Next steps on the energy frontier: LHC and beyond

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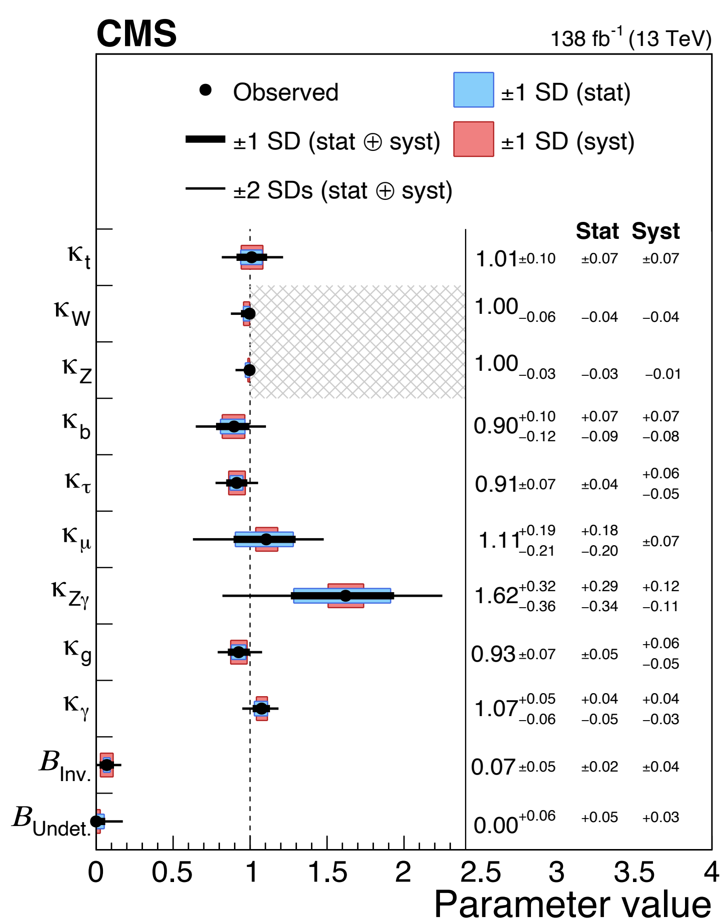
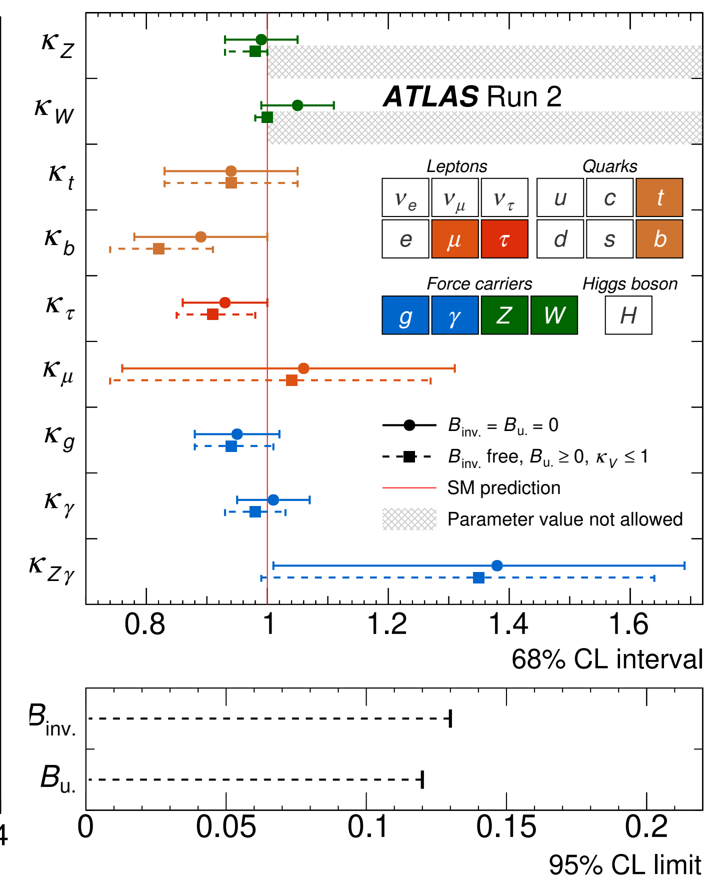
Where we are

- LHC has achieved a lot.
  - Discovered the Higgs boson, completed the SM.

Looks like Higgs

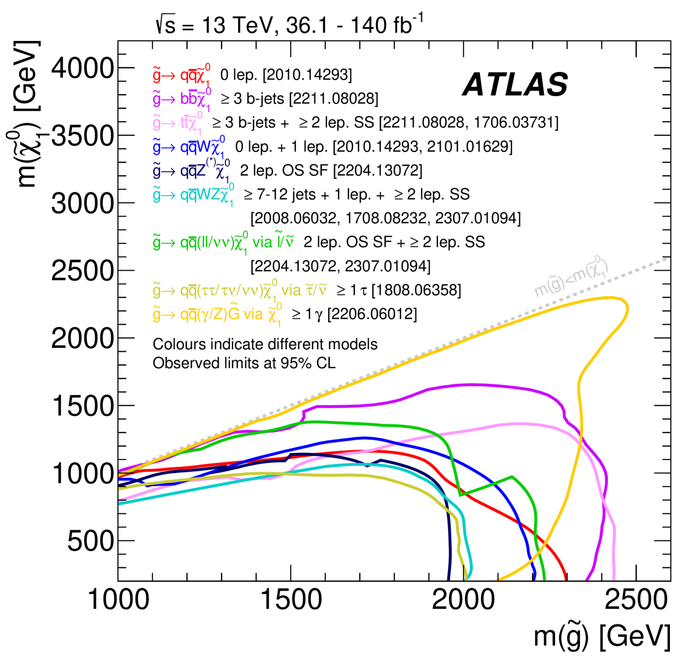


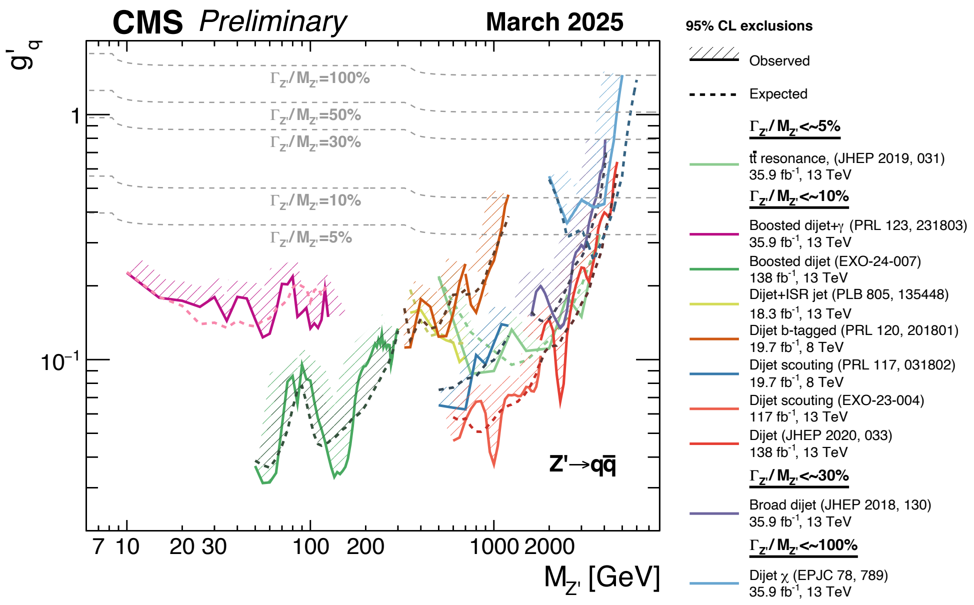


Higgs couplings. Presently, known to about 10%

Where we are

- LHC has achieved a lot.
  - Discovered the Higgs boson, completed the SM.
  - Explored TeV frontier in many ways.





Where we are

- LHC has achieved a lot.
  - Discovered the Higgs boson, completed the SM.
  - Explored TeV frontier in many ways.
- So, what’s next?

Still confused

Dark matter

Origin of the weak scale

Matter > anti-matter

Dark energy

Inflation

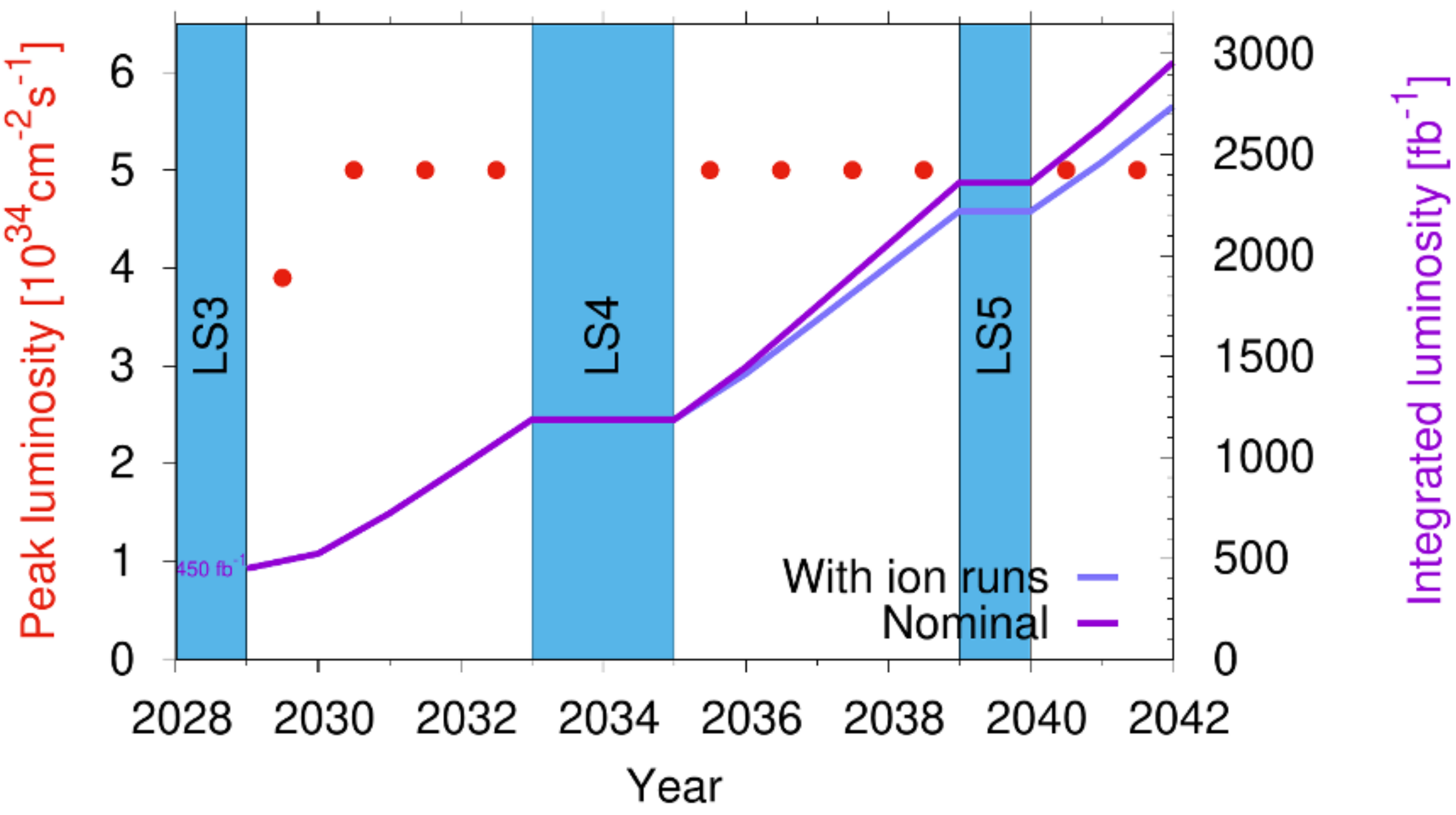
flavor

Many ideas, no confirmation.

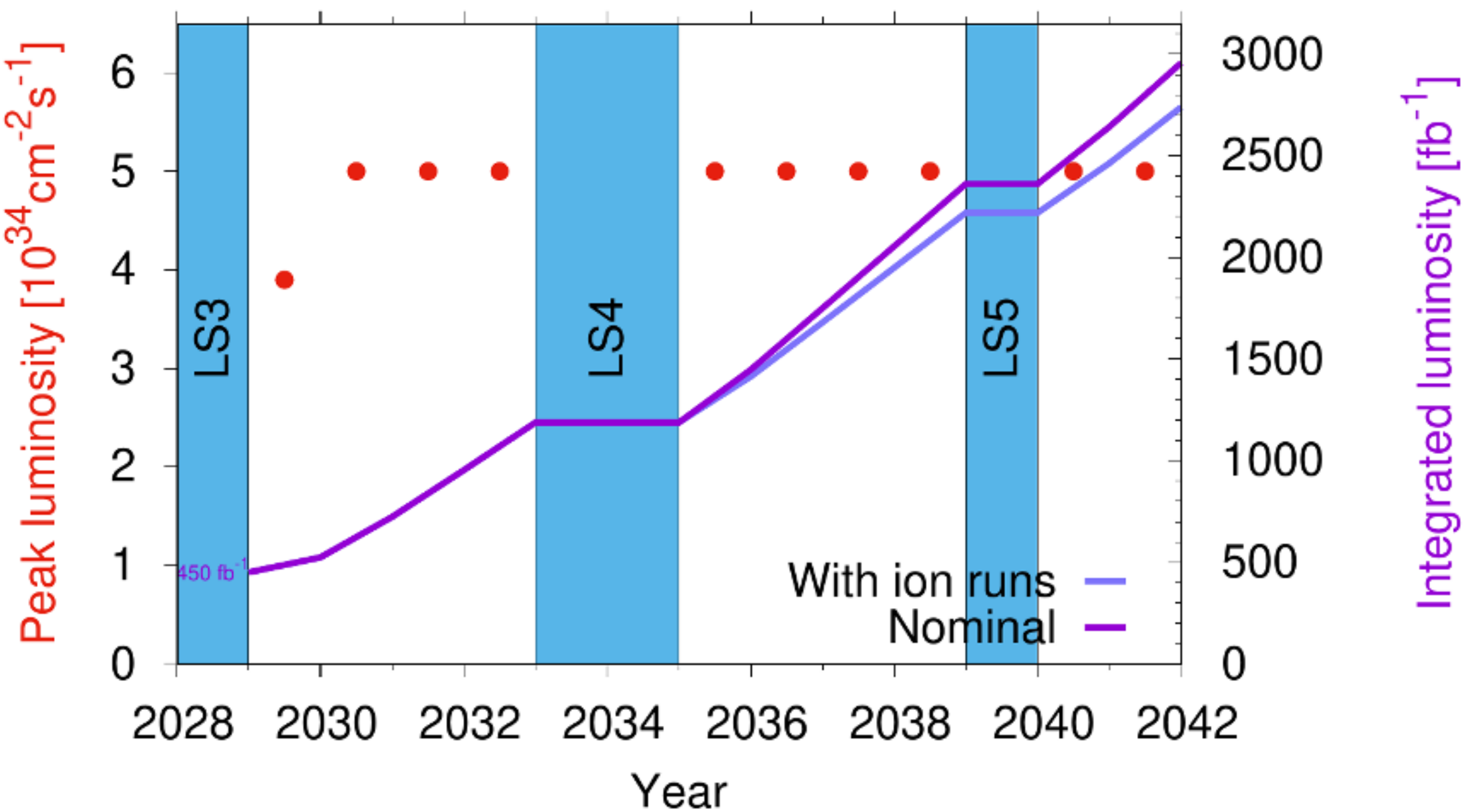
Yes, we should come up with more.

Experimental guidance will be so much needed!

For now (and next decades)



For now (and next decades)



Central question: how to extract max info from this mountain of data?

What can (HL)-LHC do?

Precision

Are we really sure the SM is it appears to be?

This is the “bread and butter”.

Prime target, the Higgs boson

Why focusing on Higgs?

Higgs is confusing.

Sure, the math is simple.
It does not give us clues for a deeper understanding.

Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)

Why focusing on Higgs?

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Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)

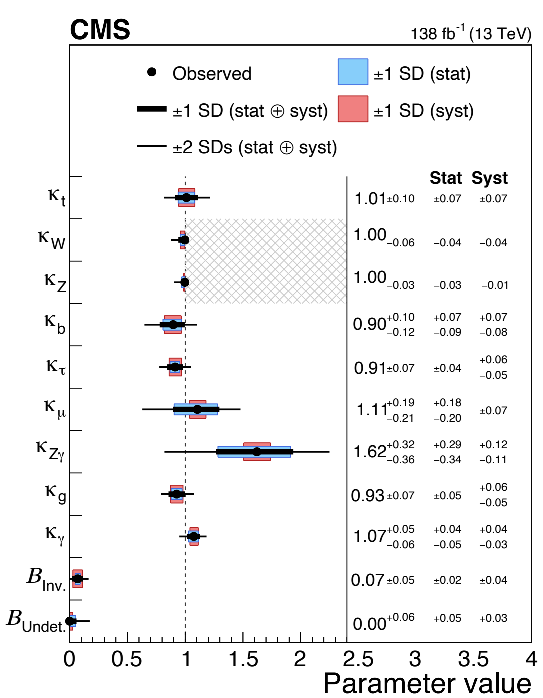
Maybe not as simple as it seems?

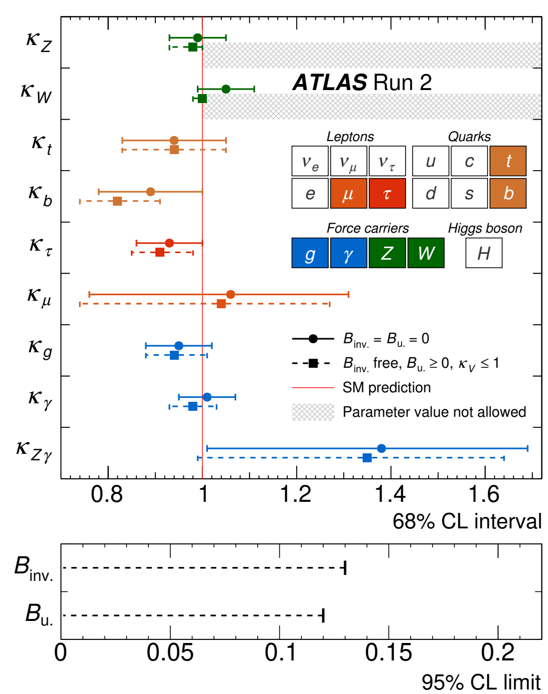
Is it elementary (like electron) or composite (like proton or pion)?

Is the Higgs the only spin-0 particle, or there are similar ones?

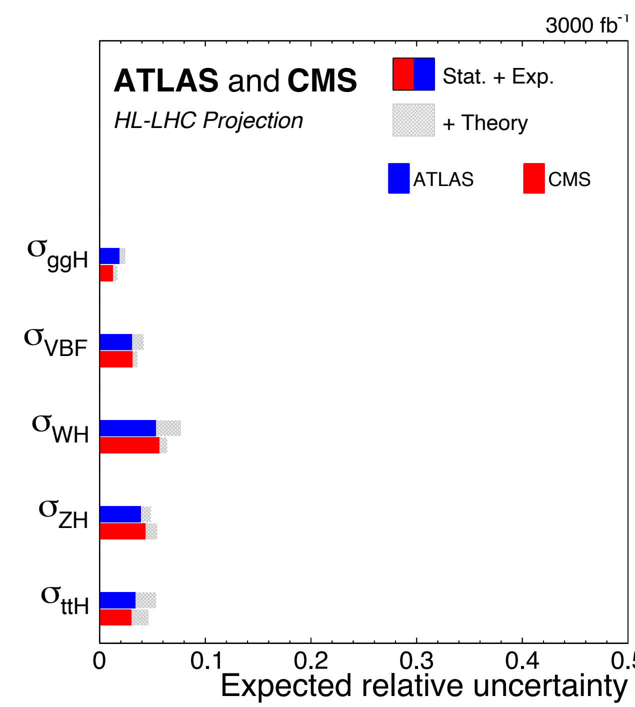
Higgs coupling

Higgs coupling other SM particles:





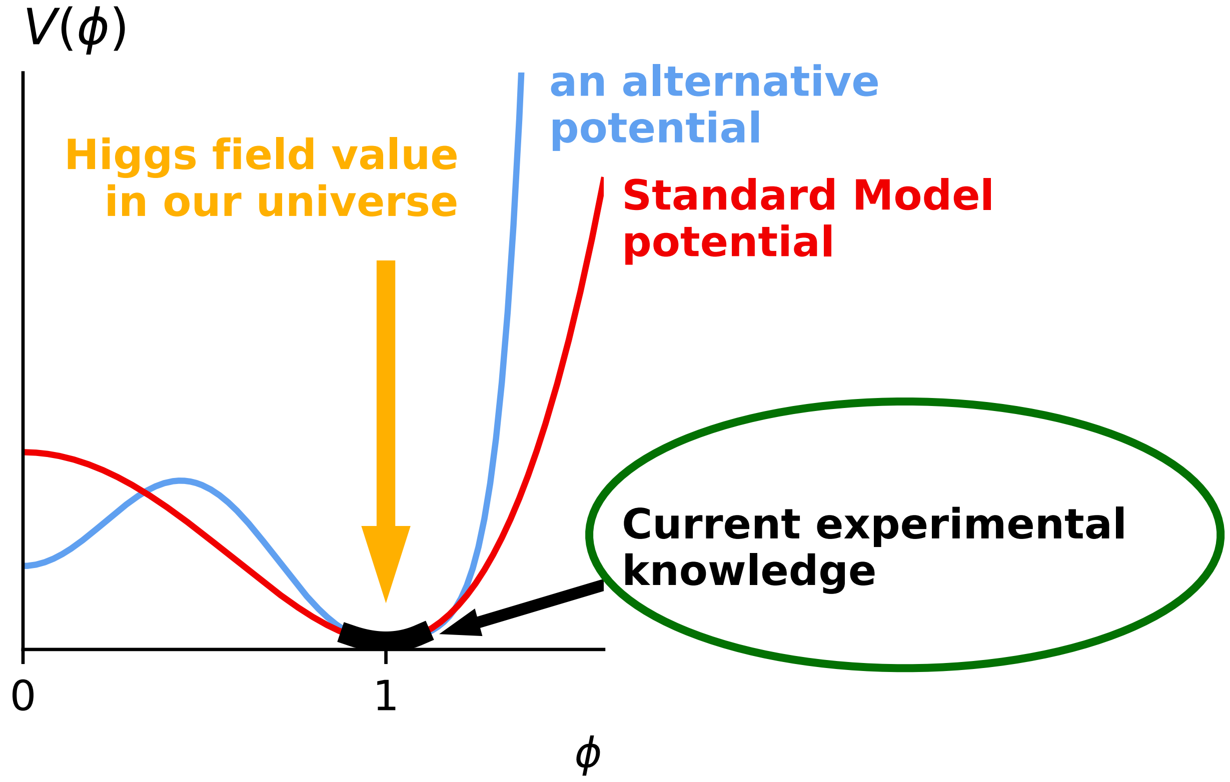
Eventually at the LHC



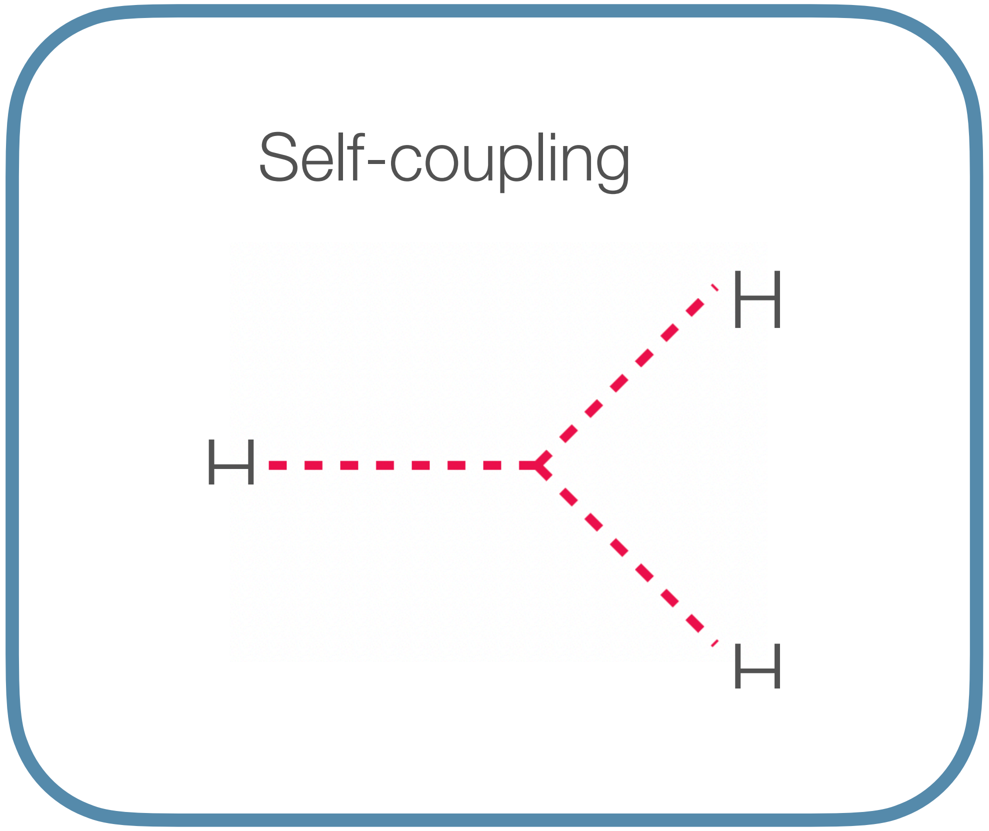
Higgs couplings. Presently, known to about 10%

1- a few %

Higgs potential



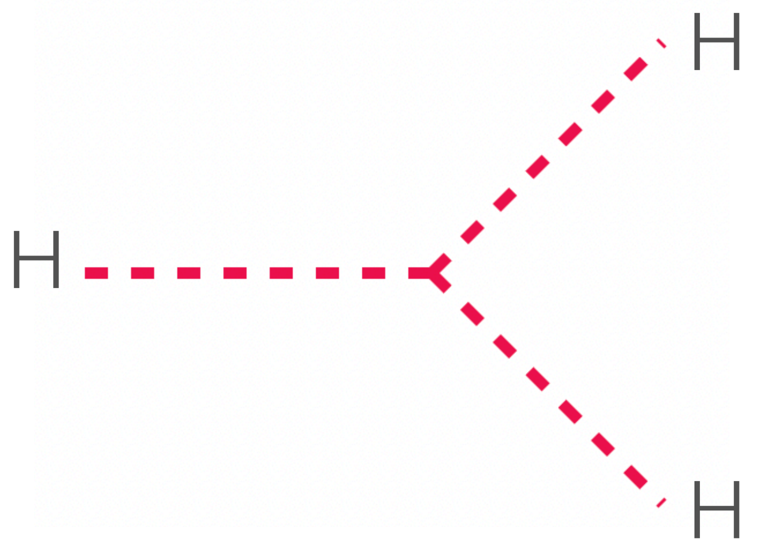
Need to go beyond this



A big focus for LHC

Comments on di-Higgs

Self-coupling



Unique kind of coupling.
Important to observe it!

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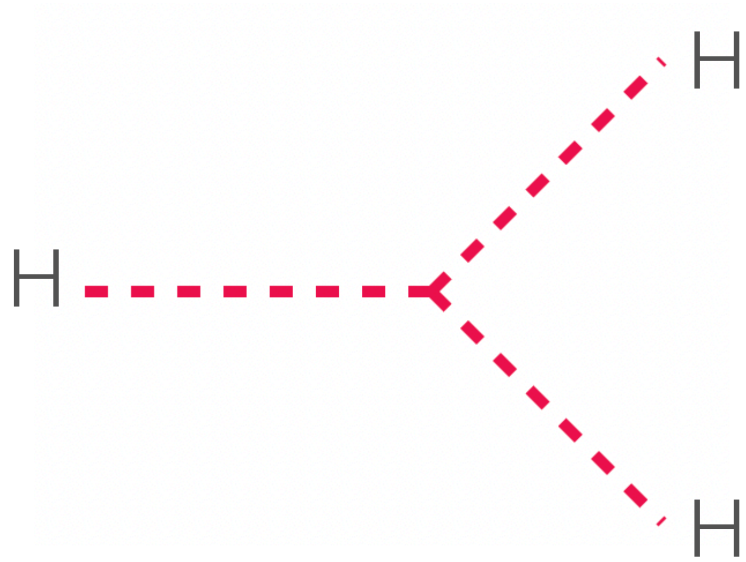
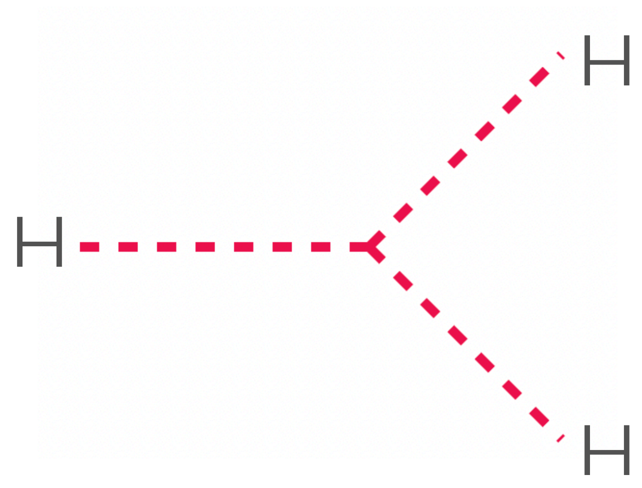


Unique kind of coupling.
Important to observe it!

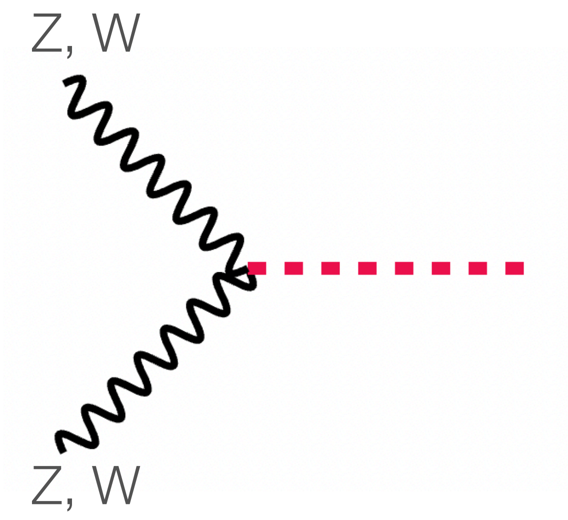
However, is this also a unique place to look for new physics?

It is unlikely new physics only shows up in self-coupling.

Self-coupling



New physics often induce changes in other Higgs coupling, such as hZ



hZZ vs Higgs self-coupling

$$\frac{1}{\Lambda^2}(H^\dagger \partial H)^2$$

$$\frac{1}{\Lambda^2}(H^\dagger H)^3$$

⇩

Modify H-Z coupling $\Rightarrow \delta_{Zh}$

Modify Higgs self-coupling $\Rightarrow \delta_{\lambda_3}$

hZZ vs Higgs self-coupling

$$\frac{1}{\Lambda^2}(H^\dagger \partial H)^2$$

$$\frac{1}{\Lambda^2}(H^\dagger H)^3$$

Modify H-Z coupling ⇒ δ_{Zh}

Modify Higgs self-coupling ⇒ δ_{λ_3}

No special symmetry, both will generally be there.

