EFT approach to top and W at FCC-ee

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FCC-ee workshop
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The SM EFT

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i O_i}{\Lambda^2}$$

- $tt\gamma/ttg$, EM/color dipole

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu} \qquad O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$

- tbW
  - V/A

$$O^{(3)}_{\varphi Q} = i(\varphi^\dagger D_\mu \tau^I \varphi)(\bar{Q}\tau^I \gamma^\mu Q) \qquad O_{\varphi\varphi} = i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

  - Weak dipole

$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu} \qquad O_{bW} = (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

- ttZ
  - V/A

$$O^{(1)}_{\varphi Q} = i(\varphi^\dagger D_\mu \varphi)(\bar{Q}\gamma^\mu Q) \qquad O_{\varphi u} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu t)$$

  - Weak dipole O_{tW}

Physics goal:
determine L_{EFT} up to dim-6

$(\bar{u}\gamma^\mu t)Z_\mu$

$$O^{(3,1+3)}_{\varphi Q} = i\left(\varphi^\dagger \tau^I D_\mu \varphi\right)\left(\bar{q}\gamma^\mu \tau^I Q\right)$$
$$O^{(1,1+3)}_{\varphi Q} = i\left(\varphi^\dagger D_\mu \varphi\right)\left(\bar{q}\gamma^\mu Q\right)$$
$$O^{(1+3)}_{\varphi u} = i\left(\varphi^\dagger D_\mu \varphi\right)\left(\bar{u}\gamma^\mu t\right)$$

$(\bar{u}\sigma^{\mu\nu} q_\nu t)V_\mu$, "weak dipole"

$$O^{(13)}_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
$$O^{(13)}_{uB} = (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

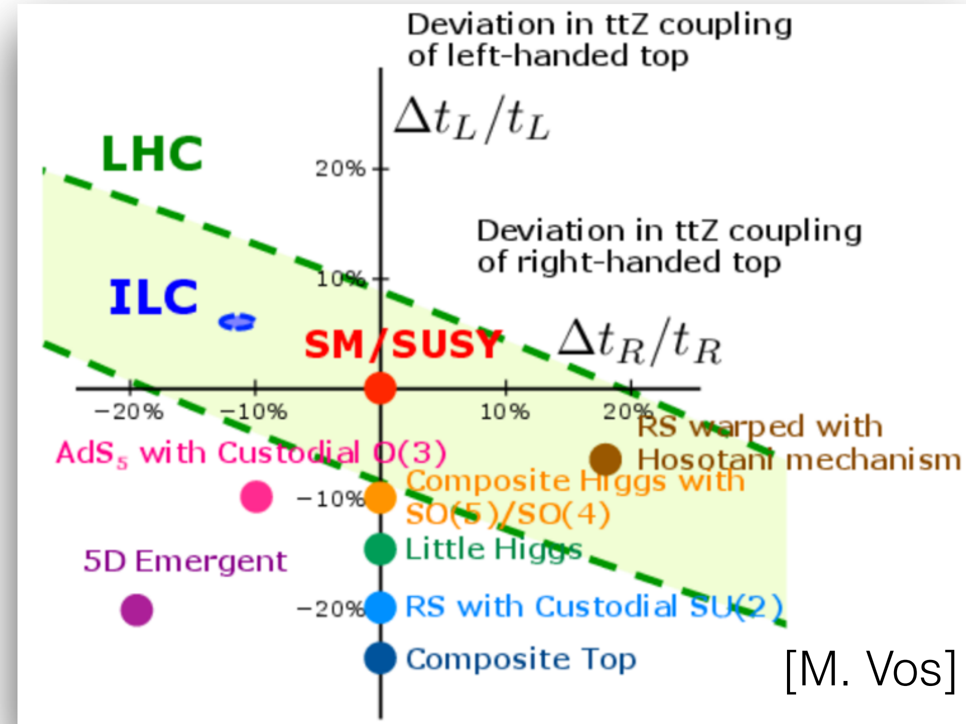
$(\bar{u}\sigma^{\mu\nu} q_\nu t)G_\mu$, "color dipole"

$$O^{(13)}_{uG} = (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$

$\bar{u}th$, "Yukawa"

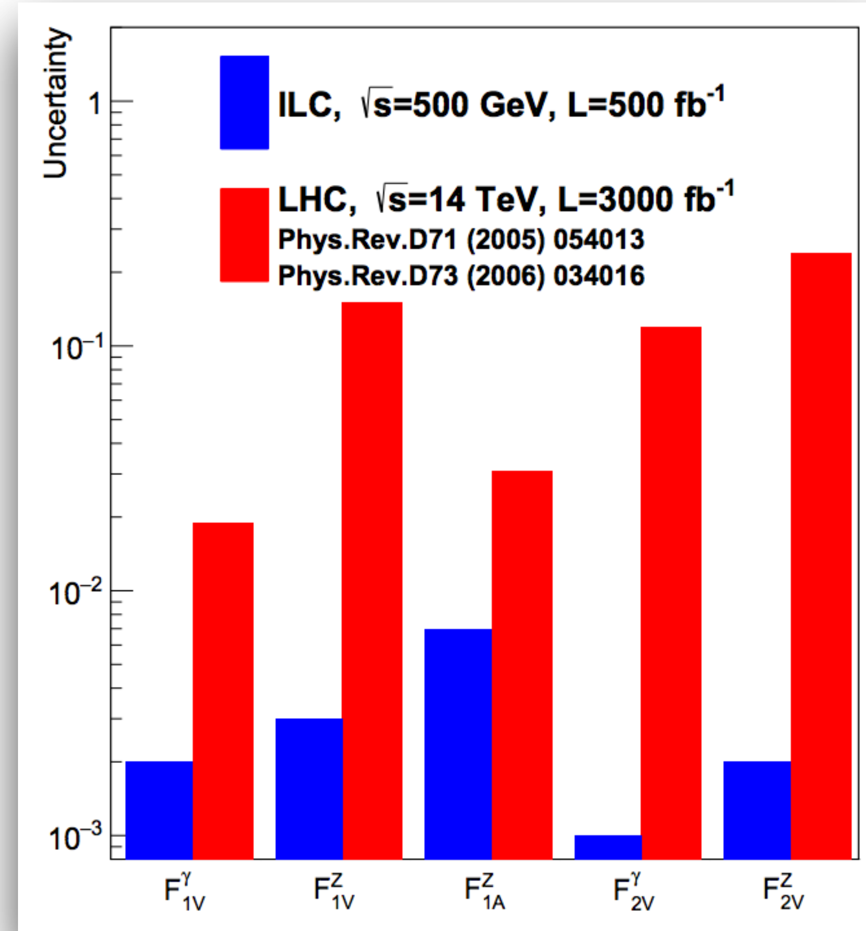
$$O^{(13)}_{u\varphi} = (\varphi^\dagger \varphi)(\bar{q}t)\tilde{\varphi}$$

Top & W couplings at LC

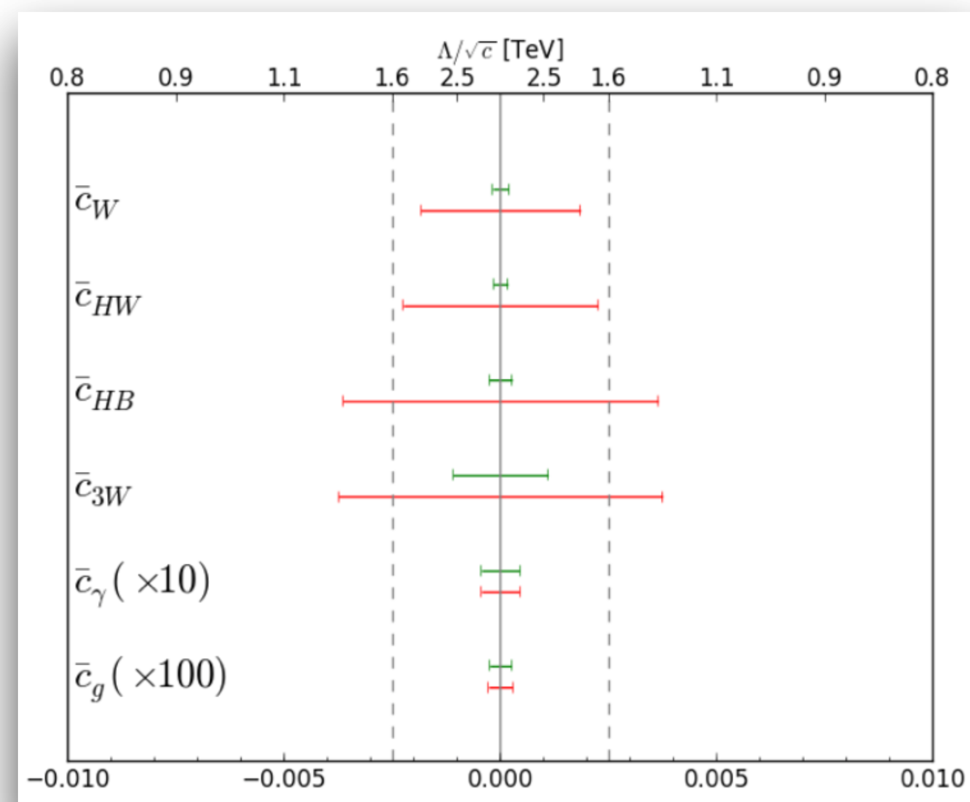


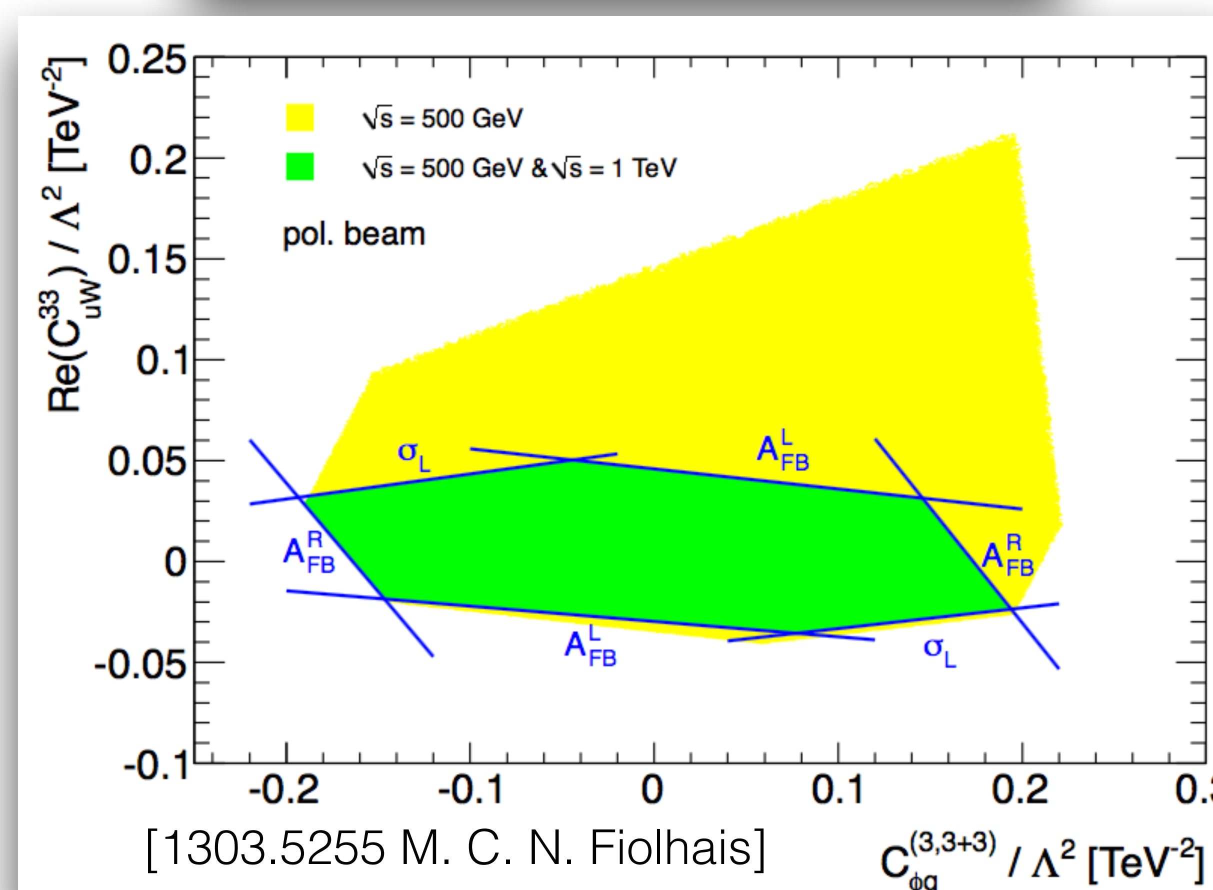
[M. Vos]

[1505.06020 M. S. Amjad et al.]



[1510.04561 J. Ellis, T. You]





[1303.5255 M. C. N. Fiolhais]

Making the most use of your EFT

A. Think globally. EFT combines all measurements, from different experiments, energies, processes, direct/indirect probes, which provide complementary information.

