

Higgs Hunting 2026

Results and prospects in the electroweak symmetry breaking sector

16-18 September
Orsay/Paris

16TH
HIGGS HUNTING

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Theory roadmap towards the FCC

Higgs Hunting 2026
September 16-18, 2026

Laura Reina

FSU | DEPARTMENT
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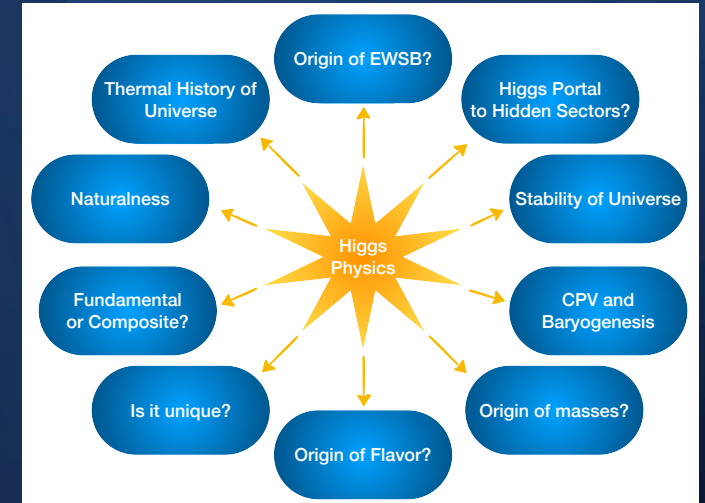


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Future Directions

Improved Precision and Energy

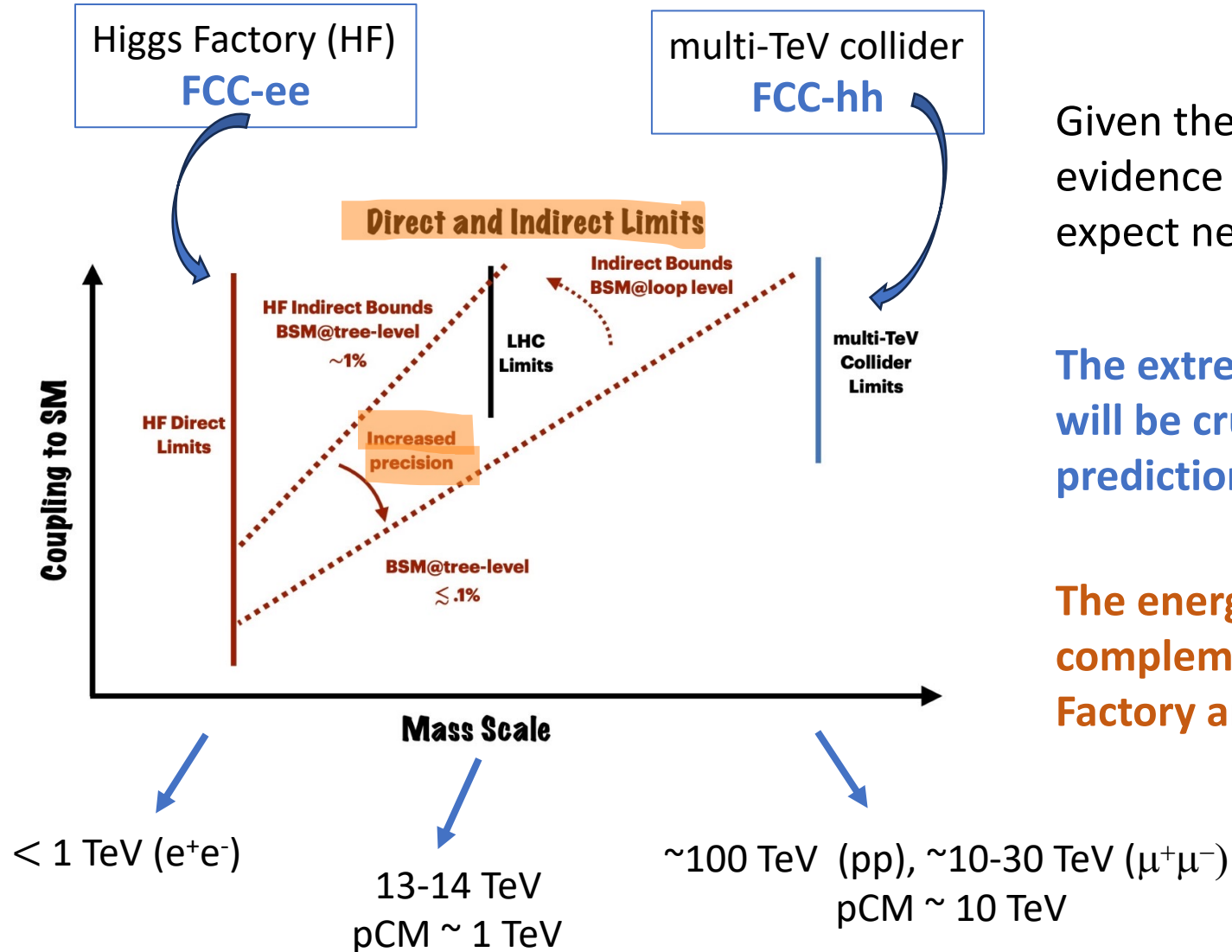


SnowmassEF- 2021

- **Exploring the nature of the Higgs boson has been central to the discussion of future colliders,** because of its intrinsic relation to the most fundamental open questions that may lead us to new physics beyond the Standard Model.
- **Exploring it further will take higher precision and higher energy.**

