Non-SUSY BSM Motivations
for
Future Circular Colliders

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Introduction

- The Higgs boson discovery at the LHC completes the standard model, but many questions in high energy physics are left unanswered.
- New physics beyond the standard model must exist, both from theoretical and experimental (observational) points of view.
- SUSY is still a leading candidate, but there are also interesting non-SUSY scenarios which will be the topic of this talk.

Introduction

- The main driving force in our understanding of our universe at the most fundamental level is the energy frontier.
  - Higher energy *pp* collider can direct access new states with higher masses and new interactions at shorter distance.
  - High luminosity e^+e^- collider can perform precise measurements to test the consistency of the theory and also probe physics at high scales indirectly.

Introduction

- There are too many possible new physics which can be tested at future colliders. Instead of discussing random new particles. new forces, or new operators, one may first focus on the cases which are motivated by the big questions that require new physics beyond the standard model.
- Certainly there can be new physics at the TeV scale which is not connected to these big questions in any obvious way. It will be as exciting if it's discovered and will raise more questions for investigations.

Big Questions

- Origin of the electroweak symmetry breaking and the hierarchy problem.
- Dark matter - Pyungwon Ko's talk
- Baryon asymmetry in the universe - Patrick Meade's talk
- Flavor in quark and lepton masses and mixings - Cai-Dian Lu's talk
- Inflation, dark energy are not likely accessible at foreseeable future colliders. However, discovery of new physics at colliders can affect our thinking of these problems.

Electroweak Symmetry Breaking

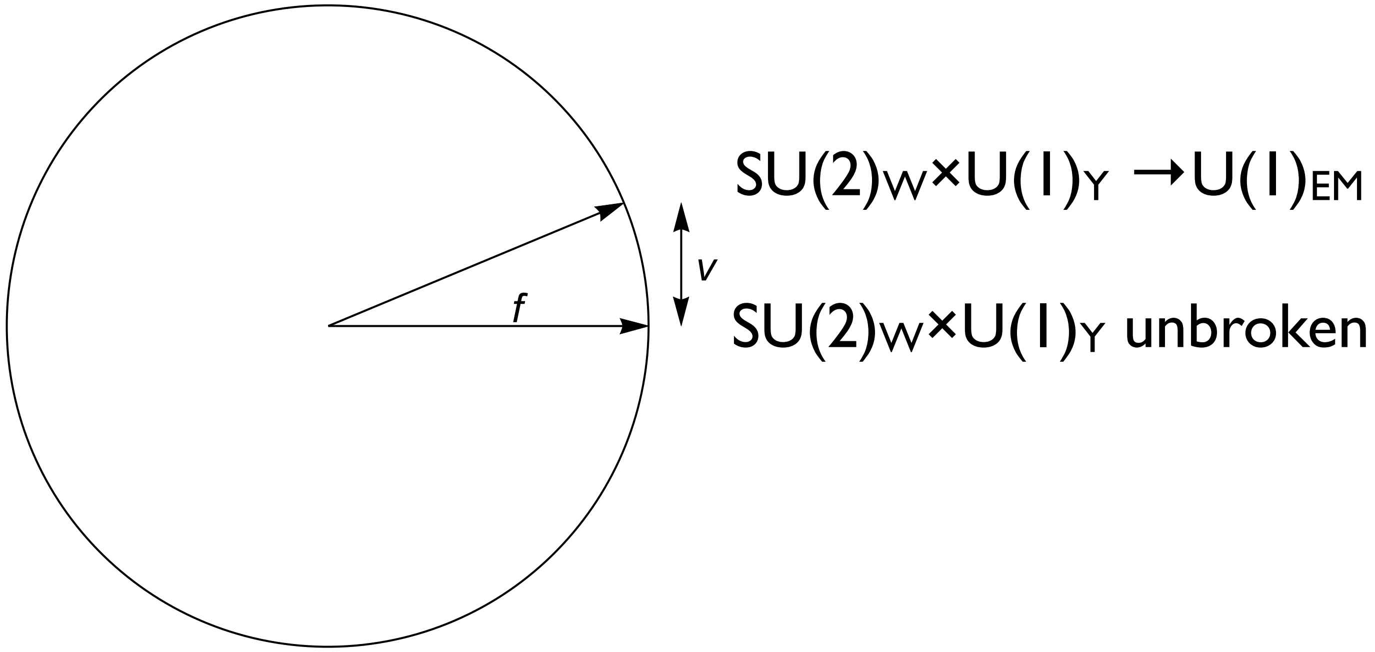
- The hierarchy problem is still the strongest indicator that there should be new physics near the weak scale.
- Of course, naturalness is only a probability statement, which cannot be used as a theorem to guarantee discovery.
- Not finding new physics so far at the LHC may be a disappointment. However, being unlucky at the LHC 7-8 TeV run can not be used to invalidate the naturalness argument based on QFT which underlies all our understanding of elementary particle physics.

