Physics Case for e+e- Colliders at 250 GeV

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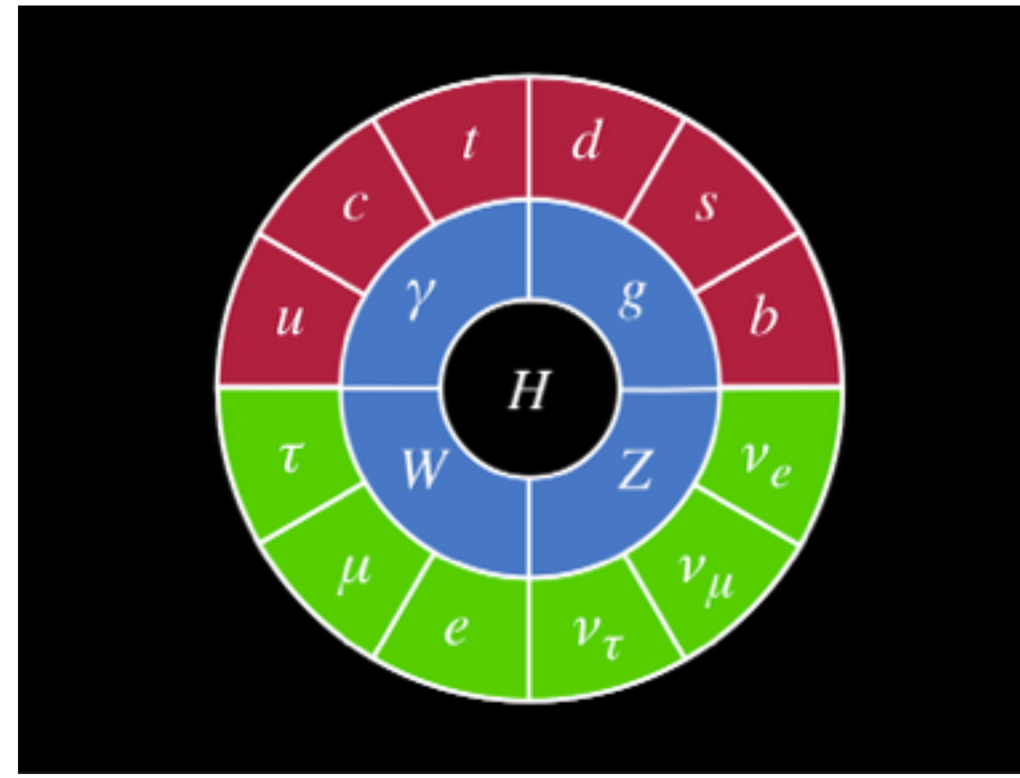
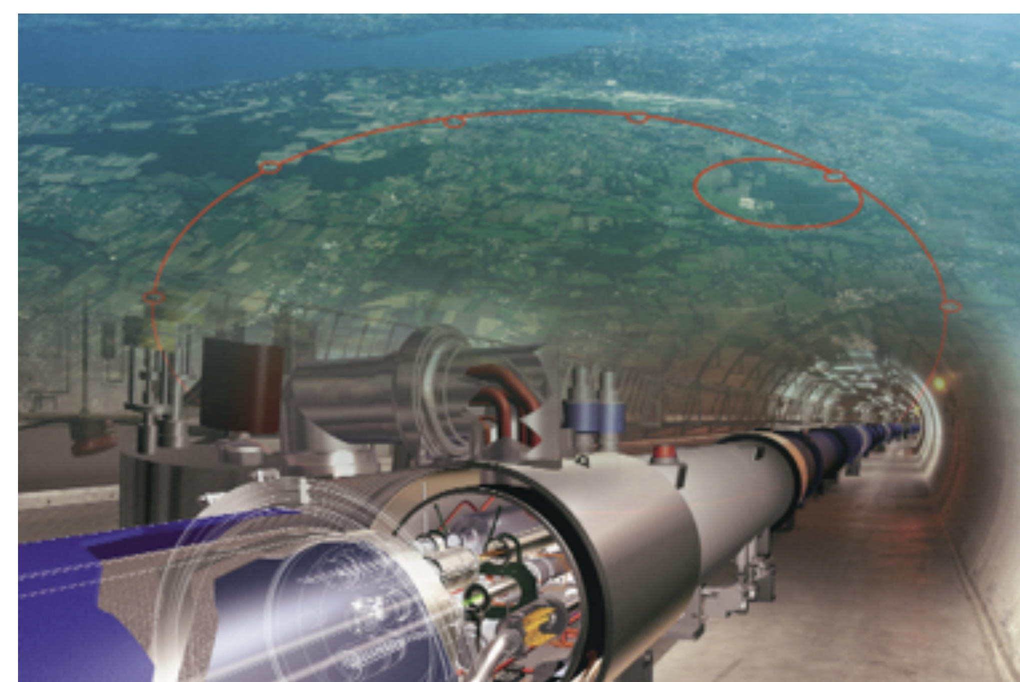
CORNELL UNIVERSITY LEPP

LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

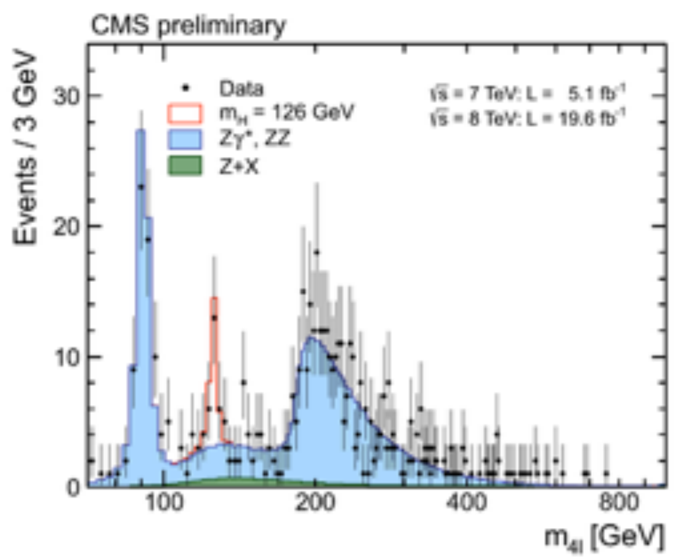
Particle Physics in 2017

- The Standard Model (SM) has been the undisputed queen of particle physics since (at least) the late 1970's
- Aspects of SM have been probed with increasing degree of precision by LEP, SLC/SLD, Tevatron, CLEO, Belle, BaBar, etc.
- Since 2010, experiments at the Large Hadron Collider (LHC) at CERN are pushing the high-energy frontier
- Higgs discovery in 2012 completes the verification of SM particle content

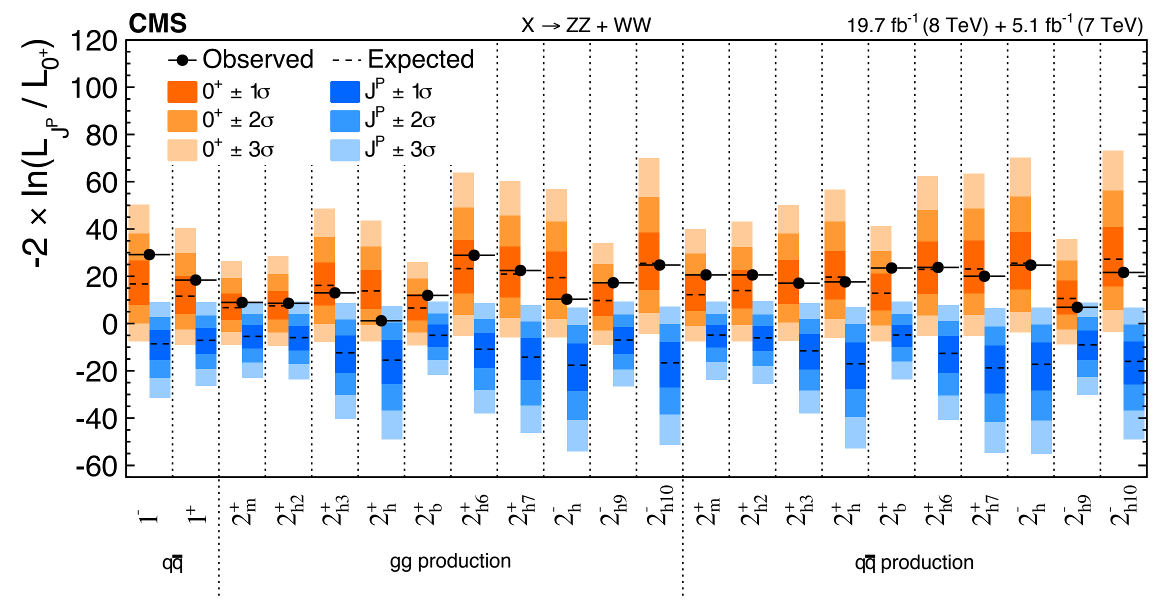




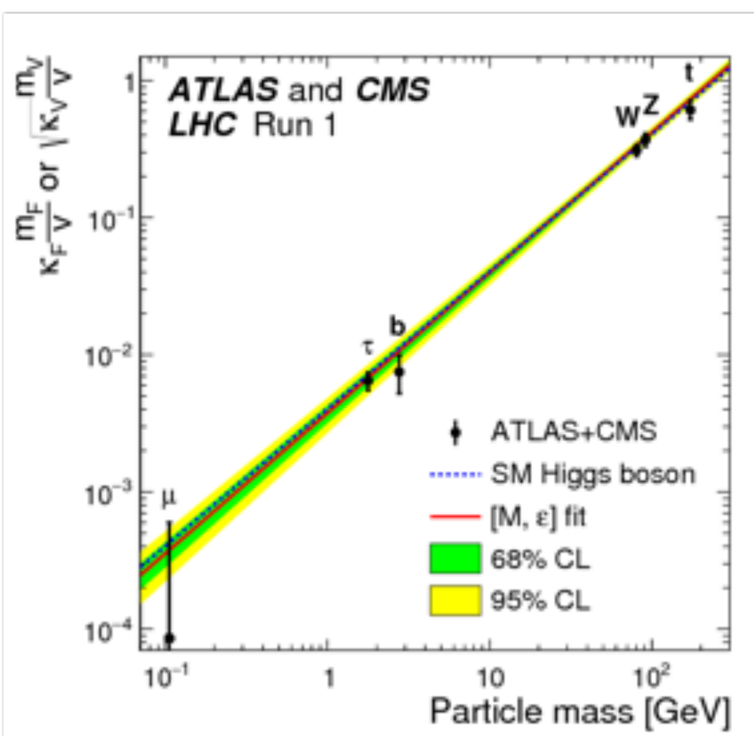
Highlights from the LHC: Higgs



It exists! m=125 GeV



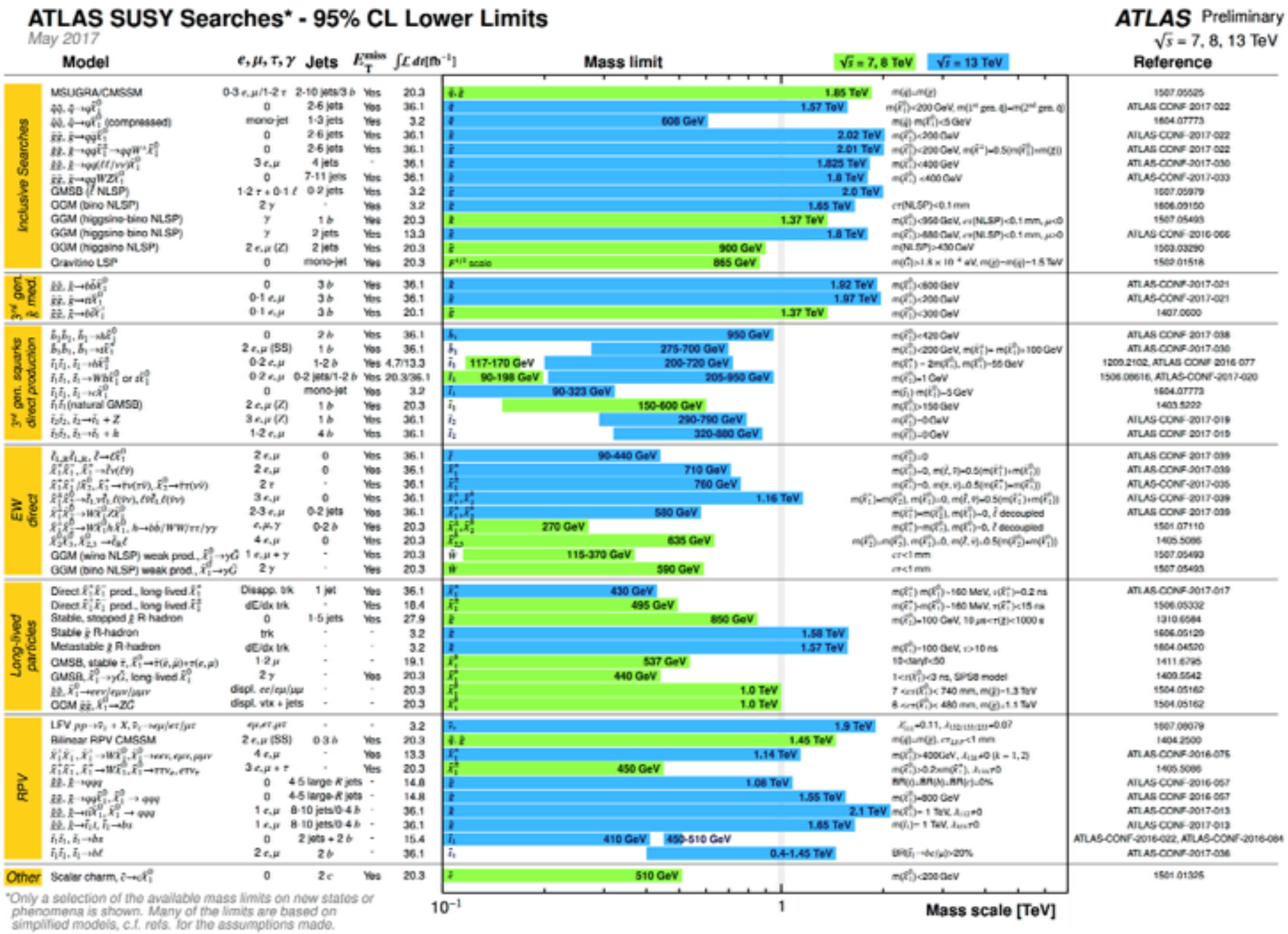
It is a spin-0 object



It couples to other particles with strength proportional to their mass (~20% level, w/some assumptions)

