Higgs and BSM

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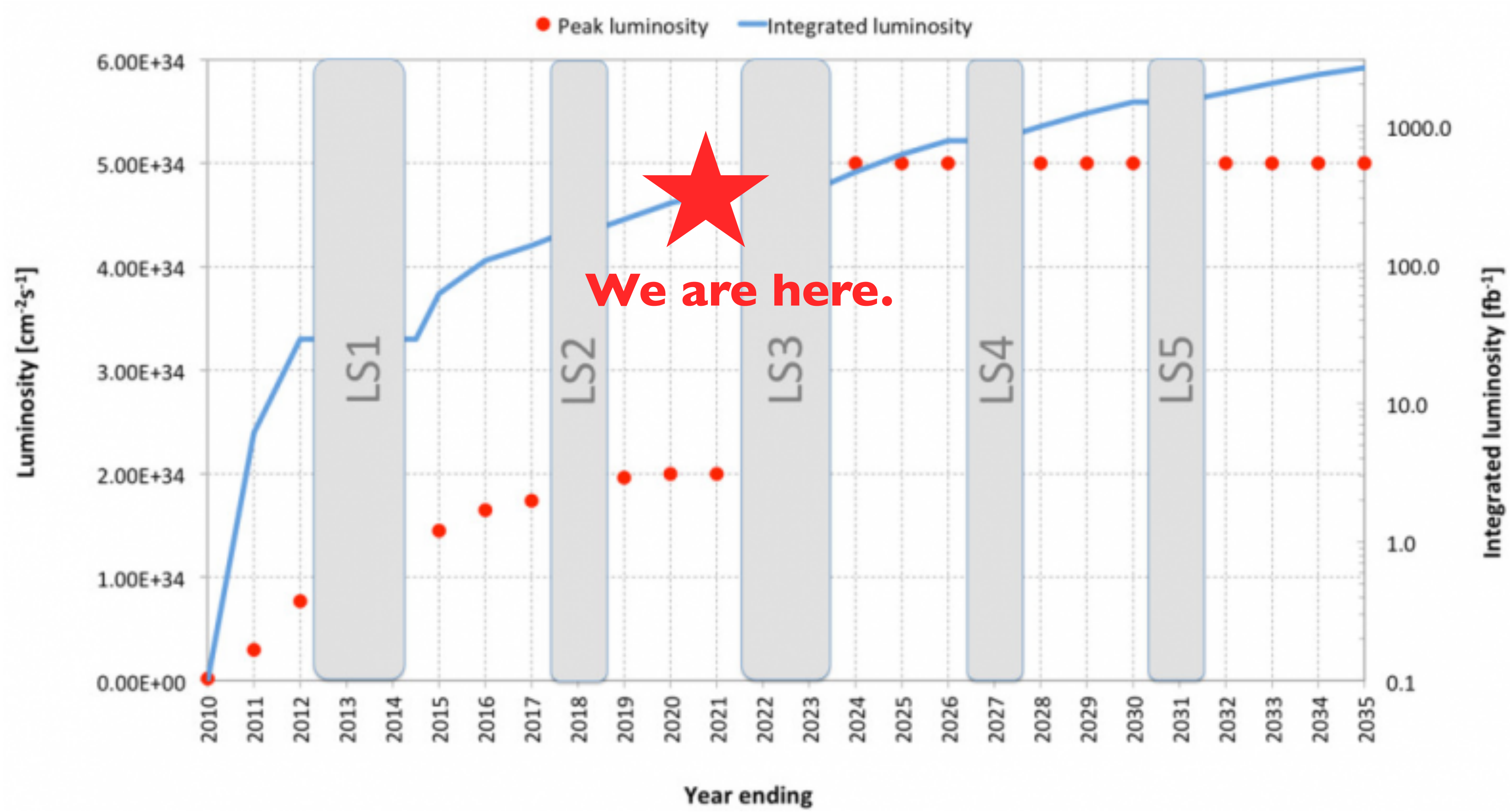
University of Chicago

Higgs potential and BSM opportunities. August, 28. NanJing

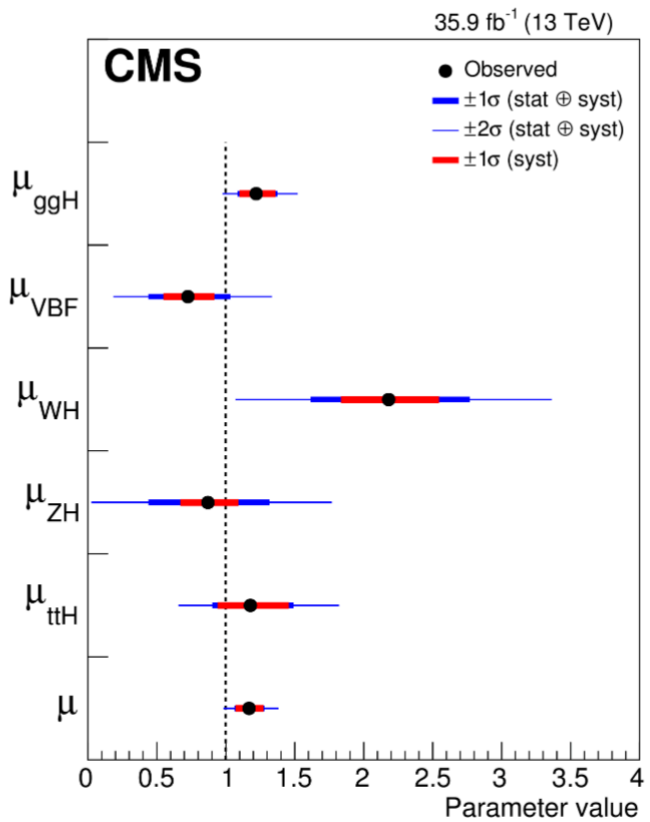
Our immediate future

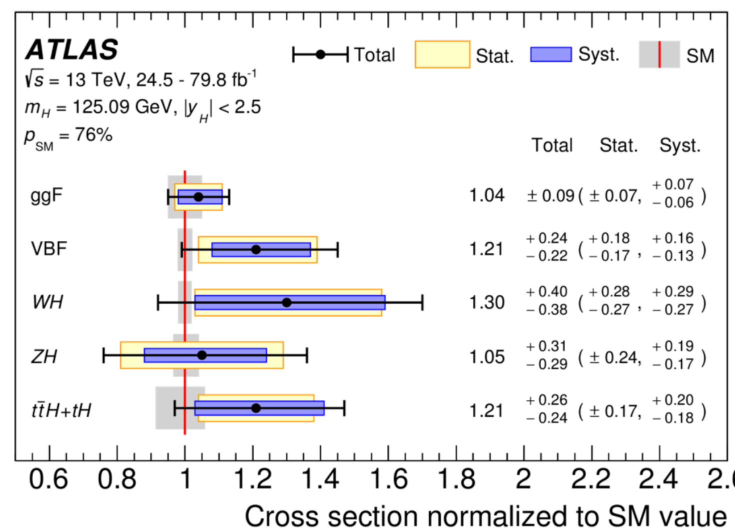


Still about 10 times amount of data to come.

Good for precision measurements and rare processes.

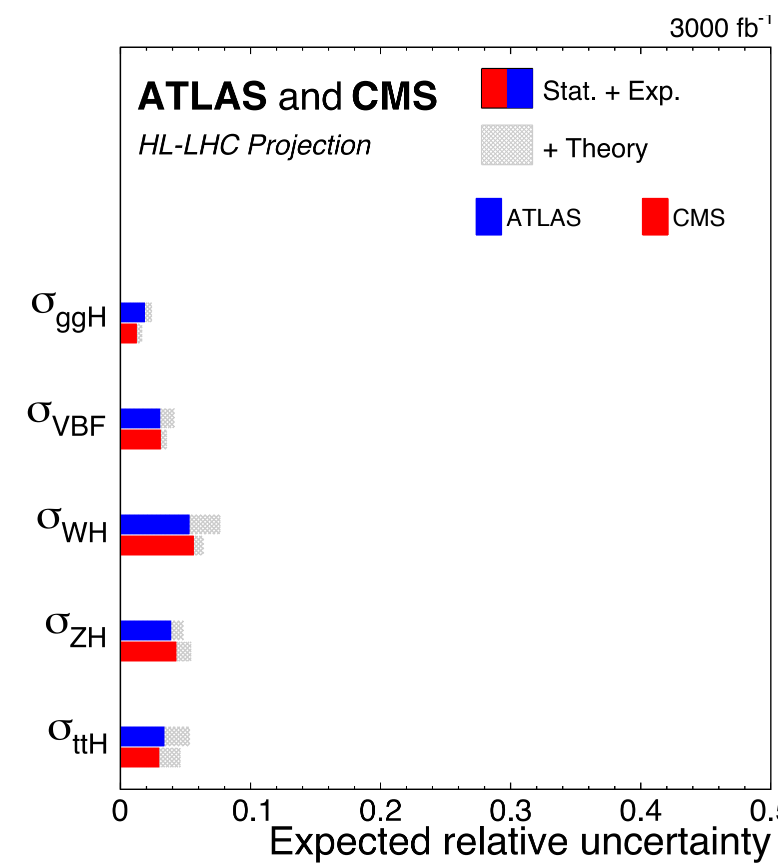
All eyes are on the Higgs





Current precision: 10(s)%

A few Percent by the end of the LHC



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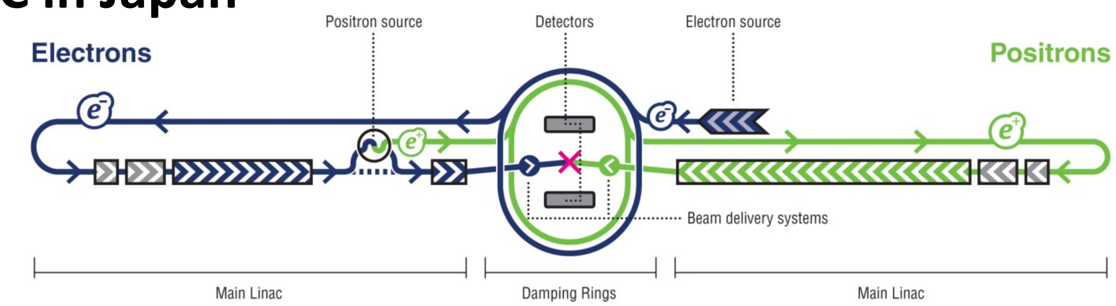
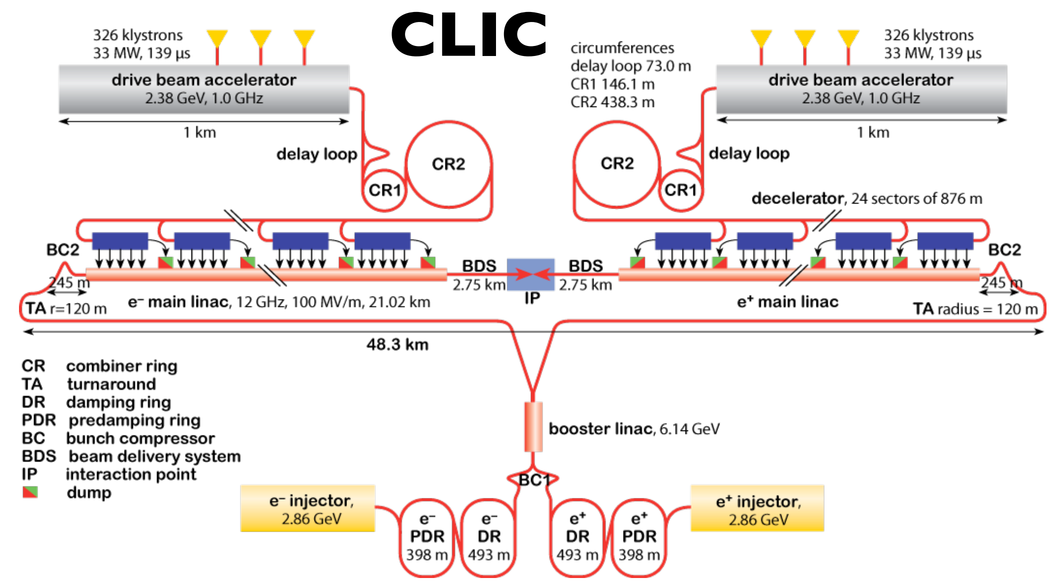
Future Colliders

