Karlsruhe Institute of Technology

Institut für Experimentelle Teilchenphysik

Teilchenphysik II - W, Z, Higgs am Collider

Lecture 14: Future of the Higgs Sector

PD Dr. K. Rabbertz, **Dr. Nils Faltermann** | 28. Juli 2023

Short Recap

- More than ten years after the discovery of a new boson, it looks like the **SM Higgs boson**
  - The SM does not work without a Higgs boson
  - But there is strong motivation that there is more ... hierarchy problem/fine-tuning, gravity, dark matter
- Supersymmetric models to extend the SM
- Higgs measurements as portal for dark matter

- For the last lecture we will focus on present topics of interest and the future of the Higgs sector

2 Higgs Doublet Models (2HDMs)

- Effective extension of SM **adding a second Higgs doublet**
- Results in **5 Higgs bosons**: h, H, A (neutral); H^{+}, H^{-} (charged)

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- Effective extension of SM **adding a second Higgs doublet**
- Results in **5 Higgs bosons**: h, H, A (neutral); H^{+}, H^{-} (charged)
- **5 free parameters**: m_A, m_H, $m_{\mathrm{H}^\pm}$, $\tan\beta$, α (angle between doublets)
  - More than in MSSM since no extra requirements, i. e. SUSY, imposed
  - In general, up to 9 free parameters but some fixed by requiring no FCNC and $m_\mathrm{h} = 125\,\mathrm{GeV}$

2 Higgs Doublet Models (2HDMs)

- Different **types of 2HDMs depending on coupling structure**

Model	u_R	d_R	e_R
Type I	ϕ_2	ϕ_2	ϕ_2
Type II	ϕ_2	ϕ_1	ϕ_1
Lepton-specific	ϕ_2	ϕ_2	ϕ_1
Flipped	ϕ_2	ϕ_1	ϕ_2

(nomenclature sometimes differs)

- **Diverse phase space**, provides **representative phenomenology** for many different models (helpful to design and interpret analyses)
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- **Diverse phase space**, provides **representative phenomenology** for many different models (helpful to design and interpret analyses)
  - MSSM is a type-II 2HDM
- Experimentally
  - MSSM-motivated Higgs-boson searches **re-interpreted in 2HDMs**
  - In addition, **specific searches fo 2HDM inspired topologies**

MSSM

- Minimal Supersymmetric Standard Model (MSSM): extend Higgs sector with an additional doublet field
- Despite the fact that the MSSM solves a few problems, it comes not without flaws:
  - Large radiative corrections necessary to end up with a Higgs boson of 125 GeV
  - μ problem: supersymmetric Higgsino mass parameter, why of the order of EWK scale instead of Planck scale, as implied by SUSY? Might solve strong CP-problem as well
- From experimental side: phase space **almost excluded entirely**

NMSSM

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- Maybe just an additional Higgs doublet is **not enough**?

→ Next-to-Minimal Supersymmetric Standard Model (**NMSSM**)
  - Extend the MSSM with an additional SU(2) singlet
- Two additional degrees of freedom:
  - 4 (SM doublet) + 4 (MSSM doublet) + 2 (NMSSM singlet) = 10
  - 3 reserved for SM gauge bosons

  → 7 Higgs bosons: h_1, h_2, H_3, a_1. A_2, $H^\pm$ (SM Higgs boson can be either h_1 or h_2)
- Mass term for the 125 GeV Higgs boson:

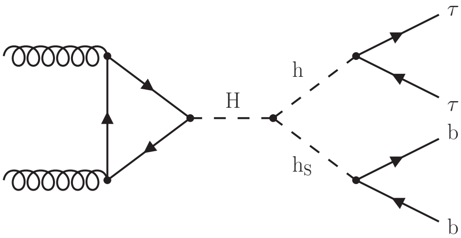
SM Higgs boson

$$m_h^2 \approx m_Z^2 \left(\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 2\beta \right) + \Delta_{rad}$$

from LO MSSM

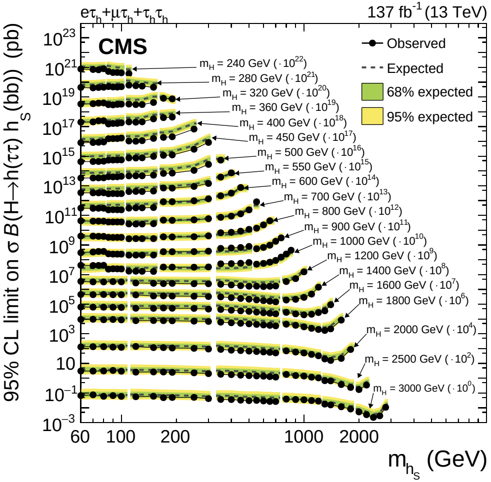
from LO NMSSM

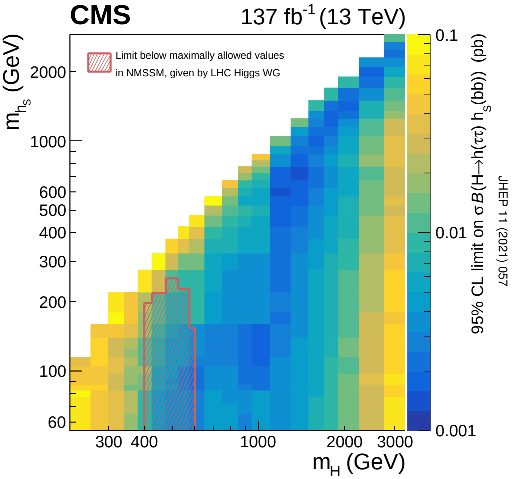
NMSSM search: $H \rightarrow h(\tau\tau)h_S(bb)$



- Cascading decay: H (heavy Higgs) $\rightarrow$ h (SM Higgs) + h_S (additional Higgs boson mainly from singlet)
  - With a high singlet contribution to h_S, highly suppressed at the LHC $\rightarrow$ $b\bar{b}$ best decay channel for h_S
  - $h \rightarrow \tau\tau$ allows to properly tag SM Higgs boson, compromise between rate and resolution
- Many different mass hypotheses for H and h_S, requires extensive and costly MC simulation for each model point

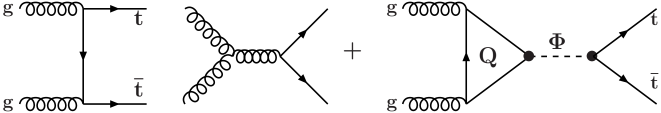
NMSSM search: $H \rightarrow h(\tau\tau)h_S(bb)$ results





Interference Effects

- **Interference effects between resonant signal and non-resonant background** can impact invariant mass distribution $\rightarrow$ indirect indication for BSM physics
- For example, heavy $\Phi = \mathrm{H}/\mathrm{A} \rightarrow \mathrm{t\bar{t}}$ production in 2HDMs



SM non-resonant bkg signal

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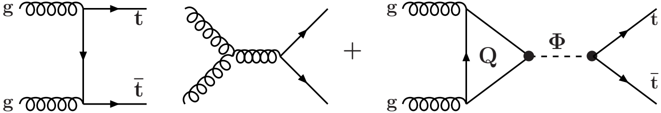

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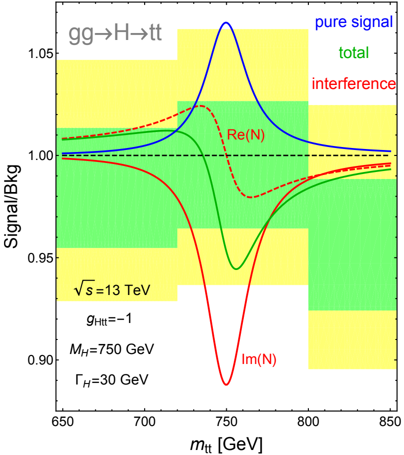
signal

- Due to interference
  - $m_{t\bar{t}}$ distribution: no resonance signal on top of background
  - Instead, **"peak-dip" structure** of $m_{t\bar{t}}$ distribution



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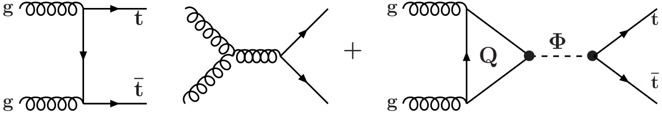

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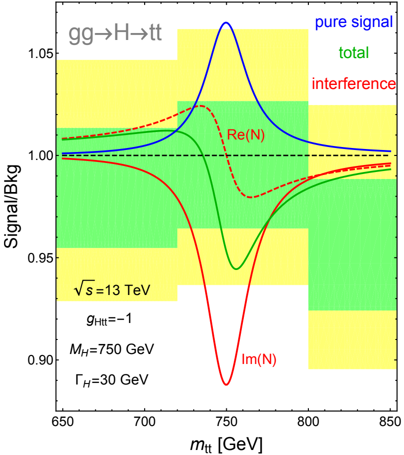
$\rightarrow$ **New analyses targeting at interference signatures**, just starting to learn how to handle and exploit



