Sustainability Strategy for the Cool Copper Collider

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Outline

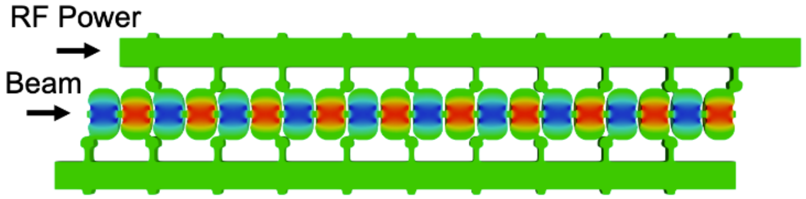
- **Introduction**
    - *The Cool Copper Collider (C^3)*
- **Comparison of carbon footprint for proposed colliders**
    - *Sensitivity comparison*
    - *Carbon footprint of operations*
    - *Carbon footprint of construction*
    - *Final comparison*
- **Conclusions**
- **Backup**

Results presented here mainly from PRX Energy 2, 047001 *"Sustainability Strategy for the Cool Copper Collider"*.
Additional info from: JINST 18 P07053, JINST 18 P09040 and PRAB 27, 061001.

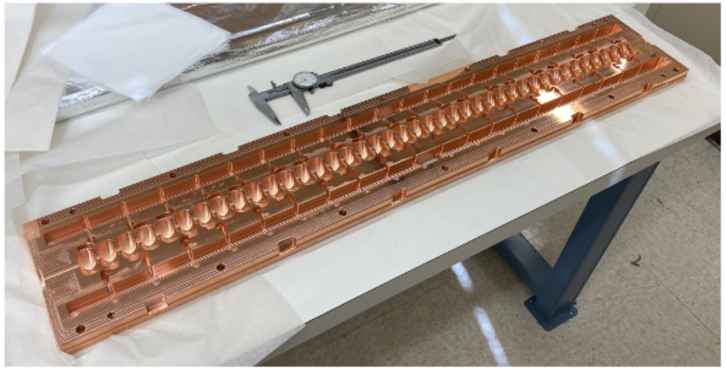
Introduction

The Cool Copper Collider

- Cool Copper Collider (C^3) : newest proposal for a linear e^+e^- collider relying on normal conducting copper accelerating technology, with a novel cavity design that utilizes distributed coupling.
- cryogenic temperature operation (LN2 at 77K), lower surface fields and higher accelerating gradients → ***cost-effective, compact 8 km footprint.***



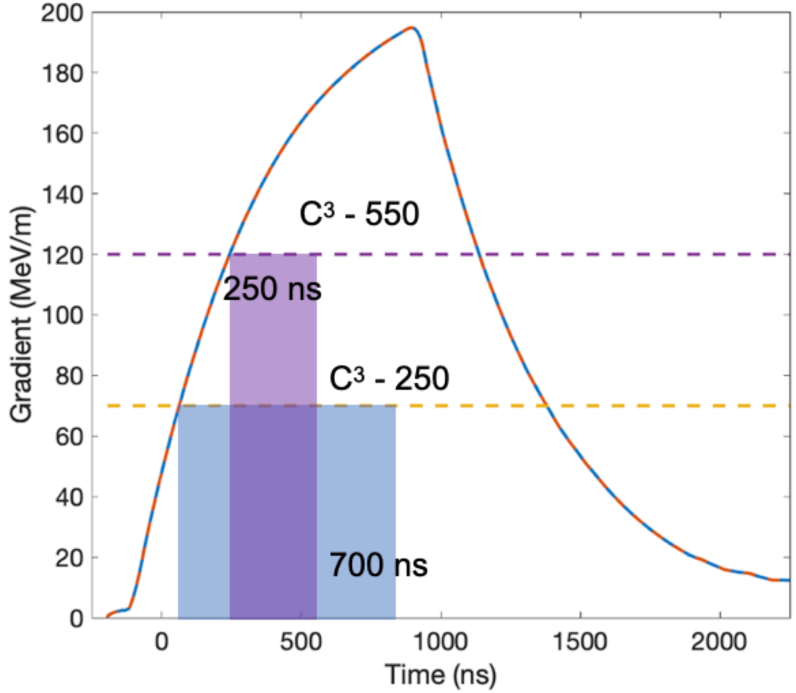
Electric field magnitude for equal power from RF manifold



Innovations

- Optimized design of RF cavities to minimize breakdown.
- Small aperture, distributed coupling from a common RF manifold → possible with precision CNC

70 MeV/m @250 GeV
120 MeV/m @550 GeV

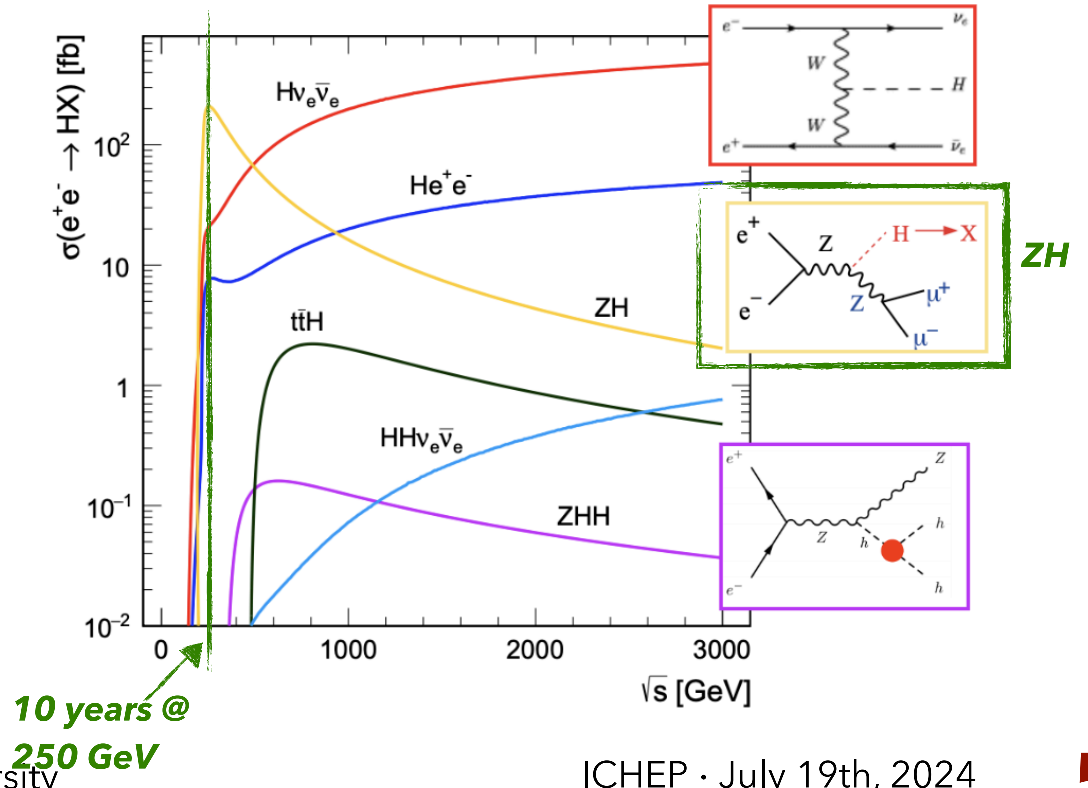


The Cool Copper Collider - *Physics*

- C^3 targeted at operations at 250 GeV (ZH mode) and 550 GeV (ZHH mode - only possible for linear colliders).
- The targeted inst. luminosity of $1.3(2.4)\times10^{34}$ cm^{-2} s^{-1} at 250 (550) GeV would allow 2 (4) ab^{-1} of statistics after ***10 years at each energy***.
- It's important to ***evaluate and optimize emissions due to construction and operation for the entire run time of the collider.***

