Higgs and New Physics

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Outline

- Why is Higgs important? (brief)

- What can the (HL)-LHC contribute?

  Highlight some promising directions.

Why focusing on the Higgs

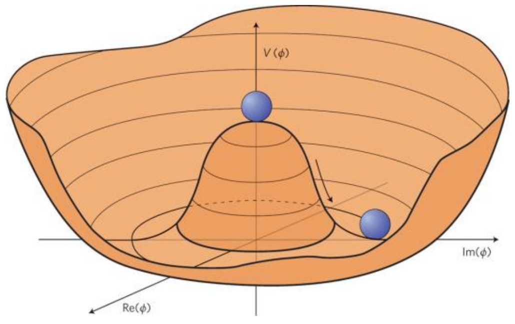
Why focusing on Higgs?

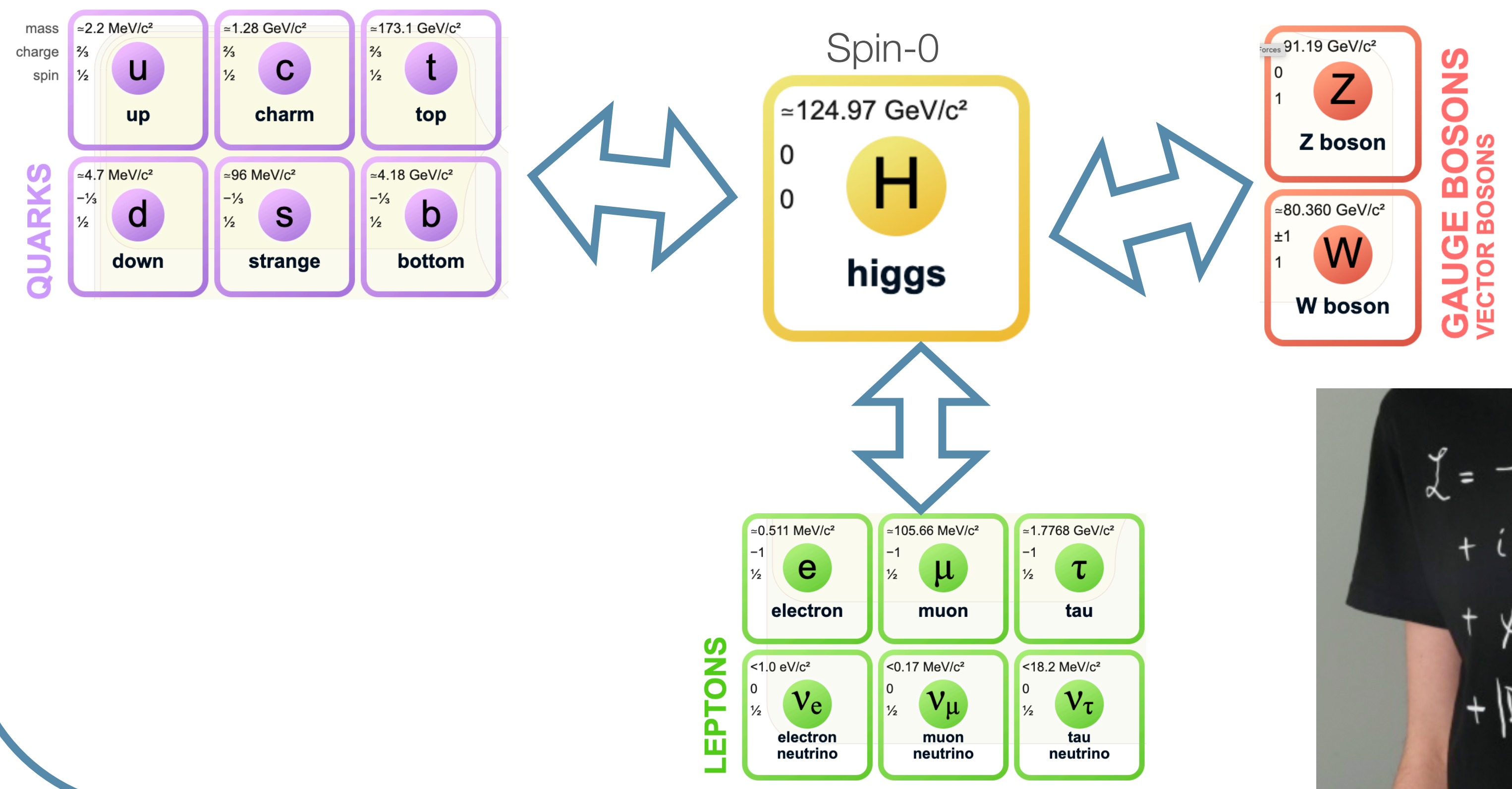
Higgs is simple.

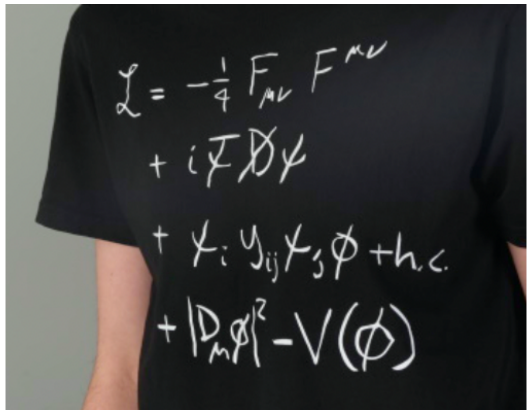
A simple “Mexican hat” potential.

⇒ Electroweak symmetry breaking

⇒ gives masses of SM particles







Why focusing on Higgs?

Yet, 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?

Yet, Higgs is confusing.

Sure, the math is simple.
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Different from other SM particles:
gauge boson (gauge symmetry), fermion (chiral symmetry)

Maybe not as simple as it seems?

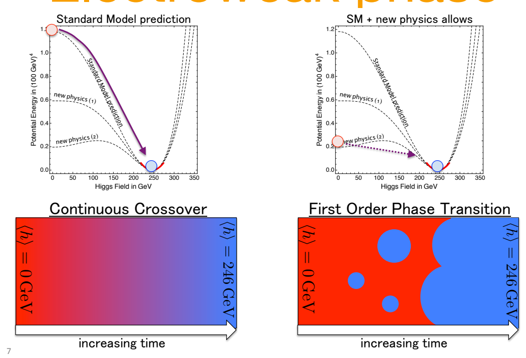
Is it elementary (like electron) or composite (like proton or pion)?

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

Where does the electroweak scale come from?

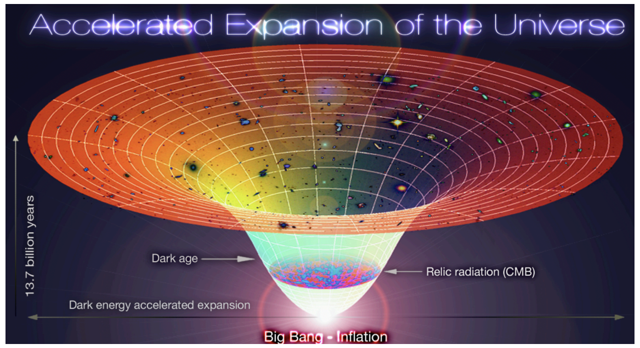
Higgs and everything else

Matter > anti-matter
Electroweak phase



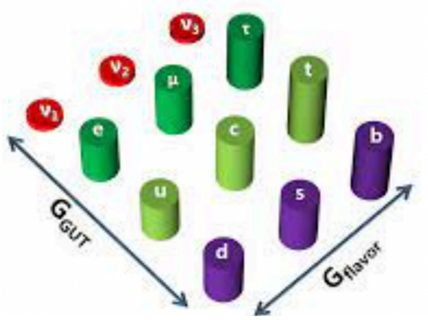
Weak interaction vs gravitation
10^2 vs 10^{18}

Higgs



Inflation, age of universe, …

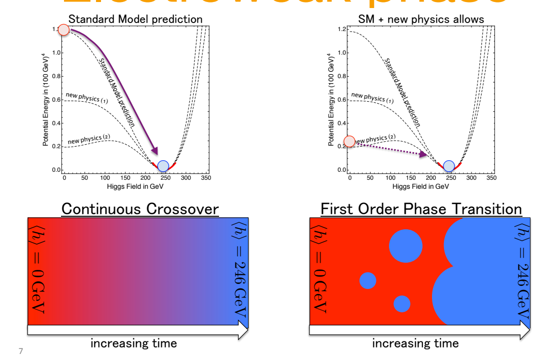
The dark world



Flavor puzzle

Higgs and everything else

Matter > anti-matter
Electroweak phase



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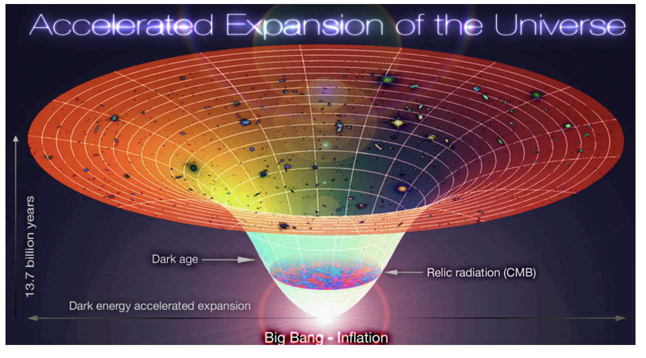

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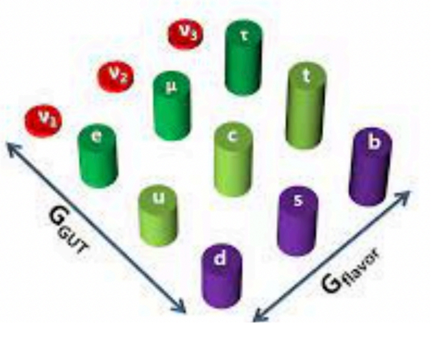
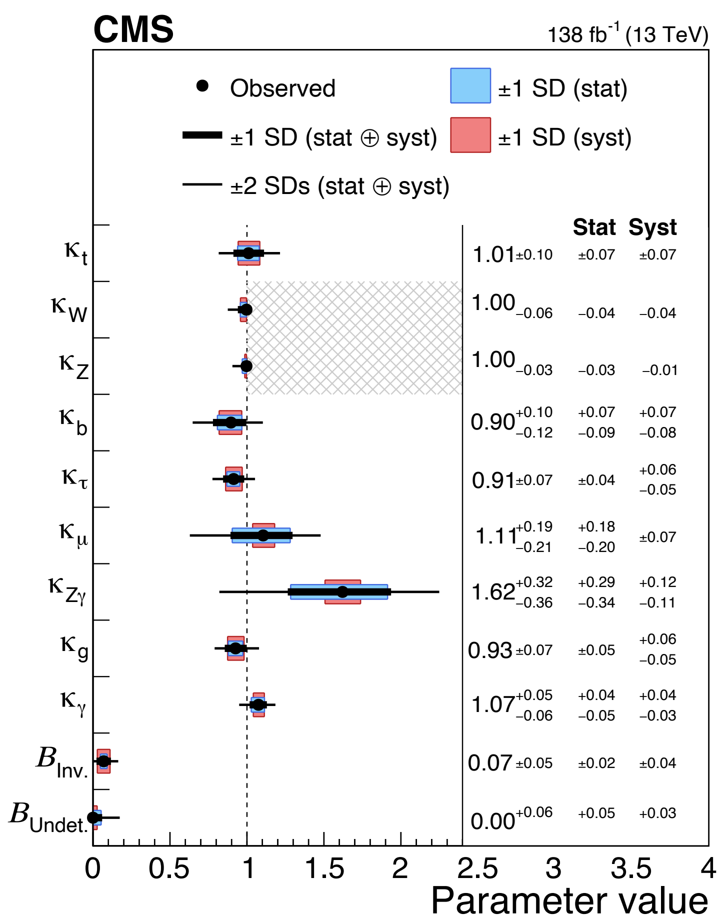


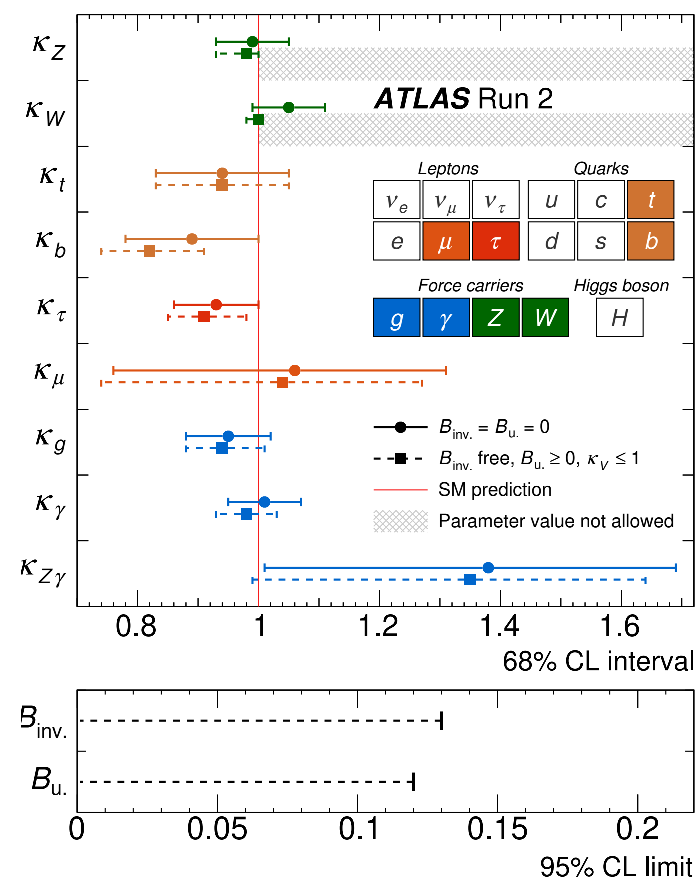
Flavor puzzle

Higgs is likely to play a role in many of these, but how?

What do we know?

Higgs coupling other SM particles:



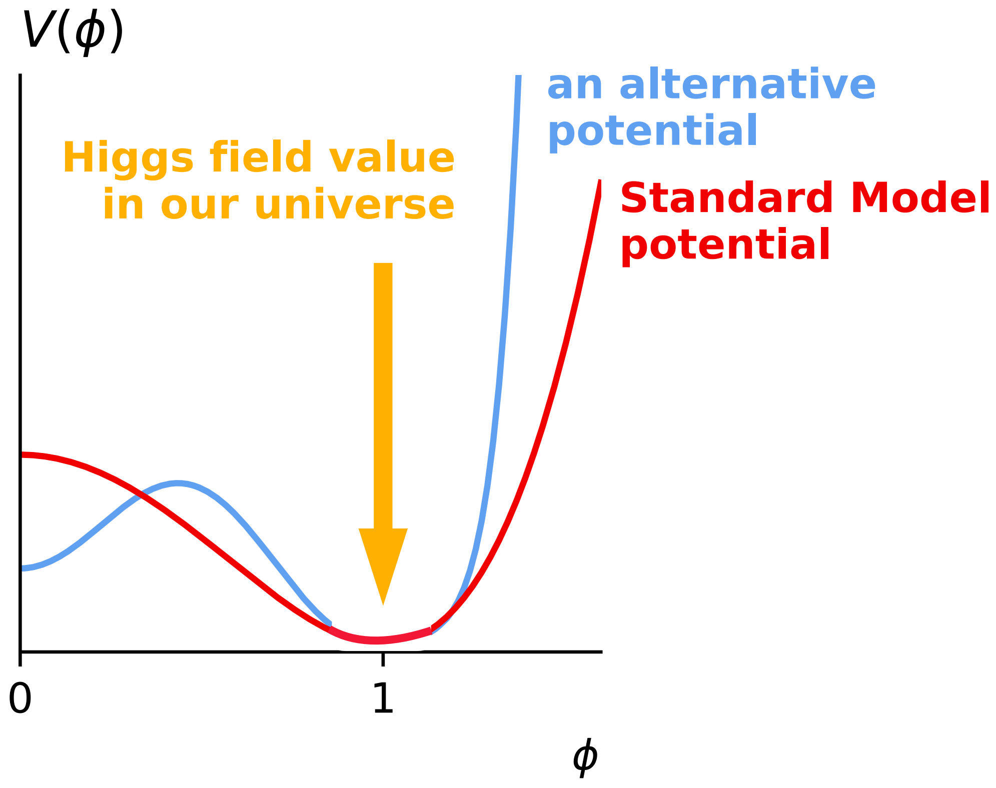


Higgs couplings. Presently, known to about 10%

Other electroweak couplings known to much better precision $\mathcal{O}(10^{-3})$.

What do we know?

Higgs potential?



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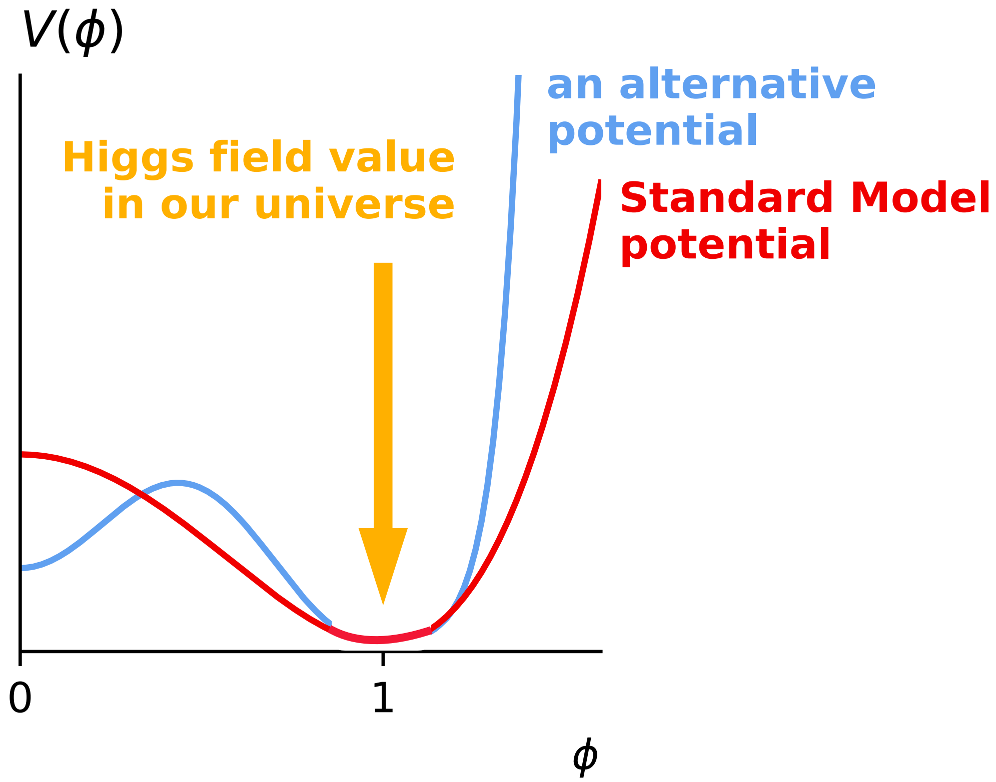
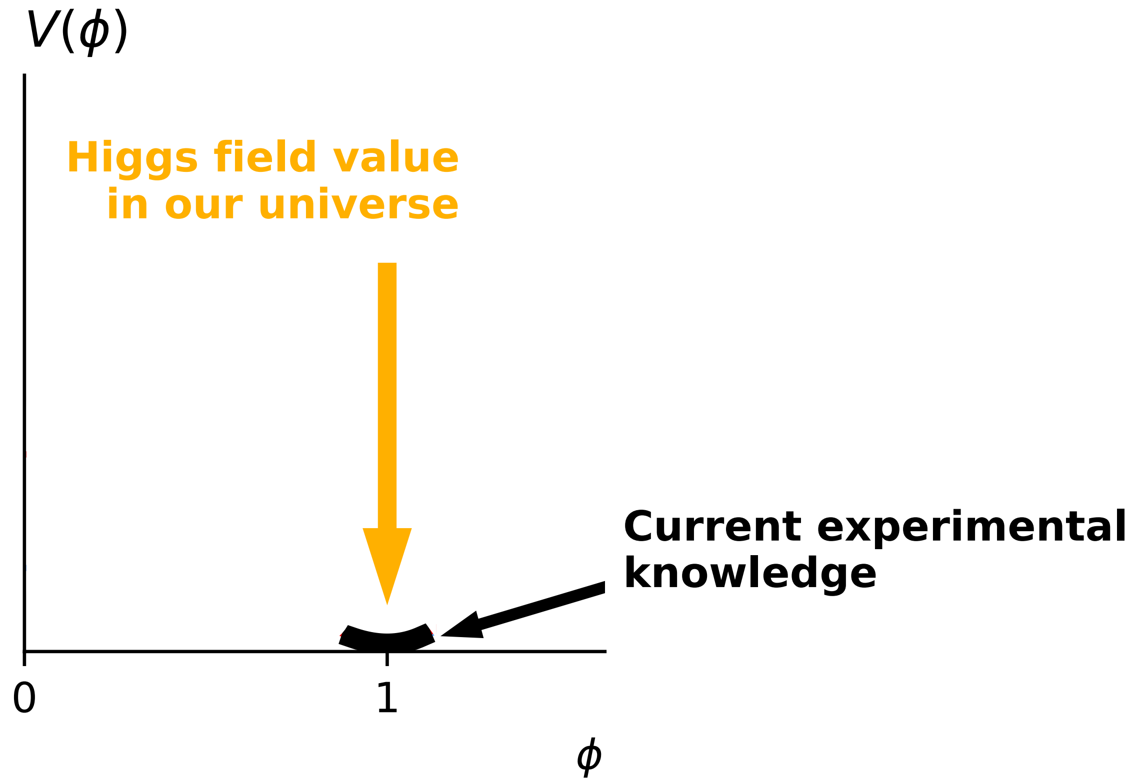
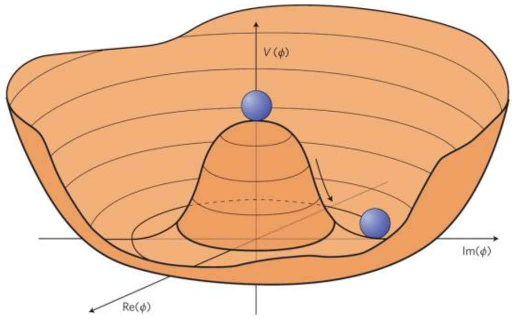


