Future colliders

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Long live the LHC

The LHC will continue to deliver science for another decade+

The HL-LHC is no longer a future collider; in our long game it's practically the present

Long live the LHC!

The LHC + HL-LHC luminosity upgrade will provide 3 ab-1 by 2041

Known SM processes
→ % level characterization of inclusive rates (c.f. 10 % at the Tevatron)
→ precision measurements of properties (i.e. W mass, top mass)
→ boosted production in previously inaccessible energy regime

New SM processes: from discovery to precision physics
→ Higgs measurements in many channels (Nature article by ATLAS, CMS)
→ rare processes probe new couplings, ttX, VV, VVV (my talk at LeptonPhoton)

The unknown (?)
→ search every corner for new phenomena
→ discover new SM processes, including di-Higgs production
→ explore new perspectives on collider data

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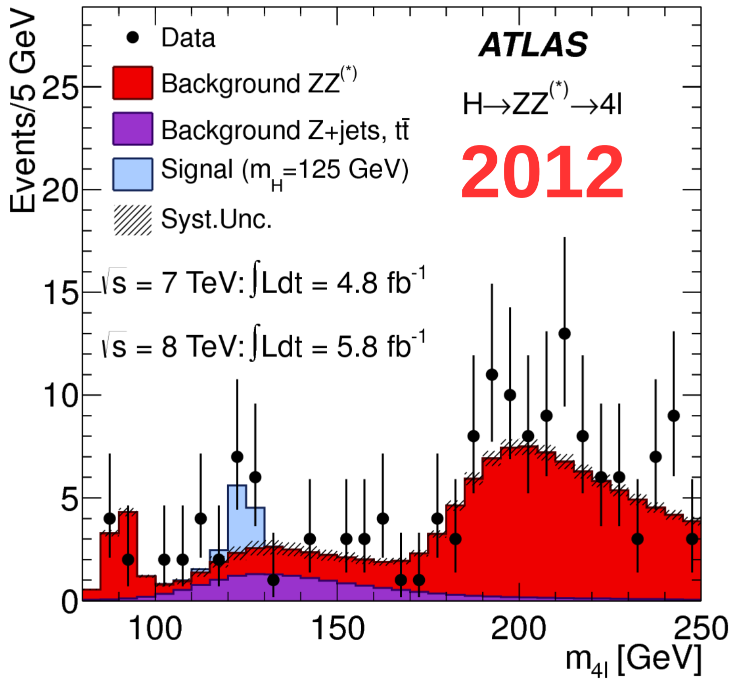
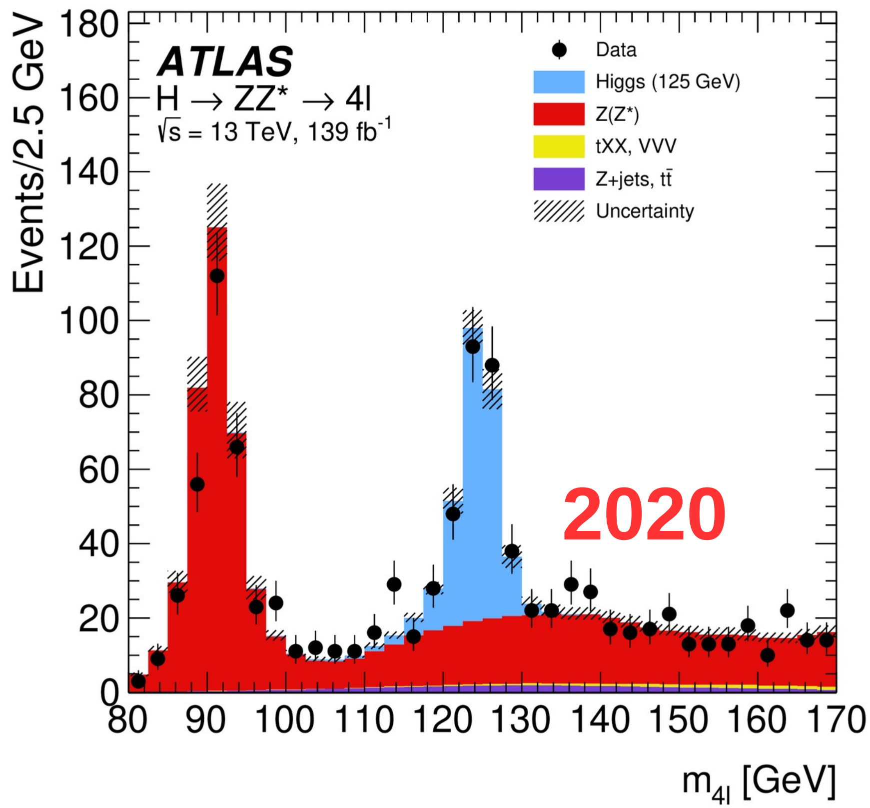
The Higgs boson – from run 1 to run 2 to HL-LHC



LHC run 2 delivered 140 fb^{-1}
LHC run 3 reached 70 fb^{-1}
HL-LHC to reach 3 ab^{-1}



The signal in the "discovery channels" has grown very robust

Higgs measurements at the LHC

Since 2012, ATLAS and CMS have characterized, with rapidly increasing precision, the couplings of the Higgs boson to SM particles:

2012: discovery
pp → H, H → ZZ*, H → $\gamma\gamma$, H → WW

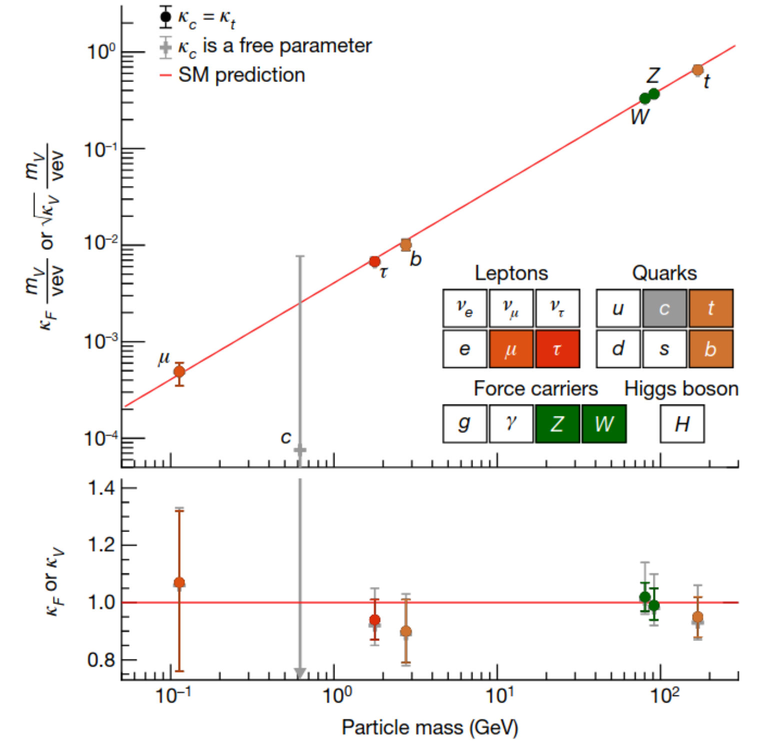
2015: evidence for H → $\tau\tau$ decay (fermions!)

2018: discovery of H → $b\bar{b}$ decay (quarks!)
discovery of VH production
discovery of $t\bar{t}$H production (Yukawa ~1!)

2020: evidence for H → $\mu\mu$ decay (2nd generation!)

2021: evidence for H → $l^+l^-\gamma$ decay

2024: evidence for H → Zγ decay



Today's talk: these measurements enable a new (and better) measurement of the bottom mass at a high scale: $m_b(m_H)$

Eagerly awaiting more, in particular legacy run 2 Higgs coupling combination

Higgs boson precision measurements at the LHC

Enough data to start filling the PDG data sheet on the H^0 boson

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022)

H^0 $J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

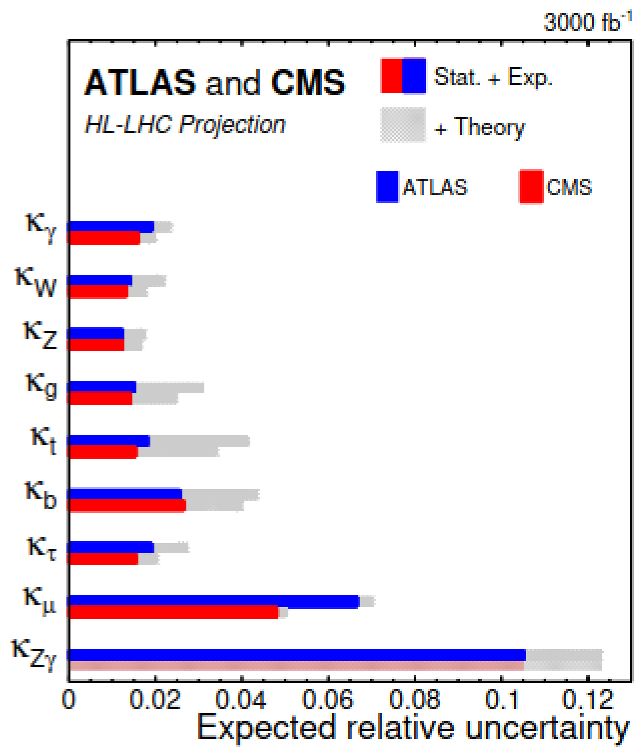
H^0 Signal Strengths in Different Channels

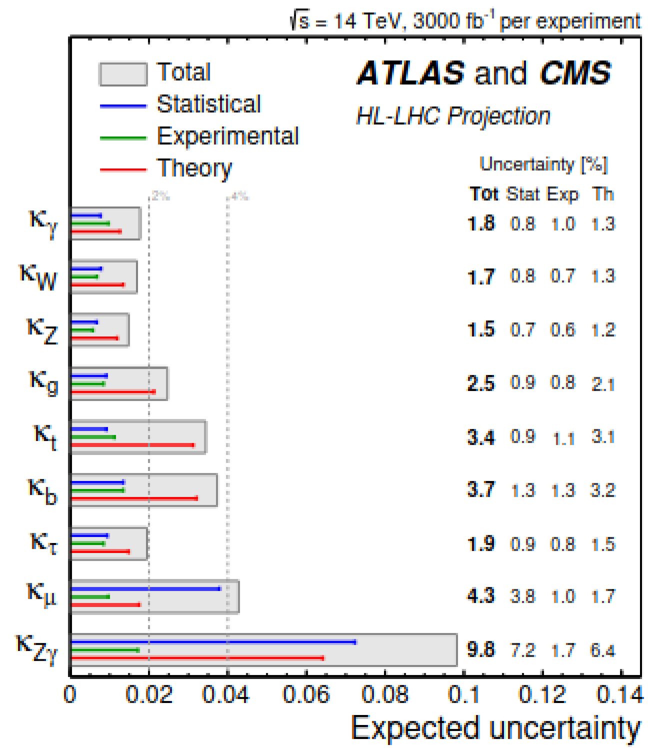
Combined Final States = 1.13 ± 0.06
$W W^* = 1.19 \pm 0.12$
$Z Z^* = 1.01 \pm 0.07$
$\gamma\gamma = 1.10 \pm 0.07$
$c\bar{c}$ Final State = 37 ± 20
$b\bar{b} = 0.98 \pm 0.12$
$\mu^+\mu^- = 1.19 \pm 0.34$
$\tau^+\tau^- = 1.15^{+0.16}_{-0.15}$
$Z\gamma < 3.6$, CL = 95%
$\gamma^*\gamma$ Final State = 1.5 ± 0.5
$t\bar{t}H^0$ Production = 1.10 ± 0.18
tH^0 production = 6 ± 4
H^0 Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV = 56 ± 4 pb

Higgs boson summary

HL-LHC projections: S2 assumes 3000/fb and progress on all fronts, halving theory uncertainties and scaling experimental uncertainties with 1/sqrt(L)

