Higgs Working Group Snowmass

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Princeton University

Sep 22 2021

Overview

Snowmass Process: *

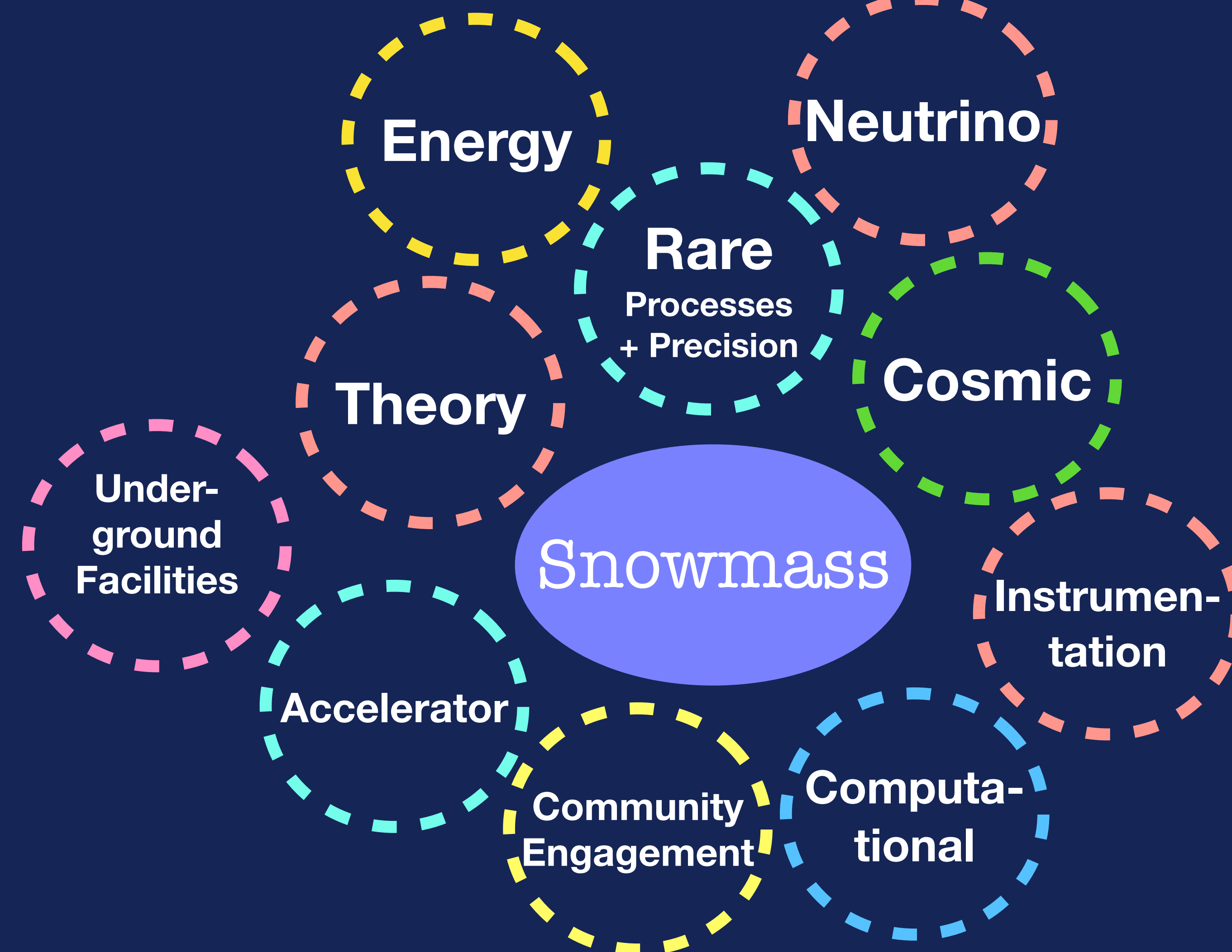
APS Division of Particles and Fields

Particle Physics Community Planning Exercise

Snowmass 2013

P5 (Particle Physics Project Prioritization Panel)

Takes the scientific input and develop a Strategic plan for the US - executed over 10 year timescale in the context of a “**20-year vision for the field**”



Final Products:

Snowmass report

Higgs/Higgs BSM working groups

- Outline the Big Questions
- Create Summary plots

Timeline:

(More on next slide)

Higgs, Higgs BSM working group meetings

Wednesday 12-2pm Indico

Pause due to Covid Pandemic

January 2021 - September 2021

Snowmass Summer Study - July 2022 UW Seattle

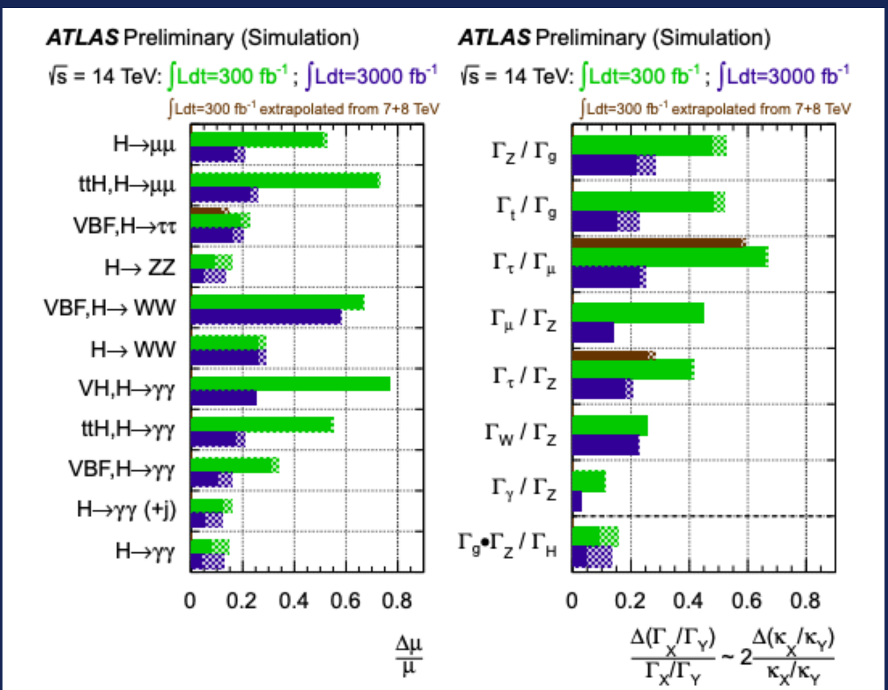


Figure 2.10: (a) Expected measurement precision on the signal strength in a selection of channels for 300 fb^{-1} and 3000 fb^{-1}. (b) Expected precisions on ratios of Higgs boson partial widths. In both figures the bars give the expected relative uncertainty for a SM Higgs with mass 125 GeV (dashed are current theory uncertainty from QCD scale and PDFs). The thin bars show extrapolations from current analysis to 300 fb^{-1}, instead of the dedicated studies for VBF channels.

Overview

Energy

Conveners:
Meenakshi Narain
Laura Reina
Alessandro Tricoli

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Topical Group	Co-Conveners
EF01: EW Physics: Higgs Boson properties and couplings	Sally Dawson (BNL), Andrey Korytov (U Florida), Caterina Vernieri (SLAC)
EF02: EW Physics: Higgs Boson as a portal to new physics	Patrick Meade (Stony Brook), Isobel Ojalvo (Princeton)
EF03: EW Physics: Heavy flavor and top quark physics	Reinhard Schwienhorst (MSU), Doreen Wackeroth (Buffalo)
EF04: EW Physics: EW Precision Physics and constraining new physics	Alberto Belloni (Maryland), Ayres Freitas (Pittsburgh), Junping Tian (Tokyo)
EF05: QCD and strong interactions:Precision QCD	Michael Begel (BNL), Stefan Hoeche (FNAL), Michael Schmitt (Northwestern)
EF06: QCD and strong interactions:Hadronic structure and forward QCD	Huey-Wen Lin (MSU), Pavel Nadolsky (SMU), Christophe Royon (Kansas)
EF07: QCD and strong interactions: Heavy Ions	Yen-Jie Lee (MIT), Swagato Mukherjee (BNL)
EF08: BSM: Model specific explorations	Jim Hirschauer (FNAL), Elliot Lipeles (UPenn), Nausheen Shah (Wayne State)
EF09: BSM: More general explorations	Tulika Bose (U Wisconsin-Madison), Zhen Liu (Maryland), Simone Griso (LBL)
EF10: BSM: Dark Matter at colliders	Caterina Doglioni (Lund), LianTao Wang (Chicago)

Motivations: The Higgs Boson is Special

The discovery of the Higgs in 2012 was an important milestone for HEP

- As far as we know, the Higgs has no spin, no charge, no structure
- It provides an exciting program for precision measurements and searches
- Many of us are still excited about it and others, especially scientists, should be excited about it!

"A self-interacting Higgs (as SM predicts) would be unlike anything yet seen in nature; all other interactions change particle identity" - N. Craig

Higgs

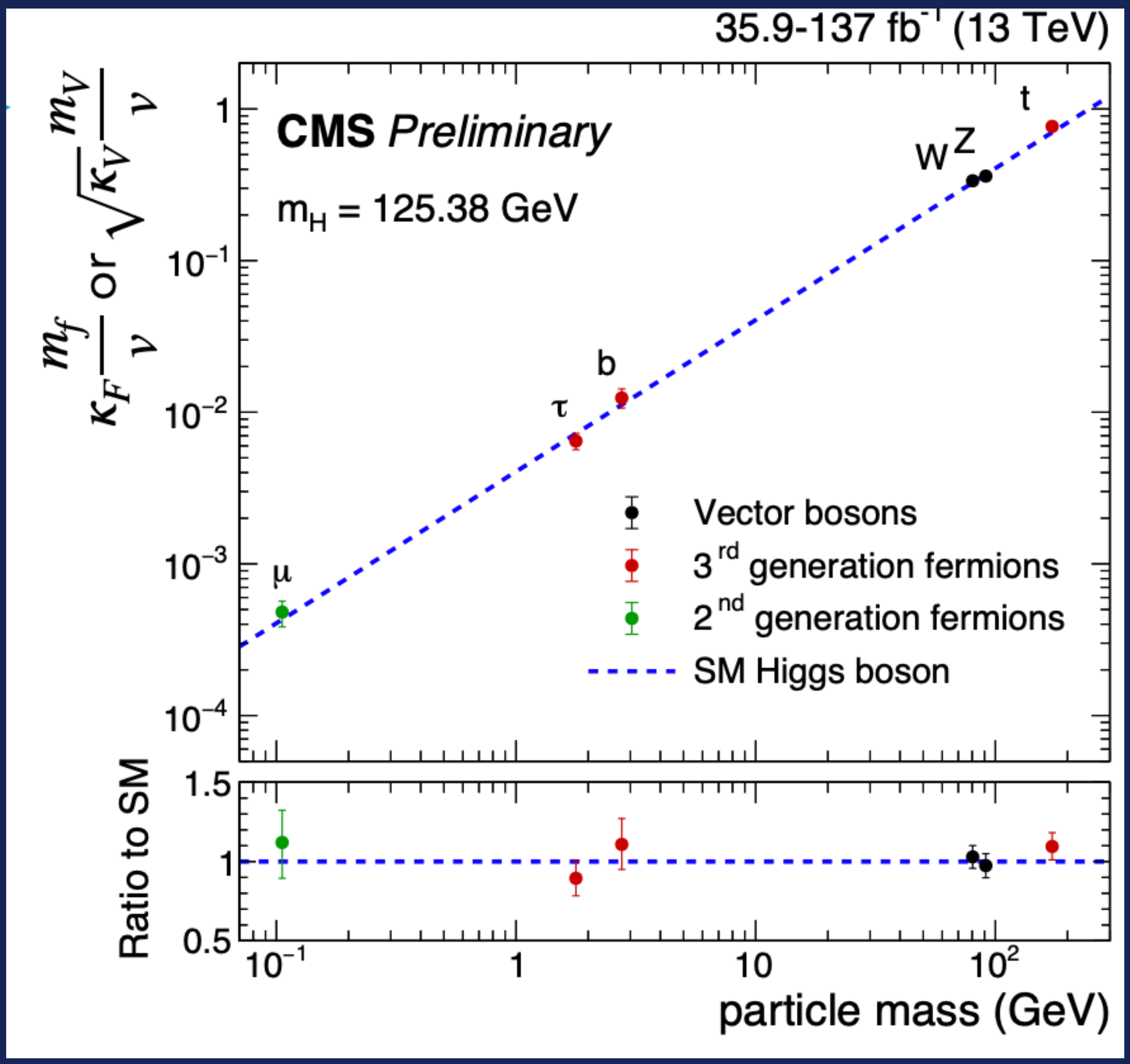
Precision measurements
- mass, width
- spin, CP, couplings
- off-shell coupling, width
- differential distributions