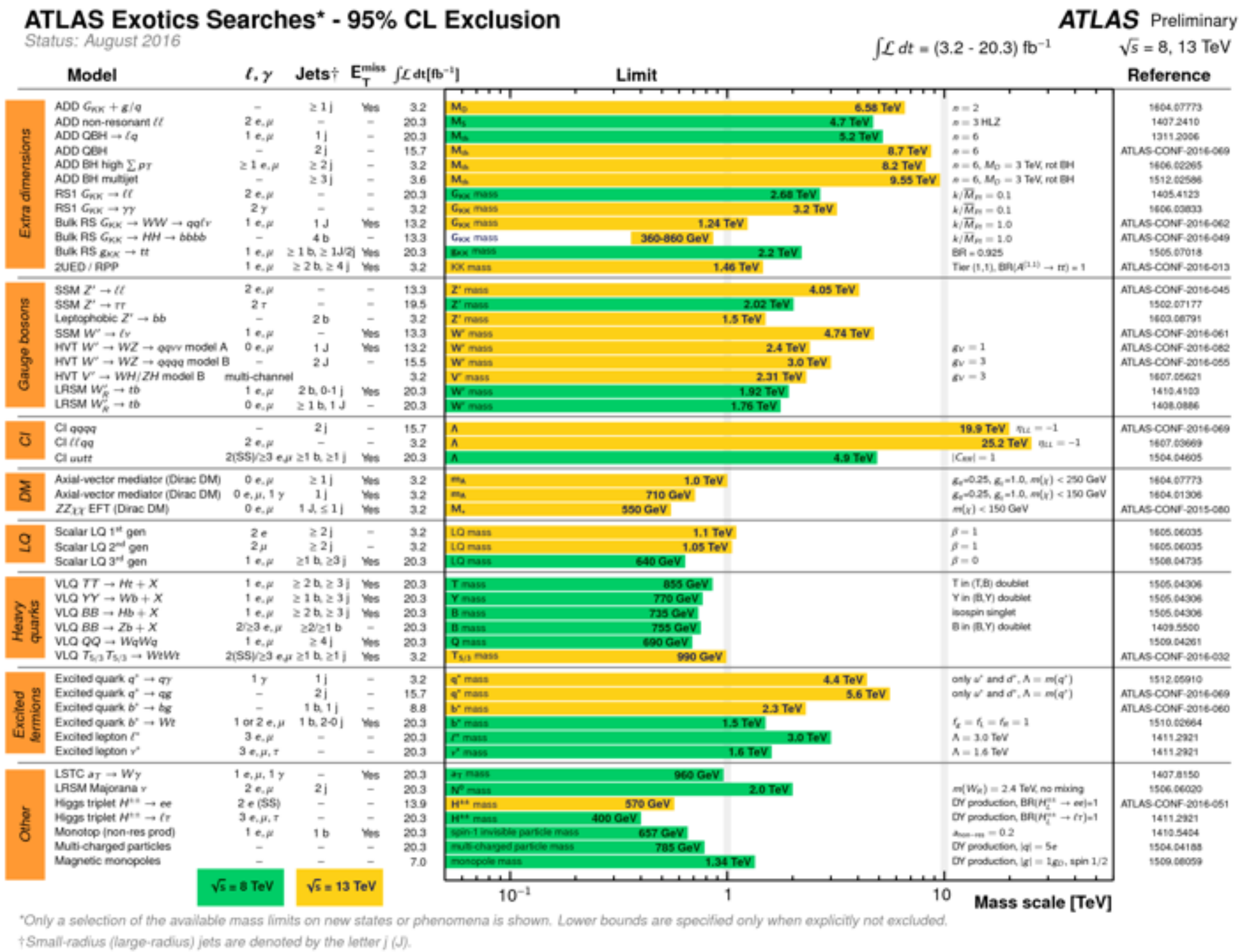
Nobel Prize 2013
Higgs and Englert

Highlights from the LHC: BSM



No SUSY so far. Bounds ~1 TeV on SUSY particle masses in many scenarios (though gaps remain).

Highlights from the LHC: EXO

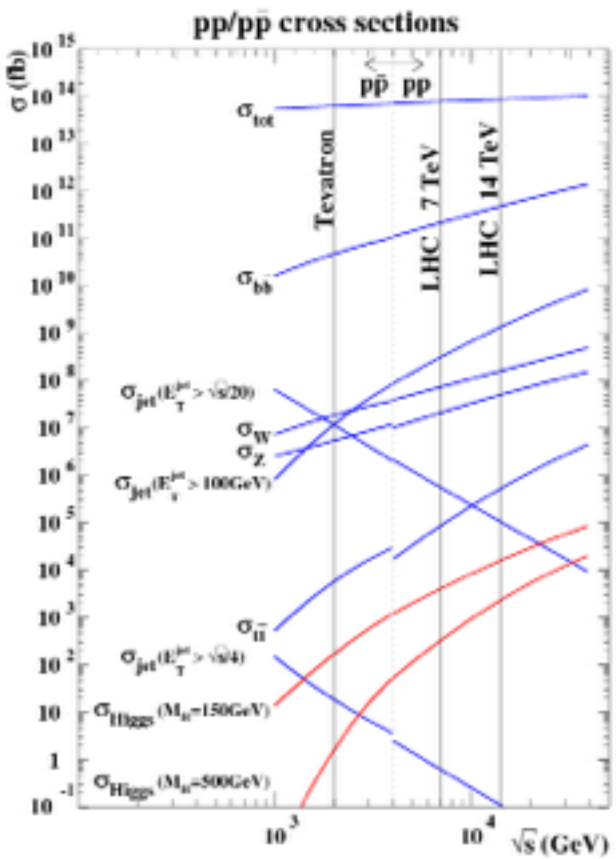


No non-SUSY BSM so far. Bounds ~1 TeV on BSM particle masses in many scenarios.

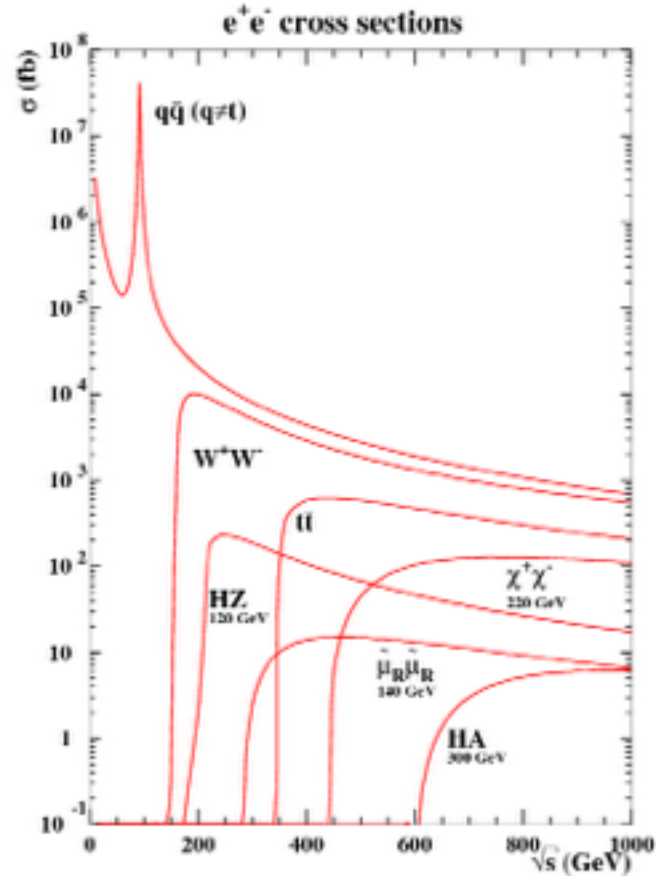
Where Do We Go From Here

- LHC results so far suggest two approaches to pursue in our exploration of the weak scale and beyond:
  - Precision studies of the properties of the Higgs particle
  - Direct searches for new phenomena at higher energy scales than probed so far
- Both approaches have potential to discover new physics. "Which one is better" depends sensitively on the nature of new physics. The only sensible strategy is to pursue both.
- This talk will focus on the precision Higgs program, for which a 250 GeV e+e- collider is an ideal tool

e+e- vs. Hadron Collider



LHC: Cross Section Oligarchy - the Strong dominate the Weak



e+e-: Cross Section Democracy

e.g. $\frac{\sigma(H)}{\sigma_{\text{total}}} \sim 10^{-10}$ $\frac{\sigma(H)}{\sigma_{\text{total}}} \sim 10^{-2}$

- Smaller Event Samples

  ~100 M Higgses at LH-LHC (3 ab-1)

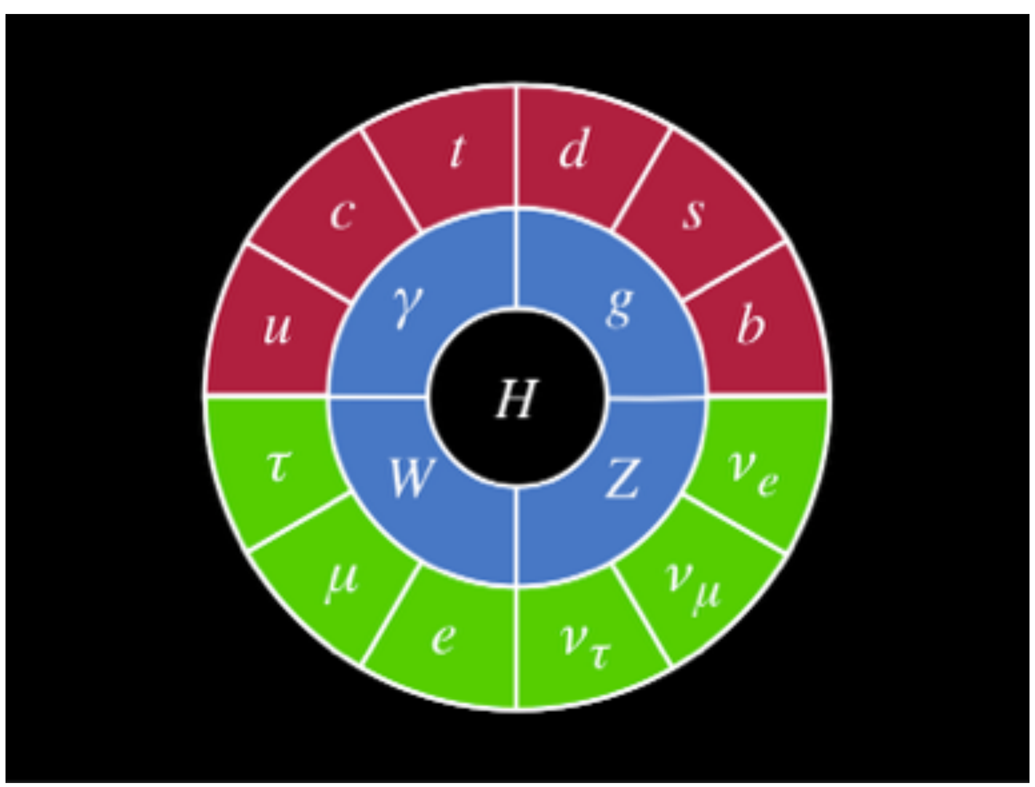
  ~1 M Higgses at e+e- facilities

- Much better S/B

- Clean environment, no pile-up

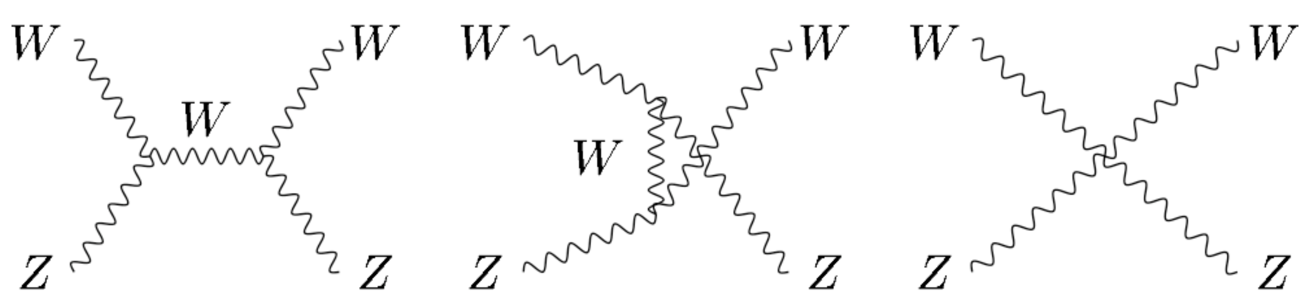
- Well-defined initial state → no pdf uncertainties, new observables using initial-state kinematics

WHAT'S SO SPECIAL ABOUT THE HIGGS?



