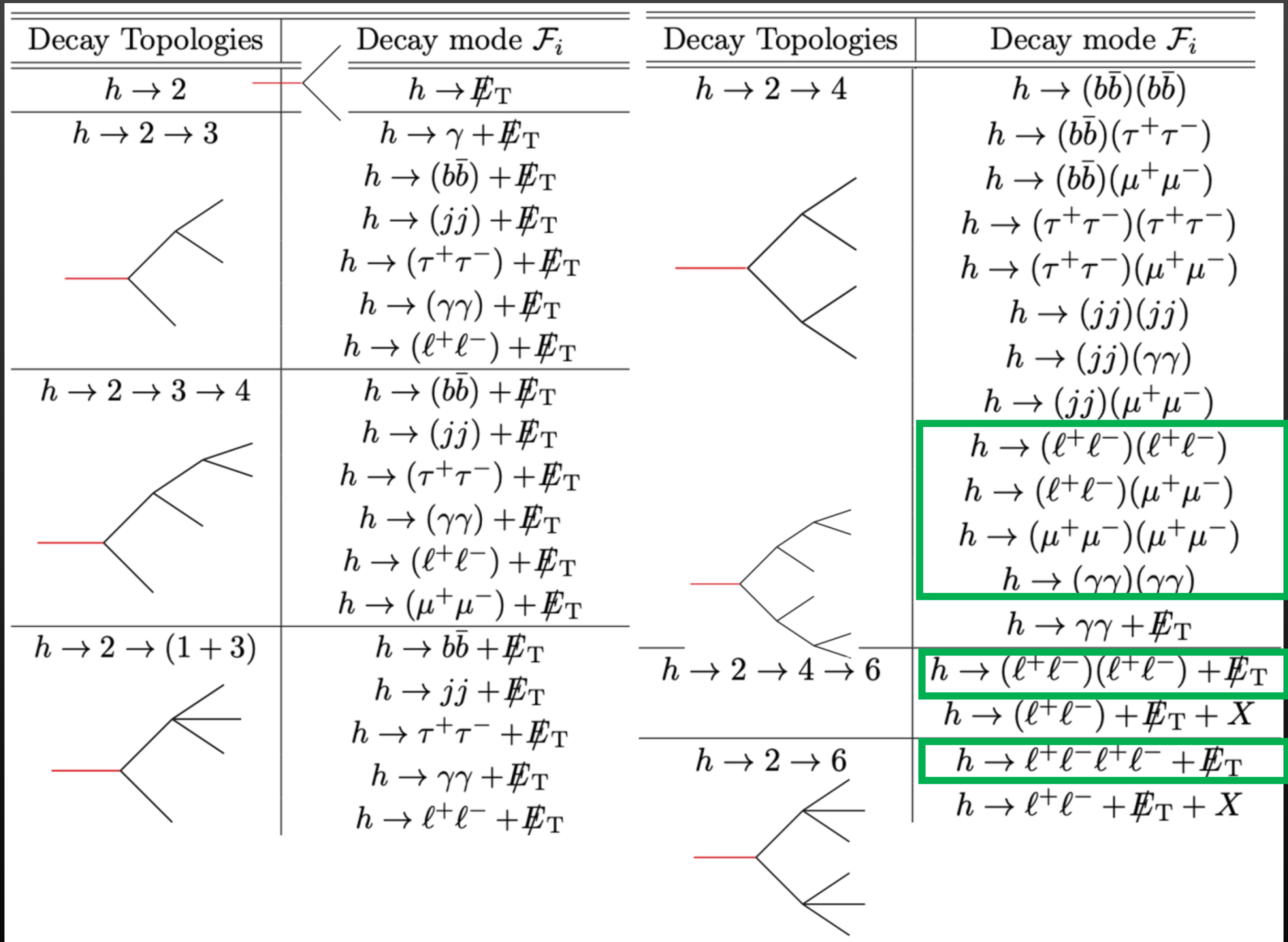


D. Curtin, ZL et al, 1312.4992

Outline

- General Motivation
- A Global View
- Case Studies
  - Electroweak Phase Transition
  - Many other cases

A global view



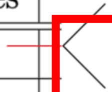
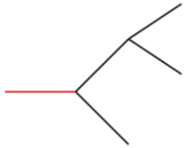
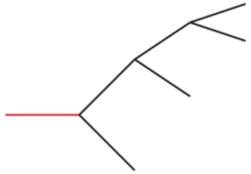
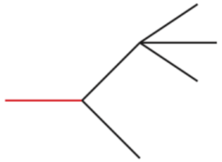
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

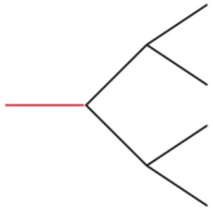
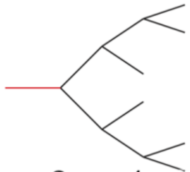
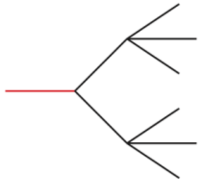
LHC's strength

HL-LHC has large number of Higgs produced (0.2 Billion), having great sensitivity to exotic decays into leptons and photons

Curtin, Essig, Gori, Jaiswal, Katz, Liu, ZL, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong 1312.4992, H. Zhang, ZL, LT Wang, 1612.09284, and corresponding updates for various future colliders

A global view

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$ $h \to \gamma\gamma + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T + X$

LHC's strength

Hard at LHC due to missing energy

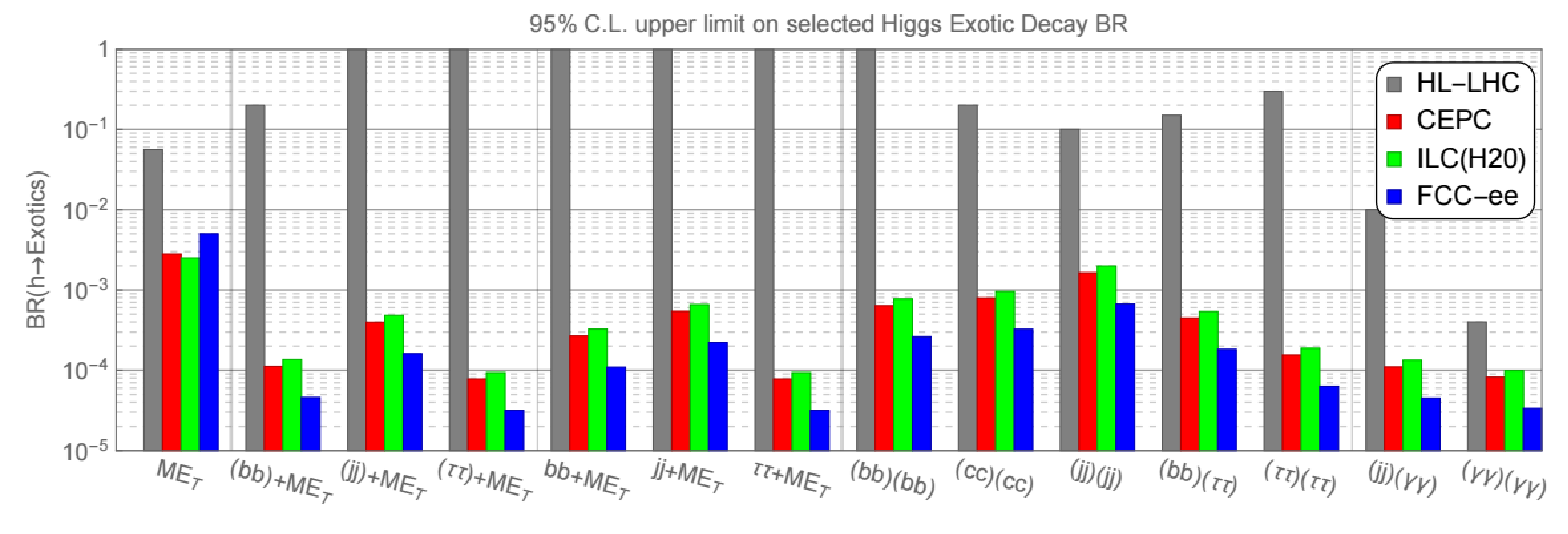
Hard at LHC due to hadronic background

(HL-)LHC will provide valuable first-hand information on these challenging channels

Future colliders cover deeper

Decay Mode	95% C.L. limit on BR LHC	HL-LHC
$\not{E}_T$	0.23	0.056
$(b\bar{b})+\not{E}_T$	[0.2]	–
$(jj)+\not{E}_T$	–	–
$(\tau^+\tau^-)+\not{E}_T$	[1]	–
$b\bar{b}+\not{E}_T$	[0.2]	–
$jj+\not{E}_T$	–	–
$\tau^+\tau^-+\not{E}_T$	–	–
$(b\bar{b})(b\bar{b})$	1.7 (0.2)	–
$(c\bar{c})(c\bar{c})$	(0.2)	–
$(jj)(jj)$	[0.1]	–
$(b\bar{b})(\tau^+\tau^-)$	0.1 [0.15]	–
$(\tau^+\tau^-)(\tau^+\tau^-)$	1.2 [0.2∼0.4]	–
$(jj)(\gamma\gamma)$	[0.01]	–
$(\gamma\gamma)(\gamma\gamma)$	7×10^{-3}	4×10^{-4}

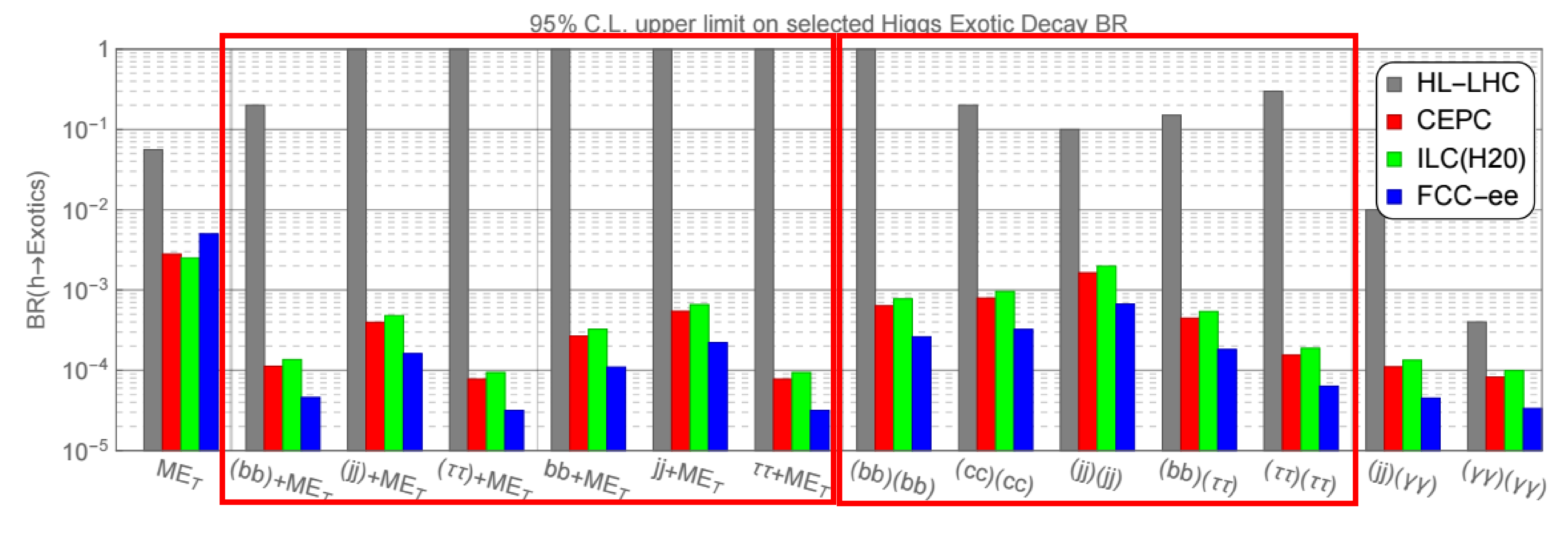
Future collider coverage



The HL-LHC are from various studies and projections available in the literature, but there are many more channels to include to fully represent the power of HL-LHC.
The lepton collider sensitivities (except for the first channel, $h \to inv$) are from our study with different $ee \to ZH$ integrated luminosities and beam polarizations for different colliders.

