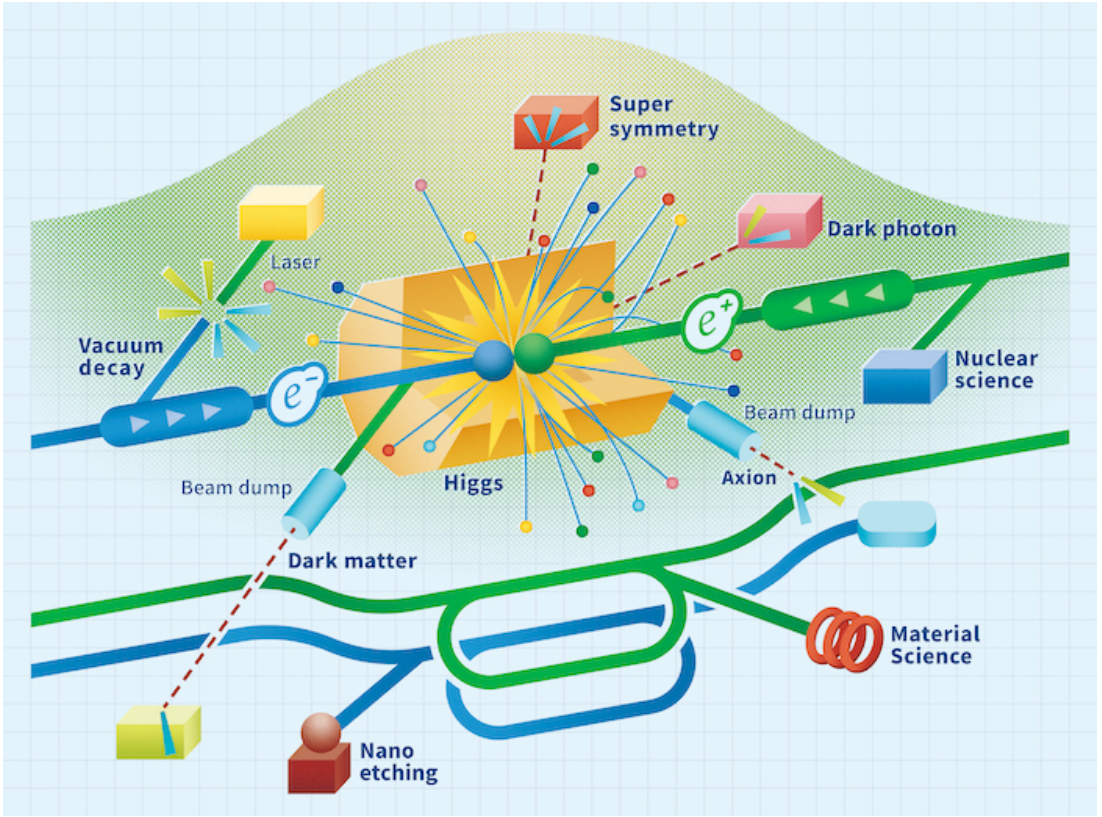
LC Vision Update & Some remarks on the Physics Case beyond 365 GeV

ILD Meeting
Paris
Oct 8, 2024

J.List



What is this Global LC Vision?

The common idea

- the exploration of the fundamental laws of our universe requires, in addition to the HL-LHC and Belle II, a long-term e+e- program over a wide range of energies - not just a “gap-filler”
- this program should start “now” by unveiling the mysteries of the Higgs boson, with an affordable project based on technology at-hand - and then evolve from there
- the long-term program should not be statically defined “today” for decades into the future, but instead the initial facility must be sufficienctly versatible to allow choices to be taken as scientific knowledge and technologies advance - or even see revolutions
- this applies to the evolution of the e+e- facility itself as well as for the choice of the best avenue to eventually explore the 10-TeV parton-energy scale, for all of which sufficient resources for R&D and demonstrators must remain available

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— and put them up for discussion at LCWS 2024!

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Task ahead: Evolve this into **a joint Linear Collider Vision input to the EPPSU**

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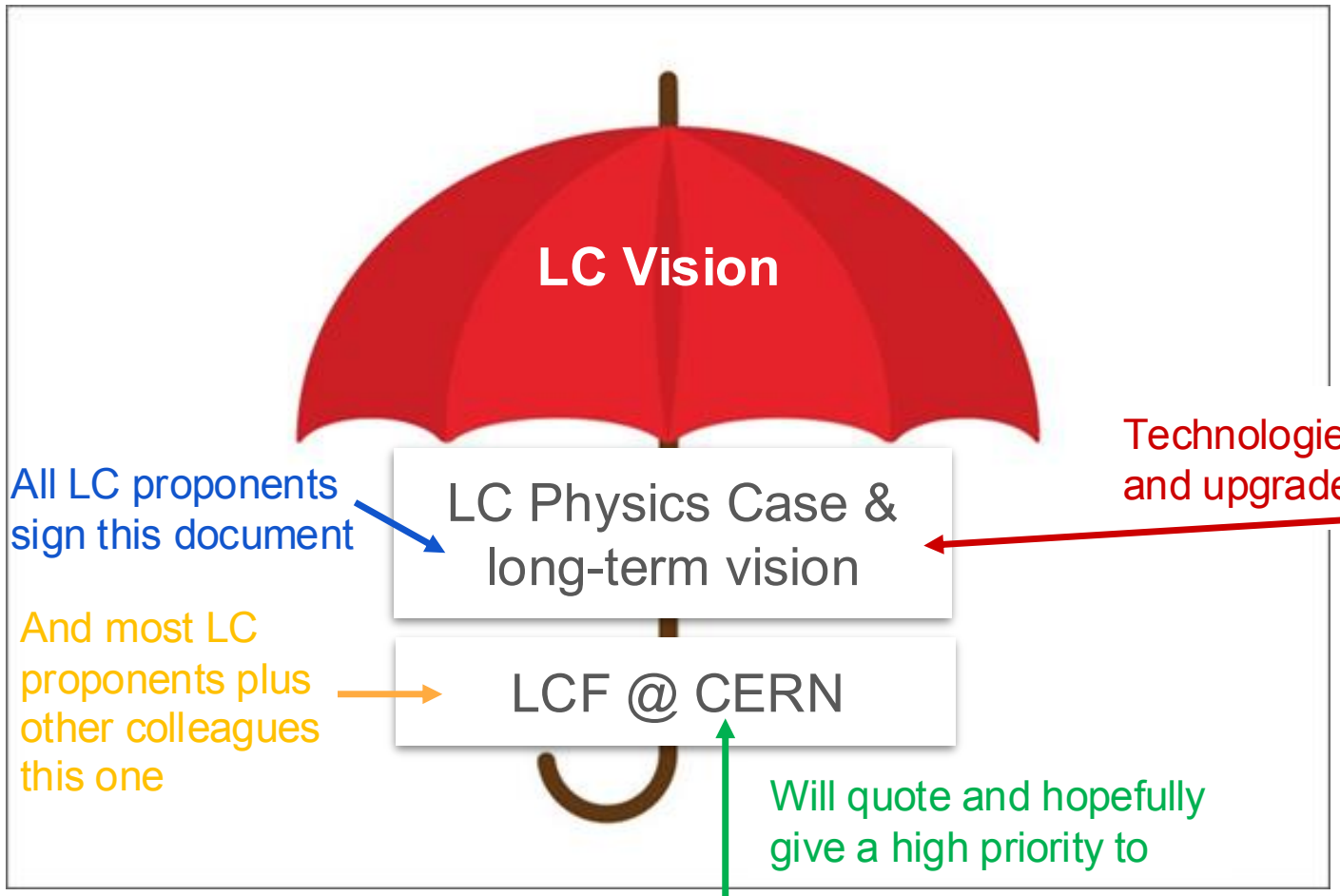
LC Vision Documents

and their relations to other EPPSU inputs

idea: S. Gessner



LC Vision Overview

Chairs: J. List, S. Stapnes

Coordination Group

Halina Abrahmovic, Erik Adli, Ties Behnke, Ivanka Bosovic, Phil Burrows, Marcel Demarteau, Yuanning Gao, Carsten Hensel, Mark Hogan, Masaya Ishino, Daniel Jeans, Imad Laktineh, Andy Lankford, Benno List, Kajari Mazumar, Shin Michizono, Emmanuela Musumeci, Tatsuya Nakada, Mihoko Nojiri, Dimitris Ntounis, Jens Osterhoff, Ritchie Patterson, Aidan Robson, Daniel Schulte, Taikan Suehara, Geoffrey Taylor, Caterina Vernieri, Marcel Vos, Georg Weiglein, Filip Zarnecki, Jinlong Zhang, Laura Monaco, Patrick Koppenburg, Hitoshi Murayama, NN Canada

Expert Team 1
"Physics-driven run plan and EPPSU documents"
Roman Poeschl, Michael Peskin

Expert Team 3
"SCRF upgrades"
Sergey Belomestnykh, Hiroshi Sakai, Marc Wenskat

Expert Team 5
"ERL upgrades"
Walid Kaabi, Vladimir Litvinenko, Kaoru Yokoya

Expert Team 7
"Beyond Collider"
Yasuhito Sakaki, Ivo Schulthess

Expert Team 2
"LCF@CERN"
Steinar Stapnes, Thomas Schörner

Expert Team 4
"C3/CLIC upgrades"
Angeles Faus-Golfe, Enrico Nanni

Expert Team 6
"Plasma upgrades"
Brian Foster, Spencer Gessner

Expert Team 8
"Alternative Collider Modes"
Tim Barklow, Gudi Moortgat-Pick

Scenarios for Expert Teams

to get started

- **let's assume we start with a Linear Facility, with 2 Beam Delivery Systems (2 IRs), length**
  - **a) ~20 km** (e.g. 250 GeV SCRF)
  - **b) ~30 km** (e.g. 550 GeV SCRF — CEPC complementarity from day-one)
- **what could "your" technology offer as**
  - **i. decision-ready in < 5 years (e.g. 2-3 year targeted engineering effort after EPPSU adoption in early 2026)?**
    - **ILC-like SCRF**
    - alternative collider modes, beyond-collider facilities?
    - anything else?
  - **ii. as upgrade, decision-ready after the first years of data-taking of initial facility (e.g. 2045-2050)?**

News

what's going on

- Expert teams are working….
- First outlines of documents exist, regular meetings of editor team to start soon

- **Informal discussions re-emphasize for LCF4CERN:**
  - 2 beam delivery systems ("sociology", but also complementary opportunities => ET8)
  - initial machine in SCRF "ILC-like"

- **mixed messages** wrt
  - relative importance of "cheapest possible Higgs Factory" vs "a really attractive LC project, complementary to CEPC from day-1"
  - **the physics need for e+e- collisions above the ttbar threshold**

Staying Up-to-date

what's coming up

- **Public e-group LCVision-General**

http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=LCVision-General

- **Updates at ECFA WS (Thursday), ILC-Europe, IDT-WG3, ILD, several national meetings…**

  => get in touch if you'd like an LC Vision talk for "your" event!

- **LC Vision Community Event**
  - **Jan 8-10 at CERN (main amphi…)**
  - **open, hybrid, …**
  - **indico coming soon, prepare your travel ! :)**

Any Questions?

A few words on Physics ;)

Linear Collider Energy Reach in EPPSU

general perception?

- **there seems to be a reasonably wide consensus about the merits of**
  - the basic 240/250 GeV (single-) Higgs program
  - and the ttbar threshold scan
- **much less consensus wrt the need for e+e- collisions *above* 350..380 GeV**

  => would a LC add anything beyond a CC ?

… national inputs are requested to comment on strategy for CERN if

- **FCC-ee too expensive => would LC be “only 2nd rate”? Or does it offer its own attractive opportunities ?**
- **CEPC goes ahead => sufficient complementarity?**

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What are the main points why LC Vision thinks that e+e- above ttbar threshold is important ?

The menu in short

Overview

1. **Observe and measure double-Higgs-Strahlung**

   => insight into shape of Higgs potential and role of EWSB in early universe

2. **Understand the top-quark and its relation to gauge boson and the Higgs**

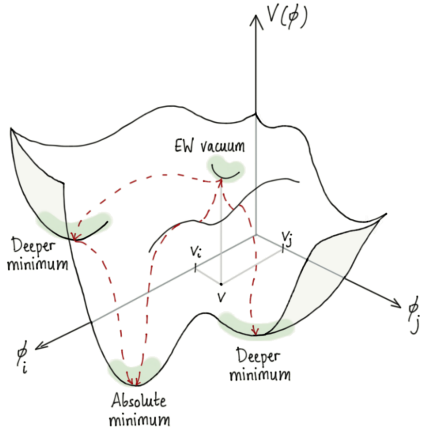
   => insight into fermion mass hierarchy, fully understand Higgs mechanism

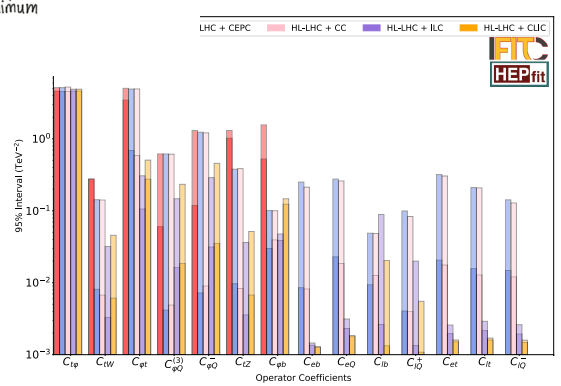
3. **Precision probes of weak gauge boson self-interactions**

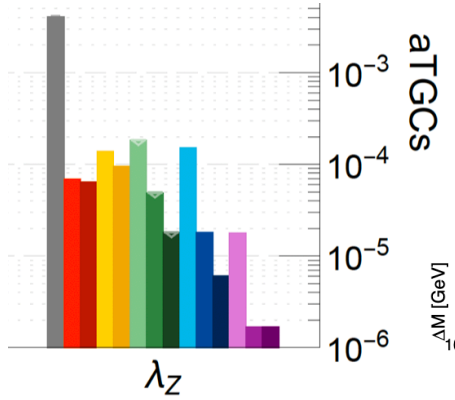
   => extremely sensitive probe for BSM, interplay with Higgs

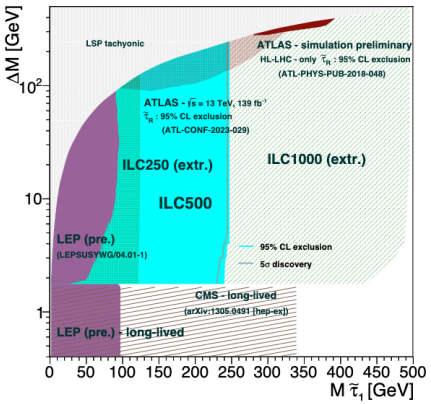
4. **loop-hole-free searches for electroweak new particles incl siblings of the Higgs**

   => discovery is the icing on the cake, opportunities complementary to pp, fixed target, direct detection, …





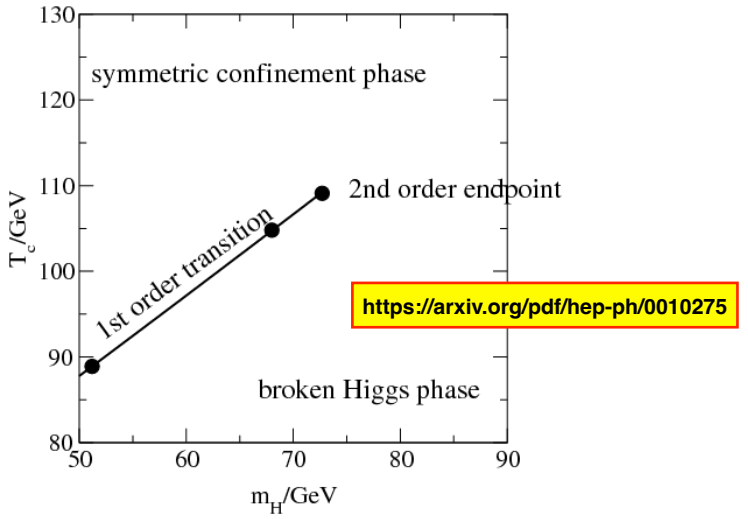




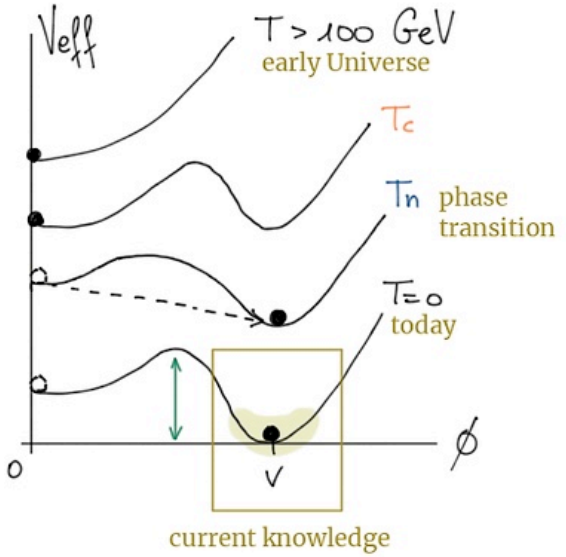
Recap: Electroweak Symmetry Breaking and Baryogenesis

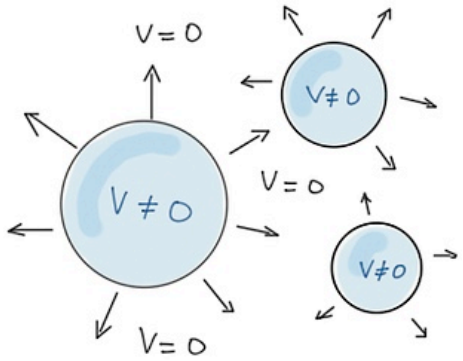
Evolution of the universe

- temperature evolution of Higgs potential ?
- **phase diagram of the electroweak sector!**
- for M_H > 75 GeV, there is no phase transition in the SM
- thus in SM no out-of-equilibrium state of the early universe for baryogenesis (requires 1st order phase transition, cf Sacharov conditions)
- need to
  - measure whether self-coupling λ_3 = 0.13 as predicted by SM - without prejudice that everything else is SM-like!
  - check whether Higgs field is indeed just one $SU(2)_L$ doublet
  - **in many extended Higgs sectors, 1st order phase transition for $\lambda_3 > \lambda_{SM}$**



https://arxiv.org/pdf/hep-ph/0010275



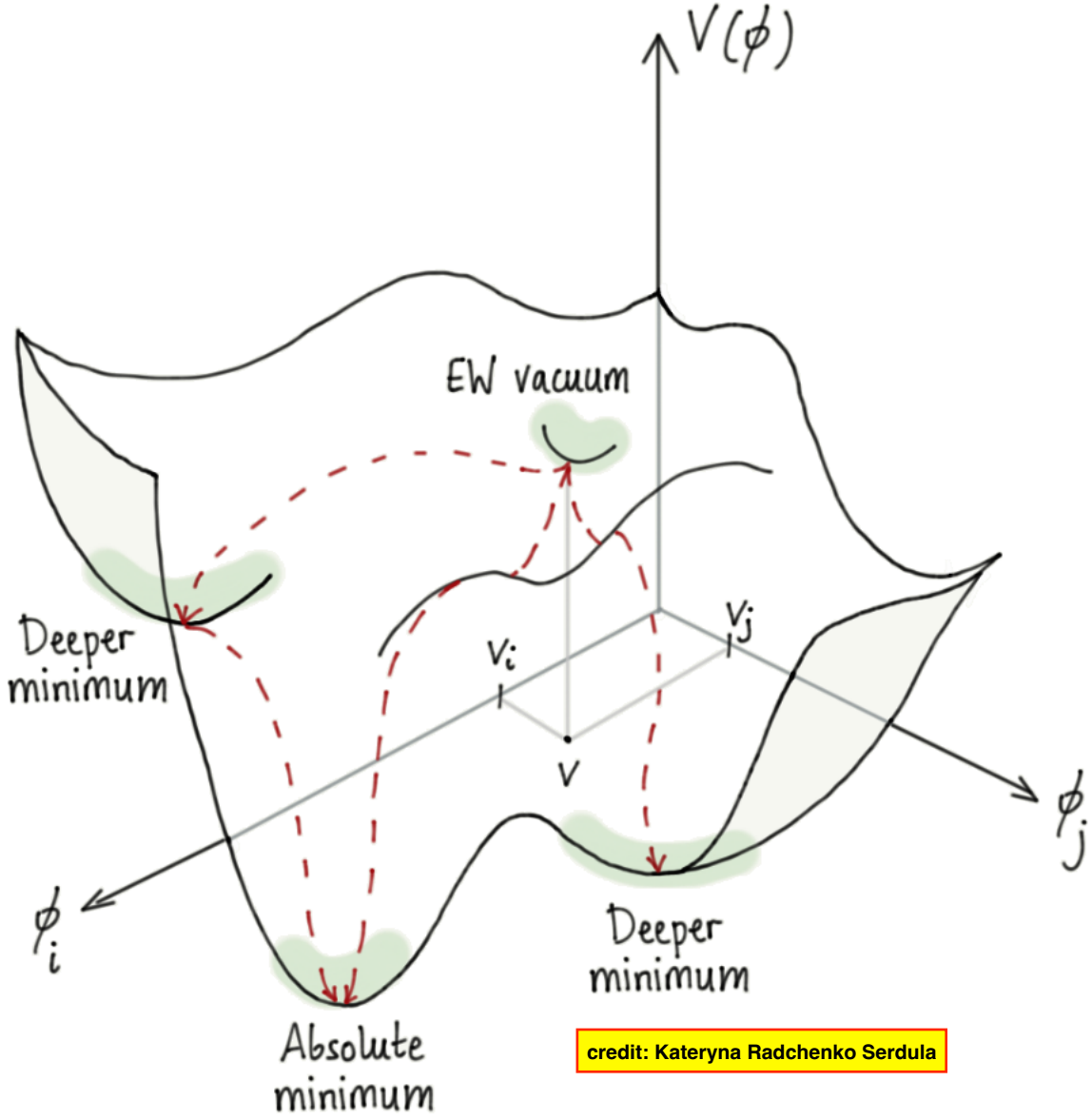


credit: Kateryna Radchenko Serdula

Higgs potential in extended Higgs Sectors

Mexican hat turns landscape with multiple minima

- more Higgs fields => much more complex potential “landscape” (even at zero-temperature)
- extra Higgs bosons
- several triple-Higgs couplings among them
- several minima
- EW vaccuum not necessarily global minimum => vacuum stability?



