"Higgs as a Portal for New Physics"
Community Planning Meeting
Snowmass 2021

Higgs and Flavors

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U.S. DEPARTMENT OF ENERGY
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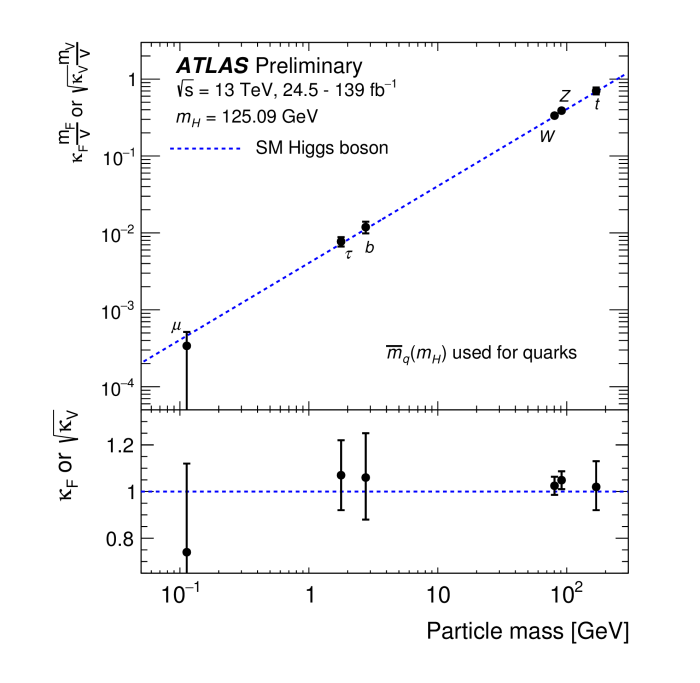
SLAC NATIONAL ACCELERATOR LABORATORY

The Experimental landscape

- We have **experimental proof that the SM Higgs boson exists**!
  - This opened a new research programme which constitutes a priority for the future of particle physics
    - Strongly connected with the programmes of **electroweak precision measurements** and **flavor physics**

- One of the most important points after the discovery: **Higgs boson couplings**
  - In the SM the **flavor structure** is **encoded** in the **Higgs couplings to the fermions**