ILC in Japan





pp collider ~100 TeV

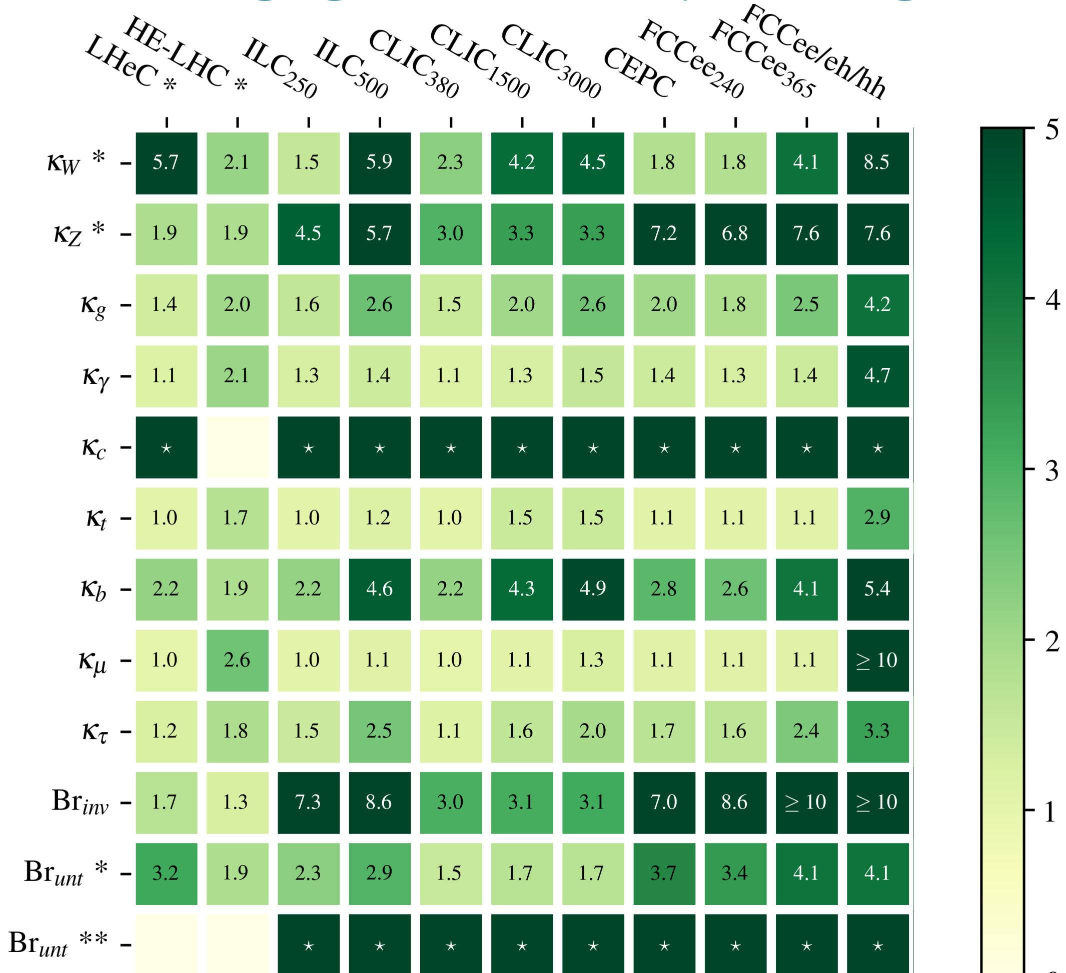
FCC-hh (CERN), SppC(China)

e^-e^+ Higgs Factory 250 GeV

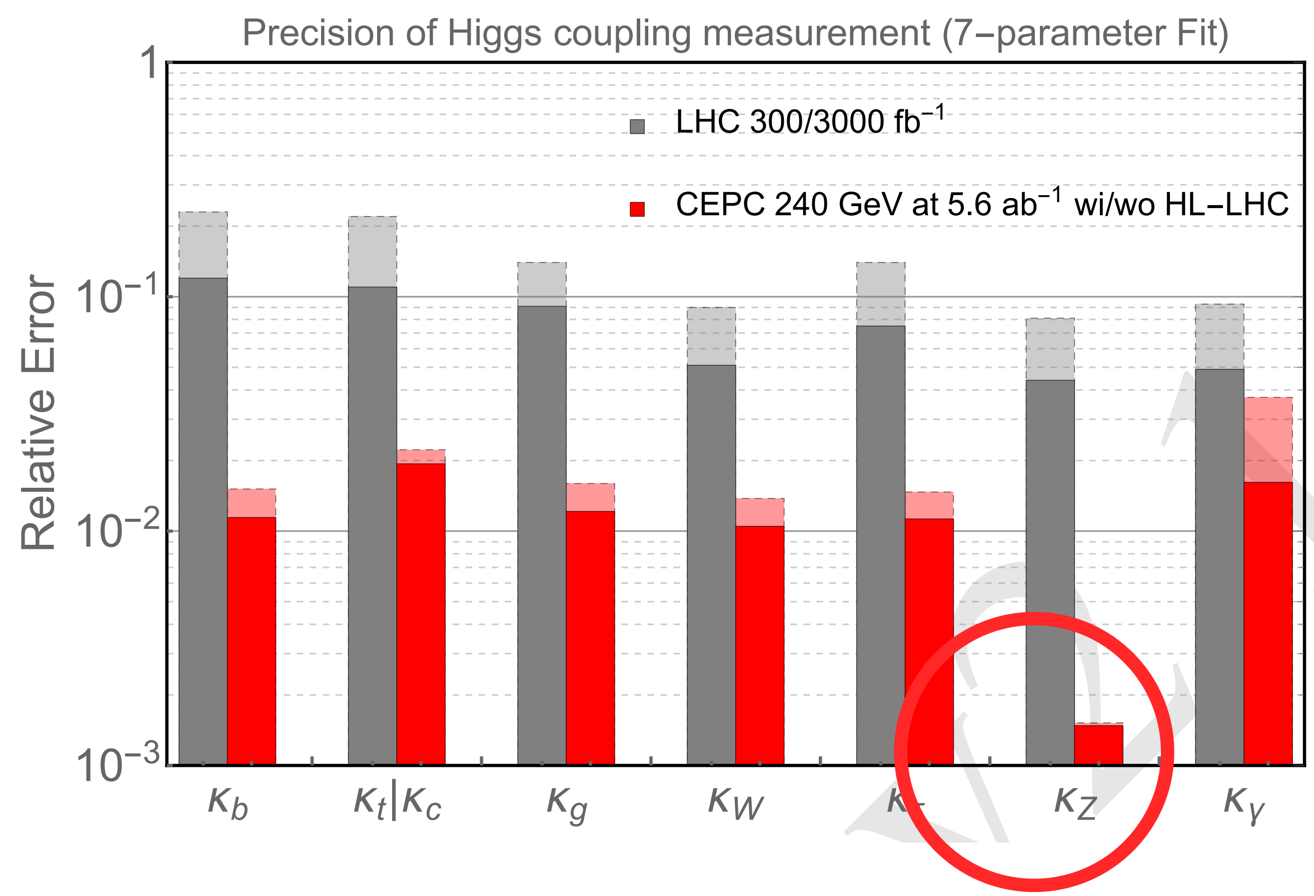
FCC-ee (CERN), CEPC(China)

Likely to get a precision machine first!

Higgs coupling at future colliders



(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC



- A large step beyond the HL-LHC.
  - Can achieve per-mil level measurement.
  - Determination of the Higgs width.

For the coming couple of decades:

Most of the progresses at the colliders will be made on precision measurements, rare processes.

One of the main targets is the Higgs boson.

The focus is on its connection with new physics.

This talk:

- What's the connection between the Higgs and BSM new physics?
    - Focus on motivation, rather than model details.
- Collider signals.

Many puzzles and opportunities

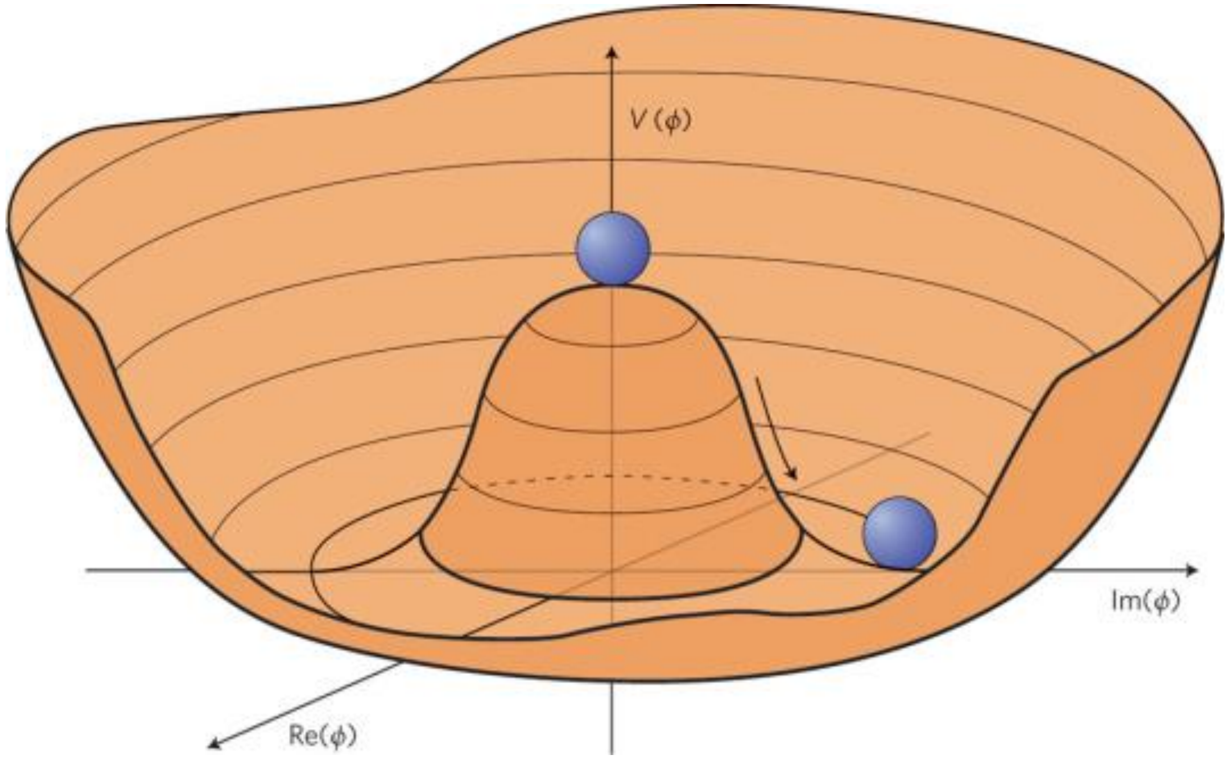
- Higgs mass, electroweak scale, "hierarchy problem".
- Higgs and electroweak phase transition, early universe, matter anti-matter asymmetry.
- Higgs as a window to dark sector.
- ...

Why is Higgs measurement crucial?

- Many ideas have been proposed, but nothing has been found yet.
- Need experiment!
- Fortunately, with Higgs, we know where to look.
- And, the clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

Electroweak symmetry breaking

“Simple” picture:

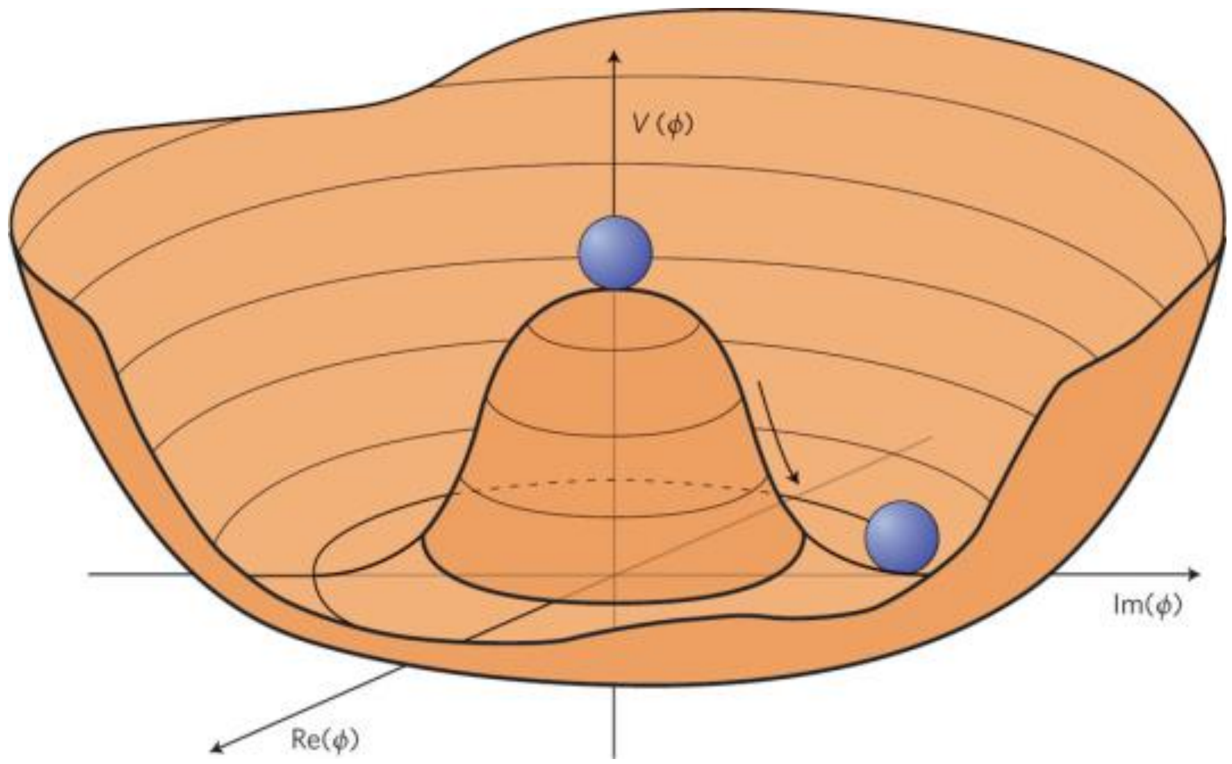


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

“Simple” picture:



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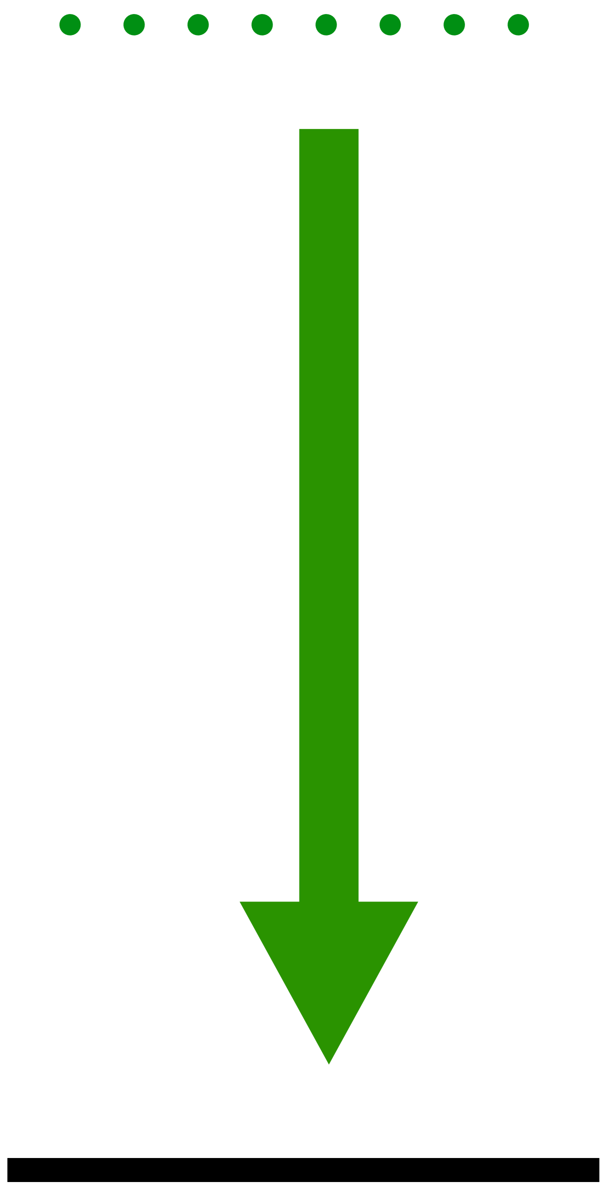
Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

However, this simplicity is deceiving.
Parameters not predicted by theory. Can not be the complete picture.

How to predict Higgs mass?