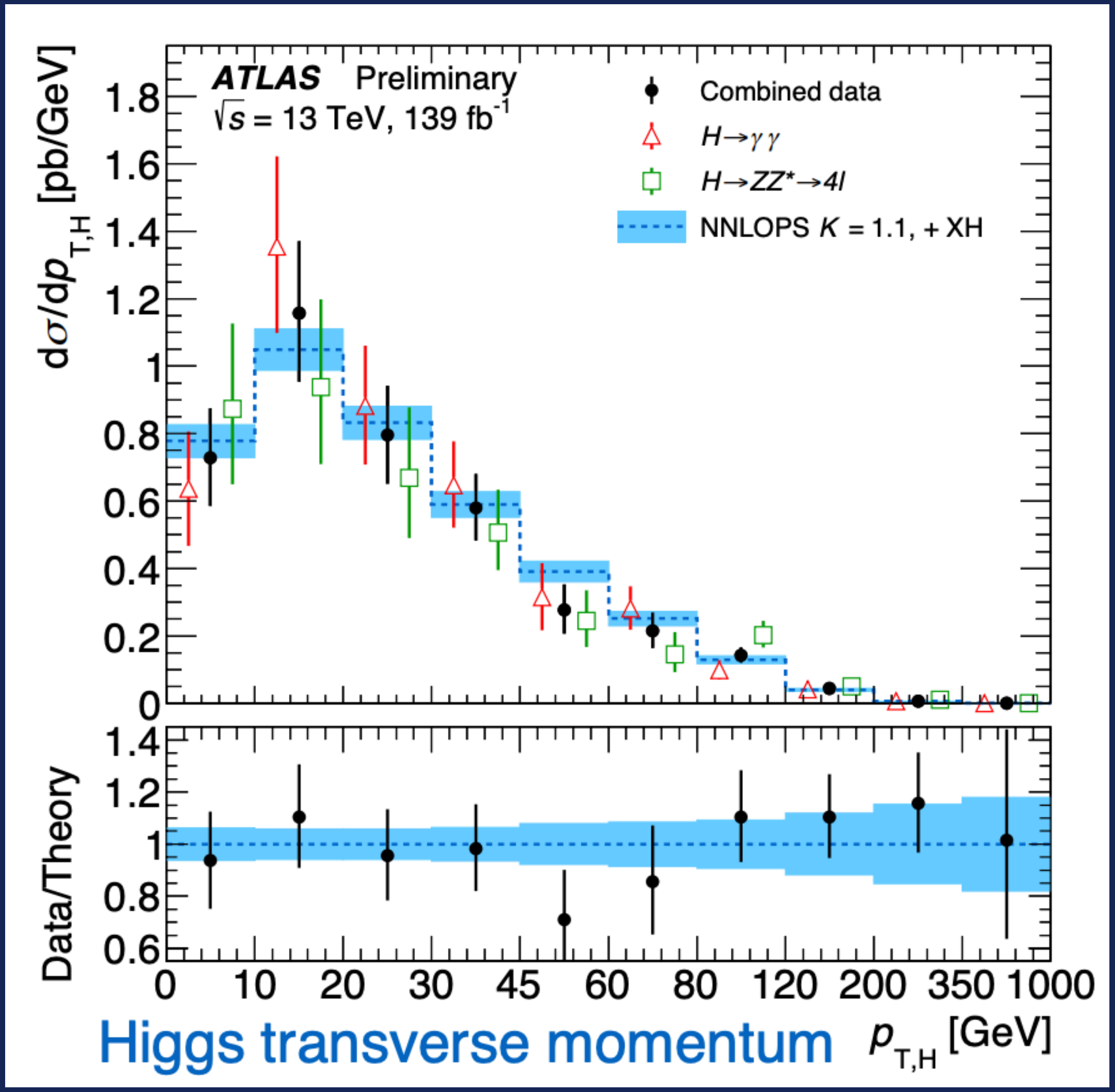
Tool for Discovery
- portal to BSM
- portal to hidden sector
- portal to DM

SM or BSM?
- Higgs Doublets
- Higgs Singlets
- Composite Higgs

Rare / beyond SM decays
- $H \to Z\gamma$
- $H \to \mu\mu$
- $H \to cc$
- $H \to \tau\mu, \tau e, e\mu$
- $H \to J/\Psi\gamma, \Upsilon\gamma$, ...

Where are we now?





Differential measurements in di-photon, ZZ, bb, etc.
Discovery of branching to 3rd generation fermions

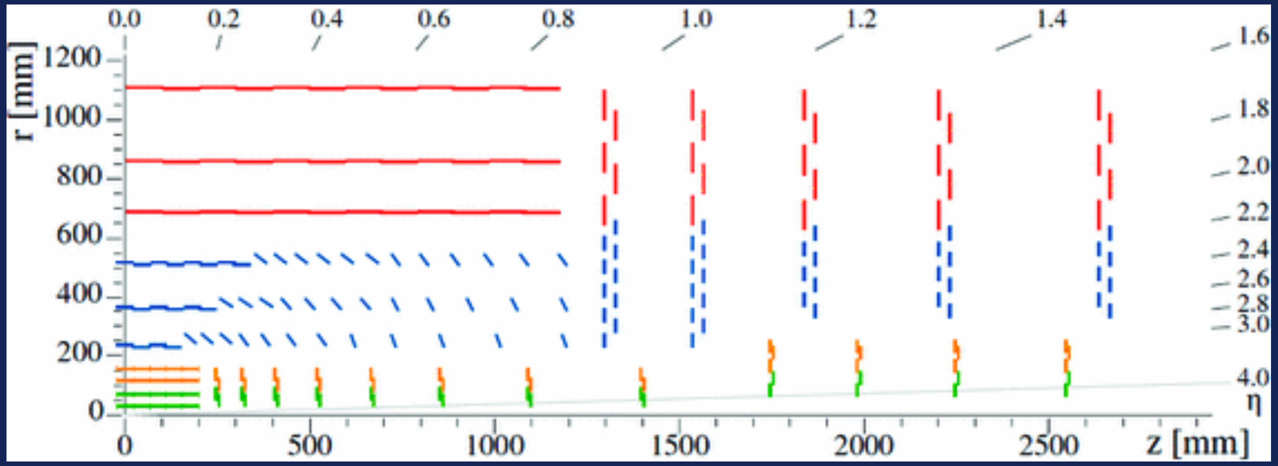
Where are we now?

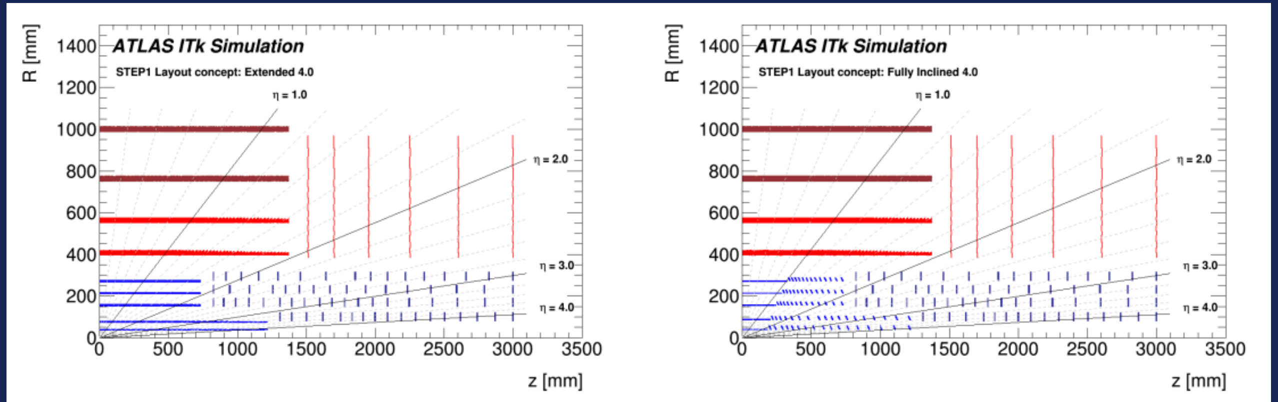
HL-LHC as a Higgs factory:

170M Higgs bosons - 120k HH pairs for 3 ab^{-1}

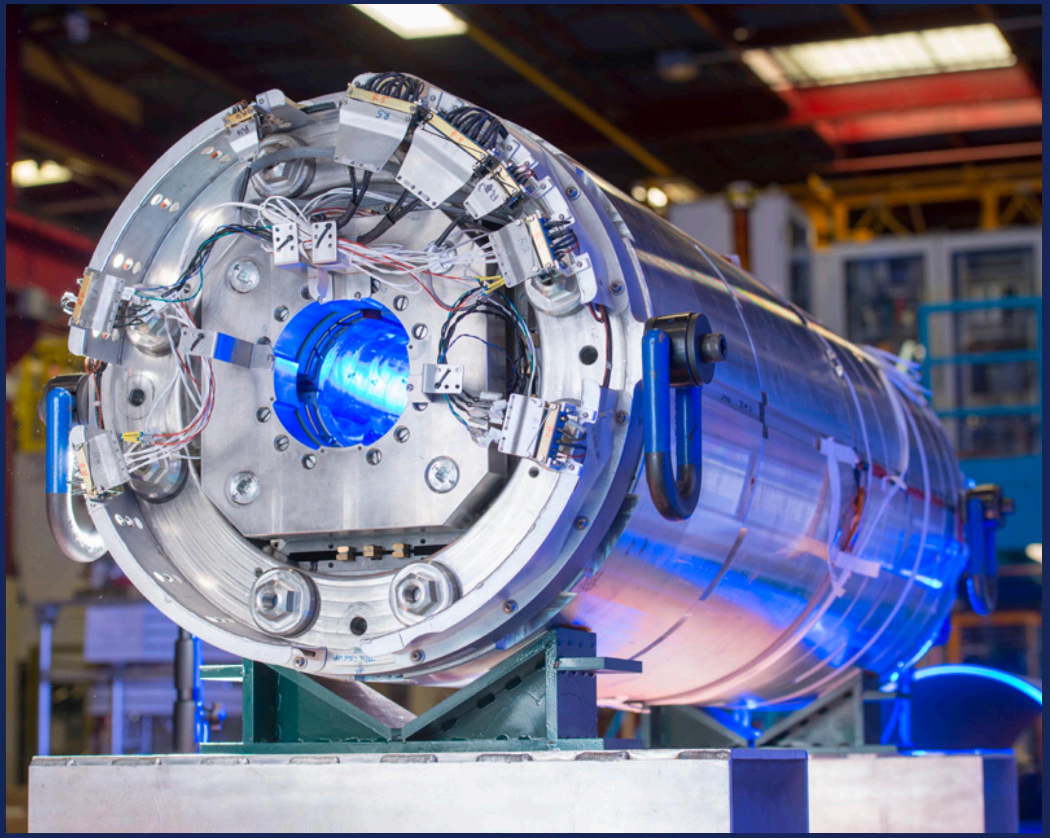
Where are we now?