Charge-Parity (CP)

- The parity (and spin) of the 125 GeV Higgs boson has been measured from angular distributions in $H \to ZZ \to 4\ell$ decays (see Lecture 12)
- Observation of $H \to \gamma\gamma$ points to Higgs boson as C-even
- Although this already rules out a purely CP-odd Higgs boson, the 125 GeV Higgs boson could be an **admixture of a purely CP-even and CP-odd state**
  - CP-violation is one of the key ingredients for the observed matter-antimatter imbalance in our Universe
  - There is CP violation in the SM (CKM matrix), but not sufficient to explain the imbalance between matter and antimatter
- Specifically search for CP-odd components in the couplings to bosons and fermions

Anomalous Coupling Parameterization: Fermions

- Extend SM Yukawa terms with an additional CP-odd coupling:

$$A\,(\mathrm{Hff}) = -\frac{m_f}{\nu}\bar{\psi}_f(\kappa_f + i\gamma_5\tilde{\kappa}_f)\psi_f$$

$$f_{CP}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2+|\tilde{\kappa}_f|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$

- The SM is recovered for $\kappa_f = +1$ and $\tilde{\kappa}_f = 0$
  - Any value $\tilde{\kappa}_f \neq 0$ will introduce a non-SM, CP-odd coupling to fermions

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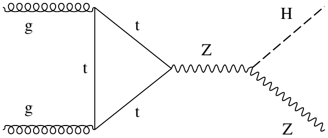
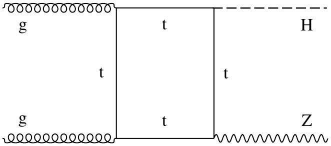
  - Any value $\tilde{\kappa}_f \neq 0$ will introduce a non-SM, CP-odd coupling to fermions
- Sensitive via $t\bar{t}$H, tH and $b\bar{b}$H production modes, but also via gg $\to$ ZH:





Anomalous Coupling Parameterization: Bosons

- For bosons ($ZZ, Z\gamma, \gamma\gamma, WW, gg$) the situation is more complicated
- Most generic extension to Higgs-gauge boson couplings:

$$A\left(HV_1V_2\right) = \frac{1}{\nu}\left[a_1^{VV} + \frac{\kappa_1^{VV}q_{V1}^2 + \kappa_2^{VV}q_{V2}^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_{V1}+q_{V2})^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^*$$
$$+ \frac{1}{\nu} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{\nu} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

with $f^{(i),\mu\nu} = \epsilon_{Vi}^{\mu} q_{Vi}^{\nu} - \epsilon_{Vi}^{\nu} q_{Vi}^{\mu}, \qquad \tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} f^{(i),\rho\sigma}$

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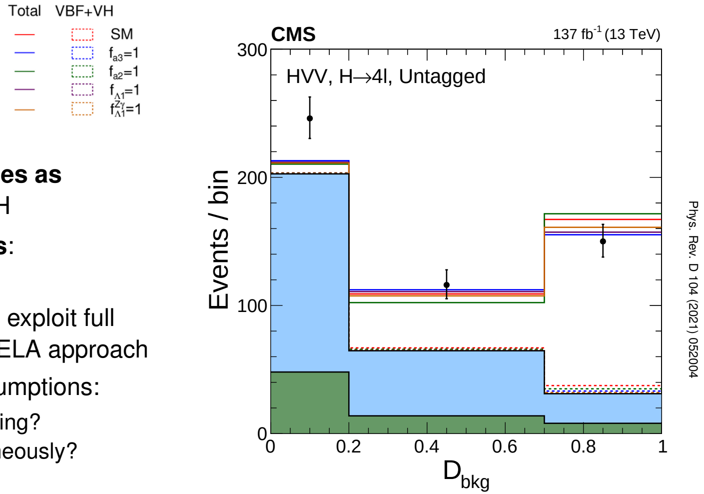
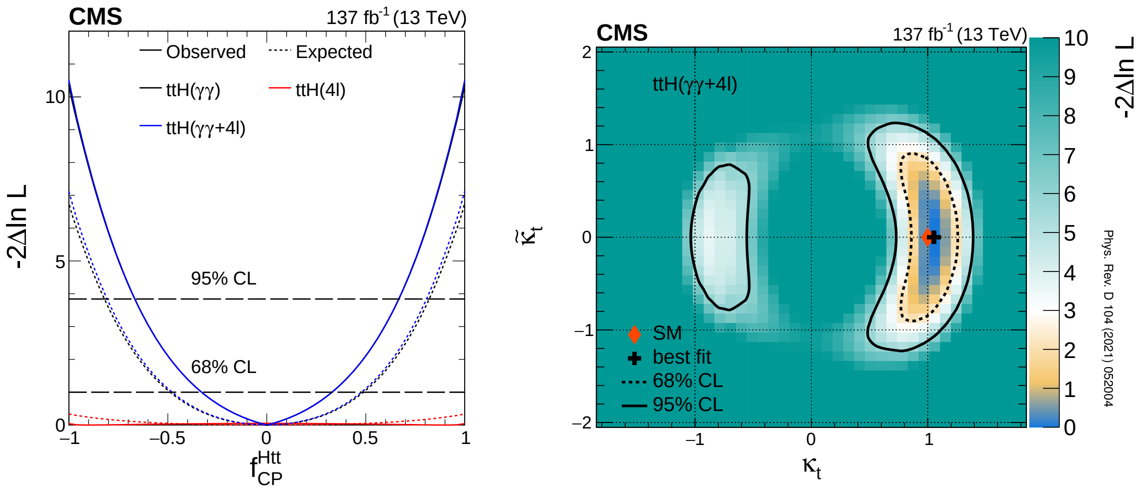
- In the SM $a_1^{ZZ} = a_1^{WW} = 2$, all other $a_{1,2,3}^{VV} = 0$
- Further constraints based on symmetry and gauge invariance:
  - $\kappa_1^{ZZ} = \kappa_2^{ZZ}$, $\kappa_1^{WW} = \kappa_2^{WW}$
  - $a_1^{Z\gamma} = a_1^{\gamma\gamma} = a_1^{gg} = \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = \kappa_1^{gg} = \kappa_2^{gg} = \kappa_1^{Z\gamma} = \kappa_3^{VV} = 0$

Coupling Analysis in H $\rightarrow 4\ell$ and H $\rightarrow \gamma\gamma$

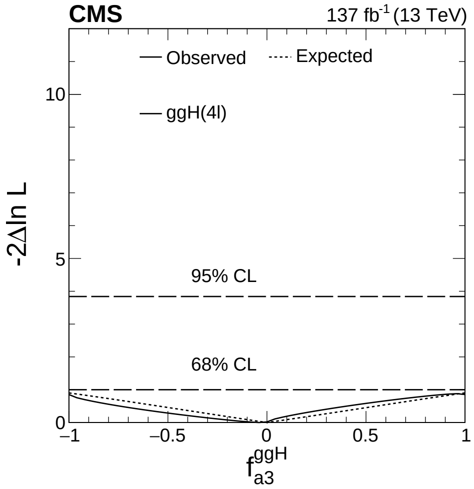


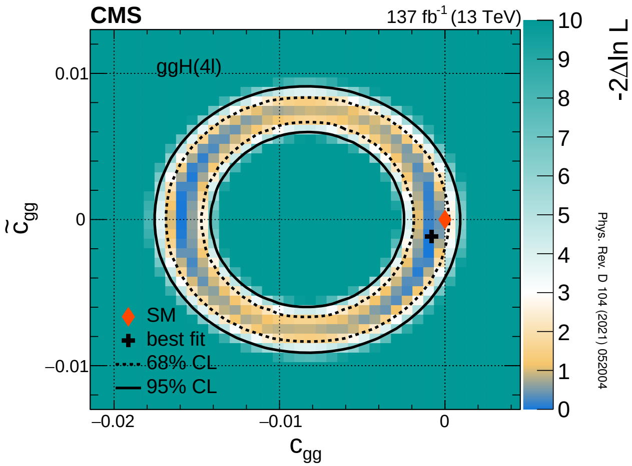
- Include **as many productions modes as possible**: ggF, VBF, VH, $t\bar{t}$H, tH, $b\bar{b}$H
- Focus on **high-purity decay modes**: H $\rightarrow \gamma\gamma$ and H $\rightarrow$ ZZ $\rightarrow 4\ell$
- Specifically the 4ℓ channel allows to exploit full angular information, heavy use of MELA approach
- Sensitivity strongly depends on assumptions:
  - variation of only one specific coupling?
  - allow all couplings to float simultaneously?