B. More than just probing "Anomalous Couplings" of a few vertices. Consistent and complete SM deviations.

C. Higher-order corrections possible. Predictions can be systematically improved.

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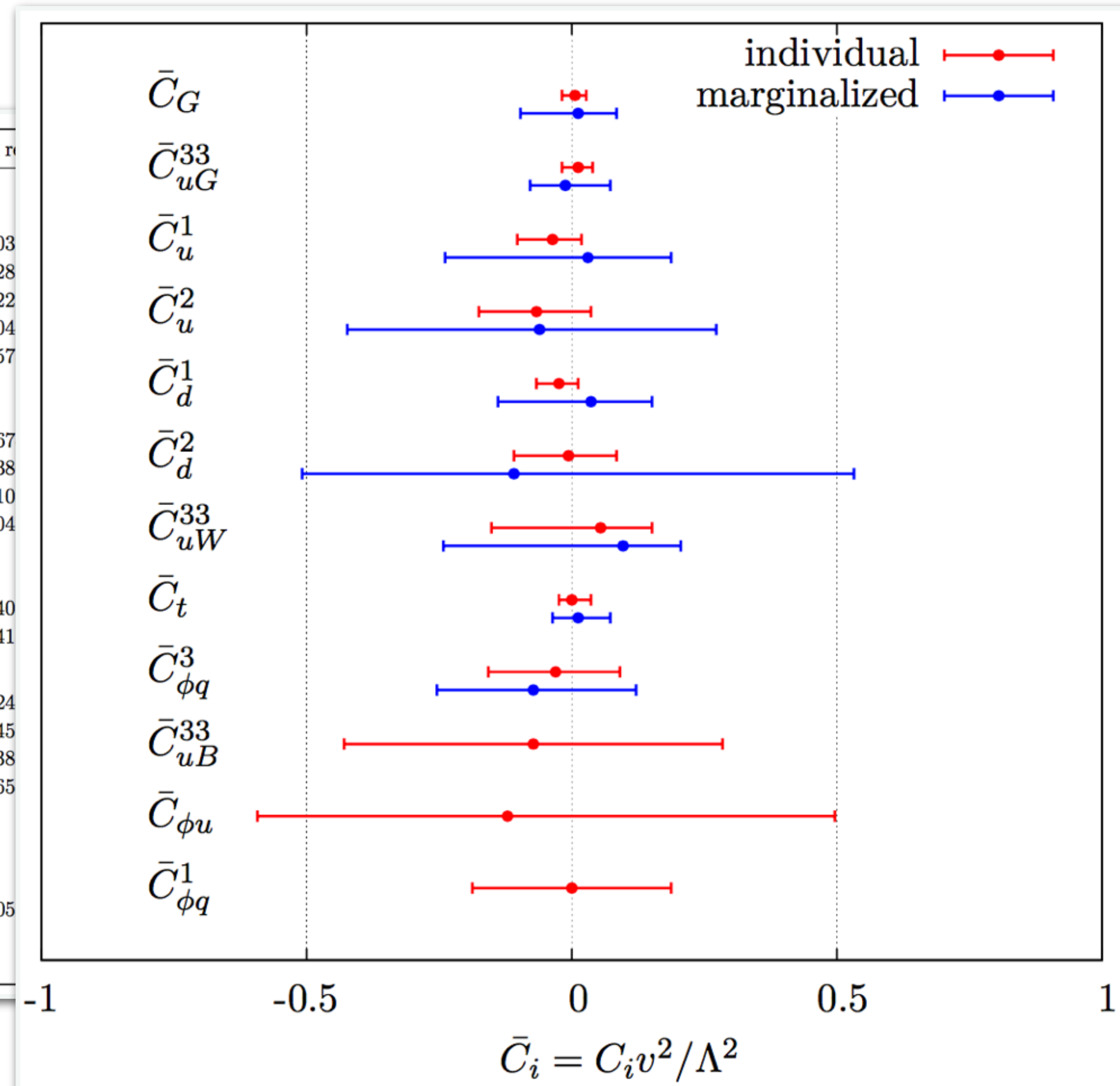
A. A global approach

- On going fitting program at the LHC

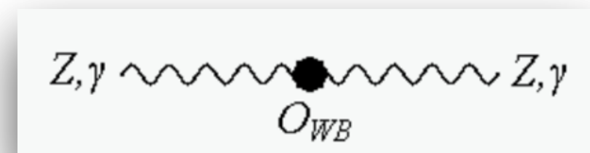
Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv r
Top pair production							
Total cross-sections:				Differential cross-sections:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	1407.03
ATLAS	7	dilepton	1202.4892	CDF	1.96	$M_{t\bar{t}}$	0903.28
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.22
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04
ATLAS	7	lepton w/ b jets	1406.5375	DØ	1.96	$M_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	1401.57
ATLAS	7	tau+jets	1211.7205				
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.67
CMS	7	all hadronic	1302.0508	CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.38
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.10
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.04
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
CMS	8	dilepton	1312.7582	DØ	1.96	Γ_{top}	1308.40
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	Γ_{top}	1201.41
Single top production				*W*-boson helicity fractions:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.24
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.45
CMS	7	t-channel (total)	1406.7844	CMS	7		1308.38
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.65
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar{t}\gamma$	1502.00586	CMS	13	$t\bar{t}$ (dilepton)	1510.05
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				

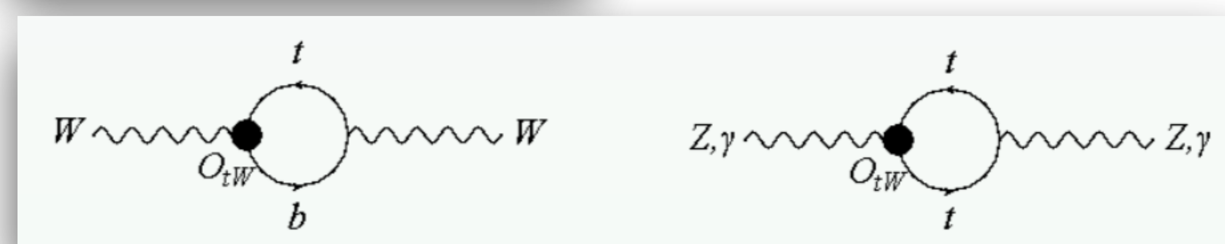


[1512.03360 A. Buckley et al.]

A. A global approach

- On going fitting program at the LHC
- More to add
- PEWM (improvement expected at future linear collider)





[1201.6670 CZ, Greiner, Willenbrock]

- Top loops mix into Dim-6 EW operators (S,T,…). Need a theory to renormalize.
- Degeneracies need to be resolved.
- This is done by doing a global fit and making use of the form factors induced by the loops.

Coefficients	Electroweak data
$\left(C_{\phi q}^{(3)} + C_{\phi q}^{(1)}\right)/\Lambda^2$	0.016 ± 0.021
$\left(C_{\phi q}^{(3)} - C_{\phi q}^{(1)}\right)/\Lambda^2$	2.0 ± 2.7
$C_{\phi t}/\Lambda^2$	1.8 ± 1.9
$C_{\phi b}/\Lambda^2$	-0.16 ± 0.10
$C_{\phi\phi}/\Lambda^2$	
C_{tW}/Λ^2	-0.4 ± 1.2
C_{bW}/Λ^2	11 ± 13
C_{tB}/Λ^2	4.8 ± 5.3
C_{bB}/Λ^2	8 ± 19

A. A global approach

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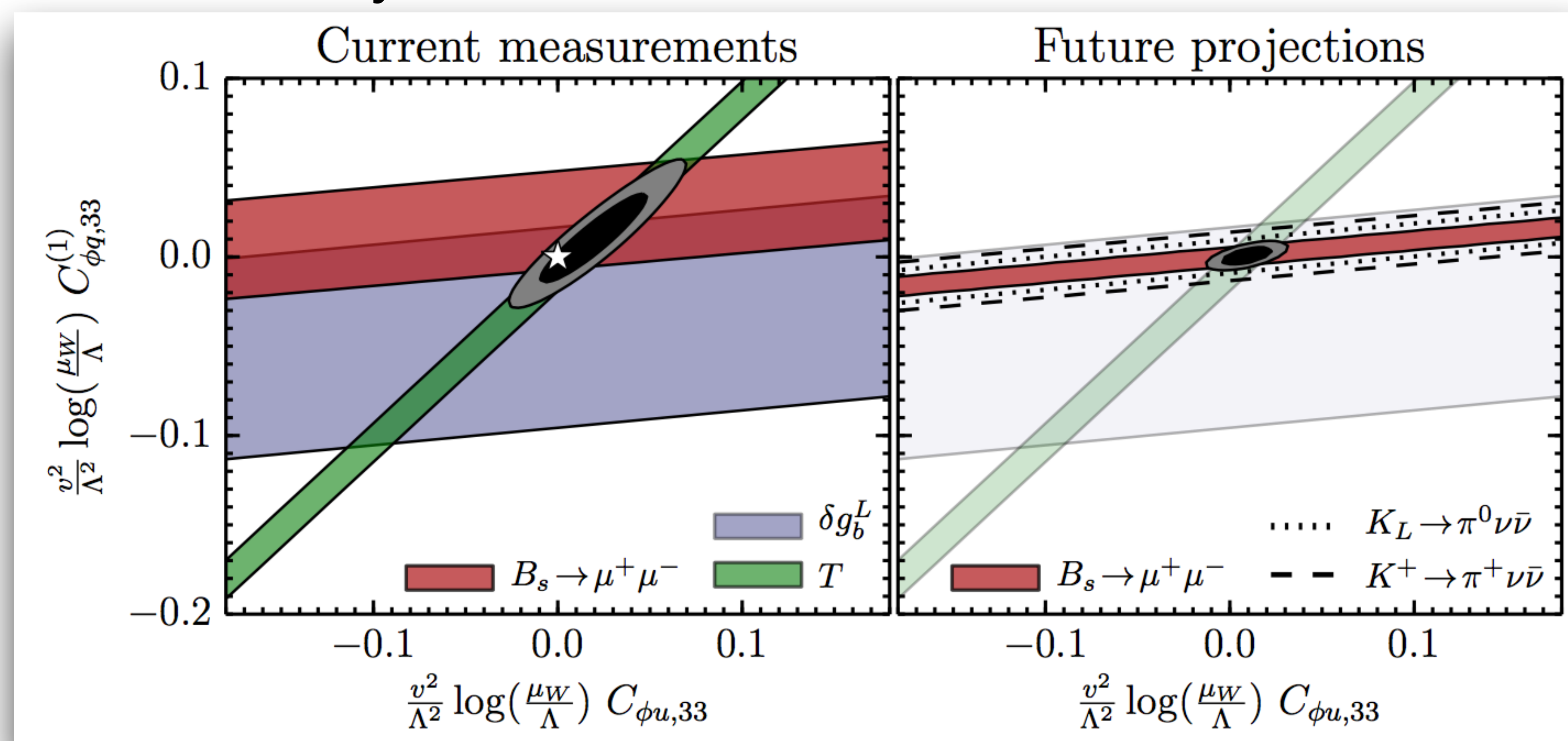
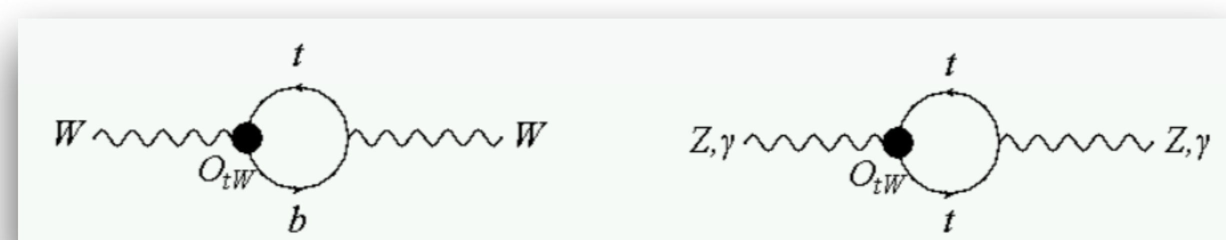
- Rare meson decays



[1408.0792 J. Brod et al.]

A. A global approach

- On going fitting program at the LHC
- More to add
- PEWM (improvement expected at future linear collider)
- Rare meson decays
- Future colliders: EFT allows for combining experiments that are
  - Performed at different scales and need RG running to be combined.
  - Probing indirect effect through loops, which can be consistently accommodated along with direct ones.



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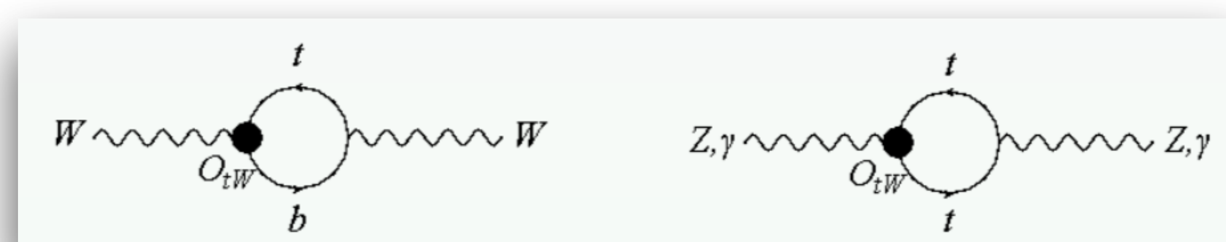

Use one framework, avoid specific underlying assumptions. Eventually everything can be combined.

