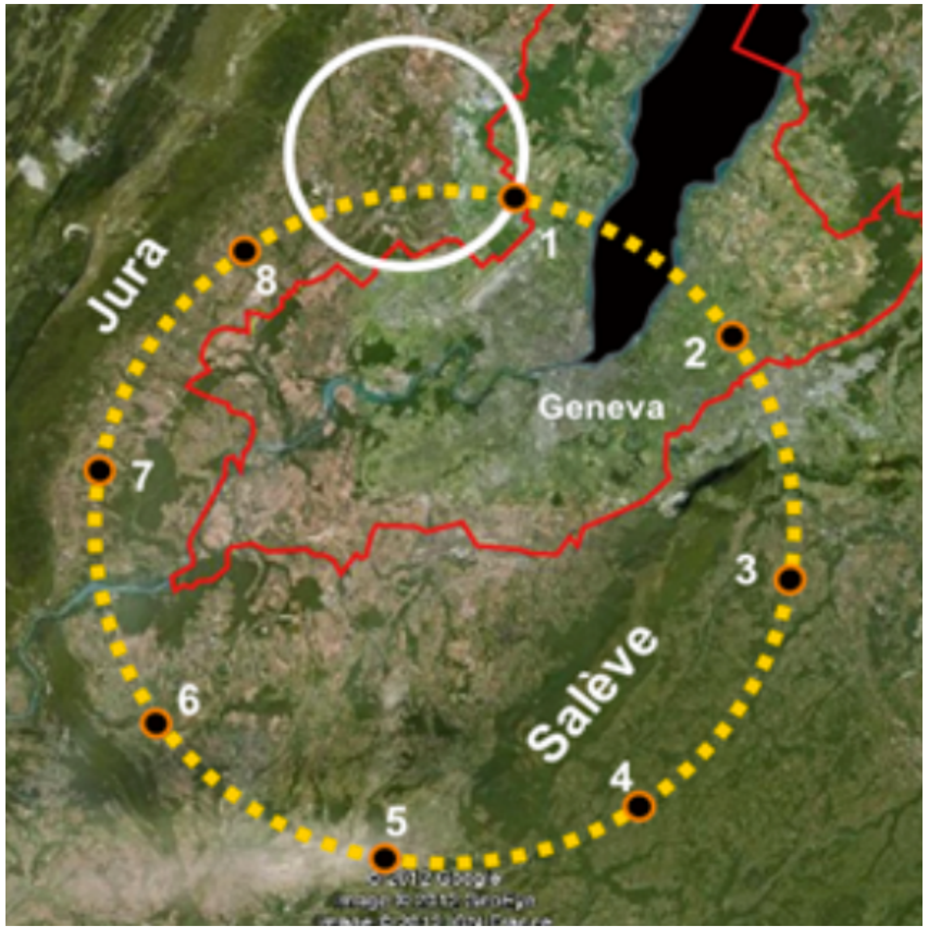
Physics at FCC

Matt Reece
Harvard University
@ FCC Week 2021, June 28



Introduction

Motivations for Beyond Standard Model

Empirical

- dark matter
- origin of primordial density perturbations
- matter/antimatter asymmetry

Theoretical puzzles

- electroweak hierarchy
- strong CP problem
- flavor: pattern of masses and mixings

Theoretical opportunities

- low-dimension “portal” operators
  (Higgs $|h|^2$, hypercharge $B_{\mu\nu}$, neutrino $h \cdot l$)

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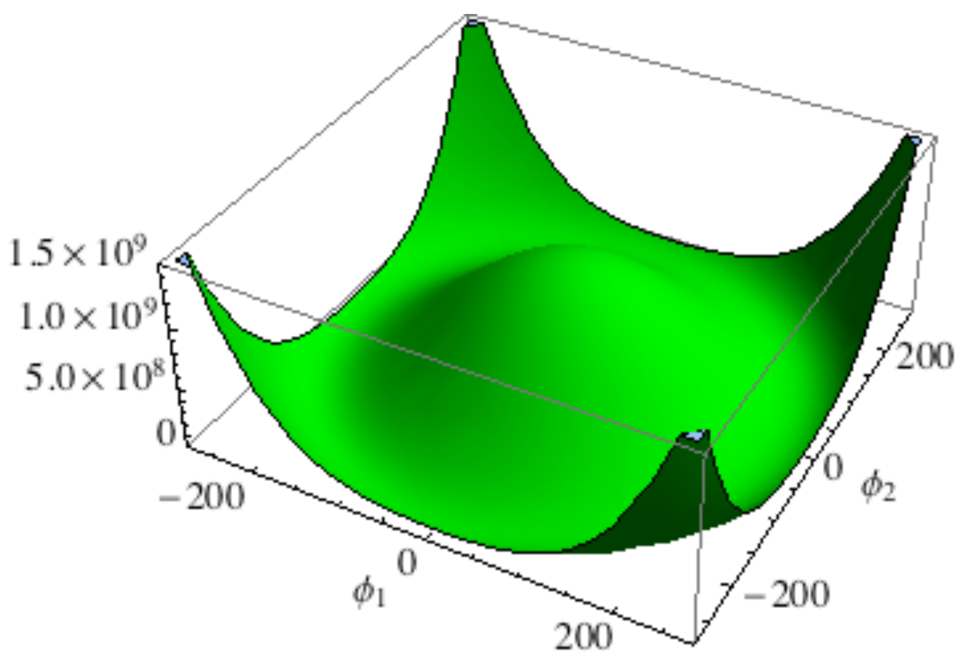
Higgs Potential

$$V(h) = -\mu^2 |h^2| + \lambda |h|^4$$



The Standard Model *assumes* this potential and scale

$$\mu \sim 100\,\mathrm{GeV}$$

but doesn't *explain* it.

(Also haven't *measured* it.)

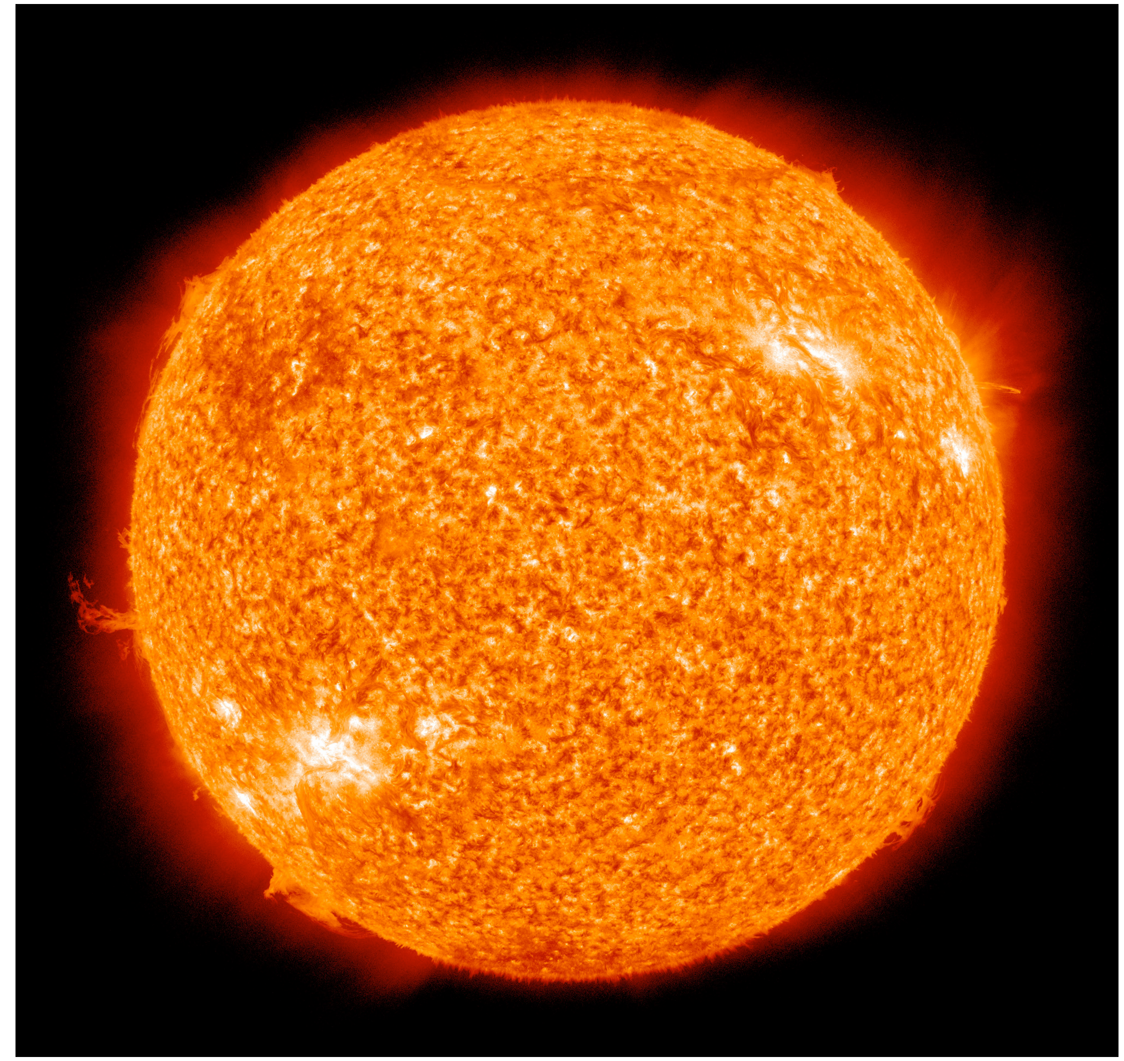
Like Landau-Ginzburg or the London equations for superconductivity; still waiting for a ***microscopic, dynamical description***, a (very loose) analogue of BCS.

Hierarchies

$M_{\rm Pl} \sim 2 \times 10^{18}\,\mathrm{GeV}$

$v_{\rm EW} \approx 246\,\mathrm{GeV}$

$\Lambda_{\rm QCD} \sim 300\,\mathrm{MeV}$



$$M_\odot \approx 2 \times 10^{30}\ \mathrm{kg}$$

$$\approx 1.1 \times 10^{57}\ \mathrm{GeV}$$

$$\approx 0.6 \left(\frac{M_{\rm Pl,unred}}{m_{\rm proton}} \right)^3 m_{\rm proton}$$

[Details: V. Weisskopf, *Science* **187**(4177):605–612 (1975); Burrows and Ostriker, *PNAS* 111 (7):2409-2416 (2014).]

Hierarchies

$M_{\rm Pl} \sim 2 \times 10^{18}\,\mathrm{GeV}$

Flat measure on $\mathscr{L}$ parameters:

$$P(\text{EW hierarchy}|\ \text{SM}) \sim \left(\frac{v_{\rm EW}}{M_{\rm Pl}}\right)^2$$

$$\sim 10^{-32}$$

$v_{\rm EW} \approx 246\,\mathrm{GeV}$

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Hierarchies

$M_{\text{Pl}} \sim 2 \times 10^{18}\,\text{GeV}$

Flat measure on $\mathscr{L}$ parameters:

$$P(\text{QCD hierarchy}|\text{ SM}) \sim \frac{1}{\log(M_{\text{Pl}}/\Lambda_{\text{QCD}})}$$

$$\sim 10^{-2}$$

$v_{\text{EW}} \approx 246\,\text{GeV}$

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Hierarchies

$M_{\text{Pl}} \sim 2 \times 10^{18}\,\text{GeV}$

$$P(\text{QCD hierarchy}|\ \text{SM}) \sim \frac{1}{\log(M_{\text{Pl}}/\Lambda_{\text{QCD}})}$$

$$\sim 10^{-2}$$

The magic of running couplings:

$$\Lambda_{\text{QCD}} \sim \Lambda_{\text{UV}} \mathrm{e}^{-8\pi^2/(bg^2)}$$

$v_{\text{EW}} \approx 246\,\text{GeV}$

$\Lambda_{\text{QCD}} \sim 300\,\text{MeV}$

SUSY as an Example (More General Idea)

$M_{\rm Pl} \sim 2 \times 10^{18}\,{\rm GeV}$

Dynamical SUSY breaking

$$P(\text{EW hierarchy}|\ \text{SUSY}) \sim \frac{1}{\log(M_{\rm Pl}/M_{\rm SUSY})}$$

$$\sim 10^{-2}$$

$M_{\rm SUSY} \sim v_{\rm EW} \approx 246\,{\rm GeV}$

$\Lambda_{\rm QCD} \sim 300\,{\rm MeV}$

(Witten, 1981)

Naturalness as Bayesian Guesswork

$$P(\text{EW hierarchy}|\text{ SM}) \sim \left(\frac{v_{\rm EW}}{M_{\rm Pl}}\right)^2 \sim 10^{-32}$$

$$P(\text{EW hierarchy}|\text{ SUSY}) \sim \frac{1}{\log(M_{\rm Pl}/M_{\rm SUSY})} \sim 10^{-2}$$

If you have no strong preconception about which theory is right, then the ***data*** that we live in a universe with a **vast hierarchy** suggests that we take ***weak-scale*** solutions to the hierarchy problem (not only SUSY!) very seriously.

FCC-ee Physics Case

Circular e^+e^-, or Linear e^+e^-?

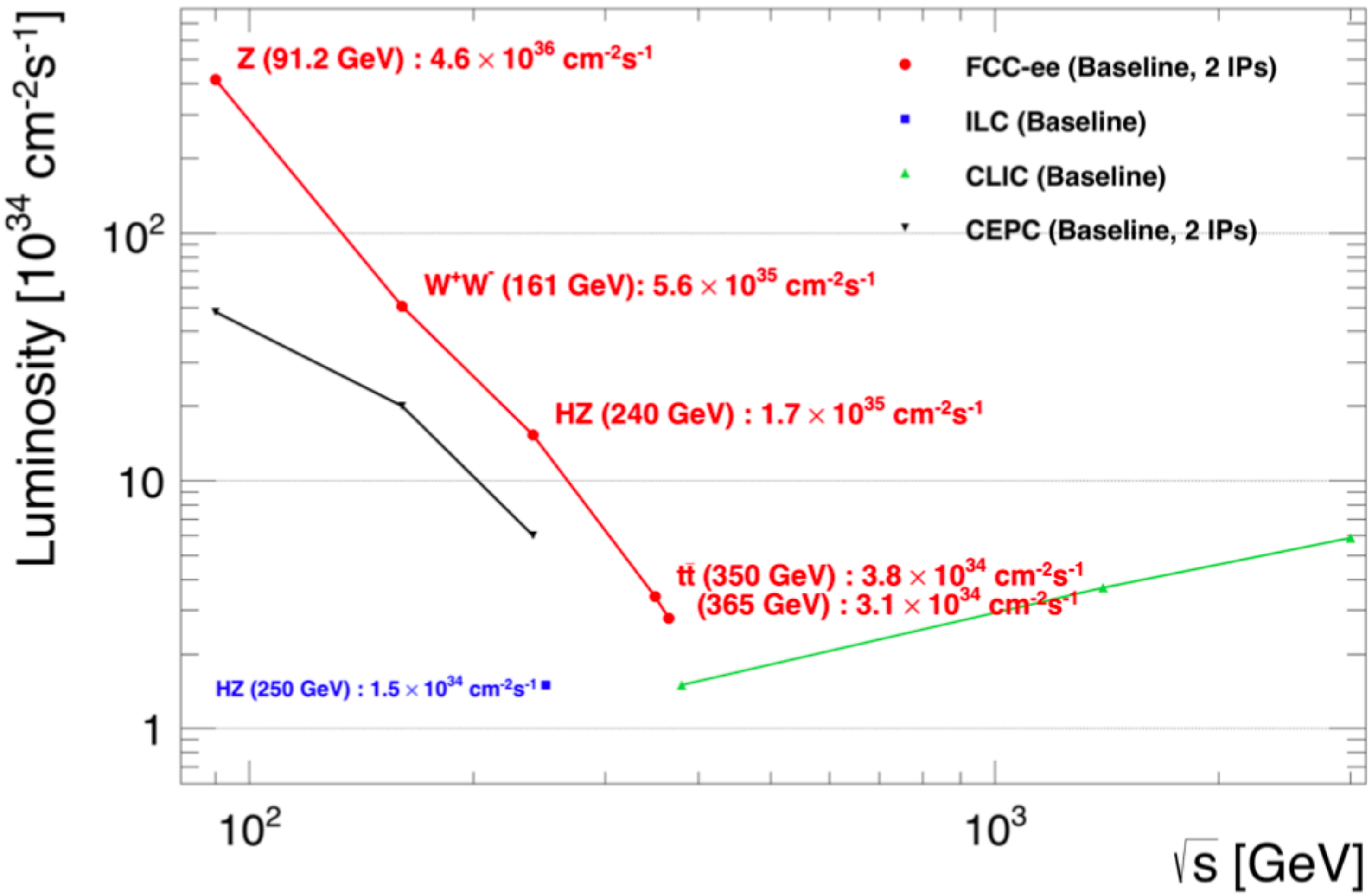
Advantages and disadvantages to each.

