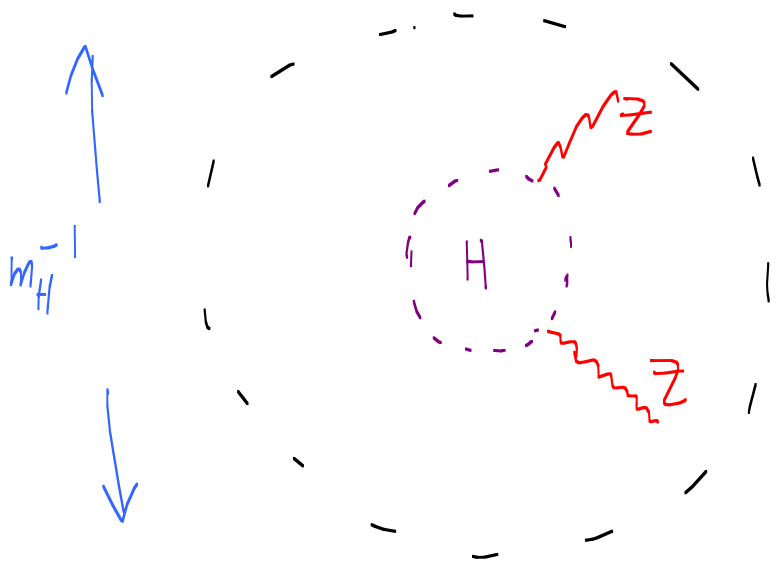
e^+e^- Higgs Factories

{Focus on CEPC/FCCee; All questions about ILC + All hard questions will be answered by Michael}

Higgs is Really New Physics!

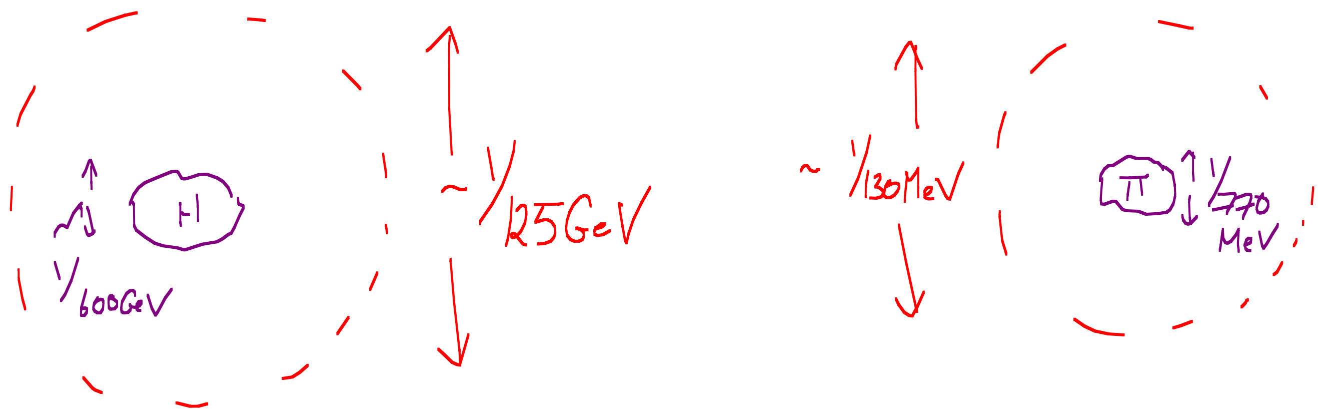
* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum
* MUST LOOK AT IT CLOSELY!

Never Seen Point-Like Scalar



So, how pointlike is it?