Future directions: precision and energy

EF Snowmass Report, 2211.11084

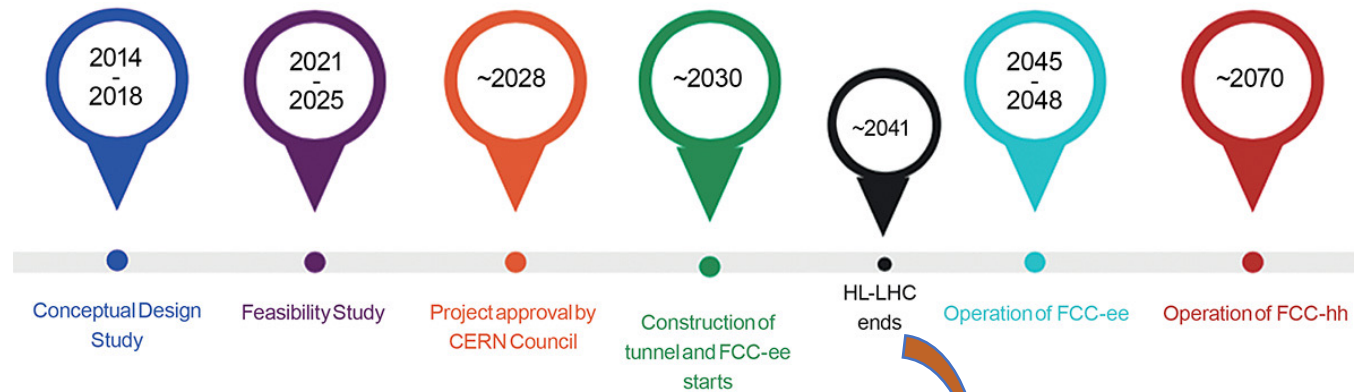


Given the level of consistency of the SM, and no clear evidence of new particles in LHC searches so far, we expect new physics effects to be small.

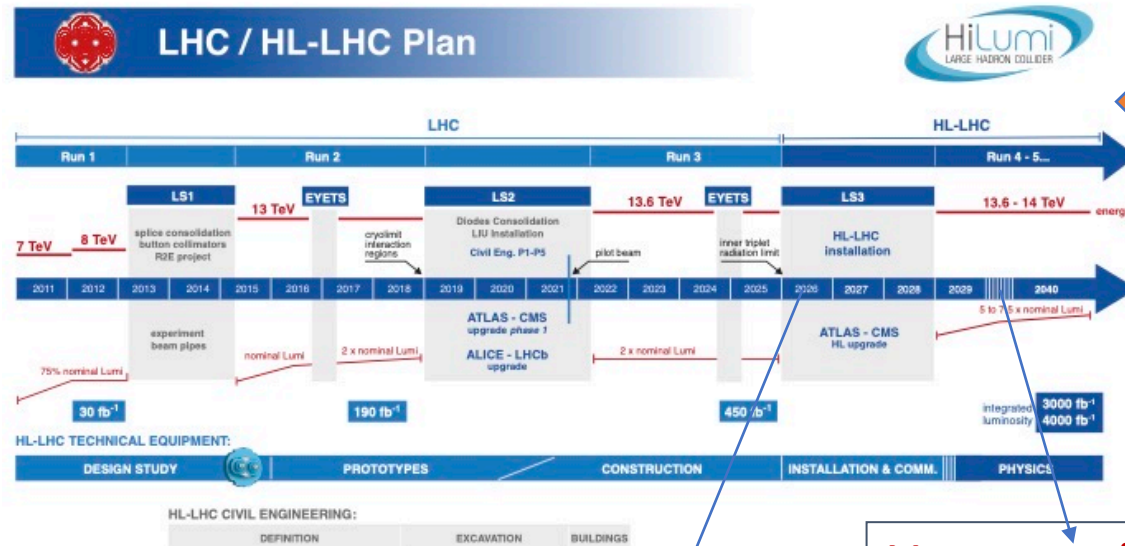
The extreme precision achievable at an e^+e^- collider will be crucial to identify small deviations from SM predictions and point to the scale of new physics.

The energies available at a multi-TeV collider will complement the precision program of a Higgs Factory and directly probe multi-TeV new physics.

This is what the FCC project will realize in a synergistic way over the span of 40+ years.



Based on the LHC legacy, which is where the roadmap to the FCC starts ...



- **Run 1: Higgs discovery**
- **Run 2: Higgs couplings**
 - outperformed expectations
- **Run 3 to HL-LHC**
 - **Higgs precision program**

20-fold increase in statistics by the end of HL-LHC!

We are here

Many years of HL running ahead of us

The LHC legacy

From Higgs discovery to Higgs precision physics and much more

- Consolidating the **SM consistency** at the quantum level.
- Exploring **Higgs couplings** beyond expected accuracy.
- Delivering a **broad program of collider precision phenomenology**.
- For the first time **exploring new physics structures** in various kinematic regimes.

