Theory Summary

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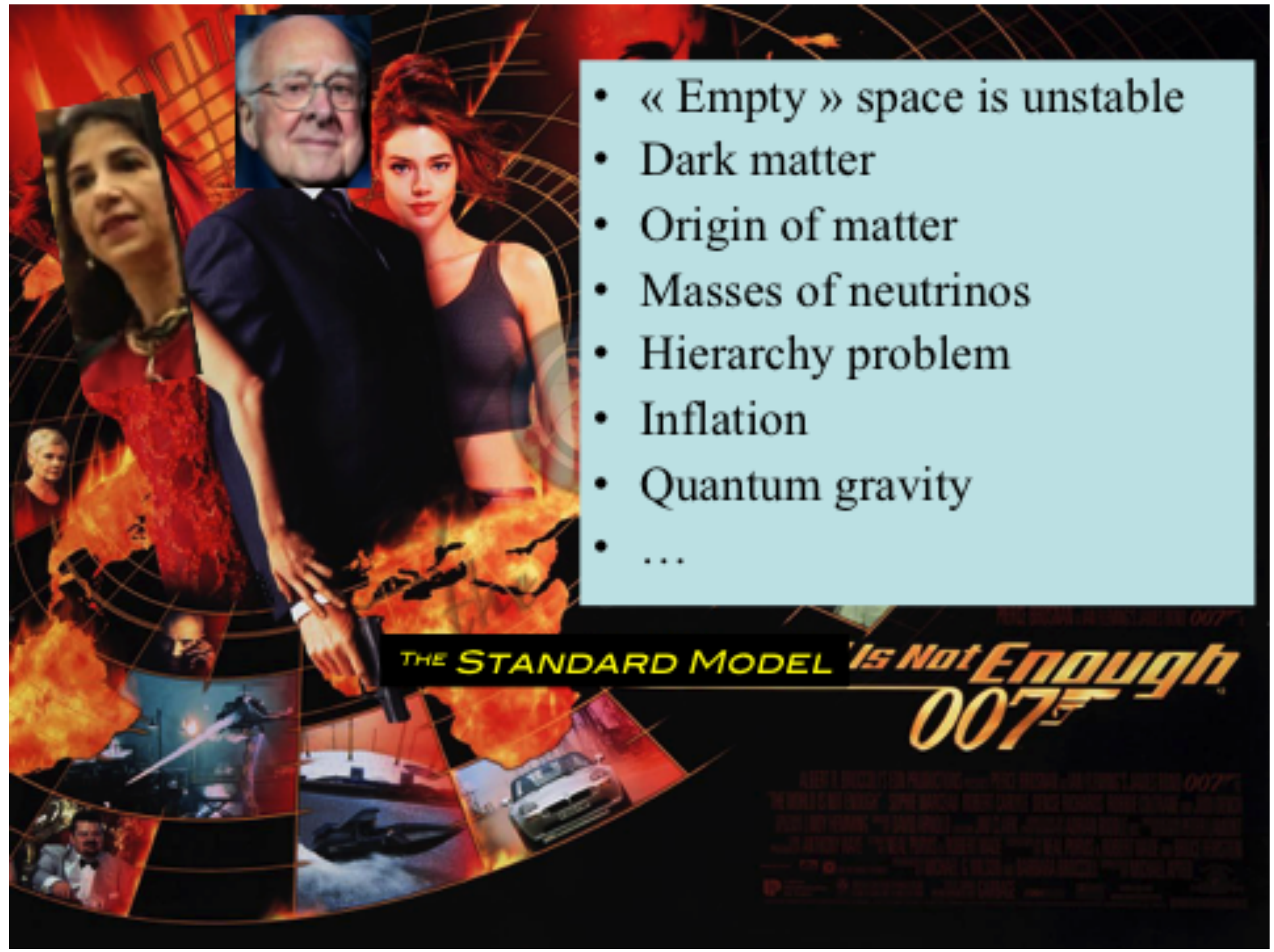
IAS Program on High Energy Physics, HKUST
Jan 26, 2017

- The discovery of the Higgs boson completes the Standard Model.

- However, there are still many unanswered questions left and there must be new physics beyond the Standard Model.



John Ellis' opening talk:

- While some of them (e.g., quantum gravity, inflation) probably occur at very high energy scales beyond the future collider reaches, many other questions may be connected to TeV scale physics which will be probed at colliders in the future.

- « Empty » space is unstable
- Dark matter
- Origin of matter
- Masses of neutrinos
- Hierarchy problem
- Inflation
- Quantum gravity
- …

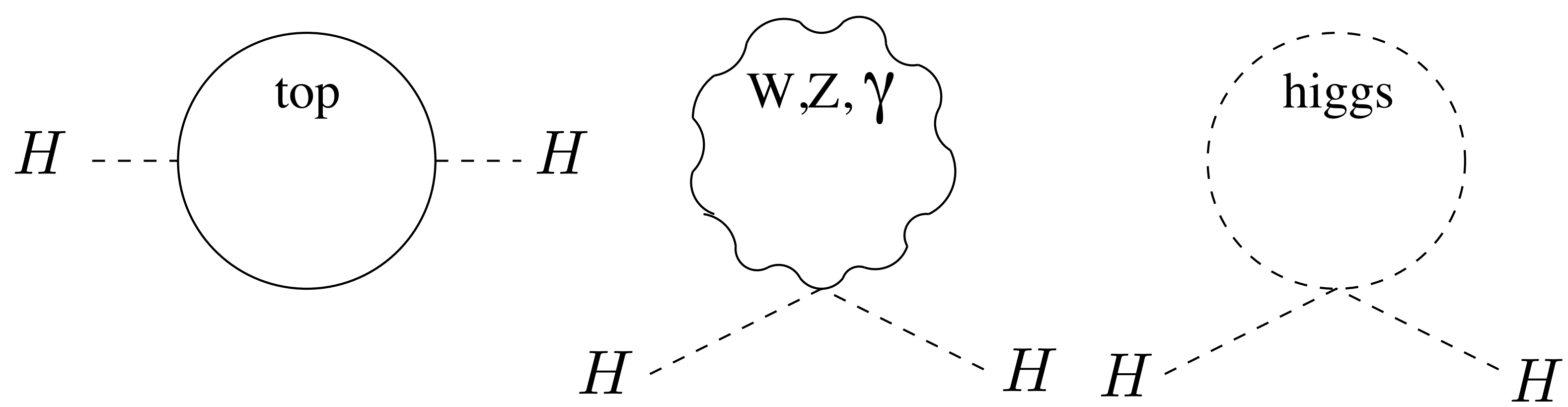
- Dark matter - WIMP

- Matter-antimatter asymmetry - baryogenesis at electroweak phase transition

- Neutrino masses - simplest type-I seesaw seems to indicate a high scale for the Majorana masses of the right-handed neutrinos. Many other models (type-II, type-III, loop induced) involve new physics at the TeV scale.

The answers to these questions are not guaranteed to connect to the TeV scale, but the possibilities are interesting enough that we should verify or exclude them with our best efforts.

- The strongest theoretical arguments for new physics comes from the hierarchy problem.



