# Effective Operator Analysis of Higgs Production at an $e^+e^-$ Linear Collider

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New Horizons at Colliders

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# Effective Operators and New Physics

- Expect new physics (NP) above some energy scale $\Lambda$.
- At low energy, will manifest itself as effective operators

$$\mathcal{L}_{\text{eff}}^{(n)} = \sum_j \frac{C_j^n(\mu)}{\Lambda^{n-4}} \mathcal{O}_j^{(n)}(\mu) \; + \text{h.c.}$$

  which we take to be constructed from SM fields plus right-handed Dirac $\nu$.
- Higher-dimension operators suppressed by increasing factors of $\Lambda \to$ Just take $n = 6$.
- Place limits on $C_j^6 \to$ limits on contributions of $\mathcal{O}_j^{(6)}$ to observable processes.

# General Strategy

- Want to constrain NP contribution to Higgs production cross-section at linear $e^+e^-$ collider.
- Operators containing only Higgs, gauge boson fields done elsewhere (Barger et al, Manohar & Wise).
  $\rightarrow$ Consider all 6D op's containing fermion, Higgs fields.
  Include right-handed neutrino, $\nu_R$.
- Ignoring (small) changes in couplings in SM Higgs production diagrams caused by operator insertion.
  $\rightarrow$ Looking at insertion of op's into new production diagrams.
- Will differentiate final states produced only by Higgsstrahlung process from those produced by WW-, ZZ-fusion in SM.
- Leaving out $Ht\bar{t}$ final state; ignoring Higgs decay.

# Operator Basis

Class 1 Op's:
Operators w/o $\nu_R$:

$$\mathcal{O}_{VR,AB} \equiv i(\bar{f}_R^A \gamma^\mu f_R^B)(\phi^+ D_\mu \phi)$$
$$\mathcal{O}_{VL,AB} \equiv i(\bar{F}^A \gamma^\mu F^B)(\phi^+ D_\mu \phi)$$
$$\mathcal{O}_{VL\tau,AB} \equiv i(\bar{F}^A \gamma^\mu \tau^a F^B)(\phi^+ \tau^a D_\mu \phi)$$
$$\mathcal{O}^f_{W,AB} \equiv g_2(\bar{F}^A \sigma^{\mu\nu} \tau^a \phi) f_R^B W^a_{\mu\nu}$$
$$\mathcal{O}^f_{B,AB} \equiv g_1(\bar{F}^A \sigma^{\mu\nu} \phi) f_R^B B_{\mu\nu}$$

$F$: left-handed fermion doublet

$f_R$: right-handed fermion

Will contribute to
all SM final states.

Class 2 Op's:
Op's with $\nu_R$:

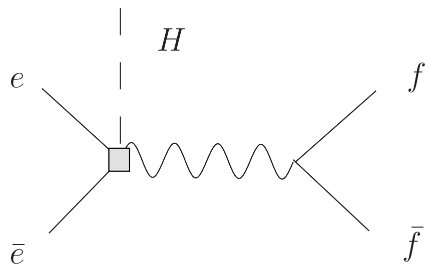
$$\mathcal{O}_{V\nu,\, AB} \equiv i(\bar{\nu}_R^A \gamma^\mu \nu_R^B)(\phi^+ D_\mu \phi)$$
$$\mathcal{O}_{\tilde{V},\, AB} \equiv i(\bar{\ell}_R^A \gamma^\mu \nu_R^B)(\phi^+ D_\mu \widetilde{\phi})$$
$$\mathcal{O}_{W,\, AB} \equiv g_2(\bar{L}^A \sigma^{\mu\nu} \tau^a \widetilde{\phi}) \nu_R^B W^a_{\mu\nu}$$
$$\mathcal{O}_{B,\, AB} \equiv g_1(\bar{L}^A \sigma^{\mu\nu} \widetilde{\phi}) \nu_R^B B_{\mu\nu}$$

$$\widetilde{\phi} = i\tau^2 \phi^*$$

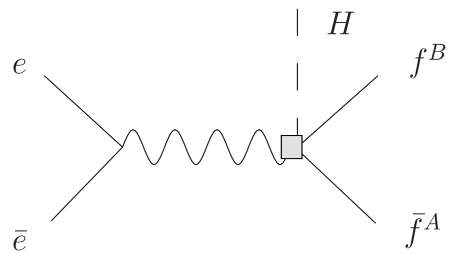
all terms + h.c.

Will only contribute to
$\not{E}$ final state.

