Higgs and New Physics

Stefania Gori
UC Santa Cruz

Chicago workshop on the circular electron-positron collider, 2019

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What do we want to learn from the Higgs?

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Many possible routes:

Higgs couplings

Higgs connection to the dark sector

Higgs rare processes

CPV in Higgs

Higgs width

Higgs exotic decays

More Higgs bosons?
Talk by S.Su

Important progress will be made at the LHC & HL-LHC.
Much more to be learned at future colliders!

Higgs couplings

Higgs couplings

Higgs precision is very much wanted to test beyond the SM (BSM) physics!

ATLAS: 1808.08238, 1806.00425
CMS: 1808.08242, CMS-PAS-HIG-18-018

A fast evolving field. Latest milestones:

Summer 2018: discovery of the Higgs decay to bottom quarks
+ direct discovery of the top-Higgs coupling (tth production)

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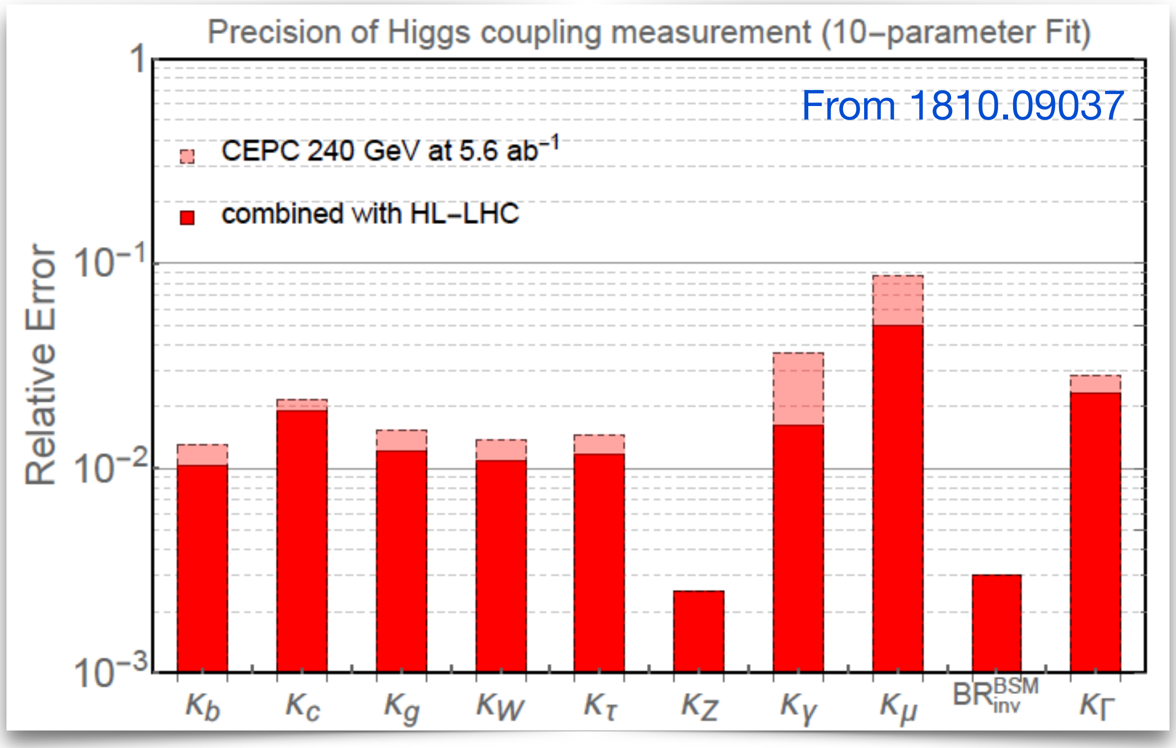
Goal of the HL-LHC: measurement of most of the couplings at the 2-5% level

Expectation at CEPC:



What do we learn on BSM?

Higgs couplings

Typical Higgs coupling deviation: $\frac{\delta g_h}{g_h} \sim \frac{g_{\rm BSM}^2 v^2}{\Lambda_{\rm BSM}^2}$

(HL-)LHC coupling measurement: $\frac{\delta g_h}{g_h} = \mathcal{O}(5\%) \Rightarrow \Lambda_{\rm BSM} > 1\,{\rm TeV} \times g_{\rm BSM}$

Typically not doing better than LHC direct searches
(caveats: BSM EW particles; strongly coupled theories; …)

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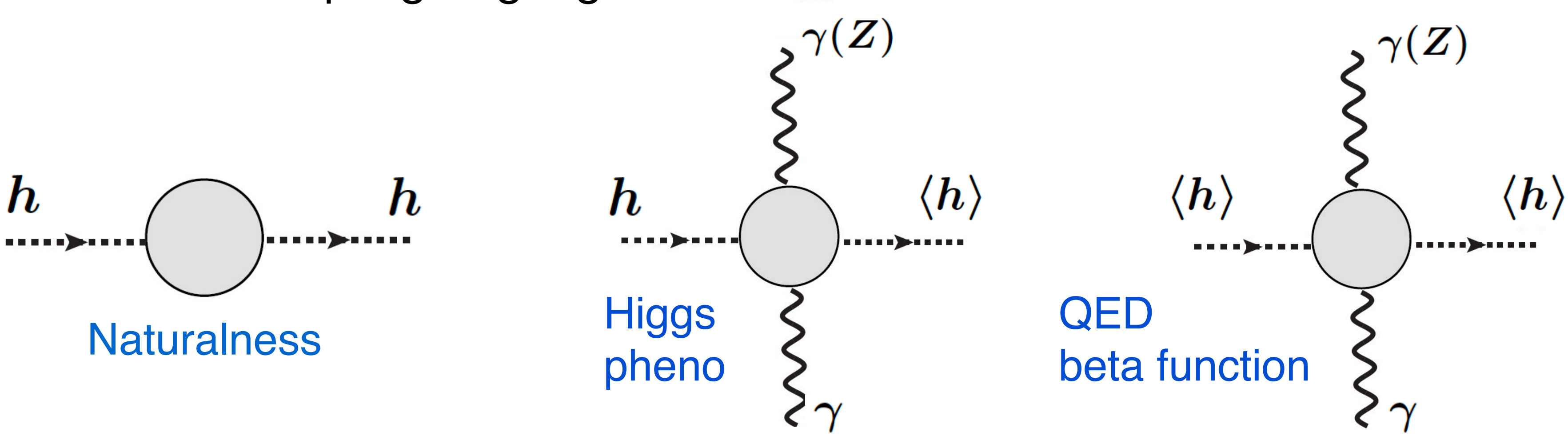
The connection to the hierarchy problem

See also M. Reece talk

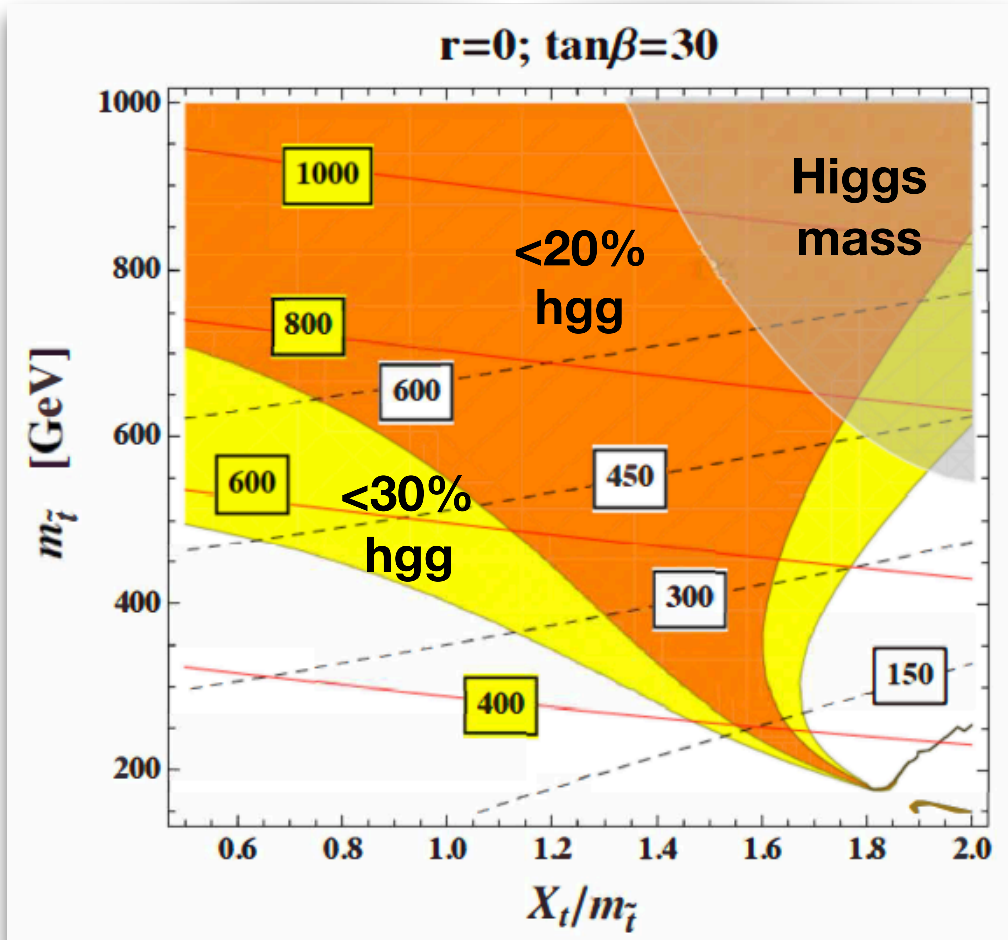
If we take the coupling to gauge bosons:



The SUSY case

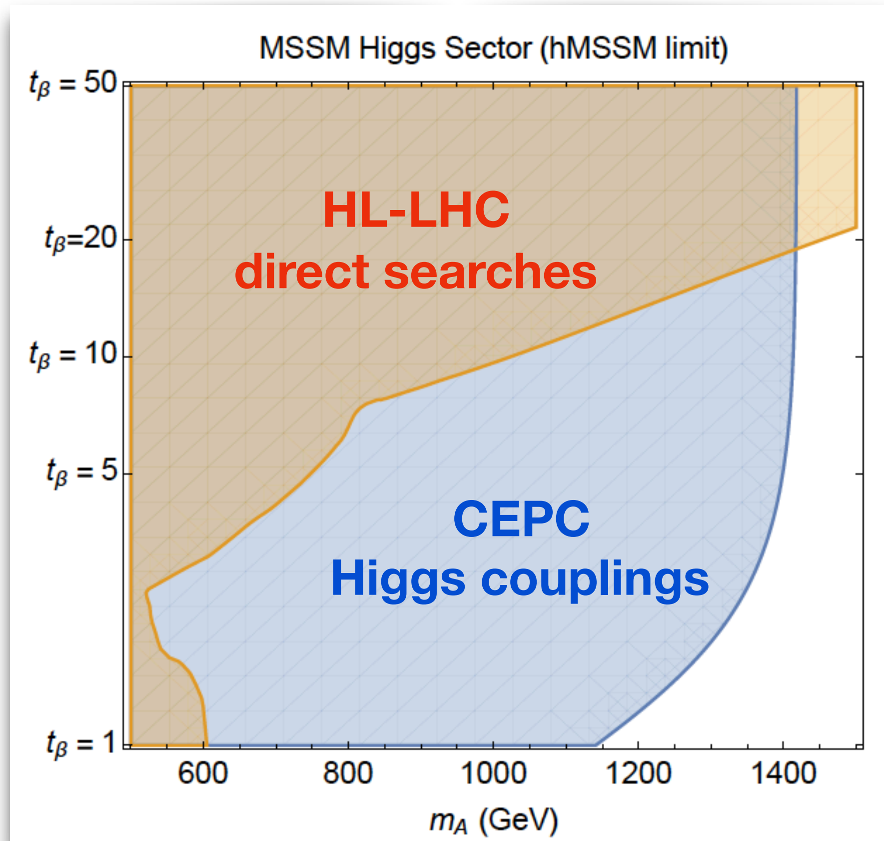
Higgs couplings

Probing stop parameter space



SG, I.Low, 1307.0496

Probing heavy Higgs parameter space



CEPC CDR, 1811.10545

Complementarity with direct searches

Higgs rare processes

The origin of mass

In the SM, the Higgs couplings to fermions are highly hierarchical.

We do not yet know if the Higgs gives mass to all quarks and leptons!

The couplings to **light generation quarks/leptons** are still very much un-known (hee (BR ~ $5*10^{-9}$), hmumu (BR ~ $2*10^{-4}$), hcc (BR ~ 3%), hss (BR ~ $2*10^{-4}$), …)

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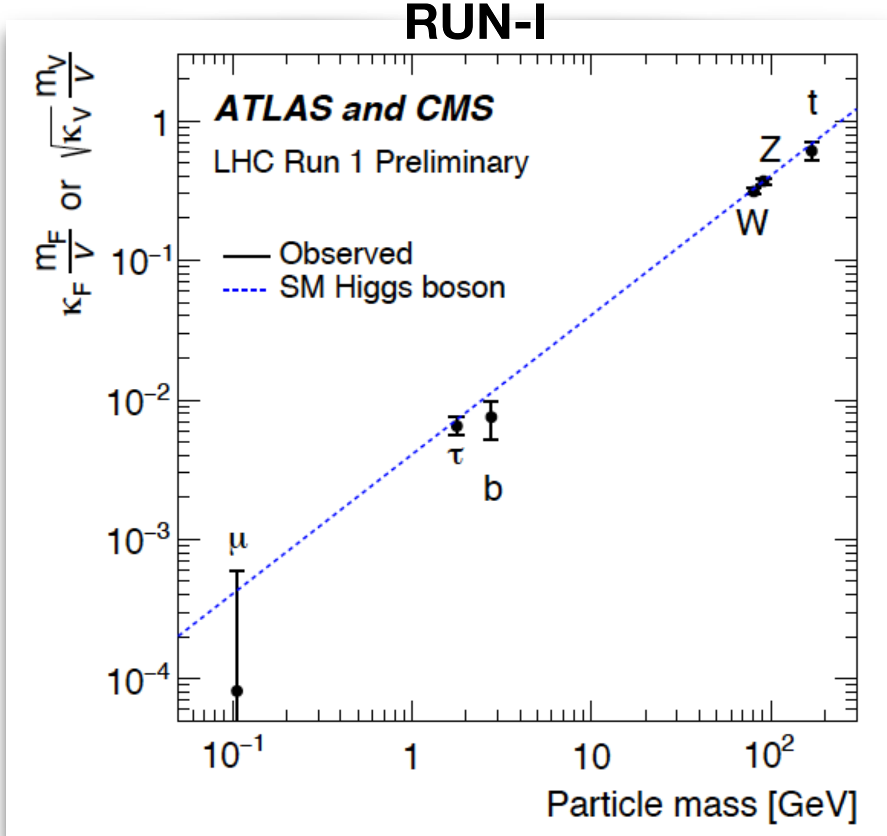
RUN-I



ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

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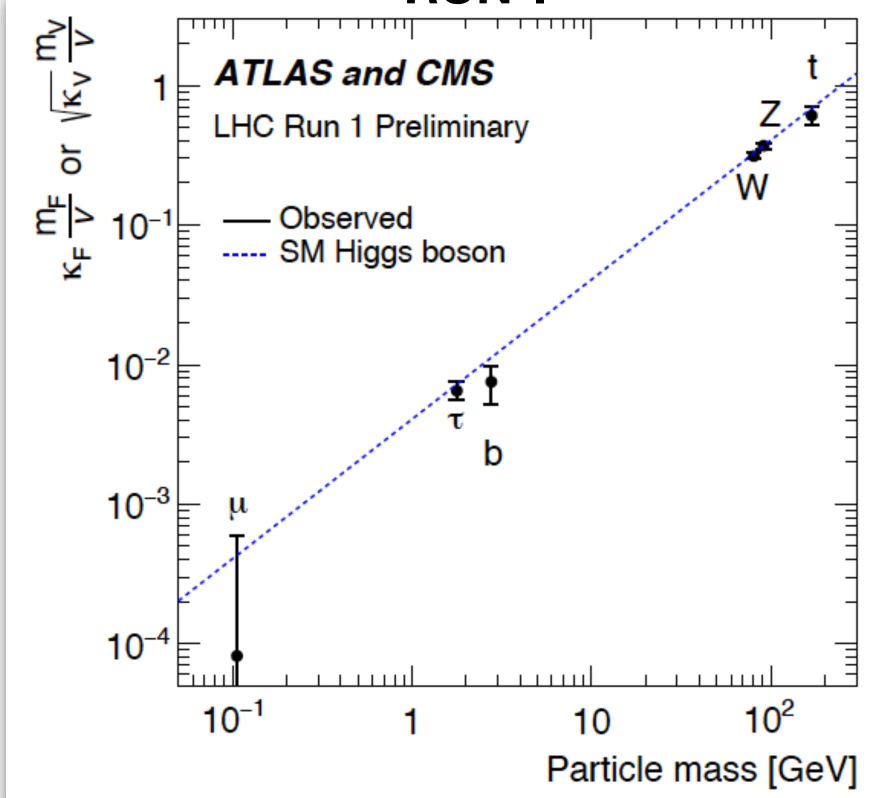

