Linear Electron Positron Colliders Vision and Prospects

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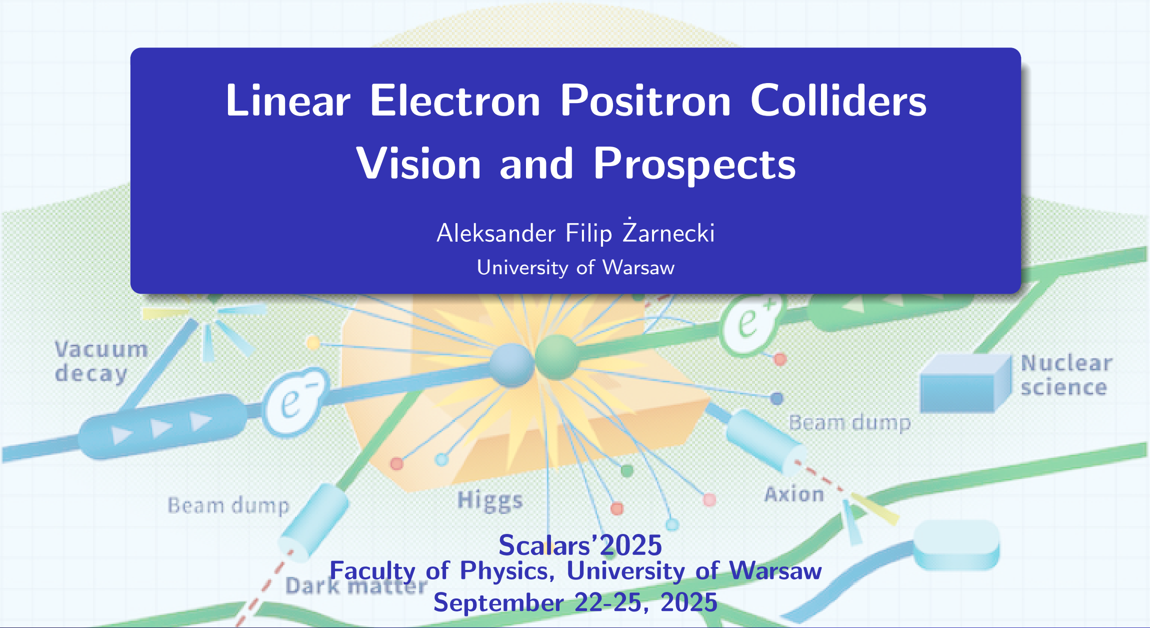
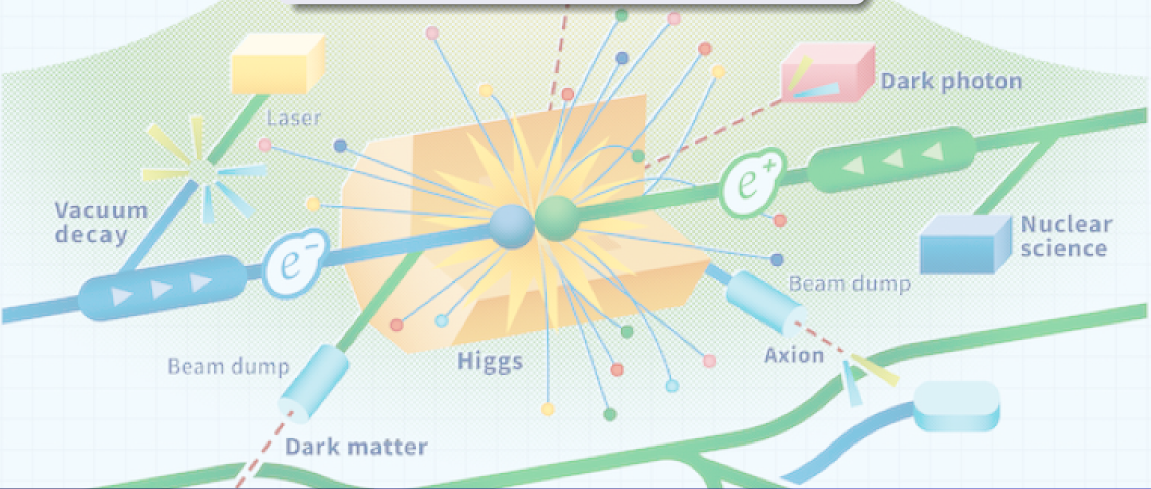
University of Warsaw



Scalars'2025
Faculty of Physics, University of Warsaw
September 22-25, 2025

Outline:

Introduction



Motivation for linear e^+e^- collider

Discovery of the Higgs boson at the LHC was a great success! But we hoped for much more...

After 16 years of LHC running, there is little progress in our understanding of the Universe!

Many open questions give us strong motivation to look for Beyond SM (BSM) physics

Dark Matter, baryon-antibaryon asymmetry, neutrino masses

But there are many possible scenarios and no firm hints on the BSM mass scale...

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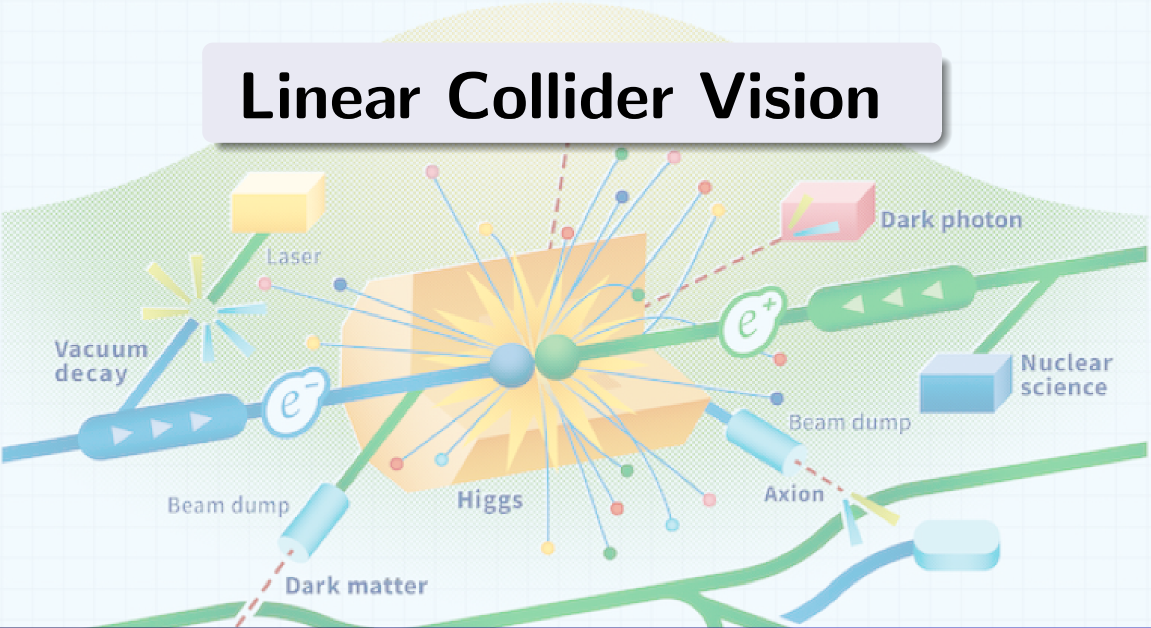
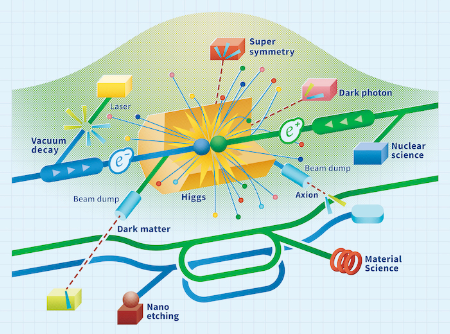
Different concepts were presented, based on established acceleration technologies, including ILC, CLIC, C^3 (see backup slides), but they have recently merged into a consistent vision ...

Linear Collider Vision



The idea born in spring 2024, presented at LCWS'2024...