Higgs and Unitarity

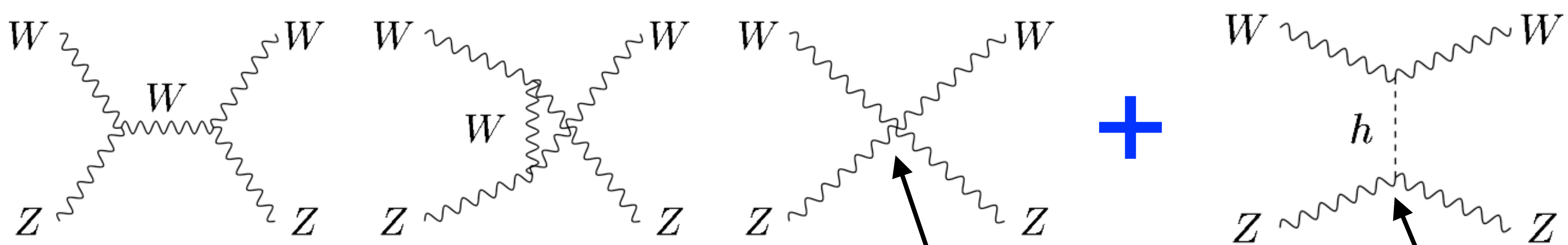
- Higgs controls the fate of the Standard Model at high energies
- It is often stated that "With the discovery of the Higgs, for the first time we have a theory that can be valid up to an arbitrarily high energy scale" (or at least the Planck scale)
- As an example, consider the process $W + Z \to W + Z$
- In the SM without the Higgs, perturbative amplitude grows with energy, eventually predict Prob>1 - nonsense!



$\mathcal{M} \propto E^2$

Higgs and Unitarity

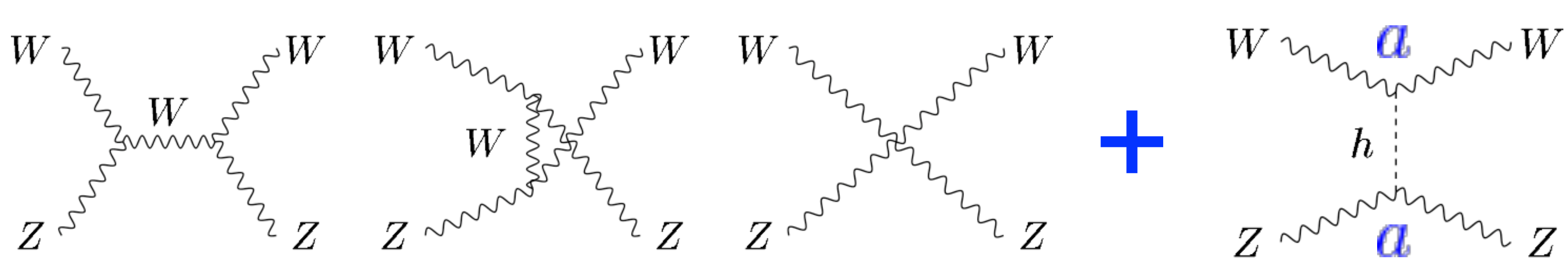
- In the SM with the Higgs, the problem is fixed



$\mathcal{M} \propto E^0\,!$

Intricate cancellation between "gauge" and "Higgs" diagrams
(closely connected to Higgs's role in generating masses)

- If the HWW coupling is not exactly SM, cancellation is spoiled:



$\mathcal{M} \propto (1-a^2)E^2$

Higgs and Unitarity

- If $a \neq 1$, the theory predicts its own demise: some new physics must save it from Prob>1, at a scale at most

$$\Lambda \sim \frac{4\pi v}{\sqrt{1-a^2}}$$

- This occurs for example in theories where Higgs is a bound state of more fundamental particles, w/size $r_h \sim 4\pi/\Lambda$

- Precision measurement of Higgs couplings provides a unique window into the fate of the SM at high energies:

$$\Delta g(hWW) = 10\% \Rightarrow \Lambda \sim 8 \text{ TeV}$$

$$\Delta g(hWW) = 1\% \Rightarrow \Lambda \sim 23 \text{ TeV}$$

$$\Delta g(hWW) = 0.3\% \Rightarrow \Lambda \sim 42 \text{ TeV}$$

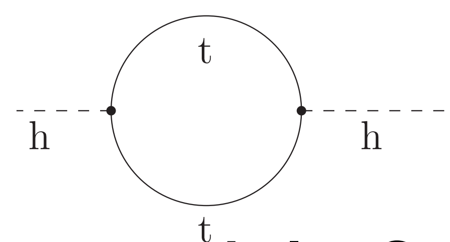
Well above direct reach of the LHC!

The Spin-less Higgs

- In the SM, the Higgs is a spin-0, elementary particle; LHC data is consistent with this hypothesis

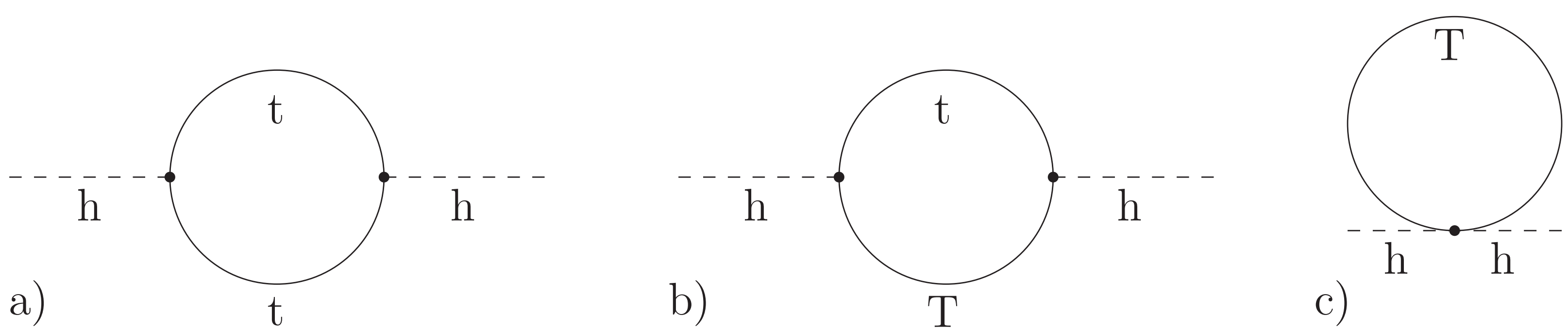
- No other spin-0, elementary particles have been seen so far

- In the SM, its existence is a mystery. Suppose there is such a particle. We can estimate its mass:



$$m_h \sim M_{\rm Pl}$$

- New physics models: Supersymmetry, Little Higgs, …

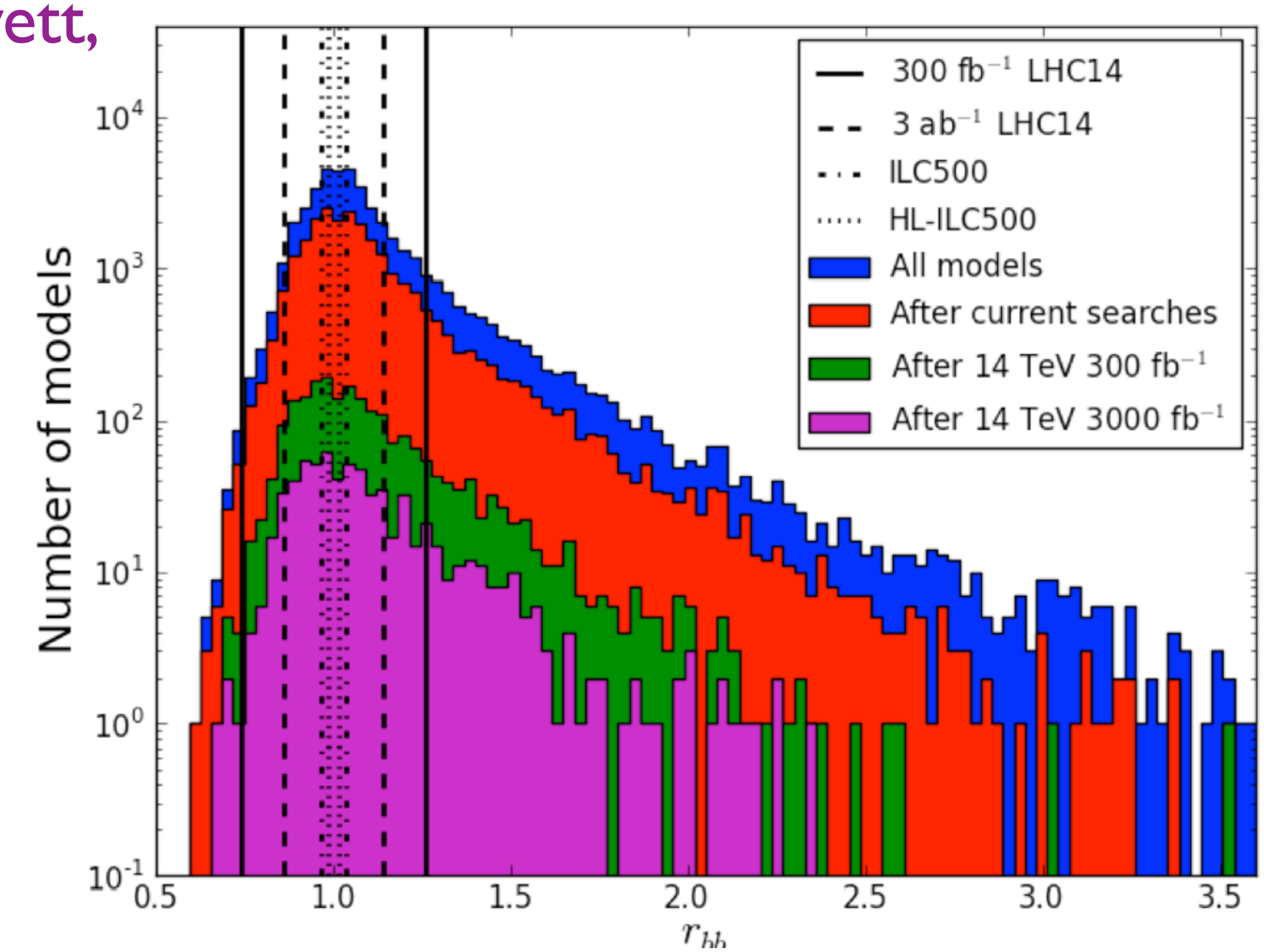


$$m_h \sim M_{\rm new}$$

- The "Naturalness Mystery" remains unresolved. Precision Higgs studies may provide the crucial hint.

Supersymmetry

[Cahill-Rowley, Hewett, Ismail, Rizzo]

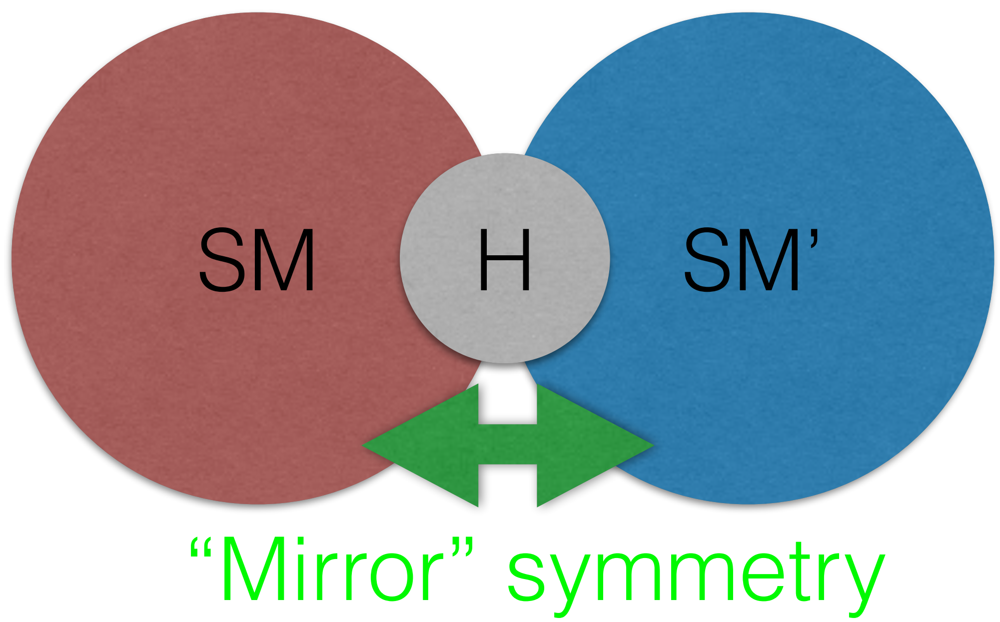


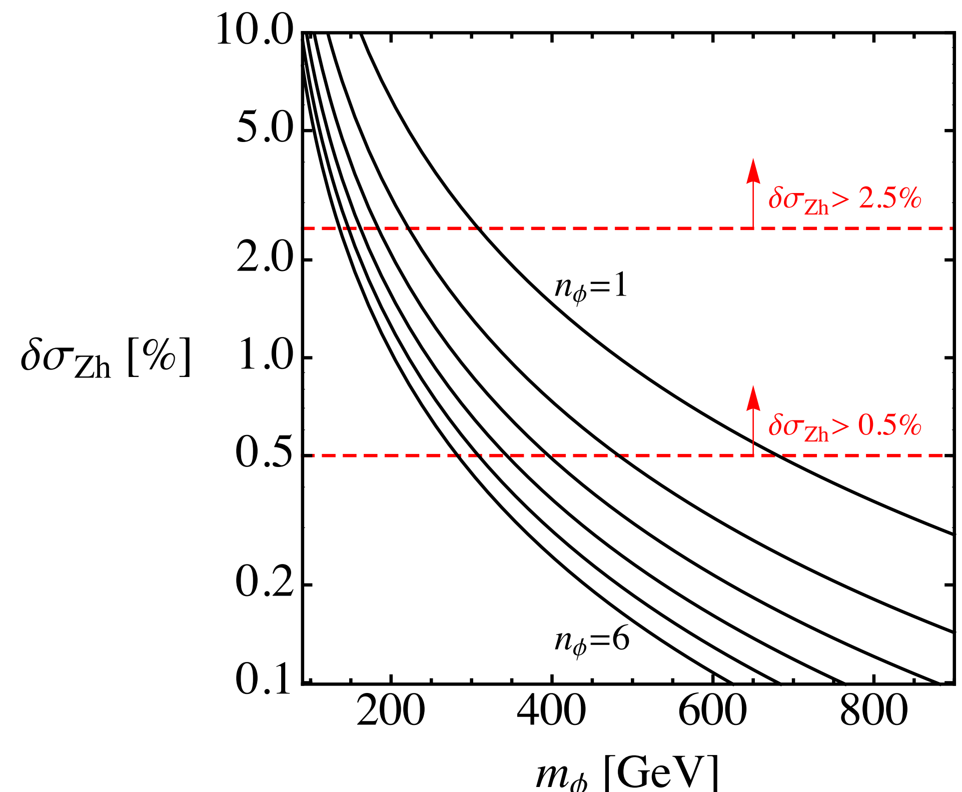
$\Gamma(h \to b\bar{b})/(SM)$

- SUSY has a vast parameter space
- Observable deviations in Higgs couplings are possible even if direct searches for superpartners make no discovery, even at HL-LHC
- Direct and Higgs coupling searches seem “orthogonal”