Discovery channel (g,Z,W,g) Expect < 2%
O(10%) today (g,b,t,τ) Expect few %
Evidence today (μ,Zγ) Expect 5-10%

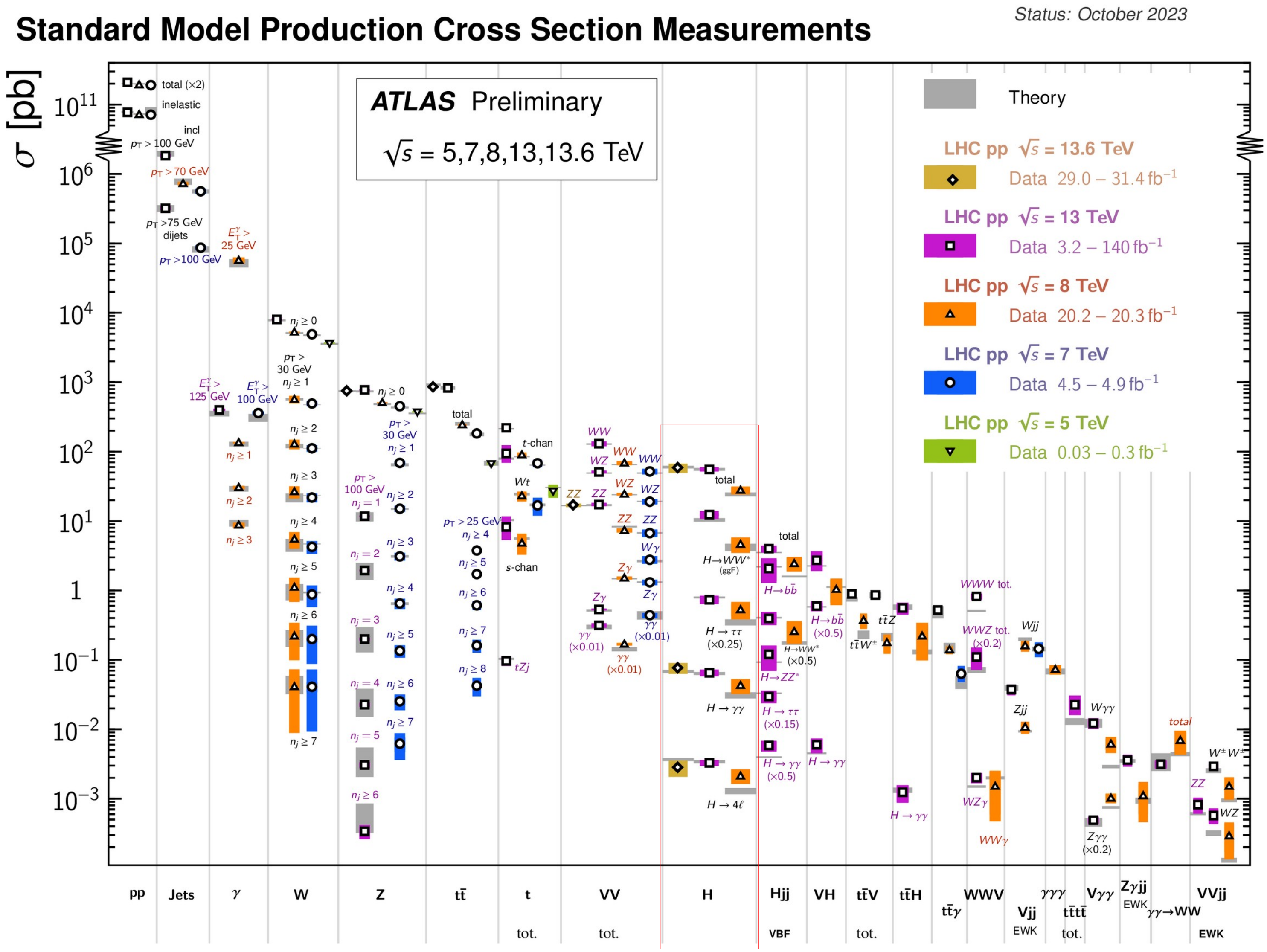




CERN Yellow Rep.Monogr. 7 (2019) 221-584, arXiv:1902.00134

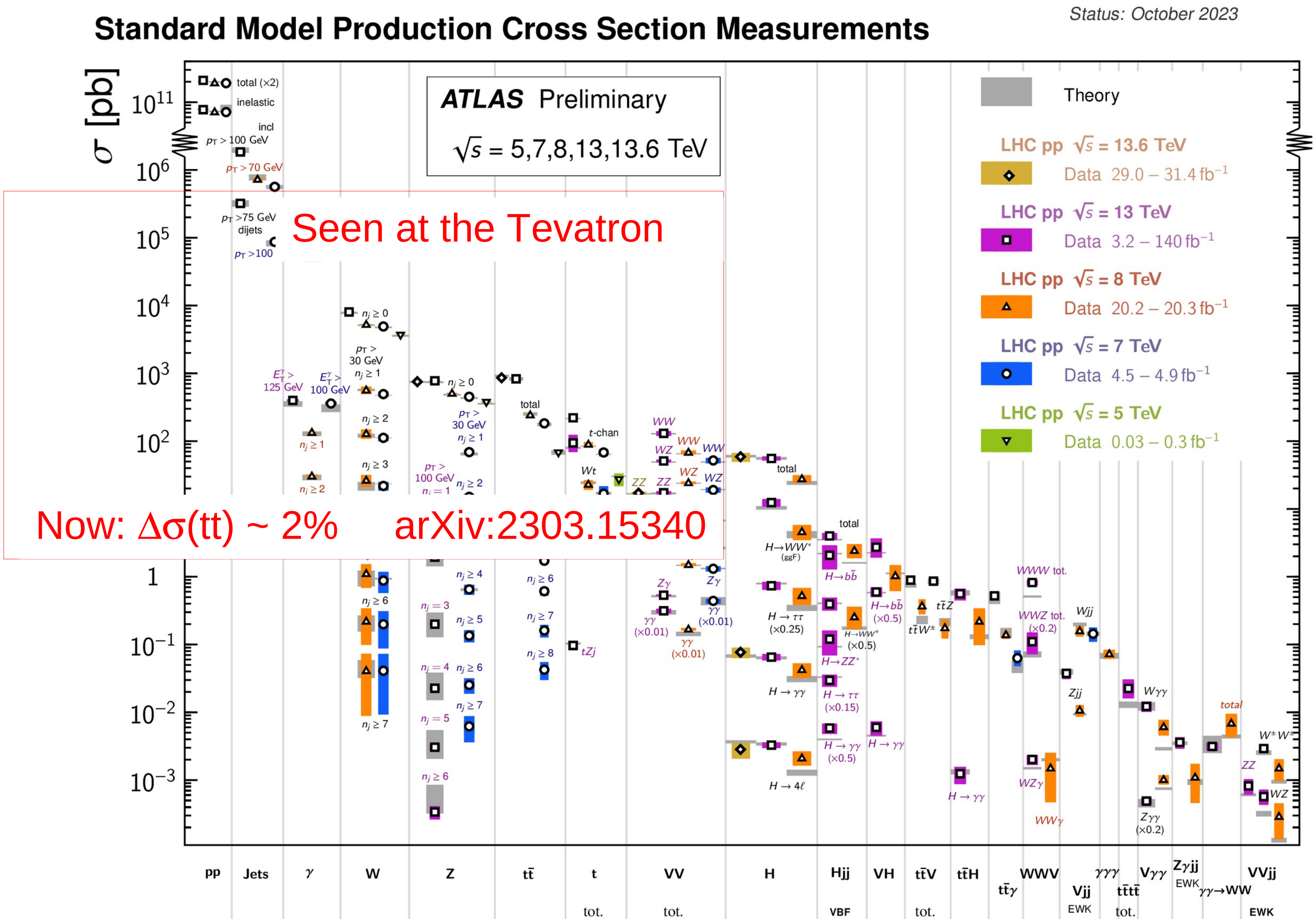
Projections for Higgs coupling measurements, derived in the “S2 scenario” and reported in the “kappa framework”

Full SM characterization

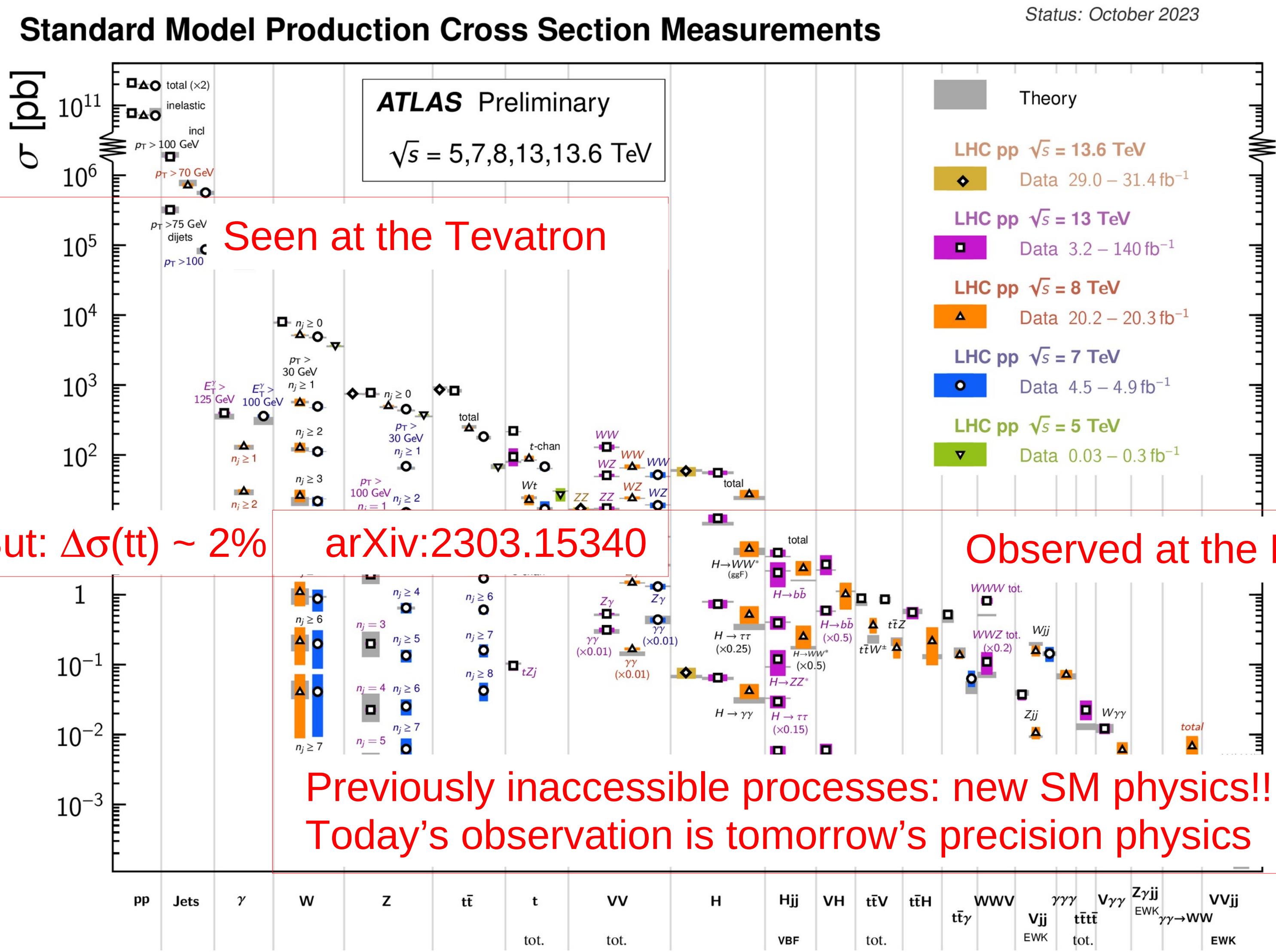


The Higgs programme

Full SM characterization



Full SM characterization



Seen at the Tevatron

But: $\Delta\sigma(tt)$ ~ 2%

arXiv:2303.15340

Observed at the LHC

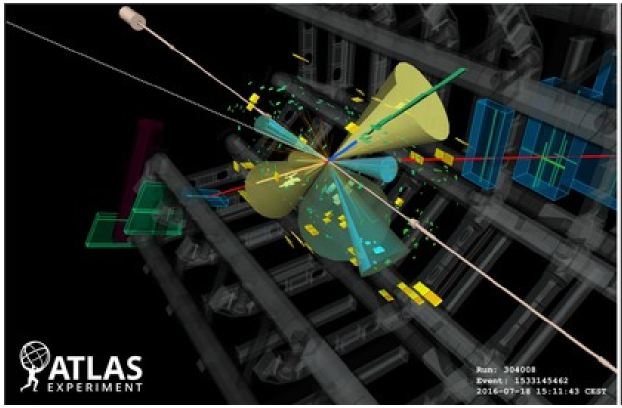
Previously inaccessible processes: new SM physics!!
Today's observation is tomorrow's precision physics

