Linear Collider Vision for the Future of Particle Physics & Higgs Focus

- **Status HEP**
- **Physics needs and some Higgs Highlights**
- **Overview Collider Designs**
- **Alternatives and R&D projects for advanced options**
- **Conclusion**

What is the current status of HEP?

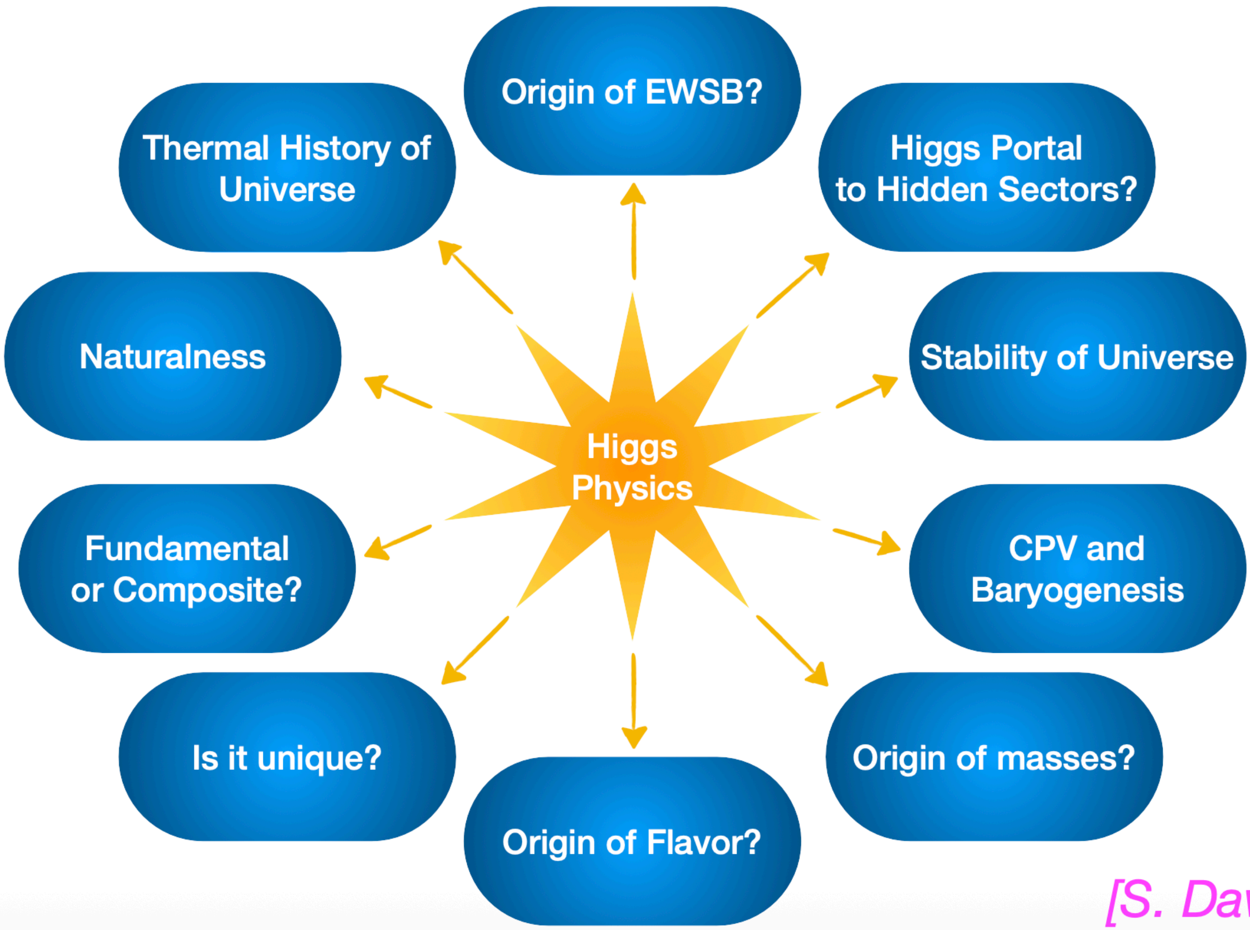
- One Higgs particle discovered in 2012
  - strongly consistent with Standard Model (SM) predictions
- Few excesses around…..(e.g. a light scalar at ~95 GeV, SUSY at ~200 GeV,…?)
  - but not (yet) confirmed discoveries
- Still open questions & strong motivation for Beyond SM (BSM) physics
  - Dark Matter, Baryon-Asymmetry, Neutrino masses, etc.
- Since scale of new physics window still unclear…..what is the best strategy to
  - *…be prepared for any findings of current LHC and future HL-LHC*
  - *…pave the path towards future possible accelerator HEP experiments*
- Optimize collider for well-known physics case (Higgs area!) in timely manner
  - i.e. with a stageable, tunable e+e- collider with polarized beams & flexible running options ….e.g. at CERN !
  - extendable with imminent new technologies but also for testing future technologies
  - in a responsible, sustainable manner as much as possible….

➡ *see talk tomorrow in BSM session*

➡Mature e+e- collider designs at $\sqrt{s}$=~250,~350,~550 GeV and beyond TeV options!

Overview open Questions

Most of the open questions of particle physics are directly related to Higgs physics and in particular to the Higgs potential



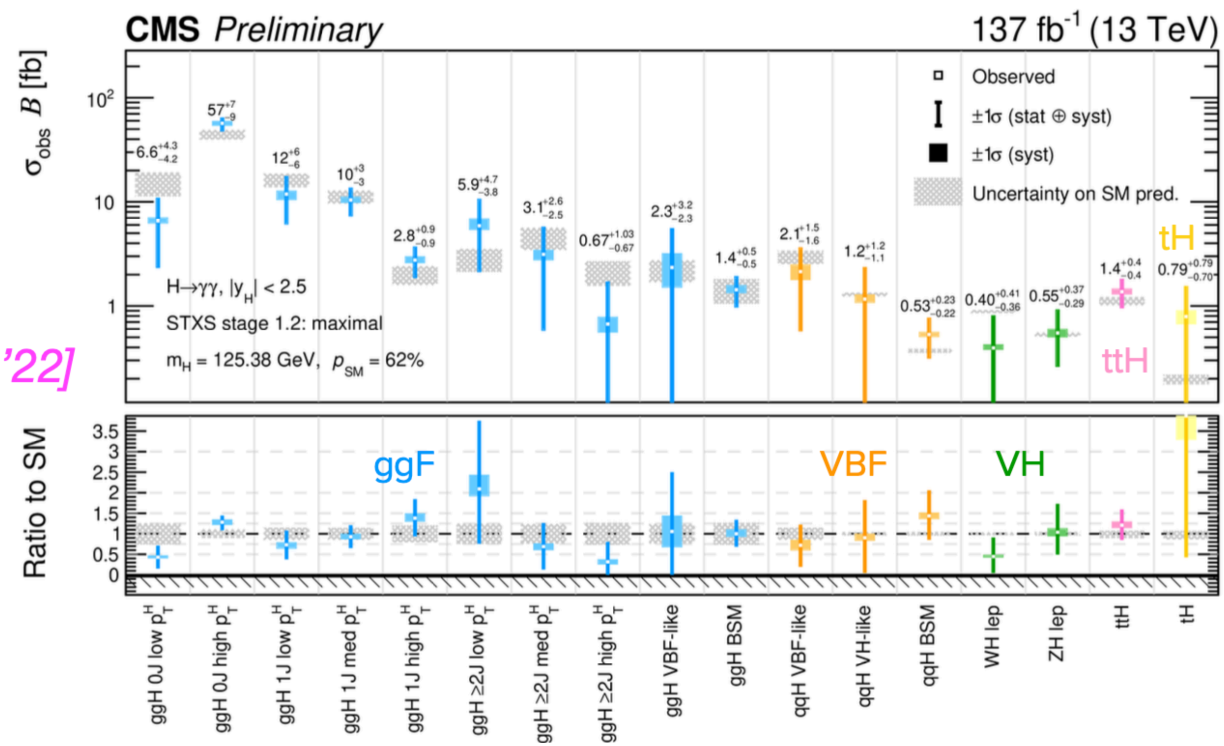
[S. Dawson et al. '22]

Properties of discovered Higgs particle

The Standard Model of particle physics uses a "minimal" form of the Higgs potential with a single Higgs boson that is an elementary particle

h125: inclusive and differential rates

[CMS Collaboration '22]



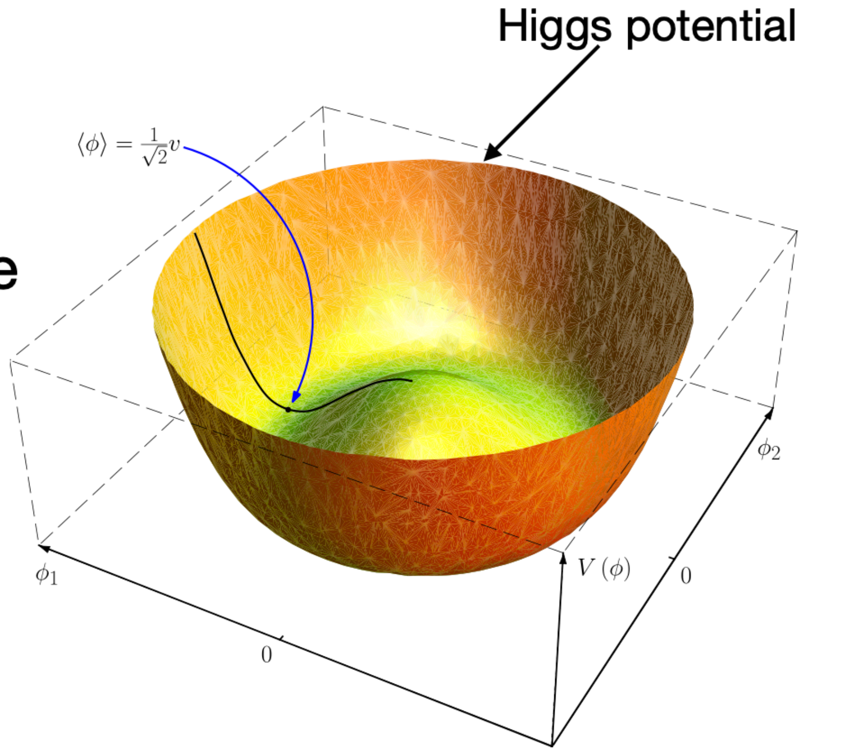
⇒SM-like properties

The LHC results on the discovered Higgs boson within the current uncertainties are compatible with the predictions of the Standard Model, but also with a wide variety of other possibilities, corresponding to very different underlying physics

In the ff, courtesy of G. Weiglein, see talk Osaka, HPNP2025

The 'holy grail' of particle physics: Higgs potential

What is the underlying dynamics of electroweak symmetry breaking? The vacuum structure with v ≠ 0 is caused by the Higgs field through the Higgs potential. We lack a deeper understanding of this!



We do not know where the Higgs potential that causes the structure of the vacuum actually comes from and which form of the potential is realised in nature. Experimental input is needed to clarify this!

Single doublet or extended Higgs sector? (new symmetry?)

Fundamental scalar or compositeness? (new interaction?)

Crucial: underlying dynamics of electroweak breaking

SM: phenomenological description of the known particles and their interactions, but we do not know the underlying dynamics (Higgs potential is just postulated in the SM)

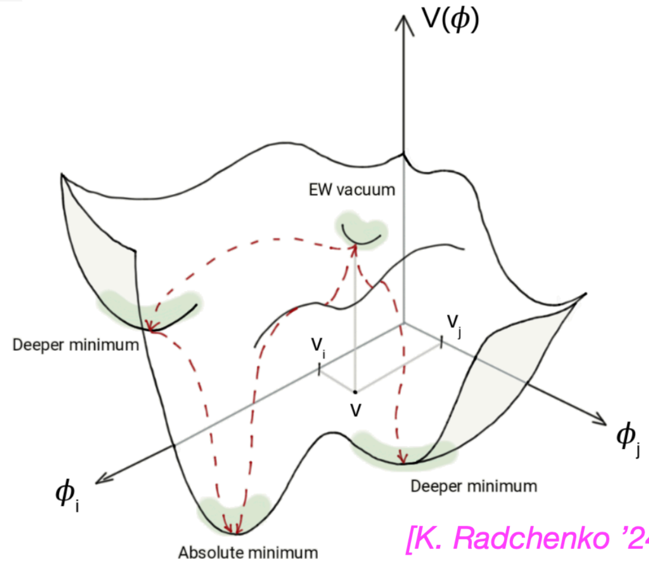
Trilinear coupling — Quartic coupling — Possible couplings involving additional scalars

$$V = 1/2\, m_h^2\, h^2 + v\, \lambda_{hhh}\, h^3 + \lambda_{hhhh}\, h^4 + \ldots + v\, \lambda_{hhH}\, h^2 H + v\, \lambda_{HHH}\, H^3 + \ldots$$

Known so far:
(h: detected Higgs at 125 GeV)

Distance of EW minimum from origin of field space: v

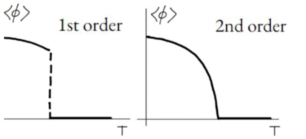
Curvature of the potential around the EW minimum: m_h



[K. Radchenko '24]

➡Trilinear coupling is crucial for the dynamics of symmetry breaking!

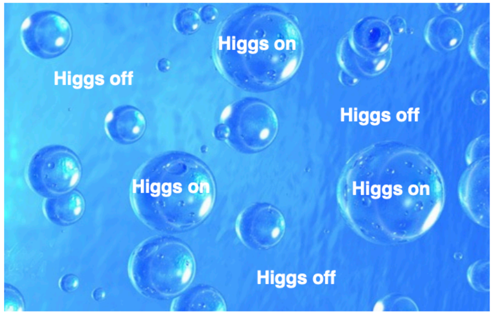
Electroweak phase transition: 1st or 2nd order?

