Summary of the GT1 contribution

SM & Beyond

Symposium national
Preparing the french contribution to the ESPPU2025

F. Couderc, M.-H. Genest and A.M. Teixeira,
on behalf of the community

Context

Update of the European strategy 2020: taking into account new developments

e+e- as Higgs factory highest priority. Longer term p-p collider at the highest achievable energy

- ✓ R&D on advanced accelerator technology
- ✓ Hadron collider @ 100TeV
- ✓ Timely realisation of ILC compatible with this strategy

French GT1 : Standard Model and Beyond

- 4 October 2024
  - outcome of the 2020 EU Strategy
  - Status reports on the different topics relevant to GT1: EWK & precision test, BSM, Dark matter and dark sectors, strong interactions, Instrumentation R&D challenges
- 13 November 2024
  - Presentations on specific topics related to GT1 (Sustainability, ECFA summary, Muon collider, Computing challenges, early career researcher)
  - Lively discussion on the GT1 physics preferences and related preferred future machines
- 20 January 2025: French Symposium on the ESPPU 2025
- **35 contributions** tagged GT1 received at https://esppu.in2p3.fr/
  - 5 institutes contributions

GT1 Contributions: a 2 pages summary

- Draft from A, F, MH annotated by the community
- Final document: GT1 contribution

Context

Preparing for the French contribution to the update

The Standard Model and Beyond

SM well established theory over the past 4 decades

EWK symmetry well understood

Last piece of the puzzle discovered in 2012: **the Higgs boson**

Mechanism for **electroweak symmetry breaking:** to be (further) tested

SM limitations

- hierarchy, stability of the EW vacuum…
- Dark matter, Dark energy ?
- CP strong ? Baryon asymmetry ?
- Neutrino masses

Yet, no sign for new physics

⇒ **Direct searche**s for new states

⇒ Precision (and consistency) **tests of the SM**

GT1 community physics goals

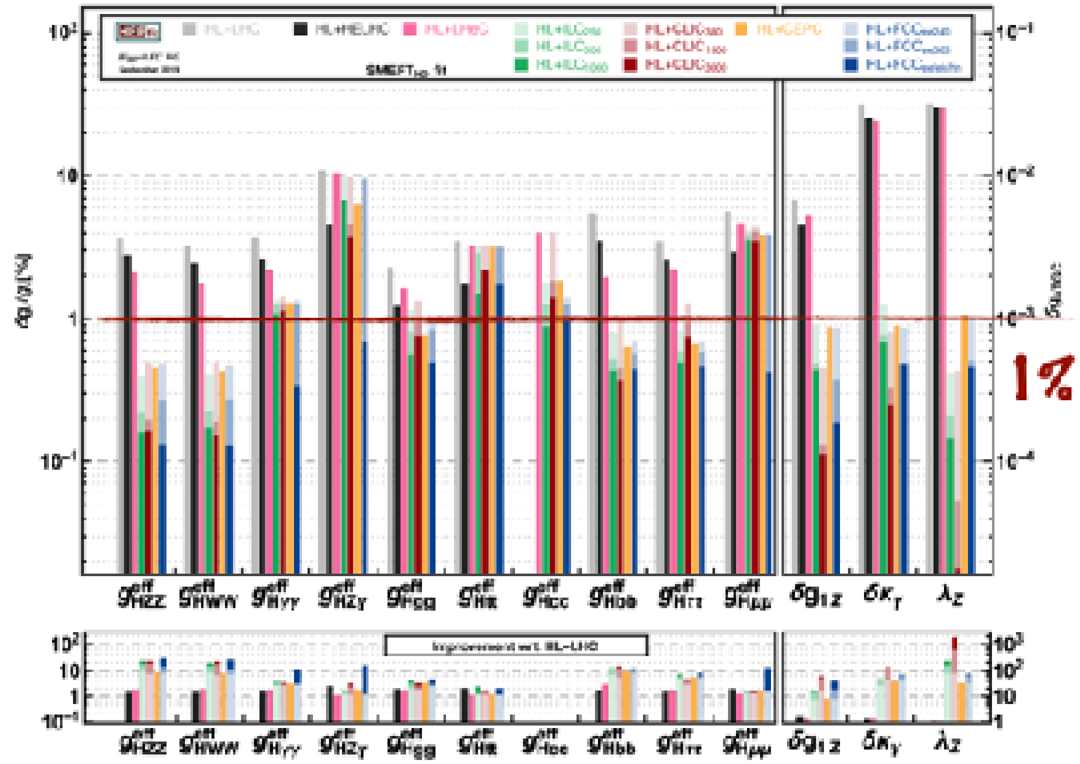
Consensus from the GT1 community : The Higgs boson as a portal to new physics

In the absence of new physics

1. the **Higgs boson properties & the Higgs potential priority**
2. top mass at the ttbar threshold matters
3. EWK precision at the Z pole is a nice addition

What precision do we need on the Higgs boson? [MM]

- Higgs coupling to fermions and boson: below the 1%
- Higgs width: direct measurement O(1%)
- Higgs boson trilinear coupling @ O(10%)
- Couplings to first family (electron) ?
- Z pole/ WW threshold affect significantly the Higgs couplings precision (up to factor 2 in aTGCs)



HL-LHC legacy (1)

High luminosity LHC - **ambitious physics programme**

- Improve upon EW precision measurements & carry out new measurements

  ⇒ strongly impact future capacity to precisely determine Higgs & EW couplings

  ⇒ deviations from SM - indirect evidence for NP!

