The Future of Higgs

Standard Model at the LHC

CERN, April 11- 14, 2022

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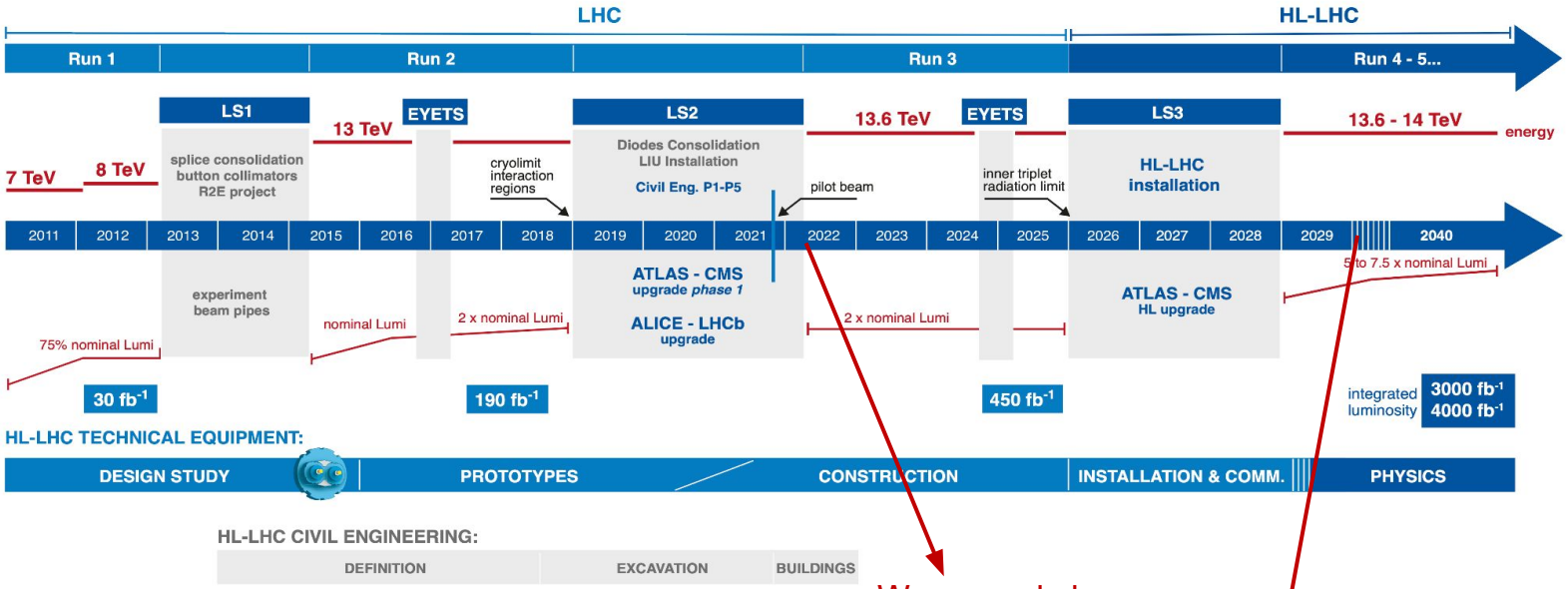
With highlights from ongoing discussions within the Snowmass Energy Frontier

Snowmass EF wiki: https://snowmass21.org/energy/start

LHC / HL-LHC Plan



We are only here

Many years of HL running ahead of us

- ➔ 2-fold increase in statistics by the end of Run 3
- ➔ 20-fold increase in statistics by the end og HL-LHC!

The LHC era: exploring the TeV scale

- **LHC Run 1**: the **Higgs discovery** has been a game changer.
- **LHC Run 2**: **entering** the era of **Higgs precision physics.**
- **LHC Run3** and the **HL-LHC**: will **push the Higgs precision program** farer.
- Updated scenarios for **future colliders** are being **proposed based on LHC results**, **HL-LHC projections**, and **theory recommendations.**
- **Intriguing results** coming from **rare processes**, **flavour physics**, **cosmology**.

