The Higgs after LHC

From the HL-LHC to future colliders

SILAFAE 2022
Quito, November 14- 18, 2022

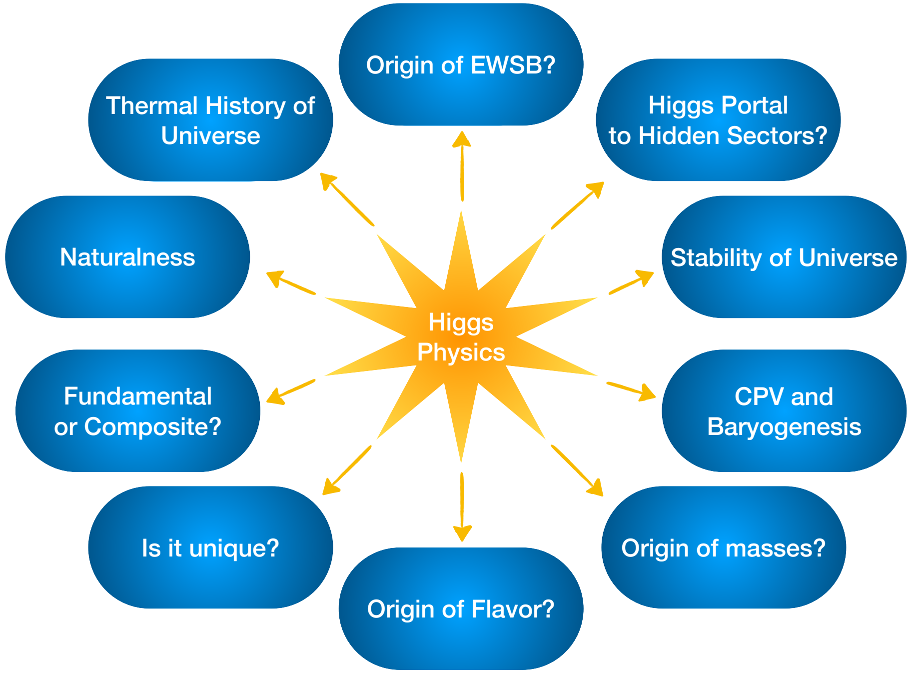
Laura Reina

FLORIDA STATE UNIVERSITY
1851

Higgs physics to answer key questions

What is the origin of the EW scale?

The discovery of the Higgs boson has sharpened the big open questions and given us a unique handle on BSM physics.



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?

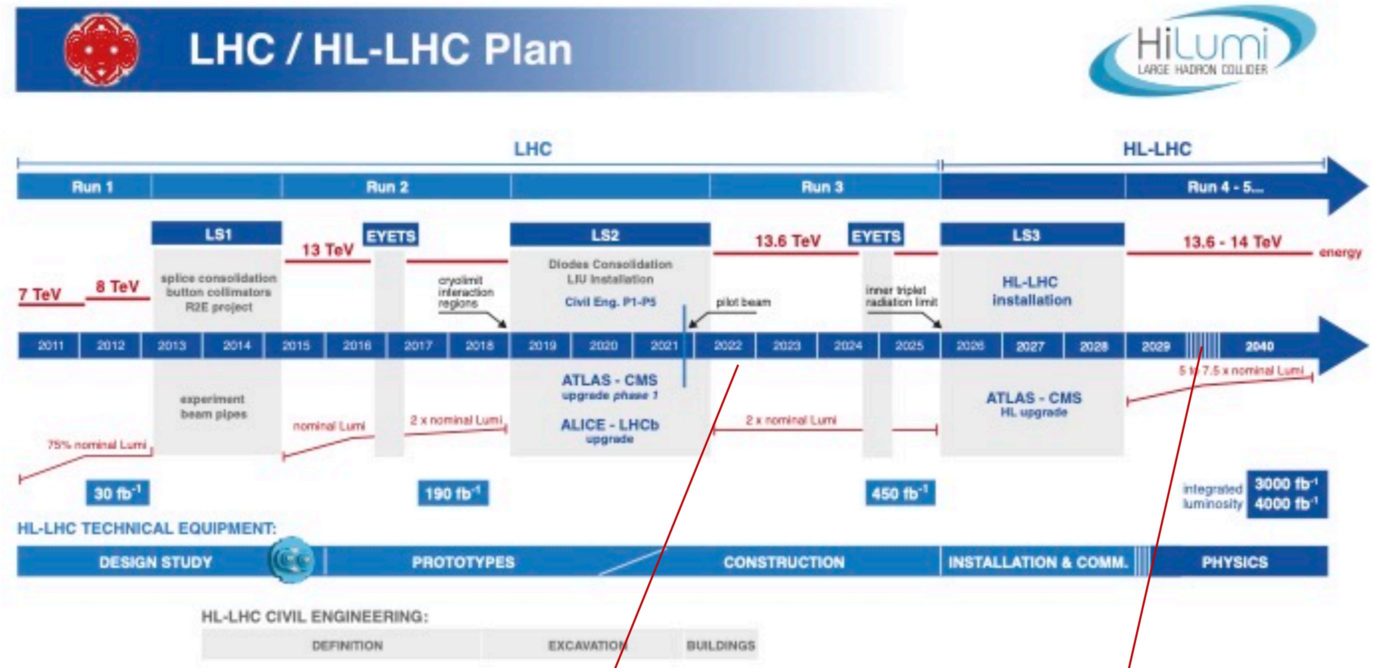
Naturalness

Thermal History of Universe

- Why the $M_H \ll M_{planck}$ **hierarchy problem**?
- What are the implications for **Naturalness**?
- Can we uncover the origin of BSM physics from precision measurement of Higgs properties (couplings, width, …). **Elementary vs composit**? **One Higgs**? **More**?
- Can we measure the shape of the **Higgs potential** ⟶ **Higgs self coupling(s)**
- Can Higgs properties give us **insights on flavor** and vice versa?
  - Couplings to heavy flavors (bottom, top, ..)
  - Couplings to light quarks and leptons

see C. Wagner's talk

The LHC era: exploring the TeV scale



We are only here

Many years of HL running ahead of us

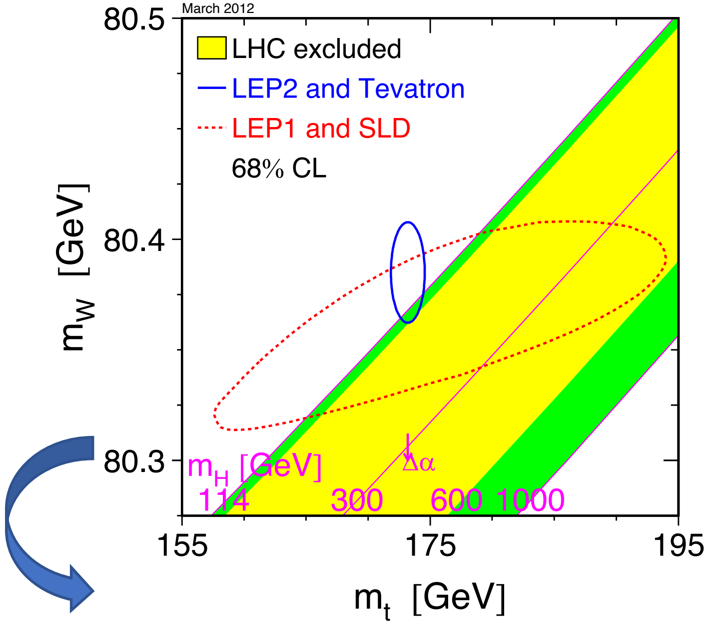
Higgs physics has been at the core of the LHC physics program

- **Run 1**: **Higgs discovery**
- **Run 2**: **Higgs couplings**
  - outperformed expectations
- **Run 3 to HL-LHC**
  - **Higgs precision program**