H. Zhang, ZL, L. Wang, 1612.09284 and corresponding updates for various future colliders

Future collider coverage

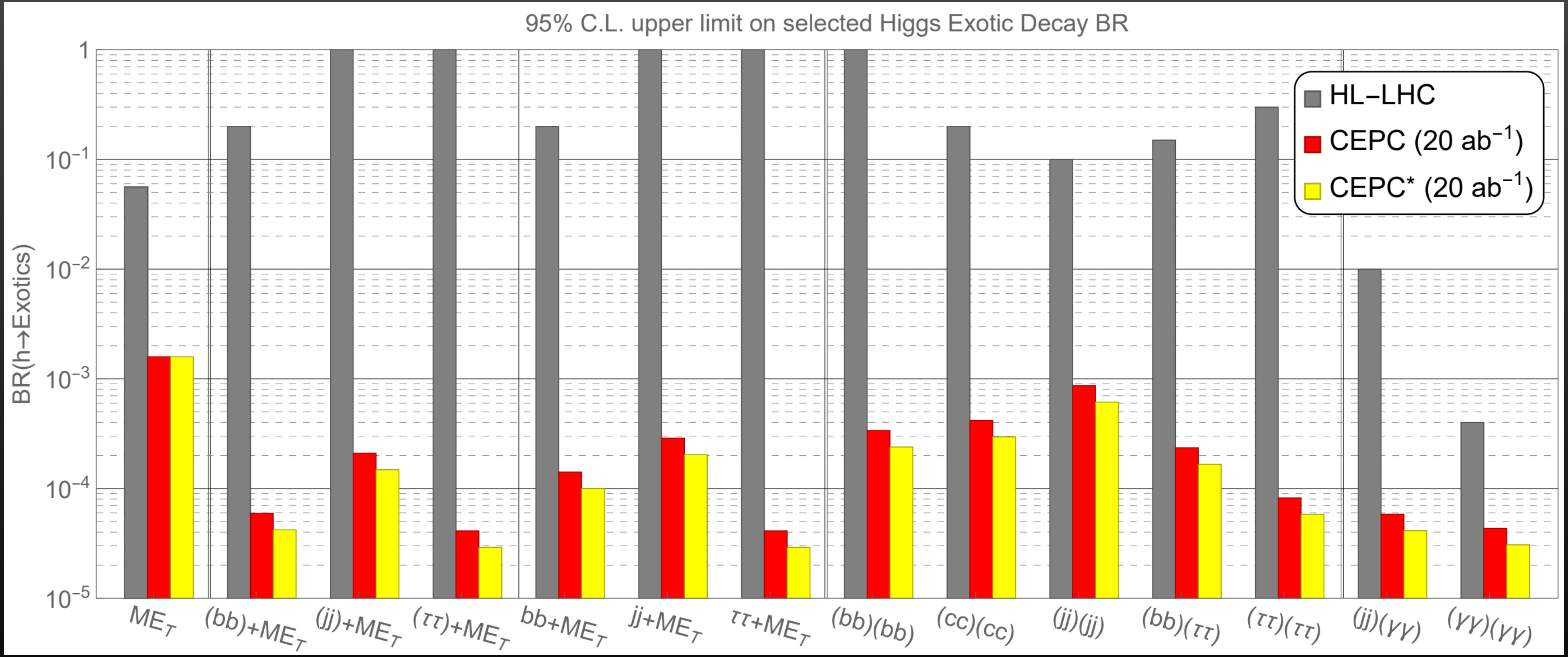


with missing Energy (SUSY motivated, DM motivated channels, e.g., recent review by Barman, Belanger, Godbole, 2010.11674), 3-4 orders of magnitude improvement for the constraints on such exotic branching fractions

$h \to 4f$ generic Higgs sector extensions, also Higgs portals , 2-3 orders of magnitude improvement for the constraints on such exotic branching fractions

CEPC & LHC updates

Based upon: H. Zhang, ZL, L. Wang, 1612.09284
Updated for: CEPC Higgs Whitepaper (1810.09037), CEPC CDR (1811.10545), CEPC Snowmass Whitepaper (2205.08553)



CEPC updated to 20 ab^{-1}
LHC limits and projections updated

Here we only selected these class of channels where CEPC is advantageous, and we haven't used all the available channels yet.

Z Exotic Decays: General Considerations

Is Z-factory powerful for BSM physics?

How does it compare to the Higgs run?

Recall that we will have 4×10^6 Higgs, and $10^{12\sim13}$ Z.

But Z width is 10^3 larger than the Higgs, which means lower BR.

Still, if a state couples to Z and Higgs in a comparable way (here vaguely defined; generally it is not necessarily true for BSM), Z can be competitive; one has to do it case by case.

Z exotic decay is also a very rich program

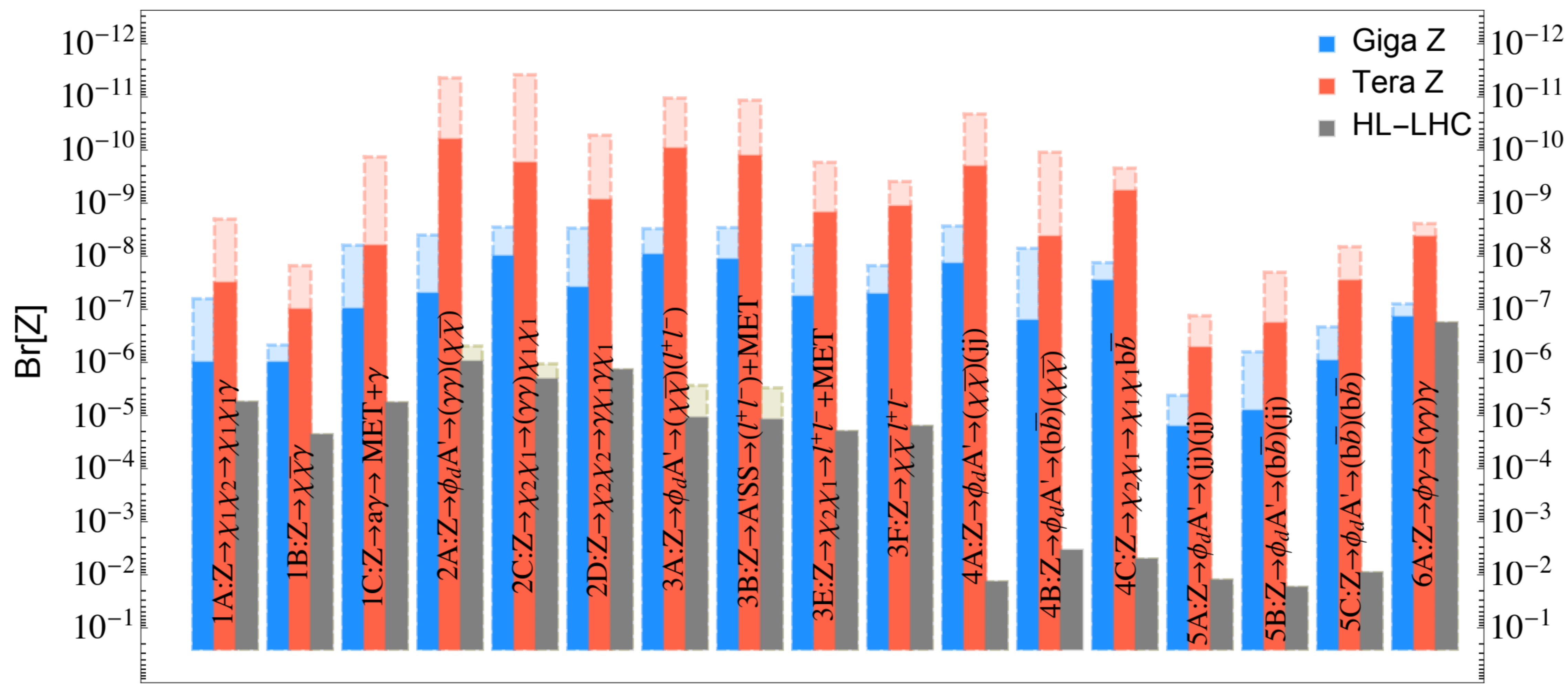
exotic decays	topologies	n_{res}	models
$Z \to \not{E} + \gamma$	$Z \to \chi_1\chi_2, \chi_2 \to \chi_1\gamma$	0	1A: $\frac{1}{\Lambda_{1A}}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$ (MIDM)
	$Z \to \chi\bar{\chi}\gamma$	0	1B: $\frac{1}{\Lambda_{1B}^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu}$ (RayDM)
	$Z \to a\gamma \to (\not{E})\gamma$	1	1C: $\frac{1}{4\Lambda_{1C}}aB_{\mu\nu}\tilde{B}^{\mu\nu}$ (long-lived ALP)
	$Z \to A'\gamma \to (\bar{\chi}\chi)\gamma$	1	1D: $\epsilon^{\mu\nu\rho\sigma}A'_{\mu}B_{\nu}\partial_{\rho}B_{\sigma}$ (WZ terms)
$Z \to \not{E} + \gamma\gamma$	$Z \to \phi_d A', \phi_d \to (\gamma\gamma), A' \to (\bar{\chi}\chi)$	2	2A: Vector portal
	$Z \to \phi_H\phi_A, \phi_H \to (\gamma\gamma), \phi_A \to (\bar{\chi}\chi)$	2	2B: 2HDM extension
	$Z \to \chi_2\chi_1, \chi_2 \to \chi_1\phi, \phi \to (\gamma\gamma)$	1	2C: Inelastic DM
	$Z \to \chi_2\chi_2, \chi_2 \to \gamma\chi_1$	0	2D: MIDM

J. Liu, LT. Wang, XP. Wang, W. Xue, 1712.07237

$Z \to \not{E} + \ell^+\ell^-$	$Z \to \phi_d A', A' \to (\ell^+\ell^-), \phi_d \to (\bar{\chi}\chi)$	2	3A: Vector portal
	$Z \to A'SS \to (\ell\ell)SS$	1	3B: Vector portal
	$Z \to \phi(Z^*/\gamma^*) \to \phi\ell^+\ell^-$	1	3C: Long-lived ALP, Higgs portal
	$Z \to \chi_2\chi_1 \to \chi_1 A'\chi_1 \to (\ell^+\ell^-)\not{E}$	1	3D: Vector portal and Inelastic DM
	$Z \to \chi_2\chi_1, \chi_2 \to \chi_1\ell^+\ell^-$	0	3E: MIDM, SUSY
	$Z \to \bar{\chi}\chi\ell^+\ell^-$	0	3F: RayDM, slepton, heavy lepton mixing
$Z \to \not{E} + JJ$	$Z \to \phi_d A' \to (\bar{\chi}\chi)(jj)$	2	4A: Vector portal
	$Z \to \phi_d A' \to (bb)(\bar{\chi}\chi)$	2	4B: Vector portal + Higgs portal
	$Z \to \chi_2\chi_1 \to bb\chi_1 + \chi_1 \to bb\not{E}$	0	4C: MIDM
$Z \to (JJ)(JJ)$	$Z \to \phi_d A', \phi_d \to jj, A' \to jj$	2	5A: Vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to jj$	2	5B: vector portal + Higgs portal
	$Z \to \phi_d A', \phi_d \to b\bar{b}, A' \to b\bar{b}$	2	5C: vector portal + Higgs portal
$Z \to \gamma\gamma\gamma$	$Z \to \phi\gamma \to (\gamma\gamma)\gamma$	1	6A: ALP, Higgs portal

Tera-Z's reach

Similar to Higgs, Z should have a huge list of all possible exotic decays. These are only the beginning.



