Effective Operators, Neutrino Mass, Muon Decay, and Higgs Production

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Topics Covered

- Erwin, JK, Ramsey-Musolf, Wang: Constraining new physics contributions to μ decay parameters using ν mass. (PRD 75, 033005)
- JK, Ramsey-Musolf: Constraints on contributions of fermionic operators to Higgs production at a linear collider. (0705.0554, submitted to PRD)

Effective Operators and New Physics

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

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

  which we take to be constructed from SM fields plus right-handed Dirac ν.
- 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.

Muon Decay

Muon Decay Parameters

The differential μ decay spectrum can be written as

$$\begin{aligned}\frac{d^2\Gamma}{dx\, d\cos\theta} &= \frac{m_\mu}{4\pi^2} W_{e\mu}^4 G_\mu^2 \sqrt{x^2 - x_0^2} \\ &\times \left[F_{IS}(x) \pm P_\mu \cos\theta\, F_{AS}(x)\right] \\ &\times \left[1 + \vec{\zeta} \cdot \vec{P}_e(x,\theta)\right]\end{aligned}$$

where

$W_{e\mu} = (m_\mu^2 + m_e^2)/2m_\mu =$ maximum e energy

$x = E_e/W_{e\mu}$ and $x_0 = m_e/W_{e\mu}$

$\vec{P}_\mu$, $\vec{P}_e = \mu$ and e polarizations

$\vec{\zeta}$ dependent on experimental configuration.

$F_{IS}(x)$ and $F_{AS}(x)$ give isotropic & anisotropic components.

Michel Parameters

$F_{IS}(x)$ and $F_{AS}(x)$ can be written in terms of Michel Parameters (MPs) ρ, η, ξ, and δ:

$$
\begin{aligned}
F_{IS} &= x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x) \\
F_{AS} &= \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta\left(4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right)\right]
\end{aligned}
$$

Michel parameters (MPs) ρ, δ and $P_\mu\xi$ will be measured by TWIST to a precision of a few $\times 10^{-4}$.

Can we use ν mass to put constraints on how NP could affect μ decay parameters?

New Physics Contributions to μ Decay

- New Physics contributions to μ decay can be described by basis of four-fermion operators:

$$\mathcal{L}^{\mu-\mathrm{decay}} = \frac{4G_\mu}{\sqrt{2}} \sum_{\gamma,\,\epsilon,\,\mu} g^\gamma_{\epsilon\mu}\ \bar{e}_\epsilon \Gamma^\gamma \nu \bar{\nu} \Gamma_\gamma \mu_\mu$$

$\Gamma^\gamma = 1$(S), γ^α(V), $\sigma^{\alpha\beta}/\sqrt{2}$(T)
μ and ϵ: μ^-, e^- chirality

- SM: $g^V_{LL} = 1$, others 0.
- MPs can be expressed in terms of $g^\gamma_{\epsilon\mu}$'s, ex:

$$\frac{3}{4} - \rho = \frac{3}{4}\left|g^V_{LR}\right|^2 + \frac{3}{2}\left|g^T_{LR}\right|^2 + \frac{3}{4}\mathrm{Re}\left(g^S_{LR} g^{T\,*}_{LR}\right) + (L \leftrightarrow R)$$

Relation of μ Decay to Neutrino Mass

- Two operators which can contribute to m_ν after EWSB are

$$\mathcal{O}^{(4)}_{M,\,AD} \equiv \bar{L}^A \tilde{\phi} \nu_R^D \quad \Longrightarrow \quad \delta m_\nu^{(4)AD} = \frac{-v}{\sqrt{2}} C^4_{M,\,AD}(v)$$

$$\mathcal{O}^{(6)}_{M,\,AD} \equiv \bar{L}^A \widetilde{\phi} \nu_R^D (\phi^+ \phi) \quad \Longrightarrow \quad \delta m_\nu^{(6)AD} = \frac{-v^3}{2\sqrt{2}\Lambda^2} C^6_{M,\,AD}(v)$$

$A, B, C, D =$ flavor indices
$\widetilde{\phi} = i\tau^2 \phi^*$

- Some terms in the NP Lagrangian $\mathcal{L}^{\mu-\mathrm{decay}}$ mix with the 4D and 6D mass operators at 1-loop order.
These terms will contribute at 1-loop to m_ν!

- We can use experimental limits on m_ν to constrain NP contributions to μ decay!

General Strategy

- Consider all 6D $SU(2) \times U(1)$-invariant operators which contribute to m_ν and/or μ decay.

$$\mathcal{L}_{\rm eff}^{(6)} = \sum_j \frac{C_j^6(\mu)}{\Lambda^2} \mathcal{O}_j^{(6)}(\mu) \; + \text{h.c.}$$

- Calculate the 1-loop contributions of these operators to m_ν.
- Limits on $m_\nu \rightarrow$ Limits on $C_j^6(\mu)$.
- Limits on $C_j^6(\mu) \rightarrow$ Limits on NP contributions to the MPs.

All results are computed to 1st order in Yukawa coupling f_{AA}.
We take upper limit on ν mass matrix elements of ~ 1 eV.

Operator Basis

- We find 5 linearly independent op's which contribute to m_ν:

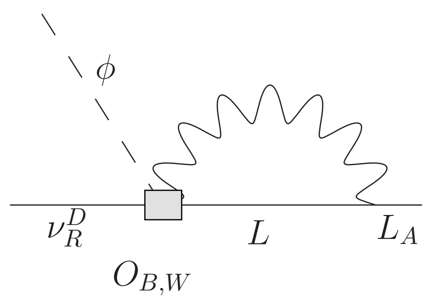
Operator	μ Decay Contribution
$\mathcal{O}^{(6)}_{B,\,AD} = g_1(\bar{L}^A\sigma^{\mu\nu}\widetilde{\phi})\nu_R^D B_{\mu\nu}$	$(m_\mu/v)^2$ suppressed
$\mathcal{O}^{(6)}_{W,\,AD} = g_2(\bar{L}^A\sigma^{\mu\nu}\tau^a\widetilde{\phi})\nu_R^D W^a_{\mu\nu}$	$(m_\mu/v)^2$ suppressed
$\mathcal{O}^{(6)}_{M,\,AD} = (\bar{L}^A\widetilde{\phi}\nu_R^D)(\phi^+\phi)$	No
$\mathcal{O}^{(6)}_{\tilde{V},\,AD} = i(\bar{\ell}^A_R\gamma^\mu\nu_R^D)(\phi^+ D_\mu\widetilde{\phi})$	$g^V_{RL,LR}$
$\mathcal{O}^{(6)}_{F,\,ABCD} = \epsilon^{ij}\bar{L}^A_i\ell^C_R\bar{L}^B_j\nu^D_R$	$g^{S,T}_{RL,LR}$

- Other 6D op's contributing to m_ν linear combinations of above.
- All other 6D operators which could contribute significantly to μ decay affect only $g_{\epsilon\mu}$ with $\epsilon=\mu$.

m_ν gives us handle on $g^{S,V,T}_{RL,LR}$!

