Naturalness and Higgs Measurements

Nathaniel Craig
University of California, Santa Barbara

Workshop on Physics at the CEPC
IHEP 08/10/15

Institute of High Energy Physics Chinese Academy of Sciences

U.S. DEPARTMENT OF ENERGY | Office of Science

CEPC precision on Higgs couplings will provide an entirely new window on physics beyond the Standard Model.

Not merely an improvement on LHC Higgs coupling measurements; it *probes entirely new possibilities.*

Testing the Higgs

- Sharp predictions for Higgs couplings in the Standard Model; *completely fixed by mass spectrum.*
- Any deviations are an unambiguous sign of new physics.
- Extensions of the Standard Model give motivated patterns and magnitudes for coupling deviations.
- The coupling reach at CEPC provides qualitatively new probes of the most motivated scenarios for physics beyond the Standard Model.

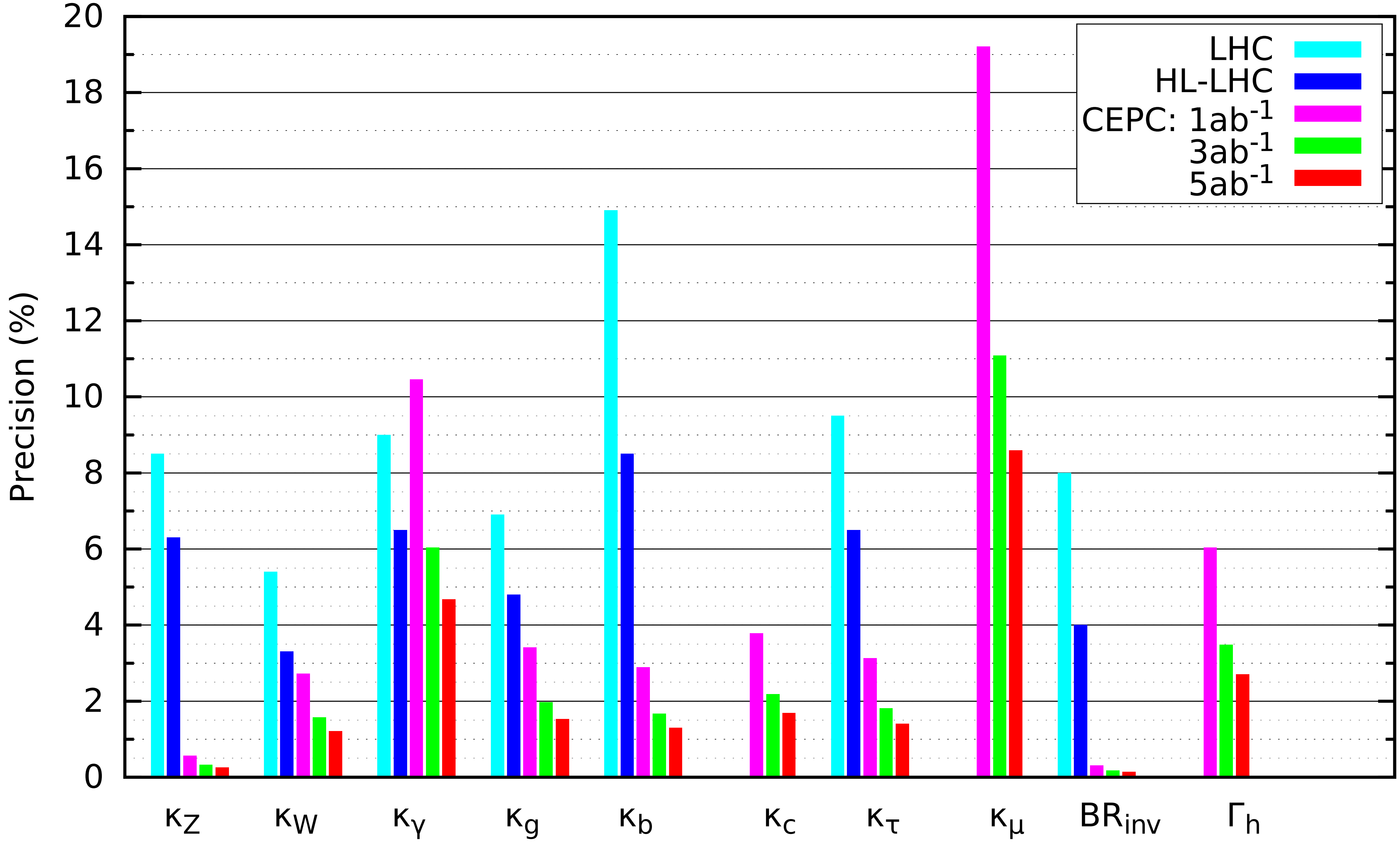
Higgs couplings at CEPC

ΔM_H	Γ_H	$\sigma(ZH)$	$\sigma(\nu\nu H) \times \mathrm{BR}(H \to bb)$
5.9 MeV	2.8%	0.51%	2.8%

Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to bb$	0.28%	0.57%
$H \to cc$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau\tau$	1.2%	1.3%
$H \to WW$	1.5%	1.6%
$H \to ZZ$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu\mu$	17%	17%
$H \to \mathrm{inv}$	–	0.28%

The benchmark precision @ 5/ab

Higgs couplings at CEPC



Inference of couplings from 7-parameter fit

Higgs & Hierarchy Problem

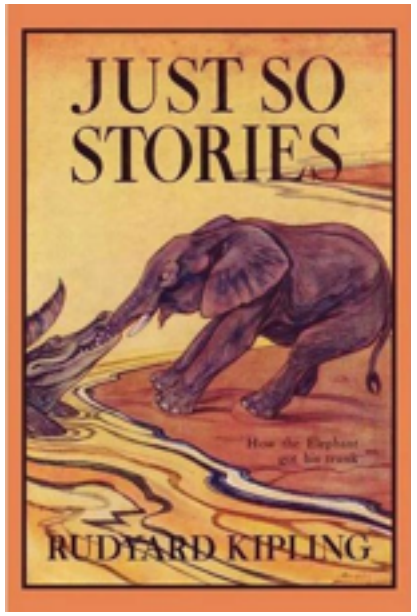
- Great triumph of Run 1 @ LHC: discovery of an SM-like Higgs @ 125 GeV.

- Great challenge for the future: sensitivity of elementary scalar mass to higher physical thresholds.

- We expect many scales above the weak scale: flavor, dark matter, neutrino mass, gauge coupling unification, PQ symmetry breaking, ...

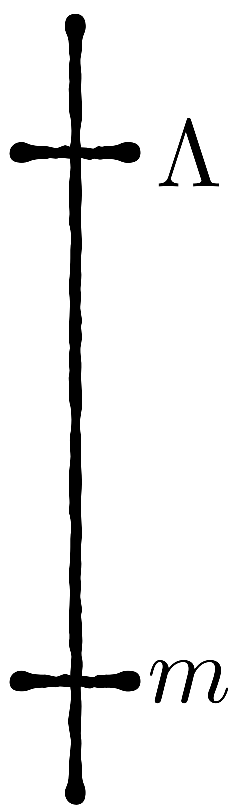
- At the very least, as far as we know a theory of quantum gravity should give physical thresholds around the string scale.

- An apparently elementary Higgs makes the hierarchy problem as pressing as ever.



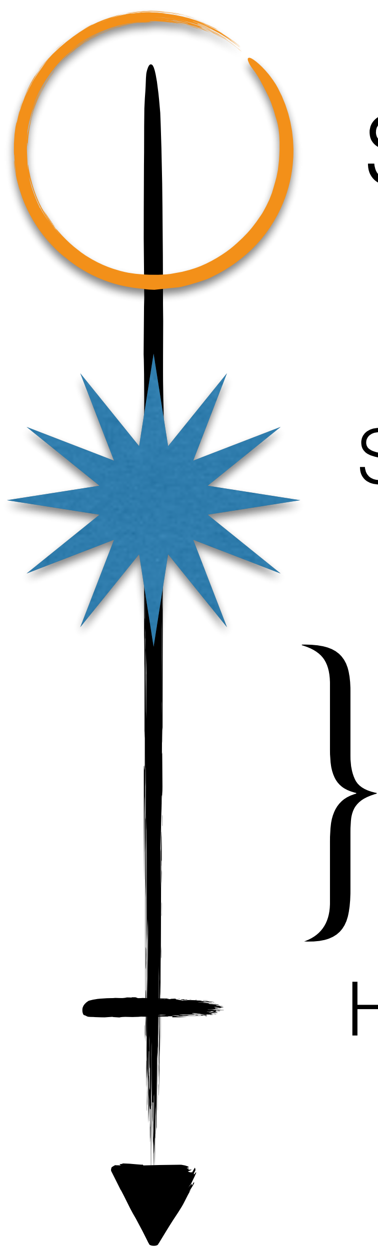
Natural vs. unnatural

Hierarchy problem is not a "just-so story"



Field	Symmetry as $m \to 0$	Implication
Spin-1/2 $m\Psi\bar{\Psi}$	$\Psi \to e^{i\alpha\gamma_5}\Psi$ (chiral symmetry)	$\delta m \propto m$ **Natural!**
Spin-1 $m^2 A_\mu A^\mu$	$A_\mu \to A_\mu + \partial_\mu \alpha$ (gauge invariance)	$\delta m \propto m$ **Natural!**
Spin-0 $m^2 \|H\|^2$	None	$\delta m \propto \Lambda$ **Unnatural!**

Hierarchy Solutions

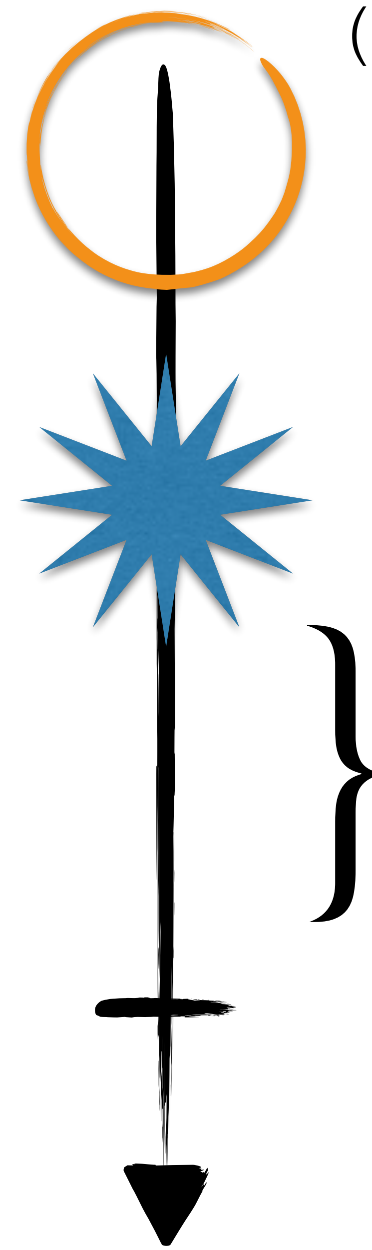


Supersymmetry

SUSY breaking
Sparticles $\tilde{m}$

$\lesssim 4\pi/G$

Higgs m_h



(compositeness, SUSY, turtles)

