PARTICLE PHYSICS AT FUTURE ENERGY FRONTIERS

Jessie Shelton

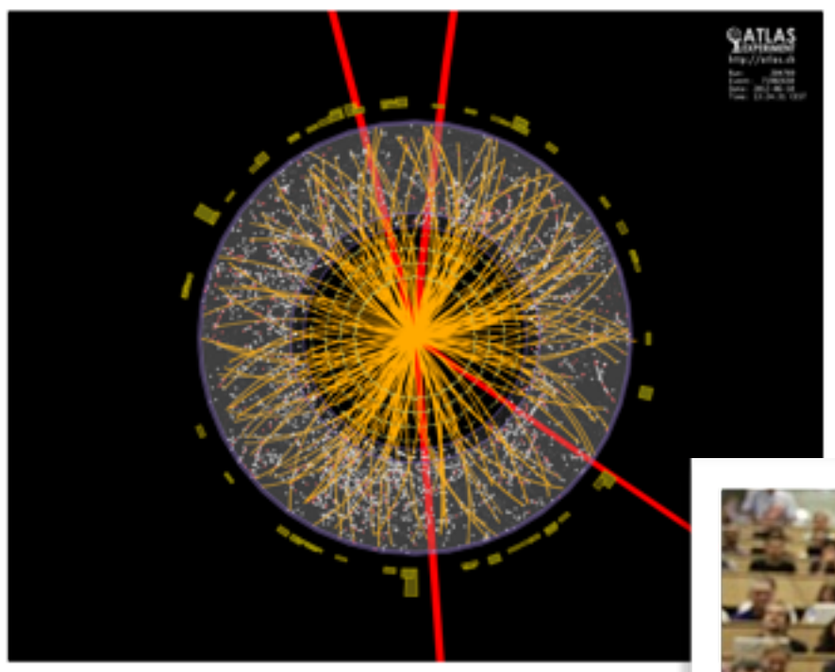
U. Illinois at Urbana-Champaign

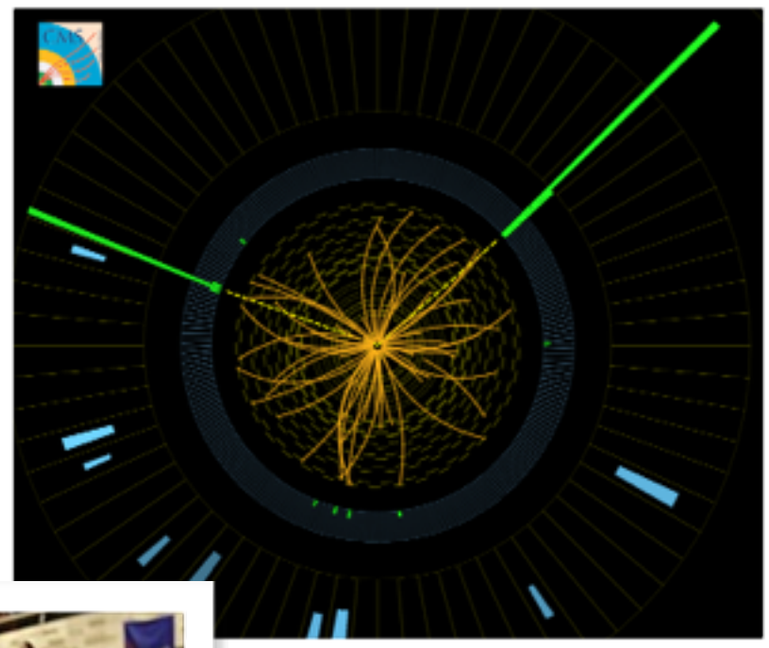
TRIUMF Science Week

July 13, 2017

The LHC and the Terascale

- Enormously successful LHC program has brought particle physics into a new era





A new and puzzling era

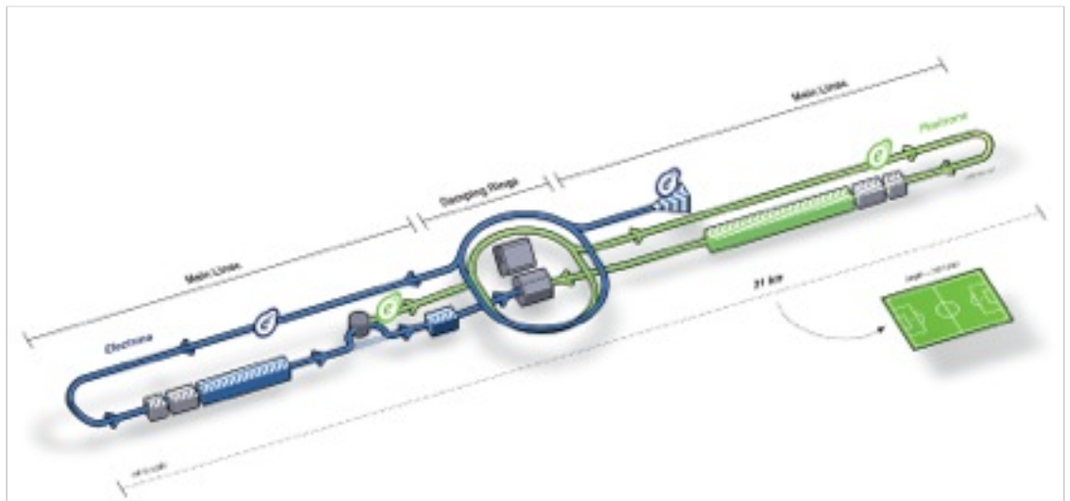
- A new era
  - SM proven to be phenomenally and mysteriously successful
  - on one hand: clear cosmological need for BSM physics
  - on the other: no clear hints from experiment regarding scale of new physics
- Major question: how to guide further exploration of the vast space of possible new physics?