Parameter	Value	
$\sqrt{s}$ (GeV)	250	550
Luminosity (cm^{-2} sec^{-1})	1.3×10^{34}	2.4×10^{34}
Number of bunches per train	133–200	75
Train repetition rate (Hz)	120	120
Bunch spacing (ns)	5.3–3.5[a]	3.5
Site power (MW)	150	175
Beam power (MW)	2.1	2.45
Gradient (MeV/m)	70	120
Geometric gradient (MeV/m)	63	108
rf pulse length (ns)	700	250
Shunt impedance (MΩ/m)	300	300
Length (km)	8	8

Target beam parameters for C^3.



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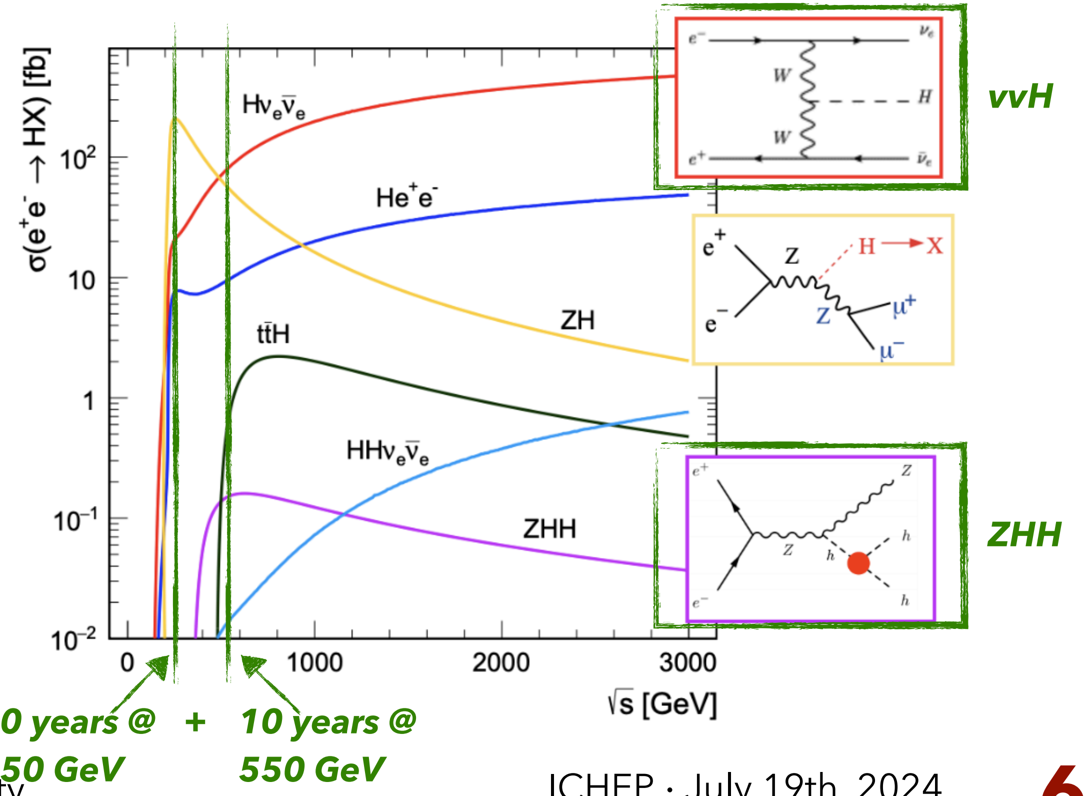


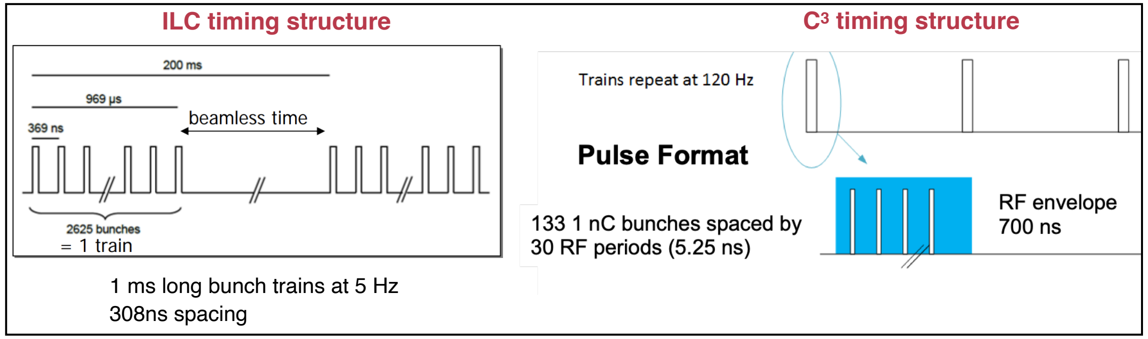
The Cool Copper Collider - *Power Optimizations*

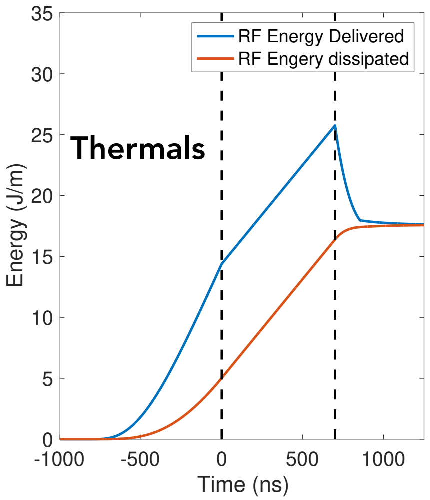
PRX Energy 2, 047001

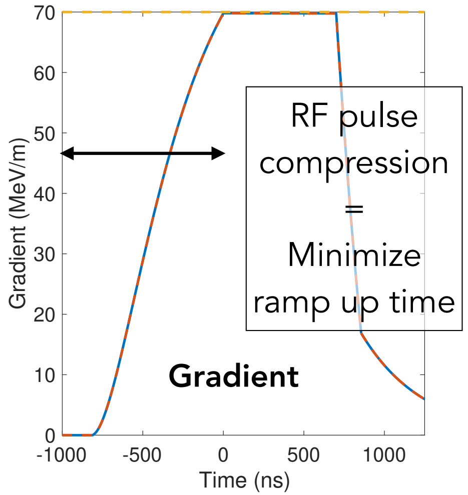
- Potential improvements for C³ coming from minimizing RF power when there is no beam loading.