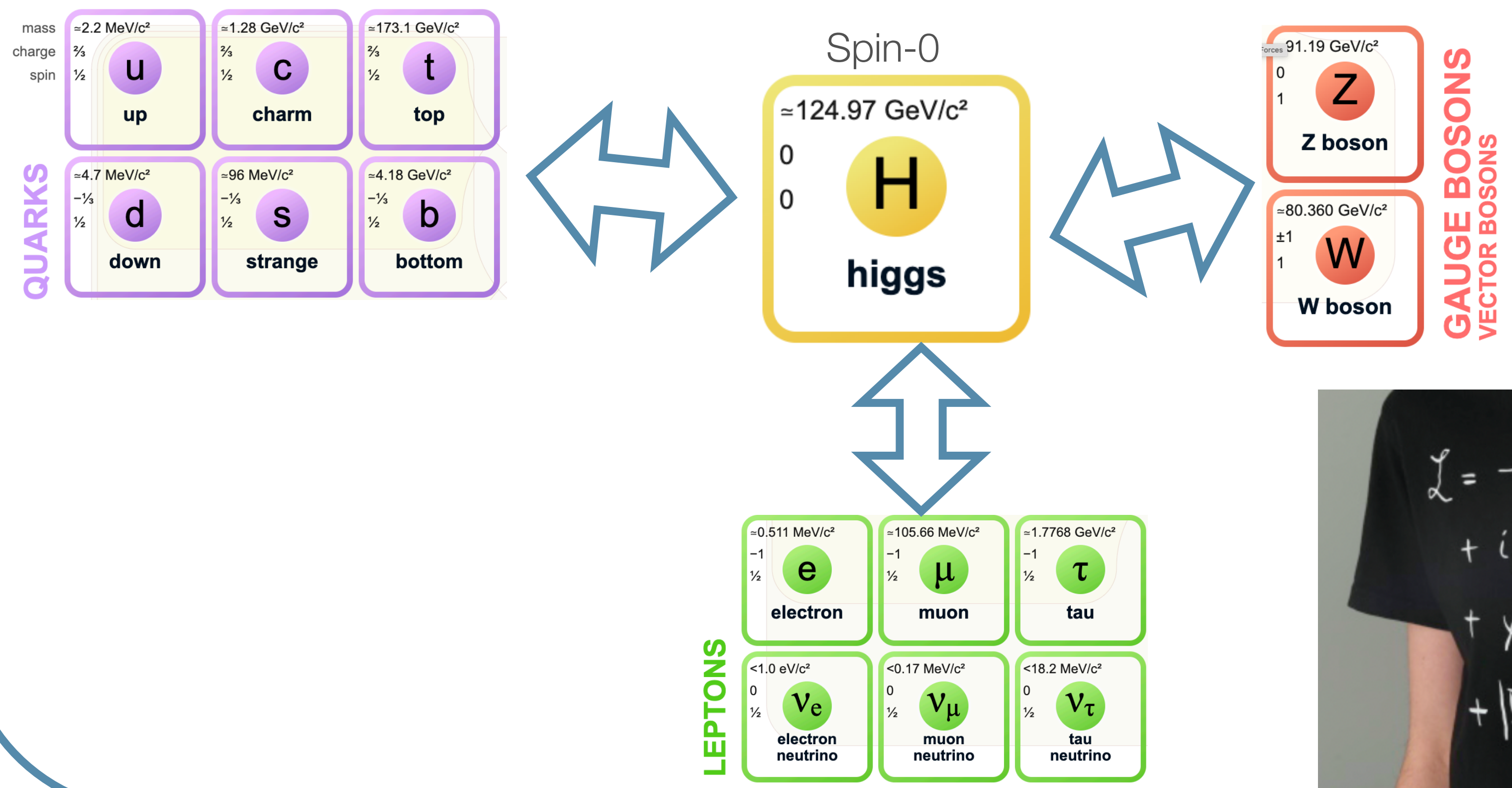


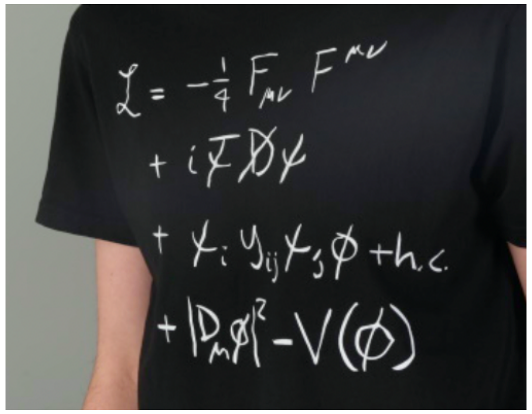
A simple "Mexican hat" potential.

⇒ Electroweak symmetry breaking

⇒ gives masses of SM particles







A simple “Mexican hat” potential ??

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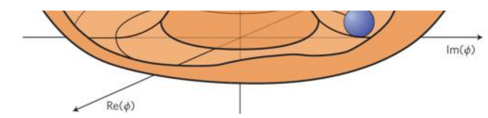

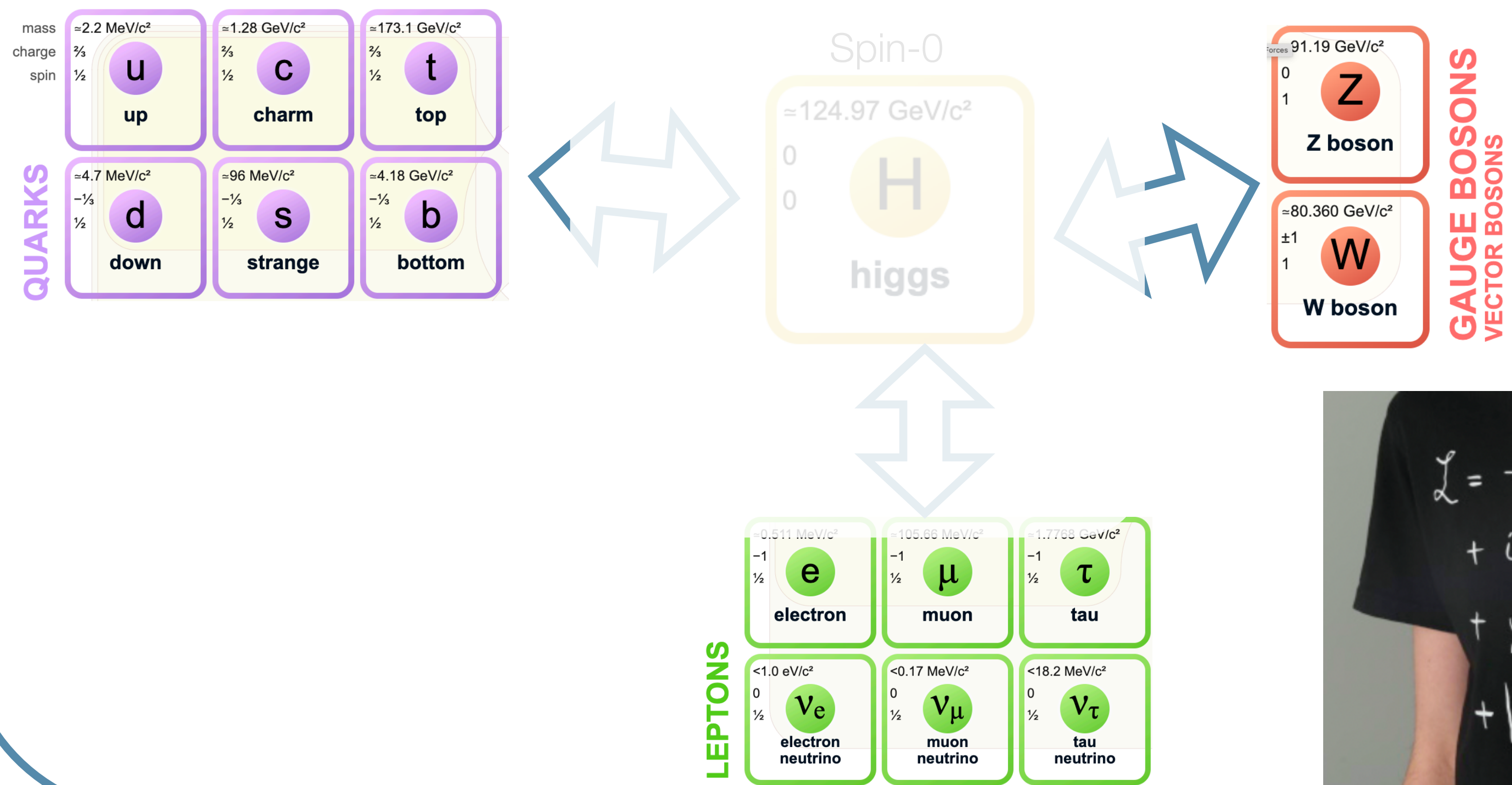

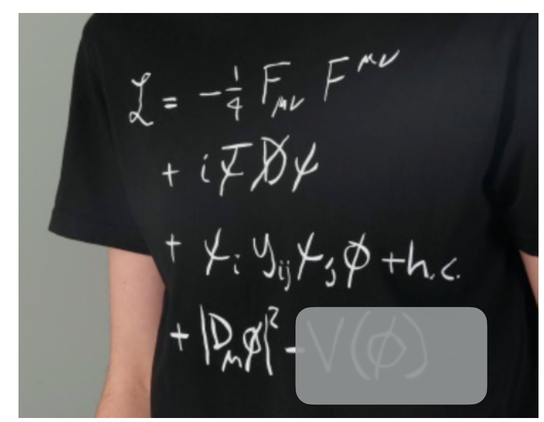

We need to know better!

What can (HL)-LHC do?

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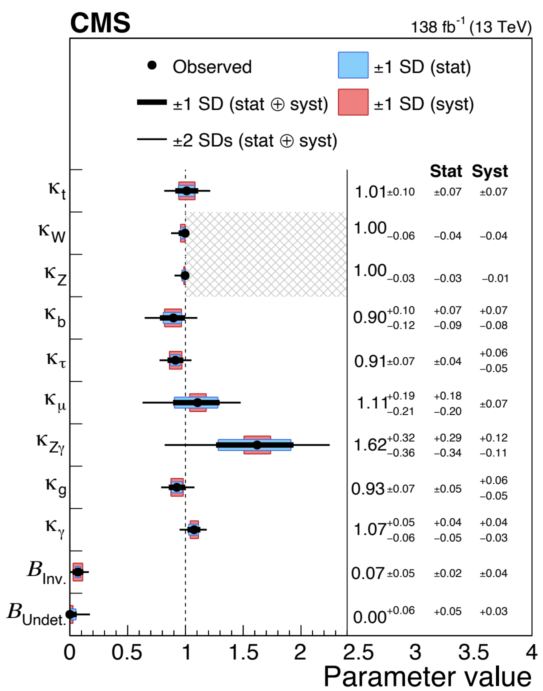
Precision

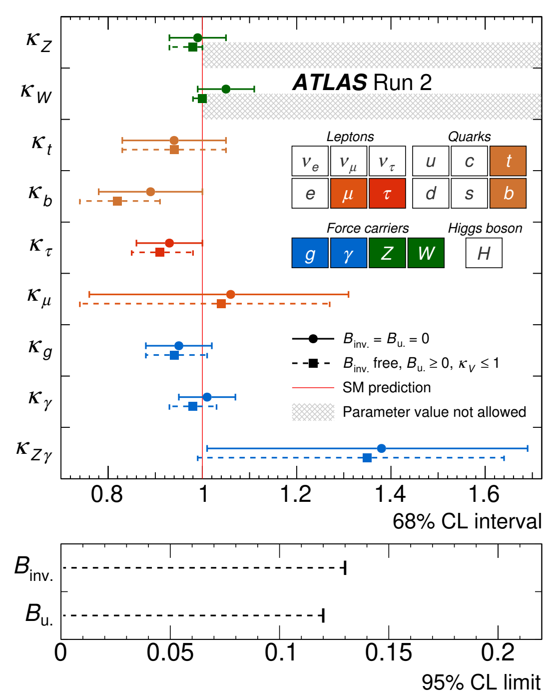
Are we really sure the SM is as simple as it appears to be?

This is the “bread and butter”.

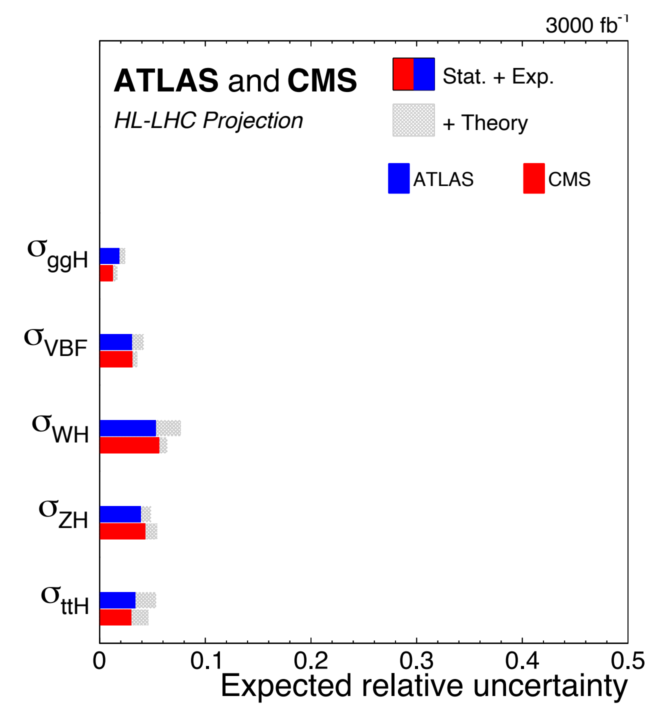
Higgs coupling

Higgs coupling other SM particles:



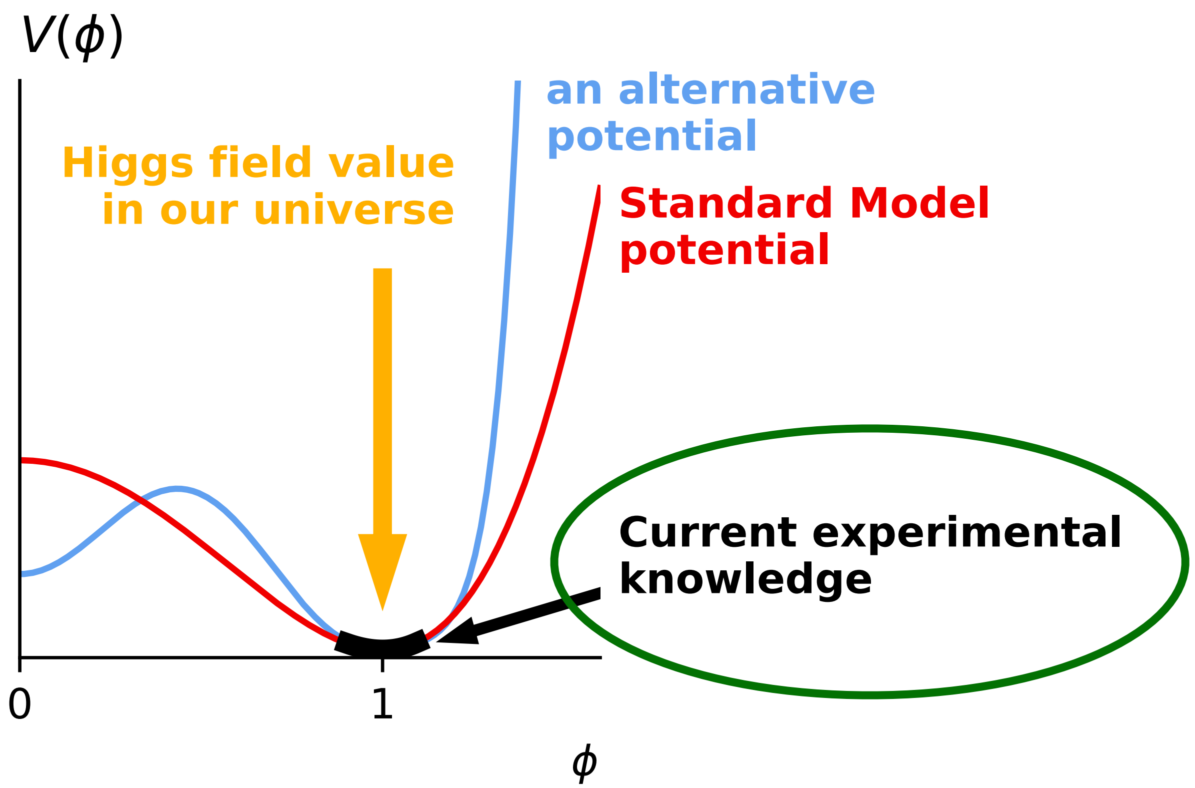


Eventually at the LHC

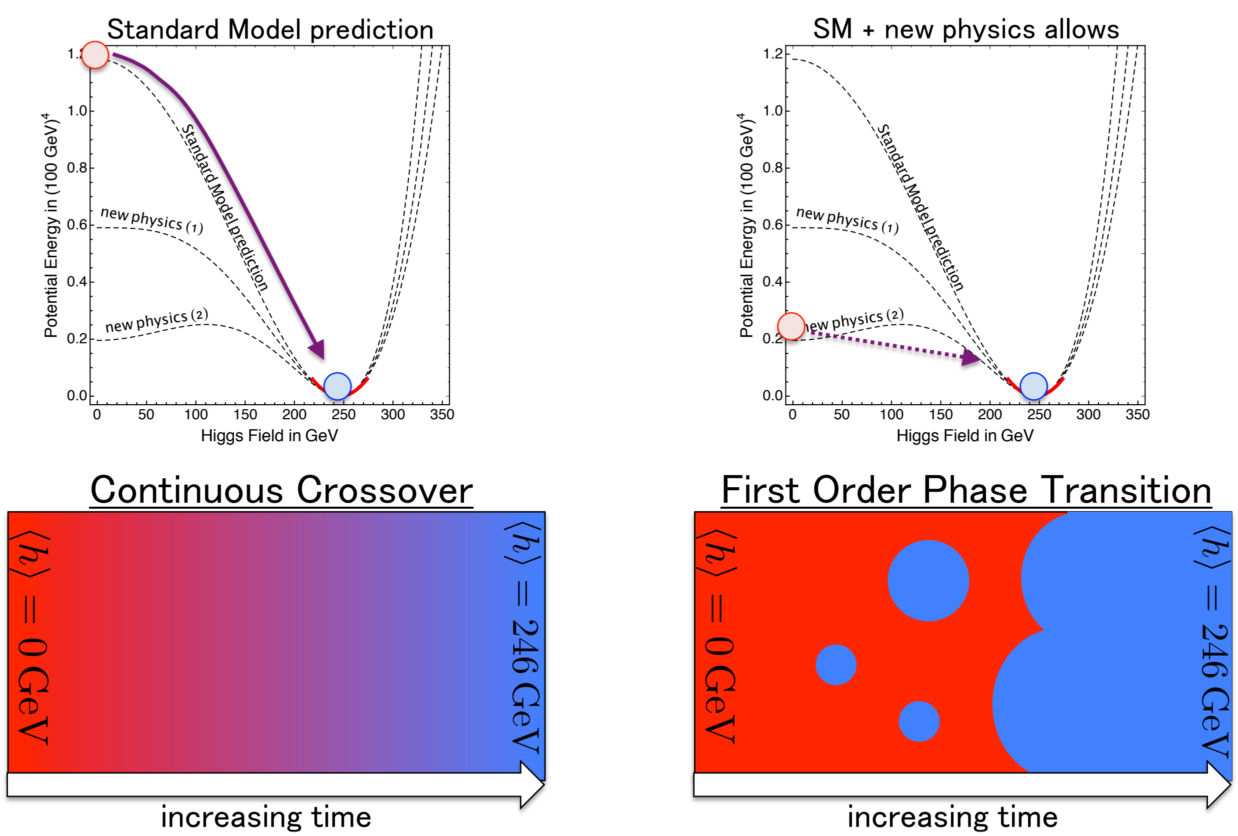


Higgs couplings. Presently, known to about 10%

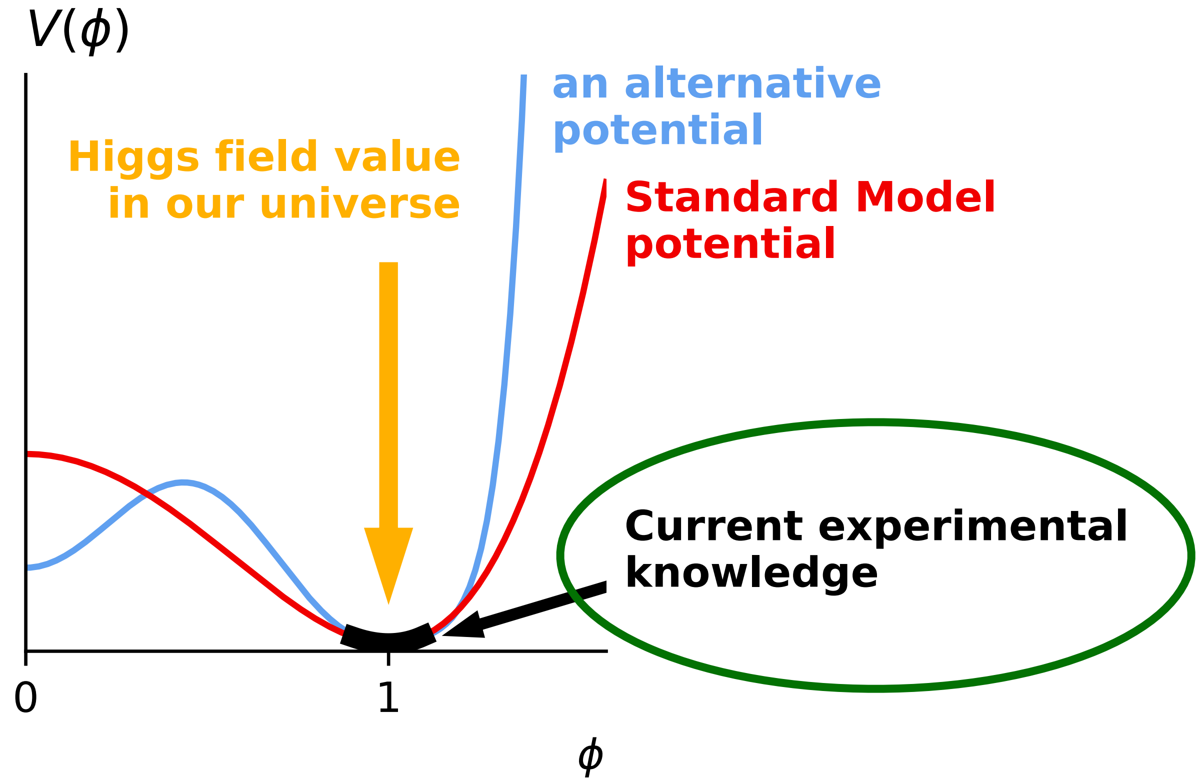
1- a few %



Need to go beyond this



How does Higgs evolve in the early universe?



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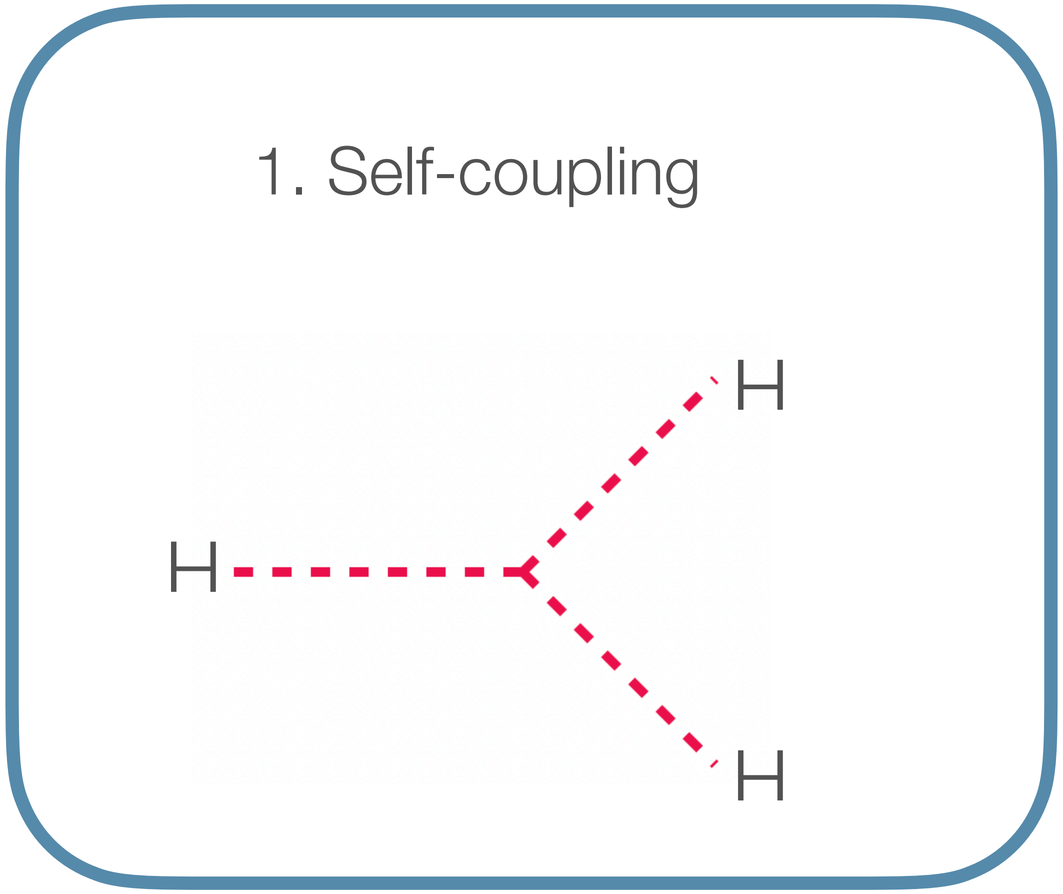
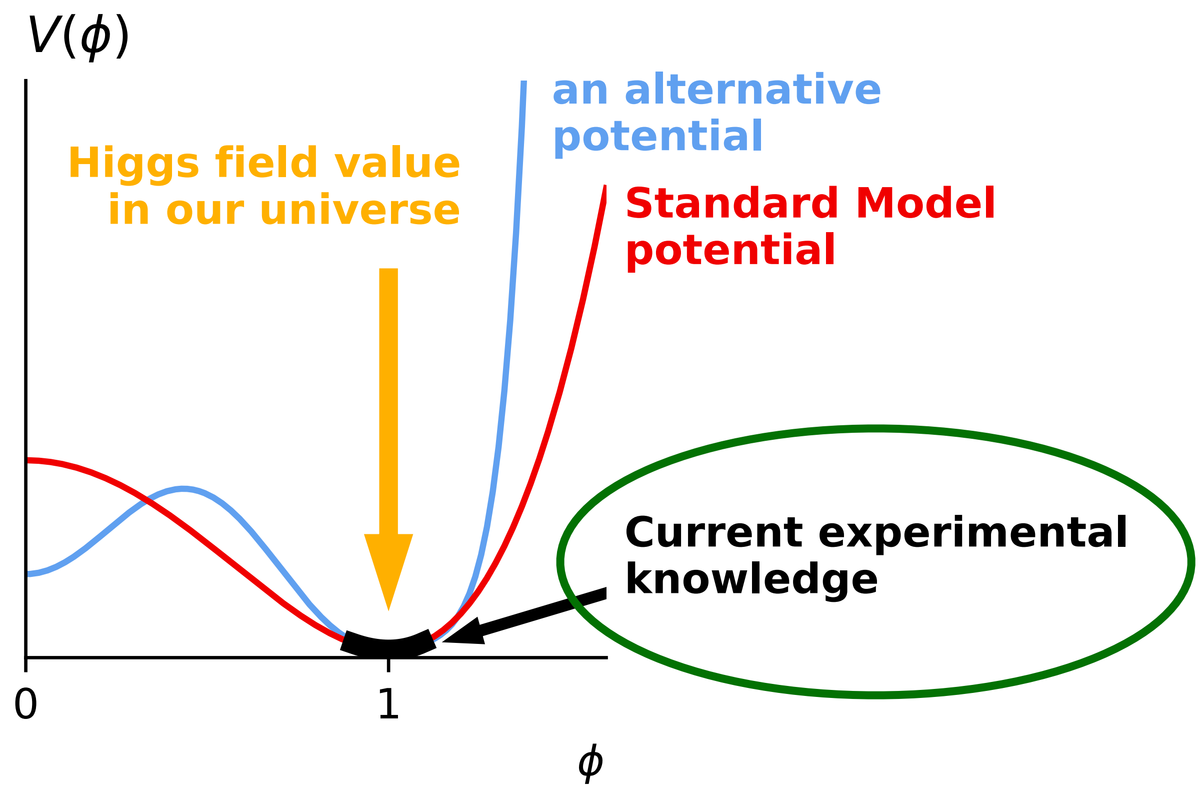


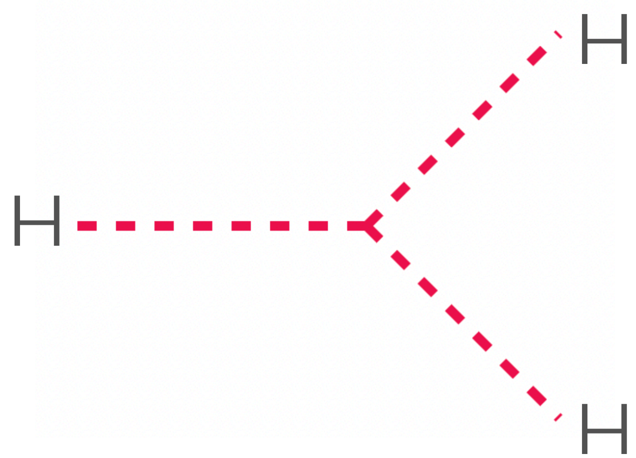
Unique kind of coupling.
Important to observe it!

Is this the best place to look for new physics?

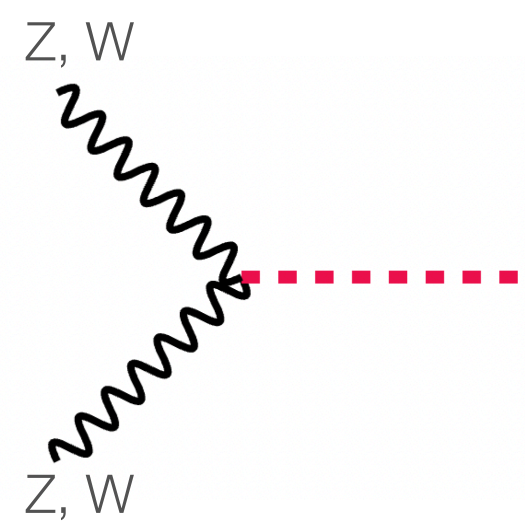


Need to go beyond this

1. Self-coupling



2. New physics in the alternative scenario often induce changes in other Higgs coupling, such as hZ



hZZ vs Higgs self-coupling

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

⇩

Modify H-Z coupling ⇒ δ_{Zh}

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

⇩

Modify Higgs self-coupling ⇒ δ_{λ_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 $\Rightarrow \delta_{Zh}$

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

No special symmetry, both will generally be there.

All dim-6 operator ⇒ similar size of modification

H-Z coupling much better measured, should be the place to first discover such a modification.

hZZ vs Higgs self-coupling

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

δ_{Zh}

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

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 $\delta_{\lambda_3} > \delta_{Zh}$

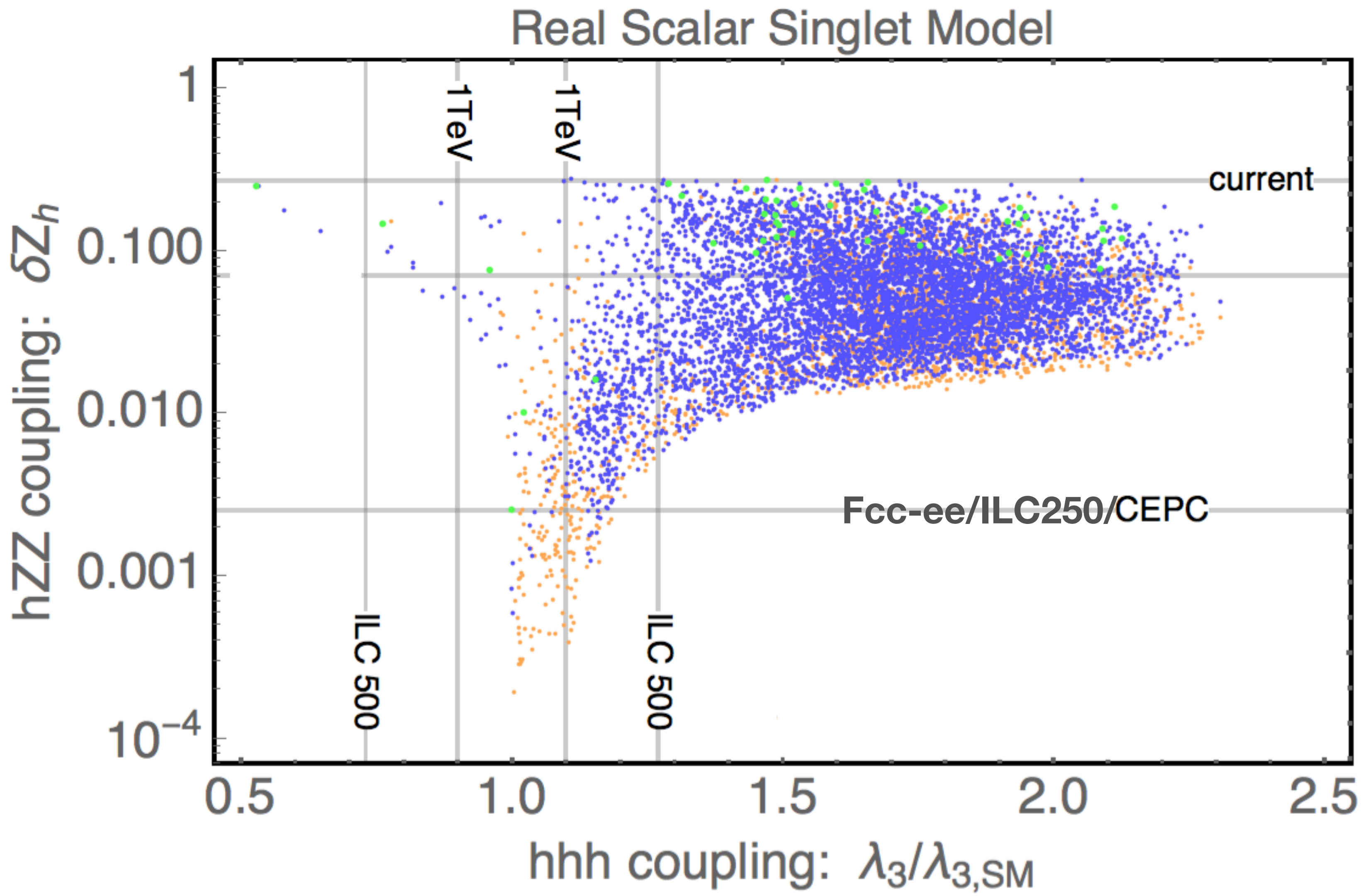
Simplest example: Higgs + singlet

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

For $m_s > m_h$, integrating out singlet

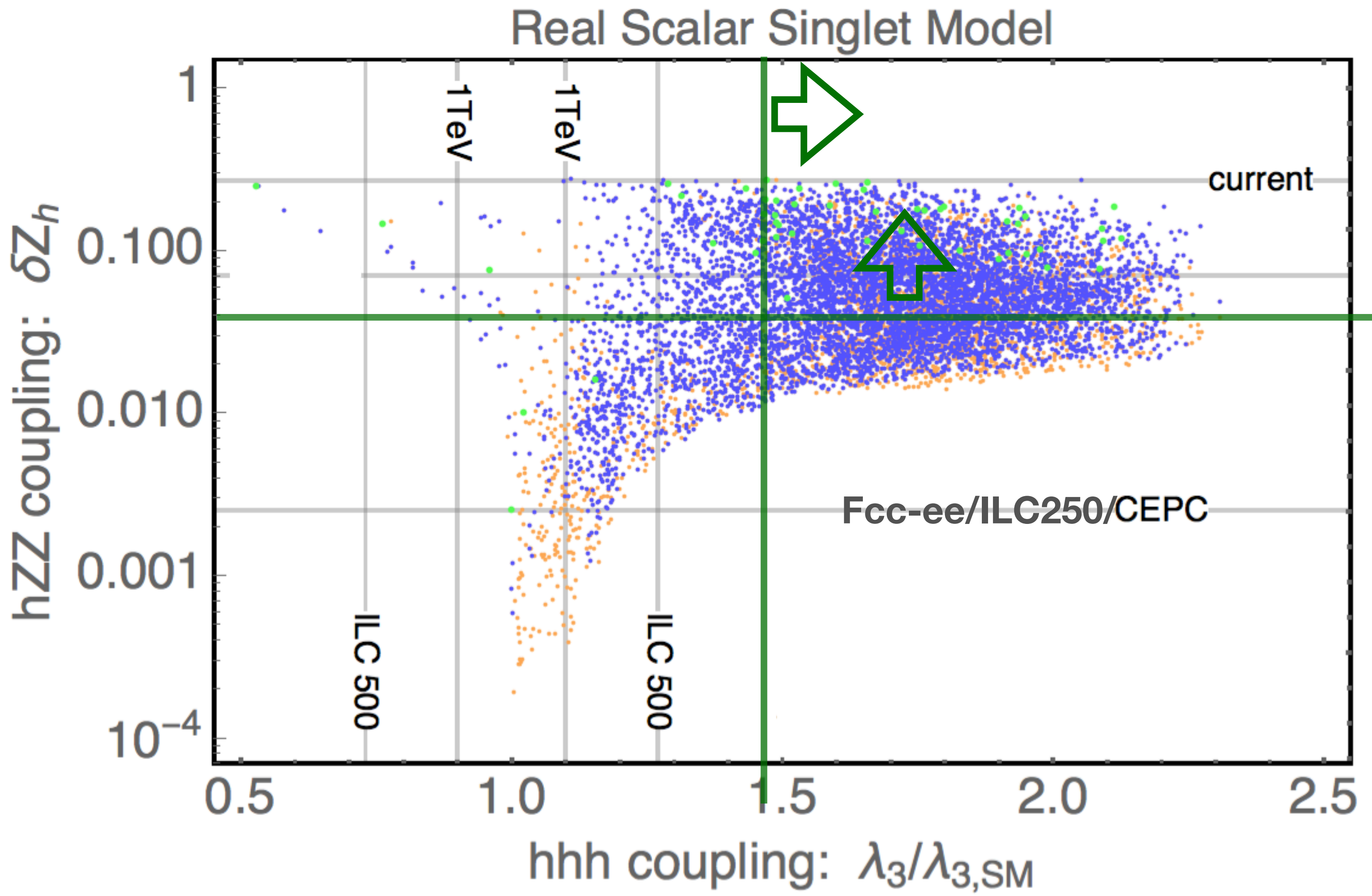
$$\Rightarrow \quad \frac{1}{\Lambda^2}(H^\dagger \partial H)^2 \quad \text{and} \quad \frac{1}{\Lambda^2}(H^\dagger H)^3$$

EW phase transition



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

EW phase transition



HL-LHC

Interesting progress.