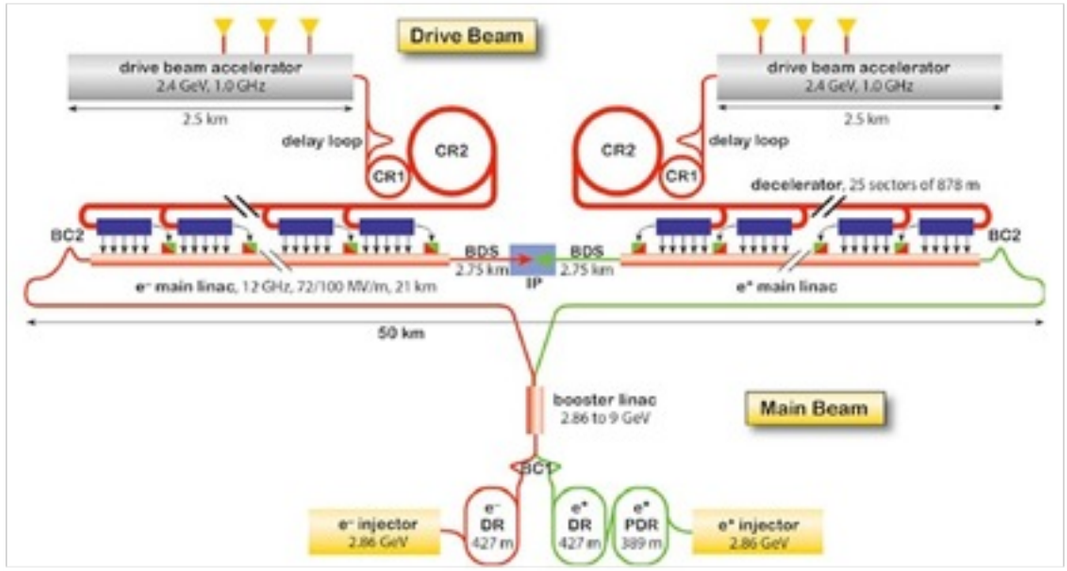
Higgs forward

- Detailed study of the Higgs boson and its related conundra is the major new opportunity provided by future energy frontier machines
  - There is no "no-lose" theorem. The SM is internally consistent
  - however, we are guaranteed to learn more about the only fundamental scalar field found in nature
    - including to what extent we know it is indeed fundamental
    - [no-lose: detailed study of fund'l scalar vs proof it isn't!]

Future Energy Frontiers

- The road forward from the LHC: linear e+e- colliders





ILC: integrated luminosities >~ ab-1 at ECM = 250 GeV, 500 GeV, smaller data set at 350 GeV

Future Energy Frontiers

- Further ahead, circular colliders scaling up LEP+LHC:

Chinese proposal:
CEPC (e+e- collider)
SppC (pp collider)

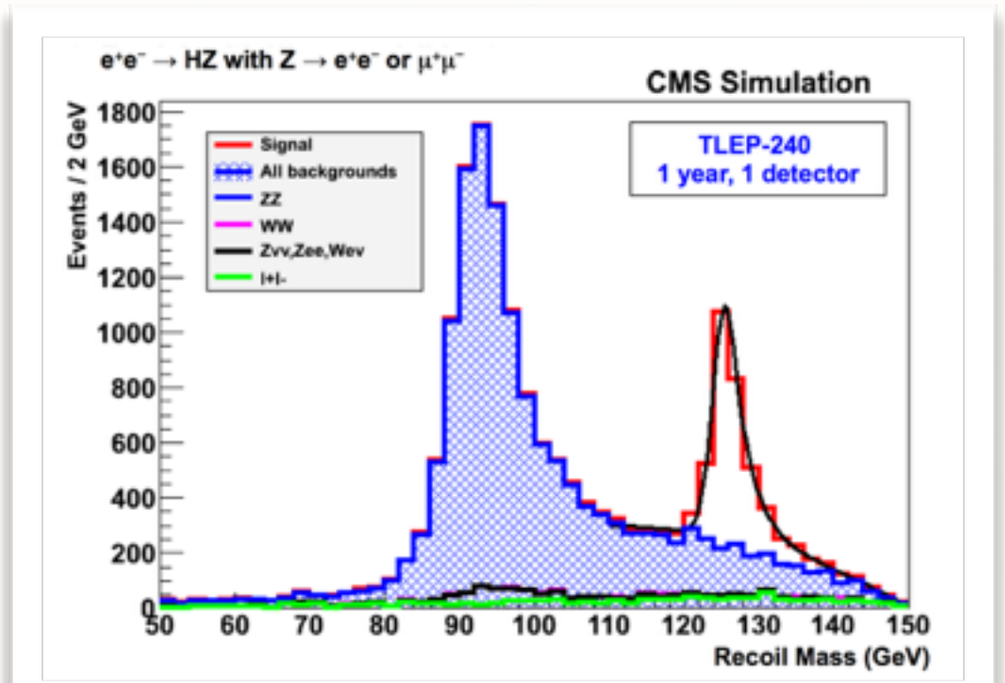
CERN proposal:
FCC-ee (e+e- collider)
FCC-hh (pp collider)

A powerful combination

- e+e- 'Higgs factories': large, well-controlled samples of Higgses enabling precision measurements
  - e.g.: measuring inclusive ZH cross section allows determination of total Higgs width

