Adam Falkowski

Theoretical motivations for ILC and LHC-HL

Orsay, 06 March 2018

Adam Falkowski

Theoretical motivations for ILC and LHC-HL

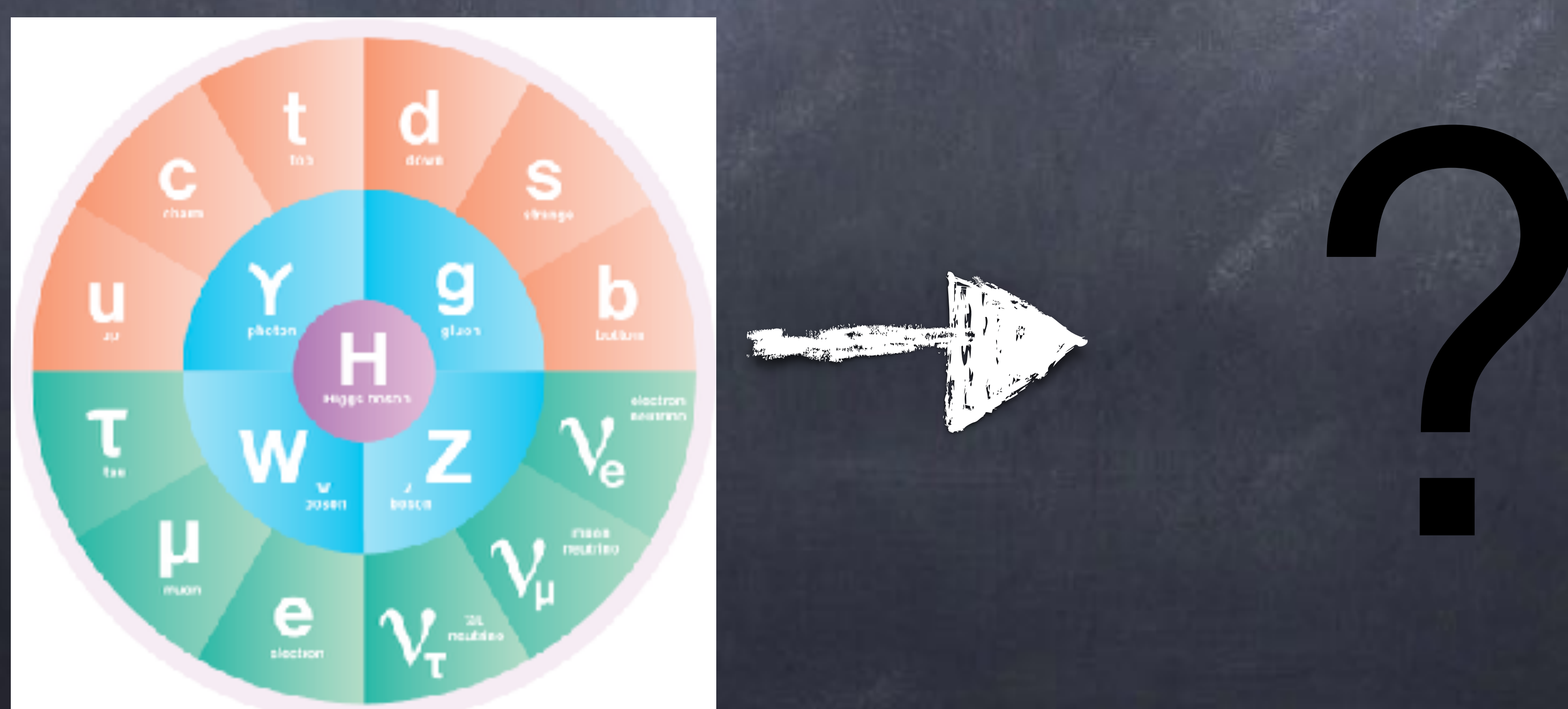
Orsay, 08 February 2018

Where are we

Status report

- SM has been excessively successful in describing all collider and low-energy experiments. Discovery of the 125 GeV Higgs boson is the last piece of puzzle that falls into place. There are no more free parameters in the SM.

- We know physics beyond SM exists (neutrino masses, dark matter, inflation, baryon asymmetry). There are also some theoretical hints for new physics (strong CP problem, flavor hierarchies, gauge coupling unifications, naturalness problem)

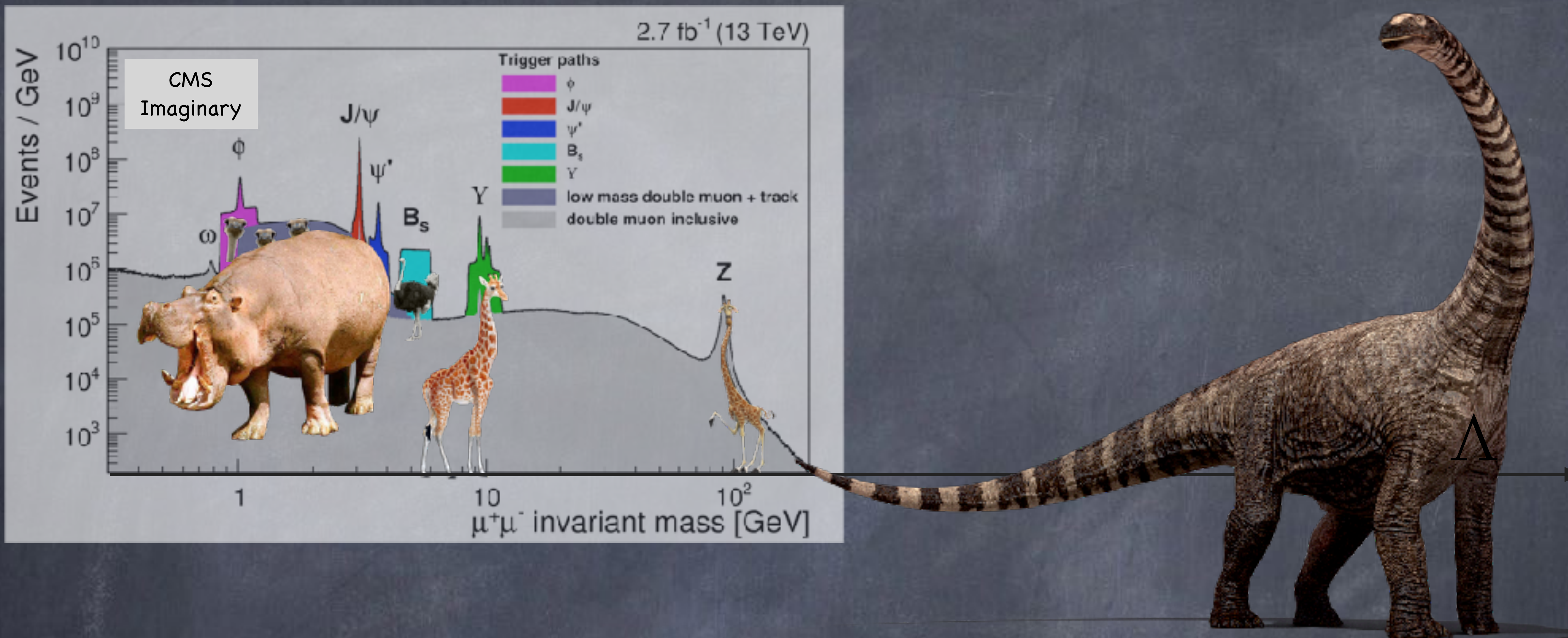


Post LHC era

- No evidence for new particles beyond the SM up to ~1 TeV
- Theoretical motivations that have been driving most new particle searches now appear highly doubtful. We don't have a good idea about the scale Λ of new physics
- Even for dark matter, there is no solid arguments that it should be accessible in high-energy colliders (and some arguments to the contrary)
- At this point, further progress most likely will come from precision measurements

?

Fantastic Beasts and Where To Find Them



- The hope is these measurements will allow us to estimate the scale Λ of new physics, as a target for the next high-energy machines (LHC-HE, FCC, RTMC)

- Furthermore, comprehensive precision program may give us partial information about BSM structure (much like observables in the Fermi Theory had taught us about W and Z well before they could be produced in colliders, or as LEP precision measurements had given us a possible window or top/Higgs masses before their respective discoveries)

Universal Language: SMEFT

Basic assumptions

- No new particles at energies directly available in experiments

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \dots \\ v + h(x) + \dots \end{pmatrix}$$

- Much as in the SM, relativistic QFT with linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

$$v \ll \Lambda \ll \Lambda_L$$

SMEFT Lagrangian expanded in inverse powers of Λ, equivalently in operator dimension D

$$\mathcal{L}_{\rm SM\ EFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda_L}\mathcal{L}^{D=5} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \frac{1}{\Lambda_L^3}\mathcal{L}^{D=7} + \frac{1}{\Lambda^4}\mathcal{L}^{D=8} + \dots$$

Generated by integrating out lepton number or B-L violating heavy particles with mass scale Λ_L, responsible for neutrino masses

$\Lambda_L \lesssim 10^{15}$ GeV

Generated by integrating out heavy particles with mass scale Λ

In large class of BSM models that conserve B-L, D=6 operators capture leading effects of new physics on collider observables at E << Λ

Subleading wrt D=5/6 if Λ_L/Λ high enough

TeV $\lesssim \Lambda \lesssim$?

