# Automating NLO Effective Field Theory with MADGRAPH5\_AMC@NLO

Cen Zhang

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June 18th, 2015 Radcor-Loopfest, UCLA

Cen Zhang (BNL)

EFT@NLO in MG5

June 18

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Our goal: take the SM Effective Field Theory, promote it to NLO in QCD, and automate it with MADGRAPH5\_AMC@NLO.



Status:

- Predictions for some effective operators have started to become available.
- Automation of the complete SM EFT at dim-6 is planned.



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EFT@NLO in MG5

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# Outline



#### **Applications** 2

- Higgs EFT
- Top, FCNC sector
- Top, flavor diagonal sector
- DM collider signal ٥





### Outline



### 2 Applications

- Higgs EFT
- Top, FCNC sector
- Top, flavor diagonal sector
- DM collider signal

### B) Summary

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### Two approaches to BSM

### Model-dependent



SUSY, 2HDM, ED,...

### Model-independent

simplified models, EFT, ...

### Search for new states

specific models, simplified models

Search for new interactions

anomalous couplings, EFT...



### The EFT approach

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{C_{i}^{(6)}O_{i}^{(6)}}{\Lambda^{2}} + \mathcal{O}(\Lambda^{-4}) \qquad \Lambda = \text{NP scale}$$

- Data  $\Leftrightarrow$  Model-Independent EFT  $\Leftrightarrow$  BSM models
- BSM goal at the LHC: determination of SM EFT up to DIM=6

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### "SM EFT"

- Based on SM symmetries.
- Number of couplings reduced by symmetries and dimensional analysis.
- QCD and EW <u>RENORMALIZABLE</u> (order by order in 1/Λ).
  - Allows for NLO accuracy!

		$X^3$		$arphi^6$ and $arphi^4 D^2$		$\psi^2 arphi^3$
ſ	$Q_G$	$f^{ABC}G^{A u}_\mu G^{B ho}_ u G^{C\mu}_ ho$	$Q_{arphi}$	$(\varphi^{\dagger}\varphi)^{3}$	$Q_{e\varphi}$	$(arphi^\dagger arphi) (ar l_p e_r arphi)$
	$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}^{A u}_{\mu} G^{B ho}_{ u} G^{C\mu}_{ ho}$	$Q_{arphi\square}$	$(\varphi^{\dagger}\varphi)\Box(\varphi^{\dagger}\varphi)$	$Q_{u\varphi}$	$(\varphi^{\dagger}\varphi)(\bar{q}_{p}u_{r}\widetilde{\varphi})$
	$Q_W$	$\varepsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$	$Q_{\varphi D}$	$\left( arphi^{\dagger} D^{\mu} arphi  ight)^{\star} \left( arphi^{\dagger} D_{\mu} arphi  ight)$	$Q_{d\varphi}$	$(arphi^{\dagger}arphi)(ar{q}_p d_r arphi)$
	$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}^{I u}_{\mu}W^{J ho}_{\nu}W^{K\mu}_{ ho}$				
ſ		$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$
	$Q_{\varphi G}$	$\varphi^{\dagger}\varphi  G^{A}_{\mu u}G^{A\mu u}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu u} e_r) \tau^I \varphi W^I_{\mu u}$	$Q^{(1)}_{arphi l}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\overline{l}_{p}\gamma^{\mu}l_{r})$
	$Q_{arphi \widetilde{G}}$	$\varphi^{\dagger} \varphi  \widetilde{G}^{A}_{\mu  u} G^{A \mu  u}$	$Q_{eB}$	$(ar{l}_p \sigma^{\mu u} e_r) arphi B_{\mu u}$	$Q^{(3)}_{arphi l}$	$(arphi^\dagger i \overleftrightarrow{D}^I_\mu arphi) (ar{l}_p  au^I \gamma^\mu l_r)$
	$Q_{\varphi W}$	$\varphi^{\dagger}\varphi W^{I}_{\mu u}W^{I\mu u}$	$Q_{uG}$	$(ar q_p \sigma^{\mu u} T^A u_r) \widetilde arphi  G^A_{\mu u}$	$Q_{arphi e}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{e}_{p}\gamma^{\mu}e_{r})$
	$Q_{arphi \widetilde{W}}$	$\varphi^{\dagger} \varphi \widetilde{W}^{I}_{\mu\nu} W^{I\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu u} u_r) \tau^I \widetilde{\varphi} W^I_{\mu u}$	$Q^{(1)}_{arphi q}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu  arphi) (ar{q}_p \gamma^\mu q_r)$
	$Q_{\varphi B}$	$\varphi^{\dagger}\varphiB_{\mu u}B^{\mu u}$	$Q_{uB}$	$(ar q_p \sigma^{\mu u} u_r) \widetilde arphi  B_{\mu u}$	$Q^{(3)}_{arphi q}$	$(arphi^\dagger i \overleftrightarrow{D}^I_\mu arphi) (ar{q}_p  au^I \gamma^\mu q_r)$
	(11)(11)	+ 22 DUU (AR)(AR) (LL)(AR)	$Q_{dG}$	$(ar q_p \sigma^{\mu u} T^A d_r) arphi  G^A_{\mu u}$	$Q_{\varphi u}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{u}_{p}\gamma^{\mu}u_{r})$
41 42 42 42	(\$24)(67%) (\$24)(67%) (\$24)(67%)	$\begin{array}{llllllllllllllllllllllllllllllllllll$	$Q_{dW}$	$(ar{q}_p \sigma^{\mu u} d_r)  au^I arphi  W^I_{\mu u}$	$Q_{arphi d}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu arphi) (ar{d}_p \gamma^\mu d_r)$
$q_{ii}^{(i)}$	$(l_{\mu}\gamma_{\mu}\tau^{\mu}L)(d_{\mu}\gamma^{\mu}\tau^{\mu}\Phi)$ $(l_{\mu}\gamma_{\mu}\tau^{\mu}L)(d_{\mu}\gamma^{\mu}\tau^{\mu}\Phi)$	$\begin{array}{cccc} Q_{a} & (q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a} & (g_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a} & (q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}\gamma n_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}\gamma n_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) & Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}\gamma n_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}q_{a})(q_{1}q_{a})(q_{1}q_{a})(q_{1}q_{a}) \\ Q_{a}^{(2)} & (q_{1}q_{1}q_{a})(q_{1}q_{$	$Q_{dB}$	$(ar q_p \sigma^{\mu u} d_r) arphi  B_{\mu u}$	$Q_{\varphi ud}$	$i(\widetilde{arphi}^{\dagger}D_{\mu}arphi)(ar{u}_{p}\gamma^{\mu}d_{r})$
		$Q_{11}^{-1} = (0_{1}\gamma_{1}T\gamma_{0})(d_{1}\gamma^{*}T\gamma_{0}) = Q_{11}^{-1} = (b_{1}\gamma_{0})(d_{1}\gamma^{*}d_{1})$				
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0	(Re)(dd)	Que entre (sector)	1			
Q <sup>[1]</sup>	$(g_{n-})_{l,k}(\mathfrak{G}_{n})$	$Q_{qqu} = e^{\alpha P_1} e_{jk} [(q_i^{cj})^T C q_i^{lq}] [(q_i^c))^T C r_0]$				
$Q_{expl}^{[0]}$	$(\mathfrak{C}T^{A}\mathfrak{n}_{r})\mathfrak{e}_{k}(\mathfrak{C}T^{A}\mathfrak{d}_{r})$	$Q_{\text{res}}^{(1)} = e^{\alpha b_{\gamma}} e_{\mu \ell  \text{sm}} \left[ (g_{\tau}^{\mu})^T C g_{\tau}^{\prime h} \right] \left[ (g_{\tau}^{\mu\nu})^T C \eta_{\tau}^{\mu} \right]$				
$q_{\rm res}^0$	(Be.)e_u(@w.)	$Q_{im}^{cm} = e^{i\pi r} (r^{i} e)_{ii} (r^{i} e)_{im} [(Q^{i})^{T} C Q^{0}] [(Q^{in})^{T} C Q]$ $\rightarrow th (r m T C q R) (r m T C q)$				
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### "SM EFT"