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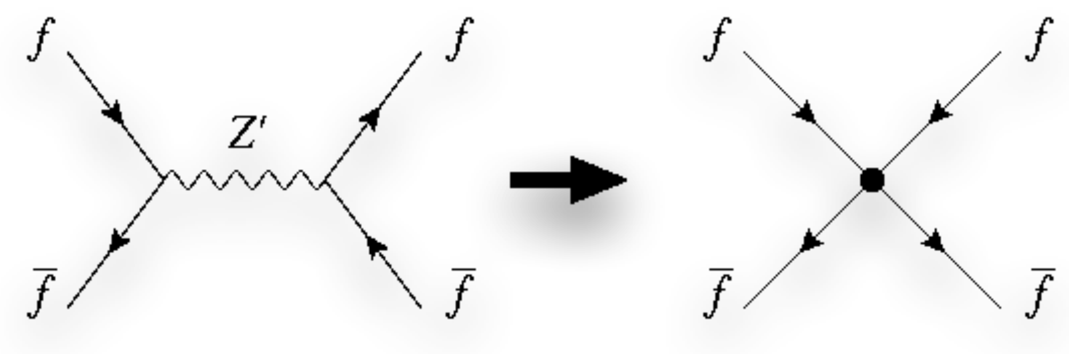
B. More than just "Anomalous Couplings"

- EFT may look less transparent BUT
  - Gauge invariance (requires tbWZ/γ, ttZH, etc., relevant in pp>tZ/γ, ee>ttH,…)
  - Consistently renormalizable, thus higher order possible
  - **More to explore.**
    - In particular, do not miss four-fermion operators in top-physics context!

B. More than just "Anomalous Couplings"



$$
\begin{aligned}
O_{lQ}^{(1)} &= (\bar{l}\gamma^{\mu} l)\,(\bar{Q}\gamma_{\mu} Q) \\
O_{eQ} &= (\bar{e}\gamma^{\mu} e)\,(\bar{Q}\gamma_{\mu} Q) \\
O_{lt} &= (\bar{l}\gamma^{\mu} l)\,(\bar{t}\gamma_{\mu} t) \\
O_{et} &= (\bar{e}\gamma^{\mu} e)\,(\bar{t}\gamma_{\mu} t)
\end{aligned}
$$

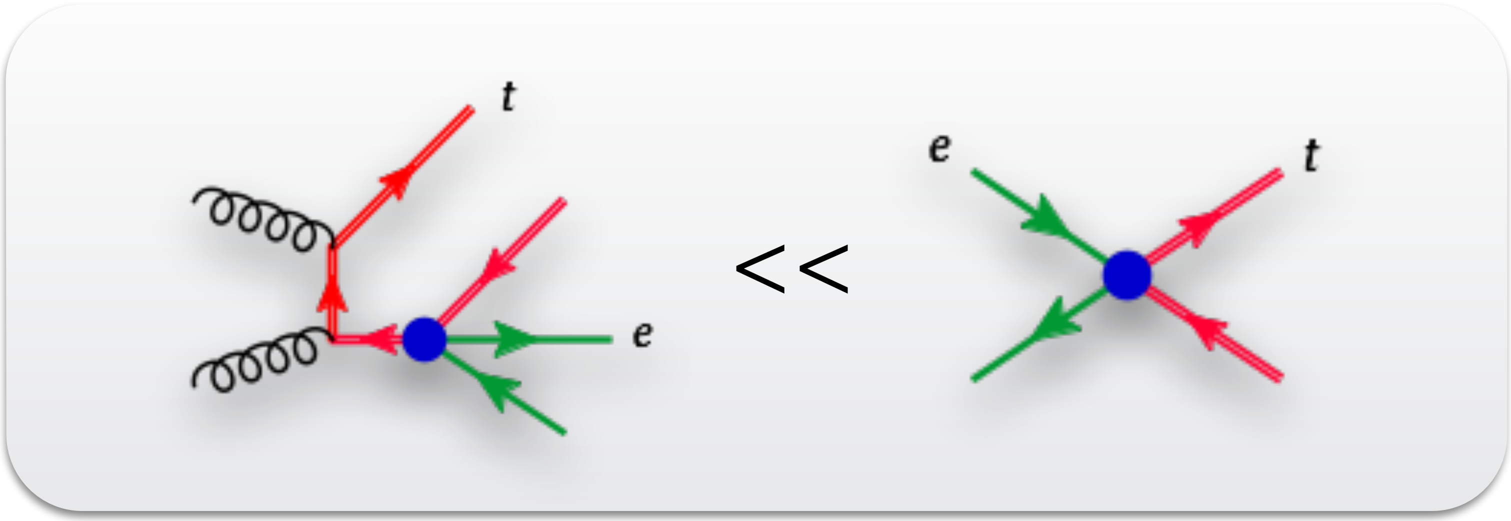
- The **four-fermion operators** are somewhat ignored the top physics. However they are well motivated:
  - BSM with heavy mediators generate 4-fs at tree level
  - Consistency: physically, there is not fundamental difference between 2-f vertices and 4-f contact interactions.
  - A complete characterization of BSM would always need all 4-f operators in any case.

[1008.3562 J. A. Aguilar-Saavedra]

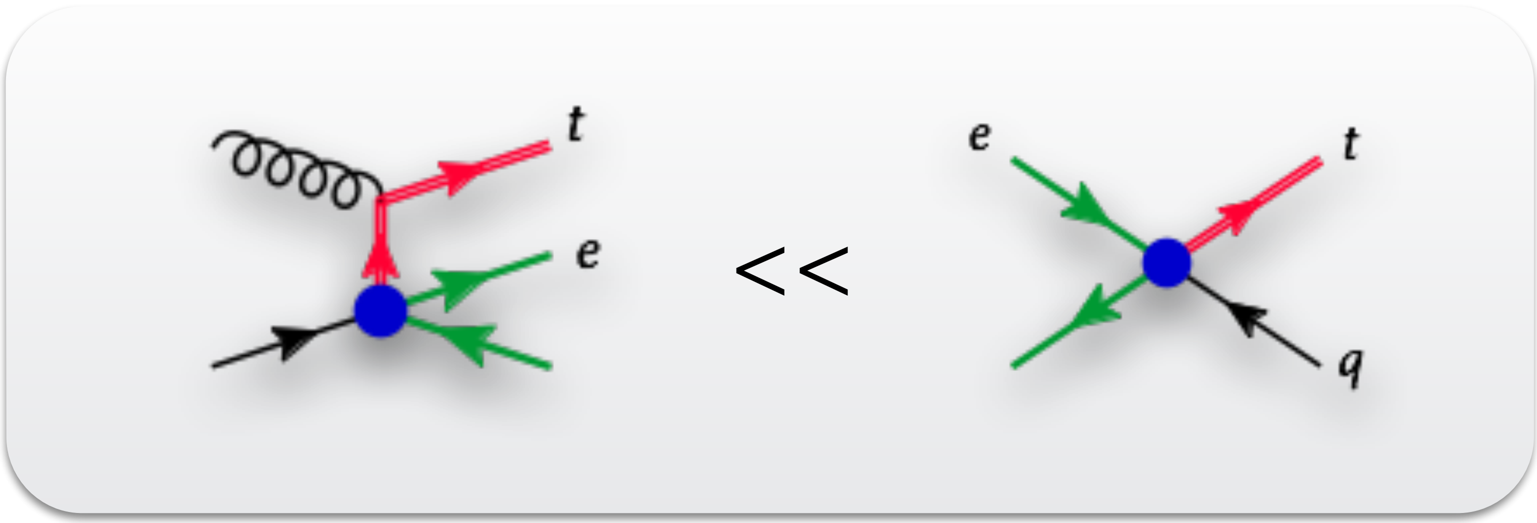
B. More than just "Anomalous Couplings"

LHC vs LC

Flavor-conserving case



Flavor-changing case



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C. Radiative corrections

Measured data is only meaningful if it is matched with theoretical calculation <u>at the same level of accuracy</u>

- Predictions systematically improvable.

$$\mathcal{O}(1) + \mathcal{O}(\alpha_s) + \mathcal{O}(1/\Lambda^2) + \mathcal{O}(\alpha_s/\Lambda^2) + \cdots$$

LO SM NLO SM LO EFT NLO EFT

- Precision efforts ongoing. *[G. Passarino 2012]* *[M. Ghezz et al. 2015]* *[R. Contino et al. 2014]* *[C. Hartmann, M. Trott 2015]* *[C. Hartmann, M. Trott 2015]*

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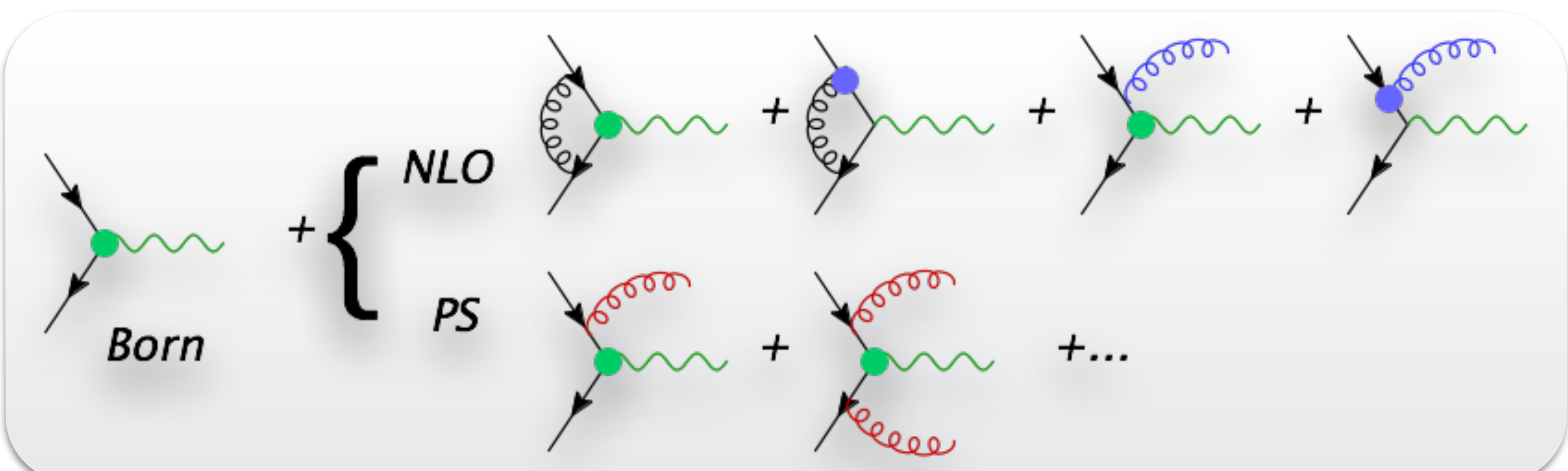
- Tools are becoming available.



being automated in MadGraph5_aMC@NLO

[1405.0301 J. Alwall et al.]

C. Radiative corrections

[1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou, CZ]

QCD corrections for top operators automated

Example #1:
tt production

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	virt	8	1	postscript	e- e+ > t t~ WEIGHTED=7 EFT=1 QED=2 [all = QCD]
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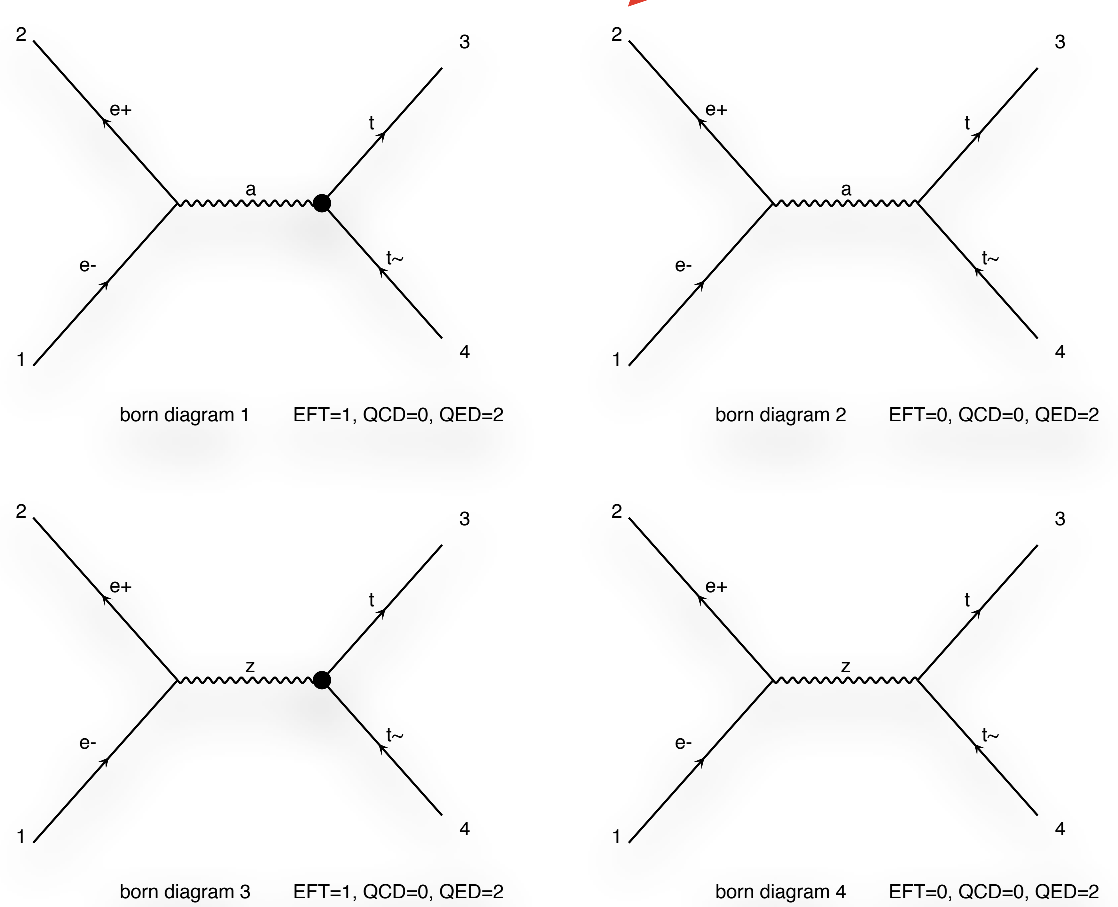

