# Sustainability Strategy for the Cool Copper Collider

## Sustainable HEP 2024

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# Outline

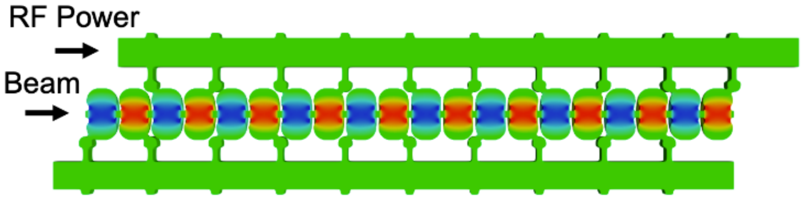
- **Introduction**
    - *The Cool Copper Collider (C$^3$)*
- **Comparison of carbon footprint for proposed colliders**
    - *Sensitivity comparison*
    - *Carbon footprint of operations*
    - *Carbon footprint of construction*
    - *Final comparison*
- **Conclusions**
- **Backup**

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 arXiv:2403.07093.

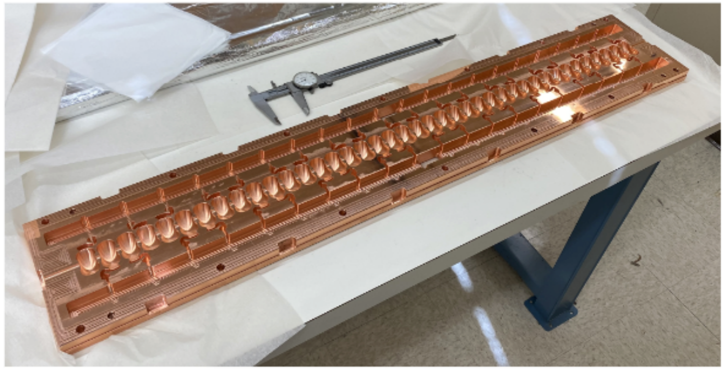
# Introduction

# 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.***



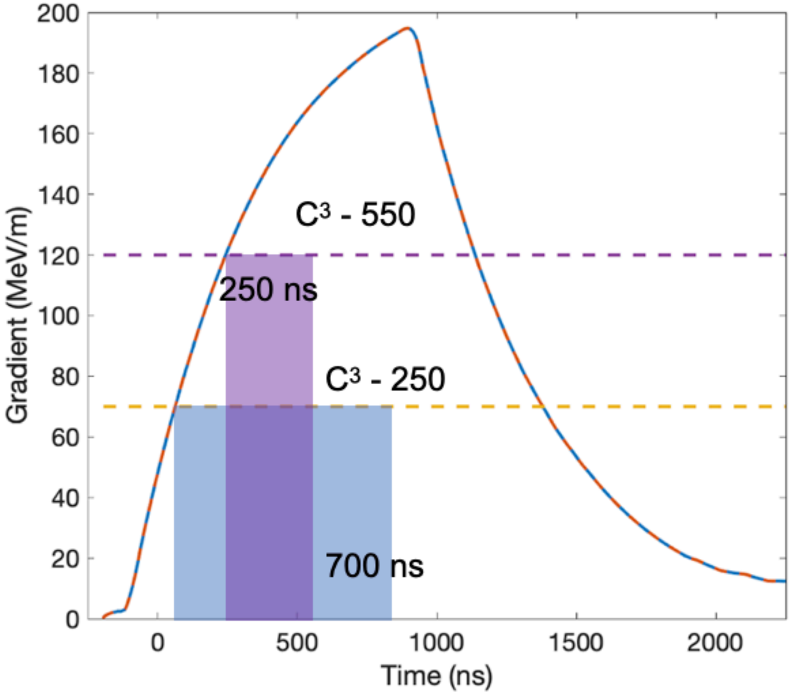
Electric field magnitude for equal power from RF manifold