Consolidating the SM consistency at the quantum level

For M_W we combine:

- ☐ All LEP 2 measurements
- ☐ Previous Tevatron average
- ☐ ATLAS and LHCb early measurements
- ☐ CDF [$M_W=(80.4335\pm0.0094)$ GeV]
- ☒ ATLAS [$M_W=(80.3665\pm0.016)$ GeV]
- ☒ CMS [$M_W=(80.3602\pm0.010)$ GeV]

$$M_W = 80.366 \pm 0.0080 \text{ GeV (without CDF)}$$

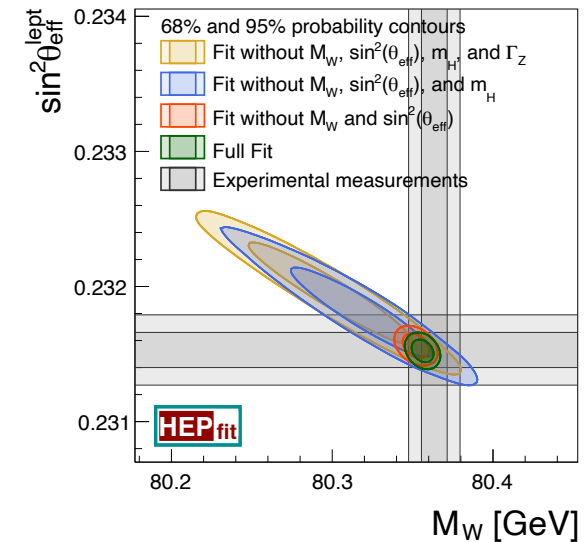
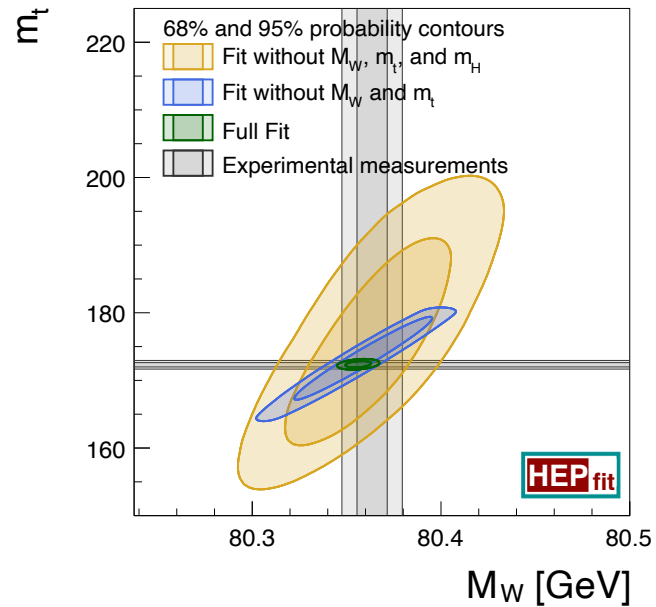
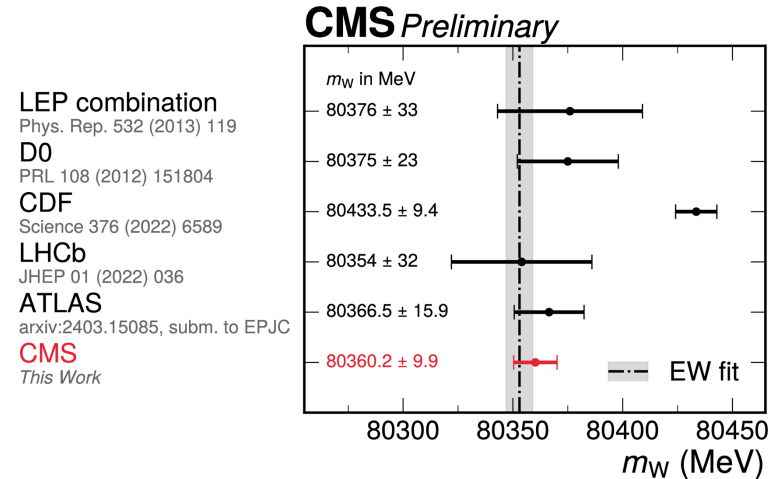
$$80.356 \pm 0.0045 \text{ GeV (from fit)}$$

For m_t we combine:

- ☐ 2016 Tevatron combination
- ☐ ATLAS Run 1 and early Run2 results
- ☐ CMS Run 1 and early Run 2 results
- ☒ CMS l+j [$m_t=(171.77\pm0.38)$ GeV]
- ☒ CMS l+j boosted [$m_t=(173.06\pm0.83)$ GeV]
- ☒ ATLAS l+j boosted [$m_t=172.95\pm0.53$ GeV]