Upgrade for Phase-2 CMS, ATLAS, and HL-LHC are well underway





(a) Extended - $\eta < |4|$ (b) Fully inclined - $\eta < |4|$



The HL-LHC as a Higgs factory:

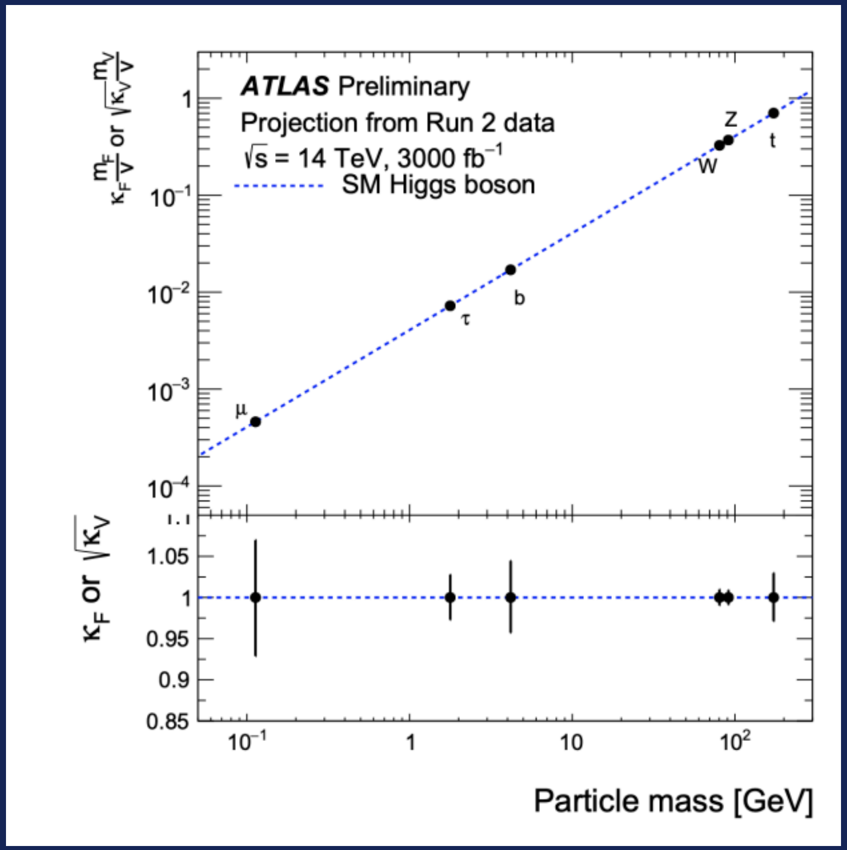
170M Higgs bosons - 120k HH pairs for 3 ab^{-1}

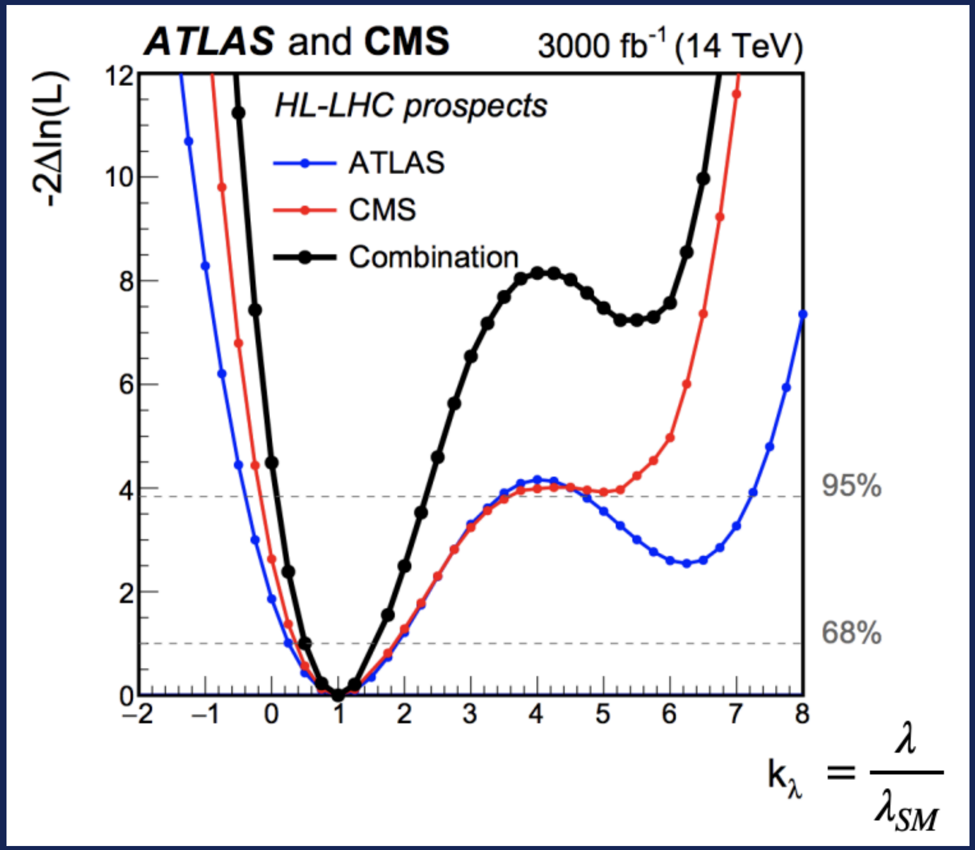
Where are we now?

1902.10229

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

- 2-4% precision for many of the Higgs couplings
- BUT much larger uncertainties on Z and charm and ~50% on the self-coupling

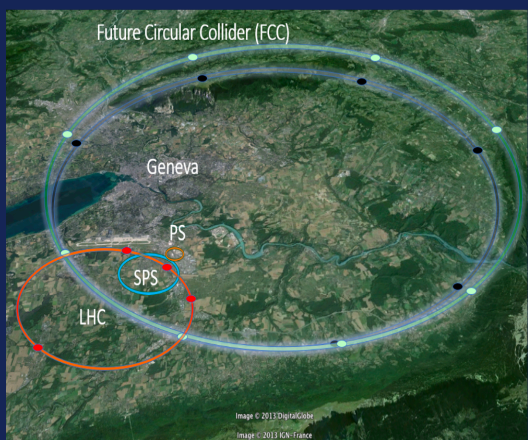




Which Machines?

Hadrons

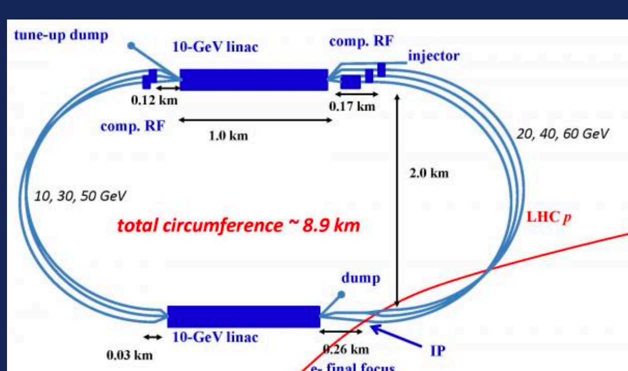
Leptons



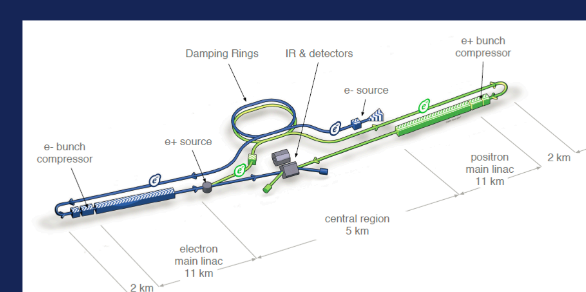
Discovery Machines
S/B ~10^{-10} w/o trigger
S/B ~0.1 with trigger
Divide CoM by partons
Stable particles
=> Quarks and Gluons

