Constrain the Triple Gauge Couplings from Future Lepton Collider

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ITP

L. Bian, J. S, Y. Zhang,
1507.02238, accepted by JHEP

Outline

- CEPC & tri-gauge boson couplings?
- WW production at the lepton collider:
- Measurements at the CEPC
- TGC measurements at LHC Run II
- Comparision for EW, TGC Higgs precision at LHC Run II and CEPC
- Conclusion

Why tri-gauge boson couplings ?

Operators beyond SM

Operators relevant with LEP

Z. Han, W. Skiba, Phys. Rev. D. 71 075009 (2005)

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

Success of EWP Physics

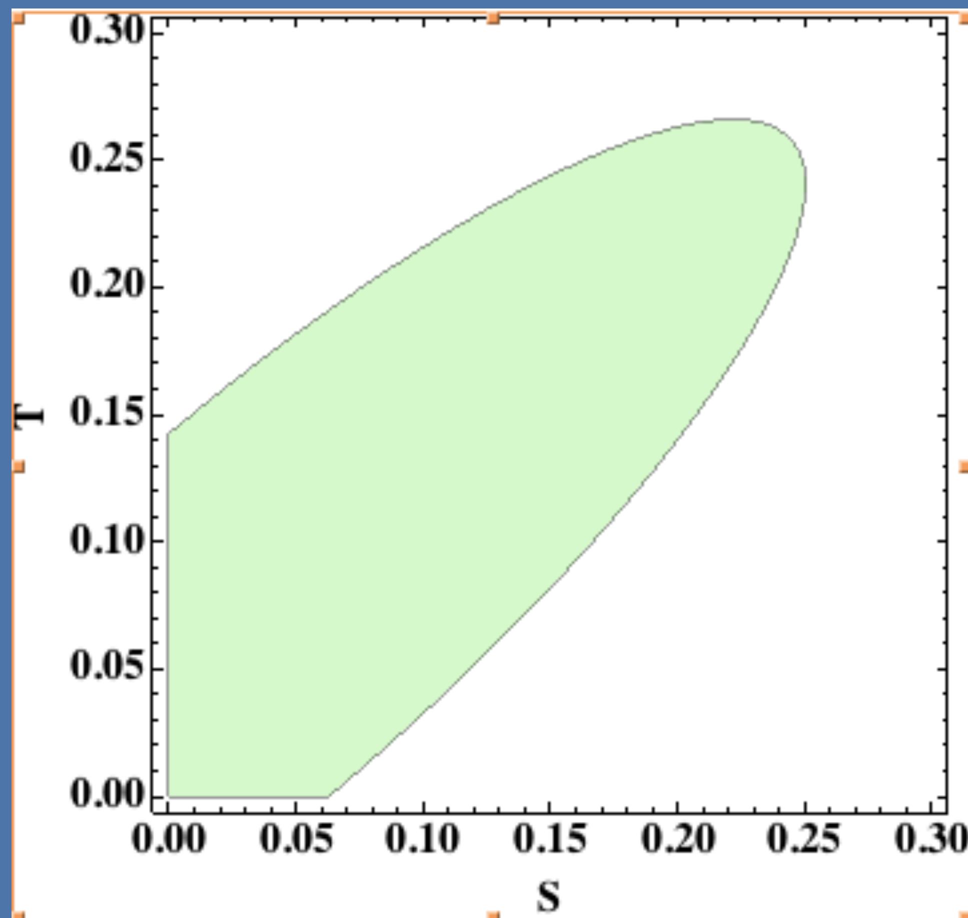
Independent Bosonic fields

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

Famous S, T parameter

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

95% C. L.



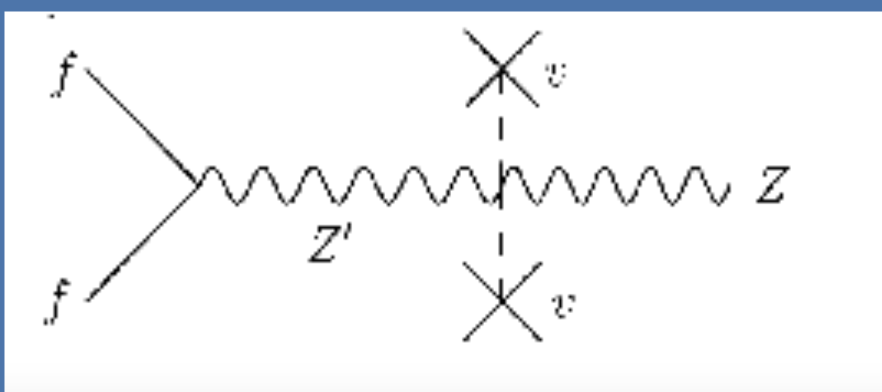
Triple gauge bosons ?

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 couplings are poorly measured!

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

a: size of gauge fermion operator



$$S = \frac{s}{2\pi} + \frac{a}{2\pi}$$

$$T = \frac{t}{8\pi e^2} + \frac{a g'^2}{8\pi e^2}$$

Disguising oblique parameters

Use the SM gauge field e.o.m, the universal gauge-fermion corrections can be reabsorbed into S,T parameter + tri-gauge couplings + higgs couplings

$$-\frac{g}{2}O_{WB} + 2g'O_h + g'O^Y_{hf} = 2iB_{\mu\nu}D^\mu h^\dagger D^\nu h,$$
$$-g'O_{WB} + g(O^t_{hl} + O^t_{hq}) = 4iW^a_{\mu\nu}D^\mu h^\dagger \sigma^a D^\nu h,$$

O_{HB}

O_{HW}

C. Grojean, W. Skiba, J. Terning
Phys. Rev. D. 73 075008 (2006)

Need to get reasonably high precision.

We neglect RHS in the past!

After the tri-gauge boson and Higgs measurements, we can not re-shift it as S,T

CEPC

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

What can it go beyond the LEP?

- EW precision (Super-Z factory)
- Tri-gauge boson precision
- Higgs precision

WW production at the lepton collider

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:

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

Tri-gauge boson at LEP

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

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

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:

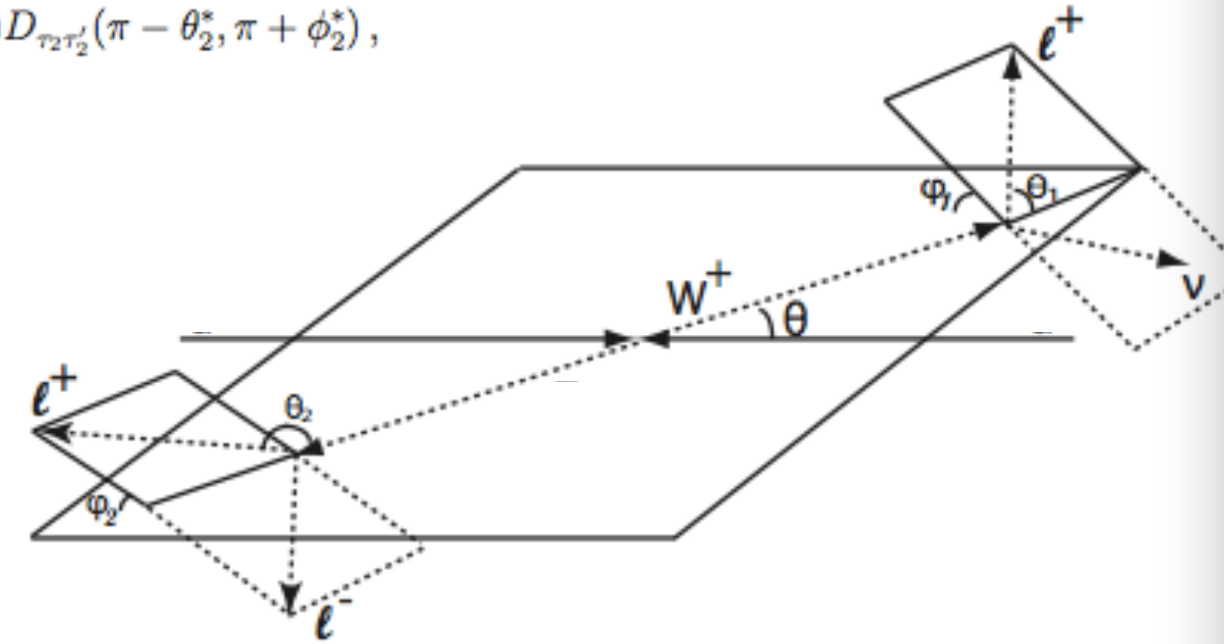
$$\Delta g_{1,Z}\,,\quad \Delta\kappa_\gamma\,,\quad \lambda_\gamma\,.$$

Kinematics

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

D:W decay matrix

C: Coupling coefficients



Production amplitude

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

Five differential variables

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

Kinematics

The parameter dependence:

$$\sigma_{\text{total}} \sim a_i \alpha_i^2 + b_i \alpha_i + \sigma_0$$

$$b(\Delta g_{1,Z}) = -0.665\,,$$
$$b(\Delta \kappa_\gamma) = -3.06\,,$$
$$b(\Delta \kappa_Z) = -1.40\,,$$

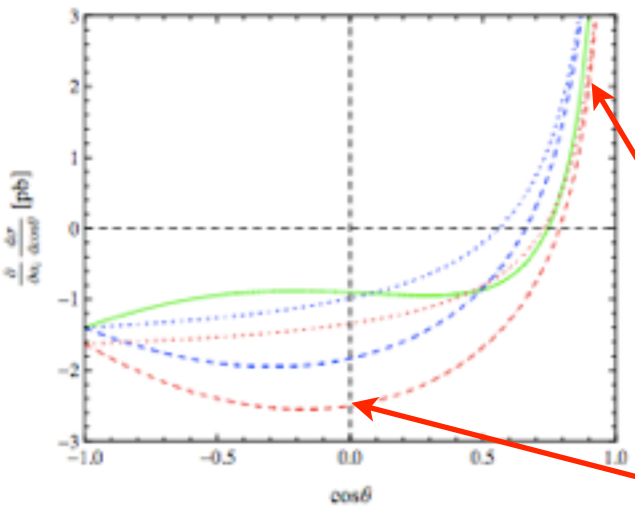
Linear term dominate in the high precision collider like CEPC.

$$b(\lambda_\gamma) = -1.52\,,$$
$$b(\lambda_Z) = -0.264\,,$$

Differential cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}, \quad \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_1^*}, \quad \frac{\mathrm{d}\sigma}{\mathrm{d}\phi_1^*}, \quad \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_2^*}, \quad \frac{\mathrm{d}\sigma}{\mathrm{d}\phi_2^*}.$$

Linear Differential Sensitivity



scattering angle

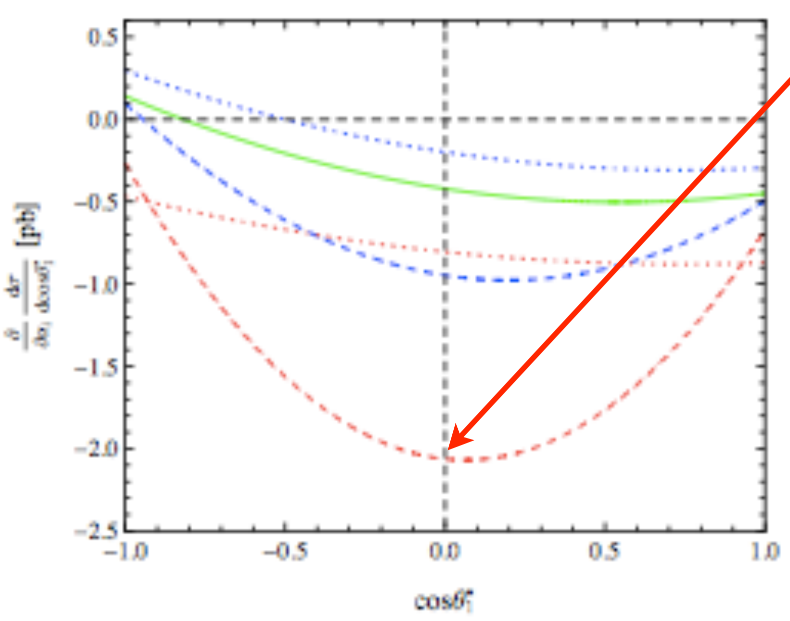
$\Delta g_{1,Z}$, $\Delta\kappa_\gamma$, $\Delta\kappa_Z$, λ_γ and λ_Z

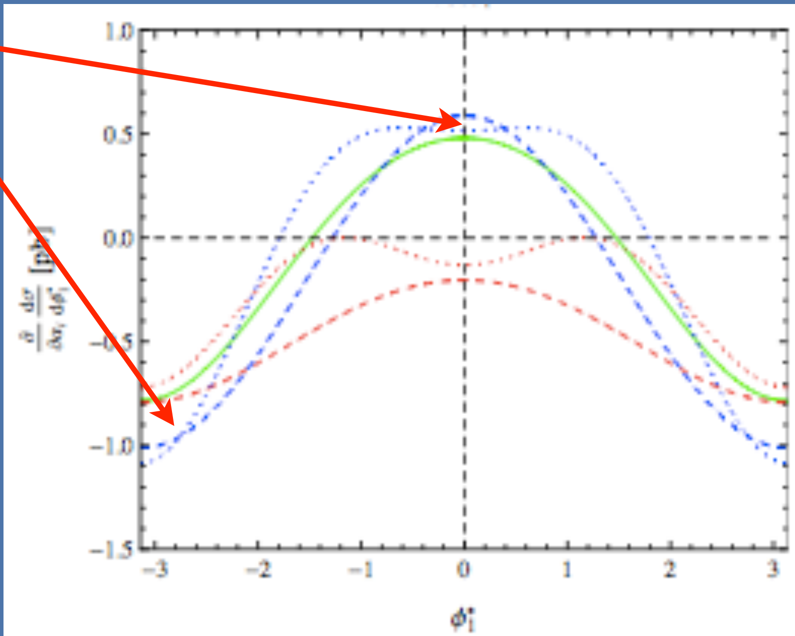
green, red dashed, blue dashed, red dotted and blue dotted