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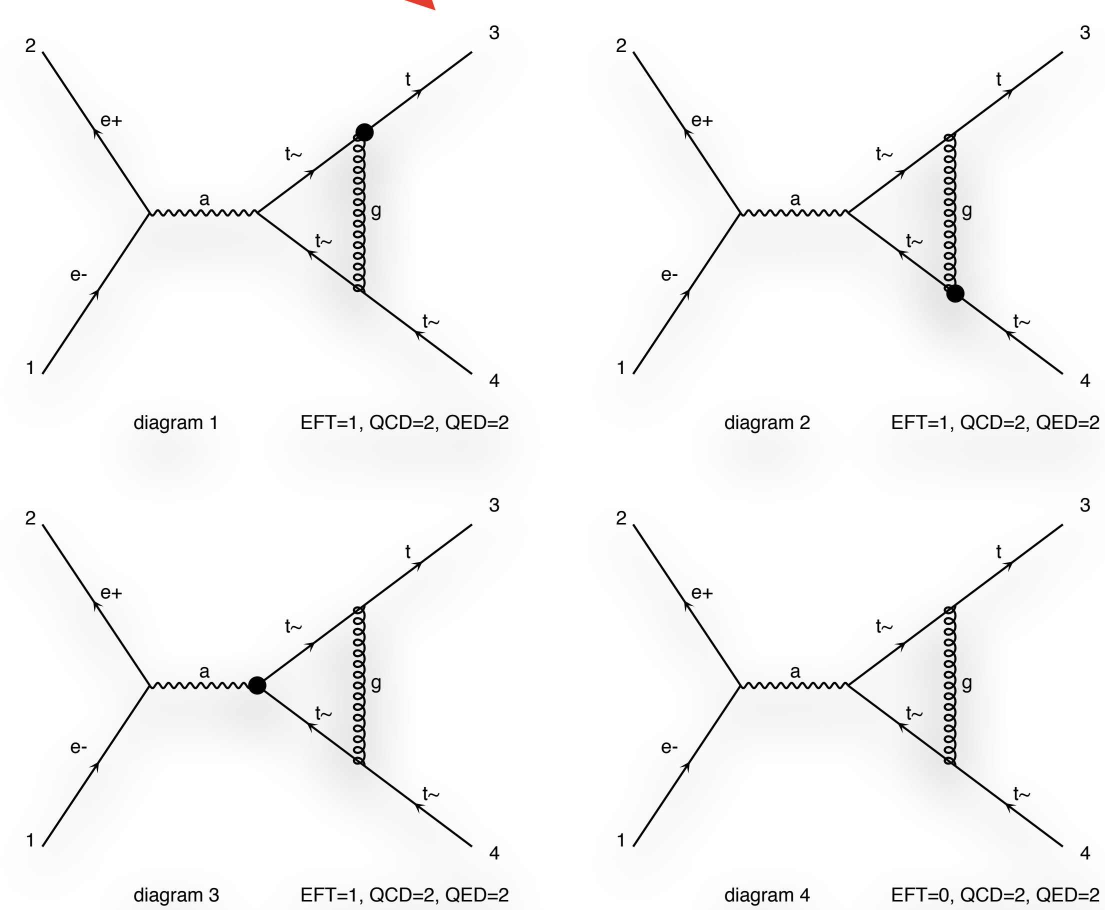

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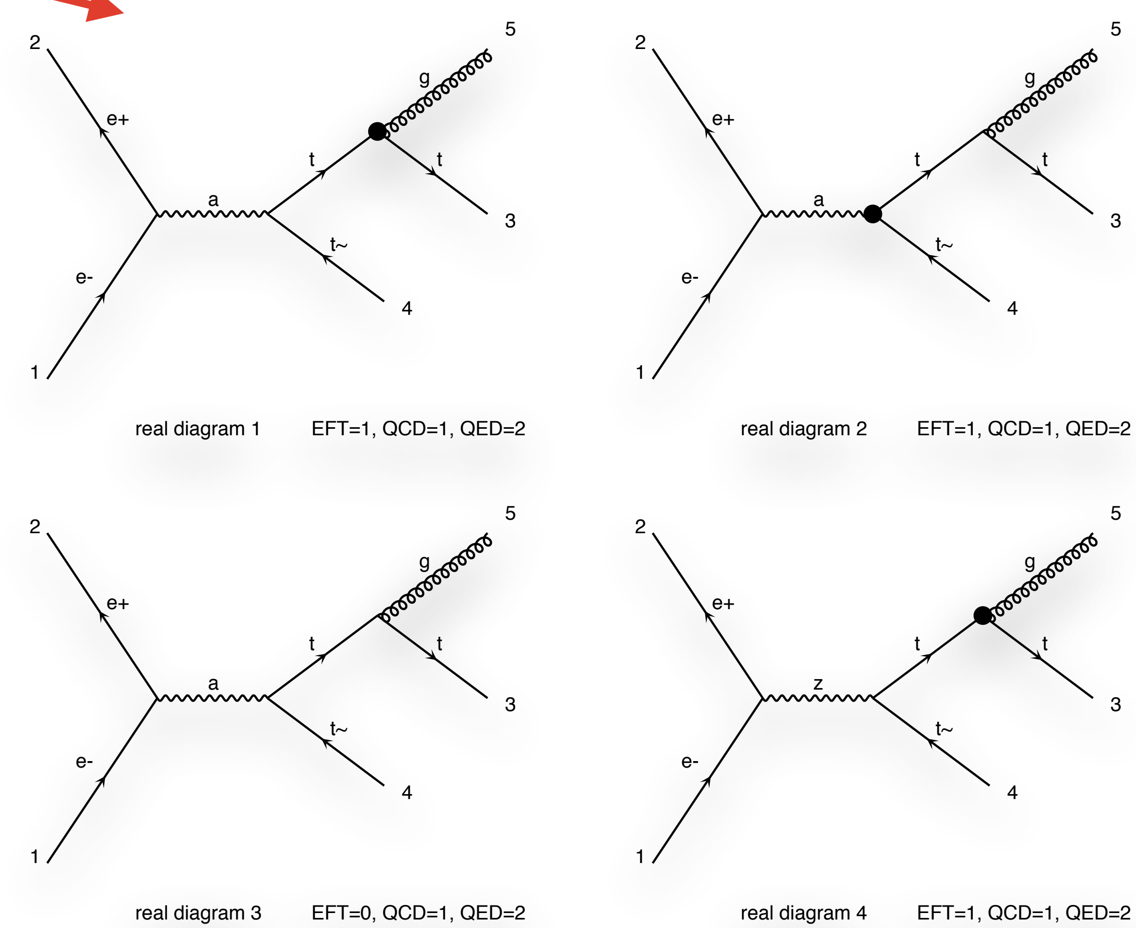

C. Radiative corrections

ee>tt at NLO up to dim-6

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\text{TeV})^2}\sigma_i^{(1)} + \sum_{i,j}^{j\geq i} \frac{C_i C_j}{(\Lambda/1\text{TeV})^4}\sigma_{ij}^{(2)}$$

500GeV	SM	$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi Q}^{(1)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{tB}$
$\sigma_{i,LO}^{(1)}$	566	0	15.3	-15.0	-1.3	273	191
$\sigma_{i,NLO}^{(1)}$	647	-6.3	18.3	-18.5	-0.94	307	216
K-factor	1.14	N/A	1.20	1.23	0.7	1.12	1.13
$\sigma_{i,LO}^{(1)}/\sigma_{SM,LO}$		0	0.03	-0.03	-0.0022	0.48	0.34
$\sigma_{i,NLO}^{(1)}/\sigma_{SM,NLO}$		0.01	0.03	-0.03	-0.0014	0.47	0.33
$\sigma_{i,LO}^{(2)}/\sigma_{i,LO}^{(1)}$		N/A	0.06	-0.06	-0.56	0.22	0.14
$\sigma_{i,NLO}^{(2)}/\sigma_{i,NLO}^{(1)}$		$\ll$	0.04	-0.05	-0.9	0.22	0.14

Cross sections (in fb) for $t\bar{t}$ production at the ILC at $\sqrt{s} = 500$ GeV.

[1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou ,CZ]

C. Radiative corrections

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	a		a	a				a	
$pp \to t\bar{q}$	A		A	A				A	
$pp \to tW$	A		A	A					
$pp \to t\bar{t}$	A							P	
$pp \to t\bar{t}\gamma$	A	A	A					P	
$pp \to t\gamma j$	A	A	A	A				P	
$pp \to t\bar{t}Z$	A	A	A	A	A	A		P	
$pp \to tZj$	A	A	A	A	A	A		P	
$pp \to t\bar{t}W$	A							P	
$e^+e^- \to t\bar{t}$	A	A	A	A	A	A		A	
$pp \to t\bar{t}H$	P						A	P	P
$pp \to tHj$	P		P	P			A	P	P
$gg \to H, Hj$	A						A		A
$gg \to HZ$	A			A	A	A	A		A

Table 1: Top-quark operators and key processes at the LHC, for the flavor-diagonal sector. Contributions which occur at the leading QCD order either at LO, or NLO, or through a top-quark loop, is marked by "a", "A" or "P". "a": result is known analytically; "A": NLO simulation within MG5_aMC is available; "P": NLO simulation is not available currently, but is planned. O_{4f} denotes any four-fermion operator.

[1601.03994 CZ]
and reference therein

Example #2:
ttZ production

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[1601.08193 Bylund, Maltoni, Tsinikos, Vryonidou ,CZ]

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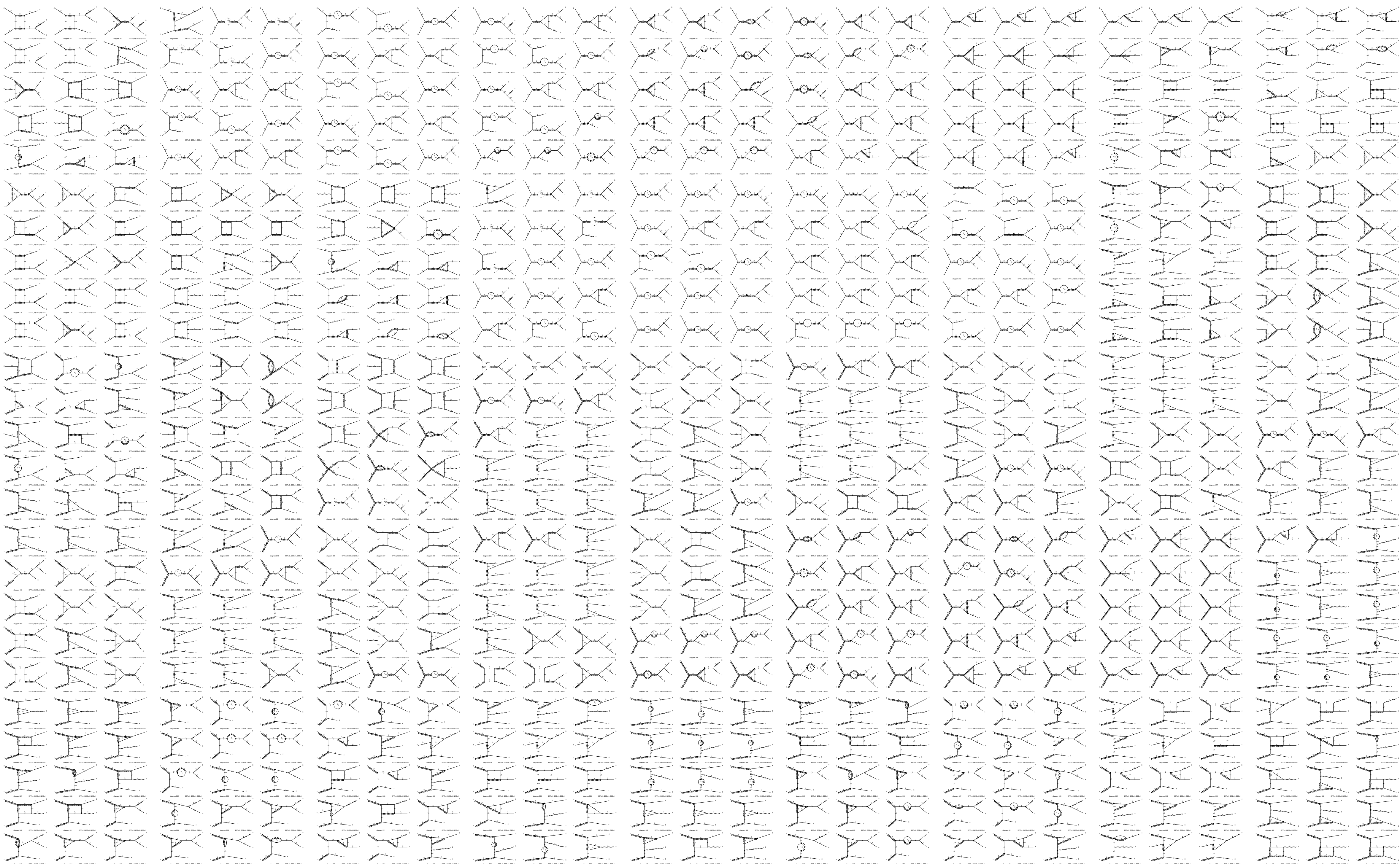
ttZ loops