ATLAS-CONF-2015-044
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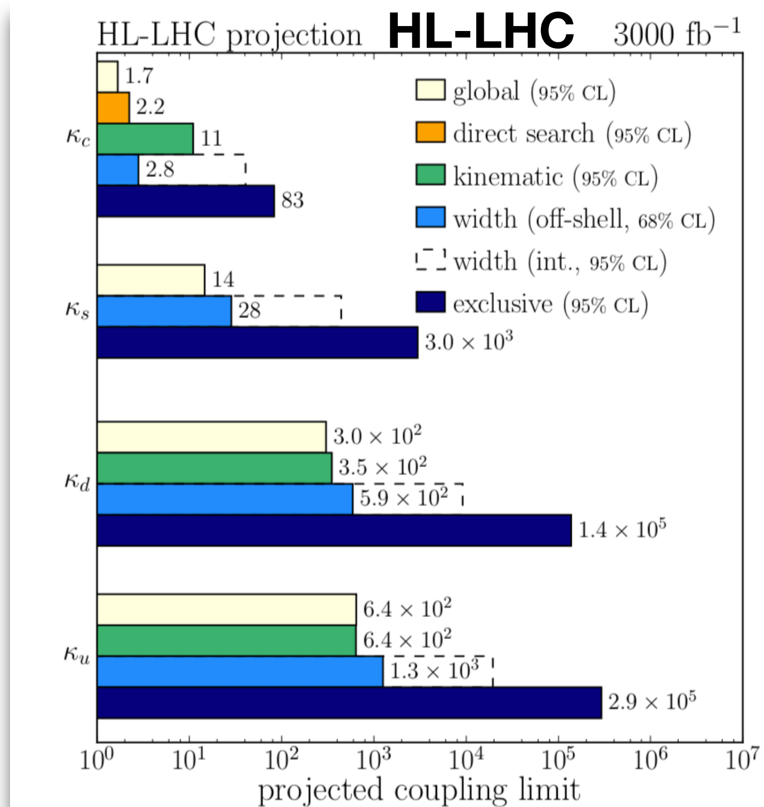
HL-LHC



From HL & HE-LHC Higgs report, Cepeda, SG, Ilten, Kado, Riva, et al., 1902.00134

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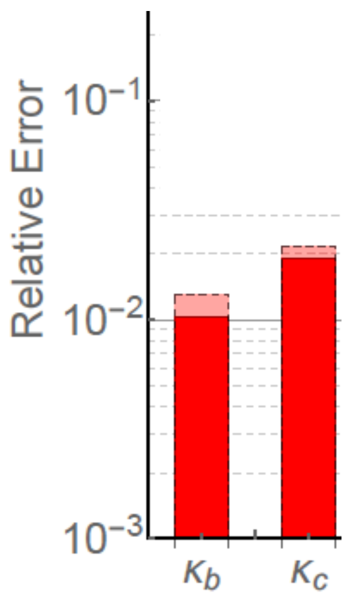
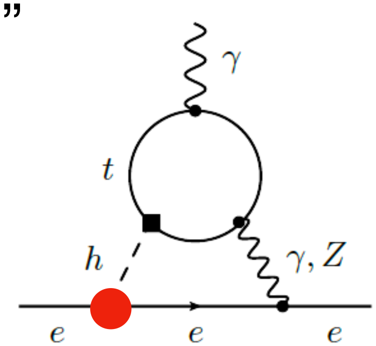


FCC-ee at Higgs pole:
"The SM sensitivity for the hee coupling can be reached in 5 years"

Implications for electric-dipole-moments



Global event shapes to probe light Yukawas, $k_s < 5$ @ CEPC   Gao, 1608.01746

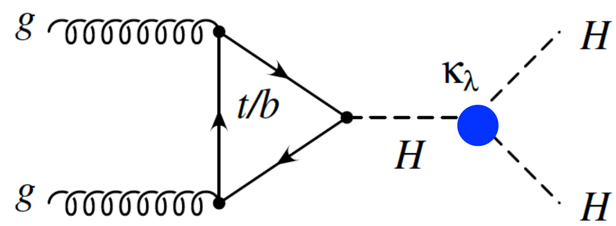
Higgs self-coupling (1)

Higgs rare processes

The Higgs self-coupling, k_λ, plays important roles:

- controls the stability of the EW vacuum
- dictates the dynamics of EW phase transition.

Possible connection to EW baryogenesis.



We still do not know what it is!

(di-Higgs cross section = $O(10^{-3})$ total Higgs cross section)

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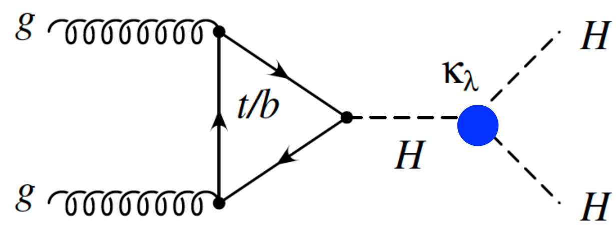

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(di-Higgs cross section = $O(10^{-3})$ total Higgs cross section)

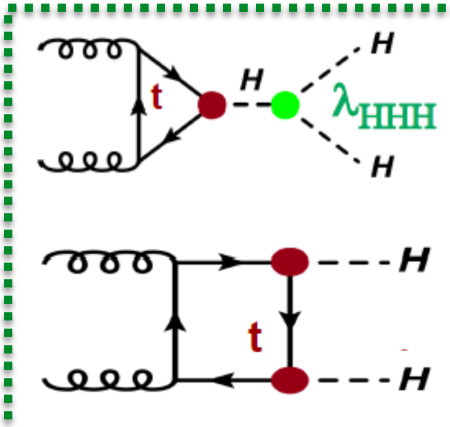
New Physics models can easily predict modified Higgs couplings.

Particularly, from the EFT prespective:

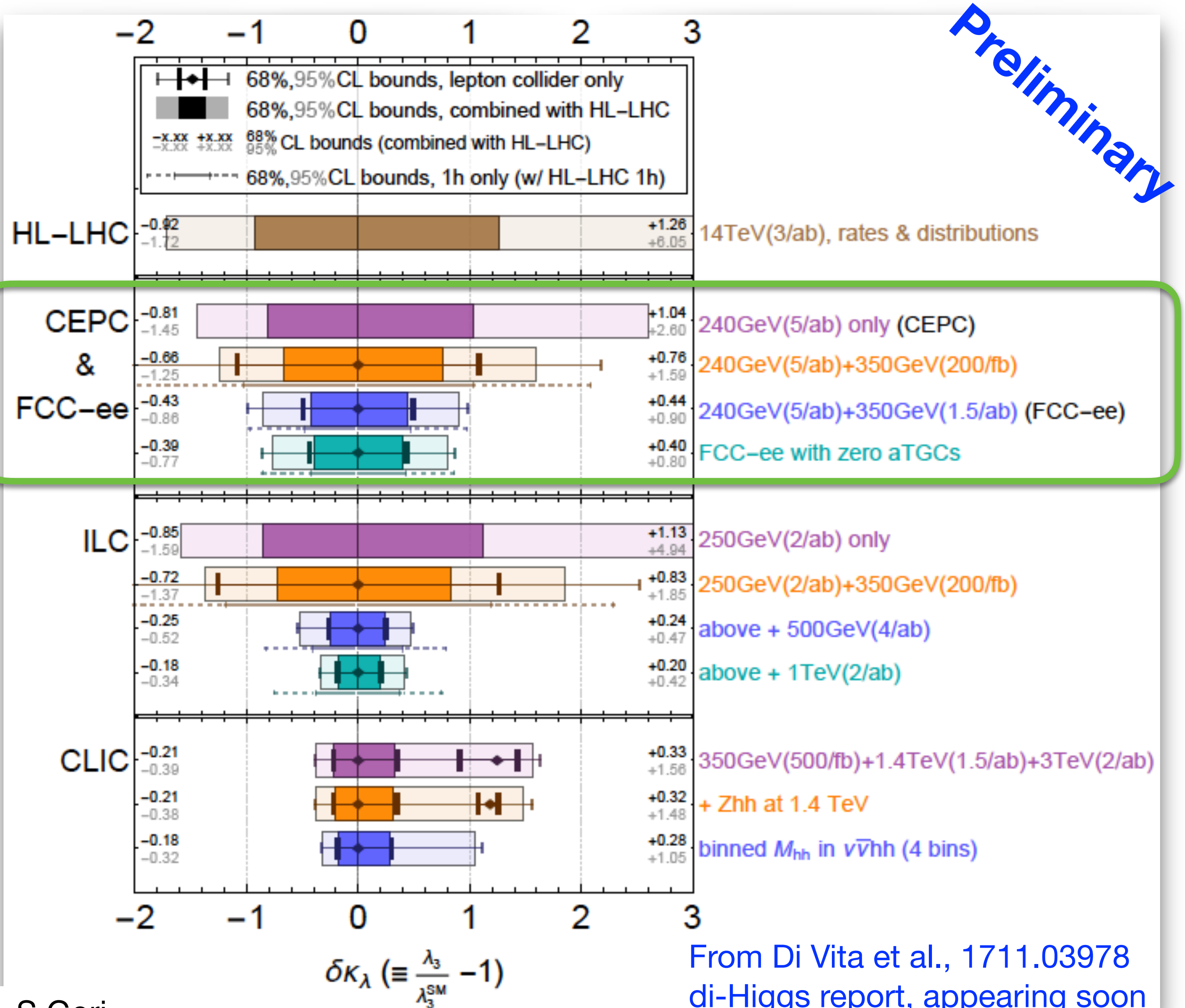
$$\mathcal{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t}\, t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu}$$

In the SM: $c_t = c_{hhh} = 1$ and $c_{ggh} = c_{tt} = c_{gghh} = 0$

Di-Higgs cross section is affected by any of this coefficient

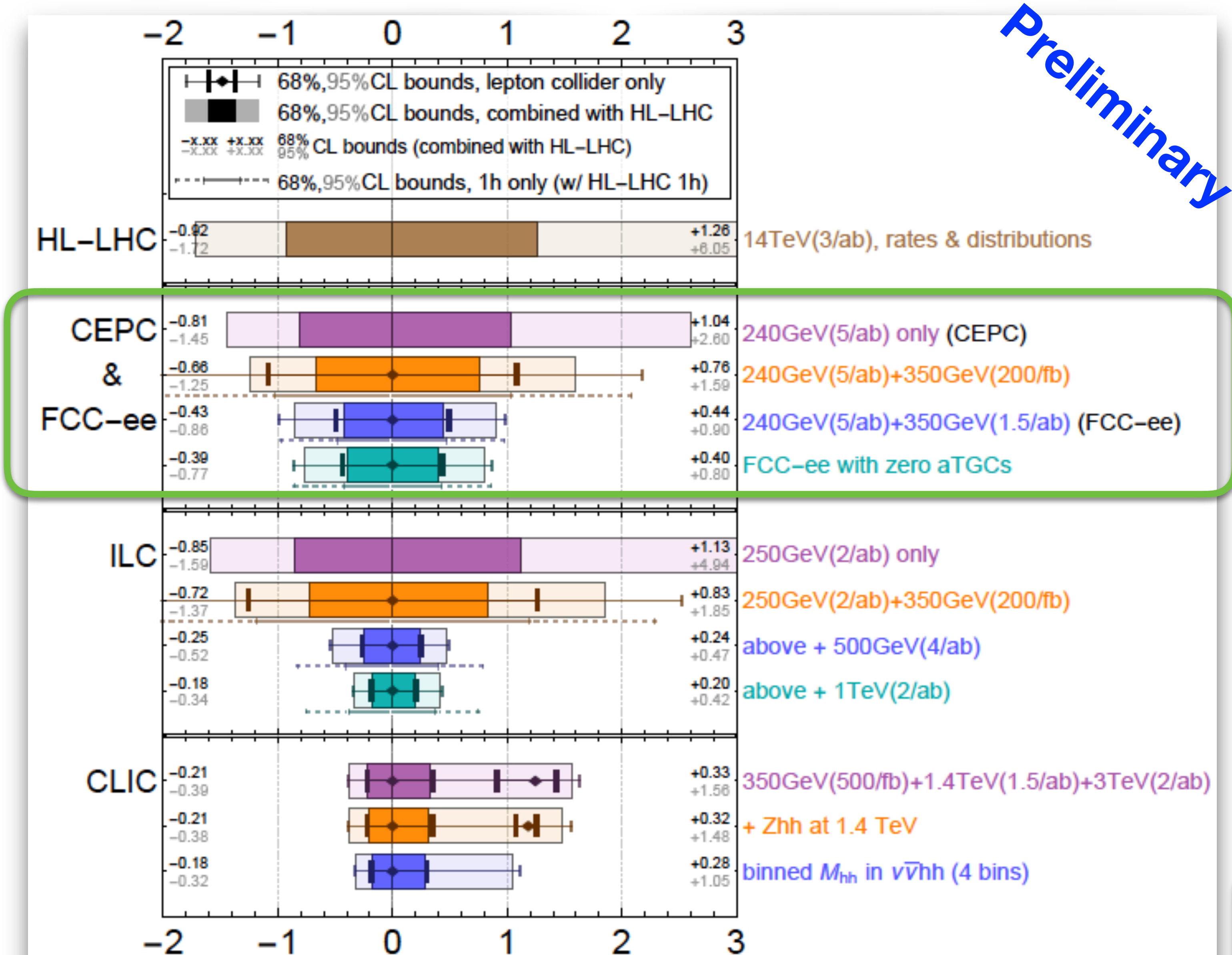


Higgs self-coupling (2)



From Di Vita et al., 1711.03978
di-Higgs report, appearing soon

Higgs self-coupling (2)



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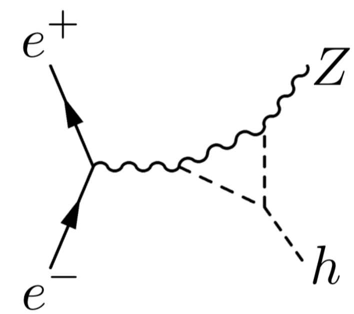
Complementarity:

di-Higgs searches
&
single Higgs production measurements



~5% measurement @100 TeV, 30/ab

CP violation in Higgs physics

Is the 125 GeV Higgs a CP even-CP odd superposition?

The CP nature of the Higgs can be measured in several couplings.

So far, the constraints on the CP odd component are weak.