azimuthal angle

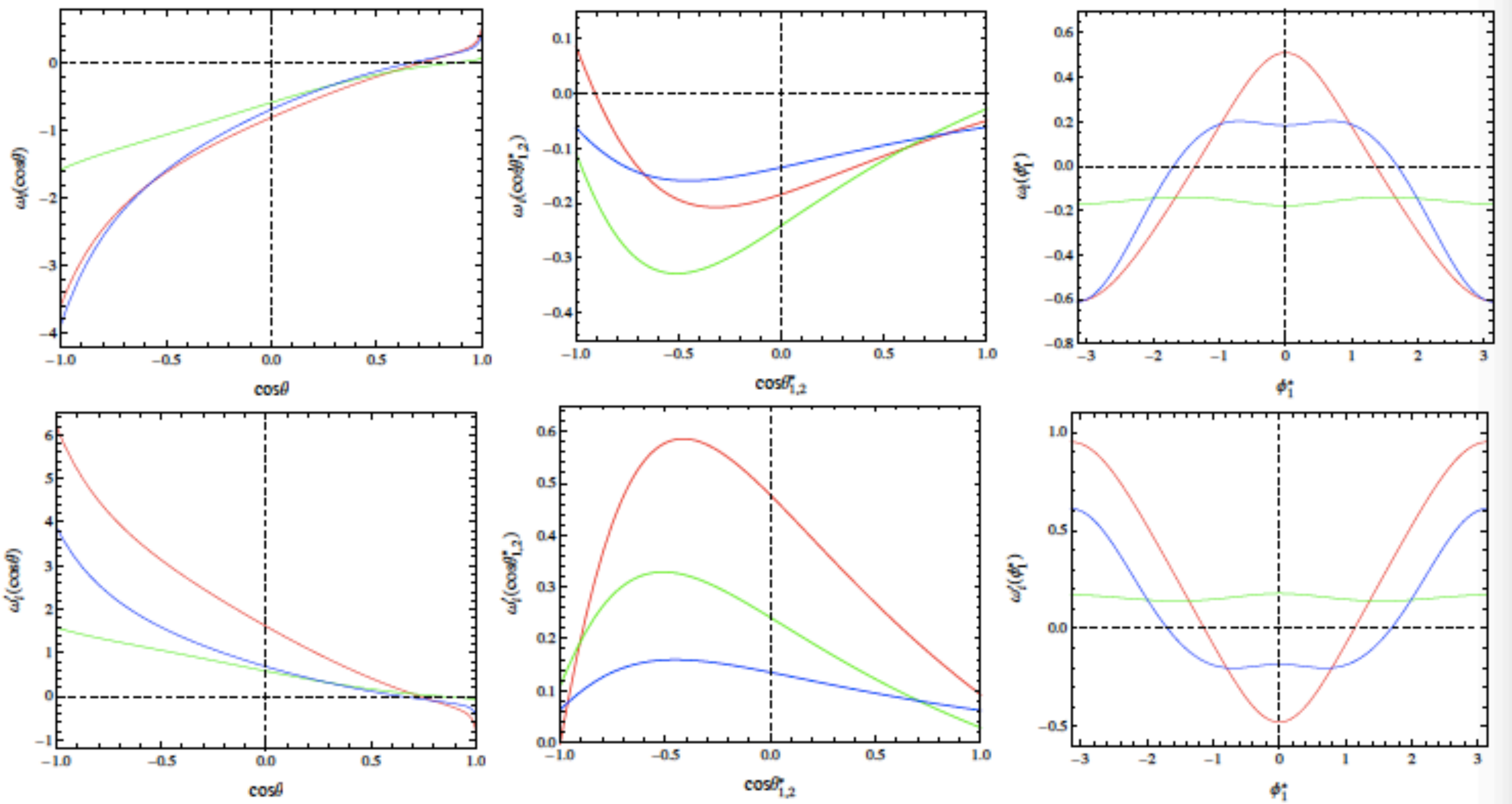
Sensitive

polar angle





Linear Differential Sensitivity



$\Delta g_{1,Z}$, $\Delta\kappa_\gamma$ and λ_γ upper

c_{HW}, c_{HB} and c_{3W} down

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

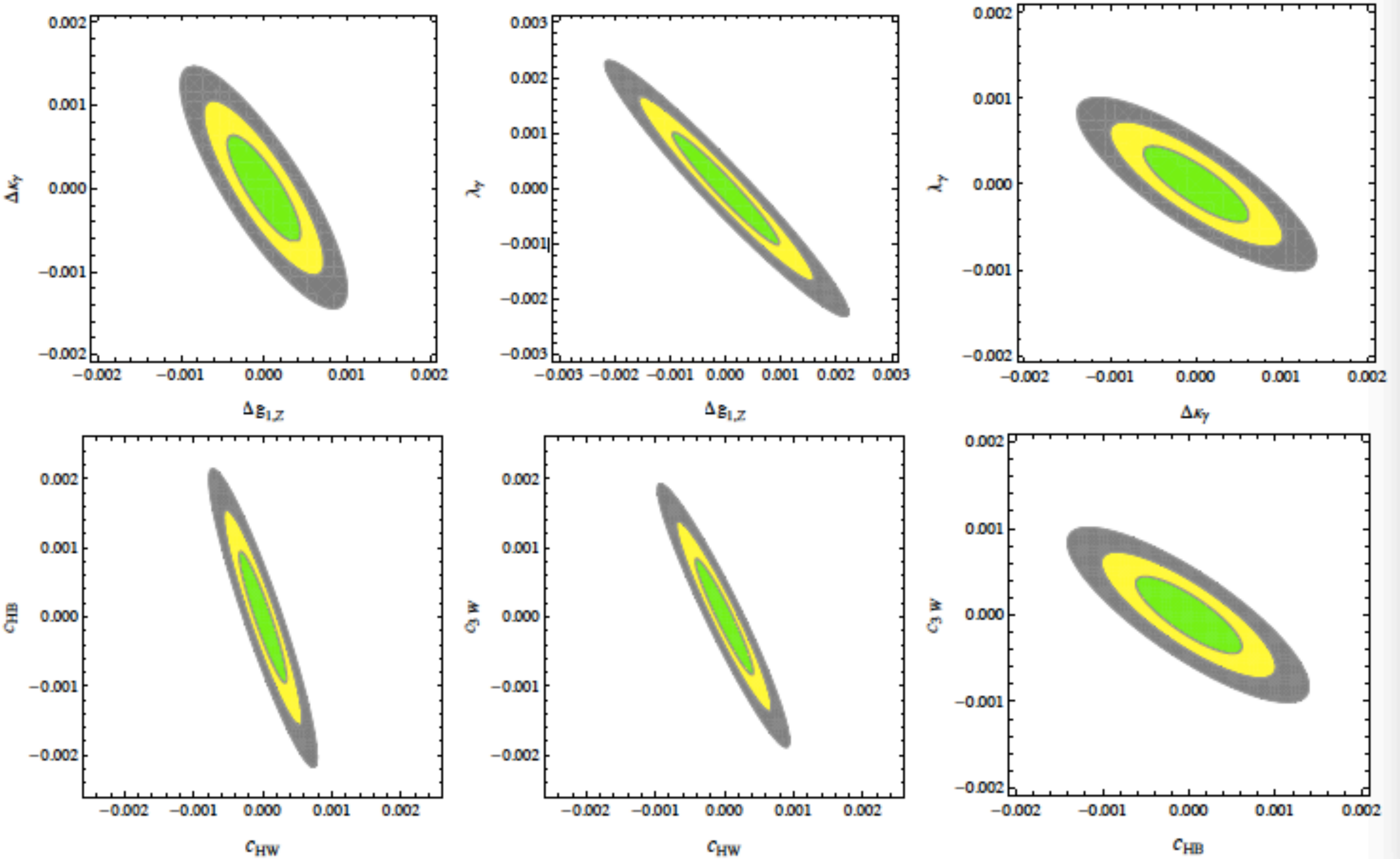
channels	$\Delta g_{1,Z}$	$\Delta\kappa_\gamma$	$\Delta\kappa_Z$	λ_γ	λ_Z
leptonic	14.49	8.02	9.82	12.70	12.00
semileptonic	5.52	2.71	3.59	4.32	4.63
hadronic	6.56	2.74	4.00	4.40	5.65
all	4.06	1.87	2.58	3.00	3.44

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

10^-3 ~ 10^-4

Two orders improvements

2D significance



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

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^{-5} in general, OK!