Scenario	rf system (MW)	Cryogenic system (MW)	Total (MW)	Reduction (MW)
Baseline 250 GeV	40	60	100	...
rf source efficiency increased by 15%	31	60	91	9
rf pulse compression	28	42	70	30
Double flat top	30	45	75	25
Halve bunch spacing	34	45	79	21
All scenarios combined	13	24	37	63

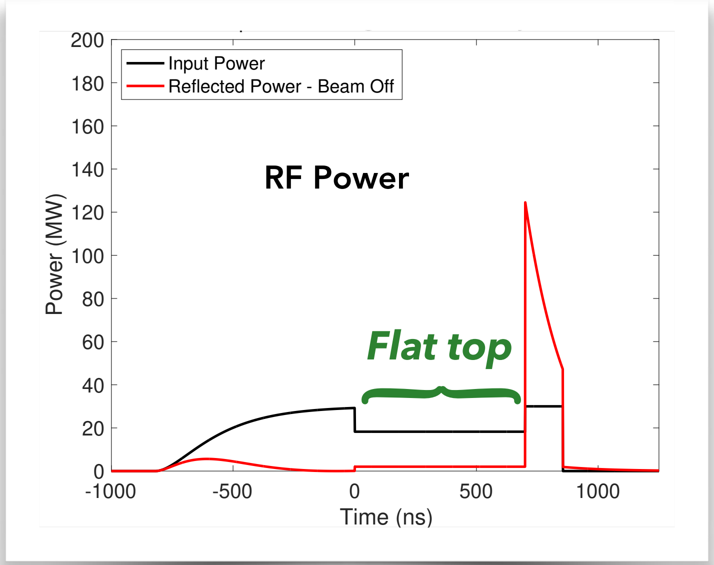
Power savings with adjustment of the main linac design and beam parameters. For 550 GeV, the percentage savings would be unchanged for a combined 79 MW reduction.







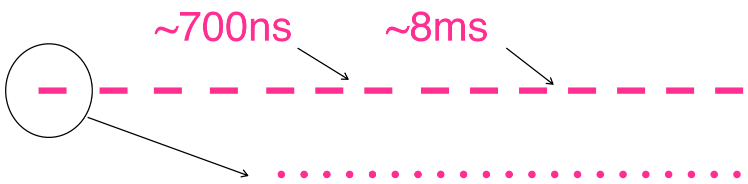
- Doubling the flat-top (700→ 1400 ns) or halving the bunch spacing (5.25→2.6ns) allows for **rep. rate reduction** (120→ 60 Hz) without loss in luminosity.
- This **reduces thermal load** by **25%**.
- Overall, power savings can reach **63MW** at 250 GeV and **79MW** at 550GeV.



The Cool Copper Collider - *Power Optimizations*

- Changes in flat-top duration, bunch spacing and rep. rate can be combined to improve the luminosity per unit power up to **3x**!
- The energy consumption throughout the entire lifetime of the machine can be reduced significantly!

Requires additional studies to evaluate feasibility on the accelerator (high-gradient tests with double flat top) and detector (evaluation of occupancy tolerances) side!



Luminosity for two beam parameter sets   Total site power consumption

					$\mathcal{L}$ (10^{34} cm^{-2} s^{-1})		P_{site} (MW)
Scenario	Flat top (ns)	Δt_b (ns)	n_b	f_r (Hz)	C^3-250 (PS1)	C^3-250 (PS2)	Both scenarios
Baseline	700	5.26	133	120	1.35	1.90	150
Double flat top	1400	5.26	266	60	1.35	1.90	125
Halve bunch spacing	700	2.63	266	60	1.35	1.90	129
Combined-half repetition rate	1400	2.63	532	60	2.70	3.80	154
Combined-nominal repetition rate	1400	2.63	532	120	5.40	7.60	180

$\mathcal{L}/P_{site}$ (10^{34} cm^{-2} s^{-1} (GW)$^{-1}$)

PS1	PS2
9.0	12.7
10.8.	15.2
10.5	14.7
17.5	24.7
30.0	42.2

Up to ~3x $\mathcal{L}/P_{site}$ gain!

Beam configuration scenarios for C^3, which include modifications in the bunch spacing Δt_b, the number of bunches per train n_b, and/or the train repetition rate f_r.

Comparative Analysis

Sensitivity comparison for future colliders

arXiv:2209.07510

- Take into account total luminosity and effect of longitudinal polarization:
  - C3/ILC-250 performs similarly to CLIC-380, C3/ILC-550 outperforms CLIC-380
  - C3/ILC-250 + 550 matches expected physics reach of FCC-ee

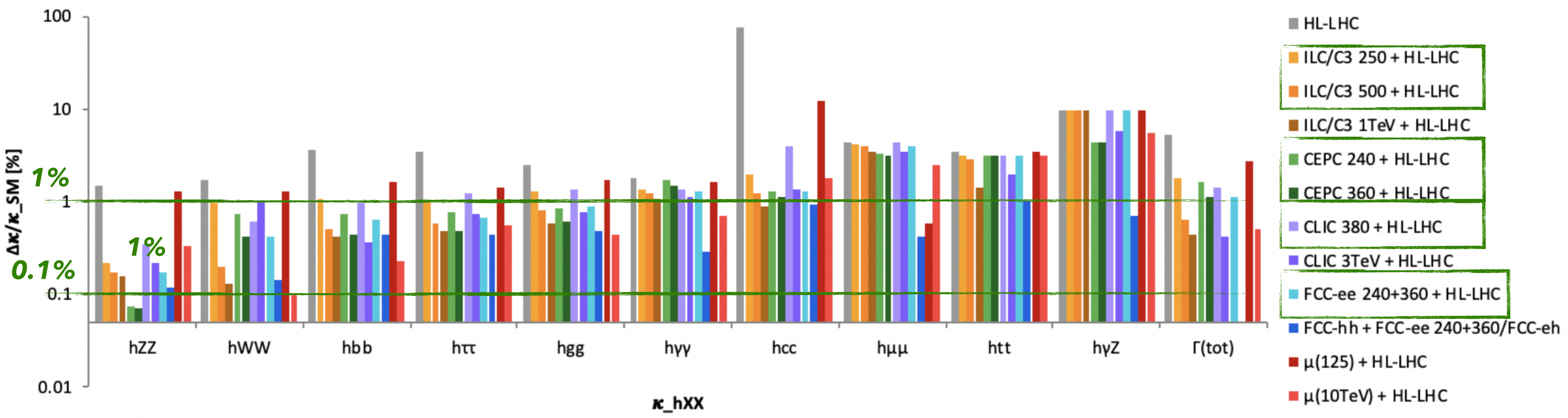
*Evaluate **average precision gain** w.r.t. HL-LHC:*

$$w = \frac{\left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC}} - \left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC+HF}}}{\left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC+HF}}}.$$

$$\left\langle \frac{\delta\kappa}{\kappa} \right\rangle = \frac{\sum_i w_i \left(\frac{\delta\kappa}{\kappa}\right)_i}{\sum_i w_i}$$

→weighs heavier most improved and most precise measurements, emphasizes individual colliders' strengths!

