Higgs:
what we have learned
And next steps

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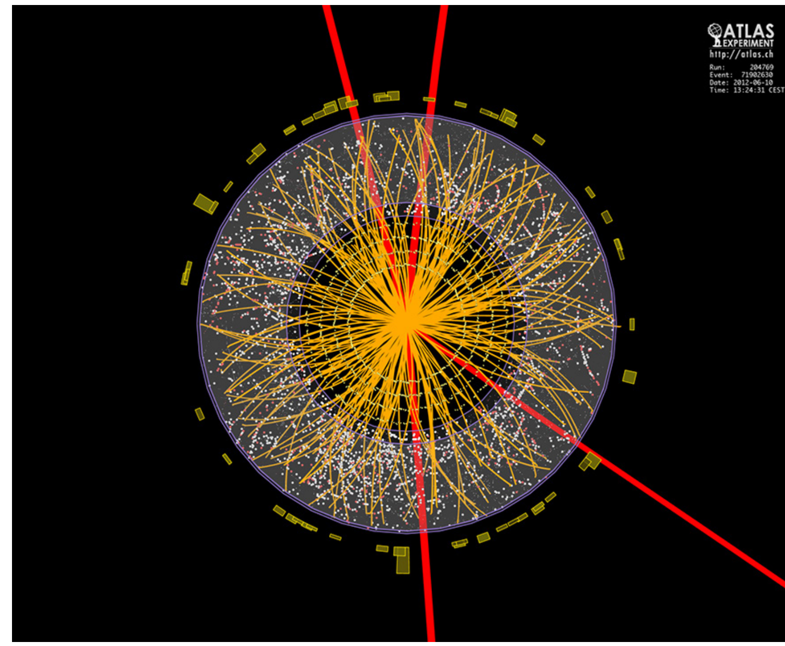
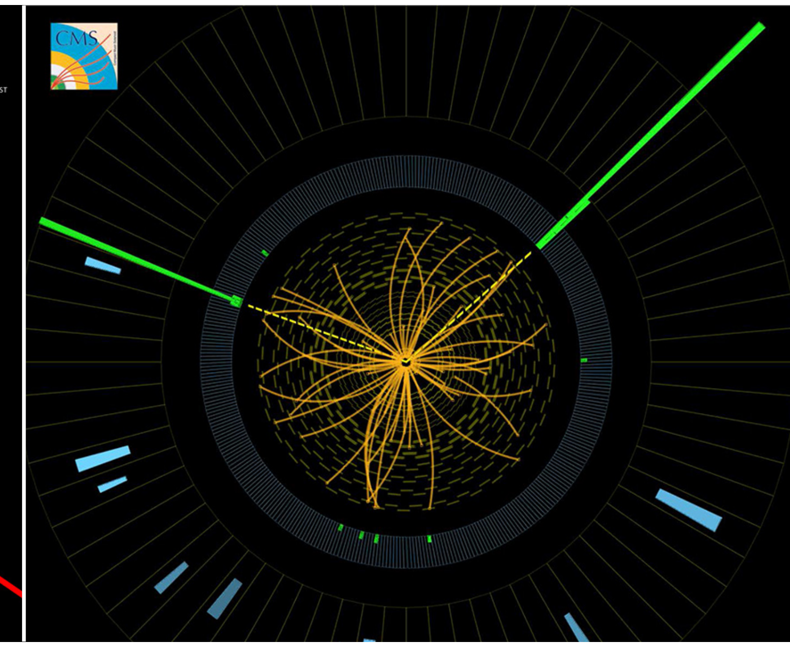
After the discovery

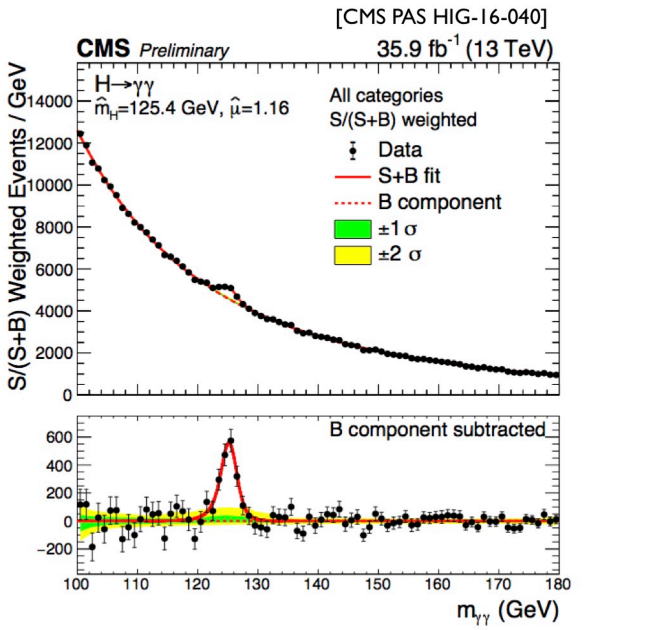




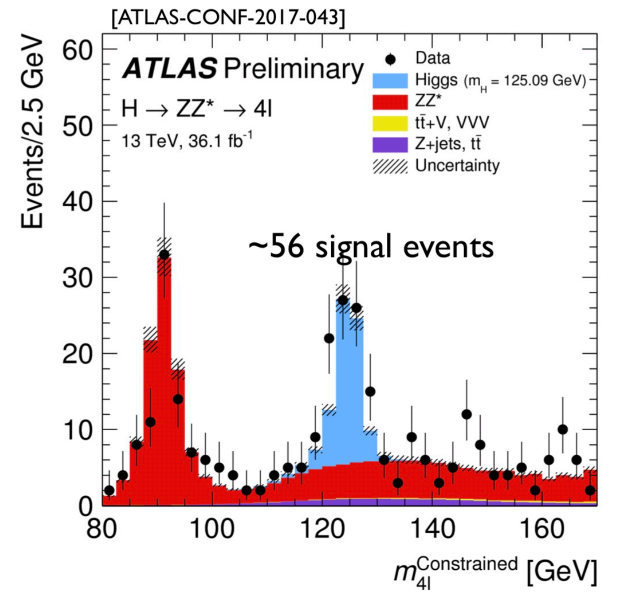
We have made significant progresses.

There is still a long way to go to understand the Higgs.
LHC can't finish the job, but it can do a lot.

Behaving like a Higgs boson

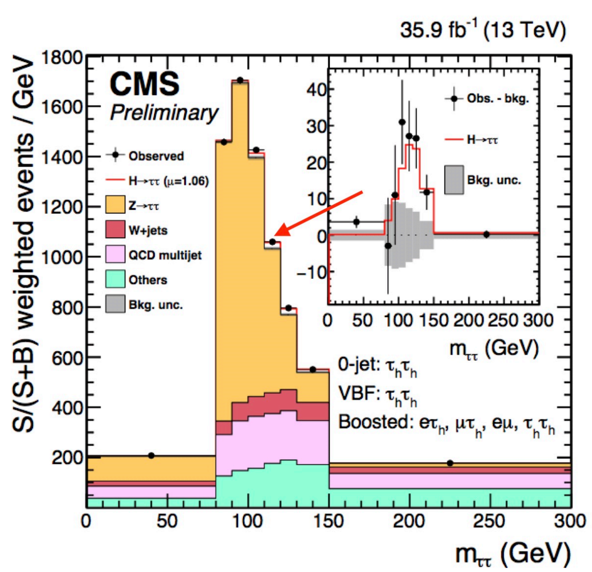


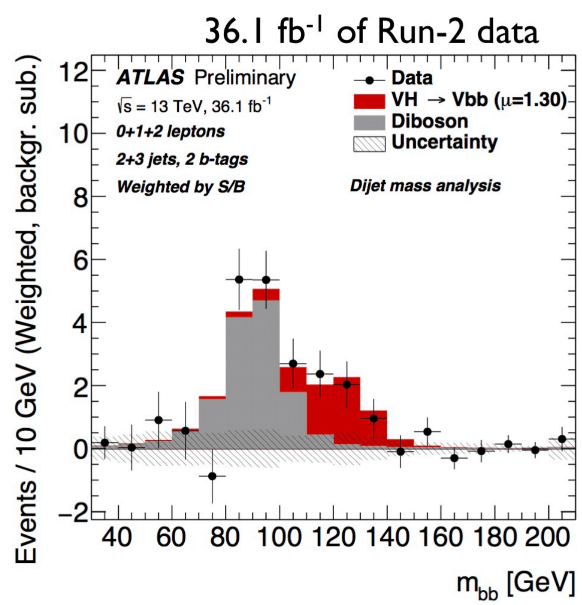
$\mu = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10}(\mathrm{stat})^{+0.09}_{-0.08}(\mathrm{exp})^{+0.06}_{-0.05}(\mathrm{theo})$



$\mu = 1.28^{+0.18}_{-0.17}(\mathrm{stat.})^{+0.08}_{-0.06}(\mathrm{exp.})^{+0.08}_{-0.06}(\mathrm{th.})$

Higgs gauge boson coupling well established.

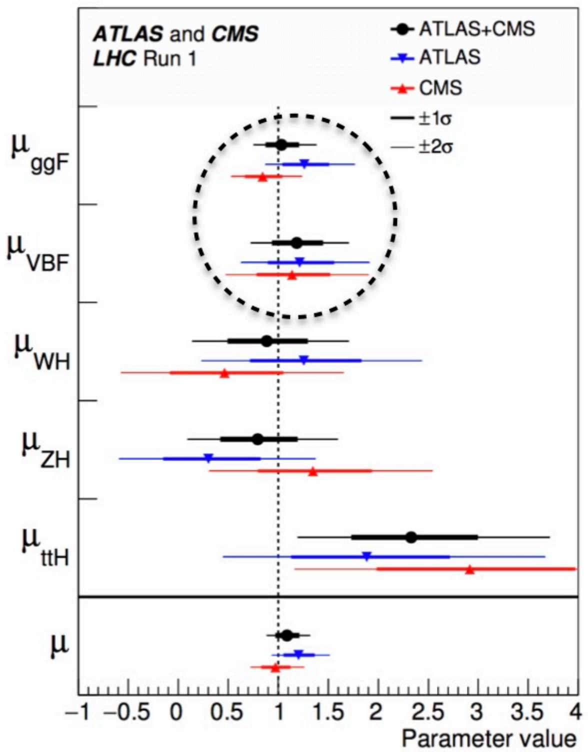


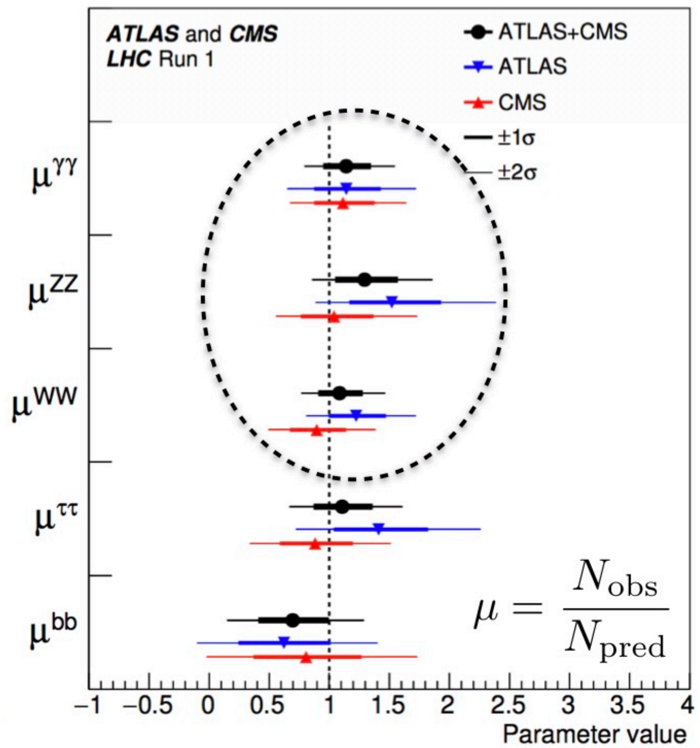


Started to see Higgs fermion coupling as well.