Buchmuller,Wyler (1986)

Grządkowski et al. 1008.4884

Alonso et al 1312.2014

Two broad classes of precision experiments

High Energy Colliders

LHC

ILC

LHC-HL

This talk

Low-energy measurements

flavor physics

atomic parity violation

dipole moments

parity violating electron scattering

neutrino scattering

…

My main interests at the moment

Precision vs Energy in EFT

Two distinct interesting situations

Observables at fixed mass scale m (e.g. Z or Higgs decays)	High-energy tails of distributions (e.g. Drell-Yan production)

$$\frac{\sigma}{\sigma_{\rm SM}} \approx |1 + \frac{c_6 m^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing measurements precision

For Higgs decays, and tree EFT operator c6 ~ g*^2 given experimental precision ε = 0.1%

$$\Lambda \gtrsim \begin{cases} 70 \text{ TeV} & g_* \sim 4\pi \\ 6 \text{ TeV} & g_* \sim 1 \end{cases}$$

$$\frac{\sigma}{\sigma_{\rm SM}} \approx |1 + \frac{c_6 E^2}{\Lambda^2}|^2$$

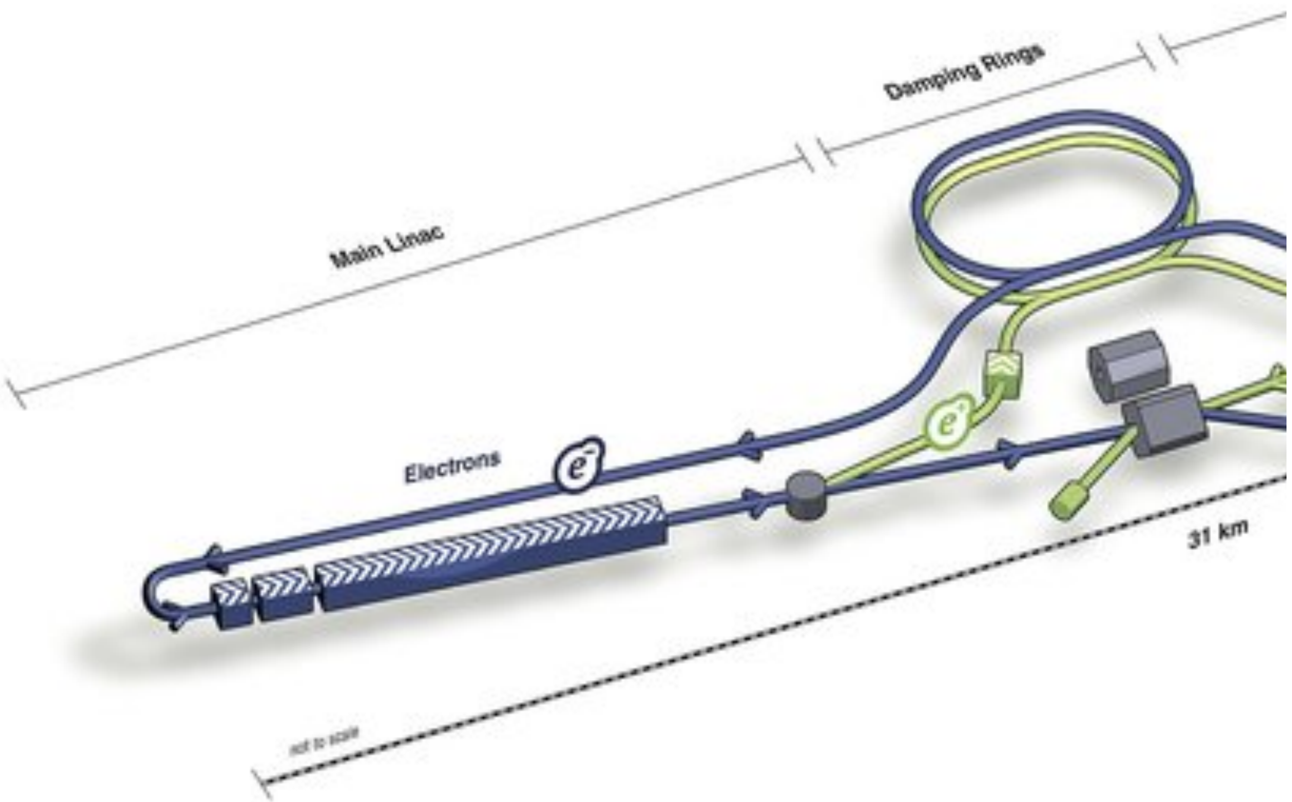
Increasing UV scales probed in EFT may be achieved by increasing energy scale of measurement

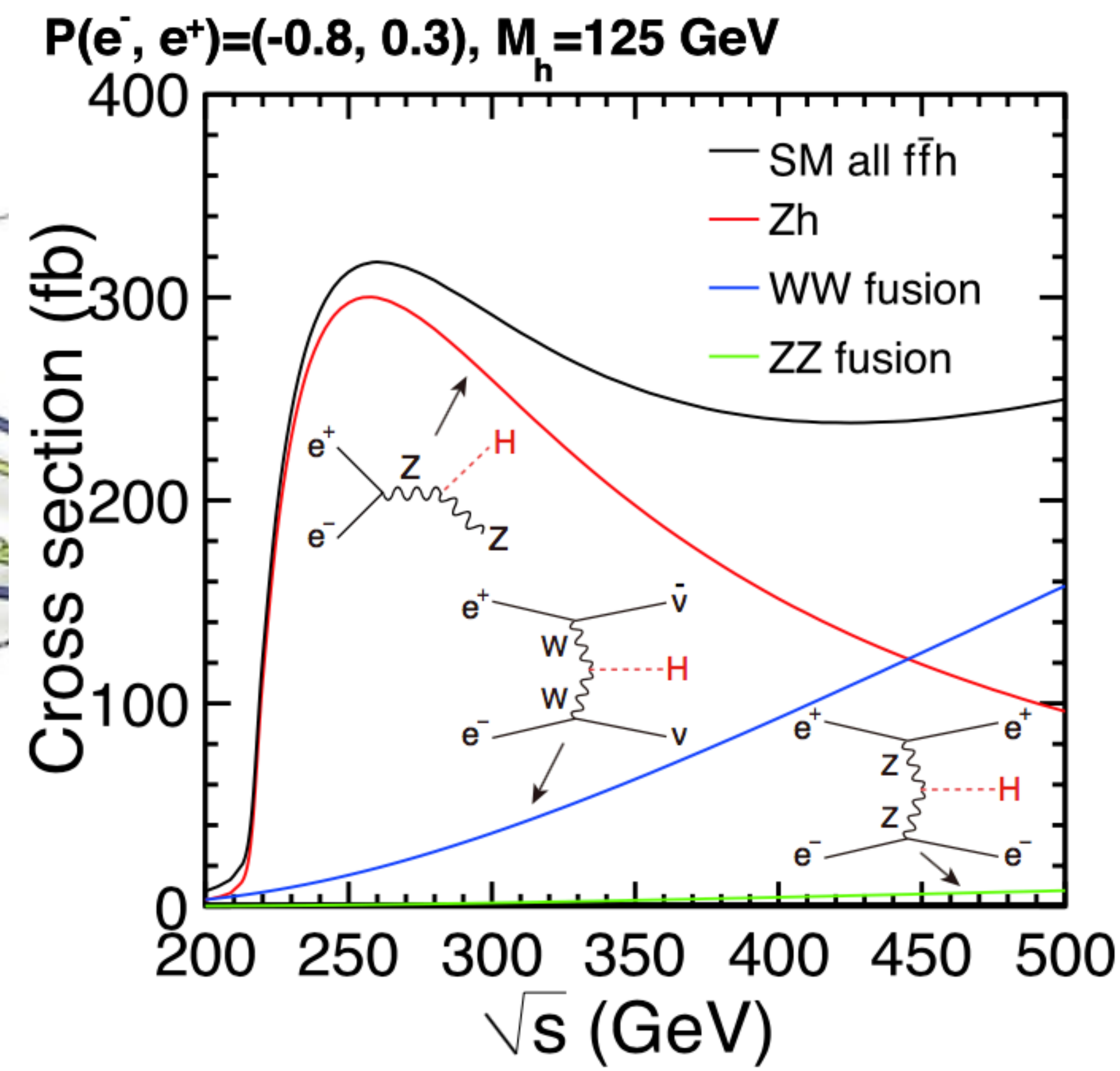
For observable at E ~ 2 TeV, and tree EFT operator c6 ~ g*^2 given experimental precision ε = 10%

$$\Lambda \gtrsim \begin{cases} 110 \text{ TeV} & g_* \sim 4\pi \\ 9 \text{ TeV} & g_* \sim 1 \end{cases}$$