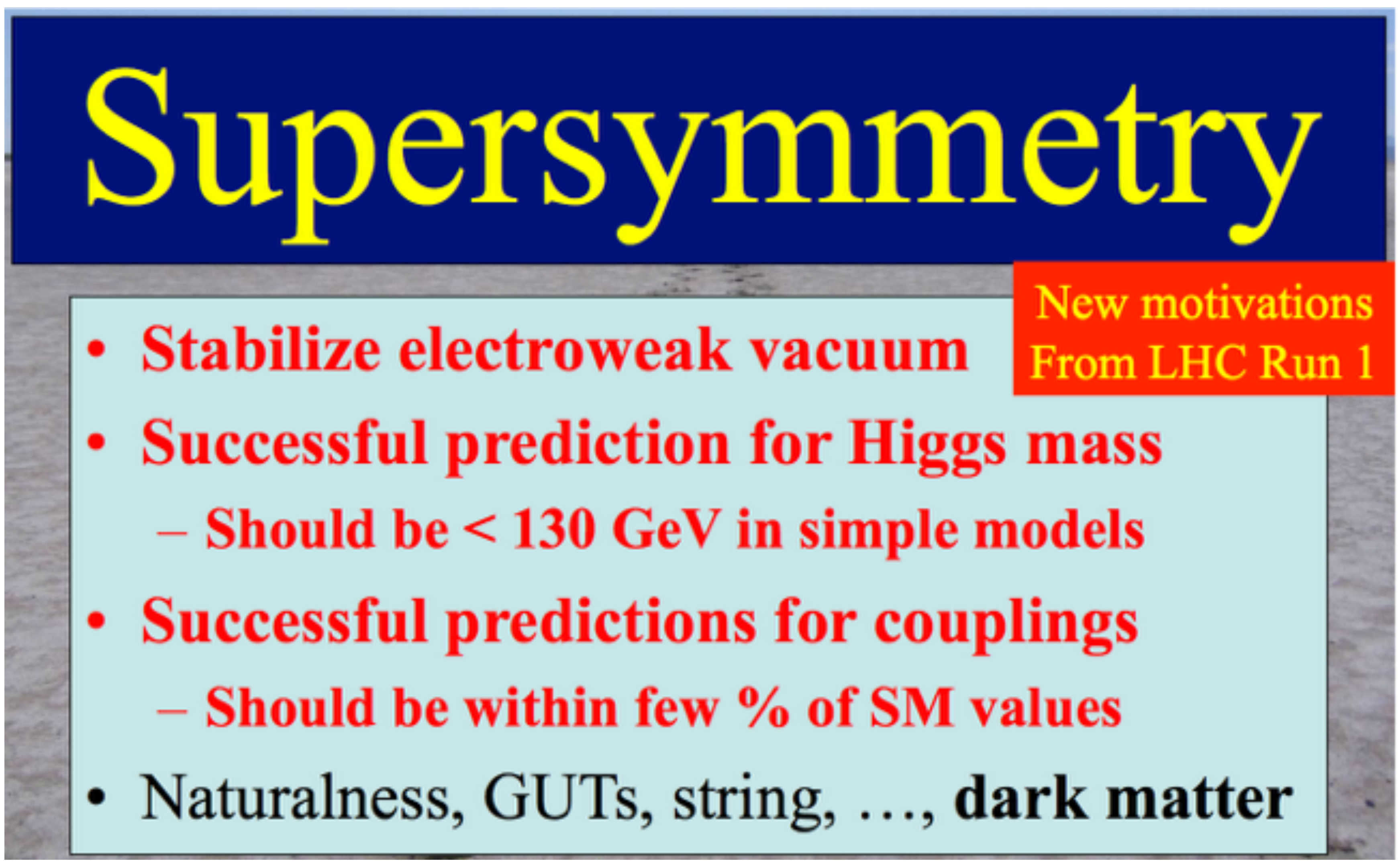
$$-\frac{3y_t^2}{8\pi^2}\Lambda^2 \qquad \frac{9g^2}{64\pi^2}\Lambda^2 \qquad \frac{\lambda^2}{16\pi^2}\Lambda^2$$

- To avoid excessive fine-tuning, new physics should occur around the TeV scale to cut off the quadratically divergent contributions to $m_H{}^2$.

Solutions to the Hierarchy Problem

- Technicolor theories are ruled out by the discovery of the light Higgs boson.

- Supersymmetry probably remains the most popular and well-motivated scenario.

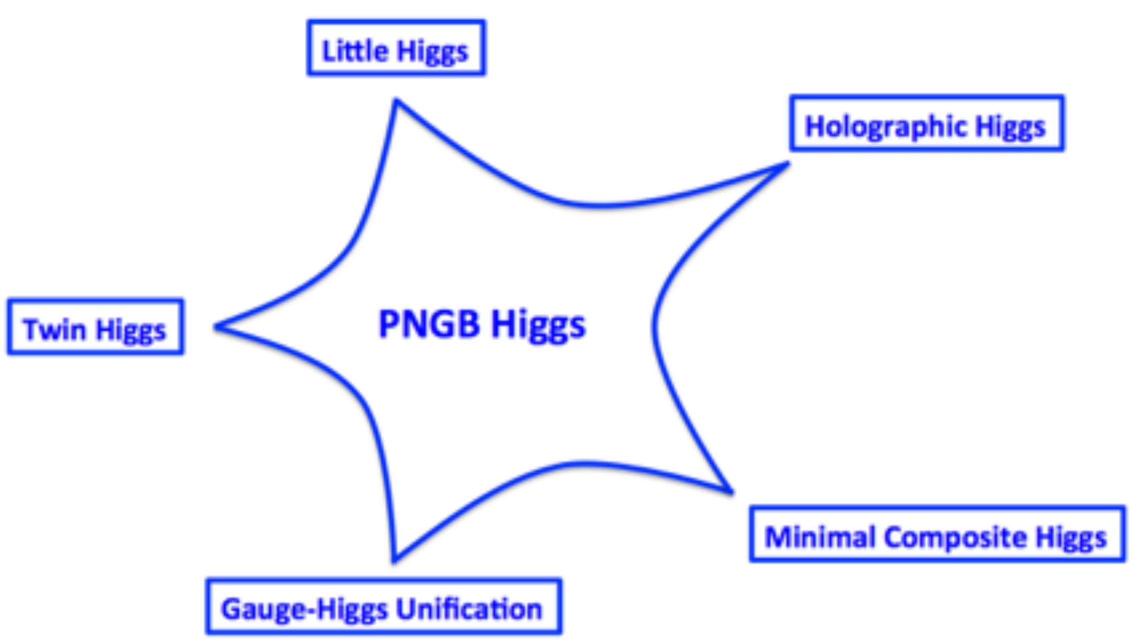


John Ellis, opening talk

Solutions to the Hierarchy Problem

- An interesting alternative is the composite Higgs boson where Higgs is a pseudo-Nambu-Goldstone boson (PNGB) of a broken global symmetry.