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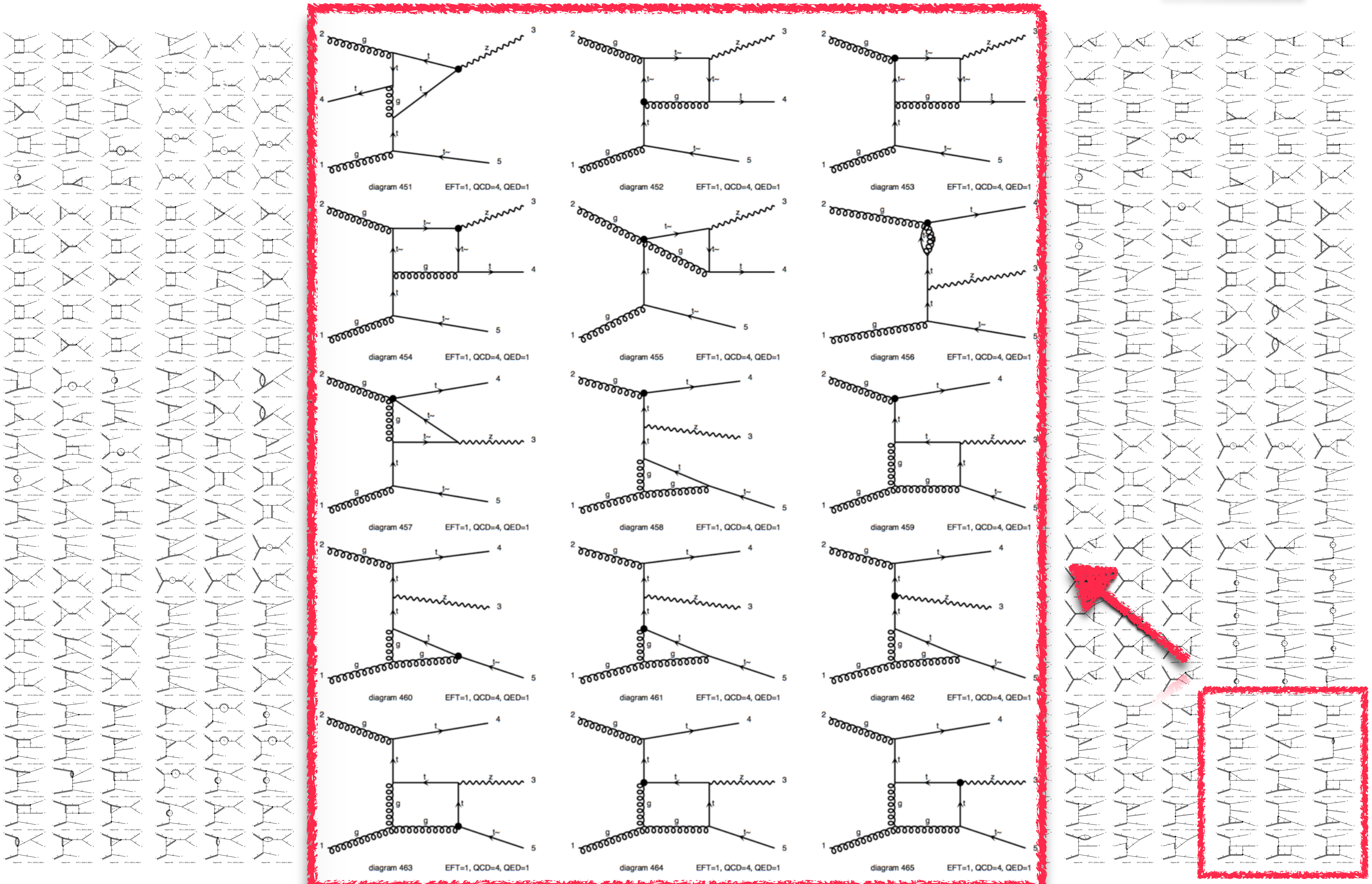

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C. Radiative corrections

EFT @ NLO:
we are not only advertising it as a possibility in principle; but we are making it possible in practice, in an automatic way, matched to MC generator, so that anyone can do NLO EFT in realistic analysis.

Top quark production

- $tt\gamma/ttg$, EM/color dipole

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu} \qquad O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$

- tbW
  - V/A

$$O^{(3)}_{\varphi Q} = i(\varphi^\dagger D_\mu \tau^I \varphi)(\bar{Q}\tau^I \gamma^\mu Q) \qquad O_{\varphi\varphi} = i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

  - Weak dipole

$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu} \qquad O_{bW} = (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

- ttZ
  - V/A

$$O^{(1)}_{\varphi Q} = i(\varphi^\dagger D_\mu \varphi)(\bar{Q}\gamma^\mu Q) \qquad O_{\varphi u} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu t)$$

  - Weak dipole O_{tW}

$$O^{(1)}_{lQ} = \left(\bar{l}\gamma^\mu l\right)\left(\bar{Q}\gamma_\mu Q\right)$$
$$O_{eQ} = \left(\bar{e}\gamma^\mu e\right)\left(\bar{Q}\gamma_\mu Q\right)$$
$$O_{lt} = \left(\bar{l}\gamma^\mu l\right)\left(\bar{t}\gamma_\mu t\right)$$
$$O_{et} = \left(\bar{e}\gamma^\mu e\right)\left(\bar{t}\gamma_\mu t\right)$$

- $t t\gamma / t t g$, EM/color dipole

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu} \qquad O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$

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no interference

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Constraints from

- Pair production

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Constraints from

- Pair production
- Decay (W-hel)

- $tt\gamma/ttg$, EM/color dipole

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu} \qquad O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi}G^A_{\mu\nu}$$

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Constraints from

- Pair production
- Decay (W-hel)
- Single top

- $t t\gamma/ttg$, EM/color dipole

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- Z>bb (LEP)

will continue to be improved
at future LC

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  - Weak dipole

no interference

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Constraints from
- Pair production
- Decay (W-hel)
- Single top
- Z>bb (LEP)

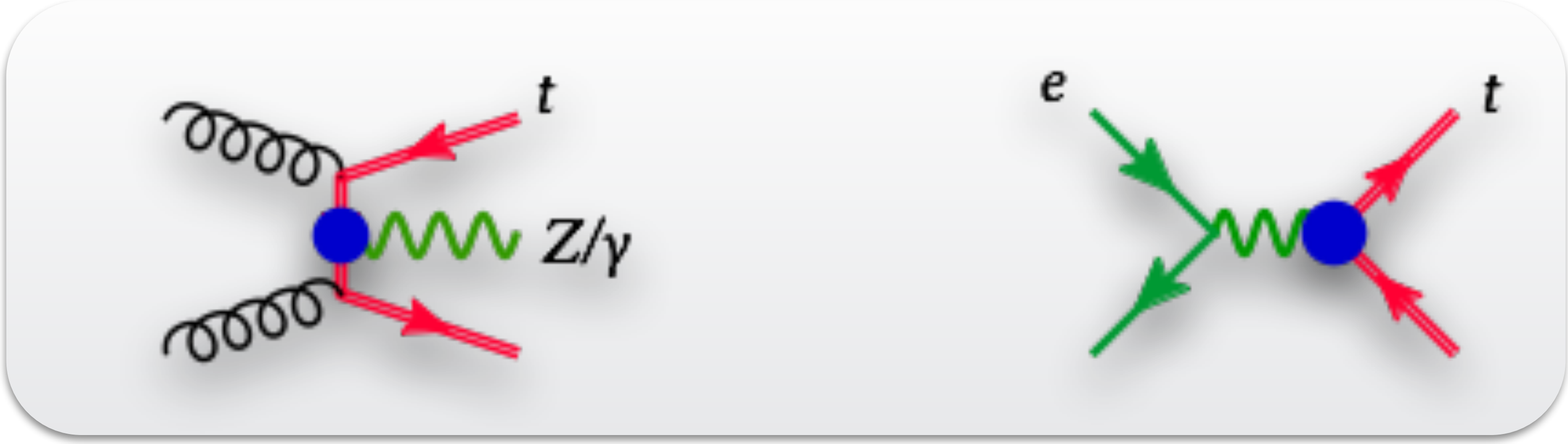
will continue to be improved at future LC

Neutral couplings can be constrained from ttZ and ttγ at the LHC, but
- Large uncertainties
- Much more sensitivity expected at future lepton colliders

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$\frac{2m_t}{\Lambda^2}\frac{e}{s_W c_W}\left(C_{tB}s_W^2\right)\sigma^{\mu\nu}q_\nu$$

LHC vs LC



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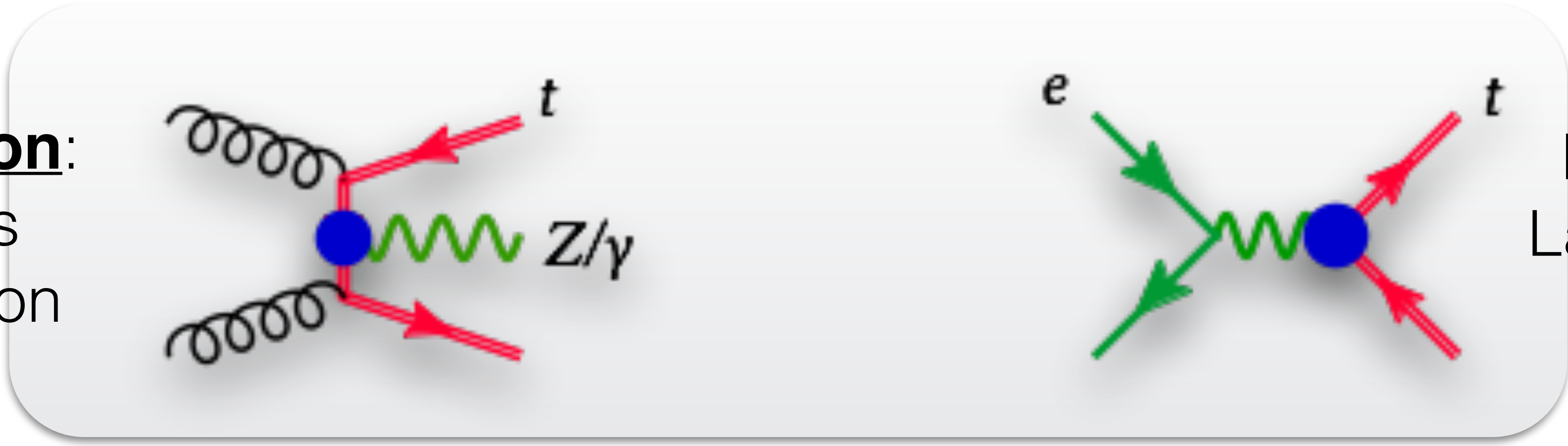
momentum plays an important role

LHC vs LC

Suppression:
SM favors
soft radiation



Enhancement:
Large momentum
guaranteed

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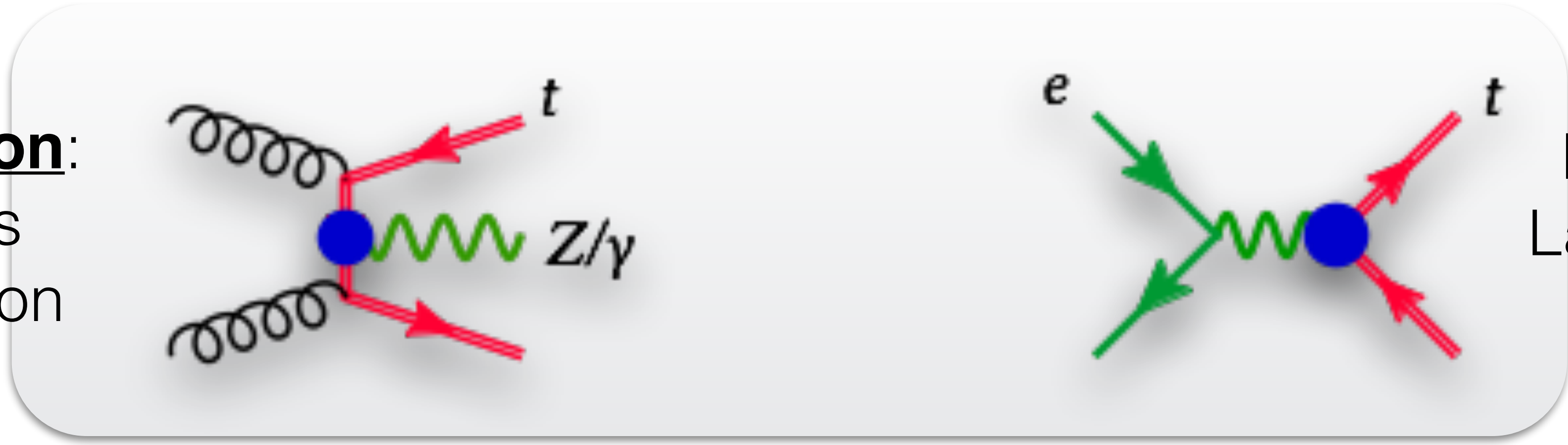

Enhancement:
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Four-fermion operators are similar

$$O_{lQ}^{(1)} = (\bar{l}\gamma^\mu l)\,(\bar{Q}\gamma_\mu Q)$$
$$O_{eQ} = (\bar{e}\gamma^\mu e)\,(\bar{Q}\gamma_\mu Q)$$
$$O_{lt} = (\bar{l}\gamma^\mu l)\,(\bar{t}\gamma_\mu t)$$
$$O_{et} = (\bar{e}\gamma^\mu e)\,(\bar{t}\gamma_\mu t)$$

Suppression:
Four-body production

Enhancement:
No propagator (s/m^2)

A comparison of HC and LC,
in terms of **"sensitivity"=$\sigma_{dim\text{-}6}/\sigma_{SM}$**
for C/Lamda^2 = 1 TeV^{-2}

Ops	PEWM bound	LHC $t\bar{t}l^+l^-$ (13 TeV)	LHC $tt\gamma$ (13 TeV)	LC $ee \to tt$ (500 GeV)
$O_{\phi t}$	[-3,7]	5%		-0.14%
O_{tB}	[-16,43]	0.1%(0.3%)	1%	33%
$O_{lQ}^{(1)}$		-1.7% (2.1%)		-468%
O_{eQ}		-0.4% (2.1%)		-190%
O_{lt}		-0.7% (2.1%)		-312%
O_{et}		-1.2% (2.1%)		-328%

proc.	TH	EXP	total
$pp \to t\bar{t}l^-l^+$	$\sim 10\%$	$\sim 15\%$	$\sim 20\%$
$pp \to t\bar{t}\gamma$	$\sim 15\%$	$\sim 25\%$	$\sim 30\%$
$e^-e^+ \to t\bar{t}$	$< 1\%$	$< 1\%$	$\sim 1\%$

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1. The way the contact operators are defined "eats" two weak couplings.
2. It also compensates the propagator suppression. Factor s/m^2 enhancement is expected.

