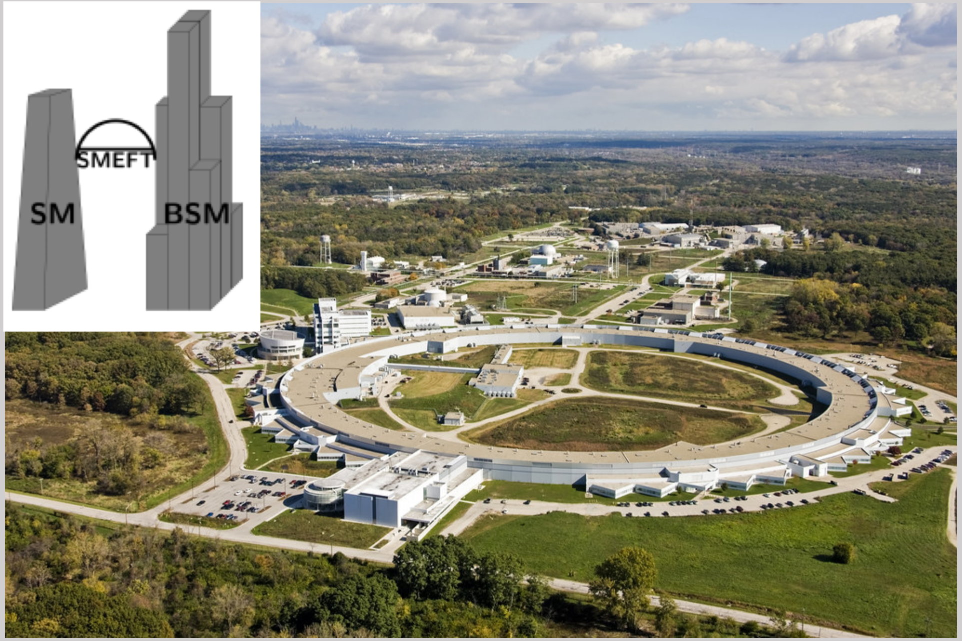
Four-Fermi Operators, Chirality and γ_5 in SMEFT

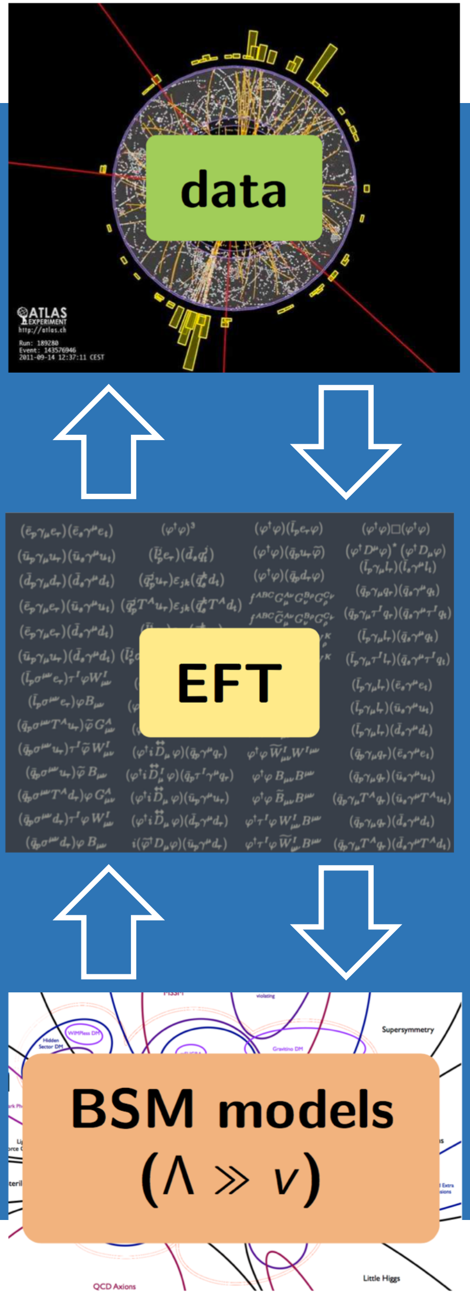
Daniel Wiegand
Northwestern University/Argonne National Lab
@In Search of New Physics using SMEFT



Based on:

Boughezal/Chen/Petriello/DW - (arXiv: 1907.00997)

The Why, the What and the How



- the Why
  - **No smoking gun(s) at LHC**
  - Standard Model Effective Theory (**SMEFT**) is a systematic way to combine and analyze data and look for New Physics in a model-independent way
  - **Radiative Corrections** increase precision and open up **new operators**

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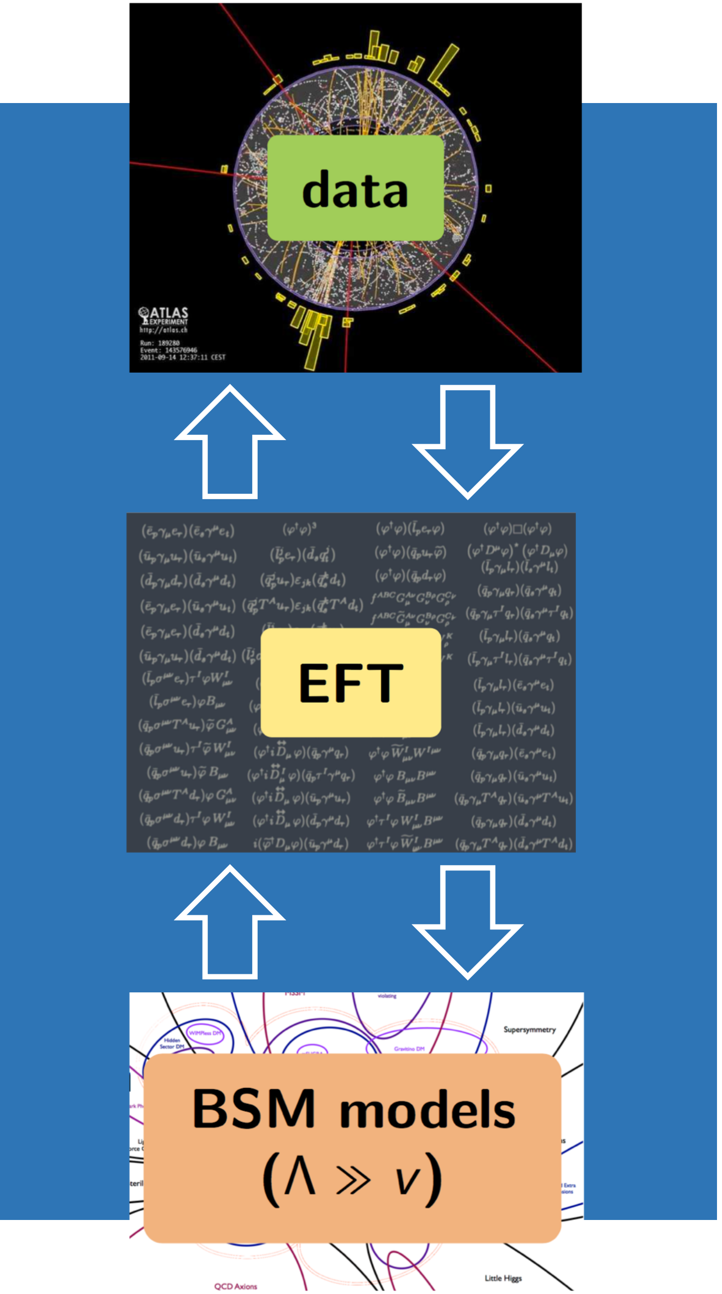