$$(p_{ee} - p_Z)^2 = s + m_Z^2 - 2\sqrt{s}E_Z$$

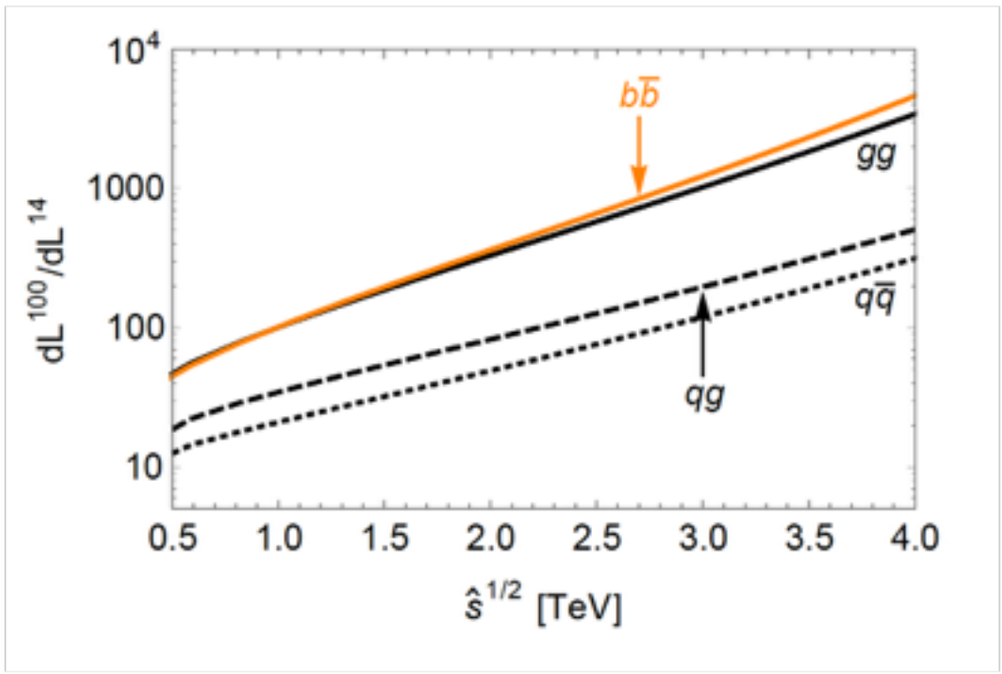
$$\delta\Gamma_h \approx 1\%$$



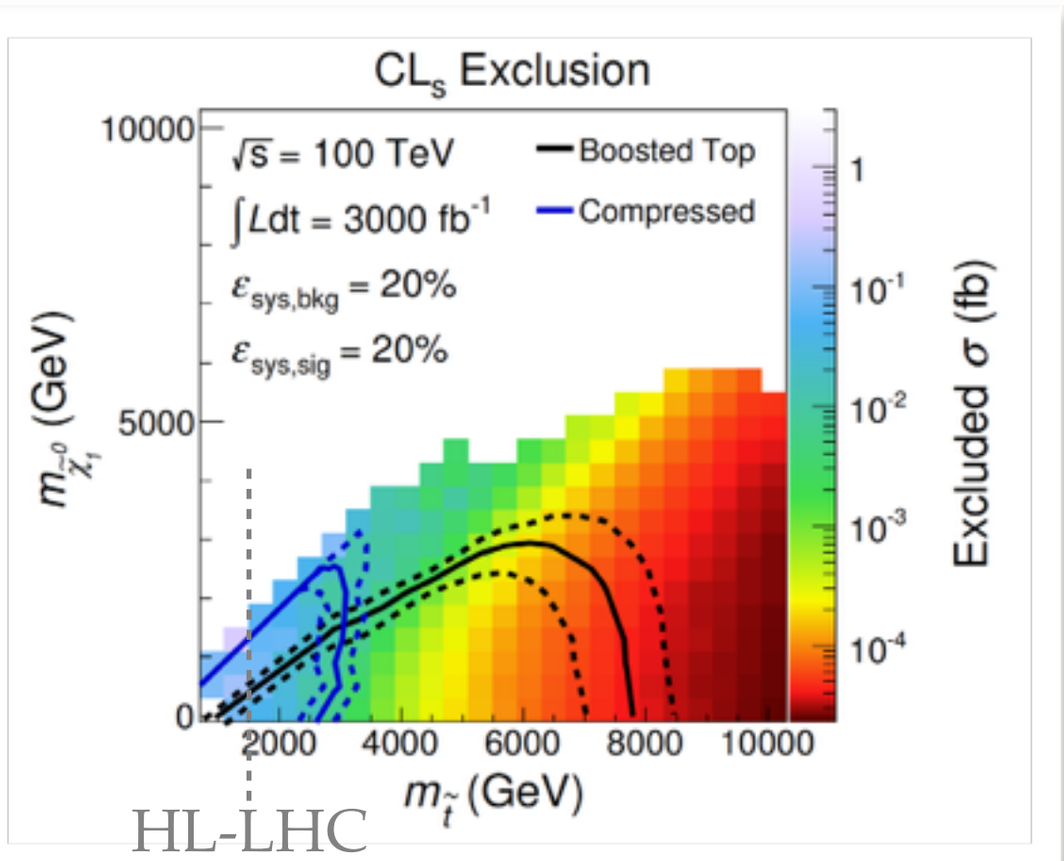
[TLEP physics case 1308.6176; Snowmass 1310.8361]

A powerful combination

- *pp* colliders: discovery machines, capable of studying high-*pT* processes in and beyond SM



ratio of parton luminosities



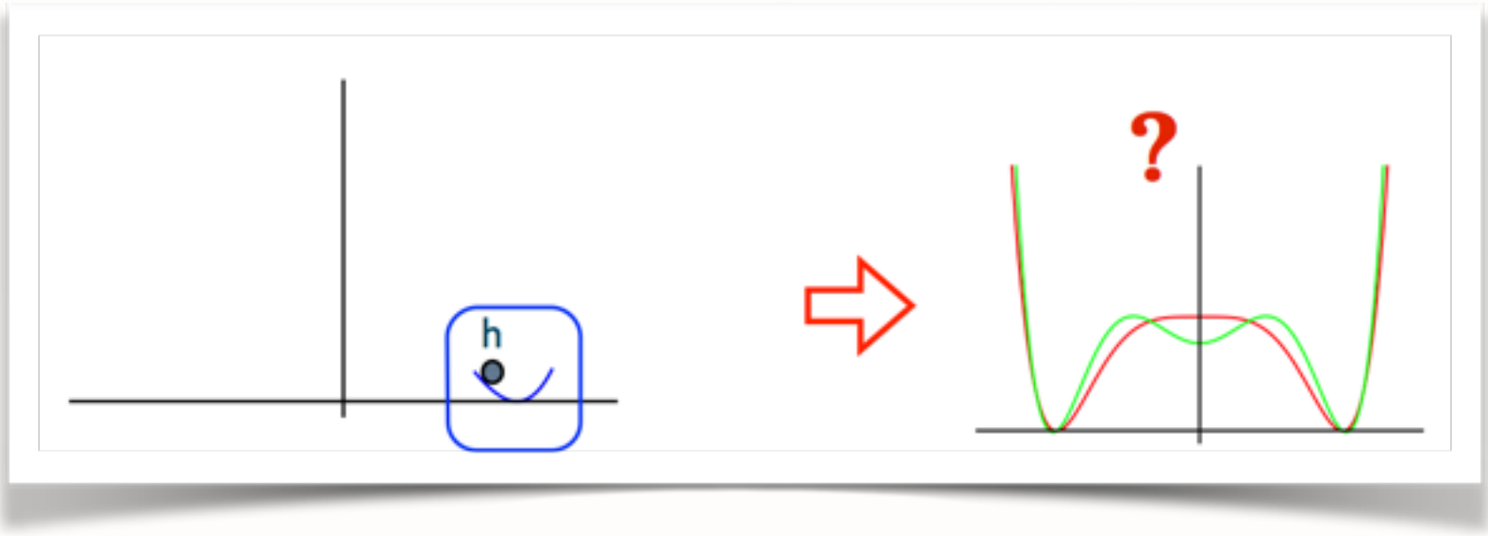
HL-LHC

reach for stops

[Arkani-Hamed, Han, Mangano, Wang; Cohen, D'Angelo, Hance, Lou, Wacker]

Studying the Higgs

- Understanding the electroweak phase transition: what is the Higgs potential?



