Higgs Naturalness Implications

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Outline

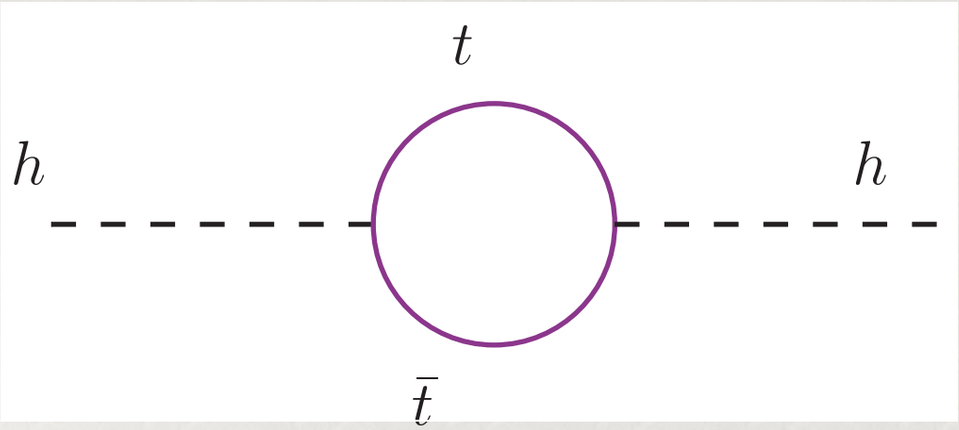
- *Naturalness: very brief 1-slide summary*
- *"Standard Naturalness":*
  - *SUSY*
  - *Composite scenarios*
- *"Exotic Naturalness":*
  - *Neutral Naturalness: TH, FS*
  - *What can FCC do to discover this scenarios?*
- *Conclusions, Outlook*

Unnaturalness of the Standard Model

EW scale within the SM as a Wilsonian effective theory:

$$\mu^2 = \mu_0^2 + \frac{3y_t^2}{4\pi^2}\Lambda^2 + \ldots$$

Slightly more technically: the higgs mass parameter gets radiative (threshold) corrections



and slightly numerically smaller contributions from the SU(2) gauge bosons

Basic problem: the SM has an unprotected relevant operator

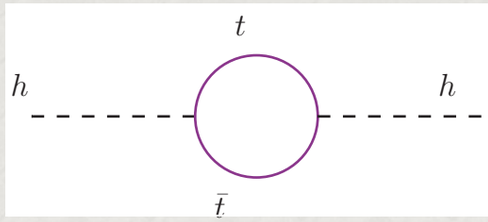
How Can We Render The SM UV Completion Natural?

What are the "tricks" that can solve the big hierarchy problem — from the EW scale all the way to the Planck scale?

- *Use symmetry to protect the relevant operators from getting large radiative corrections — SUSY is the only known symmetry which can do the job resolving the hierarchy problem all the way to the Planck scale*
- *Make sure that the underlining theory has no relevant operators — Higgs compositeness, partial compositeness etc.*

SUSY and Naturalness

SUSY guarantees the naturalness by connecting the higgs operator to the fermionic operators.
Immediate consequence of SUSY: (light?) superpartners



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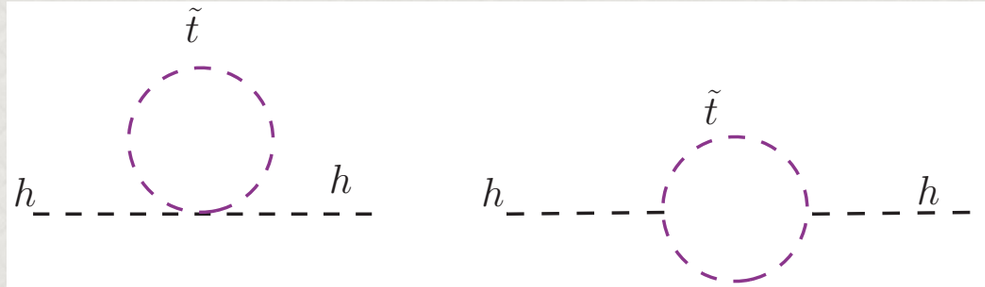
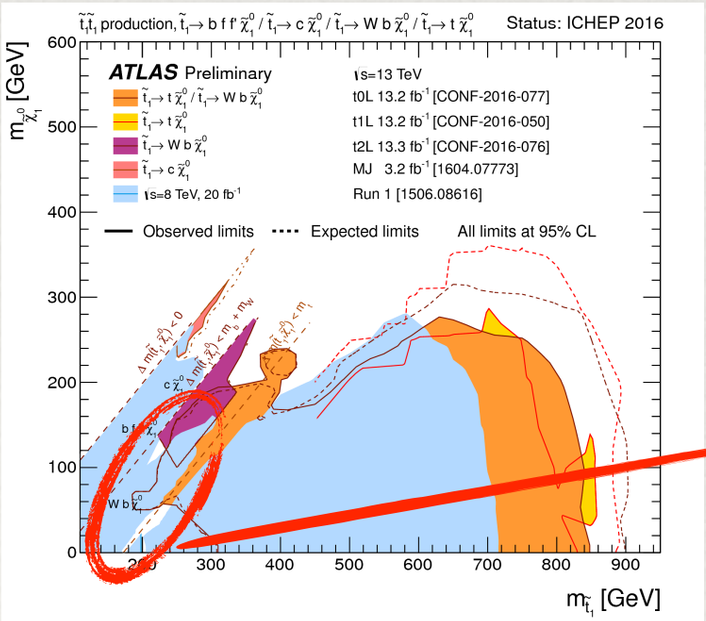