***Innovations***

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

***120 MeV/m @250 GeV***
***75 MeV/m @550 GeV***

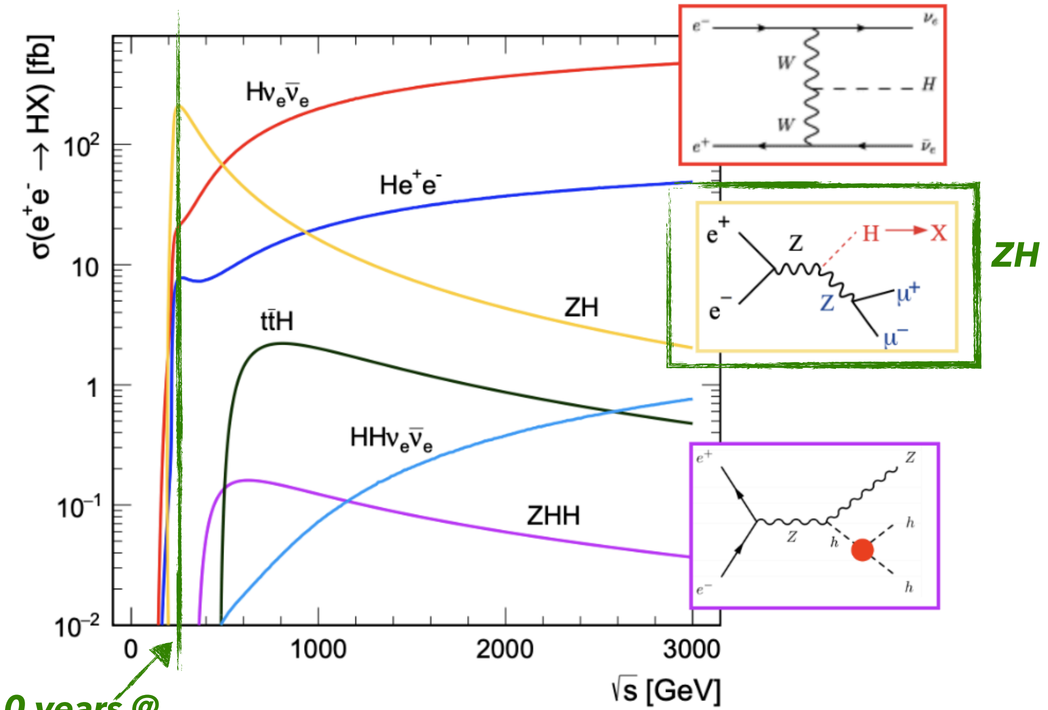


# The Cool Copper Collider - *Physics*

- $C^3$ targeted at operations at 250 GeV ($ZH$ mode) and 550 GeV ($ZHH$ mode - only possible for linear colliders).
- The targeted inst. luminosity of $1.3(2.4) \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at 250 (550) GeV would allow $2\ (4)\ \mathrm{ab}^{-1}$ 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 ($\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$) | $1.3 \times 10^{34}$ | $2.4 \times 10^{34}$ |
| 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 (M$\Omega$/m) | 300 | 300 |
| Length (km) | 8 | 8 |

*Target beam parameters for $C^3$.*



**10 years @ 250 GeV**

# The Cool Copper Collider - *Physics*

JINST 18 P07053

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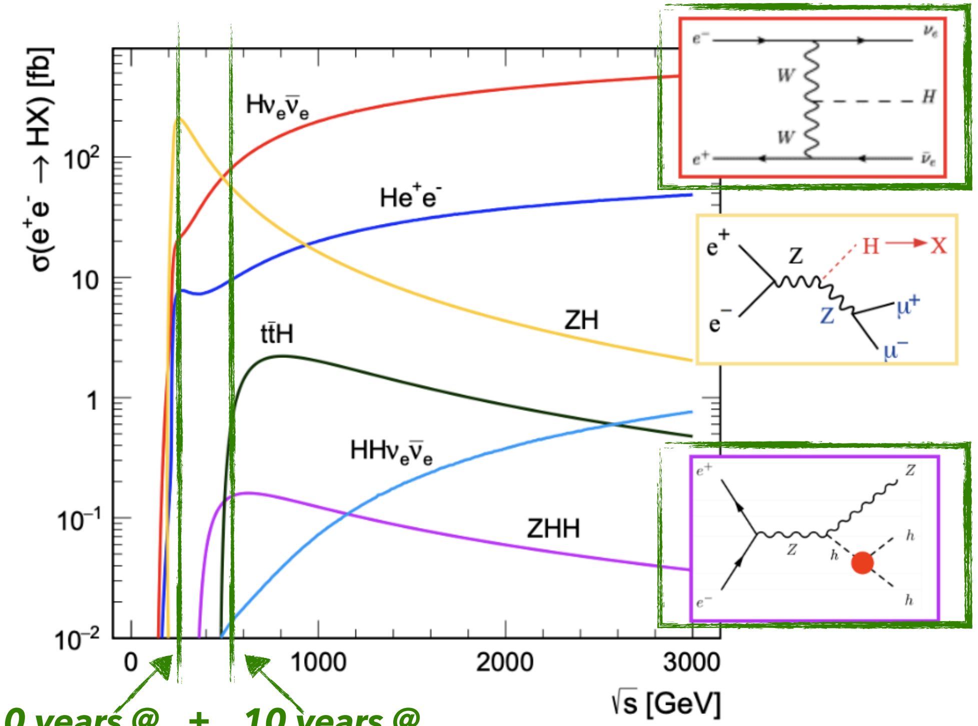