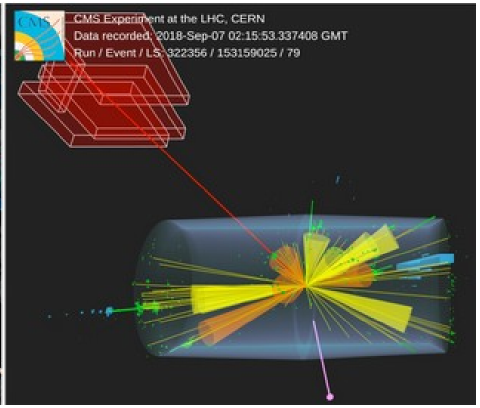
New rare processes

The “top+X” observation program: ttW (2015), ttZ (2016), ttH (2018), tttt (2022)

Today, the ttX cross section measurements have reached 6-10% precision, providing direct access to top quark EW couplings

Moriond ‘23: simulteanous ATLAS+CMS observation of 4-top-quark production





https://home.cern/news/news/physics/atlas-and-cms-observe-simultaneous-production-four-top-quarks

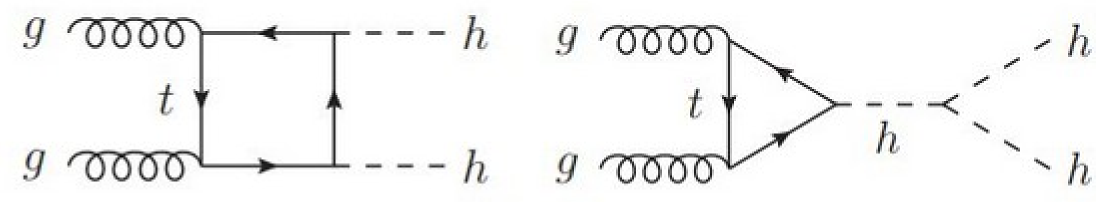
Newer and even rarer processes

The hunt for di-Higgs production is on! Lots of effort and new ideas.

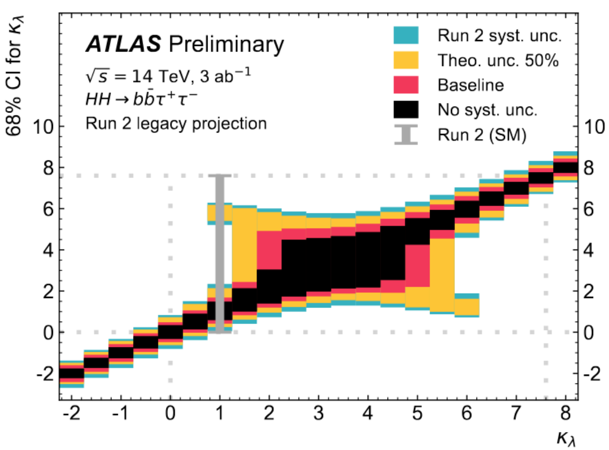
New HL-LHC projections significantly more optimistic

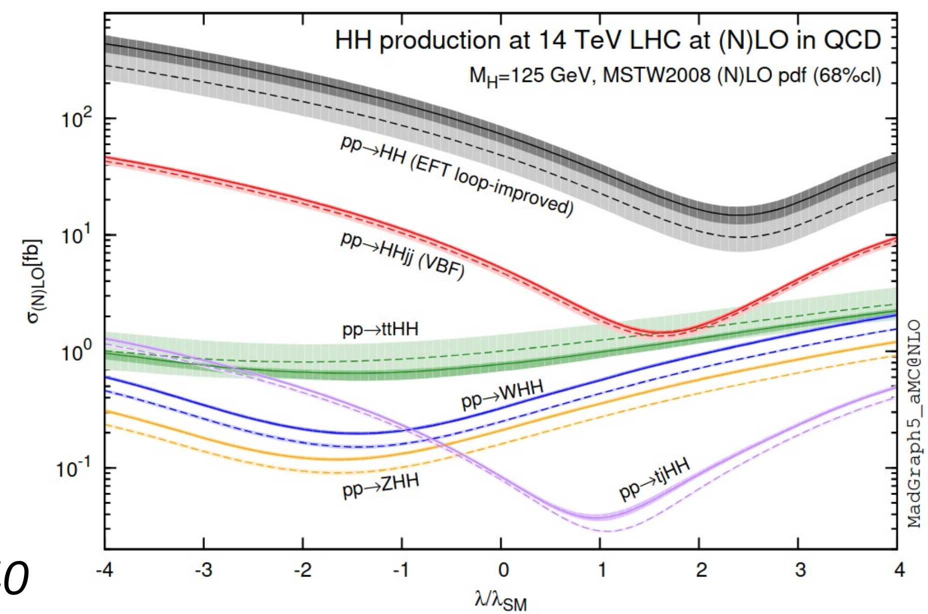
-- combination of all channels, ATLAS & CMS, likely to observe HH production

Measurement of Higgs self-coupling is complicated by interference with box diagram



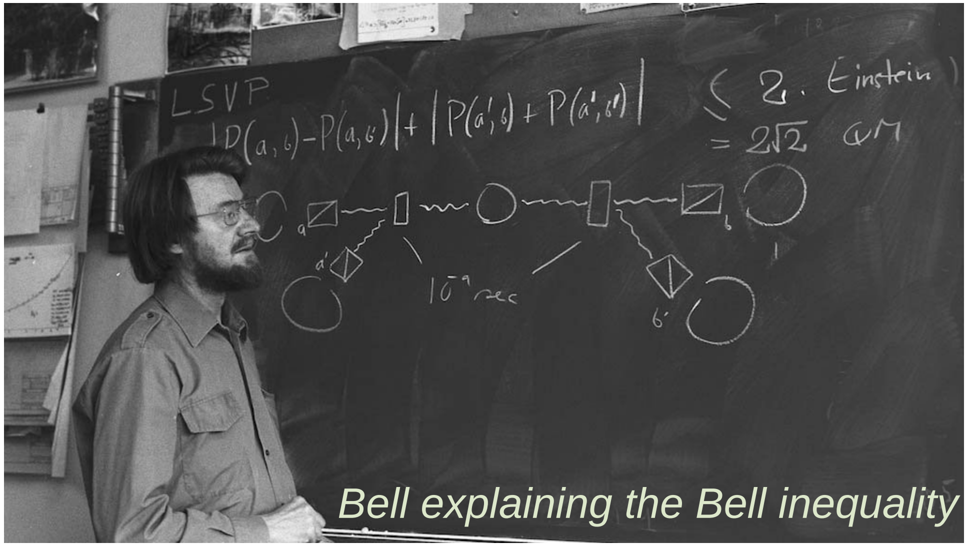
ATL-PHYS-PUB-2024-016

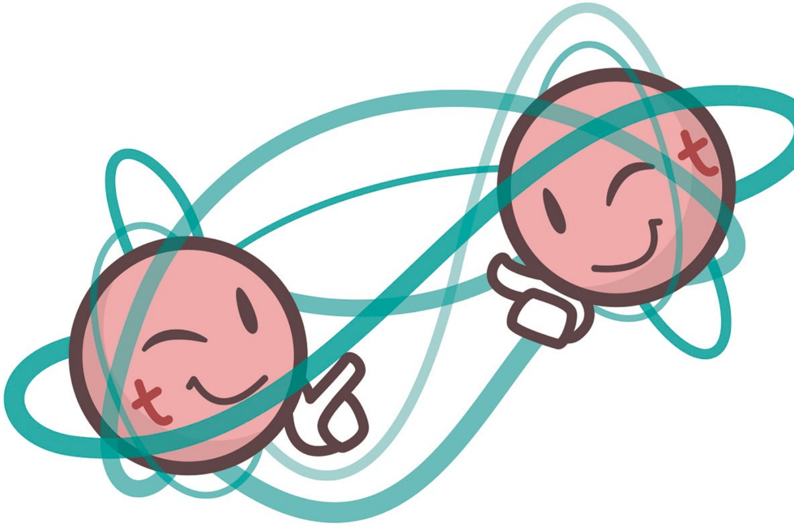




Frederix et al, arXiv:1401.7340

New uses of the same data





Two-qubit system: top quark pairs (or Higgs decay products)
Spin "measurements": polarization inferred from weak ($t \rightarrow Wb$) decays
Strength of spin correlations demonstrates the system was entangled

Afik & Nova, EPJ+ 136, arXiv:2003.02280

Observation of entanglement at the LHC

ATLAS, Nature 633, arXiv:2311.07288
CMS, ROPP 87, arXiv:2406.03976

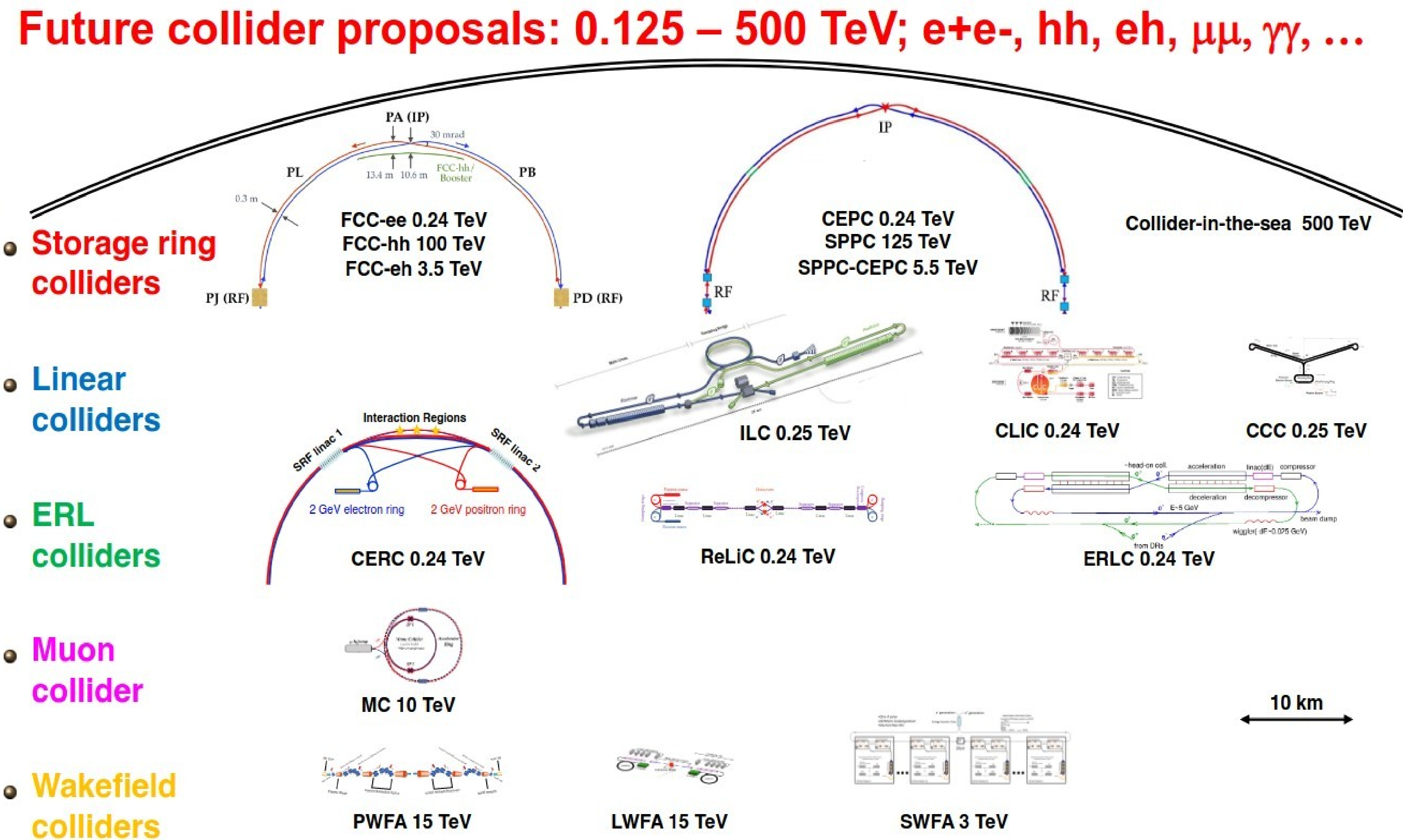
Horodecki, Horodecki, Horodecki & Horodecki, RMP81 (2009), arXiv

So, what's next?

