Standard Model Effective Theory and Four-Fermi Interactions

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@Pheno 2019

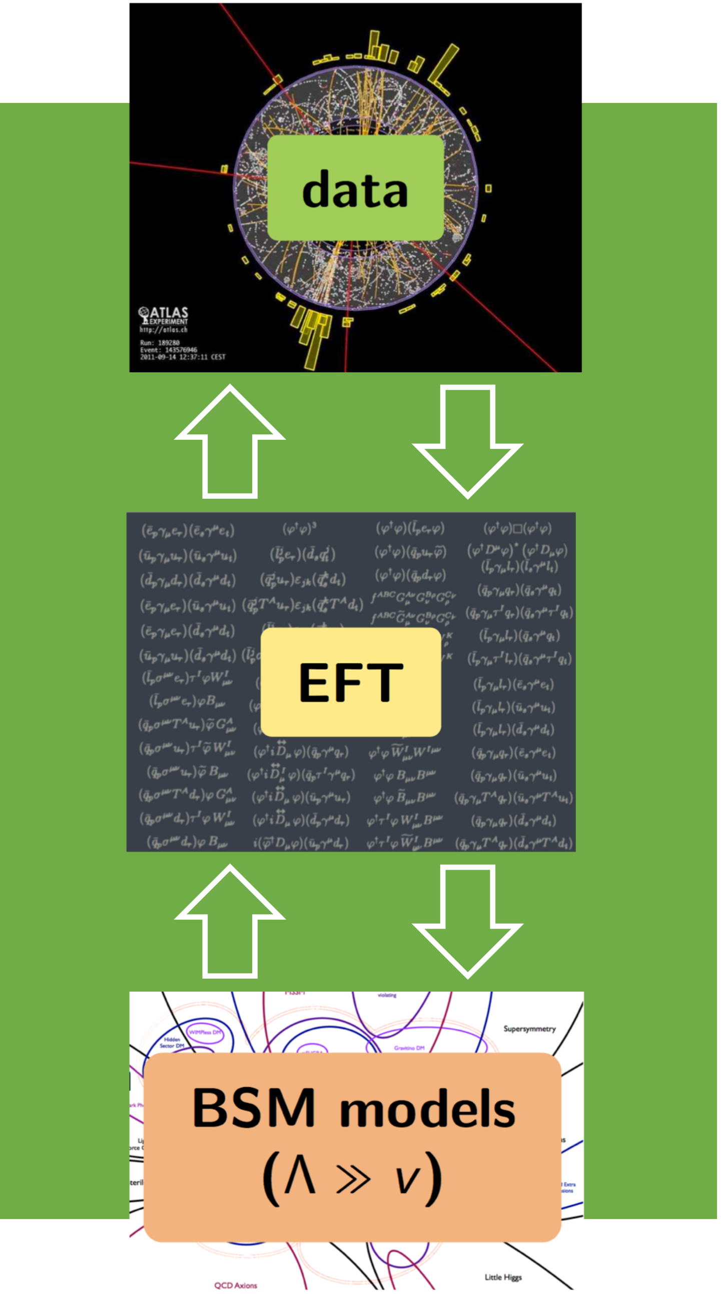
Based on:

Boughezal/Petriello/Chen/DW - (arXiv: 1905.xxxxx)

DW - (arXiv: 1905.xxxxx)