Global symmetry

Global symm. breaking
Partner particles $\tilde{m}$

$\lesssim 4\pi/G$

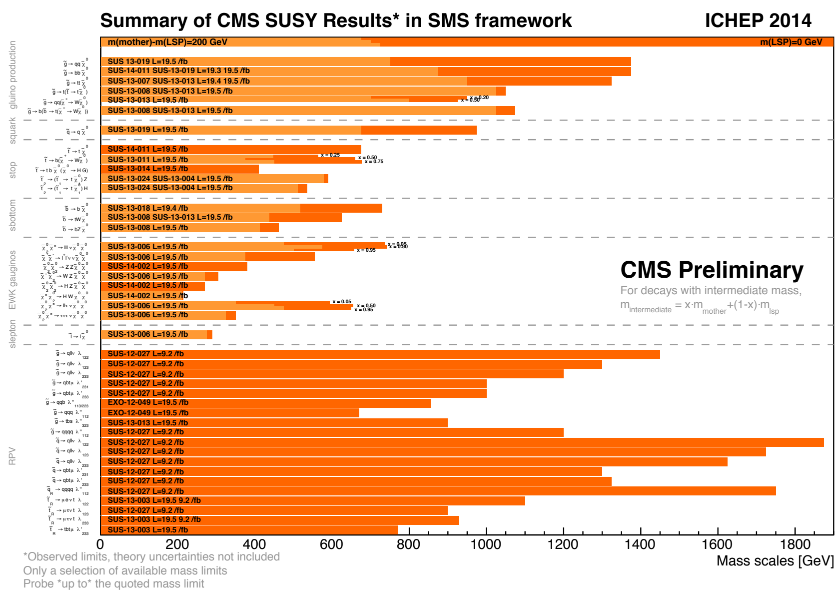
Higgs m_h

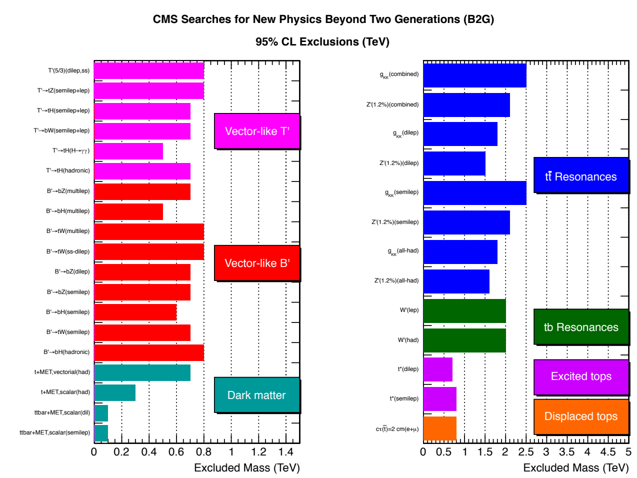
New symmetries for Higgs → new states coupling to Higgs

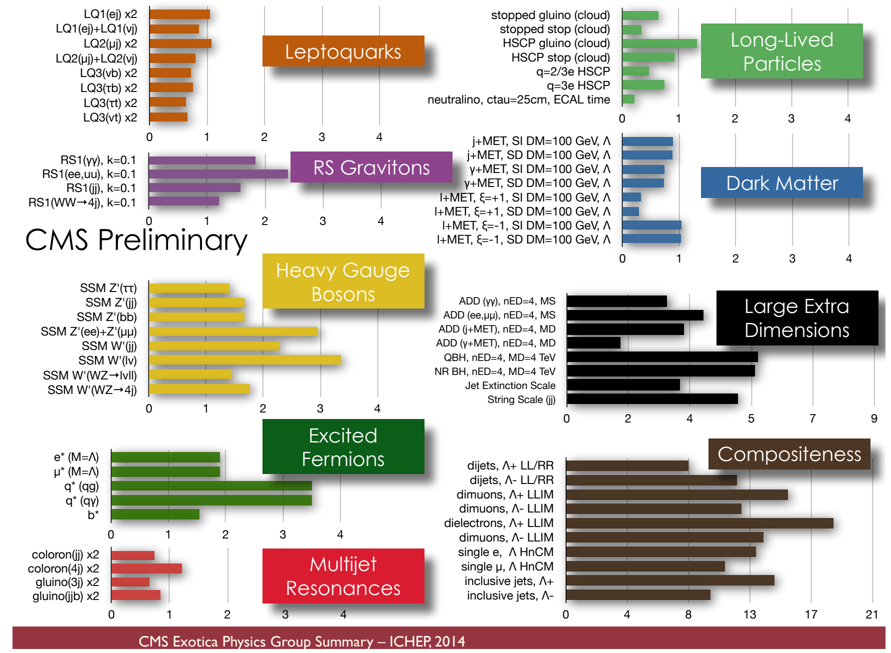
$$m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$

Totally natural: $\tilde{m} \lesssim 200\,\mathrm{GeV}$

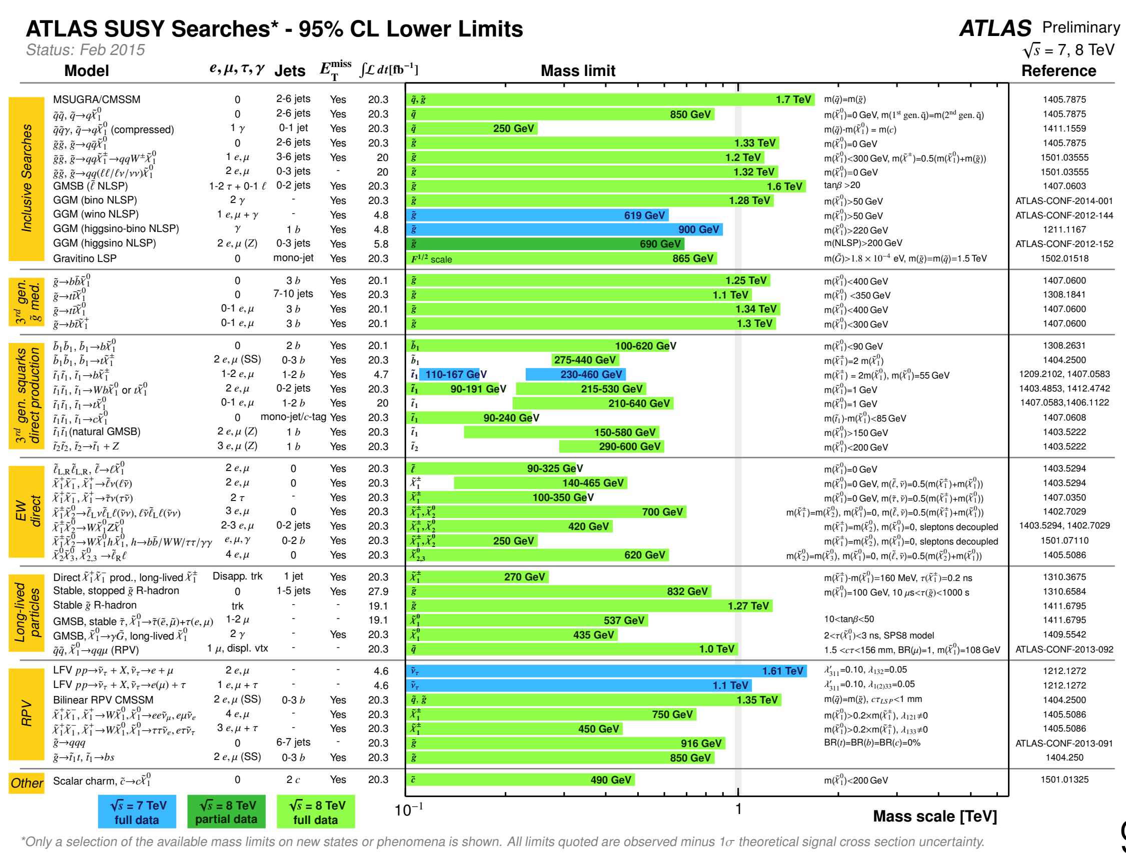
A physics driver @ LHC

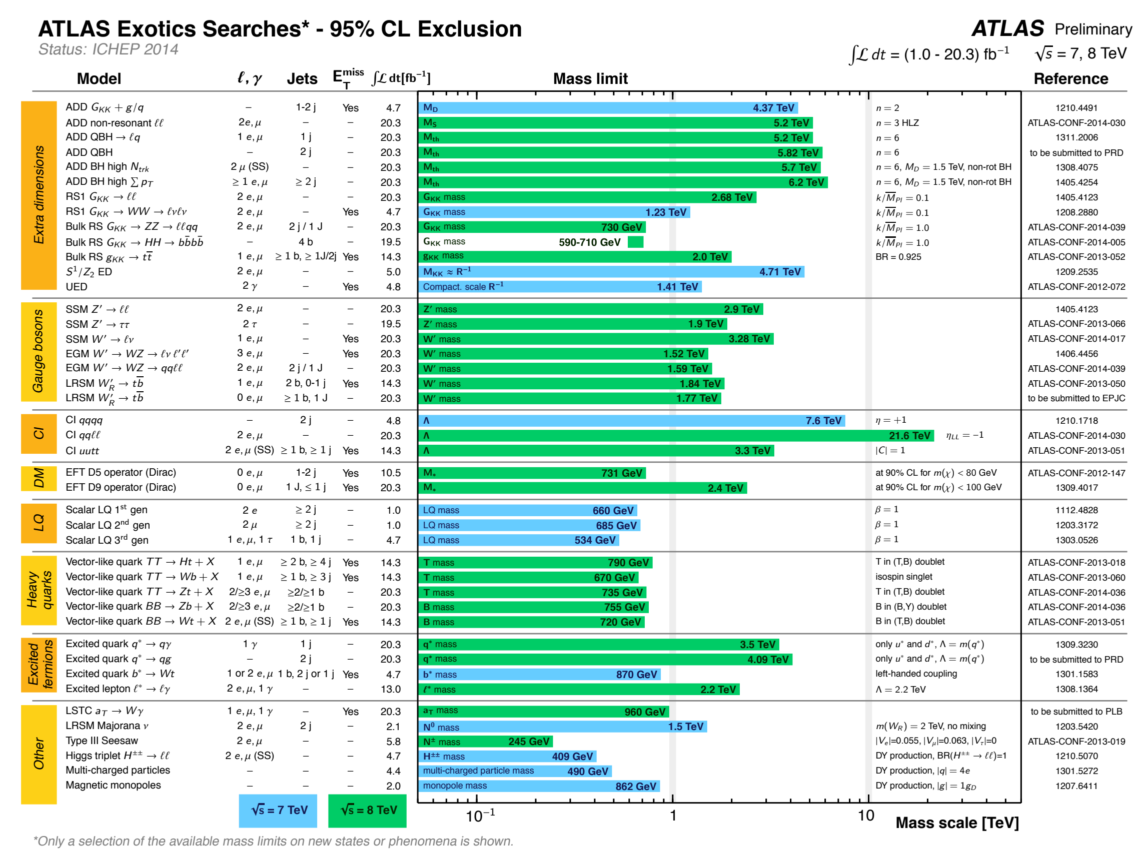






170 of these 226 channels tied to naturalness





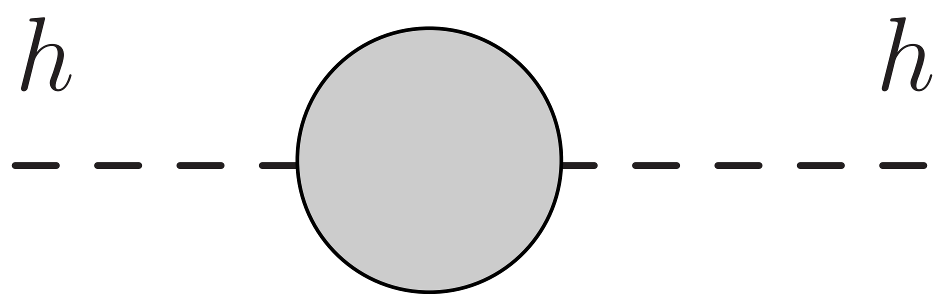
Beyond the LHC

- LHC has finite reach in direct searches for states associated with naturalness.
- There are also possible holes in search coverage well below the LHC's kinematic limits.
- The question of naturalness of the weak scale will not be settled by the LHC.
- *Precision Higgs coupling measurements (specifically, better than %-level) at CEPC can go much further.*