See Ian Low's talk

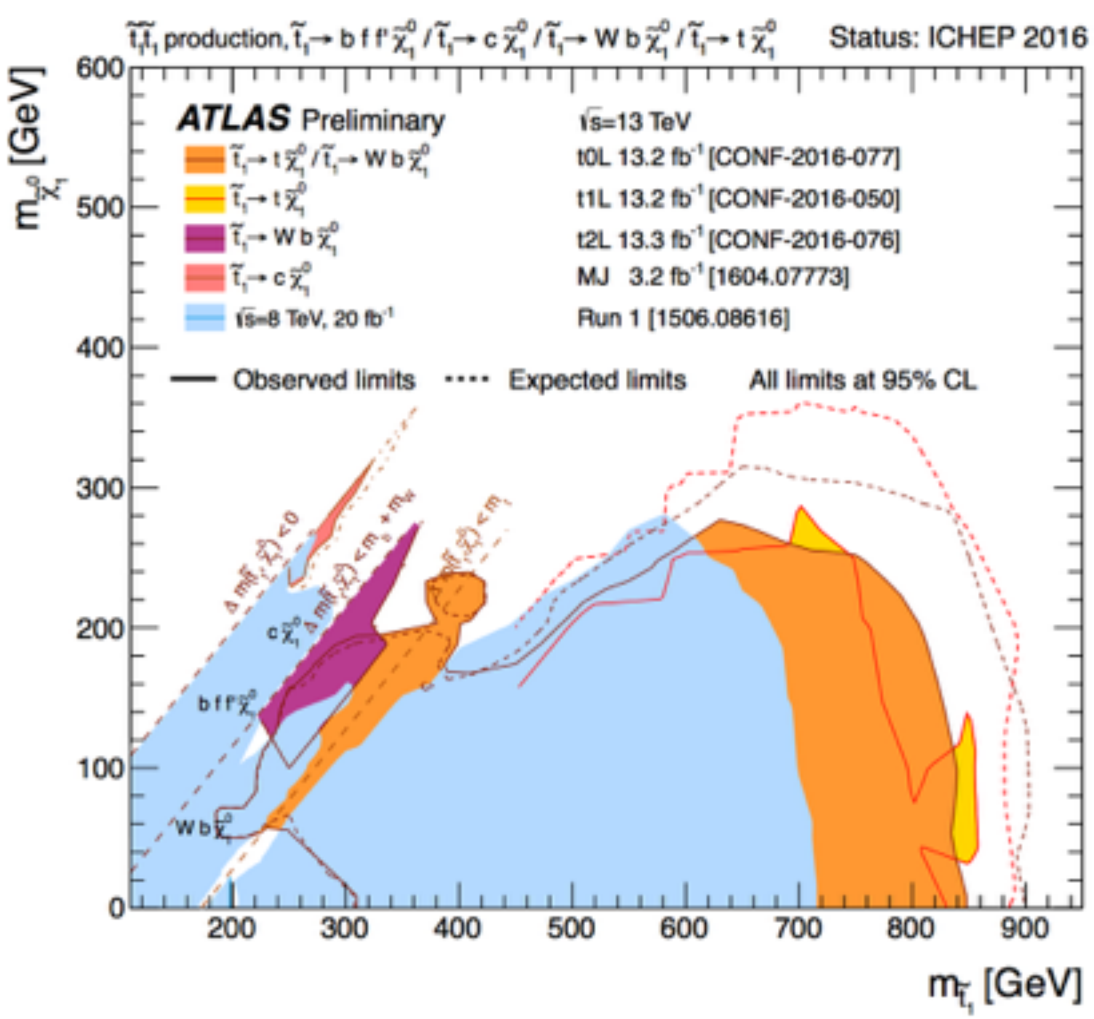


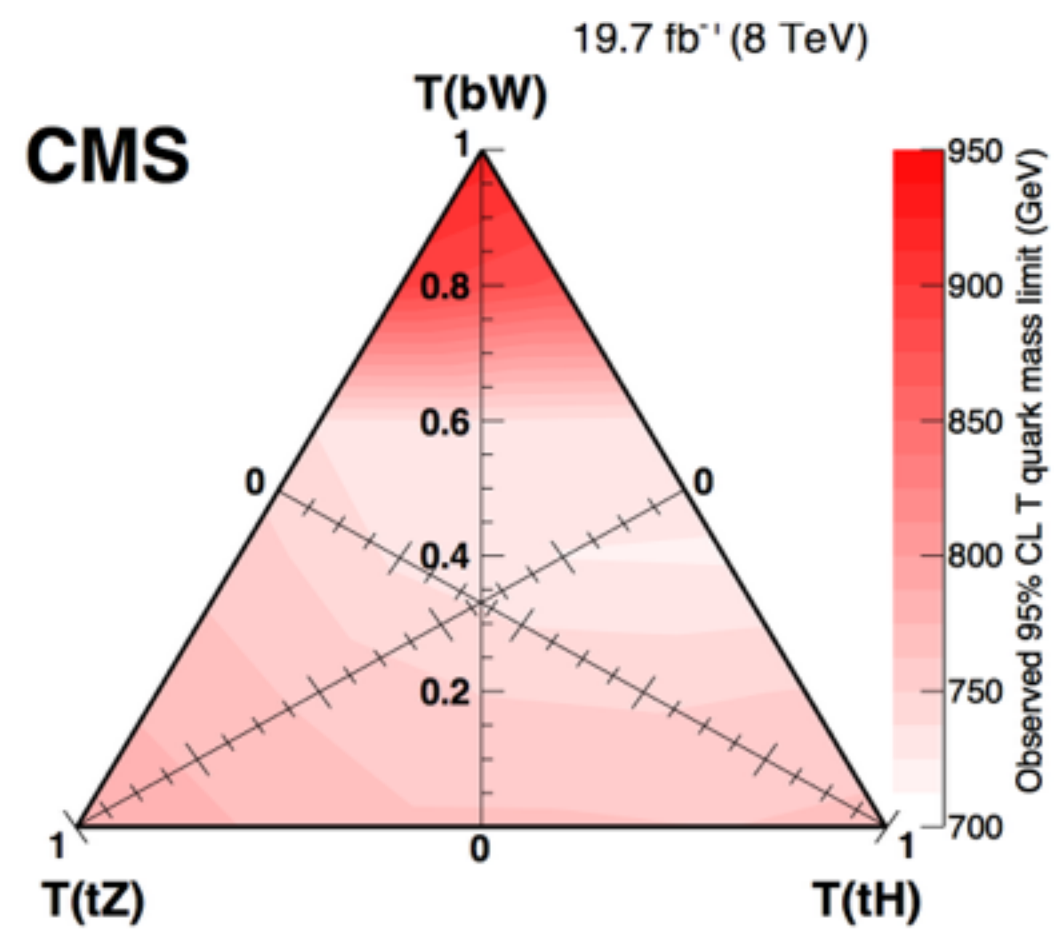
$\mathcal{G}$	$\mathcal{H}$	C	N_G	$\mathbf{r}_{\mathcal{H}} = \mathbf{r}_{SU(2)\times SU(2)}\ (\mathbf{r}_{SU(2)\times U(1)})$	Ref.
SO(5)	SO(4)	✓	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$	[11]
SU(3) × U(1)	SU(2) × U(1)		5	$\mathbf{2}_{\pm 1/2} + \mathbf{1}_0$	[10, 35]
SU(4)	Sp(4)	✓	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[29, 47, 64]
SU(4)	$[SU(2)]^2 \times U(1)$	✓*	8	$(\mathbf{2},\mathbf{2})_{\pm 2} = 2\cdot(\mathbf{2},\mathbf{2})$	[65]
SO(7)	SO(6)	✓	6	$\mathbf{6} = 2\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	G_2	✓*	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	[66]
SO(7)	SO(5) × U(1)	✓*	10	$\mathbf{10}_0 = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$	–
SO(7)	$[SU(2)]^3$	✓*	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\cdot(\mathbf{2},\mathbf{2})$	–
Sp(6)	Sp(4) × SU(2)	✓	8	$(\mathbf{4},\mathbf{2}) = 2\cdot(\mathbf{2},\mathbf{2})$	[65]
SU(5)	SU(4) × U(1)	✓*	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+5} = 2\cdot(\mathbf{2},\mathbf{2})$	[67]
SU(5)	SO(5)	✓*	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$	[9, 47, 49]
SO(8)	SO(7)	✓	7	$\mathbf{7} = 3\cdot(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	–
SO(9)	SO(8)	✓	8	$\mathbf{8} = 2\cdot(\mathbf{2},\mathbf{2})$	[67]
SO(9)	SO(5) × SO(4)	✓*	20	$(\mathbf{5},\mathbf{4}) = (\mathbf{2},\mathbf{2}) + (\mathbf{1}+\mathbf{3},\mathbf{1}+\mathbf{3})$	[34]
$[SU(3)]^2$	SU(3)		8	$\mathbf{8} = \mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0$	[8]
$[SO(5)]^2$	SO(5)	✓*	10	$\mathbf{10} = (\mathbf{1},\mathbf{3}) + (\mathbf{3},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	[32]
SU(4) × U(1)	SU(3) × U(1)		7	$\mathbf{3}_{-1/3} + \bar{\mathbf{3}}_{+1/3} + \mathbf{1}_0 = 3\cdot\mathbf{1}_0 + \mathbf{2}_{\pm 1/2}$	[35, 41]
SU(6)	Sp(6)	✓*	14	$\mathbf{14} = 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{3}) + 3\cdot(\mathbf{1},\mathbf{1})$	[30, 47]
$[SO(6)]^2$	SO(6)	✓*	15	$\mathbf{15} = (\mathbf{1},\mathbf{1}) + 2\cdot(\mathbf{2},\mathbf{2}) + (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3})$	[36]

Table 1: Symmetry breaking patterns $\mathcal{G} \to \mathcal{H}$ for Lie groups. The third column denotes whether the breaking pattern incorporates custodial symmetry. The fourth column gives the dimension N_G of the coset, while the fifth contains the representations of the GB's under $\mathcal{H}$ and $SO(4) \cong SU(2)_L \times SU(2)_R$ (or simply $SU(2)_L \times U(1)_Y$ if there is no custodial symmetry). In case of more than two SU(2)'s in $\mathcal{H}$ and several different possible decompositions we quote the one with largest number of bi-doublets.

- In either case, there should be new states, in particular colored top partners, near the weak scale to cancel the quadratic divergence.

- So far,we haven’t found any.





- These models seem to require percent-level fine tuning if they exist to address the hierarchy problem.

- Fine-tuning is a probability statement. We could be just a bit unlucky. 10^{-4} tuning is still 100 times more unlikely than 10^{-2} tuning. Extending the energy reach by one order of magnitude (through direct searches or indirect measurements) would cover 99% (in terms of probability) of the remaining unexplored (fine-tuned) territories.