Fig.1 Loop corrections are coming

The Why, the What and the How



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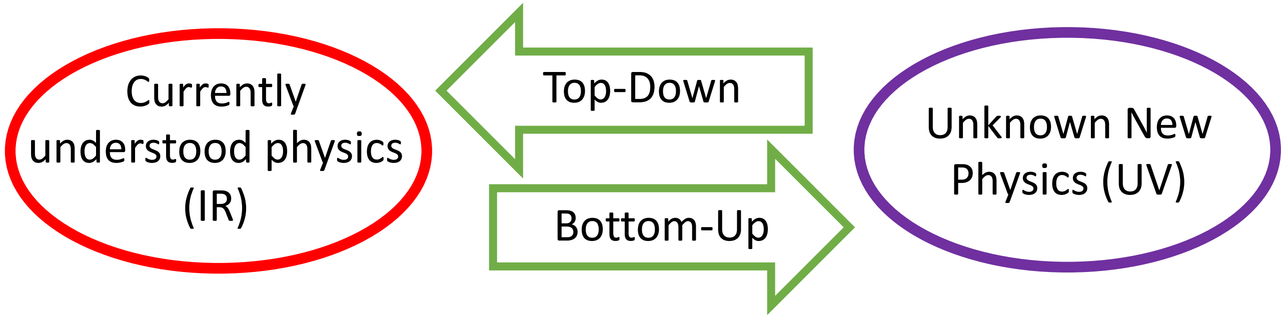
- **the Why**
  - Standard Model Effective Theory (**SMEFT**) is an attractive way to systematically look for New Physics
  - Analysis is **universally** applicable
  - **Radiative Corrections** amp precision and introduce **new operators**
- **the What**
  - Four-Fermi Operators often neglected outside tree-level analysis
  - Chirality structure iffy ⟹ Need consistent γ_5 **prescription**
- **the How**
  - (For now) simple **Charged/Neutral Current** processes:

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

    ⟹ Constrain through Data

SMEFT (I) - The basic idea



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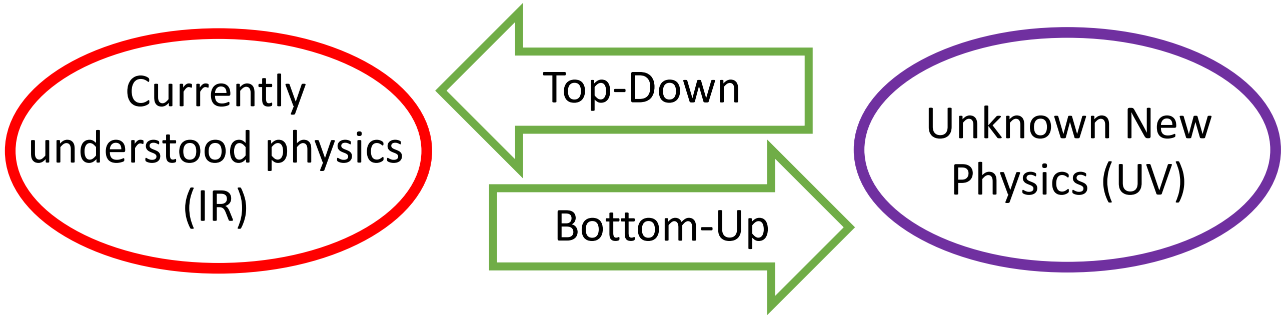

Write down all possible operators that new physics could induce

- Stay consistent with SM **symmetries**! $(\delta B \neq 0?, \delta L \neq 0?)$
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$$\mathcal{L}_{SMEFT} \supset \underbrace{\mathcal{L}_{SM} + \frac{C_5}{\Lambda}\mathcal{O}^5 + \frac{C_6^i}{\Lambda^2}\mathcal{O}_i^6}_{\text{Focus at 1-loop/Dim-6}} + \frac{C_7^i}{\Lambda^3}\mathcal{O}_i^7 + \cdots$$

SMEFT (I) - The basic idea

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
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}	$(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$	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}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p\tau^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G^A_{\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
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$Q_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$		$8: (\bar RR)(\bar RR)$		$8: (\bar LL)(\bar RR)$	
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}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
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		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
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Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
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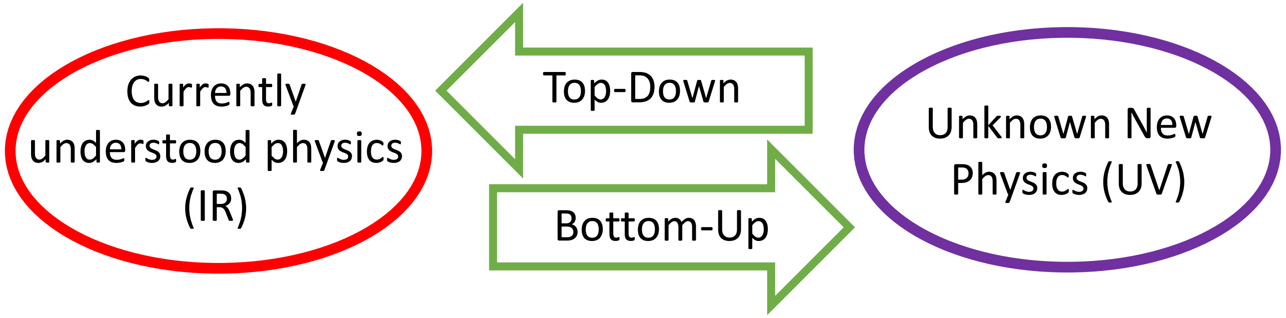
Warsaw Base:

Grzadkowski/Iskrzynski,/Misiak/Rosiek (1008.4884)



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$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \mathrm{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
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$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
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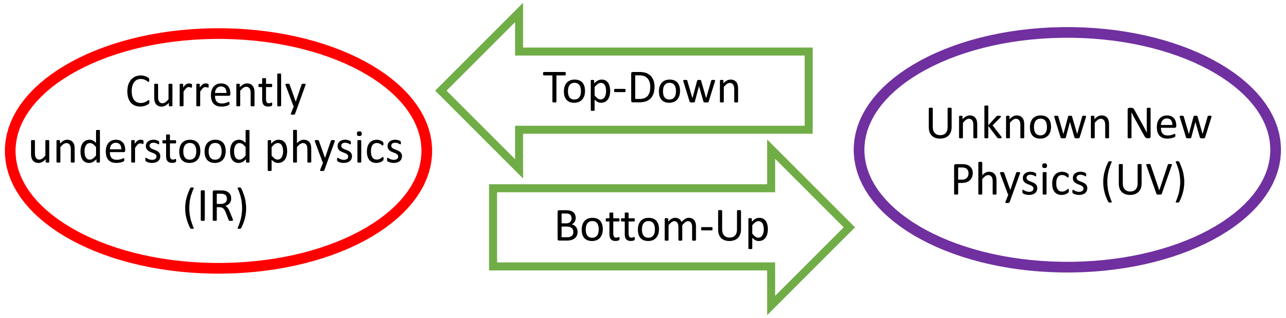

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SMEFT (II) – 4-Fermi and Beyond

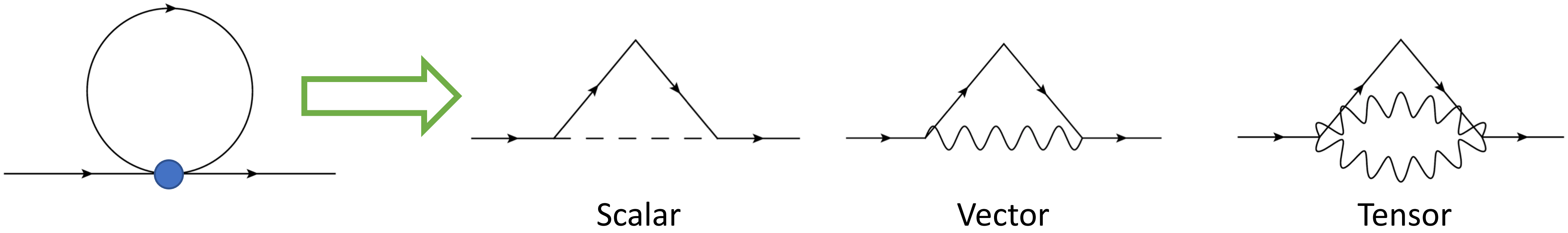
- Avoid **over-completeness** through field redefinitions/IBP/EOM *Henning/Lu/Meila/Murayama (1512.03433) Misiak et al (1008.4884) …*

- Most Feynman rules available for most packages *Dedes et al (1704.03888)*

<u>Technical Note:</u>

`FeynArts` cannot handle Dirac structure of 4-Fermi operators

Trick: Introduce Modelfile with heavy vectors/scalars carrying zero momentum (Different Topologies!)



