FeynRules

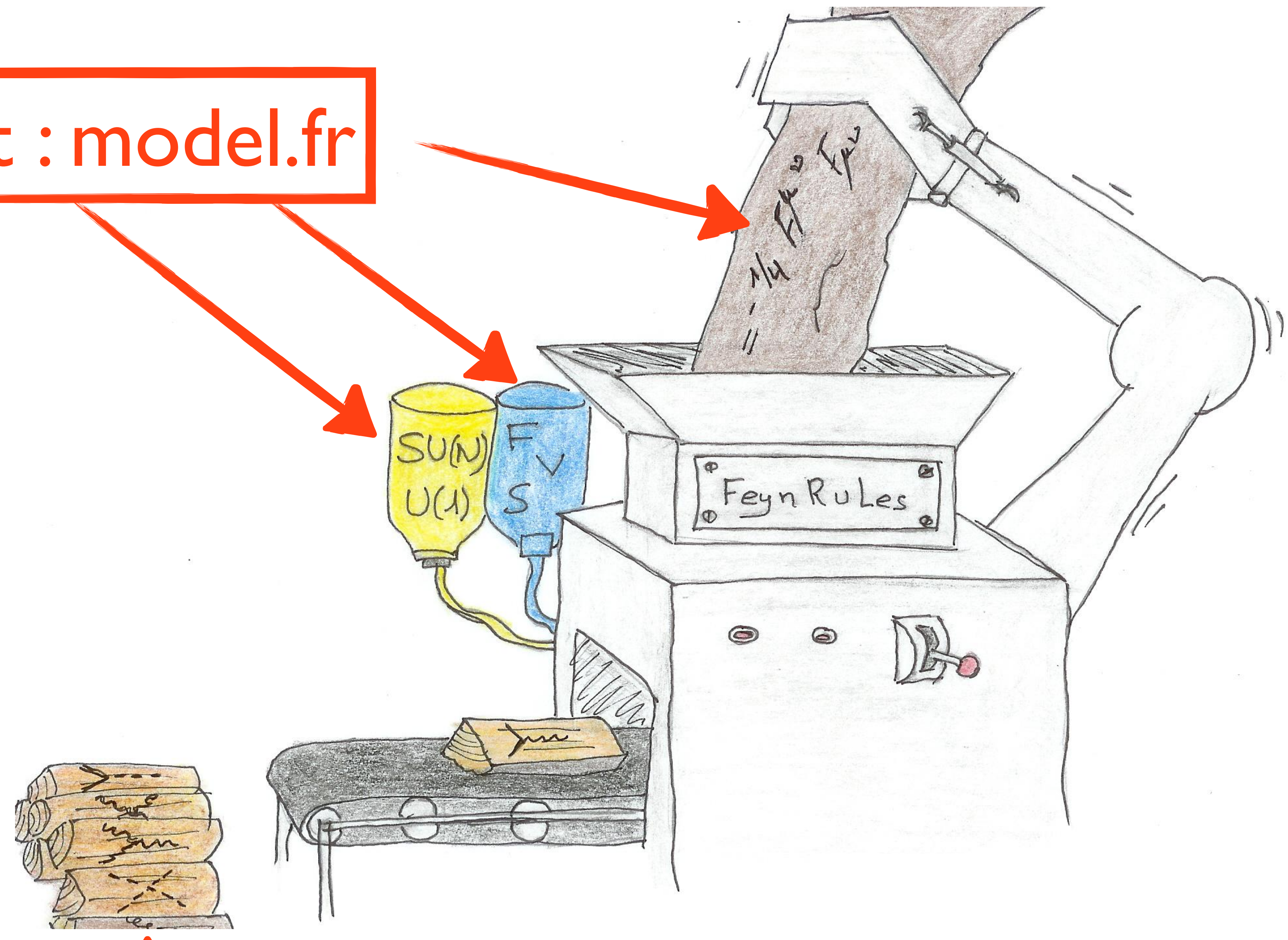
Celine Degrande (CERN)
MC4BSM @ Durham, 19/4/2018

Plan

- FeynRules in a nutshell
- New in FeynRules :
  - NLO
  - AllYourBases (Liam Moore)
- Final remarks

FeynRules

Input : model.fr



Output : vertices

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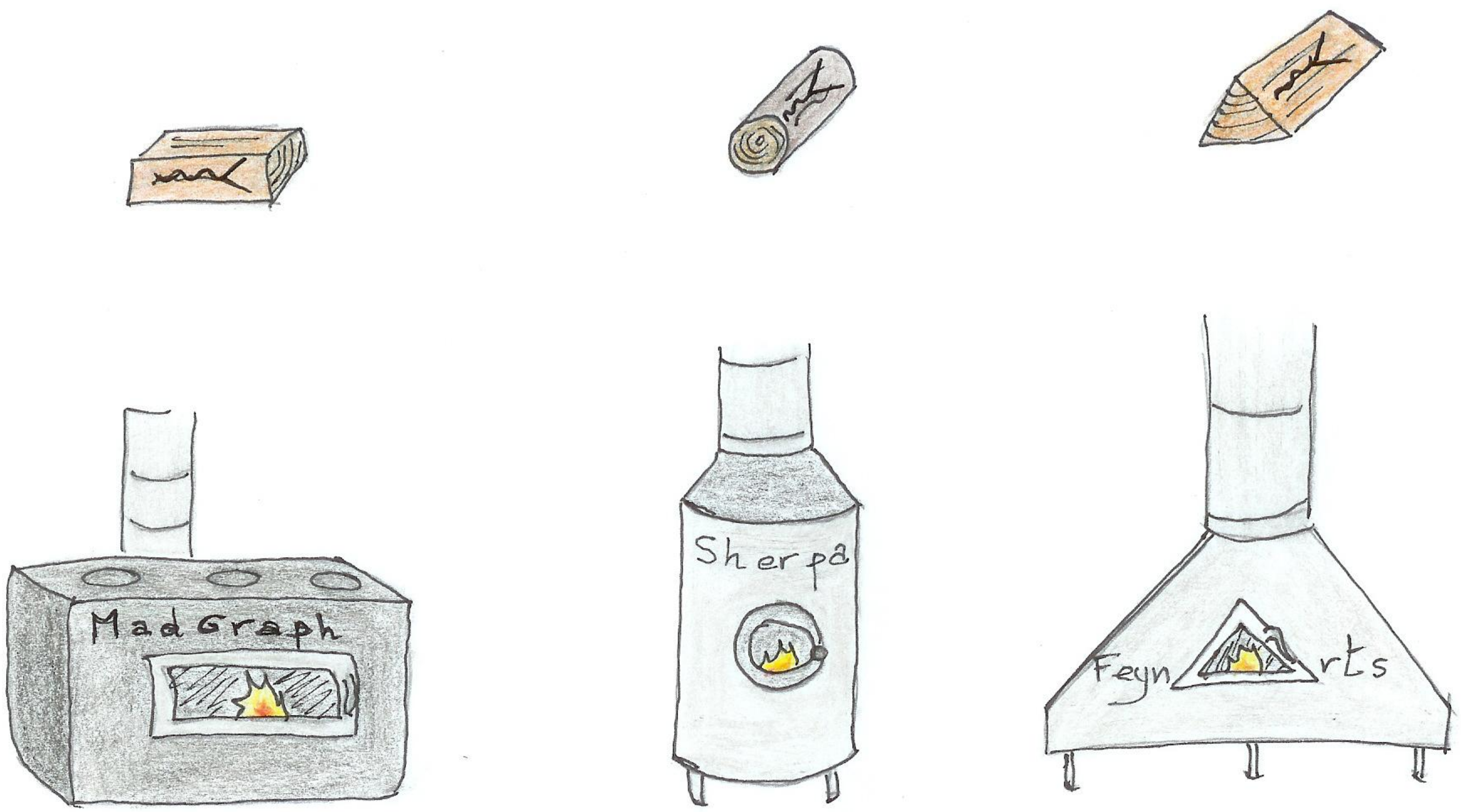
FeynRules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