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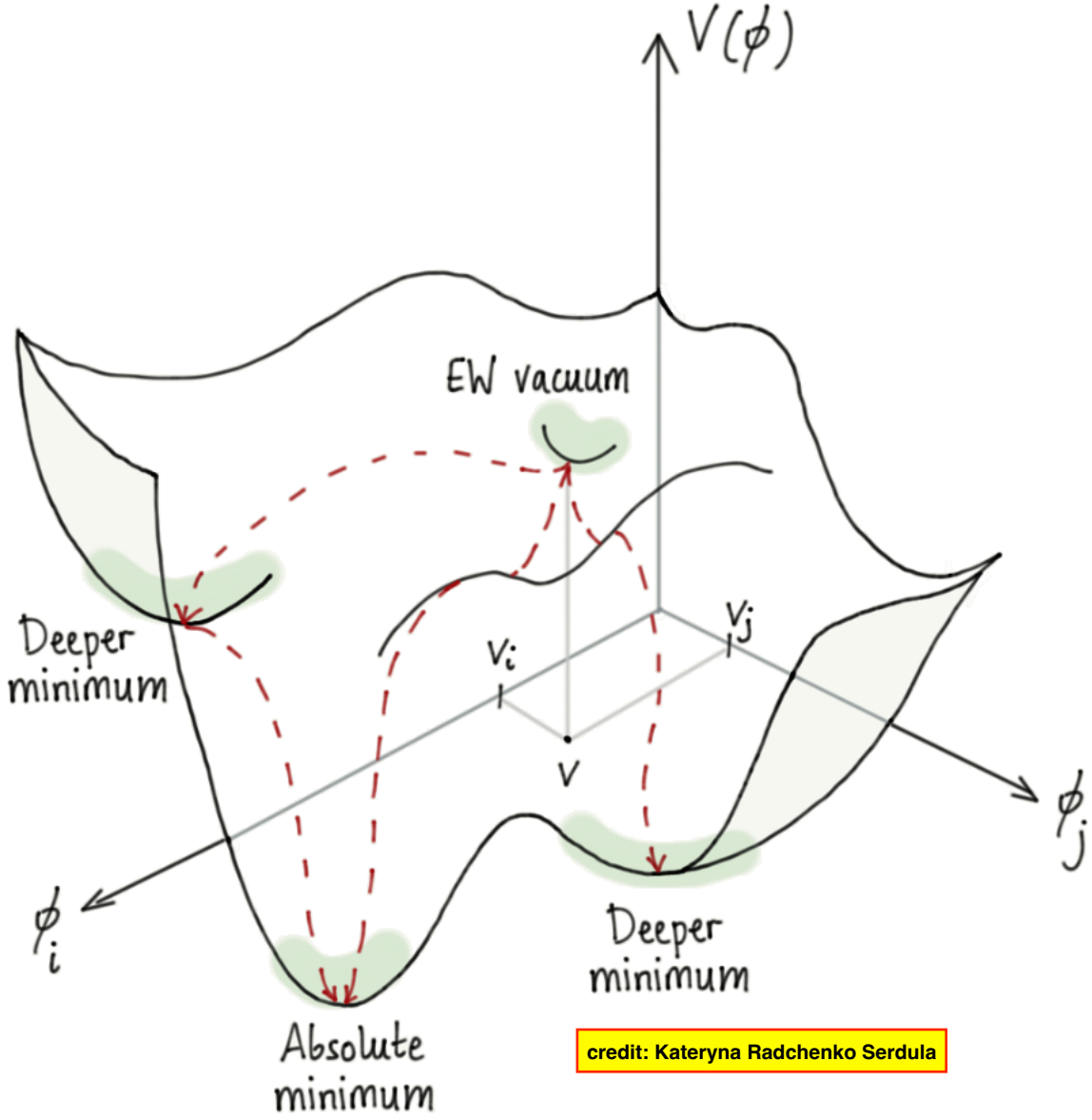
measure as many physical observables with least model-assumptions to explore this landscape - just assuming everything is like in the SM and extract one value is not sufficient!



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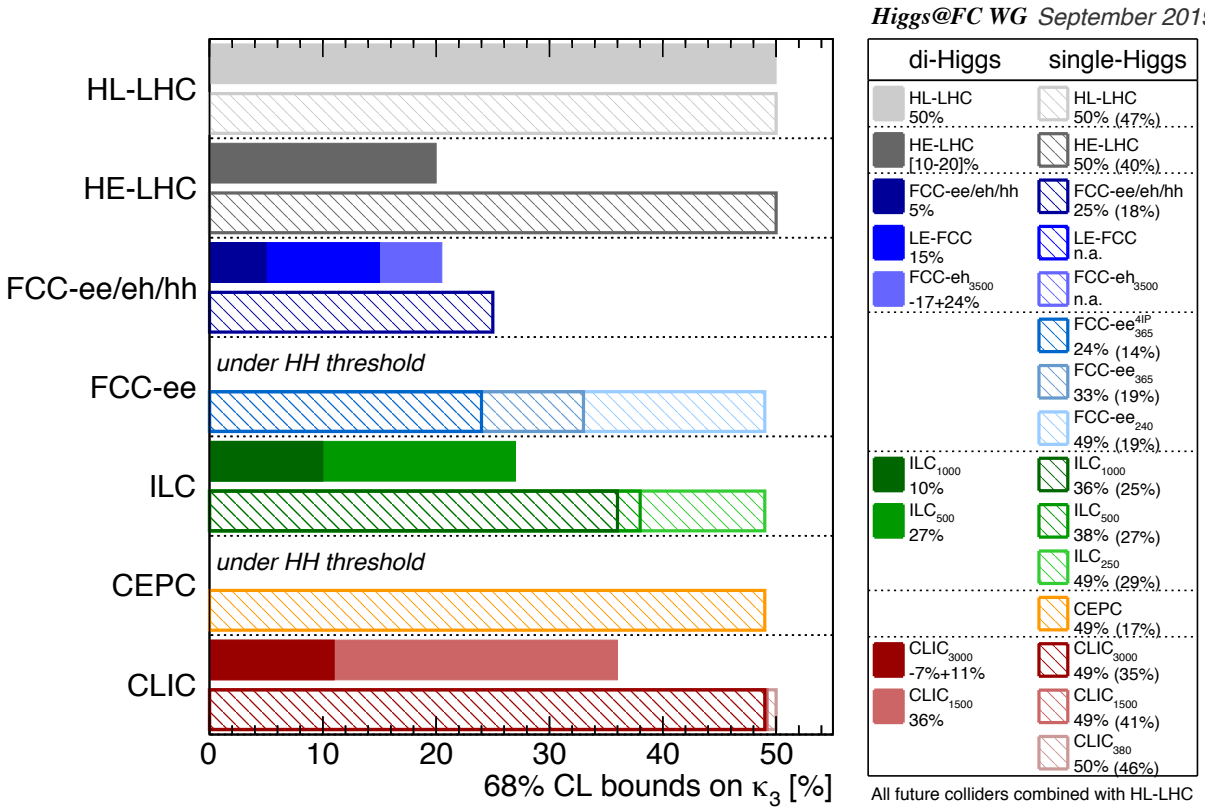
The Higgs self-coupling master plot of the last EPPSU



Higgs@FC WG *September 2019*

di-Higgs	single-Higgs
HL-LHC 50%	HL-LHC 50% (47%)
HE-LHC [10-20]%	HE-LHC 50% (40%)
FCC-ee/eh/hh 5%	FCC-ee/eh/hh 25% (18%)
LE-FCC 15%	LE-FCC n.a.
FCC-eh$_{3500}$ -17+24%	FCC-eh$_{3500}$ n.a.
	FCC-ee$^{4IP}_{365}$ 24% (14%)
	FCC-ee$_{365}$ 33% (19%)
	FCC-ee$_{240}$ 49% (19%)
ILC$_{1000}$ 10%	ILC$_{1000}$ 36% (25%)
ILC$_{500}$ 27%	ILC$_{500}$ 38% (27%)
	ILC$_{250}$ 49% (29%)
	CEPC 49% (17%)
CLIC$_{3000}$ -7%+11%	CLIC$_{3000}$ 49% (35%)
CLIC$_{1500}$ 36%	CLIC$_{1500}$ 49% (41%)
	CLIC$_{380}$ 50% (46%)

All future colliders combined with HL-LHC

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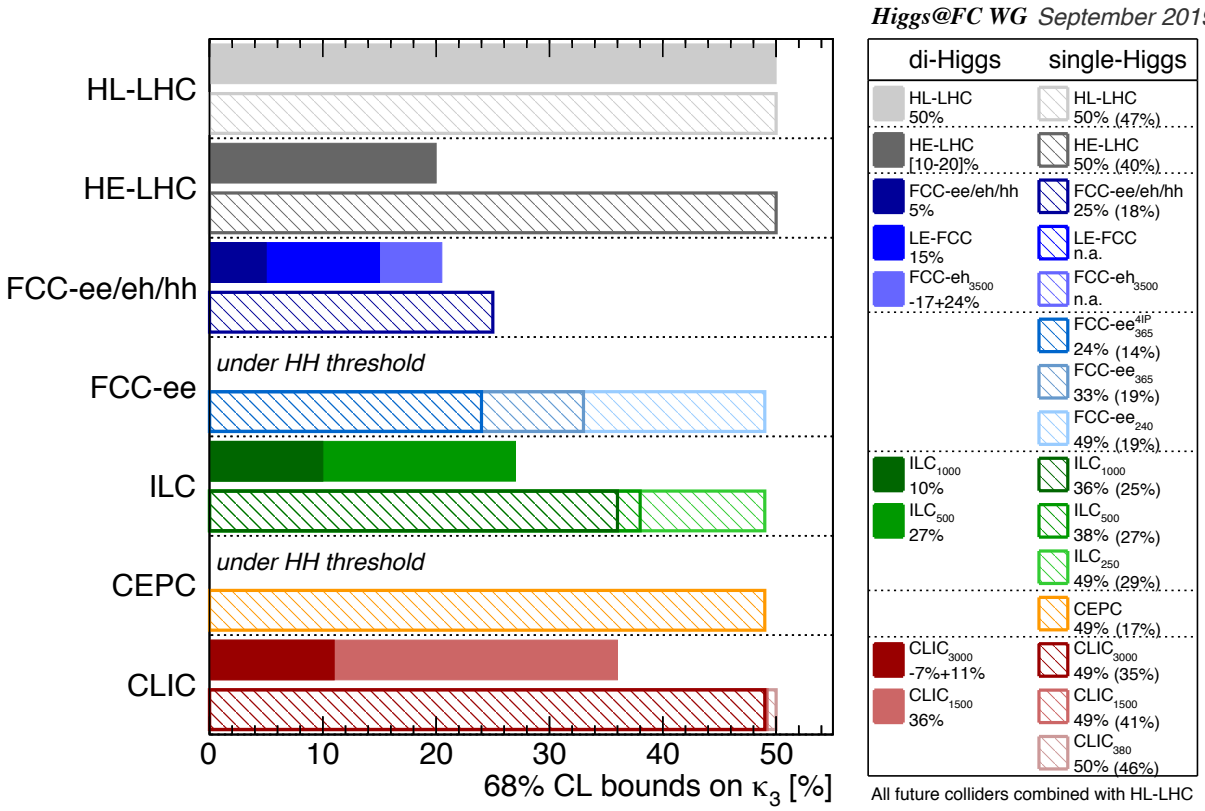

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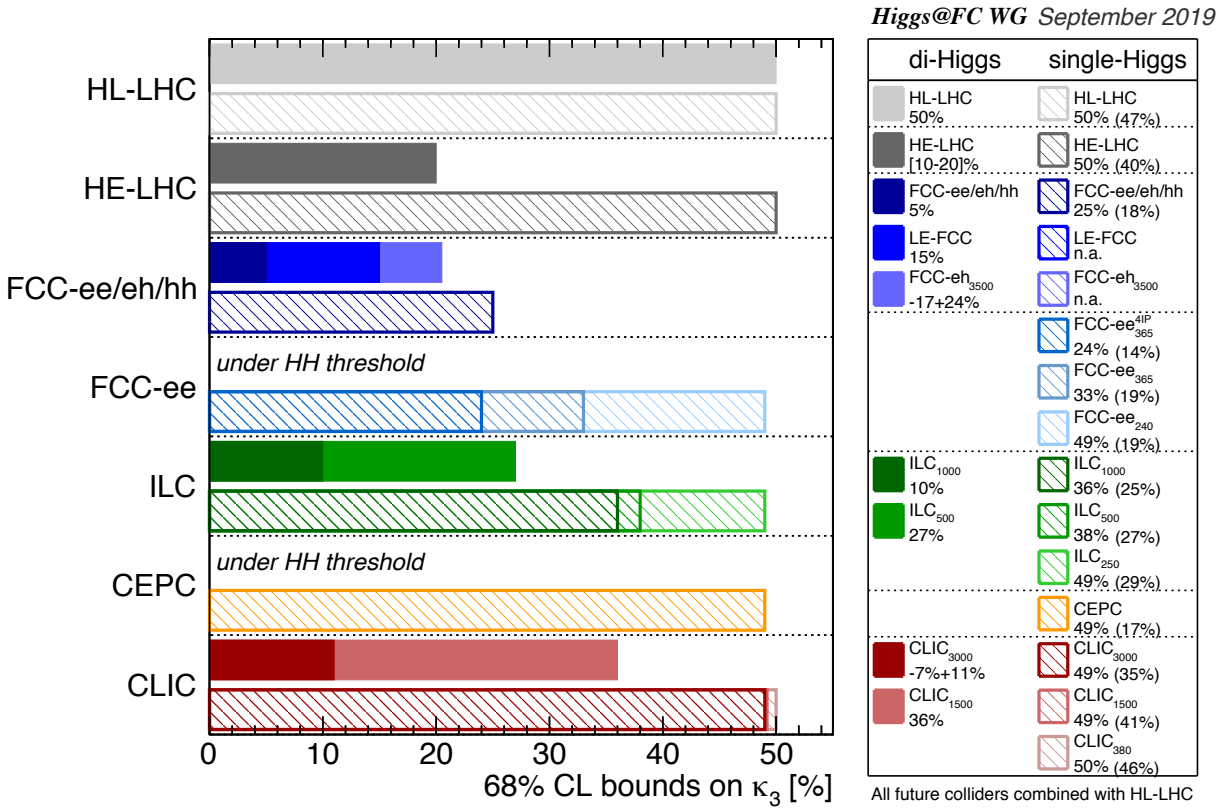

At lepton colliders, double Higgs-strahlung, $e^+e^- \to ZHH$, gives stronger constraints on positive deviations ($\varkappa 3 > 1$), while VBF is better in constraining negative deviations, ($\varkappa 3 < 1$). While at HL-LHC, values of $\varkappa 3 > 1$, as expected in models of strong first order phase transition, result in a smaller double-Higgs production cross section due to the destructive interference, at lepton colliders for the *ZHH* process they actually result in a larger cross section, and hence into an increased precision. For instance at ILC_{500}, the sensitivity around the SM value is 27% but it would reach 18% around $\varkappa_3 = 1.5$.

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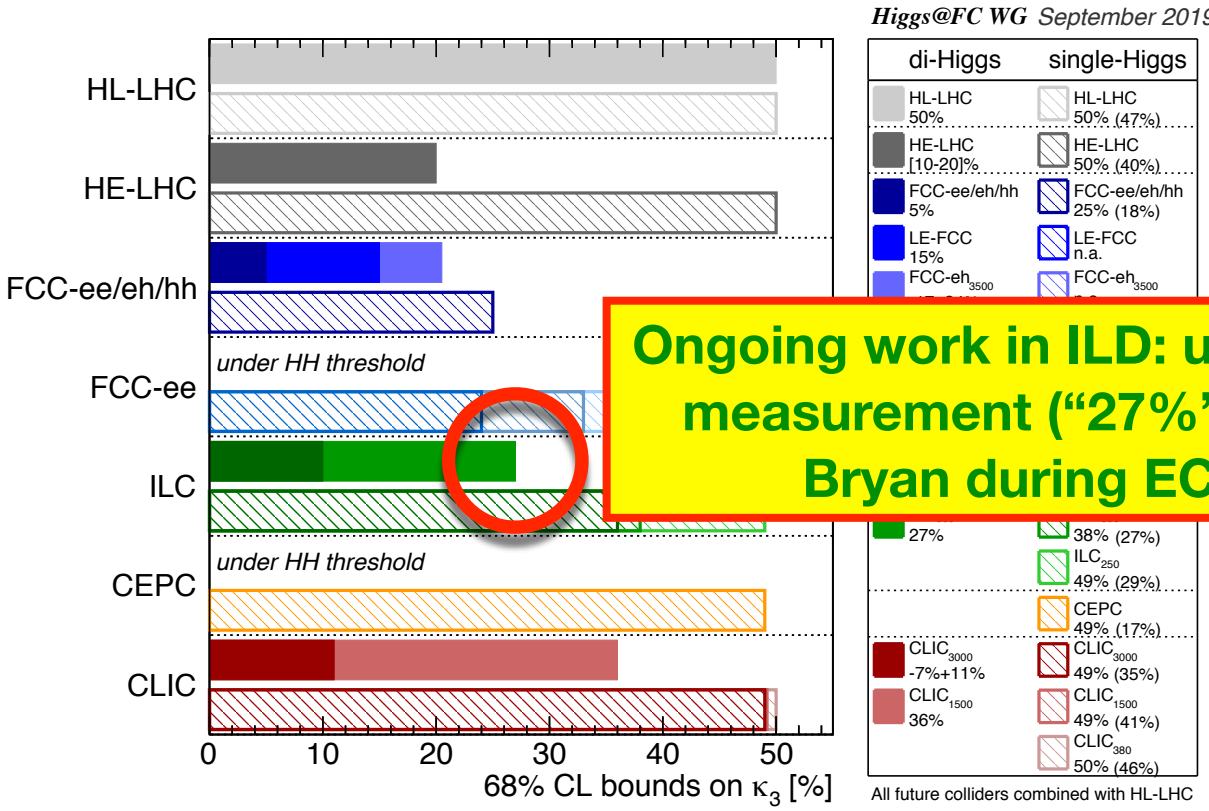

Ongoing work in ILD: update for this measurement ("27%") => talk by Bryan during ECFA WS

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Some of the typical arguments

…which you might encounter

1. Deviations of λ from SM will be small anyway

2. e+e- doesn't give relevant improvement over HL-LHC

3. λ can be extracted purely from loop corrections to ZH

1. No, deviation of λ from SM prediction can be large

even if all other couplings are SM-like

from dimensional analysis

Self-Coupling Dominance

In other words, no obstruction to having Higgs self-coupling modifications a "loop factor" greater than **all** other couplings. Could have

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M}{m_h}\right)^2\right]$$

without fine-tuning any parameters, as big as,

$$(4\pi v/m_h)^2 \approx 600$$

which is significant!