But with LHC resolution,
Higgs could be about as elementary
as a "pion":



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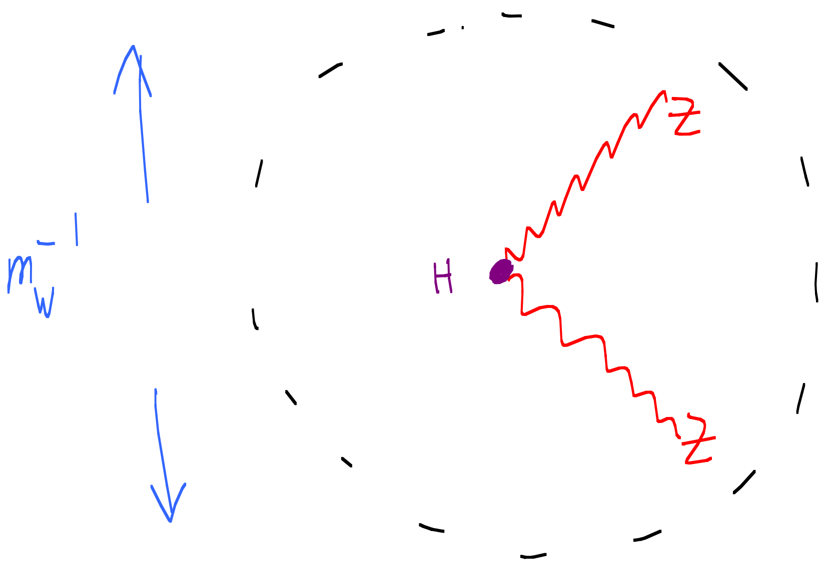
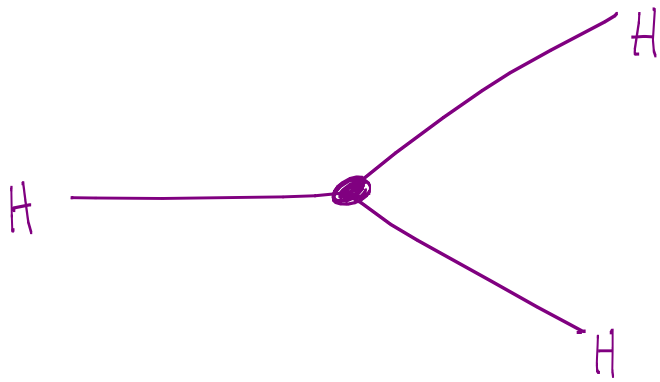


Higgs Factory

+

We will know FOR SURE if it is "a pion"

Never Seen Self-Interacting Fundamental Particles

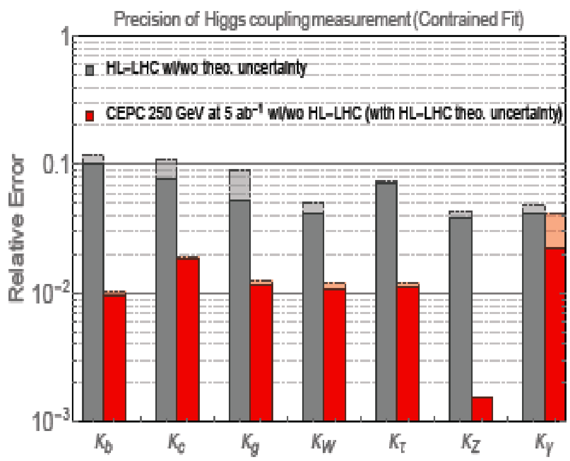


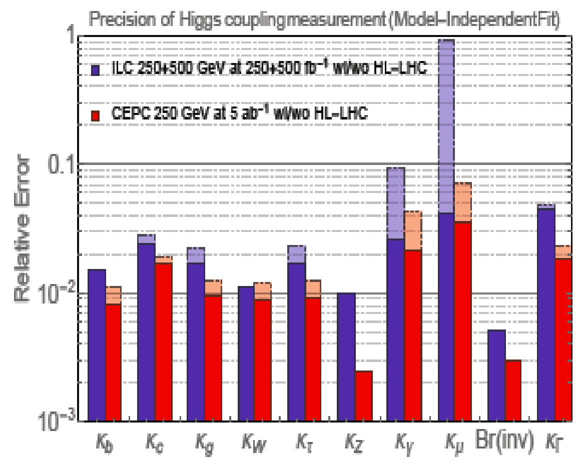
100 TeV Collider

[+ ~30% sensitivity from e^+e^-]

{ And, Obviously, huge push into energy frontier! This is a huge advantage / source of excitement for circular collider program }