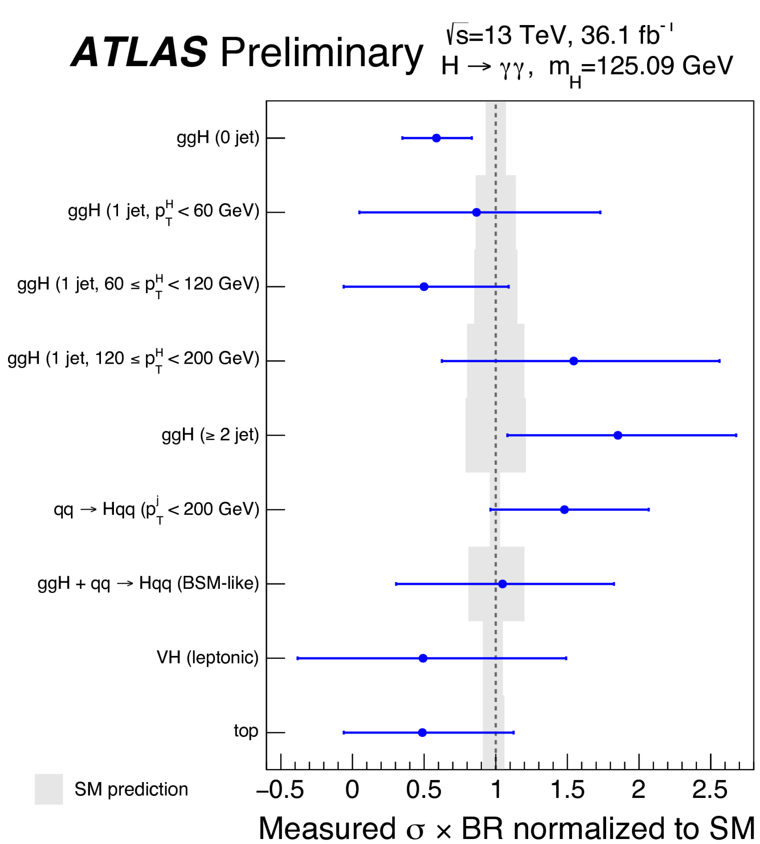
Roughly agree with Standard Model

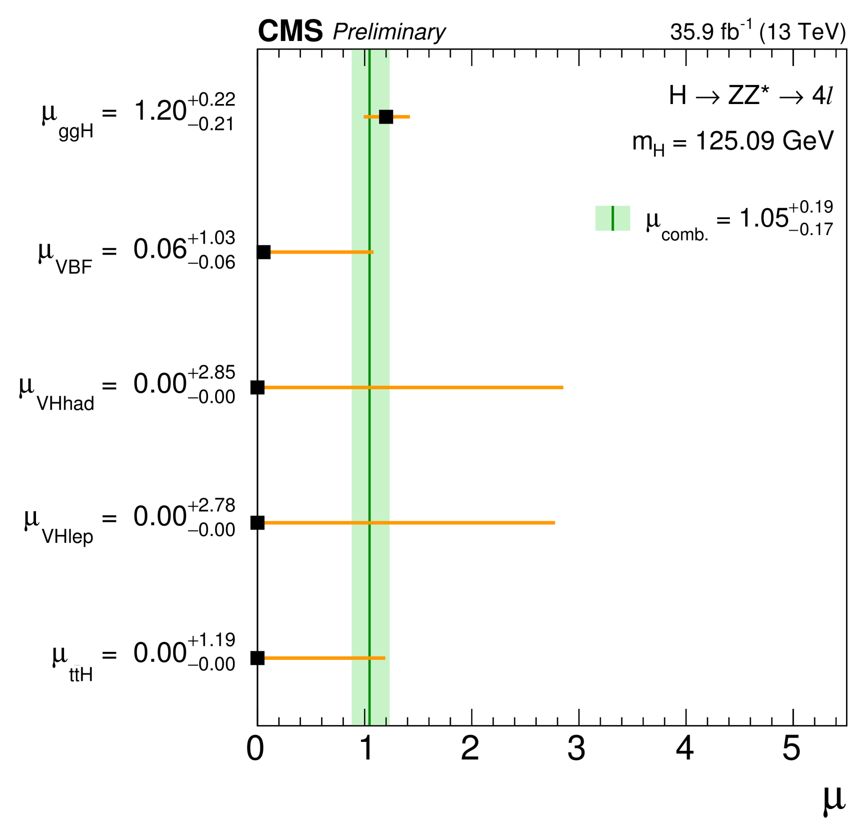
[JHEP 08 (2016) 045]





Agree to about 10-20%





Not entirely surprising

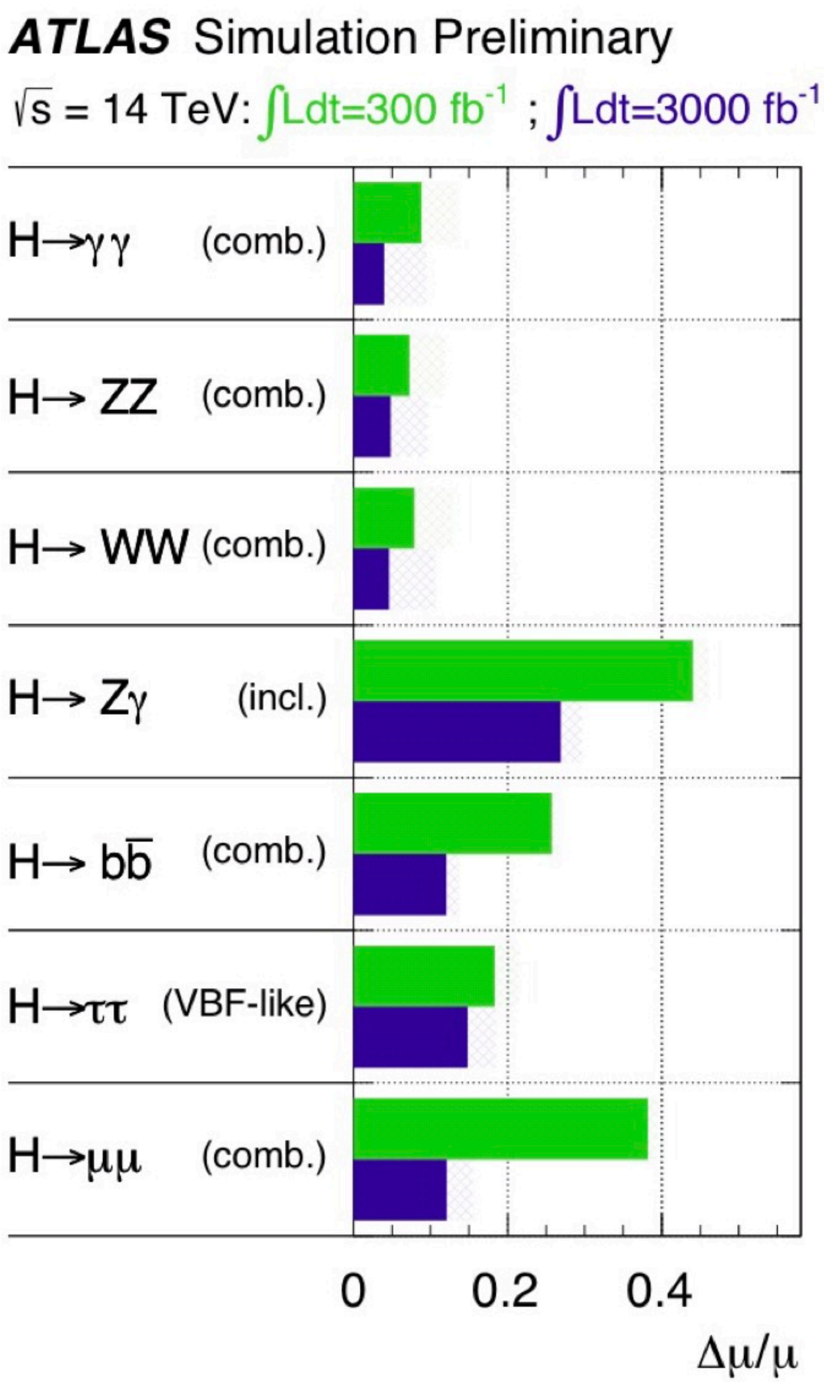
- In general, deviation induced by new physics is of the form

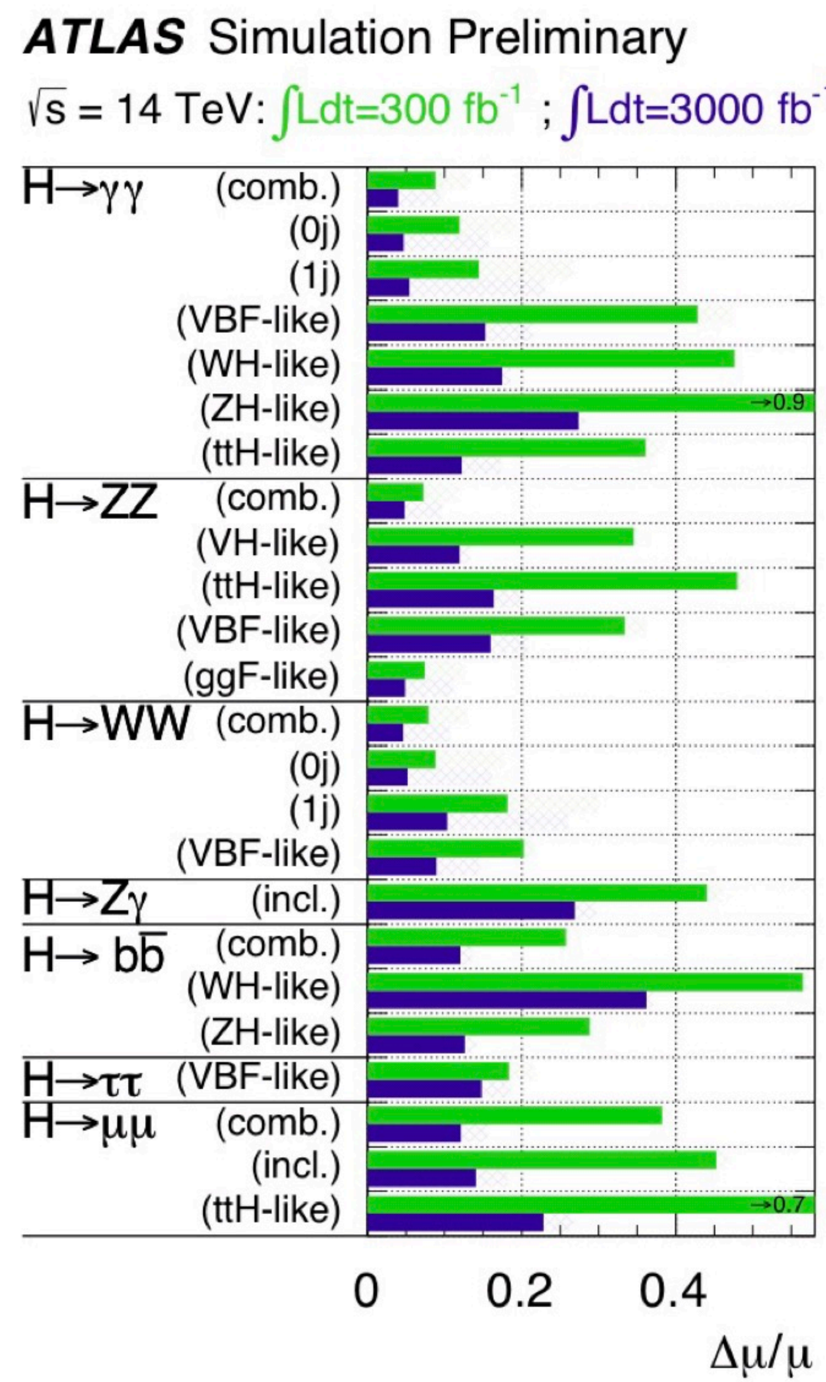
$$\delta \simeq c\frac{v^2}{M_{\rm NP}^2}$$

M_{NP} : mass of new physics
c: $O(1)$ coefficient

- Current LHC precision: 10%
  $\Rightarrow$ sensitive to M_{NP} < 500-700 GeV
- At the same time, direct searches constrain new physics below TeV already.
- Unlikely to see O(1) deviation.