Direct searches provide the most important information, but...

The cracks are here, even in the small mass regime, and they can possibly survive the HL LHC.

Compressed regions are also hard.

"Natural" SUSY Effects on the Higgs

If we insist that SUSY also takes care of the little hierarchy problem, we should expect stops to be not too heavy. This immediately has an effect on the higgs couplings to the photons and the gluons

Coupling deviation to the gluons due to the stops

$$r_g - 1 \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_1}^2} - \frac{X_t^2 m_t^2}{m_{\tilde{t}_1}^2 m\tilde{t}_2^2}\right)$$

Assuming that FCC-ee will probe the decay into gluons to the level of 1%, this will allow us an excess to the lightest stops beyond the mass scale of 1 TeV, which are unlikely to be probed fully at the LHC

What Does SUSY Do to the SM Higgs?

The simplest SUSY SM extension demands two Higgs doublets, making sure that it is a type II 2HDM — expect deviations in the Higgs couplings like in 2HDM

In the decoupling large tan β limit of the type II 2HDM the first couplings to be affected are couplings of the Higgs to the down type sector.

$$r_d = -\frac{\sin\alpha}{\cos\beta} \approx \left(1 + \frac{m_h^2}{m_A^2}\right)\left(1 + \frac{m_Z^2 \sin^2\beta}{m_A^2}\right)$$

Assuming 1% precision in these measurements, this means that heavy higgses as heavy as 2 TeV might leave imprints in FCC-ee

Another promising direction — looking for the new Higgses.*

**See talk by Shufang Su for more details*

Compositeness and Naturalness

Compositeness solves the naturalness problem guaranteeing that in the UV completion is free of relevant operators. Practically the "original version" of compositeness theory is (almost?) dead. PNGB Higgs compositeness:

- *Allows parametric separation between the scales v and f because the higgs is pNGB (symmetry!)*
- *Guarantees the existence of the higgs in the spectrum*
- *Ameliorates the flavor problem of the technicolor*