#### Commonly used in

- Higgs coupling analysis
   Taking over the "κ-framework"
- Top coupling measurements Simplifies the "anomalous coupling" approach
- Dark matter EFT

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ĺ		$X^3$			$arphi^6$ and $arphi^4 D^2$		$\psi^2 \varphi^3$		
	$Q_G$	$f^{ABC}G^{A u}_{\mu}G^{B ho}_{ u}G^{C\mu}_{ ho}$		$Q_{\varphi}$	$(\varphi^{\dagger}\varphi)^{3}$	$Q_{e\varphi}$	$(\varphi^{\dagger}\varphi)(\bar{l}_{p}e_{r}\varphi)$		
	$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_{f}$	${}^{A u}_{\mu}G^{B ho}_{ u}G^{C\mu}_{ ho}$	$Q_{\varphi \Box}$	$(\varphi^{\dagger}\varphi)\Box(\varphi^{\dagger}\varphi)$	$Q_{uarphi}$	$(\varphi^{\dagger}\varphi)(\bar{q}_{p}u_{r}\widetilde{\varphi})$		
	$Q_W$	$\varepsilon^{IJK}W^I_\mu$	$^{\nu}W^{J ho}_{ u}W^{K\mu}_{ ho}$	$Q_{\varphi D}$	$\left( arphi^{\dagger} D^{\mu} arphi  ight)^{\star} \left( arphi^{\dagger} D_{\mu} arphi  ight)$	$Q_{darphi}$	$(arphi^\dagger arphi) (ar q_p d_r arphi)$		
	$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}^{I}_{\mu}$	$^{\nu}W^{J ho}_{ u}W^{K\mu}_{ ho}$						
ſ		$X^2 \varphi^2$			$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$		
Ĩ	$Q_{arphi G}$	$\varphi^{\dagger}\varphi  G^{A}_{\mu u}G^{A\mu u}$		$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{arphi l}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\overline{l}_{p}\gamma^{\mu}l_{r})$		
	$Q_{arphi \widetilde{G}}$	$arphi^\dagger arphi  \widetilde{G}^A_{\mu u} G^{A\mu u}$		$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q^{(3)}_{arphi l}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}^{I}\varphi)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r})$		
	$Q_{\varphi W}$	$arphi^{\dagger}arphi$ V	$V^{I}_{\mu u}W^{I\mu u}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu u} T^A u_r) \widetilde{\varphi}  G^A_{\mu u}$	$Q_{arphi e}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{e}_{p}\gamma^{\mu}e_{r})$		
	$Q_{\varphi \widetilde{W}}$	$arphi^{\dagger}arphi \widehat{V}$	$\widetilde{V}^{I}_{\mu u}W^{I\mu u}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu u} u_r) \tau^I \widetilde{\varphi} W^I_{\mu u}$	$Q^{(1)}_{\varphi q}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu arphi) (ar{q}_p \gamma^\mu q_r)$		
	$Q_{\varphi B}$	$\varphi^{\dagger} \varphi$ .	$B_{\mu u}B^{\mu u}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu u} u_r) \widetilde{\varphi} B_{\mu u}$	$Q^{(3)}_{arphi q}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}^{I}\varphi)(\bar{q}_{p} au^{I}\gamma^{\mu}q_{r})$		
	(11)(11)	+ (ÂR)(ÂR)	CL1)(kn)	$Q_{dG}$	$(ar{q}_p \sigma^{\mu u} T^A d_r) arphi  G^A_{\mu u}$	$Q_{\varphi u}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu  arphi) (ar{u}_p \gamma^\mu u_r)$		
10.42	((,+,,L)((,+,+)) ((,+,,L)((,+,+)) ((,+,+,+)((,+,+)) ((,+,+,+)((,+,+,+))	$\begin{array}{cccccccccccccccccccccccccccccccccccc$		$Q_{dW}$	$(ar{q}_p \sigma^{\mu u} d_r)  au^I arphi W^I_{\mu u}$	$Q_{arphi d}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu arphi) (ar{d}_p \gamma^\mu d_r)$		
104.004	$(\tilde{l}_{\mu}\gamma_{\mu}\tau^{\mu}L)(\tilde{q}_{\nu}\gamma^{\mu}q_{\mu})$ $(\tilde{l}_{\mu}\gamma_{\mu}\tau^{\mu}L)(\tilde{q}_{\nu}\gamma^{\mu}\tau^{\mu}q_{\mu})$	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$		$Q_{dB}$	$(ar q_p \sigma^{\mu u} d_r) arphi  B_{\mu u}$	$Q_{arphi u d}$	$i(\widetilde{arphi}^{\dagger}D_{\mu}arphi)(ar{u}_{p}\gamma^{\mu}d_{r})$		
		$Q_{ud}^{(0)} = \langle 0_{\mu} \gamma_{\nu} T^{\mu} \eta_{\nu} \rangle \langle d_{\nu} \gamma^{\mu} T$	${}^{t}\mathcal{L}_{0}$ $\left  \begin{array}{c} Q_{qd}^{(1)} & (q_{0}\gamma_{1}q_{0})(\vec{e}_{1}\gamma^{a}d_{0}) \\ Q_{qd}^{(2)} & (q_{0}\gamma_{1}T^{a}q_{0})(\vec{e}_{1}\gamma^{a}T^{b}d_{0}) \\ \end{array} \right $						
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EFT@NLO in MG5