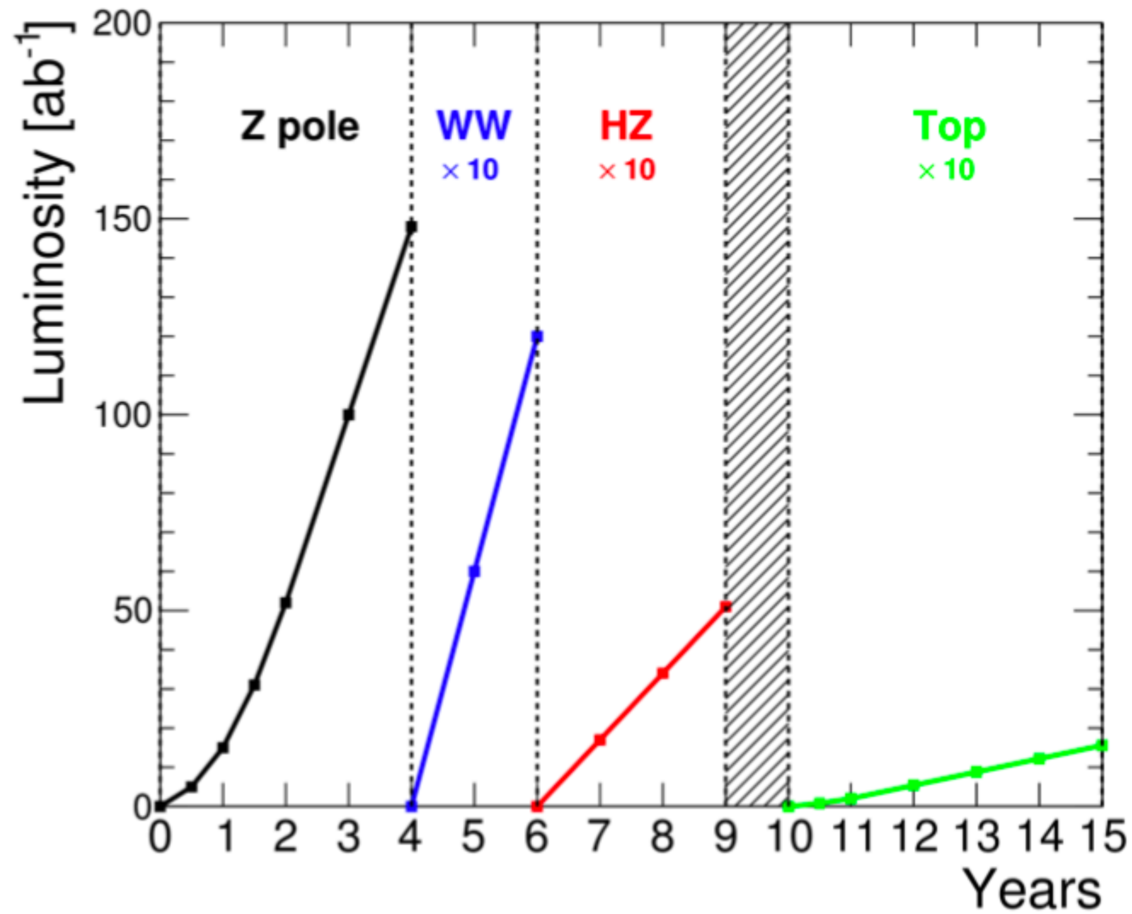
- Linear: go to higher energy. **Higher direct discovery potential *if* new electroweak states exist.**
-
- Linear: easy to reach top threshold, **improve top mass as input to electroweak fits**. But FCC-ee also gets there.

- Circular: **resonant spin depolarization** gives precise energy calibration and **Z mass & width measurement**

- Circular: future as **high energy hadron machine**. *Important to build a large enough tunnel that foreseeable magnet technology can reach desired energies!*

FCC-ee Studies the Weak Scale: Not *Just* a Higgs Factory



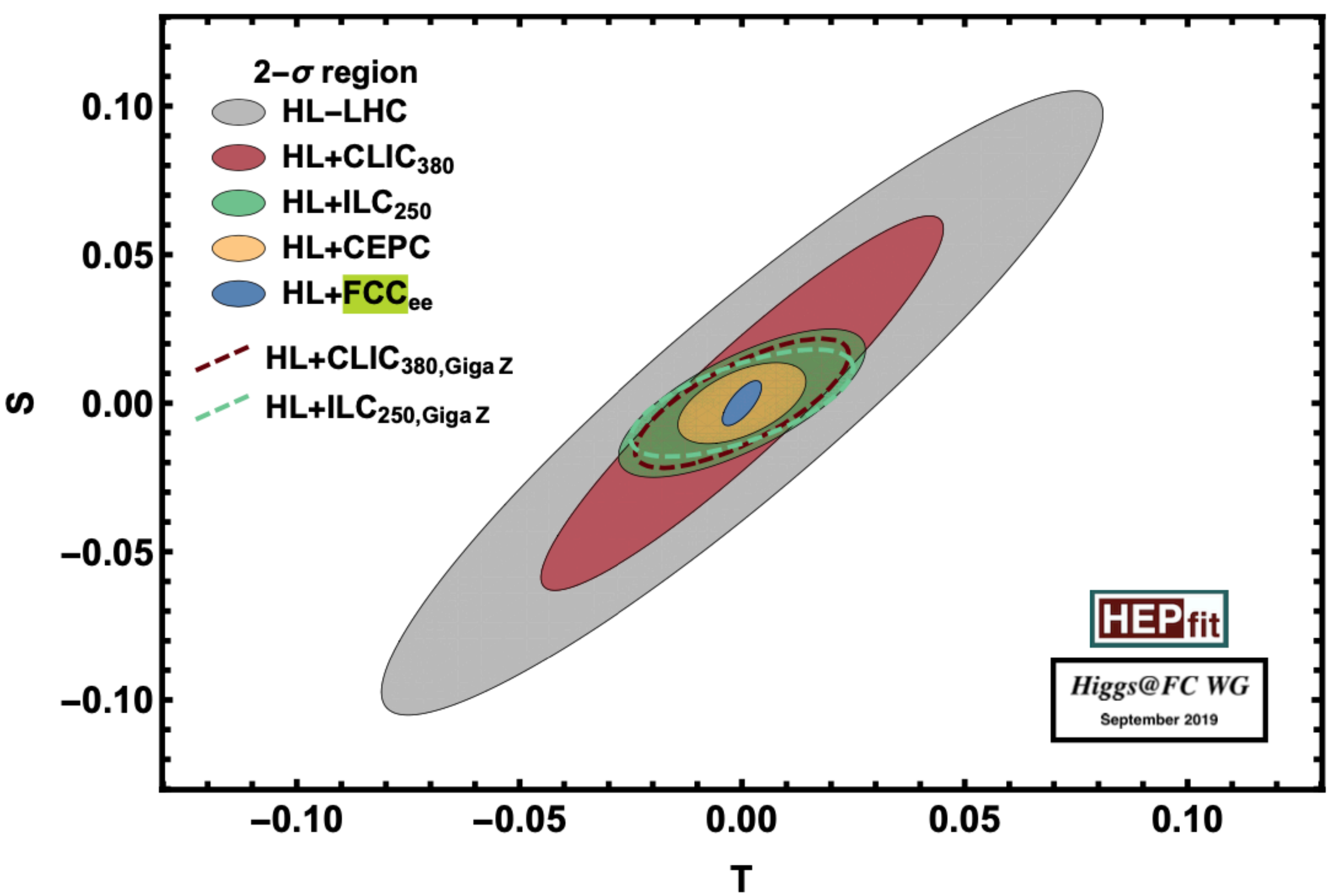


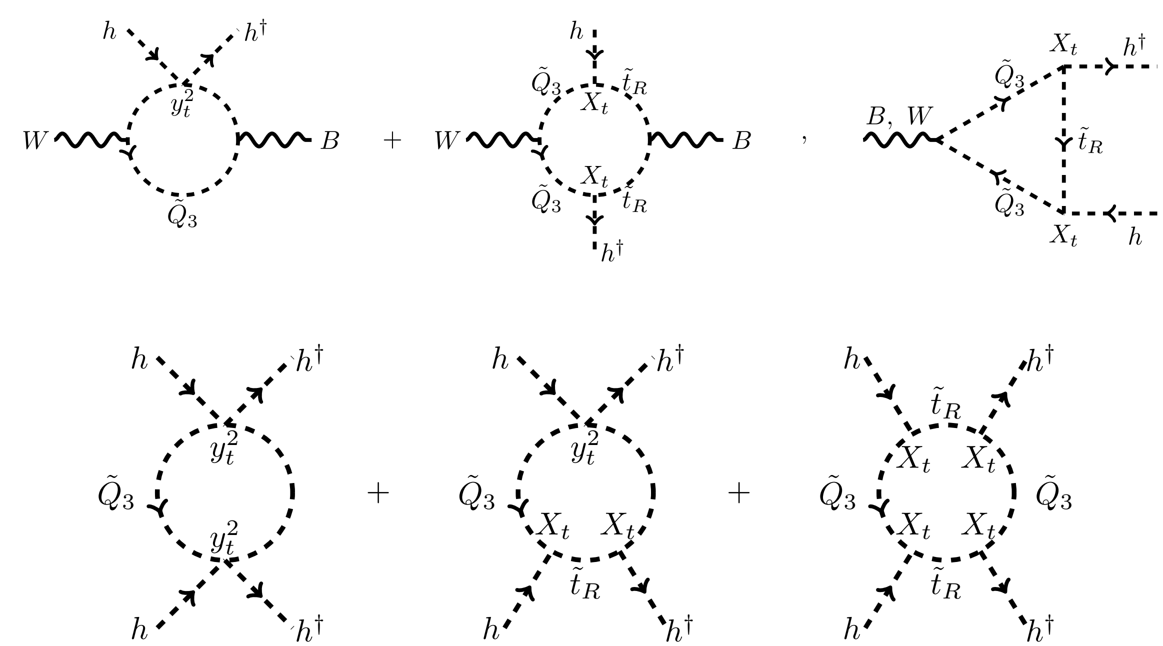
$$\sim 5 \times 10^{12}\ Z \text{ bosons}, \ \sim 10^6 \text{ Higgs bosons},$$
$$\sim 10^7\ W^+W^- \text{ pairs}, \ \sim 10^6\ t\bar{t} \text{ pairs}$$

All in a clean environment enabling unprecedented precision

Precision Electroweak Physics at FCC-ee

$$\left.\begin{array}{c} \sin^2\theta^l_{\text{eff}}\ (A_{\text{FB}}) \\ m_Z, \Gamma_Z, m_t, \alpha(m_Z) \\ m_W \end{array}\right\} \begin{array}{ll} S\text{ parameter:} & S\left(\dfrac{\alpha}{4 s_W c_W v^2}\right) h^\dagger \sigma^i h W^i_{\mu\nu} B^{\mu\nu} \\ T\text{ parameter:} & -T\left(\dfrac{2\alpha}{v^2}\right) \left|h^\dagger D_\mu h\right|^2 \end{array}$$





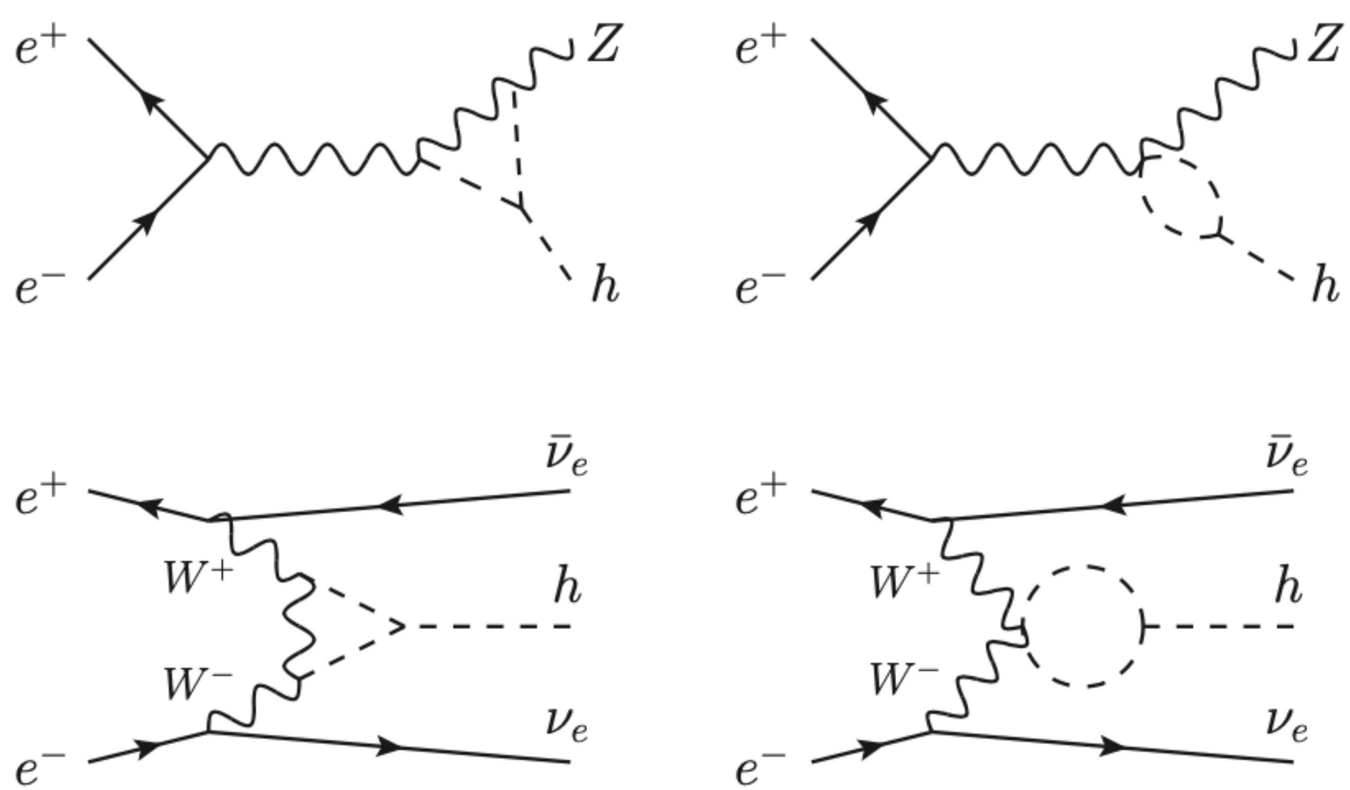
e.g.: stops in loops to ~1 TeV
(modulo caveats about blind spots)

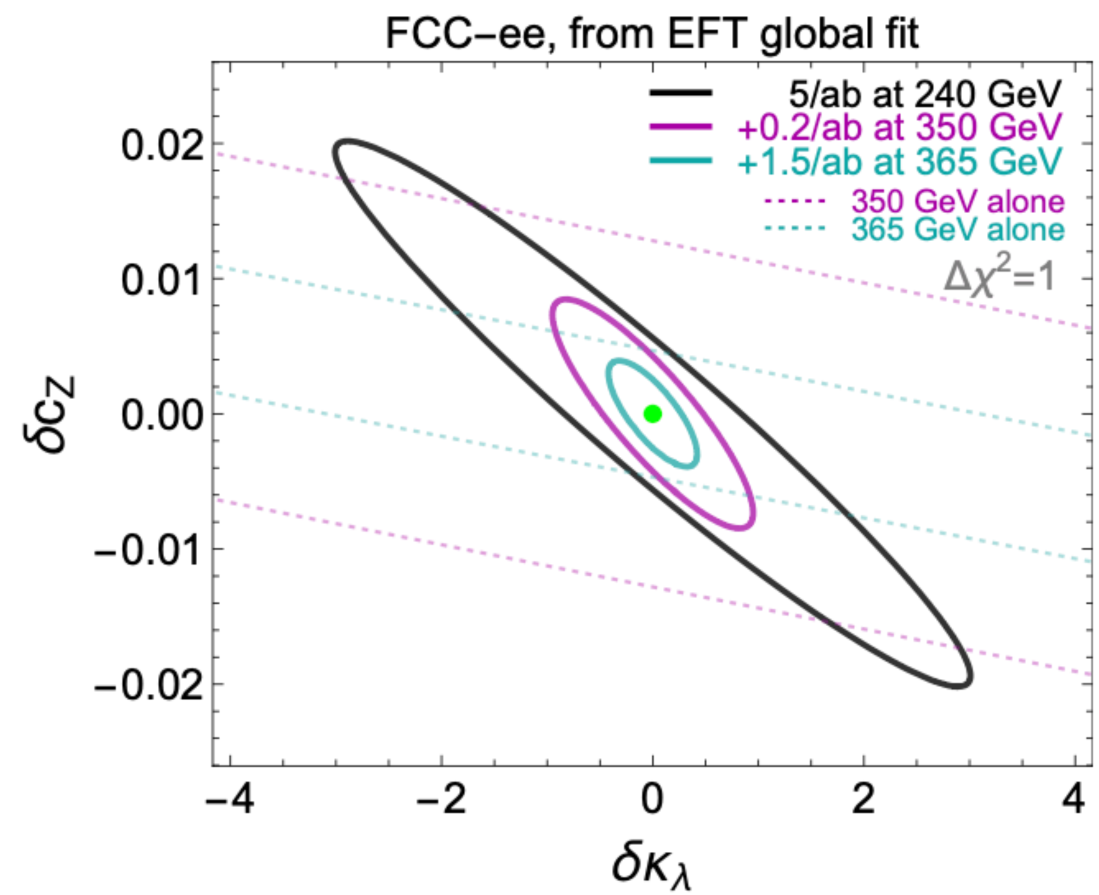
Precision Higgs Physics at FCC-ee

Collider	FCC-ee$_{240+365}$		
Lumi (ab^{-1})	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	1.3	**0.61**	0.55
$\delta g_{Hcc}/g_{Hcc}$ (%)	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	1.6	**1.01**	0.83
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.4	**0.74**	0.64
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	10.1	**9.0**	3.9
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	4.8	**3.9**	1.1
$\delta g_{Htt}/g_{Htt}$ (%)	–	–	2.4
BR$_{EXO}$ (%)	< 1.2	$<$ **1.0**	$<$ **1.0**

Higgs Self-Coupling at FCC-ee

FCC-ee can probe the Higgs trilinear coupling through its loop effects (McCullough, arXiv:1312.3322).





