Imperial College London

Science & Technology Facilities Council

(Higgs) physics at a muon collider

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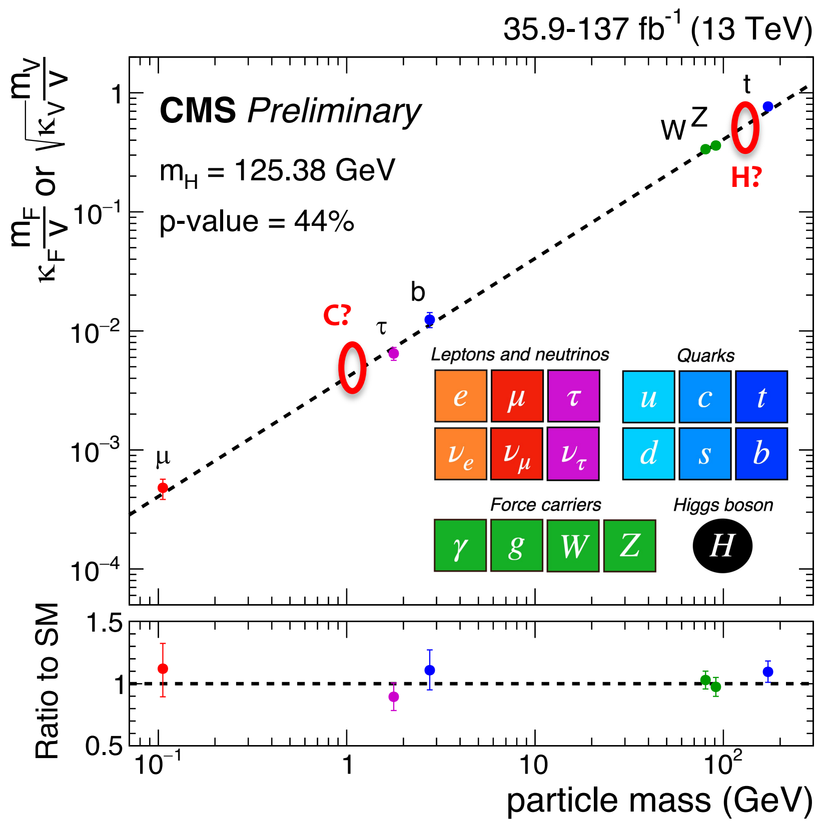
Future Higgs

Higgs physics played a large role in the Strategy update discussions

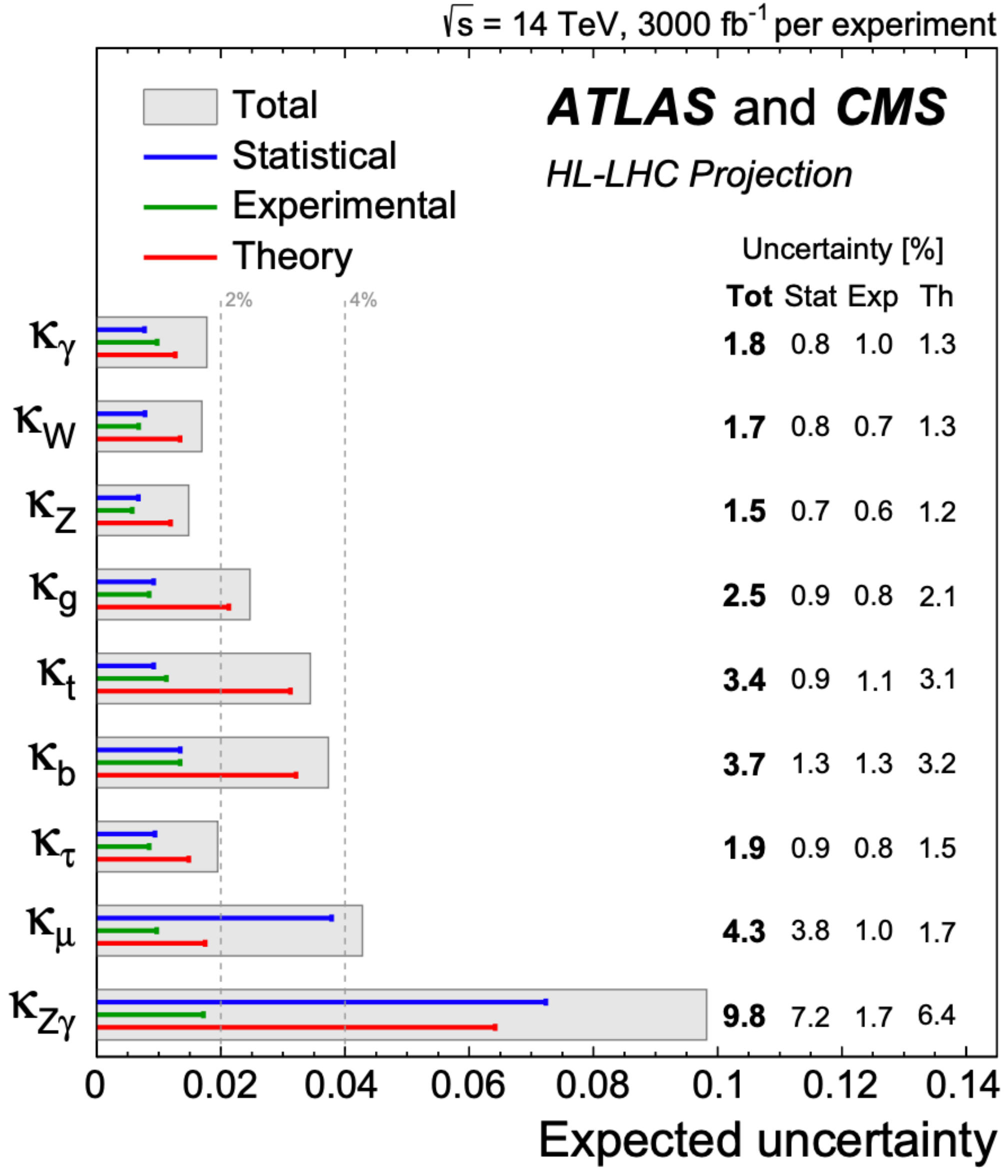
"An electron-positron Higgs factory is the highest-priority next collider…"

The LHC program will explore details of the Higgs sector, (most likely) filling in gaps of what we expect in the SM

Disclaimer : I'm not an accelerator expert, nor a muon physics expert so this is a very "Higgs biased" talk….



State of the Higgs (in 2040)



https://arxiv.org/pdf/1902.00134.pdf

Higgs couplings is a focus point of the HL-LHC (and future high-energy program)

Projections from the latest Yellow-report give us some idea as to where we'll be in ~2040 (post HL-LHC)