All dim-6 operator ⇒ similar size of modification

H-Z coupling much better measured, in principle more sensitive.

hZZ vs Higgs self-coupling

$$\frac{1}{\Lambda^2}(H^\dagger \partial H)^2$$

⇩

Modify H-Z coupling $\Rightarrow \delta_{Zh}$

$$\frac{1}{\Lambda^2}(H^\dagger H)^3$$

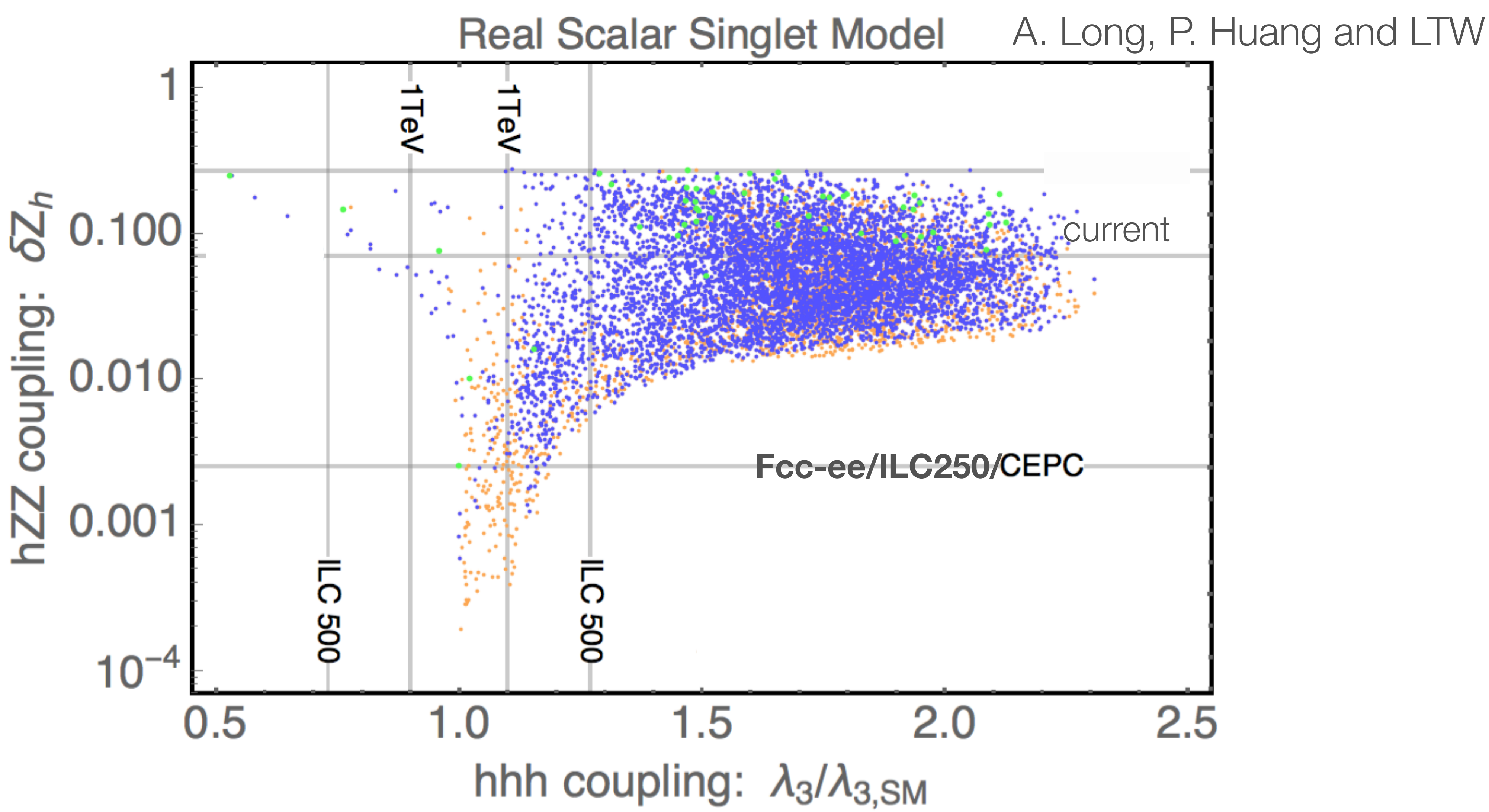
⇩

Modify Higgs self-coupling $\Rightarrow \delta_{\lambda_3}$

However, $\delta_{Zh} \propto g_z$, while δ_{λ_3} is not related to $\lambda_{3,\mathrm{SM}}$

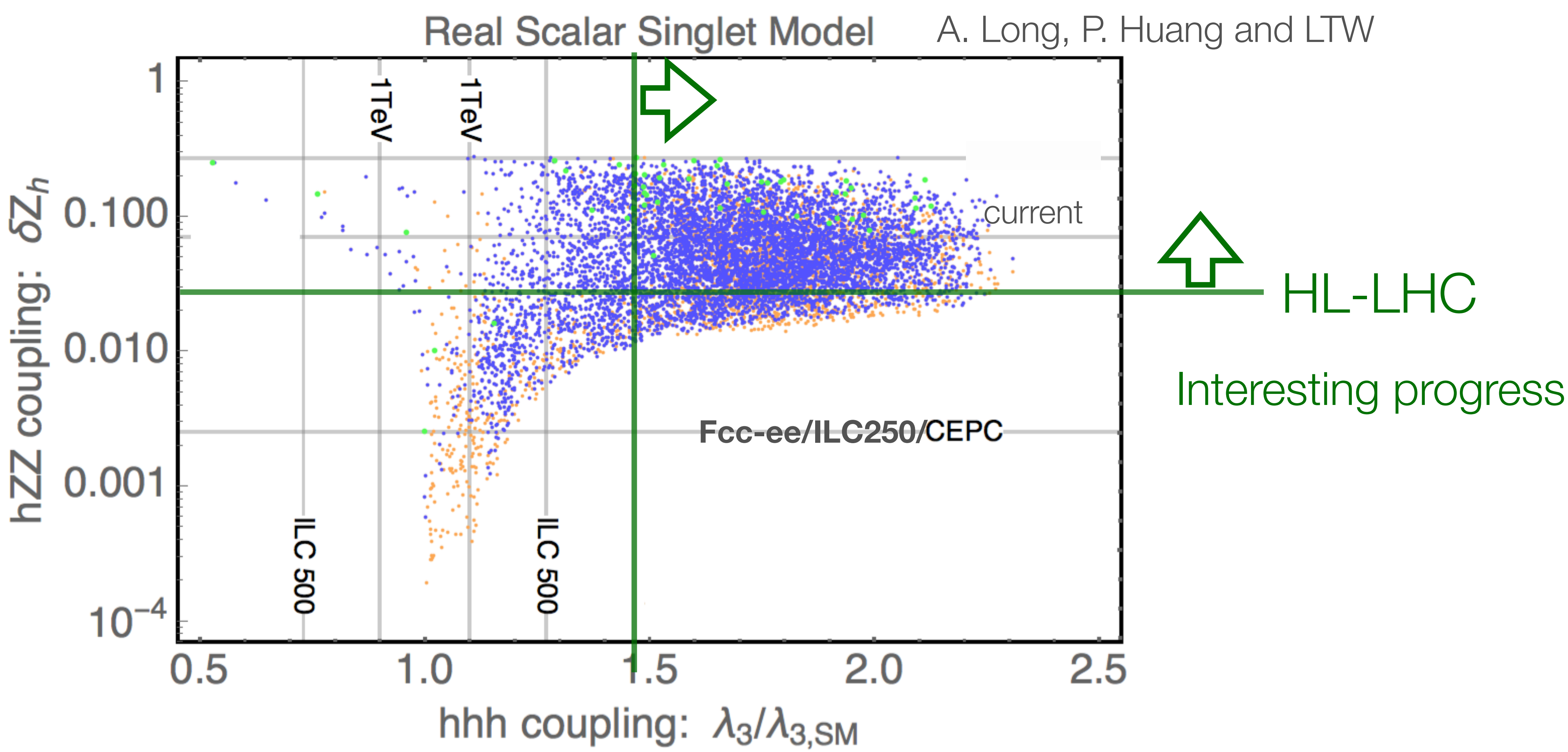
With some tuning, one can find models in which $\delta_{\lambda_3} > \delta_{Zh}$

Example: EW phase transition



Singlet + Higgs Models with 1st order EWSB, need large self-interaction

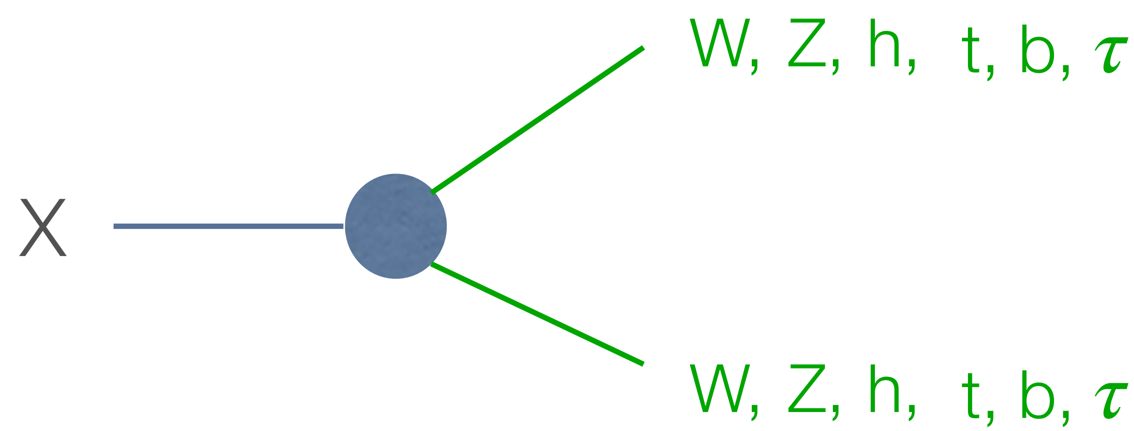
Example: EW phase transition



Singlet + Higgs Models with 1st order EWSB, need large self-interaction

di-Higgs search for resonances

X, spin 0, 1, 2



From for heavy X (~TeV), as a consequence of Goldstone equivalence theorem and SU(2) invariance,

the decay BR can be fixed

For example, for spin 0 and spin 2 resonances:

$$\mathrm{BR}(X \to ZZ) \simeq \mathrm{BR}(X \to hh) \simeq 0.5 \times \mathrm{BR}(X \to WW)$$

Is there a case in which di-higgs has an advantage?

Busy Higgs signal

Now consider coupling:

$$S(H^\dagger H)^n, \text{ with } n > 1 \qquad H^\dagger H = \frac{1}{2}\left((v+h)^2 + \sum_{i=0}^{2} a_i^2\right)$$

We have:

$$S(H^\dagger H)^n \propto (v^2)^{n-1} S\left(\Sigma_i a_i^2 \binom{n}{1} + h^2 \binom{n}{1} + 4h^2 \binom{n}{2} + \dots\right)$$

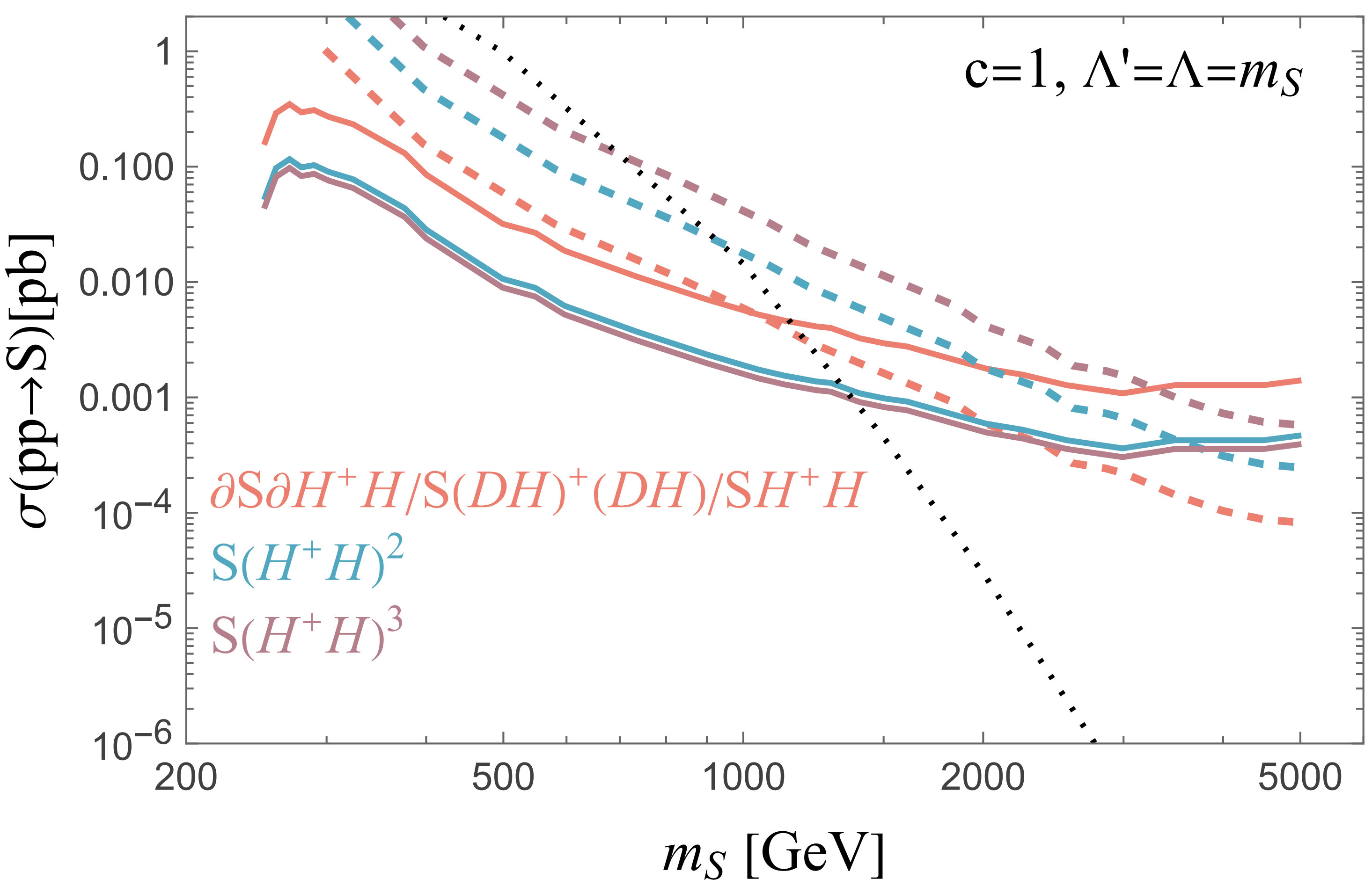
And:

$$\Gamma(S \to hh) : \Gamma(S \to WW) : \Gamma(S \to ZZ) = (2n-1)^2 : 2 : 1$$

An enhancement for the di-Higgs channel.

Could make a difference

$$\mathcal{L} \supset \frac{c_n}{\Lambda^{2n-3}} S(H^\dagger H)^n \quad \text{with} \quad n \geq 2.$$



Dashed: di-gauge boson

Solid: di-Higgs

Peiran Li, Zhen Liu, LTW in progress

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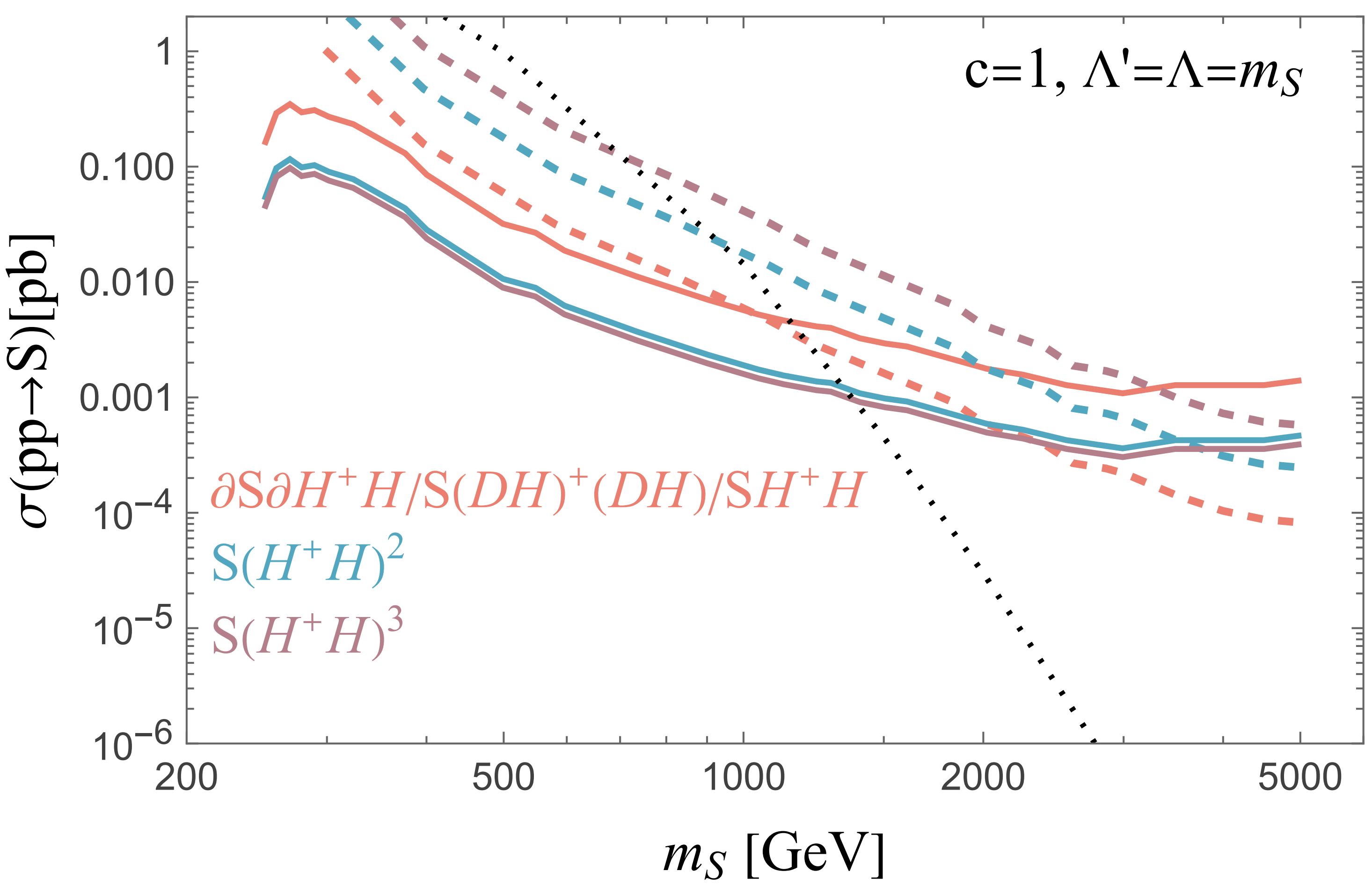


Dashed: di-gauge boson

Solid: di-Higgs

Peiran Li, Zhen Liu, LTW in progress

Caution: a rather special case. Not a generic signal.

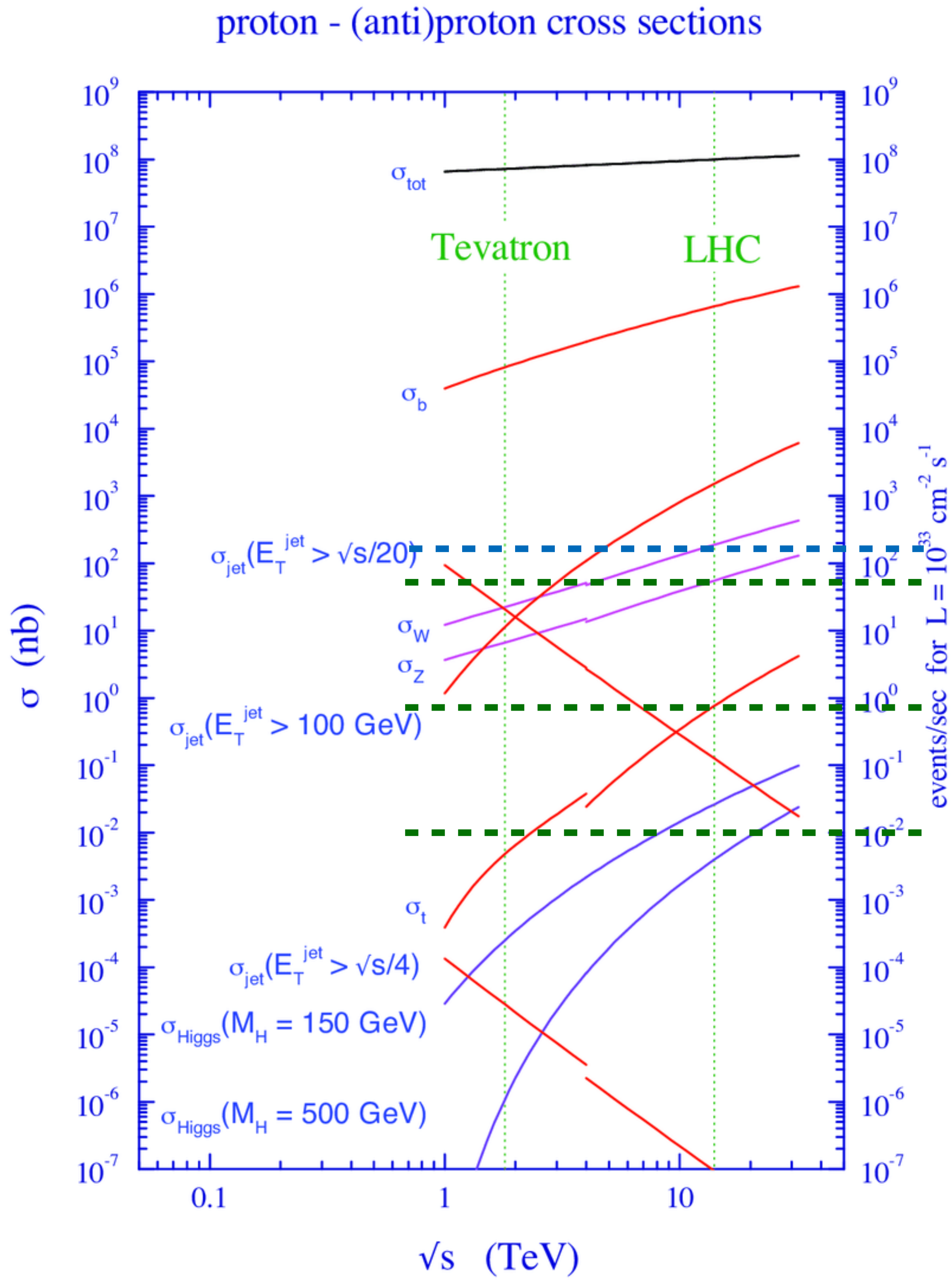
What can (HL)-LHC do?

Rare processes

Unlikely, but seeing one can teach us a lot.

Large luminosity leads to big improvements.

HL-LHC as particle factories



HL-LHC

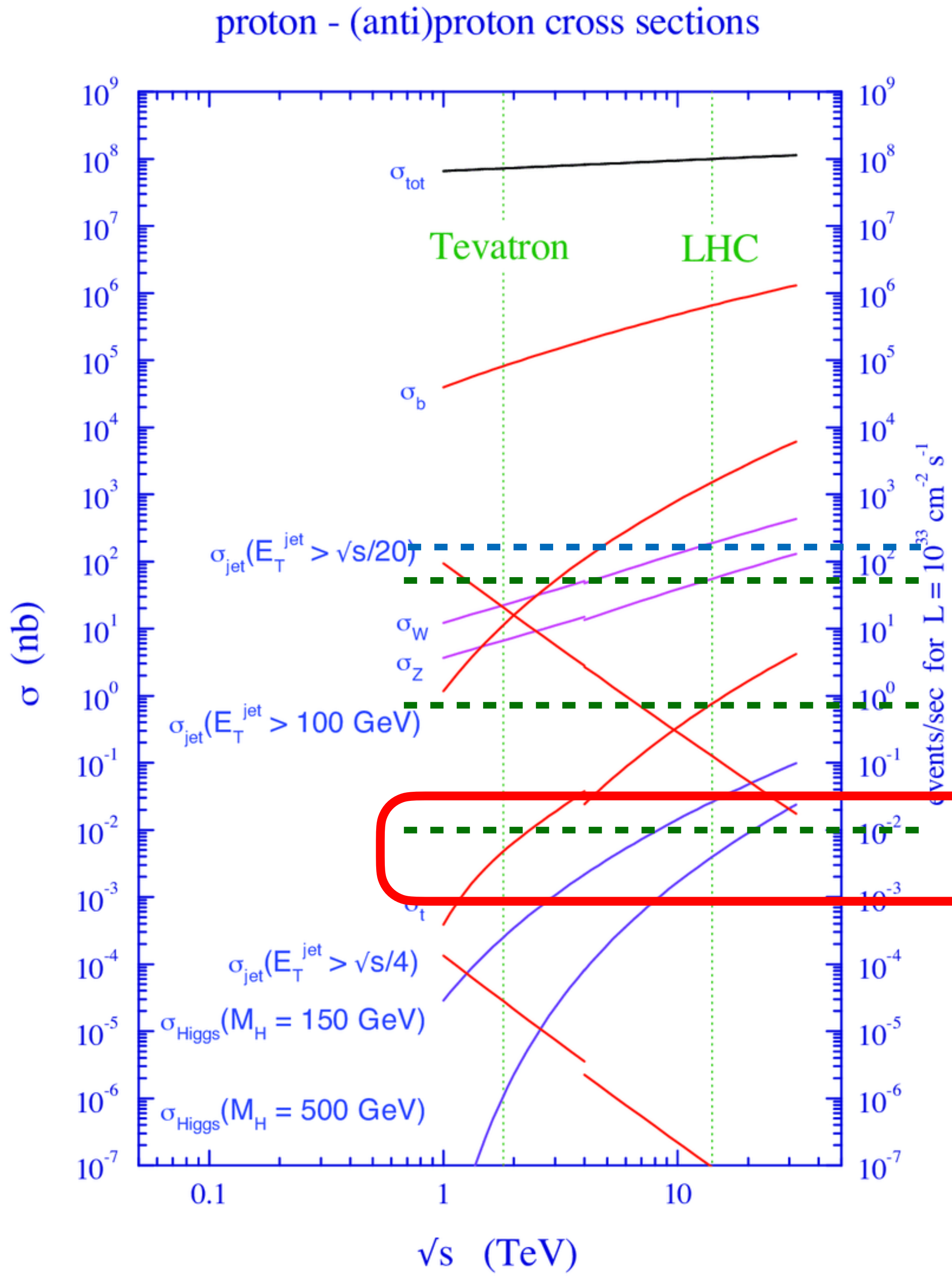
> 10^{11} W and Zs

> 10^9 tops

> 10^8 Higgses

Promising for rare decay with distinct final state!

HL-LHC as particle factories



HL-LHC

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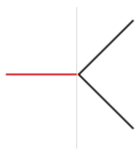
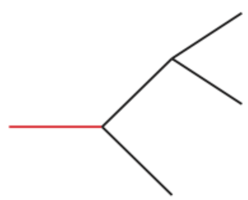
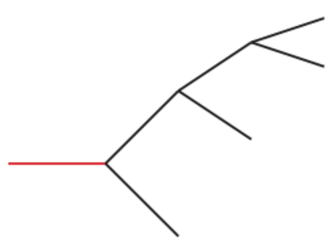
Higgs exotic decays

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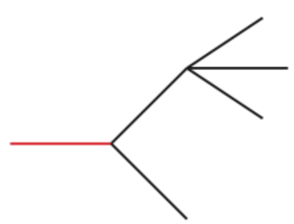
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
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	$h \to \ell^+\ell^- + \not{E}_T$

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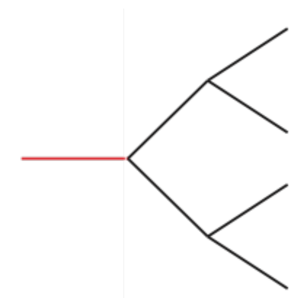
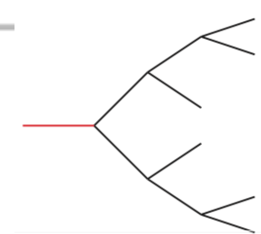
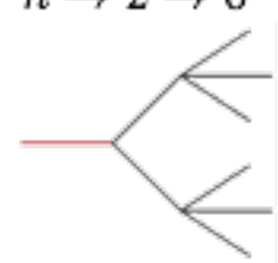
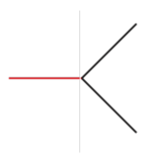
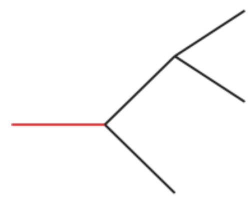
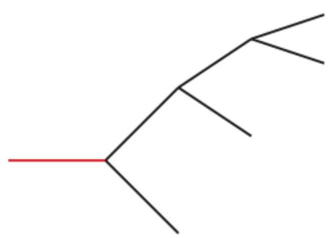
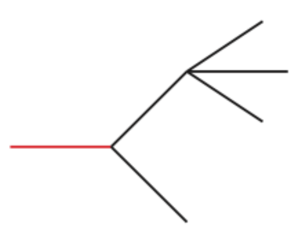
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$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

Higgs exotic decays

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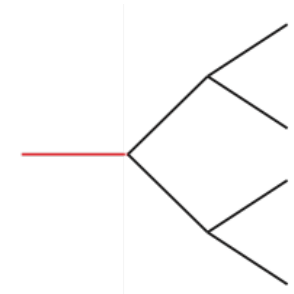
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
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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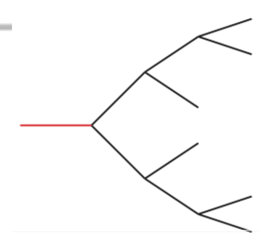
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
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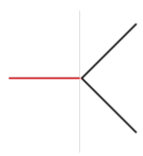
Simple, Great sensitivity from the LHC

Higgs exotic decays



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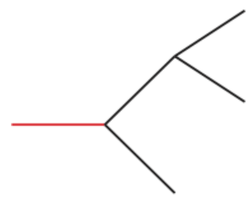
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
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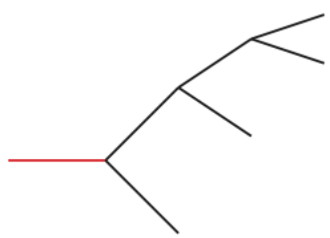
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$
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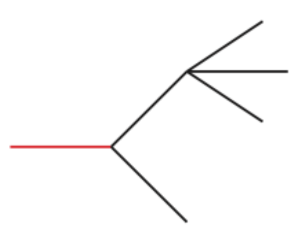
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
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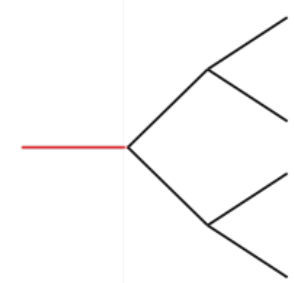
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
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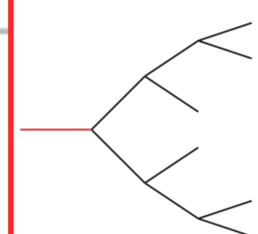
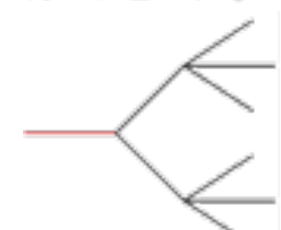
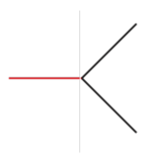
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$

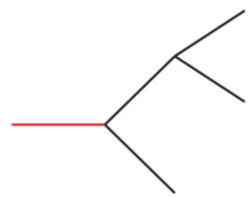
Simple, Great sensitivity from the LHC

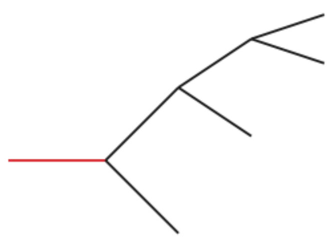
With MET, less lepton

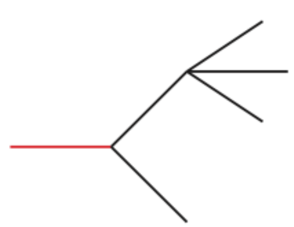
Higgs exotic decays



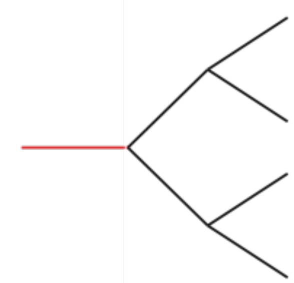
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$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

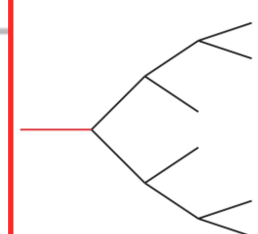






Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$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



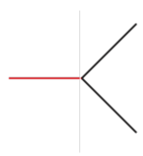


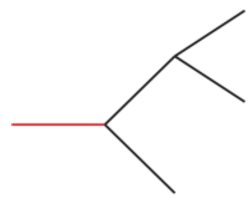
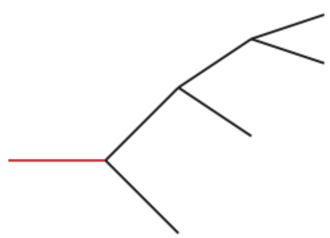
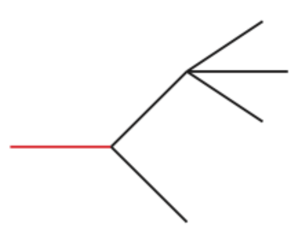
Simple, Great sensitivity from the LHC

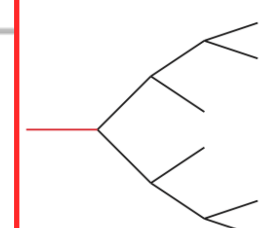
With MET, less lepton

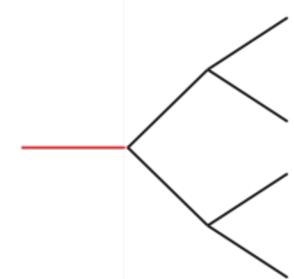
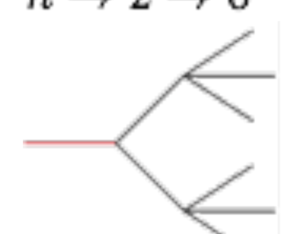
More hadronic

Higgs exotic decays



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

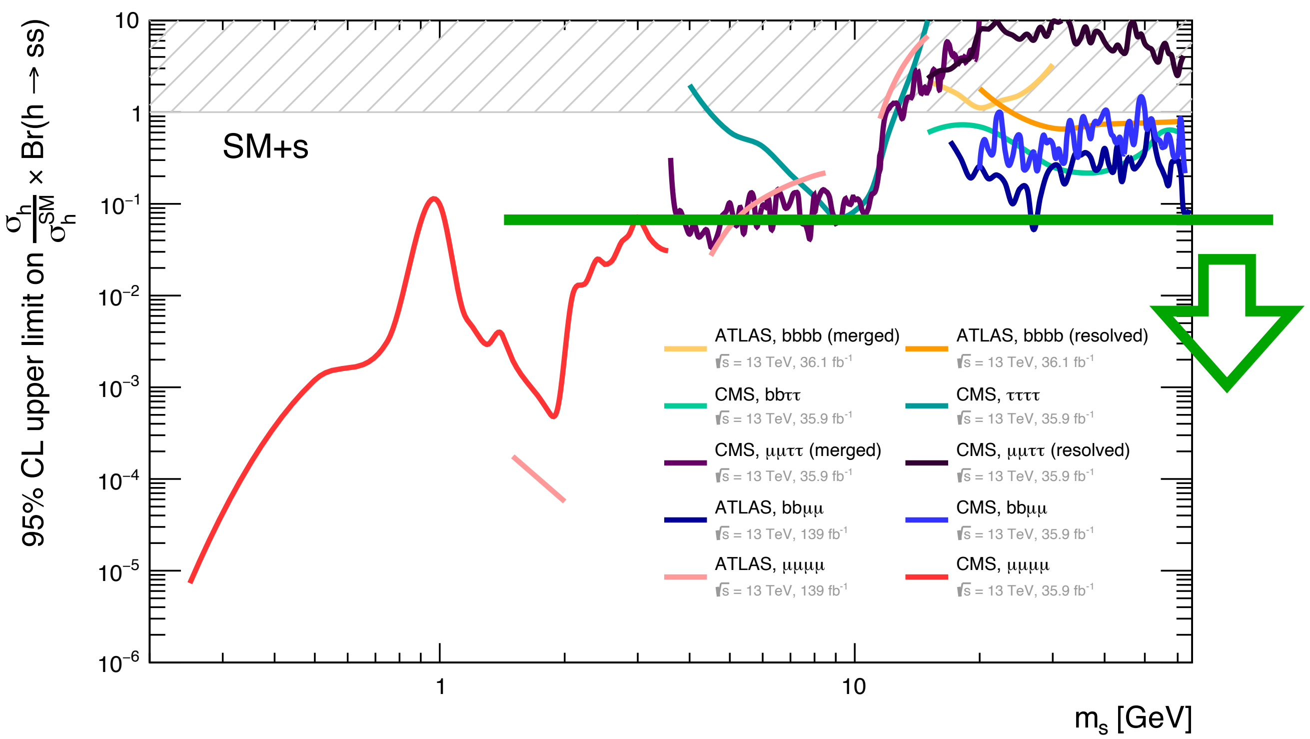
Simple, Great sensitivity from the LHC

With MET, less lepton

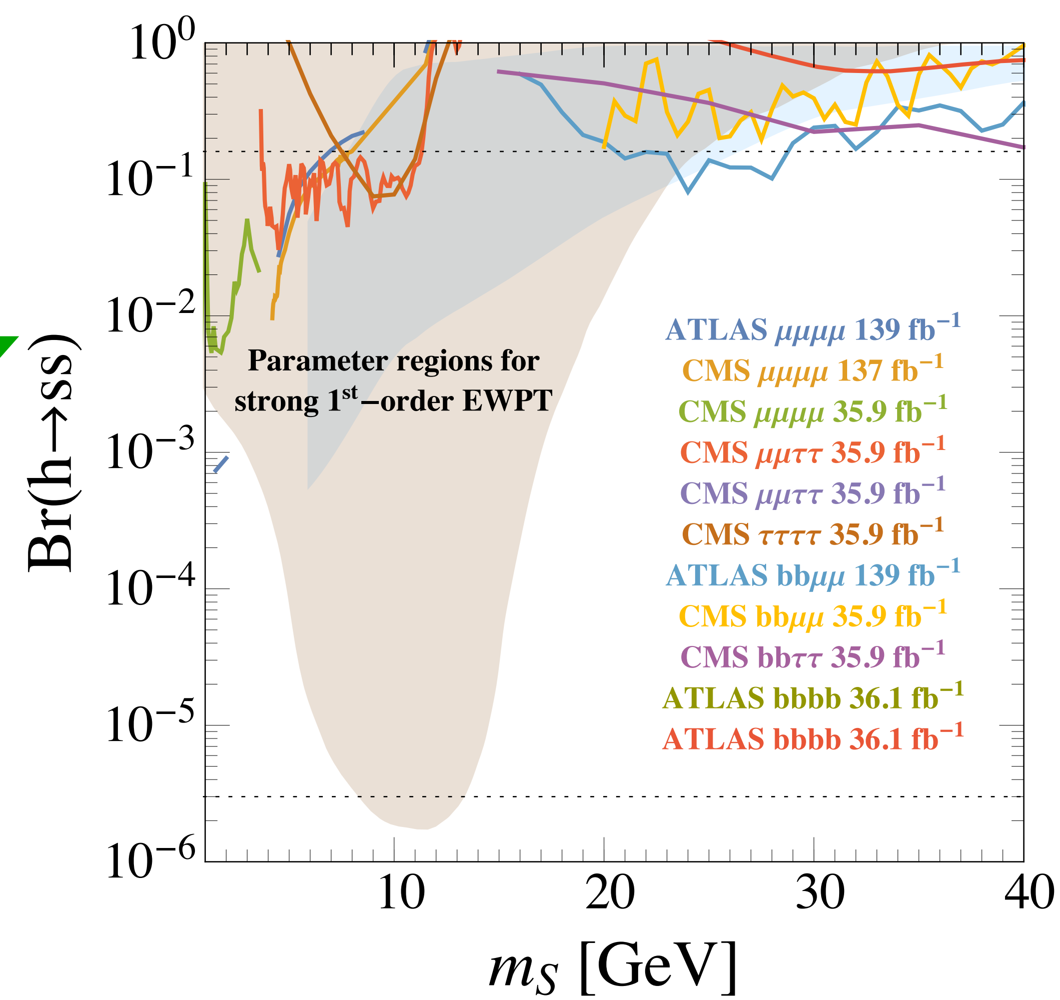
More hadronic

More challenging, but worth pursuing!