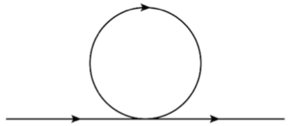
- **Renormalizable** if consistent in perturbation theory: *Grojean et al (1301.2588)*

Including dim-6 operators means expanding everything to $\mathcal{O}\left(\frac{\alpha}{\Lambda^2}\right)$

SMEFT (III) - Renormalization and γ_5

Renormalization:

- Use **on-shell scheme** analogously to SM

4-Fermi easy:  $\delta Z_f = 0$

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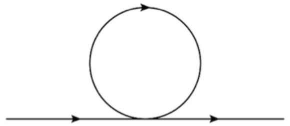
4-Fermi easy:  $\delta Z_f = 0$

- Renormalize tree-level operators in $\overline{\boldsymbol{MS}}$: $\tilde{C}_i = C_i + \delta\gamma_{ij}C^j$

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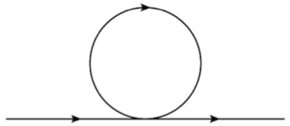
4-Fermi easy:  $\delta Z_f = 0$

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- Compare RGE with literature for check *Trott et al (1308.2627, 1310.4838, 1312.2014)*

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

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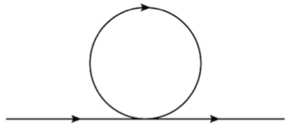
4-Fermi easy:  $\delta Z_f = 0$

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γ_5 in Dim-Reg:

Naïve “`FeynCalc`” Scheme

$$\left.\begin{aligned} &\{\gamma_5, \gamma_\mu\} = 0 \\ &\mathrm{Tr}[\gamma_5\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma] = 4i\varepsilon^{\mu\nu\rho\sigma} \end{aligned}\right\}$$

Incompatible but works

4-dim

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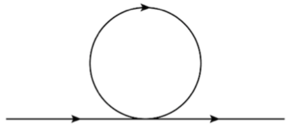
4-Fermi easy:  $\delta Z_f = 0$

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4-dim

Incompatible but works

<u>t' Hooft-Veltman Scheme (HVBM)</u>

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**

Trueman (Z. Phys. C69)

Example Applications

Charged Current: Top Decay

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)

SMEFT-QCD analysis done $m_b \neq 0$ opens more operators *Zhang (1611.05091)*

1) Slight improve on QCD **dipole** W/g-operators: $\bar{f}\sigma^{\mu\nu}f'\tilde{\phi}F_{\mu\nu}$

Not the focus here but good consistency check!

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Helicity/polarization fractions: $F_{L,+,-} = \frac{\Gamma_{L,+,-}}{\Gamma_{tot}}$ SM corrections $\mathcal{O}(\alpha)/\mathcal{O}(\alpha_s)$ suppressed in ratio

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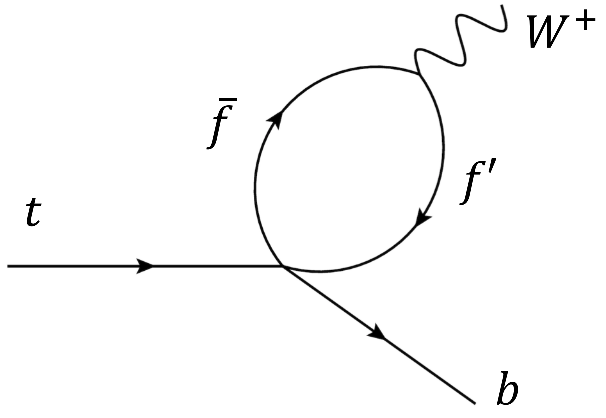
Czarnecki et al (1005.2625)

SMEFT-QCD analysis done $m_b \neq 0$ opens more operators *Zhang (1611.05091)*

1) Slight improve on QCD **dipole** W/g-operators: $\bar{f}\sigma^{\mu\nu}f'\tilde{\phi}F_{\mu\nu}$

Not the focus here but good consistency check!

2) **Four-Fermi** operators: Transverse: iffy - γ_5! Excellent benchmark!