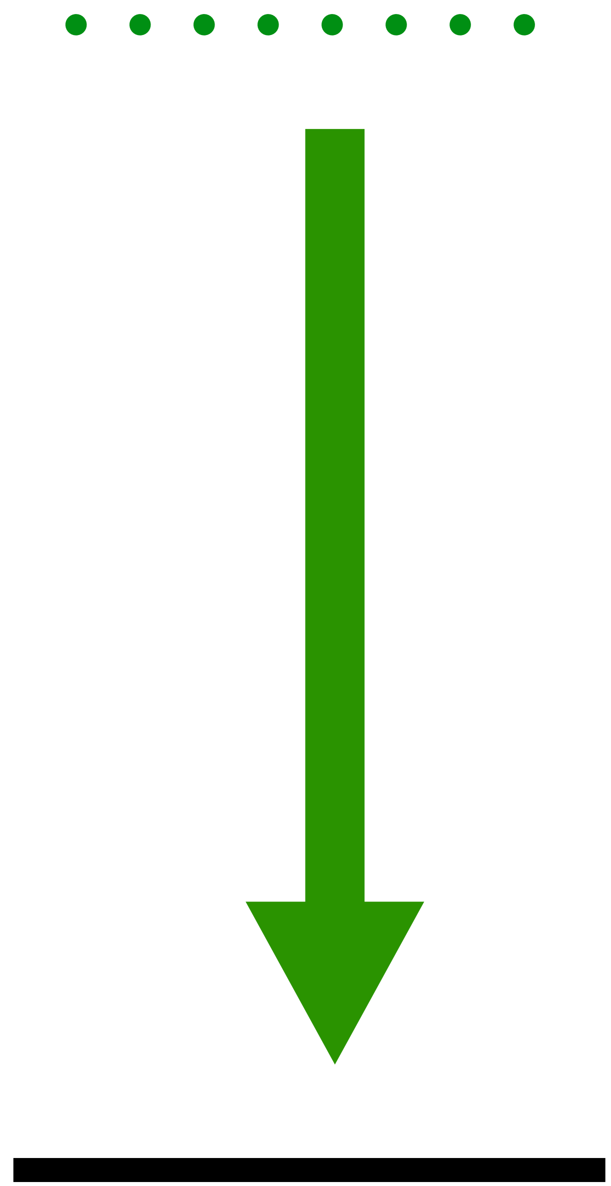


M: the energy scale of new physics responsible for EWSB

Electroweak scale, 100 GeV.

m_h , m_W …

How to predict Higgs mass?



M: the energy scale of new physics responsible for EWSB

What is this energy scale?
$M_{Planck} = 10^{19}$ GeV, …?

If so, why is so different from 100 GeV?
The so called naturalness problem

Electroweak scale, 100 GeV.
m_h , m_W …

Predicting the Higgs mass

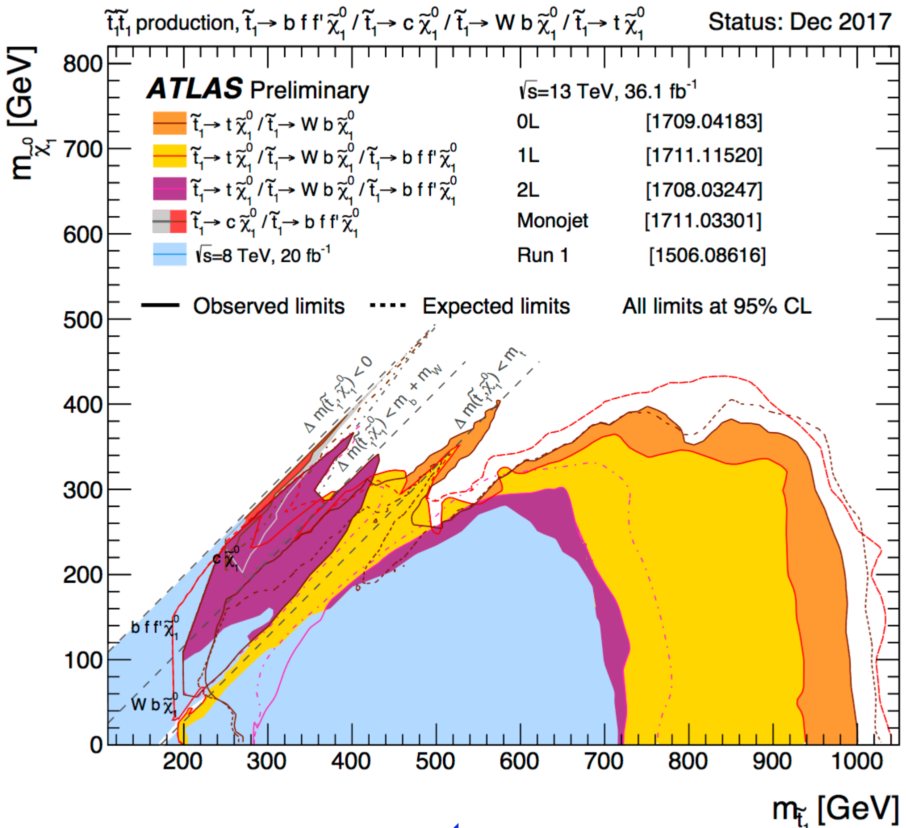
Higgs mass predicted from a fundamental theory must has the form:

$$m_h^2 = cM^2 \qquad c \sim \sum_i \frac{(\text{coupling}_i)^2}{16\pi^2}$$

- Typically, couplings are about O(0.1–1).
- Without large cancellation: M $\lesssim$ TeV.
  - New physics near weak scale!
- In particular:
  - Since top quark gives largest contribution to Higgs mass, we expect some "top-partner" to be around TeV scale.

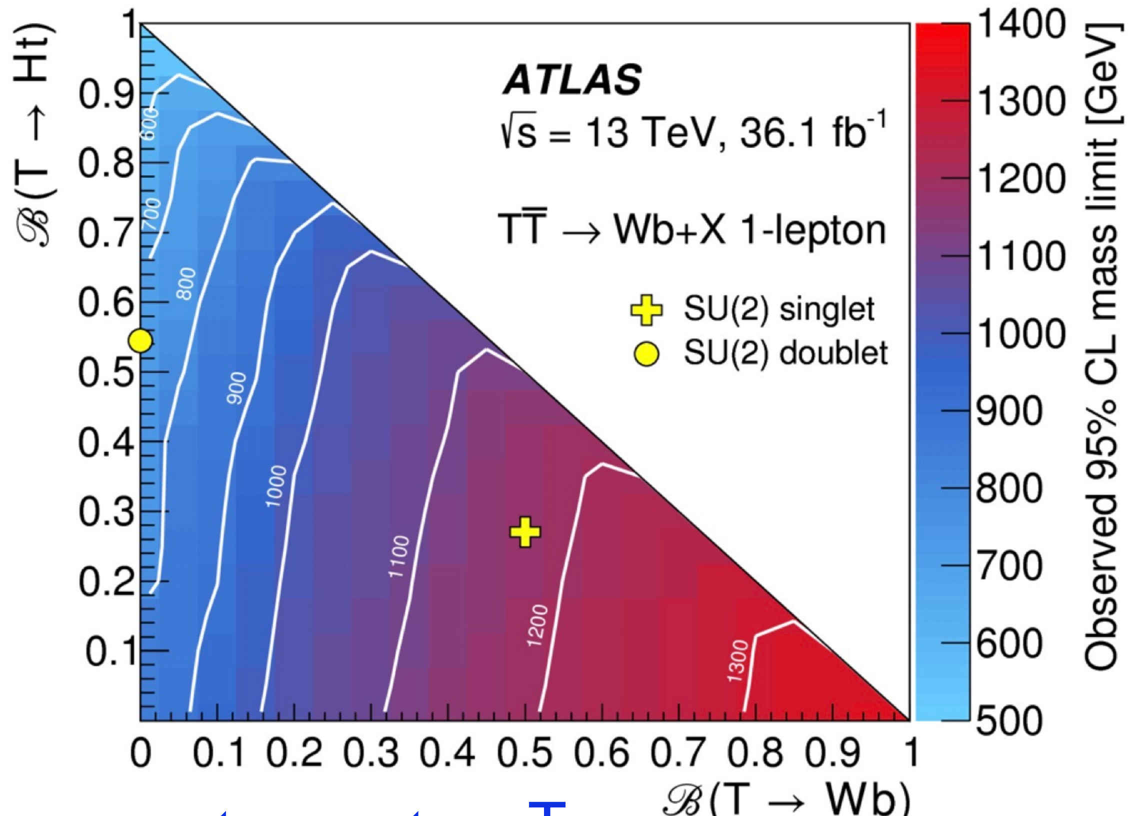
All eyes on these searches

Supersymmetry



stop

Composite Higgs

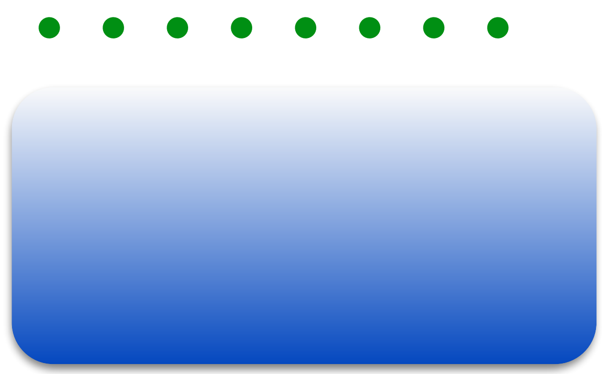


top partner, T

fine-tuning = comparison: $\frac{1}{16\pi^2} m_{\mathrm{T}}^2 \quad vs \quad m_h^2 = (125 \text{ GeV})^2$

current limit: $m_{\mathrm{T}} \sim 1 \text{ TeV}$

Naturalness of electroweak symmetry breaking



The energy scale of new physics
responsible for EWSB

Naturalness motivated
Many models, ideas.

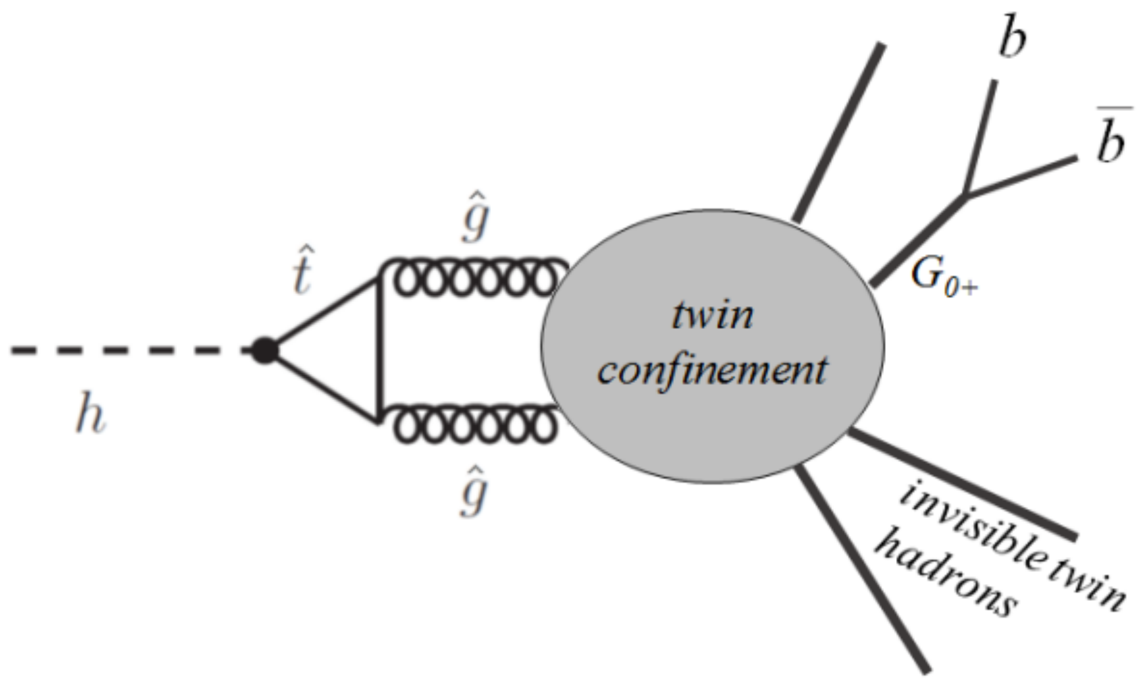
Electroweak scale, 100 GeV.
m_h , m_W ...

No matter what the model is, new physics has to couple to the Higgs to address the Higgs mass problem.

