TWENTY-SECOND LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS August, 21-27, 2025

MOSCOW STATE UNIVERSITY

A Linear Collider Vision (for the Future of Particle Physics)

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Linear Collider Vision

[The talk is based on comprehensive reports and publications of the LC Vison Team
10 pages project document arXiv:2503.24049
long document (>100 pages): arXiv:2503.19983
and recent presentations by J. List and G. Moortgat Pick]

NATIONAL INSTITUTE OF THE REPUBLIC OF SERBIA

HOW TO PROBE THE UNIVERSE?

Drawing by F. Simon

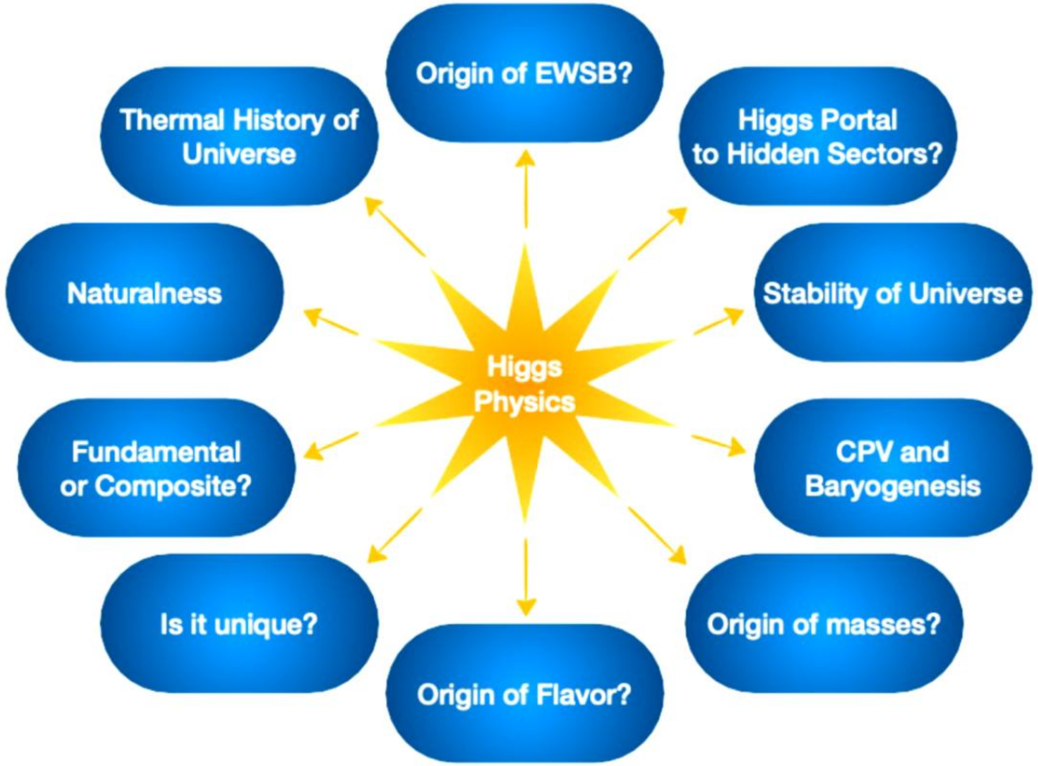
THE PROBLEM

- WE DO NOT UNDERSTAND THE UNIVERSE
  - What is it (the fabric of space-time)?
  - Evolution of the Universe (macroscopic Universe, dark energy,…)
  - Composition of the Universe (baryon asymmetry, Higgs vacuum,…)

- WE ARE TRYING TO EXPLOIT WHAT WE KNOW (CAN DO)
  - Collide particles (since the Rutherford experiment)

HIGGS BOSON AS A PORTAL TO NEW PHYSICS

- The only discovered (fundamental) scalar with not yet fully understood properties
- Opened new questions in SM (mass stabilization – hierarchy problem)
- Tight yet unknown connections to the Universe (*vev – EW baryogenesis*, vacuum stability, cosmological inflation, CPV)
- Directly coupled to massive particles (SM or BSM, DM) $\Rightarrow$ portal to unknown sectors
- Sensitive to BSM realizations $\Rightarrow$ indirect probe of New Physics $\Rightarrow$ roadmap for HEP



- ***European Strategy for Particle Physics Update (ESPPU) 2020 clearly prioritized Higgs factories***
- *Is this going to be revised in ESPPU 2025? Do we prefer Z^0 pole? TeV parton (lepton) energies?*
- *Is the Higgs potential still the 'Holly Grail' of Particle Physics?*

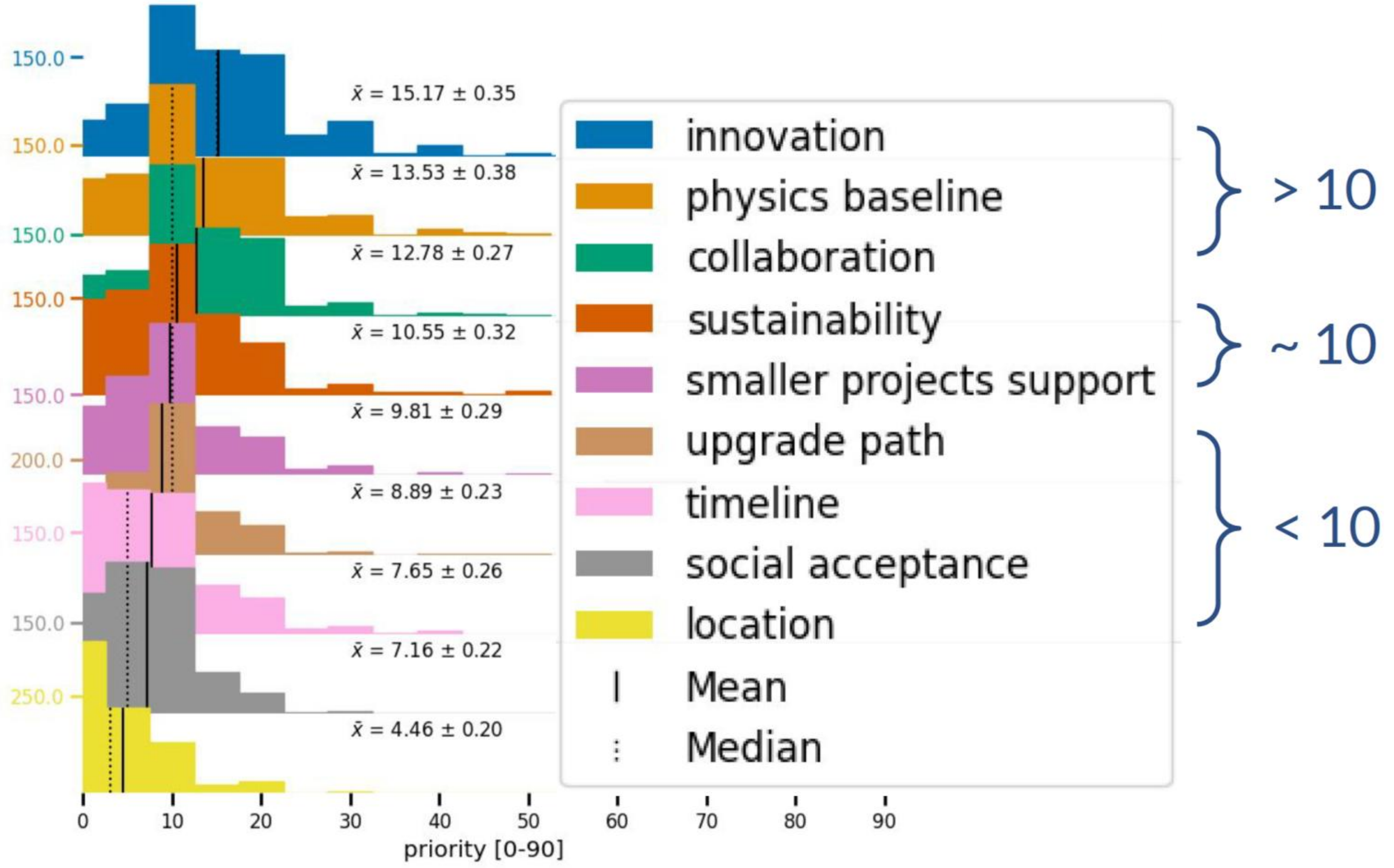
THE LANDSCAPE

- WHICH TOOLS CAN WE POSSIBLY HAVE?
  - Will China go with the CEPC?
  - If yes, should we (Europe) duplicate the machine?
  - Go directly to pp collisions?
  - Go for a linear collider?
  - Have projects in the LHC tunnel?
  - Go straight to muon collider?