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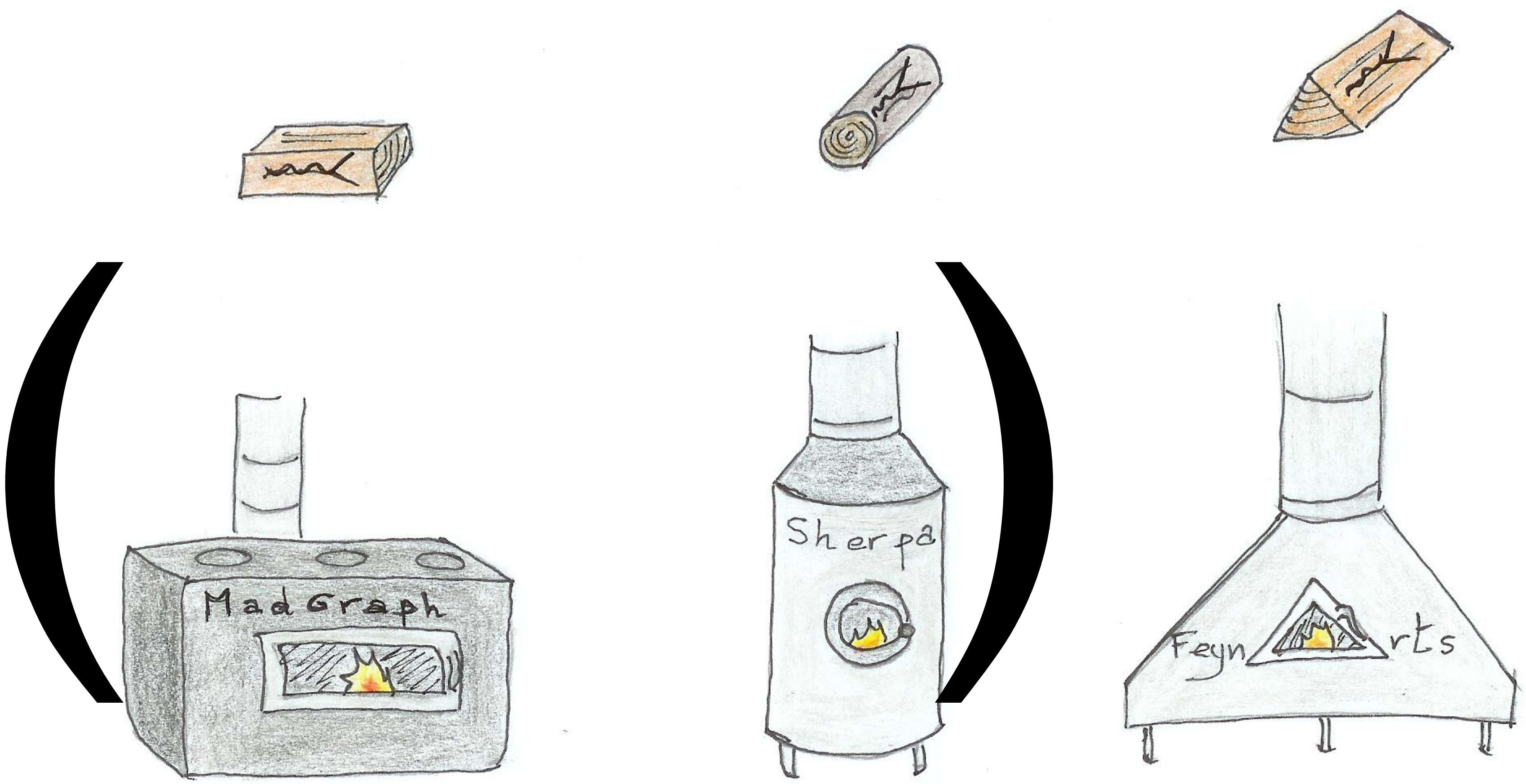
FeynRules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

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UFO

- Generator independent output with full model information
- Contains the list of particles, parameters, vertices, decays (1to 2), coupling orders
- vertices are split into Lorentz structures, colours and couplings and all are included in the model!

$$-ig_s \quad T^a_{ij} \quad \gamma_\mu$$

- Used in MG5, Herwig, Gosam, Sherpa, …

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Madgraph5_aMC@NLO

Automated NLO computation

- Computation of the born
- Computation of the real
- Computation of the loop
- Matching with parton shower 'à la' MC@NLO

MG5

MadFKS (IR)

MadLoop

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MadLoop

$$\mathcal{A}^{1-loop} = \sum_i d_i \ \mathrm{Box}_i + \sum_i c_i \ \mathrm{Triangle}_i + \sum_i b_i \ \mathrm{Bubble}_i + \sum_i a_i \ \mathrm{Tadpole}_i + R$$

- Box, Triangle, Bubble and Tadpole are known scalar integrals
- Loop computation = find the coefficients
  - Tensor reduction (OPP)
- R : rational terms should be partially provided
- UV counterterm vertices have to be provided

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To be provided : R_2

$$\bar{A}(\bar{q}) = \frac{1}{(2\pi)^4}\int d^d\bar{q}\,\frac{\bar{N}(\bar{q})}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}}, \qquad \bar{D}_i = (\bar{q}+p_i)^2 - m_i^2$$

$$\bar{N}(\bar{q}) = N(q) + \tilde{N}(\tilde{q}, q, \epsilon)$$

d 4 ε

$$R_2 \equiv \lim_{\epsilon\to 0}\frac{1}{(2\pi)^4}\int d^d\bar{q}\,\frac{\tilde{N}(\tilde{q},q,\epsilon)}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}}$$

Finite set of vertices that can be computed once for all

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Computed in MadLoop :R$_1$

Due to the ε dimensional parts of the denominators

Like for the 4 dimensional part but with a different set of integrals

$$\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j} = -\frac{i\pi^2}{2}\left[m_i^2+m_j^2-\frac{(p_i-p_j)^2}{3}\right]+\mathcal{O}(\epsilon)\,,$$

$$\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j\bar{D}_k} = -\frac{i\pi^2}{2}+\mathcal{O}(\epsilon)\,,$$

$$\int d^n\bar{q}\frac{\tilde{q}^4}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_l} = -\frac{i\pi^2}{6}+\mathcal{O}(\epsilon)\,.$$

