# *Physics of Higgs factories*

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# *What is a Higgs factory?*

## First stab

- A collider where you make many, many, Higgs bosons
- HL-LHC: ~180M Higgs bosons produced (60 pb) at 3 $ab^{-1}$
- … but the efficiency is low and there is a lot of background
- FCC-ee:  ~1.5M Higgs bosons produced ...

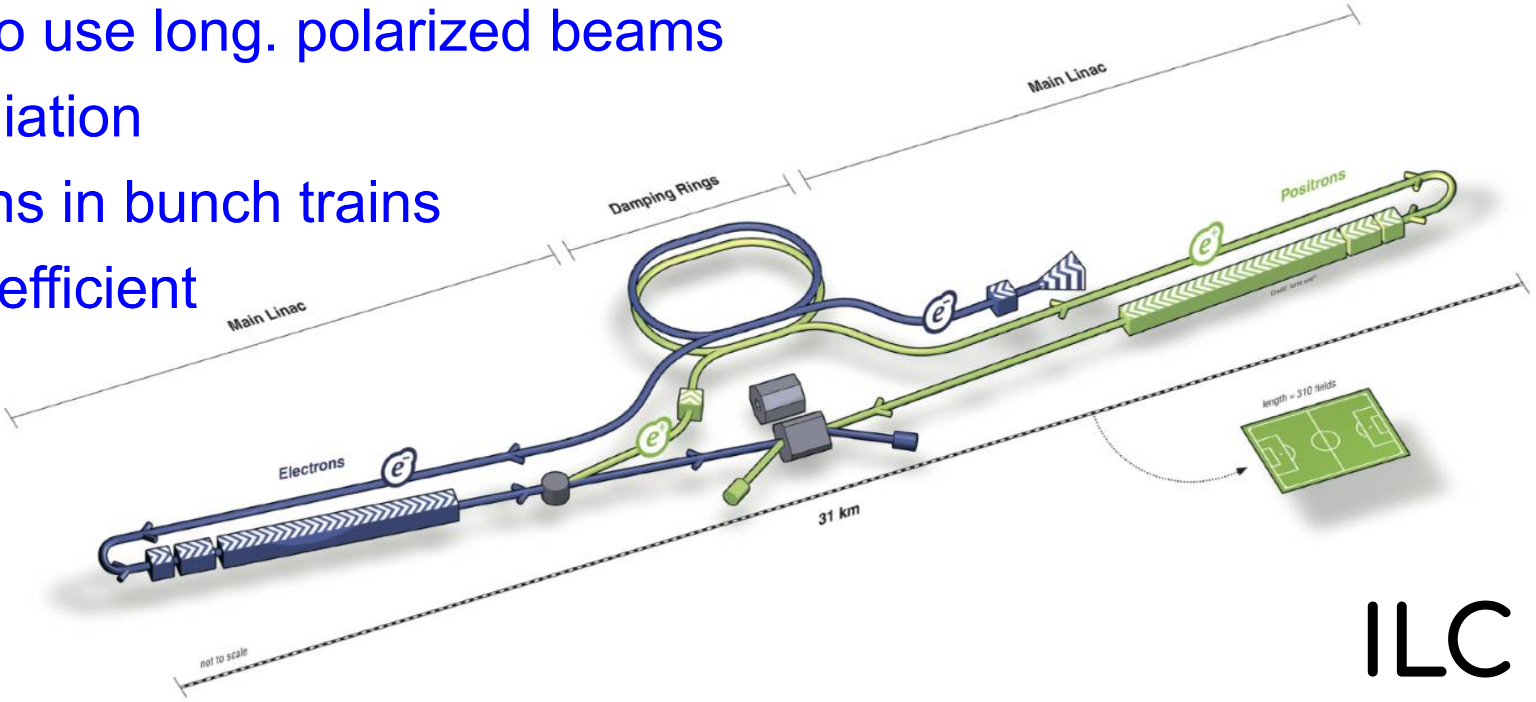
## Refining

- Many Higgs bosons produced that can be efficiently used for analysis
- Background and general beam crossing environment matters
- Usefulness of the initial state cannot be understated
- Also non-Higgs physics is interesting

# *Linear Colliders*

## ILC, C3, CLIC

- Energy reaches to TeV
- Easier to use long. polarized beams
- Low radiation
- Collisions in bunch trains
- Energy efficient



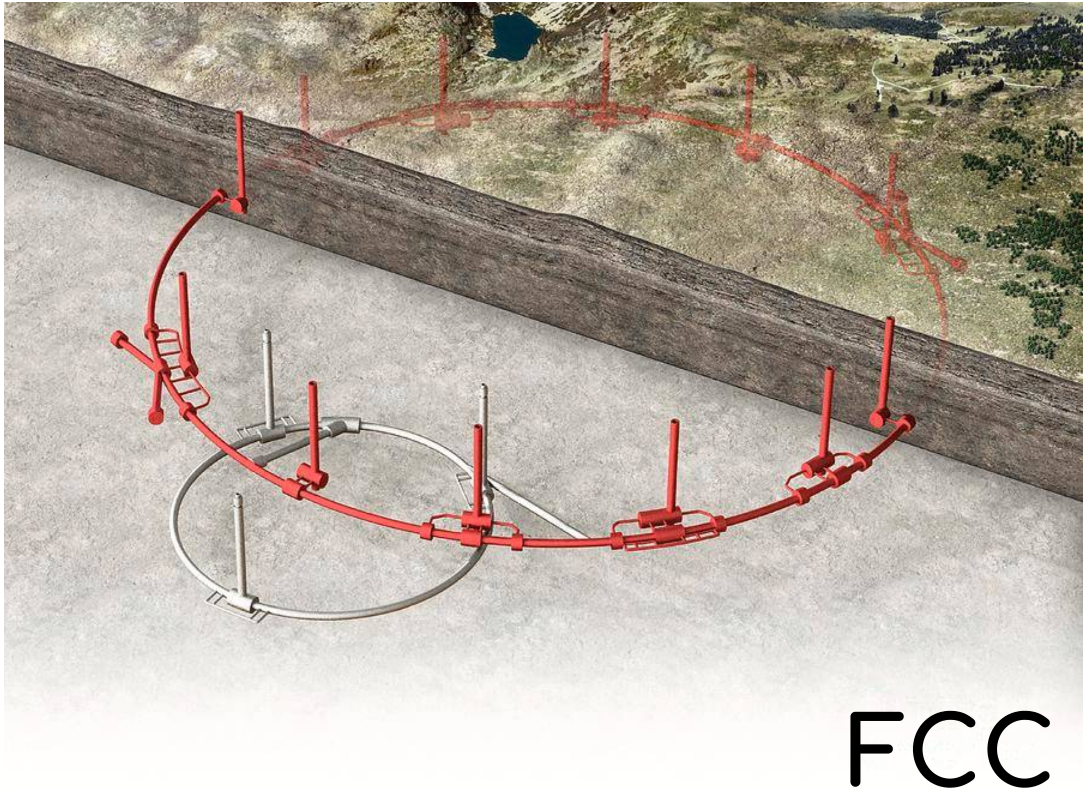

ILC

# Circular Colliders

## FCC-ee, CEPC

- Beams circulate after collisions
- Highest luminosity at Z/WW/ZH
- Synchrotron radiation limits energy range