The sense and meaning of ILC

ILC



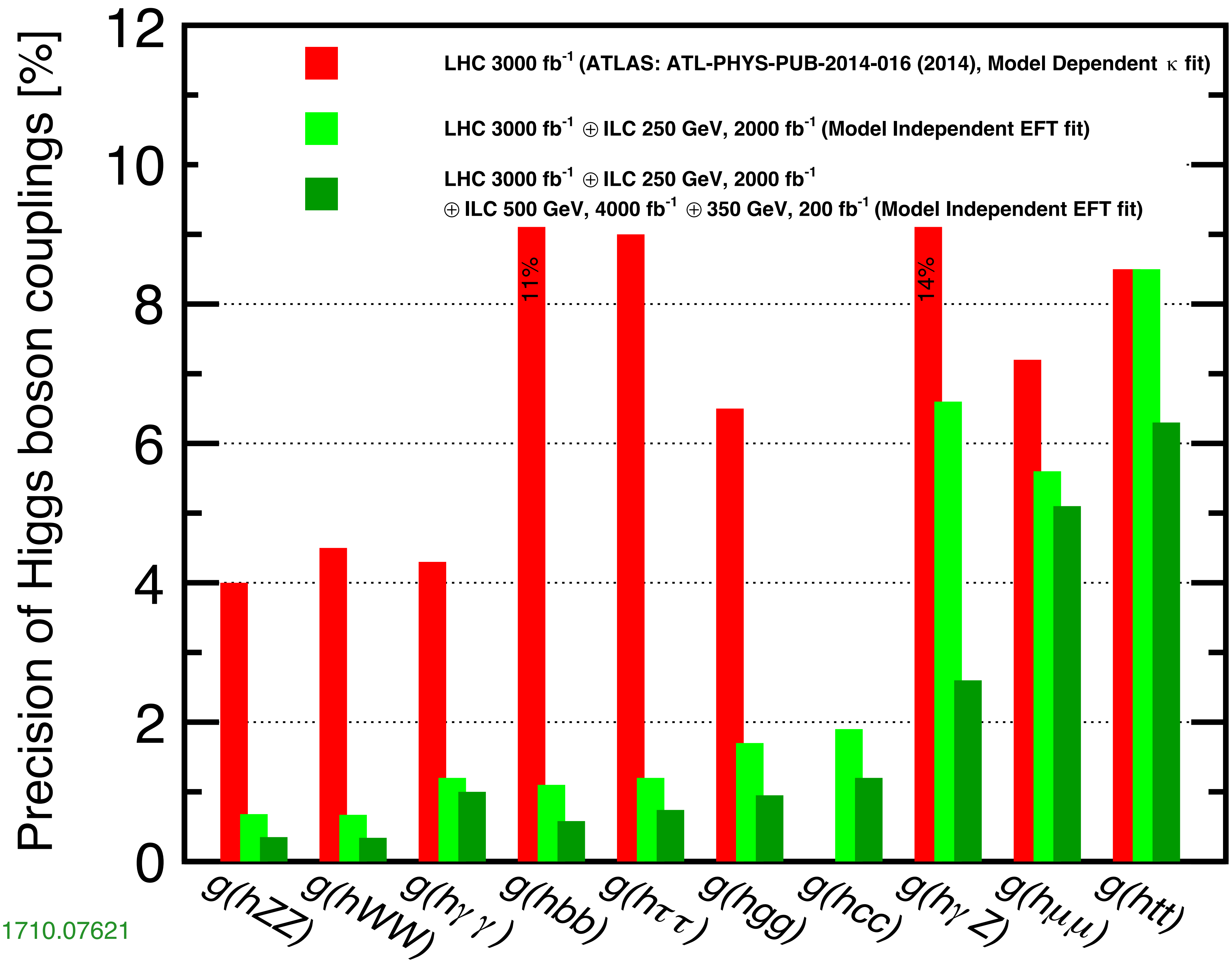


for the latest news see 1710.07621 and 1711.00568

Initially ~20km machine colliding electrons and positrons in Kitakami/Japan, with c.o.m energy of 250 GeV. Upgradable to ~30km and 500 GeV

Clean environment of e+e- collisions together with high luminosity will allow for per-mille level precision studies of Higgs boson interactions

Higgs couplings precision measurements



1710.07621

Operators to Observables to Constraints

$$\mathcal{L} \supset -\frac{c_{H\Box}}{\Lambda^2}\partial_\mu(H^\dagger H)\partial_\mu(H^\dagger H) \quad \Rightarrow \quad h \to h\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)$$

But then *all* Higgs boson couplings present in SM are universally rescaled

$$\frac{h}{v}\left[2m_W^2 W^+_\mu W^-_\mu + m_Z^2 Z_\mu Z_\mu\right] \to \frac{h}{v}\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)\left[2m_W^2 W^+_\mu W^-_\mu + m_Z^2 Z_\mu Z_\mu\right]$$

$$\frac{h}{v}\sum_f m_f \bar{f} f \to \frac{h}{v}\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)\sum_f m_f \bar{f} f$$

Bound on Wilson coefficient $c_{H\Box}$ from Higgs signal strength measurements at LHC

$$\mu = 1.09 \pm 0.11$$

$$-0.13 < \frac{v^2 c_{H\Box}}{\Lambda^2} < 0.31 \qquad @\ 95\%\ \text{CL}$$

ATLAS + CMS
1606.02266

For the negative-sign bound

$$\frac{\Lambda}{g_*} \gtrsim 0.7\ \text{TeV}. \qquad \Lambda \gtrsim \begin{cases} 9\ \text{TeV} & g_* \sim 4\pi \\ 700\ \text{GeV} & g_* \sim 1 \end{cases}$$

weakly coupled

strongly coupled

Operators to Observables to Constraints

$$\mathcal{L} \supset -\frac{c_{H\Box}}{\Lambda^2}\partial_\mu(H^\dagger H)\partial_\mu(H^\dagger H) \quad \Rightarrow \quad h \to h\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)$$

But then *all* Higgs boson couplings present in SM are universally rescaled

$$\frac{h}{v}\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right]$$
$$\to \frac{h}{v}\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right]$$

$$\frac{h}{v}\sum_f m_f \bar{f} f$$
$$\to \frac{h}{v}\left(1+\frac{c_{H\Box}v^2}{2\Lambda^2}\right)\sum_f m_f \bar{f} f$$

Bound on Wilson coefficient $c_{H\Box}$ from Higgs signal strength measurements at LHC

$$\mu = 1.000 \pm 0.001 \qquad -0.002 < \frac{c_{H\Box}v^2}{\Lambda^2} < 0.002 \qquad \text{@95\%CL}$$

ILC
3606.02266

$$\frac{\Lambda}{g_*} \gtrsim 5.5\ \text{TeV} \quad . \qquad \Lambda \gtrsim \begin{cases} 70\ \text{TeV} & g_* \sim 4\pi \\ 5.5\ \text{TeV} & g_* \sim 1 \end{cases}$$

strongly coupled
weakly coupled

Higgs couplings to matter

Effects of D=6 operators:

- Shift the SM Higgs couplings to matter
- Introduce new 2-derivative couplings to gauge bosons that are not present in the SM at tree level
- Introduce CP violating couplings to fermions and gauge bosons
- Correlated with shifts of anomalous triple gauge couplings

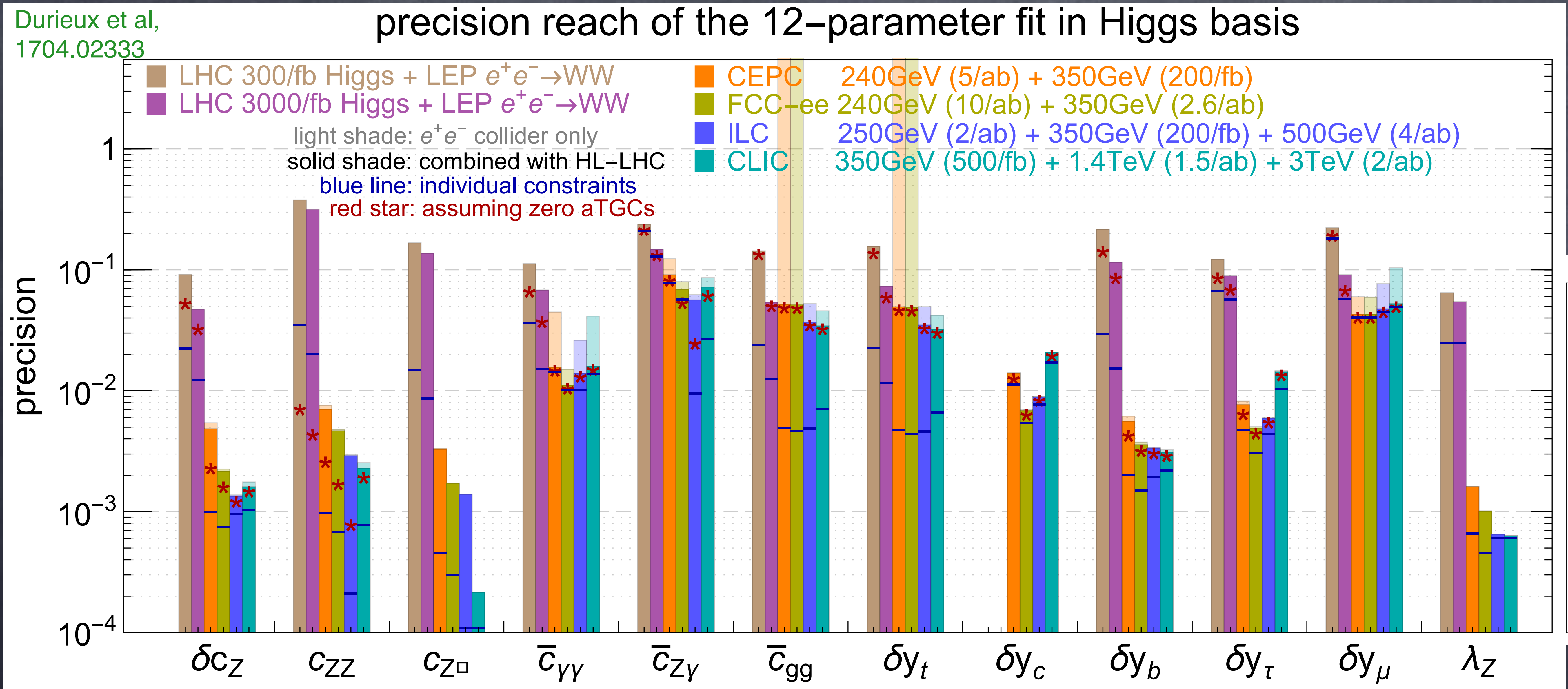
$$\begin{aligned}\mathcal{L}_{\rm hvv} = \frac{h}{v}\Big[& 2(1+\delta c_w) m_W^2 W_\mu^+ W_\mu^- + (1+\delta c_z) m_Z^2 Z_\mu Z_\mu \\ & + c_{ww}\frac{g_L^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g_L^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g_L^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \mathrm{h.c.}\right) \\ & + c_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma}\frac{e g_L}{2 c_\theta} Z_{\mu\nu} A_{\mu\nu} + c_{zz}\frac{g_L^2}{4 c_\theta^2} Z_{\mu\nu} Z_{\mu\nu} \\ & + c_{z\Box} g_L^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g_L g_Y Z_\mu \partial_\nu A_{\mu\nu} \\ & + \tilde{c}_{gg}\frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e g_L}{2 c_\theta} Z_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g_L^2}{4 c_\theta^2} Z_{\mu\nu} \tilde{Z}_{\mu\nu}\Big]\end{aligned}$$