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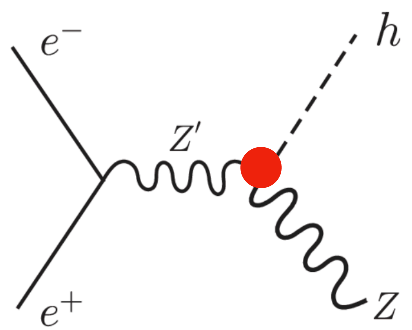
H-gauge boson couplings



σ depends on the Higgs CP properties

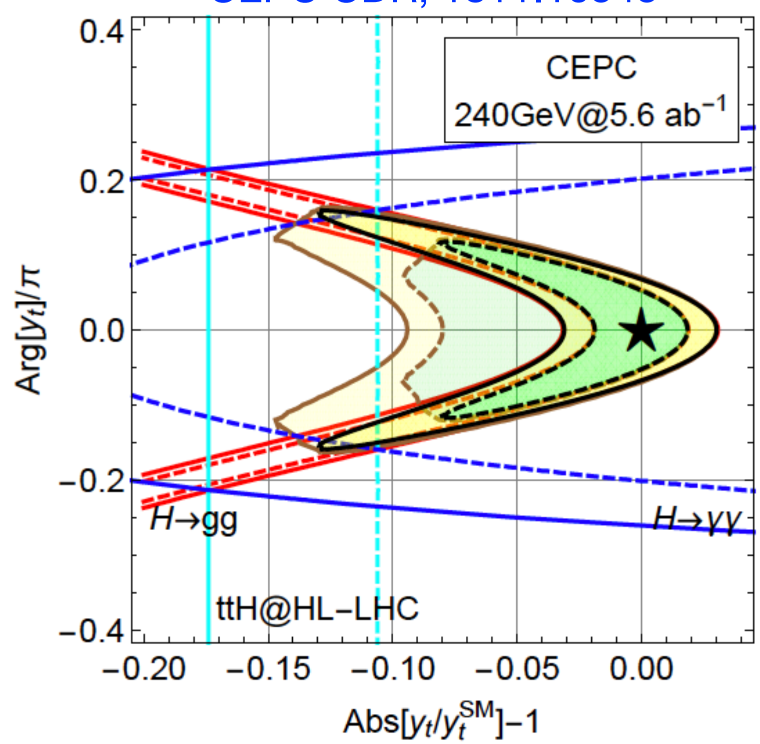
Anderson et al., 1309.4819
An et al., 1810.09037

Measurements of σ at different energies will yield useful information about anomalous HZZ couplings.

Depending on the operator, the sensitivity of CEPC is better than HL-LHC by a factor of (3-300).

H-fermion boson couplings

CEPC CDR, 1811.10545



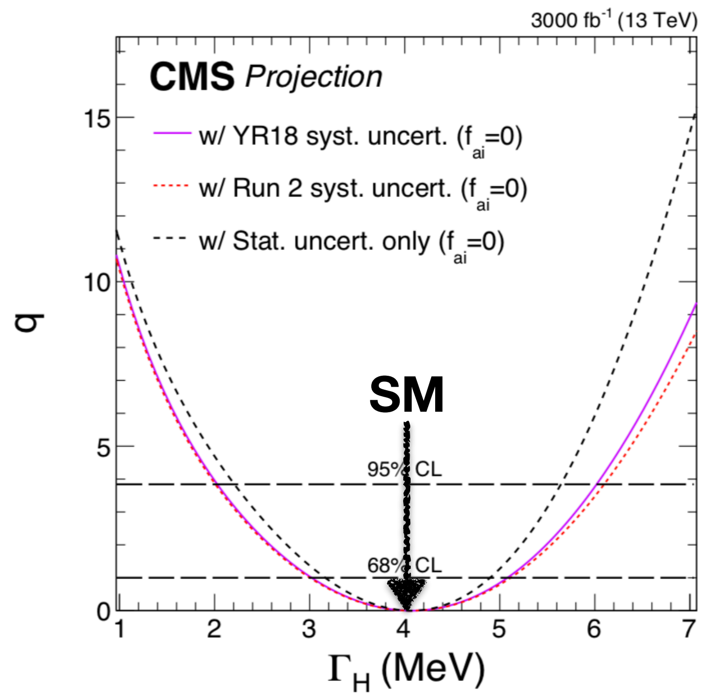
+ FCC-ee study for CPV in H→ τ τ

Higgs width

The measurement of the Higgs width is very challenging at hadron colliders.

→ Need for (model dependent) assumptions to extract information on the Higgs couplings.

Model independent determinations are interesting but not super competitive



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So  or  ?

At e^+e^- colliders, Higgs events are tagged independently of the Higgs decay mode.
Model independence!

$$\sigma(e^+e^- \to ZH) \propto g_{HZ}^2$$

$$\Gamma_H = \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

Accuracy at the ~5% level

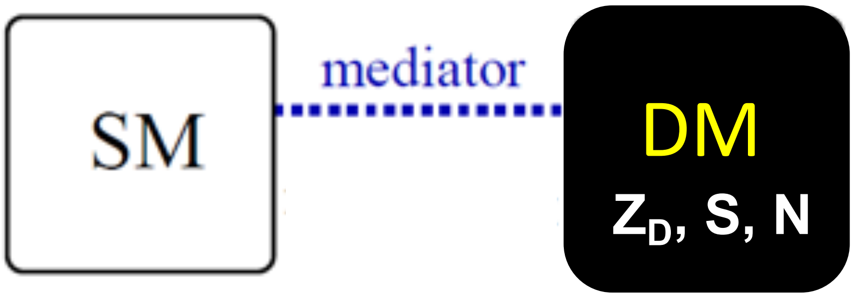
1-2% level accuracy can be reached at CEPC, FCC-ee, ILC, CLIC through the combination of all measurements.

Is the Higgs a portal to the dark sector?

Higgs exotic decays

We still do not know much about the Nature of Dark Matter (DM)

DM can live in its own dark sector



Is this connected to us?
Maybe even to the EW scale?

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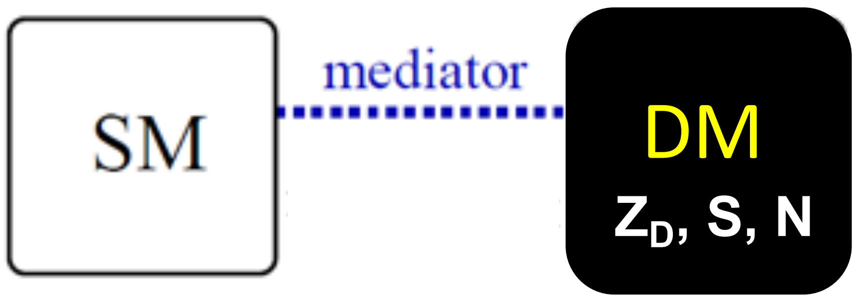

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Only a few renormalizable "portals":

$$B_{\mu\nu}F'_{\mu\nu},\ |H|^2|S|^2,\ HLN$$

Two of them involve directly the Higgs boson

Particularly, many well motivated theories lead to a sizable Higgs portal operator (eg. SUSY, twin Higgs, …)

Is the Higgs the messenger to the dark sector?

Higgs exotic decays

The SM Higgs width is tiny: ~4 MeV

⇩

If a BSM theory contains light dark particles, sizable branching ratios for the Higgs decaying into dark particles is a generic prediction

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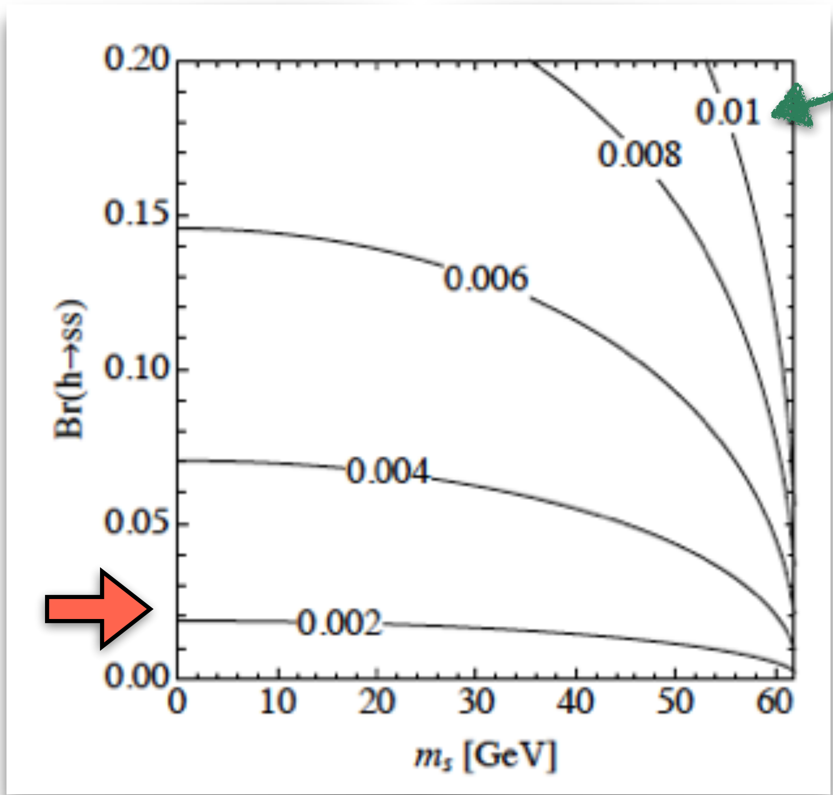
Example:

$$\frac{\xi}{2}|S|^2|H|^2$$



Value of ξ needed for the corresponding BR

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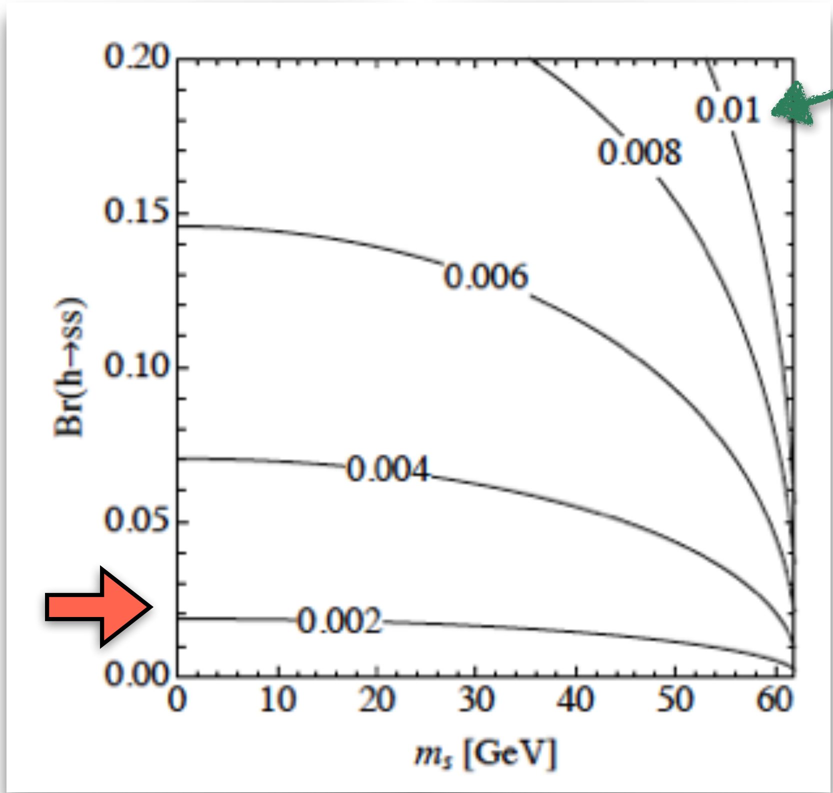

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More generically:

$B_{\mu\nu}F'_{\mu\nu} \rightarrow h \to Z Z_D$

$|H|^2|S|^2 \rightarrow h \to ss$

$HLN \rightarrow h \to LN$

Prompt golden channels

Higgs exotic decays

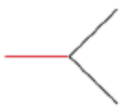
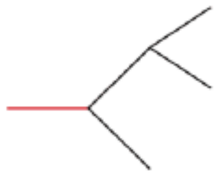
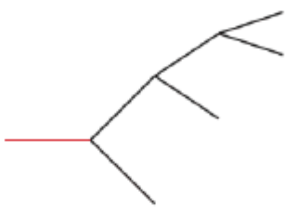
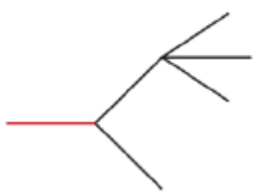
For a comprehensive list of 2-body decays leading to prompt signatures + present/future LHC bounds:

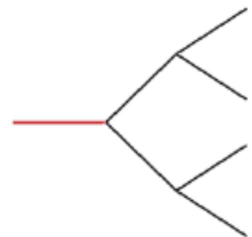
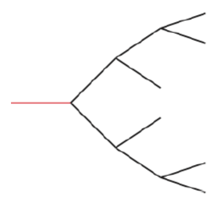
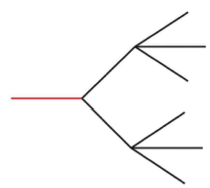
Exotic decays of the 125 GeV Higgs boson 1312.4992

David Curtin,[1,a] Rouven Essig,[1,b] Stefania Gori,[2,3,4,c] Prerit Jaiswal,[5,d] Andrey Katz,[6,e] Tao Liu,[7,f] Zhen Liu,[8,g] David McKeen,[9,10,h] Jessie Shelton,[6,i] Matthew Strassler,[6,j] Ze'ev Surujon,[1,k] Brock Tweedie,[8,11,l] and Yi-Ming Zhong[1,m]

Prompt golden channels

1312.4992

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

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

From Z. Liu

Prompt golden channels

1312.4992

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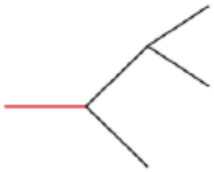
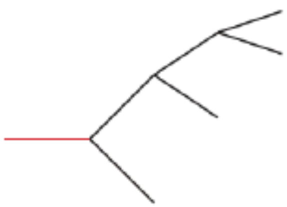
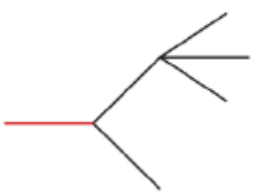
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$







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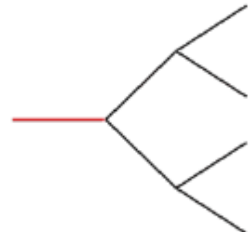
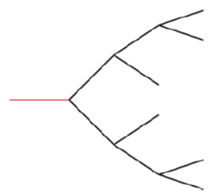
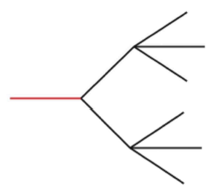
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$







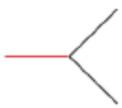
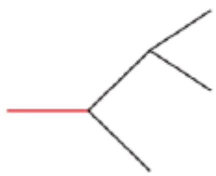
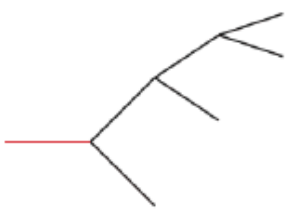
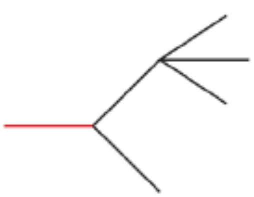
Great reach at the LHC/future hadron colliders (clean signatures)

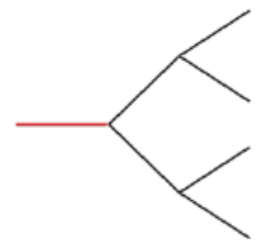
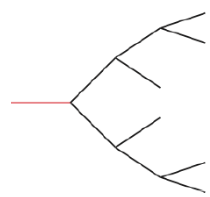
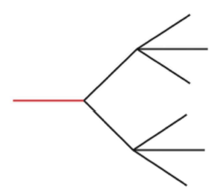
From Z. Liu

Prompt golden channels

Higgs exotic decays

1312.4992

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

Great reach at the LHC/future hadron colliders (clean signatures)

Great reach at e^+e^- colliders (hadronic/with MET signatures).