Only R = R$_1$+R$_2$ is gauge invariant ⇨ Check

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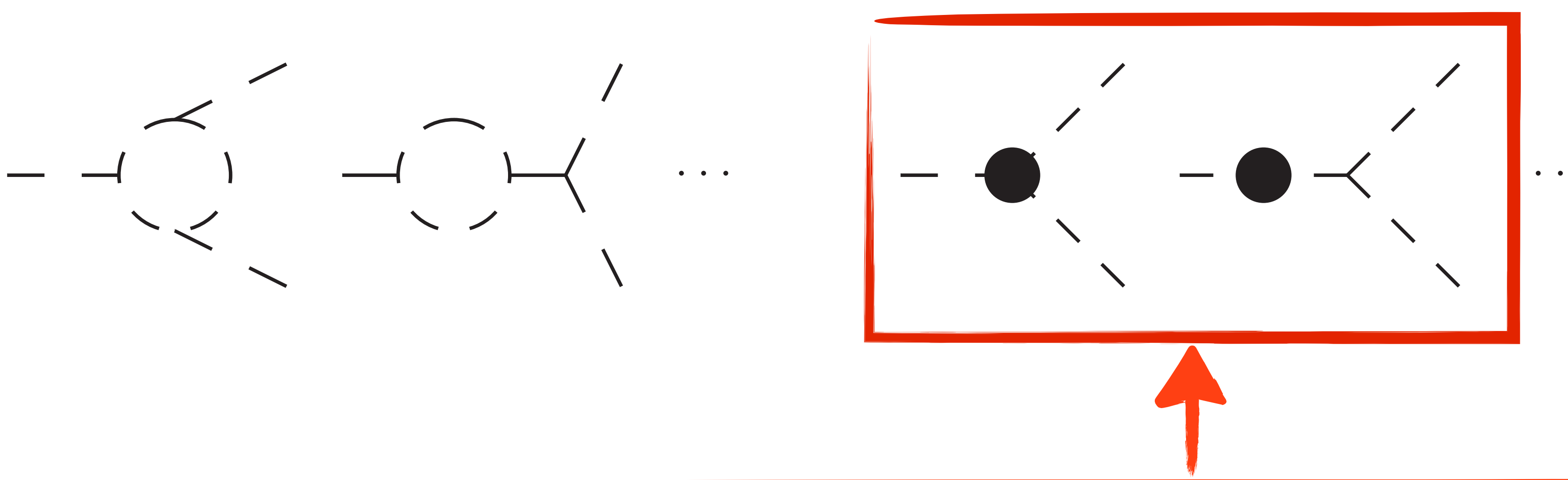
UV

$$\bar{A}(\bar{q}) = \frac{1}{(2\pi)^4}\int d^d\bar{q}\,\frac{\bar{N}(\bar{q})}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}} = K\,\frac{1}{\epsilon} + \mathcal{O}\left(\epsilon^0\right)$$



$$= 0\,\frac{1}{\epsilon} + \mathcal{O}\left(\epsilon^0\right)$$

Relations fixed by the Lagrangian (finite part)

Finite set of vertices that can be computed once for all

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Renormalization

External parameters

$$x_0 \rightarrow x + \delta x,$$

$$\phi_0 \rightarrow (1 + \frac{1}{2}\delta Z_{\phi\phi})\phi + \sum_{\chi} \frac{1}{2}\delta Z_{\phi\chi}\chi$$

Same for the conjugate field

Internal parameters are renormalised by replacing the external parameters in their expressions

$$\begin{array}{ll} gg & \left(1+\delta Z_{gg}\right) TL \\ ggg & \left(1+\frac{1}{2}\delta\alpha_s+\frac{3}{2}\delta Z_{gg}\right) TL \\ gggg & \left(1+\delta\alpha_s+2\delta Z_{gg}\right) TL \end{array}$$

Fixed by

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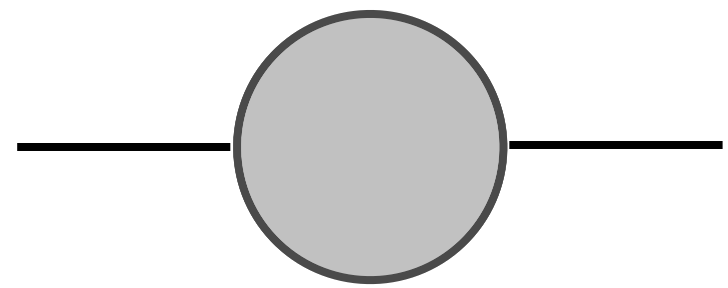
Renormalization conditions

On-shell scheme (or complex mass scheme):

Renormalized mass = Physical mass

Two-point function vanishes on-shell (No external bubbles)



$$i\delta_{ij}\left(\not p - m_i\right) + i\left[f^{L}_{ij}\left(p^2\right)\not p\gamma_- + f^{R}_{ij}\left(p^2\right)\not p\gamma_+ + f^{SL}_{ij}\left(p^2\right)\gamma_- + f^{SR}_{ij}\left(p^2\right)\gamma_+\right]$$

$$\begin{aligned}
\tilde{\Re}\left[f^{L}_{ij}\left(p^2\right)m_i + f^{SR}_{ij}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0\\
\tilde{\Re}\left[f^{R}_{ij}\left(p^2\right)m_i + f^{SL}_{ij}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0\\
\tilde{\Re}\left[2m_i\frac{\partial}{\partial p^2}\left[\left(f^{L}_{ii}\left(p^2\right) + f^{R}_{ii}\left(p^2\right)\right)m_i + f^{SL}_{ii}\left(p^2\right) + f^{SR}_{ii}\left(p^2\right)\right] + f^{L}_{ii}\left(p^2\right) + f^{R}_{ii}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0
\end{aligned}$$

Similar for the vectors and scalars

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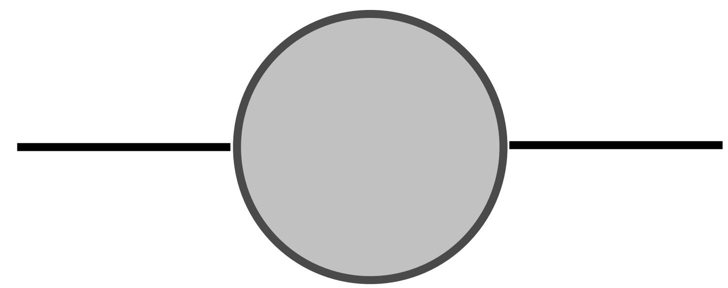
Renormalization conditions

On-shell scheme (or complex mass scheme):