C. Dimitriadi, U. Einhaus, ECR Perspectives, ECFA Venice, 2025

Statement: The main collider proposals (...) have received recognition from the ECR community. A relative majority prefers a circular e^+e^- collider, closely followed by the option “I do not know/I do not have a strong opinion”.

SOME GUIDELINES FROM THE (ECR) COMMUNITY



C. Dimitriadi, U. Einhaus, ECR Perspectives, ECFA Venice, 2025

- Physics and innovative technologies are more important than others
- The flagship project should not kill other smaller project (keep diversity)
- Location seems to be of the least importance

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**personal point of view*

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PRO:
- physics potential
- innovative technologies
- can accommodate several experiments

CONTRA:
- cost* (compromise projects diversity)
- time-scale**

cost (pp): 19 B$ (following FCCee), 27 B$ stand-alone*

**AI generated information*

*time-scale**: 2074 (following FCCee), 2055 stand-alone*

***G. Arduini - WG2a report: Project comparison (status), ECFA Venice, 2025*

THE LANDSCAPE

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PRO:
- existing infrastructure
- time-scale

CONTRA*:
- limited physics potential (i.e. LEP3: 230 GeV, 6-10 times lower $\mathcal{L}$ than FCCee)
- limited upgrade possibilities
- reducing funding for 'a flagship project' – can not be perceived as intermediate projects

**G. Arduini - WG2a report: Project comparison (status), ECFA Venice, 2025*

THE LANDSCAPE

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PRO:
- physics potential
- innovative technologies

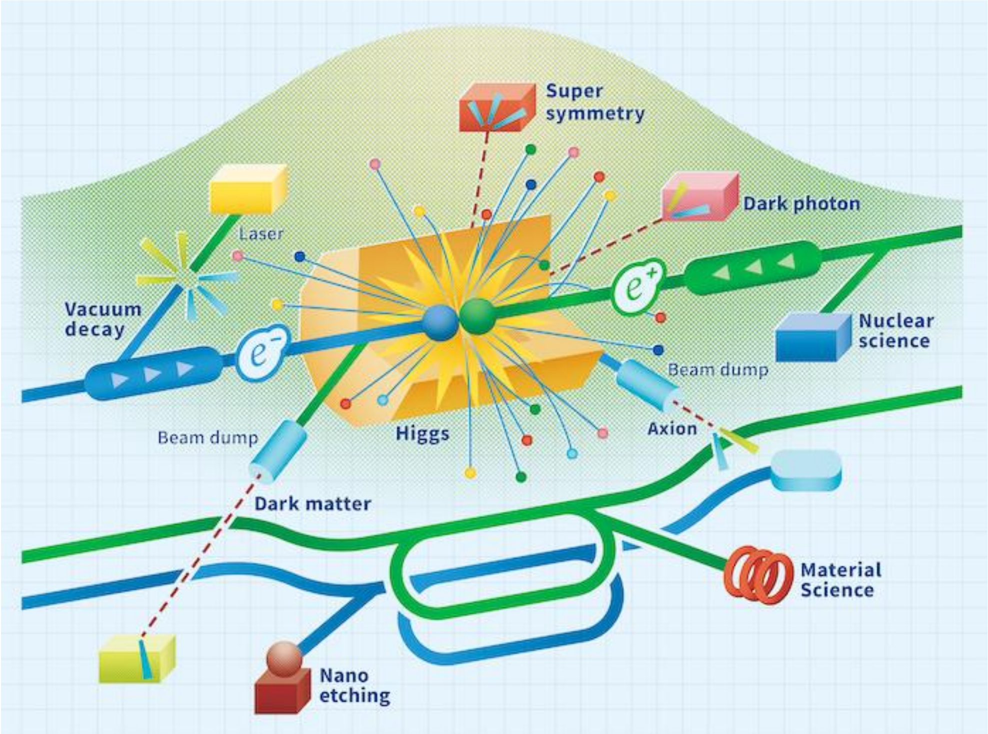
CONTRA*:
- time scale due to needed R&D time
- feasibility (beam stabilization, ν flux, high-B magnets)

**G. Arduini - WG2a report: Project comparison (status), ECFA Venice, 2025*

GO FOR A LINEAR COLLIDER?

Mature e+e- collider designs at 250 GeV, 350 GeV, 550 GeV and beyond TeV options

PRO:
- proven technology (European XFEL)
- immediately available
- less expensive* (FCCee + FCChh ~ 34B$)
- upgradable (also in technology: SCRF, ERL, plasma wakefield)
- auxiliary experiments (beam-dump, fix target)
- beam polarization (effectively increases $\mathcal{L}$, background reduction, model discrimination)