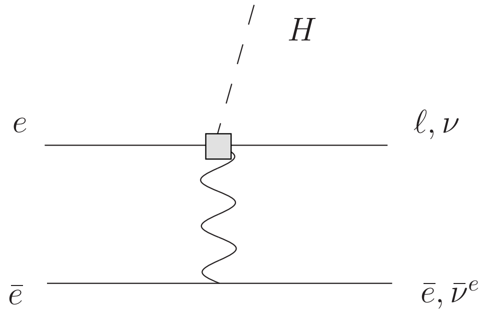
# Diagrams With Class 1 Operators

1) 


Only for $A = B = e$.
Can have on-shell $Z$.
$f = q, \ell, \nu$

2) 


Gauge Boson very off-shell $(\sqrt{s} >> M_Z)$
Diagram suppressed.

3) 


Only for $A, B = e, \ell$ or $\ell, e$.
Flavor-changing diagrams will not interfere w/SM.

Most important Class A Op's will have $A = B = e$ !

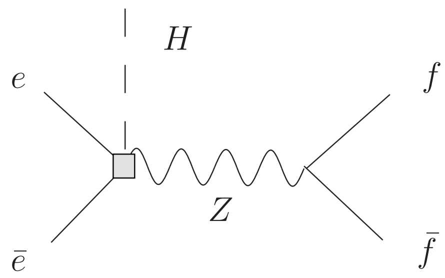
# $\mathcal{O}_{VR,ee}$

$\mathcal{O}_{VR,AB} \equiv i(\bar{f}_R^A \gamma^\mu f_R^B)(\phi^+ D_\mu \phi) + \text{h.c.} \rightarrow \bar{f}_R^A f_R^B Z H$ vertex.

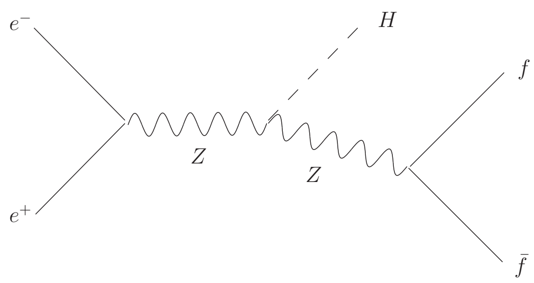
$q\bar{q}$, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\bar{\nu}$ channels: only Diag (1) contributes.

Compare to SM HZ diagram:

Diagram 1




SM HZ




Interference with HZ is related to SM HZ by

$$\frac{\sigma_{1-HZ\,\text{int}}}{\sigma_{HZ}} = -\frac{C_{VR,ee} v^2}{\Lambda^2} \frac{(s - M_Z^2)}{M_Z^2} \frac{\sin^2\theta_W}{2(\sin^4\theta_W - \frac{1}{2}\sin^2\theta_W + \frac{1}{8})}$$

$$\sim -54(-220)\frac{C_{VR,ee} v^2}{\Lambda^2} \quad \text{for } \sqrt{s} = 500\,\text{GeV}\,(1\,\text{TeV})$$

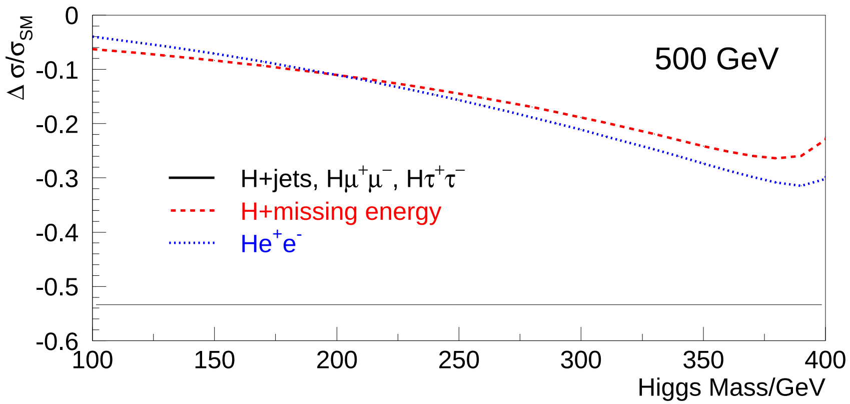
Can be large for $\sqrt{s} >> M_Z$!

# $\mathcal{O}_{VR,ee}$

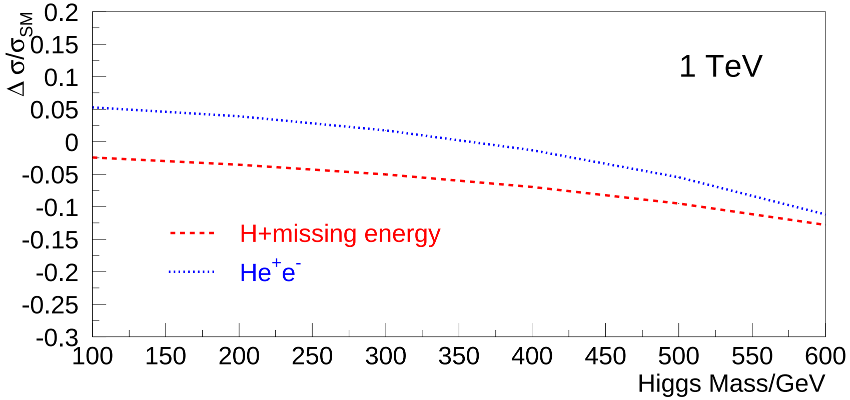
$\nu_e \bar{\nu}_e$ in final state: interference w/SM WWf suppressed by $m_e$.