Stealthy top partner. "twin"

Chacko, Goh, Harnik

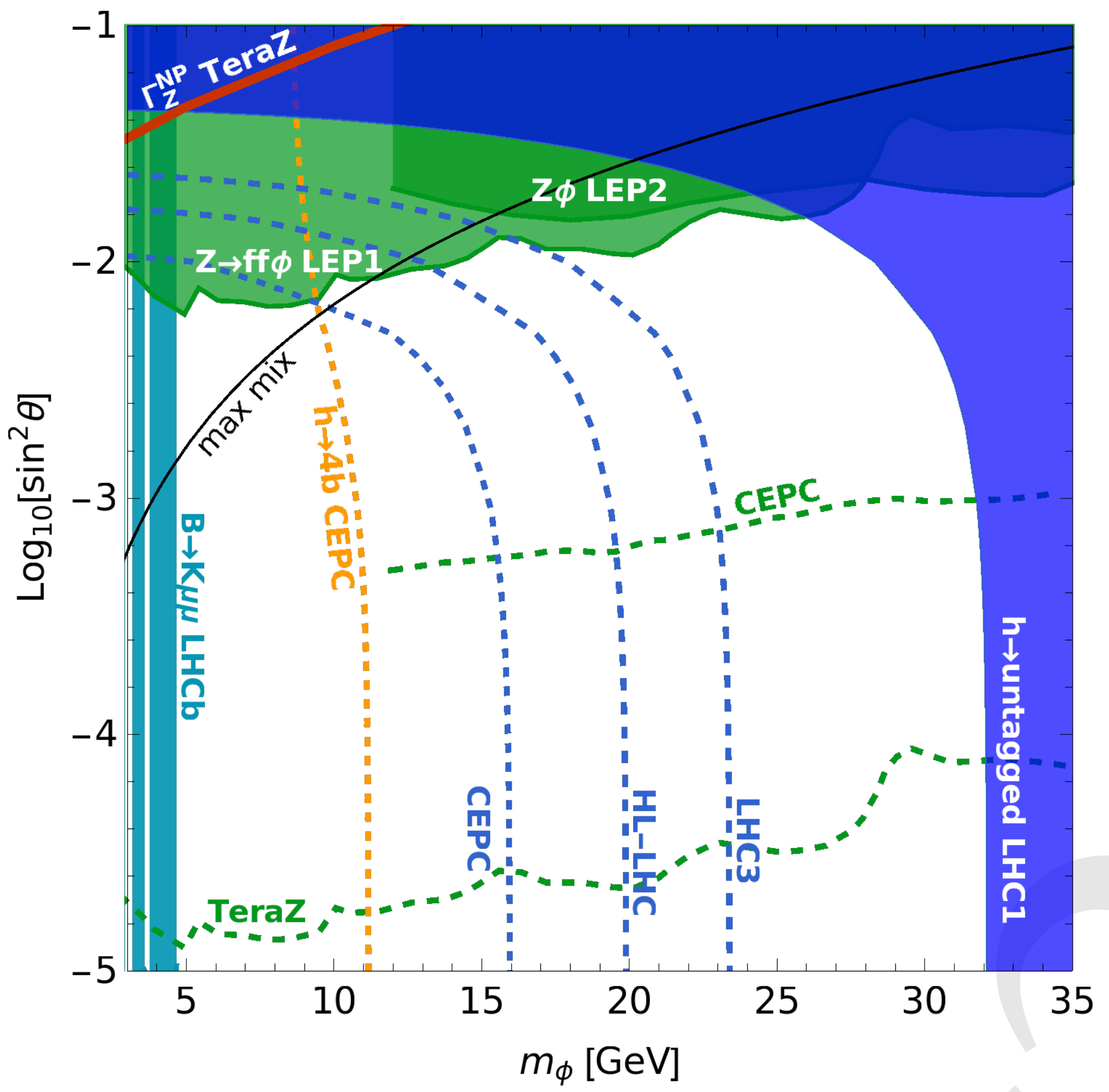
Craig, Katz, Strassler, Sundrum



- Top partner not colored. Higgs decay through hidden world and back.

- Can lead to Higgs rare decays.

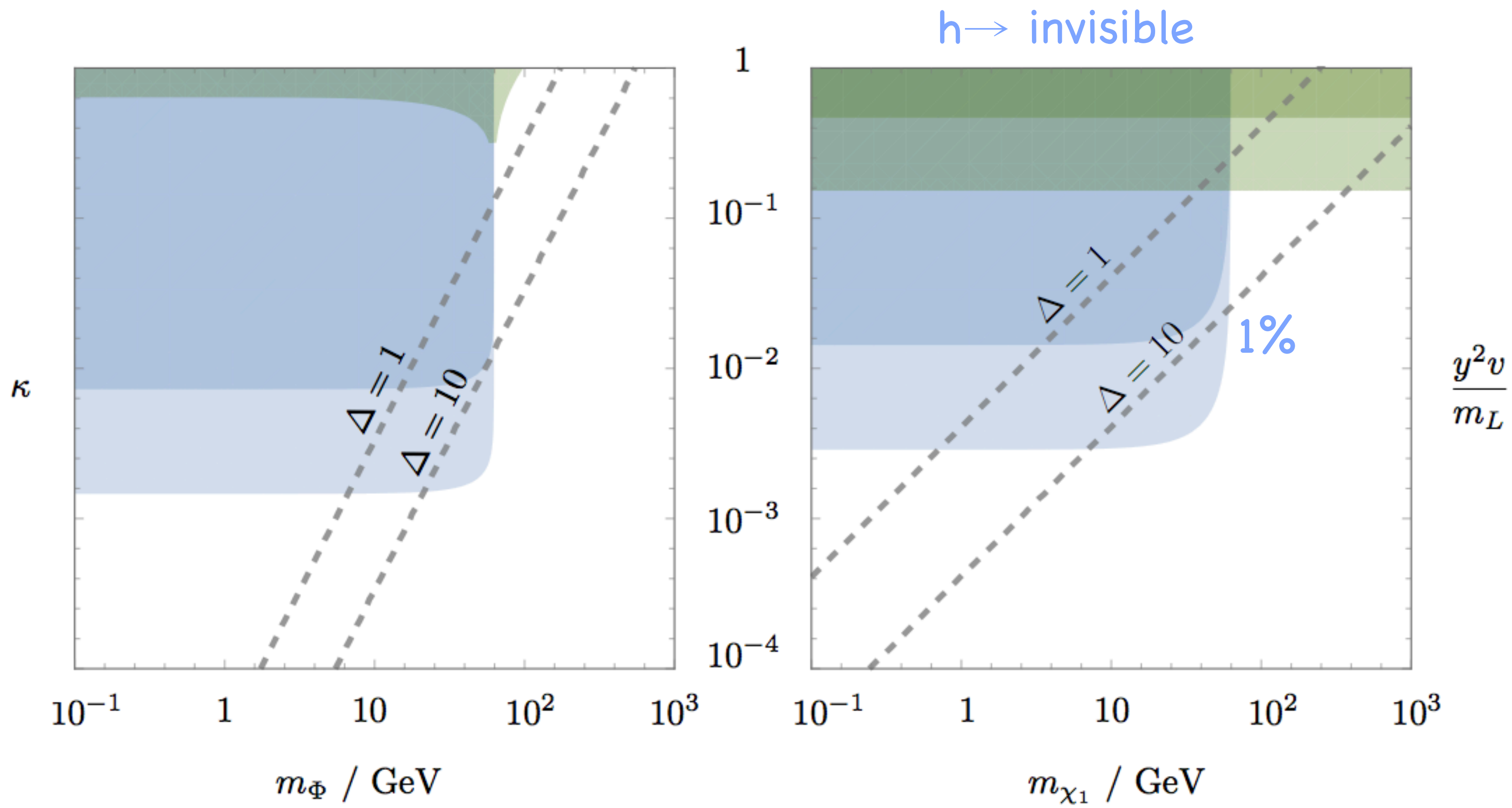
Relaxion



Cosmological evolution of a light scalar, the relaxion, sets the weak scale

Signal from relaxin-Higgs mixing,
and Higgs rare decay, $h \to \phi\phi \to 4b$ and rare Z decay

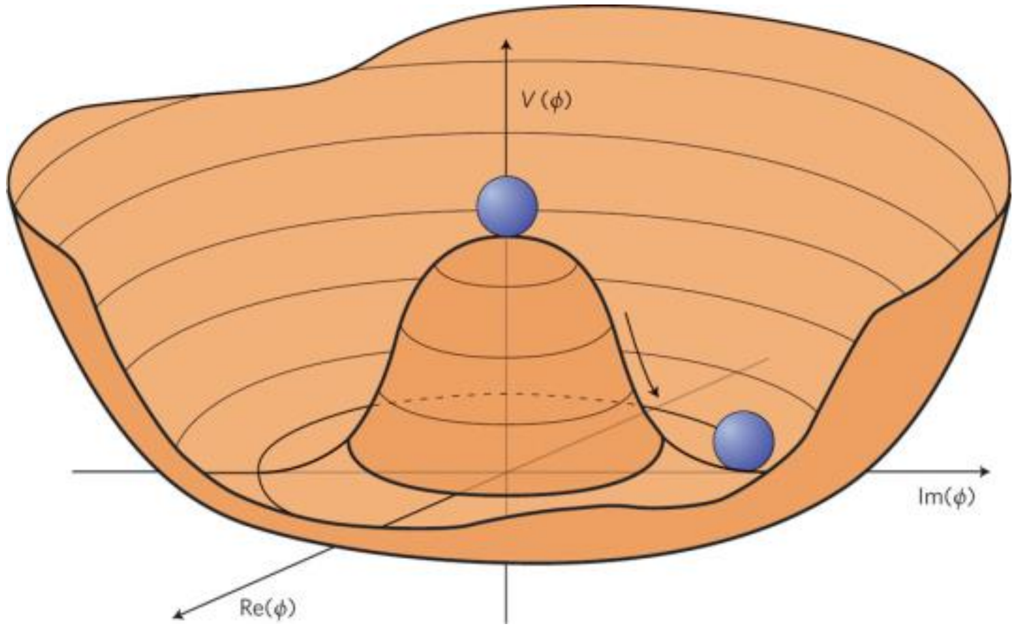
Weak gravity conjecture



- For a U(1) gauge theory, new physics at scale $gM_{Pl.}$ If g<<1, responsible for weak scale? Cheung

- This requires new physics close to weak scale couples to the Higgs boson. Craig, Garcia, Koren

Mysteries of the electroweak scale.



$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4$$

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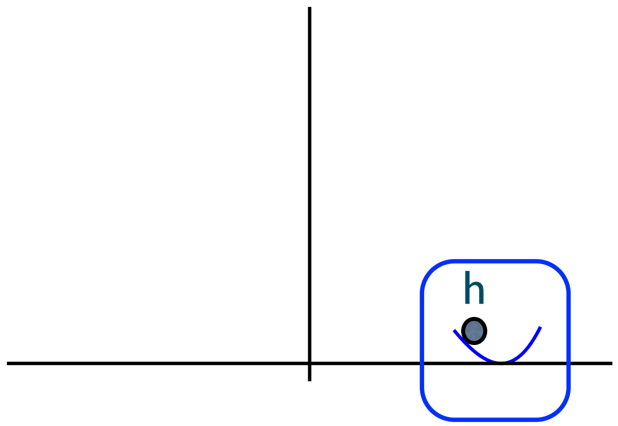
Mysteries of the electroweak scale.

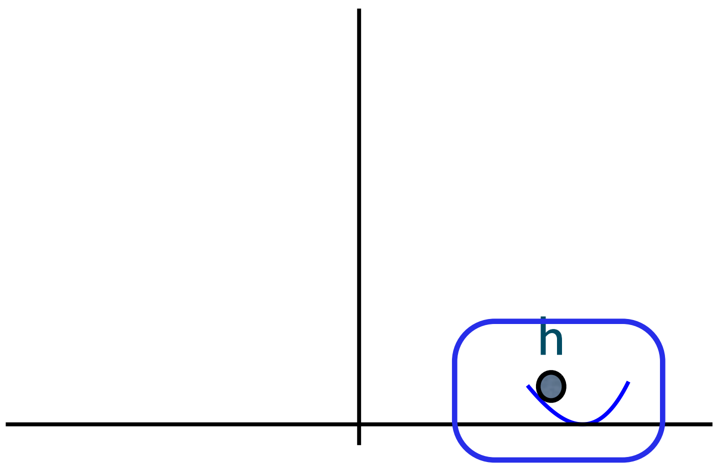


What we know now

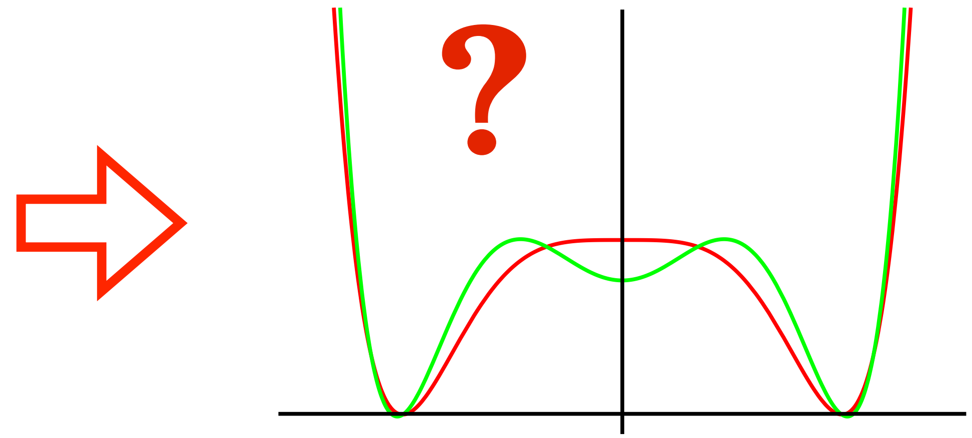
- What does the rest of the Higgs potential look like? Nature of electroweak phase transition.

- Is it connected to the matter anti-matter asymmetry?

Nature of EW phase transition



What we know from LHC
LHC upgrades won't go much further



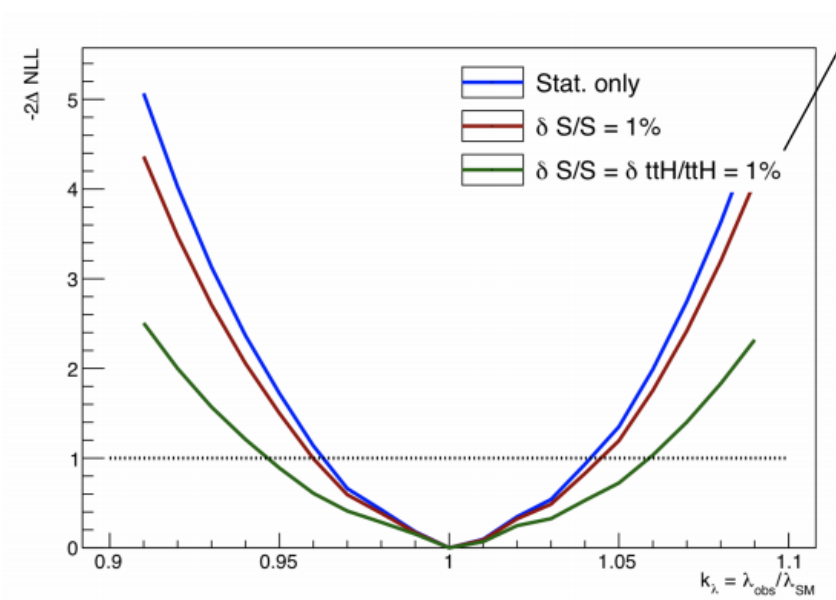
"wiggles" in Higgs potential

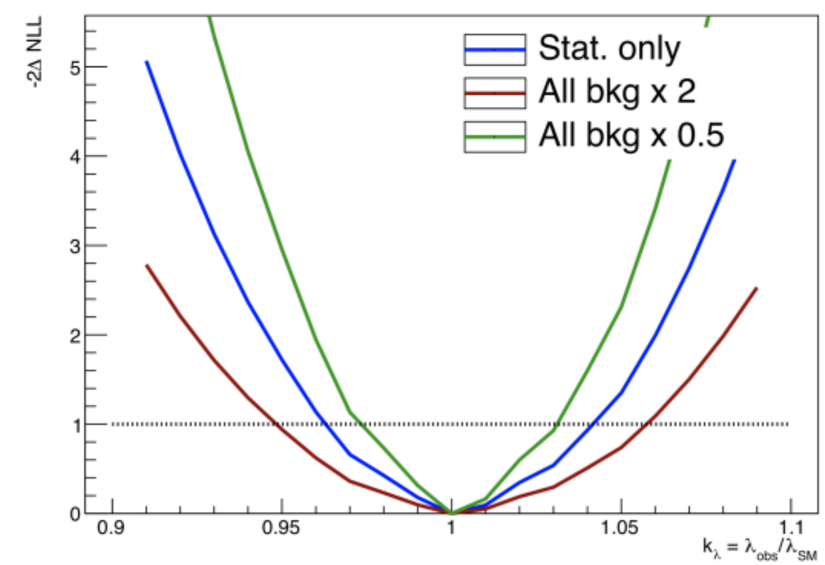
Big difference in triple Higgs coupling

Triple Higgs coupling at 100 TeV collider

Precision on the self-coupling

assuming QCD can be measured from sidebands





nominal background yields:

$\delta\kappa_\lambda$(stat) ≈ 3.5 %
$\delta\kappa_\lambda$(stat + syst) ≈ 6 %

varying (0.5x-2x) background yields:

$\delta\kappa_\lambda$(stat) ≈ 3 - 5 %

Talk by Michele Selvaggi at 2nd FCC physics workshop

But, there should be more

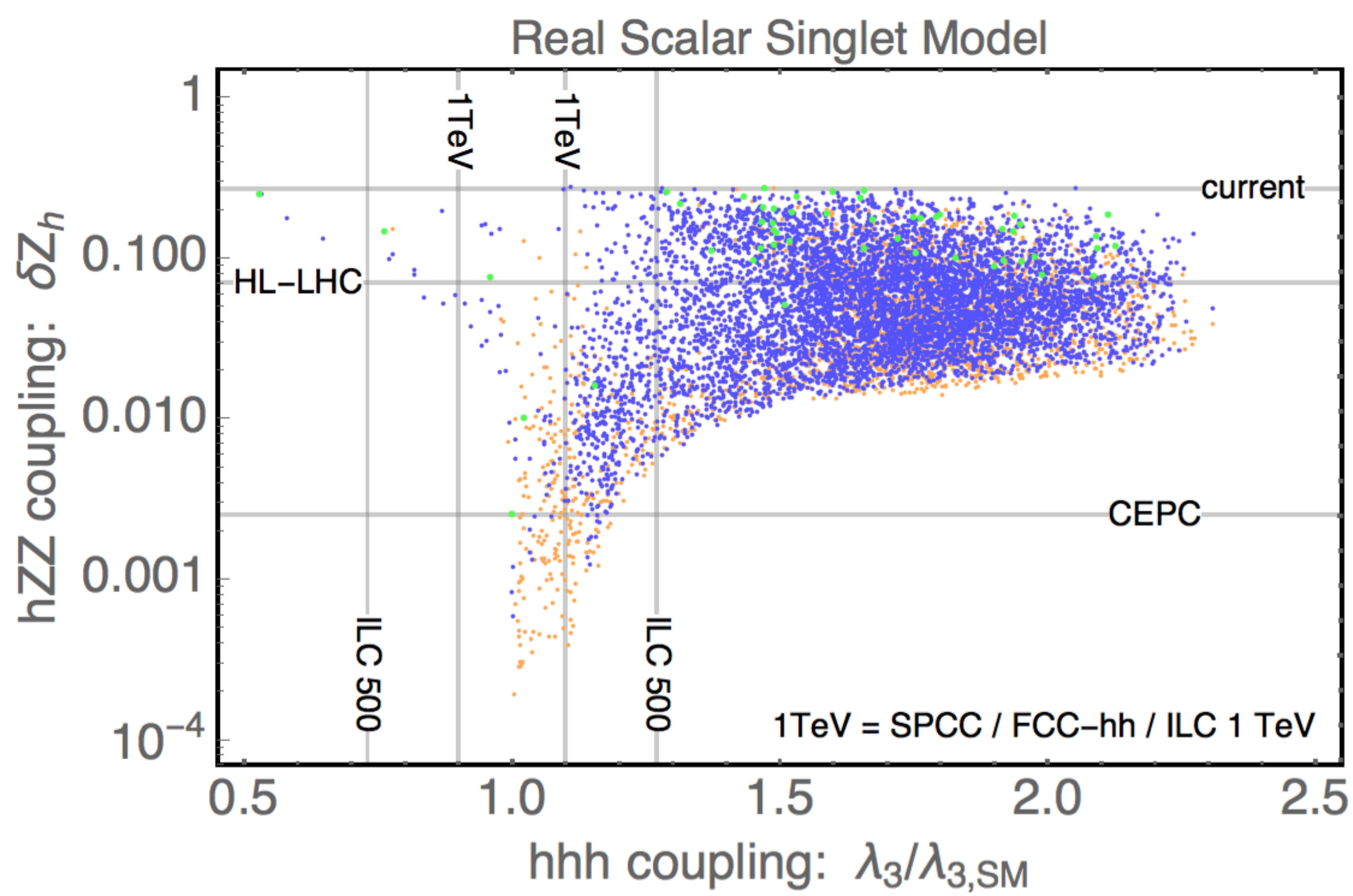
$$V(h) = \frac{m^2}{2} h^2 + \lambda h^4 + \frac{1}{\Lambda^2} h^6 + \ldots$$

- Large deviation in the Higgs potential means there is new physics close to the weak scale.

- Will leave more signature in Higgs coupling.

For example: $$\frac{[\partial(HH^\dagger)]^2}{\Lambda^2} \rightarrow \delta_{Zh} \sim \frac{v^2}{\Lambda^2}$$

Probing EWSB at higgs factories

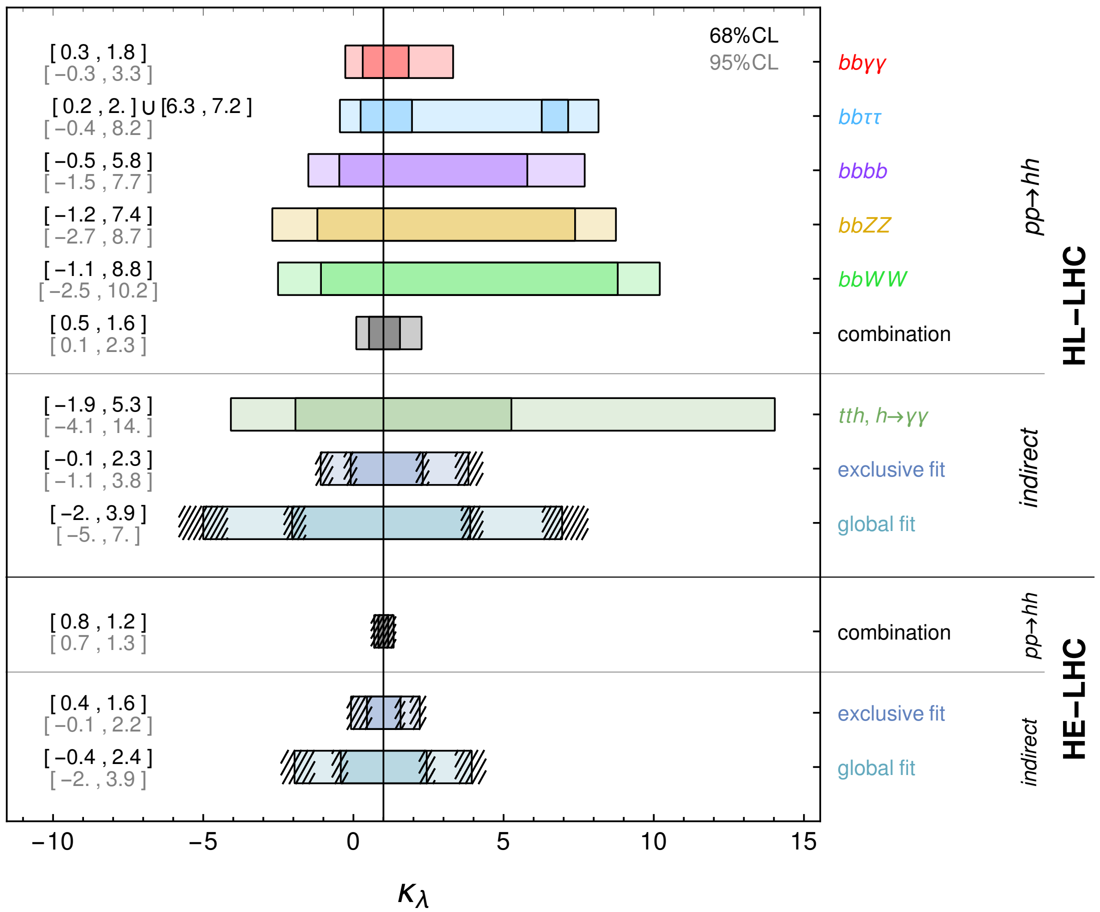


Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

Huang, Long, LTW, 1608.06619

Good coverage in model space

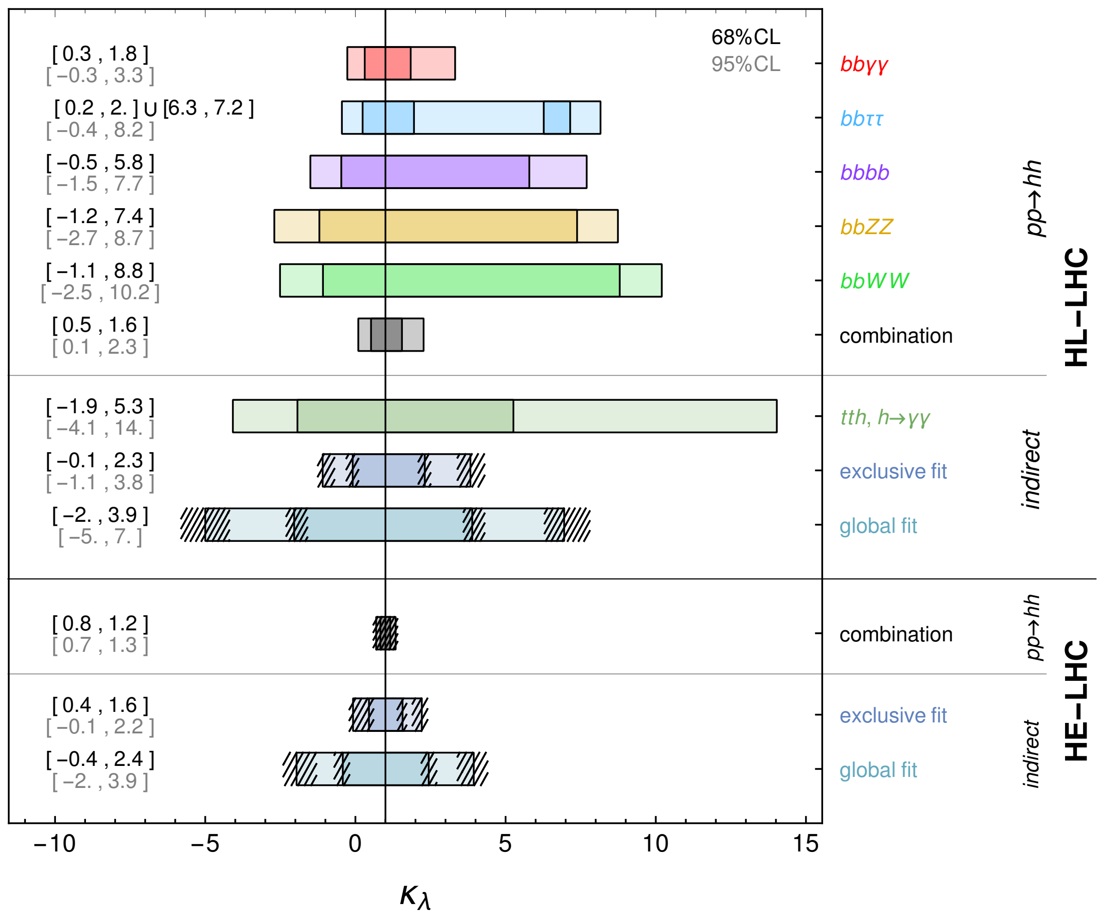
LHC measurements

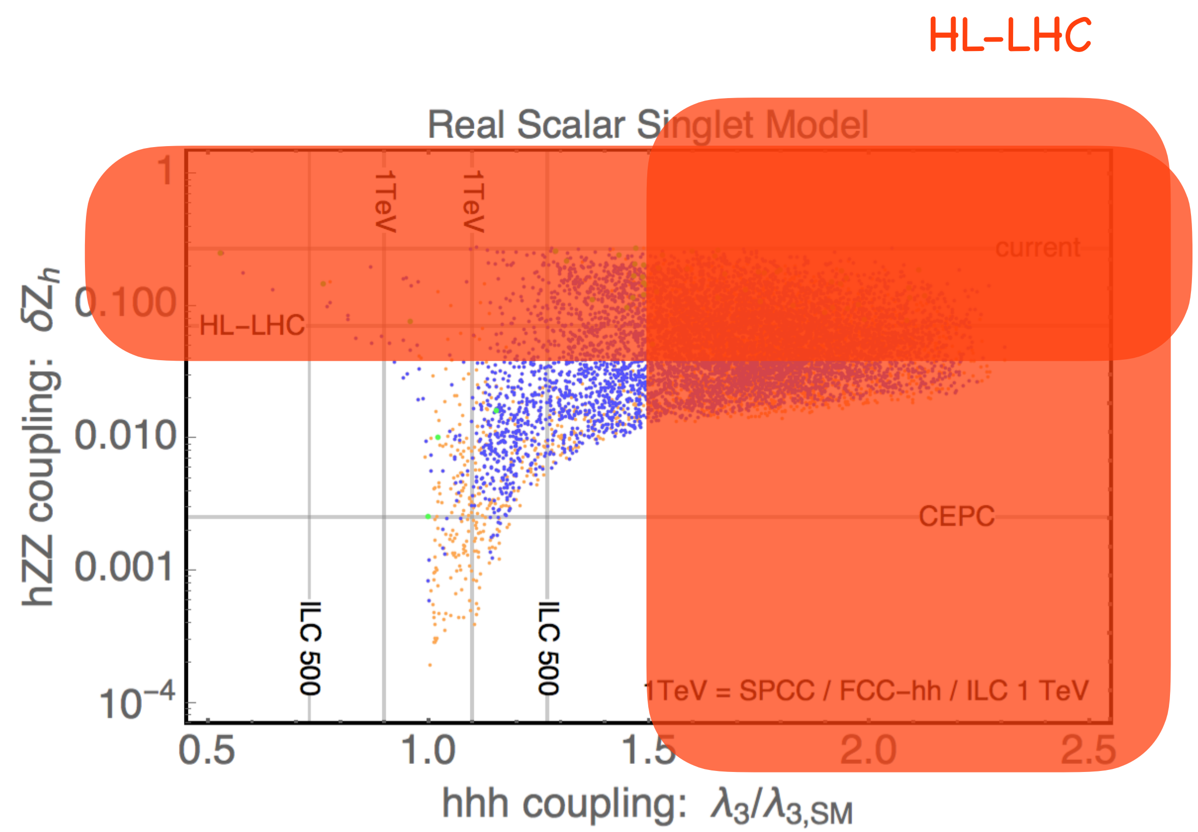


50% level measurement for Higgs self coupling at HL-LHC

Together with (a few) percent level measurement of HZ couplingat HL-LHC

LHC measurements





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50% level measurement for Higgs self coupling at HL-LHC

Together with (a few) percent level measurement of HZ couplingat HL-LHC

Singlet model with 1st order EW phase transition

LHC measurements, while not conclusive, can say a lot already

Higgs portal

- Dark sector
  - Does not carry SM quantum number.
- Dark sector coupling to the SM

$$O_{\rm SM} \cdot O_{\rm dark}$$

$O_{\rm SM}$: gauge inv. SM operator $O_{\rm dark}$: dark sector operator

- More relevant coupling ⇔ lowest dim operator
  - Lowest dimension $O_{SM} = HH^{\dagger}$. Higgs portal.
  - A unique gateway to dark sector.