ATLAS-CONF-2019-028, ATLAS-CONF-2019-005

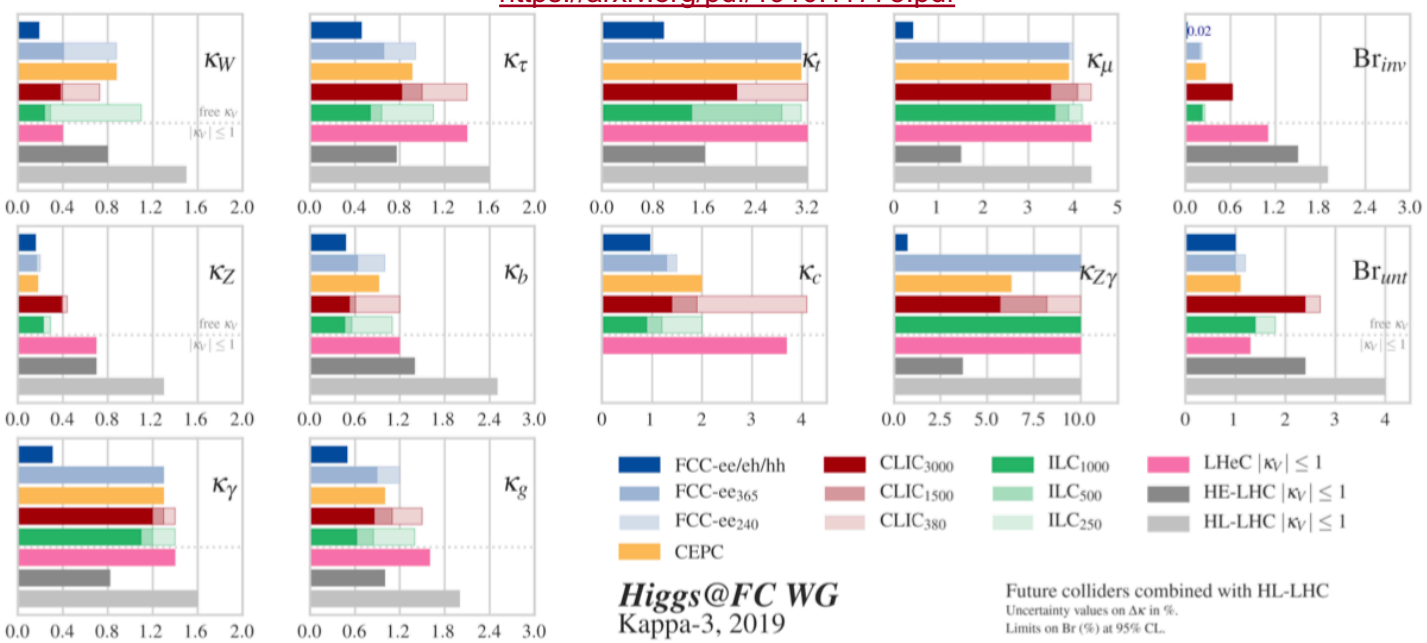


Available measurements follow the SM very well, but…

Higgs Boson Couplings

- **Yukawa coupling** of the SM Higgs boson **has been clearly established** at the LHC only up to the **third generation of fermions**
- ATLAS and CMS have recently reported **evidence that the Higgs boson decays into muons**
  - First experimental indication that the Higgs boson interacts with second-generation leptons
  - **Not yet a complete exploration of second-generation Yukawa couplings**
  - **Any deviations from SM predictions can give hints of new physics – H as a portal for new physics**
  - It is thus fundamental to **improve the accuracy of Higgs boson coupling determination**
    - **Future colliders can get to the 1% level or better** (typically 15% today)

https://arxiv.org/pdf/1910.11775.pdf



Higgs and Flavors: which ones?

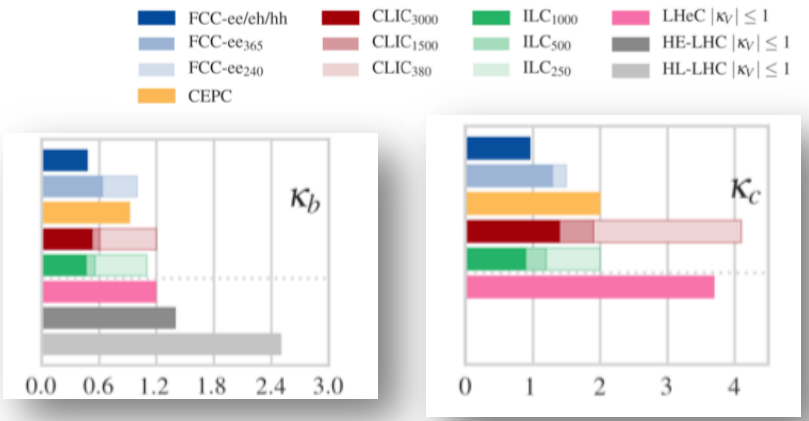
- **Higgs boson couplings to top-quarks**
  - **Not much difference between HL-LHC and e+e- machines (low $\sqrt{s}$)**

- **Higgs boson couplings to b-quarks**
  - **~ 2% at HL-LHC**
  - **~ 0.5-1% in future e^+e^- machines**
    - a factor of 2−4 better than at the HL-LHC

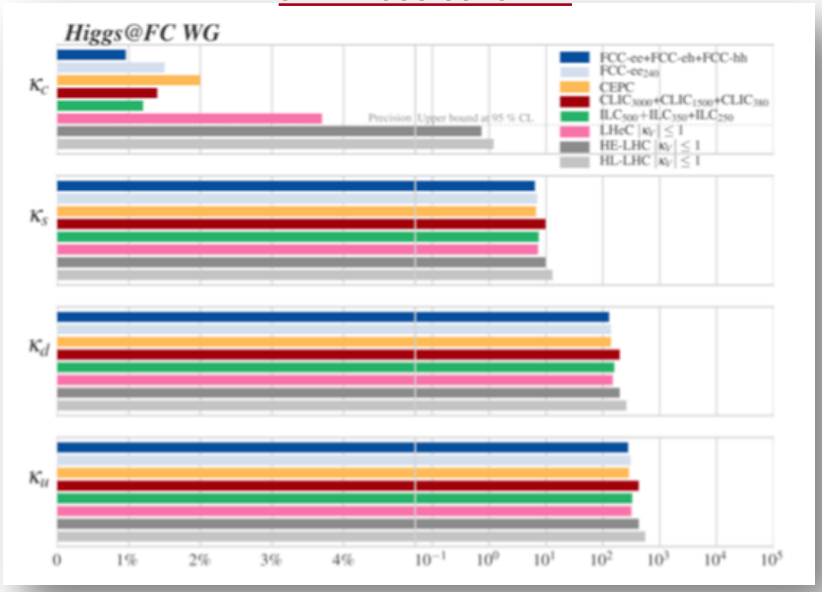
- **Higgs boson couplings to c-quarks**
  - Not easily accessible at HL-LHC
  - Expected to be measured with an accuracy of **~1% in future e^+e^- machines**

