Feedback on future collider strategy

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- Introduction
- What will the HL-LHC achieve
- Which CM energy for an e^+e^- Higgs factory
- Precision and flavour
- A few personal remarks

Discussion assumes no hint for new physics at the LHC. This question is not settled yet!

German input to European Strategy Update

The German input to European process is extremely important

- Biggest contributor to CERN
- Large and diverse particle physics community with a strong national lab, research institutions and universities

Did anything change since 2018 German input to process? Yes!

- HL-LHC Yellow Books (2 volumes) released with much more realistic extrapolations using newest Run-2 analyses
- FCC and CEPC Conceptual Design Reports released
- New Giga-Z study for ILC
- 160 written contributions to ESPP Update
- Granada Meeting
- Physics Briefing Book and accompanying studies released by Physics Preparatory Group (PPG) to ESPP Update
- Five scenarios identified by PPG and submitted for discussion with request for feedback to European Study Group (ESG)

Many thanks to KET for having this discussion and for reassessing the German input to the European strategy

High-Luminosity LHC: 2026~2037, L_{peak} up to $7\times10^{34}\ cm^{-2}s^{-1}$ (up to 200 pileup events), 3–4 ab^{-1}

HL-LHC

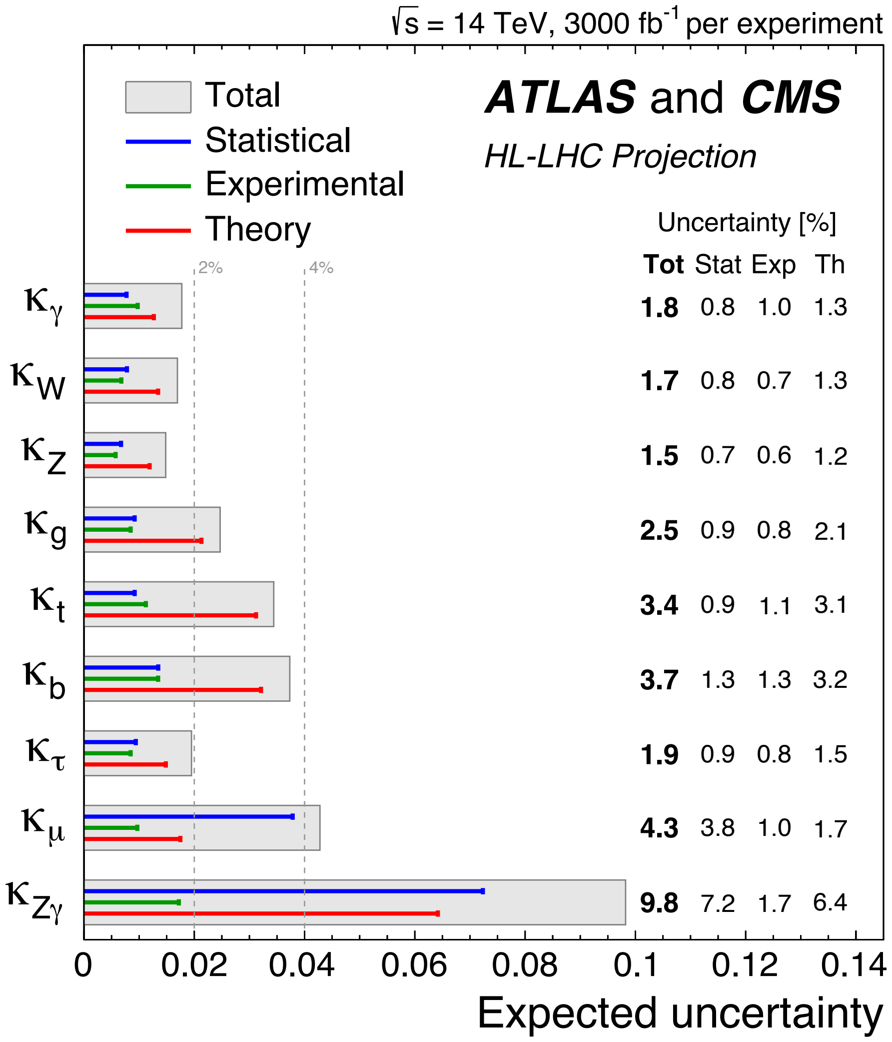
- Higgs factory (400M Higgs bosons produced) for precise Higgs coupling ratio measurements and increased rare & new physics sensitivity
- Large-scale detector upgrades required for improved robustness against pileup and radiation

Main expected Higgs results (and much more than Higgs physics!)