Results for Htt from $t\bar{t}H$ + tH

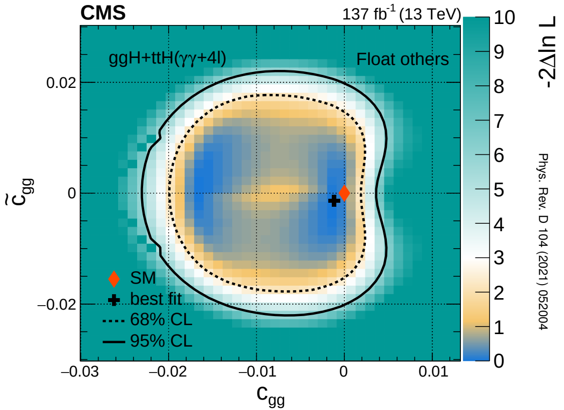


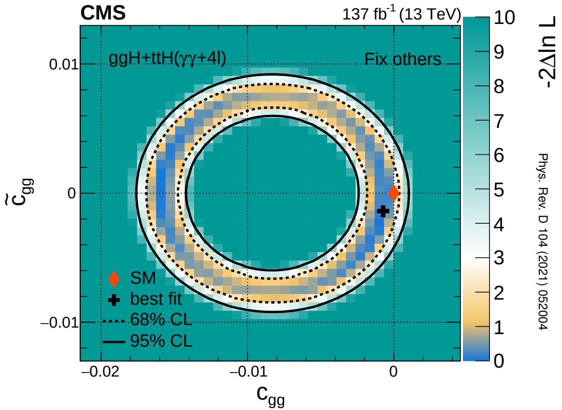
Results for Hgg from ggF





Combination of Results





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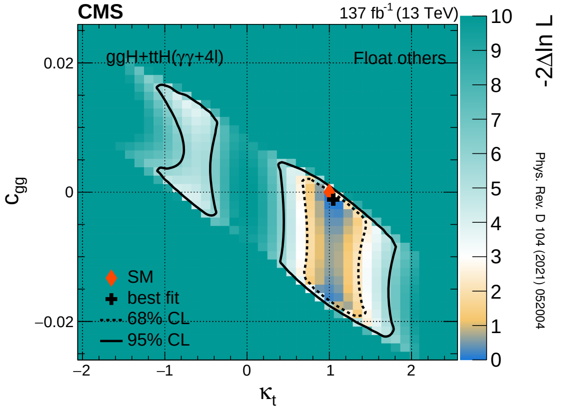
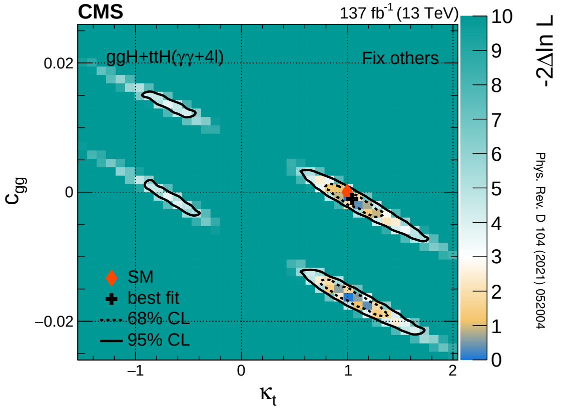
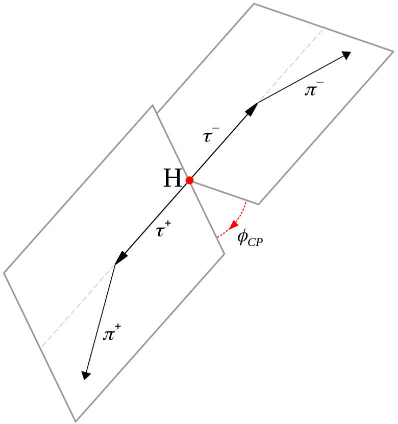
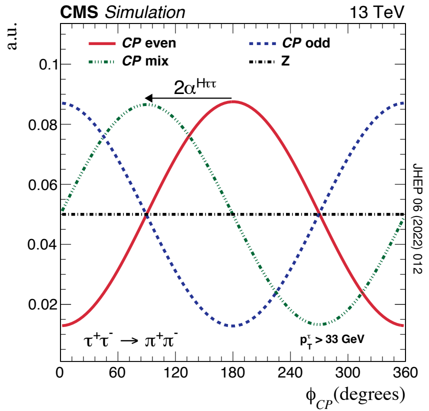




CP in the Higgs Decay: H $\rightarrow \tau\tau$

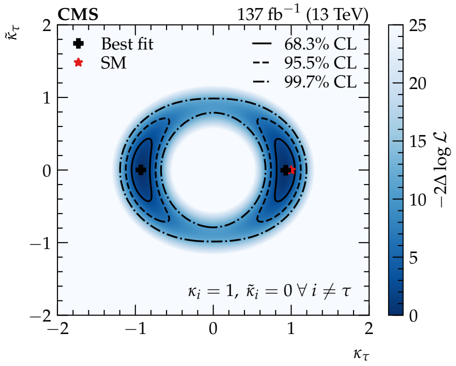


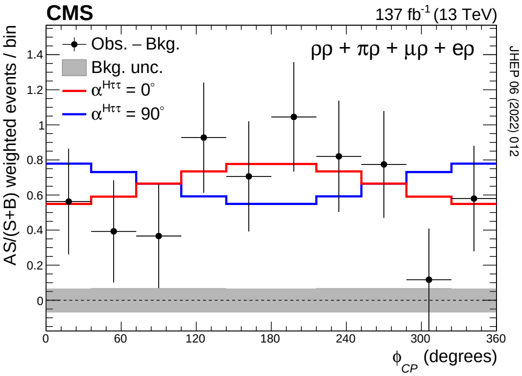


$$\tan \alpha^{H\tau\tau} = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

- CP phase from decay planes in H $\rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^- + 2\nu$ (less ν than for leptonic τ decays)

CP in the Higgs Decay: H $\to \tau\tau$

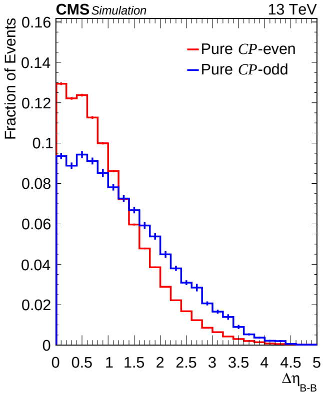


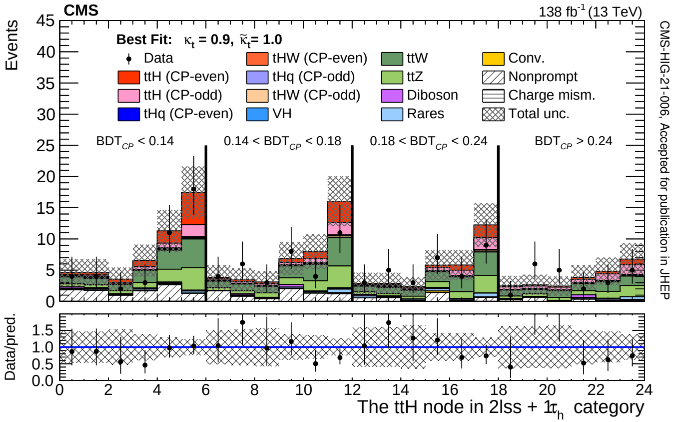


- Pure CP-odd Higgs boson rejected by 3σ
- $\alpha^{H\tau\tau} = -1 \pm 19^\circ$ observed ($0 \pm 21^\circ$ expected, assuming SM)

CP in the Higgs Production: $t\bar{t}H + tH$

- Dedicated analysts targeting $t\bar{t}H + tH$ in multilepton final states
- Exploiting kinematic differences between CP-even and CP-odd scenarios





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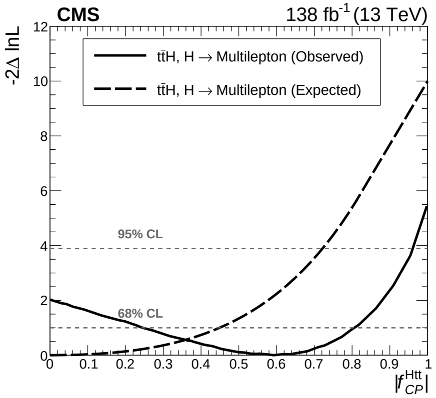

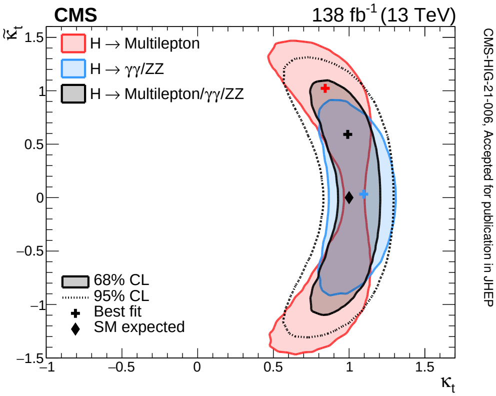

- Slight excess observed, non-zero $|f_{CP}^{Htt}|$ with 68% CL
- Combination with results from $\gamma\gamma$ and 4ℓ, more SM-like results ($b\bar{b}$ to be added soon)

Effective Field Theory

- **No clear sign for BSM physics**, despite shortcomings of SM
  - Even worse: no indication where to look
  - Vast phase-space regions to cover
  - Many different models to incorporate
- But what if new physics is beyond the reach of current colliders, e.g., the LHC?

