Effective Operators, New Physics and CEPC

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Outline

- General Picture
- Effective Operators beyond SM at CEPC (TGC as an example)
- Simplified model examples of CEPC/SPPC
- Tree Level & Loop effects; the RG running and operator mixing between different operators.
- One loop CDE calculation: Electroweakino contributes to Higgs strahlung
- Summary:

Why Effective Operators at the lepton colliders?

CEPC

Circular e^+ e^- collider with center of mass energy 240 GeV

What we use effective operators?

- Fixed energy: EFT is always valid.
- General model independent parametrization & categorization.
- Simply map to the lepton collider measurements

CEPC

Cicular e^+ e^- collider with center of mass energy 240 GeV

What can it go beyond the LEP?

- EW precision
- Tri-gauge boson precision
- Higgs precision

CEPC

Underlying Models	Simplified Models	Effective Operators	CEPC Observables
Models with new symmetries, dynamics to the interpret EWSB, naturalness, etc.	Just some new particles, or some strong dynamics	Many operators	Total cross section, angle distributions, etc

Effective Operators Beyond SM (TGC example)

Operators beyond SM

There are 81 operators up to dimension 6, including one dimension 5 operator which gives the neutrino mass (Weinberg operator)

Flavor diagonal, no B-violating.

For the 80 d=6 operators, e.o.m. and CP conserving would reduce this number

Let's see what an electron collider can do for those operators before Higgs discovery

Operators beyond SM

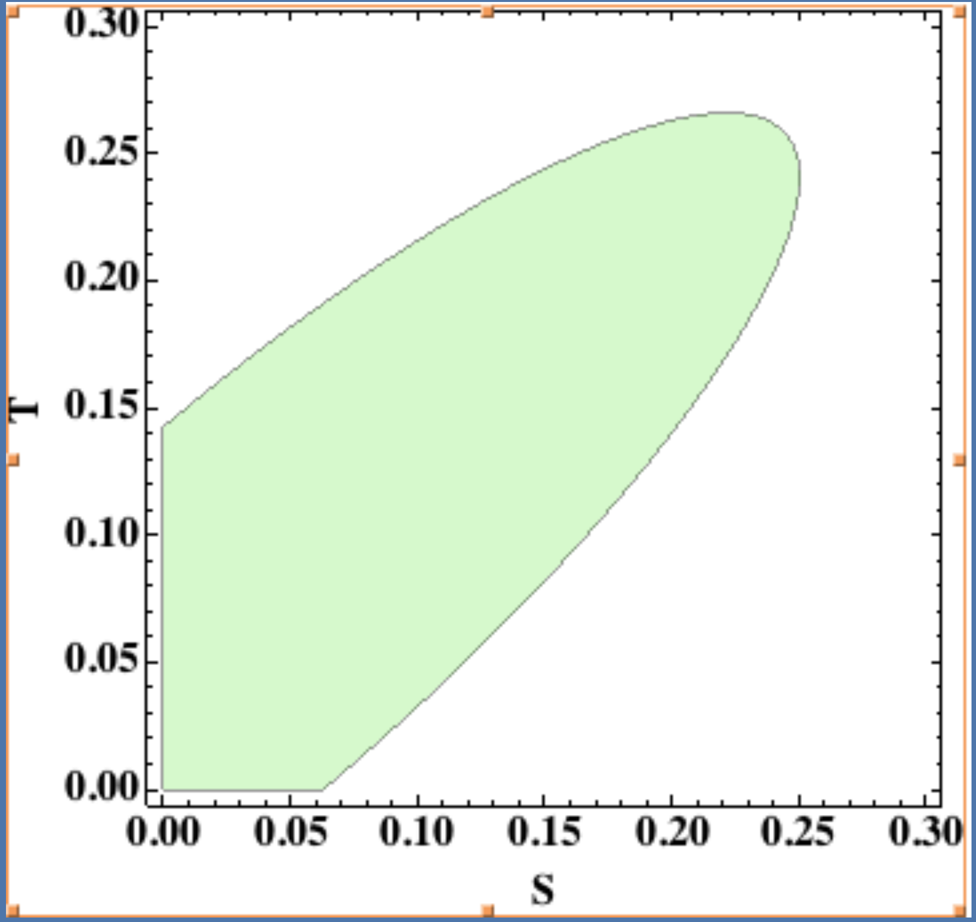
Independent observables related to LEP I, II

bosonic fields	Higgs/fermions	4-fermion
$\mathcal{O}_{WB} = \left(H^\dagger \sigma^a H\right) W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}^s_{hl} = i\left(H^\dagger D^\mu H\right)\left(\bar{L}_L \gamma_\mu L_L\right)$	$\mathcal{O}^s_{ll} = \frac{1}{2}\left(\bar{L}_L \gamma^\mu L_L\right)\left(\bar{L}_L \gamma_\mu L_L\right)$
$\mathcal{O}_h = \left(H^\dagger D_\mu H\right)^2$	$\mathcal{O}^s_{hq} = i\left(H^\dagger D^\mu H\right)\left(\bar{Q}_L \gamma_\mu Q_L\right)$	$\mathcal{O}^s_{lq} = \left(\bar{L}_L \gamma^\mu L_L\right)\left(\bar{Q}_L \gamma_\mu Q_L\right)$
$\mathcal{O}_W = \epsilon^{abc} W^{a\nu}_\mu W^{b\lambda}_\nu W^{c\mu}_\lambda$	$\mathcal{O}_{hu} = i\left(H^\dagger D^\mu H\right)\left(\bar{u}_R \gamma_\mu u_R\right)$	$\mathcal{O}_{le} = \left(\bar{L}_L \gamma^\mu L_L\right)\left(\bar{e}_R \gamma_\mu e_R\right)$
	$\mathcal{O}_{he} = i\left(H^\dagger D^\mu H\right)\left(\bar{e}_R \gamma_\mu e_R\right)$	$\mathcal{O}_{lu} = \left(\bar{L}_L \gamma^\mu L_L\right)\left(\bar{u}_R \gamma_\mu u_R\right)$
	$\mathcal{O}^t_{hl} = i\left(H^\dagger \sigma^a D^\mu H\right)\left(\bar{L}_L \gamma_\mu \sigma^a L_L\right)$	$\mathcal{O}_{ee} = \frac{1}{2}\left(\bar{e}_R \gamma^\mu e_R\right)\left(\bar{e}_R \gamma_\mu e_R\right)$
	$\mathcal{O}^t_{hq} = i\left(H^\dagger \sigma^a D^\mu H\right)\left(\bar{Q}_L \gamma_\mu Q_L\right)$	$\mathcal{O}^t_{ll} = \frac{1}{2}\left(\bar{L}_L \gamma^\mu \sigma^a L_L\right)\left(\bar{L}_L \gamma_\mu \sigma^a L_L\right)$
	$\mathcal{O}_{hd} = i\left(H^\dagger D^\mu H\right)\left(\bar{d}_R \gamma_\mu d_R\right)$	$\mathcal{O}^t_{lq} = \left(\bar{L}_L \gamma^\mu L_L\right)\left(\bar{Q}_L \gamma_\mu \sigma^a Q_L\right)$
		$\mathcal{O}_{qe} = \left(\bar{Q}_L \gamma^\mu Q_L\right)\left(\bar{e}_R \gamma_\mu e_R\right)$
		$\mathcal{O}_{ld} = \left(\bar{L}_L \gamma^\mu L_L\right)\left(\bar{d}_R \gamma_\mu d_R\right)$
		$\mathcal{O}_{eu} = \left(\bar{e}_R \gamma^\mu e_R\right)\left(\bar{u}_R \gamma_\mu u_R\right)$
		$\mathcal{O}_{ed} = \left(\bar{e}_R \gamma^\mu e_R\right)\left(\bar{d}_R \gamma_\mu d_R\right)$

Bosonic fields

95% C. L.

$$\mathcal{O}_{WB} = \left(H^\dagger \sigma^a H\right) W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_h = \left(H^\dagger D_\mu H\right)^2$$
$$\mathcal{O}_W = \epsilon^{abc} W^{a\nu}_{\mu} W^{b\lambda}_{\nu} W^{c\mu}_{\lambda}$$



Famous S, T parameter

$$a_{WB} = \frac{1}{4sc}\frac{\alpha}{v^2} S, \;\; a_h = -2\frac{\alpha}{v^2} T,$$

Tri-gauge boson at LEP

In the Hagiwara-Peccei-Zeppenfeld-Hikasa basis

$$\mathcal{L}_{\mathrm{TGC}}/g_{WWV} = ig_{1,V}\left(W^+_{\mu\nu}W^-_\mu V_\nu - W^-_{\mu\nu}W^+_\mu V_\nu\right) + i\kappa_V W^+_\mu W^-_\nu V_{\mu\nu} + \frac{i\lambda_V}{M_W^2} W^+_{\lambda\mu}W^-_{\mu\nu}V_{\nu\lambda}$$
$$+ g_5^V \varepsilon_{\mu\nu\rho\sigma}\left(W^+_\mu \overleftrightarrow{\partial}_\rho W_\nu\right)V_\sigma - g_4^V W^+_\mu W^-_\nu\left(\partial_\mu V_\nu + \partial_\nu V_\mu\right)$$
$$+ i\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}_{\mu\nu} + \frac{i\tilde{\lambda}_V}{M_W^2} W^+_{\lambda\mu}W^-_{\mu\nu}\tilde{V}_{\nu\lambda}\,. \qquad (1)$$

Only the 1st line is C and P conserving

In the SM, $g_{1,V} = \kappa_V = 1$

The W boson charge suggest $g_{1,\gamma} = 1$.