Example Applications

Charged Current: Top Decay

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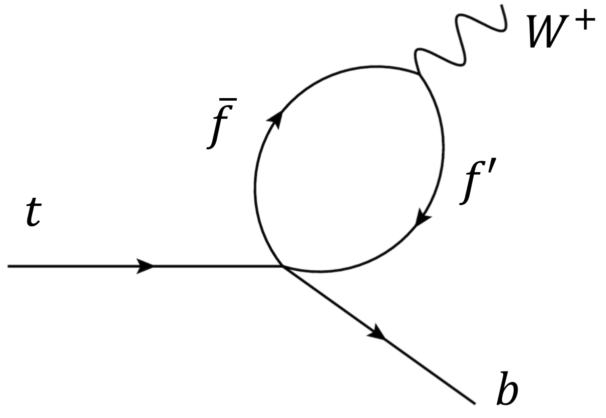

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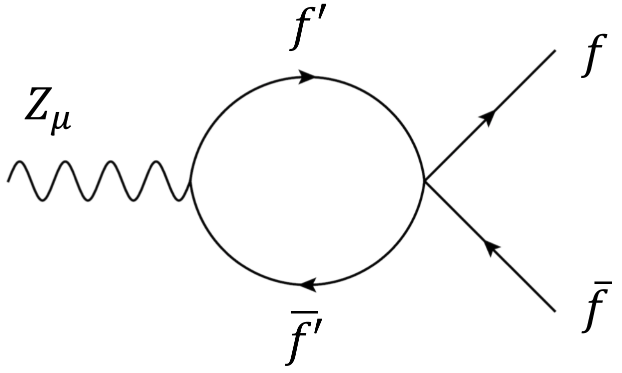
Neutral Currents: Z Decay and effective mixing angle

Z Decay partial widths: $\frac{\Gamma_{f\bar{f}}}{\Gamma_Z}$ **Effective Mixing angle(s):** $\sin\vartheta_{eff}^{ff}$

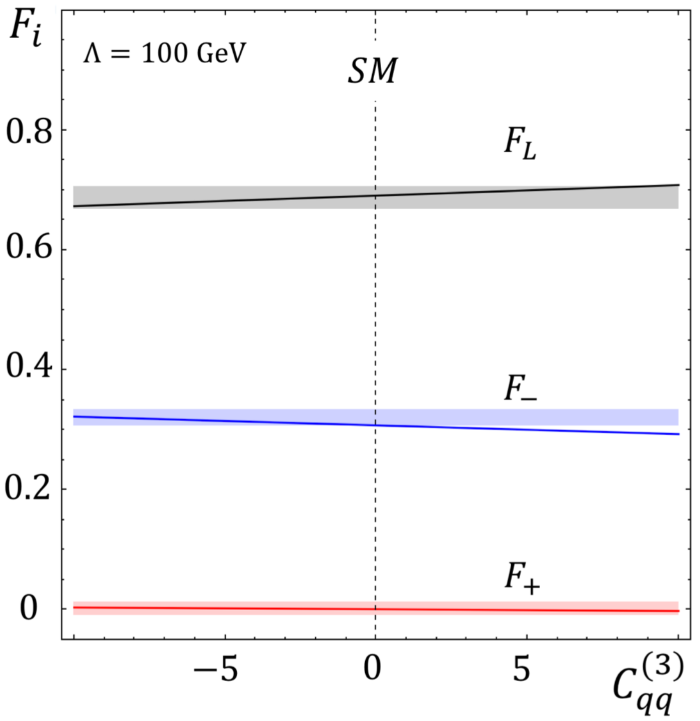


NLO SMEFT analysis done for EW *Trott et al (1611.09879)*
Dawson/Ismail (1808.05948)