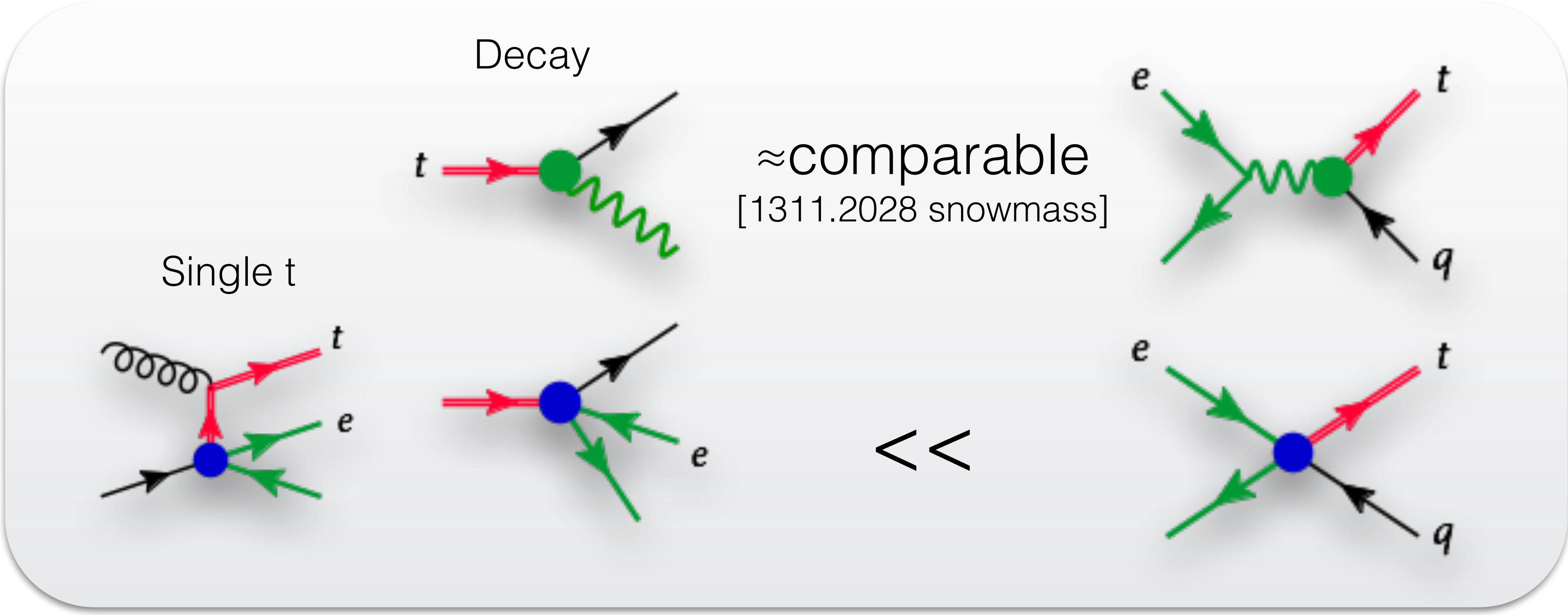
There are operators for which the sensitivities of LHC and LC are very different. They are particularly interesting in the FCC-ee context and we shouldn't miss them.

Top FCNC

LHC vs LC

2-fermion

4-fermion



See also Barbara Mele this talk

[1412.7166 Durieux, Maltoni, CZ]

Top FCNC

LHC vs LC

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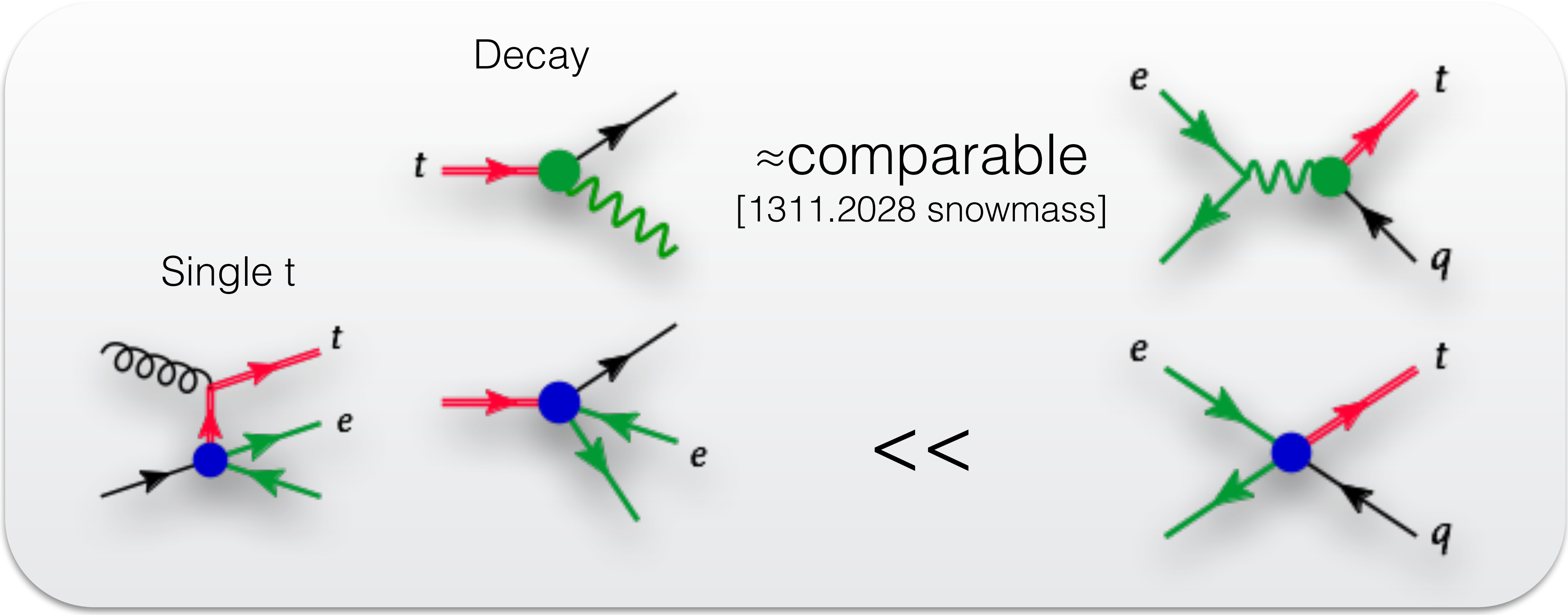

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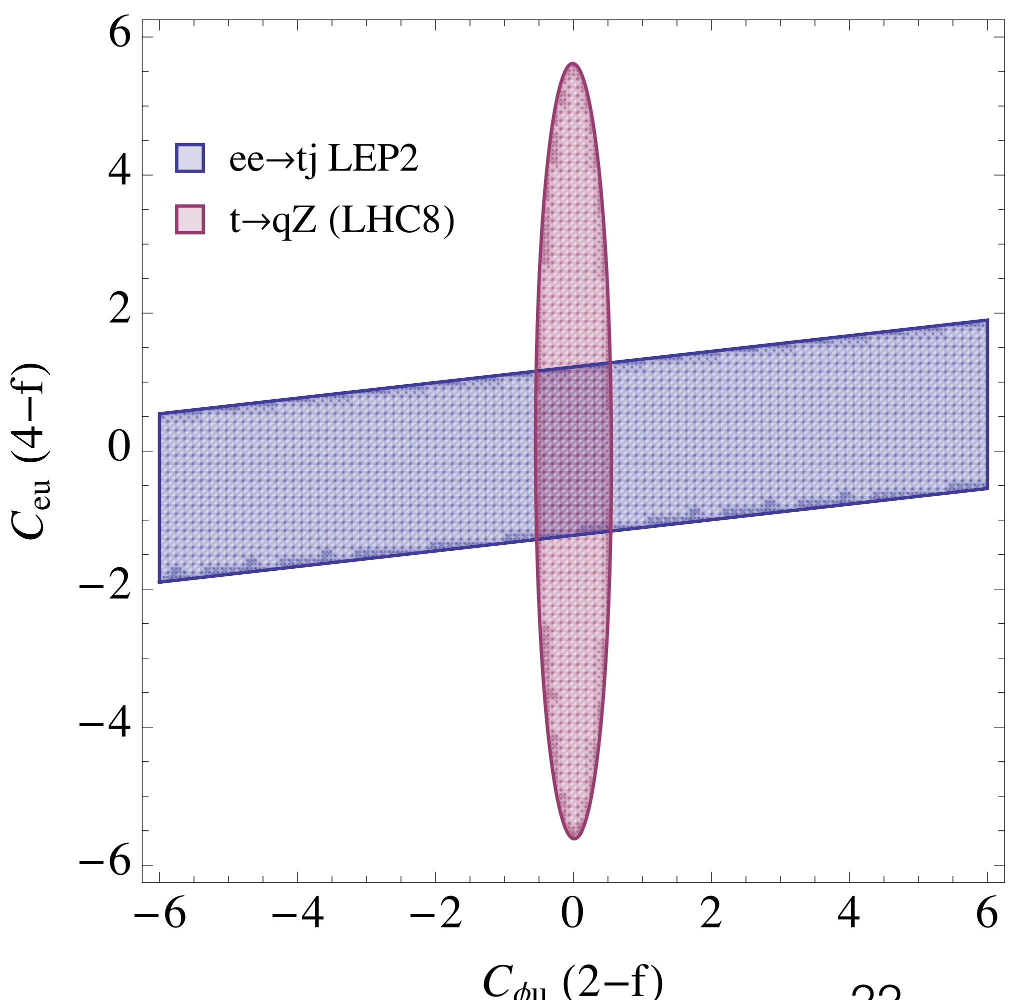
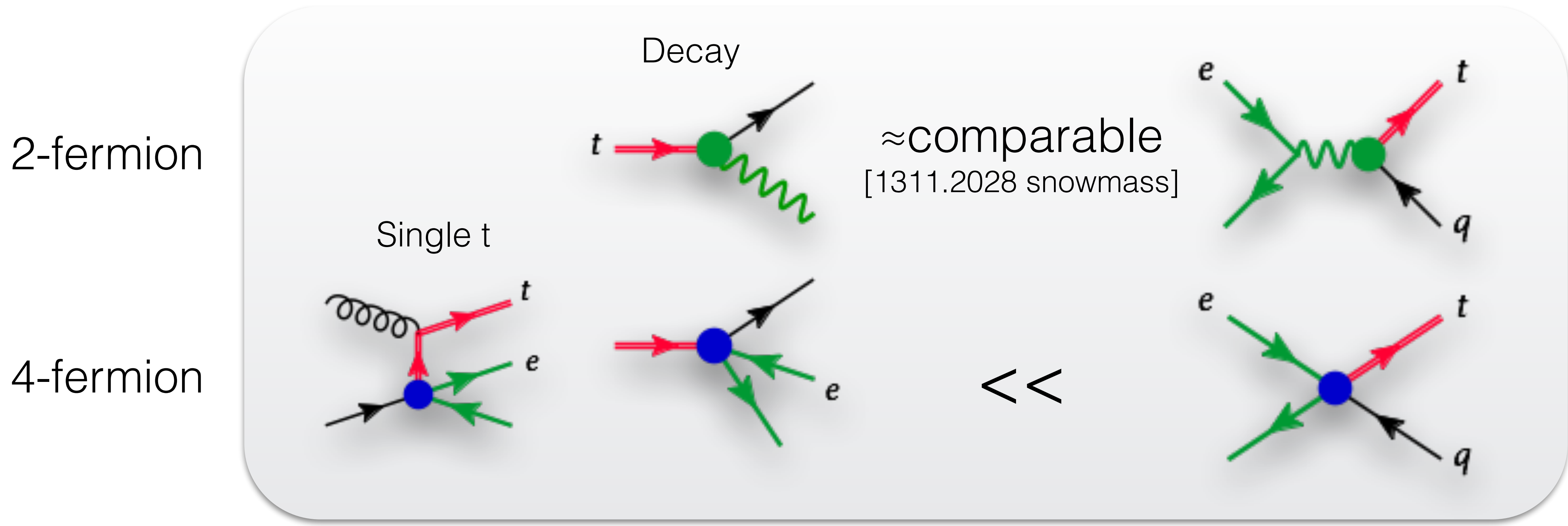
[1412.7166 Durieux, Maltoni, CZ]