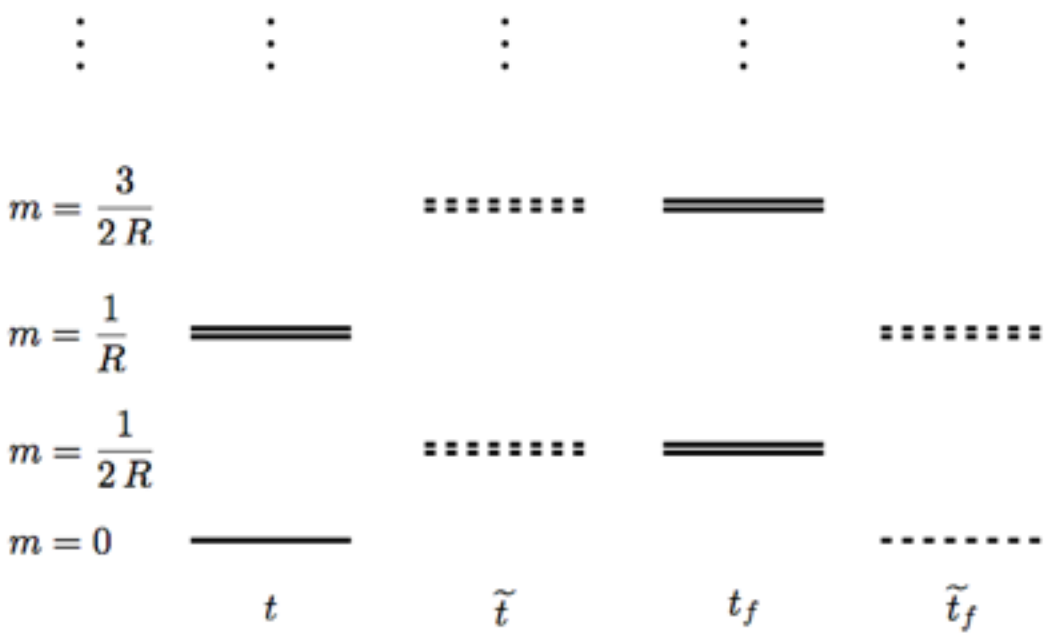
Neutral Naturalness

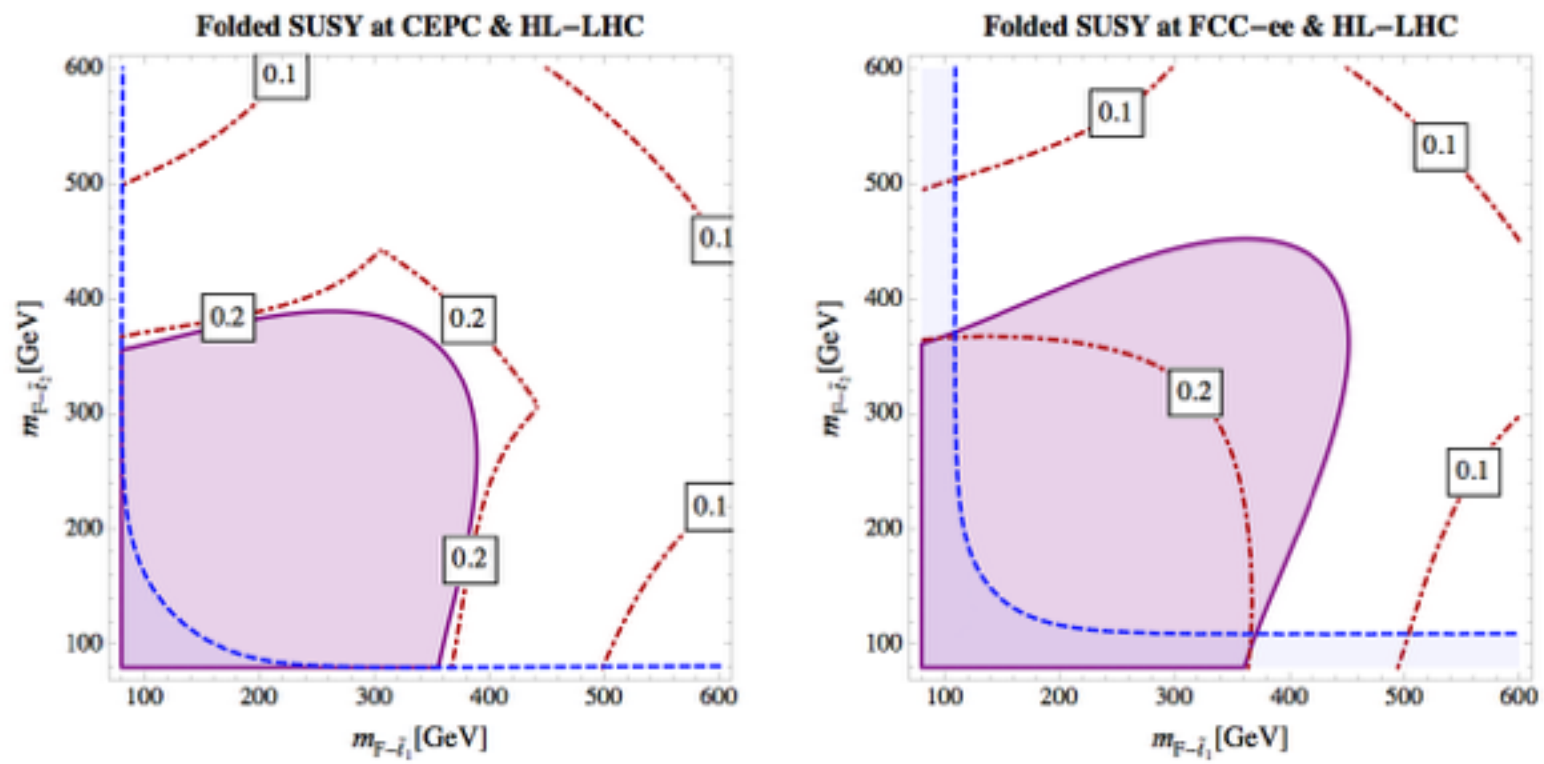
- Another effort to save naturalness of the EW breaking is to construct models with uncolored top partners.

Partner quantum #s	Global *tree-level Higgs couplings*	SUSY *loop-level Higgs couplings*
QCD x EWK	CHM, Little Higgs	MSSM
Neutral x EWK	Quirky Little Higgs Cai, HC, Terning	Folded SUSY Burdman, Chacko, Goh, Harnik
Neutral x Neutral	Twin Higgs Chacko, Goh, Harnik	????

Table by David Curtin/Nathaniel Craig

- In Folded SUSY (also quirky little Higgs), the top partners carry EW charges, not completely hidden.





(Figure by Cohen, Craig, Lou, Pinner)

J. Fan, M. Reece, L.-T. Wang, 1412.3107

- The colored KK states are expected to have multi-TeV masses, accessible at the 100 TeV collider

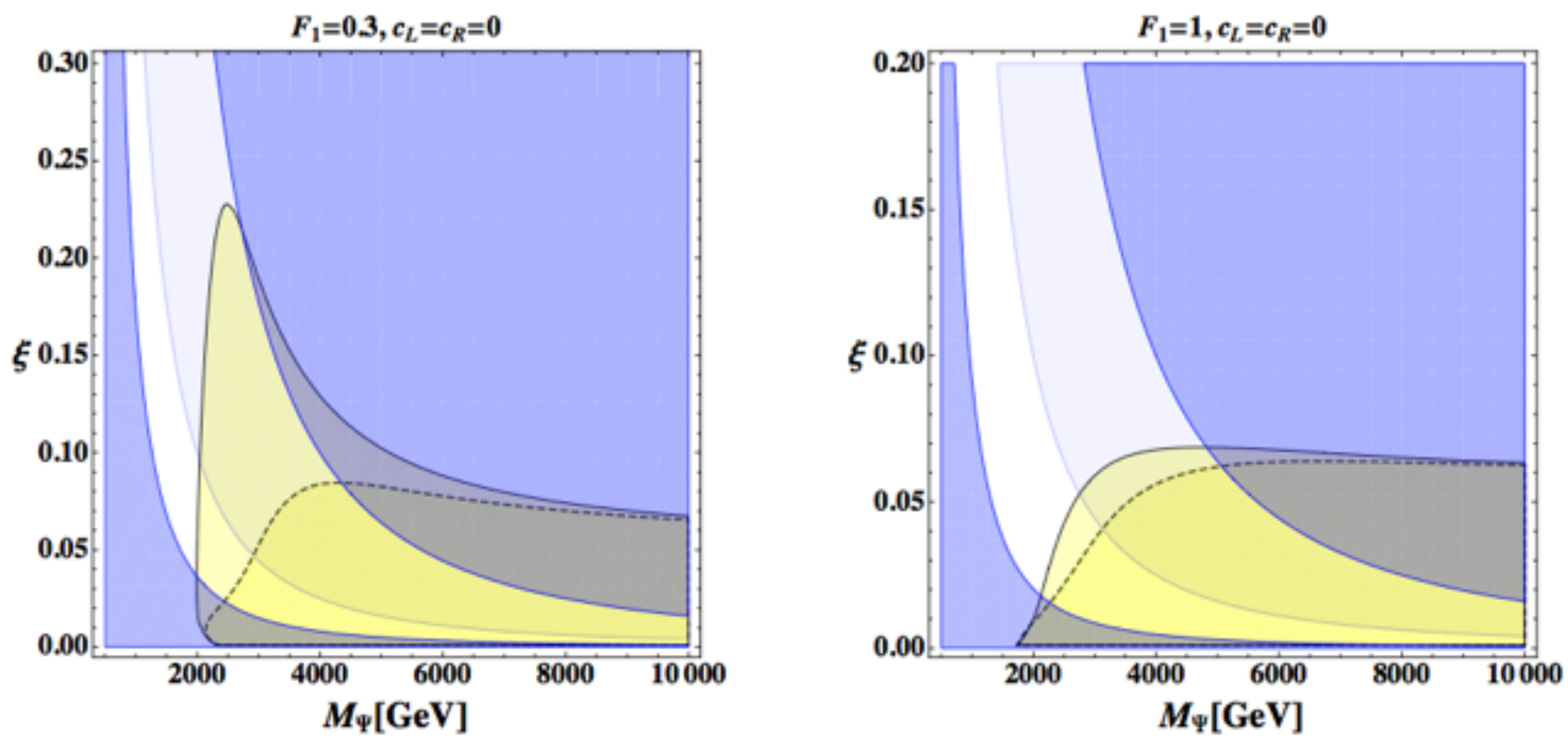
- In Twin Higgs, there is a mirror sector related to SM by an approximate Z_2 symmetry. Mirror particles are SM singlets, hard to find at colliders.