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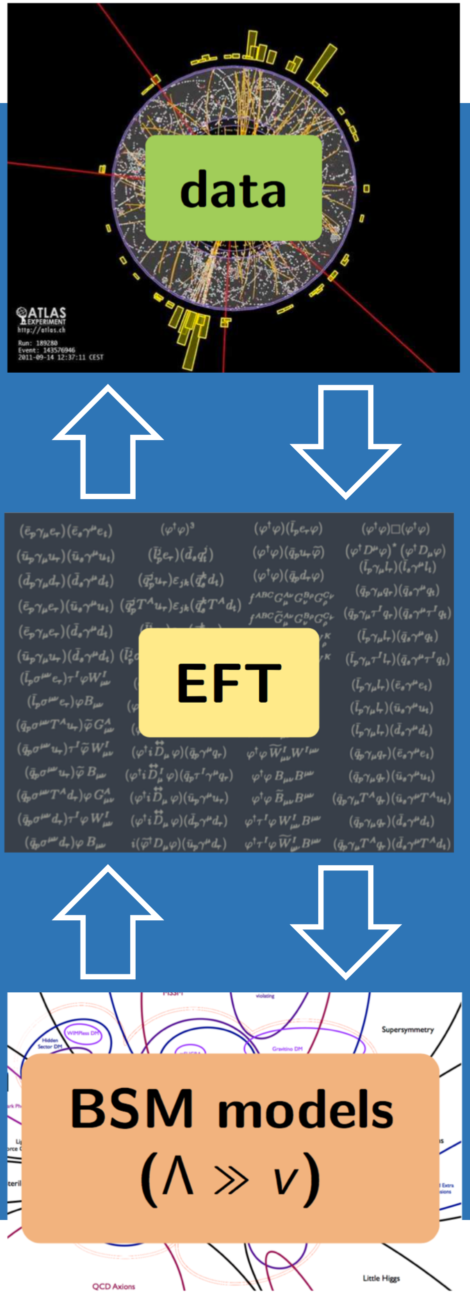
○ the What

- Four-Fermi Operators often neglected outside tree-level analysis
- Chirality structure different from SM ⟹ Need consistent γ_5 **prescription**

The Why, the What and the How



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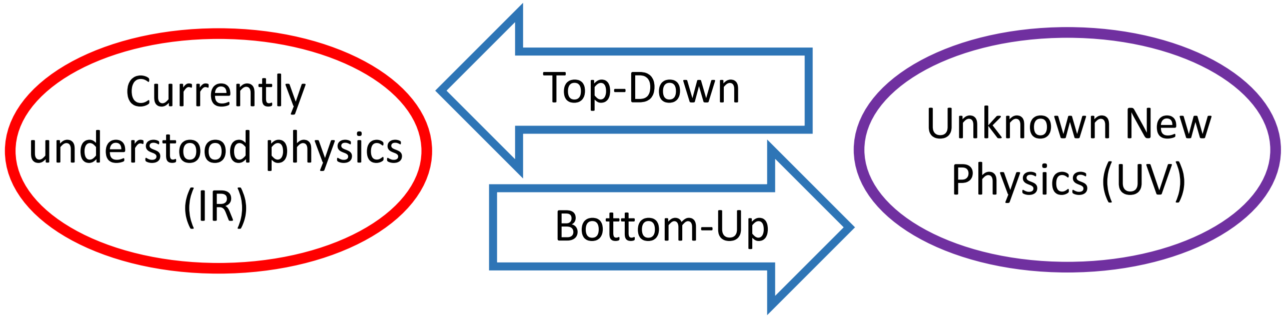
- the What
  - Four-Fermi Operators often neglected outside tree-level analysis
  - Chirality structure different from SM $\Rightarrow$ Need consistent $\boldsymbol{\gamma_5}$ **prescription**
- the How
  - (For now) simple **Charged/Neutral Current** processes:

    $\Rightarrow$ Simple enough to set up technology but still relevant
  - Make predictions in terms of new operators

    $\Rightarrow$ Constrain through Data

SMEFT - The Basic Idea



Write down all possible operators that new physics could induce

- Stay consistent with SM **symmetries**!
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$$\mathcal{L}_{SMEFT} \supset \underbrace{\mathcal{L}_{SM} + \frac{C_5}{\Lambda}\mathcal{O}^5 + \frac{C_6^i}{\Lambda^2}\mathcal{O}_i^6}_{\text{Focus at 1-loop/Dim-6 for now}} + \frac{C_7^i}{\Lambda^3}\mathcal{O}_i^7 + \cdots$$

SMEFT - The Basic Idea

$1 : X^3$		$2 : H^6$		$3 : H^4 D^2$		$5 : \psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						

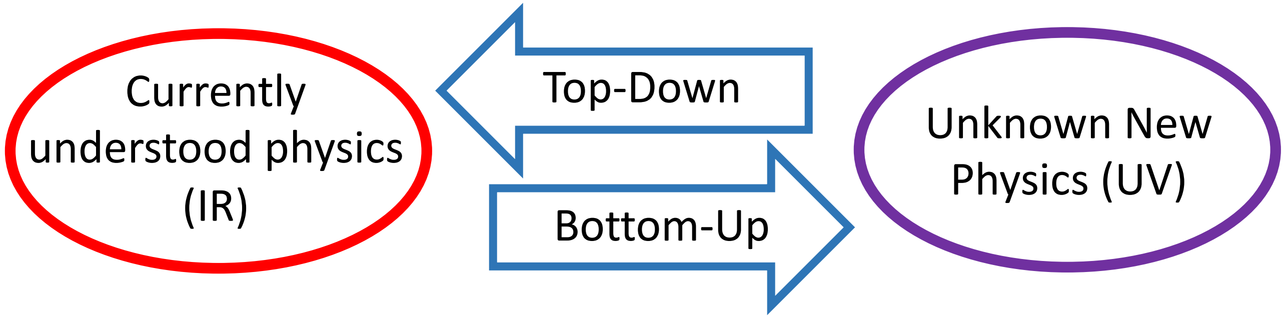
$4 : X^2 H^2$		$6 : \psi^2 X H + \text{h.c.}$		$7 : \psi^2 H^2 D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8 : (\bar{L}L)(\bar{L}L)$		$8 : (\bar{R}R)(\bar{R}R)$		$8 : (\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8 : (\bar{L}R)(\bar{R}L) + \text{h.c.}$		$8 : (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Warsaw Basis: 59 Operators $(\delta B = 0, \delta L = 0)$

Grzadkowski/Iskrzynski/Misiak/Rosiek (1008.4884)



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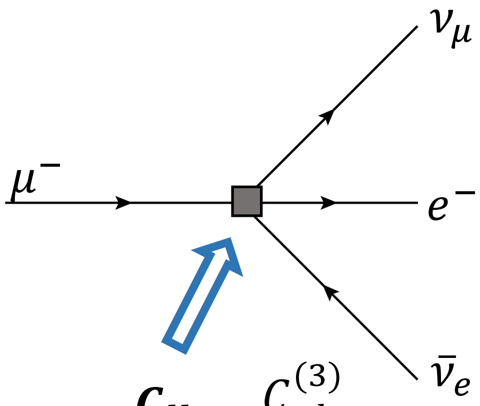
4-Fermi – Where are we?