$$\mathcal{L}_{\rm hff} = -\sum_{f=u,d,e} m_f f^c \left(I + \delta y_f e^{i\phi_f}\right) f + \mathrm{h.c.}$$

$$\begin{aligned}\mathcal{L}_{\rm tgc} - ie & \left[\left(W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+\right) A_\nu + (1+\delta\kappa_\gamma) A_{\mu\nu} W_\mu^+ W_\nu^- + \tilde{\kappa}_\gamma \tilde{A}_{\mu\nu} W_\mu^+ W_\nu^-\right] \\ & + i g_L c_\theta \left[(1+\delta g_{1,z})\left(W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+\right) Z_\nu + (1+\delta\kappa_z) Z_{\mu\nu} W_\mu^+ W_\nu^- + \tilde{\kappa}_z \tilde{Z}_{\mu\nu} W_\mu^+ W_\nu^-\right] \\ & + i\frac{e}{m_W^2}\lambda_\gamma W_{\mu\nu}^+ W_{\nu\rho}^- A_{\rho\mu} + i\frac{g_L c_\theta}{m_W^2}\lambda_z W_{\mu\nu}^+ W_{\nu\rho}^- Z_{\rho\mu} + i\frac{e}{m_W^2}\tilde{\lambda}_\gamma W_{\mu\nu}^+ W_{\nu\rho}^- \tilde{A}_{\rho\mu} + i\frac{g_L c_\theta}{m_W^2}\tilde{\lambda}_z W_{\mu\nu}^+ W_{\nu\rho}^- \tilde{Z}_{\rho\mu}\end{aligned}$$

Assuming MFV Yukawa couplings and no CP violation,
Higgs coupling deformations in EFT are described by 9 parameters
This set is extended to 10 parameters if considered in combination with
W and Z boson self-couplings

Global ILC constraints on Higgs EFT



ILC offers good coverage of Higgs EFT parameter space, even in the global picture when all dimension-6 operators are present at the same time

Global constraints on SMEFT

$$
\begin{pmatrix}
\delta g_L^{We} \\ \delta g_L^{W\mu} \\ \delta g_L^{W\tau} \\ \delta g_L^{Ze} \\ \delta g_L^{Z\mu} \\ \delta g_L^{Z\tau} \\ \delta g_R^{Ze} \\ \delta g_R^{Z\mu} \\ \delta g_R^{Z\tau} \\ \delta g_L^{Zu} \\ \delta g_L^{Zc} \\ \delta g_L^{Zt} \\ \delta g_R^{Zu} \\ \delta g_R^{Zc} \\ \delta g_L^{Zd} \\ \delta g_L^{Zs} \\ \delta g_L^{Zb} \\ \delta g_R^{Zd} \\ \delta g_R^{Zs} \\ \delta g_R^{Zb} \\ \delta g_R^{Wq_1} \\ [c_{\ell\ell}]_{1111} \\ [c_{\ell e}]_{1111} \\ [c_{ee}]_{1111} \\ [c_{\ell\ell}]_{1221} \\ [c_{\ell\ell}]_{1122} \\ [c_{\ell e}]_{1122} \\ [c_{\ell e}]_{2211} \\ [c_{ee}]_{1122} \\ [c_{\ell\ell}]_{1331} \\ [c_{\ell\ell}]_{1133} \\ [c_{\ell e}]_{1133} \\ [c_{\ell e}]_{3311} \\ [c_{ee}]_{1133} \\ [\hat{c}_{\ell\ell}]_{2222} \\ [c_{\ell\ell}]_{2332}
\end{pmatrix}
=
\begin{pmatrix}
-1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \\ -0.023 \pm 0.028 \\ 0.01 \pm 0.12 \\ 0.018 \pm 0.059 \\ -0.033 \pm 0.027 \\ 0.00 \pm 0.14 \\ 0.042 \pm 0.062 \\ -0.8 \pm 3.1 \\ -0.15 \pm 0.36 \\ -0.3 \pm 3.8 \\ 1.4 \pm 5.1 \\ -0.35 \pm 0.53 \\ -0.9 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.17 \\ 3 \pm 16 \\ 3.4 \pm 4.9 \\ 2.30 \pm 0.88 \\ -1.3 \pm 1.7 \\ 1.01 \pm 0.38 \\ -0.22 \pm 0.22 \\ 0.20 \pm 0.38 \\ -4.8 \pm 1.6 \\ 1.5 \pm 2.1 \\ 1.5 \pm 2.2 \\ -1.4 \pm 2.2 \\ 3.4 \pm 2.6 \\ 1.5 \pm 1.3 \\ 0 \pm 11 \\ -2.3 \pm 7.2 \\ 1.7 \pm 7.2 \\ -1 \pm 12 \\ -2 \pm 21 \\ 3.0 \pm 2.3
\end{pmatrix}
\times 10^{-2},
$$