Dedicated studies of **top quark** (mass, couplings, cross sections)

HL-LHC: last high-energy hadron collider for decades

only means to **directly search for new physics** in near future

Exploit full physics potential of HL-LHC

- **Higgs** boson properties, **top-quark** physics, **QCD** studies, **BSM** searches
- **Preserve data & results** for subsequent re-interpretation and enforce **FAIR principles: F**indable, **A**ccessible, **I**nteroperable, **R**eusable data and data products

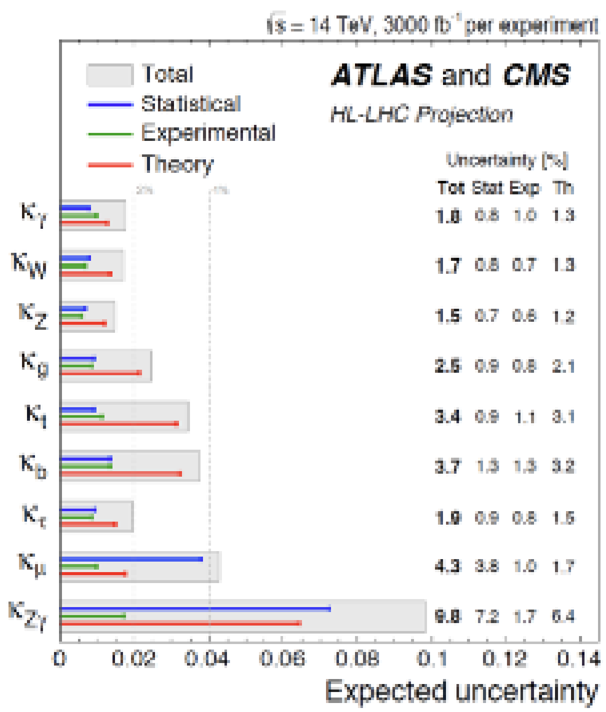
HL-LHC legacy (2)

Still some room for surprises ?

Several HL-LHC measurements will be competitive with lepton colliders counterparts

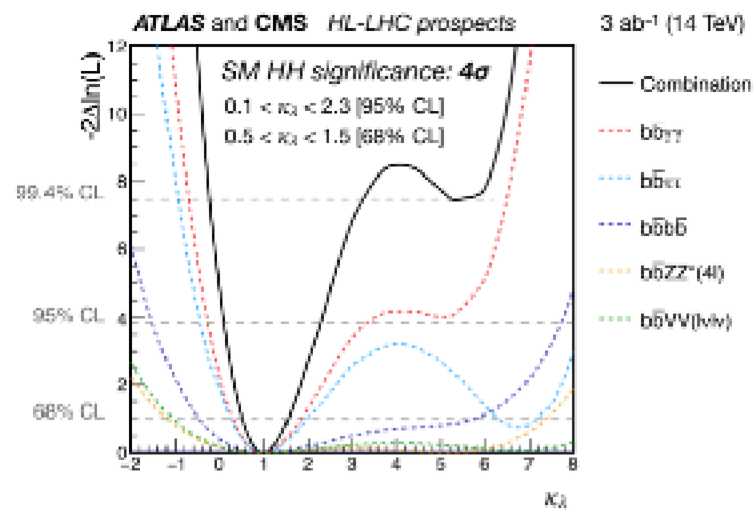
- **Rare Higgs boson decays:** μμ, Zγ, γγ
- **λ_{HHH} < 50% major milestone:** *e.g.* a competitive direct measurement requires a high energy lepton collider (or a high energy pp collider)

- Single-Higgs:
  - O(%) uncertainties



[EP 04/10/2024]

- Di-Higgs:
  - 4σ significance
  - 50% uncertainty on λ_{HHH}



Tremendous physics output

Outlined during discussions
- Long program
- Need to keep motivation for young student and scientists
- Ensure transfer of expertise