Composite Higgs

- For non-SUSY scenarios, technicolor theories without a light Higgs boson have been ruled out by the Higgs discovery.
- The composite Higgs boson from strong dynamics is generically heavy unless there is an (approximate) symmetry to protect its mass, i.e., Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of some broken global symmetry [usually SU(3)/SU(2) or SO(5)/SO(4)].
- There are many variations, e.g., little Higgs, holographic Higgs, etc., but underlying structure has a lot similarities.

Composite Higgs

- *f* is the global symmetry breaking scale. The explicit breakings create a potential for the pNGB Higgs such that the minimum is shifted a bit (by *v*) from the $SU(2)_W \times U(1)_Y$ preserving point.



The tuning is typically characterized by $\xi \equiv v^2/f^2$.

To avoid excessive fine-tuning, *f* should be close to the weak scale (~ 1 TeV).

Composite Higgs

- The new physics is characterized by 2 scales:
  - f : global symmetry breaking scale
  - $m_\rho = g_\rho f$: mass of the new states that cut of the radiative corrections to the Higgs mass, or resonances of the strong dynamics. (Typically $g_\rho > 1$ for strong dynamics and $g_\rho \sim 1$ for little Higgs type models.)
- At low energy the new physics is integrated out to generate higher-dim operators suppressed by f or m_ρ.

Strongly interacting light Higgs (SILH), Giudice, et al, hep-ph/0703164

Composite Higgs

- For $m_\rho > f$, the leading effects come from

$$\frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)+\frac{c_T}{2f^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(H^\dagger\overleftrightarrow{D}_\mu H\right)$$
$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3+\left(\frac{c_y y_f}{f^2}H^\dagger H\bar{f}_L H f_R+\text{h.c.}\right)$$

c_H : universal reduction of Higgs coupling by $1-\frac{c_H v^2}{2f^2}$

c_T : custodial SU(2) violation, $\Delta\rho=\widehat{T}=c_T\frac{v^2}{f^2}$

c_y : modification of Higgs-fermion couplings, depending on the fermion rep under the global symmetry.

c_6 : modification of Higgs self couplings.

Composite Higgs

- Operators suppressed by *m*$_\rho$ (form factors):

$$\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)(D^\nu W_{\mu\nu})^i+\frac{ic_B g'}{2m_\rho^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)(\partial^\nu B_{\mu\nu})$$

$$\widehat{S}=(c_W+c_B)\,\frac{m_W^2}{m_\rho^2}$$

- Loop suppressed operators:

$$+\frac{ic_{HW}g}{16\pi^2f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu}+\frac{ic_{HB}g'}{16\pi^2f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

$$+\frac{c_\gamma {g'}^2}{16\pi^2f^2}\frac{g^2}{g_\rho^2}H^\dagger HB_{\mu\nu}B^{\mu\nu}+\frac{c_g g_S^2}{16\pi^2f^2}\frac{y_t^2}{g_\rho^2}H^\dagger HG^a_{\mu\nu}G^{a\mu\nu}.$$

- 3rd gen often different, there are flavor-dependent operators.