Five independent variables:

$$\Delta g_{1,Z}\,,\quad \Delta\kappa_\gamma\,,\quad \Delta\kappa_Z\,,\quad \lambda_\gamma\,,\quad \lambda_Z\,,$$

Unfortunately, poorly measured at LEP because the lack of data

Tri-gauge boson at LEP

Up to D=6 level, in the SILH basis,

$$\Delta\mathcal{L} = \frac{ic_W\, g}{2M_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{ic_{HW}\, g}{M_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu}$$
$$+\frac{ic_{HB}\, g'}{M_W^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} + \frac{c_{3W}\, g}{6M_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}W_\rho^{k\,\mu}$$

The first one is constrained by the S parameter,

$$\begin{aligned}\Delta g_{1,Z} &= -\cot^2\theta_W c_{HW}\,,\\ \Delta\kappa_\gamma &= -(c_{HW}+c_{HB})\,,\\ \lambda_\gamma &= -c_{3W}\,,\end{aligned}$$

$$\lambda_\gamma = \lambda_Z,\ \Delta\kappa_Z = \Delta g_{1,Z} - \tan^2\theta_W\Delta\kappa_\gamma.$$

Three independent variables:

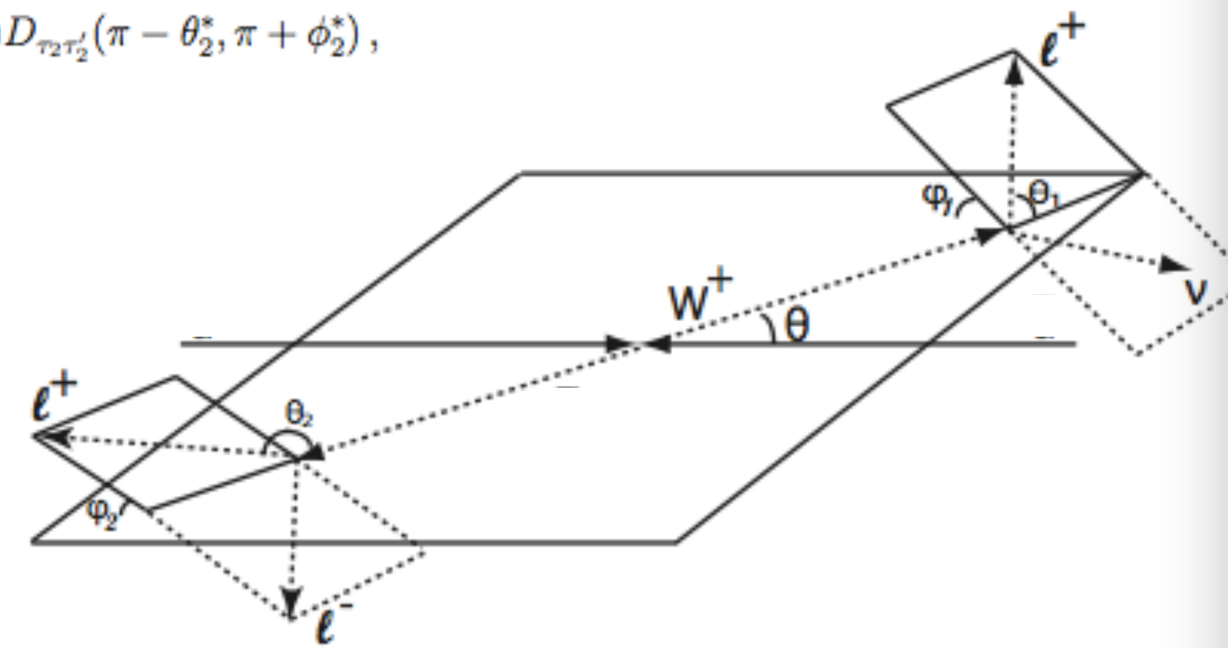
$$\Delta g_{1,Z}\,,\quad \Delta\kappa_\gamma\,,\quad \lambda_\gamma\,.$$

Kinematics

$$\frac{\mathrm{d}\sigma(e^+e^- \to W^+W^- \to f_1\bar{f}_2\bar{f}_3f_4)}{\mathrm{d}\cos\theta\,\mathrm{d}\cos\theta_1^*\mathrm{d}\phi_1^*\mathrm{d}\cos\theta_2^*\mathrm{d}\phi_2^*} = \mathrm{BR}\cdot\frac{\beta}{32\pi s}\left(\frac{3}{8\pi}\right)^2 \sum_{\lambda\tau_1\tau_1'\tau_2\tau_2'} F^{(\lambda)}_{\tau_1\tau_2}F^{(\lambda)*}_{\tau_1'\tau_2'} \times D_{\tau_1\tau_1'}(\theta_1^*,\phi_1^*)D_{\tau_2\tau_2'}(\pi-\theta_2^*,\pi+\phi_2^*)\,,$$

D: W decay matrix

C: Coupling coefficients



Production amplitude

$$F^{\lambda}_{\tau\tau'}(s,\cos\theta) = -\frac{\lambda e^2 s}{2}\Big[C^{(\nu)}(\lambda,t)\mathcal{M}^{(\nu)}_{\lambda\tau\tau'}(s,\cos\theta) + \sum_{i=1}^{7}\big(C_i^{(\gamma)}(\lambda,s,\alpha_j^{(\gamma)}) + C_i^{(Z)}(\lambda,s,\alpha_j^{(Z)})\big)\mathcal{M}^{(\nu)}_{i,\lambda\tau\tau'}(s,\cos\theta)\Big]\,,$$

Five differential variables

$$(\theta,\theta_1,\theta_2,\phi_1,\phi_2)$$

Sensitivity:

In principle, one would get five independent histograms to discriminate S and Bs:

At the lepton collider, the reducible backgrounds of WW is less than 5% after cuts

leptonic or semi-leptonic

Multi-variable methods:

BDT methods (will be used soon)

Previous LEP only use theta

$$\chi^2 \equiv \sum_i \left(\frac{N_i^{\mathrm{aTGC}} - N_i^{\mathrm{SM}}}{\sqrt{N_i^{\mathrm{SM}}}} \right)^2 ,$$

Summing over different bins for 5 distributions

Linear Differential Sensitivity

5 ab^-1

TABLE I: estimations of the reaches of sensitivities ($\times 10^{-4}$) at CEPC

channels	$\Delta g_{1,Z}$	$\Delta\kappa_\gamma$	$\Delta\kappa_Z$	λ_γ	λ_Z
leptonic	14.49	8.02	9.82	12.70	12.00
semileptonic	5.52	2.71	3.59	4.32	4.63
hadronic	6.56	2.74	4.00	4.40	5.65
all	4.06	1.87	2.58	3.00	3.44

channels	$\Delta g_{1,Z}$	$\Delta\kappa_\gamma$	λ_γ	c_{HW}	c_{HB}	c_{3W}
leptonic	5.90	9.87	6.57	3.36	9.91	6.58
semileptonic	2.19	3.33	2.35	1.18	3.34	2.35
hadronic	2.51	3.37	2.54	1.26	3.37	2.54
all	1.59	2.30	1.67	0.84	2.31	1.67

L-g. Bian, J. S, Y-c. Zhang, JHEP 1509 (2015) 206

10^-3 ~ 10^-4

Two orders improvements

Individual sensitivity

contributions		$\cos\theta$	$\cos\theta_\ell^*$	ϕ_ℓ^*	$\cos\theta_j^*$	ϕ_j^*
leptonic	$\Delta g_{1,Z}$	0.525	0.051	0.425	-	-
	$\Delta\kappa_\gamma$	0.523	0.272	0.205	-	-
	λ_γ	0.617	0.044	0.339	-	-
semi-leptonic	$\Delta g_{1,Z}$	0.650	0.032	0.261	0.031	0.027
	$\Delta\kappa_\gamma$	0.532	0.138	0.108	0.119	0.102
	λ_γ	0.709	0.025	0.192	0.024	0.050
hadronic	$\Delta g_{1,Z}$	0.850	-	-	0.080	0.070
	$\Delta\kappa_\gamma$	0.546	-	-	0.244	0.210
	λ_γ	0.827	-	-	0.056	0.118
all	$\Delta g_{1,Z}$	0.722	0.020	0.167	0.048	0.042
	$\Delta\kappa_\gamma$	0.538	0.081	0.065	0.170	0.147
	λ_γ	0.755	0.015	0.117	0.036	0.076

$$\frac{\Delta\chi^2(\Omega_k)}{\sum_k \Delta\chi^2(\Omega_k)}$$

In most cases, scattering angle and azimuthal angles are most sensitive

L-g. Bian, J. S, Y-c. Zhang, JHEP 1509 (2015) 206

Systematics?

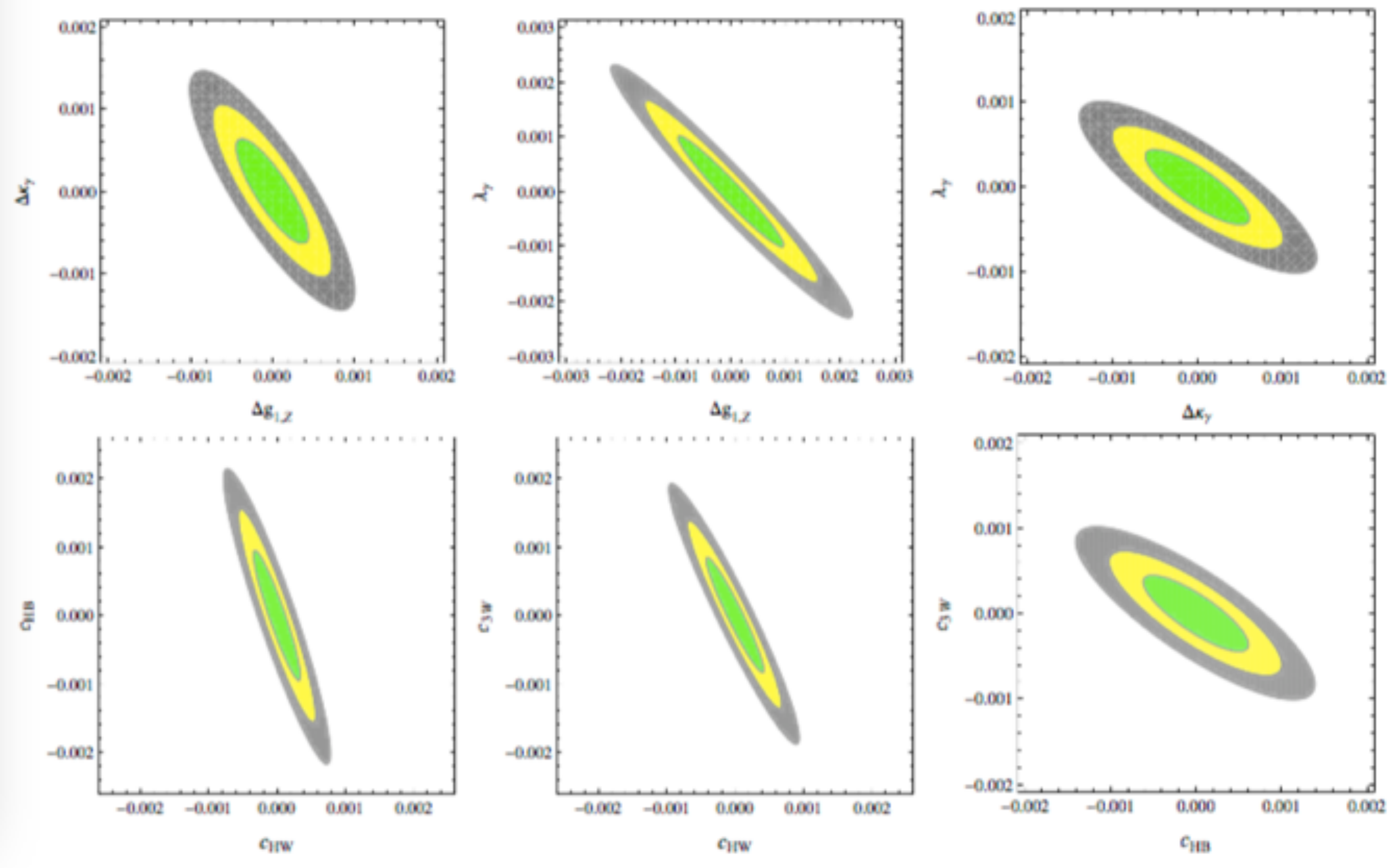
- Leptonic and semi-leptonic backgrounds are small