Higgs physics has been at the core of the LHC physics program and will continue to be for Run 3 and the HL-LHC upgrade, as well as for all future colliders currently under discussion

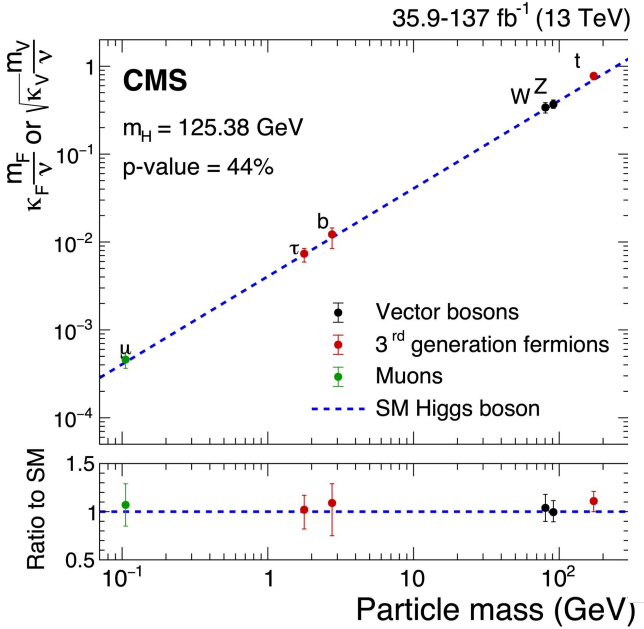
Higgs physics to answer key questions of the EF program

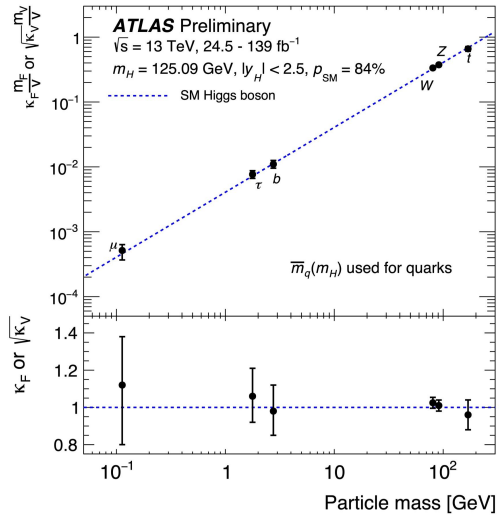
What is the origin of the EW scale?

- Can we uncover the nature of UV physics from **precision Higgs measurements** (mass, width, couplings)? How much precision do we need?
  - How accurately do we need to measure?
  - Are existing theoretical predictions sufficient for the comparison?
- Can we measure the shape of the **Higgs potential**? →Higgs self coupling(s)
- Can the **Higgs give us insight into flavor** and vice versa?
  - Couplings to **heavy flavors** (top, bottom,...).
  - Couplings to **light flavors** (charm, strange, …) and **leptons.**
- Why $M_H << M_{Planck}$? What are the implications for **Naturalness**?
  - How to connect precision and direct searches, how to achieve complementarity?
  - Sensitivity to a variety of new physics → EFT, inverse Higgs problem, ...

The Higgs discovery has given us a unique handle on BSM physics and any future plan needs to make the most out of it