- leading test: trilinear Higgs self-coupling

$$\frac{\lambda}{\lambda_{\rm SM}} \in \begin{cases} [0.891, 1.115] & \text{no background syst.} \\ [0.882, 1.126] & 25\%\ hh, 25\%\ hh + \text{jet} \\ [0.881, 1.128] & 25\%\ hh, 50\%\ hh + \text{jet} \end{cases}$$

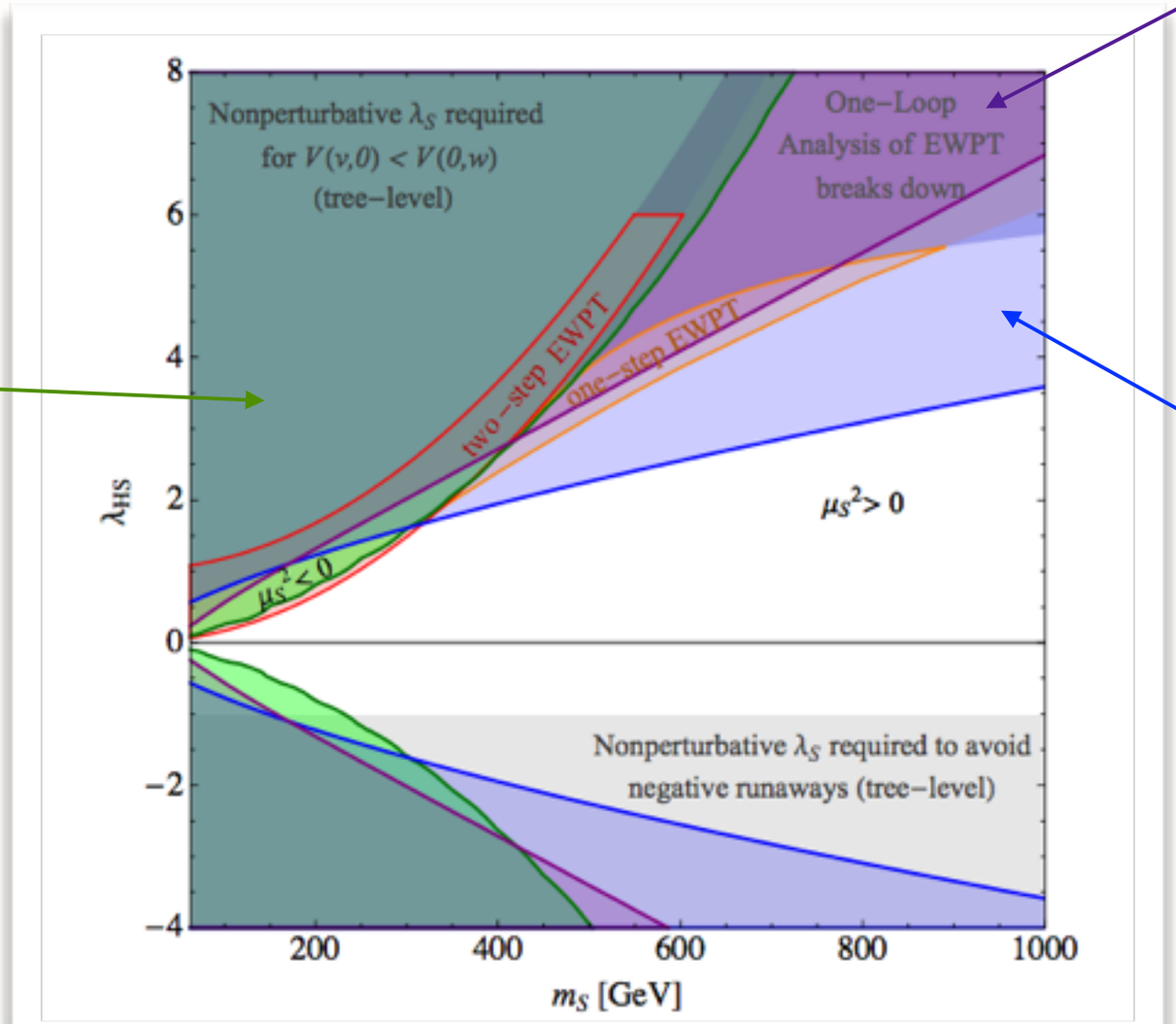
30 ab^{-1} at 100 TeV

[Arkani-Hamed, Han, Mangano, Wang; Barr, Dolan, Englert, de Lima, Spannowsky]