- **Higgs boson couplings to light-quarks**
  - **Only upper bounds**

- **What about leptons?**
  - **Factor of 2 improvement in accuracy for tau, ~4% level for muon at HL-LHC, ~5-y run at FCC-ee needed to reach sensitivity to electron coupling**



arXiv:1905.03764v2



Discussion Points

- **Light Flavors u/d/s:** the missing pieces in the (quark) Yukawa Couplings picture
  - **Can we tag strange quark jets?**
    - At which machine?
    - What are the implications on detector design? Is Cherenkov technology the only chance to get high momentum PID? What can timing information give us?
  - Are the $\boldsymbol{H \to V\gamma}$ **exclusive decays** the only accessible direct probe of the **u and d Yukawa** couplings? What would they bring to strange Yukawa coupling tests?
  - Should we focus only on light Yukawa from single Higgs analyses, or can we learn more by also looking at this in **HH production**?

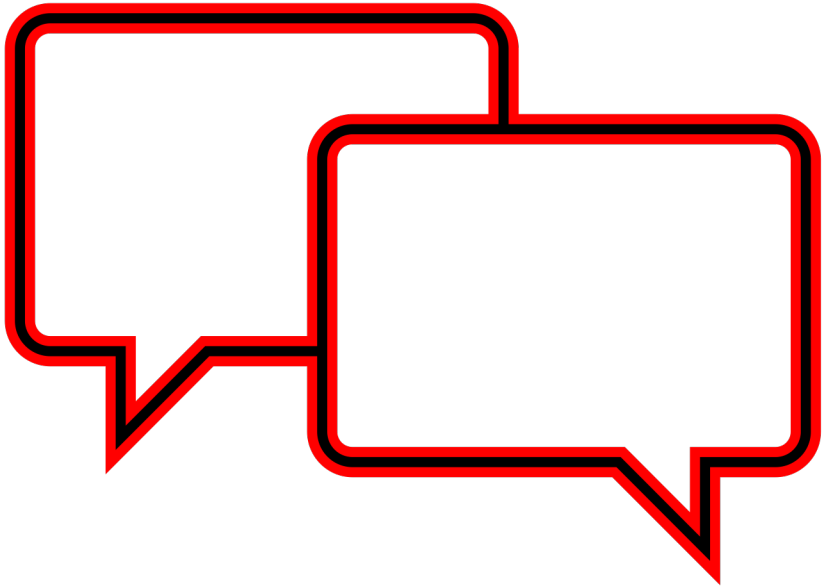
- **Heavy Flavors b** (very well advanced) **& c** (in progress)
  - b-tagging uses advanced **ML** techniques (also for double b-taggers, in large radius jets or boosted objects) and will exploit better resolution for **new trackers**
  - What about flavor-tagging in **trigger**?
  - Flavor-tagging algorithms mainly exploited in inclusive searches of direct decays $H \to b\bar{b}, c\bar{c}$, but what else can we learn from **exclusive decays** again? ($V = J/\psi \; or \; \Upsilon(1S)$)
    - Possible insights in the **sign of the coupling**

- **BSM Higgs**: interplay among flavors opens up and cross section increases dramatically
  - What promising models can be looked up experimentally?
    - 2HDM model as an example: neutral H from a $c\bar{c}$ initial state, charged H dominantly from a cs initial state
    - Interesting decay modes: $H/A \to cc, tc, \mu\mu, \tau\mu$ and $H\pm \to cb$(2nd and 3rd gen.), cs (c&s tagging), $\mu\nu$. What about bs?

- **$q/\bar{q}$ separation:** many interesting Higgs analyses could benefit from it to reduce combinatorial of multiple heavy quark jets e.g. $HH \to b\bar{b}b\bar{b}$. What experimental handles do we have?

- What about **Higgs polarization** through quarks?