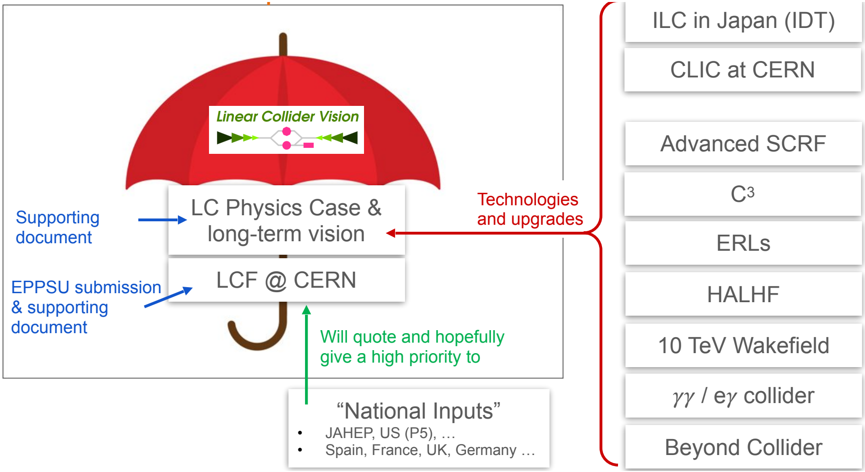
A Global Vision for a Linear Collider Facility



LCWS 2024
Tokyo University
July 10, 2024

LC Vision Team: T. Barklow, T. Behnke, M. Demarteau, A. Faus-Golfe, B. Foster, M. Hogan, M. Ishino, D. Jeans, B.List, J.List, V. Litvinenko, S. Michizono, T. Nakada, E. Nanni, M. Nojiri, M. Peskin, R. Patterson, R. Pöschl, A. Robson, D. Schulte, S. Stapnes, T.Suehera, C. Vernieri, M. Wenskat, J. Zhang

Common LC Vision prepared for the European Strategy update



J.List, LCVision Community Event, January 2025

Luminosity prospects

Linear Collider based on SCRF running at CERN can go **significantly above ILC @ Japan**

Luminosity increase expected from:

- increasing bunch-train repetition rate from 5 Hz to 10 Hz
  total power consumption @ 250 GeV still estimated to 182 MW, much below FCC-ee level
- doubling number of bunches in a train (with the same RF power thanks to higher Q_0)
- also profiting from higher klystron efficiency (65% →80%)

We expect $\mathcal{L} = 5.4 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 250 GeV, $7.7 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 550 GeV

But there is also an additional gain in sensitivity thanks to beam polarisation!
(factor 2 - 3 in most cases, up to factor 10, see backup)

⇒ at 250 GeV polarised LCF is competitive in precision/sensitivity to FCC-ee with 4 IPs

Proposed baseline for CERN

ESPPU submission: arXiv:2503.24049

- 33 km facility
- **2 interaction regions**
- initially: SCRF with 31.5 MV/m, $Q_0 = 2 \cdot 10^{10}$
- physics optimised run plan with polarised beams (following ILC polarisation scheme)
  - 3 ab^{-1} @ 250 GeV
    Higgs physics, precision measurements of W, Z and fermion pair-production
  - 100-200 fb^{-1} @ 91 GeV
    precision EW measurements at the Z-pole ($5 \cdot 10^9$ Z bosons - Giga-Z)

statistics sufficient for Higgs couplings and BSM fits to be systematics-limited (see backup)

First stage with full power for about 9.1 BCHF (5 Hz for 8.3 BCHF)

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  - 8 ab^{-1} @ 550 GeV after energy upgrade — more cavities installed in the same tunnel
    precision top, Higgs in WW fusion, di-Higgs, ttH coupling, VBS, searches...
  - 200-400 fb^{-1} @ 350 GeV
    mainly for $t\bar{t}$ threshold scan

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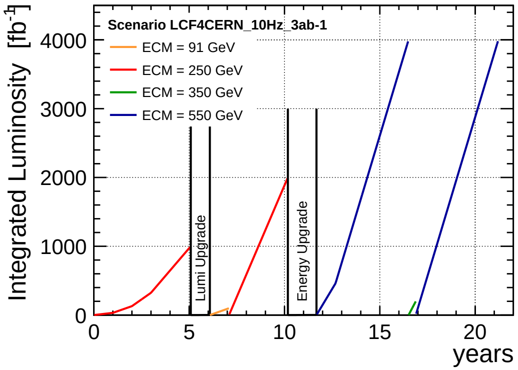
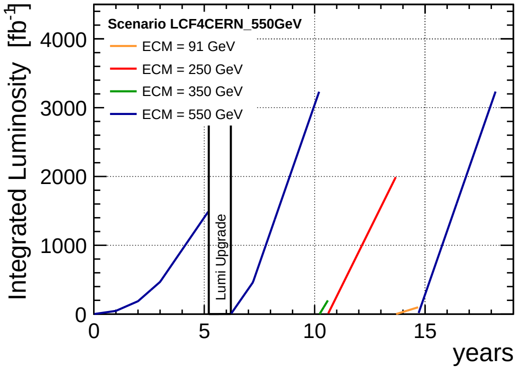
Total cost of the full power 550 GeV machine: 14.5 BCHF (still below that of full FCC-ee)

Possible running scenarios examples

Baseline scenario (start with 8.3 BCHF)



Starting at 550 GeV



The whole physics programme, including 550 GeV (!), can be done in about 20 years.

Upgrade options after 20 years (250 + 550 GeV) ESPPU submission: arXiv:2503.19983

(or earlier if required technology at hand)

Different technologies can be used for subsequent energy upgrade assuming 33 km facility

- SCRF with traveling wave acceleration ⇒ up to 1 TeV
- CLIC technology ⇒ up to 2 TeV
- cold-copper technology (C^3) ⇒ up to 3 TeV
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Luminosity upgrade options can also be considered

- Recycling Linear Collider (ReLiC) both energy and particles are recycled
- Energy Recovery Linear Collider (ERLC)

⇒ luminosity above 10^{36} cm^{-2}s^{-1} expected at 250 GeV! $\times$ 20

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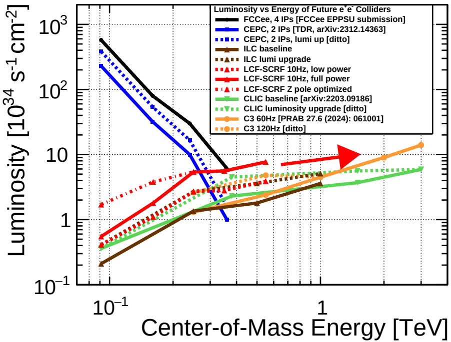
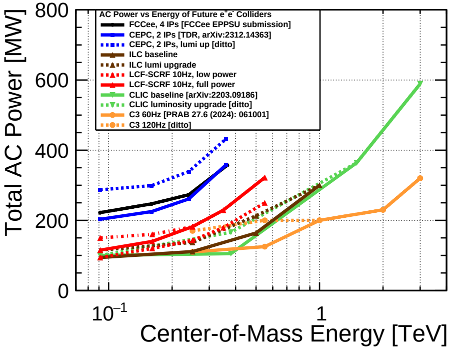
Alternative collider modes are also considered ($\gamma\gamma$, $e^-\gamma$, e^-e^-)...

All options remain open at the initial stage, we do not need to decide about the upgrade path...