Requires fit with multiple center-of-mass energies.
(Di Vita, Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon arXiv:1711.03978)

Flavor Physics at FCC-ee

FCC-ee will produce $\sim 5 \times 10^{12}\, Z$ bosons (vs 10^7 at LEP).

$\sim 10^{12}\ Z \to b\bar{b}$ decays.
(Substantially more *B* mesons than Belle II in the next decade)

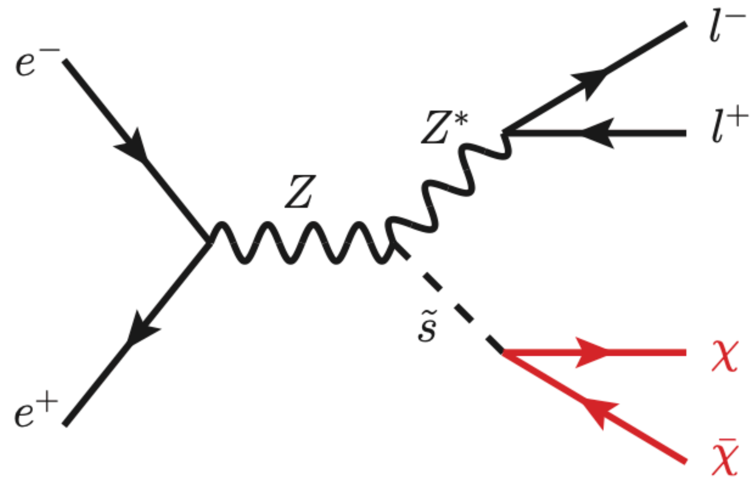
$\sim 10^{11}\ Z \to \tau^+\tau^-$ decays.

FCC-ee will serve as a high-intensity flavor factory.

Example: $b \to s\tau^+\tau^-$ transitions; e.g., kinematic reconstruction of (poorly constrained) $\overline{B}^0 \to K^{*0}\tau^+\tau^-$ process possible (Kamenik, Monteil, Semkiv, Vale Silva arXiv:1705.11106)

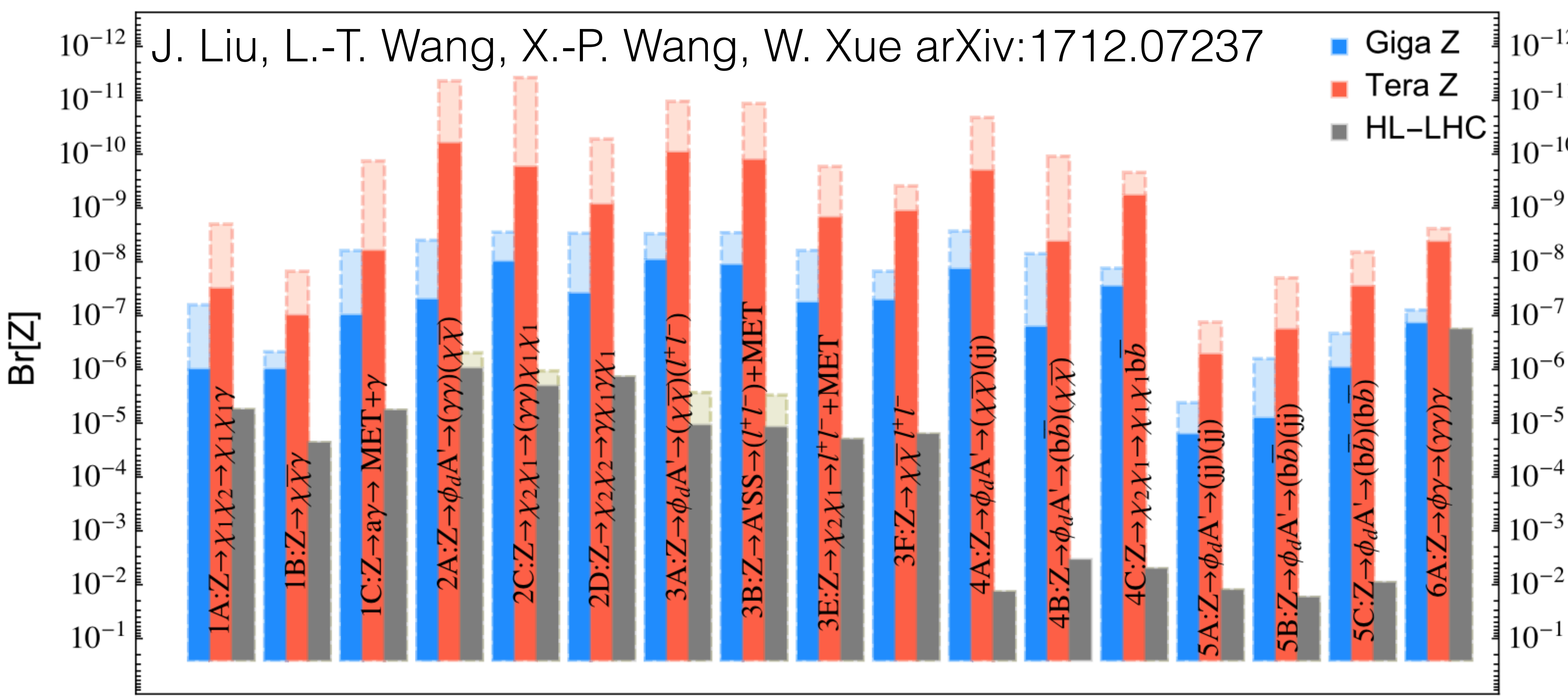
also see: Grossman, Ligeti arXiv:2106.12168

Hidden Sector Physics at FCC-ee: Exotic Z Decays



Full power of Tera-Z luminosity.

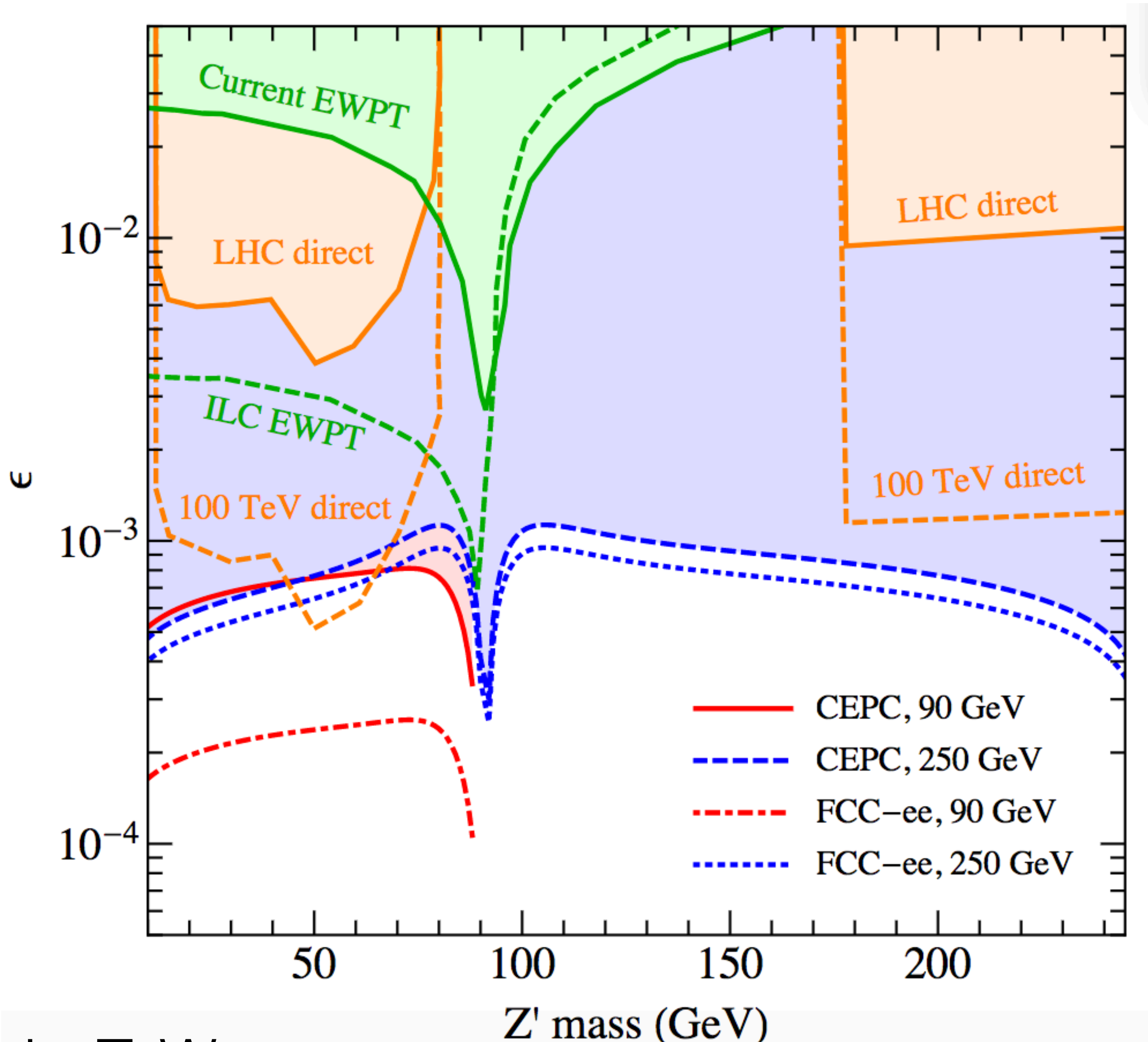
Many scenarios, e.g., dark matter, dark photons or Higgses, axion-like particles.



Hidden Sector Physics at FCC-ee: Heavy Dark Photon in Radiative Return

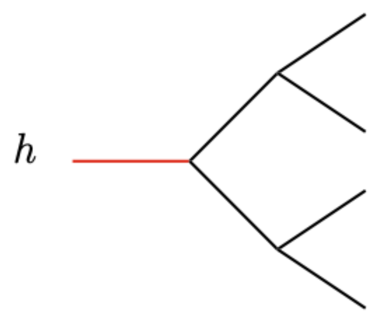
Make a dark photon in association with an ordinary photon, and do a resonance search:

$$e^+e^- \to \gamma Z_D \to \gamma\mu^+\mu^-$$



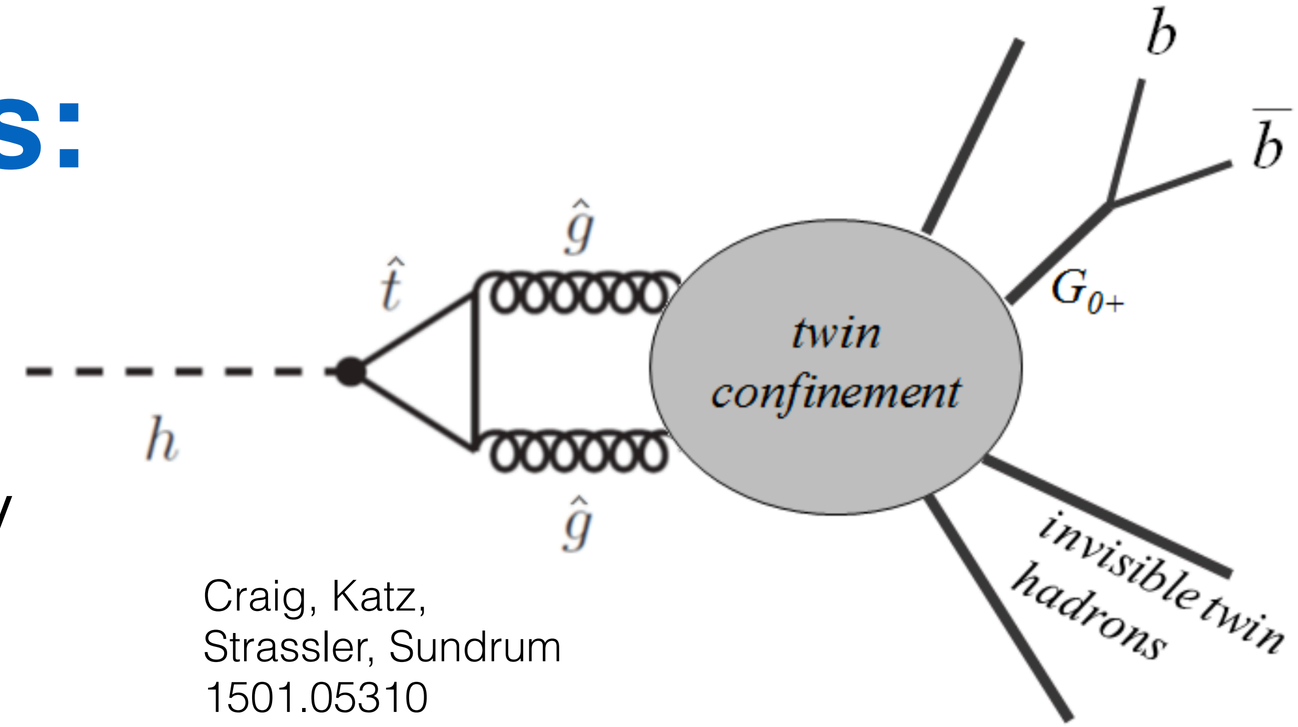
M. Karliner, M. Low, J.L. Rosner, L.-T. Wang
1503.07209

