

NLO Predictions in Effective Field Theory with MadGraph5_aMC@NLO

Cen Zhang

Brookhaven National Laboratory

May 20th, 2015
MC4BSM, Fermilab



- Predictions for EFT at NLO have started to become available through the MadGraph5_aMC@NLO platform.
- Automation of the complete SM EFT at dim-6 is planned.

Outline

1 EFT@NLO motivation

2 Applications

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

3 Summary

Outline

1 EFT@NLO motivation

2 Applications

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

3 Summary

EFT@NLO motivation

- NLO predictions in SM are automated in MG5. Ready to explore BSM possibilities.

- ▶ Renormalizable theories are taken care of by **NLOCT**, which provides UV and R2 counterterms, required at NLO.

Celine Degrande
1406.3030

- ▶ ⇒ Nonrenormalizable theories \approx EFT.

- EFT is principle “model-independent” (when new scales are heavy enough)
 - ▶ Good to have accurate and realistic predictions of rates and shapes in EFT \Rightarrow NLO+PS

EFT@NLO motivation

- NLO predictions in SM are automated in MG5. Ready to explore **BSM** possibilities.

- ▶ Renormalizable theories are taken care of by **NLOCT**, which provides UV and R2 counterterms, required at NLO.

Celine Degrande
1406.3030

- ▶ ⇒ Nonrenormalizable theories \approx **EFT**.

- EFT is principle “model-independent” (when new scales are heavy enough)

- ▶ Good to have accurate and realistic predictions of rates and shapes in EFT \Rightarrow NLO+PS

EFT@NLO motivation

- NLO predictions in SM are automated in MG5. Ready to explore BSM possibilities.
 - ▶ Renormalizable theories are taken care of by **NLOCT**, which provides UV and R2 counterterms, required at NLO.
 - ▶ ⇒ Nonrenormalizable theories \approx **EFT**.
- **EFT** is principle “model-independent” (when new scales are heavy enough)
 - ▶ Good to have accurate and realistic predictions of rates and shapes in **EFT** \Rightarrow NLO+PS

Celine Degrande
1406.3030

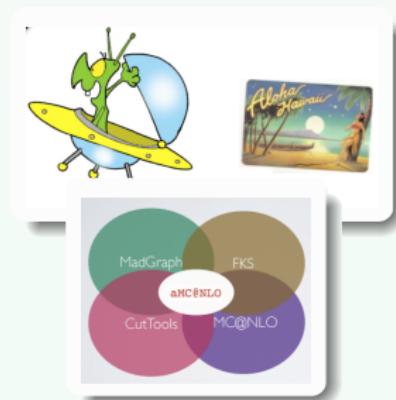
EFT@NLO motivation

- Ideal framework: MG5_aMC@NLO
 - ▶ UFO+ALOHA
(support general vertex structure)



EFT@NLO motivation

- Ideal framework: MG5_aMC@NLO
 - ▶ UFO+ALOHA
(support general vertex structure)
 - ▶ NLO automation



“SM EFT”

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4}) \quad \Lambda = \text{NP scale}$$

- Widely used in

- ▶ HEFT
 - ▶ Top couplings
 - ▶ EW precisions
 - ▶ TGC parametrization
 - ▶ Dark matter (not “SM EFT”)
 - ▶ ...

- Interesting studies/discussions

- ▶ Operator basis
 - ▶ Renormalization and non-renormalization.
 - ▶ ...

X^3	φ^6 and $\varphi^4 D^2$	$\psi^2 \varphi^3$
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ $(\varphi^\dagger \varphi)^3$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi \square}$ $(\varphi^\dagger \varphi) \square (\varphi^\dagger \varphi)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$ $(\varphi^\dagger D^\mu \varphi)^*$ $(\varphi^\dagger D_\mu \varphi)$
$Q_{\tilde{W}}$	$\epsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{d\varphi}$ $(\varphi^\dagger \varphi) (\bar{q}_p d_\mu \varphi)$
$X^2 \varphi^2$	$\psi^2 X \varphi$	$\psi^2 \varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW} $(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB} $(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG} $(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW} $(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB} $(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$
$Q_{\tilde{B}}$	$\overset{+}{\varphi} \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG} $(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$
$(L_R)(L_L)$	$(R_R)(R_L)$	$Q_{\varphi u}$ $(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \varphi W_{\mu\nu}^I$
Q_{ψ}	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu e_r)$	$Q_{\varphi d}$ $(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$
$Q_{\psi \psi}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu e_r)$	$Q_{\varphi dW}$ $(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$
$Q_{\psi \tilde{\psi}}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu \tilde{e}_r)$	Q_{dB} $(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$
$Q_{\tilde{\psi} \tilde{\psi}}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu \tilde{e}_r)$	
$Q_{\psi \psi \psi}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu e_r) (\bar{e}_p \gamma_\mu e_r)$	
$Q_{\psi \tilde{\psi} \tilde{\psi}}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu \tilde{e}_r) (\bar{e}_p \gamma_\mu \tilde{e}_r)$	
$Q_{\tilde{\psi} \tilde{\psi} \tilde{\psi}}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu \tilde{e}_r) (\bar{e}_p \gamma_\mu \tilde{e}_r)$	
$(L_R)(R_L)$ and $(L_L)(R_R)$	B -violating	
$Q_{\psi \psi}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu e_r)$	$Q_{\psi \psi}$ $\mu^{ab} \epsilon^{cd} [(\bar{e}_p^a \gamma_\mu e_r^b) (\bar{e}_p^c \gamma^\mu e_r^d)] [(\bar{e}_p^d \gamma_\mu e_r^a) (\bar{e}_p^b \gamma^\mu e_r^c)]$
$Q_{\psi \tilde{\psi}}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu \tilde{e}_r)$	$Q_{\psi \tilde{\psi}}$ $\mu^{ab} \epsilon^{cd} [(\bar{e}_p^a \gamma_\mu e_r^b) (\bar{e}_p^c \gamma^\mu \tilde{e}_r^d)] [(\bar{e}_p^d \gamma_\mu e_r^a) (\bar{e}_p^b \gamma^\mu \tilde{e}_r^c)]$
$Q_{\tilde{\psi} \tilde{\psi}}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu \tilde{e}_r)$	$Q_{\tilde{\psi} \tilde{\psi}}$ $\mu^{ab} \epsilon^{cd} [(\bar{e}_p^a \gamma_\mu e_r^b) (\bar{e}_p^c \gamma^\mu \tilde{e}_r^d)] [(\bar{e}_p^d \gamma_\mu e_r^a) (\bar{e}_p^b \gamma^\mu \tilde{e}_r^c)]$
$Q_{\psi \psi \psi}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu e_r) (\bar{e}_p \gamma_\mu e_r)$	$Q_{\psi \psi \psi}$ $\mu^{ab} \epsilon^{cd} [(\bar{e}_p^a \gamma_\mu e_r^b) (\bar{e}_p^c \gamma^\mu e_r^d)] [(\bar{e}_p^d \gamma_\mu e_r^a) (\bar{e}_p^b \gamma^\mu e_r^c)]$
$Q_{\psi \tilde{\psi} \tilde{\psi}}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu \tilde{e}_r) (\bar{e}_p \gamma_\mu \tilde{e}_r)$	$Q_{\psi \tilde{\psi} \tilde{\psi}}$ $\mu^{ab} \epsilon^{cd} [(\bar{e}_p^a \gamma_\mu e_r^b) (\bar{e}_p^c \gamma^\mu \tilde{e}_r^d)] [(\bar{e}_p^d \gamma_\mu e_r^a) (\bar{e}_p^b \gamma^\mu \tilde{e}_r^c)]$
$Q_{\tilde{\psi} \tilde{\psi} \tilde{\psi}}$	$(\bar{e}_p \gamma_\mu e_r) (\bar{e}_p \gamma^\mu \tilde{e}_r) (\bar{e}_p \gamma_\mu \tilde{e}_r)$	$Q_{\tilde{\psi} \tilde{\psi} \tilde{\psi}}$ $\mu^{ab} \epsilon^{cd} [(\bar{e}_p^a \gamma_\mu e_r^b) (\bar{e}_p^c \gamma^\mu \tilde{e}_r^d)] [(\bar{e}_p^d \gamma_\mu e_r^a) (\bar{e}_p^b \gamma^\mu \tilde{e}_r^c)]$