  < 400 GeV
- Less energy efficient



FCC

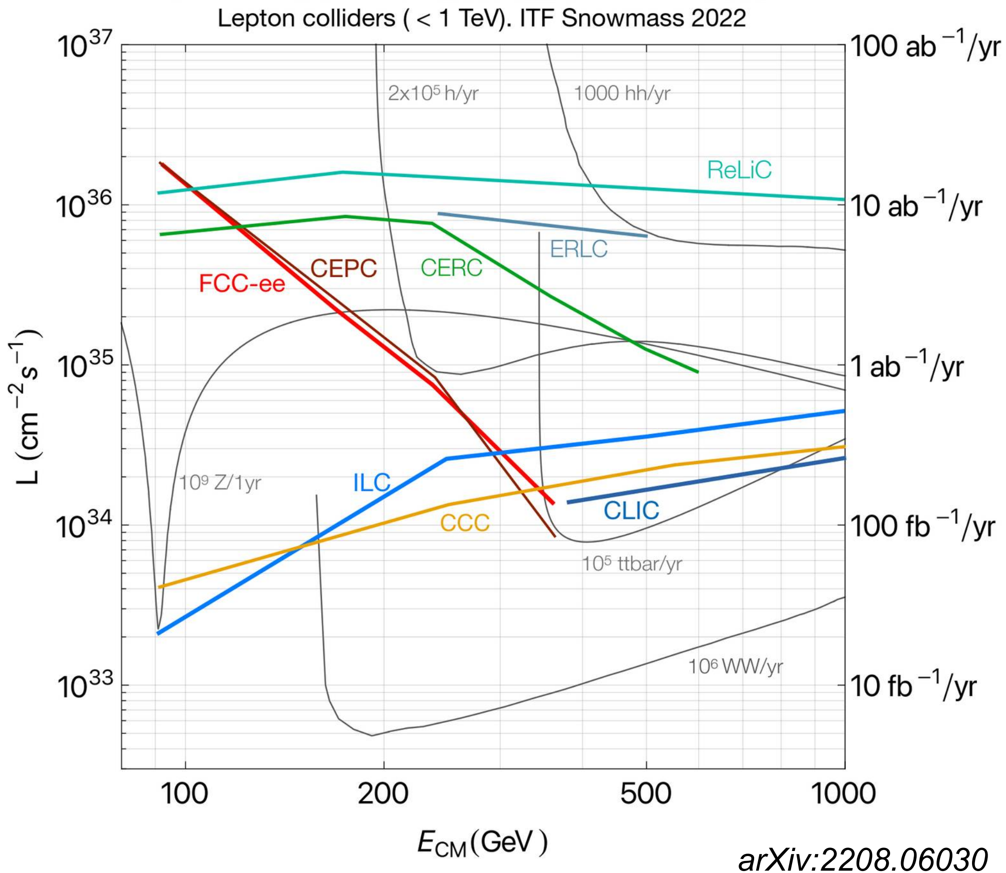
# *Physics Potential*

## Higgs Physics

- Driven by the number of Higgs bosons produced
- Linear and Circular options promise ~ same number of Higgses for proposed running

## Non-Higgs physics?

- Very different
- Precision Z and W program at circular collider
- Extension to higher energies feasible with linear colliders




*arXiv:2208.06030*

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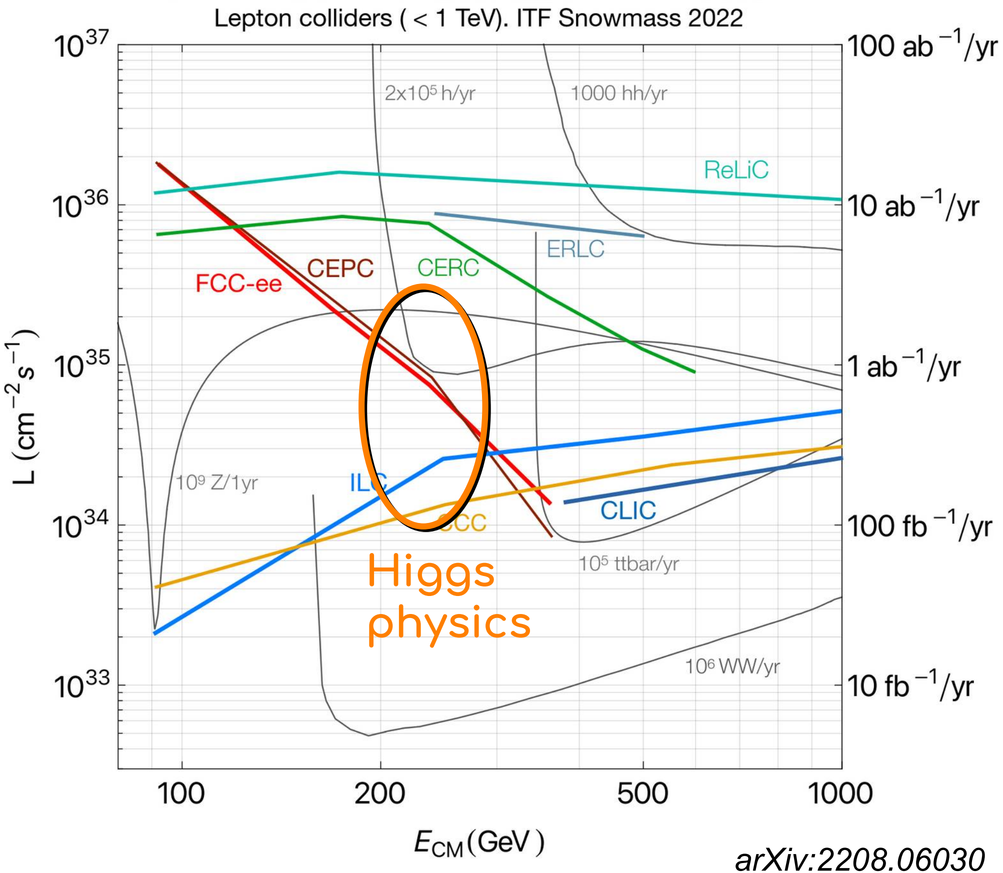


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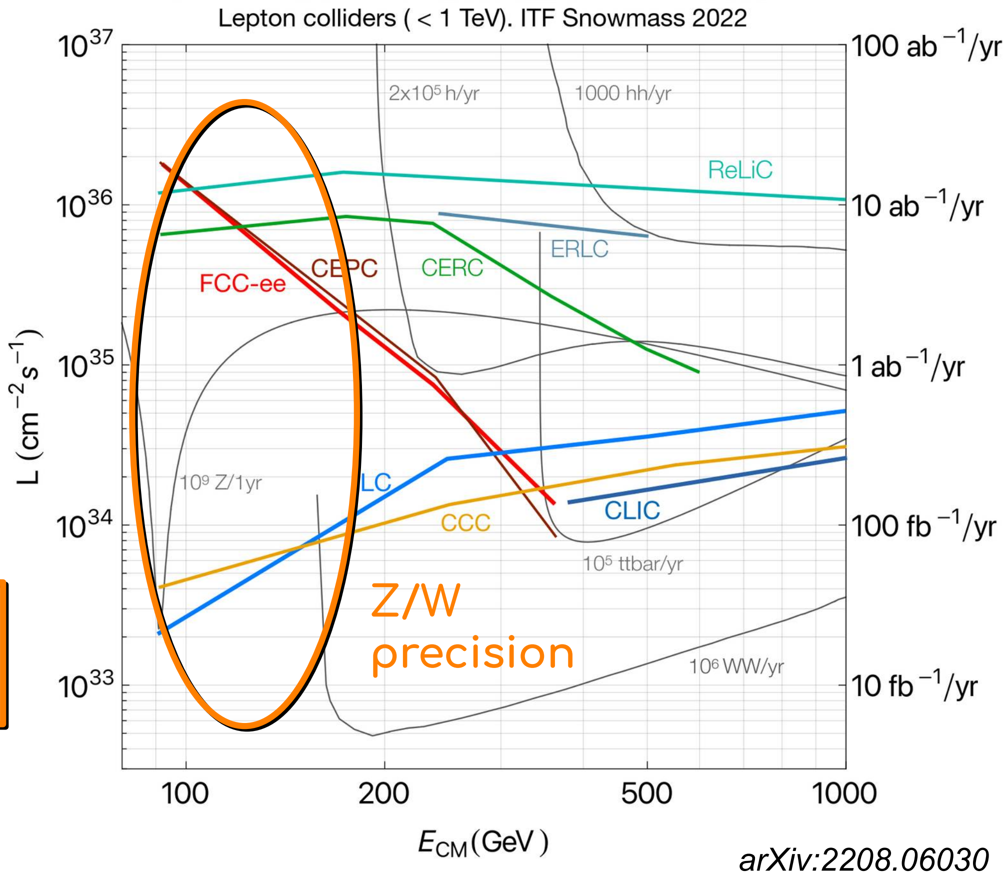