Few Comments

- Hadronic channel has large reducible backgrounds. (needs to be included)
- Bins shown later are the semi-leptonic
- Systematic uncertainties: ISR, beamstrahlung, W mass measurements, E resolution, beam energy uncertainties, etc

Constraints from LHC Run II

LHC WW process

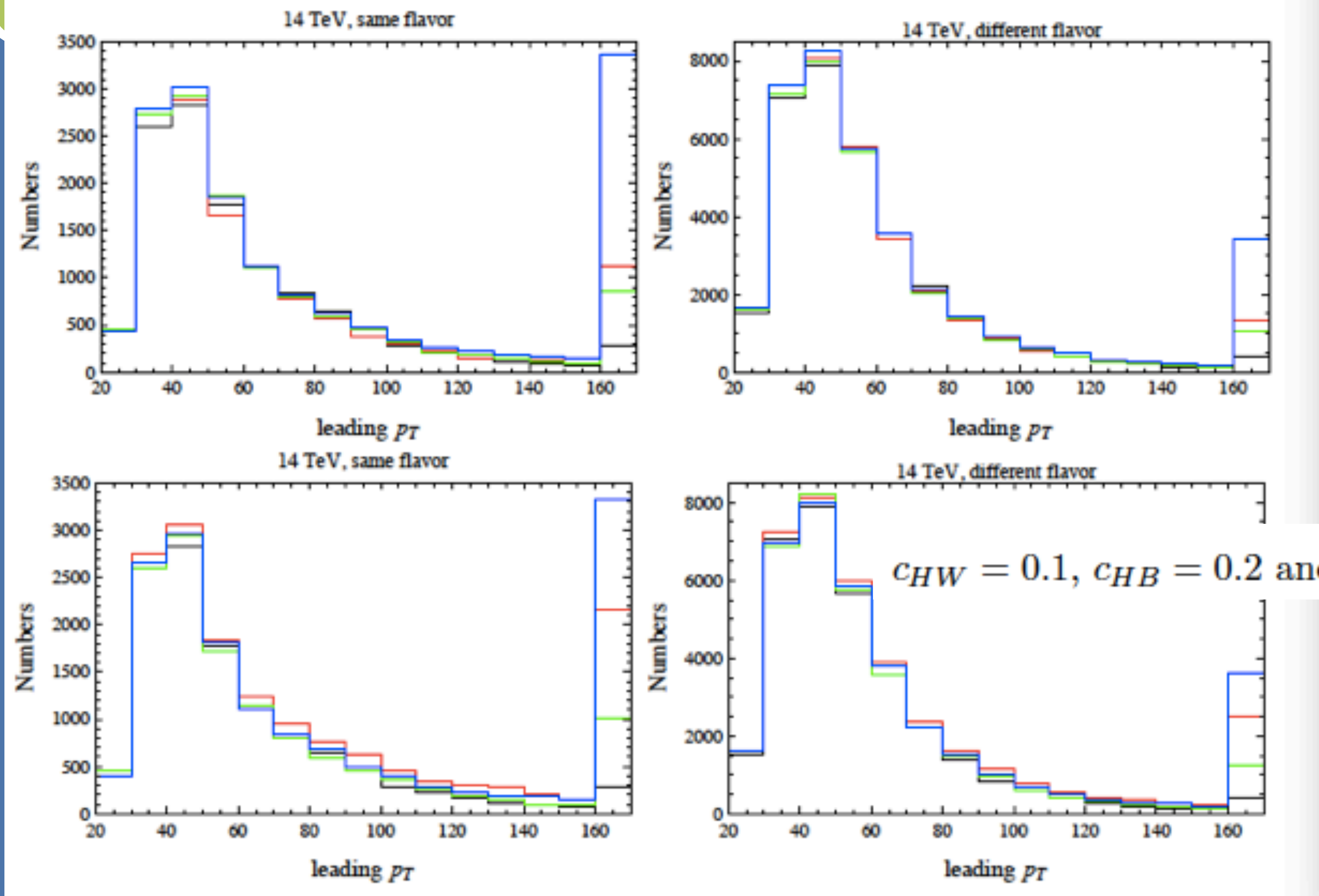
- Di-lepton channel to suppress the QCD Backgrounds.
- $l = e, \mu$, leading $p_T > 25$ GeV and subleading $p_T > 20$ GeV, $|\eta| < 2.5$, .

$\Delta R_{ll} > 0.4$, $m_{ll} > 15(10)$ GeV, $\not{E}_T > 45(15)$ GeV for the same (different) flavor channels,

- $|m_{ll} - M_Z| > 15$ GeV for the same flavor channels.

Pt distributions

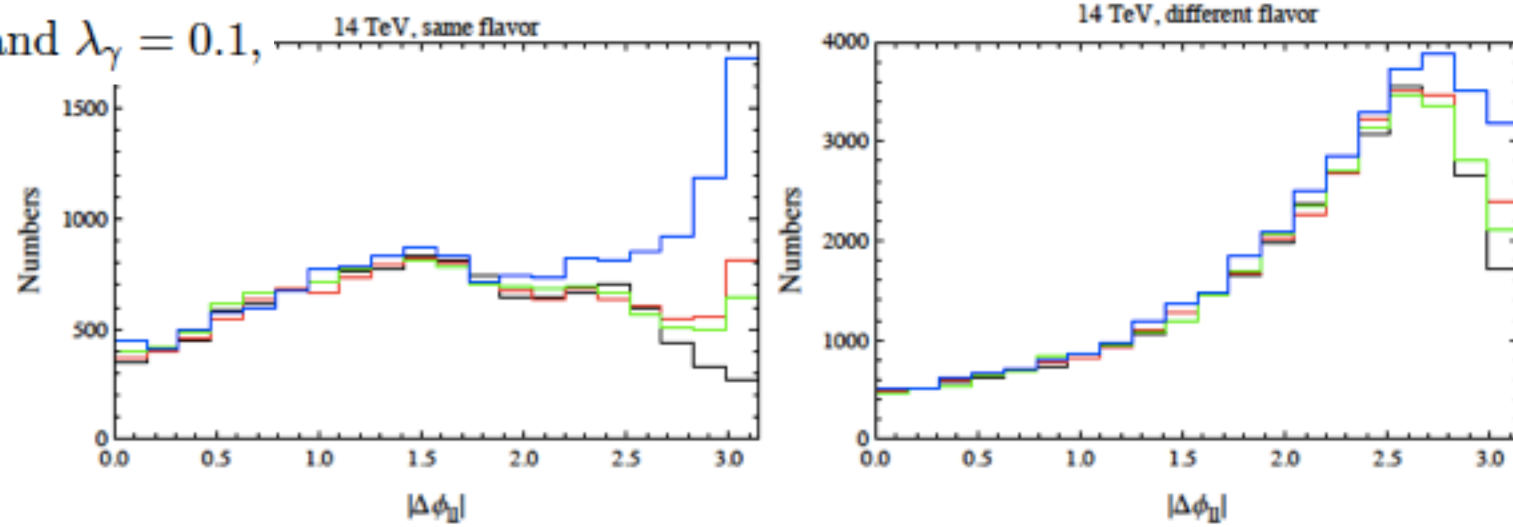
$\Delta g_{1,Z} = 0.1$, $\Delta\kappa_\gamma = 0.2$ and $\lambda_\gamma = 0.1$,