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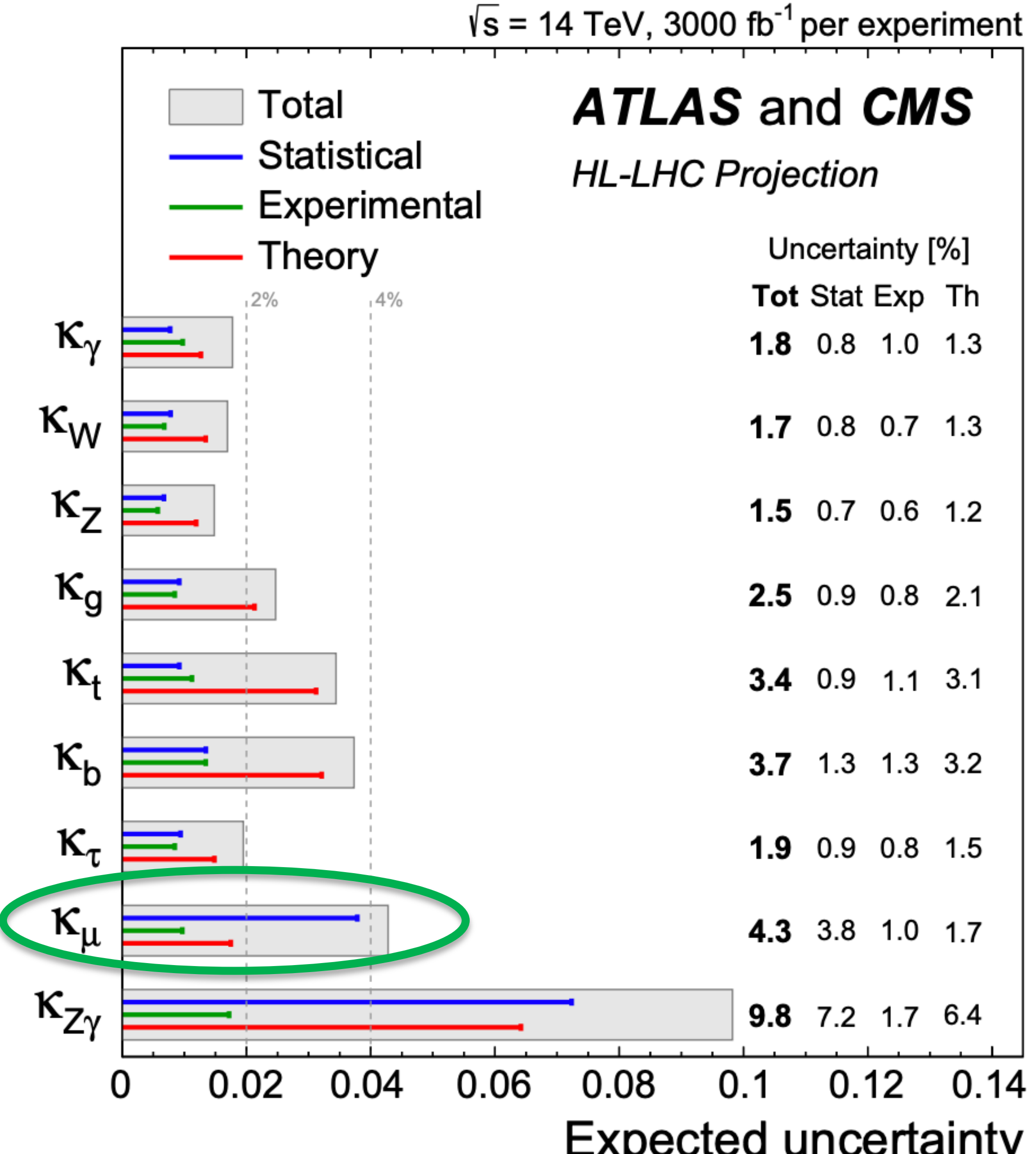

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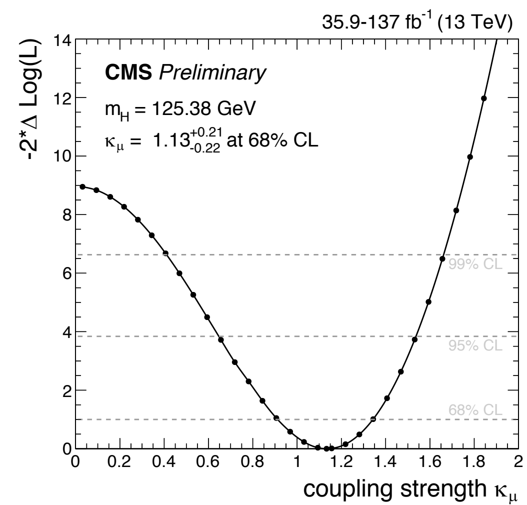
Higgs couplings is a focus point of the HL-LHC (and future high-energy program)

Projections from the latest Yellow-report give us some idea as to where we'll be in ~2040 (post HL-LHC)

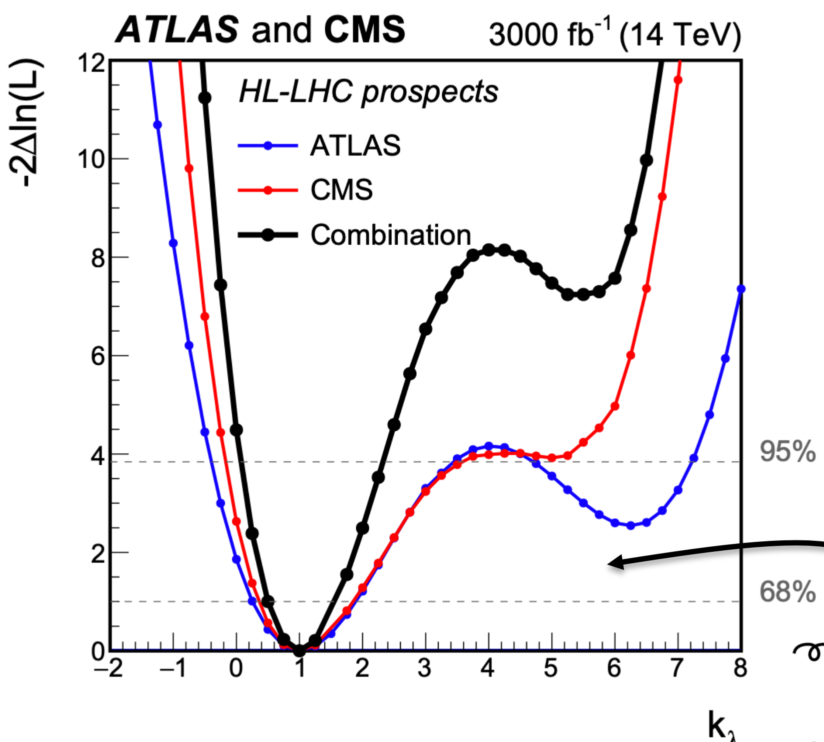
Can't predict how smart we'll get (even in the space of 2 years!)

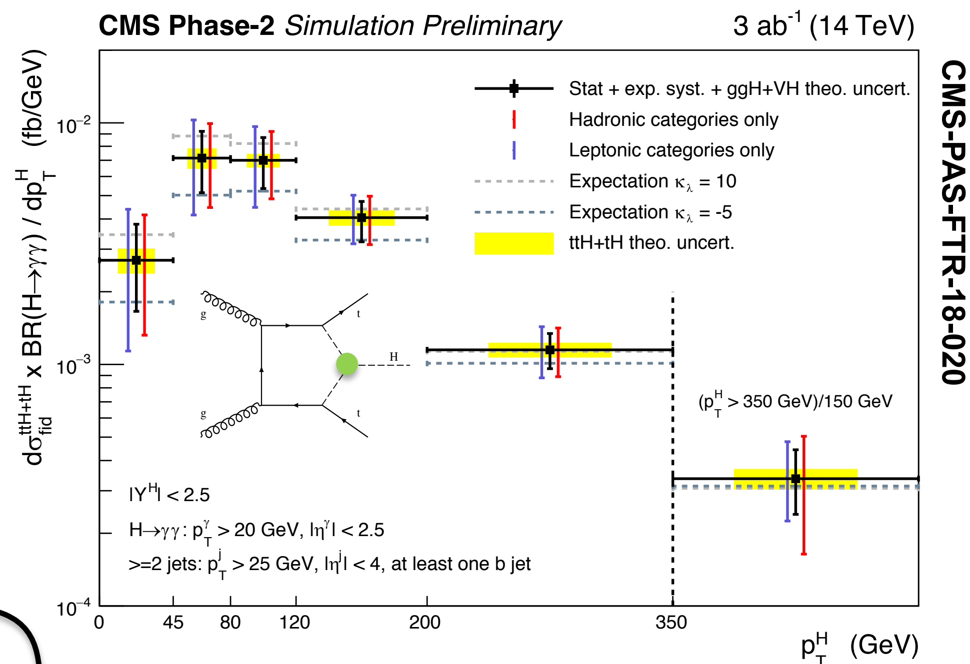


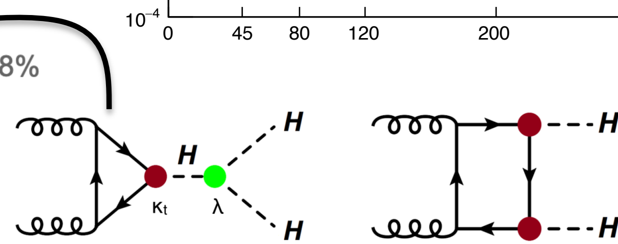
Higgs self-coupling

Personal bias – Higgs self-coupling (and in general understanding the Higgs potential) is ***the*** biggest challenge in the Higgs sector …