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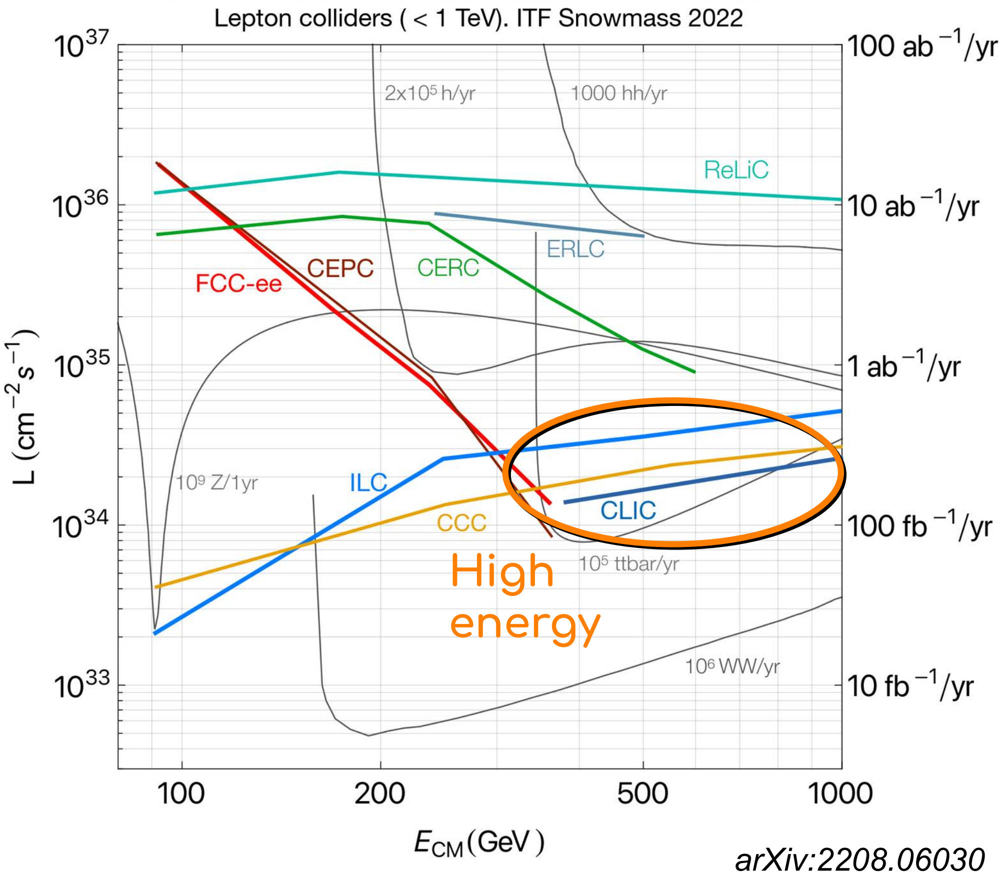



arXiv:2208.06030

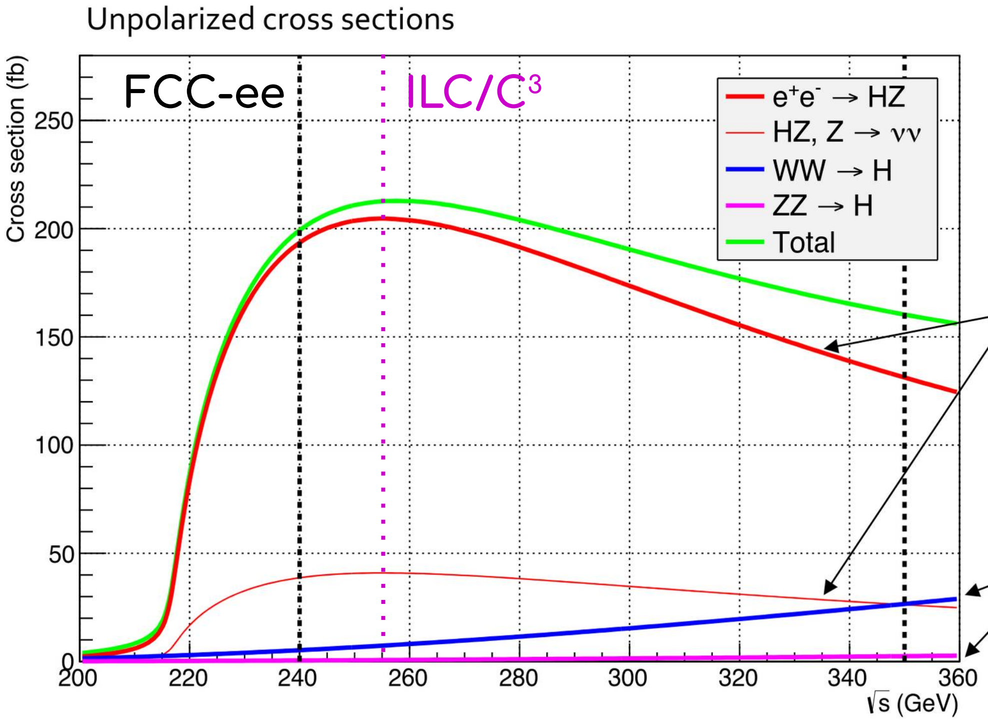
# *Higgs Production*

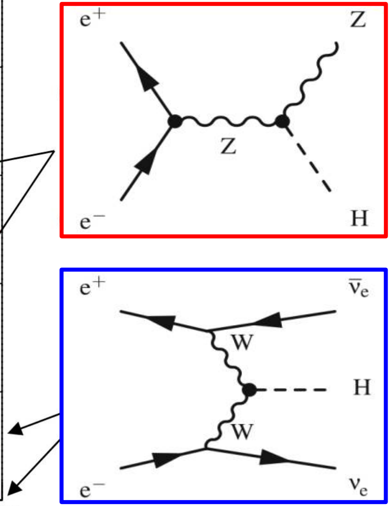
ZH Threshold turns on at 91 + 125 GeV = 216 Ge
reaches a maximum at around 255 GeV

Vector boson fusion rises steadily but is small

FCC-ee: most Higgses at 240 GeV for FCC-ee considering lumi profile

ILC/C³ best at peak




arXiv:1308.6176

# Higgs Reconstruction

## Leading strategy

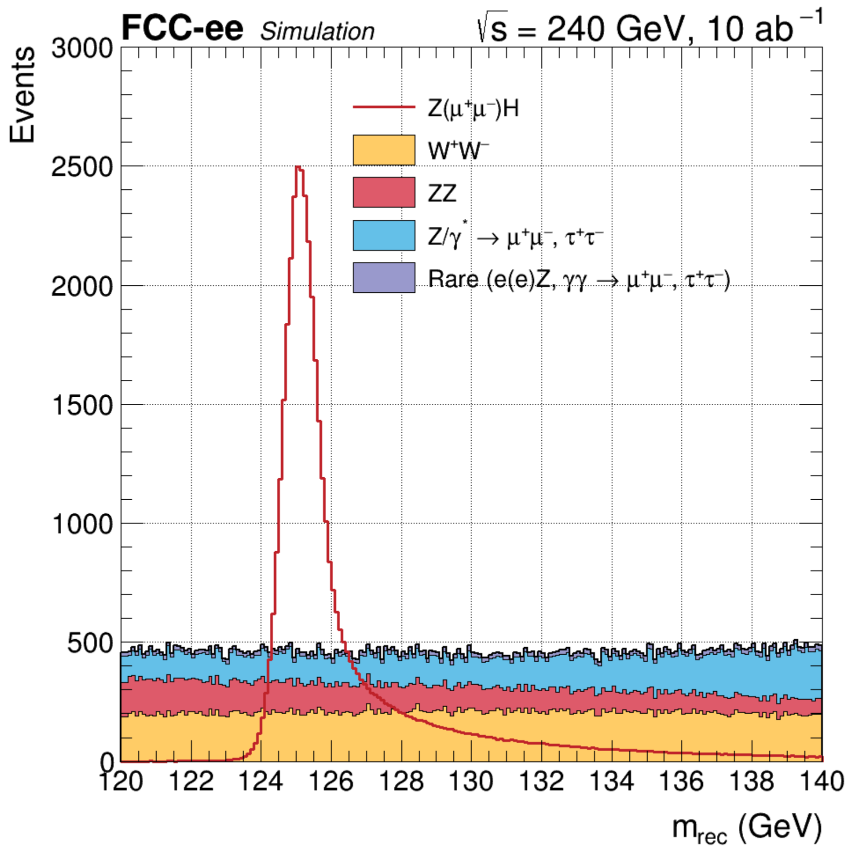
- Tag the Z boson (leptons or jets)
- Recoil mass peaks sharply at Higgs mass

$$m^2_{recoil} = (\sqrt{s} - E_{ff})^2 - p^2_{ff}$$
$$= s + m_Z^2 - 2E_{ff}\sqrt{s} \approx m_H^2$$