EFT at NLO

MG5 in principle supports but . . .

- Renormalization?

Despite being called “non-renormalizable”, higher-dimensional terms are renormalizable

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

EFT at NLO

MG5 in principle supports but . . .

- Renormalization?

Despite being called “non-renormalizable”, higher-dimensional terms are renormalizable

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

EFT at NLO

MG5 in principle supports but . . .

- Renormalization?

Despite being called “non-renormalizable”, higher-dimensional terms are renormalizable

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

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

SM NLO EFT EFT @ NLO

EFT at NLO

MG5 in principle supports but . . .

- Renormalization?

Despite being called “non-renormalizable”, higher-dimensional terms are renormalizable

- ▶ Allows for renormalization order by order in $1/\Lambda^2$
- ▶ Predictions can be systematically improved, by going to higher order in α_s , $1/\Lambda^2, \dots$
- ▶ But, operators mix: $dC_i/d\ln\mu = \gamma_{ij} C_j$

Renormalization Group Evolution of the Standard Model Dimension Six Operators

III: Gauge Coupling Dependence and Phenomenology

Rodrigo Alonso,^a Elizabeth E. Jenkins,^a Aneesh V. Manohar,^a Michael Trott^{b,1}

^a*Department of Physics, University of California at San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0319, USA*

^b*Theory Division, Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

E-mail: ralonso@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 λ 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,



EFT at NLO

MG5 in principle supports but . . .

- Renormalization?

Despite being called “non-renormalizable”, higher-dimensional terms are renormalizable

- ▶ Allows for renormalization order by order in $1/\Lambda$ ($\Lambda = \text{NP scale}$)
- ▶ Predictions can be systematically improved, by going to higher order in $\alpha_s, 1/\Lambda^2, \dots$
- ▶ UV counterterms required for NLO can be readily derived from RG results.

EFT at NLO

MG5 in principle supports but . . .

- Renormalization?

Despite being called “non-renormalizable”, higher-dimensional terms are renormalizable

- ▶ Allows for renormalization order by order in $1/\Lambda$ ($\Lambda = \text{NP scale}$)
- ▶ Predictions can be systematically improved, by going to higher order in α_s , $1/\Lambda^2, \dots$
- ▶ UV counterterms required for NLO can be readily derived from RG results.

- R2 for dimension six?

- ▶ NLOCT is able to handle most cases.
- ▶ Four-fermion operators are being studied.

Celine Degrande
1406.3030

EFT at NLO

MG5 in principle supports but . . .

- Renormalization?

Despite being called “non-renormalizable”, higher-dimensional terms are renormalizable

- ▶ Allows for renormalization order by order in $1/\Lambda$ ($\Lambda = \text{NP scale}$)
- ▶ Predictions can be systematically improved, by going to higher order in α_s , $1/\Lambda^2, \dots$
- ▶ UV counterterms required for NLO can be readily derived from RG results.

- R2 for dimension six?

- ▶ NLOCT is able to handle most cases.
- ▶ Four-fermion operators are being studied.

Celine Degrande
1406.3030

EFT at NLO

MG5 in principle supports but . . .

- Renormalization?

Despite being called “non-renormalizable”, higher-dimensional terms are renormalizable

- ▶ Allows for renormalization order by order in $1/\Lambda$ ($\Lambda = \text{NP scale}$)
- ▶ Predictions can be systematically improved, by going to higher order in α_s , $1/\Lambda^2, \dots$
- ▶ UV counterterms required for NLO can be readily derived from RG results.

- R2 for dimension six?

- ▶ NLOCT is able to handle most cases.

Celine Degrande
1406.3030

- ▶ Four-fermion operators are being studied.

$$\gamma^\mu \gamma^\nu \gamma^\rho P_L \otimes \gamma_\mu \gamma_\nu \gamma_\rho P_L = 4(4 - (x)\varepsilon) \gamma^\mu P_L \otimes \gamma_\mu P_L + E,$$

E = “evanescent” operator



EFT at NLO

MG5 in principle supports but...

- Renormalization?

Despite being called “non-renormalizable”, higher-dimensional terms are renormalizable

- ▶ Allows for renormalization order by order in $1/\Lambda$ ($\Lambda = \text{NP scale}$)
- ▶ Predictions can be systematically improved, by going to higher order in α_s , $1/\Lambda^2, \dots$
- ▶ UV counterterms required for NLO can be readily derived from RG results.

- R2 for dimension six?

- ▶ NLOCT is able to handle most cases.
- ▶ Four-fermion operators are being studied.