Higgs portal

$$\lambda O_{\rm SM} \cdot O_{\rm dark} \to \left(\lambda \frac{m_W}{g}\right) h \cdot O_{\rm dark}$$

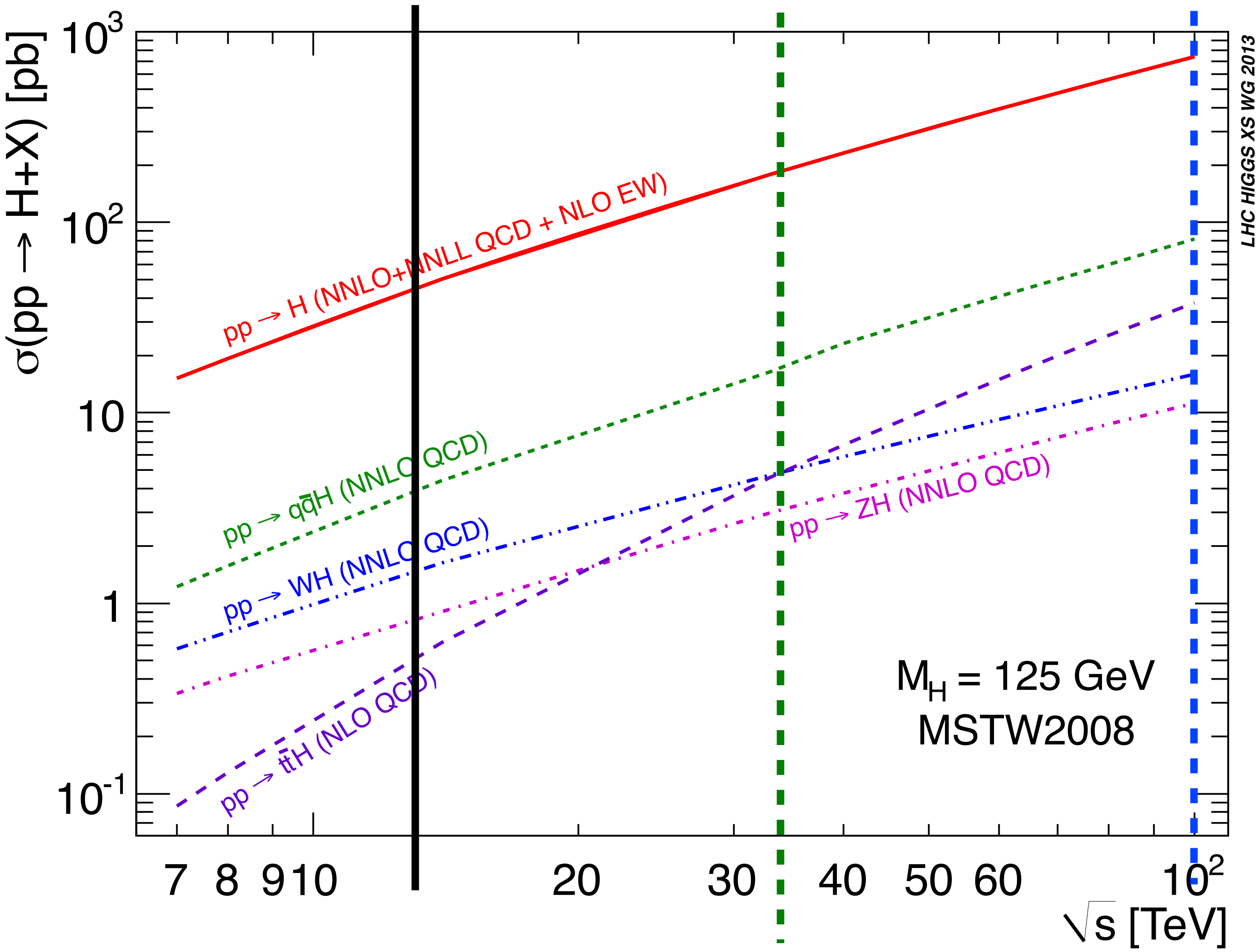
- Producing dark sector particles through the Higgs portal.
- Higgs rare decays:
  - Higgs $\to$ invisible at LHC can constrain down to a few percent.
  - A lot of room for exotic decay:

$$O_{\rm dark} = \bar{\psi}_{\rm dark}\psi_{\rm dark}, \quad \lambda = \frac{1}{\Lambda}$$

$$\Lambda \sim 10 \ \text{TeV} \ \to \ \text{BR}(h \to \bar{\psi}_{\rm dark}\psi_{\rm dark}) \leq 10^{-2}$$

Hadron collider

- The "ultimate" Higgs factories



# of Higgses in 3 ab^{-1}

14 TeV > 150 million

33 TeV > 500 million

100 TeV > 2 billion

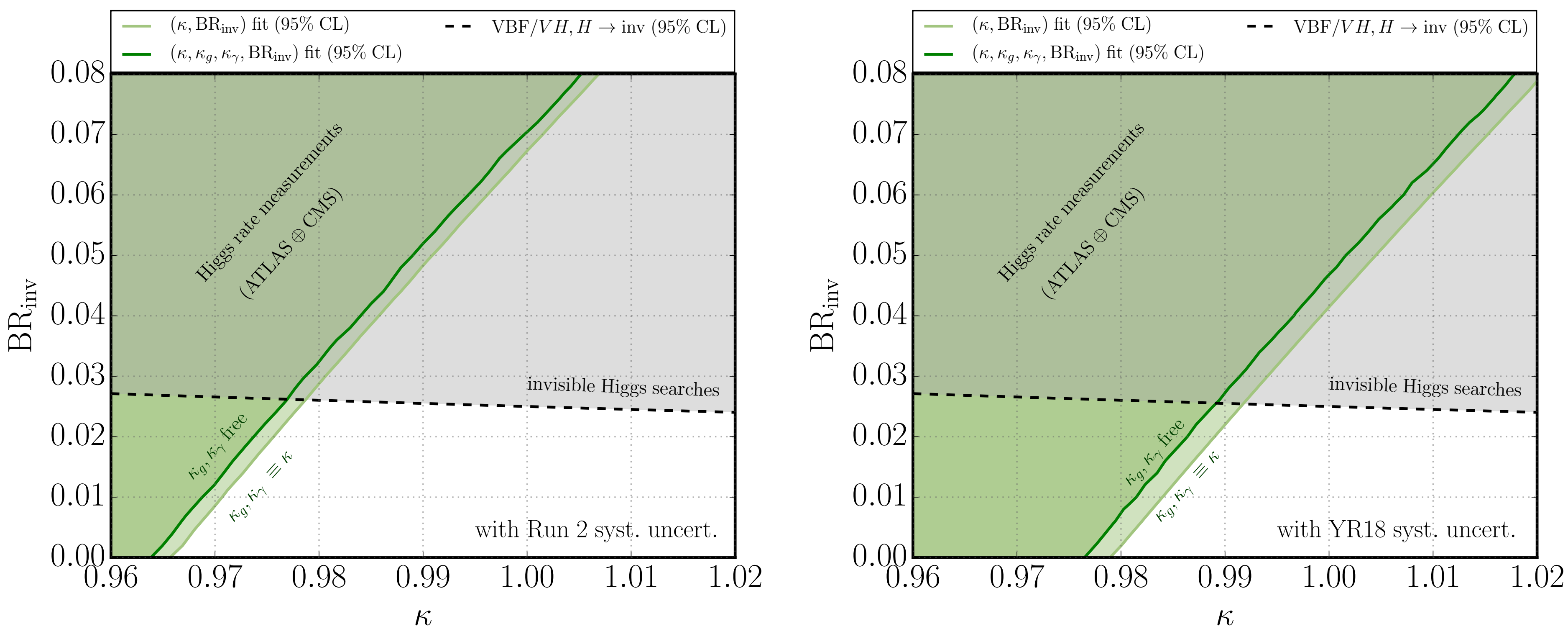
In comparison, O(million) Higgs at ee Higgs factories

Hadron collider good for rare but clean signal

In principle, can be sensitive to BR ≈ 10^{-7}

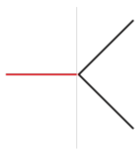
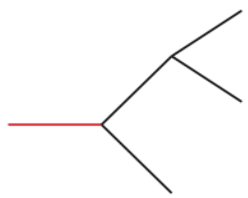
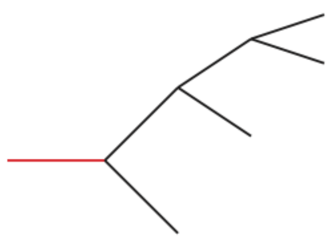
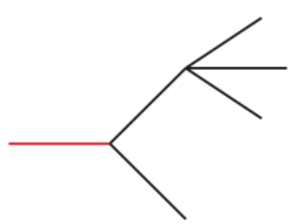
Higgs exotic decay

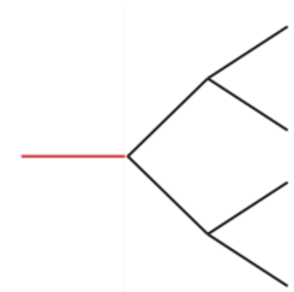
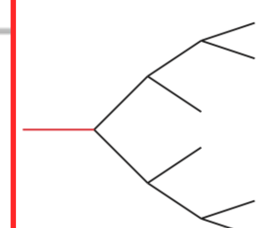
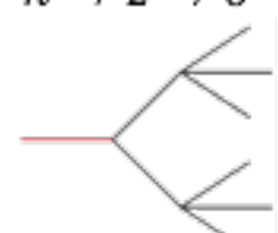
- Higgs portal. $\lambda H^{\dagger} H \mathcal{O}_{\text{exotic}}$



BR≈10^{-2} corresponds to a small coupling, which can come from integrating out new physics at around 10 - 100 TeV. Plausible!

Some possible channels

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

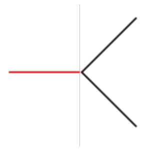
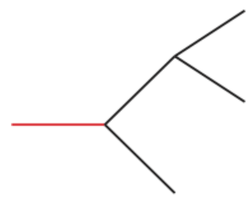
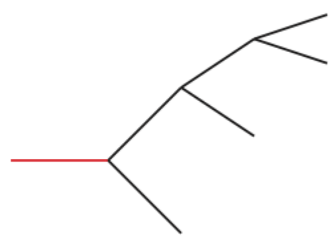
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to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

Simple, Great sensitivity from the LHC

With MET, less lepton

More hadronic

Some possible channels

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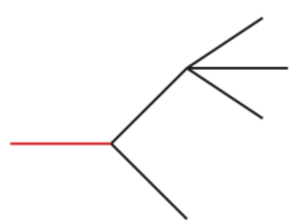
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
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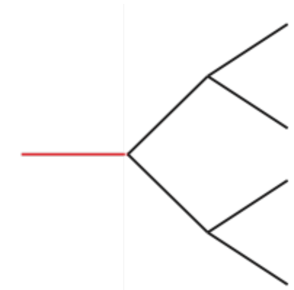
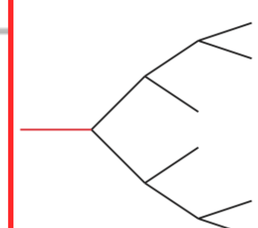
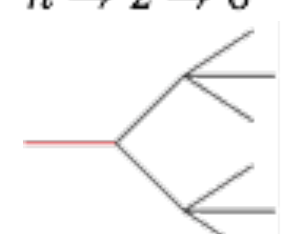
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to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

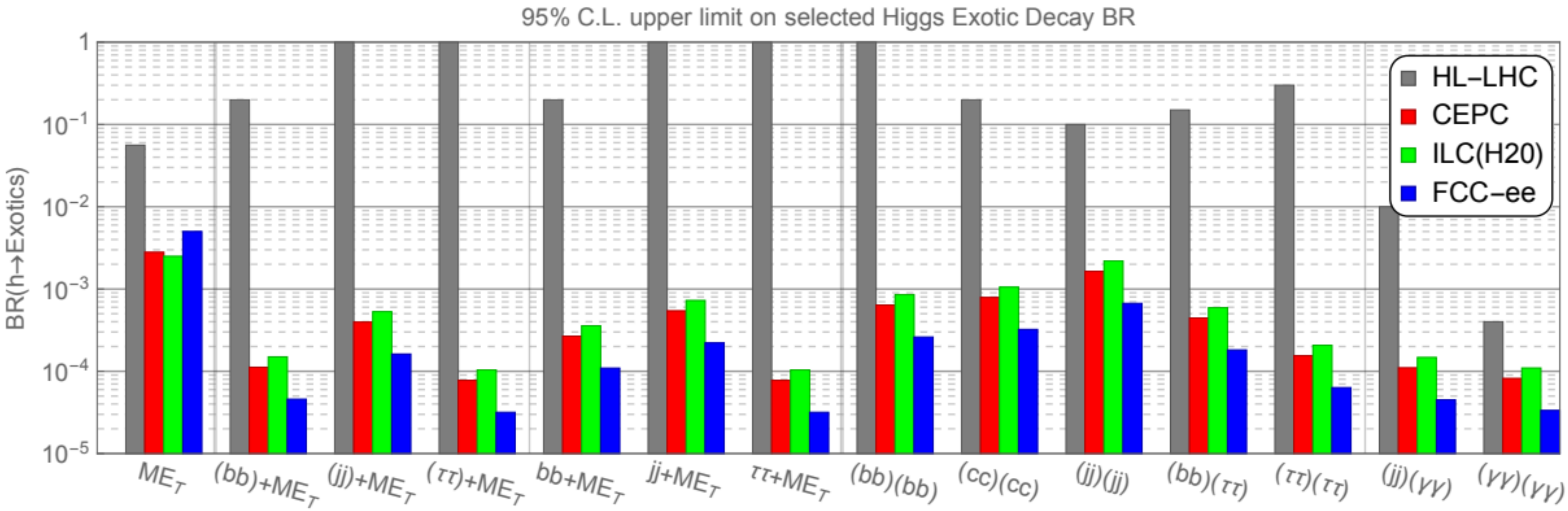
Simple, Great sensitivity from the LHC

With MET, less lepton

More hadronic

More challenging, but worth pursuing!