Durieux, MM, Salvioni. 2022

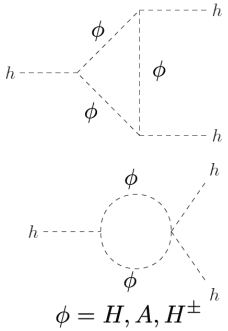
M. McCullough @ LCWS2024

or from UV complete BSM models

Concrete example: 2HDM: [taken from F. Arco '24]

Parameter scan in the 2HDM (all types):

[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]



Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
I	[-0.2, 1.2]	[0.2, 6.8]	[-1.6, 1.5]	[-2.1, 1.9]
II	[0.6, 1.0]	[0.7, 5.6]	[-1.5, 1.6]	[-1.7, 2.0]
LS	[0.5, 1.0]	[0.6, 5.6]	[-1.7, 1.7]	[-2.0, 2.1]
FL	[0.7, 1.0]	[0.8, 5.6]	[-1.6, 1.3]	[-1.9, 1.5]

(results from the effective potential)

- Very large corrections are possible! $\lambda_{hhh}^{(1)} >> \lambda_{hhh}^{(0)}$
- h couplings to heavy Higgs bosons can be large ($\lambda_{h\phi\phi} \sim 15$)
  - Even at the ***alignment limit*** !!!

(In the SM, top-loops are ~ -8%)

⇒ effect of the extended BSM Higgs sector!

S.Heinemeyer @ LCWS2024

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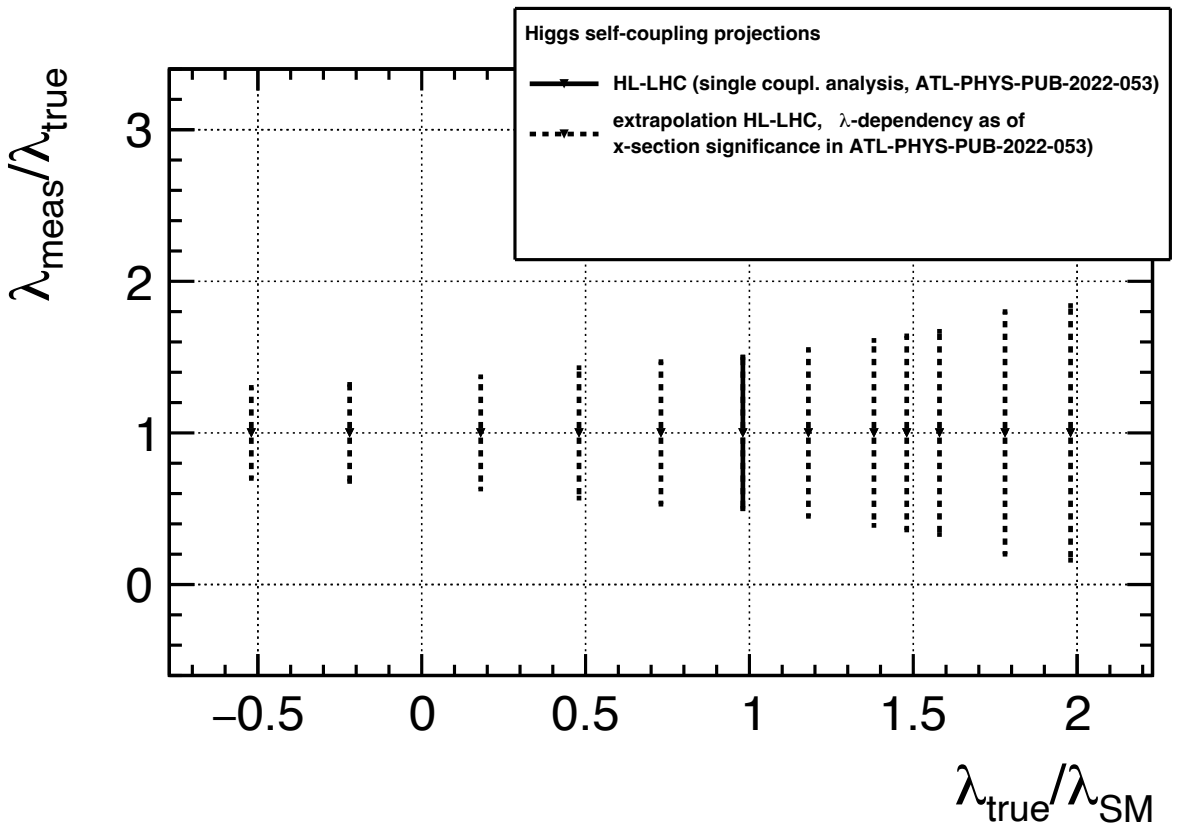
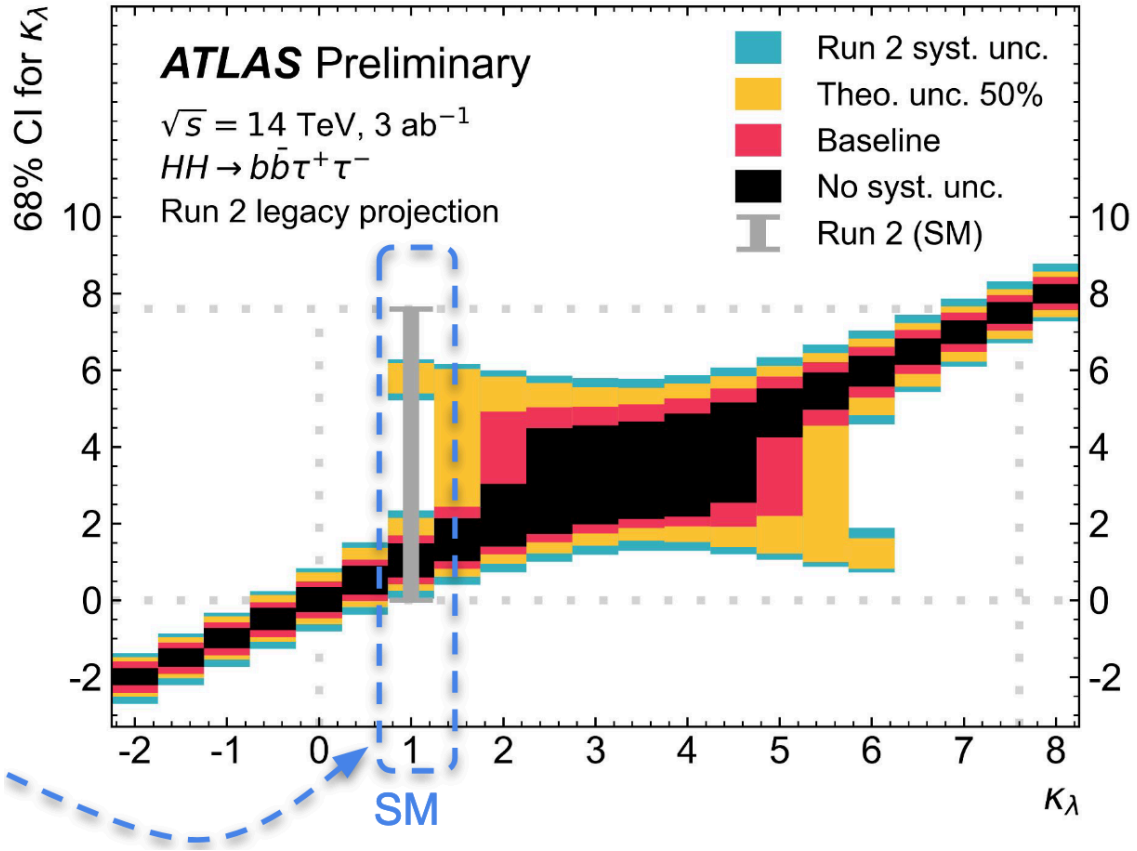
Both ILC and HL-LHC will improve analyses
Limit of “perfect” analysis at ILD500: 6%





Higgs Hunting 2024

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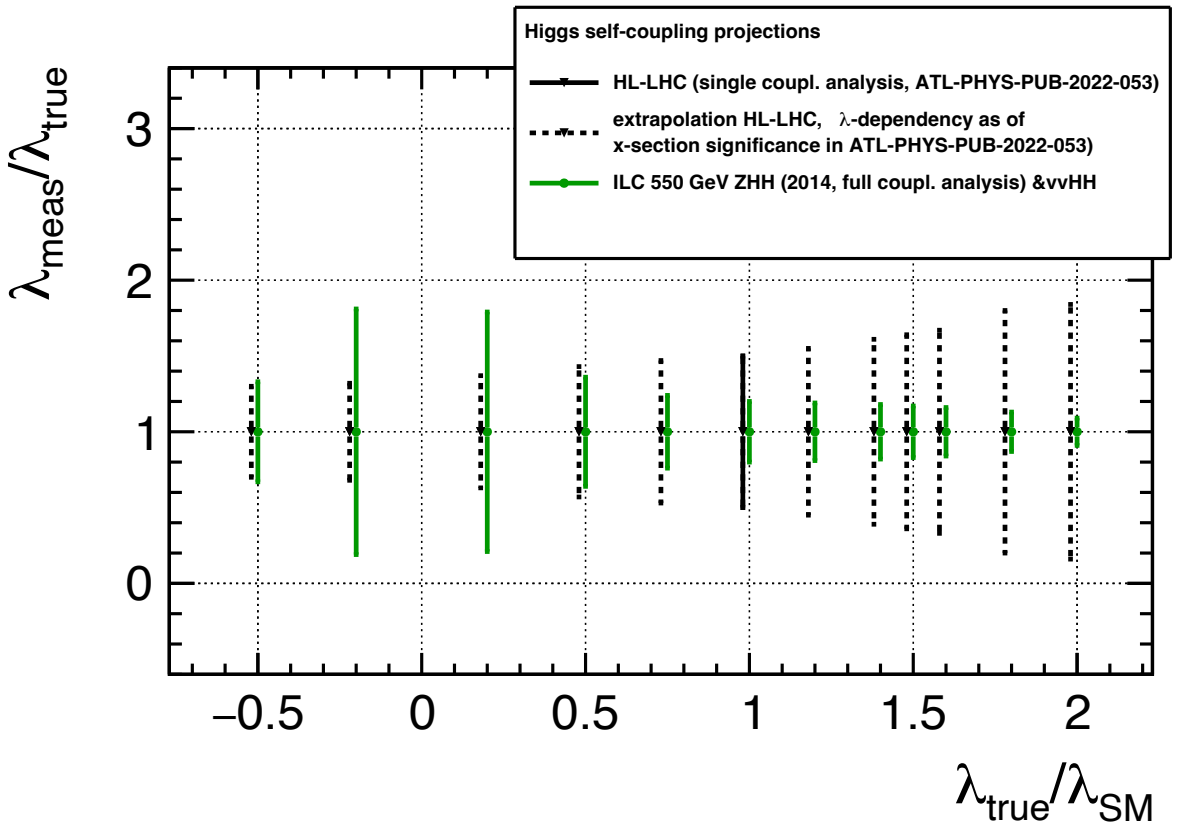

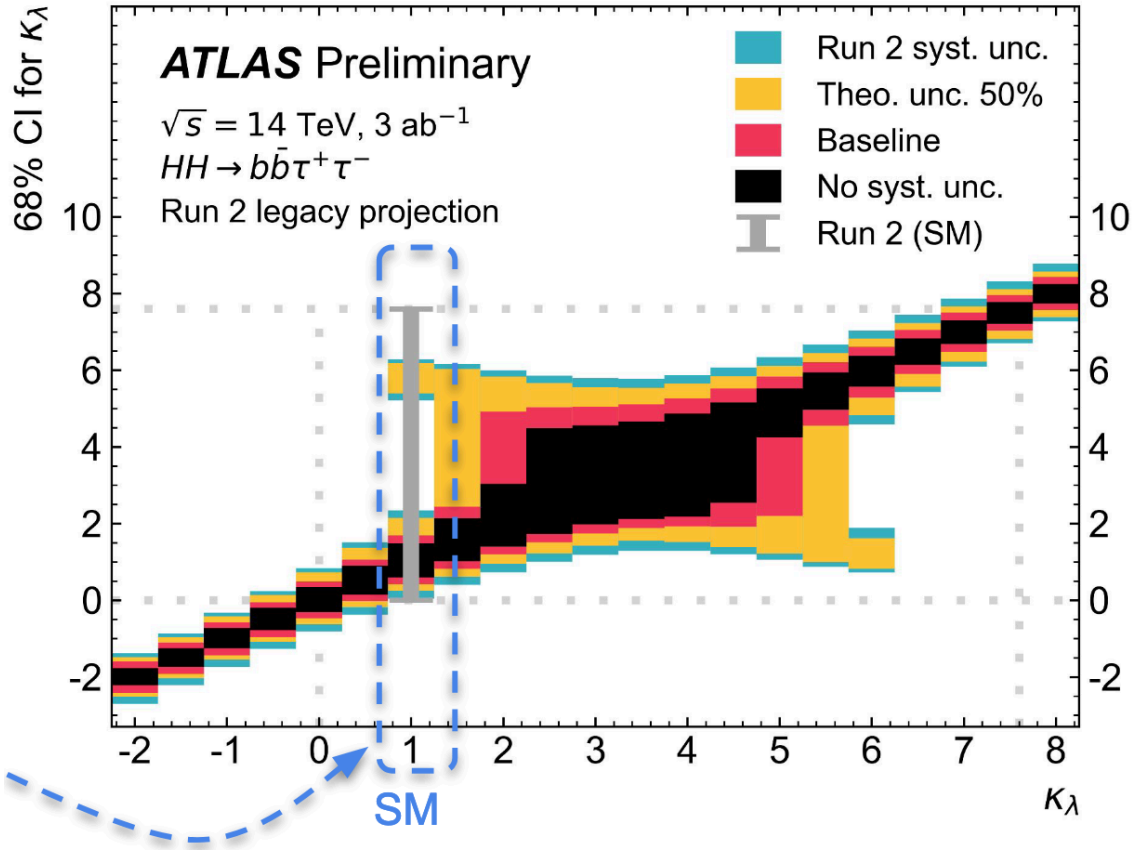

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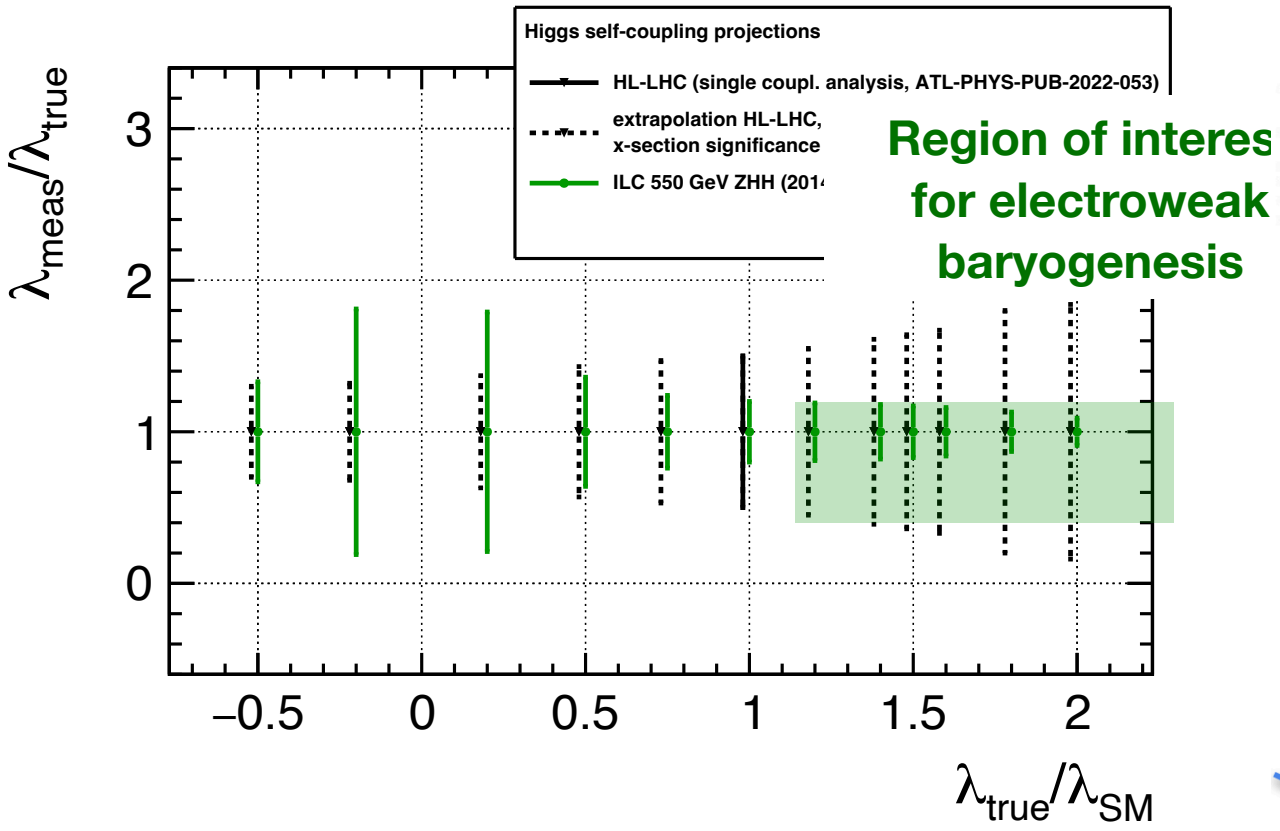

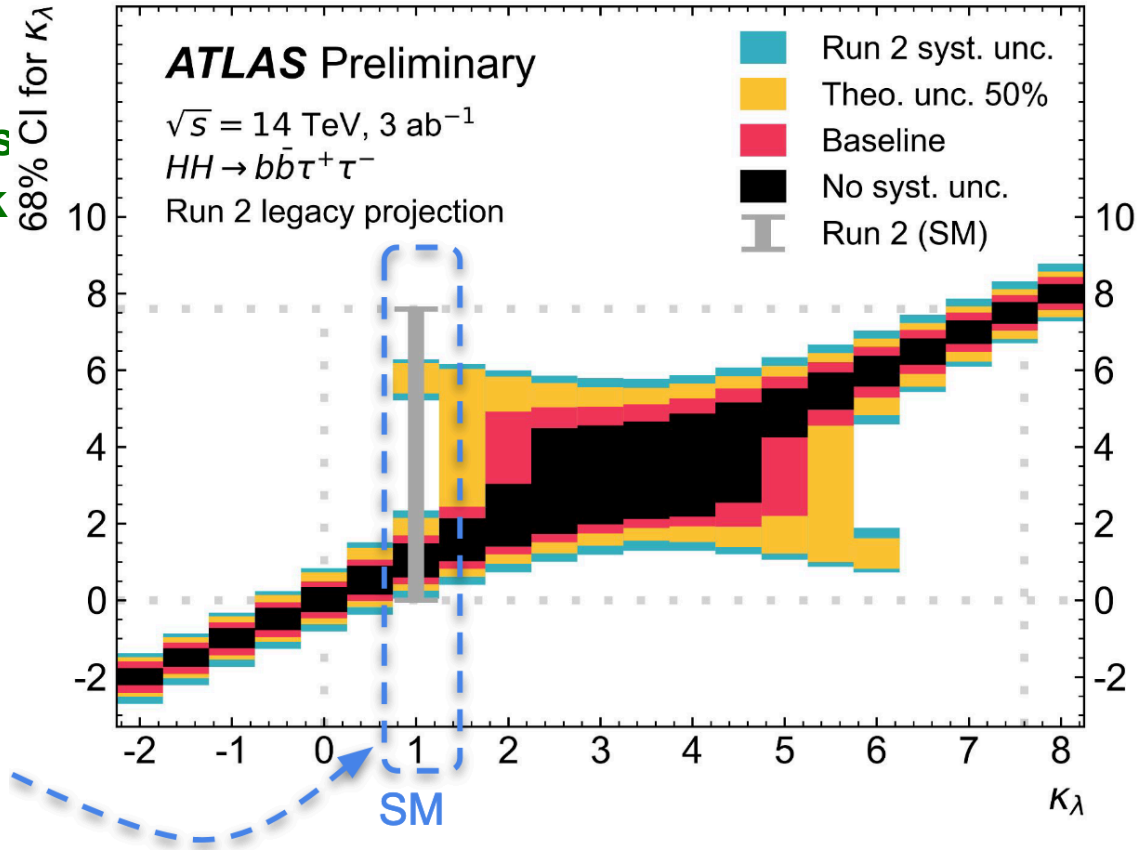

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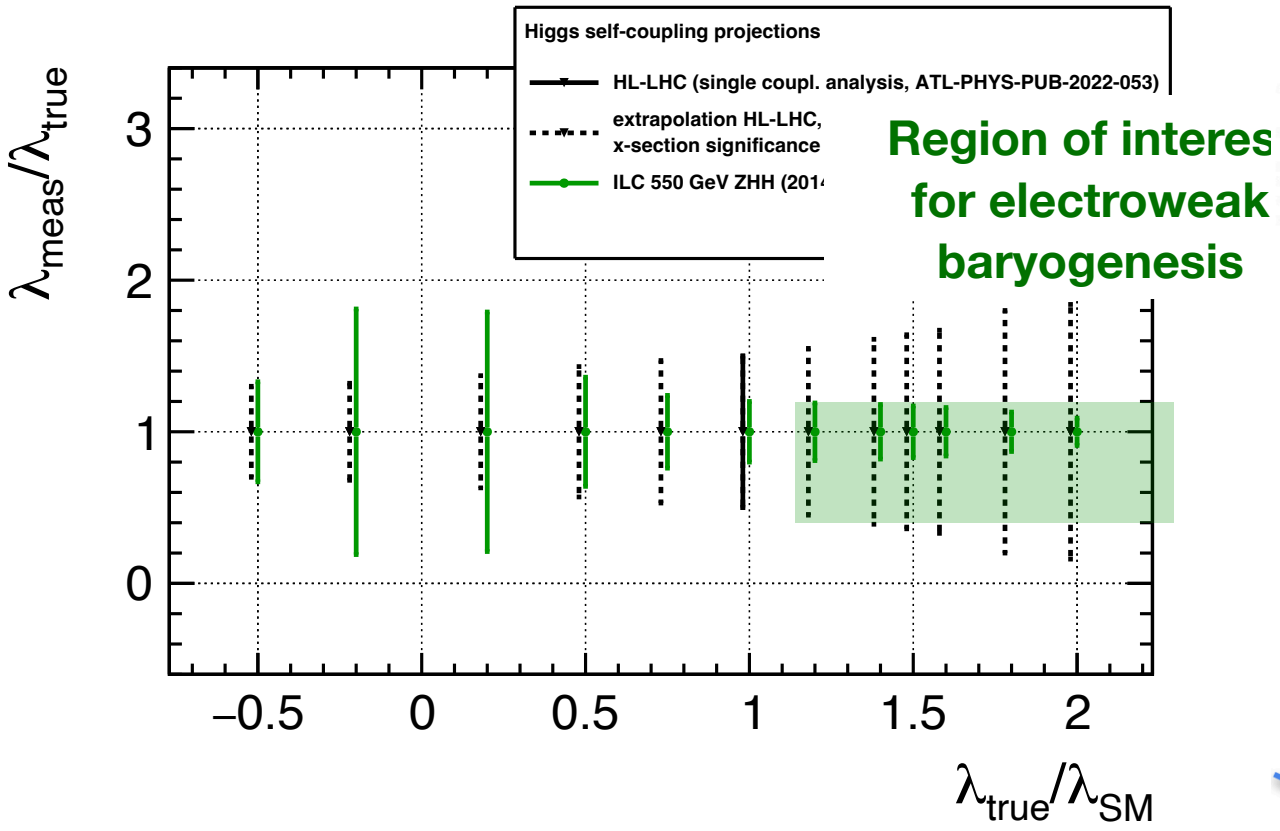

