SMEFT at future lepton colliders

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Particle physics – how did we get here?

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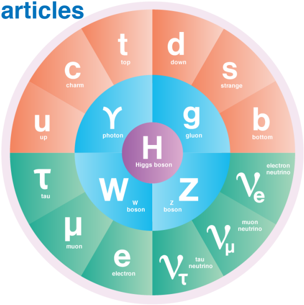
- Quantum Mechanics + Special Relativity = **Quantum Field Theory** !
  - Particles can be annihilated and created.
  - High energies ⇒ heavy new particles.
- **Build large colliders → go to high energy → discover new particles!**

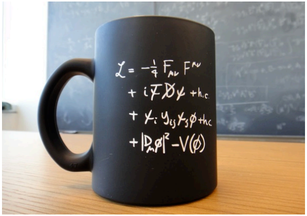
The Standard Model is complete!

particles

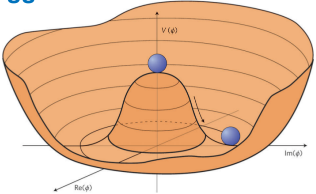


- Quarks, leptons, Gauge bosons, **Higgs**.
- **Gauge interactions:** $SU(3)_C \times SU(2)_L \times U(1)_Y$
- The Higgs vacuum expectation value (vev) breaks $SU(2)_L \times U(1)_Y$ to $U(1)_{EM}$, and gives particles masses.

interactions



Higgs mechanism



Higgs and nothing else?

- The **Higgs boson** was found at the Large Hadron Collider (LHC) in 2012.
  - Its couplings are consistent with the SM predictions.
- Evidences for physics beyond the Standard Model
  - Dark matter, Baryon asymmetry, Neutrino masses, Dark energy, ...
  - Hierarchy/Naturalness/Fine tuning problem
- **We haven’t found any new particles!**
- What’s next?
  - Build an even larger collider (~ 100 TeV)?
  - No guaranteed discovery!

A different path

- **Build large colliders → go to high energy → discover new particles!**

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  ↘ **do precision measurements → discover new physics indirectly!**

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- Higgs precision measurements
  - Measure the Higgs couplings, and see if they agree with the SM prediction.
  - Current LHC measurements are not precise enough ($\gtrsim 10\%$).

A different path

- **Build large colliders** $\rightarrow$ go to high energy $\rightarrow$ discover new particles!

  $\searrow$ **do precision measurements** $\rightarrow$ **discover new physics indirectly!**

- Higgs precision measurements
  - Measure the Higgs couplings, and see if they agree with the SM prediction.
  - Current LHC measurements are not precise enough ($\gtrsim 10\%$).

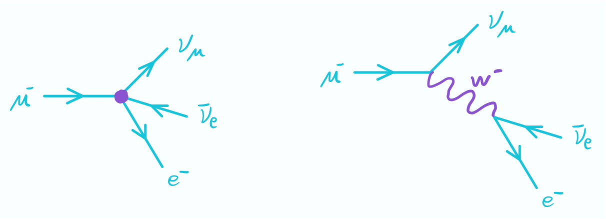
- How do we interpret the Higgs precision measurements?
  - Take your favorite model and calculate the modifications to Higgs couplings.
  - **EFT:** Bottom-up approach with general parameterization.
  - Why EFT? Well, we have no idea what the new physics is...

- **SM + Higher dimensional operators**

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots .$$

  - If $\Lambda \gg v$ and E, then **SM + dimension-6 operators** are sufficient to parameterize the physics around the electroweak scale.

A historical example: weak interaction



- **Fermi's theory of weak interaction**

$$\mathcal{L} = \frac{c_i^{(6)}}{\Lambda^2}(\bar{e}_L\gamma_\mu\nu_e)(\bar{\nu}_\mu\gamma^\mu\mu_L) + \text{h.c.}\,, \qquad \frac{c_i^{(6)}}{\Lambda^2} = \frac{-g^2/2}{m_W^2}$$

- An effective 4-fermion interaction at low energy replaced by the SM at high energy (the electroweak scale).
- Note: We don't know m_W from the measurement of muon decay!

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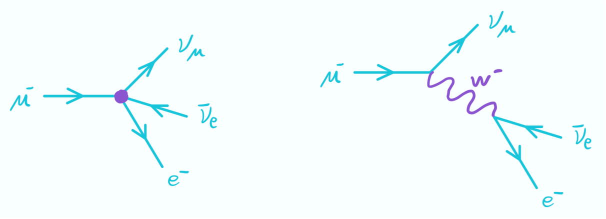

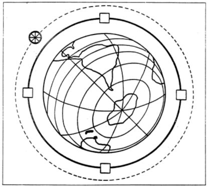

From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.

Fermi's idea of a "globaltron"

- **Fermi's theory of weak interaction**

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Why lepton colliders?

- **Higgs (and Z, W, top) factory!**
    - Large statistics, clean environment
      $\Rightarrow$ **precise measurements!**
- EFT is good for future lepton colliders.
    - A systematic parameterization of BSM contributions to Higgs and EW couplings.
    - If $v \ll \Lambda$, leading order contributions are parametrized by D6 operators.
- Future lepton colliders are also good for EFT!
    - High precision, relatively low energy $(E \ll \Lambda)$
      $\Rightarrow$ ideal for EFT studies!
    - **LHC is ideal for discovery, but ....**
- Poor measurements at the high energy tails lead to problems in the interpretation of EFT...