J. Liu, LT. Wang, XP. Wang, W. Xue, 1712.07237

Outline

- General Motivation
- A Global View
- Case Studies
  - Electroweak Phase Transition
  - Many other cases

Higgs & EWPT

One of the most generic extensions to Enhance EWPT;
An important benchmark to understand;

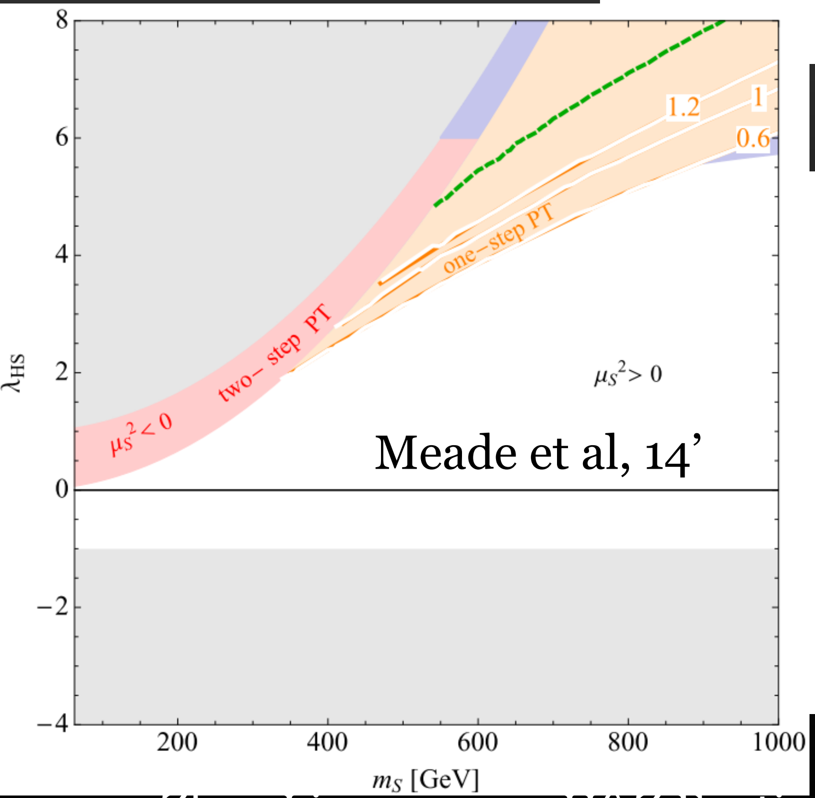
$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$
$$+(\text{explicit Z2} - \text{breaking terms})$$

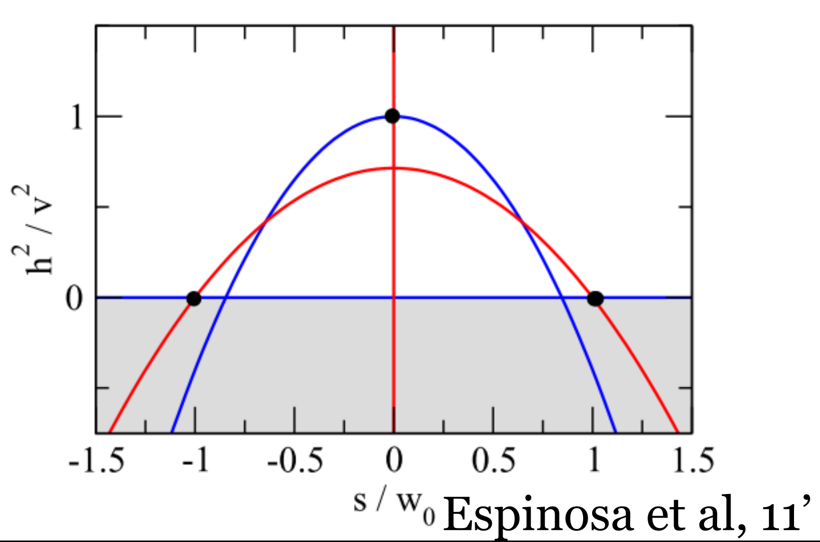
Enhancing EWPT through Singlet Extensions

One of the most generic extensions to Enhance EWPT;
An important benchmark to understand;

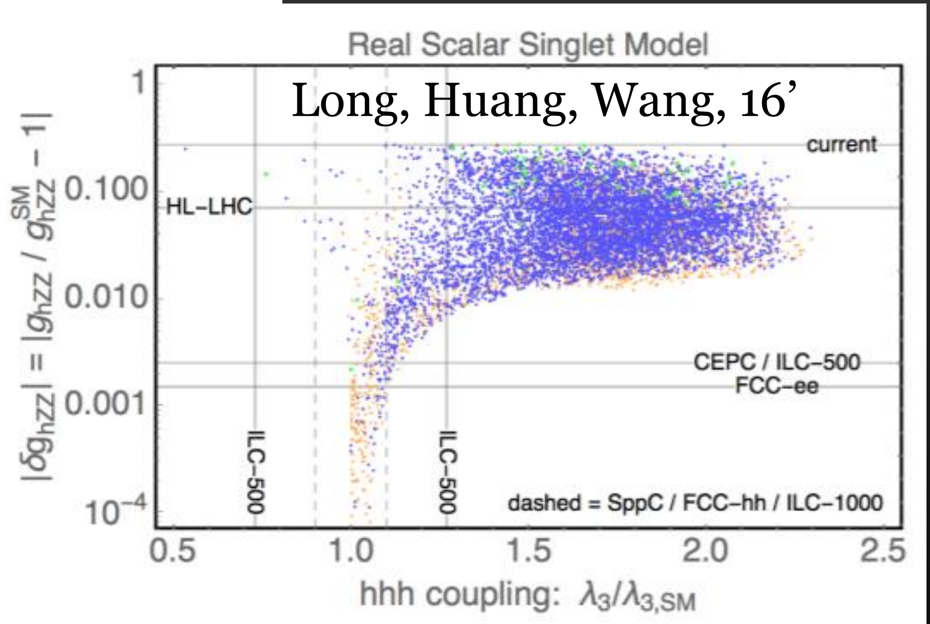
$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

$$+(\text{explicit Z2} - \text{breaking terms})$$

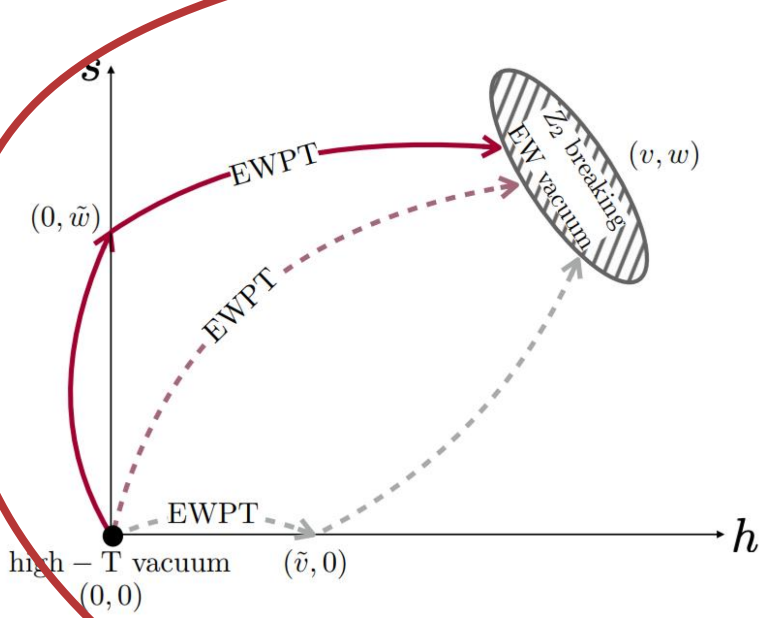


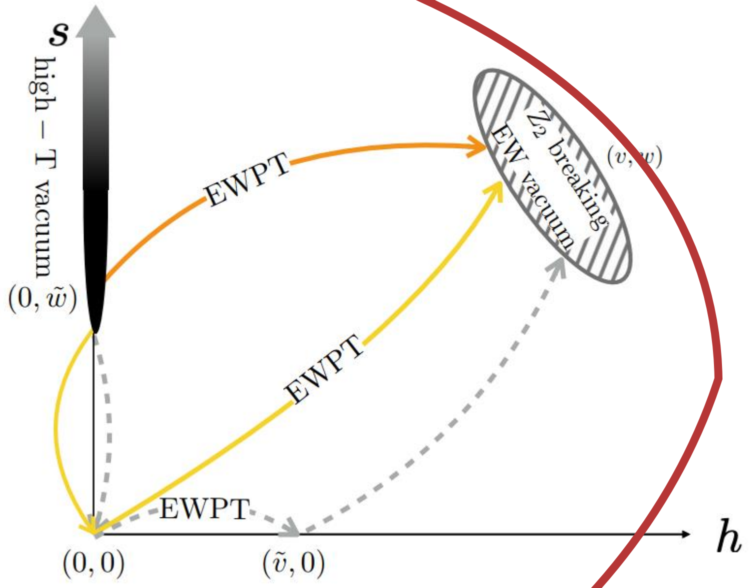


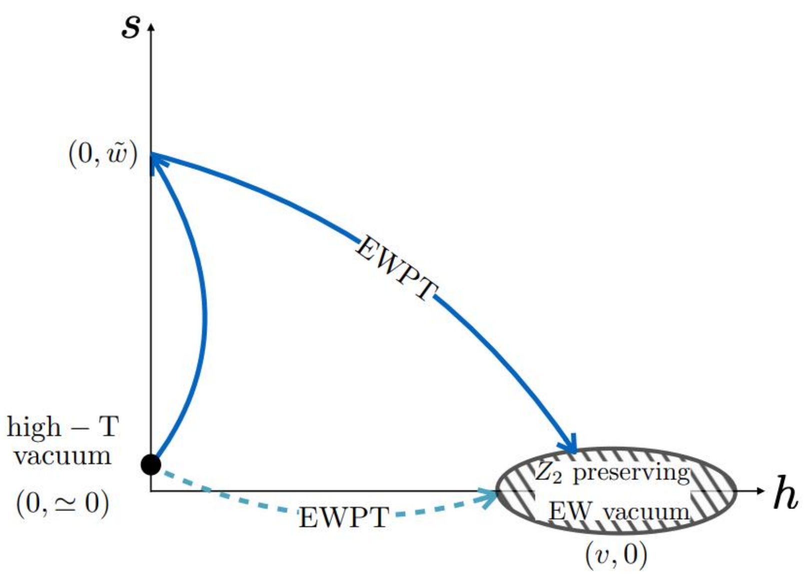
also Ramsey-Musolf et al 07'