HL-LHC projections from Run 2 data



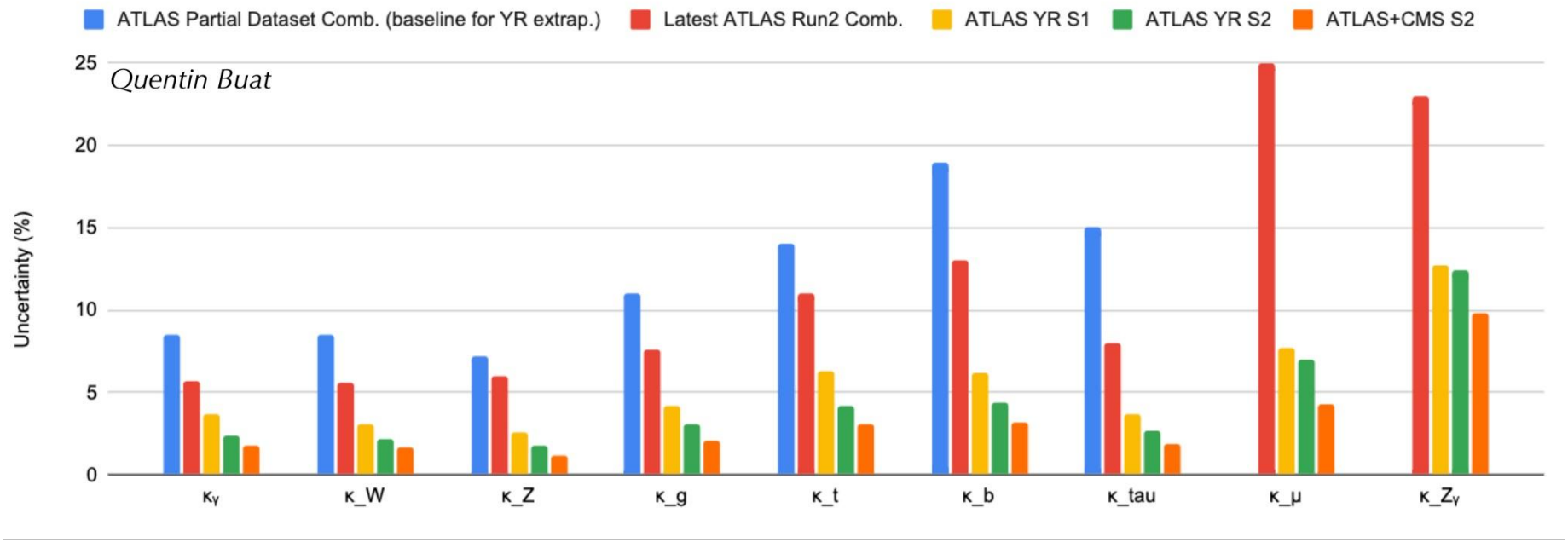


κ_i	ATLAS	CMS	HL-LHC
κ_Z	$1.02^{+0.06}_{-0.06}$	$0.96^{+0.07}_{-0.07}$	1.5%
κ_W	$1.05^{+0.06}_{-0.06}$	$-1.11^{+0.14}_{-0.09}$	1.7%
κ_t	$0.96^{+0.08}_{-0.08}$	$1.01^{+0.11}_{-0.11}$	3.4%
κ_b	$0.98^{+0.14}_{-0.13}$	$1.18^{+0.19}_{-0.27}$	3.7%
κ_τ	$1.06^{+0.15}_{-0.14}$	$0.94^{+0.12}_{-0.12}$	1.9%
κ_μ	$1.12^{+0.26}_{-0.32}$	$0.92^{+0.55}_{-0.87}$	4.3%

- HL-LHC projections from YR: **2-5% on most Higgs couplings**
- Larger uncertainties on light flavor Yukawa couplings
- **<50% on Higgs self coupling**

Being updated for Snowmass 2021

New: improvement from full LHC Run 2 measurements



Full Run 2 measurement drastically improved partial Run 2 results used for YR projections. Need to update HL-LHC projections.