$e^+e^-$ in final state: must include diagrams (2) and (3), as well as SM ZZf and interference.

Take $\frac{C_{VR,ee} v^2}{\Lambda^2} \sim \frac{1}{16\pi^2} \sim 10^{-2}$




For $\sqrt{s} = 1$ TeV, $q\bar{q}$, $\mu^+\mu^-$, $\tau^+\tau^-$ line at $-2.2$.

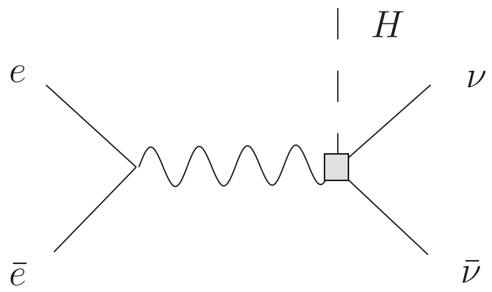


# Other Class 1 Operators

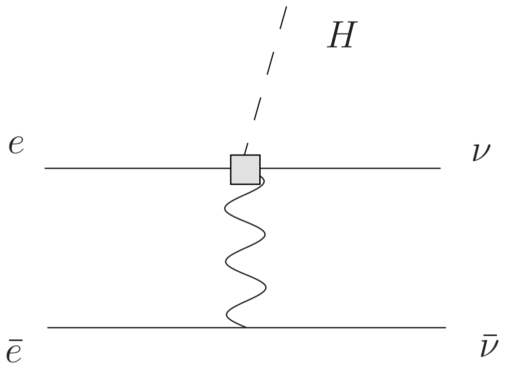
- $\mathcal{O}_{VL,ee}$, $\mathcal{O}_{VL\tau,ee}$ very similar to $\mathcal{O}_{VR,ee}$.
- Same operatorss with $A = B = \mu, \tau,$ or $q$:
  Kinematically suppressed, change in cross-section $\sim 0.1\%$.
- $\mathcal{O}_{W\ell,AB}$, $\mathcal{O}_{B\ell,AB}$:
  Tightly constrained by charged fermion EDM, magnetic moments for most $A$, $B$.
  $A = B = \tau$; $A = q^A$, $B = q^B$ cases not as well constrained, small for $C_{j,AB} v^2/\Lambda^2 = 10^{-2}$.

# Diagrams With Class 2 Operators

All Class 2 Operators contribute only to $\nu$ final state.
No interference w/SM processes.




$\mathcal{O}_{V\nu,\,AB}$, $\mathcal{O}_{W,\,AB}$, $\mathcal{O}_{B,\,AB}$ contribute.
$A, B =$ anything.
Diagram suppressed by off-shell gauge boson.

