Overview of Higgs physics and future colliders

LianTao Wang
University of Chicago

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My talk

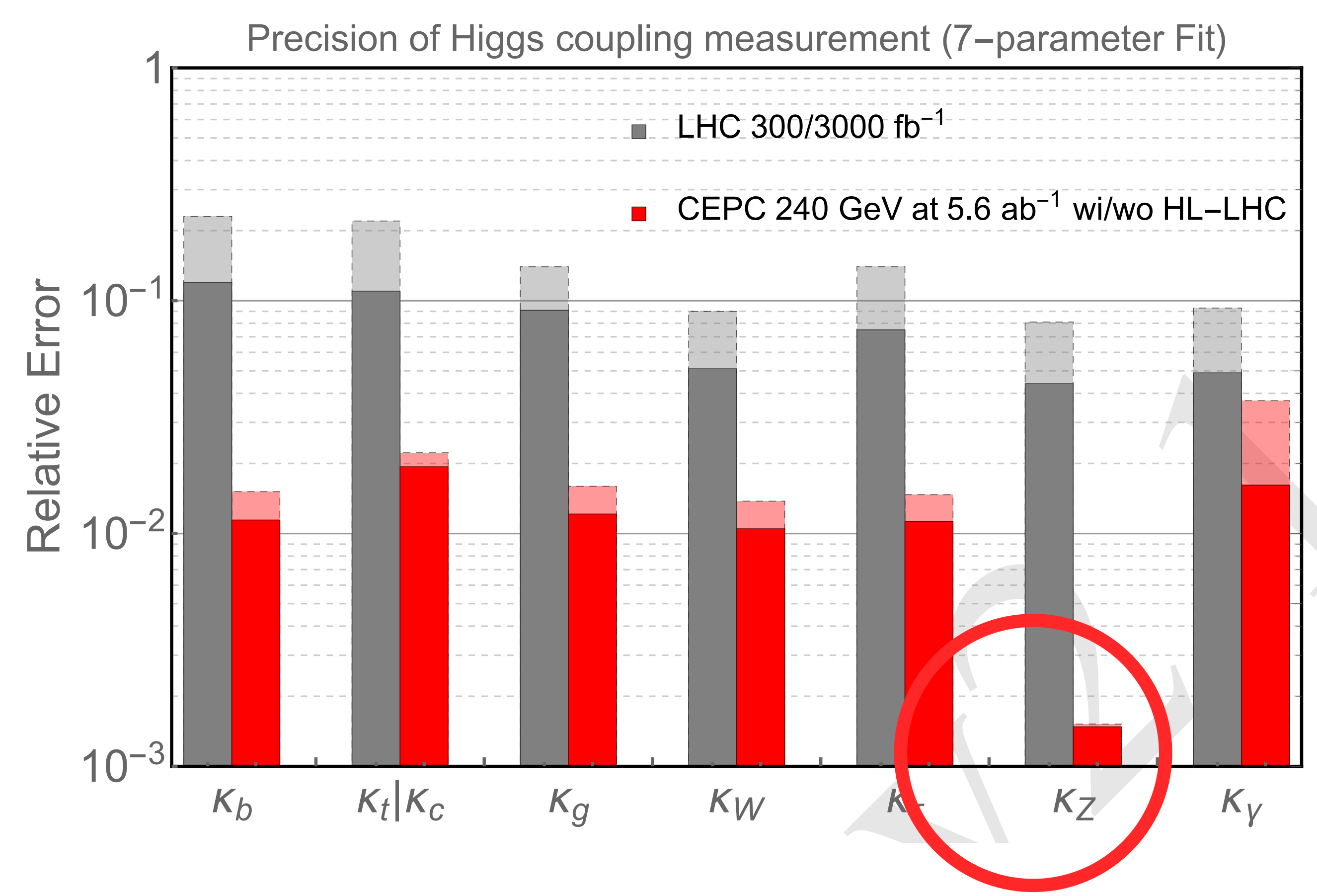
- Talks on the first day of this workshop covers the big picture and physics vision, reviewed the various colliders.

- I will focus on the Higgs physics part, and give more details.

Higgs coupling at future colliders

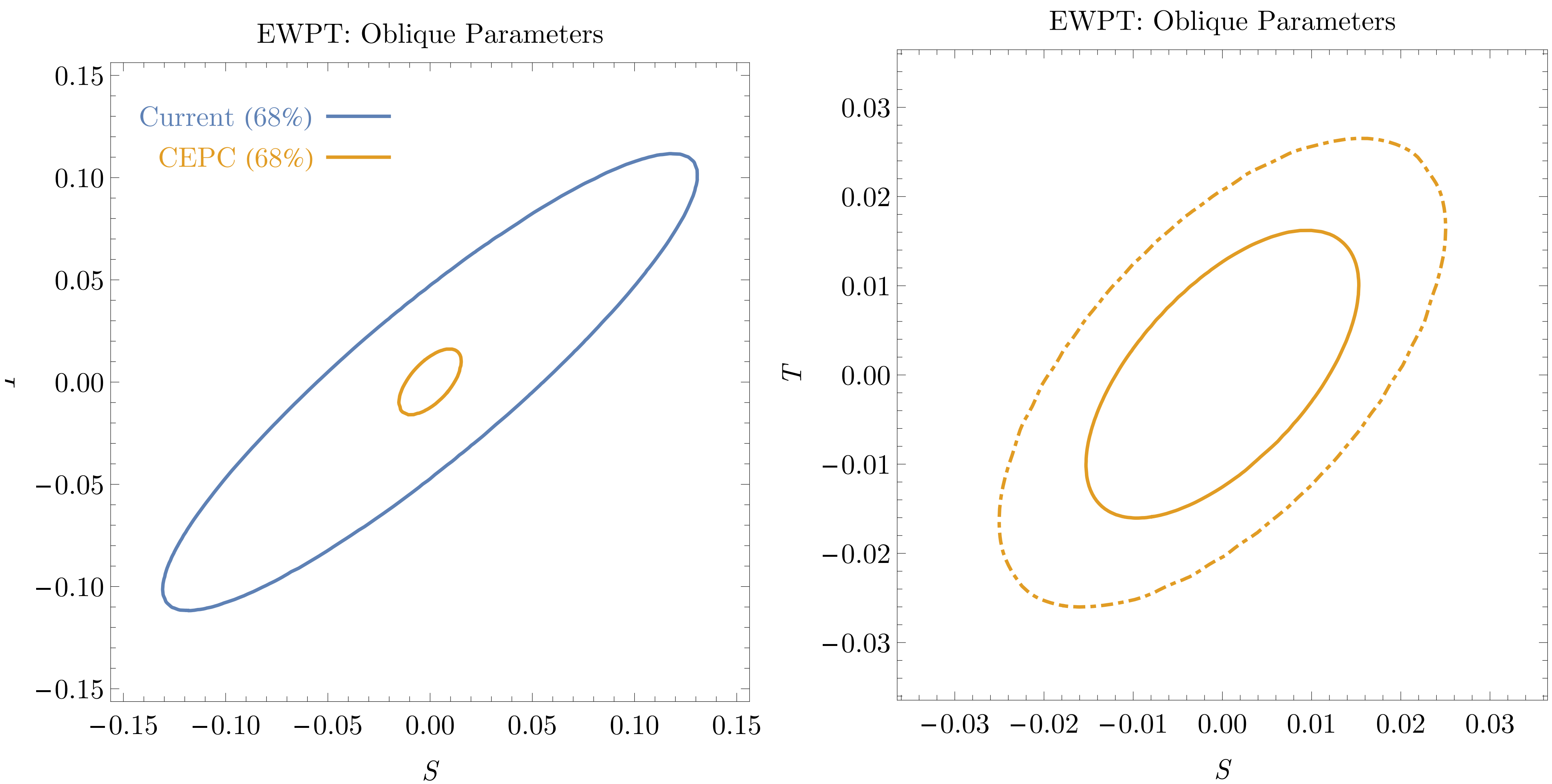
	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

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



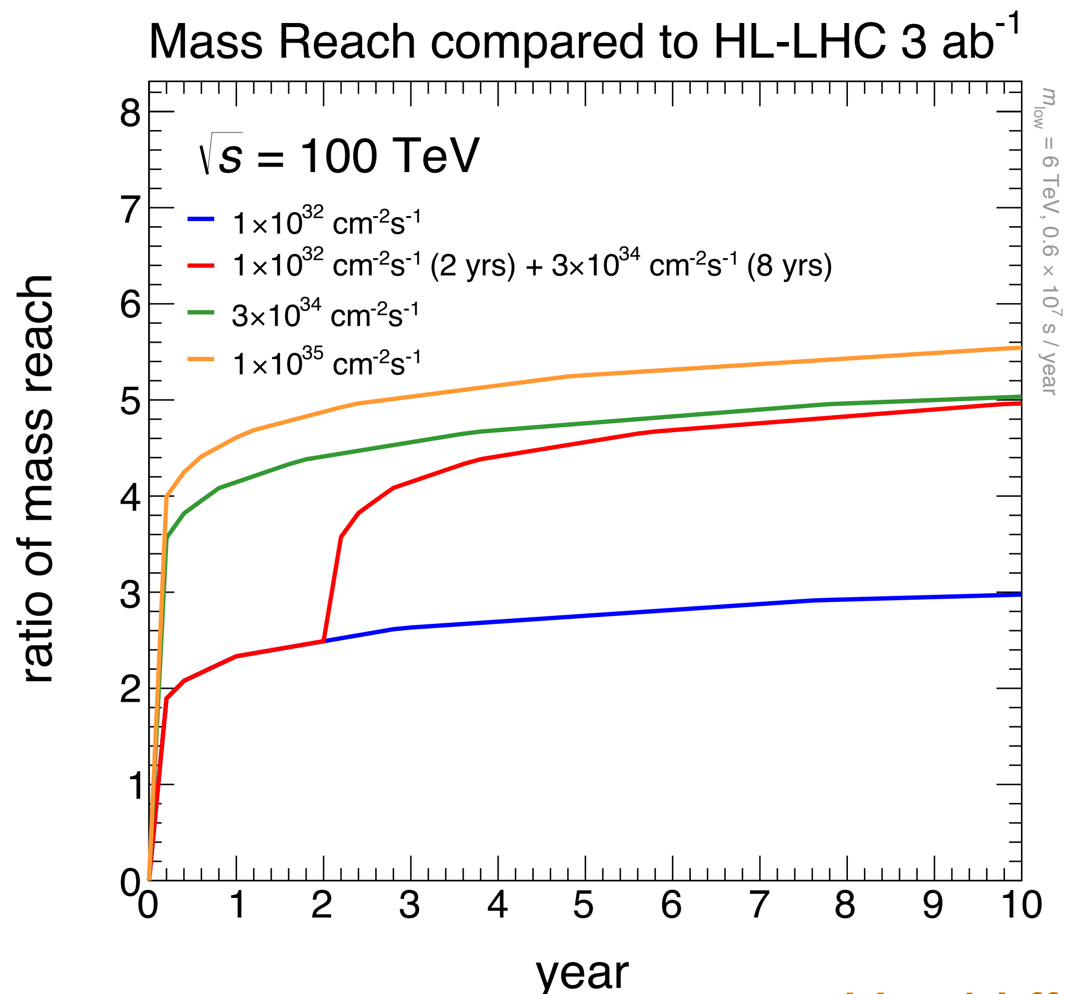
- A large step beyond the HL-LHC.
  - Can achieve per-mil level measurement.
  - Determination of the Higgs width.

Electroweak precision



FCC can do even better (by a factor of a few)