Strong bounds from **low-Energy observables**:

Below the Z Pole:

4-Fermi modifies “classic” Fermi-theory (= integrate W/Z)! ⇒ **Redefinition of tree-level relations G_F, $\sin\vartheta_{OS}$, …**



$$\boldsymbol{G_F - \frac{C_{ll}}{2\Lambda^2}} + \frac{C_{\varphi l}^{(3)}}{\Lambda^2}$$

$$\Rightarrow \quad \frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta q) \quad \Rightarrow \quad \frac{G_F}{\sqrt{2}} = \left[\frac{e^2}{8 s_W^2 M_W^2}\right](1+\Delta r)$$

Transitions into all electroweak precision calculations as input!

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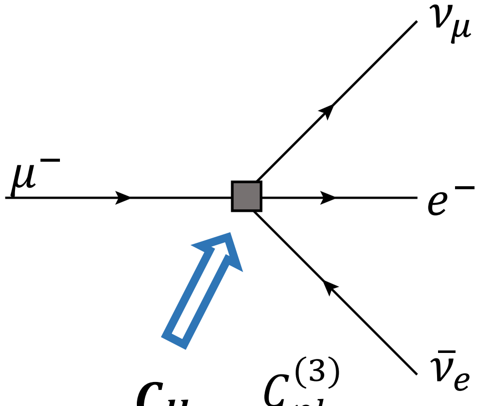

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Nucleon/ν scattering $\quad R_\nu = \dfrac{\sigma(\nu N \to \nu X)}{\sigma(\nu N \to l X)}$ (CHARM data)

DIS e^-/μ^- scattering
β, π, n^0 decay
Atomic Parity Violation

Weak charge $Q_W(Z,N)$ (PVDIS @6GeV, SPS data,…)

LO/Partial 1-loop

$(\bar{L}L)(\bar{L}L)$
$(\bar{Q}Q)(\bar{L}L)$

Falkowski et al (1706.03783)

4-Fermi – Where are we?

At the Z Pole:

Z-Pole observables: $\Gamma_Z, \sin\vartheta, \sigma_Z, R_{bb}$

W observables: $\Gamma_W, M_W - M_Z$

1-loop complete

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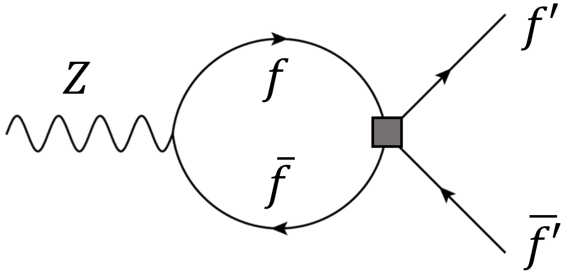

Weakest bounds, but first access to $(\bar{t}t)(\bar{b}b)$ *Dawson et al (1909.02000)*

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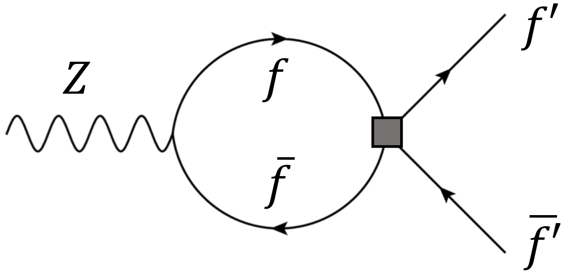

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Above the Z pole:

Low-energy di-Jet Production $\sum_q \sigma(ee \to qq) +$ FB Asymmetry (LEP2 data, also KEKB)

Møller Scattering FB Asymmetry/effective mixing angle (MOLLER/P2 data)

First Generation Leptons only

	Z Pole	Low-Energy
C_{ll}	$\{-0.004, 0.019\}$	$\{0.004, 0.011\}$
C_{lu}	$\{-0.49, 0.19\}$	$\{-0.002, 0.028\}$
$C_{qq}^{(1)}$	$\{-0.93, 1.49\}$	–

Comparison Z pole vs Low Energy Bounds ($\Lambda = 1$TeV)

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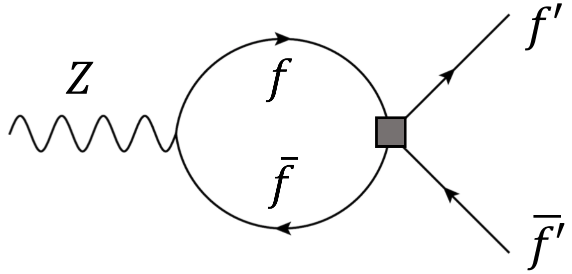

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Comparison Z pole vs Low Energy Bounds ($\Lambda = 1$TeV)

Problems:

1) Four-Quark operators comparatively badly bound
2) **Third generation** not accessible in EW (except $Z \to bb$)

4-Fermi – Where are we?

Top Quark Sector:

Single top production $(\bar{u}d)(\bar{t}b)$

Top pair (associated) production $(\bar{t}tV, \bar{t}tH)$ $(\bar{q}q)(\bar{t}t)$

Double pair production $(\bar{t}t)(\bar{t}t)$ $(\bar{t}t)(\bar{b}b)$

1-loop QCD mostly complete

Zheng (1611.0591)

Maltoni et al (1804.07773, 1901.0596)

Sullivan et al (1903.11023)

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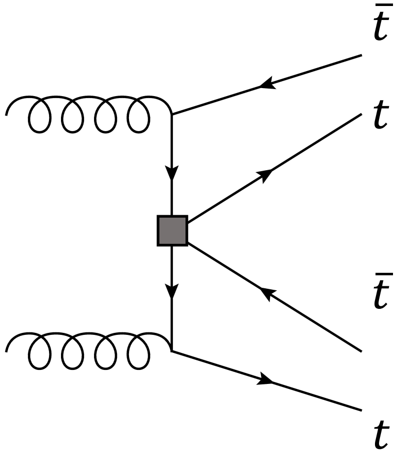
Mostly analyzing LHC data @ $\sqrt{s} = 8$TeV (some 13TeV data)

Representative bounds ($\Lambda = 1$TeV), MG5_aMC
Maltoni et al

	$C_{tt}^{(1)}$	$C_{tu}^{(1)}$	$C_{tb}^{(1)}$
	$\{-11.0, 11.0\}$	$\{-14.0, 10.0\}$	$\{-9.5, 9.9\}$



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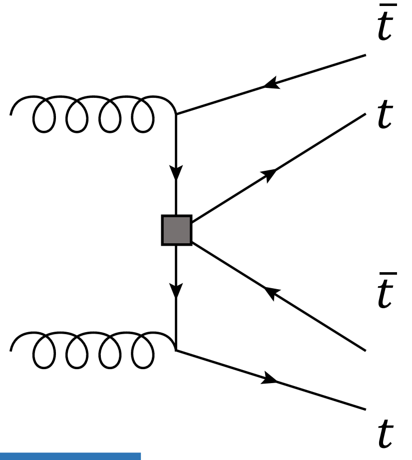

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Open Questions:

1) Is the third generation **accessible** through loop-induced processes?
2) What's the future **potential** with increased Luminosity?

