Automating NLO Effective Field Theory with MadGraph5_aMC@NLO

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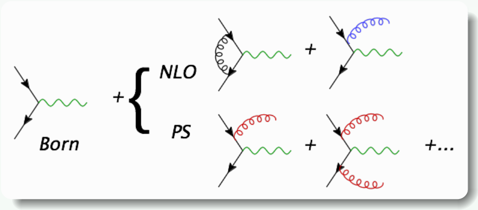
Academic Background

- 2014–present: Postdoc at Brookhaven National Lab.
- 2012–2014: Postdoc at Universite Catholique de Louvain.
  - Boss: F. Maltoni
  - Research topic: EFT @ NLO in QCD
- 2006–2011: Ph. D., University of Illinois at Urbana-Champaign
  - Boss: S. Willenbrock
  - Research topic: Top-quark EFT
- 2002–2006: B.S., Peking University

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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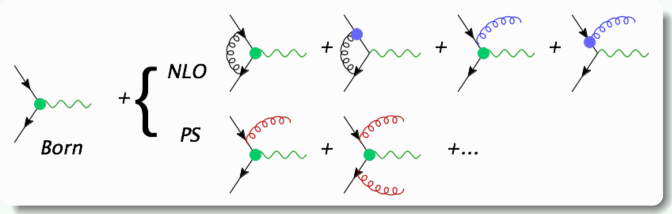

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Outline

1. Background and motivation
   - Theoretical
   - Technical
2. Applications
   - Higgs EFT
   - Top, FCNC sector
   - Top, flavor diagonal sector
   - DM collider signal
3. Summary

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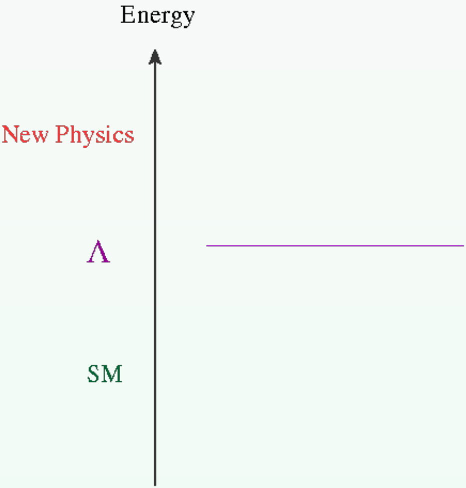
Two approaches to BSM

Model-dependent	**Model-independent**
SUSY, 2HDM, ED, . . .	simplified models, EFT, . . .
Search for new states	**Search for new interactions**
specific models, simplified models	anomalous couplings, EFT . . .
Exotic signatures	**Standard signatures**

Example: Z' boson



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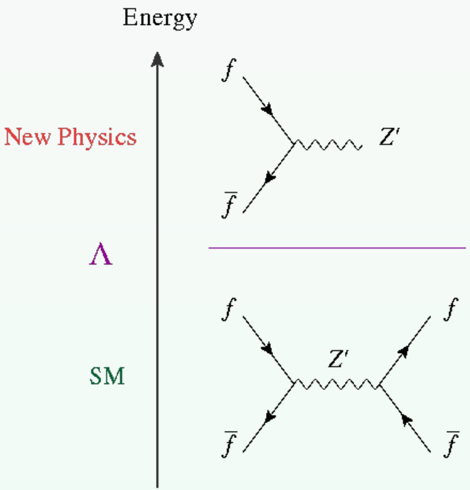

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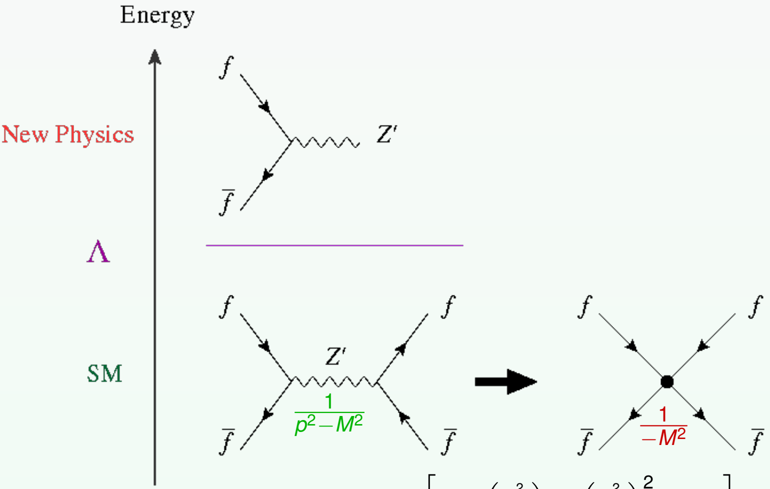

$$\frac{1}{p^2-M^2} = \frac{1}{-M^2}\left[1+\left(\frac{p^2}{M^2}\right)+\left(\frac{p^2}{M^2}\right)^2+\cdots\right]$$

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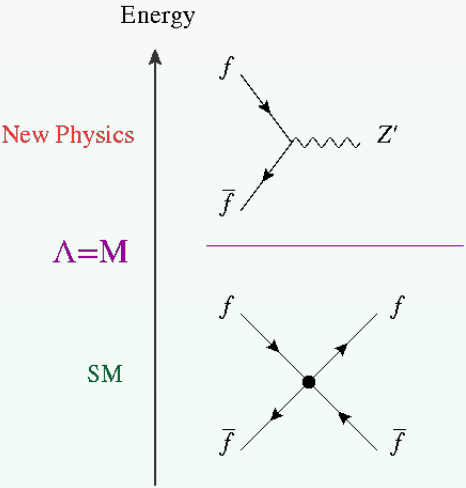

$\mathcal{L}_{\rm NP}(\varphi, Z')$

$\mathcal{L}_{\rm SM}(\varphi) + \mathcal{L}_{\rm Dim6}(\varphi) + \cdots$

where $\mathcal{L}_{\rm Dim6}(\varphi) = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$

The EFT approach

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

- Effective field theory of the standard model connects BSM models with experimental observables
- Data $\Leftrightarrow$ Model-Independent EFT $\Leftrightarrow$ BSM models
- BSM goal at the LHC: determination of SM EFT up to DIM=6

"SM EFT"

- Valid only up to the scale Λ.
- Based on SM symmetries.
- Number of couplings reduced by symmetries and dimensional analysis.
- Extends the reach of searches for NP beyond the collider energy.
- QCD and EW RENORMALIZABLE (order by order in $1/\Lambda$).
  - Allows for NLO accuracy!

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
		Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
		Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
		Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	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}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
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$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

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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
- ...

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
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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

- Allows for renormalization order by order in $1/\Lambda^2$
- Predictions can be SYSTEMATICALLY IMPROVED, by going to higher order in α_s, $1/\Lambda^2$,...

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

SM@LO SM@NLO EFT@LO EFT@NLO $\Leftarrow$ *Our goal!*

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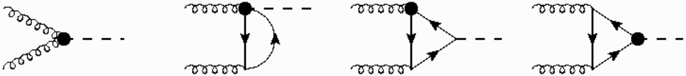
- Predictions can be SYSTEMATICALLY IMPROVED, by going to higher order in α_s, $1/\Lambda^2$,...
- But, operators mix: $dC_i/d\ln\mu = \gamma_{ij}C_j$, $\gamma_{ij} = 2499 \times 2499$ matrix

$O_{\varphi G} = (\varphi^\dagger\varphi)(G^a_{\mu\nu}G^{a\mu\nu})$ $\quad O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t_R)\tilde{\varphi}G^I_{\mu\nu}$ $\quad O_{t\varphi} = (\varphi^\dagger\varphi)(\varphi\bar{Q})t$



1205.1065
C. Degrande et al

EFT@NLO: Why?