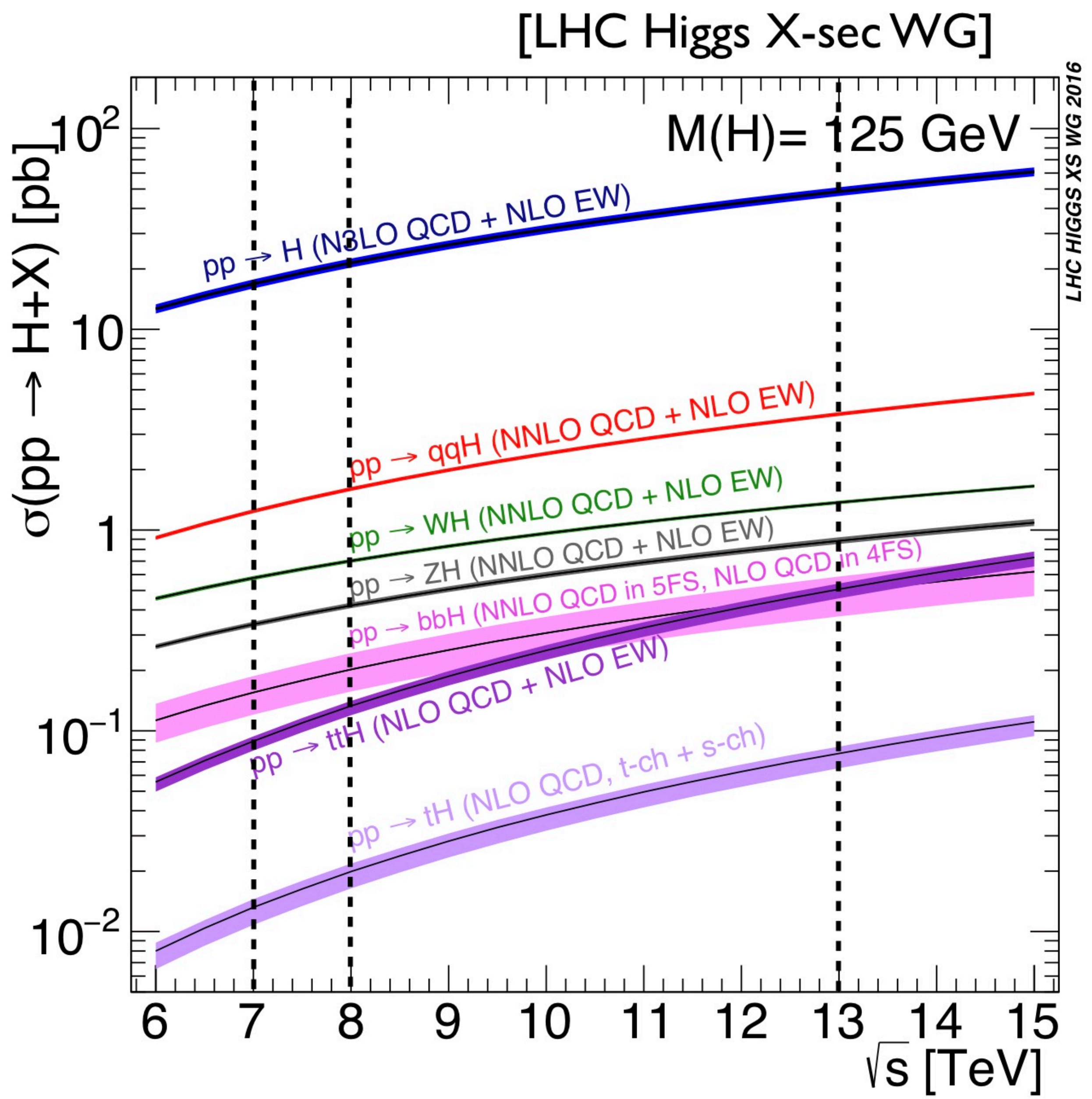
LHC entering precision measurement stage





4-5% on Higgs coupling, reach TeV new physics

LHC as a Higgs factory



> 3 million Higgses at run 2 already

100 times more by the end of HL-LHC

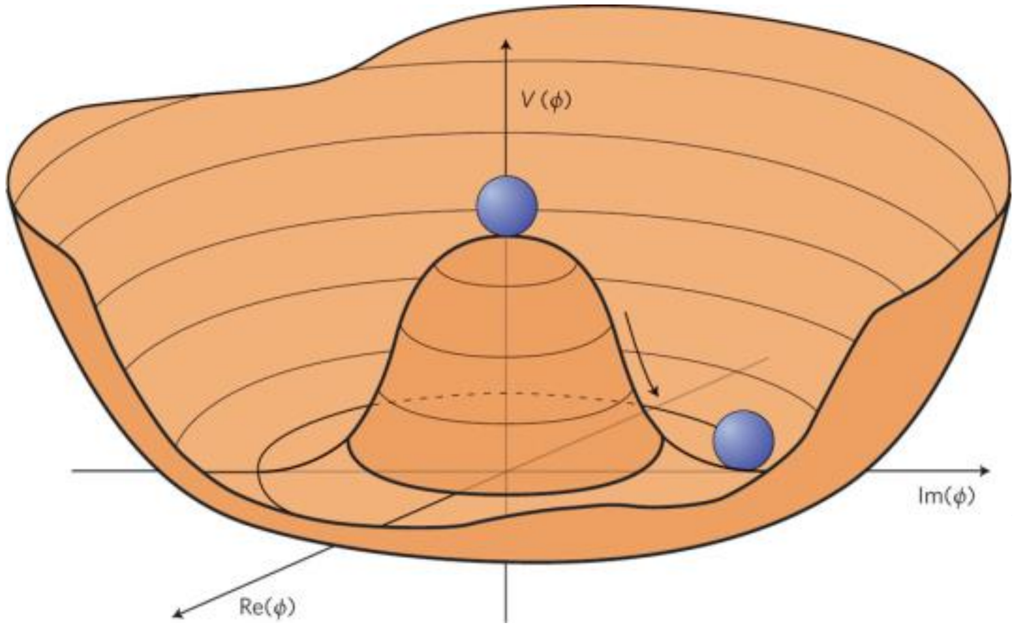
Great for clean yet very rare decay channels!

e.g. multiple leptons, displaced, etc.

Potentially 10^{-7} sensitivity on BR.

Questions to be addressed by Higgs measurement

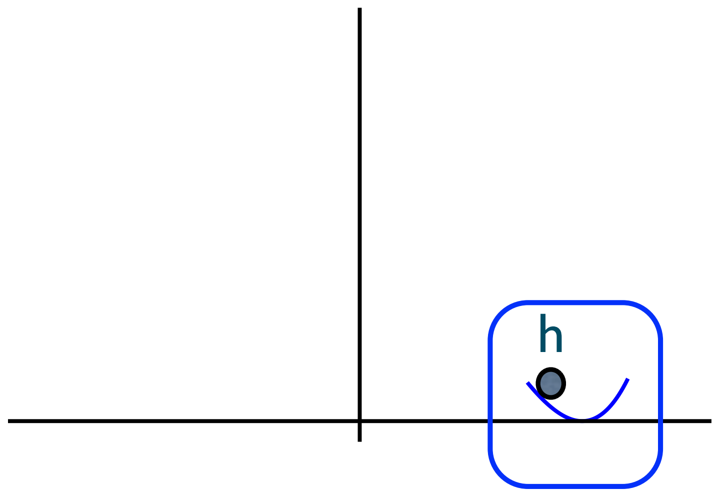
Mysteries of the electroweak scale.



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

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

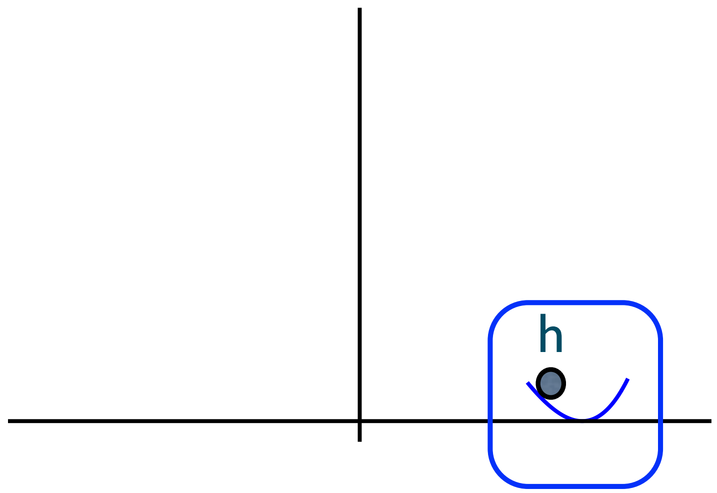
Mysteries of the electroweak scale.



What we know now

- How to predict/calculate Higgs mass?
- What does the rest of the Higgs potential look like? Nature of electroweak phase transition.

Mysteries of the electroweak scale.



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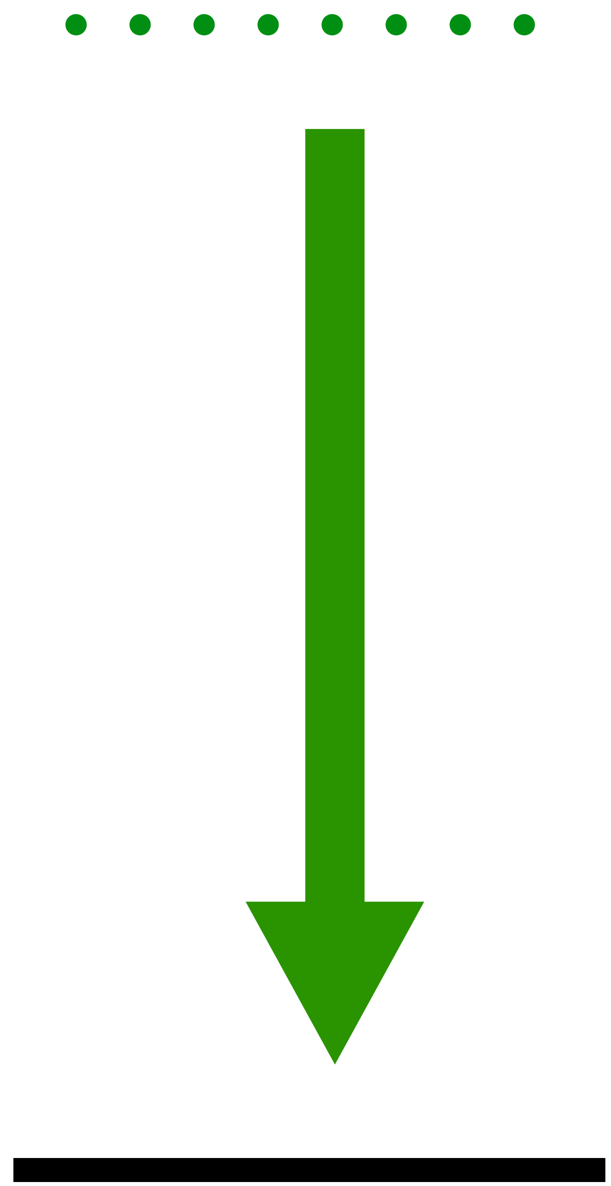
How to predict Higgs mass?



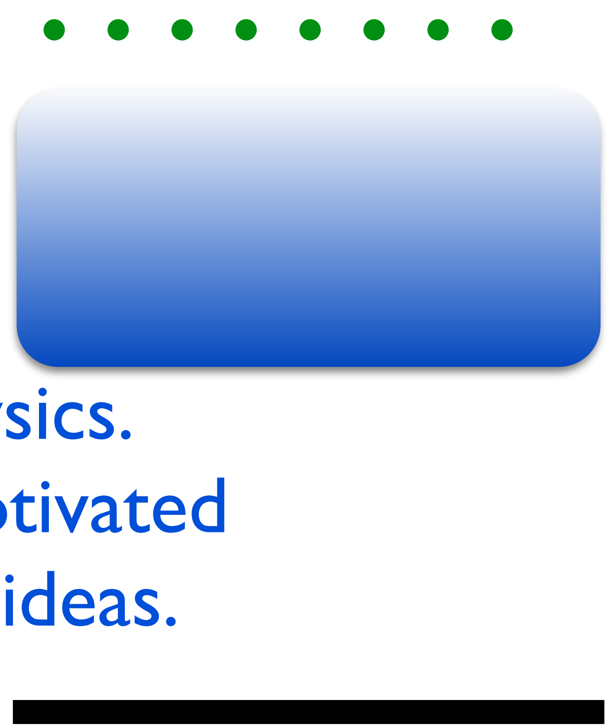
The energy scale of new physics
responsible for EWSB