Hidden Sector Physics: Exotic Higgs Decays

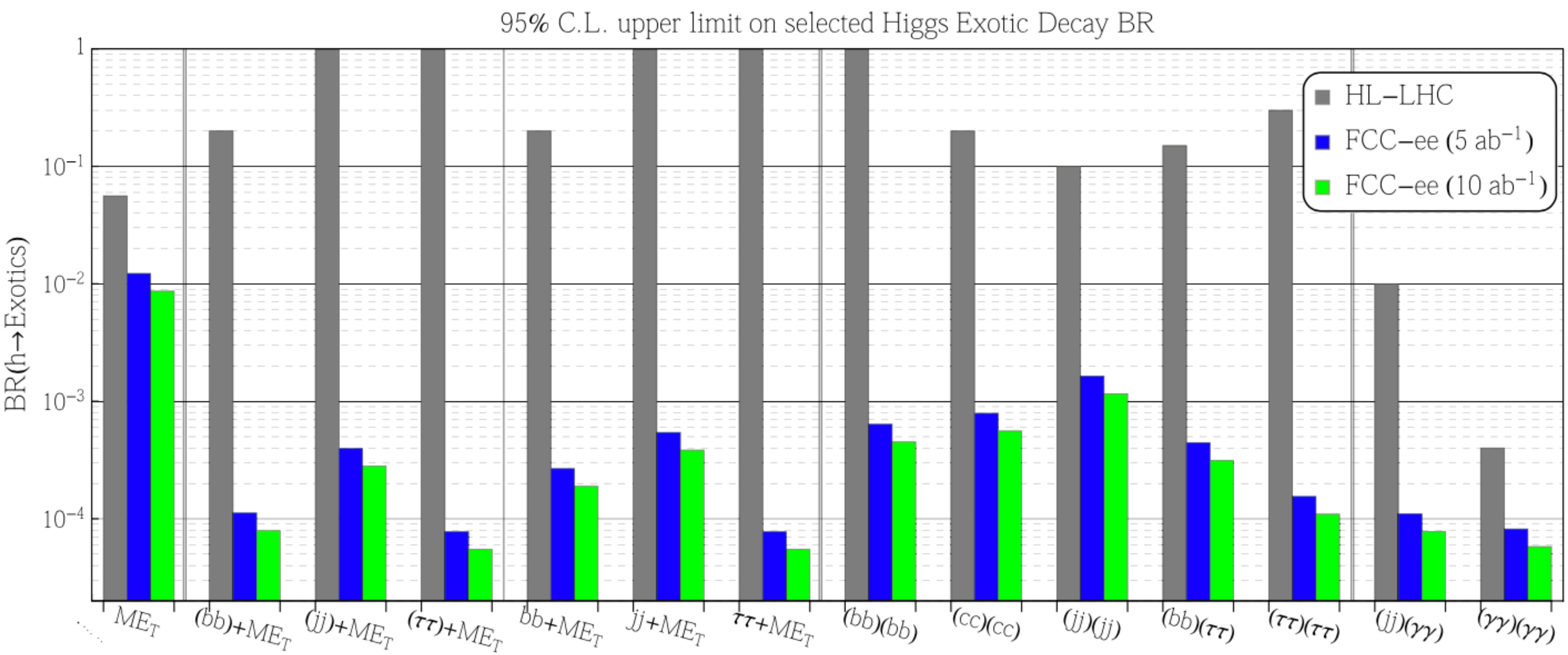


$h \to 2 \to 4$

Portal opportunity
or naturalness



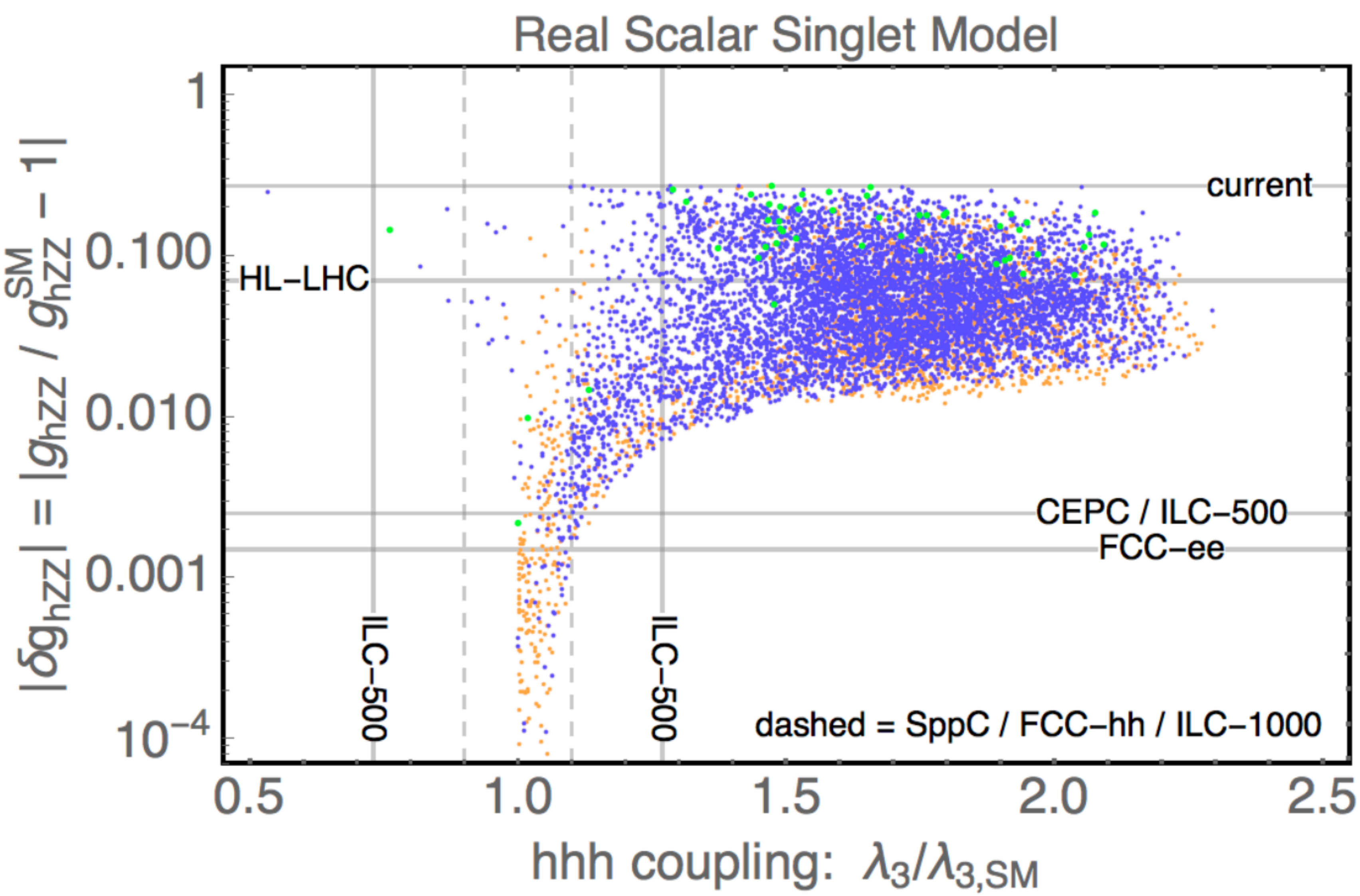
Craig, Katz, Strassler, Sundrum 1501.05310

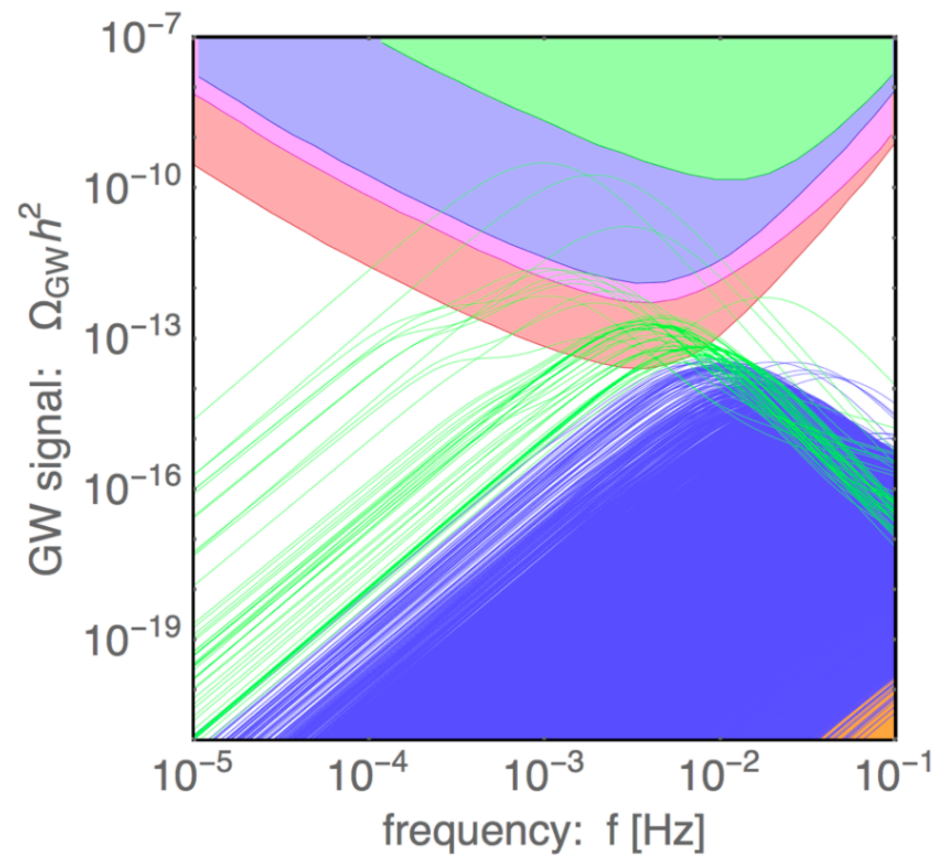


Z. Liu, L.-T. Wang, H. Zhang arXiv:1612.09284

Electroweak Phase Transition

Modify the phase transition with Higgs coupling to a **singlet scalar**.
Dominated by ***mixing***.
Phase transition can become **first-order**, even **strongly so**, and have **gravitational wave signals!**



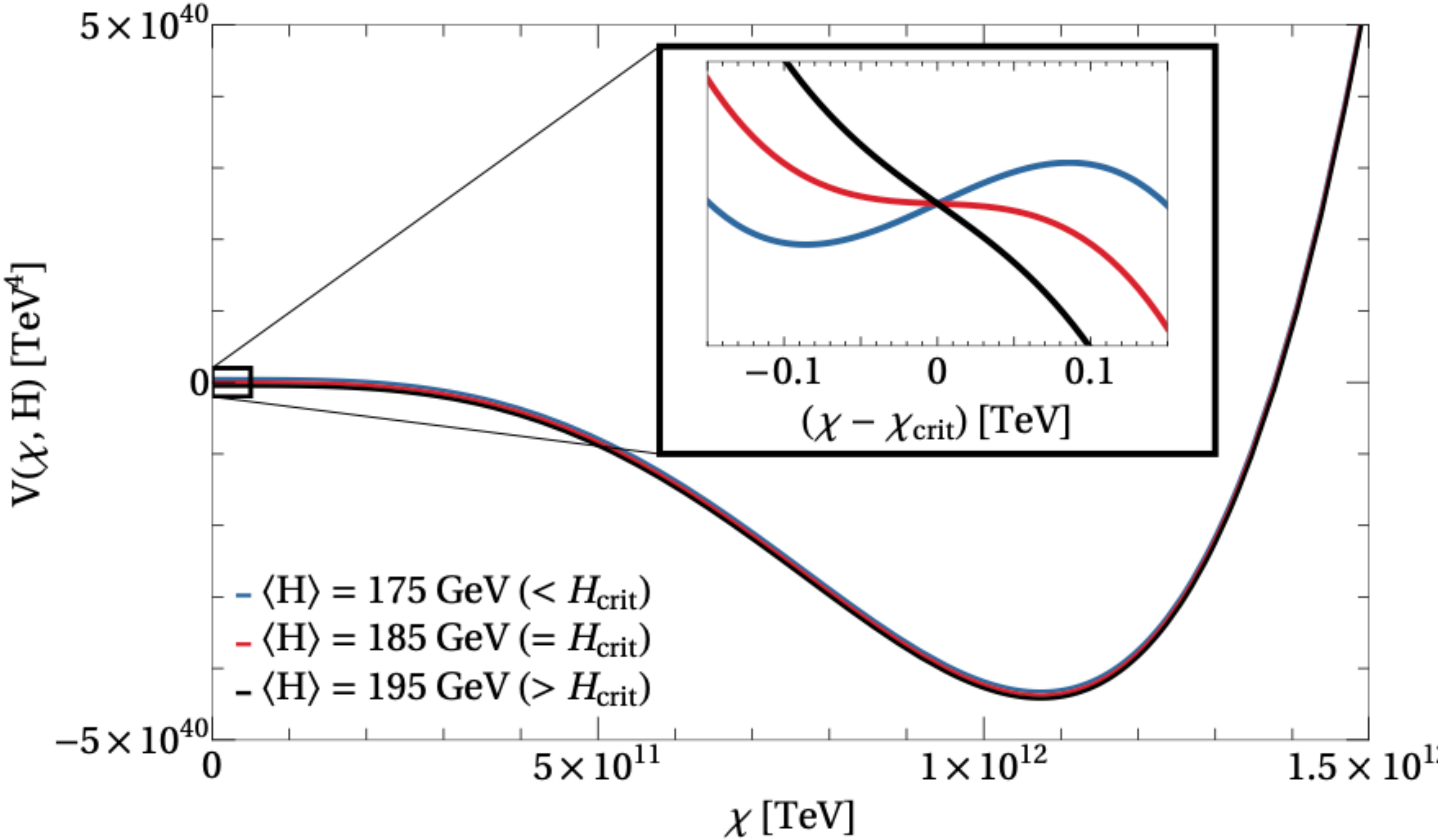


Observability at LISA!

Huang, Long, Wang 1608.06619

“Crunching Dilaton, Hidden Naturalness”

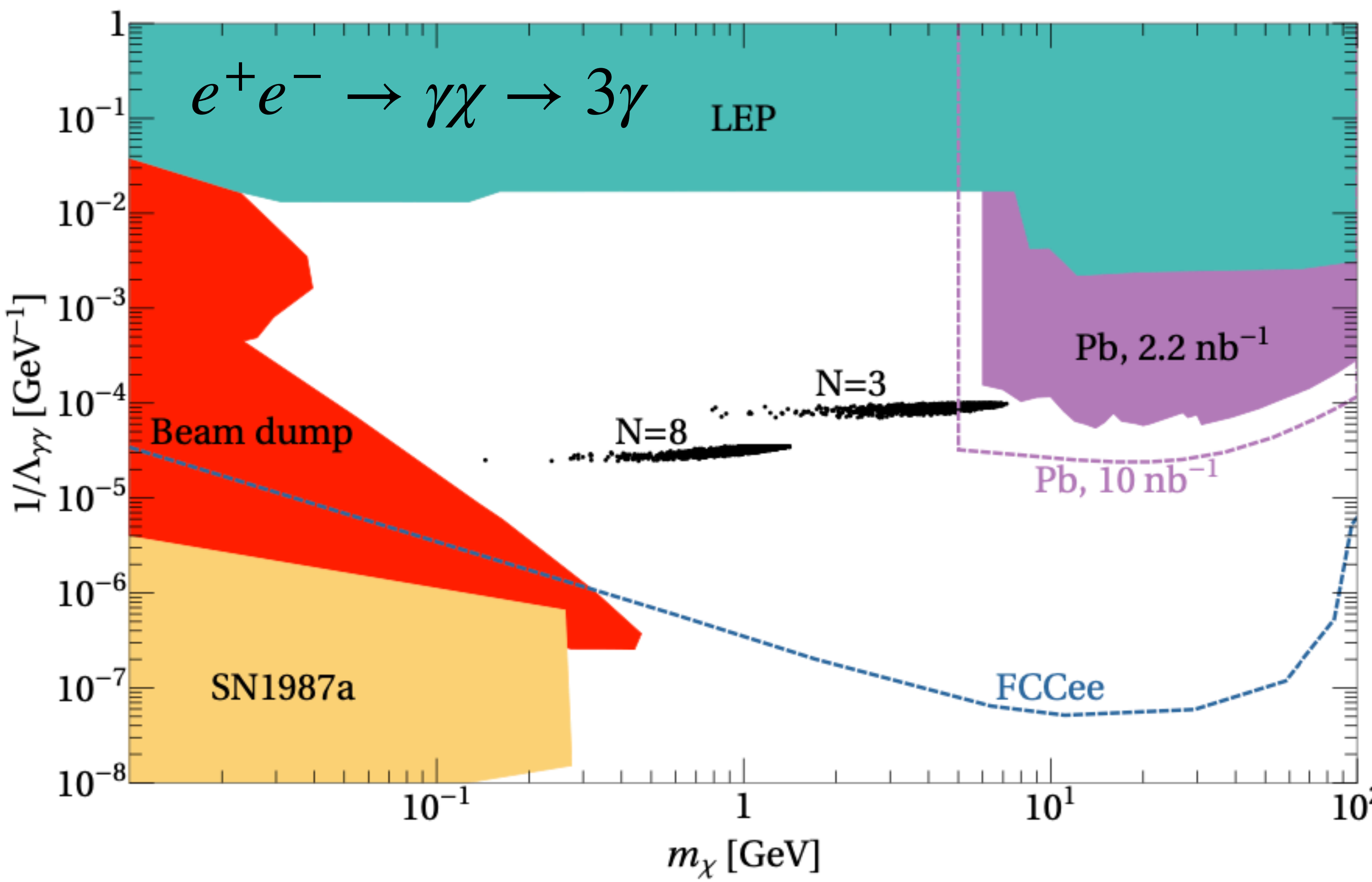
One example of a new paradigm linking the hierarchy problem to cosmological dynamics



Csáki, D’Agnolo, Geller, Ismail arXiv:2007.14396

“Crunching Dilaton, Hidden Naturalness”

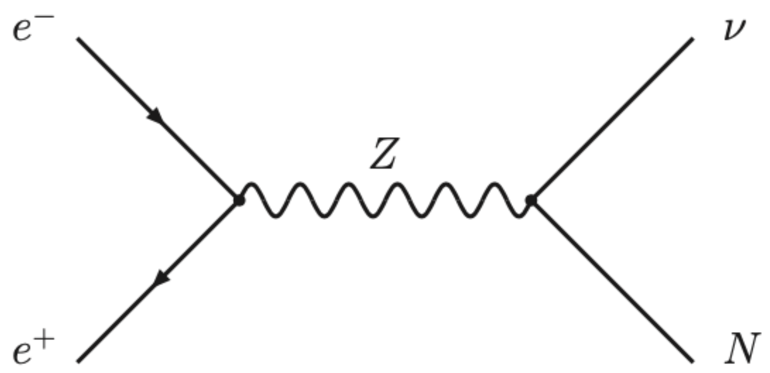
FCC-ee directly probes the dilaton scalar through its couplings to photons