Naturalness at CEPC

Very generally:

Solutions to hierarchy problem influence Higgs mass



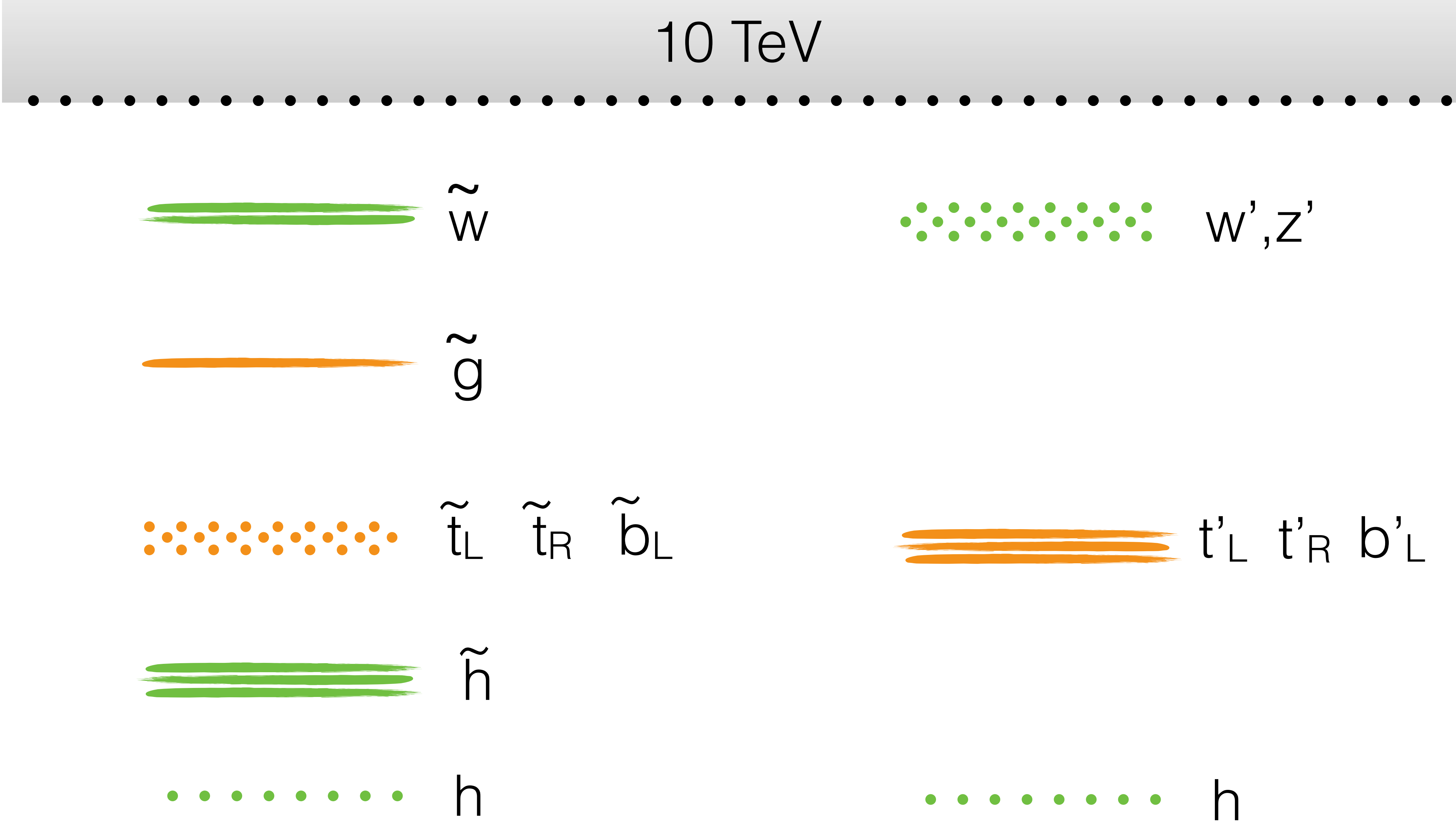
$$\propto \delta m_h^2, \delta Z_h^2$$

Generically also give Higgs wavefunction renormalization

Effects generically correlated.

Latter effects measurable in Higgs coupling deviations.

Conventional naturalness



Supersymmetry | Composite Higgs

Two conventional solutions to the hierarchy problem

Minimal supersymmetric extension of the Standard Model requires two doublets H_u, H_d

After EWSB, five physical states:

Potential SM-like Higgs

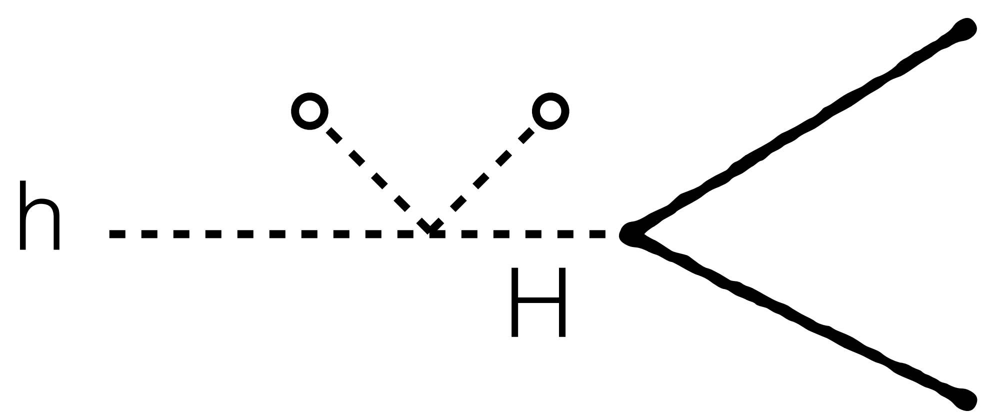
$\boxed{h, H, A, H^{\pm}}$

Neither CP-even scalar is exactly SM-like; tree-level mixing leads to Higgs coupling deviations.

Higgs potential is fixed by supersymmetry; free parameters are m_H, $\tan\beta$

SUSY at tree level

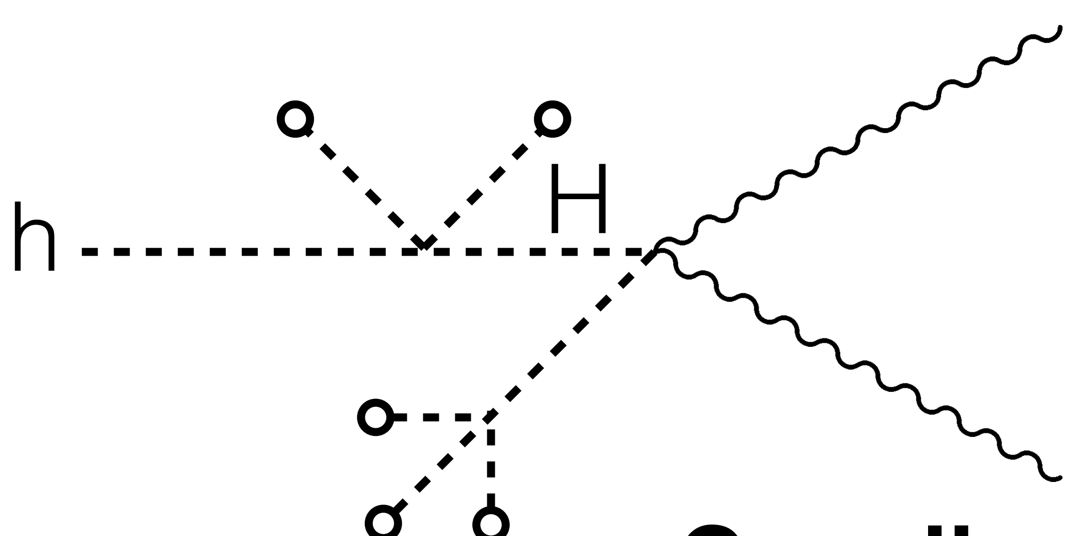
In the limit $m_h \ll m_H$ coupling deviations are clear:



$$\sim \frac{v^2}{m_H^2}$$

Leading effect in fermion couplings

Coupling to fermions



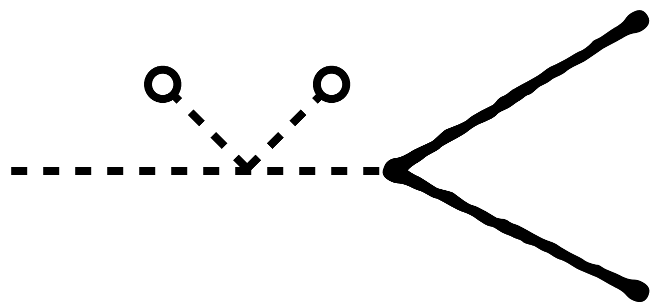
$$\sim \frac{v^4}{m_H^4}$$

Deviations are higher order in v/m_H

Coupling to gauge bosons

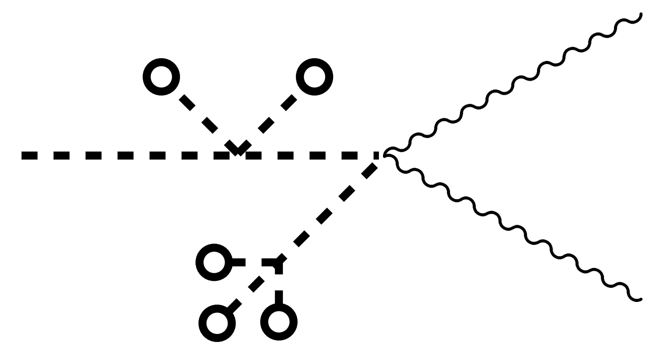
SUSY at tree level

In detail…



$$\boxed{\kappa_b = \kappa_\tau \sim 1 + \frac{2m_Z^2}{m_H^2}}$$

$$\kappa_t \sim 1 - \frac{2m_Z^2}{m_H^2}\cot^2\beta$$



$$\kappa_V \sim 1 - \frac{2m_Z^2}{m_H^4}\cot^2\beta$$

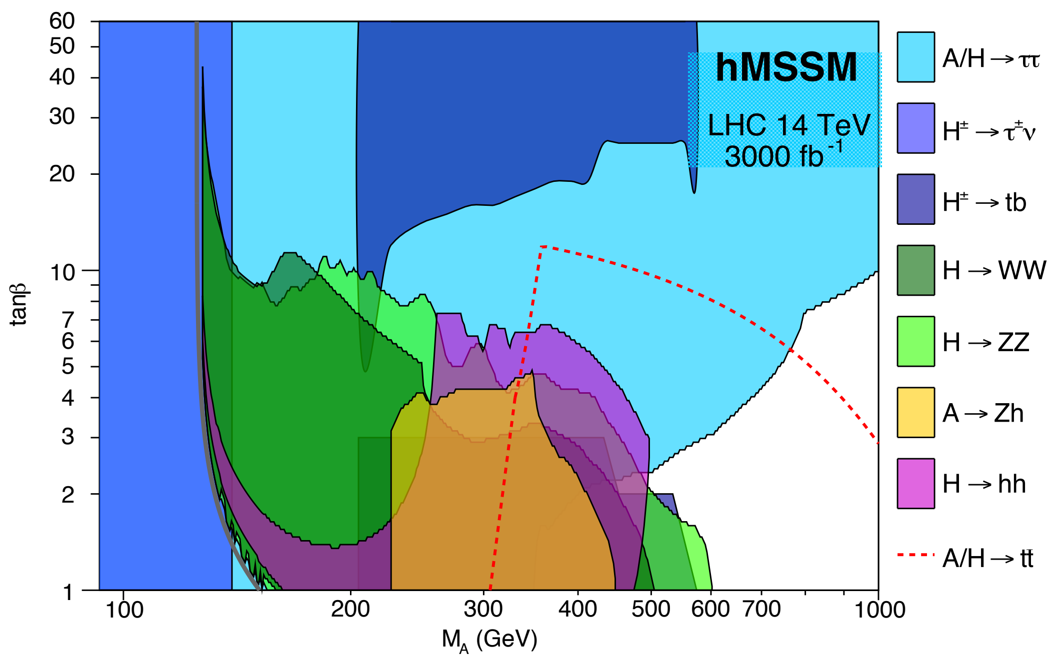
Best sensitivity in **bottom** couplings