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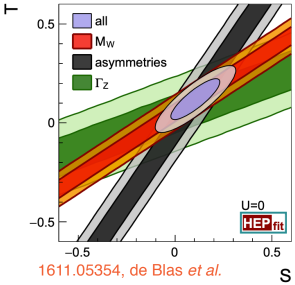
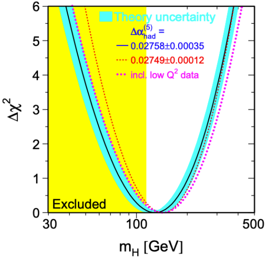
The Legacy of LEP/SLC

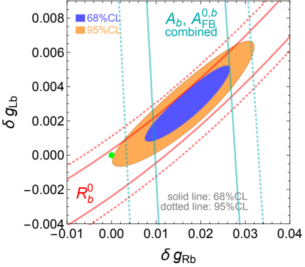
- **LEP:** circular collider before LHC
  SLC: linear collider at Stanford
- Z-factories (LEP ran up to $\sim 200\,$GeV)
- A prediction for the **Higgs mass**!
- Oblique parameters (**S&T**), $Z f\bar{f}$ couplings
  - Can be directly connected to dim-6 operators.



1611.05354, de Blas *et al.*



1508.07010, Gori, Gu, Wang

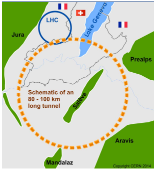


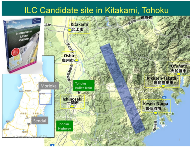
Future lepton (e^+e^-) colliders

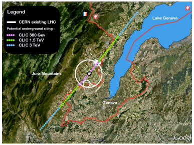
- Circular colliders
  - The Circular Electron-Positron Collider (CEPC) in China.
  - The Future Circular Collider (FCC-ee) at CERN.
  - 91 GeV(Z-pole), ~ 160 GeV(WW), 240 GeV(H) and $350(365)$ GeV($t\bar{t}$).
  - Large luminosity.
  - A natural step towards a 100 TeV hadron collider.

- Linear colliders
  - The International Linear Collider (ILC) in Japan.
  - The Compact Linear Collider (CLIC) at CERN.
  - ILC: 250 GeV, 350 GeV, 500 GeV (and possibly 1 TeV).
  - CLIC: 380 GeV, 1.5 TeV and 3 TeV.
  - Can go to higher $\sqrt{s}$, and also implement longitudinal beam polarizations.

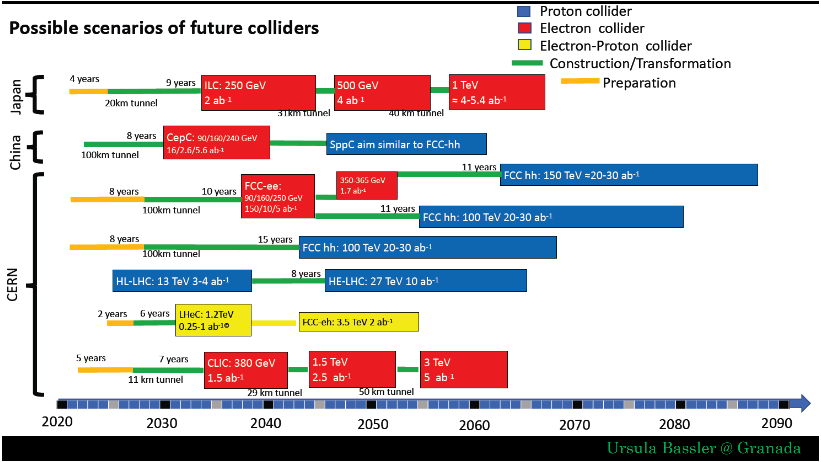
- Muon colliders, photon colliders... (not covered in this talk)



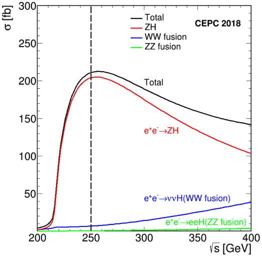


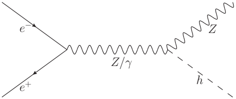


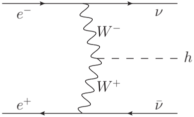
Possible timelines of future colliders

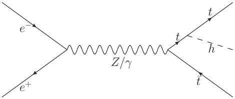


Higgs measurements





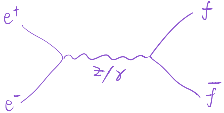




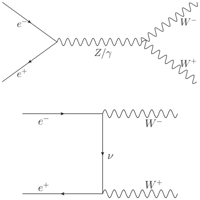
- $e^+e^- \to hZ$, cross section maximized at around 250 GeV.
- $e^+e^- \to \nu\bar{\nu}h$, cross section increases with energy.
- $e^+e^- \to t\bar{t}h$, can be measured with $\sqrt{s} \gtrsim 500$ GeV.
- $e^+e^- \to Zhh$ and $e^+e^- \to \nu\bar{\nu}hh$.

EW measurements

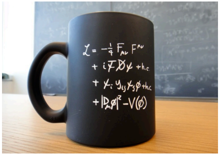
- ***Z*-pole**
  - $\sim 10^{11} - 10^{12}$ *Z*s at CEPC/FCC-ee.
  - How many *Z*s do we really need?