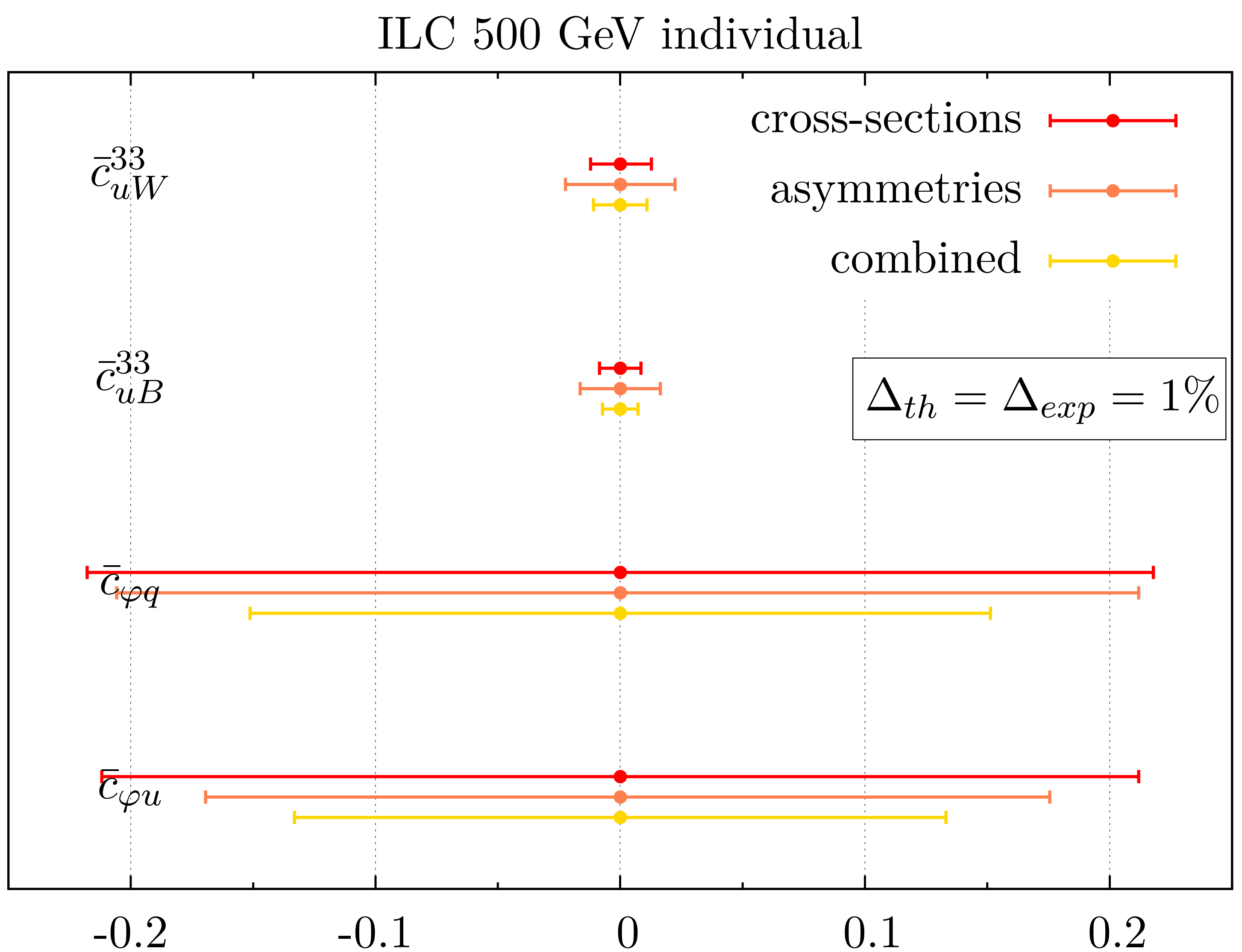
AA, Gonzalez-Alonso, Mimouni
1706.03783

$$
\begin{pmatrix}
[c_{\ell q}^{(3)}]_{1111} \\ [\hat{c}_{eq}]_{1111} \\ [\hat{c}_{\ell u}]_{1111} \\ [\hat{c}_{\ell d}]_{1111} \\ [\hat{c}_{eu}]_{1111} \\ [\hat{c}_{ed}]_{1111} \\ [\hat{c}_{\ell q}^{(3)}]_{1122} \\ [c_{\ell u}]_{1122} \\ [\hat{c}_{\ell d}]_{1122} \\ [c_{eq}]_{1122} \\ [c_{eu}]_{1122} \\ [\hat{c}_{ed}]_{1122} \\ [\hat{c}_{\ell q}^{(3)}]_{1133} \\ [c_{\ell d}]_{1133} \\ [c_{eq}]_{1133} \\ [c_{ed}]_{1133} \\ [c_{\ell q}^{(3)}]_{2211} \\ [c_{\ell q}]_{2211} \\ [c_{\ell u}]_{2211} \\ [c_{\ell d}]_{2211} \\ [\hat{c}_{eq}]_{2211} \\ [c_{\ell equ}]_{1111} \\ [c_{\ell edq}]_{1111} \\ [c_{\ell equ}^{(3)}]_{1111} \\ \epsilon_P^{d\mu}(2\text{ GeV})
\end{pmatrix}
=
\begin{pmatrix}
-2.2 \pm 3.2 \\ 100 \pm 180 \\ -5 \pm 11 \\ -5 \pm 23 \\ -1 \pm 12 \\ -4 \pm 21 \\ -61 \pm 32 \\ 2.4 \pm 8.0 \\ -310 \pm 130 \\ -21 \pm 28 \\ -87 \pm 46 \\ 270 \pm 140 \\ -8.6 \pm 8.0 \\ -1.4 \pm 10 \\ -3.2 \pm 5.1 \\ 18 \pm 20 \\ -1.2 \pm 3.9 \\ 1.3 \pm 7.6 \\ 15 \pm 12 \\ 25 \pm 34 \\ 4 \pm 41 \\ -0.080 \pm 0.075 \\ -0.079 \pm 0.074 \\ -0.02 \pm 0.19 \\ -0.02 \pm 0.15
\end{pmatrix}
\times 10^{-2}.
$$

Z coupling to LH top related by SU(2) symmetry to Zbb and Wbt couplings thus is well constrained

Z coupling to RH is very weakly constrained at present!

Opportunity for ILC



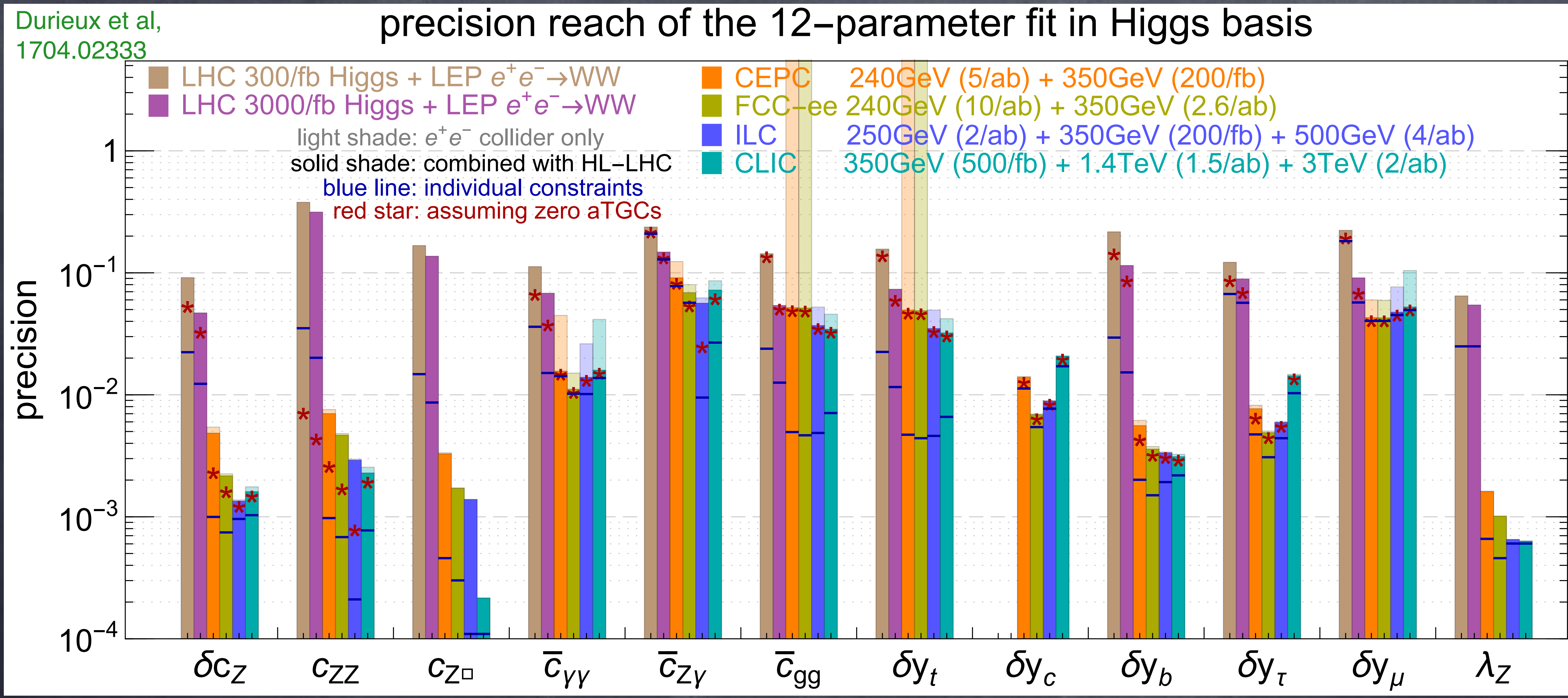
Englert, Russell
1704.01872

see also
Amjad et al
1505.06020

1% precision measurement of ZtRtR couplings is possible, which will put this coupling on similar footing as those measured by LEP

The sense and meaning of LHC-HL

Global LHC-HL constraints on Higgs EFT



For most observables, high-luminosity phase of the LHC will only bring marginal improvement of accuracy

Precision vs Energy in EFT

Two distinct general situations

Observables at fixed mass scale m (e.g. Z or Higgs decays)	High-energy tails of distributions (e.g. Drell-Yan production)

$$\frac{\sigma}{\sigma_{\rm SM}} \approx |1 + \frac{c_6 m^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing measurements precision

For Higgs decays,
and tree EFT operator c6 ~ g*^2
given experimental precision ε = 10%

$$\Lambda \gtrsim \begin{cases} 7\ {\rm TeV} & g_* \sim 4\pi \\ 0.6\ {\rm TeV} & g_* \sim 1 \end{cases}$$

$$\frac{\sigma}{\sigma_{\rm SM}} \approx |1 + \frac{c_6 E^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT may be achieved by increasing energy scale of measurement

For observable at E ~ 2 TeV,
and tree EFT operator c6 ~ g*^2
given experimental precision ε = 10%

$$\Lambda \gtrsim \begin{cases} 110\ {\rm TeV} & g_* \sim 4\pi \\ 9\ {\rm TeV} & g_* \sim 1 \end{cases}$$

Precision vs Energy in EFT

- General rule: for observables at fixed scales << 1 TeV, such as Higgs decays, the impact of LHC-HL is going to be marginal
- However, for observables where new physics effects are enhanced by E^2/Λ^2 LHC-HL can still have a significant impact