ATLAS+CMS HL-LHC 2022 study

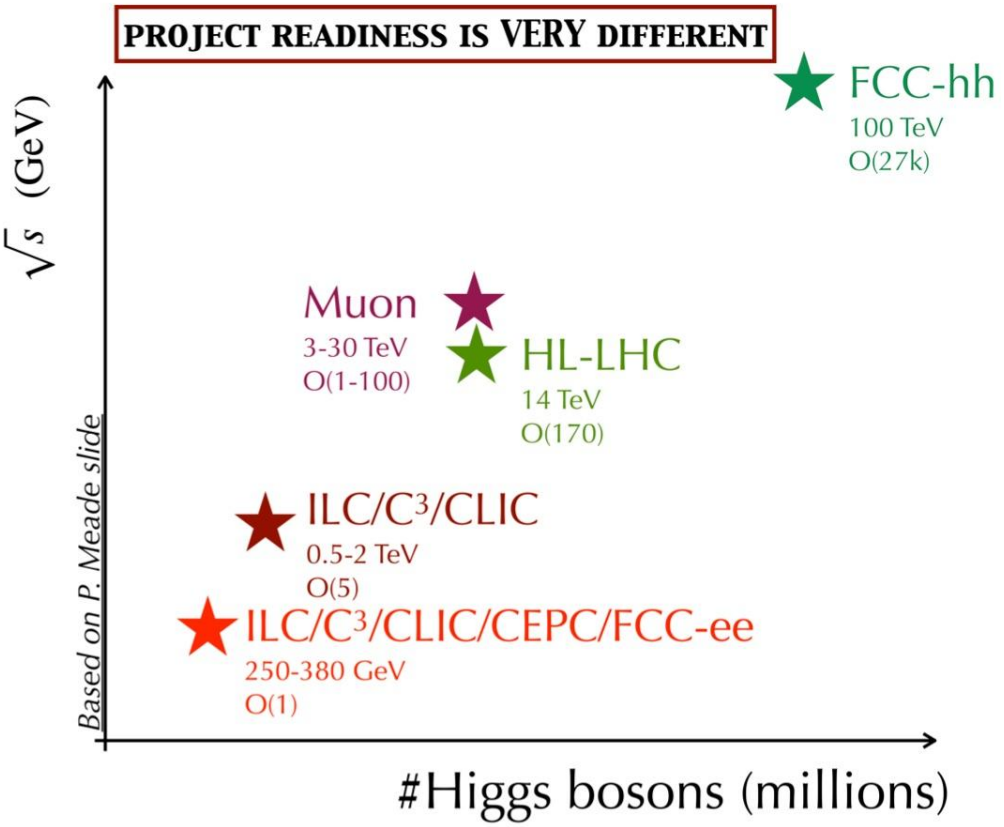
Beyond HL-LHC

LEPTON COLLIDERS

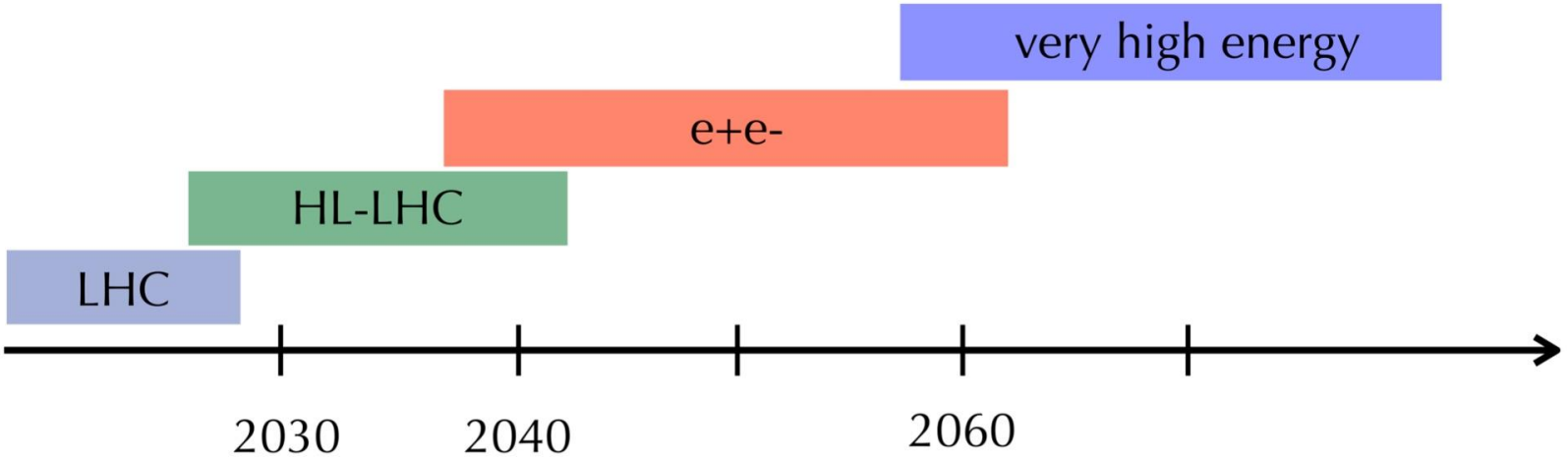
- **Circular e+e-** (CEPC, FCC-ee)
  - **90-350 GeV**
  - *strongly limited by synchrotron radiation above 350– 400 GeV*
- **Linear e+e-** (ILC, CLIC, C³)
  - **250 GeV — > 1 TeV**
  - *Reach higher energies, and can use polarized beams*
- **μ+μ-**
  - **3-30 TeV**