Interesting target:
1st order EW phase transition



A lot of room to improve!



M. Carena, J. Kozaczuk, Z. Liu, T. Ou, M. Ramsey-Musolf, J. Shelton, Y. Wang, K. Xie 2203.08206

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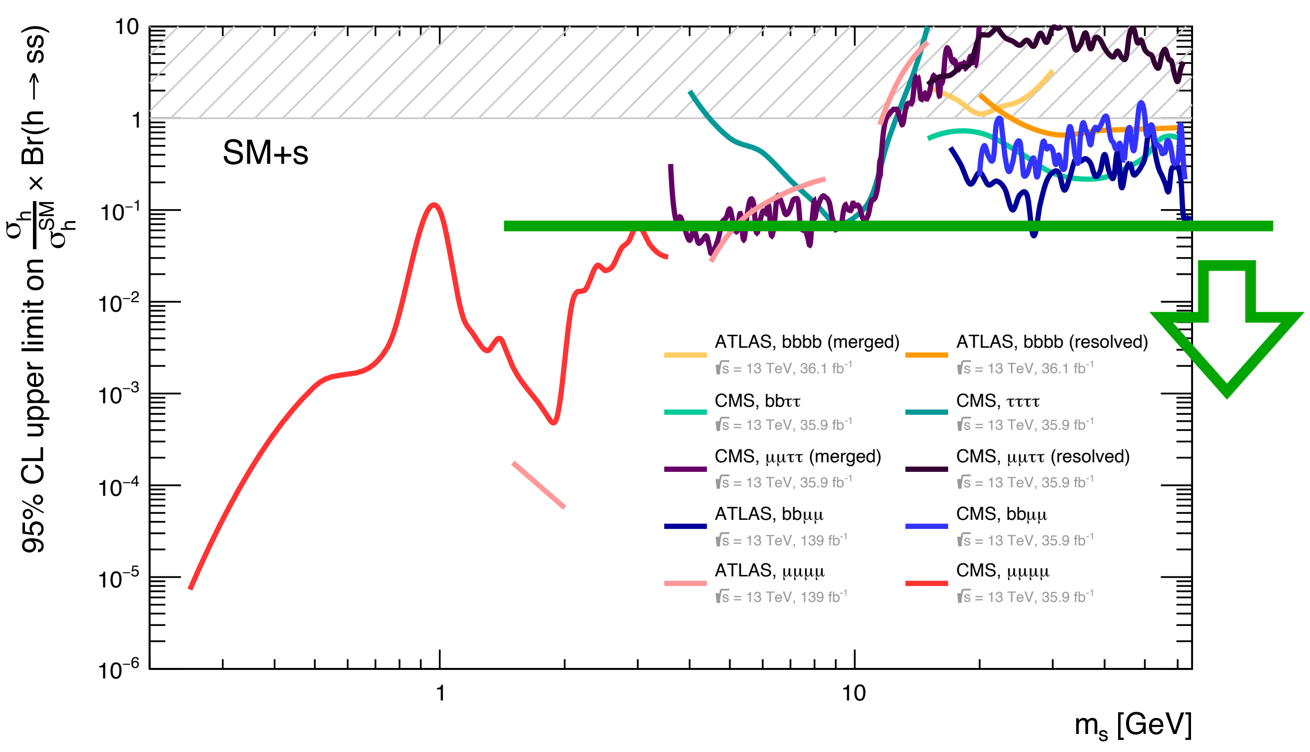

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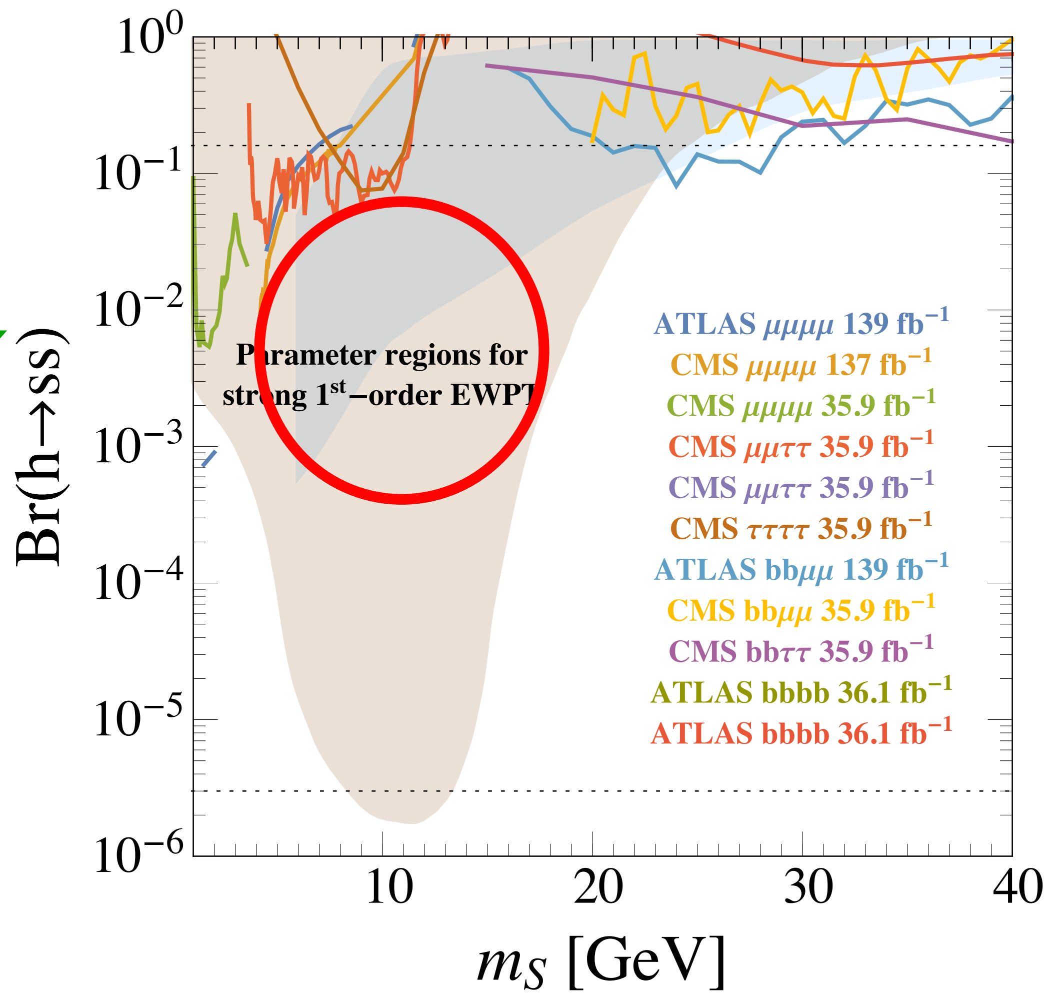

M. Carena, J. Kozaczuk, Z. Liu, T. Ou, M. Ramsey-Musolf, J. Shelton, Y. Wang, K. Xie 2203.08206

An interesting alternative

Model of a landscape, N scalars ϕ_i.

If each scalar has two vacua ⇒ 2^N vacua

Can be a large landscape for N >> 1 (e.g. $N \sim 10^2$)

R.-T. D'Agnolo, M. Ettengruber, LTW, 2512.18001

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$$\mathscr{L} \supset H^\dagger H \sum_{i,j} \frac{\lambda_{ij}}{N} \phi_i \phi_j + V(\phi), \qquad N \gg 1$$

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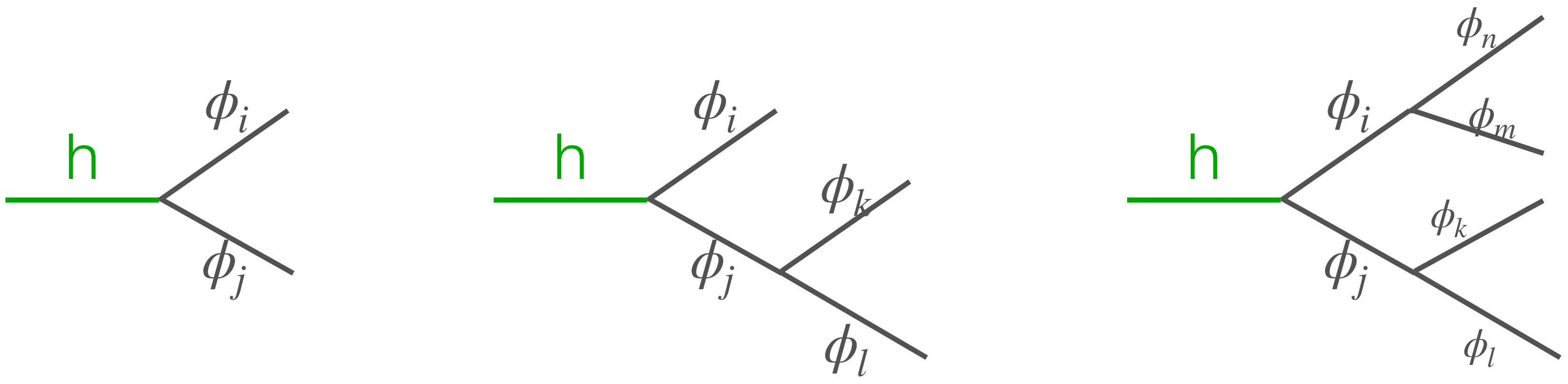
The scalars are also at weak scale. Obtaining mass from EWSB.

R.-T. D'Agnolo, M. Ettengruber, LTW, 2512.18001

Interesting alternative

Higgs decay into landscape scalars, long cascades



…

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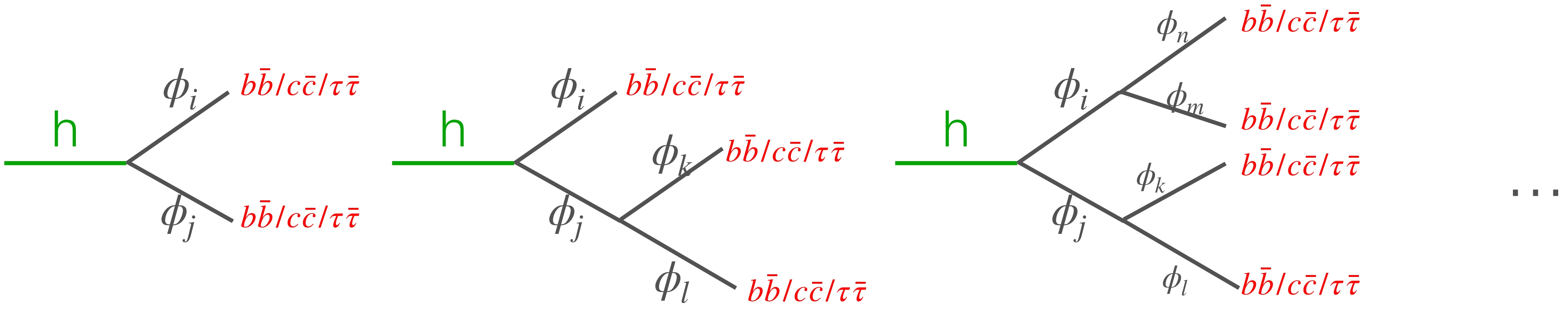
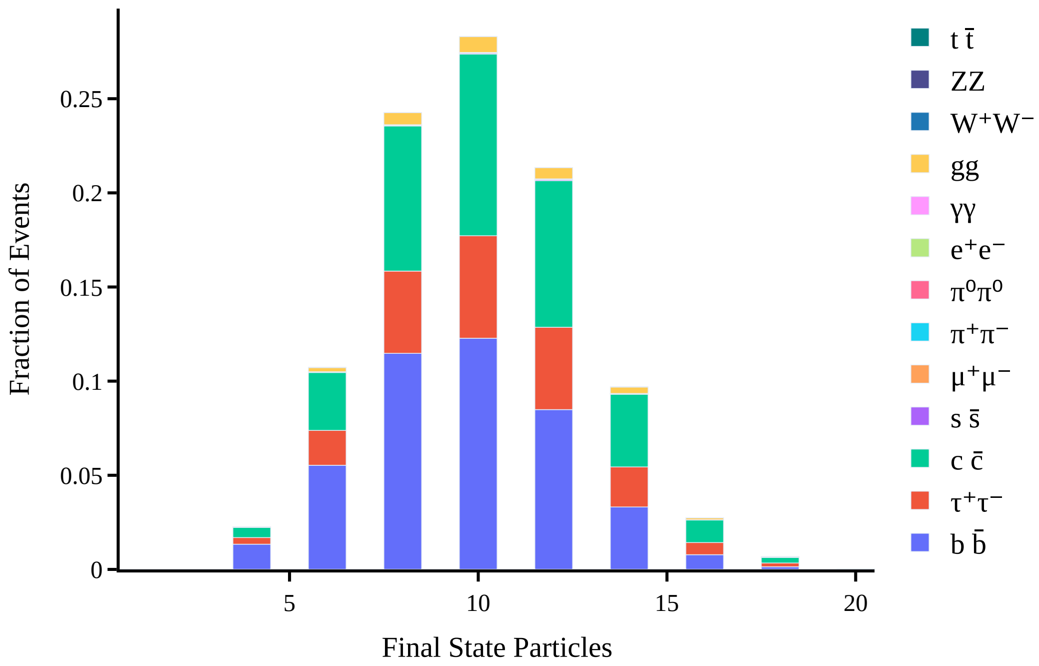
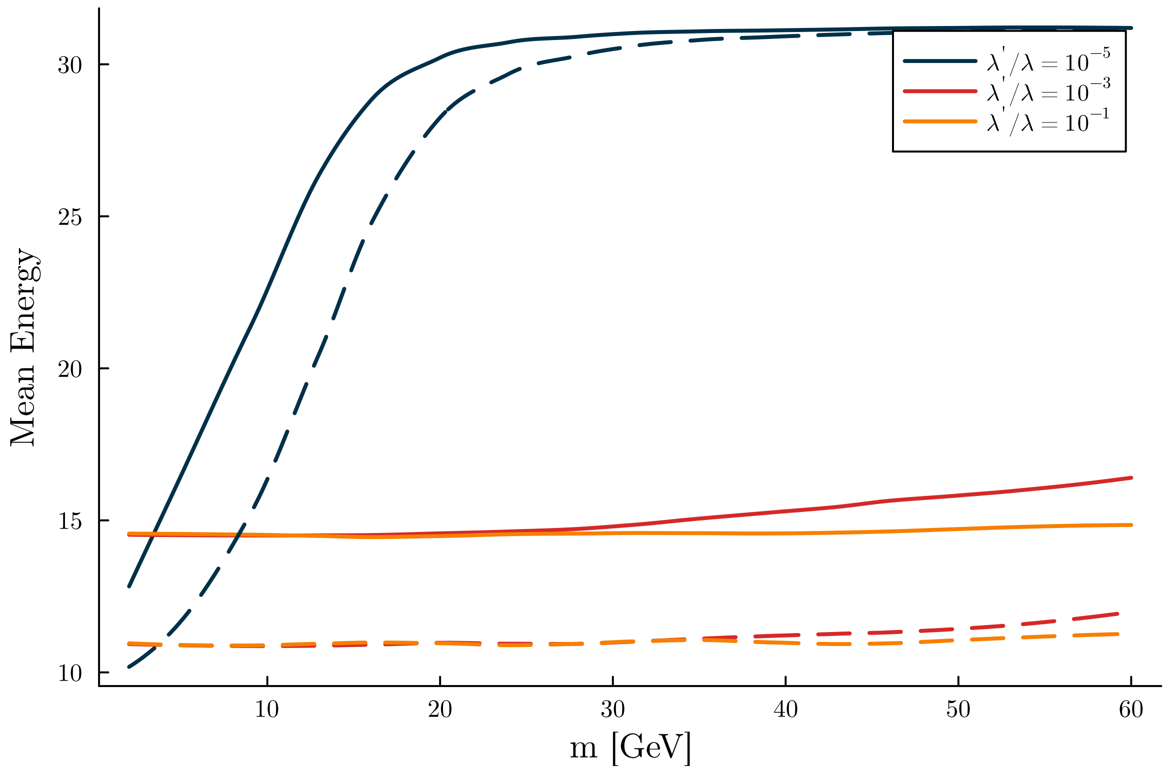


Decay from the Higgs

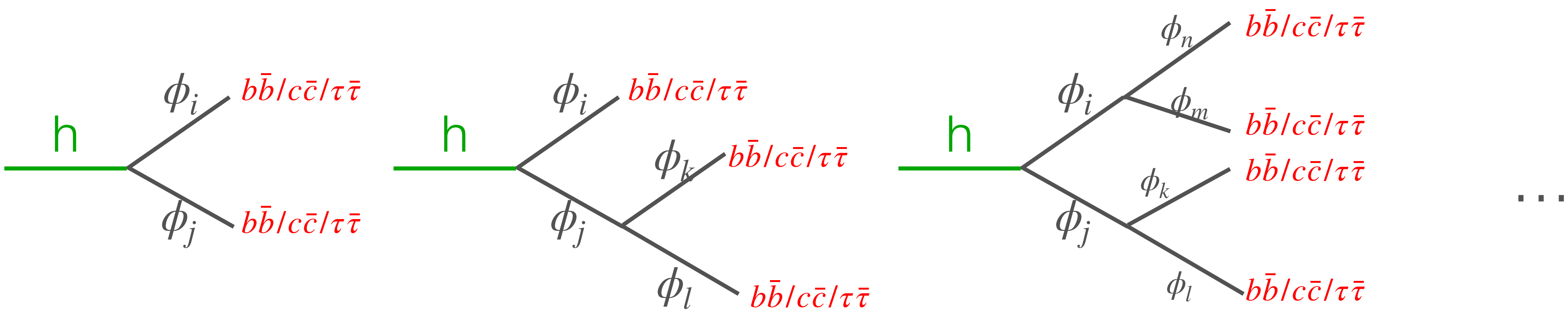




Longer cascade, higher final state multiplicity, softer decay products.

Interesting alternative

Higgs decay into landscape scalars, long cascades

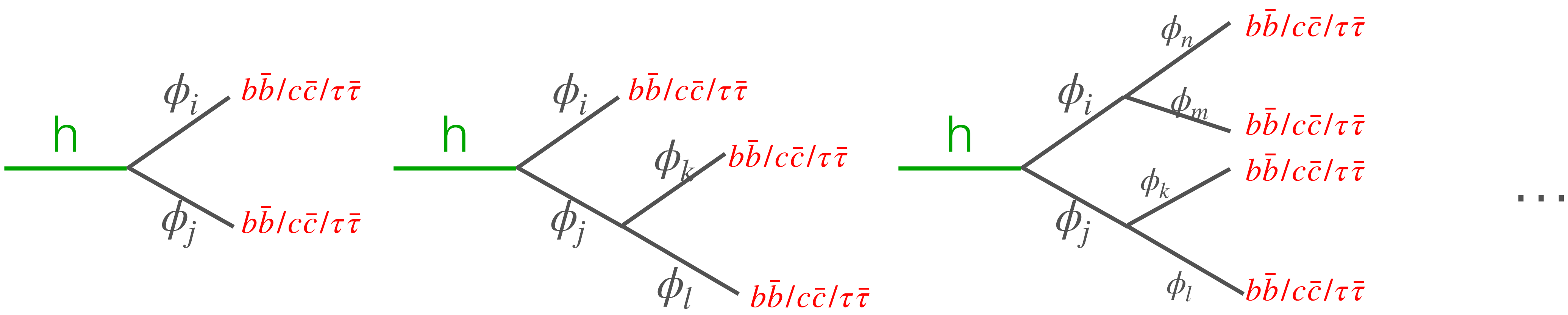


Rate into a particular final decay chain $\propto \lambda^2 \sim 1/N^2$, tiny.

However, many possible channels, total h → scalars can be sizable!

Interesting alternative

Higgs decay into landscape scalars, long cascades



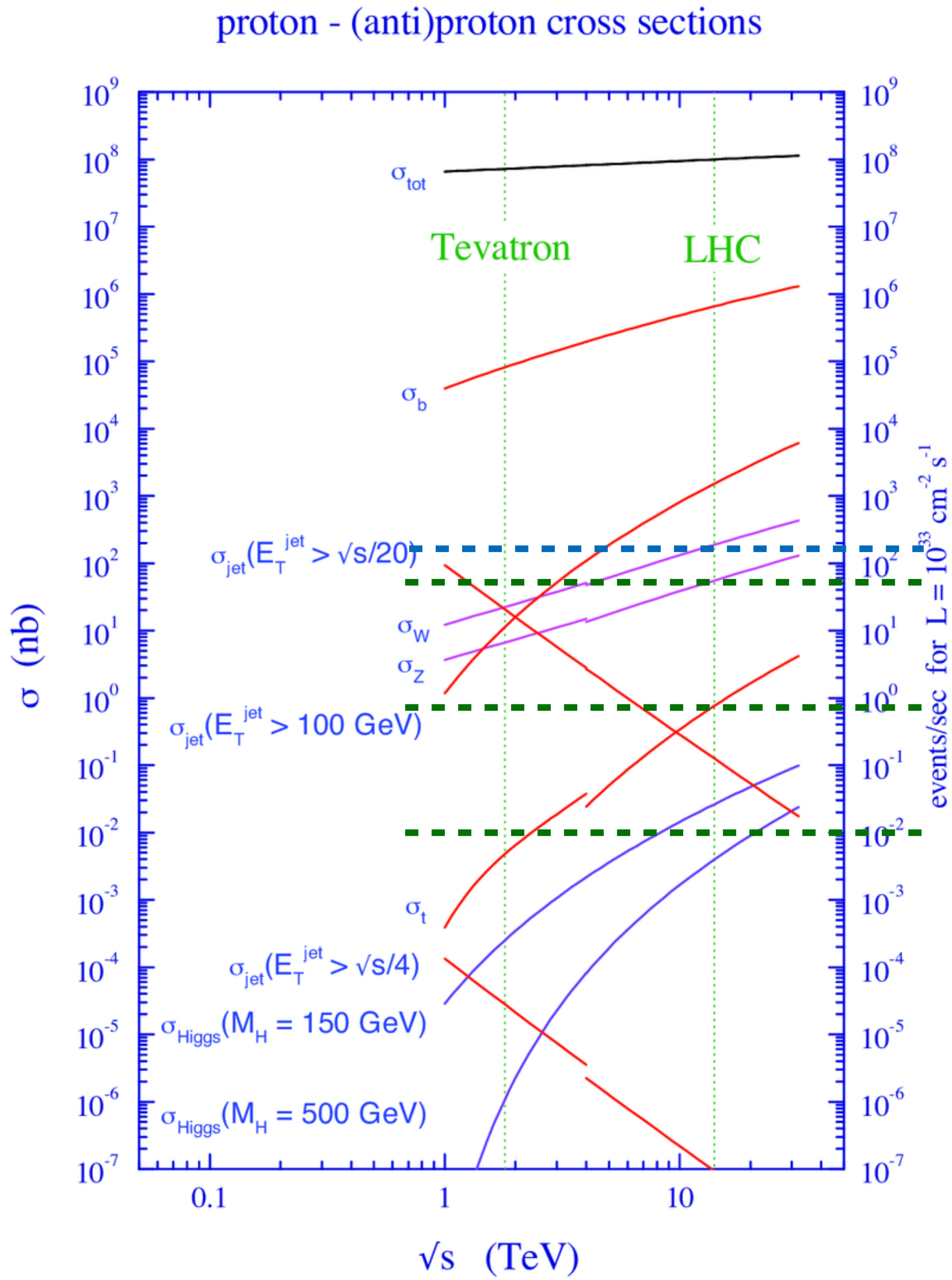
Rate into a particular final decay chain $\propto \lambda^2 \sim 1/N^2$, tiny.

However, many possible channels, total h → scalars can be sizable!

⇒ but not recontructing particular resonances.

Are we ready for this? S. Jung, Z. Liu, LTW, K. Xie 2109.03294

HL-LHC as particle factories



HL-LHC

> 10^{11} W and Zs

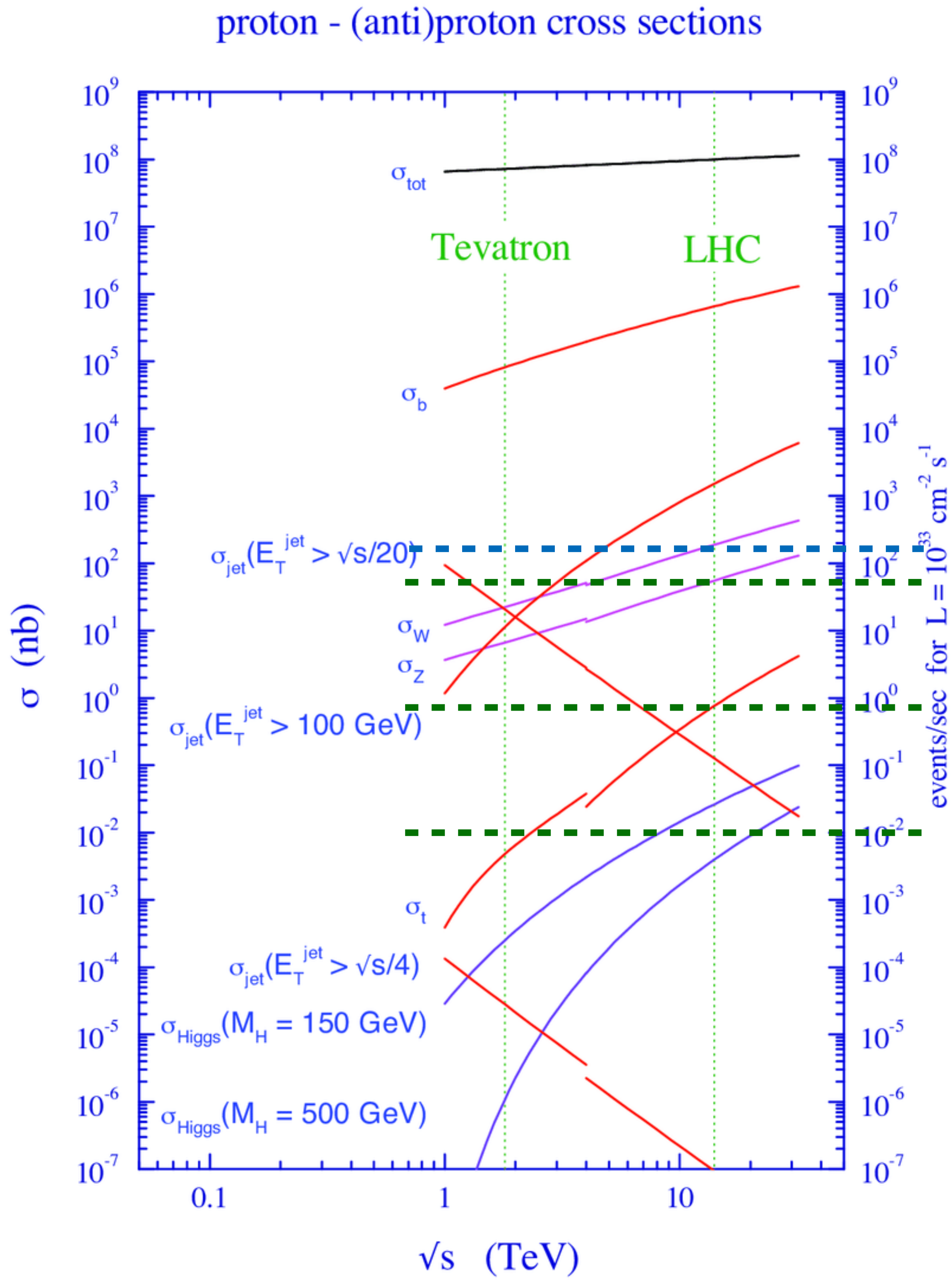
> 10^{9} tops

H. Bahl, S. Koren, LTW 2307.11154

> 10^{8} Higgses

Promising for rare decay with distinct final state!

HL-LHC as particle factories



HL-LHC

> 10^{11} W and Zs

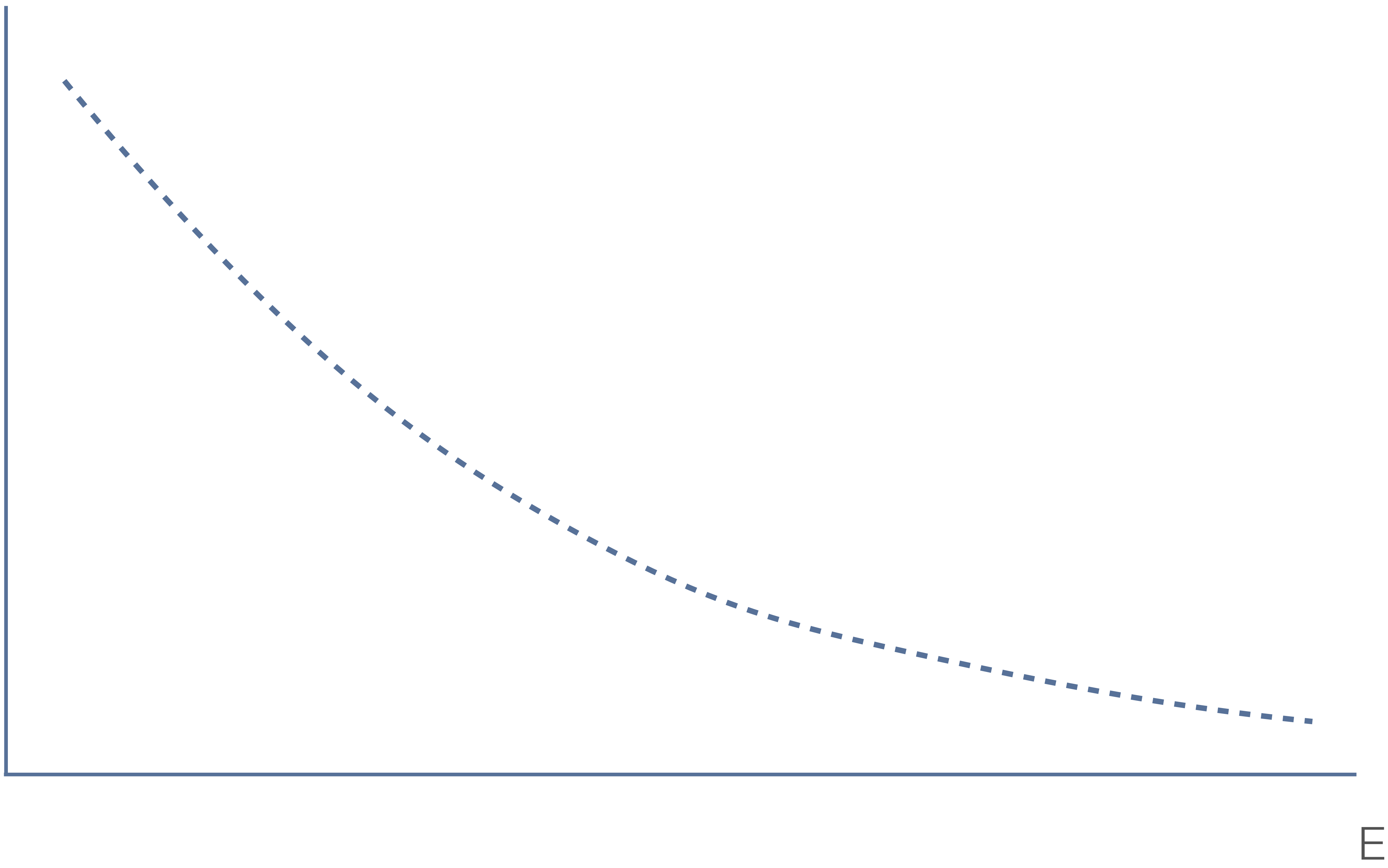
More studies and new ideas needed!

> 10^9 tops

> 10^8 Higgses

Promising for rare decay with distinct final state!