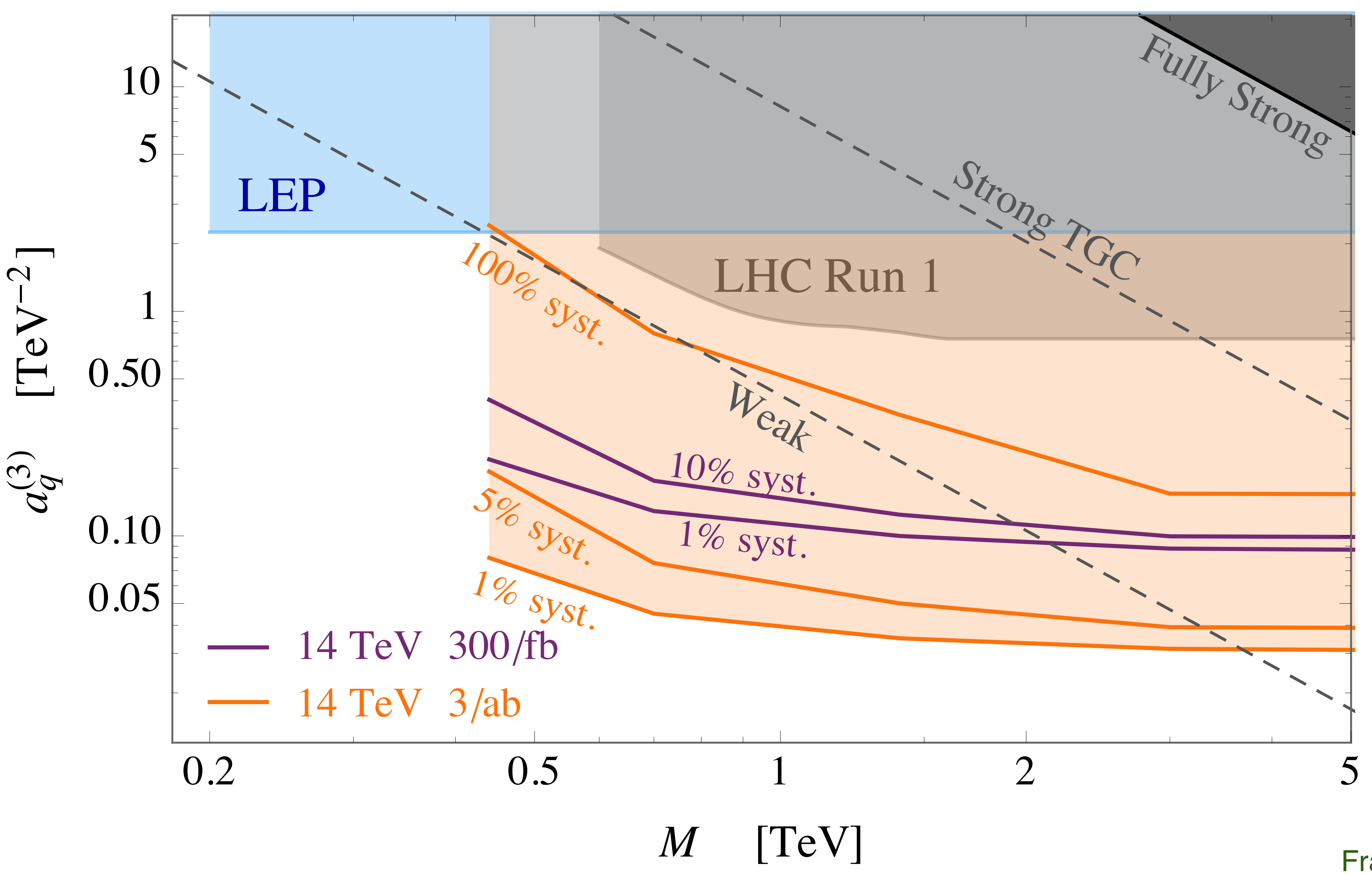
Example: Diboson production at LHC-HL

- There are exactly 4 linear combination of dimension-6 operators contributing to diboson production, interfering with the SM, and giving effects growing as energy squared
- These 4 can be measured with much better precision as LHC-HL collects more statistics on the high-energy tail of the distribution

Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2} \frac{g^2}{m_W^2} \left[c_{\theta_W} (\delta g_{uL}^Z - \delta g_{dL}^Z)/g - c_{\theta_W}^2 \delta g_1^Z \right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2} \left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{u_L} \delta g_1^Z + c_{\theta_W} \delta g_{dL}^Z / g \right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2} \left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{d_L} \delta g_1^Z + c_{\theta_W} \delta g_{uL}^Z / g \right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2} \left[Y_{f_R} t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{f_R} \delta g_1^Z + c_{\theta_W} \delta g_{fR}^Z / g \right]$

Franceschini et al 17/12.01310

Diboson production at LHC-HL

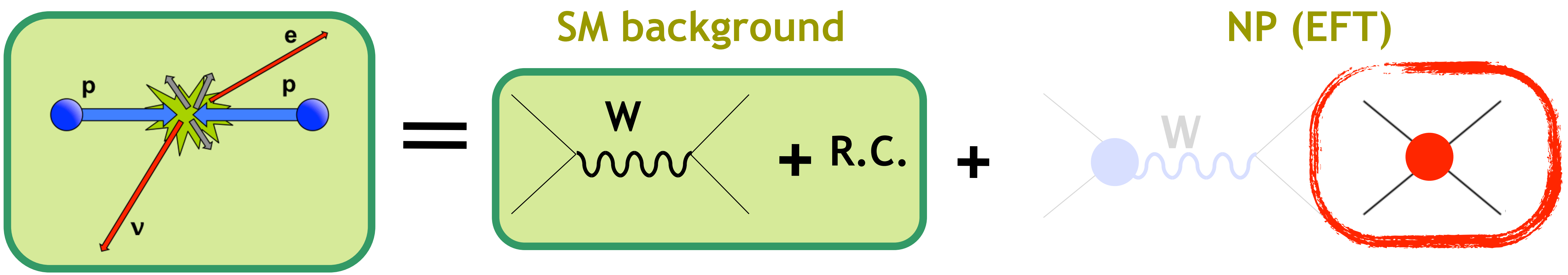


Franceschini et al
17/12.01310

Qualitative improvement in reach for new physics models with LHC-HL data

Example: Drell-Yan production in LHC-HL

Two-fermion production (via charged or neutral currents) can be affected by 4-fermion SMEFT operators



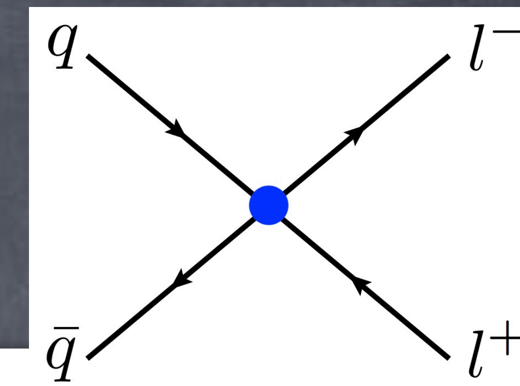
Borrowed from Martin Gonzalez-Alonso

$$\mathcal{A} \sim \mathcal{A}_{SM}\left(1+\alpha_6\frac{x^2}{\Lambda^2}+\alpha_8\frac{x^2}{\Lambda^4}+\dots\right)$$

$$\mathcal{O} \sim \mathcal{O}_{SM}\left(1+\alpha_6\frac{x^2}{\Lambda^2}+(\alpha_6^2+\alpha_8)\frac{x^2}{\Lambda^4}+\dots\right)$$

$x = (v, E) << \Lambda$

Drell-Yan production



Complementarity of LHC and low-energy measurements

$(ee)(qq)$

	$[c_{\ell q}^{(3)}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
Low-energy	0.45 ± 0.28	1.6 ± 1.0	2.8 ± 2.1	3.6 ± 2.0	-1.8 ± 1.1	-4.0 ± 2.0	-2.7 ± 2.0
$\mathrm{LHC}_{1.5}$	$-0.70^{+0.66}_{-0.74}$	$2.5^{+1.9}_{-2.5}$	$2.9^{+2.4}_{-2.9}$	$-1.6^{+3.4}_{-3.0}$	$1.6^{+1.8}_{-2.2}$	$1.6^{+2.5}_{-1.5}$	$-3.1^{+3.6}_{-3.0}$
$\mathrm{LHC}_{1.0}$	$-0.84^{+0.85}_{-0.92}$	$3.6^{+3.6}_{-3.7}$	$4.4^{+4.4}_{-4.7}$	$-2.4^{+4.8}_{-4.7}$	$2.4^{+3.0}_{-3.2}$	$1.9^{+2.5}_{-1.9}$	$-4.6^{+5.4}_{-4.1}$
$\mathrm{LHC}_{0.7}$	$-1.0^{+1.4}_{-1.5}$	5.9 ± 7.2	7.4 ± 9.0	-3.6 ± 8.7	3.8 ± 5.9	$2.1^{+3.8}_{-2.9}$	-8 ± 10

$(\mu\mu)(qq)$

	$[c_{\ell q}^{(3)}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
Low-energy	-0.2 ± 1.2	4 ± 21	18 ± 19	-20 ± 37	40 ± 390	-20 ± 190	40 ± 390
$\mathrm{LHC}_{1.5}$	$-1.22^{+0.62}_{-0.70}$	1.8 ± 1.3	2.0 ± 1.6	-1.1 ± 2.0	1.1 ± 1.2	$2.5^{+1.8}_{-1.4}$	-2.2 ± 2.0
$\mathrm{LHC}_{1.0}$	$-0.72^{+0.81}_{-0.87}$	$3.2^{+4.0}_{-3.5}$	$3.9^{+4.8}_{-4.4}$	$-2.3^{+4.9}_{-4.7}$	$2.3^{+3.1}_{-3.2}$	$1.6^{+2.3}_{-1.8}$	-4.4 ± 5.3
$\mathrm{LHC}_{0.7}$	$-0.7^{+1.3}_{-1.4}$	$3.2^{+10.3}_{-4.8}$	$4.3^{+12.5}_{-6.4}$	-3.6 ± 9.0	3.8 ± 6.2	$1.6^{+3.4}_{-2.7}$	-8 ± 11