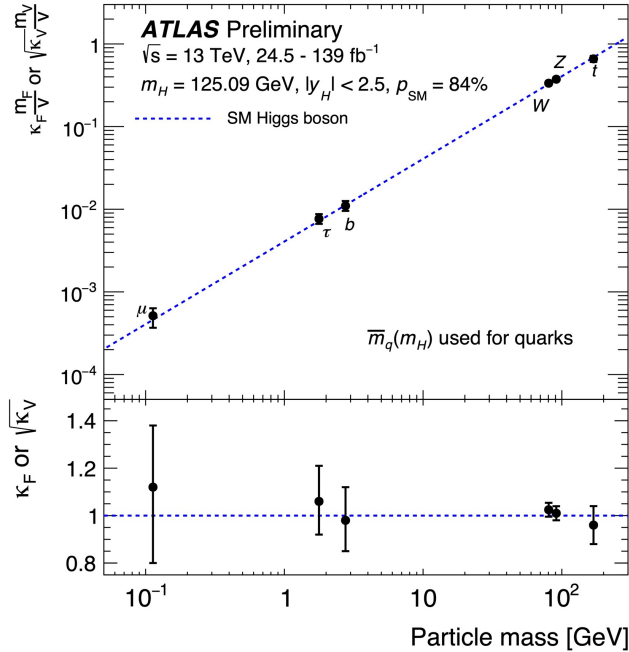
$$m_t = 172.31 \pm 0.32 \text{ GeV}$$

$$172.38 \pm 0.31 \text{ GeV (from fit)}$$



J. de Blas et al. 2204.04204,
L.R., L. Silvestrini 2511.16534 (update)

Exploring Higgs couplings



$$\kappa = g_X/g_X^{\text{SM}} = 1 + \Delta\kappa$$

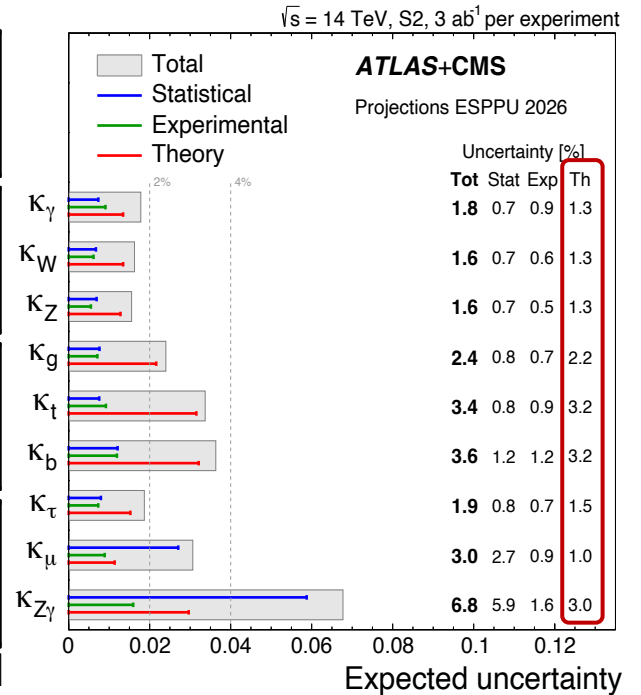
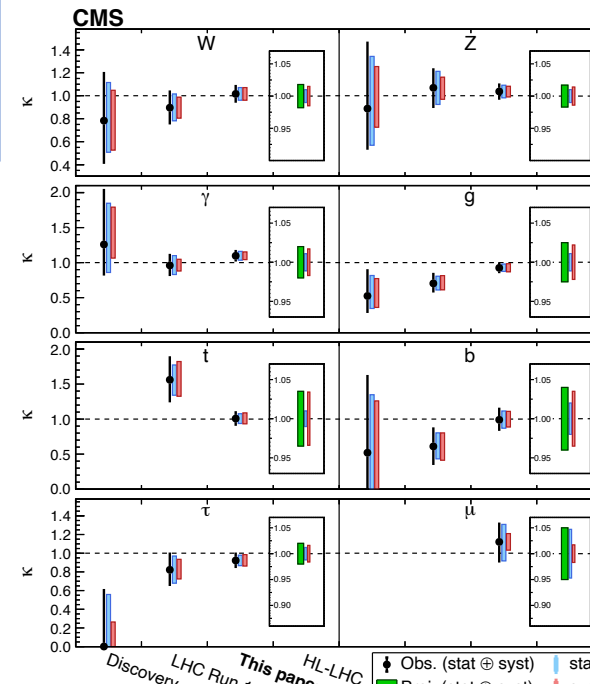
$$\Delta\kappa \propto v^2/\Lambda_{\text{BSM}}^2$$