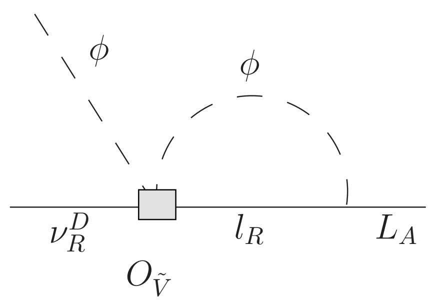
Mixing With 4D Mass Operator

We obtain order-of-magnitude estimates for the mixing of 6D operators into $\mathcal{O}^{(4)}_{M,\,AD}$:

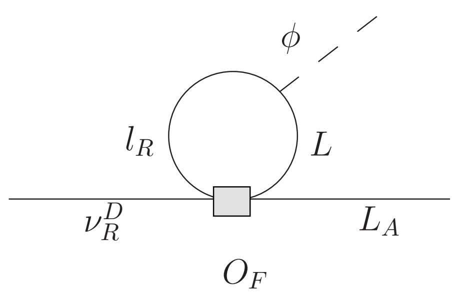


$$\mathcal{O}^{(6)}_{B,\,AD} \quad \longrightarrow \quad C^4_{M,\,AD} \sim \frac{\alpha}{4\pi\cos^2\theta_W} C^6_{B,\,AD}$$

$$\mathcal{O}^{(6)}_{W,\,AD} \quad \longrightarrow \quad C^4_{M,\,AD} \sim \frac{3\alpha}{4\pi\sin^2\theta_W} C^6_{W,\,AD}$$



$$\mathcal{O}^{(6)}_{\tilde{V},\,AD} \quad \longrightarrow \quad C^4_{M,\,AD} \sim \frac{f_{AA}}{16\pi^2} C^6_{\tilde{V},\,AD}$$



$$\mathcal{O}^{(6)}_{F,\,BABD} \quad \longrightarrow \quad C^4_{M,\,AD} \sim \frac{f_{BB}}{4\pi^2} C^6_{F,\,BABD}$$

$$\mathcal{O}^{(6)}_{F,\,ABBD} \quad \longrightarrow \quad C^4_{M,\,AD} \sim \frac{f_{BB}}{16\pi^2} C^6_{F,\,ABBD}$$

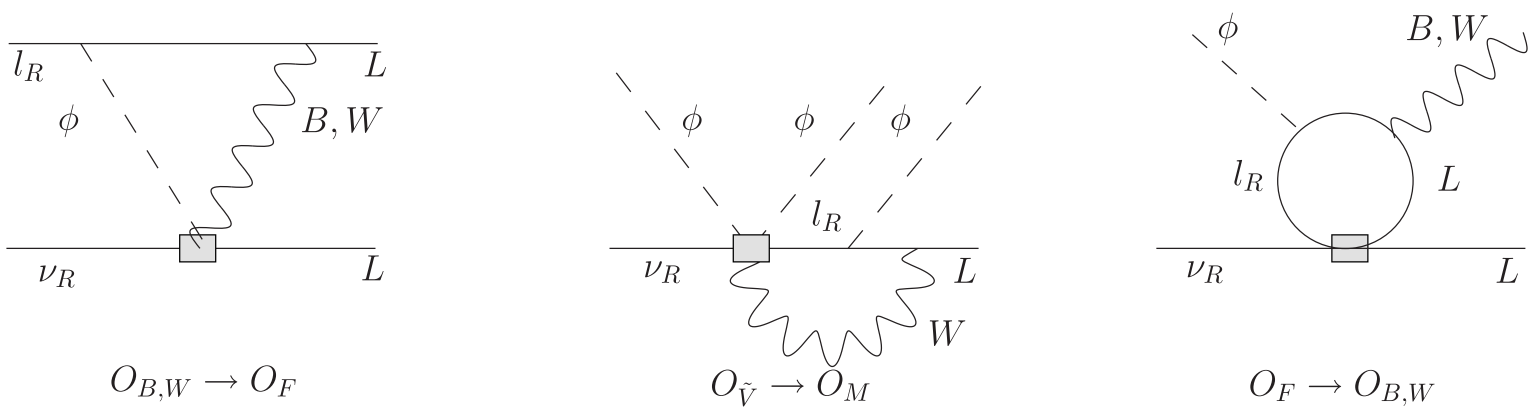
Mixing With 6D Mass Operator

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.,



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.

Mixing With 6D Mass Operator

We eventually get $C^6_{M,AD}(v)$ in terms of the $C(\Lambda)$'s:

$$
\begin{aligned}
&C^6_{M,\,AD}(v) \\
&= C^6_{M,\,AD}(\Lambda)\left[1-\left(\frac{9(\alpha_1+3\alpha_2)}{16\pi}-\frac{3\lambda}{2\pi^2}\right)\ln\frac{v}{\Lambda}\right] \\
&- \Big[-6\alpha_1(\alpha_1+\alpha_2)C^6_{B,AD}(\Lambda)+6\alpha_2(\alpha_1+3\alpha_2)C^6_{W,AD}(\Lambda) \\
&+\left(\frac{9\alpha_2 f_{AA}}{8\pi}-\frac{3f_{AA}\lambda}{8\pi^2}\right)C^6_{\tilde{V},\,AD}(\Lambda)\Big]\ln\frac{v}{\Lambda}
\end{aligned}
$$

Constraints from mixing into 6D mass op $\sim \frac{v^2}{\Lambda^2}$ weaker than expectations from 4D op.