Sensitivity from direct (HH) production and indirect (H) measurements … all have assumptions / model dependencies built in → must have multiple angles of attack! This is the strength of a pp collider







The (moving) target to beat

FCC-ee combining ZH + VBF production COMs

Caveat. These numbers change from year to year a little but overall picture is FCC-ee can do precision Higgs (O%), but misses some key channels …

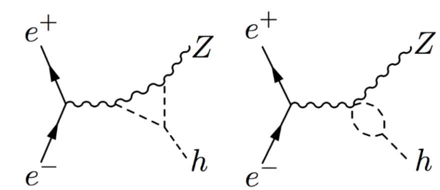
Collider	FCC-ee$_{240\rightarrow365}$
Lumi (ab^{-1})	5 + 0.2 + 1.5
Years	3 + 1 + 4
g_{HZZ} (%)	**0.17 / 0.26**
g_{HWW} (%)	**0.41 / 0.27**
g_{Hbb} (%)	**0.64 / 0.56**
g_{Hcc} (%)	**1.3 / 1.3**
g_{Hgg} (%)	**0.89 / 0.82**
$g_{H\tau\tau}$ (%)	**0.66 / 0.57**
$g_{H\mu\mu}$ (%)	**3.9 / 3.8**
$g_{H\gamma\gamma}$ (%)	**1.2 / 1.2**
$g_{HZ\gamma}$ (%)	**10. / 9.4**
g_{Htt} (%)	**2.6 / 2.6**
g_{HHH} (%)	**19. / 34.**
Γ_H (%)	**1.2**
BR$_{inv}$ (%)	**0.19**
BR$_{EXO}$ (%)	**1.0**

D. d'Enterria (ICHEP 2020)

Same production at $\mu^+\mu^-$
→ In principle, same program can be carried out (but is it worth low ECOM running for H-factory?)

Potentially no better than HL-LHC ?

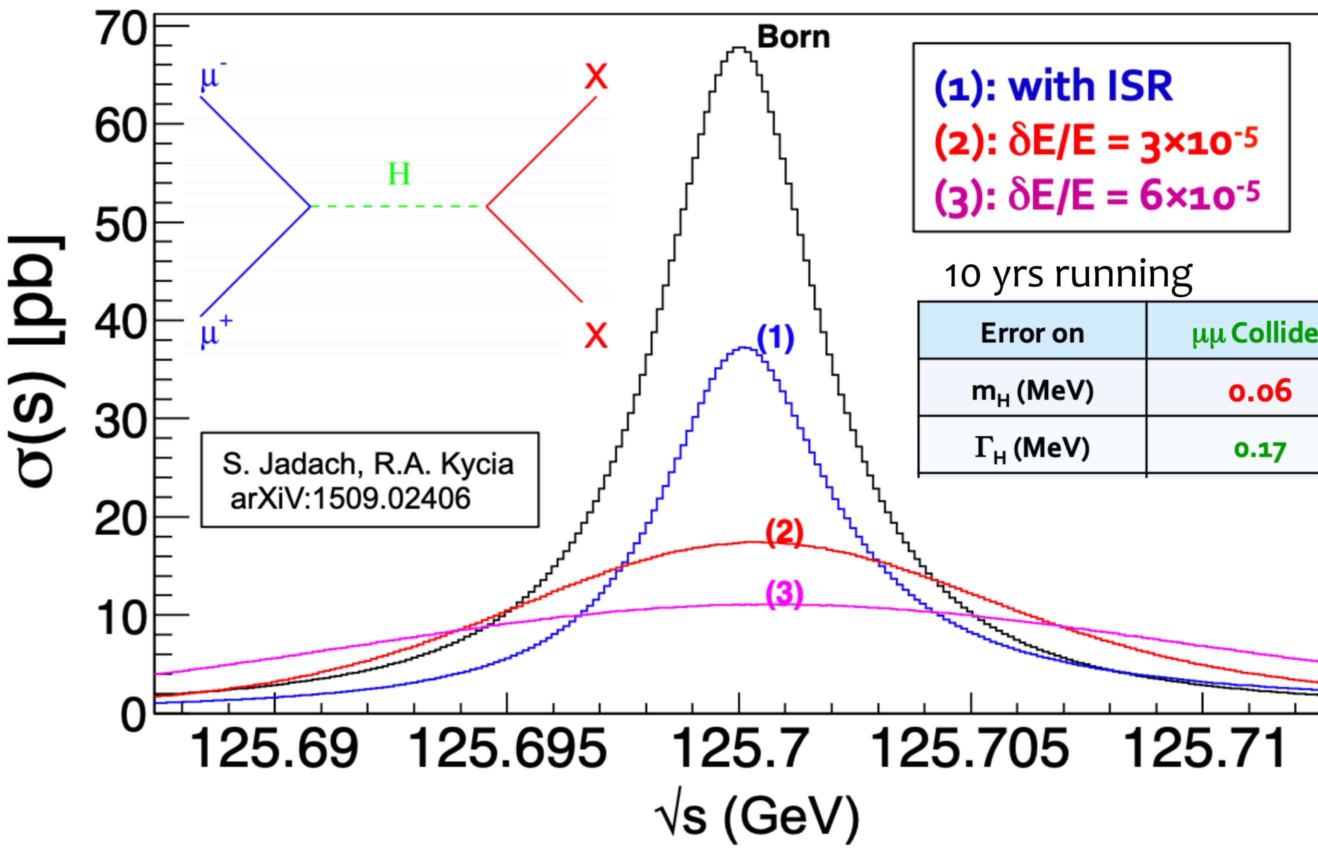
Relies on NLO corrections to single-H (model dependent)



Some model dependence from ZH →WWH energies (but its minor)

Line-shape physics (m_H pole)

At $\sqrt{s}$=125, **muon** coupling and direct mass/width measurements are greatly improved with a muon collider due to m_μ/m_e coupling enhancement + improved beam energy spread