Precision on $\Delta\kappa$



reach for Λ_{BSM}

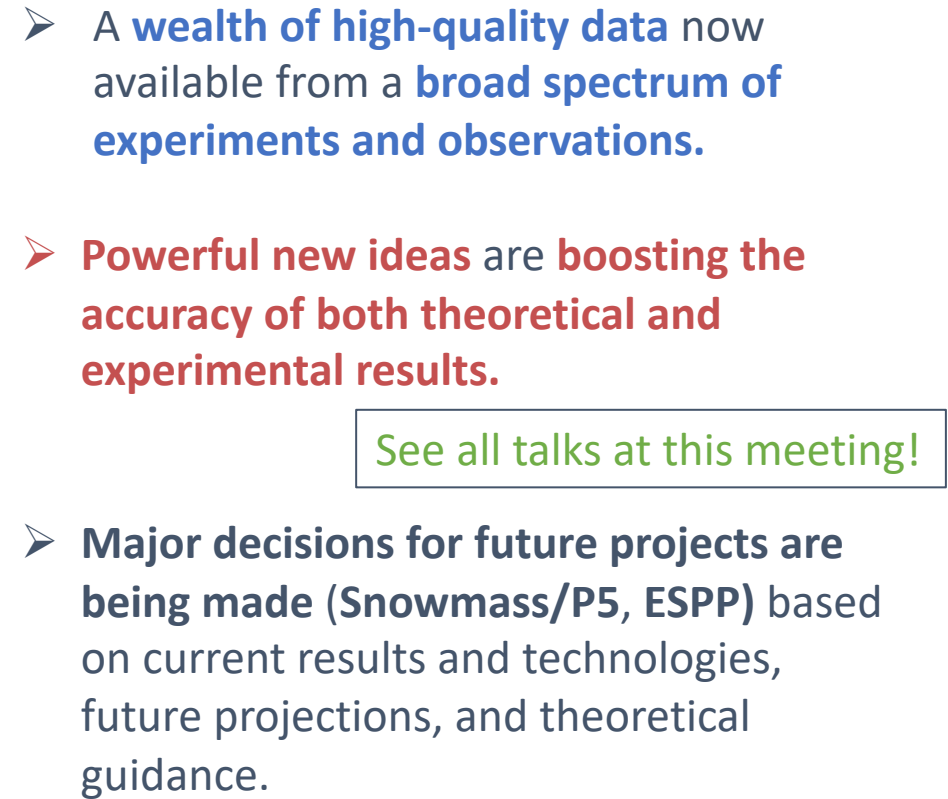
CMS, arXiv:2207.00043



- Couplings to **W/Z** at 5-10 %
- Couplings to **3rd generation** to 10-20%
- **First measurements** of 2nd generation couplings

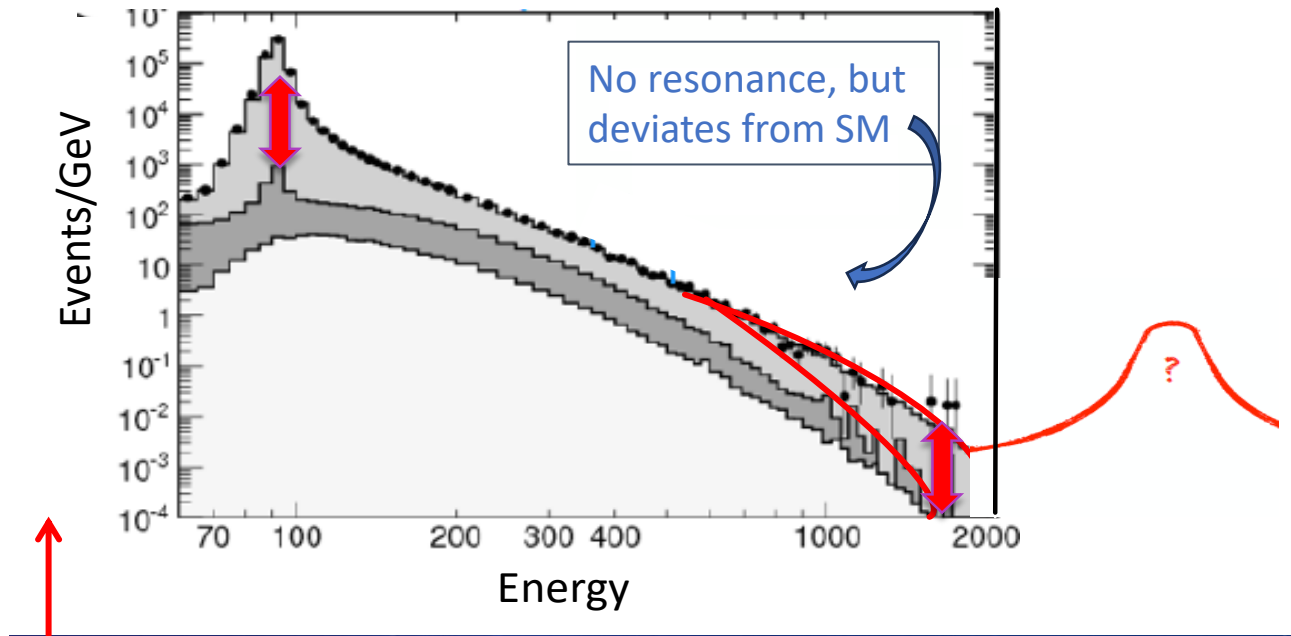
- **HL-LHC projections** based on full Run 2 data:
 - **1.6-3.6 % on main couplings**
 - **3-7% on $H \rightarrow \mu^+ \mu^-$ and $H \rightarrow Z\gamma$**
 - **< 30% on Higgs (trilinear) self-coupling**
 - **Theory could become the main limitation**

The LHC legacy – Exploring new physics over a broad spectrum of observables



See all talks at this meeting!