Neutral Naturalness

[Chacko, Goh, Harnik]



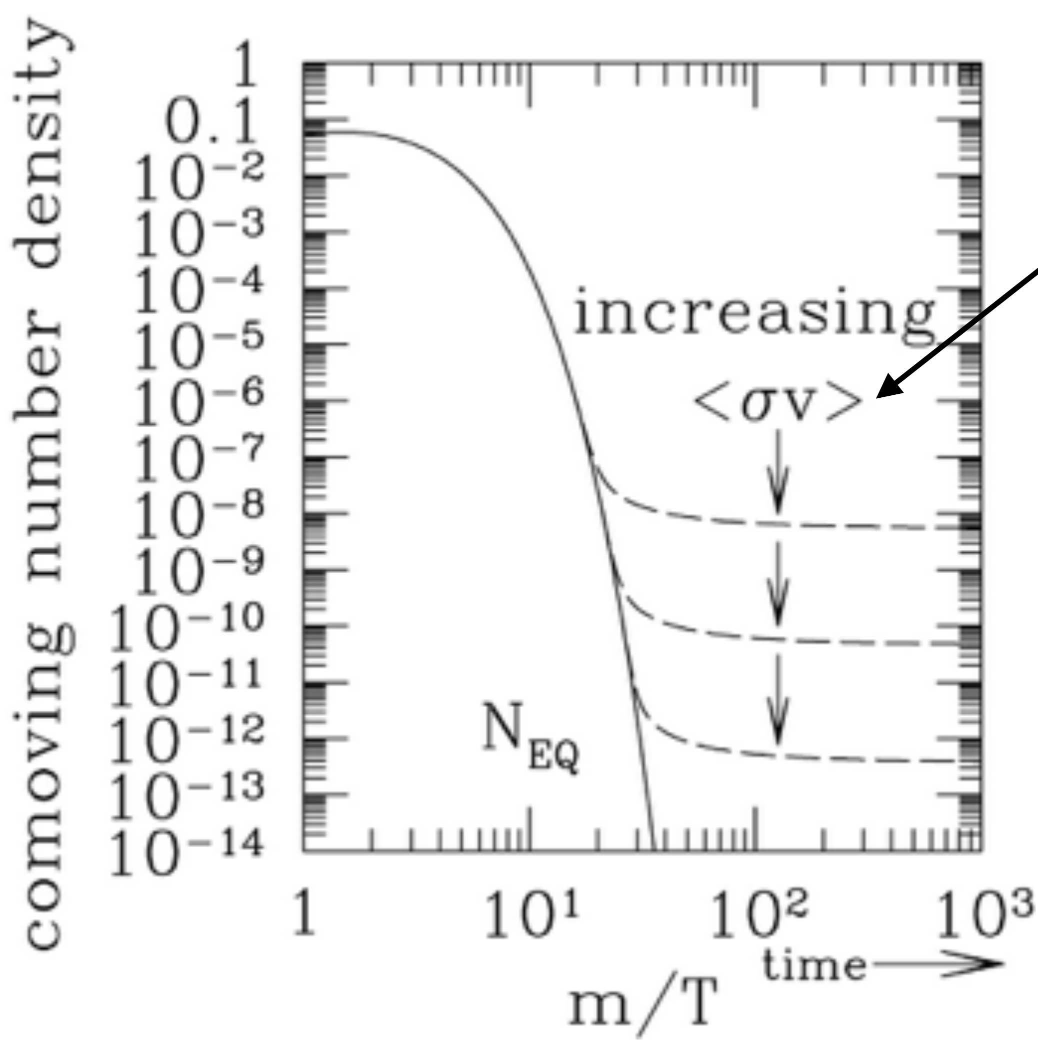


[Craig, Englert, McCullough]

- It is possible that the "partners" that stabilize the Higgs have no SM gauge charges (color, weak, or EM)
- Such partners are completely invisible to the LHC
- However they <u>must</u> couple to the Higgs → potentially observable in precision Higgs studies

Dark Sectors

- "Dark Sectors" are field(s) with no SM gauge charges
- Dark Matter may be part of the Dark Sector
- Example: Strongly-Interacting Massive Particle (SIMP)



WIMPs: $\chi\chi \rightarrow e^+e^-$

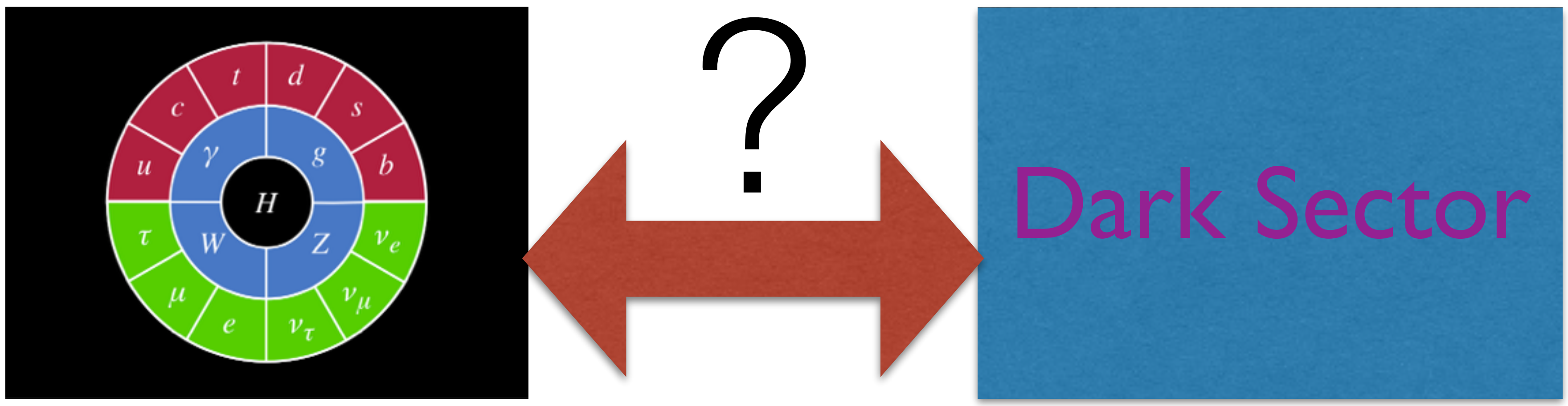
SIMPs: $\chi\chi\chi \rightarrow \chi\chi$

"SIMP Miracle": correct relic density for $m_\chi \sim 100$ MeV

SIMPs can be mesons of "Dark QCD". Expect rich spectrum of Dark states at ~GeV

[Hochberg, Kuflik, Volansky, Wacker, Murayama]

Higgs as a Portal



"visible sector"

- How can dark-sector fields interact with the SM? Not so easy: most gauge-invariant interactions must be suppressed ("non-renormalizable")

- In fact, only three unsuppressed interaction terms possible:

$$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, \qquad \text{vector portal}$$

$$(\mu\phi + \lambda\phi^2) H^\dagger H\,, \qquad \text{Higgs portal}$$

$$y_n L H N\,, \qquad \text{neutrino portal}$$

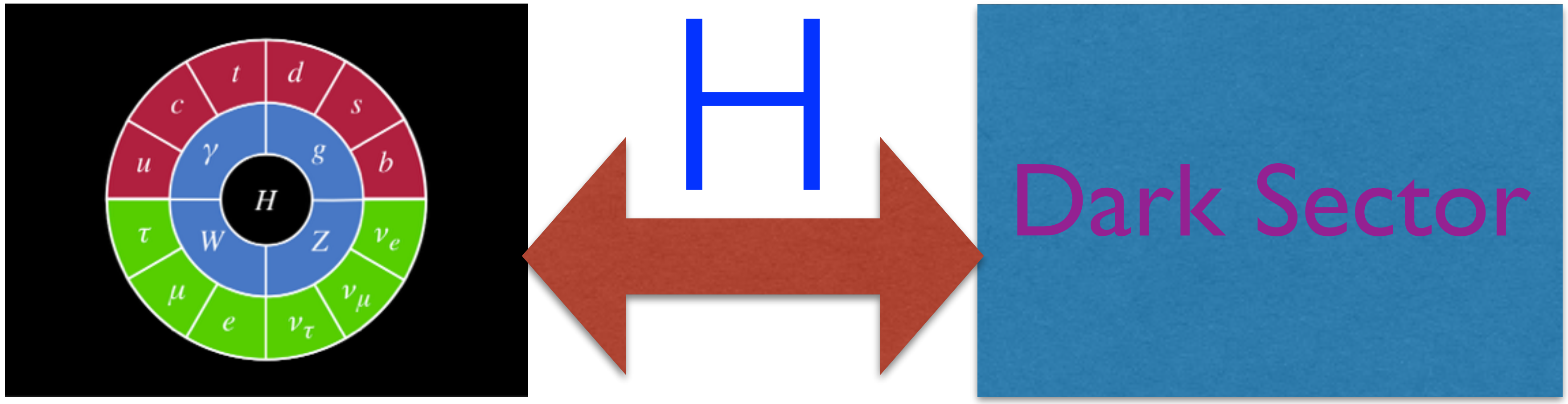
Dark Photon searches

Precision Higgs

Neutrino program

[Alexander et.al.,'16]

Higgs as a Portal

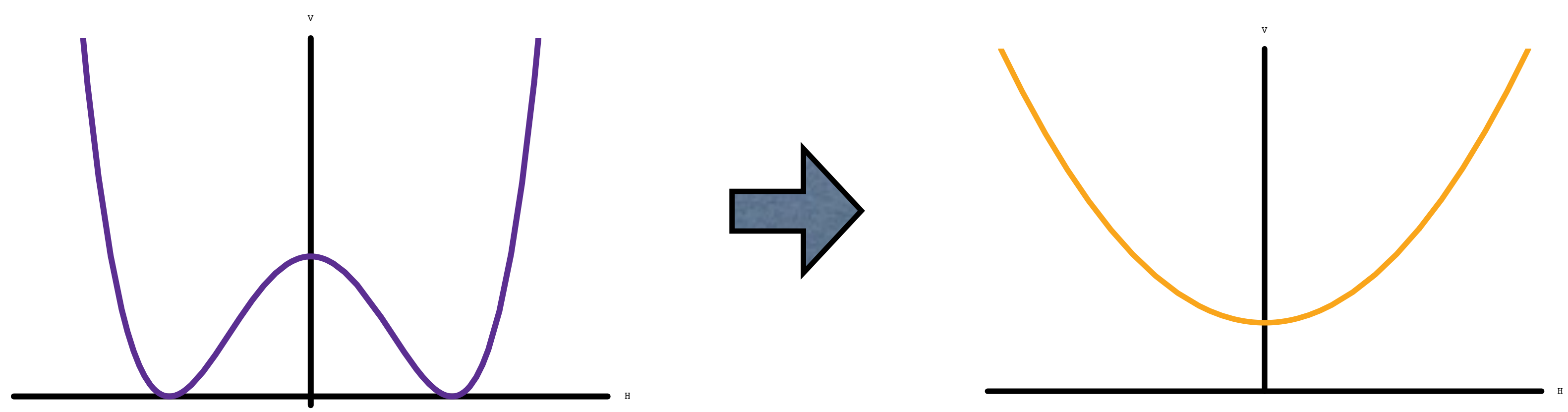


"visible sector"

- Light (even <GeV) DS particles are allowed thanks to their weak interactions with quarks, leptons
- Higgs decays to dark sector particles (e.g. $h \to SS$) may be a unique opportunity to produce them!
- Simplest scenario: $h \to \text{(invisible)}$
- But it is also possible that DS particles decay back to the SM → exotic Higgs decays (more later!)