see C.A. Florez Bustos's and F. Monticelli's talks

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

Run 1 from prediction to discovery



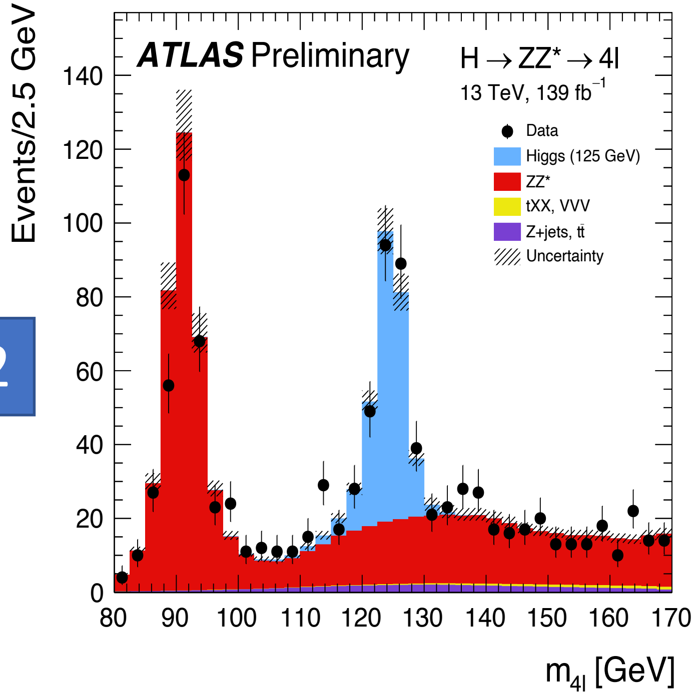
From EW fits

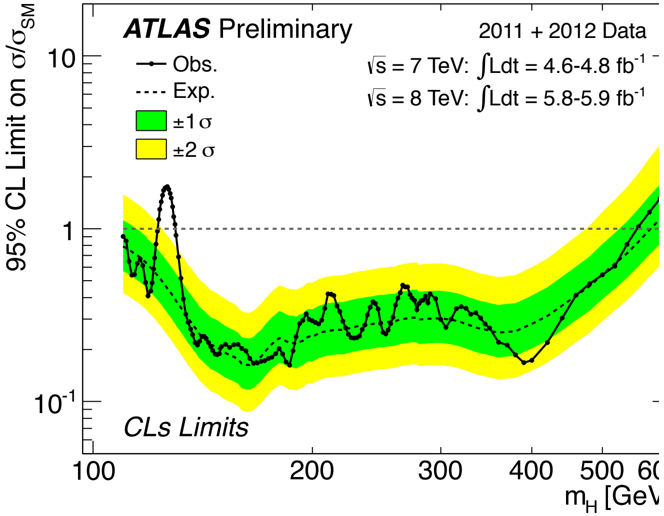
$M_H=94^{+29}_{-24}$ GeV

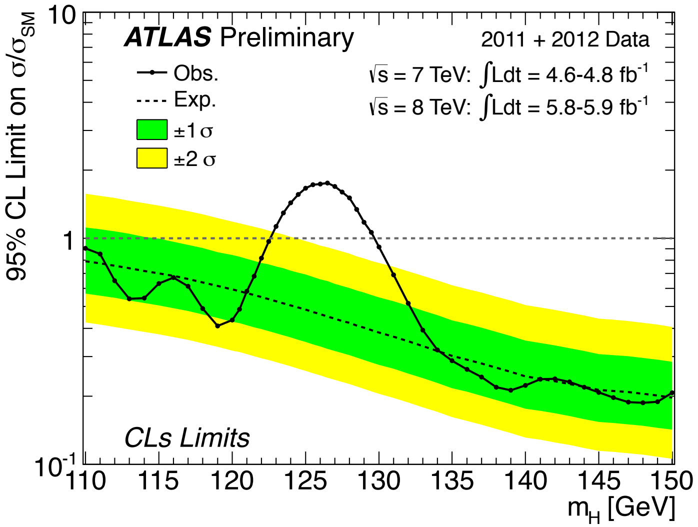
M_H < 152-171 GeV

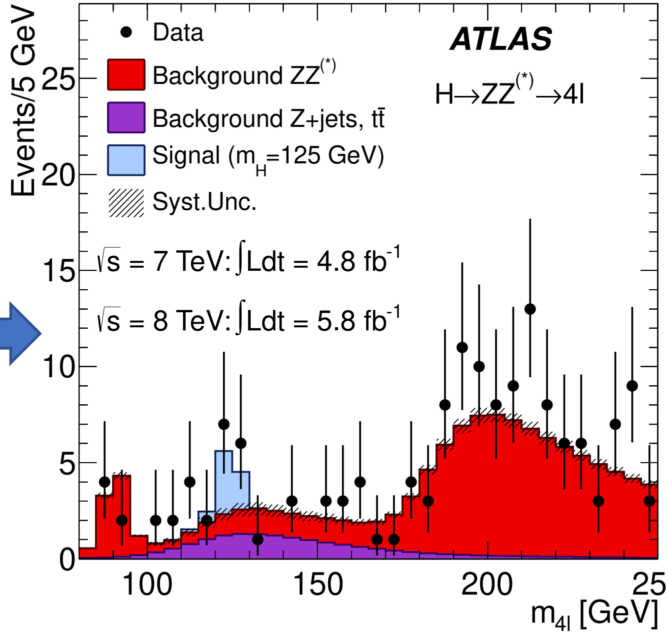
LHC@Run1+2

LHC@Run1: $M_H=125.09\pm0.24$ GeV

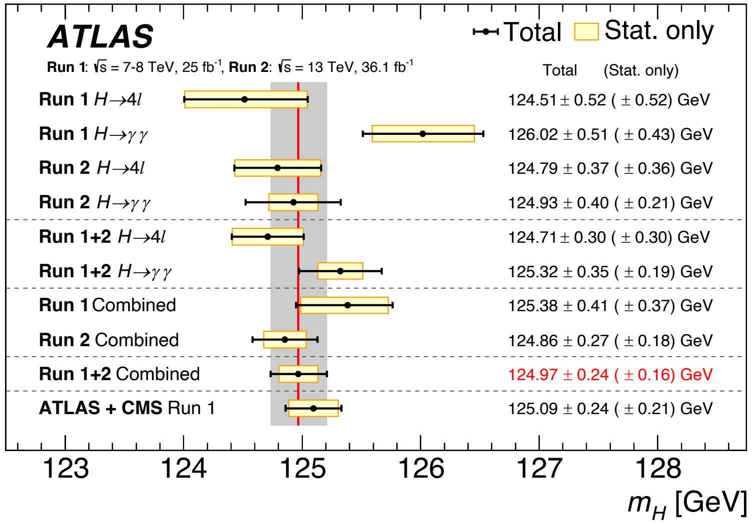


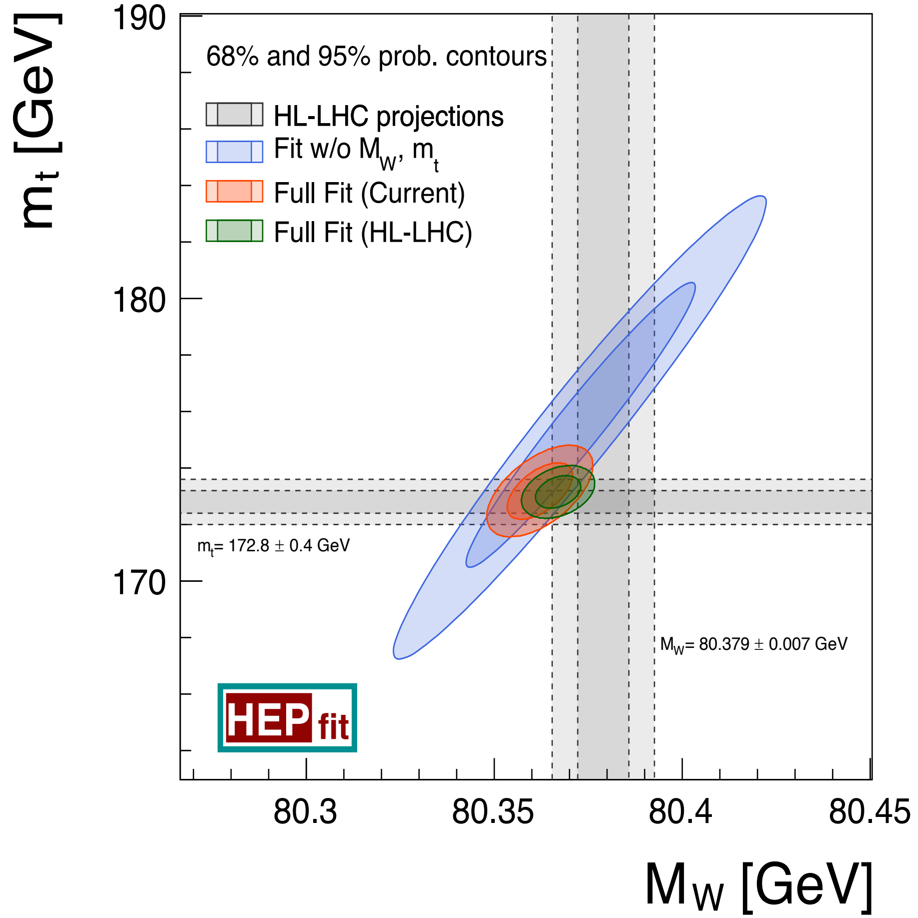


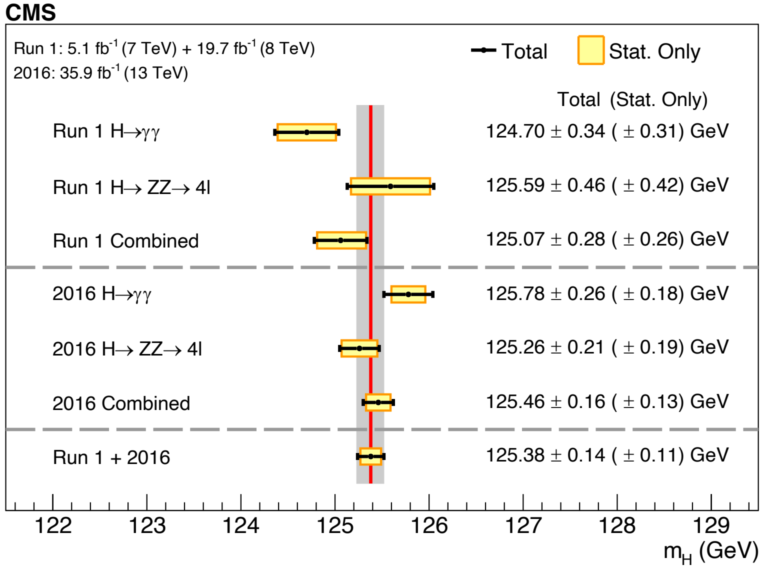




Run 1+2 from discovery to precision physics





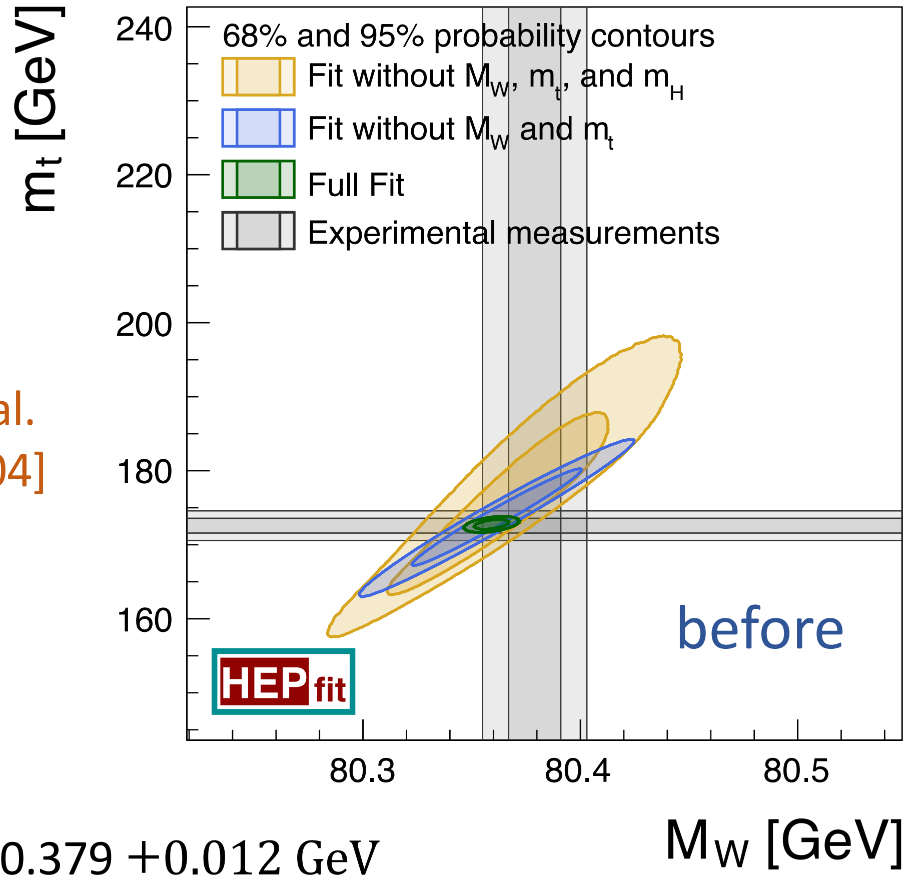


M_H promoted to EW precision observable

Stress-testing the SM

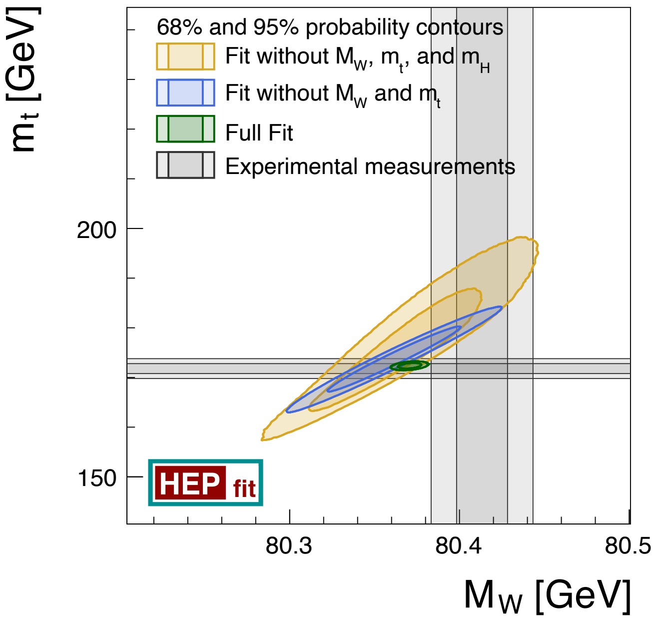
<u>A recent challenge</u>: CDF new M_W measurement

De Blas et al.
[2204.04204]



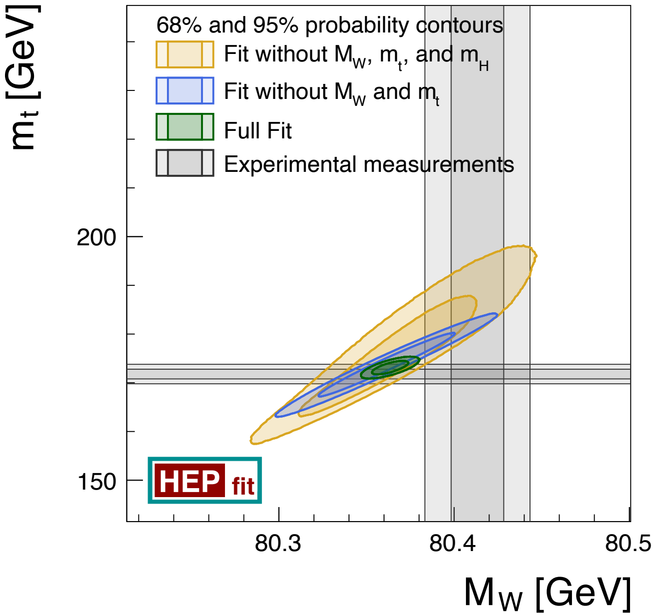
before

M_W=80.379 ±0.012 GeV



after
“standard”

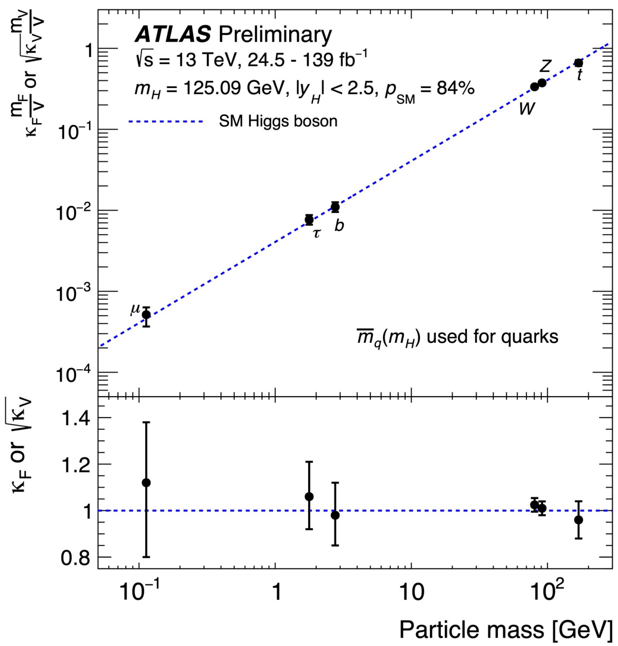
M_W=80.4133 ±0.0088 GeV

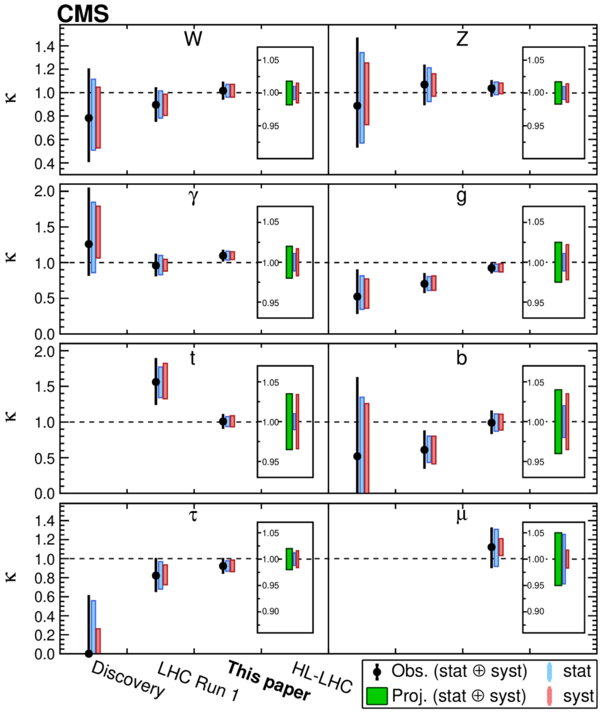


after
“conservative”

M_W=80.4133 ±0.015 GeV

Run 2 zooming in on couplings to probe the TeV scale





- Couplings to **W/Z at 5-10 %**
- Couplngs to **3rd generation to 10-20%**
- **First measurements of 2nd generation** couplings

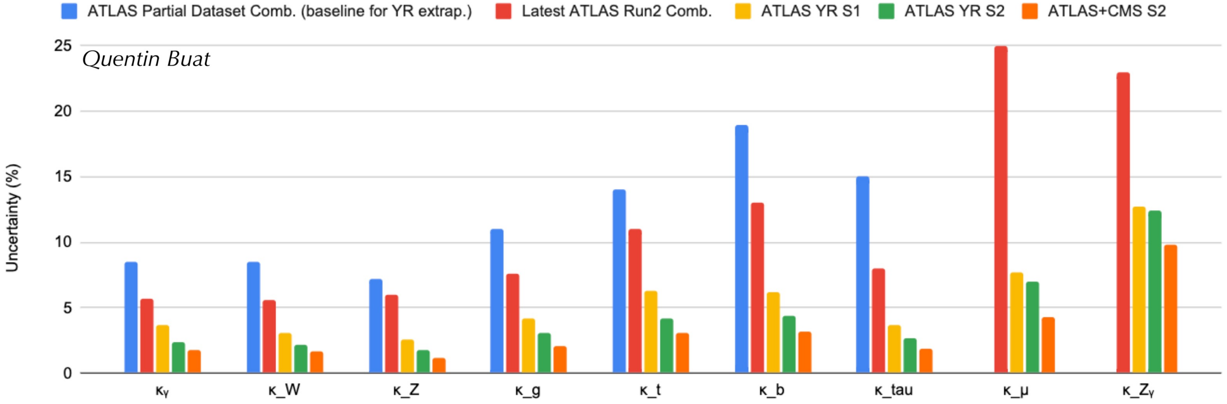
$$\kappa = g_X/g_X^{SM} = 1 + \Delta\kappa$$

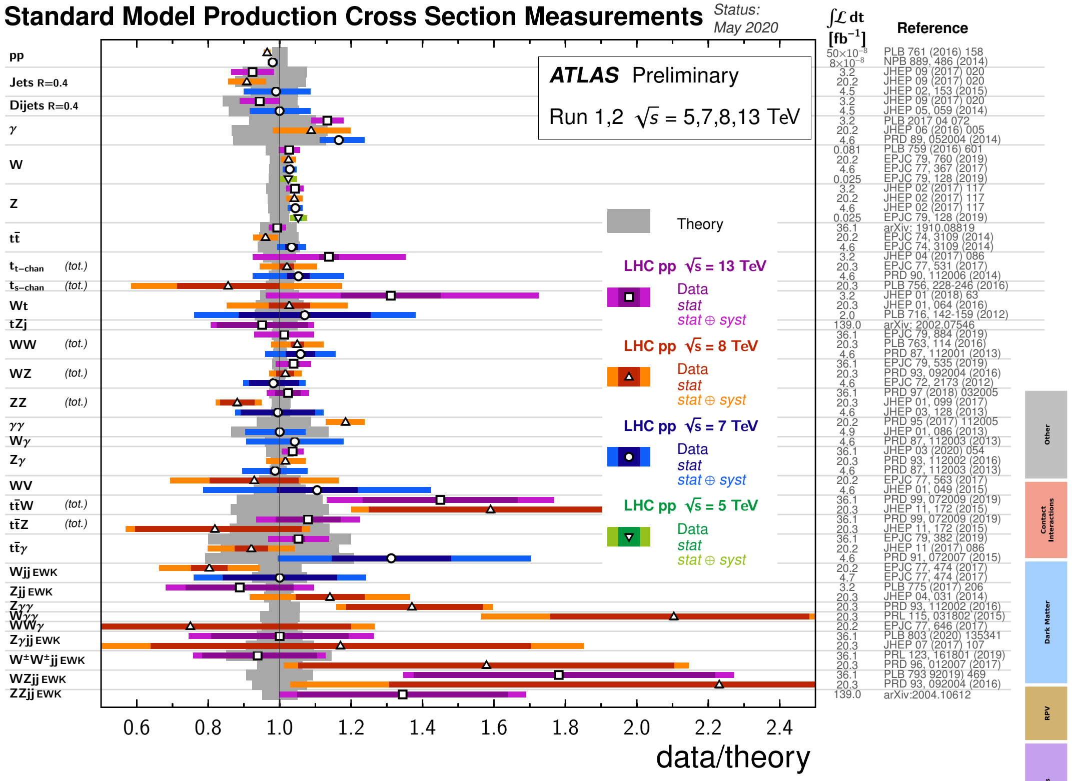
$$\Delta\kappa \propto v^2/\Lambda_{BSM}^2$$

Precision on Δκ

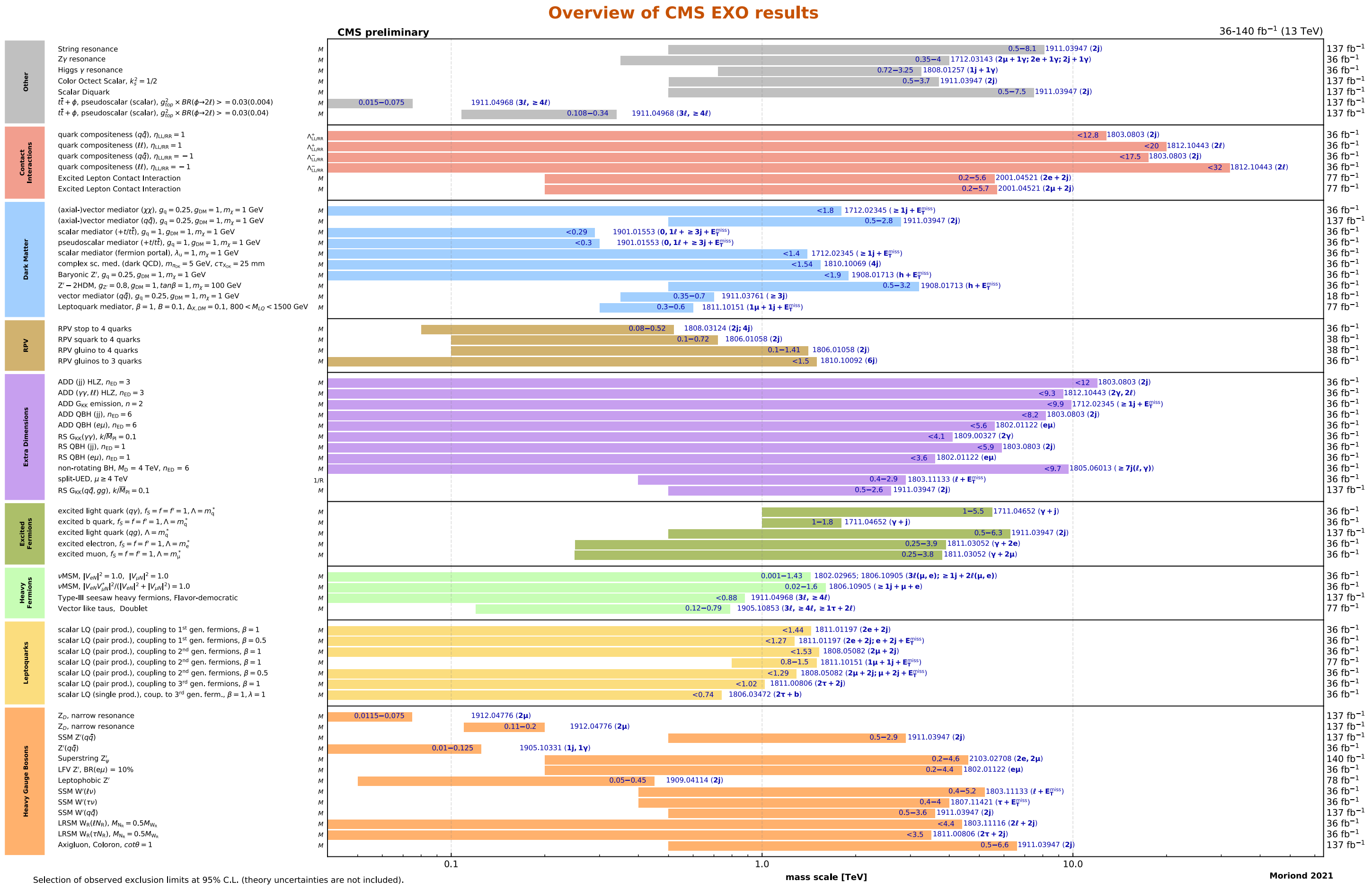
reach for Λ_{BSM}

- **HL-LHC projections** from **partial Run 2** data (YR):
  - **2-5 % on most couplings**
  - **< 50% on Higgs self-coupling.**
- **Full Run2** results **drastically improve partial Run 2 results:** better projections expected





