NLO corrections for anomalous weak boson interactions

Celine Degrande
IPPP, University of Durham

CERN, 11 Dec 2015

Plan

- Introduction : BSM@NLO
- EFT@NLO
- EW gauge boson interations at NLO in QCD
- EW gauge boson interations at NLO in QED
- Concluding remarks

Loop computation

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

- Box, Triangle, Bubble and Tadpole are known scalar integrals
- Loop computation = find the coefficients
  - Unitarity
  - Multiple cuts
  - Tensor reduction (OPP)

C. Degrande

BSM NLO : model

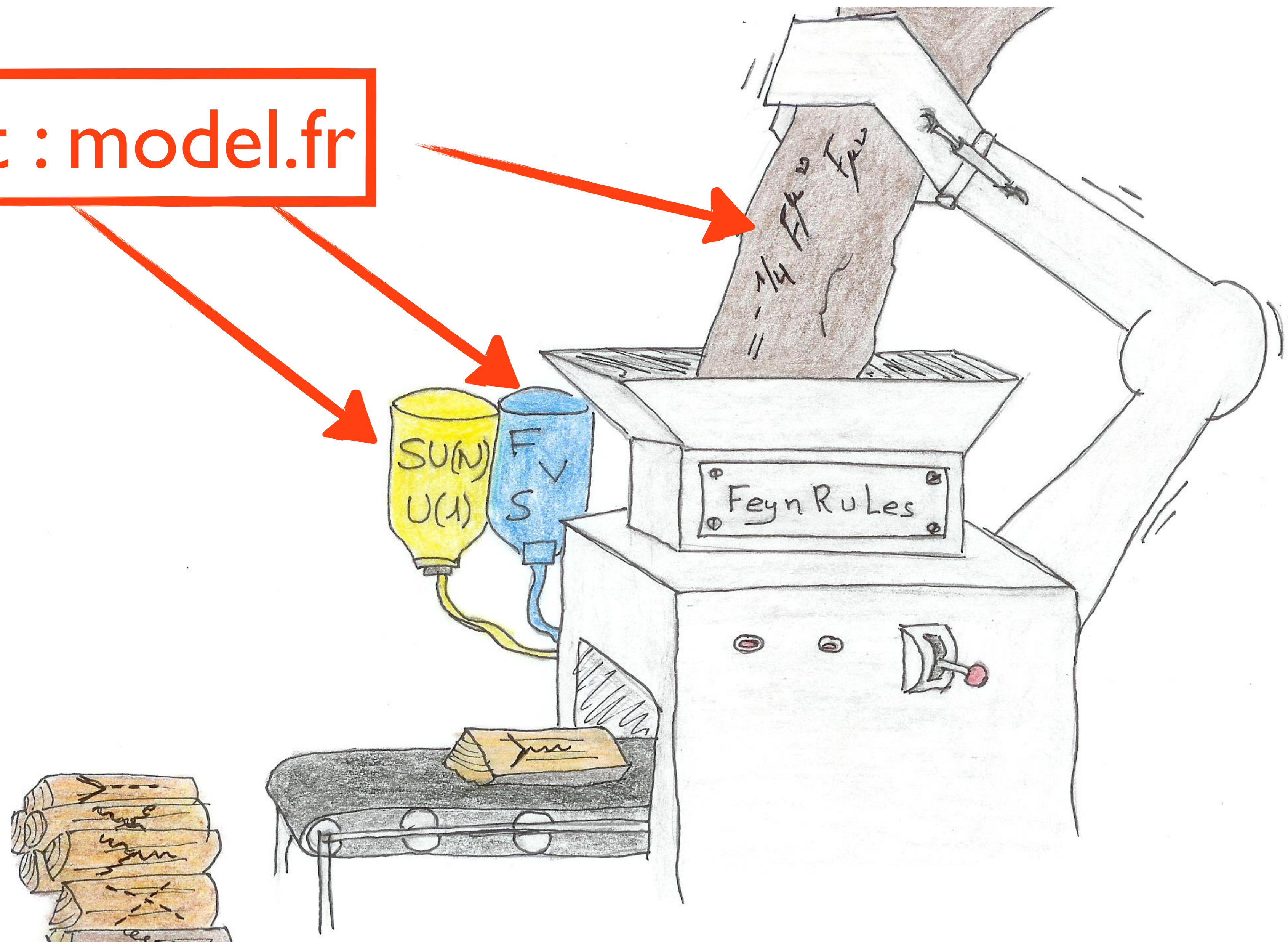
- Goal : Automate the one-loop computation for BSM models
- Required ingredients :
  - Tree-level vertices
  - R2 vertices
  - UV counterterms vertices