All colliders reach precisions for the Higgs couplings at the 0.1-1% level



Relative precision (%) of Higgs boson coupling and total Higgs boson width measurements at future colliders when combined with the HL-LHC measurements, assuming two IPs for FCC-ee and CEPC.

Power consumption over machine lifetime

PRX Energy 2, 047001

Calculate annual energy consumption for each collider accounting for down-time, efficiency and planned run schedule

Step 1: calculate energy consumption/year

$$E_{\text{annual}} = P\left[\kappa_{\text{down}}\,T_{\text{year}} + \left(1-\kappa_{\text{down}}\right)\left(T_{\text{collisions}} + T_{\text{development}}\right)\right]$$

- P: Power during collisions
- κ_{down}: Fraction of power used during down-time (taken 30%)
- $T_{\text{development}}$: Time in collision mode + 17% for machine development (1 per 6 weeks in collisions)

Step 2: sum up years running in each energy

$$E_{\text{total}} = \sum_{r\in\text{ runs}} E(r)_{\text{annual}}\,T_{\text{run}}(r)\,.$$

Linear: ~10-20 years, ~100-180 MW

Circular: ~15-20 years, ~220-360 MW

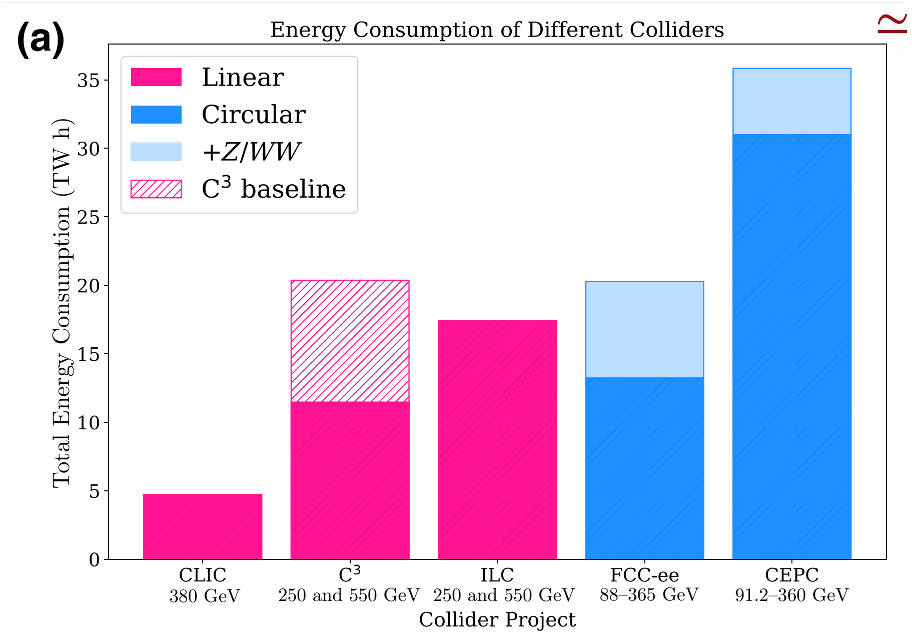
Higgs factory	CLIC [44]	ILC [12]		C^3 [11]		CEPC [59,60]				FCC [20,61,62]					
$\sqrt{s}$ (GeV)	380	250	500	250	550	91.2	160	240	360	88, 91, 94		157, 163	240	340–350	365
P (MW)	110	111	173	150 (87)	175 (96)	283	300	340	430	222		247	273	357	
$T_{\text{collisions}}$ [10^7 s/year]	1.20	1.60		1.60		1.30				1.08					
T_{run} (years)	8	11	9	10	10	2	1	10	5	2	2	2	3	1	4
$\mathcal{L}_{\text{inst}}$/IP ($\times 10^{34}$ cm^{-2} s^{-1})	2.3	1.35	1.8	1.3	2.4	191.7	26.6	8.3	0.83	115	230	28	8.5	0.95	1.55
$\mathcal{L}_{\text{int}}$ (ab^{-1})	1.5	2	4	2	4	100	6	20	1	50	100	10	5	0.2	1.5

[a]The nominal run schedule reflects nominal data-taking conditions, which ignore other run periods such as luminosity ramp-up.

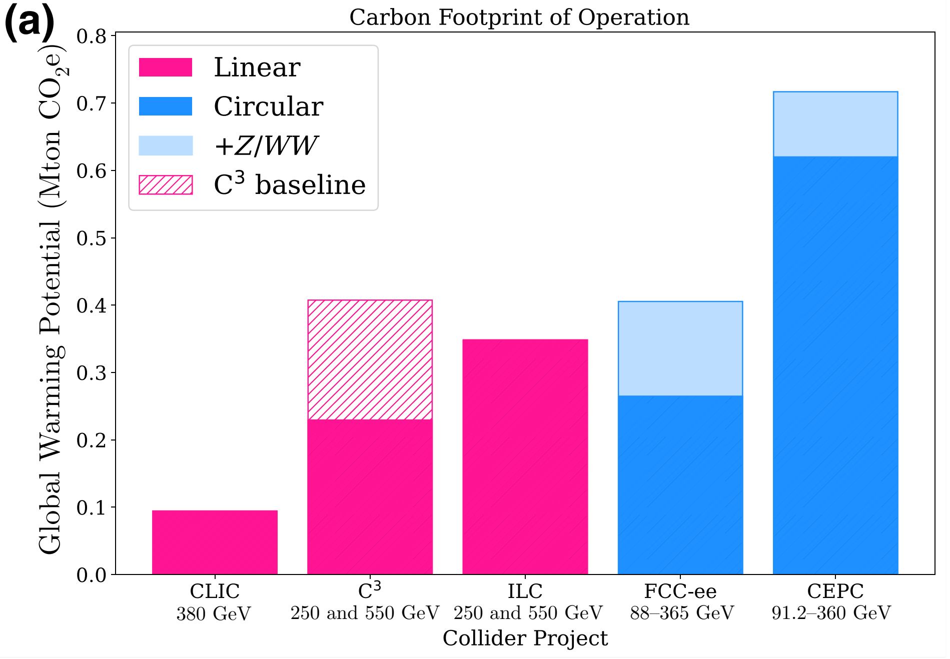
Running scenarios for Higgs factory projects.

Carbon Footprint of *operation*

$$\mathrm{GWP}_{\mathrm{operations}} = E_{\mathrm{total}} \cdot \text{carbon intensity}$$
$$\simeq E_{\mathrm{total}} \cdot (20 \text{ ton } CO_2e/\mathrm{GWh})$$



Total energy consumption in TWh for the entire run-time of each collider.