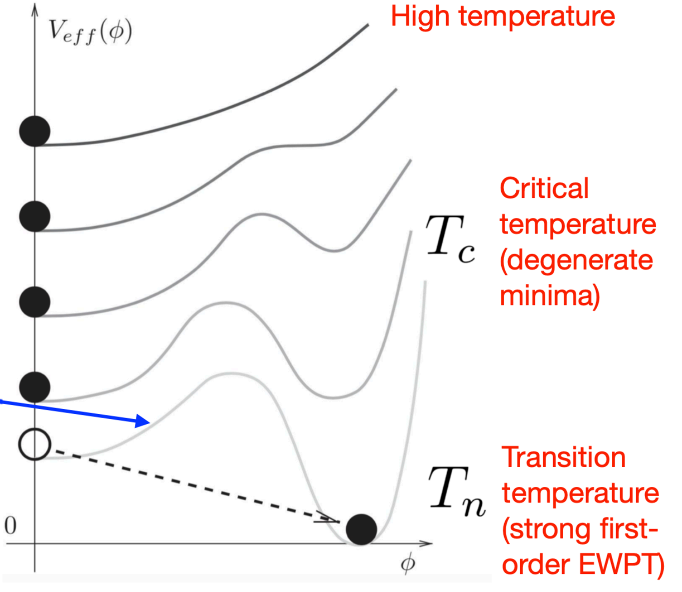


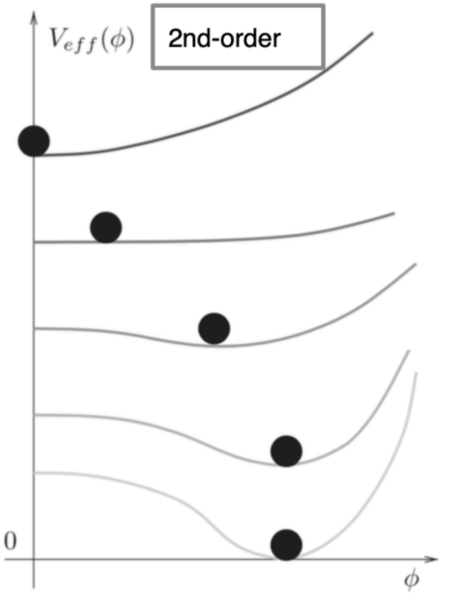
[D. Gorbunov, V. Rubakov]

Temperature evolution of the Higgs potential in the early universe:

$$V(\phi, T) = V_0(\phi) + V^{loop}(\phi, T)$$







Potential barrier depends on trilinear Higgs coupling(s)

Baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT

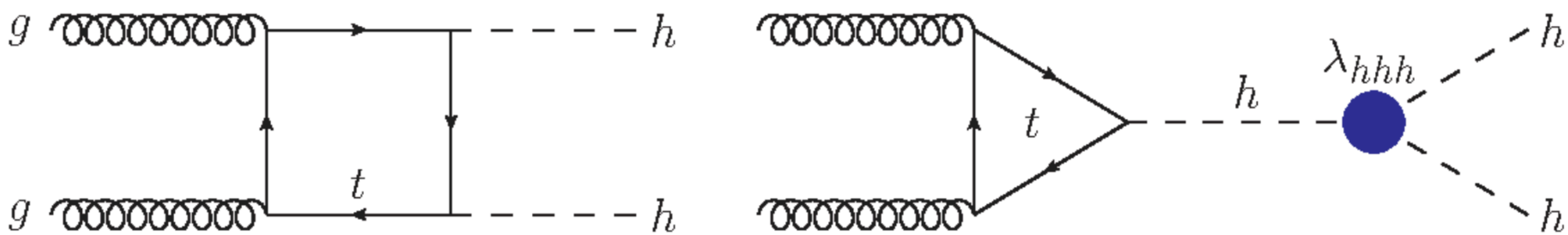
➡ If more than one field is present: Higgs potential is multidimensional function of the different scalar fields components!

➡ Deviation of trilinear Higgs coupling from SM is a typical feature of 1st order phase transition!

Trilinear Higgs coupling and Di-Higgs production mandatory!

Sensitivity to trilinear self-coupling λ_{hhh} from Higgs pair production:

- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**

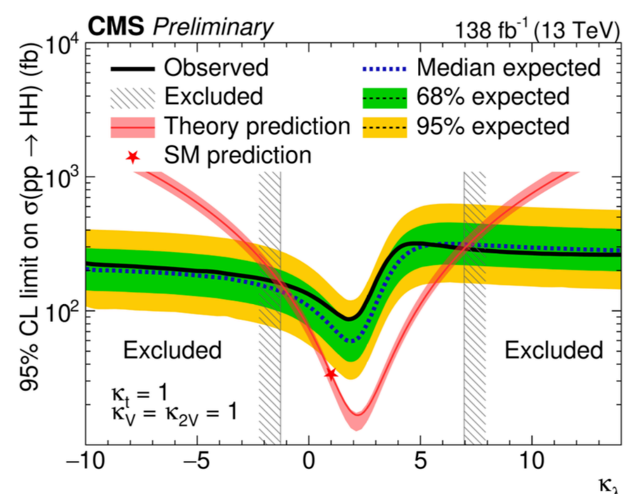


[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

⇒ Large destructive interference contribution (signal-signal interference), depends sensitively on $\varkappa_\lambda \equiv \lambda_{hhh} / \lambda_{hhh}^{SM,\,0}$

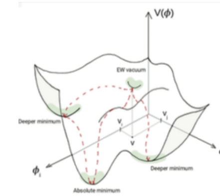
[CMS Collaboration '24]

- Experimental limits on the di-Higgs cross sections yield contraints on $\varkappa_\lambda$!



⇒ Upper bound on λ_{hhh} of currently about 7 x (SM value) $-1.4 < \varkappa_\lambda < 7.0$ at 95% C.L.

Interlude: how big can modification of λ_{hhh} be?

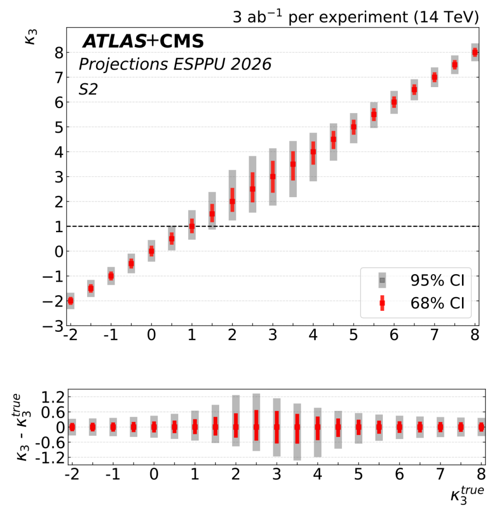


Limits from non-resonant di-Higgs production:
Upper bound on λ_{hhh} of currently about 7 x (SM value), i.e. deviation of up to 700% from the SM is allowed

- **SM:** relatively small higher-order contributions to λ_{hhh} at the level of about –7%, mostly from top loop; note: $\varkappa_\lambda \equiv \lambda_{hhh} / \lambda_{hhh}^{SM,\,0}$

HL-LHC projection

[ATLAS and CMS Collaborations '25]



- **BSM models (UV-complete):**
Generic feature of extended Higgs sectors: mass splitting between BSM Higgs states yields large enhancement of λ_{hhh}, effects of several 100% possible within existing theoretical and experimental constraints

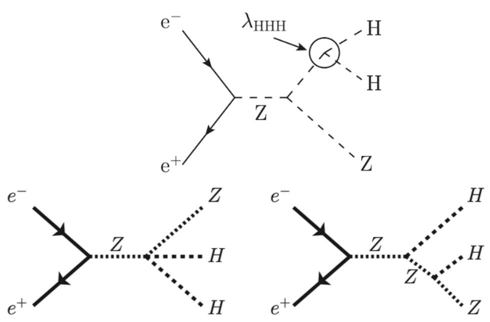
- **Effective field theories:**
BSM effects parameterised as higher-dimensional operators, large enhancement of λ_{hhh} possible, effects of several 100%

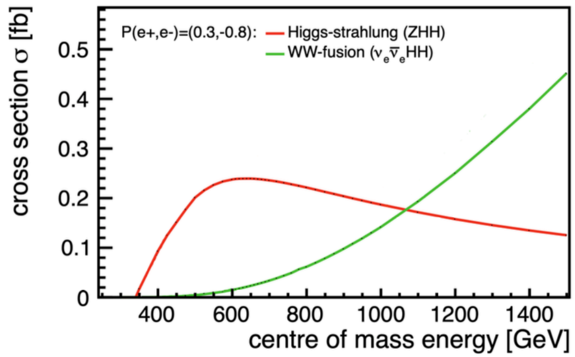
➡ *Precision not sufficient to clarify mechanism of electroweak symmetry breaking and phase transition!*

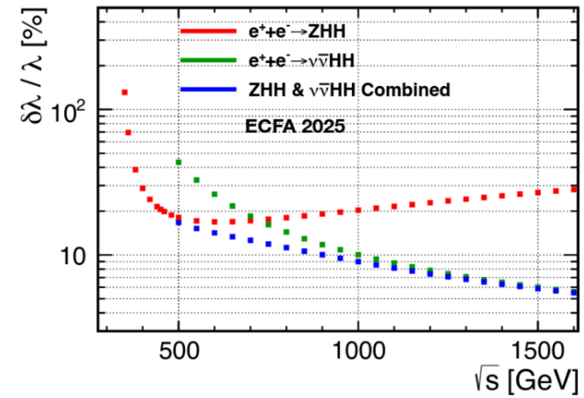
√s≥550 GeV!

Measurement of λ_{hhh} at e^+e^- Linear Colliders: Higgs pair production

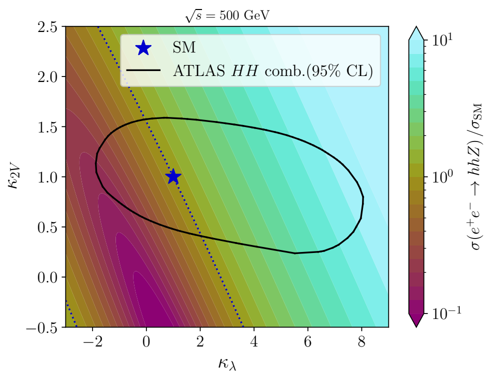
[J. List, J. Tian et al. '25]

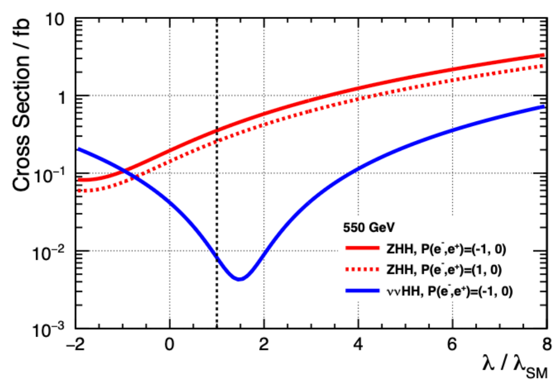


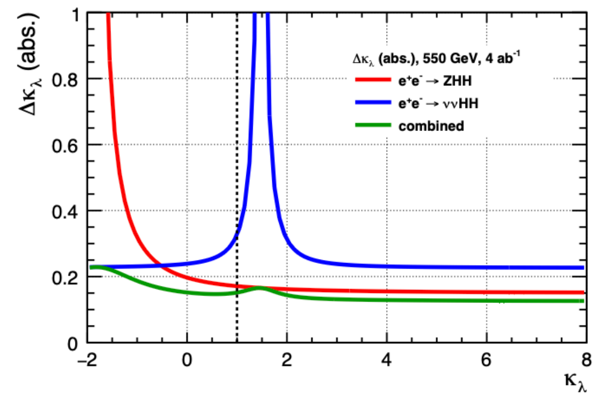




[J. Braathen, F. Arco, G. Weiglein '25]