Exploring new physics beyond total rates



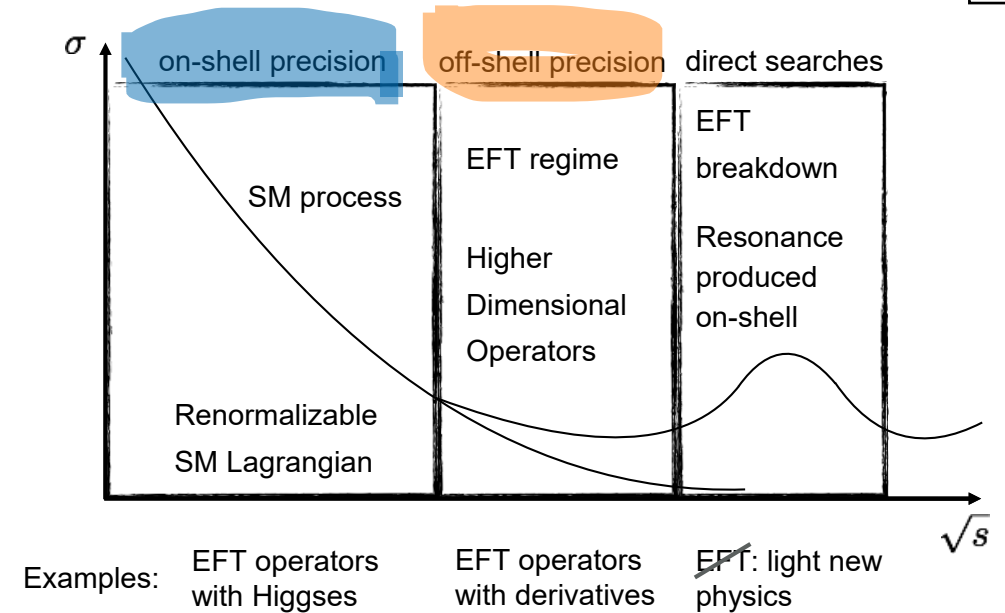
Theory is providing SM precision calculations at differential level both at **lower energy** where rates are large, and at **higher energy** where rates are small but effects of new physics may be more visible.

Extending the SM via effective interactions above the EW scale → **SMEFT**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \left(\frac{1}{\Lambda^2} \sum_i C_i O_i + \text{h.c.} \right) + O(\Lambda^{-4})$$

dim=6

dim>8



Crucial to control EFT sensitive regions

Precision and future colliders

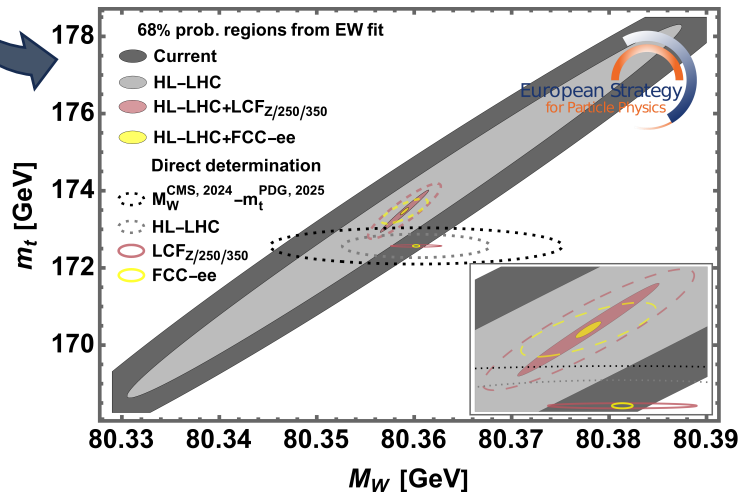
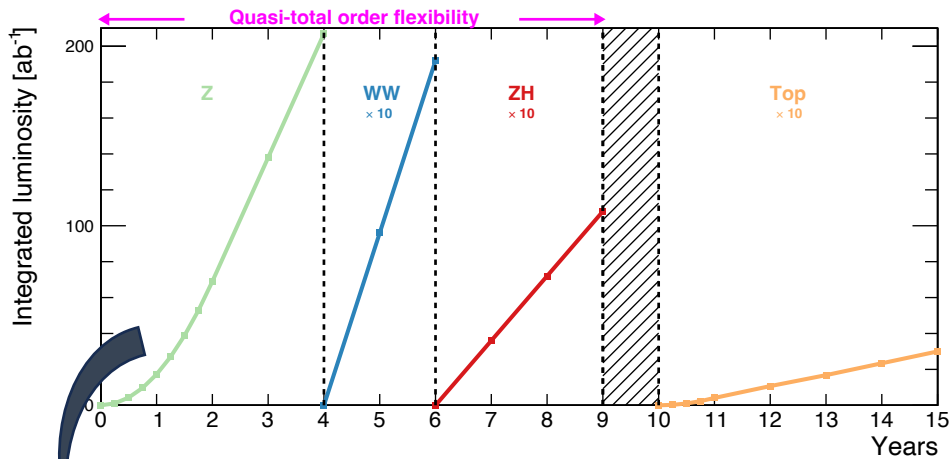
Rising to the challenge

Future collider projections are impressive. Theoretical predictions depends on:

- **Parametric uncertainties** (on SM parameters)
- **Theoretical uncertainties** (perturbative and non-perturbative quantum effects in collider observables)
- **Interpretation of anomalies/deviations** exploring **new-physics patterns** (model specific/agnostic)

All need to be controlled to **reach (sub)percent level precision** and **enable a future collider precision program.**

