Higgs Physics Report link

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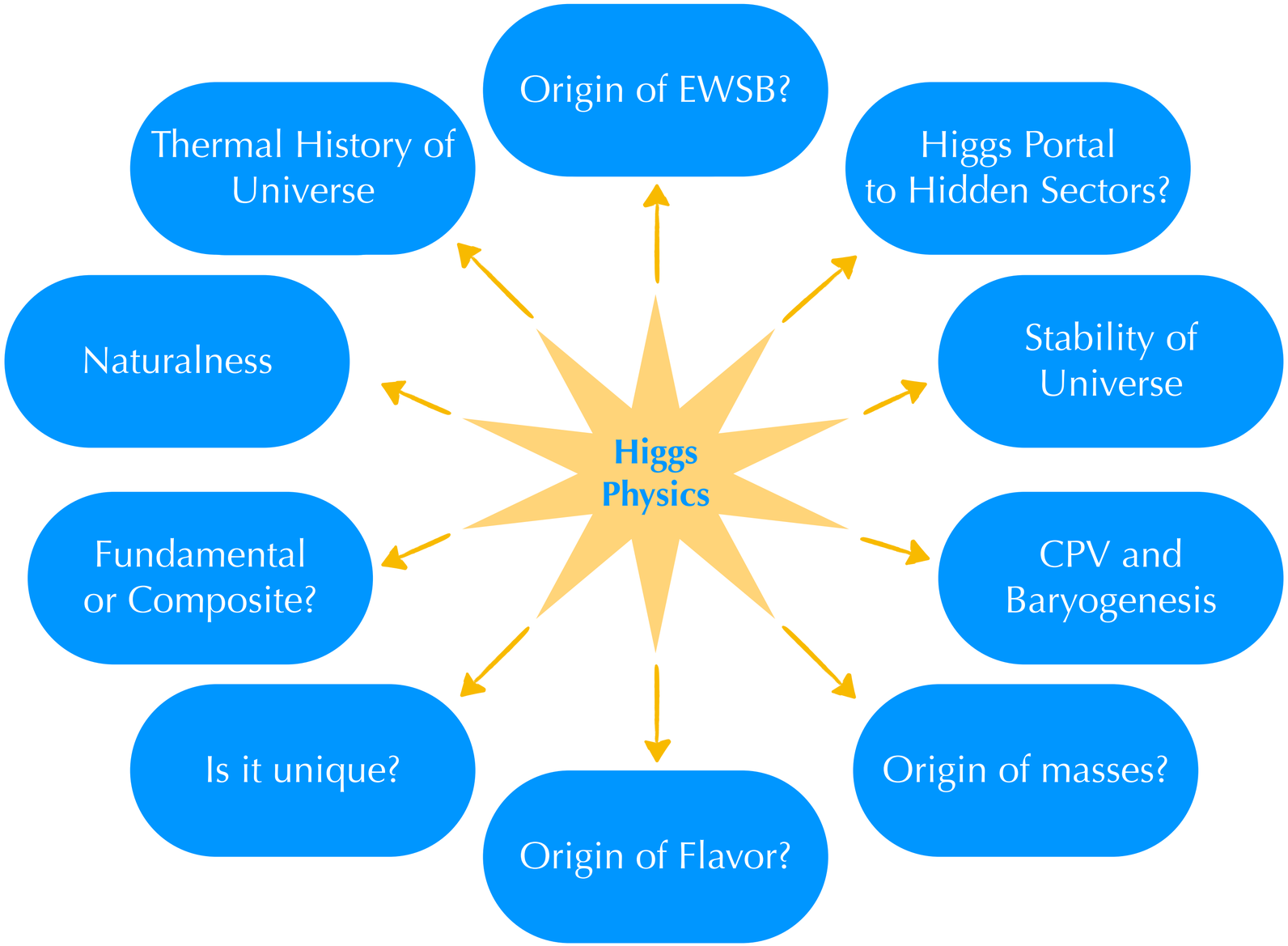
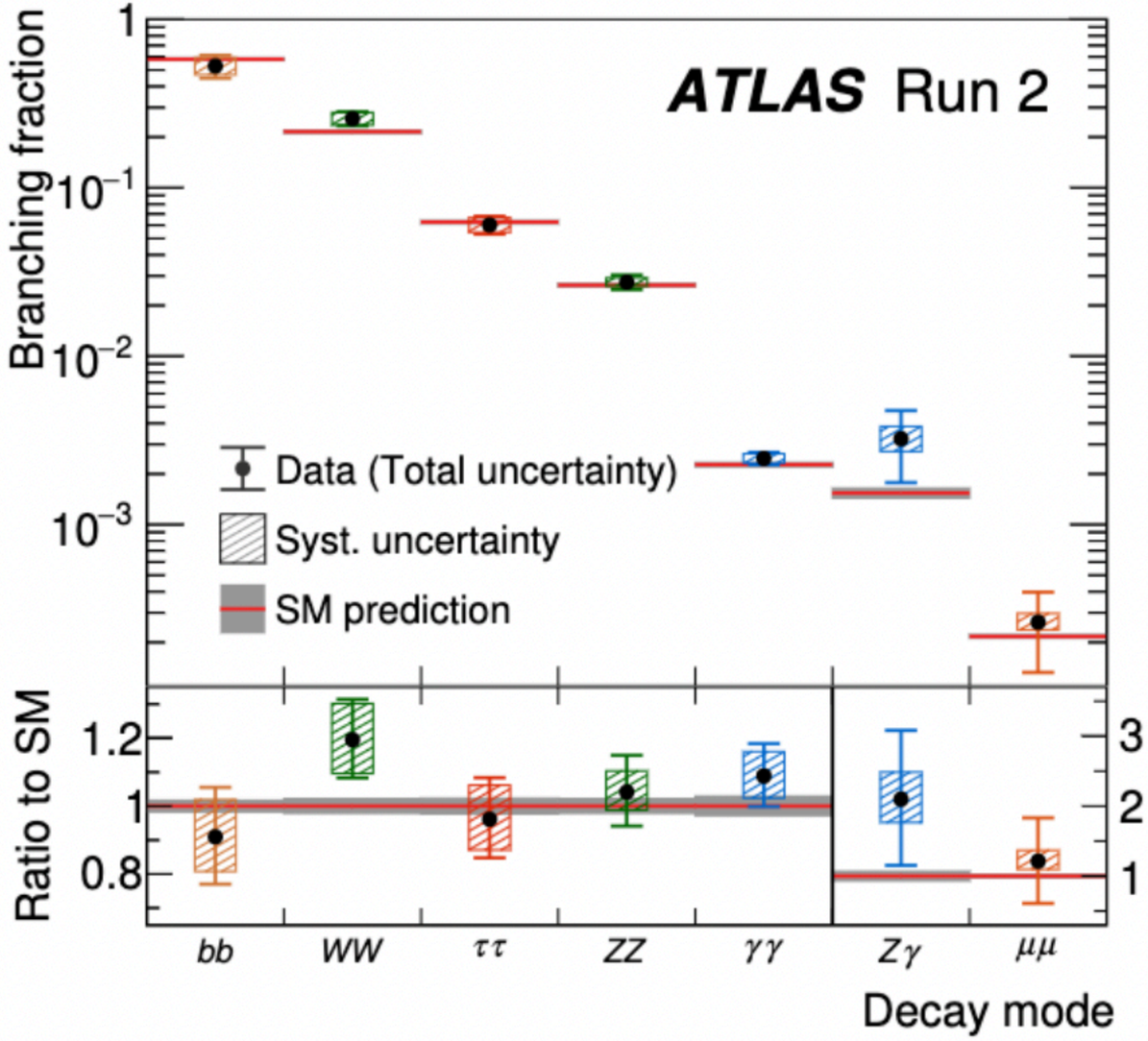
Snowmass Community Summer Study - Seattle

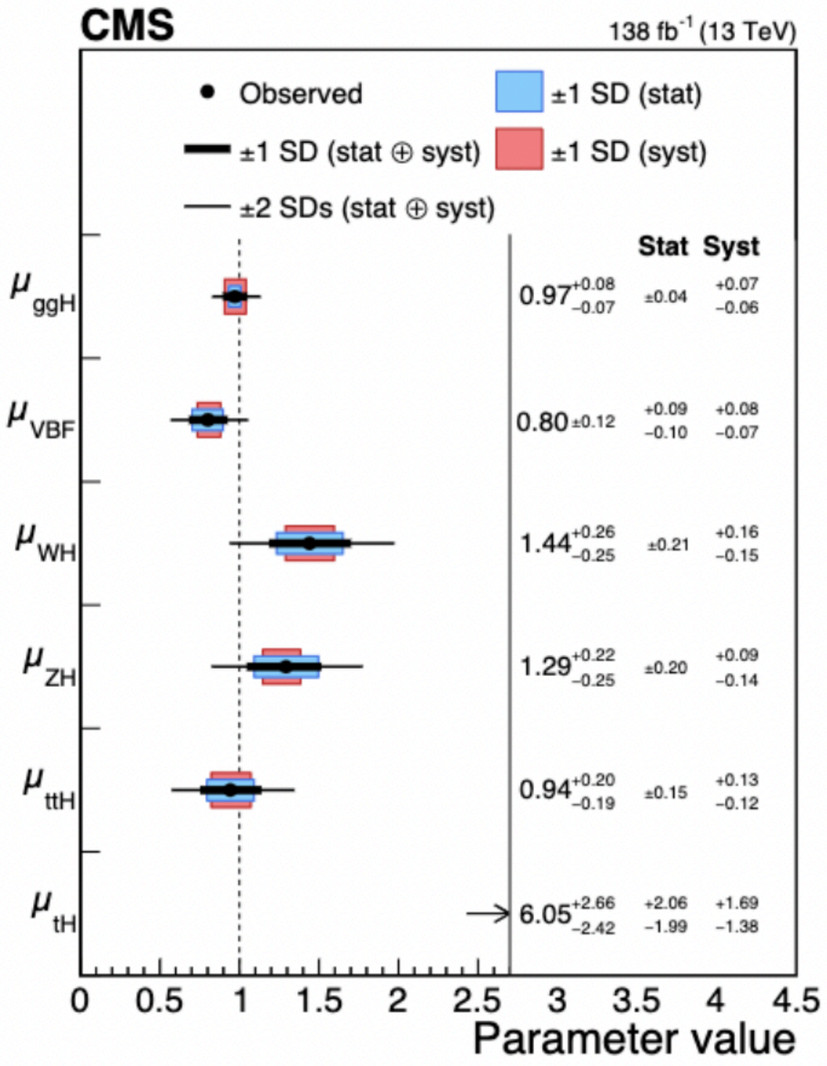
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

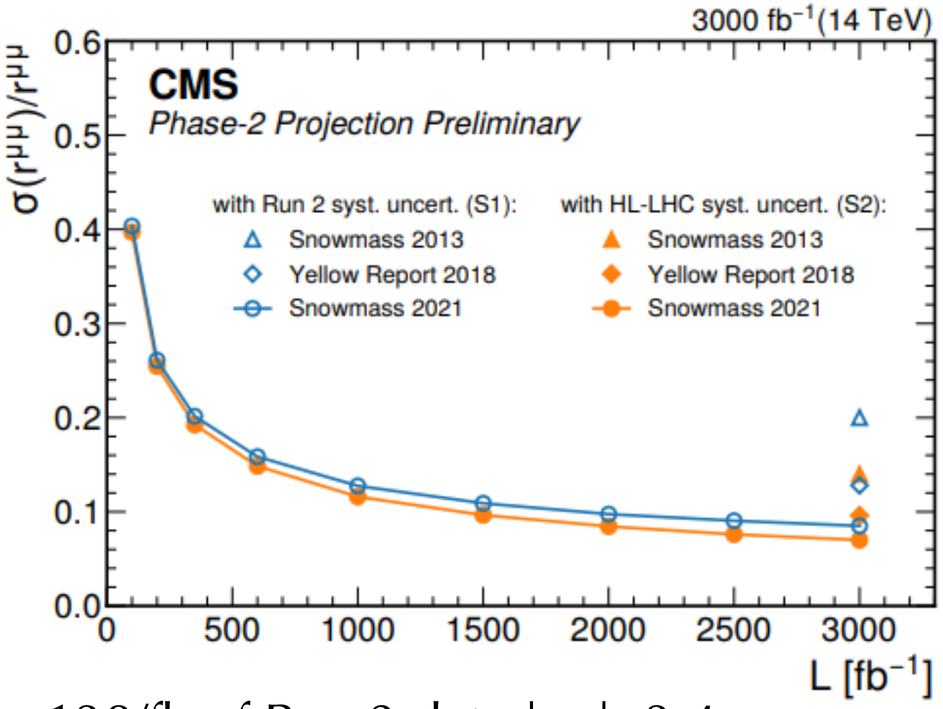

Higgs Physics
Origin of EWSB?
Higgs Portal to Hidden Sectors?
Stability of Universe
CPV and Baryogenesis
Origin of masses?
Origin of Flavor?
Is it unique?
Fundamental or Composite?
Naturalness
Thermal History of Universe

Higgs in 2022



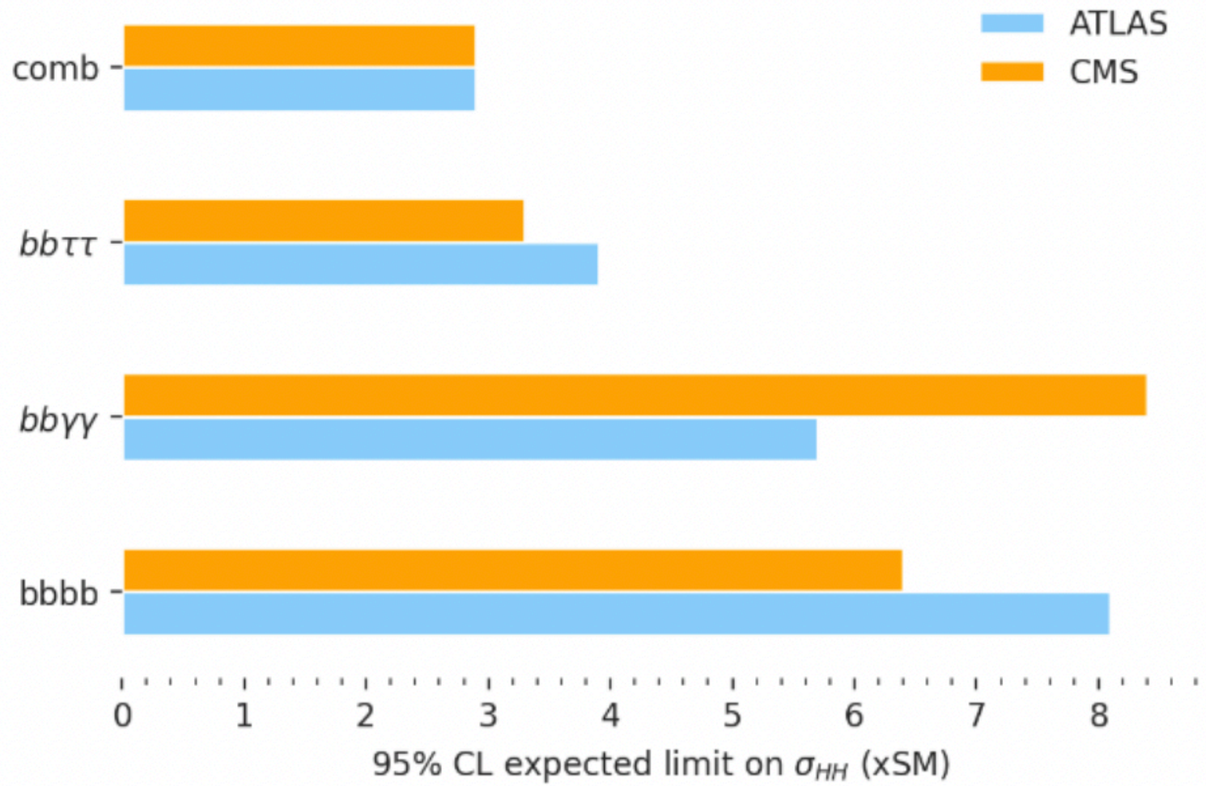


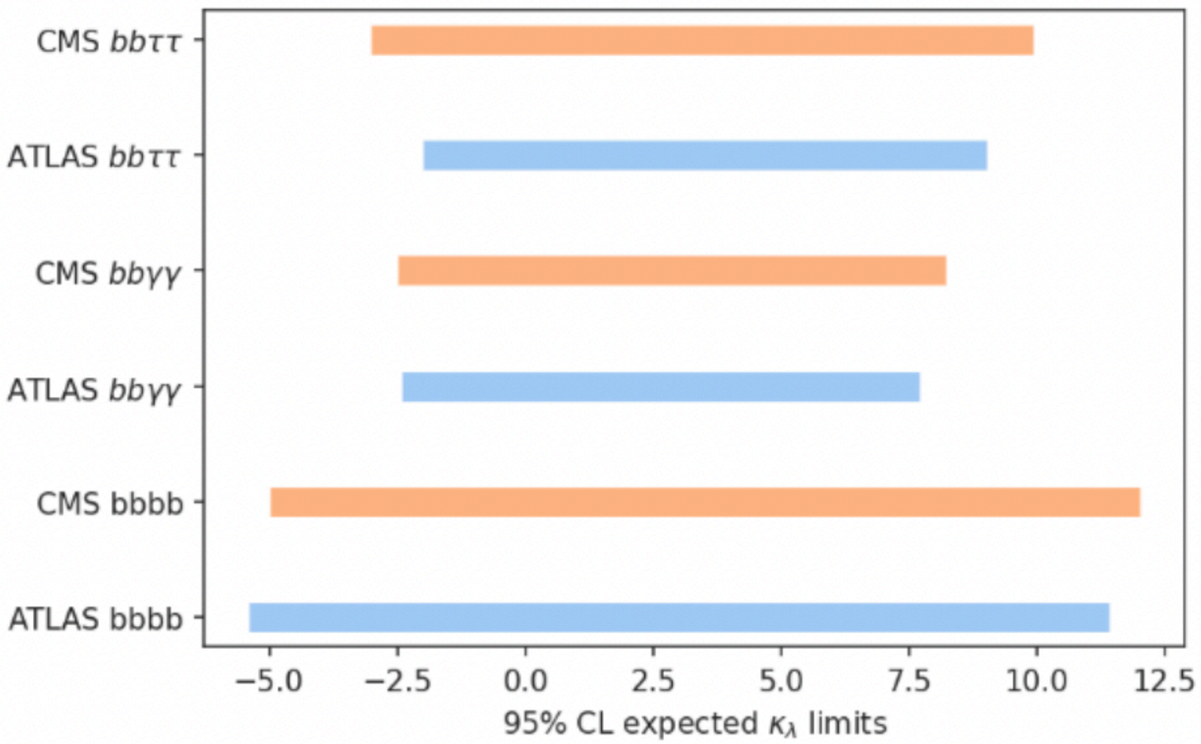
Higgs in 2022



- m_h = 125.38 ± 0.14 (CMS) / 124.92 ± 0.21 GeV (ATLAS)
- The couplings to the first and second generations have not been measured yet.
  - The Higgs coupling to the **muon** is expected to be observed during the HL-LHC running
  - Probing the **charm Yukawa** at the LHC is very challenging
    - The most stringent constraint to date is set by CMS using 138/fb of Run 2 data $|\kappa c|<3.4$
- BR(inv.) < 0.17 (0.11) is the most stringent constraint currently set by CMS exploiting the VBF topology and with 108/fb