Electroweak Phase Transition

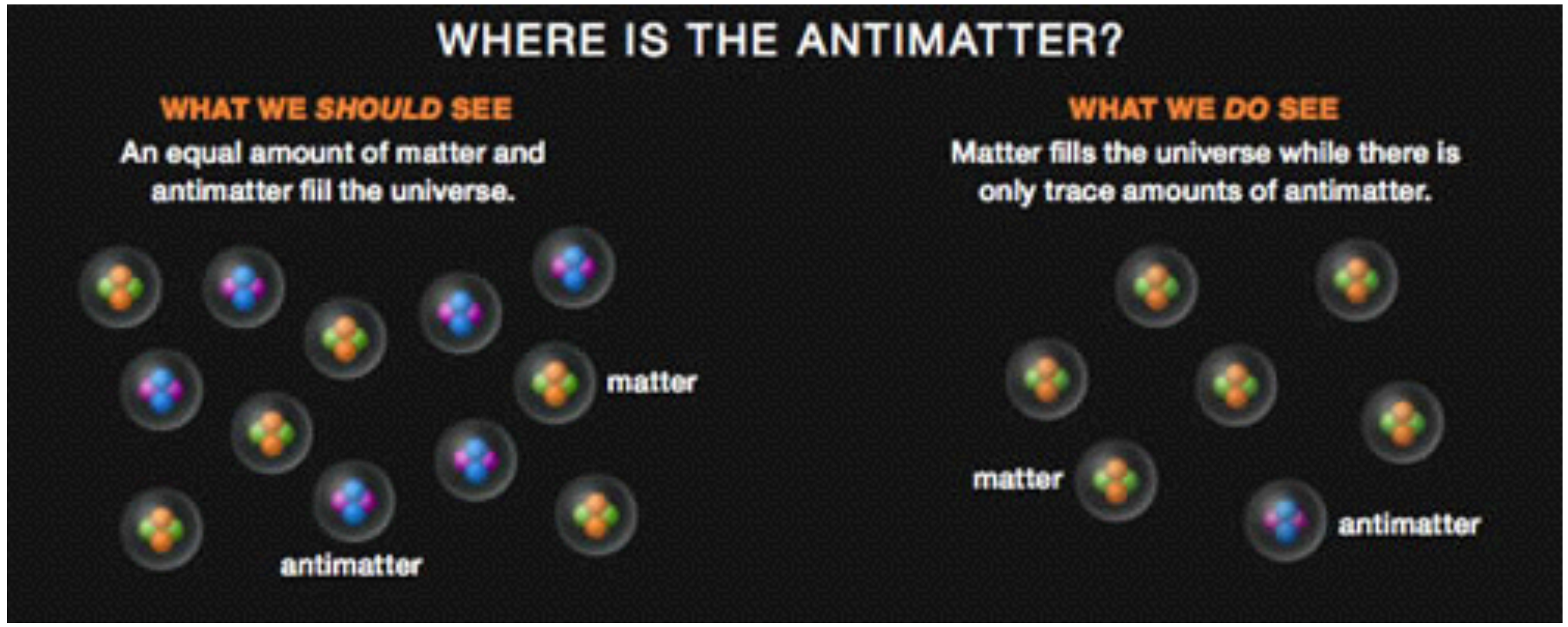
- Higgs boson moving through a plasma of quarks acquires a "thermal mass" (much like photon "plasma mass")
- At high plasma densities, EW symmetry is unbroken!



- Right after the Big Bang, the Universe was filled with dense quark plasma, was in unbroken EW phase
- As the Universe expanded and cooled, phase transition to current phase with broken symmetry - EWPT

$$kT \sim 100 - 1000 \text{ GeV}, \quad T \sim 10^{15} \text{ K}, \quad t \sim 10^{-10} \text{ sec}$$

EWPT and "Baryogenesis"

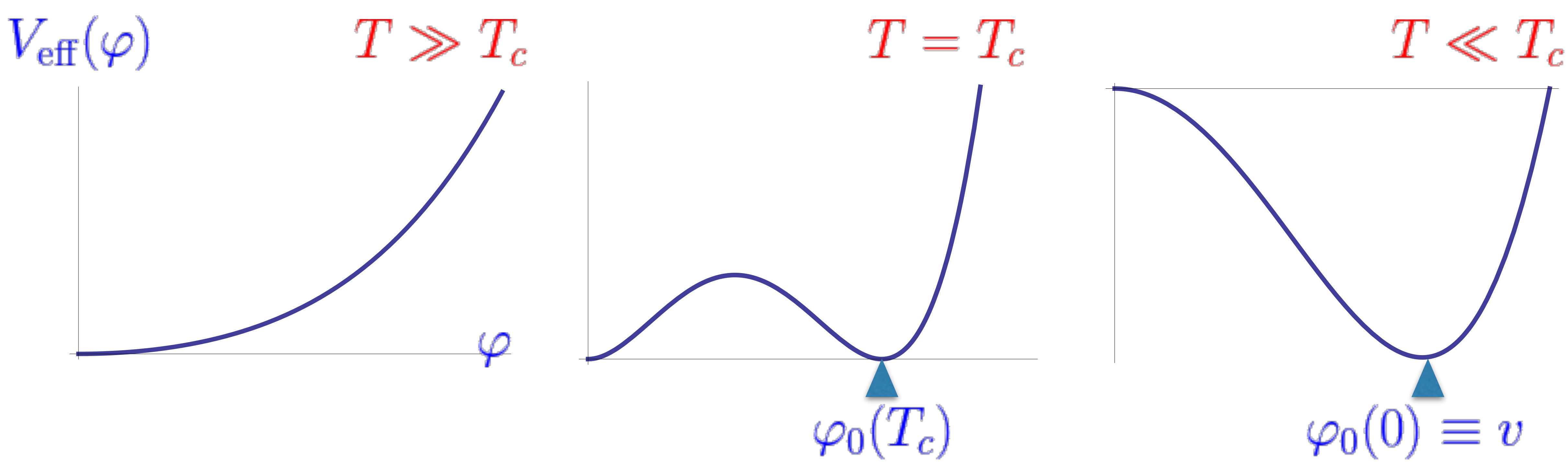


- It is believed that the observed matter-antimatter asymmetry arose dynamically, very soon (<1 sec) after the Big Bang

- Many mechanisms proposed; one of the most theoretically attractive is "Electroweak Baryogenesis", in which the asymmetry is generated during the EWPT

- It only works if transition is 1-st order (out-of-equlibrium)

First-Order EWPT



- In a 1st-order transition, bubbles of broken ("our") phase are nucleated inside the unbroken-EW phase

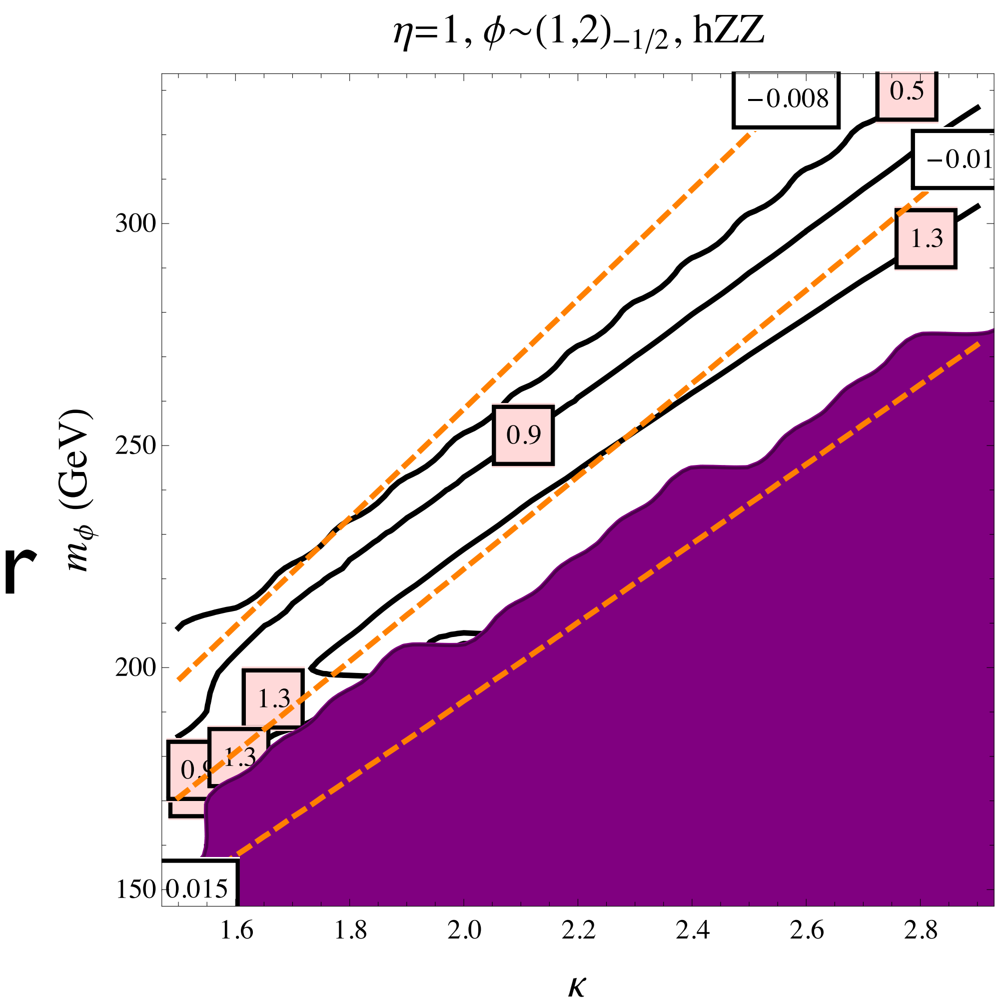
- Non-equilibrium process → satisfies one of the famous "Sakharov conditions" for generating matter-antimatter asymmetry

EWPT and Higgs Couplings

[A. Katz, MP]

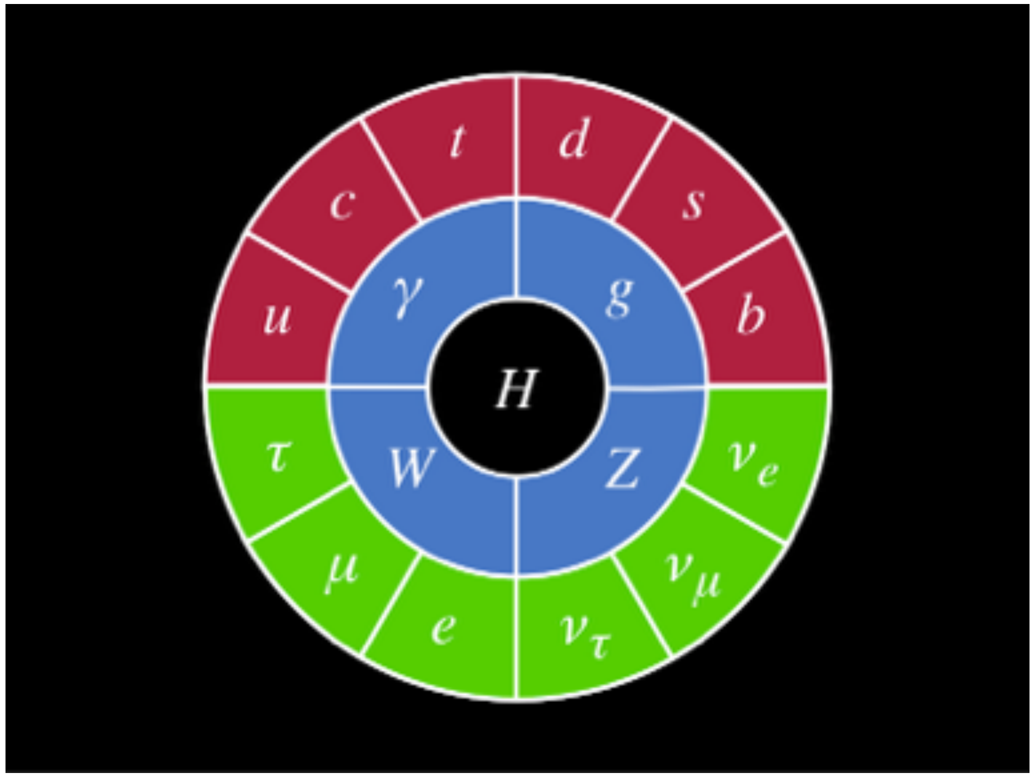
- In the SM, EWPT is 2nd-order → no EW Baryogenesis
- New particles, coupled to Higgs, may change the dynamics and re-open the window for EW Baryogenesis
- (Almost) all models with 1st order transition predict a large shift in Higgs self-coupling
- However, in many models the Higgs couplings to gluons, photon, W/Z are also shifted at 1-5%

Example: "LH Stau" model



Learn about Universe at ~1 ns after Big Bang!