Already for any tree-level computation

C. Degrande

FeynRules

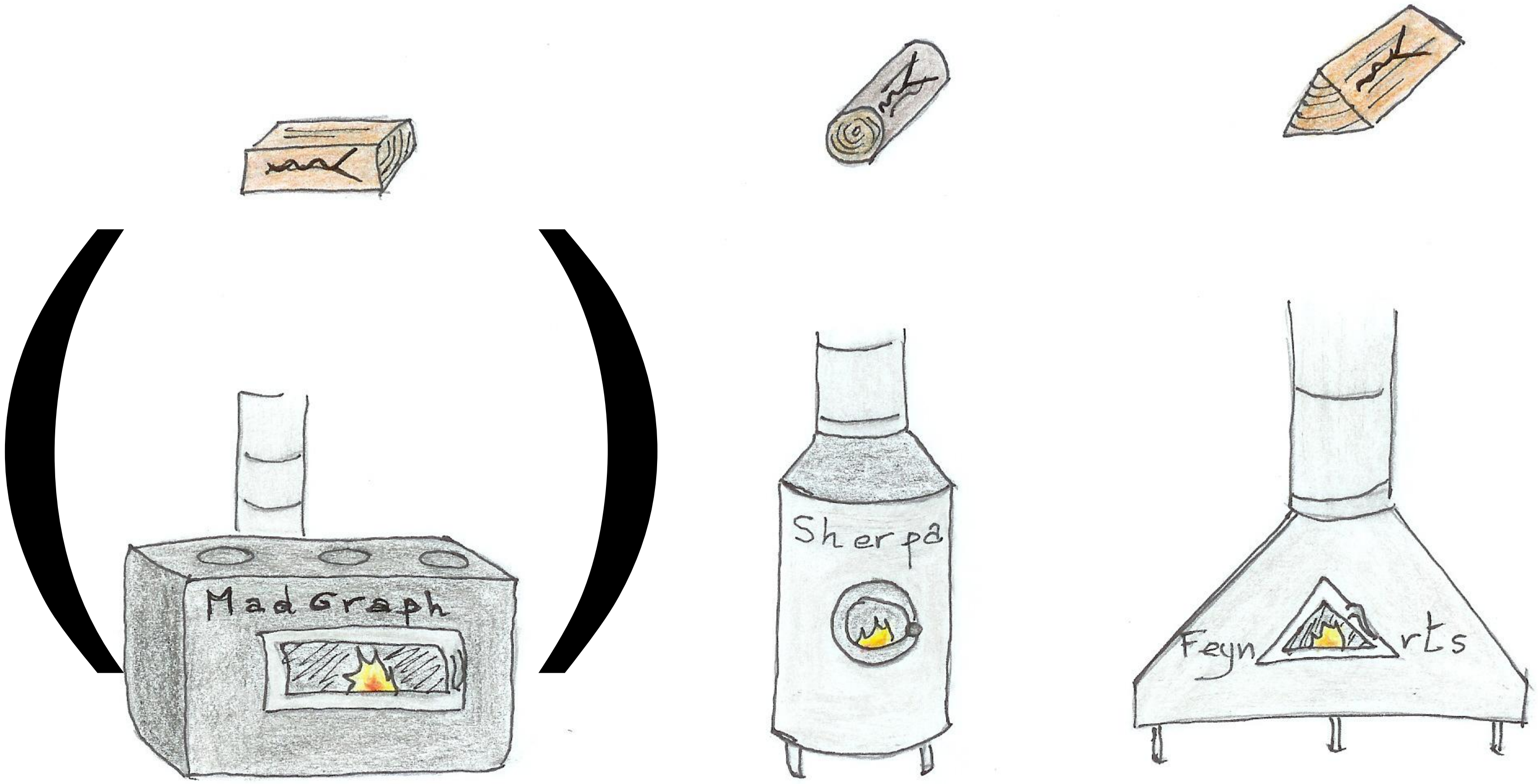
Input : model.fr



Output : vertices

C. Degrande

FeynRules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

C. Degrande

Ingredients

- Goal : Automate the one-loop computation for BSM models
- Required ingredients :
  - Tree-level vertices
  - R2 vertices
  - UV counterterms vertices

New, computed by NLOCT and FeynRules

C. Degrande

R_2

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

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

d 4 ε

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

Finite set of vertices that can be computed once for each model

Needed by Madgraph5_aMC@NLO (tool-dep.)