cost: 17 B$ (550 GeV, 2 IP @CERN), + 7 B$ for 1 TeV***

**S. Stapnes, A Linear Collider at CERN, ECFA Venice, 2025*

*** AI generated information*

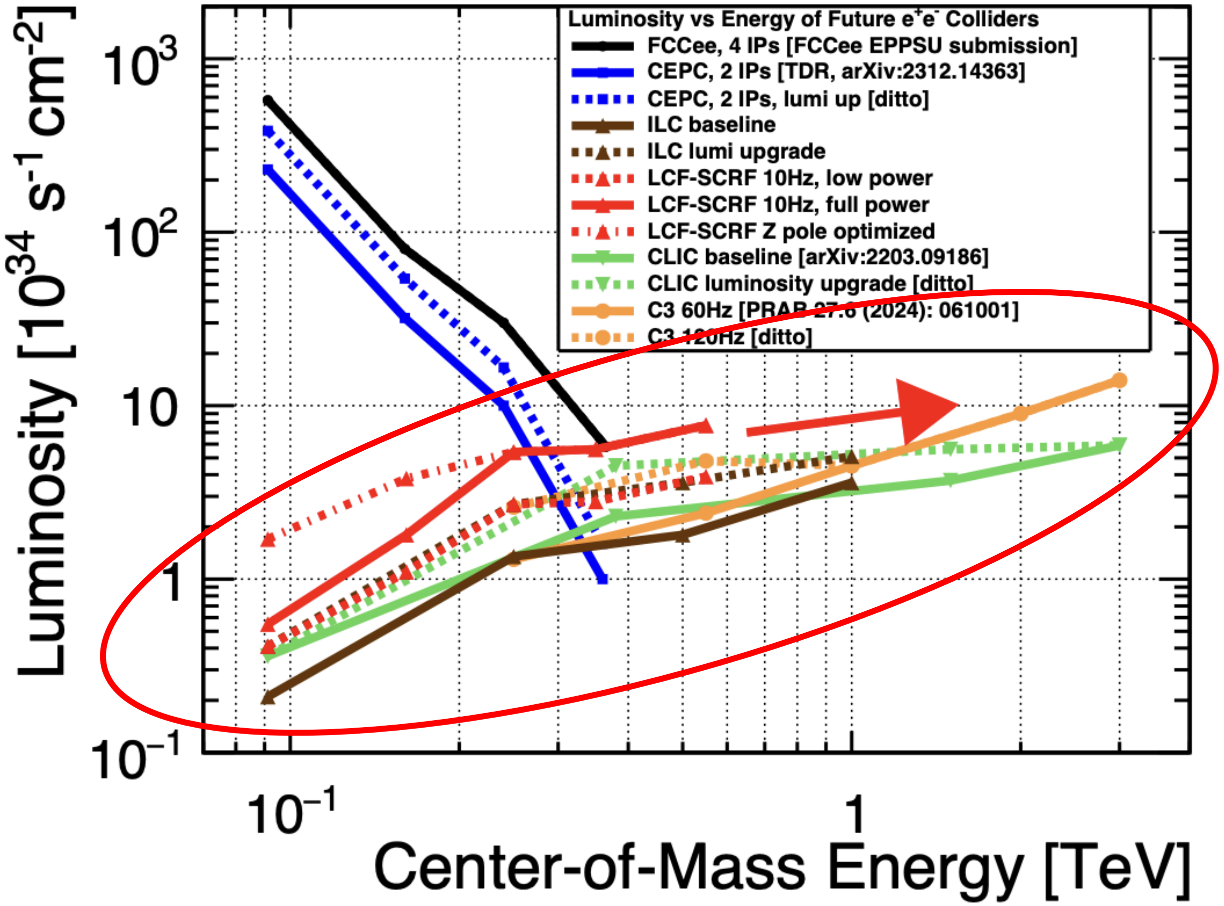
LCF PHYSICS REACH

250 GeV, ~2ab-1:
precision Higgs mass and total ZH cross-section
Higgs -> invisible (Dark Sector portal)
basic ffbar and WW program
optional: WW threshold scan
Z pole, few billion Z's: EWPOs 10-100x better than today

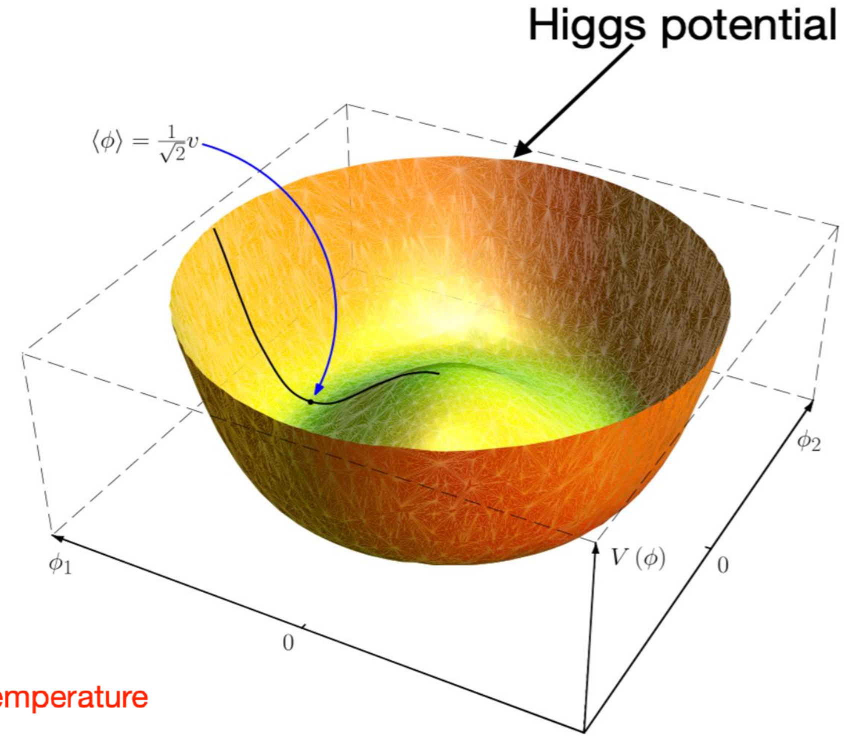
350 GeV, 200 fb-1:
precision top mass from threshold scan

500…600 GeV, 4 ab-1:
Higgs self-coupling in ZHH with ~10% precision on λ/λ_{SM}
top quark EW couplings
top Yukawa coupling incl CP structure
improved Higgs, WW and ffbar
probe Higgsinos up to ~300 GeV
probe Heavy Neutral Leptons up to ~600 GeV

800…1000 GeV, 8 ab-1:
Higgs self-coupling in VBF
further improvements in tt, ff, WW, ….
probe Higgsinos up to ~500 GeV
probe Heavy Neutral Leptons up to ~1000 GeV
direct BSM searches



WHAT IS THE UNDERLYING DYNAMICS OF EW SYMMETRY BREAKING?



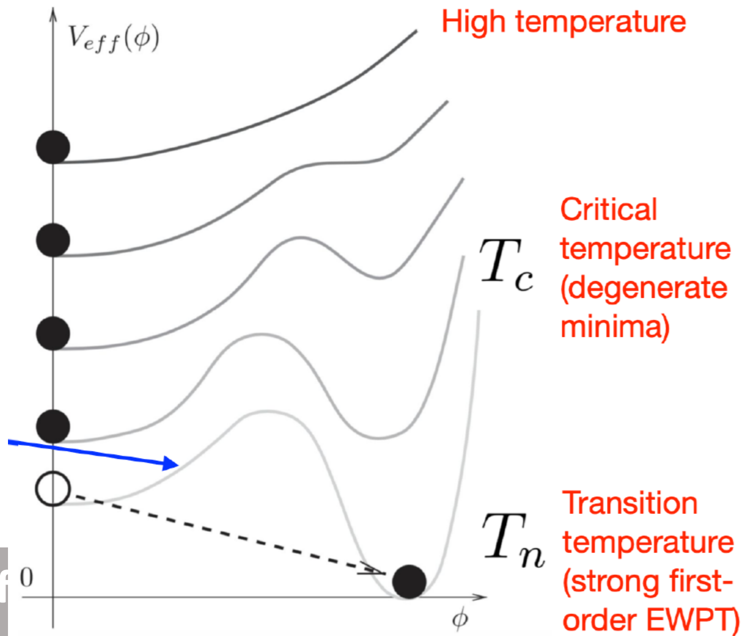
- Why the Higgs field developed vacuum expectation value ($\mu^2<0$)?

- Extended Higgs sector = new symmetry
- Composite Higgs = new interaction

- Which form of the Higgs potential is realized in nature (is $\lambda=\lambda_{SM}$)?

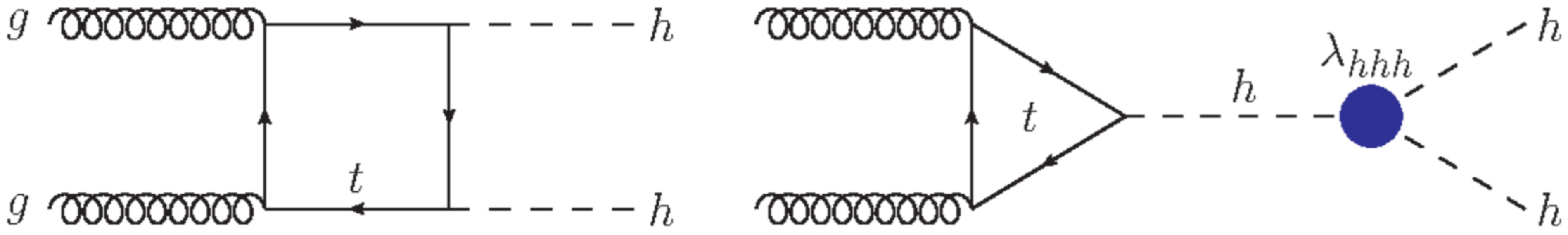
Trilinear Higgs coupling is crucial for understanding of the Higgs potential and its cosmological implications

- EW baryogenesis requires strong first-order phase transition
- $\lambda=\lambda_{SM}$ is a typical feature of the first order EWPT