Future facilities

Several facilities considered to achieve our physics goals

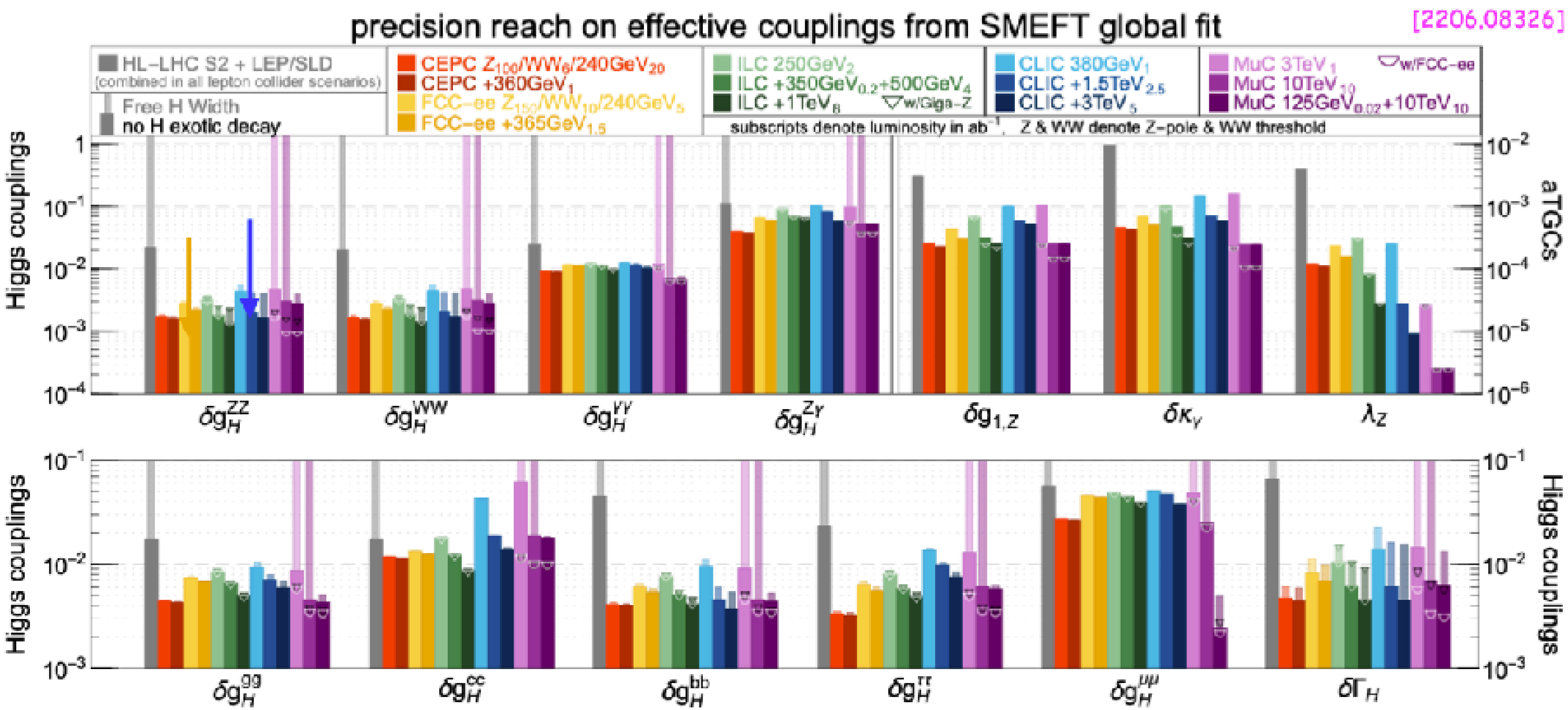
- **FCC-ee** (91 km e+e- circular collider): $90 < \sqrt{s} < 365$ GeV
  - High integrated luminosity (instantaneous lumi + up to 4 interaction points)
  - Tunnel can be re-used for a potential future hh collider
  - Electroweak physics precision thanks to $O(10^{12})$ Z boson
  - Potential for measuring **the electron Yukawa coupling - Y_e**

- **Linear collider facility** (LCF), a la CLIC or ILC: $90 < \sqrt{s} < O(1)$ TeV
  - Lower luminosity at the ZH threshold (and much lower the Z pole)
  - Up to 500GeV and > 1TeV in its most advanced version ⇒ access to λ_{HHH}

- **High energy hadron collider** ($\sqrt{s}$ 27 TeV or 100 TeV)
  - Competitive with LCF to constrain λ_{HHH}
  - Study of vector boson scattering
  - Potential for discovery
  - A low energy ($\sqrt{s} < 27$ TeV) could be a "low cost", eco-friendly alternative (if re-using LEP tunnel were possible)

Future facilities - Single Higgs

Typically gain 1 order of magnitude compared to HL-LHC



✏ Coupling deviations due to new physics*: $g = g_{SM}[1+\Delta]\ :\ \Delta = O(v^2/\Lambda^2)$

Experimental accuracy $O(0.2)$ ... $O(0.01)$ =>
Probed new physics scale: $\Lambda = 550$ GeV ... 2.5 TeV

[MM] 13/11/2024

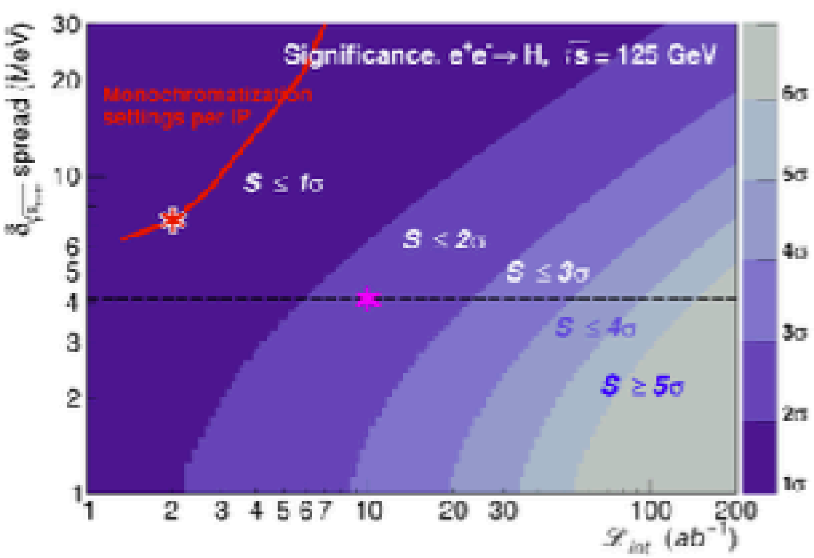
Future facilities - Higgs new ideas

[EP 04/10/2024]