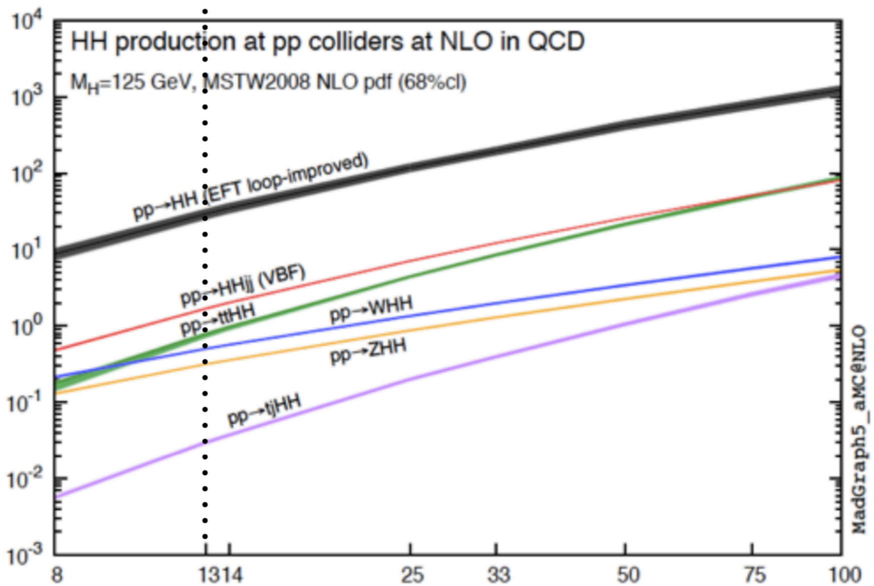


10 yrs running

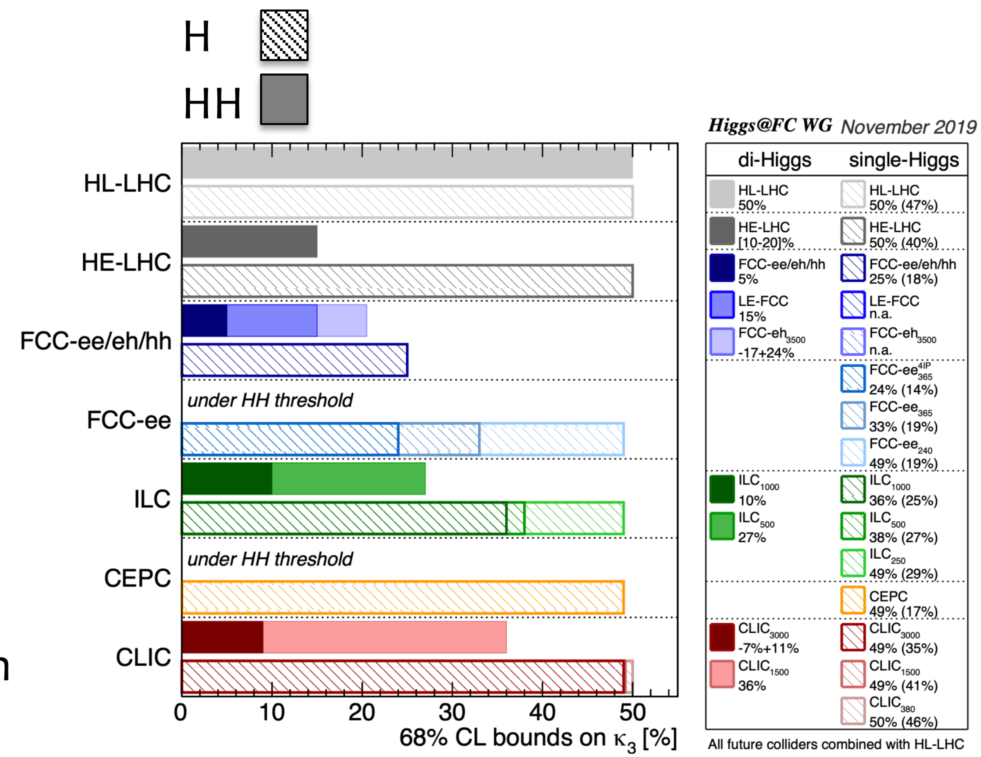
Error on	μμ Collider	ILC	FCC-ee
m_H (MeV)	0.06	30	8
Γ_H (MeV)	0.17	0.16	0.04

FCC-hh

FCC is not a complete program (even focused on Higgs) without hh running



The new physics reach is also clear (but 100TeV is not motivated by physics !)

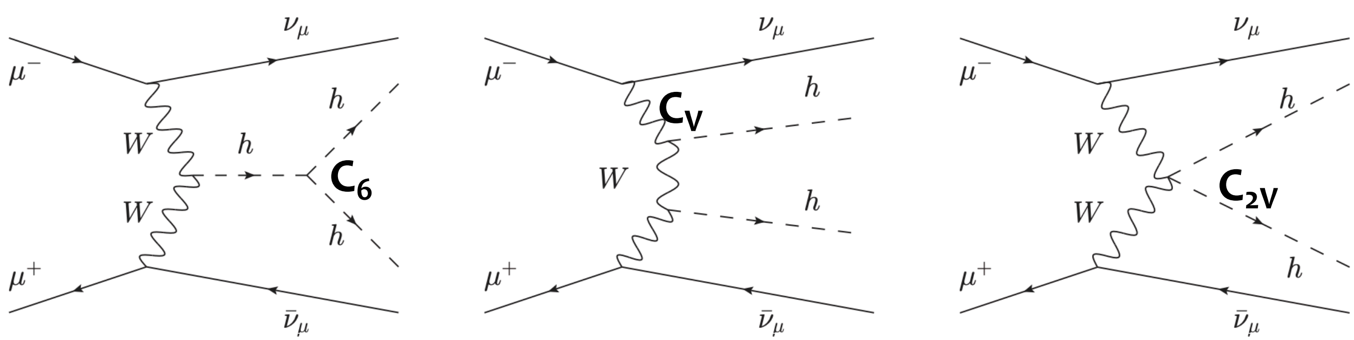


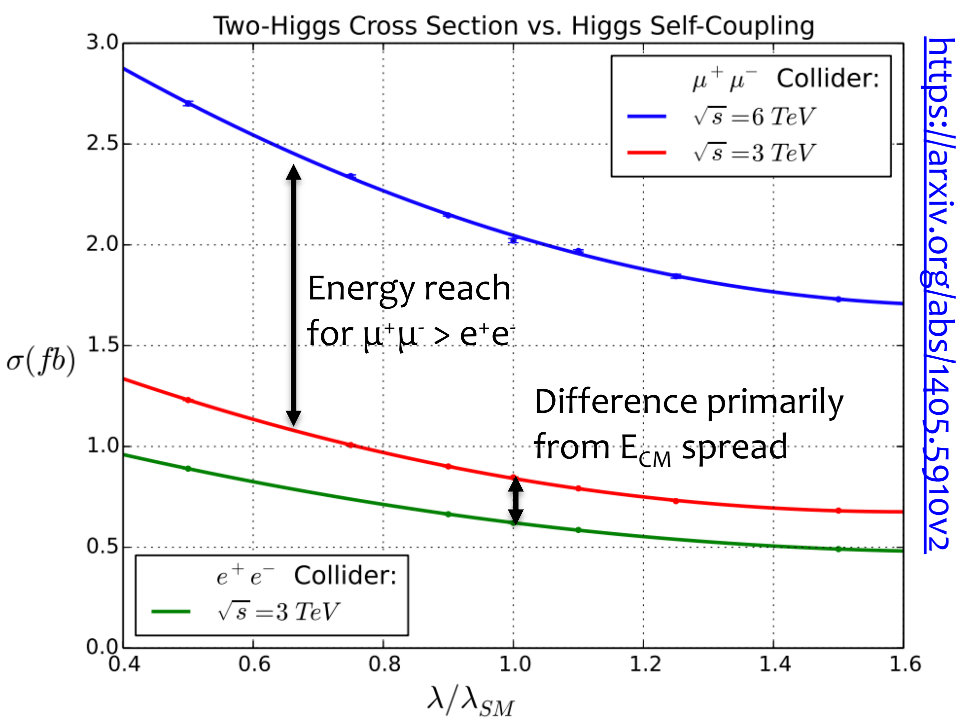
Inclusion of HH @ FCC-hh crucial to study Higgs potential in detail

→ In my (biased) opinion, this should be a ***critical*** feature of any high-p_T program

→ We don't ***need*** 100TeV to study it either

HH production at a muon collider





Prospects for HH at muon-collider

- For high COM, main production is via WW-HH
- c.f. ggHH @ LHC (40fb), FCC-hh (~1pb)
- Luminosity will be a key to achieving sensitivity