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### Renomalization

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- Allows for renormalization order by order in  $1/\Lambda^2$
- Predictions can be systematically improved, by going to higher order in  $\alpha_s$ ,  $1/\Lambda^2$ ,...

$$1 + \mathcal{O}(\alpha_s) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \cdots$$

### SM NLO EFT EFT@NLO

• But, operators mix:  $dC_i/d \ln \mu = \gamma_{ij}C_j$ ,  $\gamma_{ij} = 2499 \times 2499$  matrix

### Renomalization

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SM NLO EFT EFT @ NLO

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### MG5\_aMC@NLO

[J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro, 1405.0310]



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# Simulation chain @ LO accuracy

Model (Lagrangian)

↓ FeynRules

• Feynman Rules (in UFO form)

**↓** MadGraph

• Matrix element (matrix.f)

**↓** MADEVENT

• Parton level (events.lhe)

↓ PYTHIA/HERWIG

• Hadron level (events.hep)

**↓** PGS/DELPHES

Detector level

(E)

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Detector level

```
_ Upgrade to NLO:
MadGraph5_aMC@NLO
```

1405.0301 J. Alwall et al.



(E)

# MadGraph5\_aMC@NLO

### Event Generation at NLO LIKE AT LO

### Process generation

- import model <model\_name>-<restrictions>
- generate <process> <amp\_orders\_and\_option>
  [<mode>=<pert\_orders>]
- output <format> <folder\_name>
- launch <options>

### e.g.

#### tt production:

- > generate p p > t t~ [QCD]
- > output
- > launch

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## Simulation chain @ NLO accuracy



# Simulation chain @ NLO accuracy



# Two missing ingredients for NLO

### UV counterterms

- ► Renormalize the Lagrangian: Fields:  $\phi_0 \rightarrow (1 + \frac{1}{2}\delta Z_{\phi\phi})\phi + \sum_{\chi} \frac{1}{2}\delta Z_{\phi\chi}\chi$ ext. params:  $x_0 \rightarrow x + \delta x$ int. params:  $g(x_0) \rightarrow g(x) + \delta g$
- Compute loops and apply renorm. conditions.

### R2 counterterms

- ► Loop amplitude:  $\frac{1}{(2\pi)^4} \int d^d \bar{q} \frac{\bar{N}(\bar{q})}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}, \ \bar{D}_i = (\bar{q} + p_i)^2 m_i^2$
- Problem: numerical technique only evaluates the 4-dimensional part.
- Solution: isolate the  $\varepsilon$ -dim part of numerator:  $\overline{N}(\overline{q}) = N(q) + \widetilde{N}(\widetilde{q}, q, \varepsilon)$ Then calculate  $\varepsilon$  part analytically, once and for all.

$$R2 \equiv \lim_{\varepsilon \to 0} \frac{1}{(2\pi)^4} \int d^d \bar{q} \frac{\tilde{N}(\bar{q})}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

Good news: now both available with NLOCT

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- Problem: numerical technique only evaluates the 4-dimensional part.
- Solution: isolate the  $\varepsilon$ -dim part of numerator:  $\overline{N}(\overline{q}) = N(q) + \widetilde{N}(\widetilde{q}, q, \varepsilon)$ Then calculate  $\varepsilon$  part analytically, once and for all.

$$R2 \equiv \lim_{\varepsilon \to 0} \frac{1}{(2\pi)^4} \int d^d \bar{q} \frac{\tilde{N}(\bar{q})}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

Good news: now both available with NLOCT

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EFT@NLO in MG5

A B > A B >

5. SBOOKHAVEN

Celine Degrande

# FeynRules structure @ NLO



# Simulation chain @ NLO accuracy



### NLO models

### Automatic NLO in QCD + PS available in

- SM 🗸
- BSM, if renormalizable
  - thanks to FEYNRULES+NLOCT+UFO
- Non-renormalizable models  $\Rightarrow$  EFT @ NLO
  - ▶ Work in progress...
  - Will complete the BSM ability of MG5.