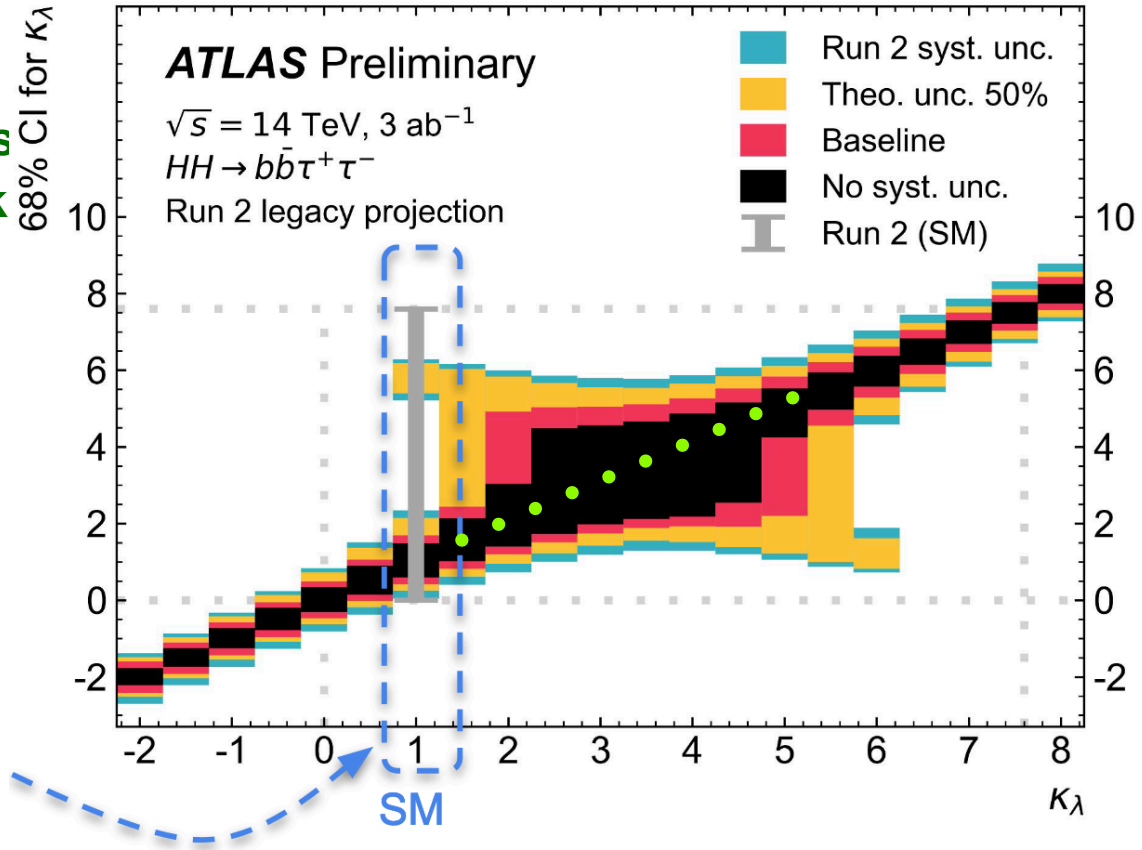

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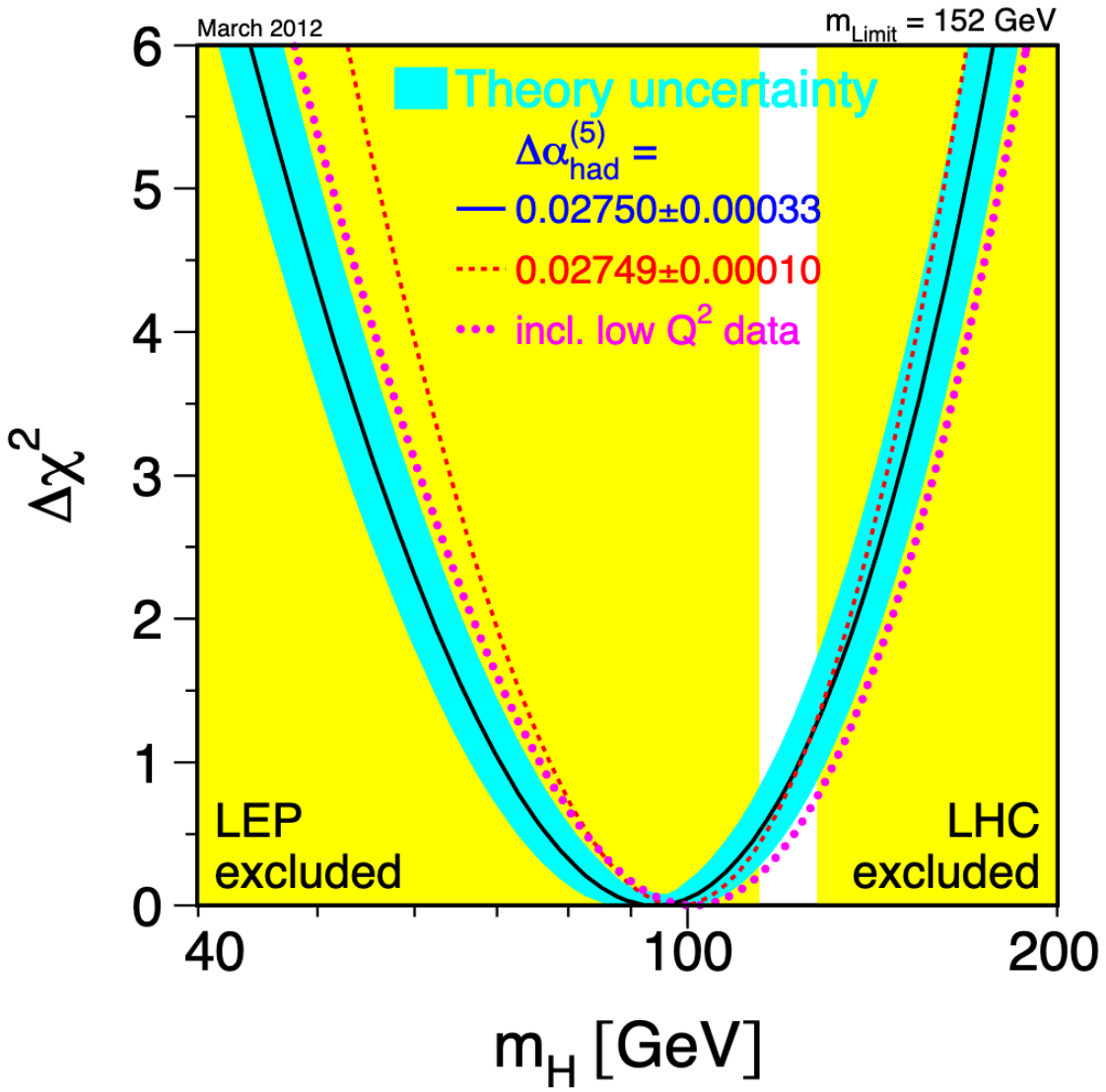
Well-known analogon:



[LEPEWWG '12]

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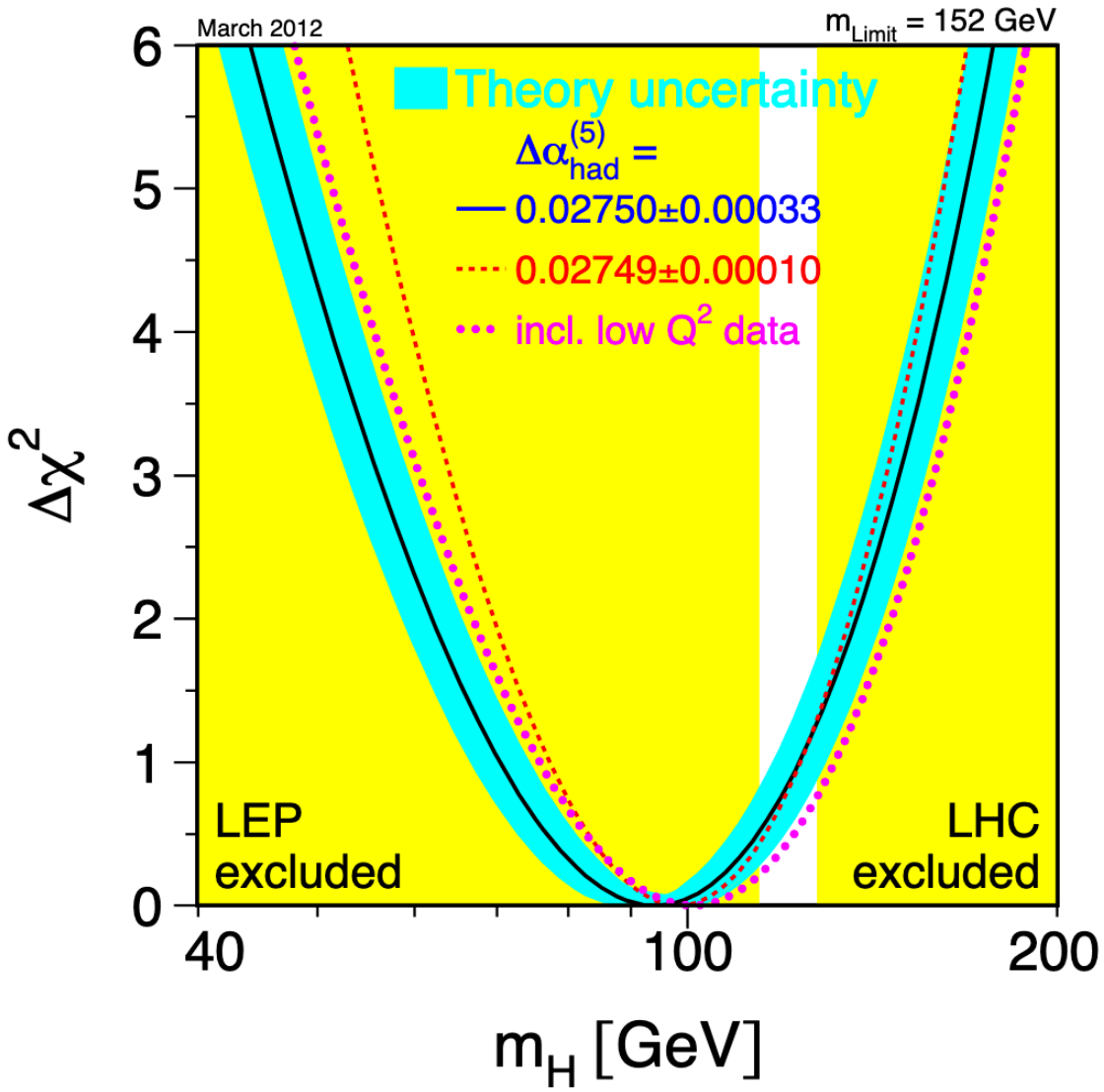

[LEPEWWG '12]

We did not claim a measurement of the Higgs-boson mass at 95 GeV from this analysis!

This is not a "measurement" of m_h, but an indirect constraint from loop-corrections within a specific model (in this case the SM)

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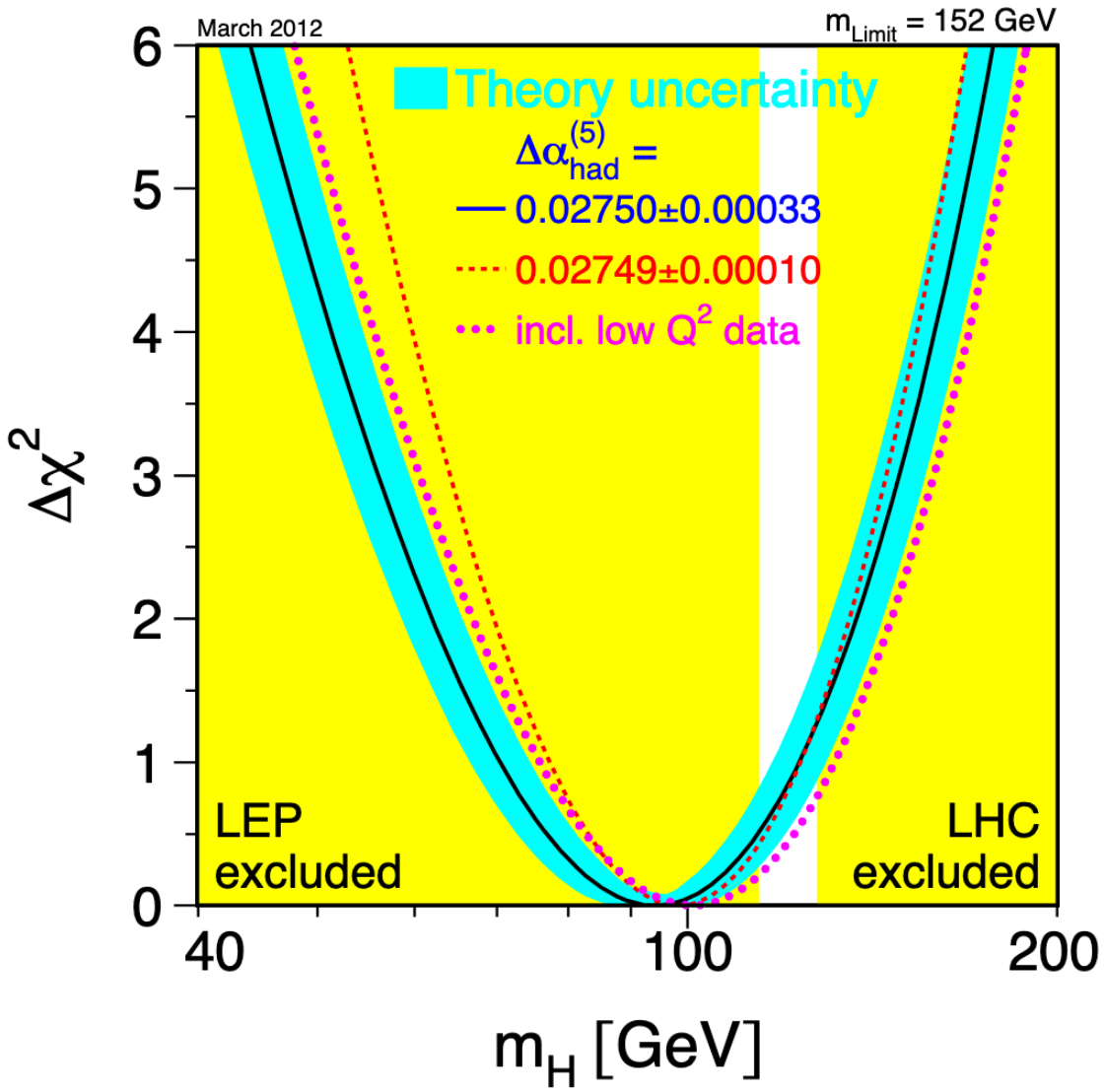


[LEPEWWG '12]

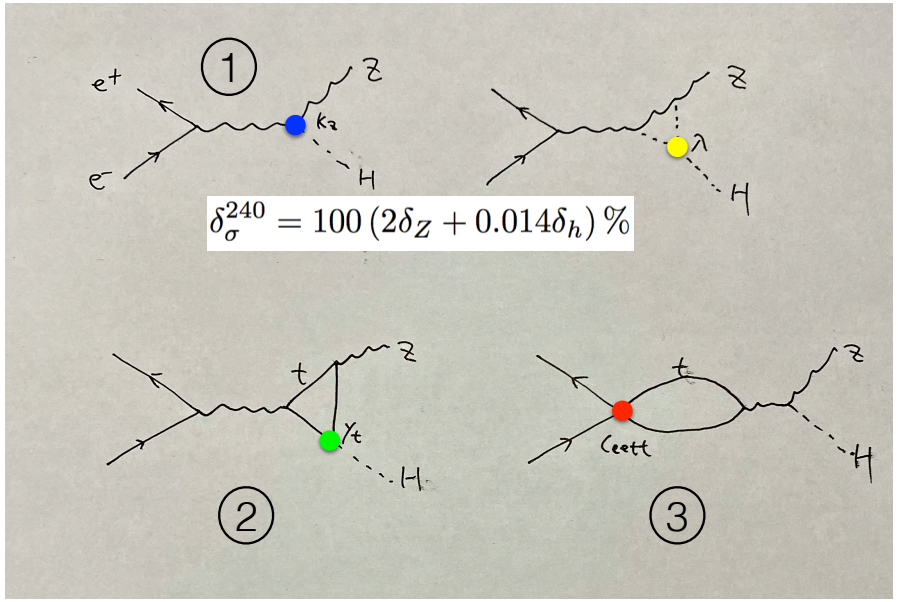
c.f. talk by G.Weiglein in WG1-GLOB session on Wednesday

We did not claim a measurement of the Higgs-boson mass at 95 GeV from this analysis!

This is not a "measurement" of m_h, but an indirect constraint from loop-corrections within a specific model (in this case the SM)

3.b) No, even within SMEFT this has not been demonstrated

NLO SMEFT calculations only recently coming up, so far only LO + the one loop diagram with the self-coupling!



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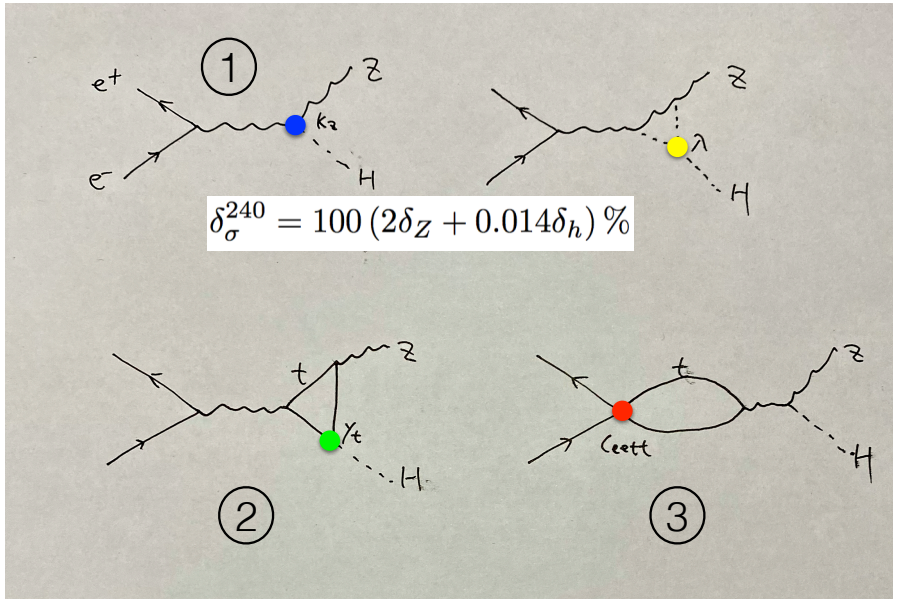
https://arxiv.org/pdf/2409.11466

Quote from conclusion of

"Through the NLO analysis presented here, we have extended previous partial results that included only a small subset of operators by incorporating the complete set of dimension-six operators contributing to the next-to-leading order corrections. Except for the contribution from the Higgs tri-linear coupling, Oϕ, current sensitivity studies for future e+e− colliders utilize LO SMEFT predictions [57, 74, 75]. In particular, our results demonstrate that limits on the Higgs tri-linear coupling are highly correlated with the contributions of other operators, including those that first occur at NLO."