THE BEST WAY TO PROBE IT ARE l^+l^- COLLISION AT HIGH ENERGIES

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



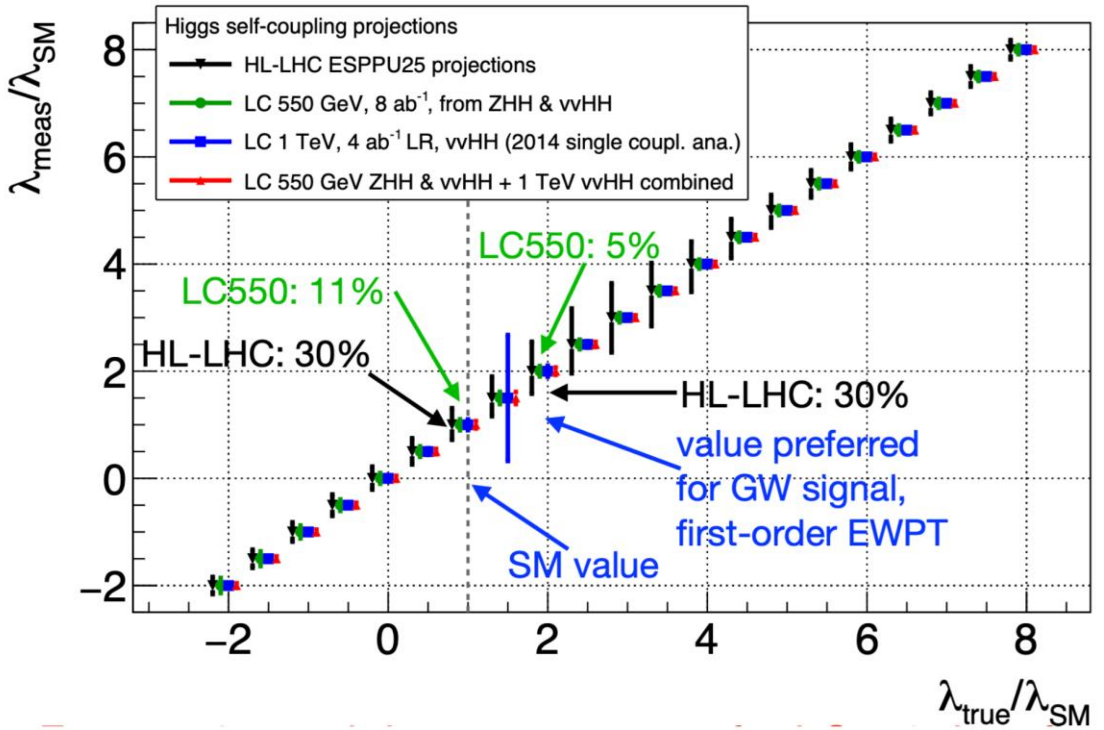
Destructive interference at hadron colliders depends critically on λ/λ_{SM}

Present LHC bound $-1.4 < \lambda/\lambda_{SM} < 7.0$ at 95% CL

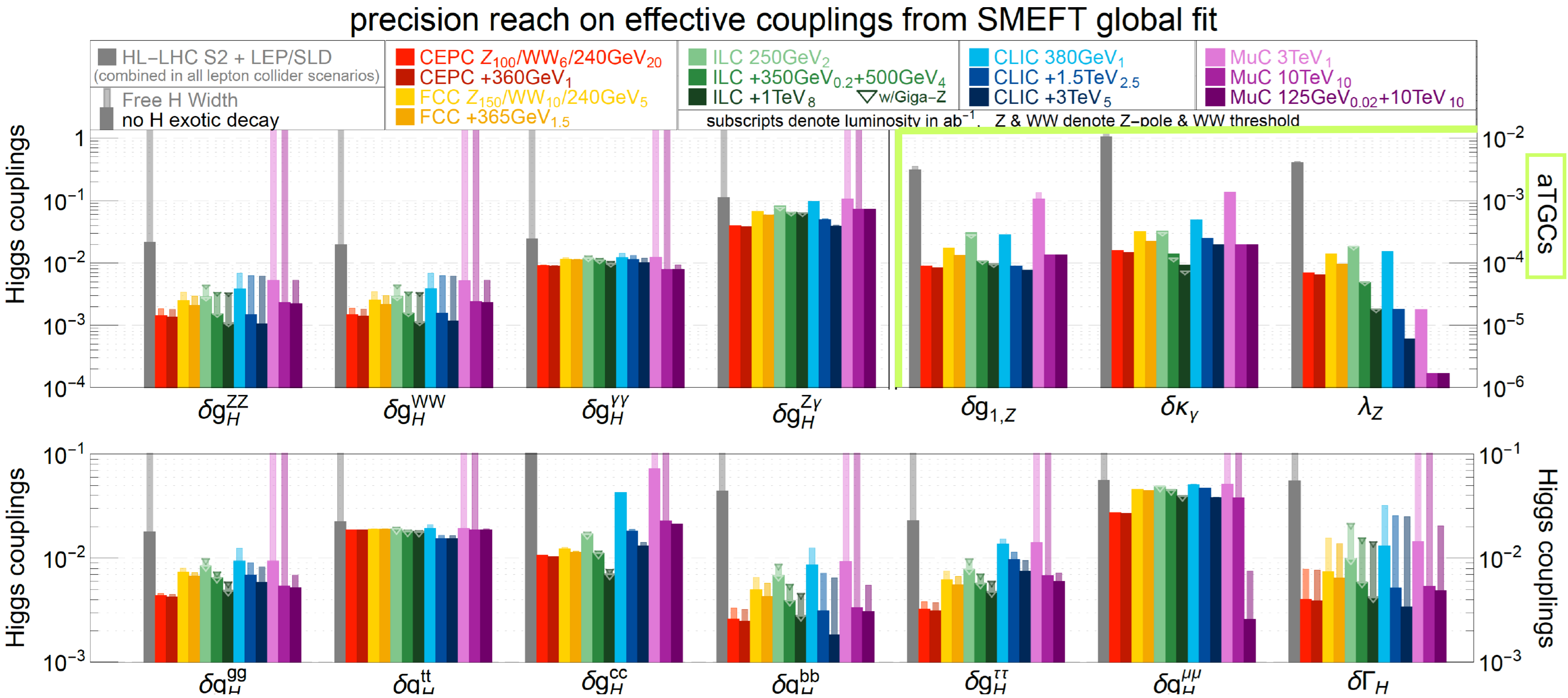
High energy (> 500 GeV) linear collider is the fastest way to reach % level precision on the Higgs potential