- The Higgs boson is a PNGB of the broken SU(4) approximate symmetry of the Higgs potential. Its couplings to SM particles are universally reduced by $\sqrt{1 - v^2/f^2}$, difficult at LHC, but no problem at a Higgs factory.

- Higgs decays to the mirror sector give invisible decay width and/or interesting displaced vertex signals, which can be tested at future colliders.

- The UV completion of Twin Higgs must contain colored states, not far above a few TeV.

Tuning



Yellow: consistent with EWPO and Higgs mass
Blue: theoretically inaccessible

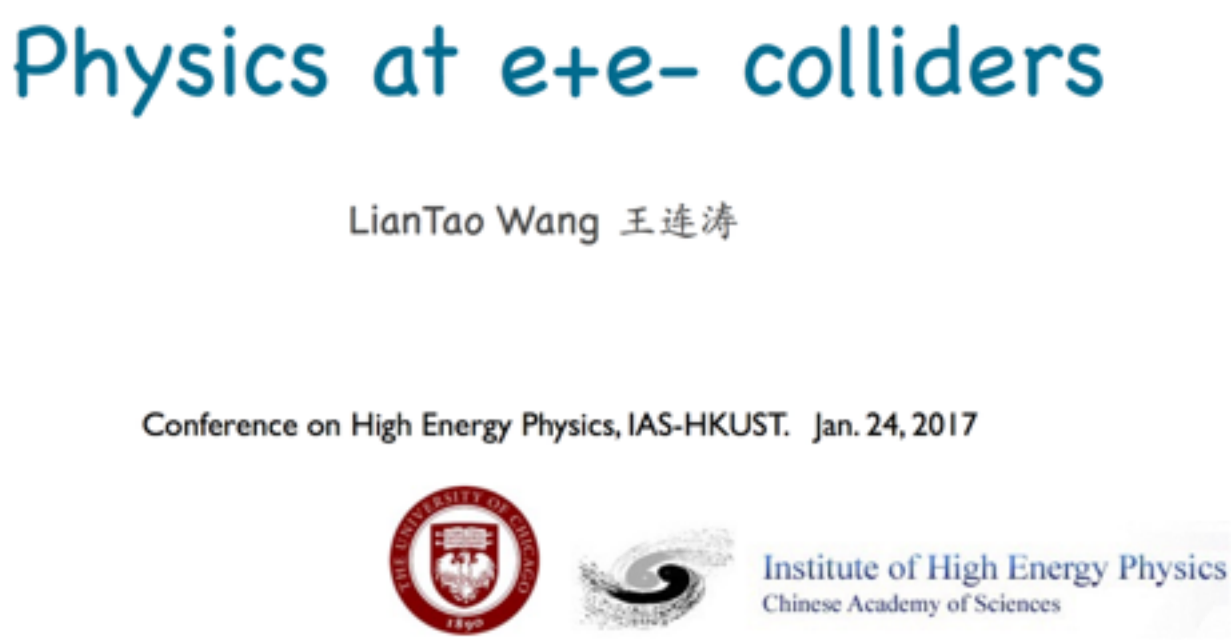
Contino, Greco, Mahbubani, Rattazzi, Torre, to appear

- These exotic colored states can be discovered beyond 10 TeV at a 100 TeV collider.

HC, Sunghoon Jung, Ennio Salvioni, and Yuhsin Tsai, 1512.02647
HC, Ennio Salvioni, and Yuhsin Tsai, 1612.03176

- Of course, not all new physics at TeV scale is necessarily related to the hierarchy problem.
  - New scalars (extended Higgs sector, …)
  - New fermions (dark matter, …)
  - New vectors (Z’, dark photon, …)
  - Hidden valley
  - …
- They may be related to the other problems (DM, EW phase transition, neutrino masses, …), or belong to a grander theory waiting for us to figure out .

- Excellent overviews of physics at future lepton and hadron colliders have been given by LianTao Wang and Michelangelo Mangano is the past two days.



- The following is a brief account of the topics discussed in the theory parallel sessions. They represent a small fraction of the physics studies for the future colliders.

- Electroweak Precision Physics

Zhijun Liang

Observable	LEP precision	CEPC precision	CEPC runs
m_Z	2 MeV	0.5 MeV	Z lineshape
m_W	33 MeV	3 MeV	ZH (WW) thresholds
A^b_{FB}	1.7%	0.15%	Z pole
$\sin^2\theta^{\text{eff}}_W$	0.07%	0.01%	Z pole
R_b	0.3%	0.08%	Z pole
N_ν (direct)	1.7%	0.2%	ZH threshold
N_ν (indirect)	0.27%	0.1%	Z lineshape
R_μ	0.2%	0.05%	Z pole
R_τ	0.2%	0.05%	Z pole

Fulvio Piccinini

- for a successful physics program, theoretical improvements needed for
  - QED corrections and their unfolding in $e^+e^- \to f\bar{f}$
  - luminosity determination

- Precision QCD study

Huaxing Zhu

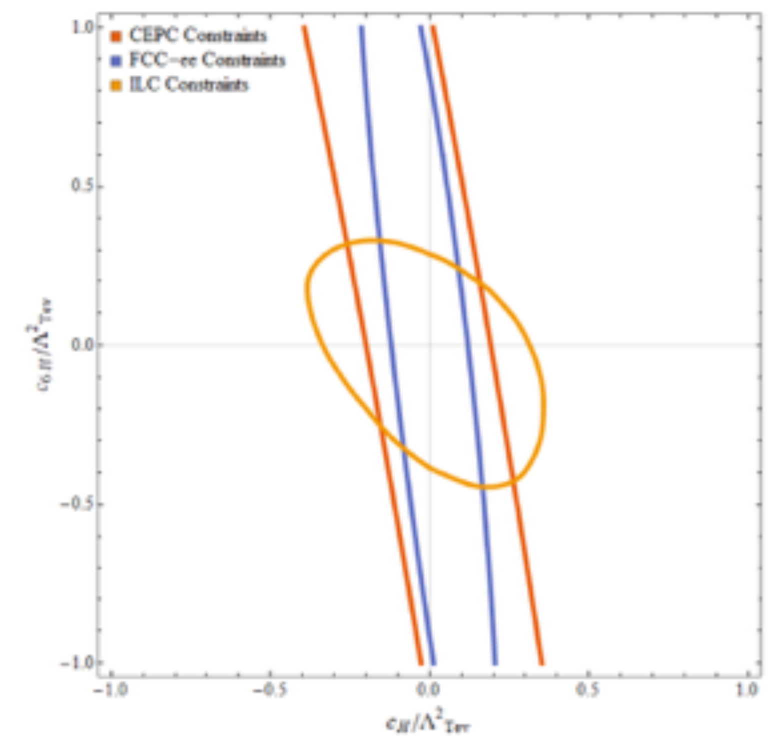
- A future e+e- machine will support a rich program of precision QCD study
  - More precision in α_s measurement
  - Understanding of non-global observable
  - Finer structure of multi-jet events
  - Testing models of hadronization
  - Monte-Carlo Tuning
  - Fragmentation function
  - Interplay with EW, Higgs, BSM
  - ……

- EFT analysis of Higgs boson at Higgs factories

Wen Han Chiu

Constraints on c_{6H}

- Fit using: $\sigma(Zh), \sigma(\nu\bar{\nu}h)_{350}$, $\sigma(Zhh)_{500}$ and $\sigma(\nu\bar{\nu}hh)_{1000}$
- CEPC Constraints:
  5 ab^{-1} of 250 GeV data at CEPC
- FCC-ee constraints:
  10 ab^{-1} of 240 GeV data, 2.5 ab^{-1} of 350 GeV data
- ILC Constraints:
  2 ab^{-1} at 250 GeV, 4 ab^{-1} at 500 GeV and 5 ab^{-1} at 1 TeV



Operators
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H\rvert^2)^2$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$
$\mathcal{O}_{6H} = \lvert H^\dagger H\rvert^3$
$\mathcal{O}_L^{(3)l} = (iH^\dagger \sigma_a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L \gamma_\mu \sigma^a L_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}_R \gamma^\mu l_R)$