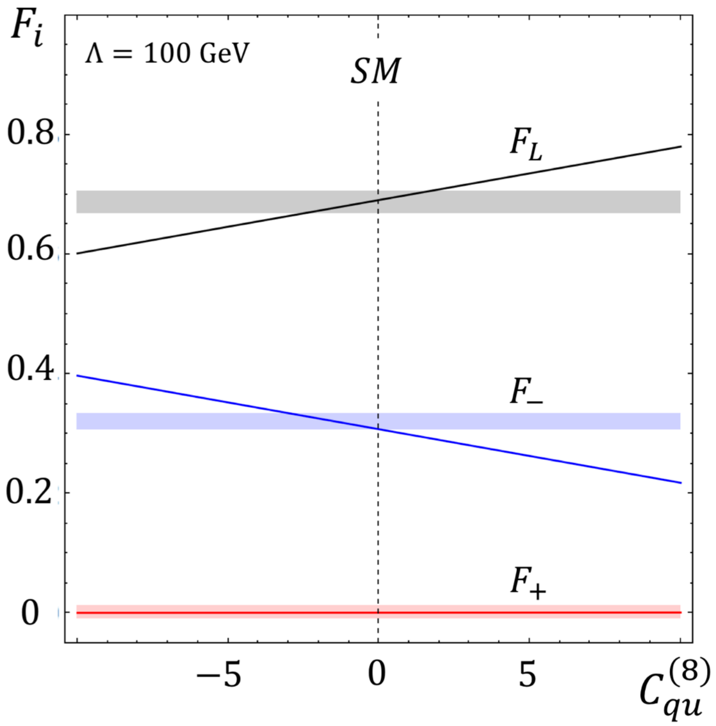
Four-Fermi operators bound through precise experimental errors

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

Results



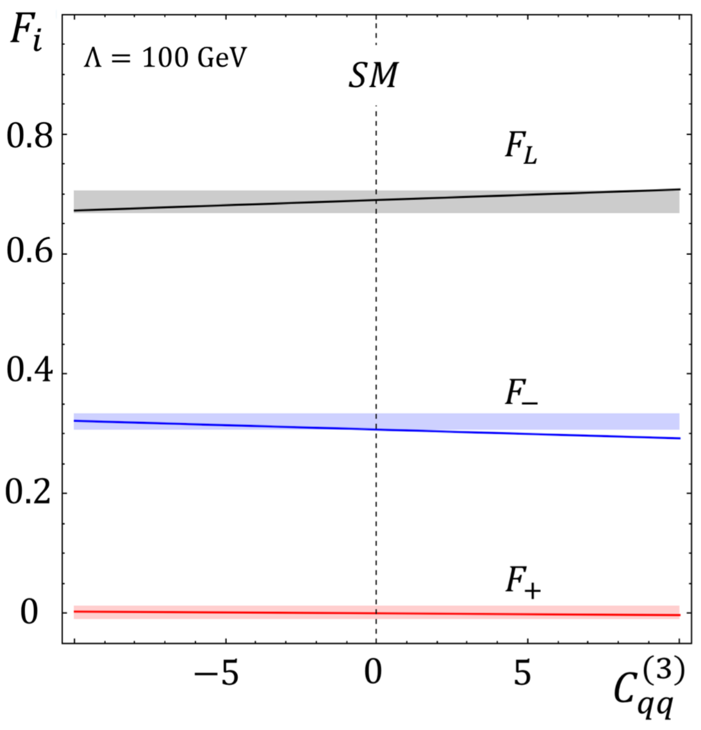
$$\frac{C_{qq}^{(3)}}{\Lambda^2}(\bar{q}\gamma^\mu\tau^I q)(\bar{q}\gamma_\mu\tau^I q)$$



$$\frac{C_{qu}^{(8)}}{\Lambda^2}(\bar{t}\gamma^\mu T^A t)(\bar{b}\gamma_\mu T^A b)$$