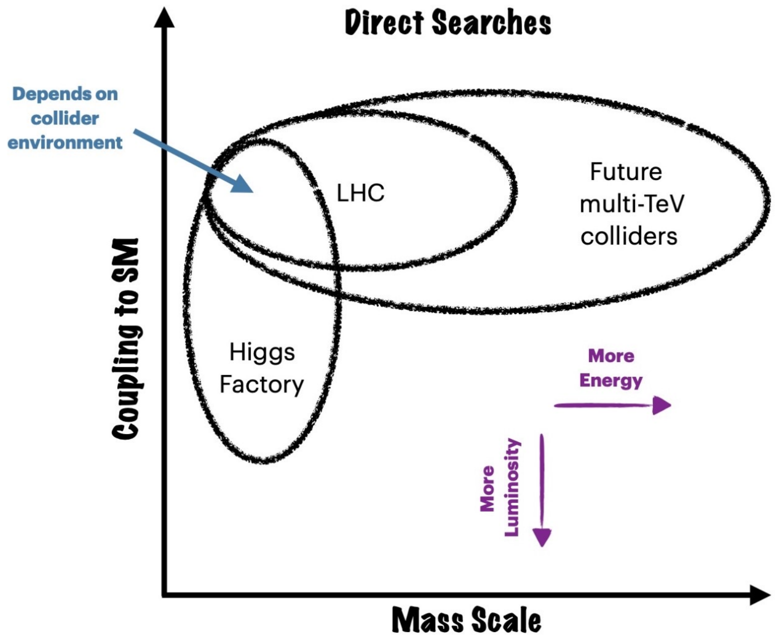
… to which we should add a unique spectrum of SM measurements and BSM direct searches!



What is the path forward beyond the HL-LHC?

Beyond the HL-LHC: Precision and Energy

New physics can be at low as at high mass scales,
Naturalness would **prefer scales close to the EW scale**, but the LHC has already placed **strong bounds around 1-2 TeV.**

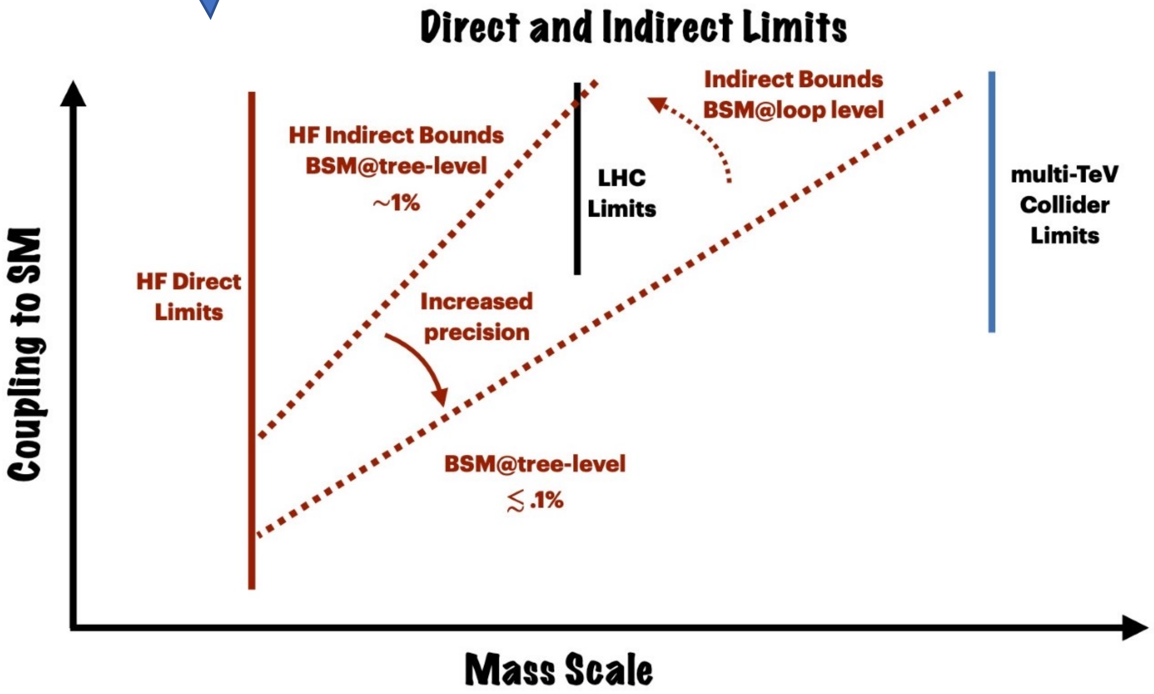


Higgs coupling measurements and direct searches will complement each other in exploring the 1-10 TeV scale and beyond.

In a simplified picture:

New physics at **tree level**:
$\delta\eta_{SM} \sim g^2_{BSM} E^2/M^2$

New physics at **loop level**:
$\delta\eta_{SM} \sim 1/16\pi^2 \times g^2_{BSM} E^2/M^2$



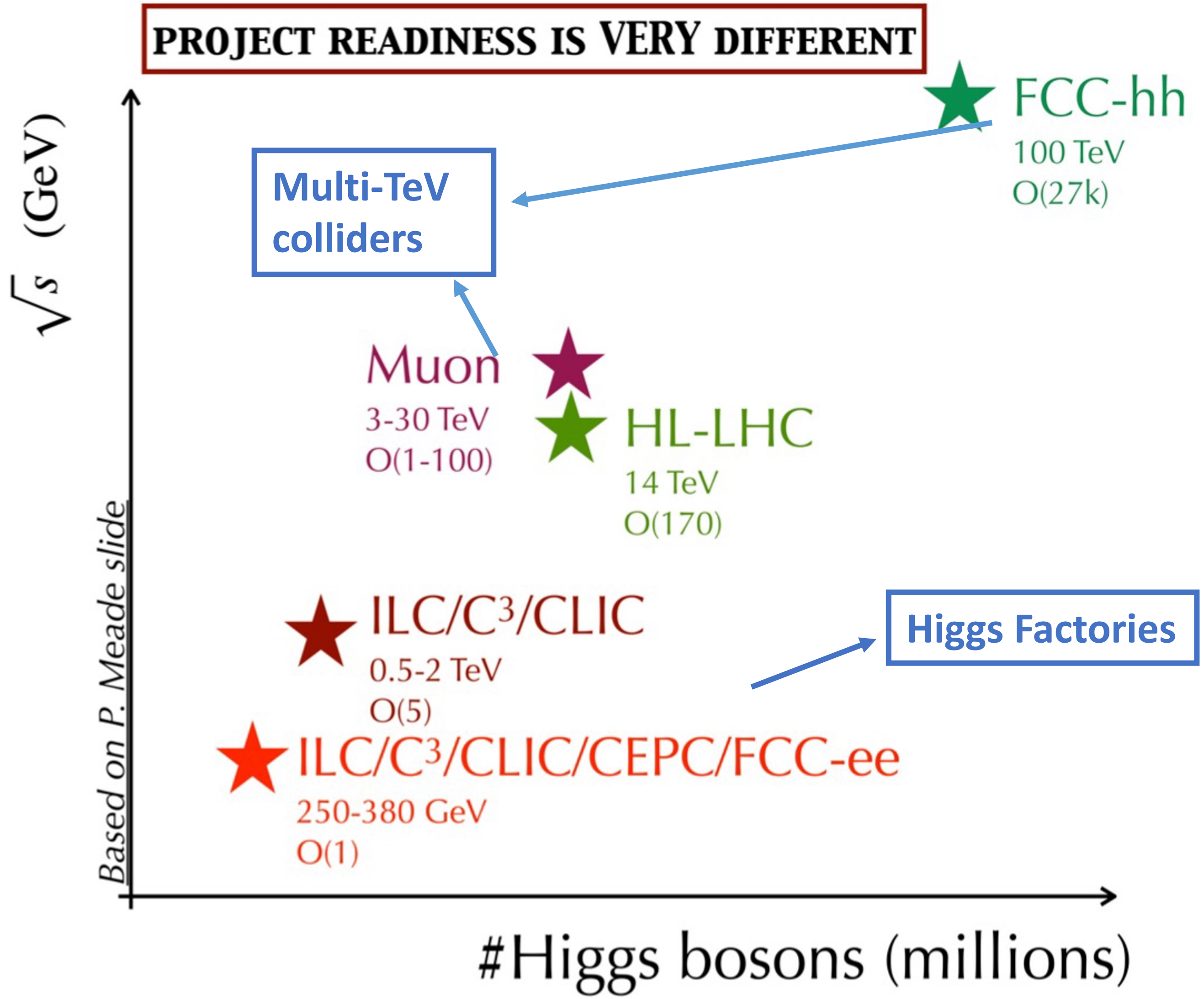
Beyond the HL-LHC: proposed future colliders

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, C^3)
  - **250 GeV — > 1 TeV**
  - *Reach higher energies, and can use polarized beams*
- **μ+μ-**
  - **3-30 TeV**

HADRON COLLIDERS

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

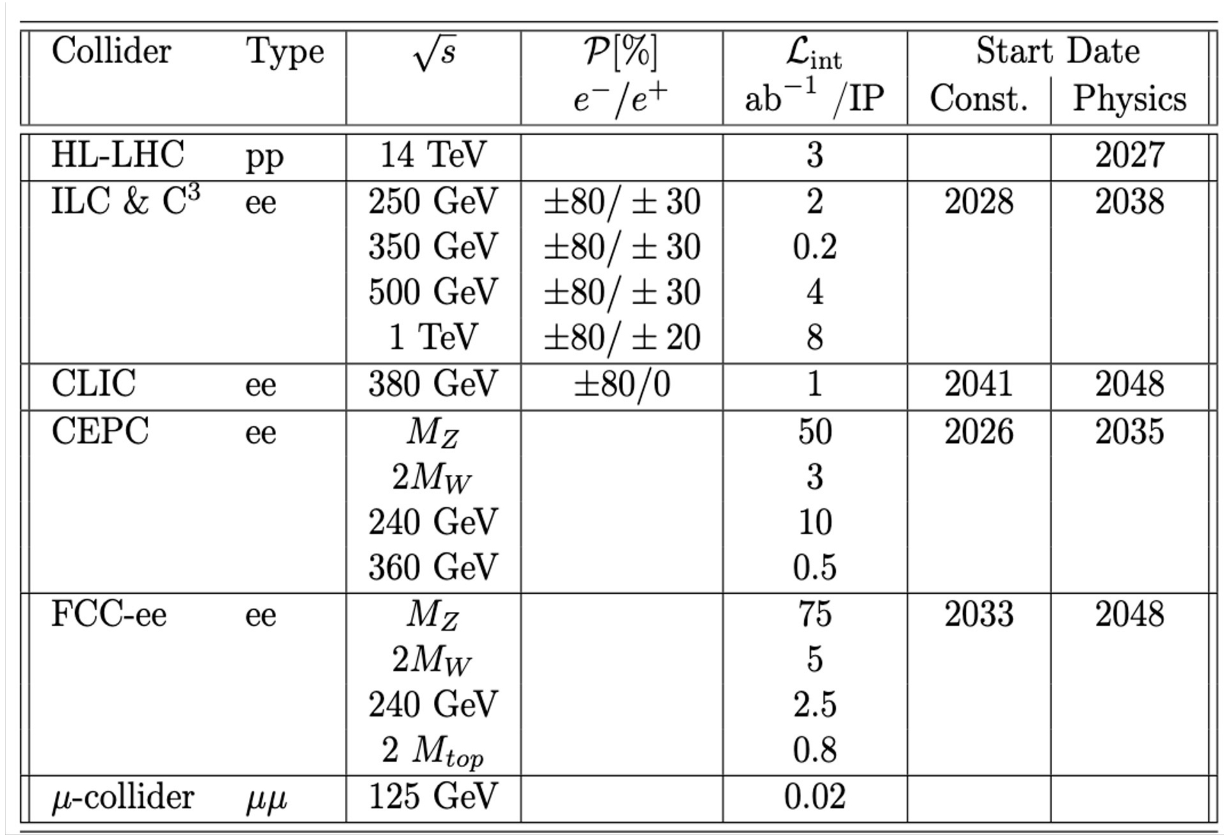


Multi-TeV colliders

Higgs Factories

Snowmass 21: EF Benchmark Scenarios

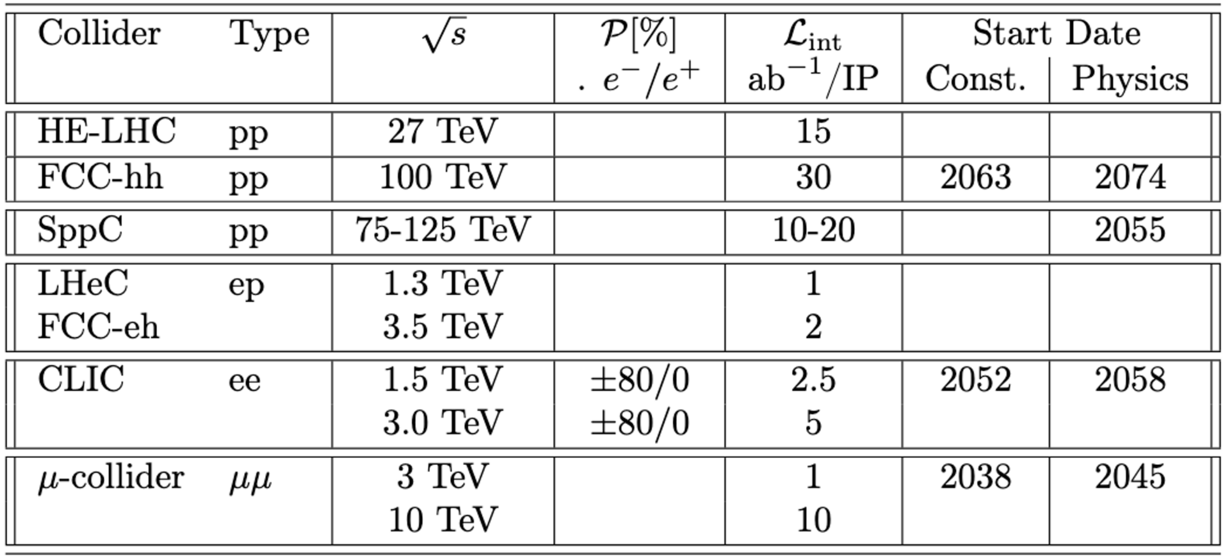
Higgs-boson factories (up to 1 TeV c.o.m. energy)



Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8	2028	2038
CLIC	ee	380 GeV	$\pm80/0$	1	2041	2048
CEPC	ee	M_Z $2M_W$ 240 GeV 360 GeV		50 3 10 0.5	2026	2035
FCC-ee	ee	M_Z $2M_W$ 240 GeV $2\ M_{top}$		75 5 2.5 0.8	2033	2048
μ-collider	$\mu\mu$	125 GeV		0.02		