2107.02686

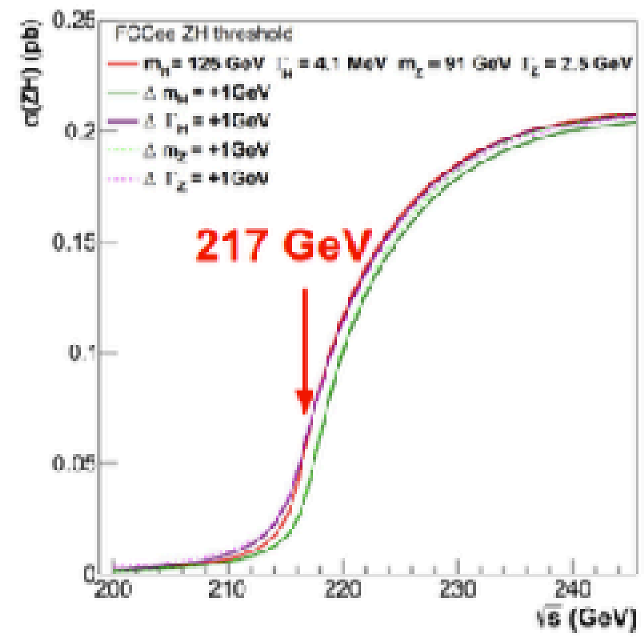
2106.15438

- e+ e– ⟶ H at $\sqrt{s}$ = 125 GeV: probe electron-Yukawa coupling
  - only way to do it?
- Small cross-section ⇒ large dataset
- Beams must be monochromatized (spread of $E_{CM} \sim \Gamma_H$) while keeping large beam luminosities
- m_H must be known at 4 MeV level



- Significance of 1.3σ/IP/year can be achieved

- e+ e– ⟶ ZH at $\sqrt{s}$ = 217 GeV: probe Higgs mass from threshold
- Needs accurate measurements of Z mass and width at the Z-pole
- SM-only assumptions ⟶ new physics can break the dependency
- Syst. effects to be evaluated