Muon Collider detector

Slide from Massimo Casarsa (ICHEP 2020)
https://indico.cern.ch/event/868940/contributions/3813908/

hadronic calorimeter

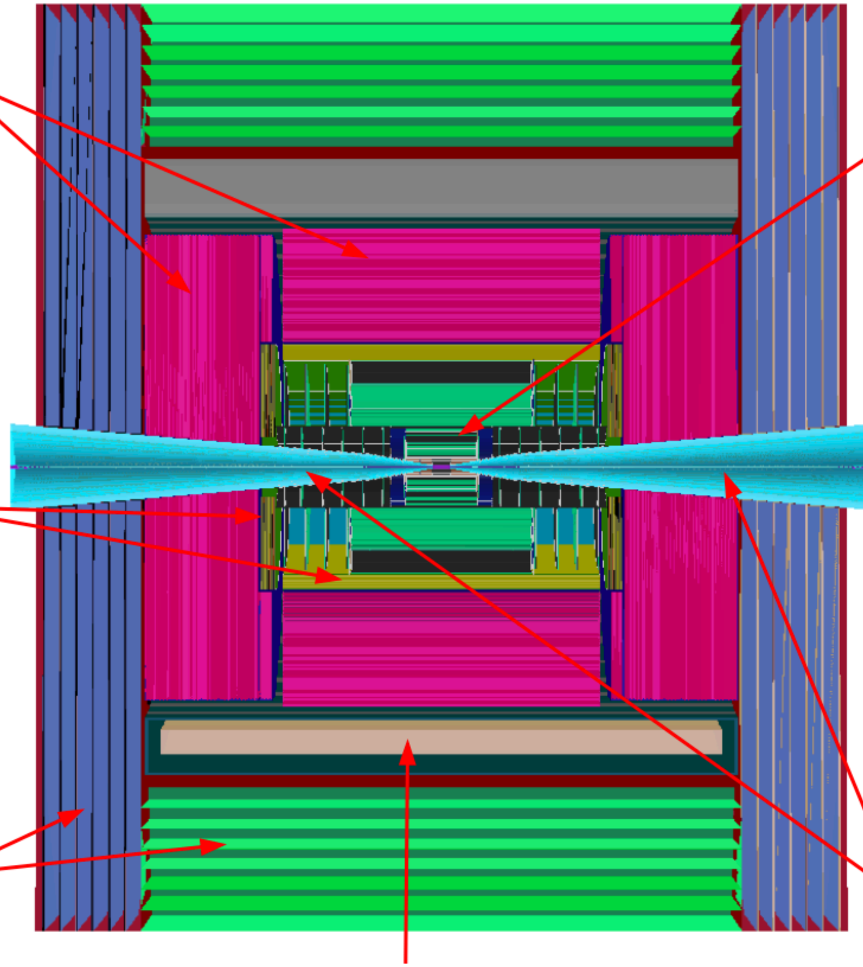
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (4T)

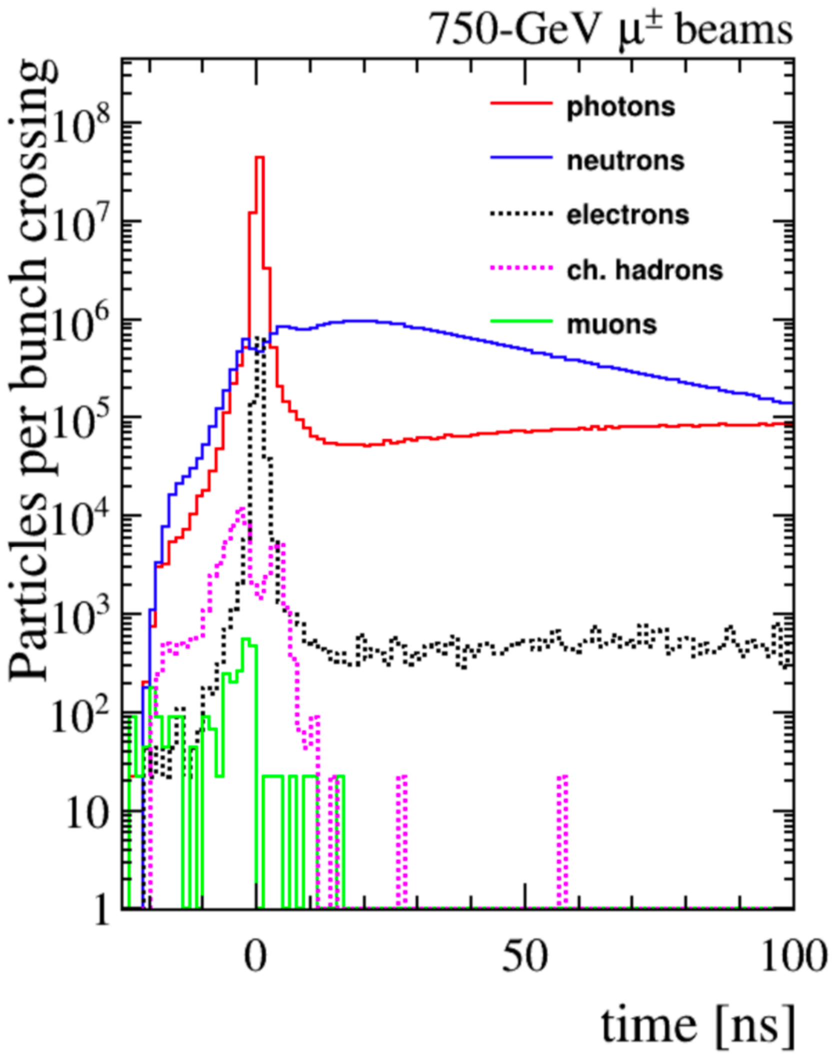
tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 50-μm thick, 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 100-μm thick, 50x50 μm^2 pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 100-μm thick, 50x50 μm^2 pixel Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

Beam-induced-backgrounds



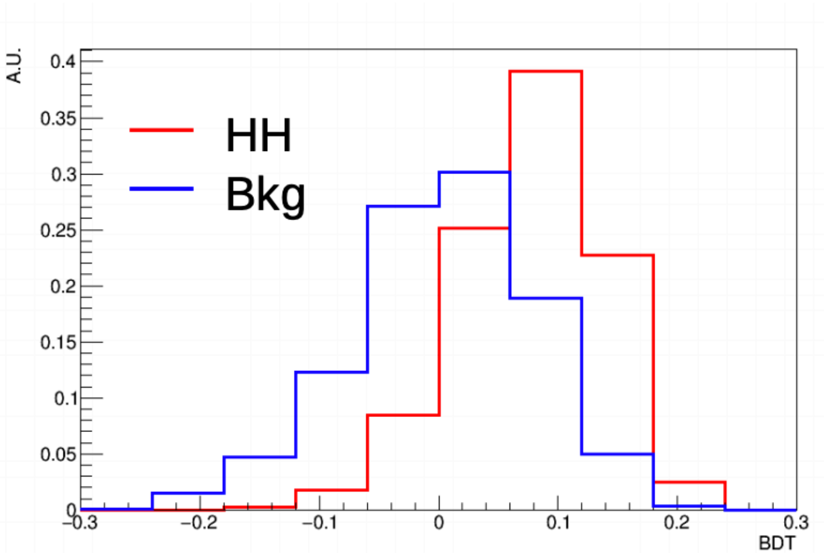
Dealing with BiB particularly challenging with muon beams. Overcome using

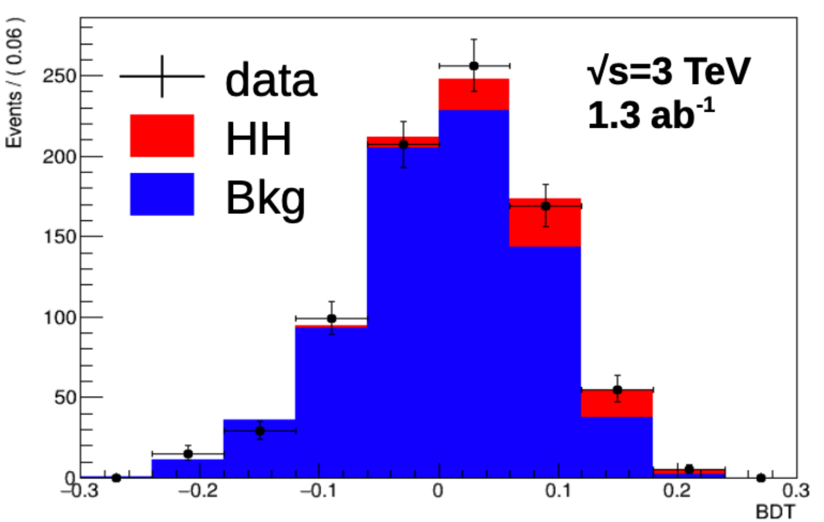
- High-granularity
- Precision timing
- AI/ML algorithms for object reconstruction