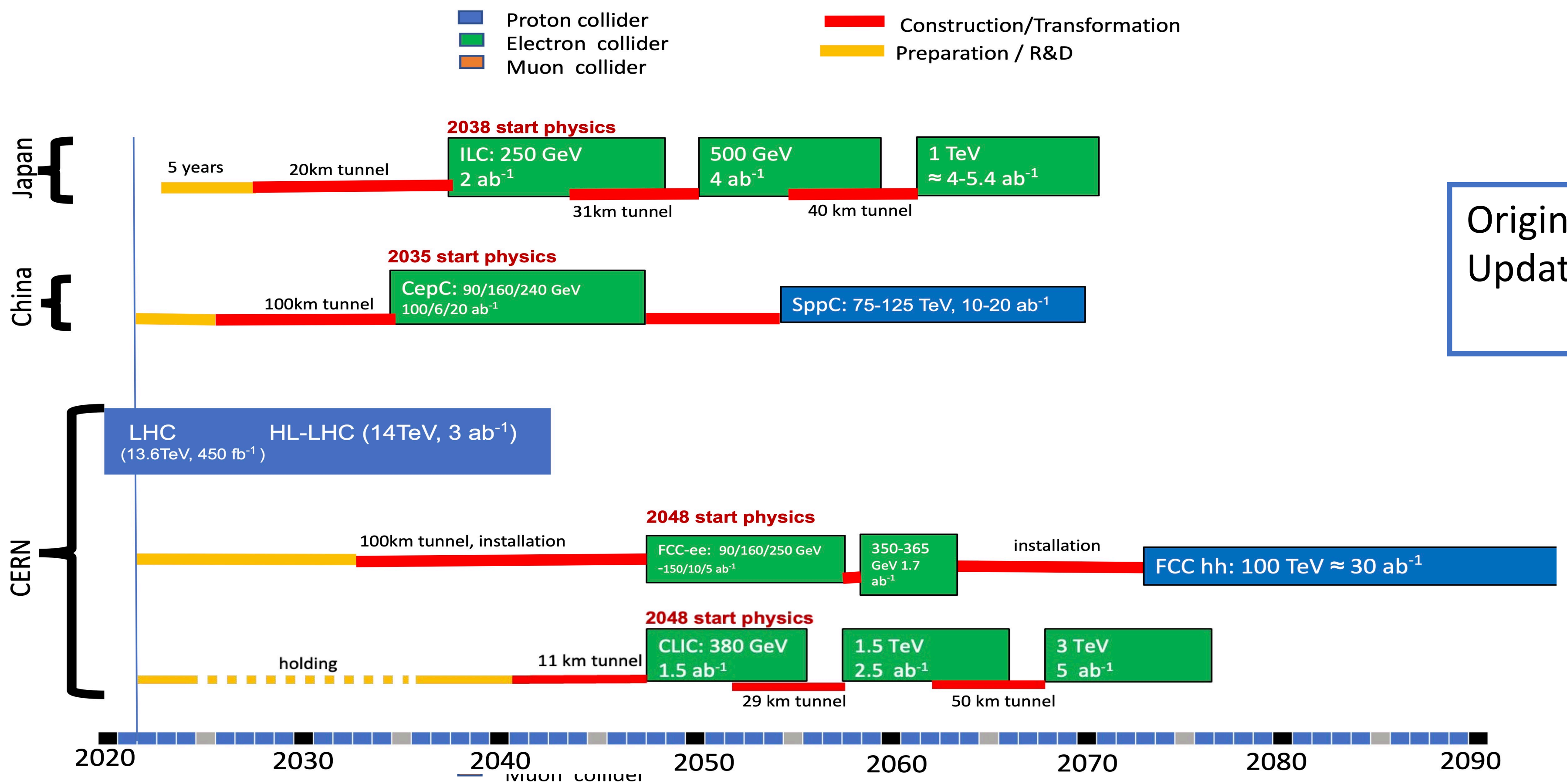
Snowmass EF wiki: https://snowmass21.org/energy/start

Multi-TeV colliders (> 1 TeV c.o.m. energy)



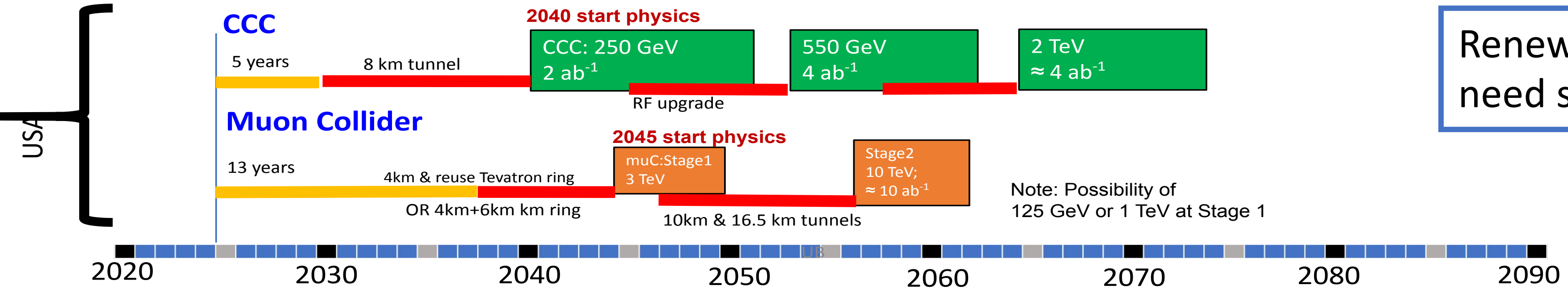
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC FCC-eh	ep	1.3 TeV 3.5 TeV		1 2		
CLIC	ee	1.5 TeV 3.0 TeV	$\pm80/0$ $\pm80/0$	2.5 5	2052	2058
μ-collider	$\mu\mu$	3 TeV 10 TeV		1 10	2038	2045

Timelines are taken from the Collider ITF report (arXiv: 2208.06030)



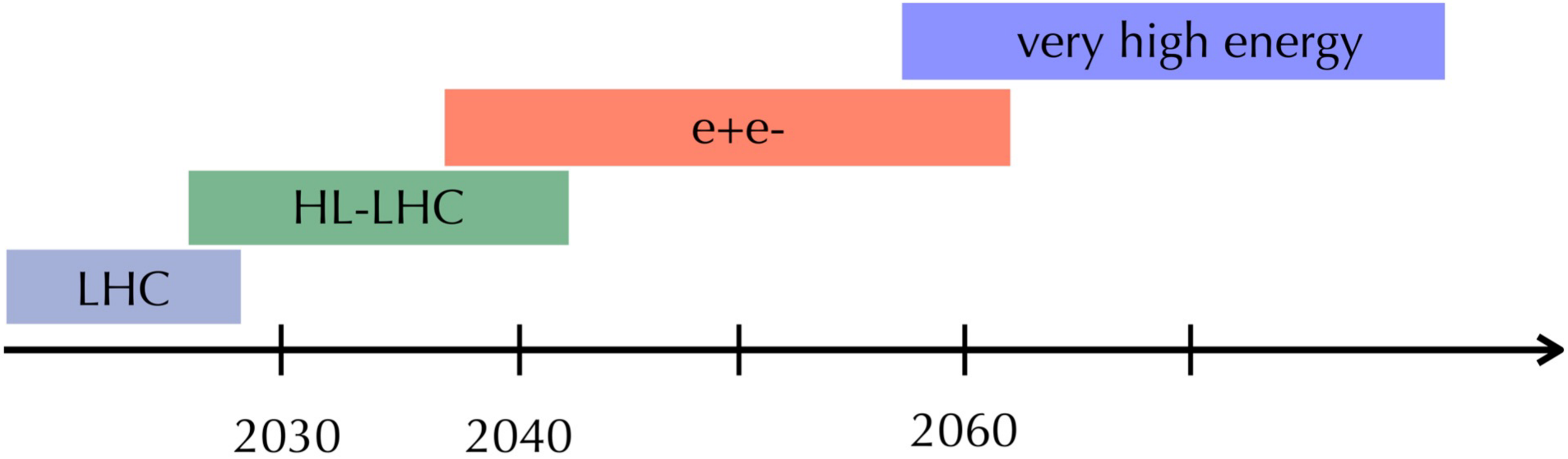
Original timeline from ESG
Updated during Snowmass 2021
(see EF Report)

Proposals emerging from Snowmass 2021 for a US based collider



Renewed interest in lepton colliders:
need supporting R&D in near future

Beyond the HL-LHC: projections for Higgs couplings

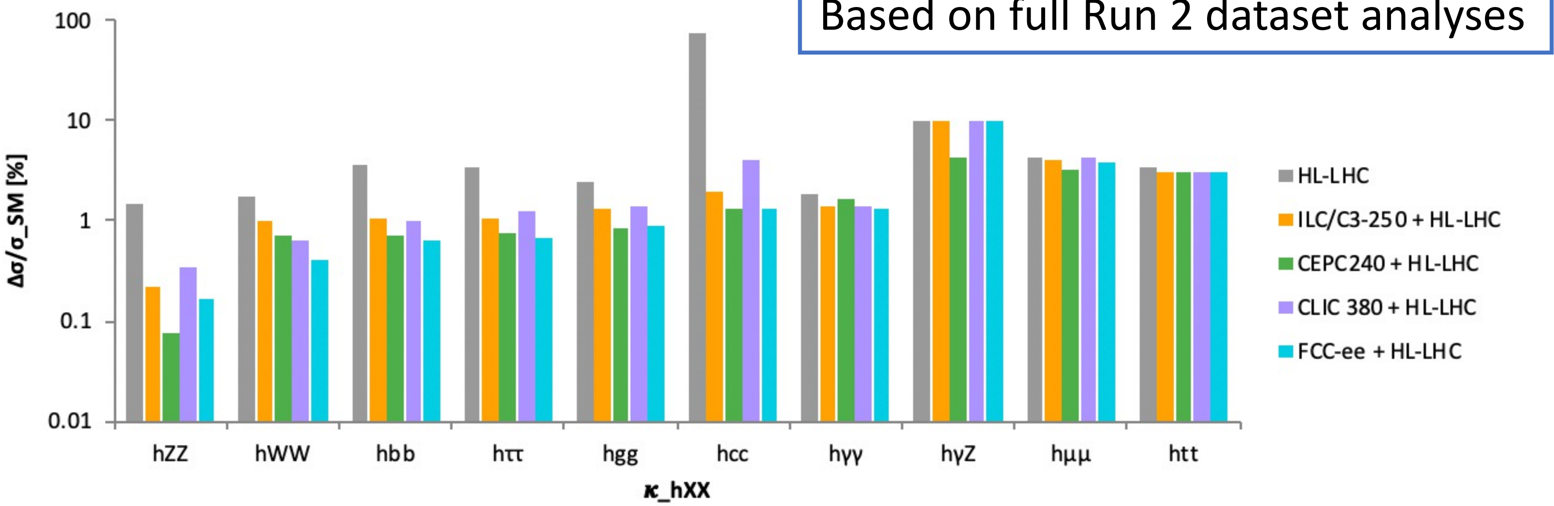


H couplings to:	**O(5-15)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

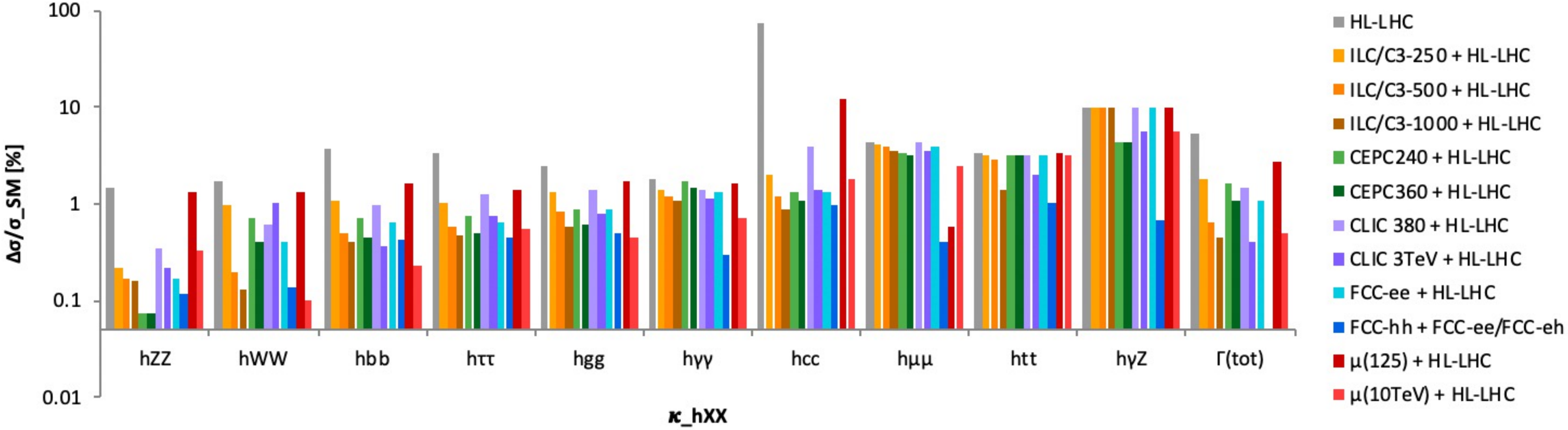
From C. Vernieri – Snowmass 21 EF Workshop - Brown U. - March 2022

Reach of future colliders for Higgs couplings: a closer look

Based on full Run 2 dataset analyses



Initial stages of future e+e- machines

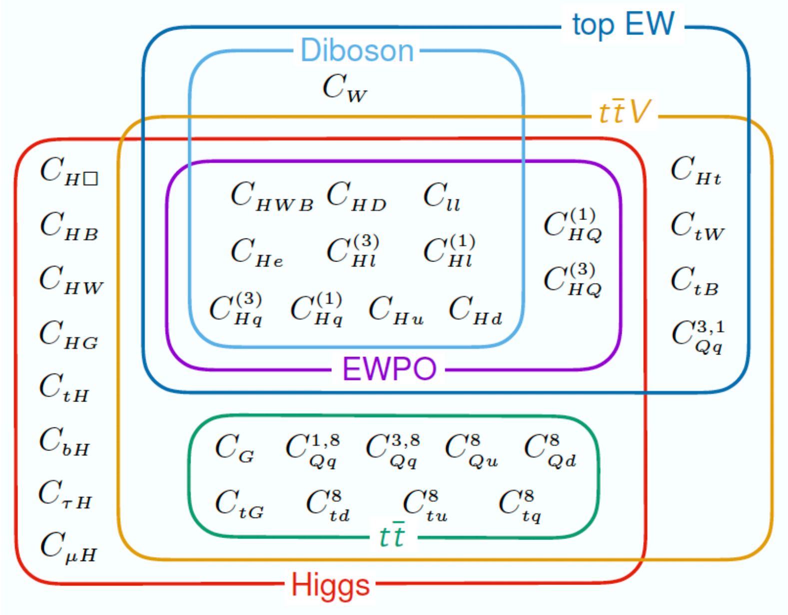


Final reach of all considered future colliders

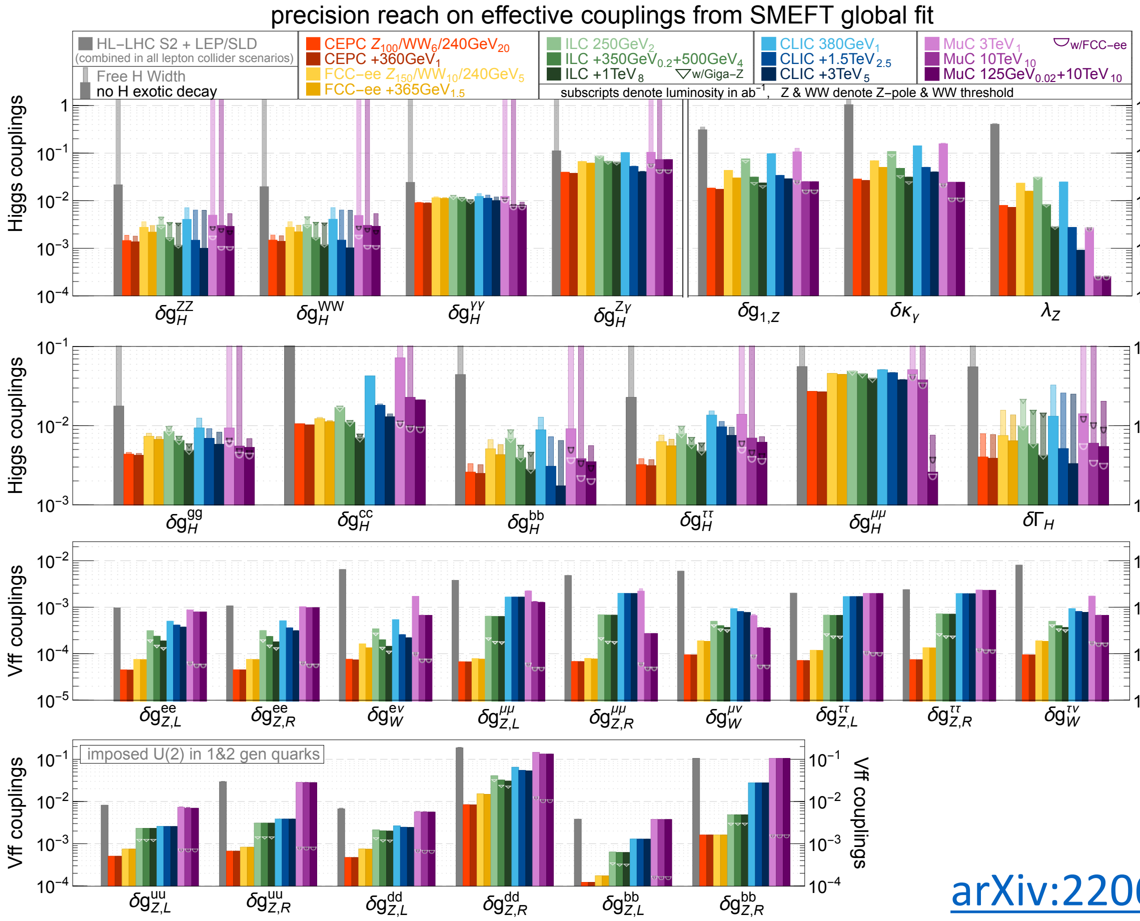
From Snowmass 2021 EF Higgs Topical Group Report arXiv:2209.07510

Constraining BSM via global EFT fits

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \left(\frac{1}{\Lambda^2}\sum_i C_i O_i + \text{h.c.}\right) + O(\Lambda^{-4})$$