- 5 MeV uncertainty can be achieved with 5 ab-1
  - 10 MeV more realistically

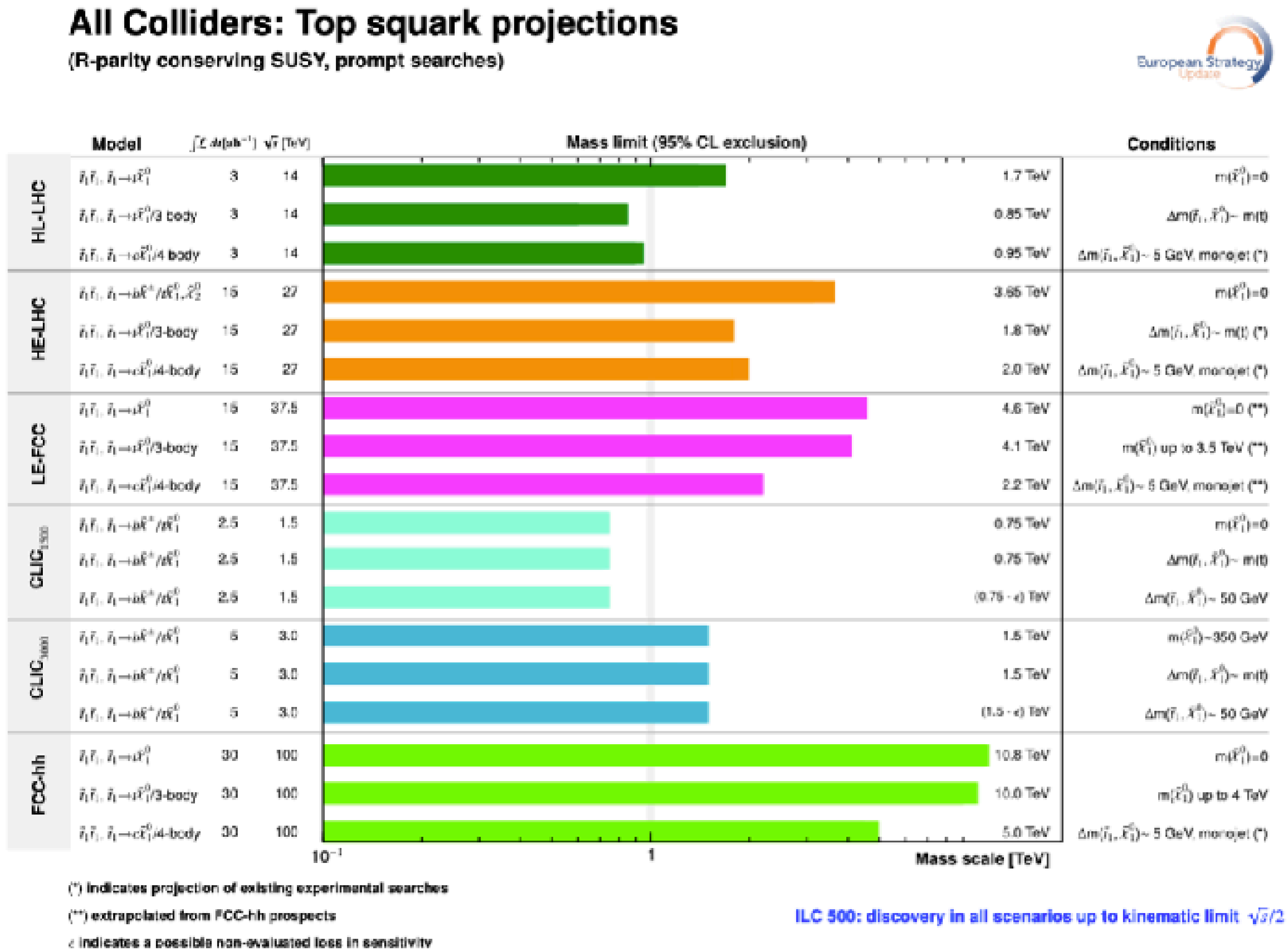
Future facilities - λ_{HHH}

	LHC	HL-LHC	FCC-ee	CEPC	LC	Muon Collider	HE-LHC 27TeV, 15ab^{-1}	FCC-hh
δ_{VV}	≲ 7% [1,2]	1.5% [5]	≲ 0.34% [6]	≲ 0.25% [8]	≲ 0.78% [6]	≲ 0.14% [12]	1.3% [5]	≲ 0.34% FCC-ee value [6]
δ_{h3}	-1.4…7.5 [3,4]	ATLAS+CMS combined 95%CL 0.1…2.3 [5] 68%CL 50% [5]	$FCC\text{-}ee_{365}$ w/HL-LHC§ ~34% [7] $FCC\text{-}ee_{365}$ 4IPs + HL-LHC§ ~21% [7]	$CEPC_{240}$ 5.6 ab^{-1} § -3…3.1 [8] HL-LHC + $CEPC_{240}$§ ≲ 20% [8]	$CLIC_{1500}$ 36% [6] $CLIC_{3000}$ -7…+11% [9] ILC_{500} 27% [10] ILC_{1000} 10% [6] update* ≲20% [11]	11% [12]	95%CL ~30% [13] 68%CL ~15% [13]	30 ab^{-1} 3.4-7.8% [14]

[MM] 13/11/2024

and refs therein

Probing new physics scale directly



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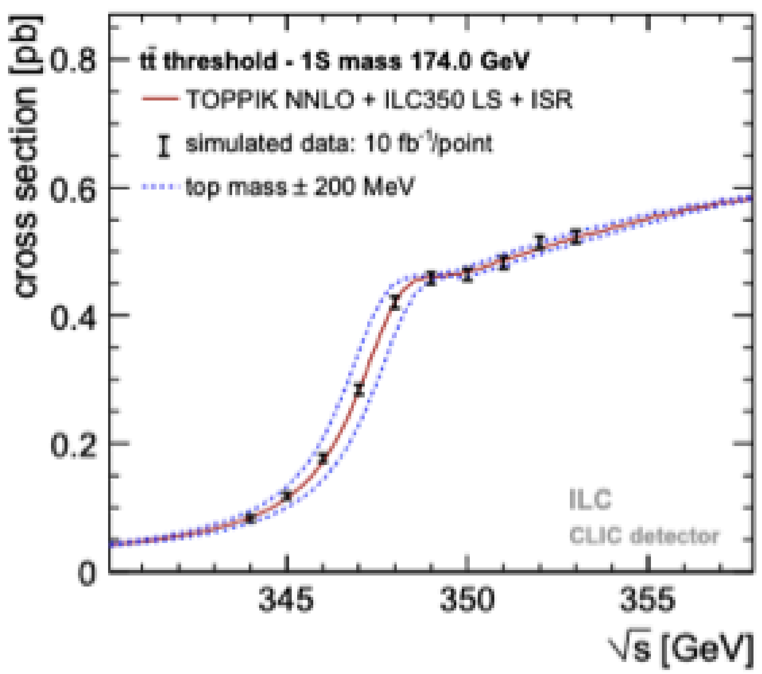
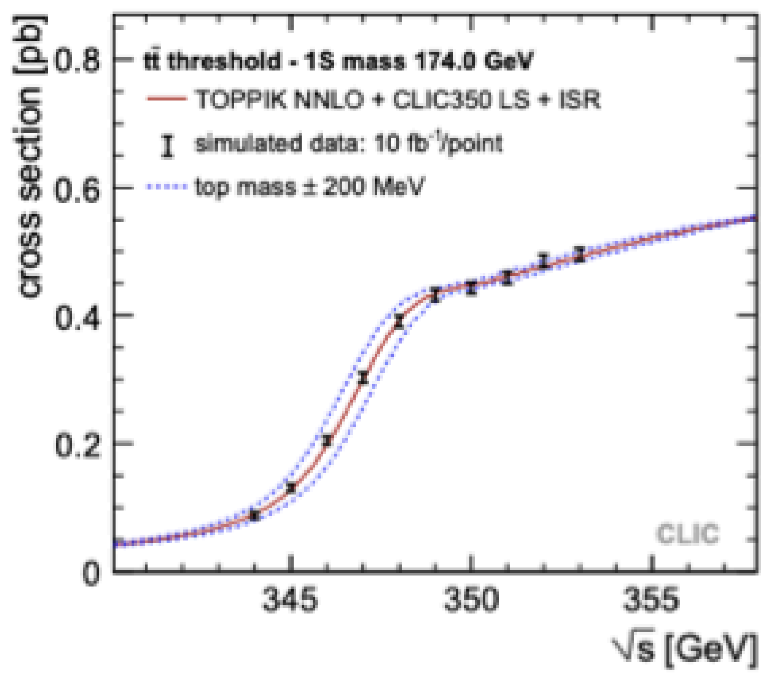
Top properties at 350 GeV





Threshold scans give well-defined m_{TOP}

Current uncertainty ~ 400 MeV from Tevatron/LHC

CLIC/FCC/ILC all expected to achieve:

- 15-20 MeV statistical
- 10-20 MeV systematic

} O (25) MeV

But presently uncertainty from theory is larger: 30 MeV (α_S), 40 MeV (HO). This will be reduced by the measurements at Z-pole.