Which new large-scale facility should HEP build?

Possible projects… to scale

https://arxiv.org/pdf/2307.04084.pdf



Criteria for decision

Scientific case, technical feasibilty, time-line

The rest of this talk

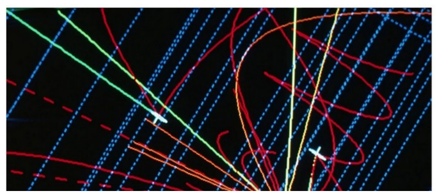
International situation

NEWS | 17 June 2024 | Correction 18 June 2024

China could start building world's biggest particle collider in 2027

The US$5 billion facility would be cheaper, bigger and faster to build than a similar one proposed by European scientists.

By Gemma Conroy



Check out their TDR

Yifang Wang (IHEP):
"We are now confident this is a real machine that we can build"
Frank Zimmerman (CERN):
"IHEP might now have more expertise in this area than does CERN"

Recent Nature article: Nature article

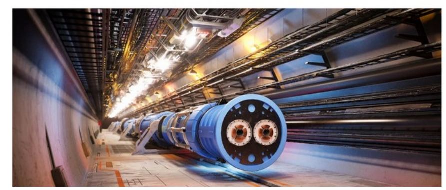
Financial viability

NEWS | 06 June 2024

CERN's $17-billion supercollider in question as top funder criticizes cost

Germany has raised doubts about the affordability of the Large Hadron Collider's planned successor.

By Davide Castelvecchi

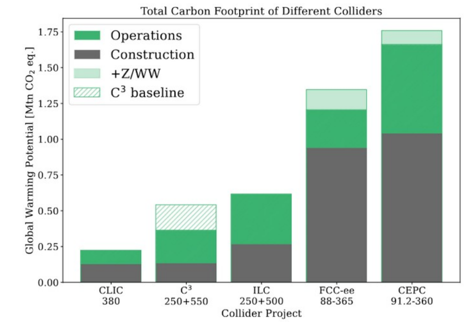


Eckart Lilienthal, BMBF
"Germany, which already contributes €267 million (US$290 million) annually to CERN — some 20% of the lab's budget — cannot afford to spend more" (*slides*)

Recent Nature article: Nature article

Sustainability

CO_2 footprint of colliders



A Sustainability Roadmap for C³

Martin Breidenbach, Brendon Bullard, Emilio Alessandro Nanni, Dimitrios Ntounis[1], Caterina Vernieri

SLAC National Accelerator Laboratory [1] & Stanford University

LDG Sustainability WG to hand in recommendations for full-life-cycle-assessments (talk here)

The future collider landscape

European, American and Asian strategies agree on big picture

— e+e- Higgs factory first:

large circular colliders: FCC-ee (CERN) and CEPC (China)
linear colliders: LC facility at CERN, ILC (Japan), CLIC (CERN), CCC (US)

— (sustainable) exploration of the energy frontier next:

large pp collider: FCC-hh (CERN), SPPC (China)
muon collider: μ-collaboration (CERN+US P5)
plasma R&D (EUPRAXIA, AWAKE), collider studies (i.e. ALEGRO, HALHF)

Snowmass report

The proposed plans in five-year periods starting in 2025 are given below.

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

European strategy update

3 | High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

The NEXT collider

The 2020 update of the European Strategy for Particle Physics approved by the CERN council in May 2020 provides a concise and clear answer:

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

This talk deals primarily with the NEXT collider,

Read the complete document:

https://home.cern/sites/home.web.cern.ch/files/2020-06/2020%20Update%20European%20Strategy.pdf

European strategy update

March 2024: CERN Council started the process

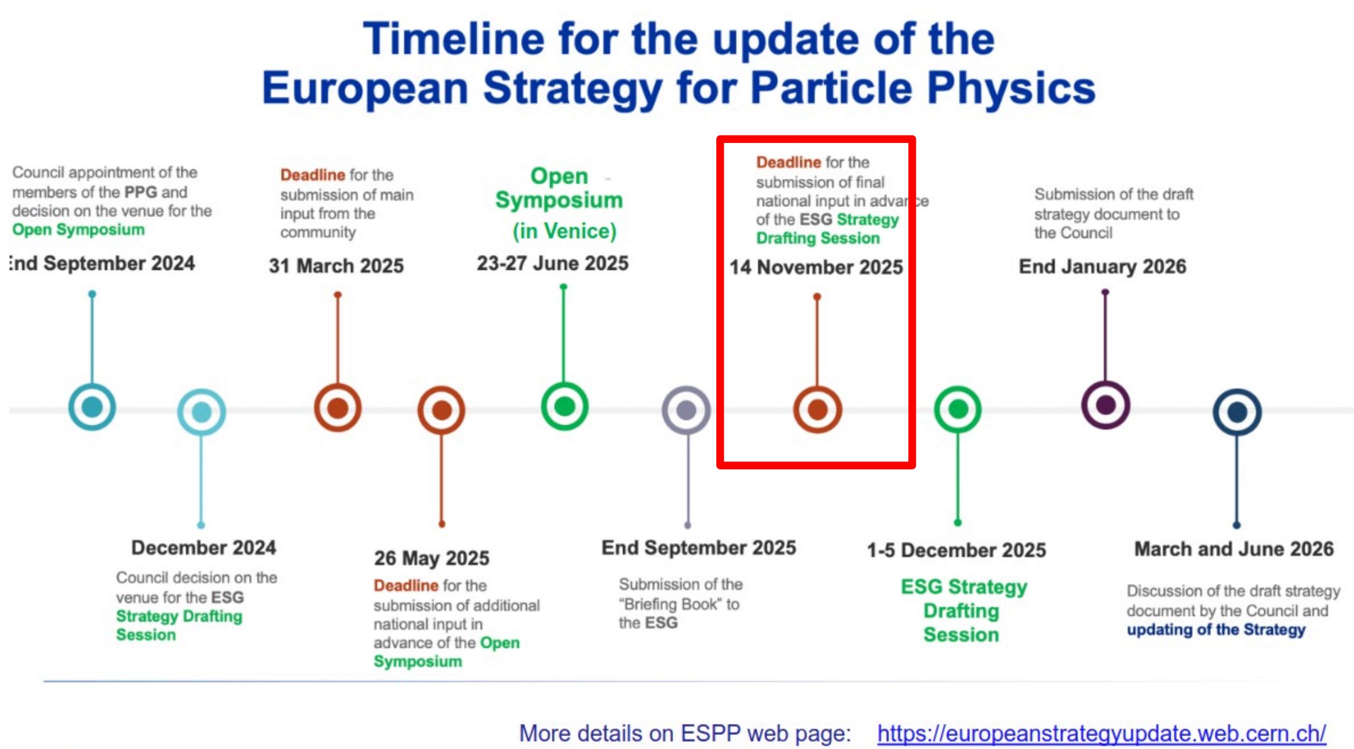
June 2024: Karl Jakobs (Freiburg) appointed Strategy Secretary

March 2025: Deadline for community input

June 2025: Open symposium

Nov 2025: Further inputs from countries

1st half 2026: Council discussions and decision



Baseline and alternatives

Karl Jakobs, ECFA plenary meeting, CERN, last week, link to the talk

Baseline and possible alternative scenarios

Current baseline – justified by 2020 Strategy – :
FCC integrated programme (FCC-ee followed by a hadron collider of at least 100 TeV)

Possible alternative scenarios (for next collider, following the HL-LHC)

- Realisation of a lower-energy hadron collider (50 – 80 TeV) on an earlier timescale (2050 – 2055)
- Linear Collider at CERN (CLIC, …)
- Muon Collider at CERN
- Further exploitation of the LHC physics programme, eventually with the addition of e-h collisions
- …

Non-exhaustive list, other scenarios may come up and be proposed by the community

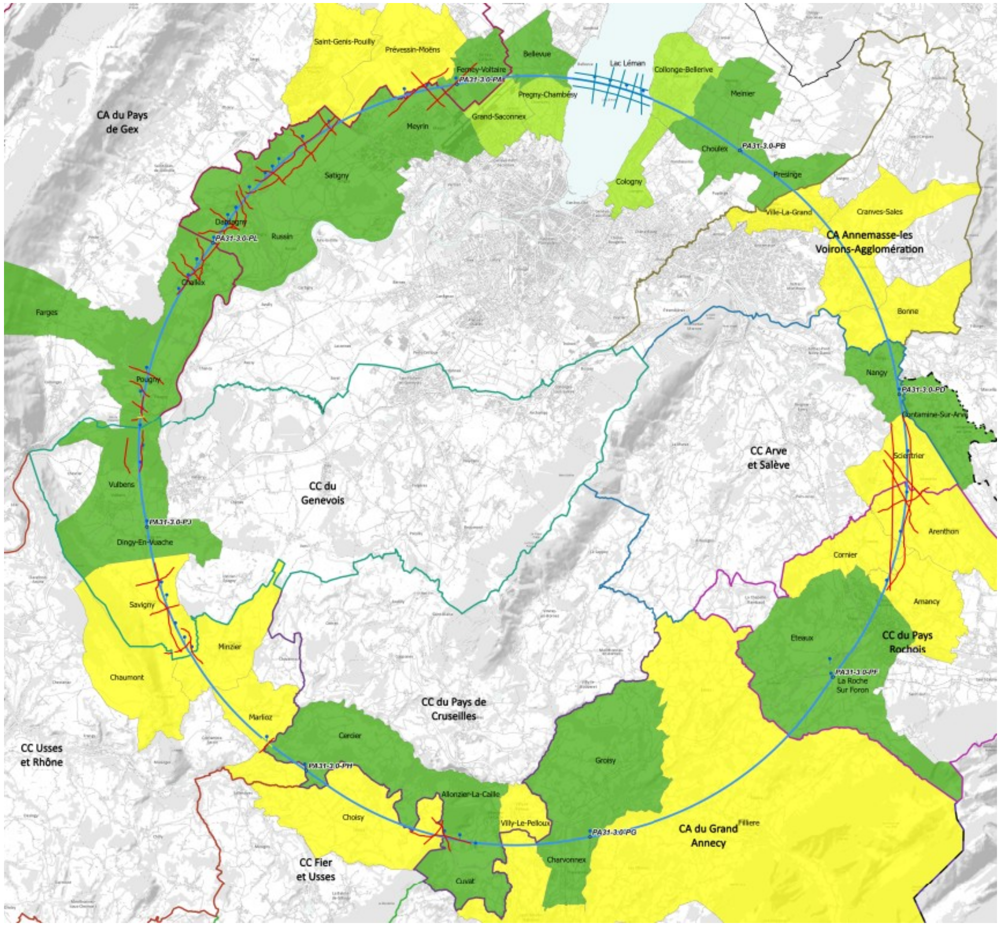
K. Jakobs, Plenary ECFA meeting, 15th November 2024

9

The baseline: FCCee+FCChh

Feasibility involves geology, road access, power supply, etc.