- $e^+e^- \to WW$, threshold scan, or "free data" at 240 GeV and above.
  - *W* mass, width, branching ratios.
  - anomalous Triple Gauge Couplings (**aTGCs**)
    - 3-TGC parameterization ⇒ full EFT parameterization
    - optimal observables...



SMEFT global analysis



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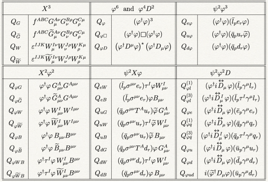
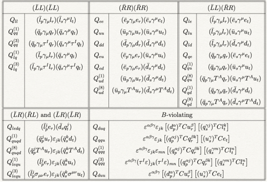


X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

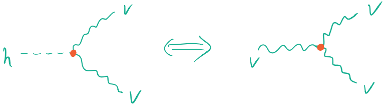
- Write down all D6 operators, **eliminate redundant ones** via field redefinition, integration by parts, equations of motion...
  - different choices of which operators to eliminate $\Rightarrow$ different bases
- 59 operators (76 parameters) for 1 generation, or 2499 parameters for 3 generations. [arXiv:1008.4884] Grzadkowski, Iskrzyński, Misiak, Rosiek, [arXiv:1312.2014] Alonso, Jenkins, Manohar, Trott.

  (See also [arXiv:2005.00008] Li, Ren, Shu, Xiao, Yu, Zheng, [arXiv:2005.00059] Murphy for d8 basis.)
- We can focus on Higgs and electroweak measurements
  - Usually ~ 20-30 parameters (instead of 2499)
  - **Why not just the Higgs?**

You can't really separate Higgs from the EW gauge bosons!

- $\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L,$
  $\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L,$
  $\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
  (or the ones with quarks)
  - modifies gauge couplings of fermions,
  - also generates $hVff$ type contact interaction.

- $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu},$
  $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
  - generate **aTGCs** $\delta g_{1,Z}$ and $\delta\kappa_\gamma$,
  - also generates HVV **anomalous couplings** such as $hZ_\mu \partial_\nu Z^{\mu\nu}$.



You also have to measure the Higgs!

- Some operators can only be probed with the **Higgs particle**.
- $|H|^2 W_{\mu\nu} W^{\mu\nu}$ and $|H|^2 B_{\mu\nu} B^{\mu\nu}$
  - $H \to v/\sqrt{2}$, corrections to gauge couplings?
  - Can be absorbed by field redefinition! This applies to any operators in the form $|H|^2\mathcal{O}_{\rm SM}$.

$$
\begin{aligned}
c_{\rm SM}\mathcal{O}_{\rm SM} \quad vs. \quad & c_{\rm SM}\mathcal{O}_{\rm SM} + \frac{c}{\Lambda^2}|H|^2\mathcal{O}_{\rm SM} \\
&= (c_{\rm SM} + \frac{c\,v^2}{2\,\Lambda^2})\mathcal{O}_{\rm SM} + \text{terms with } h \\
&= c'_{\rm SM}\mathcal{O}_{\rm SM} + \text{terms with } h
\end{aligned}
$$

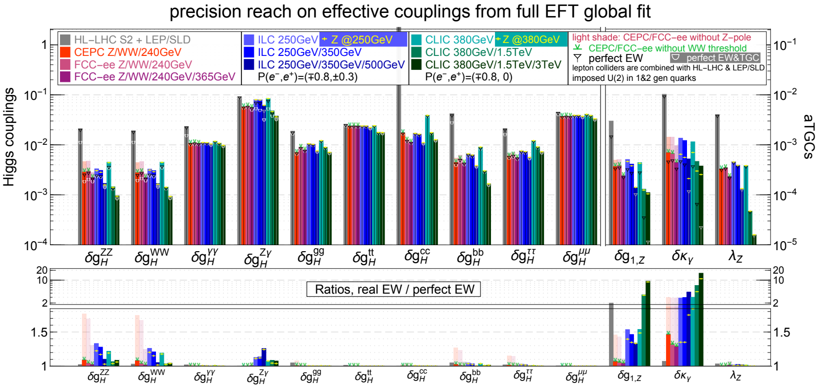
  - probed by measurements of the $h\gamma\gamma$ and $hZ\gamma$ couplings, or the hWW and hZZ anomalous couplings.
  - or Higgs in the loop (different story...)
- Yukawa couplings, Higgs self couplings, ...

Global fit

- **Global fit**
  - Simultaneously fitting all parameters with all measurements.
  - Usually ~ 20-30 parameters (instead of 2499) if we focus on Higgs and electroweak measurements.
    - Cross sections, branching ratios, differential distributions...
    - Z-pole observables, diboson process ($e^+e^- \to WW$)
- **Limits on all the $\frac{c_i^{(6)}}{\Lambda^2}$**
  - Results depend on operator bases, conventions, ...
- **Or present the results in terms of effective couplings?**
  ([arXiv:1708.08912], [arXiv:1708.09079], Peskin *et al.*)
  - $g(hZZ)$, $g(hWW)$ are defined at the scale of the relavent Higgs decay.
    $g(hZZ) \propto \sqrt{\Gamma(h \to ZZ)}\,, \quad g(hWW) \propto \sqrt{\Gamma(h \to WW)}\,.$
  - Intuitive, can be interpreted as “Higgs couplings.”
  - Gives you the illusion that you understand the results...
- Present the result with some fancy bar plots!