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

Self-coupling: bottom line

- Unique coupling, never seen before, good to see it.
- Generically, H-Z coupling (better measured) more sensitive to new physics.
- If we are lucky (e.g. 1st order EWPT), may see large deviation in self-coupling.

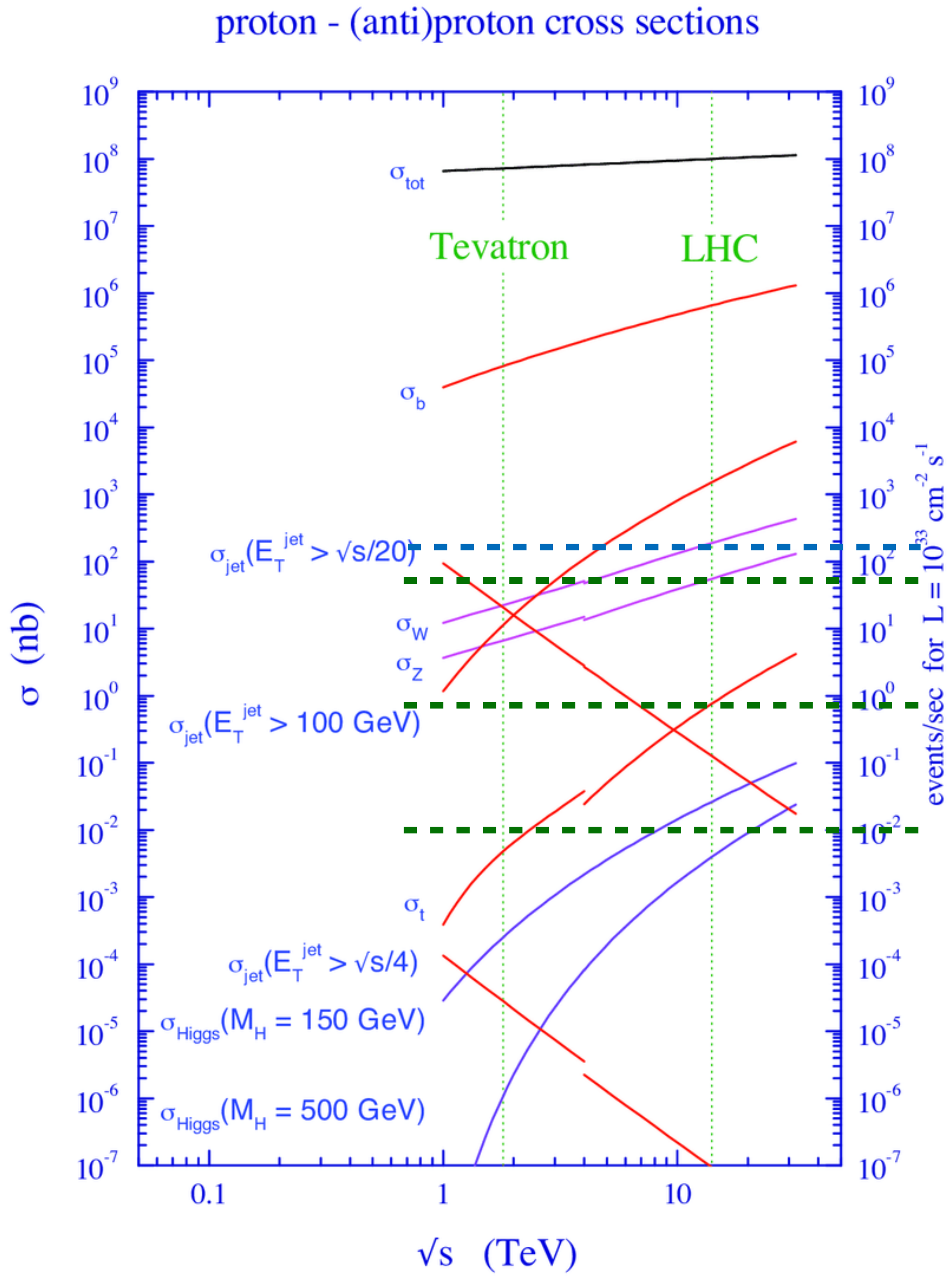
What can (HL)-LHC do?

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

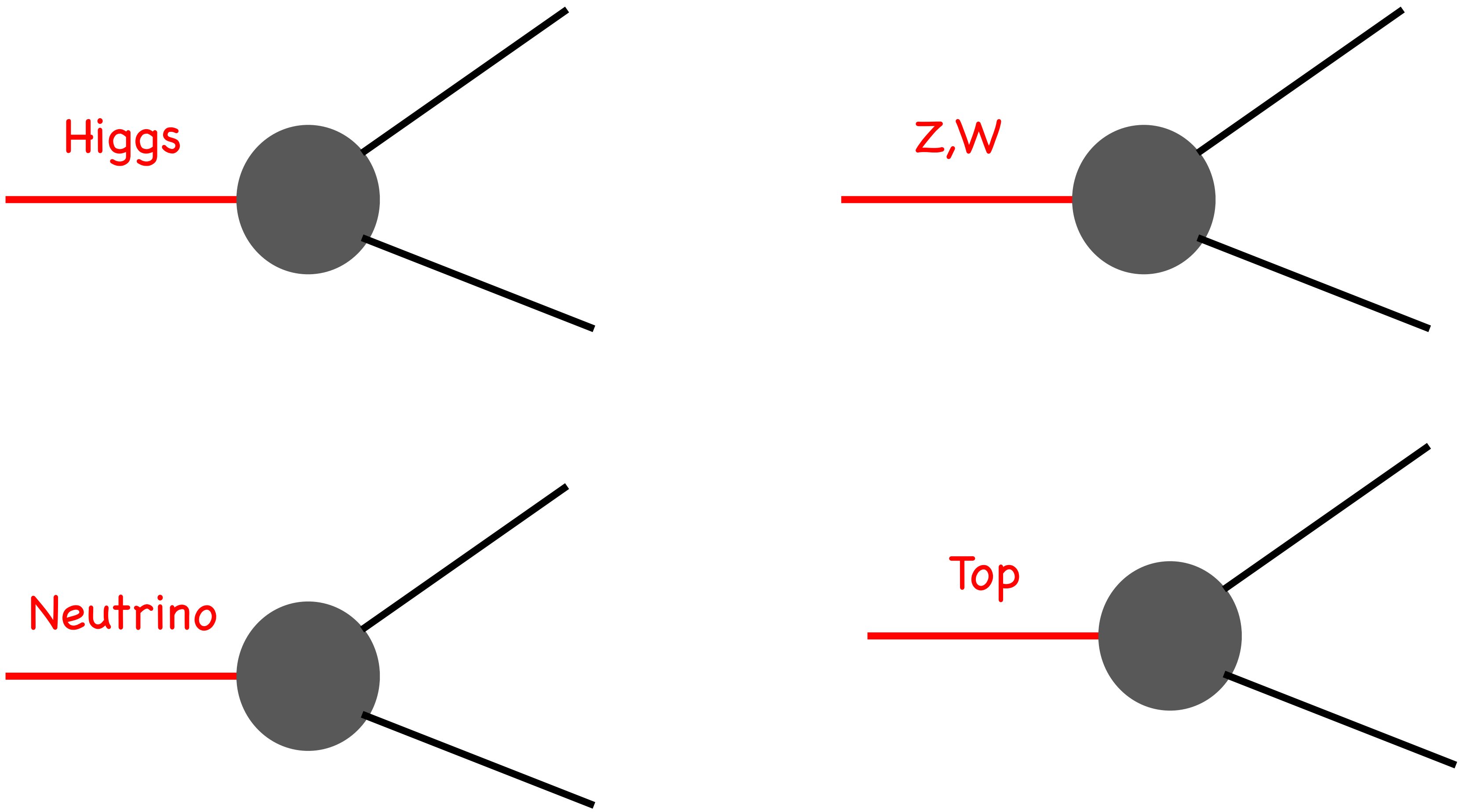
> 10^9 tops

> 10^8 Higgses

Promising for rare decay with distinct final state!

Windows into dark sector: portals

- Any known (SM) particle can in principle have small couplings to dark sector.



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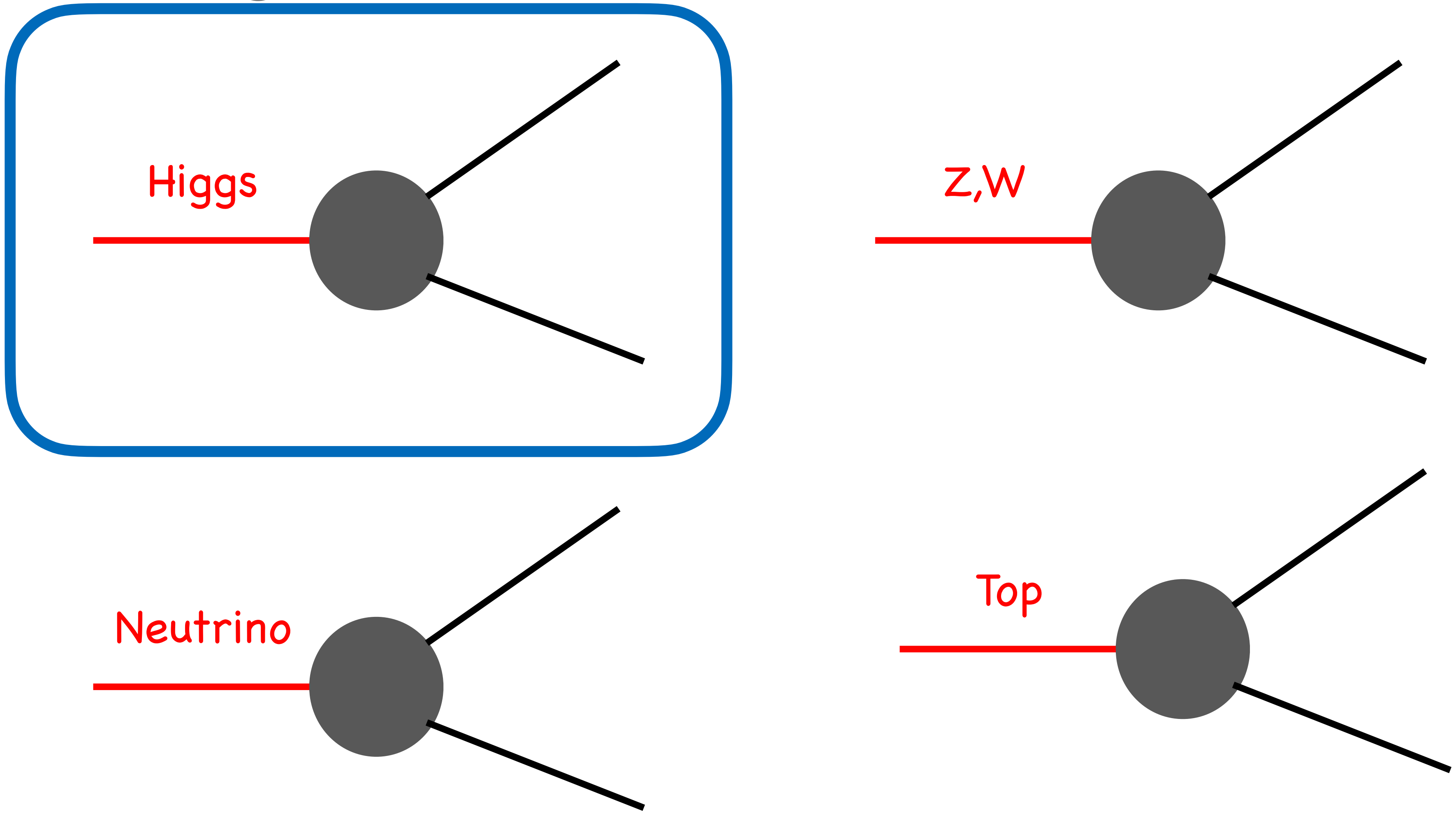
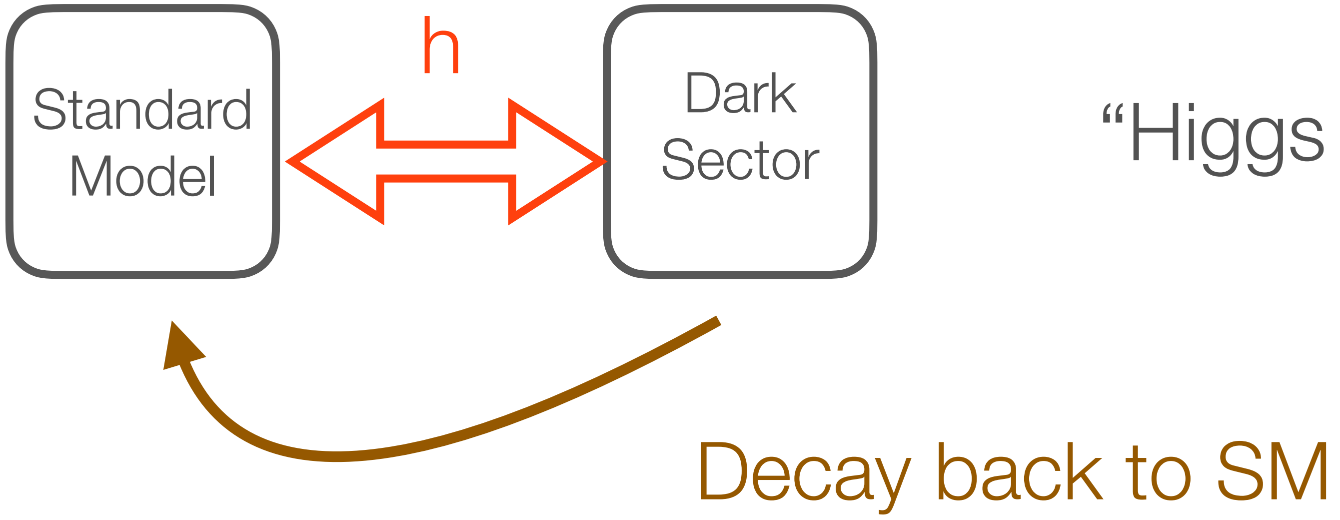


Higgs to dark sector



“Higgs portal”

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$\lambda H^\dagger H \mathcal{O}_{\rm dark}$ $\mathcal{O}_{\rm dark}$ = SM singlet

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Example 1: $\lambda H^\dagger H S^2$ to avoid fine-tuning, $\lambda \sim m_S^2/v^2$

$\mathrm{BR}(h \to SS) \sim m_S^4/(m_h^2 m_b^2) \sim$ a few % if $m_S \sim 10$ GeV

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Example 2: $\frac{H^2}{\Lambda^2} F_D^{\mu\nu} F_{D\,\mu\nu}$

$\mathrm{BR}(h \to \gamma_D \gamma_D) \sim (v/\Lambda)^4 (m_h^2/m_b^2) \sim$ a few % if $\Lambda \sim$ TeVs

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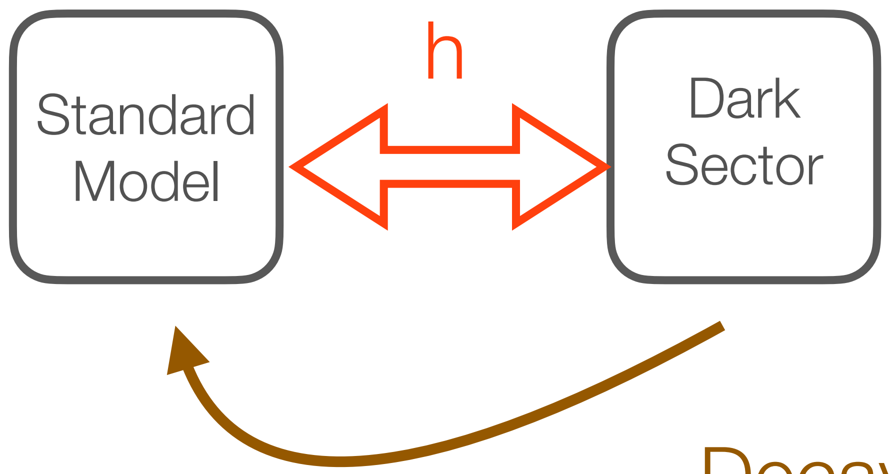
Reasonable to have a small but still sizable BR

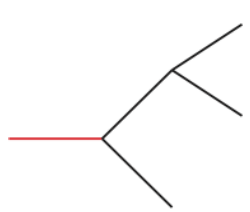
Higgs to dark sector



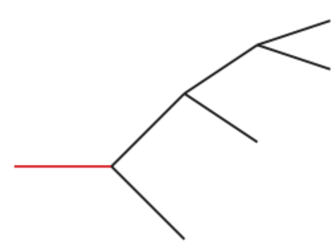
"Higgs portal"

Decay back to SM

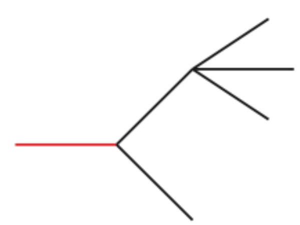
$h \to 2 \to 3$



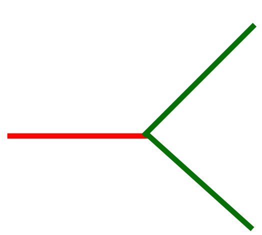
$h \to 2 \to 3 \to 4$



$h \to 2 \to (1+3)$



Long lived particles



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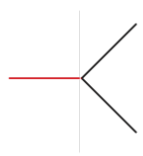
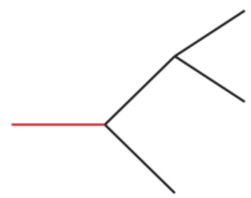
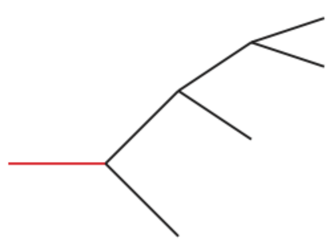
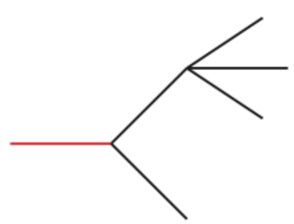
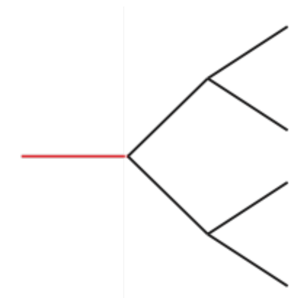
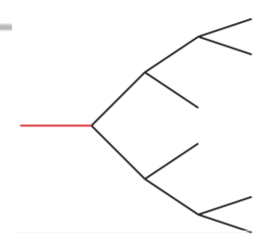
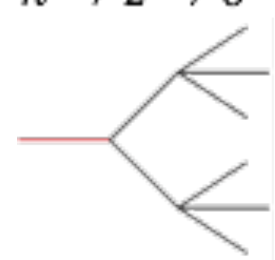
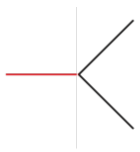
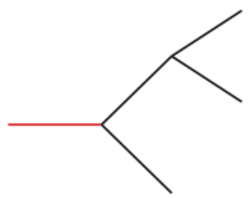
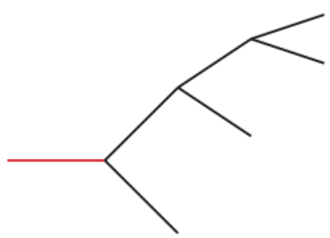
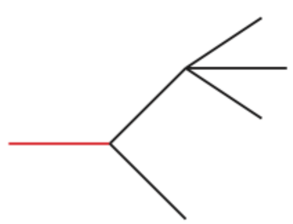
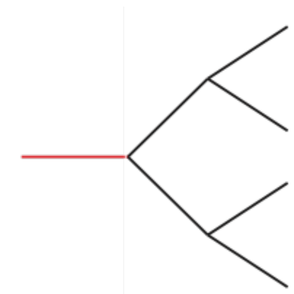
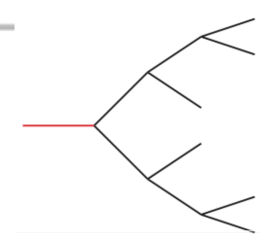
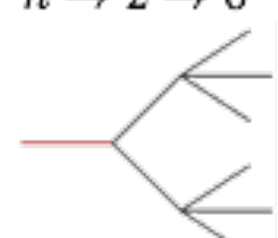
Higgs exotic decays