100-ish TeV pp collider

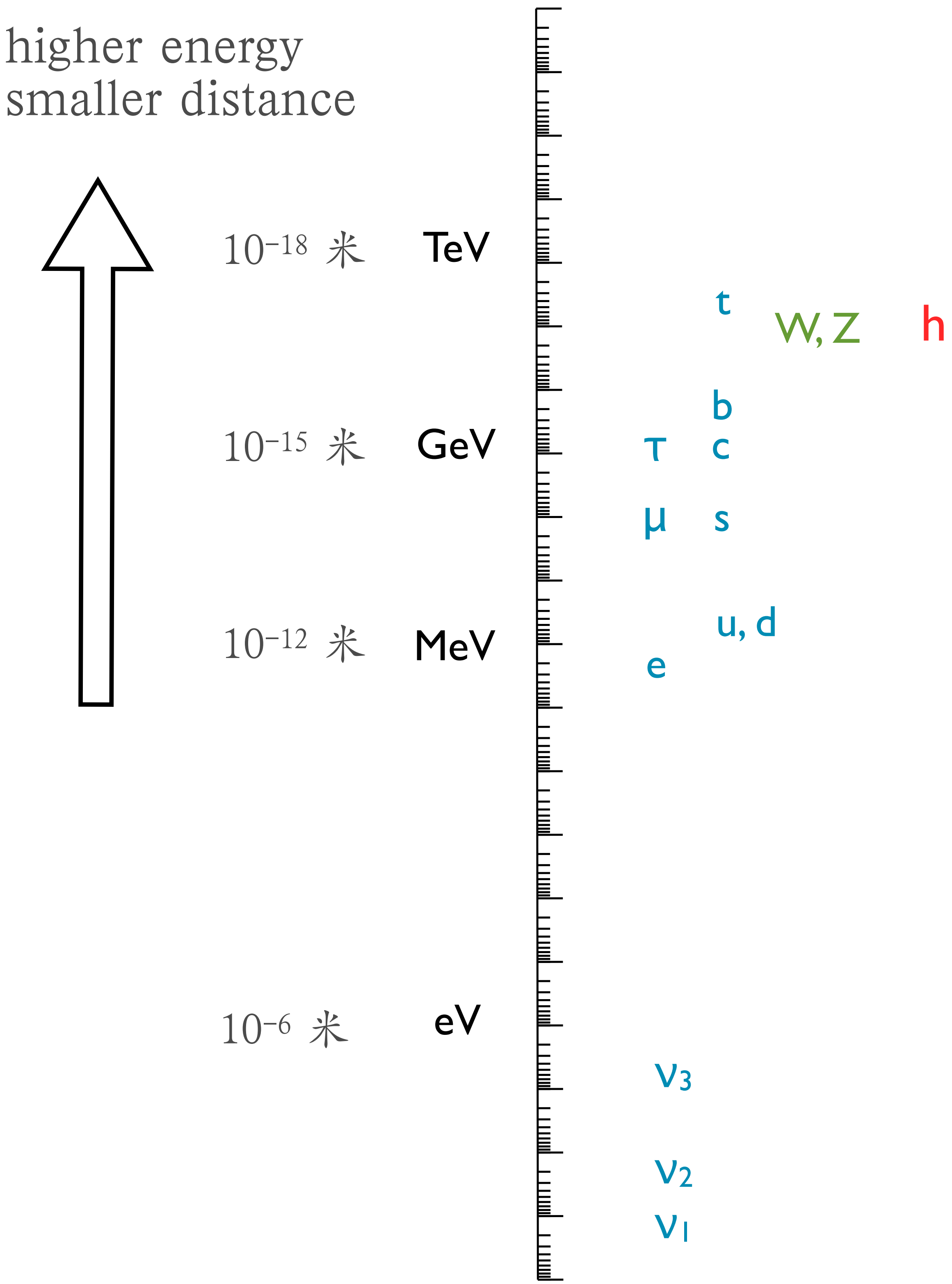


Hinchliffe, Kotwal, Mangano, Quigg, LTW

A factor of at least 5 increase in reach beyond the LHC, with modest luminosity

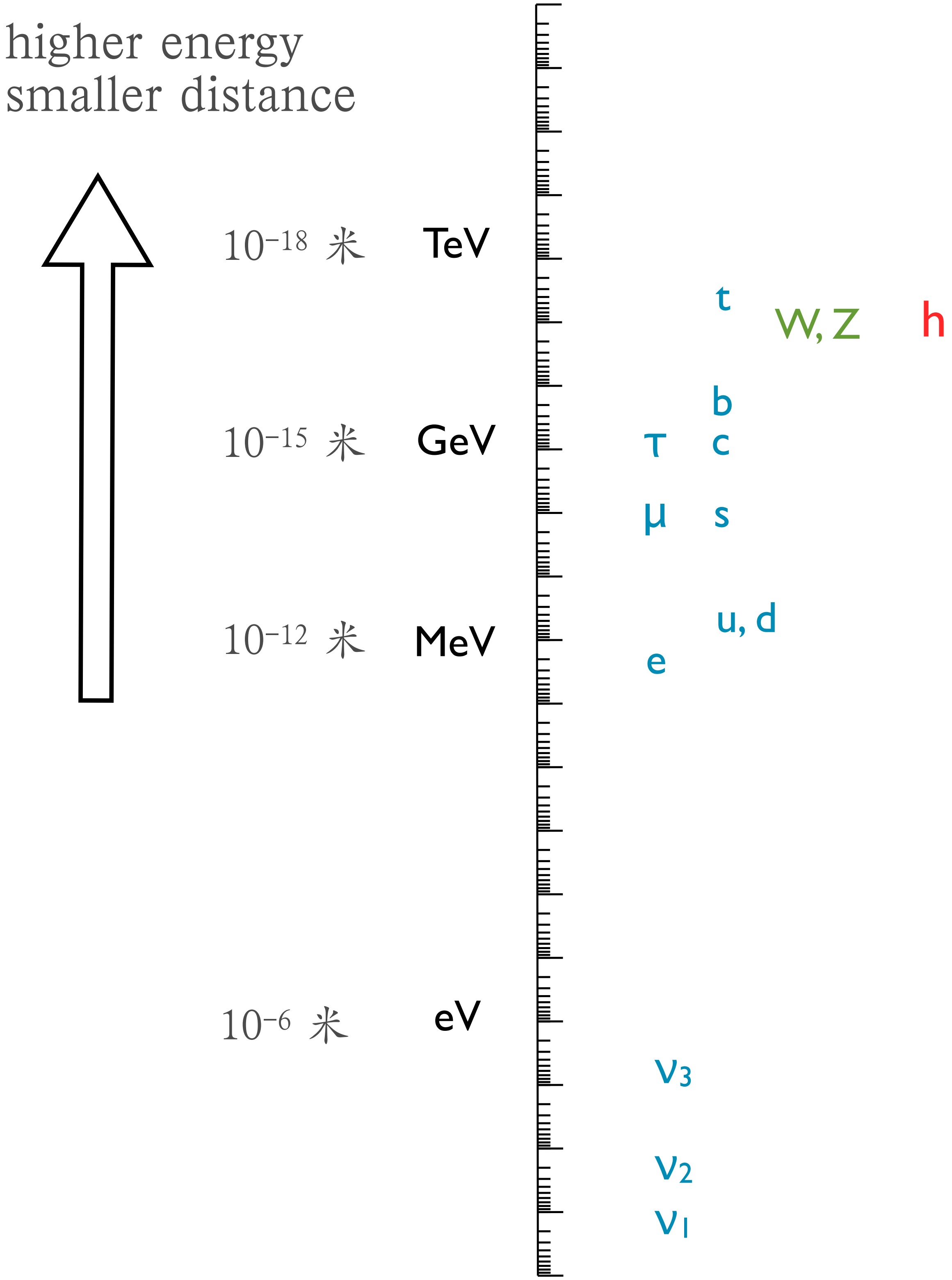
What are we looking for?

Standard Model



Amazing progresses in the last ~100 years

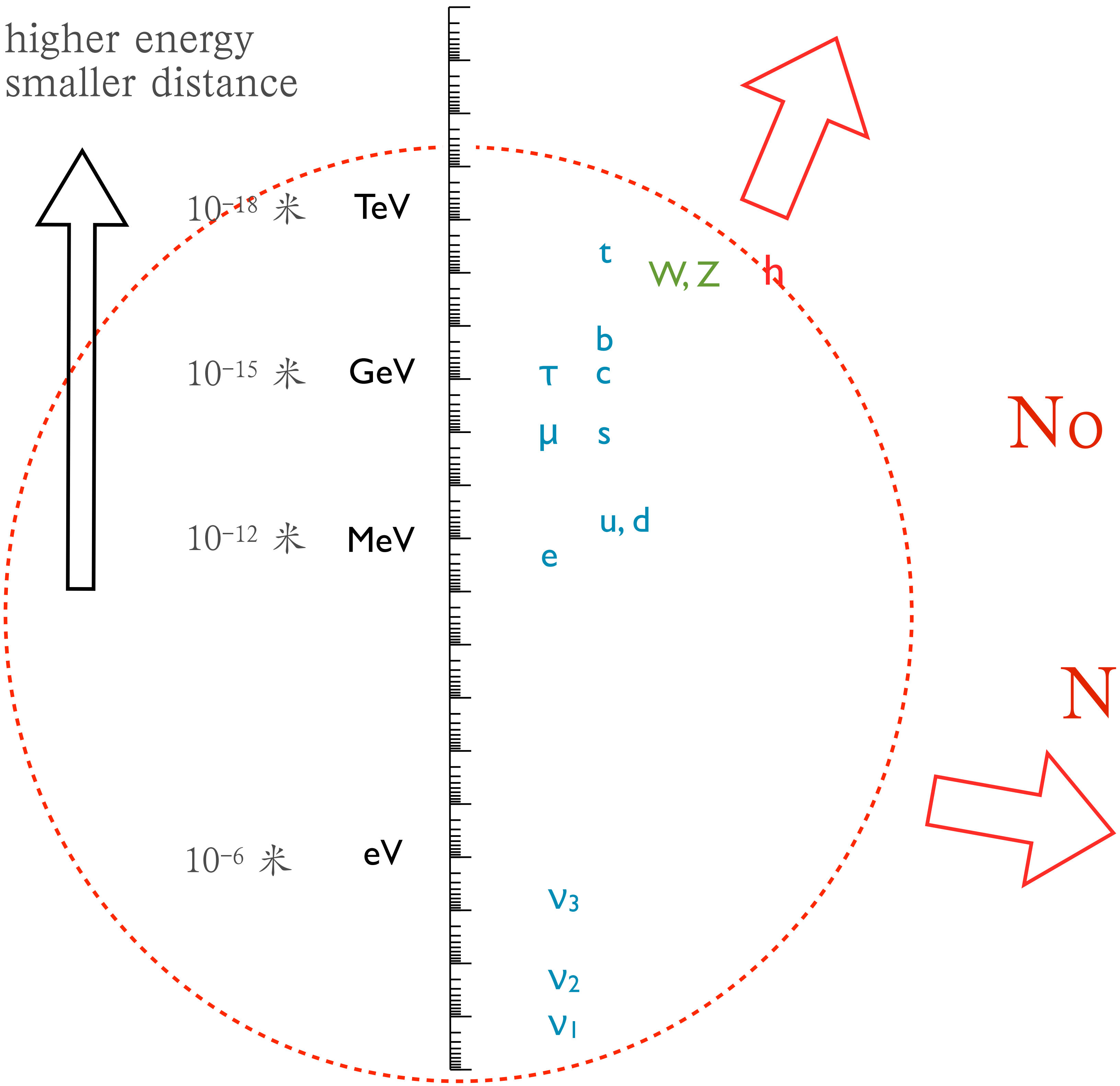
Guidance for the journey



Almost at each step, exp+theoretical consistency told us there must be something new, and how to find them.

We are getting (too) used to it.

Beginning of an new era



unknown

No exp and theoretical inconsistency

No no−lose theorem

No-lose theorem

- Often understood as a guarantee of discovering new particles, or detect deviations from the SM.

- For physics case of future colliders, it is tempting to construct No-lose theorems.
  - Sometimes viewed as necessary for successful proposal of the project.

No-lose theorem

- Can't be based on particular models.
  - Take any more, multiply mass scale by a factor of x, with $x < 10$
  - Model does not change (much).
  - Yet, this can very well be the difference between visible and invisible at a collider.

No-lose theorem

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [37]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [38]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [38]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [38]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [39]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [40]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [41]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [42]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [43]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Such deviations can be detected at Higgs factories

Demonstrates Higgs measurement lepton collider can probe a broad range of models.

No-lose theorem

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However, these are not no lose theorems. Can change model parameters to make these deviations small, invisible to Higgs coupling measurements.

There is no general no-lose theorem.

There is risk in any scientific exploration. Should not abandon them just because of the risks.

SM is not complete, many open questions

We will make significant progresses on important questions at future colliders!

Open questions in particle physics

- Electroweak symmetry breaking.
- Dark matter.
- Matter anti-matter asymmetry of the universe
- Origin of flavor structure
- CP violation
- ...

Electroweak symmetry breaking

The main physics goal of the lepton colliders

Fundamental interactions in the SM

Electromagnetism: Coulomb $\sim \frac{\alpha}{r}$

QCD: confinement $\sim r$

Weak interaction: Higgs $\sim \frac{e^{-m_{\mathrm{W}} \cdot r}}{r}$

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Well understood with many decades of exp study.

Lead to numerous breakthroughs, including the establishing QM and QFT

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Weak interaction: Higgs $\sim \frac{e^{-m_{\mathrm{W}} \cdot r}}{r}$

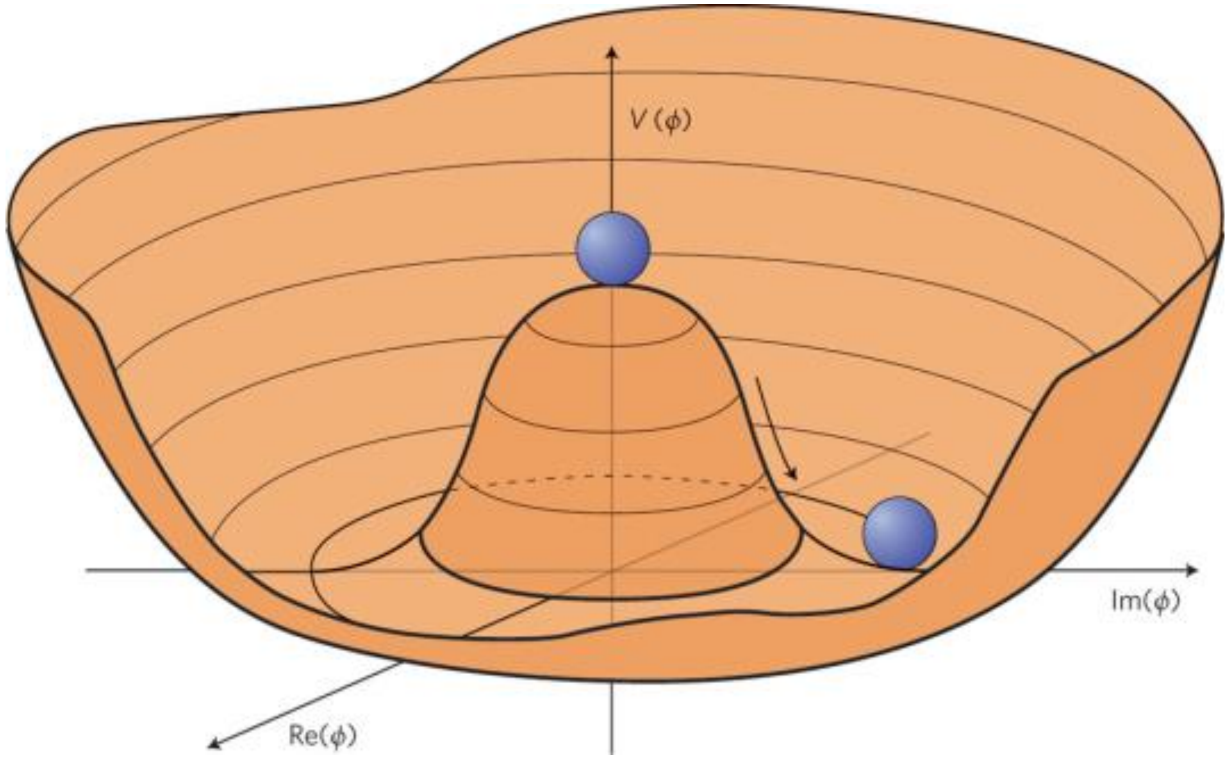
A very different type of interaction.
With a spin-0 Higgs boson, different from all other particles.
We have just barely started to study it, much to learn.

Why is Higgs puzzling?

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

h: a new kind of
elementary particle

"Simple" picture:

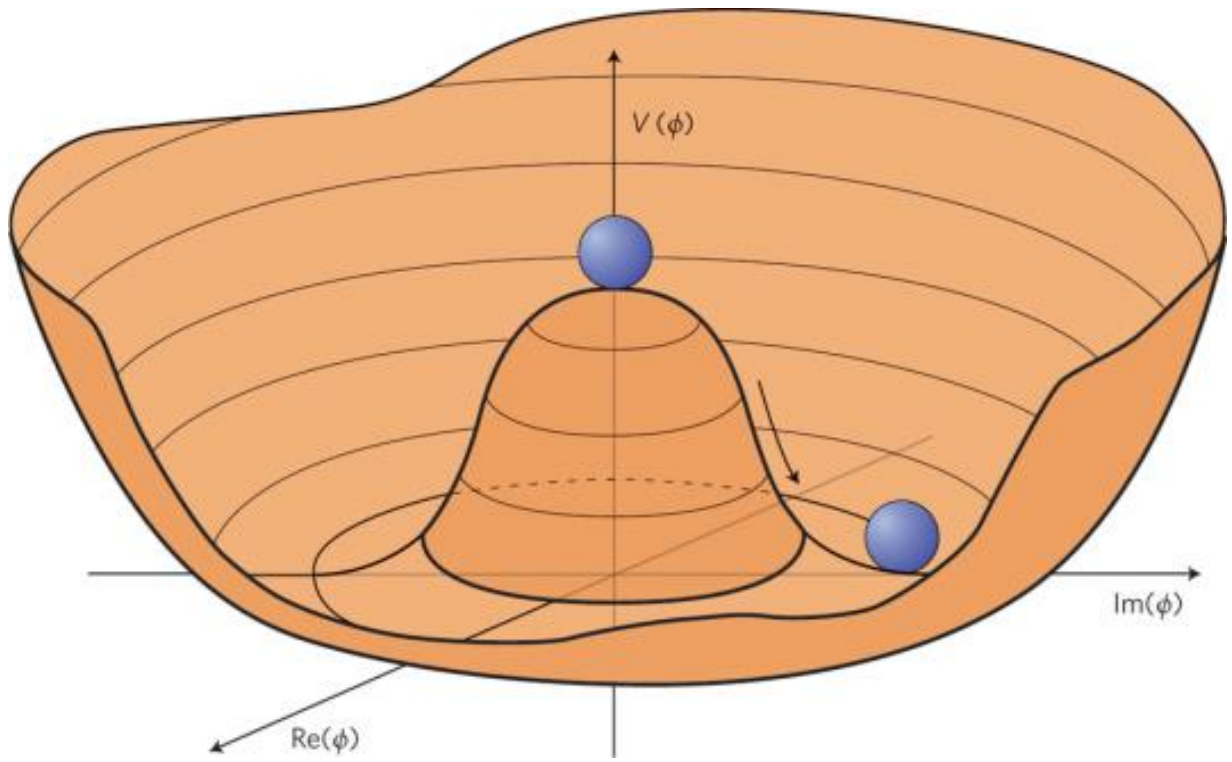


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

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

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

“Simple” picture:



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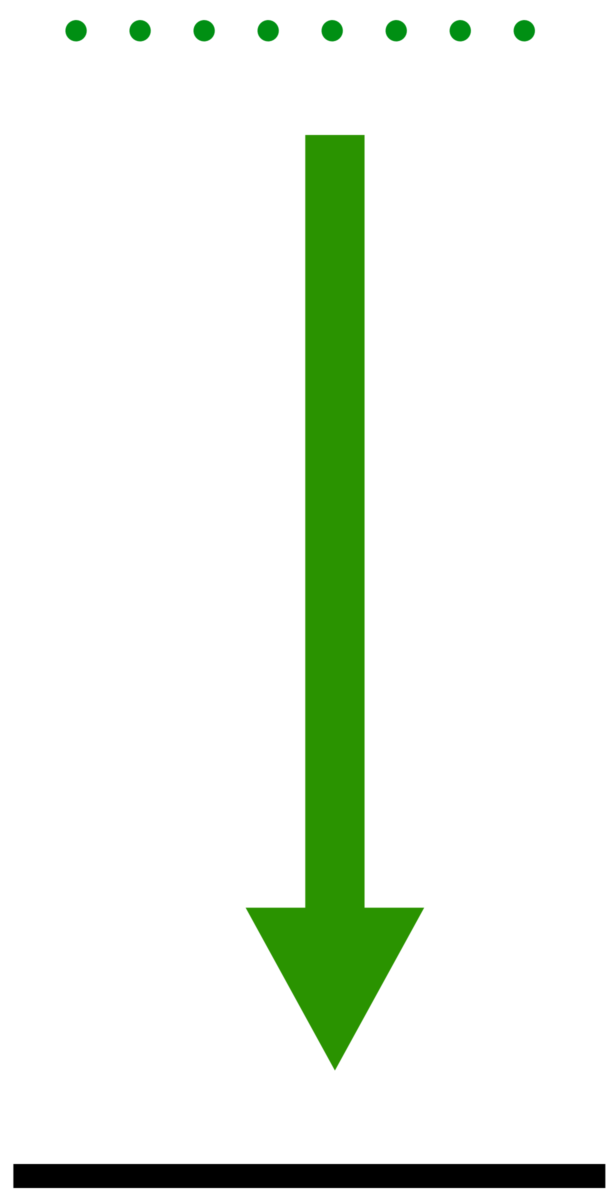
Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