- Lepton flavors: what about **Higgs to invisible**?



The big question(s)

Can we come with smart new ideas to probe Higgs and flavor?

Theory

- How can we built models that **violate the SM properties**?
- What **pattern of "partial" violation** can we have?

Experiment

- How can we **test** the (non-)universality of the **Yukawa couplings**?
- How can future **accelerators** complement each other (and HL-LHC)?
- What are the key requirements on **detector instrumentation**?

~Simultaneous results from HL-LHC and e^+e^- machines would allow to investigate better the scale of new physics and pose requirements on future machines

Some "suggestions" are in back-up, but we would very much like to hear your opinion!

Extra Slides

Discussion Points – light quarks

Light Flavors u/d/s:

- **Can we tag strange quark jets?**
  - **How do we identify strange hadrons than come from the original strange quarks and not from the fragmentation of other quarks?**
  - Lessons can be learned from the SLD experience in tagging strange jets from Z decays (Cherenkov detector with k/pi separation at all momenta)
- **At which machine? What are the implications on detector design?** Tracking ability for high pT K0s/Lambda (long flight path) needs dedicated attention (synergy with long-lived particle searches).
  - It can be comprised significantly with too few outer tracking layers in attempt to reduce material.
- How much would we need to give up on calorimetry in order to have a Cherenkov detector in place for PID?
- Given the current technology for timing detectors, what level of k/pi discrimination would we reach through velocity?

- Being looked at in Snowmass:
  - EF LoIs [StrangeQuark]
  - Somewhat related IF LoI [4D Tracking, PICOSEC]
  - Other studies [SegmentedCrystalCalorimetry, StrangeTagging,CouplingToStrange]

- Is this relevant in the context of **HH production** too? What would we gain by **studying light Yuwaka couplings in HH**?
  - https://indico.fnal.gov/event/44835/#2-probing-light-yukawa-couplin

- Theory of Enhanced Light Yukawa couplings:
  - https://indico.fnal.gov/event/44835/contributions/193558/attachments/132584/163022/200807_snowmass_ef02_sfv_homiller_nobuilds.pdf

Discussion Points – b/c quarks

arXiv:1306.5770v2
arXiv:1505.066889v2
Jet-Flavor Tagging

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- **b-tagging has reached great performance already at the LHC and a lot of efforts are being put into improving also c-tagging techniques**
  - Advanced ML techniques being exploited (GNN) also for double-b taggers
  - New trackers with improved resolutions will certainly play a big role
  - b-tagging in HLT can use re-optimized tracking and PV finding (usage of GPUs can help speed up ML algorithms)
  - ML algorithms in FPGA firmware for L1 trigger may also become a reality already at HL-LHC
  - How can SM measurements, such us Z/W+b/c (and ratios) help in constraining backgrounds?
- Being looked at in Snowmass:
  - EF LoIs [HiggsHadronicDecays, CharmInVBFAtLHC]
- but…

- The usage of these algorithms is mainly exploited in inclusive searches of direct decays $H \to b\bar{b}, c\bar{c}$, but Yukawa couplings can also be probed by looking for exclusive decays, for instance a $c\bar{c}$ vector meson and a photon

- *"Measurements of the $Hc\bar{c}$ and $Hb\bar{b}$ couplings via the direct decays $H \to b\bar{b}, c\bar{c}$ leave the overall signs of the couplings undetermined. This ambiguity is resolved by the interference that is present in $H \to V\gamma$ (where $V = J/\psi$ or $\Upsilon(1S)$), providing us with important additional information about the properties of the Higgs."*

- Similar experimental approach as $H \to Z\gamma$ searches
  - single-lepton, di-lepton or lepton-plus-photon triggers
  - high-pT photon recoiling against a lepton-antilepton pair from the V decay
  - The vector quarkonium state will be highly boosted, causing the two leptons to be close to each other in angle, with their momenta transverse to the boost axis anti-correlated

Discussion Points – exclusive decays

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- Exclusive Higgs decays to a vector meson and a photon are not only useful for b/c couplings, but in general $H \to V\gamma, V = \rho, \omega, \varphi, J/\psi, \Upsilon$ directly probe the Higgs bottom, charm strange, down and up quark Yukawas.

- Within the LHC, the Higgs exclusive decays are the only direct probe of the u and d Yukawa couplings, while if s-tagging could be implemented at the LHC, then the strange Yukawa could be probed both inclusively and exclusively.