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

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

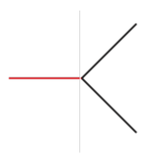
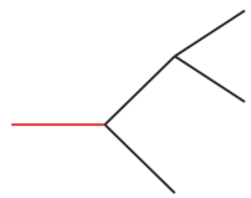
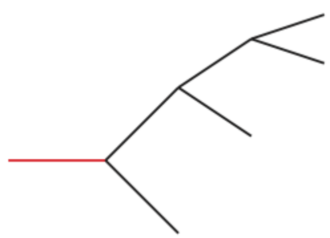
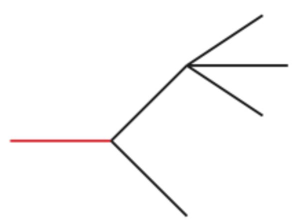
Higgs exotic decays

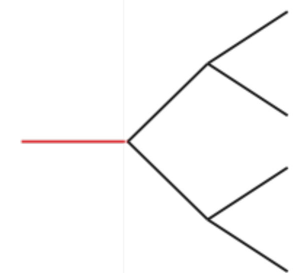
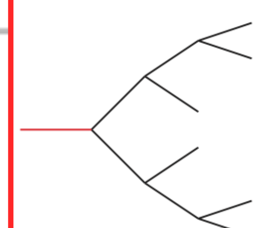
Decay Topologies	Decay mode $\mathcal{F}_i$
 $h \to 2$	$h \to \not\!\!E_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not\!\!E_T$ $h \to (b\bar{b}) + \not\!\!E_T$ $h \to (jj) + \not\!\!E_T$ $h \to (\tau^+\tau^-) + \not\!\!E_T$ $h \to (\gamma\gamma) + \not\!\!E_T$ $h \to (\ell^+\ell^-) + \not\!\!E_T$
$h \to 2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

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

Higgs exotic decays

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

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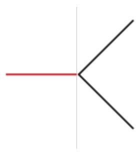
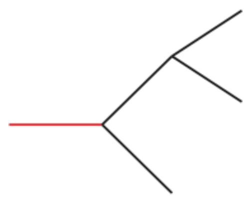
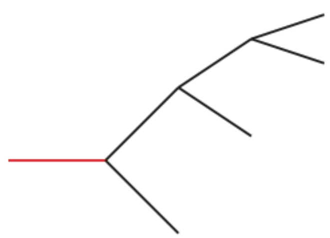
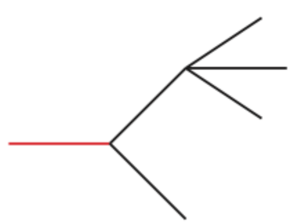
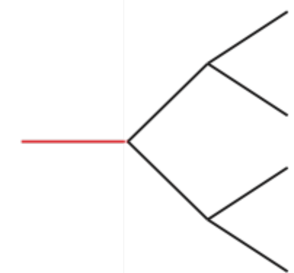
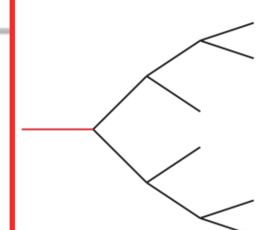
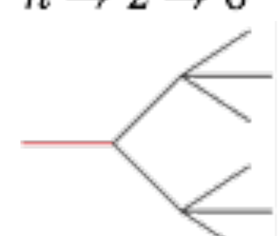
With MET, less lepton

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

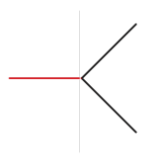




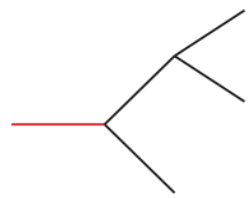
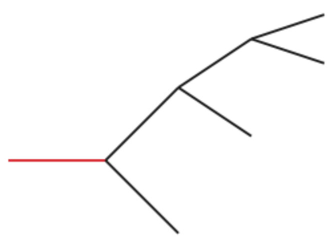
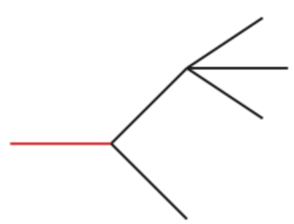
Simple, Great sensitivity from the LHC

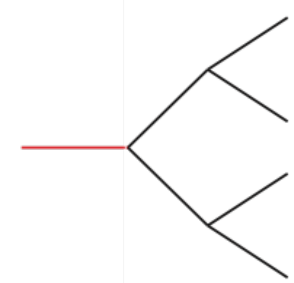
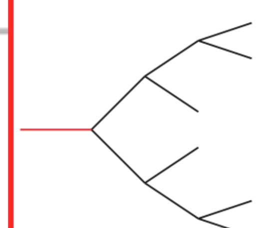
With MET, less lepton

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!

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

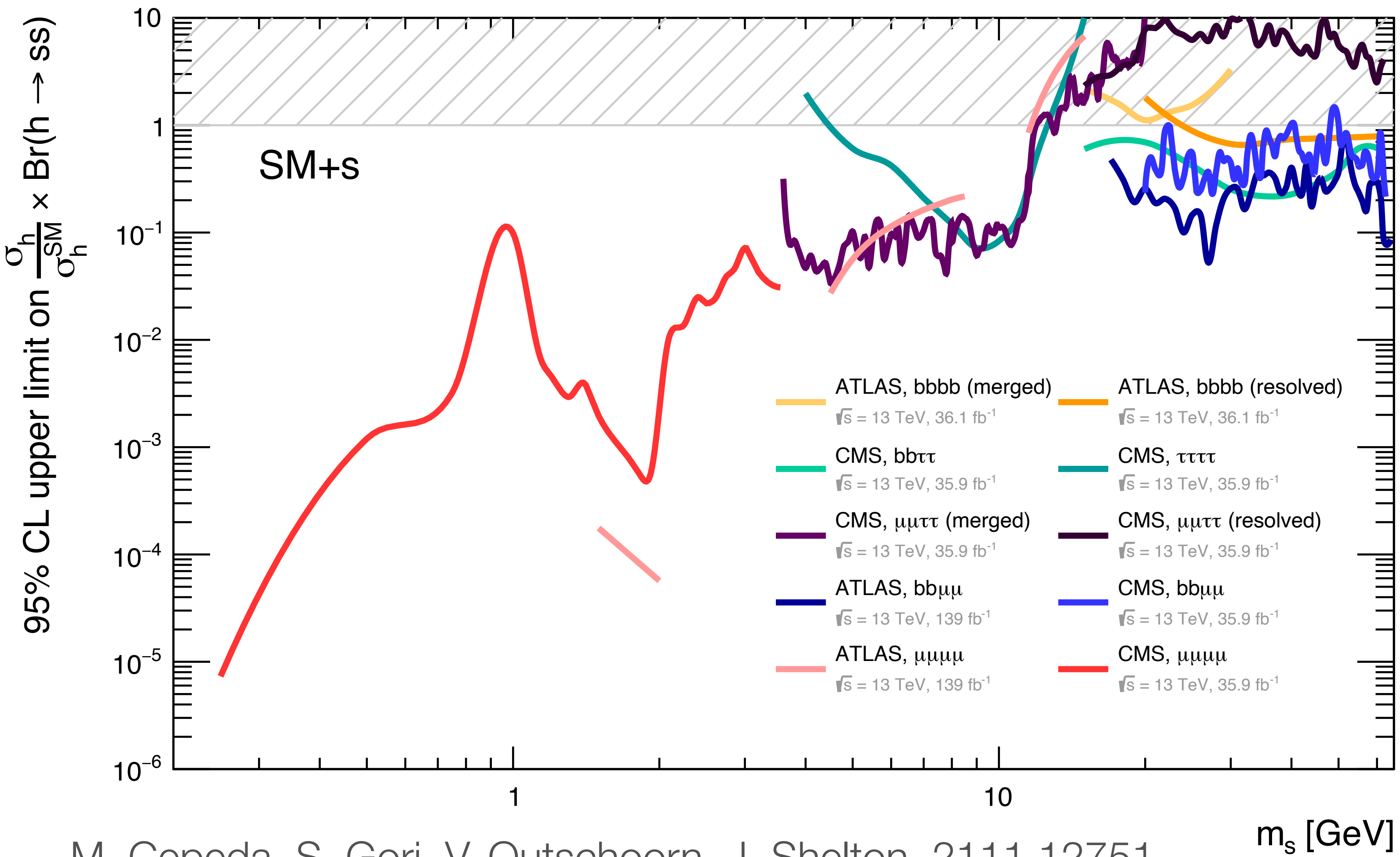
Can be significant since $\Gamma_h^{\mathrm{SM,tot}}$ is very narrow.

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

$$h \to ss \to f\bar{f}f\bar{f}$$



M. Cepeda, S. Gori, V. Outschoorn, J. Shelton, 2111.12751

Simplest example: Higgs + singlet

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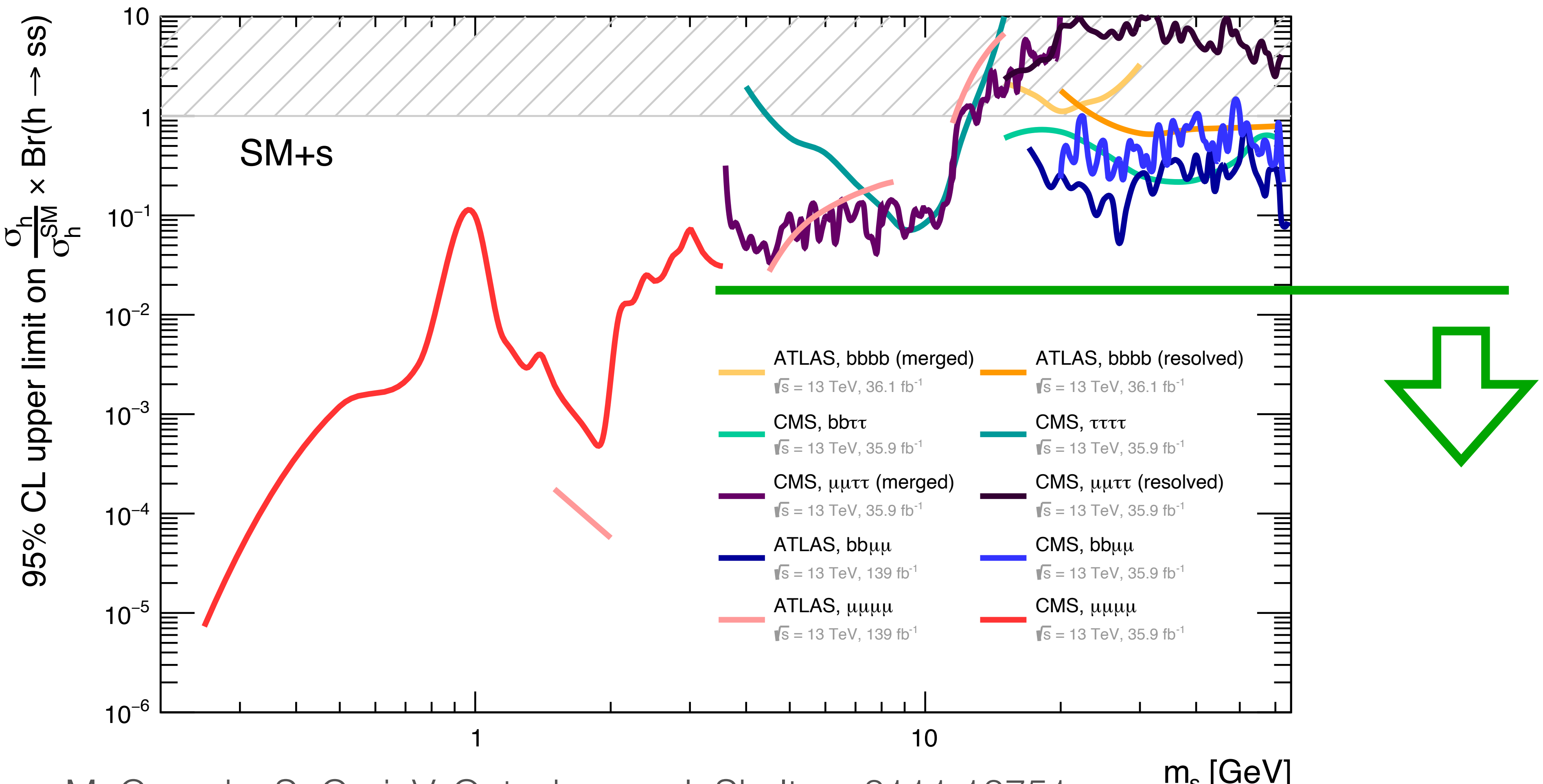


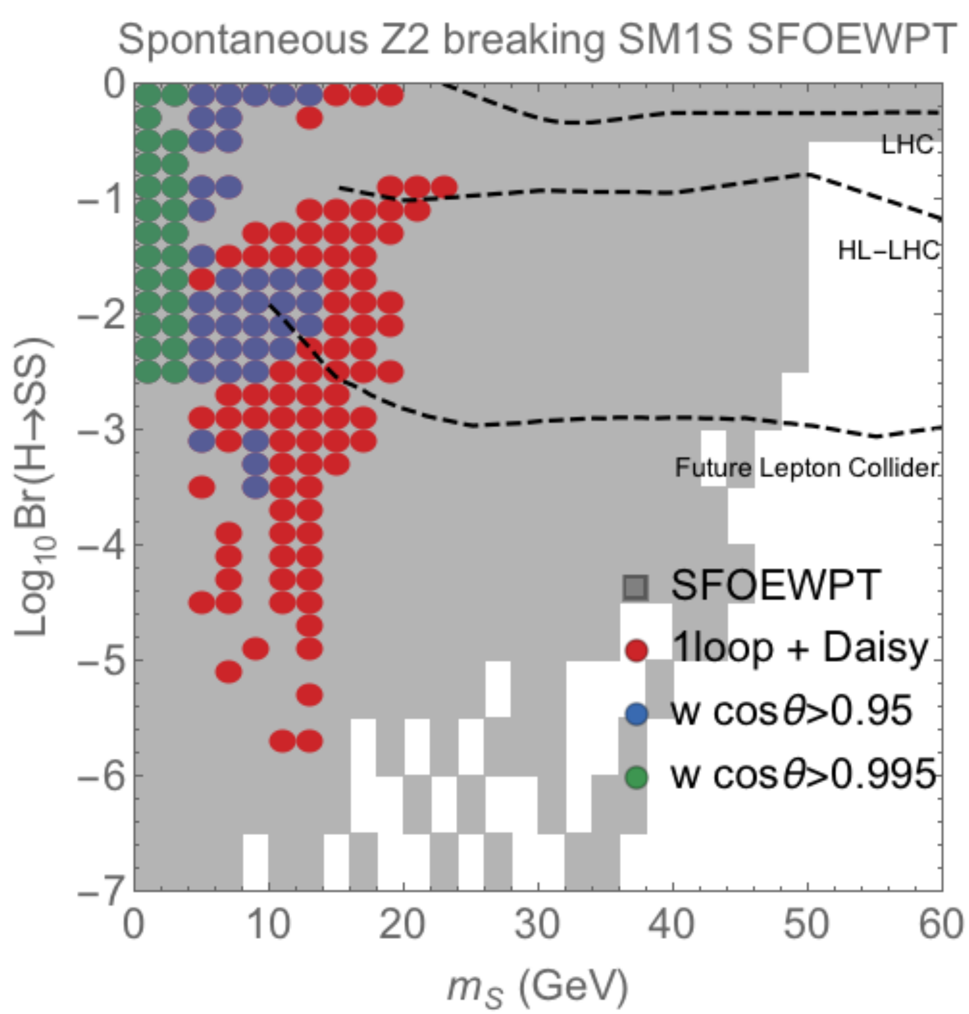
M. Cepeda, S. Gori, V. Outschoorn, J. Shelton, 2111.12751

A lot of room to improve!