“Full fit” projected on the Higgs couplings (and aTGCs)

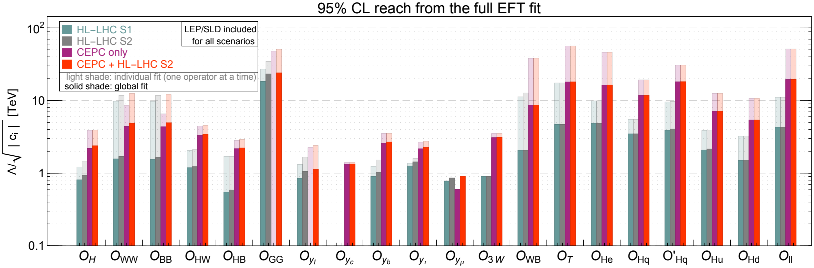
[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul, see also Higgs@FutureColliders WG report



precision reach on effective couplings from full EFT global fit

- 28-parameter fit, projected on the Higgs couplings & aTGCs.
- Lepton colliders are combined with HL-LHC & LEP/SLD.
- The *hZZ* and *hWW* couplings are not independent!

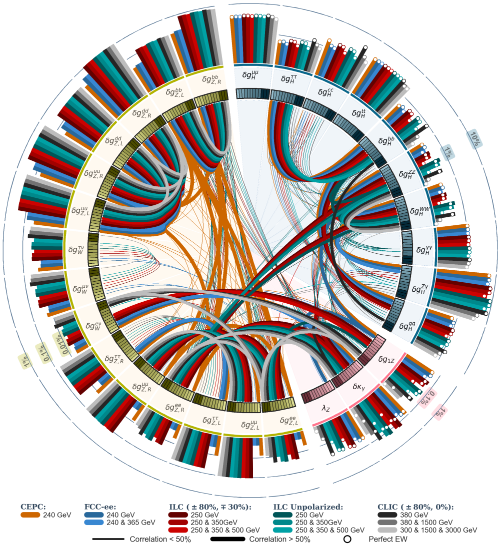
Reach on the scale of new physics



- Reach on the scale of new physics Λ.
- Note: reach depends on the couplings c_i!

State-of-the-art fit results...

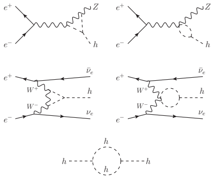
[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul

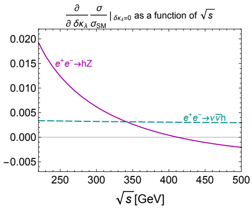


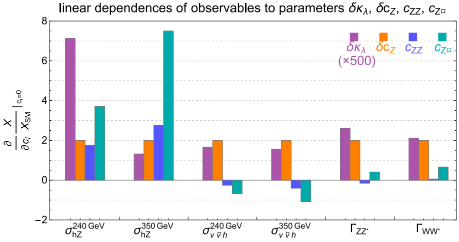
- "Full EFT fit" with Higgs and electroweak measurements.
- The correlations are shown in the center of the circle.

Triple Higgs coupling at circular colliders (240 & 350-365 GeV)

[arXiv:1711.03978] Di Vita, Durieux, Grojean, JG, Liu, Panico, Riembau, Vantalon

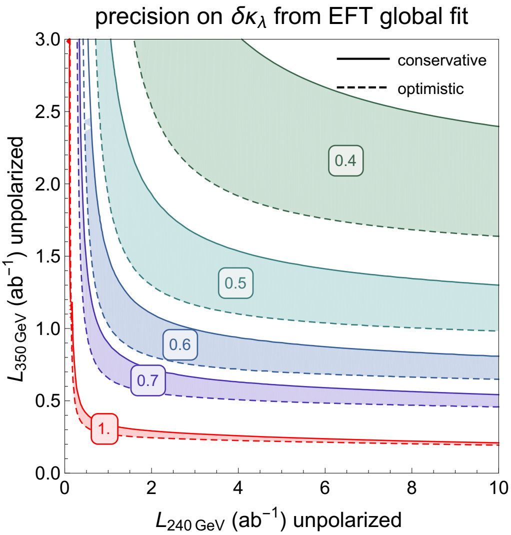






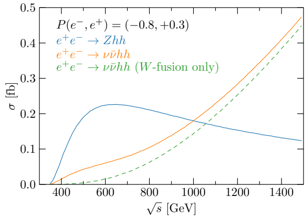
- $\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}}$,
  $\delta\kappa_\lambda \equiv \kappa_\lambda - 1 = c_6 - \frac{3}{2}c_H$,
  with $\mathcal{L} \supset -\frac{c_6\,\lambda}{v^2}(H^\dagger H)^3$.
- One loop corrections to all Higgs couplings (production and decay).
- 240 GeV: *hZ* near threshold (more sensitive to $\delta\kappa_\lambda$)
- at 350-365 GeV:
  - WW fusion
  - *hZ* at a different energy
- $h \to WW^* / ZZ^*$ also have some discriminating power (but turned out to be not enough).

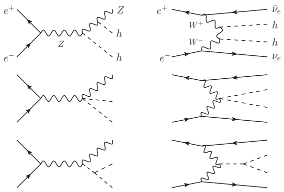
Triple Higgs coupling at circular colliders [arXiv:1711.03978]



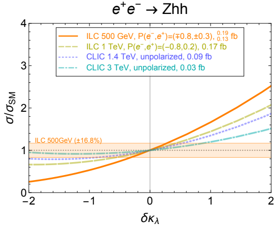
- Runs at two different energies (240 GeV and 350/360 GeV) are needed to obtain good constraints on the triple Higgs coupling (in a global fit)!