FCC-ee: New level of precision for Z-pole observables and beyond



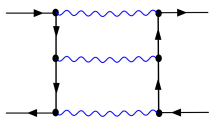
Observable	value	present $\pm$ uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	$\pm$ 2000	4	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	$\pm$ 2300	4	12	From Z line shape scan Beam energy calibration
$\sin^2 \theta_W^{\text{eff}} (\times 10^6)$	231,480	$\pm$ 160	1.2	1.2	From $A_{\text{FB}}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2) (\times 10^3)$	128 952	$\pm$ 14	3.9 0.8	small tbc	From $A_{\text{FB}}^{\mu\mu}$ off peak From $A_{\text{FB}}^{\mu\mu}$ on peak QED&EW uncert. dominate
$R_\ell^Z (\times 10^3)$	20 767	$\pm$ 25	0.05	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2) (\times 10^4)$	1 196	$\pm$ 30	0.1	1	Combined R_ℓ^Z , Γ_{tot}^Z , σ_{had}^0 fit
$\sigma_{\text{had}}^0 (\times 10^3)$ (nb)	41 480.2	$\pm$ 32.5	0.03	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2 996.3	$\pm$ 7.4	0.09	0.12	Z peak cross sections Luminosity measurement
$R_b (\times 10^6)$	216 290	$\pm$ 660	0.25	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{\text{FB}}^{b,0} (\times 10^4)$	992	$\pm$ 16	0.04	0.04	b-quark asymmetry at Z pole From jet charge
$A_{\text{FB}}^{\text{pol},\tau} (\times 10^4)$	1 498	$\pm$ 49	0.07	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	$\pm$ 0.5	0.001	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	$\pm$ 0.09	0.002	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	$\pm$ 0.04	0.00007	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	$\pm$ 9.9	0.18	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	$\pm$ 42	0.27	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2) (\times 10^4)$	1 010	$\pm$ 270	2	2	Combined R_ℓ^W , Γ_{tot}^W fit
$N_\nu (\times 10^3)$	2 920	$\pm$ 50	0.5	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	$\pm$ 290	4.2	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	$\pm$ 190	10	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{\text{top}}/\lambda_{\text{top}}^{\text{SM}}$	1.2	$\pm$ 0.3	0.015	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
$t\bar{t}Z$ couplings		$\pm$ 30%	0.5–1.5 %	small	From $\sqrt{s} = 365$ GeV run

What does this require from theory

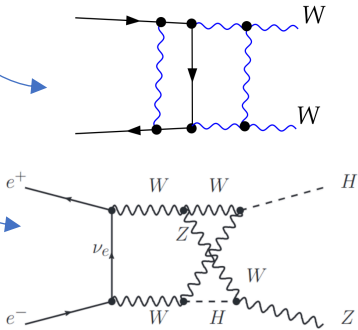
Precision for extraction from data

Quantity	Current precision	FCC-ee stat. (syst.) precision	Required theory input	Theory status as of today	Needed theory improvement [†]
m_Z (MeV)	2.0	0.004 (0.1)	non-resonant $e^+e^- \rightarrow f\bar{f}$, initial-state radiation (ISR)	NLO, ISR logarithms up to 6 th order	NNLO for $e^+e^- \rightarrow f\bar{f}$
Γ_Z (MeV)	2.3	0.004 (0.012)			
$\sin^2 \theta_{\text{eff}}^\ell$	1.6×10^{-4}	$1.2 (1.2) \times 10^{-6}$			
m_W (MeV)	9.9	0.18 (0.16)	lineshape of $e^+e^- \rightarrow WW$ near threshold	NLO ($e^+e^- \rightarrow 4f$ or EFT framework)	NNLO for $e^+e^- \rightarrow WW$, $W \rightarrow f\bar{f}'$ in EFT setup
HZZ coupling	– *	0.1%	cross section for $e^+e^- \rightarrow ZH$	NLO EW plus partial NNLO QCD/EW	full NNLO EW
m_{top} (MeV)	290	4.2 (4.9)	threshold scan $e^+e^- \rightarrow t\bar{t}$	N ³ LO QCD, NNLO EW, resummations up to NNLL, $\mathcal{O}(30 \text{ MeV})$ scale uncert.	Matching fixed orders with resummations, merging with MC, α_S (input)

- Several building blocks:**
- Initial state soft+collinear (γ) radiation (ISR)
 - EW+QCD corrections (h.o. + resummed)
 - QCD at Z-pole: multijet xsec ($\alpha_s(M_Z)$)
 - Improved parton-shower event generators
 - Non-perturbative hadronization effects



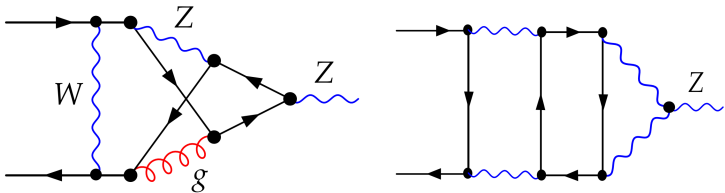
All need to be pushed beyond LEP experience
Lots of experience from LHC, but h.o. EW is new territory



2nd order EW corrections
↪ Extremely challenging

FCC feasibility study report – 2505.00272

Beyond current state of the art



Precision for prediction

Quantity	Required theory input	Theory status as of today	Needed theory improvement [‡]
Γ_Z	vertex corrections for $Z \rightarrow f\bar{f}$	NNLO + partial higher orders	N ³ LO EW + partial higher orders
$\sin^2 \theta_{\text{eff}}^\ell$			
m_W	SM corrections to the muon decay rate	NNLO + partial higher orders	N ³ LO EW + partial higher orders

FCC feasibility study report – 2505.00272

The theory community is rising to the challenge ...