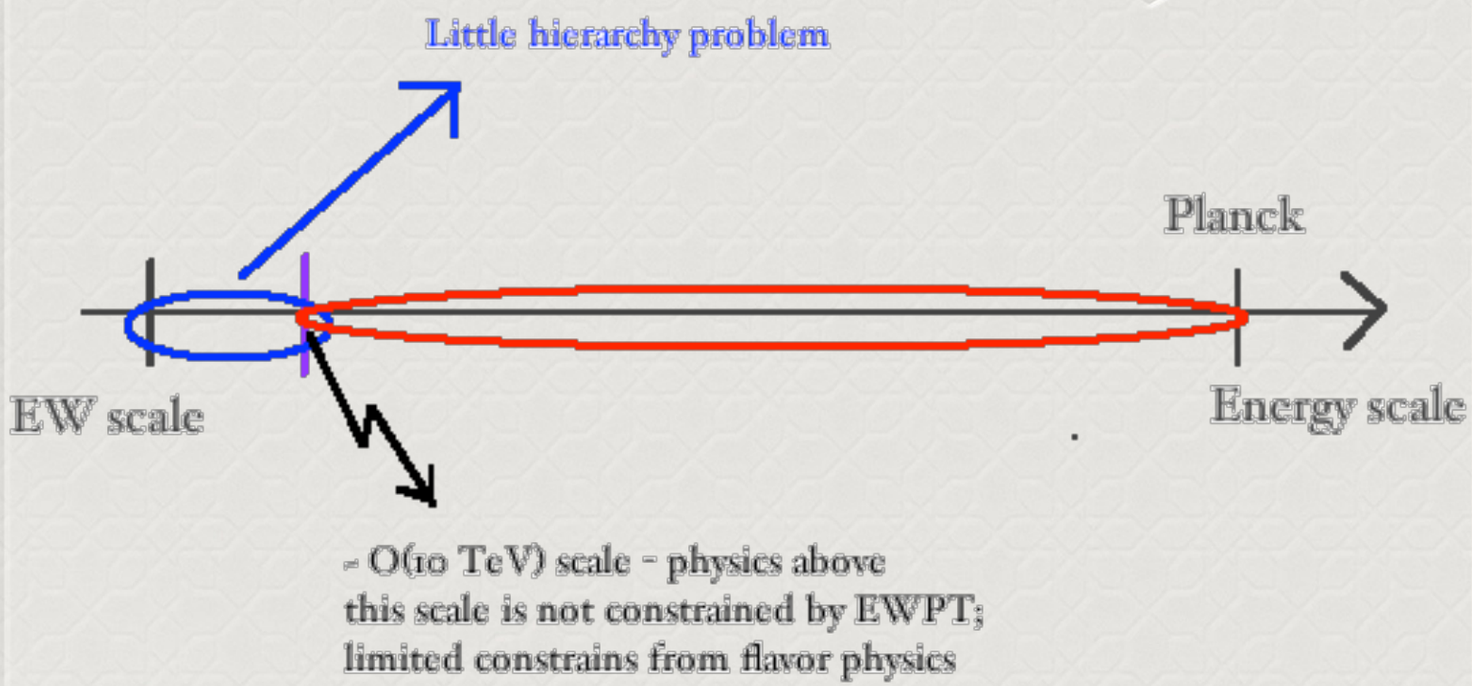
Higgs Couplings

Most important modification of the higgs couplings. In the minimal model (Minimal Composite Higgs):

$$r_{W,Z} = \sqrt{1 - \left(\frac{v}{f}\right)^2}$$

LHC will be sensitive to $(v/f)^2$ ~0.1, while the FCC-ee facilities will be able to improve this by order pf magnitude. Of course it also leaves exciting imprints in vector boson scattering (see talk by Fady Bishara).

The Little Hierarchy Problem



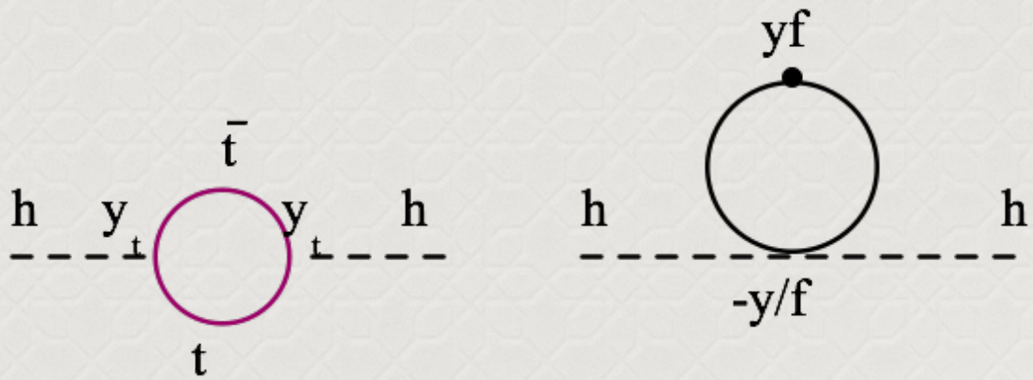
NP > 10 TeV scale is not constrained by EWPT or LHC searches. Maybe compositeness or naturalness solve the big hierarchy problem from 10 TeV to the Planck scale?

For the little hierarchy problem SUSY is not the only symmetry that can guarantee smallness of the relevant operator: all Higgs pGB scenario fit.

The Neutral Naturalness

Basic idea: the most important radiative corrections to the Higgs mass parameter come from top contributions. Top partners, that tame these contribution do not need to be colored. It will somewhat resemble the compositeness models, but there will be no colored top partners and the scale f looks pretty different.

Twin Higgs:



The 1-loop cancellations in folded SUSY work exactly as in the regular SUSY, except the fact that that the stops are SM-colorless

Neutral Naturalness Prototype Models

Fermionic partners — Twin Higgs

Largely along the lines of the little Higgs. Higgs is an approximate pGB of a large global symmetry SO(8)/SO(7). Trick: up to 5 TeV cutoff this structure can be maintained by imposing a discrete mirror symmetry, top partners are not charged under the SM color

Bosonic partners — Folded SUSY

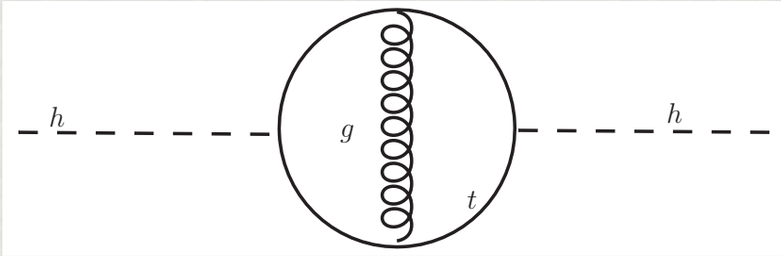
It is not SUSY!!
An extended symmetry SU(3)×SU(3)×SU(2)×U(1) with the scalar top partners are charged under a non-SM color SU(3). Descends from a 10 TeV SUSY orbifold, which insures that the couplings have the right strength.