HIGGS COUPLING MEASUREMENTS



Higgs Effective Field Theory

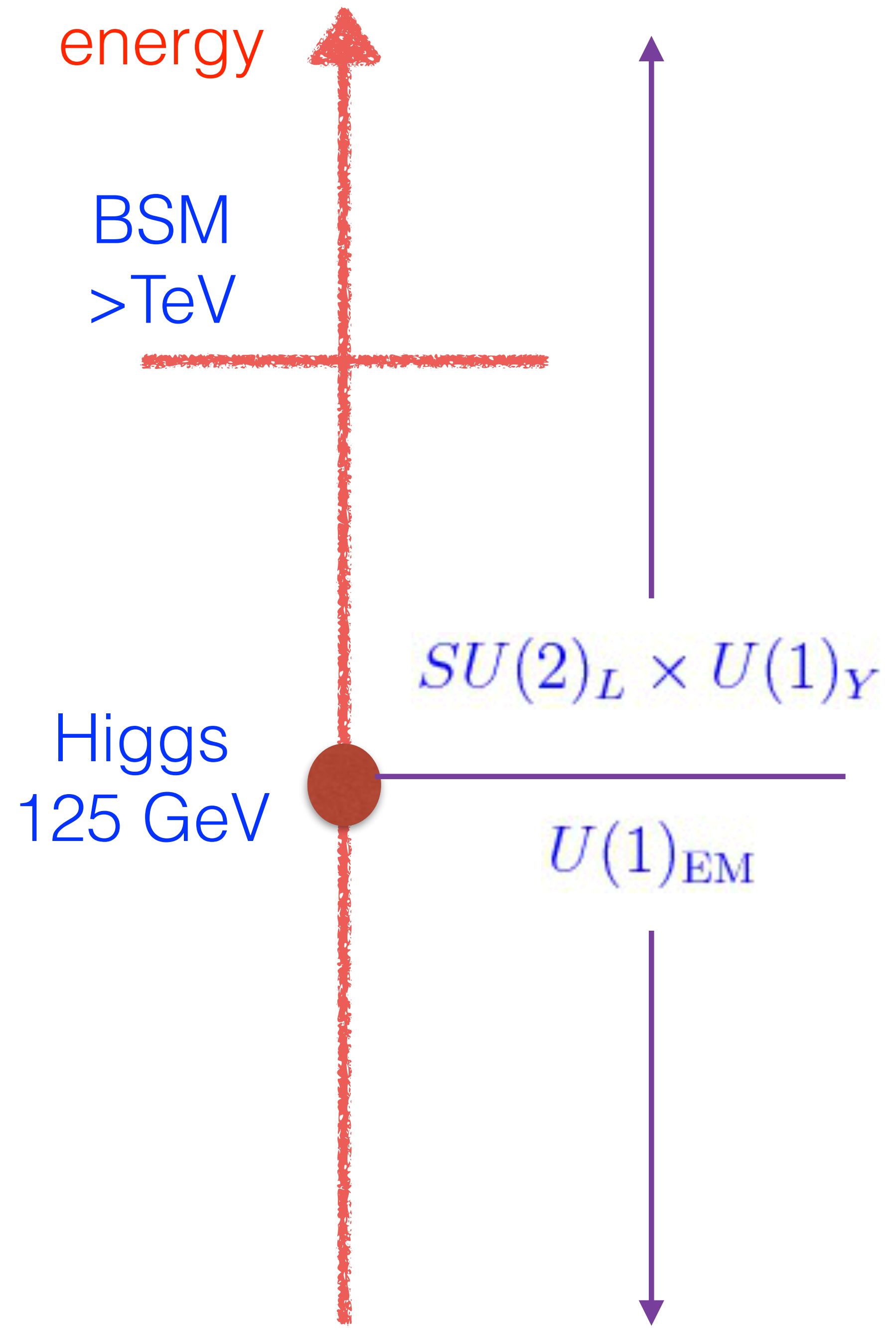
- LHC results strongly suggest that there is a significant mass gap between the Higgs and BSM particles

- In this situation, BSM corrections to Higgs properties are parametrically small:

$$\delta O \sim m_h^2 / M_{\rm BSM}^2$$

- Moreover, BSM physics must respect the full gauge symmetry of the SM

- Effective Field Theory (EFT) gives a systematic way to parametrize correction to Higgs properties under these conditions, by adding "effective operator" terms to the SM Lagrangian



Higgs Effective Field Theory

- At leading order there are 10 new operators relevant for precision Higgs program

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \Delta\mathcal{L}$$

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 + \ldots$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$

- Any new physics model (with mass gap) corresponds to a particular set of coefficients c_i

- All Higgs observables (as well as Precision Electroweak, etc.) can be expressed in terms of c_i

- "Measure Higgs couplings" = Determine c_i from data

EFT Coupling Fit

[talk by M. Peskin at this workshop]

Improved Formalism for Precision Higgs Coupling Fits

Tim Barklow, Gautier Durieux, Keisuke Fujii, Christophe Grojean, Jaiyin Gu, Sunghoon Jung, Robert Karl, Jenny List, Tomohisa Ogawa, Michael E. Peskin, Junping Tian, and Kechen Wang

- Global 20-parameter fit based on EFT formalism:
  - Precision electroweak data (current)
  - From HL-LHC (projected): $BR(h \to \gamma\gamma)/BR(h \to ZZ)$
  - From future e+e- collider (projected): $e^+e^- \to W^+W^-$

+ HIGGS DATA

EFT Coupling Fit

[talk by M. Peskin at this workshop]

[Barklow et.al., to appear]

Errors in %	ILC-250 2 ab^{-1} w. pol.	"CLIC" 2 ab^{-1} 380 GeV	"CEPC" 5 ab^{-1} no pol.	"FCC-ee" 10 ab^{-1} no pol.	full ILC 250+500 GeV
$g(hb\bar{b})$	1.5	1.2	1.1	0.8	0.6
$g(hc\bar{c})$	2.1	3.7	1.5	1.1	1.1
$g(hgg)$	1.9	2.0	1.4	1.0	0.9
$g(hWW)$	1.0	0.53	0.8	0.6	0.31
$g(h\tau\tau)$	1.6	2.0	1.2	0.9	0.8
$g(hZZ)$	1.0	0.53	0.8	0.64	0.31
$g(h\mu\mu)$	14	11	9.0	6.4	8.6
$g(hbb)/g(hWW)$	1.1	1.2	0.8	0.6	0.5
$g(hWW)/g(hZZ)$	0.033	0.029	0.036	0.03	0.02
Γ_h	3.1	2.6	2.3	1.8	1.5
$\sigma(e^+e^- \to Zh)$	0.70	0.56	0.49	0. 34	0.56
$BR(h \to inv)$	0.3	0.5	0.3	0.2	0.3
$BR(h \to other)$	1.6	1.4	1.2	0.8	1.1

EFT Coupling Fit

- An interesting example is couplings to W/Z bosons

$$\mathcal{L} = (1+\eta_Z)\frac{2m_Z^2}{v}hZ_\mu Z^\mu + \zeta_Z Z_{\mu\nu}Z^{\mu\nu} + \\ (1+\eta_W)\frac{2m_W^2}{v}hW_\mu W^\mu + \zeta_W W_{\mu\nu}W^{\mu\nu}$$

<<1 from PEW

$$\eta_W = -\frac{1}{2}c_H \qquad \eta_Z = -\frac{1}{2}c_H \boxed{- c_T}$$

$$\zeta_W = (8c_{WW})$$

$$\zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + (s_w^4/c_w^2)(8c_{BB})$$

- Compare this to the usual "kappa framework":

$$\mathcal{L} = \kappa_Z\frac{2m_Z^2}{v}hZ_\mu Z^\mu + \kappa_W\frac{2m_W^2}{v}hW_\mu W^\mu$$

- HEFT relates W and Z couplings, but introduces additional spin structure

EFT Coupling Fit

- Polarized beams play a crucial role in disentangling the two spin structures

$$\sigma = \frac{2}{3}\frac{\pi\alpha_w^2}{c_w^4}\frac{m_Z^2}{(s-m_Z^2)}\frac{2k_Z}{\sqrt{s}}(2+\frac{E_Z^2}{m_Z^2})\cdot Q_Z^2\cdot\left[1+2a+2\,\frac{3\sqrt{s}E_Z/m_Z^2}{(2+E_Z^2/m_Z^2)}\,b\right]$$

The a and b coefficients depend on beam polarization:

$e_L^- e_R^+$

$$Q_{ZL} = (\frac{1}{2}-s_w^2)\ , \qquad a_L = -c_H$$

$$b_L = c_w^2(1+\frac{s_w^2}{1/2-s_w^2}\frac{s-m_Z^2}{s})(8c_{WW})$$

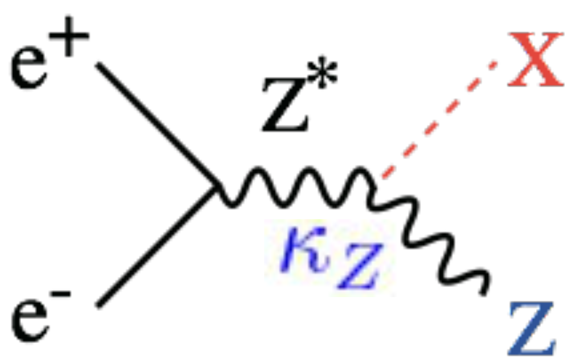
$e_R^- e_L^+$

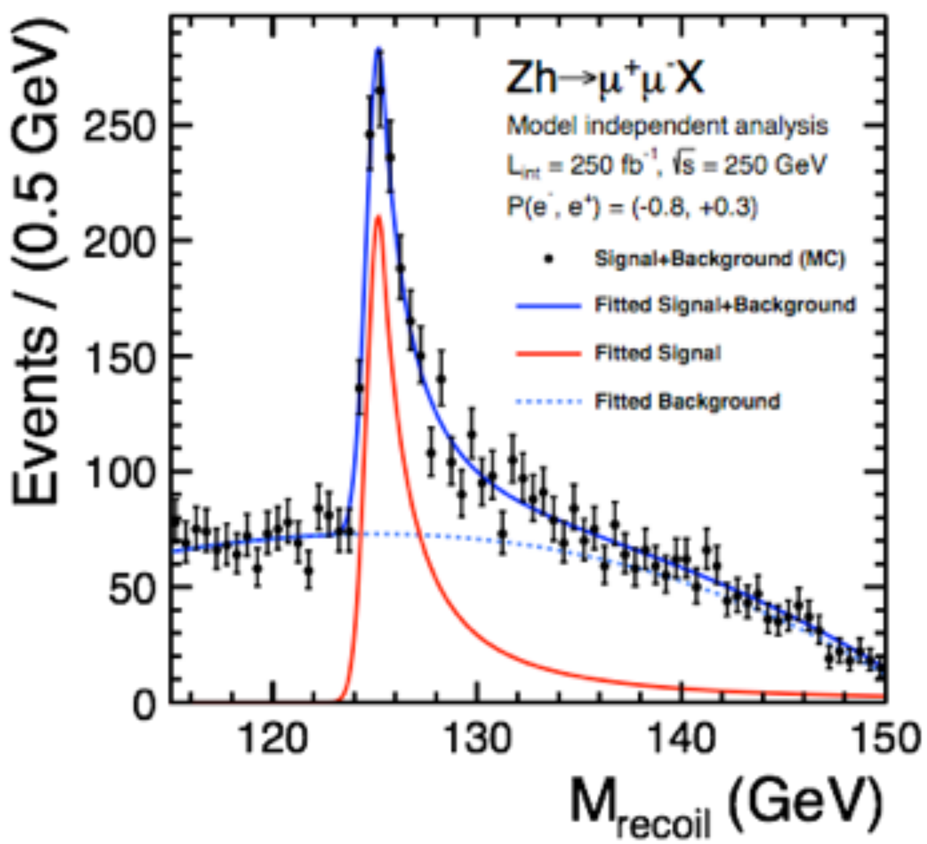
$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H$$

$$b_R = c_w^2(1-\frac{s-m_Z^2}{s})(8c_{WW})$$

- Angular distributions in $e^+e^- \to hZ$ can also be used, but have weaker analyzing power and require more luminosity to achieve the same result

Total Higgs Width





[Li et.al. (ILD Collaboration)]

- Total Higgs width is too small (4 MeV) to be measured directly. Required to infer couplings from measured rates.
- Identify Zh events by reconstructing recoil mass $M_X^2 = (p_{CM} - (p_{\ell^+} + p_{\ell^-}))^2$
- No observation of the Higgs is needed $\Rightarrow$ unbiased, model-independent measurement of cross section
- Infer κ_Z from cross-section, use it to calculate partial width
- Infer total width: $R(ZZ^*) \propto \dfrac{\boxed{\Gamma(h \to ZZ^*)}}{\Gamma_{tot}}$

Total Higgs Width in EFT

- However, $\mathrm{Br}(h \to ZZ^*) \simeq 2.5\%$. The total width measurement is statistically limited.

- In the "kappa framework", this limits the power of a 250 GeV collider. With 2 ab-1, errors on all couplings are ~3.5%, dominated by total width error. Studying W-fusion production at 500 GeV is necessary to get to ~1%.

- In the HEFT framework, W and Z couplings are not independent: they are related by the Electroweak symmetry.

- The total width can then be inferred from WW final state, for which the rate is about 8 times larger than ZZ. 1% error can be achieved with 250 GeV data alone.

- In discussions of staging options, optimization may depend on underlying theoretical framework.