**vvH**

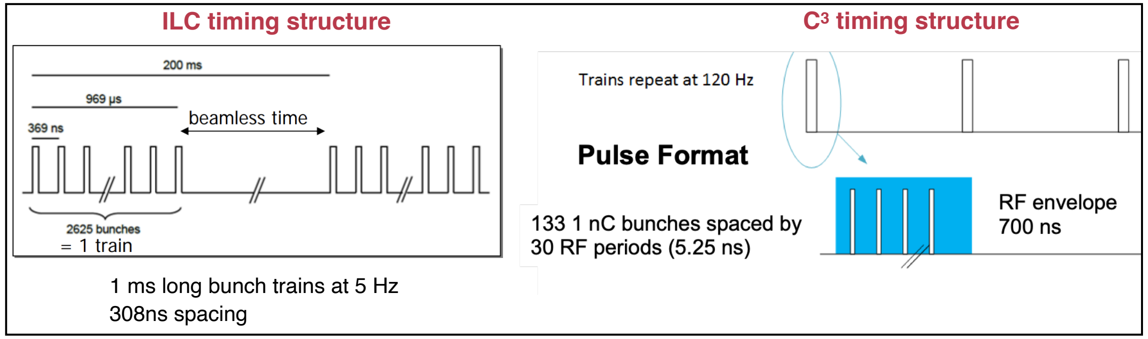
**ZHH**

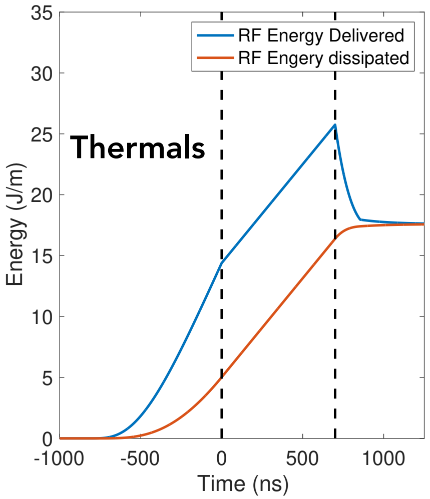
***10 years @ 250 GeV*** **+** ***10 years @ 550 GeV***

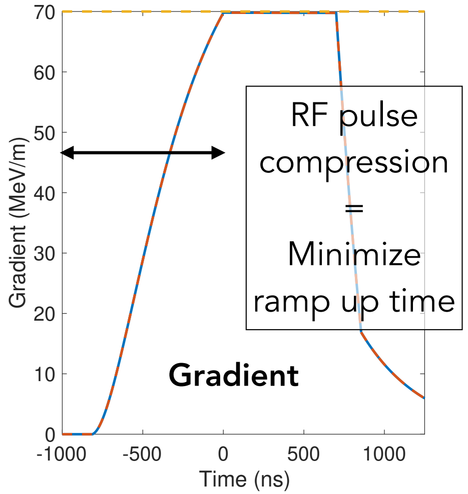
# The Cool Copper Collider - *Power Optimizations*

PRX Energy 2, 047001

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



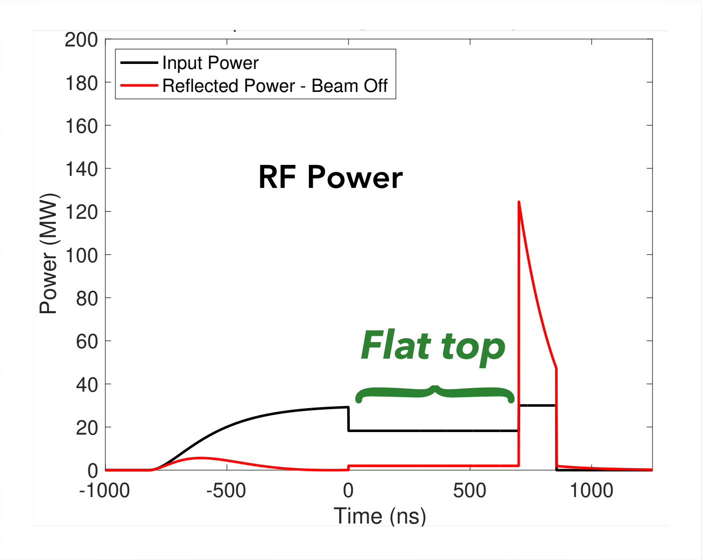




| Scenario | rf system (MW) | Cryogenic system (MW) | Total (MW) | Reduction (MW) |
|---|---|---|---|---|
| Baseline 250 GeV | 40 | 60 | 100 | . . . |
| rf source efficiency increased by 15% | 31 | 60 | 91 | 9 |
| rf pulse compression | 28 | 42 | 70 | 30 |
| Double flat top | 30 | 45 | 75 | 25 |
| Halve 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.

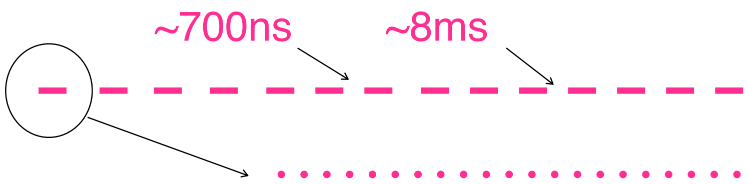


# The Cool Copper Collider - *Power Optimizations*

arXiv:2403.07093

- 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$^{-1}$) | | $P_{\text{site}}$ (MW) |
|---|---|---|---|---|---|---|---|
| Scenario | Flat top (ns) | $\Delta t_b$ (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 |

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

$\mathcal{L}/P_{\text{site}}$

($10^{34}$ 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 $\mathcal{L}/P_{\text{site}}$ gain!**