[M. Lancaster]

EWK precision at the Z pole

EWPO	Current	CEPC	FCC (ee)
M_Z [MeV]	2.1	0.5	0.1
Γ_Z [MeV]	2.1	0.5	0.1
N_ν [%]	1.7	0.05	0.03
M_W [MeV]	12	1	0.67
$A_{FB}^{0,b}$ [x10^4]	16	1	< 1
$\sin^2\theta_W^{\text{eff}}$ [x10^5]	16	1	0.6
R_b^0 [x10^5]	66	4	2–6
R_μ^0 [x10^5]	2500	200	100

LHeC can measure $\sin^2\theta_W$ as f(E).

LHeC : Mw to 10 MeV but can measure PDFs allowing HL-LHC to half PDF uncertainty and achieve O(5 MeV) Mw.
ILC/CLIC : Mw to 5 MeV similar to HL-LHC/TeV average.

[M. Lancaster]

Detector constrains to achieve these goals

- General requirements:

"Higgs Factory" Programme
- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{pT}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of $30\%/\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD
- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from $\mu\mu$)
- Stability of B-field to 10^{-6} : stability of $\sqrt{s}$ meast.

- Benchmarks for the vertex detector
  - $H \rightarrow b\bar{b}/c\bar{c}$ couplings
  - $Br(B \rightarrow K^*\tau\tau) \sim 10^{-7}$
- Benchmarks for the inner tracker momentum resolution
  - Higgs boson mass
  - $K_s \rightarrow \pi^+\pi^-$ (decay of B^+ meson)
- Benchmarks for Particle ID
  - Flavor physics measurements: $B^0_s \rightarrow D^{\pm}_s K^{\mp}$, $B \rightarrow K^*\nu\nu$, $B_s \rightarrow \phi\nu\nu$, …
  - s-quark jet identification → kaon ID ($H \rightarrow ss$, V_{ts}, V_{bs}, $H \rightarrow bs$, FCNCs, …)
- Benchmarks for calorimetry
  - hadronic: $H \rightarrow WW/ZZ$ jet separation
  - electromagnetic: flavor physics ($B_s \rightarrow D_s K$, $B_0 \rightarrow \pi^0\pi^0$, $Bs \rightarrow K^*\tau\tau$), Higgs, new physics searches (e.g. $Z \rightarrow \mu e$, $\tau \rightarrow \mu\gamma$, $e^+e^- \rightarrow a\gamma \rightarrow \gamma\gamma\gamma$), bremsstrahlung recovery, tau polarization (separate $\tau^{\pm} \rightarrow \rho^{\pm}\nu \rightarrow \pi^{\pm}\pi^0\nu$ and $\tau^{\pm} \rightarrow \pi^{\pm}\nu$)
- Benchmarks for muon spectrometer
  - $B^0 \rightarrow \mu\mu$

[EP] 04/10/2024

[J. Zhu]

Summary of the contributions

Towards future facilities: physics and R&D

Engagement towards a future Higgs factor

R&D studies: detector design, optimised detector simulations

⇒ **ILC**

⇒ **FCC-ee**

PID @ lepton collider of major interest

- ToF tracking layers could extend coverage < 3 GeV
- Expertise from IP2I and Irfu (related R&D and simulations already started)

Tracking detectors

- TPC developments (especially for ILC)

Vertex detectors

- CMOS pixel (or MAPS)
- FCC-SEED (Snail-shape vErtEx Detector) : demonstrator of the first layer (bending sensors connected in only one row of reticles)

Calorimetry

- ILD - calorimetry
- ALLEGRO calorimetry for FCC-ee
- Related readout electronics & DAQ

Beyond Higgs factories

Engage - from today! - on **longer term developments**

Muon collider: $\sqrt{s} \approx$ several TeVs

- General consensus that this is an important R&D to pursue
- **Higgs** boson **precision** measurements, exploration of **new scales**, NP discover
- technical limitations: muon cooling....

High-energy pp collision (FCC-pp / HE-LHC):

- Re-use of existing tunnel from FCC-ee or LHC
- Processes such as ttZ / ttH cross section x 100 w/r to LHC
- Sustain R&D on 16T dipoles
- Even with LHC di-pole a 100km tunnel would provide 50TeV
- ...

Plasma wave acceleration (*e.g.* AWAKE)

$\Rightarrow$ small-sized accelerators impact for physics and society!

