A Linear Collider Facility as Higgs Factory and Beyond

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Linear Collider Vision

- Introduction
- Collider
- Physics
- Summary/Outlook

DARK MATTER LAB

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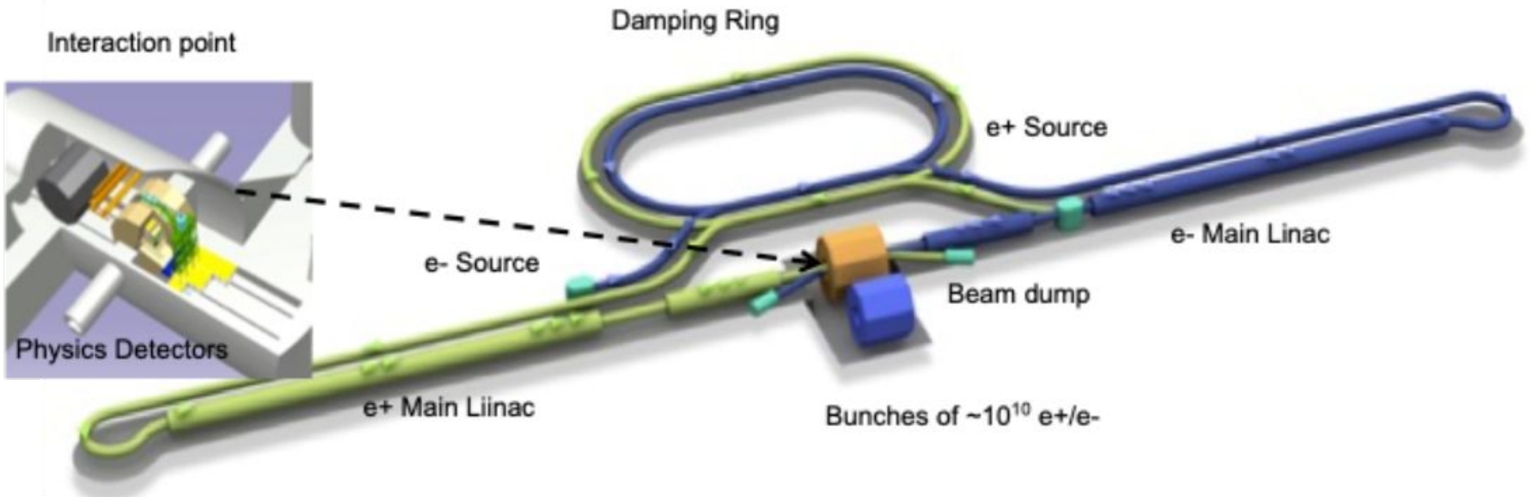
Introduction

Linear Collider Higgs Factory

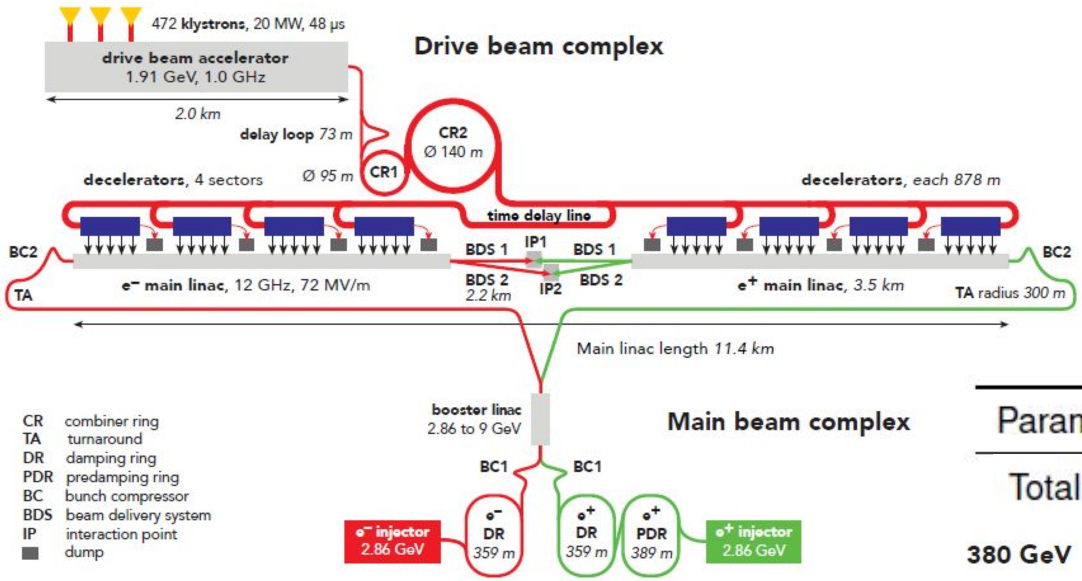
- 33 km
- 2 IPs
- attobarn^{-1} machine

SCRF baseline:

- $\sqrt{s}$=90-250GeV, UG 550GeV
- electron polarization 80%
- positron polarization 30% (working on 60%)



	91 GeV	250 GeV	350 GeV	550 GeV
$\int \mathscr{L}$ (ab^{-1})	0.1	3	0.4	8
beam polarisation (e^-/e^+; %)	80/30	80/30	80/30	80/30
(−+, +−, −−, ++) (%)	(40,40,10,10)	(45,45,5,5)	(67.5,22.5,5,5)	(40,40,10,10)



CLIC (=upgrade):

- $\sqrt{s}$=380 GeV - 2 TeV
- electron polarization 80%

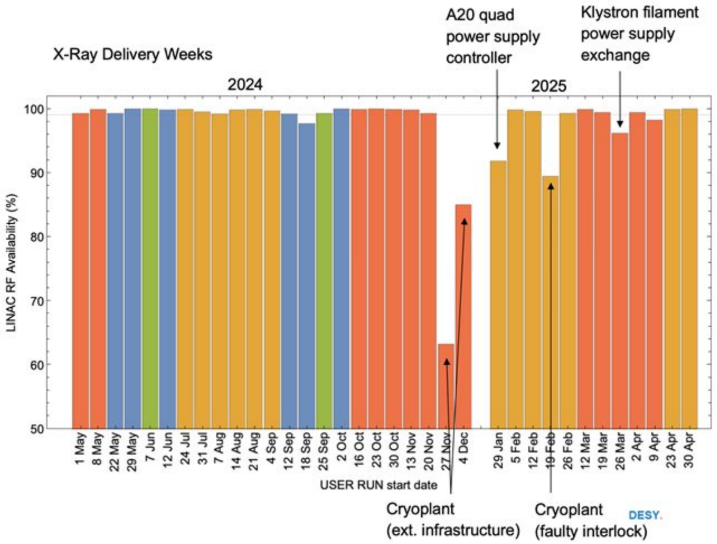
Parameter	Unit	250 GeV	380 GeV	550 GeV	1500 GeV
Total luminosity	10^{34} cm^{-2} s^{-1}	~3.0	4.5	~6.5	3.7*

380 GeV

Collider: SCRF

SCRF: euXFEL

- 5% demonstrator :)
- SCRF cavities
- 1.7 km accelerating structure
- a key question: stability?
  - >90% uptime