Luminosity and power

Comparison of different collider options

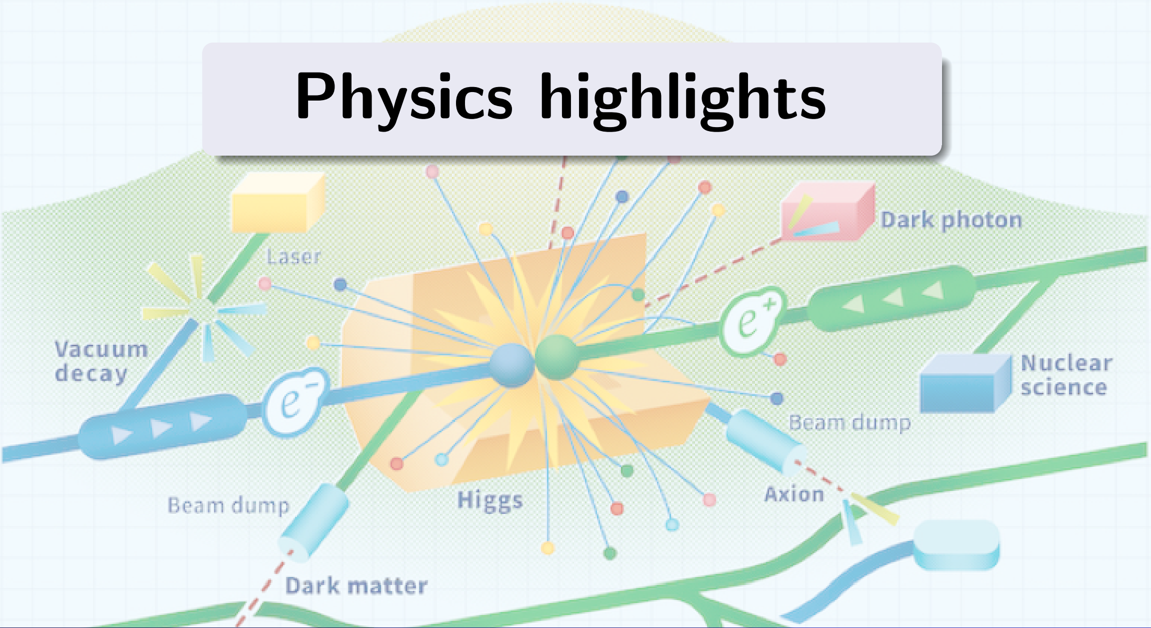




Precision gain due to polarization ∼ up to order of magnitude in luminosity!

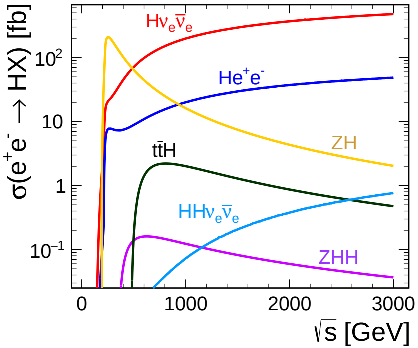
Remember $\sin^2\theta_W$ measurement at SLC vs LEP

Physics highlights



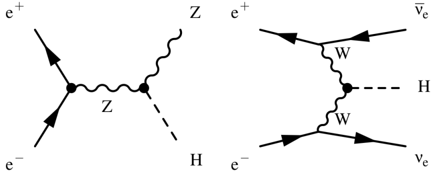
Higgs boson production

Precision Higgs measurements are clearly the primary target for future e^+e^- Higgs factory.



At 240/250 GeV dominated by Higgs-strahlung process

With high energy stage, we profit from combining two production channels:



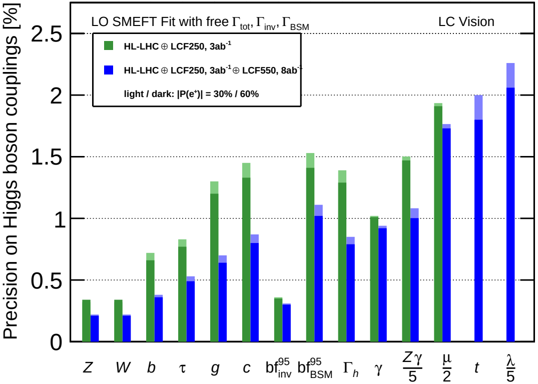
$\Rightarrow$ better control of systematic effects,
fully model independent coupling analysis

Higgs couplings from global fit

arXiv:2503.19983

Global SMEFT fit including all relevant (Higss/EW/top) measurements

Projected uncertainties on Higgs couplings for 3 ab^{-1} at 250 GeV and 8 ab^{-1} at 550 GeV



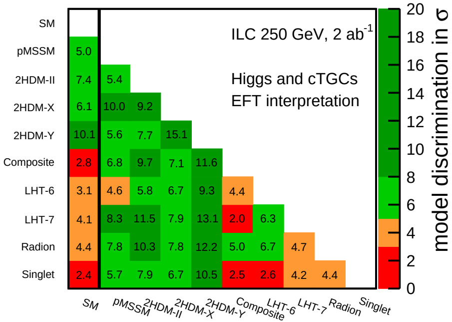
ZH and WW fusion production channels + polarization ⇒ all operators can be constrained

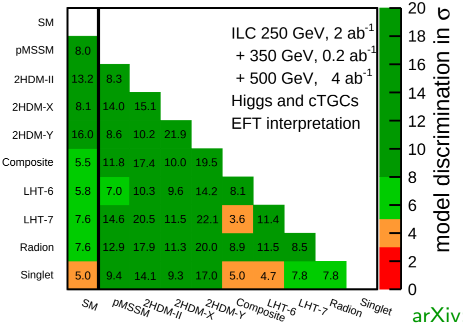
BSM model can be identified if any anomalies are found

Linear Collider Vision

Model discrimination from Higgs couplings

Precision of e^+e^- colliders allows to distinguish the SM expectations and other models from the global analysis of the Higgs boson couplings





arXiv:1710.07621

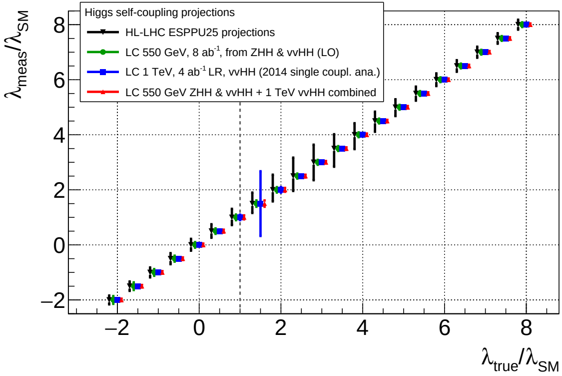
Significant ($> 5\sigma$) differences between most scenarios already at 250 GeV (left)

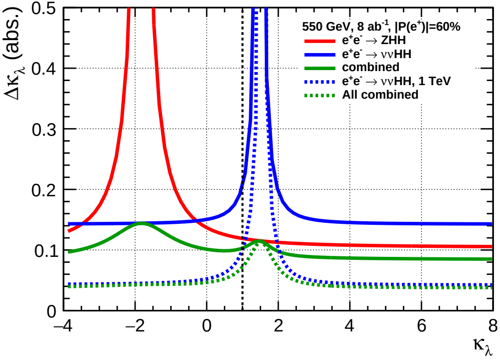
All considered BSM scenarios can be identified at $\geq 5\sigma$ after full ILC programme (H-20)

Higgs self-coupling

arXiv:2503.19983

By combining two production channels, precise measurement possible for arbitrary scenarios.



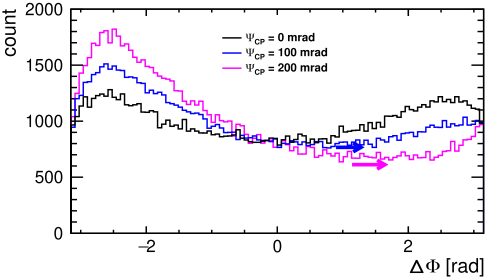


Model independent determination possible only from direct di-Higgs production, above $\sqrt{s}$ ~500 GeV

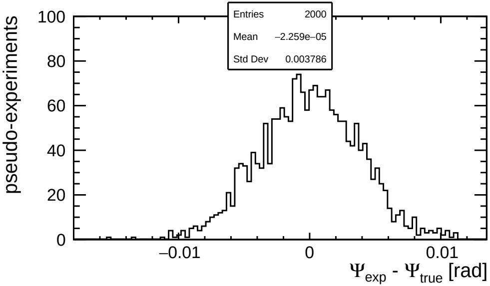
CPV mixing in the Higgs sector

arXiv:2405.05820

Unique possibility in the Z boson fusion process $e^+e^- \rightarrow e^+e^-H$ at 1 TeV ILC



Distribution of the azimuthal angle between electron and positron scattering planes is sensitive to mixing phase in Higgs sector



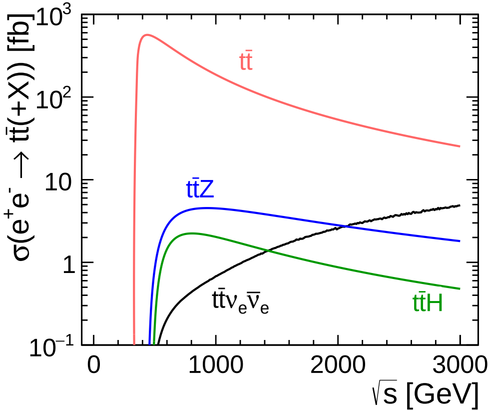
Mixing angle can be measured with statistical uncertainty of 3.8 mrad
$\Rightarrow$ CP parameter f_{CP}^{HZZ} to $1.44 \cdot 10^{-5}$

Complementary to CP mixing measurement in fermionic couplings via $H \rightarrow \tau^+\tau^-$ arXiv:1804.01241

Linear Collider Vision

Top-quark physics

Discovered 30 years ago, but precision measurements still waiting for next e^+e^- machine.