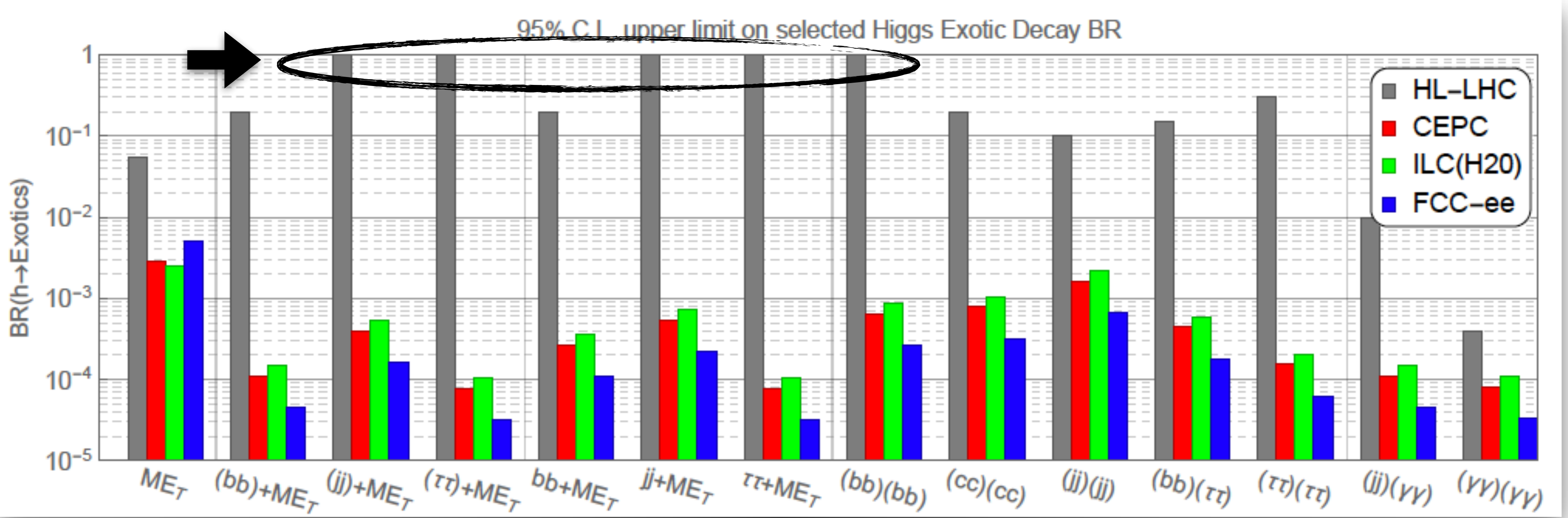
From Z. Liu

Reach for Higgs exotic decays

Higgs exotic decays

Remarkable reach!

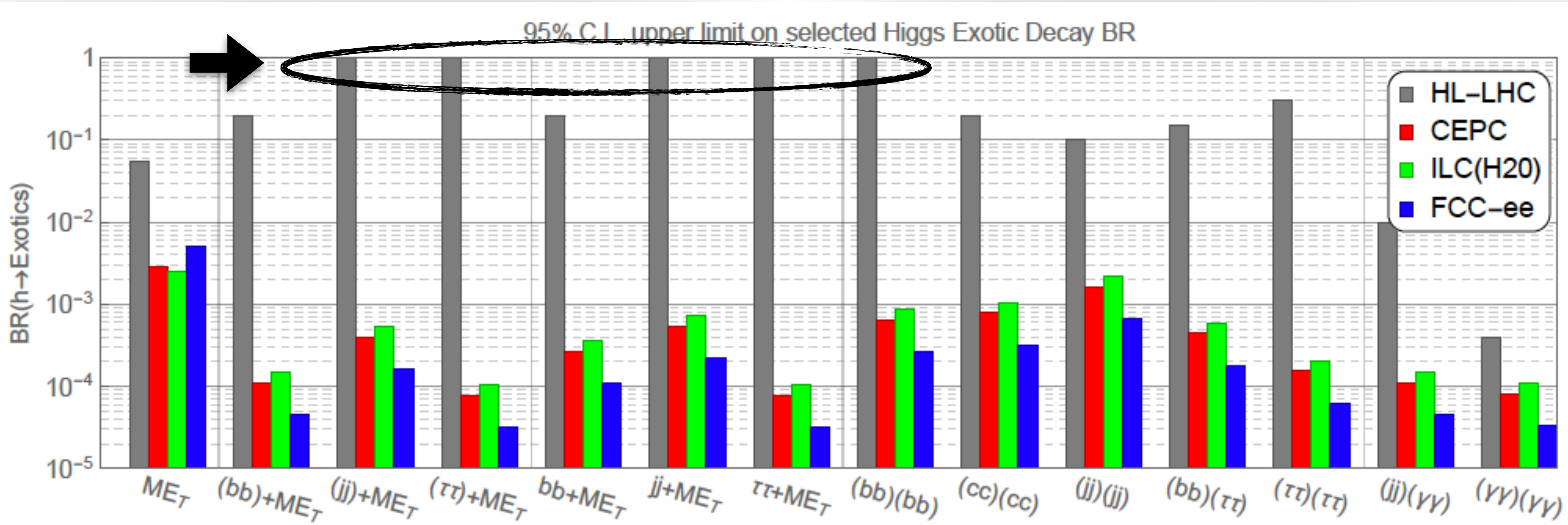
From Liu, Wang, Zhang, 1611.09284



Reach for Higgs exotic decays

Remarkable reach!

From Liu, Wang, Zhang, 1611.09284



Complementarily,

a 100 TeV hadron collider with 30/ab would produce $O(10^9)$ Higgs bosons!

Incredible reach on clean decay modes! **BR~10^{-8}** for e.g. $h \to A'A' \to$ 4 leptons

Curtin, Essig, SG, Shelton, 1412.0018

Higgs decays to long-lived particles

Long-lived particles generically arise in dark sector theories.
(So far) long-lived particles are one of the major gaps in LHC searches.

Higgs decays to long-lived particles

Higgs exotic decays

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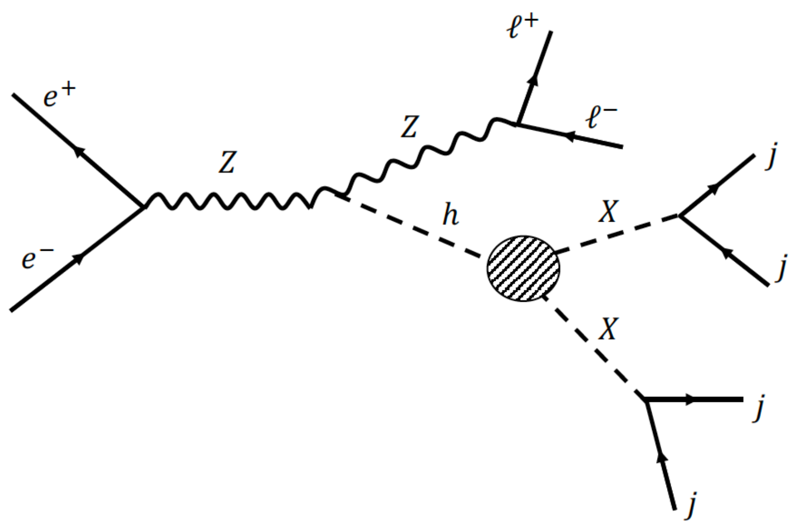
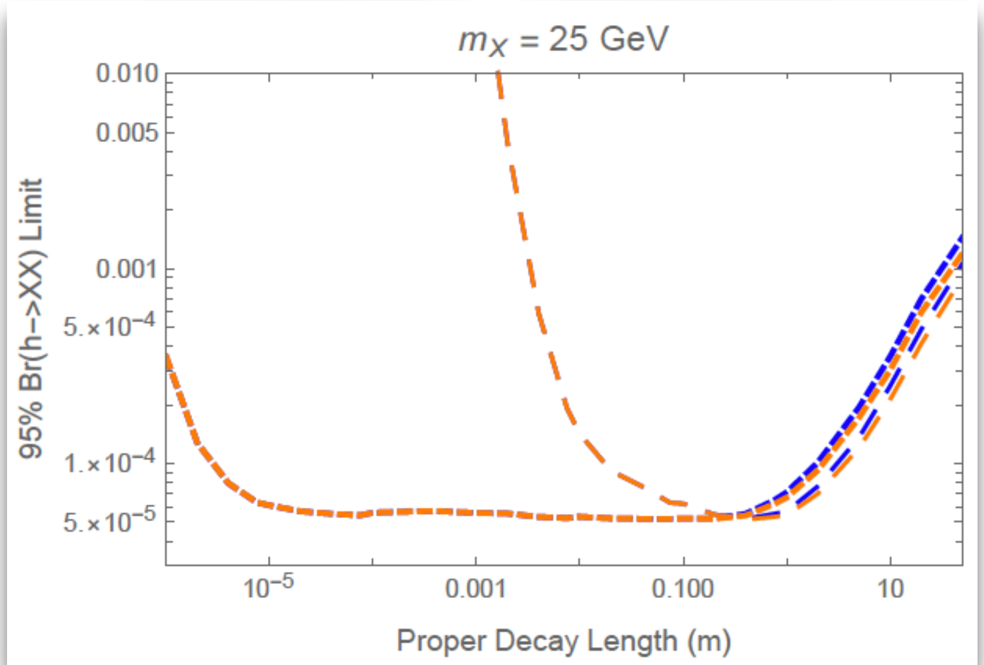
(So far) long-lived particles are one of the major gaps in LHC searches.