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

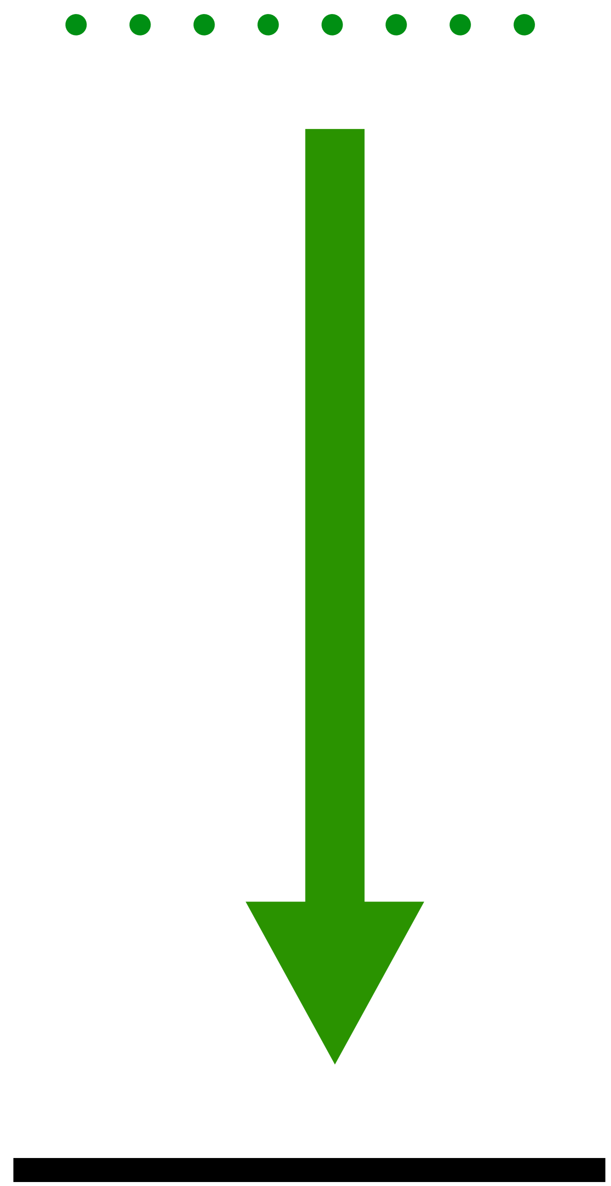
How to predict Higgs mass?



The energy scale of new physics
responsible for EWSB

Electroweak scale, 100 GeV.
m_h , m_W …

How to predict Higgs mass?



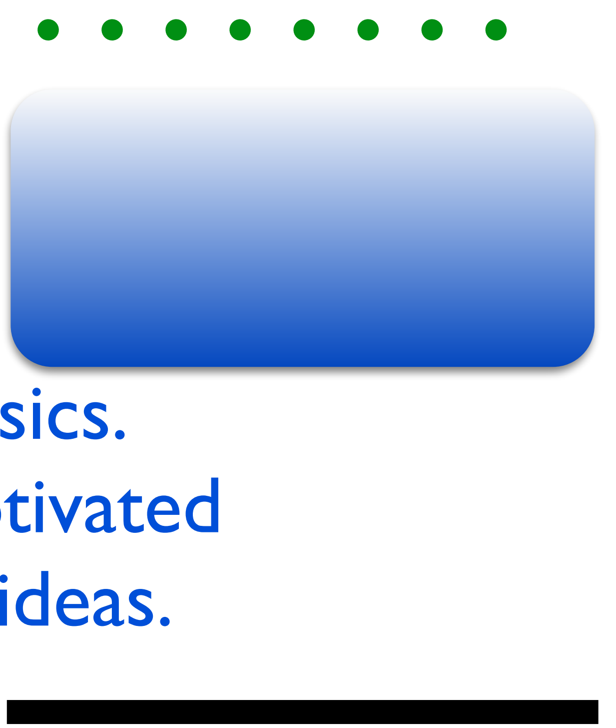
The energy scale of new physics responsible for EWSB

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 …

Toy model of scale generation

Scalar ϕ coupling to fermions

$$\mathscr{L} \supset M_\Psi(\bar{\Psi}_1\Psi_1 + \bar{\Psi}_2\Psi_2) + y\phi\bar{\Psi}_1\Psi_2 + \text{ h.c.}$$

Generating scalar potential:

$$V^\Psi(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_\Psi^4 + \underbrace{bM_\Psi^2 y^2\phi^2}_{\text{mass}} + \underbrace{cy^4\phi^4}_{\text{quartic}}\right) \times \left(\log\frac{M_\Psi^2}{\mu^2} - \ldots\right)$$

$a,\ b,\ c \sim \mathcal{O}(1)$, calculable

Coupling to another scalar, similar story

$$\mathscr{L} \supset \frac{M_\Phi^2}{2}\Phi^2 + \frac{\kappa}{2}\phi^2\Phi^2$$

$$V^\Phi(\phi) \simeq \frac{1}{16\pi^2}\left(a' M_\Phi^4 + \underbrace{b'\kappa^2 M_\Phi^2 \phi^2}_{\text{mass}} + \underbrace{c'\kappa^4\phi^4}_{\text{quartic}}\right)\left(\log\frac{M_\Phi^2}{\mu^2} + \ldots\right)$$

Producing a viable potential for ϕ

$$V^{\Psi}(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_\Psi^4 + \boxed{by^2M_\Psi^2\phi^2} + cy^4\phi^4\right) \times \left(\log\frac{M_\Psi^2}{\mu^2} - \ldots\right)$$

⇩

$$V_{\text{eff}}(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\lambda}{4}\phi^4, \qquad m_\phi^2 = -\frac{b}{16\pi^2}M_\Psi^2$$

Difficult to generate: $m_\phi \ll M_\Psi$

Expectation: new physics scale close to scalar mass

Producing a viable potential for ϕ

$$V^{\Psi}(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_{\Psi}^4 + by^2M_{\Psi}^2\phi^2 + cy^4\phi^4\right) \times \left(\log\frac{M_{\Psi}^2}{\mu^2} - \ldots\right)$$

$$V^{\Phi}(\phi) \simeq \frac{1}{16\pi^2}\left(a'M_{\Phi}^4 + b'\kappa^2M_{\Phi}^2\phi^2 + c'\kappa^4\phi^4\right)\left(\log\frac{M_{\Phi}^2}{\mu^2} + \ldots\right)$$

$$\square + \square \Rightarrow \quad m_{\phi}^2 = \frac{1}{16\pi^2}(-aM_{\Psi}^2 + bM_{\Phi}^2)$$

Producing a viable potential for ϕ

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$\square + \square \Rightarrow$

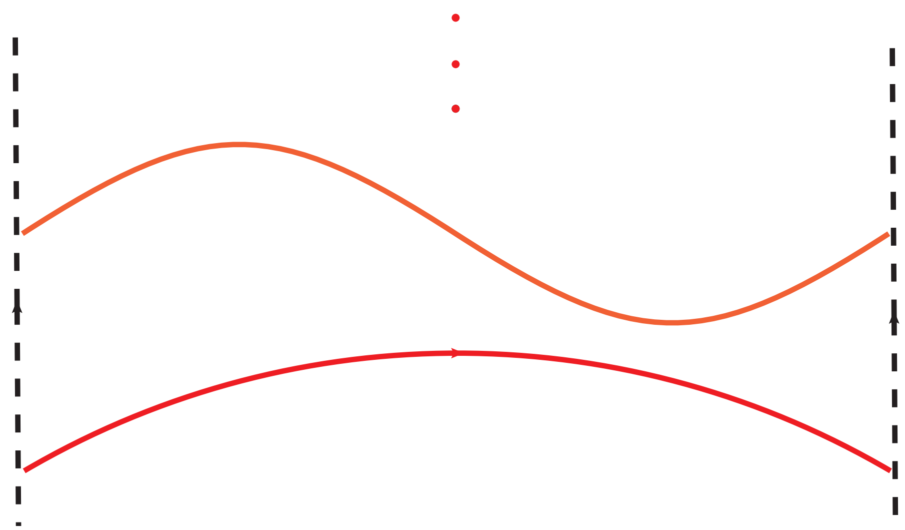
$$m_\phi^2 = \frac{1}{16\pi^2}(-aM_\Psi^2 + bM_\Phi^2)$$

Possible to have $m_\phi \ll M_{\Psi,\Phi}$ However,

need cancellation : $\sim \mathcal{O}\left(16\pi^2\frac{m_\phi^2}{M_{\Psi,\Phi}^2}\right)$ fine-tuning

tuning $\propto M_{\rm NP}^{-2}$ is sever if $m_\phi \ll M_{\rm NP}$

Higgs mass in quantum theory.
Quantum fluctuation: Zero point energy



$$\mathcal{H}_{\rm quant} = \sum_{\vec{p}} \frac{1}{2}\hbar\omega_{\vec{p}} \simeq \int^{|p|<\Lambda} \frac{d^3\vec{p}}{(2\pi)^3}\hbar\omega_{\vec{p}}$$

$$\omega_{\vec{p}} = \sqrt{\vec{p}^2 + m^2} \qquad (\hbar = 1)$$

Λ: the energy scale of new physics.

Standard Model: include fluctuations of W boson, top quark, ...

$$m_{\rm W} = g_2 h, \quad m_{\rm top} = y_t h$$

$$\mathcal{H}_{\rm quant} \simeq \frac{9}{64\pi^2} g_2^2 \Lambda^2 h^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 h^2 + \cdots$$

Naturalness problem.

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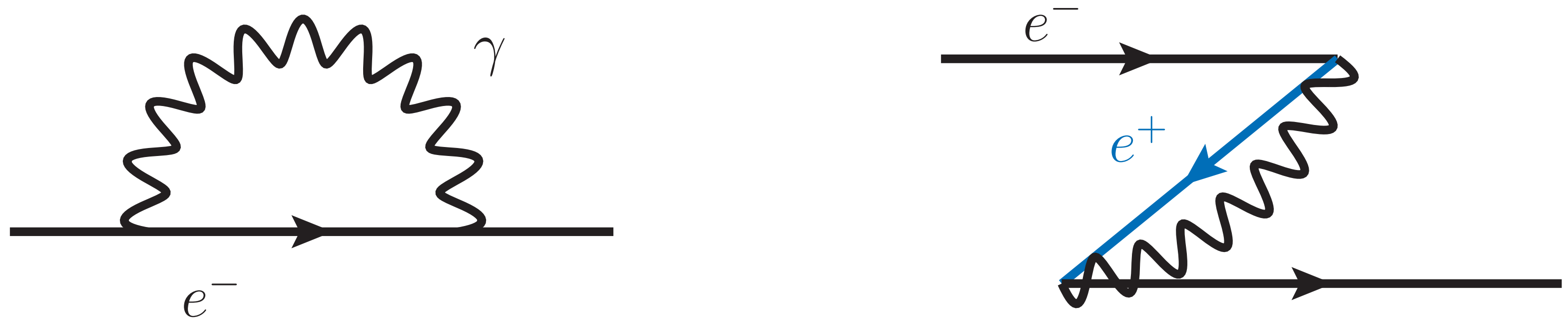
Naturalness problem.

$$\mathcal{H}_{\text{quant}} \simeq \frac{9}{64\pi^2} g_2^2 \Lambda^2 h^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 h^2 + \cdots$$

- No large cancellation $\Rightarrow$ $m_h{}^2$ (physical) ≈ $c\Lambda^2$
  - Λ≈ TeV, new physics at TeV scale!

Naturalness criterion leads to a prediction of the mass scale of new physics!!

Naturalness in nature, electron mass



$$\delta m_e \simeq \frac{\alpha}{\pi} m_e \log\left(\frac{\Lambda}{m_e}\right)$$

- From extension of spacetime symmetry:
  - Lorentz symmetry + quantum mechanics
    $\Rightarrow$ positron, doubling the spectrum!

- Log divergence (very mild). Proportional to m_e, "natural".

H. Murayama's talk

TeV Supersymmetry (SUSY)

- Supersymmetry, $|\,\text{boson}\rangle \Leftrightarrow |\,\text{fermion}\rangle$

- An extension of spacetime symmetry.

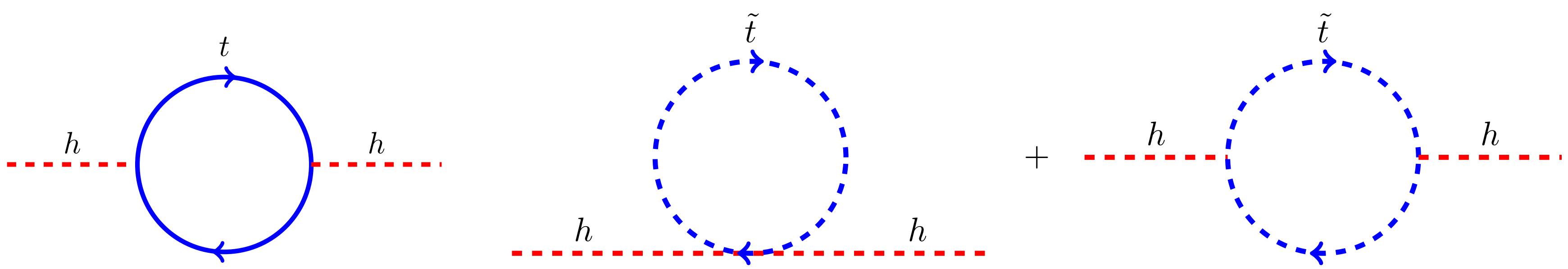
- New states: "Partners"

	spin			spin
gluon, g	1	gluino	$\tilde{g}$	1/2
$W^{\pm}$, Z	1	gaugino	$\tilde{W}^{\pm}, \tilde{Z}$	1/2
quark	1/2	squark	$\tilde{q}$	0
....		....		
Standard Model particles		superpartners		

- Mass of superpartners $\sim$TeV.