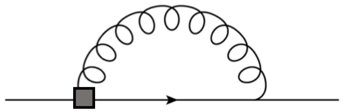
We try and answer those questions using top decay as a tech test

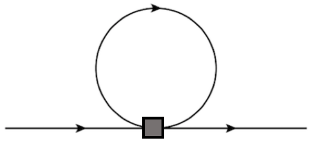
Boughezal et al (1907.00997)

4-Fermi @ NLO

Renormalization:

- **Renormalizable** if consistent in perturbation theory: *Grojean et al (1301.2588)*
- Use **on-shell scheme** analogously to SM — For Top decay only δZ_q:





- Renormalize tree-level operators in $\overline{\boldsymbol{MS}}$: $\tilde{C}_i = C_i + \delta\gamma_{ij} C^j$ — 4-Fermi: $\mathcal{O}^{(i)}_{\phi f} \sim \left(\phi^\dagger \overleftrightarrow{D}^i_\mu \phi\right)\left(\bar{f}\gamma^\mu \tau^i f\right)$
- Compare RGE with literature for check *Trott et al (1308.2627, 1310.4838, 1312.2014)*

$$\frac{d\tilde{C}_i}{d\log\mu} = \frac{\delta\gamma_{ij}}{16\pi^2}\tilde{C}^j$$

(Introduces scale-dependent Wilson Coefficients)

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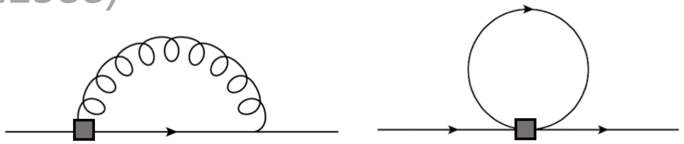

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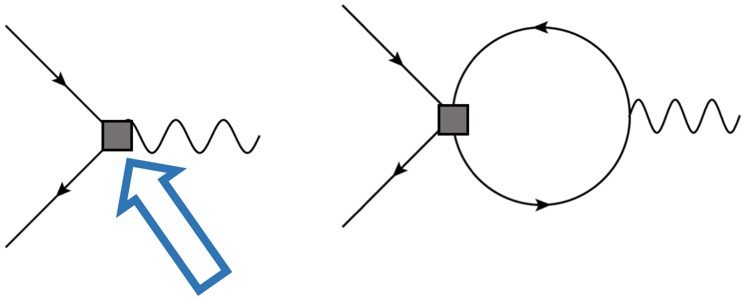
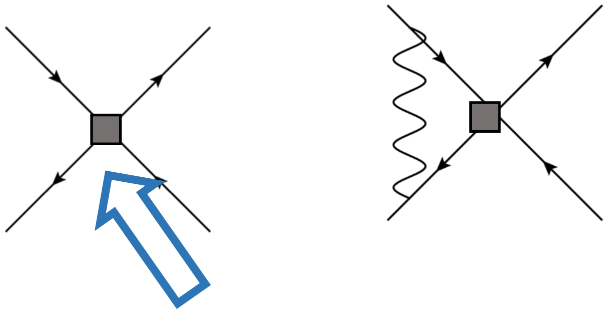
A 4-Fermi Correction to a Vertex



Vff gets renormalized

A Correction to a 4-Fermi Vertex



4-Fermi gets renormalized

Traces including 4-Fermi operators need careful treatment of chirality in **dim Reg**!

Ward Identities and Chirality

γ_5 in Dim-Reg (the story so far):

t' Hooft-Veltman Scheme (HVBM)

TRACER 1.1 – Jamin/Lautenbacher

Split into 4 and (d-4)-dim parts:

$$\gamma^{\mu} = \bar{\gamma}^{\mu} + \hat{\gamma}^{\mu}$$

Enforce extended Ward identities through finite **Counterterms/Evanescent Operators**

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Enforce extended Ward identities through finite **Counterterms/Evanescent Operators**

$\Updownarrow$

Larin Scheme

Get results from HVBM without the hassle

Price to pay:

Additional finite counterterms needed to restore chiral Ward identities

$$\left\{ \begin{array}{l} \gamma_\mu \gamma_5 \to \frac{i}{4!} \varepsilon^{\mu\nu\rho\sigma} \gamma_\nu \gamma_\rho \gamma_\sigma \\ \sigma^{\mu\nu} \gamma_5 \to -\frac{i}{2} \varepsilon^{\mu\nu\alpha\beta} \sigma_{\alpha\beta} \end{array} \right.$$

Ward Identities and Chirality

γ_5 in Dim-Reg (the story so far):

Naïve "`FeynCalc`" Scheme*

$$\{\gamma_5, \gamma_\mu\} = 0$$

$$\mathrm{Tr}[\gamma_5 \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma] = 4i\varepsilon^{\mu\nu\rho\sigma}$$

Incompatible but produces correct results

t' Hooft-Veltman Scheme (HVBM)

TRACER 1.1 – Jamin/Lautenbacher

Split into 4 and (d-4)-dim parts:

$$\gamma^\mu = \bar{\gamma}^\mu + \hat{\gamma}^\mu$$

Enforce extended Ward identities through finite **Counterterms/Evanescent Operators**

*Note on the Naïve Scheme:

- "Incompatible" means committing error $\mathcal{O}(\varepsilon)$
- Only appears in connection with triangle anomaly
- No poles to give finite contribution

Larin Scheme

Get results from HVBM without the hassle

Price to pay:

Additional finite counterterms needed to restore chiral Ward identities

$$\gamma_\mu \gamma_5 \to \frac{i}{4!}\varepsilon^{\mu\nu\rho\sigma}\gamma_\nu\gamma_\rho\gamma_\sigma$$

$$\sigma^{\mu\nu}\gamma_5 \to -\frac{i}{2}\varepsilon^{\mu\nu\alpha\beta}\sigma_{\alpha\beta}$$

Ward Identities (II)

Ward Identity for Chiral $U(2)$ $\qquad q_{L/R} \to e^{\pm i\vec{\alpha}\,\vec{\tau}/_2} q_{L/R}$