The Higgs and the phase transition

- Conclusive, complementary tests of electroweak baryogenesis mechanism

Testable at FCC-hh with direct S pair production



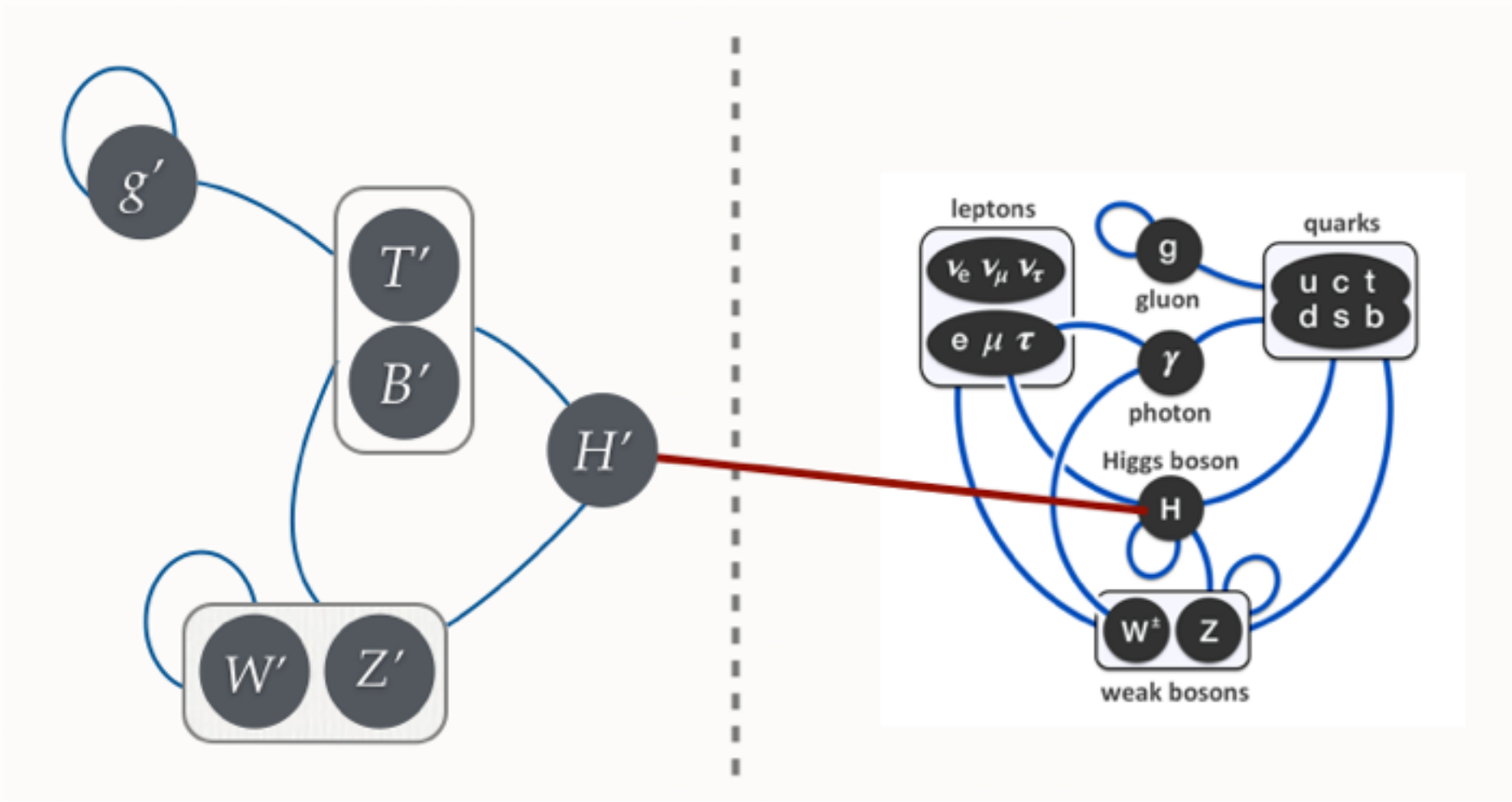
Testable at FCC-ee through h-Z coupling

Testable at FCC-hh through triple h coupling

[Curtin, Meade, Yu]

How unnatural is the Higgs?

- Neutral naturalness: top partners are charged under dark QCD, neutral under all SM gauge interactions