Phase Diagrams







Spontaneous Z2 broken S+SM: missing case

However, no clear studies on the **Spontaneous Z2 breaking** case

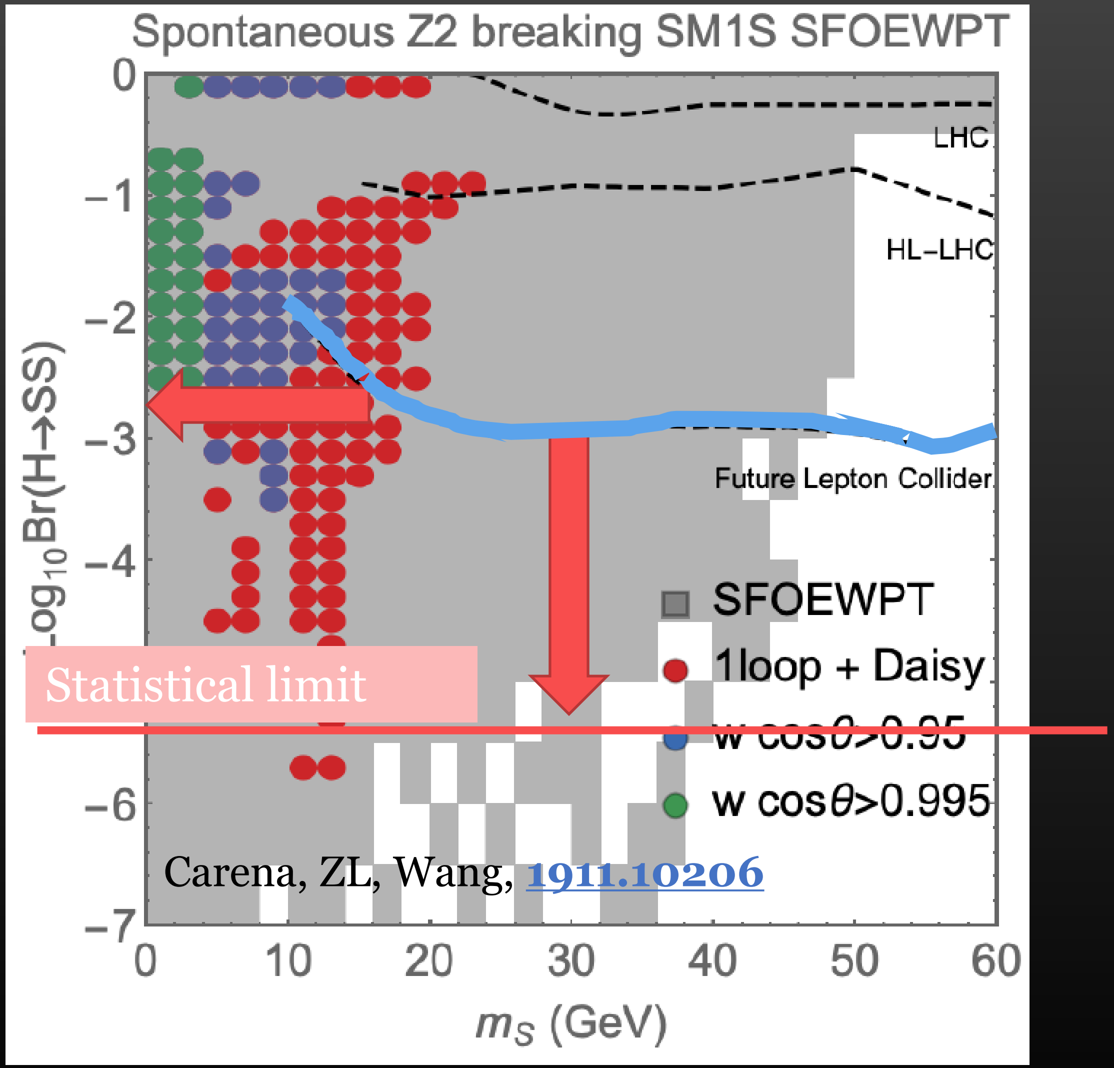
$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$
$$+(\text{explicit Z2} - \text{breaking terms})$$

Well-Motivated:

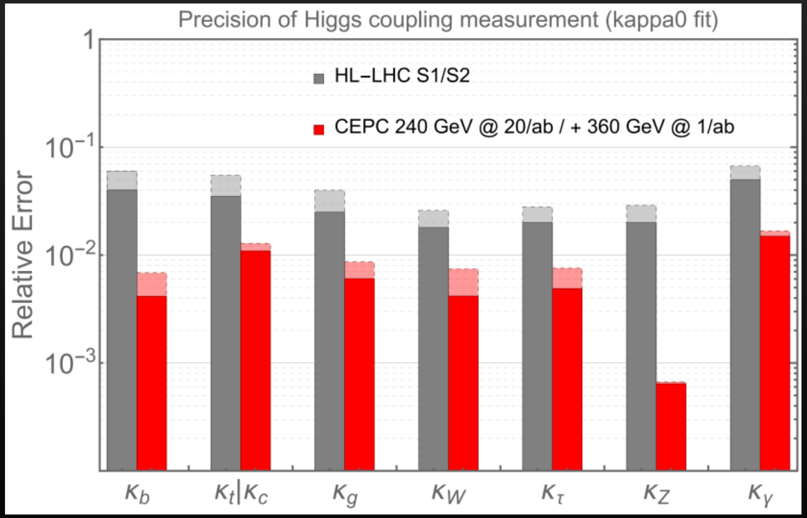
- As a generic case possible for singlet extensions, which also leads to a rich thermal history;
- As a proxy (simplified discussion; with appropriate rescaling of couplings to match the d.o.f.) to evaluate:
  - Dark sector gauge theories needs to be Higgsed;
  - Dark Higgs talks to our sector through the $(H^+H)(H_d^+H_d)$ mixing quartic;

But Challenging to achieve strongly first order EWPT, pointing us towards a light scalar mixes with the Higgs (see the phase transition analysis in M. Carena, ZL, Y.K. Wang, 1911.10206)

EWPT consideration drives H→ SS → $(jj)(jj)$



- A firm prediction of a light scalar in this model;
- Higgs exotic decay into a pair of light scalars is a crucial probe;
- Higgs exotic decays complements the Higgs precision program;
- Higgs exotic decays requires further studies of **merged jets** for lighter singlet masses;
- Also possible to have long-lived Higgs exotic decays in certain parameter space



See also Kozaczuk, Ramsey-Musolf, Shelton, 1911.10210

H→ SS → (jj)(jj)

- Preselection cuts: $|\cos\theta_{j,\ell}| < 0.98, E_{j,\ell} > 10\text{GeV},$

  Similar to some LEP analysis

  $$y_{ij} \equiv \frac{2\min\left(E_i^2, E_j^2\right)(1-\cos\theta_{ij})}{E_{vis}^2} > y_{\rm cut},$$

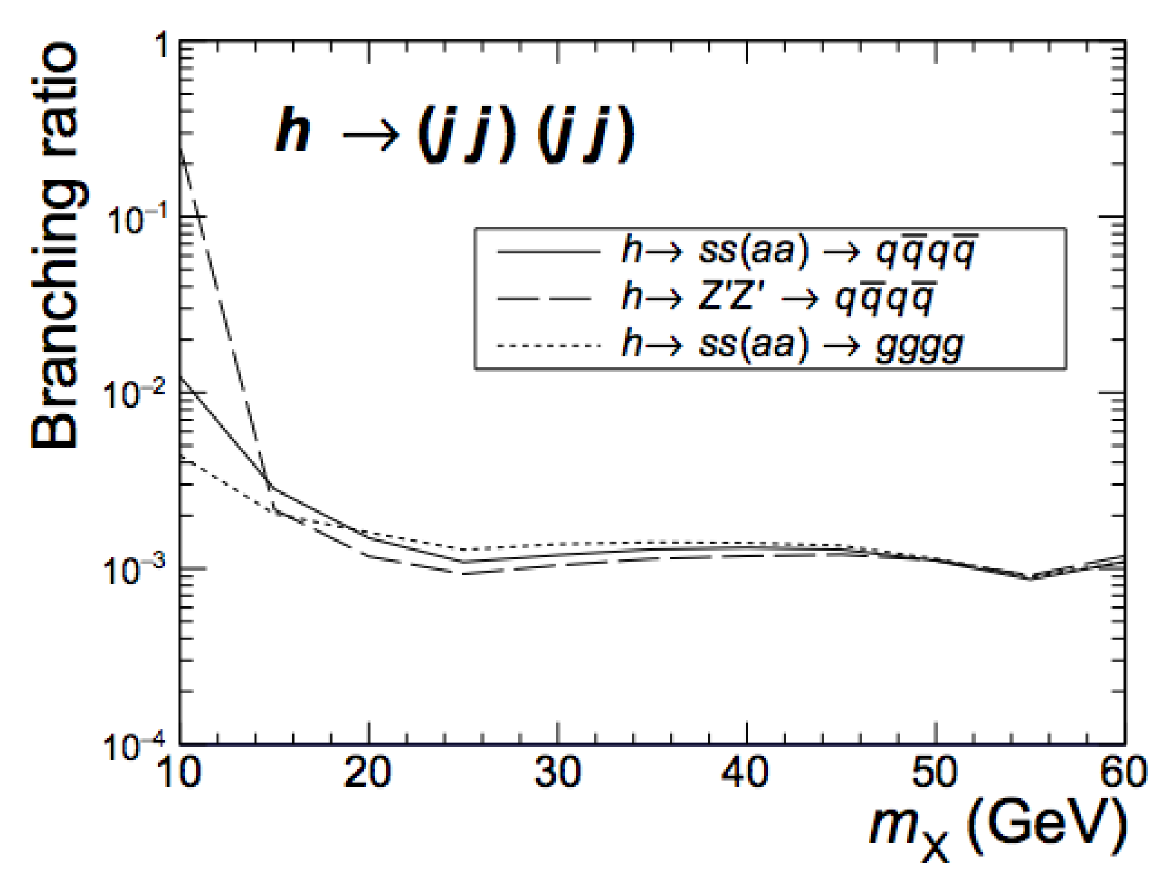
  a pair of OSSF leptons, $\theta_{\ell\ell} > 80°$

  $|m_{\ell\ell} - m_Z| < 10\text{GeV}, |m_{\rm recoil} - m_h| < 5\text{GeV}.$

- MadGraph5_aMC@NLO.