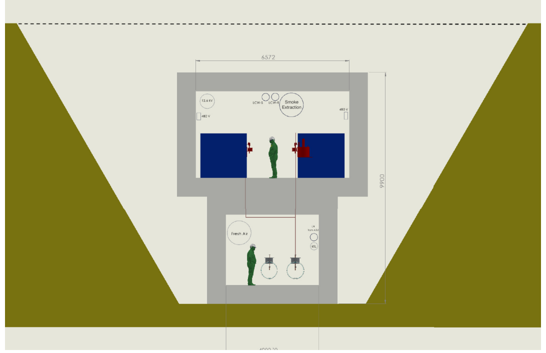


GWP in Mton CO2e for the entire run-time of each collider.

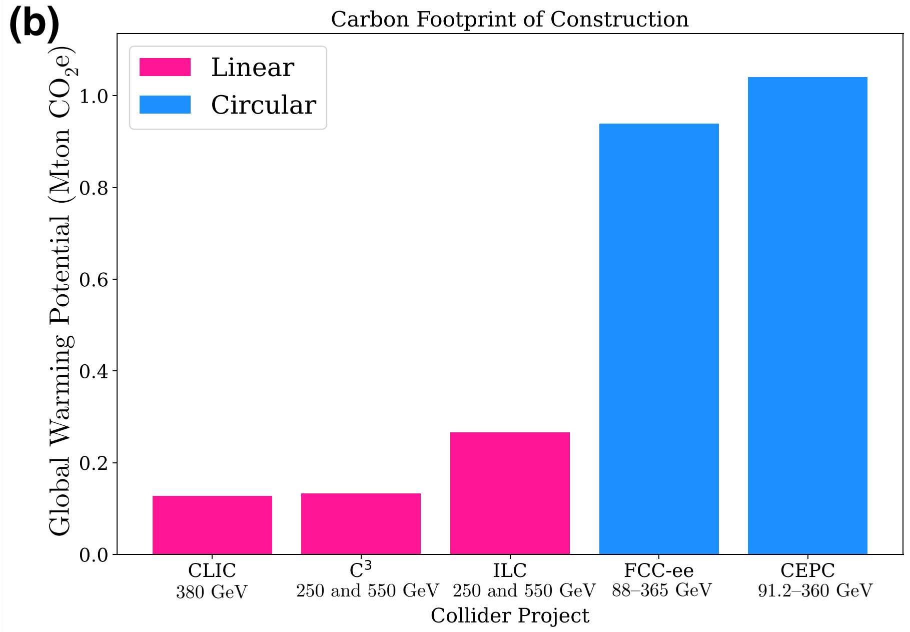
FCC and CEPC consumption driven by long run times and SR compensation, linear colliders having overall smaller energy consumption

Carbon Footprint of *construction*

- ARUP analysis: ~80% of construction emissions from materials (A1-A3), rest from material transport & construction process (A4-A5).
- GWP for tunnels **~6tn/m**
- For C^3, cut-and-cover can be used
  - Use displaced earth for shielding
  - Only ~40 km^3 must be transported



Accounting for main tunnel length, other structures and transport/construction process emissions



Project	Main tunnel length (km)	GWP (kton CO_2e)		
		Main tunnel	+ Other	+ A4-A5
FCC	90.6	578	751	939
CEPC	100	638	829	1040
ILC	13.3	97.6	227	270
CLIC	11.5	73.4	98	125
C^3	**8.0**	**133**		**146**

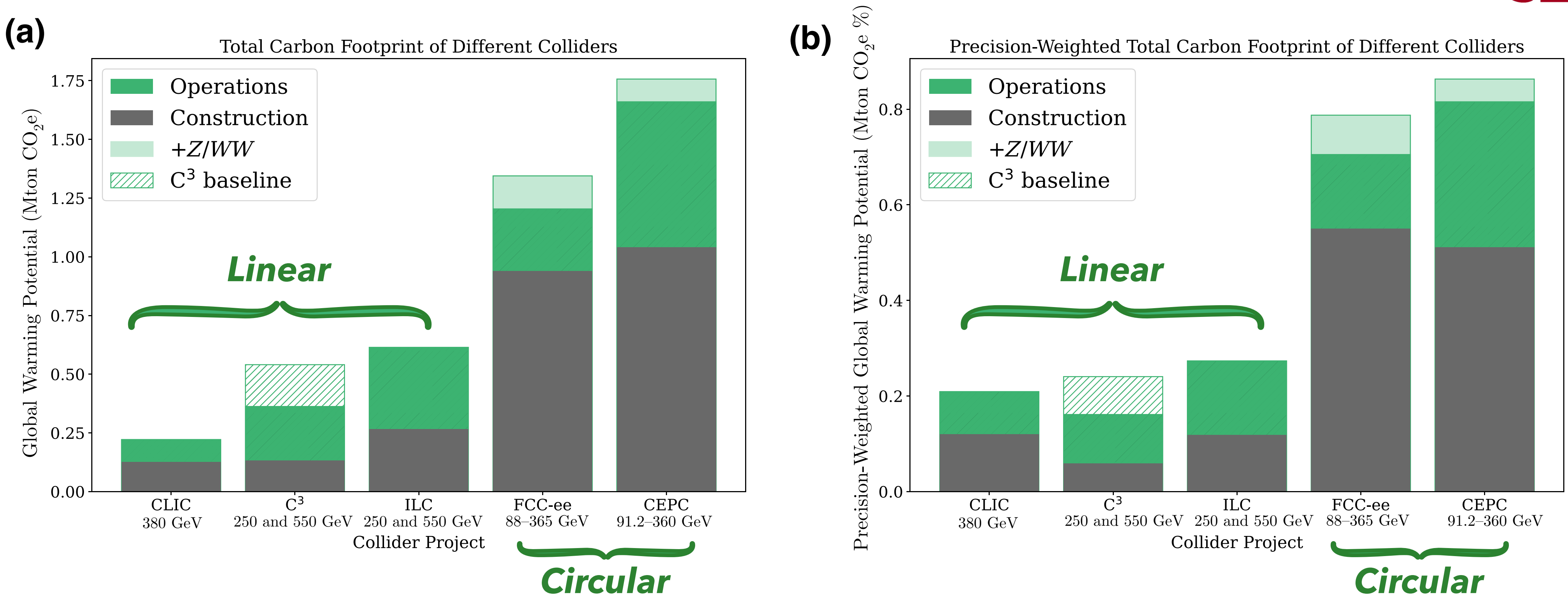
Global warming potential in Mton CO2e for various collider concepts.