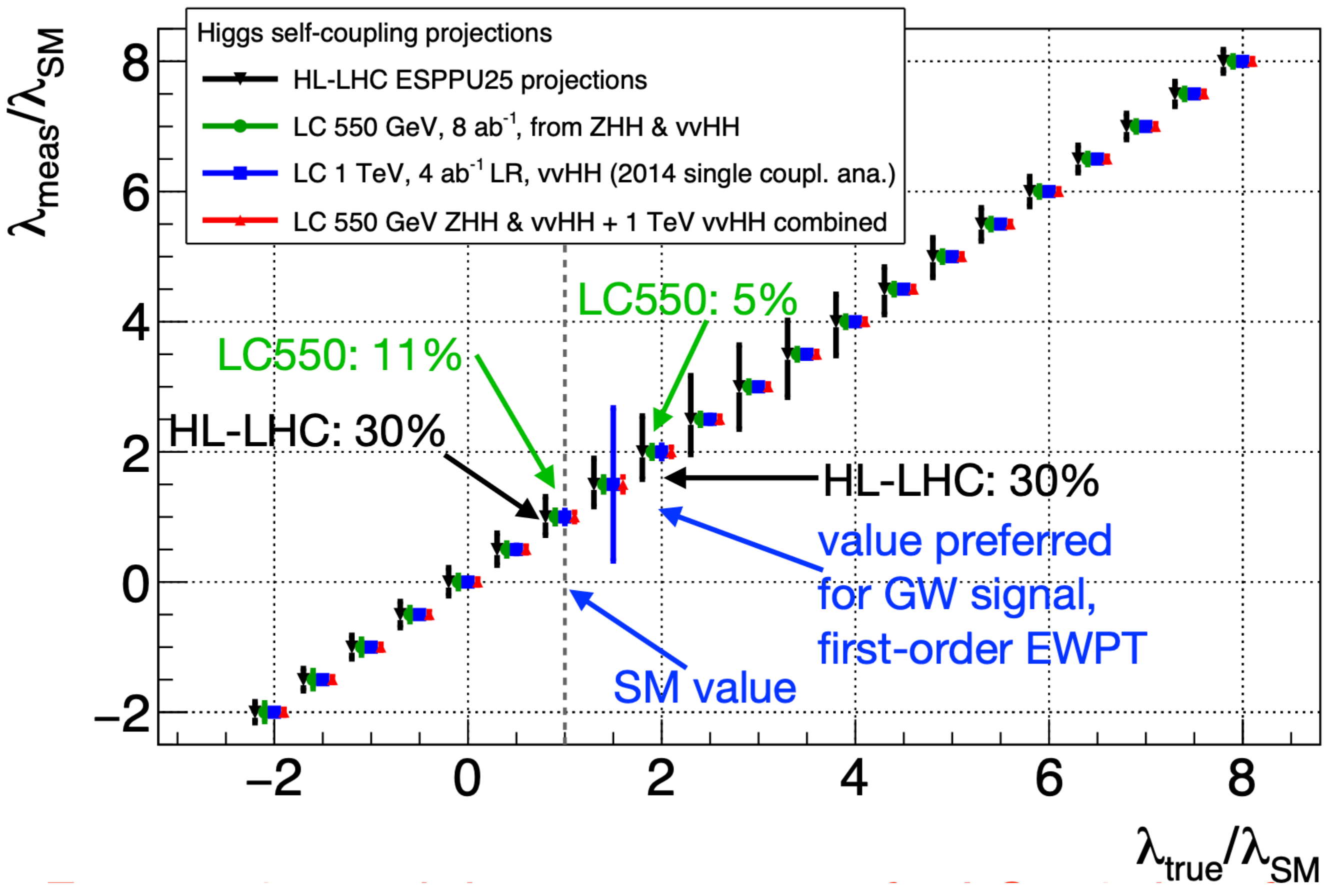






- ➡ 11 % accuracy on κ_λ for SM case at 550 GeV and with polarized beams
- ➡ Constructive interference for $\lambda>\lambda_{SM}$
- ➡ Essential to achieve √s≥550 GeV as early as possible…
- ➡ 'The safe bet physics case' !

Prospects for measuring λ_{hhh} in Higgs pair production: HL-LHC with LC550 GeV



[J. List et al. '25]

⇒ For $\varkappa_\lambda \approx 2$: much better prospects for LC550 than for HL-LHC

Reason: different interference contributions

Excellent prospects and guaranteed success!

Indirect 'measurements' of λ_{hhh} sufficient? …?

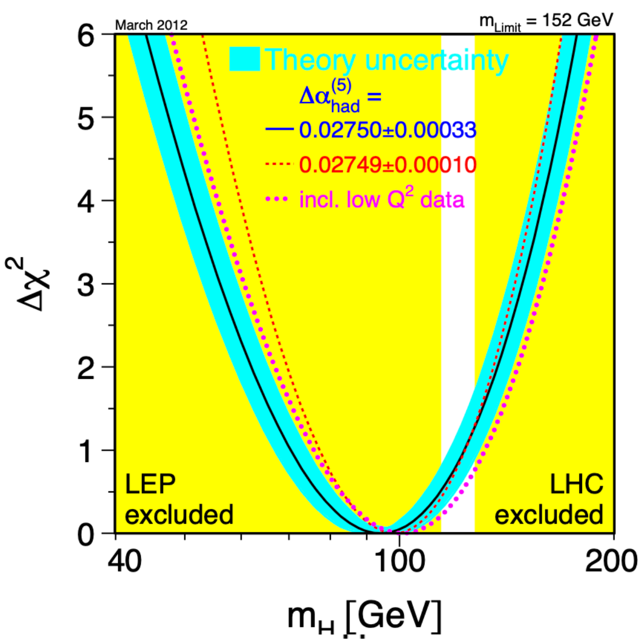
Indirect access to λ_{hhh} via

➡ *see talk M. Vellasco, Higgs Session*

- single Higgs processes: λ_{hhh} enters at 1-loop order
- electroweak precision observables: λ_{hhh} enters at 2-loop order

Loop contribution of λ_{hhh} competes with much larger lowest-order contributions, other loop contributions (e.g. top loop) that are numerically dominant and potentially with BSM loop contributions → Indirect sensitivity via loop effects is limited !!!

A lesson from the past: the "blue band plot", global fit for the Higgs-boson mass in the SM



[LEPEWWG '12]

We did not claim a measurement of the Higgs-boson mass at 95 GeV from this analysis!

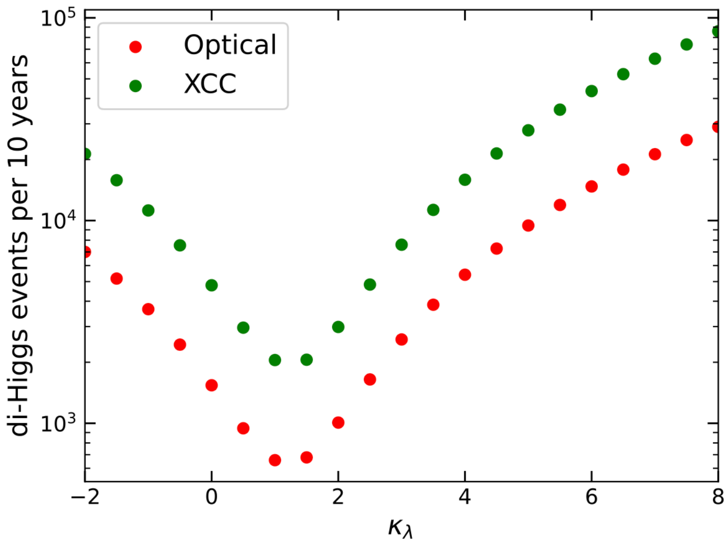
⇒ This is not a "measurement" of m_h, but an indirect constraint from loop contributions within a specific model (in this case the SM) !

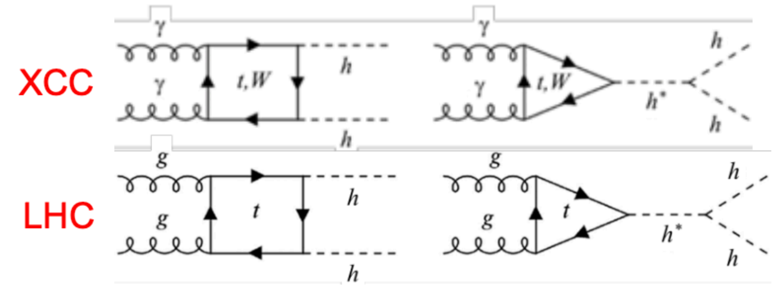
Direct production possible for λ_{hhh} at 'lower energy' ? √ ⇒ via γγ-collisions !

$\gamma\gamma \to$ hh at ≈380 GeV: optical laser and XFEL (XCC)

$\sigma(\gamma\gamma \to \text{hh})\ \mathscr{L}_{\text{int}}$

[M. Berger, J. Braathen, GMP, G. Weiglein '25]





➡ Minimum cross section at different κ_λ than at e^+e^- LC

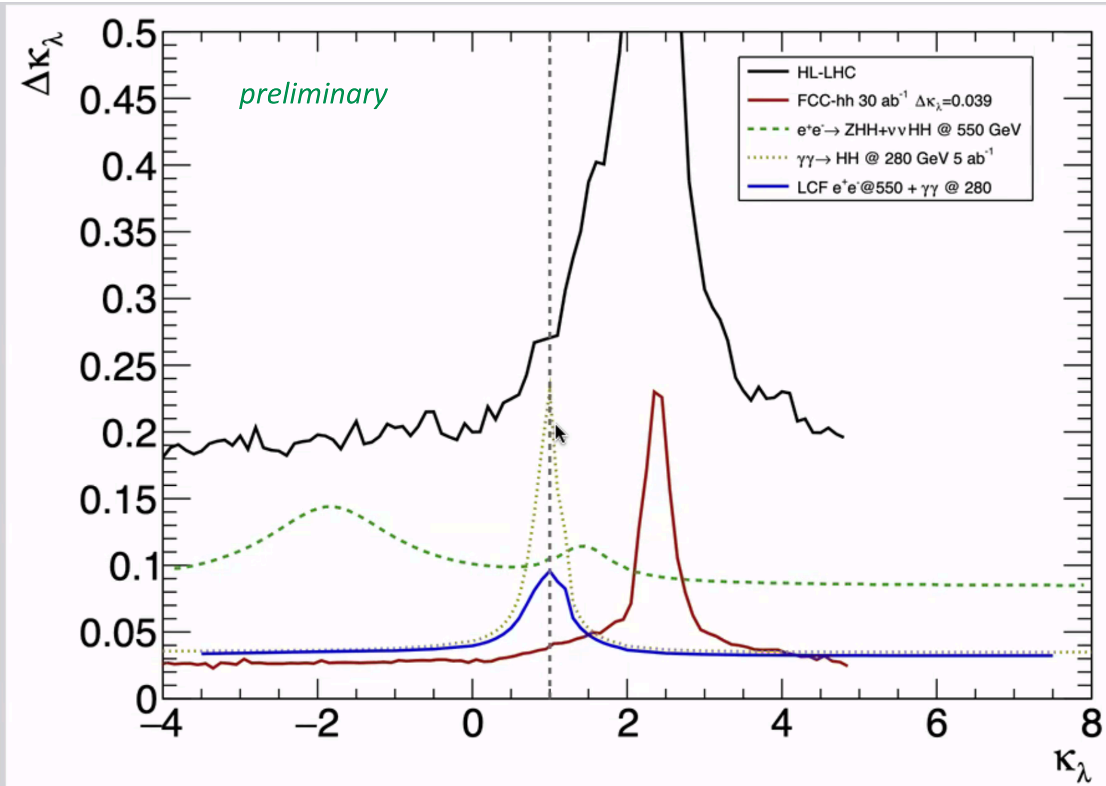
[T. Barklow'24]

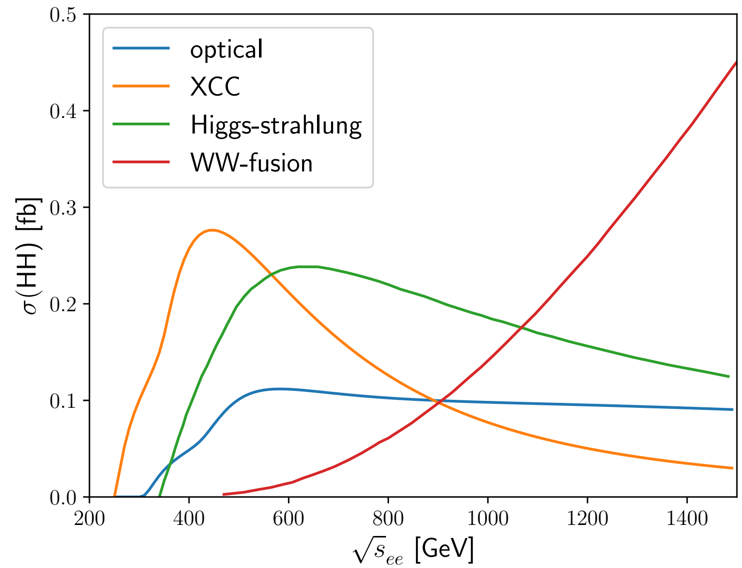
	$\sqrt{s}$ (GeV)	polarization	σ (fb)
$\gamma\gamma \to HH$	380	+100% γ +100% γ	0.40
$e^+e^- \to ZHH$	500 / 550	−80% e^- +30% e^+	0.20 / 0.22

➡ ***Complementary between both runnings: e^+e^- and γγ collisions runnings***

Expectations: λ_{hhh} precision in HL-LHC, FCC-hh, e^+e^-(@550)- and γγ-collisions

[T. Barklow'25]





➡ Minimum cross section at different κ_λ than at e^+e^- LC

➡ ***Complementary between both runnings: e^+e^- and γγ collisions runnings !!!***

➡ ***compatible with FCC-hh precision expectations…..excellent news for HEP!***

e+e− Higgs factories

High-level differences:
- Energy reach
- Luminosity

Linear

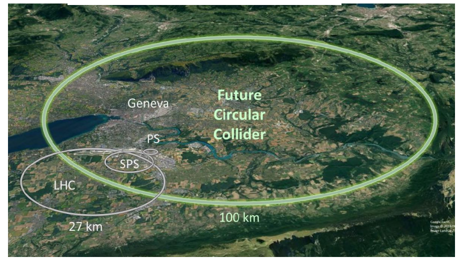
ILC
Japan

International Linear Collider

Circular

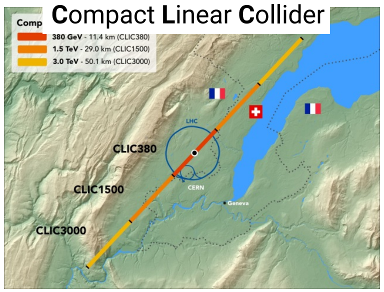
FCC-ee
CERN

Future Circular Collider



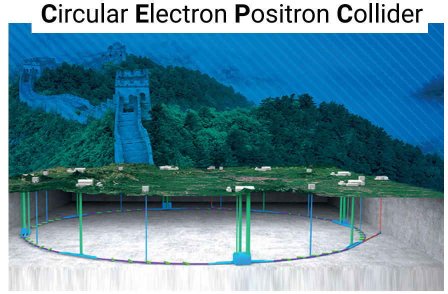
CLIC
CERN

Compact Linear Collider

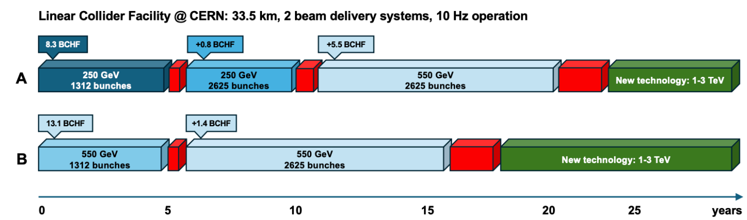


CEPC
China

Circular Electron Positron Collider

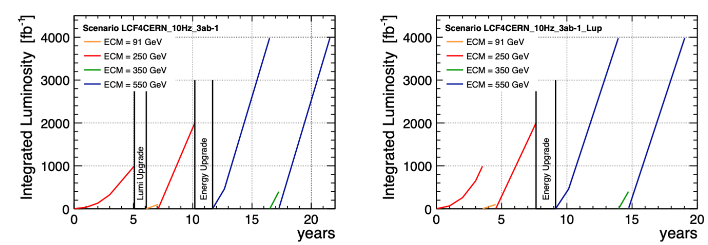


Linear Collider Facility @ CERN

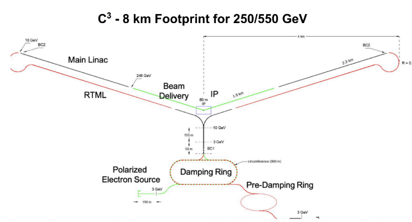


Baseline (10Hz rate)