- The ISR effect of the background is roughly mimicked by generating events with 1 additional photon (with pT>1GeV to avoid the IR divergence).

- Additional cut to suppress the ISR effect: $E_{vis} > 225\text{GeV}.$

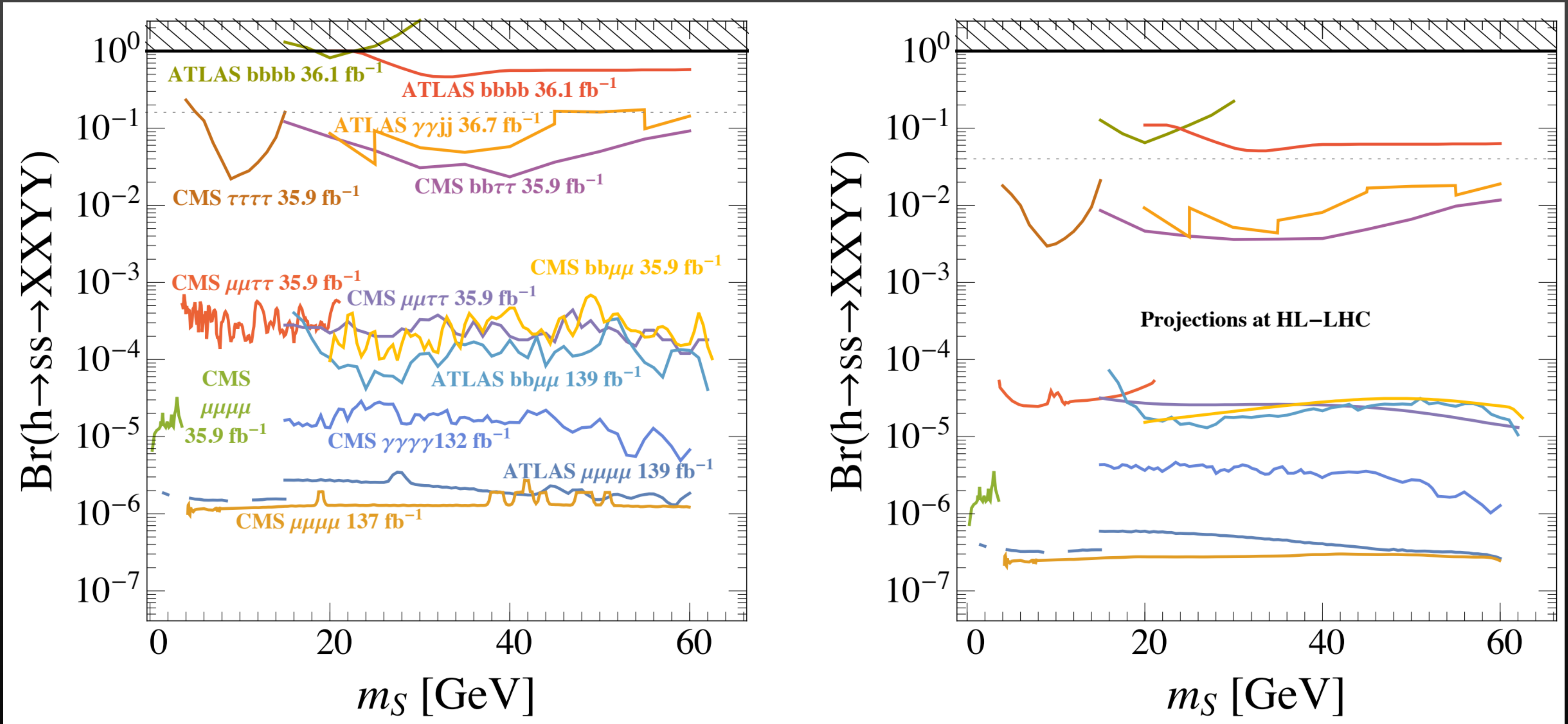


Great sensitivity on exotic BR $\mathcal{O}\left(10^{-3}\right)$

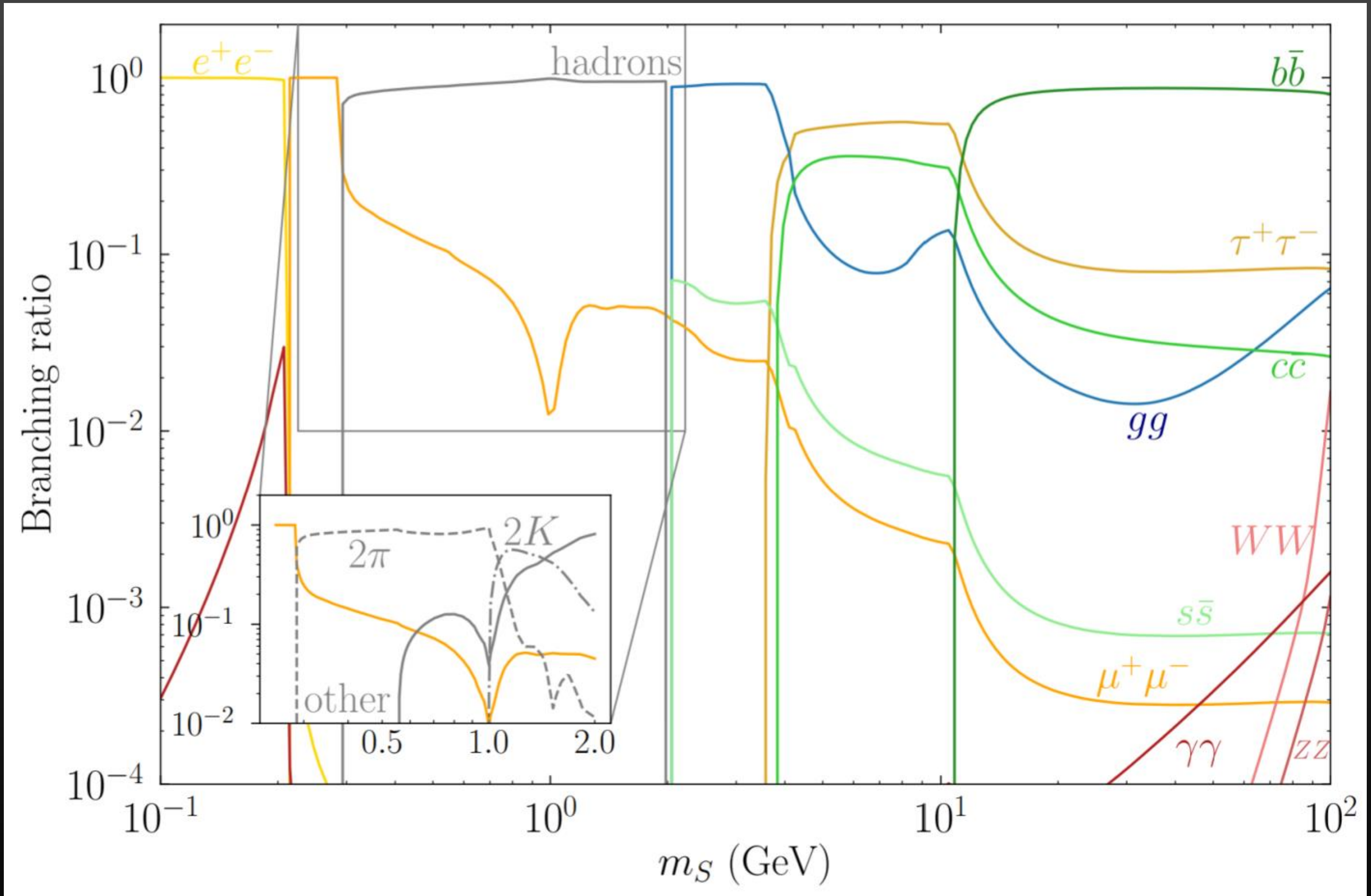
Similar (better) result archived for 4b, 4c, etc.
Room for improvement using different strategy treating collimated jets.
Room for improvement including hadronic decaying spectator Z bosons.

Nicely, SM Higgs decays are the major background.