Discovery Potential

[talk by M. Peskin at this workshop]

[Barklow et.al., to appear]

- Can ~1% level Higgs coupling measurements discover new physics not already seen at the LHC?
- Selection of 9 models with all new particles outside of projected reach of direct searches at HL-LHC

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [34]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [36]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [36]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [36]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [38]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [39]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [40]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [41]	-1.5	- 1.5	10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [42]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Discovery Potential

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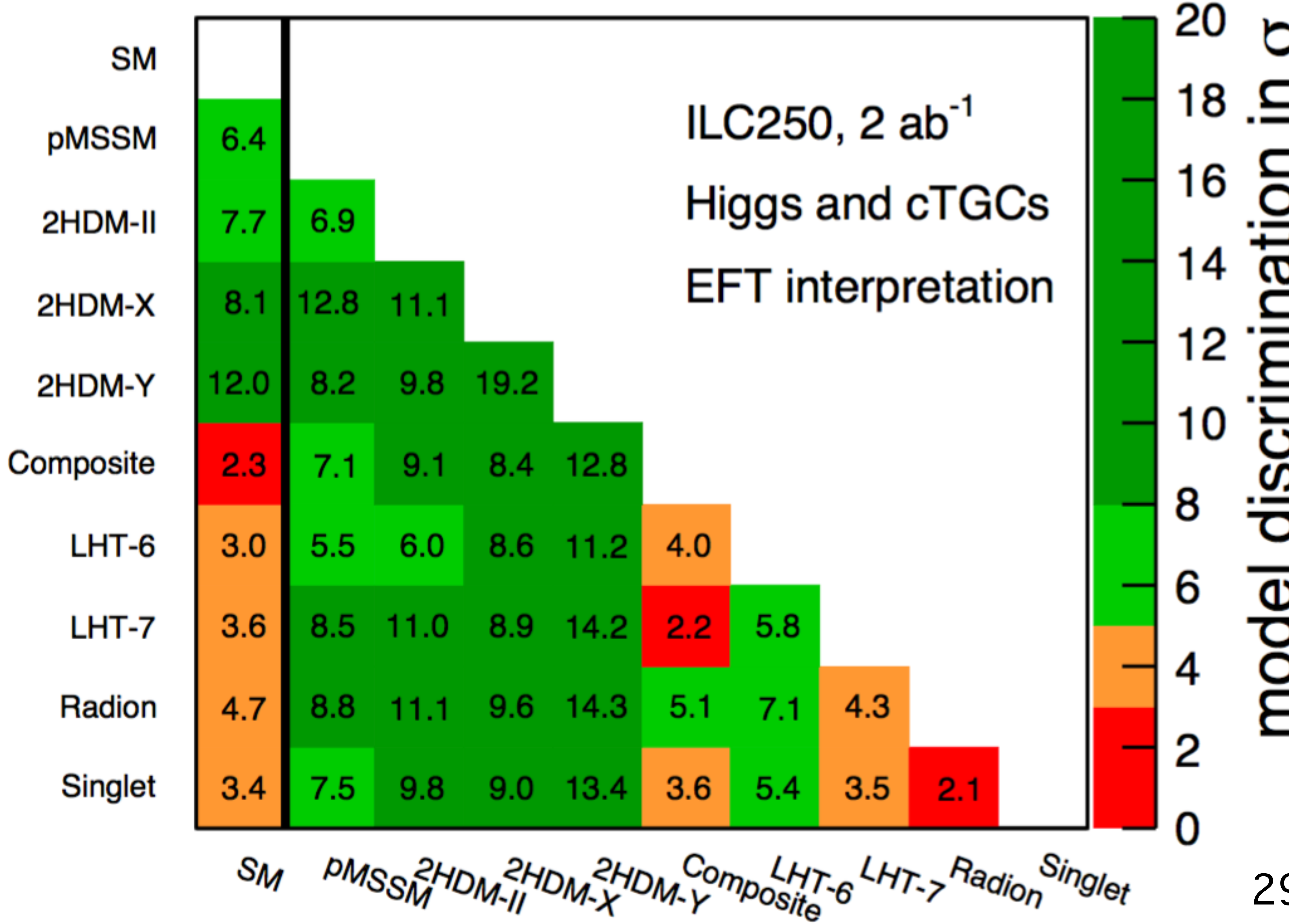
1	MSSM [34]	[illegible]	[illegible]	[illegible]	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [36]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [36]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [36]	+10.1	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.1	-0.2
5	Composite Higgs [38]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [39]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [40]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [41]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1.5	-1.0	-1.5
9	Higgs Singlet [42]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-3.5	-3.5	-3.5

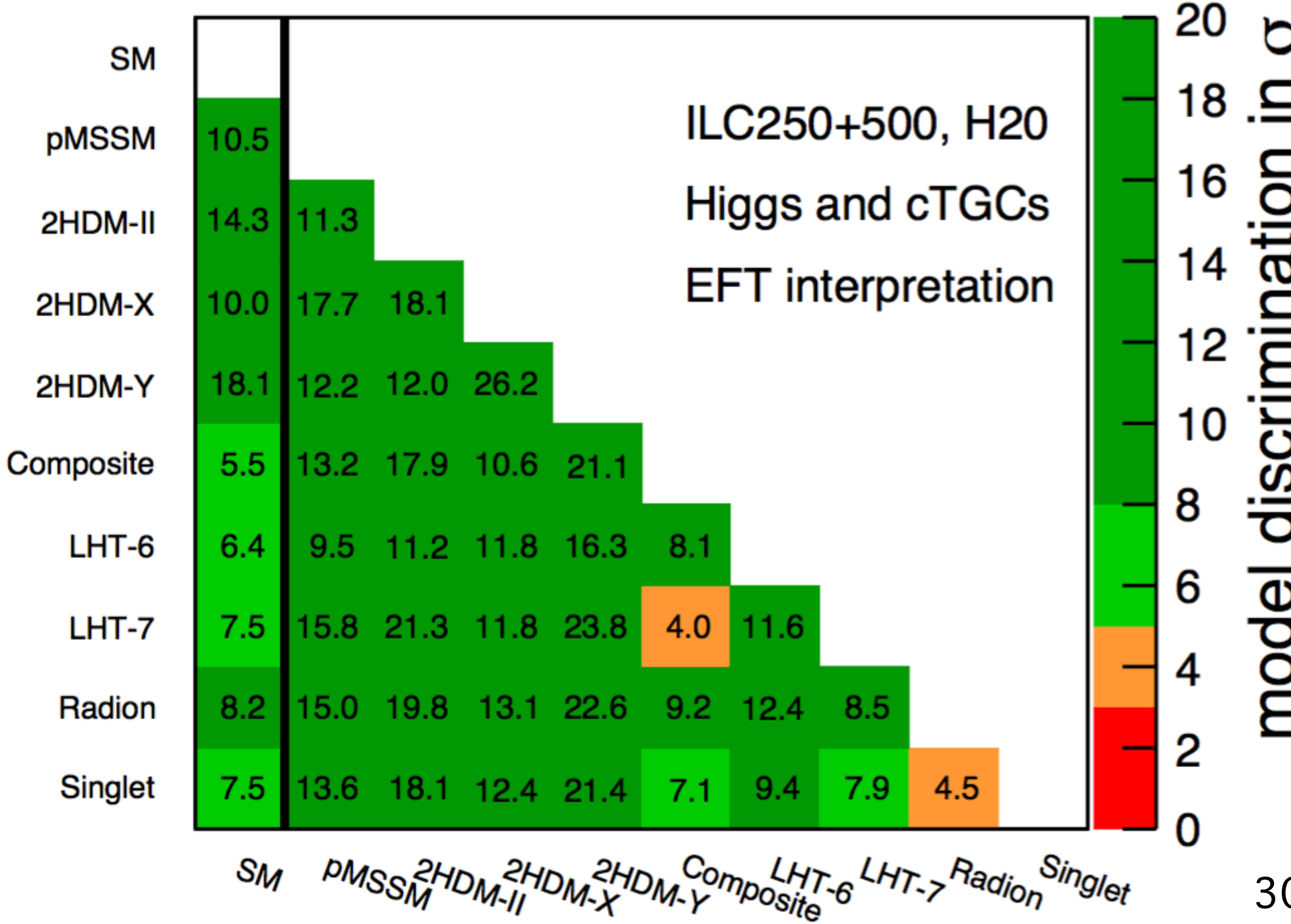
NATURALNESS

COMPOSITENESS

EW BARYOGENESIS



ILC250, 2 ab^{-1}
Higgs and cTGCs
EFT interpretation
SM
pMSSM 6.4
2HDM-II 7.7 6.9
2HDM-X 8.1 12.8 11.1
2HDM-Y 12.0 8.2 9.8 19.2
Composite 2.3 7.1 9.1 8.4 12.8
LHT-6 3.0 5.5 6.0 8.6 11.2 4.0
LHT-7 3.6 8.5 11.0 8.9 14.2 2.2 5.8
Radion 4.7 8.8 11.1 9.6 14.3 5.1 7.1 4.3
Singlet 3.4 7.5 9.8 9.0 13.4 3.6 5.4 3.5 2.1
SM pMSSM 2HDM-II 2HDM-X 2HDM-Y Composite LHT-6 LHT-7 Radion Singlet
0 2 4 6 8 10 12 14 16 18 20
model discrimination in σ



ILC250+500, H20
Higgs and cTGCs
EFT interpretation
SM
pMSSM
2HDM-II
2HDM-X
2HDM-Y
Composite
LHT-6
LHT-7
Radion
Singlet
10.5
14.3 11.3
10.0 17.7 18.1
18.1 12.2 12.0 26.2
5.5 13.2 17.9 10.6 21.1
6.4 9.5 11.2 11.8 16.3 8.1
7.5 15.8 21.3 11.8 23.8 4.0 11.6
8.2 15.0 19.8 13.1 22.6 9.2 12.4 8.5
7.5 13.6 18.1 12.4 21.4 7.1 9.4 7.9 4.5
0
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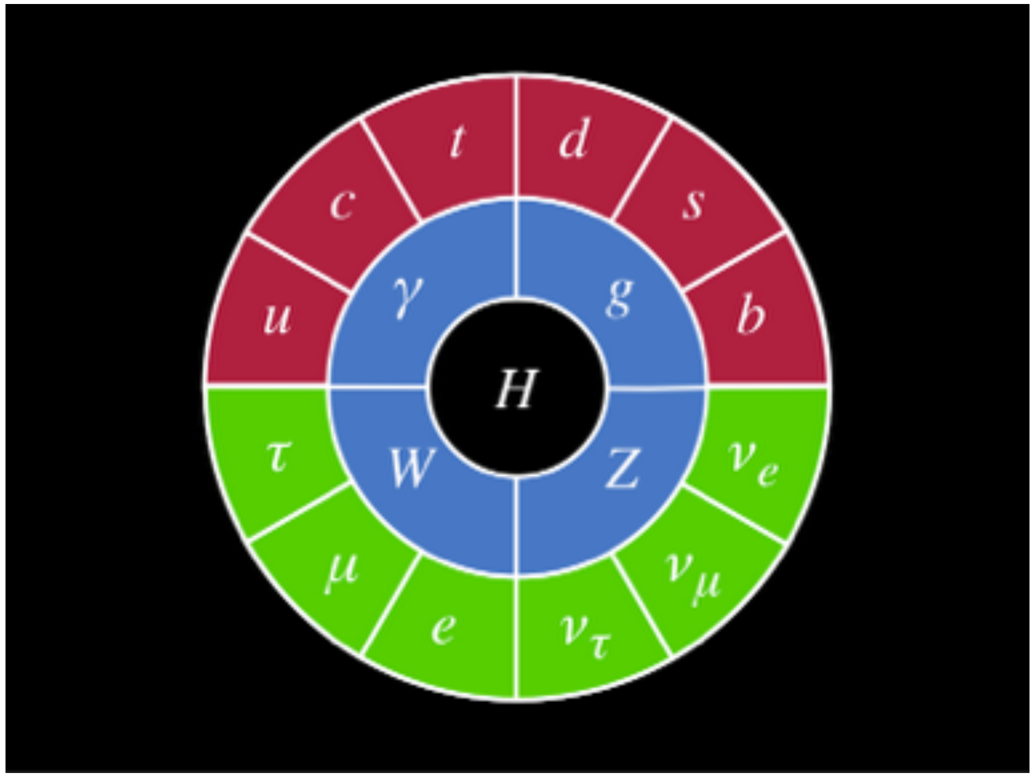
18
20
model discrimination in σ

EXOTIC HIGGS DECAYS

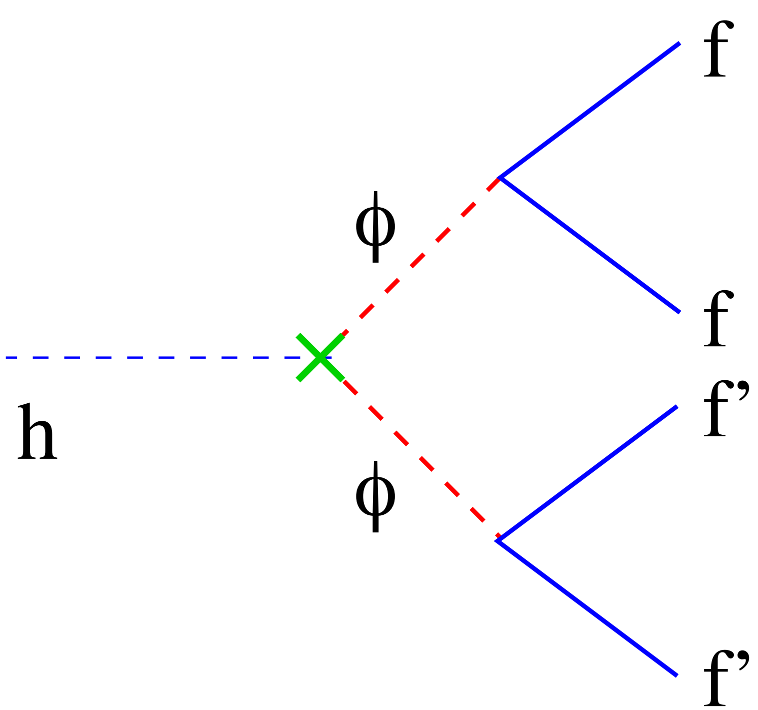


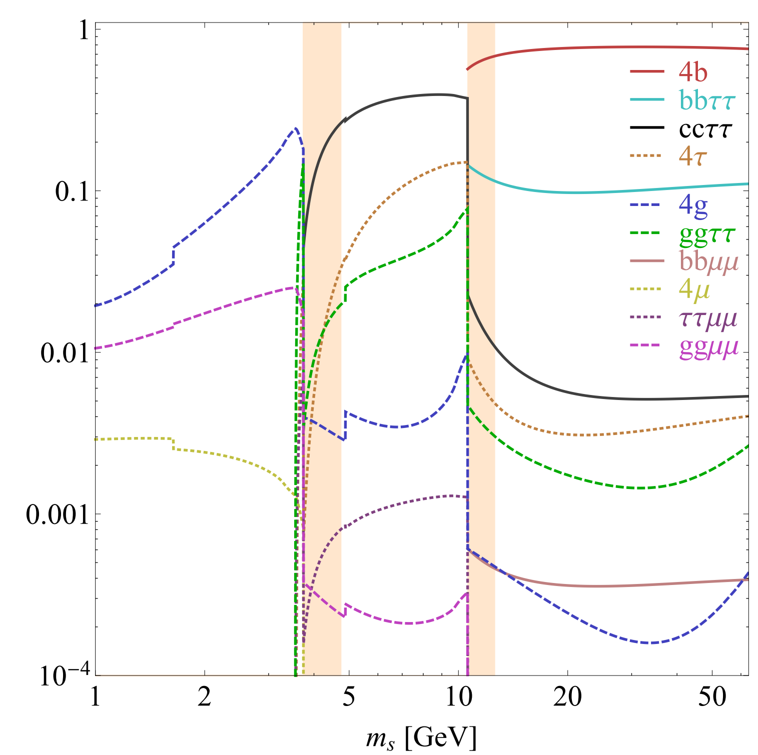
Exotic Higgs Decays

- Higgs decays may provide the only sizable production mechanism for Dark Sector states: $h \to \phi\phi$

- However the fate of ϕ is uncertain. Even very small coupling will make it decay to SM fermions if no other channel is open.