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 …

Naturalness of electroweak symmetry breaking

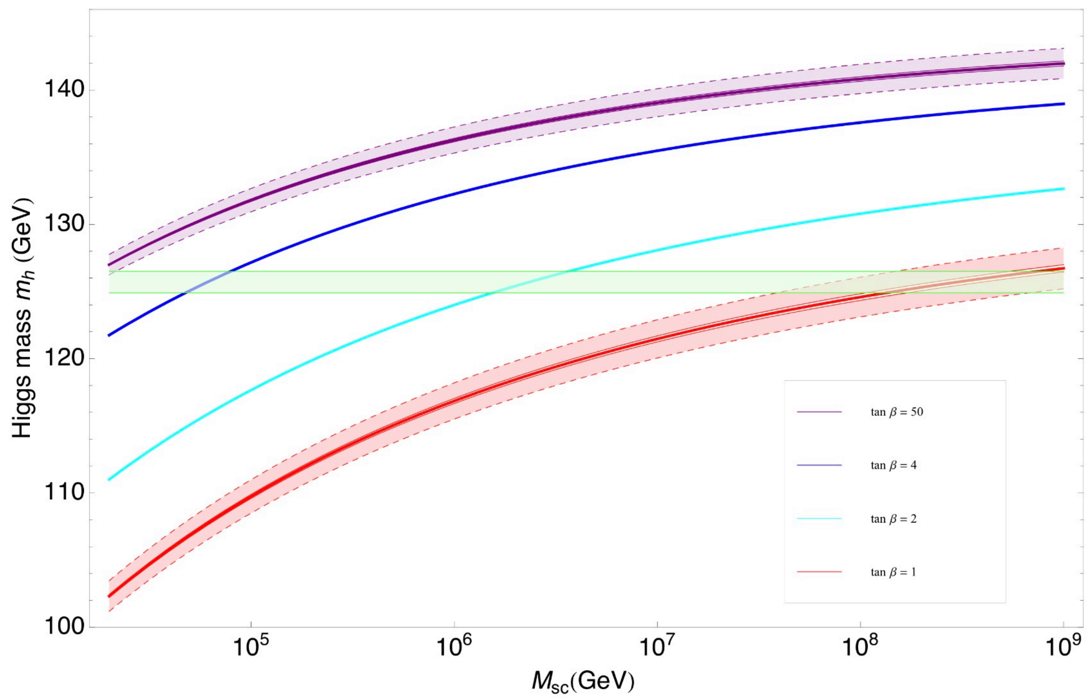


The energy scale of new physics
responsible for EWSB

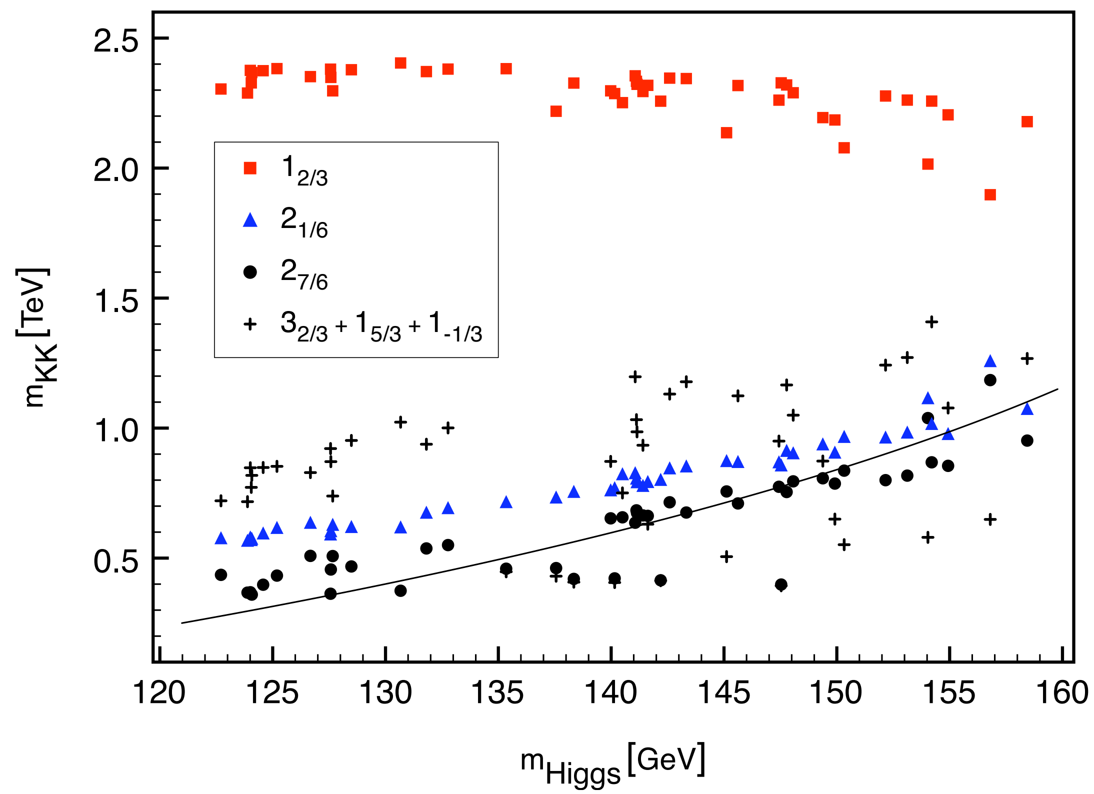
TeV new physics.
Naturalness motivated
Many models, ideas.

Electroweak scale, 100 GeV.
m_h , m_W …

A confusing picture



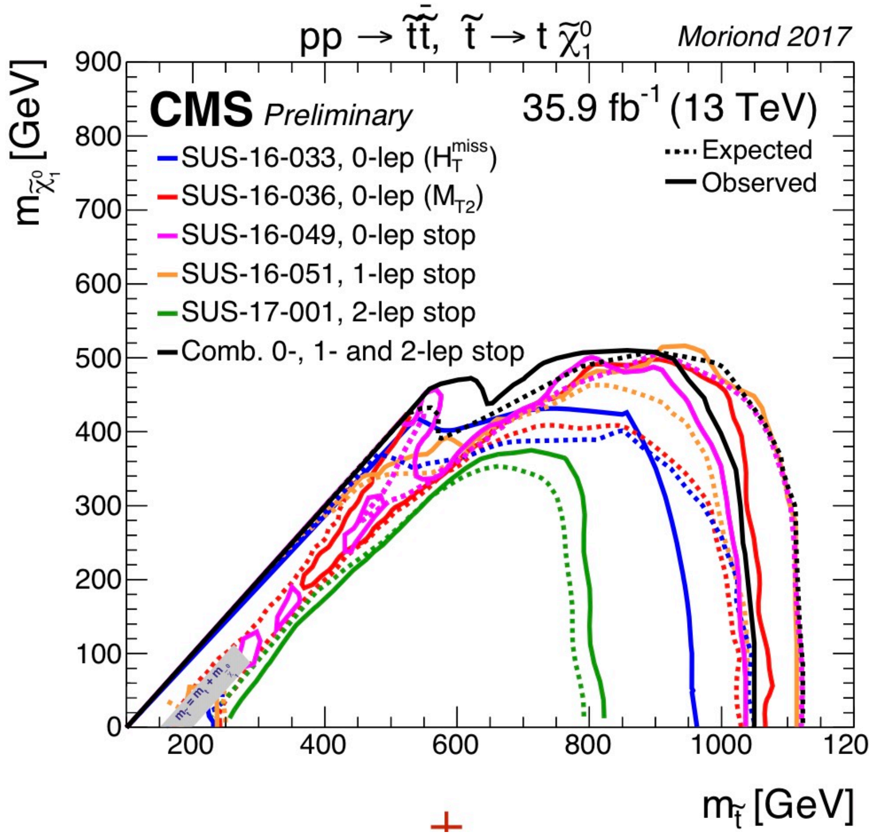
Stop too heavy to be natural

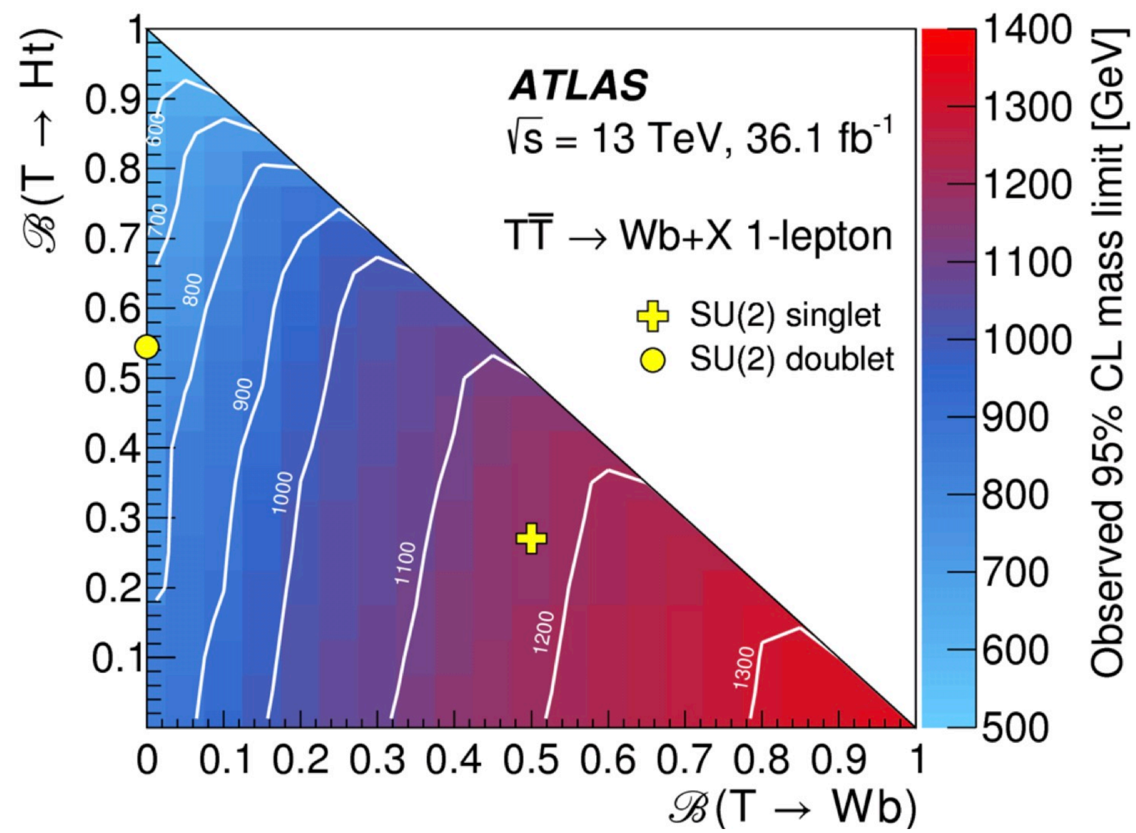


Composite top partner too light, excluded

Such conclusions too simplistic, "work around" available.
A bit uncomfortable, yes. Not time to give up just yet.

Direct searches

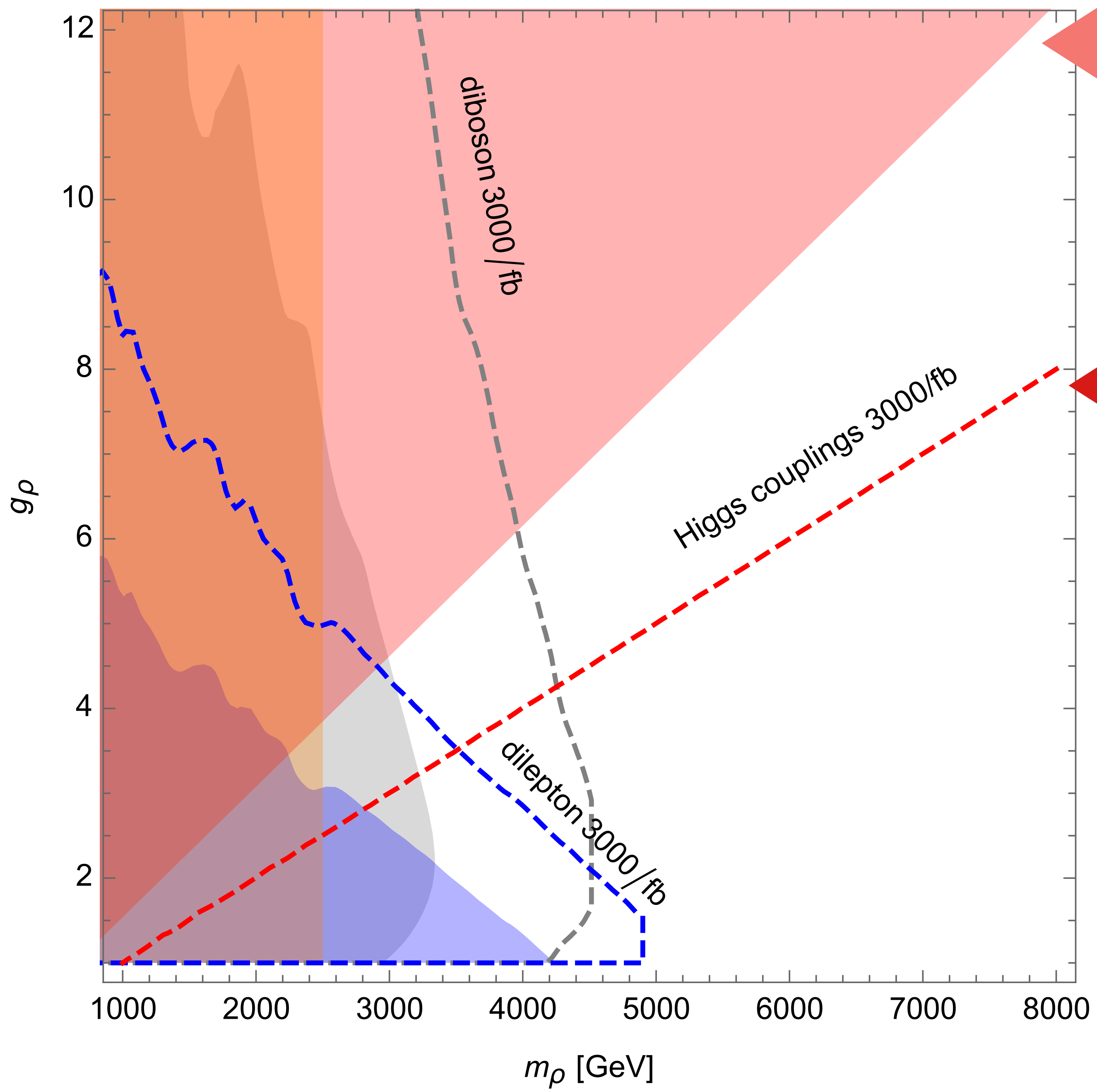




LHC will keep searching for such new particles

Future colliders, FCC-hh/SPPC, can continue the quest.