Unexpected: Form-factor



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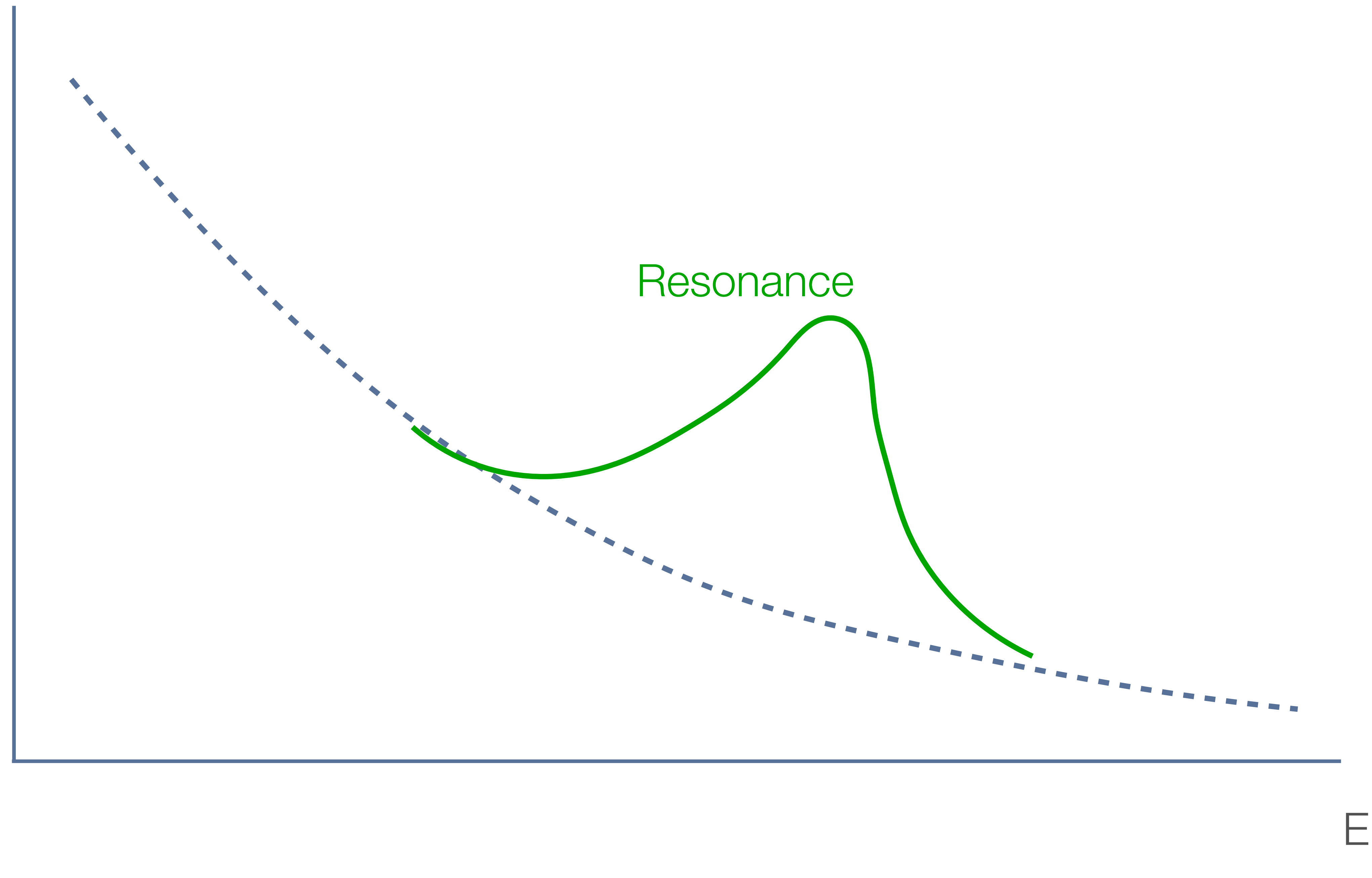
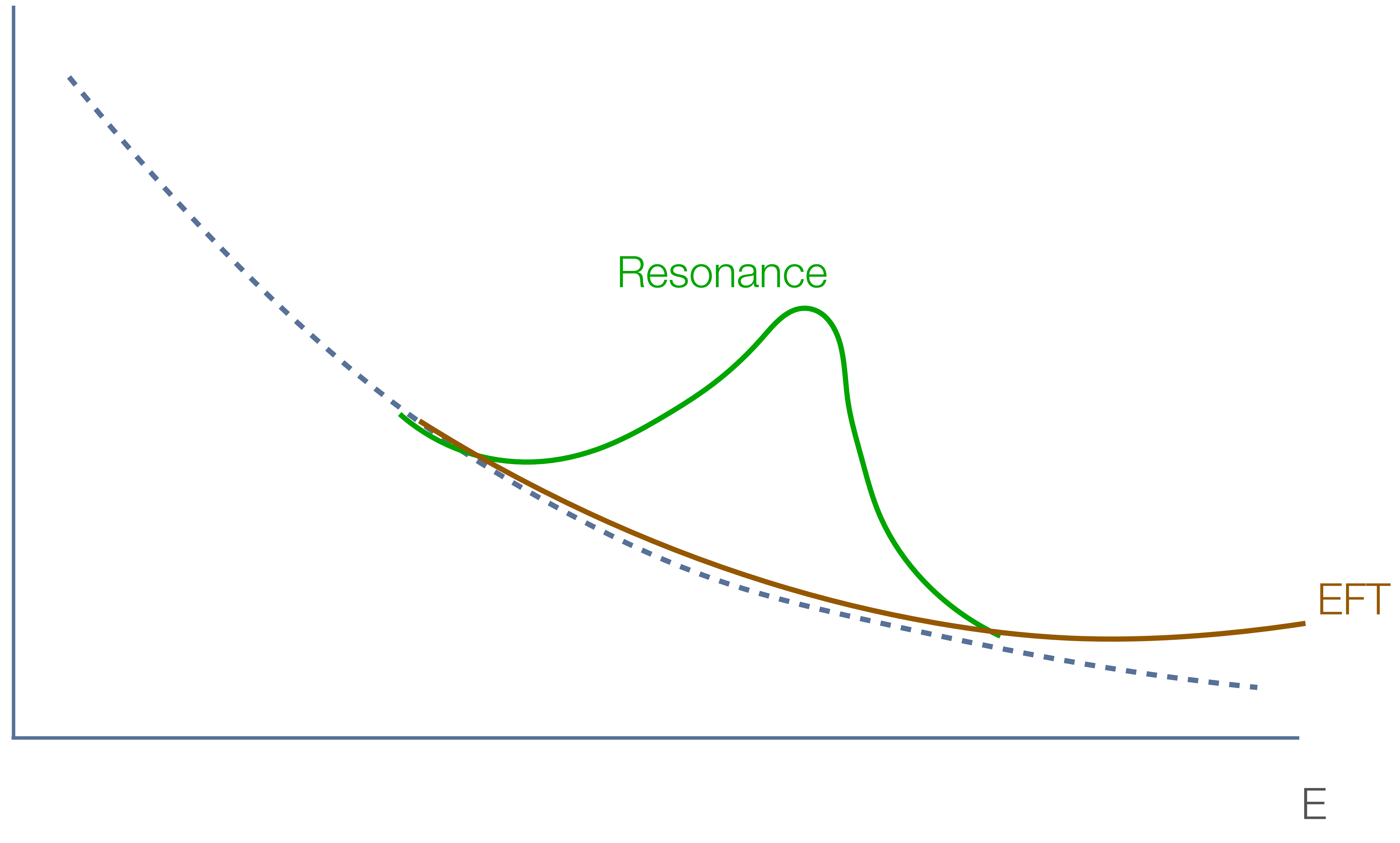
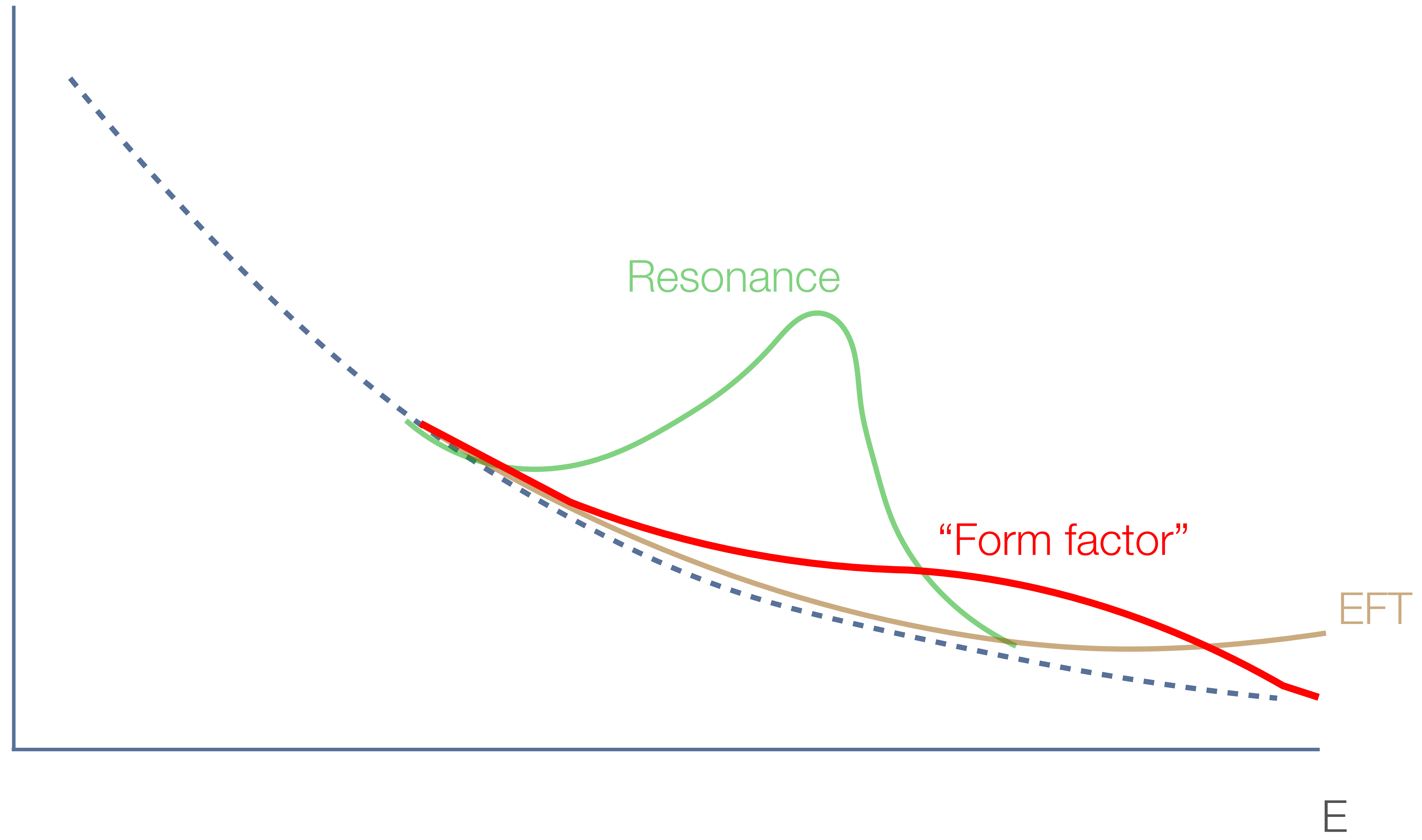


Unexpected: Form-factor

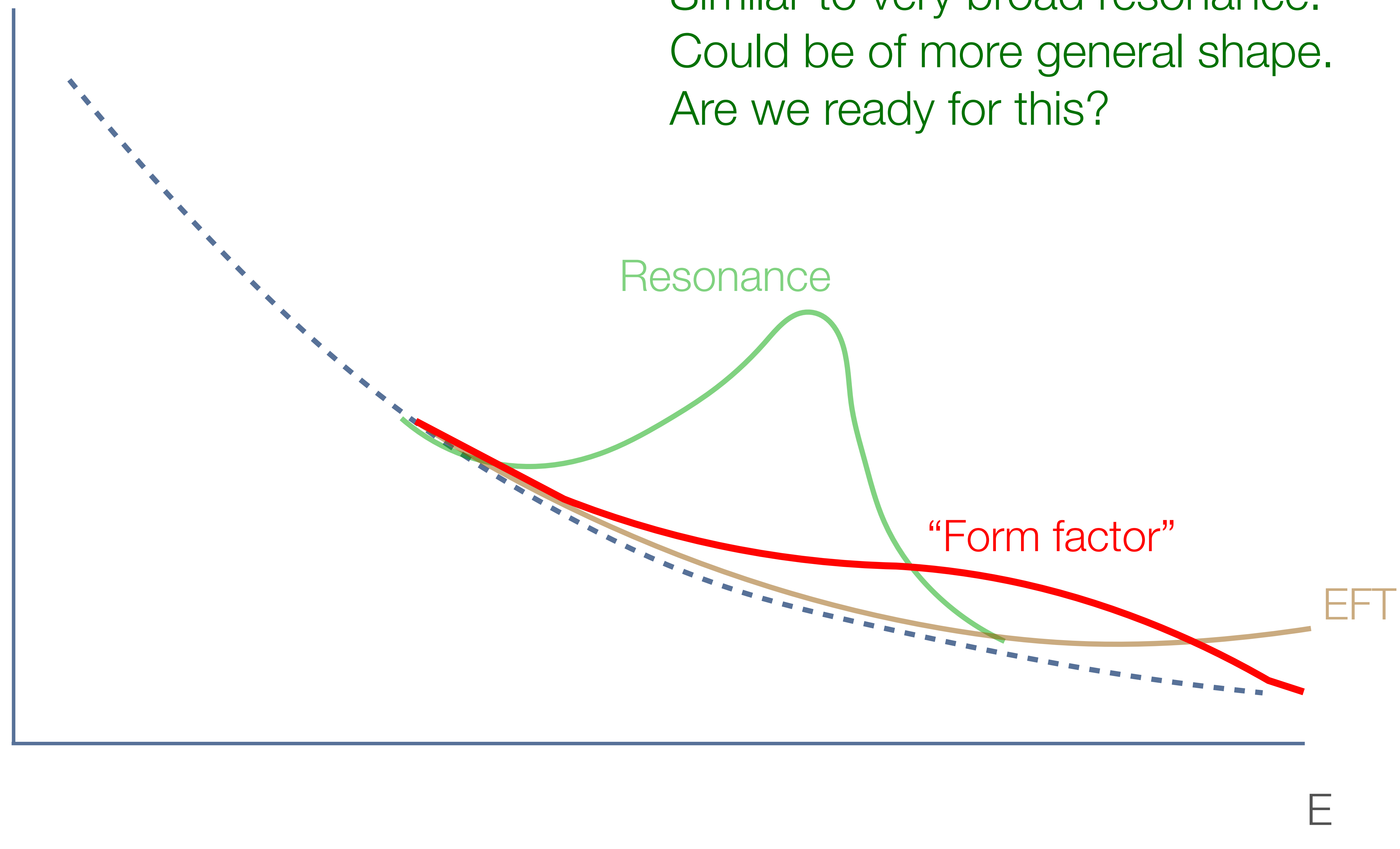


Unexpected: Form-factor



Unexpected: Form-factor

Quite exotic.
Similar to very broad resonance.
Could be of more general shape.
Are we ready for this?



The next frontier

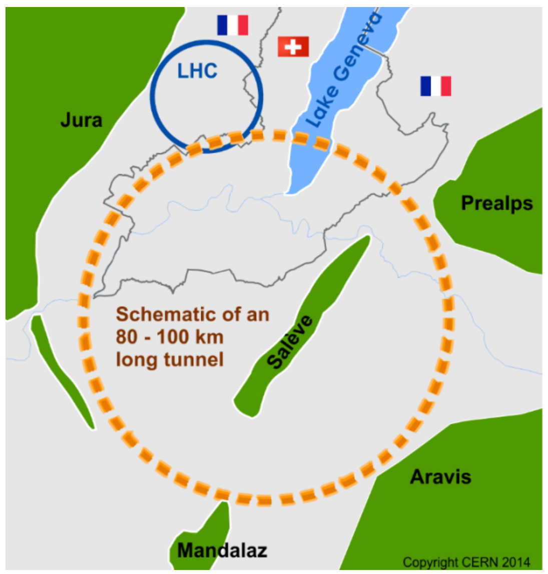
The future

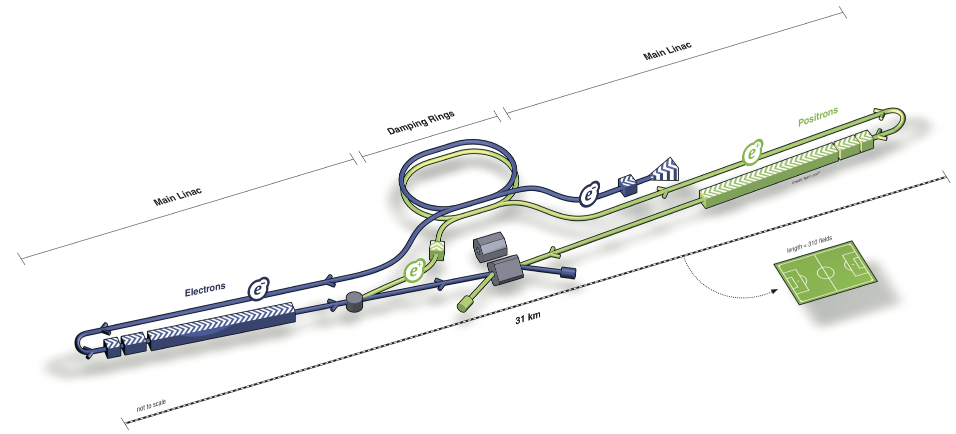
- Obviously, it would be great to have a new collider, at higher energies and intensity.

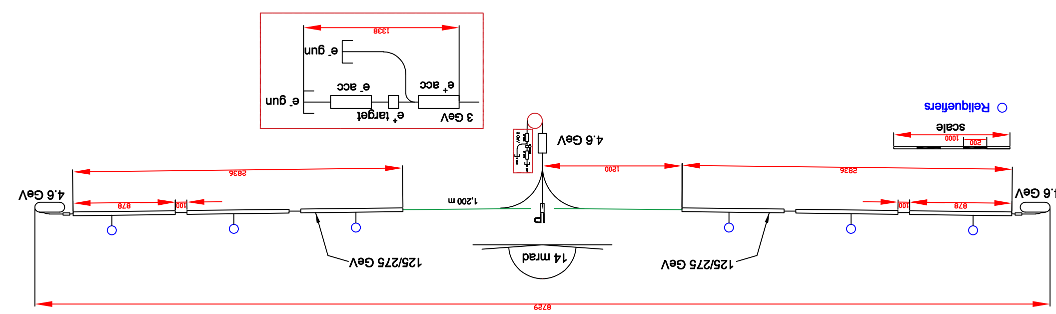
Many proposals.

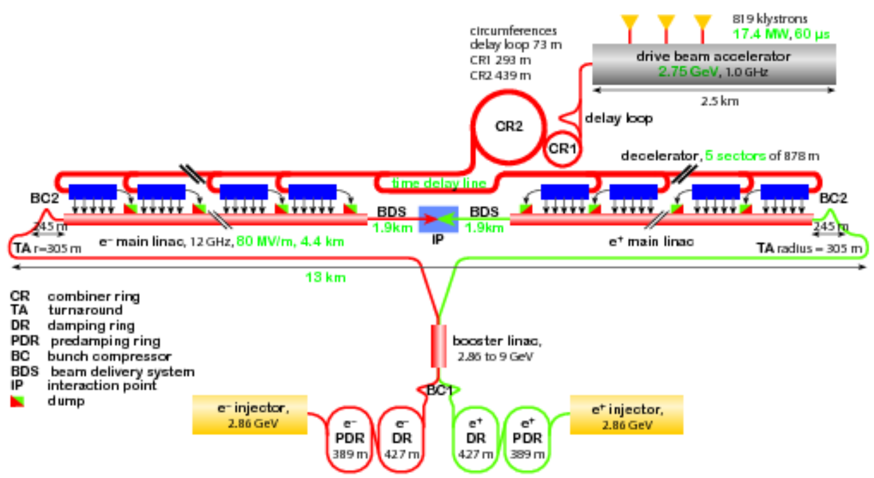
Many studies, recommendations. Snowmass/P5, European strategy…

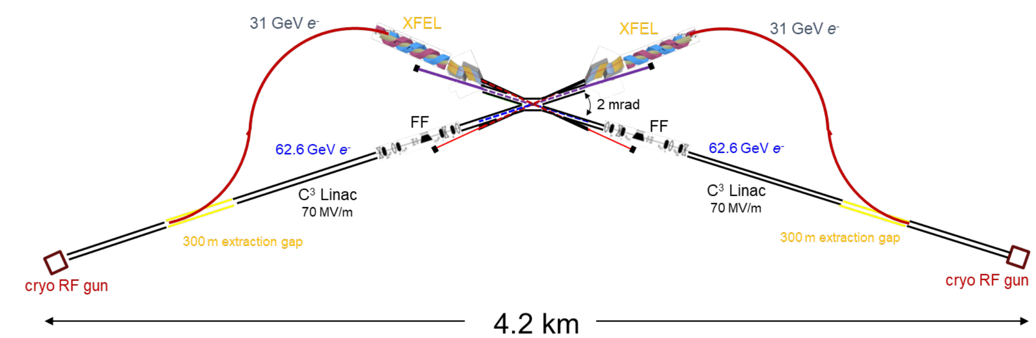
Lepton (γ) colliders $\leq$ TeV







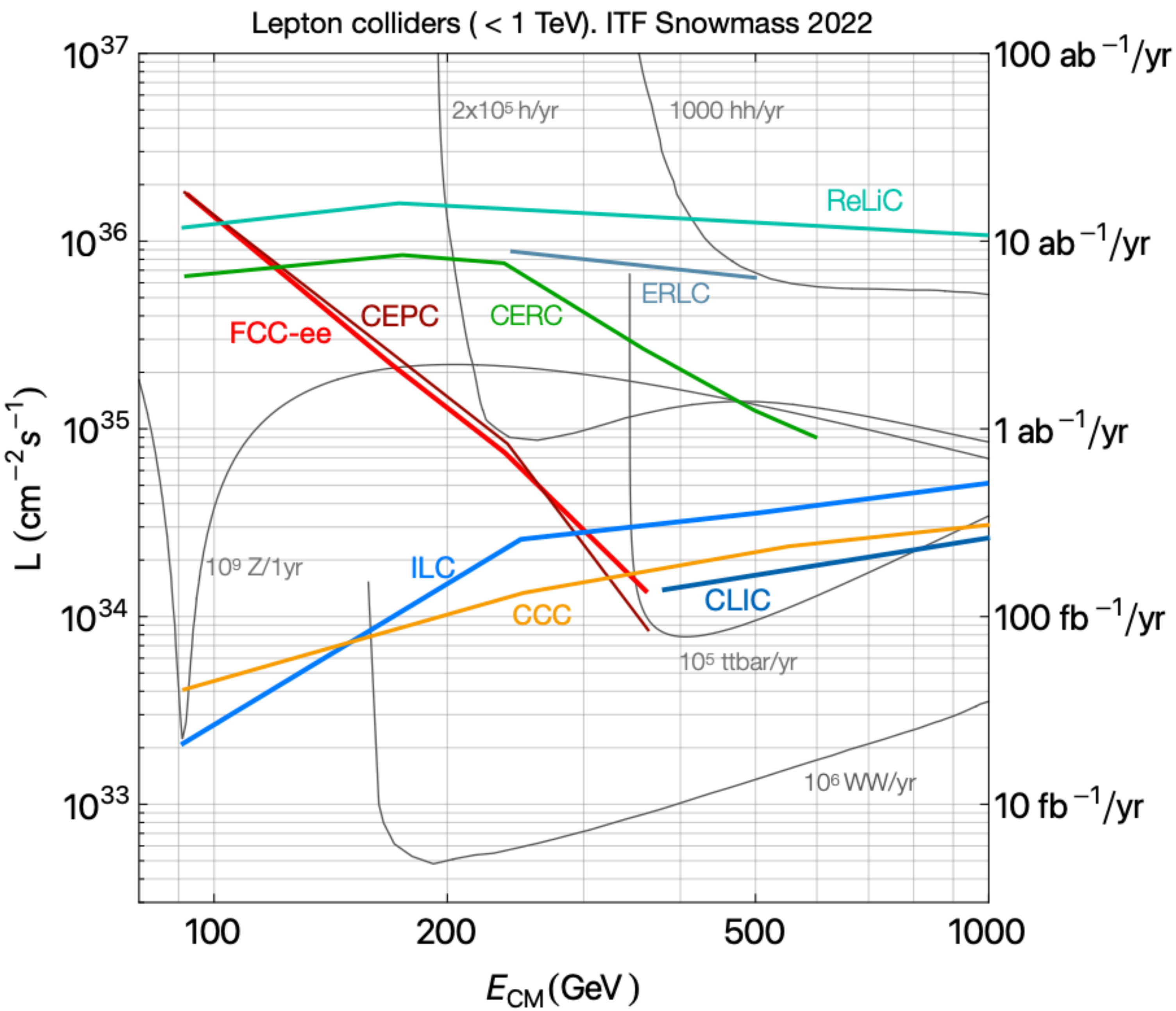




Studies of the main physics case quite mature.

I will highlight some important benchmarks.

Physics output



Main physics output:

10^6 Higgses

Similar for XCC at 125 GeV

10^9 -10^{12} Zs

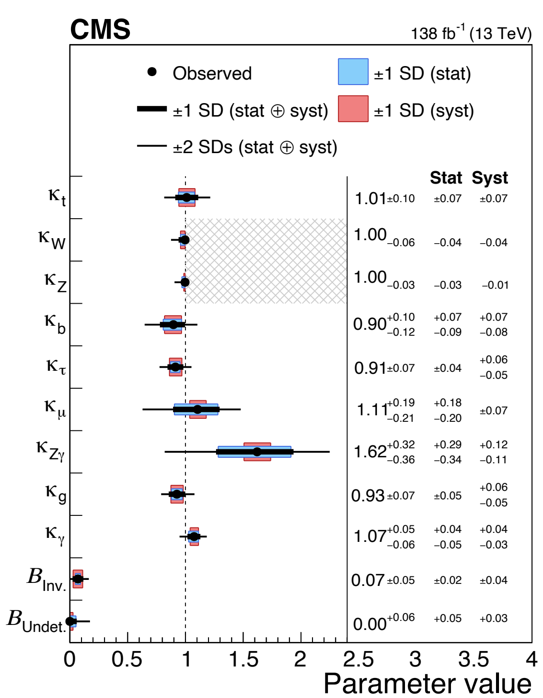
10^6 WW

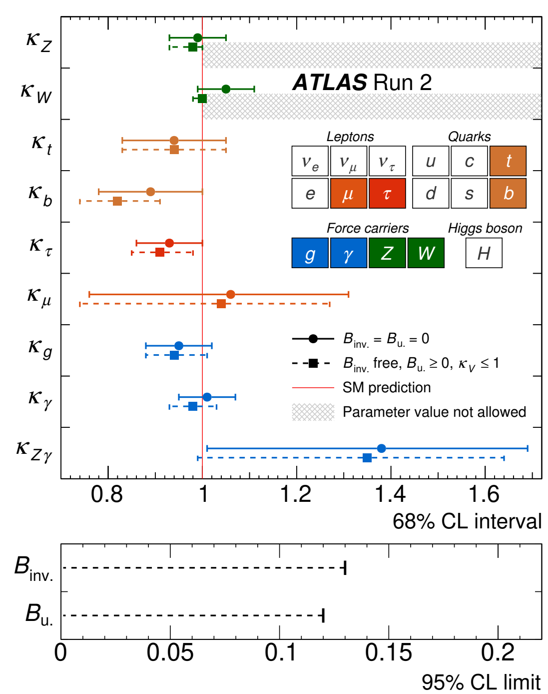
10^5 ttbar

Central theme: the electroweak scale

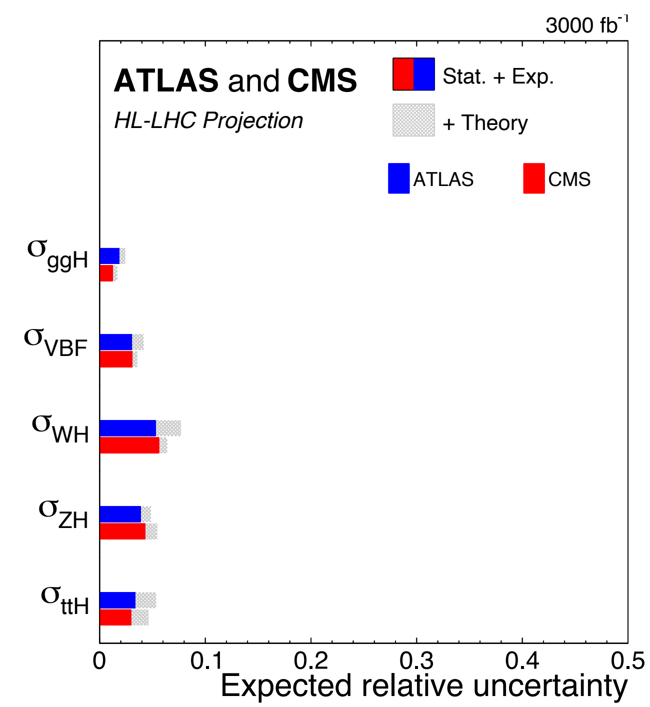
Higgs coupling

Higgs coupling other SM particles:





Eventually at the LHC



Higgs couplings. Presently, known to about 10%

1- a few %

Higgs factories needs to go meaningfully beyond this.

Signal for new physics

Coupling deviation from the Standard Model, $\delta \equiv \frac{g_{\text{exp}} - g_{\text{SM}}}{g_{\text{SM}}}$

Deviation generated by new physics: $\delta \sim g_{\text{NP}}^2 \frac{(100 \text{ GeV})^2}{M_{\text{new physics}}^2}$

g_{NP} : coupling of new physics to the SM

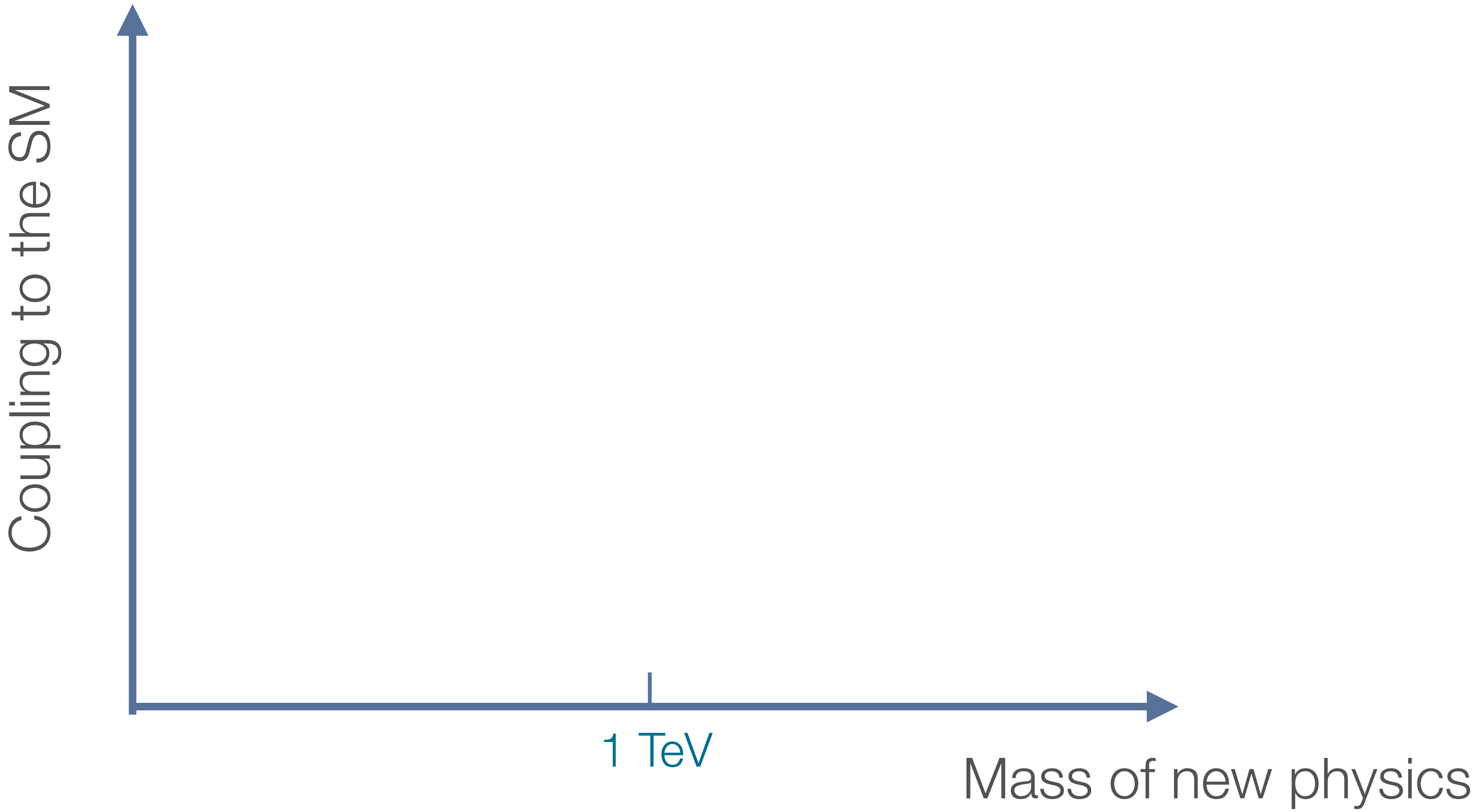
$M_{\text{new physics}}$: mass scale of new physics

Measurement precision ⇒ sensitivity on δ ⇒ reach for NP

Our target

$$\delta \equiv \frac{g_{exp} - g_{SM}}{g_{SM}}$$

$$\delta \sim g_{NP}^2 \frac{(100\ \mathrm{GeV})^2}{M_{\text{new physics}}^2}$$



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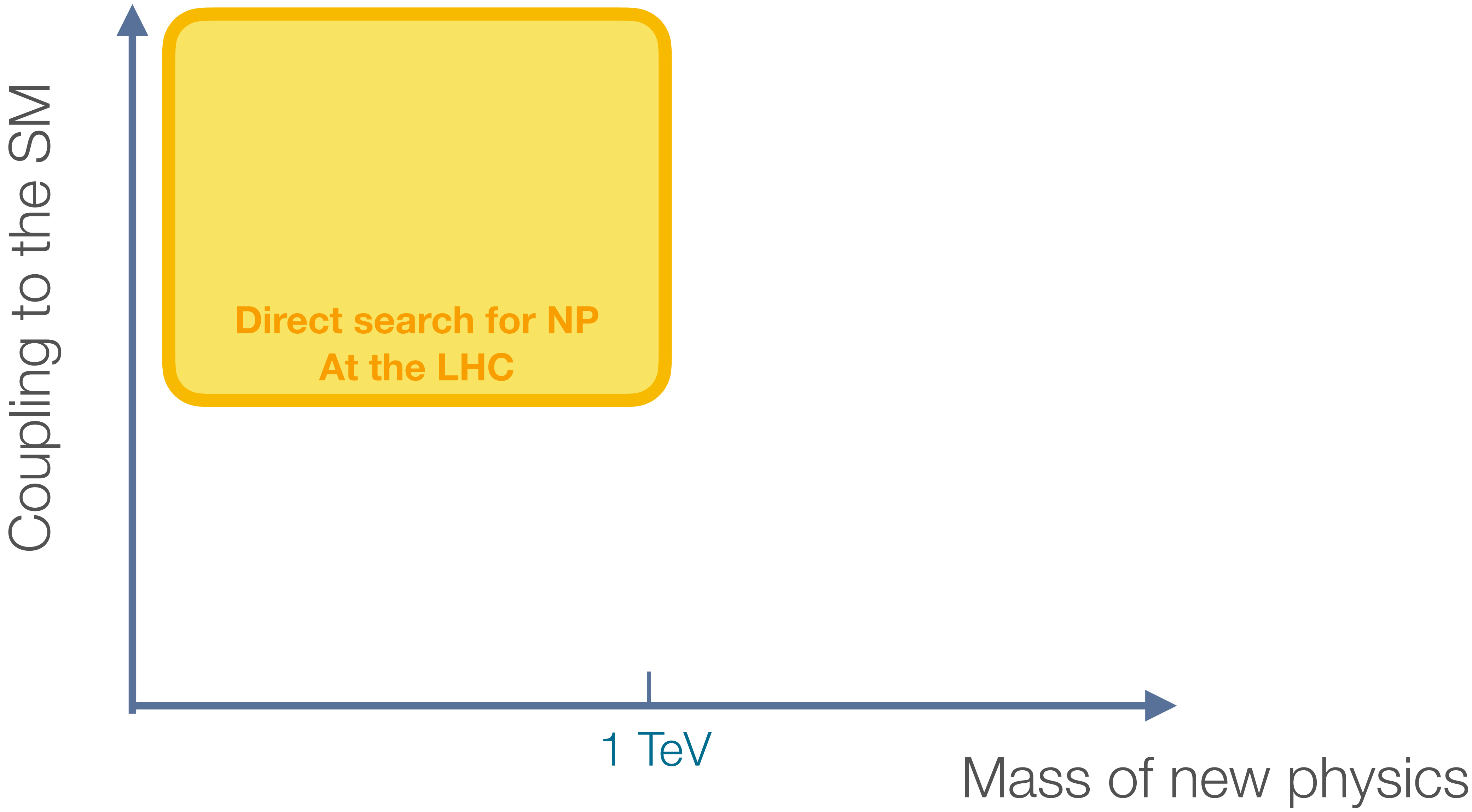