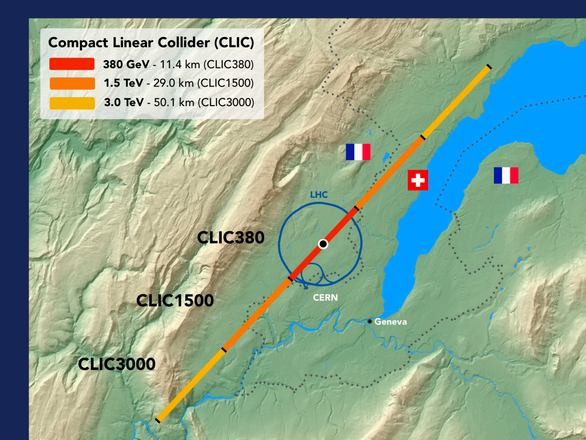
Large S/B
Polarized beams
EW couplings

Higher luminosities
Several interaction points
Limited by Synchroton radiation



Easier to polarize beams
One IP
Large Beamstrahlung





Circular

Linear

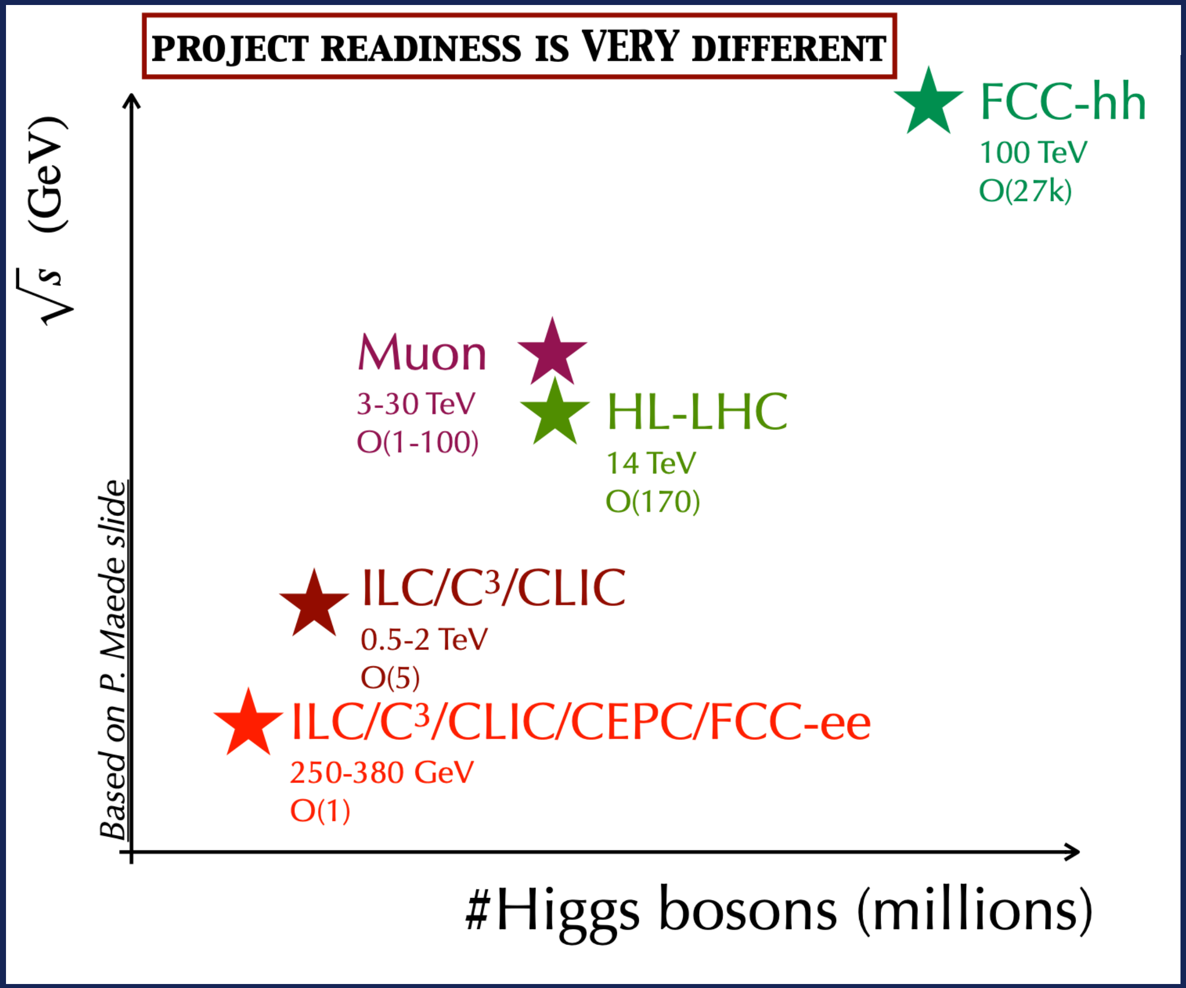
Higgs Production at Future Colliders

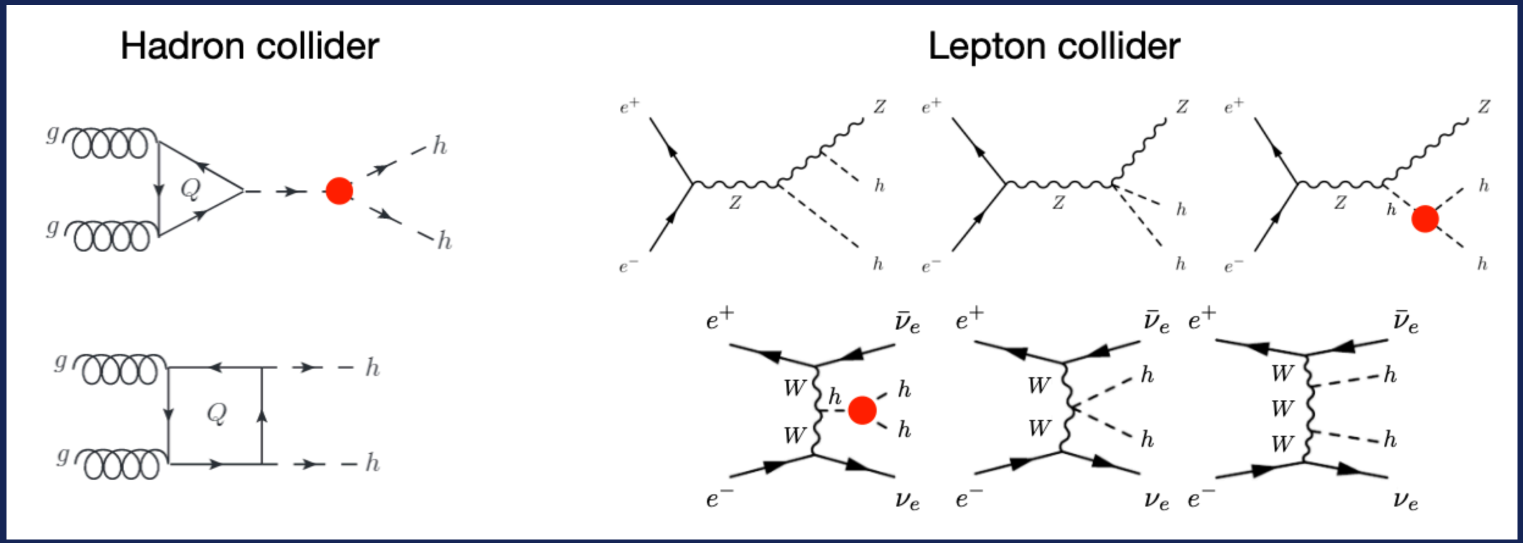
Lepton Colliders

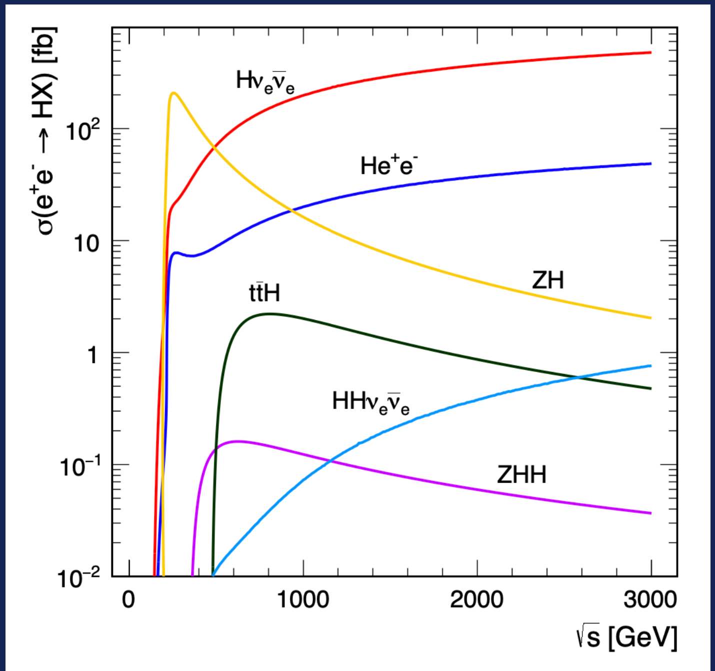
- e^+e^-
  - Circular (FCC-ee, CEPC)
    - 90-350 GeV
  - Linear (ILC, CLIC, C3)
    - 250 GeV - 3TeV
- $\mu^+\mu^-$
  - 125 GeV, 3 TeV, 10TeV+

Hadron Colliders

- 75-200 TeV (FCC-hh)







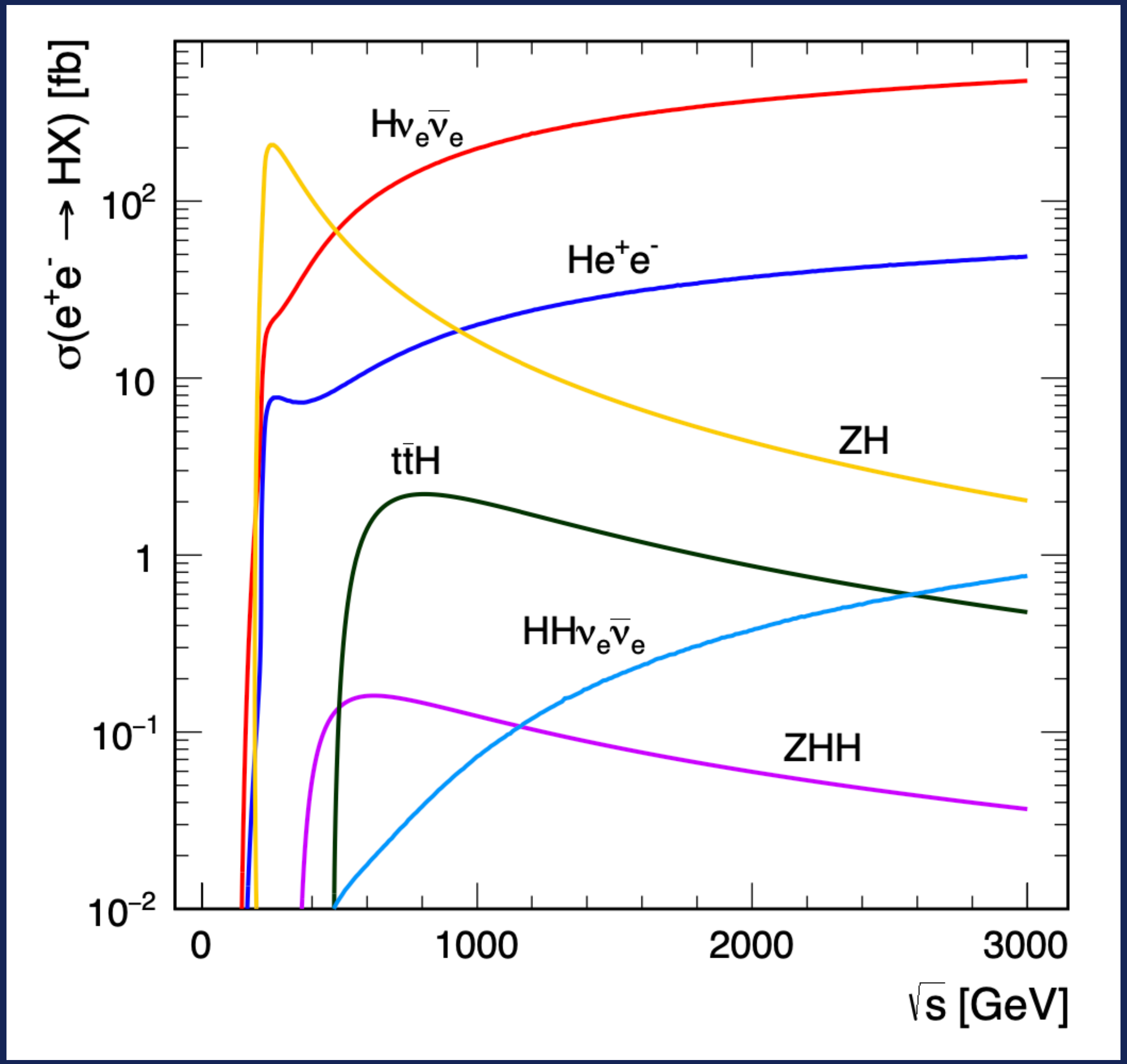
Higgs Production at e^+e^-

ZH is the dominant production mode above 250 GeV

The well defined initial states allows to tag the Higgs boson without looking into its decay with “recoil” technique

- Measurement of the inclusive ZH cross section at 0.5-1%
- Recoil technique observes all final state, including all invisible and exotic decay modes
- ZH is key for the determination of the absolute Higgs couplings

Clean environment for excellent b- and c-tagging (and beyond?) performance: bb/cc/gg separation