Electroweak scale in Supersymmetry

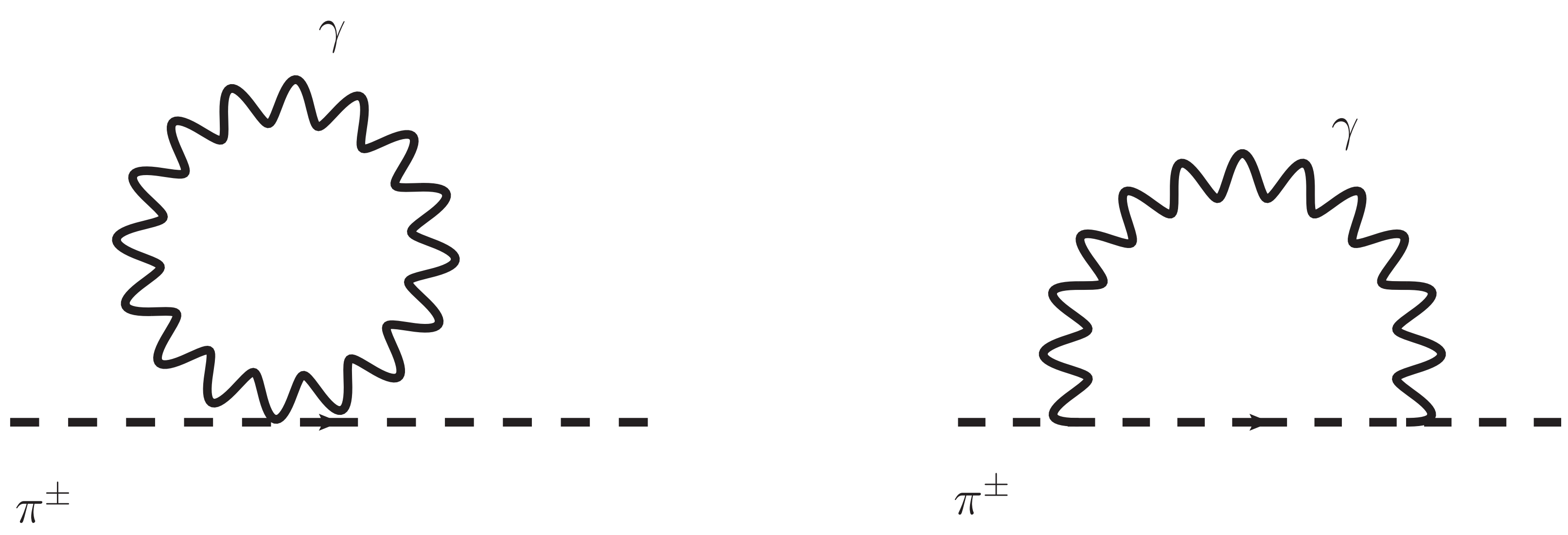
A unique property of supersymmetry:
Mass parameters evolves slowly, generating large scale separation.



$$\delta m_{H_u}^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2 \right) \log \frac{\Lambda}{\text{TeV}}.$$

Prefer light superpartners $m_{\text{SUSY}} \sim 1 \text{ TeV}$

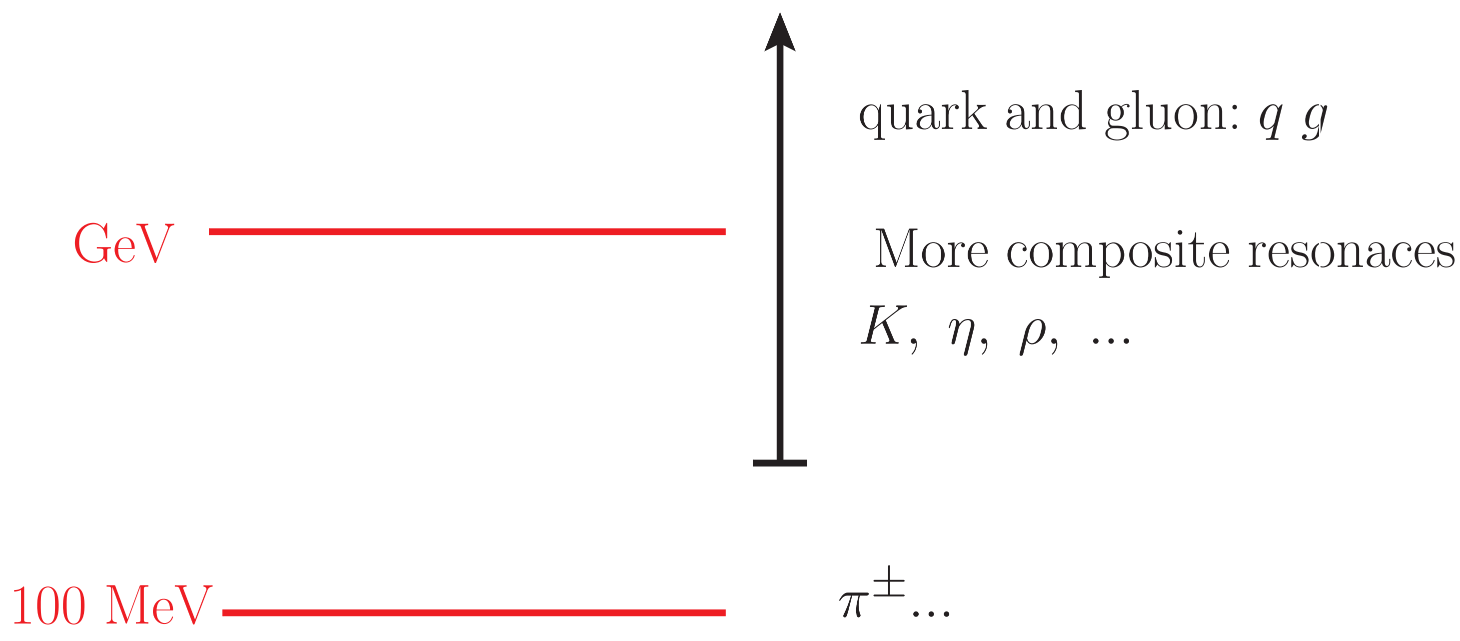
Naturalness in nature?



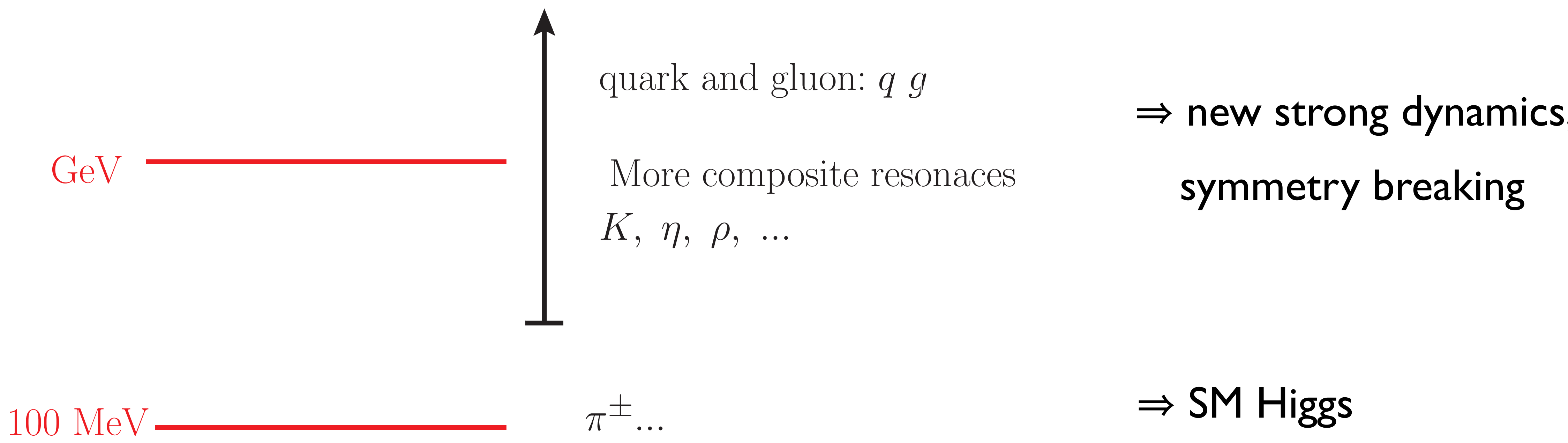
$$\delta m^2_{\pi^{\pm}} \simeq \frac{e^2}{16\pi^2}\Lambda^2$$

- Example: low energy QCD resonances: pion ....
- m_π ~ 100 MeV.
- Naturalness requires $\Lambda \approx$ GeV.
  - Indeed, at GeV, QCD $\Rightarrow$ theory of quark and gluon
  - Pion is not elementary.

“Learning” from QCD



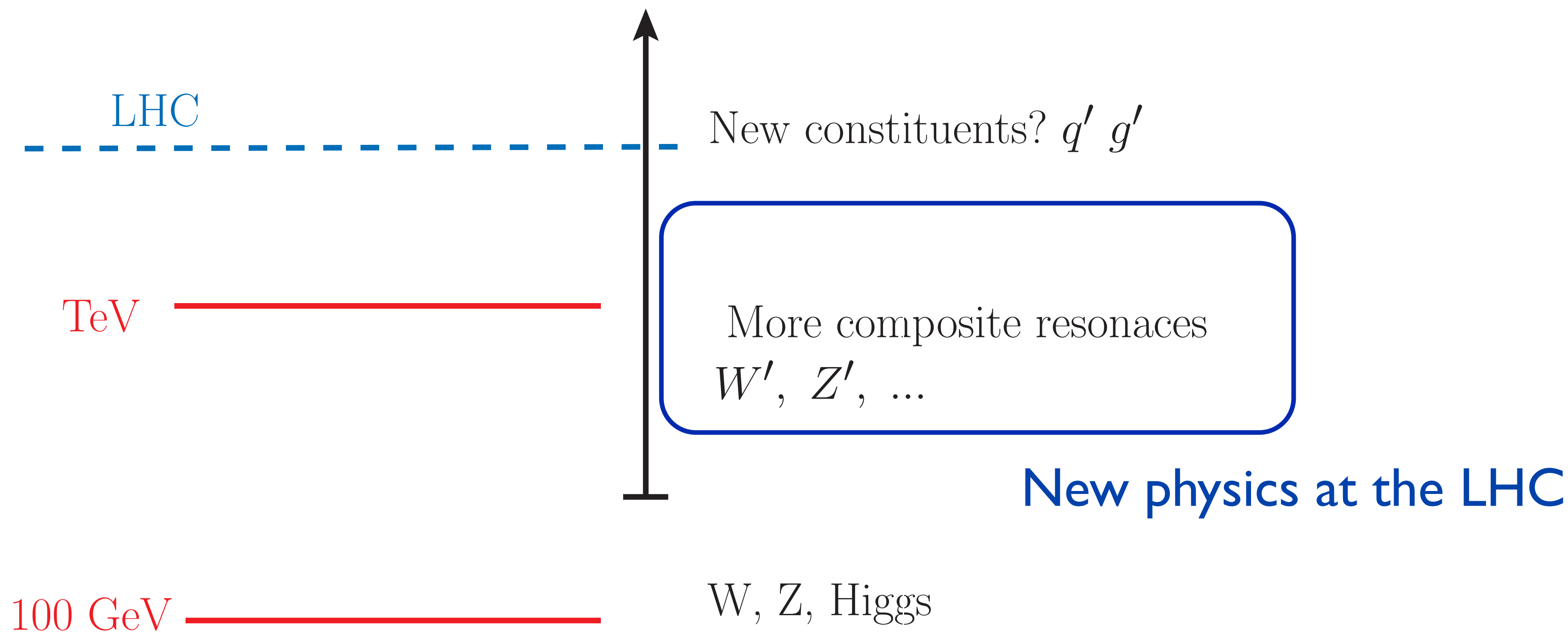
“Learning” from QCD



- Construct a new strong dynamics in which the low lying states will be the SM Higgs.

- Composite Higgs models. Still a natural theory.

Composite Higgs



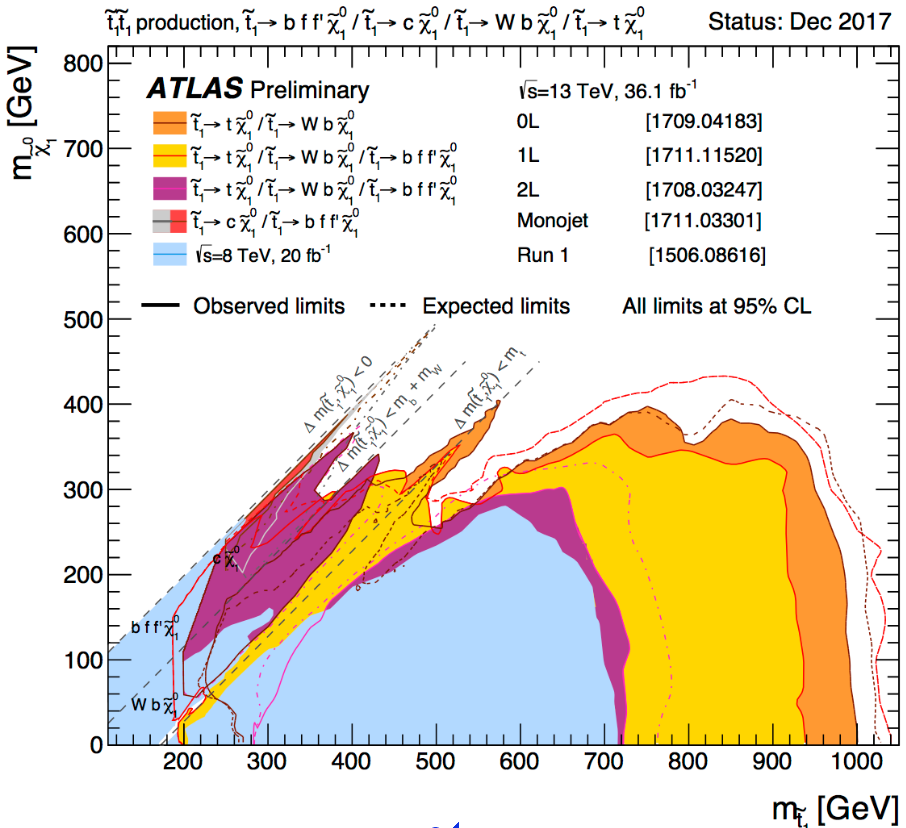
- Many many scenarios, models in this class.
- Little, fat, twin, holographic .... Higgs

– Similar scenarios: Randall-Sundrum, UED...

- Theories with Higgs + resonances.

All eyes on these searches

Supersymmetry



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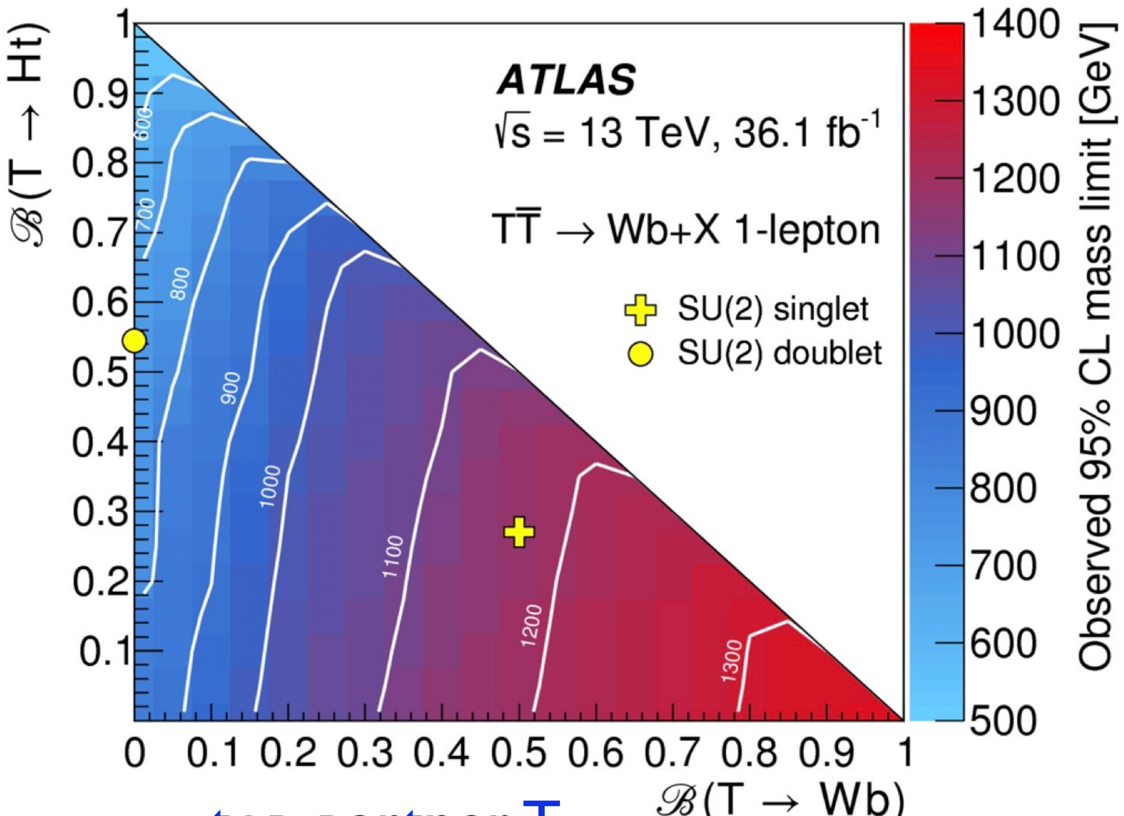
Composite Higgs



top partner, T

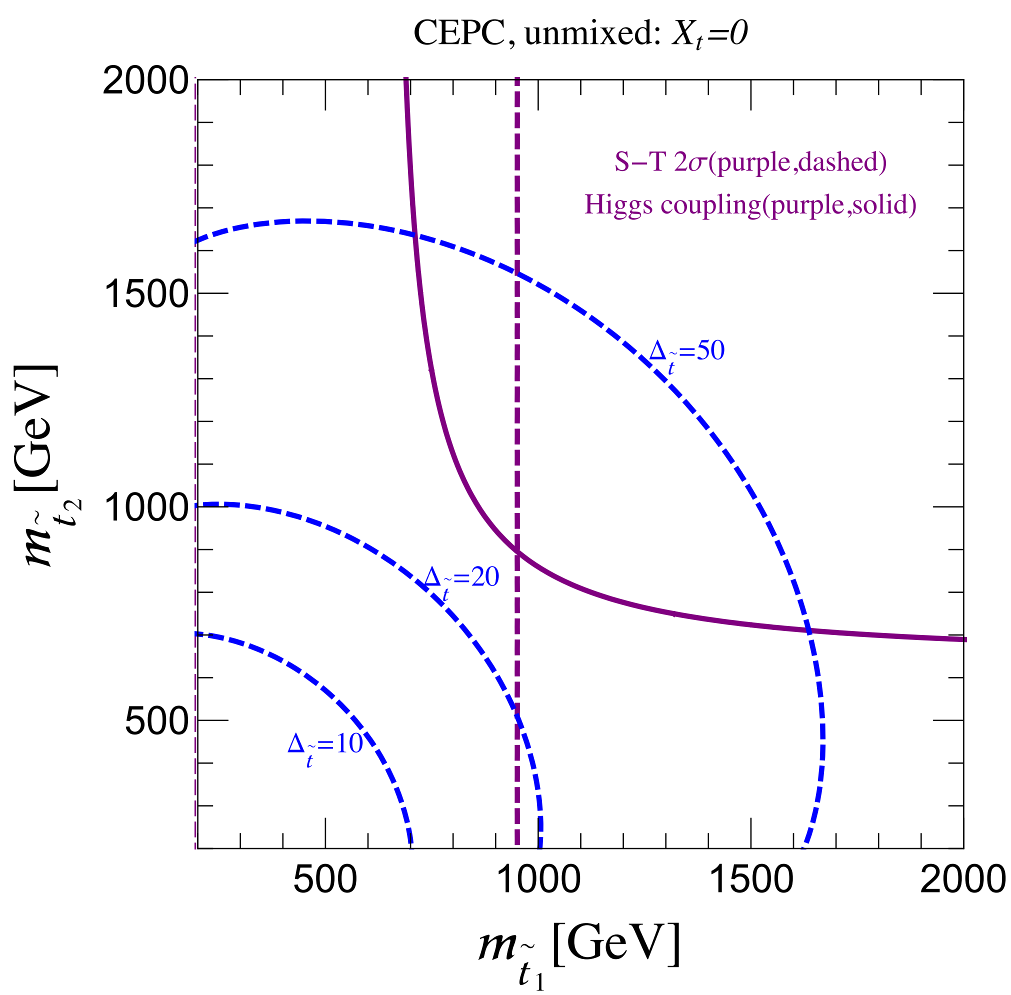
fine-tuning = comparison: $\frac{1}{16\pi^2} m_{\rm T}^2 \quad vs \quad m_h^2 = (125~{\rm GeV})^2$