Higgs Couplings

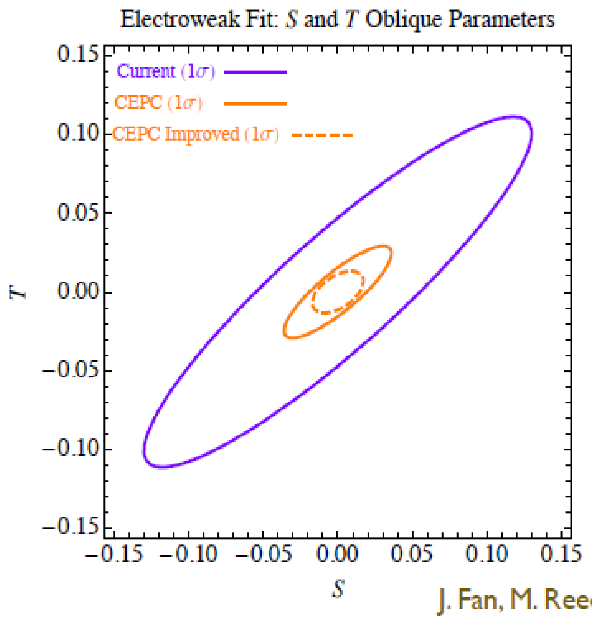




$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$

* Z-h @ sub-percent
* Model-indep measure of total width

Leap in Precision EWK



J. Fan, M. Reece, LT Wang, 1411.1054

Big Challenge To Theory Community!

Conclusions

- **Current SM predictions** for electroweak precision observables under good control (compared to experimental uncertainties)

- **LHC** will provide independent results for $\sin^2\theta_{\rm eff}$ and $M_{\rm W}$, but overall precision not substantially improved

- **ILC/CEPC/FCC-ee** with $\sqrt{s} \sim M_{\rm Z}$ will reduce exp. error of some EWPO by $\mathcal{O}(10)$
  $\rightarrow$ 3-loop (and maybe some 4-loop) corrections needed!

- **Asymptotic expansion and numerical integration techniques** are promising but more work needed

- **Open questions** in evaluation of theory errors, resummation and optimal choice of inputs

Potential of $\alpha_{QED}(m_Z)$ measurement (1)

For exploitation of precision EW measurements, need precise knowledge of $\alpha_{QED}(m_Z)$

- Standard method involves extrapolation from $\alpha_{QED}(0)$ to $\alpha_{QED}(m_Z)$
  - Dispersion integral over hadronic cross section – low energy resonances: **$\delta\alpha/\alpha = 1.1 \times 10^{-4}$**

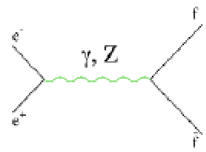
$$\boxed{\alpha^{-1}_{QED}(m_Z) = 128.952 \pm 0.014}$$

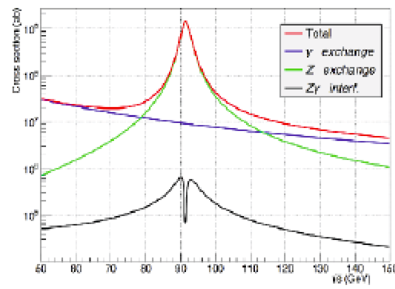
New idea: exploit large statistics of FCC-ee to measure $\alpha_{QED}(m_Z)$ directly **close to m_Z**

- Extrapolation error becomes negligible!

Two methods considered: Meast. of cross section, $\sigma(e^+e^- \to \mu^+\mu^-)$, and asymmetry, $A_{FB}^{\mu\mu}$

- γ exchange proportional to $\alpha^2_{QED}(\sqrt{s})$
- Z exchange independent of $\alpha_{QED}(\sqrt{s})$
- γZ interference proportional to $\alpha_{QED}(\sqrt{s})$

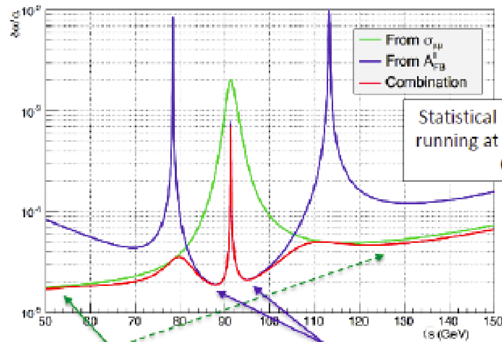




P. Janot: FCC-ee Physics Vidyo Meeting, June 29th 2015

A. Blondel

Potential of $\alpha_{QED}(m_Z)$ measurement (2)



Statistical uncertainty for one year of running at any centre-of-mass energy. Crab-waiste, 4 IP.