Results

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



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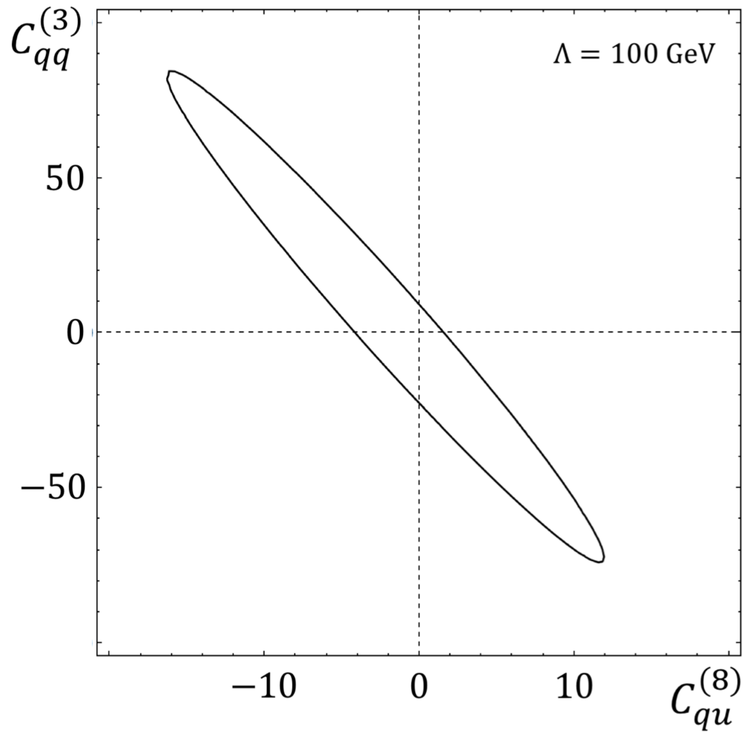
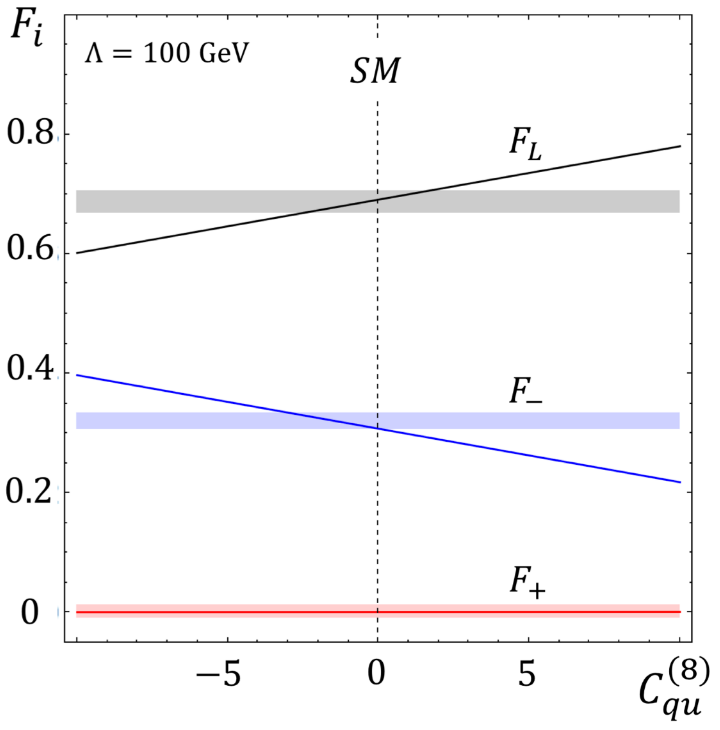


<u>Fig.2</u> Example χ^2 fit of two operators



$$\frac{C_{qu}^{(8)}}{\Lambda^2}(\bar{t}\gamma^\mu T^A t)(\bar{b}\gamma_\mu T^A b)$$