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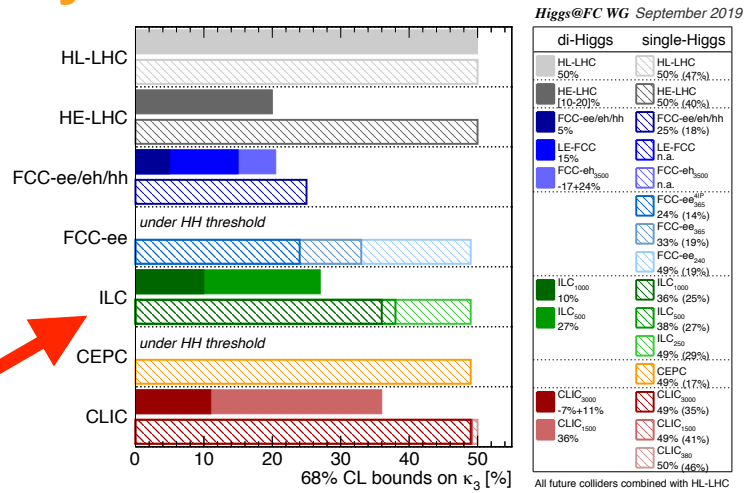
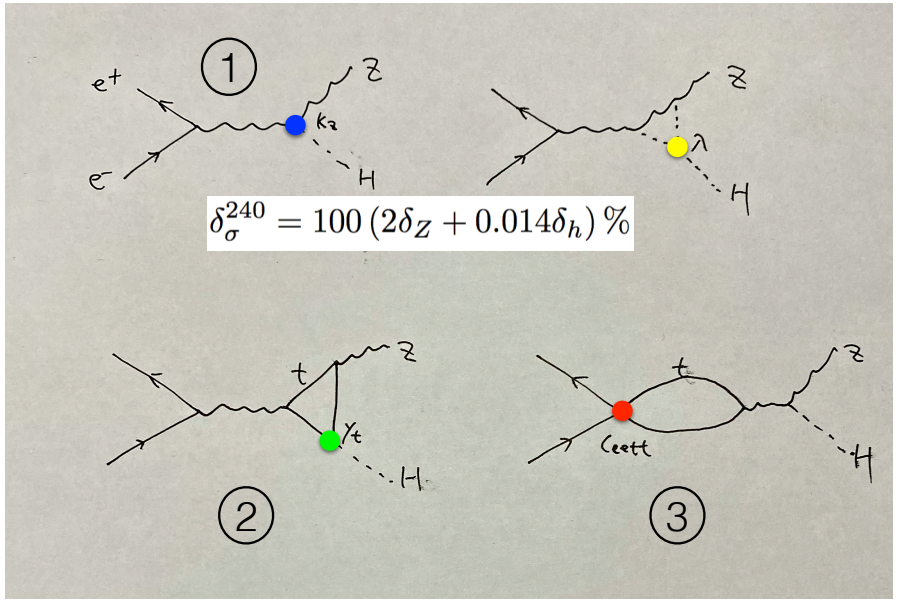
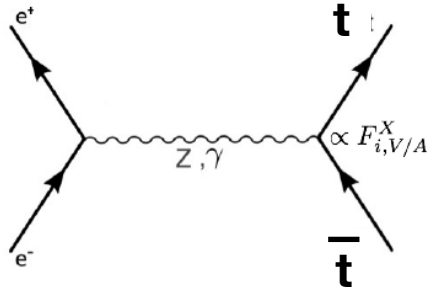




Full SMEFT analysis of Top Quark sector

Essential to understand special relation of top quark and Higgs boson



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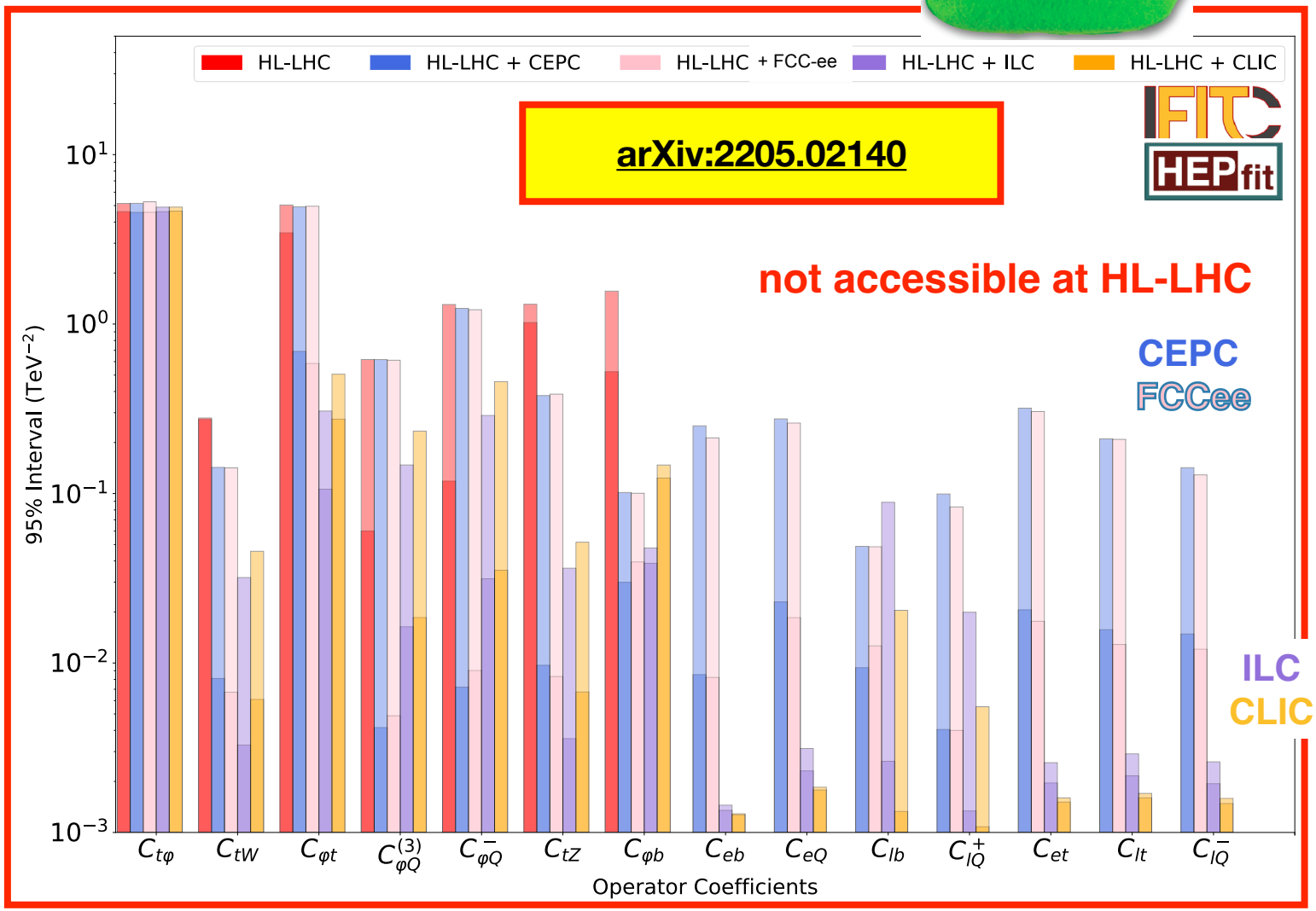

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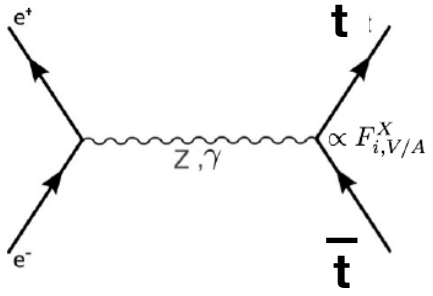

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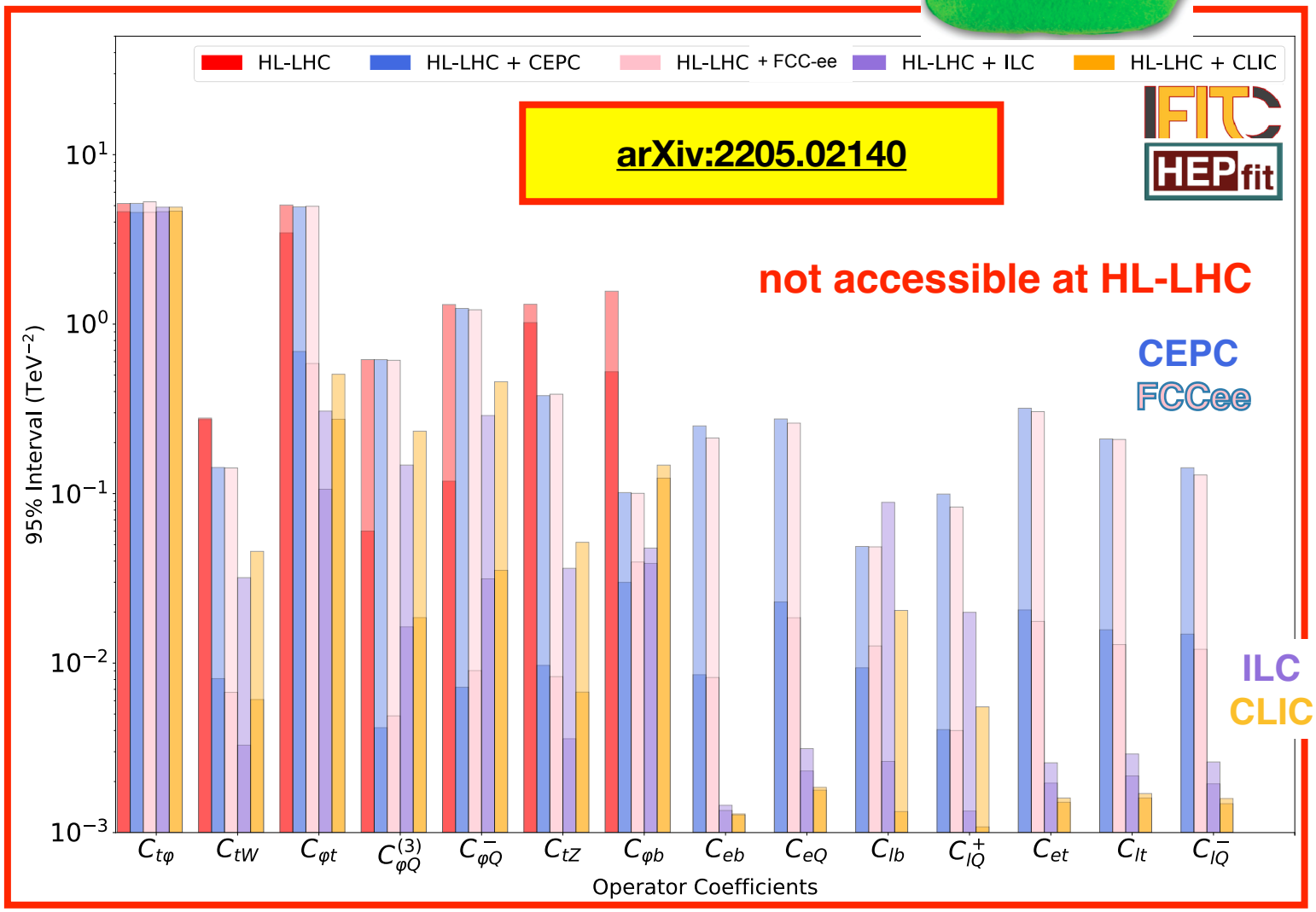

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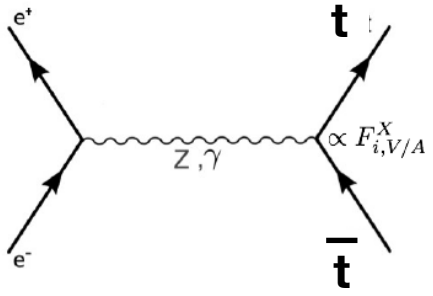

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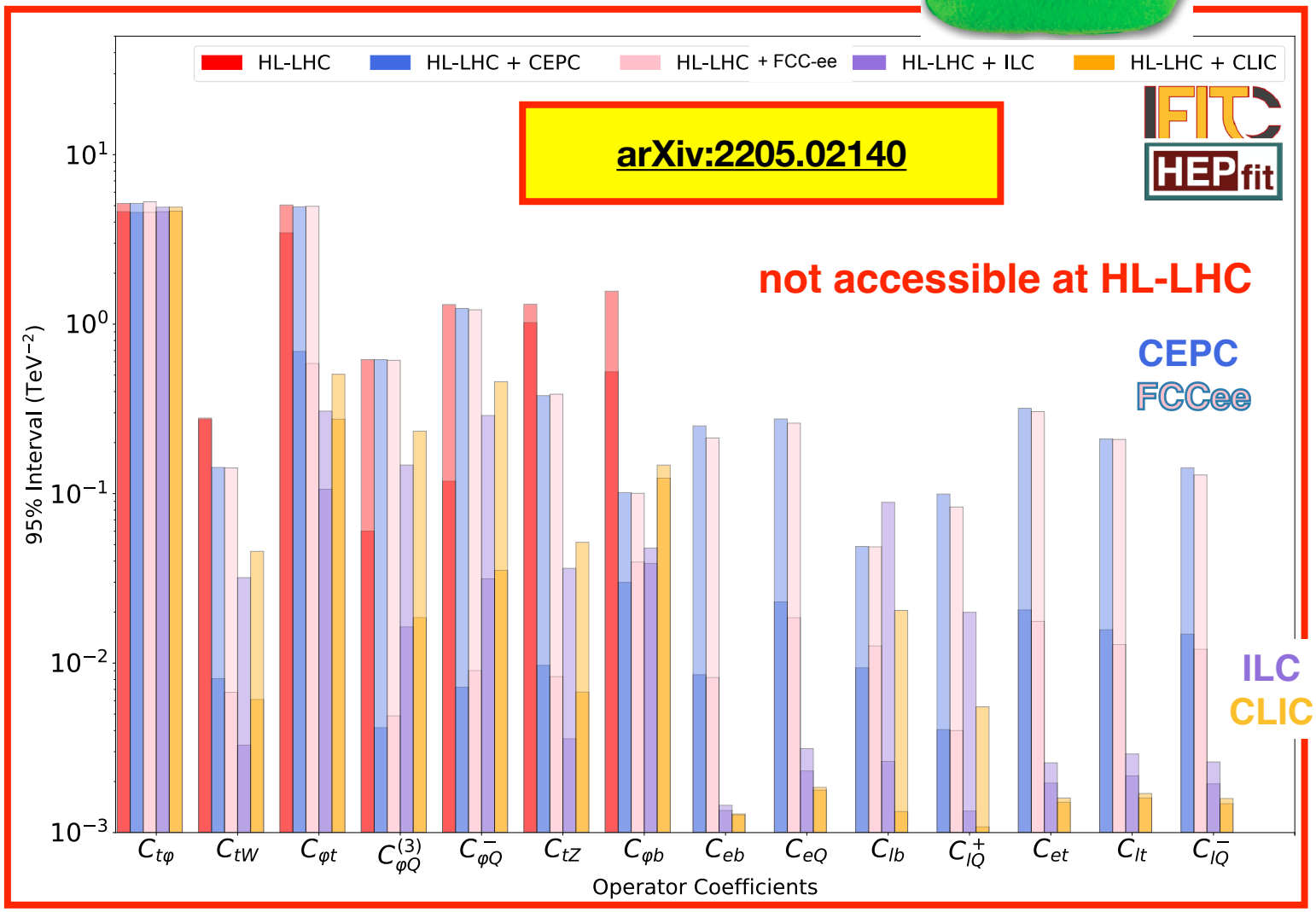

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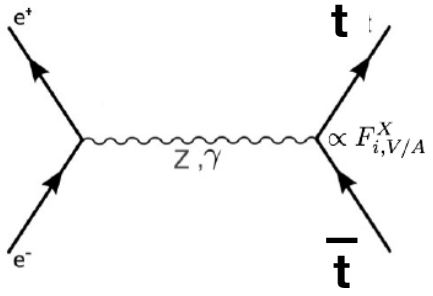

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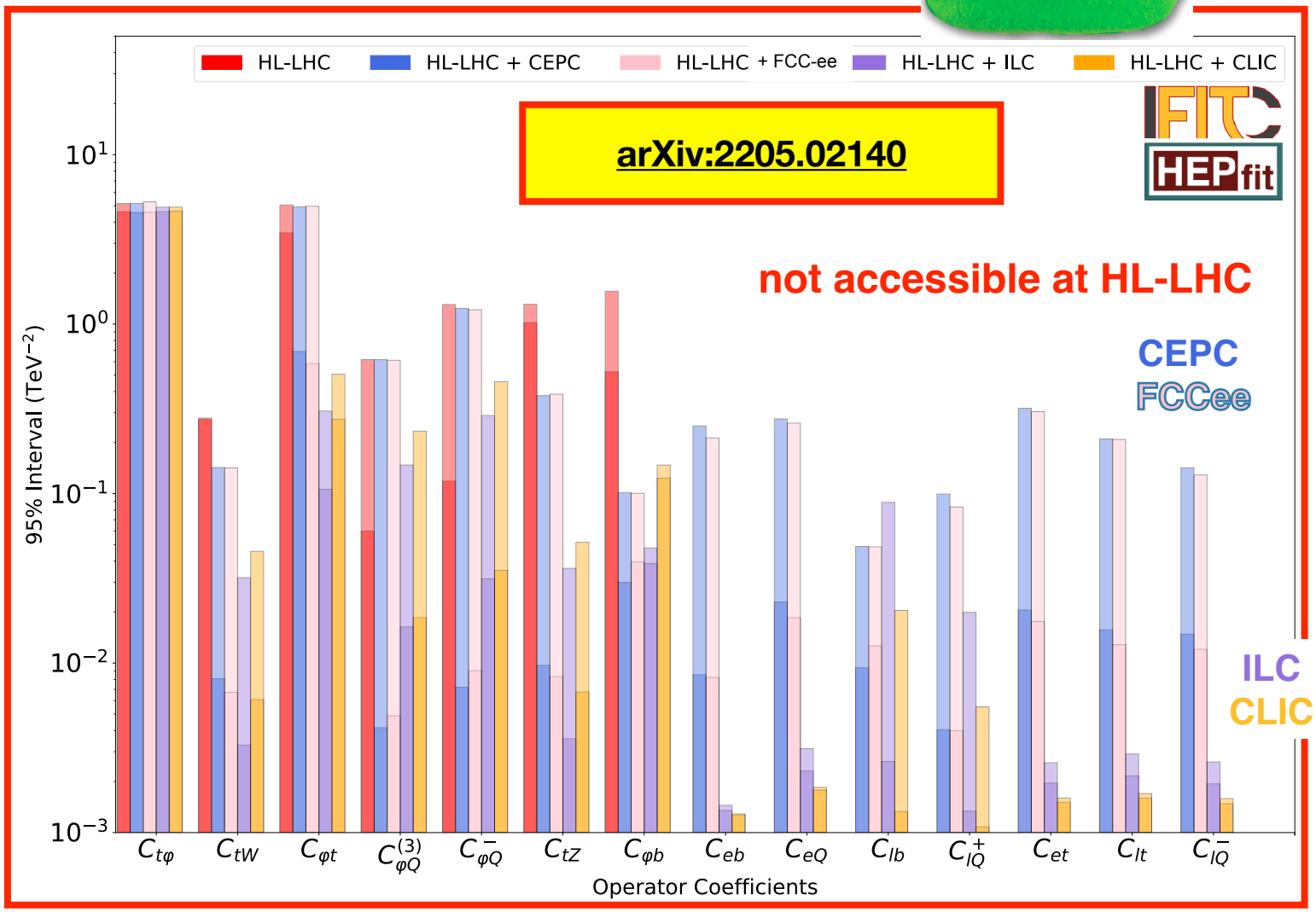