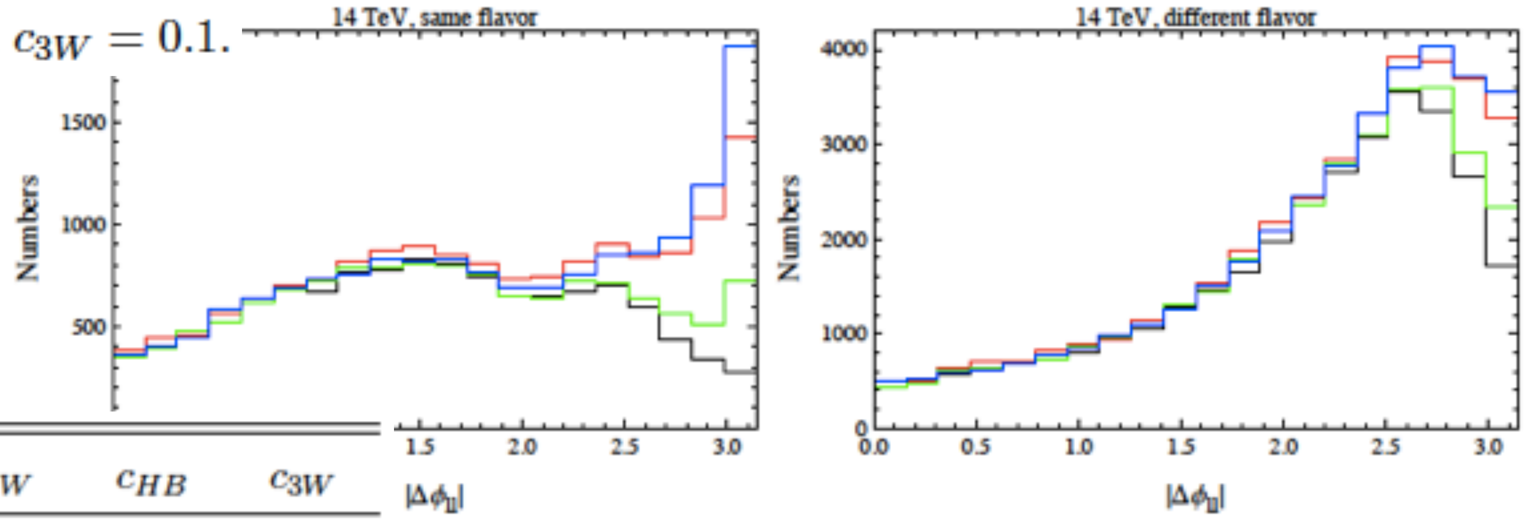
$c_{HW} = 0.1$, $c_{HB} = 0.2$ and $c_{3W} = 0.1$

Azimuthal angle

$\Delta g_{1,Z} = 0.1,\ \Delta\kappa_\gamma = 0.2$ and $\lambda_\gamma = 0.1,$



$c_{HW} = 0.1,\ c_{HB} = 0.2$ and $c_{3W} = 0.1.$



	$\Delta g_{1,Z}$	$\Delta\kappa_\gamma$	λ_γ	c_{HW}	c_{HB}	c_{3W}
300 fb^{-1}	23	73	17	14 (2.7)	73 (1.6)	17 (5.9)
3000 fb^{-1}	11	30	5.7	6.3 (3.9)	30 (2.5)	5.7 (10)