# 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

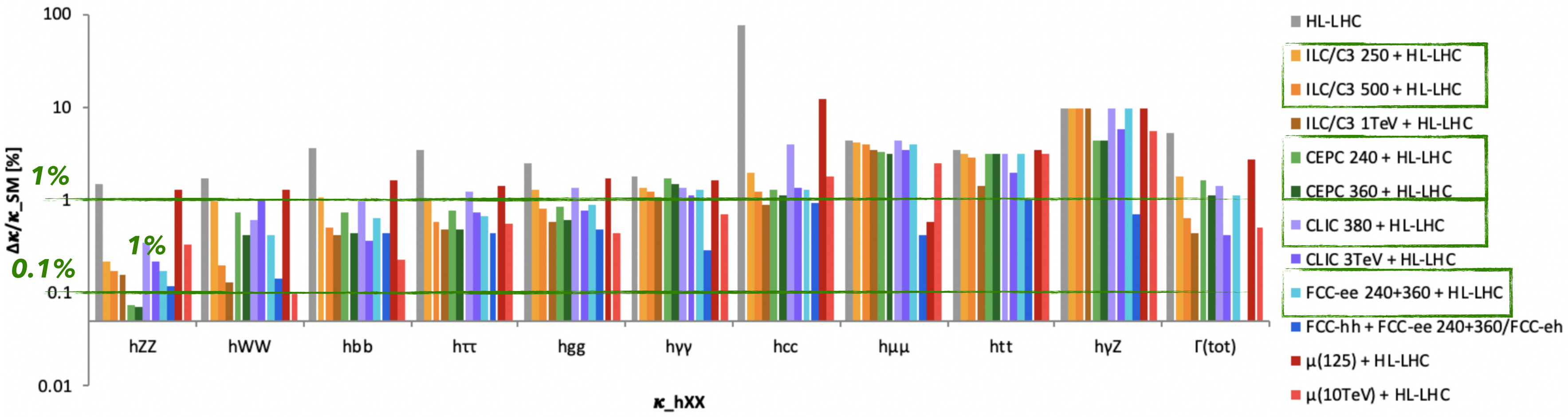
*Evaluate* ***average precision gain*** *w.r.t. HL-LHC:*

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

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

→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

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

Power during collisions

Fraction of power used during down-time (taken 30%)

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 | | | | | |
| $T_{\text{run}}$ (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.

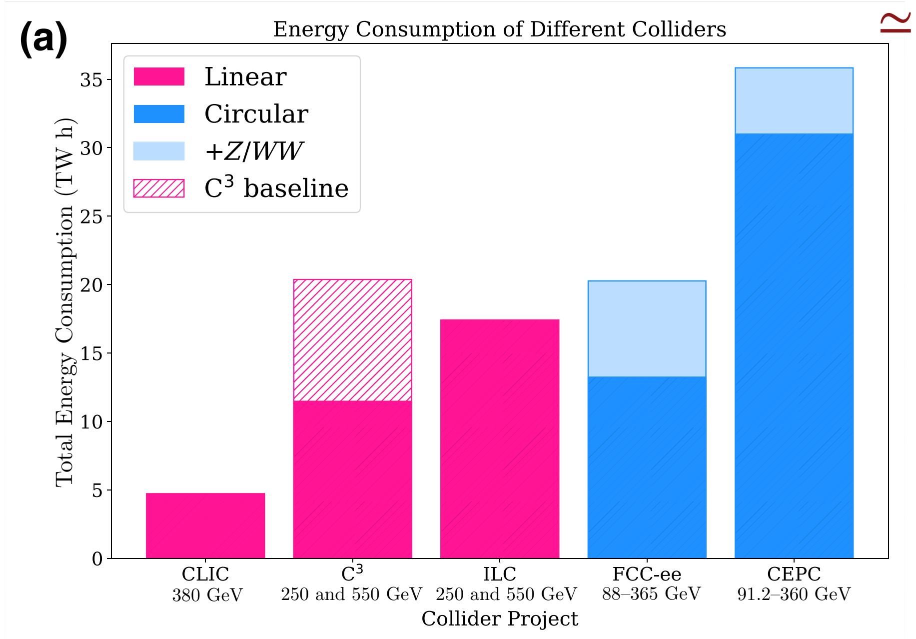
*Running scenarios for Higgs factory projects.*