- HL-LHC excellent for rare and high-q^2 Higgs processes
- Differential cross section and angular measurements
- Expect observation of $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$
- Precise top-Higgs coupling measurement
- Access to di-Higgs production

Huge challenge

- However, extrapolations are not scientific results. The data are still to be produced and collected, the HL-LHC is not a reality yet
- **Operation, Analysis and Upgrade of experiments require our strong and sustained support**



Long term future of the energy frontier

Progress in particle physics requires experiments at the energy frontier

$\rightarrow$ A high-luminosity 100 TeV hadron collider such as the FCC-hh offers a huge physics potential

	$gg \rightarrow H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

Event numbers compared to HL-LHC

FCC-hh — the *ultimate* Higgs factory

Among the FCC-hh physics highlights

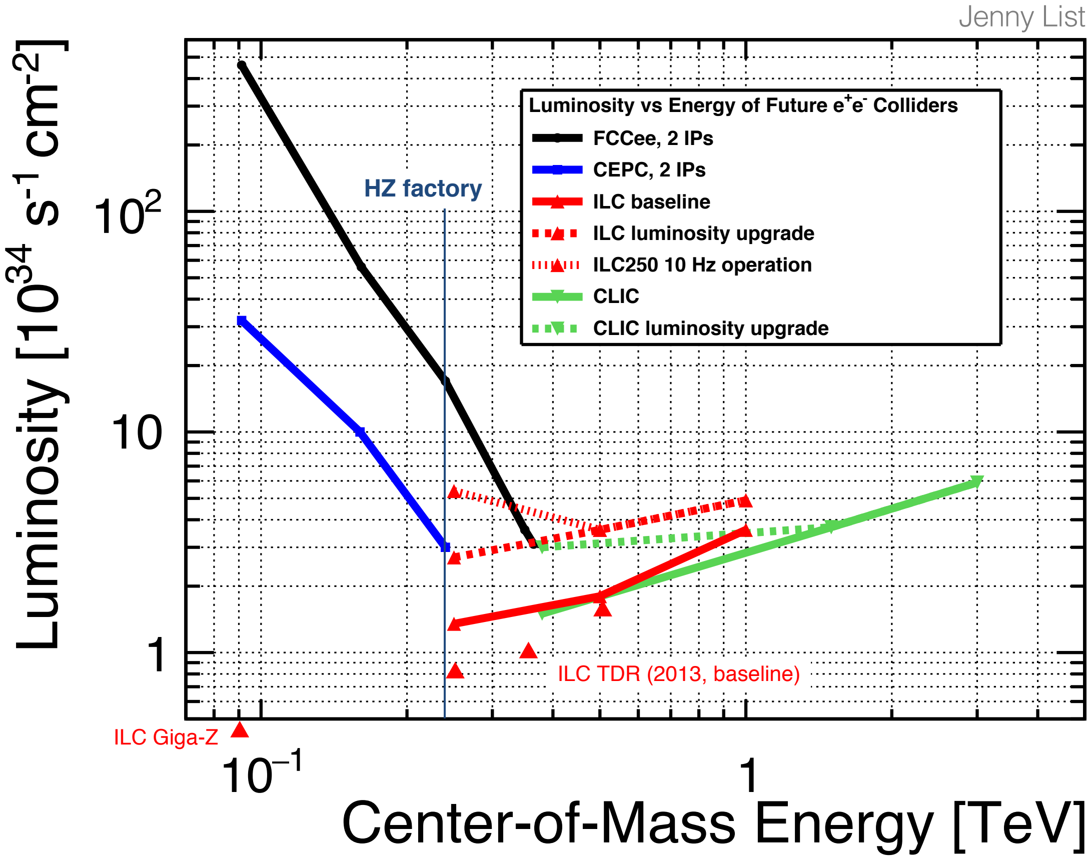
- 5σ discovery potential for new phenomena: q* up to 40 TeV, Z'_{SSM} up to 43 TeV, gluino / stop up to 16 / 10 TeV, …
- Precision probes of Higgs self coupling and rare Higgs processes (incl. $H \rightarrow$ invisible down to 10^{-4})
- Studies of SM processes such high-mass longitudinal vector boson scattering (3%), Drell-Yan up to 15 TeV mass (10%)
- WIMP dark matter sensitivity between 1 and 3 TeV
- Heavy-ion physics program with $\sqrt{s_{NN}}$ = 39 TeV for PbPb and 63 TeV for pPb

It is important to optimise the combined scientific reach of future collider projects:

$\rightarrow$ **Results of an e^+e^- collider should be complementary to a future hadron collider, and not be superseded by it**

e^+e^- : complementarity with hadron colliders is key

Highest luminosity for best precision and to probe rare and forbidden phenomena: physics the FCC-hh cannot do as well



FCC-ee (14 years of operation)

All numbers assume 2 experiments

Run duration (years)	Centre-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	$> 10^5 \times$ LEP ↓ Event Statistics
4	88-95	150	3×10^{12} visible Z decays
2	158-162	12	10^8 WW events
3	240	5	10^6 ZH events
5	345-365	1.5	10^6 $t\bar{t}$ events