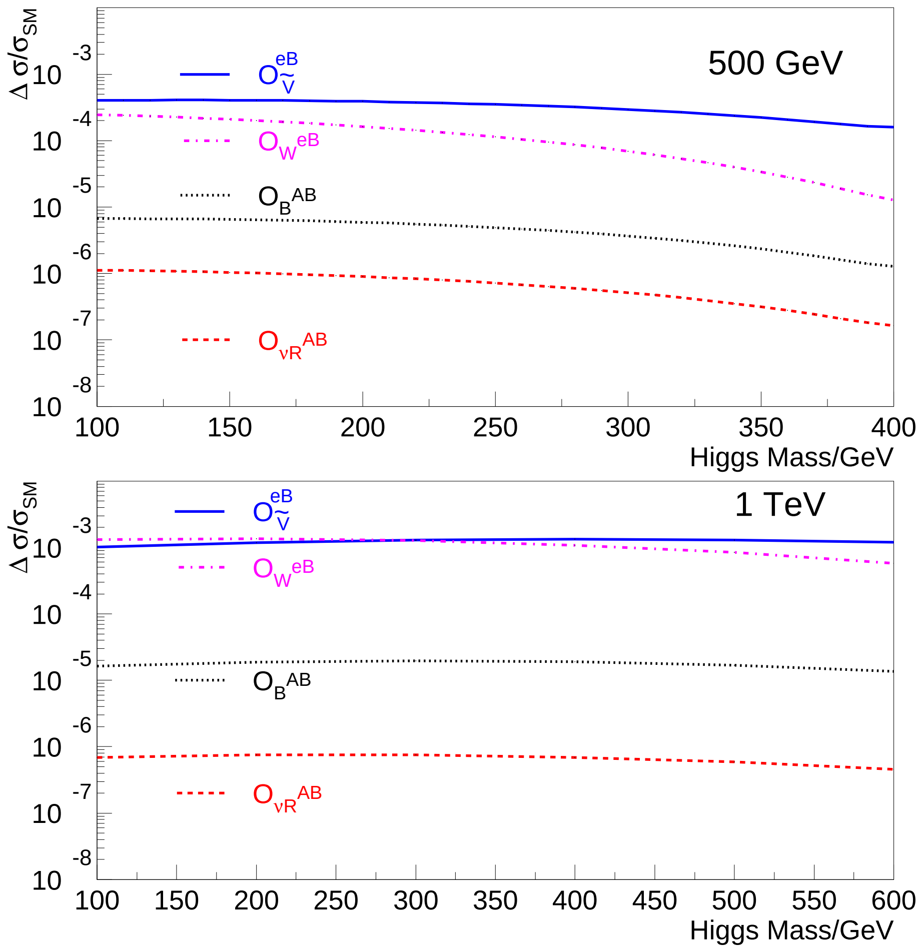



Only op's with charged-current components contribute:
$\mathcal{O}_{\tilde{V},\,eB}$, $\mathcal{O}_{W,\,eB}$.

Expect largest effects from $\mathcal{O}_{\tilde{V},\,eB}$, $\mathcal{O}_{W,\,eB}$ for same $C_j$.

# Class 2 Operators

For $\frac{C_j v^2}{\Lambda^2} = 10^{-2}$,




Taking $\frac{C_j v^2}{\Lambda^2} = 10^{-2}$ conservative: Michel spectrum implies limit on $\frac{C_{\tilde{V}} v^2}{\Lambda^2} \sim 0.2$.

# Limits on Class 1 Operators

Most important operators: $\mathcal{O}_{VR,ee}$, $\mathcal{O}_{VL,ee}$, $\mathcal{O}_{VL\tau,ee}$.
All affect coupling of Z to $e^+e^-$, Z-pole observables.

In addition, $\mathcal{O}_{VL\tau,ee}$ will affect $W^+e\bar{\nu}$ vertex, $G_\mu$:

$$\frac{G_\mu}{\sqrt{2}} = \frac{{g_2}^2}{8M_W^2}(1 + \Delta r_\mu) \quad \text{and} \quad \Delta r_\mu^{\mathrm{new}} = \frac{C_{L\tau}^{ee} v^2}{\Lambda^2}$$

$\rightarrow$ will affect many SM observables.

Using GAPP to fit $C_j$'s to precision electroweak data.

For op's of other flavors, get basic limits from Z partial widths using ZFITTER.

# Limits on Class 1 Ops at $95\%$ CL

| Op | Min$(\frac{C^j v^2}{\Lambda^2})$ | Max$(\frac{C^j v^2}{\Lambda^2})$ | |
|---|---|---|---|
| $\mathcal{O}_{VR}^{ee}$ | $-0.0012$ | $0.00044$ | |
| $\mathcal{O}_{VL}^{ee}$ | $-0.00015$ | $0.0012$ | GAPP fit results |
| $\mathcal{O}_{VL\tau}^{ee}$ | $-0.00036$ | $0.0011$ | |
| $\mathcal{O}_{VR,\mu\mu}$ | $-0.0027$ | $0.0020$ | |
| $\mathcal{O}_{VR,\tau\tau}$ | $-0.0050$ | $0.0007$ | Results from |
| $\mathcal{O}_{VL,\mu\mu}$ | $-0.0017$ | $0.0023$ | $\Gamma(Z \to \ell^{A\pm}\ell^{B\mp})$ |
| $\mathcal{O}_{VL,\tau\tau}$ | $-0.0006$ | $0.0043$ | |
| $\mathcal{O}_{VL\tau,\mu\mu}$ | $-0.0039$ | $0.0054$ | |
| $\mathcal{O}_{VL\tau,\tau\tau}$ | $-0.0006$ | $0.0043$ | |
| $\mathcal{O}_{j,e\mu}$ | $-0.0071$ | $0.0071$ | |
| $\mathcal{O}_{j,e\tau}$ | $-0.017$ | $0.017$ | |

# Contributions to Higgs Production

Corresponding changes in $Hq\bar{q}$, $H\mu^+\mu^-$, $H\tau^+\tau^-$ x-sections from interference with SM:

$\frac{\delta\sigma}{\sigma_{SM}}$ at $95\%$ CL:

| $\sqrt{s} = 500$ GeV | | | $\sqrt{s} = 1$ TeV | | |
|---|---|---|---|---|---|
| $\mathcal{O}_{VR}^{ee}$ | : | $-2\%, +6\%$ | $\mathcal{O}_{VR}^{ee}$ | : | $-10\%, +26\%$ |
| $\mathcal{O}_{VL}^{ee}$ | : | $-1\%, +7\%$ | $\mathcal{O}_{VL}^{ee}$ | : | $-4\%, +31\%$ |
| $\mathcal{O}_{VL\tau}^{ee}$ | : | $-2\%, +7\%$ | $\mathcal{O}_{VL\tau}^{ee}$ | : | $-9\%, +28\%$ |

with smaller numbers for $He^+e^-$, $H\nu\bar{\nu}$ channels. Non-interference terms can add $3\%$ to $Hq\bar{q}$, $H\mu^+\mu^-$ x-sections for $\sqrt{s} = 1$ TeV, $< 1\%$ for $\sqrt{s} = 500$ GeV and for $He^+e^-$, $H\nu\bar{\nu}$ channels.

# Limits on Class 2 Operators

$\mathcal{O}_{V\nu,AB}$ limit from invisible Z width ($1.6\sigma$ below expectation):

$$\sum_{A,B} \left| \frac{C_{V\nu}^{AB} v^2}{\Lambda^2} \right|^2 < .0068 \text{ at } 95\% \text{ CL}$$

$\mathcal{O}_{W,AB}$, $\mathcal{O}_{B,AB}$ bounded by $\nu$ mag. mom. ($\mu_\nu < 10^{-10}\ \mu_B$):

$$\left| \frac{C_{B,W}^{AB} v^2}{\Lambda^2} \right| \lesssim 10^{-5}$$

$\mathcal{O}_{\tilde{V},AB}$, take naturalness bounds from contribution to $m_\nu$:

$$\left| \frac{C_{\tilde{V}}^{eB} v^2}{\Lambda^2} \ln \frac{v}{\Lambda} \right| = (0.5\text{--}3) \times 10^{-3} \text{ for } 114 \text{ GeV} < M_H < 186 \text{ GeV}.$$

Contributions of Class 2 Op's to Higgs production negligible!

# Summary

- Three operators, $\mathcal{O}_{VR,ee}$, $\mathcal{O}_{VL,ee}$, and $\mathcal{O}_{VL\tau,ee}$, could have potentially observable effects on $Hq\bar{q}$, $H\mu^+\mu^-$, $H\tau^+\tau^-$ channels, with smaller effects in other channels.
- Same op's with $A = B = \mu, \tau, q$ contribute negligibly.
- For reasonable value of $Cv^2/\Lambda^2$, charged-fermion magnetic moment operators would have small contribution.
- Operators containing $\nu_R$'s constrained by $\Gamma_{Z,inv}$, $\nu$ magnetic moments, and $\nu$ mass to have negligible contribution.
- arXiv:0705.0554, JK and Michael J. Ramsey-Musolf.

# $\mathcal{O}_{W\ell,AB}$ and $\mathcal{O}_{B\ell,AB}$

$\mathcal{O}_{W\ell,AB}$, $\mathcal{O}_{B\ell,AB}$ $\rightarrow$ charged fermion EDM, mag. mom.

- $A = B = e$ or $\mu$: constrained by $g - 2$, EDMs.
- $A, B = e, \mu, \tau$, $A \neq B$: limits from $\tau \rightarrow \mu/e\gamma$, $\mu \rightarrow e\gamma$.
  $\rightarrow$ Only consider $A = B = \tau$, $A = q^A, B = q^B$.
- Interference with SM HZ Yukawa-suppressed.
- $C_{j,\tau\tau} v^2/\Lambda^2 = 10^{-2} \rightarrow$, non-interference terms give $< 0.1\%$ $(2\%)$ to $H\tau^+\tau^-$ at $\sqrt{s} = 500$ GeV ($1$ TeV).
- Quark operator contribution differs by factor $N_C$.
- Interference with SM can be comparable.
- Actual limits $> 10^{-2}$; take as expected upper limit.

# $\mathcal{O}_{VL,ee}$

$\mathcal{O}_{VL,ee} \equiv i(\bar{L}^e \gamma^\mu L^e)(\phi^+ D_\mu \phi) + \mathrm{hc} \rightarrow \bar{e}_L e_L ZH$, $\bar{\nu}_e \nu_e ZH$ vertices.

Interference w/ WWf not mass-suppressed.