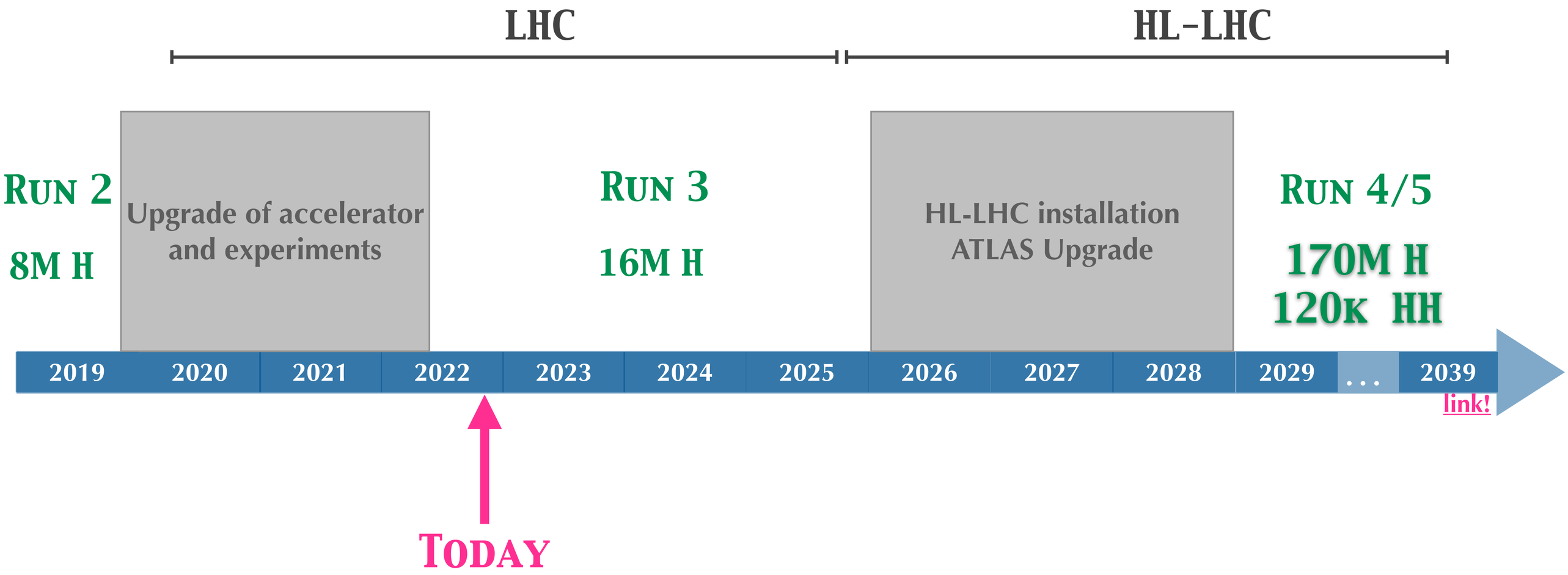
Self-coupling : HH searches at the LHC





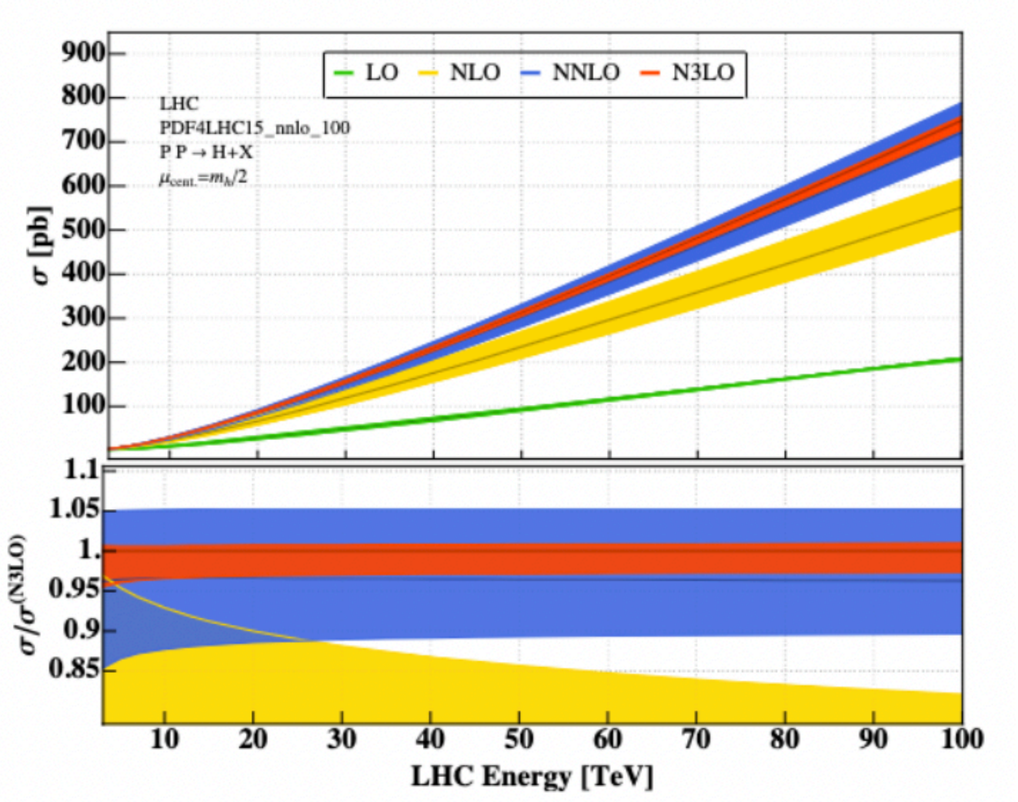
Main channels only based on full Run 2 (126-139/fb) analyses

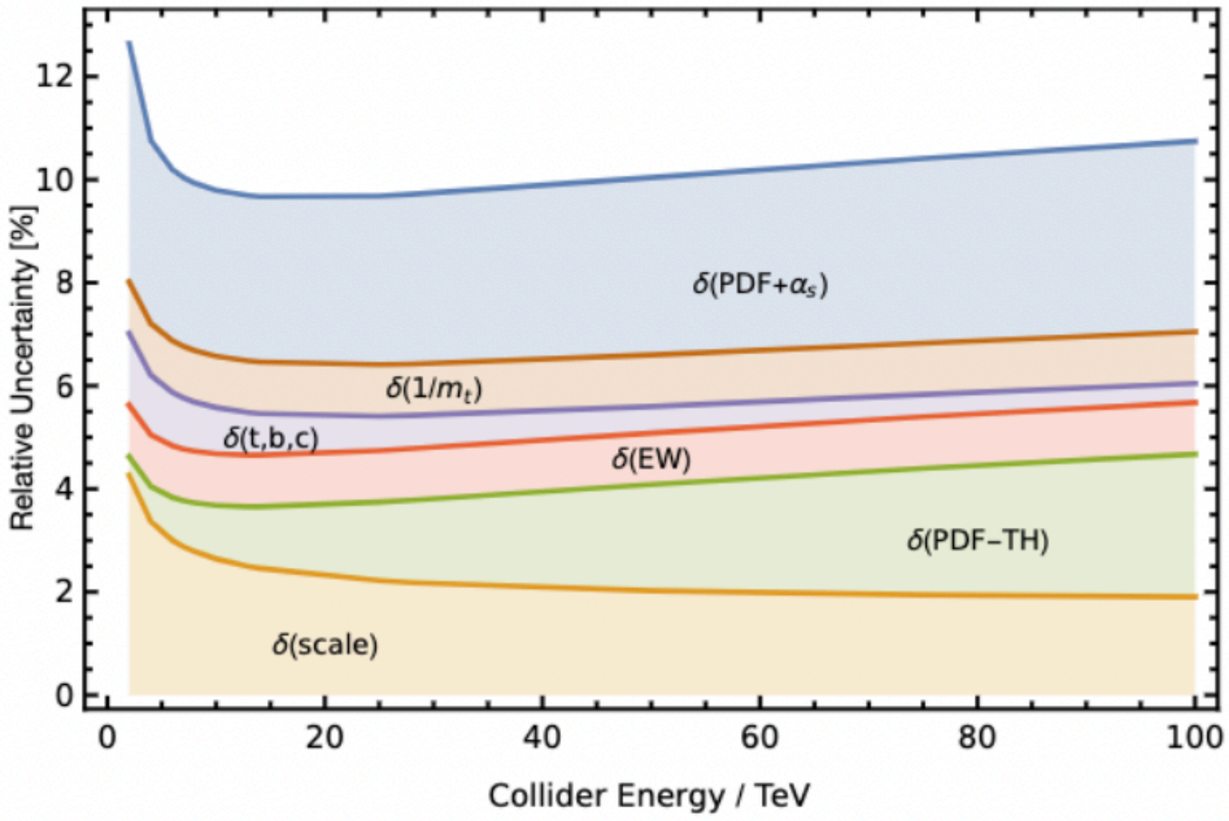
LHC → High Luminosity LHC



Status Theory Predictions

arXiv:2203.06730
arXiv:1902.00134





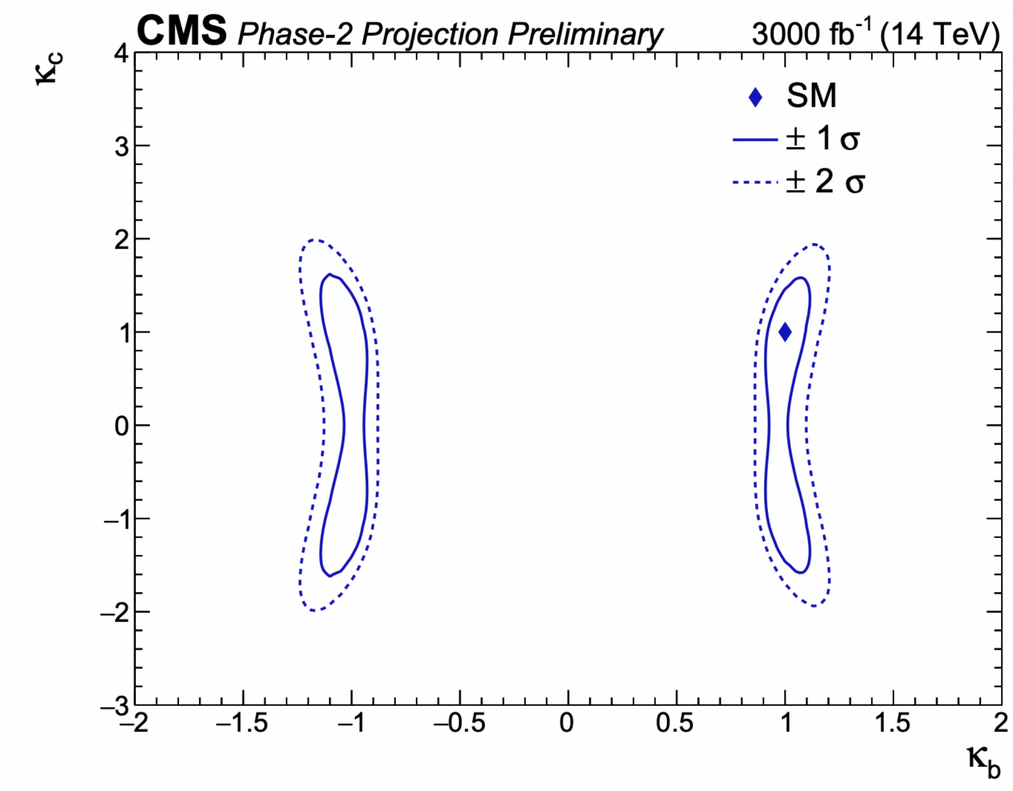
- The theory uncertainty expected to be comparable to the expected statistical and systematic uncertainties of the measurements.
  - Impressive progress so far, theory uncertainties can be reduced by a factor of two in the future

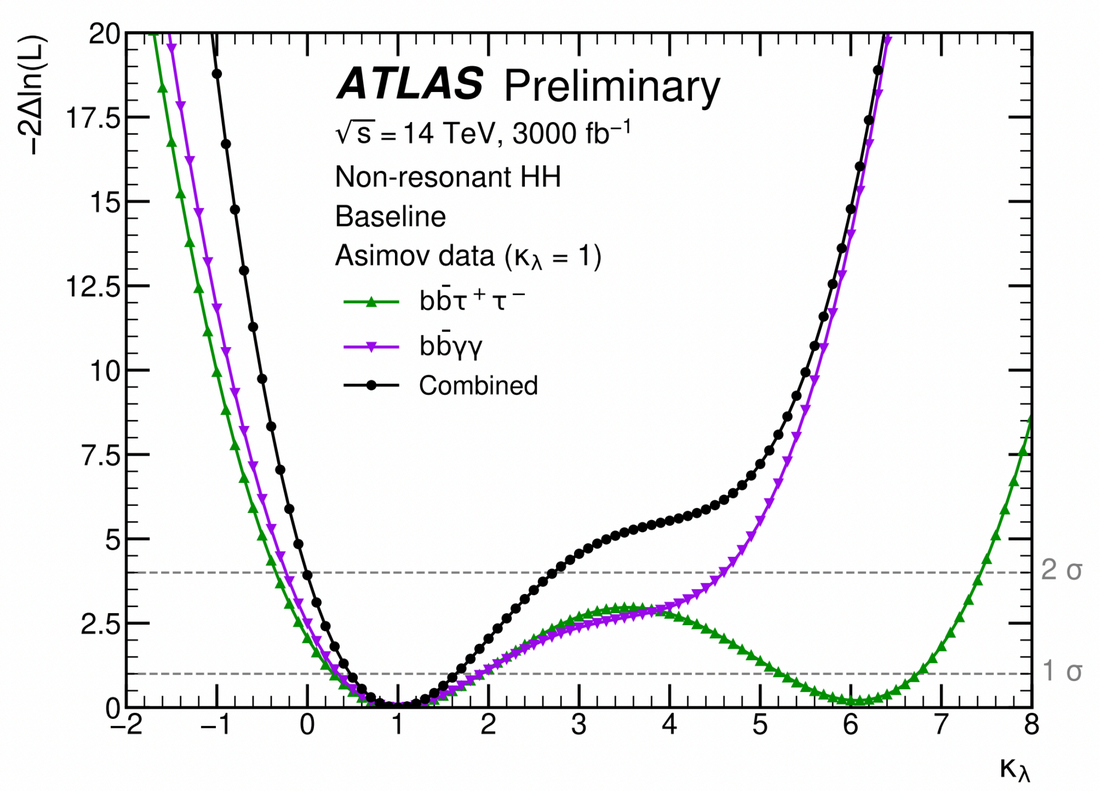
Higgs physics at the HL-LHC

ATLAS+CMS HL-LHC 2022 study

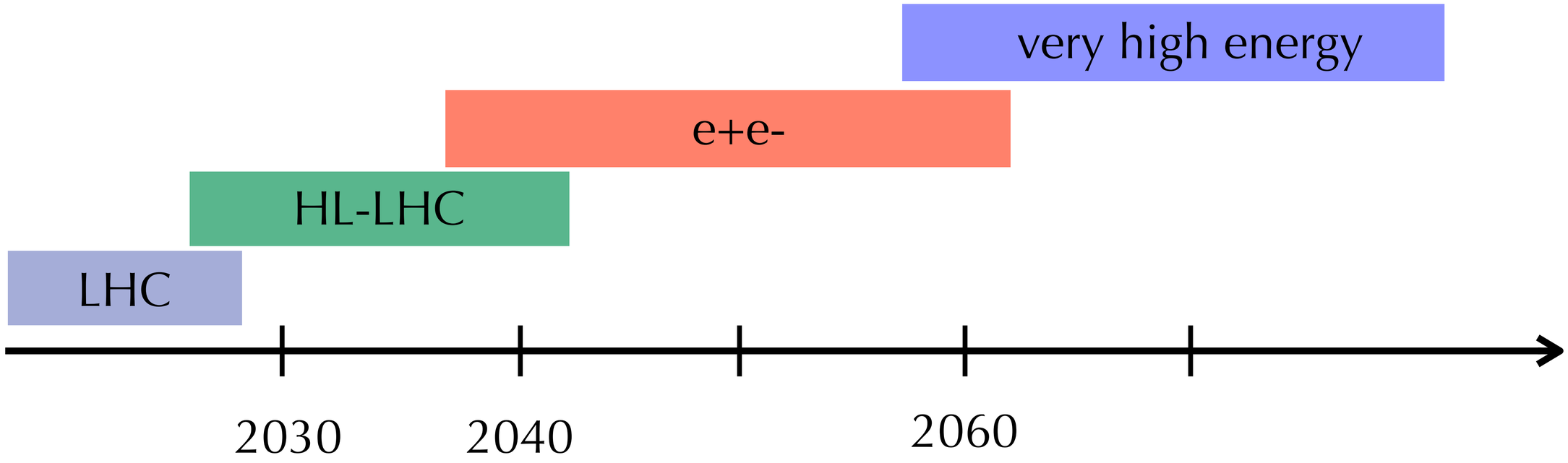
The High Luminosity era of LHC will dramatically expand the physics reach for Higgs physics:

- **2-5% precision for Higgs couplings to bosons and third generation fermions**
- **Larger uncertainties on $Z\gamma$ and charm**
- **<50% on the self-coupling**





Higgs as a guide

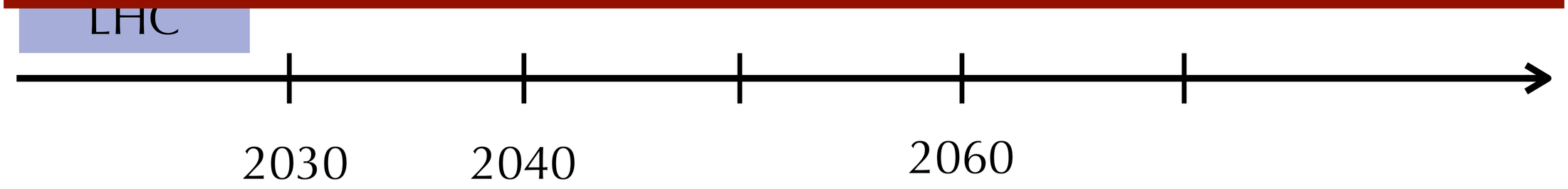


H couplings to:	**O(10)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

Higgs as a guide

Wish list beyond HL-LHC:

1. **Establish Yukawa couplings to light flavor ⟹ precision & lumi**
2. **Search for invisible/exotic decays and new Higgs ⟹ precision & lumi**
3. **Establish self-coupling ⟹ high energy**



H couplings to:	**O(10)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

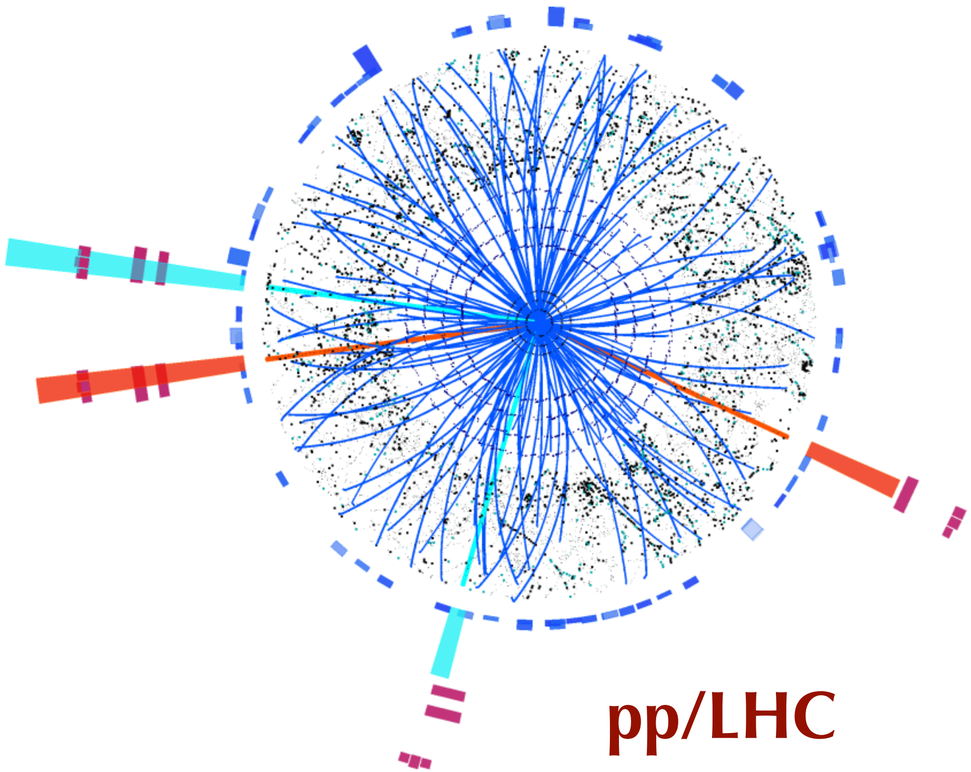
Various machines to consider

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}
HL-LHC	pp	14 TeV		6
ILC and C^3	ee	250 GeV	$\pm 80/\pm 30$	2
c.o.m almost		350 GeV	$\pm 80/\pm 30$	0.2
similar		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		2 M_{top}		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

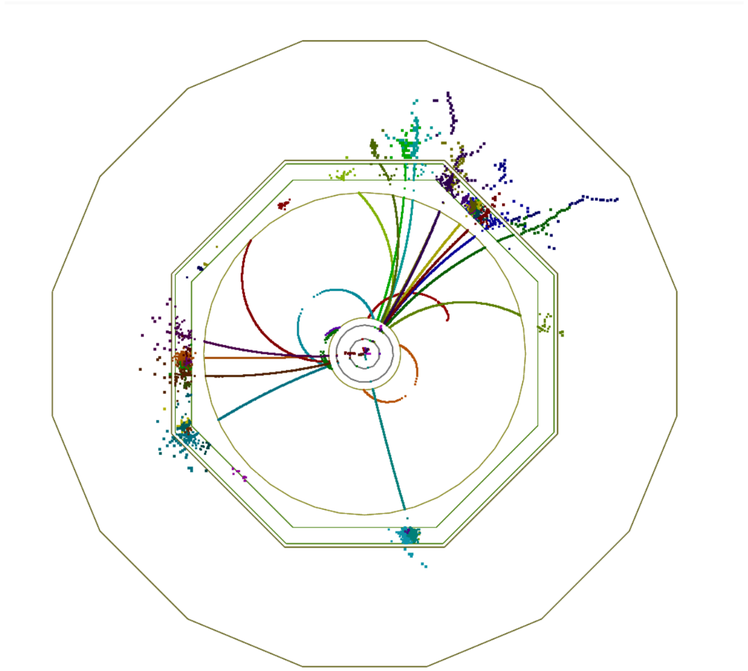
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}
HE-LHC	pp	27 TeV		15
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh		3.5 TeV		2
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5
		3.0 TeV	$\pm 80/0$	5
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10

Why leptons?

- Initial state well defined (& polarization) ⟹ High-precision measurements
- Higgs bosons appear in 1 in 100 events ⟹ Clean experimental environment and less backgrounds, trigger-less readout

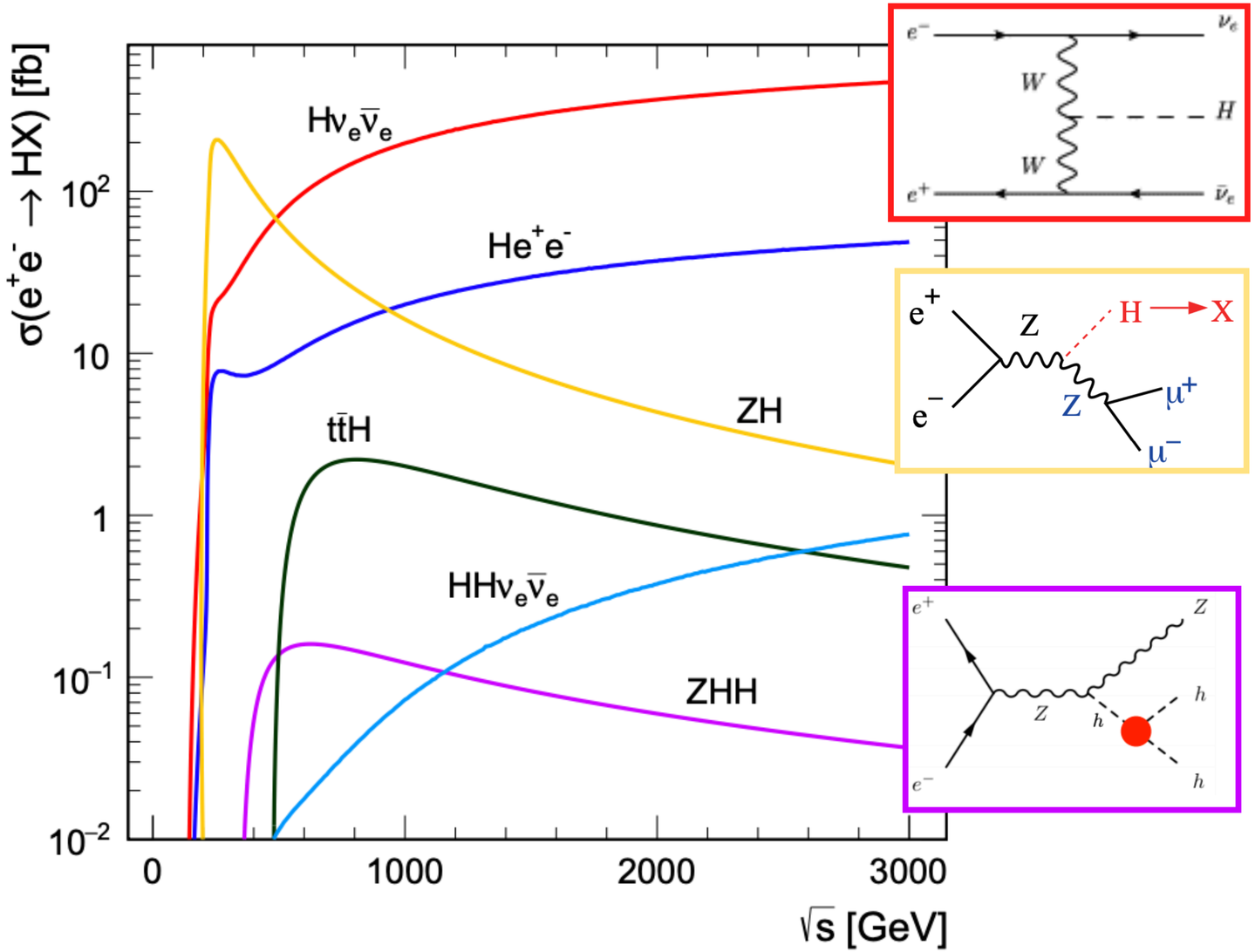


pp/LHC



e^+e^-

Higgs at e+e-

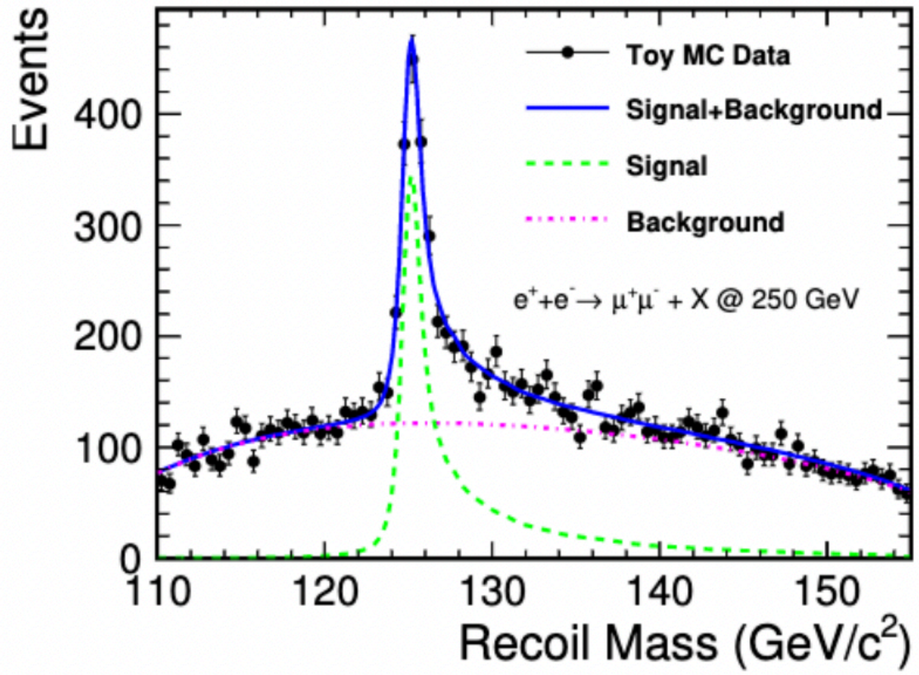


- ZH is dominant at **250 GeV**
- Above **500 GeV**
  - hVV dominates
  - tth opens up
  - hh production accessible with Zhh

Higgs at e^+e^-

arXiv:2203.07622

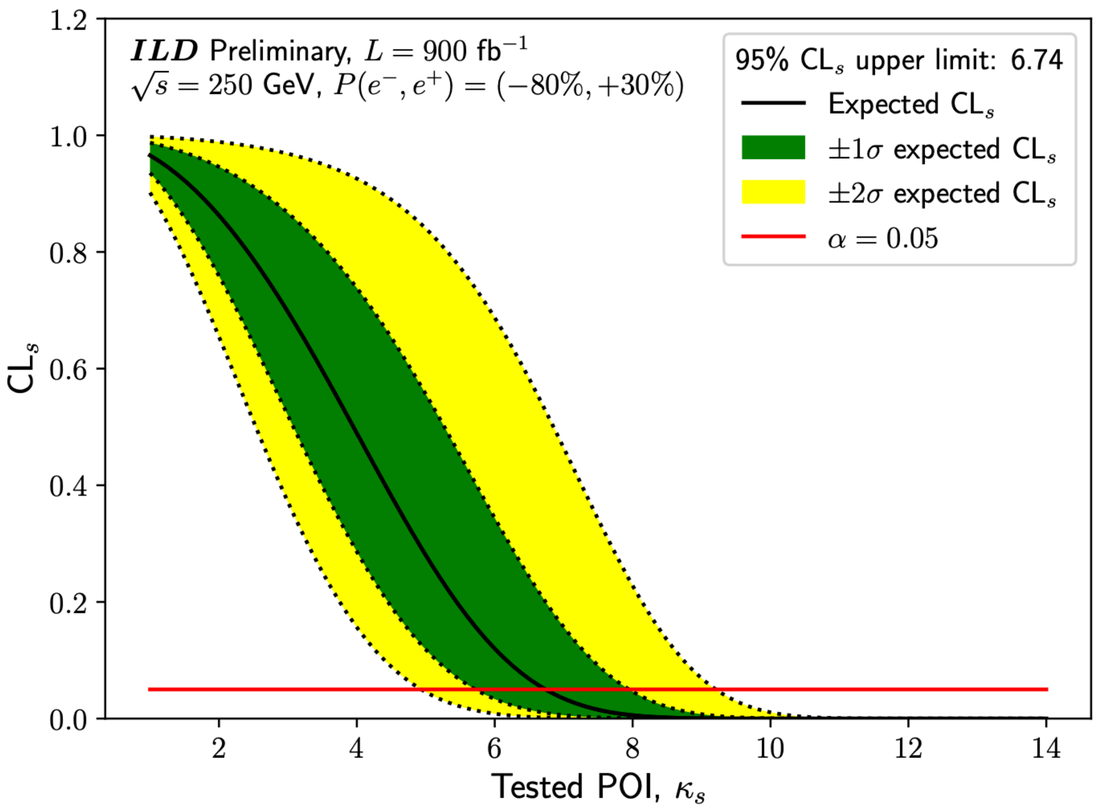
- At 250 GeV the total Zh cross section can be extracted independently of the Higgs boson's detailed properties by counting events with an identified Z boson
- The **Zh total cross section** can be measured from the area of the signal peak to ~ **O(1%) precision**
  - This **model-independent** measurement of the **hZZ** coupling is unique to e+e- colliders
- In combination with the measurement of the rate of Zh events with a h→ZZ decay, a model-independent determination of the Higgs total width can be obtained