Hidden Valleys and The Higgs Portal

Naively to maintain naturalness up the cutoff scale (~10 TeV) , we should only take care about the 1-loop divergencies

The SM color group is unimportant, 3 is merely a multiplicative factor in the top-top partner diagrams

Numerically: diagrams like



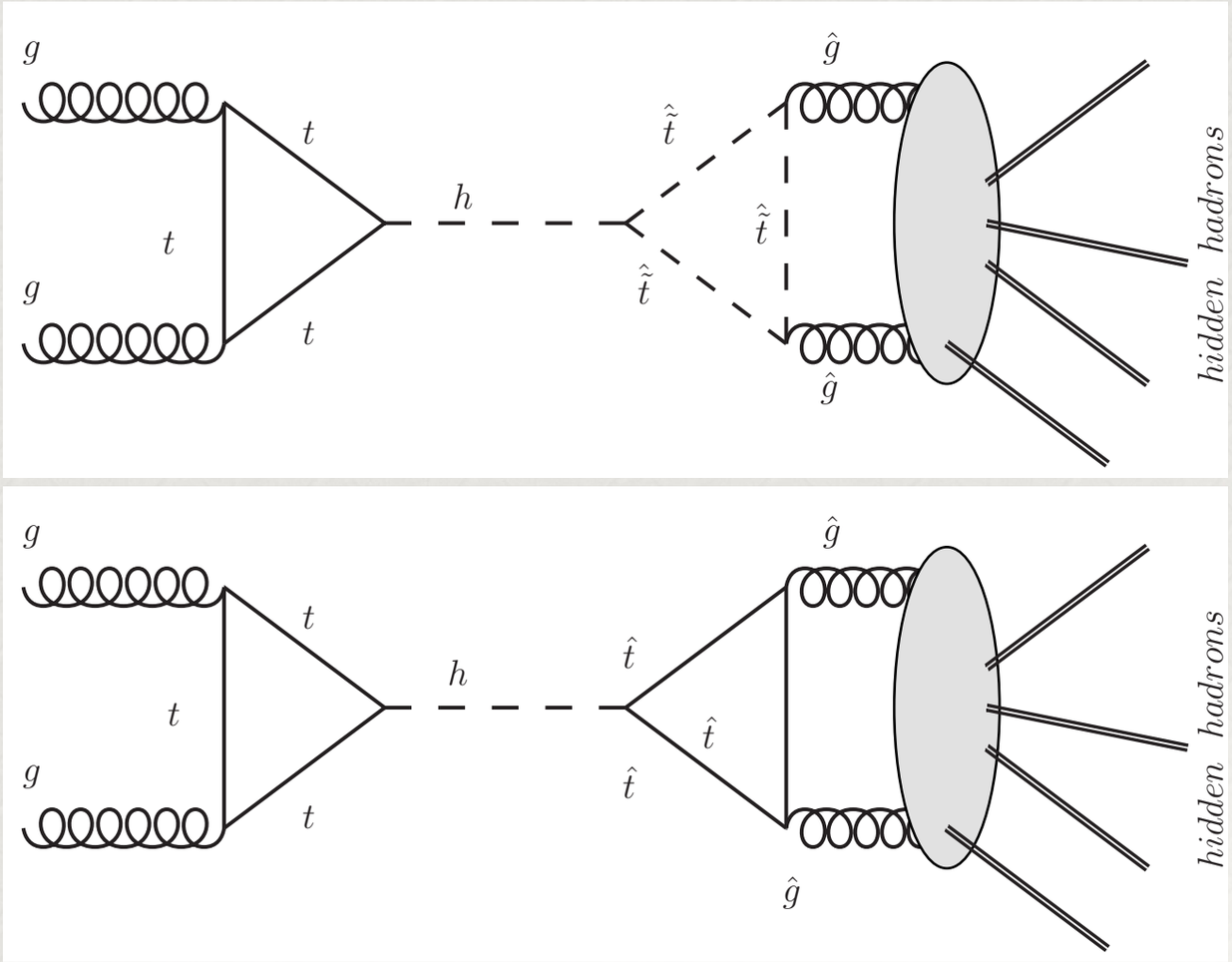
demand light gluinos in the "natural SUSY"