Stable beam time assumed:

- FCC-ee: 1.08×10^7 s
- ILC: 1.6×10^7 s
- CLIC: 1.2×10^7 s

Compare:

- SLD: $< 1.0 \times 10^7$ s
- Belle: $< 1.2 \times 10^7$ s
- LHC: $< 0.7 \times 10^7$ s

ILC (22~24 years of operation)

- Giga-Z: 0.1 ab^{-1} in 1~3 years
- 250 GeV: 2.0 ab^{-1} in 11.5 years
- 350 GeV: 0.1 ab^{-1} in 1 year
- 500 GeV: 4.0 ab^{-1} in 8.5 years

CLIC (> 20 years of operation)

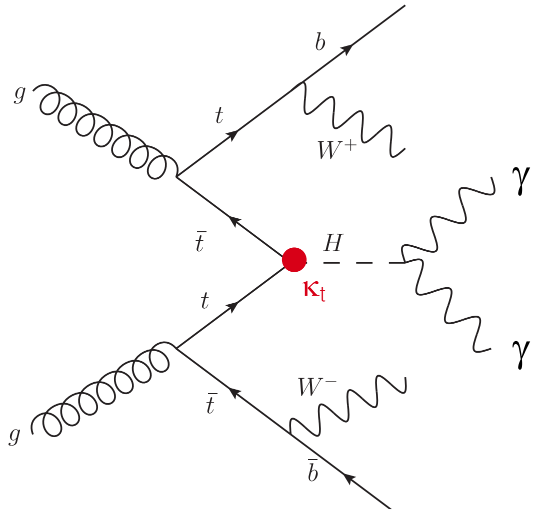
- Giga-Z: ?
- 380 GeV: 1.0 ab^{-1} in 8 years
- Upgrade to > 1 TeV in > 15 years

Another important consideration is **one vs. two running experiments!**

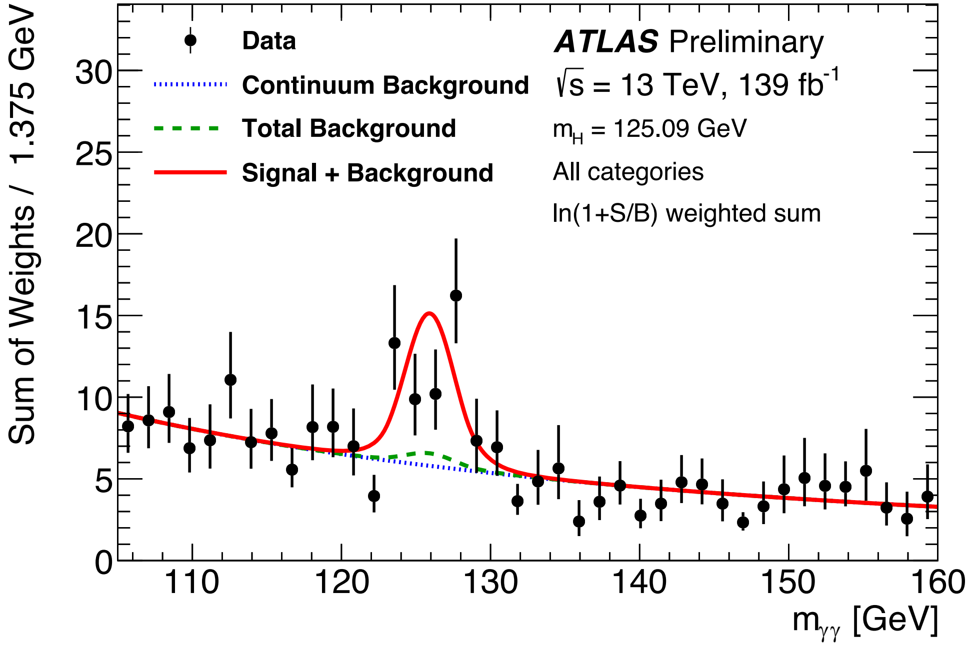
The 500 GeV question

The question whether or not an e^+e^- collider should be upgradable to at least 500 GeV depends on the expected HL-LHC and FCC-hh potential

- Main considerations:
  1) **Top-Higgs coupling measurement**
  2) **Higgs self-coupling**



1) **Top-Higgs coupling**: expectation at HL-LHC: $\sigma(\kappa_t) = 3.4\%$
   (from mostly ttH($\to \gamma\gamma$), 3.7M ttH produced in total)
   - FCC-hh: 1.0% (systematics limited)
   - ILC-500 (4 ab^{-1}, 8.5 years): 6.3% (~9k ttH produced)
     Note: strong cross-section rise for > 500 GeV (2% precision at 600 GeV)