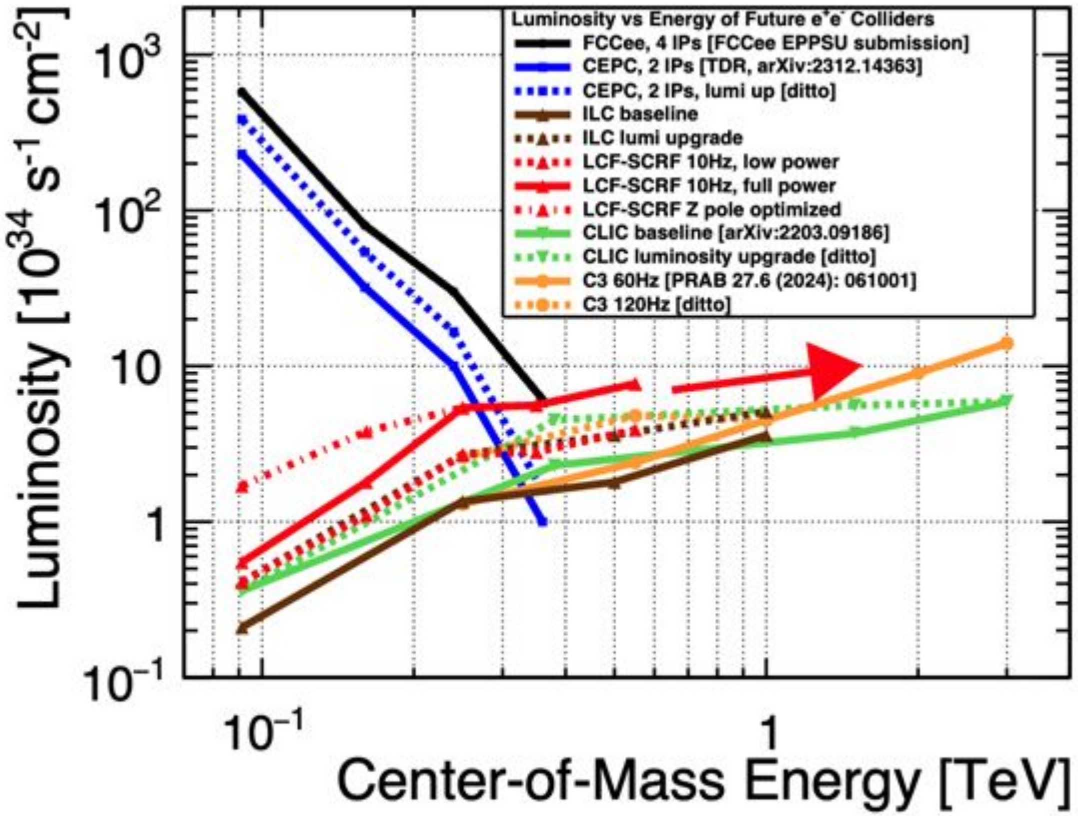
SCRF:

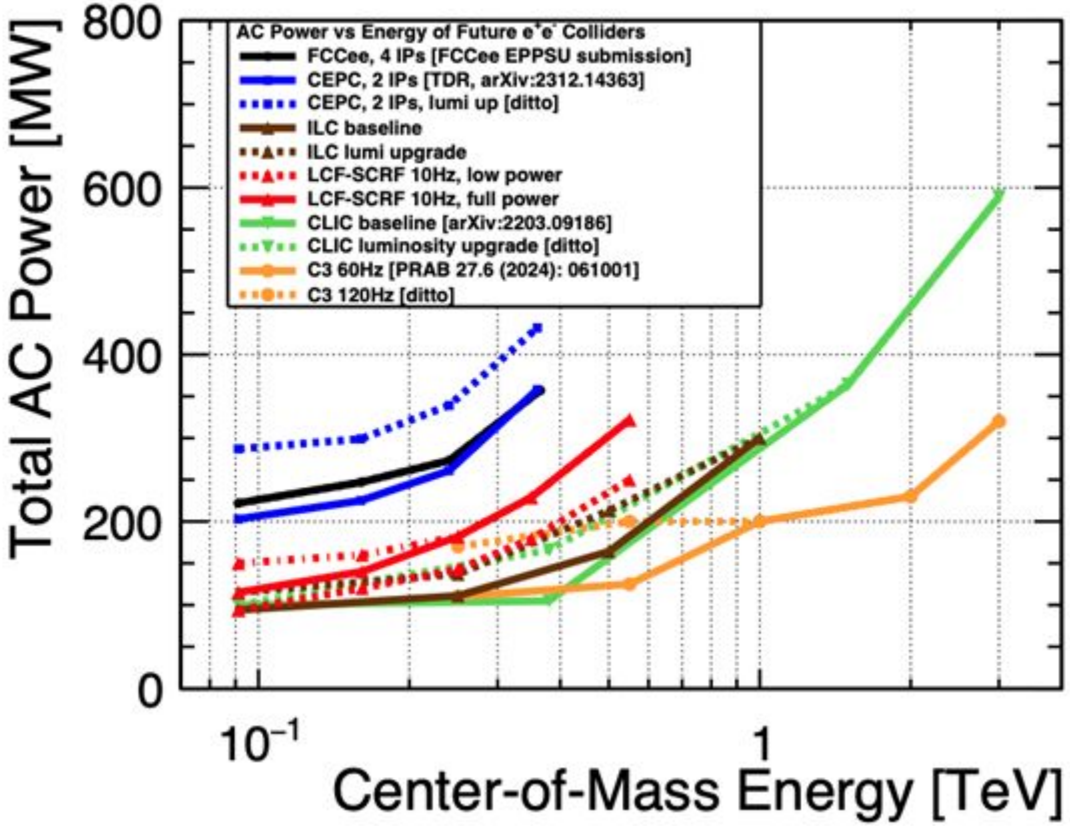
- 31.4MV/m needed
- 32-36MV/m demonstrated at KEK and Fermilab
- Single cell cavities in vertical tests >35MV/m tested

SCRF Improvements:

- quality factor x2
  - 10Hz operation
  - at cost 50% power increase instead of 100%
  - Klystron efficiency improved

Collider: Luminosity and Power





	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

Linear Collider Higgs Factory

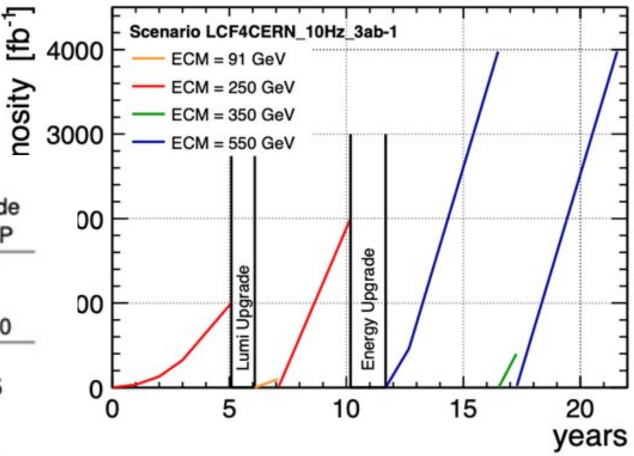
- **increases luminosity with √s**
- **no free lunch: higher √s higher power**
- **Translation: 0.8 - 1.8 TWh**
- **Typical CERN year: 1.2 TWh**

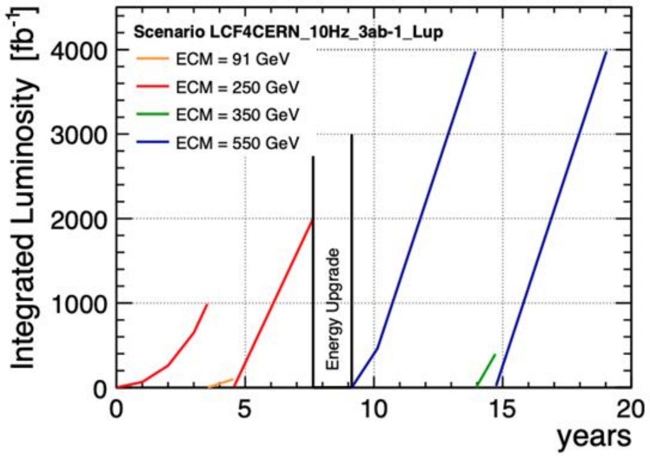
Collider: Running Scenarios

Running Scenario baseline with energy and luminosity upgrades

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	$\lvert P(e^-)\rvert / \lvert P(e^+)\rvert$	(%)	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	$\gamma\epsilon_x$	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

Table 1: 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.





Main Energy Points:

- 250 GeV: single Higgs properties
- 550 GeV: single Higgs and double Higgs properties

Further Energy Points:

- 350 GeV: top pair production
- 91 GeV: Z boson

Duration:

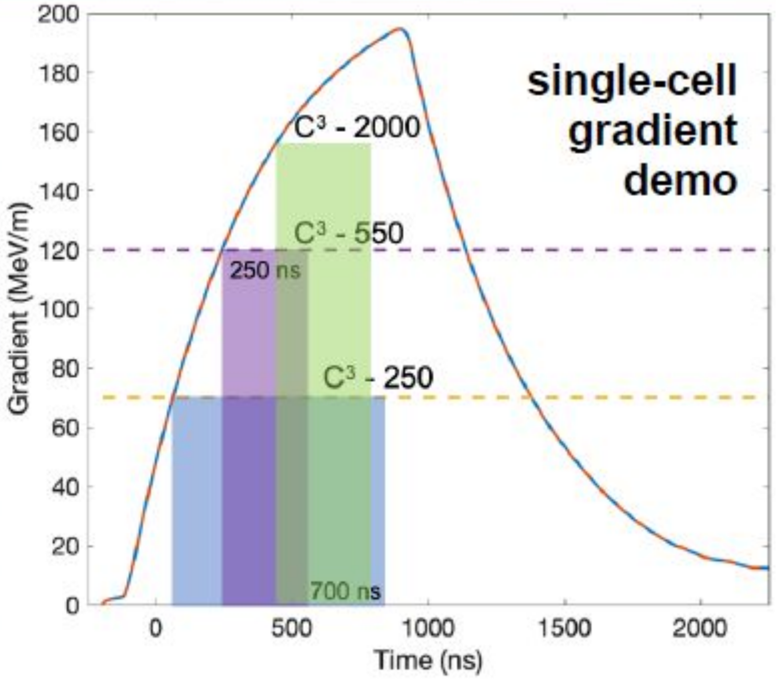
- multi decade program

Collider: More Energy with RF

Upgrade SCRF

- 5 years: 40-60MV/m
  - bulk niobium, standing wave cavities, baking
- 10 years: 60-70 MV/m
  - traveling wave, longer structures
- >10 years: 100MV/m
  - Nb3Sn or multi-layer, 4K instead of 2K
  - so far only 24MV/m reached