Celine Degrande
1406.3030

- Higher rank loop integration?

- ▶ in principle ok for rank ≤ 7 , thanks to IREGI [H. S. Shao]



Outline

1 EFT@NLO motivation

2 Applications

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

3 Summary

Outline

1 EFT@NLO motivation

2 Applications

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

3 Summary

Higgs characterisation

► HC1: "A framework for Higgs characterisation"

Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro, JHEP11(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]



Higgs characterisation

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

$$\mathcal{L}_0^f = - \sum_{f=t,b,\tau} \bar{\psi}_f (c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff} \gamma_5) \psi_f X_0$$

$$\mathcal{L}_0^V = \left\{ c_\alpha \kappa_{SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \right.$$

$$- \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu} \right]$$

$$- \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu} \right]$$

$$- \frac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right]$$

$$- \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right]$$

$$- \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right]$$

$$- \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma} A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} \right. \\ \left. + (\kappa_{H\partial W} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.) \right] \left. \right\} X_0$$

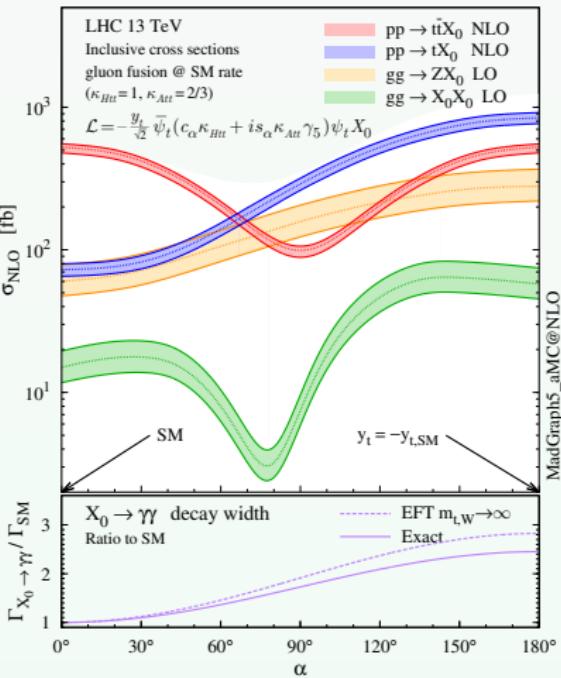
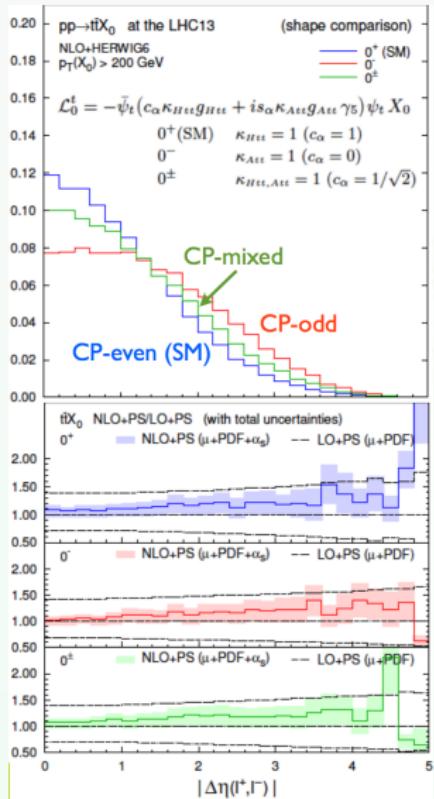
parameter	description
Λ [GeV]	cutoff scale
c_α ($\equiv \cos \alpha$)	mixing between 0^+ and 0^-
κ_i	dimensionless coupling parameter

```
./bin/mg5_aMC
>import model HC_NLO_X0
>generate p p > x0 t t~ [QCD]
>output pheno2015
>launch
```



NATIONAL LABORATORY

Higgs characterisation: ttH

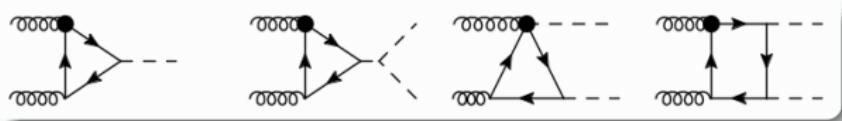


More details in arXiv:1504.00611
Real HEFT coming soon.

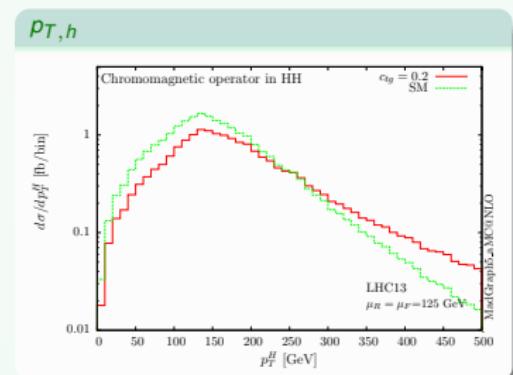
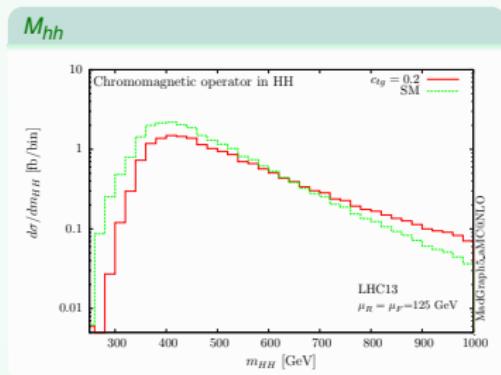
Loop-induced

Top-loop induced processes modified by top chromo-dipole operator

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



($gg > H$ [arXiv:1205.1065 C. Degrande et al.] reproduced)