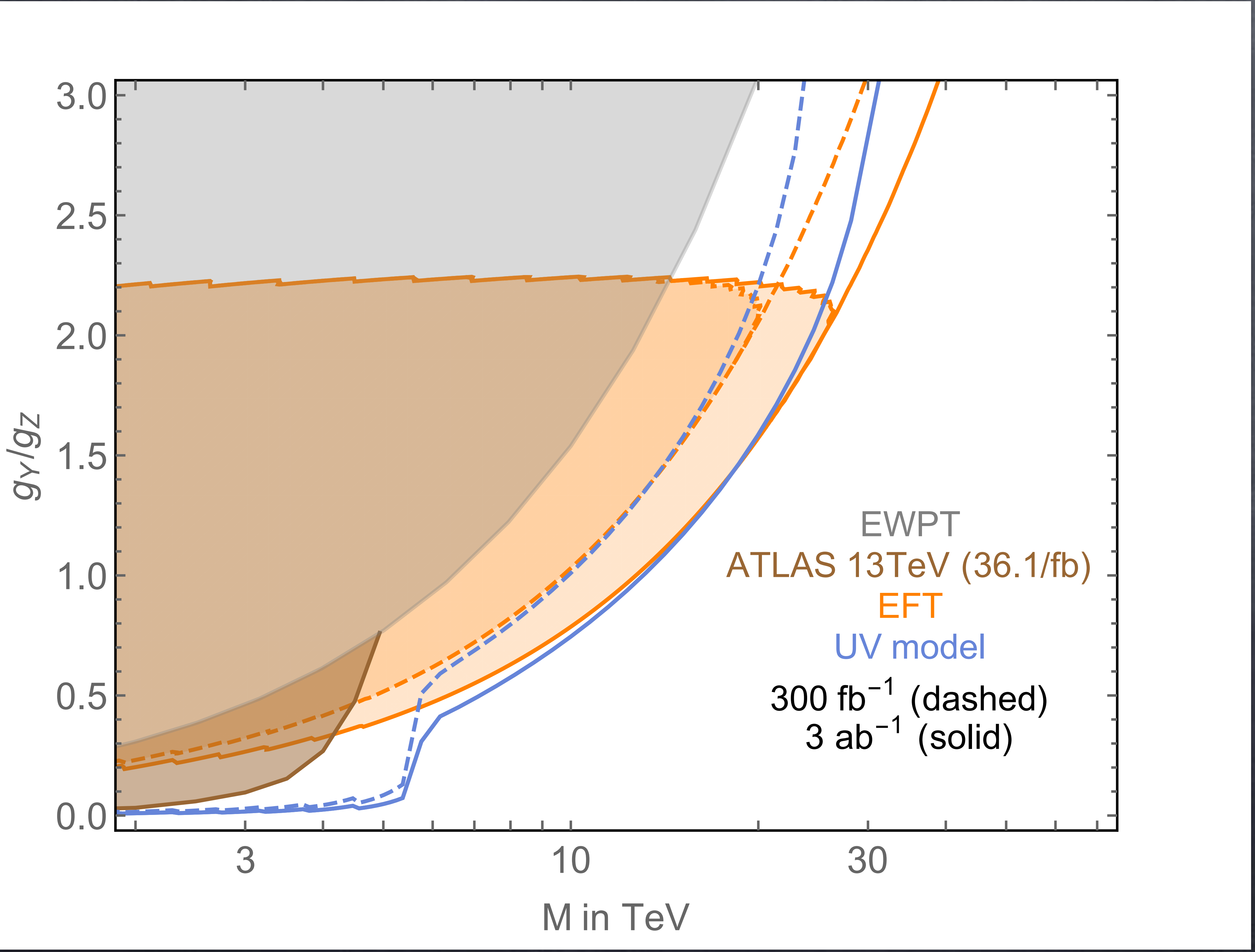
Chirality-violating operators ($\mu = 1$ TeV)

	$[c_{\ell equ}]_{1111}$	$[c_{\ell edq}]_{1111}$	$[c_{\ell equ}^{(3)}]_{1111}$	$[c_{\ell equ}]_{2211}$	$[c_{\ell edq}]_{2211}$	$[c_{\ell equ}^{(3)}]_{2211}$
Low-energy	$(-0.6 \pm 2.4)10^{-4}$	$(0.6 \pm 2.4)10^{-4}$	$(0.4 \pm 1.4)10^{-3}$	$0.014(49)$	$-0.014(49)$	$-0.09(29)$
$\mathrm{LHC}_{1.5}$	0 ± 2.0	0 ± 2.6	0 ± 0.91	0 ± 1.2	0 ± 1.6	0 ± 0.56
$\mathrm{LHC}_{1.0}$	0 ± 2.9	0 ± 3.7	0 ± 1.4	0 ± 2.9	0 ± 3.7	0 ± 1.4
$\mathrm{LHC}_{0.7}$	0 ± 5.3	0 ± 6.6	0 ± 2.6	0 ± 5.5	0 ± 6.9	0 ± 2.6

AA, Gonzalez-Alonso, Mimouni
1706.03783

Drell-Yan production at LHC-HL

Factor of 2 improvement of the scale of new physics probed by Drell-Yan processes



Alioli et al 1712.02347

Z pole measurements at LHC and LHC-HL

- For certain observables without energy squared enhancement, opportunities still opened

- For example, couplings of Z boson to light quarks were not all constrained in model independent way in LEP, and constraints can be very much improved using Drell-Yan production near Z-pole in proton-proton collisions.

Difficult to compete

$$[\delta g_L^{We}]_{ii} = \begin{pmatrix} -1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \end{pmatrix} \times 10^{-2},$$

$$[\delta g_L^{Ze}]_{ii} = \begin{pmatrix} -0.26 \pm 0.28 \\ 0.1 \pm 1.1 \\ 0.16 \pm 0.58 \end{pmatrix} \times 10^{-3}, \quad [\delta g_R^{Ze}]_{ii} = \begin{pmatrix} -0.37 \pm 0.27 \\ 0.0 \pm 1.3 \\ 0.39 \pm 0.62 \end{pmatrix} \times 10^{-3},$$

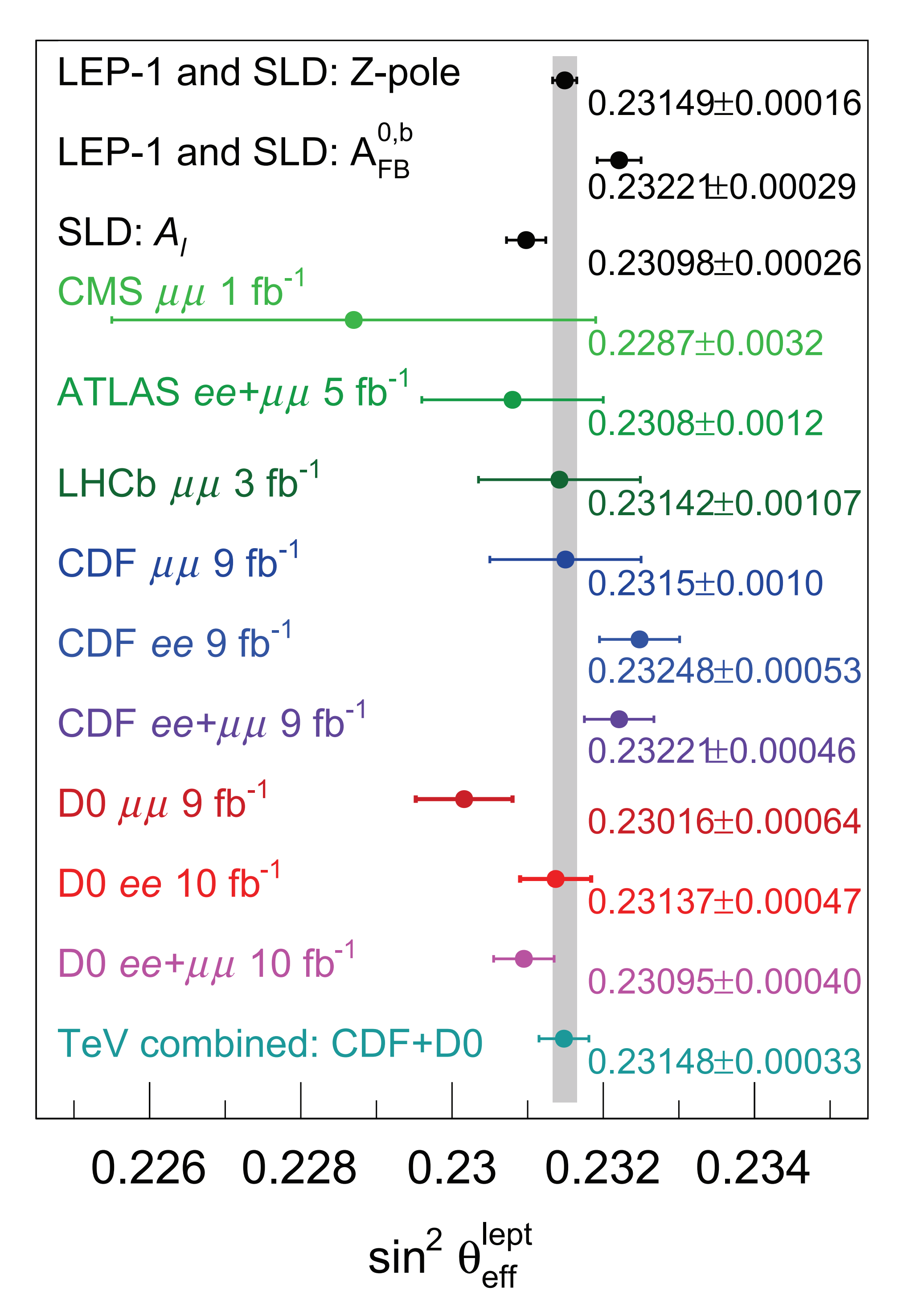
$$[\delta g_L^{Zu}]_{ii} = \begin{pmatrix} -0.8 \pm 3.1 \\ -0.16 \pm 0.36 \\ -0.28 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zu}]_{ii} = \begin{pmatrix} 1.3 \pm 5.1 \\ -0.38 \pm 0.51 \\ \times \end{pmatrix} \times 10^{-2},$$

$$[\delta g_L^{Zd}]_{ii} = \begin{pmatrix} -1.0 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.16 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zd}]_{ii} = \begin{pmatrix} 2.9 \pm 16 \\ 3.5 \pm 5.0 \\ 2.30 \pm 0.82 \end{pmatrix} \times 10^{-2}.$$