Key fact: If you want to gain maximum benefit from a measurement, a constraint, or a pattern of deviations, the theory precision should be better than the experimental precision.

- Need of loops in SMEFT once measurements are 10% precise appears again and again in the literature

  [1209.5538 Passarino], [1301.2588 Grojean, Jenkins, Manohar, Trott], [1408.5147 Englert, Spannowsky]...

- Naively, at LHC QCD corrections are significant, sometimes $\sim \mathcal{O}(1)$, not really "higher-order". e.g. $gg \to h$, $K \approx 2$ at NLO

  [1412.5594 Degrande, Maltoni, Wang, CZ], [1503.08841 Franzosi, CZ]

- Top-loop induced processes provides new information.

  [1201.6670 CZ, Greiner, Willenbrock], [1205.1065 Degrande, Maltoni]

- The EFT itself becomes nontrivial due to operator mixing, i.e. RG plays a role.

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- And the finite term from loop can be even more important.

  [1505.02646 Hartmann, Trott]

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- The EFT itself becomes nontrivial due to operator mixing, i.e. RG plays a role.

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- And the finite term from loop can be even more important.

  [1505.02646 Hartmann, Trott]

EFT@NLO: Why?

Key fact: If you want to gain maximum benefit from a measurement, a constraint, or a pattern of deviations, the theory precision should be better than the experimental precision.

- Need of loops in SMEFT once measurements are 10% precise appears again and again in the literature

  [1209.5538 Passarino], [1301.2588 Grojean, Jenkins, Manohar, Trott], [1408.5147 Englert, Spannowsky]...

- Naively, at LHC QCD corrections are significant, sometimes $\sim \mathcal{O}(1)$, not really "higher-order". e.g. $gg \to h$, $K \approx 2$ at NLO

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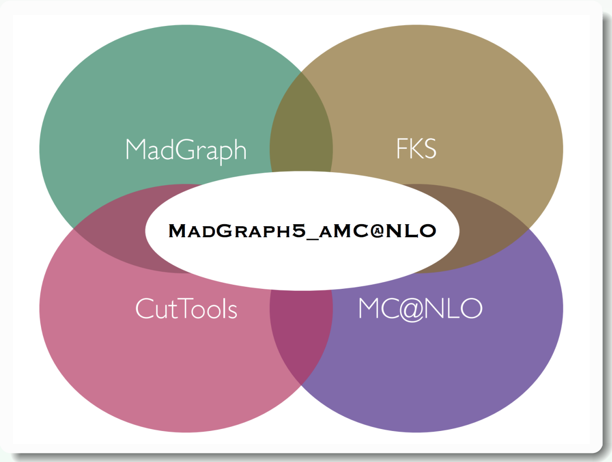
Outline

MadGraph5

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



MadGraph5

Event Generation at LO

- Process generation
  - `import model <model_name>-<restrictions>`
  - `generate <process> <amp_orders_and_option>`
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  - `launch <options>`
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  - $t\bar{t}$ production:

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  - with more options:

```
> import model loop_sm-lepton_masses
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> launch -f
```

Simulation chain @ LO accuracy

- Model (Lagrangian)

  ⇓ FeynRules
- Feynman Rules (in UFO form)

  ⇓ MadGraph
- Matrix element (`matrix.f`)

  ⇓ MadEvent
- Parton level (`events.lhe`)

  ⇓ PYTHIA/HERWIG
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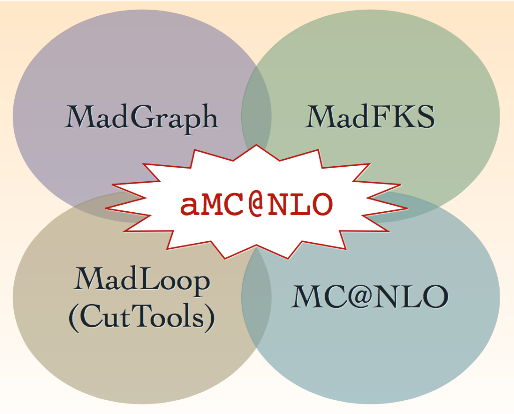
Going to NLO



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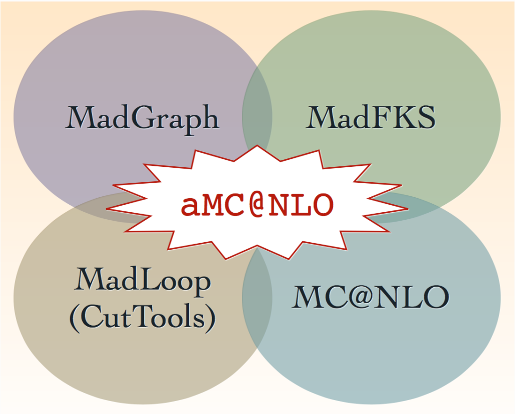

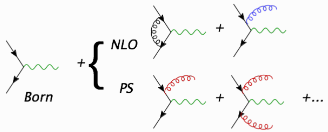

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- Detector level

Upgrade to NLO:
MADGRAPH5_AMC@NLO

1405.0301
J. Alwall et al.

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MadGraph5_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]

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>`
- Examples
  - $t\bar{t}$ production:

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

  - with more options:

```
> import model loop_sm-lepton_masses
> set complex_mass_scheme
> generate p p > e+ ve mu- vm~ b b~ /h QED=4 [QCD]
> output MyProc
> launch -f
```

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MadGraph5_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]

Event Generation at NLO LIKE AT LO

- Process generation
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  - $t\bar{t}$ production:

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> generate p p > t t~ [QCD]
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  - with more options:

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> import model loop_sm-lepton_masses
> set complex_mass_scheme
> generate p p > e+ ve mu- vm~ b b~ /h QED=4 [QCD]
> output MyProc
> launch -f
```

Only difference between LO and NLO from the user perspective

Simulation chain @ NLO accuracy

- Model (Lagrangian)

  $\Downarrow$ FEYNRULES → ?

- Feynman Rules (in UFO form)

  $\Downarrow$ MADGRAPH

- Matrix element (`matrix.f`)

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- Parton level (`events.lhe`)

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Upgrade to NLO:
MADGRAPH5_AMC@NLO

1405.0301
J. Alwall et al.

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Simulation chain @ NLO accuracy

- Model (Lagrangian)

  ⇓ FeynRules → Need CT vertices UV & R2
- Feynman Rules (in UFO form)

  ⇓ MadGraph
- Matrix element (`matrix.f`)

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Upgrade to NLO:
MadGraph5_aMC@NLO

1405.0301
J. Alwall et al.

Two missing ingredients for NLO

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

Two missing ingredients for NLO

$$
\begin{aligned}
\delta Z_{H^+H^+} = \frac{1}{16\pi^2}\Bigg[& -\frac{e^2 c_{2w}^2}{4c_w^2 s_w^2 m_{H^+}^4}\Bigg(2m_{H^+}^4\bigg(\log\bigg(\frac{M_Z m_{H^+}}{\mu^2}\bigg)-\frac{1}{\bar\epsilon}\bigg)-m_{H^+}^2 M_Z^2 \\
& +\left(m_{H^+}^2-M_Z^2\right)\bigg(1(m_{H^+},M_Z,m_{H^+})+\left(2m_{H^+}^2-M_Z^2\right)\log\bigg(\frac{M_Z}{m_{H^+}}\bigg)\bigg)\Bigg) \\
& +\Bigg\{\frac{e^2 s_1^2}{4s_w{}^2 m_{H^+}^4}\Bigg(\frac{1(M_W,m_{h_1},m_{H^+})}{\left((m_{h_1}-M_W)^2-m_{H^+}^2\right)\left((m_{h_1}+M_W)^2-m_{H^+}^2\right)} \\
& \big(+M_W^2\left(m_{h_1}^2 m_{H^+}^2-2m_{H^+}^4+5m_{h_1}^4\right)-2\left(m_{h_1}^2-m_{H^+}^2\right)\left(m_{H^+}^4+m_{h_1}^4\right)+M_W^6 \\
& -M_W^4\left(m_{H^+}^2+4m_{h_1}^2\right)\big)+m_{H^+}^2\bigg(2m_{H^+}^2\bigg(\frac{1}{\bar\epsilon}+1-\log\bigg(\frac{M_W m_{h_1}}{\mu^2}\bigg)\bigg)-2m_{h_1}^2+M_W^2\bigg) \\
& +\log\bigg(\frac{m_{h_1}}{M_W}\bigg)\left(M_W^4-3m_{h_1}^2 M_W^2+2m_{h_1}^4\right)\Bigg)+\frac{v^2\left(\lambda_4 s_1-2c_1\lambda_6\right)^2}{4m_{H^+}^4} \\
& \Bigg(\frac{M_W^4-m_{h_1}^2\left(m_{H^+}^2+2M_W^2\right)-M_W^2 m_{H^+}^2+m_{h_1}^4}{\left(m_{h_1}^4-2m_{h_1}^2\left(m_{H^+}^2+M_W^2\right)+\left(m_{H^+}^2-M_W^2\right)^2\right)}1(M_W,m_{h_1},m_{H^+}) \\
& -\bigg(\left(m_{h_1}^2-M_W^2\right)\log\bigg(\frac{m_{h_1}}{M_W}\bigg)-m_{H^+}^2\bigg)\Bigg)+h_1\to h_2, c_1\to s_1, s_1\to -c_1 \\
& +h_1\to h_3, c_1\to 0, s_1\to 1\Bigg\}+\Bigg\{\frac{v^2\left(c_1\lambda_3-\lambda_7 s_1\right)^2}{m_{H^+}^4} \\
& \Bigg(\bigg(\left(m_{H^+}^2-m_{h_1}^2\right)\log\bigg(\frac{m_{h_1}}{m_{H^+}}\bigg)-m_{H^+}^2\bigg)-\frac{\left(m_{h_1}^2-3m_{H^+}^2\right)}{4m_{H^+}^2-m_{h_1}^2}1(m_{H^+},m_{h_1},m_{H^+})\Bigg) \\
& +h_1\to h_2, c_1\to s_1, s_1\to -c_1\Bigg\}-\sum_l G_l^2\bigg(-\log\bigg(\frac{m_{H^+}^2}{\mu^2}\bigg)+\frac{1}{\bar\epsilon}+i\pi+1\bigg) \\
& -3\sum_{light}\left(G_d^2+G_u^2\right)\bigg(-\log\bigg(\frac{m_{H^+}^2}{\mu^2}\bigg)+\frac{1}{\bar\epsilon}+i\pi+1\bigg) \\
& -\frac{12G_b G_t M_b M_t}{m_{H^+}^4}\Bigg(\frac{M_b^2\left(m_{H^+}^2+2M_t^2\right)+M_t^2 m_{H^+}^2-M_b^4-M_t^4}{-2M_b^2\left(m_{H^+}^2+M_t^2\right)+\left(m_{H^+}^2-M_t^2\right)^2+M_b^4}1(M_t,M_b,m_{H^+}) \\
& -\bigg(m_{H^+}^2-\left(M_b^2-M_t^2\right)\bigg(\log\bigg(\frac{M_b}{M_t}\bigg)\bigg)\bigg)\Bigg)-\frac{3\left(G_b^2+G_t^2\right)}{m_{H^+}^4}\Bigg(1(M_t,M_b,m_{H^+}) \\
& \frac{\left(M_b^2+M_t^2\right)\left(-M_b^2\left(m_{H^+}^2+2M_t^2\right)-M_t^2 m_{H^+}^2-m_{H^+}^4+M_b^4+M_t^4\right)+m_{H^+}^6}{-2M_b^2\left(m_{H^+}^2+M_t^2\right)+\left(m_{H^+}^2-M_t^2\right)^2+M_b^4} \\
& +\left(M_b^2+M_t^2\right)\bigg(m_{H^+}^2-\left(M_b^2-M_t^2\right)\log\bigg(\frac{M_b}{M_t}\bigg)\bigg)+m_{H^+}^4\bigg(\frac{1}{\bar\epsilon}+1-\log\bigg(\frac{M_b M_t}{\mu^2}\bigg)\bigg)\Bigg)\Bigg]
\end{aligned}
$$

H^+ wavefunction in 2HDM

... automation is needed

Two missing ingredients for NLO

- UV counterterms
  - Renormalize the Lagrangian:
    Fields: $\phi_0 \to (1+\frac{1}{2}\delta Z_{\phi\phi})\phi + \sum_\chi \frac{1}{2}\delta Z_{\phi\chi}\chi$
    ext. params: $x_0 \to x + \delta x$
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  - 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 ε-dim part of numerator: $\bar{N}(\bar{q}) = N(q) + \tilde{N}(\tilde{q}, q, \varepsilon)$ Then calculate ε part analytically, once and for all.

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

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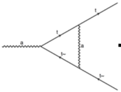
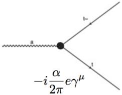
- R2 examples

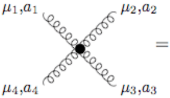


$$\supset \int d^d\bar{q}\,\frac{\tilde{q}^2}{\bar{D}_0\bar{D}_1\bar{D}_2} = -\frac{i\pi^2}{2} + \mathcal{O}(\epsilon)$$



$-i\frac{\alpha}{2\pi}e\gamma^\mu$

- Can become complicated



$$= -\frac{ig^4 N_{col}}{96\pi^2}\sum_{P(234)}\Big\{\Big[\frac{\delta_{a_1a_2}\delta_{a_3a_4}+\delta_{a_1a_3}\delta_{a_4a_2}+\delta_{a_1a_4}\delta_{a_2a_3}}{N_{col}}$$
$$+4\,Tr(t^{a_1}t^{a_3}t^{a_2}t^{a_4}+t^{a_1}t^{a_4}t^{a_2}t^{a_3})\,(3+\lambda_{HV})$$
$$-Tr(\{t^{a_1}t^{a_2}\}\{t^{a_3}t^{a_4}\})\,(5+2\lambda_{HV})\Big]\,g_{\mu_1\mu_2}g_{\mu_3\mu_4}$$
$$+12\frac{N_f}{N_{col}}Tr(t^{a_1}t^{a_2}t^{a_3}t^{a_4})\left(\frac{5}{3}g_{\mu_1\mu_3}g_{\mu_2\mu_4}-g_{\mu_1\mu_2}g_{\mu_3\mu_4}-g_{\mu_2\mu_3}g_{\mu_1\mu_4}\right)\Big\}$$

- Again automation needed.

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- Good news: now both available with NLOCT

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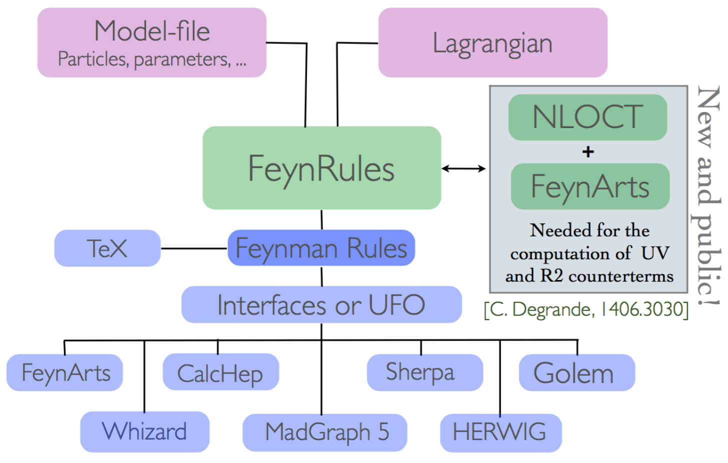
1406.3030
Celine Degrande

FeynRules structure @ NLO

FeynRules @ NLO (version 2.1)



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Upgrade to NLO:
FeynRules+NLOCT

1406.3030
C. Degrande

1310.1921
A. Alloul et al.

Upgrade to NLO:
MADGRAPH5_AMC@NLO

1405.0301
J. Alwall et al.

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The UFO @ LO

[C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, T. Reiter, 1108.2040]

coupling_orders.py

- In the SM: QCD, QED
- name
- hierarchy

vertices.py