Precision calculations for future e^+e^- colliders: targets and tools

 Jun 7, 2022, 9:00 AM → Jun 17, 2022, 6:00 PM Europe/Zurich

Parton Showers for future e^+e^- colliders

 Apr 24, 2023, 9:00 AM → Apr 28, 2023, 5:00 PM Europe/Zurich

QCD for Higgs physics at FCC-ee

 Wednesday May 22, 2024, 2:00 PM → 6:00 PM Europe/Zurich

Gearing up for Future Colliders — Workshop on Radiative Corrections at Future Lepton Colliders

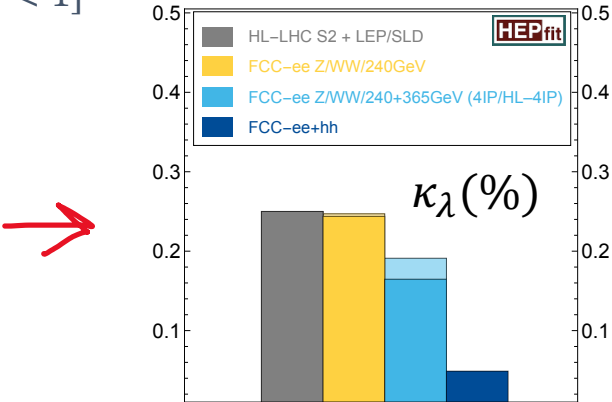
 Jun 29, 2026, 9:00 AM → Jul 3, 2026, 7:00 PM Europe/Zurich

And more ...

Higgs couplings to sub-percent level, with exceptions

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	—	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$ \kappa_S $ (%)	—	+29 -67	+29 -67
Γ_H (%)	—	0.78	0.69
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}

[(*) $\rightarrow |\kappa_V| < 1$]

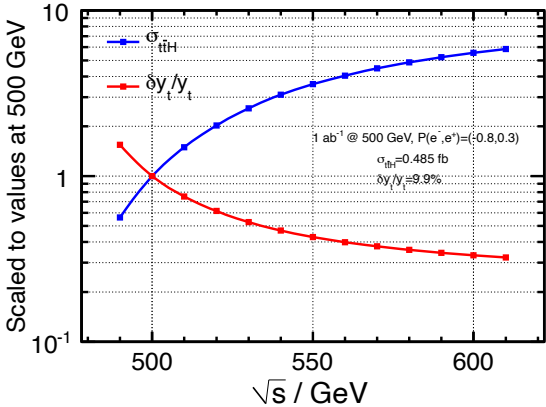
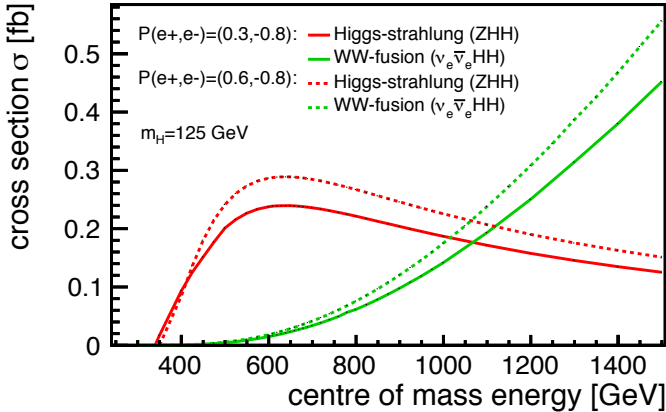


To compare with FCC-ee sub-percent precision:

- $e^+e^- \rightarrow ZH$ at NNLO EW
[Chen et al. 2209.14953, Freitas et al. 2209.07612]
- differential hadronic Higgs decays at N3LO QCD

For top-quark Yukawa, and Higgs self-coupling, κ_μ , κ_γ , $\kappa_{Z\gamma}$:
HL-LHC measurements will remain the state of the art till FCC-hh

Need to focus on $t\bar{t}+X$, HH, and rare decays processes at the LHC.



Energy matters:
tH and HH, need >500 GeV

In summary

- After the HL-LHC, the **FCC physics program** will provide the **next level of both precision and energy** to explore new physics.
- **Higgs-boson precision physics central to this exploration**, given its relation to all fundamental open questions. **Strong synergy with all FCC-ee measurements** (Z-pole, WW , $t\bar{t}$).
- The realization of the physics program of the FCC requires theory to match the experimental precision. The **huge ongoing effort for the HL-LHC precision program** will naturally lead us there.
- **Sharpening strategies for interpretation** of anomalies and their correlation will be equally important. Ongoing **EFT studies** for HL-LHC have been the **backbone of future collider studies** and will continue to play a major role.
- It will be crucial **to enable precision for those measurements that will be unique to the HL-LHC** till the FCC-hh comes on line (ex.: y_t , λ_3 but also flavour physics at LHC-b).