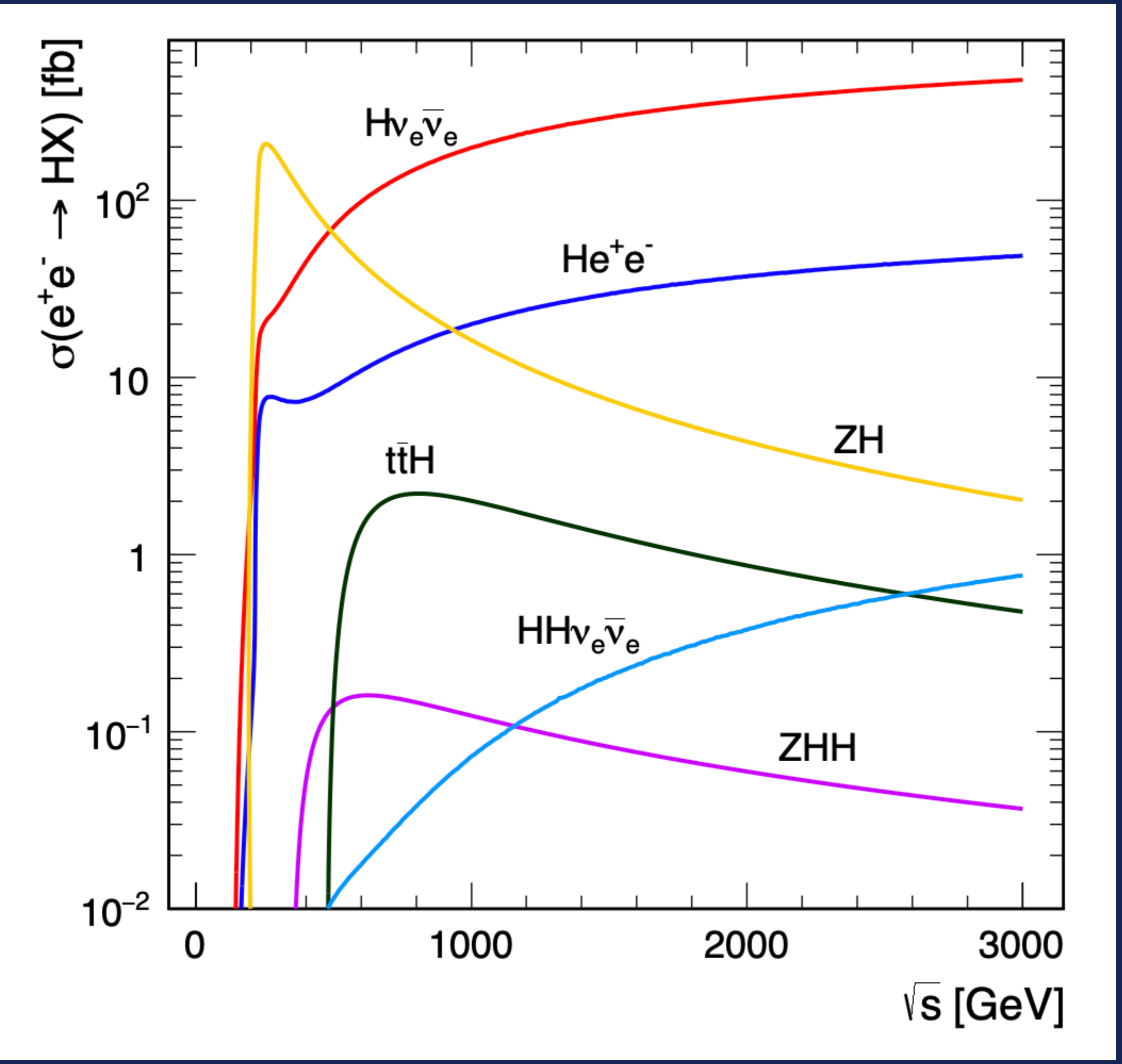


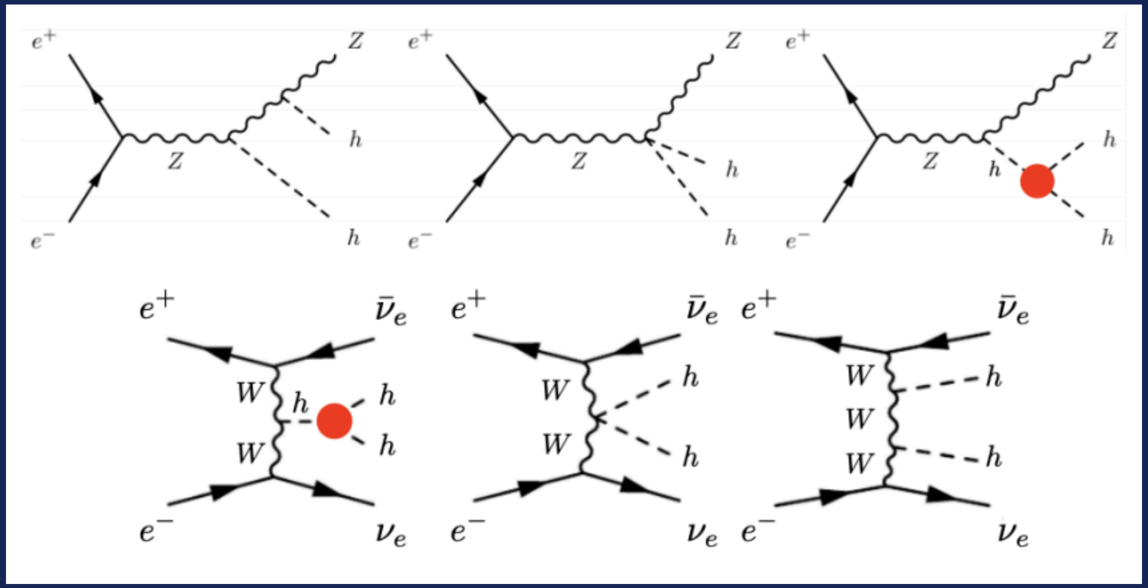
Higgs Production at e+e-

ttH can be probed at CoM energies above ~450 GeV

The self-coupling can be probed at e+e- through double Higgs with ZHH ~500GeV and ννHH ≥1TeV

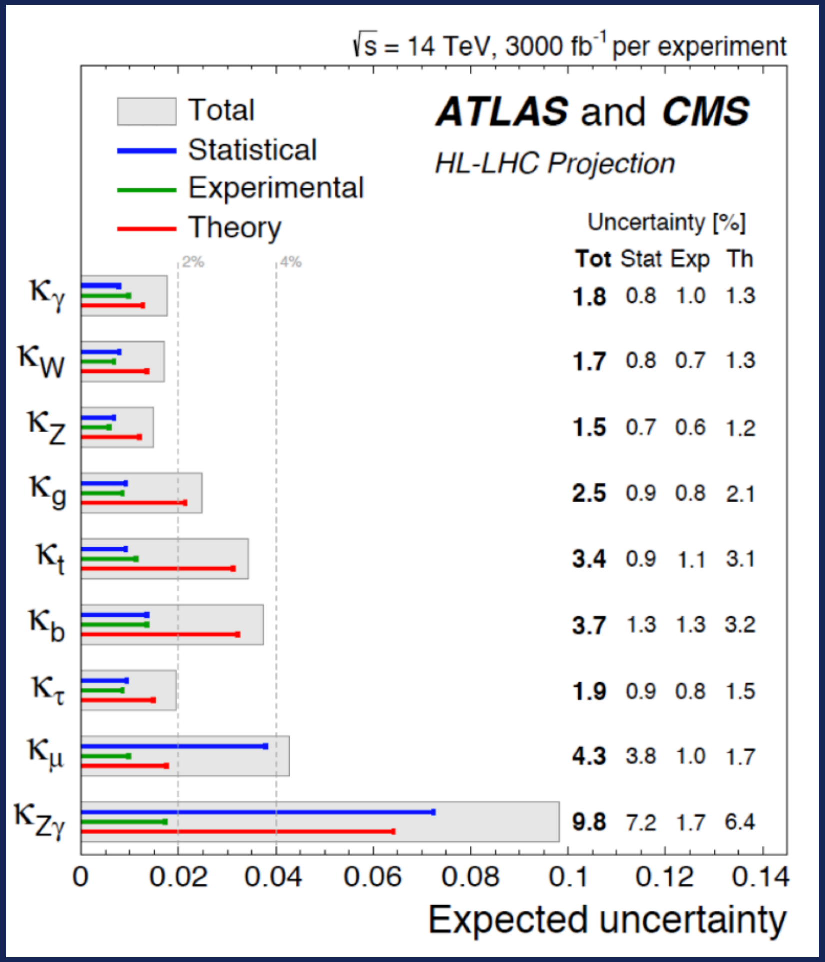
- The use of polarized beams could increase the cross-section by a factor ~2

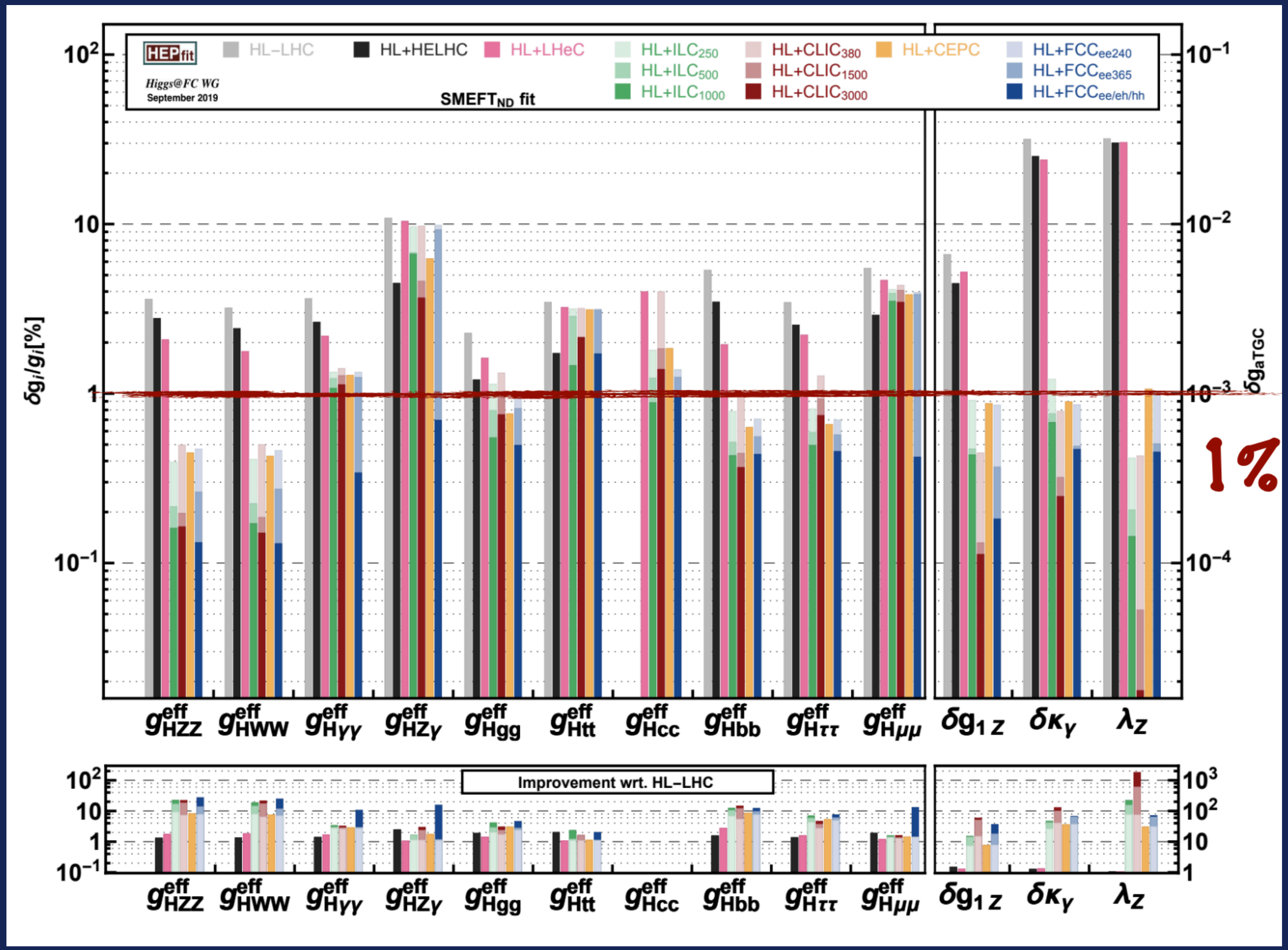




Higgs Couplings at Future Colliders

Future colliders under consideration will improve with respect to the HL-LHC the understanding of the Higgs boson couplings ~1-5%





Complementarity between HL-LHC and future colliders (depending on their timeline) will be the key to explore the Higgs sector

Higgs Self Coupling

arXiv:1910.00012

Sensitivity to:

models where we expect new particles of few hundred GeV mass

mixing of the Higgs boson with a heavy scalar with a mass of order 1 TeV

loop diagram effects created by any new particle strong coupling to the Higgs

typical quantum corrections to the Higgs self-coupling generated by loop diagrams

Higgs Self Coupling

arXiv:1910.00012

Sensitivity to:

models where we expect new particles of few hundred GeV mass

mixi TeV

loop he

Higg

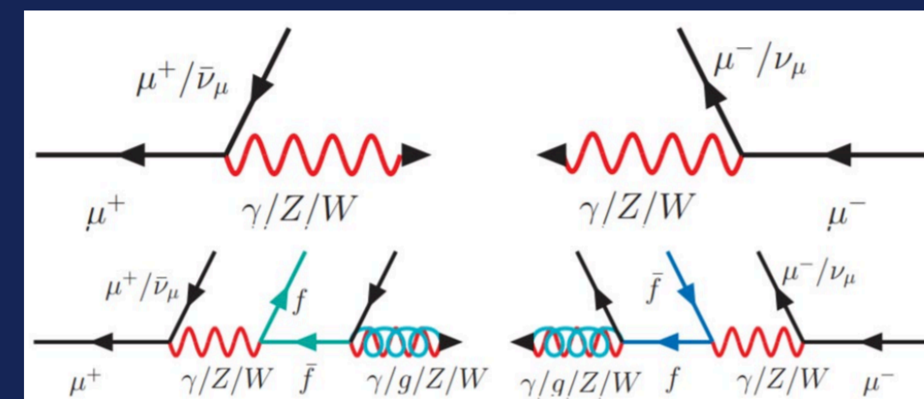
Planning to define new physics benchmarks for resonant and non-resonant HH that we could use for interpretations as the precision on the self-coupling improves