Top FCNC

LHC vs LC



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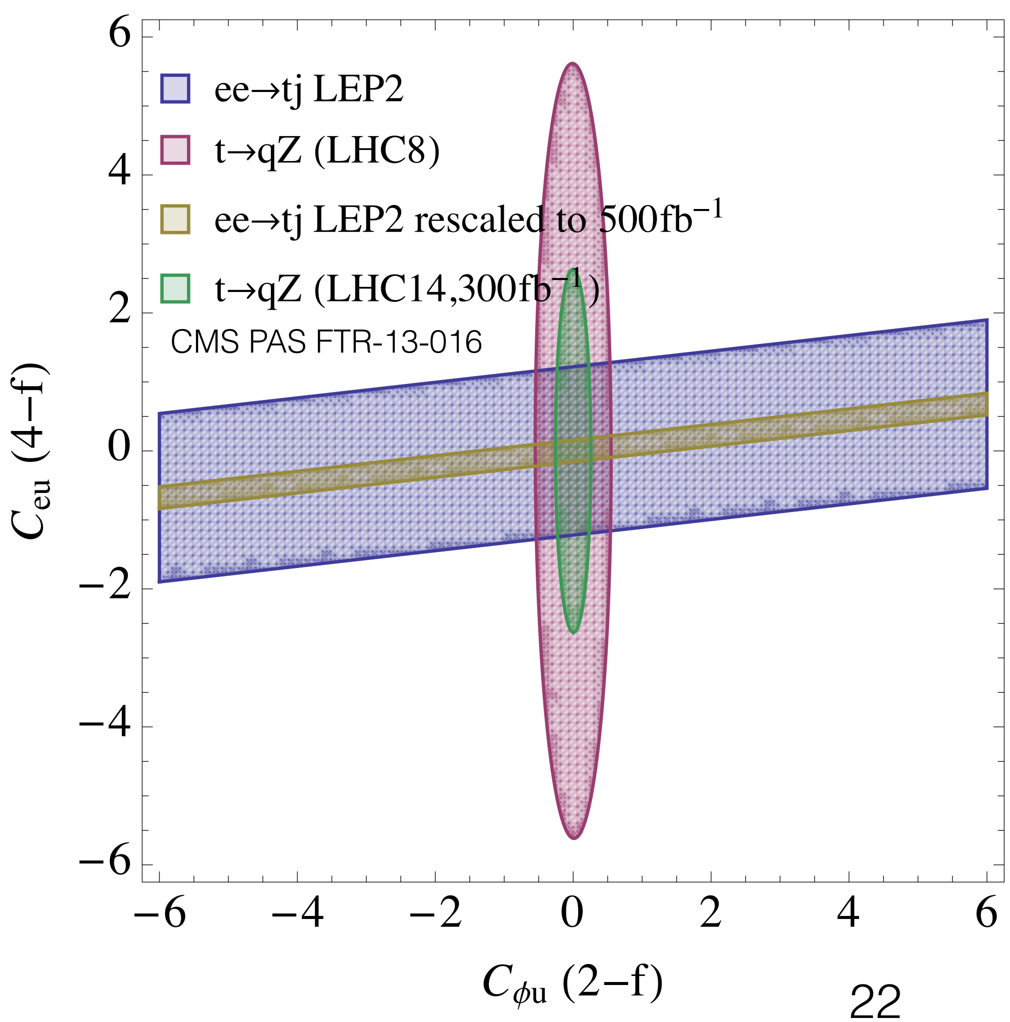
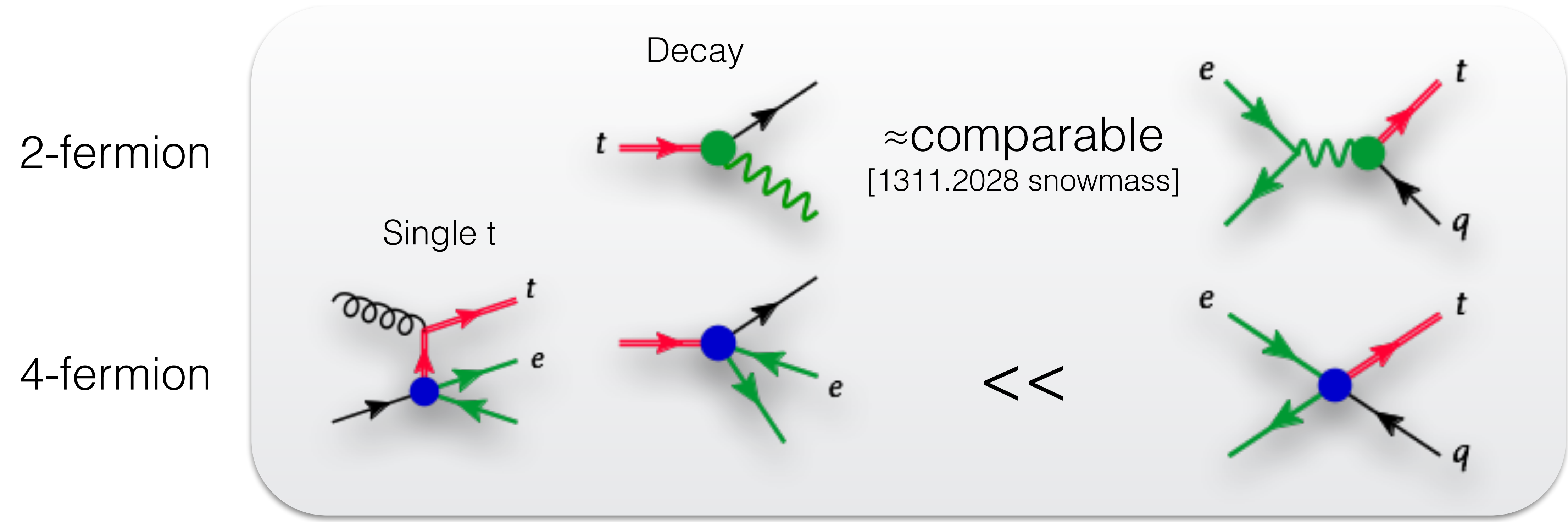


Top FCNC LHC vs LC



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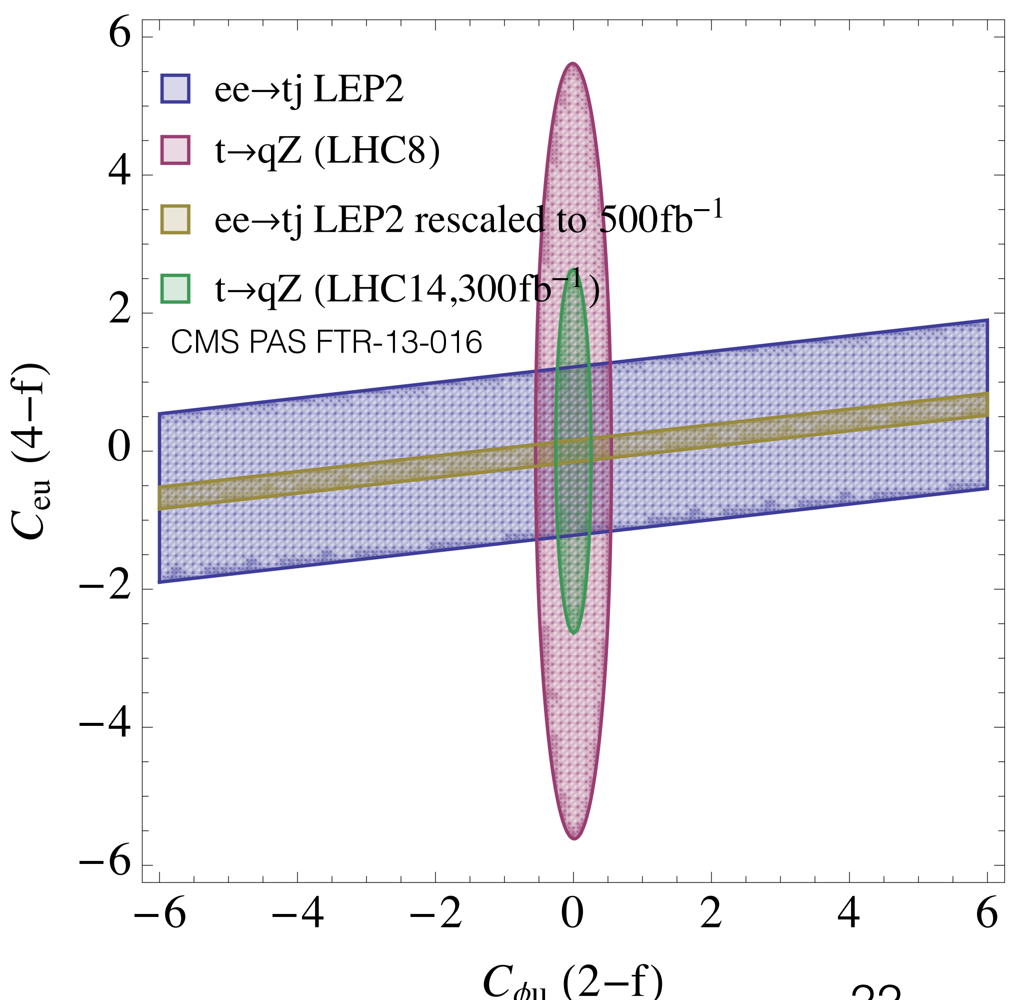
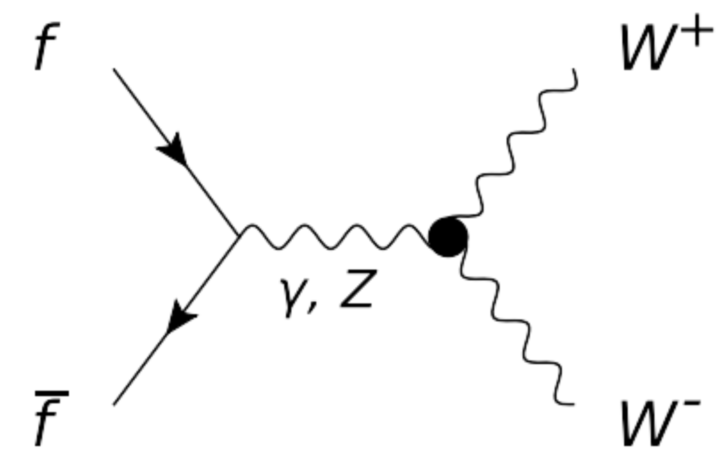


- In terms of both 2-f and 4-f, LEP2 and LHC are complementary
- Same for HL-LHC and future ee collider

W-pair production



CP-even

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$
$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi),$$

CP-odd

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu\Phi)^\dagger \tilde{W}^{\mu\nu}(D_\nu\Phi),$$

EW sector probed by PEWM+TGC+Higgs: 8+3+8

assuming flavor symmetry

1. PEWM (10^{-3})

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ (+) $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L\sigma^a\gamma^\mu L_L)\,(\bar{L}_L\sigma^a\gamma_\mu L_L)$
$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$
$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}^{(3)\,q}_L = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$

Mainly from Z-pole: only 8 d.o.f
(10 would appear in BW/Warsaw)

[A. Falkowski and F. Riva 2014]

2. TGC (10^{-2})

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$ (-) $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$
$\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon_{abc}W^{a\,\nu}_{\mu}W^b_{\nu\rho}W^{c\,\rho\mu}$

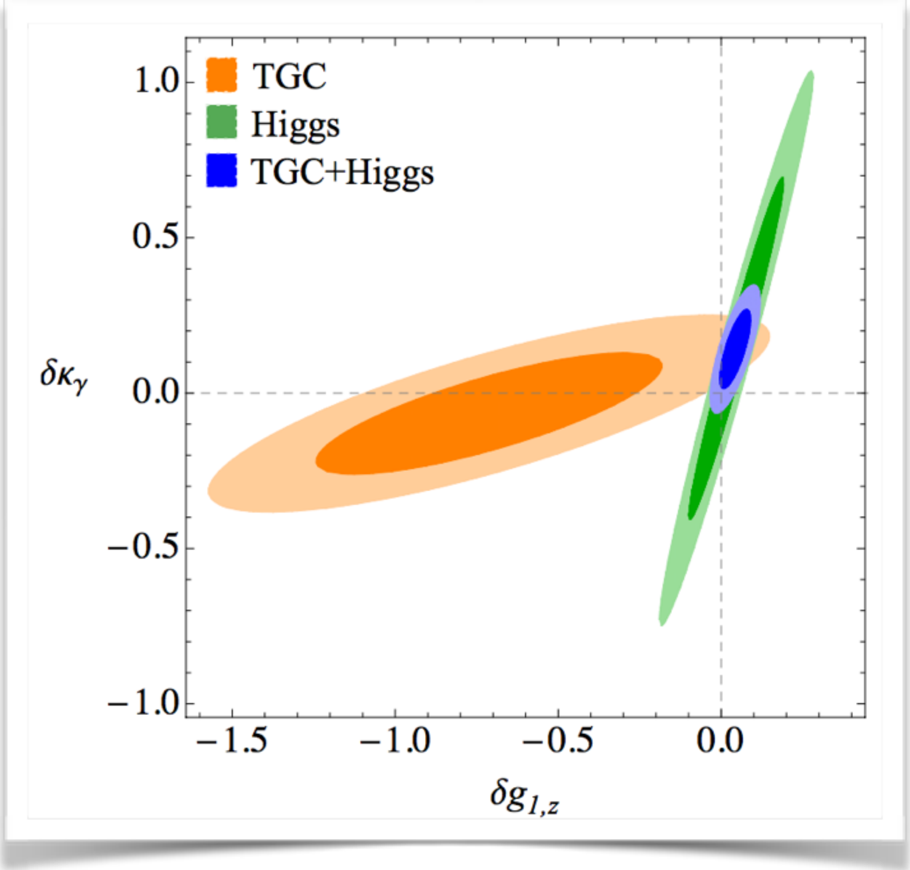
W-pair production: $g_1^Z,\ \kappa_\gamma,\ \lambda_Z$

- In principle, WW also test 4 more parameters, from the PEWM class.
- They decouple because at LEP, they are measured with ~O(10) better accuracy.
- However this may change in future.