C.Y. Chen, S. Dawson, F. Maltoni, E. Vryonidou, CZ

Outline

1 EFT@NLO motivation

2 Applications

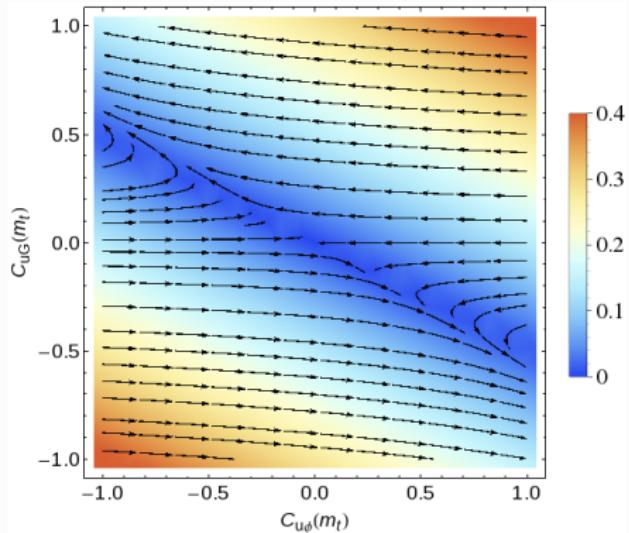
- Higgs EFT
- Top, FCNC sector
- Top, flavor diagonal sector
- DM collider signal

3 Summary

Top FCNC@NLO

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

Mixing between color-dipole and Yukawa



Operators

$$\begin{aligned} O_{uG}^{(13)} &= y_t g_S (\bar{q} \sigma^{\mu\nu} T^A t) \tilde{\varphi} G_{\mu\nu}^A \\ O_{uW}^{(13)} &= y_t g_W (\bar{q} \sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I \\ O_{uB}^{(13)} &= y_t g_Y (\bar{q} \sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} \\ O_{u\varphi}^{(13)} &= -y_t^3 (\varphi^\dagger \varphi) (\bar{q} t) \tilde{\varphi} \end{aligned}$$

Anomalous dimension

$$\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}$$

FCNC operators

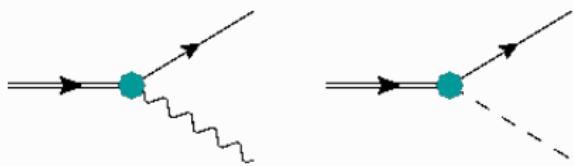
1 $(\bar{u}\gamma^\mu t)Z_\mu$

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

$$O_{\varphi Q}^{(1,1+3)} = i \left(\varphi^\dagger D_\mu \varphi \right) \left(\bar{q} \gamma^\mu Q \right)$$

$$O_{\varphi u}^{(1+3)} = i \left(\varphi^\dagger D_\mu \varphi \right) \left(\bar{u} \gamma^\mu t \right)$$

FCNC t decay



2 $(\bar{u}\sigma^{\mu\nu} q_\nu t) V_\mu$, "weak dipole"

$$O_{uW}^{(13)} = (\bar{q} \sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I$$

$$O_{uB}^{(13)} = (\bar{q} \sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu}$$

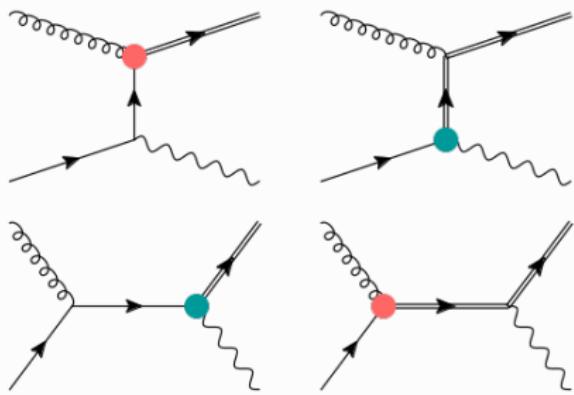
3 $(\bar{u}\sigma^{\mu\nu} q_\nu t) G_\mu$, "color dipole"

$$O_{uG}^{(13)} = (\bar{q} \sigma^{\mu\nu} T^A t) \tilde{\varphi} G_{\mu\nu}^A$$

4 $\bar{u} t h$, "Yukawa"

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

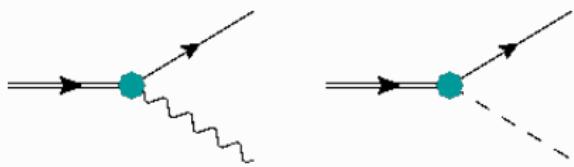
FCNC t production



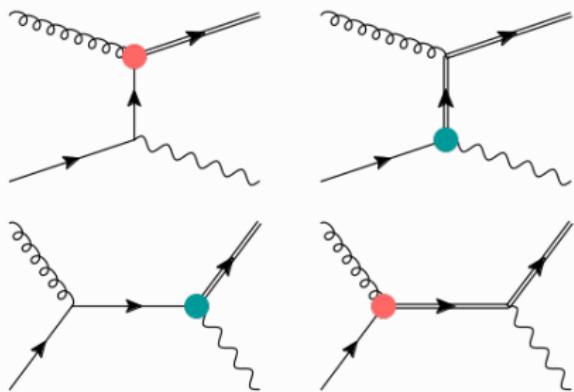
FCNC processes

- 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 $pp \rightarrow t\gamma, pp \rightarrow tZ, pp \rightarrow th$.
 - Competitive limits
 - More kinematic variables accessible.
 - Probe higher scale.
 - NLO corrections are significant.

FCNC t decay



FCNC t production



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
```

$pp \rightarrow tZ$

Coefficient	LO		NLO	
	$\sigma[\text{fb}]$	Scale uncertainty	$\sigma[\text{fb}]$	Scale uncertainty
$C_{\bar{q}u}^{(1+3)}$ = 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%
$C_{\bar{q}u}^{(2+3)}$ = 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%

$pp \rightarrow t\gamma$

Coefficient	LO		NLO	
	$\sigma[\text{fb}]$	Scale uncertainty	$\sigma[\text{fb}]$	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%

$pp \rightarrow th$

Coefficient	LO		NLO	
	$\sigma[\text{fb}]$	Scale uncertainty	$\sigma[\text{fb}]$	Scale uncertainty
$C_{u\phi}^{(13)}$ = 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%

Outline

1 EFT@NLO motivation

2 Applications

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

3 Summary

Top flavor conserving

Based on:
Diogo B. Franzosi and CZ, arXiv:1503.08841
and work in progress



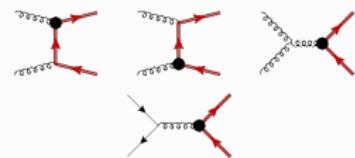
Chromo-dipole operator

Top-CMDM in $t\bar{t}$ production

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