Note only $C_{\tilde{V},AD}$ multiplied by fermion Yukawa coupling f_{AA}.

Will use this result in Higgs production analysis later...

Contributions to g's

Expectations on contributions of the 6D operators to the g's:

Source	$\|g^S_{LR}\|$	$\|g^T_{LR}\|$	$\|g^S_{RL}\|$	$\|g^T_{RL}\|$	$\|g^V_{LR}\|$	$\|g^V_{RL}\|$
$\mathcal{O}^{(6)}_{F,\,122D}$	4×10^{-7}	2×10^{-7}	-	-	-	-
$\mathcal{O}^{(6)}_{F,\,212D}$	4×10^{-7}	-	-	-	-	-
$\mathcal{O}^{(6)}_{F,\,112D}$	None	None	-	-	-	-
$\mathcal{O}^{(6)}_{F,\,211D}$	-	-	8×10^{-5}	4×10^{-5}	-	-
$\mathcal{O}^{(6)}_{F,\,121D}$	-	-	8×10^{-5}	-	-	-
$\mathcal{O}^{(6)}_{F,\,221D}$	-	-	None	None	-	-
$\mathcal{O}^{(6)}_{\tilde{V},\,2D}$	-	-	-	-	8×10^{-7}	-
$\mathcal{O}^{(6)}_{\tilde{V},\,1D}$	-	-	-	-	-	2×10^{-4}
Global*	0.088	0.025	0.417	0.104	0.036	0.104
Two-loop†	10^{-4}	10^{-4}	10^{-2}	10^{-2}	10^{-4}	10^{-2}

*Gagliardi et. al

† Prezeau & Kurylov

Contributions to g's

- Expected size of g's
  - ~ 4 orders of mag. stronger than experimental results,
  - ~ 2 orders of mag. stronger than results of Prezeau & Kurylov.
- Two operators, $\mathcal{O}^{(6)}_{F,112D}$ and $\mathcal{O}^{(6)}_{F,221D}$, contribute to μ decay but are not directly constrained by m_ν.
- Large contribution from $\mathcal{O}^{(6)}_{F,112D}$ or $\mathcal{O}^{(6)}_{F,221D}$ could indicate interesting flavor physics.
- Limits could be evaded if we allow fine-tuning between operators.

Contributions to Michel Parameters

Of ρ, δ and $P_\mu \xi$, only ρ is independent of $g^{S,V,T}_{RR,LL}$:

$$\frac{3}{4} - \rho = \frac{3}{4}\left|g^V_{LR}\right|^2 + \frac{3}{2}\left|g^T_{LR}\right|^2 + \frac{3}{4}\mathrm{Re}\left(g^S_{LR} g^{T\,*}_{LR}\right) + (L \leftrightarrow R)$$

If all $\mathcal{O}^{(6)}_{F,\,ABCD}$ have similar coefficients, would naively expect contribution to $\frac{3}{4} - \rho \lesssim 10^{-7}$.

If TWIST sees a nonzero $\frac{3}{4} - \rho$, might be sign of some interesting flavor-dependent physics.

μ *Decay Summary*

No Michel Parameters directly constrained, but....

- $m_\nu \lesssim 1eV \rightarrow$ Model-independent expectations on $g^V_{RL,LR}$ 4 orders of magnitude tighter than current experimental results.
- With the exception of 2 operators unconstrained due to their flavor structure, contributions to $g^{S,T}_{RL,LR}$ similarly constrained.
- Two unconstrained operators might be the first place to look if TWIST sees nonzero $\rho - \frac{3}{4}$.
- PRD 75, 033005, hep-ph/0602240.

Higgs Production at a Linear e^+e^- Collider

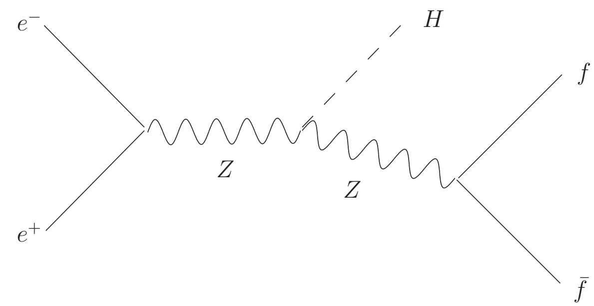
New Physics and the Higgs Cross-Section

- Can we constrain how NP could show up in the Higgs production cross-section at a linear e^+e^- collider?
- Operators containing only Higgs and gauge boson fields done elsewhere (Barger et al, Manohar & Wise).
- What about operators containing fermions?
- Can operators containing ν_R's affect the production cross-section?

SM Higgs Production at e^+e^- Collider

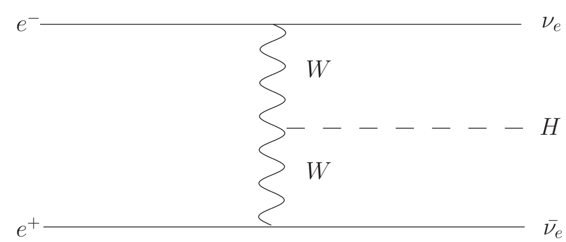
Higgs Production at LC occurs mainly via 3 processes:

Higgsstrahlung (HZ)



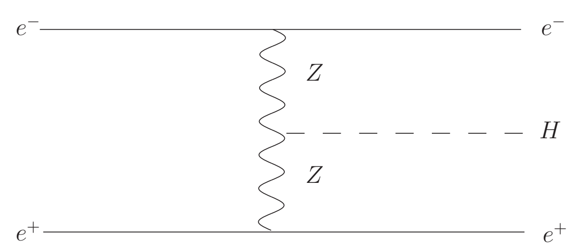
$f\bar{f} = q\bar{q}, \nu\bar{\nu}, \ell^+\ell^-$

W^+W^--fusion (WWf)