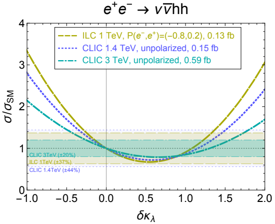
Double-Higgs measurements ($e^+e^- \to Zhh$ & $e^+e^- \to \nu\bar{\nu}hh$) [arXiv:1711.03978]

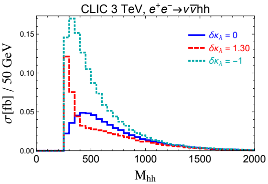




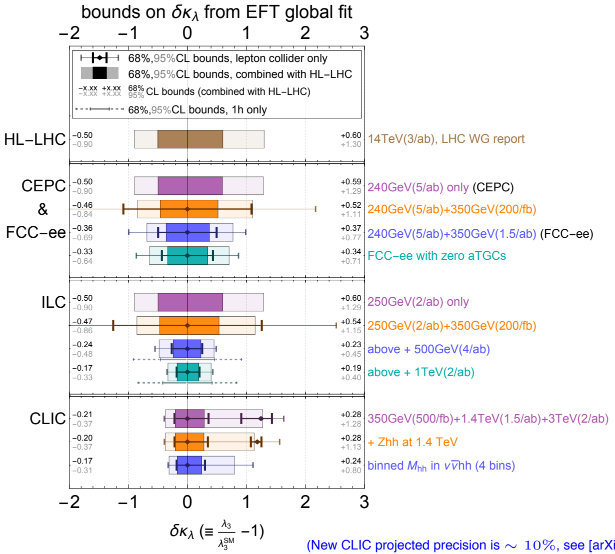
- Destructive interference in $e^+e^- \to \nu\bar{\nu}hh$! The square term is important.
- *hh* invariant mass distribution helps discriminate the "2nd solution."


$e^+e^- \to Zhh$


$e^+e^- \to \nu\bar{\nu}hh$

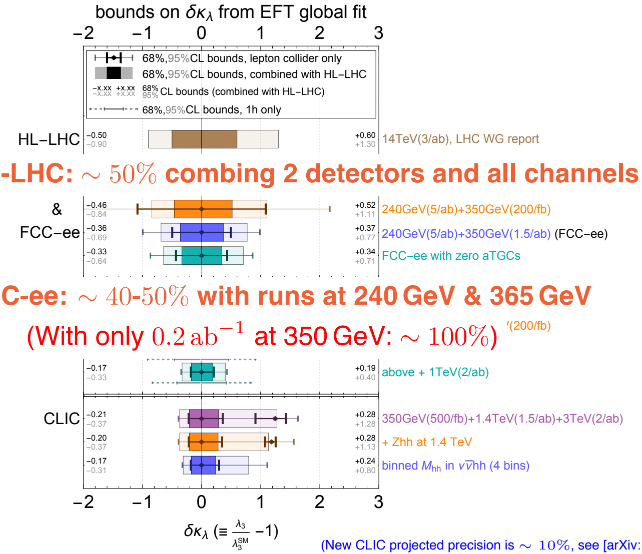

CLIC 3 TeV, $e^+e^- \to \nu\bar{\nu}hh$

Triple Higgs coupling from global fits [arXiv:1711.03978]



(New CLIC projected precision is $\sim 10\%$, see [arXiv:1901.05897] Roloff *et al.*)

Triple Higgs coupling from global fits [arXiv:1711.03978]



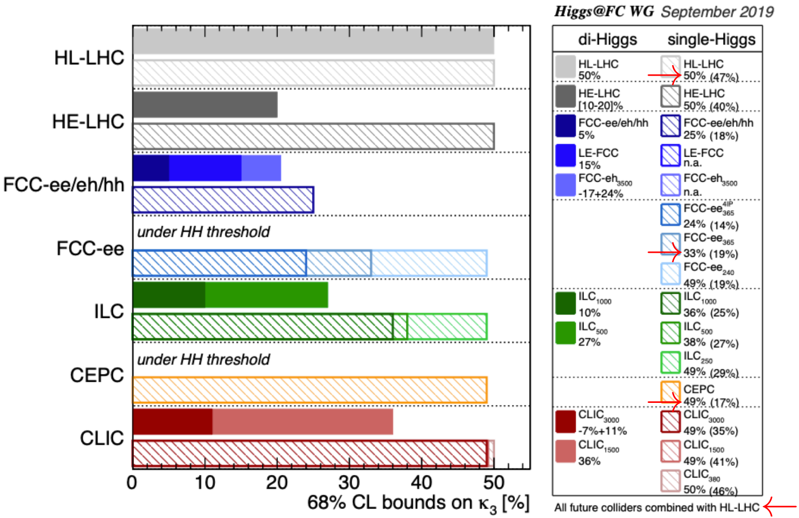
HL-LHC: $\sim 50\%$ combing 2 detectors and all channels

FCC-ee: $\sim$ 40-50% with runs at 240 GeV & 365 GeV

(With only $0.2\,\mathrm{ab}^{-1}$ at 350 GeV: $\sim 100\%$)

(New CLIC projected precision is $\sim 10\%$, see [arXiv:1901.05897] Roloff *et al.*)