Csáki, D’Agnolo, Geller, Ismail arXiv:2007.14396

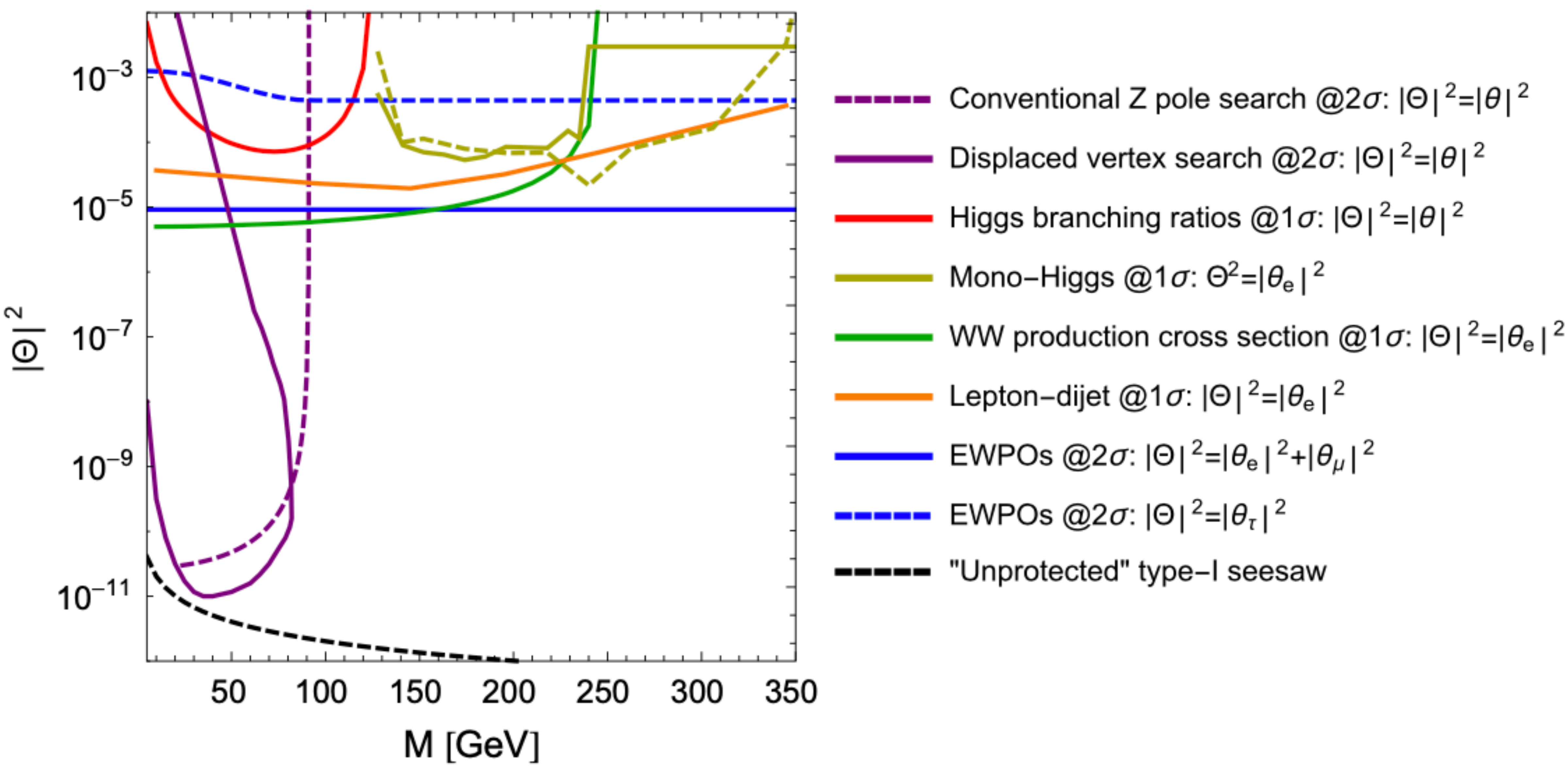
FCC curve based on Bauer, Heiles, Neubert, Thamm ’17/’18

Neutrino Physics at FCC-ee



Sterile $N \to \ell^{\pm}W^{\mp}, \nu Z, \nu h$

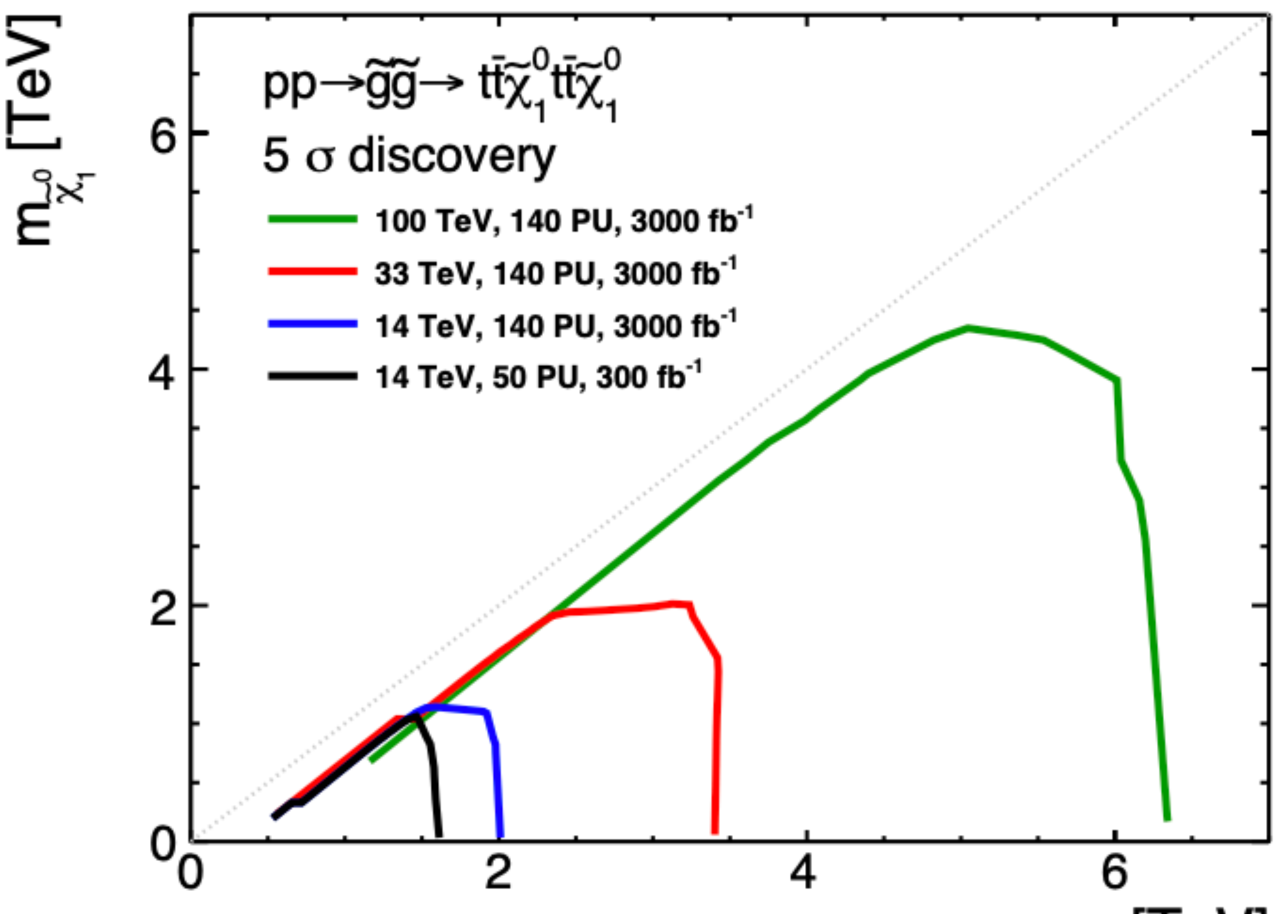
Nonminimal models allow range of mixing angles (not correlated with mass as in minimal seesaw)



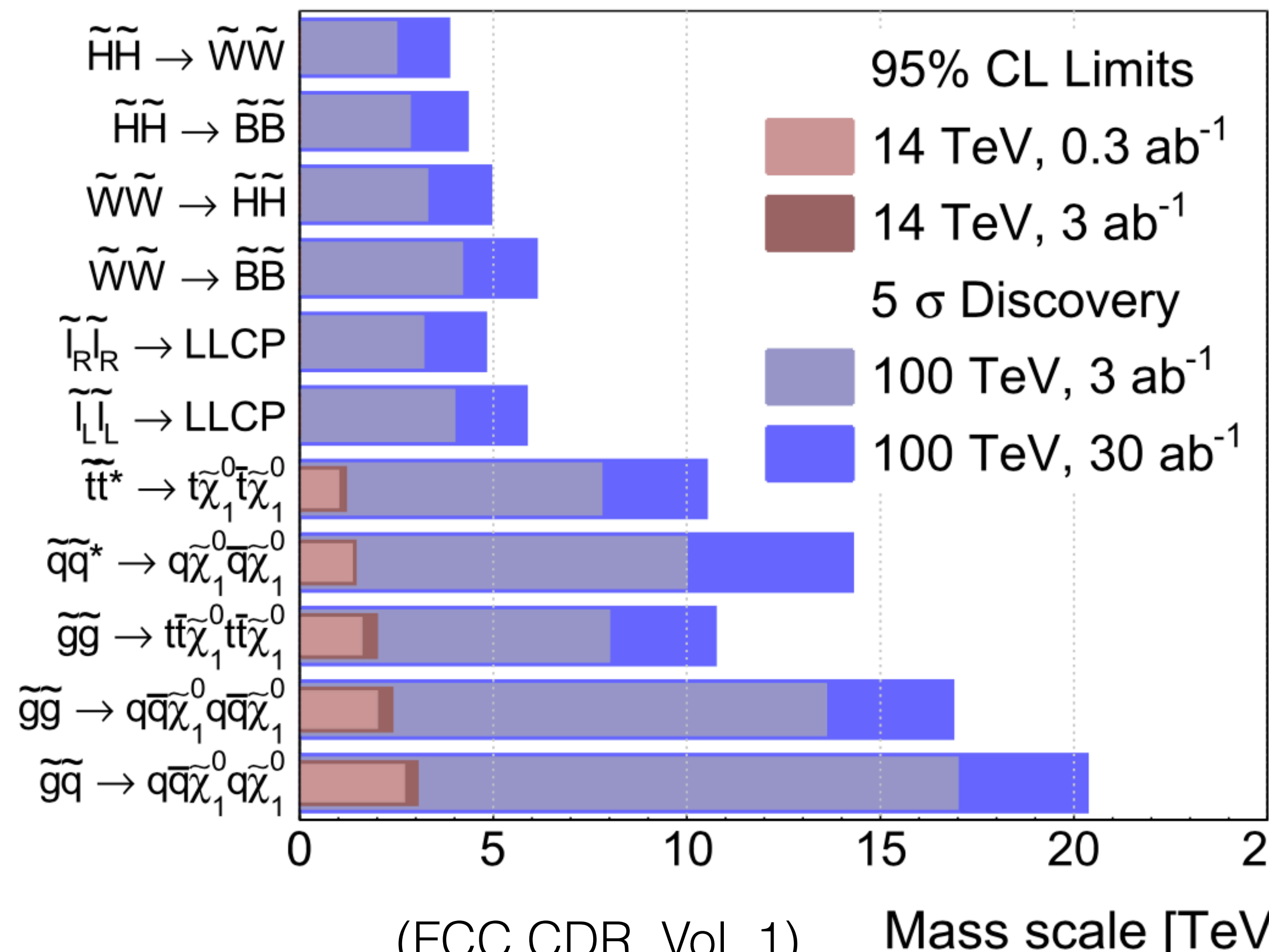
Antusch, Cazzato, Fischer '16

FCC-hh Physics Case

Direct Mass Reach at 100 TeV FCC-hh



Golling et al., 1606.00947



(FCC CDR, Vol. 1)

ε	High-scale mediation	Low-scale mediation
stop	$5\times10^{-5}\left(\frac{10\ \text{TeV}}{m_{\tilde t}}\right)^2$	$2\times10^{-3}\left(\frac{10\ \text{TeV}}{m_{\tilde t}}\right)^2$
gluino	$7\times10^{-6}\left(\frac{17\ \text{TeV}}{m_{\tilde g}}\right)^2$	$6\times10^{-3}\left(\frac{17\ \text{TeV}}{m_{\tilde g}}\right)^2$

source: European Strategy briefing book

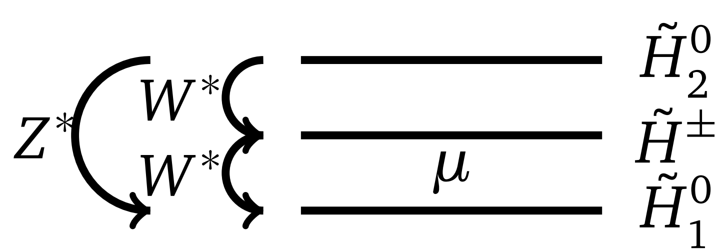
SU(2) Multiplet Dark Matter

Simple models, but some continue to evade direct and indirect detection experiments.

SU(2)$_L$ multiplets by definition involve **multiple** states, some charged

$\}\delta m \sim \frac{\alpha}{\pi} m_W$ (tree-level dim 7)

Wino charged -> neutral: **disappearing track**

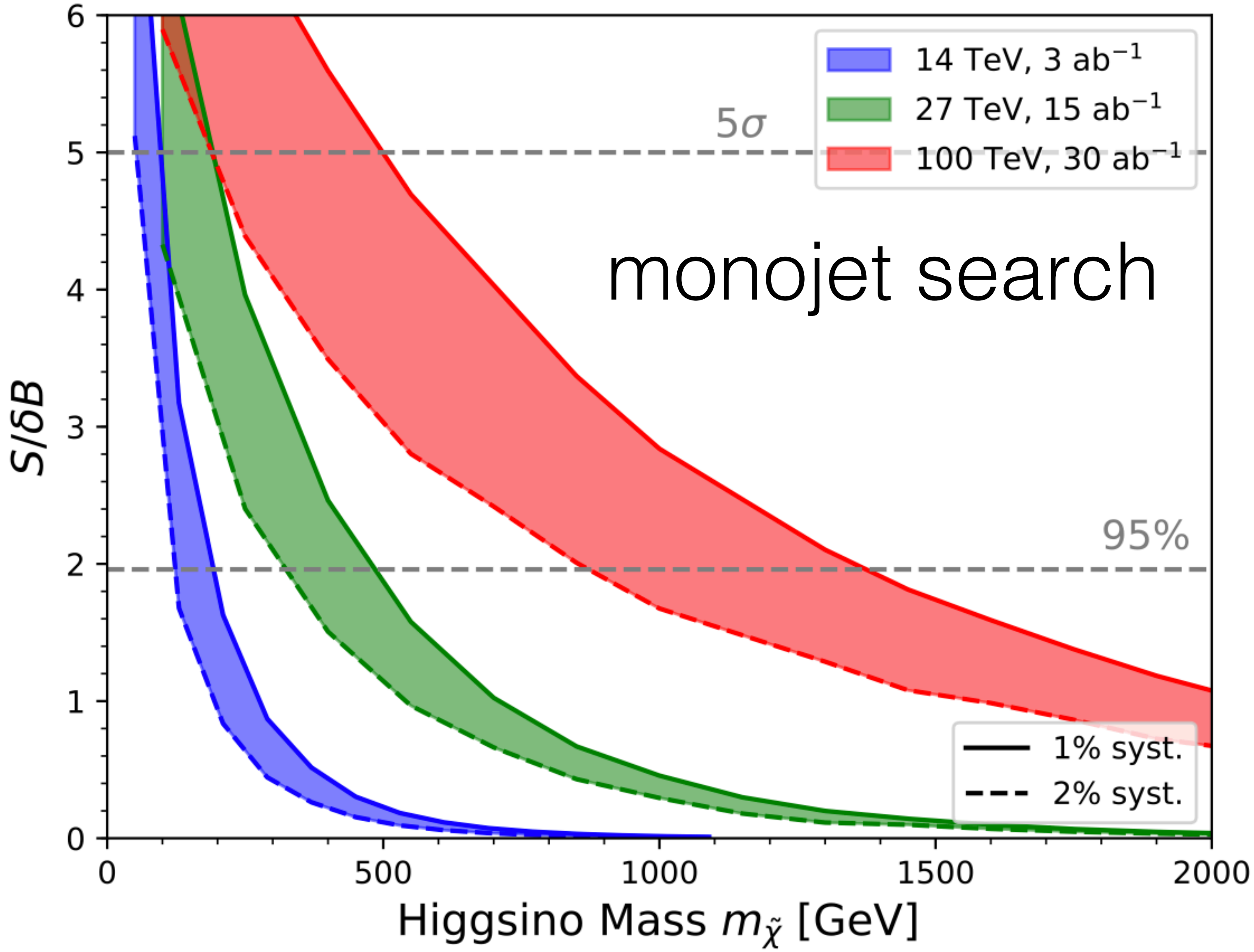


$\}\delta m \sim \frac{m_Z^2}{M_2}$

Higgsino (toughest case) charged -> neutral, neutral -> neutral: **soft leptons or jets**

SU(2) Multiplet DM at 100 TeV

The thermal relic Higgsino (mass ~ 1 TeV) can be excluded at FCC-hh.