Renormalized mass = Physical mass

Two-point function vanishes on-shell (No external bubbles)



$$i\delta_{ij}\left(\not p - m_i\right) + i\left[f_{ij}^{L}\left(p^2\right)\not p\gamma_- + f_{ij}^{R}\left(p^2\right)\not p\gamma_+ + f_{ij}^{SL}\left(p^2\right)\gamma_- + f_{ij}^{SR}\left(p^2\right)\gamma_+\right]$$

$$\begin{aligned}
\widetilde{\Re}\left[f_{ij}^{L}\left(p^2\right)m_i + f_{ij}^{SR}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0\\
\widetilde{\Re}\left[f_{ij}^{R}\left(p^2\right)m_i + f_{ij}^{SL}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0\\
\widetilde{\Re}\left[2m_i\frac{\partial}{\partial p^2}\left[\left(f_{ii}^{L}\left(p^2\right)+f_{ii}^{R}\left(p^2\right)\right)m_i + f_{ii}^{SL}\left(p^2\right)+f_{ii}^{SR}\left(p^2\right)\right] + f_{ii}^{L}\left(p^2\right)+f_{ii}^{R}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0
\end{aligned}$$

Similar for the vectors and scalars

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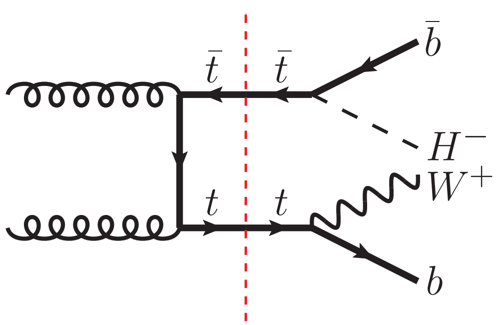
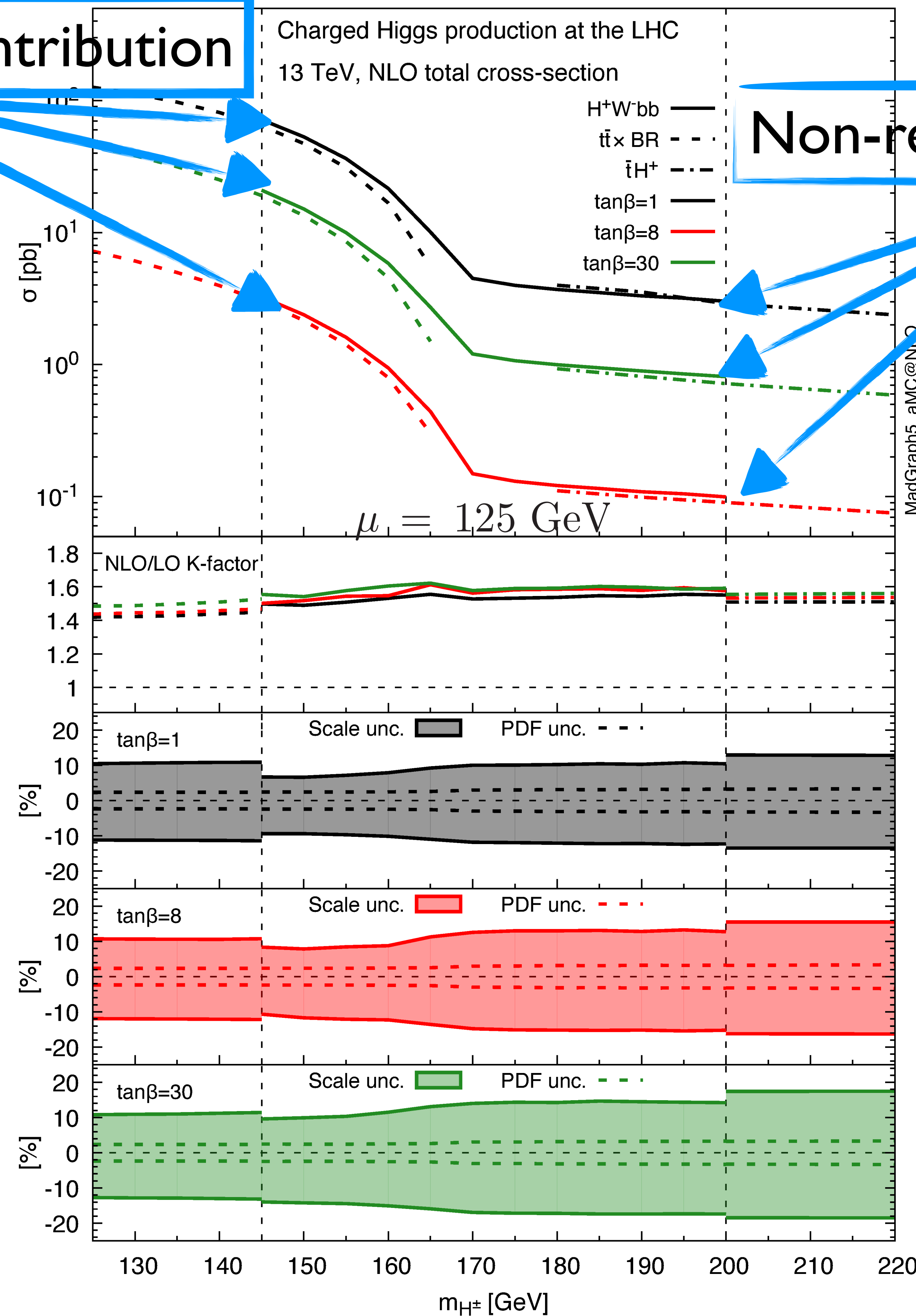
H^+ production : $m_H \sim m_t$

Single-resonant contribution

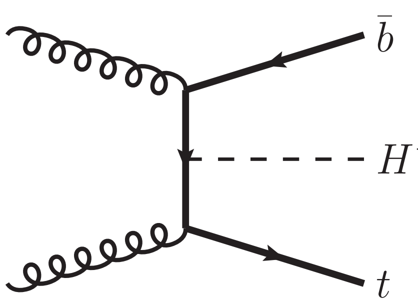
Non-resonant contribution

$$\frac{m_t}{2} \lesssim \mu \lesssim m_t$$





$$\mu = (m_t + m_{H^\pm} + m_b)/3$$



Errors are reduced by a factor ~2

CD, R. Frederix, V. Hirschi, M. Ubiali, M. Wiesemann, M. Zaro
Phys.Lett. B772 (2017) 87-92

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BSM@NLO

- Goal : Automate the one-loop computation for BSM models
- Required ingredients :
  - Tree-level vertices — Done(FeynRules)
  - R2 vertices (OPP)
  - UV counterterm vertices — Missing
- Solution : UFO at NLO