CEPC: ~1.2% precision in κ_b (combined 7-param fit)

Reach comparison

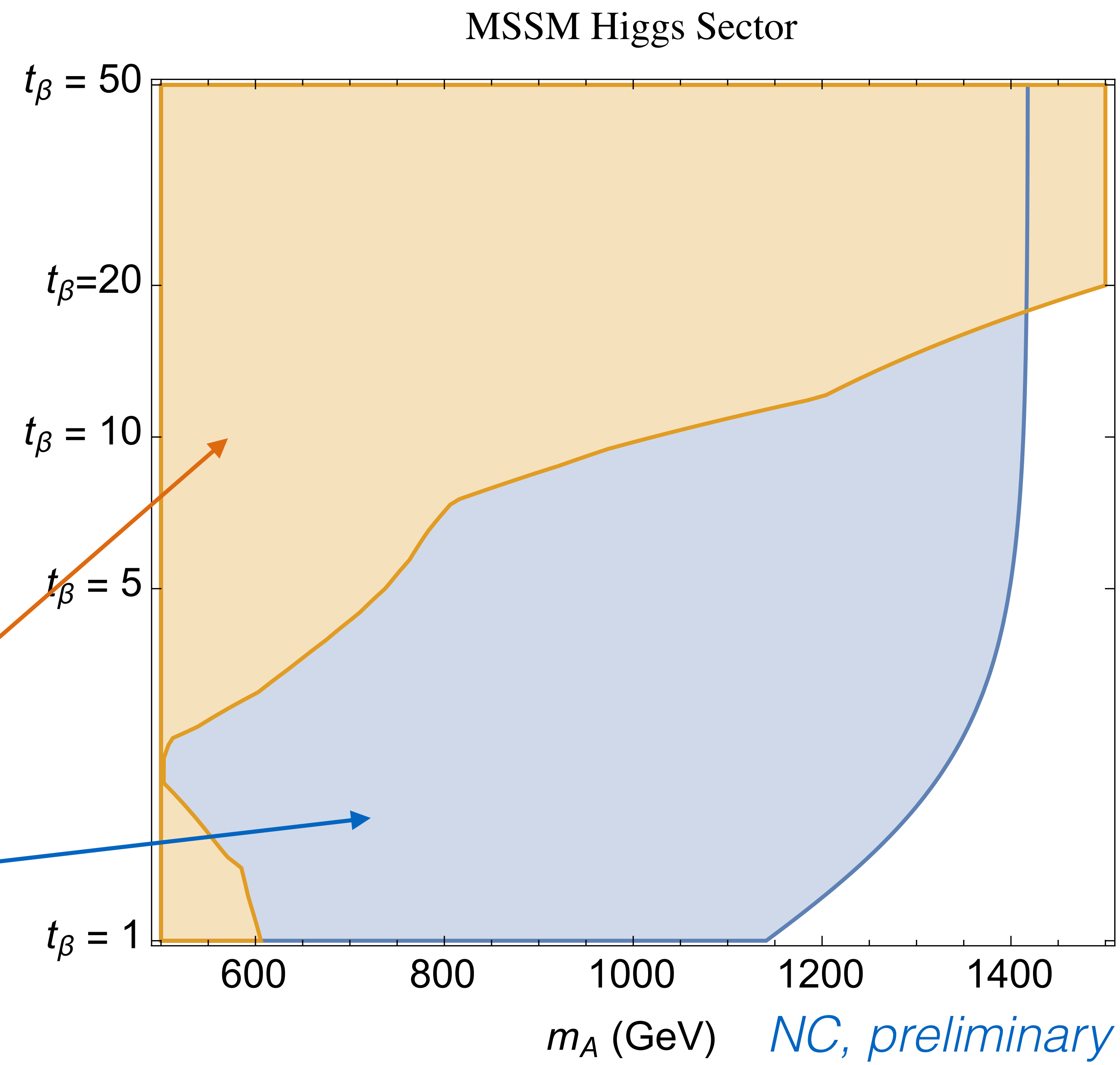
HL-LHC direct reach vs. CEPC coupling reach

Djouadi, Maiani, Polosa, Quevillon, Riquer [1502.05653]



HL-LHC reach (direct)

CEPC reach (indirect)

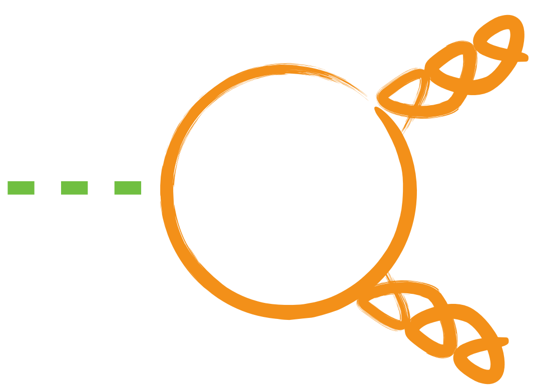


Cover the "wedge" region to 1.2 TeV

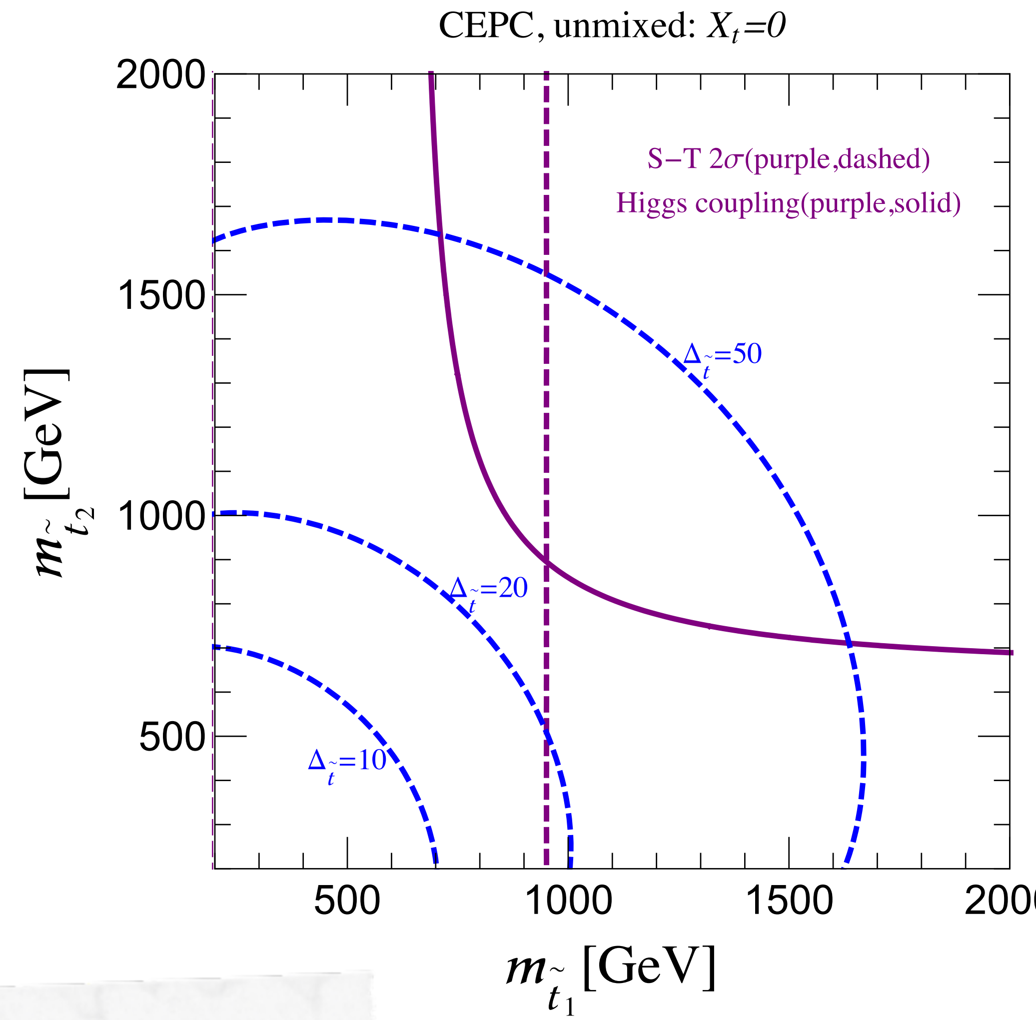
SUSY at loop level

Fan, Reece, Wang [1412.3107]

Superpartners can contribute to loop-level Higgs couplings



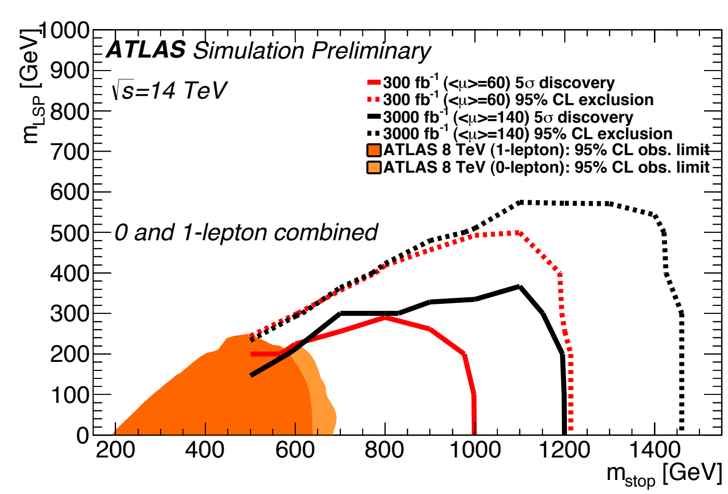
$$(\kappa_g - 1) \sim \frac{m_t^2}{4m_{\tilde{t}}^2}$$