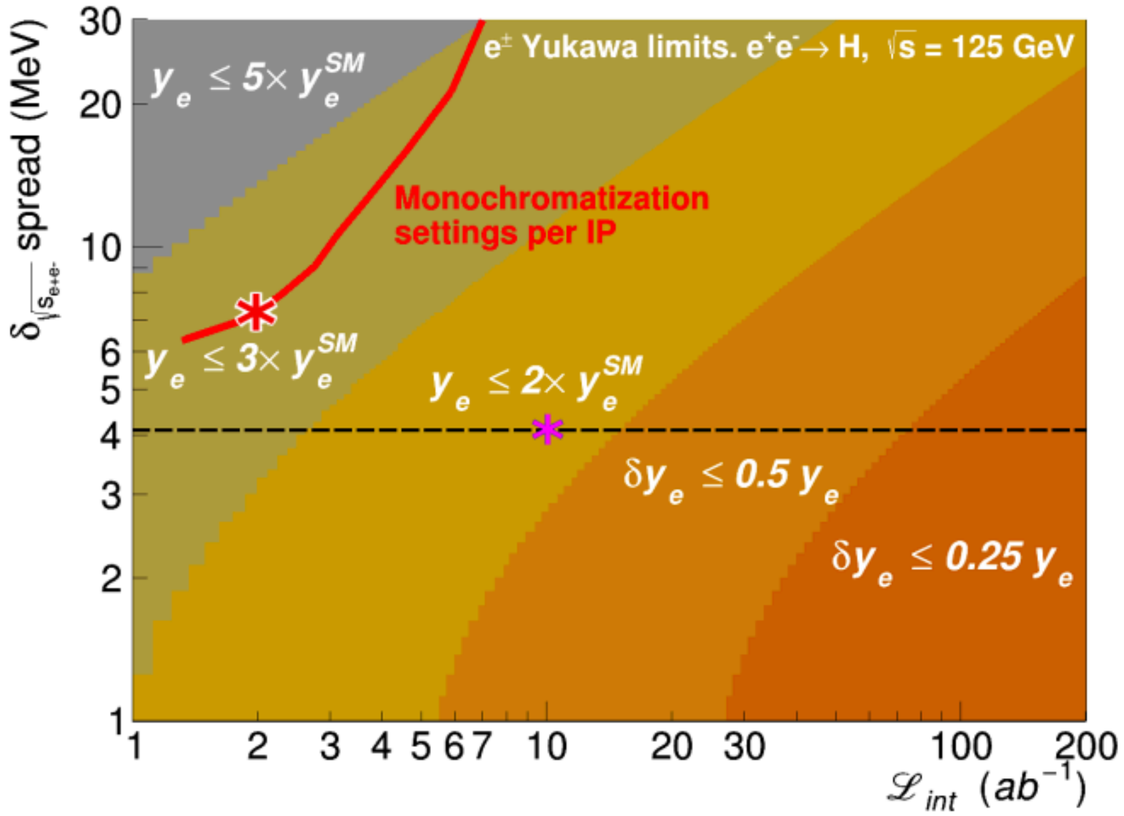


strange and electron Yukawa

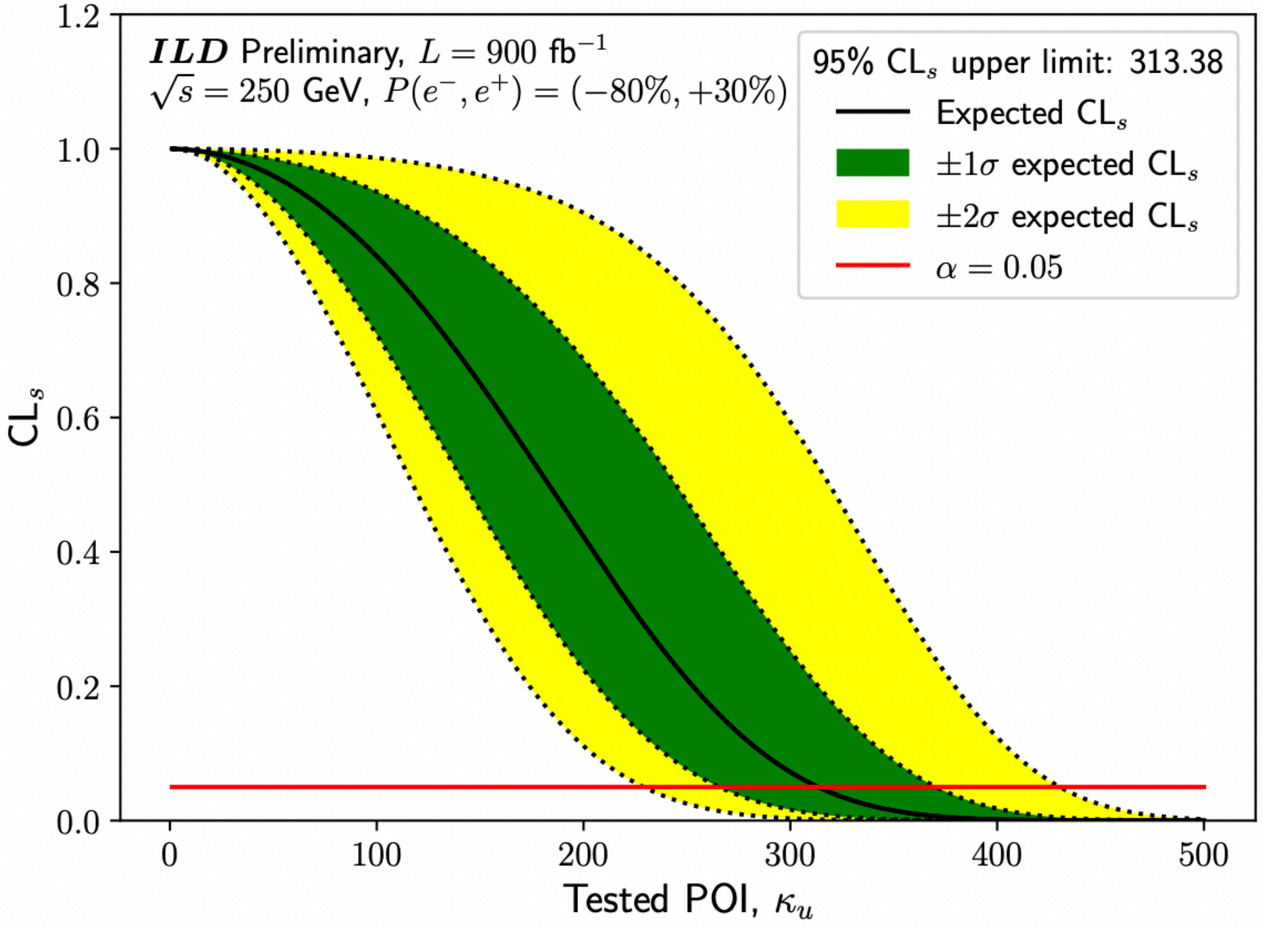
arxiv:2107.02686
arXiv:2203.07535

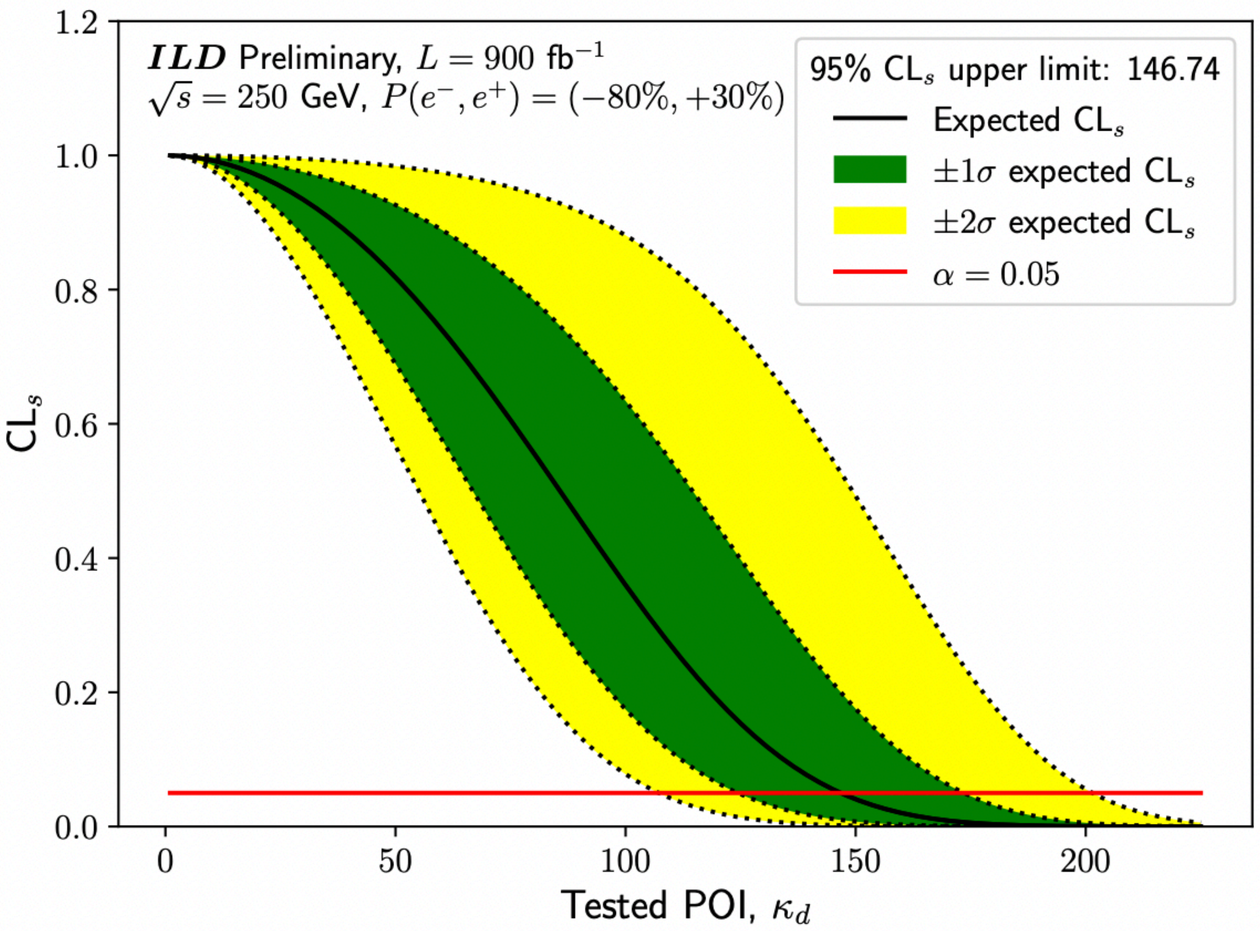
- ILD combined limit of κs < 6.74 at 95% CL with 900/fb at 250 GeV (i.e. half dataset)
- **Electron** Yukawa at FCC-ee with a dedicated 4 years run at the Higgs mass
  - $\kappa_e < 1.6$ at 95% CL



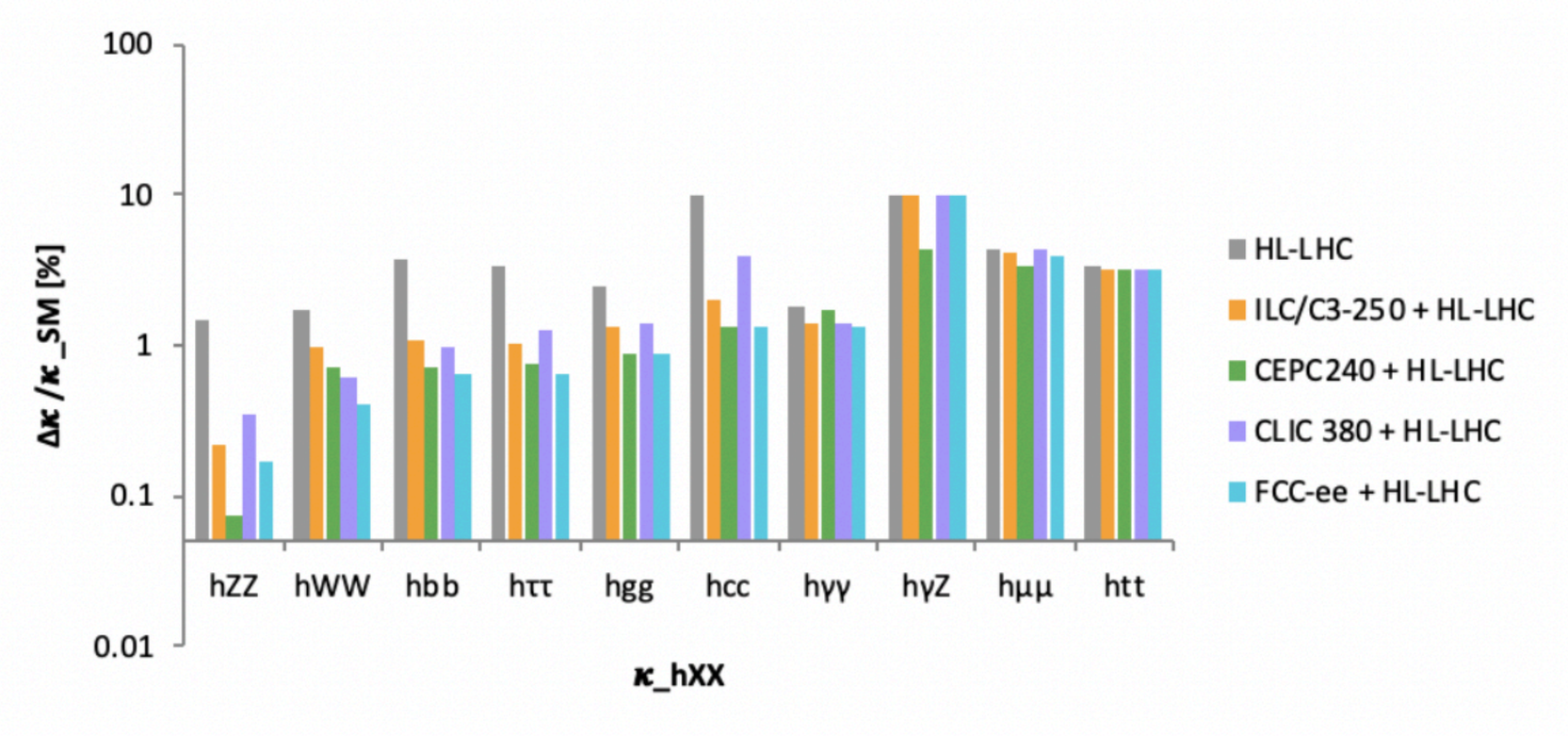


Light Yukawa ?