```
your_shell> ./bin/mg5
MG5_aMC> import model Top_EFT_model
MG5_aMC> generate p p > t t~ EFT=1 [QCD]
MG5_aMC> output some_DIR
MG5_aMC> launch
```

LO diagrams at $\mathcal{O}(C/\Lambda^2)$



- Total cross section: $K = 1.43$ at LHC 8 TeV

Cross sections

β_1	LO [pb TeV 2]	NLO [pb TeV 2]	K factor
Tevatron	$1.61^{+0.66}_{-0.43}$ (+41%)	$1.810^{+0.073}_{-0.197}$ (+4.05%)	1.12
LHC8	$50.7^{+17.3}_{-12.4}$ (+34%)	$72.62^{+9.26}_{-10.53}$ (+12.7%)	1.43
LHC13	$161.6^{+48.0}_{-36.2}$ (+29.7%)	$239.5^{+29.0}_{-31.8}$ (+12.1%)	1.48
LHC14	$191.3^{+55.6}_{-42.2}$ (+29.0%)	$283.0^{+33.6}_{-36.9}$ (+11.9%)	1.48

Limits

	LO [TeV $^{-2}$]	NLO [TeV $^{-2}$]
Tevatron	[-0.33, 0.75]	[-0.32, 0.73]
LHC8	[-0.56, 0.41]	[-0.42, 0.30]
LHC14	[-0.56, 0.61]	[-0.39, 0.43]

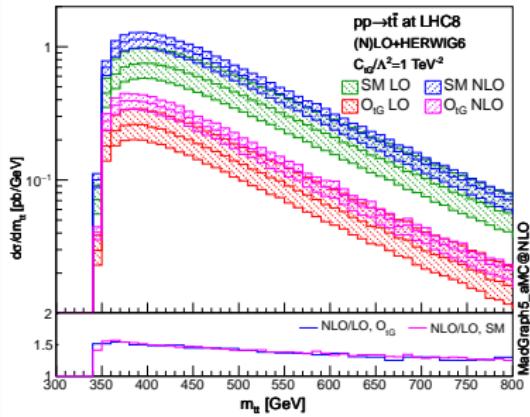
Chromo-dipole operator

- Distributions

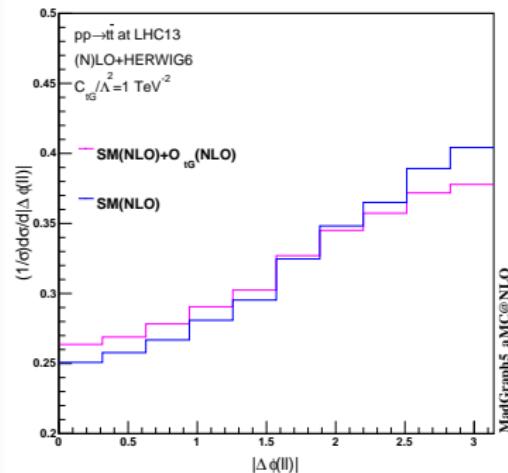
$$A_{FB} = 0.095 + C_{tG} \times 0.021(\text{TeV}/\Lambda)^2$$

- Spin correlation taken into account by MADSPIN.

$t\bar{t}$ invariant mass



Decayed top: spin correlation



Full set of top couplings

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

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

- tbW

- ▶ V/A

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

- ▶ Weak dipole

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

- ttZ

- ▶ V/A

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

- ▶ Weak dipole O_{tW}

- ttH

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



Towards NLO global analysis

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \rightarrow bW \rightarrow bl^+\nu$	X		X	X				X		
$pp \rightarrow t\bar{q}$	X		X	X				X		
$pp \rightarrow tW$	X		X	X				X	X	X
$pp \rightarrow t\bar{t}$	X						X	X	X	X
$pp \rightarrow t\bar{t}\gamma$	X	X	X				X	X	X	X
$pp \rightarrow t\bar{t}Z$	X	X	X	X	X	X	X	X	X	X
$pp \rightarrow t\bar{t}h$	X						X	X	X	X

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

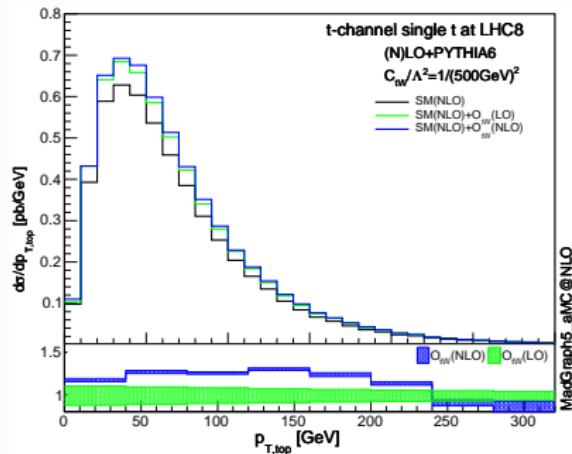
we aim to provide:

- NLO simulation for all “ $pp \rightarrow \dots$ ” processes.
- All two-quark operators included.
- Four-fermion operators planned.

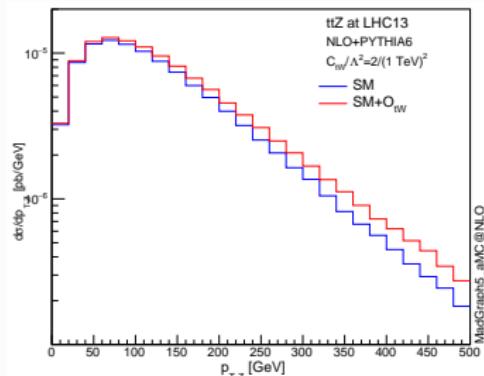
i.e. everything needed for a global analysis of top couplings at NLO accuracy.

Some preliminary results:

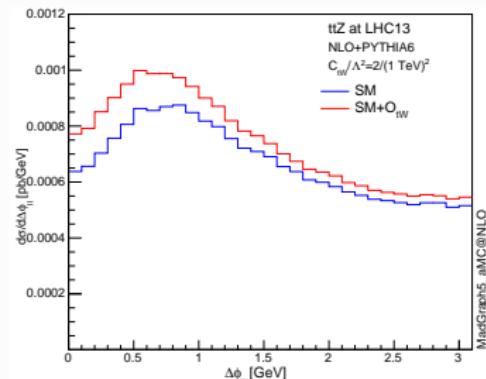
t-channel singl top



ttZ @ LHC13, pT of Z



ttZ @ LHC13, $\Delta\phi_{\parallel}$



Weak dipole (O_{tw}) in:

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

Outline

1 EFT@NLO motivation

2 Applications

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

3 Summary

DM at collider

- Dark matter EFT provides a framework for mono-X searches at the LHC, with minimum number of free parameters

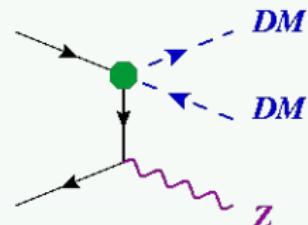
Q.-H. Cao, C.-R. Chen, C. S. Li, and H. Zhang, arXiv:0912.4511

M. Beltran, D. Hooper, E. W. Kolb, Z. A. Krusberg, and T.M. Tait, arXiv:1002.4137

Y. Bai, P.J. Fox, and R. Harnik, arXiv:1005.3797

J. Goodman, M. Ibe, A. Rajaraman, T.M. Tait, et al., arXiv:1008.1783

P. J. Fox, R. Harnik, J. Kopp, and Y. Tsai, arXiv:1109.4398