- Direct Higgs reconstruction not required, model independent $\sigma_{ZH}$ measurement
- Dominant background: WW, ZZ and Z/γ*

## Challenges

- Detectors: resolution, tracking, vertexing, timing, angular
- Flavour tagging for Higgs couplings
- Jet reconstruction algorithms

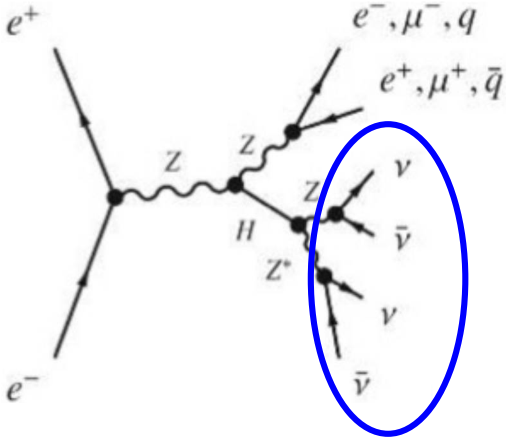



This plot does not work at hadron colliders.

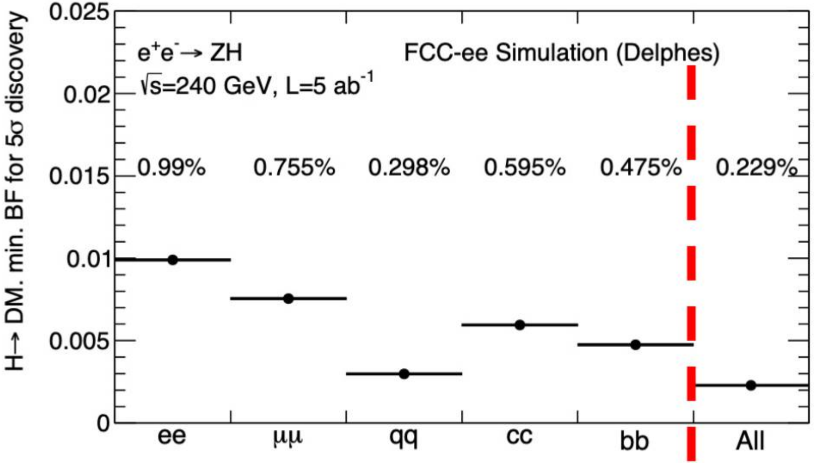
# Higgs Invisible Width

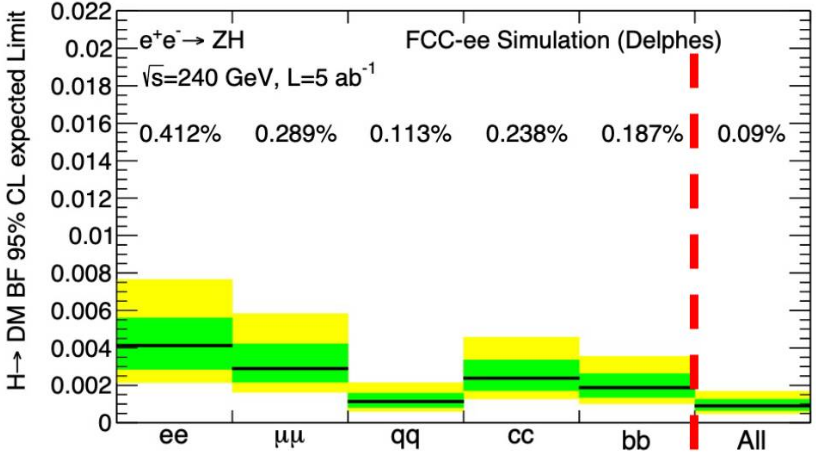
## Higgs boson: portal to dark world

- Reconstruct recoil mass
- Require no more activity beyond Z boson
- Measure H→ZZ→νννν
- Then remove as SM background

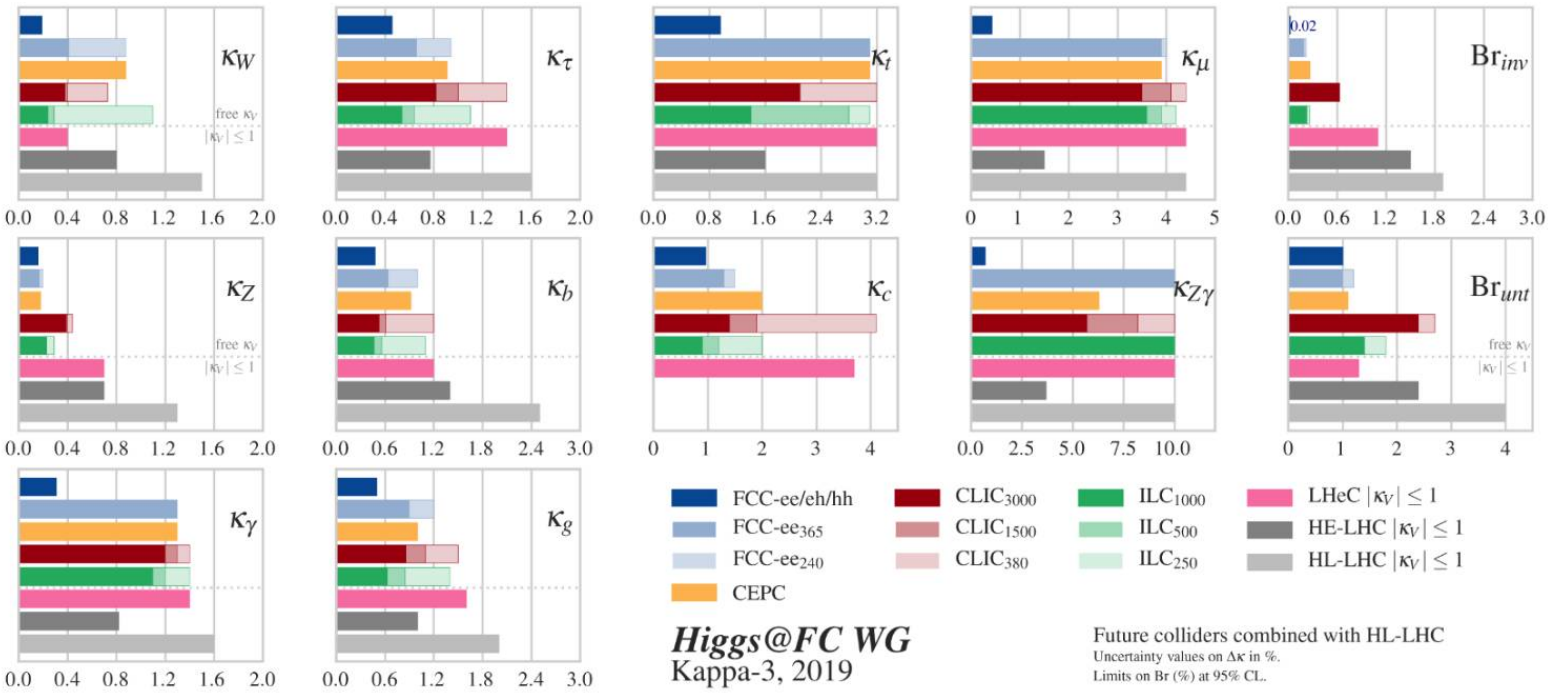



Invisible decay products



# Higgs Couplings Precision




Not very dependent on the $e^+e^-$ option

- Sensitivity to Higgs coupling is mostly around a percent
- Details of the uncertainties are dependent on the specific implementations