(full backgrounds simulation in semi-leptonic using whizard)

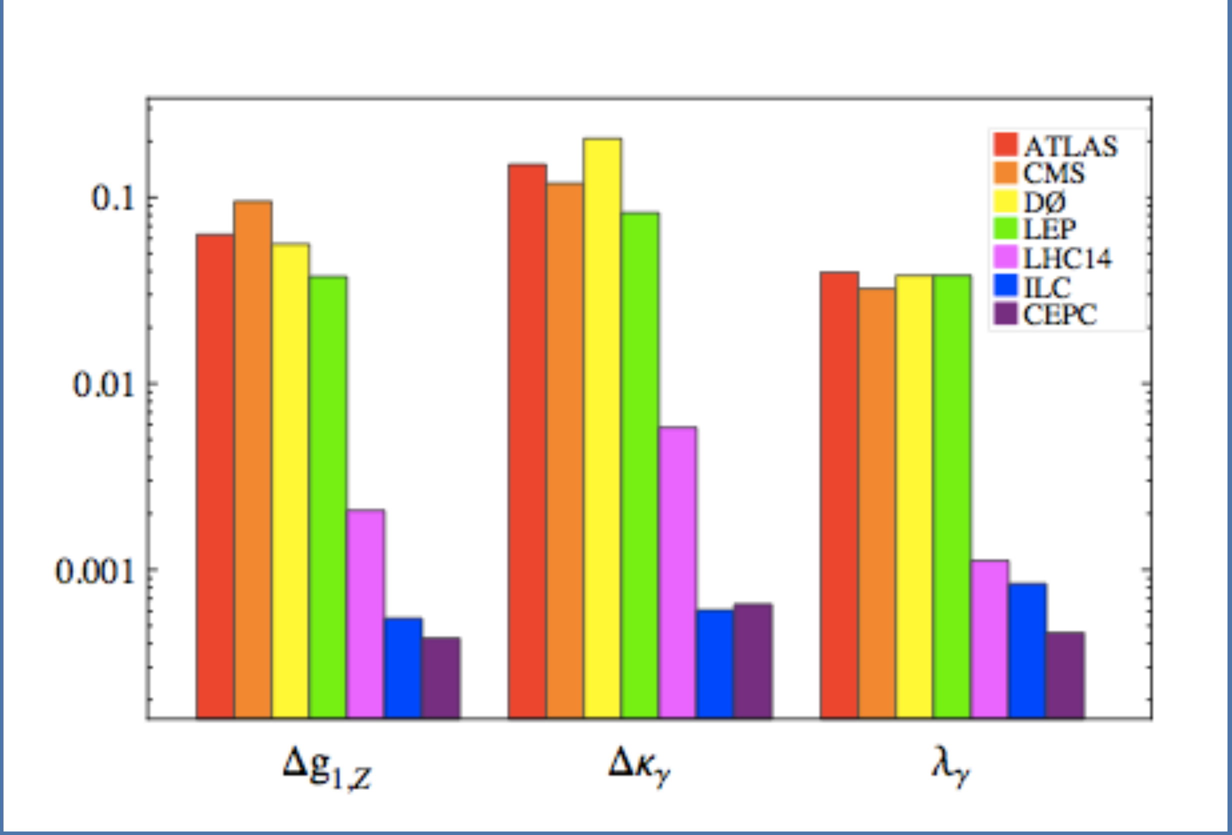
- Precision W mass. 3 MeV at CEPC
- Beam energy uncertainty. 10ppm ~ 1 MeV
- Detector simulation and radiative corrections are roughly at the same order. (ILC notes)
- < 10^{-4} in general, OK!

Notice if one includes the calculation uncertainties from Monta Carlo, the systematic uncertainties can be bigger

2D plot for CEPC



TGC Comparision



Improve more than two orders of magnitude at the CEPC

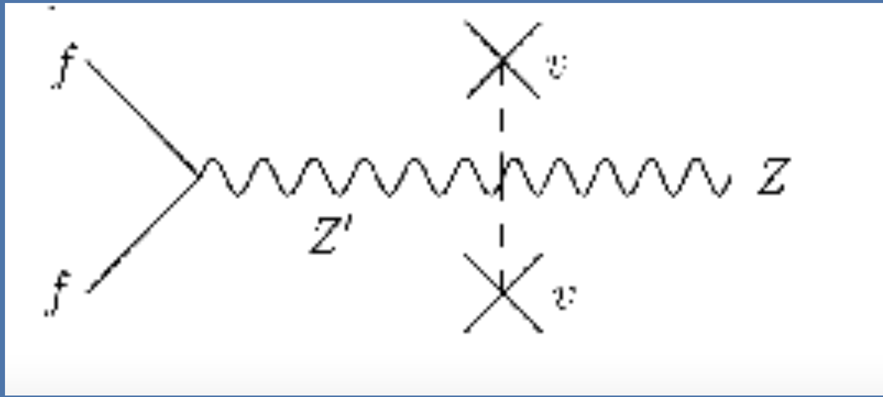
L-g. Bian, J. S, Y-c. Zhang
JHEP 1509 (2015) 206

Why tri-gauge boson ?

Why learning the tri-gauge boson coupling is important?

Our current super-simplified EW constraints (S,T) are based on the facts that tri-gauge boson coupling are poorly measured!

Fermion gauge boson corrections arise very common in new physics models (a Z' model)



$$
\begin{aligned}
S &= \frac{s}{2\pi} + \frac{a}{2\pi} \\
T &= \frac{t}{8\pi e^2} + \frac{a g'^{\,2}}{8\pi e^2}
\end{aligned}
$$

EW & TGC Interplay

$$
\begin{aligned}
-\frac{2gscv^2}{\alpha}\mathcal{O}_S - \frac{g'v^2}{\alpha}\mathcal{O}_T + g'\mathcal{O}^Y_{hf} &= 2g'\mathcal{O}_{HB} - g'\mathcal{O}_{h2} + \frac{g'}{2}\mathcal{O}_{BB} - \frac{g'}{2}\mathcal{O}_{h3}, \\
-\frac{4g'scv^2}{\alpha}\mathcal{O}_S + g(\mathcal{O}^t_{hl} + \mathcal{O}^t_{hq}) &= 4g\mathcal{O}_{HW} - 6g\mathcal{O}_{h2} + g\mathcal{O}_{WW} - g\mathcal{O}_{h3},
\end{aligned}
$$

$$
\begin{aligned}
c_{HB} &\sim \frac{\alpha g^2}{4c^2}\Delta S \sim \frac{\alpha g^2}{2}\Delta T \sim 2c_{h2} \sim g^2 \Delta g_{hZZ}/g_{hZZ}, \\
c_{HW} &\sim \frac{\alpha g^2}{4s^2}\Delta S \sim \frac{2}{3}c_{h2} \sim \frac{g^2}{3}\Delta g_{hZZ}/g_{hZZ},
\end{aligned}
$$

EW & TGC Interplay

	future prospects	c_{HW}	c_{HB}
HL-LHC	-	6.3×10^{-4}	3×10^{-3}
CEPC	-	1.2×10^{-4}	3.3×10^{-4}
S: HL-LHC	0.13	5×10^{-4}	1.4×10^{-4}
T: HL-LHC	0.09	–	1.6×10^{-4}
$\frac{\Delta g_{hZZ}}{g_{hZZ}}$: HL-LHC	0.03	4.5×10^{-3}	1.3×10^{-2}
S: CEPC	0.04	1.6×10^{-4}	4.2×10^{-5}
T: CEPC	0.03	–	5.3×10^{-5}
$\frac{\Delta g_{hZZ}}{g_{hZZ}}$: CEPC	0.002	3×10^{-4}	9×10^{-4}

one sigma

Examples of how CEPC observables constraint operators

L-g. Bian, J. S, Y-c. Zhang
JHEP 1509 (2015) 206

Effective Operators in the simplified models at the CEPC

Operators beyond SM

Practically, this is more complicated since we need to consider redundant operators for convenience.

Consider a simple case where one integrate out a vector SU(2)_L triplet in MCHM.

$$+\frac{1}{g_{\rho_L}^2 f^2}\mathcal{O}_W + \frac{1}{g_{\rho|_R}^2 f^2}\mathcal{O}_B + \frac{g^2}{g_{\rho_L}^2 m_{\rho_L}^2}\mathcal{O}_{2W} + \frac{g'^2}{g_{\rho_R}^2 m_{\rho_R}^2}\mathcal{O}_{2B}.$$

The first two terms are related with the S parameter,

$$\mathcal{O}_B = \mathcal{O}_{HB} + \mathcal{O}_{BB} + \mathcal{O}_{WB}\,,$$
$$\mathcal{O}_W = \mathcal{O}_{HW} + \mathcal{O}_{WW} + \mathcal{O}_{WB}\,,$$

W & Y can be rewrite using the e.o.m. of the gauge fields

$$(D_\nu W^{\nu\mu})^a = -\frac{1}{2}g(ih^\dagger \overleftrightarrow{D}^\mu \sigma^a h + \bar{l}\gamma^\mu\sigma^a l + \bar{q}\gamma^\mu\sigma^a q),$$
$$\partial_\nu B^{\nu\mu} = -\frac{1}{2}g'(ih^\dagger \overleftrightarrow{D}^\mu h) - g'\sum_f Y_f \bar{f}\gamma^\mu f,$$

Operators beyond SM

But certainly we can do those e.o.m. and generate too many independent operators to do the constrain:

Therefore, one should include all the redundant operators for the fits

$\mathcal{O}_{GG}$	$=$	$g_s^2 \lvert H\rvert^2 G^a_{\mu\nu} G^{a,\mu\nu}$	$\mathcal{O}_H$	$=$	$\frac{1}{2}(\partial_\mu \lvert H\rvert^2)^2$
$\mathcal{O}_{WW}$	$=$	$g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_T$	$=$	$\frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$
$\mathcal{O}_{BB}$	$=$	$g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_R$	$=$	$\lvert H\rvert^2 \lvert D_\mu H\rvert^2$
$\mathcal{O}_{WB}$	$=$	$2gg' H^\dagger \tau^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_D$	$=$	$\lvert D^2 H\rvert^2$
$\mathcal{O}_W$	$=$	$ig(H^\dagger \tau^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_6$	$=$	$\lvert H\rvert^6$
$\mathcal{O}_B$	$=$	$ig' Y_H (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu}$	$\mathcal{O}_{2G}$	$=$	$-\frac{1}{2}(D^\mu G^a_{\mu\nu})^2$
$\mathcal{O}_{3G}$	$=$	$\frac{1}{3!} g_s f^{abc} G^{a\mu}_\rho G^{b\nu}_\mu G^{c\rho}_\nu$	$\mathcal{O}_{2W}$	$=$	$-\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$
$\mathcal{O}_{3W}$	$=$	$\frac{1}{3!} g \epsilon^{abc} W^{a\mu}_\rho W^{b\nu}_\mu W^{c\rho}_\nu$	$\mathcal{O}_{2B}$	$=$	$-\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$