Pair-production at the threshold (threshold scan)

- top-quark mass and width

Pair-production above the threshold

- electroweak couplings
- rare decays

Additional processes open at high energies

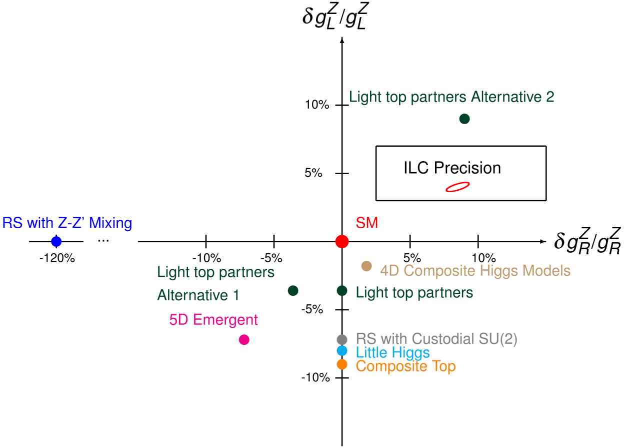
- top Yukawa coupling
- CP properties
- BSM constraints

Top quark couplings

arXiv:2503.19983

Beam polarization allows for direct access to top quark couplings to the Z boson from the angular distributions above threshold.

Percent level measurement of left and right couplings allows for discrimination between many BSM scenarios ⇒

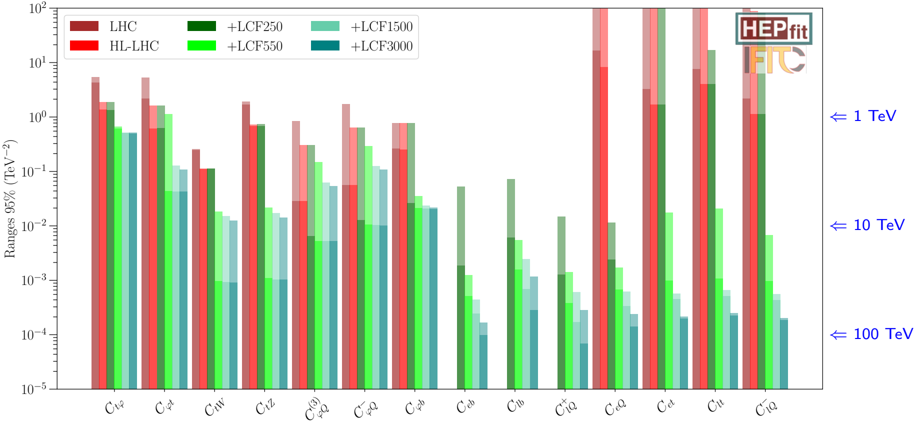


for ILC at 500 GeV with 4 ab^{-1}

BSM sensitivity

arXiv:2503.11518

Expected 95% CL bounds from global fit of 30 SMEFT operators with top and bottom quarks.



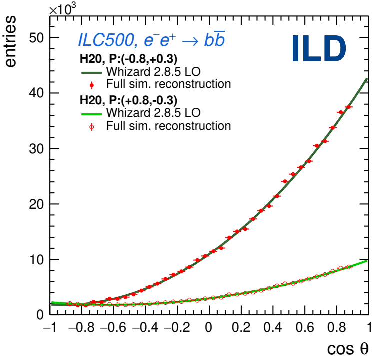
solid-colored bars show the limits from fits for individual Wilson coefficients; the lightly-shaded bars show the limits from a global fit including all operators

Linear Collider Vision

Indirect BSM sensitivity

arXiv:2403.09144

Per mille level precision for heavy quarks, profiting from excellent flavor tagging capabilities



GHU vs SM discrimination power (σ-level) — ILD

	ILC250♦ (no pol.) C	R	Z	ILC250 C	R	Z	ILC250 +500 C	R	Z	ILC250 +500 +1000* C	R	Z
B_3^+	0.1	0.4	0.5	0.1	0.7	0.8	0.5	1.3	1.3	1.6	2.5	2.5
B_3^-	0.1	0.4	0.5	0.3	0.9	0.9	0.9	2.7	2.7	3.3	6.7	6.8
B_2^+	0.2	0.7	0.8	0.3	1.5	1.6	0.9	2.2	2.3	3.0	4.4	4.5
B_2^-	0.2	0.7	0.7	0.5	1.4	1.5	1.7	4.6	4.8	6.3	>10	>10
B_1^+	0.3	1.6	1.7	0.7	3.2	3.5	1.5	4.4	4.7	4.3	6.8	7.0
B_1^-	0.5	1.4	1.4	0.9	2.7	2.8	3.3	9.6	9.9	>10	>10	>10
A_2	0.6	3.3	3.6	0.9	4.8	5.3	4.3	>10	>10	>10	>10	>10
A_1	0.8	3.9	4.2	1.0	5.0	5.5	5.3	>10	>10	>10	>10	>10

Z-fermion couplings
- *C: Current precision*
- *R: ILC250 (Rad. Ret.)*
- *Z: Giga-Z*

< 3 σ; 3-4 σ; 4-5 σ; > 5 σ

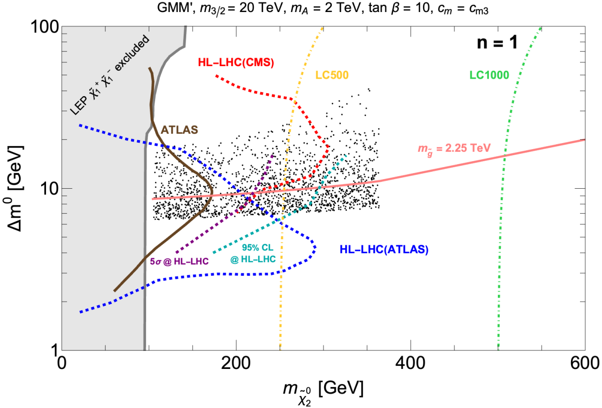
BSM model discrimination significantly improves with beam polarization and energy

Extreme statistics of Z-pole not really needed...

Direct BSM sensitivity   SUSY

arXiv:2007.09252

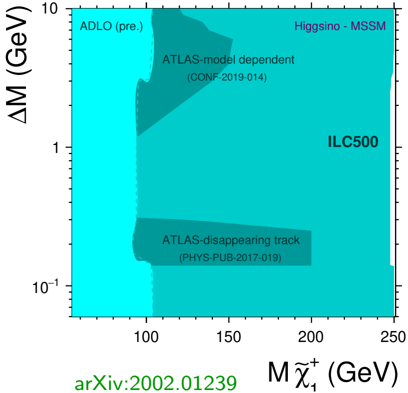
Naturalness: higgsino mass parameter μ is expected to be of the order the weak scale



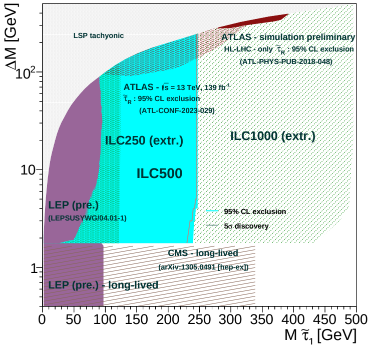
HL-LHC experiments will not be able to probe all possible scenarios ⇒ perfect case for LC

Direct BSM sensitivity SUSY

Examples of dedicated full simulation studies from ILD



arXiv:2002.01239

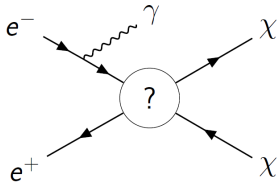


arXiv:2410.14622

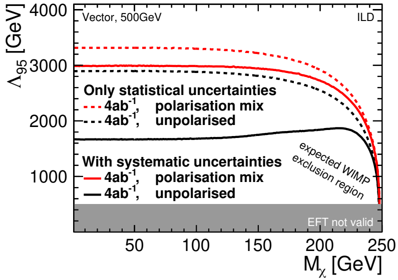
All scenarios can be accessed almost up to the kinematic limit. No holes left...