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## NLO models

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# Missing ingredients for NLO EFT

### • UV counterterms

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- Coming from mixing matrix (2499X2499).
- Large project: calculate loops, identify UV divergence, use EoM and other identities to project onto standard dim-6 operator basis.

# Missing ingredients for NLO EFT

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Renormalization Group Evolution of the Standard Model Dimension Six Operators

III: Gauge Coupling Dependence and Phenomenology

Rodrigo Alonso,<sup>a</sup> Elizabeth E. Jenkins,<sup>a</sup> Aneesh V. Manohar,<sup>a</sup> Michael Trott<sup>b,1</sup>

<sup>a</sup> Department of Physics, University of California at San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0319, USA
<sup>b</sup> Theory Division, Physics Department, CERN, CH-1211 Geneva 23, Switzerland *E-mail*: ralonsod@ucsd.edu, ejenkins@ucsd.edu, amanohar@ucsd.edu,

michael.trott@cern.ch

ABSTRACT: We calculate the gauge terms of the one-loop anomalous dimension matrix for the dimension-six operators of the Standard Model effective field theory (SM EFT). Combining these results with our previous results for the  $\lambda$  and Yukawa coupling terms completes the calculation of the one-loop anomalous dimension matrix for the dimension-six operators.

There are 1350 *CP*-even and 1149 *CP*-odd parameters in the dimension-six Lagrangian for 3 generations, and our results give the entire 2499 × 2499 anomalous dimension matrix. We

discuss how the renormalization of the dimension-six operators, and the additional renormalization of the dimension  $d \leq 4$  terms of the SM Lagrangian due to dimension-six operators,

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# Missing ingredients for NLO EFT

### UV counterterms

- Coming from mixing matrix (2499X2499).
- Large project: calculate loops, identify UV divergence, use EoM and other identities to project onto standard dim-6 operator basis.

### R2 counterterms

- Mostly ok with NLOCT.
- Exceptions: 4-quark operators
  - Loop induced fermion flow:  $\gamma^{\mu} P_L \otimes \gamma_{\mu} P_L \Rightarrow \gamma^{\mu} \gamma^{\nu} \gamma^{\rho} P_L \otimes \gamma_{\mu} \gamma_{\nu} \gamma_{\rho} P_L$
  - Problem: Cannot be reduced to the standard 4-fermion operator basis (which is not complete in D dimension)
  - Solution: Need to define E="evanescent" operators,
    - $\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}P_{L}\otimes\gamma_{\mu}\gamma_{\nu}\gamma_{\rho}P_{L}=4(4-(x)\varepsilon)\gamma^{\mu}P_{L}\otimes\gamma_{\mu}P_{L}+E$
  - Result: Scheme dependence enters R2.

# NLO EFT strategy

- While existing automation is not feasible for an effective theory start from arbitrary operator, we proceed by considering certain subsets of operators and processes.
- Choose operator sets that are:
  - "Closed" under RG runnning.
  - Relevant for LHC.
  - E.g.
    - HEFT
    - ▶ Тор
    - DM, EFT and simplified models
    - ▶ ...
- Long term goal is to have complete dim-6 Lagrangian.

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### Outline



### 2 Applications

- Higgs EFT
- Top, FCNC sector
- Top, flavor diagonal sector
- DM collider signal

### B) Summary

# Outline



#### **Applications** 2

- Higgs EFT



# Higgs characterisation

HCI: "A framework for Higgs characterisation" Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro, JHEPII (2013)043 [arXiv:1306.6464]

►HC2: "Higgs characterisation via VBF/VH: NLO and parton-shower effects" Maltoni, Mawatari, Zaro, EPJC74(2014)2710 [arXiv:1311.1829]

►HC3: "Higgs characterisation at NLO in QCD: CP properties of the top Yukawa" Demartin, Maltoni, Mawatari, Page, Zaro, EPJC74(2014)3065 [arXiv:1407.5089]

►HC4: Higgs production in association with a single top quark at the LHC Demartin, Maltoni, Mawatari, Zaro, EPJCxx(2015)xxxx [arXiv:1504.00611]

Sec.11 (spin/CP) in YR3 of the LHC Higgs Cross Section Working Group (HXSWG) de Aquino, Mawatari [arXiv:1307.1347]

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# Higgs characterisation

- Framework for studying Higgs couplings
- The following operators are implemented: (in EW broken phase)