High construction GWP for circular colliders driven by tunnel length

Carbon intensity for operation depends on hosting site and operation timeline

Total Carbon Footprint - *Comparison*

PRX Energy 2, 047001



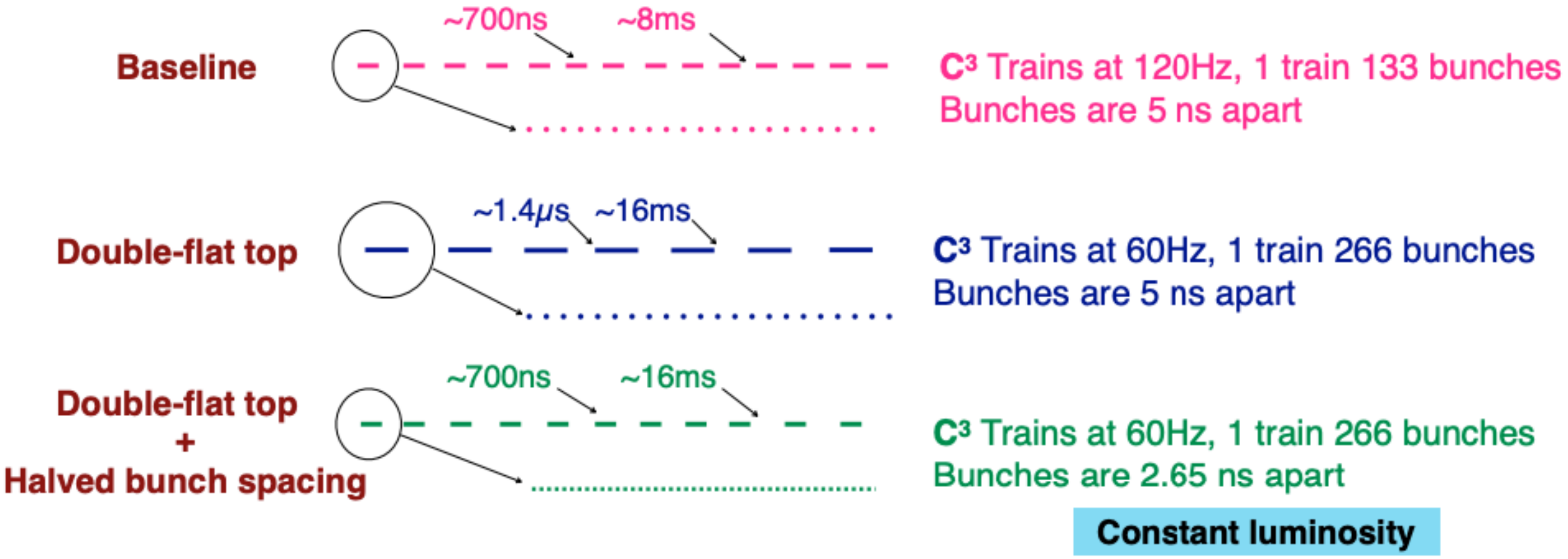
Total global warming potential from construction and operation for all collider concepts, (a) unweighted and (b) weighted with respect to the average coupling precision for each collider.

Accounting for physics impact, linear colliders are overall superior in terms of GWP.
Circular colliders limited by requirements for large-radius tunnels.
C^3's compact size can offer unique benefits for a sustainable collider.

Conclusions

Conclusions - *Sustainable parameter set for C^3*

- C^3 emerges as one of the most sustainable options for an e^+e^- Higgs factory.
- The halved-bunch spacing scenario was recently chosen as the sustainability-oriented parameter set and achieves the ***same luminosity*** with ~***30% less total site power consumption***.
- Implications of this parameter set on detector performance are currently under evaluation,



Scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125

Conclusions

- We presented an outline of the envisaged sustainability strategy for C^3 and proposed a framework for the physics-weighted evaluation of the carbon footprint of various colliders.
- Linear colliders have overall smaller carbon footprints, with circular collider limited by construction emissions due to the required large tunnel lengths.
- **C^3** with power savings can serve as a **cost-effective**, **compact** and **sustainable** option for the realization of a future e^+e^- collider.
- Regardless of which collider is built in the end, it is essential that sustainability considerations are integrated in its design and operations from its conception.

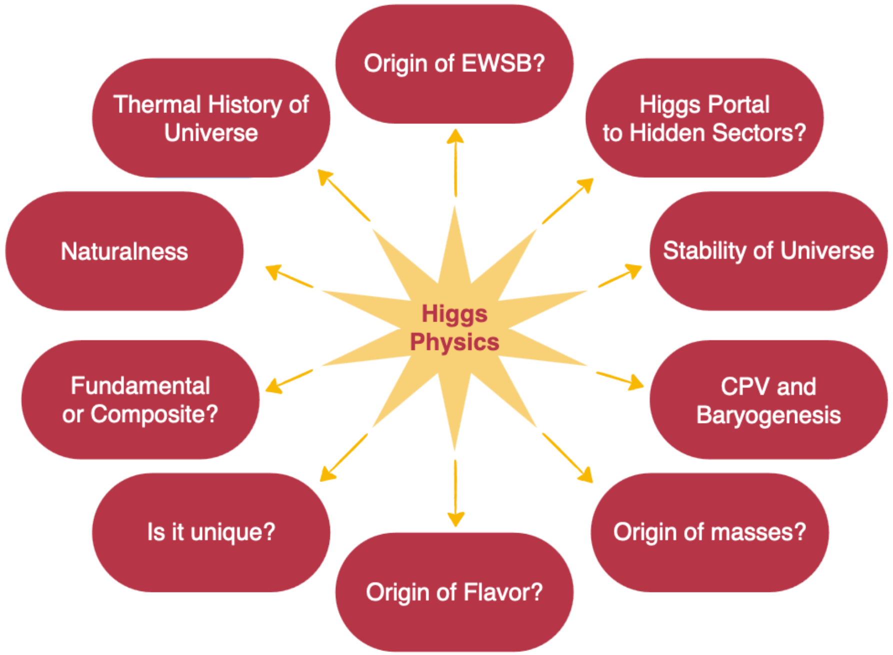
Thank you for your attention!