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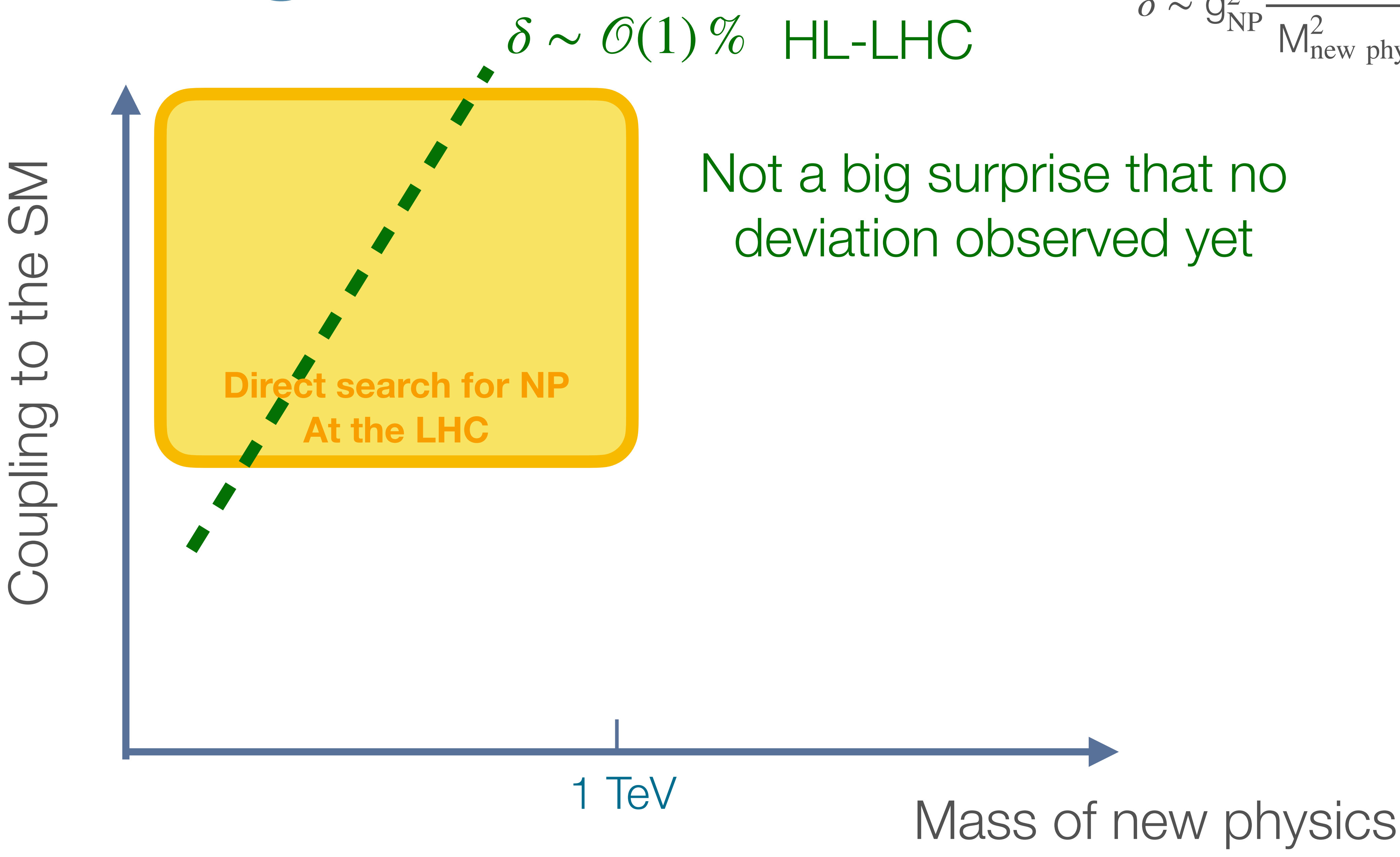

Not a big surprise that no deviation observed yet

Our target

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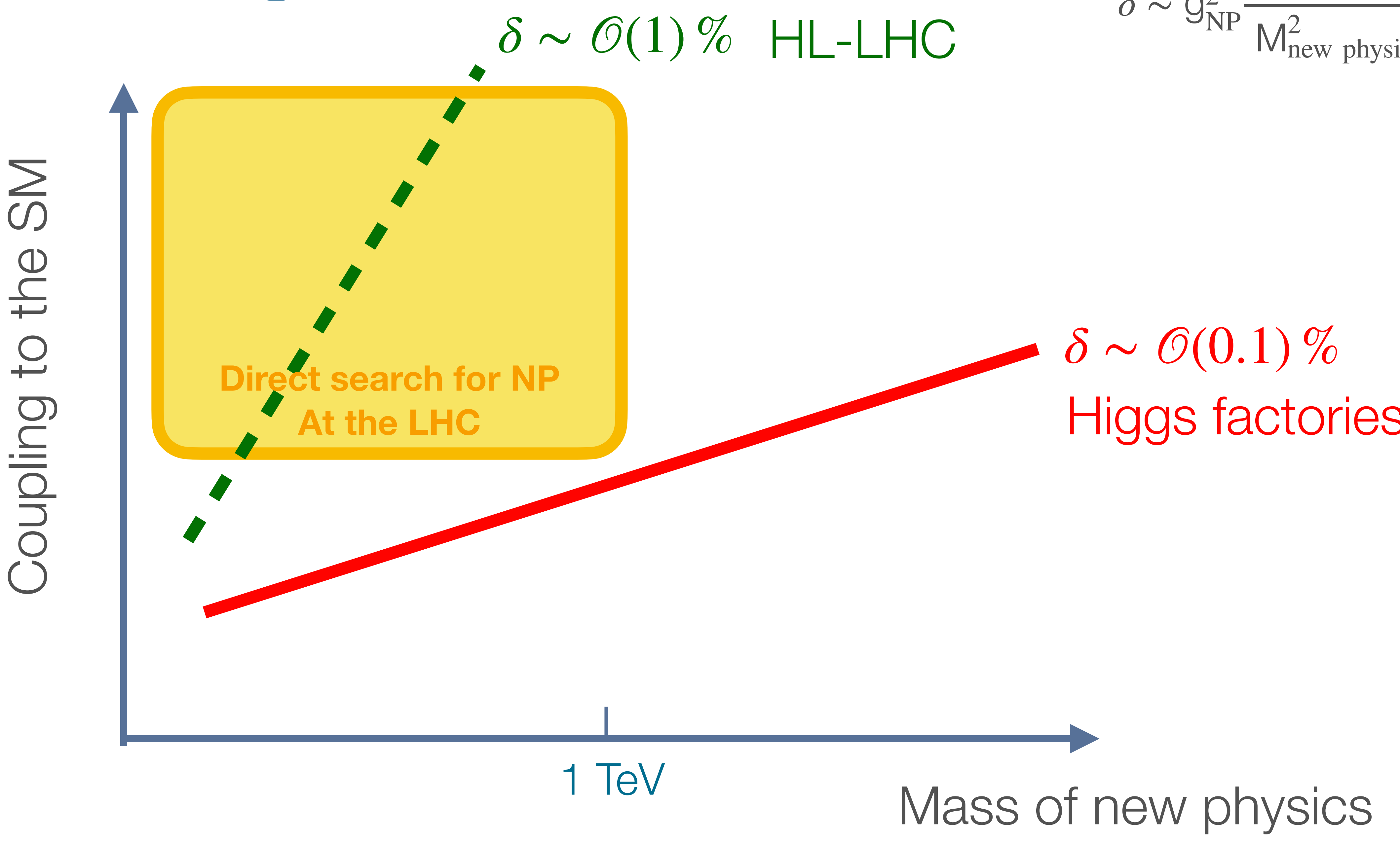
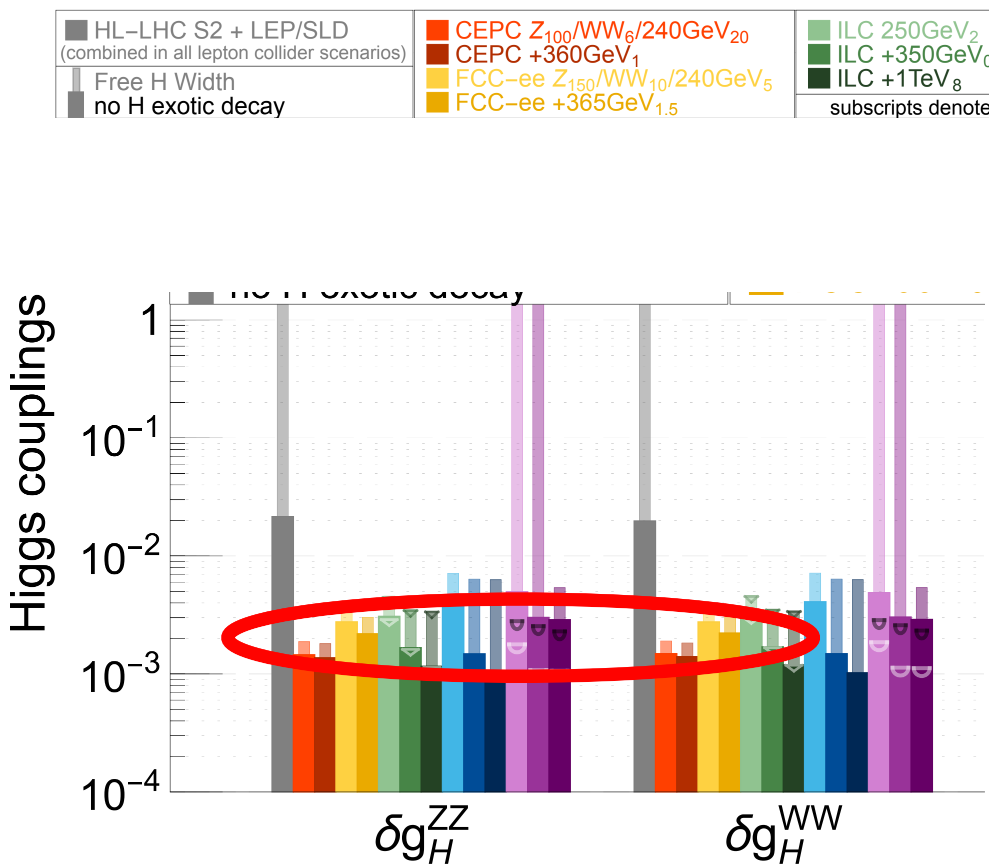
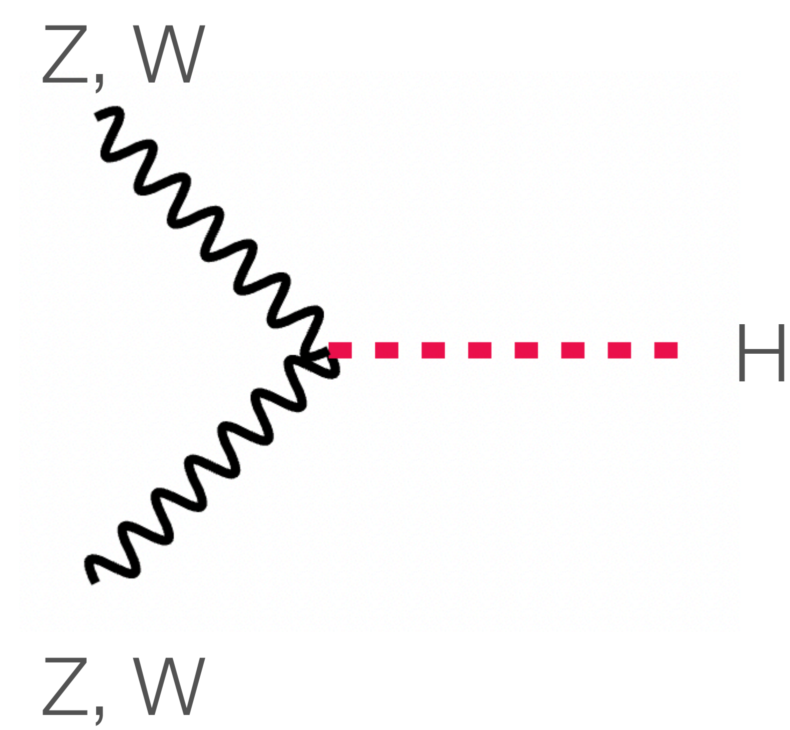
$$\delta \sim g_{NP}^2 \frac{(100\ \text{GeV})^2}{M_{\text{new physics}}^2}$$



The Higgs measurements

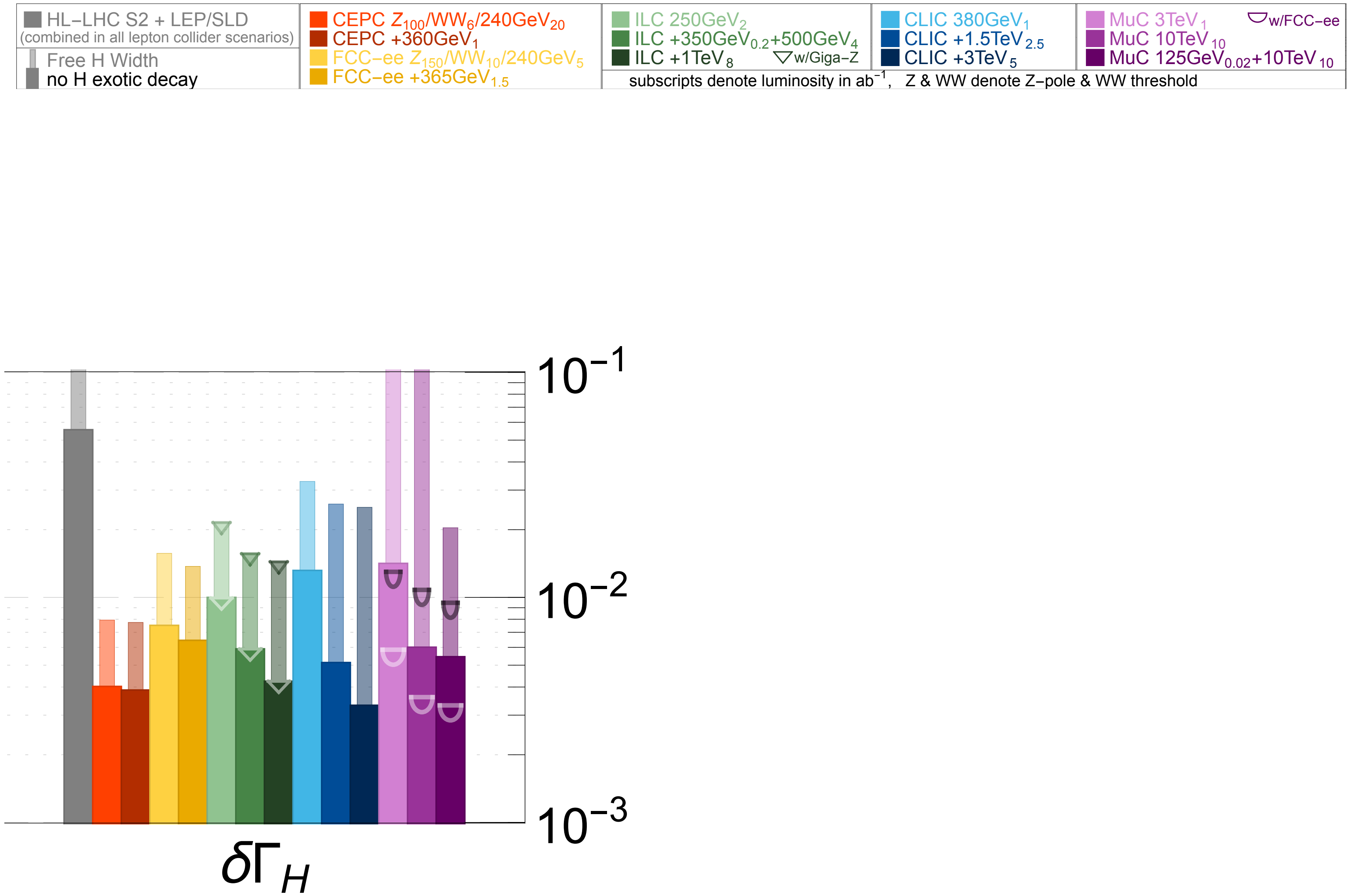




Measuring crucial Higgs coupling up to 10^{-3}

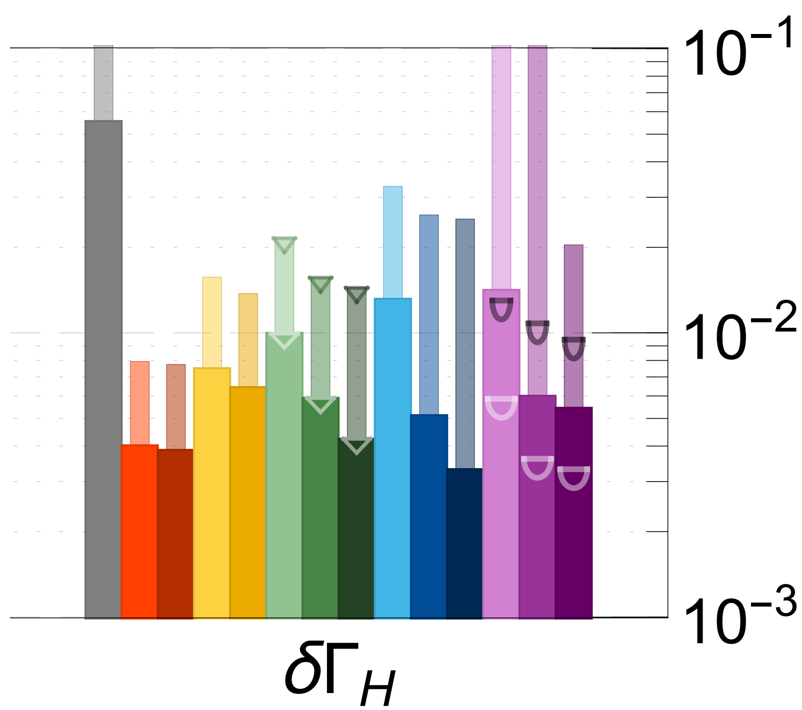
Needs 10^6 Higgses

The Higgs measurements

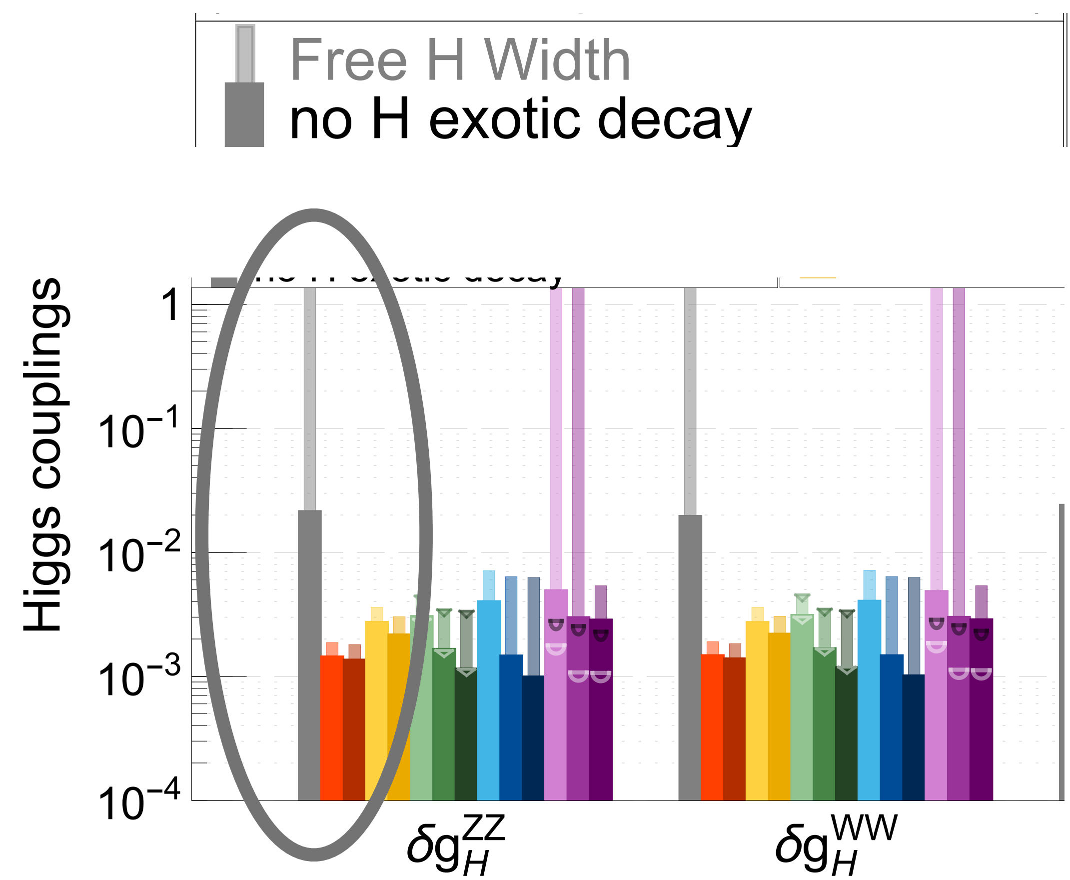


Higgs width measurement

The Higgs measurements

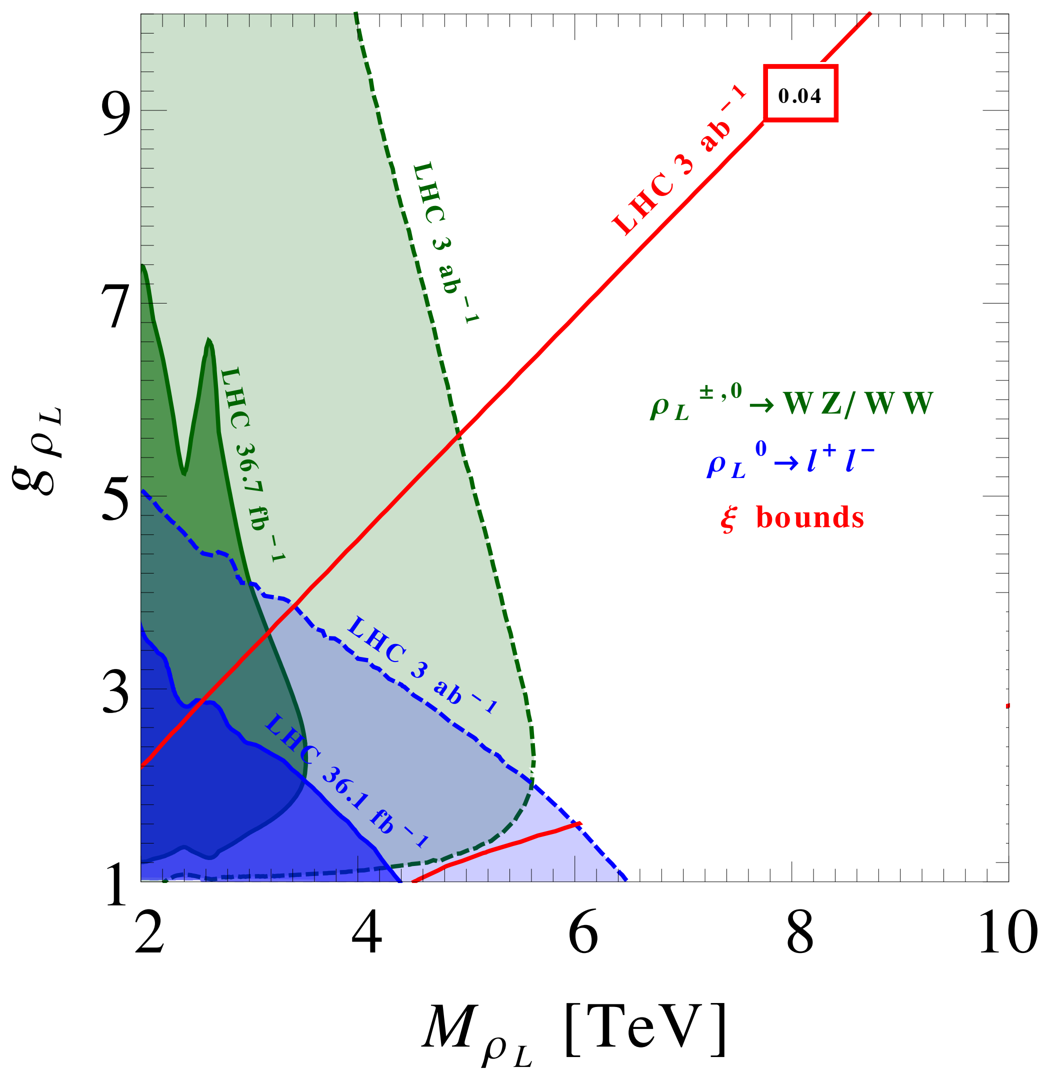


Higgs width measurement



Significant impact on other coupling measurement

Is the Higgs composite?



Perhaps the Higgs is similar to the pion?

Would make it naturally light, since it is not elementary.

If so, will be other composite resonances

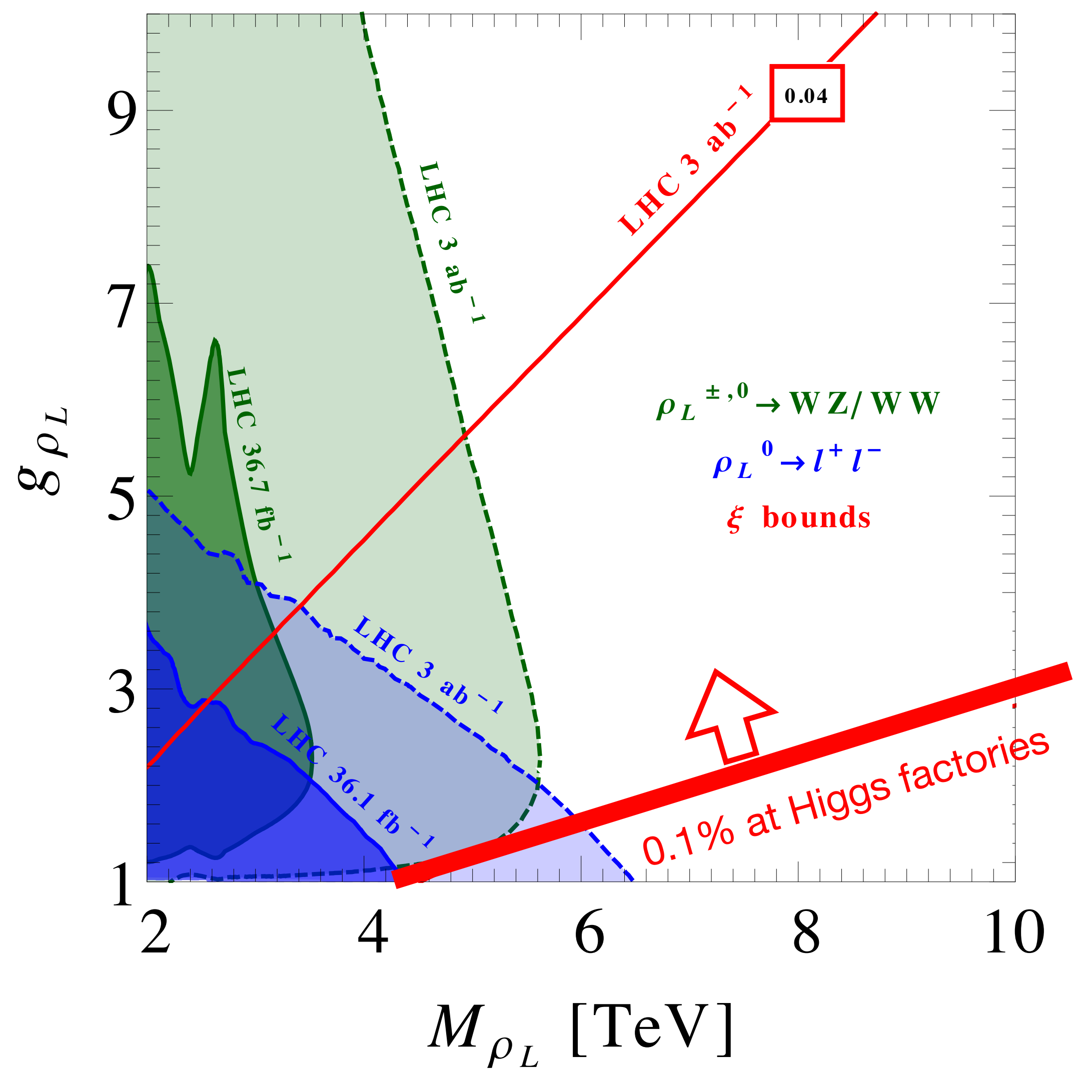
Direct search for composite resonances

Higgs coupling measurements

Composite ≠ elementary

Different couplings

Is the Higgs composite?



Perhaps the Higgs is similar to the pion?

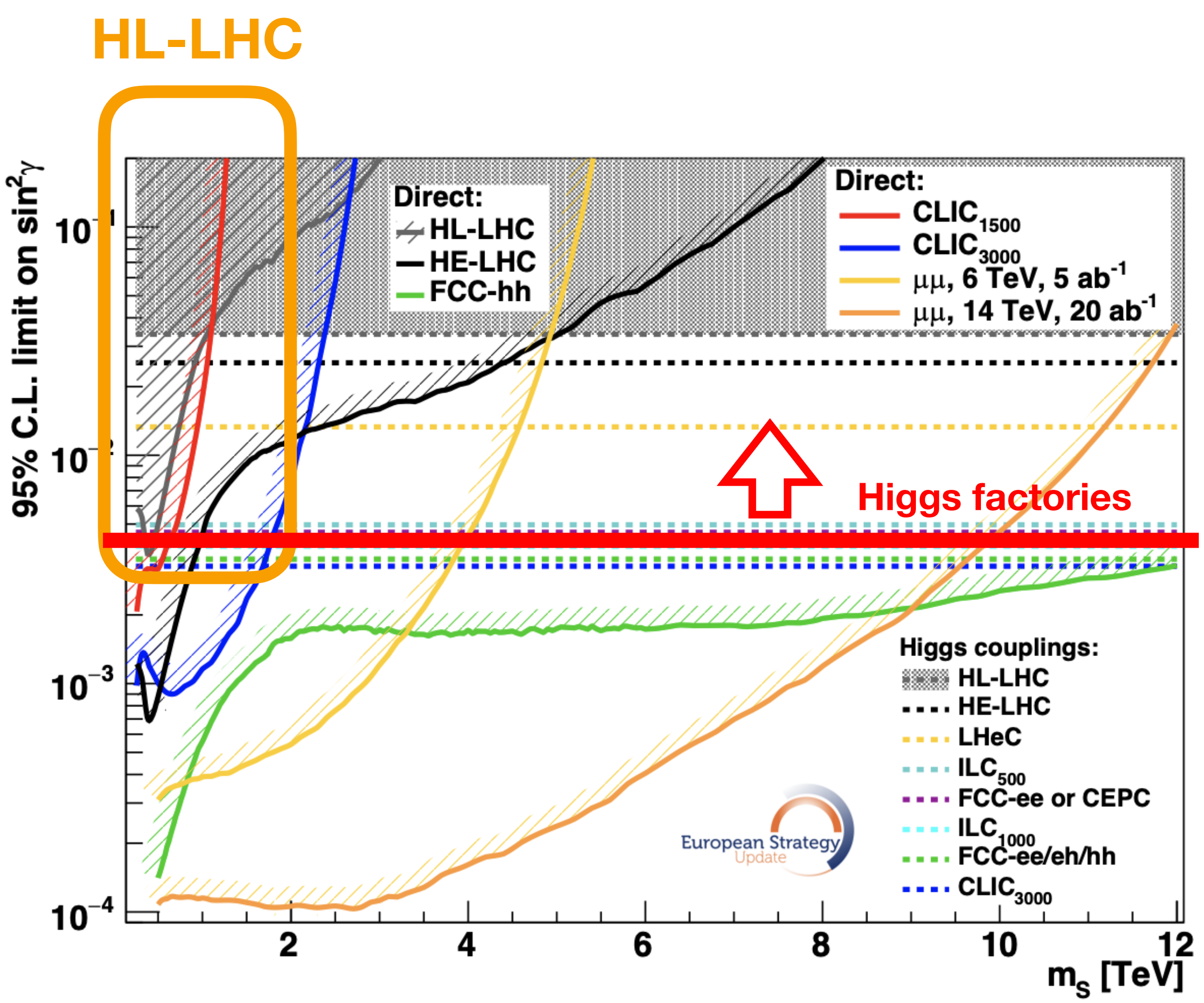
- Would make it naturally light, since it is not elementary.
- If so, will be other composite resonances

Direct search for composite resonances

Higgs coupling measurements

- Composite ≠ elementary
- Different couplings

Is the Higgs boson alone?