- On the experimental side, both ATLAS and CMS have reported upper bounds on $H \to J/\psi\gamma$, $H \to \varphi\gamma$ and $h \to \rho\gamma$
- These processes receive contributions from two amplitudes, only one of which is proportional to the Yukawa coupling

- Since the contribution proportional to the Yukawa is smaller, the largest sensitivity to the Higgs q-quark coupling is via the interference between the two diagrams.

- **The prospects for probing light quark Yukawas within future LHC runs employing the direct probe from exclusive decays are not competitive with indirect limits that can be set from production or global fit or inclusive search for c-Yukawa.**
  - However, the information coming from **exclusive decays will be relevant regardless of the global fit sensitivity**. For example, a limit of $|ys/yb| \lesssim 50$ could be set at HL-LHC and $ys/yb \lesssim 25$ at FCC-hh.

Discussion Points – exclusive decays

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- More specifically for Yukawa coupling to strange:
  - Focus would be on exclusive $\boldsymbol{H} \rightarrow \boldsymbol{\phi} + \boldsymbol{\gamma}$ decay, rather than the full h->ssbar with jet reconstruction
    - One expects a handful of such rare decay events with the ~1.5 million Higgs expected at the **FCC-ee**
    - This direct decay interferes with the (more probable) $\mathbf{H} \rightarrow \boldsymbol{\gamma\gamma}^{*} \rightarrow \boldsymbol{\phi\gamma}$ **channel**, and one needs to disentangle the dependence of the yields on k_gamma and k_s (the k_gamma coupling should be known with good accuracy...).
    - We need to take a closer look at it and try to estimate the actual sensitivity to k_s
    - If potentially relevant a simulation analysis can be carried out

Discussion Points – q vs $\bar{q}$

Stolen from Su Dong's Heavy-quark Tagging

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- Many interesting Higgs analyses could benefit from $q/\bar{q}$ separation to reduce combinatorial of multiple heavy quark jets e.g.
  - $HH \rightarrow b\bar{b}b\bar{b}$ has a 4 b-jet final state
    - HH benchmarks discussed during an EF1+EF2 meeting
      - (https://indico.fnal.gov/event/44932/contributions/196379/attachments/134130/166221/qq-dihiggs-benchmark.pdf)
  - $ttH(b\bar{b})$ has 4 b jets and some W $\rightarrow \bar{c}s$ jets

- EW production asymmetries and spin analysis mostly requires $q/\bar{q}$ separation

- CP violation in Higgs sector?

- What handles do we have for $q/\bar{q}$ separation?
  - Semi-leptonic decays to charged leptons – low BR
  - Jet charge – low analyzing power
  - Vertex charge to separate B+/B-
  - Vertex charge dipole $b \rightarrow W^{-}c$ vs $\bar{b} \rightarrow W^{+} + \bar{c}$
  - $b \rightarrow c \rightarrow s(K^{-})$ vs $\bar{b} \rightarrow \bar{c} \rightarrow \bar{s}\ (K^{+})$

Discussion Points – flavor violating decays

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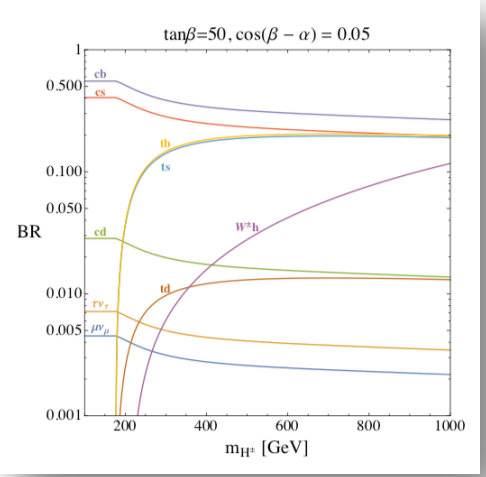
Flavorful Higgs



When considering **BSM models**, the interplay among couplings opens up

- **2 Higgs Doublet Model (2HDM) as an example**: one doublet (approximately the 125 GeV H) couples mainly to the 3rd generation, while second doublet couples mainly to 1st and 2nd generation
  - Largest production mode of the neutral H from a $c\bar{c}$ initial state, charged H dominantly from a cs initial state
  - Most interesting decay modes: $H/A \to cc, tc, \mu\mu, \tau\mu$ and $H\pm \to cb$, $\boldsymbol{cs}$ (complementarity between s&c-tag – need only one leg s-tag), $\mu\nu$.
  - What other promising models?