From $\sigma_{\mu\mu}$ measurement
- Sensitivity best "far" away from Z peak, particularly at the low side
- Systematics (normalisation) probably a killer

From $A_{FB}^{\mu\mu}$ measurement
- Sensitivity best at 88 and 95 GeV
- Experimental systs. looks controlable; further studies needed
- Theoretical systs. to large degree cancel by "averaging" over 88 and 95 GeV point

By running six months at each of 88 and 95 GeV points:
- ➢ Could potentially reach a precision of : $\delta\alpha/\alpha = 2 \times 10^{-5}$

A. Blondel

* Powerful + Complementary probes of Higgs couplings

$[\Lambda^2 \mathcal{L}_6]$: $[\partial h^\dagger h]^2$, $h^\dagger h \; h f f^c$, $h^\dagger h F^2$ ← Higgs Factory

$(h^\dagger h)^3$ ← 100 TeV   } Totally Generic

$(h^\dagger D^\mu h)^2$, $h^\dagger W^{\mu\nu} B_{\mu\nu} h$, $h^\dagger \overleftrightarrow{D}_\mu h \bar{f} \bar{\sigma}^\mu f$

↑ Z factory

Λ probed to (multi-) TeV scale

Hierachy of coupling dependencies

$\frac{1}{\Lambda^2}(h^\dagger h)^3$ — no log running at leading order → $\frac{1}{\Lambda^2}(\partial h^\dagger h)^2$ — big enough to be comp. → S, T param. ops

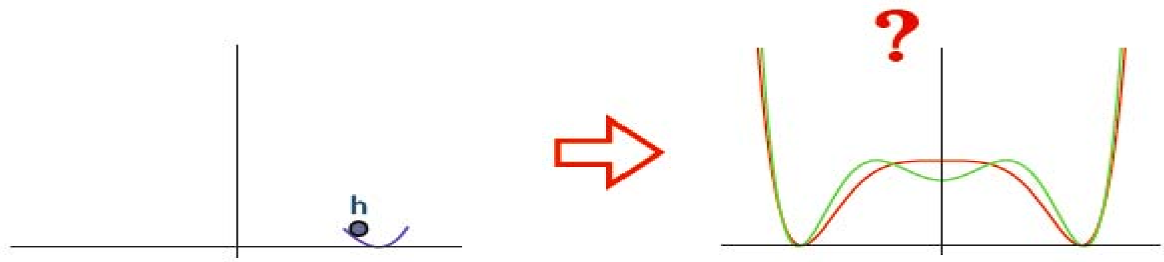
100 TeV best probe

Calculable correction to

Higgs Fact. Best Probe

Z factory best probe

The Electroweak Transition



What is Shape of Potential?

$$V(h) \longrightarrow m^2 h^\dagger h + \lambda (h^\dagger h)^2$$

Landau–Ginzburg...

NOT INNOCUOS!

$$V(h) \overset{?}{\longrightarrow} \lambda (h^\dagger h)^2 + \frac{1}{\Lambda^2} (h^\dagger h)^3$$

$$V(h) \overset{?}{\longrightarrow} \lambda (h^\dagger h)^2 \log \frac{h^\dagger h}{\Lambda^2}$$

} LHC won't tell us!

(O(1) Deviations in HHH coupling)

How is Electroweak Symmetry Restored?