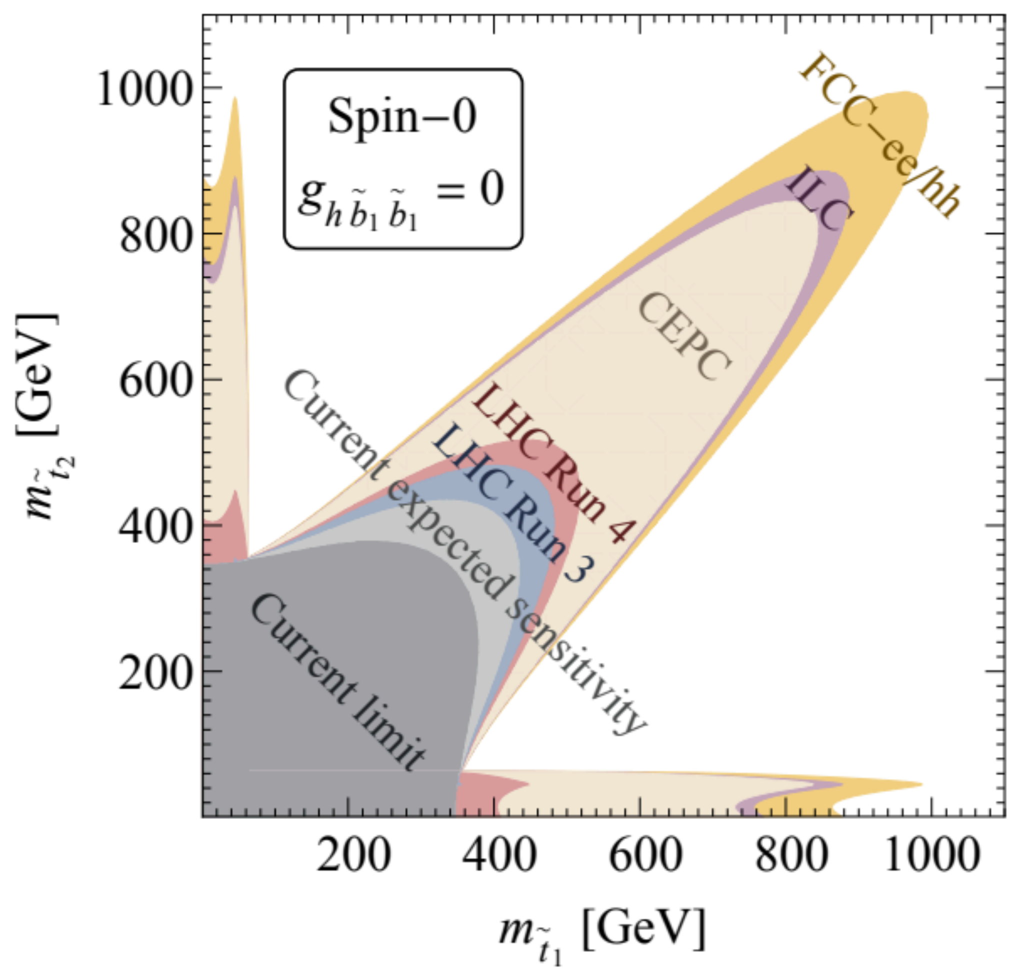
current limit: $m_{\rm T} \sim 1~{\rm TeV}$

My view: not a big problem yet.

Naturalness in SUSY

- LHC searches model dependent, many blind spots.

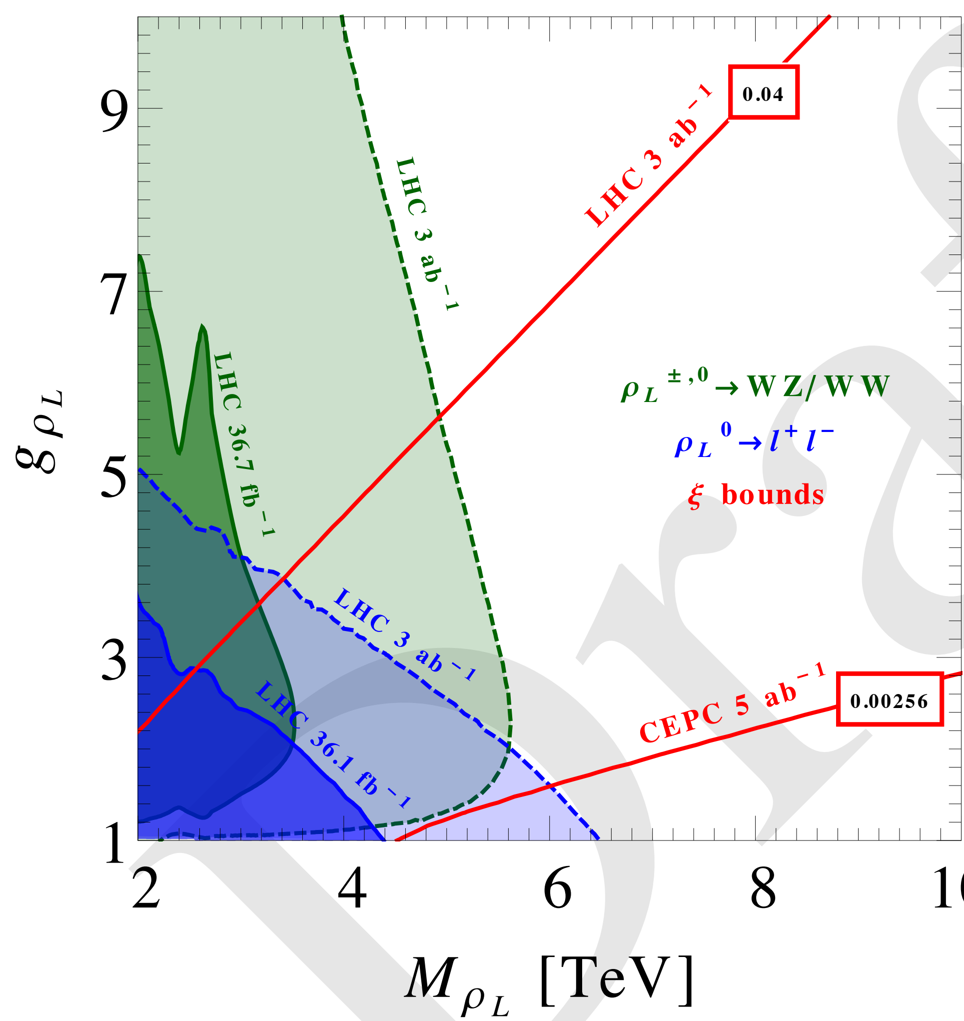


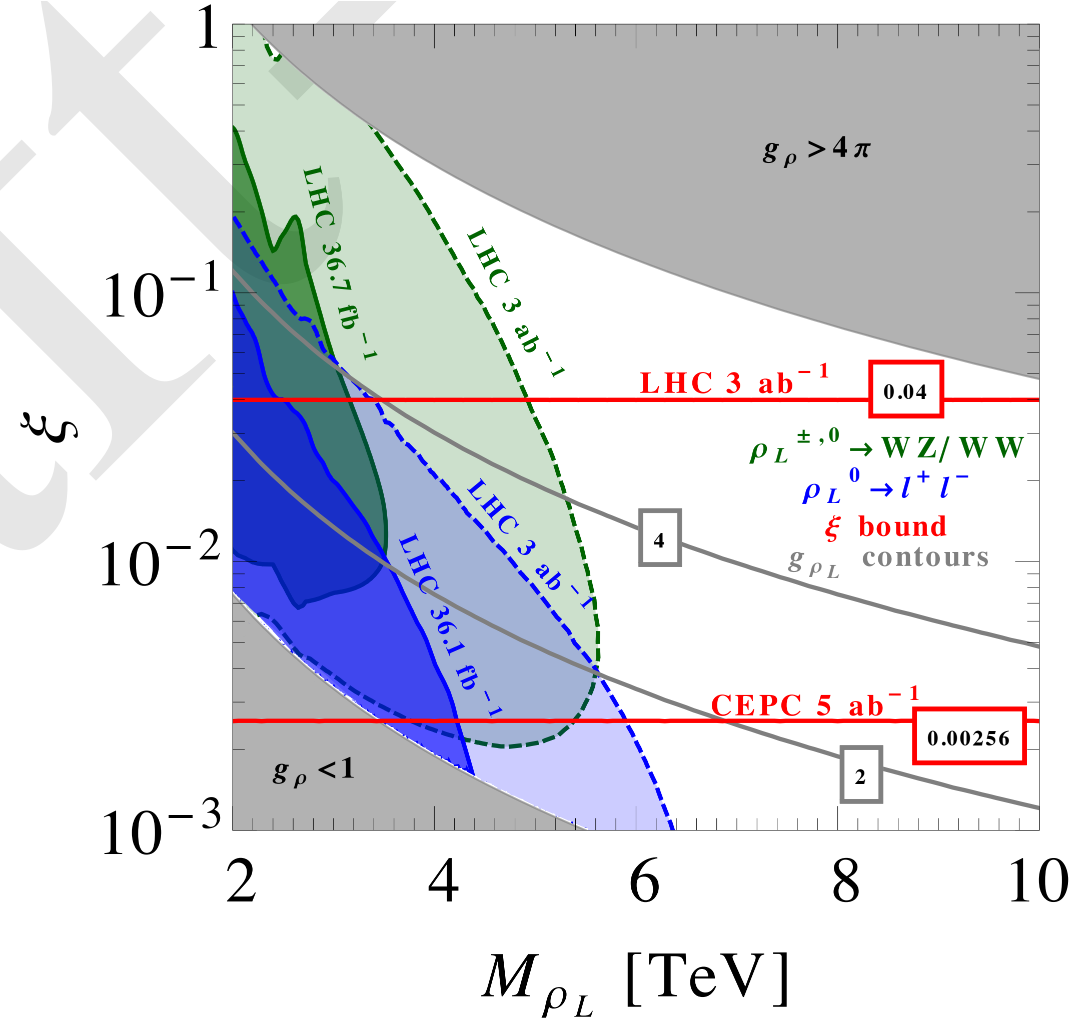


- Testing fine-tuning down to percent level.

Composite Higgs

Ke-Pan Xie



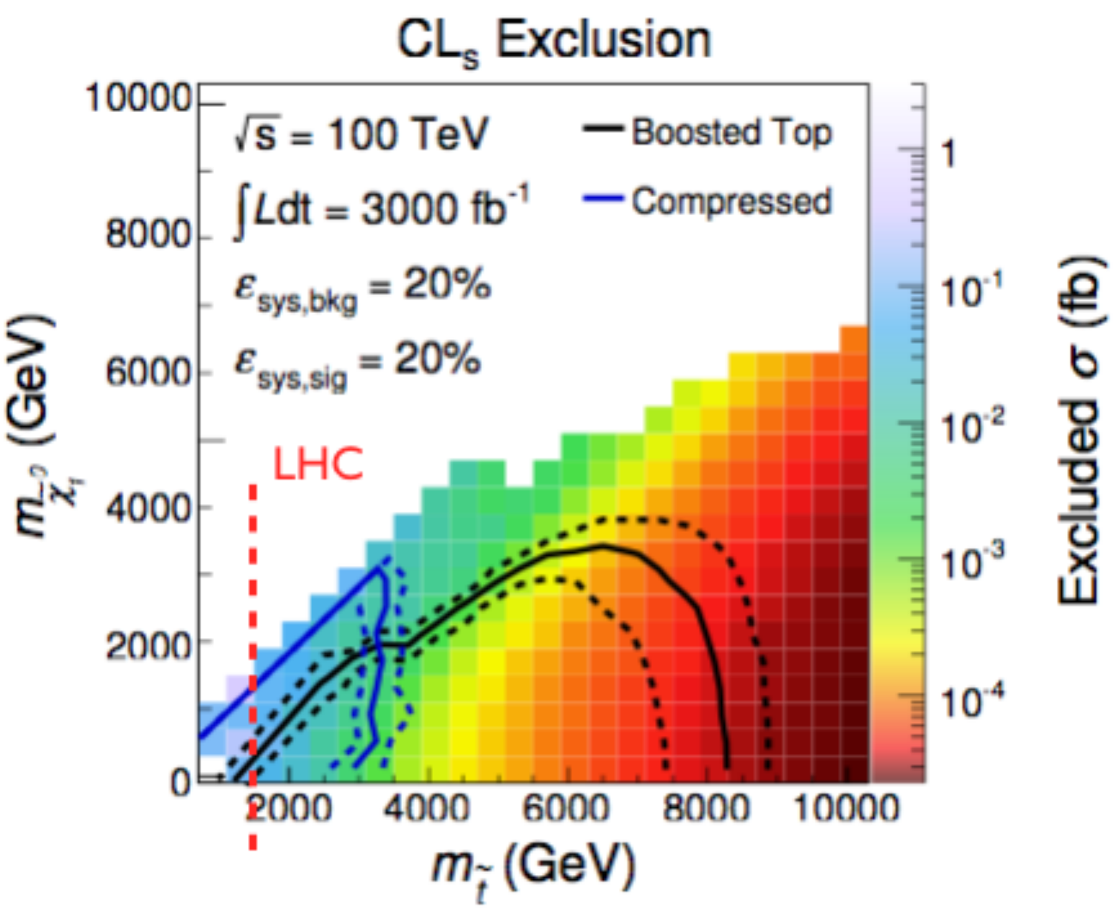


$$\text{fine}-\text{tuning} \propto \xi = \frac{v^2}{f^2} \qquad \delta_{Zh} \simeq 1 - \xi$$