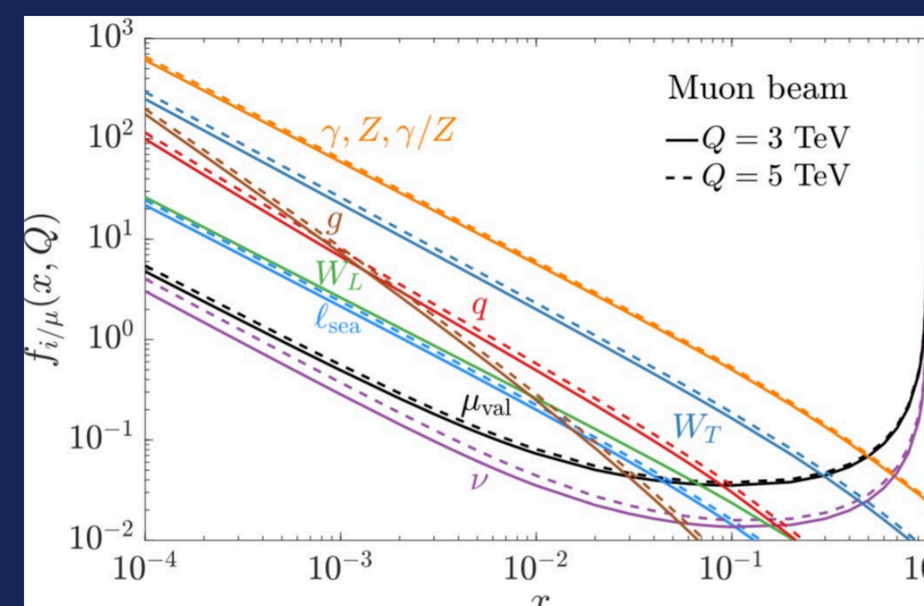
typical quantum corrections to the Higgs self-coupling generated by loop diagrams

Higgs Couplings: Muon Collider

Renewed (or continued) Interest in Muon Colliders

	Fit Result [%]		
	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27





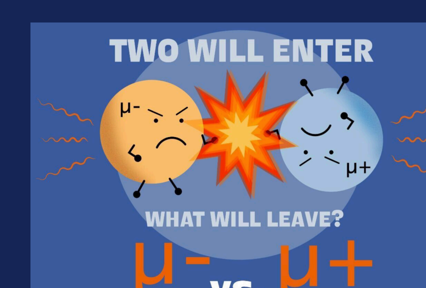
High energy muon colliders actually collider a mix of EWK states

Combination with other machines to improve precision measurements

2005.10289

2103.14043

and more

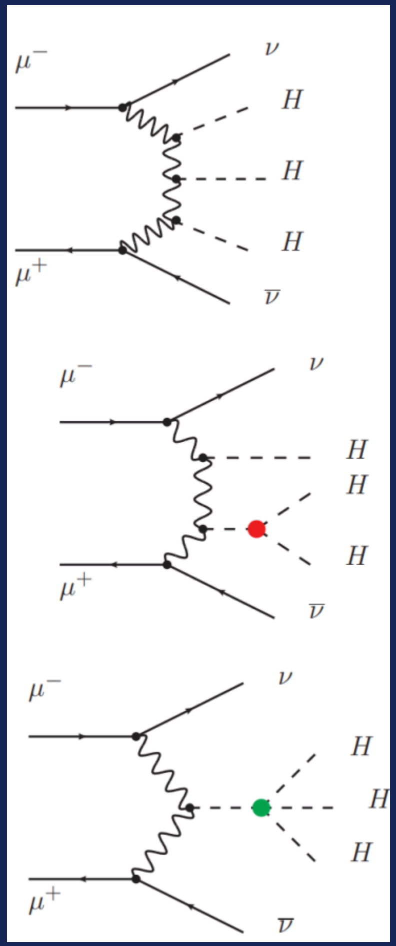


Beyond λ3

$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

Table 7: Summary table of the expected accuracies at 95% C.L. for the Higgs couplings at a variety of muon collider collider energies and luminosities.

2008.12204
T. Han, D. Liu, I. Low, X. Wang



$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	Constraints on δ_4 (with $\delta_3 = 0$) x-sec only, acceptance cuts		
		1 σ	2 σ	3 σ
6	12	$[-0.50, 0.70]$	$[-0.74, 0.95]$	$[-0.93, 1.15]$
10	20	$[-0.37, 0.54]$	$[-0.55, 0.72]$	$[-0.69, 0.85]$
14	33	$[-0.28, 0.43]$	$[-0.42, 0.58]$	$[-0.52, 0.68]$
30	100	$[-0.15, 0.30]$	$[-0.24, 0.38]$	$[-0.30, 0.45]$
3	100	$[-0.34, 0.64]$	$[-0.53, 0.82]$	$[-0.67, 0.97]$

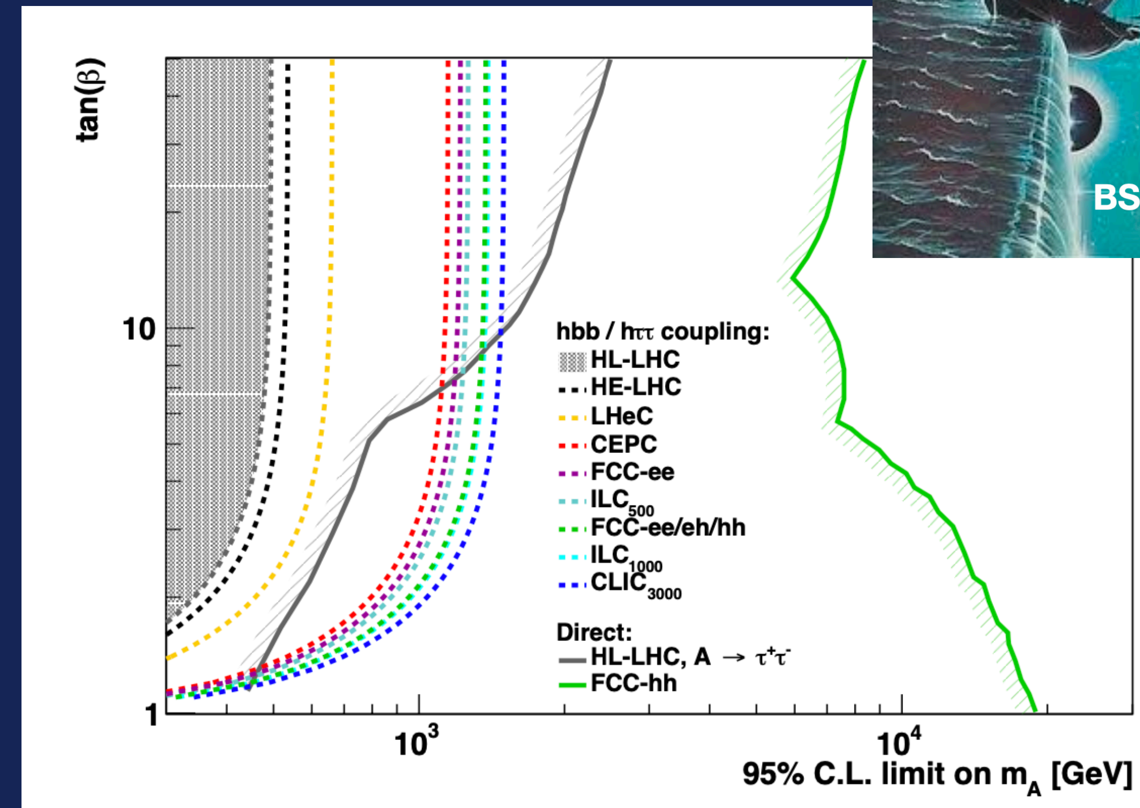
Table 6: Constraints on δ_4 (δ_3 =0) for the c.m. energies and the instantaneous luminosities in table 1 once the geometric acceptance cuts p_T >20 GeV and $|\eta| < 3$ are applied to the Higgs decay products. The bounds are obtained from the total expected cross sections for the process $\mu^+\mu^- \to HHH\nu\bar{\nu}$. The Higgs bosons are produced on-shell and decayed to $b\bar{b}$ pairs but no branching ratio is applied.

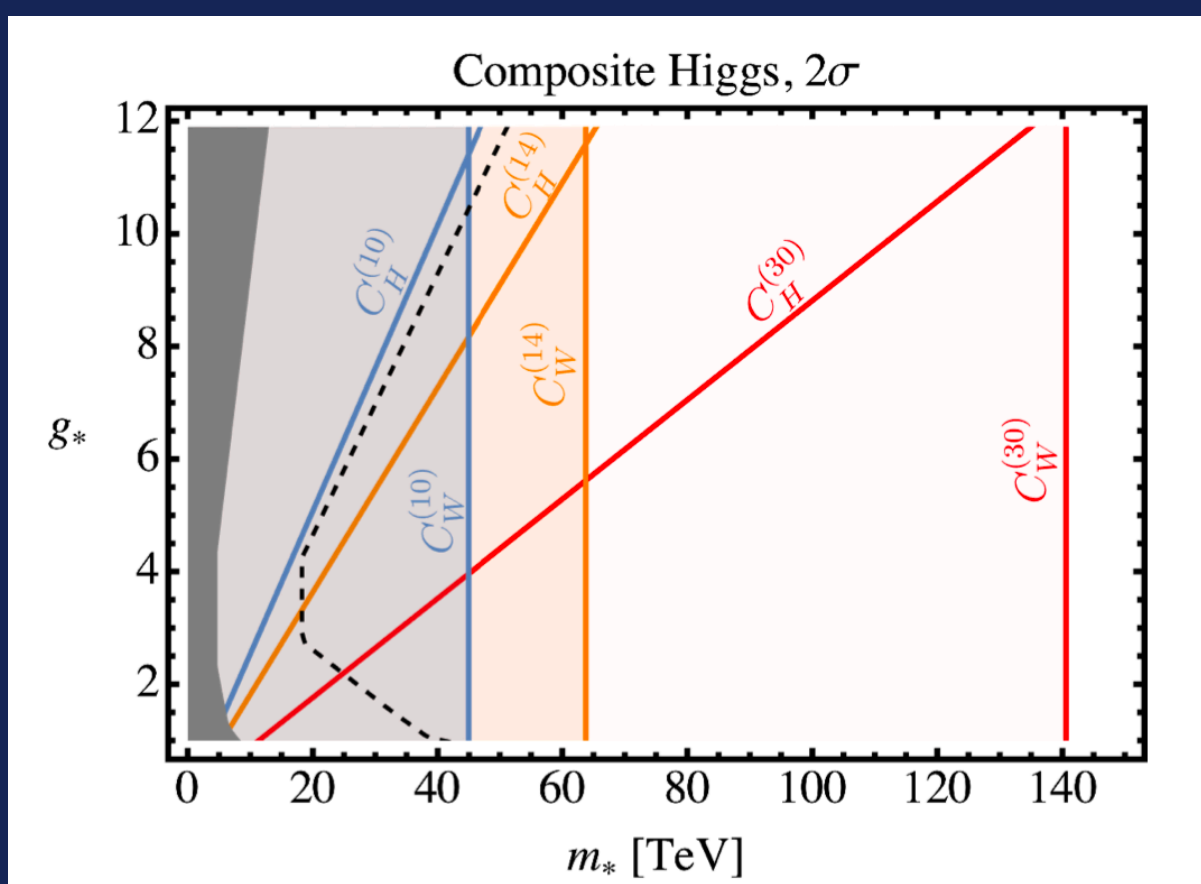
2003.13628 M. Chiesa, F. Maltoni, L. Mantani, B. Mele, F. Piccinini, X. Zhao