CP conserving bosonic operators

The CHM

In the CCWZ formulism of MCHM, integrating out the heavy spin one vector meson "rho" and axi-vector meson "a"

$$\Delta\mathcal{L} = -\frac{\Delta^2}{4g_a^2}(d^{\hat{a}}_{\mu\nu})^2 - \frac{1}{4g_{\rho_L}^2}(E^{aL}_{\mu\nu})^2 - \frac{1}{4g_{\rho_R}^2}(E^{aR}_{\mu\nu})^2 - \frac{1}{2}\frac{1}{m_{\rho_L}^2 g_{\rho_L}^2} D_\mu E^{aL\mu\nu} D_\rho E^{aL\rho}{}_\nu - \frac{1}{2}\frac{1}{m_{\rho_R}^2 g_{\rho_R}^2} D_\mu E^{aR\mu\nu} D_\rho E^{aR\rho}{}_\nu + \cdots ,$$

$$= -\frac{\Delta^2}{g_a^2 f^2}\left(\mathcal{O}_W + \mathcal{O}_B - (\mathcal{O}_{HW} + \mathcal{O}_{HB})\right) + \frac{1}{g_{\rho_L}^2 f^2}\mathcal{O}_W + \frac{1}{g_{\rho_R}^2 f^2}\mathcal{O}_B + \frac{g^2}{g_{\rho_L}^2 m_{\rho_L}^2}\mathcal{O}_{2W} + \frac{g'^2}{g_{\rho_R}^2 m_{\rho_R}^2}\mathcal{O}_{2B}.$$

rho contributes to S, W, Y

a contributes to -S, TGC

One loop diagram not finished

D. Liu, J. S, in progress

Real singlet for EWPT

$$\Delta\mathcal{L} = \frac{1}{2}\left(\partial_\mu \Phi\right)^2 - \frac{1}{2}m^2\Phi^2 - A\left|H\right|^2\Phi - \frac{1}{2}k\left|H\right|^2\Phi^2 - \frac{1}{3!}\mu\Phi^3 - \frac{1}{4!}\lambda_\Phi\Phi^4.$$

Tree Level:

$$\begin{aligned}\Delta\mathcal{L}_{\text{eff,tree}} &= -A\left|H\right|^2\Phi_c + \frac{1}{2}\Phi_c\left(-\partial^2 - m^2 - k\left|H\right|^2\right)\Phi_c - \frac{1}{3!}\mu\Phi_c^3 - \frac{1}{4!}\lambda_\Phi\Phi_c^4 \\ &\approx \frac{1}{2m^2}A^2\left|H\right|^4 + \frac{A^2}{m^4}\mathcal{O}_H + \left(-\frac{kA^2}{2m^4} + \frac{1}{3!}\frac{\mu A^3}{m^6}\right)\mathcal{O}_6.\end{aligned}$$

One loop:

$$\begin{aligned}\Delta\mathcal{L}_{\text{eff,1-loop}} &= \frac{1}{2(4\pi)^2}\frac{1}{m^2}\left[-\frac{1}{12}(P_\mu U)^2 - \frac{1}{6}U^3\right] \\ &= \frac{1}{(4\pi)^2}\frac{1}{m^2}\left(\frac{k^2}{12}\mathcal{O}_H - \frac{k^3}{12}\mathcal{O}_6\right).\end{aligned}$$

EW scalar doublet (Stop)

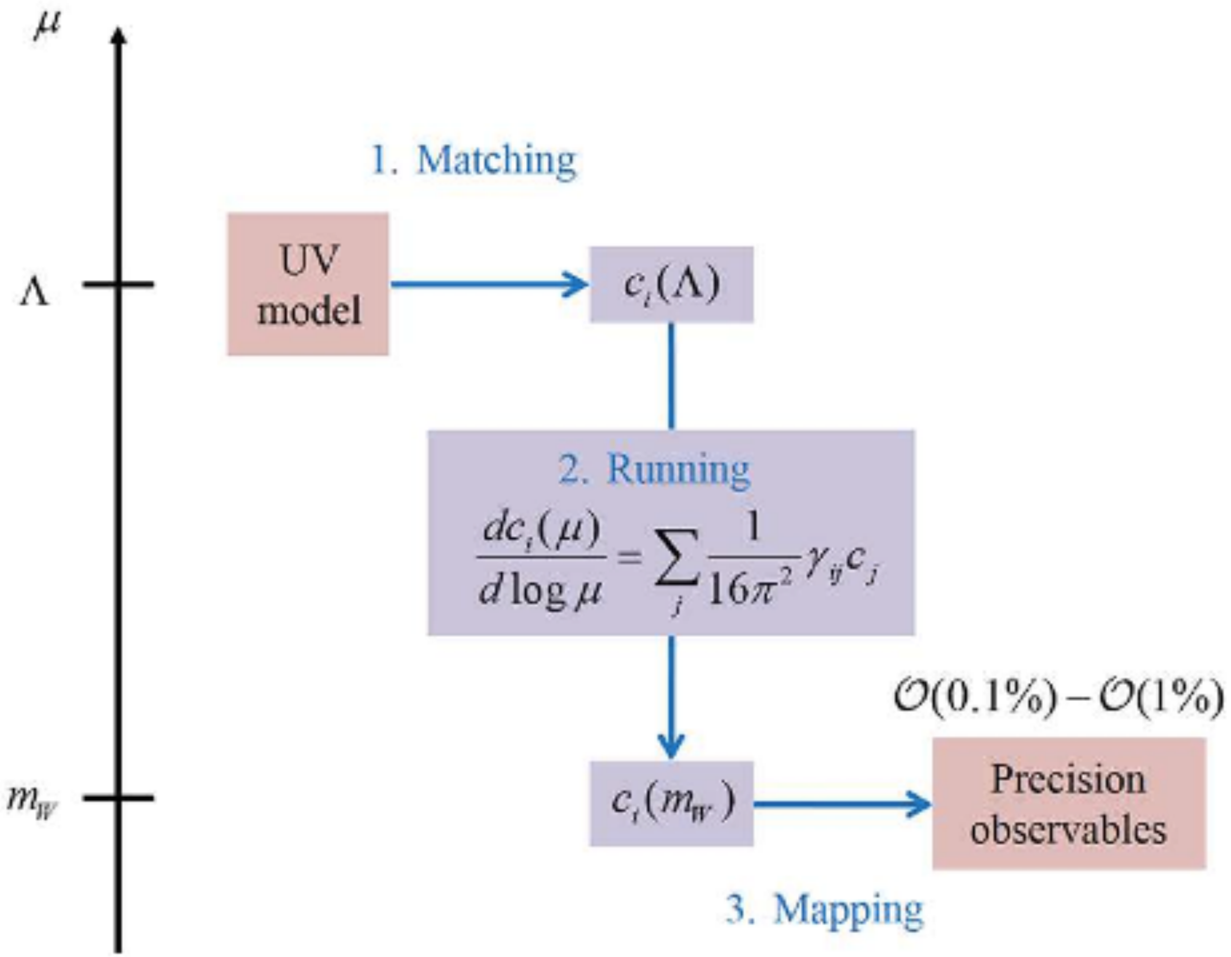
$$\mathcal{L} \supset |D_\mu \Phi|^2 - m^2 |\Phi|^2 - \frac{\lambda_\Phi}{4} |\Phi|^4 + \left(\eta_H |H|^2 + \eta_\Phi |\Phi|^2\right)\left(\Phi \cdot H + \text{h.c}\right)$$
$$- \lambda_1 |H|^2 |\Phi|^2 - \lambda_2 |\Phi \cdot H|^2 - \lambda_3 \left[\left(\Phi \cdot H\right)^2 + \text{h.c.}\right],$$

$c_H = \frac{1}{(4\pi)^2}\left[6\eta_\Phi\eta_H + \frac{1}{12}\left(4\lambda_1^2 + 4\lambda_1\lambda_2 + \lambda_2^2 + 4\lambda_3^2\right)\right]$	$c_{BB} = \frac{1}{(4\pi)^2}\frac{1}{12}Y_\Phi^2(2\lambda_1 + \lambda_2)$	$c_{3W} = \frac{1}{(4\pi)^2}\frac{1}{60}g^2$
$c_T = \frac{1}{(4\pi)^2}\frac{1}{12}\left(\lambda_2^2 - 4\lambda_3^2\right)$	$c_{WW} = \frac{1}{(4\pi)^2}\frac{1}{48}(2\lambda_1 + \lambda_2)$	$c_{2W} = \frac{1}{(4\pi)^2}\frac{1}{60}g^2$
$c_R = \frac{1}{(4\pi)^2}\left[6\eta_\Phi\eta_H + \frac{1}{6}\left(\lambda_2^2 + 4\lambda_3^2\right)\right]$	$c_{WB} = -\frac{1}{(4\pi)^2}\frac{1}{12}\lambda_2 Y_\Phi$	$c_{2B} = \frac{1}{(4\pi)^2}\frac{1}{60}4g'^2Y_\Phi^2$

$$c_6 = \eta_H^2 + \frac{1}{(4\pi)^2}\left[\frac{3}{2}\lambda_\Phi\eta_H^2 + 6\eta_\Phi(\lambda_1 + \lambda_2) - \frac{1}{6}\left(2\lambda_1^3 + 3\lambda_1^2\lambda_2 + 3\lambda_1\lambda_2^2 + \lambda_2^3\right) - 2\left(\lambda_1 + \lambda_2\right)\lambda_3^2\right]$$

Tree-loop level contributions & RG running effects:

Operators beyond SM



Future CEPC makes it just like B, flavor physics

Can have both tree and loop results at the UV

RG running: one loop UV operators contribute to IR (weak scale) operators

Weak scale operators maps to the Observable.