- Alternatively, simplified models are proposed to incorporate the complete degrees of freedom, i.e. without integrating out propagators.

J. Alwall, P. Schuster, and N. Toro, arXiv:0810.3921

D. Alves et al., arXiv:1105.2838

J. Goodman and W. Shepherd, arXiv:1111.2359

DM at NLO

- DM processes in MadGraph5_aMC@NLO are being investigated.

F. Maltoni, K. Mawatari, A. Martini, M. Backovic

M. Neubert, J. Wang, CZ

O. Mattelaer, E. Vryonidou

M. Kraemer, M. Pellen

B. Fuks, ...

- General framework, simplified models for the moment, (**EFT** will come later?)
- Currently s -channel simplified models for effective operators $D1 - D14, C1 - C6, R1 - R4$ plus EW

DM at NLO

- DM processes in MadGraph5_aMC@NLO are being investigated.

F. Maltoni, K. Mawatari, A. Martini, M. Backovic

M. Neubert, J. Wang, CZ

O. Mattelaer, E. Vryonidou

M. Kraemer, M. Pellen

B. Fuks, ...

- General framework, simplified models for the moment, (EFT will come later?)
- Currently s-channel simplified models for effective operators $D1 - D14, C1 - C6, R1 - R4$ plus EW

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

$$\begin{aligned}\mathcal{L}_{SM}^{Y_0} = & \sum_{i,j} [\bar{d}_i (g_{d_{ij}}^S + ig_{d_{ij}}^P) d_j \\ & + \bar{u}_i (g_{u_{ij}}^S + ig_{u_{ij}}^P) u_j] Y_0\end{aligned}$$

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

$$\begin{aligned}\mathcal{L}_{SM\,EW}^{Y_0} = & \frac{1}{\Lambda} g_{h1}^S (D^\mu \phi)^\dagger (D_\mu \phi) Y_0 + g_{h2}^S \Lambda |\phi|^2 Y_0 \\ & + \frac{1}{\Lambda} B_{\mu\nu} (g_B^S B^{\mu\nu} + g_B^P \tilde{B}^{\mu\nu}) Y_0 \\ & + \frac{1}{\Lambda} W_{\mu\nu}^i (g_W^S W^{i,\mu\nu} + g_W^P \tilde{W}^{i,\mu\nu}) Y_0\end{aligned}$$



DM at NLO

- DM processes in MadGraph5_aMC@NLO are being investigated.

F. Maltoni, K. Mawatari, A. Martini, M. Backovic

M. Neubert, J. Wang, CZ

O. Mattelaer, E. Vryonidou

M. Kraemer, M. Pellen

B. Fuks, ...

- General framework, simplified models for the moment, (**EFT** will come later?)
- Currently s -channel simplified models for effective operators $D1 - D14, C1 - C6, R1 - R4$ plus **EW**

$$\mathcal{L}_{SM}^{Y_1} = \sum_{i,j} [\bar{d}_i \gamma_\mu (g_{d_{ij}}^V + i g_{d_{ij}}^A \gamma_5) d_j$$

$$+ \bar{u}_i \gamma_\mu (g_{u_{ij}}^V + i g_{u_{ij}}^A \gamma_5) u_j] Y_1^\mu$$

$$\mathcal{L}_{X_D}^{Y_1} = \frac{i}{2} g_{X_C}^V (X_C^* (\partial_\mu X_C) - (\partial_\mu X_C^*) X_C) Y_1^\mu$$

$$+ \bar{X}_D \gamma_\mu (g_{X_D}^V + i \gamma_5 g_{X_D}^A) X_D Y_1^\mu$$

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

DM at NLO

- DM processes in MadGraph5_aMC@NLO are being investigated.

F. Maltoni, K. Mawatari, A. Martini, M. Backovic

M. Neubert, J. Wang, CZ

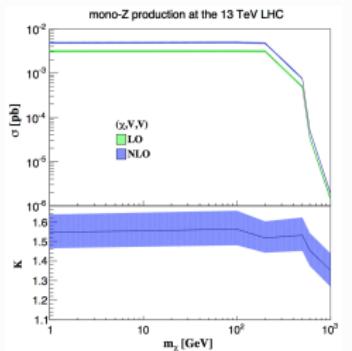
O. Mattelaer, E. Vryonidou

M. Kraemer, M. Pellen

B. Fuks, ...

- General framework, simplified models for the moment, (**EFT** will come later?)
- Currently s-channel simplified models for effective operators **D1 – D14, C1 – C6, R1 – R4** plus **EW**
- Generic framework for mono-X signals: automatic NLO+PS for arbitrary process.