Higgs BSM

Towards Snowmass Report

- Higgs Doublets
- Higgs Singlets
- Composite Higgs





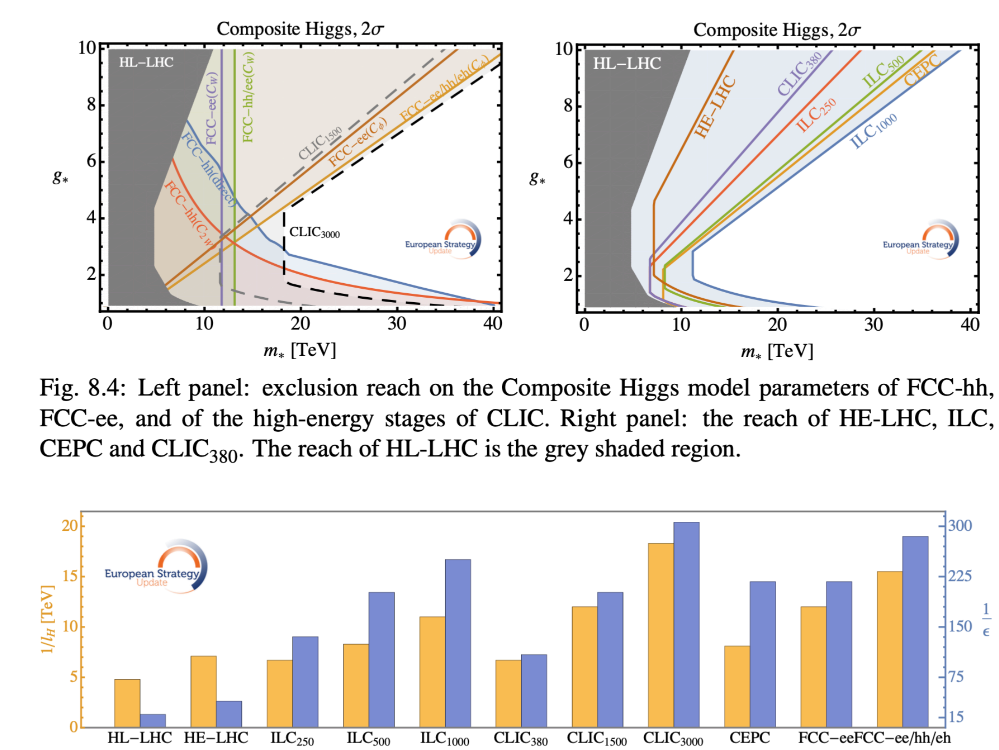


Fig. 8.4: Left panel: exclusion reach on the Composite Higgs model parameters of FCC-hh, FCC-ee, and of the high-energy stages of CLIC. Right panel: the reach of HE-LHC, ILC, CEPC and $CLIC_{380}$. The reach of HL-LHC is the grey shaded region.

Fig. 8.5: Exclusion reach of different colliders on the inverse Higgs length $1/\ell_H = m_*$ (orange bars, left axis) and the tuning parameter $1/\varepsilon$ (blue bars, right axis), obtained by choosing the weakest bound valid for any value of the coupling constant g_*.

Machine Integrated Luminosity and $\sqrt{s}$ Benchmark

Energy Frontier Collider Study Scenarios

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
		1.5 TeV	$\pm80/0$	2.5
		3.0 TeV	$\pm80/0$	5
CEPC	ee	M_Z		16
		$2M_W$		2.6
		240 GeV		5.6
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh	ep	3.5 TeV		2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10
		14 TeV		20
		30 TeV		90

Note for muon-collider: It is important to note that the plan is not to run subsequently at the various c.o.m etc. These are reference points to explore and assess the physics potential and technology. The luminosity can be varied to determine how best to exploit the physics potential.

Other options to explore:

- Muon collider at a very high energy (>30 TeV?)[Need to consolidate growing list of c.o.m. energies]
- FCC pp >200 TeV? and ~75 TeV documenting sensitivity loss
- Very high energy e+e- collider
- Other emerging ideas:, e.g. γ-γ collider, and the C^3 e^+e^- collider [C^3=Cool Copper Collider]

Polarization can add to precision measurements and BSM searches

Snowmass Timeline

Still time to contribute to the planning process

1/21-6/21	6/30/21	7/12/21	8/30/21	9/24/21	3/15/22	5/31/22	6/30/22	7/22	9/30/22	10/31/22
Activity Slowdown	Restart of Activities	DPF Meeting + Snowmass Townhall	Now, EF restart Workshop	Snowmass day	Deadline Contributed Paper Submission	Prelim. TG Reports	Prelim. Frontier Reports	Community Summer Study (UW-Seattle)	Final Reports	Snowmass Book & ArXiv docs

- **Sept. 24, 2021: Snowmass Day,** https://indico.fnal.gov/event/50538/
  - Plenary session 12:00-2:00pm (eastern time) with short talks from all frontiers
  - EF parallel session 2:30pm-5:00pm (eastern time) with highlights by topical group
  - Early Career (EC) will be chosen as speakers: they will provide their own perspective and highlight EC studies
- **Winter 2021-2022: few one-day virtual EF workshops by topic (SM, Higgs, BSM, Colliders,…)**
  - Check progress towards March deadline for contributed papers
  - Discuss overlap with other frontiers
- **Spring 2022: EF workshop to review contributed papers**
  - Focus on main themes and messages by contributed papers, towards May deadline for TG reports.
  - Converge on summary plots and other contributions involving multiple TGs or multiple frontiers
- **March-July 2022: circulations of preliminary TG and EF reports, then public readings**

Snowmass Day this Friday!!

Key Questions

Which physics beyond the Standard Model can be probed by precision measurements of Higgs couplings?

How precise do these measurements need to be in order to probe BSM physics scenarios?

How are direct searches for new Higgs-like particles complementary to precision Higgs coupling measurements

Does the Higgs boson result from the scalar potential of the Standard Model?

How can measurements of double Higgs boson production be improved to better probe the potential ?

Which is the target precision for this? - taking into account the correlations with the other Higgs measurements

How can measurements in the Higgs sector be combined with measurements in other sectors to improve our understanding of high scale physics?

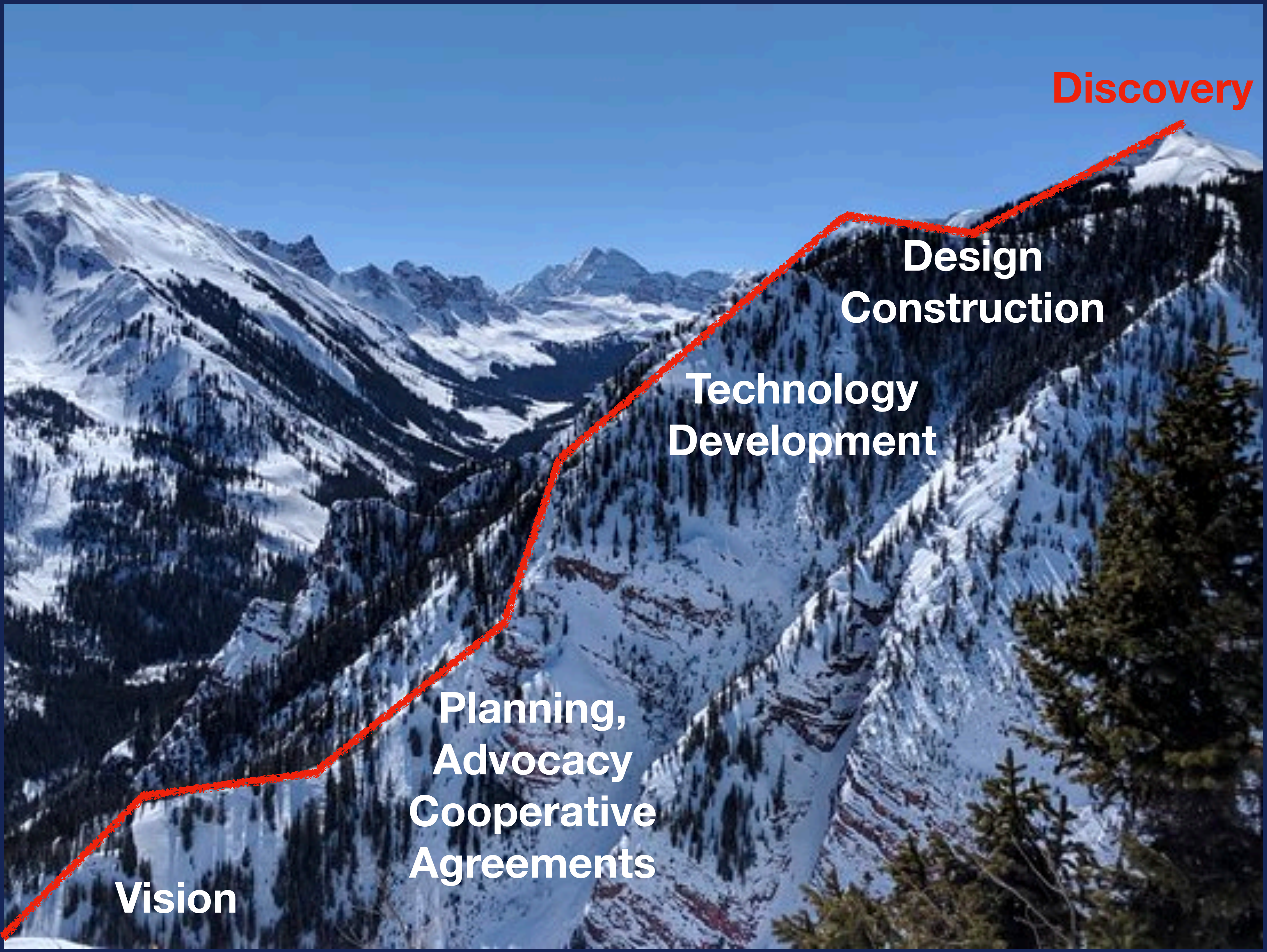
What theory calculations are needed to enable the theory precision to match the projected experimental precision of future measurements?

Summary Plots/tables

- Higgs couplings (from the ESG)
- Include updated list of machines and their parameters
- Re-visit some of the assumptions (i.e. flavor..)
- Some example maps of new physics phase space to constraints on EFT operators
- New physics benchmarks for resonant and non-resonant HH that we could use for interpretations as the precision on the self-coupling improves
- Higgs Doublet and Singlet plots (models to be finalized)

More discussions taking place this fall

Going Forward



Higgs Couplings

Key questions:

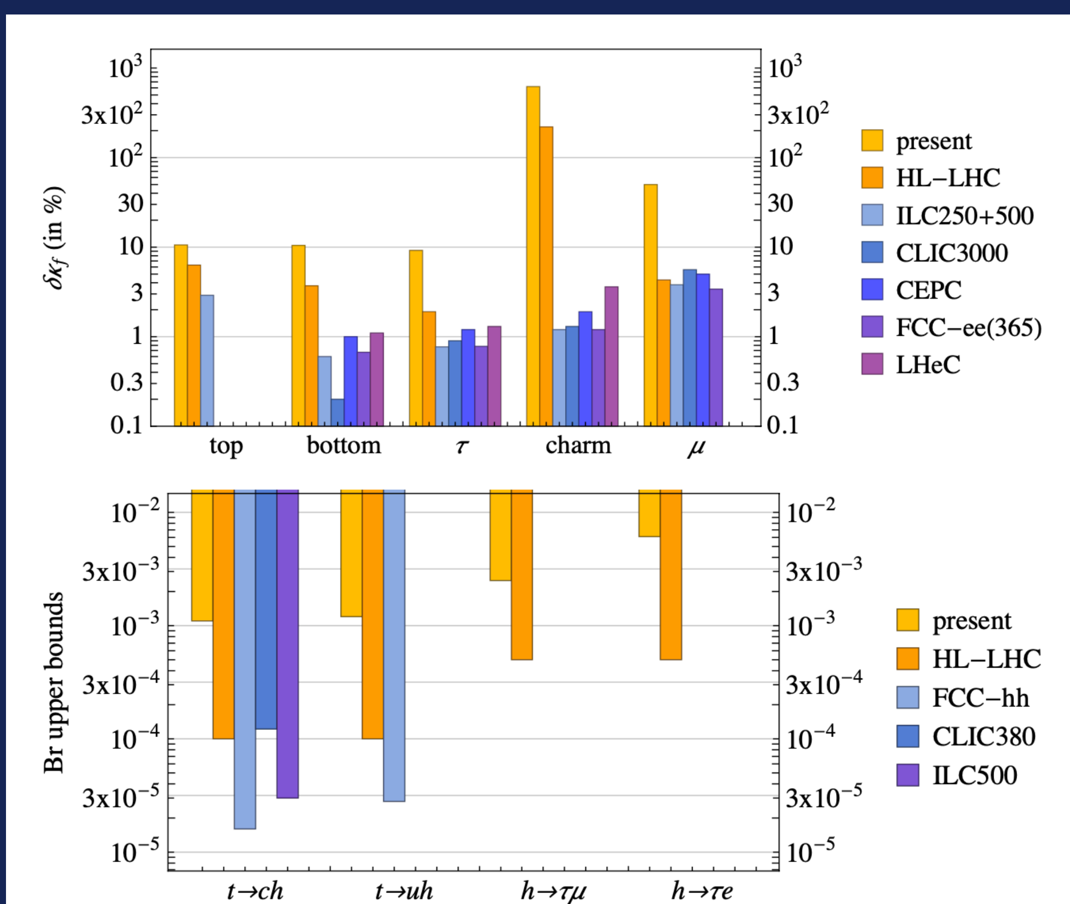
What precision can be achieved?