SM $\qquad$ **Fermion masses** break chiral symmetry

$$\left\langle \partial_\mu(\bar{t}(x)\gamma^\mu\gamma_5 t(x))t(x_1)\bar{t}(x_2)\right\rangle = \boldsymbol{2im_t\langle(\bar{t}(x)\gamma_5 t(x))t(x_1)\bar{t}(x_2)\rangle}$$

Trueman (Z. Phys. C69)

$$-i\gamma_5\langle t(x)\bar{t}(x_2)\rangle\delta(x-x_1) - i\langle t(x_1)\bar{t}(x)\rangle\gamma_5\delta(x-x_2)$$

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SMEFT (QCD) Fermion masses and $\boldsymbol{\frac{v}{\sqrt{2}} C_{tg}\bar{t}\sigma^{\mu\nu}T^A t G^A_{\mu\nu}}$ break chiral symmetry

$$\left.\begin{aligned}
&\langle \partial_\mu (\bar{t}(x)\gamma^\mu\gamma_5 t(x)) t(x_1)\bar{t}(x_2)\rangle = 2im_t\langle(\bar{t}(x)\gamma_5 t(x))t(x_1)\bar{t}(x_2)\rangle \\
&\quad -i\gamma_5\langle t(x)\bar{t}(x_2)\rangle\delta(x-x_1) - i\langle t(x_1)\bar{t}(x)\rangle\gamma_5\delta(x-x_2) \\
&\quad \boldsymbol{-\sqrt{2}iC_{tg}v\langle\bar{t}(x)\sigma^{\mu\nu}\gamma_5 T^A t(x)G^A_{\mu\nu}(x)t(x_1)\bar{t}(x_2)\rangle}
\end{aligned}\right\}$$

Larin, Naïve and HVBM Scheme obey this Ward Identity

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Larin, Naïve and HVBM Scheme obey this Ward Identity

SMEFT (4-Fermi) Fermion masses and e.g. $\boldsymbol{C^{(1)}_{qt}\,(\bar{q}_L\gamma^\mu q_L)(\bar{t}_R\gamma_\mu t_R)}$ break chiral symmetry

$$\left\langle \partial_\mu(\bar{t}(x)\gamma^\mu\gamma_5 t(x)) b(x_1)\bar{b}(x_2)\right\rangle = im_t\left\langle(\bar{t}(x)\gamma_5 t(x))b(x_1)\bar{b}(x_2)\right\rangle$$
$$-i\gamma_5\left\langle b(x)\bar{b}(x_2)\right\rangle\delta(x-x_1) - i\left\langle b(x_1)\bar{b}(x)\right\rangle\gamma_5\delta(x-x_2)$$
$$\boldsymbol{-2iC^{(1)}_{qt}\left\langle\bar{t}(x)\gamma^\mu P_L t(x) b(x_1)\gamma_\mu P_R \bar{b}(x_2)\right\rangle}$$

Naïve and HVBM Scheme obey this Ward Identity

A Technical Note

- Feynman rules implemented in many packages *Dedes et al (1704.03888)*

`FeynRules, CalcHEP, SHERPA, MadGraph`

Maltoni et al (1412.5594)

Here:
`FeynRules/FeynCalc`

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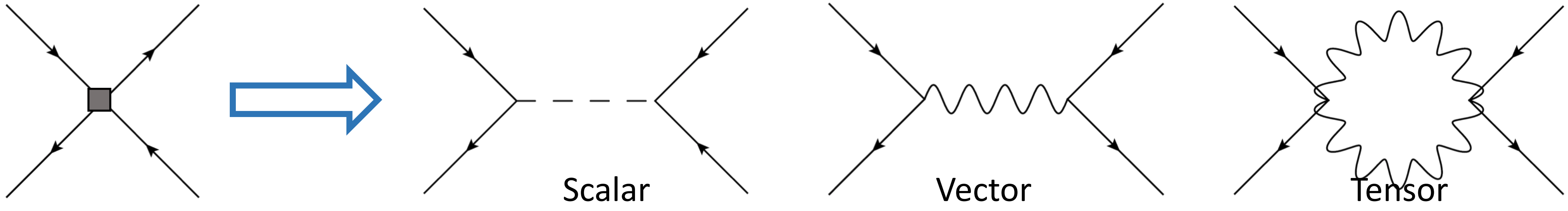
The Technical Note:

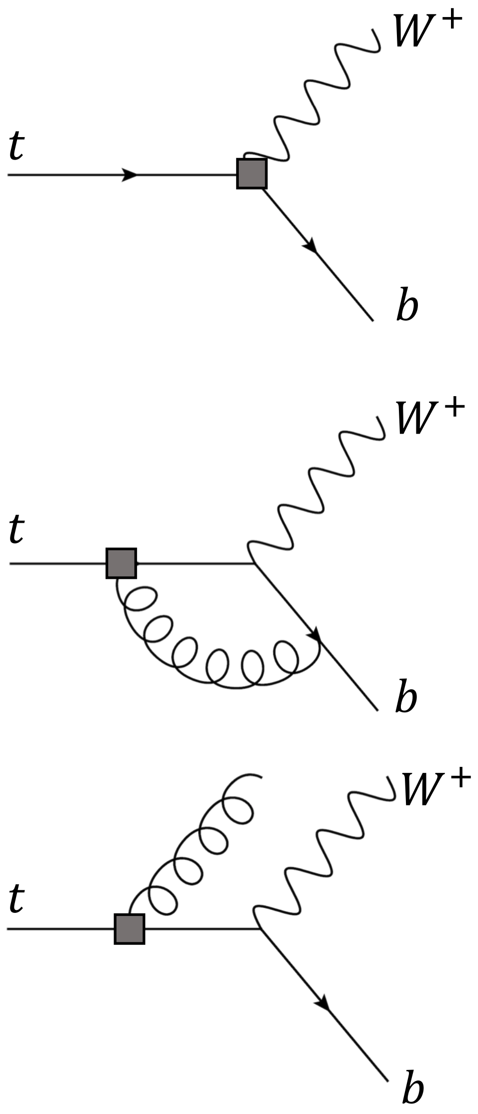
`FeynArts` has a hard time handling the **Dirac structure** of 4-Fermi operators

Trick: Introduce Modelfile with heavy vectors/scalars carrying zero momentum (=integrated out)



N.B. The tensor structure's momentum-independent propagators, do **not** lead to higher loops. Technically easier to implement into `FeynArts` than Gravitons.