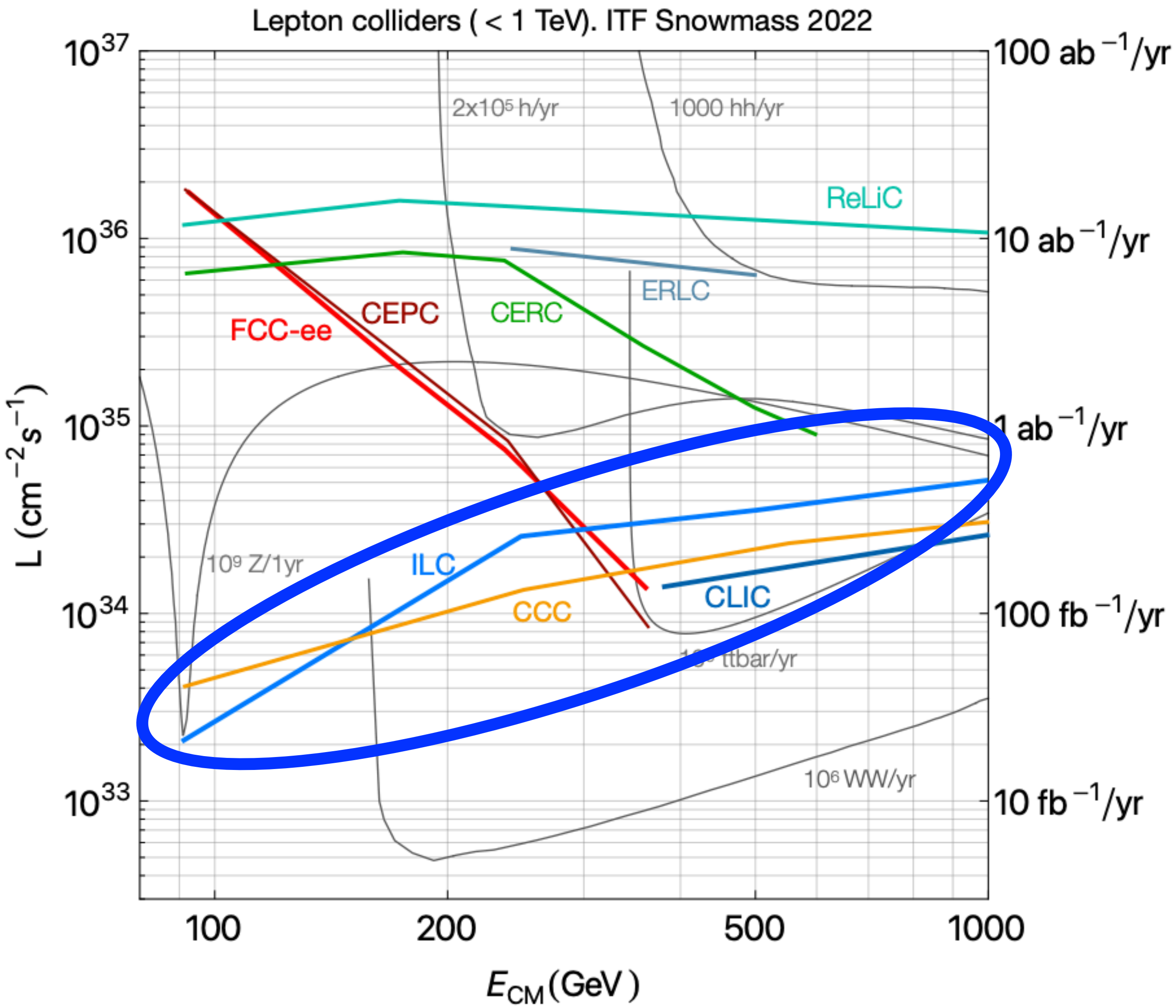


Maybe Higgs boson has some partners?

Will change Higgs behavior by interacting with it.

Simplest example:
Higgs coupling to one other spin-0 boson

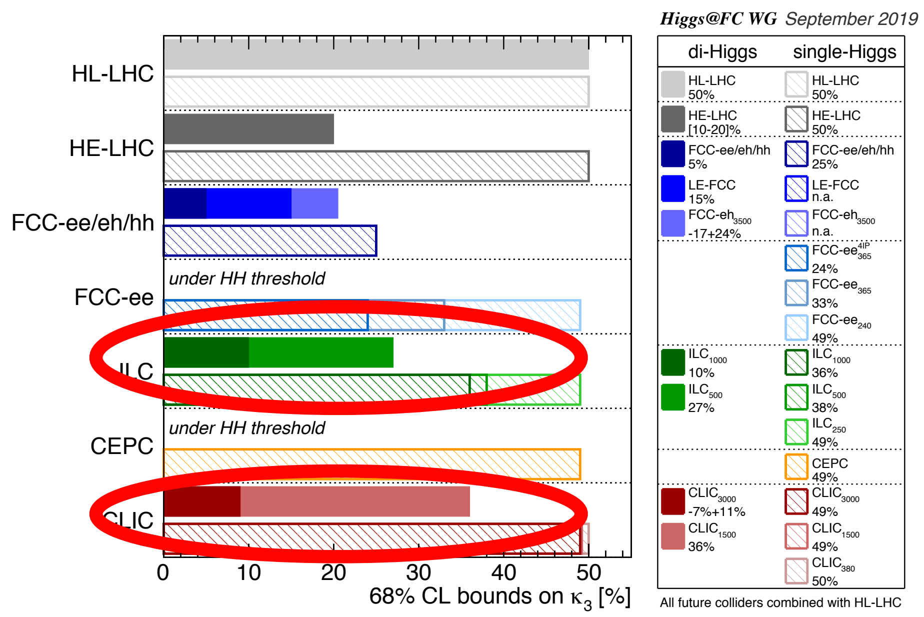
Linear options

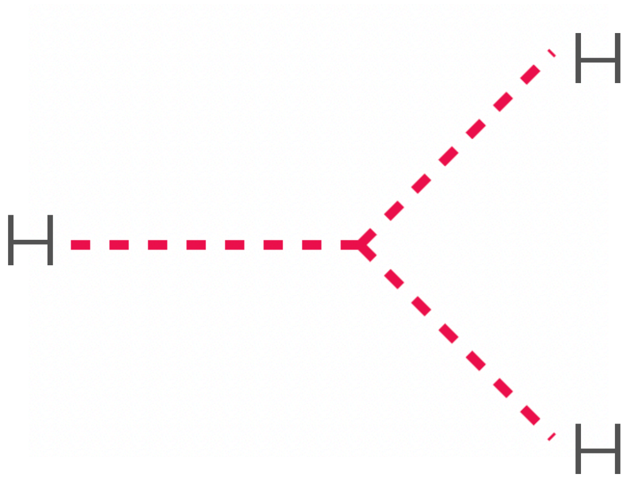


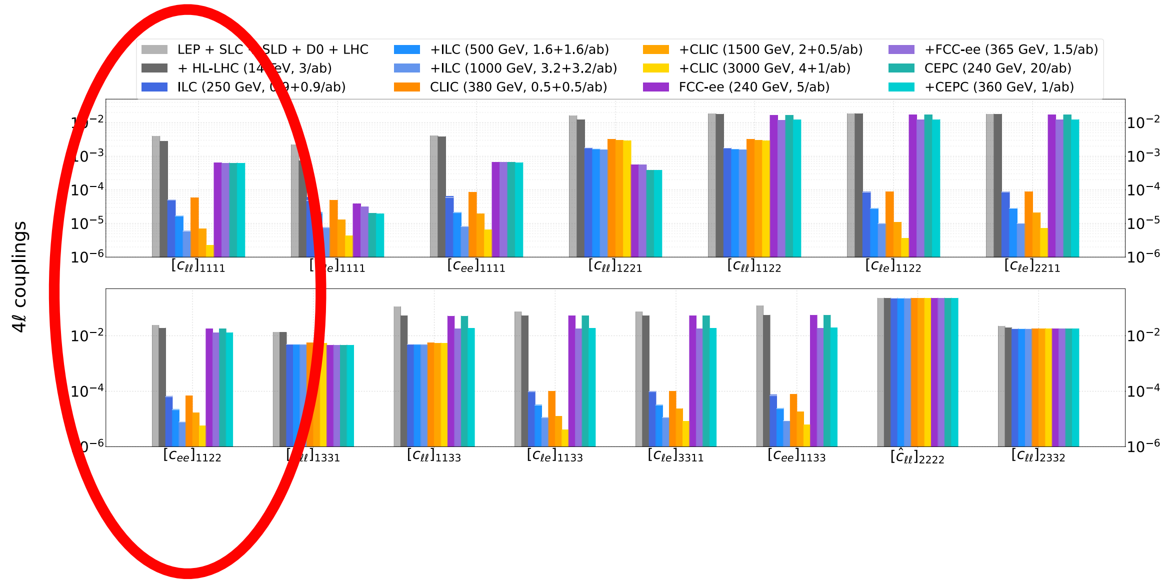
Longitudinal polarization.
Better at resolving certain signals

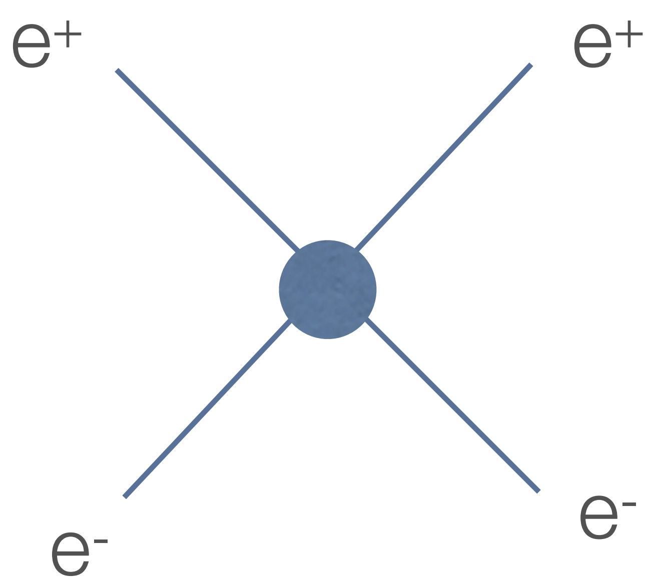
Can go to higher energies

Higher energies, polarization





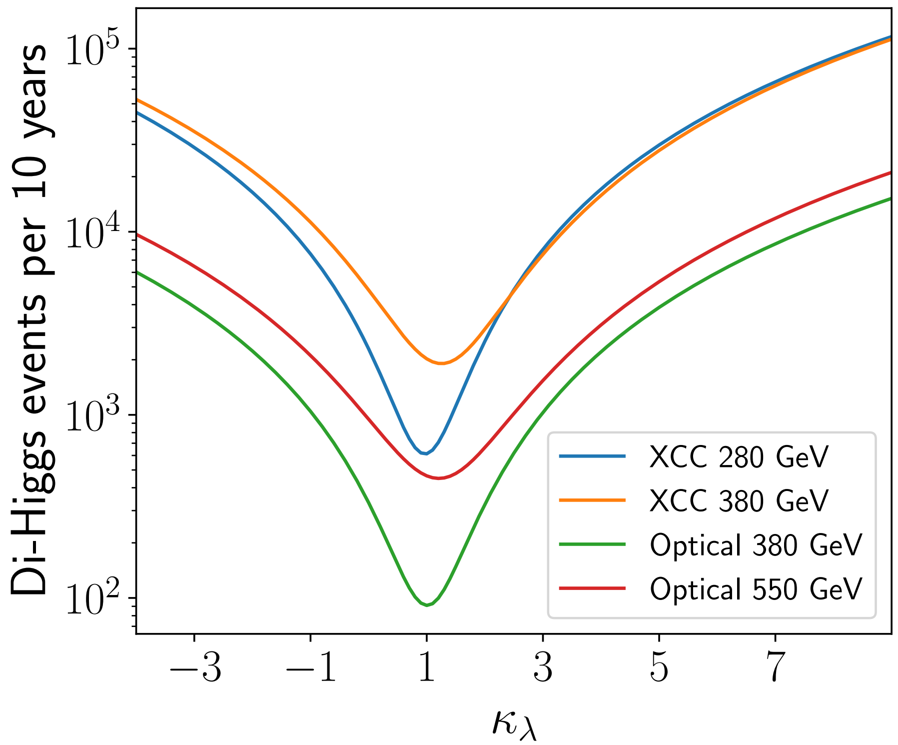


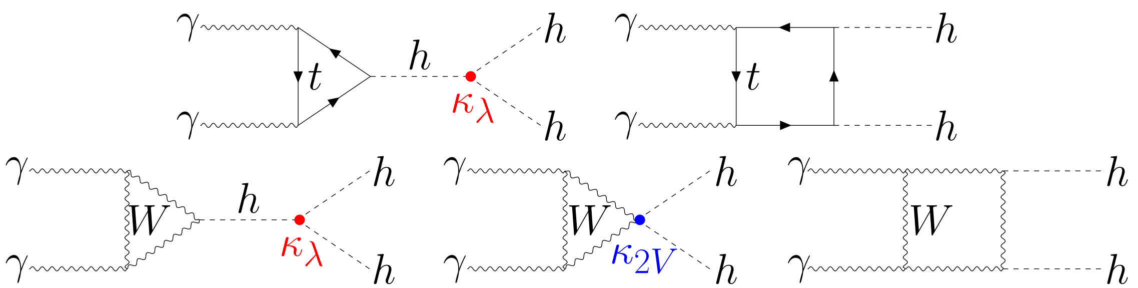


J. Blas, Y. Du, C. Grojean, J. Gu, V. Miralles, M. Peskin, J. Tan, M. Vos,, E. Vryonidou, 2206.08326

Photon collider

Marten Berger, Johannes Braathen, Gudrid Moortgat-Pick, and Georg Weiglein, 2510.05012



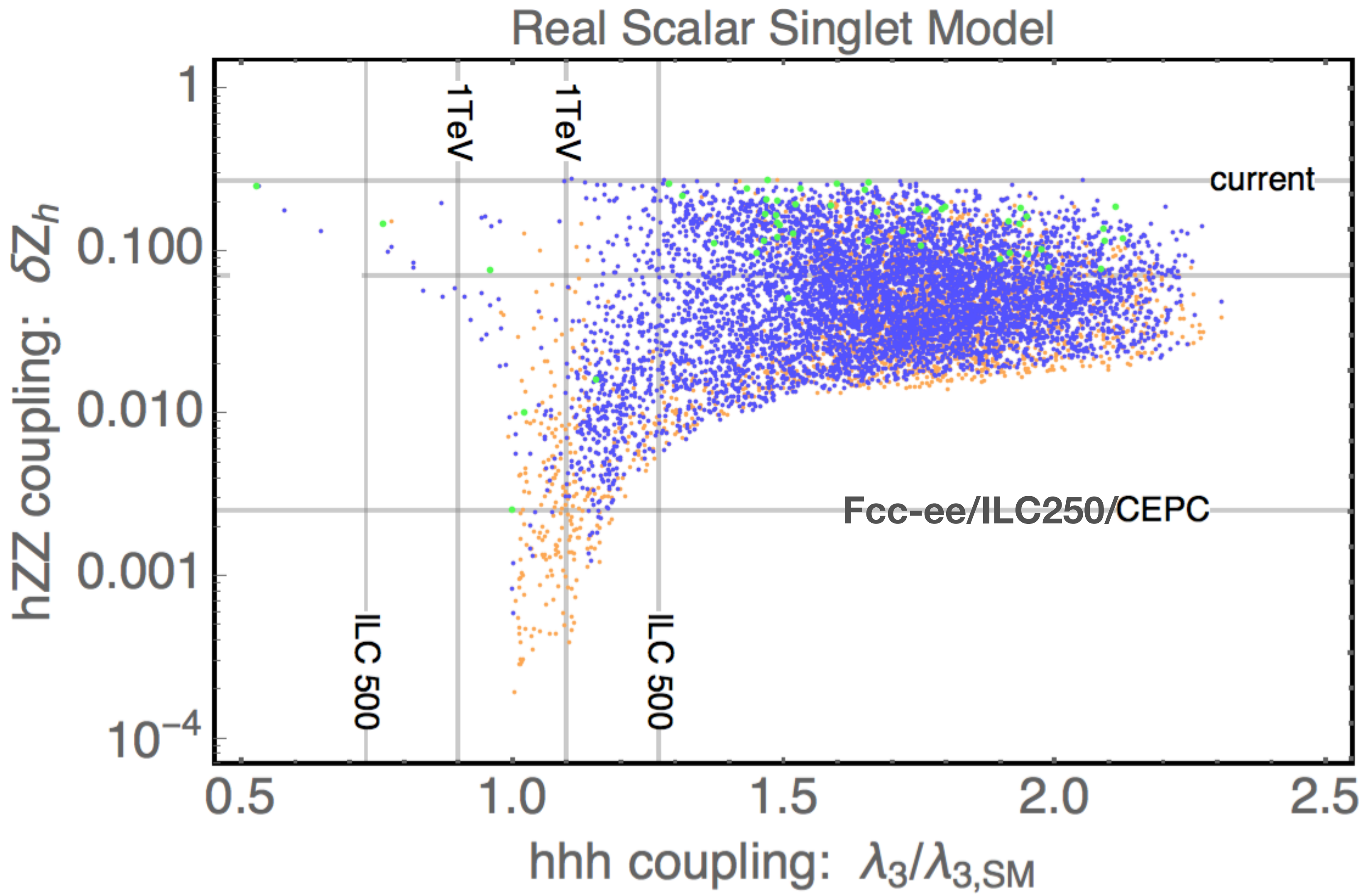


di-Higgs.

$\delta\kappa_\lambda \sim 5\,\%$ T. Barklow et. Al.

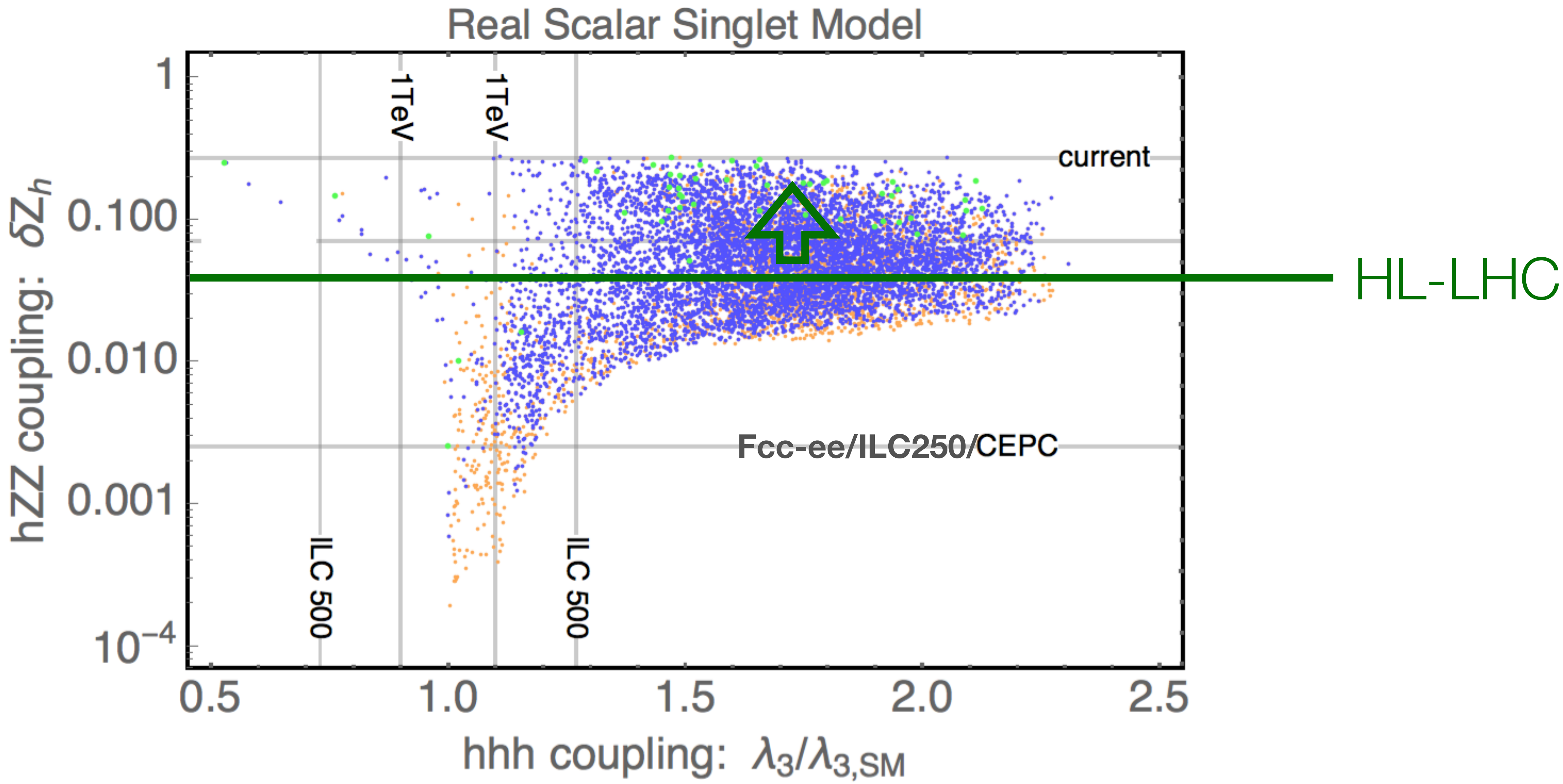
Looking forward to the final words on these studies.

EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

EW phase transition



A typical (simplest) model, Higgs mixes with a singlet

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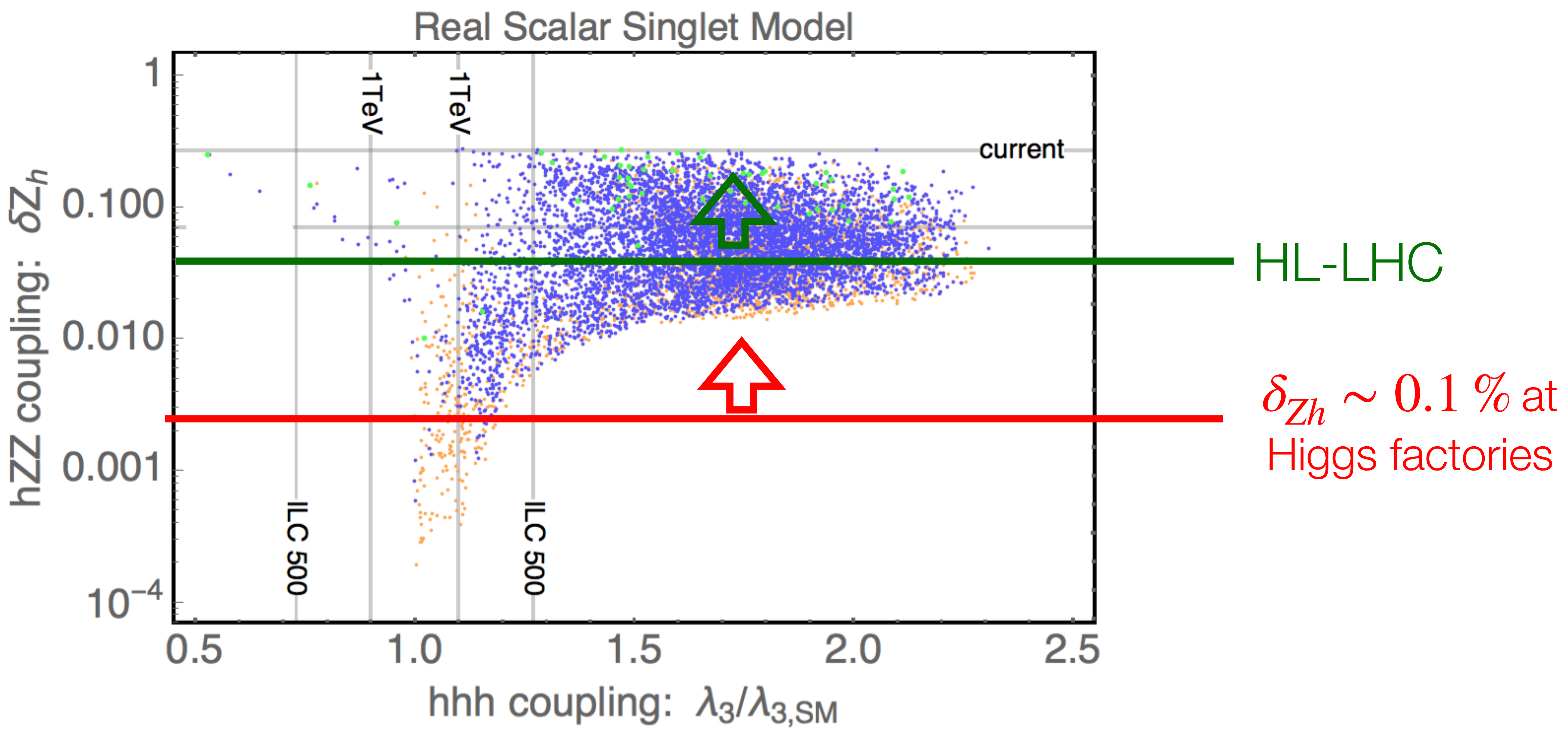

A typical (simplest) model, Higgs mixes with a singlet

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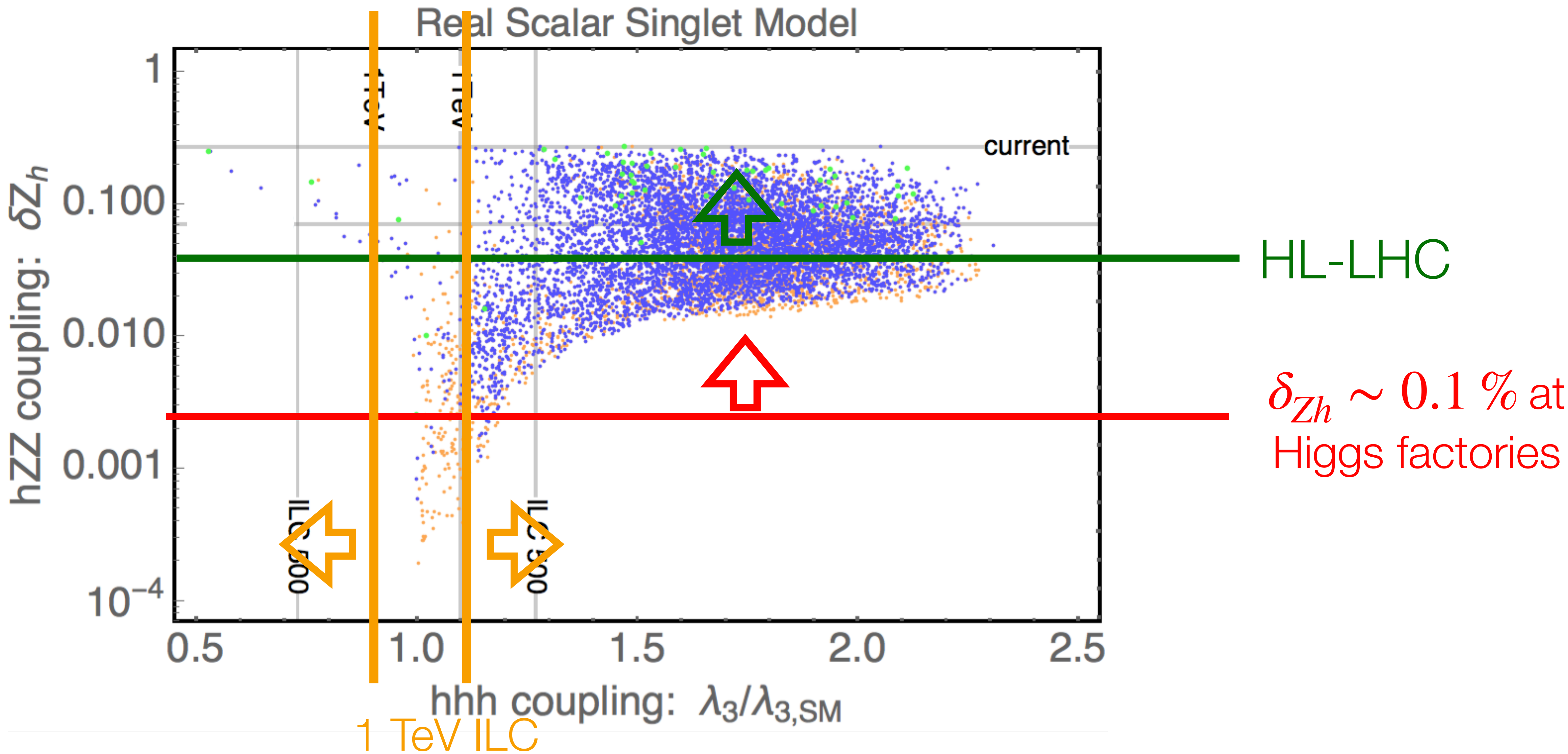
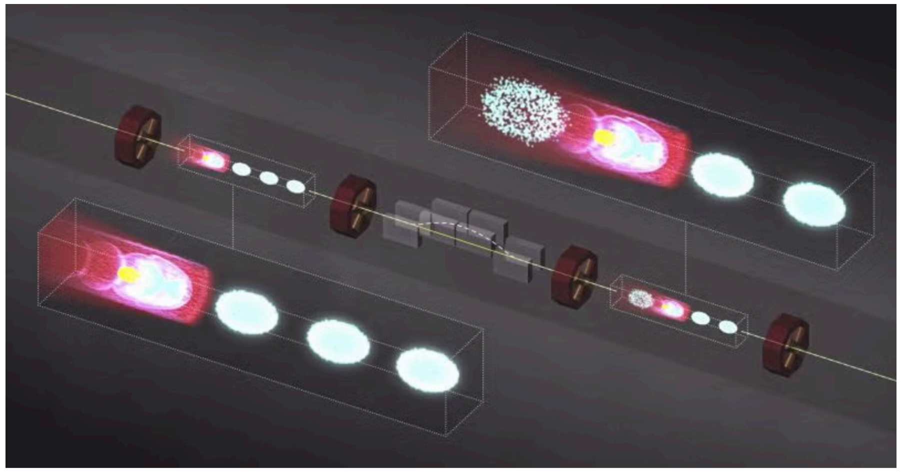


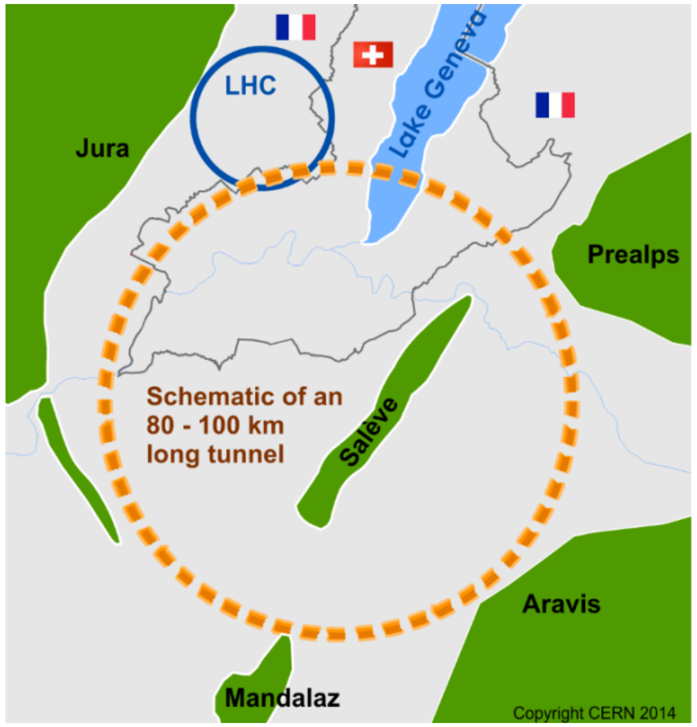
A typical (simplest) model, Higgs mixes with a singlet

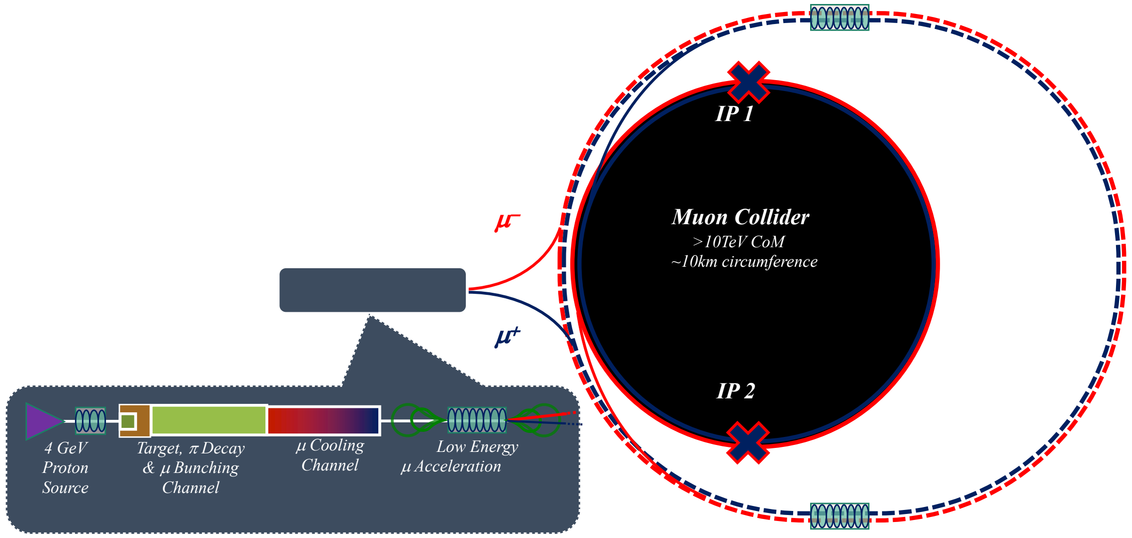
More to do in physics studies

- What can further enrich the physics program?
  - Searches complementary to LHC.
    - Higgs rare decay, Z-pole flavor physics, …
  - Fixed target.
  - …
- Some studies already, need to do more.

The 10 TeV pCM frontier







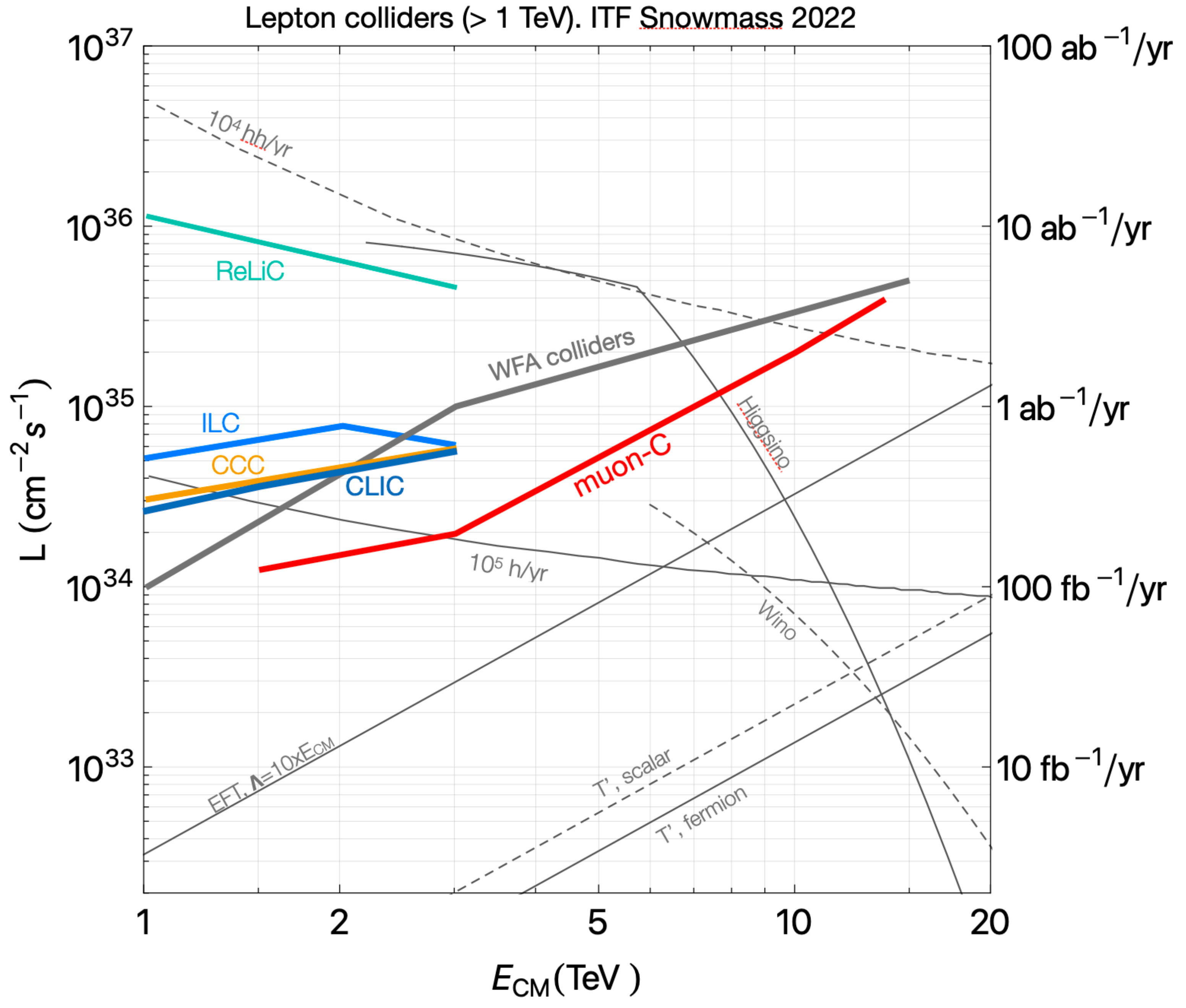
Study for 10 TeV pCM

- So far, most studies are done in the context of muon collider and 100 TeV pp collider.
- However, the point is really go to 10 TeV pCM
  - Qualitatively, e+ e- and $\gamma\gamma$ should work just as well.
  - Needs more studies!