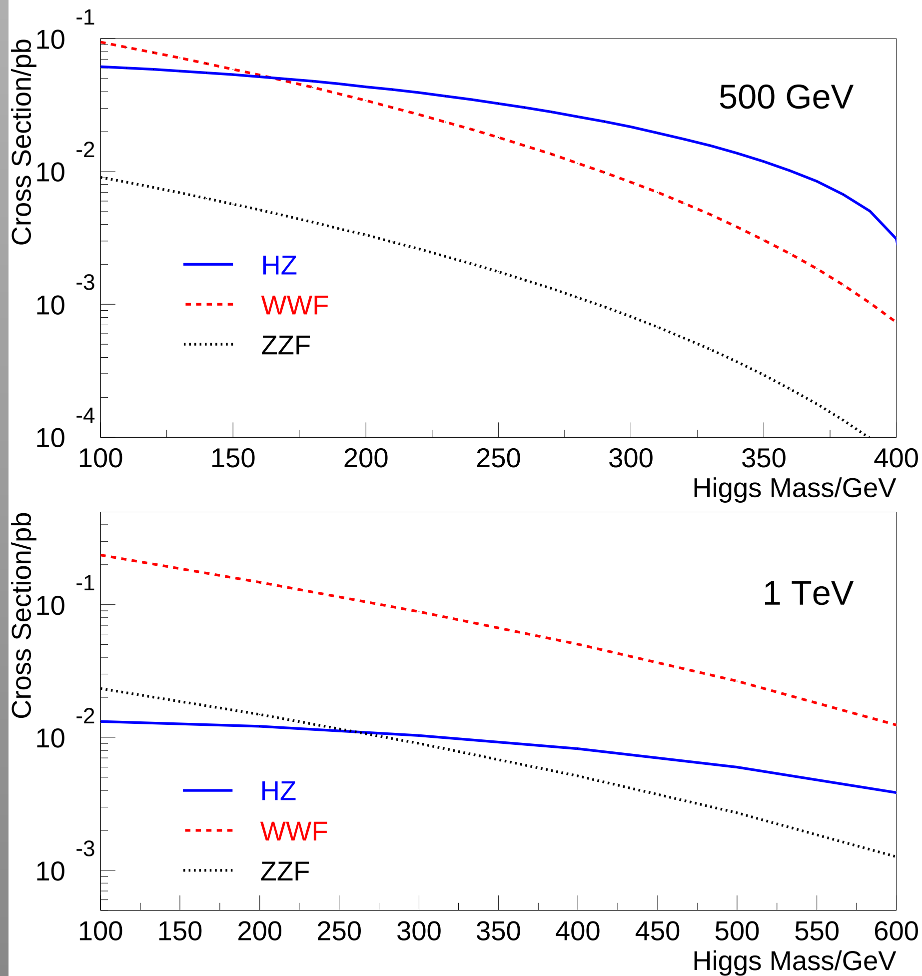
final state w/ $\nu_e\bar{\nu}_e$

ZZ-fusion (ZZf)



final state w/ e^+e^-

SM Higgs Production



Low $\sqrt{s}$

$\downarrow$

HZ dominates

High $\sqrt{s}$

$\downarrow$

W^+W^- fusion dominates

ZZ fusion $< W^+W^-$ fusion by order of magnitude.

*Cross-sections computed with Calchep.

Higgs Production Channels

- Higgs + jets
  $\sim 65\%$ of HZ $\rightarrow$ important at low $\sqrt{s}$.
- Higgs + missing energy
  100% of WWf, $\sim 20\%$ of HZ $\rightarrow$ important at high $\sqrt{s}$.
- Higgs + charged leptons
  e^+e^-: 100% of ZZf, clean channel for mass reconstruction & cross-section measurement.
  $\mu^+\mu^-$: important for mass recon. & cross-section.
  $\tau^+\tau^-$: not as useful for mass reconstruction.
  Expected statistical error on cross-section $\sim 3\%$ for combined He^+e^-, $H\mu^+\mu^-$ channels w/ 500 fb^{-1} of data.

General Strategy

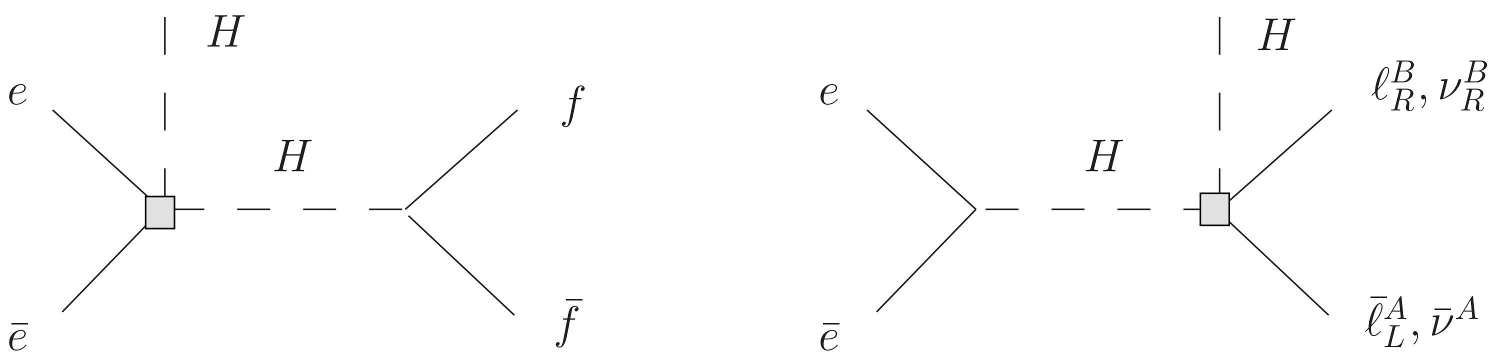
- Consider all 6D operators containing fermion and Higgs fields.
- Include right-handed (Dirac) neutrino.
- Ignoring changes in couplings in SM Higgs production diagrams caused by operator insertion (constrained to be small).
- Instead, looking at cases where operators inserted into new production diagrams.
- Leaving out $Ht\bar{t}$ final state; ignoring Higgs decay.

Operator Basis

Class A, Mass Op's (A, B = flavor indices, $\widetilde{\phi} = i\tau^2\phi^*$):

$$\mathcal{O}^{L}_{M,\,AB} \equiv (\bar{L}^A \phi \ell^B_R)(\phi^+\phi) + \text{h.c.}$$
$$\mathcal{O}^{\nu}_{M,\,AB} \equiv (\bar{L}^A \widetilde{\phi} \nu^B_R)(\phi^+\phi) + \text{h.c.}$$

Plus analogous terms for quarks.