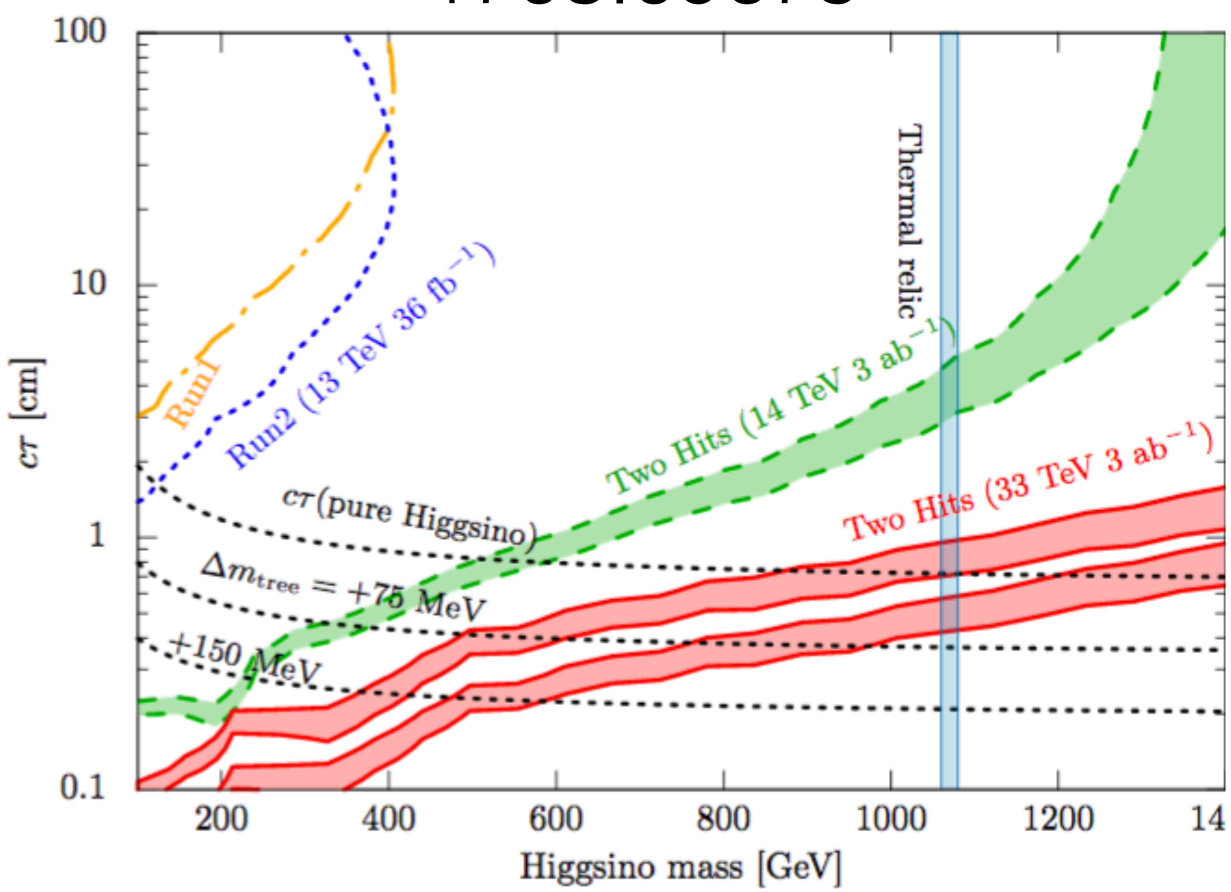


T. Han, S. Mukhopadhyay, and X. Wang, arXiv:1805.00015

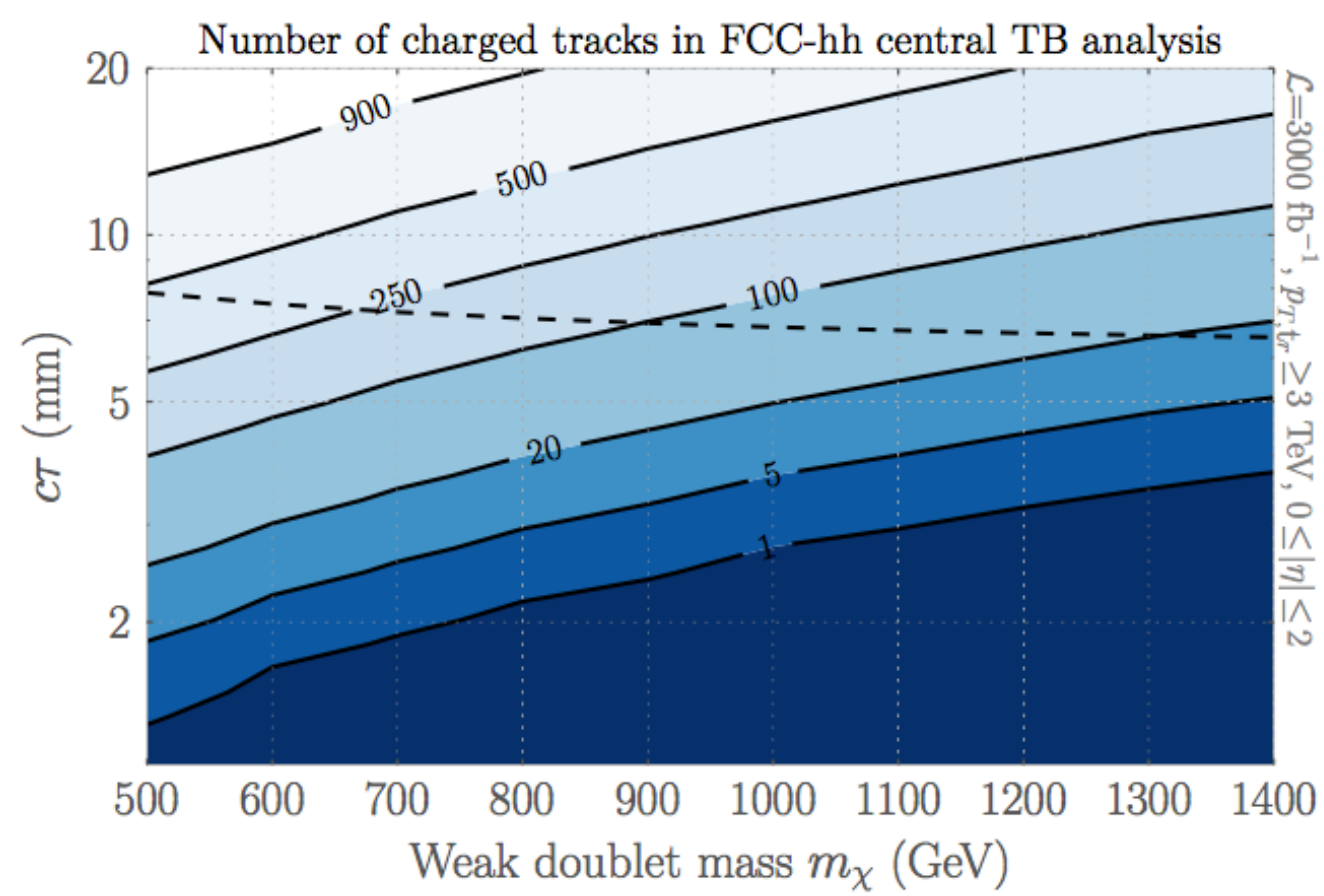
Higgsinos and Disappearing Tracks

The mildly long lifetime of a chargino can provide an additional handle on the very pure higgsino corner of parameter space:

Fukuda, Nagata, Otono, Shirai
1703.09675



Mahbubani, Schwaller, Zurita
1703.05327



Precision Higgs Measurements

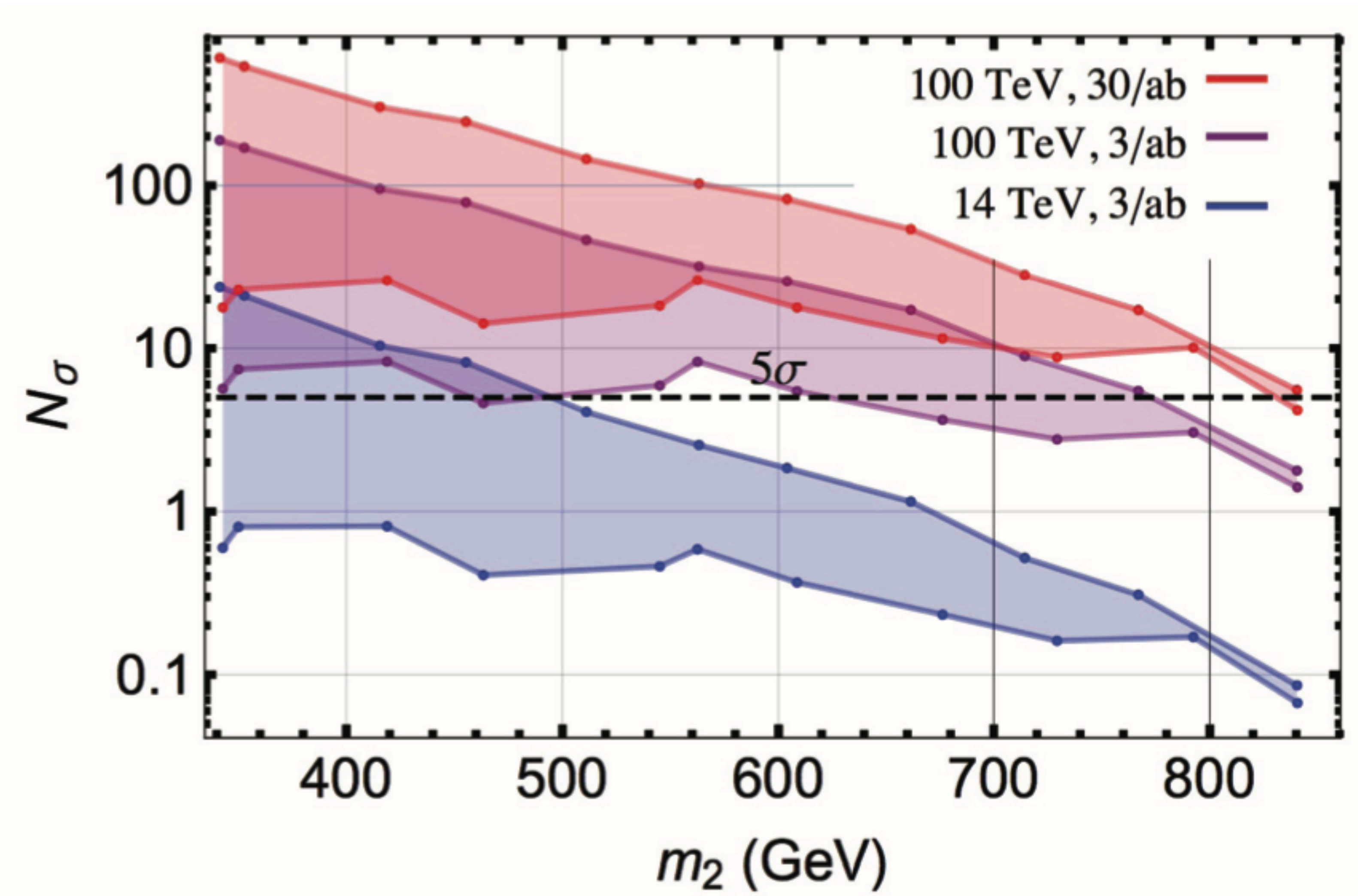
Table 1.2: Target precision for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling λ. Notice that Lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(\mathrm{HH})\times\mathrm{B}(\mathrm{H}\to\gamma\gamma)\mathrm{B}(\mathrm{H}\to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = \mathrm{B}(\mathrm{H}\to\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}\mathrm{H})\times\mathrm{B}(\mathrm{H}\to b\bar{b})/\sigma(t\bar{t}\mathrm{Z})\times\mathrm{B}(\mathrm{Z}\to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H}\to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

from: Future Circular Collider Study, Vol. 3 (FCC-hh CDR)

Singlet Scalar with Higgs Mixing

Resonant di-Higgs production: $h_2 \to 2h_1 \to 4\tau, b\bar{b}\gamma\gamma$



Parameter space with **strongly first-order phase transition** can be probed

Kotwal, No, Ramsey-Musolf, Winslow 1605.06123

(Also see 4b studies for HL-LHC by Li, Ramsey-Musolf, Willocq, 1906.05289)

Electroweak Phase Transition "Nightmare" Scenario

Singlet scalar with a $\mathbb{Z}_2$ symmetry $\phi \mapsto -\phi$

$$V(h,\phi) = V_{\rm SM}(h) + \frac{1}{2}M^2\phi^2 + c_\phi |H|^2\phi^2$$

No *mixing* with the Higgs boson. **Stable, invisible.**

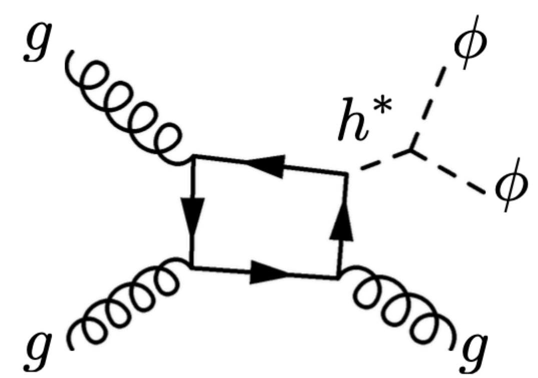
After EWSB: $h\phi^2$ vertex. Light ϕ: invisible width of Higgs.

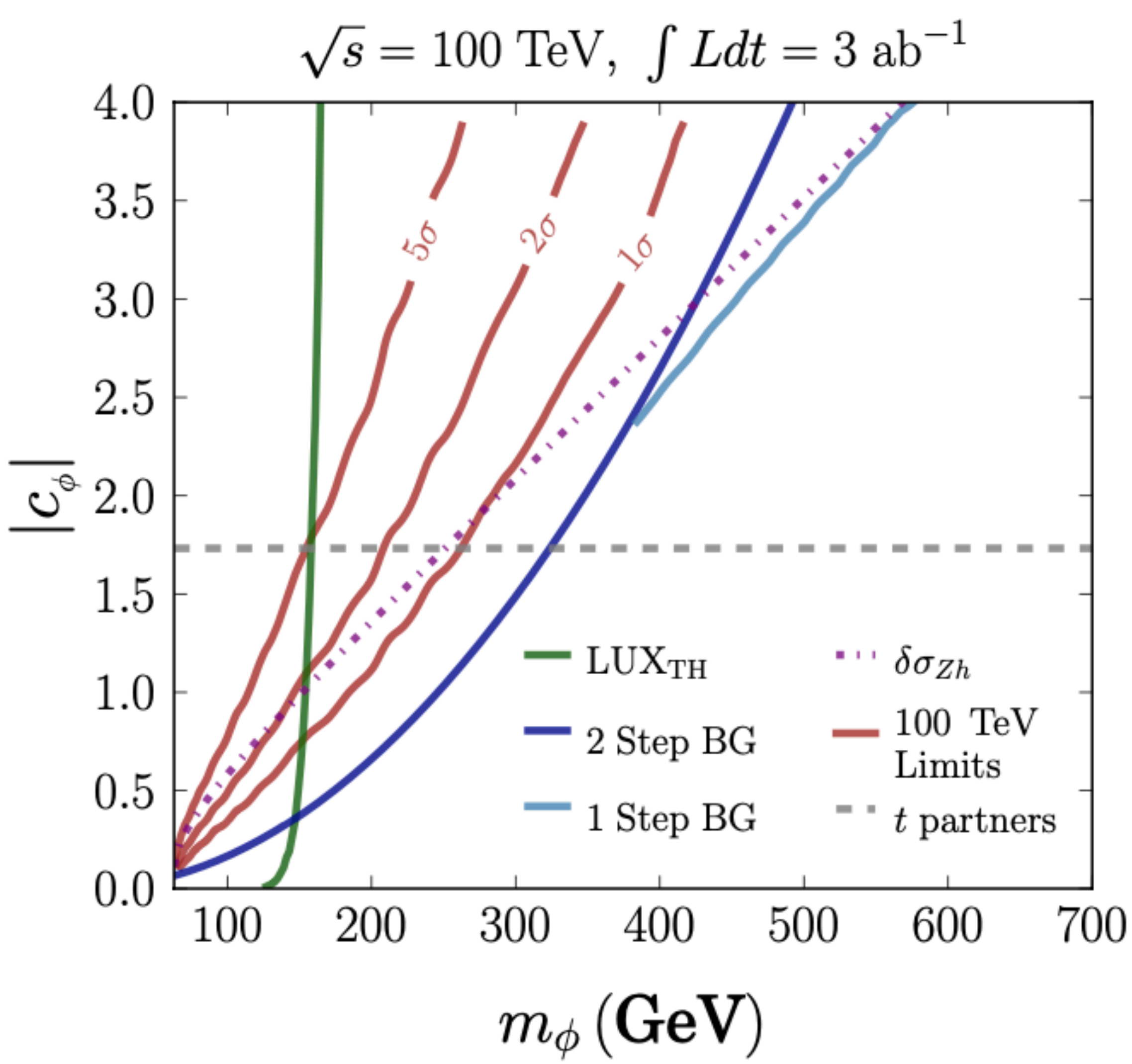
$m_\phi > \frac{1}{2}m_h$: difficult!