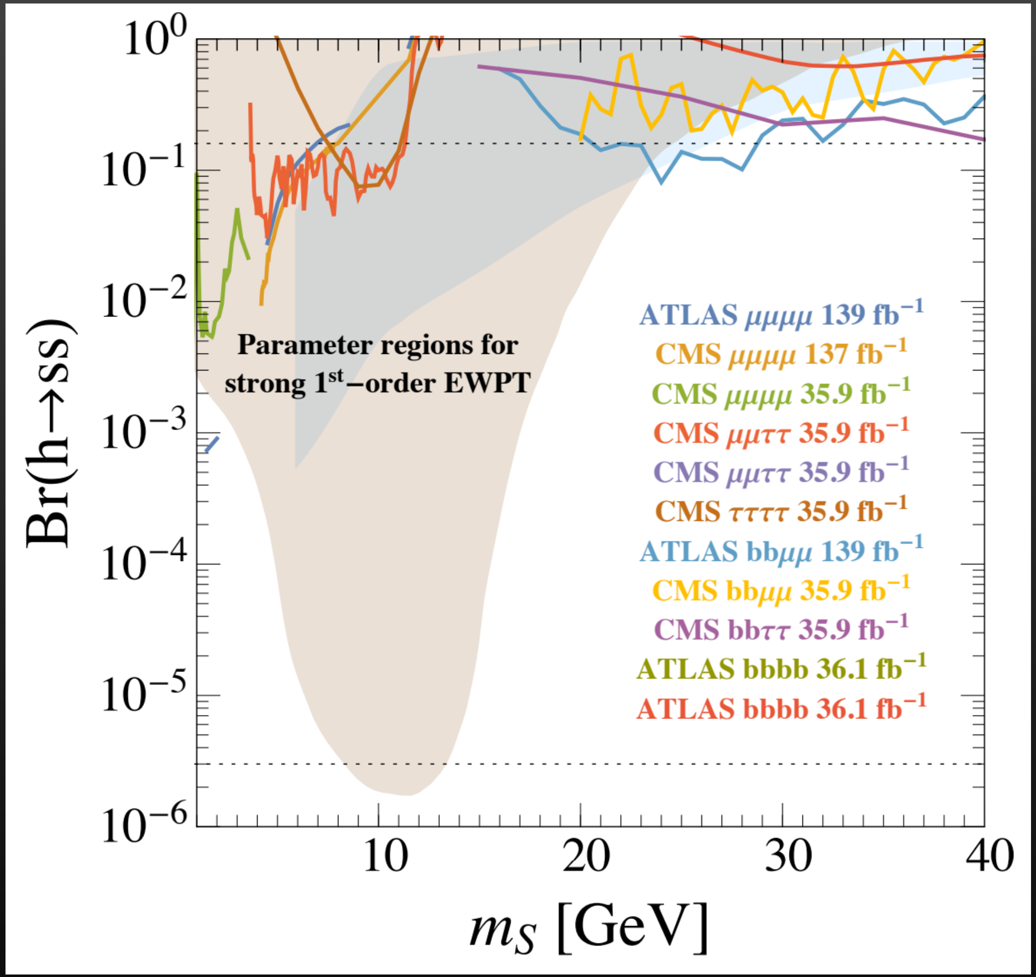
LHC and Updated Projections

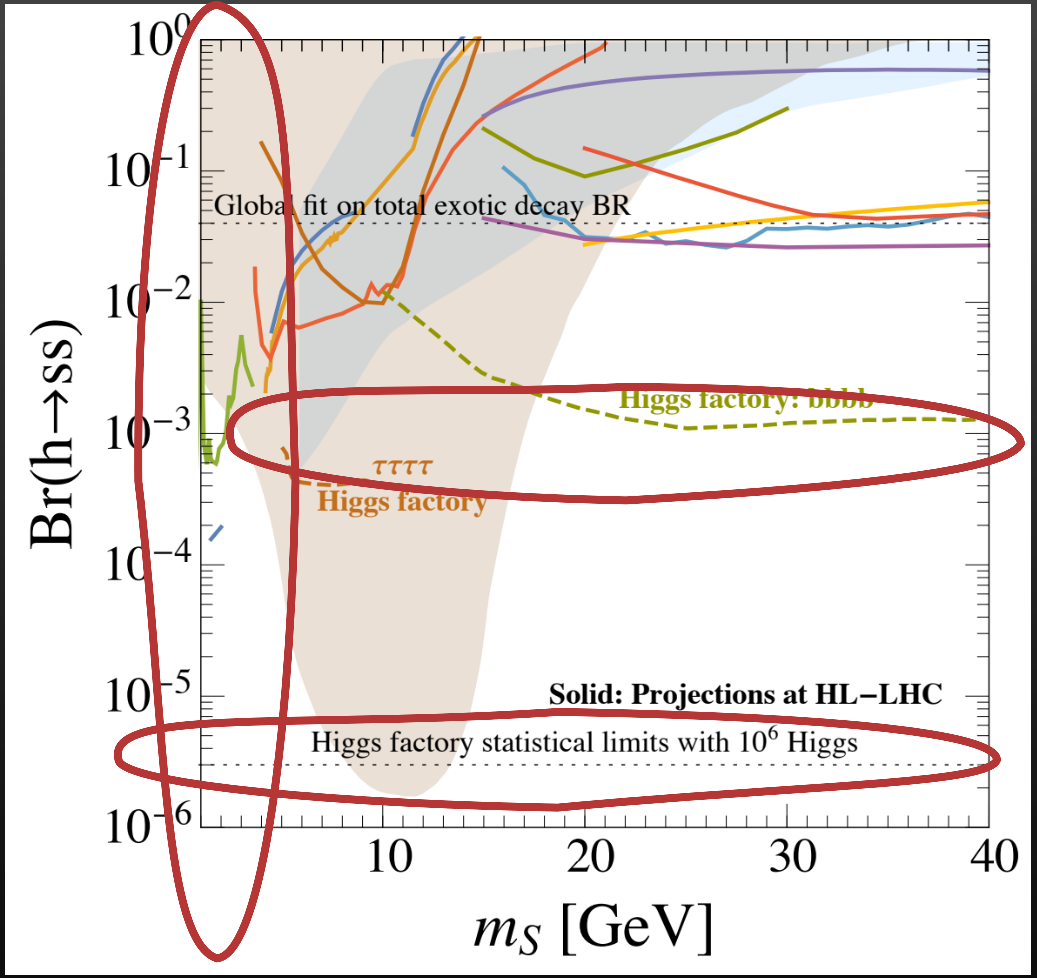


Light Higgs Branching Ratios



Translated Into Exotic BR to SS





Carena, Kozaczuk, ZL, Ou, Ramsey-Musolf, Shelton, Wang, Xie, 2203.08206

Outline

- General Motivation
- A Global View
- Case Studies
  - Electroweak Phase Transition
  - Many other cases

A quest for N scalars

Large N of scalar fields, coupling feebly to Higgs
Must take the whole ensemble of different # of final state particles to discover

Beyond first-order EWPT, we need sizable CPV, and an alternative approach is to make EWPT at high T (~TeV or even 100 TeV), typically, this requires large N (~O(100)) of scalar fields.

- High T electroweak phase transition
- Electroweak non-restoration

(explored by various groups, M. Carena, C. Krause, ZL, and Y. Wang, 2104.00638; A. Glioti, R. Rattazzi, and L. Vecchi, 1811.11740; P. Meade and H. Ramani, 1807.07578; I. Baldes and G. Servant 1807.08770...)

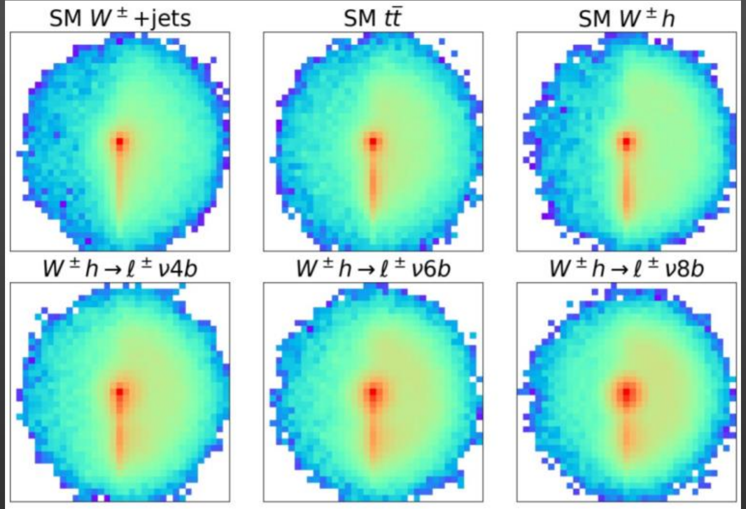
Recent reconsiderations of naturalness, also introduce large N scalar fields,

- N-Naturalness (Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner, 1607.06821)
- Naturalness with a trigger (Arkani-Hamed, D'Agnolo, Kim, 2012.04652)

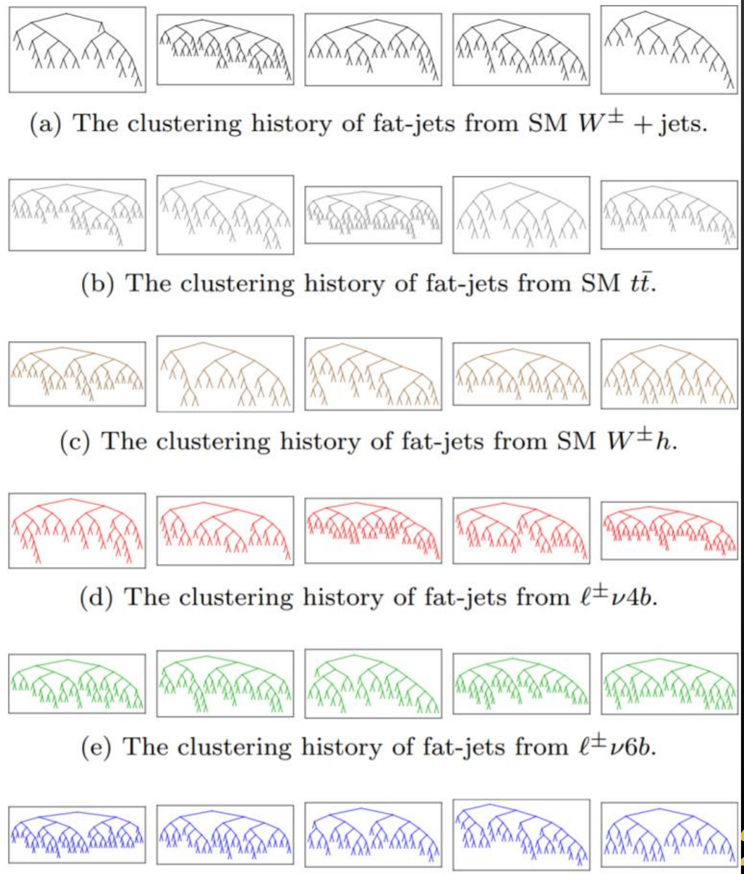
Similar pheno will arise, e.g., composite neutrinos (Chacko, Fox, Harnik, ZL, 2012.01443), dark showers (Shelton, Knapen, Xu, 2103.01238), etc.

A quest for N scalars

Cross section [Unit: fb]	Higgs exotic decay			SM		
	$\ell^\pm\nu 4b$	$\ell^\pm\nu 6b$	$\ell^\pm\nu 8b$	$W^\pm$ + jets	$t\bar{t}$	$W^\pm h$
Boosted $\ell^\pm$	8.21	7.66	7.04	2.53×10^5	6.21×10^3	5.48
fat-jet	7.01	6.56	6.03	2.01×10^5	4.95×10^3	4.66
b-veto	6.17	5.80	5.35	1.96×10^5	2.17×10^3	4.07
Mass window	3.34	3.19	2.99	5.66×10^3	400	2.08
Efficiency	1.37%	1.36%	1.34%	0.96%	0.25%	1.31%



Studying the possibilities to look for Higgs exotic decays into un-fixed number of scalars to bb
Comparatively used CNN, RecNN, and PFN…



(a) The clustering history of fat-jets from SM $W^\pm$ + jets.

(b) The clustering history of fat-jets from SM $t\bar{t}$.

(c) The clustering history of fat-jets from SM $W^\pm h$.

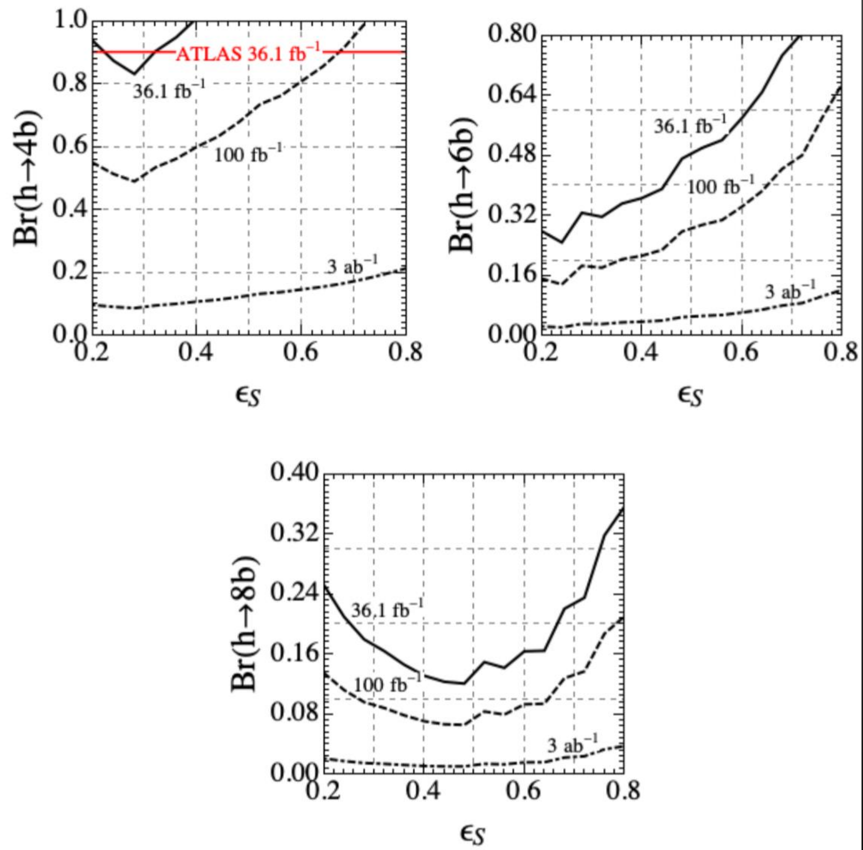
(d) The clustering history of fat-jets from $\ell^\pm\nu 4b$.