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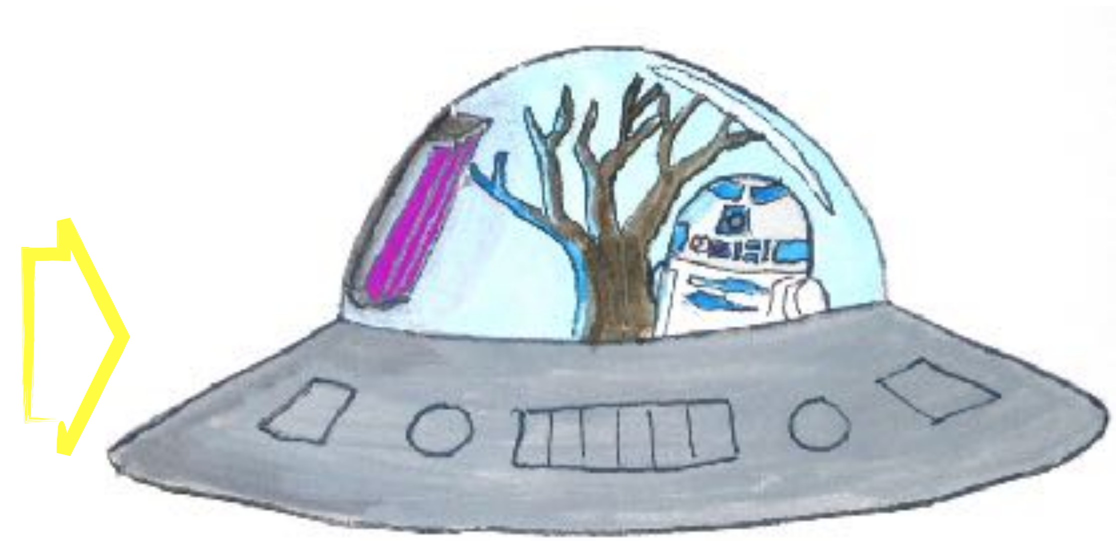
How does it work?

FeynRules

Renormalize the Lagrangian

model.mod

model.gen



model.nlo

FeynArts

Write the amplitudes

NLOCT.m

Compute the NLO vertices

CD, Comput.Phys.Commun. 197 (2015) 239-262

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R2 :Validation

- tested* on the SM (QCD:P. Draggiotis et al. +QED:M.V. Garzelli et al)
- tested* on MSSM (QCD:H.-S. Shao, Y.-J. Zhang) : test the Majorana

*Analytic comparison of the expressions

UV Validation

- SM QCD : tested* (W. Beenakker, S. Dittmaier, M. Kramer, B. Plumper)
- SM EW : tested* (expressions given by H.-S. Shao from A. Denner)

*Analytic comparison of the expressions

Tests in event generators

- aMC@NLO
- The SM QCD has been tested by V. Hirschi (Comparison with the built-in version)
- SM EW (MZ scheme): comparison to published results for ME by H.-S. Shao and V. Hirschi
- Various BSM
  - gauge invariance
  - pole cancelation

Test EW

```
== a a > t t~ ['QED'] ==
== a a > t t~ a ['QED'] ==
== a a > w+ w- ['QED'] ==
== a b > t w- ['QED'] ==
== d~ d > w+ w- ['QCD'] ==
== d~ d > w+ w- ['QED'] ==
== d~ d > z z ['QCD'] ==
== d~ d > z z ['QED'] ==
== e+ e- > t t~ a ['QED'] ==
== e+ e- > t t~ g ['QED'] ==
== g b > t w- ['QED'] ==
== g g > h h ['QCD'] ==
== g g > t t~ ['QED'] ==
== g g > t t~ g ['QED'] ==
== g g > t t~ h ['QCD'] ==
== g g > t t~ h ['QED'] ==
== h h > h h ['QED'] ==
== h h > h h h ['QED'] ==
== t t~ > w+ w- ['QED'] ==
```

```
== u b > t d ['QED'] ==
== u d~ > t b~ ['QED'] ==
== u g > t d b~ ['QED'] ==
== u u~ > a a ['QED'] ==
== u u~ > e+ e- ['QED'] ==
== u u~ > g a ['QCD QED'] ==
== u u~ > u u~ ['QCD QED'] ==
== u u~ > u u~ a ['QCD QED'] ==
== u u~ > u u~ g ['QCD QED'] ==
== u u~ > w+ w- ['QED'] ==
== u u~ > z a ['QED'] ==
== u u~ > z z ['QED'] ==
== u~ d > w- z ['QCD'] ==
== u~ d > w- z ['QED'] ==
== u~ u > w+ w- ['QCD'] ==
== u~ u > w+ w- ['QED'] ==
== u~ u > z z ['QCD'] ==
== u~ u > z z ['QED'] ==
== ve ve~ > e+ e- ['QED'] ==
== w+ w- > h h ['QED'] ==
```

Massive and massless b

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Restrictions/Assumptions

- Renormalizable Lagrangian, maximum dimension of the operators is 4
- Feynman Gauge
- $\{\gamma_\mu, \gamma_5\} = 0$
- ‘t Hooft-Veltman scheme
- On-shell scheme for the masses and wave functions
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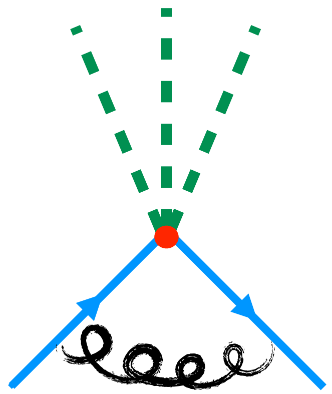
EFT at NLO



In the loop: same as SM

$$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$$

$$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$$

$$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$

$$\varphi^\dagger \varphi \, G^A_{\mu\nu} G^{A\mu\nu}$$

More momenta: higher rank of the integral numerator

Additional gamma algebra $(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$

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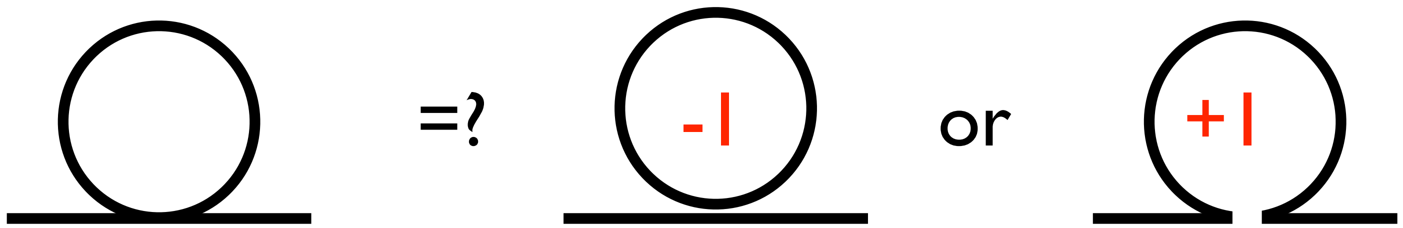
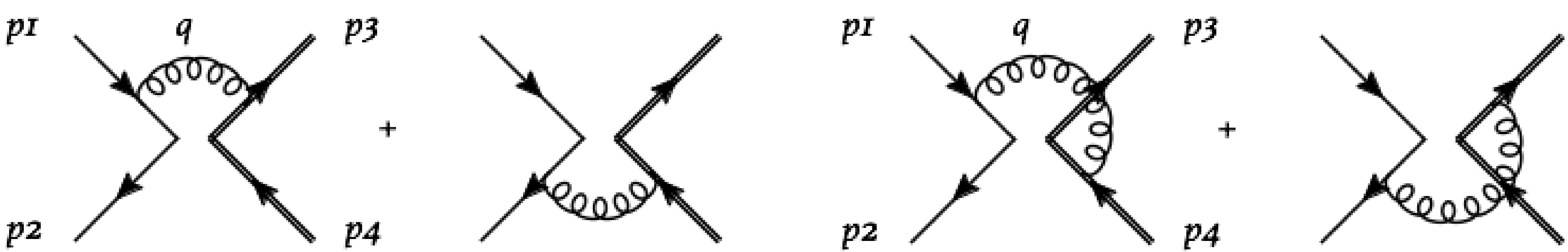
EFT at NLO