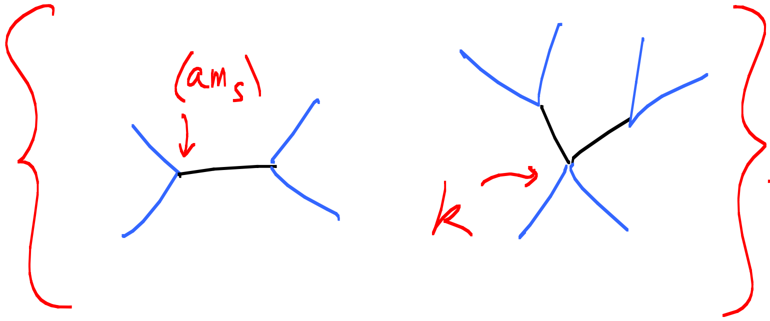
Was Transition 1st Order?

LHC Won't Come Close to Settling This

But $\mathcal{O}(1)$ deviations in HHH — $(h^\dagger h)^3/\Lambda^2$

+ $\delta Z_h \gtrsim$ Few % — $\partial (h^\dagger h)^2/\Lambda^2$

Perfect For Higgs Factory [+ 100 TeV pp!]



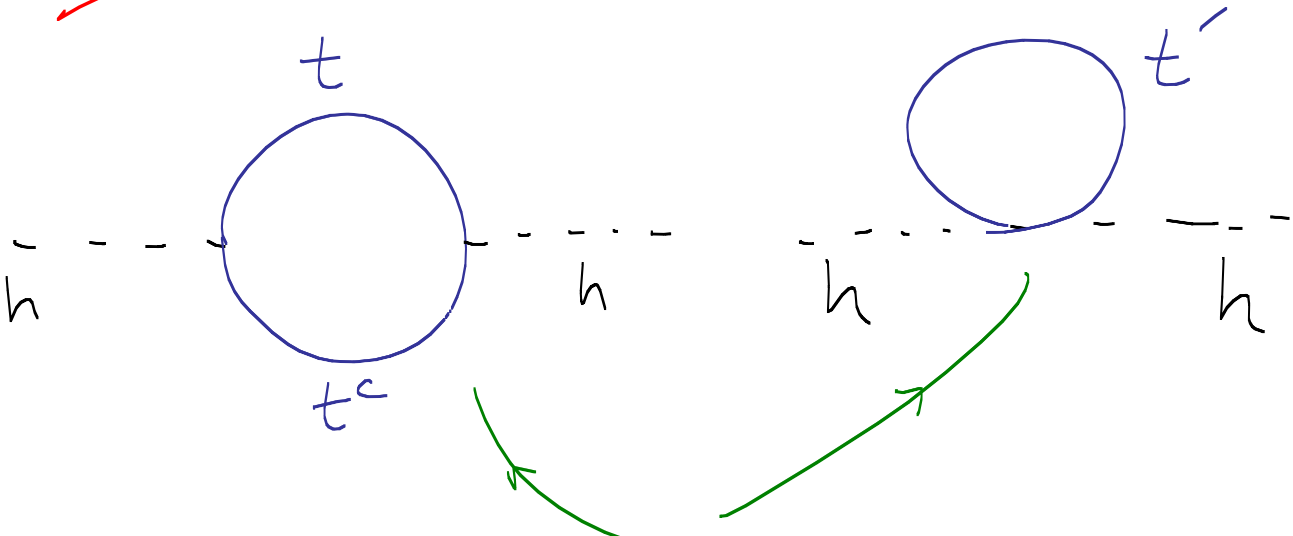
$$\lambda (h^\dagger h)^2 + \frac{K a^2}{m_S^2} (h^\dagger h)^3 + \frac{a^2}{m_S^2} (\partial_\mu h^\dagger h)^2$$

$$\Downarrow$$

$$\delta Z_h \sim \frac{\lambda}{K} \gtrsim \frac{\sqrt{\lambda}}{4\pi} \sim 0.03 \,!$$