Parameter	unit	2018 CDR [1]	2023 Optimised
Total circumference	km	97.75	90.657
Total arc length	km	83.75	76.93
Arc bending radius	km	13.33	12.24
Arc lengths (and number)	km	8.869 (8), 3.2 (4)	9.617 (8)
Number of surface sites	—	12	8
Number of straights	—	8	8
Length (and number) of straights	km	1.4 (6), 2.8 (2)	1.4 (4), 2.031 (4)
superperiodicity	—	2	4



FCC mid-term report to CERN council,
http://cds.cern.ch/record/2888566?ln=en
https://doi.org/10.17181/mhas5-1f263

No technical show-stoppers so far

Financial viability discussed with council

US P5 panel provides recommendations
https://www.usparticlephysics.org/2023-p5-report/

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Karl Jakobs, ECFA plenary meeting, CERN, last week, link to the talk

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- …

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K. Jakobs, Plenary ECFA meeting, 15th November 2024

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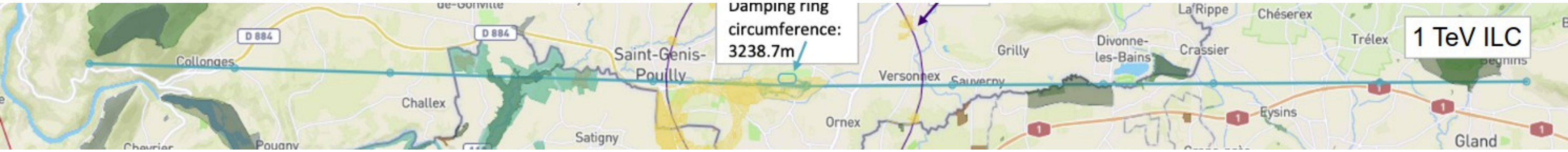
The main alternative

An **alternative** “linear collider facility @CERN” is being developed by LC vision team
-- CERN-site-specific studies from ILC/CLIC + inputs from ILC, CCC, HALHF --



- **Initial phase at 250 GeV based on SCRF in 20 km tunnel**
  Two interaction points/experiments

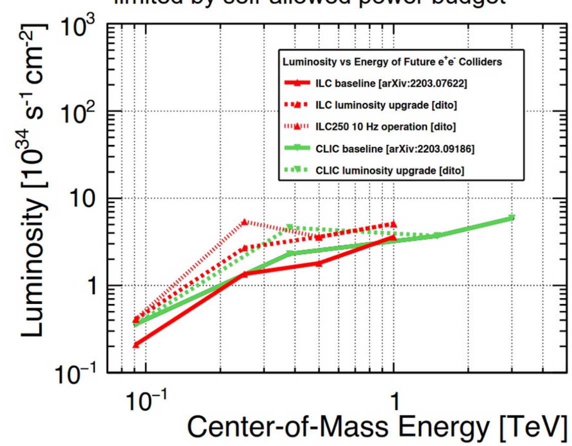
Fits in CERN budget, small CO2 footprint

- Energy upgrade: the natural next step
  up to 500-600 GeV with 60 MV/m SCRF
  up to 1 TeV with “warm/cool” copper
  up to ?? TeV with (hybrid) wakefield
  extension of tunnel only if all else fails

Complementary to CEPC/SPPC, should China go ahead

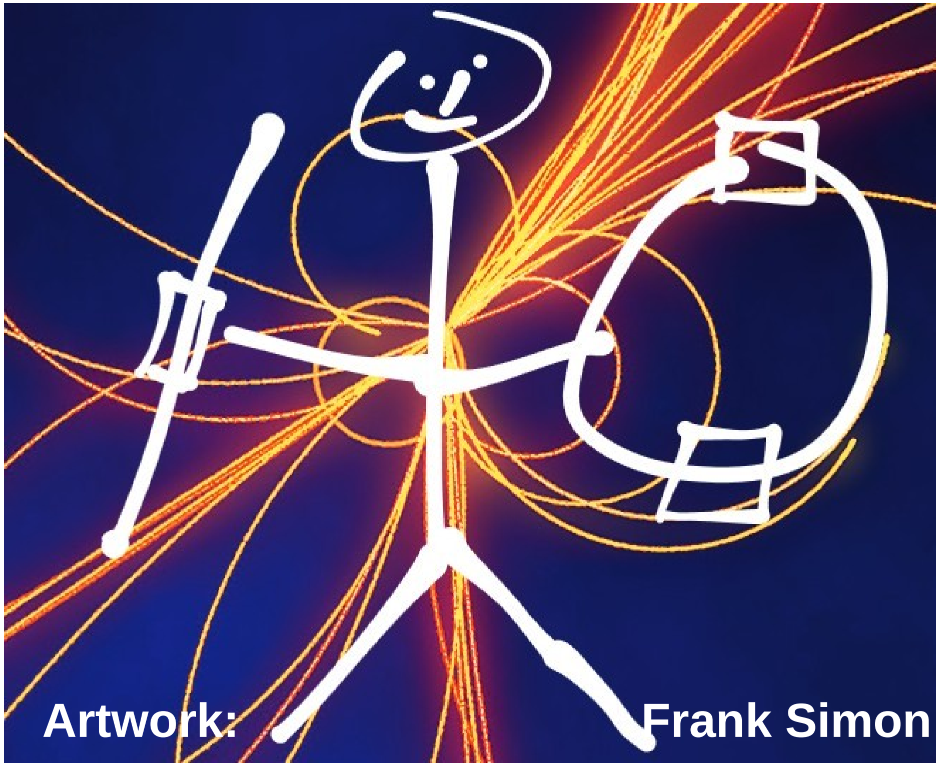
- Luminosity upgrade: few x 10^{36} $s^{-1}cm^{-2}$ with ERL
- γγ/eγ collider options
- Physics-beyond-colliders programme

Based on classic ILC/CLIC luminosity assumptions limited by self-allowed power budget



Further alternatives are being worked out
-- early hadron collider, muon collider, …

So, a Higgs factory. Would you like that circular or linear(*)?



(*) I assume one will be built, but see:
Blondel & Janot, Circular and linear e^+e^- colliders: another story of complementarity, arXiv:1912.11771

Circular or linear

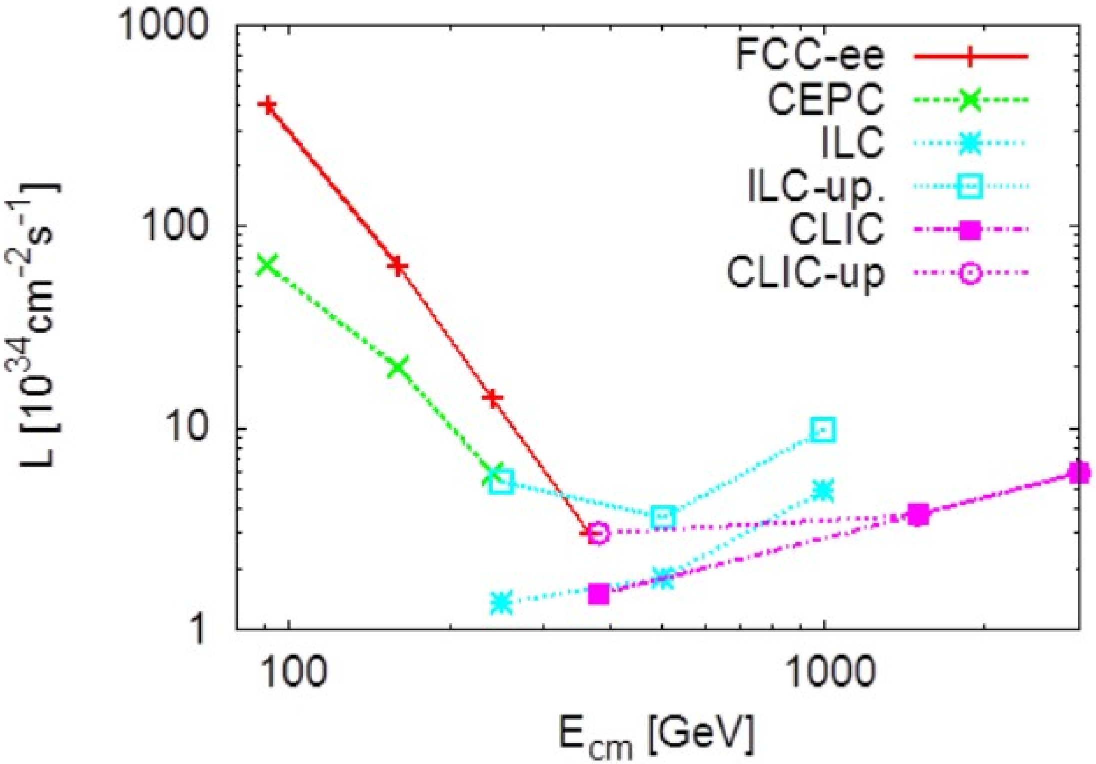
FCCee/CEPC excell at low energy (10^{12} Z-bosons!)

Synchrotron radiation prevents operation above ~360 GeV

At linear colliders luminosity increases with sqrt(s)

ILC/CCC/CLIC are the avenue to reach 400-1000 GeV

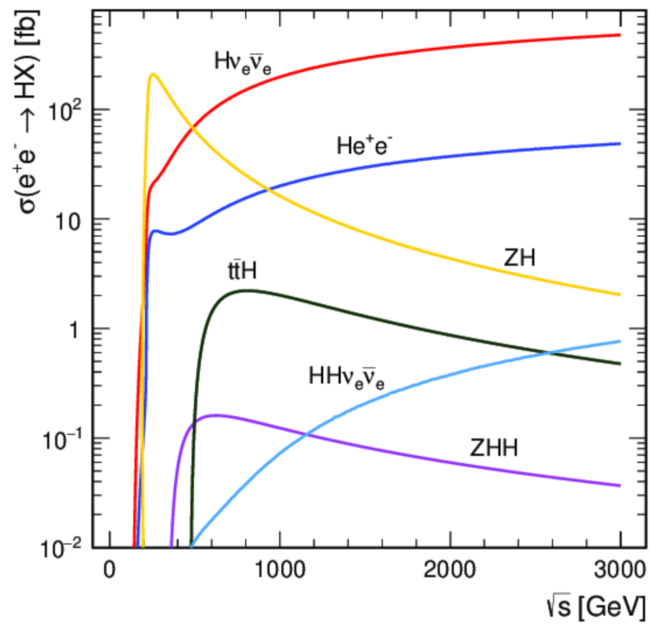
https://arxiv.org/pdf/1910.11775.pdf

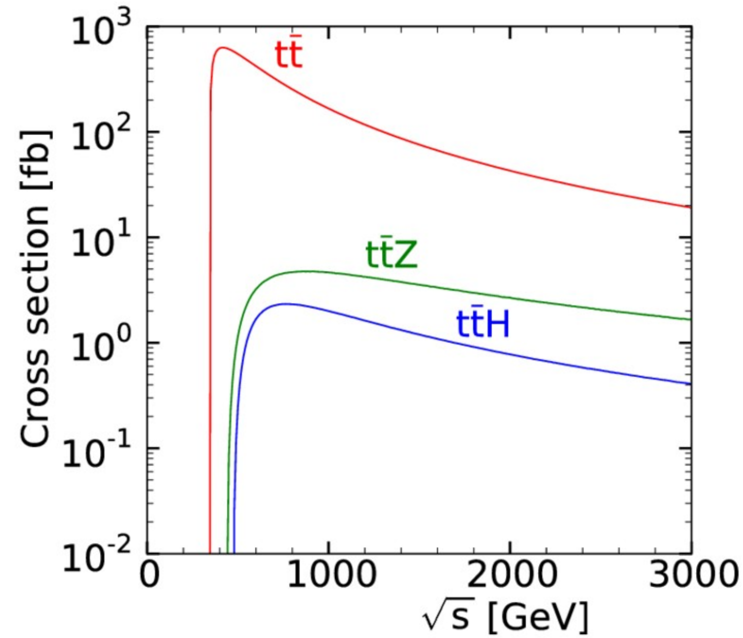


Small print: there is a trade-off between luminosity and power consumption, instantaneous luminosity must be folded with operation schedule

Higgs and top production thresholds

The ideal facility covers a broad energy range.