Higgs coupling vs direct search



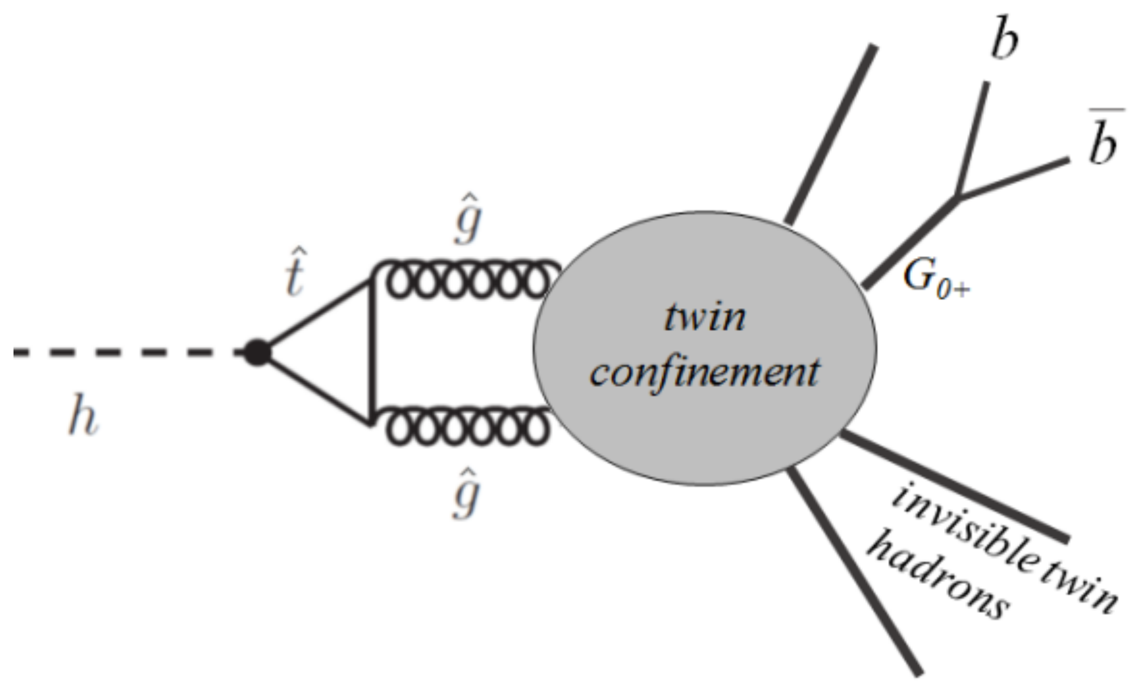
Excluded by current Higgs Coupling measurements

Reach of HL-LHC

Stealthy top partner. "twin"

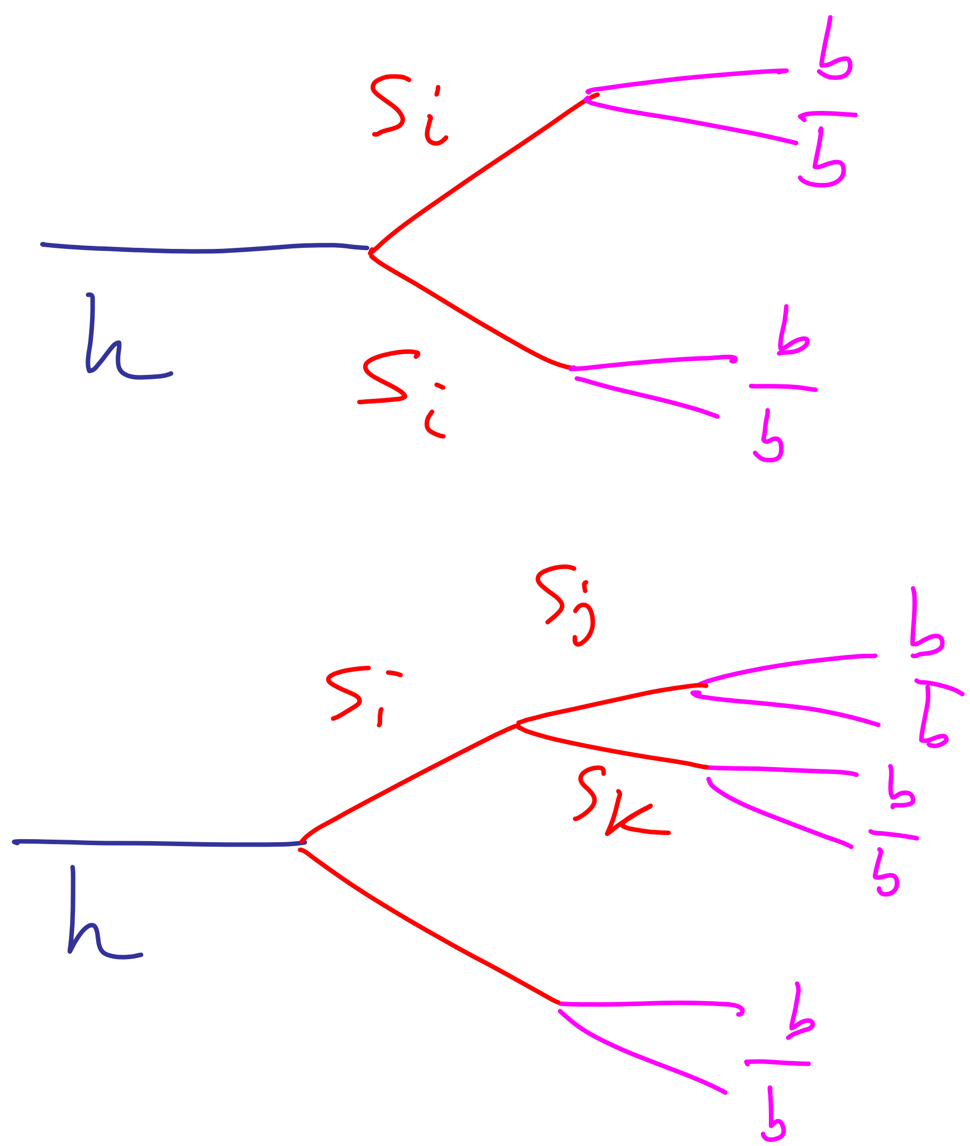
Chacko, Goh, Harnik

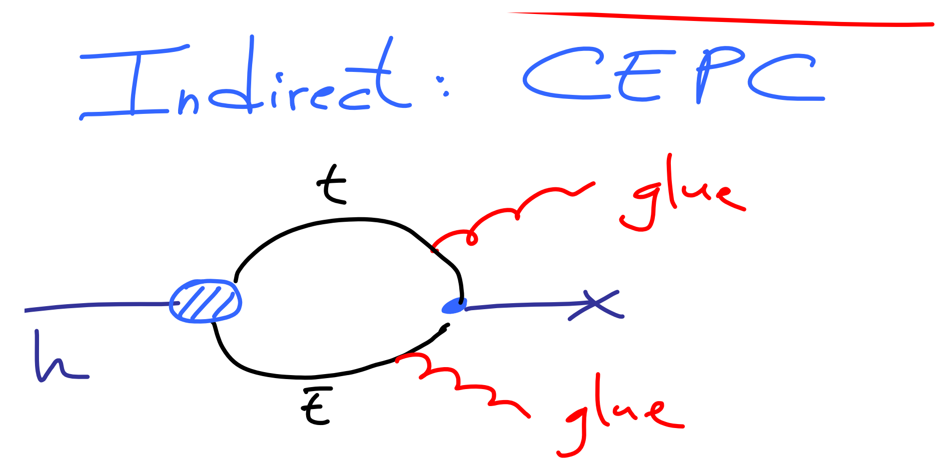
Craig, Katz, Strassler, Sundrum



- Top partner not colored. Higgs decay through hidden world and back.
- Lead to Higgs rare decays.

More exotic ideas





$K_g \sim \left(\frac{m_t^2}{\Lambda^2}\right) \sim 10\%$ Easy @CEPC

$K_\gamma \sim$ few % Possible@ CEPC

Low scale landscape

Higgs rare decay.

"fat" Higgs

Higgs coupling

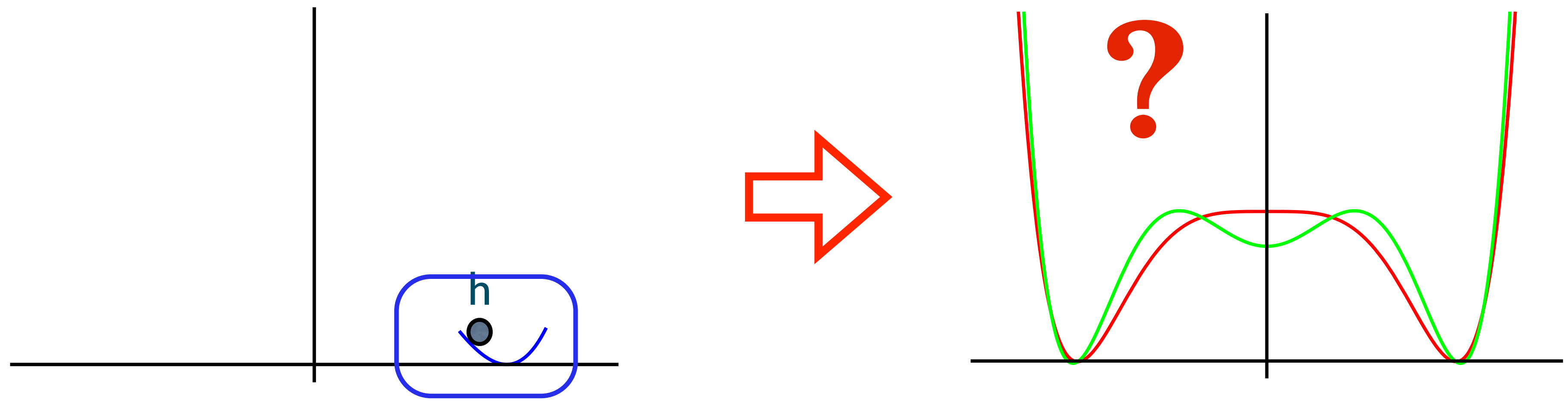
Can't hide from the Higgs.

Talk by Arkani-Hamed CEPC workshop Sept. 2016

Bottom line on naturalness

- It is the most pressing question of EWSB.
  - How should we predict the Higgs mass?
- We have ideas, but maybe not the right one.
  - No confirmation of any of the proposed models.
  - Confusion is good for physics. Challenging the foundation of our understanding of Quantum Field Theory.
  - Need experimental guidance.
- Fortunately, with Higgs, we know where to look.
  - Clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

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 measurement

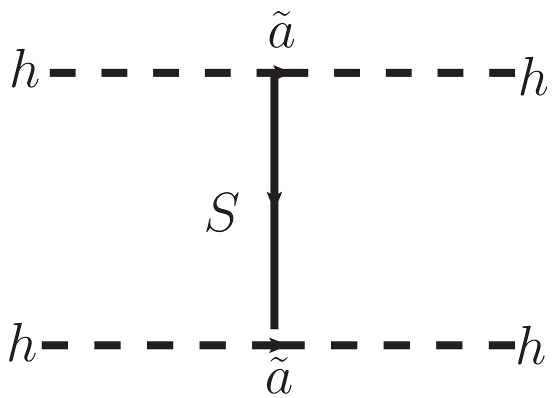
- Very difficult at HL-LHC: “order 1”

- 100 TeV pp collider or 1 TeV ILC can reach about 10%.