Highly mass-suppressed → Will not consider further.

Operator Basis

Class B Operators: Operators w/o ν_R:

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

F: left-handed fermion doublet

f_R: right-handed fermion

Class A ops can contribute to all final states.

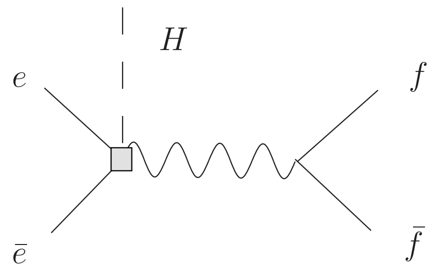
Operator Basis

Class C Operators: Operators containing ν_R:

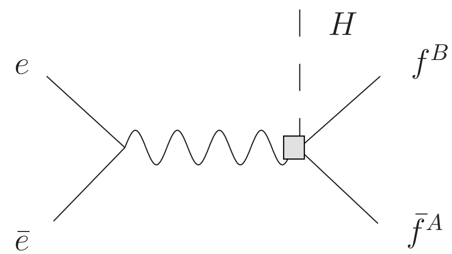
$$
\begin{aligned}
\mathcal{O}_{V\nu,\,AB} &\equiv i(\bar{\nu}_R^A\gamma^\mu\nu_R^B)(\phi^+D_\mu\phi) + h.c. \\
\mathcal{O}_{\tilde{V},\,AB} &\equiv i(\bar{\ell}_R^A\gamma^\mu\nu_R^B)(\phi^+D_\mu\widetilde{\phi}) + \mathrm{h.c.} \\
\mathcal{O}_{W,\,AB} &\equiv g_2(\bar{L}^A\sigma^{\mu\nu}\tau^a\widetilde{\phi})\nu_R^B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

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

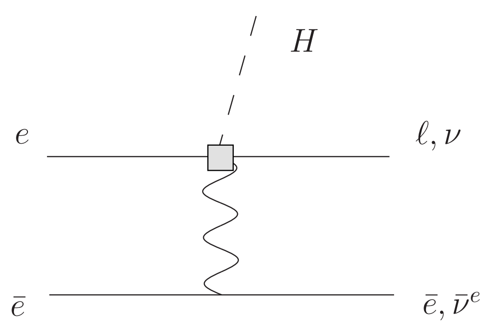
Diagrams With Class B Operators

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 ℓ, e.
Flavor-changing diagrams will not interfere w/SM.

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

$\mathcal{O}_{VR,AB}$

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

Will consider two cases:

- $A = B = e$
  $\rightarrow$ Will contribute to all final states.
- $A = B \neq e$
  $\rightarrow$ Final states of $\bar{f}_R^A f_R^B$.

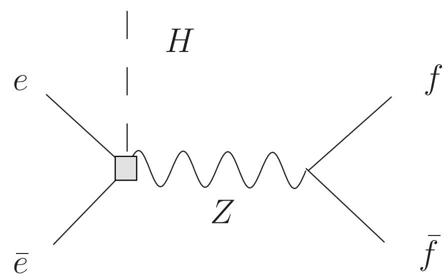
Will ignore FCNC case here.

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

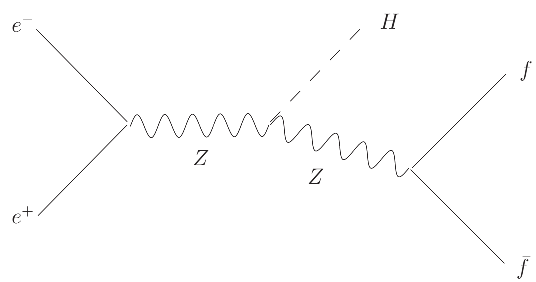
$q\bar{q}$, $\mu^+\mu^-$, $\tau^+\tau^-$, $\nu\bar{\nu}$ channels: only Diag (1) contributes.

Compare to SM HZ diagram:

Diagram 1



SM HZ



Interference with HZ is related to SM HZ by

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

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

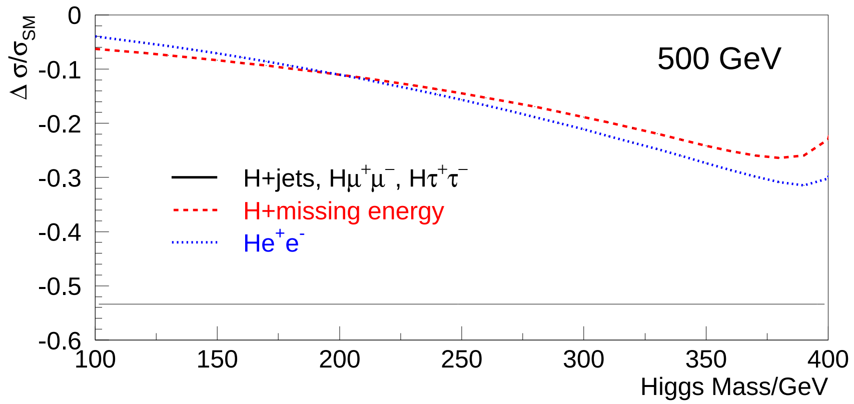
Can be large for $\sqrt{s} >> M_Z$!

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

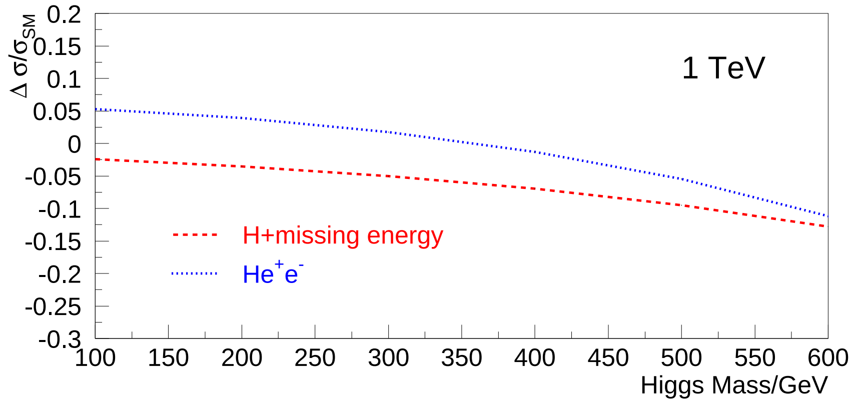
$\nu_e\bar{\nu}_e$ in final state: interference w/SM WWf suppressed by m_e.