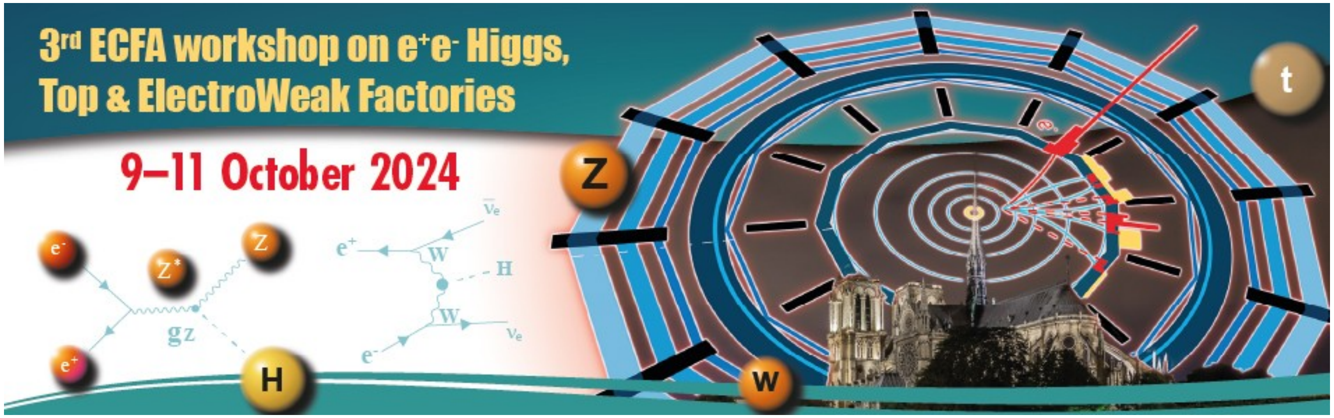
Z-pole measurements	91 GeV
Higgs coupling measurements	~ 250 GeV
Top quark pair production	~ 350 GeV
VBF, ttH, HH production	~ 500-600 GeV

ECFA Higgs/top/EW factory studies

Let’s focus first on what these machines have in common.

ECFA study: neutral terrain to further develop the e+e- “Higgs factory” physics case

Indeed, many joint studies on new topics were presented in Paris



Precision measurements

The LHC as a precision machine ($t\bar{t}$ cross section example)

$$\sigma_{t\bar{t}} = 829 \pm 1\ (\text{stat}) \pm 13\ (\text{syst}) \pm 8\ (\text{lumi}) \pm 2\ (\text{beam})\ \text{pb},$$

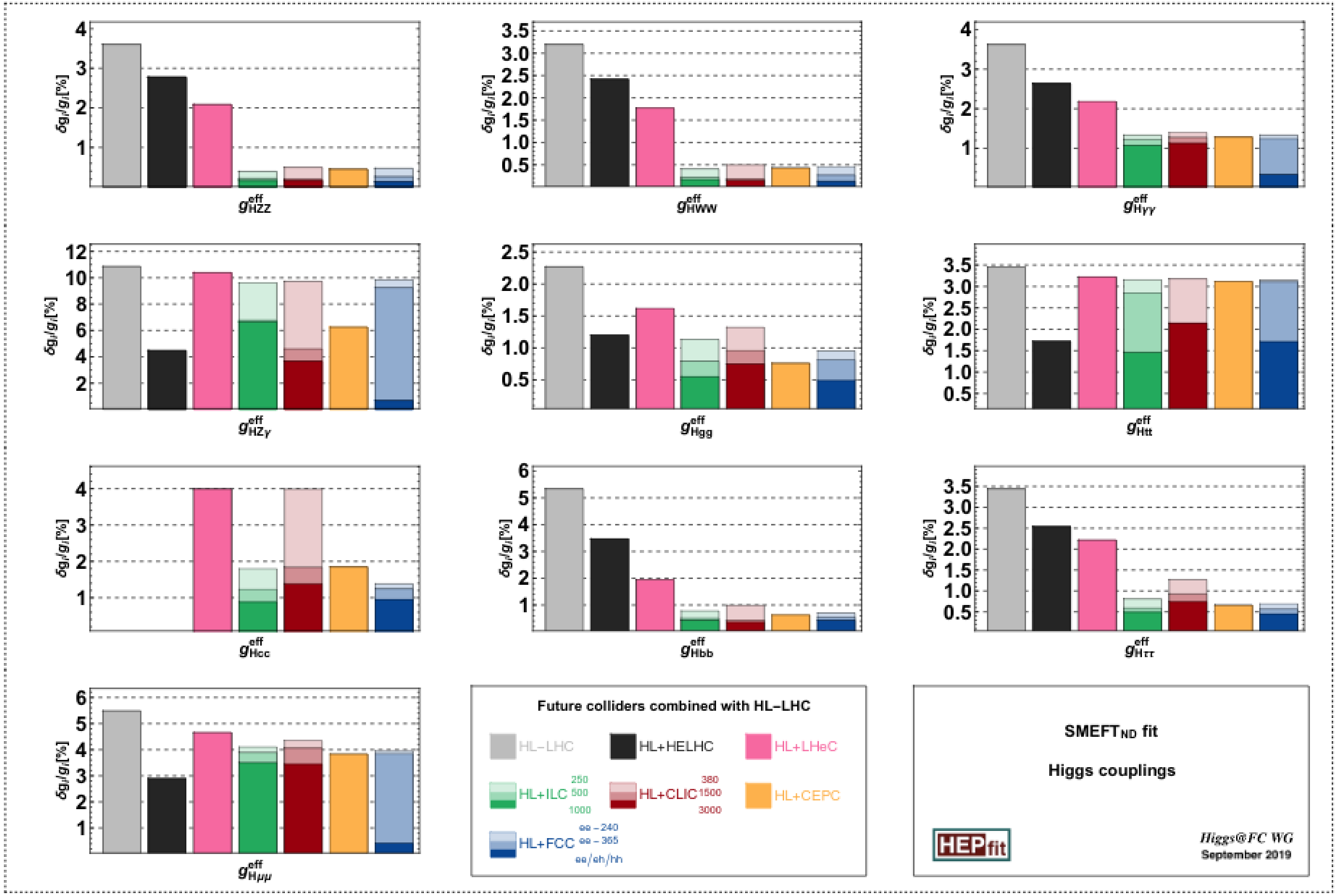
ArXiv:2303.15340

	Stat.	Syst.	Lumi.	Theory
LHC tour-de-force	0.1%	1.5% modelling	0.8% *arXiv:2212.09379*	4% *NNLO+NNLL*
e+e- hyper precision	few x *0.1%* *arXiv:1807.02441*	*0.1%*	*0.1%*	*0.1%* *N3LO, arXiv:2209.14259*

LHC is reaching surprising precision, and theory is not far behind
However, e+e- colliders can do an order of magnitude better
Caveats: LHC can do better differential measurements; theory still has time to catch up

Higgs couplings

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

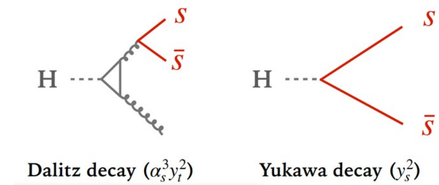


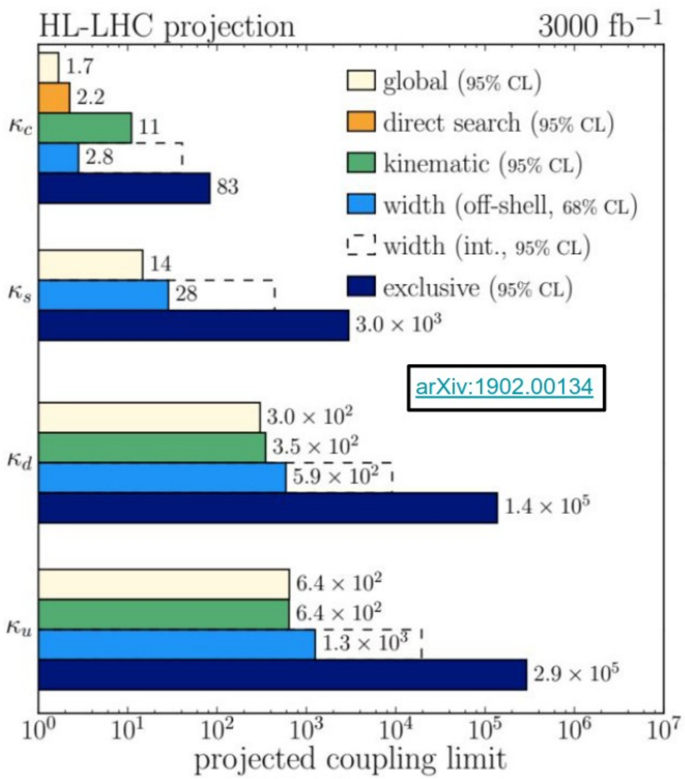
All Higgs factory projects (/ / /) do excellent Higgs physics; great improvement over LHC legacy ( )

Note: inputs have large uncertainty; lepton and hadron colliders are hard to compare on the same footing

Higgs to strange coupling

The Higgs-to-strange coupling is impossible to measure
BR(H → ss) = 0.024%, strange tagging requires PID





At an e+e- Higgs factory, can we:
- define a Higgs to strange coupling theoretically?
yes, see this talk
- control fragmentation systematics?
yes, Z-pole run is ideal to settle this
- design a detector with excellent Particle ID?
yes, but PID comes at a prize
(→ specialized flavour experiment?)
- tag strange quarks?
yes, ML-based taggers are getting better fast!
- measure the strange quark Yukawa?
yes, at O(100%) precision

Higgs to strange coupling

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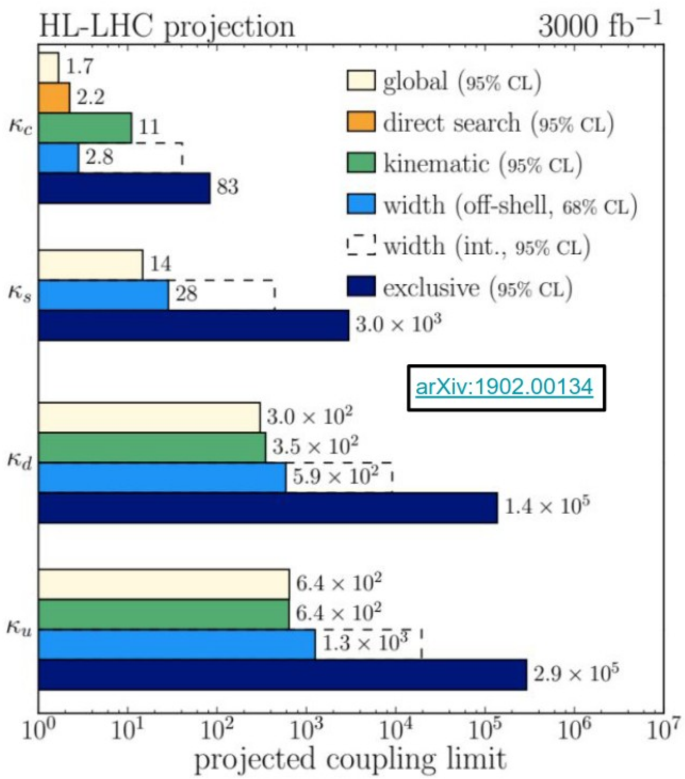
Very hard

BR(H→ss) = 0.024%, strange tagging req s PID



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- tag strange quarks?