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	$\times 10^{34}$ 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



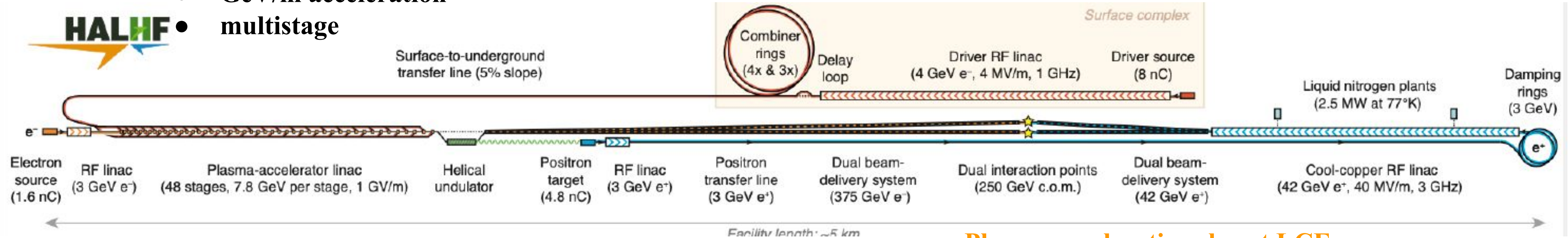
C^3: Cool Copper Collider

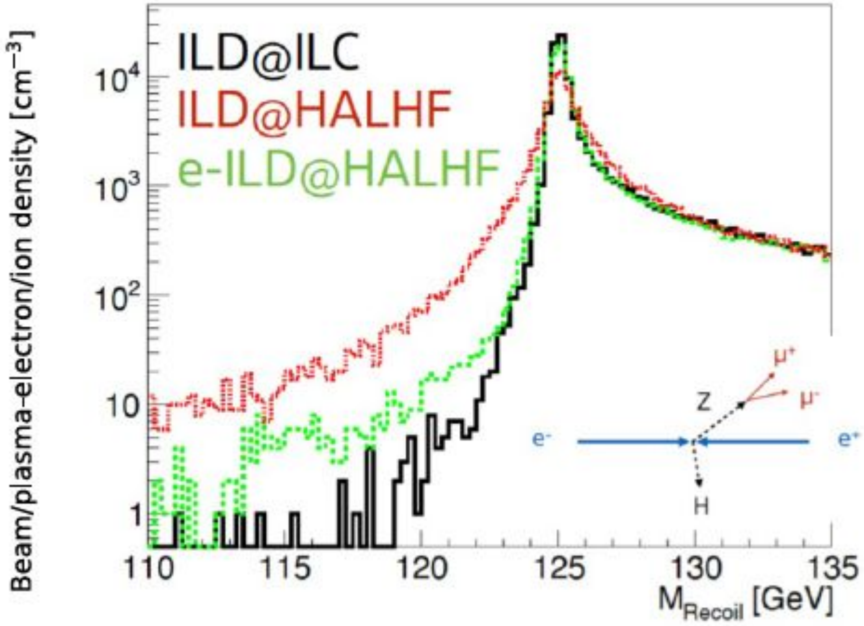
- Temperature: 80K (LN_2)
- Gradient: 155 MV/m
- √s up to 3TeV in 33 km
- R&D and system design

Collider: More Energy with Plasma

Plasma acceleration:

- GeV/m acceleration
- multistage



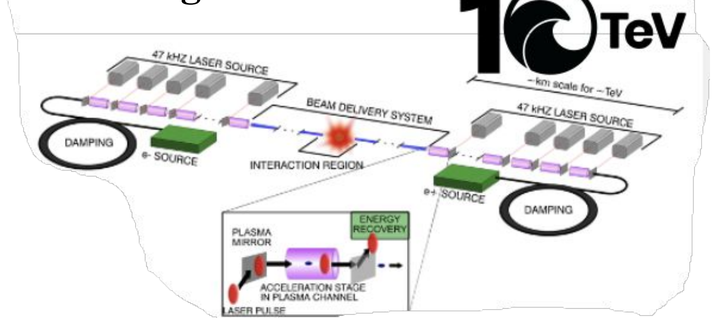


HALHF

- SCRF: positrons
- Plasma: electrons
- Smaller footprint

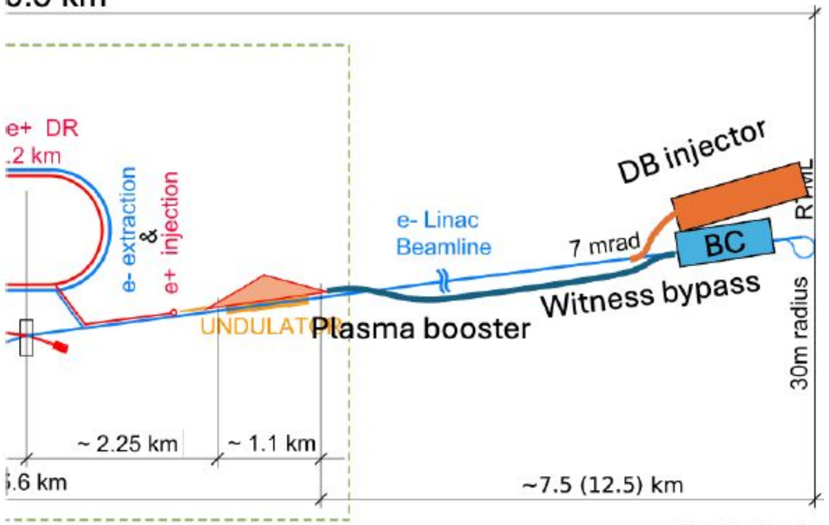
Plasma acceleration: 10TeV

- full facility
- demonstrate high current, non divergent beams…..

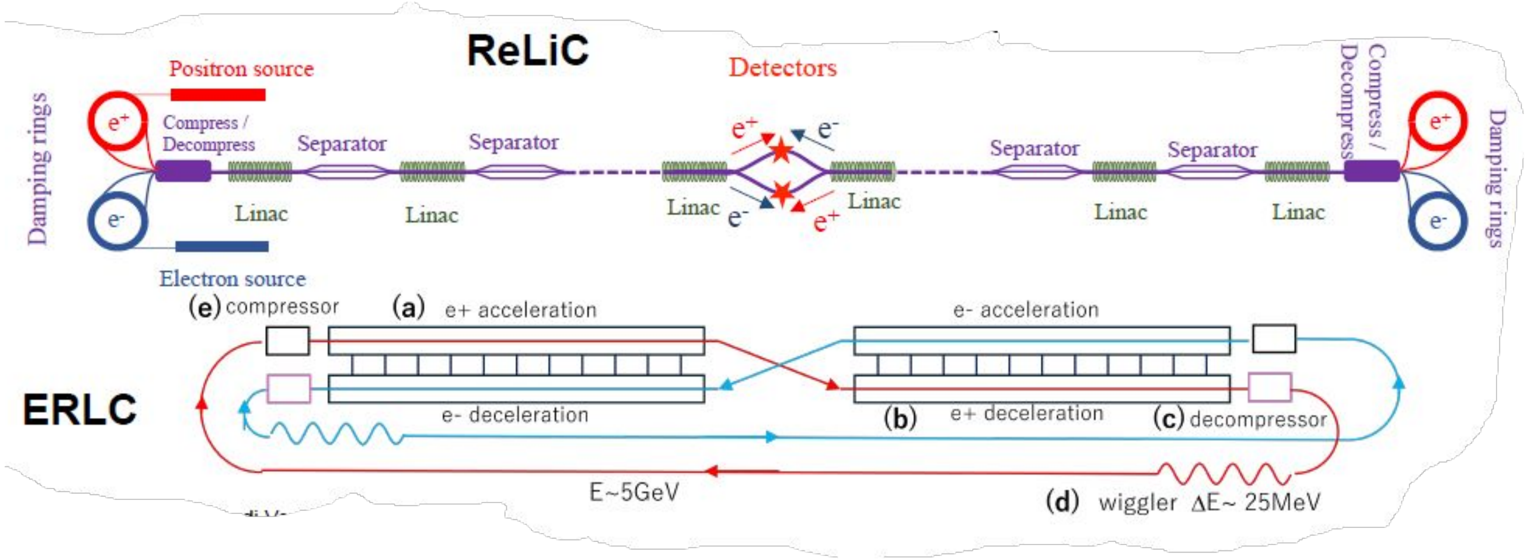


Plasma acceleration: boost LCF

- Plasma boost electrons (and SCRF positrons)
- 137GeV x 550 GeV ~ 550 GeV
- many exciting open questions