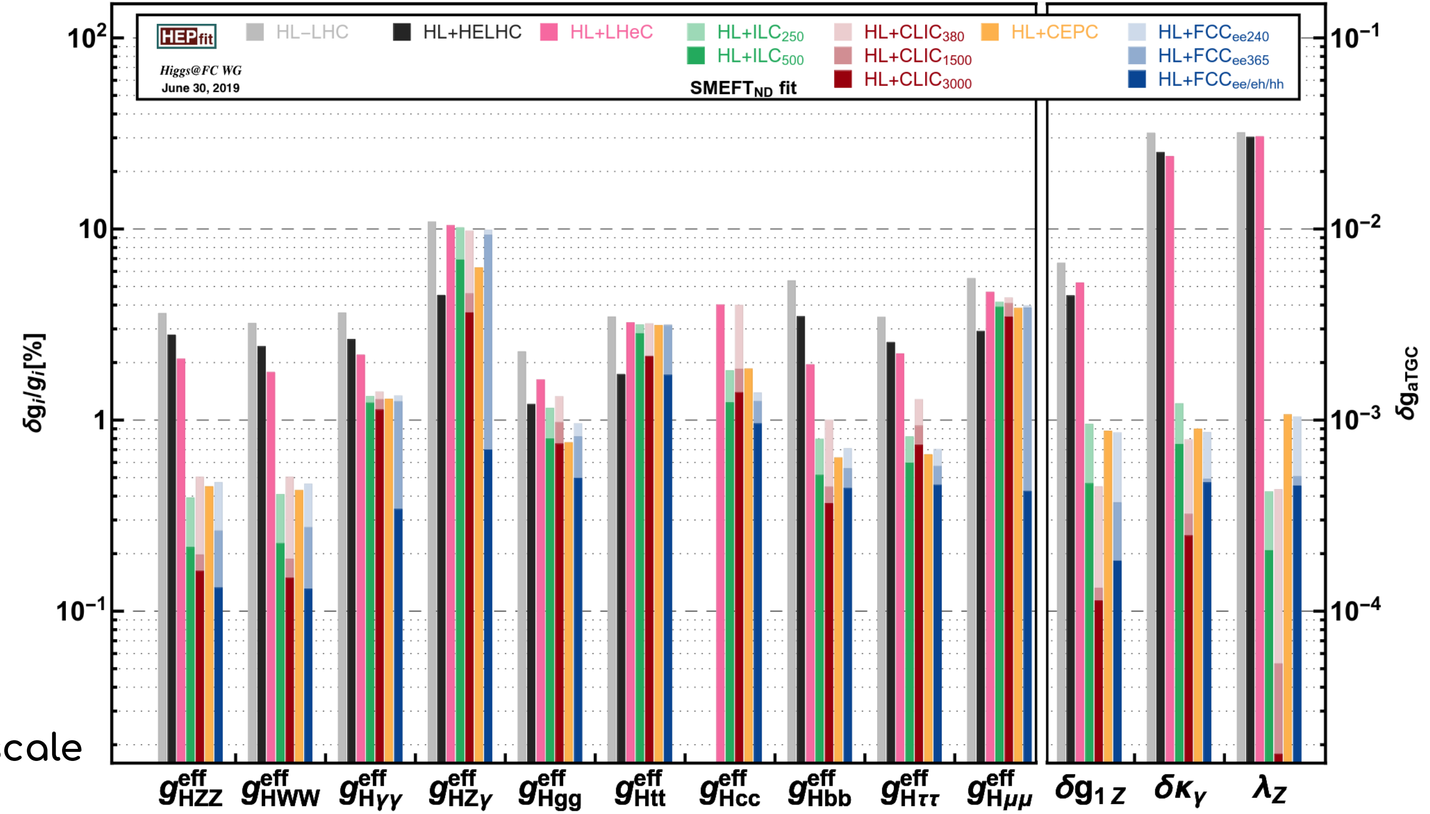
arXiv:2206.08326

# Higgs Couplings Precision

Sensitivity to deviations for

- Different effective Higgs couplings
- and aTGC

Note logarithmic scale




Higgs couplings

aTGC

arXiv:2206.08326

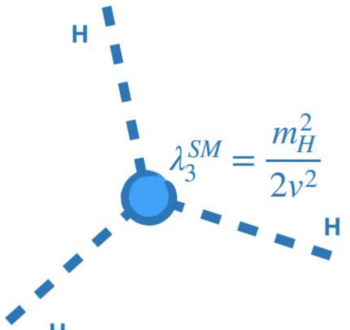
# Higgs Self Coupling

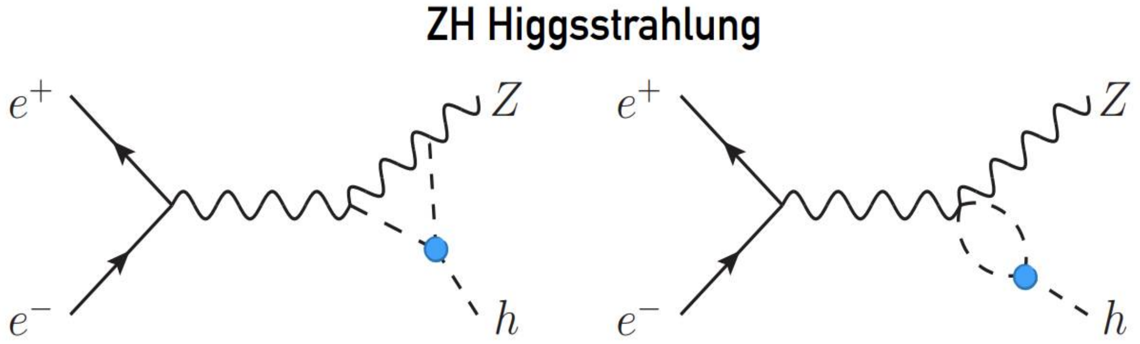
## Trilinear Higgs self coupling $\lambda_3$

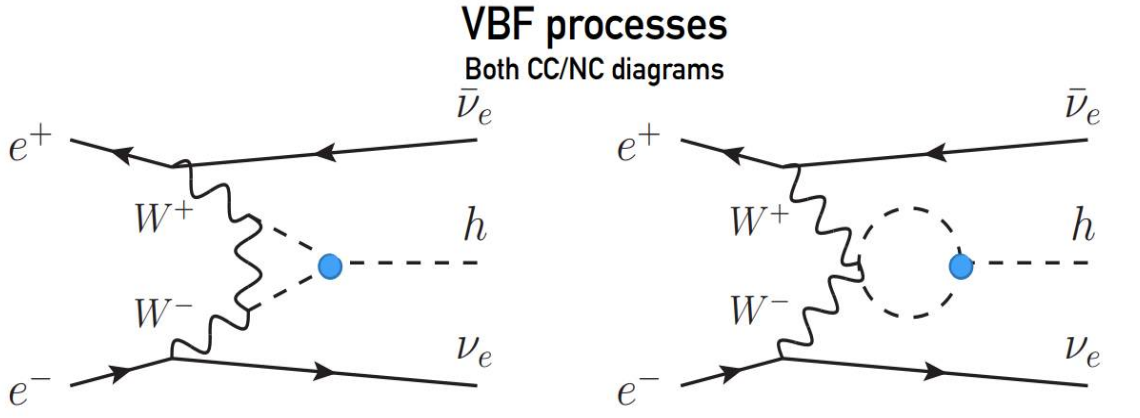
- Probe indirectly
- Single Higgs boson cross
- section