# Carbon Footprint of *operation*

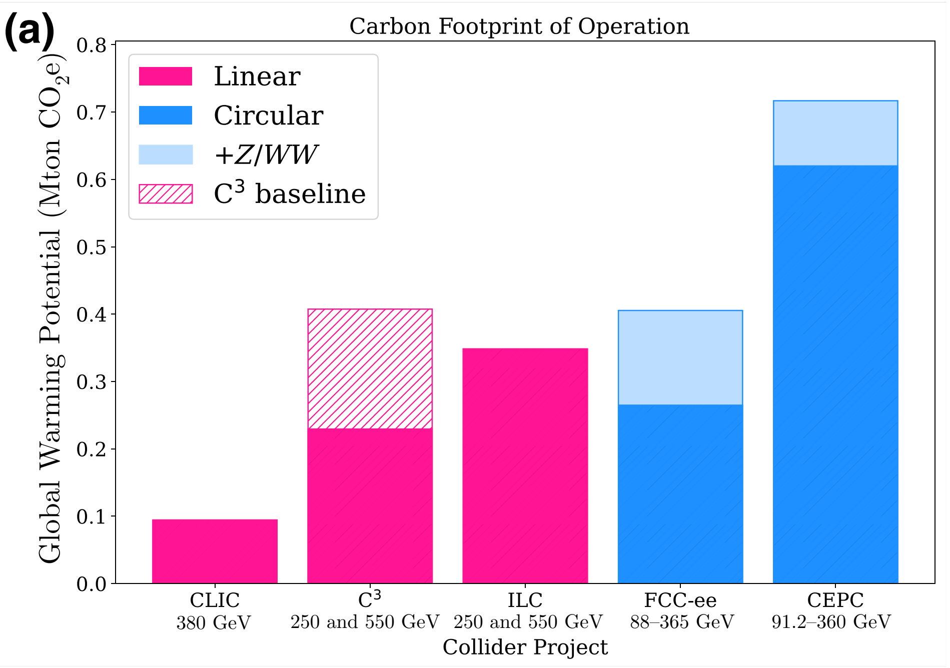
PRX Energy 2, 047001

$$\mathrm{GWP}_{\mathrm{operations}} = E_{\mathrm{total}} \cdot \mathrm{carbon\ \ intensity}$$

$$\simeq E_{\mathrm{total}} \cdot (20\ \mathrm{ton\ \ CO_2/GWh})$$



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



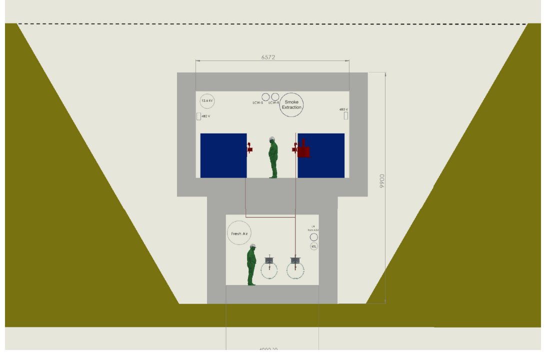
*GWP in Mton CO2e for the entire run-time of each collider.*

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

# Carbon Footprint of *construction*

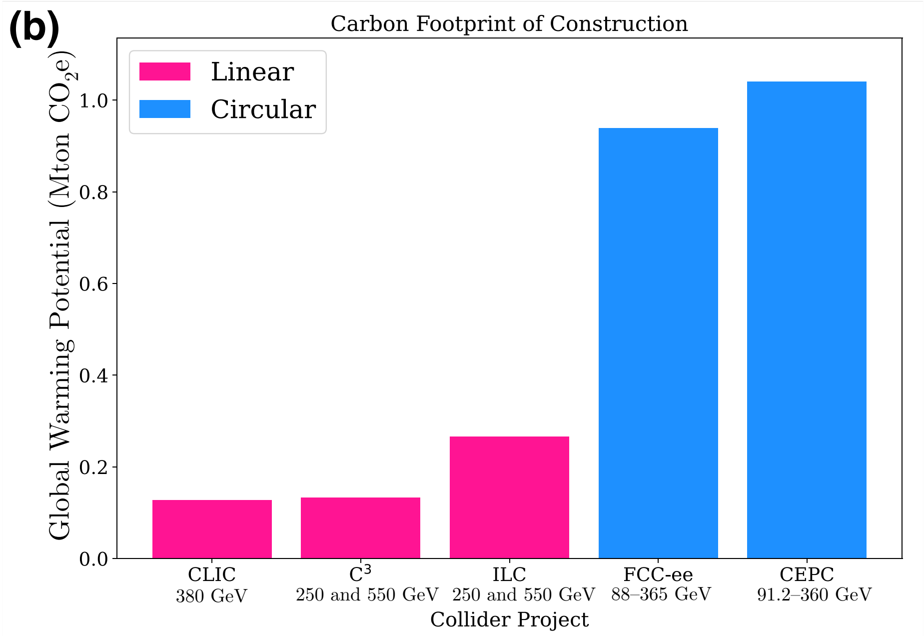
PRX Energy 2, 047001

- 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



| Project | Main tunnel length (km) | GWP (kton CO$_2$e) | | |
|---|---|---|---|---|
| | | 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** |