Opportunit knocking

Efrati,AA,Soreq 1503.07872

Meanwhile…



LHC and others often dwell on analyses that give exactly zero amount of useful information

Personal Remarks

- High-energy physics is receiving some bad press these days, in part deservedly
- Supersymmetry/extra dimensions/black holes as motivations for future colliders may easily backfire and make easy targets for ridicule
- It is not obvious that in ~15 years particle physics will still be a dynamic research domain and will continue stirring public imagination
- A realistic and physicswise interesting program is crucial for the exploration of fundamental physics to continue in the long run

Final Words

- In the coming years, precision measurements will play a central role in exploring fundamental physics
- EFT is the universal language for precision measurements
- ILC and LHC-HL are especially useful for probing Higgs, diboson, and top quark processes, as the corresponding EFT operators are difficult to access otherwise
- These experiments will allow one to indirectly study physics well beyond the scale actually directly probed at colliders
- Especially in hadron colliders, better interactions with theorists may be helpful to avoid wasting resources for analyses which are of little use

Backup

Operators to Observables

To correctly take into account effects of dimension-6 operator, it is convenient to rewrite SM EFT in terms of mass eigenstates after electroweak symmetry breaking. Moreover, it is convenient to work with Lagrangian that is canonically normalized, kinetic terms are 2-derivative, and SM relations between gauge couplings and input observables are preserved

Example (always arise for composite Higgs)

$$\begin{aligned}\mathcal{L} \supset & \frac{c_{H\Box}(H^\dagger H)\Box(H^\dagger H)}{\Lambda^2} \\ = & -\frac{c_{H\Box}\partial_\mu(H^\dagger H)\partial_\mu(H^\dagger H)}{\Lambda^2} \\ = & -\frac{c_{H\Box}\partial_\mu(v+h)^2\partial_\mu(v+h)^2}{4\Lambda^2} \\ = & -\frac{c_{H\Box}v^2}{\Lambda^2}\partial_\mu h\partial_\mu h + \ldots\end{aligned}$$

This operator modifies Higgs boson kinetic term. To retrieve canonical normalization we need to rescale:

$$h \to h\left(1 + \frac{c_{H\Box}v^2}{2\Lambda^2}\right)$$

$$\frac{1}{2}(\partial_\mu h)^2 \to \frac{1}{2}(\partial_\mu h)^2\left(1 + \frac{v^2}{\Lambda^2}c_{H\Box}\right)$$

Note that everything that is order $1/\Lambda$^4 has to be consistently ignored in my calculation, otherwise I need to also take into account dimension-8 operator

Many possible D=6 operators!

One example of non-redundant set, so-called SILH basis

Giudice et al hep-ph/0703164
Contino et al 1303.3876

Table 97: Bosonic D=6 operators in the SILH basis.

Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2}\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2}\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 98: Two-fermion dimension-6 operators in the SILH basis. They are the same as in the Warsaw basis, except that the operators $[O_{H\ell}]_{11}$, $[O'_{H\ell}]_{11}$ are absent by definition. We define $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$. In this table, e, u, d are always right-handed fermions, while ℓ and q are left-handed. For complex operators the complex conjugate operator is implicit.

Vertex		Yukawa and Dipole	
$[O_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i\gamma_\mu\ell_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_e]_{ij}$	$\frac{\sqrt{2m_{e_i}m_{e_j}}}{v^3} H^\dagger H \bar{\ell}_i H e_j$
$[O'_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i\sigma^k\gamma_\mu\ell_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$	$[O_u]_{ij}$	$\frac{\sqrt{2m_{u_i}m_{u_j}}}{v^3} H^\dagger H \bar{q}_i \widetilde{H} u_j$
$[O_{He}]_{ij}$	$\frac{i}{v^2}\bar{e}_i\gamma_\mu e_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_d]_{ij}$	$\frac{\sqrt{2m_{d_i}m_{d_j}}}{v^3} H^\dagger H \bar{q}_i H d_j$
$[O_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i\gamma_\mu q_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v}\bar{\ell}_i\sigma^k H\sigma_{\mu\nu}e_j W^k_{\mu\nu}$
$[O'_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i\sigma^k\gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$	$[O_{eB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v}\bar{\ell}_i H\sigma_{\mu\nu}e_j B_{\mu\nu}$
$[O_{Hu}]_{ij}$	$\frac{i}{v^2}\bar{u}_i\gamma_\mu u_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i\tilde{H}\sigma_{\mu\nu}T^a u_j G^a_{\mu\nu}$
$[O_{Hd}]_{ij}$	$\frac{i}{v^2}\bar{d}_i\gamma_\mu d_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i\sigma^k\tilde{H}\sigma_{\mu\nu}u_j W^k_{\mu\nu}$
$[O_{Hud}]_{ij}$	$\frac{i}{v^2}\bar{u}_i\gamma_\mu d_j \tilde{H}^\dagger D_\mu H$	$[O_{uB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i\tilde{H}\sigma_{\mu\nu}u_j B_{\mu\nu}$
		$[O_{dG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i H\sigma_{\mu\nu}T^a d_j G^a_{\mu\nu}$
		$[O_{dW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i\sigma^k H\sigma_{\mu\nu}d_j W^k_{\mu\nu}$
		$[O_{dB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i H\sigma_{\mu\nu}d_j B_{\mu\nu}$

Table 99: Four-fermion operators in the SILH basis. They are the same as in the Warsaw basis [614], except that the operators $[O_{\ell\ell}]_{1221}$, $[O_{\ell\ell}]_{1122}$, $[O_{uu}]_{3333}$ are absent by definition. In this table, e, u, d are always right-handed fermions, while ℓ and q are left-handed. A flavour index is implicit for each fermion field. For complex operators the complex conjugate operator is implicit.

$(\bar{L}L)(\bar{L}L)$ and $(\bar{L}R)(\bar{L}R)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$O_{\ell\ell}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu\ell)(\bar{\ell}\gamma_\mu\ell)$	O_{ee}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{e}\gamma_\mu e)$	$O_{\ell e}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu\ell)(\bar{e}\gamma_\mu e)$
O_{qq}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{q}\gamma_\mu q)$	O_{uu}	$\frac{1}{v^2}(\bar{u}\gamma_\mu u)(\bar{u}\gamma_\mu u)$	$O_{\ell u}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu\ell)(\bar{u}\gamma_\mu u)$
O'_{qq}	$\frac{1}{v^2}(\bar{q}\gamma_\mu\sigma^i q)(\bar{q}\gamma_\mu\sigma^i q)$	O_{dd}	$\frac{1}{v^2}(\bar{d}\gamma_\mu d)(\bar{d}\gamma_\mu d)$	$O_{\ell d}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu\ell)(\bar{d}\gamma_\mu d)$
$O_{\ell q}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu\ell)(\bar{q}\gamma_\mu q)$	O_{eu}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{u}\gamma_\mu u)$	O_{eq}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{e}\gamma_\mu e)$
$O'_{\ell q}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu\sigma^i\ell)(\bar{q}\gamma_\mu\sigma^i q)$	O_{ed}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{d}\gamma_\mu d)$	O_{qu}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{u}\gamma_\mu u)$
O_{quqd}	$\frac{1}{v^2}(\bar{q}^j u)\epsilon_{jk}(\bar{q}^k d)$	O_{ud}	$\frac{1}{v^2}(\bar{u}\gamma_\mu u)(\bar{d}\gamma_\mu d)$	O'_{qu}	$\frac{1}{v^2}(\bar{q}\gamma_\mu T^a q)(\bar{u}\gamma_\mu T^a u)$
O'_{quqd}	$\frac{1}{v^2}(\bar{q}^j T^a u)\epsilon_{jk}(\bar{q}^k T^a d)$	O'_{ud}	$\frac{1}{v^2}(\bar{u}\gamma_\mu T^a u)(\bar{d}\gamma_\mu T^a d)$	O_{qd}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{d}\gamma_\mu d)$
$O_{\ell equ}$	$\frac{1}{v^2}(\bar{\ell}^j e)\epsilon_{jk}(\bar{q}^k u)$			O'_{qd}	$\frac{1}{v^2}(\bar{q}\gamma_\mu T^a q)(\bar{d}\gamma_\mu T^a d)$
$O'_{\ell equ}$	$\frac{1}{v^2}(\bar{\ell}^j\sigma_{\mu\nu}e)\epsilon_{jk}(\bar{q}^k\sigma^{\mu\nu}u)$				
$O_{\ell edq}$	$\frac{1}{v^2}(\bar{\ell}^j e)(\bar{d}q^j)$				

Full set has 2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014, Henning et al 1512.03433