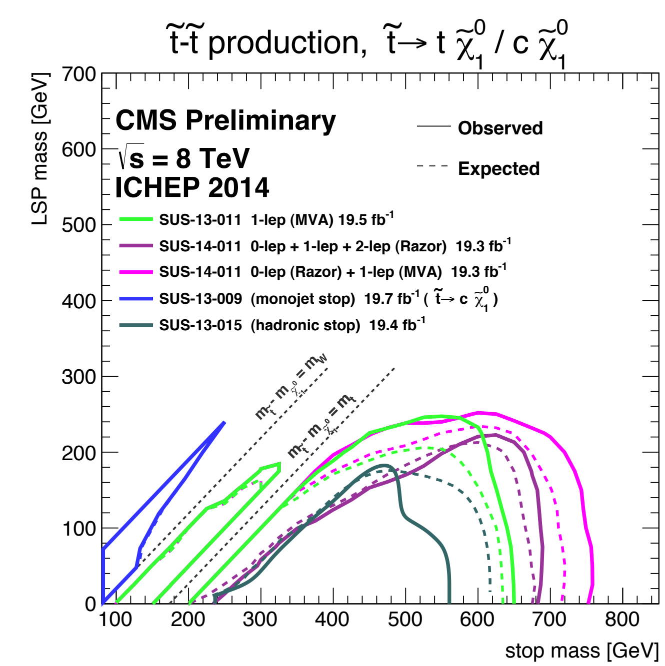


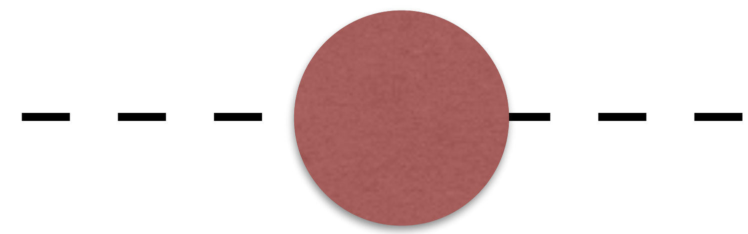
Stop contributions to hgg coupling most constraining

Ensures no gaps remain, tests naturalness to 5% level

See also M. Reece's talk







Higgs mixes w/ heavy resonances, couplings dictated by symmetries (as in the chiral lagrangian)

$$\kappa_V \sim \sqrt{1-\frac{v^2}{f^2}} \sim 1 - \frac{v^2}{2f^2} + \ldots$$

f = decay constant of pNGB Higgs

Coupling deviation contributes to precision electroweak

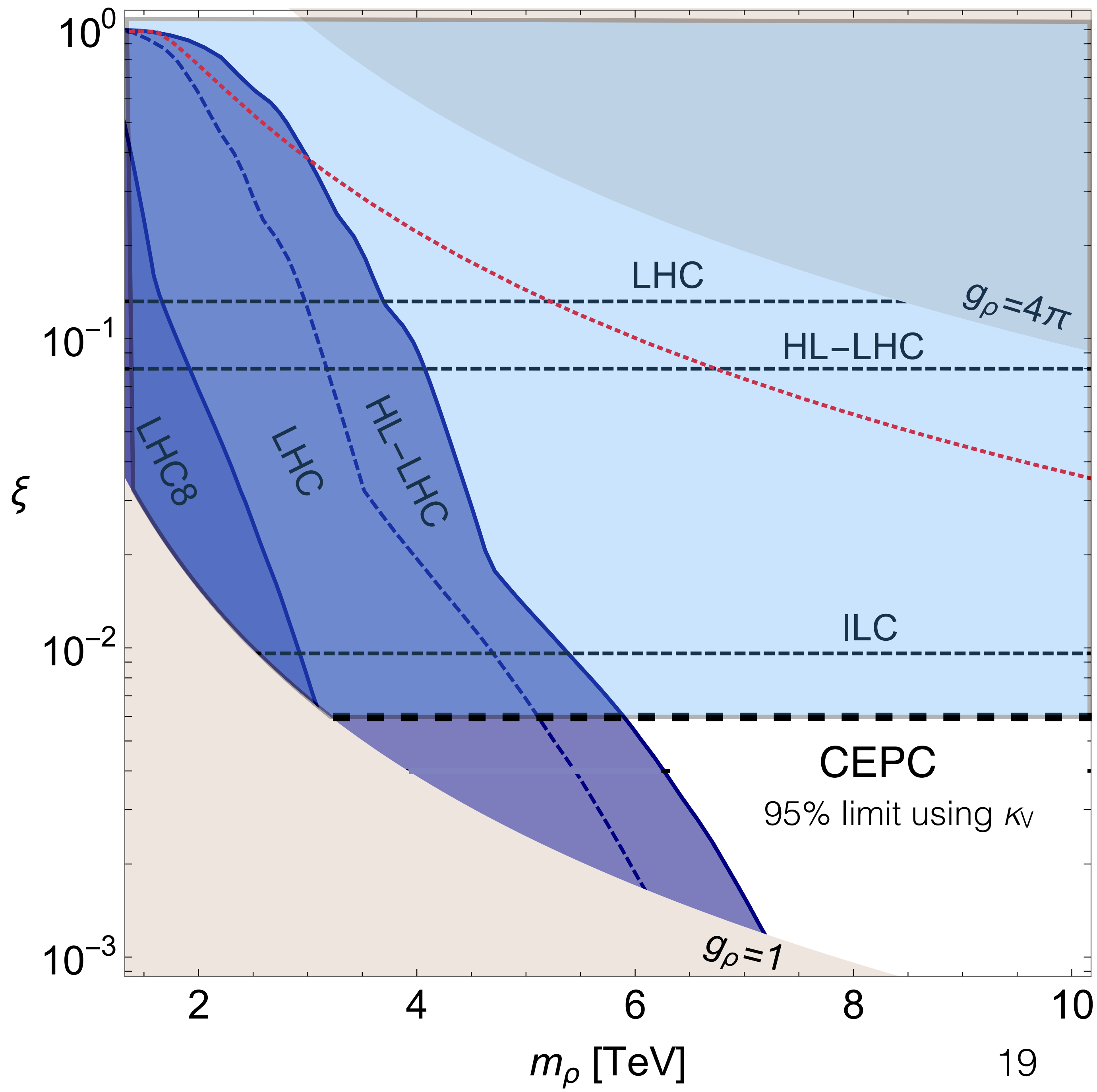
Pre-LHC constraints *as good as reach of LHC Higgs coupling measurements*

$$\to \delta\kappa_V \lesssim 5\%$$

Reach comparison

Adopted from

[Thamm, Torre, Wulzer, 1502.01701]

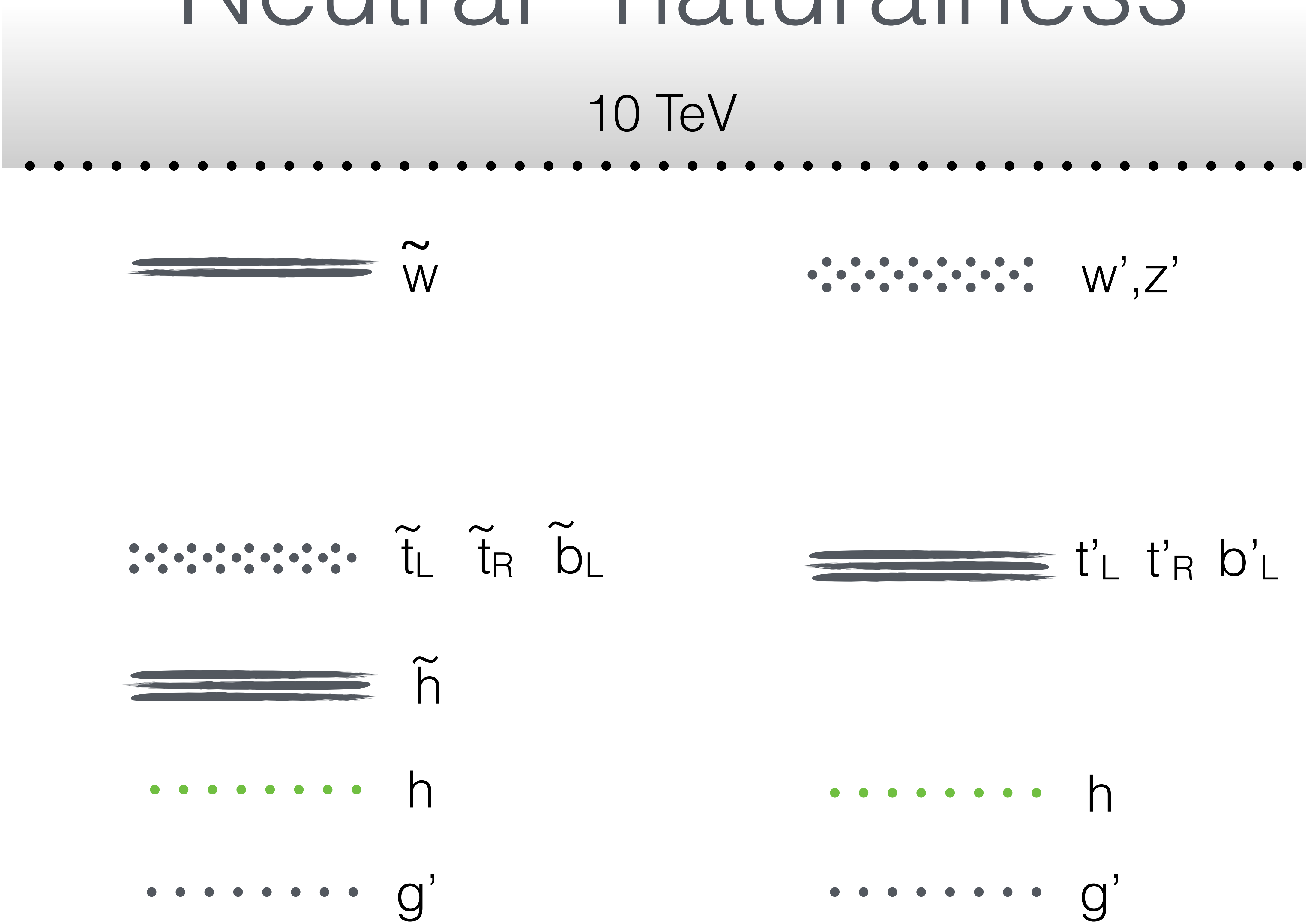


CEPC coupling sensitivity constrains *f* well beyond existing precision electroweak limits

Also far exceeds direct LHC reach for heavy resonances

Pushes naturalness of composite models to below the 1% level

“Neutral” naturalness



(Scalar theories under study)

Twin Higgs
[Chacko, Goh, Harnik ‘05]