Why 10 TeV?

e+e- : 1-10s TeV

- The energy frontier!

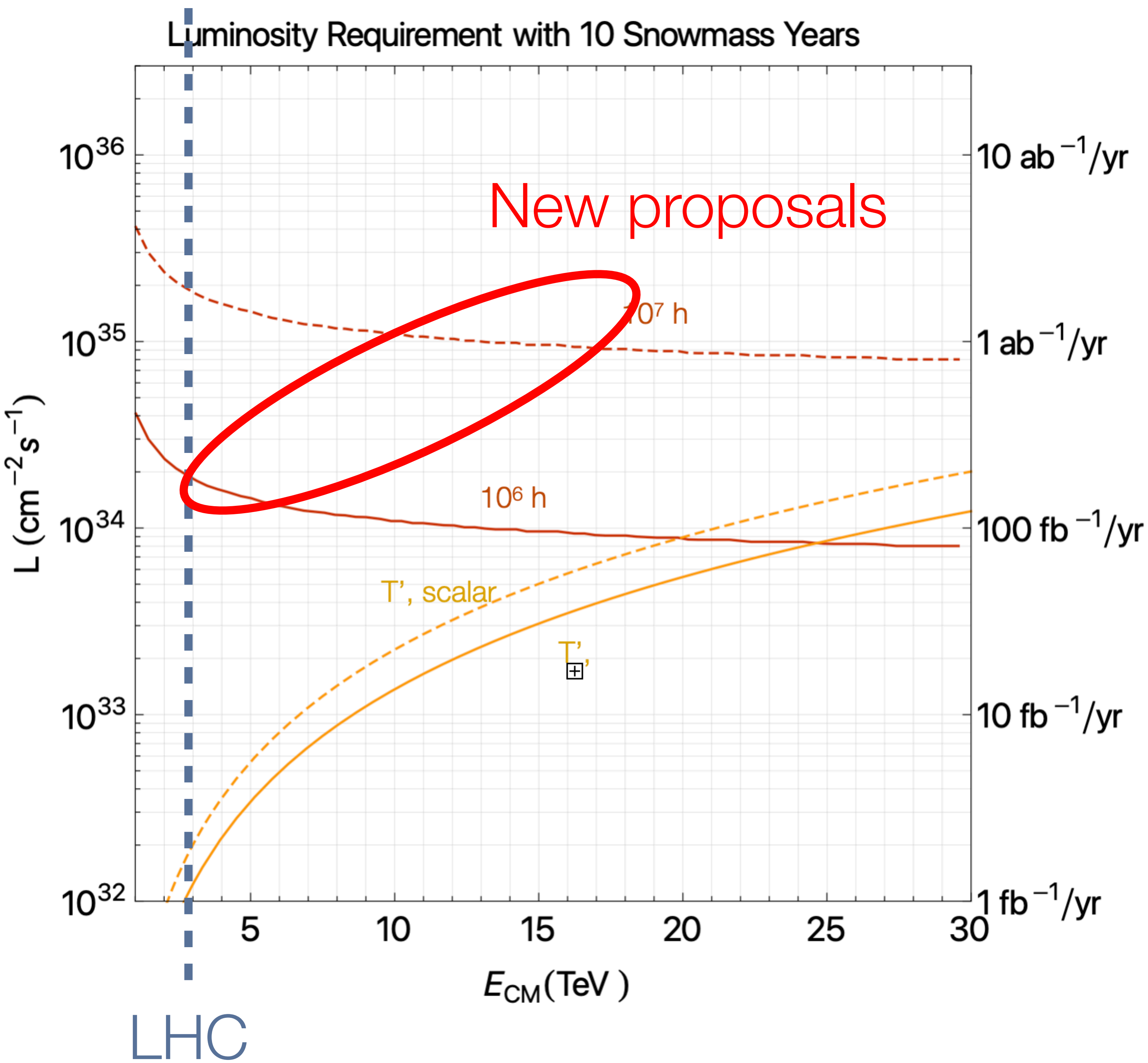


Naturalness

Fine-tuning $\propto M_{\rm NP}^2$

10 TeV muon collider reach 5-10 beyond LHC.
~100 times better test of naturalness!

Top partner



Pair production

reach = 0.45xE_{CM}

Examples:
SUSY stop
Composite T
…

Spectacular signal, energetic final states.

$T' \to Wb, Zt, ht$

No need for high lumi.

A big step beyond the LHC!

Energy⇒precision

- The effect of heavy new physics can be parameterized by higher dimensional (EFT) operators.
  - Precision measurement targeting these operators.
- Their effect grows at higher energies.
  - e.g. if new physics lead to dim-6 operators

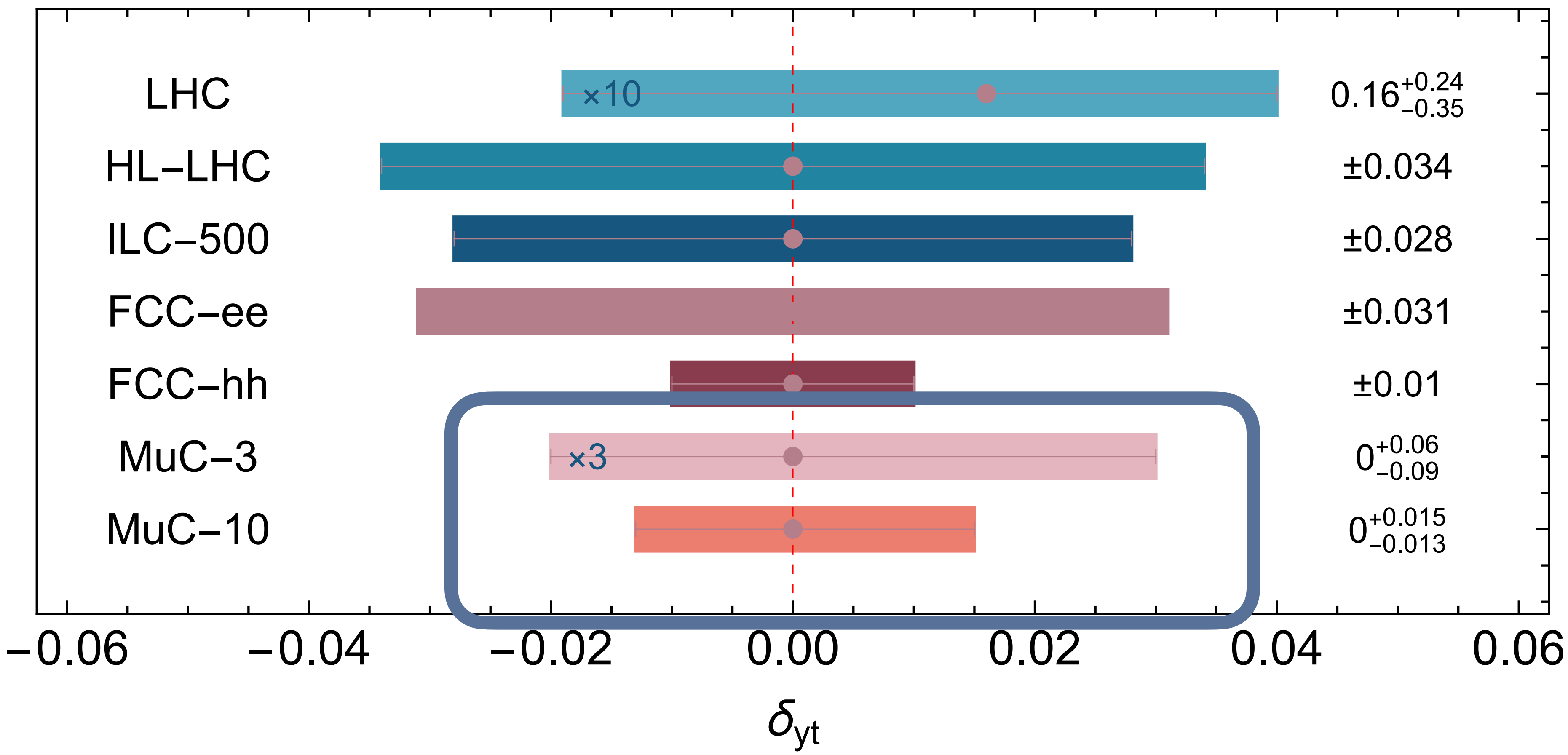
$$\frac{\mathcal{O}^{(6)}}{\Lambda_{\rm NP}^2} \to d\sigma \propto E^2$$

Higher energy ⇒ better sensitivity, better precision

10 TeV pCM can reach $\Lambda_{\rm NP} \sim 50~\mathrm{TeV}$

Top quark - Higgs coupling

Liu, Lyu, Mahbube, LTW 2308.06323



Higher energies lead to better precision.

Limited by precision on very energetic particles.

Should be similar to e^+e^- and $\gamma\gamma$. Would be useful to verify!

Testing WIMP dark matter

Simplest WIMP model

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
(1,3,ϵ)	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
(1,5,ϵ)	Dirac	6.6 TeV
(1,7,0)	Majorana	48.8 TeV
(1,7,ϵ)	Dirac	16 TeV

Correct relic abundance
$\Rightarrow$ Thermal targets

Reach up to thermal target
$\approx$
complete coverage for WIMP candidate

Way beyond LHC reach.

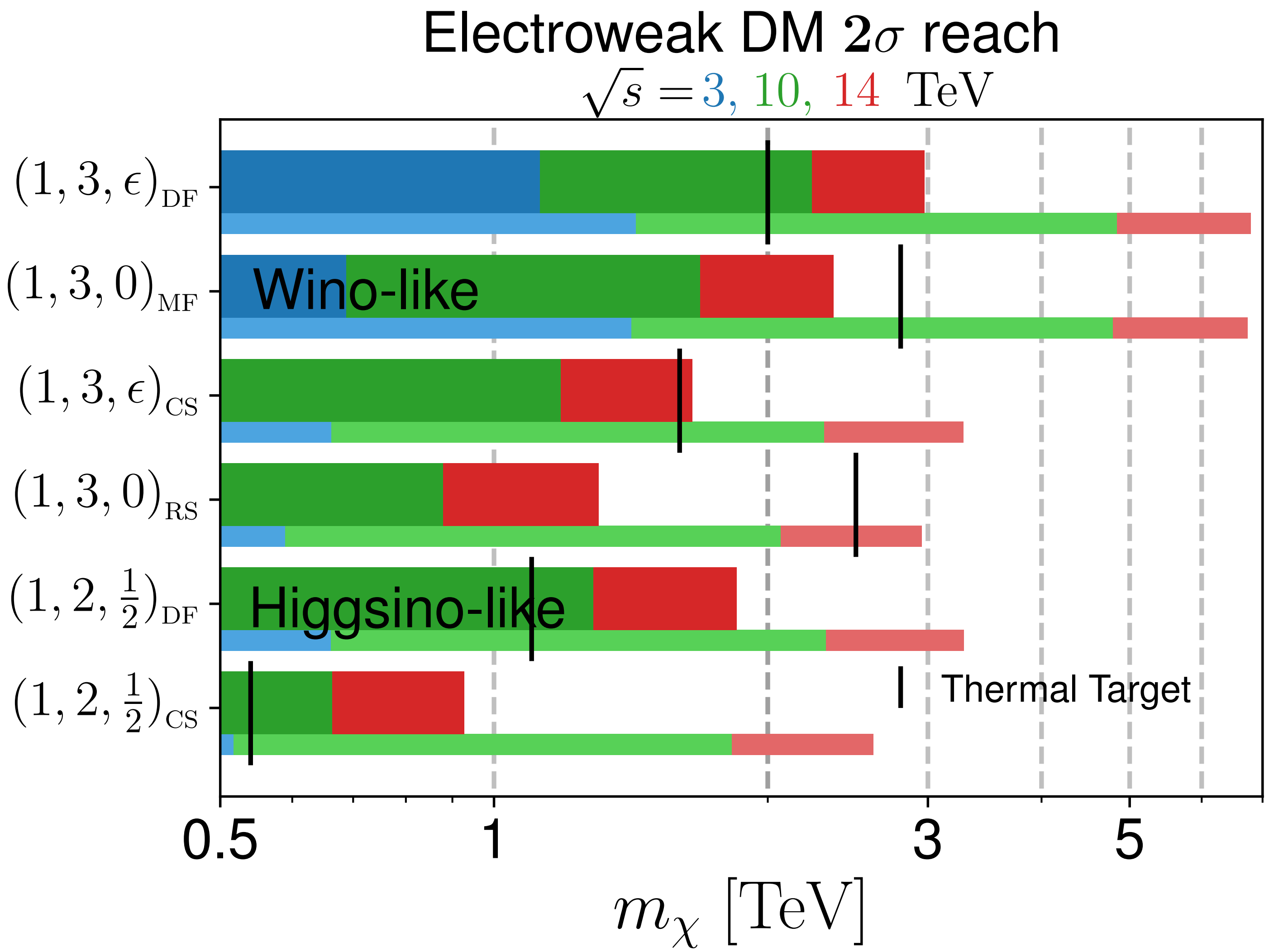
DM in EW multiplet

Mitridate, Redi, Smirnov, Strumia, 1702.01141

S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, D. Redigolo, L. Vittorio, 2107.09688

WIMP reach

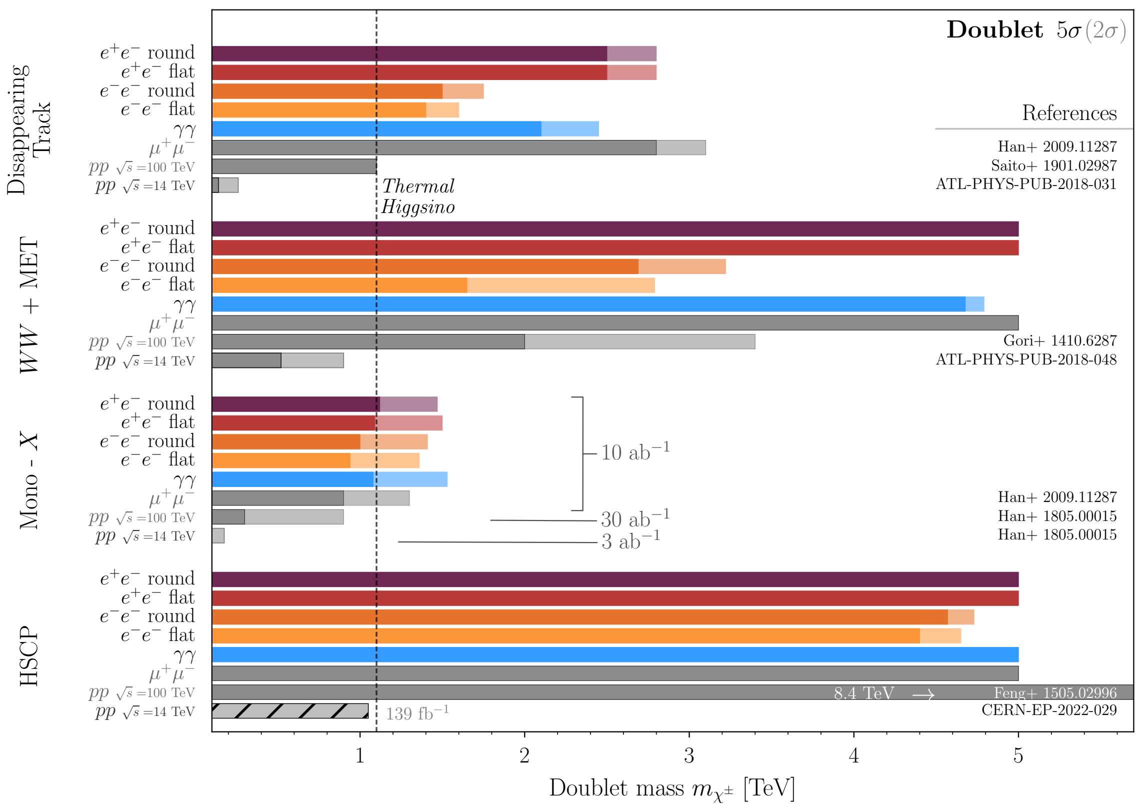
T. Han, Z. Liu, X. Wang, LTW, 2009.11287, 2203.07351

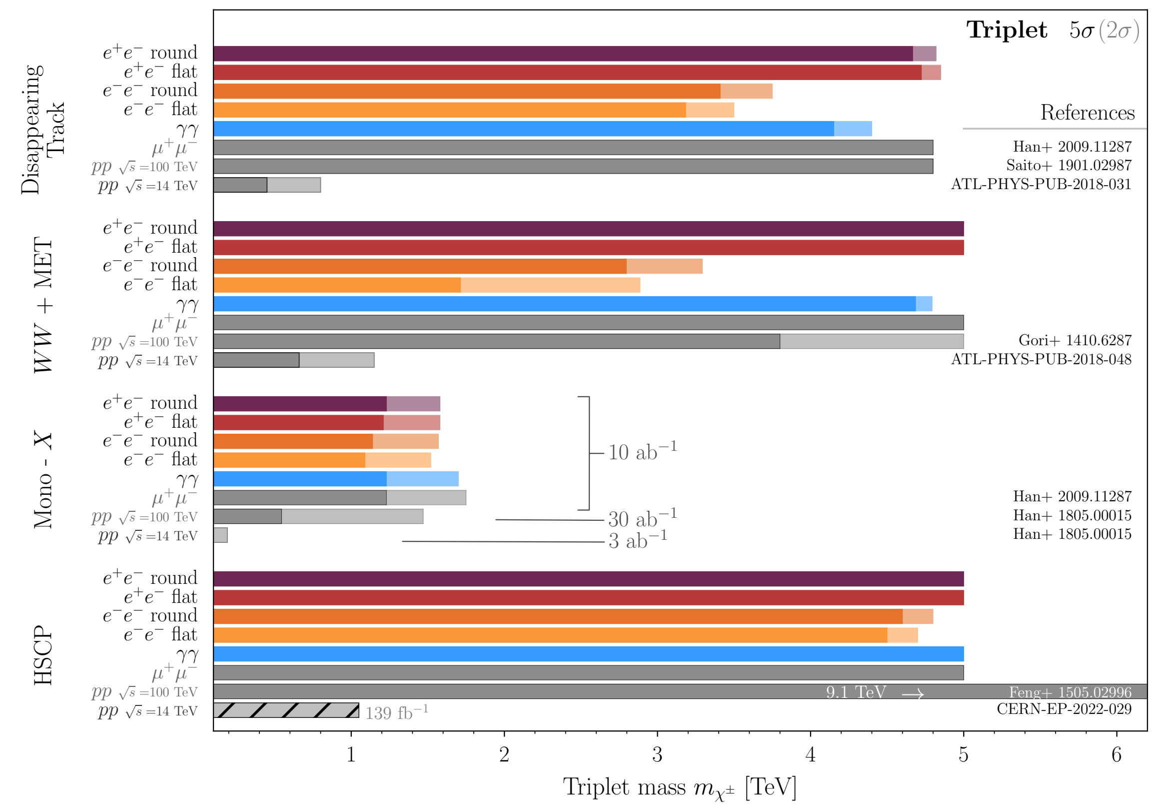


Study for muon collider with full BIB still lacking.

Different challenge for e+ e- and $\gamma\gamma$.

WIMP at wake field collider





Beam-beam does not affect reach too much.

So Chigusa, Simon Knapen, Toby Opferkuch, Inbar Savoray, Christiane Scherb, Weishuang Linda Xu, 2512.09995

Flavor (CP)

Main question: what is the scale and mechanism flavor physics?

Lepton flavor violation

Exp limit: $\mathrm{BR}(\mu \to 3\mathrm{e}) < 10^{-12}$

Constraint: $\frac{c}{\Lambda^2}(e\Gamma\mu)(e\Gamma e), \quad \Lambda > 2 \times 10^2\ \mathrm{TeV}$

Exp limit: $\mathrm{BR}(\tau \to 3\mu) < 2.1 \times 10^{-8}$

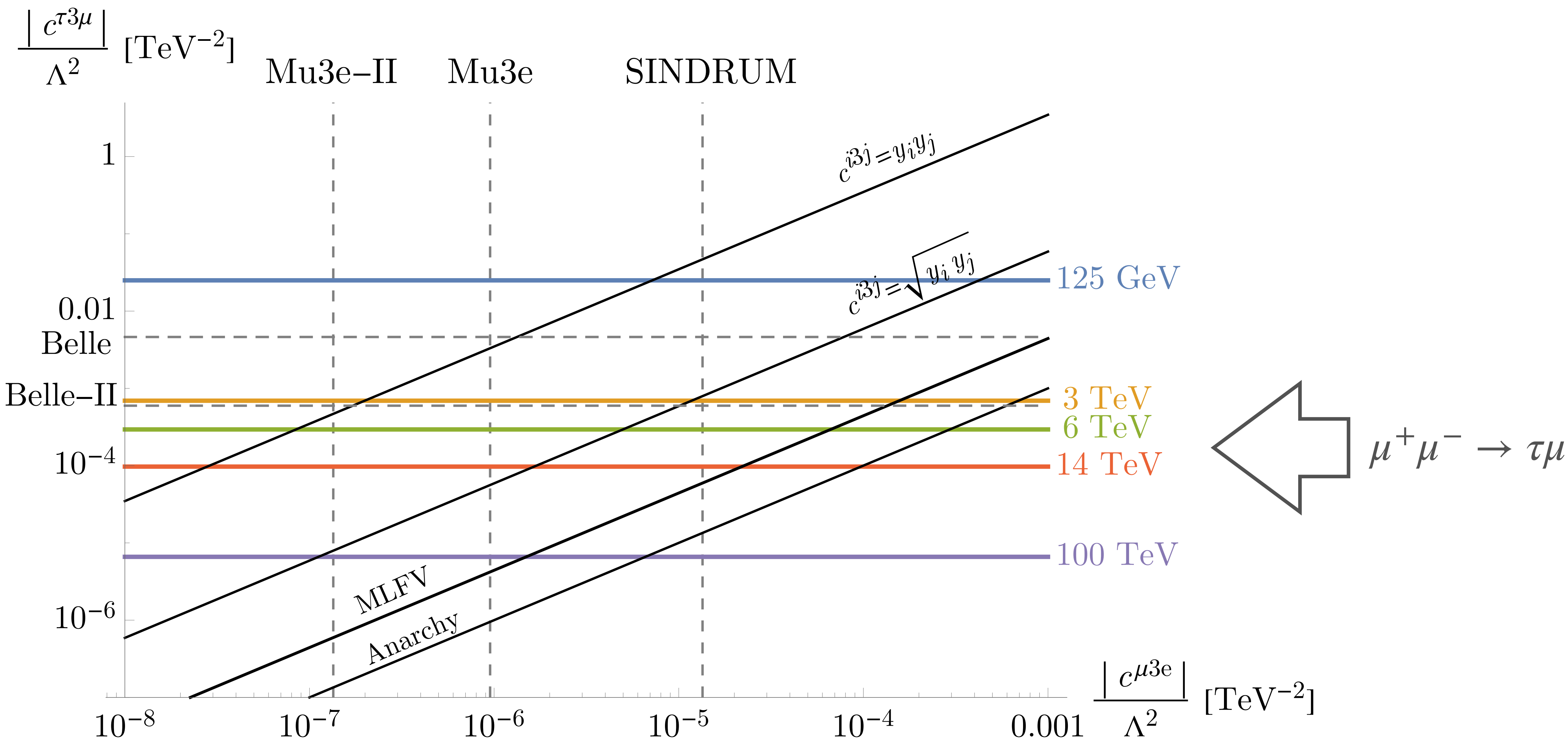
Constraint: $\frac{c}{\Lambda^2}(\mu\Gamma\tau)(\mu\Gamma\mu), \quad \Lambda > 10\ \mathrm{TeV}$

Flavor scale beyond weak scale. Sometime known as the “little hierarchy”

However, 10 TeV remains possible for new flavor physics!

Flavor violation: EFT study

S. Homiller, Q. Lu, M. Reece, 2203.08825, Smasher's guide



Direct probe at muon colliders: $\mu^+\mu^- \to \ell_i \ell_j$

Sensitivity comes from the high energy part. Similar reach for $e^+ e^-$

How about "real" flavor physics

- Most naive limit on scale of flavor physics $\Lambda_{\text{flavor}} > 100\text{s TeV}$
- However, in many scenarios of flavor generation, there are suppressions.
  - Extra-dimension.
  - partial compositeness.
  - …

Arkarni-Hamed and Schmaltz, 9903417
Arkani-Hamed, Dimopoulos, Dvali, March-Russell, 9811448
Fitzpatrick, Perez, Randall, 07101869 …

D. B. Kaplan, 1991
…
Rattazzi, Ricci 2402.09503

New flavorful resonances can appear around 10 TeV.

More work needed: models + collider pheno

Looking ahead

Happening,right?

The European Strategy for Particle Physics:
2026 Update

A. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN.

However, history taught us that there will still be a lot of uncertainties ahead.

Other options, and steps beyond to 10 TeV pCM, will need to be vigorously pursued.

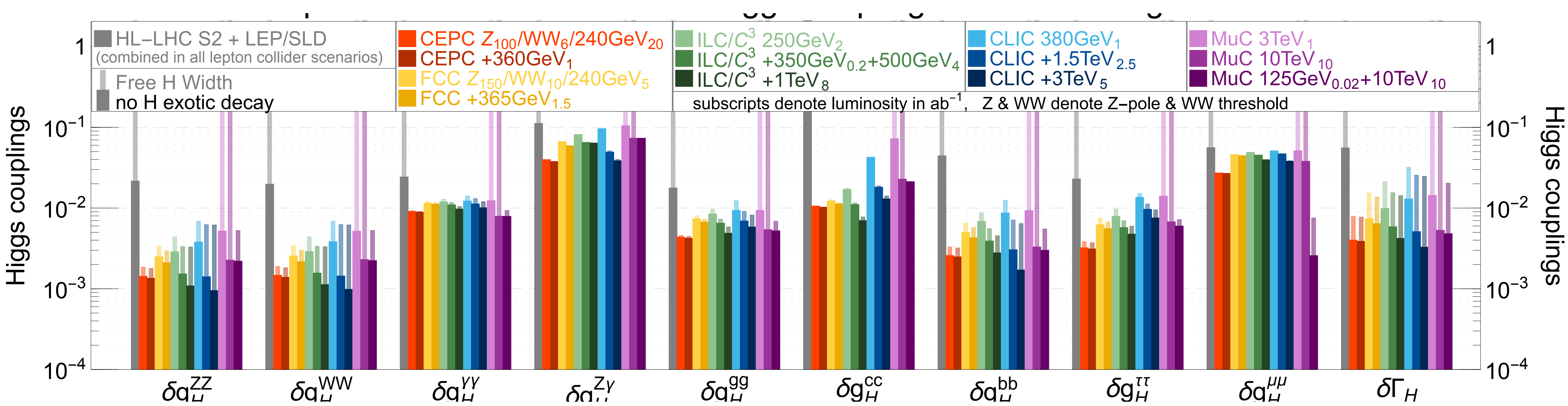
Conclusion

- We are in uncertain times.
  - Many unanswered questions, no clear path forward.
- There are also many opportunities
  - Much more data from LHC to come.
  - Many new proposals to study.
- Time to think big, think long term!

A lot to look forward to…

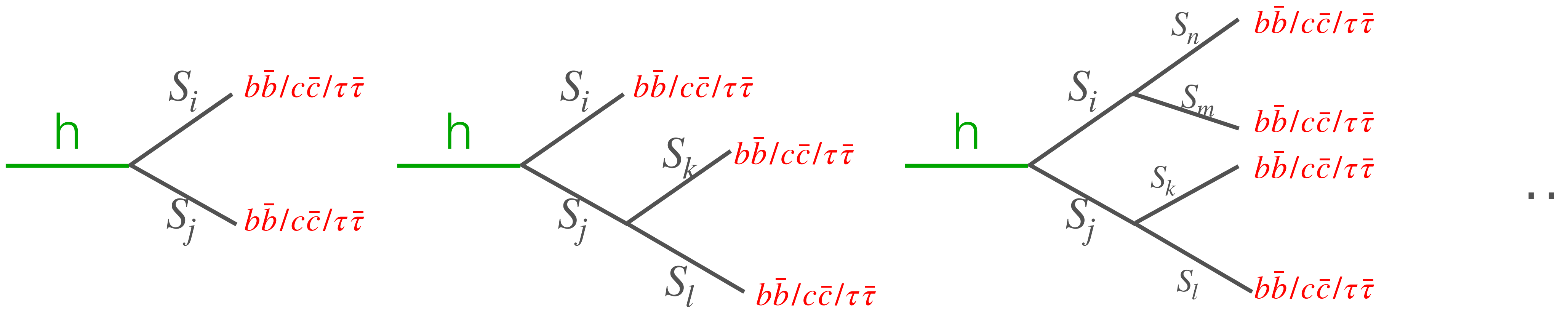
Extra

The Higgs measurements



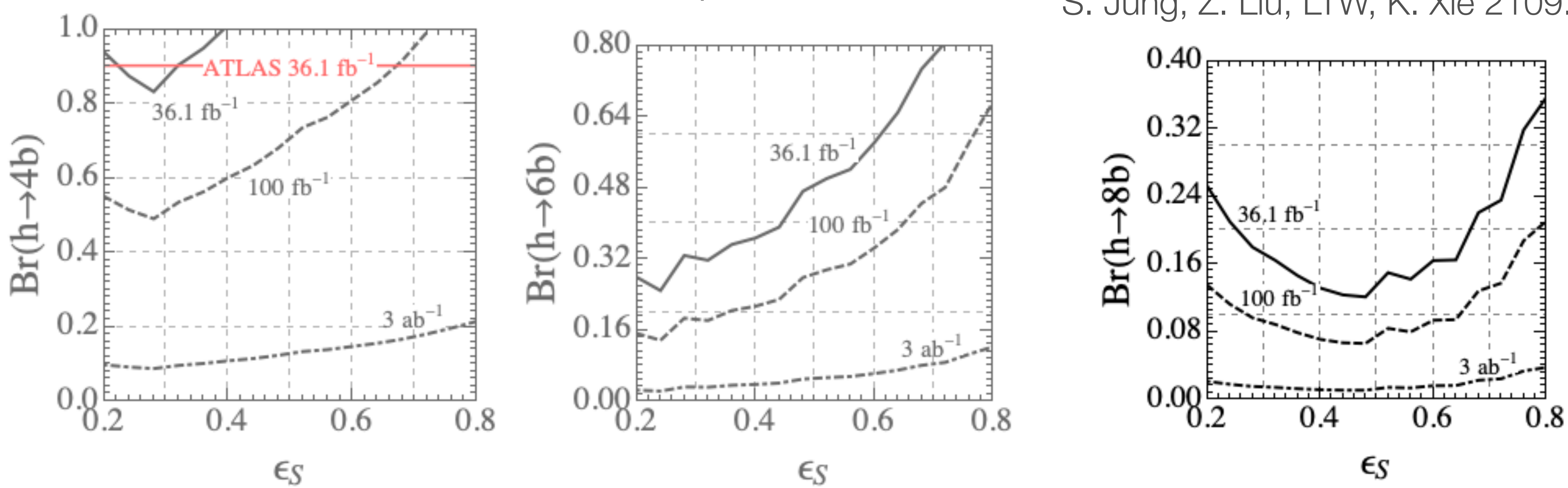
Overall, a big step beyond the LHC

Are we ready for this?



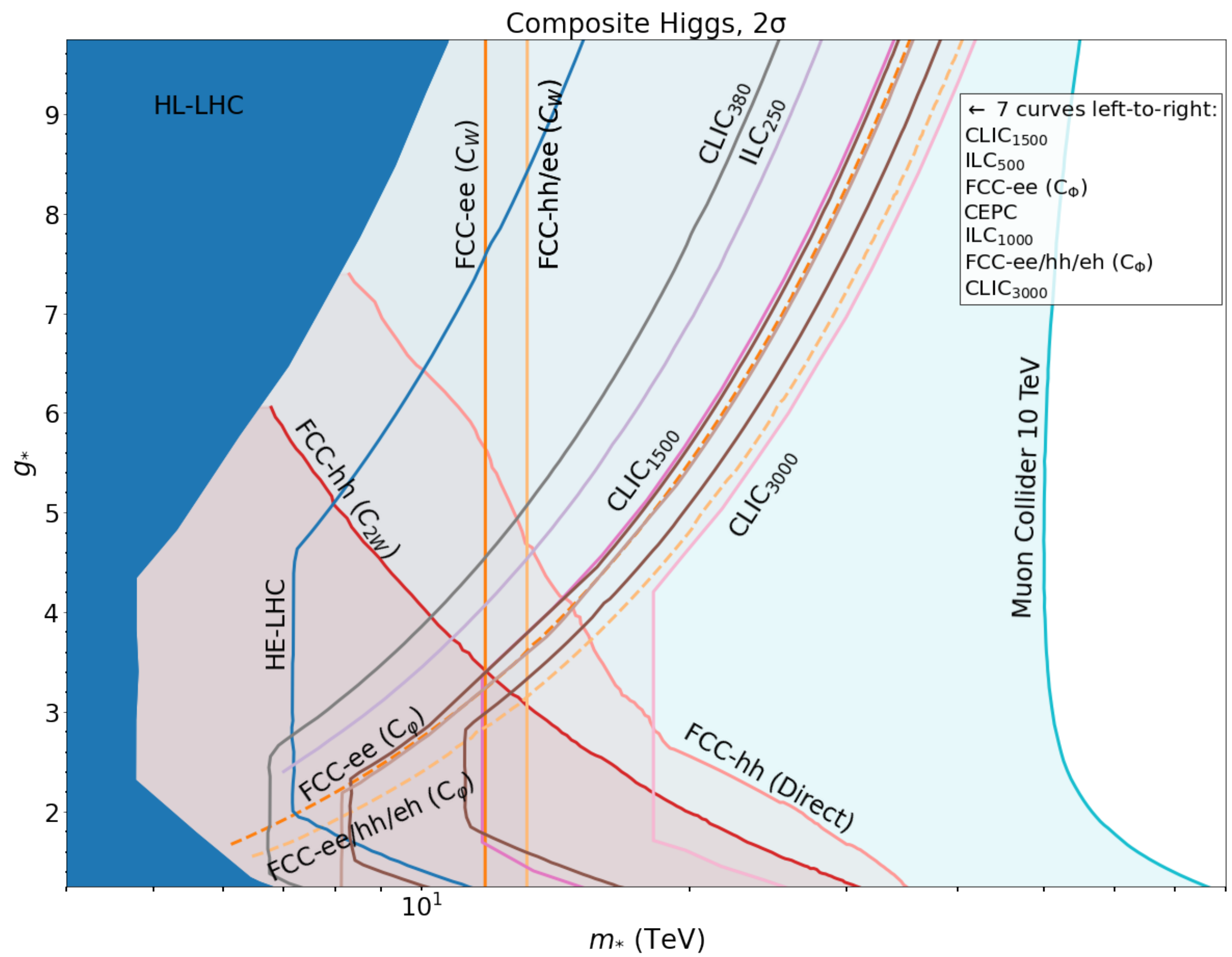
$Wh \to \ell\nu + bs$

S. Jung, Z. Liu, LTW, K. Xie 2109.03294



New ideas to trigger and tag on this kind of final states?