$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1 + \kappa_\lambda C_1)$$

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}$$



# Higgs Self Coupling

## Cross section measurement

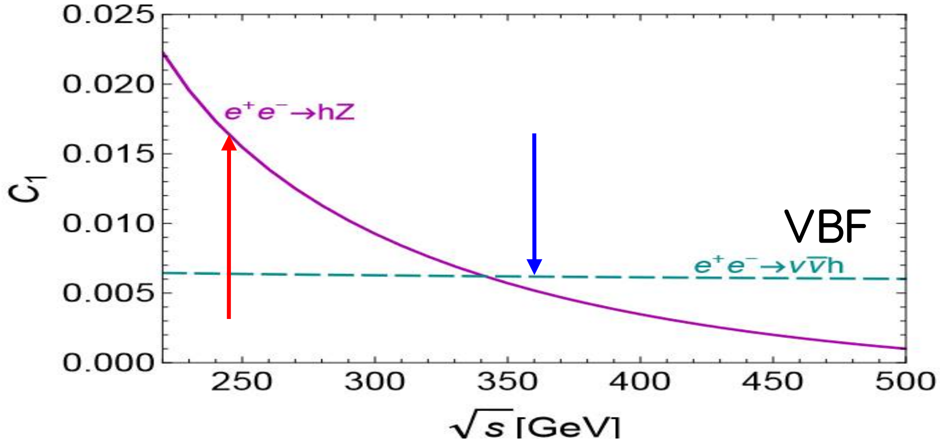
- Precision of ~1% (relies on Z→qq)
- Probing NLO deviations from SM

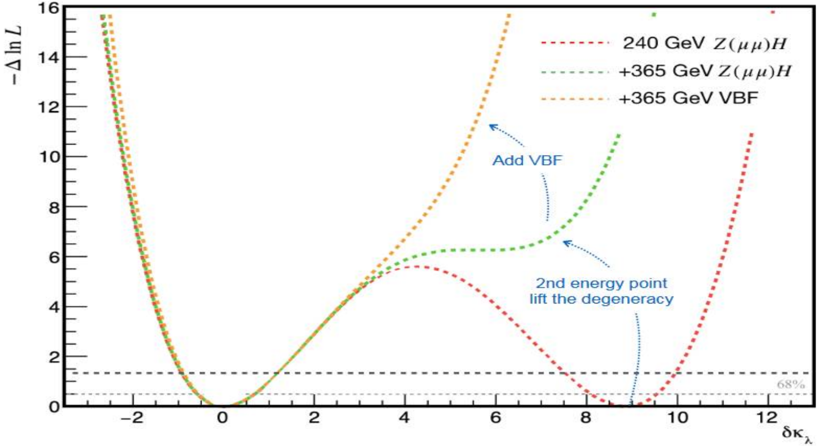
$$\delta\kappa_\lambda = \kappa_\lambda - 1$$

- C1 is sensitive to √s
- Exploit different √s to resolve ambiguities

$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1 + \kappa_\lambda C_1)$$

Projecting to reach
$\Delta\kappa_\lambda$ ~ 30% (FCC-ee study)

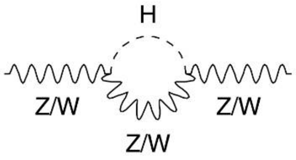


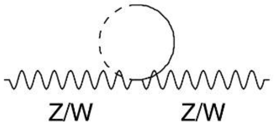



# Higgs Mass

$m_H$ enters radiative corrections

$$\sin^2\theta_W = \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{A^2}{1-\Delta r}$$




$\Delta r \sim \ln(m_H)$

$\Delta r \sim m_t^2$

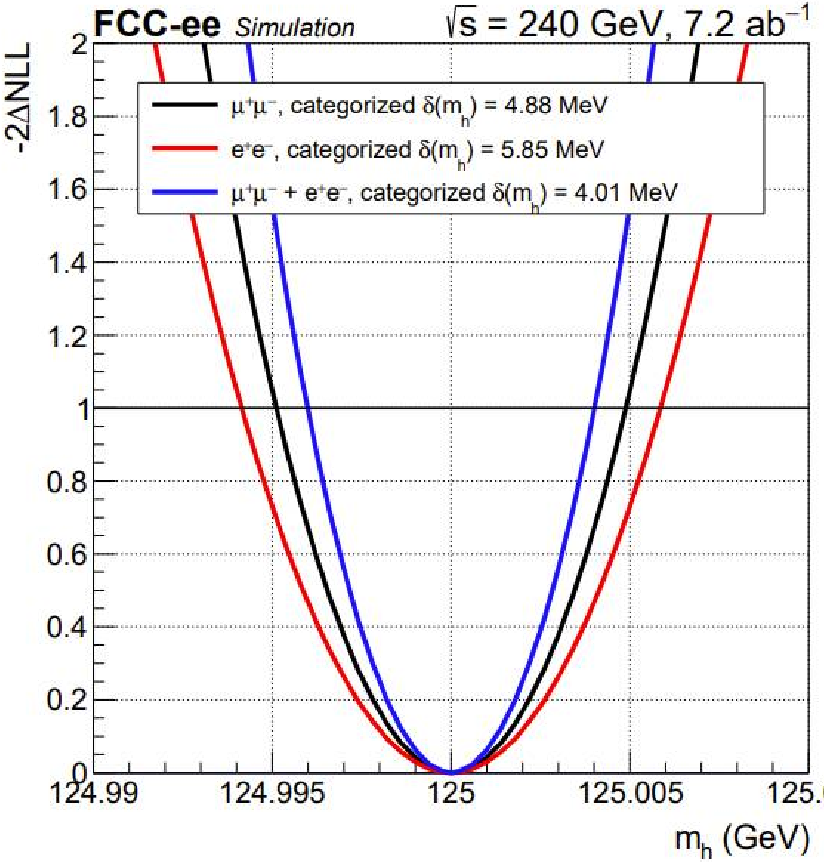
$\Delta r \sim$ new physics?

## Needs for Higgs factory

- Cross-sections at sub-percent level
- $\Delta m_H < O(10)$ MeV to control radiative corrections

## Roadmap for $\Delta m_H$

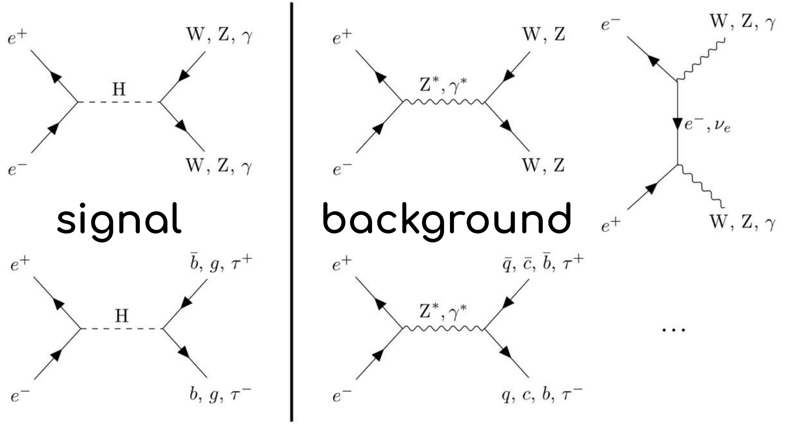
- Now: 150 MeV     HL-LHC: 20 MeV
- Higgs Factory: 4 MeV