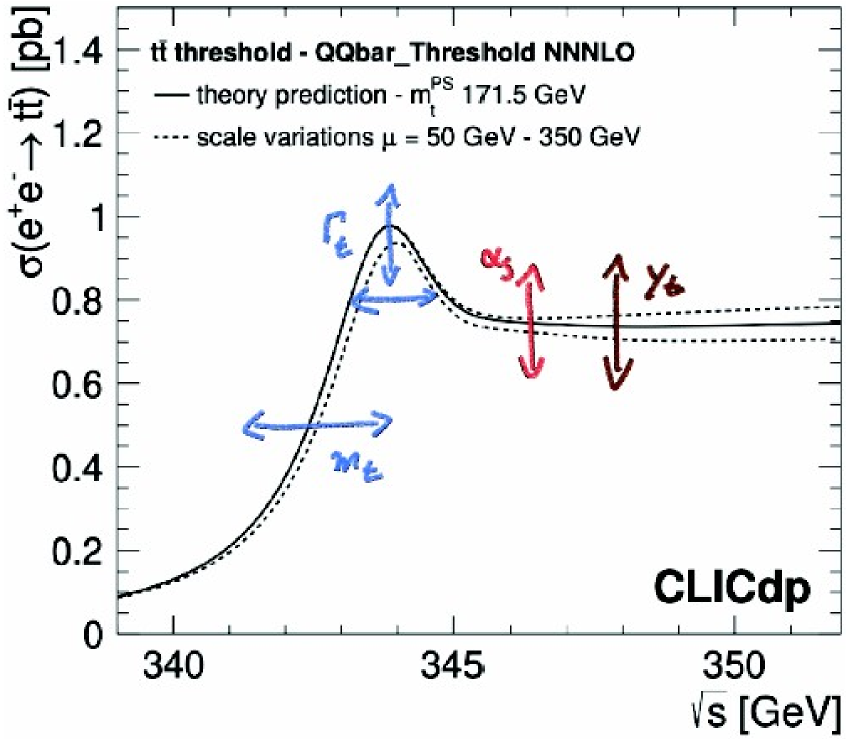
yes, ML-based taggers are getting better fast!

- measure the strange quark Yukawa?

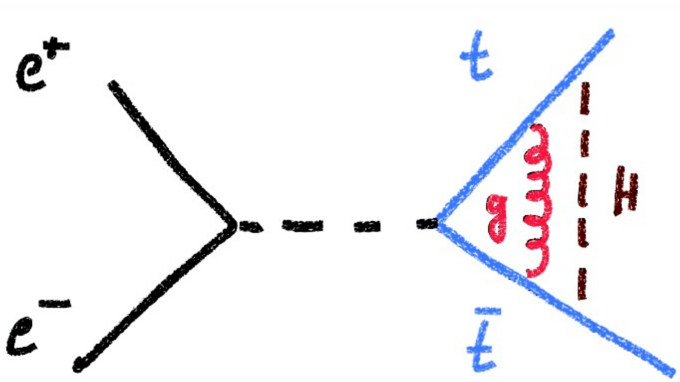
yes, at O(100%) precision

e+e- threshold scan

A scan of the e^+e^- center-of-mass energy through the pair production threshold allows for the ultimate mass measurement *(Gusken & Kuhn ‘85, Peskin & Strassler ‘91)*
Experimental studies: Martinez & Miquel, hep-ph/020735, Seidel et al., arXiv:1303.3758
Part of the operation plan for all e+e- collider projects: Higgs & top factory!

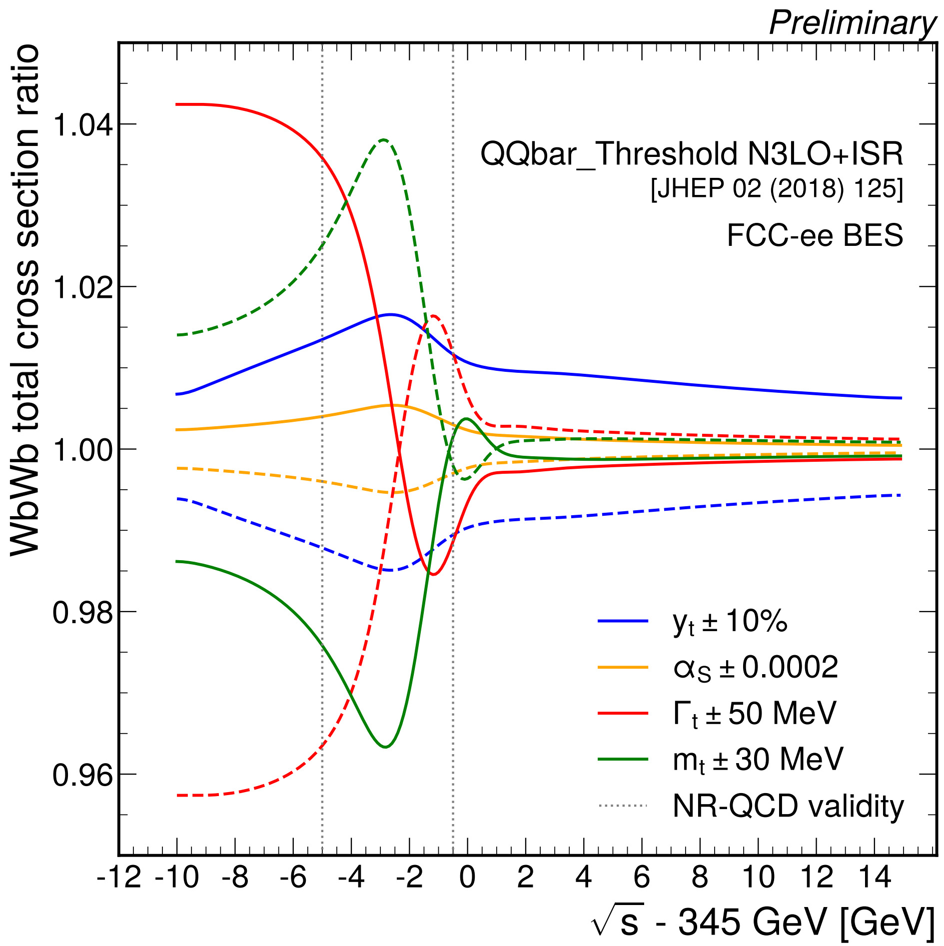


Calculation: Beneke et al.
Art-work: Frank Simon



The threshold position is sensitive to the top quark mass, the shape to the width
The normalization is sensitive to strong coupling and top quark Yukawa coupling
Just measure the cross section vs. sqrt(s) shape and derive all parameters

Top quark mass from threshold scan



Fast-simulation study in FCCee environment, using state-of-the-art tools

Profile likehood fit, **in-situ control of b-tagging efficiency and background**

Statistical uncertainty: < 10 MeV
with 410/fb over 10 scan points

Theory uncertainty ~40 MeV
Fit of PS "threshold" mass

Machine-related uncertainties OK
- beam energy calibration
- luminosity calibration
- BES from synchrotron radiation (circular)
- luminosity spectrum shape (linear)

Talks by Matteo Defranchis and Ankita Mehta

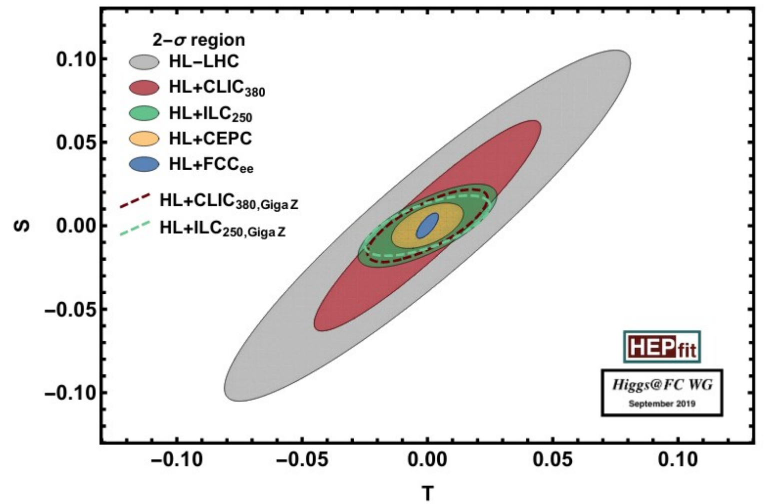
Z-pole

Revisit Z-pole physics expored by LEP and SLC, with much greater luminosity, better detectors and more advanced theory

Improve EW precision observables, but not only:
- flavour physics 10^{12} Z → bb/cc
- tau-physics 10^{11} Z → $\tau\tau$
- QCD with easy initial state

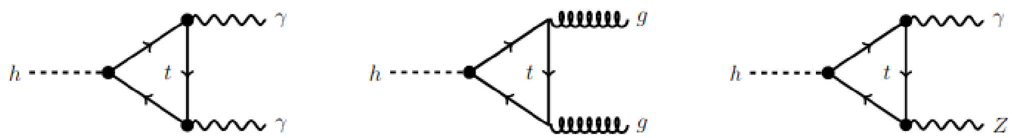
(Reference table for Snowmass21 reports)

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	0.2 – 1.0	Ratio of hadrons to leptons; acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	0.4 – 1.6	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
σ_{had}^0 ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{\text{pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W



"TeraZ" run of circular colliders: 10^6 times LEP
"GigaZ" run of linear colliders: 10^3 times SLC

The top Yukawa coupling at a lepton collider



250 GeV run offers “indirect” sensitivity to the top Yukawa

Δy/y < 1% from H→ gg — *Mitov et al., arXiv:1805.12027*

Δy/y < 1% from H→ γγ — *Jung et al., arXiv:2006.14631*

Assuming the SM for all other couplings

500+ GeV run offers a “direct” measurement in ttH production

<3% precision — *Price et al., arXiv:1409.7157*

robust in global analysis — *Jung et al.,arXiv:2006.14631*

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	12.2	5.06	3.14	2.60	1.48	2.96
	Indiv. fit	10.2	3.70	2.82	2.34	1.41	2.52

Top-SMEFT fit on prospects, de Blas et al., 2206.08326

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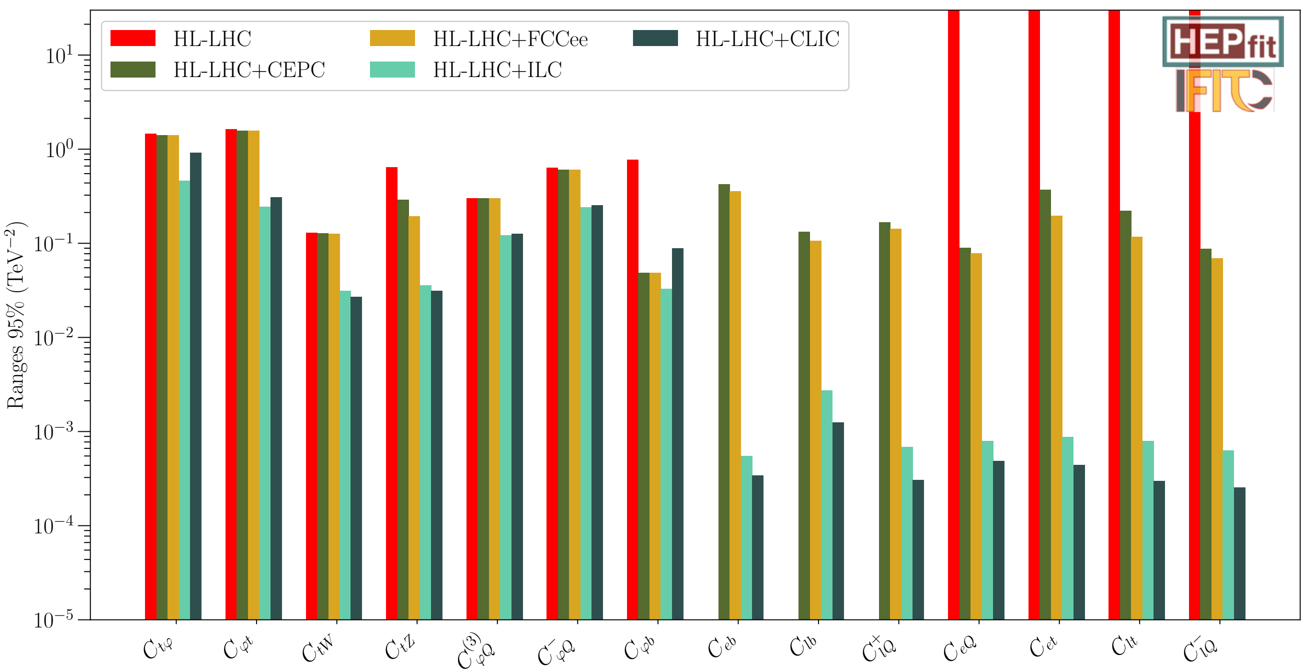
SMEFT fit HL-LHC + e+e- collider