(at FCC/ee+eh+hh/~2080s)*

E. Laenen, Outstanding questions in PP, ECFA Venice, 2025



LC CAN DELIVER BASIC HIGGS MEASUREMENTS ON EQUAL FOOTING WITH OTHER e^+e^- COLLIDERS



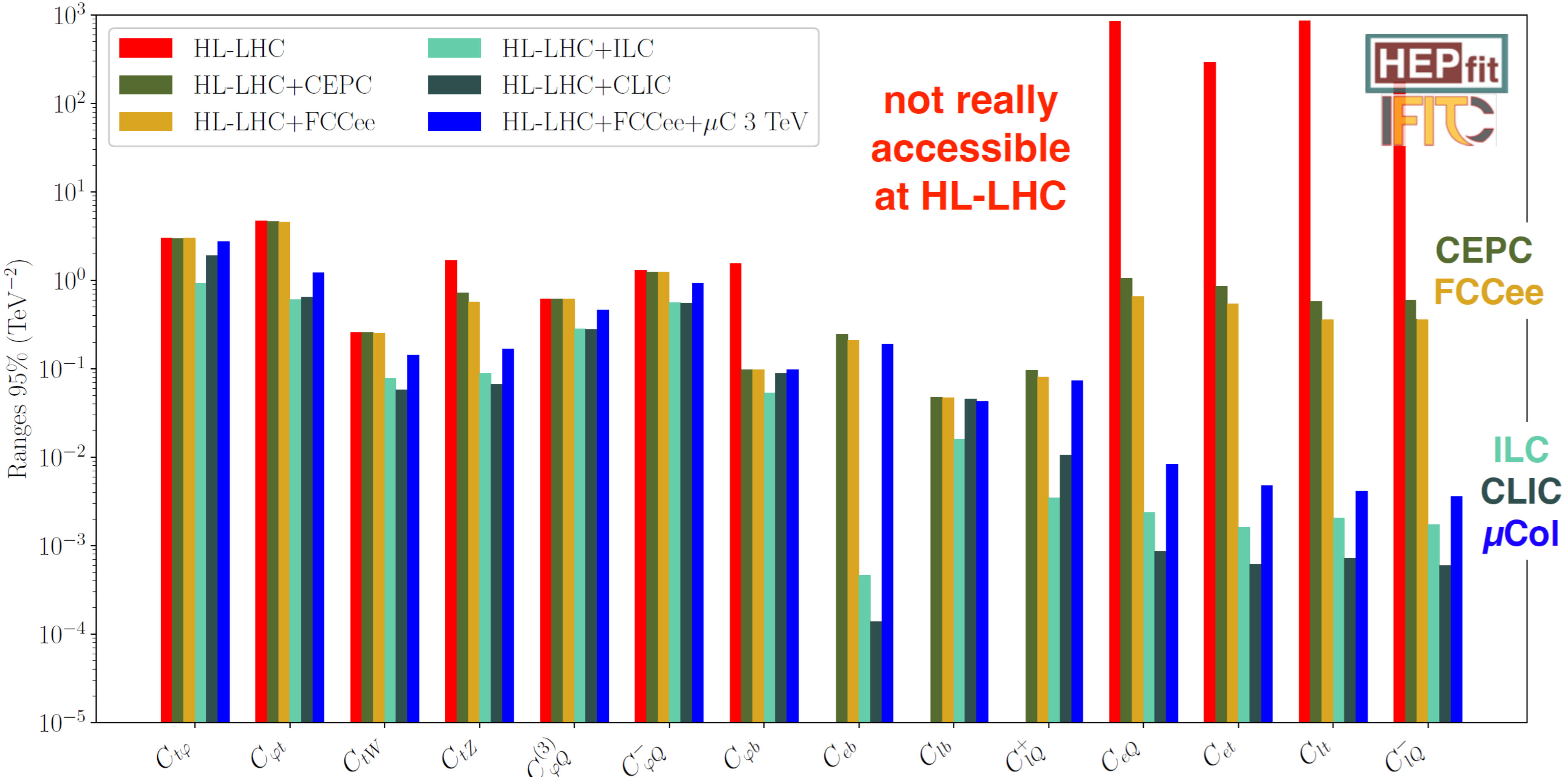
arXiv:2206.08326

ADDED VALUE TO HL-LHC IN THE TOP SECTOR

SMEFT analysis + 1TeV ILC

based on arXiv:2205.02140

High energies and beam polarization in some cases lift degeneracies between operators

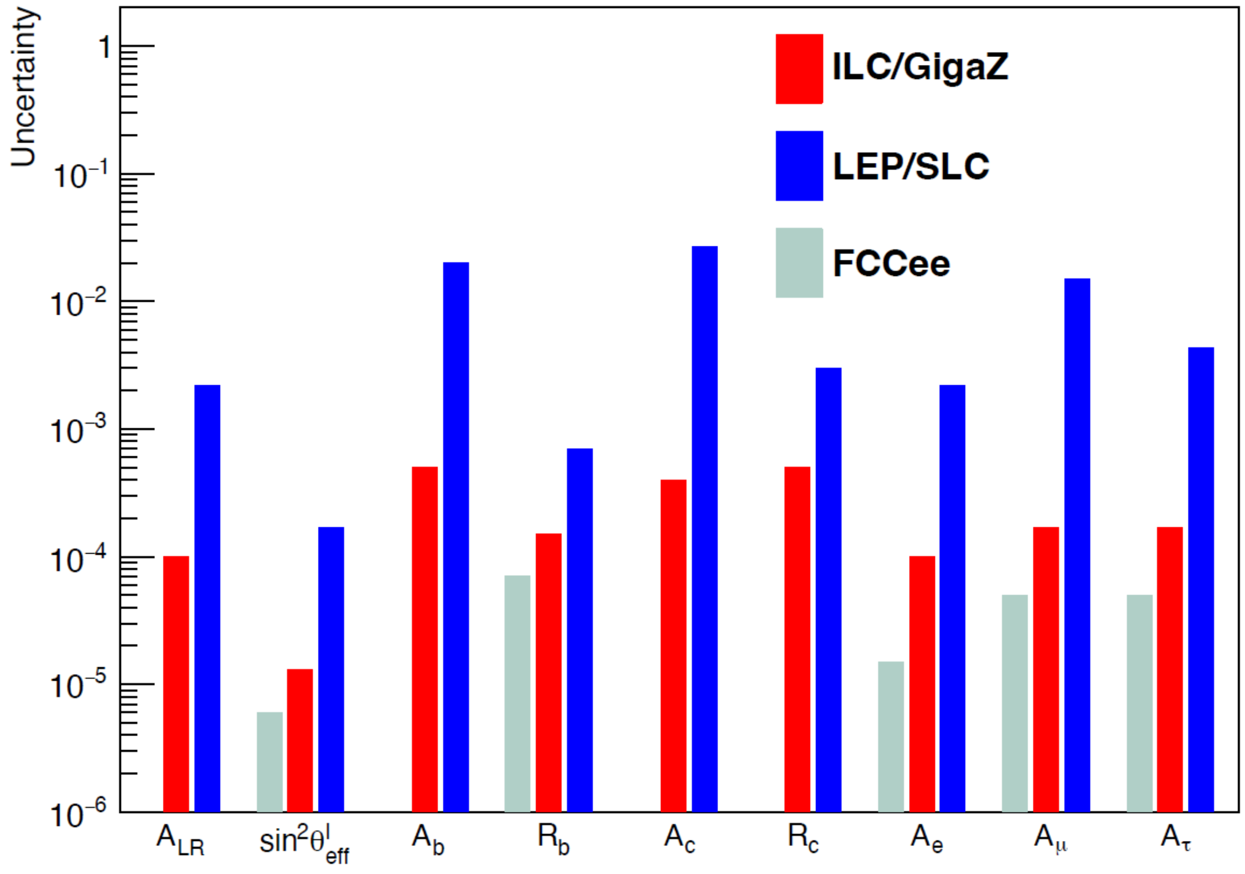


LET'S DISCUSS SOME CRITICISM (TO THE LC PHYSICS PROGRAM)

arXiv:1908.11299

Z^0 pole is more important (than thought initially)