Evanescent operators: $O_{ut}^{(8)} = \left(\bar{u}\gamma^{\mu}T^{A}u\right)\left(\bar{t}\gamma_{\mu}T^{A}t\right)$



$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}P_R \otimes \gamma_{\mu}\gamma_{\nu}\gamma_{\rho}P_R = E + (16 - 4a\varepsilon)\gamma^{\mu}P_R \otimes \gamma_{\mu}P_R$$
$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}P_R \otimes \gamma_{\rho}\gamma_{\nu}\gamma_{\mu}P_R = -E + [4 - (12 - 4a)\varepsilon]\gamma^{\mu}P_R \otimes \gamma_{\mu}P_R$$

Extra R2 (gauge invariant)
Change the UV matching

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EFT at NLO

- UV counterterms :
  - Basis reduction needed for the anomalous matrix (By Liam Moore)
    - Check (R. Alonso, E. E. Jenkins, A. V. Manohar, M. Trott, JHEP 1404 (2014) 159)
  - MSbar : $1/\varepsilon$ from the amplitudes not from the renomalization
  - Running (UFO 2.0)

Top FCNC

CD, F. Maltoni, J. Wang, C. Zhang, PRD91 (2015) 034024

	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%

$$qg \to tB$$

$$B = \gamma, Z, h$$

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + H.c.$$

Small when constraints from $ug \to t$ are taken into account

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

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

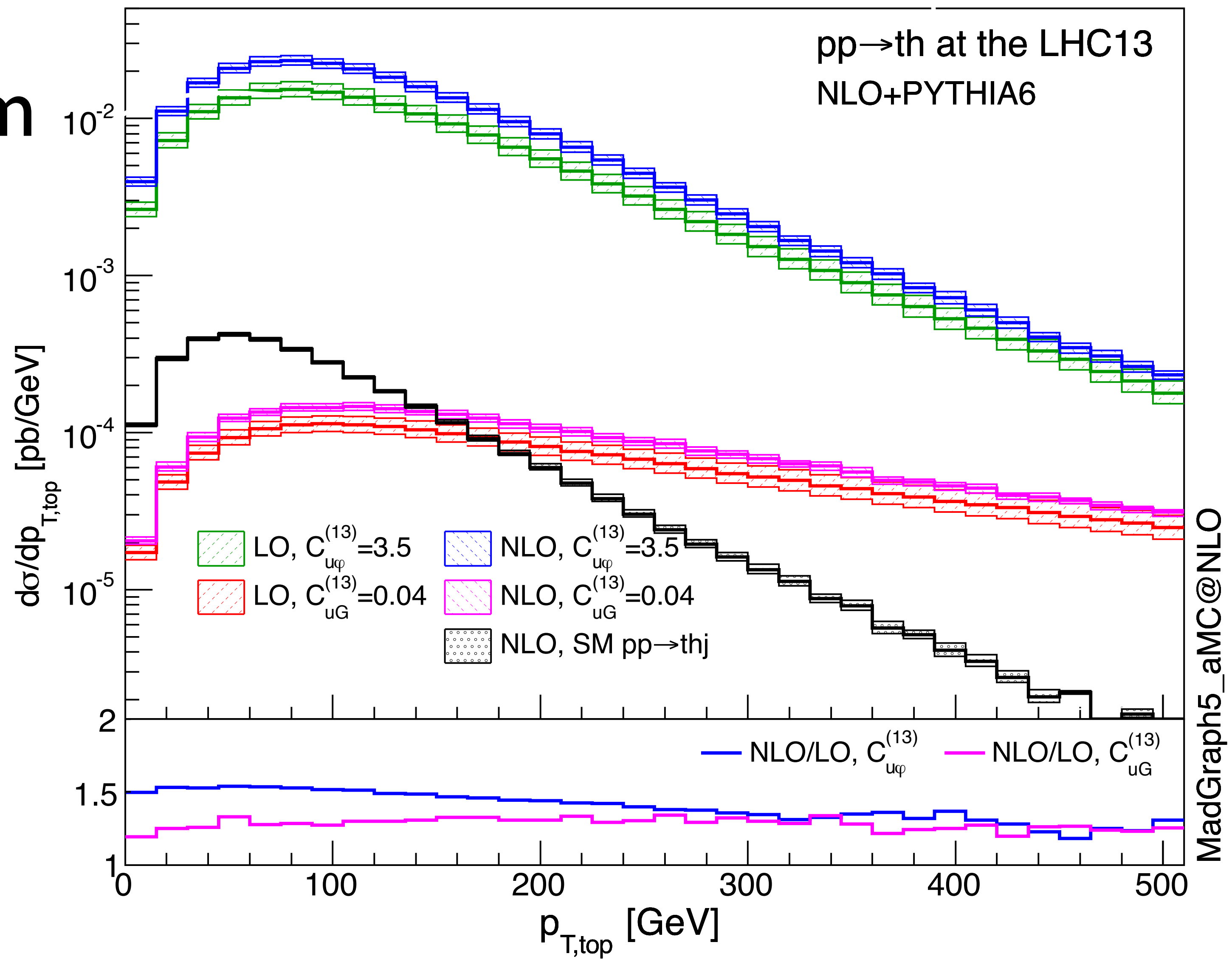
$$O_{\varphi u}^{(i+3)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{u}_i \gamma^\mu t)$$

$$O_{uB}^{(i3)} = g_Y (\bar{q}_i \sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu},$$

$$O_{uG}^{(i3)} = g_s (\bar{q}_i \sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu},$$

$$O_{uW}^{(i3)} = g_W (\bar{q}_i \sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O_{u\varphi}^{(i3)} = (\varphi^\dagger \varphi)(\bar{q}_i t)\tilde{\varphi}$$