Interesting target: 1st order EW phase transition

Extra scalar wants to be light, with sizable coupling to the Higgs

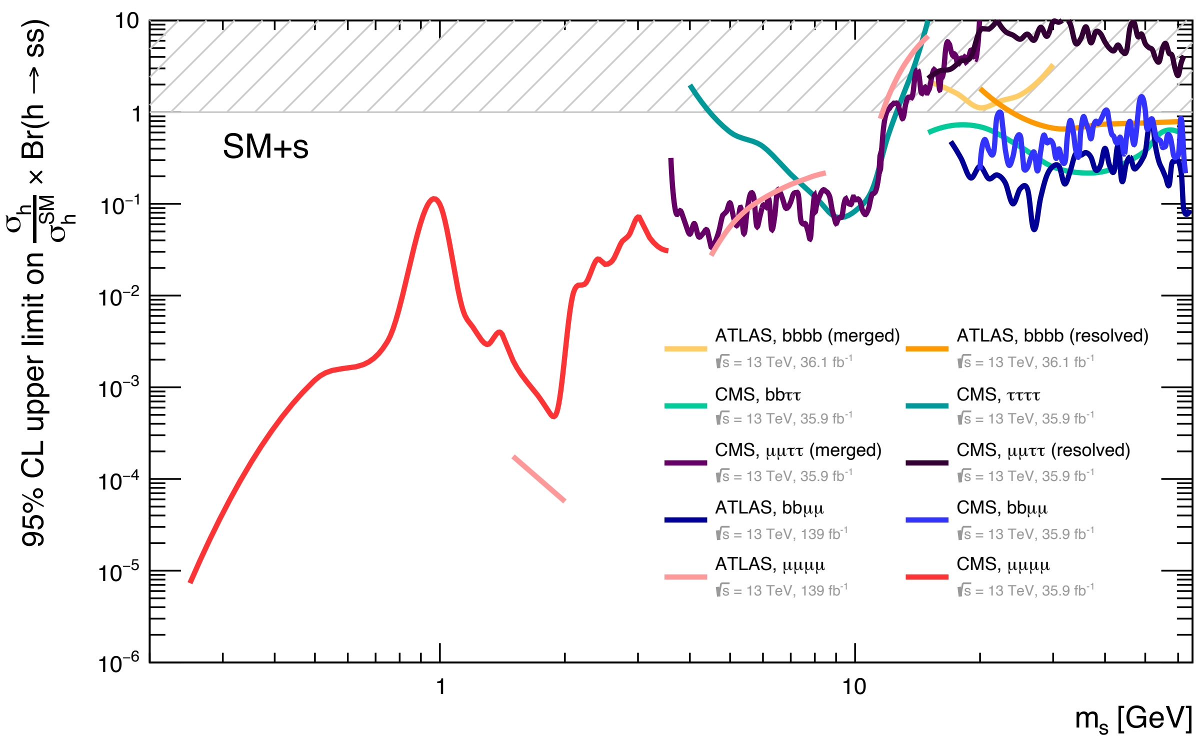
Singlet extension, h→ss

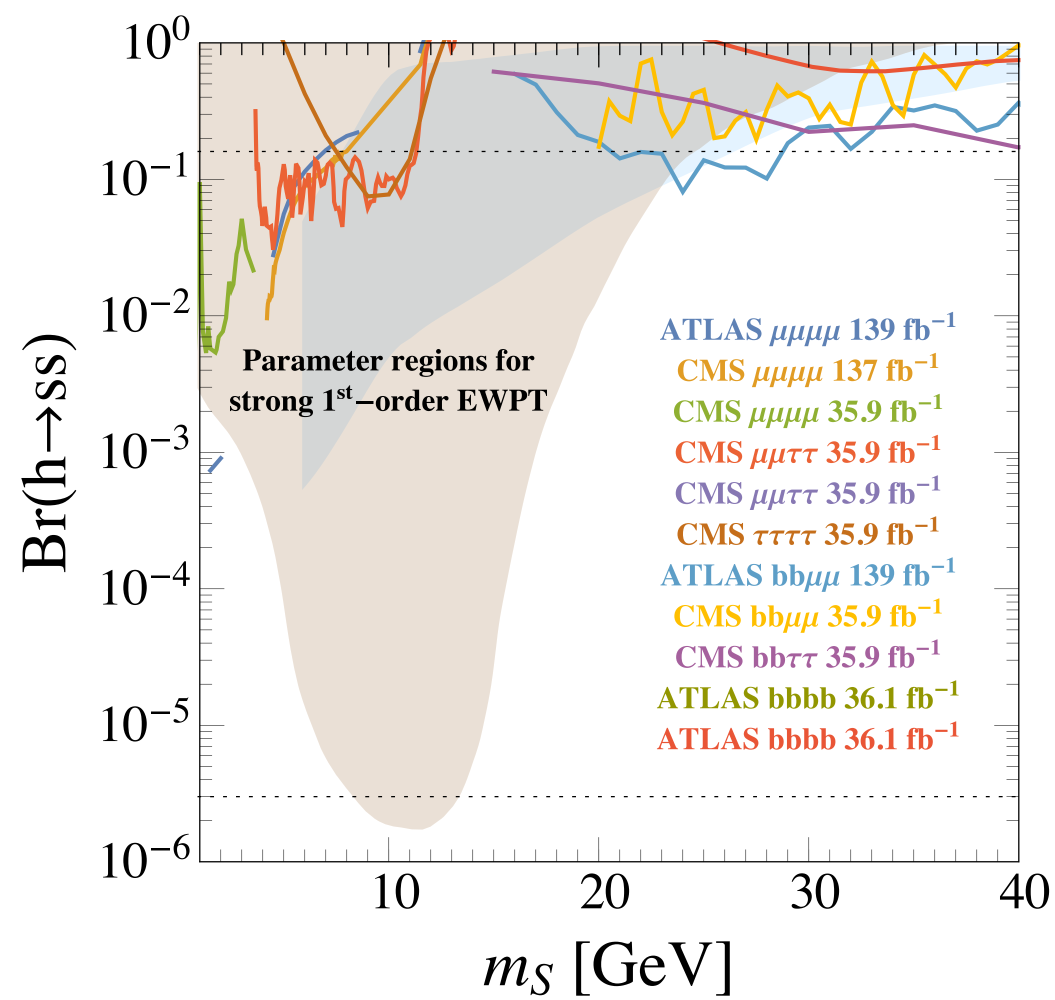


Carena, Liu, Wang, 1911.10206

Kozaczuk, Ramsey-Musolf, Shelton, 1911.10210

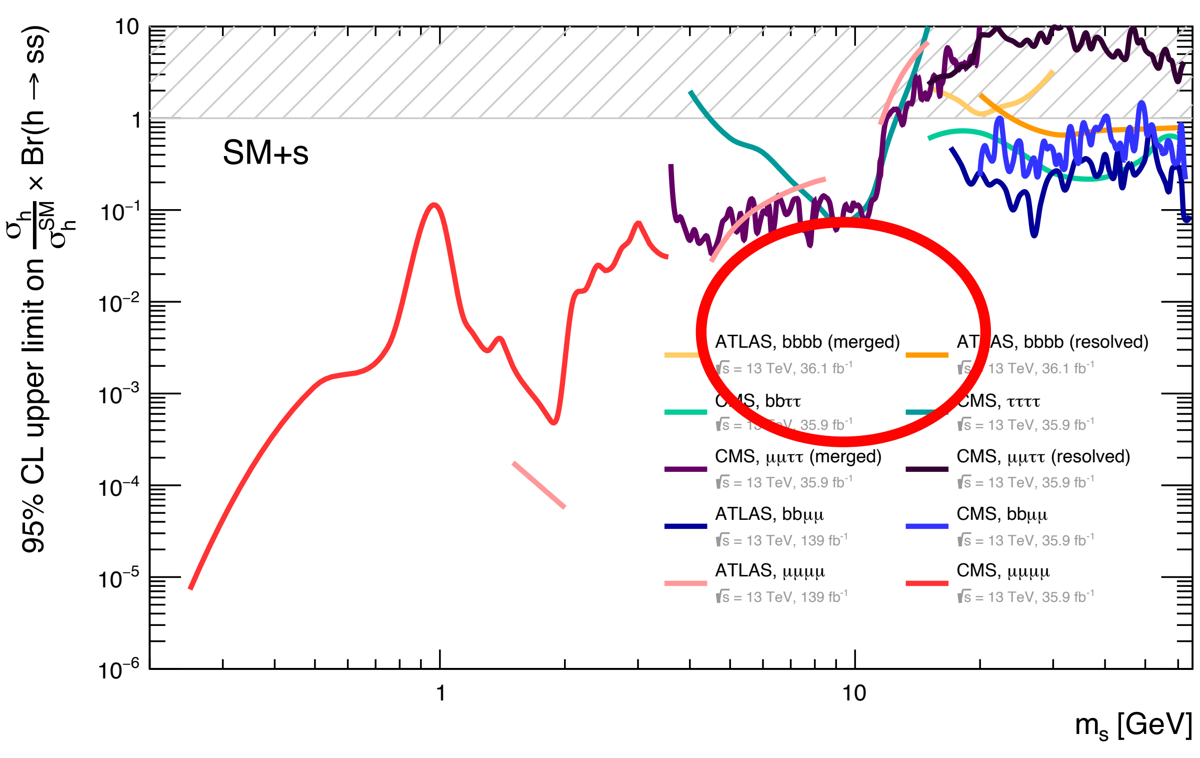
Interesting target:
1st order EW phase transition

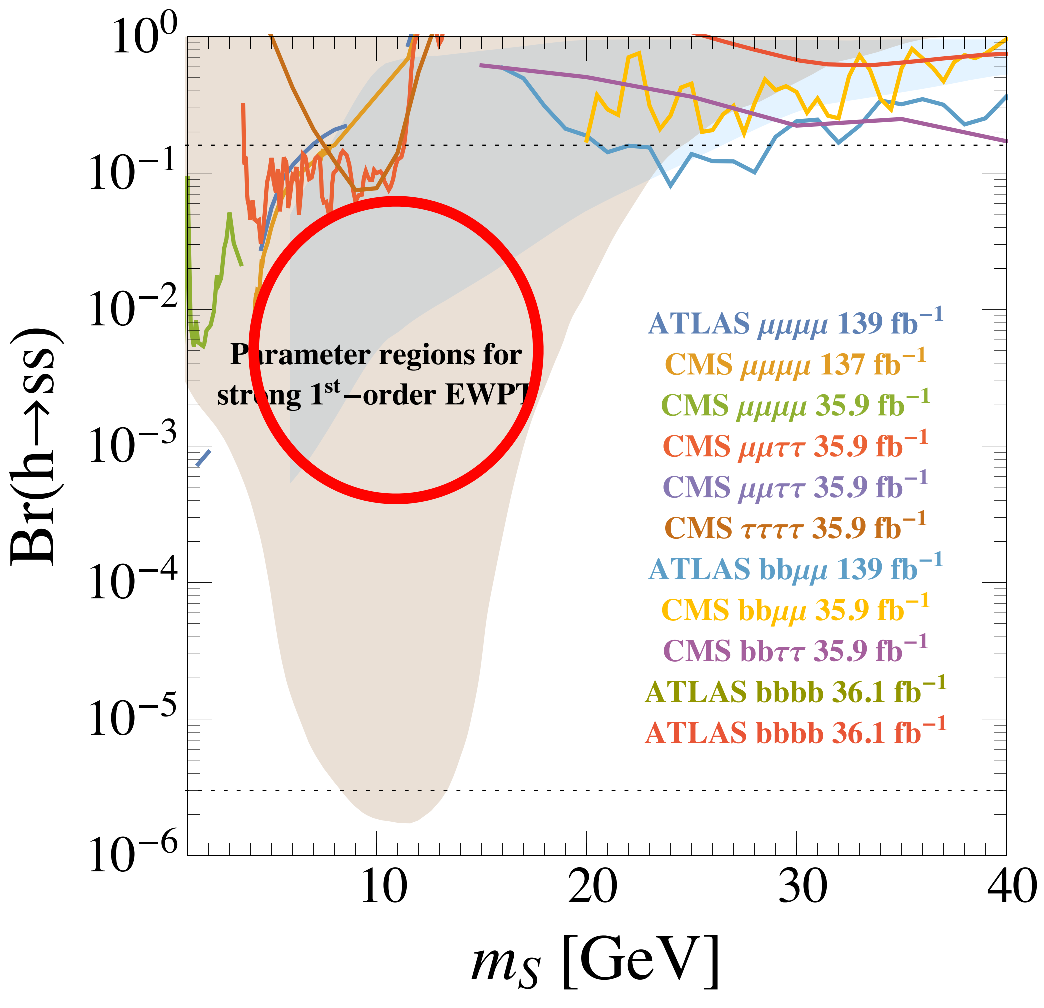




M. Carena, J. Kozaczuk, Z. Liu, T. Ou, M. Ramsey-Musolf, J. Shelton, Y. Wang, K. Xie 2203.08206

Interesting target: 1st order EW phase transition





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

Interesting alternative

Toy model of a landscape, N scalars S_i .

If each scalar has two vacua ⇒ 2^N vacua

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

Interesting alternative

Toy model of a landscape, N scalars S_i .

If each scalar has two vacua ⇒ 2^N vacua

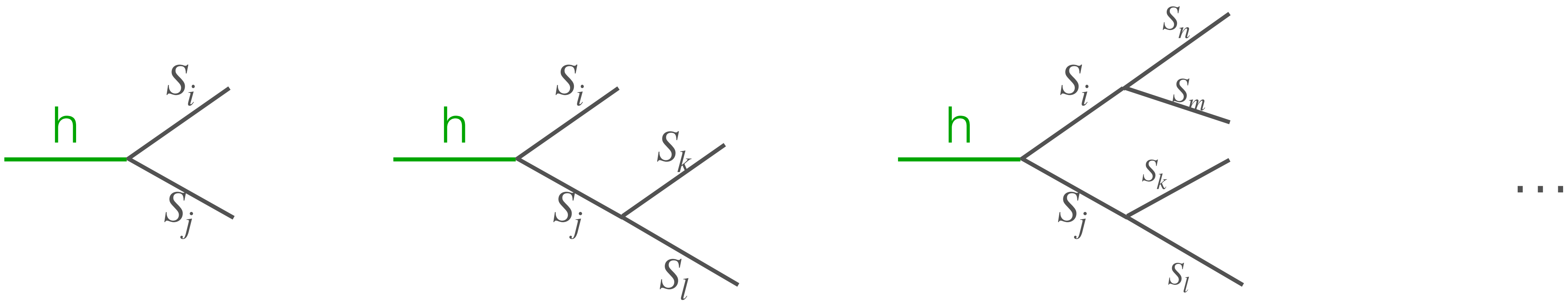
Can be a large landscape for N >> 1 (e.g. N$\sim 10^2$)

Connection to the Higgs mass, Higgs couples to the scalars

$$\mathscr{L} \supset H^\dagger H \sum_{i,j}^{N} \lambda_{ij} S_i S_j + \ldots, \qquad N \gg 1$$

Interesting alternative

If m_S not too far away from weak scale, some of them with have $m_{S_i} < 0.5 \times m_h$



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

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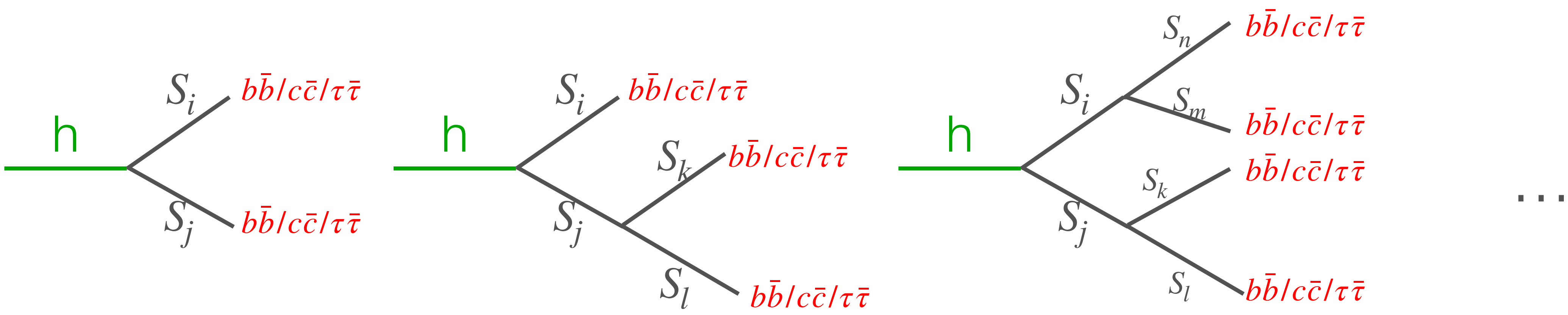
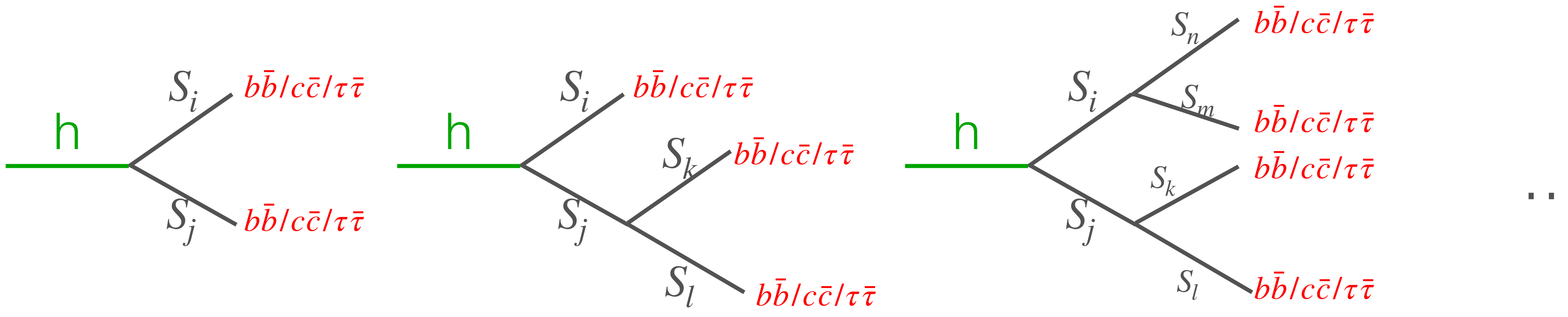


Rate into a particular final decay chain $\propto \lambda^2 \sim 1/N^2$, tiny.

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

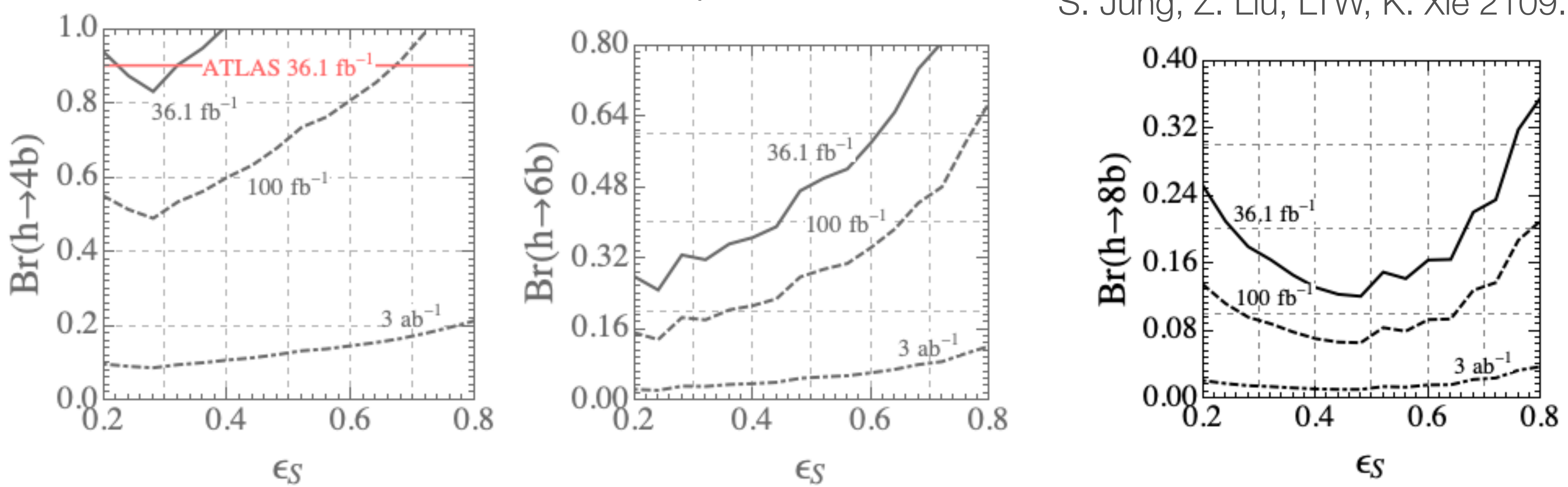
⇒ b/c/τ rich states, but not recontructing particular resonances.

Are we ready for this?



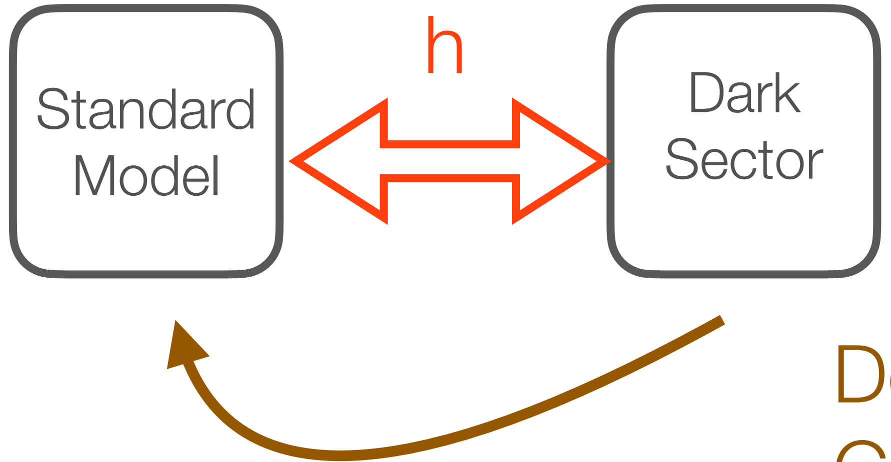
$Wh \to \ell\nu + bs$

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

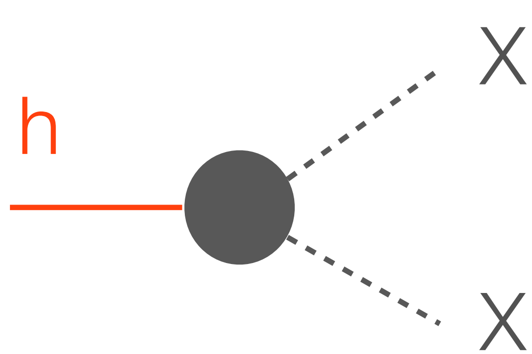


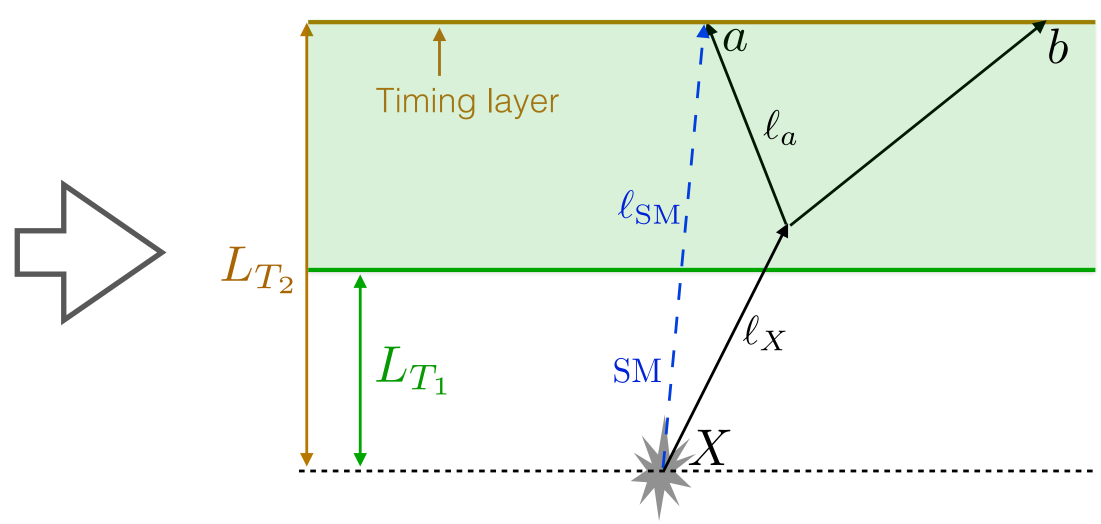
New ideas to trigger and tag on this kind of final states?