EW + Higgs

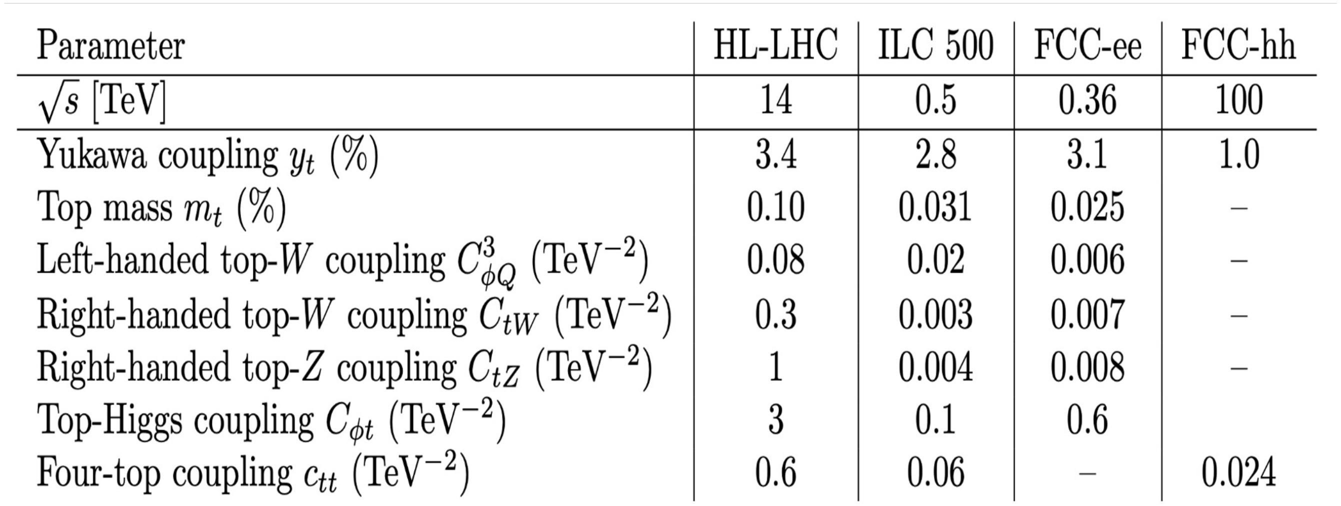


arXiv:2206.08326

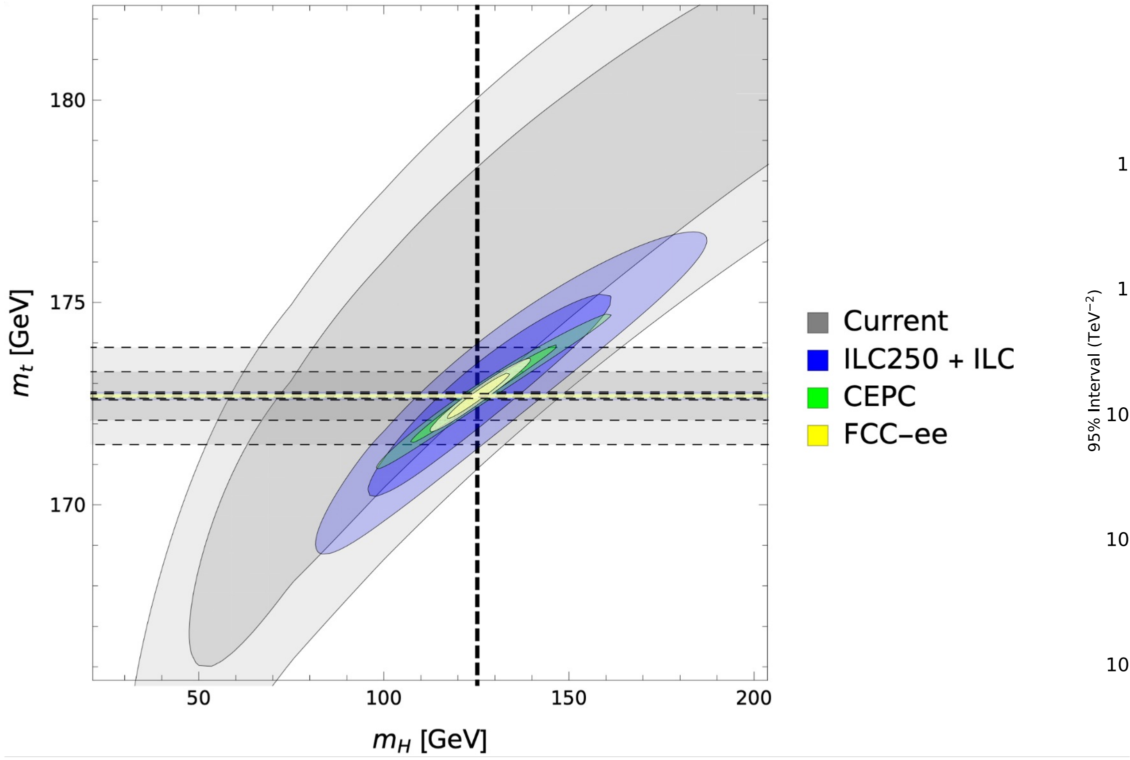
EFT connects different processes with large correlations: pattern of coefficients give insights on underlying BSM model

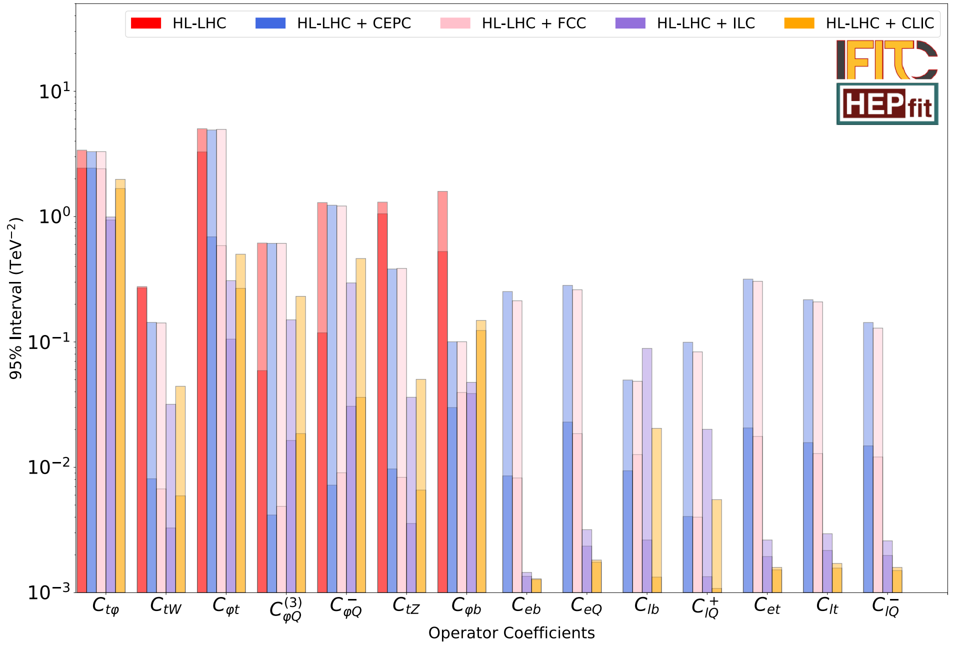
Interplay with top-quark precision measurements

Stress testing the SM and exploring anomalous couplings



Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (%)	0.10	0.031	0.025	–
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08	0.02	0.006	–
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3	0.003	0.007	–
Right-handed top-Z coupling C_{tZ} (TeV^{-2})	1	0.004	0.008	–
Top-Higgs coupling $C_{\phi t}$ (TeV^{-2})	3	0.1	0.6	
Four-top coupling c_{tt} (TeV^{-2})	0.6	0.06	–	0.024

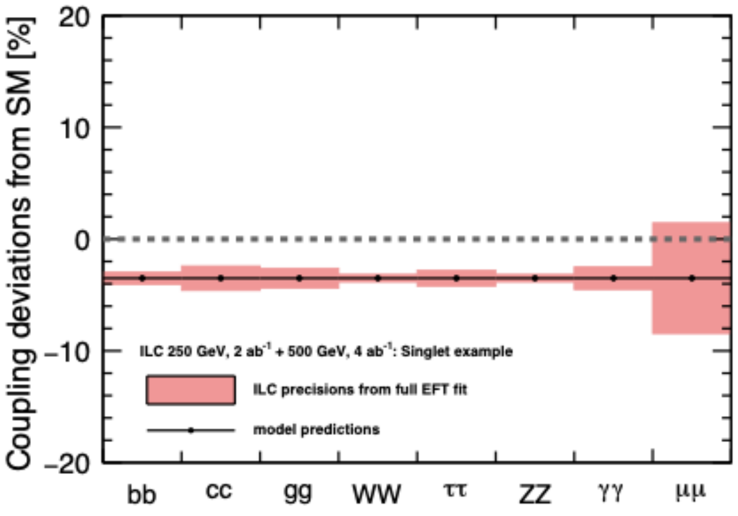




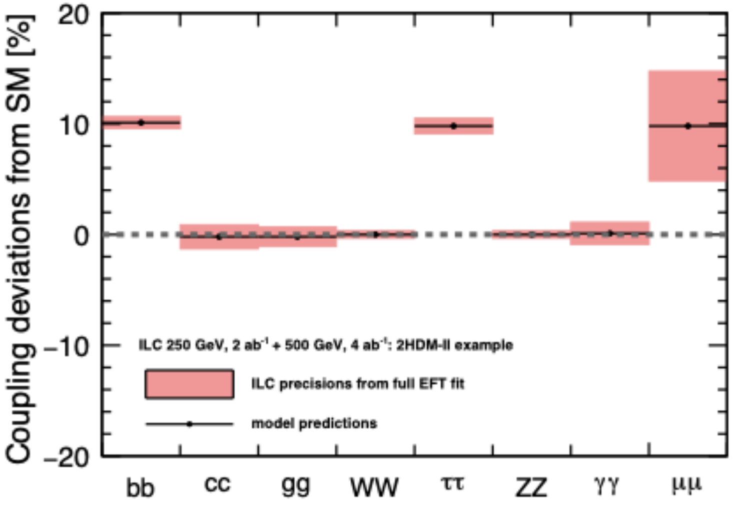
From Snowmass 2021 EF HF and EW TG's Reports arXiv:2209.11267, arXiv:2209.08078

Disentangling models from EFT patterns

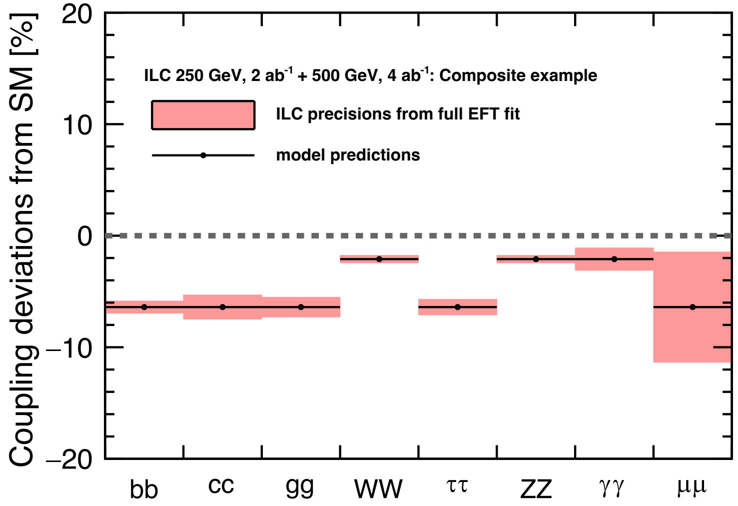
The “inverse Higgs” problem



additional scalar singlet
(m_S=2.8 TeV, max mixing)



2HDM-II
(MH=600 GeV, tanβ=7)

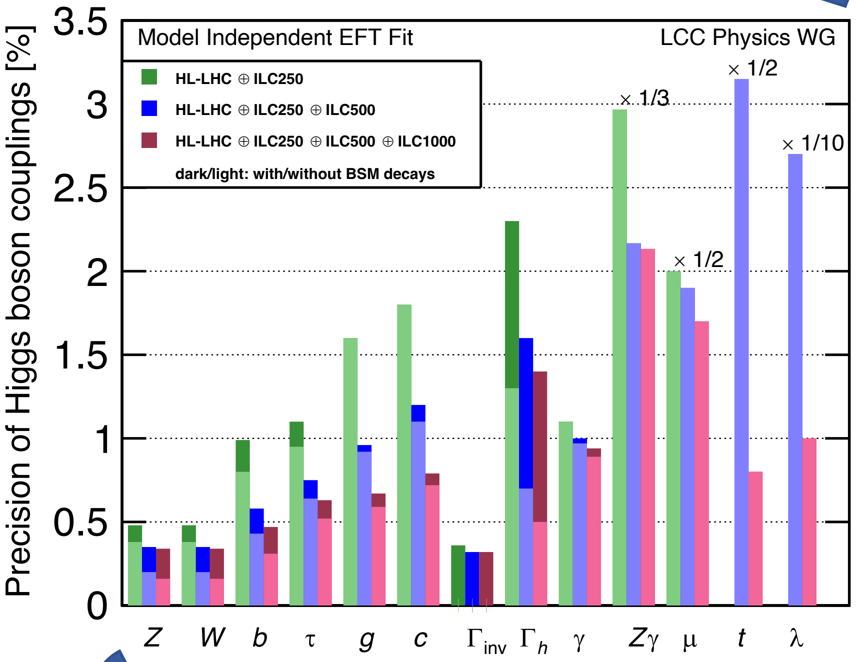


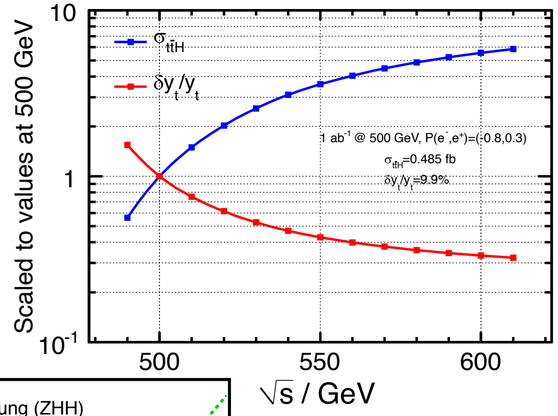
Composite Higgs
(f=1.2 TeV)

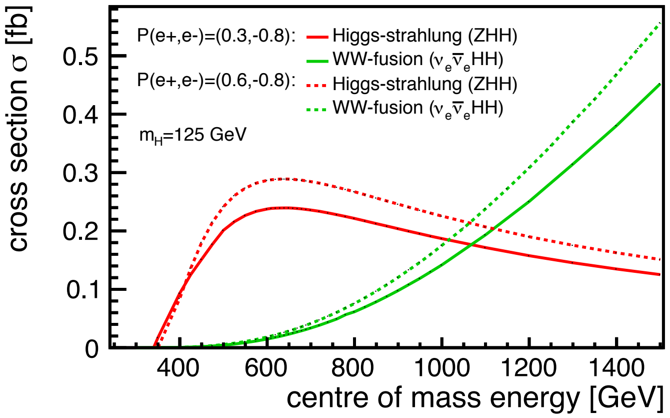
Snowmass 2021: ILC white paper (arXiv: 2203.07622)

Examples to illustrate the **different patterns of Higgs coupling deviations** from **different BSM models**