Counting the EFT

Further Cuts: $\Delta\phi_{ll} > 170°$

leading $p_T > 300$ GeV

> 500 GeV

300 fb^{-1}

3000 fb^{-1}

$\tilde{\Lambda} \sim \tilde{g} M_W / \sqrt{c_i}$

$\tilde{g} < 0.3^8.$

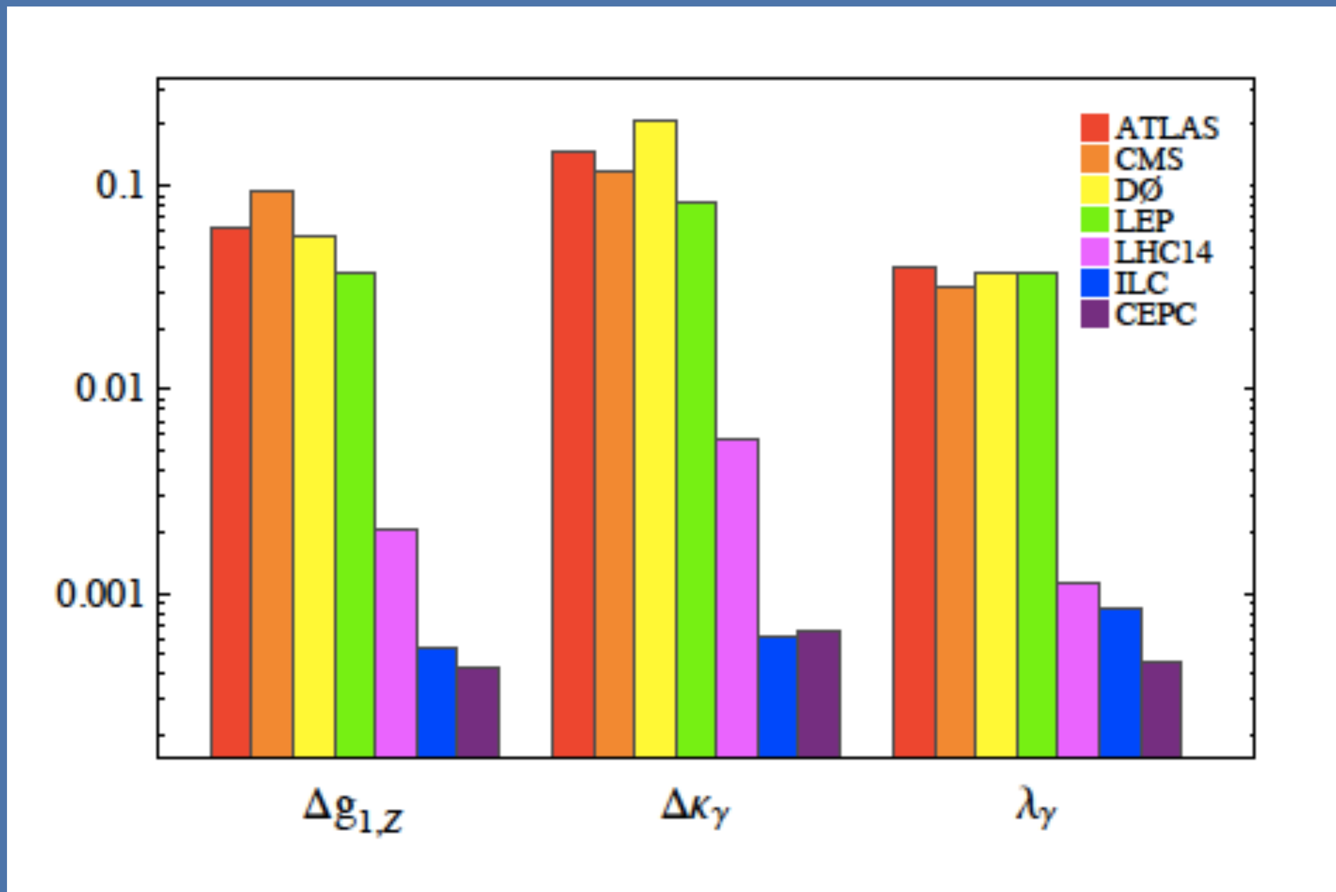
Can be relaxed

$p_T > 160$ GeV would be 1.2 times smaller than those by using $p_T > 300$

Helicity combinations

	$\Delta g_{1,Z}$	$\Delta\kappa_\gamma$	λ_γ
ATLAS [20, 23]	$[-0.055, 0.071]$	$[-0.150, 0.150]$	$[-0.039, 0.040]$
CMS [24, 26]	$[-0.095, 0.095]$	$[-0.104, 0.134]$	$[-0.036, 0.028]$
D0 [18]	$[-0.031, 0.081]$	$[-0.158, 0.255]$	$[-0.034, 0.042]$
LEP [14]	$[-0.054, 0.021]$	$[-0.099, 0.066]$	$[-0.059, 0.017]$
LHC14	$[-0.0021, 0.0021]$ $([-0.0045, 0.0045])$	$[-0.0058, 0.0058]$ $([-0.014, 0.014])$	$[-0.0011, 0.0011]$ $([-0.0033, 0.0033])$
ILC [30]	$[-0.00055, 0.00055]$ $([-0.00035, 0.00035])$	$[-0.00061, 0.00061]$ $([-0.00037, 0.00037])$	$[-0.00084, 0.00084]$ $([-0.00051, 0.00051])$
CEPC	$[-0.00043, 0.00043]$ $([-0.00031, 0.00031])$	$[-0.00065, 0.00065]$ $([-0.00045, 0.00045])$	$[-0.00046, 0.00046]$ $([-0.00033, 0.00033])$

Comparision



Current and future 95% C.L. constraints

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}

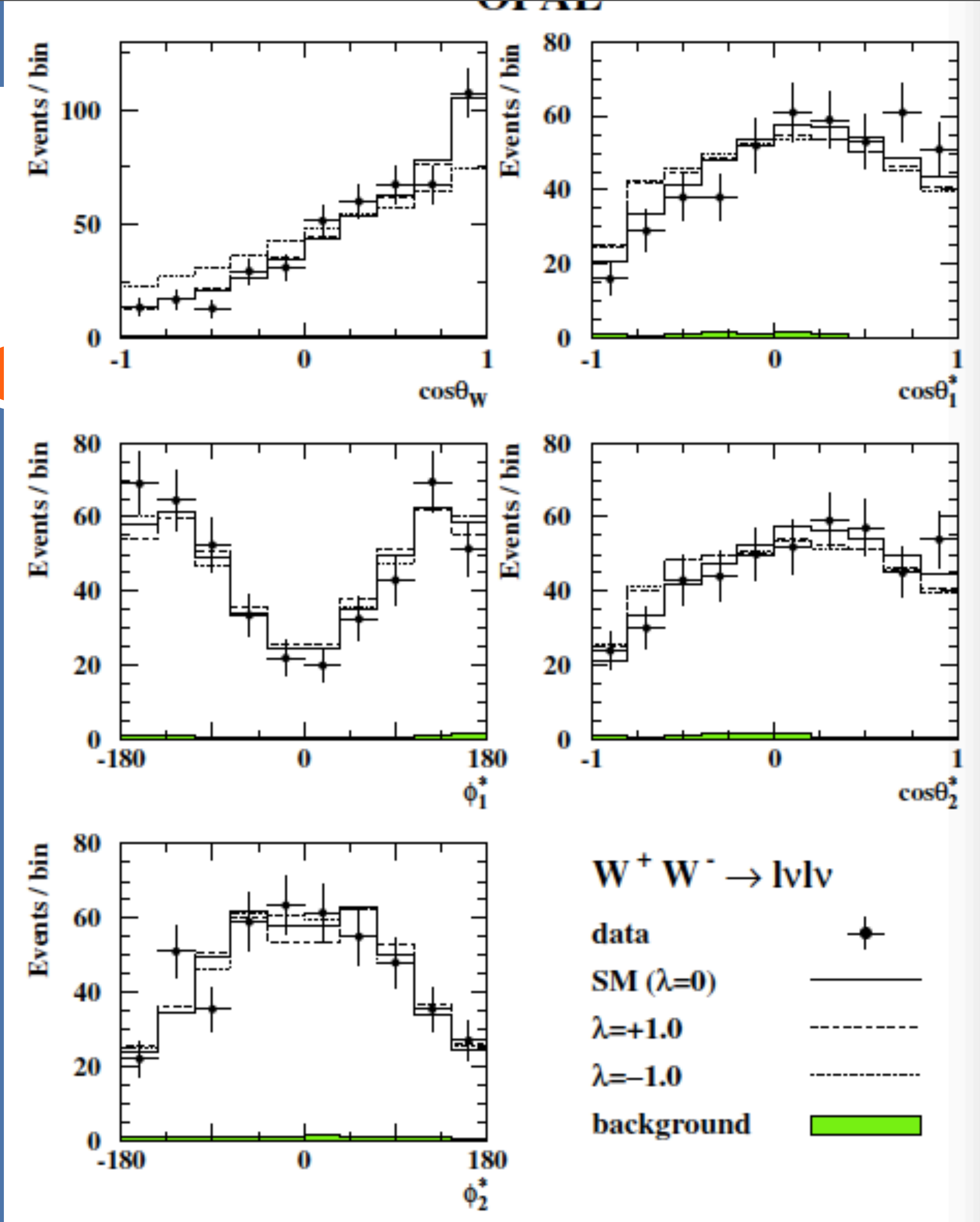
one sigma

Conclusion

- CEPC can greatly improve the TGC by more than 2 orders of magnitudes
- At the LHC, TGC can be improved by more than one order of magnitude and not too far ways from S, T precision for some operators. In general, it is much better than Higgs precision.
- At the CEPC, TGC not far way from S, T precisions and slightly better than Higgs precision.