Start immediately with full power (1316->2625 bunches in train)



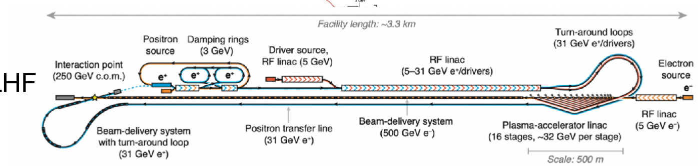
CCC



- 250 GeV — *ZH* threshold
- 350 GeV — *tt* threshold
- 550 GeV — *HHH* coupling
- ca. 1.5 TeV technology limit

- Based on superconducting RF (liquid nitrogen)
- Proposed at SLAC; very compact machine

HALHF



Source: Foster, D'Arcy & Lindstrøm, preprint at arXiv:2303.10150 (2023)

- 250 GeV — *ZH* threshold
- 365 GeV — *tt* threshold
- 10-30 TeV ?? technology limit

- New idea: e^- plasma acceleration, e^+ conventional LinAc
- ca. 10 years R&D needed to demonstrate feasibility
- Extremely compact: 3-4 km size

In the ff, courtesy of S. Stapnes, see talk at ESPP, Venice 25

Linear Collider Facility (LCF) @ CERN – common implementation studies for two starting technologies:

Status of the International Linear Collider

ICFA ILC International Development Team and ILC-Japan*

Revised from the document submitted on 31 March 2025
for the European Strategy for Particle Physics Update 2026

16 May 2025, with an additional revision on 26 May 2025

Abstract

oposal for a CERN future project but provides information on the Inter-
r (ILC) considered for Japan in order to facilitate the European Strategy
ontext. It describes progress to date, ongoing engineering studies, updated
nachine at $\sqrt{s}$ =250 GeV and the situation in Japan. The physics of the
ere, but jointly for all Linear Collider projects in a separate document "A
or the Future of Particle Physics" submitted for the forthcoming European

Linear Collider Vision

The Linear Collider Facility (LCF) at CERN

updated version May 26, 2025

Contact persons: Jenny List* Steinar Stapnes†

on behalf of the LCVision Editorial Board: Masaya Ishino (U. Tokyo), Benno List (DESY), Jenny List (DESY), Tatsuya Nakada (EPFL Lausanne), Michael Peskin (SLAC), Roman Pöschl (IJCLab), Aidan Robson (U. Glasgow), Thomas Schörner (DESY/CERN), Steinar Stapnes (CERN)

In this paper we outline a proposal for a Linear Collider Facility as the next flagship project for CERN. This proposal offers the opportunity for a timely, cost-effective and staged construction of a new collider that will be able to comprehensively map the Higgs boson's properties, including the Higgs field potential, thanks to a large span in centre-of-mass energies and polarised beams. A comprehensive programme to study the Higgs boson and its closest relatives with high precision requires data at centre-of-mass energies from the Z pole to at least 1 TeV. It should include measurements of the Higgs boson in both major production mechanisms, $e^+e^- \to ZH$ (Higgs-strahlung) and $e^+e^- \to \nu\bar{\nu}H$ (WW fusion), precision measurements of gauge boson interactions as well as of the W boson, Higgs boson and top-quark masses, measurement of the top-quark Yukawa coupling through $e^+e^- \to t\bar{t}H$, measurement of the Higgs boson self-coupling through HH production, and precision measurements of the electroweak couplings of the top quark. In addition, e^+e^- collisions offer discovery potential for new particles complementary to HL-LHC. The facility we propose robustly satisfies these scientific goals. With a total length of 33.5 km, two interaction regions as well as additional R&D and fixed-target experiments, it offers significant flexibility to take into account scientific and strategic developments. From today's perspective, we propose to equip the Linear Collider Facility in a first stage with superconducting RF cavities for polarised e^+e^- collisions at a centre-of-mass energy of 250 GeV with a luminosity of $2.7 \times 10^{34}\,cm^{-2}s^{-1}$, which requires an investment of about 8.3 BCHF. With a preparatory phase of eight years, followed by ten years of construction starting earliest in 2034, this first stage could start beam commissioning and data-taking a decade later. First upgrades comprise doubling of the luminosity for 0.8 BCHF and an increase of energy up to at least 550 GeV, which can be achieved with the same accelerator technology for about 5.5 BCHF. Later stages will involve further increase of luminosity and energy as well as other new capabilities that will further enhance the Higgs programme and extend the discovery potential for new physics. These upgrades will primarily be accomplished by accelerator technology innovations rather than by additional civil construction.

LCF@CERN focussed on starting with ILC SCRF technology; benefits from all the ILC developments, CLIC CE and infrastructure studies at CERN, and link to new technologies as potential upgrades: https://indico.cern.ch/event/1439855/contributions/6461433/

Superconducting RF, parameters for 90, **250**, 350, **550** GeV

The Compact Linear e^+e^- Collider (CLIC)

Input to the European Strategy for Particle Physics Update 2025
on behalf of the CLIC and CLICdp Collaborations

26 May 2025

Contact persons: E. Adli,[1)] D. Dannheim, A. Robson, S. Stapnes

Abstract

The Compact Linear Collider (CLIC) is a TeV-scale high-luminosity linear e^+e^- collider studied by the international CLIC and CLICdp collaborations hosted by CERN. CLIC uses a two-beam acceleration scheme, in which normal-conducting high-gradient 12 GHz accelerating structures are powered via a high-current drive beam. For an optimal exploitation of its physics potential, CLIC is foreseen to be built and operated in stages. The initial stage will have a centre-of-mass energy of 380 GeV, with a site length of 11 km. The 380 GeV stage optimally combines the exploration of Higgs and top-quark physics, including a top threshold scan near 350 GeV. A higher-energy stage, still using the initial single drive-beam complex, can be optimised for any energy up to 2 TeV. Parameters are presented in detail for a 1.5 TeV stage, with a site length of 29 km. Since the 2018 ESPPU reporting, significant effort was invested in CLIC accelerator optimisation, technology developments and system tests, including collaboration with and gaining experience from new-generation light sources and free-electron lasers. CLIC implementation aspects at CERN have covered detailed studies of civil engineering, electrical networks, cooling and ventilation, scheduling, and costing. The CLIC baseline at 380 GeV is now 100 Hz operation, with a luminosity of $4.5\times10^{34}\,cm^{-2}s^{-1}$ and a power consumption of 166 MW. Compared to the 2018 design, this gives three times higher luminosity-per-power. The new baseline has two beam-delivery systems, allowing for two detectors operating in parallel, sharing the luminosity. The cost estimate of the 380 GeV baseline is approximately 7.2 billion CHF. The construction of the first CLIC energy stage could start as early as ~2034-2035 and beam commissioning and first beams would follow a decade later, marking the beginning of a physics programme spanning 20-30 years and providing excellent sensitivity to Beyond Standard Model physics, through direct searches and via a broad set of precision measurements of Standard Model processes, particularly in the Higgs and top-quark sectors. This report summarises the CLIC project, its implementation and running scenarios, with emphasis on new developments and recent progress. It concludes with an update on the CLIC detector studies and on the physics potential in light of the improved accelerator performance. The physics potential includes results from the 3 TeV energy stage, which was studied in detail for the CLIC CDR in 2012 and the CLIC Project Implementation Plan of 2018.

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CLIC@CERN, Linear Collider Facility starting with NCRF technology: https://indico.cern.ch/event/1439855/contributions/6461475/

Normal conducting RF, parameters for 90, 250, **380**, 550, **1500** GeV

Future Colliders Comparative Evaluation - Working Group Report

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May 26th, 2025

Abstract

In anticipation of the completion of the High-Luminosity Large Hadron Collider (HL-LHC) programme by the end of 2041, CERN is preparing to launch a new major facility in the mid-2040s. According to the 2020 European Strategy for Particle Physics (ESPP), the highest-priority next collider is an electron–positron Higgs factory, followed in the longer term by a hadron–hadron collider at the highest achievable energy.

The CERN directorate established a Future Colliders Comparative Evaluation working group in June 2023. This group brings together project leaders and domain experts to conduct a consistent evaluation of the Future Circular Collider (FCC) and alternative scenarios based on shared assumptions and standardized criteria.

This report presents a comparative evaluation of proposed future collider projects submitted as input for the Update of the European Strategy for Particle Physics. These proposals are compared considering main performance parameters, environmental impact and sustainability, technical maturity, cost of construction and operation, required human resources, and realistic implementation timelines.

An overview of the international collider projects within a similar timeframe, notably the CEPC in China and the ILC in Japan is also presented, as well as a short review of the status and prospects of new accelerator techniques.

Comparative report: https://indico.cern.ch/event/1439855/contributions/6542430/

A physics-driven, polarised operating scenario for a Linear Collider

Stage 1: 250-380 GeV
precision Higgs mass and total σ(ZH)
precision Higgs couplings and total width to % level,
even tests of CP-violating couplings (pol. beams essential!)
resonance/compositeness search in ffbar, WW to 10's TeV
1-yr excursion to the Z pole - $\sin^2\theta_W$ to 3e-6

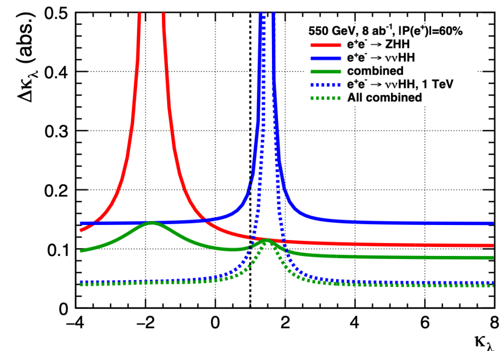
95% C.L. (2σ)limit				
Experiments	CEPC	CLIC	CLIC	ILC
Processes	HZ	W-fusion	Z-fusion	HZ, $Z\to\mu^+\mu^-$
$\sqrt{s}$ [GeV]	240	3000	1000	250
Luminosity [fb^{-}	5600	5000	8000	5000
$(\lvert P_-\rvert, \lvert P_+\rvert)$				(90%, 40%)
$\tilde{c}_{HZZ}$ ($\times10^{-2}$]	[-1.6, 1.6]	[-3.3, 3.3]	[-1.1, 1.1]	[-1.1, 1.0]

Stage 2: 550 GeV
precision Higgs couplings and total width to sub-% level
top quark Yukawa to 3%, Higgs self-coupling to 11%
top quark electroweak couplings to 0.1%
resonance/compositeness search in ffbar, WW to 50 TeV
1-yr excursion to the ttbar threshold - mt to 40 MeV

➡ *see talk K. Mekala, Top&EW Session*
➡ *see talk J. Klamka, BSM Session*

All discoveries of deviations from the SM can be verified in complementary reactions at higher energy, e.g. H self-coupling visible in two complementary HH production channels.

Higher energies: 1000 GeV or above
top quark Yukawa to 1%, Higgs self-coupling in WW fusion
Higgsino search to 500 GeV
follow up HL-LHC discoveries of new Higgs and electroweak states

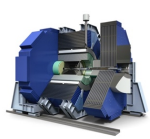


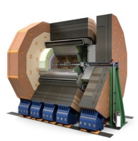
ZHH
WW fusion
combined

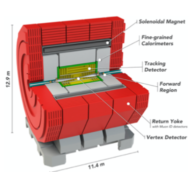
From J.List/M.Peskin

Fixed target program: dark sector, nonlinear QED

The projections are supported by full-simulation studies with detailed
detector designs and machine backgrounds.