All 3 are being pursued at the HL-LHC
→ eg in CMS : HGCAL, MTD (o(10)ps)
and PFvtx@triggers to deal with immense Pile-up

→ HL-LHC will also be a testing ground for these technologies

HH(bbbb) example





Example analysis for H(bb)H(bb) @ 3TeV

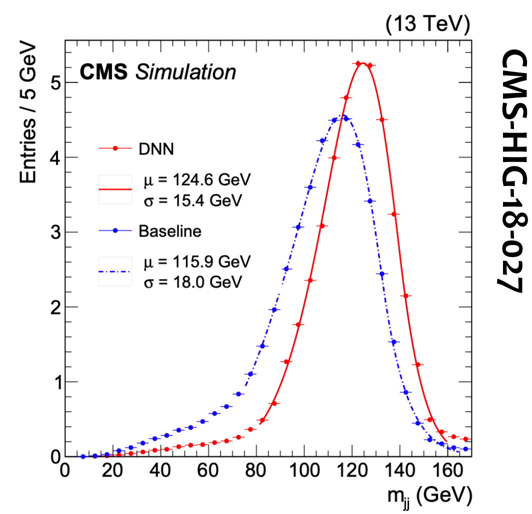
- BDT based background rejection
  - Background is mainly dominated by ZZ and H+bb events.
- ~33% uncertainty on x-section with 1.3 ab^{-1} of data

Clearly room for improvement e.g

→ improvement in mass resolution from DNN b-jets calibs

→ use multiple decay modes in combination

→ m_{HH} shape information …

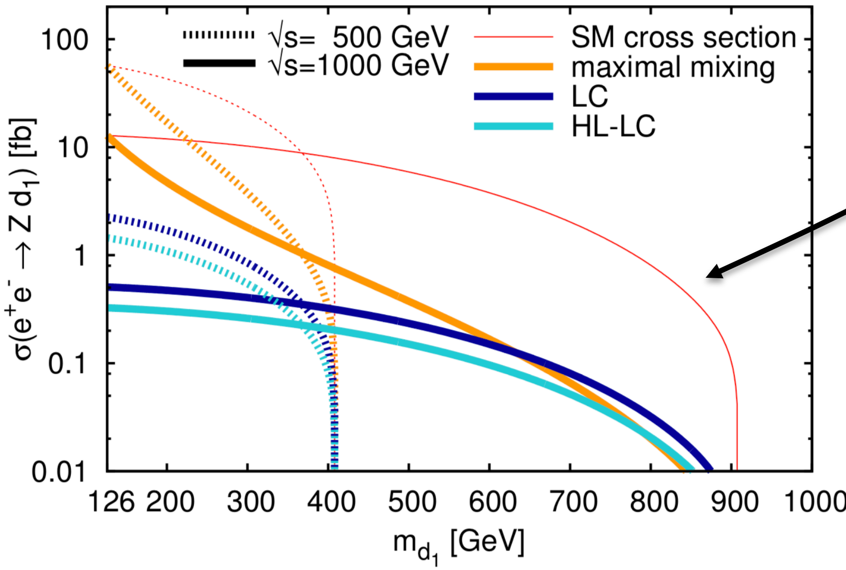


Lorenzo Sestini (ICHEP 2020)
https://indico.cern.ch/event/868940/contributions/3813545/

Mass scales

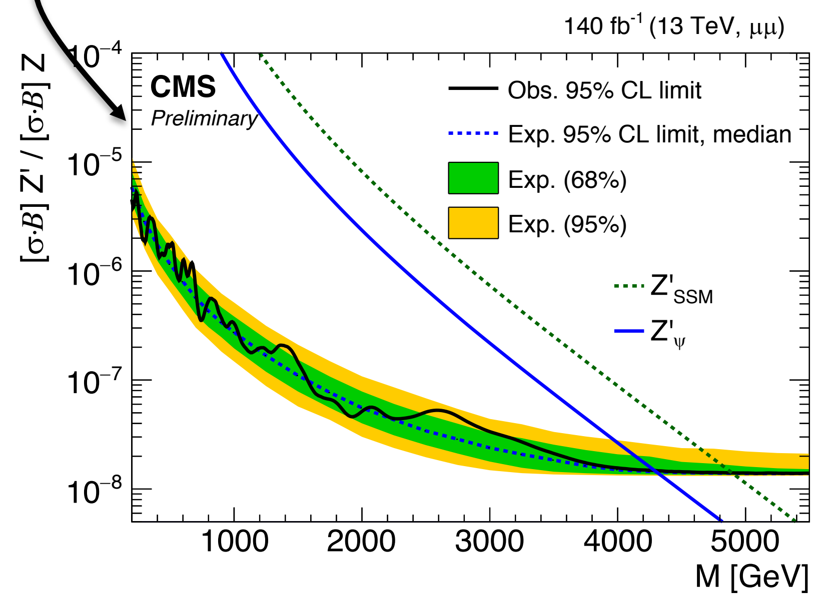
Reach of muon collider in terms of energy a clear selling point

Production x-section



Heavy scalar in Dark portal model

Z' resonances coupling to leptons excluded up to O(TeV) scales



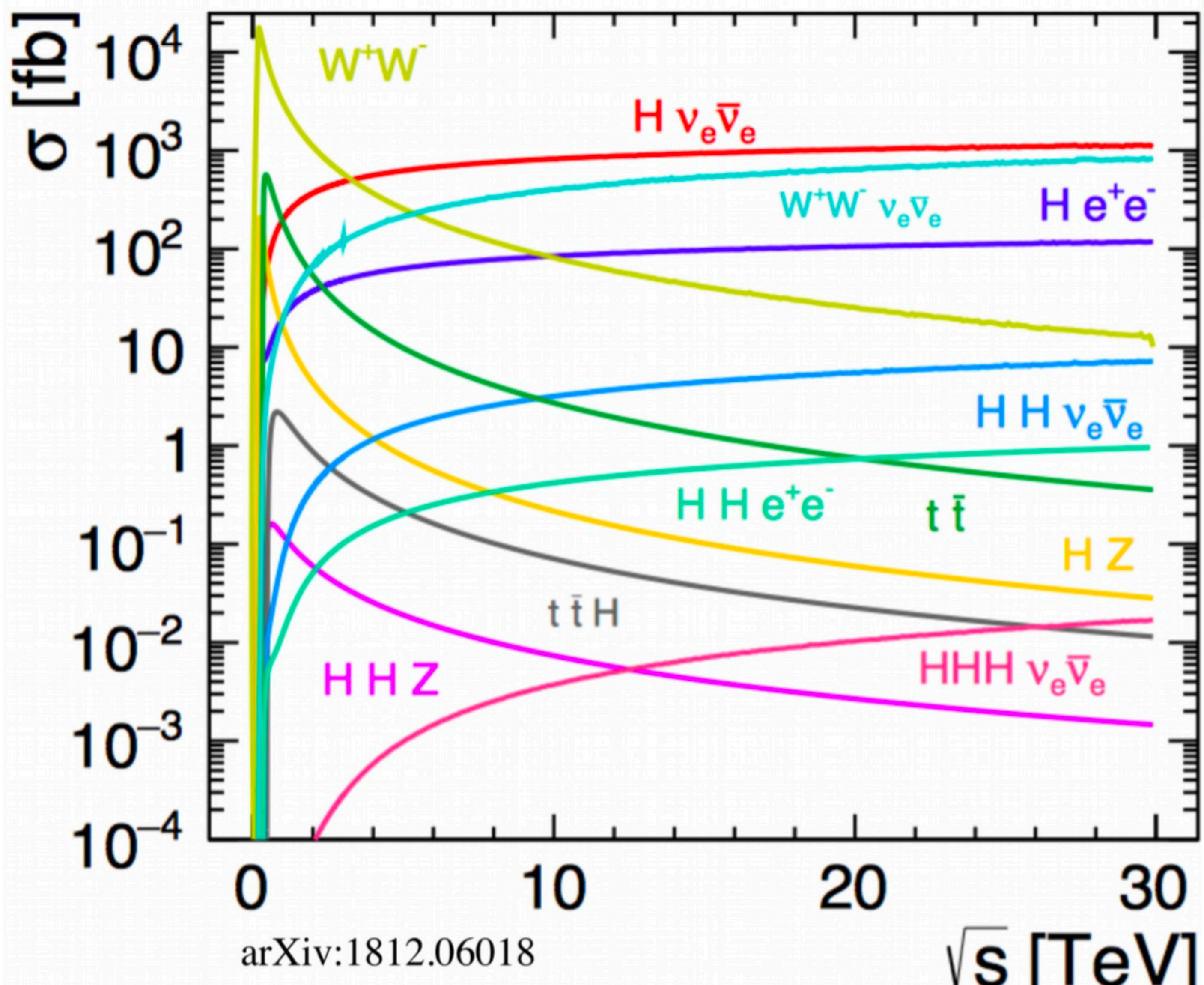
Always a trade off between mass reach and coupling strength (energy vs lumi/background)