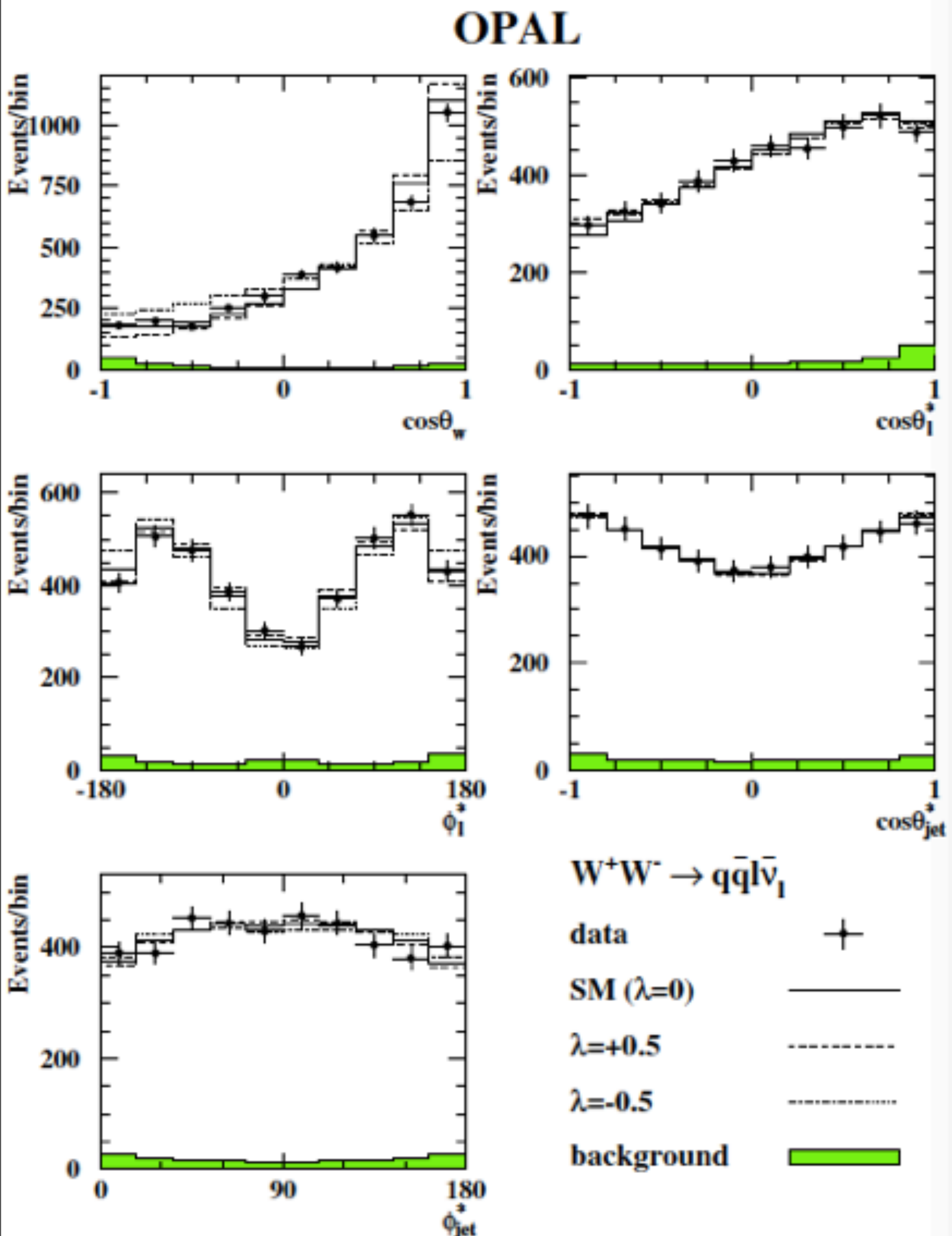
Backup slice

Leptonic

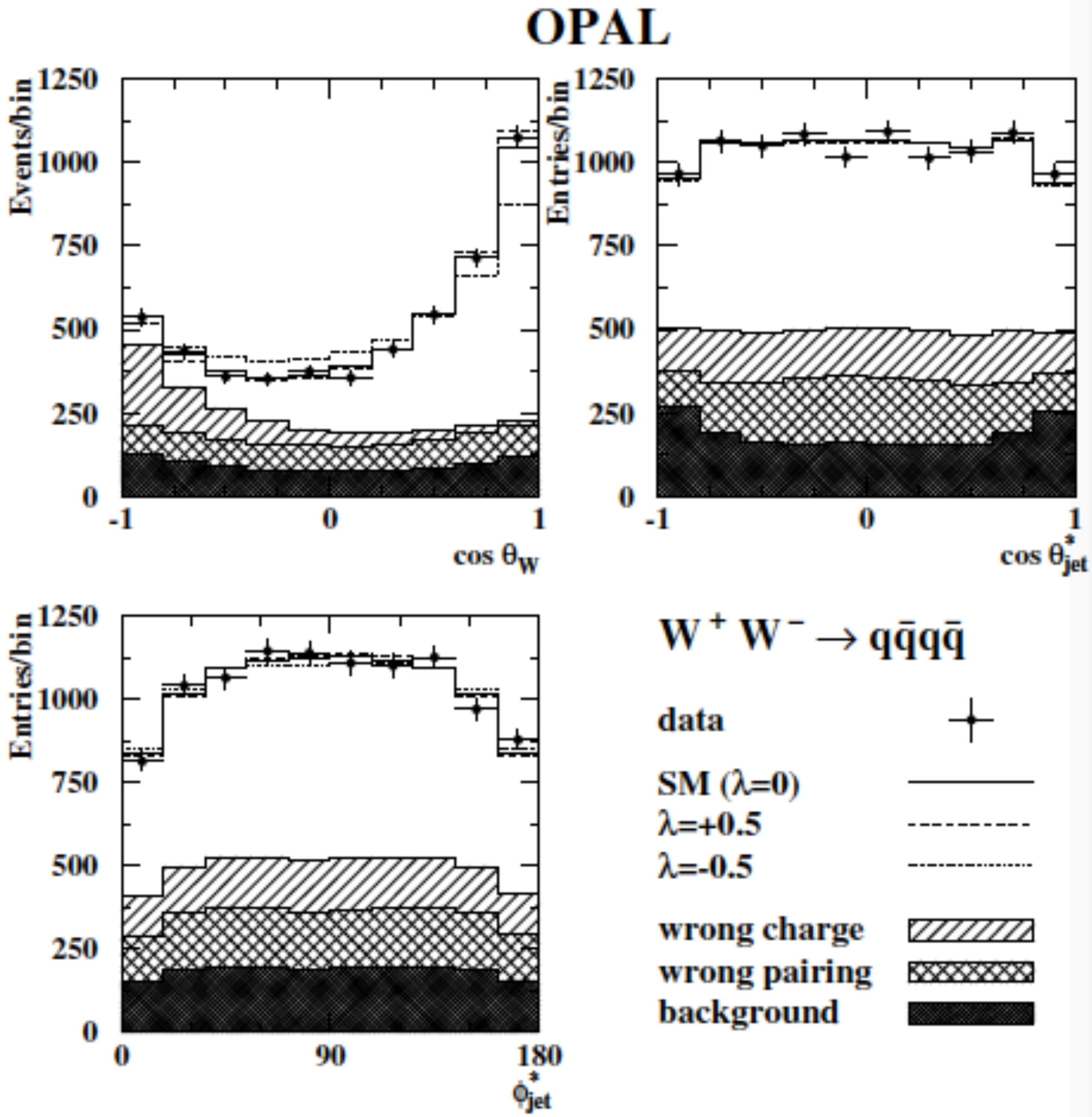


OPAL
Events / bin
$\cos\theta_W$
$\cos\theta_1^*$
ϕ_1^*
$\cos\theta_2^*$
ϕ_2^*
$W^+W^- \to l\nu l\nu$
data
SM (λ=0)
λ=+1.0
λ=–1.0
background