Composite Higgs



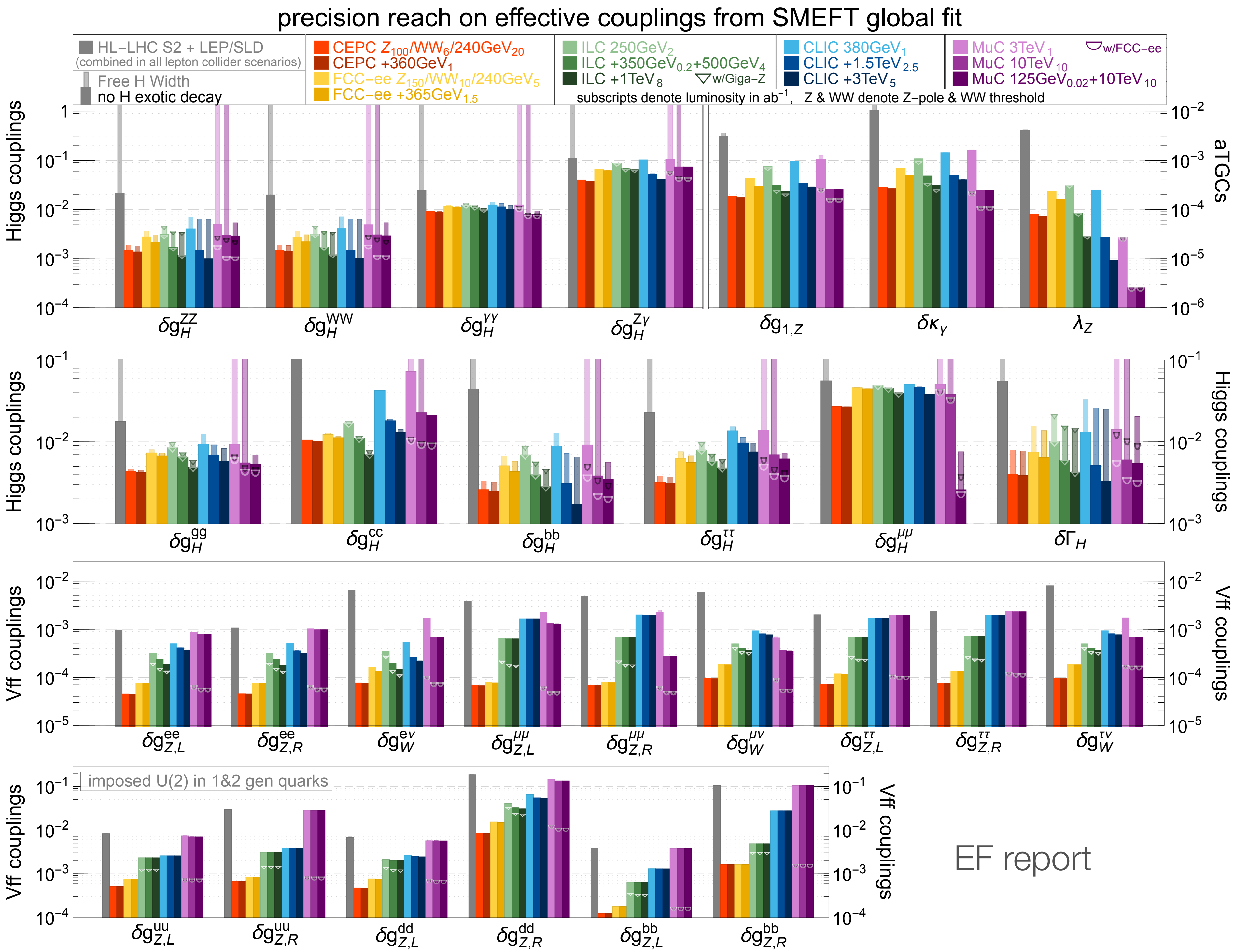
Limited by precision on very energetic particles.

Should be similar to e^+e^- and $\gamma\gamma$

Good to verify!

$$\frac{c_\phi}{\Lambda^2}\frac{1}{2}\partial_\mu\left(\phi^\dagger\phi\right)\partial^\mu\left(\phi^\dagger\phi\right)$$

A full suite of measurements



EF report

Based on:

Collider	$\sqrt{s}$	P [%] e^-/e^+	$L_{\rm int}$ ab^{-1}
ILC	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8
ILC-GigaZ	m_Z	$\pm80/\pm30$	0.1
CLIC	380 GeV 500 GeV 1 TeV	$\pm80/0$ $\pm80/0$ $\pm80/0$	1 2.5 5
CEPC	m_Z $2m_W$ 240 GeV $2m_t$		60 / 100 3.6 / 6 12 / 20 – / 1
FCC-ee	m_Z $2m_W$ 240 GeV $2m_t$		150 10 5 1.5

Simplest example: Higgs + singlet

$$\mathscr{L} \supset V(H) + V(S) + \lambda H^\dagger H S^2$$

For $m_s < 0.5 \times m_h$

After EWSB, $\Gamma(h \to ss) \propto (\lambda v)^2$.

Can be significant since $\Gamma_h^{\mathrm{SM,tot}}$ is very narrow.

If $\langle S \rangle = 0$, missing energy

If $\langle S \rangle \neq 0$, singlet mixes with Higgs, prefers to decay to heavy fermion

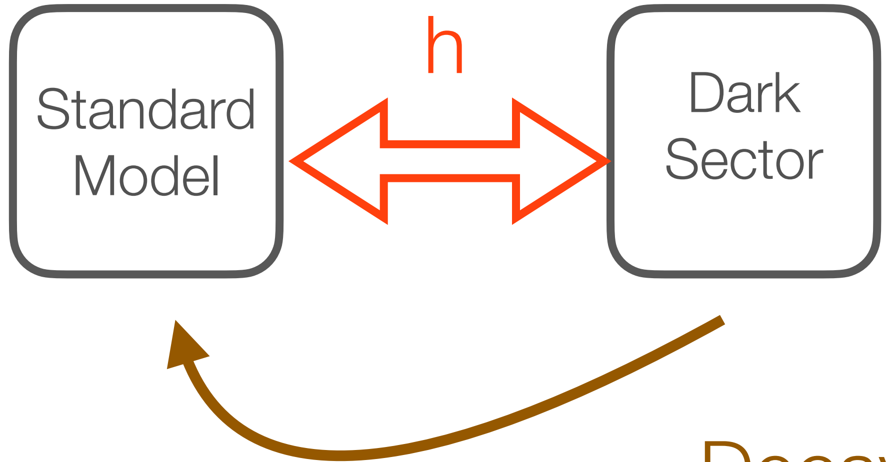
Simplest example: Higgs + singlet

$$\mathscr{L} \supset V(H) + V(S) + \lambda H^\dagger H S^2$$

For $m_s > m_h$, integrating out singlet

$$\Rightarrow \quad \frac{1}{\Lambda^2}(H^\dagger \partial H)^2 \quad \text{and} \quad \frac{1}{\Lambda^2}(H^\dagger H)^3$$

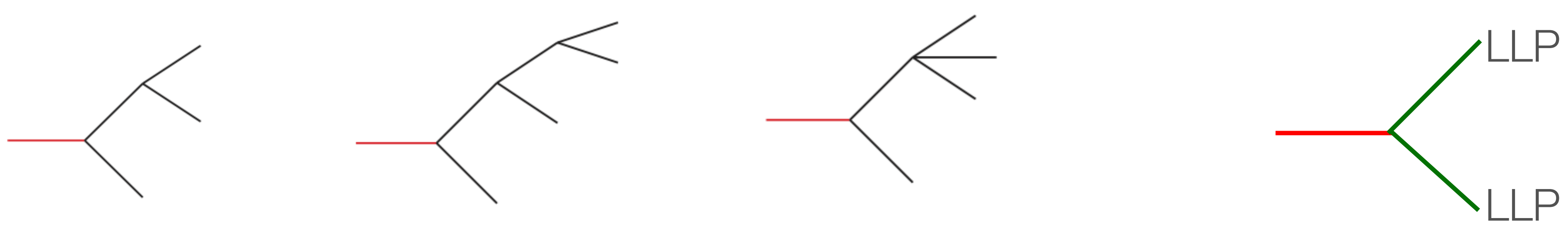
Higgs to dark sector



"Higgs portal"

Decay back to SM

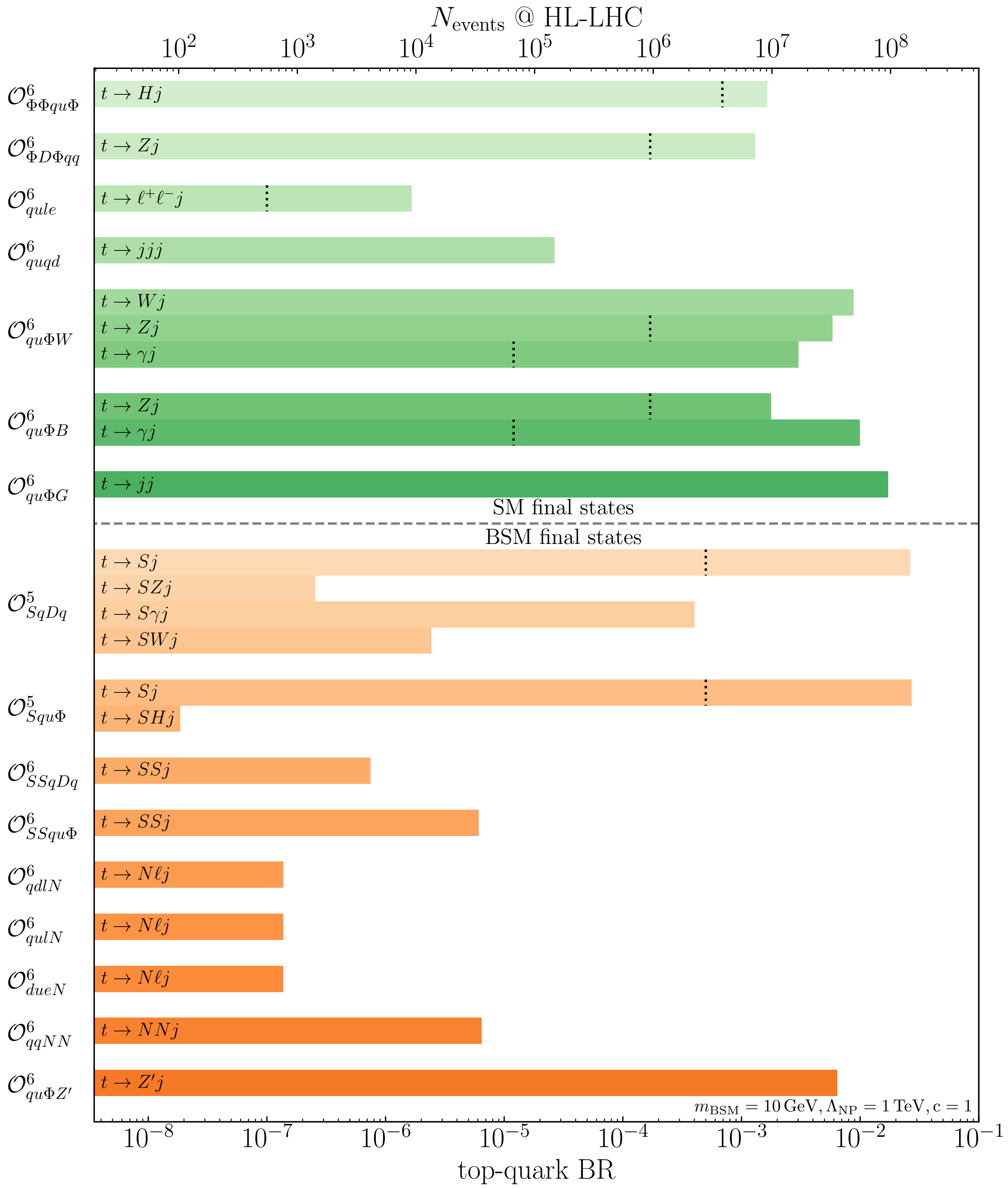
$h \to 2 \to 3$ $h \to 2 \to 3 \to 4$ $h \to 2 \to (1+3)$ Long lived particles



....

Similarly: top rare decay

H. Bahl, S. Koren, LTW 2307.11154



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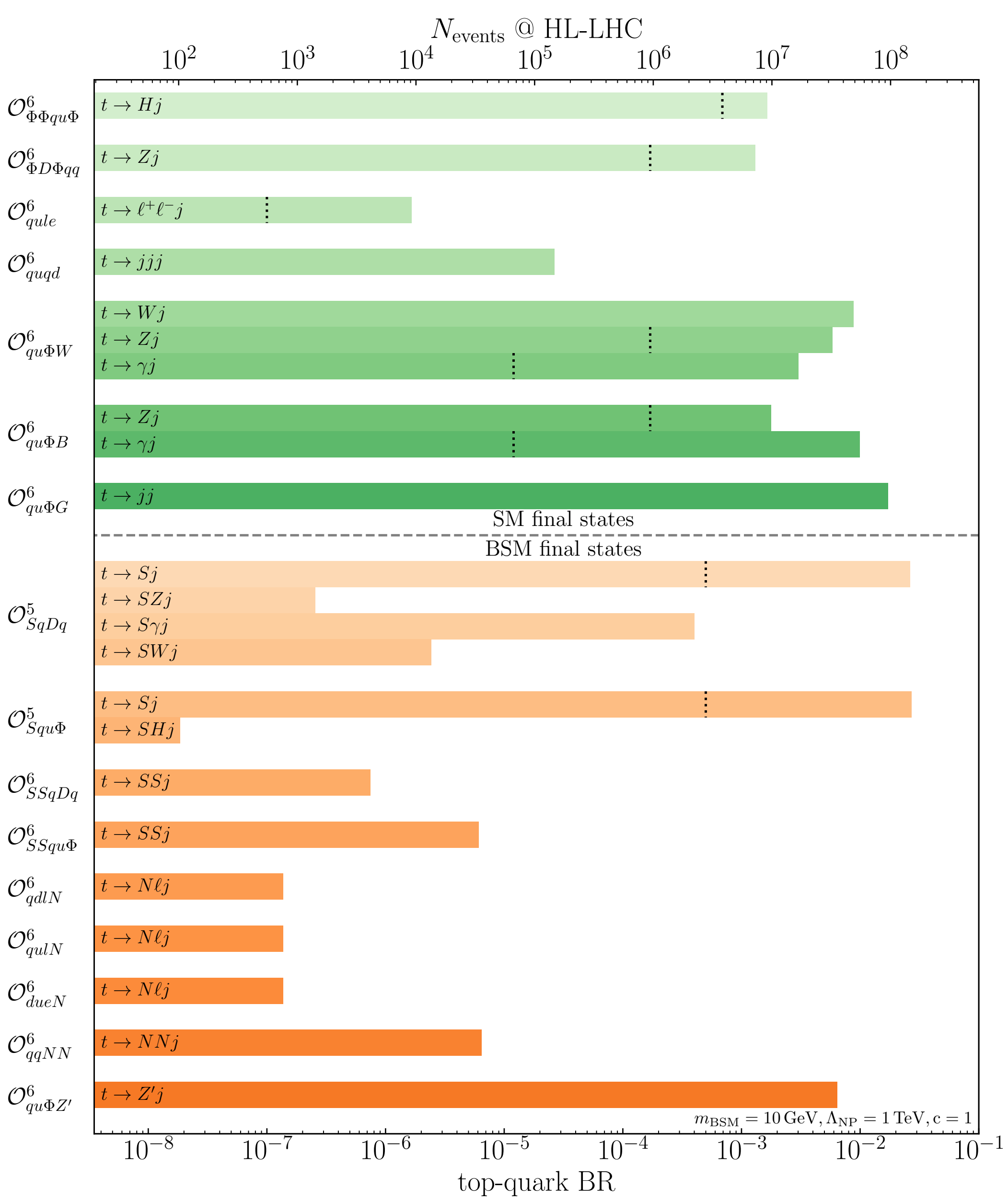
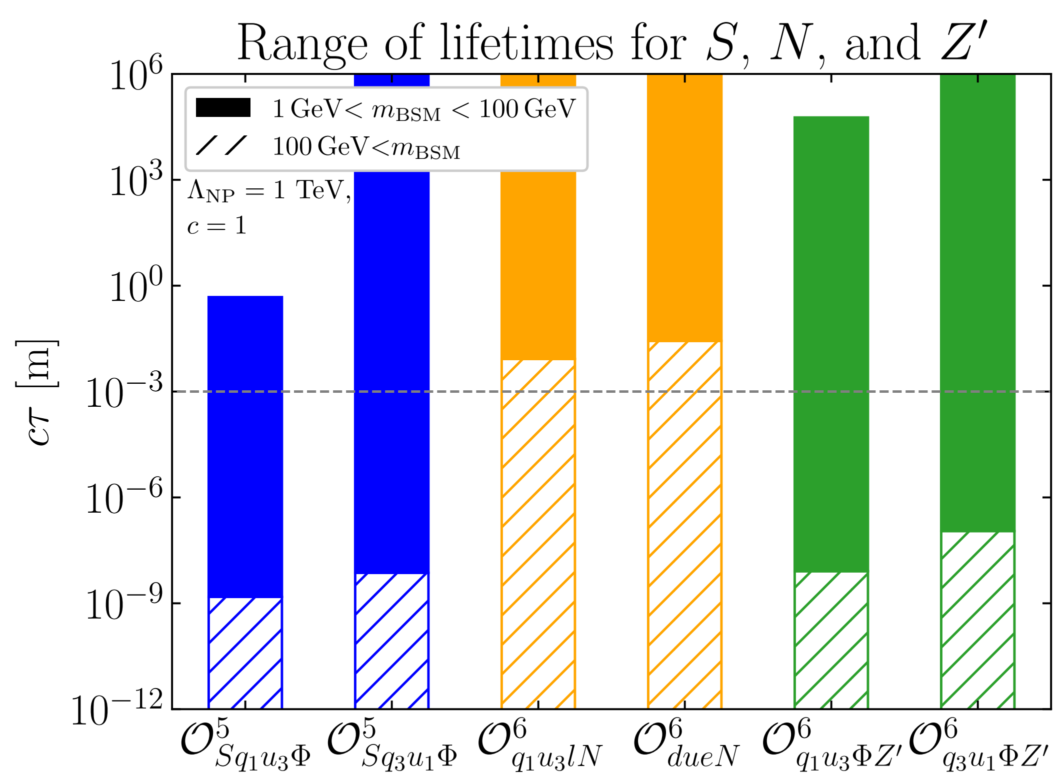
H. Bahl, S. Koren, LTW 2307.11154

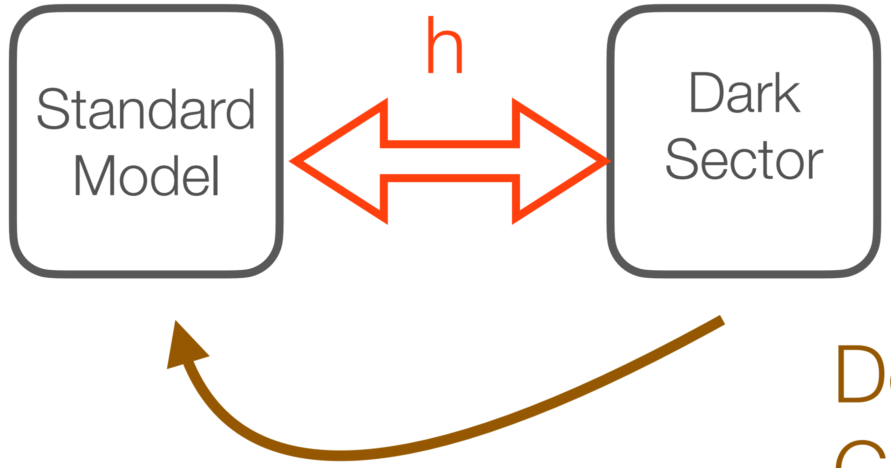




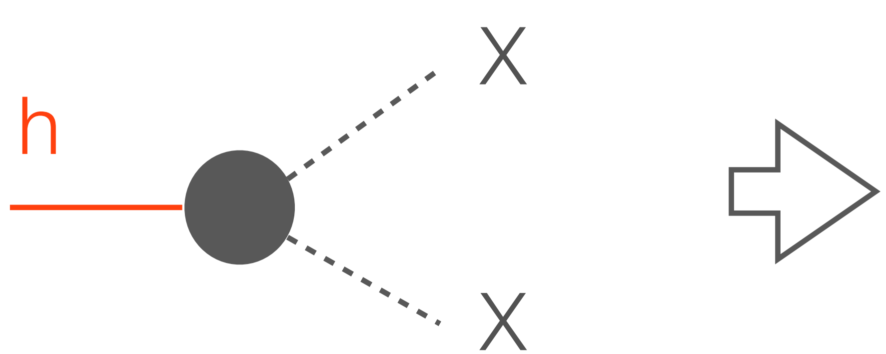
Can have LLPs

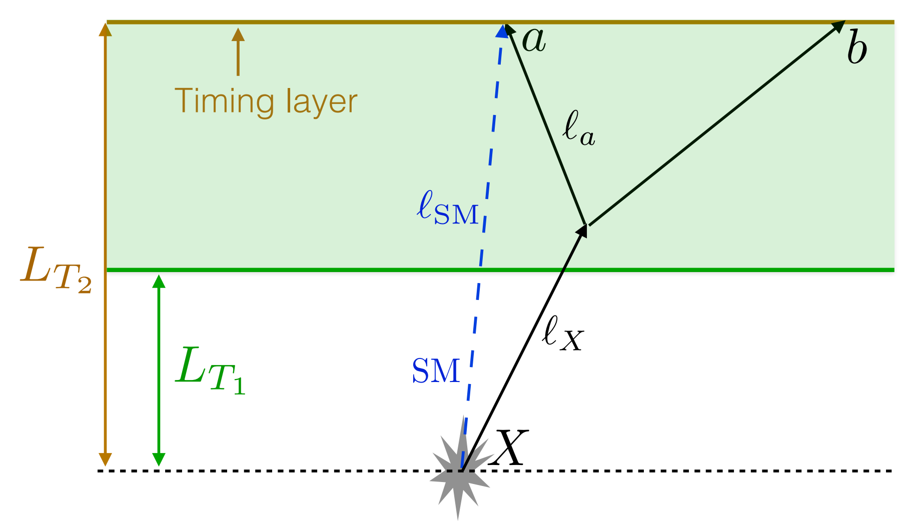
Can use the other top as trigger

Long lived particle (LLP)



Decay back to SM
Can be long lived.
cτ can be 1 km or more

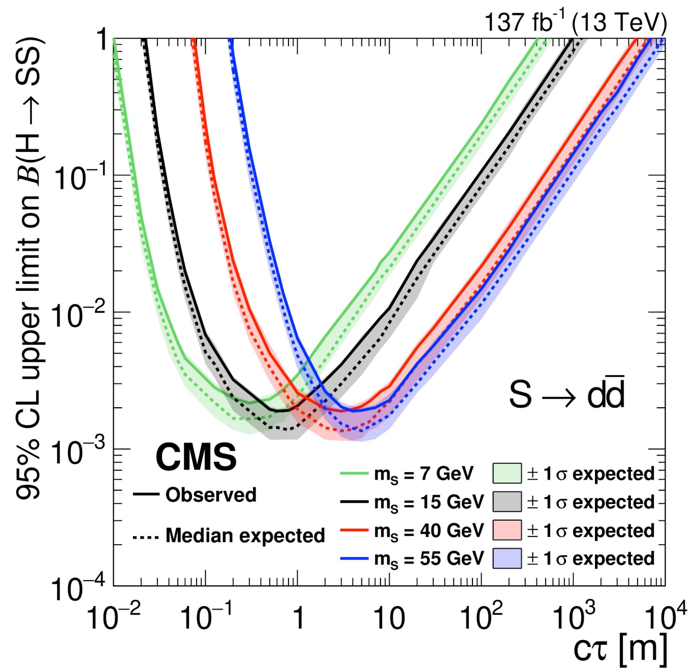


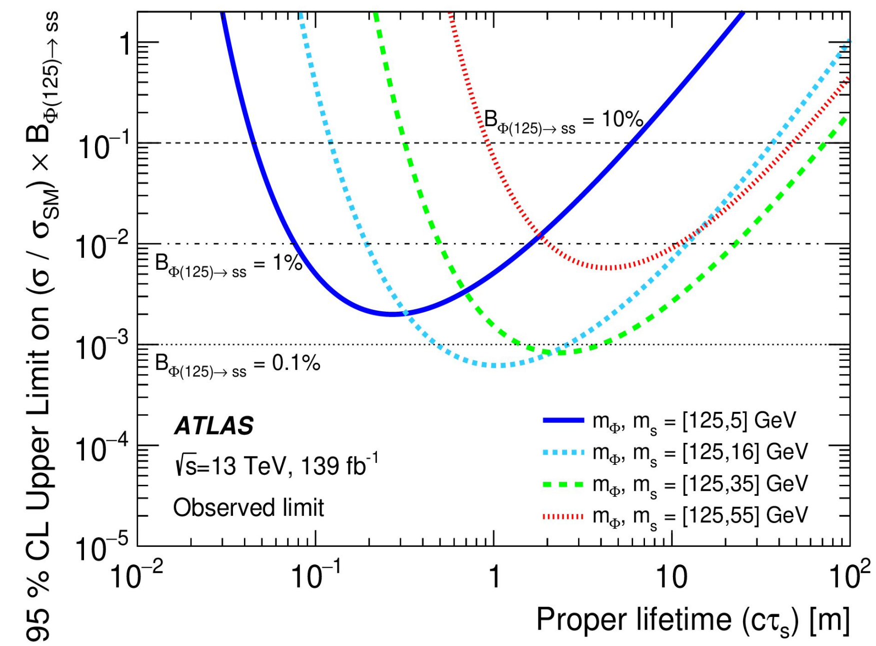


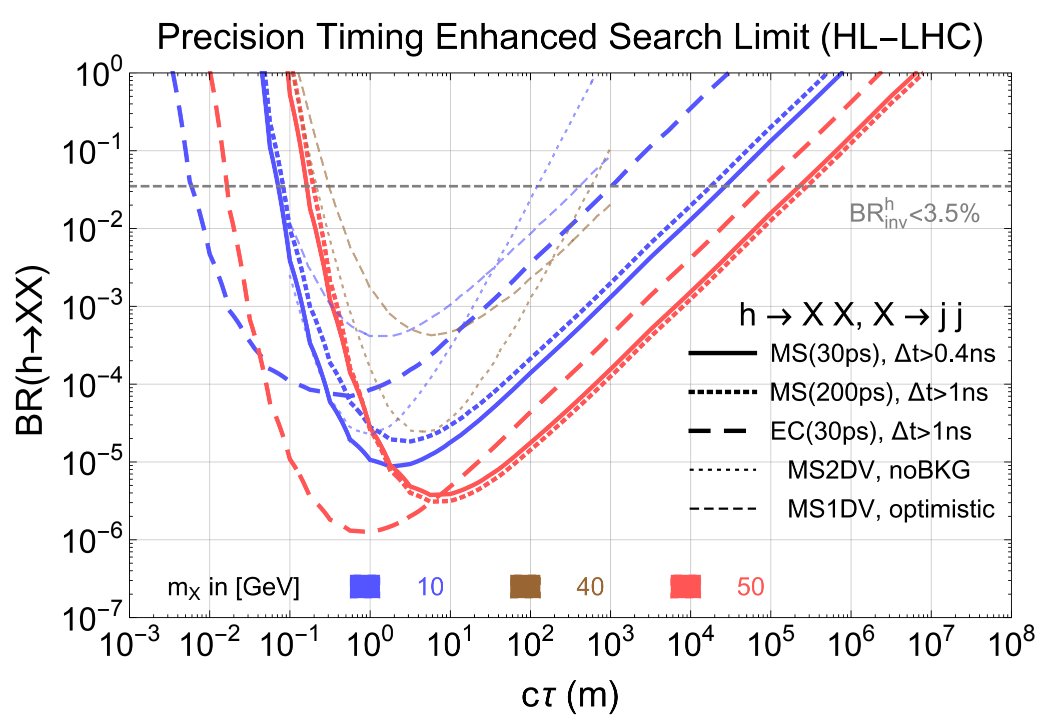
Higgs portal long lived particles

$h \to XX$

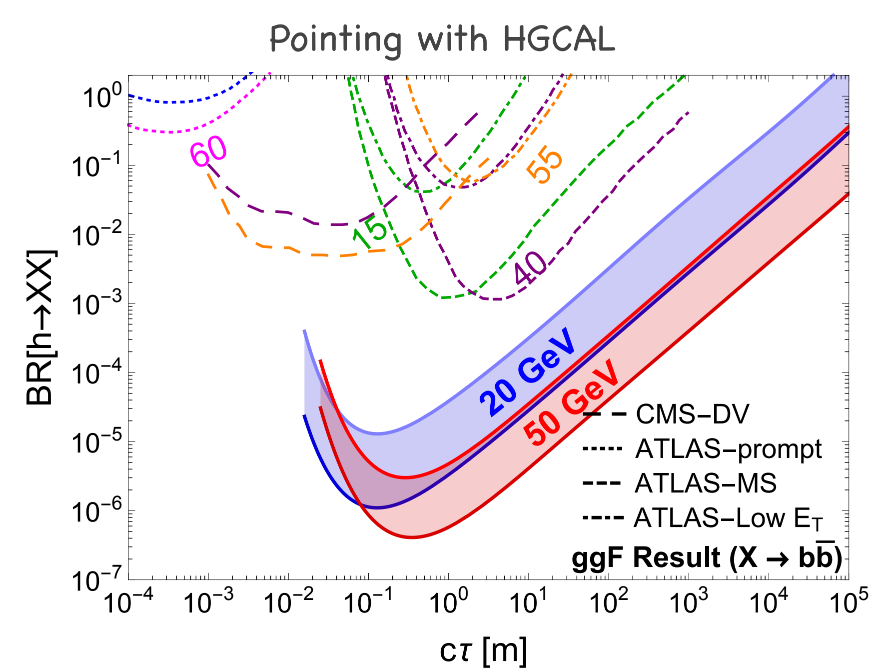
X: LLP





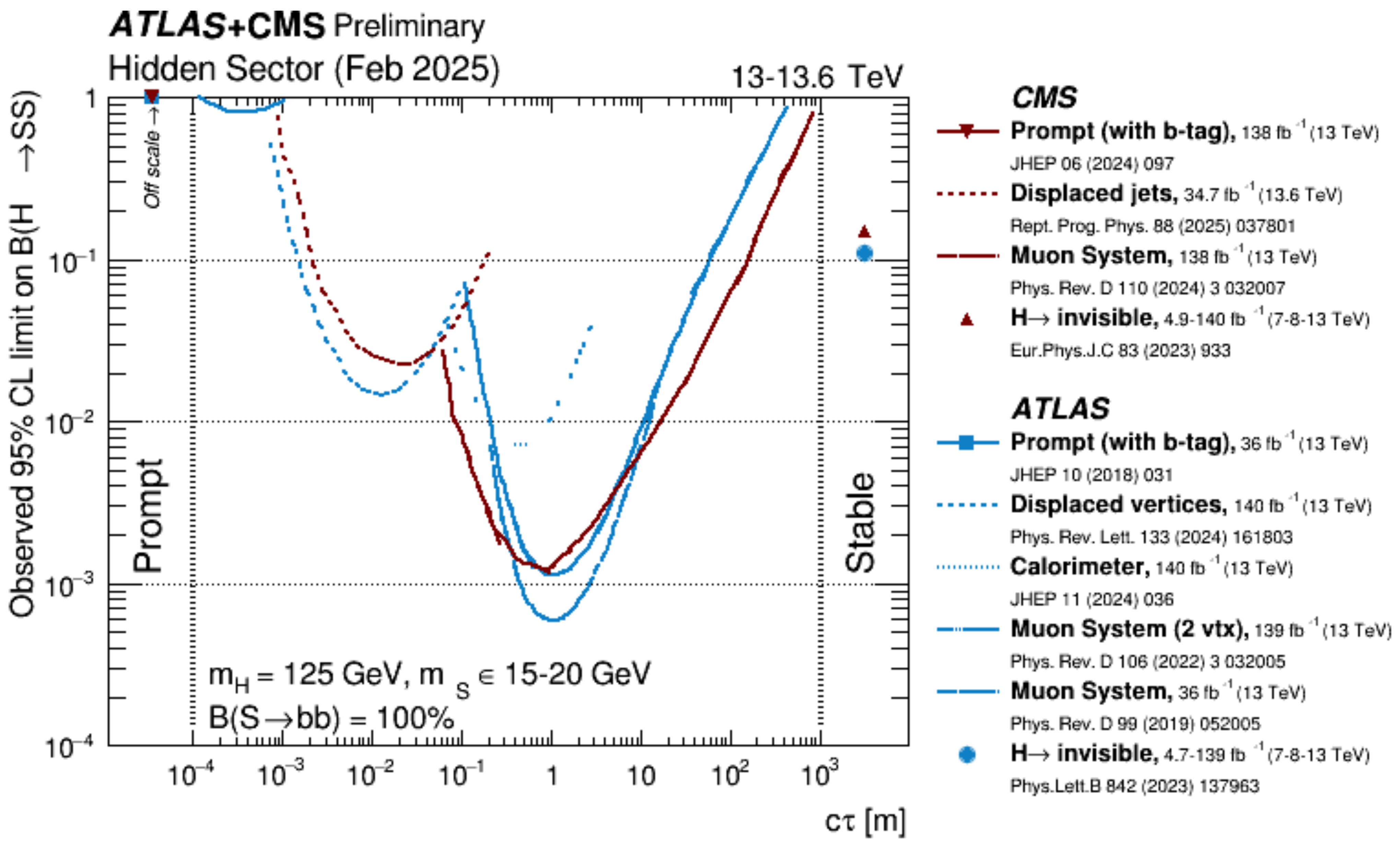


J. Liu, Z. Liu and LTW, 1805.05957



J. Liu, Z. Liu, X. Wang and LTW, 2005.10836

Potential to do better, BR(h→XX) < 10^{-5}



Still room for new ideas.

Higgs self-coupling