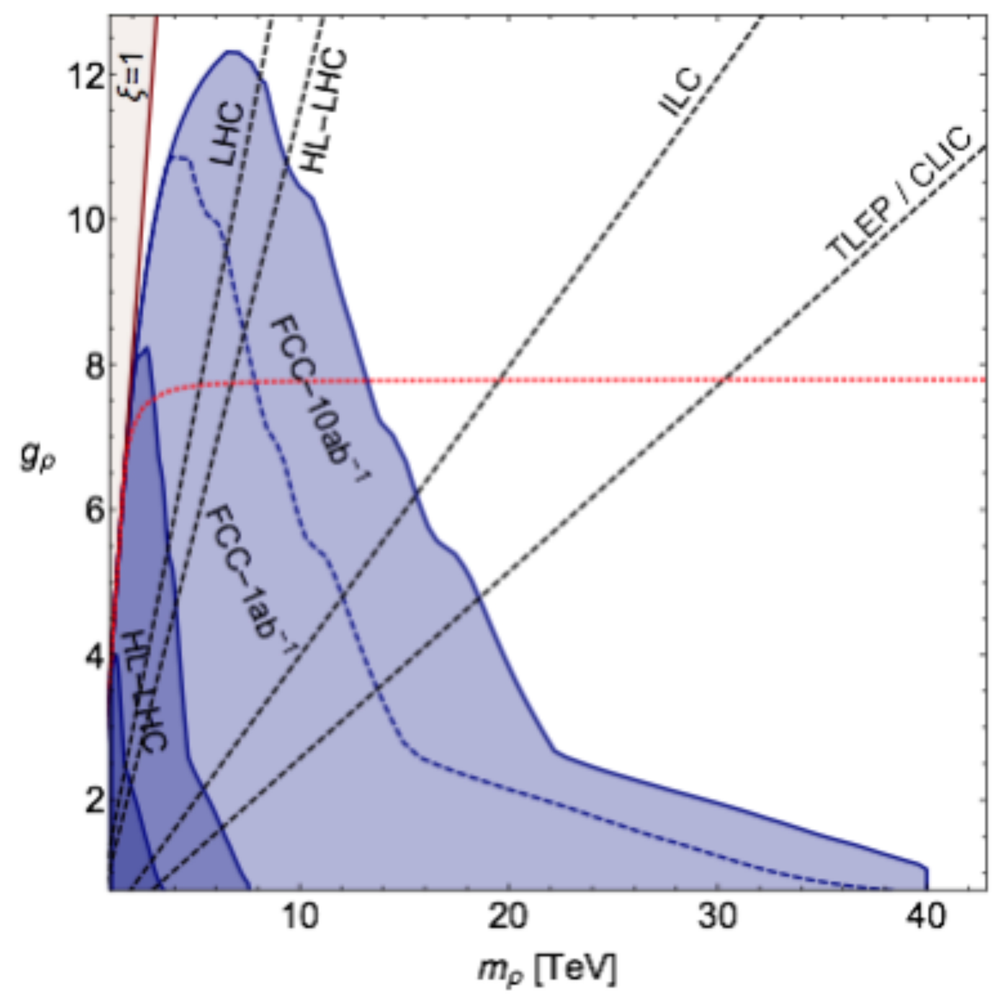
Higgs coupling: good test of fine-tuning

Testing naturalness at 100 TeV pp collider

Cohen et. al., 2014



Pappadopulo, Thamm, Torre, Wulzer, 2014

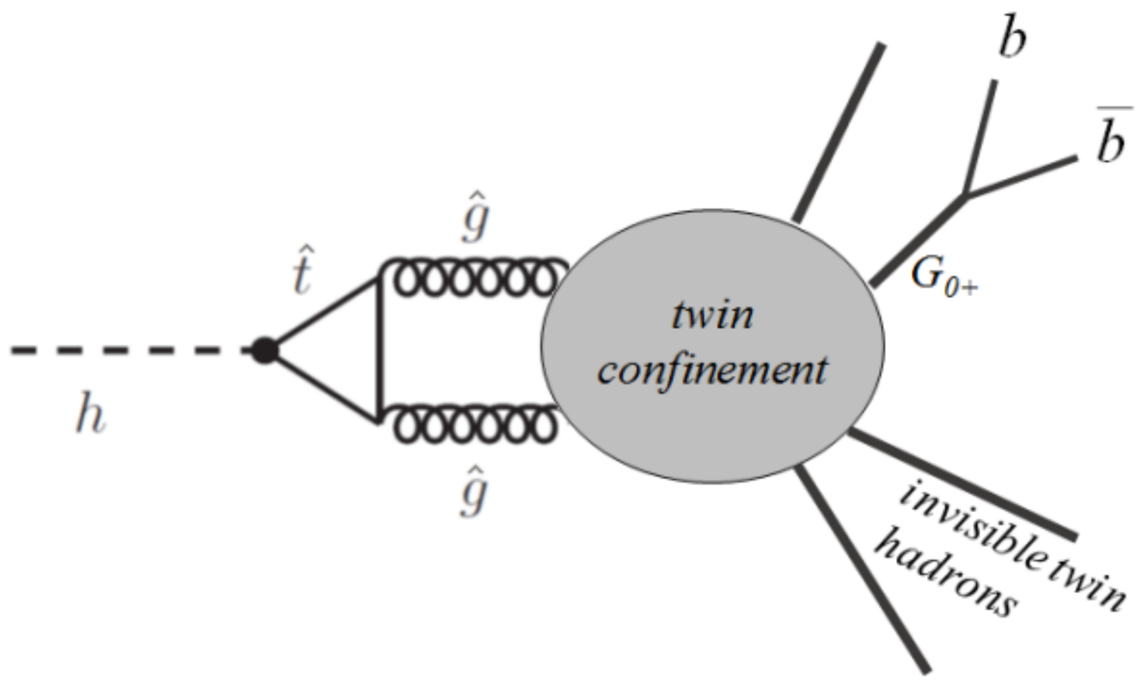


Fine tuning: $(M_{NP})^{-2}$

Stealthy top partner. "twin"

Chacko, Goh, Harnik

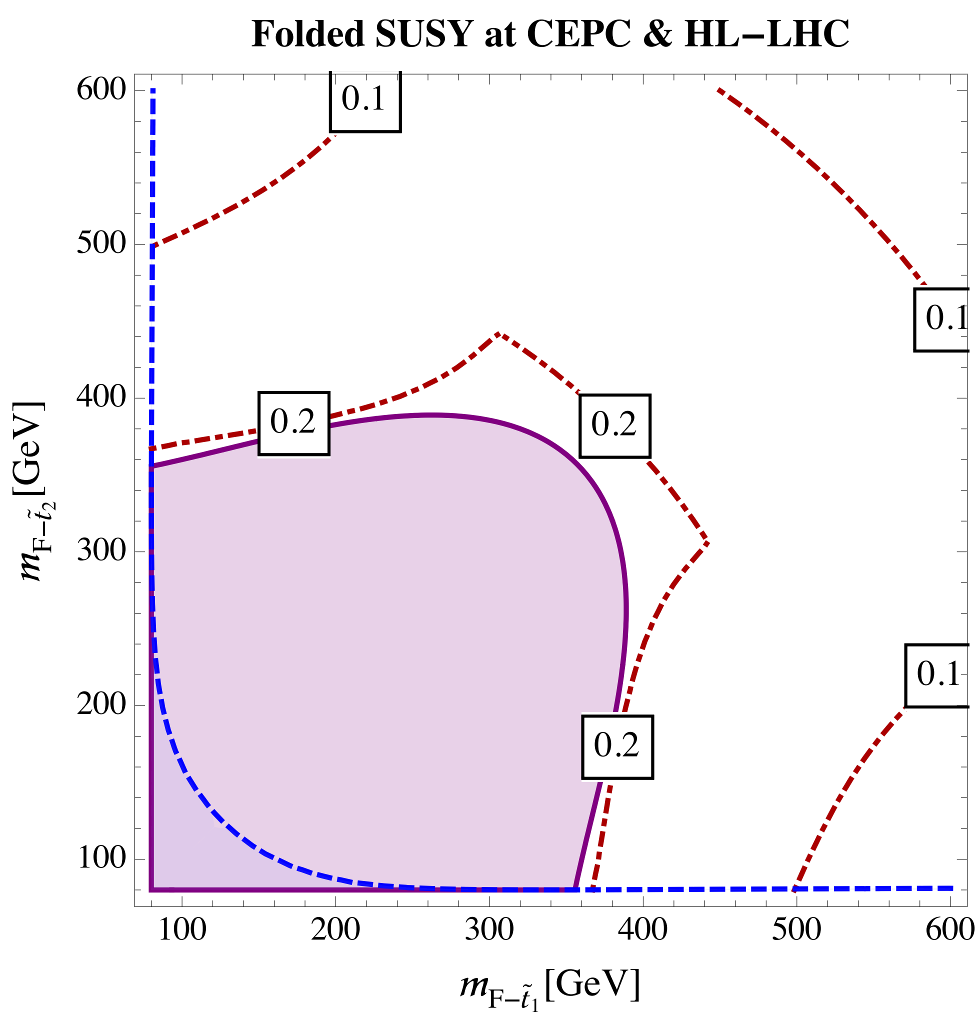
Craig, Katz, Strassler, Sundrum

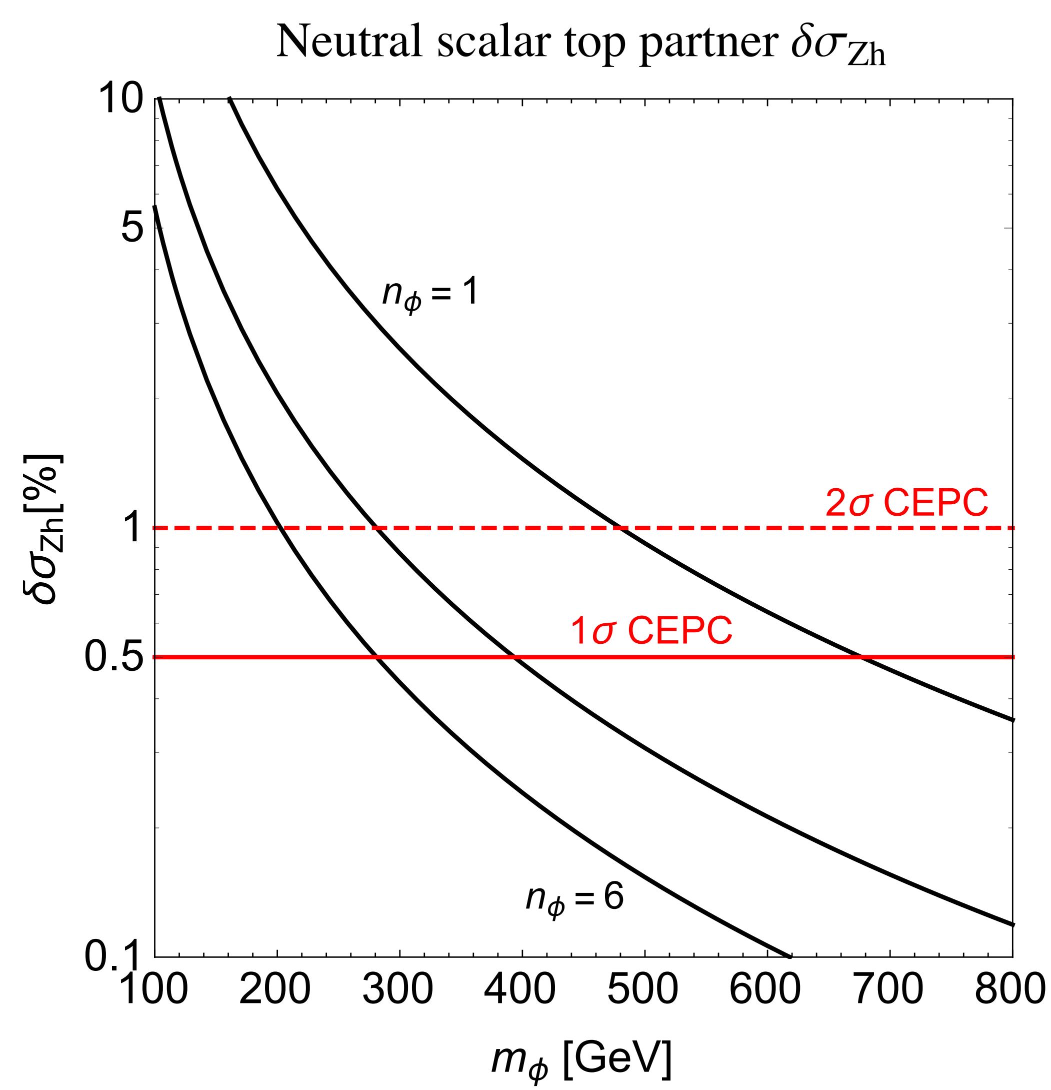


- Top partner not colored. Higgs decay through hidden world and back.

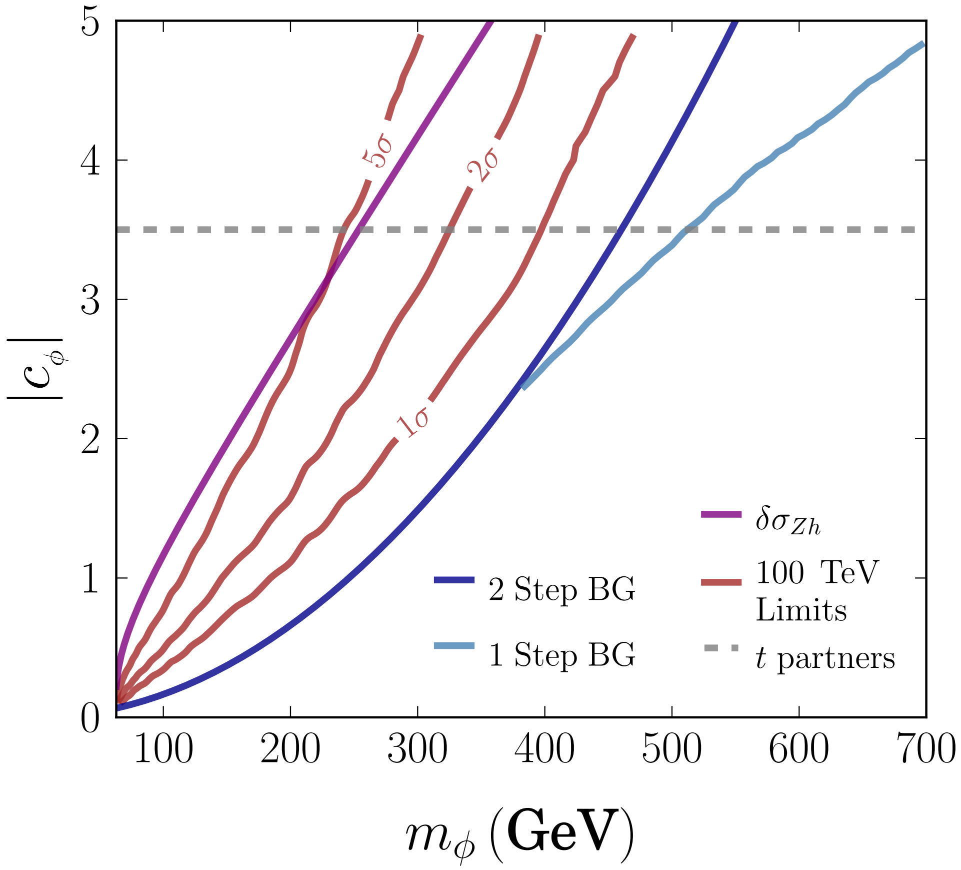
- Can lead to Higgs rare decays.