Triple Higgs coupling (Higgs@FutureColliders WG, [arXiv:1905.03764])

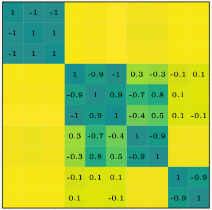


Top EFT [arXiv:1807.02121] Durieux, Perelló, Vos, Zhang

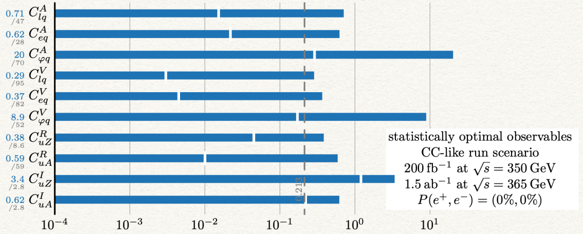
$$
\begin{aligned}
O^{1}_{\varphi q} &\equiv \tfrac{y_t^2}{2}\ \bar{q}\gamma^{\mu}q\ \ \varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi, & O_{uG} &\equiv y_t g_s\ \ \bar{q}T^{A}\sigma^{\mu\nu}u\ \ \epsilon\varphi^{*}G^{A}_{\mu\nu},\\
O^{3}_{\varphi q} &\equiv \tfrac{y_t^2}{2}\ \bar{q}\tau^{I}\gamma^{\mu}q\ \ \varphi^{\dagger}i\overleftrightarrow{D}^{I}_{\mu}\varphi, & O_{uW} &\equiv y_t g_W\ \ \bar{q}\tau^{I}\sigma^{\mu\nu}u\ \ \epsilon\varphi^{*}W^{I}_{\mu\nu},\\
O_{\varphi u} &\equiv \tfrac{y_t^2}{2}\ \bar{u}\gamma^{\mu}u\ \ \varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi, & O_{dW} &\equiv y_t g_W\ \ \bar{q}\tau^{I}\sigma^{\mu\nu}d\ \ \epsilon\varphi^{*}W^{I}_{\mu\nu},\\
O_{\varphi ud} &\equiv \tfrac{y_t^2}{2}\ \bar{u}\gamma^{\mu}d\ \ \varphi^{T}\epsilon\, iD_{\mu}\varphi, & O_{uB} &\equiv y_t g_Y\ \ \bar{q}\sigma^{\mu\nu}u\ \ \epsilon\varphi^{*}B_{\mu\nu},
\end{aligned}
$$

$$
\begin{aligned}
O^{1}_{lq} &\equiv \tfrac{1}{2}\ \bar{q}\gamma_{\mu}q\ \ \bar{l}\gamma^{\mu}l,\\
O^{3}_{lq} &\equiv \tfrac{1}{2}\ \bar{q}\tau^{I}\gamma_{\mu}q\ \ \bar{l}\tau^{I}\gamma^{\mu}l,\\
O_{lu} &\equiv \tfrac{1}{2}\ \bar{u}\gamma_{\mu}u\ \ \bar{l}\gamma^{\mu}l,\\
O_{eq} &\equiv \tfrac{1}{2}\ \bar{q}\gamma_{\mu}q\ \ \bar{e}\gamma^{\mu}e,\\
O_{eu} &\equiv \tfrac{1}{2}\ \bar{u}\gamma_{\mu}u\ \ \bar{e}\gamma^{\mu}e,
\end{aligned}
$$

- Also need to include **top dipole** interactions and *eett* contact interactions!
- Hard to resolve the top couplings from $4f$ interactions with just the 365 GeV run.
    - Can't really separate $e^+e^- \to Z/\gamma \to t\bar{t}$ from $e^+e^- \to Z' \to t\bar{t}$.
    - Is that a big deal?



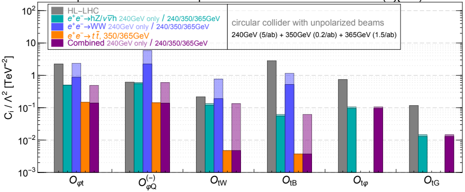
1	-1	-1							
-1	1	1							
-1	1	1							
			1	-0.9	-1	0.3	-0.3	-0.1	0.1
			-0.9	1	0.9	-0.7	0.8	0.1	
			-1	0.9	1	-0.4	0.5	0.1	-0.1
			0.3	-0.7	-0.4	1	-0.9		
			-0.3	0.8	0.5	-0.9	1		
			-0.1	0.1	0.1			1	-0.9
			0.1		-0.1			-0.9	1



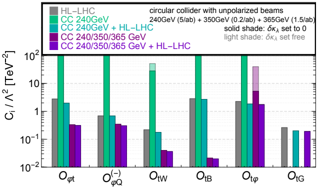
statistically optimal observables
CC-like run scenario
200 fb^{-1} at $\sqrt{s} = 350$ GeV
1.5 ab^{-1} at $\sqrt{s} = 365$ GeV
$P(e^+, e^-) = (0\%, 0\%)$

Top operators in loops [arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang

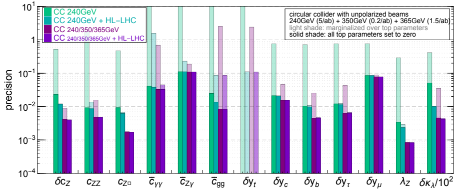
precision of individual operator coefficients at LHC and CC ($\Delta\chi^2$=1)