Higgs exotic decay at lepton colliders



Complementary to hadron collider searches

Long lived particle and Higgs portal.

$$\mu X H^\dagger H \quad H = \frac{1}{\sqrt{2}}(v+h)$$

$$\to \mu v X h \to \frac{\mu v}{m_h^2}\frac{m_b}{v} X b\bar{b}$$ Last step: integrating out Higgs

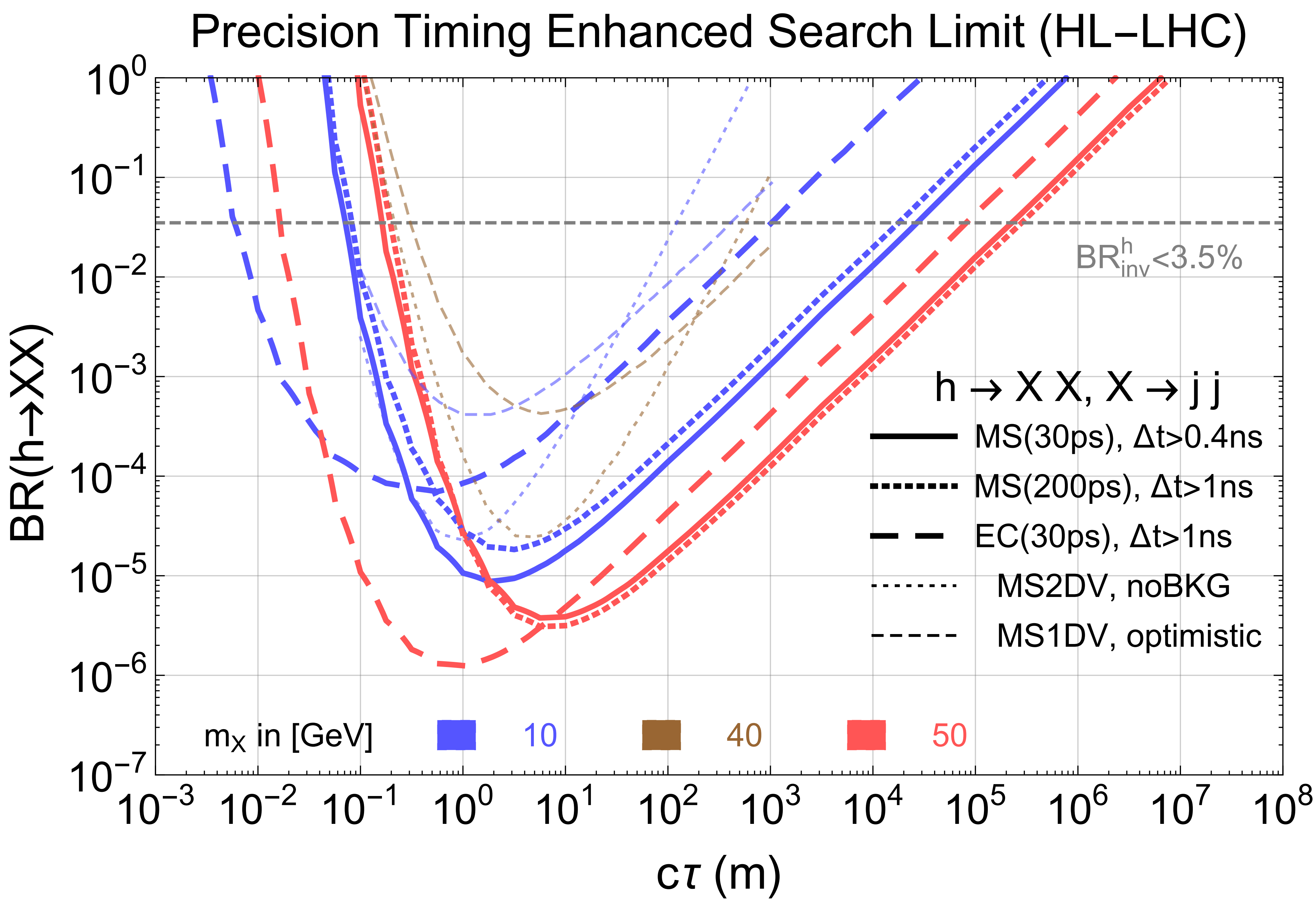
At the LHC: $pp \to h \to X \ldots, \quad X \to b\bar{b}$

If $\frac{\mu v}{m_h^2}\frac{m_b}{v} \sim 10^{-7} \;\to\; c\tau \sim m$

LLPs with small mixings to Higgs: twin sector, ALPs, relaxion, extra-singlet...
With various degrees of motivation. Similar signal.

Sensitivity to Higgs portal

Jia Liu, Zhen Liu, LTW



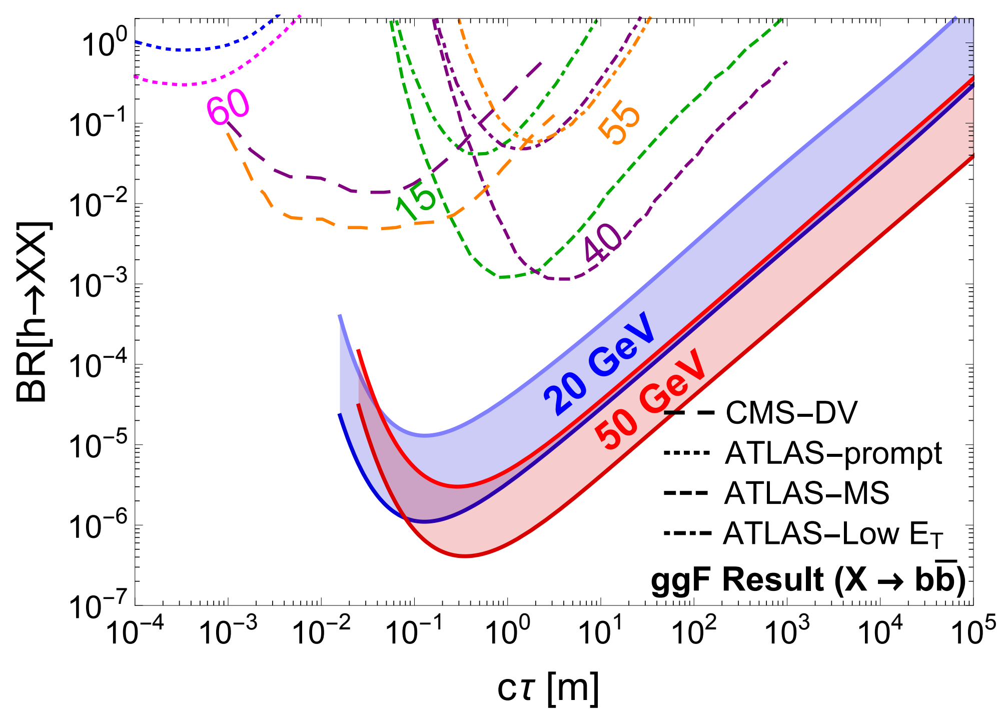
For example, for $\mathrm{BR}(h \to XX) \sim 10^{-3}$

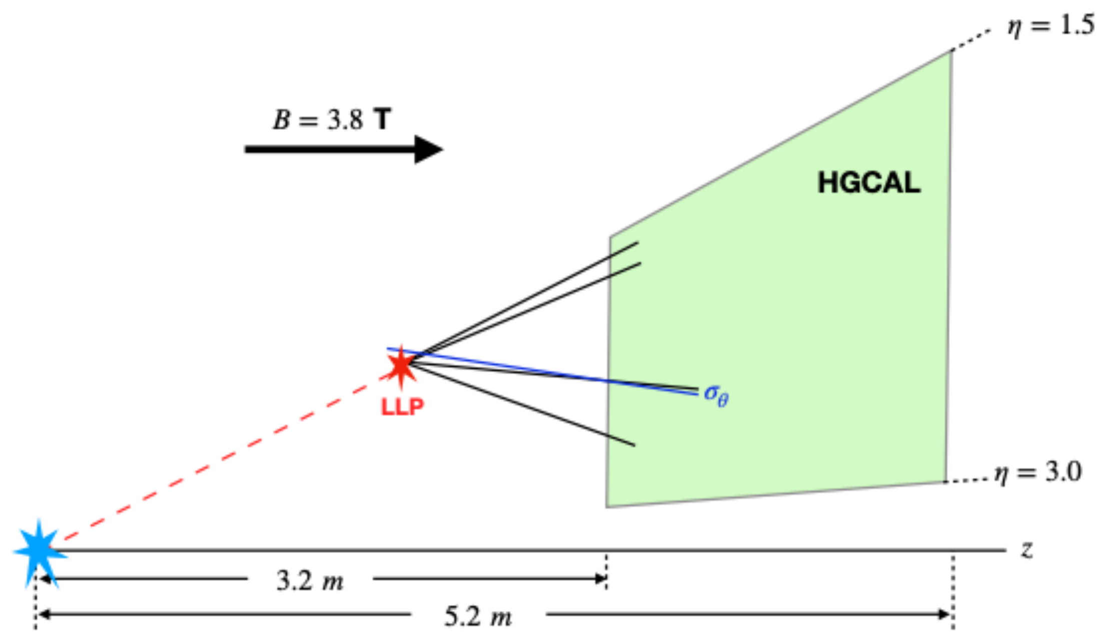
EC(MS) reach can be $c\tau \sim 10^{3}(10^{4})$ meters

LLP

- h →XX, X long-lived

J. Liu, Z. Liu, XP Wang, LTW 2005.10836





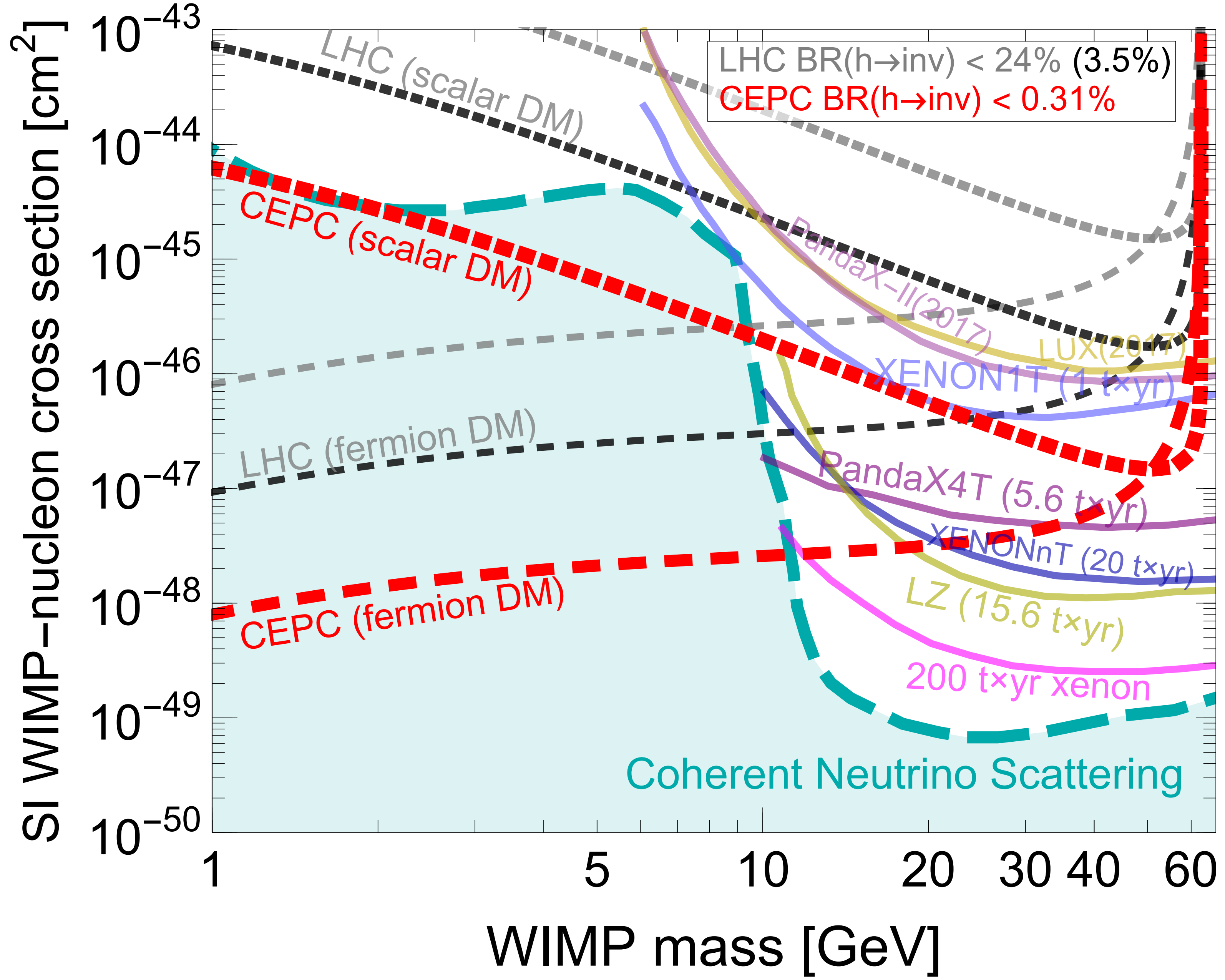
Using the pointing capability of CMS HGCAL

Best sensitivity ≈ 10^{-7}, can reach cτ ≈ 10^3 m with BR ≈ 10^{-3}

In addition, precise timing could also help.