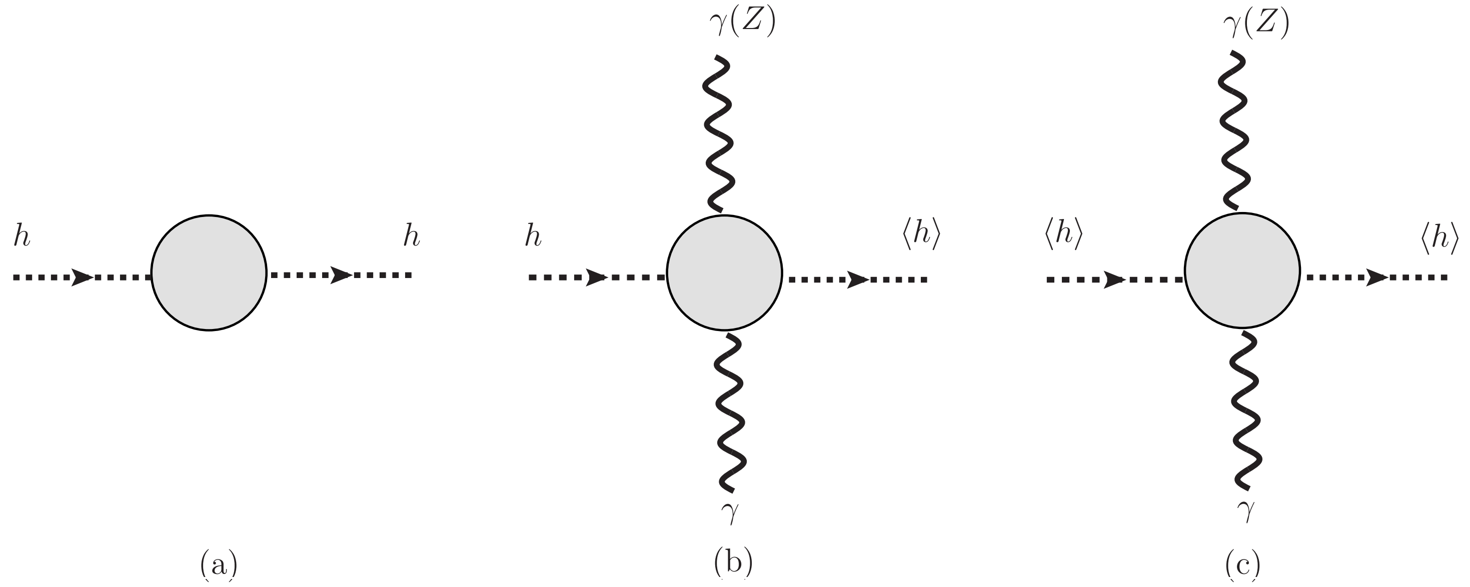
$$\frac{c_t y_t}{f^2}H^\dagger H\bar{q}_L\tilde{H}t_R+h.c.+\frac{ic_R}{f^2}H^\dagger D_\mu H\bar{t}_R\gamma^\mu t_R+\frac{c_{4t}}{f^2}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$$

$$\frac{c_q y_b}{f^2}H^\dagger H\bar{q}_LHb_R+\frac{c_q y_t}{f^2}H^\dagger H\bar{q}_L\tilde{H}t_R+h.c.+\frac{ic_L^{(1)}}{f^2}H^\dagger D_\mu H\bar{q}_L\gamma^\mu q_L$$

$$+\frac{ic_L^{(3)}}{f^2}H^\dagger\sigma^iD_\mu H\bar{q}_L\gamma^\mu\sigma^iq_L+\frac{c_{4q}}{f^2}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)\,.$$

Composite Higgs

- The new particles (resonances) which cut off the quadratic contributions to the Higgs mass from the SM fields generically carry SM charges. They contribute c_γ and c_g at one loop, modifying the $h \to \gamma\gamma$, $h \to gg$ couplings.



Gori and Low, arXiv:1307.0496

They can also produce corrections to EW observables.

Precision Measurements

- Measurements at Z pole: The precision of LEP of EW observables is ≳ 0.1%, sensitive to dim-6 operators suppressed by 1/(a few TeV)^2. The next e^+e^- collider may reduce the uncertainties by factors of 10-100, probing scales 3-10 times higher.
  - Important measurements for composite Higgs: $\widehat{S}$, $\widehat{T}$, $Z \to b\bar{b}$, etc.