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

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

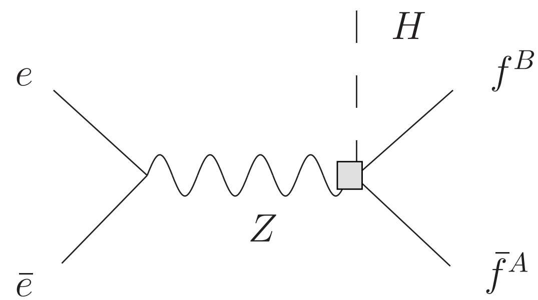


For $\sqrt{s} = 1$ TeV, $q\bar{q}$, $\mu^+\mu^-$, $\tau^+\tau^-$ line at -2.2.



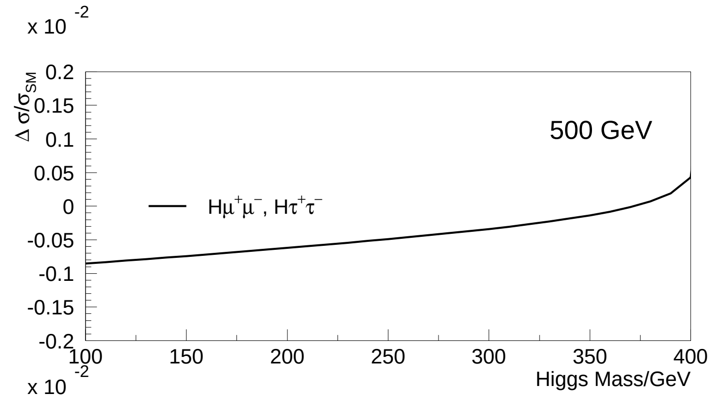
$\mathcal{O}_{VR,\mu\mu}$

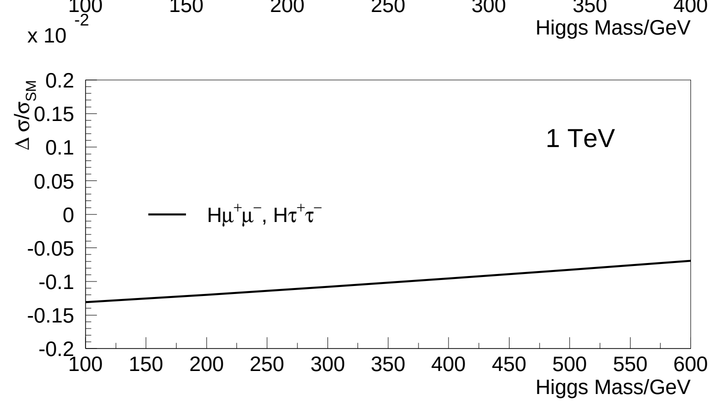
Only Diag. (2) is relevant:



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.

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

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

Interference w/ WWf not mass-suppressed.

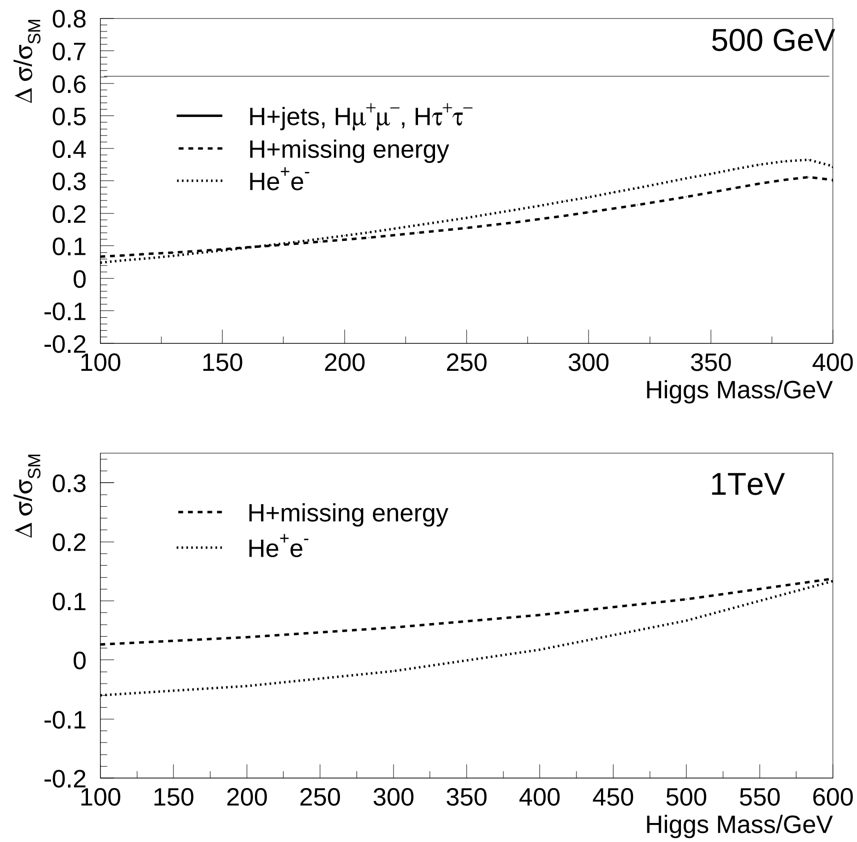
Otherwise similar to $\mathcal{O}_{VR,ee}$.