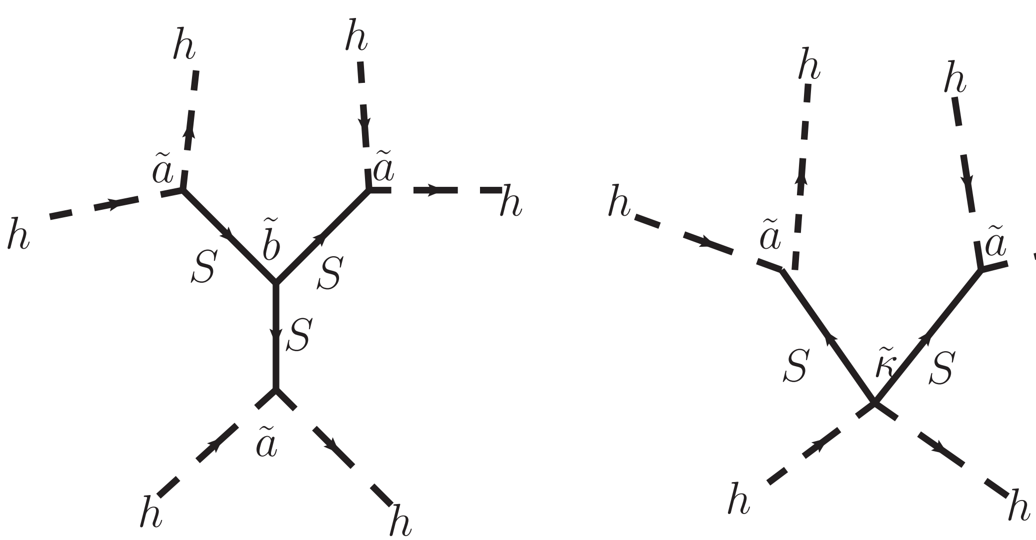
- However, if new physics modifies electroweak phase transition, it will also generate corrections to other Higgs couplings.
  - e.g. Generating sizable deviations in Higgs-Z coupling.

For example

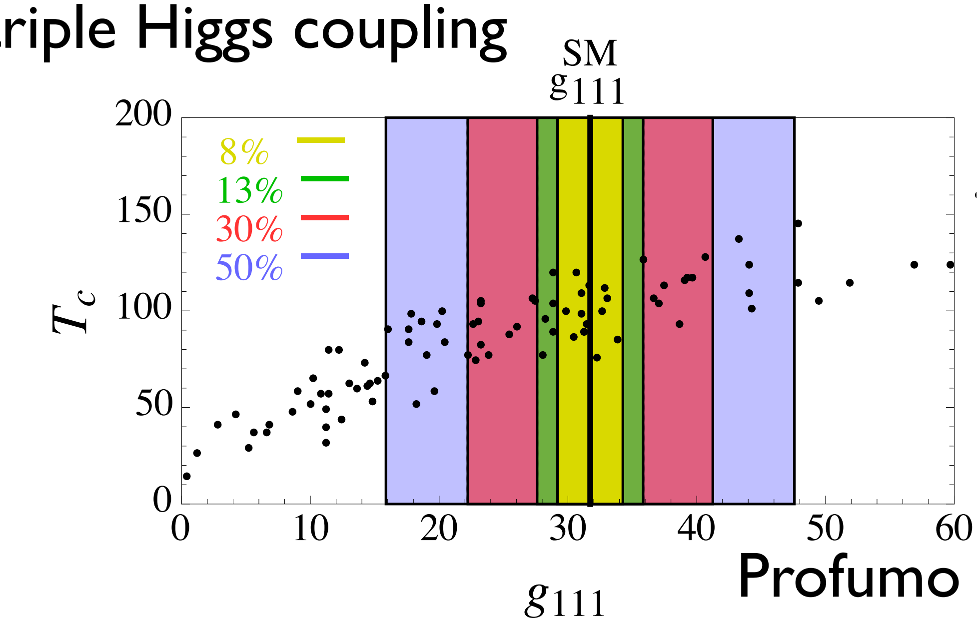
$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