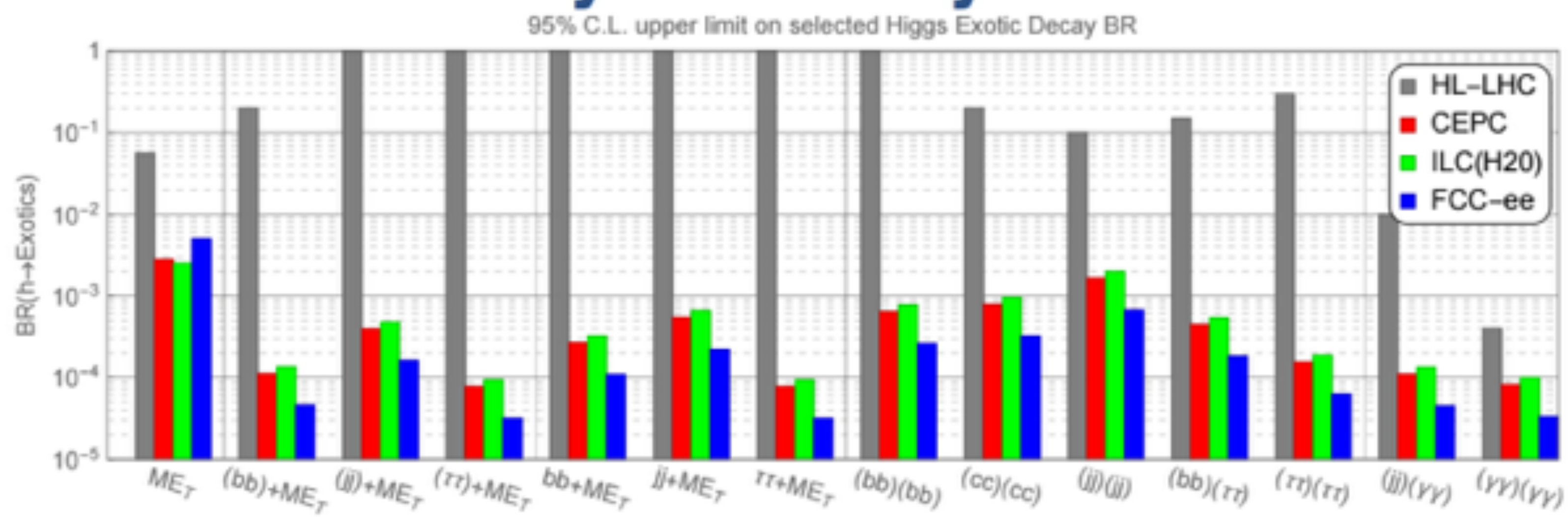
- Exotic and rare Higgs decays

Wei-Ming Yao Zhen Liu

Updated studies for CEPC

	PreCDR (Jan 2015)	Now (Aug 2016)
σ(ZH)	0.51%	0.50%
σ(ZH)*Br(H→bb)	0.28%	0.21%
σ(ZH)*Br(H→cc)	2.1%	2.5%
σ(ZH)*Br(H→gg)	1.6%	1.3%
σ(ZH)*Br(H→WW)	1.5%	1.0%
σ(ZH)*Br(H→ZZ)	4.3%	4.3%
σ(ZH)*Br(H→ττ)	1.2%	1.0%
σ(ZH)*Br(H→γγ)	9.0%	9.0%
σ(ZH)*Br(H→Zγ)	-	~4 σ
σ(ZH)*Br(H→μμ)	17%	17%
σ(vvH)*Br(H→bb)	2.8%	2.8%
Higgs Mass/MeV	5.9	5.0
σ(ZH)*Br(H→inv)	95%. CL = 1.4e-3	1.4e-3
Br(H→ee/emu)	-	1.7e-4/1.2e-4
Br(H→bbχχ)	$<10^{-3}$	3.0e-4

Exotic Decay summary



We visualize the sensitivity on Higgs exotic decay branching factions with some reasonable choice of model parameters.

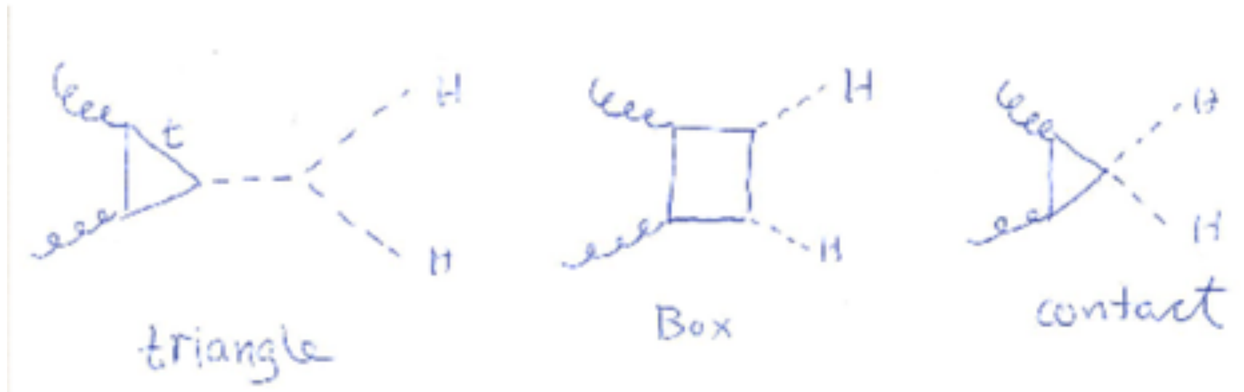
The HL-LHC are from various studies and projections available in the literature; The lepton collider sensitivities (except for the first channel, $h \to inv$) are from our study with different $ee \to ZH$ integrated luminosities and beam polarizations for different colliders.

Fermilab

- Higgs self coupling and double Higgs production

Kingman Cheung; Gang Li; Ligong Bian (presented by Yun Jiang)

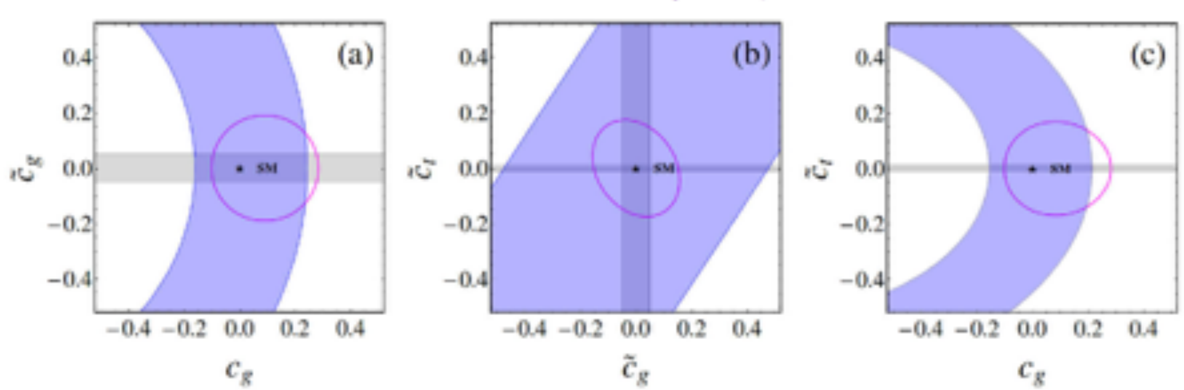
Double Higgs production can probe Higgs self coupling and new physics coupled to Higgs



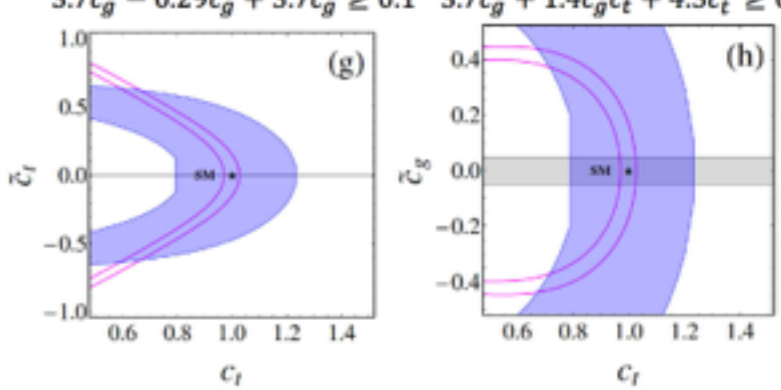
$\mathcal{L} = 30\text{ab}^{-1}$ Sensitivities to Higgs effective couplings

5σ discovery of NP, where the SM hh is treated as bkg

$$\mathcal{L}_{\text{eff}} = -\frac{m_t}{v}\bar{t}(c_t + \tilde{c}_t\gamma_5)th - \frac{m_t}{2v^2}\bar{t}(c_{2t} + \tilde{c}_{2t}\gamma_5)th^2 - c_{3h}\frac{m_h^2}{2v}h^3 + \frac{\alpha_s h}{12\pi v}(c_g G^A_{\mu\nu}G^{A,\mu\nu} + \tilde{c}_g G^A_{\mu\nu}\tilde{G}^{A,\mu\nu}) + \frac{\alpha_s h^2}{24\pi v^2}(c_{2g} G^A_{\mu\nu}G^{A,\mu\nu} + \tilde{c}_{2g} G^A_{\mu\nu}\tilde{G}^{A,\mu\nu})$$