Neutral fermionic partners

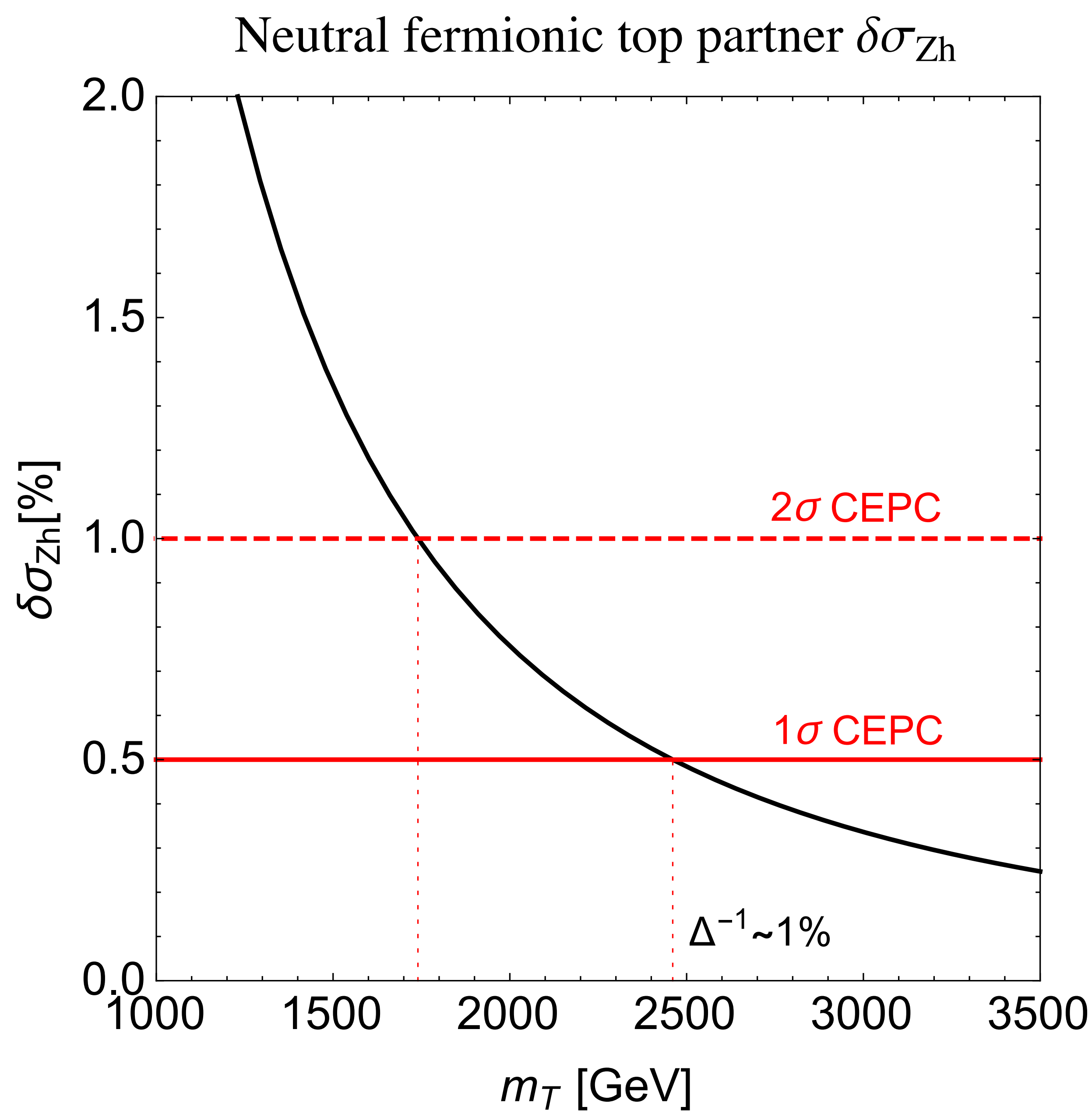
e.g. *Twin Higgs*

No direct sensitivity @ LHC

Higgs is a pNGB; coupling deviations like those of composite Higgs models

$$\kappa_V \sim \sqrt{1 - \frac{v^2}{f^2}} \sim 1 - \frac{v^2}{2f^2} + \ldots$$

f sets mass scale for neutral top partners; definitive and test of "neutral" naturalness.



Neutral scalar partners

Enforce naturalness by couplings to the Higgs of the form $y_t^2 |H|^2 |\Phi|^2$

Just like stops in SUSY, but neutral under the SM

No direct sensitivity @ LHC.

How to probe experimentally with the Higgs ?

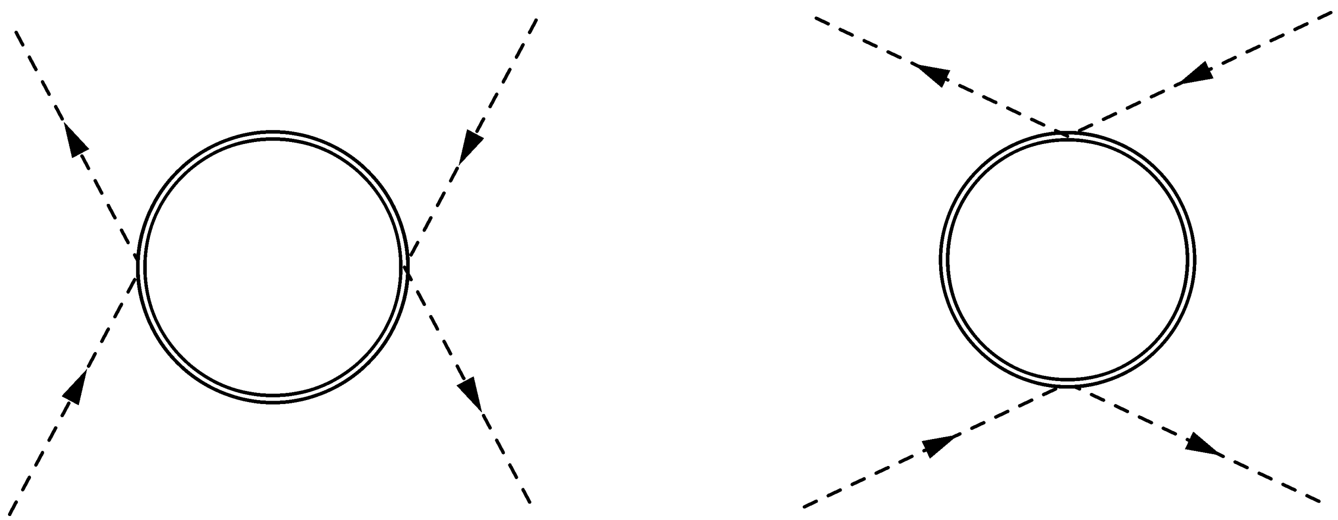
- No tree-level coupling deviations.
- No loop-level contributions to loop-level couplings.
- But there are *oblique corrections.*

Neutral scalar partners

Loops of neutral scalars generate Higgs "oblique" operator

[Englert, McCullough 1303.1526; NC, Englert, McCullough 1305.5251]

$$\boxed{\frac{1}{2}\frac{c_H}{m_\Phi^2}\left(\partial_\mu |H|^2\right)^2}$$



See also M. McCullough's talk

$$c_H \sim \frac{n_\Phi y_t^2}{16\pi^2}$$

After EWSB,

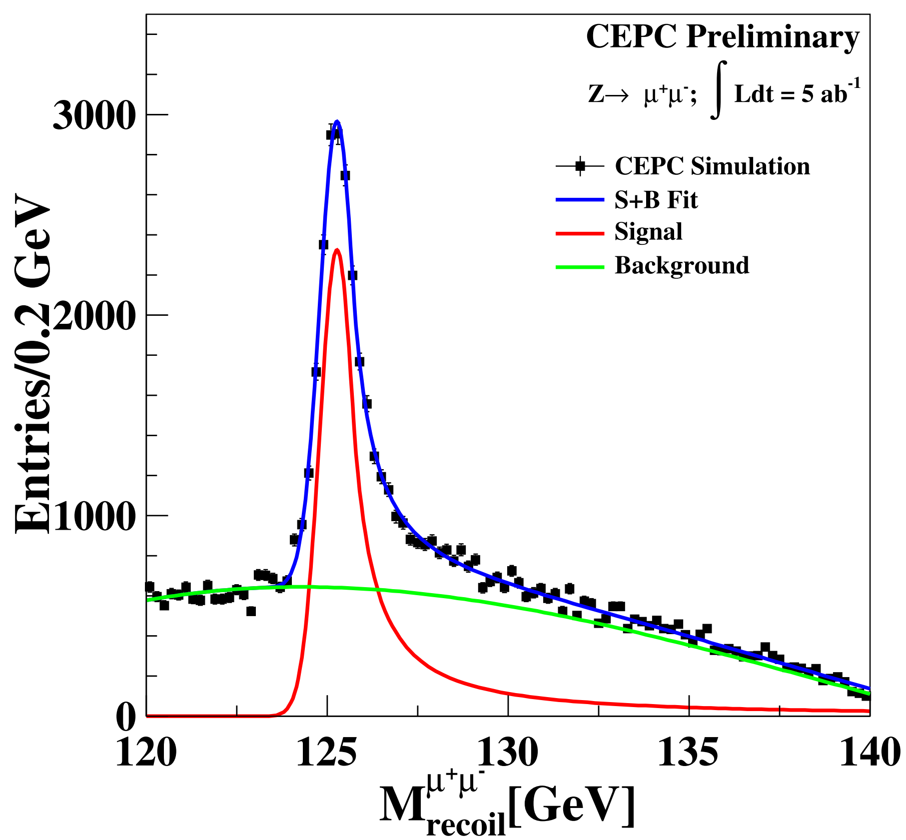
$$\frac{1}{2}\frac{c_H}{m_\Phi^2}\left(\partial_\mu |H|^2\right)^2 \to \left(1 + 2c_H\frac{v^2}{m_\Phi^2}\right) \times \frac{1}{2}(\partial_\mu h)^2$$

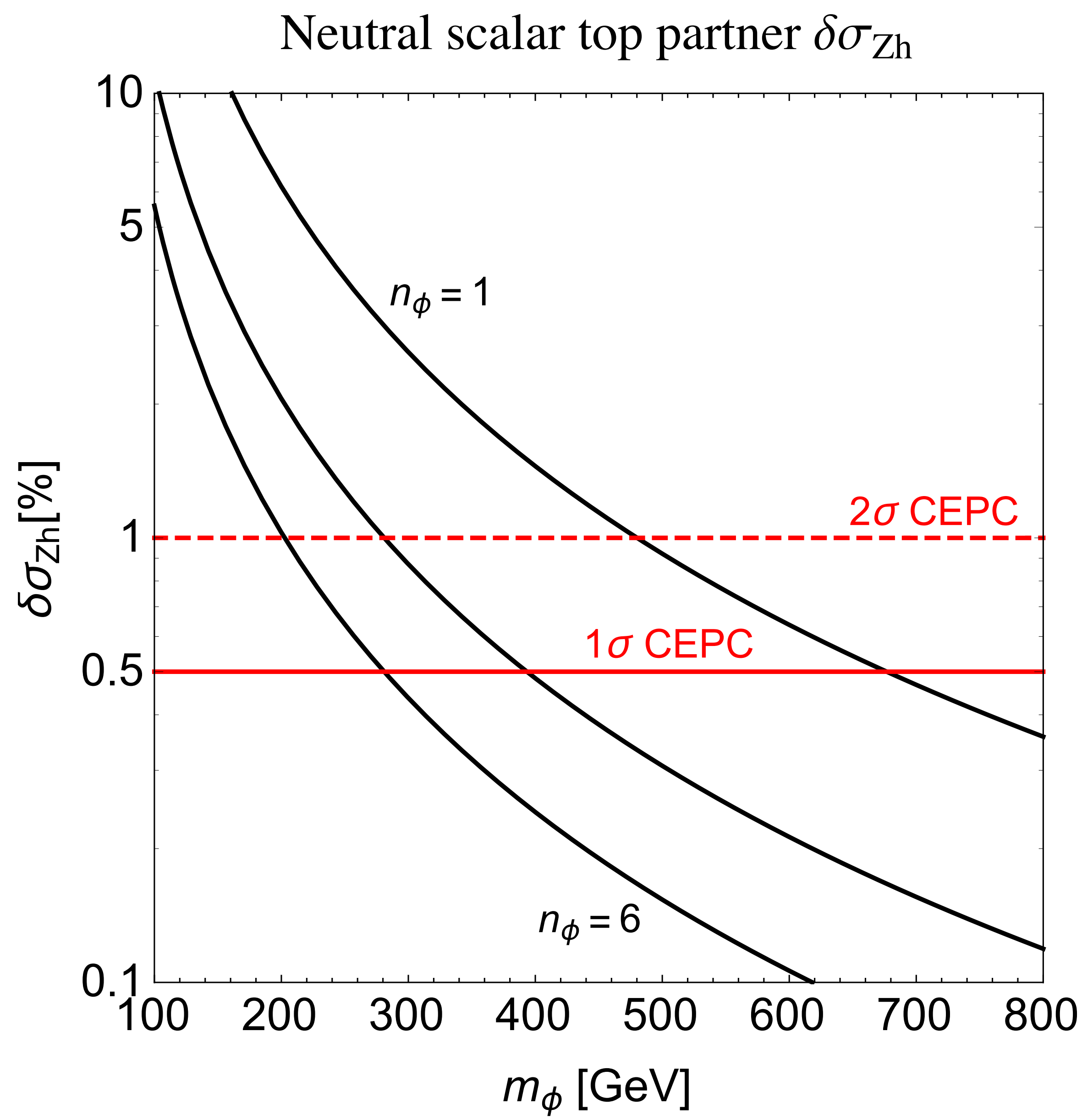
Looks like wavefunction renormalization for the physical Higgs.