$$\begin{split} \mathcal{L}_{0}^{f} &= -\sum_{\substack{t=t,b,\tau\\ t=t,b,\tau}} \bar{\psi}_{f} \Big( c_{\alpha} \kappa_{Hff} g_{Hff} + i s_{\alpha} \kappa_{Aff} g_{Aff} \gamma_{5} \Big) \psi_{f} X_{0} \\ \mathcal{L}_{0}^{V} &= \bigg\{ c_{\alpha} \kappa_{SM} \Big[ \frac{1}{2} g_{HZZ} Z_{\mu} Z^{\mu} + g_{HWW} W_{\mu}^{+} W^{-\mu} \Big] \\ &- \frac{1}{4} \Big[ c_{\alpha} \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_{\alpha} \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \widetilde{A}^{\mu\nu} \Big] \\ &- \frac{1}{2} \Big[ c_{\alpha} \kappa_{H2\gamma} g_{H2\gamma} Z_{\mu\nu} A^{\mu\nu} + s_{\alpha} \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \widetilde{A}^{\mu\nu} \Big] \\ &- \frac{1}{4} \Big[ c_{\alpha} \kappa_{H2\gamma} g_{H2\gamma} Z_{\mu\nu} A^{\mu\nu} + s_{\alpha} \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \widetilde{A}^{\mu\nu} \Big] \\ &- \frac{1}{4} \Big[ c_{\alpha} \kappa_{H2\gamma} g_{H\gamma} Z_{\mu\nu} Z^{\mu\nu} + s_{\alpha} \kappa_{A\gamma\gamma} g_{A\gamma\gamma} Z_{\mu\nu} \widetilde{A}^{\mu\nu} \Big] \\ &- \frac{1}{4} \Big[ c_{\alpha} \kappa_{H2\gamma} Z_{\mu\nu} Z^{\mu\nu} + s_{\alpha} \kappa_{A\gamma\gamma} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \Big] \\ &- \frac{1}{2} \frac{1}{4} \Big[ c_{\alpha} \kappa_{H2\gamma} Z_{\mu\nu} Z^{\mu\nu} + s_{\alpha} \kappa_{A\chi\nu} W_{\mu\nu}^{+} \widetilde{W}^{-\mu\nu} \Big] \\ &- \frac{1}{4} \Big[ c_{\alpha} \kappa_{H0\gamma} A_{\nu} \partial_{\mu} A^{\mu\nu} + \kappa_{H02} Z_{\nu} \partial_{\mu} Z^{\mu\nu} \\ &+ \Big( \kappa_{H0W} W_{\nu}^{+} \partial_{\mu} W^{-\mu\nu} + h.c. \Big) \Big] \bigg\} X_{0} \end{split}$$

parameter	description
$\Lambda ~[{ m GeV}]$	cutoff scale
$c_{\alpha} (\equiv \cos \alpha)$	mixing between $0^+$ and $0^-$
$\kappa_i$	dimensionless coupling parameter

Higgs EFT

# Higgs characterisation: ttH





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#### EFT@NLO in MG5

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# Outline



### 2 Applications

- Higgs EFT
- Top, FCNC sector
- Top, flavor diagonal sector
- DM collider signal

### <sup>3</sup> Summary



# Top FCNC@NLO

- C. Degrande, F. Maltoni, J. Wang and CZ, arXiv:1412.5594 Automatic NLO for FCNC processes.
- G.Duriex, F. Maltoni and CZ, arXiv:1412.7166 A global approach to FCNC couplings.





$$\begin{split} & O_{\mathcal{U}G}^{(13)} = y_t g_S(\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} \\ & O_{\mathcal{U}W}^{(13)} = y_t g_W(\bar{q}\sigma^{\mu\nu}\tau^l t)\tilde{\varphi}W^l_{\mu\nu} \\ & O_{\mathcal{U}B}^{(13)} = y_t g_Y(\bar{q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu} \\ & O_{\mathcal{U}g}^{(13)} = -y_t^3(\varphi^{\dagger}\varphi)(\bar{q}t)\tilde{\varphi} \end{split}$$



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### **FCNC** operators

$$\begin{aligned} & (\bar{u}\gamma^{\mu}t)Z_{\mu} \\ & O_{\varphi Q}^{(3,1+3)} = i\left(\varphi^{\dagger}\tau^{I}D_{\mu}\varphi\right)\left(\bar{q}\gamma^{\mu}\tau^{I}Q\right) \\ & O_{\varphi Q}^{(1,1+3)} = i\left(\varphi^{\dagger}D_{\mu}\varphi\right)\left(\bar{q}\gamma^{\mu}Q\right) \\ & O_{\varphi u}^{(1+3)} = i\left(\varphi^{\dagger}D_{\mu}\varphi\right)\left(\bar{u}\gamma^{\mu}t\right) \end{aligned}$$

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

$$\begin{aligned} O^{(13)}_{uW} &= (\bar{q}\sigma^{\mu\nu}\tau^l t)\tilde{\varphi}W^l_{\mu\nu}\\ O^{(13)}_{uB} &= (\bar{q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu} \end{aligned}$$

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

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

ūth, "Yukawa"

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





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EFT@NLO in MG5

# FCNC processes

- We provide an NLO UFO based on dim-6 FCNC operators, that allows to make NLO predictions in an automatic way.
- Focus on single top production *pp* → *tγ*, *pp* → *tZ*, *pp* → *th*.
  - Competitive limits
  - More kinematic variables accessible.
  - Probe higher scale.
  - NLO corrections are significant.





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Top, FCNC sector

# FCNC production at NLO

your\_shell> ./bin/mg5
MG5\_aMC> import model Top\_FCNC
MG5\_aMC> generate p p > t z \$\$ t~ NP=2 [QCD]
MG5\_aMC> output
MG5\_aMC> launch

#### $pp \rightarrow tZ$

		LO	NLO				
Coefficient	$\sigma[{\rm fb}]$	Scale uncertainty	$\sigma[{\rm fb}]$	Scale uncertainty			
$C_{\varphi u}^{(1+3)} = 1.0$	905	+12.9% - 10.9%	1163	+6.2% - 5.6%			
$C_{uW}^{(13)} = 0.9$	1737	+11.5% - 9.8%	2270	+6.6% - 6.2%			
$C_{uG}^{(13)} = 0.04$	30.1	+17.5% - 13.8%	36.0	+3.8% - 5.2%			
$C_{uG}^{(31)} = 0.04$	29.4	+17.7% - 13.9%	34.9	+3.4% - 5.1%			
$C^{(2+3)}_{\varphi u} = 1.0$	73.2	+10.4% - 9.3%	107	+6.5% - 5.9%			
$C_{uW}^{(23)} = 1.1$	172	+7.5% - 7.2%	255	+6.1% - 5.2%			
$C_{uG}^{(23)} = 0.09$	6.92	+11.3% - 9.9%	10.6	+5.8% - 5.4%			
$C_{uG}^{(32)} = 0.09$	6.58	+11.5% - 10.1%	10.0	+5.7% - 5.3%			