```
your_shell> ./bin/mg5
MG5_aMC> import model DM_simp_NLO_UFO
MG5_aMC> generate p p > z xd xd~ [QCD]
MG5_aMC> output
MG5_aMC> launch
```



Outline

1 EFT@NLO motivation

2 Applications

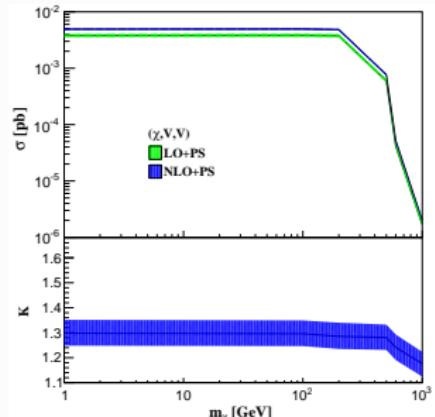
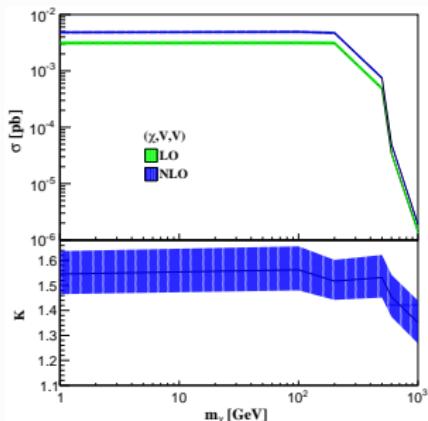
- Higgs EFT
- Top, FCNC sector
- Top, flavor diagonal sector
- DM collider signal

3 Summary

Summary

- Predictions for EFT at NLO have started to become available through the MadGraph5_aMC@NLO platform.
- Automation of the complete SM EFT at dim-6 is planned.

Backups



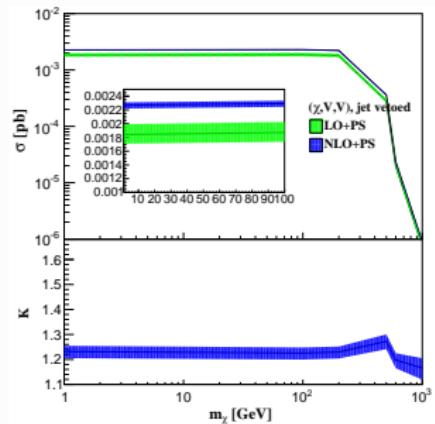
Mono-Z at LHC 13:

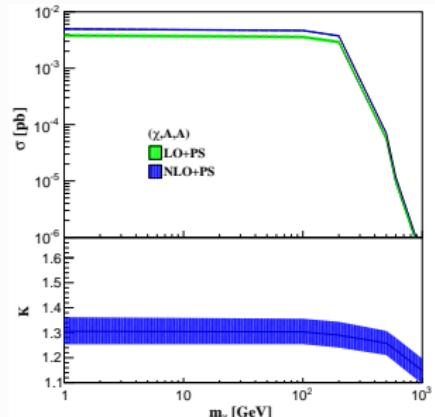
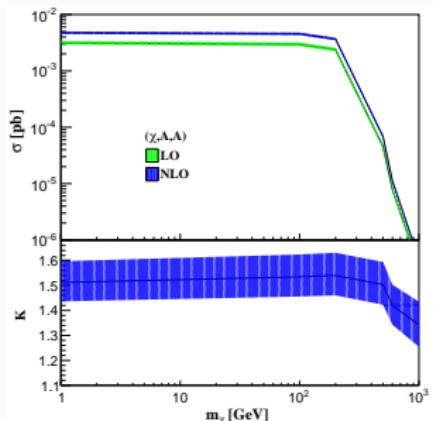
- $(\bar{X}_D \gamma^\mu X_D)(\bar{q} \gamma^\mu q)$
- $M_{Med} = 1000$ GeV.
- Cuts follow CMS mono-Z at 8 TeV.

Top left: Fixed order.

Top right: PS.

Bottom right: PS + jet veto.





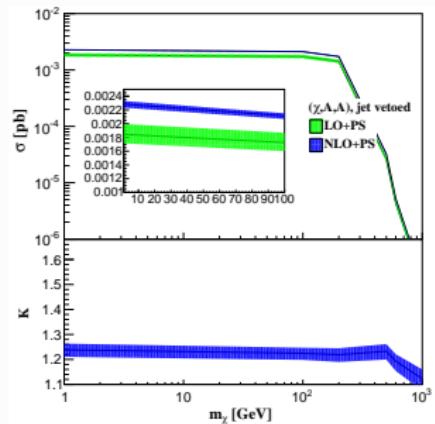
Mono-Z at LHC 13:

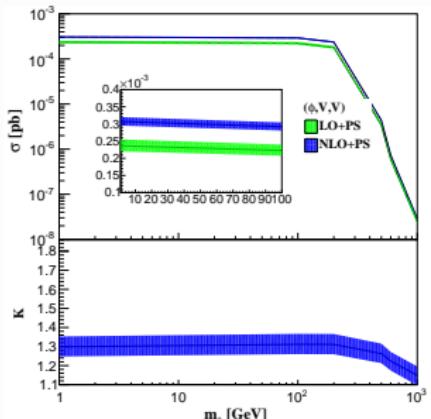
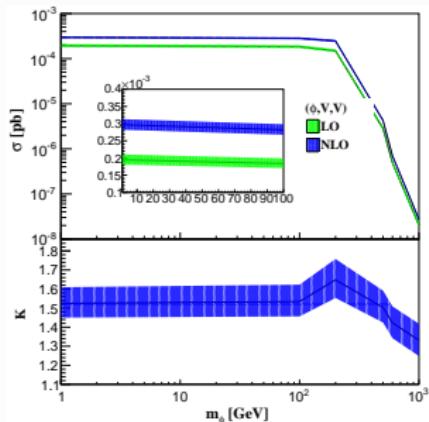
- $(\bar{X}_D \gamma^\mu \gamma^5 X_D)(\bar{q} \gamma^\mu \gamma^5 q)$
- $M_{Med} = 1000$ GeV.
- Cuts follow CMS mono-Z at 8 TeV.

Top left: Fixed order.

Top right: PS.

Bottom right: PS + jet veto.





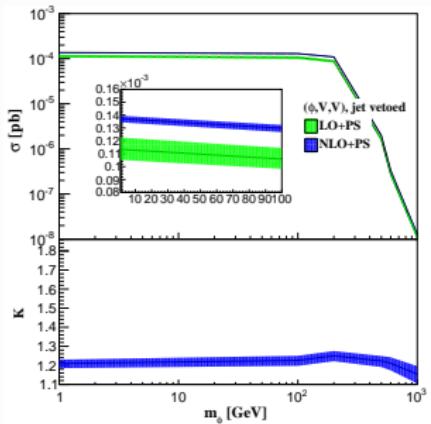
Mono-Z at LHC 13:

- $i(X_c^\dagger \partial_\mu X_c - \partial_\mu X_c^\dagger X_c)(\bar{q}\gamma^\mu\gamma^5 q)$
- $M_{Med} = 1000$ GeV.
- Cuts follow CMS mono-Z at 8 TeV.

Top left: Fixed order.

Top right: PS.

Bottom right: PS + jet veto.

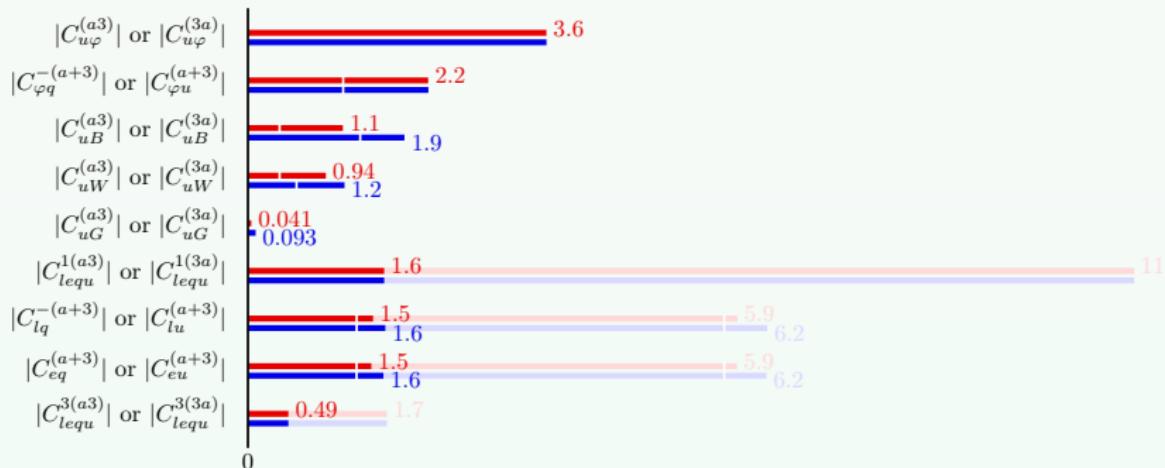