Neutral scalar partners

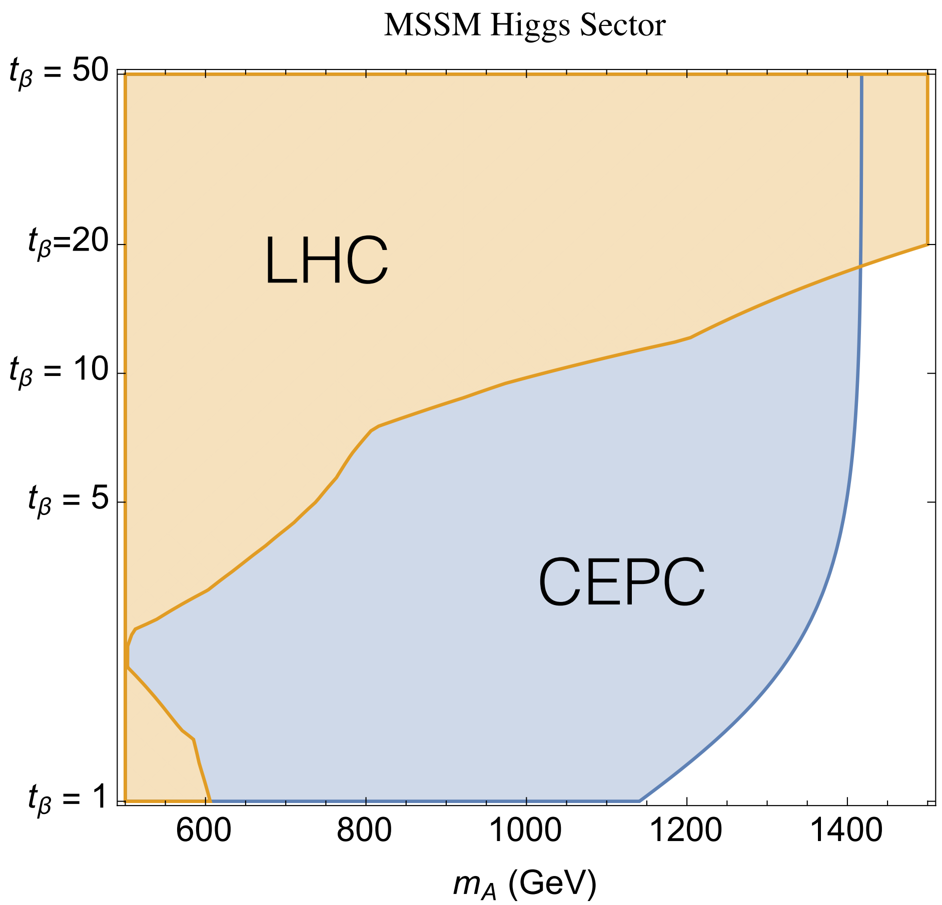
Canonically normalize kinetic term→shift *all* Higgs couplings

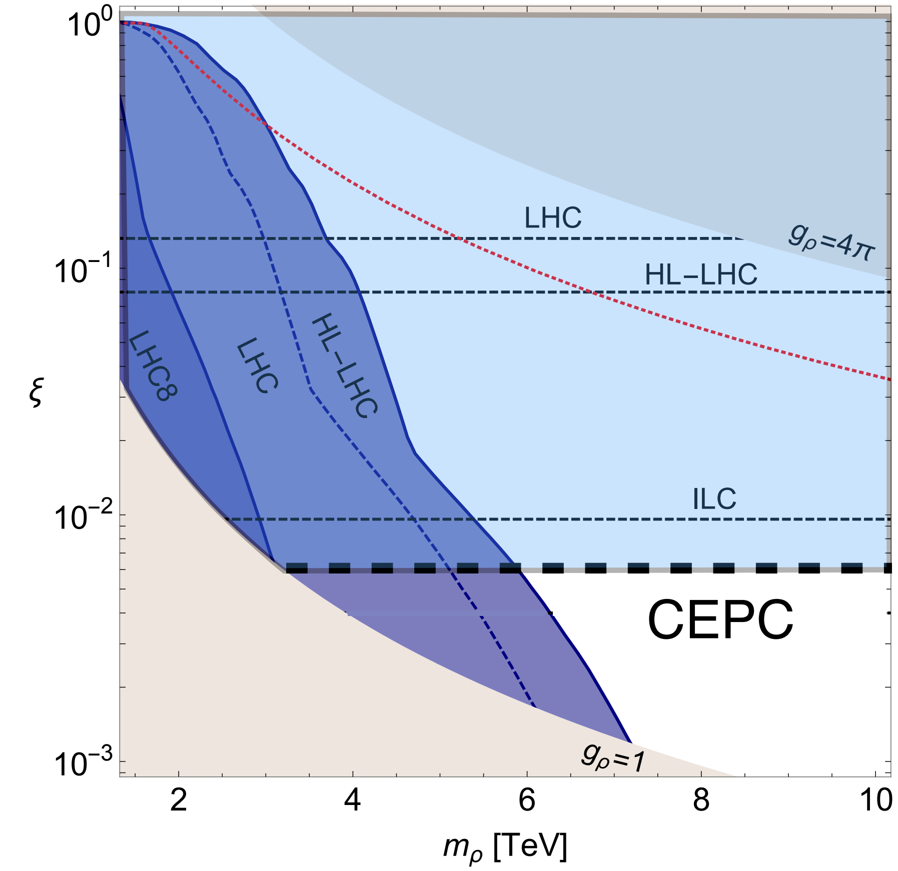
Shift drops out of all coupling ratios; can't be measured at LHC.

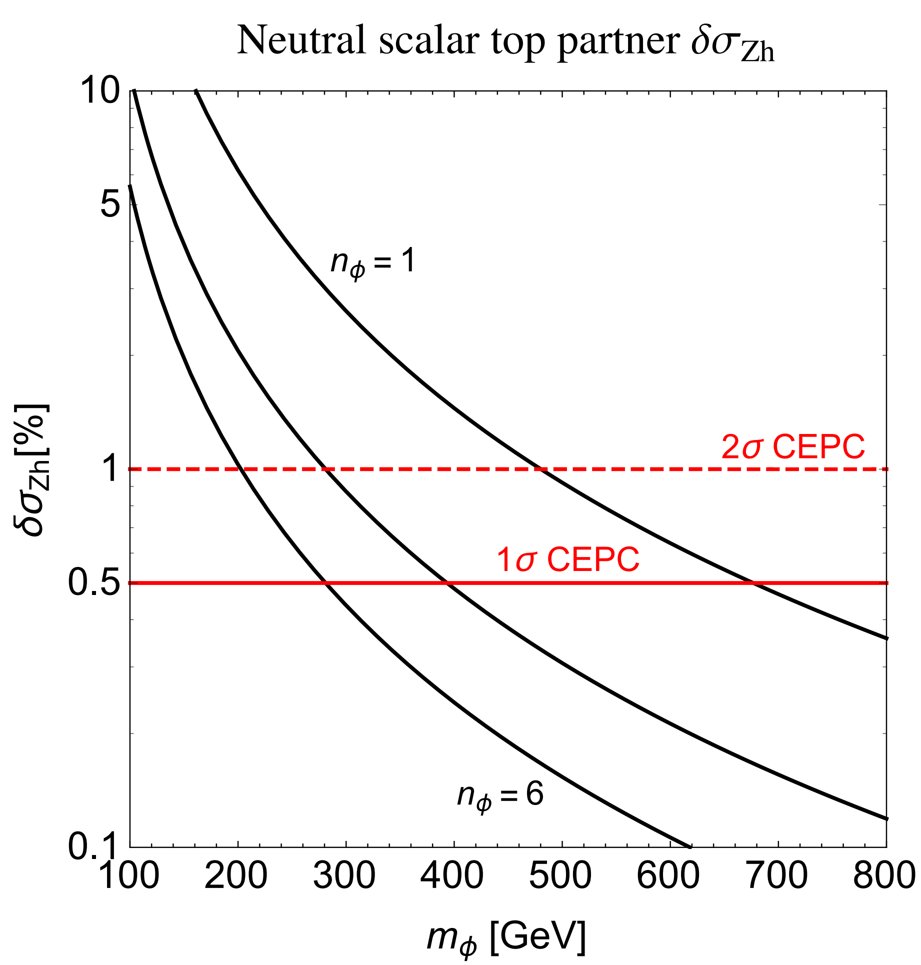


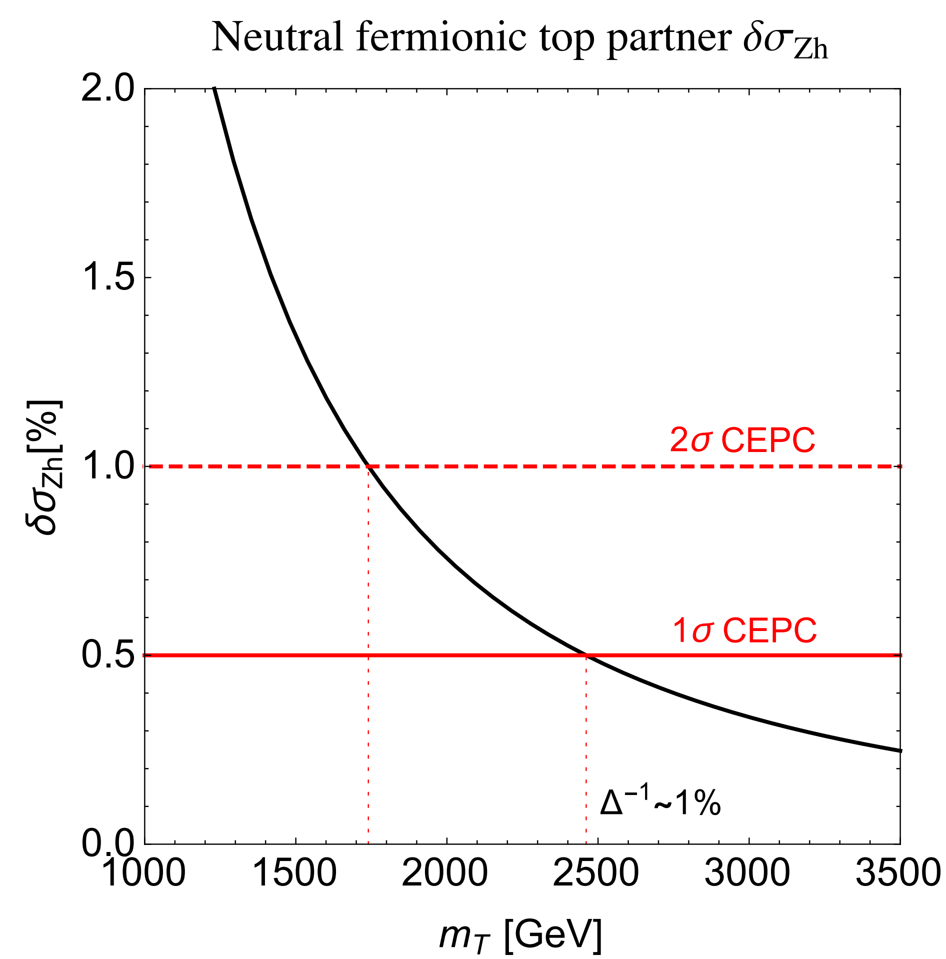


But measure $\delta\sigma_{Zh}$ directly at CEPC via Z recoils.