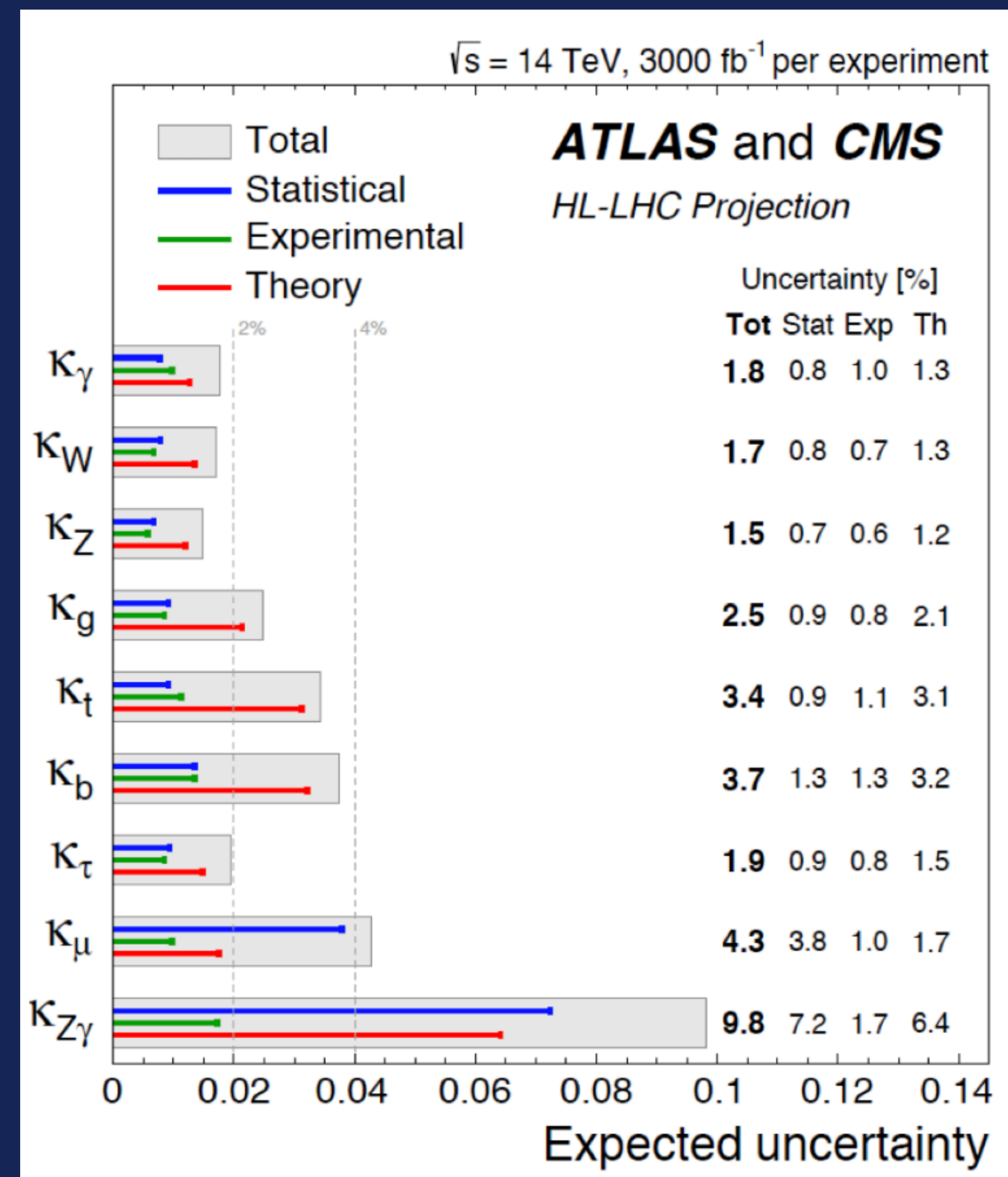
What precision is needed?

What about Higgs and flavor?

Technologies needed (trigger, ML, etc.)

Complementarity across frontiers and collider scenarios





Higgs Couplings

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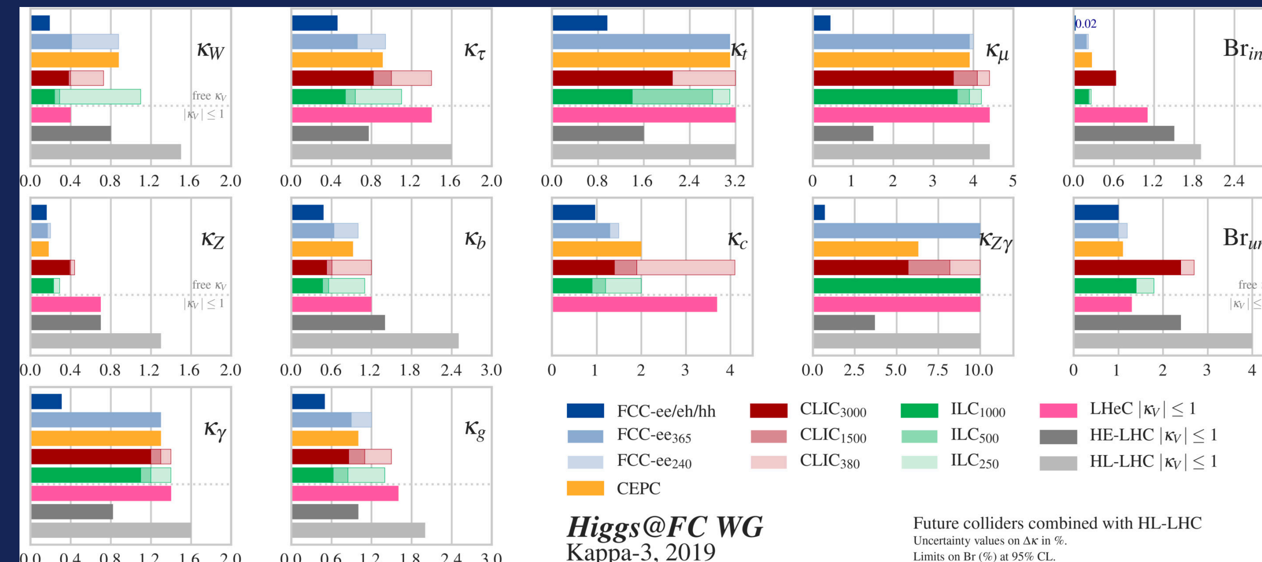


	Fit Result [%]		
	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27

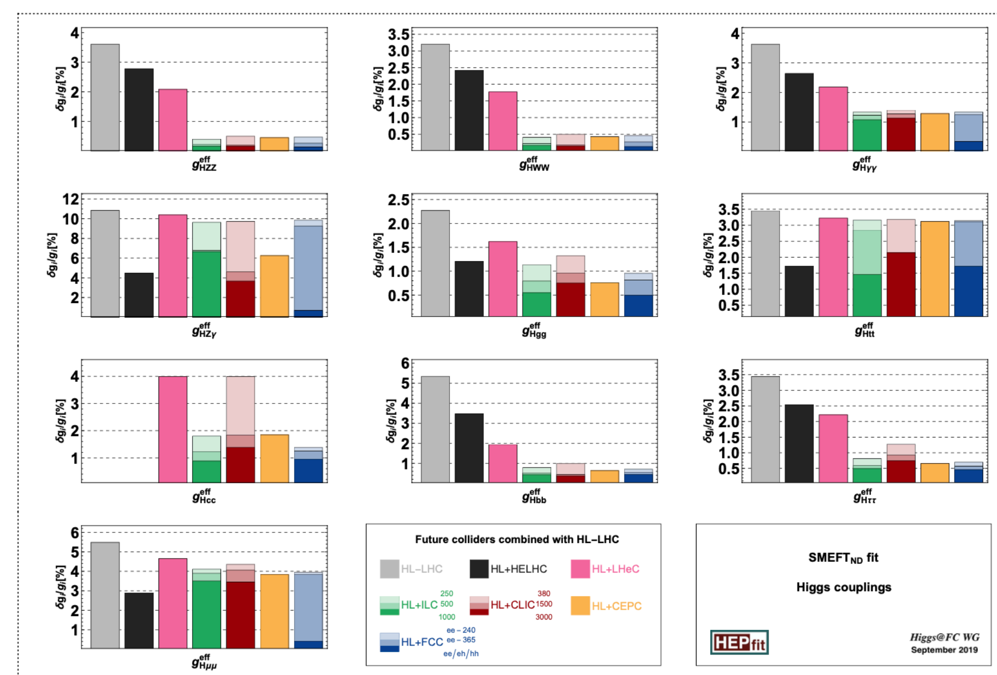


Fig. 3.9: 68% probability reach on Higgs couplings at the different future colliders from the Global fit SMEFT$_{\rm ND}$. For details, see Ref. [39].

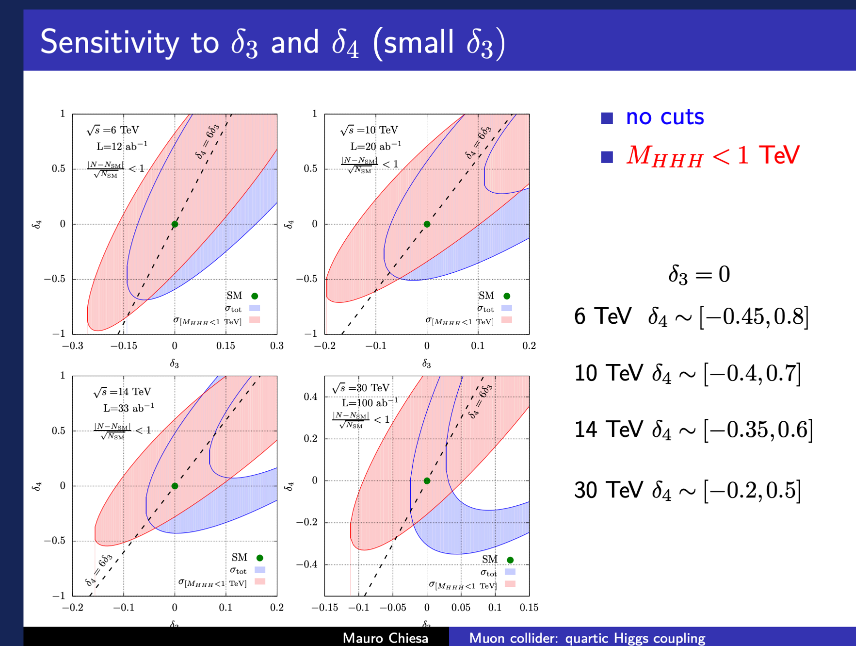
Higgs Self-Coupling

Resonant di-Higgs production is fundamental in search for new physics

BSM models predict cross section enhancement

Large variety of final states investigated: trade-off between BR and purity

Work towards defining community goals



	collider	single-H	HH	combined
	HL-LHC	100-200%	50%	50%
	CEPC_{240}	49%	–	49%
	ILC_{250}	49%	–	49%
	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%

These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.