A general coding:

All bosonic operators

$$\mathcal{O}_{GG} = g_s^2 (H^\dagger H) G^a_{\mu\nu} G^{a\mu\nu}, \quad \mathcal{O}_H = \frac{1}{2}(\partial_\mu |H|^2)^2$$

$$\mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\mu\nu}, \quad \mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}^\mu H)^2$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_R = |H|^2 |D_\mu H|^2$$

$$\mathcal{O}_{WB} = 2gg'(H^\dagger \tau^a H) W^a_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_D = |D^2 H|^2$$

$$\mathcal{O}_W = ig(H^\dagger \tau^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}, \quad \mathcal{O}_6 = |H|^6$$

$$\mathcal{O}_B = ig' Y_H (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu}, \quad \mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^a_{\mu\nu})^2$$

$$\mathcal{O}_{3G} = \frac{1}{3!} g_s f^{abc} G^{a\nu}_\mu G^{b\lambda}_\nu G^{c\mu}_\lambda, \quad \mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon^{abc} W^{a\nu}_\mu W^{b\lambda}_\nu W^{c\mu}_\lambda, \quad \mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$

Han & Skiba basis

(1) Operators that modify gauge boson propagators

$$O_{WB} = (h^\dagger \sigma^a h) W^a_{\mu\nu} B^{\mu\nu}, O_h = (h^\dagger D^\mu h)(D_\mu h^\dagger h). \tag{6}$$

(2) Operators that affect tree level SM gauge-fermion couplings

$$O^s_{hl} = i(h^\dagger D_\mu h)(\bar{l}\gamma^\mu l) + h.c., O^t_{hl} = i(h^\dagger D_\mu \sigma^a h)(\bar{l}\gamma^\mu \sigma^a l) + h.c. \tag{7}$$

$$O_{he} = i(h^\dagger D_\mu h)(\bar{e}\gamma^\mu e) + h.c., O^s_{hq} = i(h^\dagger D_\mu h)(\bar{q}\gamma^\mu qq) + h.c. \tag{8}$$

$$O^t_{hq} = i(h^\dagger D_\mu \sigma^a h)(\bar{q}\gamma^\mu \sigma^a q) + h.c., O_{hu} = i(h^\dagger D_\mu h)(\bar{u}\gamma^\mu u) + h.c. \tag{9}$$

$$O_{hd} = i(h^\dagger D_\mu h)(\bar{d}\gamma^\mu d) + h.c.. \tag{10}$$

(3) Four-fermion opertors

$$O^t_{ll} = \tfrac{1}{2}(\bar{l}\gamma^\mu \sigma^a l)(\bar{l}\gamma_\mu \sigma^a l), O^s_{lq} = \tfrac{1}{2}(\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q) \tag{11}$$

$$O^t_{lq} = \tfrac{1}{2}(\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q), O_{le} = (\bar{l}\gamma^\mu l)(\bar{e}\gamma_\mu e) \tag{12}$$

$$O_{qe} = (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e), O_{lu} = (\bar{l}\gamma^\mu l)(\bar{u}\gamma_\mu u) \tag{13}$$

$$O_{ld} = (\bar{l}\gamma^\mu l)(\bar{d}\gamma_\mu d), O_{ee} = \tfrac{1}{2}(\bar{e}\gamma^\mu e)(\bar{e}\gamma_\mu e) \tag{14}$$

$$O_{eu} = (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u), O_{ed} = (\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d) \tag{15}$$

$$O^s_{ll} = \tfrac{1}{2}(\bar{l}\gamma^\mu l)(\bar{l}\gamma_\mu l). \tag{16}$$

(4) Operators that modify triple gauge boson couplings

$$O_W = \epsilon^{abc} W^{a\nu}_\mu W^{b\lambda}_\nu W^{c\mu}_\lambda, (O_{WB}). \tag{17}$$

Han & Skiba basis

Use E.O.M. to change basis

$$\mathcal{O}'_T = -2O_h^{(3)} - O_h^{(1)} + 3\lambda O_h - \frac{1}{2}(\Gamma_e O_{eh} + \Gamma_u O_{uh} + \Gamma_d O_{dh}) - m^2|h|^4 \tag{18}$$

$$\mathcal{O}'_W = g^2(\frac{3}{2}O_h^{(1)} + O_{hl}^{(3)} + O_{hq}^{(3)} - \frac{3}{2}\lambda O_h + \frac{1}{4}(\Gamma_e O_{eh} + \Gamma_u O_{uh} + \Gamma_d O_{dh}) + \frac{1}{2}m^2|h|^4 \tag{19}$$

$$\begin{aligned}\mathcal{O}'_B = \frac{1}{2}g'^2(2O_h^{(3)} + O_h^{(1)} - 3\lambda O_h + \frac{1}{2}(\Gamma_e O_{eh} + \Gamma_u O_{uh} + \Gamma_d O_{dh}) + m^2|h|^4 \\ -\frac{1}{2}O_{hl}^{(1)} - O_{he} + \frac{1}{6}O_{hq}^{(1)} + \frac{2}{3}O_{hu} - \frac{1}{3}O_{hd})\end{aligned} \tag{20}$$

$$\begin{aligned}\mathcal{O}'_{2W} = -\frac{1}{2}g^2(\frac{3}{2}O_h^{(1)} + 2O_{hl}^{(3)} + 2O_{hq}^{(3)} + \frac{1}{2}O_{ll}^{(3)} + \frac{1}{2}O_{qq}^{(1,3)} + O_{lq}^{(3)} - \frac{3}{2}\lambda O_h \\ +\frac{1}{4}(\Gamma_e O_{eh} + \Gamma_u O_{uh} + \Gamma_d O_{dh}) + \frac{1}{2}m^2|h|^4)\end{aligned} \tag{21}$$

$$\begin{aligned}\mathcal{O}'_{2B} = -\frac{1}{2}g'^2(O_h^{(3)} + \frac{1}{2}O_h^{(1)} - \frac{3}{2}\lambda O_h + \frac{1}{4}(\Gamma_e O_{eh} + \Gamma_u O_{uh} + \Gamma_d O_{dh}) + \frac{1}{2}m^2|h|^4 \\ -\frac{1}{2}O_{hl}^{(1)} - O_{he} + \frac{1}{6}O_{hq}^{(1)} + \frac{2}{3}O_{hu} - \frac{1}{3}O_{hd} \\ +\frac{1}{2}O_{ll}^{(1)} + 2O_{ee} + \frac{1}{18}O_{qq}^{(1,1)} + \frac{8}{9}O_{uu}^{(1)} + \frac{2}{9}O_{dd}^{(1)} + O_{le} - \frac{1}{6}O_{lq}^{(1)} \\ -\frac{2}{3}O_{lu} + \frac{1}{3}O_{ld} - \frac{1}{3}O_{qe} - \frac{4}{3}O_{ue} + \frac{2}{3}O_{de} + \frac{2}{9}O_{qu}^{(1)} - \frac{1}{9}O_{qd}^{(1)} - \frac{4}{9}O_{ud}^{(1)})\end{aligned} \tag{22}$$

$$\mathcal{O}'_{BB} = 2g'^2 O_{hB}, \quad \mathcal{O}'_{WB} = gg' O_{WB}, \quad \mathcal{O}'_{WW} = 2g^2 O_{hW} \tag{23}$$

$$\mathcal{O}'_{3W} = \frac{1}{3!}gO_W, \quad \mathcal{O}'_H = O_{\partial h}, \quad \mathcal{O}'_6 = 3O_h \tag{24}$$

RG Runnings

$$\{\mathcal{O}'_H, \mathcal{O}'_T, \mathcal{O}'_B, \mathcal{O}'_W, \mathcal{O}'_{2B}, \mathcal{O}'_{2W}, \mathcal{O}'_{BB}, \mathcal{O}'_{WW}, \mathcal{O}'_{WB}, \mathcal{O}'_{3W}\} \ .$$

Running effect

$$\begin{pmatrix} c_{BB}(m_W) \\ c_{WW}(m_W) \\ c_{WB}(m_W) \\ c_{3W}(m_W) \end{pmatrix} = \begin{pmatrix} 0.914758 & 0.000128298 & -0.0185242 & -3.25679e-05 \\ 3.10393e-06 & 0.90556 & -0.00165509 & -0.0154459 \\ -0.00332701 & -0.012287 & 0.875589 & 0.00314274 \\ 0 & 0 & 0 & 0.885251 \end{pmatrix} \begin{pmatrix} c_{BB}(\Lambda) \\ c_{WW}(\Lambda) \\ c_{WB}(\Lambda) \\ c_{3W}(\Lambda) \end{pmatrix},$$

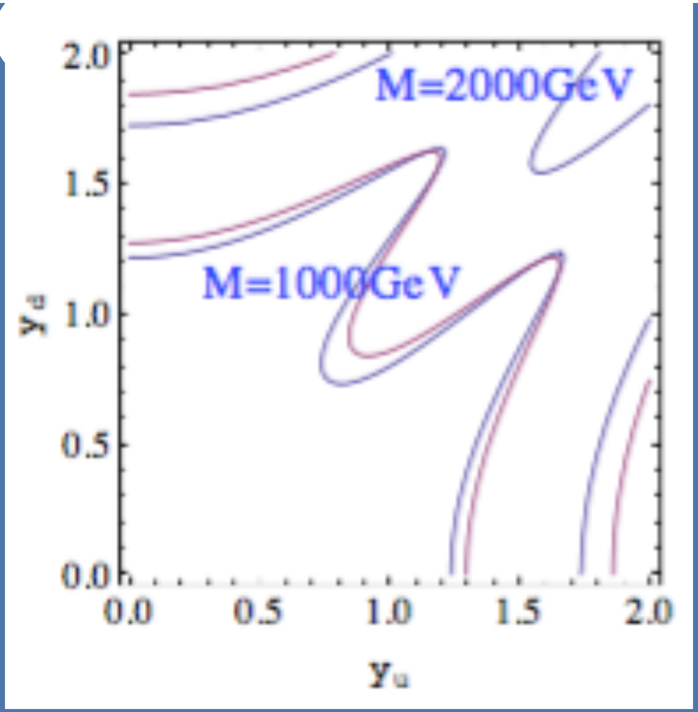
$$\left(c_H, c_T, c_B, c_W, c_{2B}, c_{2W}\right)^t (m_W)$$

$$= \begin{pmatrix} 0.817183 & 0.0232377 & -0.0014199 & 0.00975445 & 0.00106505 & -0.034927 \\ -0.00221894 & 0.78282 & 0.00274073 & 0.00146195 & -0.00199478 & -0.000736735 \\ 0.00455058 & 0.022526 & 0.909505 & -0.00299701 & -0.025421 & 0.00151002 \\ 0.00444872 & 0.00442166 & -0.000270172 & 0.857823 & -3.50986e-05 & -0.068742 \\ 2.91354e-06 & 1.4471e-05 & 0.00114785 & -1.90868e-06 & 0.94341 & 9.59124e-07 \\ 1.01829e-05 & 1.01354e-05 & -1.47944e-06 & 0.0038691 & -0.00138992 & 0.824636 \end{pmatrix} \begin{pmatrix} c_H(\Lambda) \\ c_T(\Lambda) \\ c_B(\Lambda) \\ c_W(\Lambda) \\ c_{2B}(\Lambda) \\ c_{2W}(\Lambda) \end{pmatrix}$$