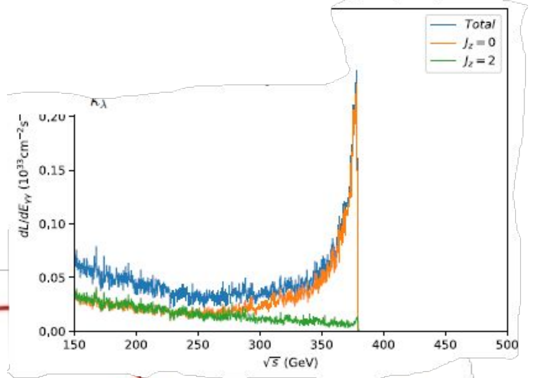


Collider: More luminosity with ERL and Further Ideas



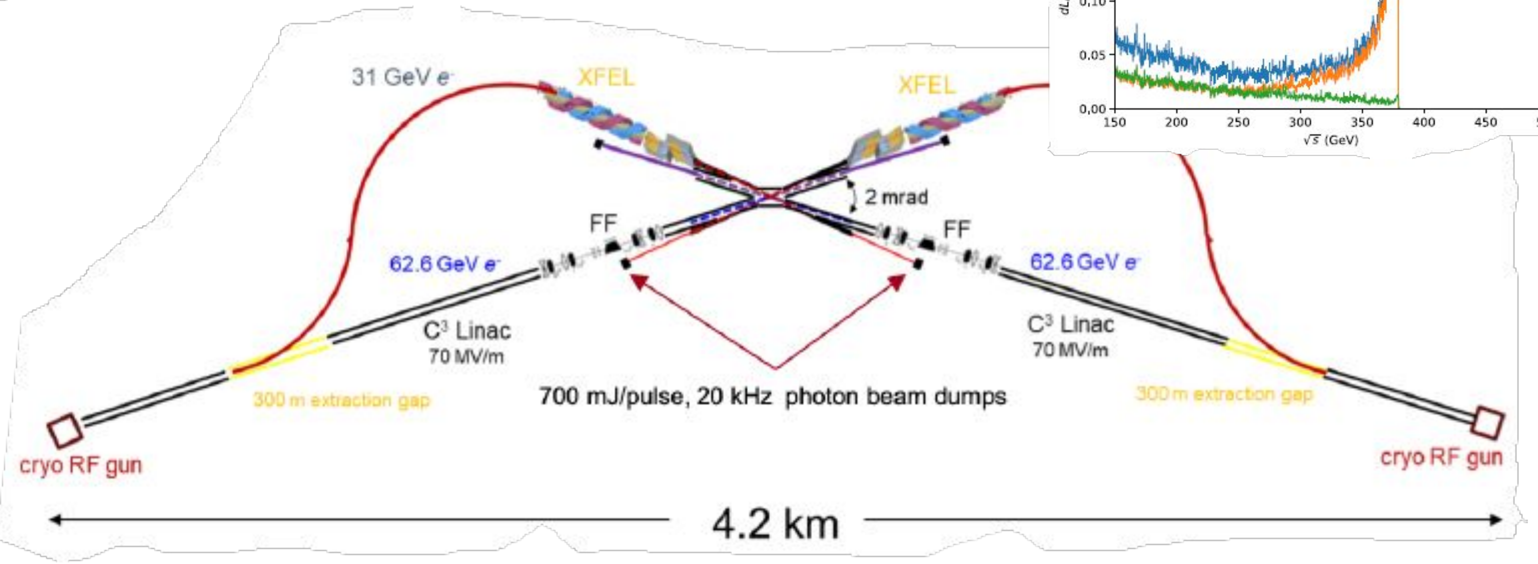
ERL: Energy Recovery Linac

- Reuse beam particles and energy
- Increases Luminosity by x50!
- needs limited BST



Photon Collider

- high intensity laser on beam
- possibility of XFEL
- Spin-0 Luminosity peak
- γγ→HH (different behaviour)



Beam Dump

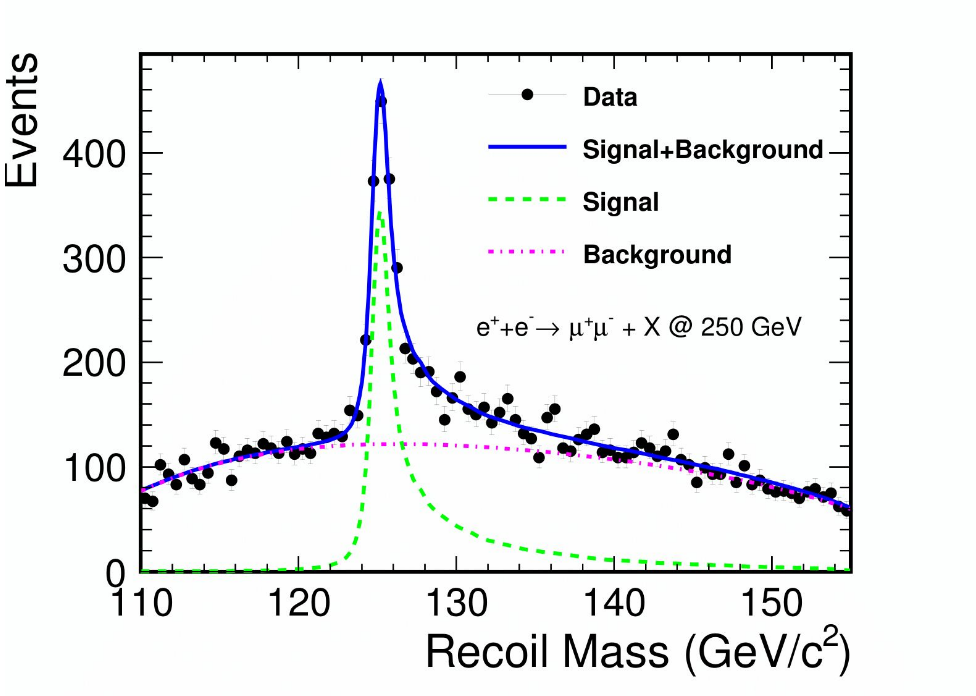
- before IP (concentrated beam):
  - super-LUXE SFQED
- after IP (divergent, E spectrum) 10^15 EOT:
  - dark photons, ALP, super-SHIP

Physics: Higgs

Central messages:

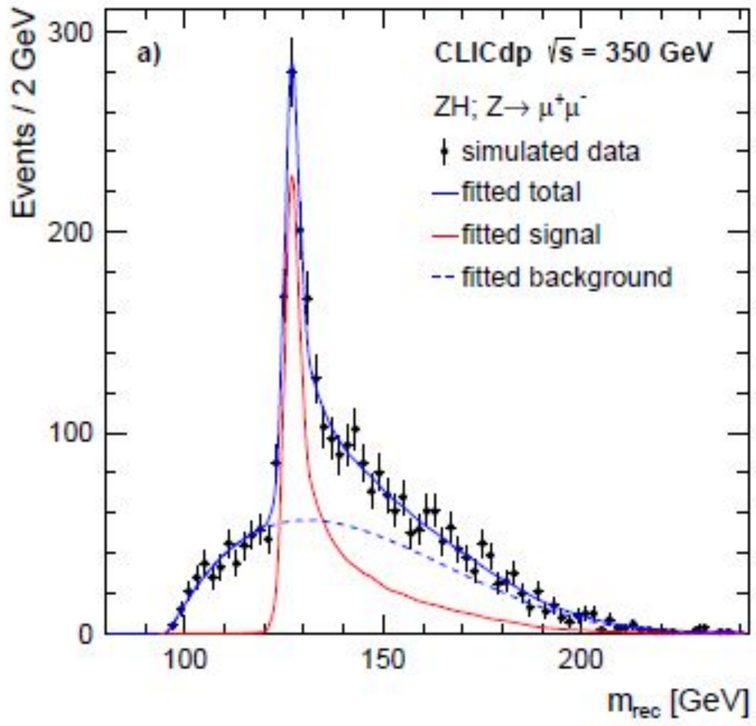
- **Luminosity != Luminosity (polarisation)**
- **√s is √s**
    - **to first order: ISR**
    - **Beamstrahlung (part of simulation for more than 10 years)**