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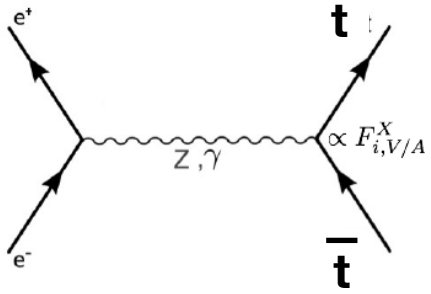

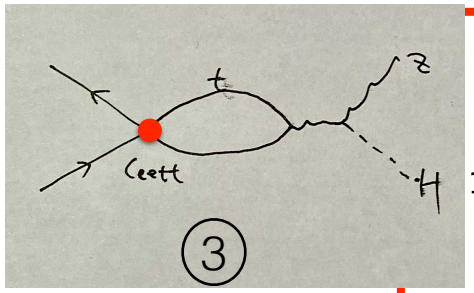

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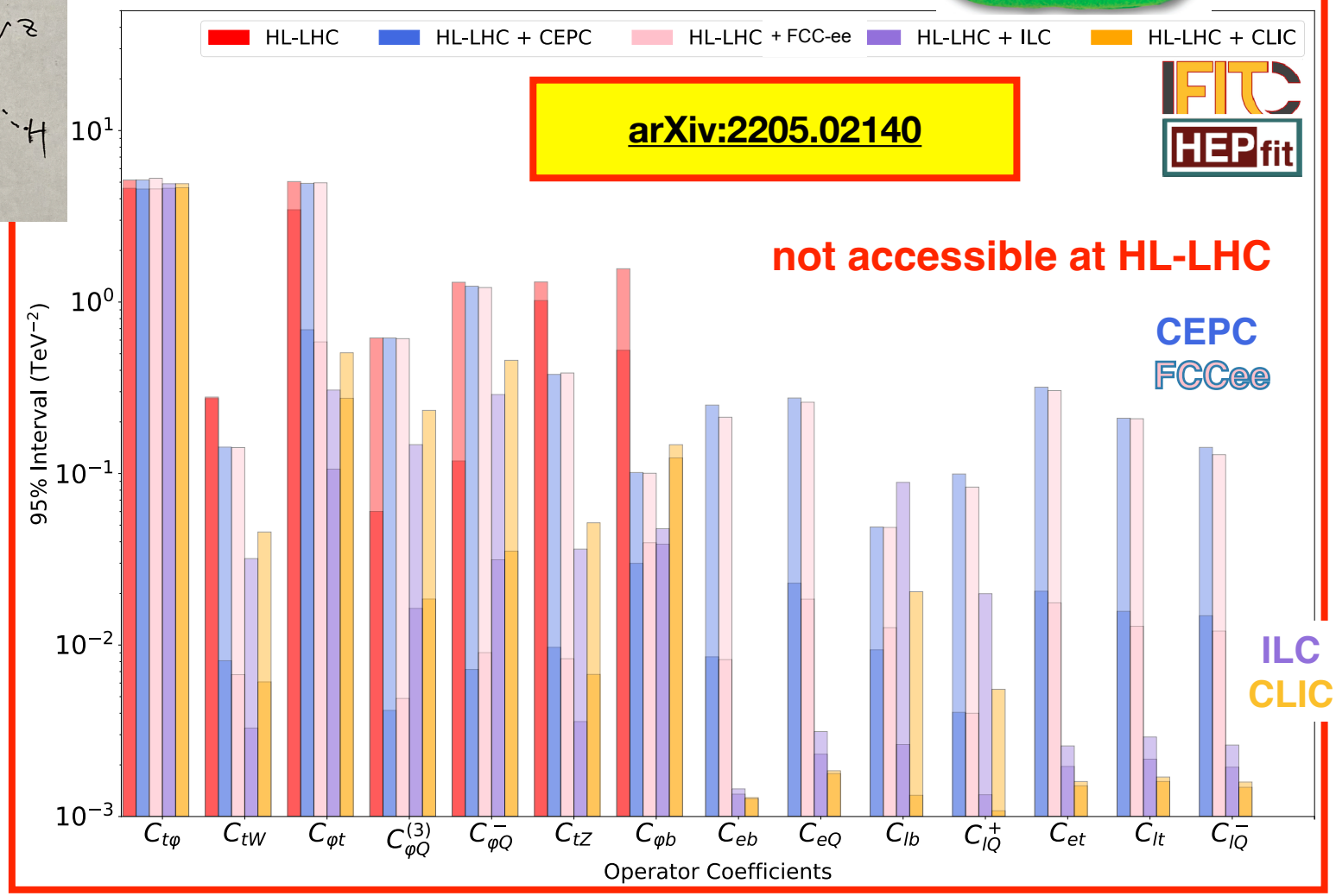

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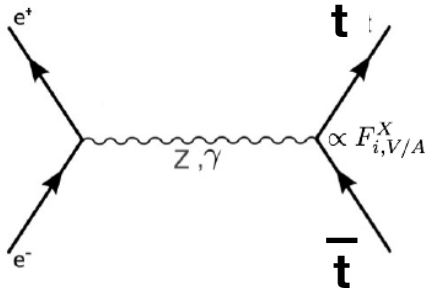

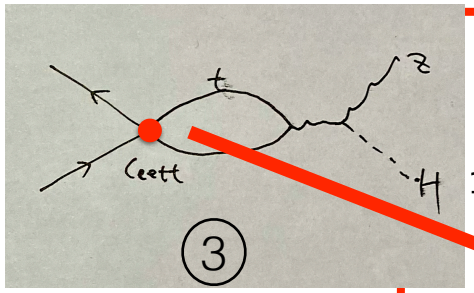

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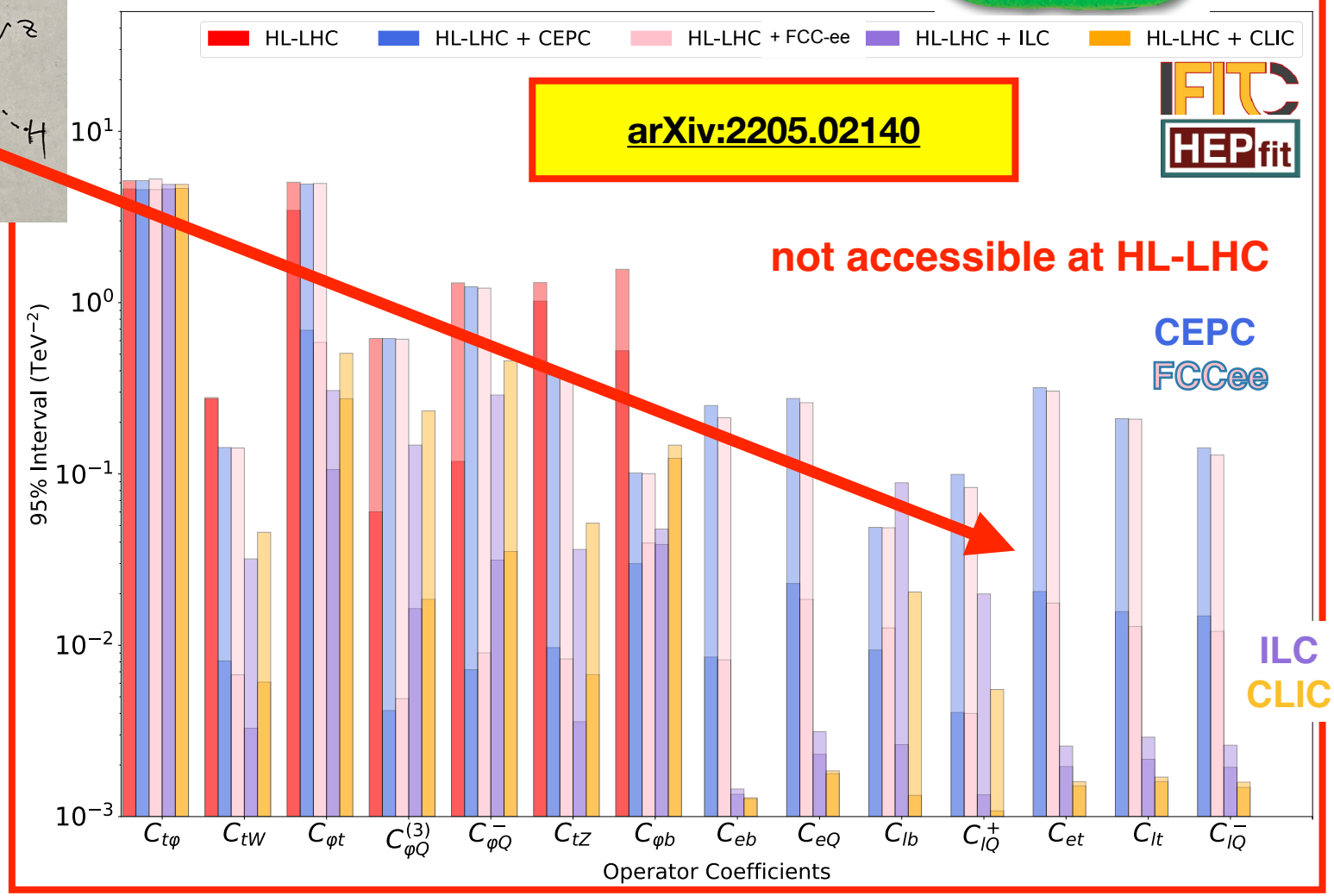
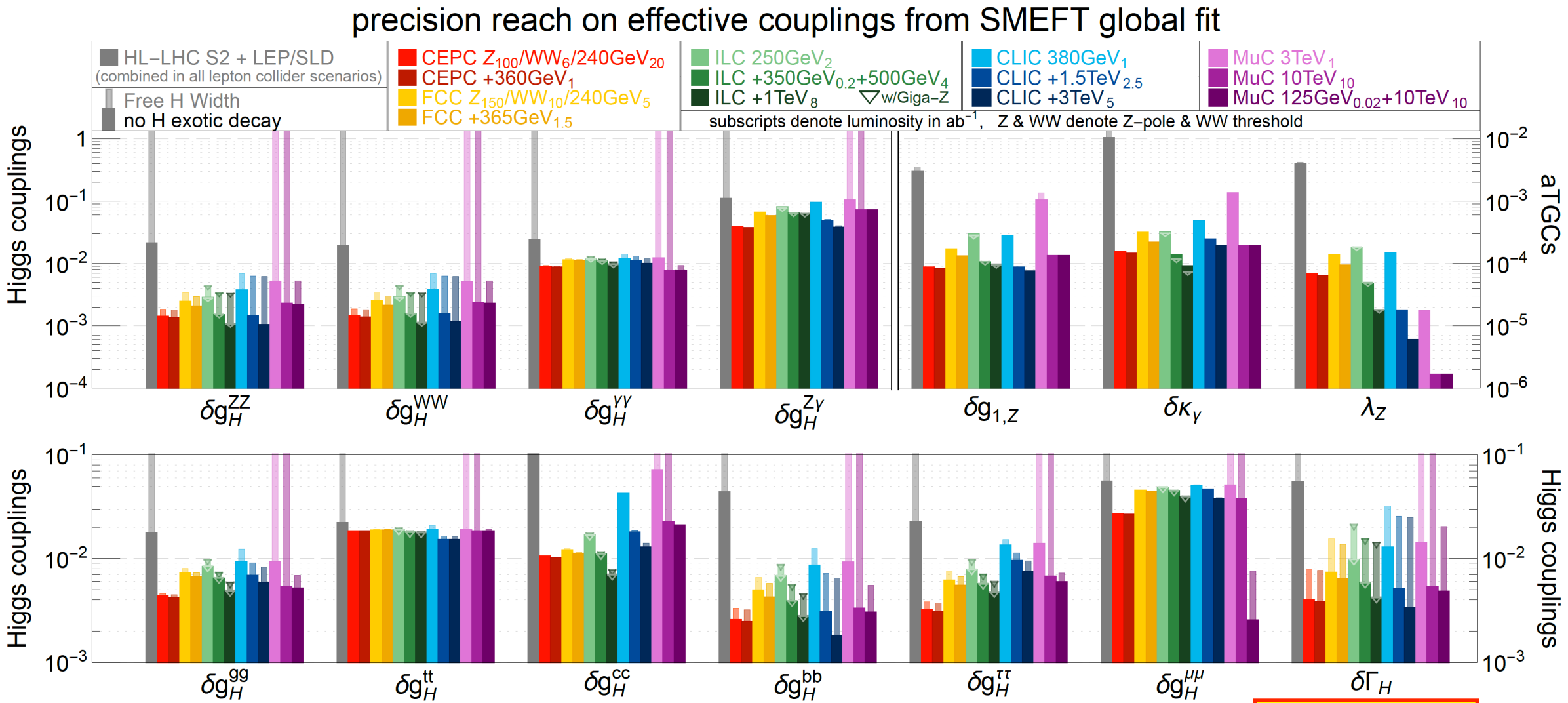


Triple Gauge Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



arXiv:2206.08326

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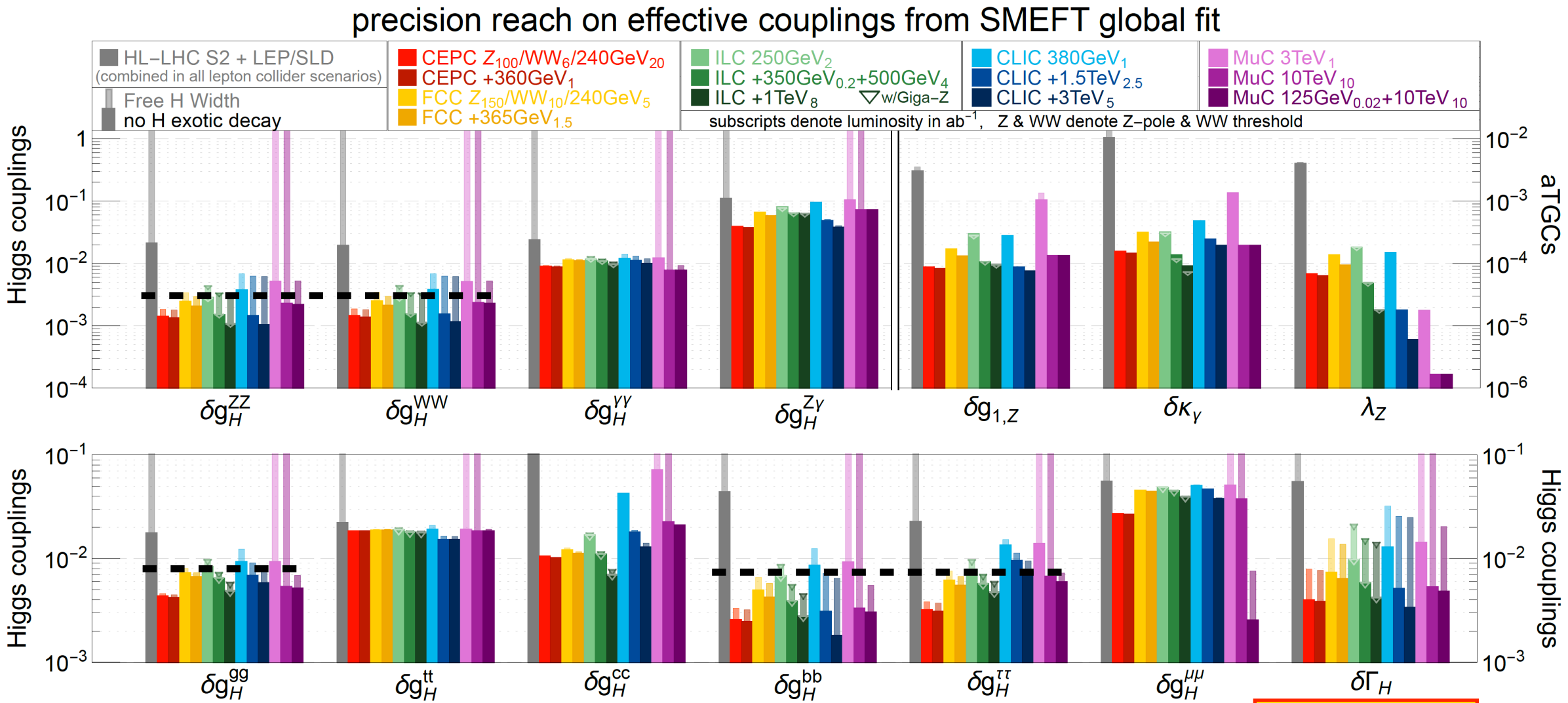

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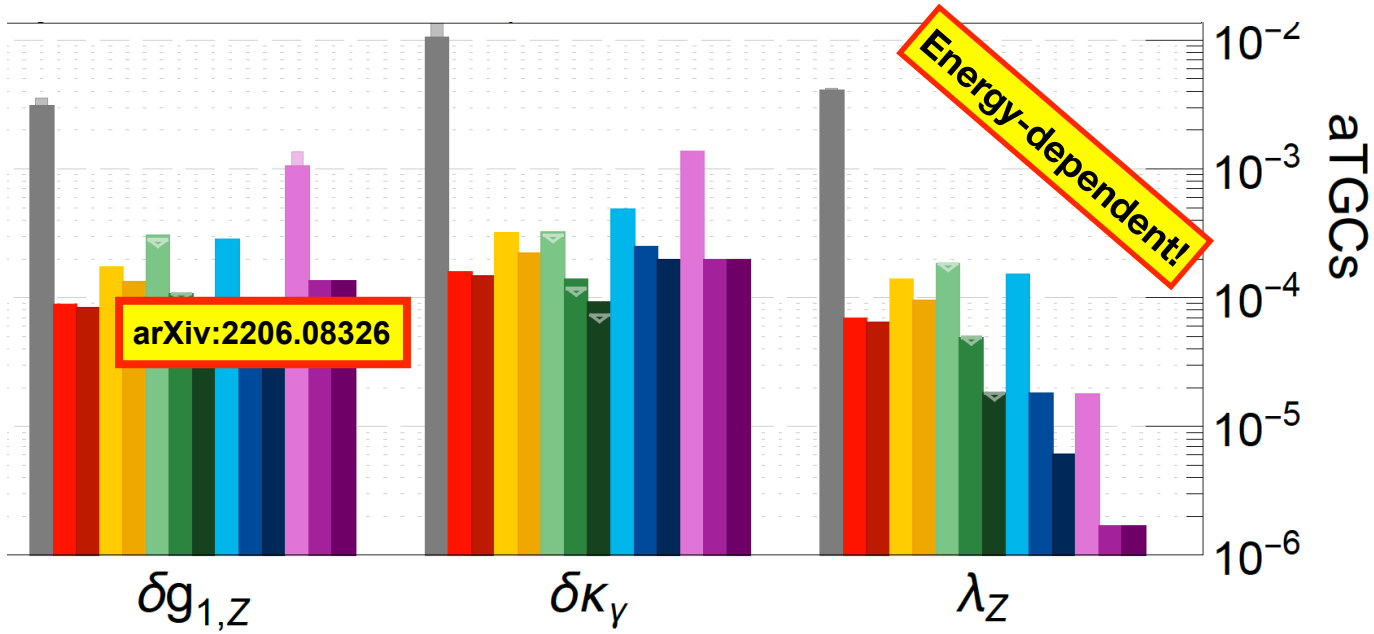
TGC in SMEFT and beyond

using optimal observables

- Within SMEFT (Jorge de Blas et al):
  - three “LEP” couplings (no detector, no systematics)
  - ~100x gain beyond HL-LHC!
  - for some couplings strong ECM-dependence



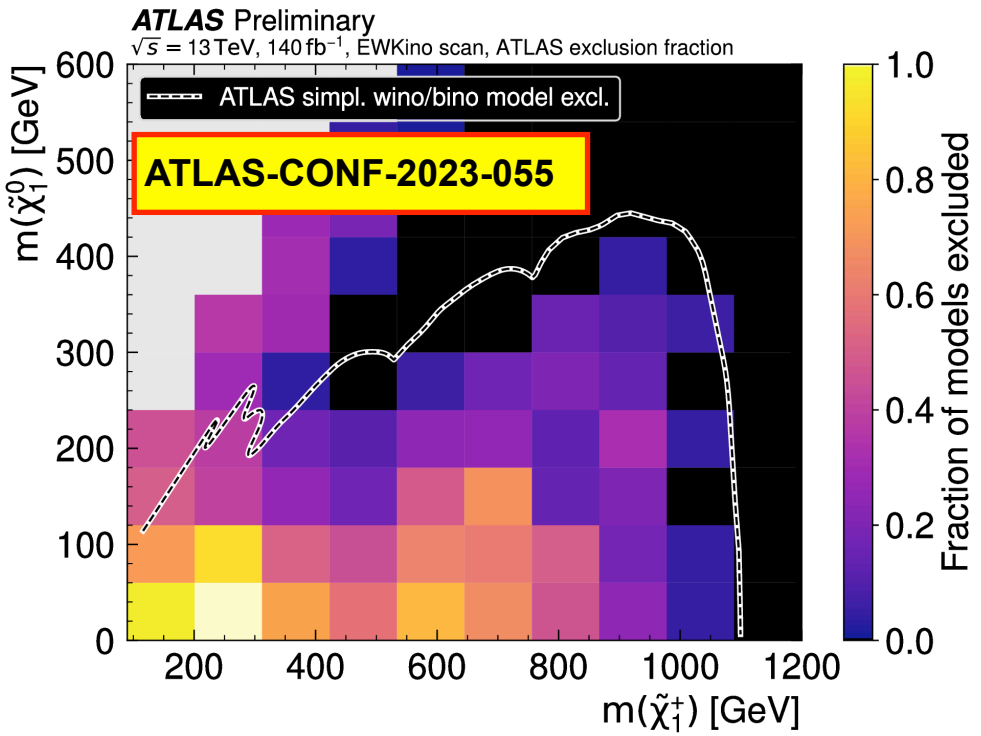
- Far beyond SMEFT - Markus Diehl et al 2003 (!)
  - all 28 real parameters (no detector, no background…)
  - **can disentangle all at 500 GeV with polarised beams**

Eur.Phys.J.C 27 (2003) 375-397
& Eur.Phys.J.C 32 (2003) 17-27

Light Higgsinos

Or: beware what LHC limits really mean!