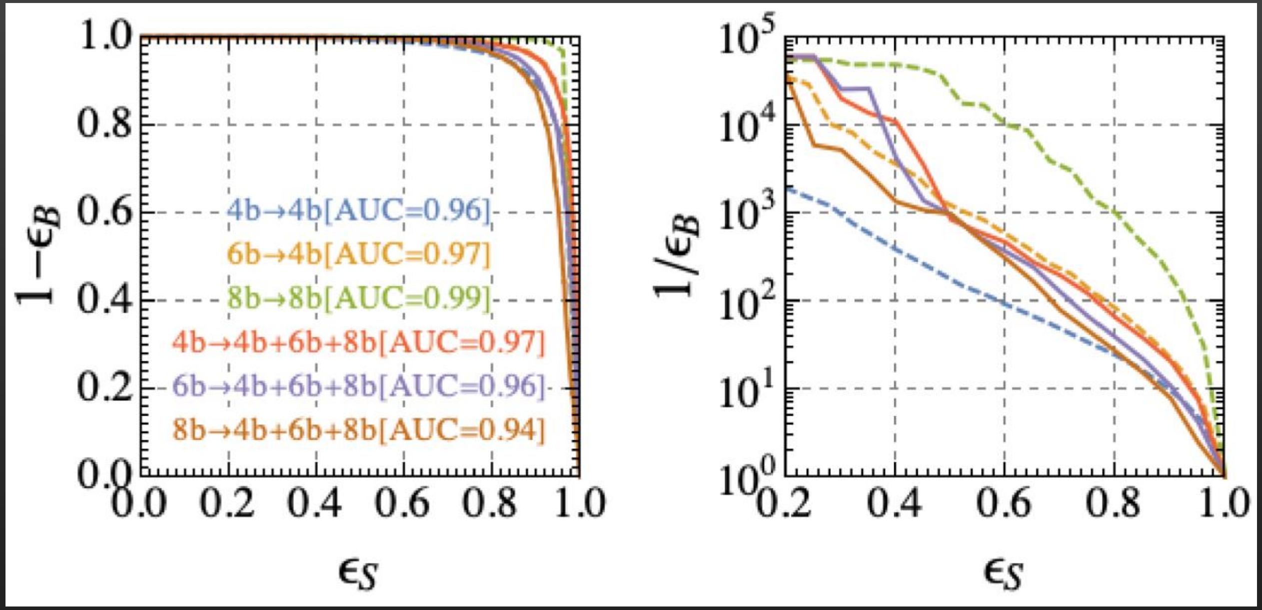
(e) The clustering history of fat-jets from $\ell^\pm\nu 6b$.

(f) The clustering history of fat-jets from $\ell^\pm\nu 8b$.

S. Jung, ZL, L. Wang, Ke-Pan Xie, 2109.03294

Semi-inclusive Higgs Exotic Decays



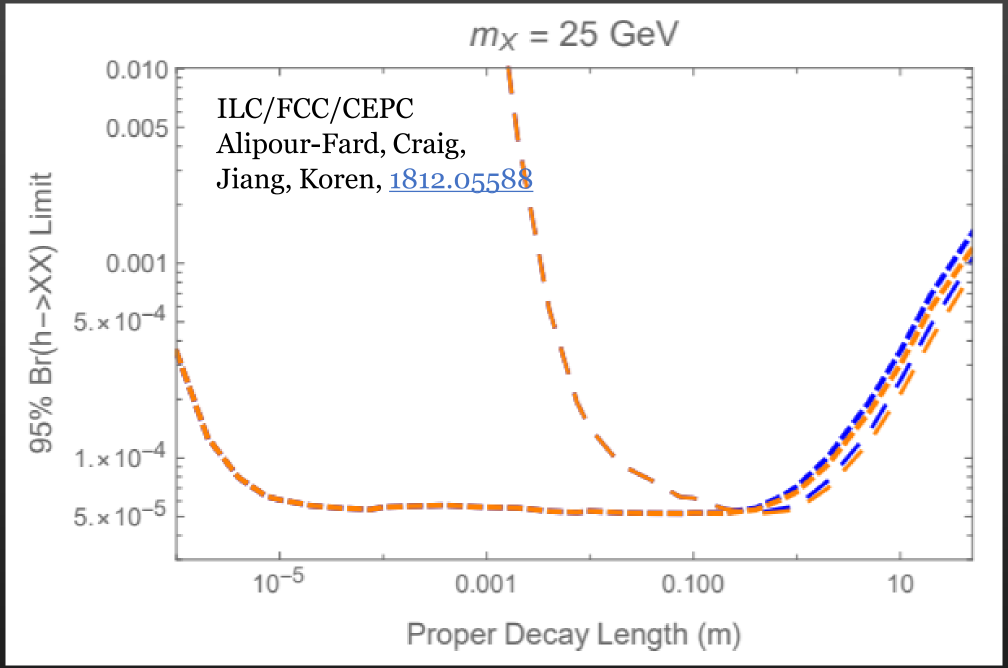


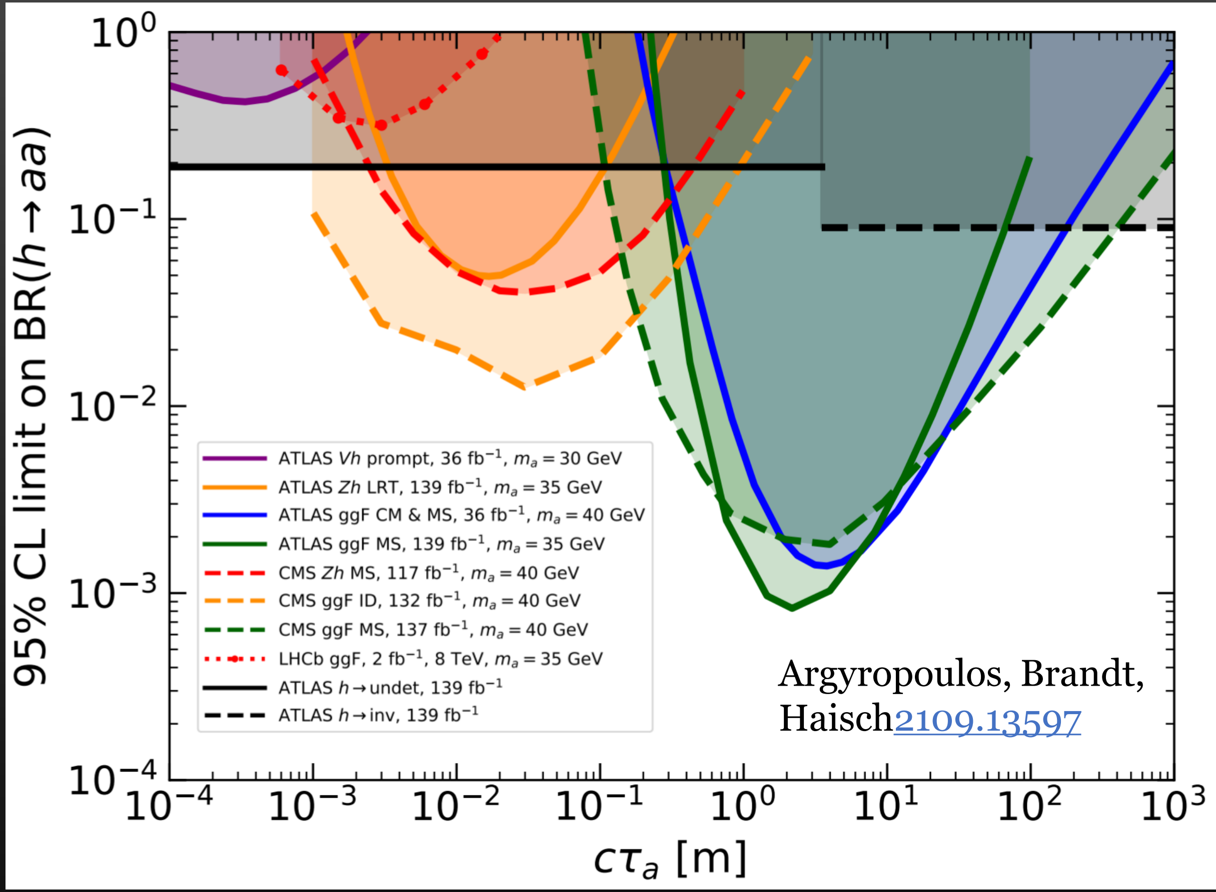
Our study done Pythia+Delphes, and shows compatible results with current ATLAS exotic search

Although trained a particular unmixed (signal) sample, achieved good performance on other Higgs exotic decay samples without additional training.
Consider this as a semi-inclusive Higgs exotic decay search
Different from optimized supervised learning and anomaly detection.