Accelerator	LCF	CLIC	CLIC	CLIC	CLIC
$\sqrt{s}$	250 GeV	350 GeV	350 GeV	1.4 TeV	3 TeV
$\mathscr{L}$	2.7ab^{-1}	2.2ab^{-1}	4.3ab^{-1}	4ab^{-1}	5ab^{-1}
Δm_H	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]
HZ Recoil	12	52	38		
$\nu_e\bar{\nu}_e H \to \nu_e\bar{\nu}_e b\bar{b}$				29	28



The Higgs:

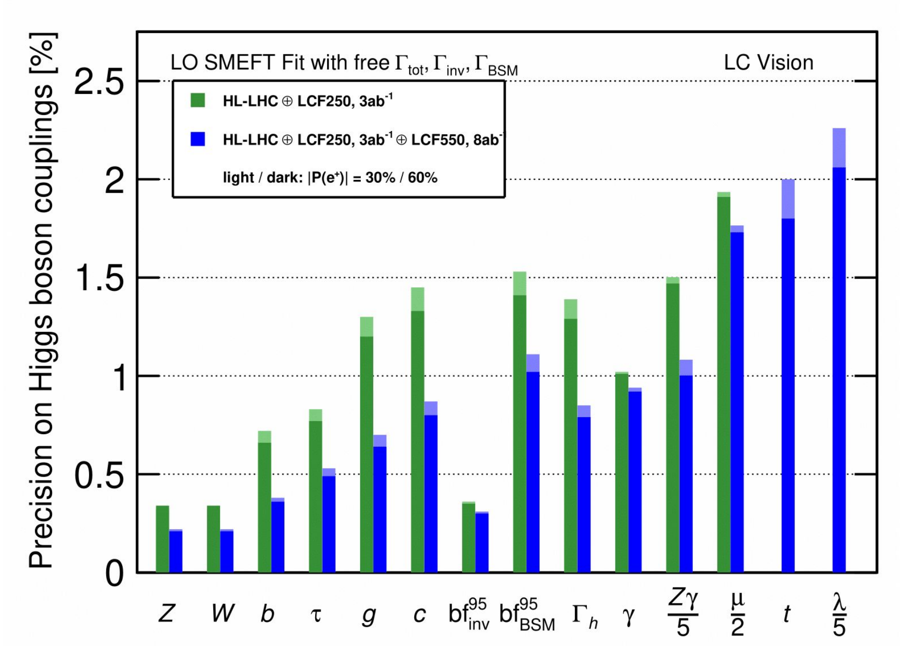
- **ZH recoil mass measurement**
- **total cross section yields absolute coupling**
- **can be done “at threshold” and at 380 GeV (courtesy of incoming CERN DG)**



Physics: Higgs

Higgs couplings:

- improvement over the excellent results from the HL-LHC
- fuller picture of the Higgs
- W fusion for width determination
- percent and better precision
- polarization provides different information
- Exciting prospects for BSM (EFT or your preferred physics model)

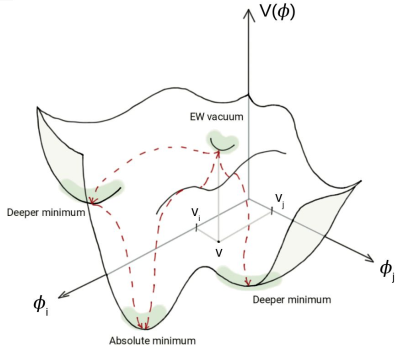


Collider $\sqrt{s}$ $\mathscr{L}$	LCF 250 GeV 2.7ab^{-1} [%]	LCF 350 GeV 0.135ab^{-1} [%]	CLIC 350 GeV 2.2ab^{-1} [%]	CLIC 350 GeV 4.3ab^{-1} [%]	LCF 500 6.4ab^{-1} [%]	LCF 1 TeV 6.4ab^{-1} [%]	CLIC 1.4 TeV 4ab^{-1} [%]	CLIC 3 TeV 5ab^{-1}
σ_{HZ}	0.62	2.5	0.79	0.56	0.8		2.0	4.3
$\sigma_{HZ}\cdot BR_{b\bar{b}}$	0.41	2.1	0.41	0.29	0.5			
$\sigma_{HZ}\cdot BR_{c\bar{c}}$	2.5	15	7	5	3.6			
$\sigma_{HZ}\cdot BR_{gg}$	2.1	11.4	2.9	2.1	3.0			
$\sigma_{HZ}\cdot BR_{\tau\tau}$	0.98	5.5	3.0	2.1	1.2			
$\sigma_{HZ}\cdot BR_{ZZ}$	5.5	34			6.9			
$\sigma_{HZ}\cdot BR_{WW}$	1.4	7.6	2.4	1.7	1.6			
$\sigma_{HZ}\cdot BR_{\gamma\gamma}$	10				10			
$\sigma_{HZ}\cdot BR_{inv}$	0.19	1.2	0.3	0.2	0.42			
$\sigma_{\nu_e\bar{\nu}_e H}\cdot BR_{b\bar{b}}$	2.5	2.5	0.9	0.6	0.30	0.30	0.2	0.2
$\sigma_{\nu_e\bar{\nu}_e H}\cdot BR_{c\bar{c}}$		26	12	9	2.5	1.6	3.7	4.4
$\sigma_{\nu_e\bar{\nu}_e H}\cdot BR_{gg}$		11	4.8	3.4	1.6	1.3	3.6	2.7
$\sigma_{\nu_e\bar{\nu}_e H}\cdot BR_{\tau\tau}$		22			2.8	1.5	2.6	2.8
$\sigma_{\nu_e\bar{\nu}_e H}\cdot BR_{\mu\mu}$					28	16	23	16
$\sigma_{\nu_e\bar{\nu}_e H}\cdot BR_{ZZ}$		27			3.4	2.2	3.4	2.5
$\sigma_{\nu_e\bar{\nu}_e H}\cdot BR_{WW}$		7.8			0.96	0.88	0.6	0.4
$\sigma_{\nu_e\bar{\nu}_e H}\cdot BR_{\gamma\gamma}$					7.6	4.6	9	6
$\sigma_{e^+e^-H}\cdot BR_{b\bar{b}}$							1.1	1.5

Physics: Higgs Self-coupling

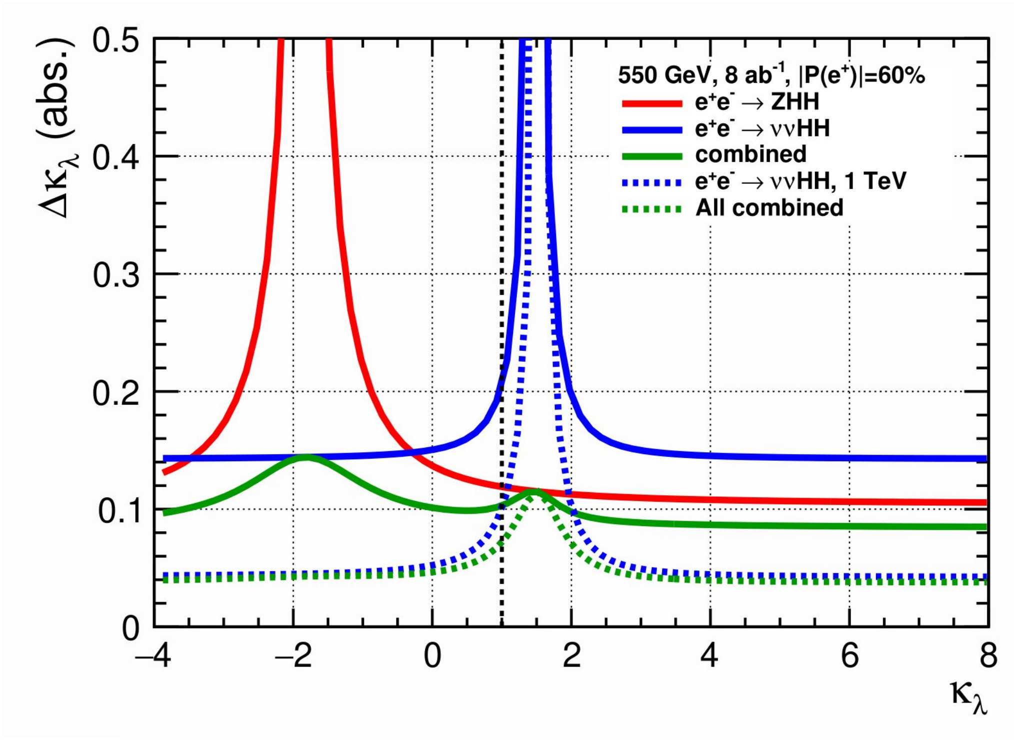
The Higgs potential:

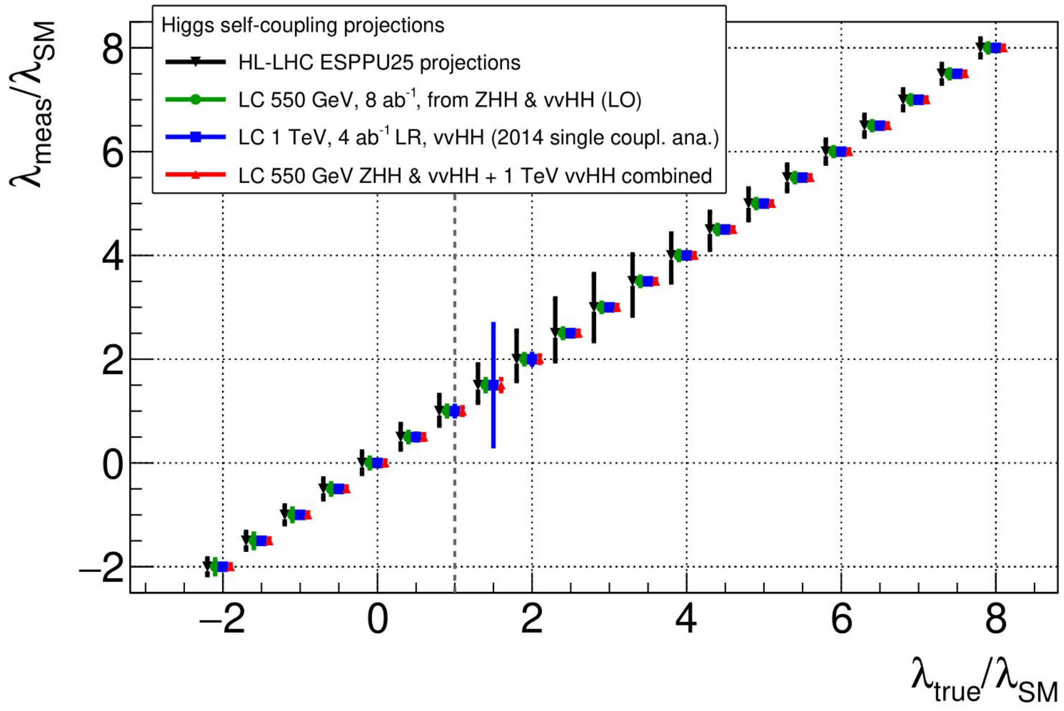
- **Is it Standard?**



How to get a complete picture:

- **precision measurements single Higgs (quantum corrections)**
- **direct measurement HH production (needs √s ZHH fusionHH)**





Standard or not:

- **sensitivity depends on the production mechanism**
- **complementarity of proton and electron machines**

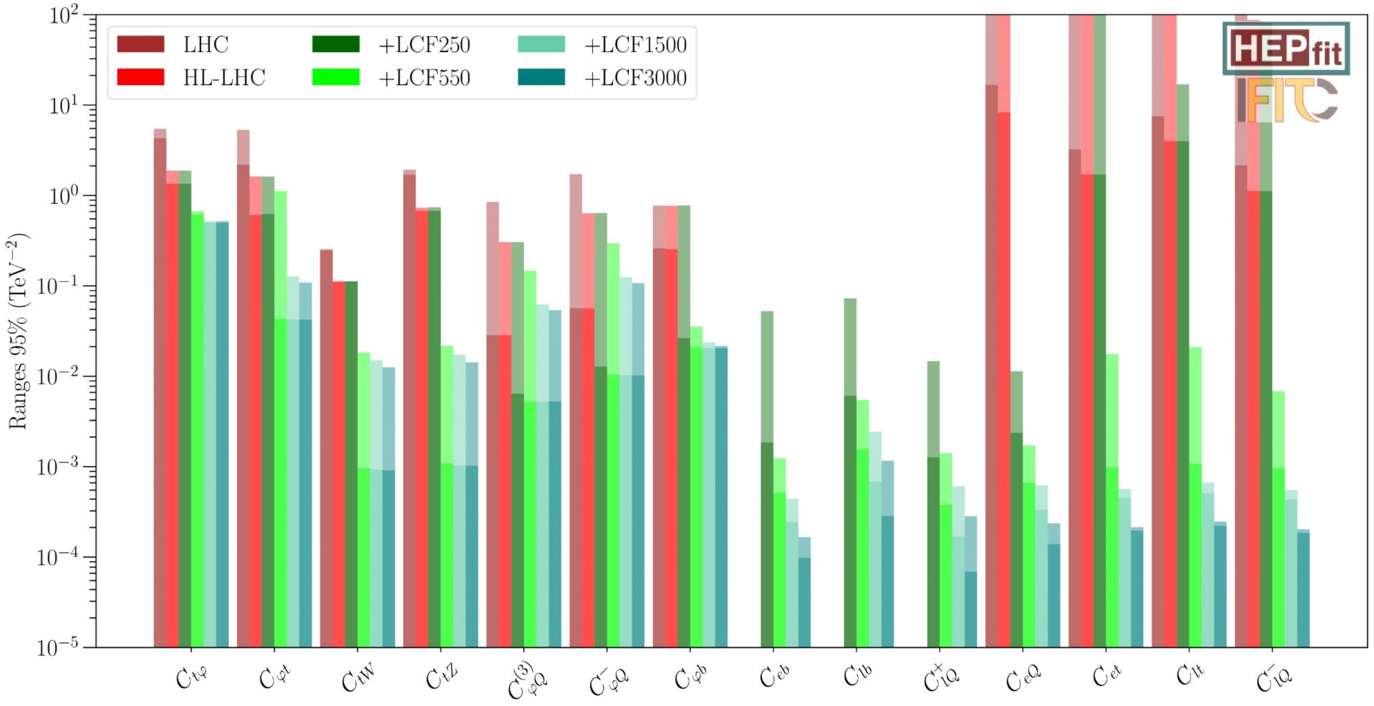
Physics: Top

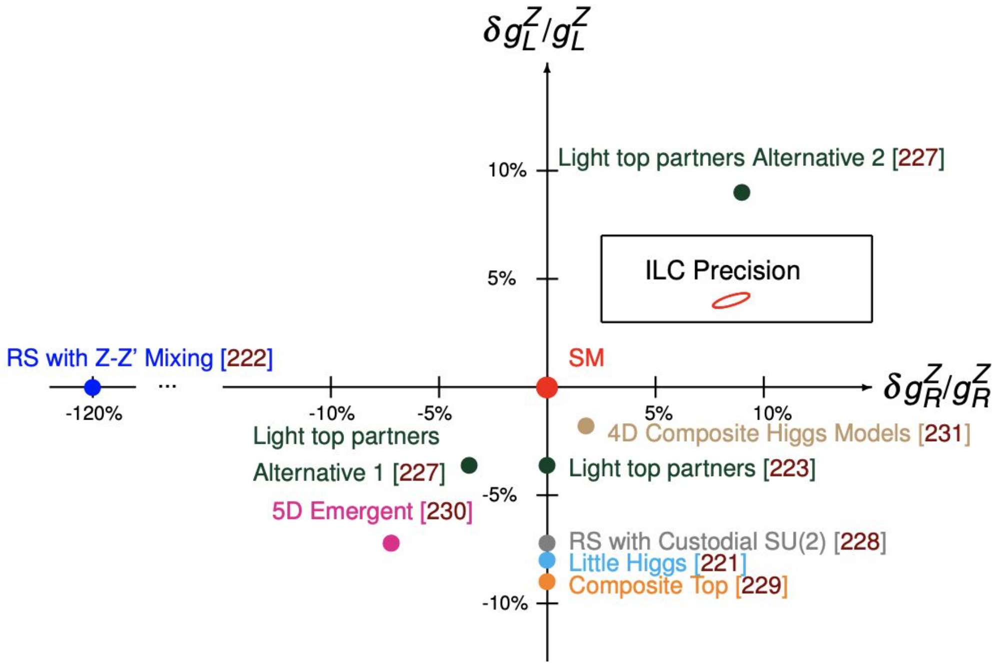
Top quark measurements:

- Mass measurement (threshold or above)
- detailed measurement of couplings

EFT fit:

- improvement on HL-LHC expectations
- further couplings probed





Couplings:

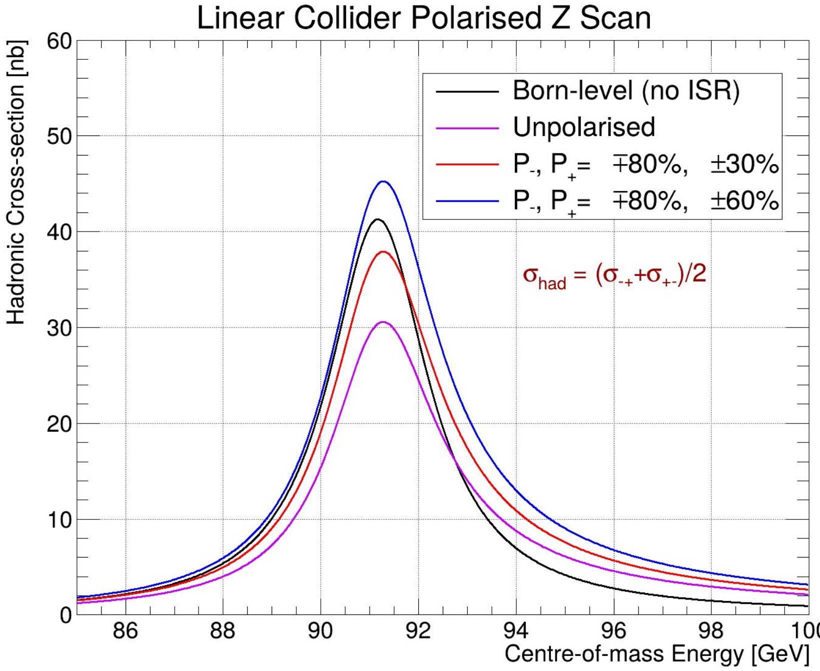
- precise couplings could point to concrete physics models

Physics: Electroweak

Measuring Electroweak Properties:

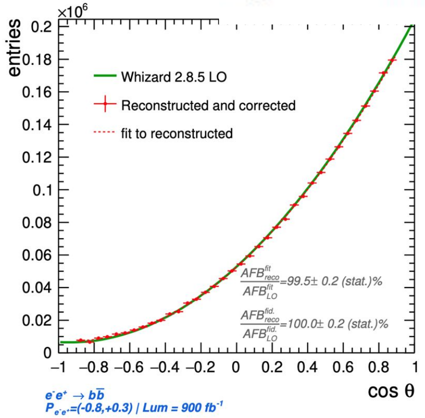
- **Z pole: Giga Z production**
- **Polarization $\sin^2\vartheta_W$ (SLC/LEP)**

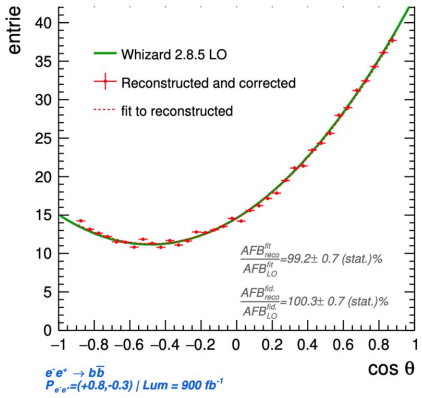
Quantity	SM Value	Current Precision $\delta[10^{-4}]$	Snowmass $\delta_{stat.}[10^{-4}]$	Snowmass $\delta_{sys.}[10^{-4}]$	Prospect ESPPU 2026 $\delta_{stat.}[10^{-4}]$	Prospect ESPPU 2026 $\delta_{sys.}[10^{-4}]$
M_W[GeV]	80.379	1.5			0.08	0.2
M_W[GeV]†						0.09
M_Z[GeV]	91.1876	0.23	0.006	0.022	(0.002)‡	0.022
Γ_Z[GeV]	2.4952	9.4	0.2	0.5	(0.07)‡	0.5
$1/R_e$	0.0482	24.	2.	5.	0.9	0.9
A_e	0.1513	139.	1.5	1.2	1.5(0.8)‡	1.2
$1/R_\mu$	0.0482	16.	2.	2.	0.9	0.9
$1/R_\tau$	0.0482	22.	2.	2.	0.9	0.9
A_μ	0.1515	991.	2.	5.	7.	2.7 (1.3)*
A_τ	0.1515	271.	2.	5.	8.	2.7 (1.3)*
R_b	0.2163	31.	0.4	7.	0.7	0.6
A_b	0.935	214.	1.	5.	0.9	2.7 (1.3)*
R_c	0.1721	174.	2.	30.	1.4	2.5
A_c	0.668	404.	3.	5.	4.	2.7(1.3)*
R_s	$\approx R_b$	N.A.			1.6	0.3
A_s	0.895	1011.			6.	2.7(1.3)*

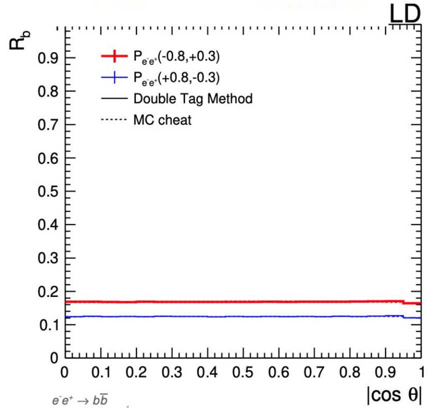


Studying bbar pairs:

- **A_{FB}**
- **Polarization leads to different sensitivities (full simulation)**