French involvement in the FCC

Several contributions dedicated to FCC

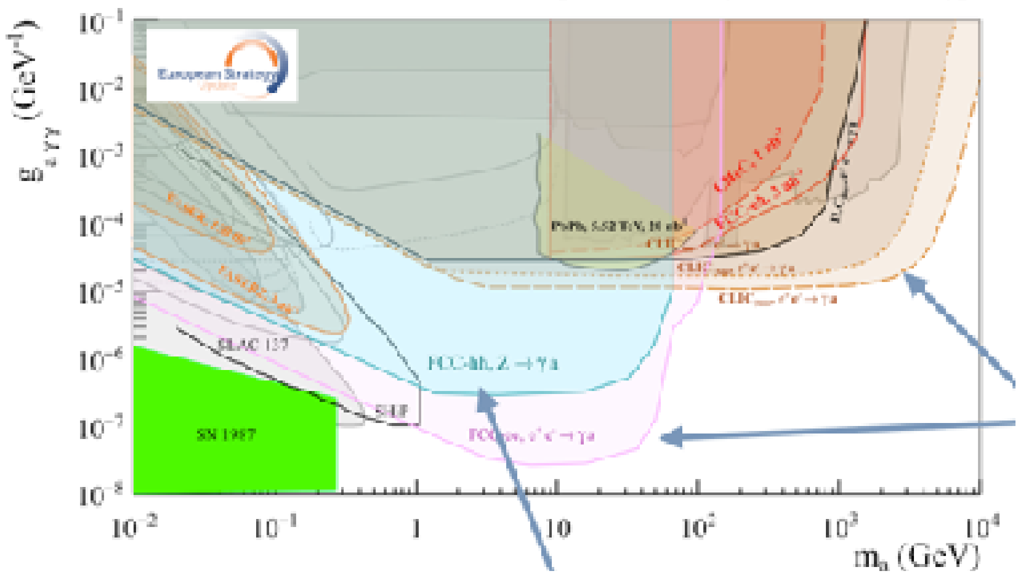
Physics analysis and R&D are covered

FCC feasibility study will be delivered in March 2025

FCC France community

- ~ 60 physicists and engineers
- 12 French groups: 11 from IN2P3 + CEA/IRFU

[V. Sanz (04/10/2024)]



French community physics interests

- Z pole and EWK observables
- Higgs boson physics in general
- α_s determination at several energies
- BSM searches and interpretations:
  - feebly interacting particles down to sub-GeV ALPs, light pseudo scalars (monochromatic photon in $Z \to \gamma a$ decays)
  - SMEFT up to 10-100TeV
  - Composite scalar $e^+e^- \to Z \to \phi\gamma$ (scale of compositeness also from higher energies)
- ttbar threshold (365GeV) for precision top-quark physics
- Single top @ 240GeV: FCNC
- …

French involvement in an LCF

Several contributions dedicated to LCF

Long standing involvement of the French community both on Physics analysis and R&D

Studies on cost and sustainability on going

Stressing some key features of an LCF

Polarisation and higher energy reach than FCC

Somewhat cheaper than a FCC, could be built in parallel with HL-LHC operations

Studies on cost and sustainability on going

French community physics interests

- Higgs boson physics in general
- ttH @ 500GeV
- ttbar threshold
- And more…

NB: contributions are likely not covering all the physics topics in which the French community is actively interested in

Challenge: sustainability

Several contributions dedicated to sustainability issues

Strong interest from the community & dedicated session tomorrow

Environmental footprint of HEP projects

assess and promote reduction of environmental impact
ensure exemplary role of HEP community (feasibility studies & decision-making)

From infrastructure

proper use of **excavated material**, development of **low carbon-concrete options**, **ecological material** for surface buildings, preservation of **bio-diversity**

... to accelerators & detectors - mitigate cooling and cryogeny!

energy recovery linac, new technologies for operation at **4K** (instead of 2K)
reduce **power consumption** of detectors
replacement of **gases** (HFCs, PFCs and SF_6) - **banning GWP entirely** in the future

... to collaboration activities - **optimised** to reduce impact

Questioning the choice for the next facility

- **CEPC vs FCC-ee**: does it really make sense to have both machines ?
- **Reusing the LHC tunnel for LHeC or HE-LHC** more sustainable on the “short” term

Challenge: computing

Several contributions dedicated to computing issues

Strong interest from the community & dedicated session tomorrow

Data volume/rates not slowing down - entering the hexascale realm

Increasing volumes of data: detector granularity & timing precision,
larger samples of real (and simulated) data
preservation of data!

⇒ Size and accessibility of repository (FAIR!)

Increasing computational needs: Heterogeneous resources, energy consumption

⇒ Software optimisation - best exploitation of **new processor** technologies and increased **parallelisation**

Machine Learning and Artificial Intelligence usage

high impact on data acquisition performance
object reconstruction, data processing, detector simulation, ..., final analyses

⇒ Comprehensive training offer and a multidisciplinary approach to resources

Challenge: attractiveness and expertise

Person-power for the next program

- LHC teams committed to run the LHC experiments analysing current data, conducting the upgrades and commissioning of the HL-LHC
- From LHC but not only, **additional person-power is required** HL-LHC data can be exploited during the construction of the next collider

Transfer of expertise

- Education and training of young physicist crucial for the needs of field
- Key expertise of current groups to get involved now in the development of future detectors
- This expertise must be maintained and transferred: electronics, information technology, instrumentation, independently of the choice of the next collider.

About the next project

- Competition with other research-field large infrastructures is an issue
- Next collider at CERN: scientific reasons + maintain expertise
- Risk of sizeable delays given the European context: loss of attractiveness for young scientist

Non-collider searches

Dedicated session tomorrow

- DM searches, **both WIMPs (XENON, DarkSide) and axions (MadMax)**
  - unique experimental opportunity to continue pursuing
  - growing size: proposal to create a new European network to foster cross-institutional collaborations

- Precision measurements **complemented by non-collider approaches, e.g.:**
  - $\sin^2\theta_W$ at different energy scales
  - experimental setups (e.g. PAX) to measure α_{QED} with a precision $O(10^{-11})$

- Societal applications **(*e.g*. biomedical imaging) should also continue to be supported**

Conclusions

Executive summary

GT1 contribution to the ESPPU 2025 (2 pages summary)

Given the peculiar nature of the **Higgs boson** and its role in the SM, this particle **deserves a thorough study of its couplings and properties**.