 $pp \rightarrow t\gamma$ 

		LO	NLO				
Coefficient	$\sigma[{\rm fb}]$	Scale uncertainty	$\sigma$ [fb]	Scale uncertainty			
$C_{uB}^{(13)} = 1.0$	546	+14.4% - 11.8%	764	+6.9% - 6.4%			
$C_{uG}^{(13)} = 0.04$	1.00	+12.0%-10.2%	2.34	+15.2% - 11.5%			
$C_{uG}^{(13)}$ , veto	0.739	+11.50% - 9.8%	1.19	+7.7% - 6.5%			
$C_{uB}^{(23)} = 1.9$	152	+10.6% - 9.6%	258	+6.8% - 6.0%			
$C_{uG}^{(23)} = 0.09$	0.590	+12.1% - 11.1%	1.95	+16.4% - 12.3%			
$C_{uG}^{(23)}$ , veto	0.457	+12.2% - 11.2%	1.04	+10.3% - 8.9%			

#### $\textit{pp} \rightarrow \textit{th}$

		LO	NLO				
Coefficient	$\sigma[{\rm fb}]$	Scale uncertainty	$\sigma[{\rm fb}]$	Scale uncertainty			
$C_{u\varphi}^{(13)} = 3.5$	2603	+13.0% - 11.0%	3858	+7.4% - 6.7%			
$C_{uG}^{(13)} = 0.04$	40.1	+16.5% - 13.2%	50.7	+4.0% - 5.2%			
$C_{u\phi}^{(23)} = 3.5$	171	+9.7% - 8.7%	310	+7.3% - 6.3%			
$C_{uG}^{(23)} = 0.09$	9.53	+11.0% - 9.7%	16.6	+5.5% - 5.1%			

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# Outline





### Applications

- Higgs EFT
- Top, FCNC sector
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- DM collider signal

### 3 Summary



# Chromo-dipole operator

Top-CMDM in  $t\bar{t}$  production [D. B. Franzosi and CZ]

•  $\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + C_{tG}O_{tG}/\Lambda^2$ 

your\_shell> ./bin/mg5 MG5\_aMC> import model Top\_EFT\_model MG5\_aMC> generate p p > t t  $\sim$  EFT=1 [QCD] MG5\_aMC> output some\_DIR MG5 aMC> launch



• Total cross section: K = 1.43 at LHC 8 TeV

#### Cross sections

$\beta_1$	LO [pb TeV <sup>2</sup> ]	NLO [pb TeV <sup>2</sup> ]	K factor
Tevatron	$1.61^{+0.66}_{-0.43} \ (-27\%)$	$1.810^{+0.073}_{-0.197} \stackrel{(+4.05\%)}{_{(-10.88\%)}}$	1.12
LHC8	$50.7^{+17.3}_{-12.4} (+34\%)_{(-25\%)}$	$72.62^{+9.26}_{-10.53}$ $^{(+12.7\%)}_{(-14.5\%)}$	1.43
LHC13	$161.6^{+48.0}_{-36.2}$ $(+29.7\%)_{(-22.4\%)}$	$239.5^{+29.0}_{-31.8} \ {}^{(+12.1\%)}_{(-13.3\%)}$	1.48
LHC14	$191.3^{+55.6}_{-42.2}$ $(+29.0\%)$	$283.0^{+33.6}_{-36.9} \stackrel{(+11.9\%)}{_{(-13.1\%)}}$	1.48



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### Chromo-dipole operator

- Distributions
  - $A_{FB}=0.095+C_{tG} imes 0.021({
    m TeV}/\Lambda)^2$
- Spin correlation taken into account by MADSPIN.



# Full set of top couplings

ttγ/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

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

● ttZ

V/A

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

ttH

$$O_{t\varphi} = (\varphi^{\dagger}\varphi)(\bar{Q}t)\tilde{\varphi}$$

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# Towards NLO global analysis

Process	$O_{tG}$	$O_{tB}$	$O_{tW}$	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$	O <sub>4f</sub>	$O_G$	$O_{\varphi G}$
$t \rightarrow bW \rightarrow bl^+ \nu$	Х		Х	X	1			Х		
ho p  ightarrow tar q	Х		Х	Х				Х		
ho p  ightarrow t W	Х		Х	Х				Х	Х	Х
$pp  ightarrow t\overline{t}$	Х						Х	Х	Х	Х
$pp  ightarrow t \overline{t} \gamma$	Х	Х	Х				Х	Х	Х	Х
$pp  ightarrow t \overline{t} Z$	Х	Х	Х	Х	Х	Х	Х	Х	Х	Х
$pp  ightarrow t\overline{t}h$	Х						Х	Х	Х	Х

 $(O_G = g_s t^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\rho} G^{C\mu}_{\rho} \text{ and } O_{\varphi G} = g_s^2 \left(\varphi^{\dagger} \varphi\right) G^A_{\mu\nu} G^{A\mu\nu} \text{ are included because they mix with other top-quark operators and play a role in NLO calculations.)}$ 

we aim to provide:

- NLO simulation for all " $pp \rightarrow \cdots$ " processes.
- All two-quark operators included.
- Four-fermion operators planned.

i.e. everything needed for a global analysis of top couplings at NLO accuracy.



### Some preliminary results:



Weak dipole  $(O_{tW})$  in:

- Top left: *t*-channel single top,  $p_T$  top, LHC8.
- Top right: *ttZ* production,  $p_T$  Z, LHC13. ۲
- Bottom right: *ttZ* production,  $\Delta_{\phi}$  of • leptons from Z, LHC13.