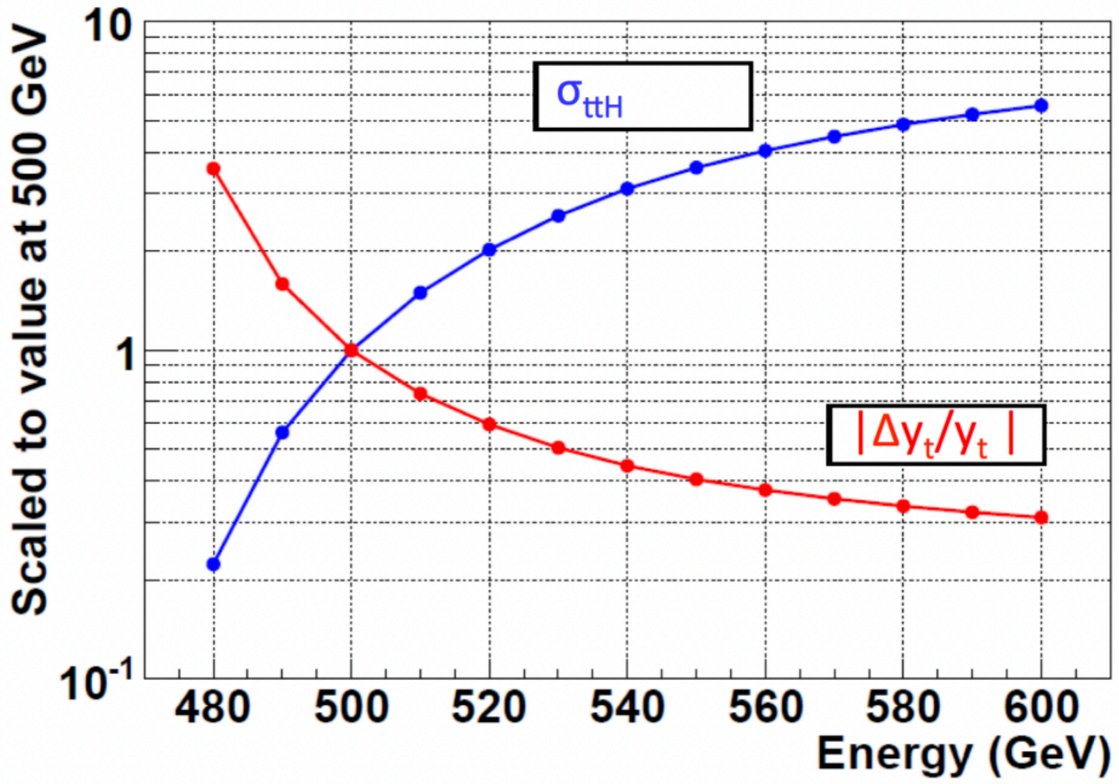
Higgs Boson couplings

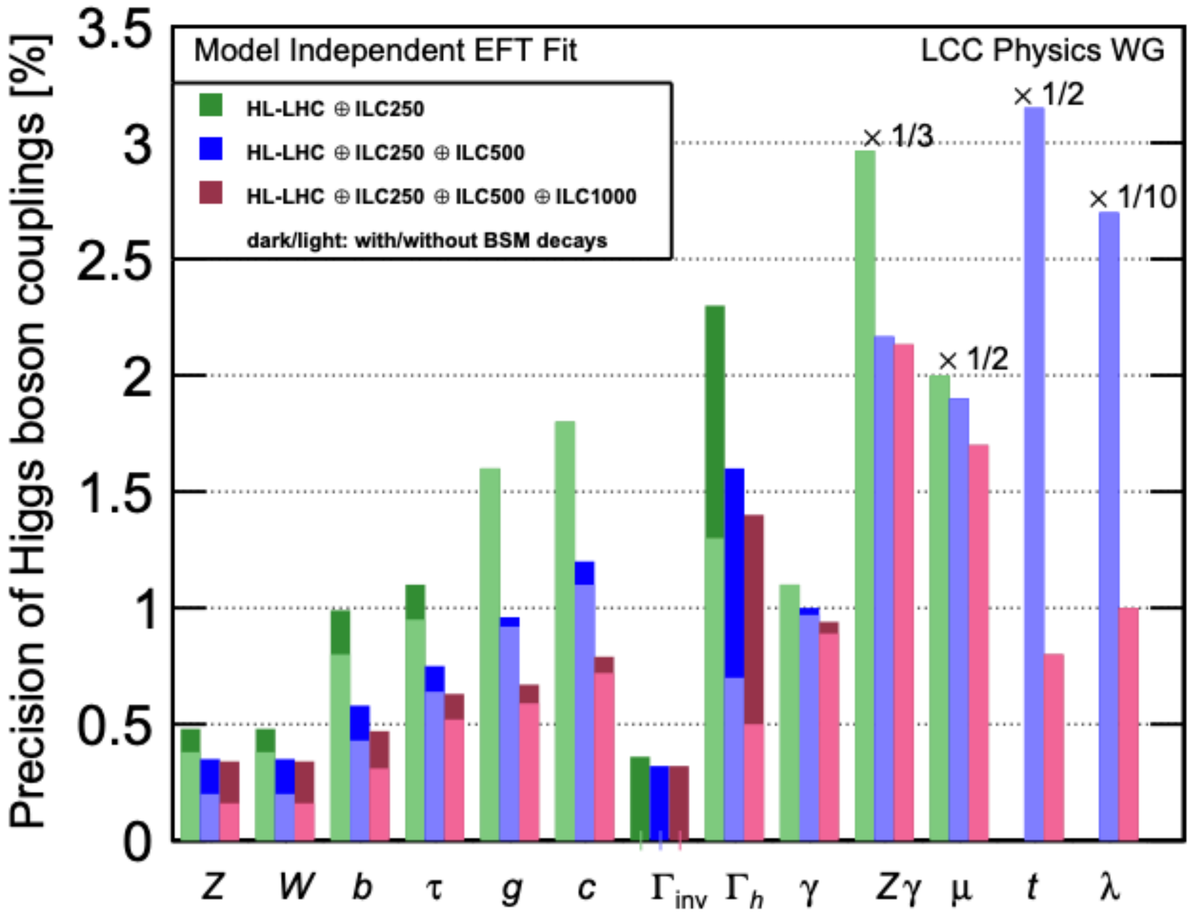


- All the e+e- machines being considered at ~ 250 GeV energy collisions will improve with respect to the HL-LHC the understanding of the Higgs boson couplings - 1-5%
  - **Coupling to charm** quark could be measured with an accuracy of ~1% in future e+e- machines
  - **Couplings to μ/γ/Zγ** benefit the most from the large dataset available at HL-LHC
  - At low energy top-Higgs and self-coupling coupling is not accessible, > 500 GeV is required

Higgs couplings for ILC

arXiv:2203.07622
arXiv:1506.07830

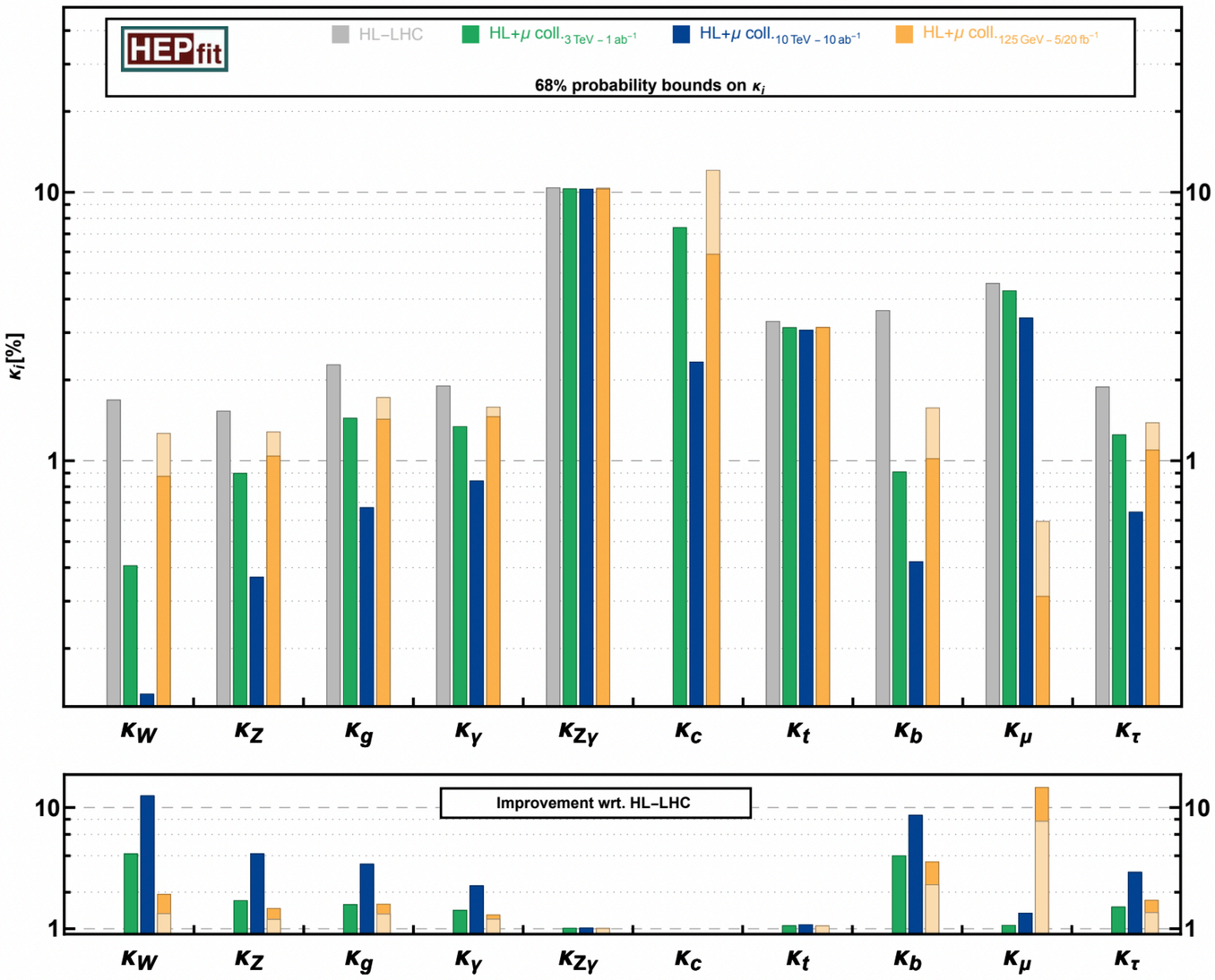


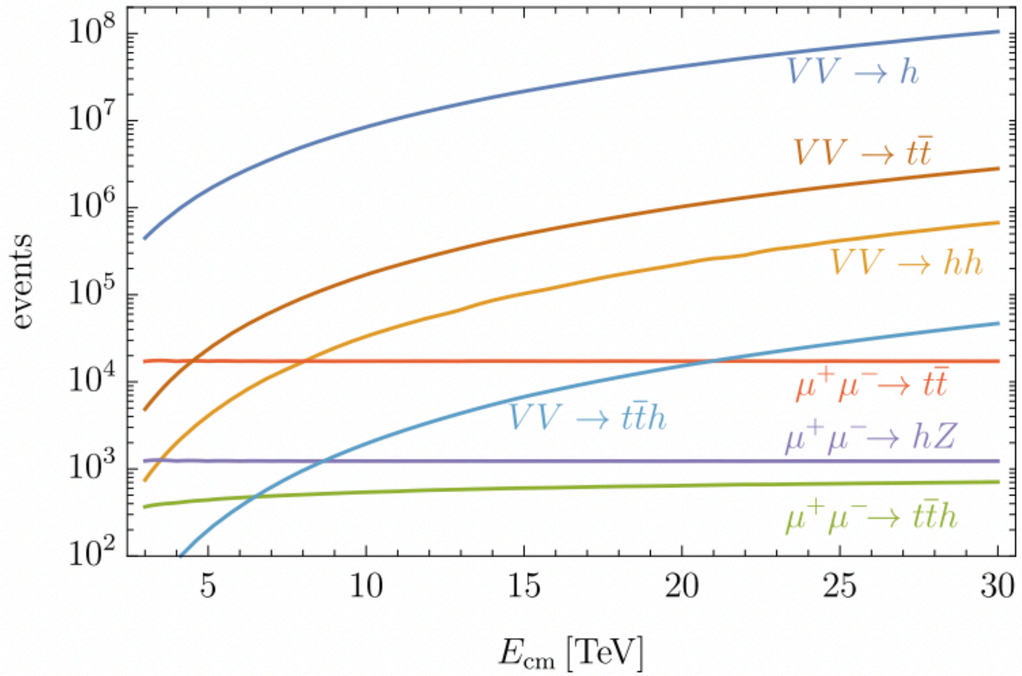


From 500 to 550 GeV a factor two gain in precision on the Higgs-top coupling

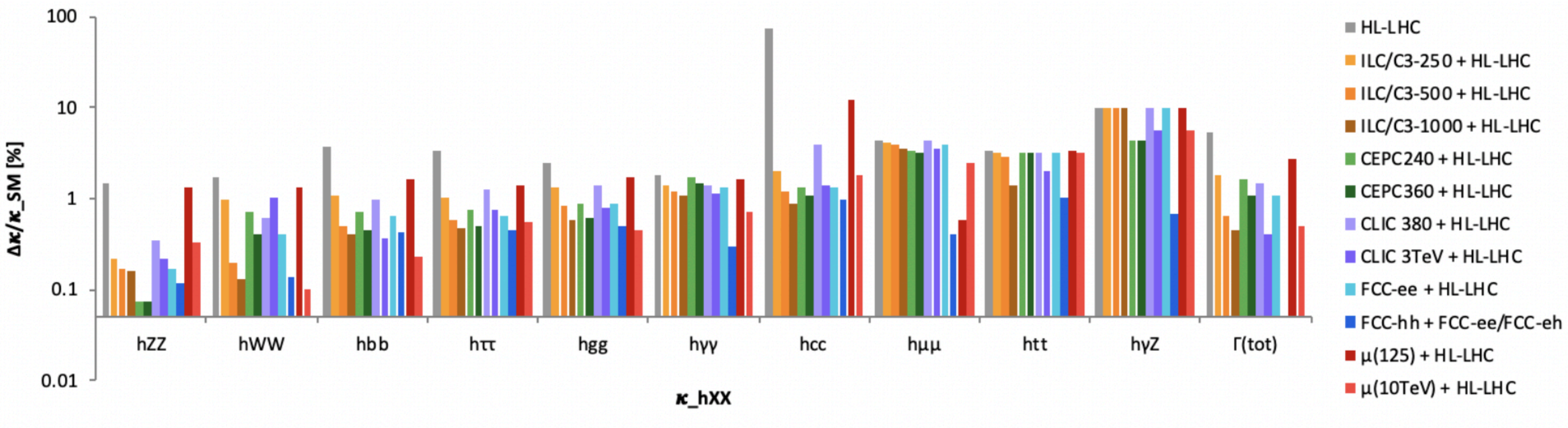
Higgs couplings at the muon collider

arXiv:2203.07261





Higgs couplings at future machines



- The Zγ interaction remains difficult to measure at all future machines
- Higher energy collision is required (factor 2 from 500 to 550 GeV e+e-) to further constraints the Higgs-top coupling
- These results are based on the κ_0 scenario of the ESG (combined with projections for HL-LHC results) and do not allow for BSM decays

The Higgs self-coupling at future colliders

collider	Indirect-h	hh	combined
HL-LHC [68]	100-200%	50%	50%
ILC_{250}/C^3-250 [49, 50]	49%	–	49%
ILC_{500}/C^3-550 [49, 50]	38%	20%	20%
$CLIC_{380}$ [52]	50%	–	50%
$CLIC_{1500}$ [52]	49%	36%	29%
$CLIC_{3000}$ [52]	49%	9%	9%
FCC-ee [53]	33%	–	33%
FCC-ee (4 IPs) [53]	24%	–	24%
FCC-hh [69]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [57]	-	15-30%	15-30%
μ(10 TeV) [57]	-	4%	4%

Not updated (yet) since the YR, although new projections available based on full Run 2 dataset

CP properties

arXiv:2205.07715

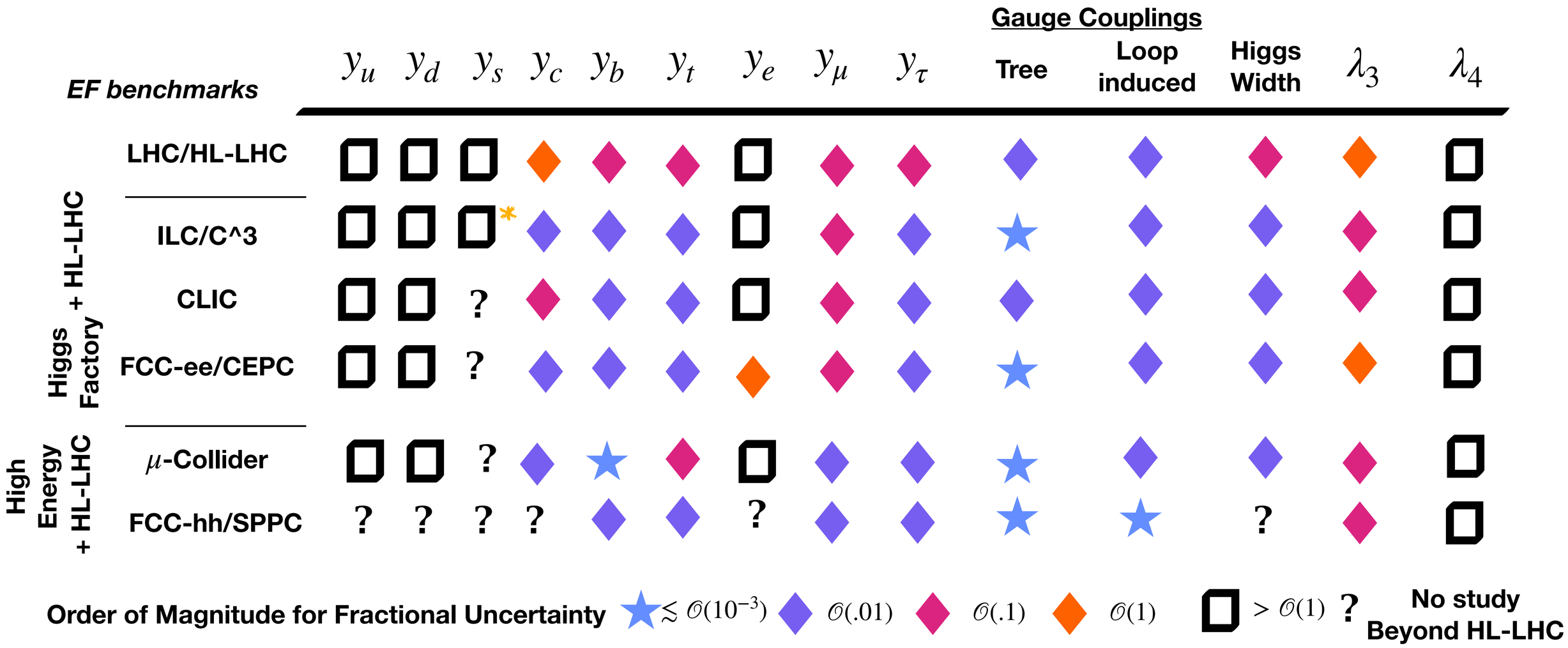
- Most processes could be studied at an e+e- collider with the beam energy above the tth threshold.
- Future e+e- colliders are expected to provide comparable sensitivity to HL-LHC in hff couplings, and potentially higher sensitivity in hZZ couplings.
- The muon collider operating at the Higgs boson pole allows to measure the CP structure of the hμμ vertex with the beam polarization

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	125	125	≥ 500	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	20,000	250	350	500	1,000	250			
HZZ/HWW	$4\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.4\cdot10^{-4}$	$1.1\cdot10^{-4}$	$4\cdot10^{-5}$	$8\cdot10^{-6}$	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	$\sim$1	✓	–	–	–	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Higgs width

- The measurement of the width is also extremely sensitive to high scale new physics.
- **HL-LHC** can constrain the Higgs boson width indirectly from the ZZ→4l channel $4.1^{+.7}_{-.8}$ MeV ~17% accuracy
  - The indirect measurement is more akin to an absolute coupling normalization and can be viewed as part of the larger ``Higgs without Higgs'' framework.
- The full **FCC-ee** program (combined with HL-LHC) allows for a 1% measurement of the Higgs width.
- Using a SMEFT fit, the **ILC** finds similar results for the full program, but with just the initial 250 GeV run, a 2% measurement on the total width can be obtained.
- A muon collider running at 125 GeV can obtain a model independent measurement of the Higgs total width 2.7% with 5/fb by using a line-shape measurement
  - A high energy muon collider should obtain a similar order of magnitude precision using the indirect methods employed at the LHC with the same theoretical assumptions, and the FCC-hh could in principle also use these methods with further study.