Application: Top Decay



Tree-level, virtual correction, real emission

<u>Observables:</u> total width and final state W helicity

Total Width: Γ_{tot}

Helicity/polarization fractions: $F_{L,+,-} = \frac{\Gamma_{L,+,-}}{\Gamma_{tot}}$

SM corrections $\mathcal{O}(\alpha)/\mathcal{O}(\alpha_s)$ suppressed in ratio

Fischer et al (9811482)
Czarnecki et al (1005.2625)

Tree-level: $\boldsymbol{C_{tW}}, C_{bW}, C_{\phi tb}$

NLO: $\boldsymbol{C_{tg}}, C_{tb}$

C_{tW}, C_{tg} analysis had been done *Zhang (1611.05091)*

Update: $m_b \neq 0$ opens more operators

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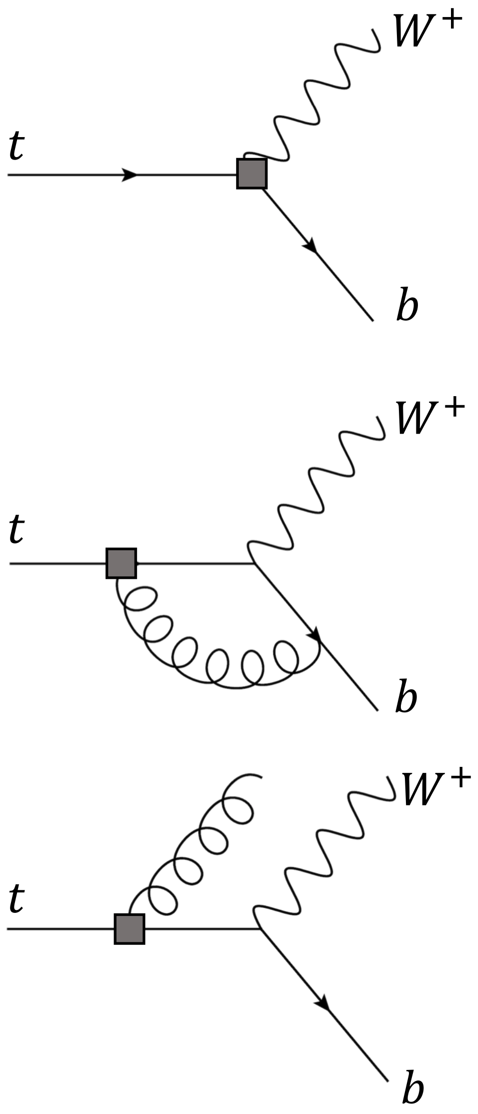

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- Main constraints from total width Γ_{tot}
- F_+ sensitive to C_{bg}

Update on previously found bounds. Analysis of remaining operators

QCD not the focus here but good consistency check for machinery!

QCD results

All coefficients given, assuming $\Lambda = 500\text{GeV}$

	Current	HL-LHC ($f_{\text{syst}} = 1/2$)	HL-LHC ($f_{\text{syst}} = \frac{1}{\sqrt{N}}$)
C_{tW}	$-0.05 < C_{tW} < 0.17$	$\lvert C_{tW}\rvert < 0.04$	$\lvert C_{tW}\rvert < 0.01$
C_{tg}	$-13.37 < C_{tg} < 4.88$	$\lvert C_{tg}\rvert < 3.33$	$\lvert C_{tg}\rvert < 0.75$
C_{bW}	$-0.47 < C_{bW} < 2.07$	$\lvert C_{bW}\rvert < 0.45$	$\lvert C_{bW}\rvert < 0.10$
C_{bg}	$-32.72 < C_{bg} < 5.63$	$\lvert C_{bg}\rvert < 6.87$	$\lvert C_{bg}\rvert < 1.57$
$C_{\phi tb}$	$-4.15 < C_{\phi tb} < 12.84$	$\lvert C_{\phi tb}\rvert < 3.06$	$\lvert C_{\phi tb}\rvert < 0.69$

1-parameter fit exclusion limits at 90% CL

(The reach assumes **optimistic** ($\frac{1}{\sqrt{N}}$) and **pessimistic** systematics scaling)

Vary one Wilson coefficient at a time, rest is zero

Single-parameter χ^2 fit

$$\chi^2 = \sum_{ij} \left(\mathcal{O}_i^{theo} - \mathcal{O}_i^{exp}\right)\left(\sigma_{ij}^2\right)^{-1}\left(\mathcal{O}_j^{theo} - \mathcal{O}_j^{exp}\right)$$

(Error correlation σ from CMS)

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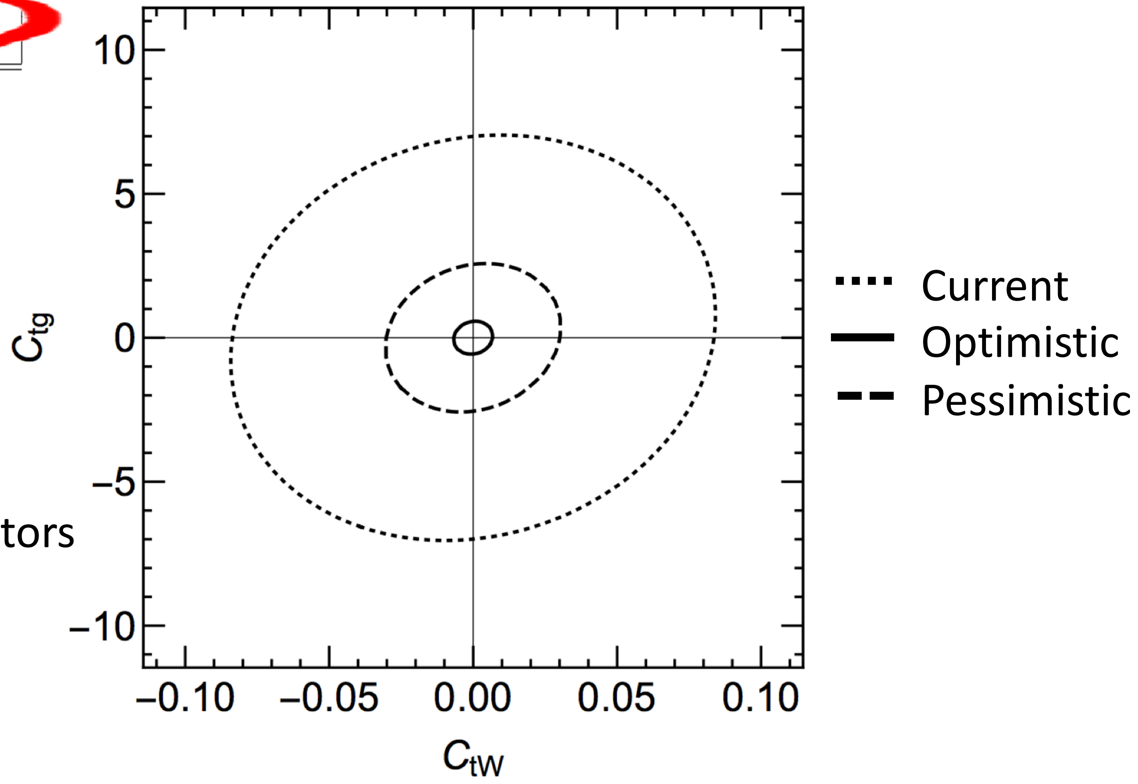
Study potential correlation between operators
2-dimensional χ^2 fit (95% CL)