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

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

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

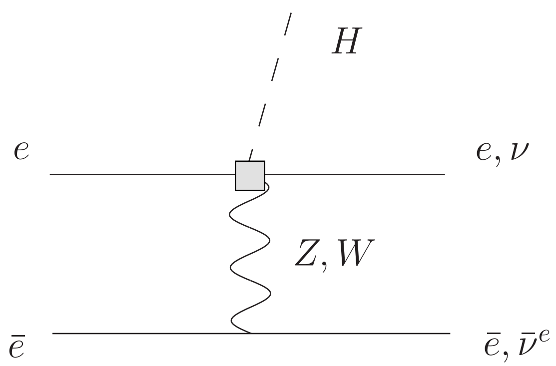
Taking $\frac{C_{VR,\mu\mu} v^2}{\Lambda^2} = 10^{-2}$,



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

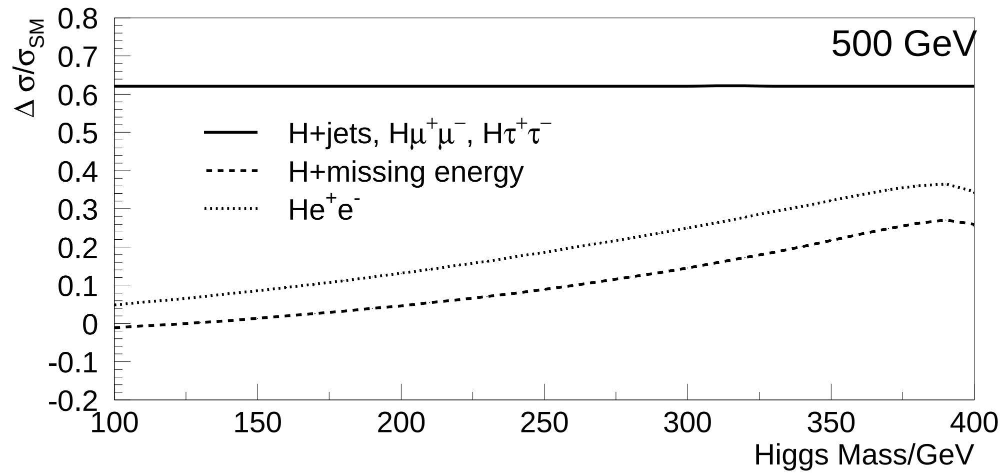
$\mathcal{O}_{VL\tau,ee}$

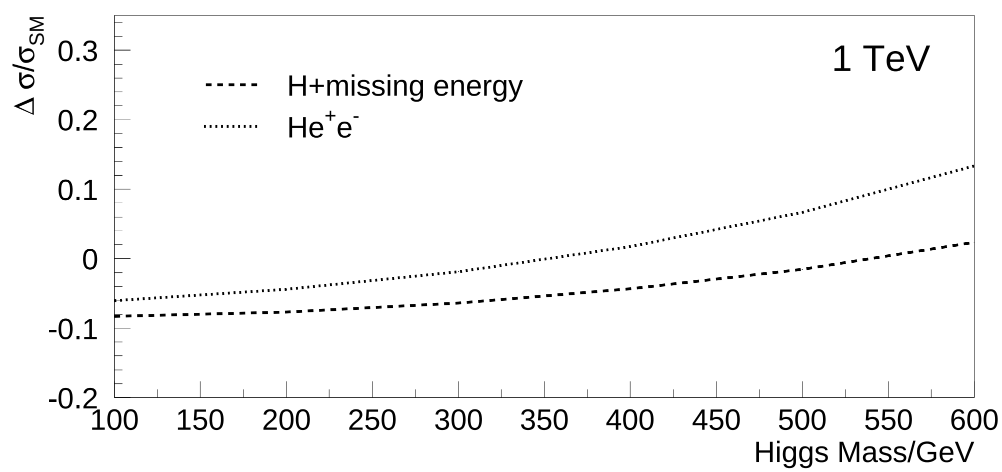
- $Hq\bar{q}$, $H\mu^+\mu-$ and $H\tau^+\tau^-$: same as $\mathcal{O}_{VL,ee}$.
- Contains charged current: $\bar{e}\nu W^-$ vertex.
- Must include diagram (3) in missing energy channel:



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

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.

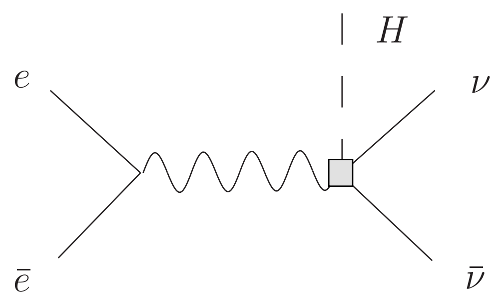
$\mathcal{O}_{W\ell,AB}$ **and** $\mathcal{O}_{B\ell,AB}$

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

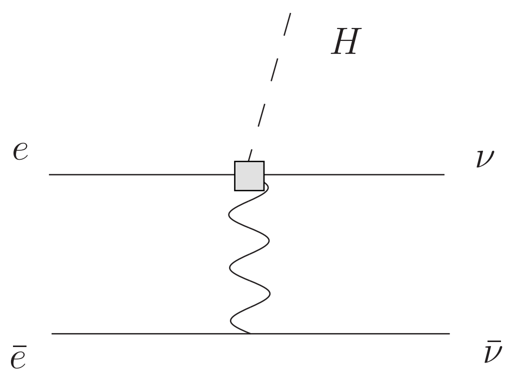
- $A = B = e$ or μ: constrained by $g - 2$, EDMs.
- $A, B = e, \mu, \tau$, $A \neq B$: limits from $\tau \rightarrow \mu/e\gamma$, $\mu \rightarrow e\gamma$. $\rightarrow$ Only consider $A = B = \tau$, $A = q^A, B = q^B$.
- Interference with SM HZ Yukawa-suppressed.
- $C_{j,\tau\tau}v^2/\Lambda^2 = 10^{-2} \rightarrow$, 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.

Diagrams With Class C Operators

All Class C Operators contribute only to ν 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.