- Final states are highly model-dependent, depending on both mass and couplings





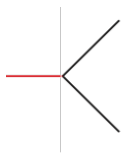
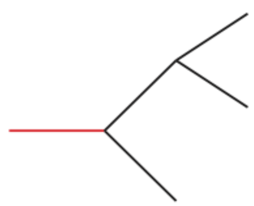
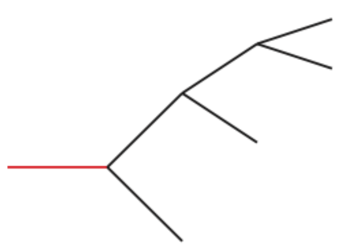
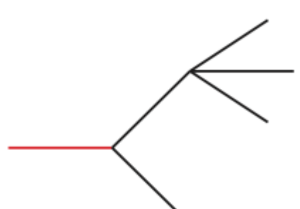
$$\mathrm{BR}(\phi\phi \to (f\bar{f})(f'\bar{f}'))$$

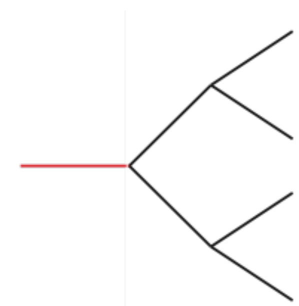
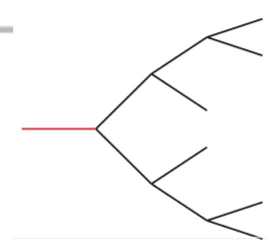
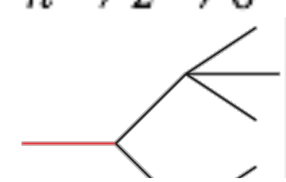
Example: $\Gamma(\phi \to f\bar{f}) \;\propto\; m_f^2$ from Higgs mixing.

Exotic Higgs Decays

- There may also be cascades, stable "LSP" in the dark sector, etc.

- A broad variety of topologies, final states are possible

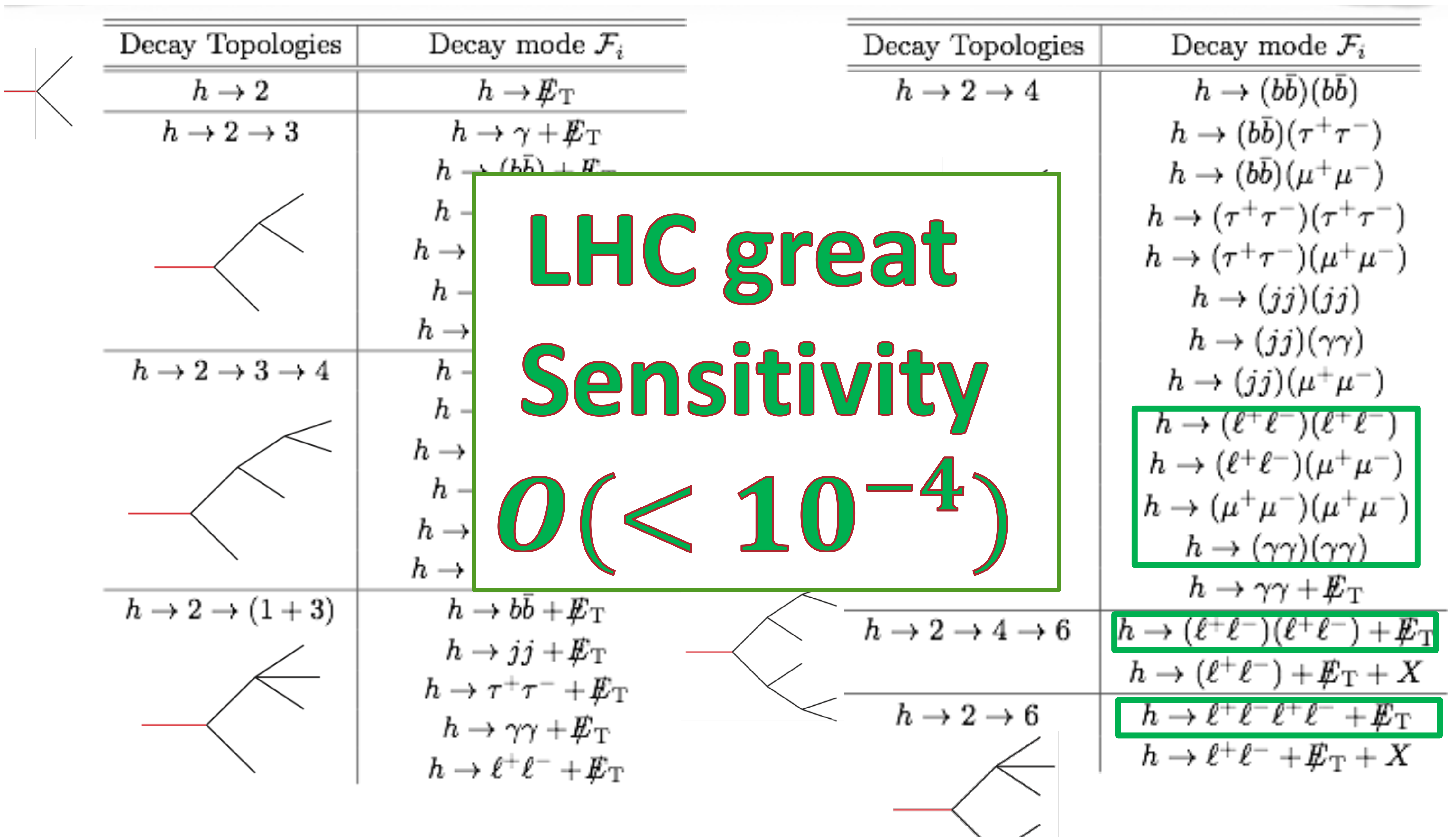
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to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

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

[Curtin, Essig et.al.]

Exotic Higgs Decays

- There may also be cascades, stable "LSP" in the dark sector, etc.
- A broad variety of topologies, final states are possible



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
	$h \to$
	h
	$h \to$
$h \to 2 \to 3 \to 4$	h
	h
	$h \to$
	h
	$h \to$
	$h \to$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_{\mathrm{T}}$
	$h \to jj + \not{E}_{\mathrm{T}}$
	$h \to \tau^+\tau^- + \not{E}_{\mathrm{T}}$
	$h \to \gamma\gamma + \not{E}_{\mathrm{T}}$
	$h \to \ell^+\ell^- + \not{E}_{\mathrm{T}}$

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

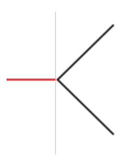
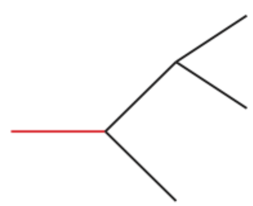
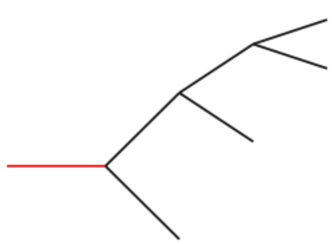
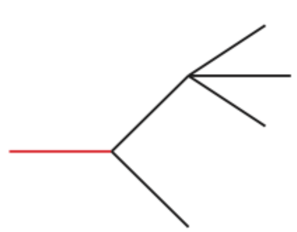
LHC great Sensitivity $O(< 10^{-4})$

[Zhen Liu, LCWS16 talk]

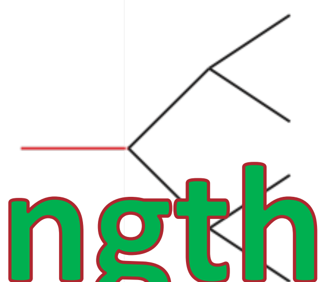
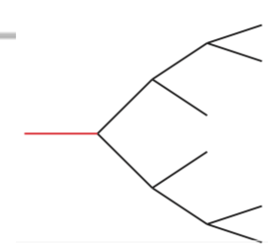
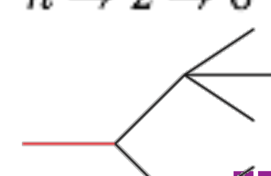
Exotic Higgs Decays

- There may also be cascades, stable "LSP" in the dark sector, etc.

- A broad variety of topologies, final states are possible

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

LC's Strength

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

[Zhen Liu, LCWS16 talk]

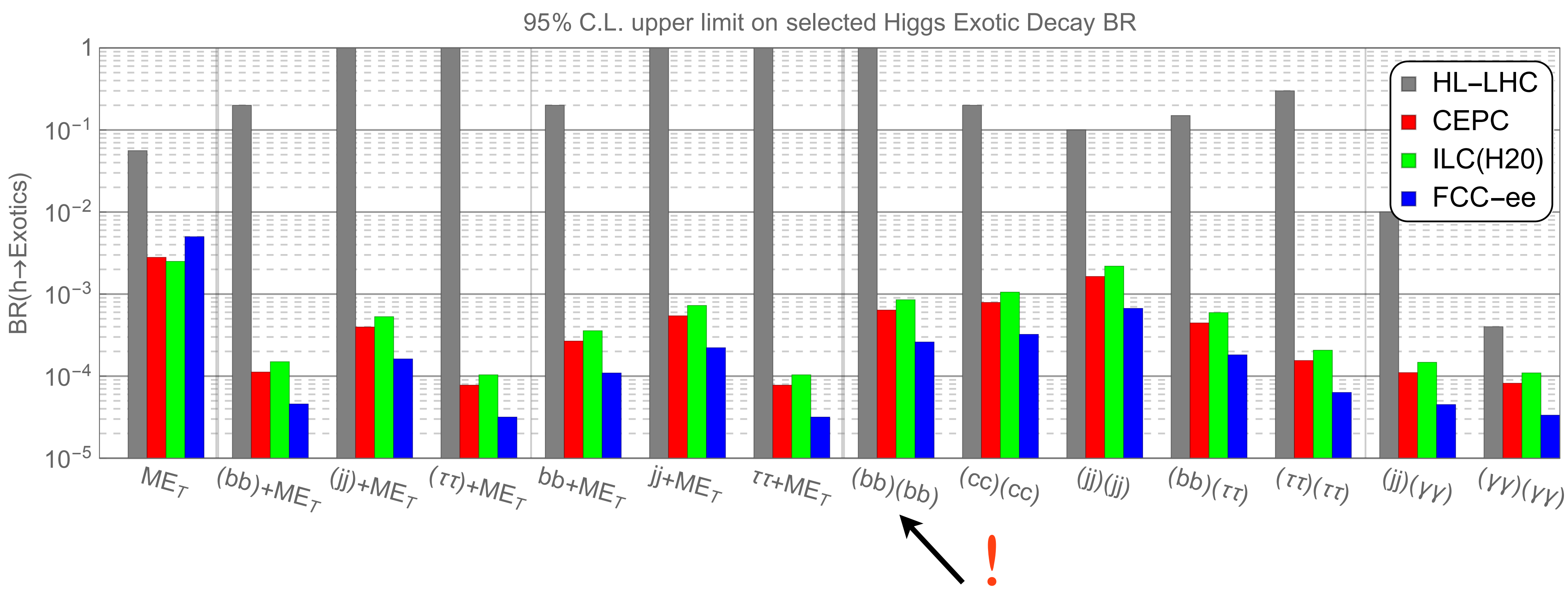
Exotic Higgs Decays

- A comparative collider study: [Liu, Wang, Zhang 2016]

$$\mathrm{ILC} = 2\,\mathrm{ab}^{-1}\ @\ 250\,\mathrm{GeV}$$

$$\mathrm{CEPC} = 5\,\mathrm{ab}^{-1}\ @\ 240\,\mathrm{GeV}$$

$$\mathrm{FCC\text{-}ee} = 30\,\mathrm{ab}^{-1}\ @\ 240\,\mathrm{GeV}$$



- Dramatic improvement over HL-LHC in hadronic final states

Other Physics Topics

- Hermetic search for new physics up to ~125 GeV (extending LEP2). Light Higgsinos may remain hidden at HL-LHC if mass splittings are small. [H. Baer]
- Four-fermi interactions: $e^+e^- \to q\bar{q}, b\bar{b}$. Probe the structure of b couplings, address LEP anomalies. [R. Poeschl]
- Top FCNC: Search for $e^+e^- \to t\bar{c}$. [M. Vos]
- …

Conclusions

- A program of precision studies of the Higgs boson properties offers unique opportunities to extend our knowledge of laws of physics at short distances
- Higgs boson has many special properties that make it worth exploring:
  - Controls the fate of the Standard Model at high energies
  - The first known spin-less particle - “naturalness mystery”
  - Plays key role in electroweak phase transition in early universe, may give rise to matter-antimatter asymmetry
  - Can serve as a portal to Dark Sector, possibly including the dark matter particle

Conclusions

- A 250 GeV electron-positron collider can perform the measurements required to take the next step in the Precision Higgs program

  - 1%-level precision on many of the Higgs couplings, large improvement over HL-LHC measurements

  - Sensitivity to models not accessible to direct searches at HL-LHC, through Higgs coupling shifts

  - Model discrimination power if deviations from the SM are observed

  - Sensitive searches for well-motivated exotic Higgs decays not accessible at HL-LHC

LET'S BUILD IT!