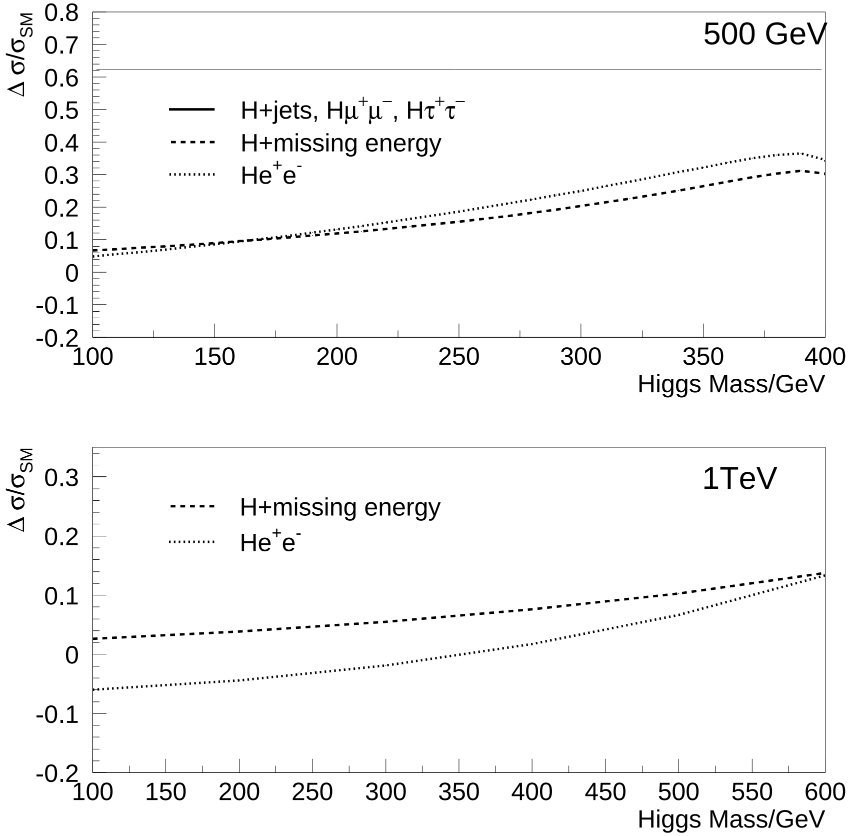
Otherwise similar to $\mathcal{O}_{VR,ee}$.

$$\frac{\sigma_{1-HZint}}{\sigma_{HZ}} = \frac{C_{VL,ee} v^2}{\Lambda^2} \frac{(s - M_Z^2)}{M_Z^2} \frac{(\frac{1}{2} - \sin^2\theta_W)}{2(\sin^4\theta_W - \frac{1}{2}\sin^2\theta_W + \frac{1}{8})}$$

$$\sim 62(255) \frac{C_{VL,ee} v^2}{\Lambda^2} \quad \text{for } \sqrt{s} = 500\,\text{GeV}\ (1\text{TeV})$$

# $\mathcal{O}_{VL,ee}$

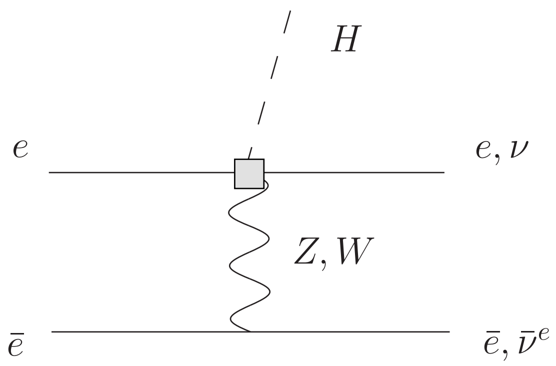
Taking $\frac{C_{VR,\mu\mu}v^2}{\Lambda^2} = 10^{-2}$,




Will not consider $\mathcal{O}_{VL,\ell\ell}$ and $\mathcal{O}_{VL,qq}$ cases.