- LHC does very well on probing some BSM phase space
- but beware that exclusion regions are extremely model-dependent, especially for electroweak new particles (eg charginos, staus, …)
- ILD study of full detector simulation for two benchmark points ★★ - motivated by leptogenesis & gravitino DM - and extrapolation to full plane
- conclusions:
  - loop-hole free discovery / exclusion potential up to ~ half E_{CM}
  - even in most challenging cases few % precision on masses, cross-sections etc
  - SUSY parameter determination, cross-check with cosmology



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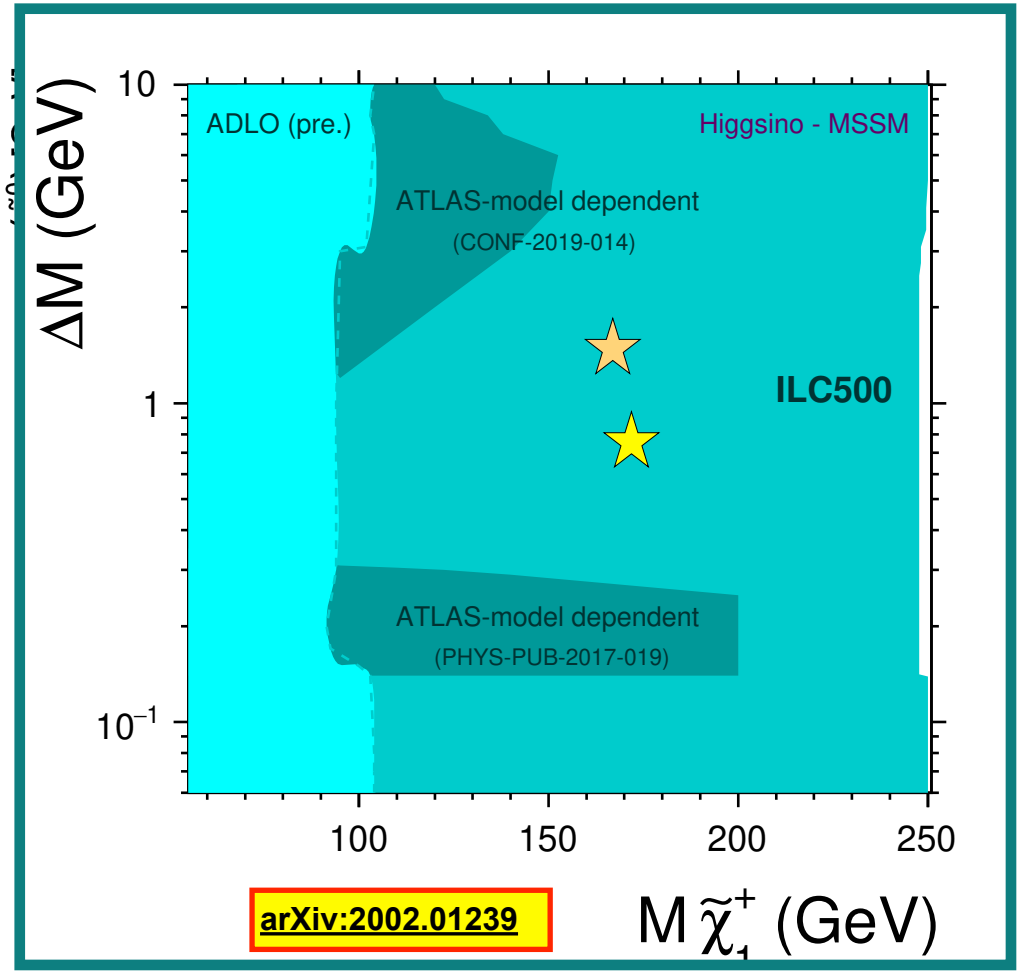

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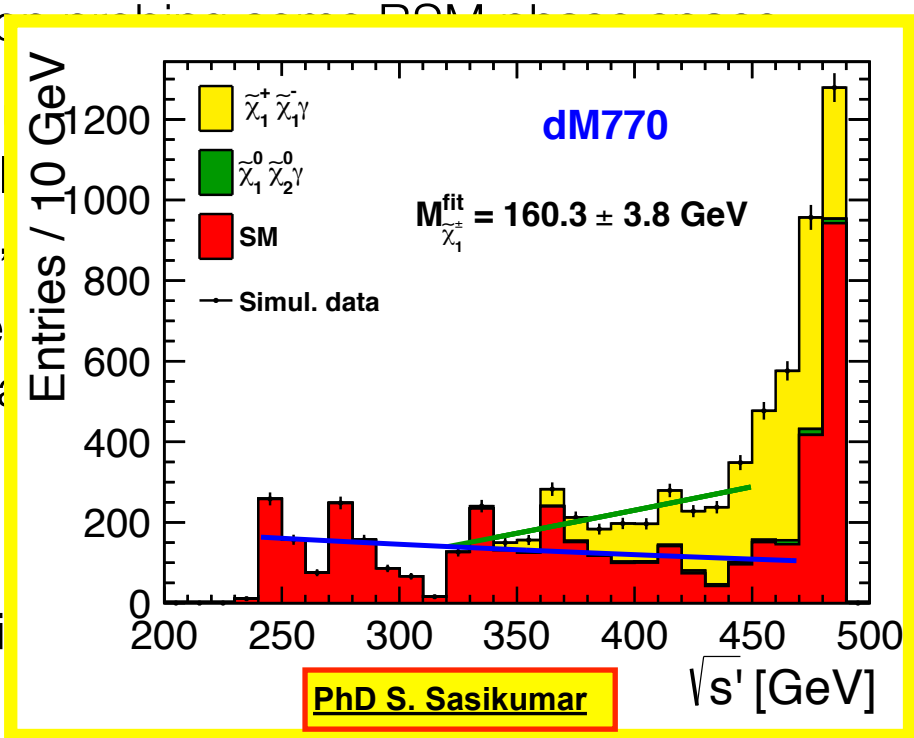

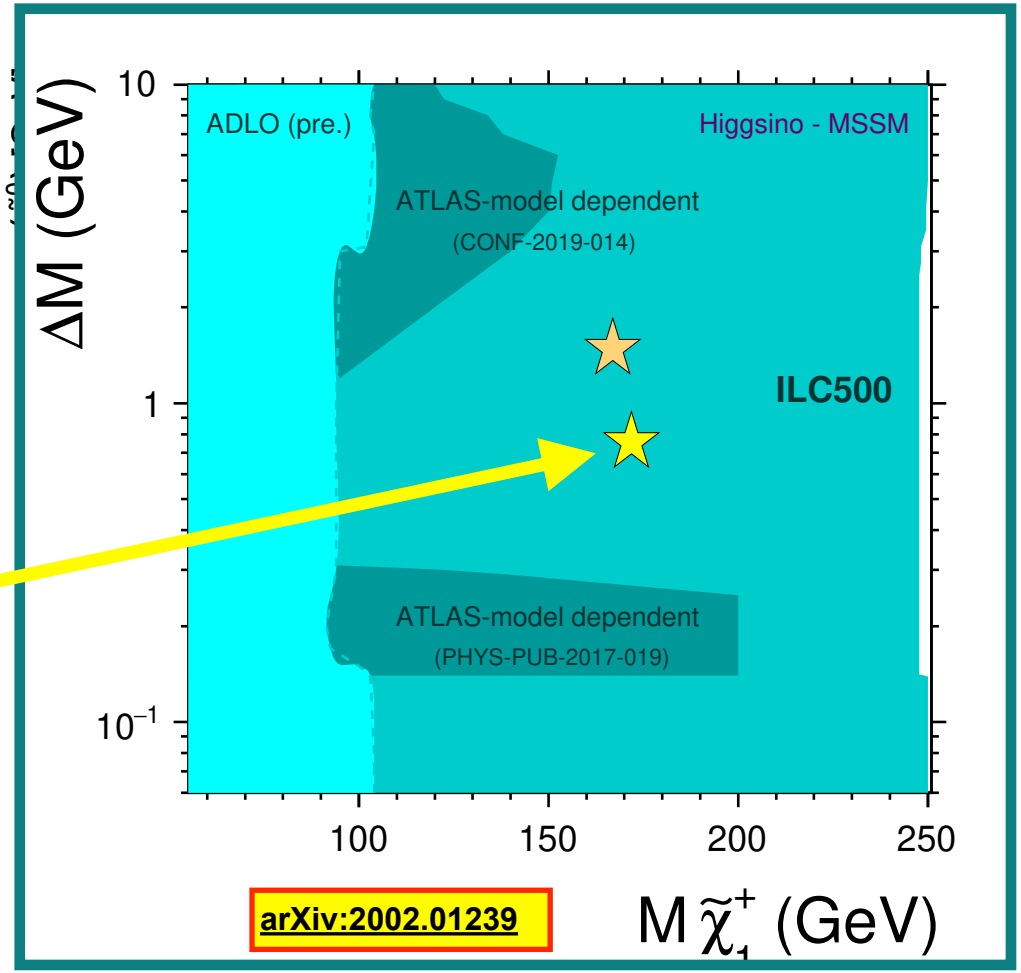

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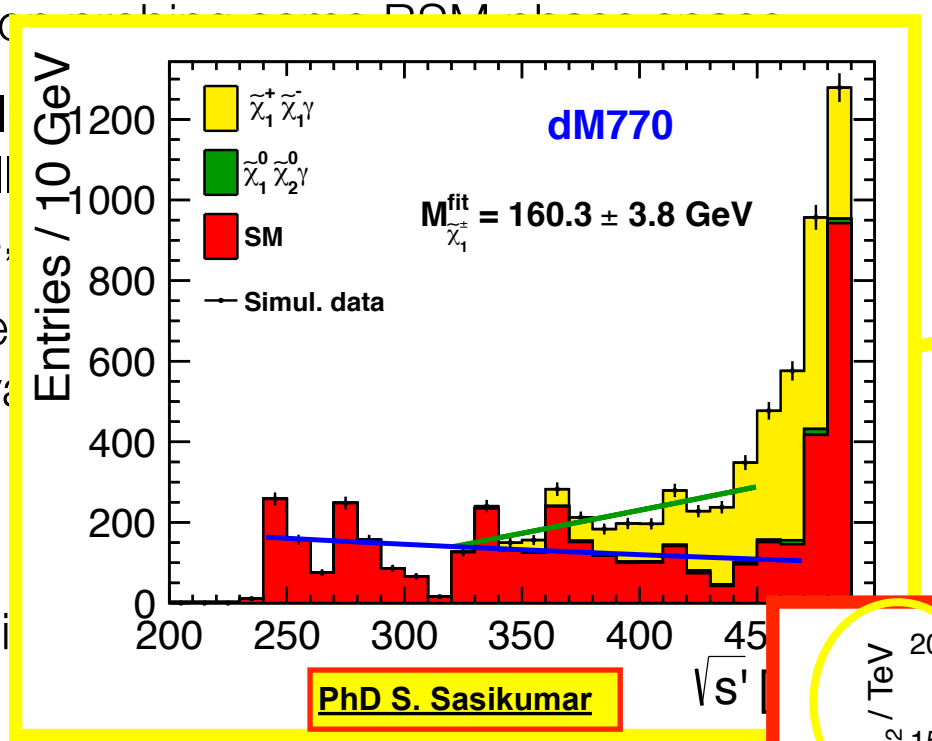

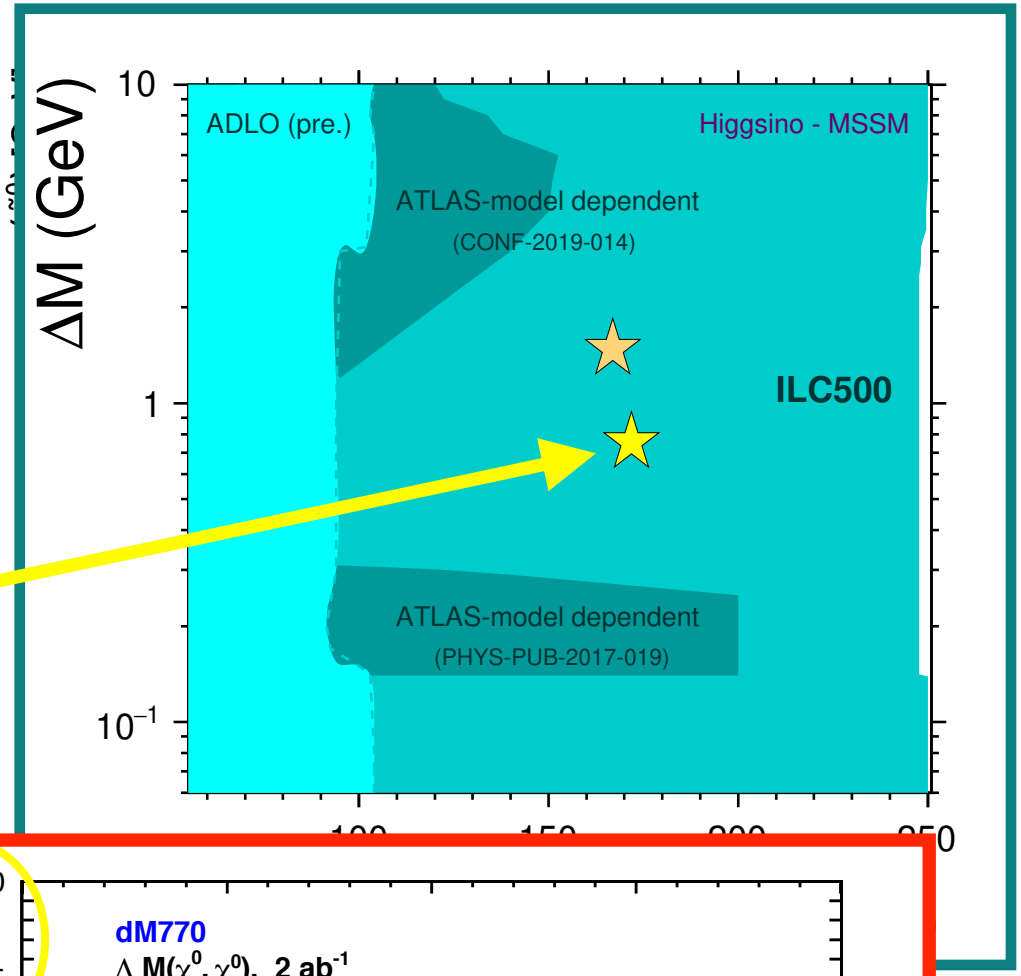

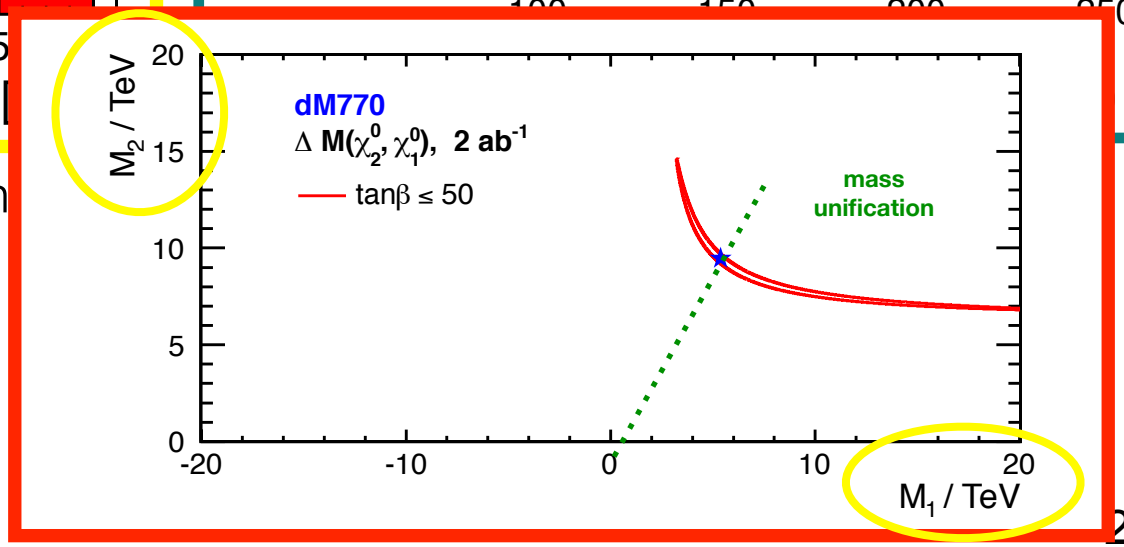

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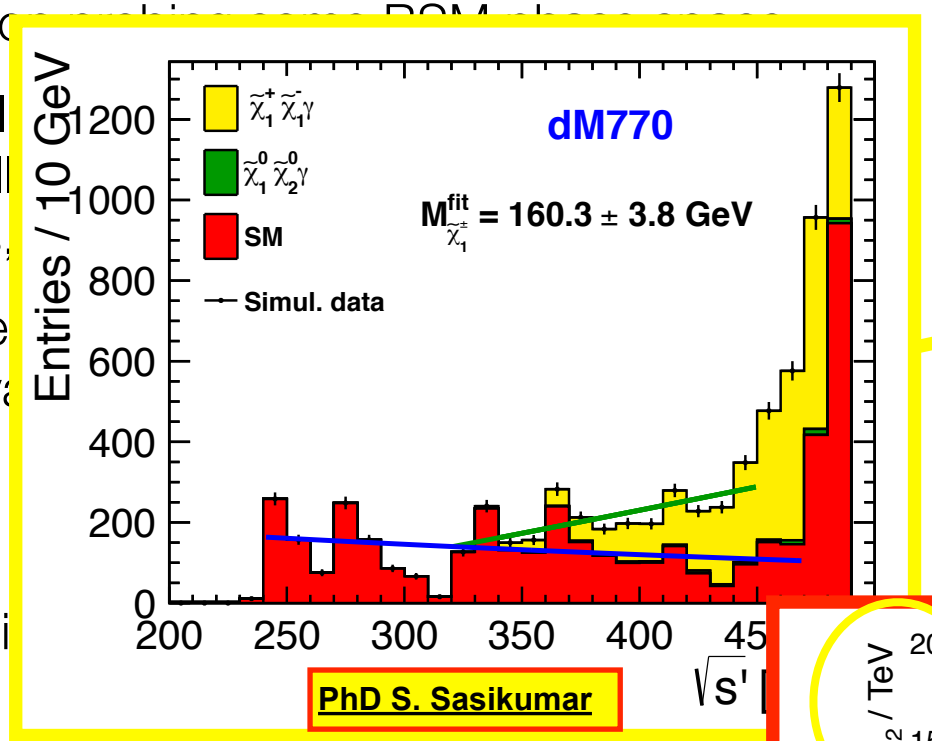