The case of e^+e^- Higgs factories

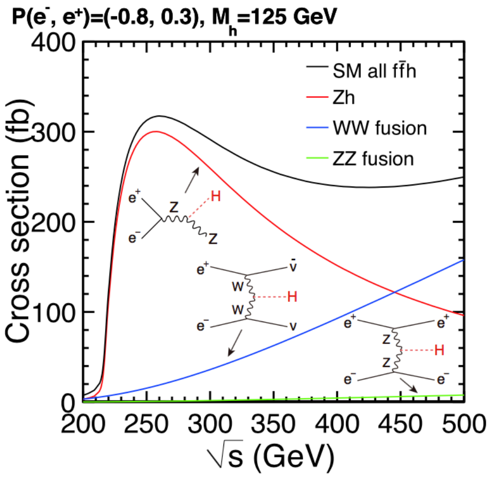




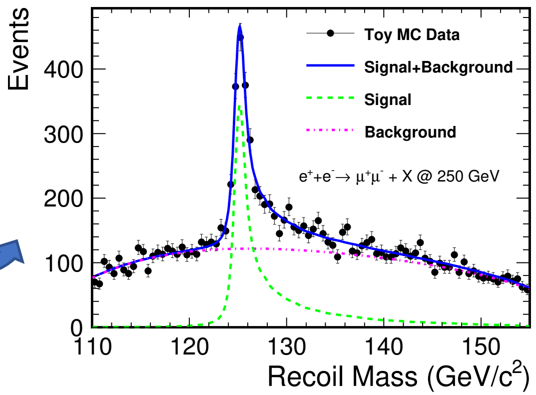


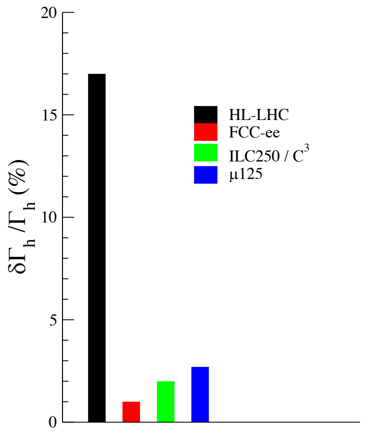
Energy matters

top-Yukawa, HH, extended Higgs sectors need >500 GeV

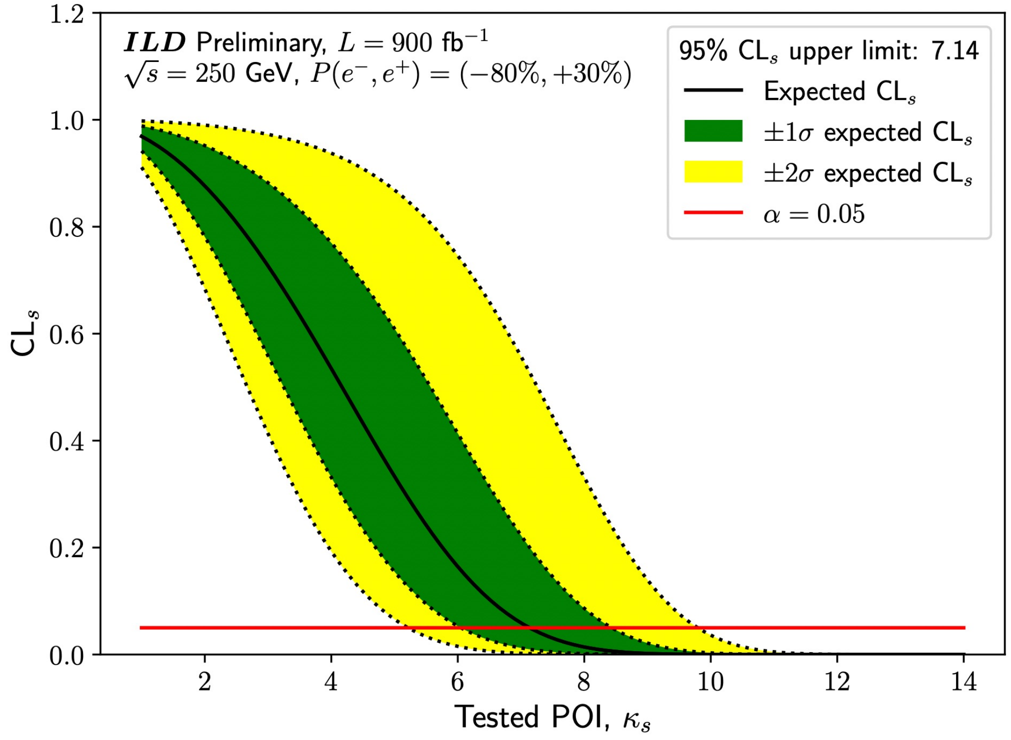


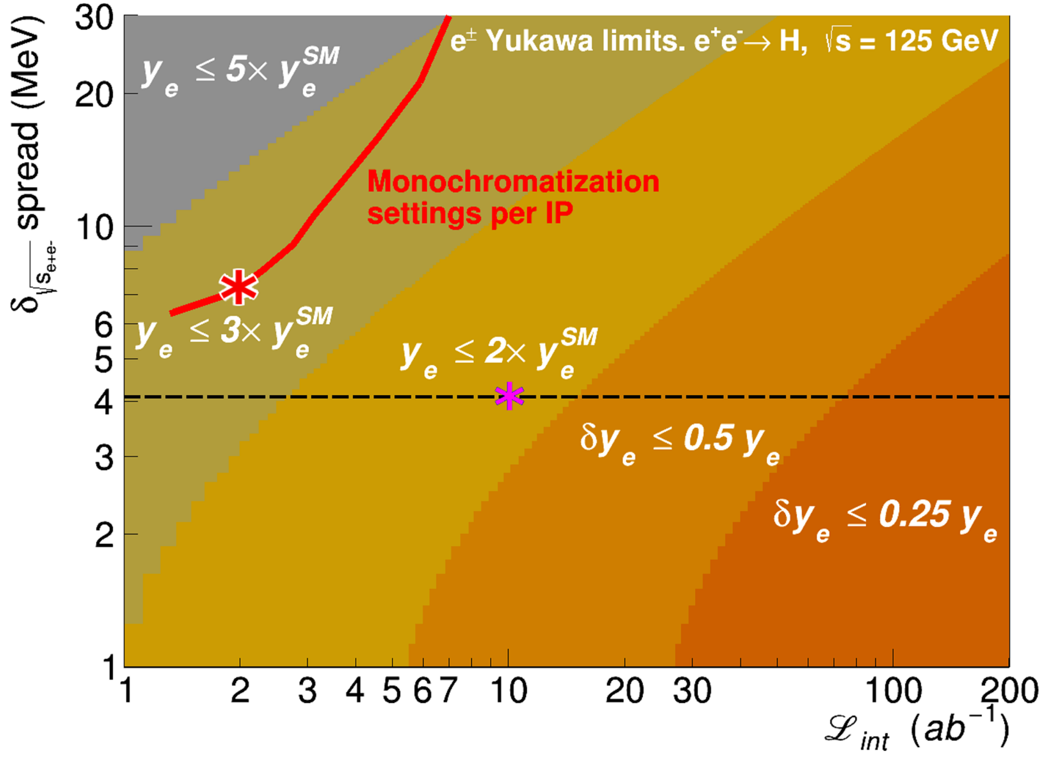
Model-independent Γ_H measurment





Reach for light fermion Yukawa couplings: highlights





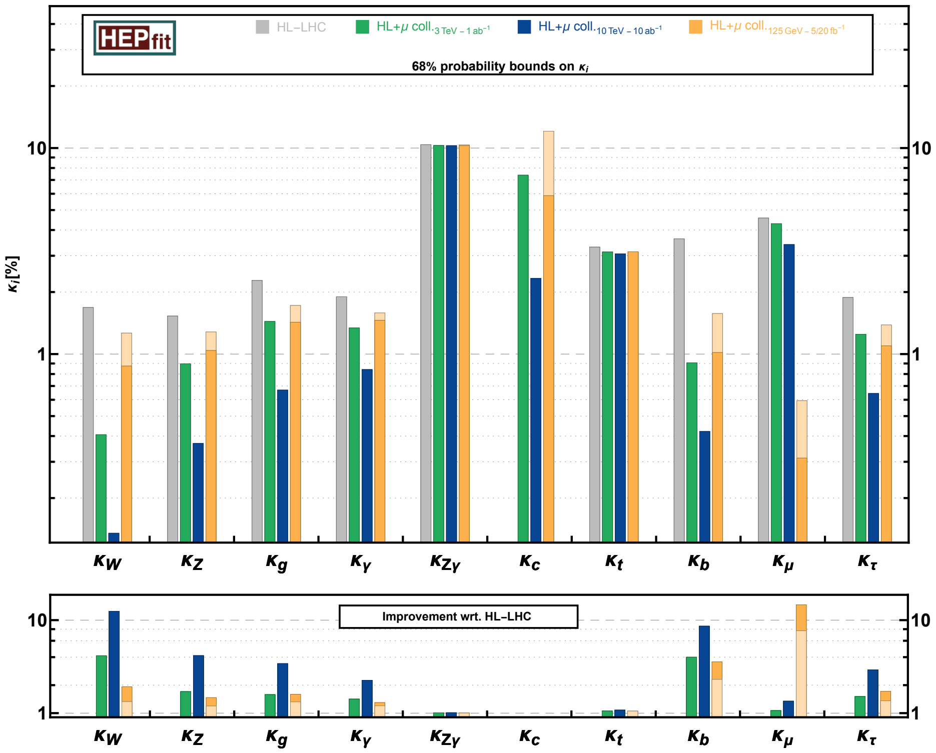
- Studying ZH with Z going to leptons and neutrinos
- $\kappa_s < 7.14$ at 95% c.l.

arXiv:2203.07535

- Electron Yukawa at FCC-ee (s-channel H)
- $\kappa_e < 1.6$ at 95% c.l.

arXiv:2107.02686

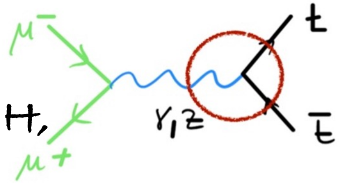
The case of a Muon Collider



- **Many stages/upgrades:**
  - 125 GeV on-Higgs resonace
  - 3 TeV
  - 10 TeV
  - >10 TeV (14, 30, … TeV)
- **Lepton collider**
  - Cleaner environment → **precision**
- **… but high energy**
  - Pushing the EF → **discovery**
- **Competitive/complementary to ~100 TeV hadron collider**
- **Contained size**
  - M_μ~ 200 m_e → reduced synchrotron radiation (x 1.6 x10^{-9})
- **New physics regimes**
  - E > Λ_{EW}
  - EW radiation

Snowmass 21 EF Higgs TG Report (arXiv:2209.07510) & MuC Forum Report (arXiv:2209.01318)

$\sqrt{s} \lesssim$ 1-5 TeV

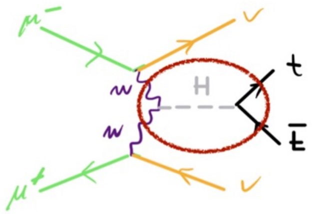


$$\sigma_s \sim \frac{1}{s}$$

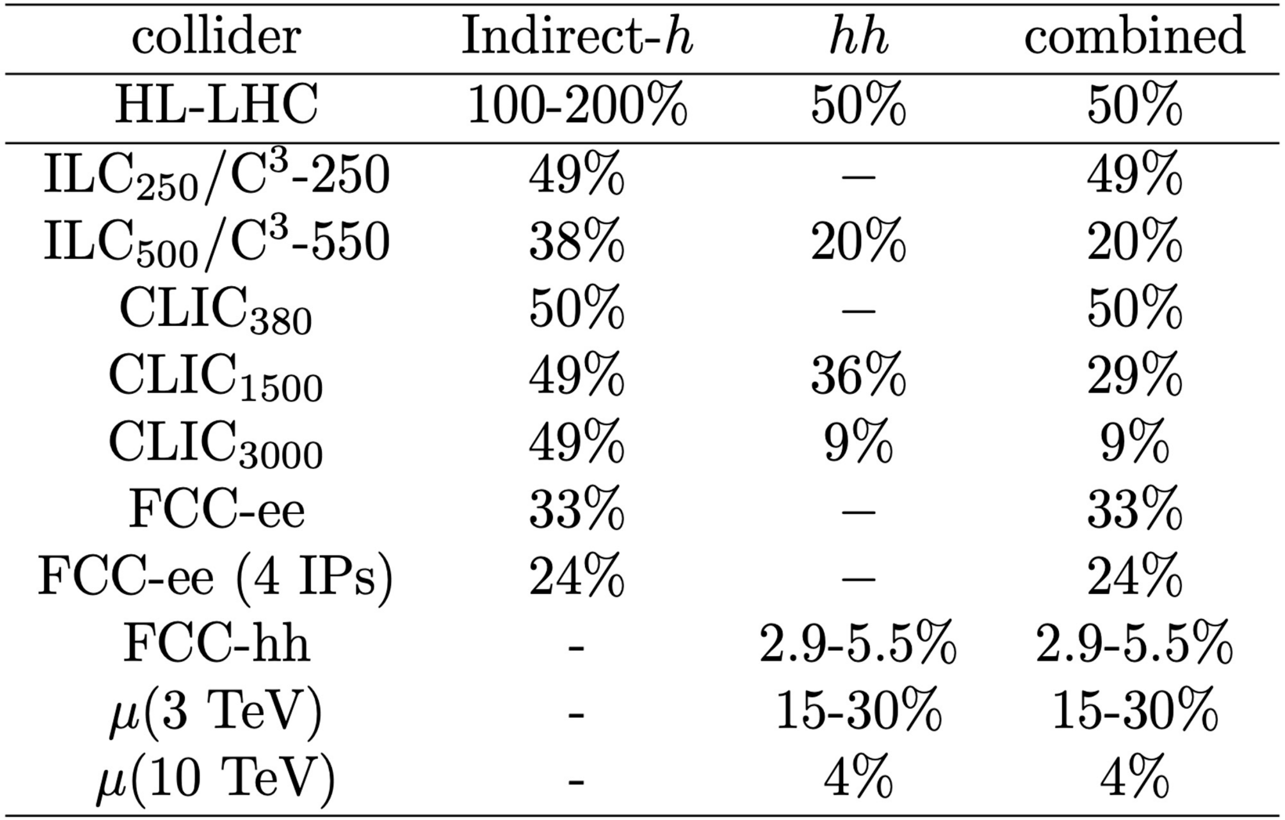
⬌

$$\sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$

$\sqrt{s} \gtrsim$ 1-5 TeV

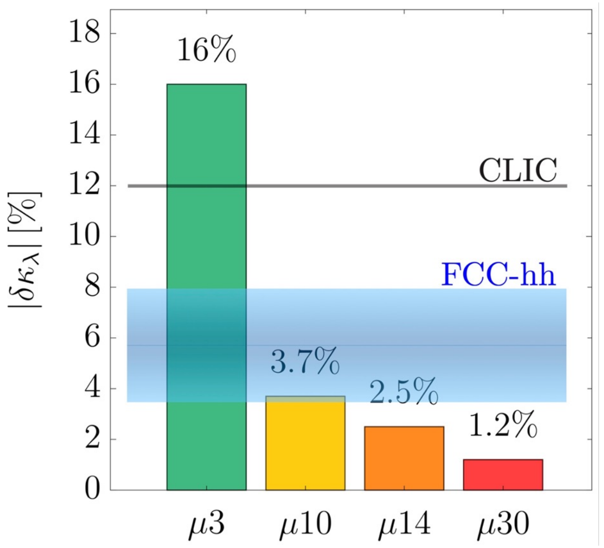


Reach for Higgs self-coupling



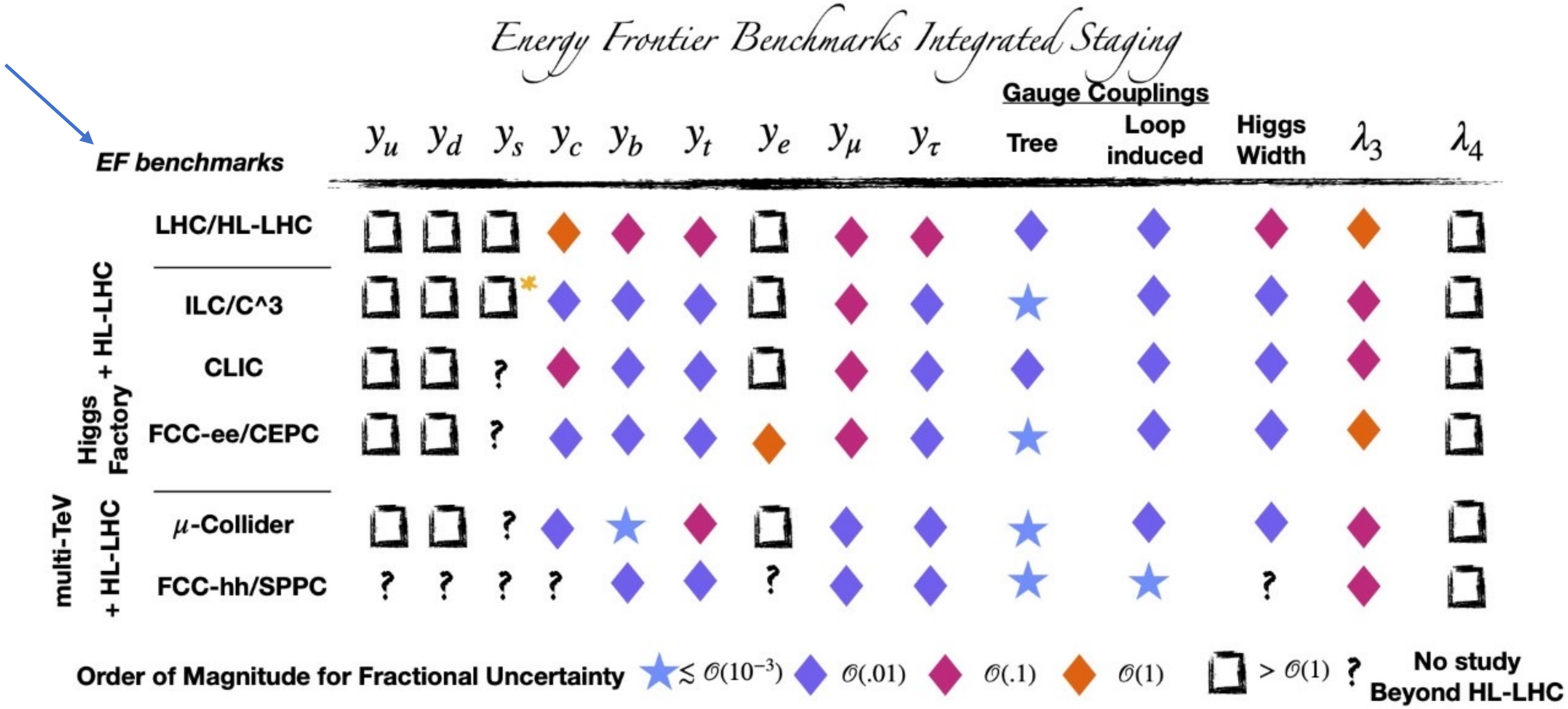
collider	Indirect-h	hh	combined
HL-LHC	100-200%	50%	50%
ILC$_{250}$/C^3-250	49%	—	49%
ILC$_{500}$/C^3-550	38%	20%	20%
CLIC$_{380}$	50%	—	50%
CLIC$_{1500}$	49%	36%	29%
CLIC$_{3000}$	49%	9%	9%
FCC-ee	33%	—	33%
FCC-ee (4 IPs)	24%	—	24%
FCC-hh	-	2.9-5.5%	2.9-5.5%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