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



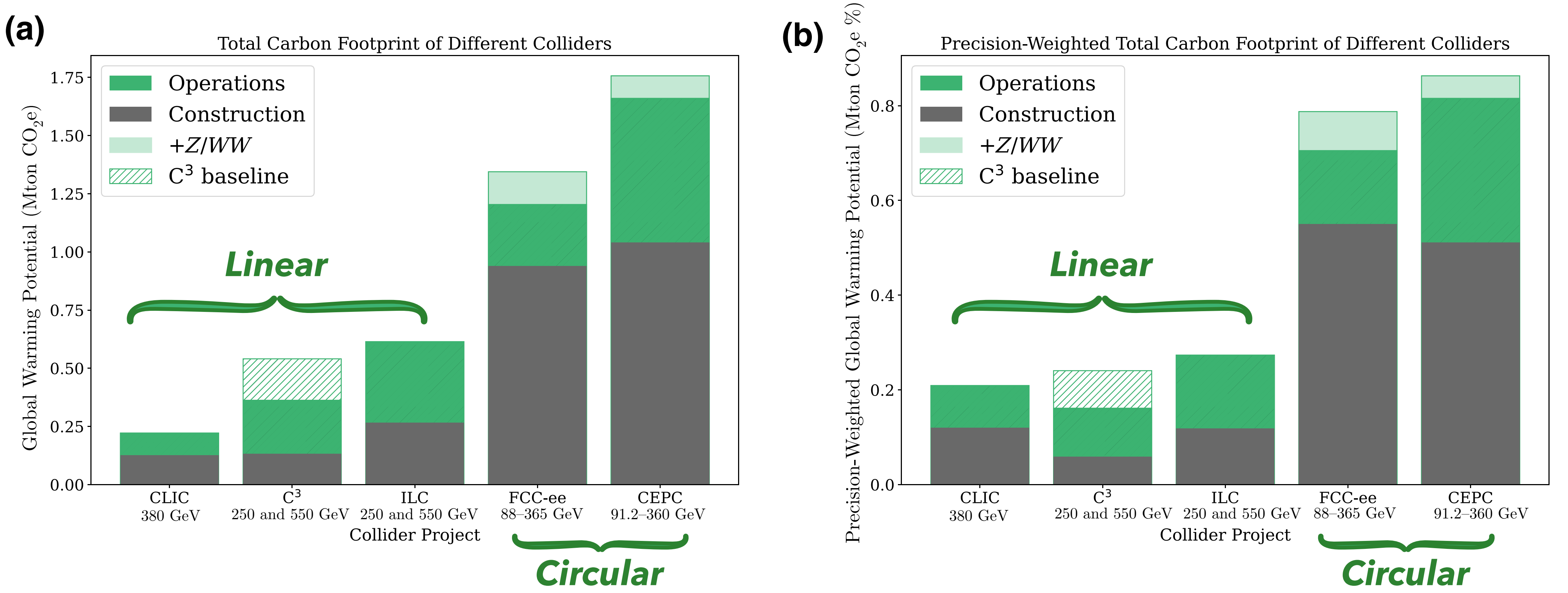
*Global warming potential in Mton CO2e for various collider concepts.*

***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

- 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.

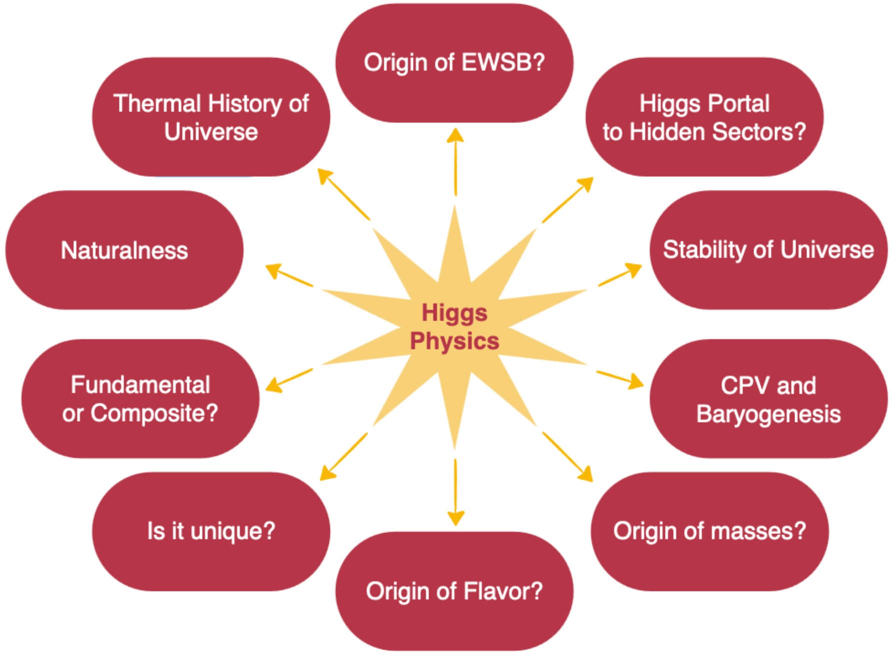
**Thank you for your attention!**

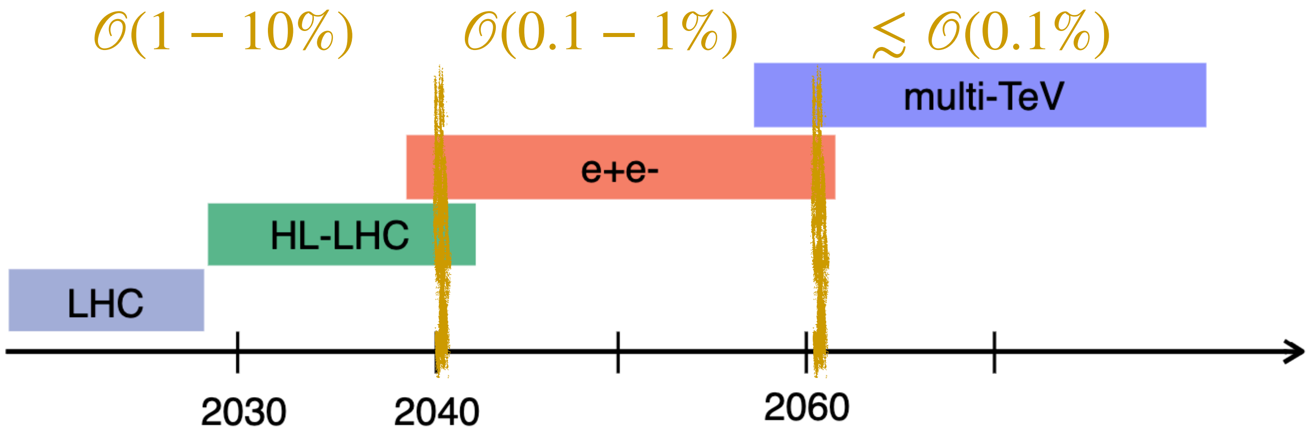
**For more information on C$^3$, visit:**
**https://web.slac.stanford.edu/c3/**