NN analog: global SU(3) of top partners must be gauged

The Higgs Portal

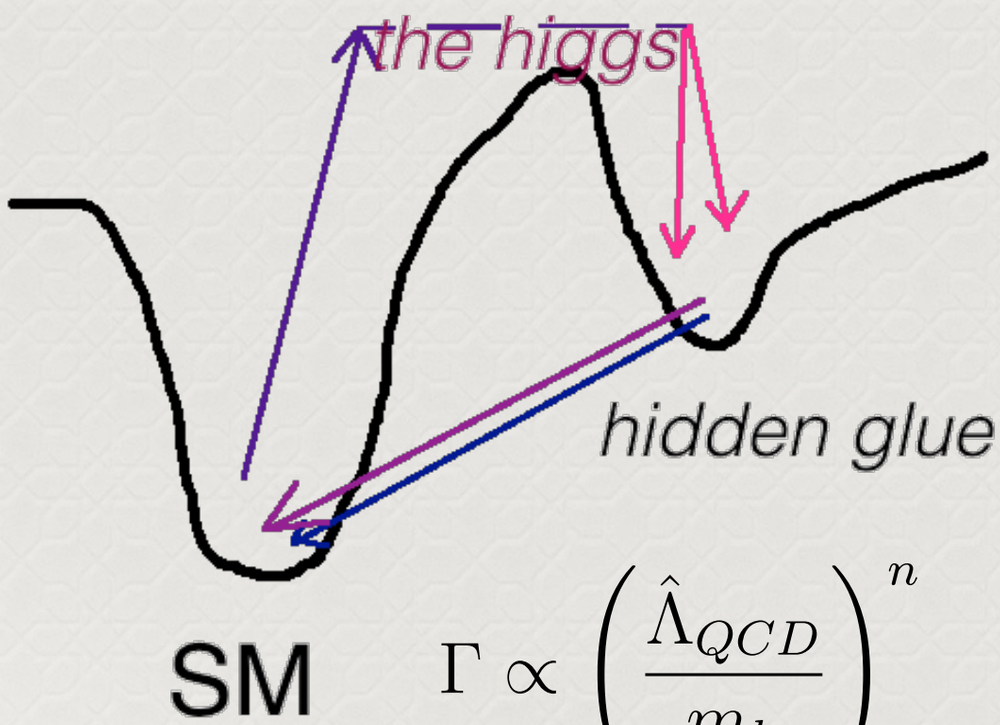
With the confining hidden valley higgs exotic decays are guaranteed:

Both in the folded SUSY and in the Twin Higgs scenario Higgs is a unique portal into the hidden valley of confining SU(3):



The Hidden Valley Signals

Prediction of NN: confining hidden valley of another color SU(3)



$$\Gamma \propto \left(\frac{\hat{\Lambda}_{QCD}}{m_h}\right)^n$$

Potentially displaced vertices

What is the lightest hidden particle?

- *Mirror twin Higgs — the hidden valley include nearly massless particles*
- *Folded SUSY: the lightest particles are the glueballs of the confining SU(3)* $m \sim \Lambda_{QCD'} \gtrsim \Lambda_{QCD}$
- *Fraternal Twin Higgs — the hidden valley spectrum is qualitatively similar to the Folded SUSY, but might also include stable mesons*