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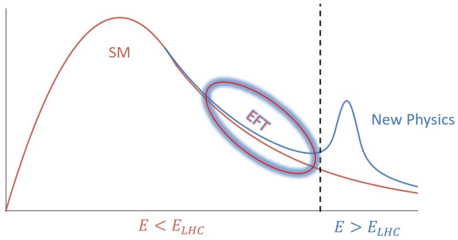

- Extend SM Lagrangian by generic higher-order operators, suppressed by BSM energy scale

$\rightarrow$ **Effective Field Theory (EFT)**

- Even if new physics is out of reach for direct detection, effects might be visible in SM distributions at a lower energy
- Historically: Fermi four-point interaction of weak decay, later explanation via massive W boson propagator

EFT parameterization

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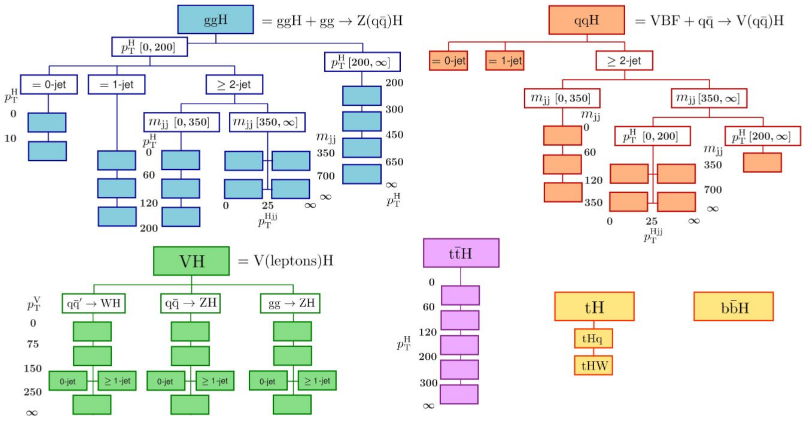
- Two different approaches:
  - **Higgs Effective Field Theory (HEFT)**: Higgs field as SU(2)×U(1) singlet, older, less restrictive
  - **Standard Model Effective Field Theory (SMEFT)**: Higgs field as part of SU(2)×U(1) doublet, more recent, motivated by low Higgs boson mass

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \mathcal{L}^{(d)}$$
$$= \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda}\mathcal{O}_i^{(5)} + \sum_j \frac{c_j}{\Lambda^2}\mathcal{O}_j^{(6)} + \sum_k \frac{c_k}{\Lambda^3}\mathcal{O}_k^{(7)} + \sum_l \frac{c_l}{\Lambda^4}\mathcal{O}_l^{(8)} + \dots$$

number of add. parameters	12	2499	948	36971

- Both approaches self-consistent, extending the SM systematically with operators following a given scheme
- In SMEFT:
  - Dimension 5 often neglected (lepton flavor violation, Majorana ν masses)
  - Dimension 6 and 8 mostly studied at the LHC, complicated fits, different bases for operators possible

Simplified Template Cross Sections



- Common definition of differential distributions between experiment and theory
- **Simplified Template Cross Sections (STXS)**
  - Easy way to combine measurements across different experiments
  - Minimizing theoretical uncertainties
- Categorization by similar production mechanisms and final-state topologies

The Hunt for Couplings to 2nd Fermions

- Couplings to heaviest fermions (=third generation) already precisely measured
  - **Top quark**: indirect via loops, directly from $t\bar{t}H$ and tH production
  - **Bottom quark**: dominant decay channel, combination of multiple production channels
  - **Tau lepton**: also from decays, less frequent, but easier to analyze

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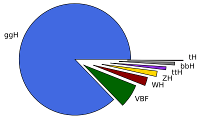
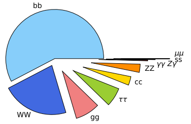
- Second-generation fermions impose additional challenges:
  - **Charm quark**: $\mathcal{B}(\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}) \approx 20 \times \mathcal{B}(\mathrm{H} \to \mathrm{c}\bar{\mathrm{c}})$, experimentally even more challenging than $\mathrm{b}\bar{\mathrm{b}}$
  - **Strange quark**: Impossible at the LHC due to $\mathcal{B}(\mathrm{H} \to \mathrm{s}\bar{\mathrm{s}})$ and missing signature
  - **Muon**: Clean signature, but very low $\mathcal{B}(\mathrm{H} \to \mu\mu)$, large EWK background

Production mode	Cross section (pb)	Decay channel	Branching fraction (%)
ggH	48.31 ± 2.44	bb	57.63 ± 0.70
VBF	3.771 ± 0.807	WW	22.00 ± 0.33
WH	1.359 ± 0.028	gg	8.15 ± 0.42
ZH	0.877 ± 0.036	$\tau\tau$	6.21 ± 0.09
ttH	0.503 ± 0.035	cc	2.86 ± 0.09
bbH	0.482 ± 0.097	ZZ	2.71 ± 0.04
tH	0.092 ± 0.008	$\gamma\gamma$	0.227 ± 0.005
		$Z\gamma$	0.157 ± 0.009
		ss	0.025 ± 0.001
		$\mu\mu$	0.0216 ± 0.0004





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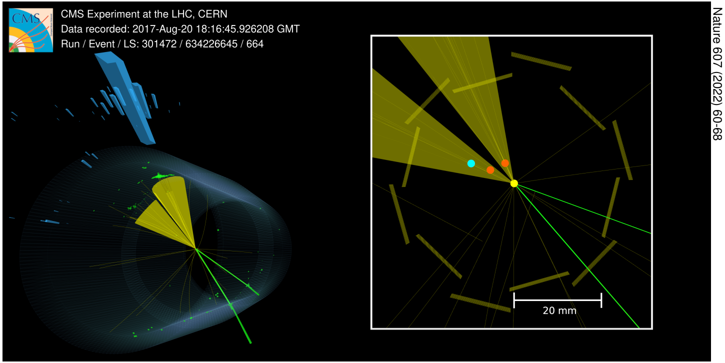
Status H $\rightarrow$ cc



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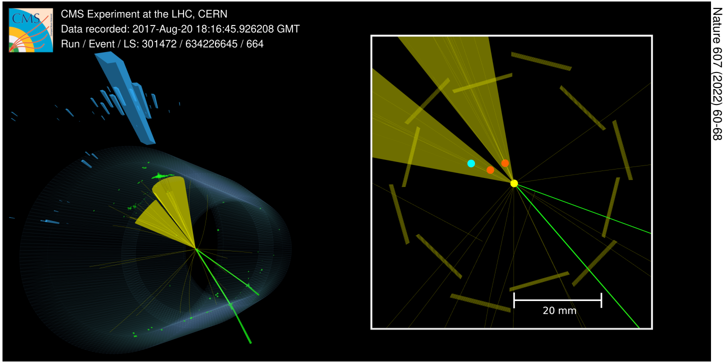
- Historically similar procedure as H $\rightarrow$ bb (VH) analysis:
  - Exploit long lifetime of B(D) hadrons, reconstruct secondary vertex for **b(c) tagging**
  - Reject most jets stemming from lighter quarks (u, d and s quarks) or gluons
  - Hcc coupling measurement relies on correctly identifying jets from charm quarks

Status H $\rightarrow$ cc



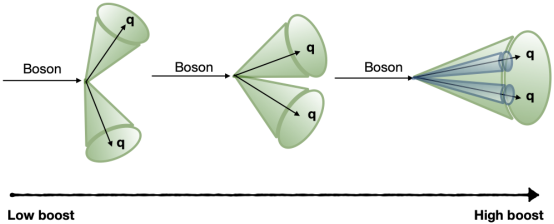
Nature 607 (2022) 60-68

- Historically similar procedure as H $\rightarrow$ bb (VH) analysis:
  - Exploit long lifetime of B(D) hadrons, reconstruct secondary vertex for **b(c) tagging**
  - Reject most jets stemming from lighter quarks (u, d and s quarks) or gluons
  - Hcc coupling measurement relies on correctly identifying jets from charm quarks

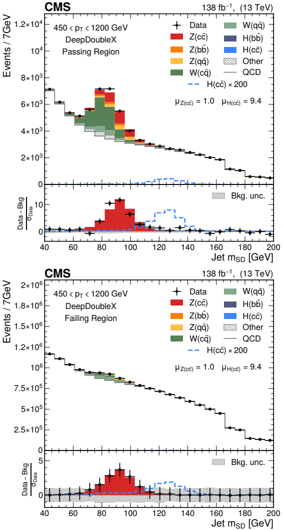
- Large background contribution, even when targeting only best production modes (VH)
- Sensitivity limited by systematic uncertainties of c tagging and background modeling
  - Will not improve with more data nor can one expect significant improvement of these uncertainties

$\rightarrow$ Think about complementary approaches to measure the Hcc coupling

Analysis of Boosted Final States



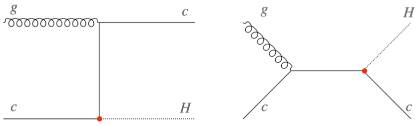
- Boosted (high-p_T) regime, where both jets from the Higgs boson decay merge into a single, **large-radius jet**
- Validated with Z $\rightarrow$ cc, measured as $\mu(\mathrm{Z}) = 1.00^{+0.17}_{-0.14}\,(\mathrm{syst}) \pm 0.08\,(\mathrm{theo}) \pm 0.06\,(\mathrm{stat})$
- Observed (expected) upper limit at 95% CL on $\sigma(\mathrm{H})\mathcal{B}(\mathrm{H} \rightarrow \mathrm{cc})$ times SM prediction: **47 (39)**



Accepted for publication in Phys. Rev. Lett.