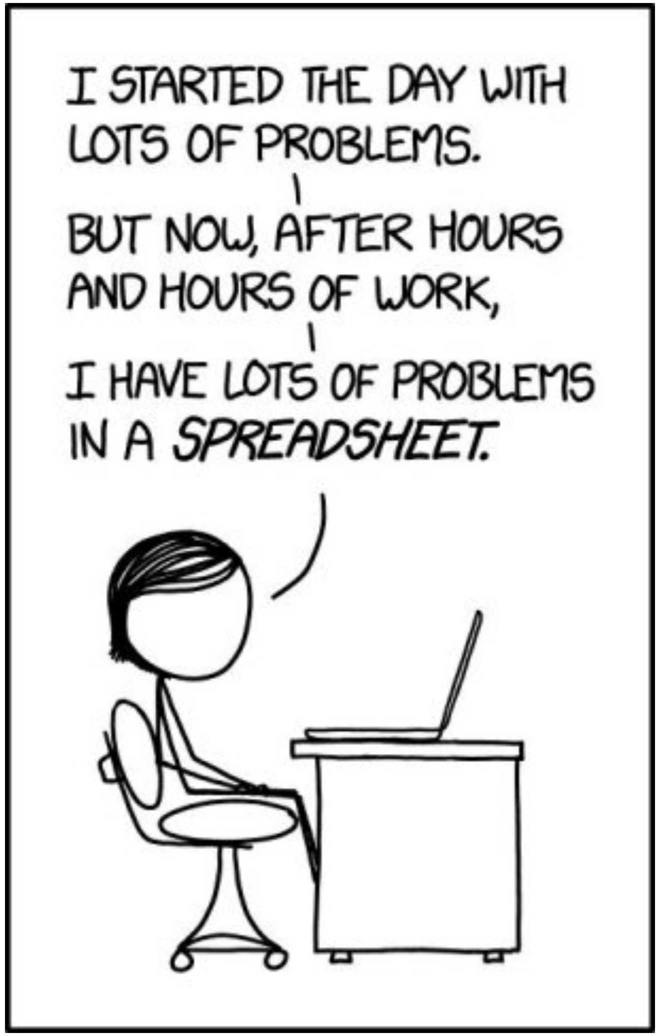
*<u>**Disclaimer:**</u> This is an illustrating example - Proper bounds from other Processes!

BUT First step of filling 4-Fermi bounds into SMEFT Top Fitter program *Willenbrock/Zhang (1008.3869v3)*

… and now what?

SMEFT has been the framework to go about constraining new physics!

- Systematic way to evaluate data/link seemingly unrelated results
- Parametrize new physics data in **model-independent** way
- Active field with plenty to do!



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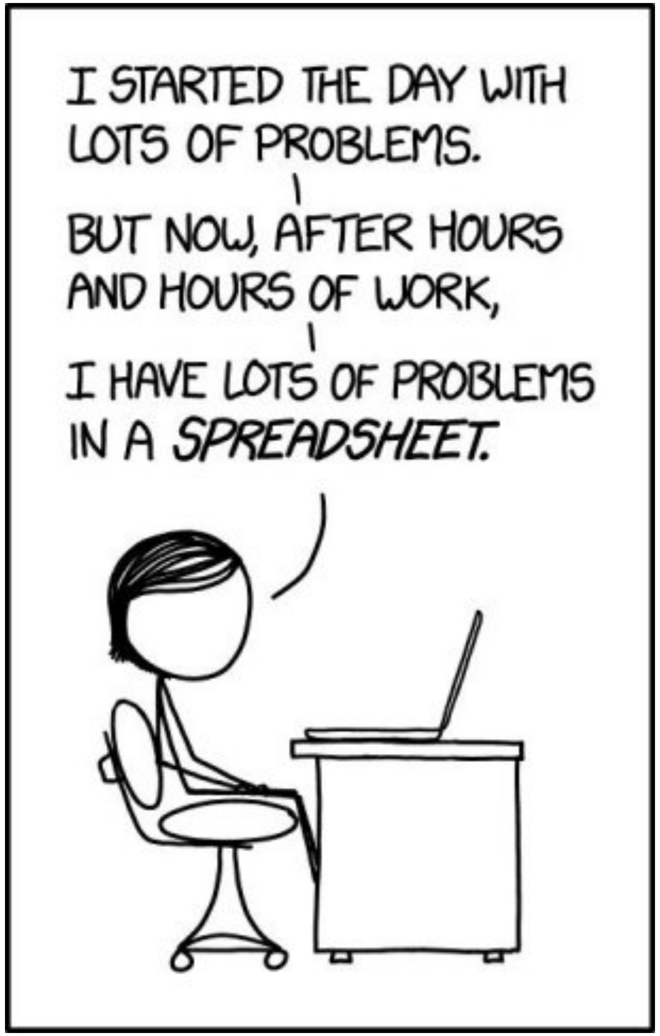
- Where to go from here?

  - **Tools/Machinery are set up!**
    ⮡ Get decent bounds from more involved processes
  - Inaccesseable operators?
    ⮡ We are open to ideas!
  - Completely different Processes?
    ⮡ To LHC or not to LHC?



Thanks!