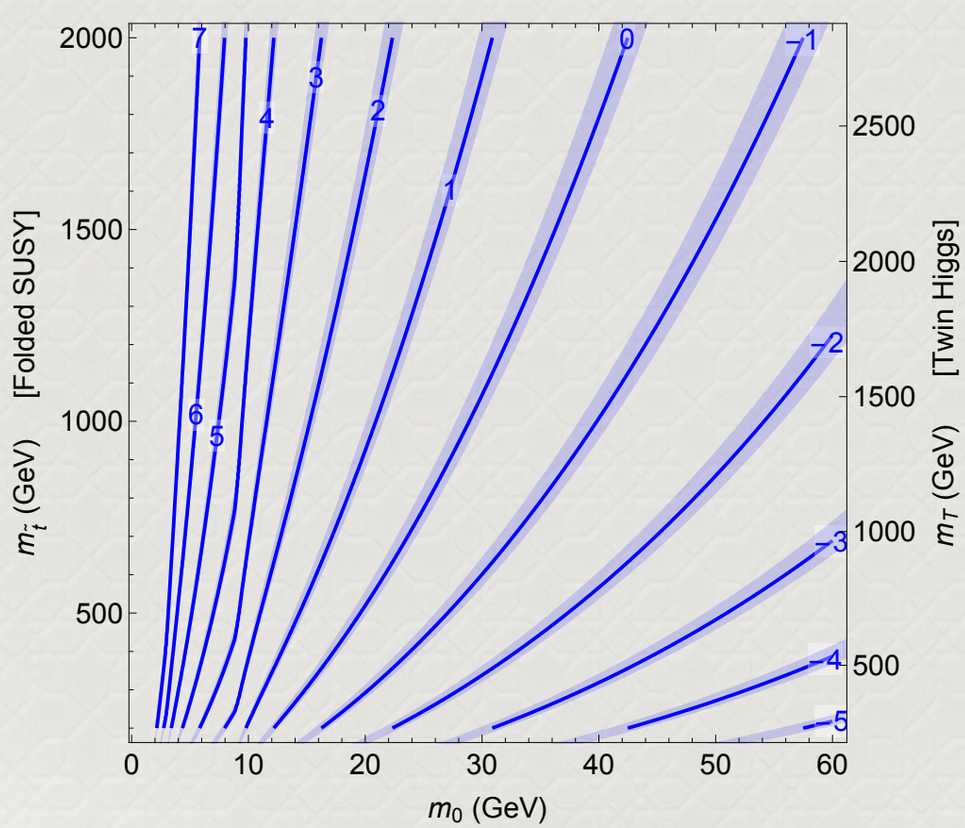
Decay Lengths

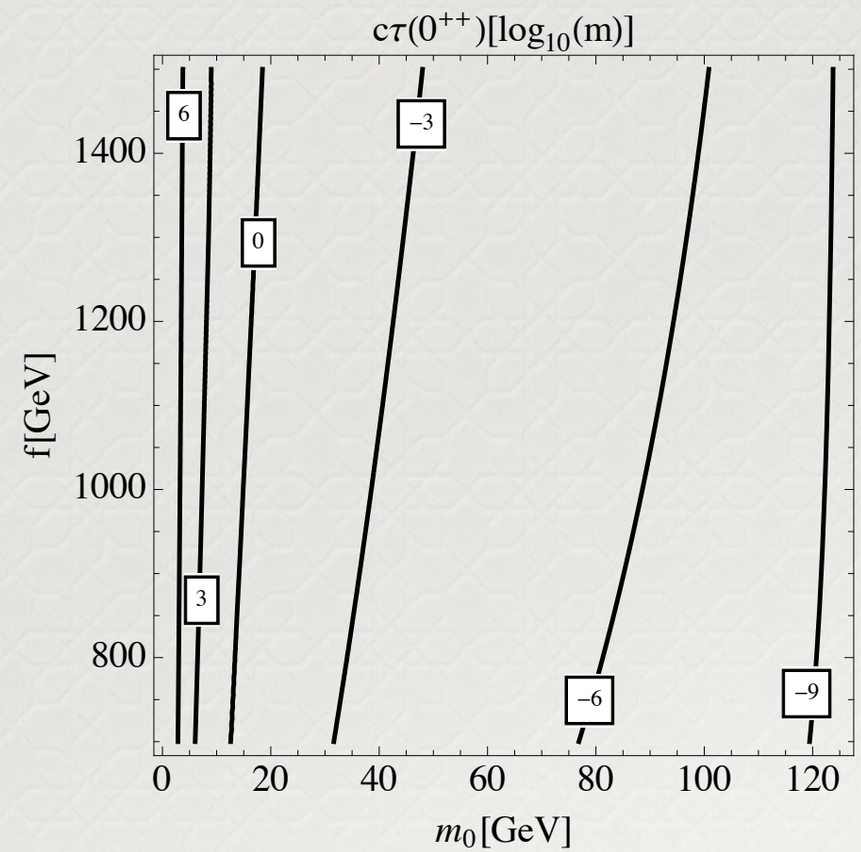
Lightest glueball decay lifetime (decay via the off shell higgs):

$$\Gamma_{G_{0+}\to YY} = \left(\frac{\hat{\alpha}_3 v f_0}{6\pi f^2 (m_h^2 - m_0^2)}\right)^2 \Gamma^{SM}_{h\to YY}(m_0^2)$$

$$\propto m_0^3$$

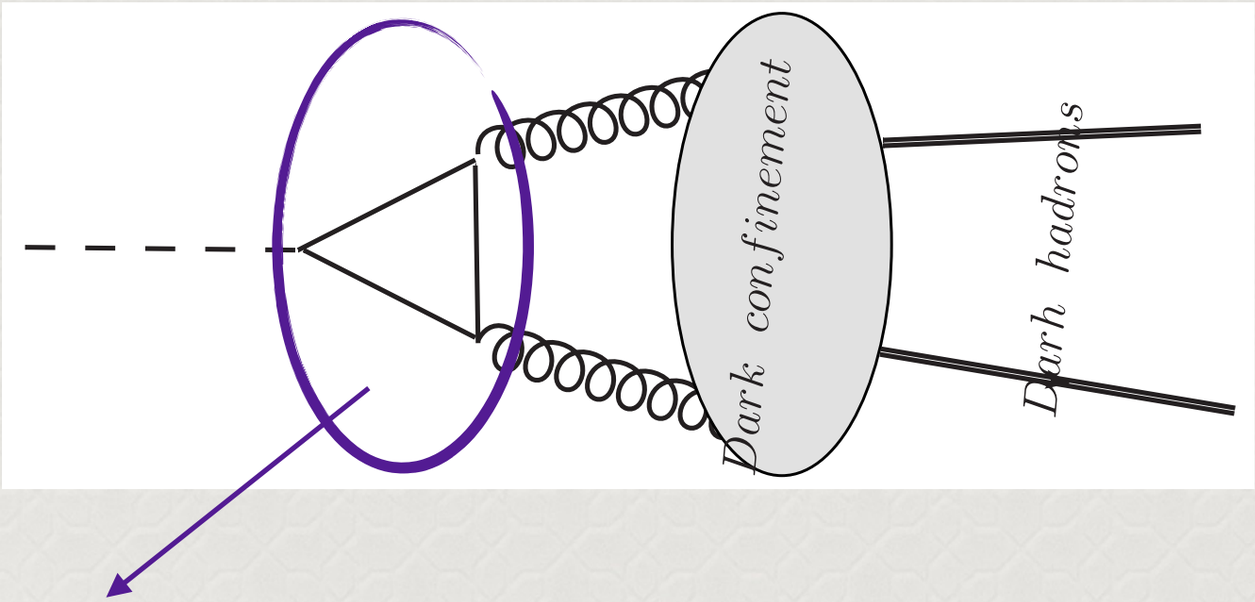
Scaling as the 7th power of mass provides a wide range of possibilities