Associated Hc Production

- Idea: try to not focus on H $\rightarrow$ cc decays, but on **associated production of the Higgs boson and charm quark**
  - Large variety of different Higgs boson decay channels to analyze, better mass resolution for Higgs boson candidates (bad resolution for H $\rightarrow$ cc due to hadronic shower components and neutrinos inside c jets)
  - Still end up with additional charm quarks in the final state, c-tagged jets as probes to reject background events



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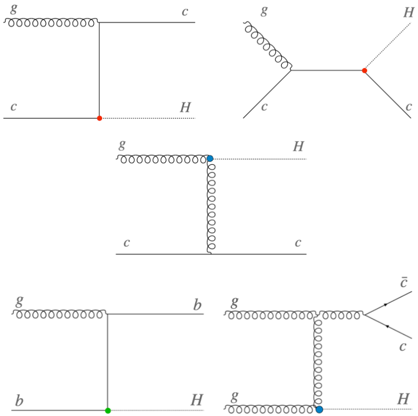
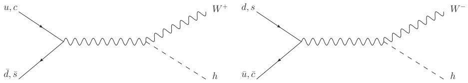
- Irreducible Hc background from Hgg vertex via top quark loop
- Further reducible background from the same diagram with bottom quarks and multiple charm quark
- New analysis concept, focusing on H $\rightarrow \gamma\gamma$ for now, currently no public result available



Charge Asymmetry in VH Production

- Extend idea and remove charm quark completely from the final state
  $\rightarrow$ **charge asymmetry in VH production**
- Higher cross section for W^+H production than for W^-H due to valence quarks in the proton



Charge Asymmetry in VH Production

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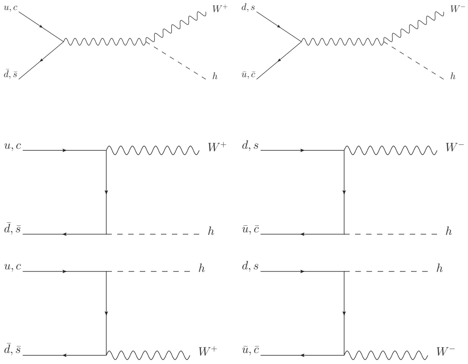
  $\rightarrow$ **charge asymmetry in VH production**
- Higher cross section for W^+H production than for W^-H due to valence quarks in the proton
- VH production not only via boson-mediated *s* channel diagrams, but also via quark-mediated *t* **channel diagrams**
- Only bosons are produced, can pick easiest ($\rightarrow$ mostly leptonic) final states for analysis:
  - W $\rightarrow \ell\nu$ needs to know the W charge
  - H $\rightarrow$ WW, H $\rightarrow \tau\tau$, H $\rightarrow \gamma\gamma$
- Precise knowledge of proton PDF necessary

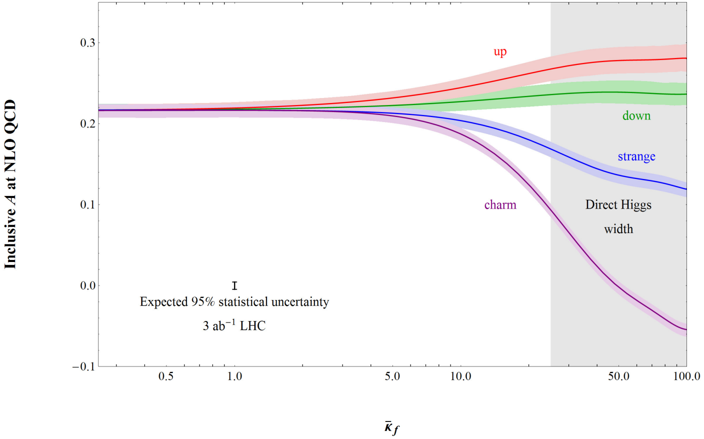


Charge Asymmetry in VH Production

- Sensitive observable: **asymmetry**

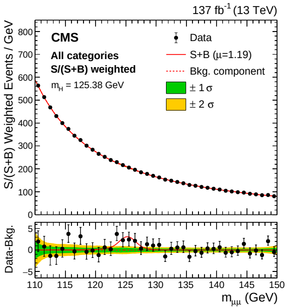
$$A = \frac{\sigma(\mathrm{W}^+\mathrm{H}) - \sigma(\mathrm{W}^-\mathrm{H})}{\sigma(\mathrm{W}^+\mathrm{H}) + \sigma(\mathrm{W}^-\mathrm{H})}$$

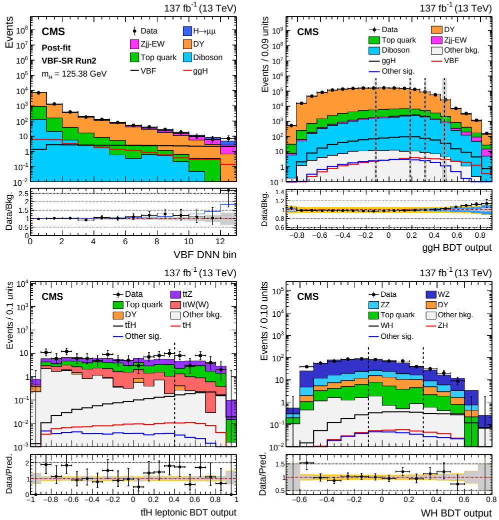
- Many systematic uncertainties will cancel out
- Targeting more towards deviations from SM that change $A \rightarrow$ hint for BSM
- Currently limited in precision by the LHC data statistics
  - Highly relevant for HL-LHC



Status H $\rightarrow \mu\mu$

- Large background requires heavy use of **ML-techniques** (BDTs, DNNs)
- Analysis statistically limited, more data will increase sensitivity $\rightarrow$ Run 3
- Still, improvements can be made on more fronts: muon resolution and scale, event categorization, new ML-techniques