- ATLAS and CMS HL-LHC updated
- FCC-hh updated [arXiv:2004.03505]
- Added MuC reach:



arXiv:2203.07256

Higgs precision reach of Future Colliders: a summary

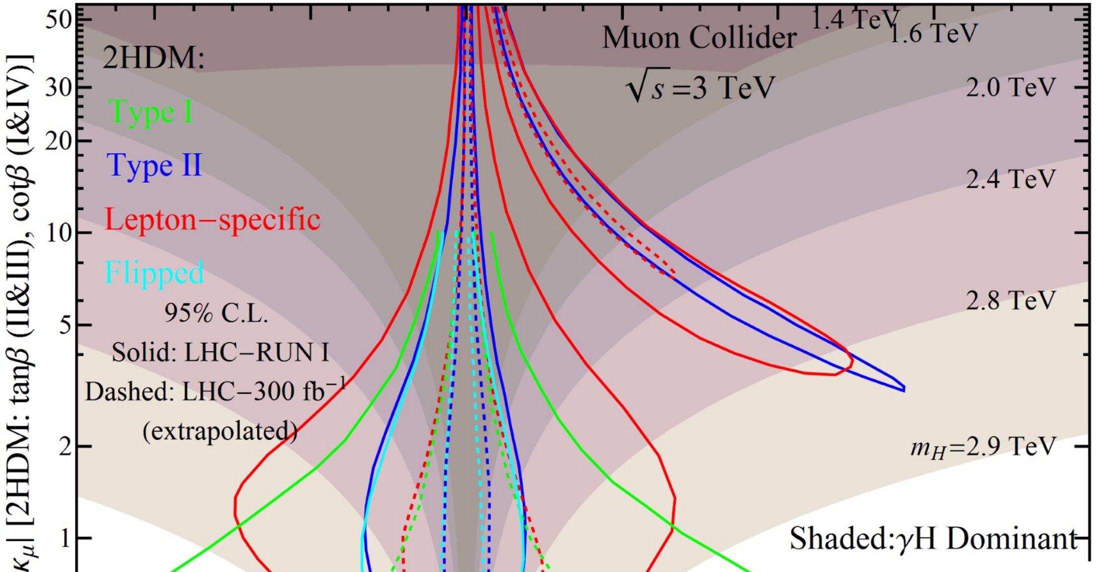


Energy Frontier Benchmarks Integrated Staging

	EF benchmarks	y_u	y_d	y_s	y_c	y_b	y_t	y_e	y_μ	y_τ	Gauge Couplings Tree	Gauge Couplings Loop induced	Higgs Width	λ_3	λ_4
	LHC/HL-LHC	☐	☐	☐	🔶	♦	♦	☐	♦	♦	🔷	🔷	♦	🔶	☐
Higgs Factory + HL-LHC	ILC/C^3	☐	☐	☐*	🔷	🔷	🔷	☐	♦	🔷	★	🔷	🔷	♦	☐
	CLIC	☐	☐	?	♦	🔷	🔷	☐	♦	🔷	🔷	🔷	🔷	♦	☐
	FCC-ee/CEPC	☐	☐	?	🔷	🔷	🔷	🔶	♦	🔷	★	🔷	🔷	🔶	☐
multi-TeV + HL-LHC	μ-Collider	☐	☐	?	🔷	★	♦	☐	🔷	🔷	★	🔷	🔷	♦	☐
	FCC-hh/SPPC	?	?	?	?	🔷	🔷	?	🔷	🔷	★	★	?	♦	☐

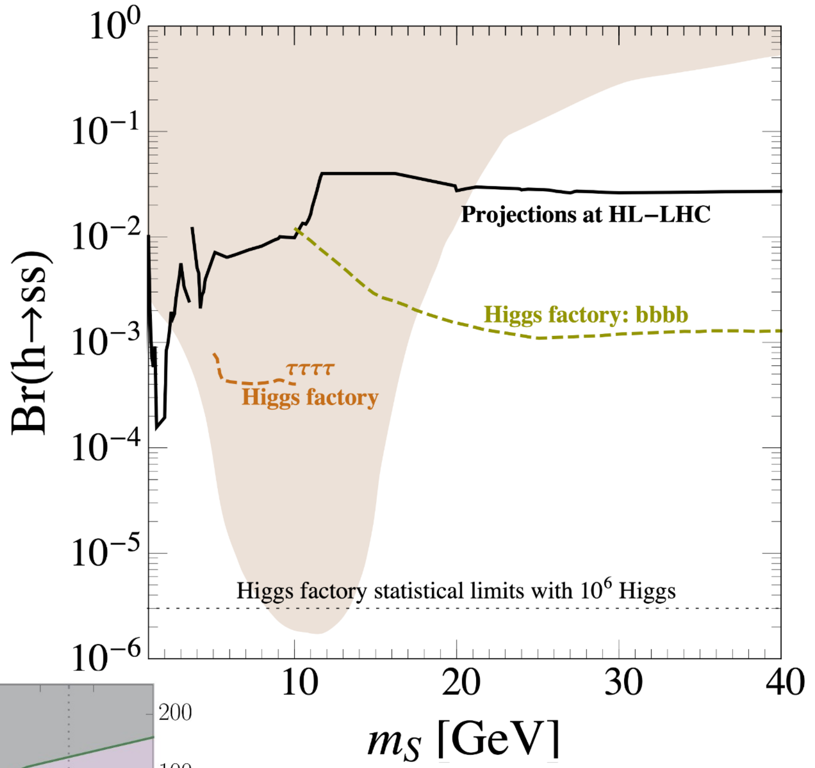
Order of Magnitude for Fractional Uncertainty ★ $\lesssim \mathcal{O}(10^{-3})$ 🔷 $\mathcal{O}(.01)$ ♦ $\mathcal{O}(.1)$ 🔶 $\mathcal{O}(1)$ ☐ $> \mathcal{O}(1)$? No study Beyond HL-LHC

Extended Higgs sectors - direct BSM portal

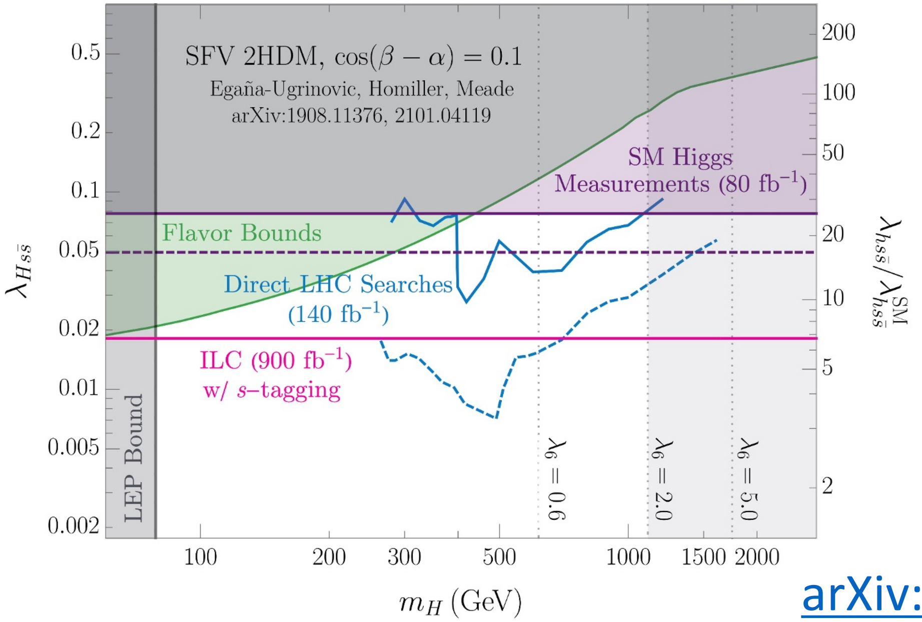


arXiv:2203.07261

Extended Higgs sectors: 2HDM, extra singlets, …



arXiv:2203:08206

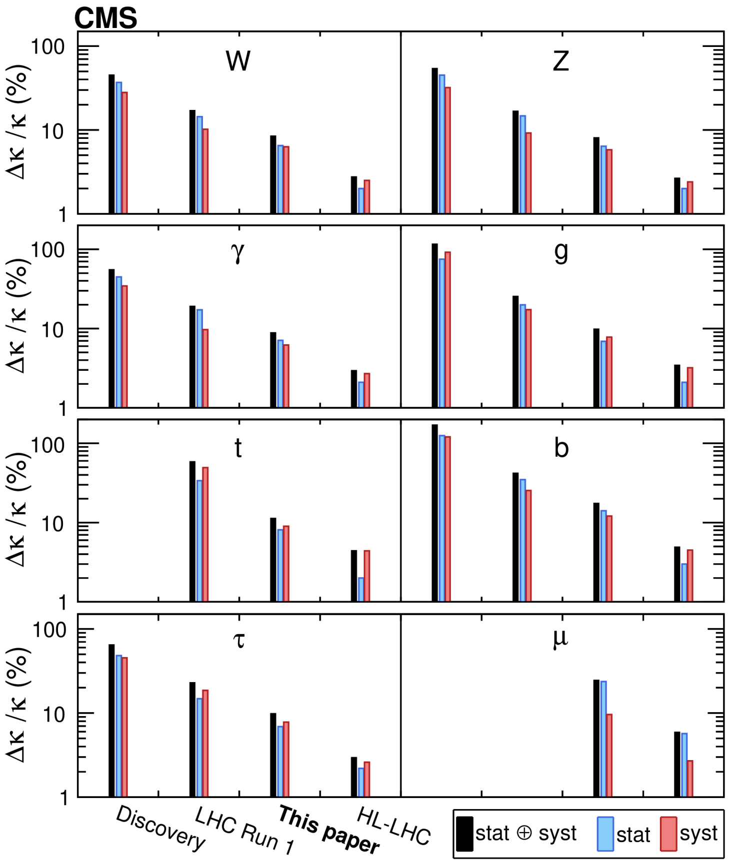


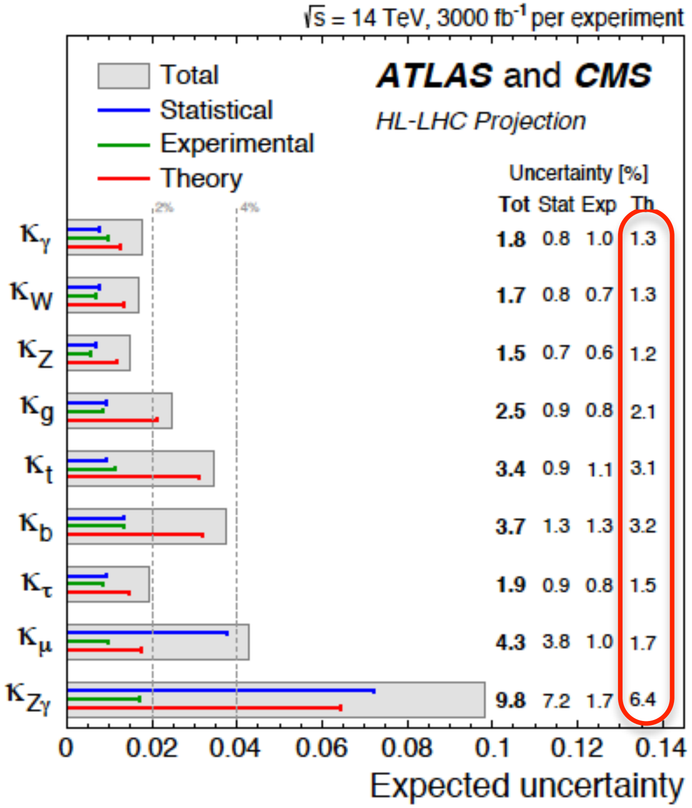
arXiv:2203:07535

Higgs and flavor: probing anomalous Hss coupling

Towards higher precision and higher energies

HL-LHC zooming on couplings, a little more …





Generically:

$\Delta\kappa/\kappa \sim O(v^2/\Lambda^2)$

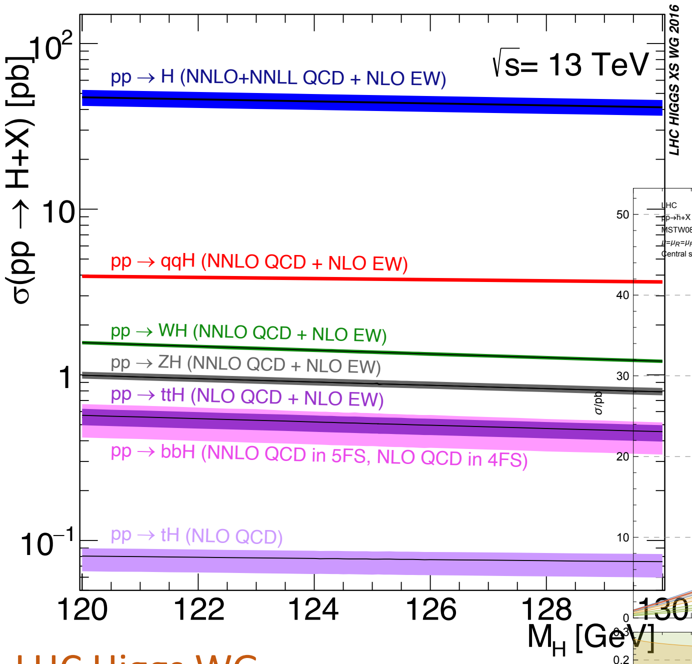
For new physics at 1 TeV expect deviations of O(6%)

Improved systematics probes higher scales

Theory could become main limitation

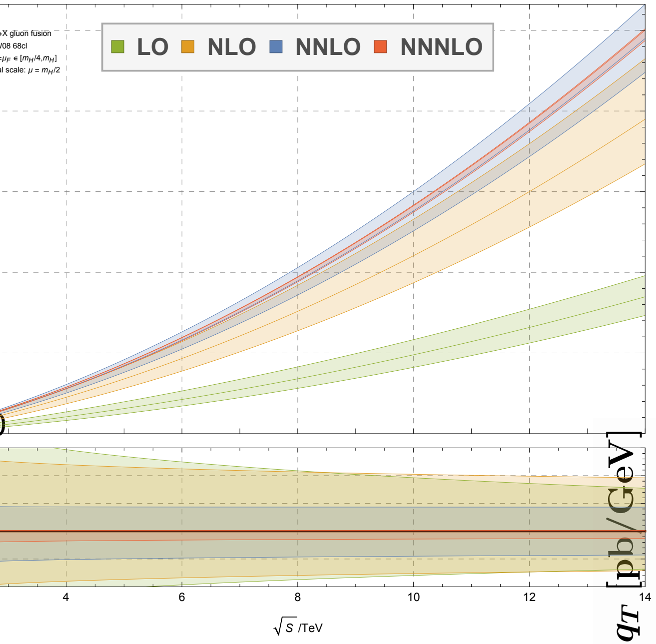
Theory need to improve modeling and interpretation of LHC events, in particular when new physics may not be a simple rescaling of SM interactions

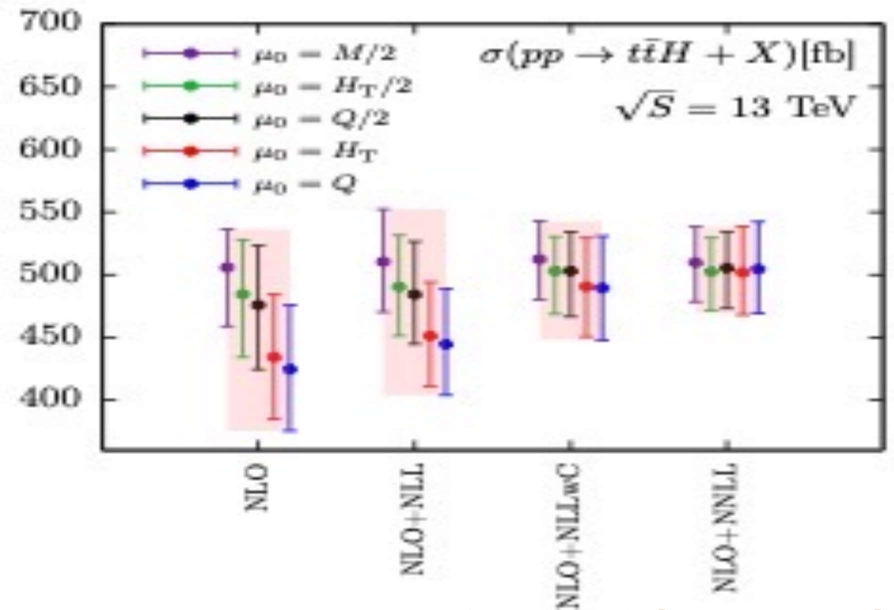
Theory has come a long way



LHC Higgs WG

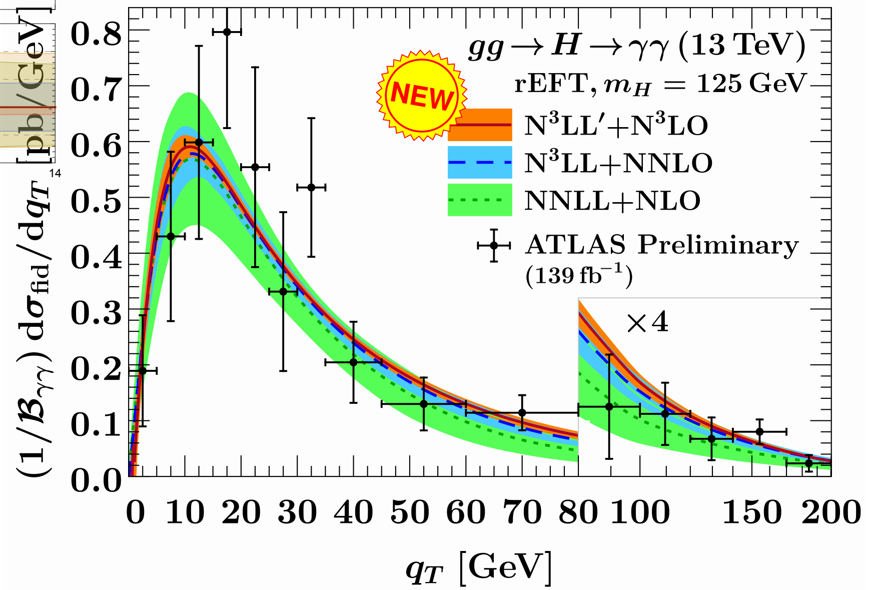
Anastasiou et al. [1502.06056]