Direct BSM sensitivity mono-photon signature

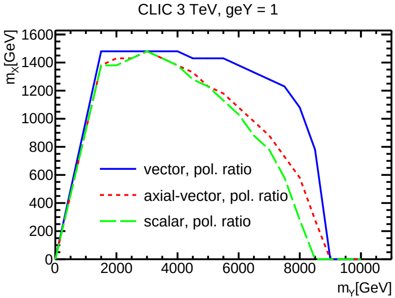
The most general way to look for DM particle production
Hard photon radiation from the initial state allows us to detect production of the invisible final states



Sensitivity to mediator masses far beyond $\sqrt{s}$



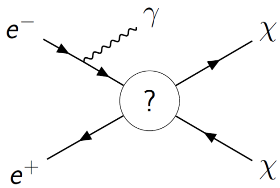
arXiv:2001.03011



arXiv:2103.06006

Linear Collider Vision

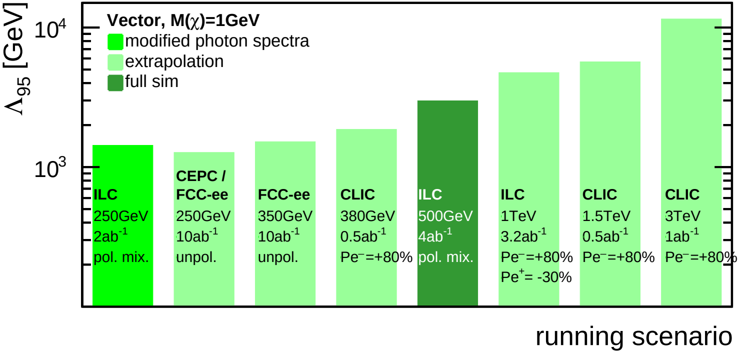
Direct BSM sensitivity mono-photon signature



The most general way to look for DM particle production

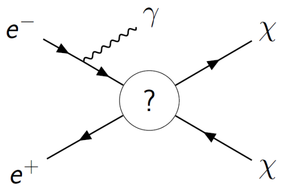
Sensitivity significantly enhanced by beam polarisation !

Also important for identification of the possible BSM scenario



Physics highlights: BSM

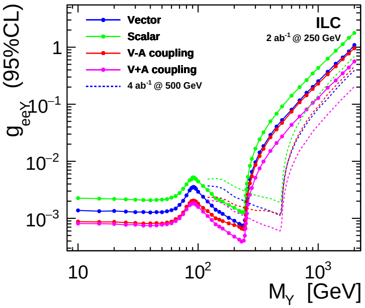
Direct BSM sensitivity mono-photon signature

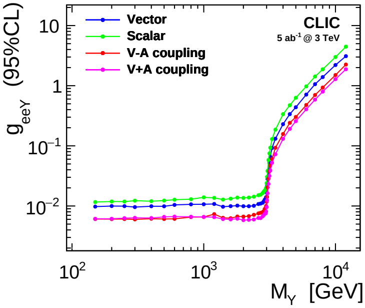


$\mathcal{O}(10^{-3} - 10^{-2})$ limits on the mediator coupling to electrons

up to the kinematic limit $M_Y \leq \sqrt{s}$

more stringent than from direct resonance search

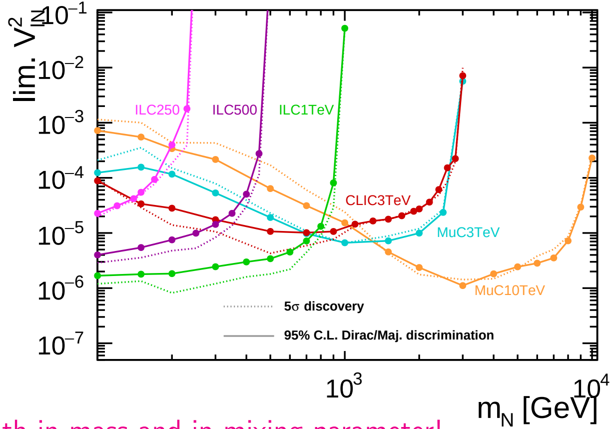




arXiv:2107.11194

Direct BSM sensitivity

Change of 5σ discovery and 95% identification range for Heavy Neutral Leptons with energy



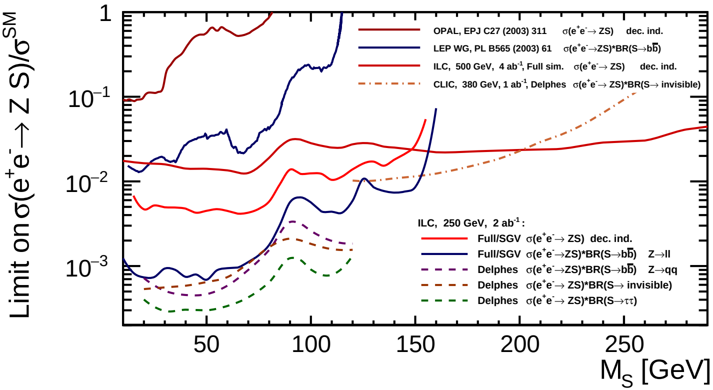
Sensitivity increase both in mass and in mixing parameter!

arXiv:2312.05223

Direct BSM sensitivity

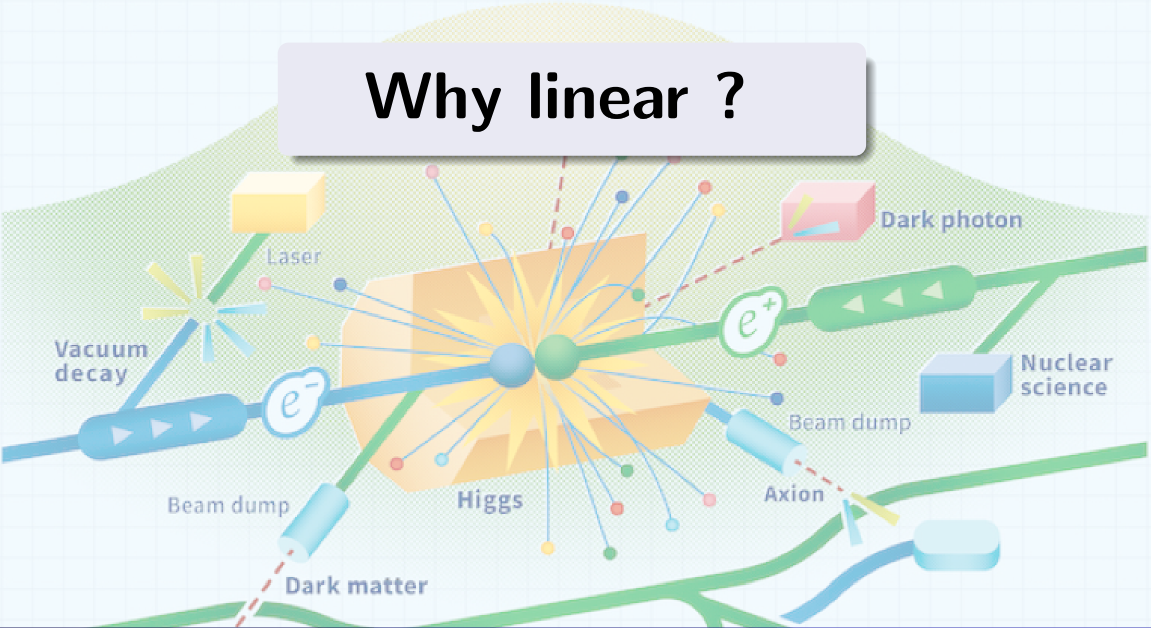
see dedicated parallel session contribution for details

Summary of Exotic scalar search results from different linear collider studies



Multiple search strategies possible ⇒ high sensitivity and model discrimination potential

Why linear ?