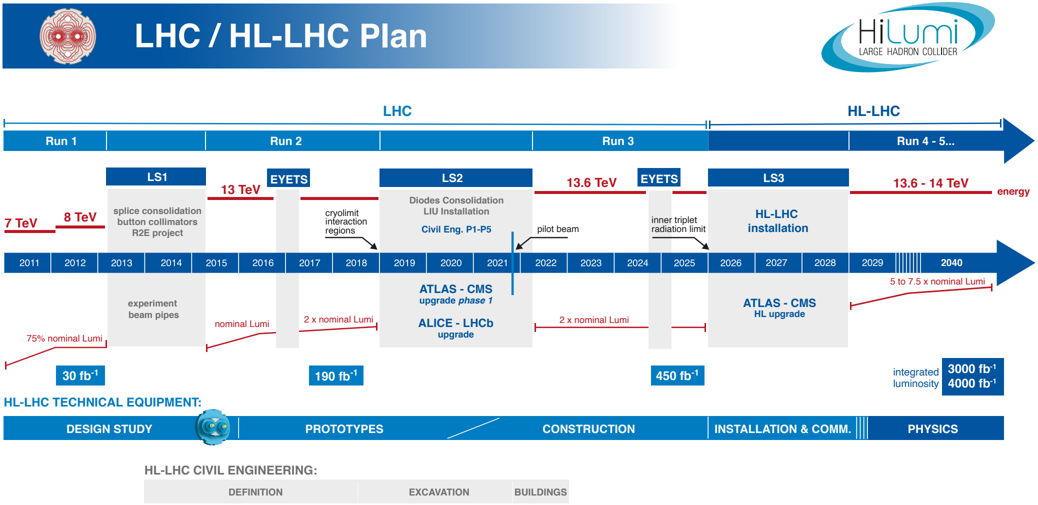




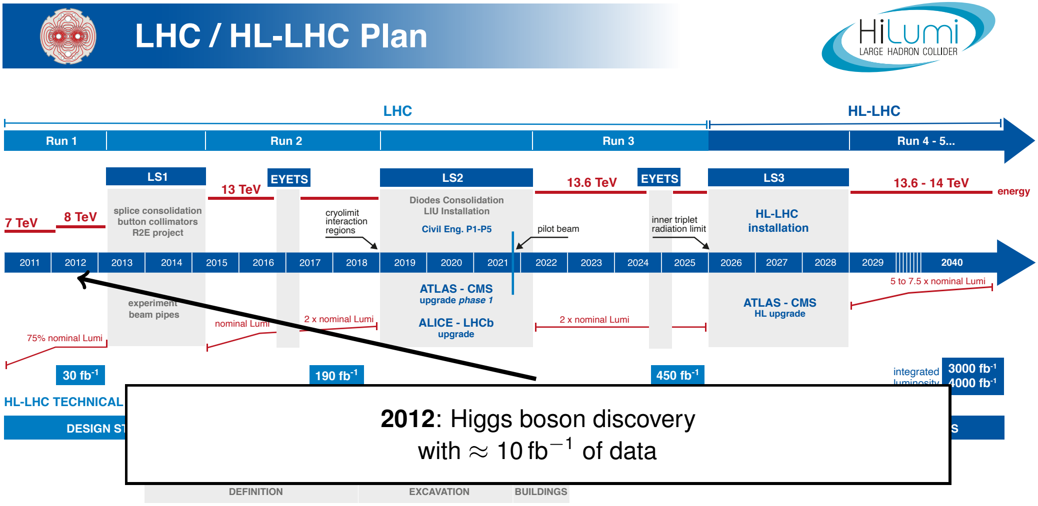
JHEP 01 (2021) 148

The Past, the Present and the Future of the LHC

Karlsruhe Institute of Technology

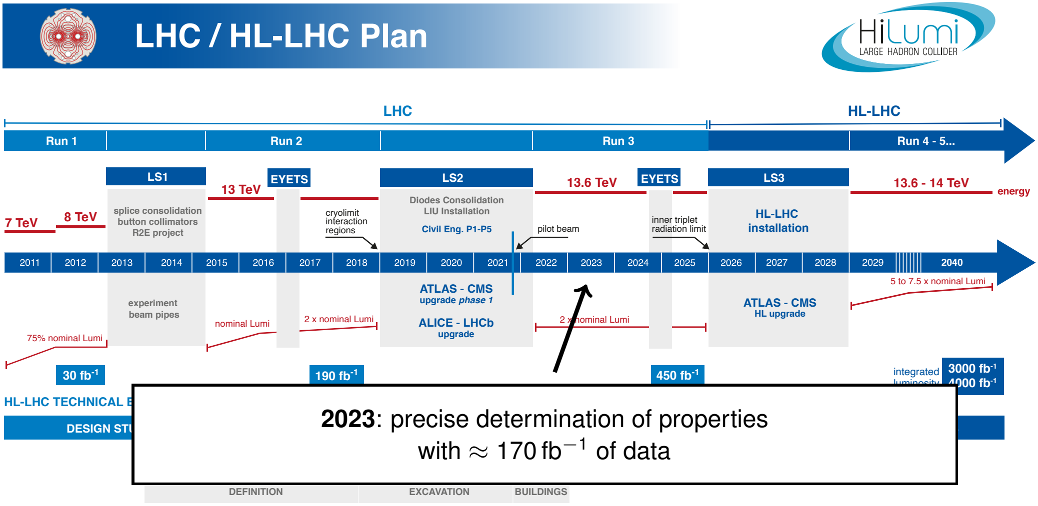


The Past, the Present and the Future of the LHC



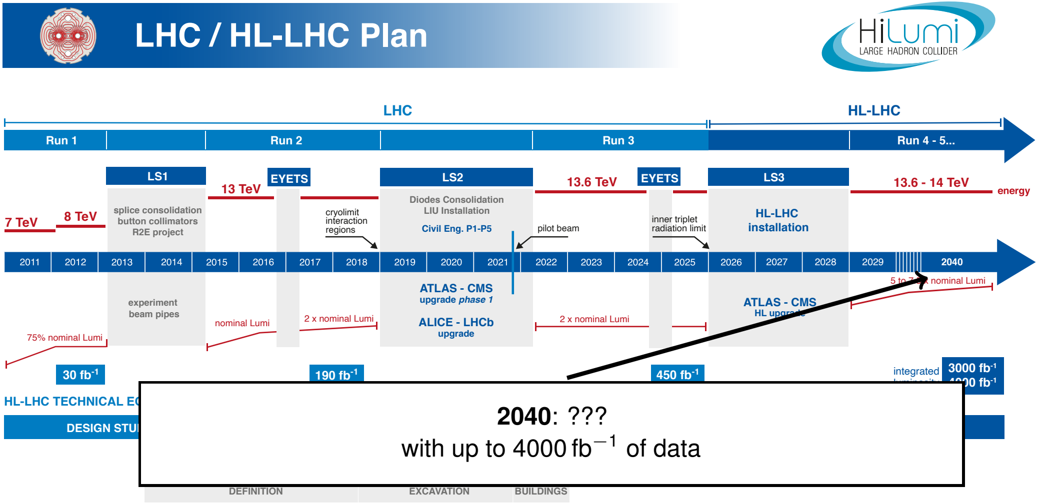
2012: Higgs boson discovery
with $\approx 10\,\mathrm{fb}^{-1}$ of data

The Past, the Present and the Future of the LHC



2023: precise determination of properties with $\approx 170\,\mathrm{fb}^{-1}$ of data

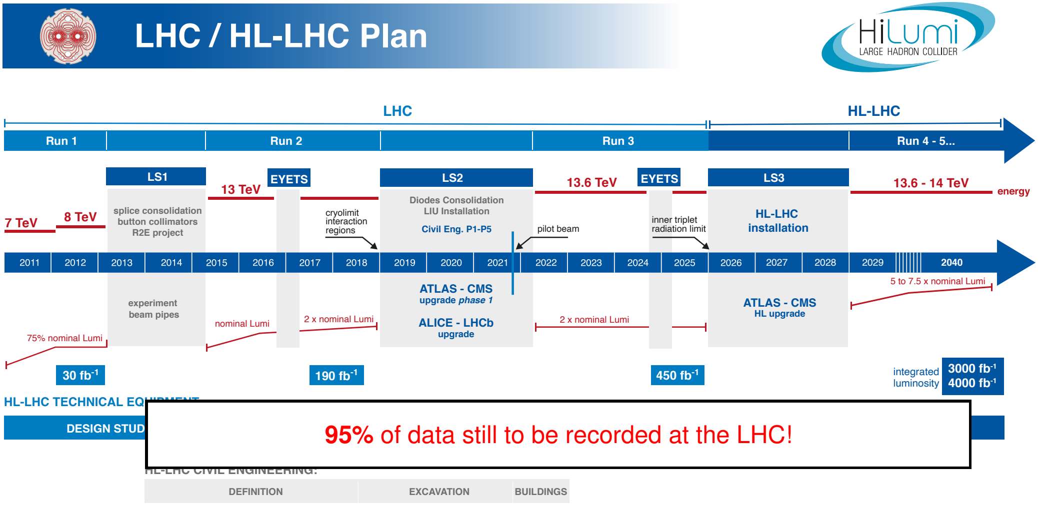
The Past, the Present and the Future of the LHC



2040: ???

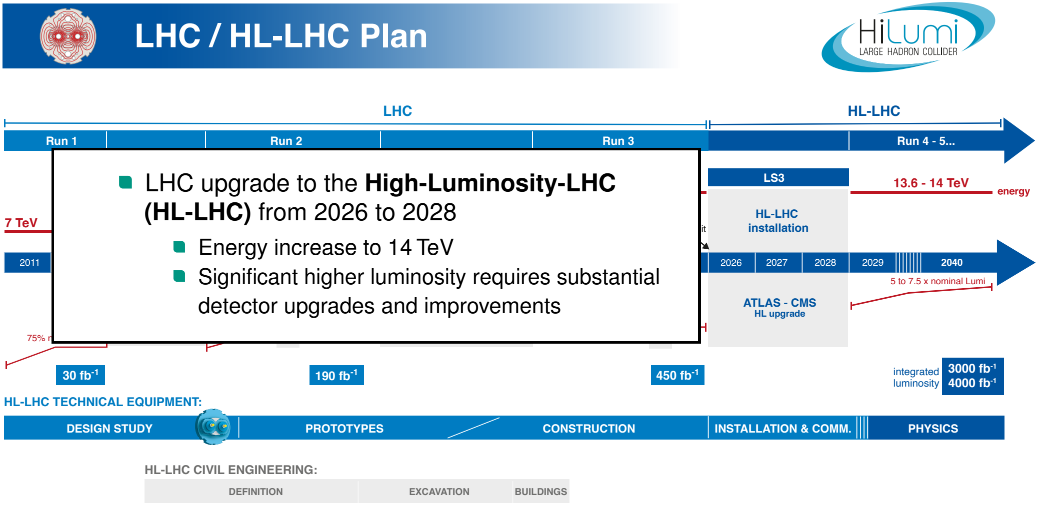
with up to 4000 fb^{-1} of data

The Past, the Present and the Future of the LHC



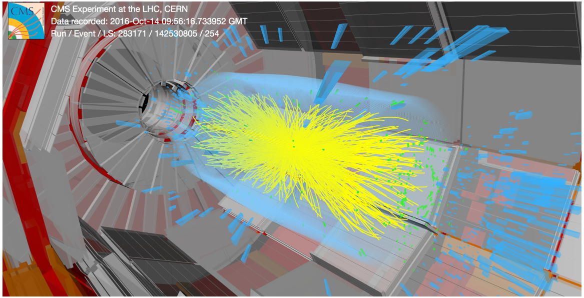
95% of data still to be recorded at the LHC!