Kulesza et al. [1812.08622]

Bliss et al. [2102.08039]



Several backgrounds also know at
NLO QCD+EW or improved NLO (+NNLL)
(e.g. W/Z+j, ttbb, ttW, ttZ, ttγ, …)

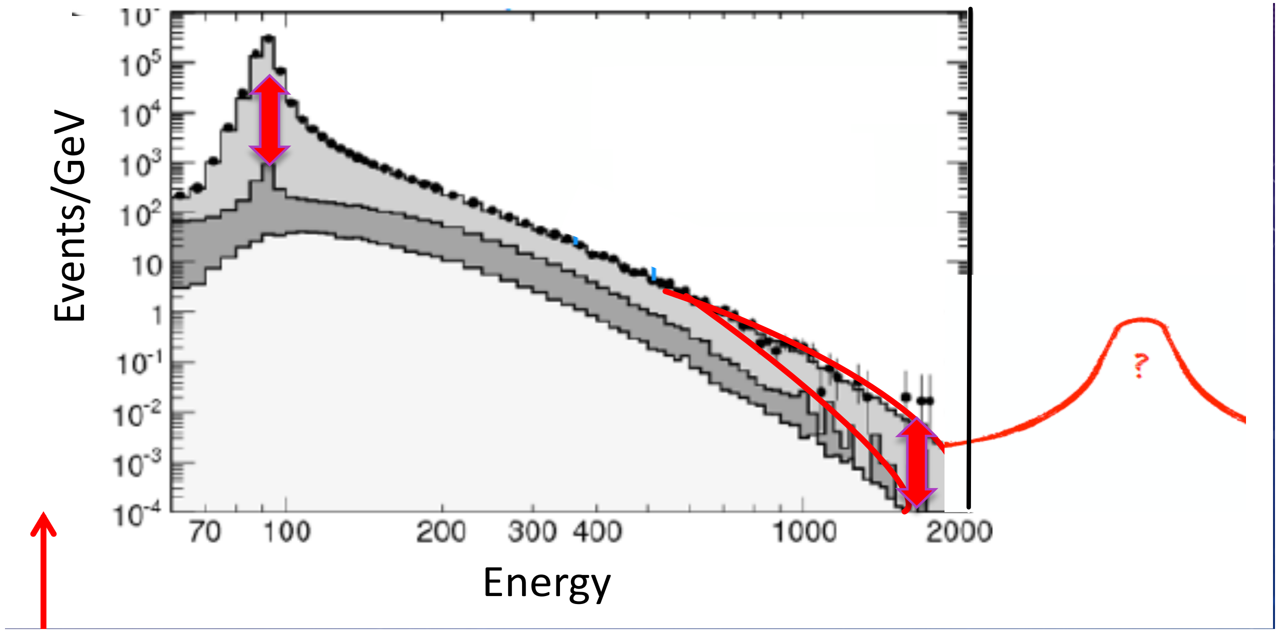
Beyond total rates

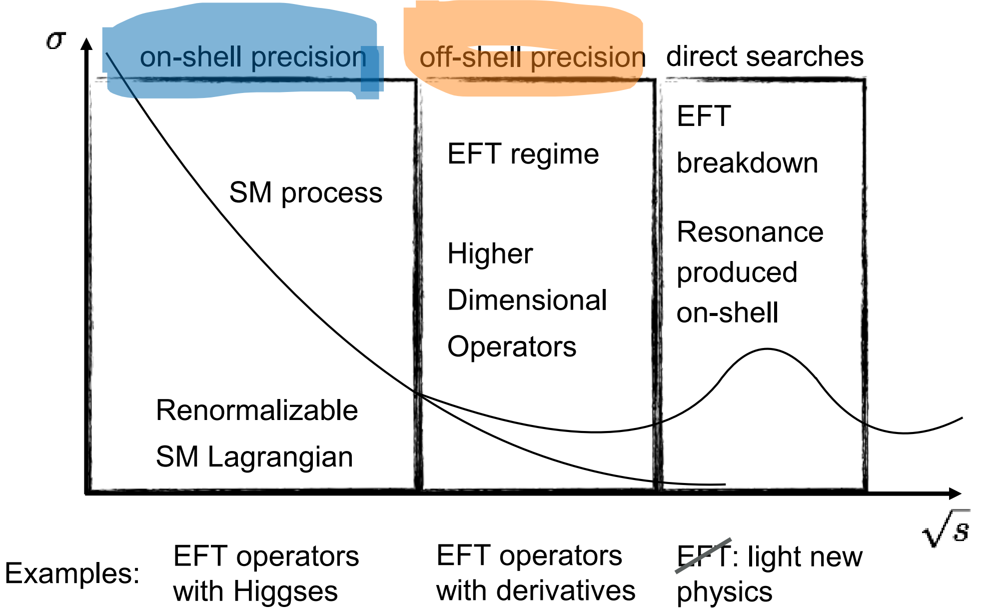
Extending the SM via effective interactions above the EW scale ⟶ **SMEFT**

dim=6

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \left(\frac{1}{\Lambda^2} \sum_i C_i O_i + \text{h.c.} \right) + O(\Lambda^{-4})$$

dim>8



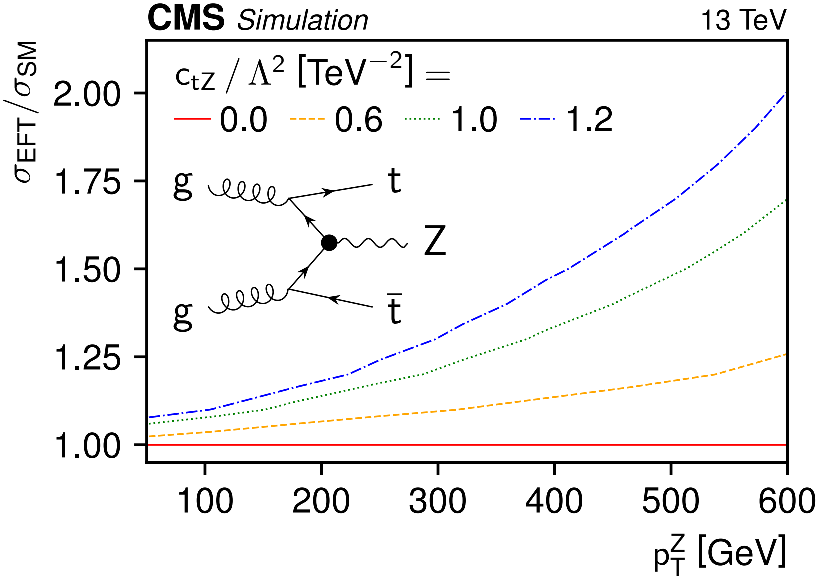


Need SM precision calculations at differential level both at **lower energy,** where rates are large and at **higher energy** where rates are small but effects of new physics may be more visible.

Crucial to control EFT sensitive regions

… exploring boosted kinematics and off-shell signatures

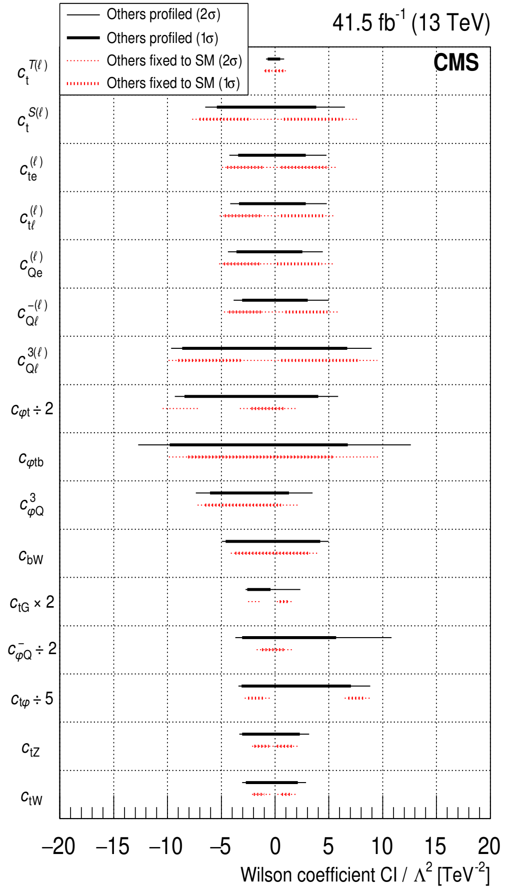
Top pair + boosted Z/H



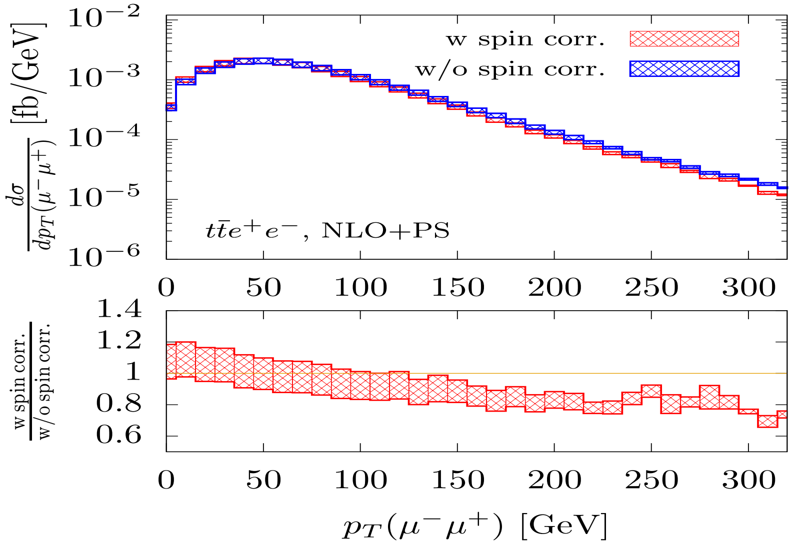
$$\delta\eta_{SM} \sim g_{BSM}^2 \frac{E^2}{M^2}$$

Effects in tails of distributions but also anomalous shapes

Top+additional leptons

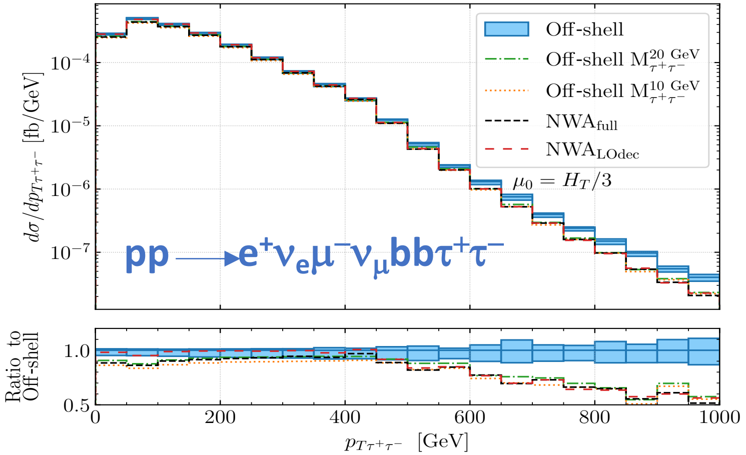


[CMS: arXiv:2012.04120]



M. Ghezzi et al. [2112.08892]

Off-shell studies



G. Bevilacqua et al. [2203.15688]

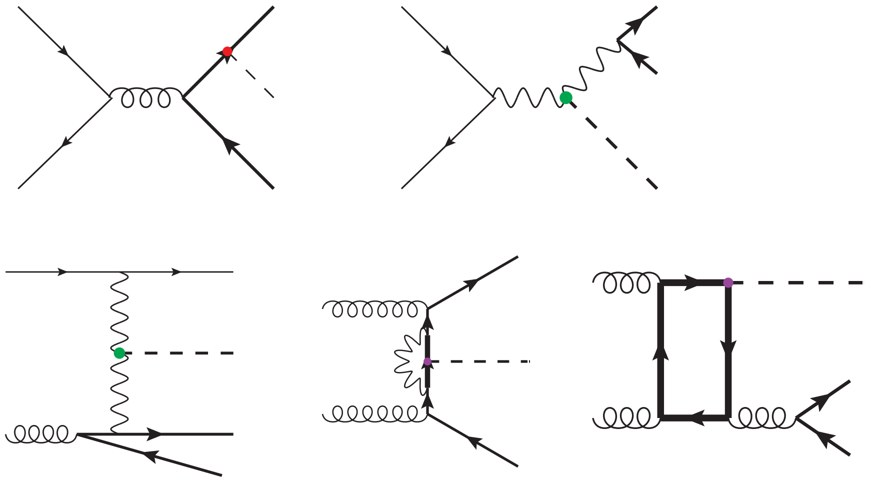
Pointing to the need for precision in modelling signatures from $t\bar{t}$+X processes in regions where on-shell calculations may not be accurate enough

… deploying new techniques to interpret complex signatures

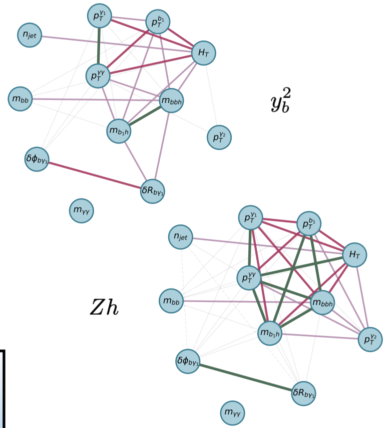
The case of **bbH production including QCD+EW corrections**
The extraction of y_b seems lost

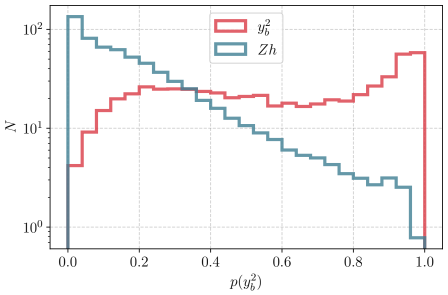
``RIP Hbb'' (Pagani et al., arXiv:2005.10277)

ratios	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(\kappa_Z^2)} \equiv \frac{\sigma_{\mathrm{NLO}_{\mathrm{QCD+EW}}}}{\sigma_{\mathrm{NLO}_{\mathrm{all}}}}$ (y_b vs. κ_Z)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)}$ (y_b vs. y_t)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)+\sigma(\kappa_Z^2)}$ (y_b vs. κ_Z and y_t)
NO CUT	0.69	0.32	0.28
$N_{j_b} \geq 1$	0.37 (0.48)	0.19	0.14
$N_{j_b} = 1$	0.46 (0.60)	0.20	0.16
$N_{j_b} \geq 2$	0.11	0.11	0.06



A kinematic-shape based analysis based on game theory (Shapley values) and BDT techniques opened new possibilities
"Resurrecting Hbb with kinematic shapes"
(Grojean et al., arXiv:2011.13945)





New techniques will open the possibility of turning problematic processes into powerful probes of the quantum structure of the SM.

Summary

- **The Higgs discovery has been fundamental in opening new avenues to explore physics beyond the SM** and the Higgs-physics program ahead of us promises to start answering some of the remaining fundamental questions in particle physics.

- **Collider physics** remains as a **unique and necessary test of any BSM hypothesis**.

- **Many new directions have been explored during the Snowmass 2021 exercise**, **building on previous studies (ESG)**, and have indicated the need to explore the TeV scale beyond LHC reach by pushing both **precision (Higgs factories) and energy (multi-TeV colliders)**.

- **Increasing the accuracy on SM observables** (Higgs, top, EW) could allow to **test higher scales**: a factor of 10 in precision could allow to test scale in the 10 TeV and beyond.

- **Direct evidence of new physics will boost this process**, as the discovery of the Higgs boson has prompted us in this new era of LHC physics.