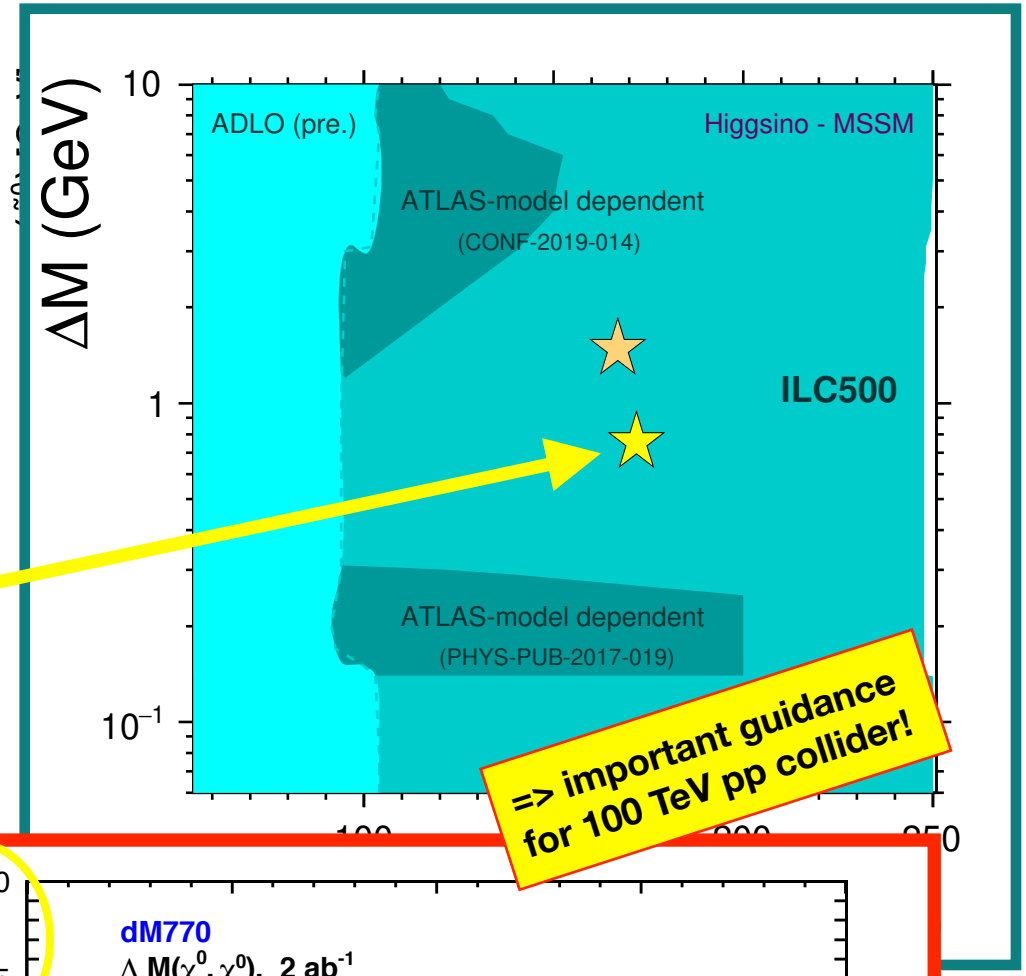

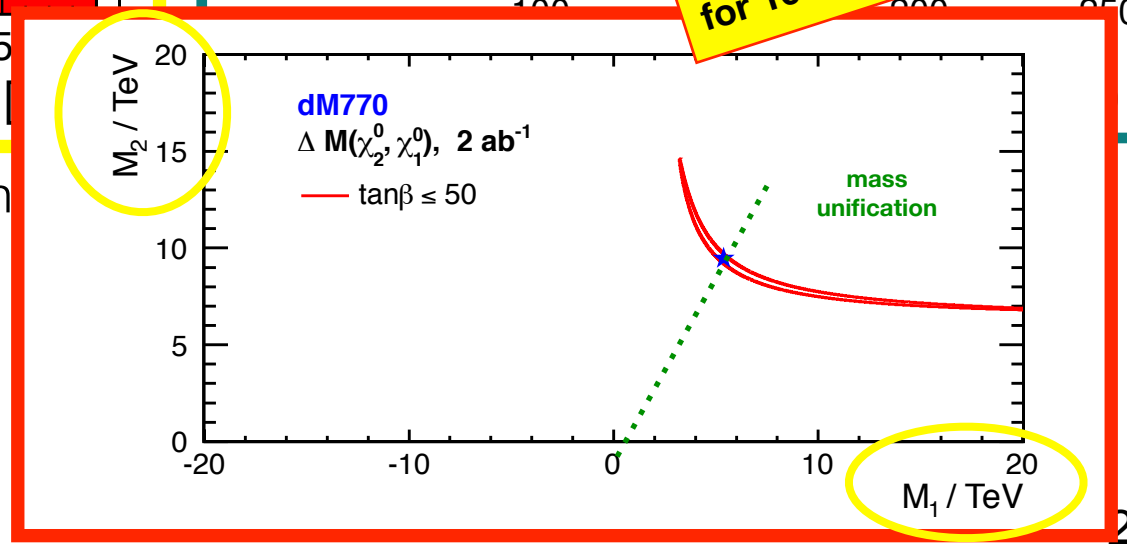

Light Partners of the Tau

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LEP,
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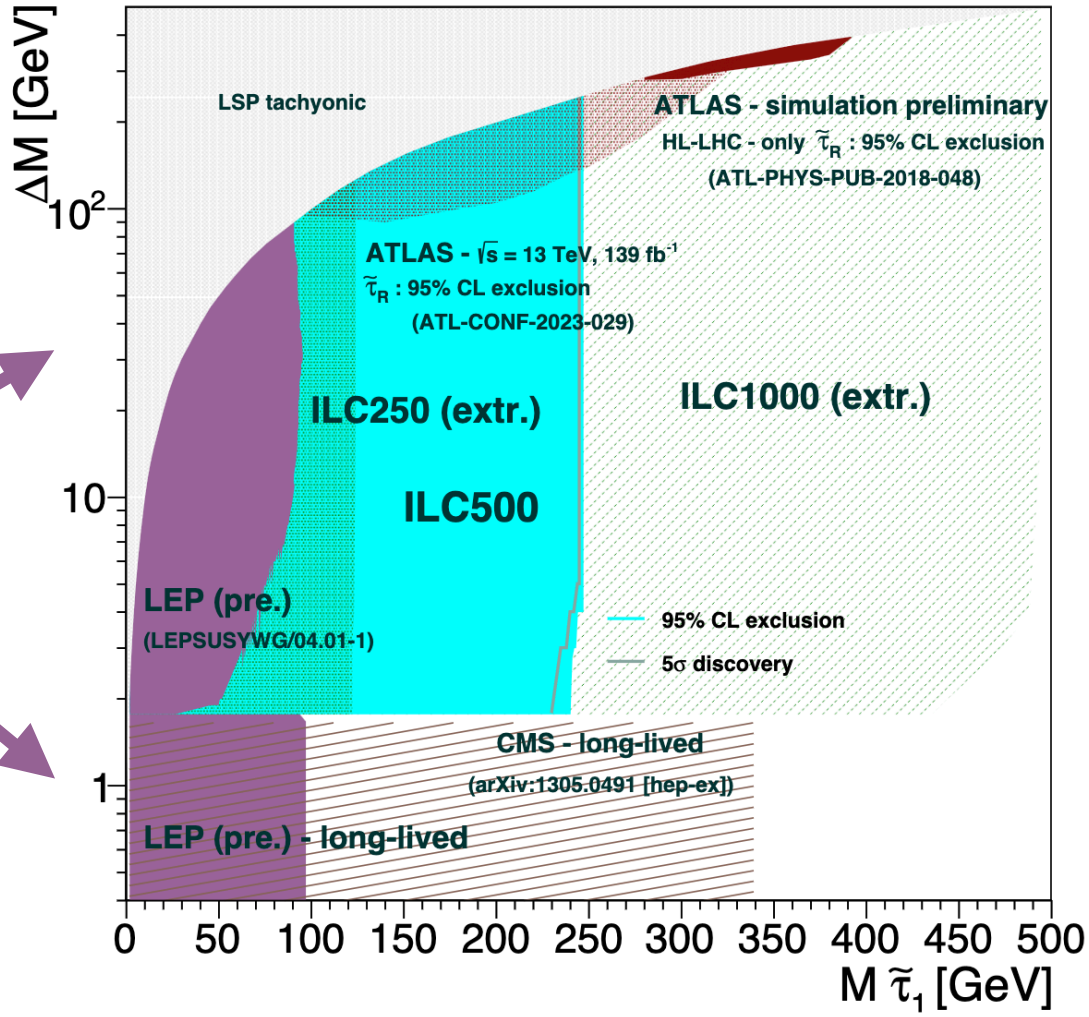

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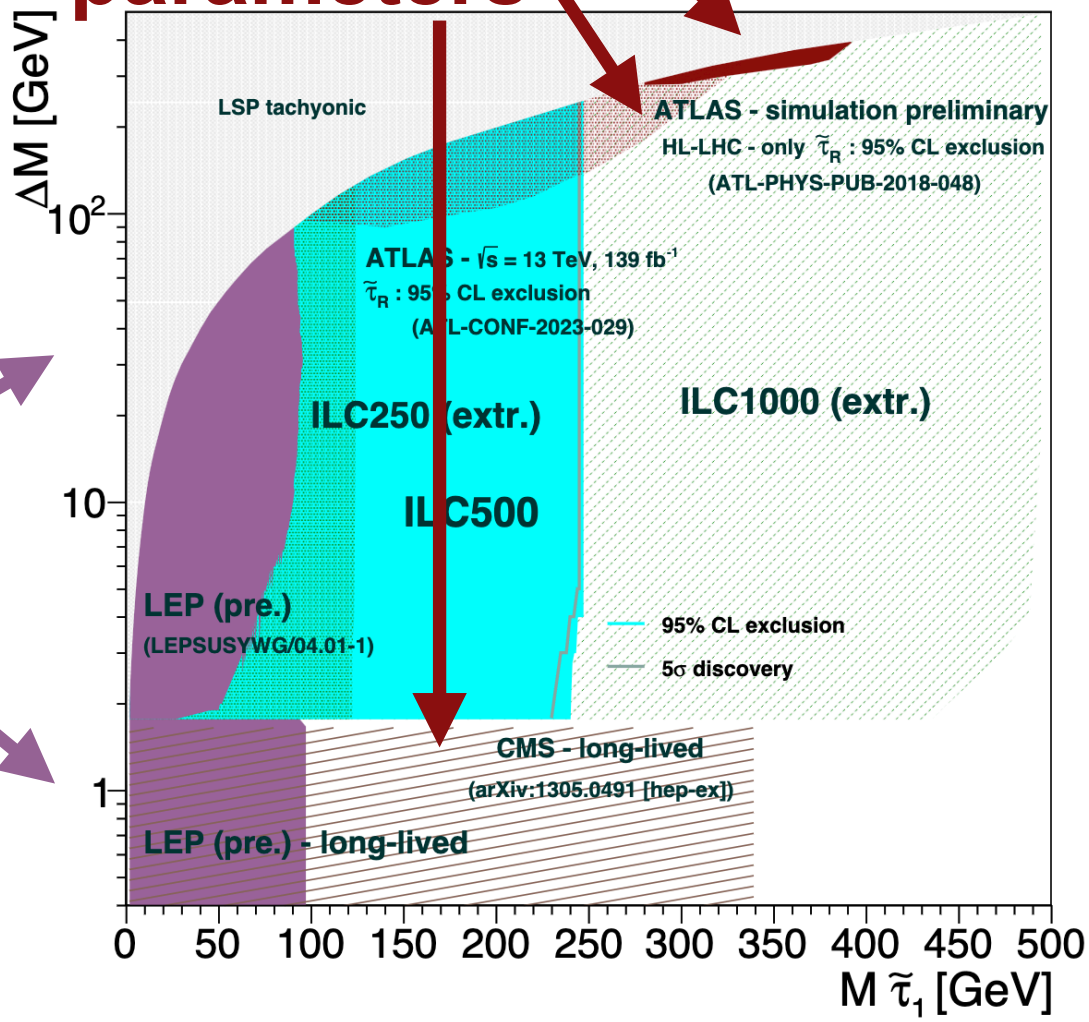
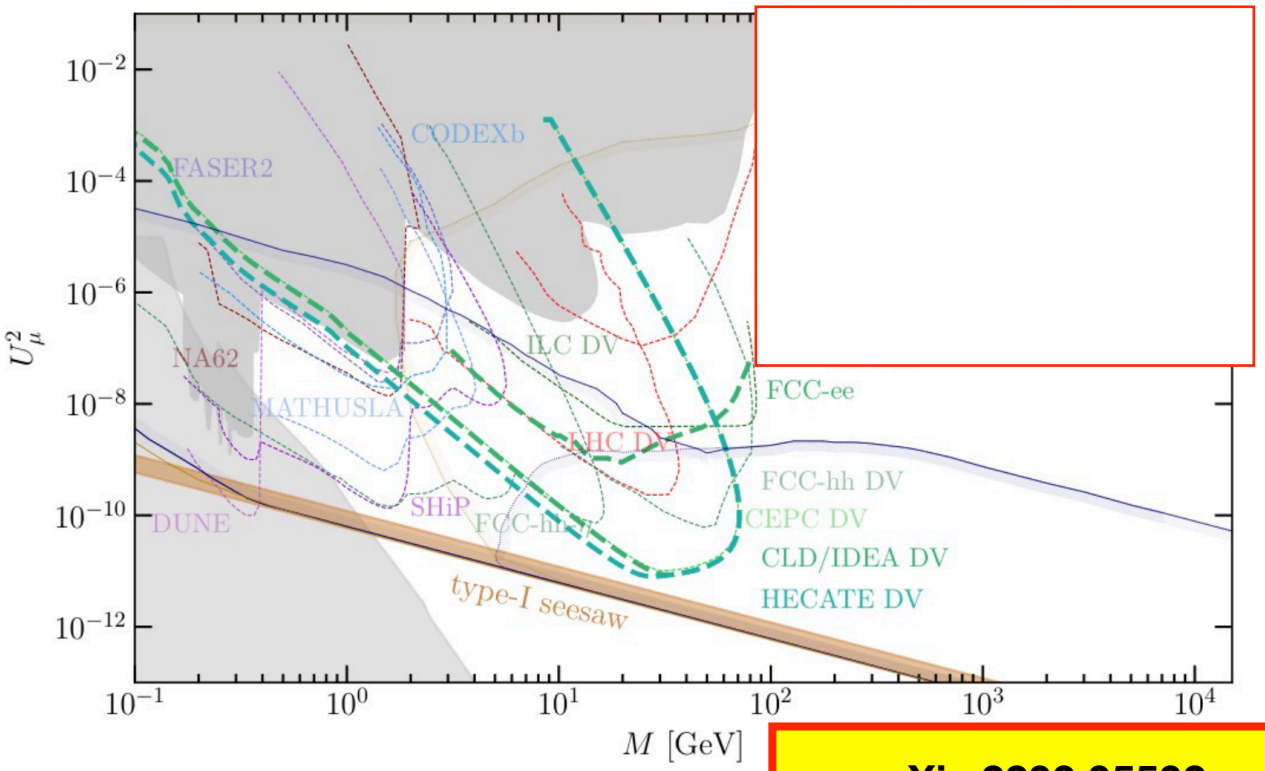


Heavy Neutral Leptons

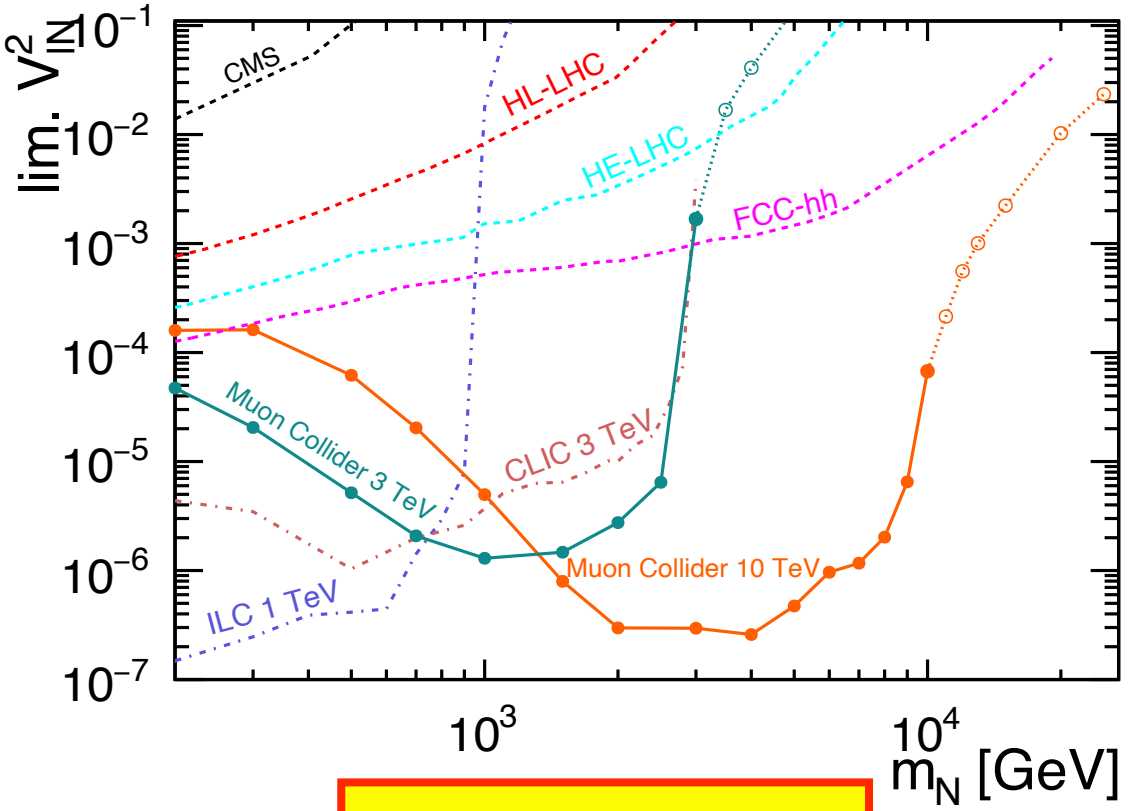
Discovery reach for lepton colliders - complementary to FCC-hh

in Z decays with displaced vertices…



arXiv:2203.05502

…and at high masses in prompt decays



arXiv:2301.02602

So in case someone asks you:

Why 500 GeV (and beyond)

1. **Observe and measure double-Higgs-Strahlung**

   => insight into shape of Higgs potential and role of EWSB in early universe

2. **Understand the top-quark and its relation to gauge boson and the Higgs**

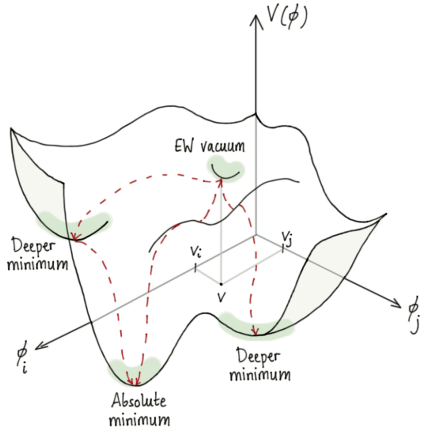
   => insight into fermion mass hierarchy, fully understand Higgs mechanism

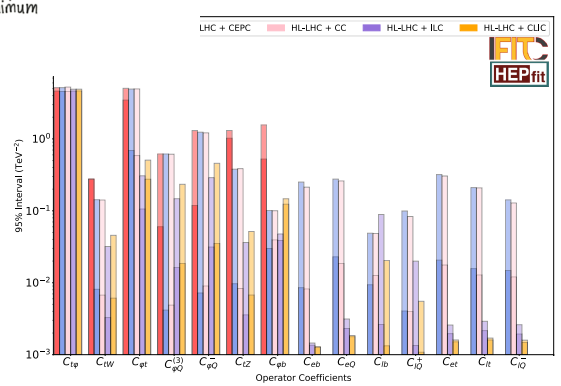
3. **Precision probes of weak gauge boson self-interactions**

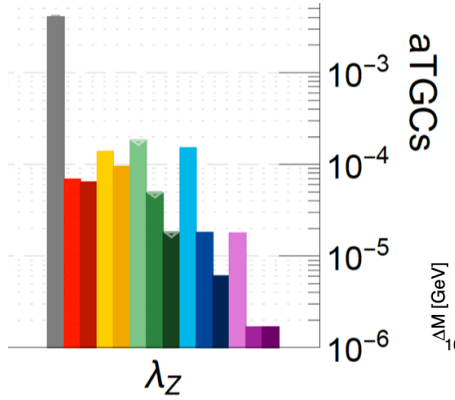
   => extremely sensitive probe for BSM, interplay with Higgs

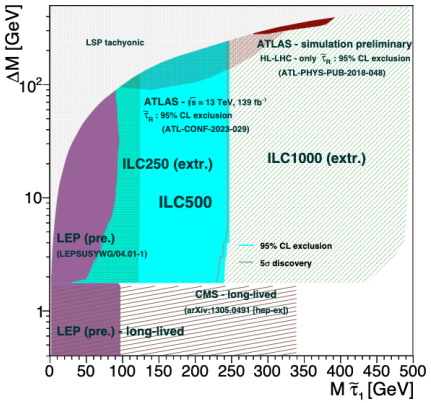
4. **loop-hole-free searches for electroweak new particles incl siblings of the Higgs**

   => discovery is the icing on the cake, opportunities complementary to pp, fixed target, direct detection, …









Any Questions?