Long lived particle (LLP)



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

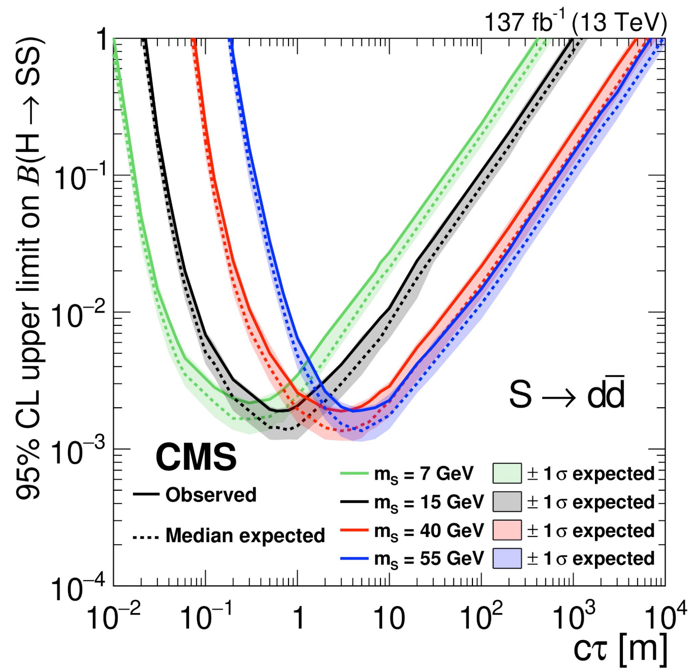


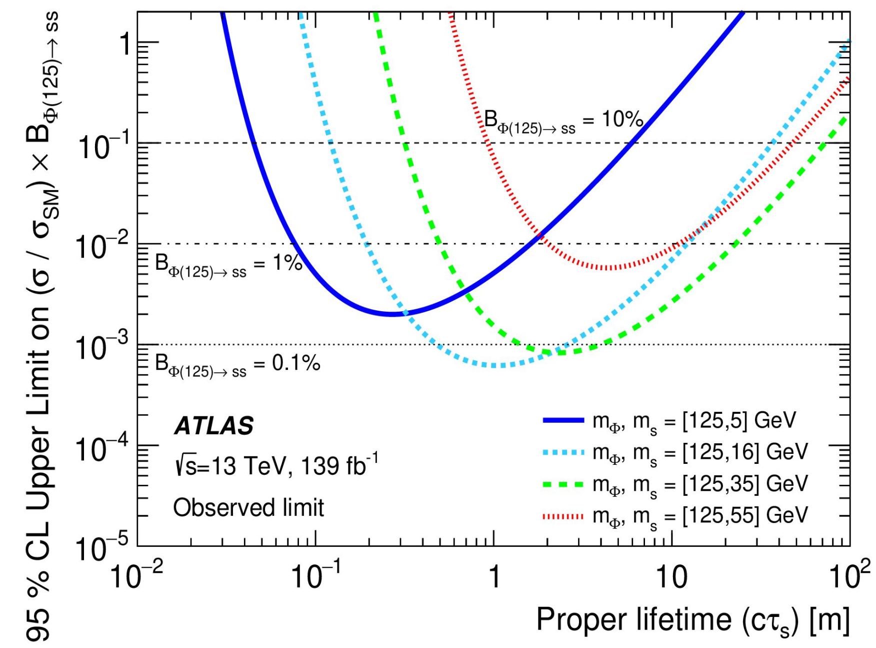


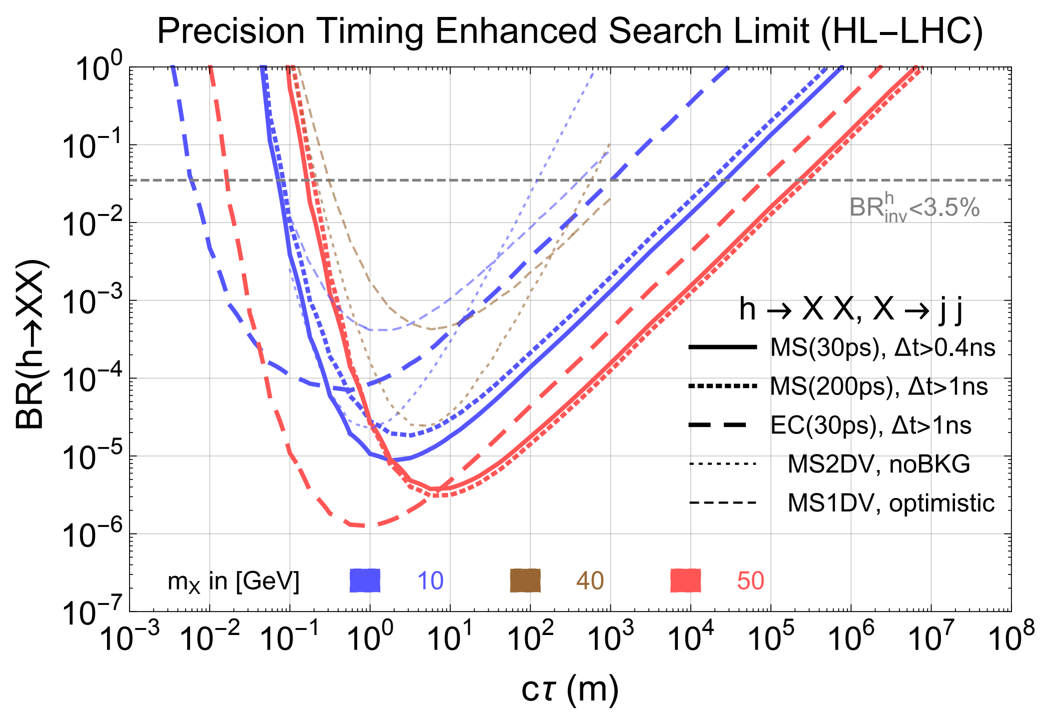
Higgs portal long lived particles

$h \to XX$

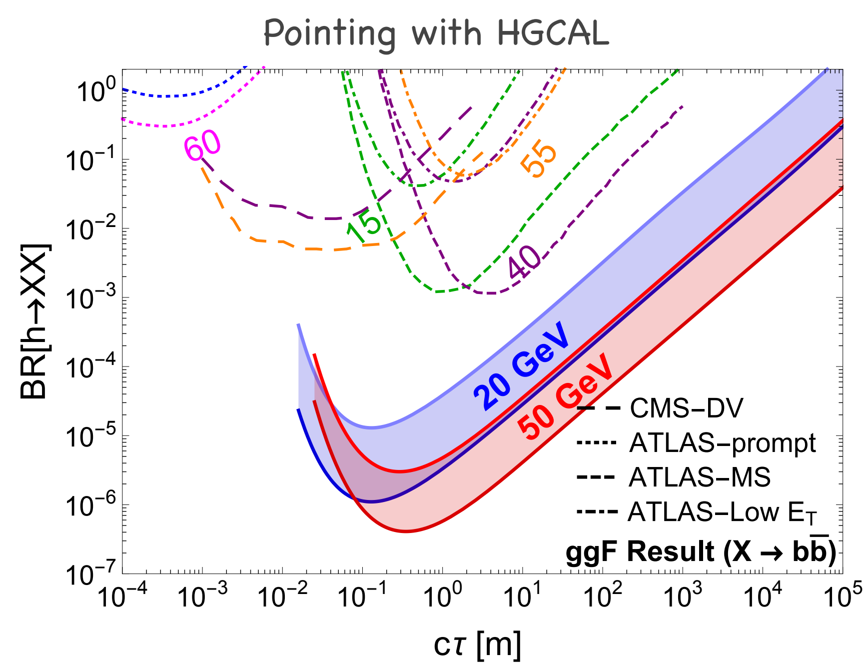
X: LLP







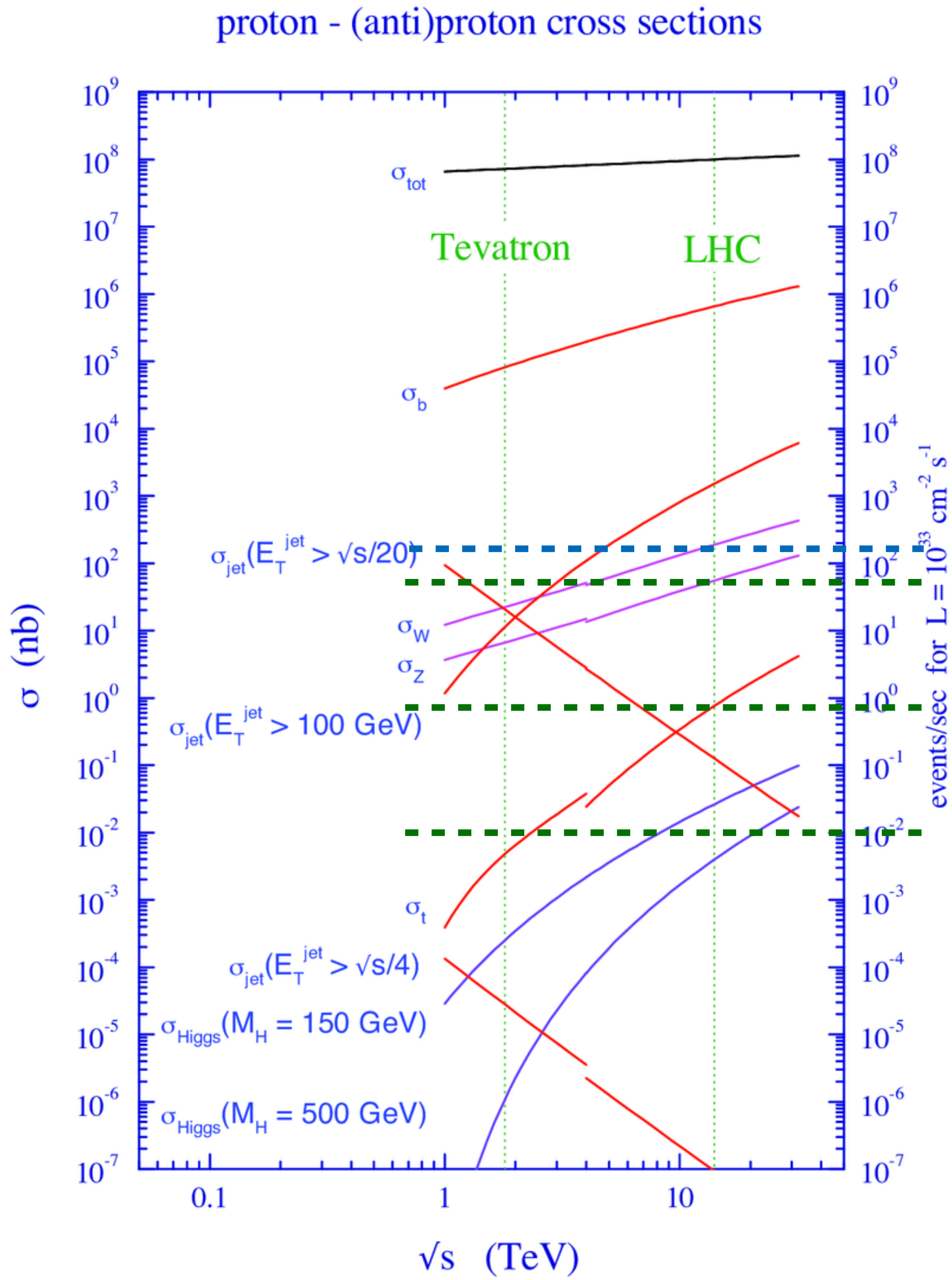
J. Liu, Z. Liu and LTW, 1805.05957



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

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

HL-LHC as particle factories



HL-LHC

> 10^{11} W and Zs

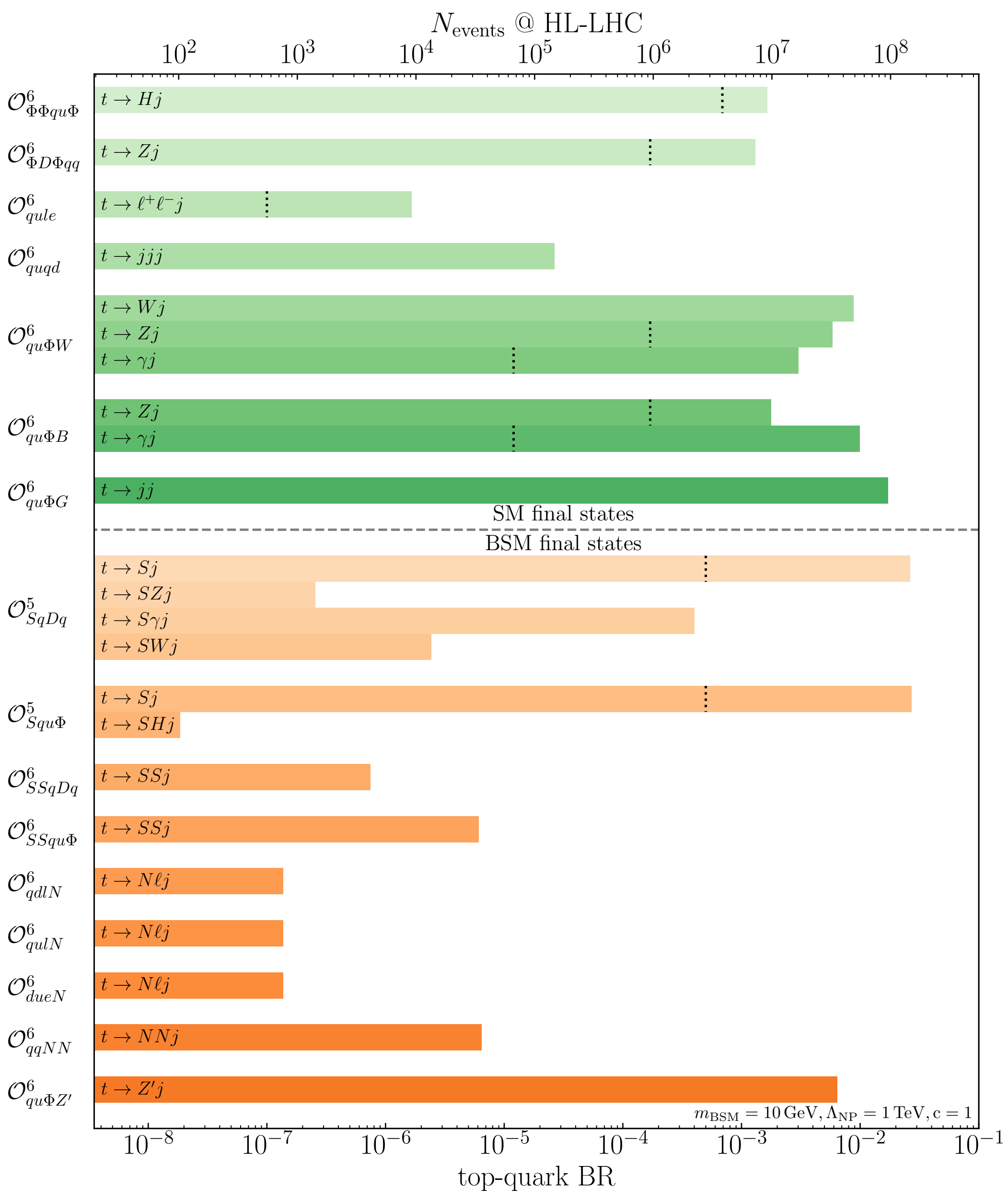
> 10^9 tops

> 10^8 Higgses

Promising for rare decay
with distinct final state!