HADRON COLLIDERS

- **75-200 TeV** (FCC-hh)



Beyond HL-LHC Projections



H couplings to:	**O(5-15)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

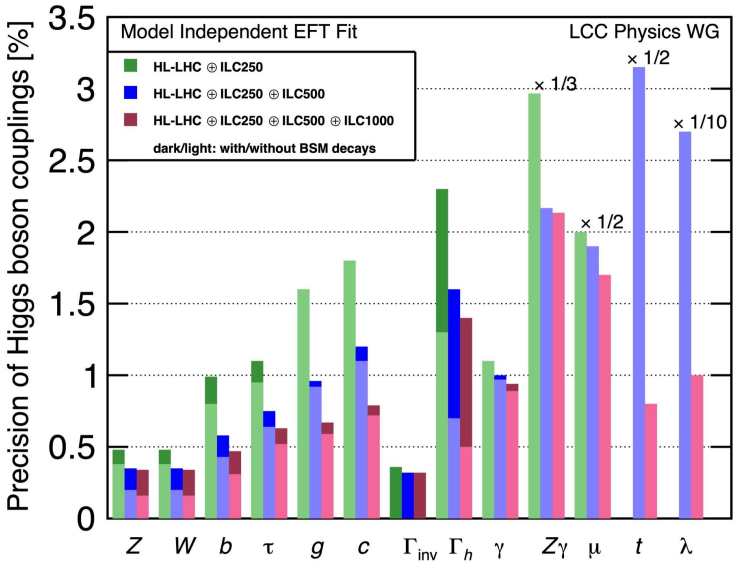
From C. Vernieri - EF Workshop - Brown U. - March 2022

New: Timelines and complementarities being explored

- **Update reach** of propose facilities
- **Continuity with HL-LHC**: ideally no gap
- **Energy matters**: **top-Yukawa**, **HH**, **extended Higgs sectors need >500 GeV**
  - LC: what energy after 250 GeV?
  - e.g.: e+e- scenarios at 550-600 GeV now being considered (C^3, ILC)
  - Muon collider reach: updated projections for low/high energies (250 GeV, 3-10 TeV, 30 TeV)
- Growing interest in **light-quarks and lepton couplings**
  - New for Snowmass 2021:
    - Access to s-Yukawa
    - Access to e-Yukawa
- **BSM Higgs**
    - CP properties
    - Rare decays (flavor changing, etc.)

New: ILC reach on Higgs couplings will be updated

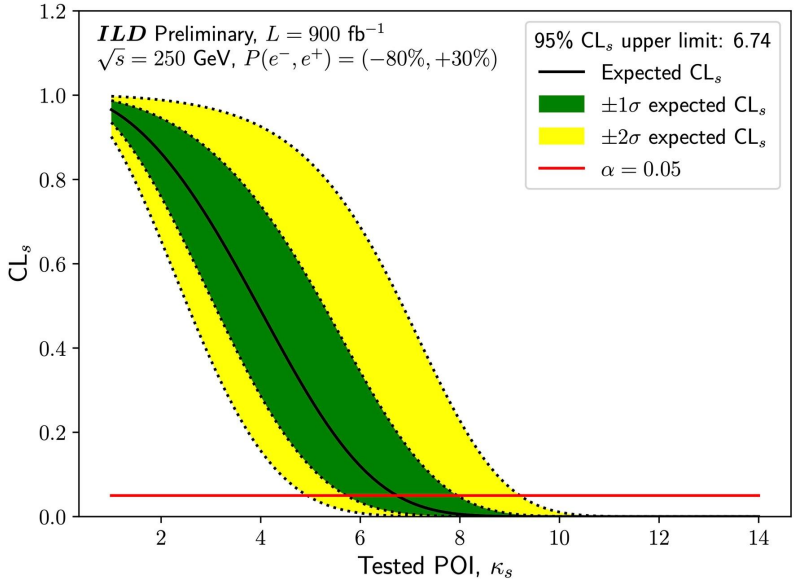
	ILC250		ILC500		ILC1000	
coupling	full	no BSM	full	no BSM	full	no BSM
hZZ	0.49	0.38	0.35	0.20	0.34	0.16
hWW	0.48	0.38	0.35	0.20	0.34	0.16
hbb	0.99	0.80	0.58	0.43	0.47	0.31
$h\tau\tau$	1.1	0.95	0.75	0.63	0.63	0.52
hgg	1.6	1.6	0.96	0.91	0.67	0.59
hcc	1.8	1.7	1.2	1.1	0.79	0.72
$h\gamma\gamma$	1.1	1.0	1.0	0.96	0.94	0.89
$h\gamma Z$	8.9	8.9	6.5	6.5	6.4	6.4
$h\mu\mu$	4.0	4.0	3.8	3.7	3.4	3.4
htt	—	—	6.3	6.3	1.0	1.0
hhh	—	—	20	20	10	10
Γ_{tot}	2.3	1.3	1.6	0.70	1.4	0.50
Γ_{inv}	0.36	—	0.32	—	0.32	—