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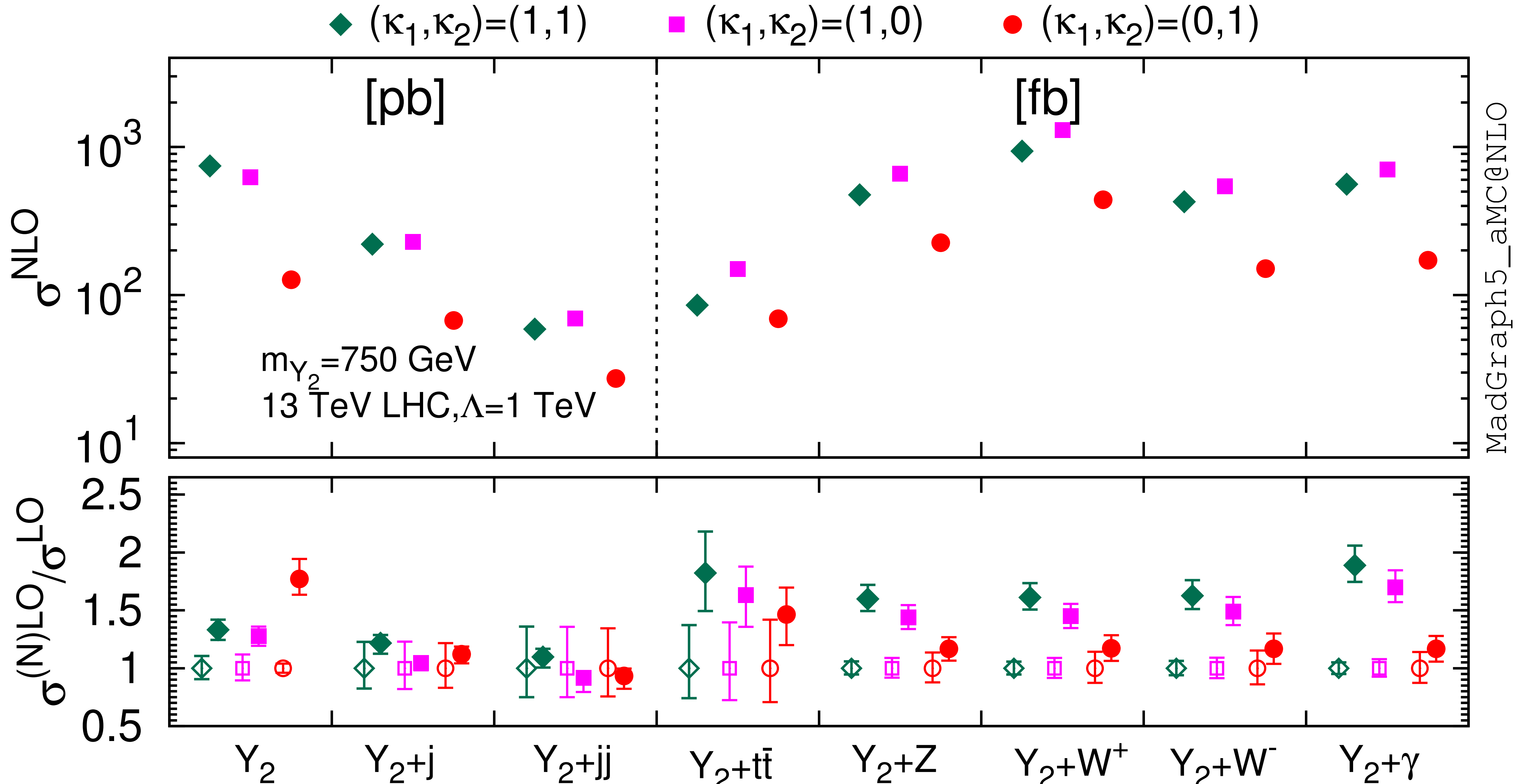
Spin-2



Process	Couplings set
$pp \to Y_2, Y_2+j, Y_2+jj$	$\kappa_1 = \kappa_g, \kappa_2 = \kappa_{q,t}$
$pp \to Y_2 + t\bar{t}$	$\kappa_1 = \kappa_{g,q}, \kappa_2 = \kappa_t$
$pp \to Y_2 + Z$	$\kappa_1 = \kappa_{g,q,t}, \kappa_2 = \kappa_{B,W,H}$
$pp \to Y_2 + W^\pm$	$\kappa_1 = \kappa_{g,q,t}, \kappa_2 = \kappa_{B,W,H}$
$pp \to Y_2 + \gamma$	$\kappa_1 = \kappa_{g,q,t}, \kappa_2 = \kappa_{B,W,H}$
$pp \to Y_2 + H$	$\kappa_1 = \kappa_{g,q,t}, \kappa_2 = \kappa_{B,W,H}$
$Y_2 \to jj$	$\kappa_1 = \kappa_g, \kappa_2 = \kappa_{q,t}$
$Y_2 \to t\bar{t}$	$\kappa_1 = \kappa_g, \kappa_2 = \kappa_t$

Scale+pdf+param. unc.

$$\mathcal{L}^{Y_2}_{\mathrm{V,f}} = -\frac{\kappa_{V,f}}{\Lambda} T^{V,f}_{\mu\nu} Y_2^{\mu\nu}$$

G. Das, CD, V. Hirschi, F. Maltoni, H.-S. Shao, Phys.Lett. B770 (2017) 507-513

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Restrictions/Assumptions

- Renormalizable Lagrangian, maximum dimension of the operators is 4 → EFT with max 4F (Evanescent op.)
- Feynman Gauge → any gauge (any rank for EFT)
- $\{\gamma_\mu, \gamma_5\} = 0$
- ‘t Hooft-Veltman scheme
- On-shell scheme for the masses and wave functions
- $\overline{\text{MS}}$ by default for everything else (zero-momentum possible for fermion gauge boson interaction)

→ MZ scheme for EW coupling

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Operators bases in the SMEFT

$$\mathcal{L}_{\text{BSM}}(\{\Phi_{\text{SM}}\}, \{\boldsymbol{\mathcal{X}}_{\text{NP}}\}) \rightarrow \mathcal{L}_{SM}(\{\Phi_{\text{SM}}\}) + \frac{C_i}{\Lambda^2}\mathcal{O}_i(\{\Phi_{\text{SM}}\}) + \ldots$$

- Below heavy thresholds, UV states decouple $\leftrightarrow$ local operators $\mathcal{O}_i$
- BSM model determines pattern of effective couplings $\frac{C_i}{\Lambda^2} = \frac{f(g_{\boldsymbol{\mathcal{X}}})}{m^2_{\boldsymbol{\mathcal{X}}}}$

$D \geq 6$ operators exhibit nontrivial relationships - $\mathcal{O}_i^{(6)} = k_{ij}\mathcal{O}_j^{(6)}$:

e.g. : $(\bar{u}\gamma^\mu T^A u)(\bar{t}\gamma_\mu T^A t) = \frac{1}{2}(\bar{u}\gamma^\mu t)(\bar{t}\gamma_\mu u) - \frac{1}{6}(\bar{u}\gamma^\mu u)(\bar{t}\gamma_\mu t)$

Redundancies eliminated by **fixing an operator basis**. Several options:

- Model-independent choice e.g. **Warsaw** **(Grzadkowski++ 1008.4884)**
- Choose for UV interpretation e.g. **SILH** **(Giudice++ 0703164)**
- Simplicity of relationship to observables e.g. **Mass** **(Gupta++ 1405.0181)**

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The Warsaw procedure

Warsaw - tackle problem systematically at $D = 6$. In a nutshell:

- Divide operators into classifications according to generic building blocks: $\{X, \psi, \varphi, D\}$, e.g. $(\varphi^\dagger\varphi)G^A_{\mu\nu}G^{A\,\mu\nu} \in \boxed{X^2\varphi^2}$
- Impose a hierarchy: fewer $D_\mu \implies$ 'lower' classification
- For each classification with $n_D \geq 1$, use identities (e.g. IBP) to express operators as $\mathcal{O}^{(6)}(\{\varphi\}) \propto \frac{\delta \mathcal{S}_0}{\delta \varphi_i}$, the classical EoM
- Use EoM as far as possible, e.g. $i\not{D}u \to \Gamma_u^\dagger \widetilde{\varphi}^\dagger q$ to eliminate D_μ

Result: proof all operators expressible as a linear combination of 59, spread over 12 classifications.