# 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.

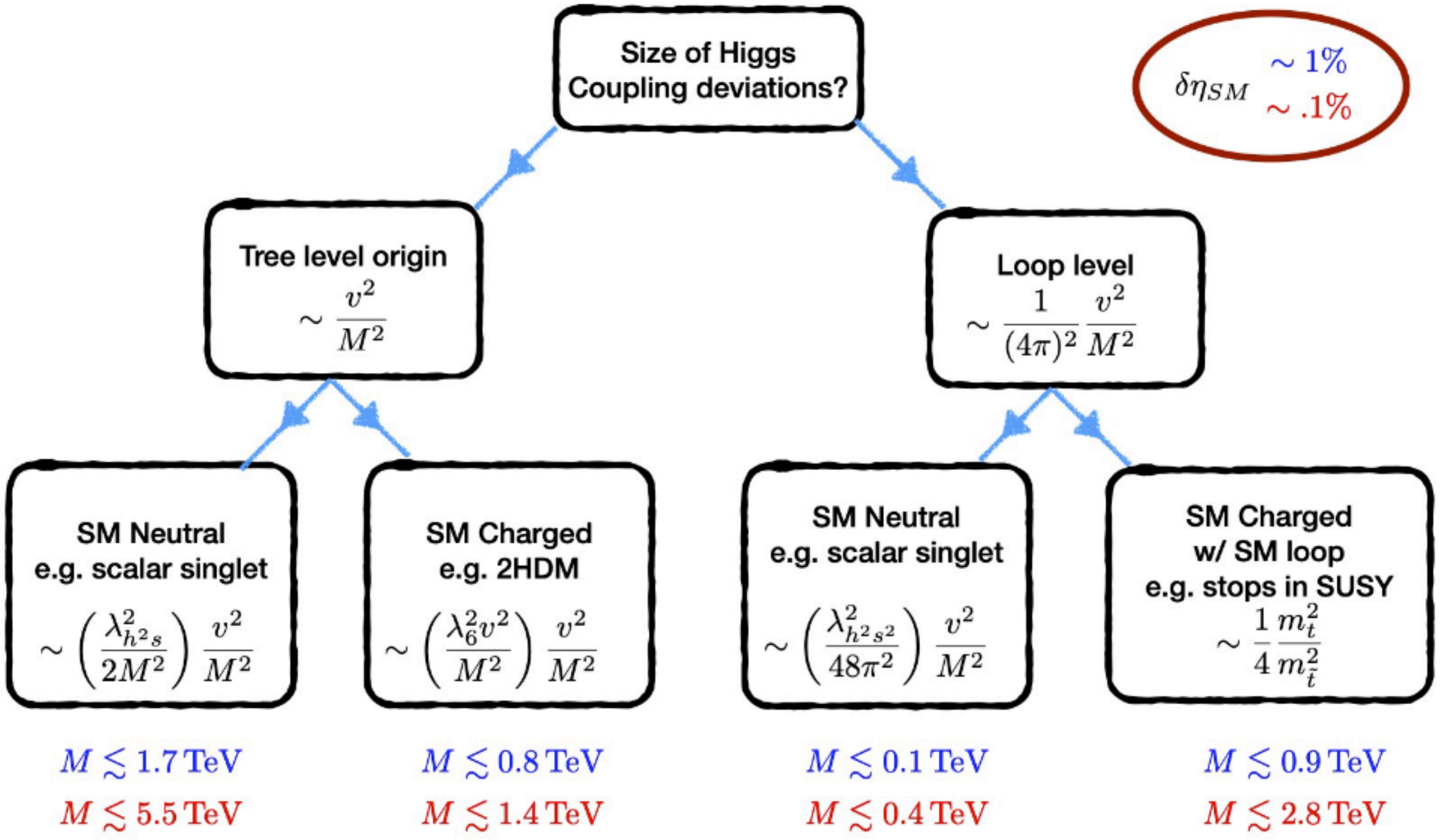




Snowmass EF01 & EF02 Report

# Benefits of $e^+e^-$ colliders

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



Size of Higgs Coupling deviations?