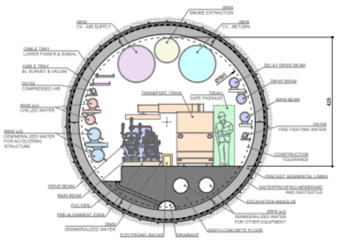


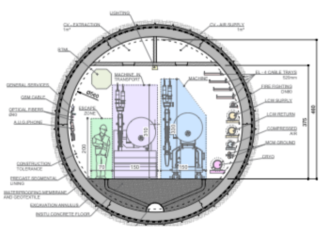
Much more in arXiv:250319983

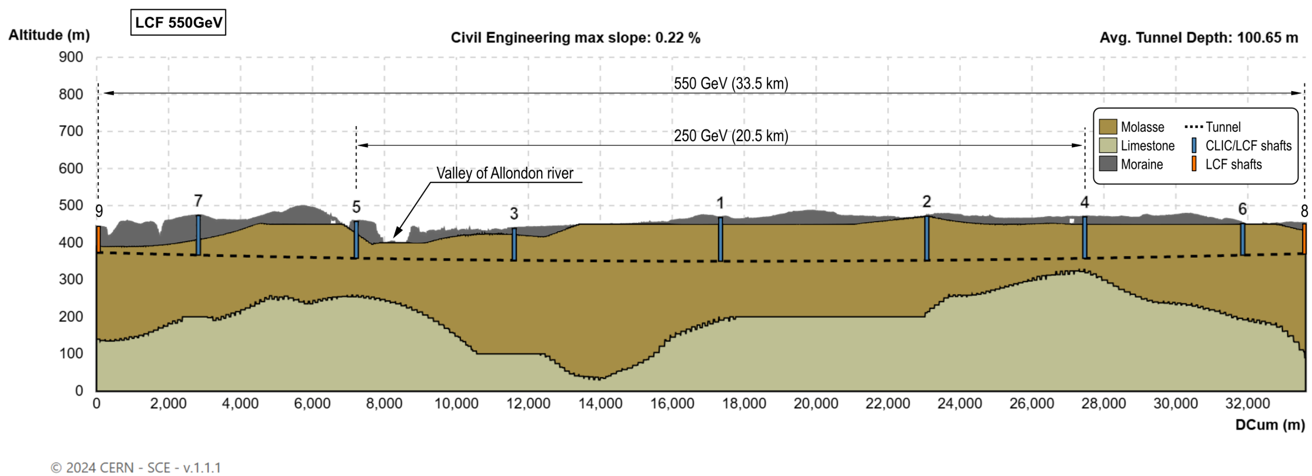
Linear Collider @ CERN – Civil Engineering I

Layout used for costing and drawings. Not final, can be translated, rotated and shafts can be moved.

Start with mature technology, can expand in length and/or technology



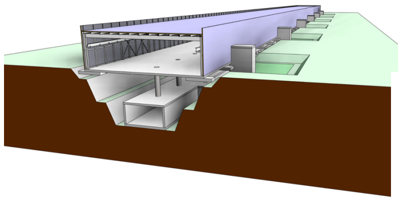


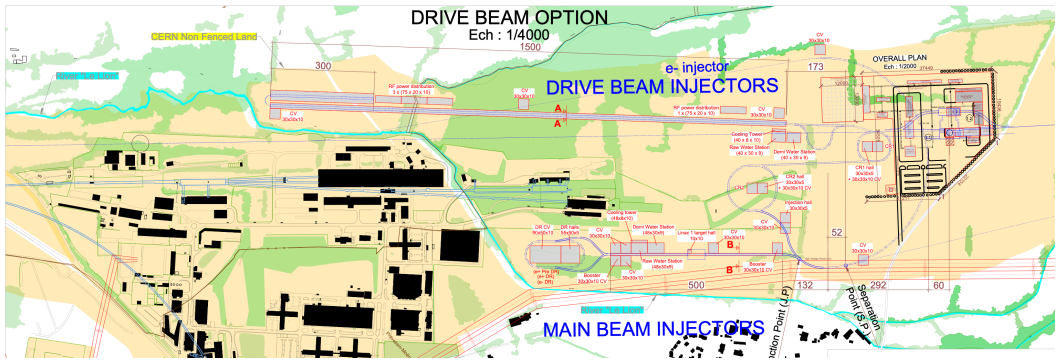


Energy reach and flexibility:

- Physics opportunities from Z-pole to TeV(s)
- Flexible (E,L,cost, power) to adapt to development in physics and technology
- Lower cost to get to Higgs and top than a circular machine (initial machine)
- Power similar to LHC, or lower, for initial configuration
- Footprint (length/location) similar to LHC

Linear Collider @ CERN – Civil Engineering II





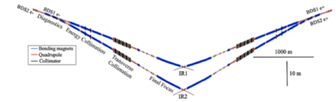
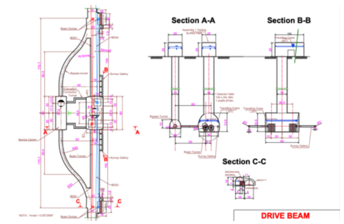


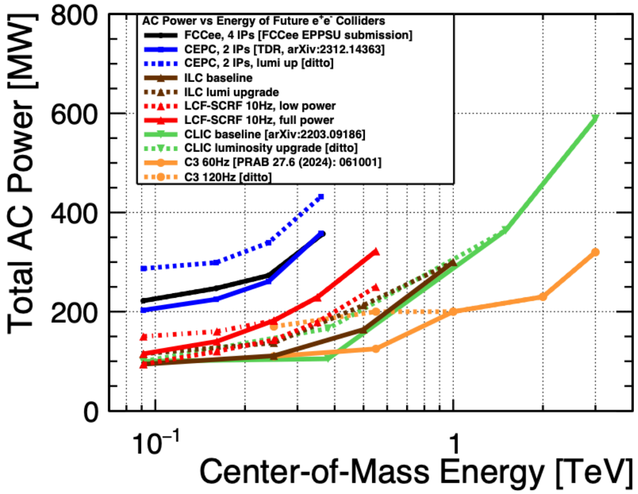
Figure 3: Schematic layout of CLIC operating with two detectors. From [16].



CE studies for LC at CERN over the last ~15 years:

- CLIC, up to 3 TeV. Contract with Amberg Engineering for CDR in 2012-2013.
- ILC up 1 TeV. Contract with Amberg Enginering for the TDR in 2012-13.
- CLIC up to 3 TeV, TOT (layout tool) with ARUP (engineering/consulting company), for the Project Implementation Report 2018
- For the ESPP 2025, LCF/ILC up to 550 GeV, CLIC NCRF to 1.5 TeV, in both cases ~30km (29.5 and 33.5), using Geoprofiler layout tool
- Injectors and experimental areas on Prevessin site (“CERN attributed land”)

Power and energy



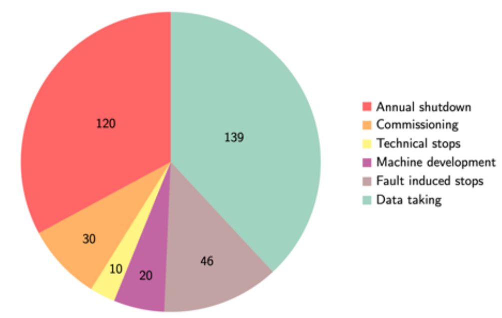
Power at 250-550 GeV in the 140-320 MW range for the LC projects above

Depends on energy AND luminosity (as shown earlier)

With a running scenario on the right this corresponds to 0.8 - 1.8 TWh annually

CERN is currently consuming 1.2 – 1.3 TWh annually

CERN “standard” running scenario used to convert to annual energy use, specify power for each state → energy



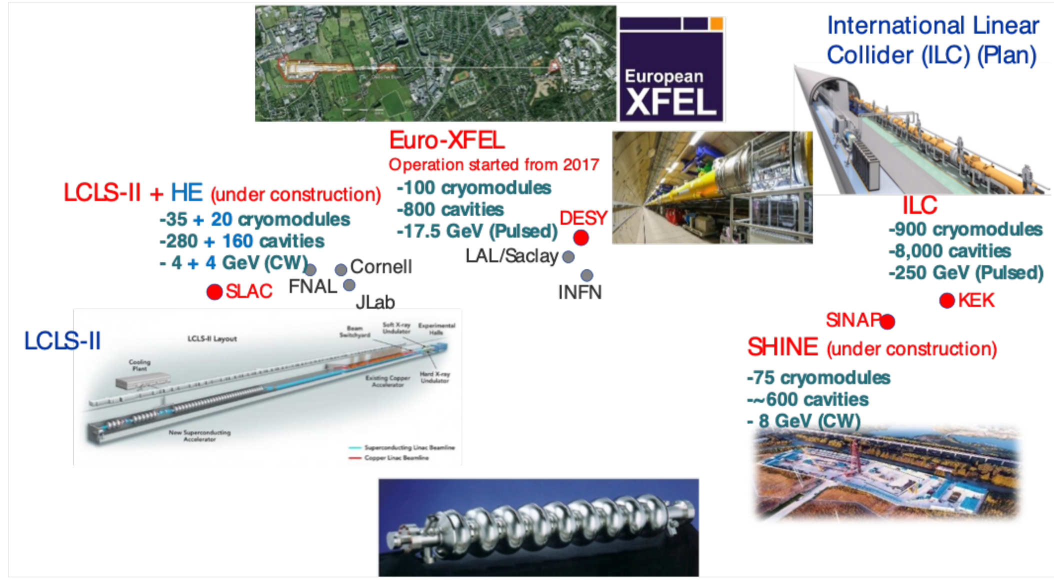
A decade of studies to reduce power:
Designs optimisations, SRF cavities (grad,Q), cryo efficiency, RF power system (klystrons, modulators, components), RF to beam efficiencies, improved magnets, operation when power is abundant, heat recovery, nanobeams and more.

	LCF 250 (LP)	LCF 550 (FP)	CLIC 380	CLIC 1500
Power (MW)	144	320	166	287
Energy annually (TWh)	0.8	1.8	0.8	1.4

From the ILC250 accelerator facility to the CERN

The ILC implementation is extensively studies in Japan, civil engineering, integration locally, environmental impacts, etc

Undulator based polarized positron source



How would we implement a SCRF based LC at CERN:

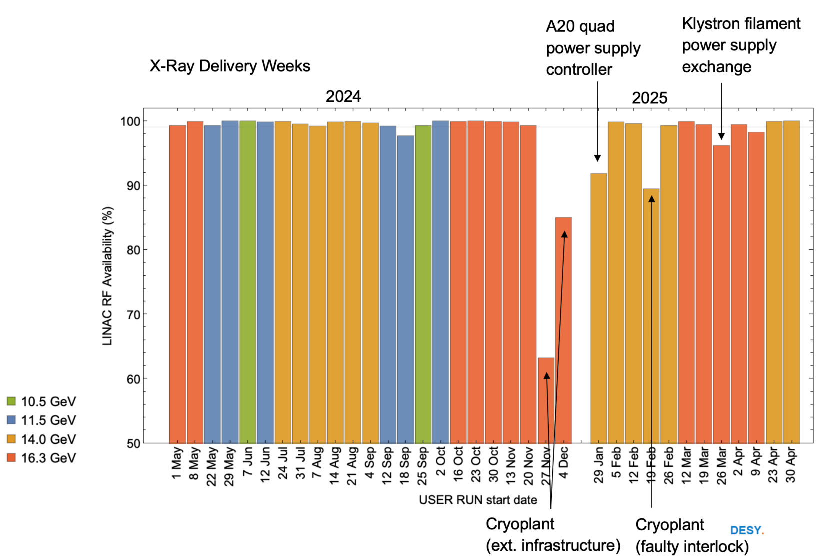
- Consider implementation of energies above 250 GeV (even initially), similar to the ILC TDR, specifically 550 GeV
- Increase luminosity wrt to parameters used recently (ILC@Japan) and share on two IPs
  - Key changes: Bunch trains 5 Hz to 10 Hz, double numbers of bunches per train
- Consider if such a facility can use improved or other RF technologies in the future (a true LC facility) – stimulate wide R&D and open options for the future (see talk later today by J.List)

- Combine with CLIC footprint/studies as much as possible.
- Cost estimate as for CERN projects in CHF, with CE costs from CERN

LCF with SCRF

Why SCRF:

- Very detailed and mature technical design and industrialisation, several FEL linacs build and being operated
- Can be upgraded in Energy and Luminosity
- Worldwide interest in technology
- Large technology interest in Europe (EUXFEL and several other projects), and leading industries in Europe
- Could it be exploited to reduce work and financial load on CERN during the HL period (lab support outside for in-kind cryomodules for example as foreseen for ILC – and also in Europe) ?
- Can this be turned into a financing advantage and/or schedule advancement ?



EU-XFEL performance 2024-25

On-going technical studies in Europe – the ILC technology network topics

European ITN related studies (dedicated funding from Japan combined with European resources) are distributed over five main activity areas:

ML related tasks
- SRF and ML elements: Cavities and Cryo Module, Crab-cavities, ML quads and cold BPMs

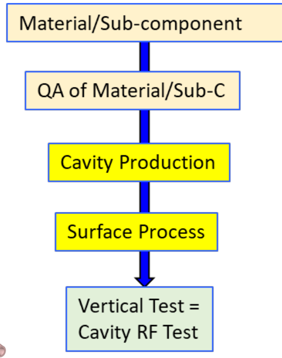
Sources *➡ see talk on Wednesday*
- Pulsed magnet and wheel/target
- Prototyping

Damping Ring including kickers
- Low Emittance Rings

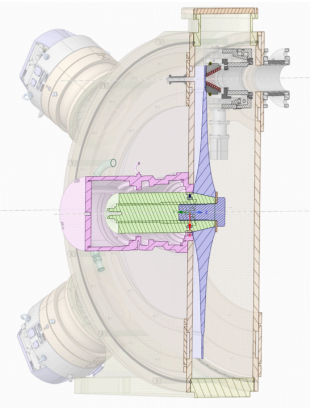
ATF activities, final focus and nanobeams
- ATS and MDI

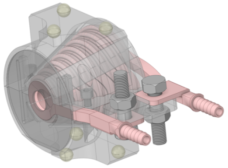
Implementation
- CE, Cryogenics
- Sustainability, Life Cycle Assessments
- EAJADE (EU funding) for training of young scientists (linear and circular machines)

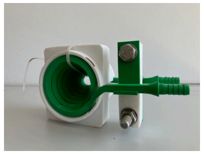
Studies in labs distributed across CERN, UK, Germany, France, Italy, Spain