ATLAS $H \to \gamma\gamma$ signal with Run-2 data (139 fb^{-1})
Alone providing already 13% measurement of κ_t

ATLAS-CONF-2019-004

The 500 GeV question (continued)

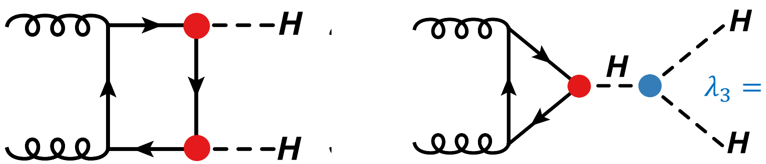
2) Higgs self-coupling via di-Higgs production

- LHC: 40 fb (37 fb ggF) cross section → 240k HH produced

  Best channels: bbγγ (BR = 0.26%), bbττ (7.3%), bbbb (34%).

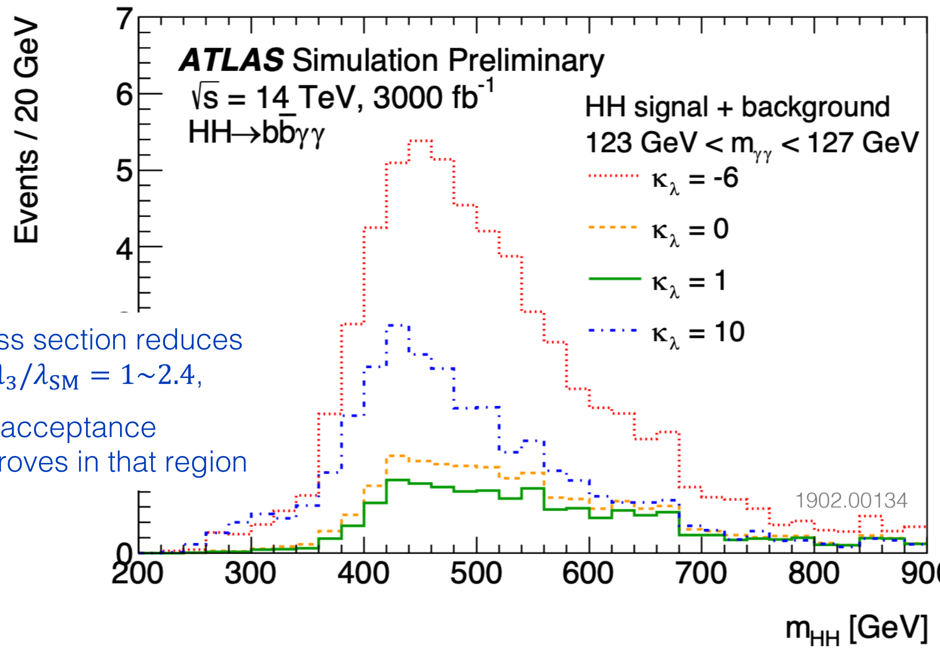
  Exploit machine learning and m_{HH} mass spectrum to directly constrain λ_3 (instead of optimising for HH, as done so far)

  Simple analyses so far (but realistic S/B), expect to improve further. Also constraints from λ_3 in loops.



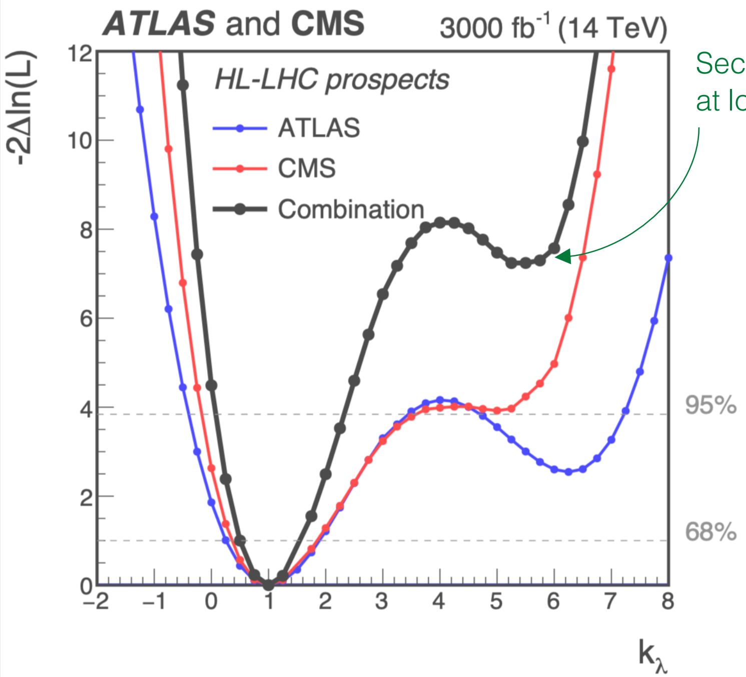
$\lambda_3 = \frac{m_H^2}{2v^2} \sim 0.13$