$\delta\eta_{SM}$ $\sim 1\%$ $\sim .1\%$

Tree level origin $\sim \frac{v^2}{M^2}$

Loop level $\sim \frac{1}{(4\pi)^2}\frac{v^2}{M^2}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2 s}}{2M^2}\right)\frac{v^2}{M^2}$

SM Charged e.g. 2HDM $\sim \left(\frac{\lambda_6^2 v^2}{M^2}\right)\frac{v^2}{M^2}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2 s^2}}{48\pi^2}\right)\frac{v^2}{M^2}$

SM Charged w/ SM loop e.g. stops in SUSY $\sim \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}}^2}$

$M \lesssim 1.7\,\mathrm{TeV}$ $M \lesssim 5.5\,\mathrm{TeV}$

$M \lesssim 0.8\,\mathrm{TeV}$ $M \lesssim 1.4\,\mathrm{TeV}$

$M \lesssim 0.1\,\mathrm{TeV}$ $M \lesssim 0.4\,\mathrm{TeV}$

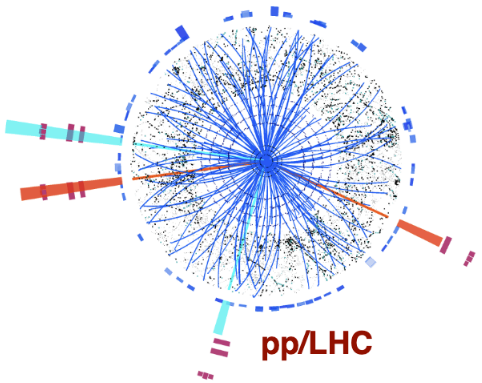
$M \lesssim 0.9\,\mathrm{TeV}$ $M \lesssim 2.8\,\mathrm{TeV}$

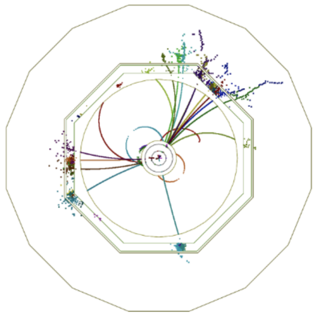
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

Snowmass EF01 & EF02 Report

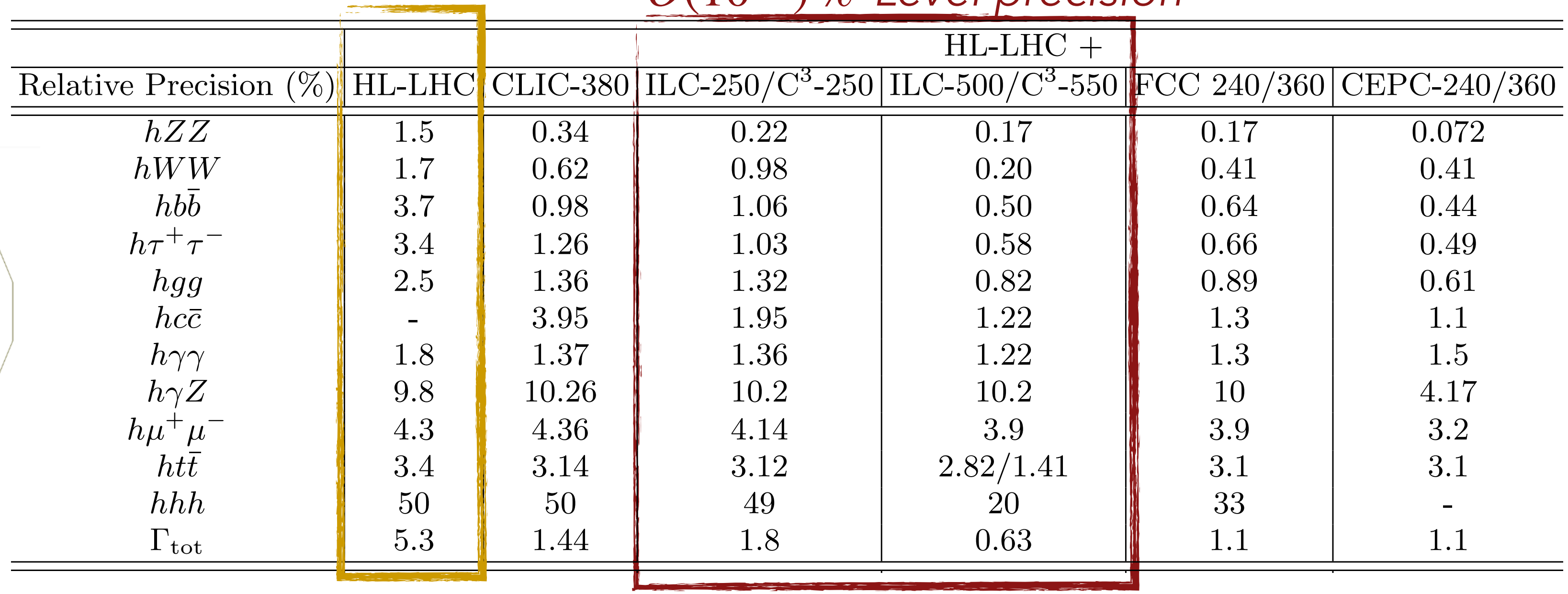
# Benefits of $e^+e^-$ colliders

- 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*


pp/LHC


$e^+e^-$

$\sim O(10^{-1})\,\%$ *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 | - |
| $\Gamma_{\text{tot}}$ | 5.3 | 1.44 | 1.8 | 0.63 | 1.1 | 1.1 |

$\sim \mathcal{O}(1)\,\%$ *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 |
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| $ht\bar{t}$ | 3.4 | 3.14 | 3.12 | 2.82/1.41 | 3.1 | 3.1 |
| $hhh$ | 50 | 50 | 49 | 20 | 33 | … |
| $\Gamma_{\text{tot}}$ | 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:*

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

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