shift in h-Z coupling

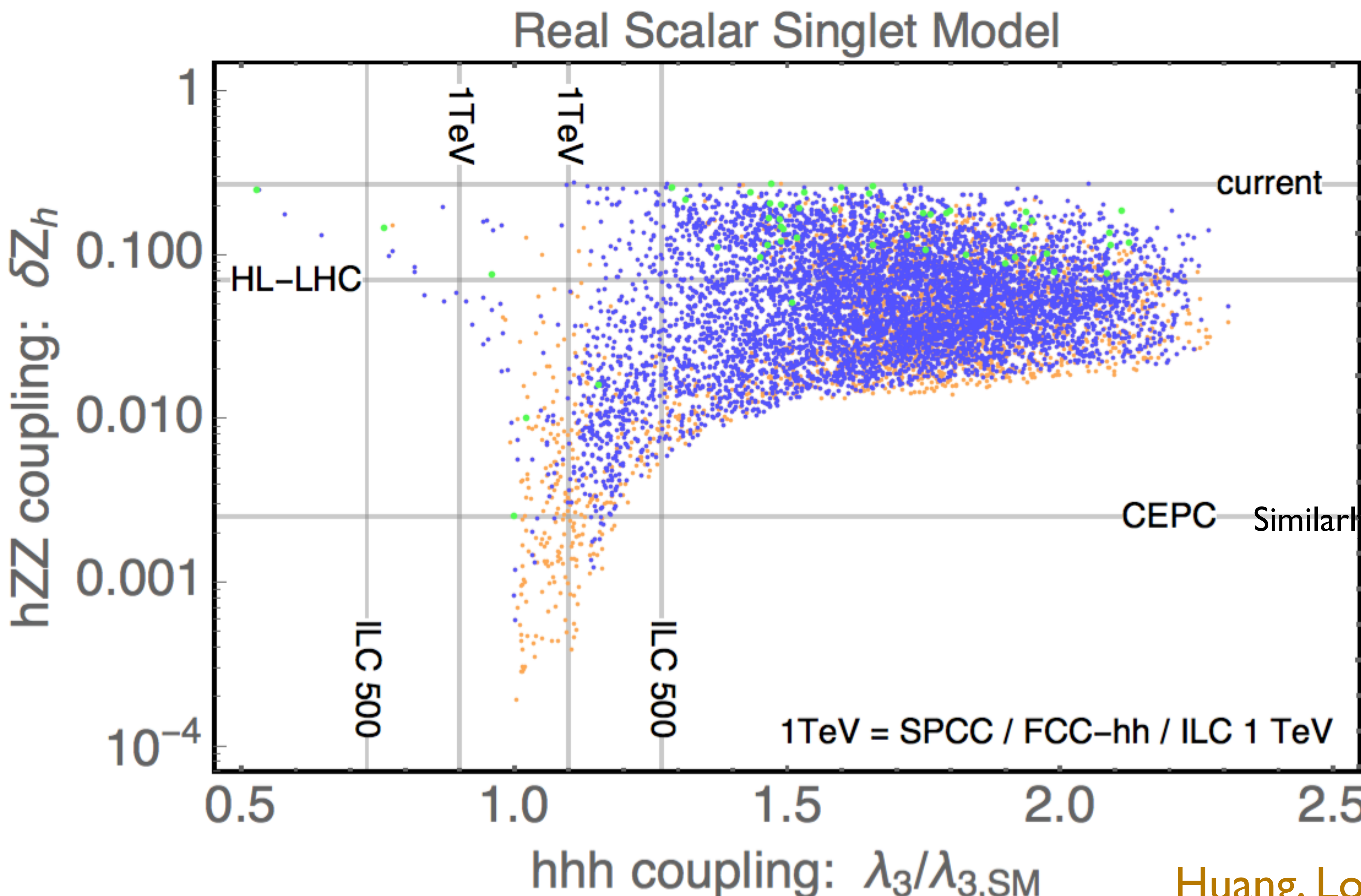


triple Higgs coupling



Profumo et al

Probing nature of EW phase transition

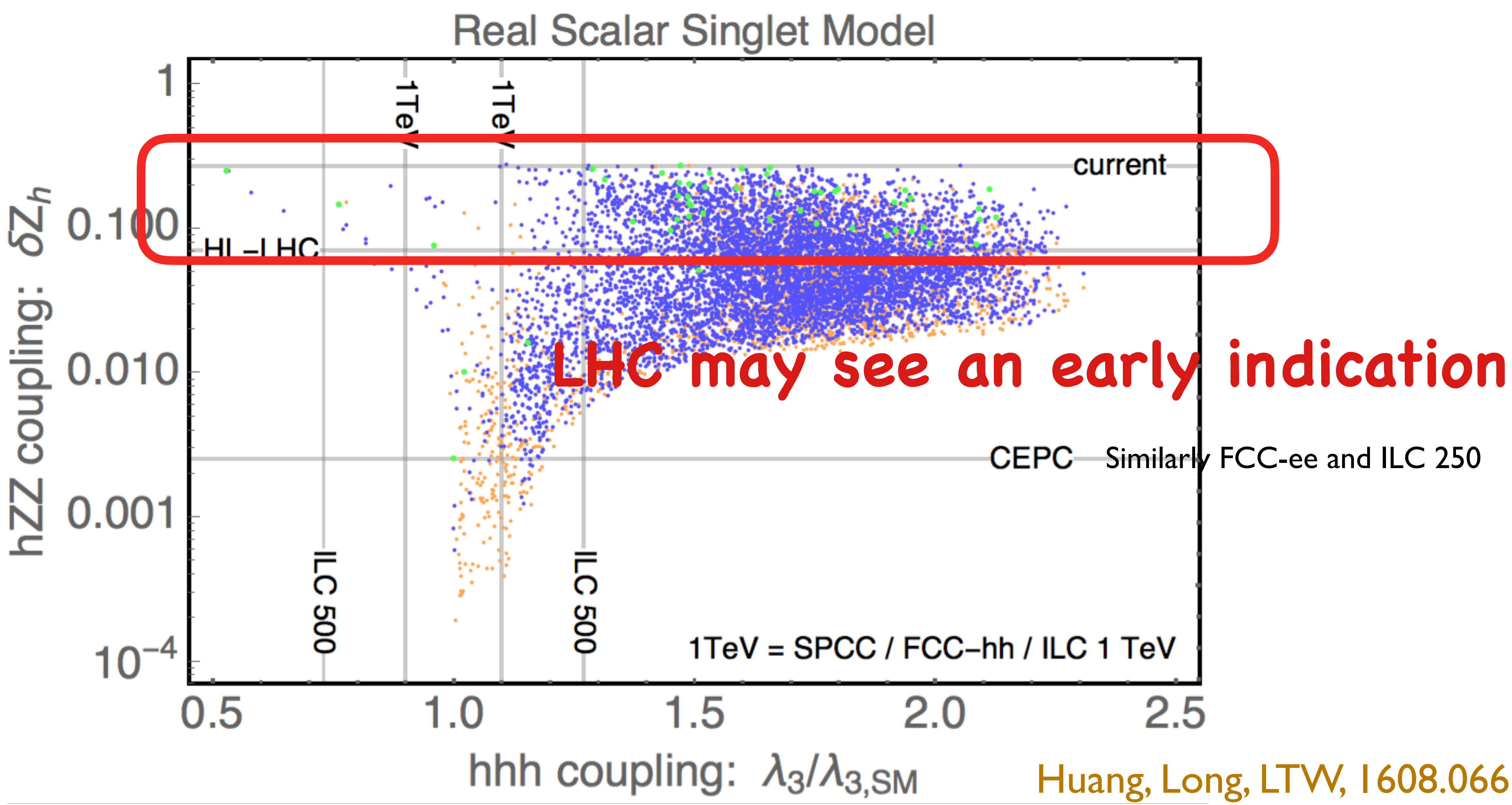


Similarly FCC-ee and ILC 250

Huang, Long, LTW, 1608.06619

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

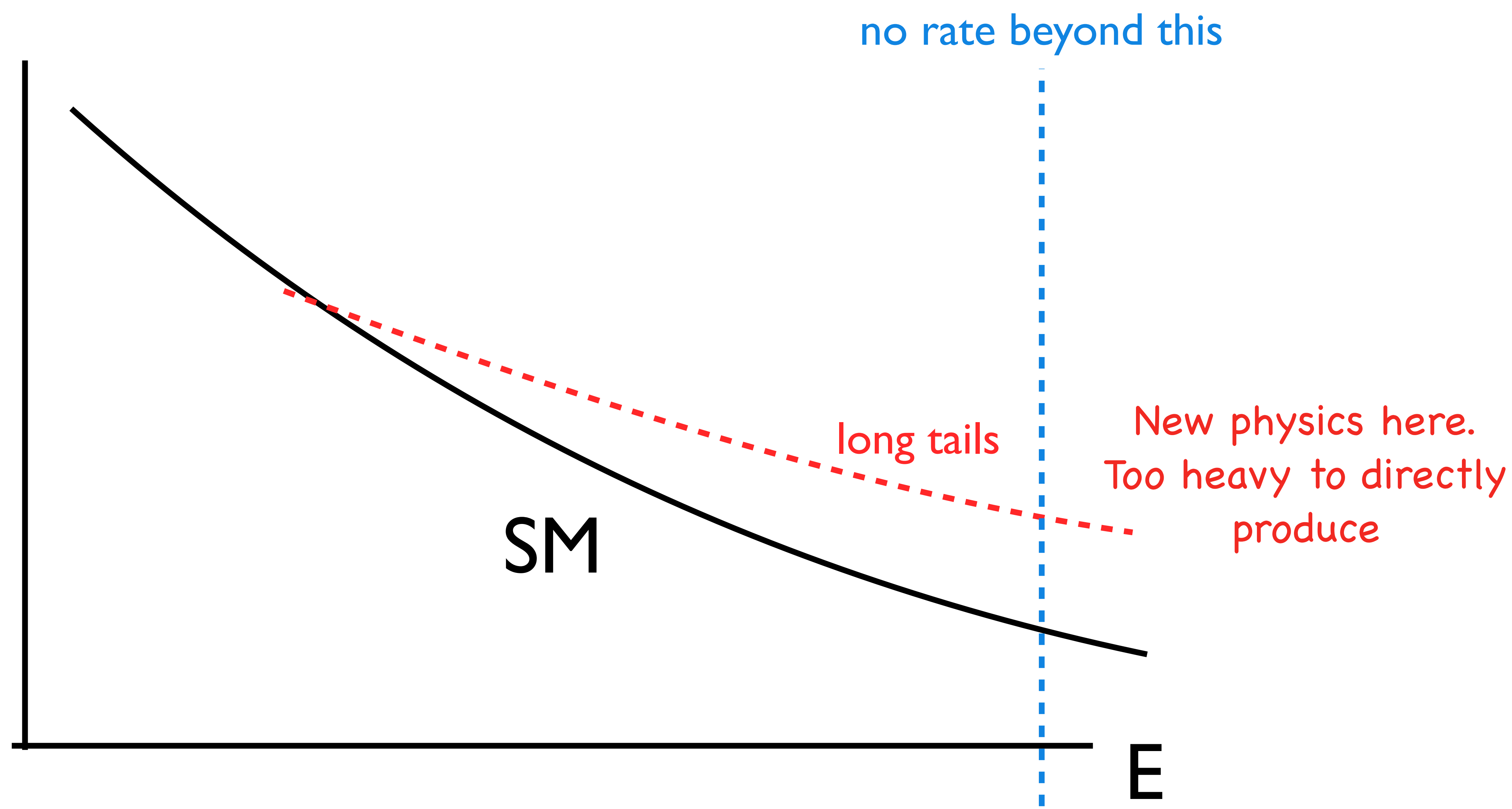
Probing nature of EW phase transition



Huang, Long, LTW, 1608.06619

Beyond Higgs coupling measurements.

Broad features with di-boson.



- Closely related to electroweak symmetry breaking

- Difficult. Systematics important.

Effect captured by:

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}, \qquad \mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}, \qquad \mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_{\mu} W^b_{\nu\rho} W^{c\rho\mu}, \qquad \mathcal{O}_T = \frac{g^2}{2}(H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}_\mu) H$$

$$\mathcal{O}^u_R = ig^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{u}_R \gamma^\mu u_R, \qquad \mathcal{O}^d_R = ig^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{d}_R \gamma^\mu d_R$$

$$\mathcal{O}^q_L = ig^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \gamma^\mu Q_L, \qquad \mathcal{O}^{(3)q}_L = ig^2 \left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \sigma^a \gamma^\mu Q_L$$

dim 6

$${}_8\mathcal{O}_{TWW} = g^2 \mathcal{T}^{\mu\nu}_f W^a_{\mu\rho} W^{a\,\rho}_{\nu} \qquad {}_8\mathcal{O}_{TBB} = g'^2 \mathcal{T}^{\mu\nu}_f B_{\mu\rho} B^\rho_\nu$$

$${}_8\mathcal{O}_{TWB} = g g' \mathcal{T}^{a\,\mu\nu}_f W^a_{\mu\rho} B^\rho_\nu, \qquad {}_8\mathcal{O}_{TH} = g^2 \mathcal{T}^{\mu\nu}_f D_\mu H^\dagger D_\nu H$$

$${}_8\mathcal{O}^{(3)}_{TH} = g^2 \mathcal{T}^{a\,\mu\nu}_f D_\mu H^\dagger \sigma^a D_\nu H$$

$$\mathcal{T}^{\mu\nu}_f = \tfrac{i}{4}\bar{\psi}(\gamma^\mu \overleftrightarrow{D}^\nu + \gamma^\nu \overleftrightarrow{D}^\mu)\psi \qquad \mathcal{T}^{a,\,\mu\nu}_f = \tfrac{i}{4}\bar{\psi}(\gamma^\mu \overleftrightarrow{D}^\nu + \gamma^\nu \overleftrightarrow{D}^\mu)\sigma^a\psi$$

dim 8

Precision measurement at the LHC possible?

LEP precision tests probe NP about Λ~2 TeV

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{m_W^2}{\Lambda^2} \sim 2 \times 10^{-3}$$

At LHC

Signal-SM interference

E ~ TeV $\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^2}{\Lambda^2} \sim 0.25$

Without interference

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^4}{\Lambda^4} \sim 0.05$$

LHC has potential.

Both interference and energy growing behavior crucial

Helicity structure at LHC

$$f_L \bar{f}_R \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_B$	$\mathcal{O}_{3W}$	$\mathcal{O}_{TWW}$
$(\pm, \mp)$	1	0	0	0	0	0	$\frac{E^4}{\Lambda^4}$
$(0, 0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	0	$\frac{E^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

$$f_R \bar{f}_L \to W^+ W^-$$

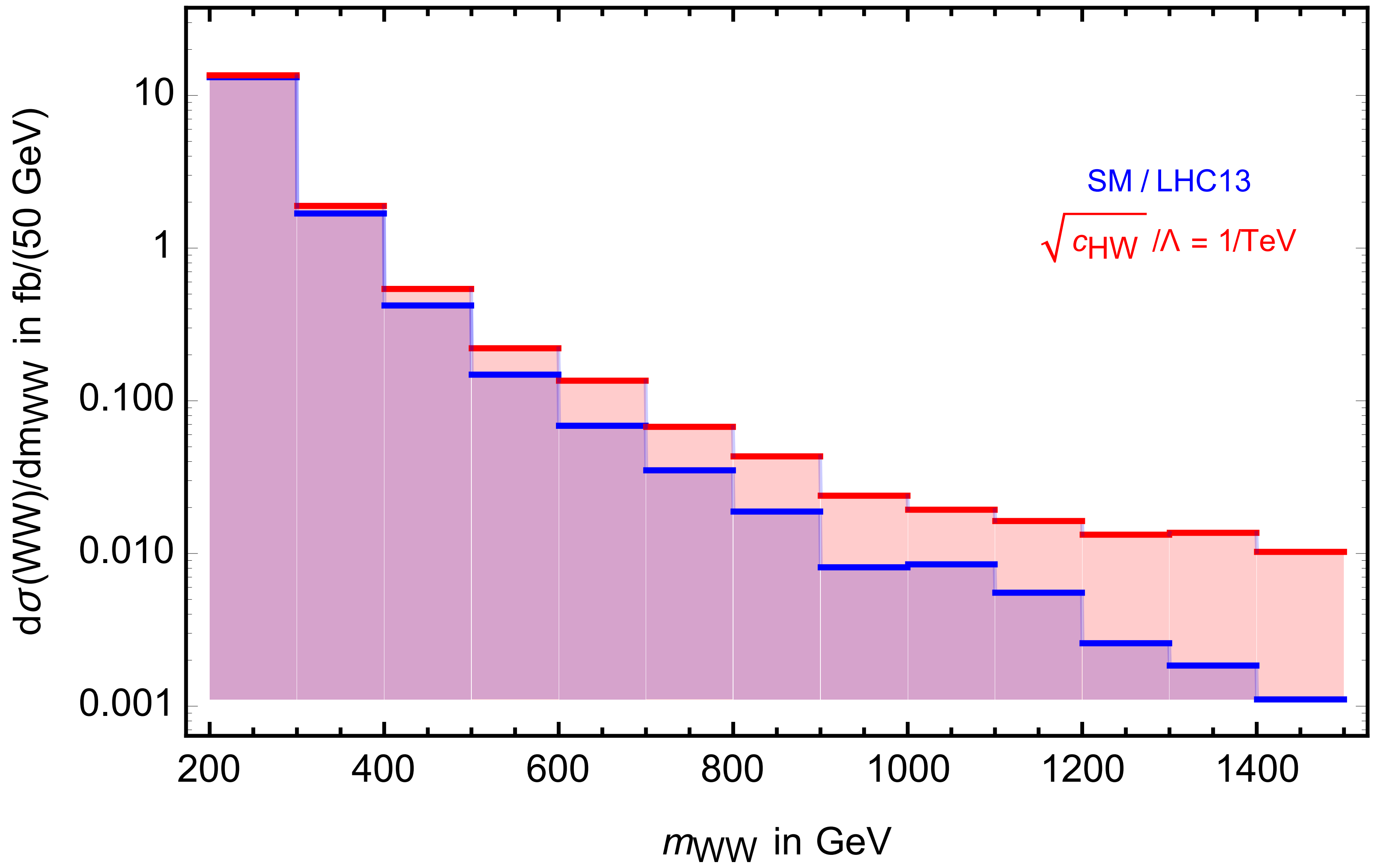
growing with energy

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_B$	$\mathcal{O}_{3W}$	$\mathcal{O}_{TWW}$
$(\pm, \mp)$	0	0	0	0	0	0	$\frac{E^4}{\Lambda^4}$
$(0, 0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{m_W^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	0	$\frac{m_W^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

- Whether interference or not depends on polarization of WW. Polarization differentiation can be crucial.

- Need large SM piece to interfere with. Longitudinal (0,0) most promising.

Growing with energy



Where to look?

"tail" parameterized by $\frac{\mathcal{O}}{\Lambda^d}$ $\Lambda \approx$ scale of NP

$$\sigma_{\text{signal}} \propto \frac{1}{E^n}\left(\frac{E}{\Lambda}\right)^d \qquad \sigma_{\text{SM}} \propto \frac{1}{E^n}$$

E: energy bin of the measurement

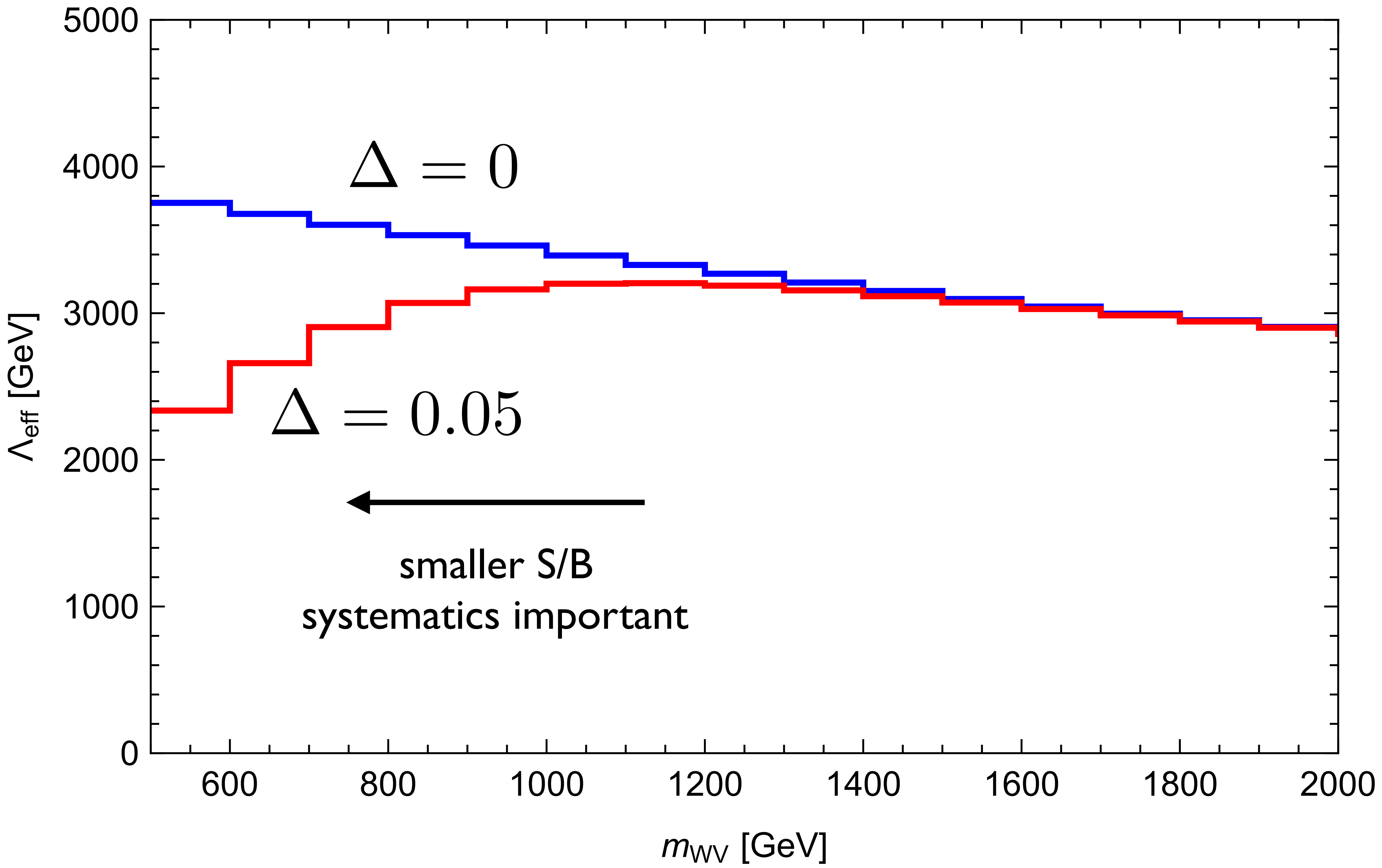
n: 5-8 falling parton luminosity

$$\frac{S}{\sqrt{B}} \sim \sqrt{\frac{\mathcal{L}}{E^n}}\left(\frac{E}{\Lambda}\right)^d$$