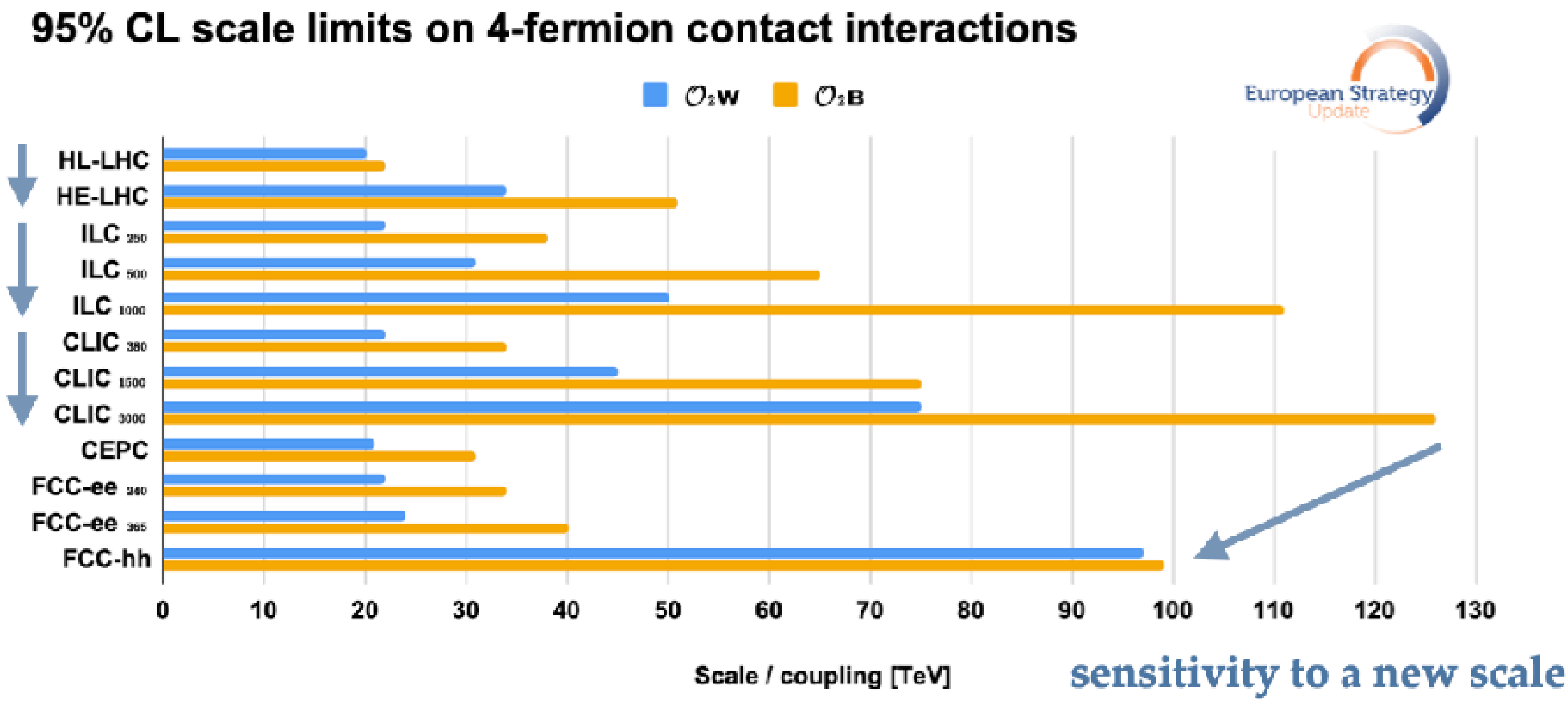
The **FCC-ee**, thanks to its high integrated luminosity delivered in a short amount of time, appears to be the ideal machine to achieve this goal. It provides in addition a large amount of data at the **Z pole** (O(10^{12}) bosons) allowing for a large variety of stringent electroweak tests of the SM, possibly paving the way to a **future hadron collider**. If such an ambitious project is not deemed feasible, a **LCF at CERN** (operating up to at least 500 GeV) is a noteworthy alternative approach, **its high energy program (directly addressing the Higgs boson trilinear coupling)** making it a complementary machine to any other potential circular collider project with a center of mass energy below 365 GeV.

The community also stresses the importance of a sustained R&D on both colliders and detectors, recognising the broad and **promising physics case of a muon collider**, covering both precision and Higgs-boson physics, and its potential for the discovery of high energy resonances.

Backups

Probing new physics scale indirectly

Constrains on Wilson operators from the different facilities



[VS] 04/10/2024

Refs from slide 11

[1] CMS Coll., CMS-PAS-HIG-19-005 (2020)
[2] ATLAS Coll., ATLAS-CONF-2021-053 (2021)
[3] ATLAS Coll., Phys. Lett. B 843 (2023) 137745
[4] CMS Coll., CMS-HIG-23-006
[5] M. Cepeda et al., arXiv:1902.00134 [hep-ph]
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