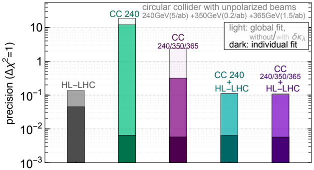
precision of top operator coefficients (global fit, $\Delta\chi^2$=1)



precision of the Higgs parameters at CC (global fit, $\Delta\chi^2$=1)

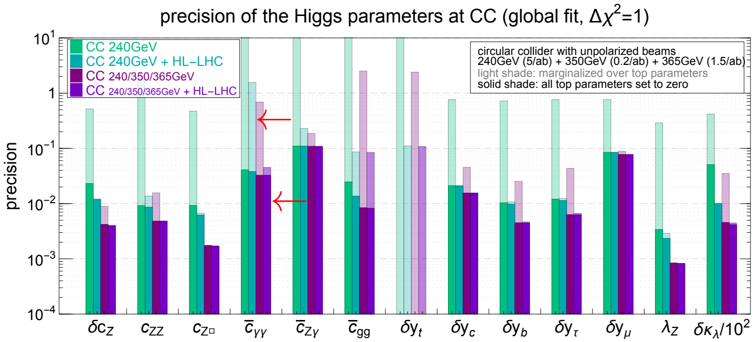


precision reach on the top Yukawa coupling

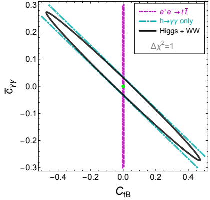


- Higgs precision measurements have sensitivity to the top operators in the loops.
    - But it is challenging to discriminate many parameters in a global fit!
- HL-LHC helps, but a 360 or 365 GeV run is better.
- Indirect bounds on the top Yukawa coupling.

Top operators in loops



- $O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\varphi} B_{\mu\nu} + h.c.$ is not very well constrained at the LHC, and it generates dipole interactions that contributes to the $h\gamma\gamma$ vertex.
- Deviations in $h\gamma\gamma$ coupling $\Rightarrow$ run at ~ 365 GeV to confirm?

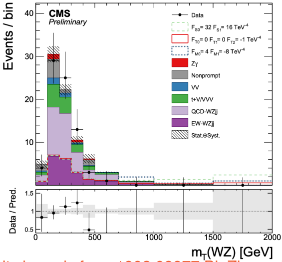


Probing dimension-8 operators?

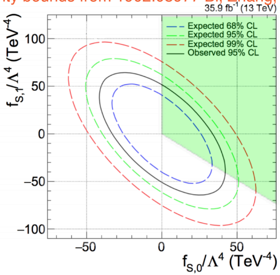
- The dimension-8 contribution has a large energy enhancement ($\sim E^4/\Lambda^4$)!
- It is difficult for LHC to probe these bounds.
  - Low statistics in the high energy bins.
  - Example: Vector boson scattering.
  - $\Lambda \lesssim \sqrt{s}$, the EFT expansion breaks down!
- Can we separate the dim-8 and dim-6 effects?
  - Precision measurements at several different $\sqrt{s}$?

    (A **very** high energy lepton collider?)
  - Or find some special process where dim-8 gives the leading new physics contribution?

CMS-PAS-SMP-18-001



positivity bounds from 1902.08977 Bi, Zhang, Zhou

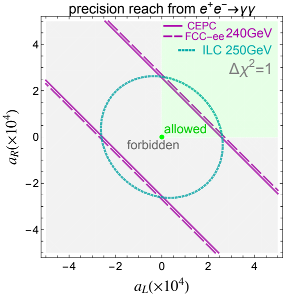


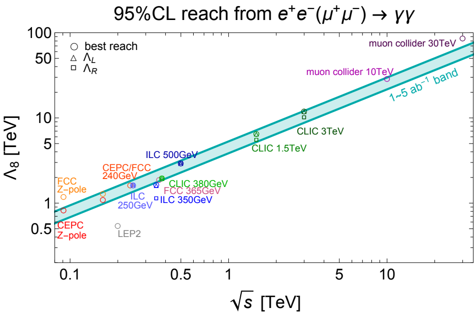
The diphoton channel [arXiv:2011.03055] JG, Lian-Tao Wang, Cen Zhang

- $e^+e^- \to \gamma\gamma$ (or $\mu^+\mu^- \to \gamma\gamma$), SM, non-resonant.
- Leading order contribution: **dimension-8 contact interaction**.
  ($f^+f^- \to \bar{e}_L e_L$ or $e_R\bar{e}_R$)

$$\mathcal{A}(f^+f^-\gamma^+\gamma^-)_{\mathrm{SM+d8}} = 2e^2\frac{\langle 24\rangle^2}{\langle 13\rangle\langle 23\rangle} + \frac{a}{v^4}[13][23]\langle 24\rangle^2 \,.$$

- Can probe dim-8 operators (and their positivity bounds) at a **Higgs factory** (~ 240 GeV)!





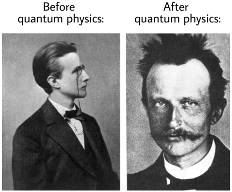
Conclusion

- **Precision measurement** (especially of the Higgs boson) **is the future!**
- **Lepton colliders are Higgs** (and also Z, W, top) **factories!**
- **SMEFT is the ideal framework!** (but is not everything...)