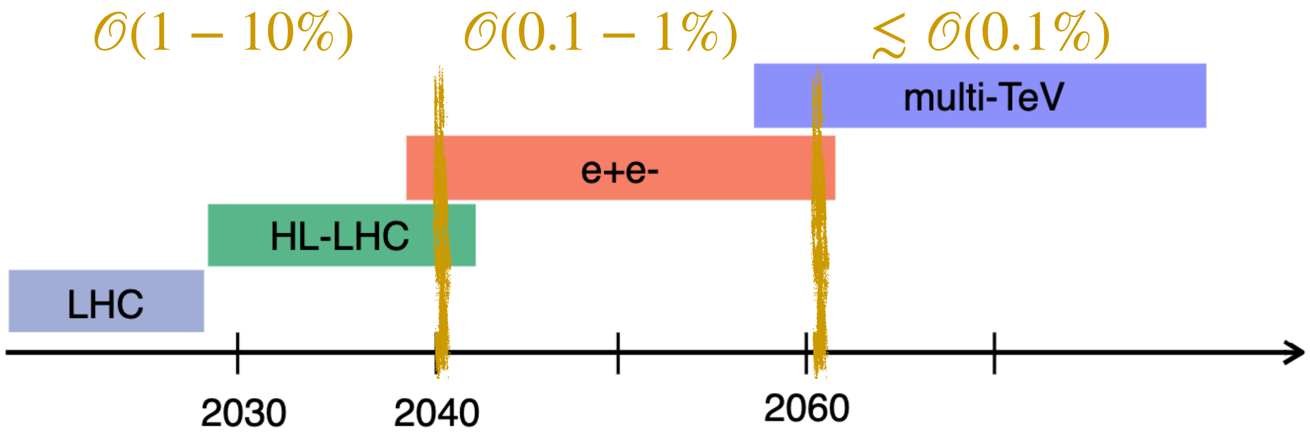
For more information on C^3, visit: **https://web.slac.stanford.edu/c3/**

Backup

Benefits of e^+e^- colliders

- The Higgs boson is the latest experimentally verified addition to the SM and a pathway to answering many fundamental questions in Particle Physics and beyond.
- This requires measurements of its properties with precision at the percent and sub percent level, which lies beyond the capabilities of HL-LHC.

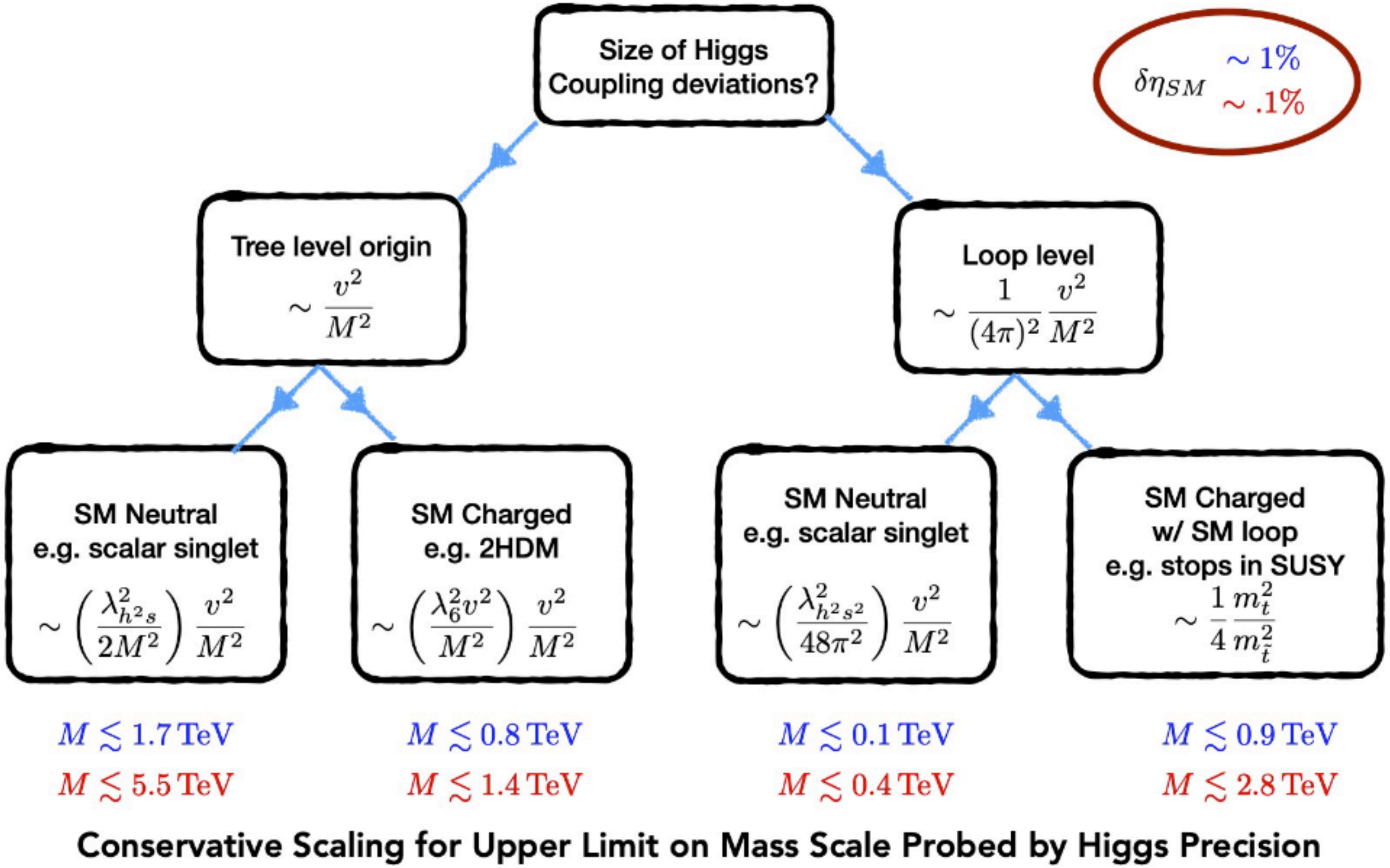




[Snowmass EF01 & EF02 Report](#)

Benefits of e^+e^- colliders

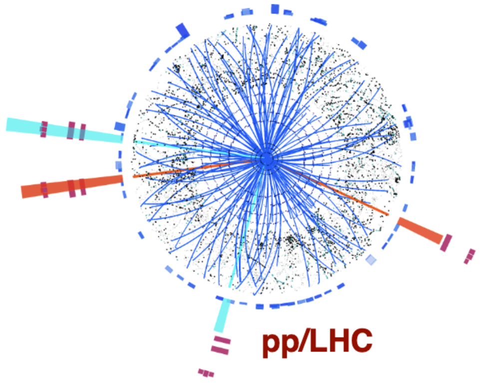
- Higgs precision measurements at the percent and sub-percent level enables tests of new Physics at the **TeV** scale.

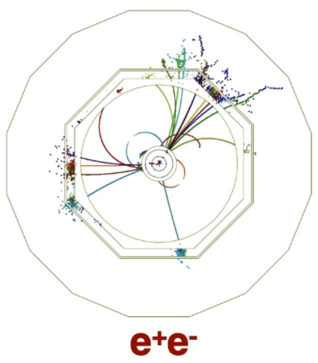


Snowmass EF01 & EF02 Report

Benefits of e^+e^- colliders

- Electron-positron colliders are precision machines that can serve as **Higgs factories**. They offer:
  - *A well-defined initial state*
  - *A "clean" and trigger less experimental environment*
  - *Longitudinal polarization (only possible at linear machines) → increases sensitivity to EW observables, suppresses backgrounds, controls systematics*