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#### ttZ @ LHC13, pT of Z





# Outline



### 2 Applications

- Higgs EFT
- Top, FCNC sector
- Top, flavor diagonal sector
- DM collider signal

### Summary



### DM at collider

- Early Run I searches for mono-X signatures at ATLAS and CMS were based on DM EFT.
- However, it has become clear that a contact interaction is often not the correct description for the signals to which the LHC is sensitive.
- While the EFT integrates out the degrees of freedom of the (heavy) intermediate particle, "simplified models" with directly accessible mediators describe this richer phenomenology.



Technically, simplified models are also simpler to implement...

# ATLAS-CMS DM forum



 Currently, NLO implementation available only for mono-*j* and mono-γ in EFT, with POWHEG and MCFM.

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# DM with MG5\_aMC

### • DM simplified models in the FeynRules/NLOCT and MG5\_aMC framework

- DM simplified model: C. Degrande (Durham), K. Mawatari (VU Brussels), J. Wang (Mainz), CZ
- mono-j with vector mediator: F. Maltoni, M. Backovic, A. Martini (UC Louvain), K. Mawatari (VU Brussels)
- mono-j with scalar mediator: M. Kraemer, M. Pellen (Aachen)
- mono-EW: M. Neubert, J. Wang (Mainz), CZ
- Ioop-induced: O. Mattelaer, E. Vryonidou (UC Louvain)
- t-channel models: B. Fuks,... (Strasbourg)
- To provide a public framework (for experimentalists) to perform accurate and automatic simulations for DM production.
- Equally useful for theorists (user friendly, flexible framework, can be systematically improved).

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### Status

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• s-channel simplified model.

$$\begin{split} \mathcal{L}_{X_D}^{\gamma_0} &= \frac{1}{2} \Lambda g_{X_R}^S X_R X_R Y_0 \\ &+ \Lambda g_{X_C}^S X_C^* X_C Y_0 \\ &+ \overline{X}_D (g_{X_D}^S + i g_{X_D}^P) X_D Y_0 \end{split}$$

$$egin{aligned} \mathcal{L}_{SM}^{\mathbf{Y}_{\mathbf{0}}} &= \sum_{i,j} \left[ ar{d}_i(g_{d_{ij}}^S + ig_{d_{ij}}^{\mathcal{P}}) d_j 
ight. \ &+ ar{u}_i(g_{u_{ij}}^S + ig_{u_{ij}}^{\mathcal{P}}) u_j 
ight] \mathbf{Y}_{\mathbf{0}} \end{aligned}$$

$$\mathcal{L}_{SMg}^{Y_0} = \frac{1}{\Lambda} G_{\mu\nu}^a (g_g^S G^{a,\mu\nu} + g_g^P \tilde{G}^{a,\mu\nu}) Y_0$$

$$\mathcal{L}_{SM EW}^{Y_0} = \frac{1}{\Lambda} g_{h1}^S (D^{\mu}\phi)^{\dagger} (D_{\mu}\phi) Y_0 + g_{h2}^S \Lambda |\phi|^2 Y_0$$

$$+ \frac{1}{\Lambda} B_{\mu\nu} (g_g^S B^{\mu\nu} + g_B^P \tilde{B}^{\mu\nu}) Y_0$$

 $+ \frac{1}{4} W^{i}_{\mu\nu} (g^{S}_{W} W^{i,\mu\nu} + g^{P}_{W} \tilde{W}^{i,\mu\nu}) Y_{0}$ 

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### **Status**

• s-channel simplified model.

$$\begin{split} \mathcal{L}_{X_D}^{Y_1} &= \frac{i}{2} g_{X_C}^V (X_C^*(\partial_\mu X_C) - (\partial_\mu X_C^*) X_C) Y_1^\mu \\ &+ \overline{X}_D \gamma_\mu (g_{X_D}^V + i \gamma_5 g_{X_D}^A) X_D Y_1^\mu \end{split}$$

$$\begin{split} \mathcal{L}_{SM}^{\mathbf{Y}_{1}} &= \sum_{i,j} \left[ \bar{d}_{i} \gamma_{\mu} (g_{d_{ij}}^{V} + ig_{d_{ij}}^{A} \gamma_{5}) d_{j} \right. \\ &+ \bar{u}_{i} \gamma_{\mu} (g_{d_{ij}}^{V} + ig_{d_{ij}}^{A} \gamma_{5}) u_{j} \right] \mathbf{Y}_{1}^{\mu} \end{split}$$

$$\mathcal{L}_{SM\,EW}^{Y_1} = g_h^V \, \frac{i}{2} \left( \phi^\dagger D_\mu \phi - D_\mu \phi^\dagger \phi \right) \, Y_1^\mu$$



# s-channel validation

### Spin-1 mediator

### $\tau^+\tau^-+j$

- > (import model loop\_sm)
- > generate p p > ta- ta+ j / a
  [QCD]
- > output
- > launch

### Spin-0 mediator

### $t\bar{t}\tau^+\tau^-$

- > (import model loop\_sm)
- > output
- > launch

#### DM+j

- > import model DMsimp\_NLO
- > generate p p > xd xd~ j
  [QCD]
- > output
- > launch

#### DM+tt

- > import model DMsimp\_NLO
- > generate p p > t t~ xd xd~
  [QCD]
- > output
- > launch

### s-channel validation

• SM Z + H production vs. mediator production

#### SM Z + H

- > (import model loop\_sm)
- > generate p p > z h [QCD]
- > output
- > launch



### $Z + Y_0$

- > import model DMsimp\_EW\_NLO
- > generate p p > z y0 /a
  STR=0 EW=1 [QCD]
- > output
- > launch

#### $Y_1 + H$

- > import model DMsimp\_NLO
- > generate p p > y1 h STR=0
   EW=1 [QCD]
- > output
- > launch