A lesson from history

- In 1875, a young Max Planck was told by his advisor Philipp von Jolly not to study physics, since there was nothing left to be discovered.
  - **Planck did not listen.**

Max Planck:



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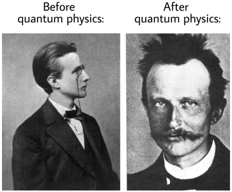
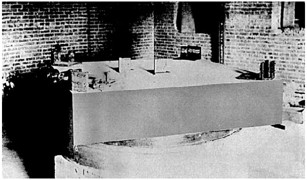


- In 1887, Michelson and Morley tried to find ether, the postulated medium for the propagation of light that was widely believed to exist.
  - **They didn't find it.**



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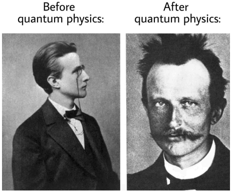

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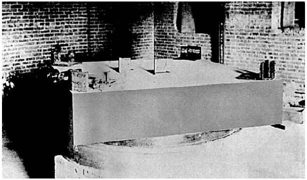

  - "Our future discoveries must be looked for in the sixth place of decimals." — Albert A. Michelson

即将毕业却还没有找到理想的博后职位吗？

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- 可通过ajo申请 (https://academicjobsonline.org/ajo/jobs/17873) 或直接发我邮箱

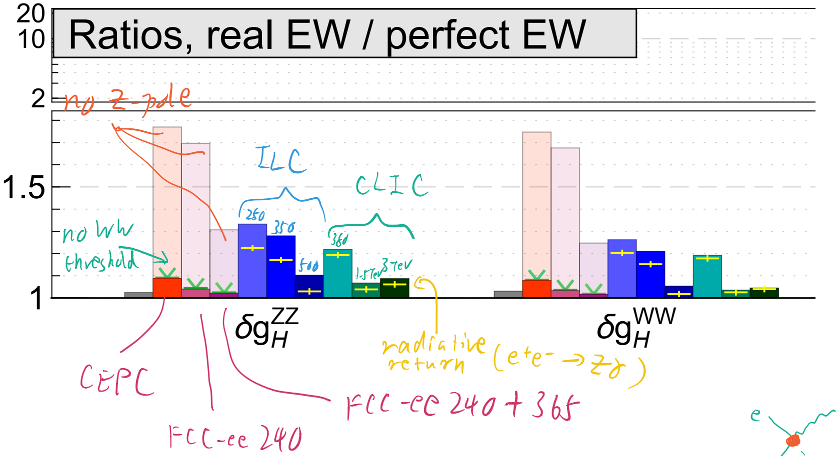
backup slides

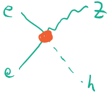
D6 operators

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H \rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H \rvert^2 \bar{q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H \rvert^2 \bar{q}_L H d_R + \text{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H \rvert^2 \bar{l}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

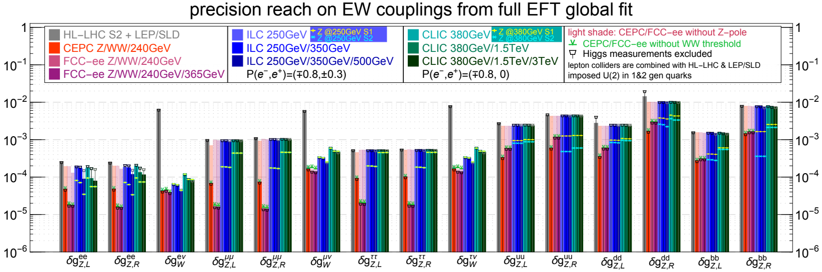
- SILH' basis (eliminate $\mathcal{O}_{WW}$, $\mathcal{O}_{WB}$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH' basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$)

Z-pole run is also important for Higgs couplings!





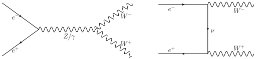
Reach on the (h)Vff couplings



- $(h)Zff$ couplings are still best probed by future Z-pole runs.
- Higgs and diboson measurements at high energy (at linear colliders) are also sensitive to the $(h)Zee$ couplings, but can not resolve them from other parameters.
- Linear colliders: Using radiative return ($e^+e^- \to Z\gamma$) to measure Z observables at high energy?

A refined *WW* analysis using Optimal Observables (OO)

- TGCs (and additional EFT parameters) are sensitive to the differential distributions!
  - One could do a fit to the binned distributions of all angles.
  - Not the most efficient way of extracting information.
  - Correlations among angles are sometimes ignored.

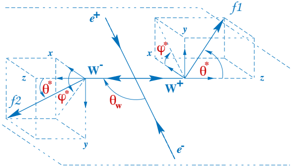


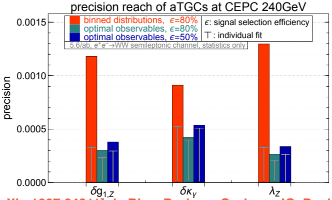
- What are optimal observables?

  (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - For a given sample, there is an upper limit on the precision reach of the parameters.
  - In the limit of large statistics (everything is Gaussian) and small parameters (leading order dominates), this "upper limit" can be derived analytically!

$$\frac{d\sigma}{d\Omega} = S_0 + \sum_i S_{1,i}\, g_i \,,$$

- The optimal observables are given by $\mathcal{O}_i = \frac{S_{1,i}}{S_0}$, and are functions of the 5 angles.





[arXiv:1907.04311] de Blas, Durieux, Grojean, JG, Paul