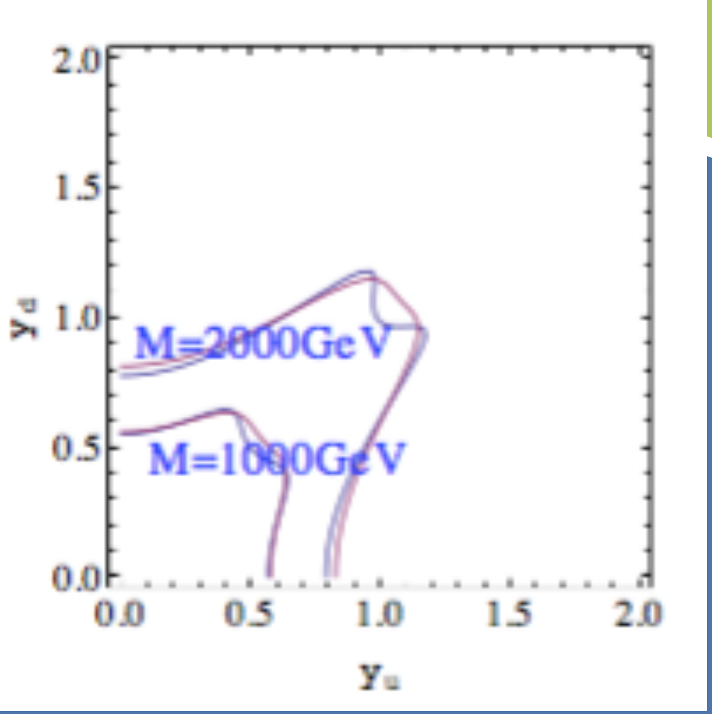
Vector fermion example

$$\begin{aligned}
\mathcal{L} \supset \frac{m}{(4\pi)^2}\Bigg[&-\frac{2(|y_u|^6+|y_d|^6)}{15M^2}\mathcal{O}_6 \\
&-\frac{28(|y_u|^4+|y_d|^4)-12|y_u|^2|y_d|^2}{15M^2}\mathcal{O}_H+\frac{2(|y_u|^2-|y_d|^2)^2}{5M^2}\mathcal{O}_T-\frac{34(|y_u|^4+|y_d|^4)+24|y_u|^2|y_d|^2}{15M^2}\mathcal{O}_R \\
&-\frac{|y_u|^2+|y_d|^2}{48M^2}\mathcal{O}_{WW}-\frac{(1+16Y+32Y^2)|y_u|^2+(1-16Y+32Y^2)|y_d|^2}{48M^2}\mathcal{O}_{BB} \\
&+\frac{(3+8Y)|y_u|^2+(3-8Y)|y_d|^2}{24M^2}\mathcal{O}_{WB} \\
&+\frac{7(|y_u|^2+|y_d|^2)}{60M^2}\mathcal{O}_W+\frac{7(|y_u|^2+|y_d|^2)}{60M^2}\mathcal{O}_B \\
&+\frac{53(|y_u|^2+|y_d|^2)}{20M^2}\mathcal{O}_{HW}+\frac{53(|y_u|^2+|y_d|^2)}{20M^2}\mathcal{O}_{HB} \\
&+\frac{|y_u|^2+|y_d|^2}{15M^2}\mathcal{O}_D\Bigg] \\
+\frac{1}{(4\pi)^2}&\frac{f(m)(|y_u|^2+|y_d|^2)}{M^2}\mathcal{O}_{GG}\,, \qquad (31)
\end{aligned}$$

Vector fermion example



EW + Higgs fit

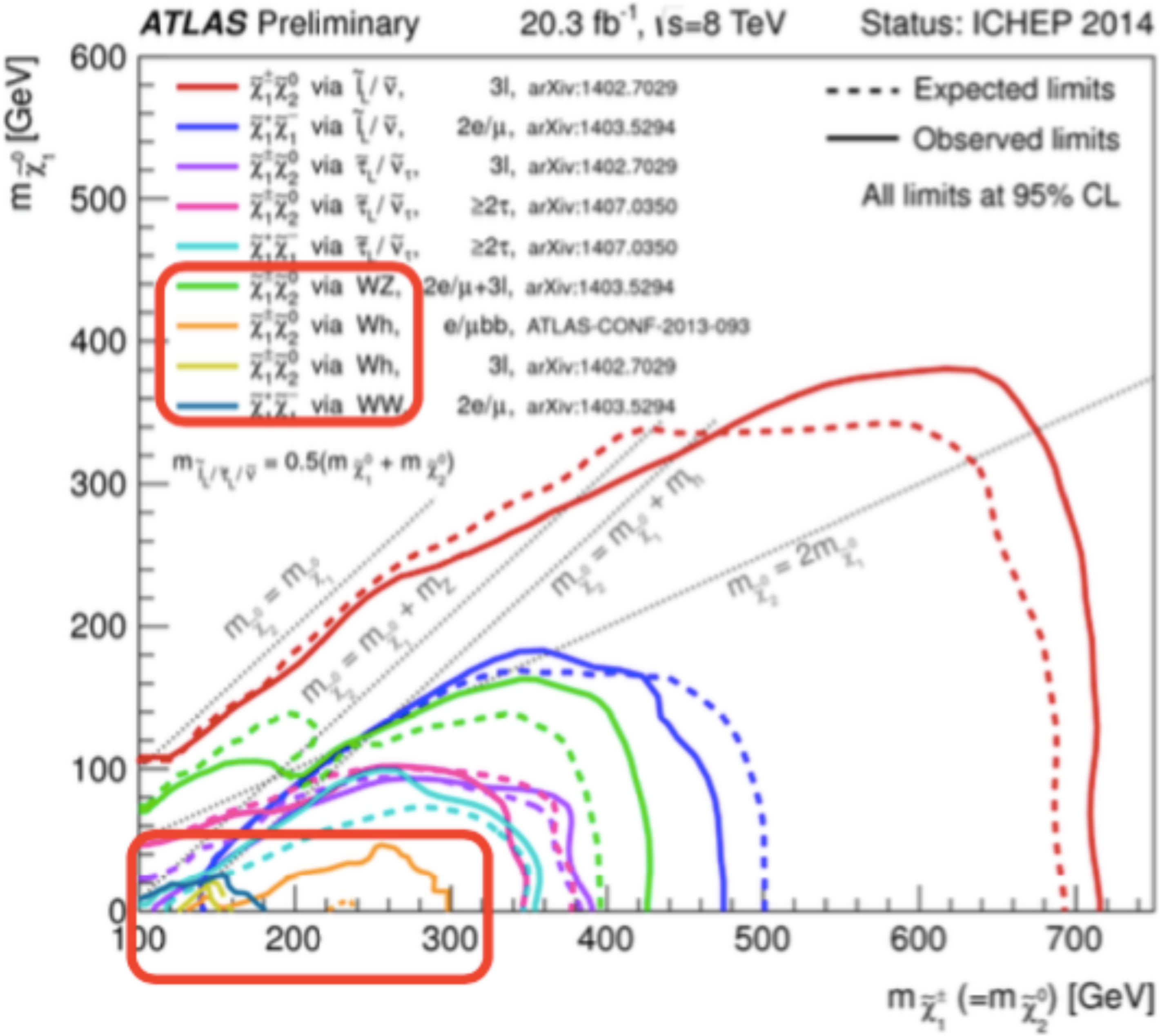


Future EW + Higgs fit

Blue is the one with RG running

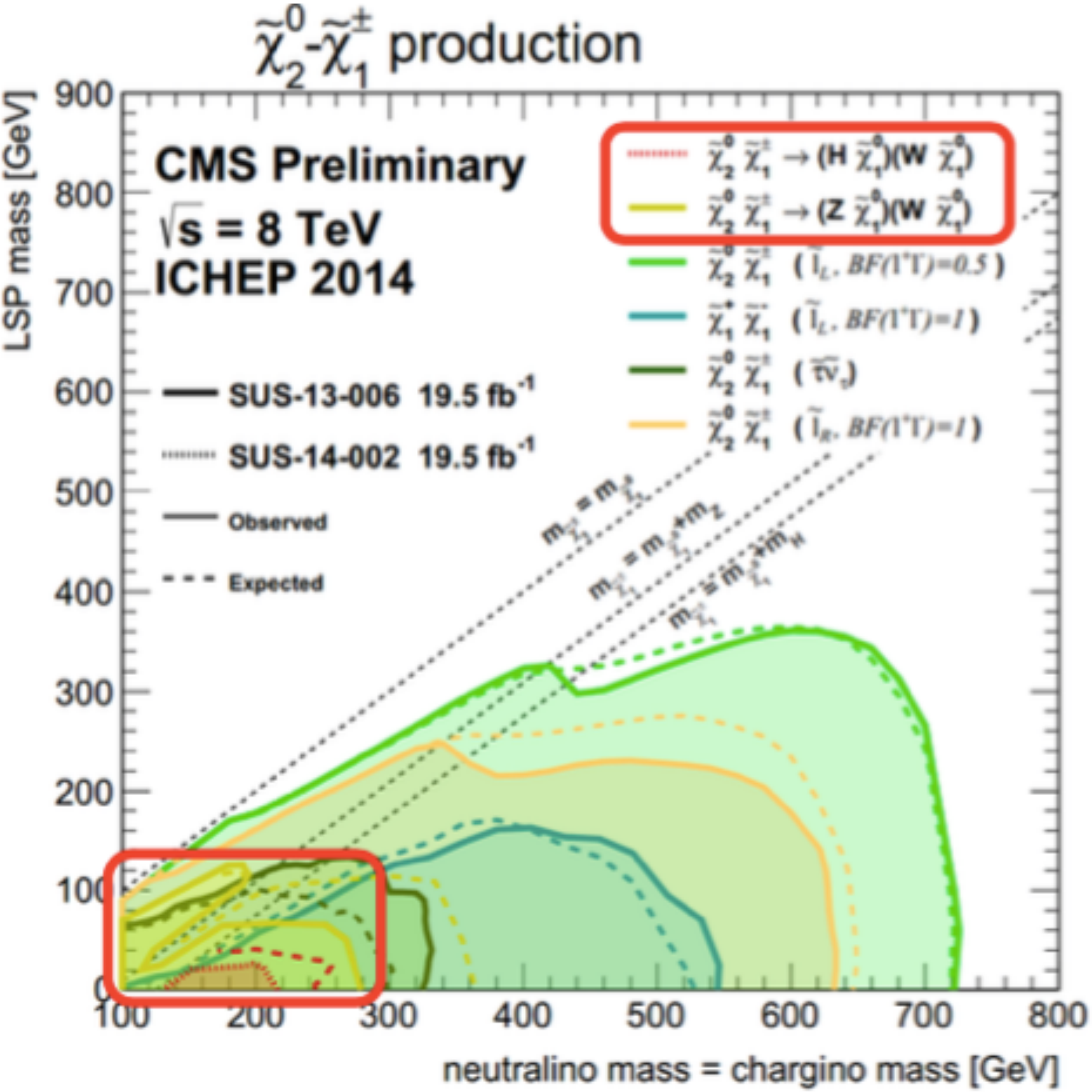
Electroweakino and Higgs Strahlung:

Difficult Electrowino Search



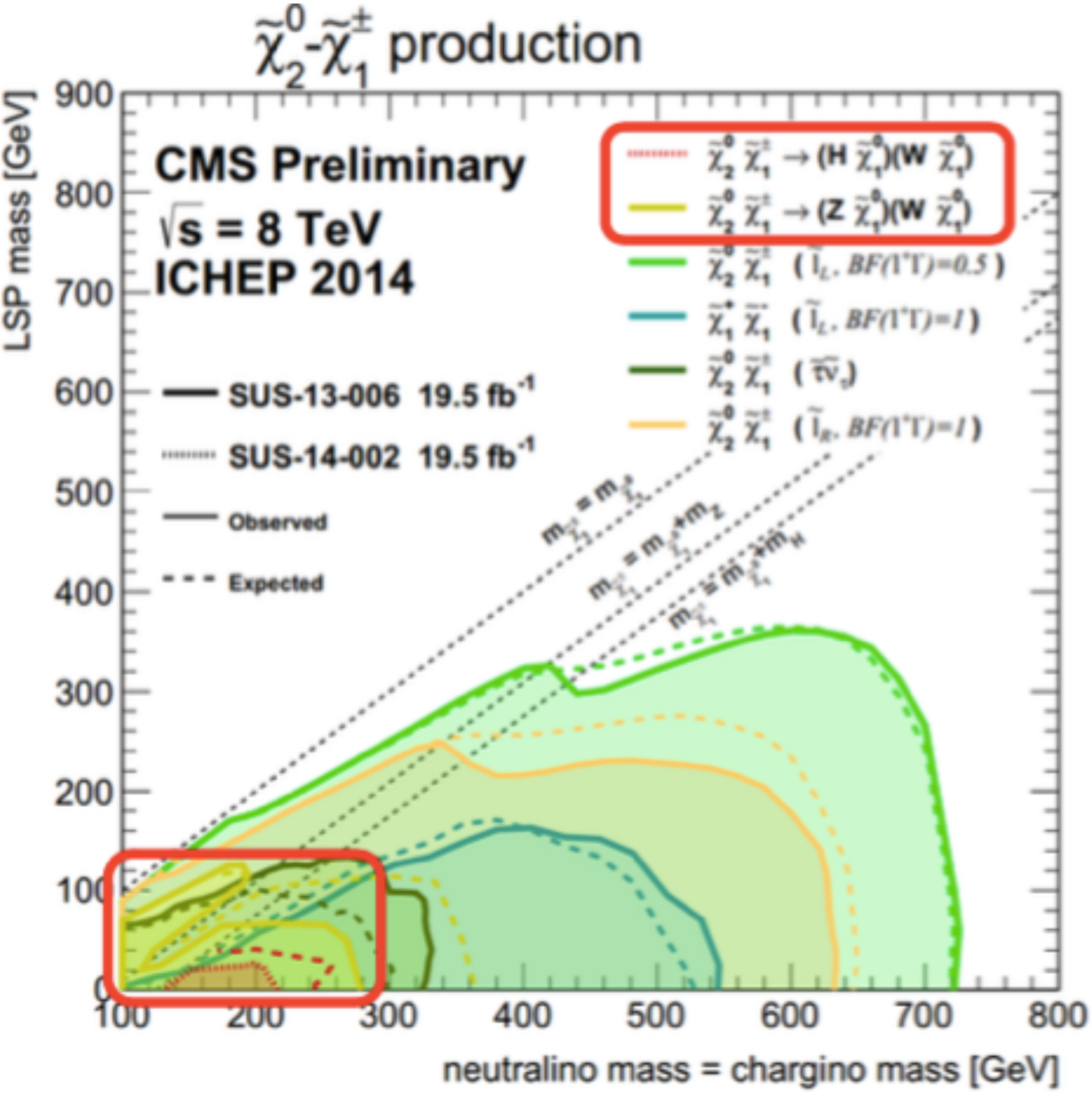
Without sleptons, very difficult even for mass splitting < mZ

Difficult Electrowino Search



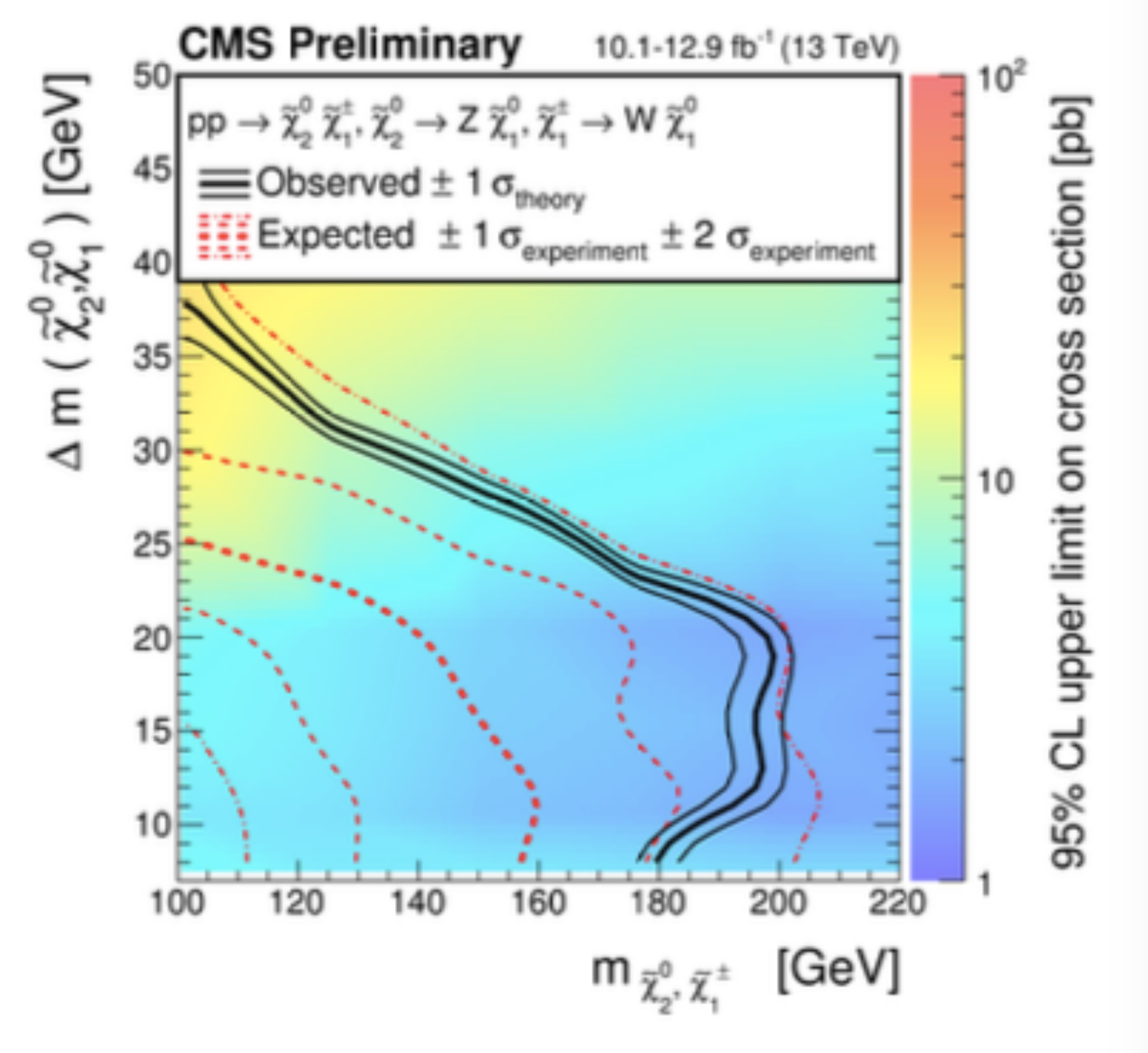
Without sleptons, very difficult even for moderate mass splitting

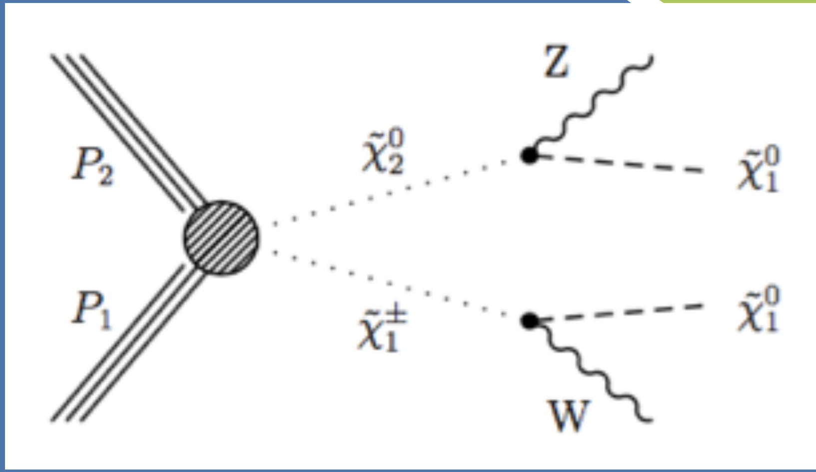
Difficult Electrowino Search



Without sleptons, very difficult even for moderate mass splitting

Searches with Soft Leptons





Seems there are some sensitivities now

Indirect Search Still Hard

If degenerate, then it is just way too difficult (even comparing with stops)

Unlike stops, this is even much difficult in EWPT indirect constrains / searches

Electroweakinos are in general much more degenerate, small contribution to T

Stops has large effect on the Higgs production rate at the hardon colliders

Electroweakinos only has small contributions

Only measurable at lepton colliders!!!