Naturalness

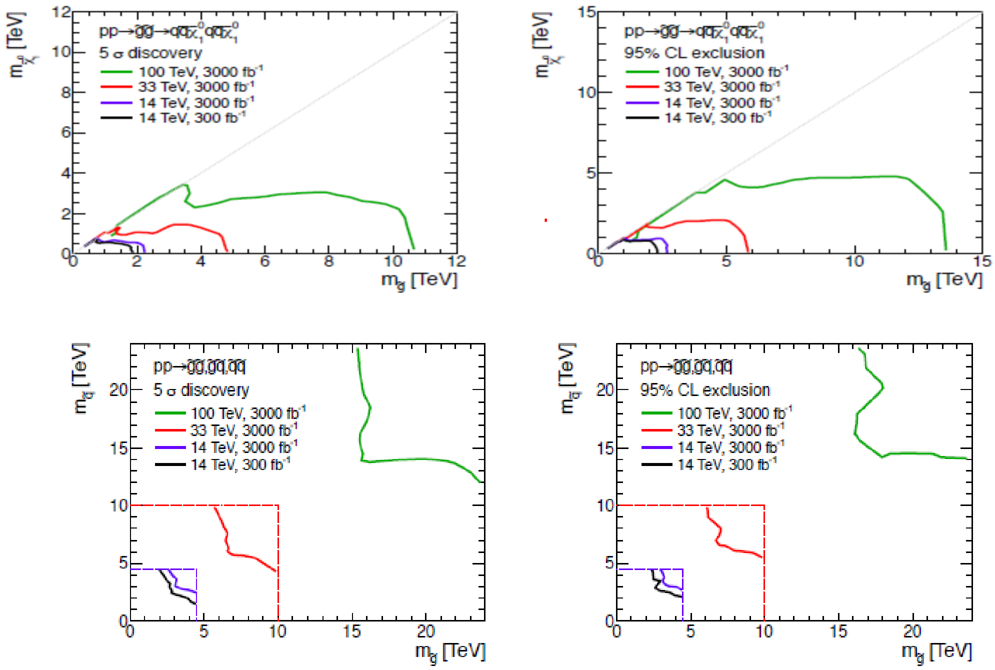
Expectation of New Part. At LHC



$$\delta m_h^2 = \frac{3\lambda_t^2}{8\pi^2}\Lambda^2$$

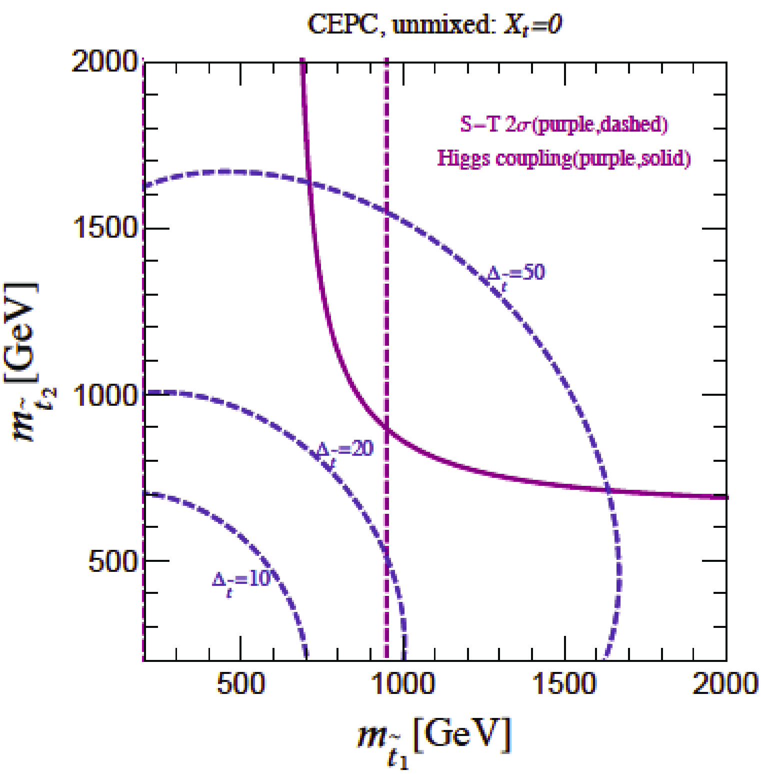
COLORED top partners $\lesssim$ 400 GeV

100 TeV Collider Crucial Here



But "Hadronic Muck Gaps" possible...

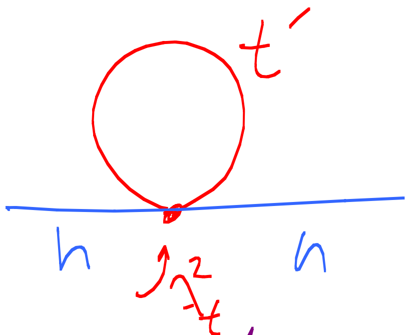
Stops have nowhere to Hide!