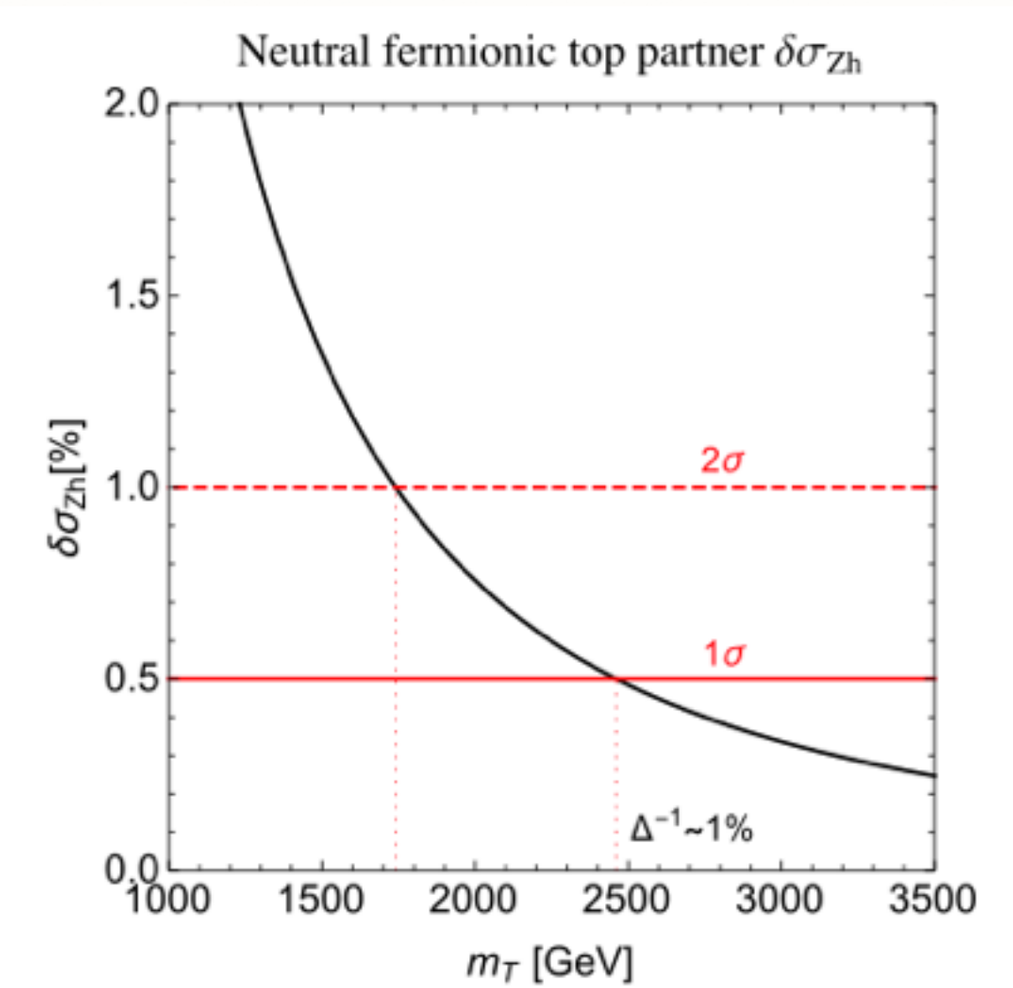


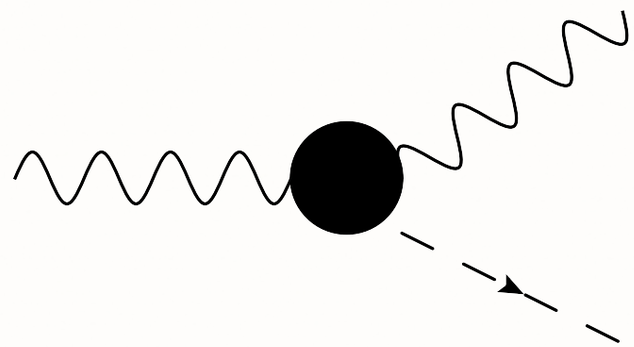
- Leading signal: Higgs-dark Higgs mixing

[Chacko, Goh, Harnik; Craig, Katz, Strassler, Sundrum]

How unnatural is the Higgs?

- Test Higgs-singlet mixing with precision h-Z coupling measurement





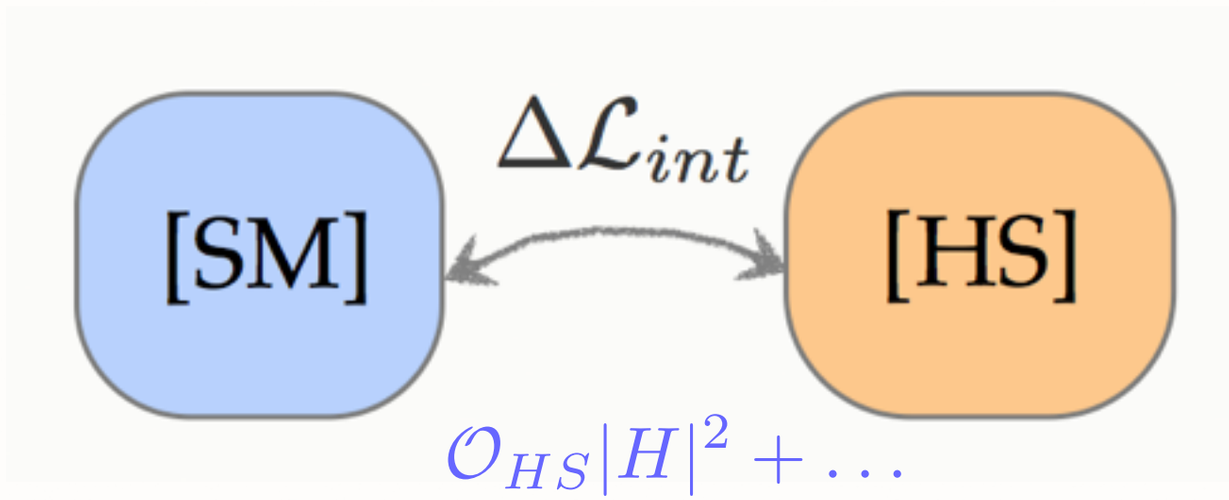
[Craig]

How unnatural is the Higgs?

- Standard SUSY already looks unnatural: ~% level tuning
- if you accept ~10^{-6} tuning, mini-split SUSY: light (TeV-scale) gauginos, heavy (loop factor heavier) sfermions
  - making sfermions heavy easily explains lack of flavor, EDM signals while meshing nicely with $m_h = 125$ GeV
  - lighter gauginos are a natural outcome of SUSY-breaking mechanisms, and maintain unification, dark matter candidate
- General prediction: gluinos accessible at 100 TeV

Higgs as a portal

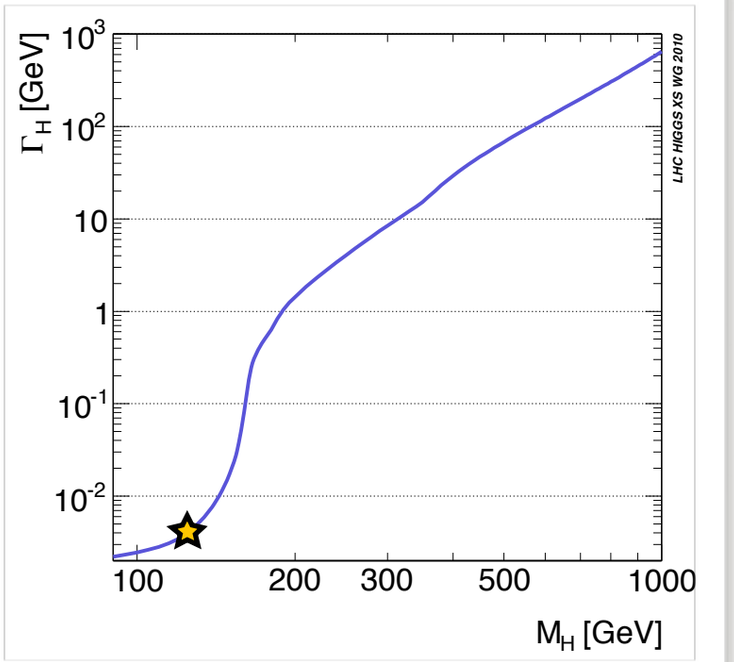
- Higgs is one of the most sensitive windows onto new physics if it's uncharged under SM gauge interactions:

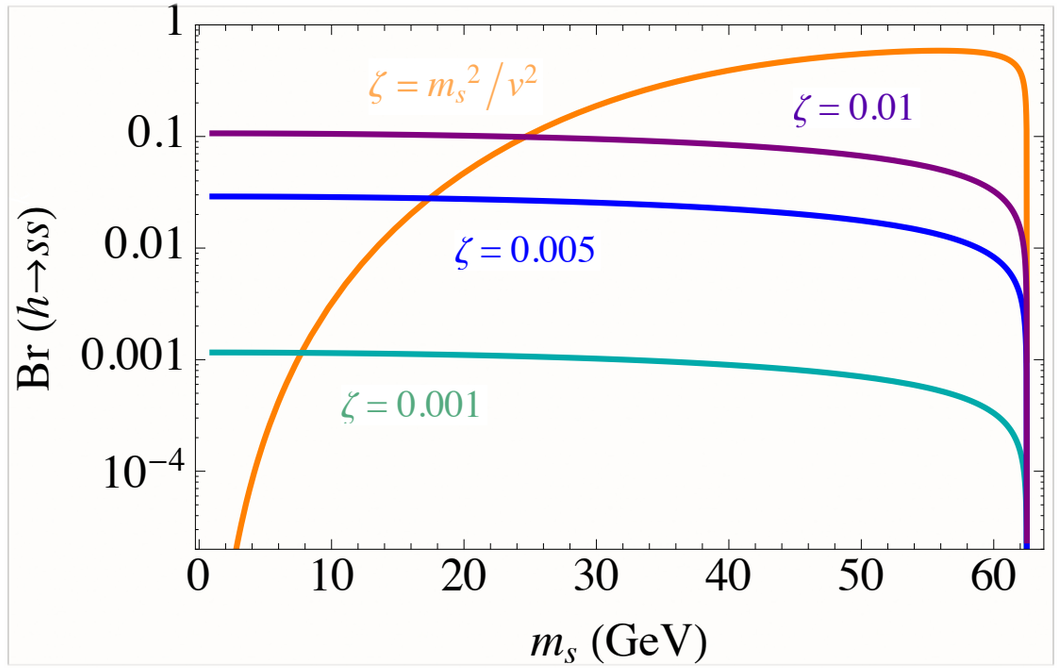


- if NP heavy: precision Higgs couplings, off-shell Higgs portal production
- if NP light…

Higgs as a portal

- Exotic decays of SM Higgs: powerful probe of hidden sectors
  - thanks in part to coincidentally small SM Higgs width:





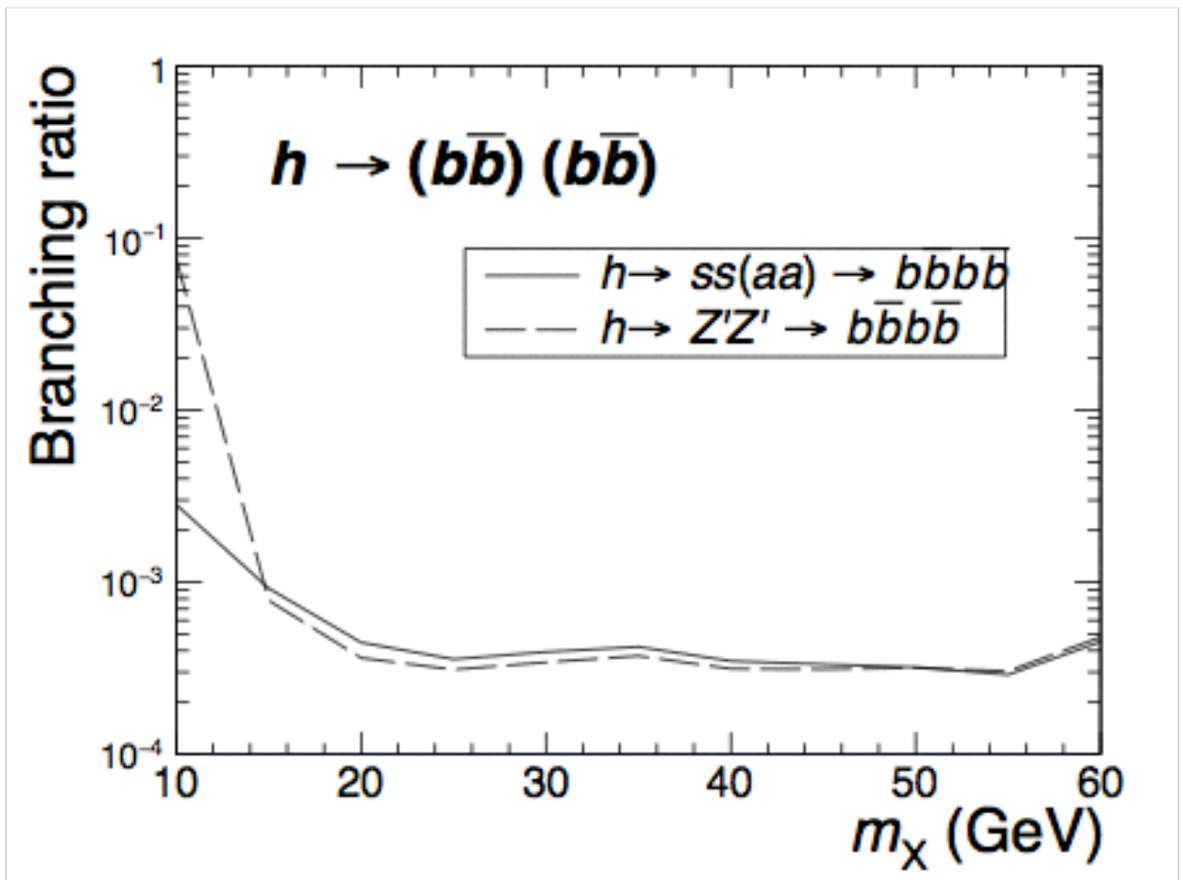
- Critical advantage of high-energy colliders: large samples of on-shell Higgs bosons