Higgs Exotic Branching Ratios

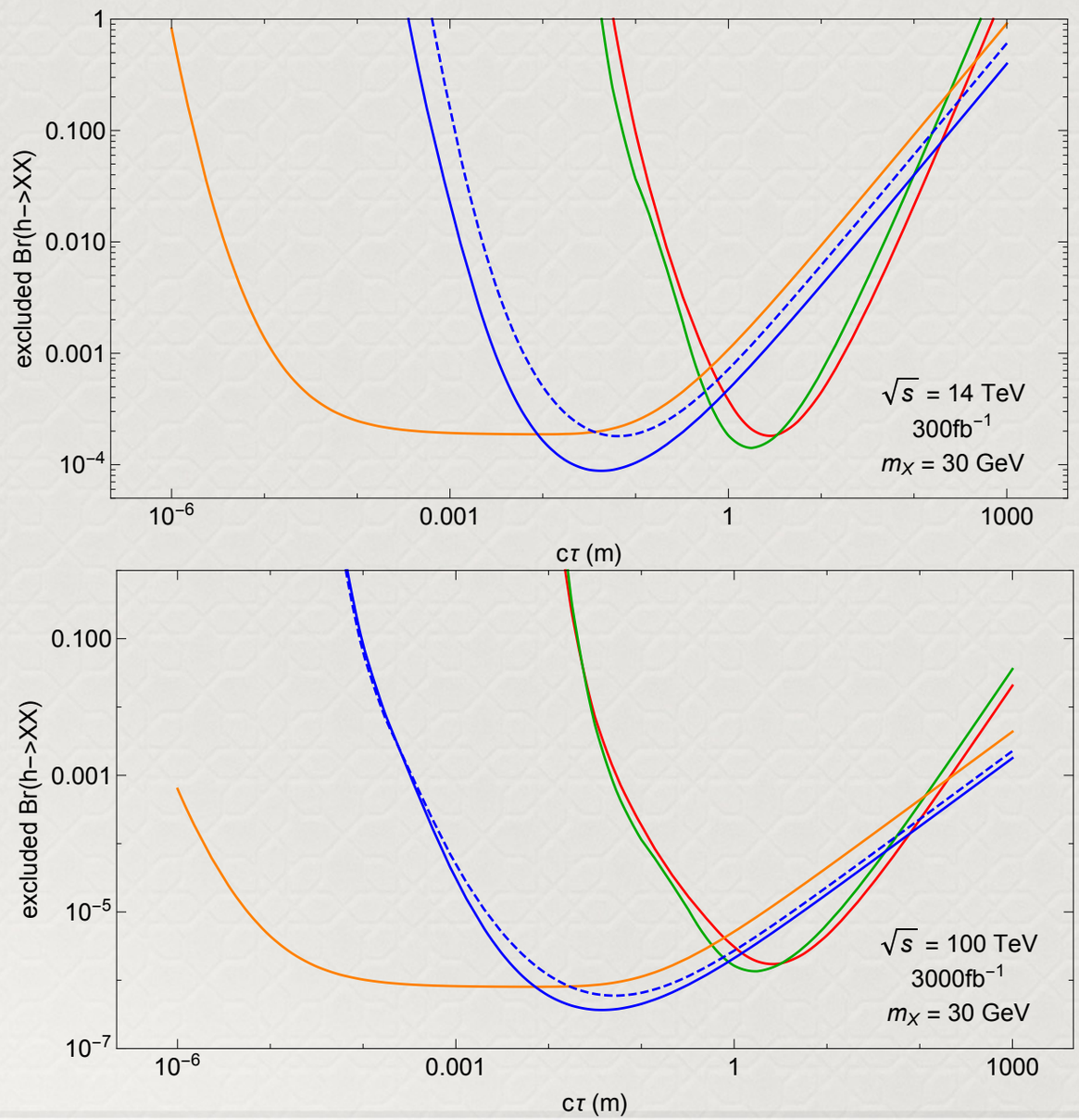
Irreducible decays into the hidden valley



This part is similar to the h→gg except that we have misalignment suppression in the twin higgs and the scalar loop + folded stop mass suppression in FSUSY

Taking into account all the suppressions the irreducible rate in the range 0.1%... 1% is natural. If more FT is involved it can be smaller

Potential Reach: LHC vs FCC-hh



Potential reach estimated by Curtin and Verhaaren, assuming zero background in $h \rightarrow 0^{++}0^{++}$