Summary plot



How we get to new physics from here?

Higgs Inverse problem of how to map from observables to new physics

New from the ESG update

- Phenomenology of a **strong electroweak phase transition**
  - It can manifest through shifts in the Higgs cubic coupling, but could still occur without any deviation in this coupling
  - Deviations in all types of observables are also possibly correlated with the phase transition, including exotic Higgs decays
- **Flavored phenomenology**
  - Flavor violating decays
  - Flavor preserving deviations in light quarks Yukawas : studies for direct probes of this at e+e- colliders and related resonance probes from the LHC and other colliders
- **Singlet phenomenology**
  - introduction of scalar resonance decaying to particles with different masses
- Viable models of **triple-Higgs production** at the HL-LHC and beyond
  - Triple Higgs and quad Higgs measurements should be pursued at future colliders.

Size of Higgs Coupling deviations?

$\delta\eta_{SM}$ $\sim 1\%$ $\sim .1\%$

Tree level origin
$$\sim \frac{v^2}{M^2}$$

Loop level
$$\sim \frac{1}{(4\pi)^2}\frac{v^2}{M^2}$$

SM Neutral
e.g. scalar singlet
$$\sim \left(\frac{\lambda^2_{h^2 s}}{2M^2}\right)\frac{v^2}{M^2}$$

$M \lesssim 1.7\,\mathrm{TeV}$

$M \lesssim 5.5\,\mathrm{TeV}$

SM Charged
e.g. 2HDM
$$\sim \left(\frac{\lambda_6^2 v^2}{M^2}\right)\frac{v^2}{M^2}$$

$M \lesssim 0.8\,\mathrm{TeV}$

$M \lesssim 1.4\,\mathrm{TeV}$

SM Neutral
e.g. scalar singlet
$$\sim \left(\frac{\lambda^2_{h^2 s^2}}{48\pi^2}\right)\frac{v^2}{M^2}$$

$M \lesssim 0.1\,\mathrm{TeV}$

$M \lesssim 0.4\,\mathrm{TeV}$

SM Charged
w/ SM loop
e.g. stops in SUSY
$$\sim \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}}^2}$$

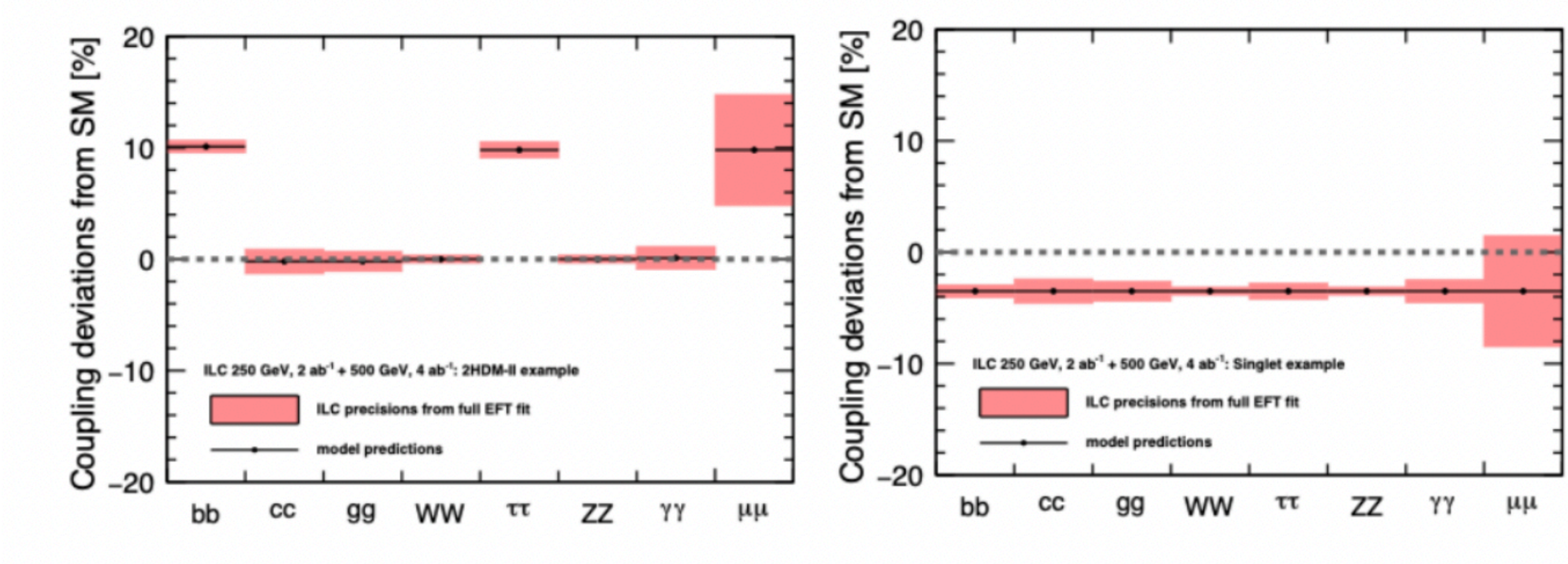
$M \lesssim 0.9\,\mathrm{TeV}$

$M \lesssim 2.8\,\mathrm{TeV}$

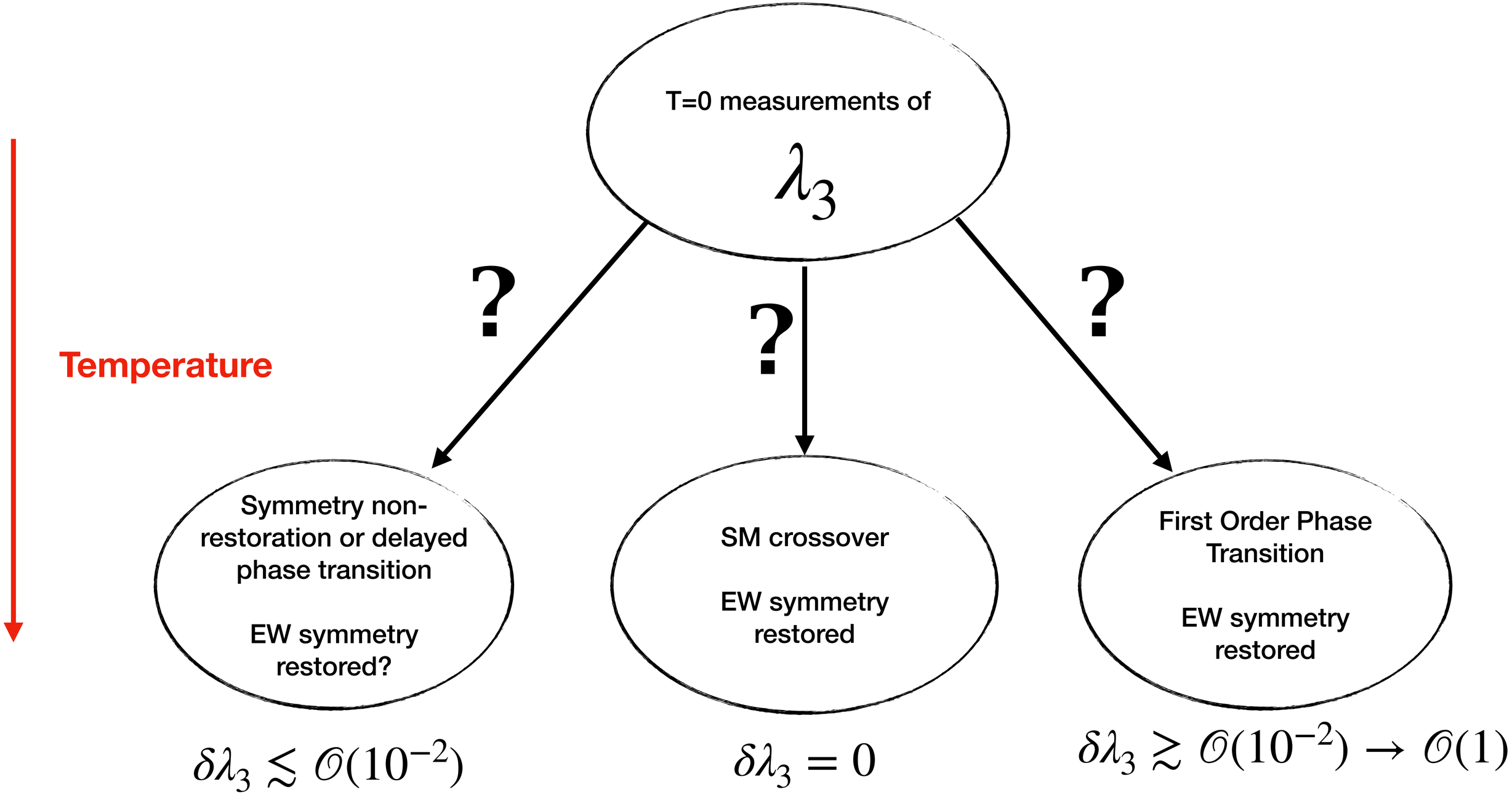
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

An example of complementarity

arXiv:2203.07622

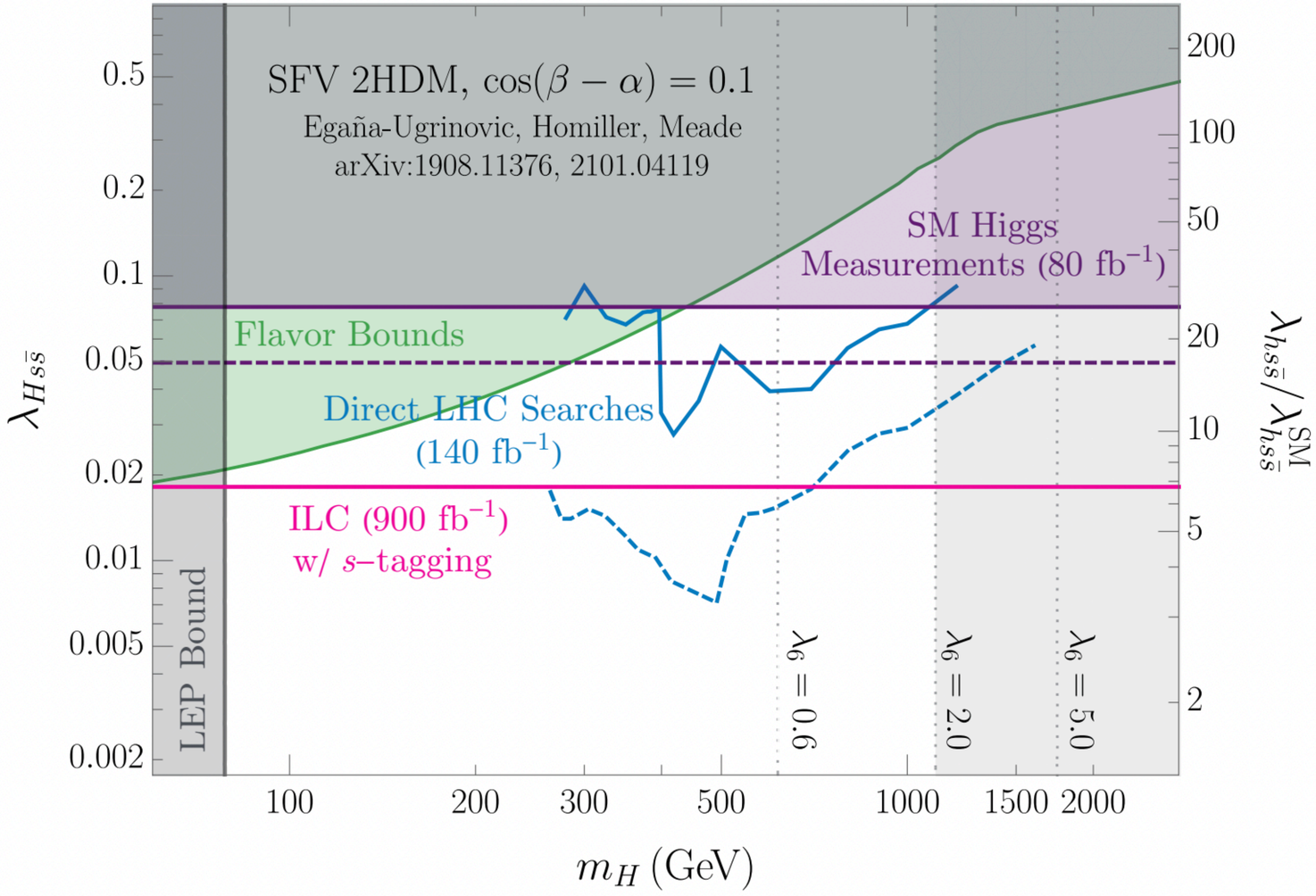


- Pattern of deviations associated with a particular parameter point in a 2HDM model is quite different from a singlet model
  - 2HDM with a 600 GeV mass scale and asinglet with a 2.8 TeV scalar. Both of these are clearly out of the direct search reach of circular e+e− Higgs factories despite having the precision to test them via Higgs couplings
  - High energy collisions would be then required to study such new particles


T=0 measurements of
λ_3
?
?
?
Temperature
Symmetry non-restoration or delayed phase transition
EW symmetry restored?
SM crossover
EW symmetry restored
First Order Phase Transition
EW symmetry restored
$\delta\lambda_3 \lesssim \mathcal{O}(10^{-2})$
$\delta\lambda_3 = 0$
$\delta\lambda_3 \gtrsim \mathcal{O}(10^{-2}) \to \mathcal{O}(1)$