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Key	Challenge
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6) keV	$<$ 100 keV	$E_{\rm beam}$ calibration	QED corrections
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{\rm had}$)	2495200 ± 2300	Z Line shape scan	8 (10) keV	$<$ 100 keV	$E_{\rm beam}$ calibration	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	$<$ 0.001	Statistics	QED corrections
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	$<$ 0.004		Bhabha scat.
N_ν	... and sterile ν's	2.92 ± 0.05	Zγ, 161 GeV	0.0010 (12)	$<$ 0.001	Statistics	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	$<$ 0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ϵ_3, $\Delta\alpha_{\rm had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	$<$ 0.000015	4 bunch scheme, 2exp	Design experiment
m_W (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{\rm had}$	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	$<$ 0.5 MeV	$E_{\rm beam}$, Statistics	QED corrections
$m_{\rm top}$ (MeV)	Input	173200 ± 900	t$\bar{\rm t}$ threshold scan	10 (12) MeV	$<$ 10 MeV	Statistics	Theory interpretation

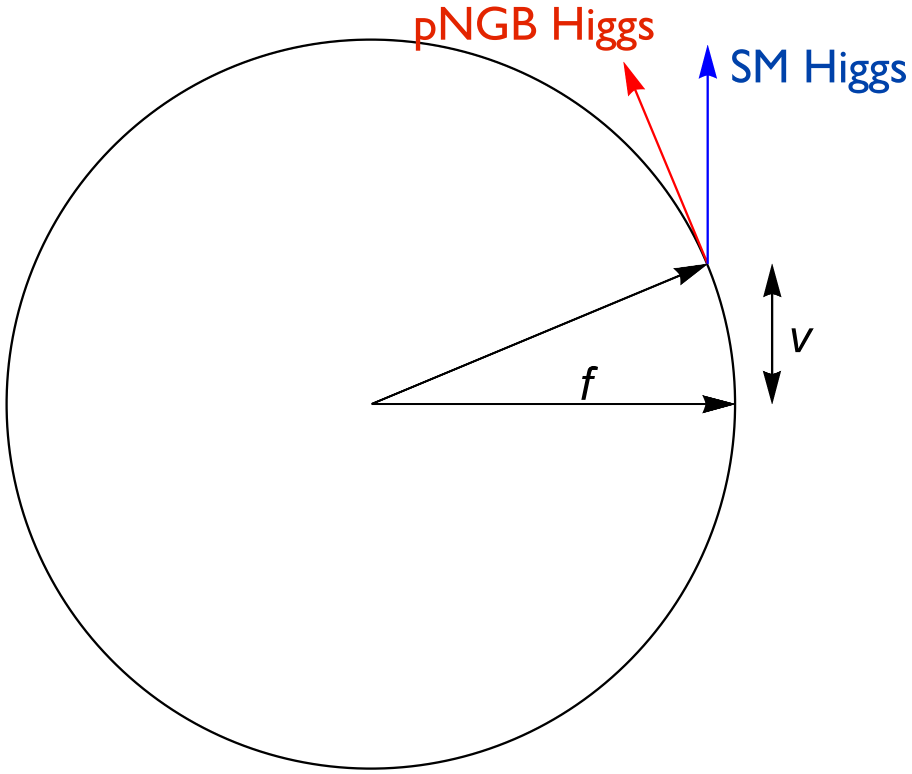
The TLEP Design Study Working Group, arXiv:1308.6176

Higgs Couplings

- c_H: most important parameter. It's possible to build models with other parameters suppressed.
  - c_T can be suppressed by a custodial symmetry.
  - Effects from tree-level mixings between SM fields and new fields may be suppressed by a Z_2 symmetry (e.g., T-parity in little Higgs models).
  - Loop induced effects are not suppressed by this Z_2 though, so measurements of $h \to gg, \gamma\gamma$ are important tests of the new states which solve the hierarchy problem. (However, they can even be absent if the new states don't carry SM charges, e.g., Twin Higgs.)

Higgs Couplings

- c_H is always $O(1)$ in pNGB Higgs. If it is the only deviation, the Higgs decay branching fractions are not modified and it would be hard at a hadron collider (maybe $W_L W_L$ scattering). A high luminosity e^+e^- collider could measure κ_V down to ~0.2% through Zh production cross section, probing f up to ~4 TeV.