Laser
Dark photon
Vacuum decay
Nuclear science
Beam dump
Axion
Beam dump
Higgs
Dark matter

What do we gain? from beam polarization

Parity violation is a cornerstone of the Standard Model!

Left-handed particles are fundamentally different from right-handed ones.

It should be obvious that the model can not be fully tested without the beam polarization...

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LCF design assumes both electron and positron beam polarization.

Four independent measurements instead of one:

- possible signal enhancement and better background control
- increase accuracy of precision measurements, access to chiral observables
- more input to global fits, crucial for separation of all EFT operators
- can remove ambiguity in many BSM studies
- significantly reduce sensitivity to systematic effects

What do we gain? from running at 550 GeV and above

High energy running crucial to complete the precision exploration of the Higgs.

- Higgs from WW fusion ⇒ complementary measurements, independent BSM constraints
  almost all Higgs events @ 250 GeV are from higgs-strahlung, $e^+e^- \rightarrow ZH$
- Access to direct HH pair production
  Uncertainty on the self-coupling: 11% at 550 GeV, 10% at 1000 GeV (for κ_λ=1, 8 ab^{-1})
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- Extended range of indirect and direct BSM searches

Technology readiness

Future Colliders Comparative Evaluation WG Report

LCF is the most mature collider option for CERN

Intense R&D ongoing in the framework of the ILC Technology Network (ITN):

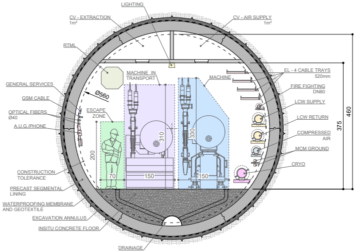
- Superconducting 1.3 GHz RF technology well established and (pre)industrialized (TRL 7)
  Significant progress since Eu-XFEL construction (largest ever "prototype"):
  higher cavity quality and gradients, new materials (cost reduction), higher klystron efficiency...
- Undulator-based positron source - mature and feasible — See presentation at EPS-HEP'2025
  Key technological innovation, required positron yield $\sim$ SLC $\times$ 100 $(5 \cdot 10^{14}/\mathrm{s})$
  Principle tested with E-166 experiment @ SLAC (2005), stable undulator performance confirmed at Eu-XFEL, ongoing tests on rotating target, no material damage observed
- Nanobeam technology - essential for the luminosity — also for PETRA IV and SUPER-KEKB
  Final focus design developed and tested at FFTB at SLAC and ATF-2 at KEK.
  Parameters corresponding to the LCF vertical beam size achieved within 10% at ATF-2.
  Avoiding wakefield effects, when running at full intensity, remains an important R&D issue.

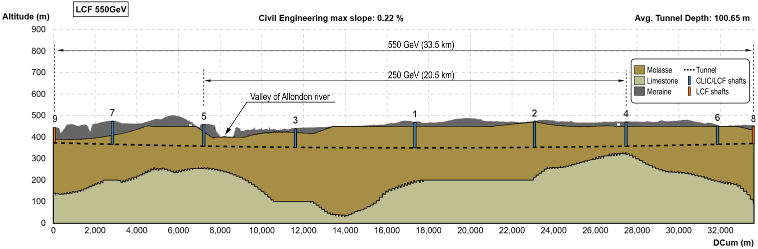
Design status

arXiv:2503.24049

Civil Engineering studies for LC at CERN ongoing since about 15 years !
Started for CLIC CDR (2012) but also addressing the SCRF option (ILC up to 1 TeV).

Cross section and geological profile of the possible location for LCF@CERN
as used for detailed costing of the facility





Injectors and experimental areas can fit on Prevessin site ("CERN attributed land")

Cost profile

LCF baseline is 550 GeV machine!

Cost to first physics (250 GeV) is only 8 – 9 BCHF

⇒ affordable within the current CERN budget, without substantial external contributions.

Cost of second stage (550 GeV) upgrade is another 5.5 BCHF

⇒ but only after initial stage completed and running...

Upgrade to 1 – 3 TeV will require additional investment of $\mathcal{O}$(10 BCHF)

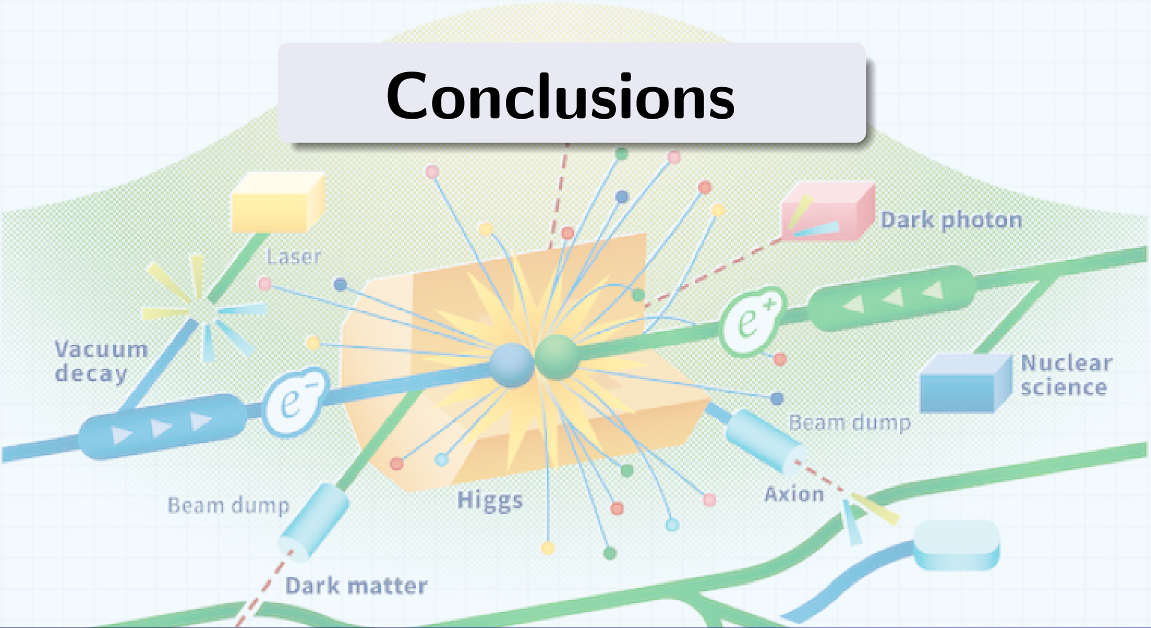
⇒ only after another $\mathcal{O}$(10 years) of running the facility

Significant cost reduction possible with new emerging technologies

⇒ we can stay flexible, decision about the upgrade strategy can be taken after first data...

Funding of the project distributed over many years, much easier to fit in the CERN budget

Conclusions



Linear Collider Vision and Prospects

Linear Collider option offers excellent opportunities for precision measurements over the full range of properties of the Higgs boson and top quark, and for physics discoveries.

First stage based on mature technologies, affordable within the CERN budget.
Could do physics shortly after the end of the HL-LHC program.

Multiple options for later stages provide a flexible response to possible developments in particle physics, including the discovery of new particles at the HL-LHC, competition with the CEPC in China, and the development of new accelerator technologies.