S. Jung, ZL, L. Wang, Ke-Pan Xie, 2109.03294

Neutral Naturalness: Long-Live Sigantures

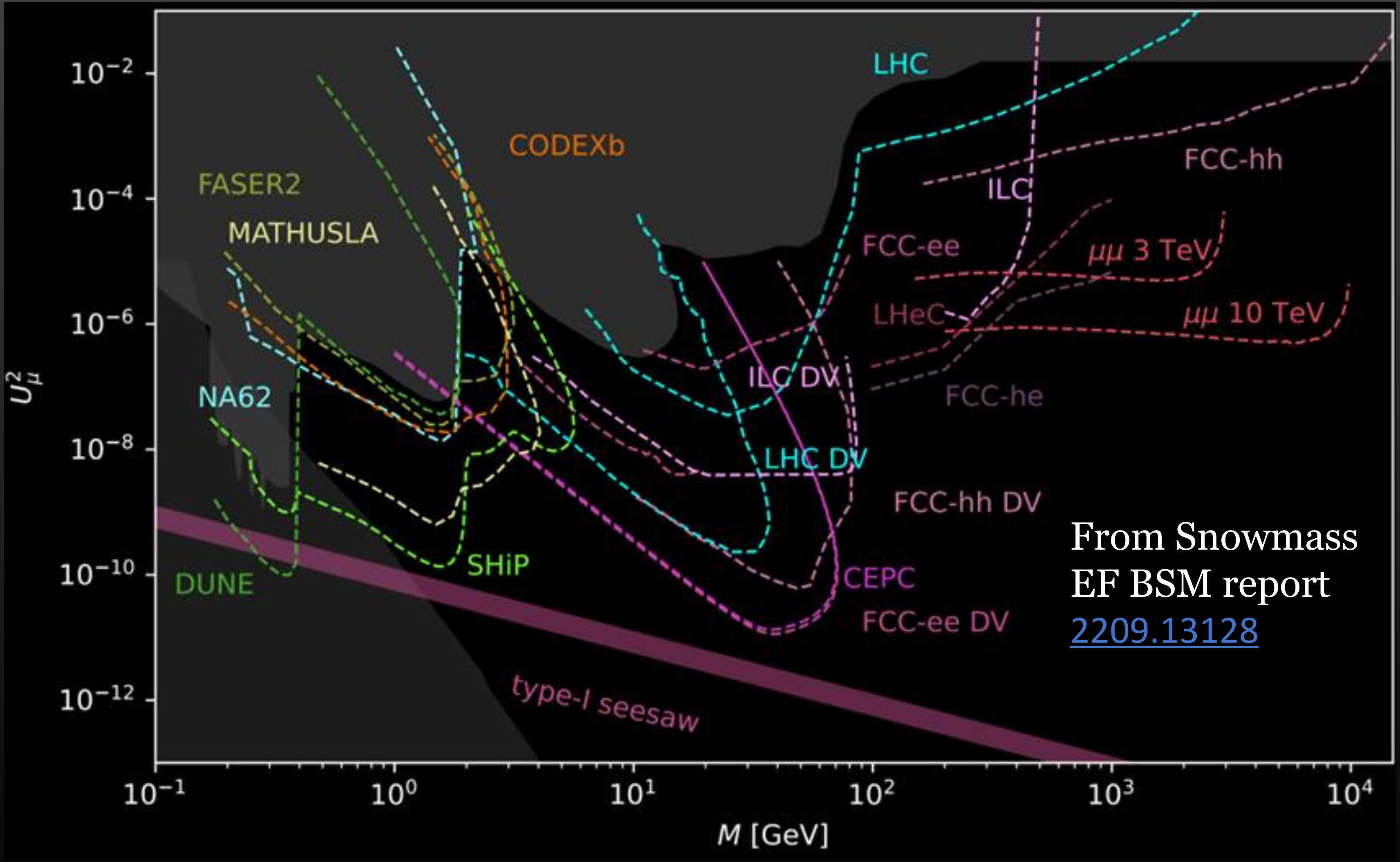




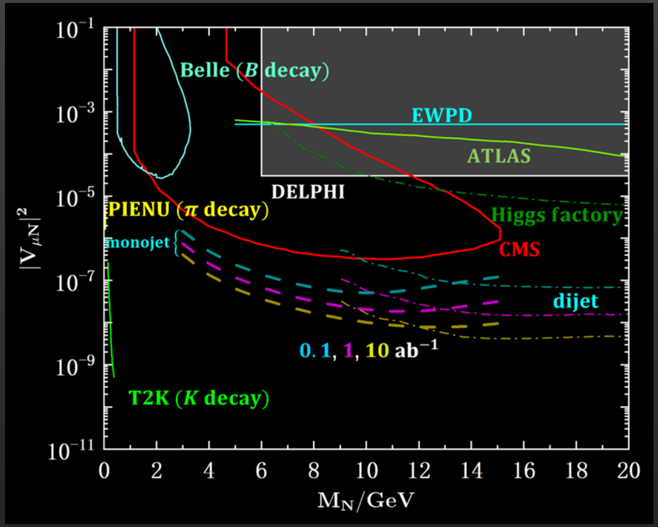
See also
Motivation: Craig, Katz, Strassler, Sundrum, 1501.05310
Alipour-Fard, Craig, Gori, Koren, Redigolo, 1812.09315
Cheung, Wang, 1911.08721
Using timing information at the LHC (J. Liu, ZL, L. Wang, 1805.05957)
Using high granularity calorimetry at the LHC (J. Liu, ZL, L. Wang, X. Wang, 2005.10836)
These features will become even more universally useful at CEPC since particles are not highly boosted.

LHC vibrant program on such signature build in recent years! And more to come!

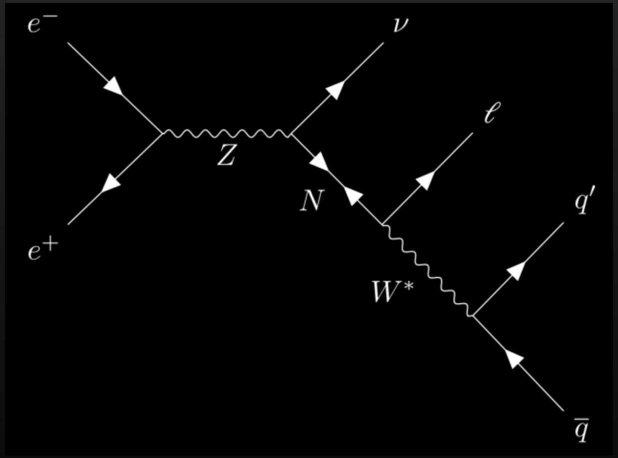
HNL (Z dominant)



From Snowmass EF BSM report [2209.13128](https://arxiv.org/abs/2209.13128)



Shen, Ding, Qin, [2201.05831](https://arxiv.org/abs/2201.05831)



Axion-Like Particles

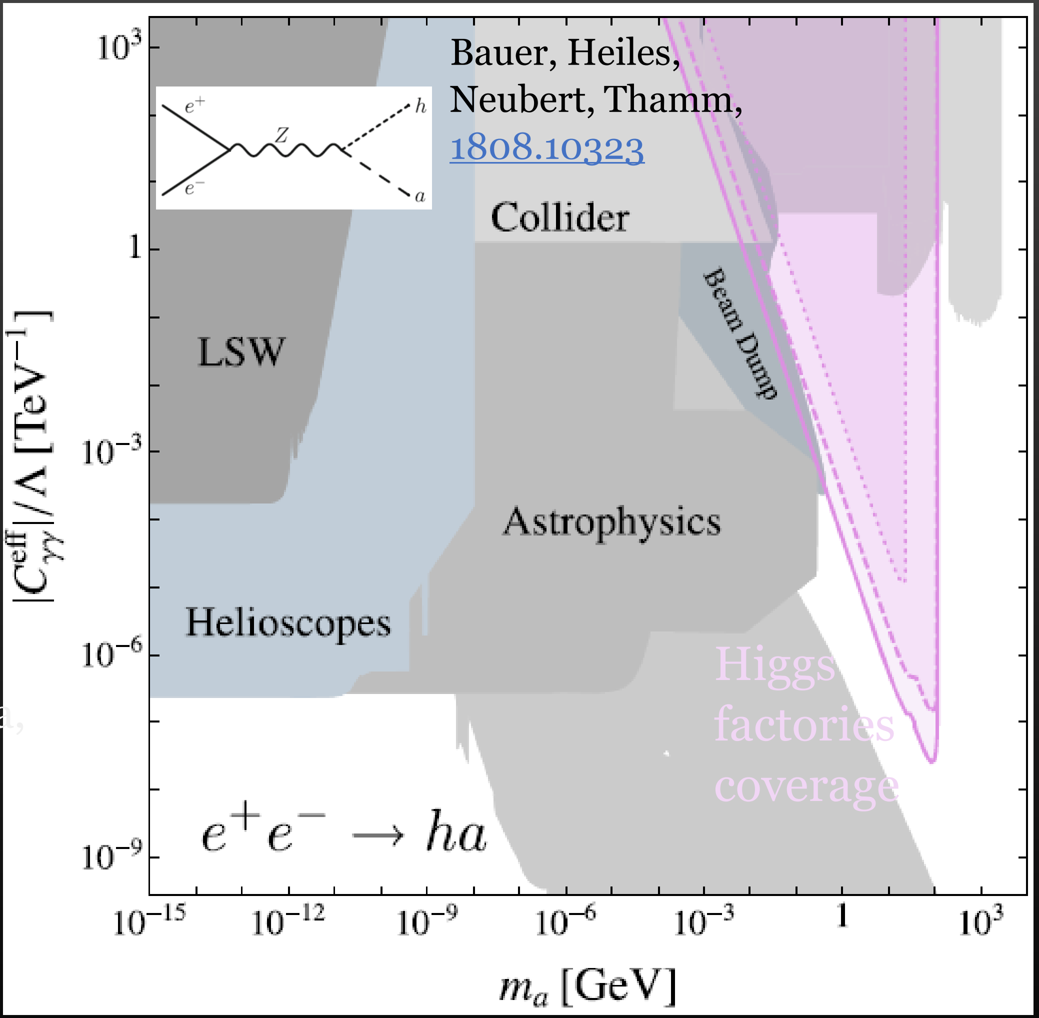
$$\mathcal{L}_{\text{eff}}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2}(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{Zh}}{\Lambda^3}(\partial^\mu a)\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \cdots$$

Here the pheno discussion requires

1) sizable HZa or Haa coupling;
2) Photon dominance of lepton dominance in decay.

One shall consider general Axion-Like theories, e.g., motivated by Rubakov, 97' Berezhiani, Gianfagna, Giannotti, 00' Hook, 14', Dimopoulos, Hook, Huang, Marques-Tavares, 16' Gherghetta, Nagata, Shifman, 16' Agrawal, Howe, 17', 17'
Hook, Kumar, ZL, Sundrum, 19'
Csaki, Ruhdorfer, Shirman, 19'
Gherghetta, Khoze, Pomarol, Shirman, 20'
Kelly, Kumar, ZL, 20'

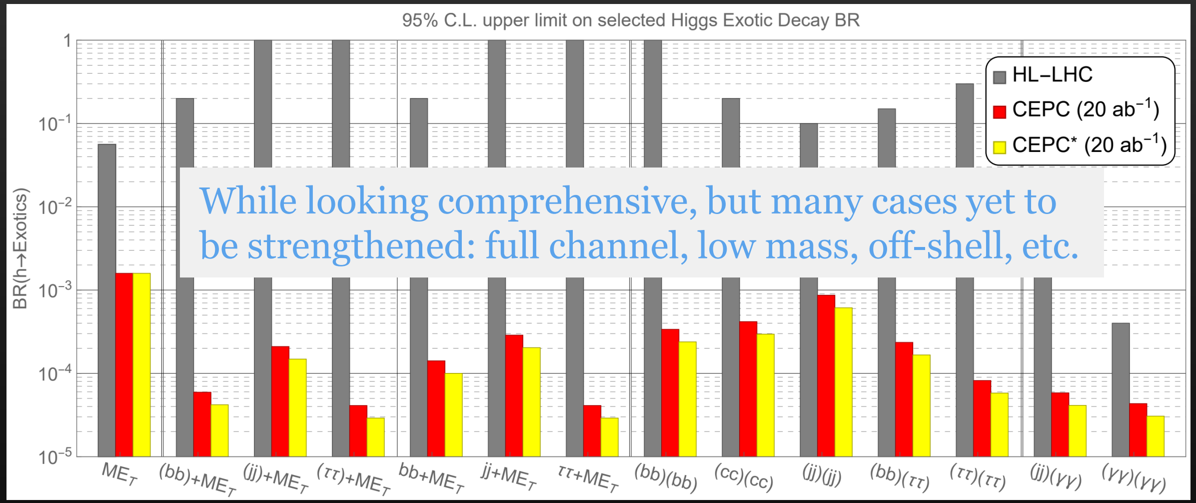
Hadronic decays are particularly motivated given its relation to the Strong CP Puzzle



Summary

- Higgs & Z Exotic Decay well-motivated BSM opportunity
- Many cases to consider, implement and improve
  - Electroweak Phase Transition
  - Neutral Naturalness
  - Heavy Neutral Leptons
  - Axion-Like Particles
  - Dark Showers
  - …

Also
Higgs/Z flavor violating decays
Higgs/Z decays to mesons
Exotic Higgs/Z productions
+ many more
Direct BSM productions



Thank you!