- LO diagrams contributing with negative interference
- Box diagram dominates inclusive production
- Sensitivity to H self-coupling rises at low m_{HH}



Cross section reduces for $\lambda_3/\lambda_{SM} = 1{\sim}2.4$,

But acceptance improves in that region



Second minimum constrained at low m_{HH} mainly from bbγγ

Extrapolated HL-LHC sensitivity

$$-0.52 < \frac{\lambda_3}{\lambda_3^{SM}} < 1.50$$

But no dedicated analysis optimisation on λ_3 yet

The 500 GeV question (continued)

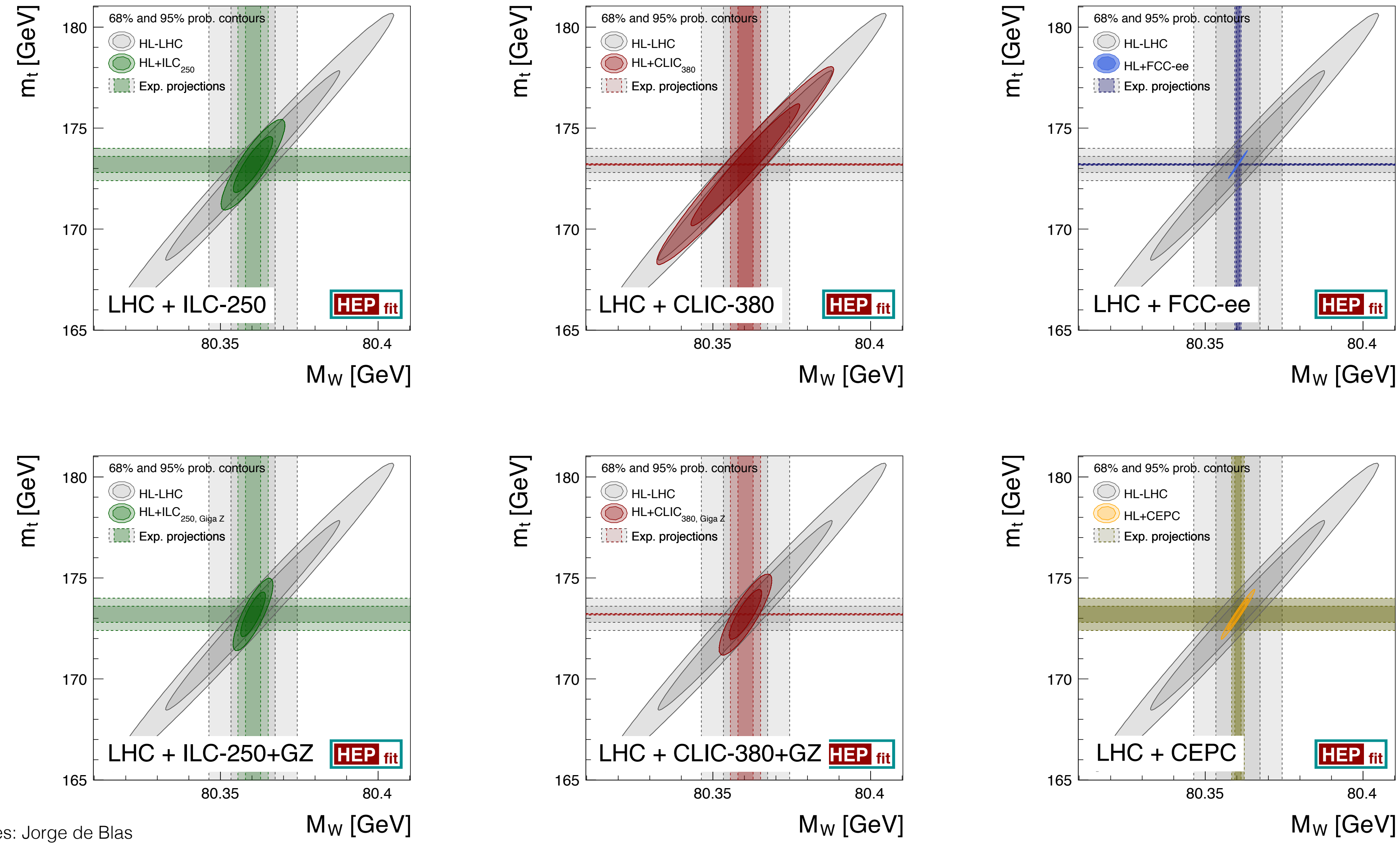
2) **Higgs self-coupling:** expected precision on λ_3

- HL-LHC: < 50% (HH) + some constraint from λ_3 in loops
- FCC-ee: 21% from λ_3 in loops* (EFT), note also information from energy dependence of λ_3 at 240 and 365 GeV
- ILC-500: 27% (HH), 32% (λ_3 in loops) [The ILC a Global Project, 1903.01629]
- ILC-1000 and CLIC-3000 achieve ~10% (36% for CLIC-1500)
- FCC-hh: 5% (HH), 530 × events at HL-LHC

A precise measurement of the Higgs self-coupling at the few percent level can only be provided by the combination of an e^+e^- collider and FCC-hh.