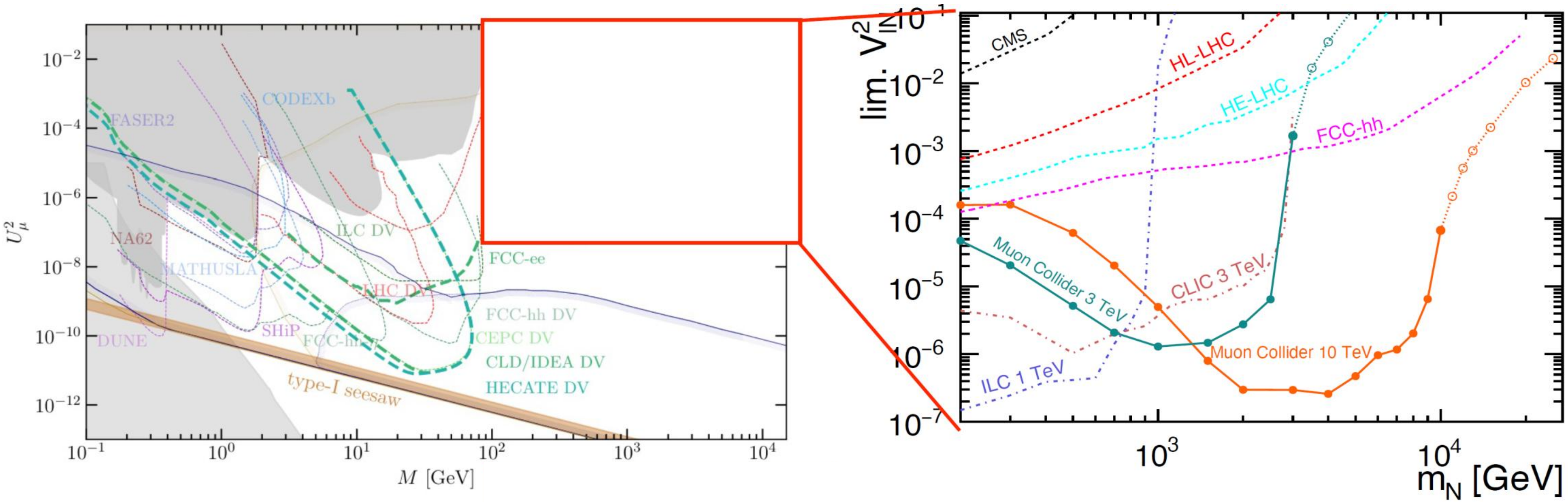
- Giga-Z does not compare to Tera-Z in statistical precision
- BUT, we have do decide do we want $\delta(\lambda/\lambda_{SM})$~ 20% and Tera-Z (i.e. FCCee) or $\delta(\lambda/\lambda_{SM})$ <10% and Giga-Z EW studies
- AND, theoretical uncertainties would have to follow Tera-Z statistical precision



LET'S DISCUSS SOME CRITICISM (ON THE LC PHYSICS PROGRAM)

Direct BSM searches are the most relevant

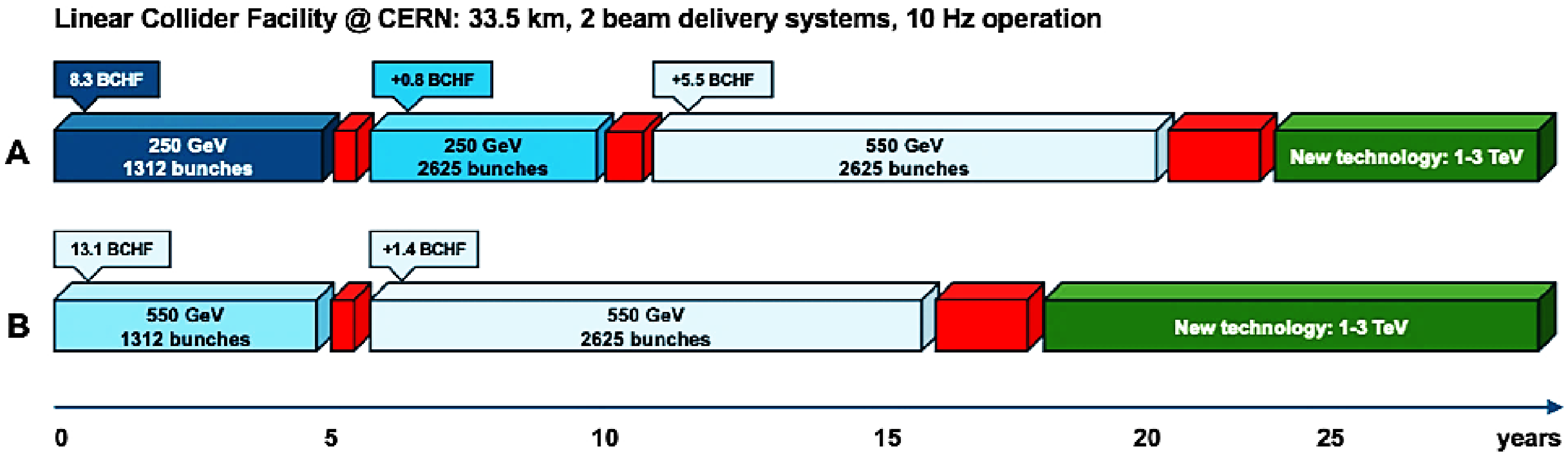
arXiv:2203.05502, arXiv:2301.02602

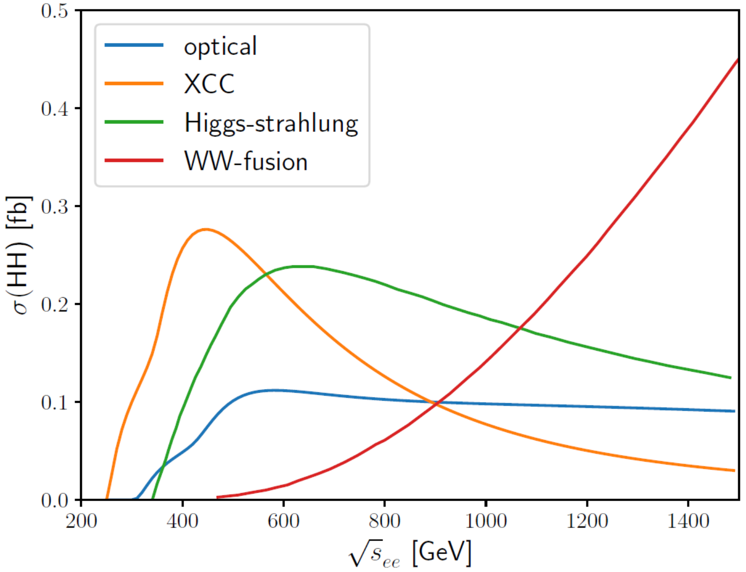


- Often (example on Heavy Neutral Leptons) one low-energy (<500 GeV) e^+e^- machine is not enough
- LC is flexible to extensions (so is FCCee, but more expensive)
- Or, to really force direct searches at 10(s) TeV one could go to muon collider (time-scale, feasibility, etc.)