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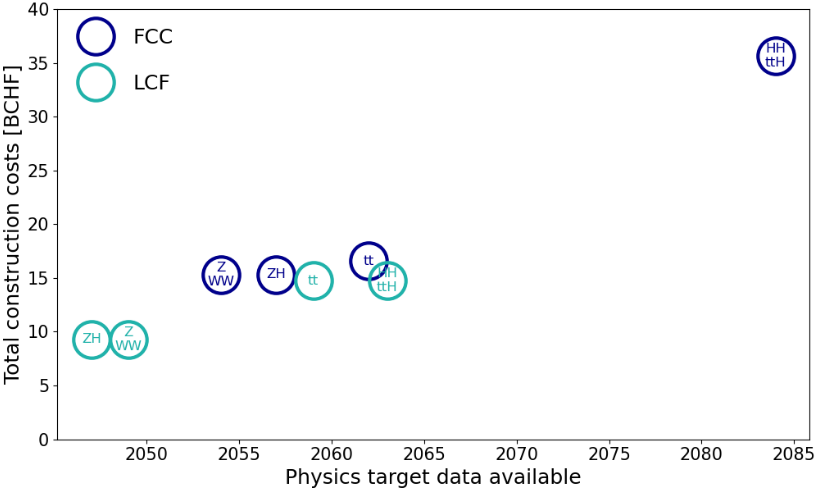
Ambitious flagship project, but not saturating the CERN community and its resources
Will allow for significant European contribution to other projects outside CERN.

In 20 years, we can develop revolutionary new methods for particle acceleration.
We need them for the future of the field. But resources need to be available...

Conclusions

Linear Collider Facility is just a better option for precision Higgs studies...

My personal comparison



References

LC Vision

Submissions to ESPPU 2026:

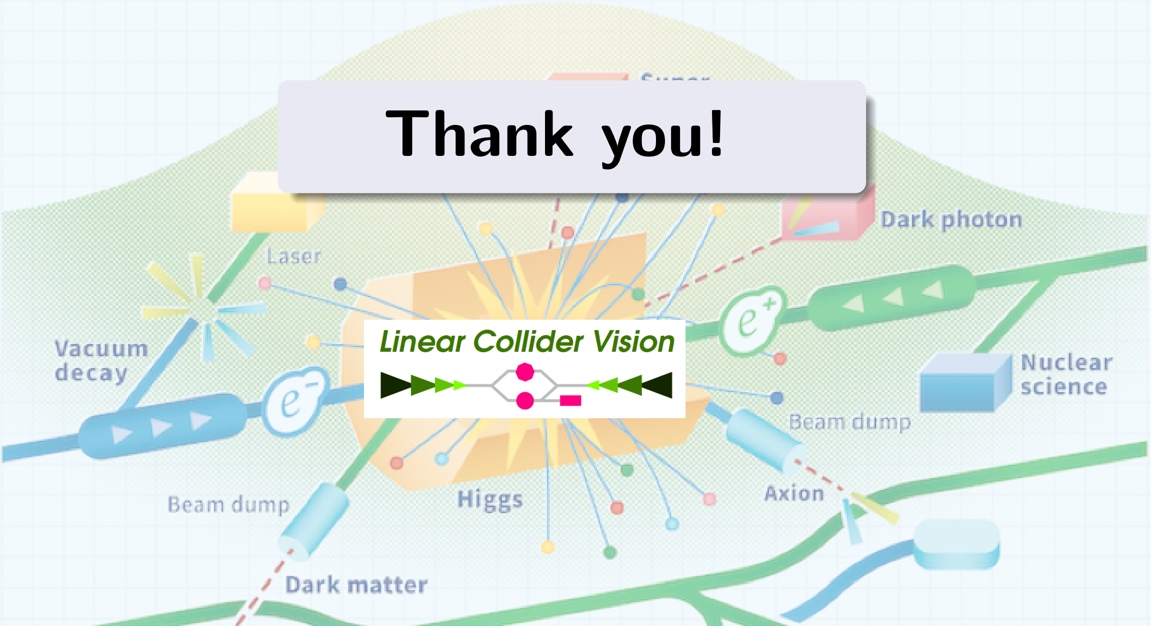
- A Linear Collider Vision for the Future of Particle Physics: arXiv:2503.19983
- The Linear Collider Facility (LCF) at CERN: arXiv:2503.24049

More details on the submission and document updates can be found on this indico page
You can also find the link to subscribe to LCVision-General e-mail list there

See also

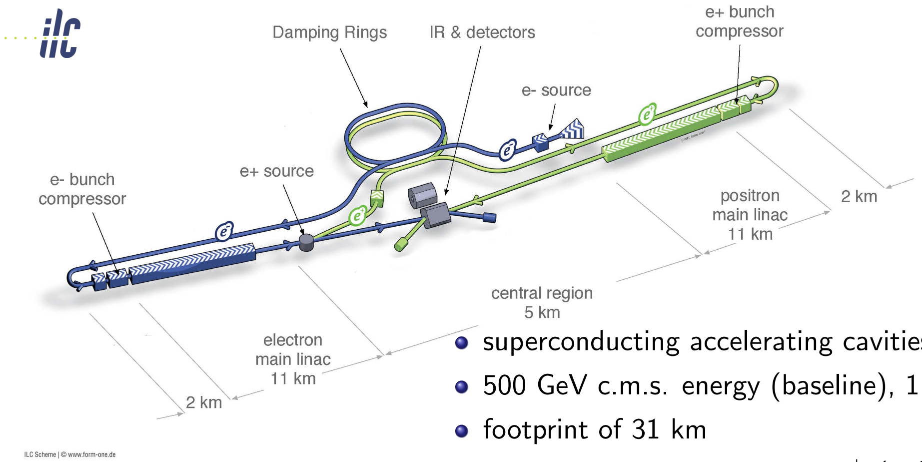
- ECFA Higgs, electroweak, and top factory study
  CERN Yellow Reports: Monographs CERN-2025-005, arXiv:2506.15390
- Future Colliders Comparative Evaluation WG Report: ESPPU submission
- To build or not to build: FCC *my very personal point of view* arXiv:2504.20267

Thank you!



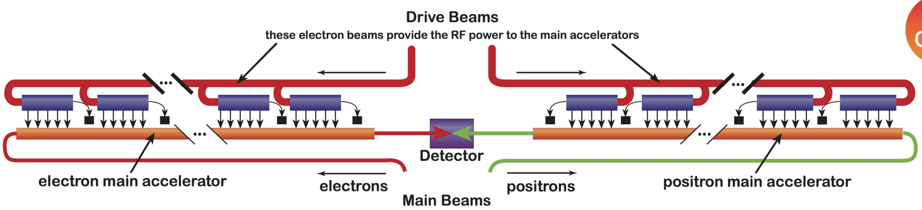
Linear Collider Vision

International Linear Collider Technical Design (TDR) presented in 2013 arXiv:1306.6328



- superconducting accelerating cavities
- 500 GeV c.m.s. energy (baseline), 1 TeV upgrade option
- footprint of 31 km
- polarisation for both e^- and e^+ (80%/30%)

Compact LInear Collider

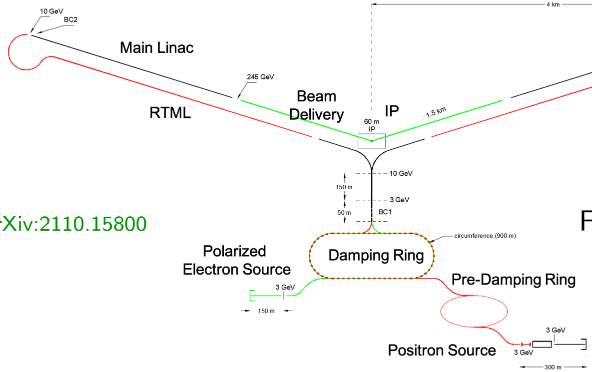


Conceptual Design (CDR) presented in 2012 arXiv:1209.2543

- high gradient, two-beam acceleration scheme
- staged implementation plan with energy of 380 GeV, 1.5 TeV and TeV
- footprint of 11, 30 and 50 km
- e^- polarisation (80%) only

see also arXiv:1812.07987

Cool Copper Collider - C^3



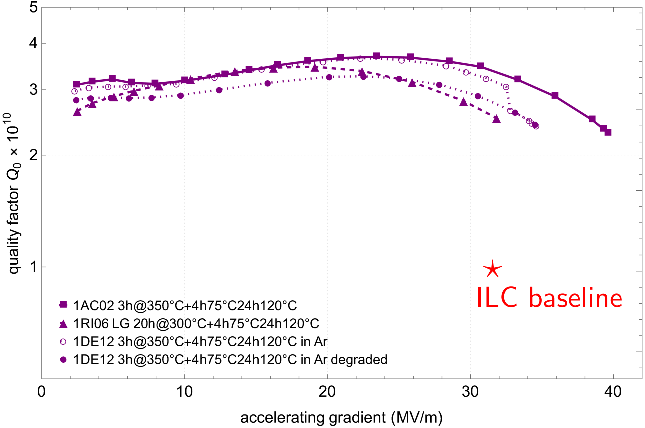
arXiv:2110.15800

First proposed in 2018 arXiv:1807.10195

- accelerating gradient up to 120 MeV/m
- reduced RF power with cryogenic copper
- 8 km footprint for 250 GeV and 550 GeV
- upgrade path up to 3 TeV (33 km)
- e^- polarisation (80%) only