```
V_37 = Vertex(name = 'V_37',
              particles = [ P.g, P.g, P.g, P.g ],
              color = [ 'f(-1,1,2)*f(3,4,-1)',
                        'f(-1,1,3)*f(2,4,-1)',
                        'f(-1,1,4)*f(2,3,-1)' ],
              lorentz = [ L.VVVV1, L.VVVV3, L.VVVV4 ],
              couplings = {(0,0):C.GC_12,
                           (1,1):C.GC_12,
                           (2,2):C.GC_12})
```

lorentz.py

```
VVVV1 = Lorentz(name = 'VVVV1',
   spins = [ 3, 3, 3, 3 ],
   structure = 'Metric(1,4)*Metric(2,3) '+
               '- Metric(1,3)*Metric(2,4)')
```

couplings.py

```
GC_12 = Coupling(name = 'GC_12',
                 value = 'complex(0,1)*G**2',
                 order = {'QCD':2})
```

parameters.py

```
G = Parameter(name = 'G',
      nature = 'internal',
      type = 'real',
      value = '2*cmath.sqrt(aS)*cmath.sqrt(cmath.pi)',
      texname = 'G')
```

The UFO @ NLO

Apart from tree level vertices, UV/R2 vertices are added.

coupling_orders.py

- `perturbative_expansion`

  Specifies the kind of loops supported by the model

CT_parameters.py

```
P = CTParameter(name = 'MyUVCTParam',
    type = 'complex',
    value = {-1:'singlePoleExpression',
              0:'finitePart'},
    texname = 'MadRules')
```

CT_vertices.py

```
V_R2GUU = CTVertex(name = 'V_R2GUU',
                   particles = [ P.u__tilde__, P.u, P.G ],
                   color = [ 'T(3,2,1)' ],
                   lorentz = [ L.FFV1 ],
                   loop_particles =[[[P.u,P.G]]],
                   couplings = {(0,0,0):C.R2_GQQ},
                   type = 'R2')

V_UVGUU = CTVertex(name = 'V_UVGUU',
           particles = [ P.u__tilde__, P.u, P.G ],
           color = [ 'T(3,2,1)' ],
           lorentz = [ L.FFV1 ],
           loop_particles = [[[P.u],[P.d],[P.s]],
                             [[P.c]],[[P.b]],[[P.t]],[[P.G]]],
           couplings = {
           (0,0,0):C.UV_GQQq,(0,0,1):C.UV_GQQc,
           (0,0,2):C.UV_GQQb,(0,0,3):C.UV_GQQt,(0,0,4):C.UV_GQQg},
           type = 'UV')
```

The Model Database @ NLO. . .

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM (18)	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models (5)	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models (4)	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories (8)	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous (0)	
NLO MODELS (100000)	3 MODELS FOR NOW

http://feynrules.irmp.ucl.ac.be/wiki/NLOModels

Available models

Description	Contact	Reference	FeynRules model files	UFO libraries
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089	-	HC_NLO_X0_UFO.zip
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz

NLO models

Automatic NLO in QCD + PS available in

- SM ✓
- BSM, if renormalizable ✓
  - thanks to FeynRules+NLOCT+UFO

- Non-renormalizable models ⇒ EFT @ NLO
  - Work in progress. . .
  - Will complete the BSM ability of MG5_aMC.

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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.

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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: 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 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,

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
  - Top
  - DM, EFT and simplfied models
  - ...
- Long term goal is to have complete dim-6 Lagrangian.

Outline

Outline

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]

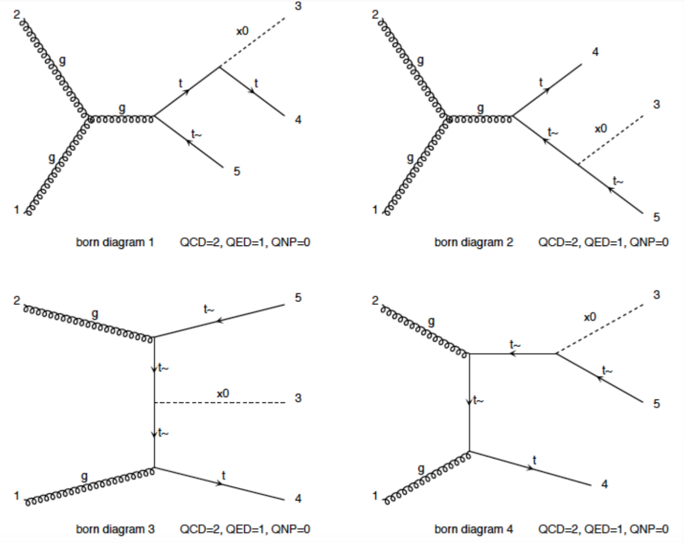
Higgs characterisation

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

$$
\begin{aligned}
\mathcal{L}_0^f &= -\sum_{f=t,b,\tau} \bar\psi_f \left(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff}\,\gamma_5\right)\psi_f X_0 \\
\mathcal{L}_0^V &= \Big\{ c_\alpha \kappa_{\rm SM}\left[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\right] \\
&\quad -\frac{1}{4}\left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\right] \\
&\quad -\frac{1}{2}\left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\right] \\
&\quad -\frac{1}{4}\left[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\right] \\
&\quad -\frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\right] \\
&\quad -\frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\right] \\
&\quad -\frac{1}{\Lambda} c_\alpha\Big[\kappa_{H\partial\gamma}\, A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} \\
&\qquad + \left(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\right)\Big]\Big\} X_0
\end{aligned}
$$

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
```


2
g
g
1
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3
t
t
4
t~
5
born diagram 1 QCD=2, QED=1, QNP=0
2
g
g
1
4
t
3
t~
x0
t~
5
born diagram 2 QCD=2, QED=1, QNP=0
2
g
t~
5
t~
x0
3
t~
g
1
t
4
born diagram 3 QCD=2, QED=1, QNP=0
2
g
x0
3
t~
t~
5
t~
g
1
t
4
born diagram 4 QCD=2, QED=1, QNP=0