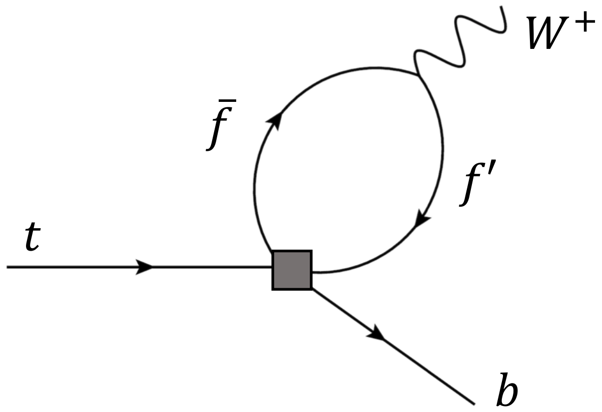


Top Decay (II)

Observables: Again final state W helicity

Total Width: Γ_{tot}

Helicity/polarization fractions: $F_{L,+,-} = \frac{\Gamma_{L,+,-}}{\Gamma_{tot}}$



- NLO potentially sensitive to: $\boldsymbol{C_{qu}^{(1)}}$, $\boldsymbol{C_{qu}^{(8)}}$, $C_{qq}^{(1)}$, $\boldsymbol{C_{qq}^{(3)}}$ and $C_{lq}^{(3)}$

- Most interesting: purely third generation operators

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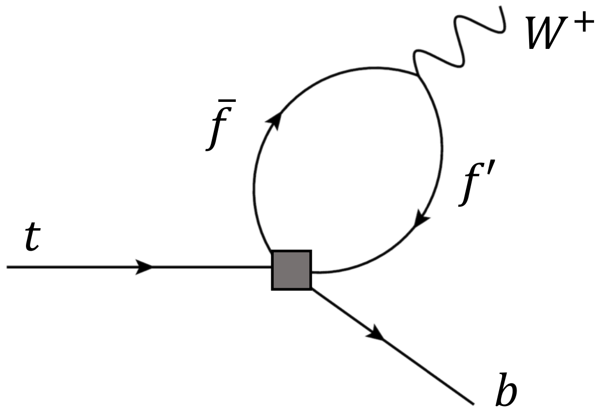

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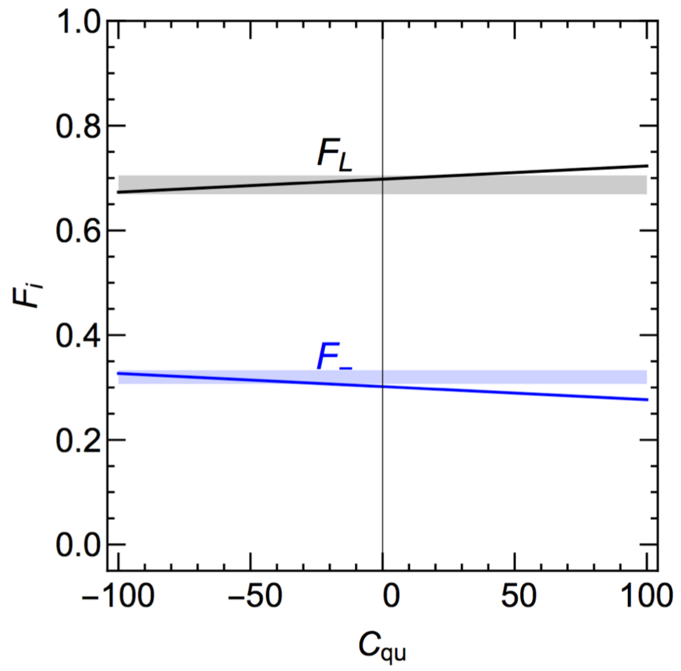
- Most interesting: purely third generation operators

Note: (Exact) **flat direction**:

$$C_{qu} = C_{qu}^{(1)} + \frac{4}{3} C_{qu}^{(8)} \quad \text{from} \quad (\gamma^\mu P_L)_{bb} (\gamma_\mu P_R)_{tt}$$

- Γ_{tot} and Helicity fractions only weakly sensitive since Experimental error too large right now.
- Combine with second process with different color structure to break degeneracy?



1σ experimental error bands

4-Fermi Results

All coefficients given, assuming $\Lambda = 500\text{GeV}$

Observables: Total Width (Γ_{tot}) and two helicity fractions (F_L and F_-)

	Current	HL-LHC ($f_{\text{syst}} = 1/2$)	HL-LHC ($f_{\text{syst}} = \frac{1}{\sqrt{N}}$)
$C_{qq}^{(1)}$	$-167.21 < C_{qq}^{(1)} < 254.73$	$\lvert C_{qq}^{(1)}\rvert < 105.48$	$\lvert C_{qq}^{(1)}\rvert < 17.23$
$C_{qq}^{(3)}$	$-34.73 < C_{qq}^{(3)} < 22.80$	$\lvert C_{qq}^{(3)}\rvert < 14.38$	$\lvert C_{qq}^{(3)}\rvert < 2.35$
C_{qu}	$-181.94 < C_{qu} < 26.91$	$\lvert C_{qu}\rvert < 37.80$	$\lvert C_{qu}\rvert < 8.53$
$C_{lq}^{(3)}$	$-151.22 < C_{lq}^{(3)} < 230.36$	$\lvert C_{lq}^{(3)}\rvert < 95.40$	$\lvert C_{lq}^{(3)}\rvert < 15.58$

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Vary one Wilson coefficient at a time, rest is zero

Single-parameter χ^2 fit

- Bounds very weak at this point
- **BUT** potential with future data! $\mathcal{O}(1)$ Coefficients achievable