Production process



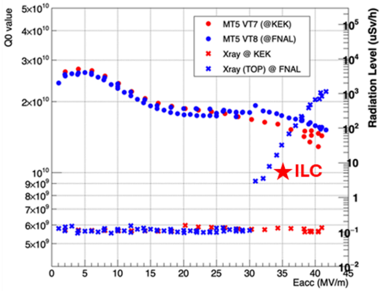




➡ see talks P. McIntosh and A. Faus-Golfe, ESPP, Venice 25

Results from FG 9-cell cavity using 2-step baking **KEK and FNAL**

Possible to achieve > 40 MV/m with high Q_0

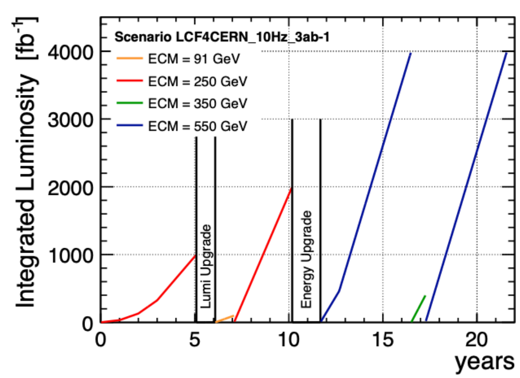


LCF – SCRF – ESPP parameters

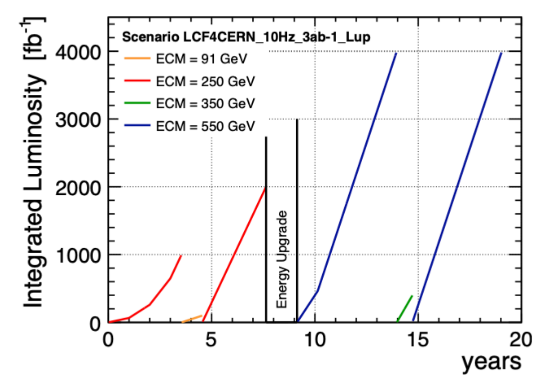
Quantity Name	Symbol	Unit LCF	Initial-250 250 LP	Upgrades 250 FP	550 FP	Initial-550 550 LP	Upgrade 550 FP
Centre-of-mass energy	$\sqrt{s}$	GeV	250	250	550	550	550
Inst. luminosity	$\mathscr{L}$	$(10^{34} cm^{-2}s^{-1})$	2.7	5.4	7.7	3.9	7.7
Polarisation	$\|P(e^-)\|/\|P(e^+)\|$	(%)	80 / 30	80 / 30	80 / 60	80 / 30	80 / 60
Repetition frequency	f_{rep}	Hz	10	10	10	10	10
Bunches per pulse	n_{bunch}	1	1312	2625	2625	1312	2625
Bunch population	N_e	10^{10}	2	2	2	2	2
Linac bunch interval	Δt_b	ns	554	366	366	554	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	8.8	5.8	8.8
Beam pulse duration	t_{pulse}	μs	727	897	897	727	897
Average beam power	P_{ave}	MW	10.5	21	46	23	46
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35
RMS hor. beam size at IP	σ_x^*	nm	516	516	452	452	452
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7	5.6	5.6	5.6
Lumi frac. in top 1 %	$\mathscr{L}_{0.01}/\mathscr{L}$	%	73	73	58	58	58
Lumi in top 1 %	$\mathscr{L}_{0.01}$	$(10^{34} cm^{-2}s^{-1})$	2.0	4.0	4.5	2.2	4.5
Site AC power	P_{site}	MW	143	182	322	250	322
Annual energy consumption		TWh	0.8	1.0	1.8	1.4	1.8
Site length	L_{site}	km	33.5	33.5	33.5	33.5	33.5
Average gradient	g	MV/m	31.5	31.5	31.5	31.5	31.5
Quality factor	Q_0	10^{10}	2	2	2	2	2
Construction cost		BCHF	8.29	+0.77	+5.46	13.13	+1.40
Construction labour		kFTE y	10.12		+3.65	13.77	
Operation and maintenance		MCHF/y	156	182	322	273	322
Electricity		MCHF/y	66	77	142	115	142
Operating personnel		FTE	640	640	850	850	850

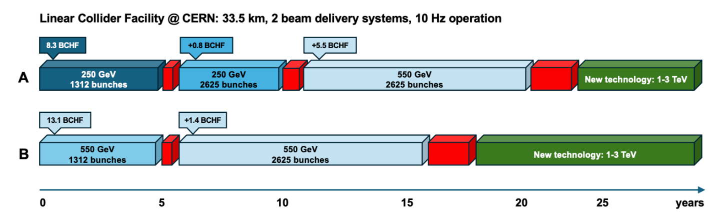
Summary table of the LCF accelerator parameters in the initial 250 GeV configuration and possible upgrades, as well as in an initial 550 GeV configuration and its luminosity upgrade

Baseline (10Hz rate)



Start immediately with full power (1316->2625 bunches in train)





Note: tunnel extension to allow a 550 GeV upgrade is included in the initial programme

Schedule towards a LC@CERN

Prep phase I:

Definition of the placement scenario

Design optimisation and finalization

Main technologies R&D conclusions

(Pre)Technical Design Report - two IPs at CERN

Construction*:

Civil engineering

Construction of components

Installation and hardware commissioning

2026-28	T0, T0+5	T1, T1+10	T1+11

Prep phase II:

Site investigation and preparation

Implementation studies with the Host states

Environmental evaluation & project authorisation processes

Industrialisation of key components

Engineering design completion

Beam-commissioning

followed by physics

T0 is determined by a process in 2028-29 to validate the progress and promise of the project for a further development towards implementation.

T1 will be determined by the processes needed, by the CERN Council and with host-states, for project approval and to start construction

*The construction phase is extended with respect to the technically-limited schedules to allow a transfer time into construction, and to avoid the resource conflict between HL-LHC operation and initiating beam commissioning for a next collider

Next Steps towards a Linear Collider @ CERN

Project implementation: foresee 3+5-year preparatory periods, then construction ~10 years

- Ideally starting preparation after conclusion of EPPSU in mid-2026
- Split in two phases, the first to establish final parameters and layout for a LC (see main points below)
- 2026-28 (resource estimate ~25-35 MCHF and ~150-180 FTEy), main topics below

Site Layout Refinement:
The next step is to refine the LC site layout, including shaft placement and detailed designs for surface and underground areas.

Accelerator Complex Design Optimisation:
The detailed design of the LC accelerator complex, especially its interfaces with civil engineering and detector systems (BDS and interaction area), will be further developed, with a particular focus on optimising the LC@CERN parameters.

Technology R&D with international partners:
Research on SCRF and X-band technologies, including RF sources, e- and e+ sources, nanobeam systems, beam delivery and damping rings.

Detector R&D:
Aligned with Higgs factory and broader technology initiatives

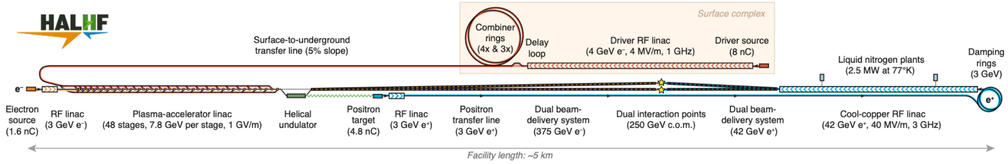
Main points

- A Linear Collider at CERN has a very attractive and broad physics programme and is a very flexible facility
- A Linear Collider as a staged project can be implemented at 7-9 BCHF for the first stage
- Upgrading to - at least - 550 GeV is possible, to be implemented taking into account physics and resources as the programme and field evolve
- A ~3 year programme is suggested to establish a LC baseline, building on and extending existing international collaborative R&D
  - Need more detailed implementation study to validate and optimize an LC@CERN (as outlined for 2026-28)
  - Guidance about energy, performance and cost goals from the ESPP update crucial
- An LC can be completed in parallel with the HL LHC programme (to the extend resources allow)
- There are many opportunities for international support (technology and capabilities) in the preparation phases and during a potential construction

In the ff, courtesy of J. List, see talk at ESPP, Venice 25

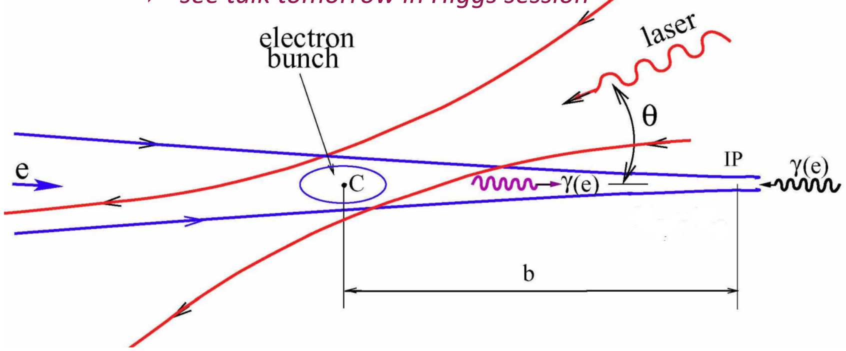
Upgrade options: energy, lumi, γγ, beyond

- **go for higher energies:**
  - advanced SCRF
  - cool copper cavities
  - warm copper cavities
  - wakefield acceleration



- **go for higher luminosity - ERL:**
  - ReLiC / ERLC
- **go for photon collisions:**
  - with optical lasers or a la XCC
- **beyond-collider opportunities**
  - beam dump / fixed-target / R&D ….

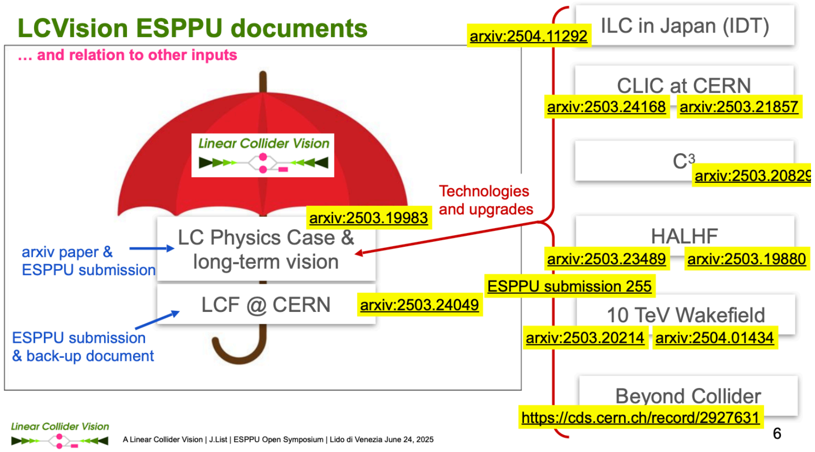
➡ *see talk tomorrow in Higgs session*



LCVision reviewed
how these could be embedded as upgrade of initial facility
— obviously each technology could be used for a stand-alone project, too!

LCVision: started at LCWS2024 in view of ESPPU

- **all linear colliders share the same scientific goals:**
  - formulate a coherent physics program
  - define energy stages etc science-driven



- **beyond an individual technology:**
  - design a linear collider *facility*
  - infrastructure compatible with various technologies
  - plus beam-dump / fixed-target exp's / R&D facilities

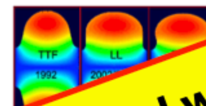
- **study the Higgs in e+e- now - but maintain flexibility for the future:**
  - start now with an *affordable* project
  - maintain scientific diversity
  - strengthen accelerator R&D towards 10 TeV pCM collider
  - **decide on upgrades / new projects based on future developments - or even break-throughs:**
    - **scientifically: a discovery at HL-LHC or elsewhere**
    - **technologically: higher gradients / muon cooling / high-field magnets**

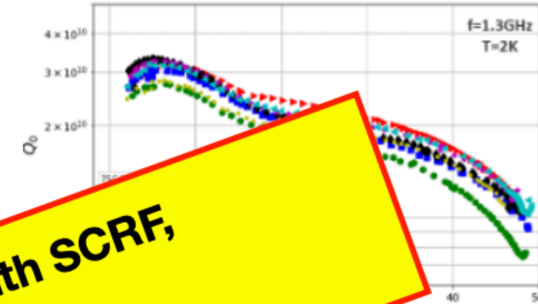
Superconducting RF Upgrade

Need ~60 MV/m to reach 1 TeV in LCF tunnel

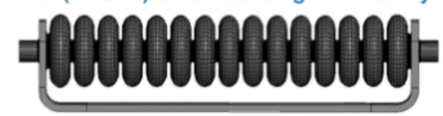
- SCRF is one of the key directions of Accelerator R&D Roadmap
  - significant synergies with ERL needs
  - needs to be accompanied by R&D on high-efficiency klystrons, couplers, He refrigerators, …
  - progress is funding limited
- **5-year horizon:** standing-wave, bulk niobium ca…
  - new baking: **2-step (75º/120º) or mid-T …**
  - new shapes
- **10-year horizon:** trav… …EN"
  - substantiall… …agnetic quench limit
  - 2…
  - hi… …> longer structures
- **>10-ye… …gn:** Nb3Sn or multilayer cavities **100 MV/m**
  - ~2x … …nsition T than Nb: 2K -> 4K
  - ~2x higher DC superheating field than Nb
  - to-date only reached gradients up to 24MV/m with Nb3Sn

Excellent chances to reach ≥1 TeV in LCF tunnel with SCRF, at reduced power consumption, minimal changes apart from cryomodules