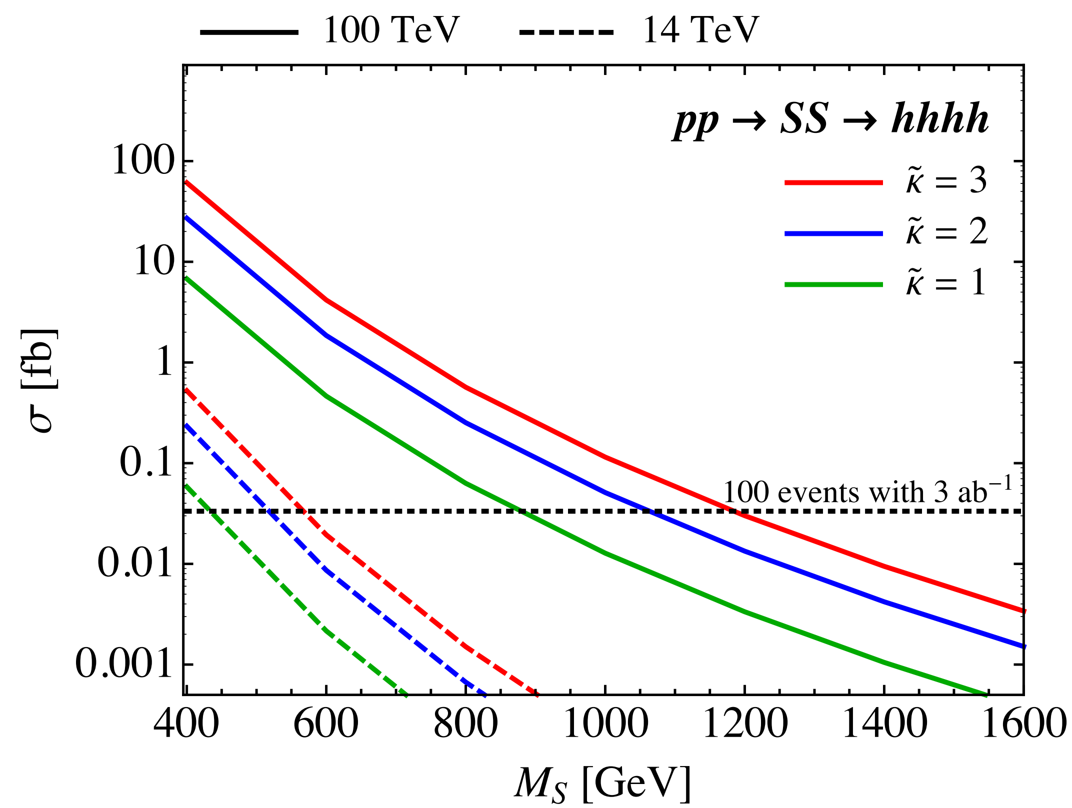
Scalar top partner:





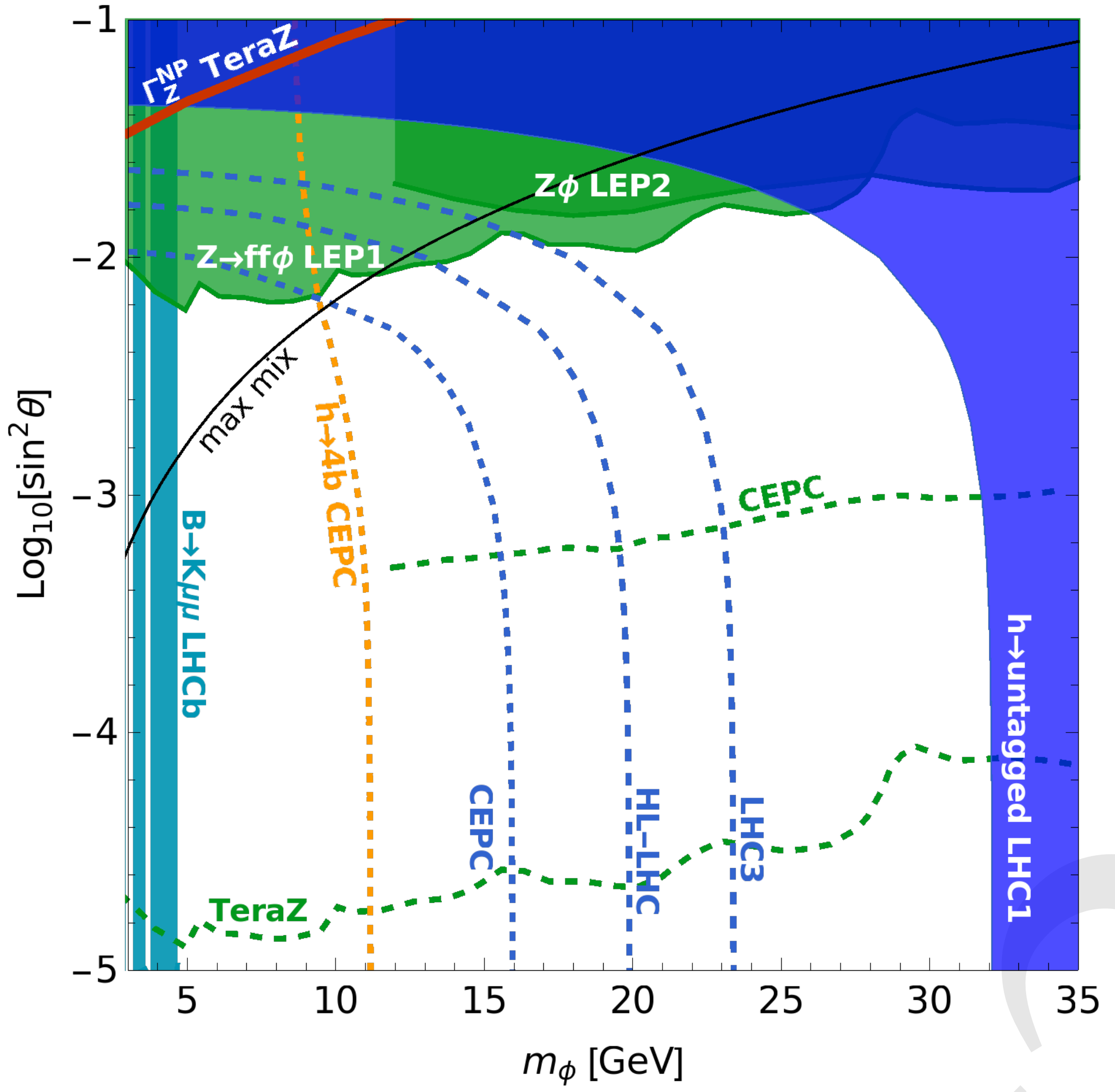
At 100 TeV pp collider





Difficult search, especially if the top partner has a Z_2 symmetry (thus stable)

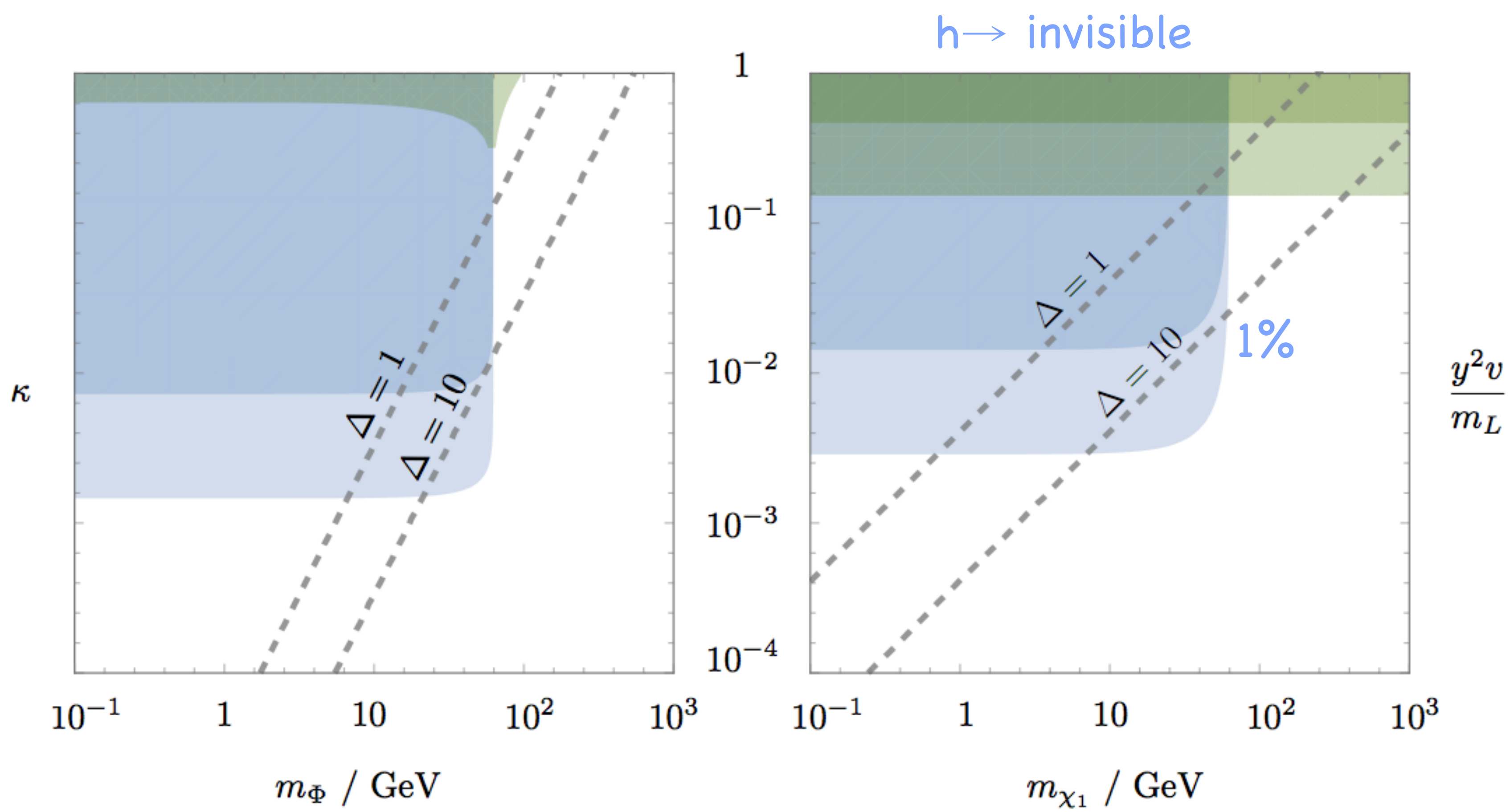
Relaxion



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



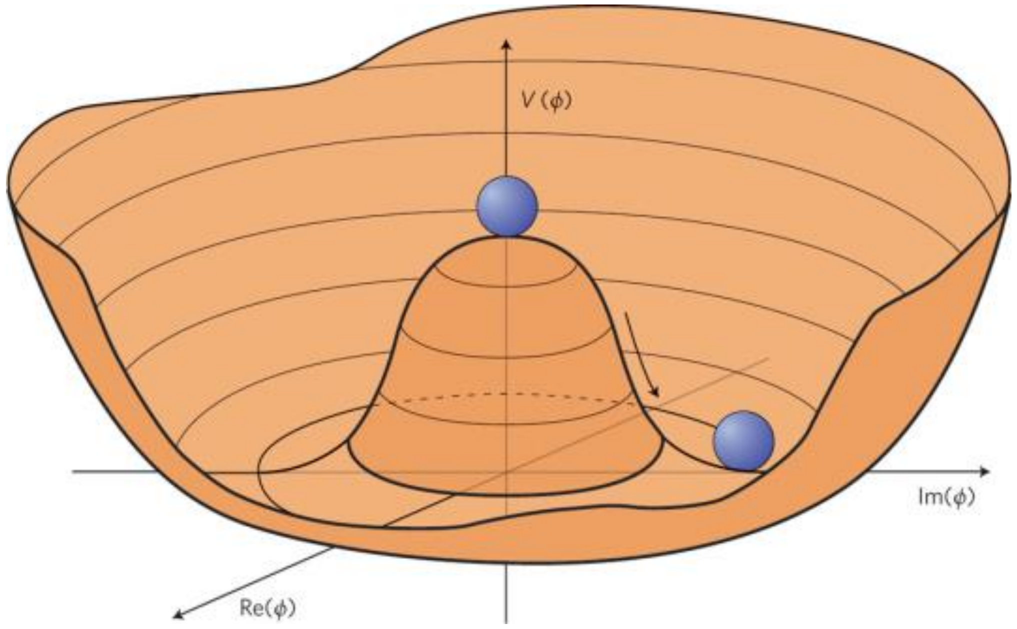
- For a U(1) gauge theory, new physics at scale $gM_{Pl.}$ If g<<1, responsible for weak scale? Cheung

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

Why is Higgs measurement crucial?

- Naturalness is the most pressing question of EWSB.
  - How should we predict the Higgs mass?
- We may not have the right idea. No confirmation of any of the proposed models.
- 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.

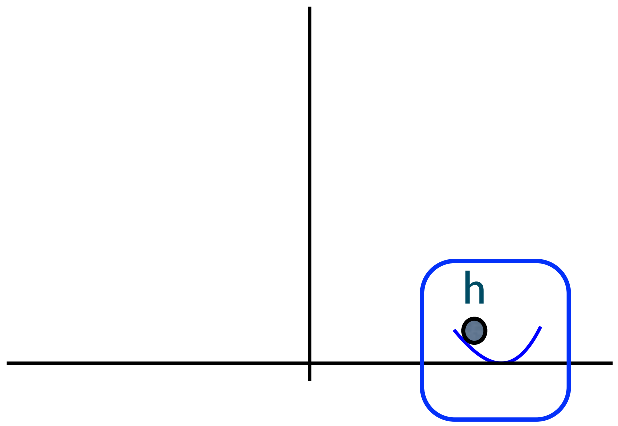
Mysteries of the electroweak scale.



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

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

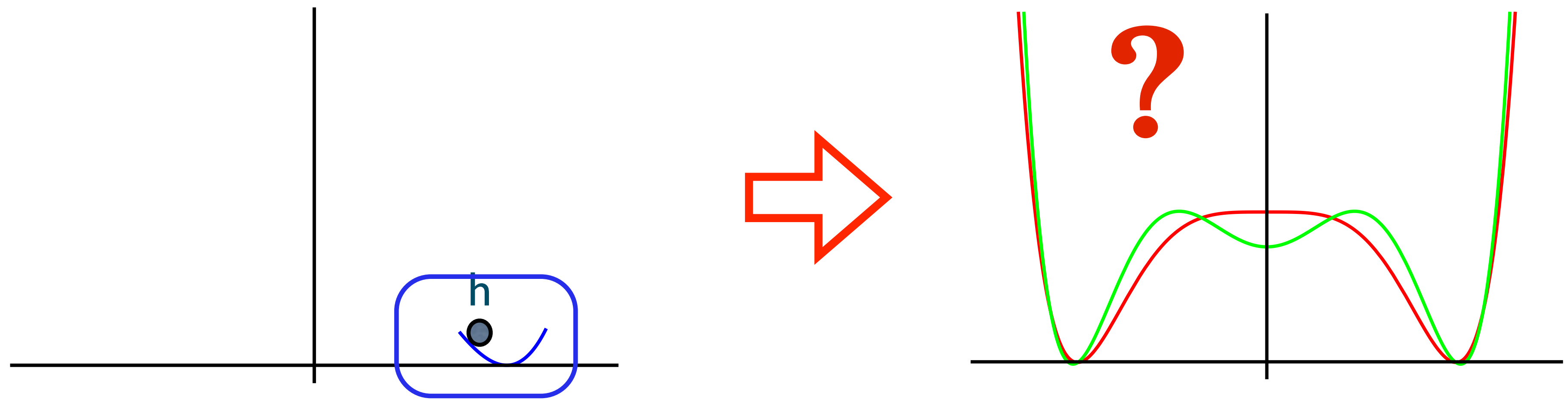
Mysteries of the electroweak scale.



What we know now

- 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

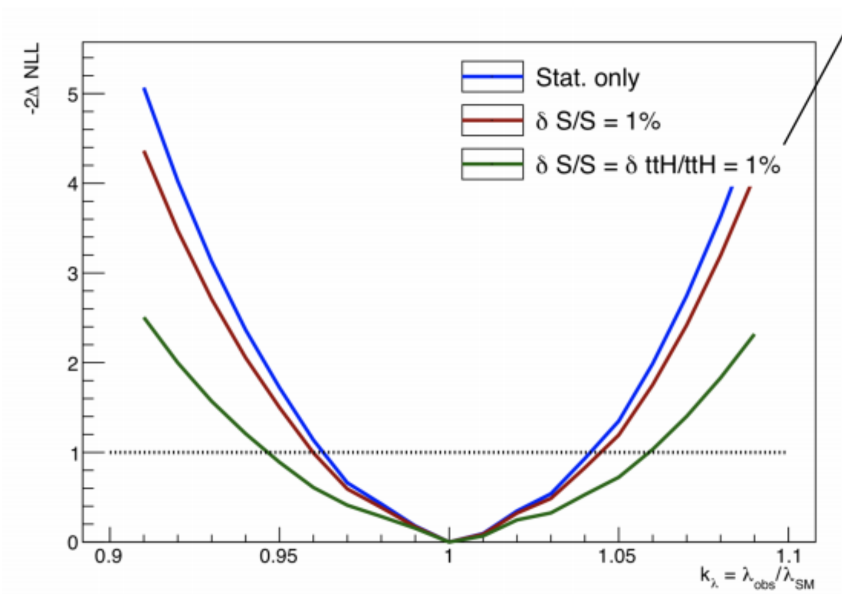
"wiggles" in Higgs potential

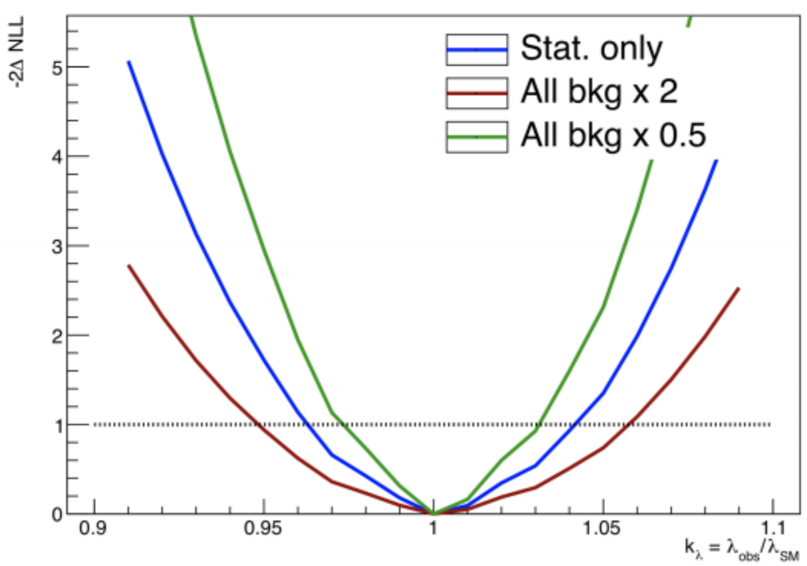
Big difference in triple Higgs coupling

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

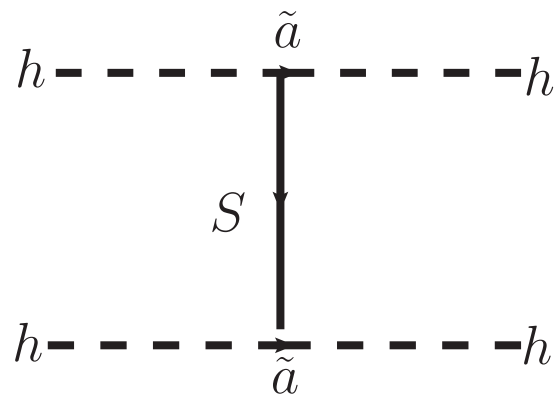
But, there should be more

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

- 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.