Various techniques are presented, including 1 DV (blue + orange) and 2 DV (green and red)

**More in a talks by C. Verhaaren & D. Curtin*

plot from Curtin & Verhaaren; 2016

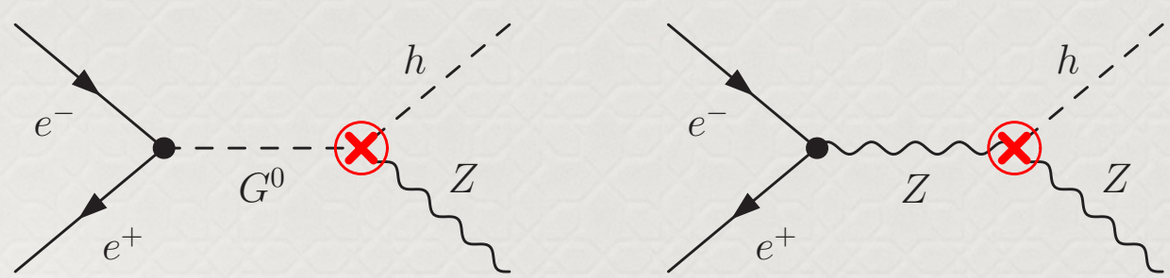
More on the To-Do List: Strategies

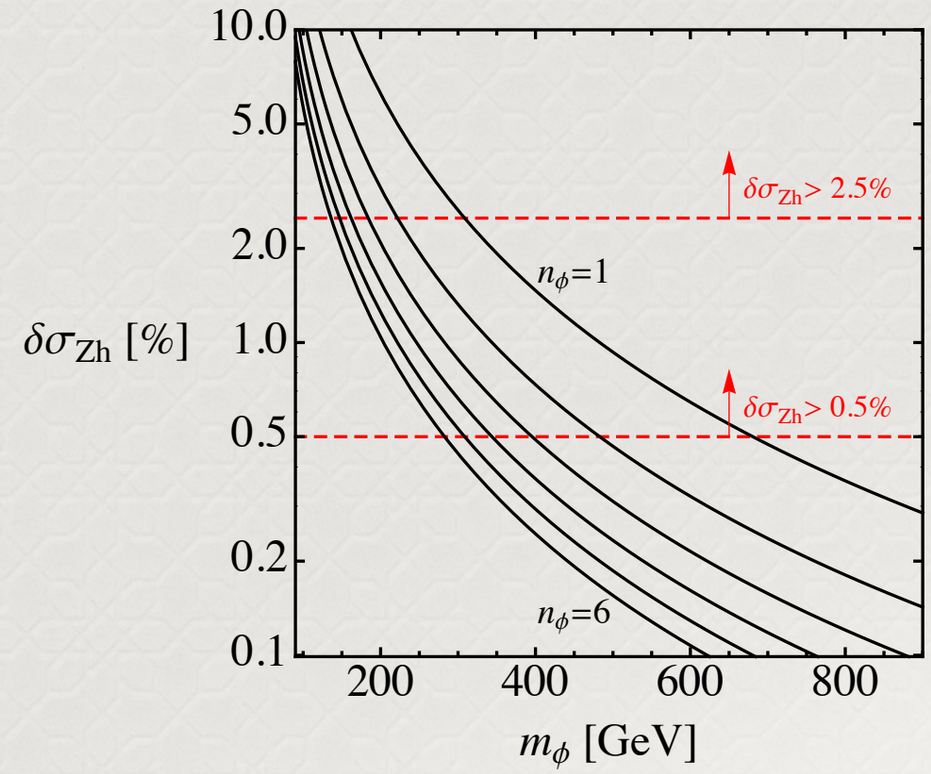
- *Until now the signature which attracted most attention was h→2 identical hidden hadrons. In the case of light hidden valleys more showering in the hidden sector is likely*
- *Signatures h→many + MET are not unlikely with softer signals and multiple DVs.*
- *What are the realistic backgrounds in the FCC-hh*
- *Is the LHC strategy "rescaled" to the size of FCC is ideal or should we try different strategies at the FCC-hh?*

Can We "Measure" the Colorless Top Partners

Top partners: charged under the EW (FSUSY) or completely sterile. Direct measurements — impossible. But what about their effects on the higgs?

Higgs self energy is renormalized ☛ couplings to Z are affected





plot from Craig, Englert, McCullough; 2013

Conclusions

- *Higgs measurements can play an important role in cornering (or discovering) NP*
- *Although direct searches for the superpartners is the main path to study SUSY, some "cracks" in parameter space can be easier accessed via the Higgs searches*
- *In the composite Higgs models deviations of the higgs BRs from the SM are directly related to the FT*
- *Exciting rare exotic Higgs decays are generically predicted by neutral naturalness models and FCC-hh will be able to make important gains in this direction*
- *Ideal FCC-hh search strategies for the exotic higgs decays in the context of the neutral naturalness are yet to be studied*