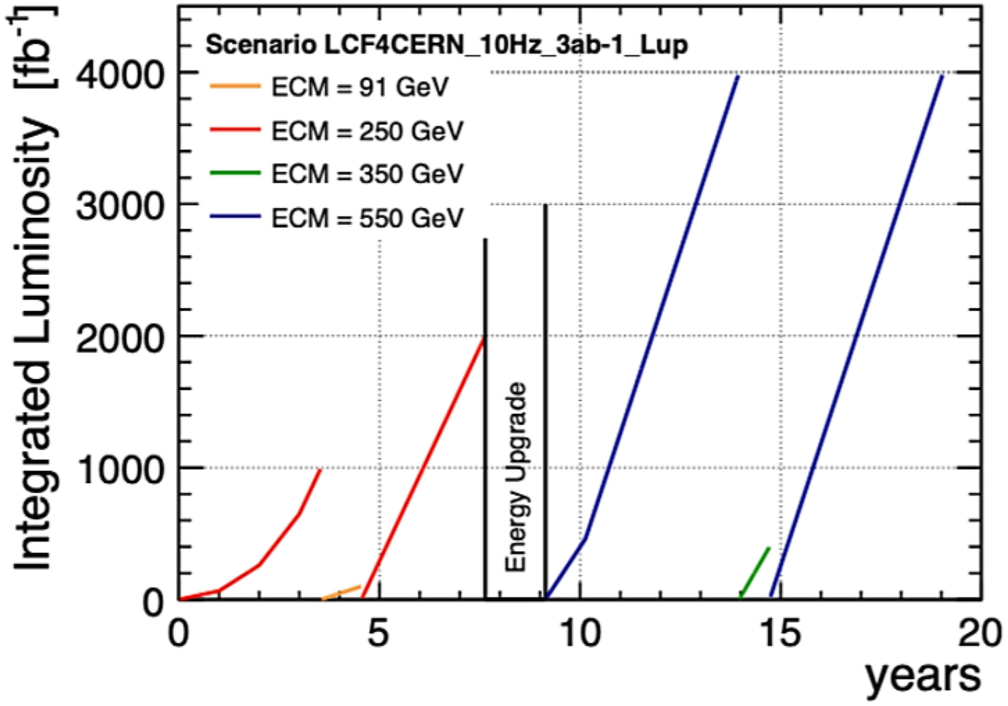
LCF FOR CERN

- LC Vision promotes LCF for CERN https://arxiv.org/abs/2503.24049
- Supported by ITN (accelerator studies at KEK and CERN and laboratories in UK, Germany, France, Italy, Spain)
- A linear collider facility (LCF): ILC-like based on SCRF, 31 km (550 GeV) with XFEL-like tunnel (5.2-5.6)m
- Key changes w.r.t. the ILC: Bunch trains 5 Hz to 10 Hz, double numbers of bunches per train (1316 → 2625)
- A full life-cycle assessment according to ISO standards (ARUP study) https://edms.cern.ch/document/2917948/1
- 2 interaction regions: 2nd Beam Delivery System by switching on train-by-train basis have been designed
- 2nd interaction region offers complementary physics opportunities (γγ, eγ with optical or x-ray lasers)
- SCRF upgrade: Excellent chances to reach ≤ 1 TeV in the same tunnel (60 MV/m)





LCF MAIN PARAMETERS

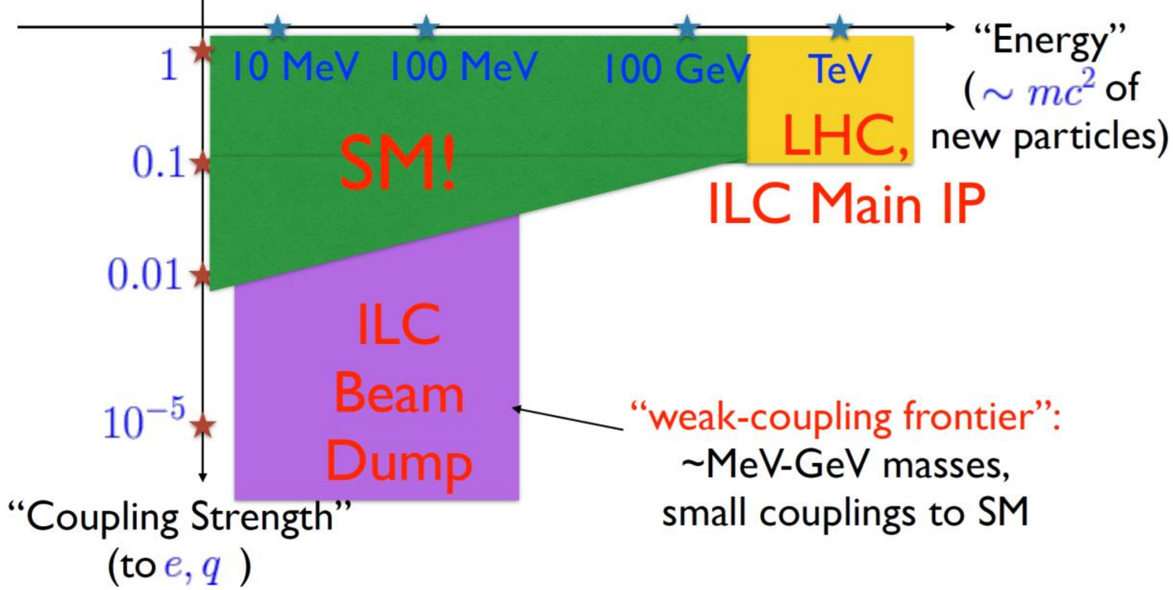


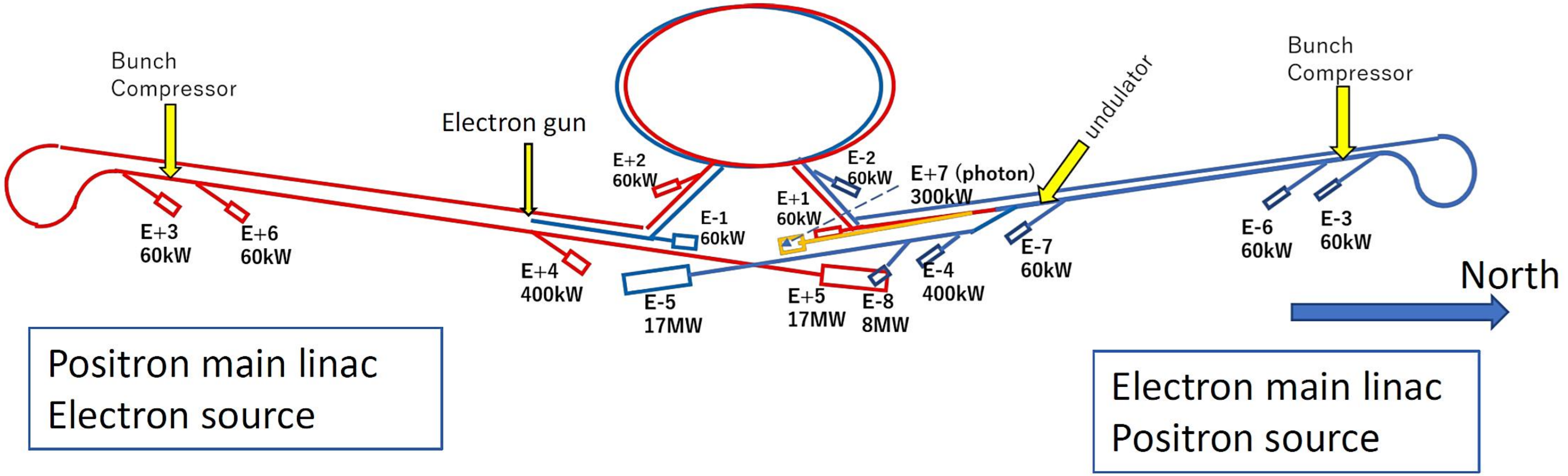
Quantity Name	Symbol	Unit	Initial-250 250 LP	Upgrades 250 FP	550 FP	Initial-550 550 LP	Upgrade 550 FP
Centre-of-mass energy	$\sqrt{s}$	GeV	250	250	550	550	550
Inst. luminosity	$\mathscr{L}$	$(10^{34} cm^{-2} s^{-1})$	2.7	5.4	7.7	3.9	7.7
Polarisation	$\lvert P(e^-)\rvert / \lvert P(e^+)\rvert$	(%)	80 / 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	$\gamma\varepsilon_x$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\varepsilon_y$	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

AUXILIARY RESEARCH PROGRAM

- Fix target experiments:
  - extraction of bunches before IP, mono-energetic, extremely stable, few 10^{10} particles @ 1-10 Hz (non-perturbative QED)
- Beam dump experiments:
  - disrupted beam after IP, broad energy spectrum up to 10^{15} electrons on target / s (feebly interacting particles, dark photons, axions, ALPs)

ILCX program arXiv:2203.07622





SUMMARY

- Discovery of H(125) completed the SM particle spectrum and taught us how the EW symmetry was broken. However, it does not tell us why it was broken (why μ2 < 0?). To address this question we need to go beyond the SM.
- Higgs studies are opening a window to BSM and to a better understanding of the Universe (DM, CPV, EWBG..).