MSSM Higgs Sector
$t_\beta = 50$
$t_\beta=20$
$t_\beta = 10$
$t_\beta = 5$
$t_\beta = 1$
LHC
CEPC
600
800
1000
1200
1400
m_A (GeV)

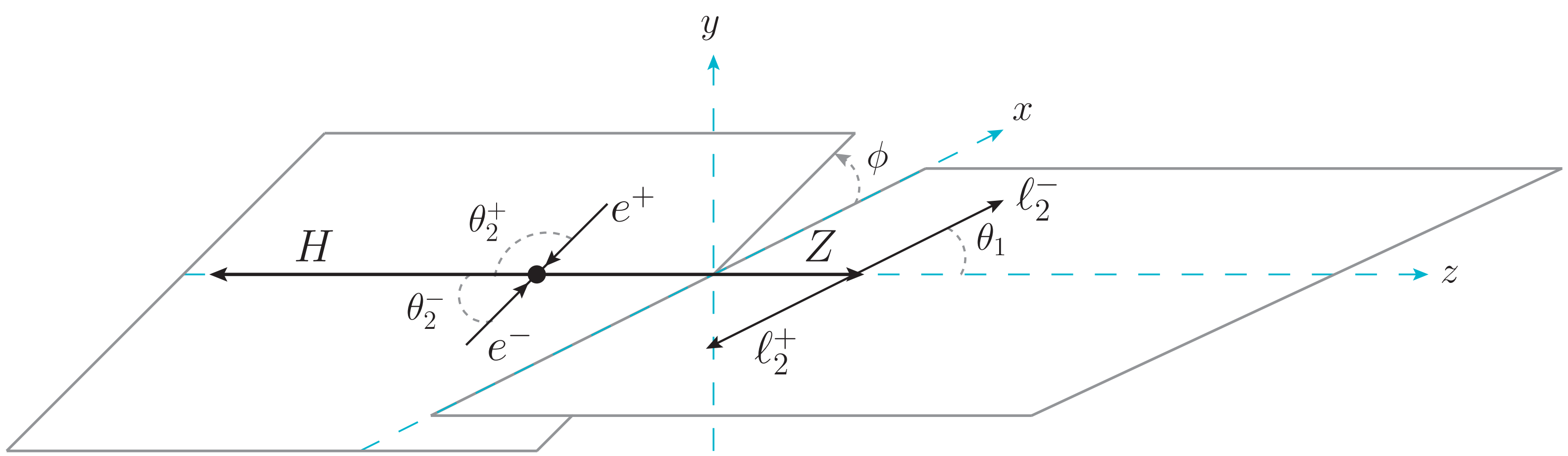

10^0
10^{-1}
10^{-2}
10^{-3}
ξ
LHC
HL-LHC
ILC
$g_\rho=4\pi$
LHC8
LHC
HL-LHC
CEPC
$g_\rho=1$
2
4
6
8
10
m_ρ [TeV]


Neutral scalar top partner $\delta\sigma_{Zh}$
10
5
1
0.5
0.1
$\delta\sigma_{Zh}$[%]
$n_\phi = 1$
$n_\phi = 6$
2σ CEPC
1σ CEPC
100
200
300
400
500
600
700
800
m_ϕ [GeV]


Neutral fermionic top partner $\delta\sigma_{Zh}$
2.0
1.5
1.0
0.5
0.0
$\delta\sigma_{Zh}$[%]
2σ CEPC
1σ CEPC
Δ^{-1}~1%
1000
1500
2000
2500
3000
3500
m_T [GeV]

Beyond couplings

$$\mathcal{L}_{\rm eff} \supset c_{ZZ}^{(1)} H Z_\mu Z^\mu + c_{ZZ}^{(2)} H\, Z_{\mu\nu} Z^{\mu\nu} + c_{Z\widetilde{Z}} H\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu} + c_{AZ} H\, Z_{\mu\nu} A^{\mu\nu} + c_{A\widetilde{Z}} H Z_{\mu\nu} \widetilde{A}^{\mu\nu}$$
$$+ H Z_\mu \bar{\ell} \gamma^\mu \left(c_V + c_A \gamma_5\right) \ell + Z_\mu \bar{\ell} \gamma^\mu (g_V - g_A \gamma_5) \ell - g_{\rm em} Q_\ell A_\mu \bar{\ell} \gamma^\mu \ell,$$



Beneke, Boito, Wang [1406.1361]

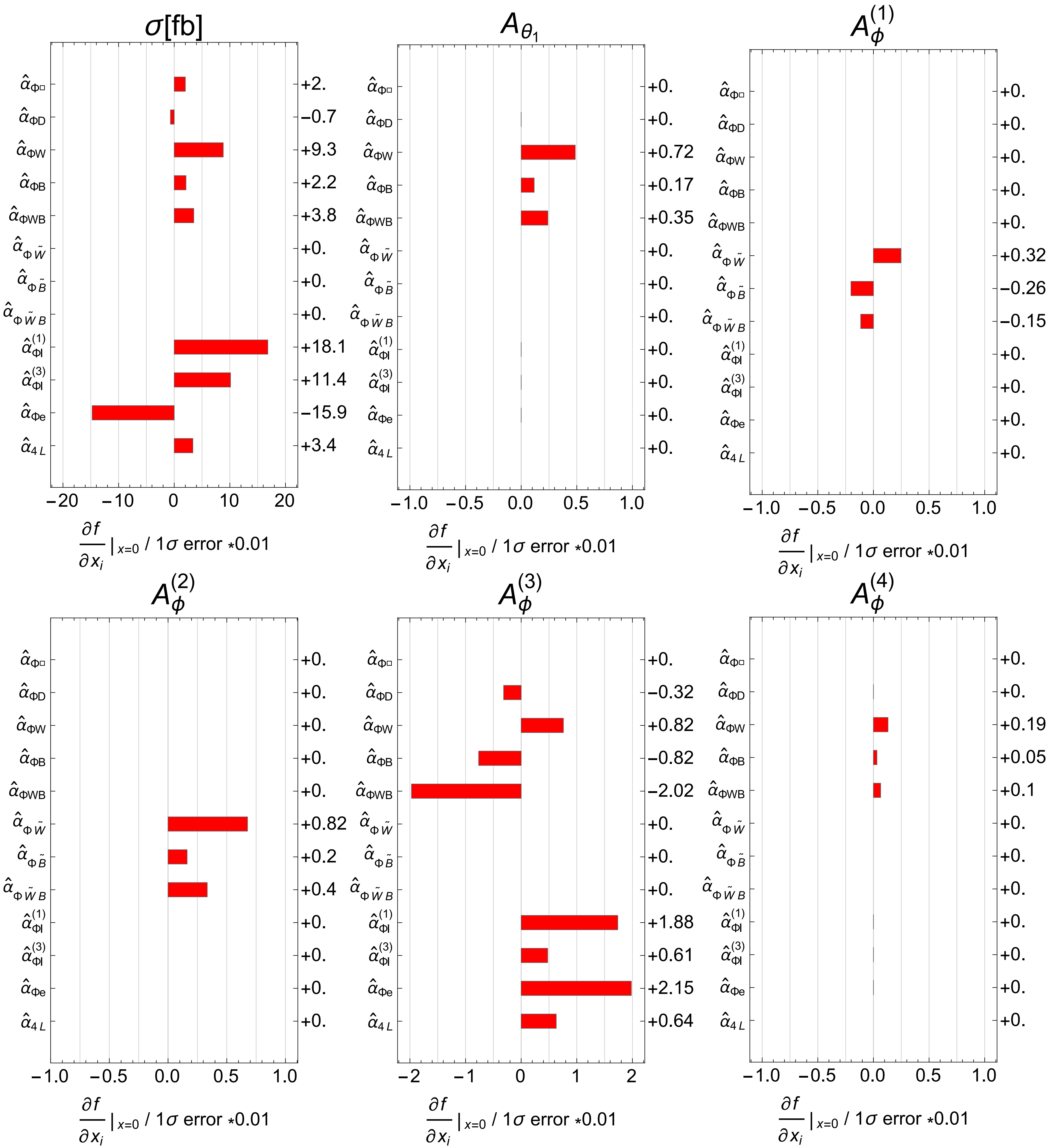
Studies to date focus on coupling shifts; much more information in tensor structure, accessible in angular variables

$$\mathcal{A}_{\theta_1} = \frac{1}{d\Gamma/dq^2} \int_{-1}^{1} d\cos\theta_1 \;\mathrm{sgn}(\cos(2\theta_1))\, \frac{d^2\Gamma}{dq^2 d\cos\theta_1}$$

$$\mathcal{A}_\phi^{(1)} = \frac{1}{d\Gamma/dq^2} \int_0^{2\pi} d\phi \;\mathrm{sgn}(\sin\phi)\, \frac{d^2\Gamma}{dq^2 d\phi} \qquad \mathcal{A}_\phi^{(3)} = \frac{1}{d\Gamma/dq^2} \int_0^{2\pi} d\phi \;\mathrm{sgn}(\cos\phi)\, \frac{d^2\Gamma}{dq^2 d\phi}$$

$$\mathcal{A}_\phi^{(2)} = \frac{1}{d\Gamma/dq^2} \int_0^{2\pi} d\phi \;\mathrm{sgn}(\sin(2\phi))\, \frac{d^2\Gamma}{dq^2 d\phi} \qquad \mathcal{A}_\phi^{(4)} = \frac{1}{d\Gamma/dq^2} \int_0^{2\pi} d\phi \;\mathrm{sgn}(\cos(2\phi))\, \frac{d^2\Gamma}{dq^2 d\phi}$$

NC, Jiayin Gu, Zhen Liu, Kechen Wang, *In Progress*



CEPC sensitive not only to coupling shifts, but different tensor structures.

- Truncate flat directions in the HEFT.
- Improve BSM reach by using added information.
- Distinguish between different BSM models with similar total cross section shifts.

Conclusions

With sub-percent level precision in many channels, CEPC:

- Places strong constraints on tree-level corrections to tree-level couplings, *exceeding reach of direct searches.*
- Also constrains loop-level corrections to loop-level couplings, *covering holes in direct searches at LHC.*
- Most impressively, constrains loop-level corrections to tree-level couplings. *Qualitatively new territory.*

Covers the parameter space of Higgs deviations motivated by naturalness.