* $\sigma_{ZH}^{\mathrm{NLO}} \approx \sigma_{ZH}^{\mathrm{NLO,SM}}(1 + 0.014\,\delta\kappa_3)$

Electroweak precision and rare phenomena physics



FCC-ee is an electroweak and flavour factory

> 5 times better precision on *S*, *T* oblique parameters
[1905.03764]

3–4 orders of magnitude improved sensitivity to LFV in Z decays

Flavour: $2{\times}10^{11}$ tau decays, $B_s \to \tau\tau$ and $B \to K^*\tau\tau$ in $2{\times}10^{12}$ bb events

Searches for weakly coupled particles

Figures: Jorge de Blas
private communications

Feedback to the European Strategy Group, a few personal remarks

- As a community we should promote the **projects with the largest scientific reach** and **lowest technical risk**, not (or not primarily) the ones we believe the policy makers may accept (or like). If we are not convinced and united, we will convince no one else. If we are convinced to have the best scientific projects, we can move mountains!

- There seems to be consensus that the next collider should be an **e^+e^- "Higgs factory"**. Given the arguments I tried to convey, I would wish the German community emphasised the **importance of such a machine as next step, w/o prioritising a concrete project**.

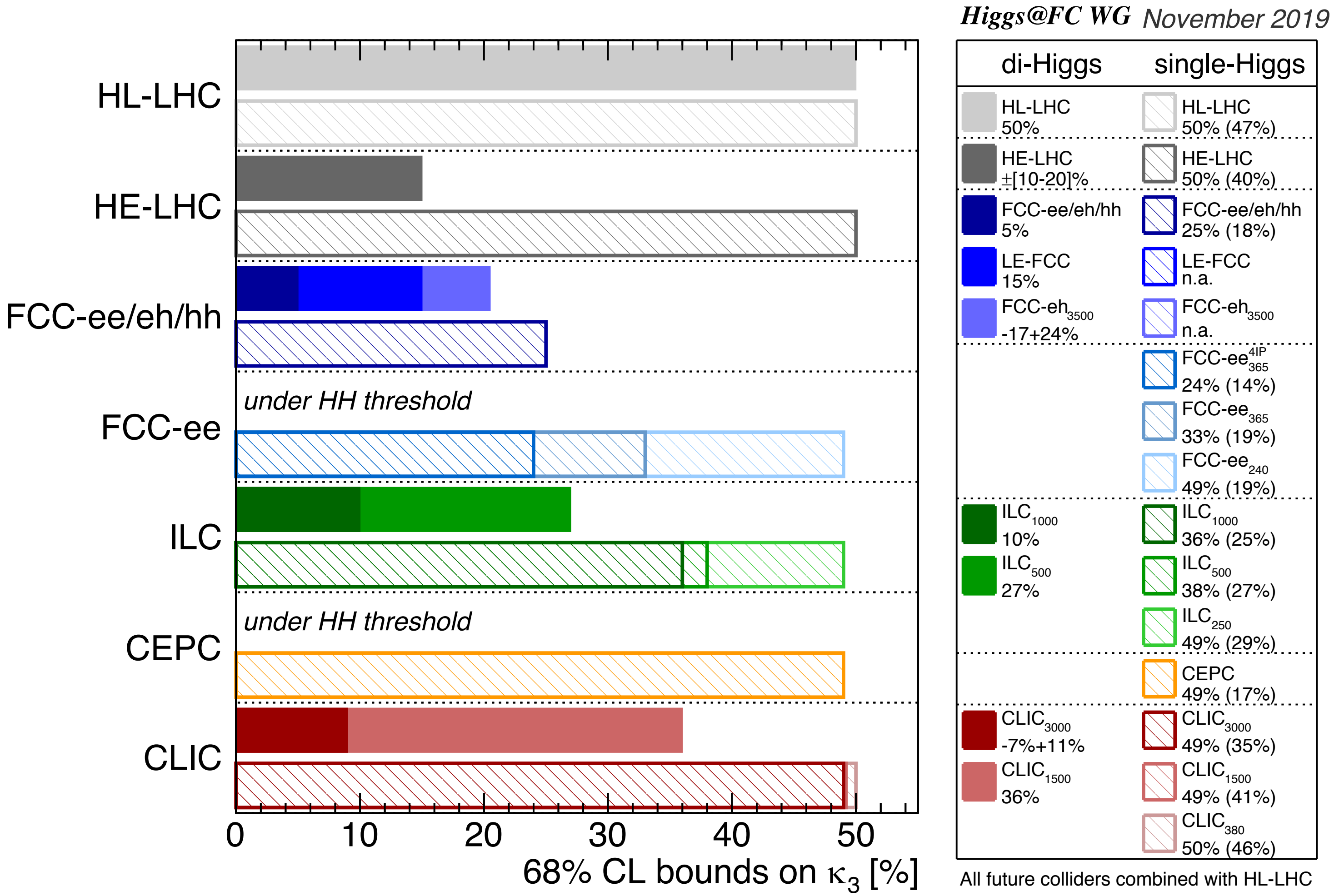
- If Japan moves forward with the ILC, a decision is taken. Since, so far, this has not been the case **we should not close the door to an FCC-ee at CERN**. Its advantages (highest luminosity ≤ HZ, at least two experiments, lowest technical risk) counterbalance the shortcomings (inefficient > tt). **The FCC-ee is a phenomenal machine.**