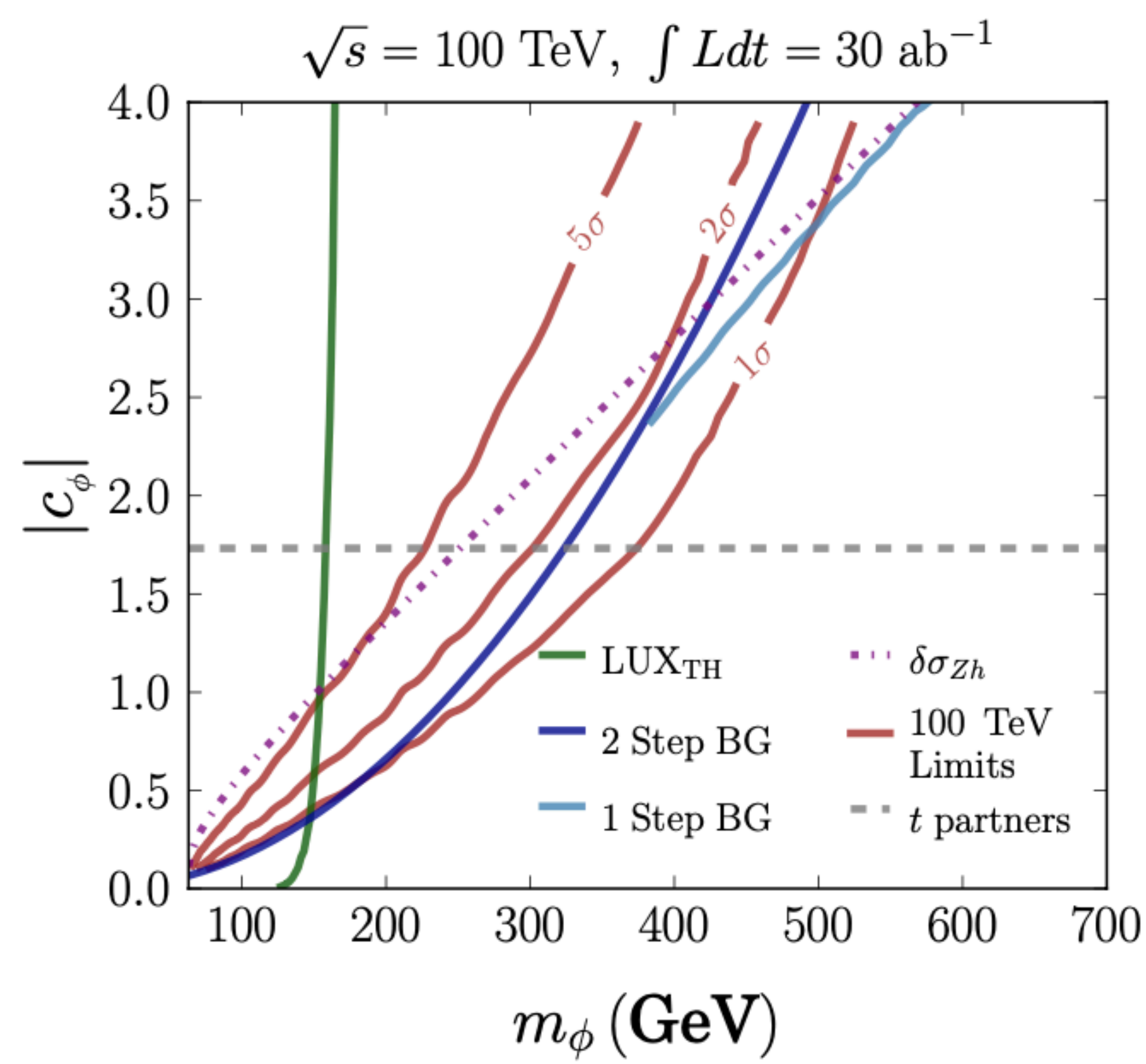
Curtin, Meade, Yu 1409.0005

The Higgs Portal Above Threshold

VBF $\phi\phi jj$ (forward jets) and gluon fusion



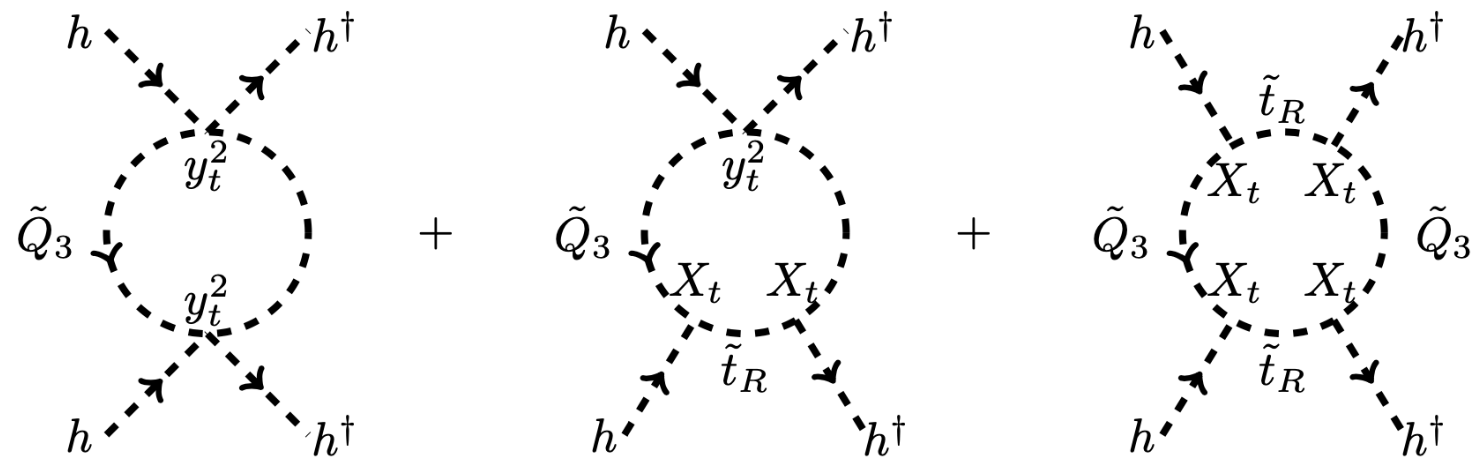


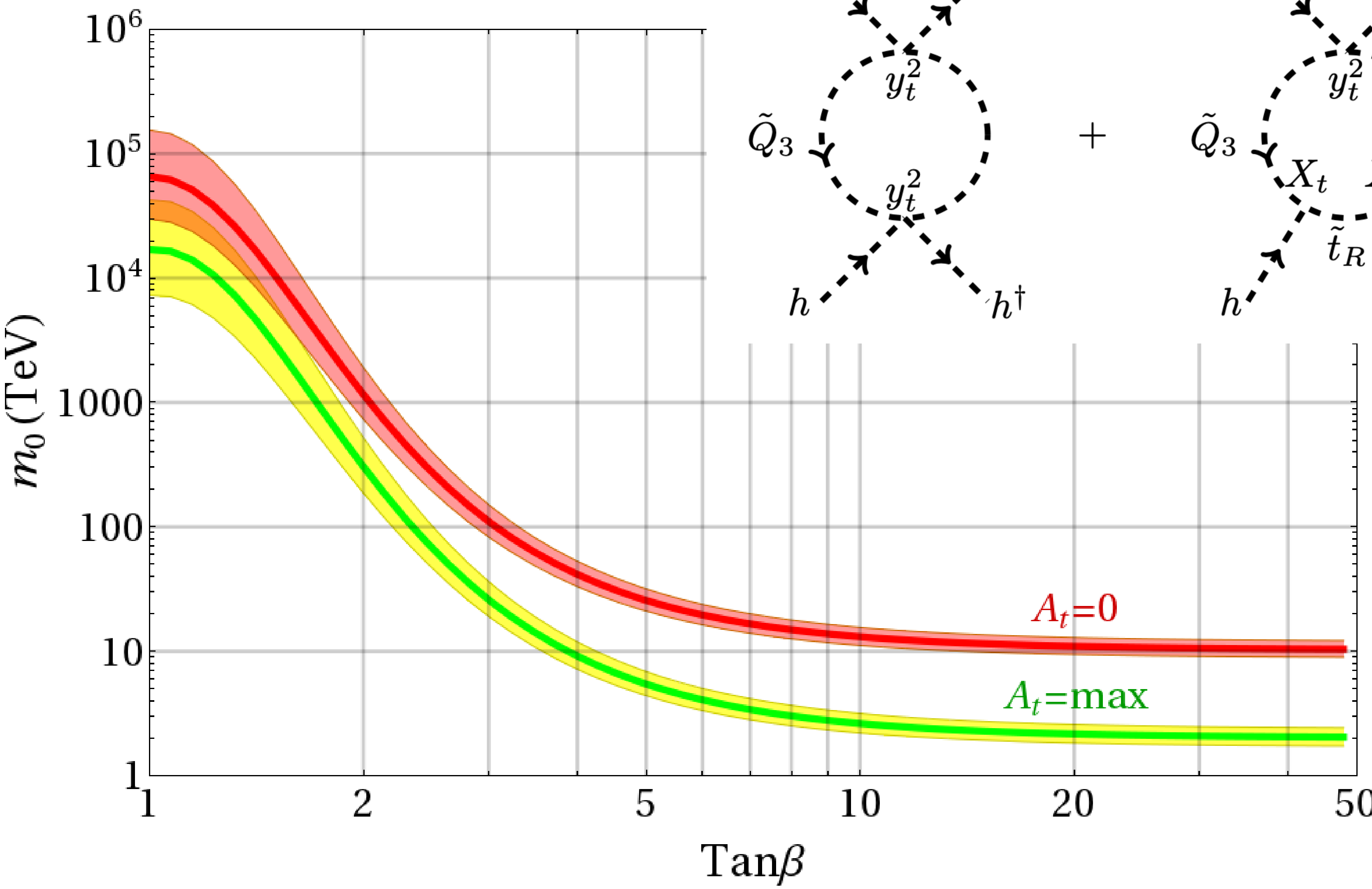


(Craig, Lou, McCullough, Thalapillil arXiv:1412.0258)

Why is the Higgs Mass 125 GeV?

In the MSSM, largely depends on the stop mass and $\tan\beta$.





In the simplest models, this points to

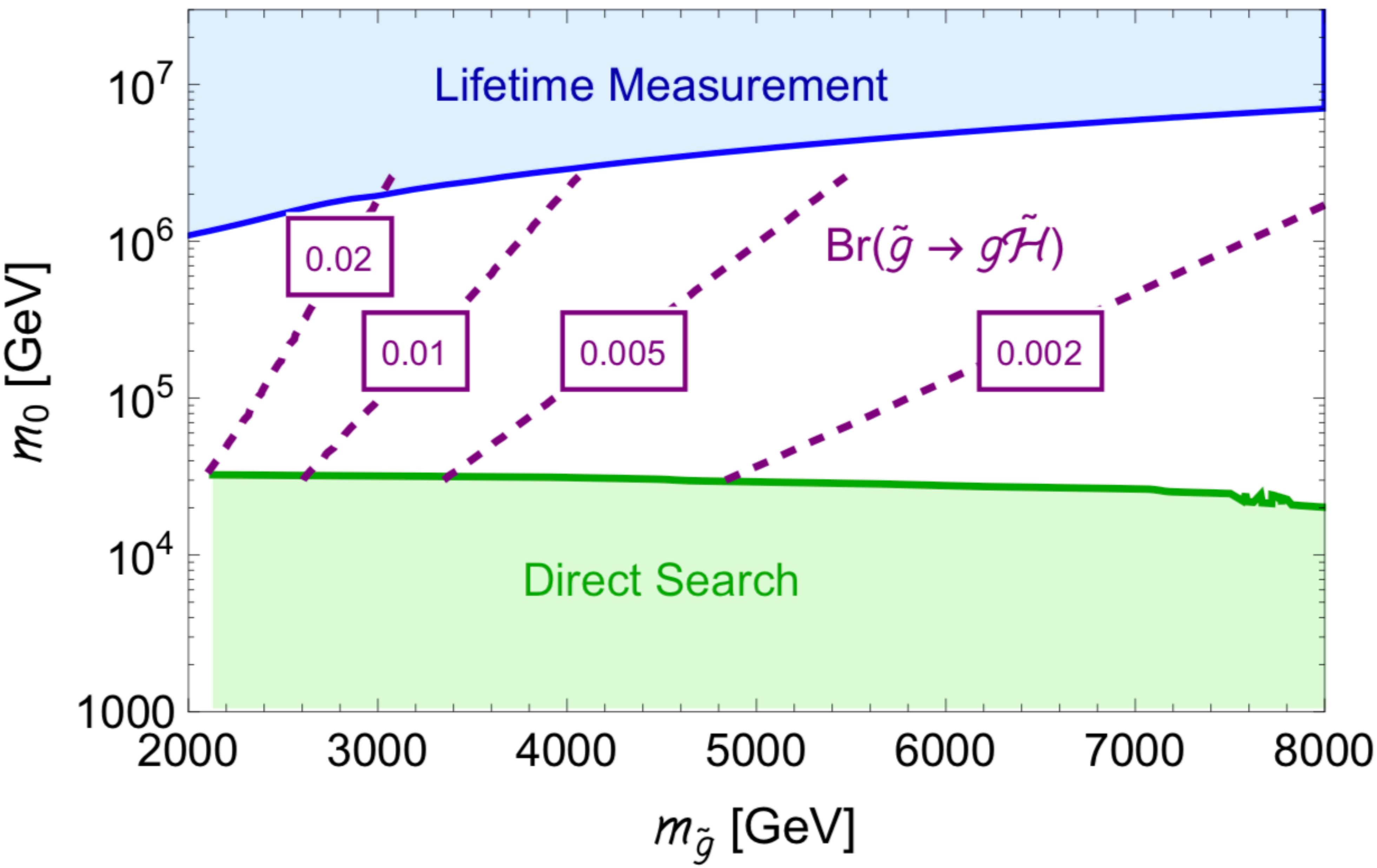
$$m_{\tilde{t}} \gtrsim 10\,\text{TeV}$$

Can we test this?