C. Degrande

R_1

Due to the ϵ dimensional parts of the denominators

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

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

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

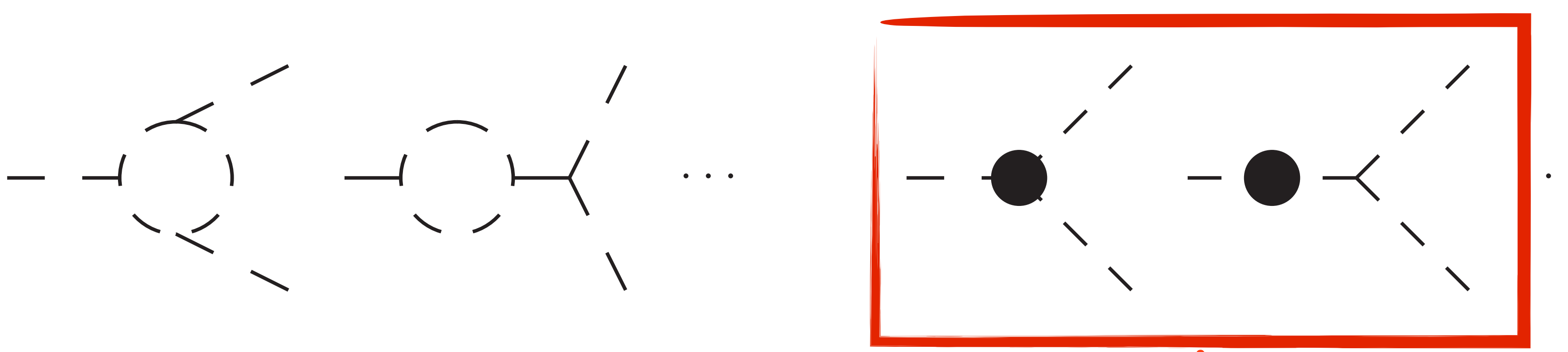
$$\int d^n\bar{q}\frac{\tilde{q}^4}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_l} = -\frac{i\pi^2}{6}+\mathcal{O}(\epsilon)\,.$$

Only $R = R_1+R_2$ is gauge invariant $\Rightarrow$ Check

C. Degrande

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)

On-shell renormalization

Finite set of vertices that can be computed once for each model

C. Degrande

Renormalization

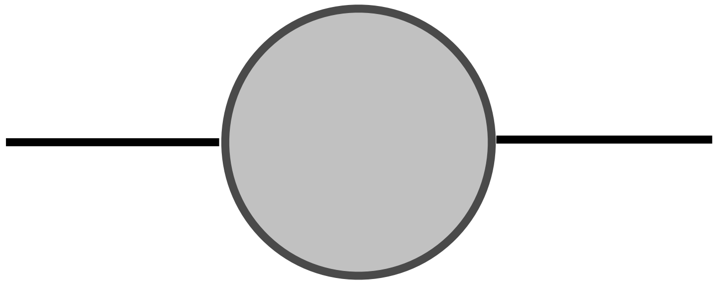
External parameters

$$
\begin{aligned}
x_0 &\rightarrow x + \delta x, \\
\phi_0 &\rightarrow (1 + \frac{1}{2}\delta Z_{\phi\phi})\phi + \sum_{\chi} \frac{1}{2}\delta Z_{\phi\chi}\chi
\end{aligned}
$$

On-shell scheme:

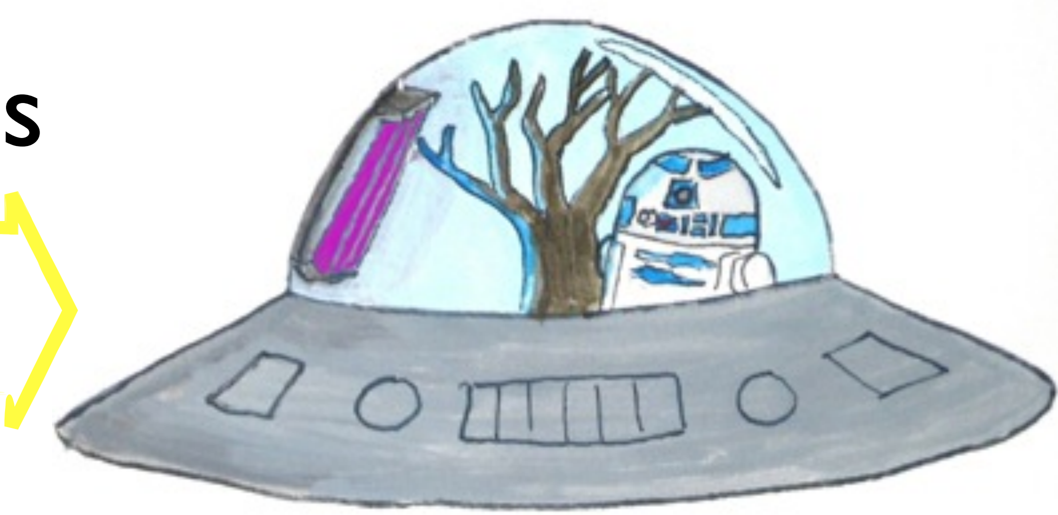
Renormalized mass = Physical mass

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



Ingredients

- Goal : Automate the one-loop computation for BSM models
- Required ingredients :
  - Tree-level vertices
  - R2 vertices
  - UV counterterms vertices
- Result : UFO at NLO



Done for renomalizable models (<=dim4)

C. Degrande

EFT@NLO

- EFT are renormalizable order by order

Need EFT not ano. vertices !

$\bar{Q}_L H \sigma^{\mu\nu} G_{\mu\nu} t_R$

$H^\dagger H G_{\mu\nu} G^{\mu\nu}$

- Max dim of CT vertices depends on the model (FF, VV, SS, FFV, FFS, VVV, VVS, VSS, SSS, VVVV, VVSS, SSSS,...?)

C. Degrande

EFT@NLO

- Higher powers of the loop momentum in the vertices

$$\mathcal{L} = ig_{WWV}\Big(g_1^V(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^{\nu+}_\mu W^{-\rho}_\nu V^\mu_\rho$$
$$+ig_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - ig_5^V \epsilon^{\mu\nu\rho\sigma}(W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu)V_\sigma$$
$$+\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2}W^{\nu+}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho\Big),$$

$$\Downarrow$$

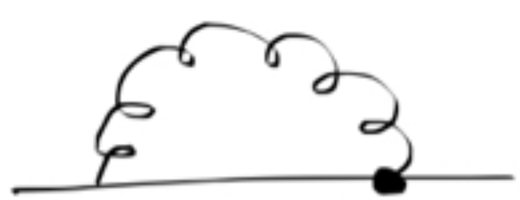
- Higher powers of the loop momentum in the numerators of the integral

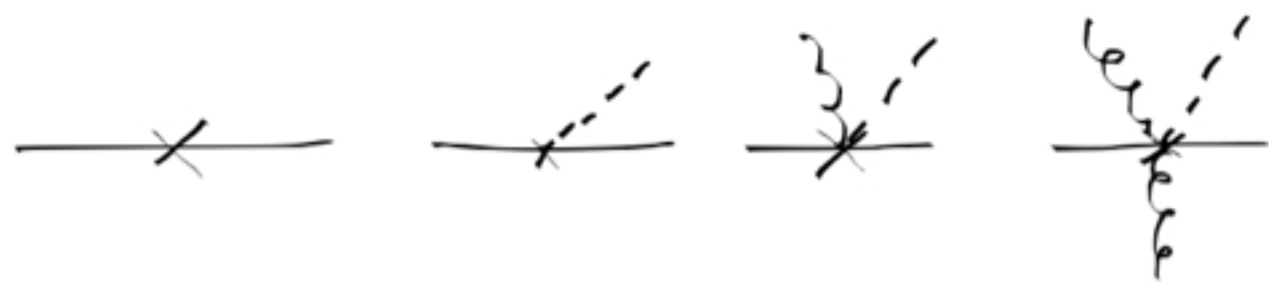
C. Degrande

EFT@NLO

- Basis versus full set

$$\bar{Q}_L H \sigma^{\mu\nu} G_{\mu\nu} t_R \qquad \boxed{\bar{Q}_L H \gamma_\mu \gamma_\nu D^\mu D^\nu t_R}$$





$$\frac{1}{\epsilon}\left(ap^2 + b\gamma^\mu p_\mu + cm\right)$$

- Needed to know the running

C. Degrande

EFT@NLO

For QCD

C. Degrande

EW gauge boson interations at NLO in QCD

No QCD corrections to EW gauge boson interactions

Recipe = SM with NLO QCD (i.e. tree-level vertices, R2 and UV) + LO(tree-level only) EW dim6

C. Degrande

EW gauge boson interations at NLO in QED

- FR/MG5_aMC are starting NLO in QED for the SM and renomalizable (dim<=4) BSM
- All the issues of NLO for EFT
- $\alpha_{EW} = 0.01$

C. Degrande

Concluding remarks

- NLO in QCD for EW gauge boson interactions : Done (Trivial)
- NLO in QED for EW gauge boson interactions :
  - Not for the near future
  - Expected to be small