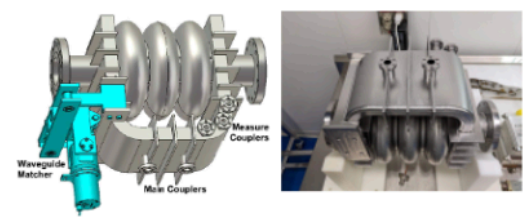




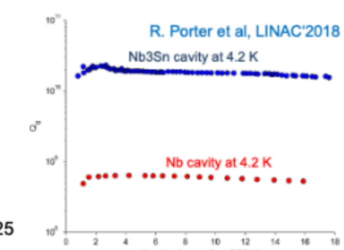
ILC (TESLA) 9-cell standing wave cavity



Traveling wave 15-cell SRF cavity



Proof-of-principle 3-cell cavity



Linear Collider Vision

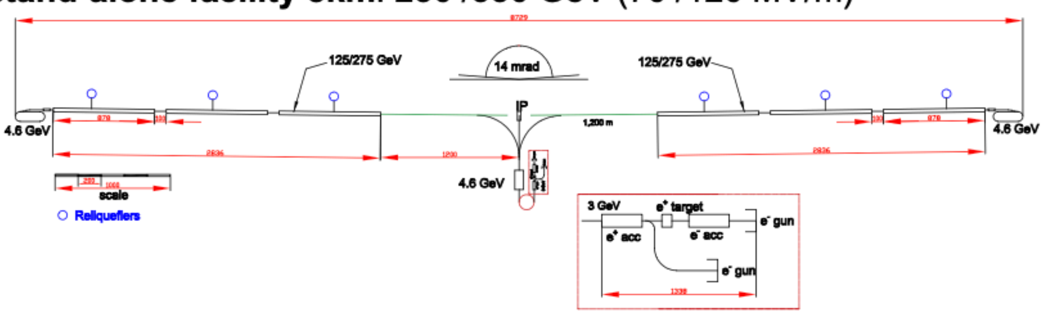
A Linear Collider Vision | J.List | ESPPU Open Symposium | Lido di Venezia June 24, 2025

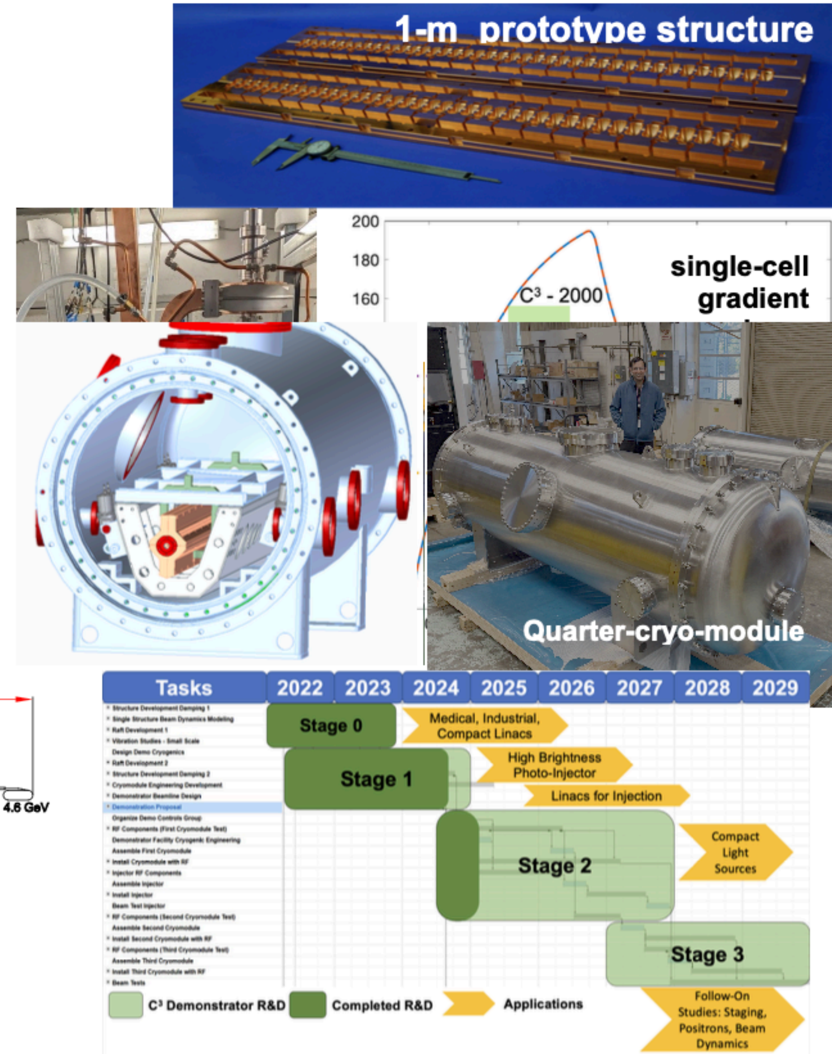
9

Cool Copper Technology

Idea and R&D

- **C3 technology:**
  - normal-conducting C-band copper cavities
  - operated at cryogenic temperatures (LN_2 ~80K)
  - gradients demonstrated up to 155 MV/m
- R&D:
  - plan towards demonstrator established during Snowmass
  - since then significant progress on system design, accelerator structure design, high gradient testing, vibration measurements, damping materials, alignment system, low-level rf & klystrons, … and **cryo-module design**
- **stand-alone facility 8km**: 250 /550 GeV (70 /120 MV/m)





Cool Copper Technology

the route to 3 TeV

- studied in context of LCVision
- **LCF injector complex and damping rings compatible with C3:**
  - larger LCF DRs = lower risk
  - replace fast->slow kickers (kick whole trains)
  - bunch compressor length / emittance sufficient

  => substantial part of infrastructure could be reused
- cryo-plants need modification
- SRF cryomodules could be sold / donated for XFELs / medical linacs /.. round the world
- to be considered in design of beam delivery systems and dumps

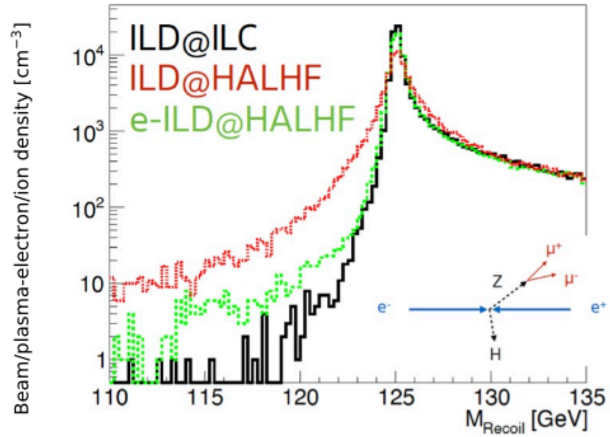
Parameter	Unit	Value	Value	Value
Centre-of-Mass Energy	GeV	1000	2000	3000
Site Length	km	20	20	33
Main Linac Length (per side)	km	7.5	7	10.5
Accel. Grad.	MeV/m	75	155	155
Flat-Top Pulse Length	ns	500	195	195
Cryogenic Load at 77 K	MW	14	20	30
Est. AC Power for RF Sources	MW	68	65	100
Est. Electrical Power for Cryogenic Cooling	MW	81	116	175
Est. Site Power	MW	200	230	320
RF Pulse Compression		N/A	3X	3X
RF Source efficiency (AC line to linac)	%	50	80	80
Luminosity	$x10^{34}$ $cm^{-2}s^{-1}$	$\sim$4.5	$\sim$9	$\sim$14
Single Beam Power	MW	5	9	14
Injection Energy Main Linac	GeV	10	10	10
Train Rep. Rate	Hz	60	60	60
Bunch Charge	nC	1	1	1
Bunch Spacing	ns	3	1.2	1.2

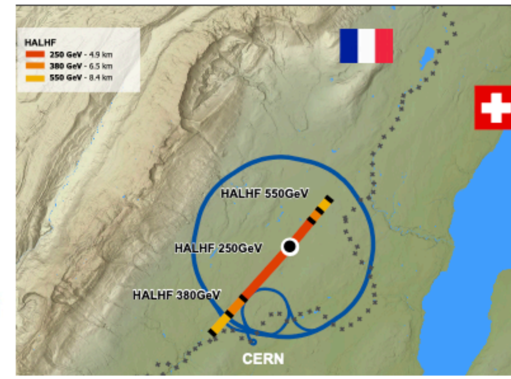
Sustainability: C3 can be 2-4x more power efficient in TeV regime than CLIC / ILC
Very exciting R&D target for the next decade!

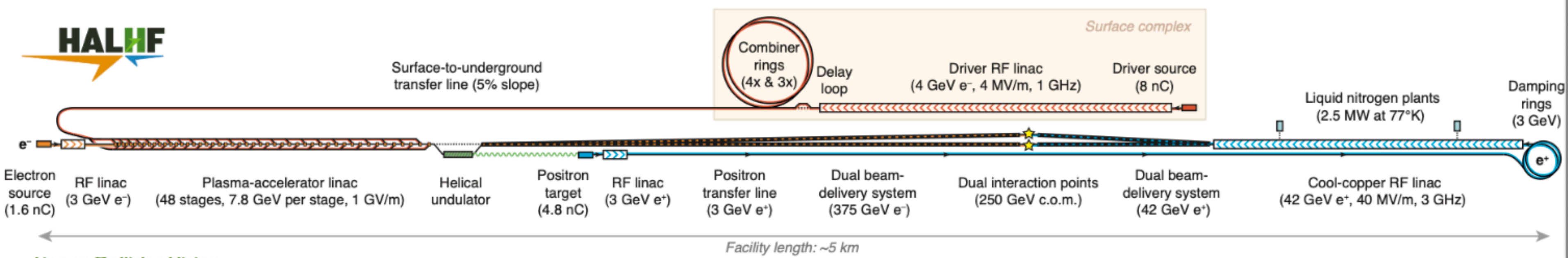
HALHF

Hybrid-Asymmetric Linear Higgs Factory

- e+e- LC using e-beam-driven plasma wakefield acceleration for the e- beam…
- …and RF cavities for the e+ beam
- => asymmetric collisions with γ=1.67 (HERA: γ=3), luminosity ~ILC baseline
- site-length and cost - **small & cheap:**
  - 250 GeV: 4.9 km, 3.8 BCHF
  - 550 GeV: 8.4 km, 6.3 BCHF
- if **R&D** successful - estimated **need**:
  213 MCHF & 341 FTEyrs over ~15 years







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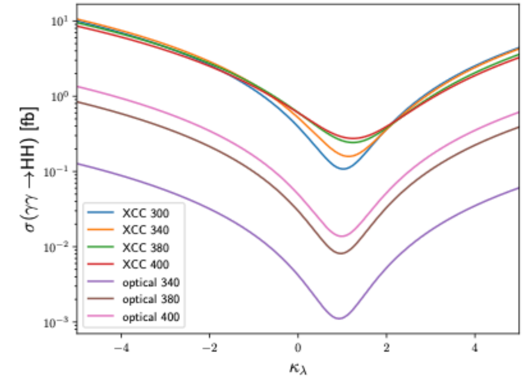
➡ *see talk tomorrow in Higgs session*

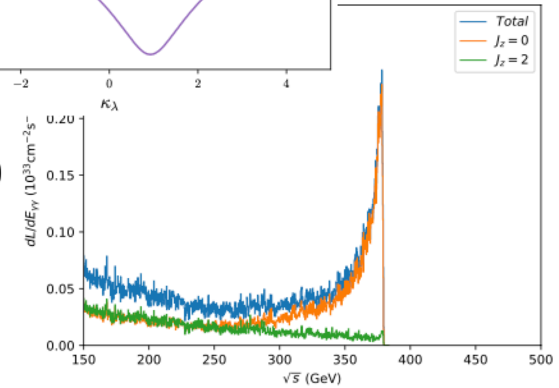
Photon-Photon / Photon-Electron Collisions



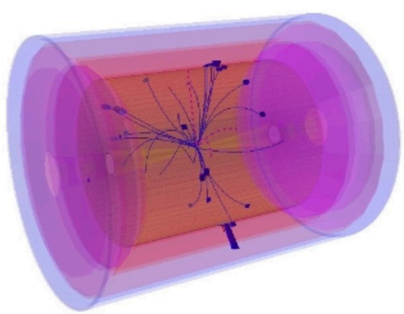
energy-dependent minimum in HH cross section

- **γγ / eγ offers unique complementary physics opportunities**
  e.g. self-coupling in **γγ➔HH** with different BSM behaviour than e+e- / pp
- high-intensity lasers convert e beam(s) into γ beam(s) directly at the IP => spin-0 luminosity spectrum sharply peaked
- two methods:
  - optical lasers “classic” scheme
  - **recent: X-ray lasers from X-FELs integrated into the facility (XCC)**

sharp spin-0 lumi peak

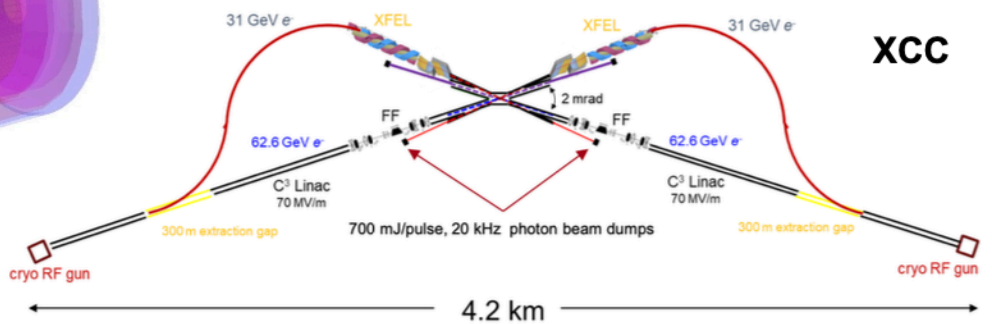


Final Focus parameters	SCRF + Optical Laser	C3 + XFEL
Electron energy [GeV]	250	190
Electron beam power [MW]	10.5	2.1
β_x/β_y [mm]	1.5/0.3	0.01/0.01
$\gamma\epsilon_x/\gamma\epsilon_y$ [nm]	2500/30	60/60
σ_x/σ_y at e^-e^- IP [nm]	88/4.3	1.3/1.3
σ_z [μm]	300	10
Bunch charge [$10^{10}e^-$]	2	0.62
Bunches/train at IP	2625	93
Train Rep. Rate at IP [Hz]	5	120
Bunch spacing at IP [ns]	366	5.2
σ_x/σ_y at IPC [nm]	176/37.5	5,2/5.2
$\mathscr{L}_{\text{geometric}}$ [$10^{34}\text{cm}^2\ \text{s}^{-1}$]	12	180
δ_E/E [%]		0.1
L^* (QD0 exit to e^-e^- IP) [m]	3.8	1.5 or 3.0
d_{cp} (IPC to IP) [μm]	2600	40
crossing angle [mrad]	20	2 or 20