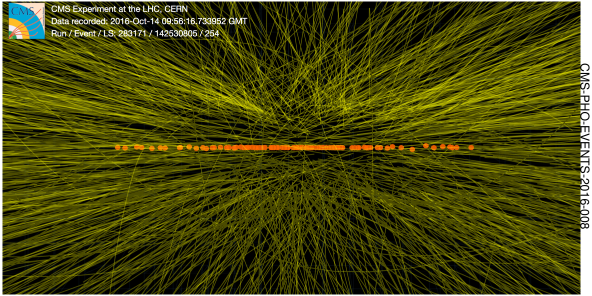
The Past, the Present and the Future of the LHC



- LHC upgrade to the **High-Luminosity-LHC (HL-LHC)** from 2026 to 2028
  - Energy increase to 14 TeV
  - Significant higher luminosity requires substantial detector upgrades and improvements

Pileup at the HL-LHC





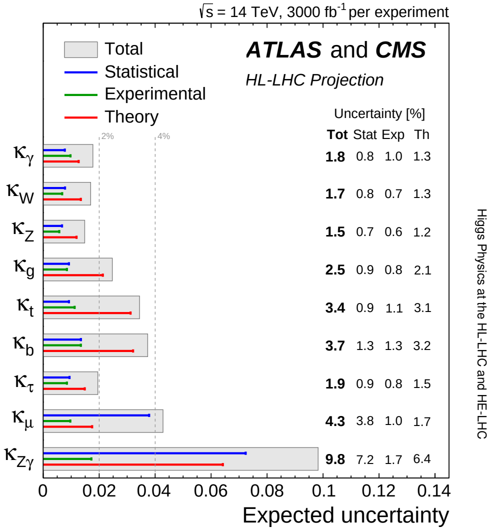
CMS-PHO-EVENTS-2016-008

- More instantaneous luminosity $\rightarrow$ more pileup interactions

Era	Luminosity (in $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	Average PU interactions
Run 2	≈ 1.5	35
Run 3	≈ 2.0	50
HL-LHC lower end	≈ 5.0	140
HL-LHC higher end	≈ 7.5	200

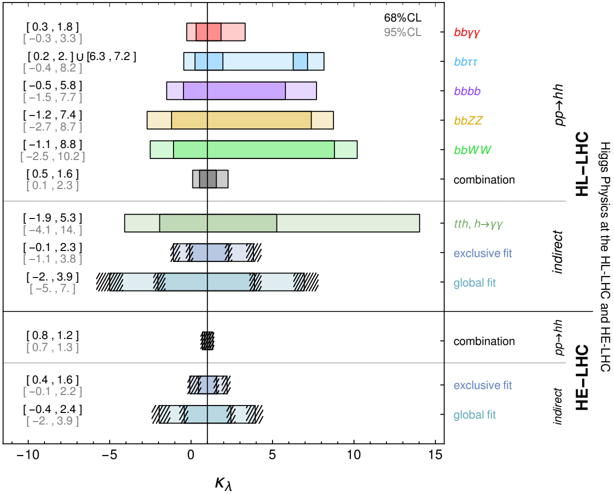
Higgs Physics at the HL-LHC: Couplings

- Measure Higgs couplings at even higher precision (than 10%)
  - Precision on κ_γ, κ_V, κ_g, κ_q systematically limited, gain particularly in κ_t
  - Access to κ_μ (precision of 4% estimated, statistically limited)



Higgs Physics at the HL-LHC: Di-Higgs

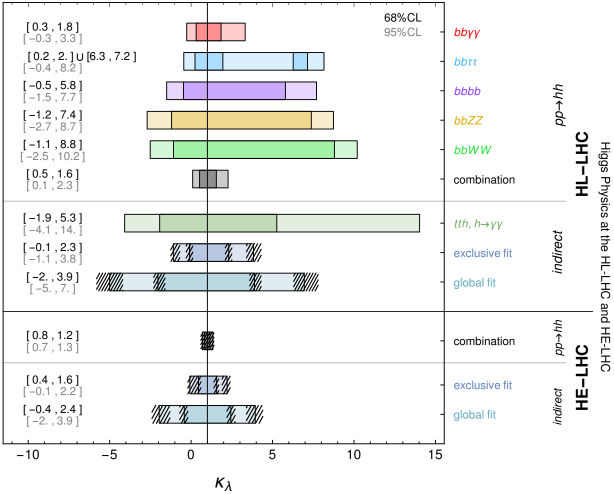
- Ultimate test of the SM: Higgs self-coupling
  - Implications to the Higgs potential



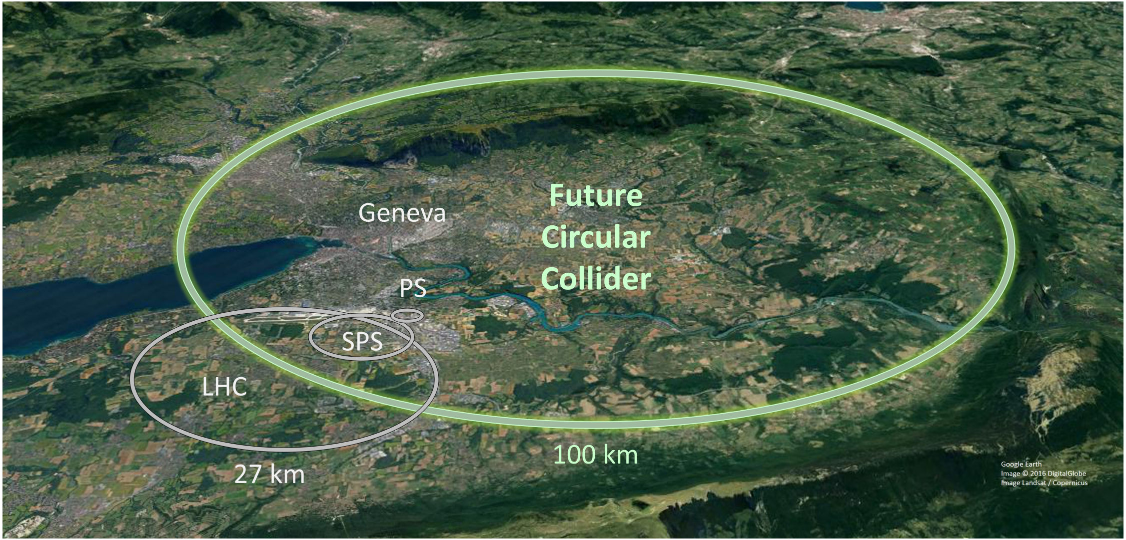
Higgs Physics at the HL-LHC: Di-Higgs

- Ultimate test of the SM: Higgs self-coupling
  - Implications to the Higgs potential
- **High-Energy-LHC (HE-LHC)**
  - Potential energy upgrade for the LHC:

    → up to 27 TeV center-of-mass energy
  - Possible with new magnet technology (4 → 8 T), replacing NbTi LHC dipole magnets with NbSn
  - Reuse of the existing LHC tunnel



Future Circular Collider



Future Circular Collider: Potential Roadmap

- **Future Circular Collider (FCC)**, a new 100 km tunnel, LHC (+SPS, PS) as pre-accelerators

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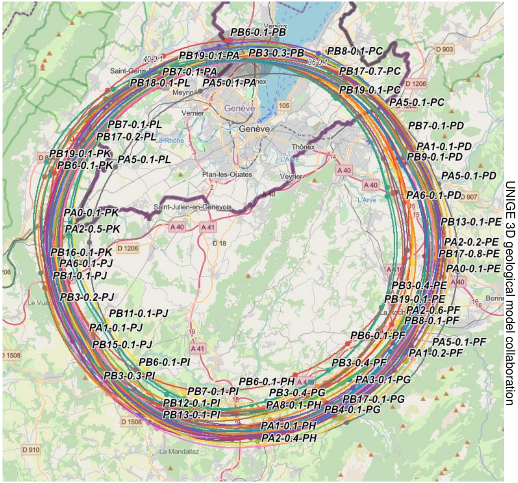
  - Geological studies, feasibility, prototype design of accelerator and detector components