~ $\mathcal{O}(10^{-1})$ % *Level precision*

			HL-LHC +			
Relative Precision (%)	HL-LHC	CLIC-380	ILC-250/C^3-250	ILC-500/C^3-550	FCC 240/360	CEPC-240/360
hZZ	1.5	0.34	0.22	0.17	0.17	0.072
hWW	1.7	0.62	0.98	0.20	0.41	0.41
$hb\bar{b}$	3.7	0.98	1.06	0.50	0.64	0.44
$h\tau^+\tau^-$	3.4	1.26	1.03	0.58	0.66	0.49
hgg	2.5	1.36	1.32	0.82	0.89	0.61
$hc\bar{c}$	-	3.95	1.95	1.22	1.3	1.1
$h\gamma\gamma$	1.8	1.37	1.36	1.22	1.3	1.5
$h\gamma Z$	9.8	10.26	10.2	10.2	10	4.17
$h\mu^+\mu^-$	4.3	4.36	4.14	3.9	3.9	3.2
$ht\bar{t}$	3.4	3.14	3.12	2.82/1.41	3.1	3.1
hhh	50	50	49	20	33	-
Γ_{tot}	5.3	1.44	1.8	0.63	1.1	1.1

~ $\mathcal{O}(1)$ % *Level precision*

Sensitivity comparison for future colliders

- Take into account total luminosity and effect of longitudinal polarization:
  - C3/ILC-250 performs similarly to CLIC-380, C3/ILC-550 outperforms CLIC-380
  - C3/ILC-250 + 550 matches expected physics reach of FCC-ee

		HL-LHC +				
Relative precision (%)	HL-LHC	CLIC at 380 GeV	ILC at 250 GeV/C^3 at 250 GeV	ILC at 500 GeV/C^3 at 550 GeV	FCC at 240 GeV/360 GeV	CEPC at 240 GeV/360 GeV
hZZ	1.5	0.34	0.22	0.17	0.17	0.072
hWW	1.7	0.62	0.98	0.20	0.41	0.41
$hb\bar{b}$	3.7	0.98	1.06	0.50	0.64	0.44
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$h\gamma Z$	9.8	10.26	10.2	10.2	10	4.17
$h\mu^+\mu^-$	4.3	4.36	4.14	3.9	3.9	3.2
$ht\bar{t}$	3.4	3.14	3.12	2.82/1.41	3.1	3.1
hhh	50	50	49	20	33	...
Γ_{tot}	5.3	1.44	1.8	0.63	1.1	1.1
Weighted average	...	0.94	0.86	0.45	0.59	0.49

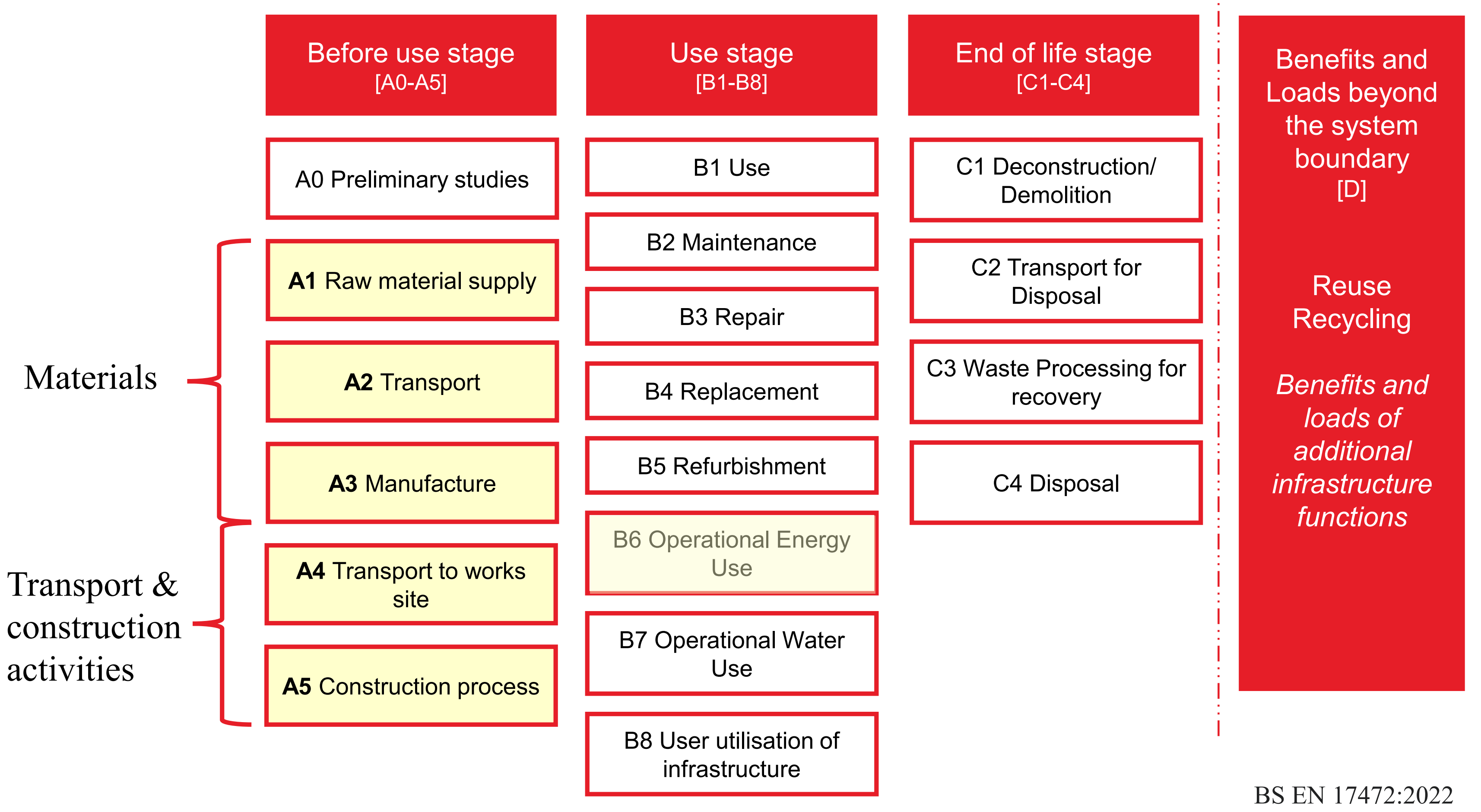
Relative precision (%) of Higgs boson coupling and total Higgs boson width measurements at future colliders when combined with the HL-LHC measurements, assuming two IPs for FCC-ee and CEPC.

Evaluate average precision gain w.r.t. HL-LHC:

$$w = \frac{\left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC}} - \left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC+HF}}}{\left(\frac{\delta\kappa}{\kappa}\right)_{\text{HL-LHC+HF}}}.$$

$$\left\langle \frac{\delta\kappa}{\kappa} \right\rangle = \frac{\sum_i w_i \left(\frac{\delta\kappa}{\kappa}\right)_i}{\sum_i w_i}$$

Life Cycle Assessment



ARUP analysis

Lifecycle assessment has been evaluated for ILC and CLIC linear accelerator concepts
→ extended to include estimates for energy production emissions and other facilities

C^3 Sustainable Parameter Set

Scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125