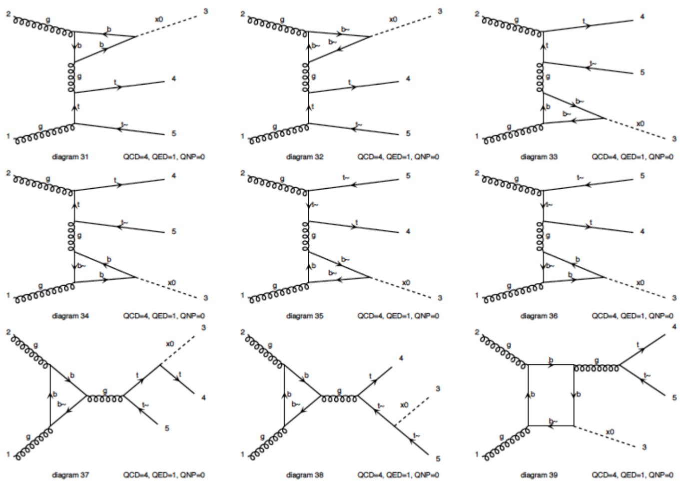
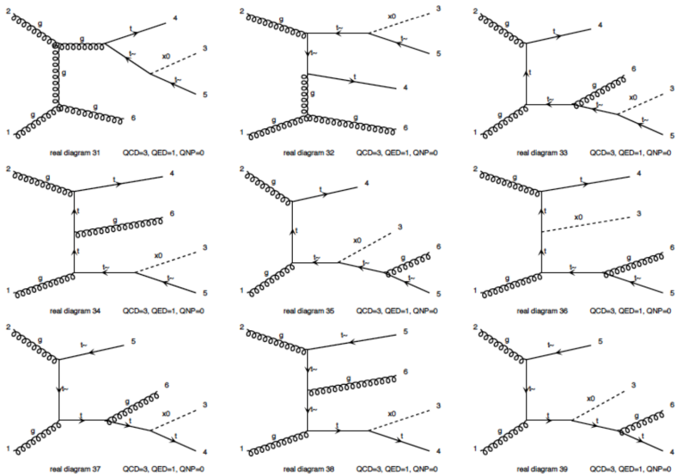


diagram 31 QCD=4, QED=1, QNP=0
diagram 32 QCD=4, QED=1, QNP=0
diagram 33 QCD=4, QED=1, QNP=0
diagram 34 QCD=4, QED=1, QNP=0
diagram 35 QCD=4, QED=1, QNP=0
diagram 36 QCD=4, QED=1, QNP=0
diagram 37 QCD=4, QED=1, QNP=0
diagram 38 QCD=4, QED=1, QNP=0
diagram 39 QCD=4, QED=1, QNP=0



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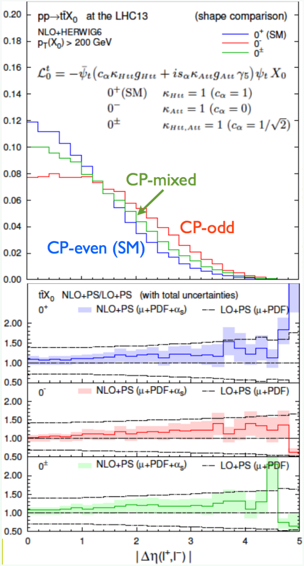
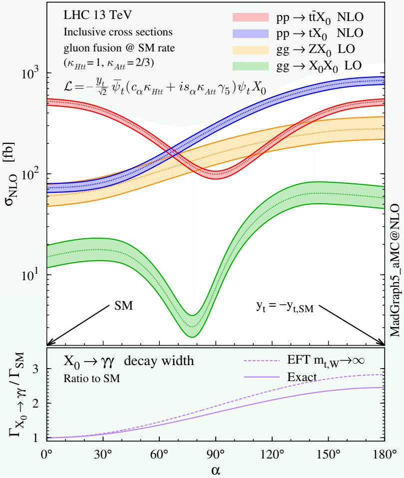
Higgs characterisation: ttH



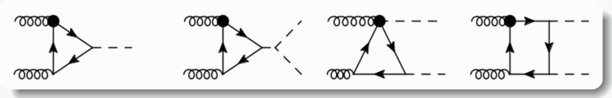


More details in arXiv:1504.00611
Real HEFT under validation
(C. Degrande, B. Fuks, K. Mawatari, K. Mimasu, V. Sanz)

Loop-induced

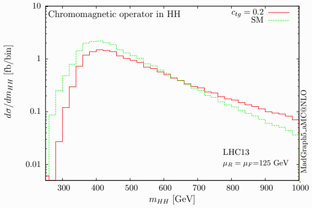
Loop-induced processes lead to new technical challenges [O. Mattelaer, V. Hirschi]
Top-loops modified by top chromo-dipole operator (modifies gtt vert)

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

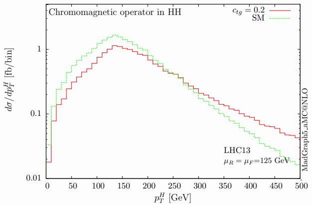


($gg > H$ [arXiv:1205.1065 C. Degrande et al.] reproduced)

M_{hh}



$p_{T,h}$



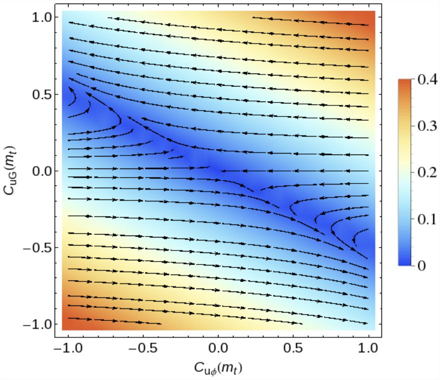
F. Maltoni, E. Vryonidou, CZ

Outline

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.

Mixing between color-dipole and Yukawa



Operators

$$O^{(13)}_{uG} = y_t g_s(\bar{q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$
$$O^{(13)}_{uW} = y_t g_W(\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O^{(13)}_{uB} = y_t g_Y(\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O^{(13)}_{u\varphi} = -y_t^3(\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}$$

Anomalous dimension

$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}$$

FCNC operators

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

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

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

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

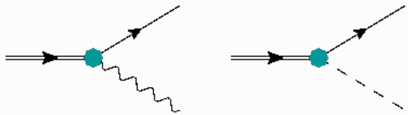
3. $(\bar{u}\sigma^{\mu\nu}q_{\nu}t)G_{\mu}$, "color dipole"

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

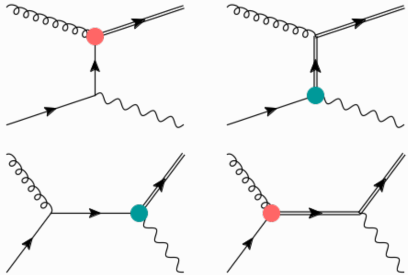
4. $\bar{u}th$, "Yukawa"