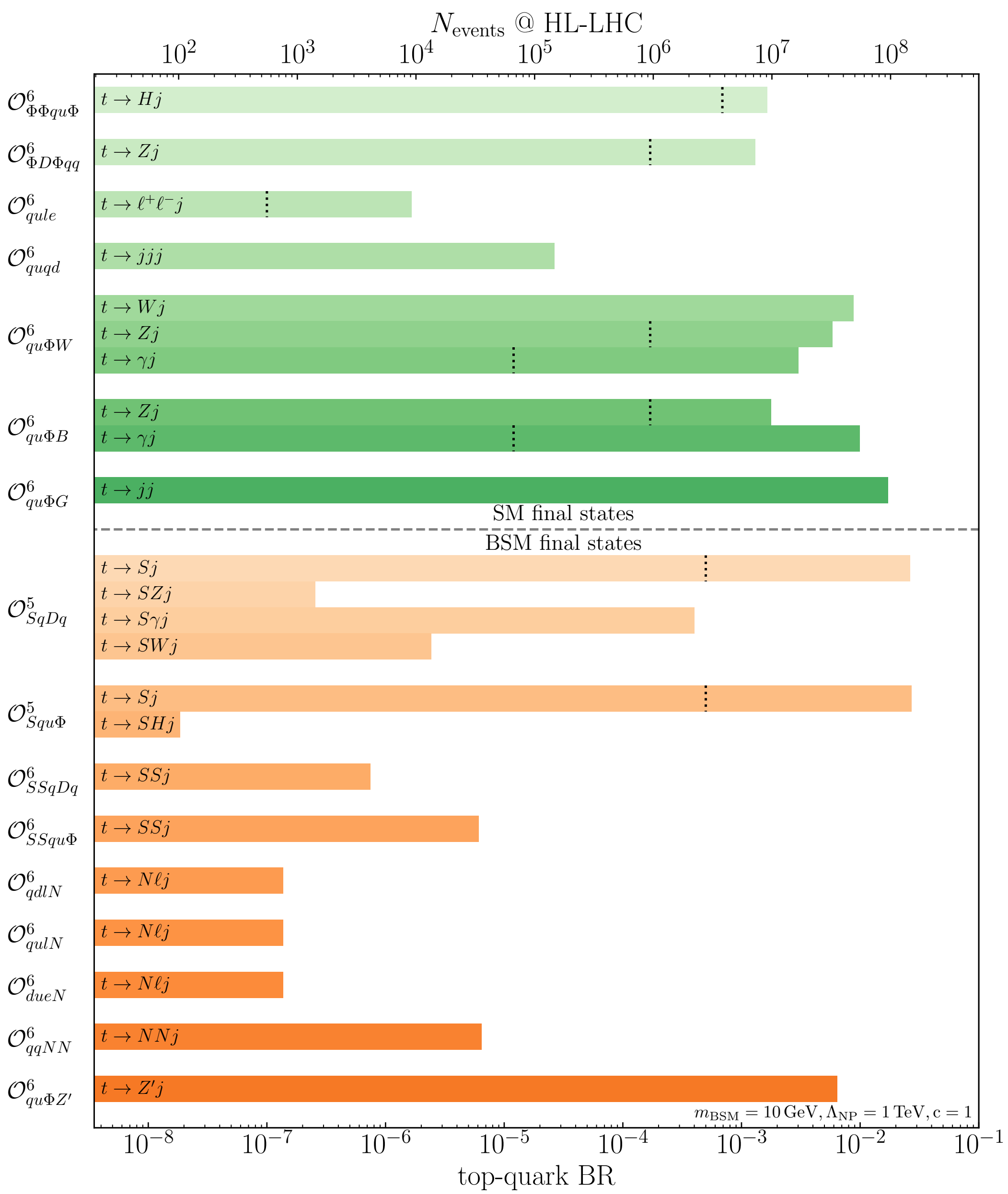
Similarly: top rare decay

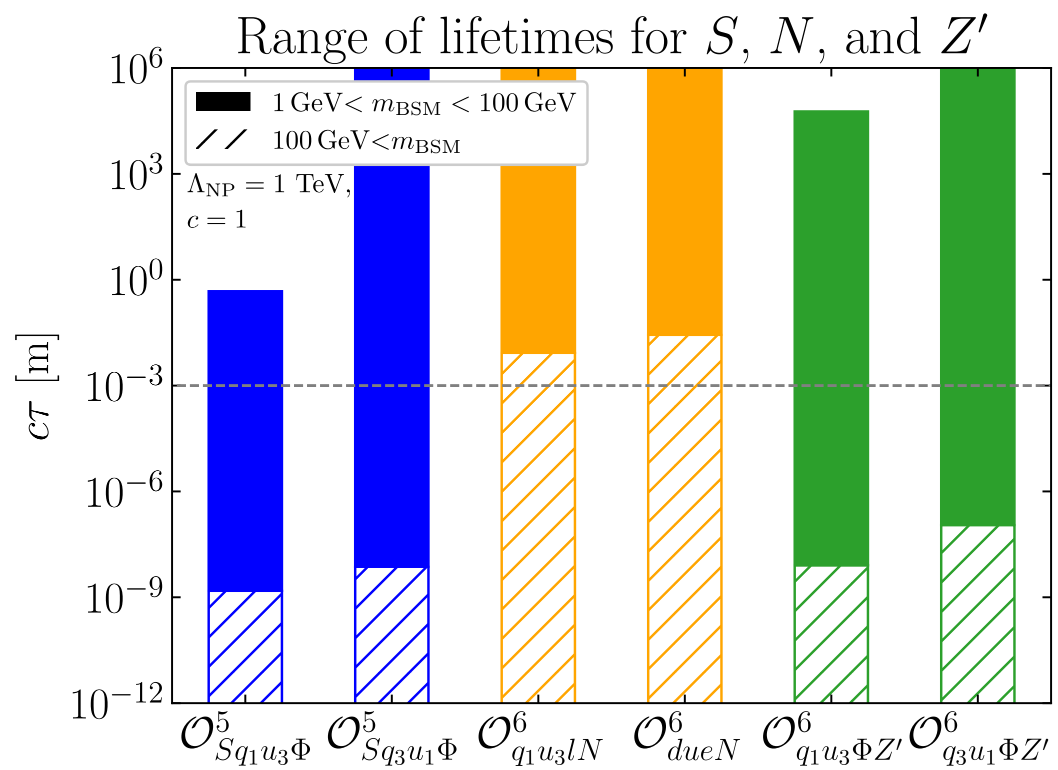
H. Bahl, S. Koren, LTW 2307.11154



Similarly: top rare decay

H. Bahl, S. Koren, LTW 2307.11154

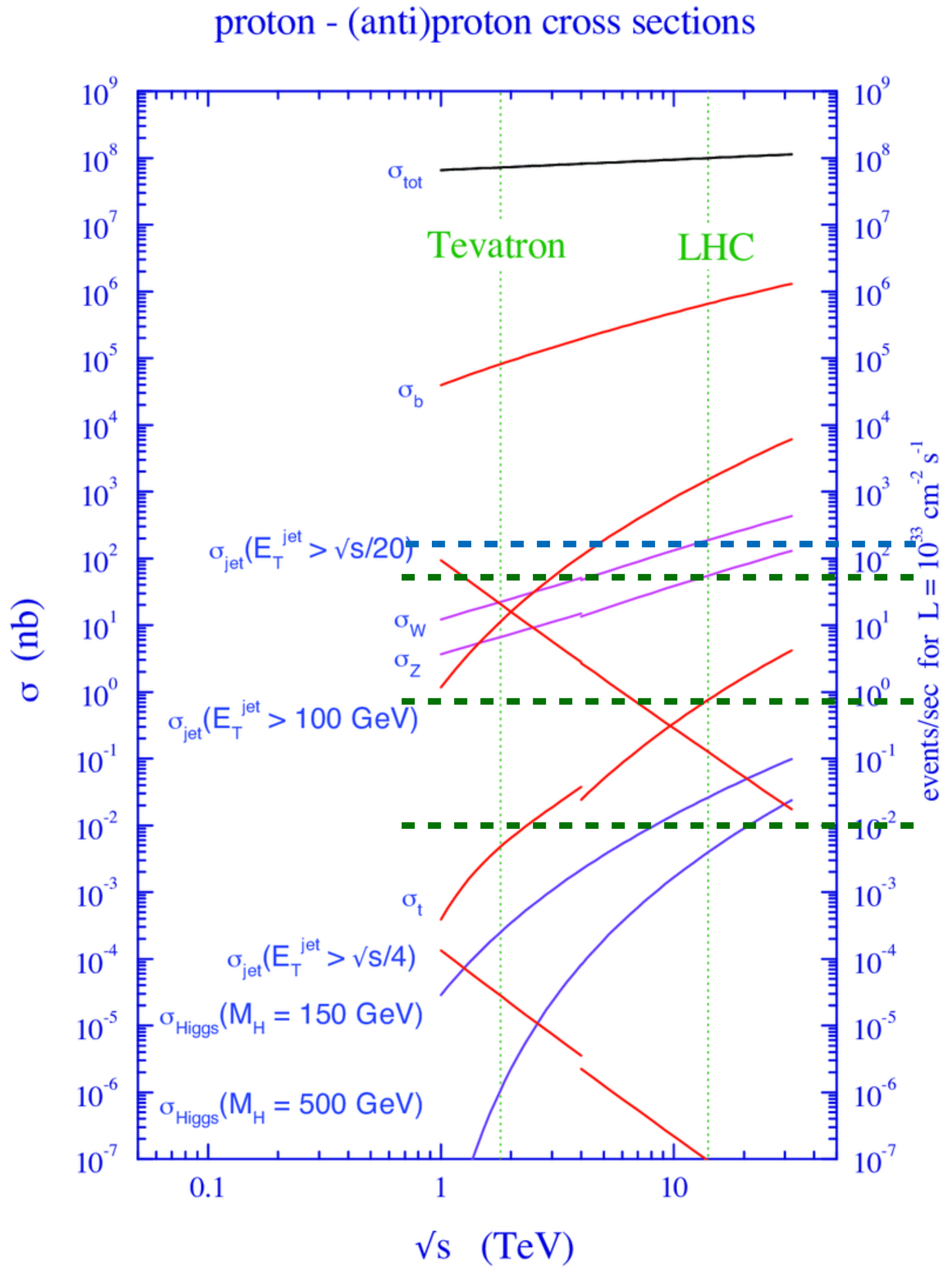




Can have LLPs

Can use the other top as trigger

HL-LHC as particle factories



HL-LHC

> 10^{11} W and Zs

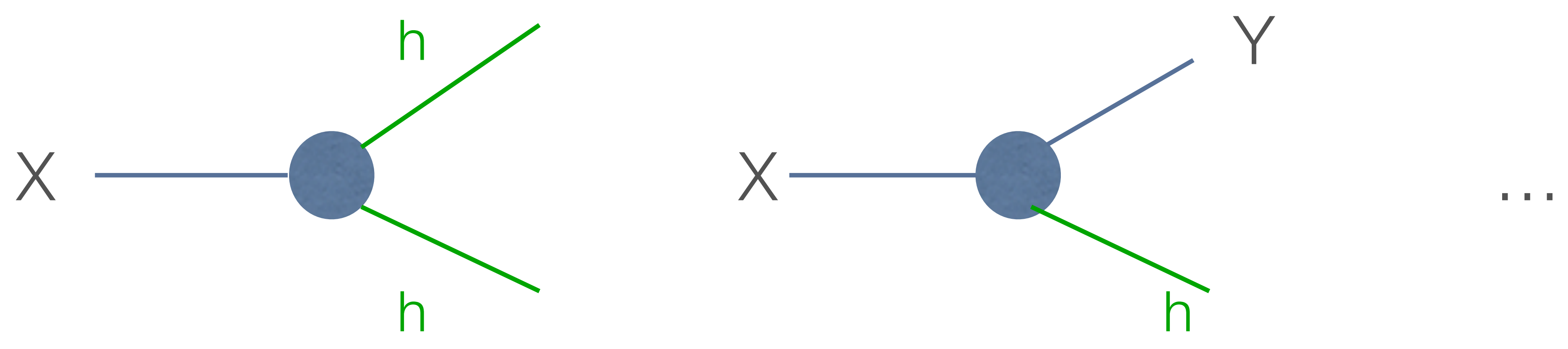
More studies needed!

> 10^9 tops

> 10^8 Higgses

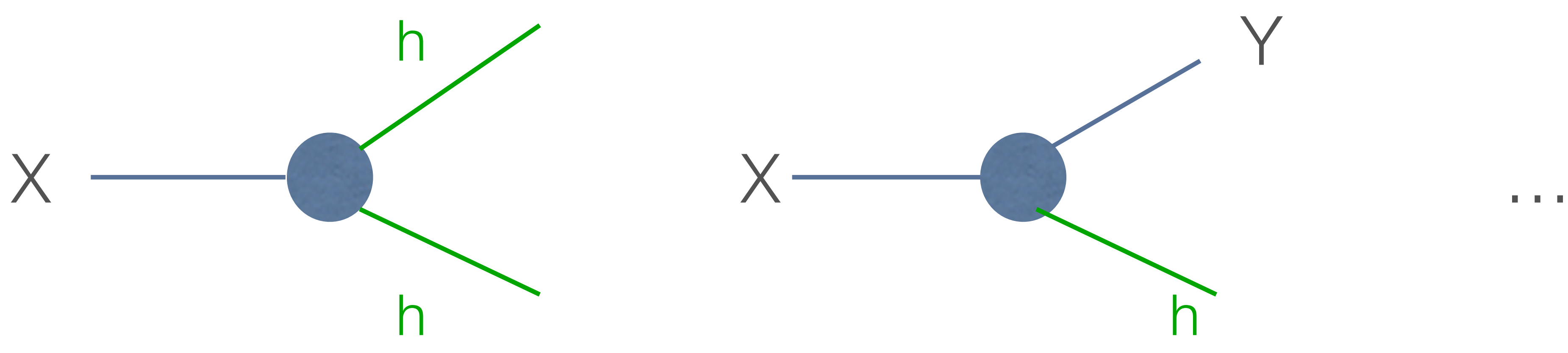
Promising for rare decay with distinct final state!

Aside: comment on Higgs final state



Useful, however:

Aside: comment on Higgs final state



Useful, however:

From Goldstone equivalence theorem, for heavy X, we expect to have channels with $h \leftrightarrow Z_L$, may also have channels with W_L

Need to be careful whether the Higgs final state is the most sensitive channel.

Summary

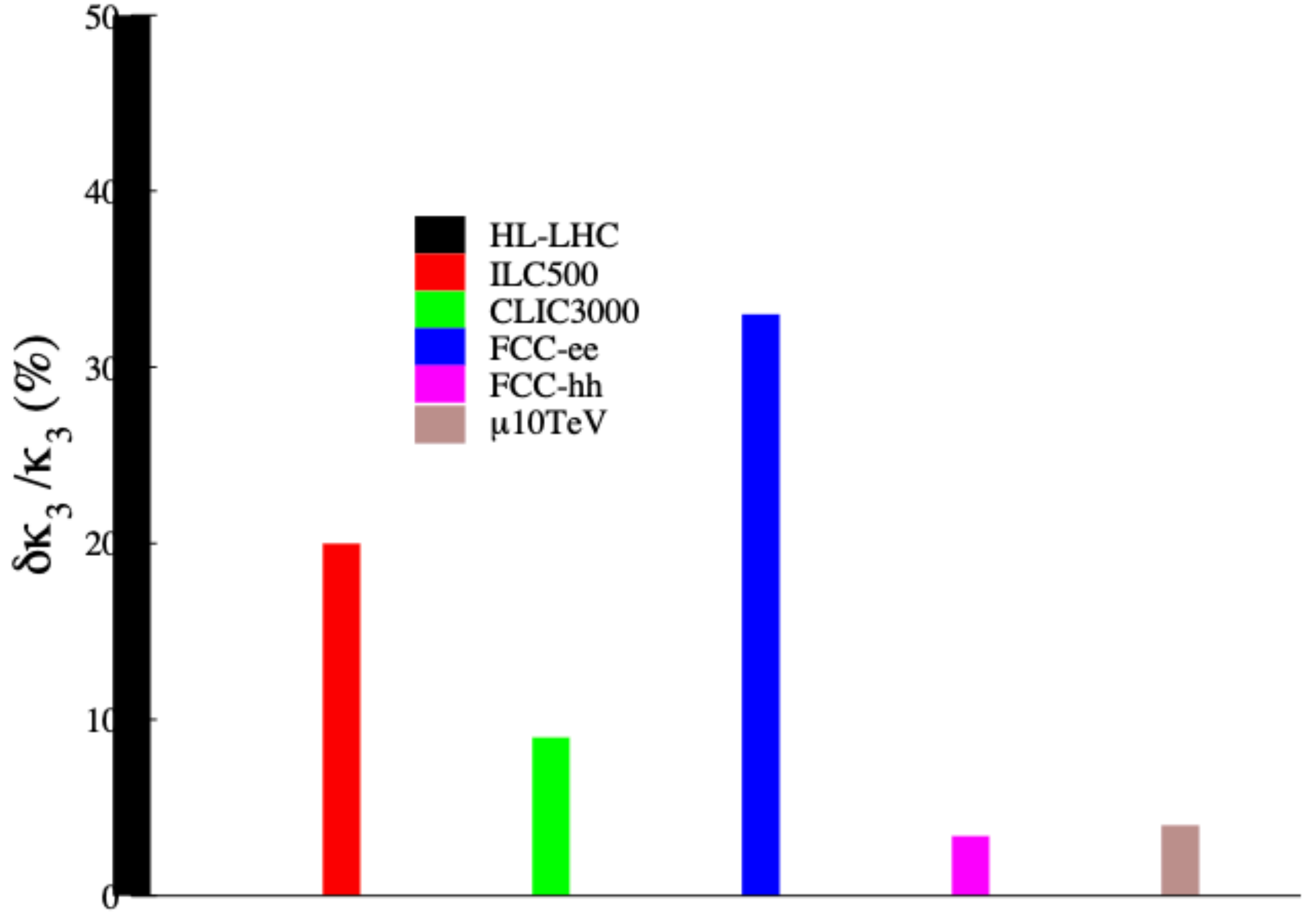
- Higgs boson is *there*. It is *important*, and yet *mysterious*.
  - *Need a better picture to understand it!*
- Higgs boson is also an obvious place to look for new physics.

In particular, exotic decays can benefit a lot from higher statistics.

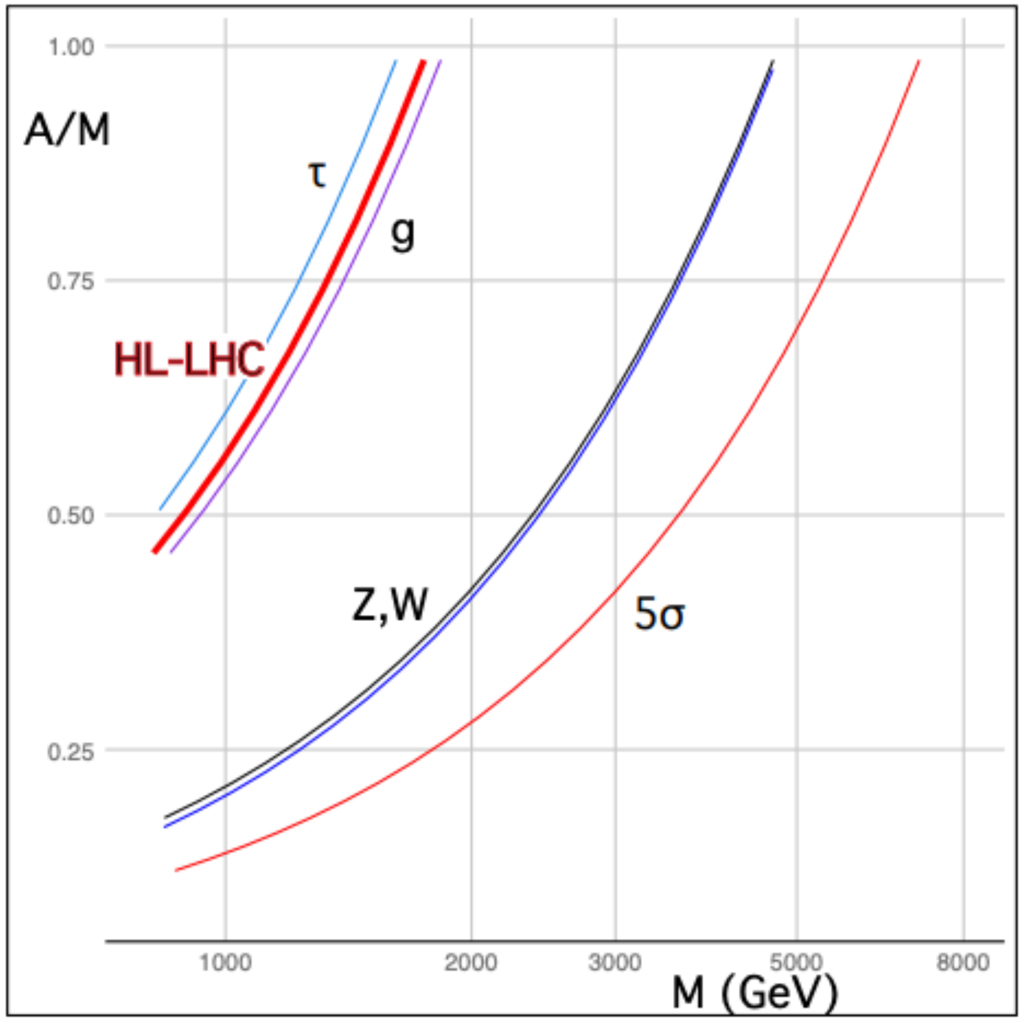
A lot to look forward to...

Extra

Higgs self-coupling

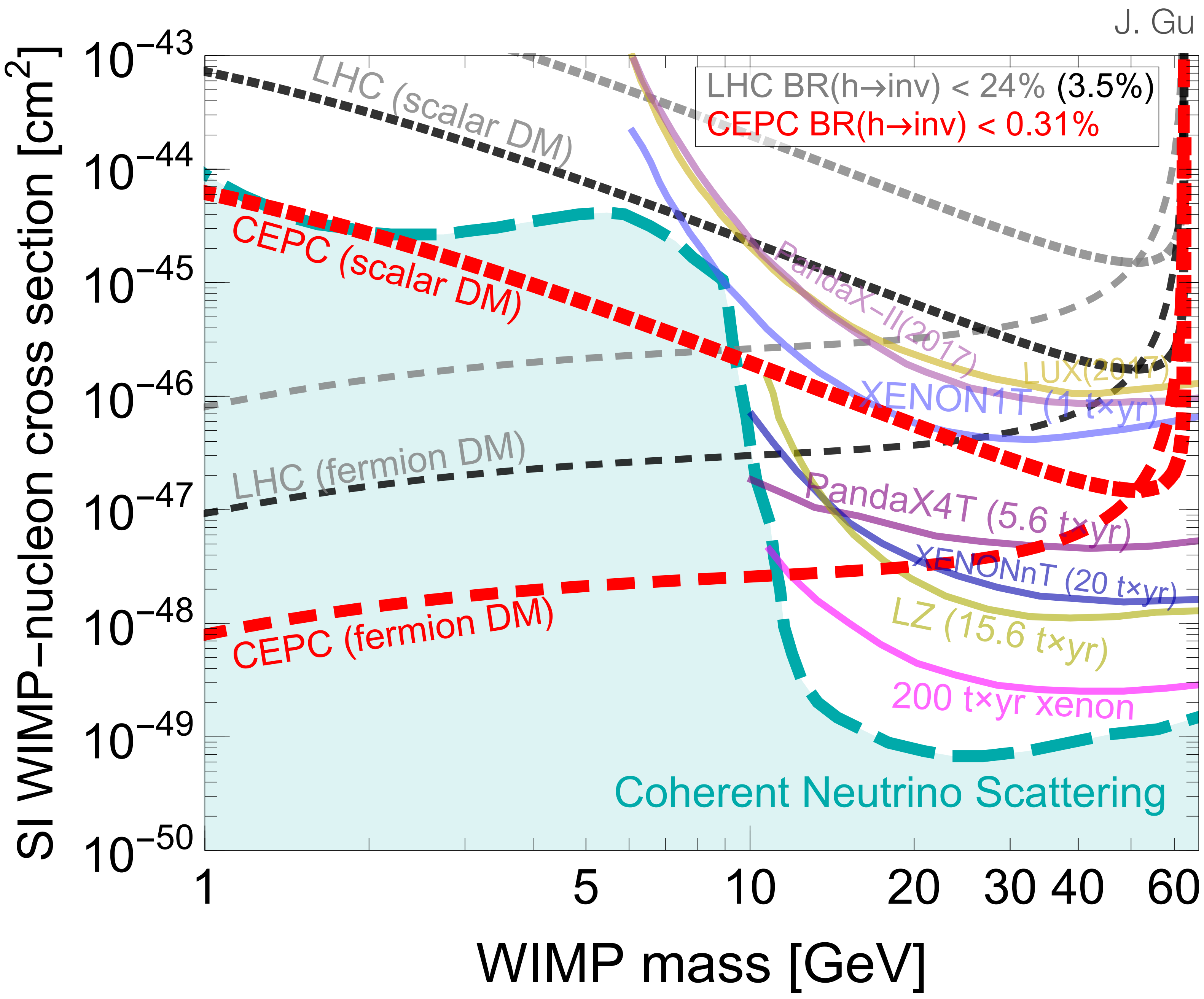


Higgs+singlet



Higgs portal dark matter

$$\mathcal{O} = H^\dagger H X_{\rm dm} X_{\rm dm} \Rightarrow h \to X_{\rm dm} X_{\rm dm}$$



Windows into dark sector: portals

- Any known (SM) particle can in principle have small couplings to dark matter/dark sector.