Semi-leptonic



hadronic channel



Operators beyond SM

$e^+e^- \to W^+W^-$ **at LEP 2** (Tri-gauge boson)

$$\Delta\mathcal{L} = i a_{WB} v^2 g W^+_\mu W^-_\nu (c A^{\mu\nu} - s Z^{\mu\nu}) + 6 i a_W W^{-\mu}_\nu W^{+\lambda}_\mu (s A^\nu_\lambda + c Z^\nu_\lambda).$$

EWWG

$$\begin{aligned}\frac{\mathcal{L}_{WWV}}{g_{WWV}} = {} & i g_1^V (W^+_{\mu\nu} W^{-\mu} V^\nu - W^-_{\mu\nu} W^{+\mu} V^\nu) + i\kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{i\lambda_V}{\Lambda_\chi^2} W^+_{\mu\nu} W^{-\nu}_\rho V^{\rho\mu} \\ & - g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) + g_5^V \epsilon^{\mu\nu\rho\lambda} \left[W^+_\mu (\partial_\rho W^-_\nu) - (\partial_\rho W^+_\mu) W^-_\nu \right] V_\lambda \\ & + i\tilde{K}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{i\tilde{\lambda}_V}{\Lambda_\chi^2} W^+_{\mu\nu} W^{-\nu}_\rho \tilde{V}^{\rho\mu},\end{aligned}$$

$$\Delta\kappa_\gamma = \frac{v^2 c}{s} a_{WB},$$

$$\Delta\kappa_Z = -\frac{v^2 s}{c} a_{WB},$$

$$\Delta\lambda_\gamma = \Delta\lambda_Z = \frac{3 v^2 g}{2} a_W.$$

Unfortunately, poorly measured because of lack of data

Operators beyond SM

Unfortunately in LEP II means great for CEPC

Other modes give 30 MeV

$$\Delta M_W = 10^6\left(-1.73a_h - 2.08a^t_{hl} + 1.04a^t_{ll} - 3.80a_{WB}\right),$$

ΔM_W [MeV]	LEP2	ILC	ILC	e^+e^-	TLEP
$\sqrt{s}$ [GeV]	161	161	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480	600	3000×4
$P(e^-)$ [%]	0	90	90	0	0
$P(e^+)$ [%]	0	60	60	0	0
systematics	70			?	< 0.5
statistics	200			2.3?	0.5
experimental total	210	3.9	1.9	>2.3	< 0.7
beam energy	13	0.8-2.0	0.8-2.0	0.8-2.0	0.1
radiative corrections	-	1.0	1.0	1.0	1.0
total	210	4.1-4.5	2.3-2.9	>2.6-3.2	< 1.2

LEP II only has total 3fb inverse data, comparing to 3000fb inverse

Improvement would be much more than measuring Mw

The

- Old EWPT can be improved a lot (like Mw) ! Too precise to keep only d=6 operators?
- Tri-gauge boson coupling will be greatly improved. Break down of S,T formulism.

I haven't even talked about Higgs yet!

The Higgs coupling!

With Higgs, everything would be so so so different!

Any vev insertion would be replaced by a higgs or two higgs, etc

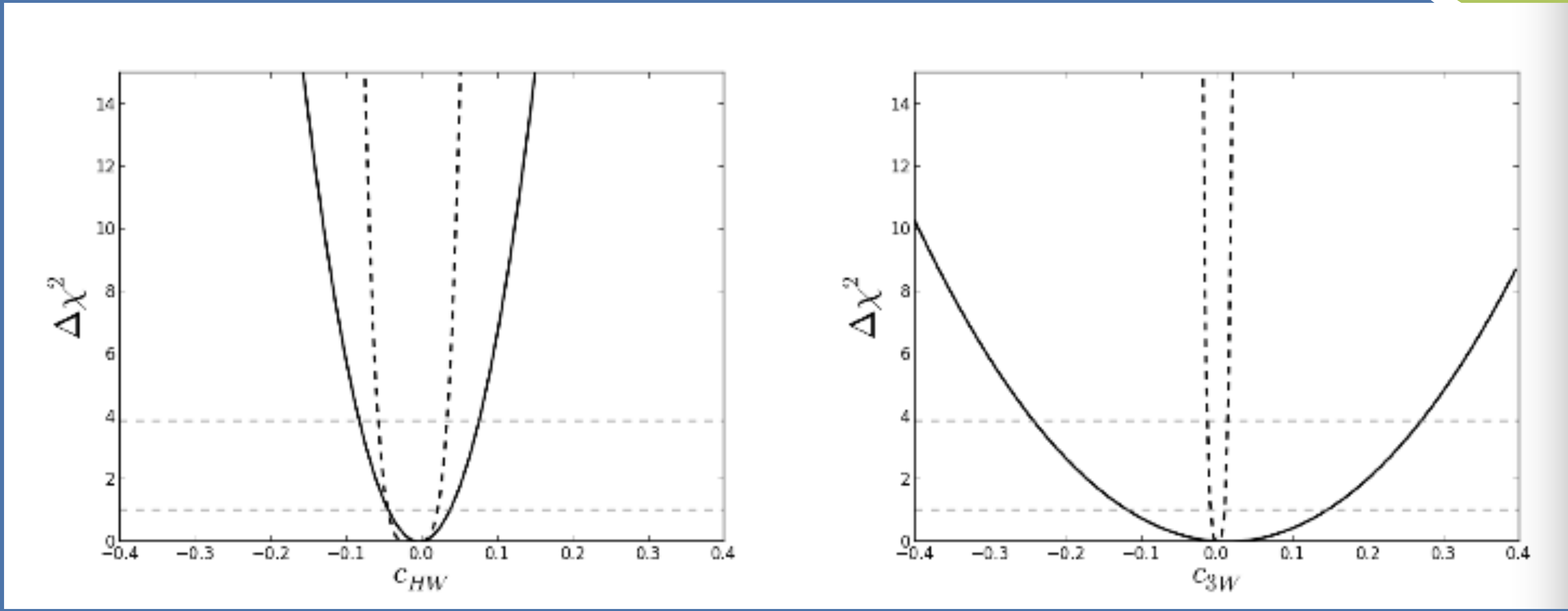
Operators contribute to S parameter

$$a_{WB} h^\dagger W^{a\mu\nu} \sigma^a h B_{\mu\nu}$$

$$\Pi'_{Z\gamma} = -a_{WB} v^2 (c^2 - s^2), \quad \Pi'_{\gamma\gamma} = -2 a_{WB} v^2 sc, \quad \Pi'_{ZZ} = 2 a_{WB} v^2 sc.$$

Clearly, with an extra factor of 2, this is the hVV couplings.

The Higgs coupling!



J. Ellis, V. Sanz and T. You, 1410.7703