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### Status

- s-channel simplified model.
  - ► mono-j/Z



### DM k factor

- A scan over DM and mediator masses
- $(\bar{X}_D \gamma^\mu X_D) Y_{1\mu}, Y_{1\mu} (\bar{q} \gamma^\mu q)$
- LHC13,  $\mu = \sum_{i} M_{T,i}/2$

$m_{DM}/{ m GeV}$		$M_{med}/{ m GeV}$									
1	10	20	50	100	200	300	500	1000	2000	10000	
10	10	15	50	100						10000	
50	10		50	95	200	300				10000	
150	10				200	295	500	1000		10000	
500	10						500	995	2000	10000	
1000	10							1000	1995	10000	

$m_{DM}/{ m GeV}$					K-fa	actor				
1	1.52	1.52	1.52	1.47	1.43	1.39	1.38	1.36	1.30	1.30
10	1.51	1.50	1.51	1.45						1.28
50	1.43		1.44	1.46	1.42	1.39				1.31
150	1.38				1.38	1.41	1.38	1.36		1.26
500	1.35						1.36	1.37	1.31	1.26
1000	1.26							1.27	1.31	1.16

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### Status

- s-channel simplified model.
  - ► mono-j/Z
  - mono-ttbar

# DM example: mono-ttbar



### Status

- s-channel simplified model.
  - mono-j/Z
  - mono-ttbar
  - loop-induced (new feature, see Monday talk [Valentin Hirschi, Olivier Mattelaer])

# DM example: loop-induced mono-j



### Status

- s-channel simplified model.
  - ► mono-j/Z
  - mono-ttbar
  - loop-induced
  - ▶ ...
- More benchmark models/processes coming soon.



### Outline



### Summary

Our goal: take the SM Effective Field Theory, promote it to NLO in QCD, and automate it with MADGRAPH5\_AMC@NLO.

Status:

- Predictions for some effective operators have started to become available.
  - Completed: H characterisation, Top FCNC, Top color dipole.
  - Under validation: HEFT, Top EW, DM simplified models.
  - Planned: Top-Higgs, Top CP-odd, four-quark contact, DM EFT...
- Final goal: complete SM EFT at dim-6.

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### Backups



### NLO elements

- Virtual: MadLoop (+CutTools)
  - Loop integral reduction using OPP method.
  - Need UV and R2 counterterms.

$$\begin{split} A(\bar{q}) &= \frac{N(q)}{D_0 D_1 \cdots D_{m-1}}, \qquad N(q) &= \sum_{\substack{i_0 < i_1 < i_2 < i_3 \\ i_0 < i_1 < i_2 < i_3 \\ i_0 < i_1 < i_2 < i_3 \\ i_0 < i_1 < i_2 \\ i_0 < i_1 < i_1 \\ i_0 < i_1 \\ i_0 < i_1 \\ i_1 \\ i_0 < i_1 \\ i_$$

### Real: MadFKS

- Computes real ME and soft-collinear counterterms.
- Organizes the integration of n and n+1 body cross section.
- Generates events to be showered.

EFT@NLO in MG5

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#### Summar

### FCNC results

•  $pp \rightarrow t\gamma$  and  $pp \rightarrow th$  at NLO+PS:  $p_T$  distribution for top (A=1 TeV)

 $pp \rightarrow t\gamma$ 





# Toy fit FCNC

#### a global fit for the FCNC sector at NLO can already be performed.



### Toy fit flavor-diagonal

Use 8 TeV data, total cross section only.

- Following processes are included
  - W helicity from top decay.
  - tt production.
  - Single top production, all 3 channels.
  - $t\bar{t}Z$  and  $t\bar{t}\gamma$ .
  - Assuming  $Z \rightarrow b\bar{b}$  takes the SM value.
- Simple χ<sup>2</sup> fit.
- Limits (Λ = 1 TeV, 95%) (preliminary)

	$C_{tG}$	$C^{(-)}_{\phi Q}$	$C_{\phi t}$	$C_{tB}$	$C_{tW}$
NLO	[4 .3]	[-3.2,1.7]	[-9.0,5.9]	[-163,373]	[-2.4,1.4]
LO	[6 .5]	[-3.6,1.9]	[-10.6,6.9]	[-222,506]	[-2.4,1.6]

 Key message: this is not a serious fit, but it demonstrates that the theoretical ingredients for performing a global fit are already available.



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Summary

### DM example: mono-Z



### Mono-Z at LHC 13:

- $(\bar{X}_D \gamma^\mu X_D)(\bar{q}\gamma^\mu q)$
- *M<sub>Med</sub>* = 1000 GeV.
- Cuts follow CMS mono-Z at 8 TeV.

Top left: Fixed order. Top right: PS. Bottom right: PS + jet veto.



Cen Zhang (BNL)

EFT@NLO in MG5

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### DM example: mono-Z



### Mono-Z at LHC 13:

- $(\bar{X}_D \gamma^\mu \gamma^5 X_D) (\bar{q} \gamma^\mu \gamma^5 q)$
- M<sub>Med</sub> = 1000 GeV.
- ۰ Cuts follow CMS mono-Z at 8 TeV.

Top left: Fixed order. Top right: PS. Bottom right: PS + jet veto.



EFT@NLO in MG5

Summary

### DM example: mono-Z



### Mono-Z at LHC 13:

- $i(X_c^{\dagger}\partial_{\mu}X_c \partial_{\mu}X_c^{\dagger}X_c)(\bar{q}\gamma^{\mu}q)$
- *M<sub>Med</sub>* = 1000 GeV.
- Cuts follow CMS mono-Z at 8 TeV.

Top left: Fixed order. Top right: PS. Bottom right: PS + jet veto.



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