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

FCNC t decay



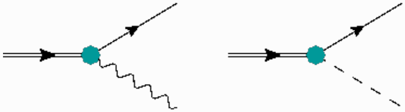
FCNC t production



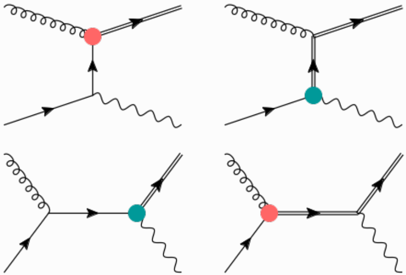
FCNC processes

- We provide an NLO UFO based on dim-6 FCNC operators, that allows to make NLO predictions in an automatic way.
  - Validated against [Y. Zhang et al. 11] [B. H. Li et al. 11] [Y. Wang et al. 11]
- Focus on single top production $pp \to t\gamma$, $pp \to tZ$, $pp \to th$.
  - 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
```

$pp \to tZ$

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[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	$+3.4\% - 5.1\%$
$C_{\varphi u}^{(2+3)} = 1.0$	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	$+5.7\% - 5.3\%$

$pp \to t\gamma$

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[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	$+10.3\% - 8.9\%$

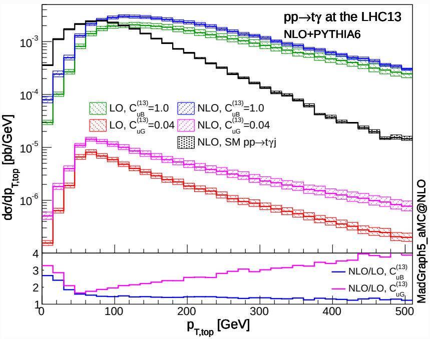
$pp \to th$

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[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	$+4.0\% - 5.2\%$
$C_{u\varphi}^{(23)} = 3.5$	171	$+9.7\% - 8.7\%$	310	$+7.3\% - 6.3\%$
$C_{uG}^{(23)} = 0.09$	9.53	$+11.0\% - 9.7\%$	16.6	$+5.5\% - 5.1\%$

FCNC results

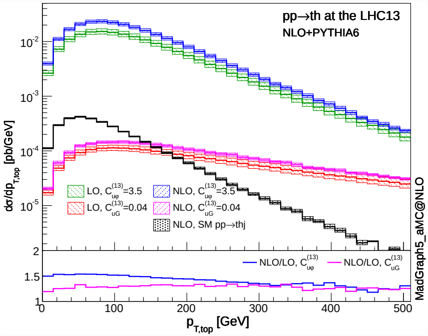
- $pp \to t\gamma$ and $pp \to th$ at NLO+PS: p_T distribution for top (Λ=1 TeV)

$pp \to t\gamma$



$pp \to t\gamma$ 13 TeV

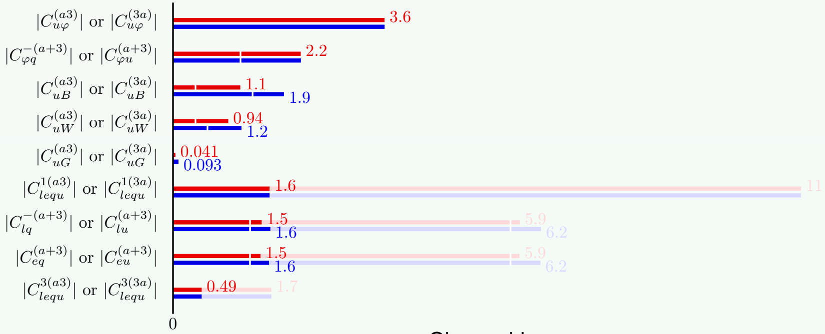
$pp \to th$



$pp \to th$ 13 TeV

Toy fit FCNC

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



$\Lambda = 1$ TeV
red: a=1 (tuX)
blue: a=2 (tcX)

Observables:
$t \to qh$
$t \to qZ$
$pp \to t, \bar{t}$
$pp \to t\gamma, \bar{t}\gamma$
$e^+e^- \to tj, \bar{t}j$

Outline

Chromo-dipole operator

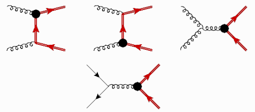
Top-CMDM in $t\bar{t}$ production [D. B. Franzosi and CZ]

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

- We provide an NLO UFO , that allows to make NLO predictions for ttbar production, in the presence of anomalous top chromo-dipole, in an automatic way.

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

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



Cross sections

β_1	LO [pb TeV^2]	NLO [pb TeV^2]	K factor
Tevatron	$1.61^{+0.66}_{-0.43}$ $\begin{smallmatrix}(+41\%)\\(-27\%)\end{smallmatrix}$	$1.810^{+0.073}_{-0.197}$ $\begin{smallmatrix}(+4.05\%)\\(-10.88\%)\end{smallmatrix}$	1.12
LHC8	$50.7^{+17.3}_{-12.4}$ $\begin{smallmatrix}(+34\%)\\(-25\%)\end{smallmatrix}$	$72.62^{+9.26}_{-10.53}$ $\begin{smallmatrix}(+12.7\%)\\(-14.5\%)\end{smallmatrix}$	1.43
LHC13	$161.6^{+48.0}_{-36.2}$ $\begin{smallmatrix}(+29.7\%)\\(-22.4\%)\end{smallmatrix}$	$239.5^{+29.0}_{-31.8}$ $\begin{smallmatrix}(+12.1\%)\\(-13.3\%)\end{smallmatrix}$	1.48
LHC14	$191.3^{+55.6}_{-42.2}$ $\begin{smallmatrix}(+29.0\%)\\(-22.0\%)\end{smallmatrix}$	$283.0^{+33.6}_{-36.9}$ $\begin{smallmatrix}(+11.9\%)\\(-13.1\%)\end{smallmatrix}$	1.48

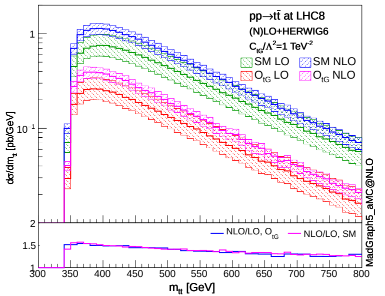
Limits

	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]

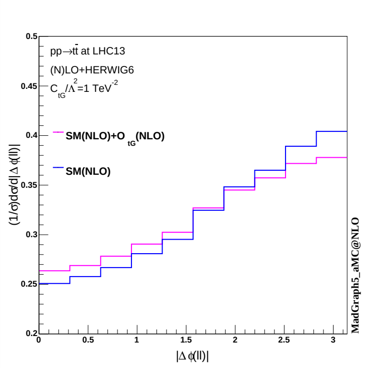
Chromo-dipole operator

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

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

- tbW
  - V/A

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

  - Weak dipole

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

- ttZ
  - V/A

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

  - Weak dipole O_{tW}
- ttH

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

Towards NLO global analysis

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

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

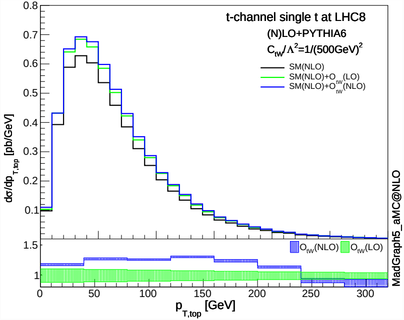
we aim to provide a framework for experimentalists to completely measure top-quark couplings:

- NLO simulation for all "$pp \to \cdots$" 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:

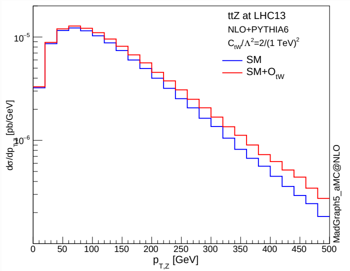
t-channel singl top



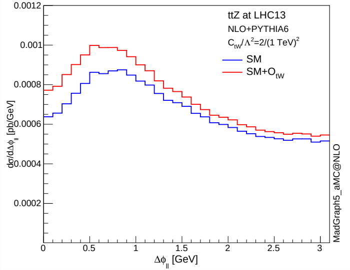
Weak dipole (O_{tW}) in:

- Top left: t-channel single top, p_T top, LHC8.
- Top right: ttZ production, p_T Z, LHC13.
- Bottom right: ttZ production, Δ_ϕ of leptons from Z, LHC13.
- See also [Rontsch and Schulze].

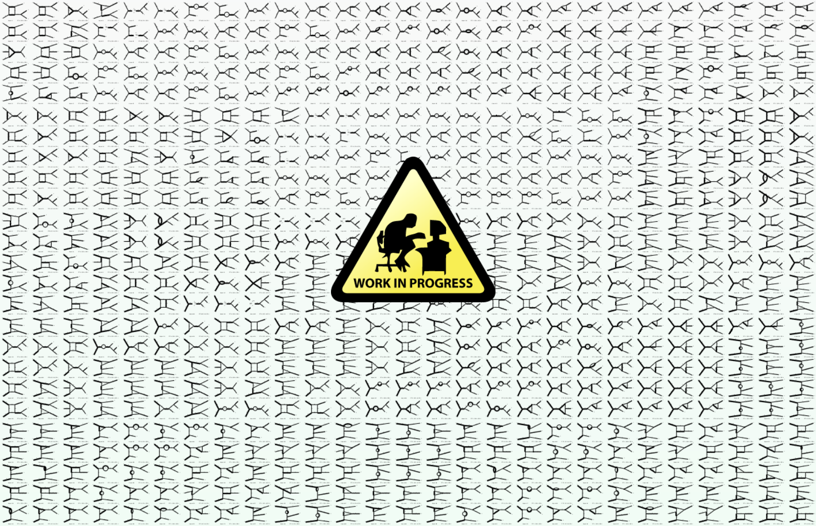
ttZ @ LHC13, pT of Z



ttZ @ LHC13, $\Delta\Phi_{ll}$



ttZ at one loop



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 $Z \to b\bar{b}$ 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.

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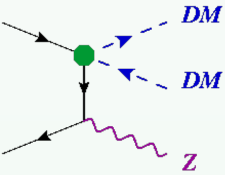
Outline

DM at collider

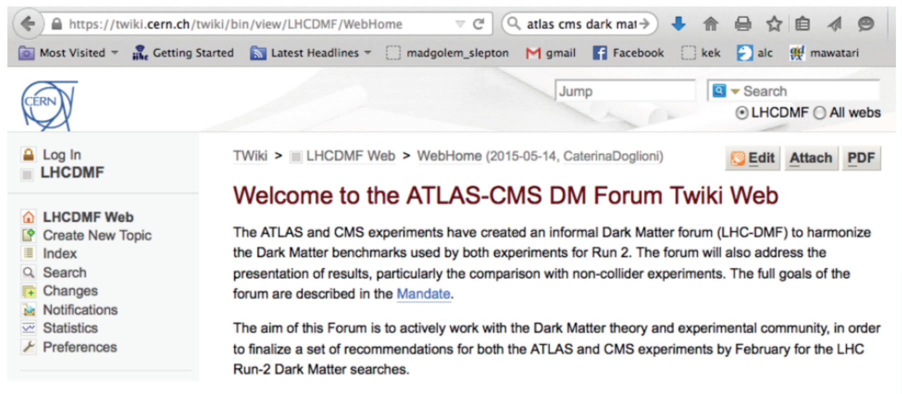
- Early Run I searches for mono-X signatures at ATLAS and CMS were based on DM EFT.
- However, it has become clear that a contact interaction is often not the correct description for the signals to which the LHC is sensitive.
- While the EFT integrates out the degrees of freedom of the (heavy) intermediate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



[see Y. Yang’s talk]

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.

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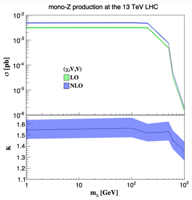
```
your_shell> ./bin/mg5
MG5_aMC> import model DM_simp_NLO_UFO
MG5_aMC> generate p p > z xd xd~ [QCD]
MG5_aMC> output
MG5_aMC> launch
```

$\Rightarrow$



Status

- s-channel simplified model.

$$\mathcal{L}_{X_D}^{Y_0} = \frac{1}{2}\Lambda\, g^S_{X_R} X_R X_R Y_0 + \Lambda\, g^S_{X_C} X_C^* X_C Y_0 + \overline{X}_D (g^S_{X_D} + i g^P_{X_D}) X_D\, Y_0$$

$$\mathcal{L}_{SM}^{Y_0} = \sum_{i,j} \left[\bar{d}_i (g^S_{d_{ij}} + i g^P_{d_{ij}}) d_j + \bar{u}_i (g^S_{u_{ij}} + i g^P_{u_{ij}}) u_j \right] Y_0$$

$$\mathcal{L}_{SMg}^{Y_0} = \frac{1}{\Lambda} G^a_{\mu\nu} (g^S_g\, G^{a,\mu\nu} + g^P_g\, \tilde{G}^{a,\mu\nu})\, Y_0$$

$$\mathcal{L}_{SM\,EW}^{Y_0} = \frac{1}{\Lambda} g^S_{h1}\, (D^\mu \phi)^\dagger\, (D_\mu \phi)\;\; Y_0 + g^S_{h2} \Lambda\, |\phi|^2\;\; Y_0 + \frac{1}{\Lambda} B_{\mu\nu} (g^S_B\, B^{\mu\nu} + g^P_B\, \tilde{B}^{\mu\nu})\, Y_0 + \frac{1}{\Lambda} W^i_{\mu\nu} (g^S_W\, W^{i,\mu\nu} + g^P_W\, \tilde{W}^{i,\mu\nu})\, Y_0$$

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Status

- s-channel simplified model.

$$\mathcal{L}_{X_D}^{Y_1} = \frac{i}{2}\, g^V_{X_C} (X_C^* (\partial_\mu X_C) - (\partial_\mu X_C^*) X_C)\, Y_1^\mu + \overline{X}_D \gamma_\mu (g^V_{X_D} + i\gamma_5 g^A_{X_D}) X_D\, Y_1^\mu$$

$$\mathcal{L}_{SM}^{Y_1} = \sum_{i,j} [\bar{d}_i \gamma_\mu (g^V_{d_{ij}} + i g^A_{d_{ij}} \gamma_5) d_j + \bar{u}_i \gamma_\mu (g^V_{u_{ij}} + i g^A_{u_{ij}} \gamma_5) u_j]\, Y_1^\mu$$

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

s-channel validation

- Spin-1 mediator

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