$3.7c_g^2 - 0.29c_g + 3.7\tilde{c}_g^2 \geq 0.1$ $\quad 3.7\tilde{c}_g^2 + 1.4\tilde{c}_g\tilde{c}_t + 4.5\tilde{c}_t^2 \geq 0.1$ $\quad 3.7c_g^2 - 0.29c_g + 4.5\tilde{c}_t^2 \geq 0.1$

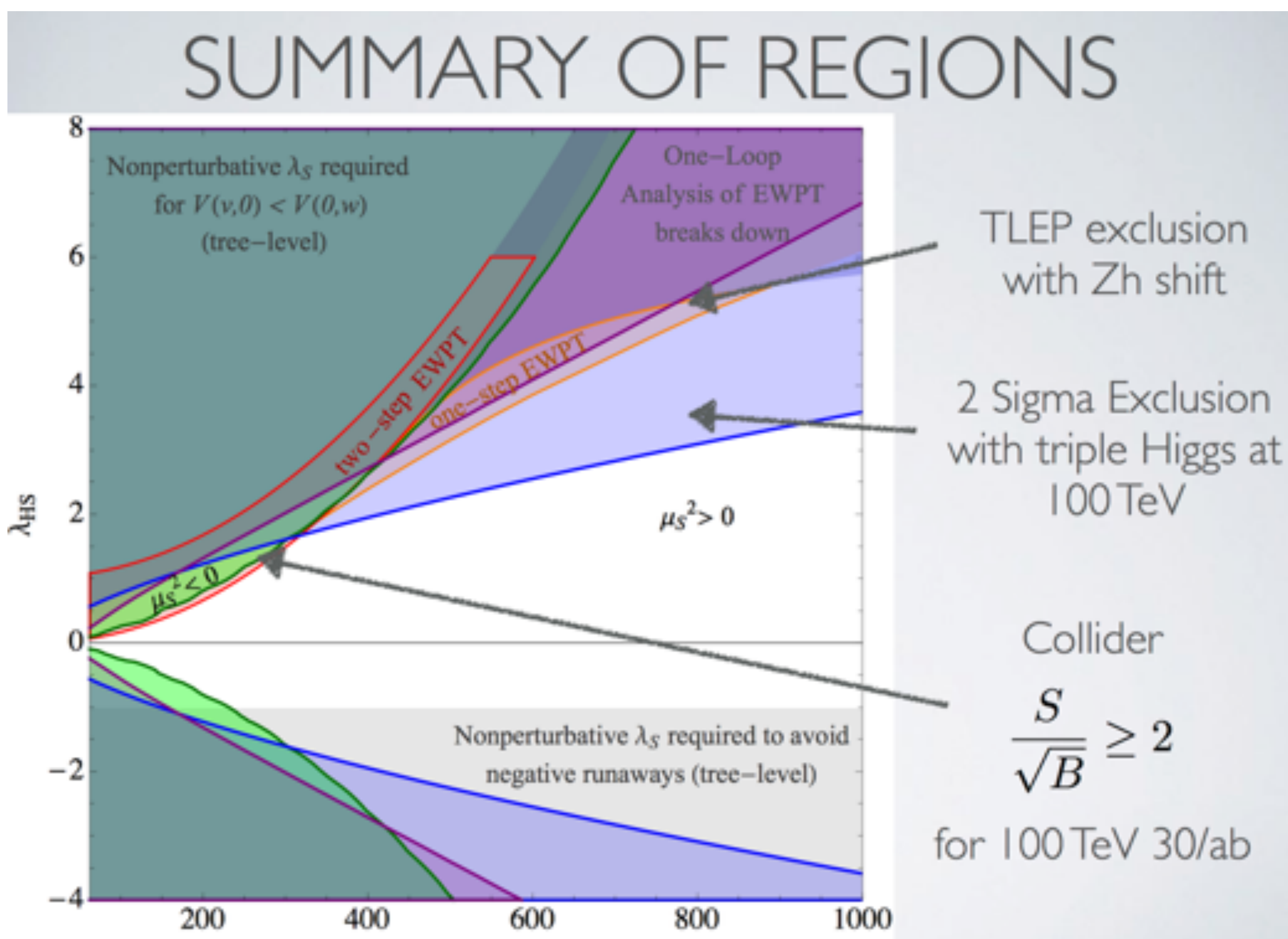


Additional CP-violating interaction has to be included to respect the strict EDM constraints if double Higgs production in NP models is discovered outside the grey region

- Higgs self coupling is important to determine the type of EW phase transition, and hence the possibility of EW baryogenesis

Patrick Meade: Nightmare scenario: SM+singlet, singlet doesn't mix with the Higgs and is heavier than half of the Higgs mass.

$$V_0 = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{HS} h^2 S^2 + \frac{1}{4}\lambda_S S^4$$



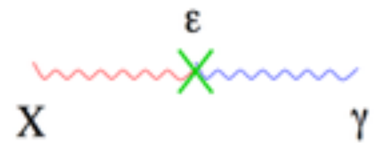
- Dark photon

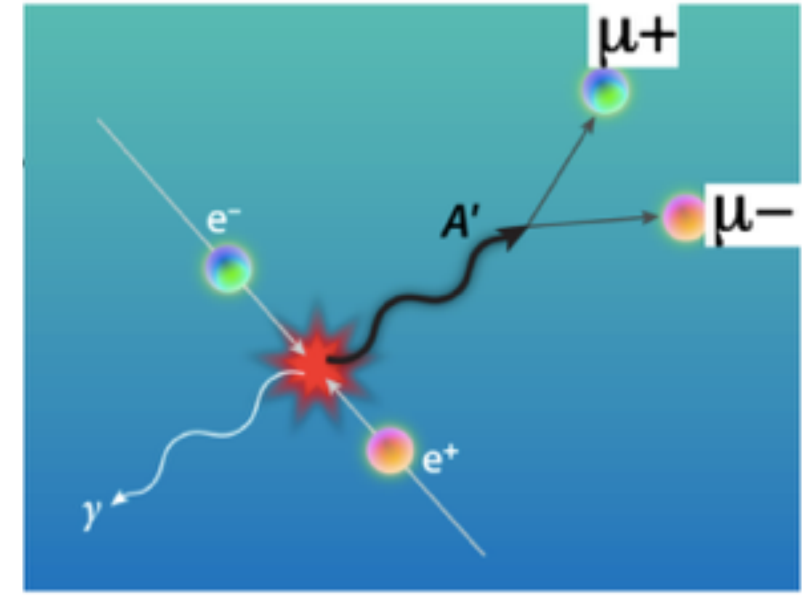
Xiao-Gang He

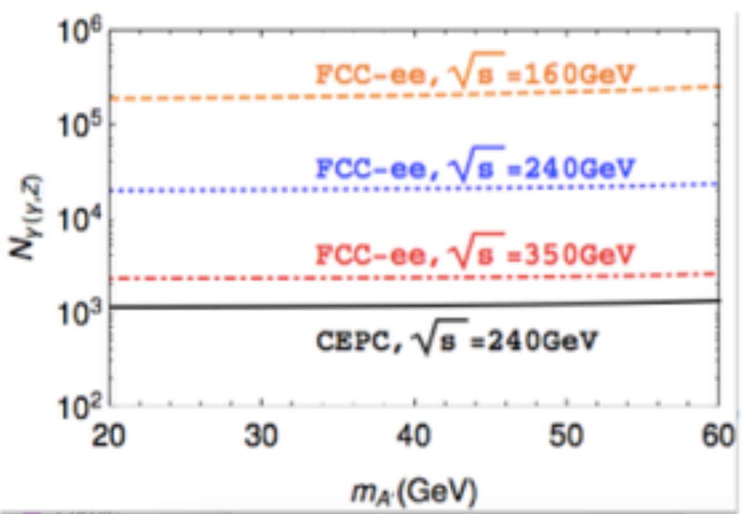
$$L = -\tfrac{1}{4} F_{\mu\nu}F^{\mu\nu} - \tfrac{1}{4} X_{\mu\nu}X^{\mu\nu}$$