I realized that even without a cutoff, as long as every term allowed by symmetries is included in the Lagrangian, there will always be a counterterm available to absorb every possible ultraviolet divergence by renormalization of the corresponding coupling constant. Non-renormalizable theories, I realized, are just as renormalizable as renormalizable theories.

“Effective Field Theory, Past and Future”, Steven Weinberg, 2009

Toy fit FCNC

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



Observables:

$$\Lambda = 1 \text{ TeV}$$

red: a=1 (tuX)

blue: a=2 (tcX)

$$t \rightarrow qh$$

$$t \rightarrow qZ$$

$$pp \rightarrow t, \bar{t}$$

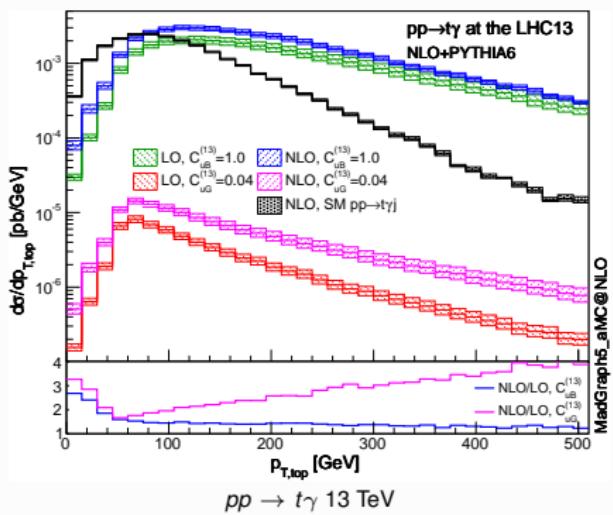
$$pp \rightarrow t\gamma, \bar{t}\gamma$$

$$e^+ e^- \rightarrow tj, \bar{t}j$$

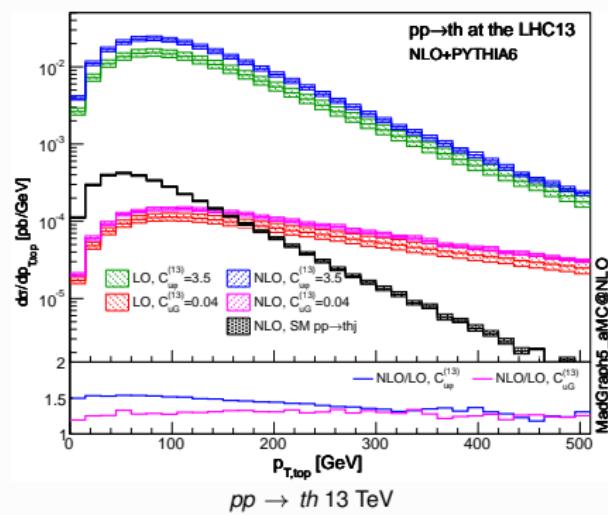
FCNC results

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

$pp \rightarrow t\gamma$



$pp \rightarrow th$



Toy fit flavor-diagonal

- Use 8 TeV data, total cross section only.
- Following processes are included
 - ▶ W helicity from top decay.
 - ▶ $t\bar{t}$ 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^2 fit.
- Limits ($\Lambda = 1$ 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.

Top-DM couplings

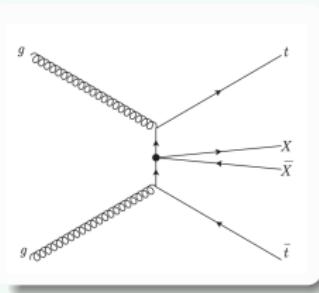
- Scalar mediated quark-DM interactions:

$$O = \frac{m_q}{\Lambda^3} \bar{q} q \bar{\chi} \chi$$

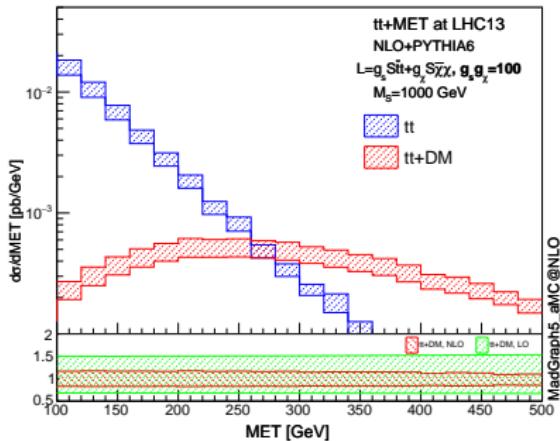
where m_q is fixed by minimal flavor violation.

- DM production in association with t can enhance the reach of the LHC.

Lin, Kolb, Wang
1303.6638



MET



Transverse mass