If we did discover something like this at the LHC e^+e^- couldn't study it (directly)….

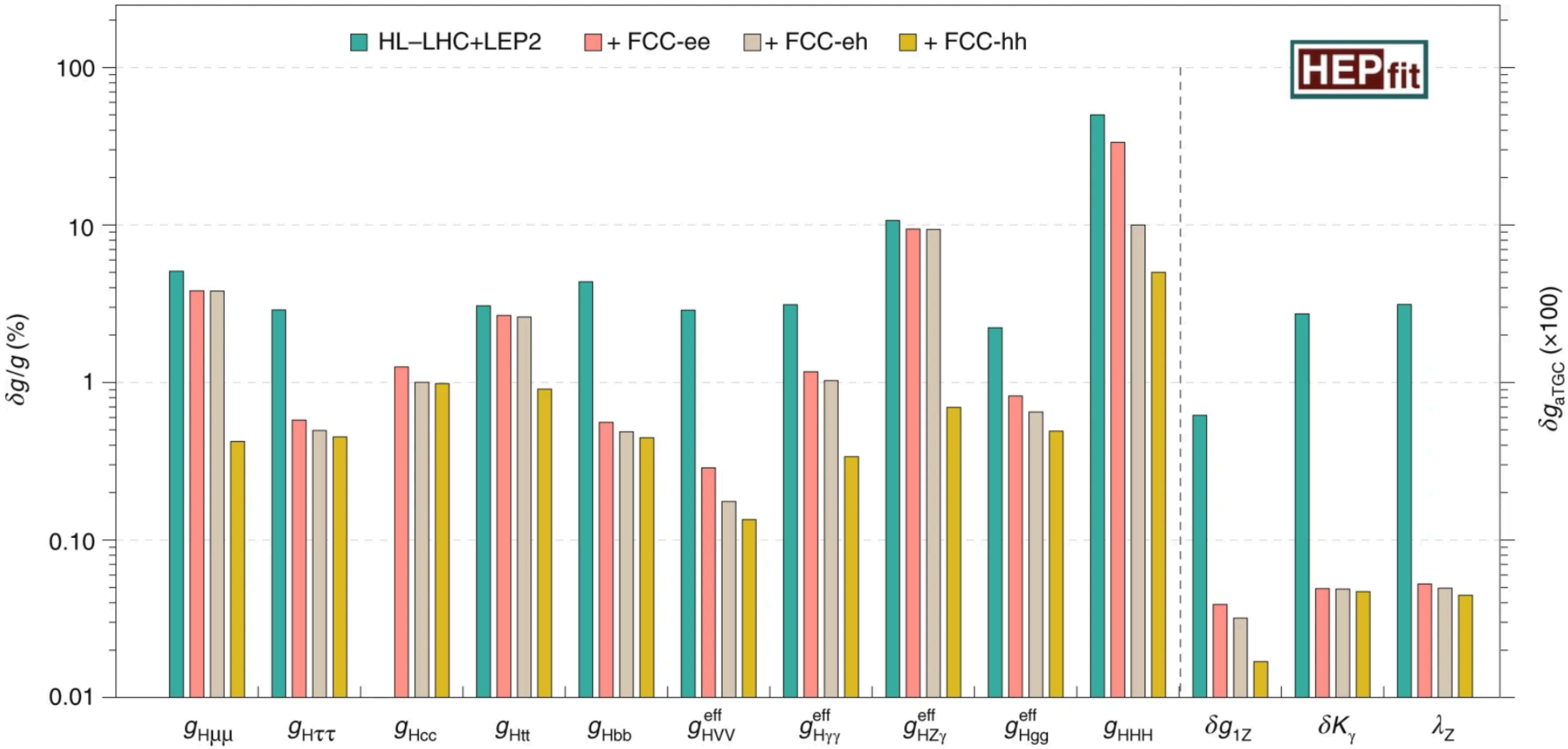
Backup

Lepton collider X-sections

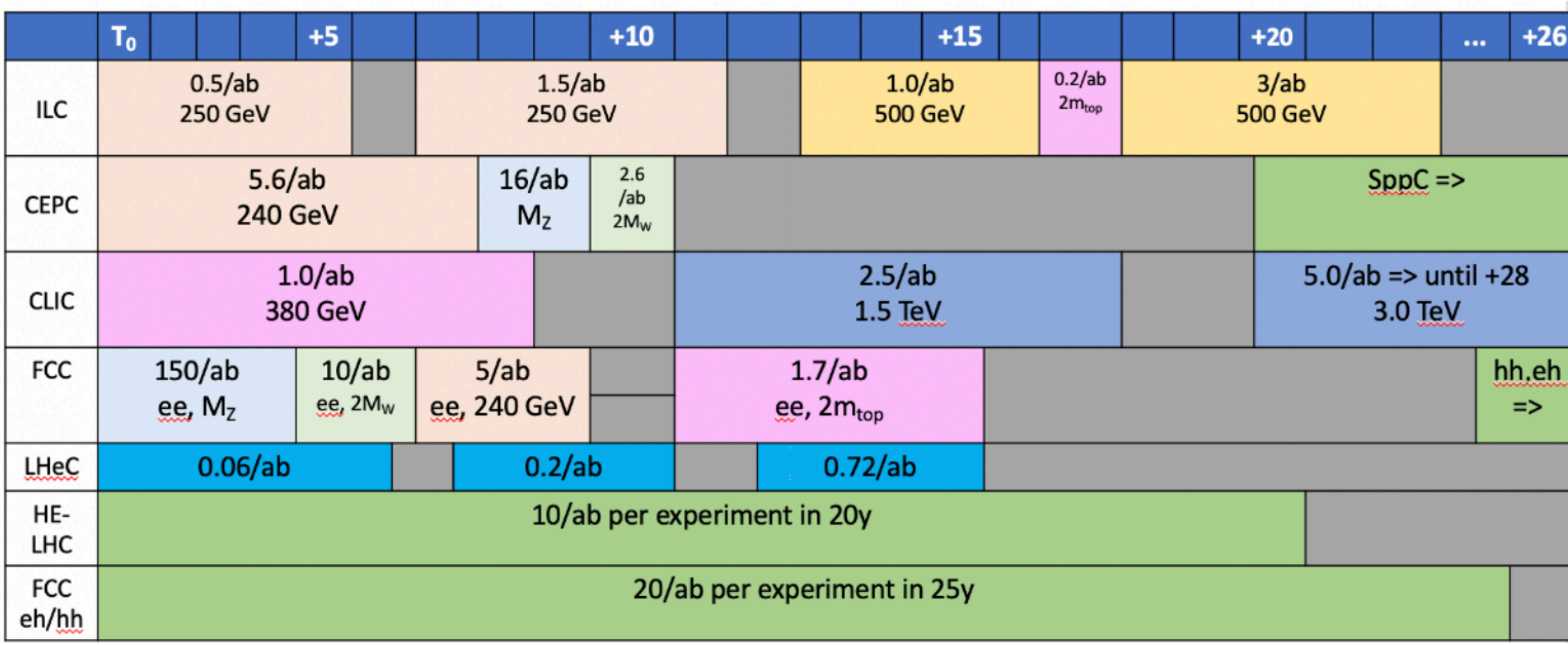
WW-scattering at high Energies can probe dynamics of the EWK sector