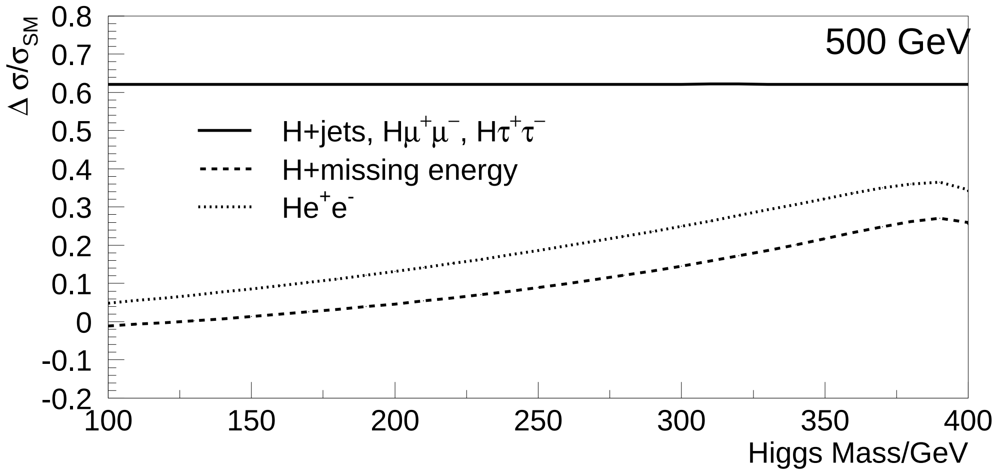
# $\mathcal{O}_{VL\tau,ee}$

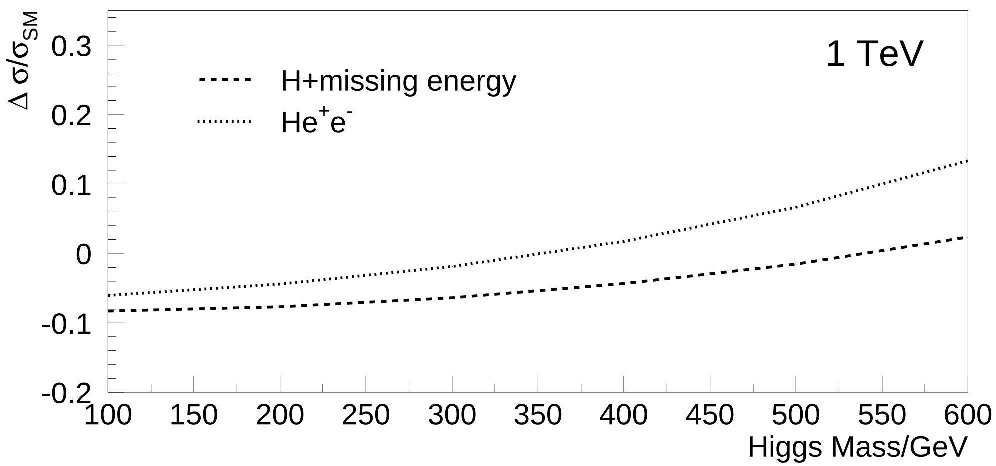
- $Hq\bar{q}$, $H\mu^+\mu-$ and $H\tau^+\tau^-$: same as $\mathcal{O}_{VL,ee}$.
- Contains charged current: $\bar{e}\nu W^-$ vertex.
- Must include diagram (3) in missing energy channel:



# $\mathcal{O}_{VL\tau,ee}$

For $\frac{C_{VL\tau,ee}v^2}{\Lambda^2} = 10^{-2}$,




Will not consider $\mathcal{O}_{VL\tau,\ell\ell}$ and $\mathcal{O}_{VL\tau,qq}$ cases.

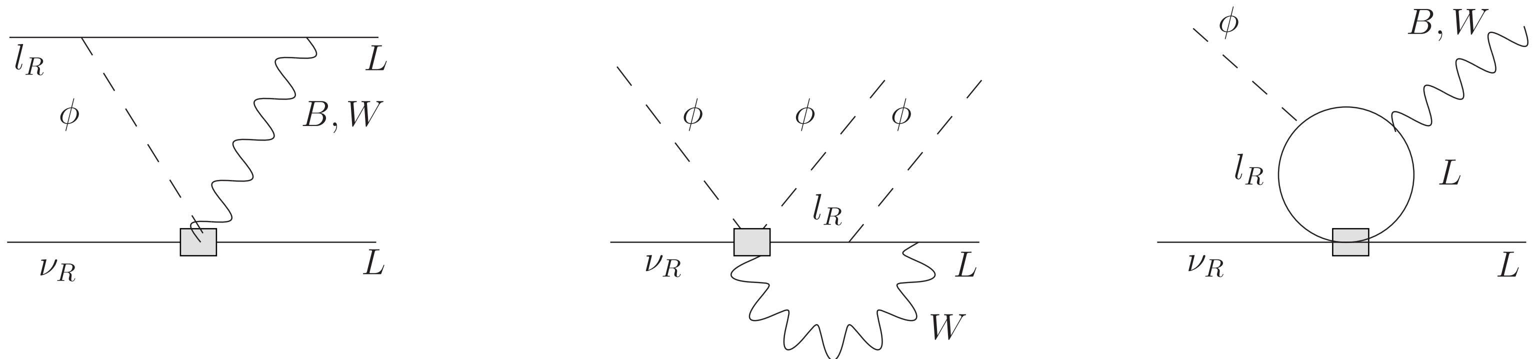
# Mixing With 6D Mass Operator

For mixing into $\mathcal{O}^{(6)}_{M,\,AD}$, must do complete RG analysis.