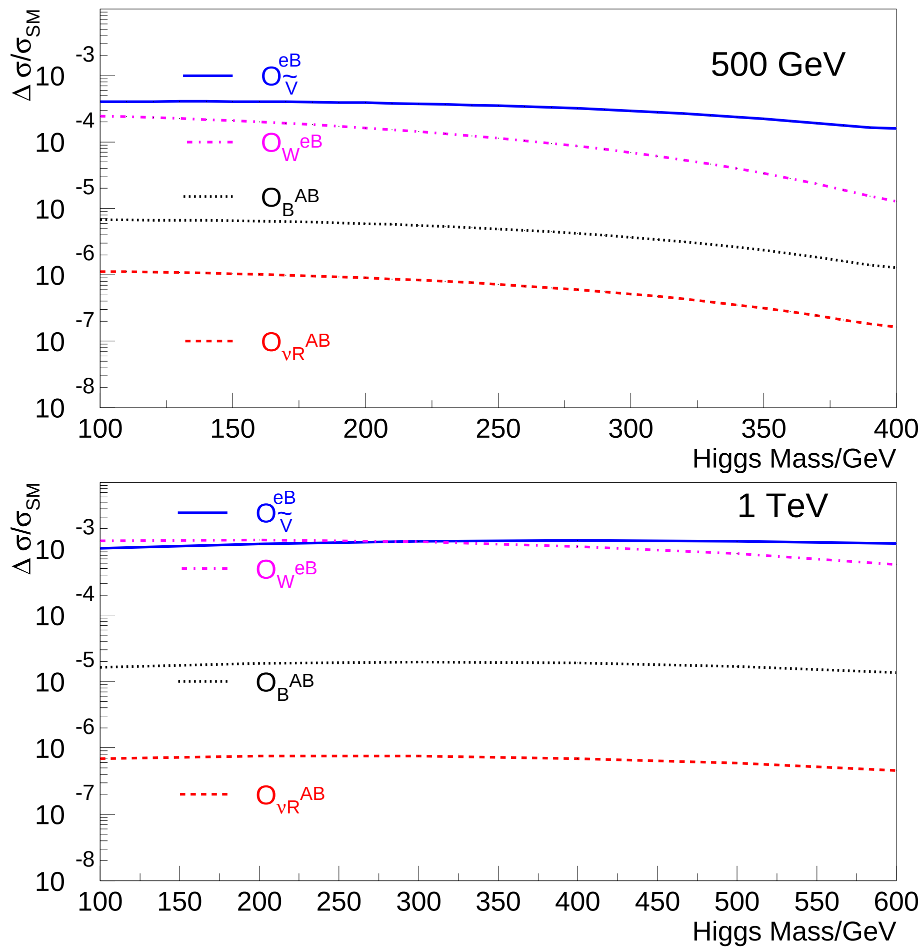


Only op's with charged-current components contribute:
$\mathcal{O}_{\tilde{V},\,eB}$, $\mathcal{O}_{W,\,eB}$.

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

Class C 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 B 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_μ:

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

$\rightarrow$ will affect many SM observables.

Using GAPP to fit C_j's to precision electroweak data: Z-pole, $\nu - e$ scattering, Moller scattering, Q_W, G_μ.

Op's of other flavors: get basic limits from Z partial widths using ZFITTER, compare to exp.

Limits on Class B 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
$\mathcal{O}_{VL\tau}^{ee}$	-0.00036	0.0011
$\mathcal{O}_{VR,\mu\mu}$	-0.0027	0.0020
$\mathcal{O}_{VR,\tau\tau}$	-0.0050	0.0007
$\mathcal{O}_{VL,\mu\mu}$	-0.0017	0.0023
$\mathcal{O}_{VL,\tau\tau}$	-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

GAPP fit results

Results from $\Gamma(Z \to \ell^{A\pm}\ell^{B\mp})$

Contributions of Class B Ops 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		
$\mathcal{O}^{ee}_{VR}$	:	$-2\%, +6\%$	$\mathcal{O}^{ee}_{VR}$	:	$-10\%, +26\%$
$\mathcal{O}^{ee}_{VL}$	:	$-1\%, +7\%$	$\mathcal{O}^{ee}_{VL}$	:	$-4\%, +31\%$
$\mathcal{O}^{ee}_{VL\tau}$	:	$-2\%, +7\%$	$\mathcal{O}^{ee}_{VL\tau}$	:	$-9\%, +28\%$

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 C Operators

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

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

$\mathcal{O}_{W,AB}$, $\mathcal{O}_{B,AB}$ bounded by ν magnetic moments ($\mu_\nu < 10^{-10}\ \mu_B$):

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

For $\mathcal{O}_{\tilde{V},AB}$, we take results from μ decay analysis.

Limits on Class C Operators

So, for $\mathcal{O}_{\tilde{V},AB}$, we take result from mixing of 6D operators into 6D mass operator:

$$\left|\frac{C^{eB}_{\tilde{V}} v^2}{\Lambda^2} \ln \frac{v}{\Lambda}\right| = (0.5 - 3) \times 10^{-3}$$

with range on $C^{eB}_{\tilde{V}}$ for $114\,$GeV $< M_H < 186\,$GeV.

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

Higgs 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 operators with $A = B = \mu, \tau, q$ contribute negligibly.
- For reasonable value of Cv^2/Λ^2, charged-fermion magnetic moment operators would have small contribution.
- Operators which contain ν_R's are constrained by $\Gamma_{Z,inv}$, ν magnetic moments, and ν mass to have negligible contribution.
- 0705.0554, submitted to PRD.

Flavor-changing Neutral Currents

Can also consider flavor non-conserving case $A \neq B$.

Only consider $He^{\pm}\tau^{\mp}$, $He^{\pm}\mu^{\mp}$ cases; $H\tau^{\pm}\mu^{\mp}$ small.

Cross-sections (ab) for $\frac{C_{j,e\ell}v^2}{\Lambda^2} = 10^{-2}$

$\sqrt{s} = 500$ GeV

M_H/GeV	100	250	400
$\mathcal{O}_{VR,e\ell}$	3.4	0.72	0.024
$\mathcal{O}_{VL,e\ell}$, $\mathcal{O}_{VL\tau,e\ell}$	3.2	0.67	0.023

$\sqrt{s} = 1$ TeV

M_H/GeV	100	300	500
$\mathcal{O}_{VR,e\ell}$	28.	14.	4.2
$\mathcal{O}_{VL,e\ell}$, $\mathcal{O}_{VL\tau,e\ell}$	27.	13.	4.1

FCNCs in Class A 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):

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

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?