will use X or A' for dark photon

$$\epsilon X_{\mu\nu} F^{\mu\nu}$$







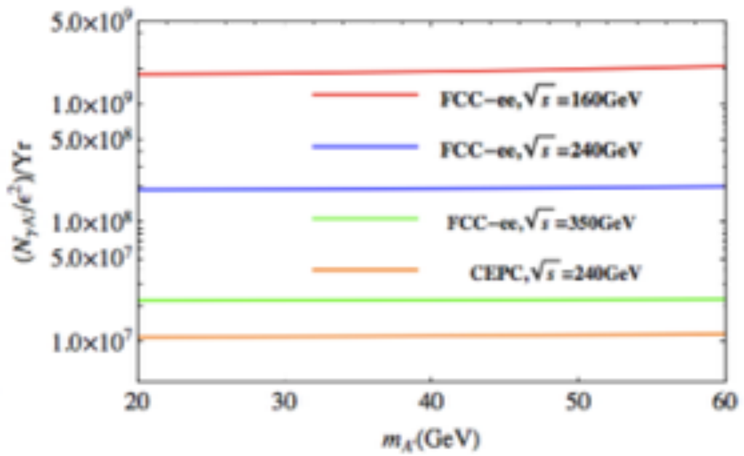
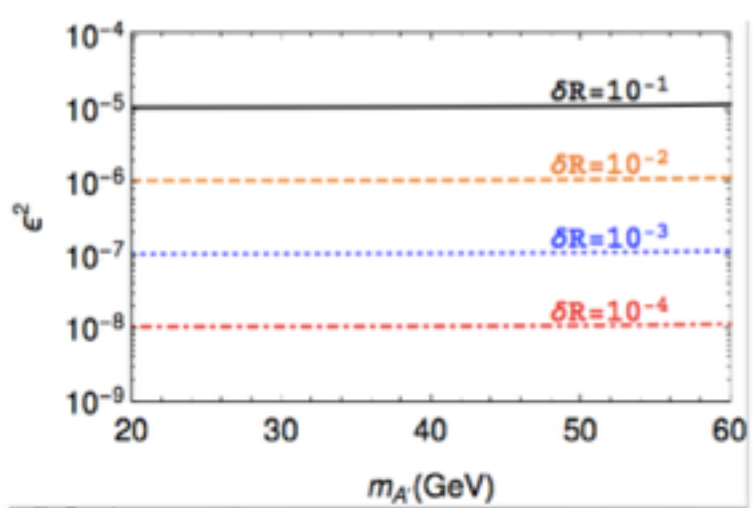
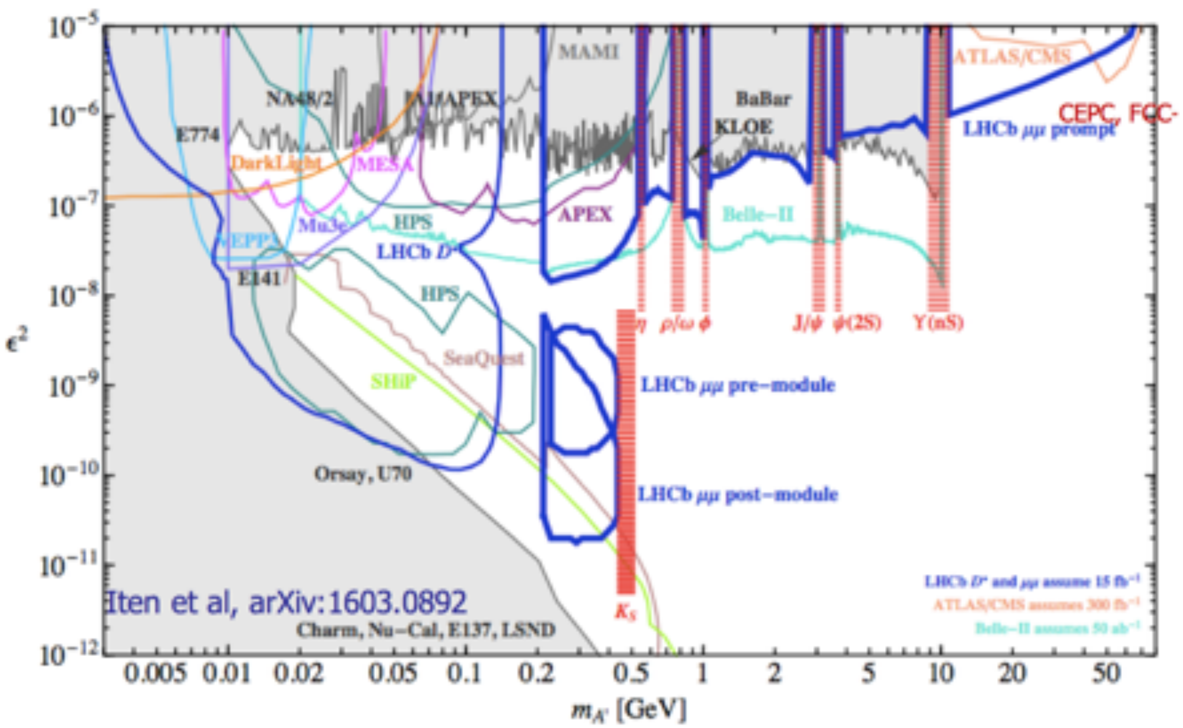


FIG. 3: $N_{\gamma\gamma}$ and $N_{\gamma A'}/\epsilon^2$ as functions of $m_{A'}$ for CEPC ($\sqrt{s}$ = 240 Ge[V]
($\sqrt{s}$ = 160, 240, 350 GeV) for one year running.



CEPC may have advantage probing dark photon at 10 to a few 10s (<<m_Z) GeV mass range.



- Models and the corresponding phenomenologies

  - Two Higgs doublet models- Jeremy Bernon

    Higgs is SM-like ⇒ alignment or decoupling

The **alignment without decoupling** limit will be probed critically at the LHC for Type II scenarios.

If decoupling occurs however, a **100 TeV collider** will prove essential for direct observation of the heavy state.

Non-degenerated spectra should be considered with attention as they bring numerous new signatures complementary to the standard decay channels.

- A family model - Fang Ye

$$\mathcal{L}_k = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2 + \mathrm{Tr}(|D_\mu \eta|^2) + \bar{\psi} i \gamma_\mu D^\mu \psi,$$

$$SU(2)_1 \times SU(2)_2 \times U(1)_Y$$

$$< \eta >= \frac{1}{\sqrt{2}} \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix} \quad \Big\downarrow$$

$$SU(2)_L \times U(1)_Y$$

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 e^{i\xi} \end{pmatrix} \quad \Big\downarrow$$

SM EW group $\qquad Q = Y + T_1^3 + T_2^3$

	$SU(2)_1$	$SU(2)_2$	$U(1)_Y$
Q_{aL}	2	1	$\frac{1}{6}$
Q_{3L}	1	2	$\frac{1}{6}$
U_{iR}	1	1	$\frac{2}{3}$
D_{iR}	1	1	$-\frac{1}{3}$
L_{aL}	2	1	$-\frac{1}{2}$
L_{3L}	1	2	$-\frac{1}{2}$
E_{iR}	1	1	-1
Φ_1	2	1	$\frac{1}{2}$
Φ_2	1	2	$\frac{1}{2}$
η	2	2	X

Table 1. EW Spectrum

Phenomenological constraints: EWPO, FCNC, Higgs data

- Axial vector Z’ - Wai-Yee Keung

Motivated by the DM direct detection constraints. Anomaly cancellation requires new fermions carrying SM and Z’ charges.

Name	n_G	Lepto-phobic/philic?
♯1. Universal Model	3	✗
♯2. /w DM Model	3	✗
♯3. *L*-phobic Model	3	Leptophobic
♯4. *L*-philic Model	3	Leptophilic
♯5. 1G-Model	1	N/A
♯6. *t*-*b*-Model	1	Leptophobic

Field	♯1	♯2	♯3	♯4	♯5	♯6
$z[Q_L]$	1	1	1	0	1	1
$z[u_R]$	-1	-1	-1	0	-1	-1
$z[d_R]$	-1	-1	-1	0	-1	-1
$z[L_L]$	1	1	0	1	1	0
$z[e_R]$	-1	-1	0	-1	-1	0
$z[\chi_L]$	-	9	9	-9/4	1	1
$z[\chi_R]$	-	-9	-9	9/4	-1	-1
$z[Q'_L]$	1	1	1	-	-	-
$z[Q'_R]$	3	-1	0	-	1	1
$z[u'_L]$	-3	-2	-2	-2	-1	-1
$z[u'_R]$	4	3	-1	5/2	-	-
$z[d'_L]$	3	-6	-2	2	-1	-1
$z[d'_R]$	4	5	11	-5/2	-	-
$z[L'_L]$	-9	-82/3	-49/12	-157/48	-	-
$z[L'_R]$	-3	-28/3	95/12	-13/48	1	0
$z[e'_L]$	-13	-100/3	103/6	-85/24	-1	0
$z[e'_R]$	-16	-127/3	67/6	-121/24	-	-
$z[\nu_R]$	-	-	-	-	1	1
$N[\nu_R]$	-	-	-	-	2	2
b_{m_z}	45	207	198	153/8	17	14
$b_{m_z} + b_M$	860	15038/3	14065/12	90697/192	34	28
$\mathcal{A}^{\rm SM}_{Z'Z'Z'} + \mathcal{A}^{\rm DM}_{Z'Z'Z'}$	45	45+1458	36+1458	$9 - 729/32$	15+2	12+2

- Thanks to all speakers who contributed to this conference. You are also encouraged to contribute to the White paper. For details, see http://iasprogram.ust.hk/hep/2017/white_papers.html

- There are more studies to be done to realize the full potentials of future colliders, and help them to become realities.