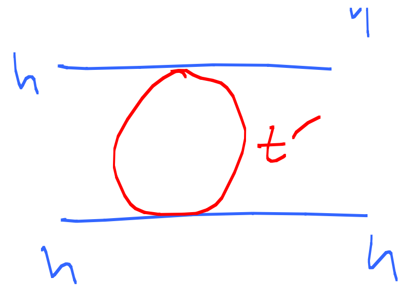
higgs/Z coupling shifts, can't be hidden in hadronic muck

Neutral Naturalness

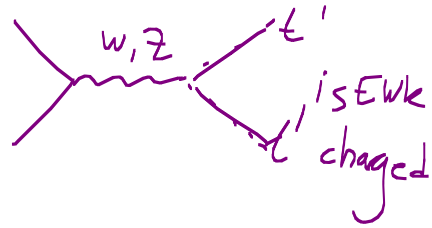
"Twin Higgs"
"Folded SUSY"

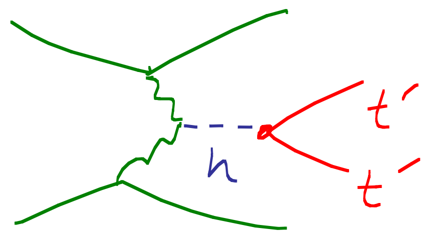


Uncolored top partners,
"3" from partner to $SU(3)_{color}$



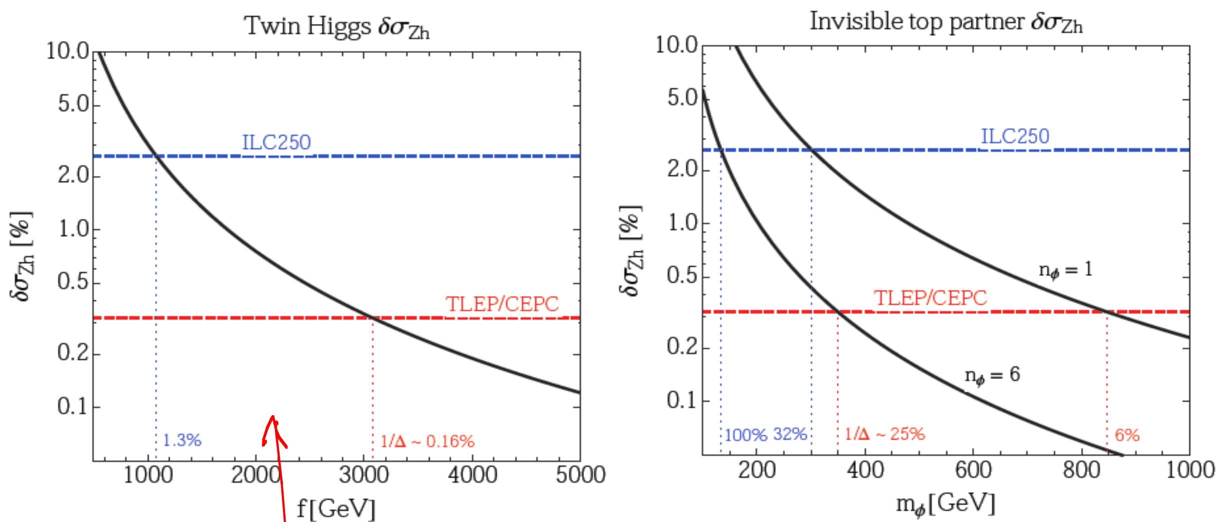
EWk charged





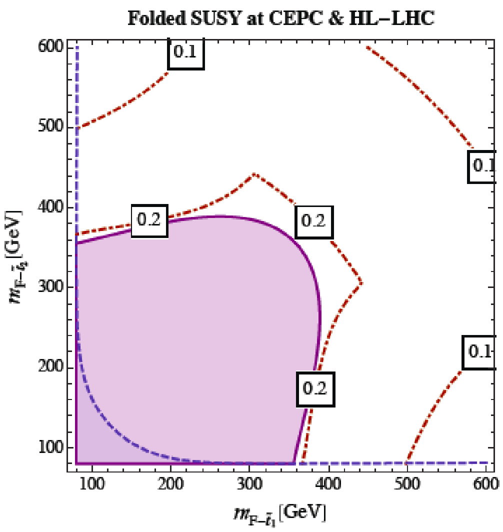
production @ 100 TeV

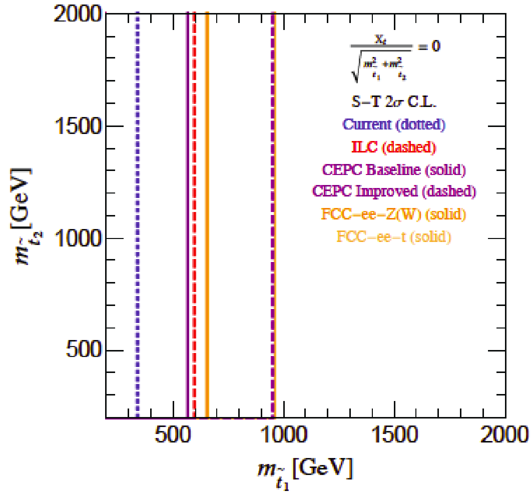
Naturalness "No-Lose" Thm



If it's "a pion" $\delta Z_h \sim \frac{v^2}{f^2}$,
WE WILL KNOW

Electroweak Charged t's





CEPC + FCC-ee

* Main difference: FCC target Z higher (10 vs. 5 ab^{-1})
  * Higgs coupling precision $\propto \frac{1}{\sqrt{Z}}$
  * Not much impact on precision EW (better for rare Z decays)

* Also plans to go to $t\bar{t}$ threshold

CEPC + FCC-ee / ILC

* Lower $\mathcal{L}$ in early (250 – 500) stage – not as good in Higgs couplings
* $\bar{t}t$ threshold
* Measure of $t\bar{t}H$ coupling @ 15% – 7% [500 → 550]
  HHH " " @ 30% – 10% [500 → 1000]
* Production of "ewk-ino" states
* Very nicely complementary