For example

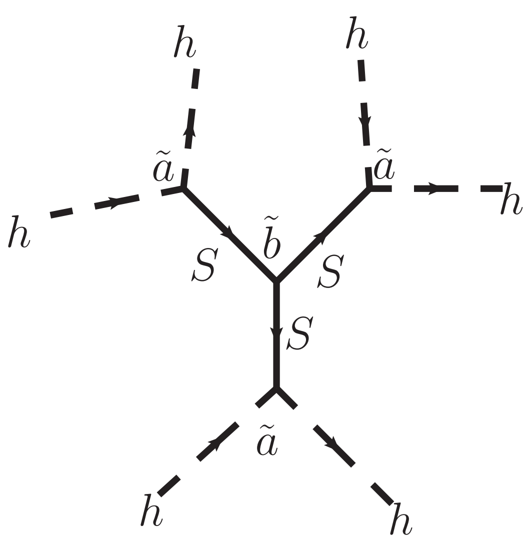
$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$

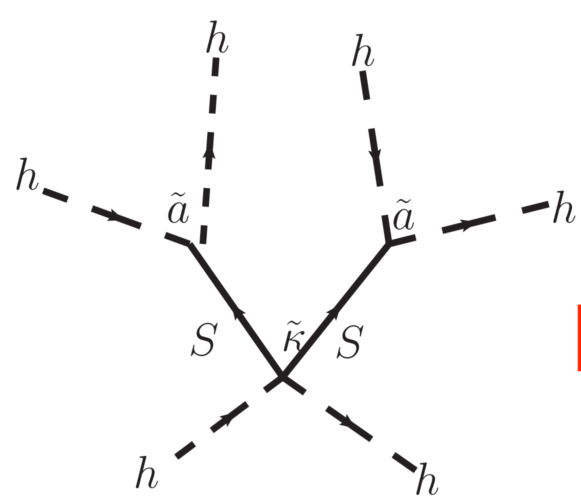


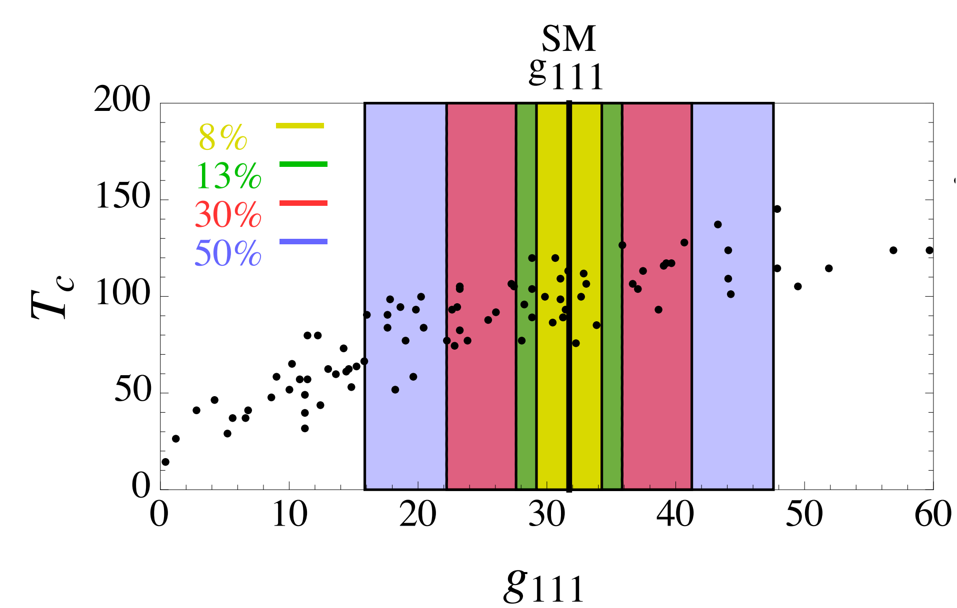
$$\frac{c}{m_S^2}\left(h^\dagger \partial h\right)^2$$

shift in h-Z coupling

$$\delta_{Zh} \sim c\frac{v^2}{m_S^2}$$

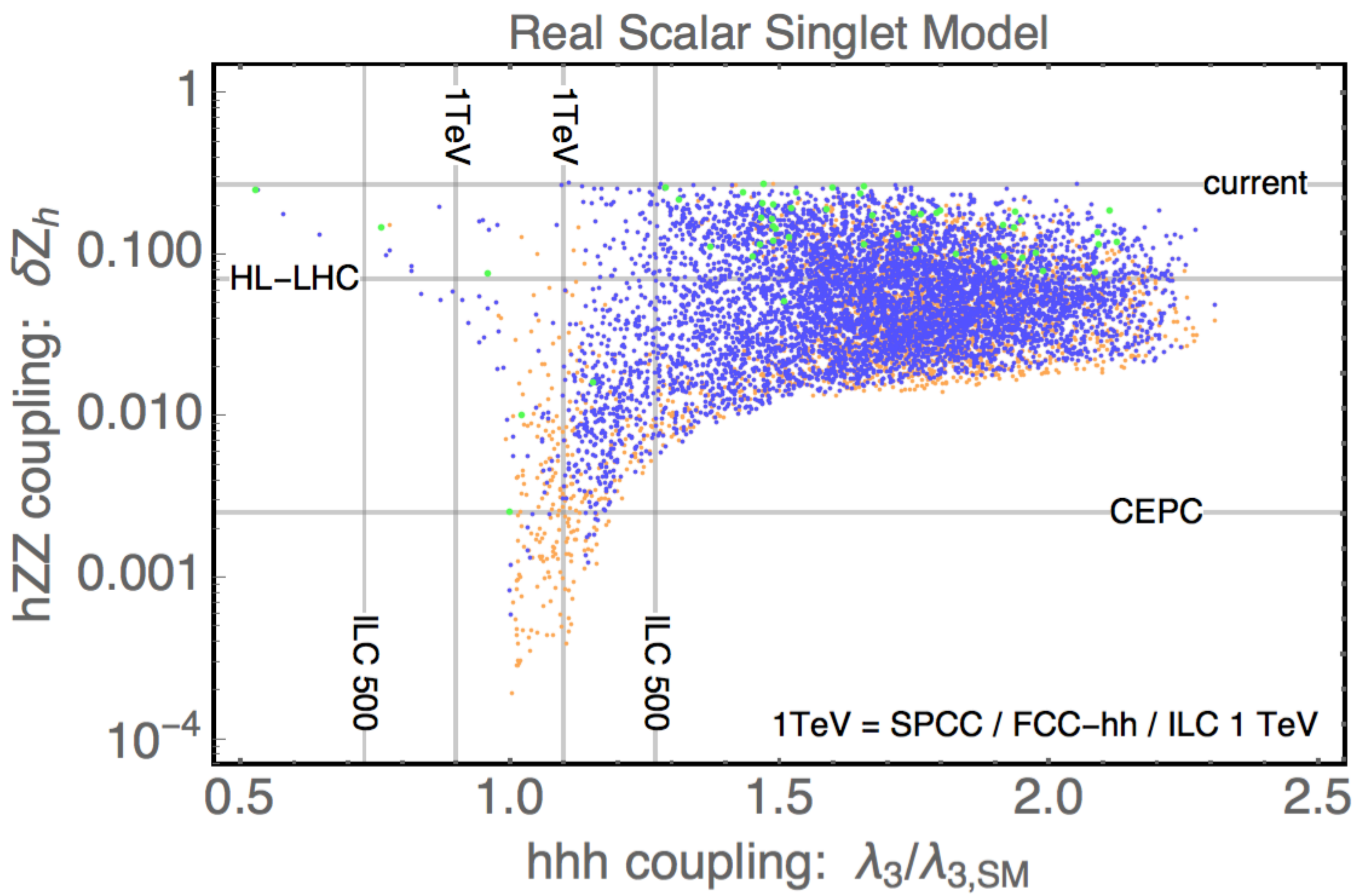






triple Higgs coupling

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

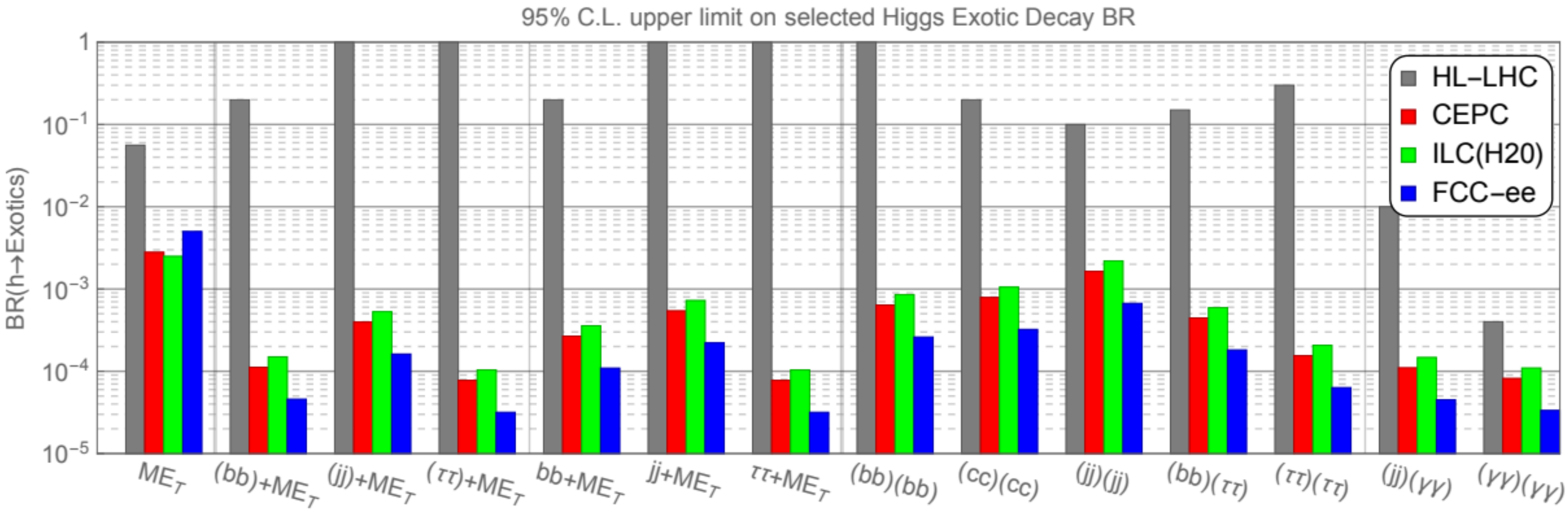
Huang, Long, LTW, 1608.06619

Good coverage in model space

More exotic searches

Higgs exotic decay

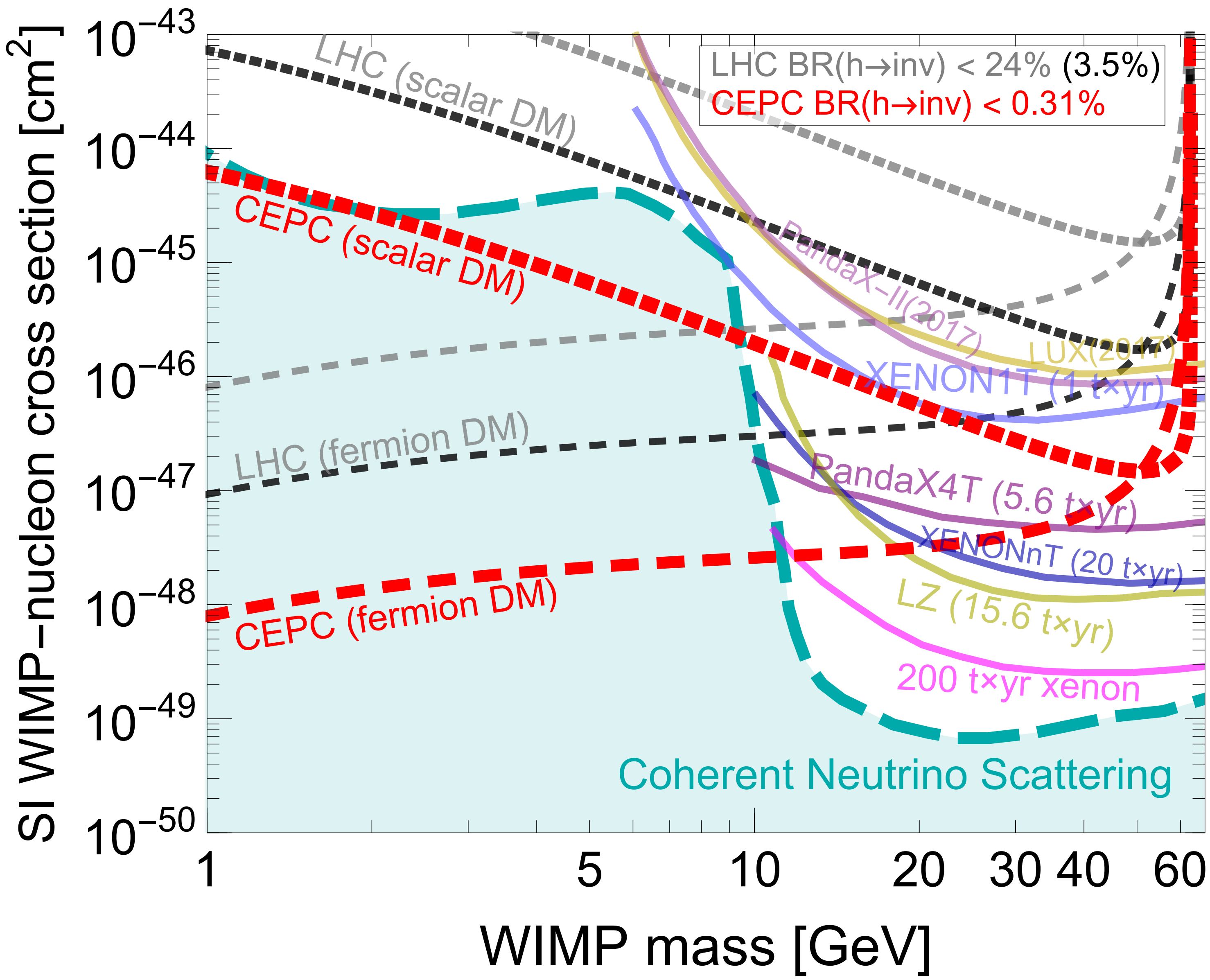
Zhen Liu, Hao Zhang, LTW



Complementary to hadron collider searches

Higgs portal dark matter

Jiayin Gu



Conclusions

- Origin of the electroweak scale is a major open question in particle physics.
- Solving it is a key part of the future of high energy physics.
- Future colliders will be instrumental to achieve this goal.
- Much more left to be done (design/physics).
    - Goal of this workshop: initiate more effort in this direction.

Probing NP with precision measurements

- Lepton colliders: ILC, FCC-ee, CEPC, CLIC

  clean environment, good for precision.

- We are going after deviations of the form

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

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

- Take for example the Higgs coupling.
  - LHC precision: 5-10% $\Rightarrow$ sensitive to M_{NP} < TeV
  - However, M_{NP} < TeV largely excluded by direct NP searches at the LHC.
  - To go beyond the LHC, need 1% or less precision.