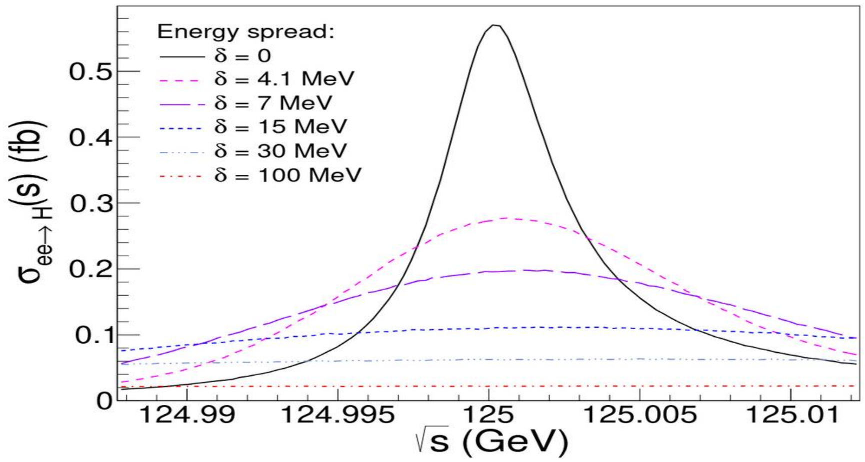


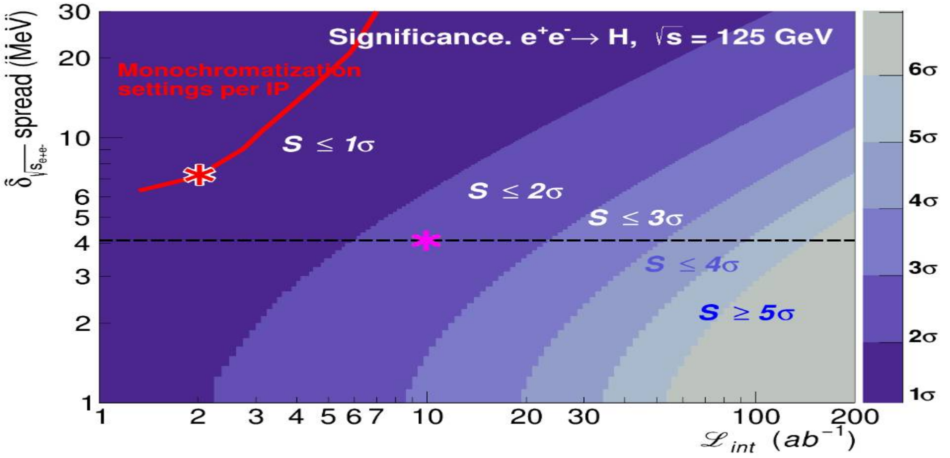
# Electron Yukawa Coupling

## Measure e+e- → H →$e^+e^-$: how?

- $\Gamma_H$ is 4.1 MeV, measure $m_H$ at MeV level
- Dial collider $E_{CM}$ to $m_H$
- Monochromatize energy: ~ 4 MeV spread
- Signal is tiny and background is very large
- 1.3 std significance per IP and per year

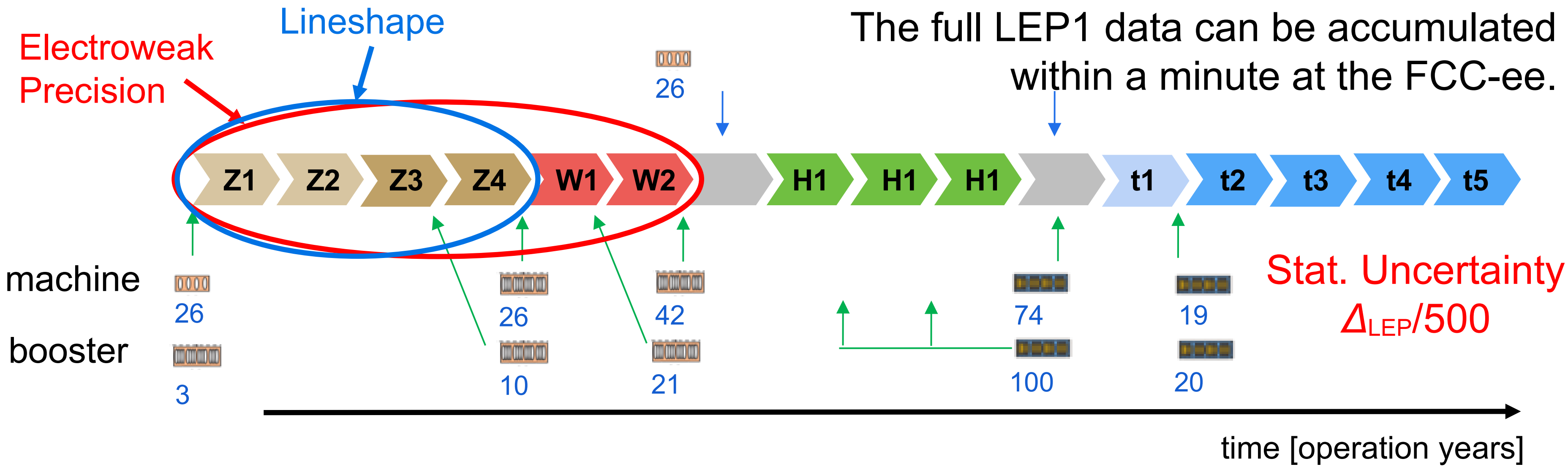



arXiv:2107.02686

# 'Circular Electroweak Opportunity'




| Working point | Z, years 1-2 | Z, later | WW, years 1-2 | WW, later | ZH | $t\bar{t}$ | |
|---|---|---|---|---|---|---|---|
| $\sqrt{s}$ (GeV) | 88, 91, 94 | | 157, 163 | | 240 | 340–350 | 365 |
| Lumi/IP ($10^{34}$ cm$^{-2}$s$^{-1}$) | 70 | 140 | 10 | 20 | 5.0 | 0.75 | 1.20 |
| Lumi/year (ab$^{-1}$) | 34 | 68 | 4.8 | 9.6 | 2.4 | 0.36 | 0.58 |
| Run time (year) | 2 | 2 | 2 | 0 | 3 | 1 | 4 |
| Number of events | $6\,10^{12}$ Z | | $2.4\,10^{8}$ WW | | $1.45\,10^{6}$ HZ + 45k WW → H | $1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW → H | |

# Lineshape Summary

Z pole run

| Quantity | current | ILC250 | ILC-GigaZ | FCC-ee | CEPC | CLIC380 |
|---|---|---|---|---|---|---|
| $\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$) | 17.8* | 17.8* | | 3.8 (1.2) | 17.8* | |
| $\Delta m_W$ (MeV) | 12* | 0.5 (2.4) | | 0.25 (0.3) | 0.35 (0.3) | |
| $\Delta m_Z$ (MeV) | 2.1* | 0.7 (0.2) | 0.2 | 0.004 (0.1) | 0.005 (0.1) | 2.1* |
| $\Delta m_H$ (MeV) | 170* | 14 | | 2.5 (2) | 5.9 | 78 |
| $\Delta\Gamma_W$ (MeV) | 42* | 2 | | 1.2 (0.3) | 1.8 (0.9) | |
| $\Delta\Gamma_Z$ (MeV) | 2.3* | 1.5 (0.2) | 0.12 | 0.004 (0.025) | 0.005 (0.025) | 2.3* |
| $\Delta\sigma^0_{\text{had}}$ (pb) | 37* | | | 0.035 (4) | 0.05 (2) | 37* |
| $\delta R_e$ ($\times 10^3$) | 2.4* | 0.5 (1.0) | 0.2 (0.5) | 0.004 (0.3) | 0.003 (0.2) | 2.7 |
| $\delta R_\mu$ ($\times 10^3$) | 1.6* | 0.5 (1.0) | 0.2 (0.2) | 0.003 (0.05) | 0.003 (0.1) | 2.7 |
| $\delta R_\tau$ ($\times 10^3$) | 2.2* | 0.6 (1.0) | 0.2 (0.4) | 0.003 (0.1) | 0.003 (0.1) | 6 |
| $\delta R_b$ ($\times 10^3$) | 3.0* | 0.4 (1.0) | 0.04 (0.7) | 0.0014 (< 0.3) | 0.005 (0.2) | 1.8 |
| $\delta R_c$($\times 10^3$) | 17* | 0.6 (5.0) | 0.2 (3.0) | 0.015 (1.5) | 0.02 (1) | 5.6 |

arXiv:2206.08326

# Lineshape Summary

WW threshold run

| Quantity | current | ILC250 | ILC-GigaZ | FCC-ee | CEPC | CLIC380 |
|---|---|---|---|---|---|---|
| $\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$) | 17.8* | 17.8* | | 3.8 (1.2) | 17.8* | |
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# Asymmetry Summary

| Quantity | current | ILC250 | ILC-GigaZ | FCC-ee | CEPC | CLIC380 |
|---|---|---|---|---|---|---|
| $\Delta A_e$ $(\times 10^5)$ | 190* | 14 (4.5) | 1.5 (8) | 0.7 (2) | 1.5 | 64 |
| $\Delta A_\mu$ $(\times 10^5)$ | 1500* | 82 (4.5) | 3 (8) | 2.3 (2.2) | 3.0 (1.8) | 400 |
| $\Delta A_\tau$ $(\times 10^5)$ | 400* | 86 (4.5) | 3 (8) | 0.5 (20) | 1.2 (6.9) | 570 |
| $\Delta A_b$ $(\times 10^5)$ | 2000* | 53 (35) | 9 (50) | 2.4 (21) | 3 (21) | 380 |
| $\Delta A_c$ $(\times 10^5)$ | 2700* | 140 (25) | 20 (37) | 20 (15) | 6 (30) | 200 |