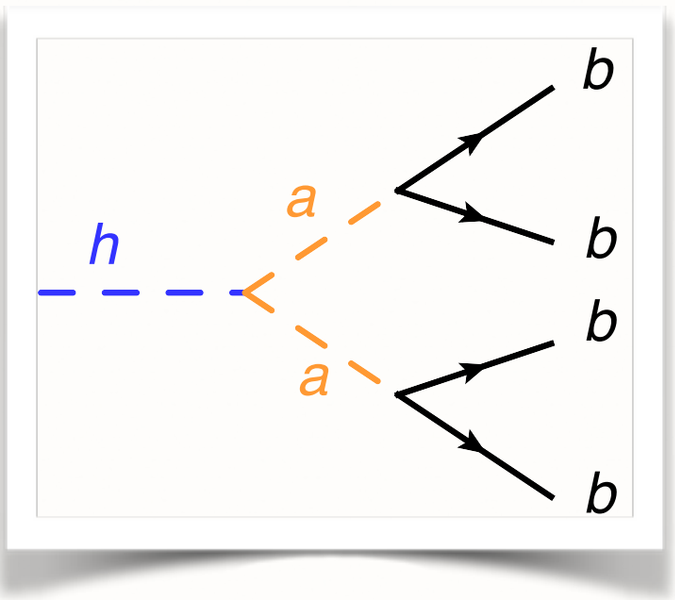
Exotic Higgs decays

- lepton machines
  - FCC-ee: 240 GeV, 10 ab^{-1}: 10^6 Higgses
  - smaller data sets limit statistical reach
  - clean: benefits for (e.g.) all-hadronic modes
  - inclusive measurements are possible
- hadron machines
  - FCC-hh: 100 TeV, 3 fb^{-1}: 10^8 Higgses
  - enormous Higgs samples: fantastic statistical reach for clean decay modes
  - high backgrounds; trigger concerns?

Exotic Higgs decays

- All-hadronic modes like the extremely well motivated $h \to ss(aa) \to 4b$ have excellent prospects at lepton colliders

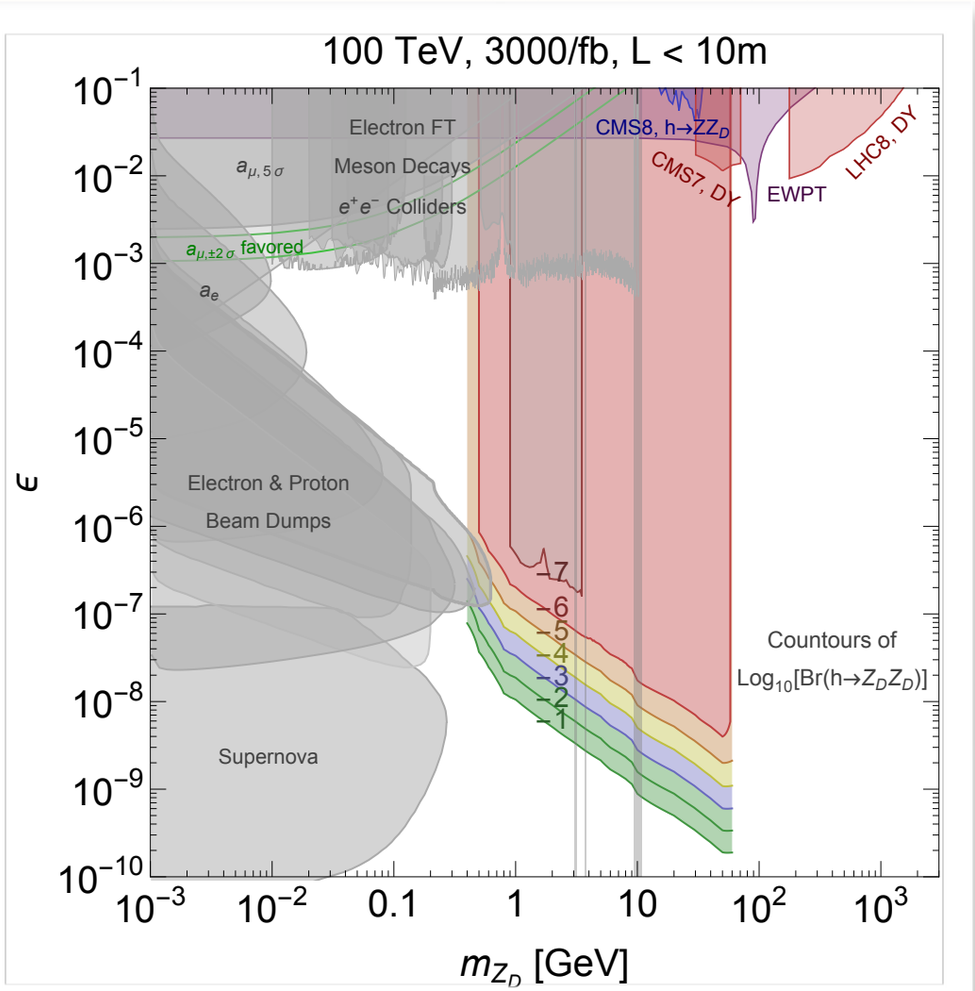


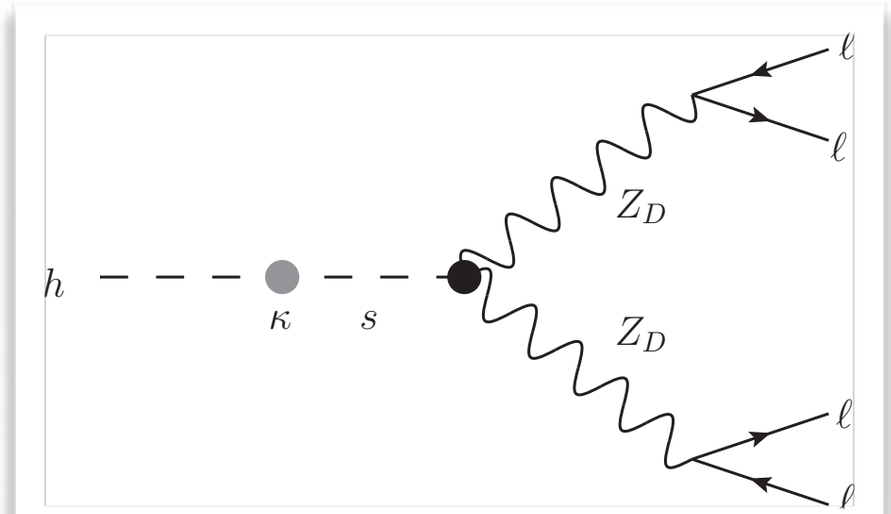


[Liu, Wang, Zhang]

Exotic Higgs decays

- Clean modes, on the other hand, can be probed at hadron colliders to exquisite precision





[Curtin, Essig, Gori, JS]

Conclusions

- Future energy frontier colliders offer a great deal of information out of reach of our current machines
- We will for sure learn more about the SM Higgs:
  - self-couplings
  - *ttH* yukawa
- Higgs offers many motivated reasons to expect new physics…
  - learn a lot either way!