- I believe that the long term **goal of a O(100 TeV) hadron collider for discovery physics should be emphasised**. While it is essential that particle physics remains diverse and supports collider as well as non-collider projects, the **flagship projects provide the largest scientific return**.

- **CERN**, as the European Laboratory of Particle Physics, **is predestined to host such a hadron collider**. The way towards it could be realised via a circular e^+e^- collider with its own complementary physics potential.

- Finally, I believe it is important that the German community **re-emphasises its long-term support for the High-Luminosity LHC**. Although approved, it is not a reality yet: **operation, analysis and upgrade of experiments and accelerator require our strong and lasting engagement**.

Extra slide 1 — Higgs self-coupling

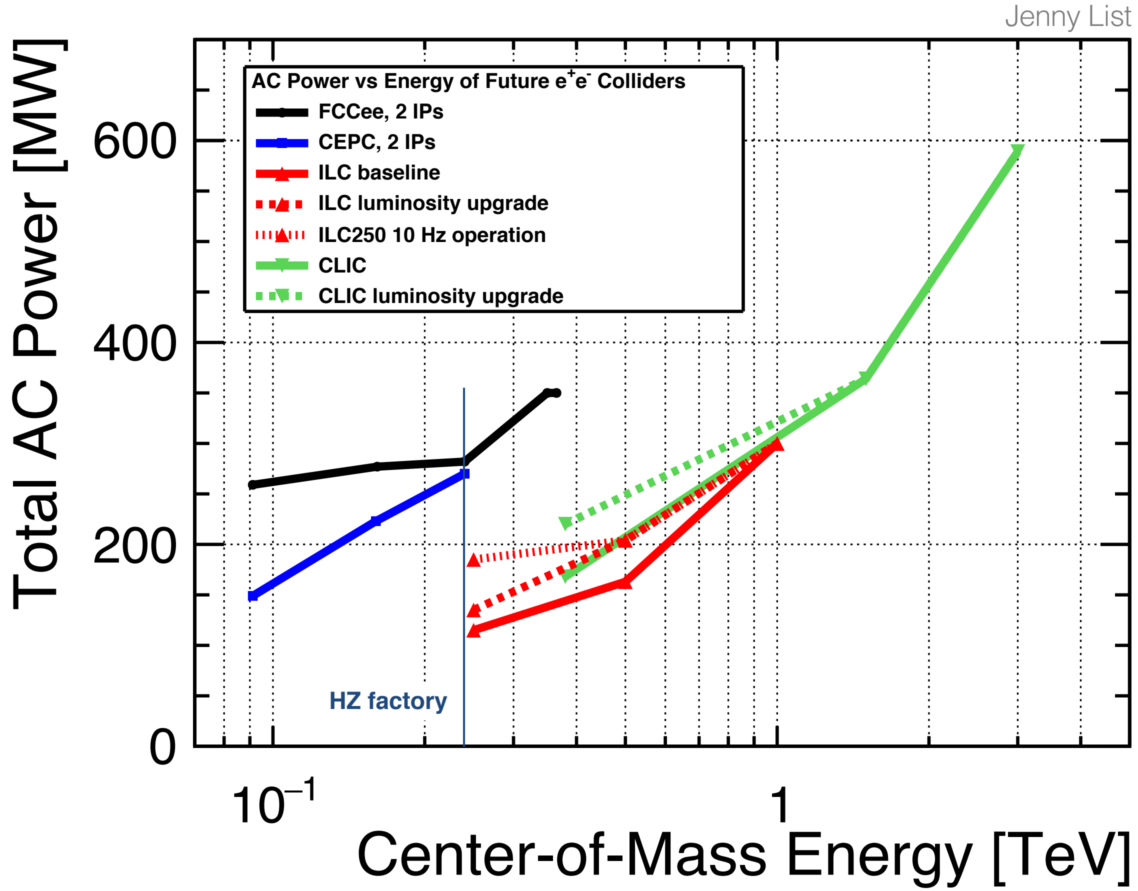


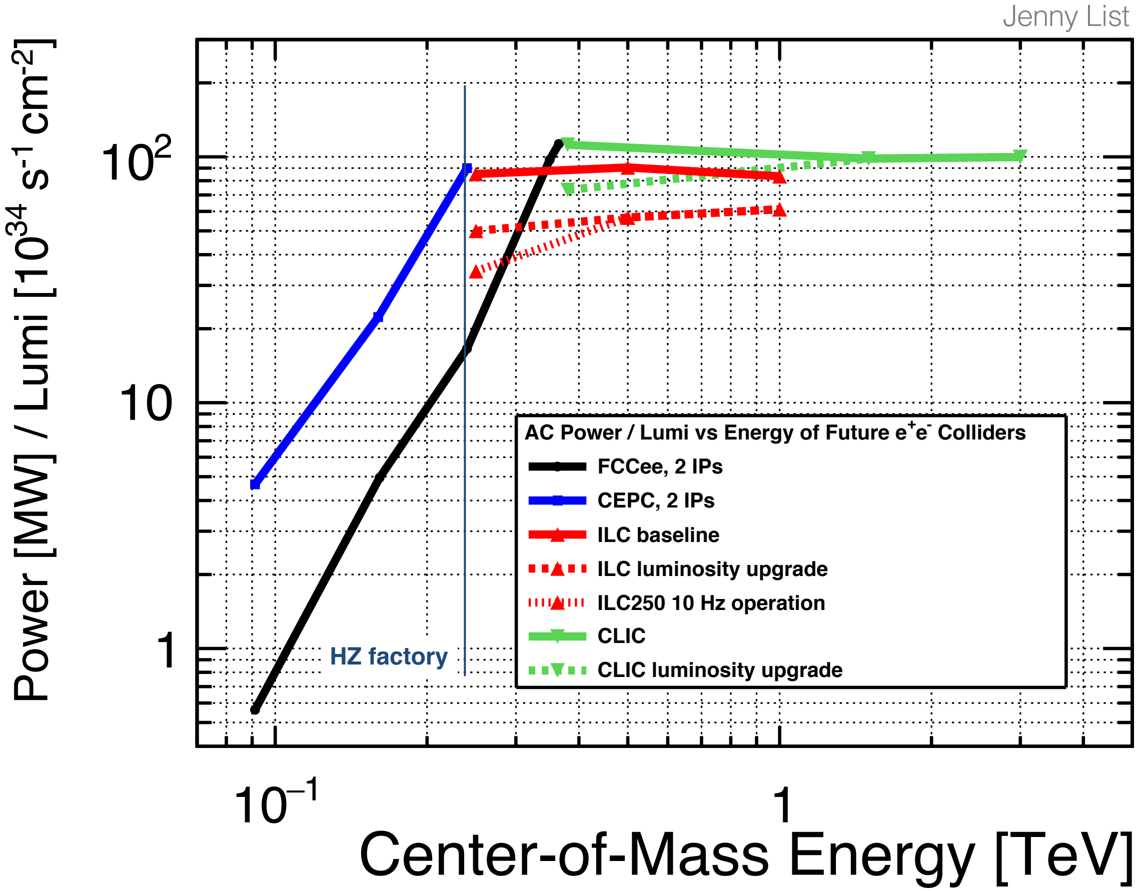
Graphical overview of constraints on Higgs self-coupling expected for future colliders

Figure from 1905.03764:

Sensitivity at 68% probability on the Higgs cubic self-coupling at the various FCs. All values reported correspond to a simplified combination of the considered collider with HL-LHC. Only numbers for Method (1), i.e. "di-H excl.", corresponding to the results given by the future collider collaborations, and for Method (4), i.e. "single-H glob." are shown (the results for Method (3) are reported in parenthesis). For Method (4) we report the results computed by the Higgs@FC working group. For the leptonic colliders, the runs are considered in sequence. For the colliders with $\sqrt{s} < 400$ GeV, Method (1) cannot be used, hence the dash signs. Due to the lack of results available for the ep cross section in SMEFT, we do not present any result for LHeC nor HE-LHeC, and only results with Method (1) for FCC-eh.

Extra slide 2 — Power consumption





Extra slide 2 — $e^+e^- \rightarrow H+X$ cross sections