Higgs Couplings

- Other coefficients can be tested by various Higgs branching fractions. They can be tested to ~1%.

$$\Gamma\left(h \to f\bar{f}\right)_{\mathrm{SILH}} = \Gamma\left(h \to f\bar{f}\right)_{\mathrm{SM}}\left[1 - \xi\left(2c_y + c_H\right)\right]$$

$$\Gamma\left(h \to W^+W^-\right)_{\mathrm{SILH}} = \Gamma\left(h \to W^+W^{(*)-}\right)_{\mathrm{SM}}\left[1 - \xi\left(c_H - \frac{g^2}{g_\rho^2}\hat{c}_W\right)\right]$$

$$\hat{c}_W = c_W + \left(\frac{g_\rho}{4\pi}\right)^2 c_{HW}$$

$$\Gamma\left(h \to ZZ\right)_{\mathrm{SILH}} = \Gamma\left(h \to ZZ^{(*)}\right)_{\mathrm{SM}}\left[1 - \xi\left(c_H - \frac{g^2}{g_\rho^2}\hat{c}_Z\right)\right]$$

$$\hat{c}_Z = \hat{c}_W + \tan^2\theta_W\left[c_B + \left(\frac{g_\rho}{4\pi}\right)^2 c_{HB}\right]$$

$$\Gamma\left(h \to gg\right)_{\mathrm{SILH}} = \Gamma\left(h \to gg\right)_{\mathrm{SM}}\left[1 - \xi\ \mathrm{Re}\left(2c_y + c_H + \frac{4y_t^2 c_g}{g_\rho^2 I_g}\right)\right]$$

$$c_{\gamma Z} = \frac{c_{HB} - c_{HW}}{4\sin 2\theta_W}$$

$$\Gamma\left(h \to \gamma\gamma\right)_{\mathrm{SILH}} = \Gamma\left(h \to \gamma\gamma\right)_{\mathrm{SM}}\left[1 - \xi\ \mathrm{Re}\left(\frac{2c_y + c_H}{1 + J_\gamma/I_\gamma} + \frac{c_H - \frac{g^2}{g_\rho^2}\hat{c}_W}{1 + I_\gamma/J_\gamma} + \frac{\frac{4g^2}{g_\rho^2}c_\gamma}{I_\gamma + J_\gamma}\right)\right]$$

$$\Gamma\left(h \to \gamma Z\right)_{\mathrm{SILH}} = \Gamma\left(h \to \gamma Z\right)_{\mathrm{SM}}\left[1 - \xi\ \mathrm{Re}\left(\frac{2c_y + c_H}{1 + J_Z/I_Z} + \frac{c_H - \frac{g^2}{g_\rho^2}\hat{c}_W}{1 + I_Z/J_Z} + \frac{4c_{\gamma Z}}{I_Z + J_Z}\right)\right]$$

Strongly interacting light Higgs (SILH), Giudice, et al, hep-ph/0703164

Higgs Couplings

Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different* e^+e^- *facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil* HZ *process at lower energies.* ‡*ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.*