```
> (import model loop_sm)
> generate p p > ta- ta+ j / a
  [QCD]
> output
> launch
```

DM+j

```
> import model DMsimp_NLO
> generate p p > xd xd~ j
  [QCD]
> output
> launch
```

- Spin-0 mediator

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

```
> (import model loop_sm)
> generate p p > t t~ ta- ta+
  / a z [QCD]
> output
> launch
```

DM+$t\bar{t}$

```
> import model DMsimp_NLO
> generate p p > t t~ xd xd~
  [QCD]
> output
> launch
```

s-channel validation

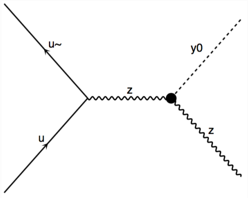
- SM $Z + H$ production vs. mediator production

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
```

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, $\mu = \sum_i M_{T,i}/2$

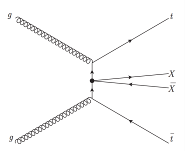
m_{DM}/GeV	M_{med}/GeV									
1	10	20	50	100	200	300	500	1000	2000	10000
10	10	15	50	100						10000
50	10		50	95	200	300				10000
150	10				200	295	500	1000		10000
500	10						500	995	2000	10000
1000	10							1000	1995	10000

m_{DM}/GeV	K-factor									
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