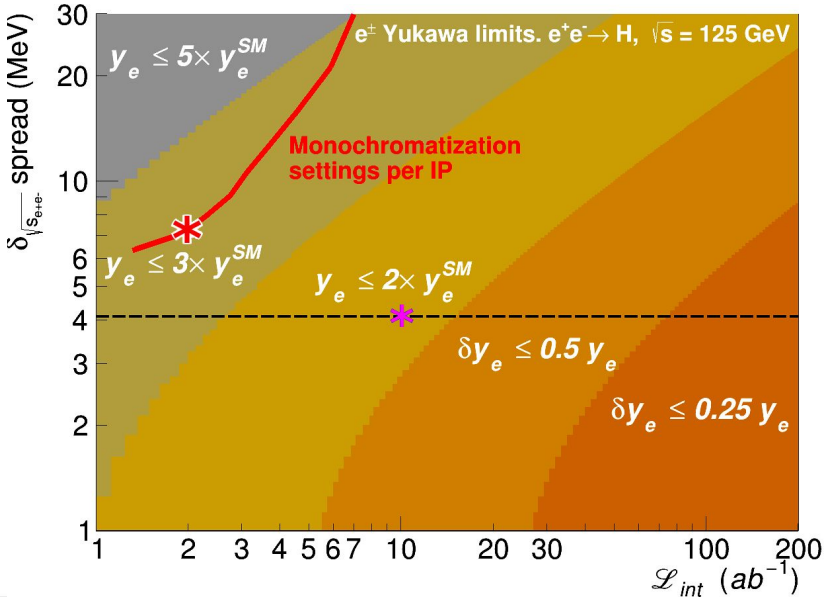


Overall comparison of e^+e^- options: linear vs circular, polarization, etc. → **e^+e^- forum**

arXiv:2203.07622

New: reach for light-quark and lepton Yukawas





- Studying ZH with Z going to leptons and neutrinos
- κ_s<6.74 at 95% c.l.

arXiv:2203.07535

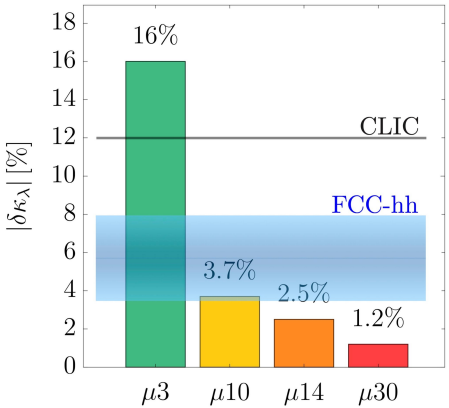
- Electron Yukawa at FCC-ee
- κ_e< 1.6 at 95% c.l.