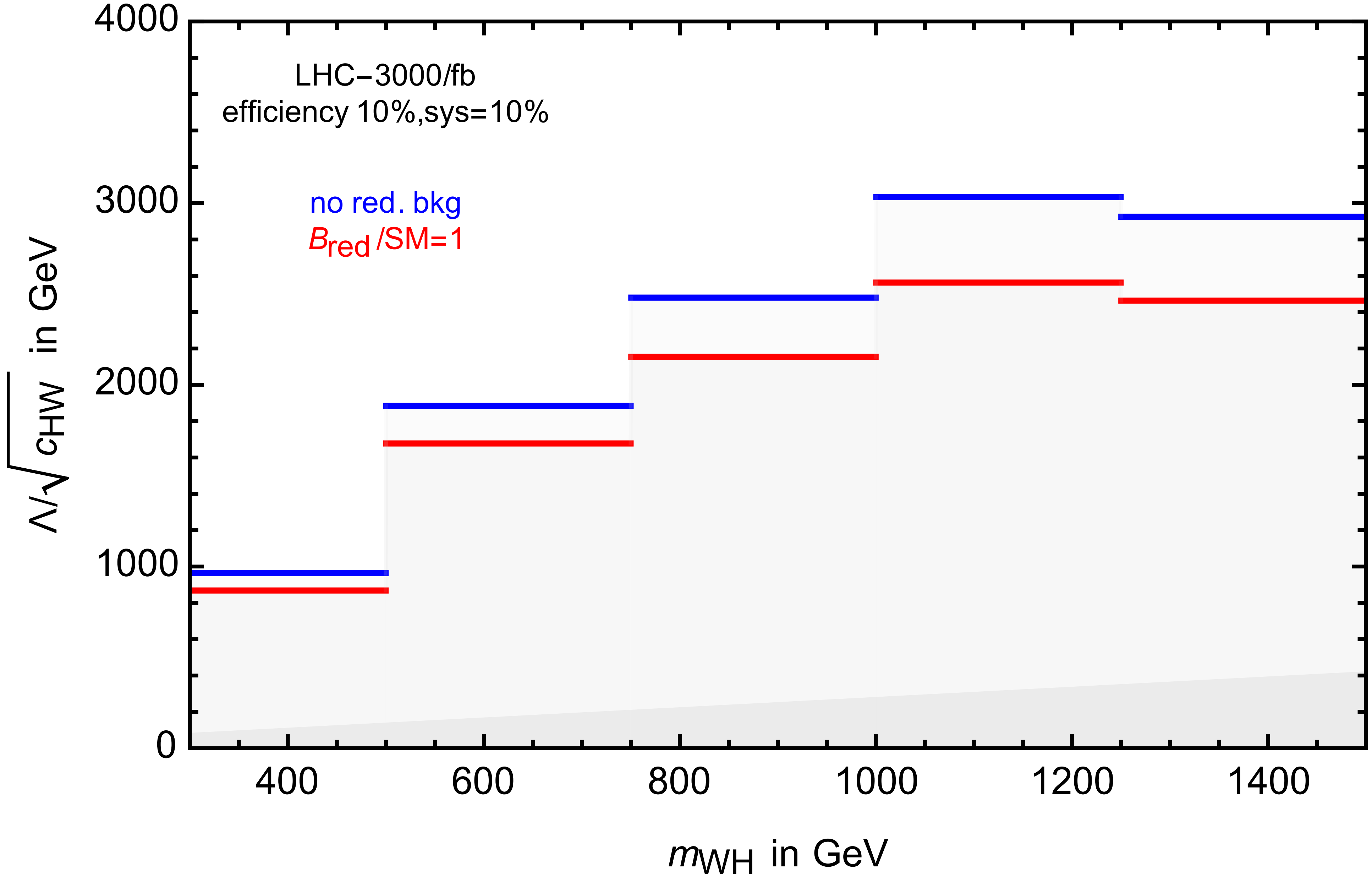
$\mathcal{L}$ = integrated luminosity

- For small d, lower E with higher reach. (e.g. dim 6, d=2)
  - Limited by systematics.

The role of systematics



Projecting the reach: Wh channel



Can set interesting limit!

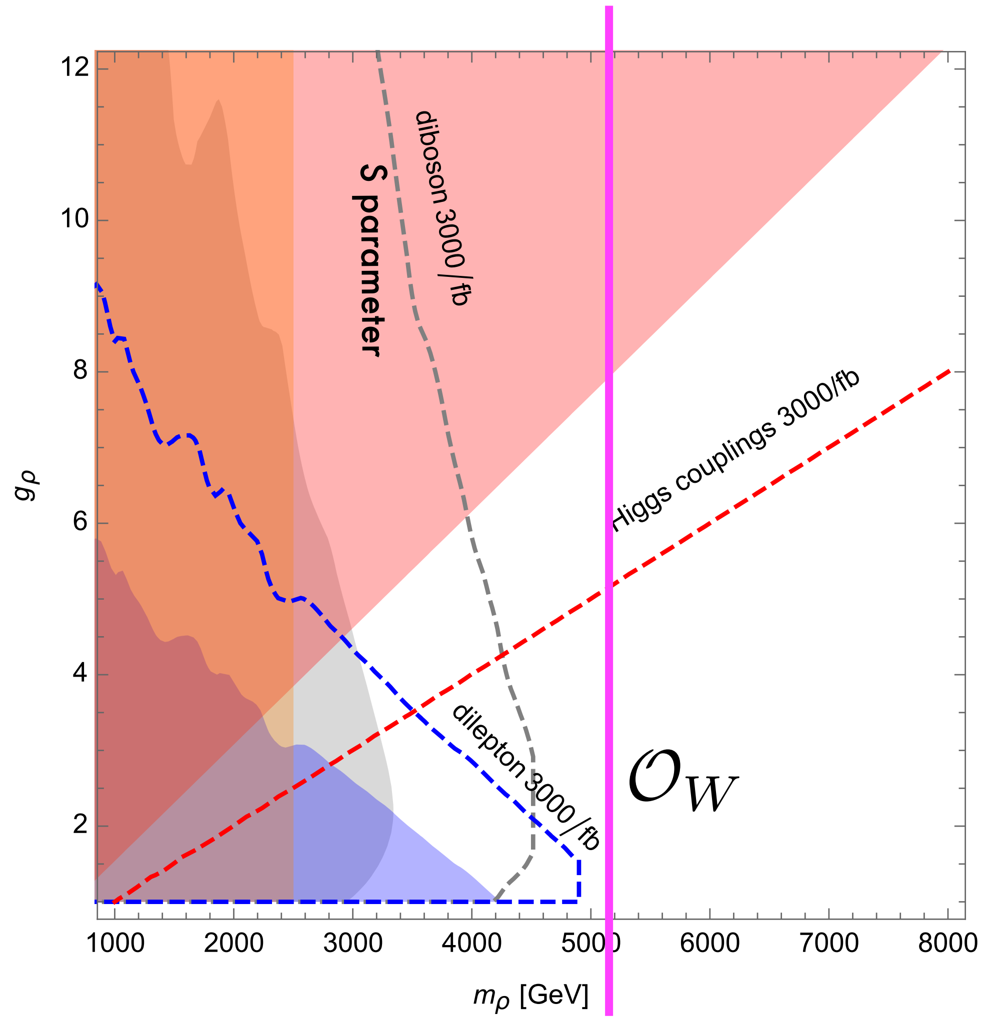
LHC benchmarks

Λ[TeV]	$\mathcal{O}_W$	$\mathcal{O}_B$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{3W}$
LEP	2.5	2.5	0.3	0.3	0.4
$WV(\ell + jets)$	4.8(1.9)	1.5(0.71)	4.8(1.9)	1.5(0.71)	1.2
$W^{\pm}h(\ell bb)$	(4.0,2.9,2.3)		(4.0,2.9,2.3)		
$W^{\pm}h(\ell + \ell\nu\ell\nu)$	1.6		1.6		
$h \to Z\gamma$			1.7	1.7	

- (blue box) ideal case, perfect pol tagging, no systematics
- (orange box) tagging eff 50%, mis-tagging rate 10%, no systematics
- (red box) reducible bkg 0, 3, 10 times of the irreducible rate
- (green box) interference effect not important.

– Can beat LEP precision if some of these benchmarks can be reached.

Direct searches of composite resonance



Shaded areas:
current bounds

Most optimistic case can be competitive with direct narrow resonance searches.

The resonance may be broad, not covered by direct searches.

Conclusion

- Entering a precision era of the LHC, with Higgs the prime target.
- Understanding Higgs is a central question in particle physics.
  - Higgs mass, electroweak phase transition.
  - The current picture is confusing. Opportunity for big discoveries.
- LHC will lead the way, setting the stage for next steps.

Triple Higgs coupling at 100 TeV pp collider
30 ab^{-1}

$$\frac{\lambda}{\lambda_{\rm SM}} \in \begin{cases} [0.891, 1.115] & \text{no background syst.} \\ [0.882, 1.126] & 25\%\ hh, 25\%\ hh+\text{jet} \\ [0.881, 1.128] & 25\%\ hh, 50\%\ hh+\text{jet} \end{cases}$$

Barr, Dolan, Englert, de Lima, Spannowsky

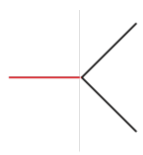
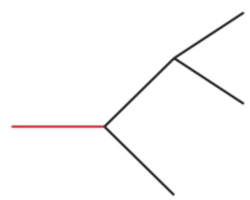
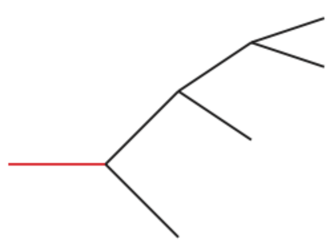
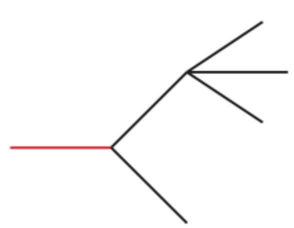
ILC 500: 27%
ILC ultimate, 1 TeV 5 ab-1: 10%

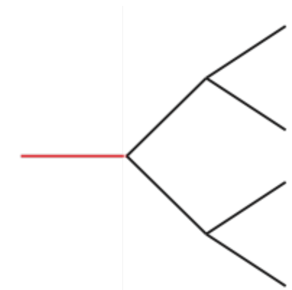
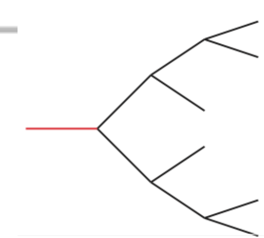
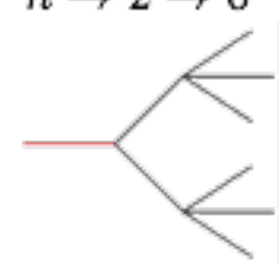
But, there should be more

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

- 1st order EW phase transition means there is new physics close to the weak scale.
- Can be difficult to discover at the LHC.
  - Maybe only couple weakly to the Higgs.
- Will leave more signature in Higgs coupling.

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

adapted from slides of Zhen Liu

Good sensitivity from the LHC

Helicity structure at LHC

$$f_L \bar{f}_R \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_B$	$\mathcal{O}_{3W}$	$\mathcal{O}_{TWW}$
$(\pm, \mp)$	1	0	0	0	0	0	$\frac{E^4}{\Lambda^4}$
$(0, 0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	0	$\frac{E^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

$$f_R \bar{f}_L \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_B$	$\mathcal{O}_{3W}$	$\mathcal{O}_{TWW}$
$(\pm, \mp)$	0	0	0	0	0	0	$\frac{E^4}{\Lambda^4}$
$(0, 0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{m_W^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	0	$\frac{m_W^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

growing with energy

SM piece is small. Interference does not grow with E.