Status

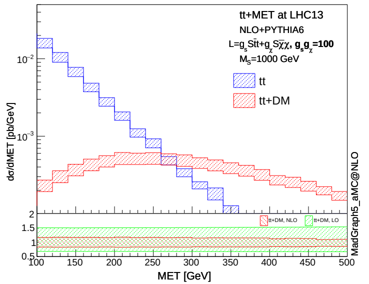
- s-channel simplified model.
  - mono-j/Z
  - mono-ttbar

DM example: mono-ttbar

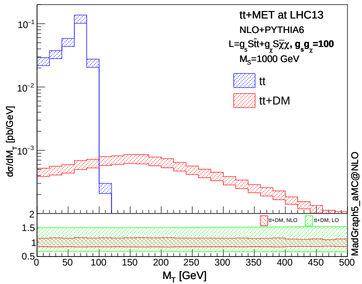


Lin, Kolb, Wang
1303.6638

MET



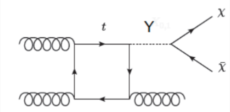
Transverse mass



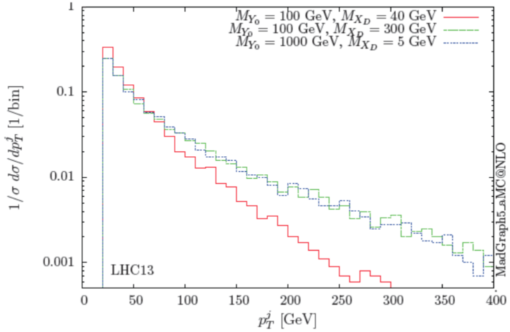
Status

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

DM example: loop-induced mono-j



p_T jet



g g ⟶ χ χ j

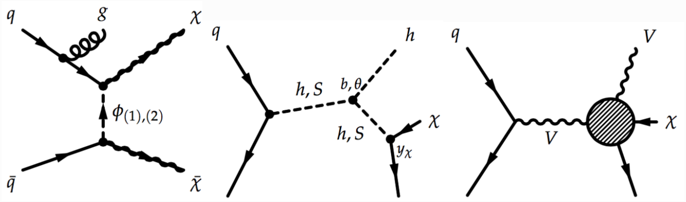
Spin-0 mediator: scalar couplings to both top and Dirac spinor DM

Shape comparison: Normalised to 1

Mediator width: Calculated automatically with MG5_aMC@NLO

Status

- s-channel simplified model.
  - mono-j/Z
  - mono-ttbar
  - loop-induced
  - …
- Available at `http://feynrules.irmp.ucl.ac.be/wiki/DMsimp`
- 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

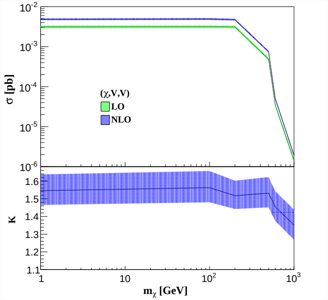
NLO elements

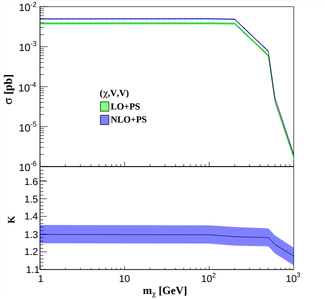
- Virtual: MadLoop (+CutTools)
  - Loop integral reduction using OPP method.
  - Need UV and R2 counterterms.

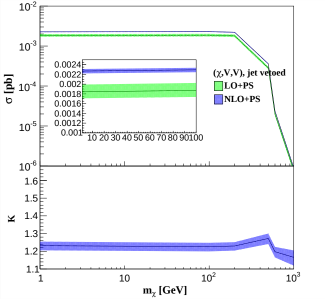
$$A(\bar{q}) = \frac{N(q)}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}, \qquad N(q) = \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)\right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i$$
$$+ \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)\right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i$$
$$+ \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1)\right] \prod_{i \neq i_0, i_1}^{m-1} D_i$$
$$+ \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0)\right] \prod_{i \neq i_0}^{m-1} D_i$$
$$+ \tilde{P}(q) \prod_{i}^{m-1} D_i .$$

- 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.

DM example: mono-Z





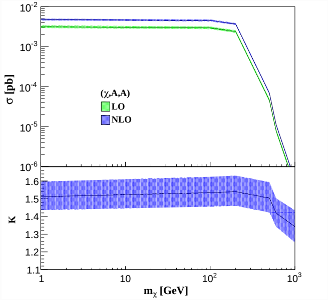


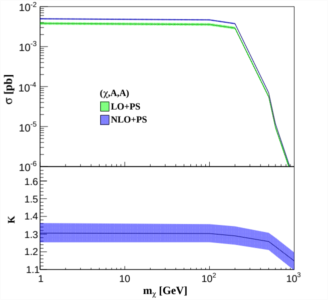
Mono-Z at LHC 13:

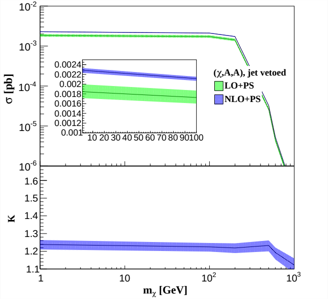
- $(\bar{X}_D \gamma^\mu X_D)(\bar{q}\gamma^\mu q)$
- $M_{Med} = 1000$ GeV.
- Cuts follow CMS mono-Z at 8 TeV.

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

DM example: mono-Z







Mono-Z at LHC 13:

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

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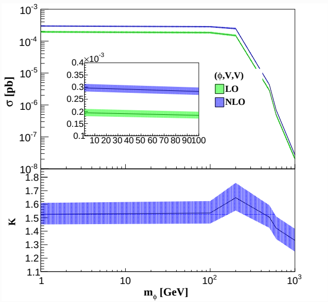

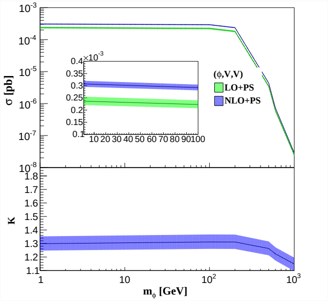

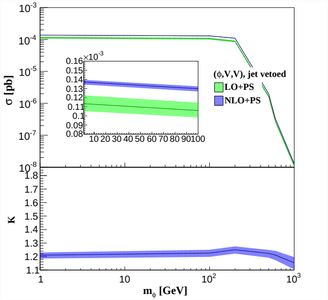

Mono-Z at LHC 13:

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

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

EFT@NLO: How?

Loop = pole + logs + finite pieces

- pole + logs are process-independent
- finite pieces are not

SMEFT evolution

$$LO : A_{SMEFT} = A_{SM} + A_i a^i , \quad a_i = \text{dim 6 coef.}$$

$$RGE \text{ (logs only)} : a_i \to Z_{ij}(L) a^j , L = ln(\Lambda / M_H)$$

$$NLO \text{ (logs and finite)} : A_{SMEFT} = A_{SM} + A_k(L, const) a^k$$

Automation: Why?

In general

- Saves time and manpower.
- Avoid bugs.
- Available for experimentalists.
- Can implement shower, cuts, and detector effects.

For the purpose of EFT@NLO, doesn't make sense to provide results for 2499 operators individually...