3. New from Higgs

$\mathcal{O}_H = [\partial_\mu(H^\dagger H)]^2$
$\mathcal{O}_{BB} = \frac{g'^2}{4}\|H\|^2 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{WW} = \frac{g^2}{4}\|H\|^2 W^a_{\mu\nu}W^{a\mu\nu}$
$\mathcal{O}_{GG} = \frac{g_s^2}{4}\|H\|^2 G^A_{\mu\nu}G^{A\mu\nu}$
$\mathcal{O}_{y_u} = y_u\|H\|^2\bar{Q}_L\widetilde{H}u_R$
$\mathcal{O}_{y_d} = y_d\|H\|^2\bar{Q}_L H d_R$
$\mathcal{O}_{y_e} = y_e\|H\|^2\bar{L}_L H e_R$
$\mathcal{O}_6 = \lambda\|H\|^6$

[A. Falkowski et al. 2015]



"Accidental flat direction"

$$\delta g_{1,Z} = -0.83 \pm 0.34,\ \delta\kappa_\gamma = 0.14 \pm 0.05,\ \lambda_Z = 0.86 \pm 0.38,$$

$$\rho = \begin{pmatrix} 1 & -0.71 & -0.997 \\ \cdot & 1 & 0.69 \\ \cdot & \cdot & 1 \end{pmatrix}$$

[1411.0669 Falkowski and Riva]

To lift the degeneracy,

- Add Higgs data
- Use polarized beam
- Go to higher energy

200 GeV

$$\bar{\delta}^{\rm NP}\sigma_L = 0.0192(c_{HW} + c_W) + 0.00345(c_{HW} + c_{HB} - 4c_{WB}) + 0.00667 c_{3W}$$

$$\bar{\delta}^{\rm NP}\sigma_R = -1.32(c_{HW} + c_W) + 0.640(c_{HW} + c_{HB} - 4c_{WB}) - 0.0898 c_{3W}$$

500 GeV

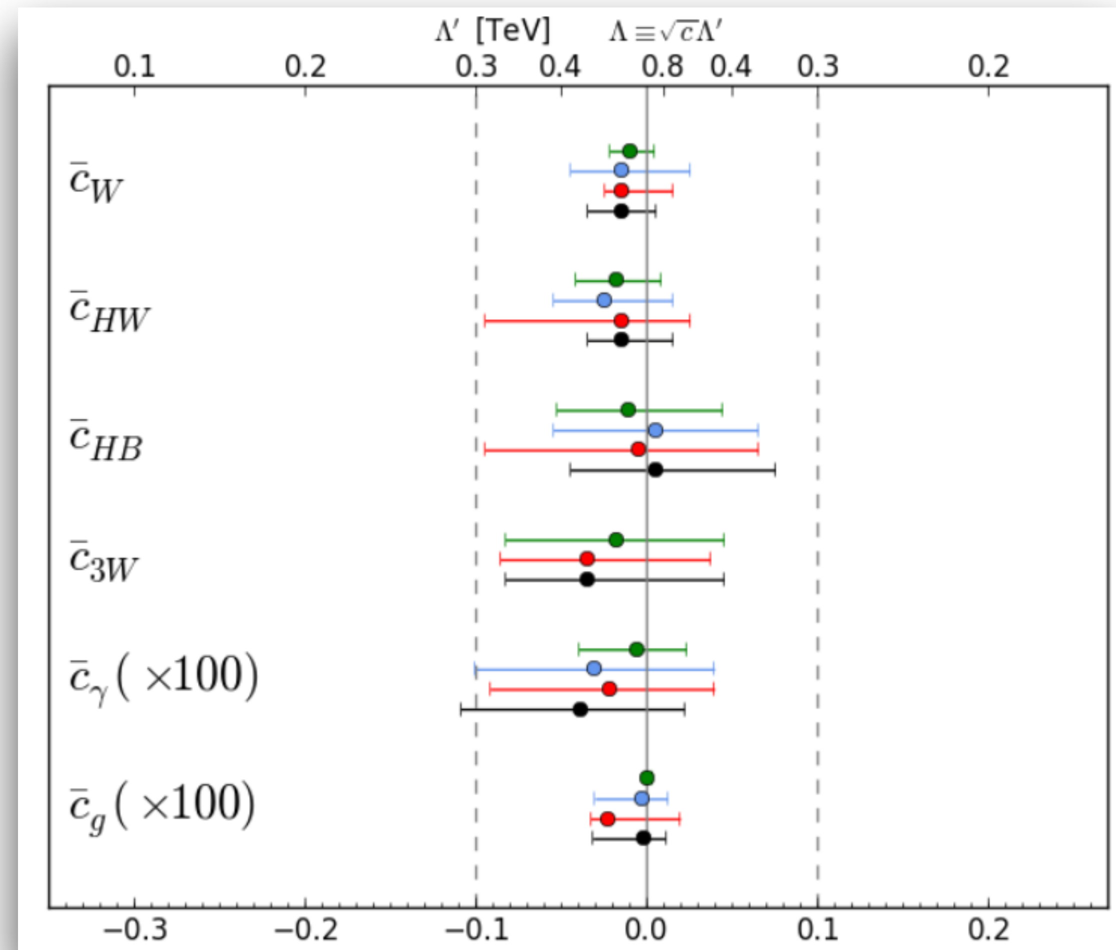
$$\bar{\delta}^{\rm NP}\sigma_L = 0.0835(c_{HW} + c_W) + 0.0277(c_{HW} + c_{HB} - 4c_{WB}) + 0.0191 c_{3W}$$

$$\bar{\delta}^{\rm NP}\sigma_R = -8.25(c_{HW} + c_W) + 6.64(c_{HW} + c_{HB} - 4c_{WB}) - 0.0426 c_{3W}$$

[1507,01594 D. Wells and Z. Zhang]

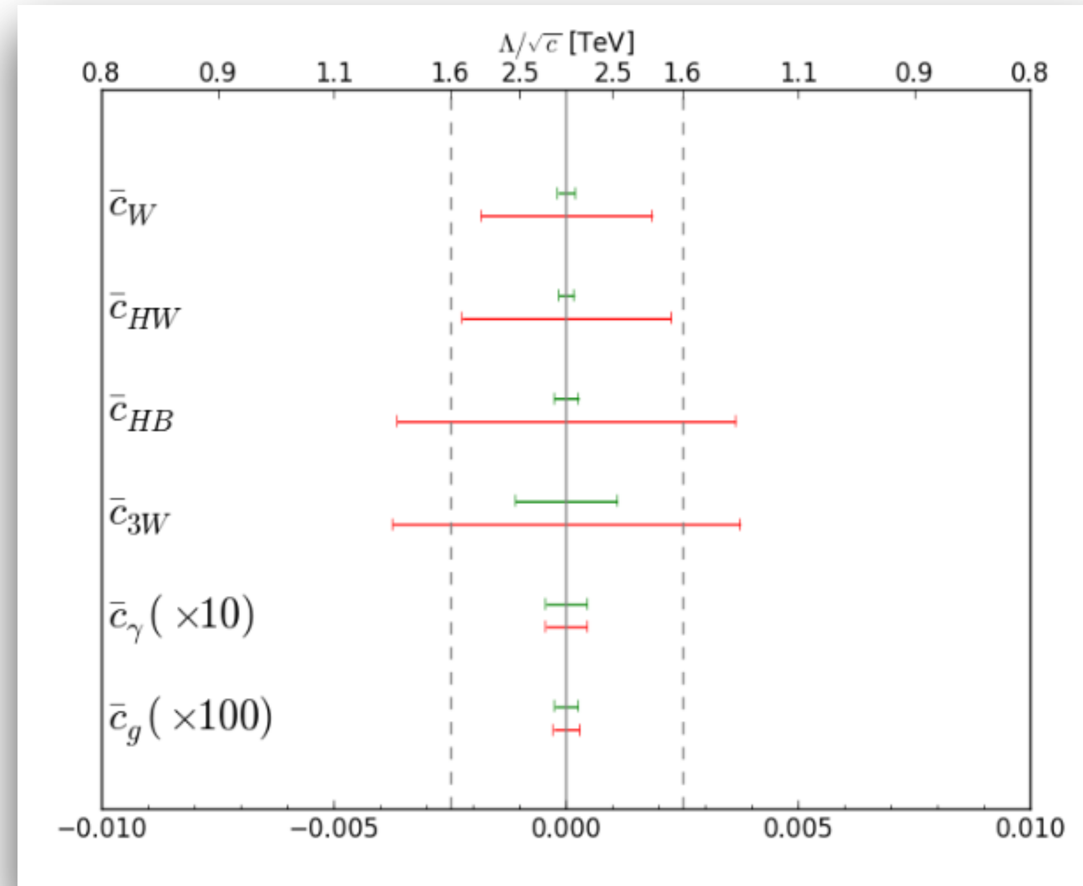
LHC current status

[1404.3667,1410.7703 Ellis, Sanz, You]



FCC-ee projection

[1510.04561 Ellis, You]



Higgs, TGC, combination

O(10^2) improvement

single, marginalized

ILC projection
[1506.07830 Barklow]
[J. List]

g_1^Z	8.5×10^{-4}
κ_γ	9.2×10^{-4}
λ_γ	7×10^{-4}

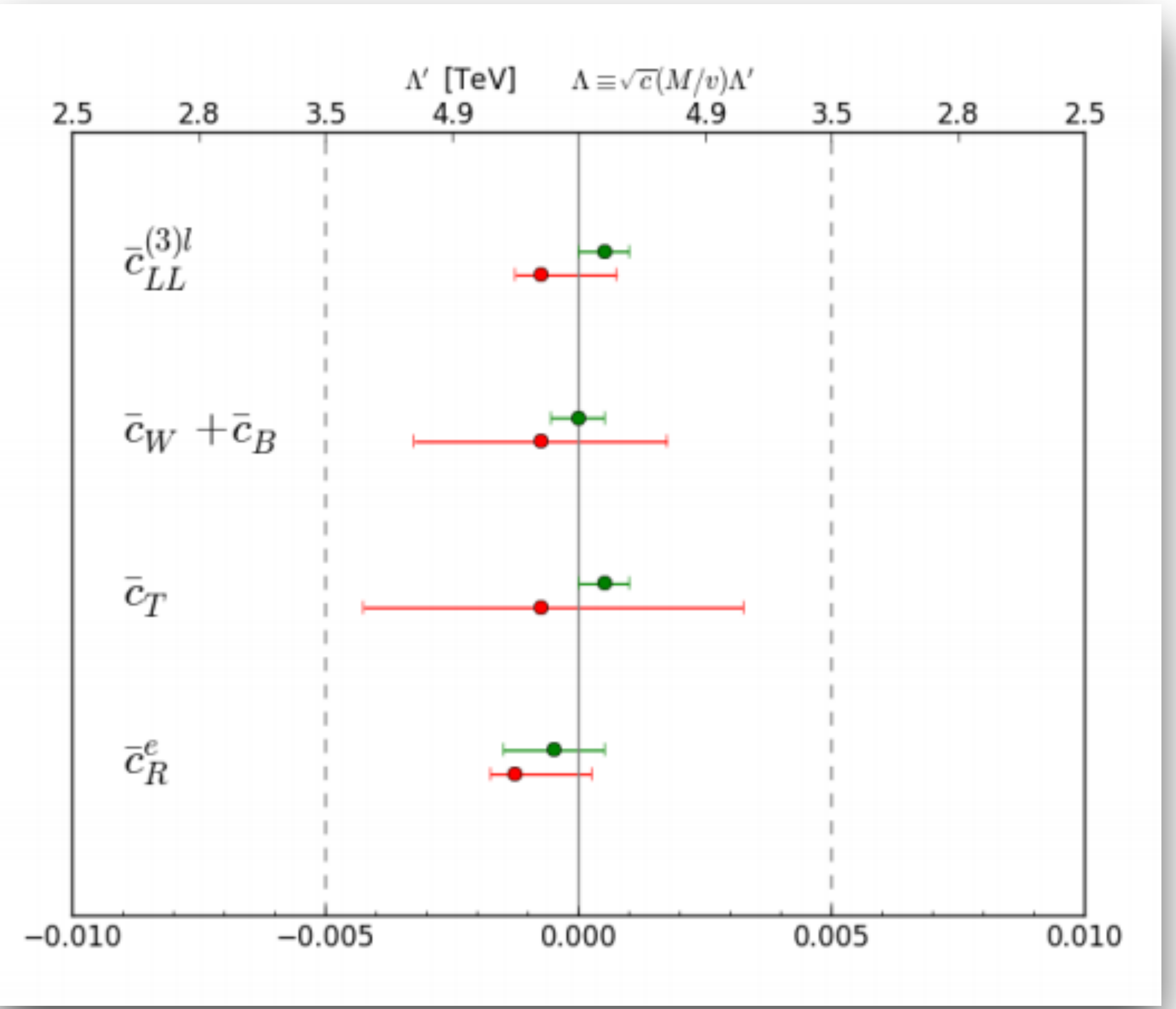
Summary

- EFT approach to top/W physics at future linear colliders.
- In EFTheorests' mind, one should make the most use of SM EFT, by
  - Taking it as a global approach, include current and future measurements in one framework.
  - Apart from anomalous couplings, investigating all possible SM deviations, in particular 4-fermions are very interesting in this context.
  - Including higher-order corrections in EFT are becoming available. More than just a "possibility in principle", but will become possible for anybody in any analysis.

Thank you for your attention

LHC current status

[1404.3667,1410.7703 Ellis, Sanz, You]



FCC-ee projection

[1510.04561 Ellis, You]