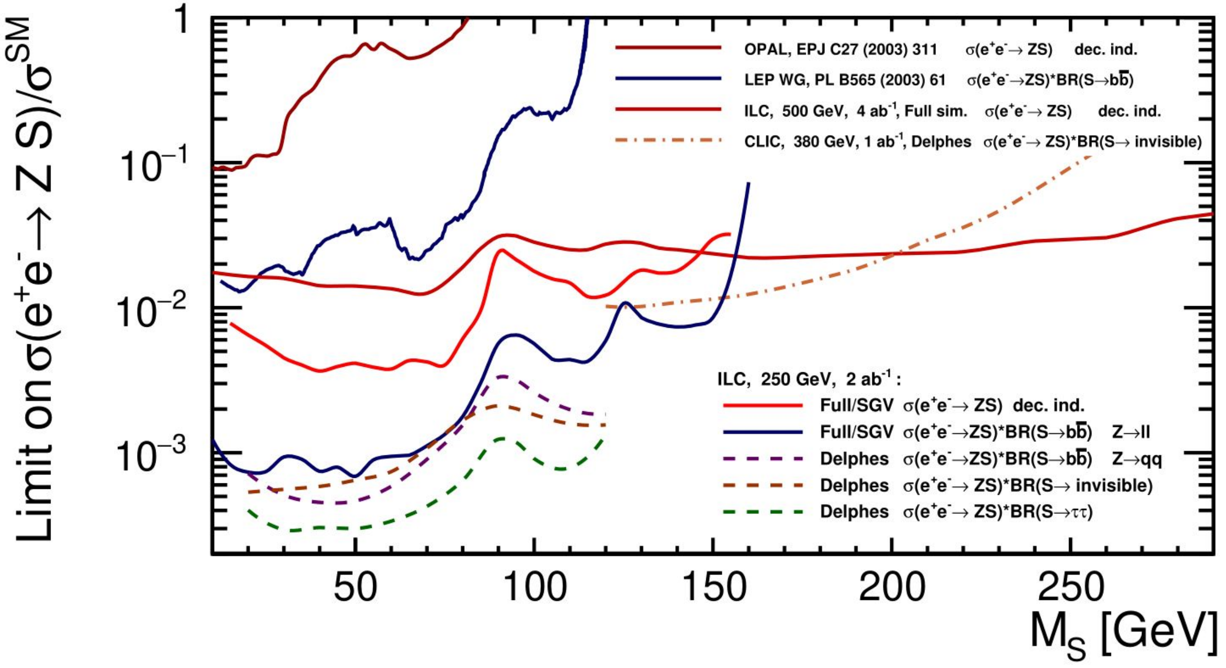


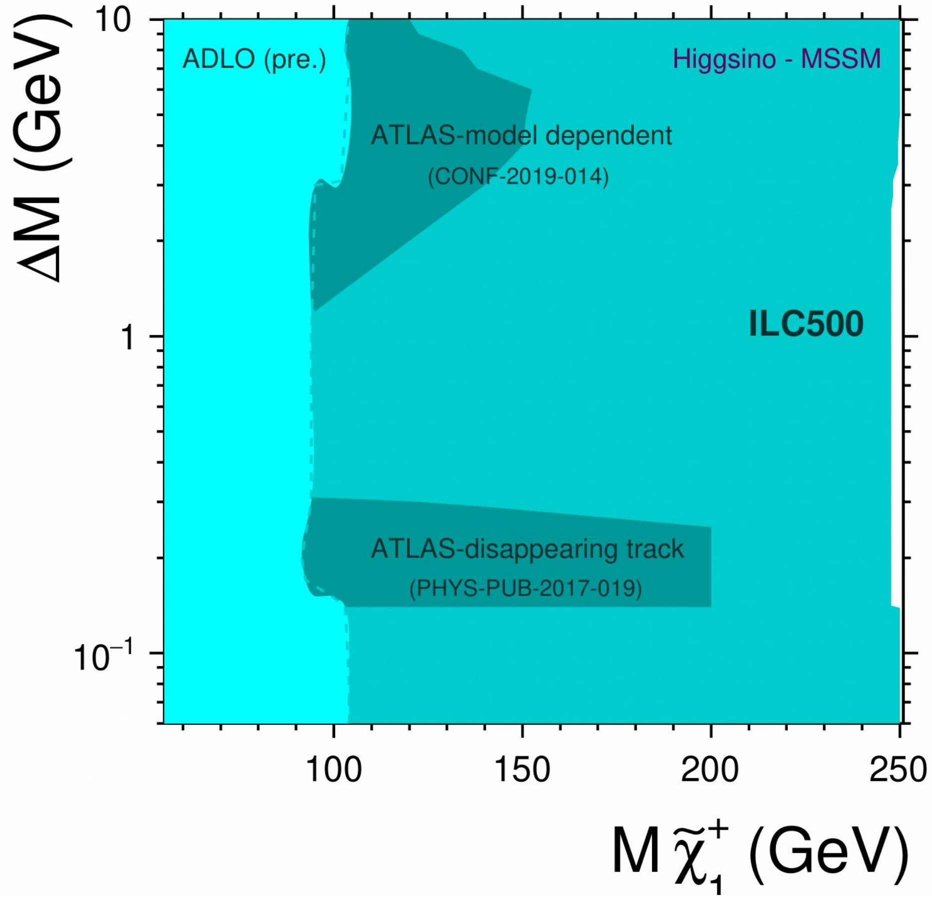


Physics: New Physics in real models (kind of)

Do not give up hope:

- Search for exotic scalars recoiling against the Z
- Many channels
- improve on the coupling strength limits

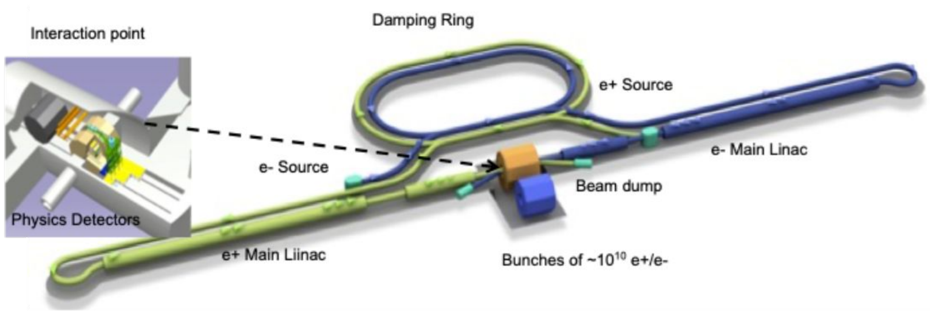


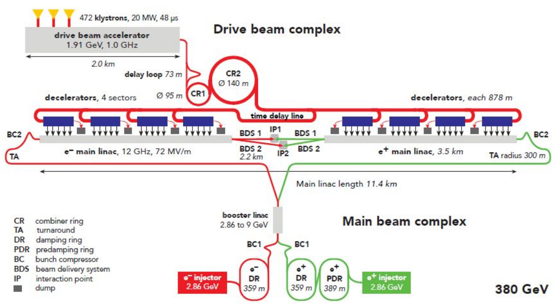


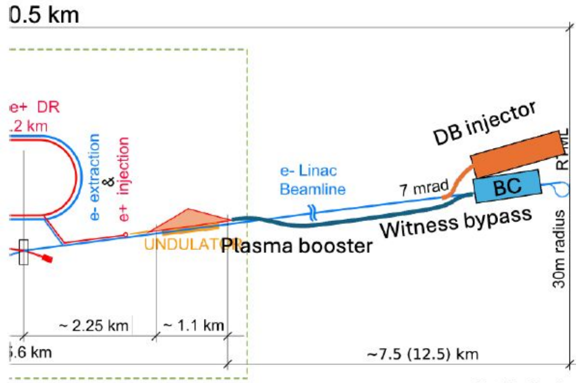
Direct searches: supersymmetry (or course)

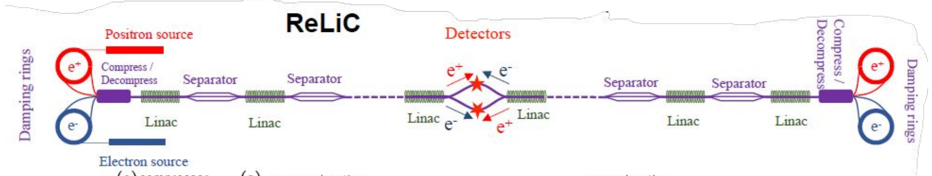
- motivated by DM
- difficult regions can be excluded extending LEP and LHC limits

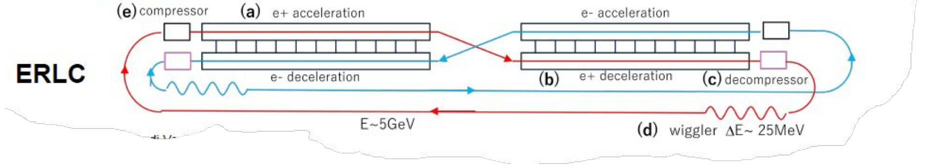
Summary/Outlook

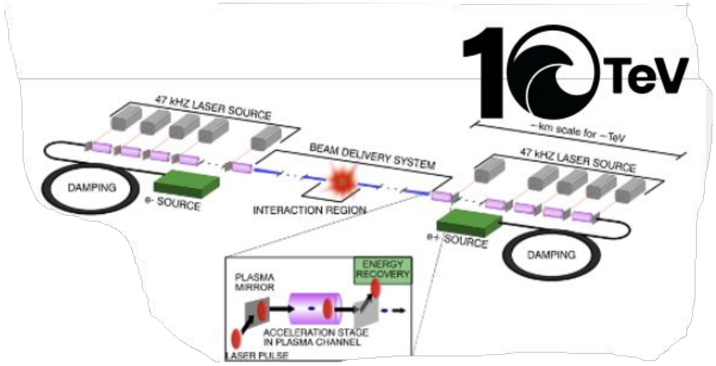


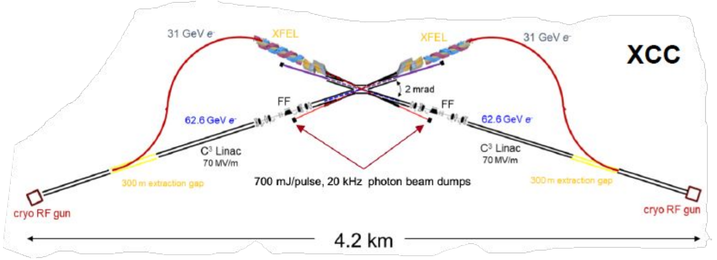












Summary:

- **A linear collider is an attractive option for a Higgs Factory and beyond:**
  - **Copious production of Higgs bosons**
  - **access to polarized beams**
  - **flexibility and exciting energy and luminosity upgrade perspectives**

Outlook:

- The CERN Council Decision on the next flagship project