Must take into account mixing between all 6D op's:

$$\mathcal{O}^{(6)}_{B,\,AD},\ \mathcal{O}^{(6)}_{W,\,AD},\ \mathcal{O}^{(6)}_{M,\,AD},\ \mathcal{O}^{(6)}_{\tilde{V},\,AD},\ \mathcal{O}^{(6)}_{F,\,AAAD},\ \mathcal{O}^{(6)}_{F,\,ABBD},\ \mathcal{O}^{(6)}_{F,\,BABD}$$

e.g.,




$O_{B,W} \to O_F$ $\qquad$ $O_{\tilde{V}} \to O_M$ $\qquad$ $O_F \to O_{B,W}$

and many more....

Calculations done using Dim Reg in background field gauge.

Renormalize using minimal subtraction.

Then solve for coefficients $C^6_j(v)$ using the RGE.

# FCNCs in Class 1 Operators

Get limits on $\mathcal{O}_{VR,e\ell}$, $\mathcal{O}_{VL,e\ell}$, and $\mathcal{O}_{VL\tau,e\ell}$ for $\ell \neq e$ using limits on $\Gamma(Z \to e^{\pm}\mu^{\mp}, e^{\pm}\tau^{\mp})$ :

$95\%$ CL ranges (same for all 3 operators):

$$\frac{C_{j,e\mu}v^2}{\Lambda^2}: \pm 0.0071, \qquad \frac{C_{j,e\tau}v^2}{\Lambda^2}: \pm 0.017$$

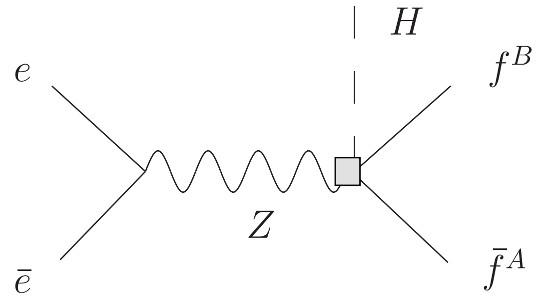
For $He^{\pm}\tau^{\pm}$ case, these limits give (events/$ab^{-1}$ data):

| $M_H$/GeV | $100$ | $300$ | $500$ |
|---|---|---|---|
| $\mathcal{O}_{VR,e\ell}$ | $81.$ | $40.$ | $12$ |
| $\mathcal{O}_{VL,e\ell}$, $\mathcal{O}_{VL\tau,e\ell}$ | $78.$ | $38.$ | $12$ |

Numbers smaller for $e^{\pm}\mu^{\pm}$, $\sqrt{s} = 500$ GeV cases. Observable?

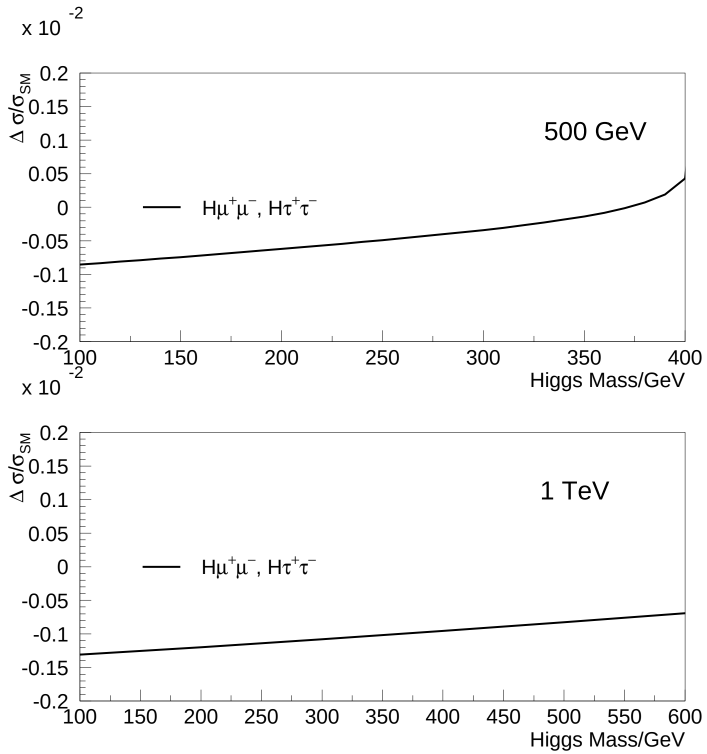
# $\mathcal{O}_{VR,\mu\mu}$

Only Diag. (2) is relevant:




Strongly kinematically suppressed due to off-shell $Z$.

Taking $\frac{C_{VR,\mu\mu} v^2}{\Lambda^2} = 10^{-2}$,




Results for $\mathcal{O}_{VR,\tau\tau}$ identical.
Results for $\mathcal{O}_{VR,qq}$ similar.