Progress in SCRF technology

The modified baking process allows for higher gradients and much higher Q_0 values

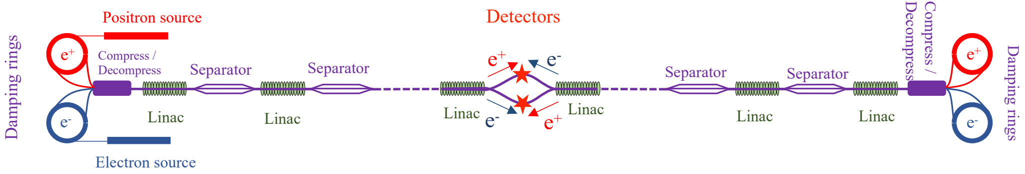


arXiv:2407.12570

Upgrade options

arXiv:2203.06476 arXiv:2503.19983

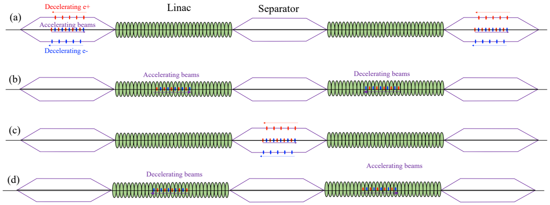
Schematic of Recycling Linear e^+e^- Collider (ReLiC) with two detectors.



Conventional standing wave SCRF technology

Combination of electric and magnetic field used to separate accelerating and decelerating bunches

Highly polarized electron and positions beams

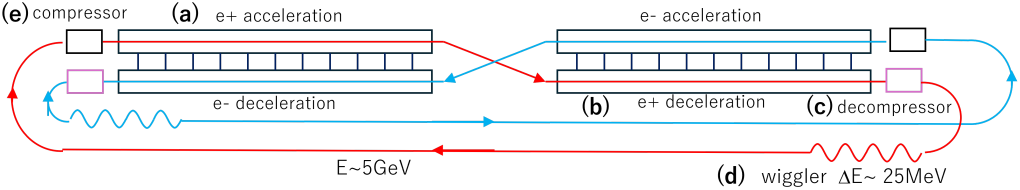


Linear Collider Vision

Upgrade options

arXiv:2105.11015 arXiv:2503.19983

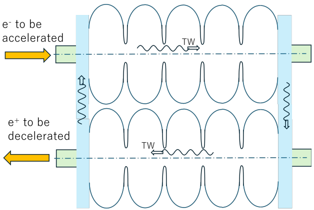
Schematic of Energy Recovery Linear Collider (ERLC).



Principle similar to CLIC but there is no separate drive beam

Dedicated Twin-Axis Cavities for RF power transfer

K.Yokoya @ LCWS2024

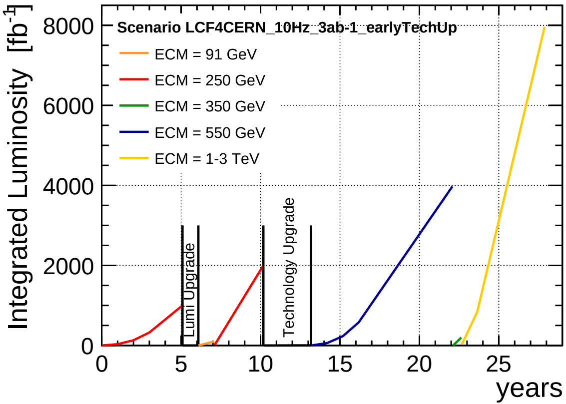


Linear Collider Vision

Running scenario example

arXiv:2503.19983

Early technology switch to extend energy range.



Role of polarisation (selection)

arXiv:hep-ph/0507011

SM:		
top threshold	Improvement of coupling measurement	factor 3
$t\bar{q}$	Limits for FCN top couplings reduced	factor 1.8
CPV in $t\bar{t}$	Azimuthal CP-odd asymmetries give access to S- and T-currents up to 10 TeV	$P^{\rm T}_{e^-} P^{\rm T}_{e^+}$ required
W^+W^-	Enhancement of $\frac{S}{B}$, $\frac{S}{\sqrt{B}}$	up to a factor 2
	TGC: error reduction of $\Delta\kappa_\gamma$, $\Delta\lambda_\gamma$, $\Delta\kappa_Z$, $\Delta\lambda_Z$	factor 1.8
	Specific TGC $\tilde{h}_+ = {\rm Im}(g_1^{\rm R} + \kappa^{\rm R})/\sqrt{2}$	$P^{\rm T}_{e^-} P^{\rm T}_{e^+}$ required
CPV in γZ	Anomalous TGC $\gamma\gamma Z$, γZZ	$P^{\rm T}_{e^-} P^{\rm T}_{e^+}$ required
HZ	Separation: $HZ \leftrightarrow H\bar{\nu}\nu$	factor 4 with RL
	Suppression of $B = W^+\ell^-\nu$	factor 1.7
Precision measurements of the Standard Model at GigaZ:		
Z-pole	Improvement of $\Delta \sin^2\theta_W$	factor 5–10
	Constraints on CMSSM space	factor 5
CPV in $Z \to b\bar{b}$	Enhancement of sensitivity	factor 3

Table 4.1: Some of the physics examples given in this report. The case of having both beams polarized is compared with the case of using only polarized electrons; in many cases $(|P_{e^-}|, |P_{e^+}|) = (80\%, 60\%)$ is compared to $(|P_{e^-}|, |P_{e^+}|) = (80\%, 0\%)$, cf. see corresponding chapter; B (S) denotes background (signal); CPV (RPV) means CP (R-parity) violation.

Z-pole statistics   required for global analysis of Higgs measurements

From the perspective of Higgs coupling measurement, at least 10^9 Z events collected at the Z-pole would already saturate the expected precision (from the FCC-ee mid-term report)

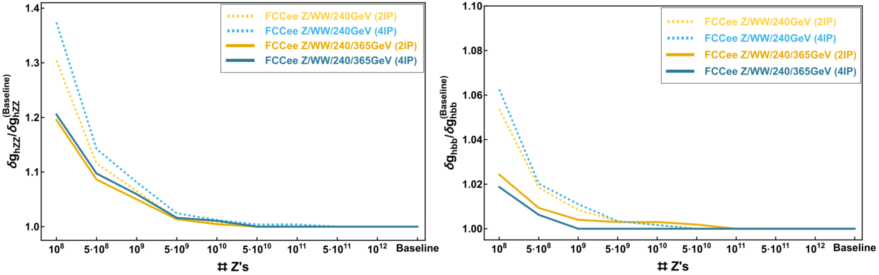


Fig. 351 Estimated decrease in the precision of the HZZ (left) and Hbb (right) couplings as a result of a reduction in the running time, and hence luminosity collected at the Z pole. The ratio between the expected precision using the set of EW precision measurements for the different number of Z events and the baseline of 4×10^{12} (6×10^{12} for 4 IPs) events is shown for the FCC-ee programme up to 240 GeV and up to 365 GeV.

Backup slides

Linear Collider Vision

BSM sensitivity vs energy

The sequential impact of the separate $\sqrt{s}$ runs at the FCC-ee in the SMEFT fit based on $\mathcal{O}(\Lambda^{-2})$ calculations.

Shown is the limit improvement relative the expected HL-LHC reach ⇒

Impact of precision measurements at the Z-pole is much smaller than those of high energy stages

ECFA Higgs/EW/Top Factory Report arXiv:2506.15390