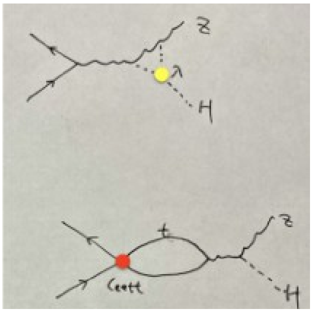
EFT for e+e-: Durieux et al. , arXiv:1807.02121
top EW fit HL-LHC/e+e-: Durieux et al., arXiv:1907.10619
Snowmass top couplings, arXiv:2205.02140
Global SMEFT fit, J. De Blas et al., arXiv:2206.08326
Snowmass report, Schwienhorst et al., arXiv:2209.11267

four-quark operators (qqtt): no progress (not shown)
two-fermion top-boson: O(1) → O(0.1)
Two-lepton-two-top (lltt): XXX → O(10^{-1} - 10^{-3})



Snowmass SMEFT fit based on Durieux et al., with updated operating scenarios

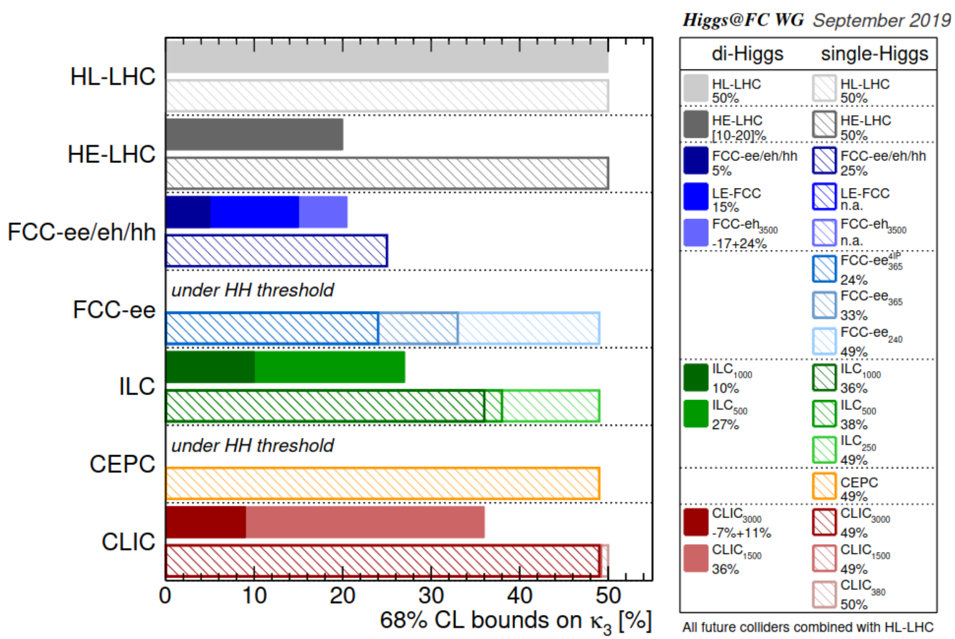
Higgs self-coupling: the holy grail of HEP



Indirect model-dependent probe of the Higgs self-coupling

Matthew McCullough
Phys. Rev. D **90**, 015001 – Published 1 July 2014; Erratum Phys. Rev. D **92**, 039903 (2015)

Indirect method takes advantage of sensitivity of ZH cross section to:
- Higgs self-coupling at NLO (McCullough, arXiv:1312.3322)
- other operators at LO (di Via et al., arXiv:1711.03978)
- many more operators at NLO (Dawson et al., arXiv:2406.03557, arXiv:2409.11466)



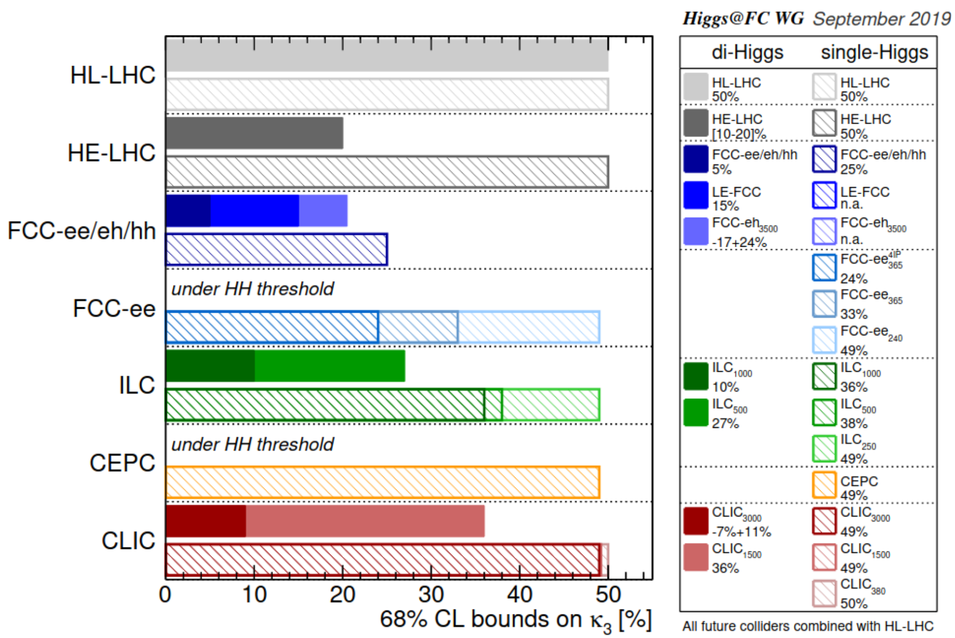
A truly global SMEFT analysis is needed

Preliminary: some degradation of self-coupling from ZH, even when $e^+e^- \rightarrow t\bar{t}$ run is included
(Junping Tian, Jorge de Blas and others)

Physics briefing book of previous streategy update: https://arxiv.org/pdf/1910.11775

Higgs self-coupling: the holy grail of HEP

Direct method **takes advantage of di-Higgs production**
Robust: the self-coupling enters at tree-level. Other couplings are constrained by single-Higgs programme (possible exception: extractio at hadron collider requires top Yukawa to 1% precision)



- e+e- collider: 20% at sqrt(s) = 500 GeV
Full-simulation study by J. List et al.
room to improve jet clustering, signal vs. background separation techniques

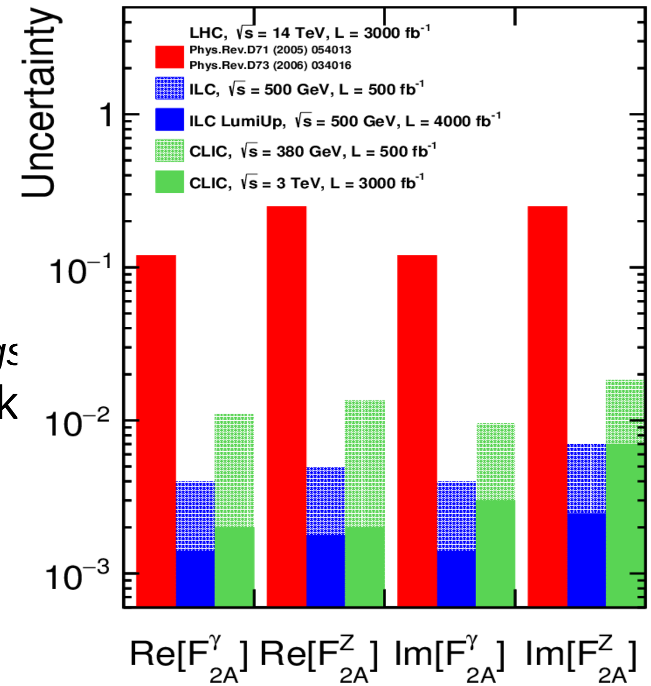
- hadron collider: 3-8% at sqrt(s) = 100 TeV
Fast-simulation study by Mangano, Ortona, Selvaggi, arXiv:2004.03505
Requires improved theory uncertainty
(1% vs. 10% in full NLO, arXiv: 1608.04798)
"*validate through full simulations of more realistic detector designs in the presence of pile-up*"

Physics briefing book of previous streategy update: https://arxiv.org/pdf/1910.11775

What about discrete symmetries? One slide

CP violation in Higgs and top sectors
Somewhat underexplored in future collider studies

Very tight constraints from low-energy probes
(i.e. electron dipole moment)
see Cirigliano et al. Is there room for CP violation in the top-Higgs
Combine with the more hermetic (but individually weak
new colliders:
Top: W. Bernreuther et al., EPJC78 (2018)
Higgs: ILC, a global project, arXiv:1903.01629



Lepton Universality bounds

Decay mode relative precision	$B(W \to e\nu)$	$B(W \to \mu\nu)$	$B(W \to \tau\nu)$	$B(W \to qq)$
LEP2	1.5%	1.4%	1.8%	0.4%
FCC-ee	$3 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$1 \cdot 10^{-4}$

New opportunities for **FCNC and FV interactions**, *as motivated by David Marzocca,* Higgs factories extend discovery potential in, e.g., e+e- → tc production and not-too-conspicuous exotic Higgs decays.

Global priorities

European, American and Asian strategies agree on big picture

— e^+e^- Higgs factory first:

large circular collider: FCC-ee (CERN) and CEPC (China)
linear collider: ILC (Japan), CLIC (CERN), CCC (US)

— exploration of the energy frontier next:

large pp collider: FCC-hh (CERN), SPPC (China)
muon collider: μ-collaboration (CERN+US)
plasma: R&D (EUPRAXIA, AWAKE), designs (i.e. ALEGRO, Hybrid)

Cool Copper Collider: high accelerating gradient in normal-conducting cavities at low temperature
https://arxiv.org/abs/2203.07646

Muon collider R&D is reinforced in EU and US
https://arxiv.org/abs/2209.01318

Hybrid asymmetric collider: e- benefit from plasma wakefield acceleration, e+ use classical acceleration: 3 km Higgs factory
https://arxiv.org/abs/2303.10150

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plasma: R&D (EUPRAXIA, AWAKE), designs (i.e. ALEG

More compact solutions are possible if we invest in accelerator technology

Cool Copper Collider: high accelerating gradient ... ducting cavities at low temperature
https://arxiv.org/abs/2203.07646

Muon collider R&D is reinforced in EU
https://arxiv.org/abs/2209.01318

Hybrid asymmetric collider: e- ben... asma wakefield acceleration, e+ use classical acceleration: 3 km H... actory
https://arxiv.org/abs/2303.10150

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Summary

The LHC and HL-LHC will continue to deliver
Guaranteed science: precision + rare SM processes
Keep an eye out for : searches + new ideas

Next stop: a Higgs (+top+EW) factory
Strategy update 2024-2026 to decide which one
Excellent Higgs physics, whichever the choice
Complementary advantages: Z-pole vs. high energy

Invest in the accelerating technology
Sustainable exploration of the energy frontier in the second half of the 21st century requires higher-field magnets and/or a muon collider and/or wakefield acceleration

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