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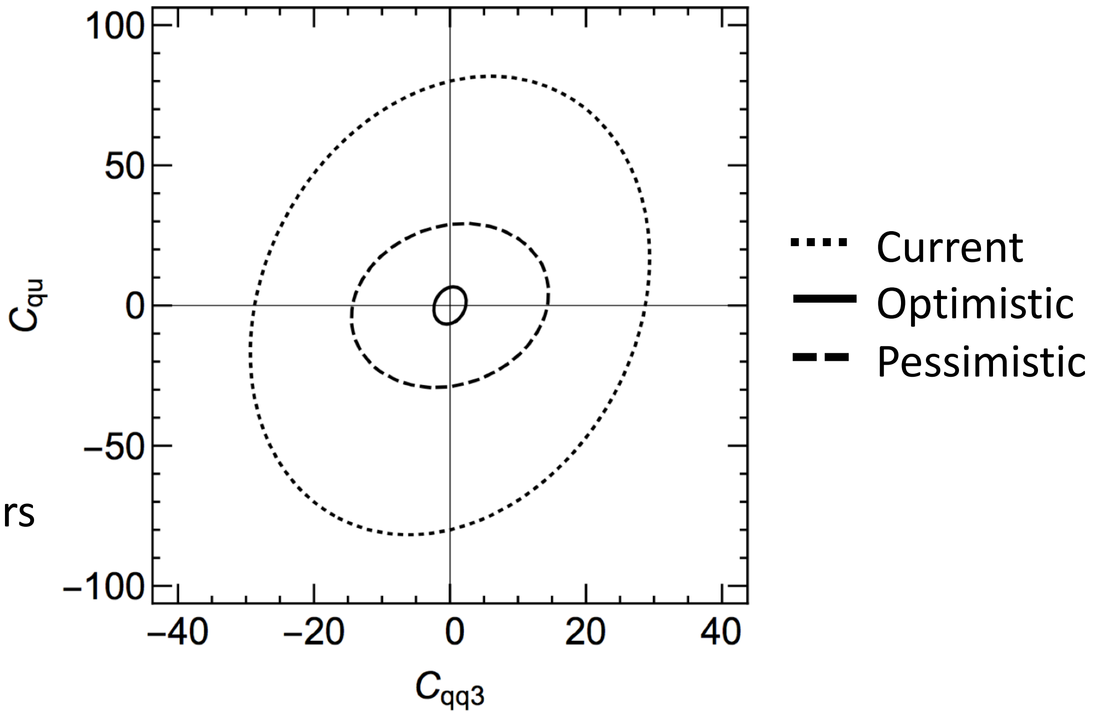
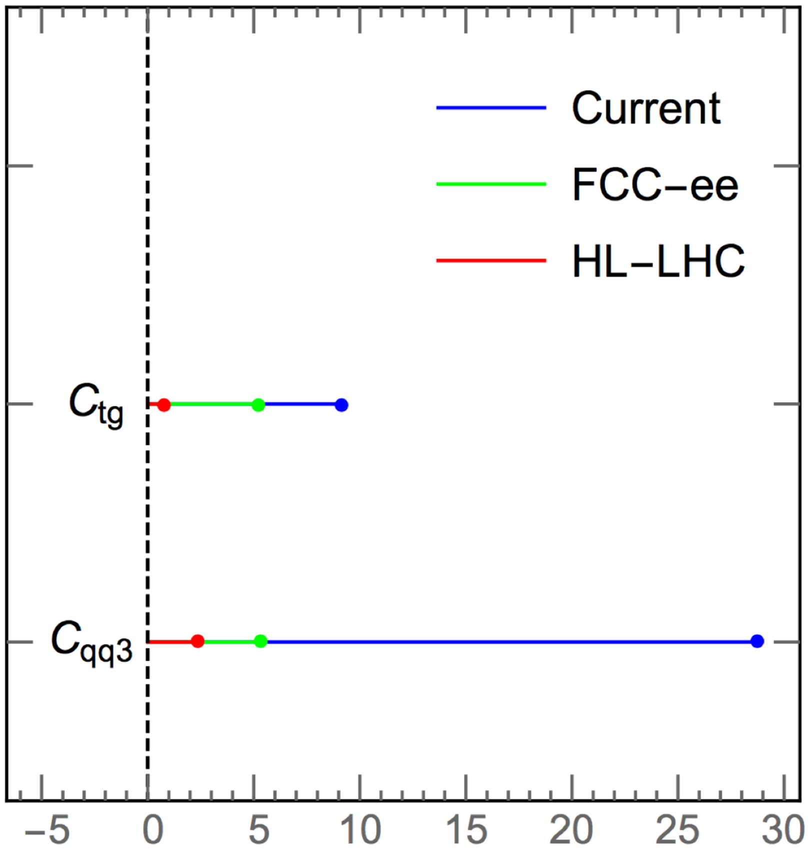


Future Reach

All coefficients given, assuming $\Lambda = 500\text{GeV}$



Projection for bounds with future data from HL-LHC (optimistic) and FCC-ee

Look at the coefficients we are most sensitive to, and their future potential:

<u>Projection for FCC-ee</u>

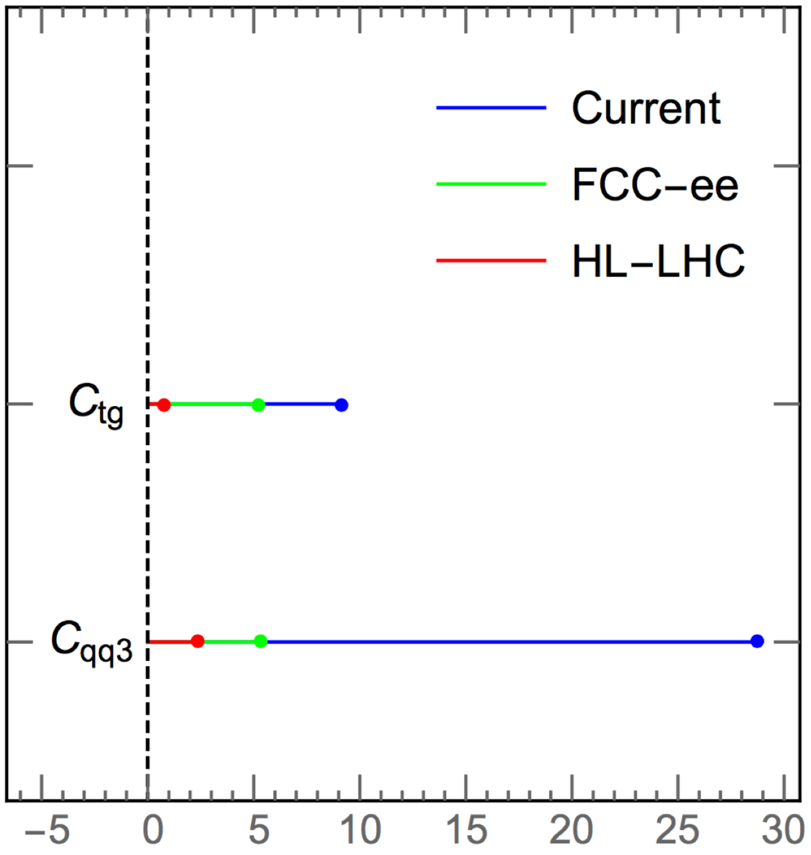
Projected bound on top width: 95MeV

<u>Projection for HL-LHC ($3ab^{-1}$)</u>

Statistical error down/Systematic the same $\frac{1}{\sqrt{N}}$ (**optimistic**)

Future Reach

All coefficients given, assuming $\Lambda = 500\mathrm{GeV}$



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Projected bound on top width: $95\mathrm{MeV}$

<u>Projection for HL-LHC ($3ab^{-1}$)</u>

Statistical error down/Systematic the same $\frac{1}{\sqrt{N}}$ (**optimistic**)

Potential of getting coefficients down to **order unity**!

Comparable to the bounds derived from 4 heavy quark finale state

Summary and Conclusions

SMEFT is a practical framework to constrain new physics!

SMEFT has additional sources of **chiral symmetry breaking**

⇒ Requires a differentiated **treatment of γ_5**

⇒ We presented a consistent strategy for loop calculations

Operators contributing at the **loop-level**

⇒ NLO corrections increase precision and
lead to sensitivity of data to new operators

⇒ Constraints are **well within the reach of future experiments**

Thanks!