Experimental capabilities of tagging b/c/s are of paramount importance for mapping out the Higgs-Flavor puzzle!

- **Complementarity offered by future colliders**
  - LHC and future hadron colliders
    - h(125)->μμ, μt
    - Flavor violating decays of t->hc
    - First detection of heavy H/A through flavor conserving/violating modes with c-tagging
  - e+e- Higgs factories
    - Best sensitivity for h(125)->cc
  - Higher energy e+e- linear collider
    - Clean measurements of varieties of H/A (if reachable) production and decays to illuminate the Higgs/fermion generation hierarchy

Discussion Points – others

- What about Higgs to invisible?
  - Being looked at in Snowmass:
    - EF LoIs [ILC/SiD, FCC-ee]

- What about $t\bar{t}HH$?
  - Large deviations would already be excluded by ttH (need to take into account a combined analysis)
  - Being looked at in Snowmass:
    - EF LoIs [HL-LHC]

- What about Higgs polarization through quarks?
  - Inspired by arXiv:1505.02771v2
  - In this paper, while challenging, it is shown that the polarization of b and c quarks can also be measured at the LHC, despite hadronization
  - Knowing how to extract the b-quark polarization could facilitate a variety of interesting measurements.
    - In $H \to b\bar{b}$ decays one could examine whether the Higgs coupling to b quarks has a CP-violating component $h\bar{b}\gamma^5 b$, in analogy to the $h \to \tau^+\tau^-$case

Cross-sections

B Theoretical Cross Sections and Partial Width Uncertainties

Table 18. Cross sections for the main production channels expected for Higgs boson production at the different types of colliders (as defined in Table 1).

pp collider	Cross Section σ [pb] Total	ggH	VBF	WH	ZH	$t\bar{t}H$	tH	$ggHH$
LHC (13 TeV)	56	48.6	3.77	1.36	0.88	0.510	0.074	0.031
HL-LHC	62	54.7	4.26	1.50	0.99	0.613	0.090	0.037
HE-LHC	168	147	11.8	3.40	2.47	2.86	0.418	0.140
FCC_{hh}	936	802	69	15.7	11.4	32.1	4.70	1.22

e^+e^- collider ($\mathscr{P}_{e^-}/\mathscr{P}_{e^+}$)	Cross Section σ [fb] Total	VBF CC/NC	ZH	$t\bar{t}H$	ZHH (CC VBF)
CEPC	199	6.19/0.28	192.6		
FCC-ee	199	6.19/0.28	192.6		
ILC_{250} (-80/30)	313	15.4/0.70	297		
ILC_{500} (-80/30)	262	158/7.8	96	0.41	0.2
$CLIC_{380}$ (0/0)	160	40/7.4	113	–	0.029 (0.0020)
$CLIC_{1500}$(0/0)	329	290/30	7.5	1.3	0.082 (0.207)
$CLIC_{3000}$(0/0)	532	480/49	2	0.48	0.037 (0.77)
$CLIC_{380}$ (-80/0)	209	68/8.7	133	–	0.034 (0.0024)
$CLIC_{1500}$(-80/0)	574	528/35	8.8	1.70	0.97 (0.37)
$CLIC_{3000}$(-80/0)	921	860/57	2.4	0.61	0.043 (1.38)
$CLIC_{380}$ (+80/0)	112	13/6.0	93	–	0.024 (0.0016)
$CLIC_{1500}$(+80/0)	91	59/24	6.2	0.89	0.068 (0.045)
$CLIC_{3000}$(+80/0)	138	96/40	1.7	0.34	0.30 (1.56)

e^-p collider ($\mathscr{P}_{e^-}$)	Cross Section σ [fb] Total	VBF CC/NC	tH	HH (CC VBF)
LHeC (0)	130	110/20	0.07	0.01
HE-LHeC (0)	247	206/41	0.37	0.04
FCC_{eh} (0)	674	547/127	4.2	0.26
LHeC (-80)	221	197/24	0.12	0.02
HE-LHeC (-80)	420	372/48	0.67	0.07
FCC_{eh} (-80)	1189	1040/149	7.6	0.47

Timeline

https://indico.fnal.gov/event/24264/contributions/75978/attachments/128521/155690/Energy-Frontier-Kick-off-meeting.pdf