- LCF offers high-precision Higgs measurements at an immediate time scale
- LCF offers 550 GeV and above operation required to resolve the Higgs self-coupling at a percent level
- Capable to operate from the Z-pole to a TeV scale, LCF offers full Higgs/top/EW e+e- physics program
- LCF is upgradable in novel and conventional ways (plasma wakefield acceleration, advanced SCRF, ERL, etc.) and versatile (γγ/eγ collisions, auxiliary experiments)
- Tunable to a potential HL-LHC discovery at any stage of operation

If CEPC is going to be realized, LCF is an optimal concurrent and complementary machine for exploration of BSM (that can be hosted at CERN or elsewhere)

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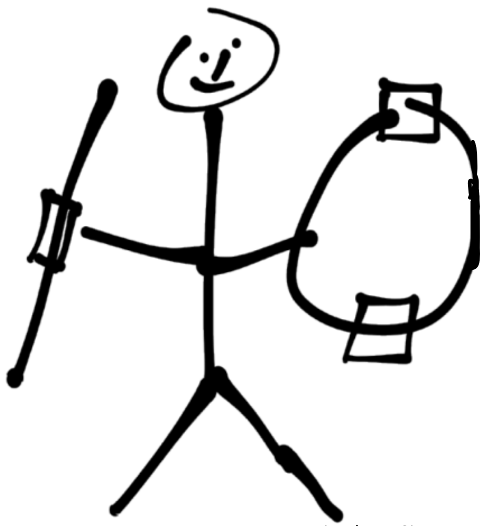
AND, IF NOT….

- Both circular (FCC like) and LC-like machines offer attractive physics program and upgrade options
- Everybody can find his/her own preferred physics model to prove that a certain machine is ‘better’*
- Time-scale is important*
- Funding as well
- It is clear that very many parameters enter the equation …



Drawing by F. Simon

**personal point of view*

Sources

ID	Title	Contact
40	The Linear Collider Facility (LCF) at CERN	Jenny List
57	HALHF: a hybrid, asymmetric, linear Higgs factory using plasma- and RF-based acceleration	Brian Foster
78	The Compact Linear e+e- Collider (CLIC)	Erik Adli
97	ESPPU INPUT: C3 within the "Linear Collider Vision"	Emilio Nanni
140	A Linear Collider Vision for the Future of Particle Physics	Jenny List
152	US Muon Collider Community White Paper for the European Strategy for Particle Physics Update	Sergo Jindariani
154	Midterm Review of the European Accelerator R&D Roadmap	Mike Seidel
165	A Possible Future Use of the LHC Tunnel	Marco Drewes
174	Phase-One LHeC	Krzysztof Piotrzkowski
188	LEP3: A High-Luminosity e+e– Higgs & Electroweak Factory in the LHC Tunnel	Tiziano Camporesi

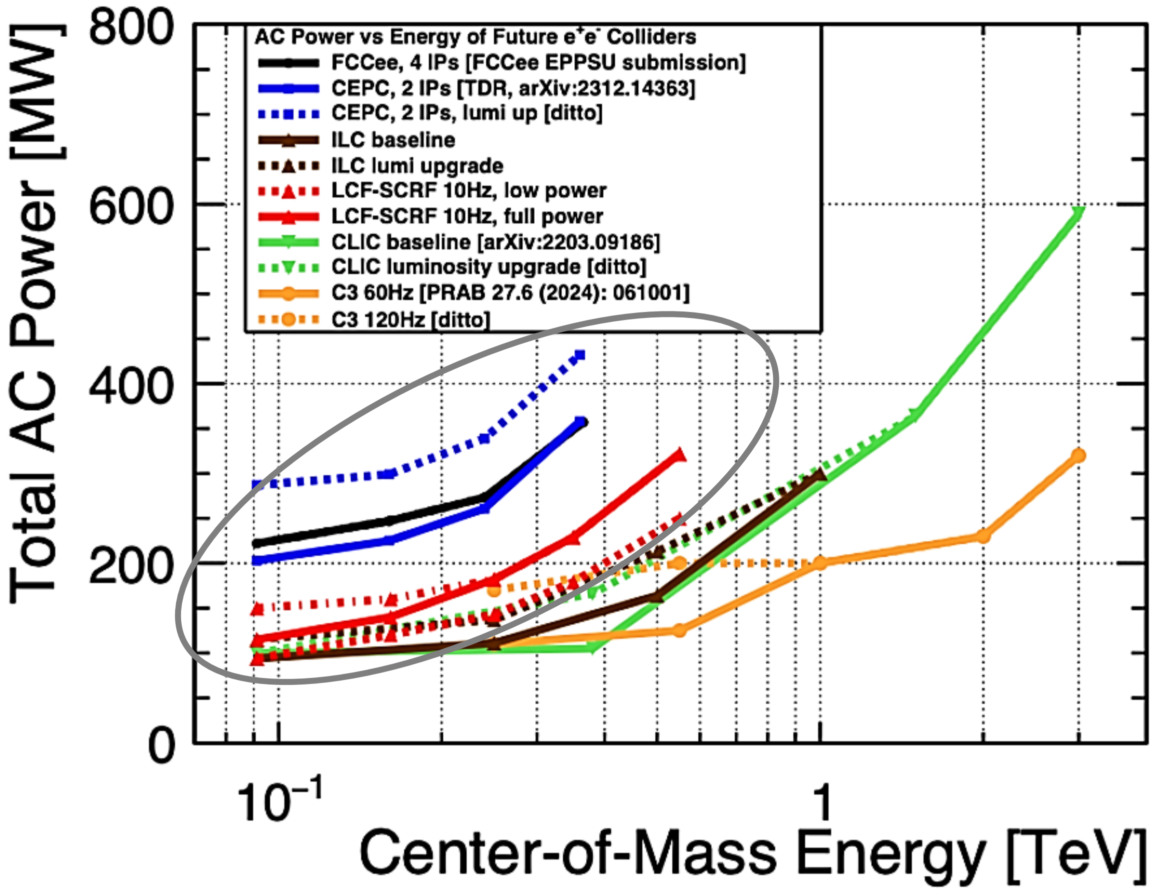
СПАСИБО!

BACKUP

POWER CONSUMPTION

A decade of studies to reduce power:

- Designs optimizations
- SRF cavities (gradient, Q),
- cryo efficiency
- RF power system (klystrons, modulators, components),
- RF to beam efficiencies
- improved magnets
- heat recovery
- nanobeams



Re-use of the LHC tunnel

LEP3:

- **Pre-conceptual design** with operation limited to 230 GeV, but not yet validated by simulation studies to confirm performance (luminosity, power consumption, …)
- Large SC RF system, possible need for SC magnets, and high-energy booster installed in the same tunnel of the collider demand for integration studies to assess extent of the civil engineering
- Prospected luminosity x IP number lower by a factor 6 to 10 as compared to FCC-ee, power consumption comparable to that of FCC-ee (at low energy).
- Resources for operation comparable to LHC

Re-use of the LHC tunnel

LHeC:

- **Detailed conceptual design developed** and based on high-current high-energy ERL
- Civil engineering required for the ERL tunnel
- Requires **demonstration of high-current multi-turn energy recovery** → PERLE @ IJCLab
- Technically-driven schedule for LHeC implies **operation after the end of the presently planned HL-LHC programme at the earliest**
- Yearly electricity consumption comparable to FCC-ee at low energy and expected operation resources comparable to LHC

General considerations for options using the LHC tunnel:

- major infrastructure investments and operating costs
- delay of the implementation of a next-generation collider by at least one decade

cannot be considered as “bridge” options but as alternative to other proposed colliders

Muon Collider

- Muon Collider (MC) ambitions to approach 10 TeV pCM energy.
- **MC has not yet reached a maturity level that gives sufficient confidence in its feasibility**.
- **Demonstration of 6D cooling is a necessary condition** to assess feasibility and performance
- A variety of technological challenges are associated with the various acceleration steps
- The technical design of the demonstrator and its construction demand resources significantly exceeding the present level.
- A **detailed timeline cannot be defined at present but only sketched** with some decision points.