arXiv:2107.02686

New: updated reach for Higgs self coupling

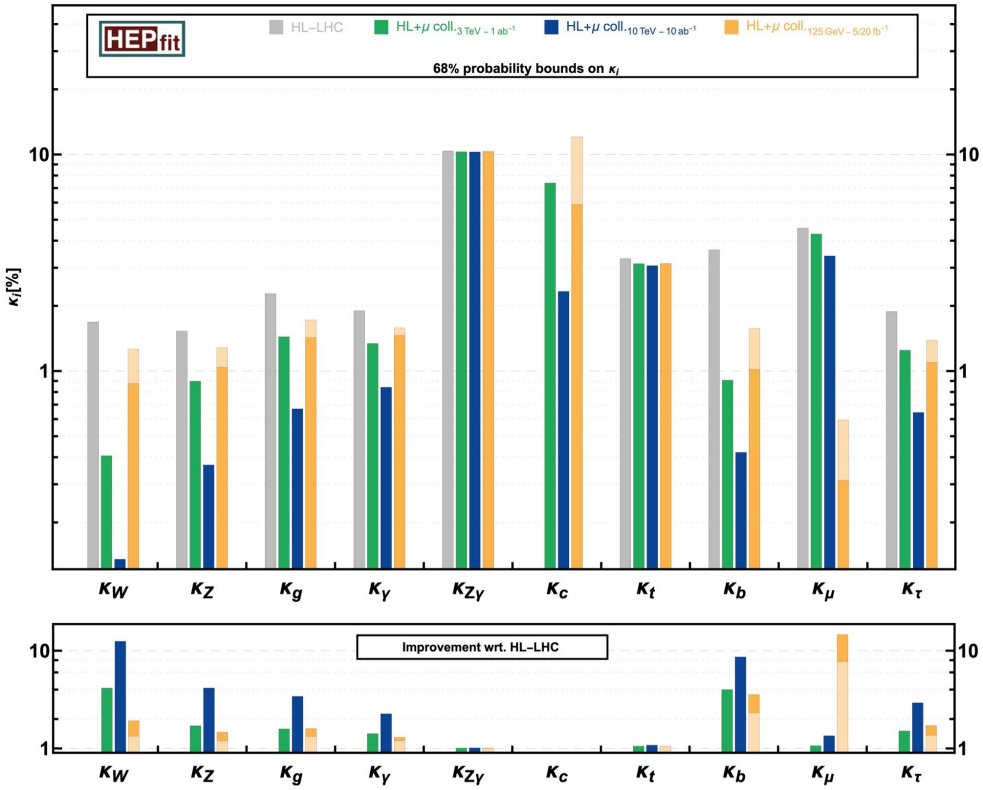
collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
$CEPC_{240}$	49%	–	49%
$C^3\,ILC_{250}$	49%	–	49%
$C^3\,ILC_{500}$	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
* FCC-hh	-	5%	5%

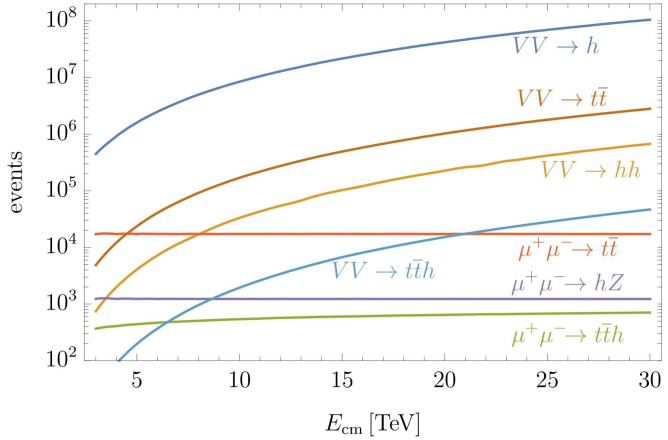
- ATLAS and CMS HL-LHC updated
- FCC-hh updated arXiv:2004.03505
- Muon Collider reach:

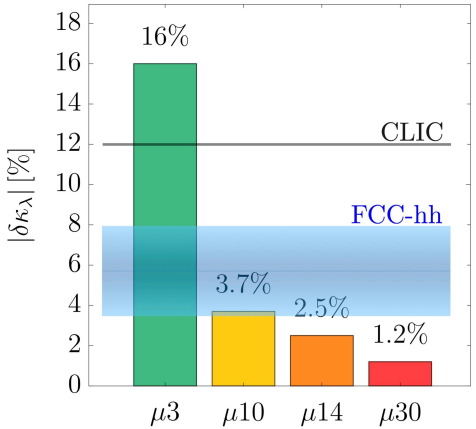


arXiv:2203.07256

New: Muon collider reach on Higgs couplings



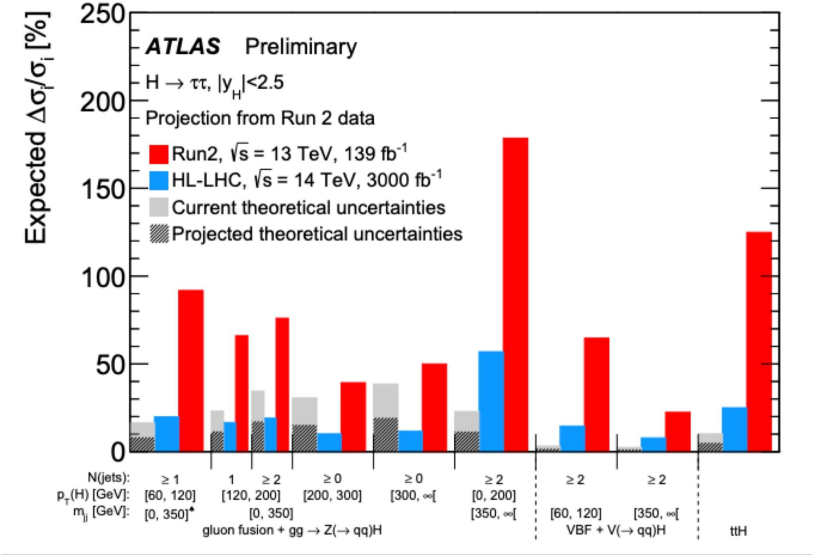


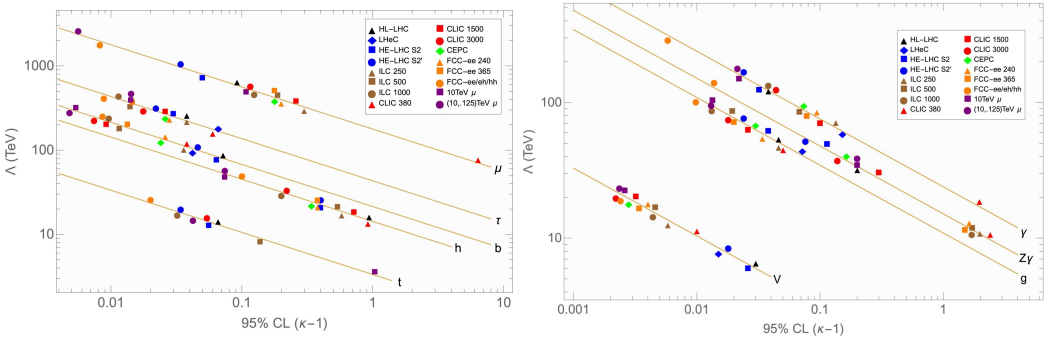


arXiv:2203.07261

arXiv:2203.07256

New: constraining and interpreting BSM signatures





Exploring measurement of high-p_T(H) spectrum

- Sensitivity to EFT (BSM grows with E)

[ATLAS+CMS HL-LHC 2022 study]

Higgs coupling sensitivity to scale of new physics via unitarity bounds

- Model independent indications for future colliders

[arXiv:2203.09512]

Summary

- **The Higgs physics program ahead of us is extremely intriguing** and promises to start answering some of the remaining fundamental questions in particle physics.
- **Many new directions have been explored during the ongoing Snowmass 2021 exercise**, building on previous studies (ESG)
- The **upcoming studies will focus on** some fundamental questions that we see as **challenges and opportunities for Higgs physics:**
    - Why exploring the Higgs is important?
    - What do we learn from precision measurements of Higgs couplings?
    - How do we make connections with BSM models?
    - How can we enhance the complementarity between precision measurement and new physics searches?