Higgs portal dark matter

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



Higgs and EFT

Higgs and EFT

$$\mathscr{L} = \mathscr{L}^{\text{SM}}_{\text{renormalizable}} + \sum_{i,n} \frac{c_{i,n}}{\Lambda^n} \mathscr{O}_i^{(4+n)}$$

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  - Accidental symmetries of the renormalizable part (such as lepton, baryon number, custodial,...) can be broken.

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- Effect of heavy new physics (not being able to produce directly) parameterized by $O^{(4+n)}$s.
- Many $O^{(4+n)}$s contains the Higgs. They are excellent starting points of parameterizing possible new physics effects and deviation in the Higgs couplings.

Precision from high energies at LHC

Measurement limited by: $$\frac{\delta\sigma}{\sigma} < \delta_{\text{systematic}} \oplus \frac{1}{\sqrt{N}}$$

- Coupling measurement at low energy have significant systematic error.

$$\frac{\delta\sigma}{\sigma} \sim \frac{v^2}{\Lambda^2} \sim \delta_{\text{systematic}}$$

- Effect of new physics grow with energy.
  - Beneficial to measure at higher energy $E > m_{Z,W,h}$ if systematics does not grow as fast

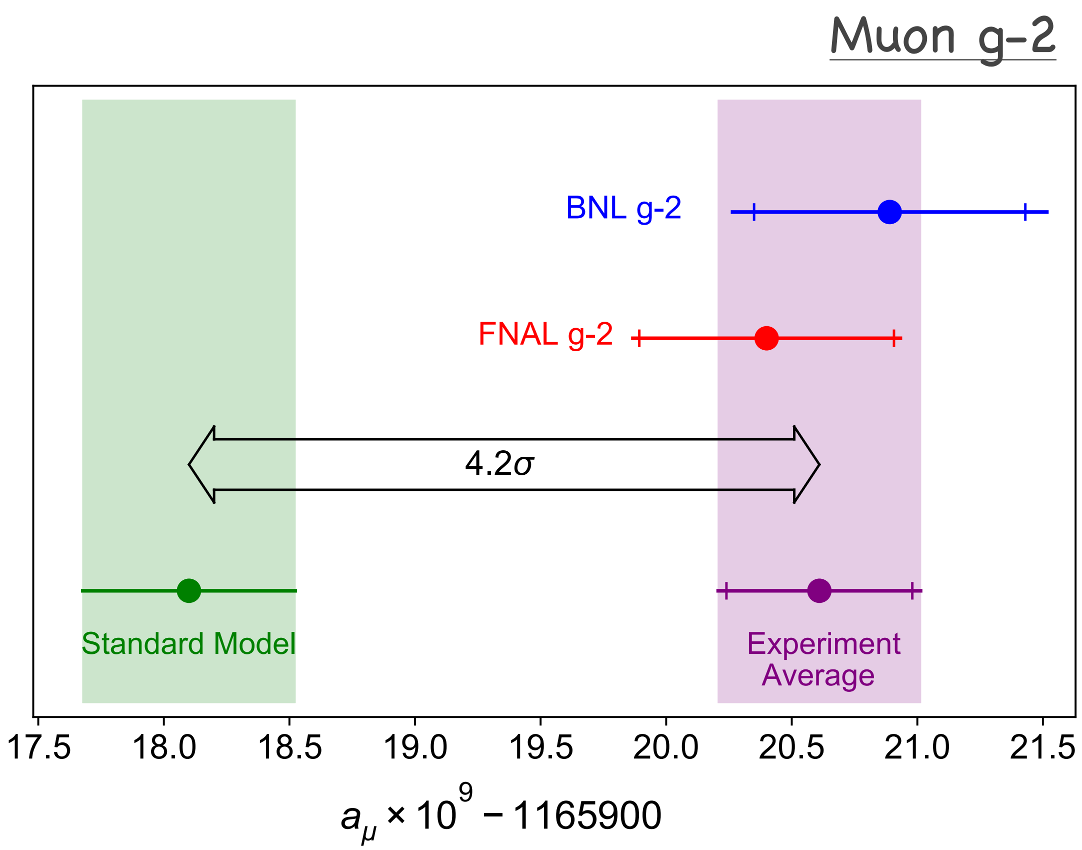
$$\frac{\delta\sigma}{\sigma} \sim \frac{E^2}{\Lambda^2} \sim \delta_{\text{systematic}}$$

⇨ probing higher NP scales Λ

EFT ≠ everything

- EFT is a great tool, applying broadly to cases where heavy new physics can be integrated out.
- However, it is important to keep in mind the there are cases where EFT does not cover.
- Obviously, not applicable in direct production of new physics particles.
  - For example: Higgs exotic decay.

Or this



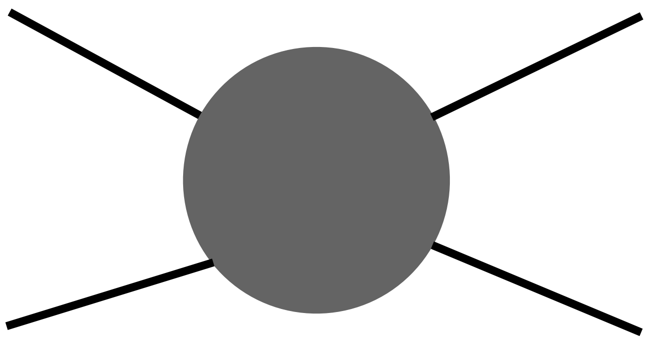
$$\mathscr{L} \supset \frac{e}{16\pi^2}\frac{m_\mu}{\Lambda^2} H\bar{L}\sigma_{\mu\nu}\mu_R F^{\mu\nu} \;\rightarrow\; \delta a_\mu \simeq \frac{e}{16\pi^2}\frac{m_\mu^2}{\Lambda^2}$$

Disagreement with SM $\Rightarrow \Lambda \sim 300$ GeV, "light"!

LHC should be able to directly produce this new physics and discover it!

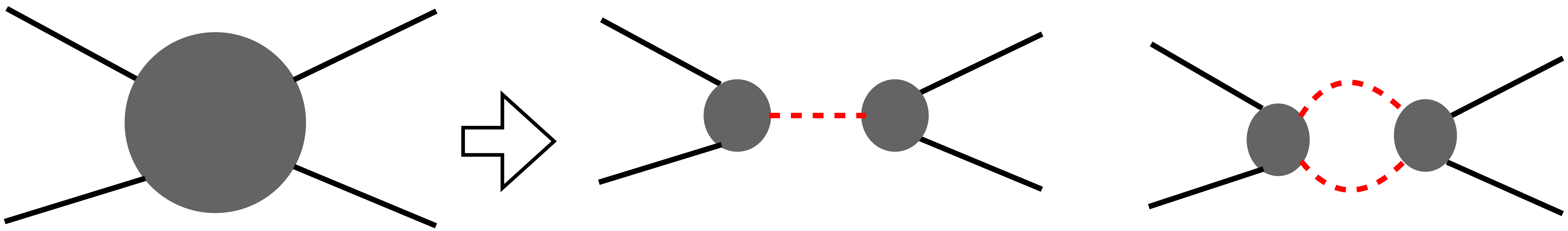
EFT ≠ everything

Focus on scattering with SM external states



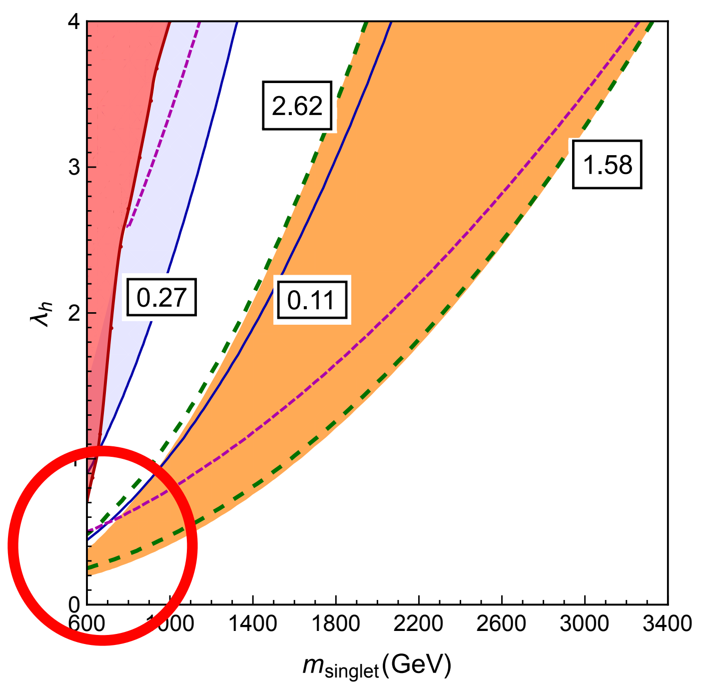
- Modeled with an EFT operator: amplitude $\propto E^n$, n=1, 2...
- However, there can be important exceptions.

EFT ≠ everything



– Light particle

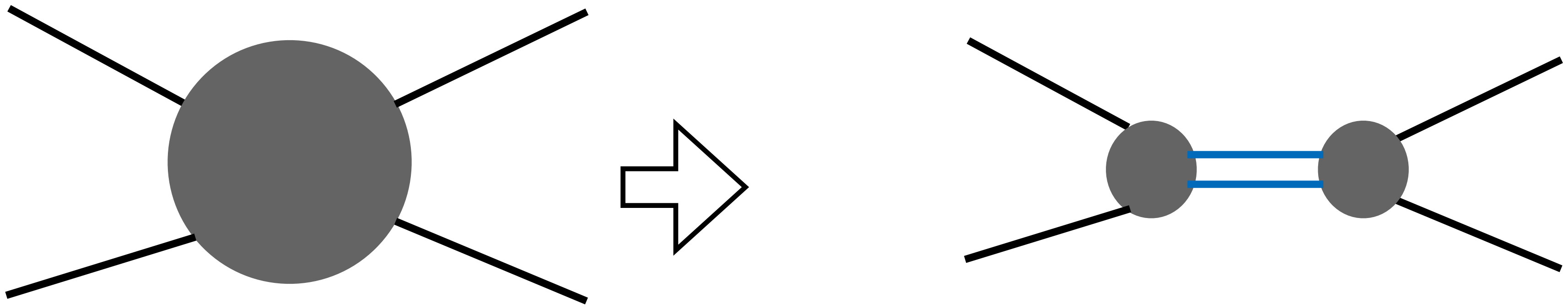
Amplitude will deviate (soften) from the prediction of the contact EFT operator.



For example: light singlet scalar for first order EW phase transition.

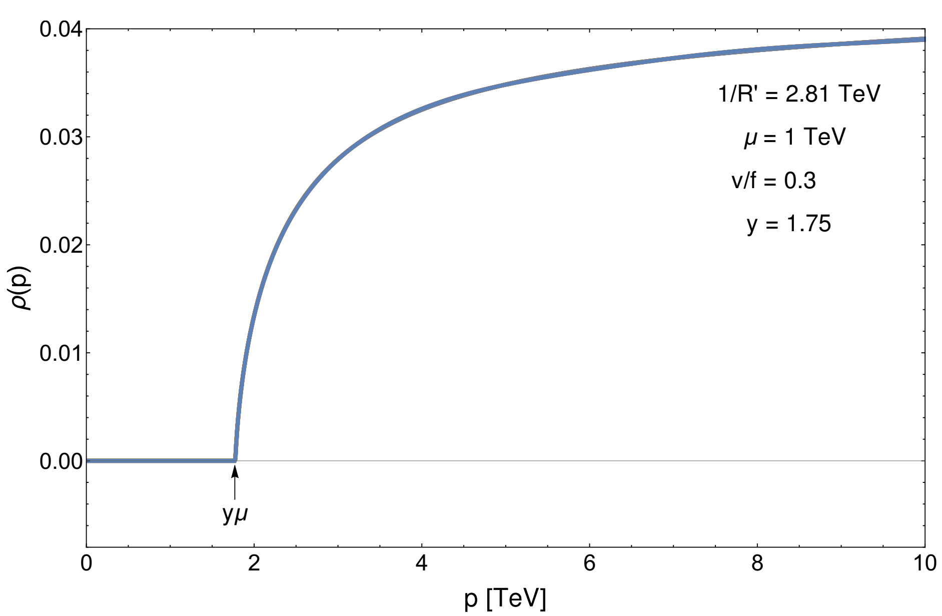
Huang, Joglekar, Li, Wagner, 1512.00068

EFT ≠ everything



- Strongly coupled, broad resonance, continuum, ...

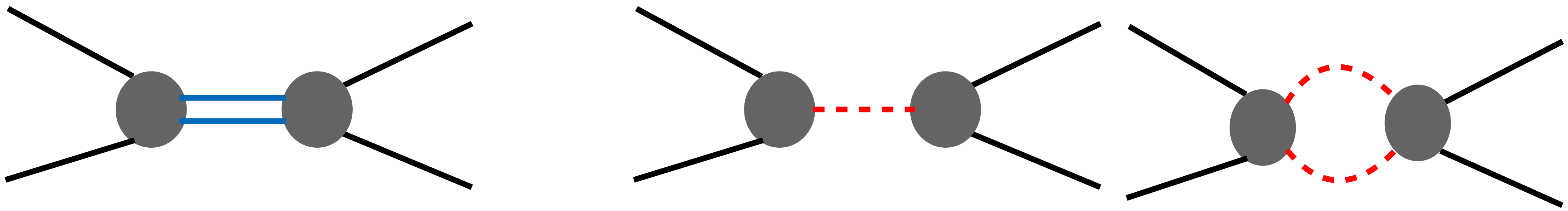
In this case, the amplitude can be a general form factor: $f(q^2)$



e.g.: top partner as a continuum

Csaki, G. Lee, S. Lee, Lombardo, Telem, 1811.06019

Bottom line:



- These new physics may not be easy to discover directly. Precision measurement could be the main (only) window.

- In addition to energy dependence, we need to measure as a broad range of kinematical distribution as possible.

Conclusions

- Higgs boson will be the center of focus for the search for new physics in the coming decades.
  - HL-LHC, future Higgs factories.
- Several important angles.
  - Naturalness: coupling measurements, rare decay.
  - EW phase transition: coupling measurements
  - Window to dark sector: rare decay
  - ...
- Much to look forward to!