Flavor violating 2HDM

arXiv:2203.07535



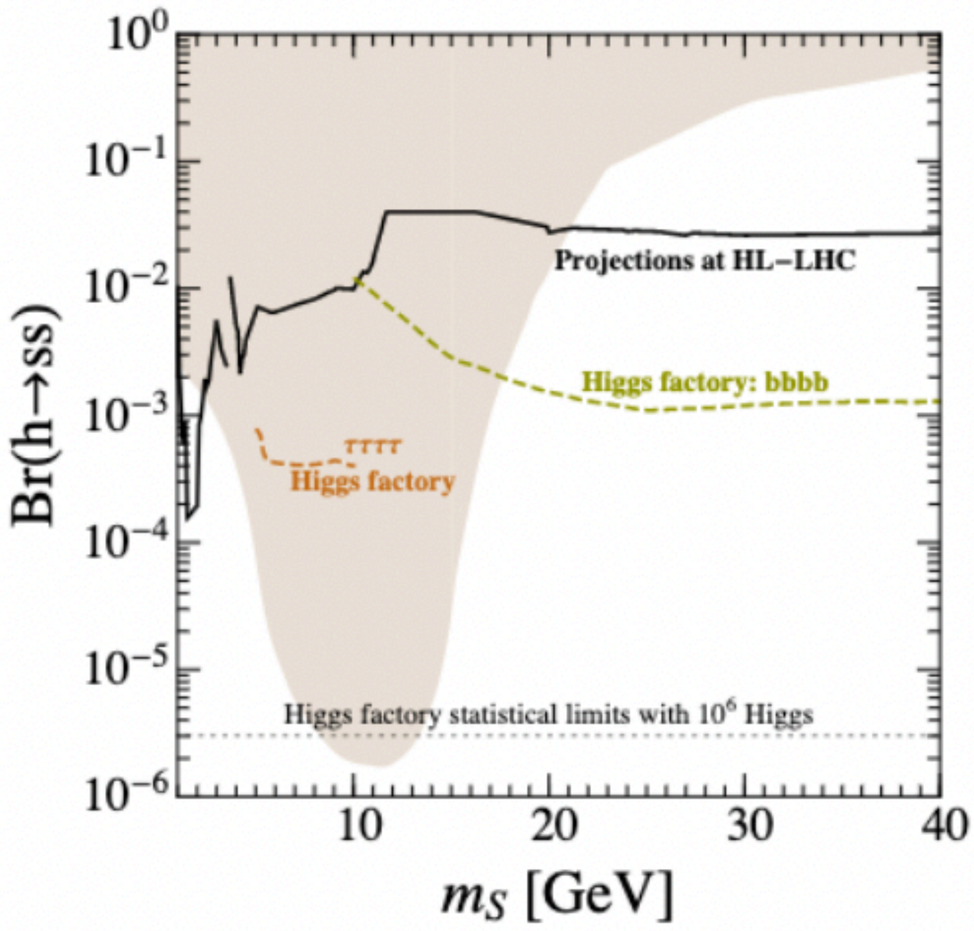
A spontaneous flavour violating (SFV) 2HDM allows for large couplings of additional Higgs to strange/light quarks while suppressing flavor-changing neutral currents

Exotic Higgs Decays

arXiv:2203.07622
arXiv:2203.08206
arXiv:1612.09284

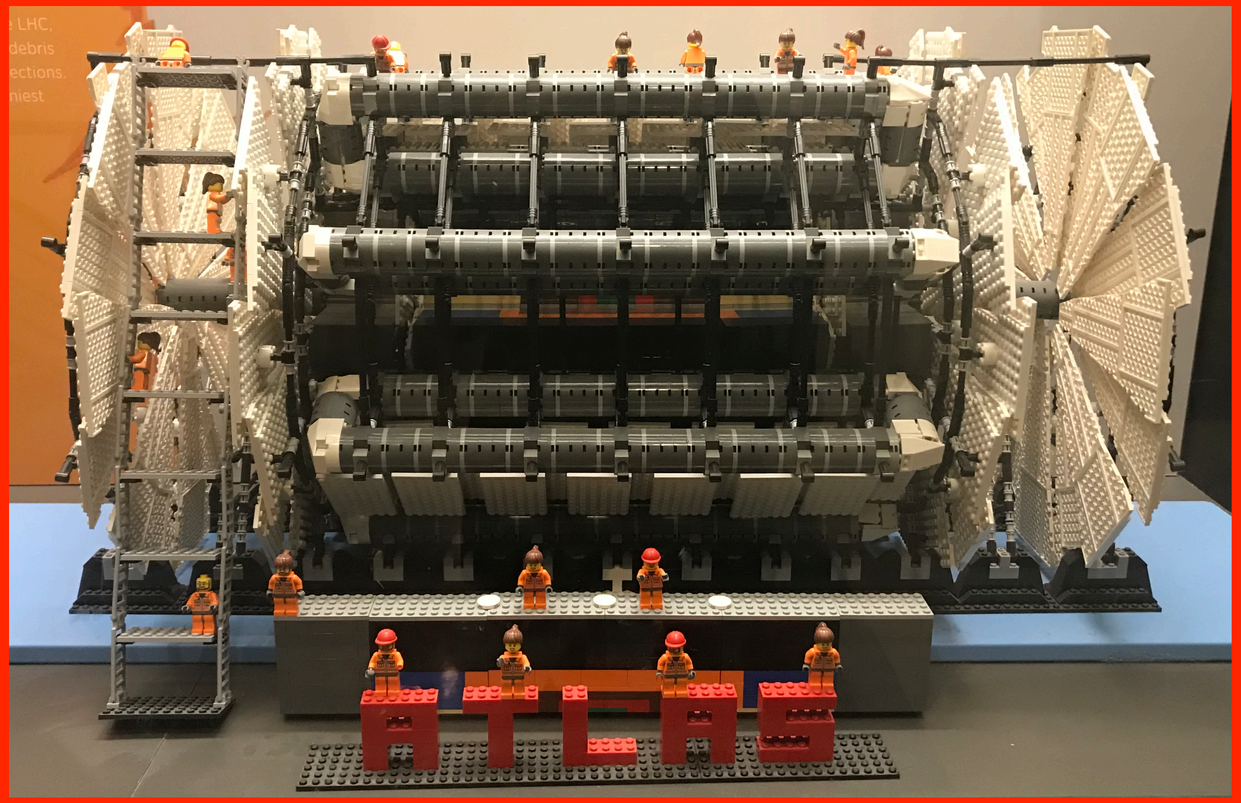
- At low energy, e+e- running near the Zh maximum cross section extra bounds on h→ anything can be derived
  - One order of magnitude improvement over HL-LHC
- Connection to allowed phase transitions as a function of the light scalar mass and the branching ratio h→SS
  - Both the HL-LHC and future Higgs factories can probe the region with an allowed electroweak phase transition.

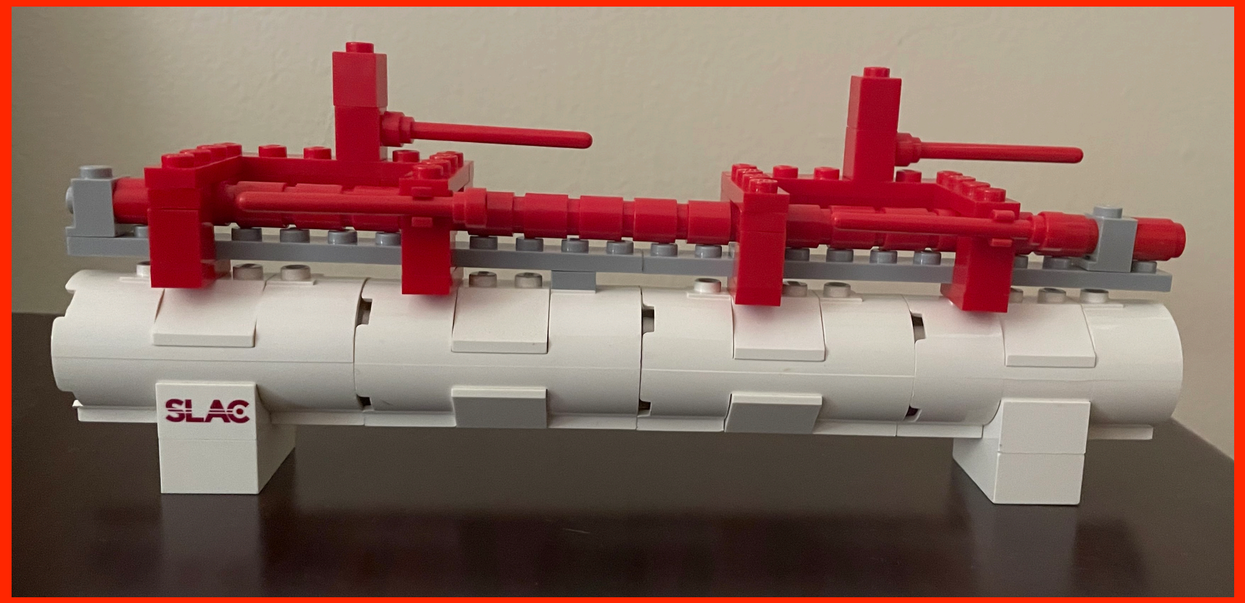
Channel	HL-LHC	ILC	FCC-ee
E_T^{miss}	0.056	.0025	.005
$b\bar{b}b\bar{b}$	0.2	9×10^{-4}	3×10^{-4}
$b\bar{b}E_T^{miss}$	0.2	2×10^{-4}	5×10^{-5}
$jj\gamma\gamma$	0.01	2×10^{-4}	3×10^{-5}



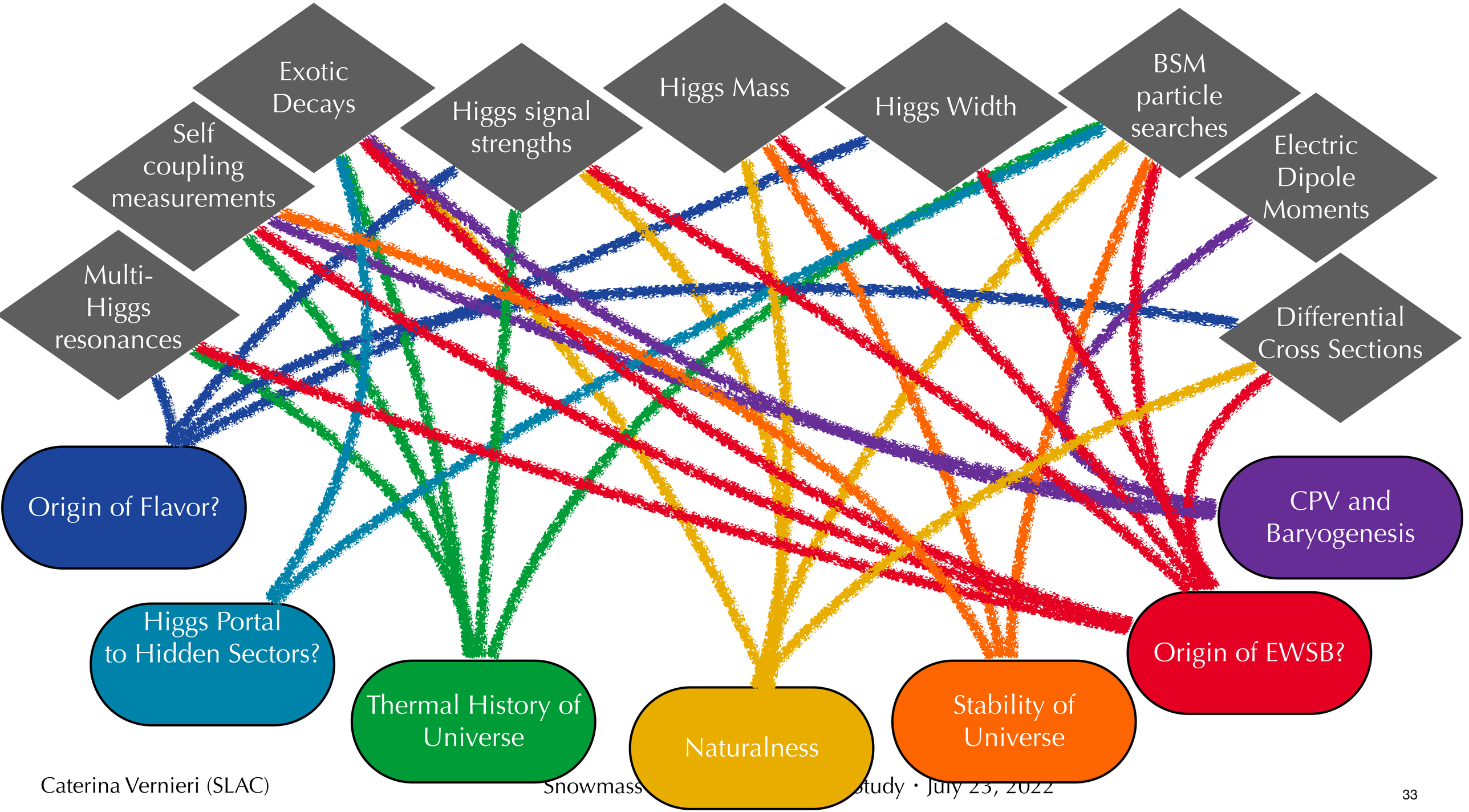
Towards the final version of the report:

Please share with us your thoughts on the report





Extra


Exotic Decays
Self coupling measurements
Multi-Higgs resonances
Higgs signal strengths
Higgs Mass
Higgs Width
BSM particle searches
Electric Dipole Moments
Differential Cross Sections
Origin of Flavor?
Higgs Portal to Hidden Sectors?
Thermal History of Universe
Naturalness
Stability of Universe
Origin of EWSB?
CPV and Baryogenesis

One note on polarization

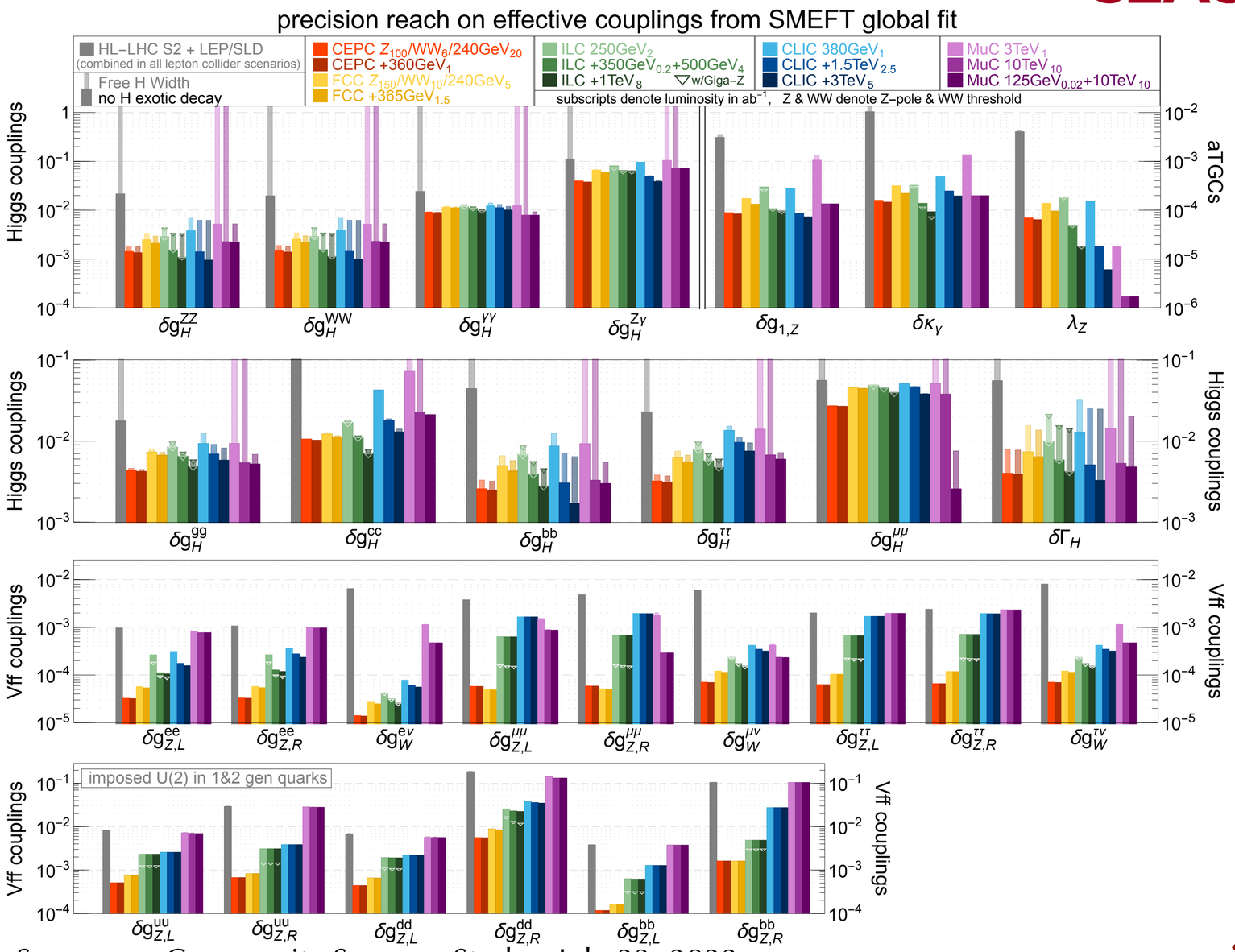
arXiv:1708.08912
arXiv:1801.02840

- There are extensive comparisons between the FCC-ee plan and the C³/ILC runs that show they are rather **compatible to study the Higgs Boson**
- When analyzing Higgs couplings with SMEFT, 2 ab^{-1} of polarized running is essentially equivalent to 5 ab^{-1} of unpolarized running.
  - **Electron polarization is essential** for this
  - There is almost no difference in the expectation with and without **positron polarization**.
    - more cross-checks of systematic errors.
    - relevant at high energy (> TeV) where the most important cross sections are initiated from $e^-_L e^+_R$