Alipour-Fard, Craig, Jiang, Koren,1812.05588

CEPC / FCC-ee reach



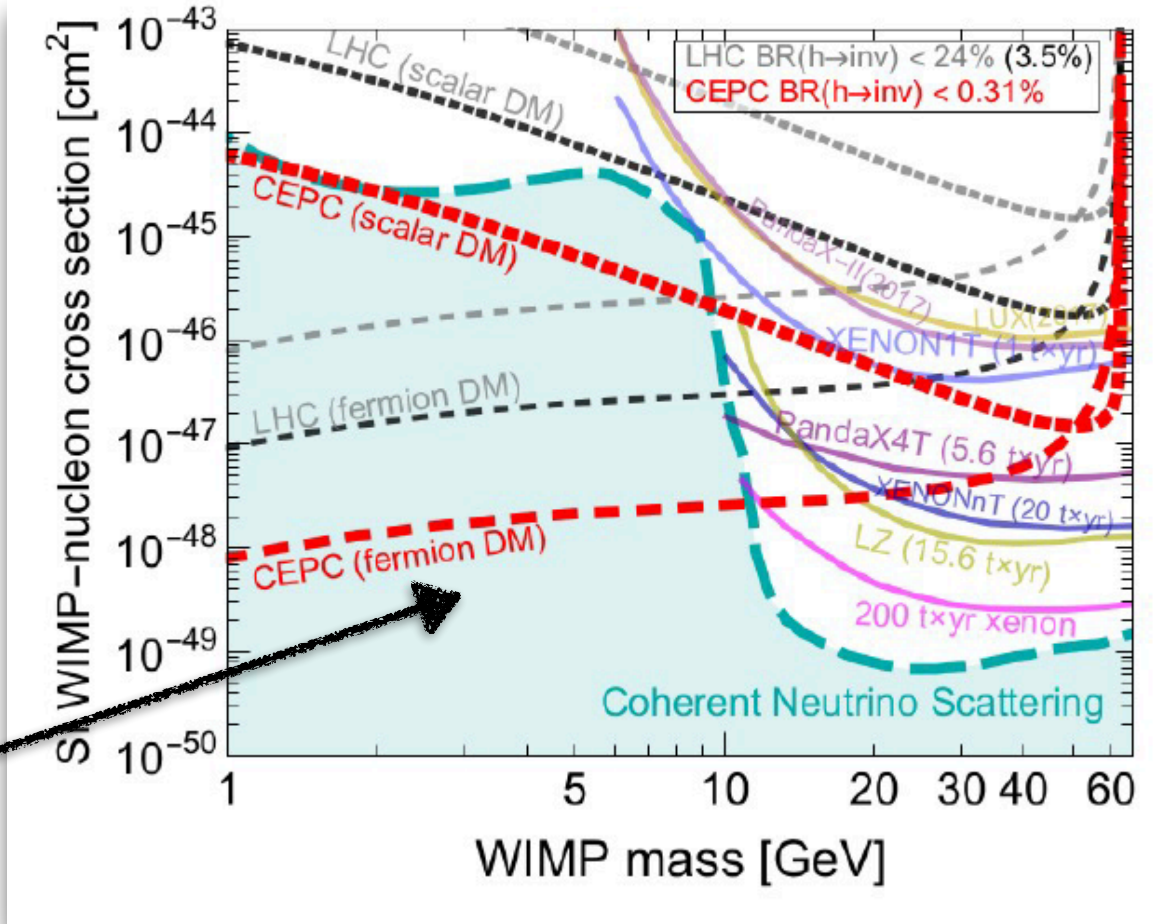
These limits are competitive with LHC forecasts based on conventional Higgs triggers. Note that these latter forecasts assume zero background.

The Higgs-DM connection

Higgs connection to the dark sector

The bound on the Higgs invisible width can be interpreted in terms of DM models.

Depending on the model, the invisible Higgs reach can be compared to the reach of direct detection experiments:



Particularly relevant at low DM masses

Many dark sector opportunities

Higgs connection to the dark sector

Beyond the Higgs connection, e^+e^- colliders can directly produce a large set of dark particles.

Mono-photon searches to explore invisibly decaying dark particles + many visible searches

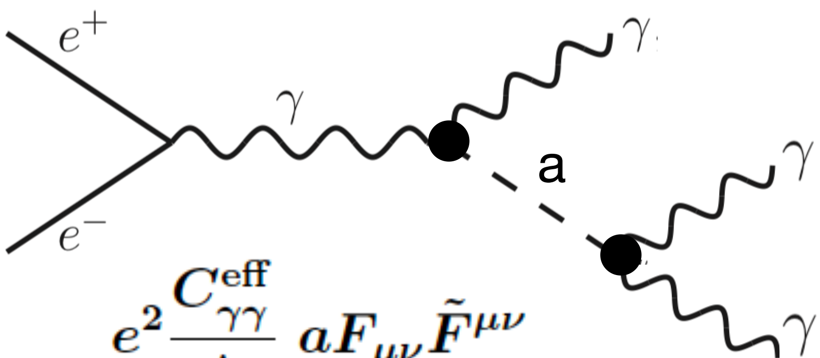
Many dark sector opportunities

Higgs connection to the dark sector

Beyond the Higgs connection, e^+e^- colliders can directly produce a large set of dark particles.

Mono-photon searches to explore <u>invisibly</u> decaying dark particles + many <u>visible</u> searches

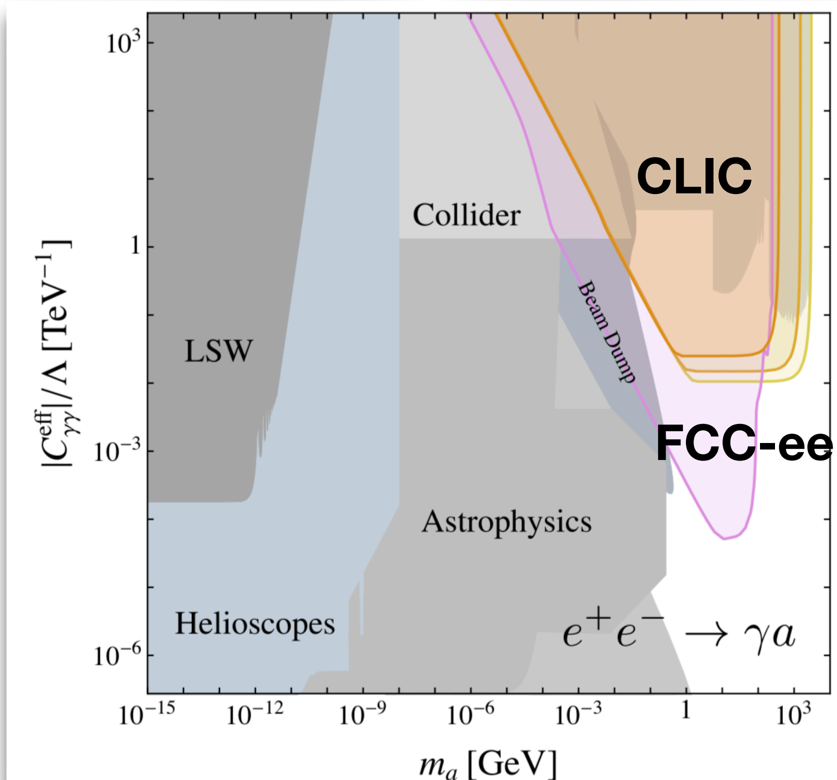
<u>For example</u>, **axion-like-particles** could be produced from e^+e^- collisions…



$$e^2 \frac{C^{\rm eff}_{\gamma\gamma}}{\Lambda}\, a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

… probing new territory

Bauer, Heiles, Neubert, Thamm, 1808.10323



Many more studies needed!

Conclusions & Outlook

The Higgs is special!

- Brand new particle (nothing like that has been observed before 2012!).
- It easily couples to any new Physics.

The HL-LHC will do a great job in exploring its properties

BUT

many questions won't be answered by the HL-LHC.

Need for
- precision studies
- novel measurements of the Higgs in a new (clean) environment

Complementarity with direct searches of new particles / DM