$\gamma\gamma \to$ **HH** $\to$ **4b**

XCC



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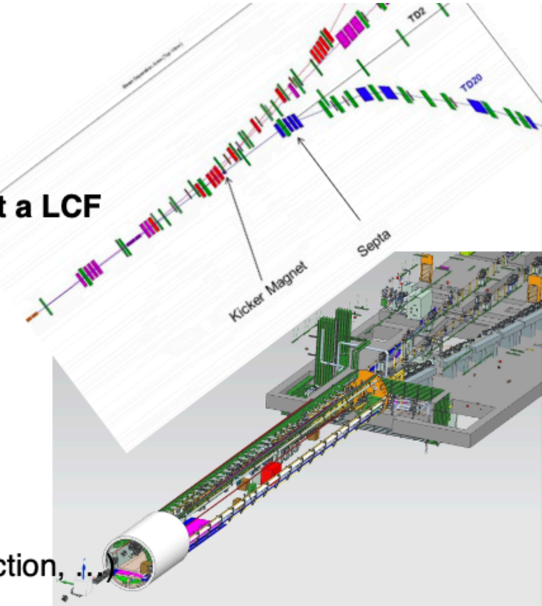
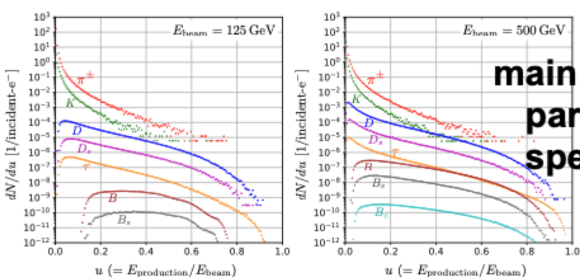
Non-colliding Options / Dump Experiments



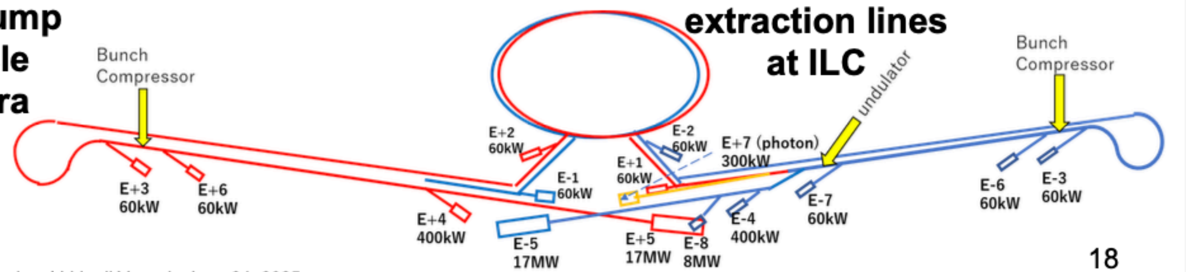
Beam-dump / fixed-target / R&D / irradiation

- **Ample opportunities to foresee beam extraction / dump instrumentation / far detectors at a LCF**
  - extraction of bunches before IP -> mono-energetic, extremely stable, few 10^{10} @ 1-10 Hz
    => super-LUXE (SF-QED χ = O(few hundred) & BSM search), super-LDMX, …
  - disrupted beam after IP -> broad energy and highly divergent, but up to 10^{15} eot / s
    super-SHIP, generic dark photon and ALP searches
    => together with e+e- cover all Dark Sector portals
- **Low-emittance, mono-energetic beams ideal for**
  - high-rate detector and beam instrumentation tests
  - creating **low-emittance beams of photons / muons / neutrons** for various applications (hadron spectroscopy, material science, irradiation, tomography, radioactive isotope production, …)
  - **accelerator development:**
    - high-gradient accelerating structures, new final focus schemes, deceleration (for ERLs), beam and laser driven plasma, …
    - from extracted beam to test small setups - **to large-scale demonstrators for upgrades of the main facility**



main dump particle spectra

dumps / extraction lines at ILC



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Conclusions

- **Timing: Higgs precision measurements are required NOW!**
  - ➡ at least 550 GeV should be envisioned to resolve the trilinear coupling a.s.a.p. !
  - ➡ Safe physics case!
- **Flexibility: responsive to future physics developments**
  - Stageable, tuneable, polarized beams
  - exploit several running options (γγ, eγ, etc.)
  - goal: possible switch to upgrade technology at any stage
  - exploit both colliding- and non-colliding experiments
- **Availability: $\sqrt{s}$=550 GeV done; further accelerator R&D for *multi TeV***
  - Mature design matching all needs available!
  - enable prototyping of essential parts of the system
  - apply new technology (e..g. PWA in combination with SRF, ERL, etc.)
  - goal: upgrades to higher energies & to higher lumi in shorter tunnels
  - adapt new experimental tools (e.g. polarized e+) for *all* designs

➡ ***The LCF will be best prepared for the 'Unknown', will lead to exciting physics results and state-of-the-art technologies!***

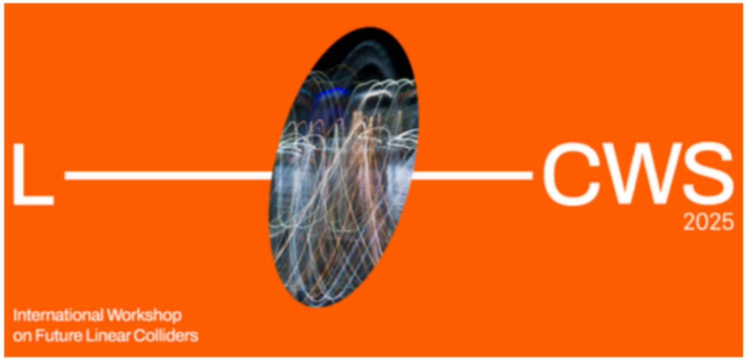
Invitation: please, feel welcome to join !

- *You could*

- sign-up for LCVision mailing list (CERN e-group):
  http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=LCVision-General

- **sign up on supporter list for the LCVision documents:**
  - either following link on https://agenda.linearcollider.org/event/10624/program
  - or directly on https://www.ppe.gla.ac.uk/LC/LCVision/index.php?show=instadmin&skey=etUI1visTy25

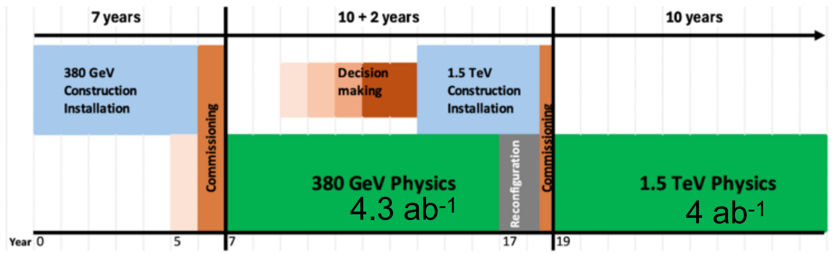
- **join us at LCWS2025: October 20-24 in Valencia, Spain**



- *and stayed tuned for new results/developments/prototypes, etc….*
- *this HEP future will be great & exciting !*

The CLIC ESPP parameters

Key parameters for 380 GeV and 1.5 TeV stages of CLIC. Parameters for energy options at 250 GeV and 550 GeV are also given; for these options the power and luminosity are scaled, based on the 380 GeV and 1.5 TeV designs. ∗The luminosity for the 1.5 TeV machine has not been updated to reflect recent alignment studies [15]. If the same method is applied, the luminosity at 1.5 TeV is expected to reach 5.6 x 10^{34} cm^{-2} s^{-1}

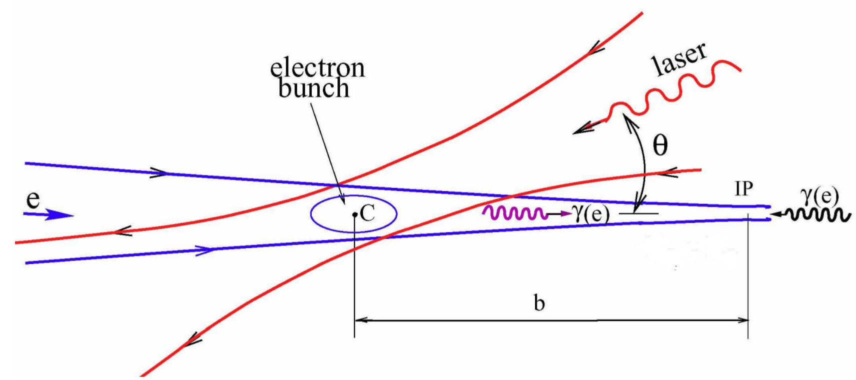


Parameter	Unit	**380 GeV**	**1.5 TeV**	250 GeV	550 GeV
Centre-of-mass energy	GeV	380	1500	250	550
Repetition frequency	Hz	100	50	100	100
Nb. of bunches per train		352	312	352	352
Bunch separation	ns	0.5	0.5	0.5	0.5
Pulse length	ns	244	244	244	244
Accelerating gradient	MV/m	72	72/100	72	72
Total luminosity	$10^{34}\,cm^{-2}s^{-1}$	4.5	3.7^{*}	∼3.0	∼6.5
Lum. above 99% of $\sqrt{s}$	$10^{34}\,cm^{-2}s^{-1}$	2.7	1.4	∼2.1	∼3.2
Total int. lum. per year	fb^{-1}	540	444	∼350	∼780
Power consumption	MW	166	287	∼130	∼210
Main linac tunnel length	km	11.4	29.0	11.4	∼15
Nb. of particles per bunch	10^9	5.2	3.7	5.2	5.2
Bunch length	μm	70	44	70	70
IP beam size	nm	149/2.0	60/1.5	∼184/2.5	∼124/1.7

- Z pole performance, 6.3×10^{32} – 1.2×10^{34} cm^{-2} s^{-1}
  - The latter number when accelerator configured for Z running (e.g. early or at the end of the first stage)
- An alternative upgrade to 550 GeV, maintaining the repetition rate at 100 Hz and two IPs, is also considered. A possible implementation would be to start with a longer tunnel by 5 km from the beginning adding about 25 % to the initial cost of the CE of the baseline 380 GeV machine.

Gamma-gamma collider

- Addition to e^+e^- colliders
- Compton backscattering
- Getting access to $\gamma\gamma$ and γe processes



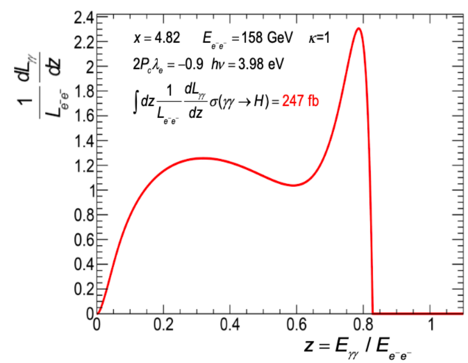
V. I. Telnov 2020

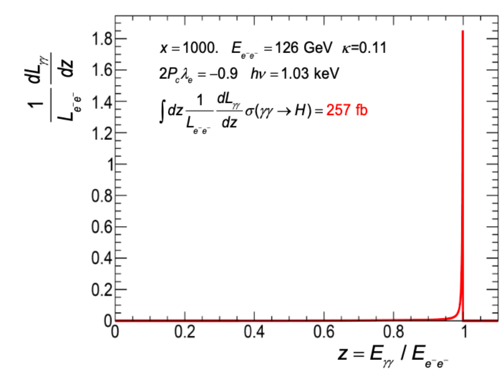
$$\omega_m \approx \frac{x}{x+1}E_0 \qquad x = \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3\left[\frac{E_0}{\text{TeV}}\right]\left[\frac{\omega_0}{\text{eV}}\right] = 19\left[\frac{E_0}{\text{TeV}}\right]\left[\frac{\mu\text{m}}{\lambda}\right]$$

Laser is decisive:

a) optical

b) XFEL-like





Short reminder: why polarized $e^{\pm}$ needed?

- **Important issue: measuring amount of polarization**
  - **limiting systematic uncertainty for high statistics measurements**
  - **Compton polarimeters (up- /downstream): envisaged uncertainties of ΔP/P=0.25%**
- **Advantage of adding positron polarization:**
  - **Substantial enhancement of eff. luminosity and eff. polarization**
  - **new independent observables**
  - **handling of limiting systematics and access to in-situ measurements: ΔP/P=0.1% achievable!**
  - ***allows exploitation of transversely-polarized beams!***
- **Physics impact: Higgs-Physics, WW/Z/top-Physics, New Physics !**

Literature: polarized e+e- beams at a LC (only a few examples)

- *LCC-Physics Group: 'The role of positron polarization for the initial 250 GeV stage of ILC', arXiv: 1801.02840*
- *G. Moortgat-Pick et al. (~85 authors) : `Pol. positrons and electrons at the LC', Phys. Rept. 460 (2008), hep-ph/0507011*
- *G. Wilson: `Prec. Electroweak measurements at a Future e+e- LC', ICHEP2016, R. Karl, J. List, LCWS2016, 1703.00214*
- *many more (only few examples): 1206.6639, 1306.6352 (ILC TDR), 1504.01726, 1702.05377, 1908.11299,2001.03011, …*
- *G. Moortgat-Pick, H. Steiner, `Physics opportunities with pol. e- and e+ beams at TESLA, Eur.Phys.J direct 3 (2001)*
- *T. Hirose, T. Omori, T. Okugi, J. Urakawa, Pol. e+ source for the LC, JLC, Nucl. Instr. Meth. A455 (2000) 15-24,….*