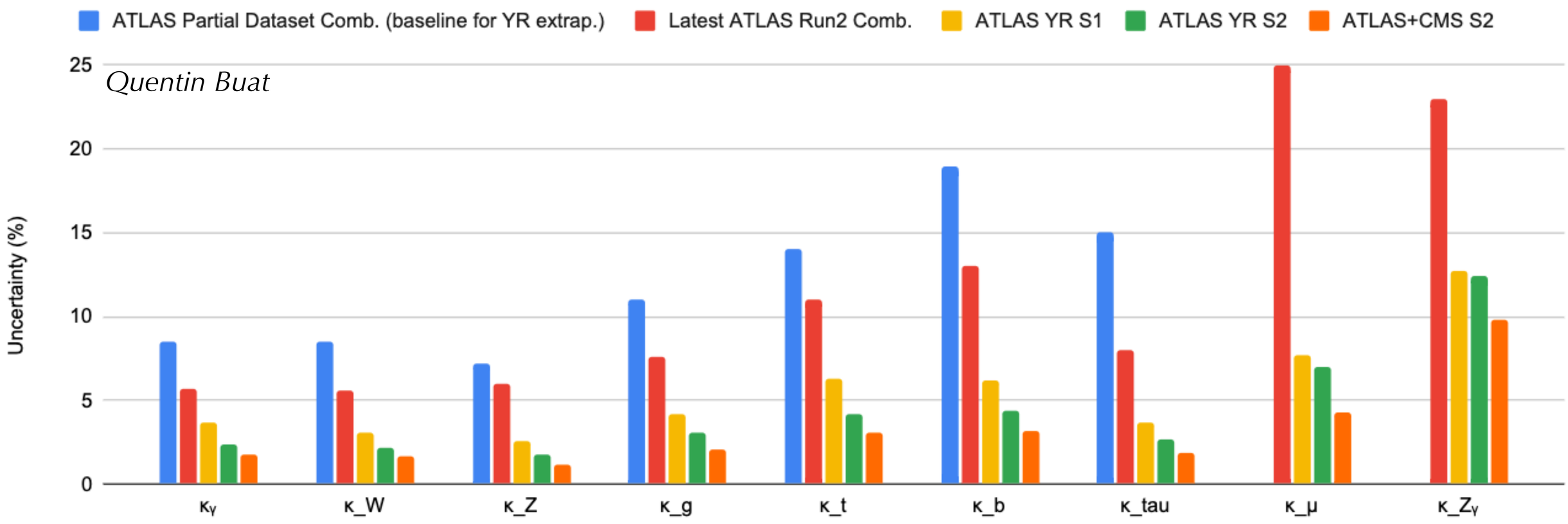
coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

Global fit results - from EF04

- Solid has no exotic Higgs decays, the light fits the width



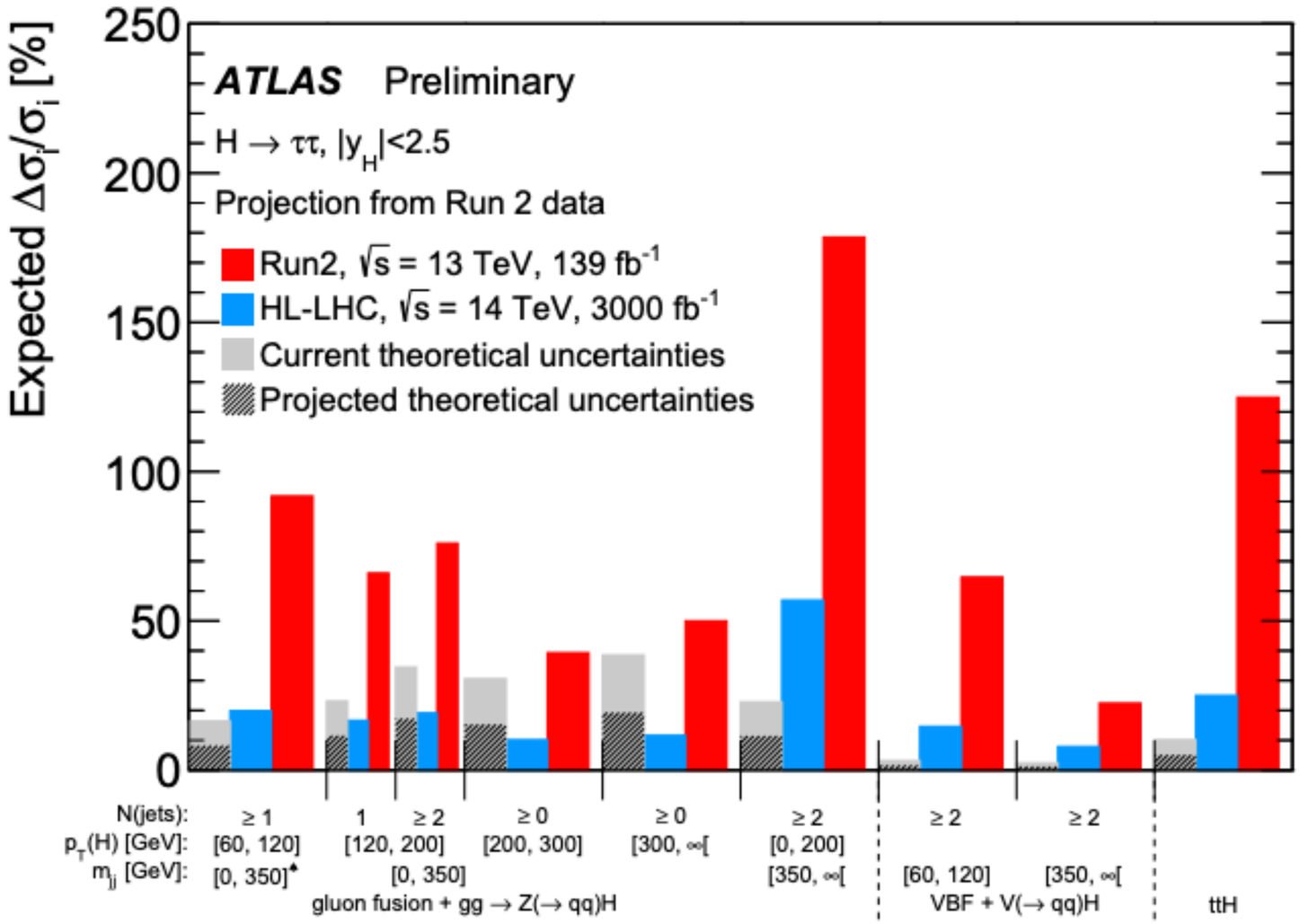
New from HL-LHC



YR projections based on analyses of partial Run 2 dataset
Full Run 2 measurements have drastically improved previous results
We need to update our HL-LHC projections

Higgs production at large p_T

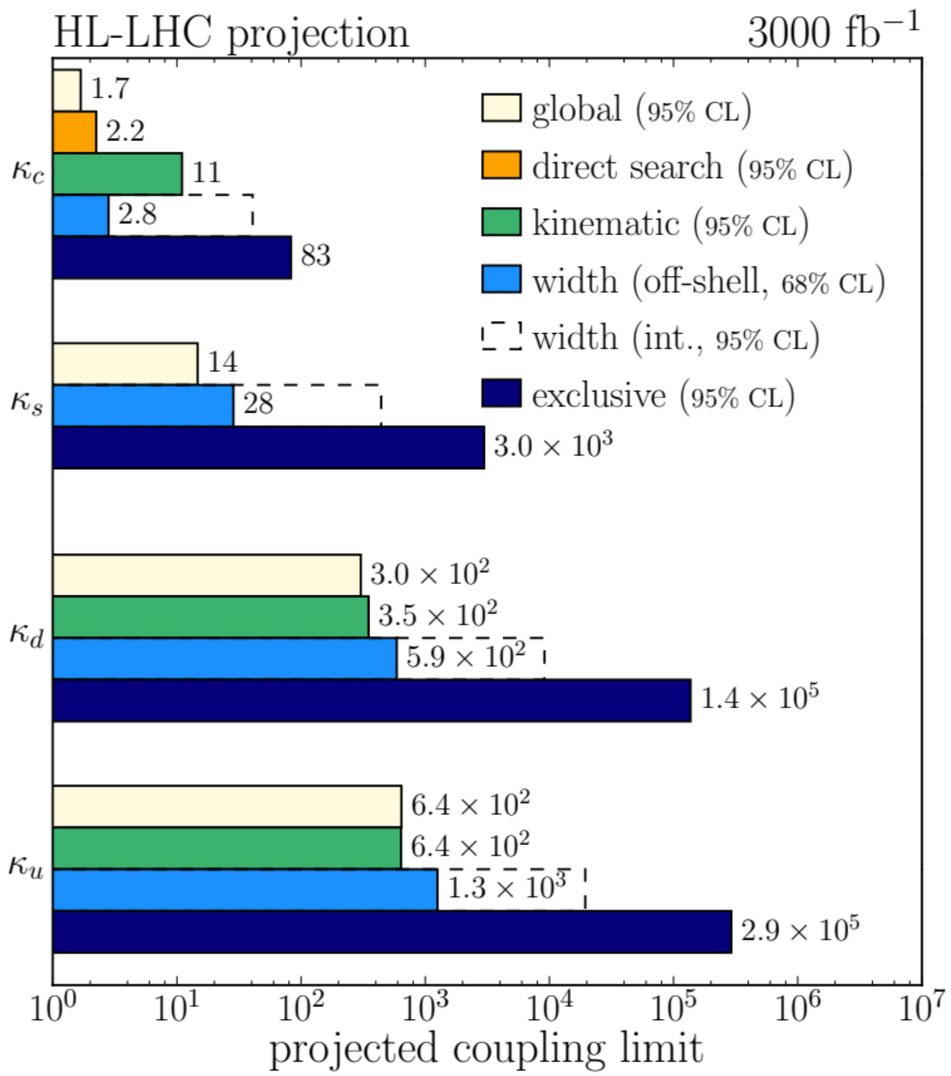
ATLAS+CMS HL-LHC 2022 study



Prospects for light quark couplings at HL-LHC

CERN-LPCC-2018-04

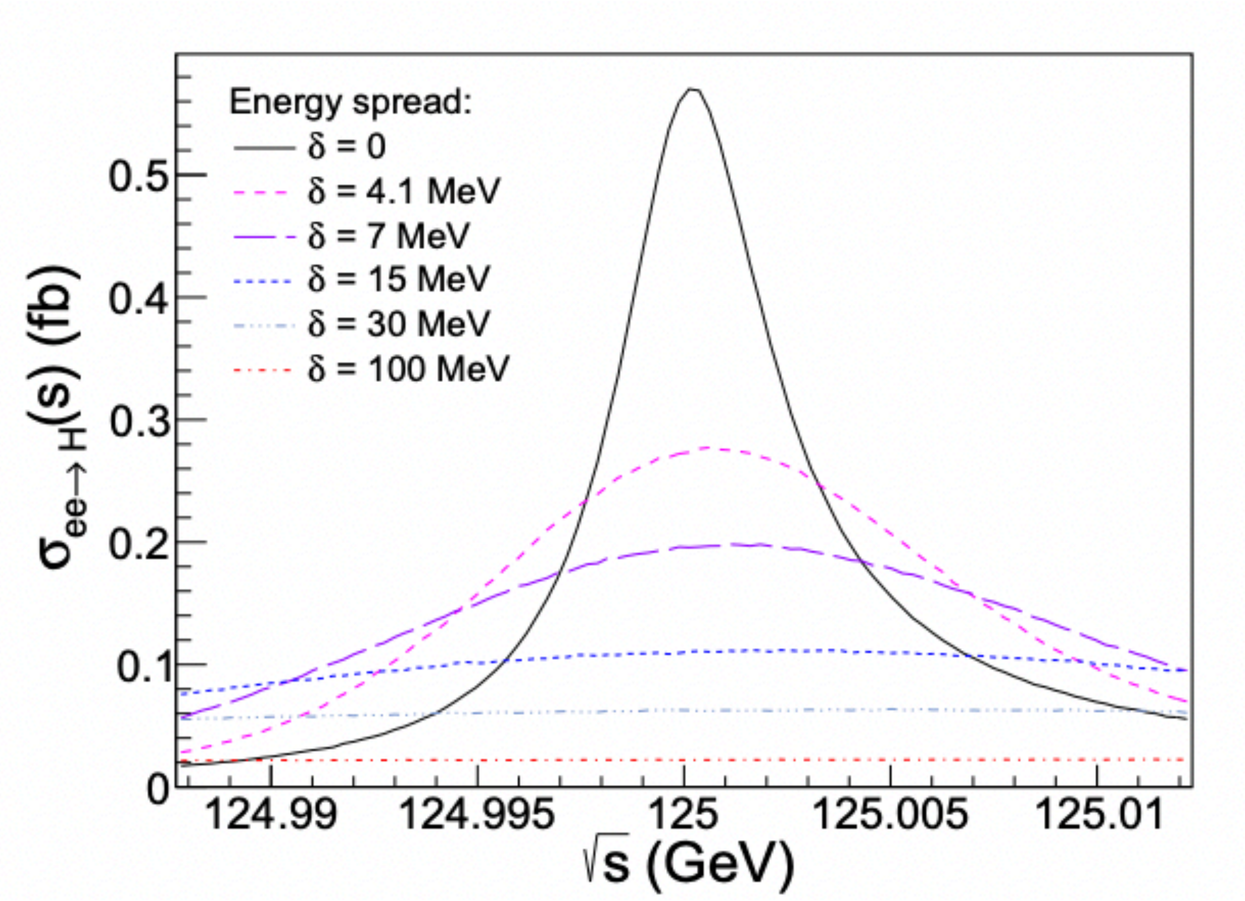
- Exclusive decays to γ+meson include contributions from light quark Yukawa couplings
- Interpretation of Higgs width constraint: direct measurement and via off-shell
- Interpretation of kinematic distributions
- Direct search for H→cc
- Global fit of all Higgs couplings (assuming no other BSM decays)

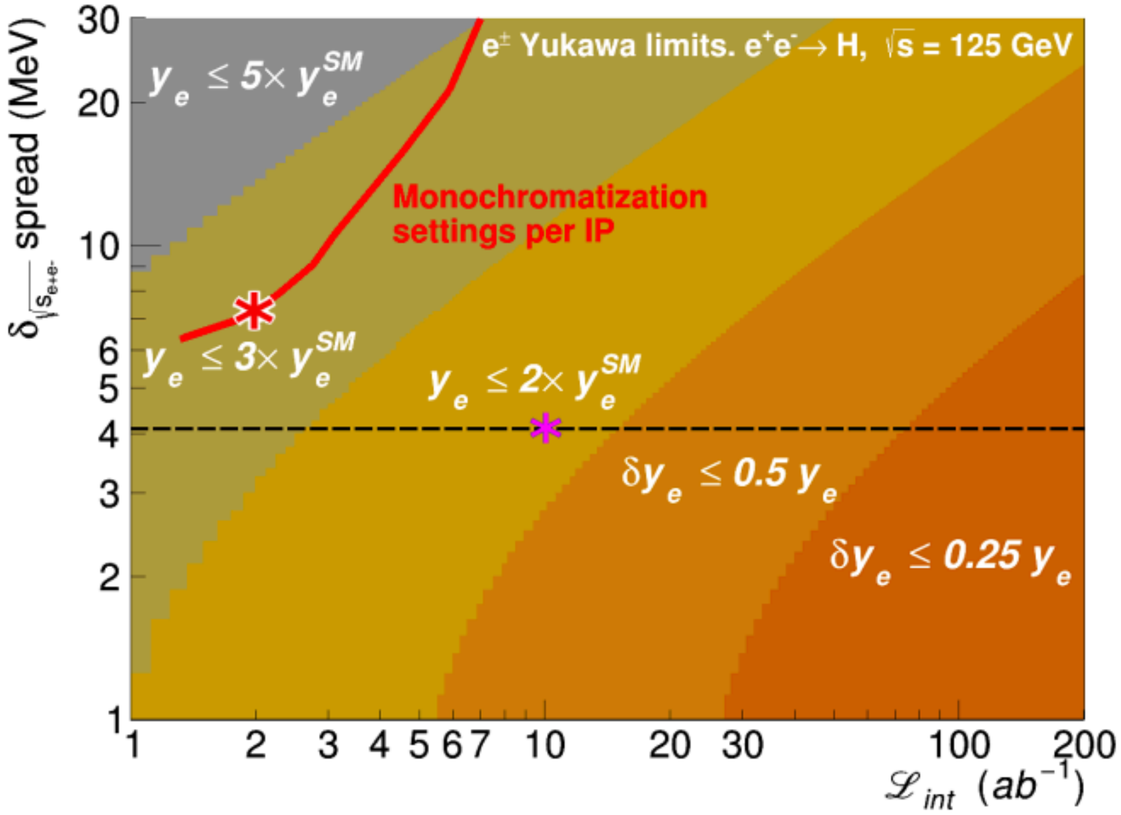


Higgs-electron Yukawa

arxiv:2107.02686

- **Electron** Yukawa at FCC-ee with a dedicated 4 years run at the Higgs mass
  - $\kappa_e < 1.6$ at 95% CL





Extended Higgs sector

arXiv:2203.07261