Arvanitaki, Craig, Dimopoulos, Villadoro
1210.0555

LHC partial discovery scenario

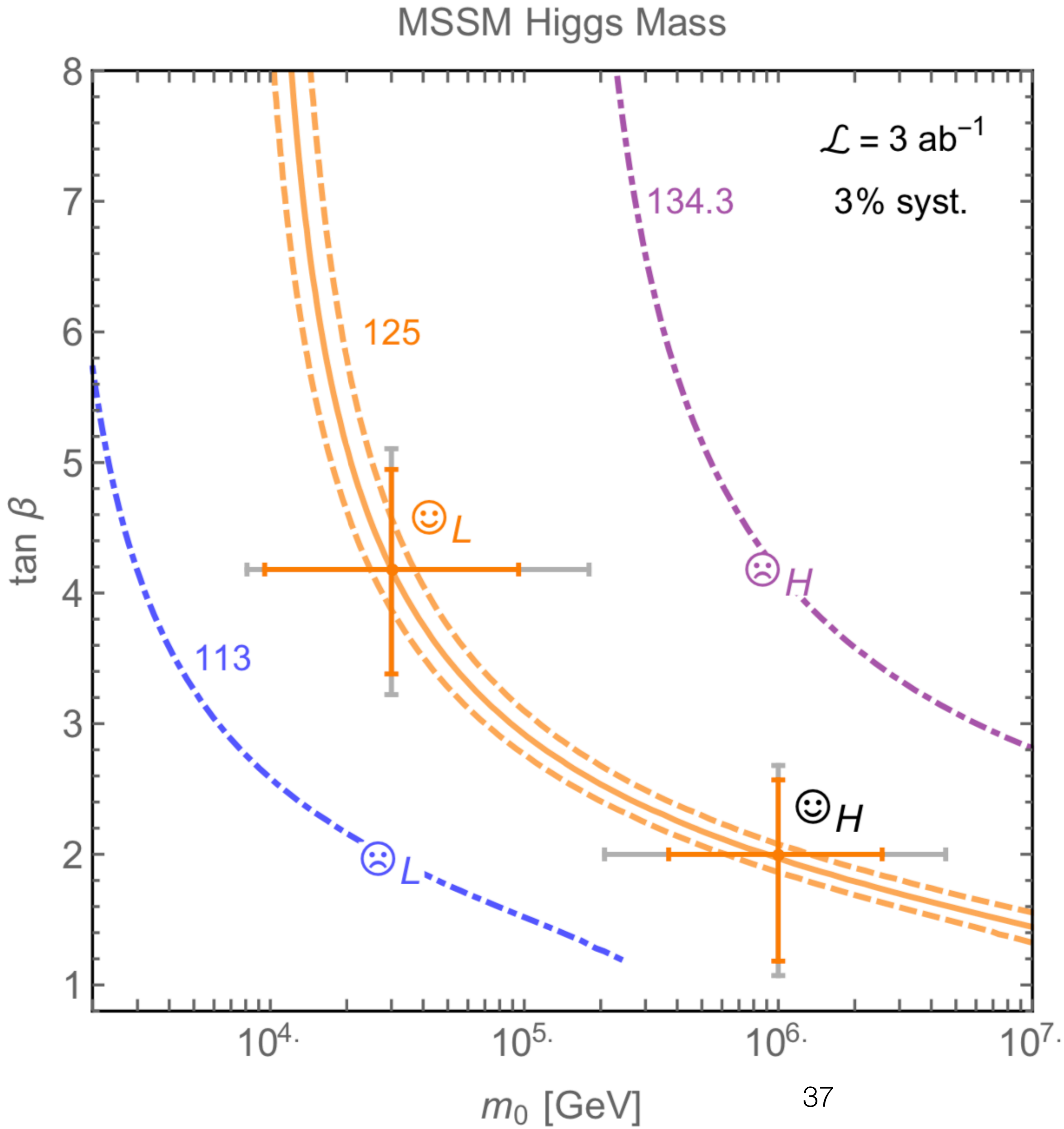
We may get only *part* of the spectrum. **Example: split SUSY**. Even at a 100 TeV collider, can't make the scalar superpartners. But the 100 TeV collider would be a **gluino factory.**



Can we learn where the scalars are?

Agrawal, Fan, MR, Xue '17

Testing the MSSM Higgs mass hypothesis



Precision physics @ future hadron collider could answer **big question**: where does the Higgs mass come from?

Would open up **new big question**: where does the SUSY breaking scale come from?

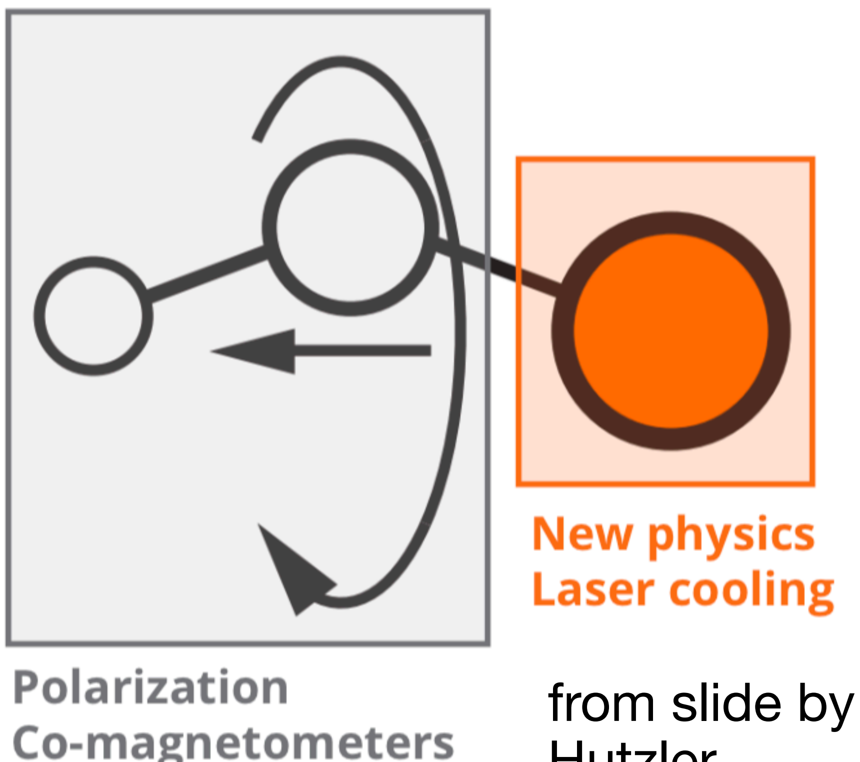
Agrawal, Fan, MR, Xue ’17

FCC in Context

EDM Precision on the Horizon

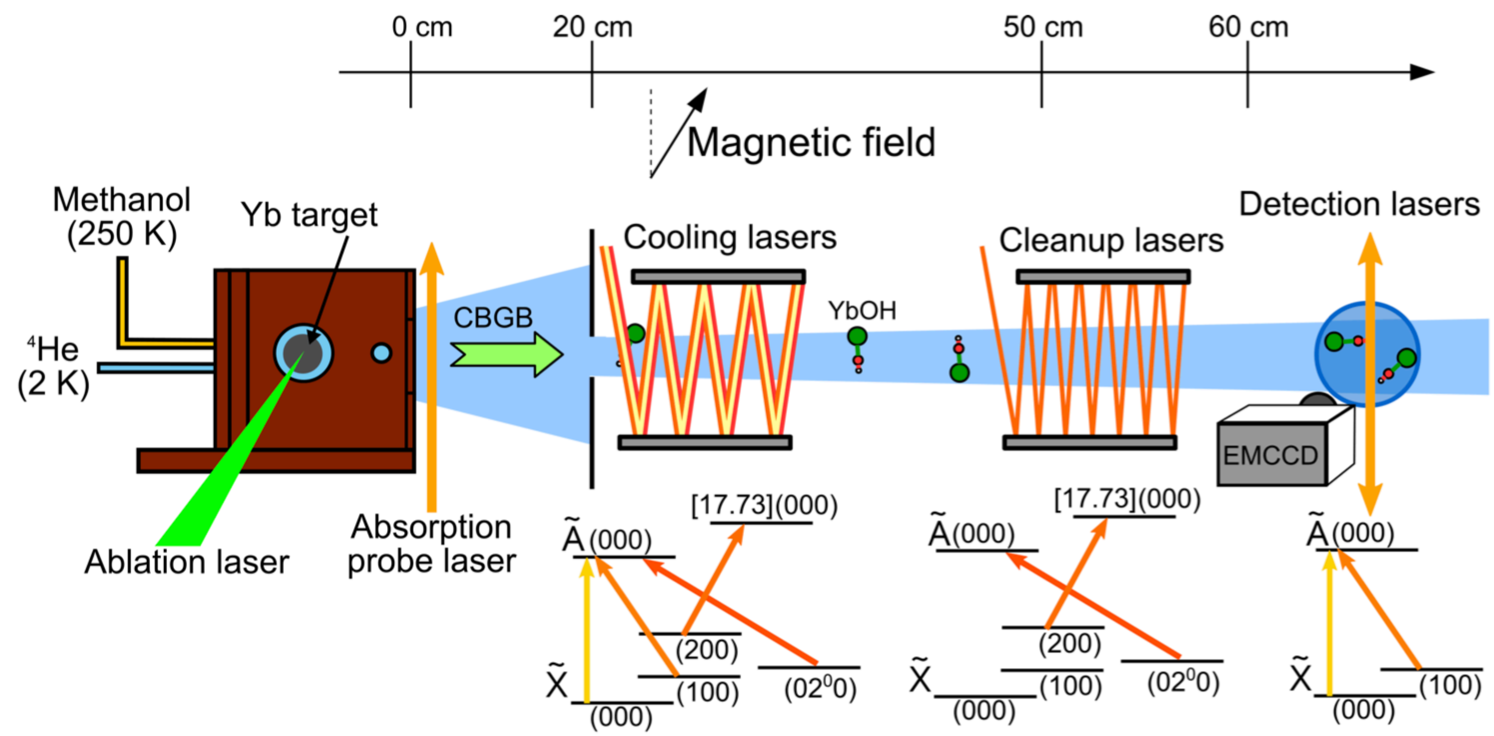
One of several parallel approaches:

Polyatomic Molecules (e.g., YbOH)



from slide by N. Hutzler

Hutzler, Kozyryev 1705.11020

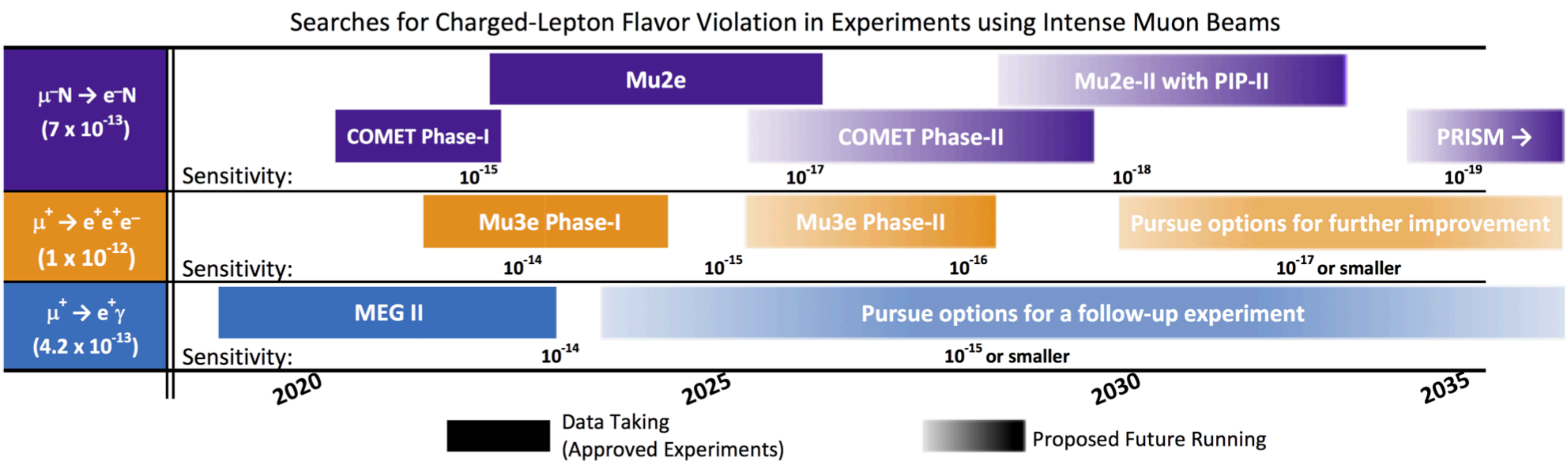


Laser cooling achieved

(Augenbraun et al., 1910.11318)

Electron EDM: $10^{-29} e\,\mathrm{cm} \longrightarrow 10^{-32} e\,\mathrm{cm}$ **!**

Charged Lepton Flavor Violation

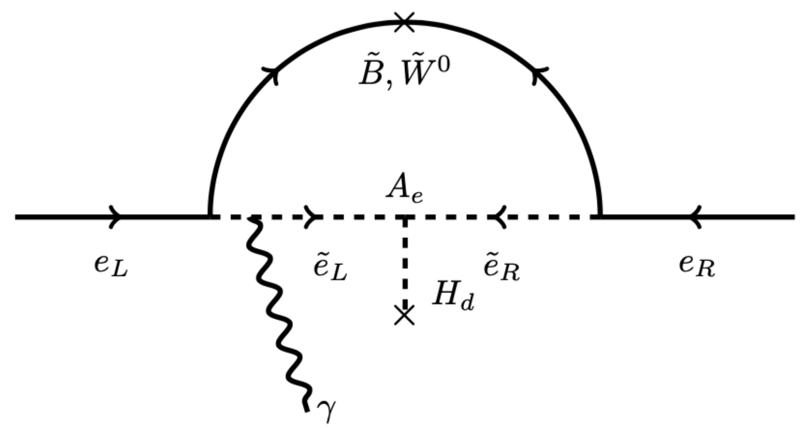


Source: Baldini et al., 1812.06540, submission to 2020 European Strategy from COMET, MEG, Mu2e and Mu3e collaborations

Could CP and Flavor Lead the Way?

EDM, 1-loop

electron-flavored

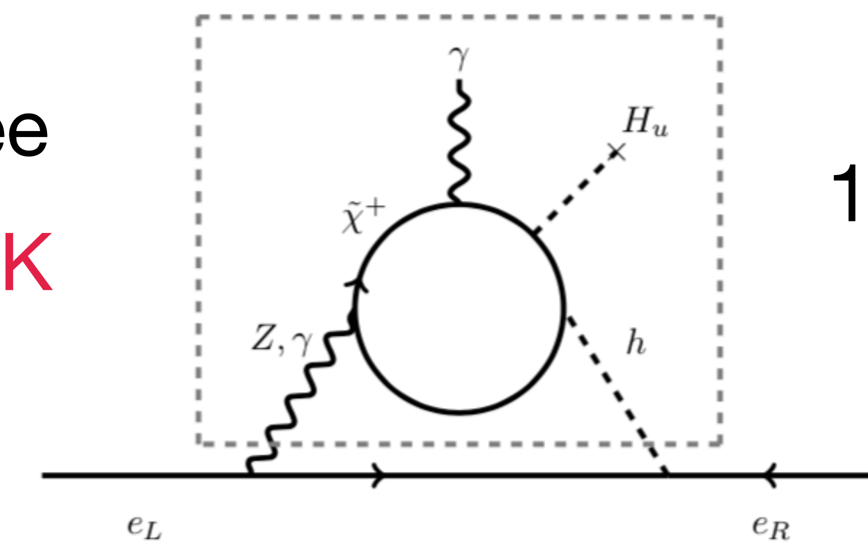


10^{-32} *e* cm $\Longrightarrow$ ~ **1 PeV (!)**

(*if* O(1) CP phase)

EDM, 2-loop Barr-Zee

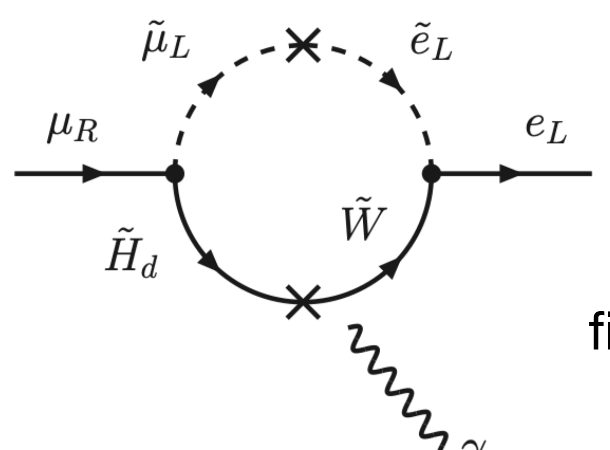
Anything Higgs+EWK



10^{-32} *e* cm $\Longrightarrow$ ~ **50 TeV (!)**

(*if* O(1) CP phase)

μ→e, 1-loop,
flavor violating



10^{-19} on Al $\Longrightarrow$ ~ **50+ TeV (!)**

(*if* large flavor violation)

fig. from 1308.3653: Altmannshofer, Harnik, Zupan

(w/ electron Yukawa spurions on all diagrams)

The Role of Colliders

If a precision physics experiment (EDMs, CLFV, flavor physics at Belle II, muon $g-2$, etc) makes a discovery, we will learn ***the coefficient of one higher-dimension operator*** and little else.

Only a collider can **produce** and **systematically characterize** the underlying new physics!

We should support “Physics Beyond Colliders” as a stepping stone—it may provide us our strongest argument for building the next energy-frontier collider!

Conclusions

Colliders offer opportunities to not just discover that the Standard Model is incomplete, but to ***fully uncover*** **the nature of the new physics.**

FCC will define the agenda for particle physics well into the 21st century.

FCC-ee and FCC-hh both have exciting, complementary roles to play in this agenda.

The future of particle physics requires new energy-frontier colliders like FCC!