But - when decomposition of redundant operators is necessary (e.g. in matching, NLO calculations) it must be done by hand.

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AllYourBases-Automatic basis reduction in FeynRules

AllYourBases - get FeynRules to derive explicit decomposition of any operator onto the Warsaw basis automatically:

$$\mathcal{L}_{\text{eff}} \supset C_j \mathcal{O}_j^{(6)}, \quad \mathcal{O}_j^{(6)} = \sum_{i=1}^{59} k_{ij} \mathcal{O}_i^{\text{Warsaw}}$$

. . . by directed application of necessary identities at Lagrangian level:

- EoMs: $(D^\rho G_{\rho\mu})^A \to g_s \sum \left(\bar{q}\gamma_\mu T^A q\right)\ , \ldots$
- Fierz identities: $M^I_{ij} M^I_{kj} \to \sum c_J M^J_{il} M^J_{kj}\ , M^J \in \{\Gamma^A, T, \tau, \delta \ldots\}$
- Integration-by-Parts: $\mathcal{A}^\mu (D_\mu \mathcal{B}) \to -(D_\mu \mathcal{A})\mathcal{B}^\mu + \boxed{T}$
- Gamma matrix algebra: $\eta_{\mu\nu}\gamma_\rho \to \gamma_\nu \eta_{\mu\rho} + i\gamma_\mu \sigma_{\nu\rho} + i\epsilon^\sigma_{\nu\rho\mu}\gamma_\sigma\gamma_5$
- Bianchi identities: $(D_\mu X_{\nu\rho})^A + (D_\rho X_{\mu\nu})^A + (D_\nu X_{\rho\mu})^A = 0 \ldots$

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A simple example

$\mathcal{O} = (\varphi^\dagger\varphi)(D_\mu\varphi^\dagger D^\mu\varphi)$ can be integrated-by-parts to use EoM(φ):

$$(D^\mu D_\mu\varphi)^j = \mu^2\varphi^j \;-\; \lambda\,(\varphi^\dagger\varphi)\,\varphi^j \;-\; \bar{e}\,\Gamma_e^\dagger l^j \;+\; \varepsilon_{jk}\bar{q}^k\,\Gamma_u u \;-\; \bar{d}\,\Gamma_d^\dagger q^j$$

. . . and the coefficients in the EoM become those of the decomposition of this operator onto the Warsaw basis classifications, represented as:

$$\boxed{\varphi^4 D^2} \to \boxed{\varphi^4 D^2} + \boxed{\varphi^3\psi^2} + \boxed{\varphi^6} + \mu^2\boxed{\varphi^4} + \boxed{T} + \boxed{E}$$

- AllYourBases identifies and applies the necessary algebraic steps (in this case, just integration-by-parts) recursively.
- Returns a FeynRules expression for the operator's decomposition

In FeynRules syntax:

```
O = (Phibar[i]Phi[i])(DC[Phibar[j],mu] DC[Phi[j],mu])
```

. . . returns:

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Returns:

```
DC[Phi[j], μ] DC[Phi†[l], μ] IndexDelta[j, i] IndexDelta[l, k] Phi[k] Phi†[i] +
 del[del[Phi[l] Phi†[k], mu], mu] IndexDelta[j, i] IndexDelta[l, k] Phi†[i] Phi†[j] +
```

$\phi^4 D^2$

```
 lR[s1, p].LL[s2, j, r] yl[p, r]† IndexDelta[s1, s2] IndexDelta[j, i] IndexDelta[l, k]
  Phi[l] Phi†[i] Phi†[k] + dR[s1, p, a].QL[s2, j, r, b] yd[p, r]† IndexDelta[a, b]
  IndexDelta[s1, s2] IndexDelta[j, i] IndexDelta[l, k] Phi[l] Phi†[i] Phi†[k] -
```

$\phi^3 \psi^2$

```
 μ² IndexDelta[j, i] IndexDelta[l, k] Phi[j] Phi[l] Phi†[i] Phi†[k] -
```

$\phi^4 D^2$

```
 uR[s1, r, a].QL[s2, m, p, b] yu[p, r]† Eps[j, m] IndexDelta[a, b]
  IndexDelta[s1, s2] IndexDelta[i, j] IndexDelta[k, l] Phi[i] Phi[k] Phi†[l] -
```

$\phi^3 \psi^2$

```
 μ² IndexDelta[i, j] IndexDelta[k, l] Phi[i] Phi[k] Phi†[j] Phi†[l] + lam IndexDelta[j, i]
  IndexDelta[l, n] IndexDelta[m, k] Phi[j] Phi[l] Phi[m] Phi†[i] Phi†[k] Phi†[n] +
 lam IndexDelta[i, j] IndexDelta[k, m] IndexDelta[l, n] Phi[i] Phi[k] Phi[l]
  Phi†[j] Phi†[m] Phi†[n] + QL[s1, j, r, a].dR[s2, p, b] IndexDelta[a, b]
  IndexDelta[s1, s2] IndexDelta[i, j] IndexDelta[k, l] Phi[i] Phi[k] Phi†[l] yd[p, r] +
 LL[s1, j, r].lR[s2, p] IndexDelta[s1, s2] IndexDelta[i, j] IndexDelta[k, l] Phi[i]
  Phi[k] Phi†[l] yl[p, r] - QL[s1, m, p, a].uR[s2, r, b] Eps[j, m] IndexDelta[a, b]
  IndexDelta[s1, s2] IndexDelta[j, i] IndexDelta[j, k] Phi[l] Phi†[i] Phi†[k] yu[p, r]
```

$\mu^2 \phi^4$

ϕ^6

$\phi^3 \psi^2$

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AYB-in short

AllYourBases automates laborious procedure prevalent in EFT calculations.

- Explicit operator relationships in $\mathcal{L}^{(6)}_{\text{SMEFT}}$ are derived by a symbolic implementation of the Warsaw procedure in FeynRules
- Applications in aiding calculations involving redundant operators, e.g. matching calculations, renormalization, translating limits. . .
- Algorithm only partially tied to $D = 6$ SM, very feasible to generalise to $D > 6$, non-SM theories in future. . .
- Currently in testing and validation. . .

Summary

- BSM in HE tools made easy in FeynRules

- Automatic BSM@NLO
  - Renormalizable (Public)
  - For EFT (Private)
- Automatic basis reduction for EFT (under validation)

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