A few points to note

- Z pole running creates substantially improved precision for all 'LEP' measurements by close to 3 orders of magnitude (statistically speaking)
- Major work for experimental and theory community to bring that precision to bear

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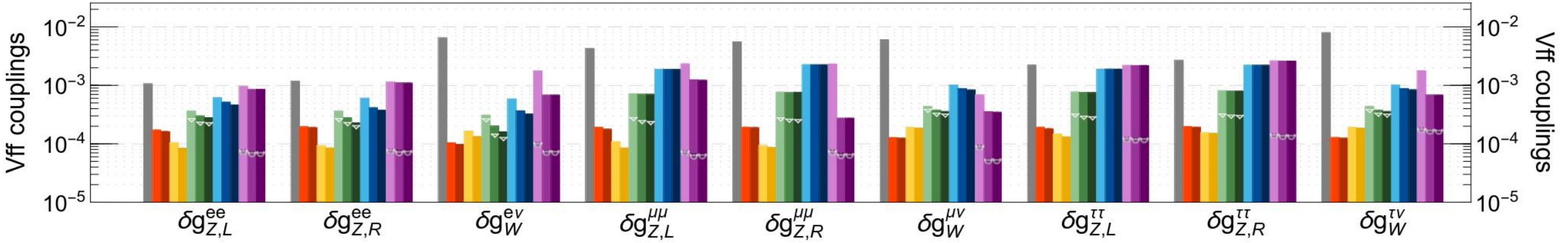
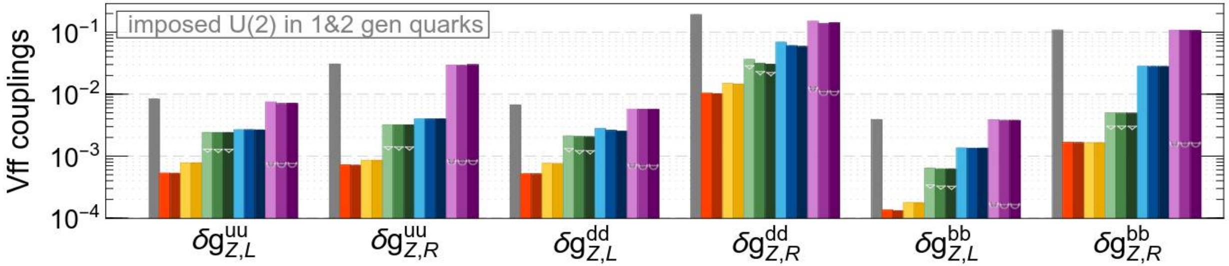
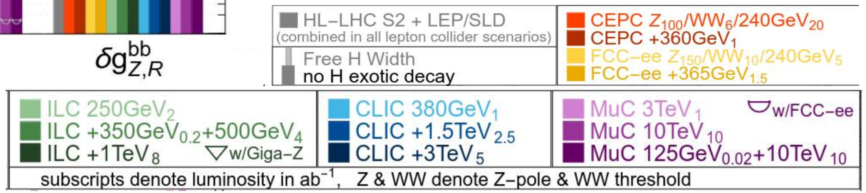
# *Global Fit focus W/Z couplings*




Note logarithmic scale




As expected

- Precision on couplings of W and Z bosons to fermions is more competitive at circular collider

*arXiv:2206.08326*

# Physics at the $t\bar{t}$ threshold

Typical plan for top threshold

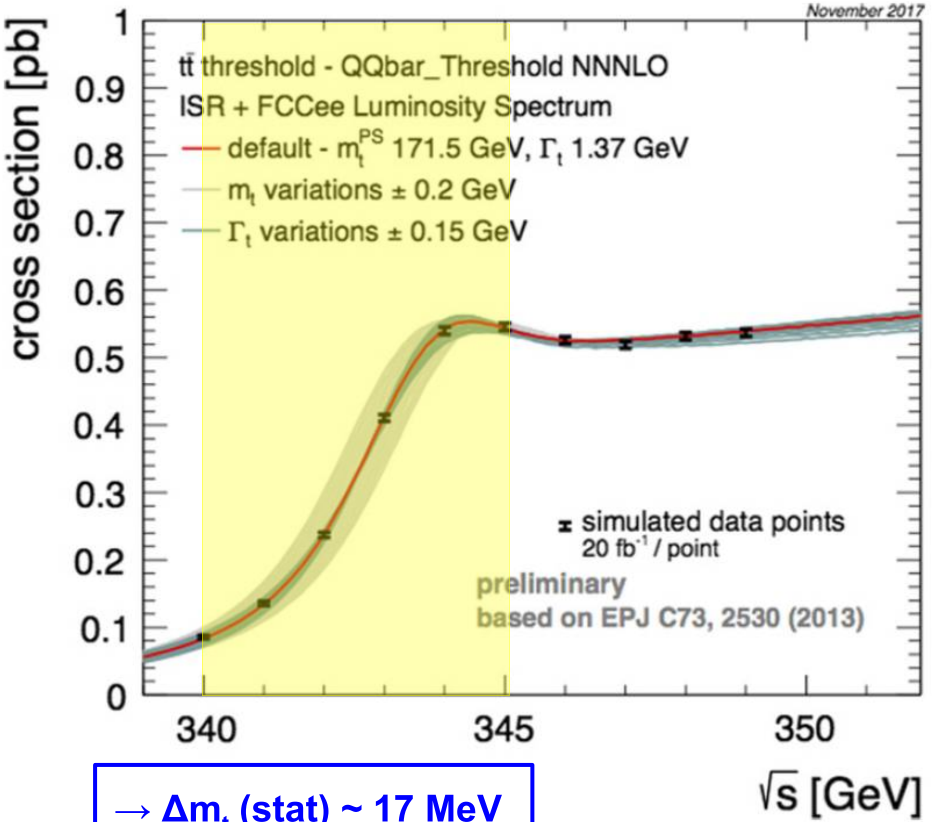
- 1 yr scan 340–350 GeV: ~ 1.4 $ab^{-1}$
- 4 yr at 365 GeV: ~ 2.3 $ab^{-1}$

Measure Top mass and width (similar as WW)

- From HL-LHC: $\Delta m_t$ = 0.5 GeV
- Width and mass are not fully correlated
- Constrain backgrounds (below) and ttH (above)
- Scan [340, 345], 6 points ~ 25 $fb^{-1}$ each

At 365 GeV, with 2.3 $ab^{-1}$

- Top and Higgs properties
- ee → $\nu\nu$H: total XS, couplings, width




→ $\Delta m_t$ (stat) ~ 17 MeV
→ $\Delta\Gamma_t$ (stat) ~ 45 MeV

# Conclusions

Candidates for Higgs Factories split into linear and circular

- Very similar and excellent Higgs physics program
- Detector requirements and designs are very similar too

Physics X-factor of linear colliders

- Center-of-mass energy reach higher and can be extended
- Allows study of four fermion couplings and other new physics

Physics X-factor of circular colliders

- At Z and WW energies the luminosity is substantially larger
- Several order of magnitude improvement of all  LEP measurements including couplings to W and Z bosons
- Provide infrastructure for future hadron collider