Higgs/EWK couplings



Timelines



T_0
+5
+10
+15
+20
...
+26
ILC
0.5/ab 250 GeV
1.5/ab 250 GeV
1.0/ab 500 GeV
0.2/ab $2m_{top}$
3/ab 500 GeV
CEPC
5.6/ab 240 GeV
16/ab M_Z
2.6 /ab $2M_W$
SppC =>
CLIC
1.0/ab 380 GeV
2.5/ab 1.5 TeV
5.0/ab => until +28 3.0 TeV
FCC
150/ab ee, M_Z
10/ab ee, $2M_W$
5/ab ee, 240 GeV
1.7/ab ee, $2m_{top}$
hh,eh =>
LHeC
0.06/ab
0.2/ab
0.72/ab
HE-LHC
10/ab per experiment in 20y
FCC eh/hh
20/ab per experiment in 25y

Comparison table (alone)

JHEP01(2020)139

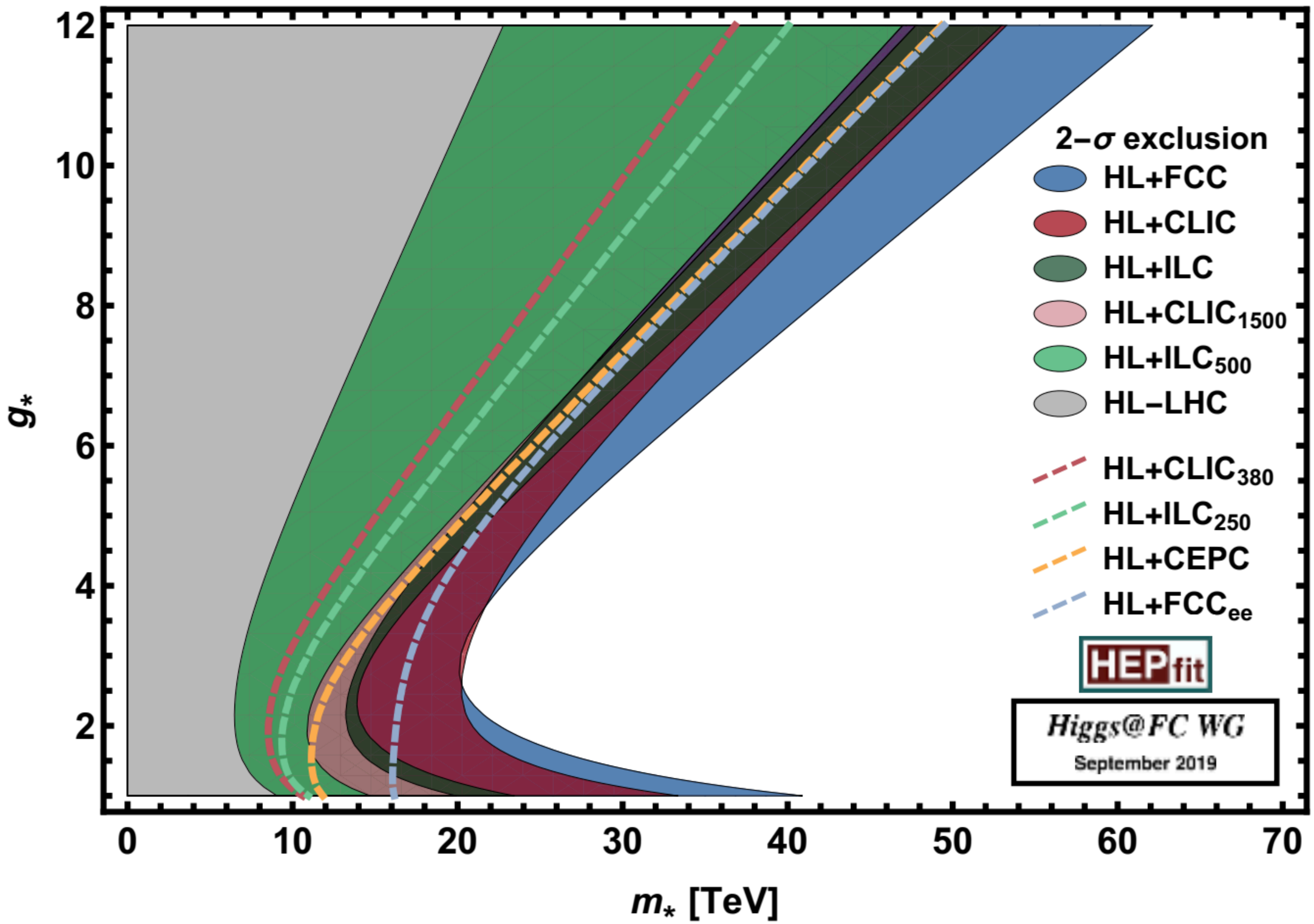
kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

Comparison table (+HL-LHC)

JHEP01(2020)139

kappa-3	HL-LHC & ILC$_{250}$	ILC$_{500}$	ILC$_{1000}$	CLIC$_{380}$	CLIC$_{1500}$	CLIC$_{3000}$	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
κ_W [%]	1.0	0.29	0.24	0.73	0.40	0.38	0.88	0.88	0.41	0.19
κ_Z[%]	0.29	0.22	0.23	0.44	0.40	0.39	0.18	0.20	0.17	0.16
κ_g[%]	1.4	0.85	0.63	1.5	1.1	0.86	1.	1.2	0.9	0.5
κ_γ [%]	1.4	1.2	1.1	1.4*	1.3	1.2	1.3	1.3	1.3	0.31
$\kappa_{Z\gamma}$ [%]	10.*	10.*	10.*	10.*	8.2	5.7	6.3	10.*	10.*	0.7
κ_c [%]	2.	1.2	0.9	4.1	1.9	1.4	2.	1.5	1.3	0.96
κ_t [%]	3.1	2.8	1.4	3.2	2.1	2.1	3.1	3.1	3.1	0.96
κ_b [%]	1.1	0.56	0.47	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ [%]	4.2	3.9	3.6	4.4*	4.1	3.5	3.9	4.	3.9	0.43
κ_τ [%]	1.1	0.64	0.54	1.4	1.0	0.82	0.91	0.94	0.66	0.46
BR$_{\text{inv}}$ (<%, 95% CL)	0.26	0.23	0.22	0.63	0.62	0.62	0.27	0.22	0.19	0.024
BR$_{\text{unt}}$ (<%, 95% CL)	1.8	1.4	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

NP scales



12
10
8
6
4
2
0
10
20
30
40
50
60
70
g_*
m_* [TeV]
2−σ exclusion
HL+FCC
HL+CLIC
HL+ILC
HL+CLIC1500
HL+ILC500
HL−LHC
HL+CLIC380
HL+ILC250
HL+CEPC
HL+FCCee
Higgs@FC WG
September 2019

Self-coupling vs X-section