UNIGE 3D geological model collaboration

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- **Research and development phase**: 2020–2040
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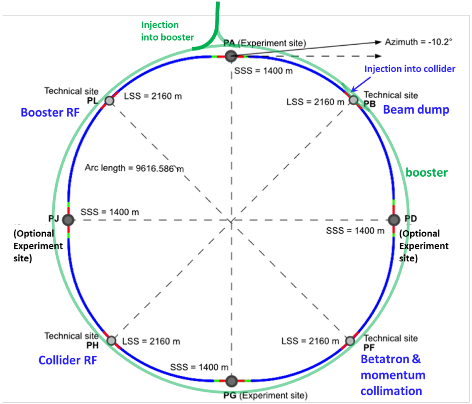
- **FCC-ee**, e^+e^- collider: 2045–2063
  - Precision measurements for Higgs, electroweak and top quark physics
  - Variable energy from 90–350 GeV (Z boson to $t\bar{t}$ thresholds, maybe even higher)



FCC week 2023

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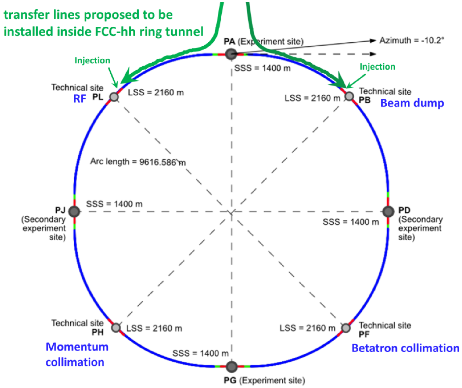
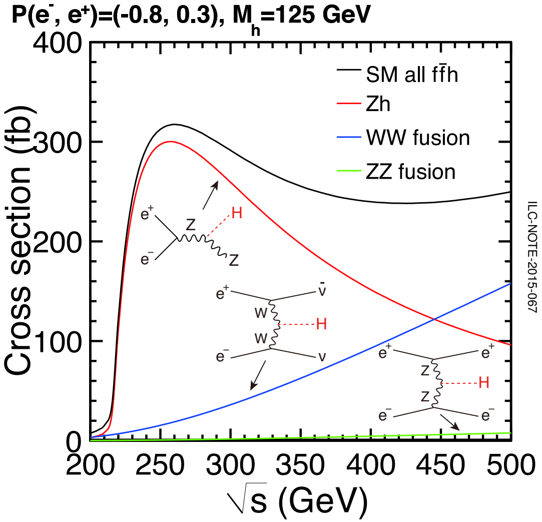
  - Precision measurements for Higgs, electroweak and top quark physics
  - Variable energy from 90–350 GeV (Z boson to $t\bar{t}$ thresholds, maybe even higher)
- **FCC-hh**, proton-proton collider: 2070–2095
  - Next milestone on the energy frontier, 100 TeV
  - Discovery machine for new physics
  - Potential hybrid FCC-eh for PDFs



FCC week 2023

Higgs-Boson Production at the FCC-ee

- Higgs boson production dominantly via
  - $e^+e^- \to ZH$ "Higgsstrahlung"
  - $e^+e^- \to \nu\bar{\nu}H$ "W fusion"
  - $e^+e^- \to e^+e^-H$ "Z fusion"



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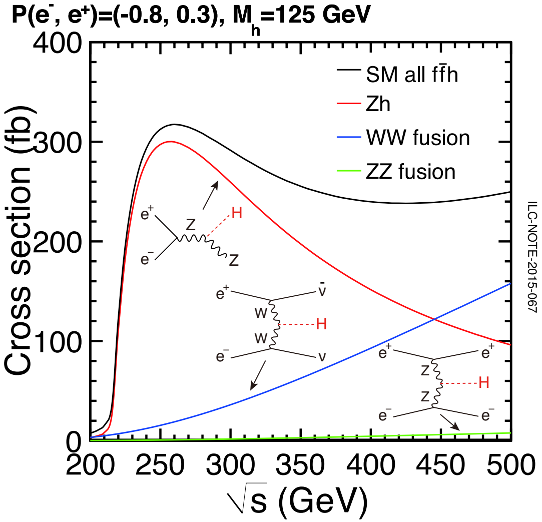
  - $e^+e^- \rightarrow \nu\bar{\nu}H$ "W fusion"
  - $e^+e^- \rightarrow e^+e^-H$ "Z fusion"
- Higgstrahlung: identify H events without looking at H decay by recoil of Z
  - Can determine **total width** Γ_H (with W-fusion information)
  - Observe exotic or invisible decay modes
  - Very precise mass (0.02 % level) and cross-section measurement (sub-% level)



Di-Higgs Production at the FCC-ee

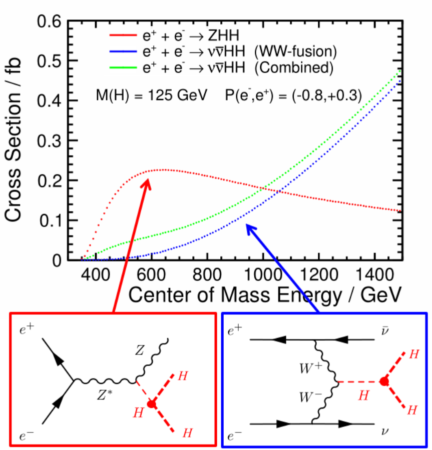
- With even higher energies, **di-Higgs** production becomes accessible at the FCC-ee
  - Significant production cross section via ZHH at around 500 GeV
  - VBF-like production ($\nu\nu$HH) becomes relevant for energies higher than 1 TeV
- But higher beam energy $\rightarrow$ higher synchrotron radiation loss ($\propto E^4$)

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10¹¹]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0

FCC week 2023

- Most likely not possible for a circular collider this size $\rightarrow$ e^+e^- linear collider
- But certainly at the FCC-hh

Cross section vs CM energy (e+e-)



Diagrams with triple-Higgs coupling

slide from T. Tanabe at Higgs Coupling Conference, 2016

Potential at the FCC-hh

Karlsruhe Institute of Technology

- Hadron colliders are discovery machines (W, Z, top, Higgs)
- 100 TeV center-of-mass energy allows to directly search for high-mass resonances
- Precision on Higgs boson couplings and trilinear self-coupling

	$gg \to H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(H) \times B(H \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(H) \times B(H \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(H) \times B(H \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(H) \times B(H \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(HH) \times B(H \to \gamma\gamma)B(H \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = B(H \to \mu\mu)/B(H \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = B(H \to \gamma\gamma)/B(H \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H \to \gamma\gamma)/B(H \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = B(H \to \mu\mu\gamma)/B(H \to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}H) \times B(H \to b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(H \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

FCC-hh: The Hadron Collider

Sustainability in High Energy Physics

- A new collider will be **expensive**: construction, operation, maintenance, ...
- On top: environmental impacts and footprint
- How can we justify all these costs?

Sustainability in High Energy Physics

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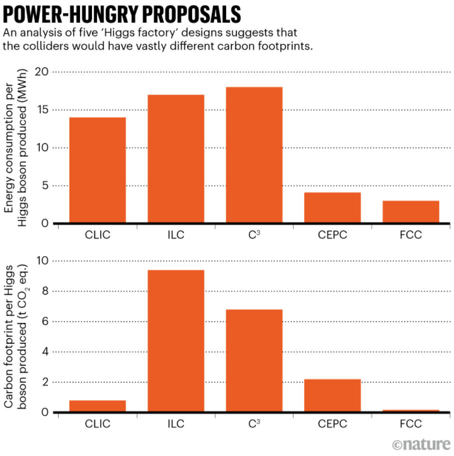
- On top: environmental impacts and footprint
- How can we justify all these costs?

- Future colliders aim for energy efficiency
  - Incorporated already into the design of the collider
- Job opportunities, well-trained personal for industry
- Fundamental research will create spinoff technologies
  - Magnet technology, radiation therapy, material science, WWW
- Socio-economic impact analysis:

→ **Benefits will outweigh the costs**



DOI: https://doi.org/10.1038/d41586-022-03551-5

Summary: Future Higgs-Physics

- Complementary Higgs-physics programme at **HL-LHC** and the (potential) **Future Circular Collider**
- Expect ultimate precision at sub-percent level on Higgs-boson coupling measurements
- Precision on self-coupling below 10% in the long run
  - Rich physics programme with strong case

  $\rightarrow$ understanding electroweak symmetry breaking!
- The SM is complete with the Higgs boson, but we know that **there is more**
- Potential Master thesis...?

W, Z and Higgs @ ETP

- **ETP has strong contributions to the W/Z/H programme of the CMS Collaboration**
  - 2nd generation coupling to the Higgs boson: Hcc and H$\mu\mu$ (nils.faltermann@kit.edu)
  - H $\rightarrow \tau\tau$: SM measurements and (N)MSSM searches (roger.wolf@cern.ch)
  - Z+jets: measurement of proton PDFs (klaus.rabbertz@kit.edu)
- **Get in touch** with newest developments in particle physics
  - Event reconstruction, statistical analysis, machine learning techniques, theory developments
  - Work with students around the world
- If you are interested, **contact us**

Institut für Experimentelle Teilchenphysik