[* Nothing Better Geopolitically than for ILC to move forward – competition is GOOD!]

Other Higgs Measurements with CEPC & ILC G-20 at 8.1 yrs

	CEPC 250 GeV 5000 fb^{-1}	ILC 250 + 350 + 500 GeV 500 + 250 + 500 fb^{-1}	*Combined*
Δm_H	5.9 MeV	25 MeV	5.7 MeV
$\frac{\Delta g_{HHH}}{g_{HHH}}$	36 %	76 % 30% w/ 4 ab^{-1}	33 %
$\frac{\Delta g_{ttH}}{g_{ttH}}$	–	16.6 %	16.6 %
$\frac{\Delta g_{ttH}^{(*)}}{g_{ttH}}$	–	6.7 %	6.7 %

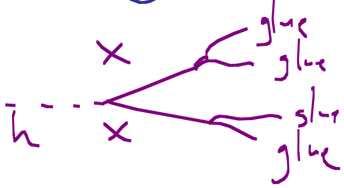
*Assumes ILC 500 GeV running actually takes place at $\sqrt{s} = 550$ GeV

Two Broad Directions for Future Studies

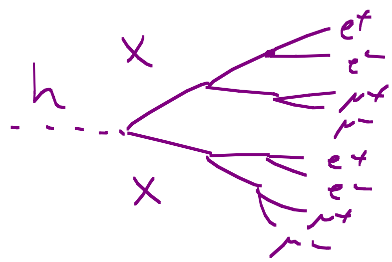
* Can we beat down systematics to fully use ~10^{10}–10^{12} Z's [beyond only factor ~10 improvement on S,T!]

* New physics in rare higgs, Z-decays!

e.g.



displaced, or



lepton jets

The questions raised by the accelerating universe, and the higgs discovery, both go to the heart of our understanding of the nature of spacetime, quantum mechanics + the vacuum.

Shining a powerful spotlight on the Higgs is our most effective tool for attacking these mysteries experimentally

Case is Simple + Clear