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%	0.19%	$< 0.19\%$			

Higgs Working Group Report, Snowmass 2013

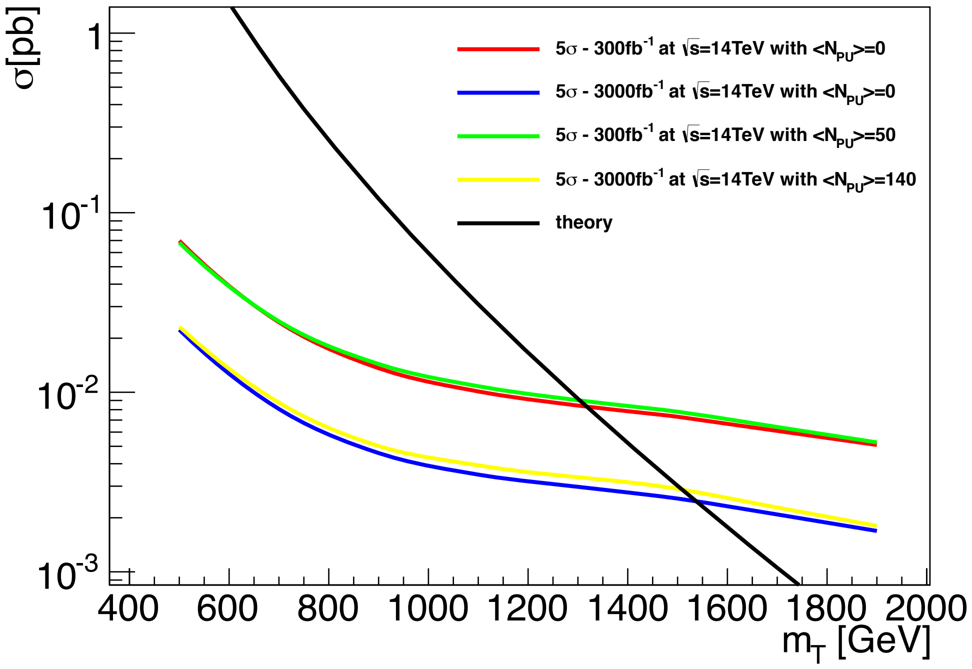
Precision Measurements

- Measurements at a 100 TeV collider
  - The Higgs self coupling can be measured to ~8%, which constrains c_6. (Higgs Working Group Report, Snowmass 2013)
  - $W_L W_L$ scattering tests c_H.
  - $ht\bar{t}$ coupling (if no ILC)

Of course, the real excitement of a 100 TeV collider is that it can discover new states directly.

Direct Searches

- The new states that cut off the quadratic divergent contribution to Higgs mass are expected to be close to ~1 TeV.
- In particular, the largest contribution in the SM comes from top quark loop. The (colored) top partner are expected to be seen first. LHC run II can extend discovery reach to ~ 1.3 TeV.



New Particles Working Group,
Snowmass 2013

Direct Searches

- LHC has decent coverage of the most natural range of top partner mass. However, it is unlikely to uncover the whole structure of new strong dynamics. E.g., vector resonances with only EW charges (ρ) are likely to be heavier than 2-3 TeV (S parameter), beyond the reach of the LHC.

- A 100 TeV *pp* collider will greatly extend the reaches of the new states, allowing us to reconstruct the complete picture if this scenario is realized in nature.

Twin Higgs

Chacko, Goh, Harnik, hep-ph/0506256

- Twin Higgs was designed to be a natural model for EW symmetry breaking which can completely evade LHC detection.
- It's postulated that there is a Z_2 symmetry between SM and a mirror sector. The Higgs sector has an enlarged accidental SU(4) global symmetry due to the Z_2 symmetry. The Higgs boson is a PNGB of the broken SU(4).
- The fields that cancel the quadratic divergence from the SM to the Higgs are mirror world fields, which do not carry SM charges.

Twin Higgs

- However, it won't evade the next generation colliders.
  - As a pNGB Higgs, $c_H \neq 0$ can be determined at the e^+e^- collider.
  - SM Higgs mixes with the mirror world Higgs. If mirror world has light states which the Higgs boson can decay to ⇒ invisible Higgs width.
  - It's only an EFT up to 5-10 TeV. Something new (SUSY or strong dynamics) has to come in before that scale. A 100 TeV *pp* collider will be able to uncover the underlying mechanism.

Other New Physics Connected to Higgs

- $(H^\dagger H)$ is a SM singlet. It's easy to couple to new fields, even in the hidden sector. Any such new interaction can modify the Higgs couplings, in particular, c_H. There are many well-motivated scenarios with such couplings.
  - Dark matter with Higgs portal.
  - Electroweak baryogenesis.

See talks this afternoon.

Conclusions

- The Higgs discovery completes the standard model which started its development in the 1960's.
- The origin of EW symmetry breaking and the hierarchy problem hint that new physics is near. Composite Higgs is an interesting possibility besides the most popular supersymmetry.
- New discoveries will open a new chapter in physics and it will be even more exciting. The next high energy colliders will play the crucial roles in advance human's knowledge in the most fundamental frontier.