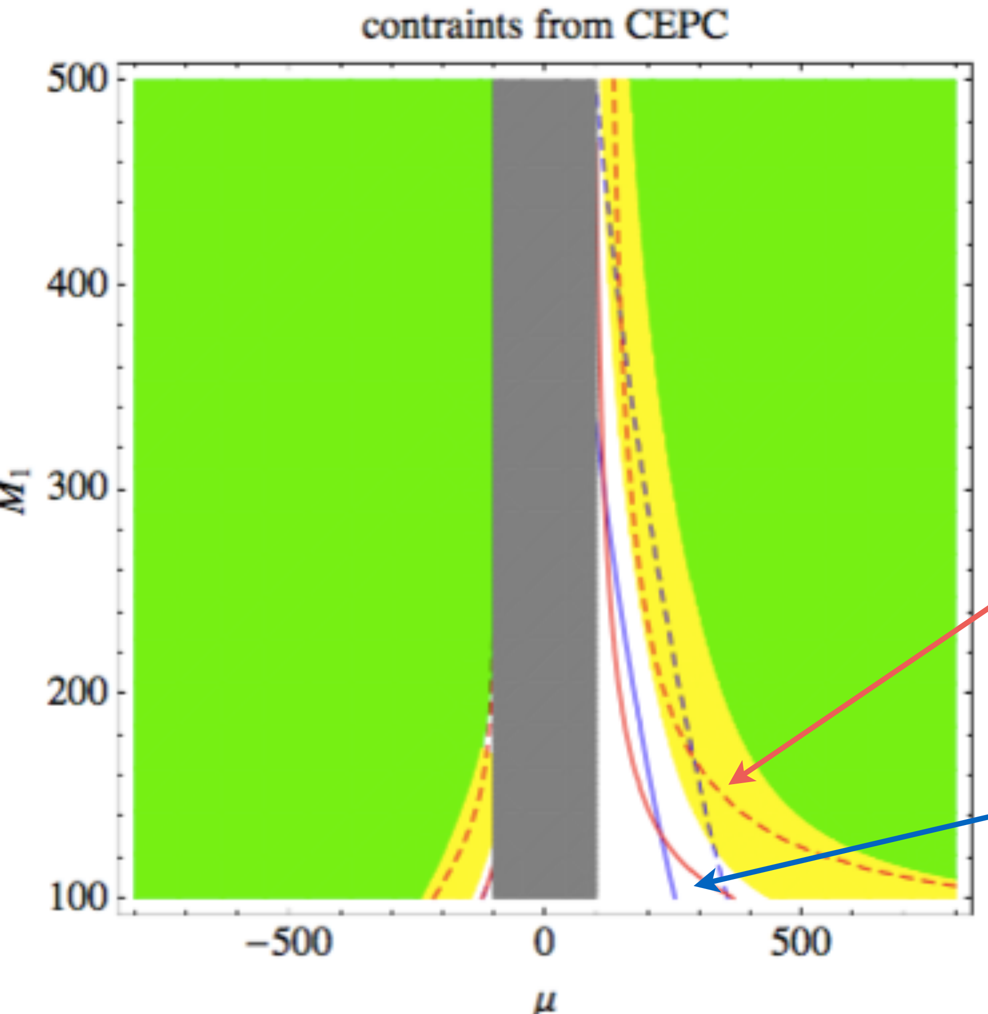
The CDE methods

The one-loop Higgs effective theory can be calculated through the Covariant Derivative Expansion (CDE) methods or the direct Feymann diagram calculations.

The Covariant Derivative Expansion Methods is good since one obtained ALL operators by integrating out heavy particles in an expansion of p/M

This is more important unlike old times we need to calculate S & T

The results



$\tan[\beta] = 1$

$M_2 = 2M_1$ gaugino unification

Higgs constrains

Only use the total ZH production

EW precision

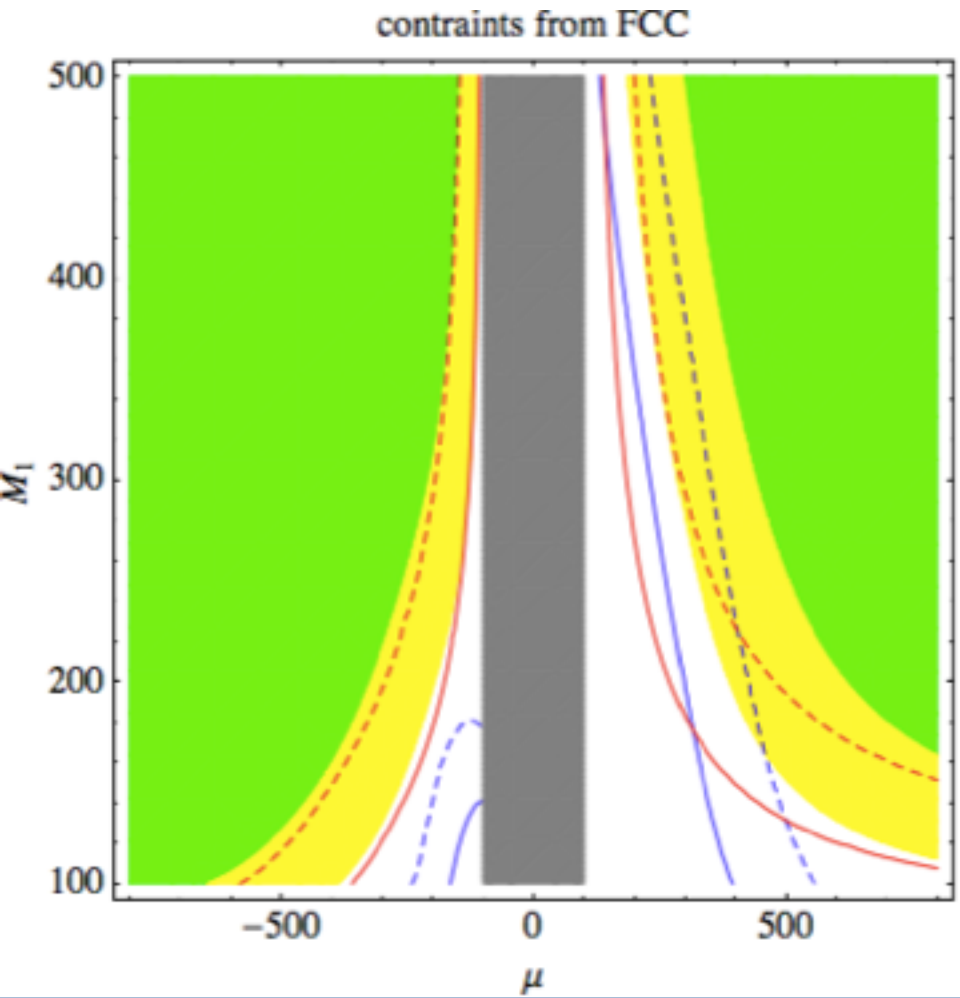
Angles not so useful

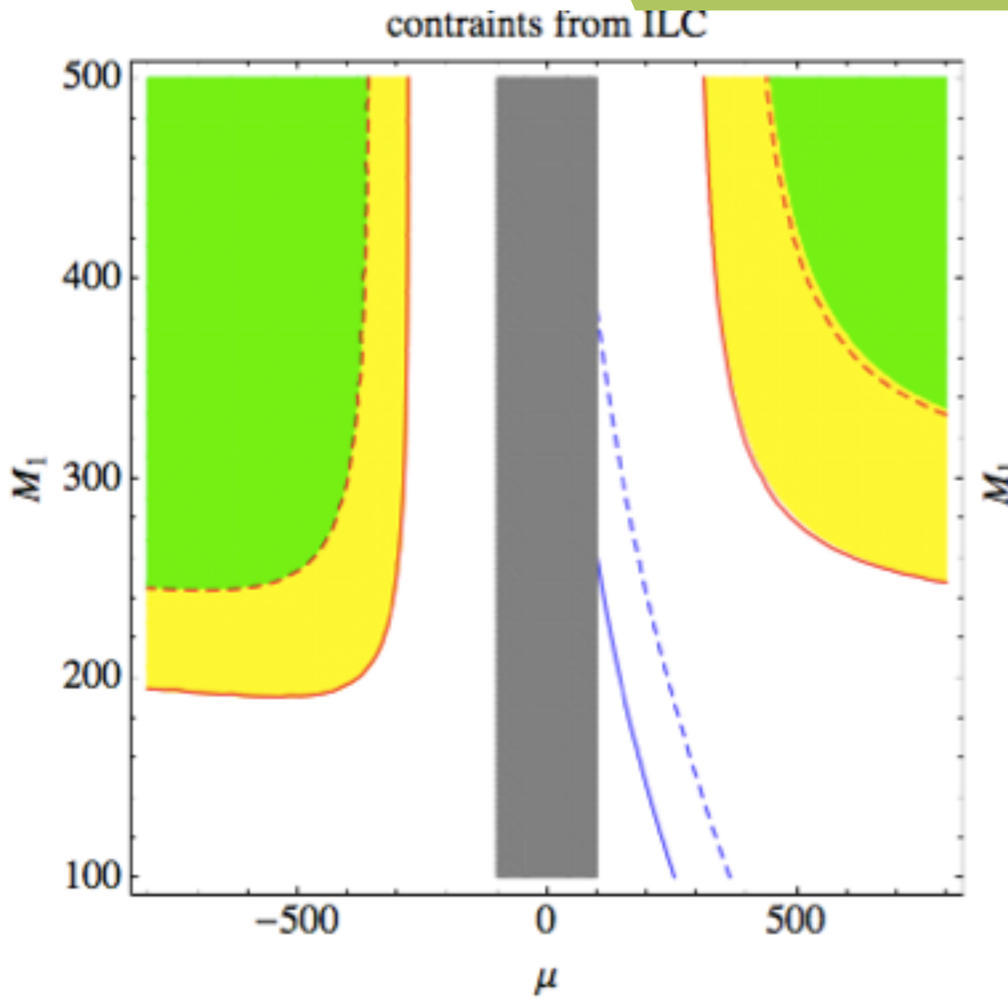
Combined results in the region plot

Need to combine TGC

H-y Han, R. Huo, M-y. Jiang, J. S, in progress

The results





At high energies, the Higgs strahlung became much more constraining

Need to calculate Loops

Electroweak

$$\epsilon_{Zh,I} = \frac{1}{1-\eta_Z^2}\left[\begin{array}{l} -\frac{2s}{\Lambda^2}\left(c_Z^2 c_{2W} + s_Z^2 c_{2B}\right) \\ +I_{VH}(\eta_h,\eta_Z)\frac{16 m_Z^2}{\Lambda^2}\left(c_Z^4 c_{WW} + s_Z^4 c_{BB} + c_Z^2 s_Z^2 c_{WB}\right) \\ +\left(1+2\eta_Z^2-\eta_Z^4\right)\frac{2s}{\Lambda^2}\left(c_Z^2 c_W + s_Z^2 c_B\right) \\ +\left(2-\eta_Z^2\right)\frac{2v^2}{\Lambda^2}\left(-2c_T + c_R\right) \end{array}\right] + \frac{2m_h^2}{\Lambda^2}c_D$$
$$+\frac{2eQ_f c_Z^2 s_Z}{g(T_f^3 - s_Z^2 Q_f)}\left\{\begin{array}{l} -\frac{s}{\Lambda^2}\left(c_{2W} - c_{2B} - c_W + c_B\right) \\ +I_{VH}(\eta_h,\eta_Z)\frac{4m_Z^2}{\Lambda^2}\left[2c_Z^2 c_{WW} - 2s_Z^2 c_{BB} - \left(c_Z^2 - s_Z^2\right)c_{WB}\right] \end{array}\right\}$$

$$c_{2B} = \frac{2g'^2}{15\mu^2}$$
$$c_{2W} = \frac{2g^2\left(2\mu^2 + M_2^2\right)}{15\mu^2 M_2^2}$$

dominate operators

Summary

- EFT is the perfect bridge to connect the underlying theory with the lepton precision collider observables
- CEPC experimental TDR will tells us how well they can measure on various observables, which constrain those BSM operators (TGC as a good example)
- Operators will then maps into simplified models
- Simplified models tells us physics (Higgs self-couplings and EW phase transition, etc, CW Higgs potential; Vector mesons and CHMs, etc)
- We can even learn something unique: degenerate electroweakinos