UCLouvain
Institut de recherche en mathématique et physique
Centre de Cosmologie, Physique des Particules et Phénoménologie

Review on Feynman rules and matrix elements calculators

Celine Degrande

Plan

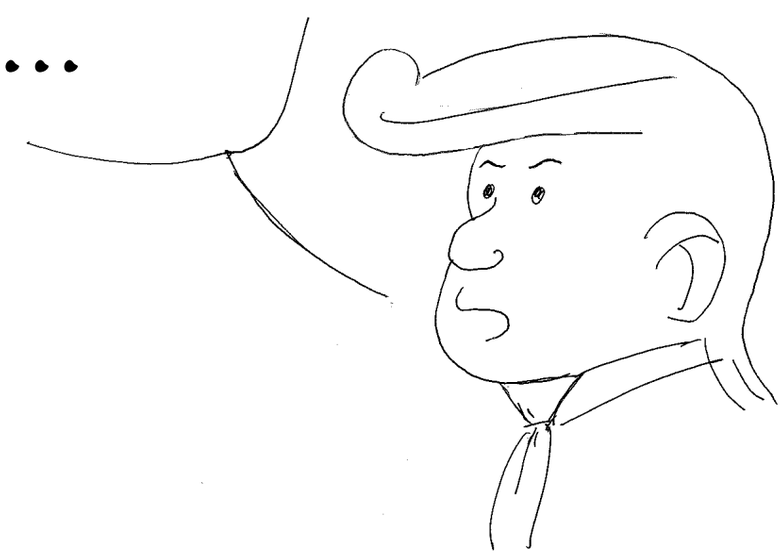
- Introduction
- Little Recap
- NLO
- EFT @ NLO
- Summary

Introduction

Disclaimer

- Focus on automated BSM
- Focus on recent development
- No recasting (B. Fuks)
- No DM

This is the best country, we have the best doctors, the best drugs,…



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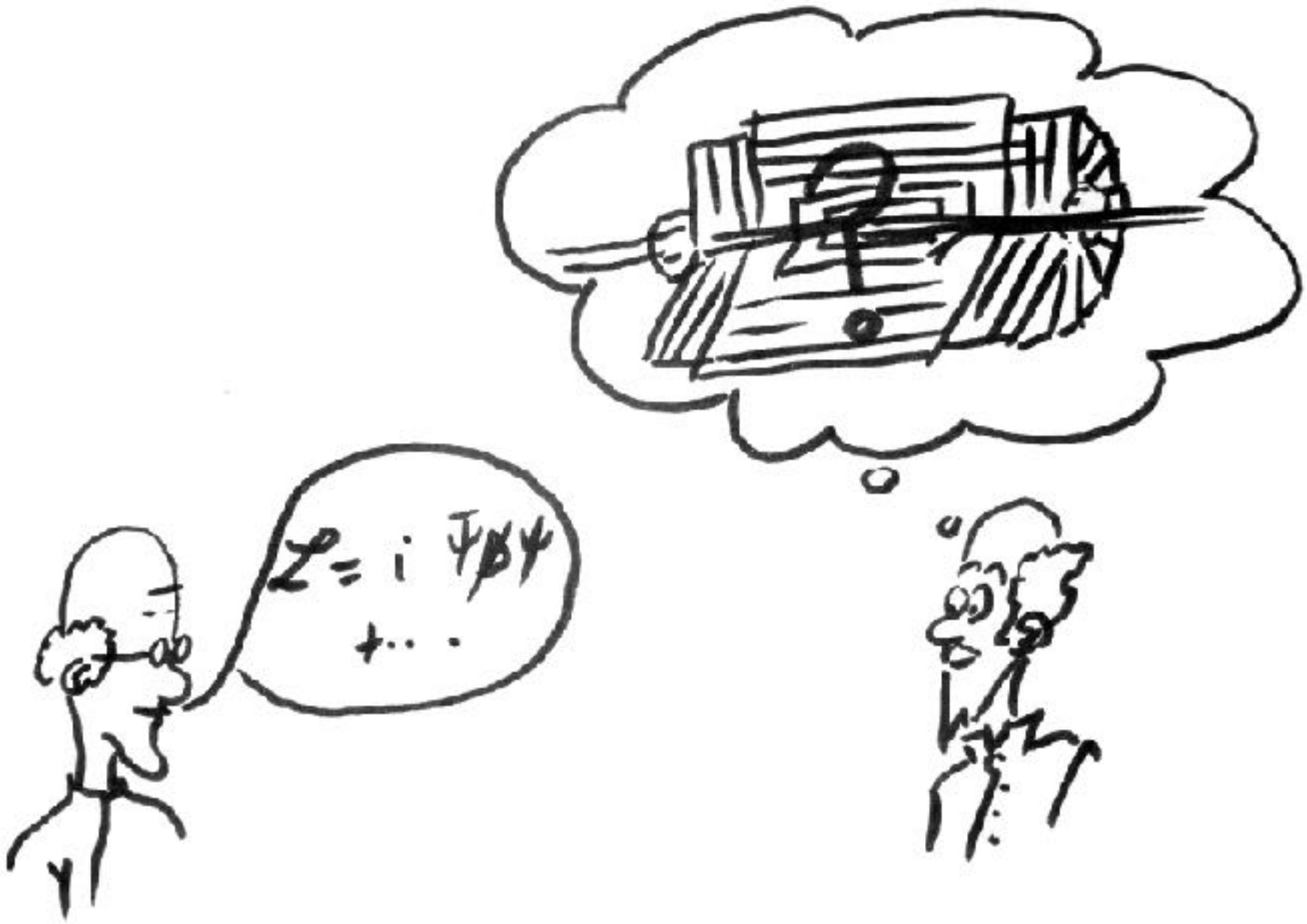
Why BSM simulation?



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Why automated tools

- Algorithmic
- Less error prone
- Long $f^{abc}G^{a}_{\mu\nu}G^{b\nu\rho}G^{c\mu}_{\rho} \ni$ 4 gluons vertex

$$
\begin{aligned}
&6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_1^{\mu_4} p_2^{\mu_3} \eta_{\mu_1,\mu_2} - 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_1^{\mu_3} p_2^{\mu_4} \eta_{\mu_1,\mu_2} + 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_1^{\mu_3} p_3^{\mu_4} \eta_{\mu_1,\mu_2} + \\
&6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_2^{\mu_3} p_3^{\mu_4} \eta_{\mu_1,\mu_2} + 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_1^{\mu_4} p_4^{\mu_3} \eta_{\mu_1,\mu_2} + 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_2^{\mu_4} p_4^{\mu_3} \eta_{\mu_1,\mu_2} - \\
&6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} \eta_{\mu_3,\mu_4} p_1 \cdot p_3 \eta_{\mu_1,\mu_2} - 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} \eta_{\mu_3,\mu_4} p_1 \cdot p_4 \eta_{\mu_1,\mu_2} - 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} \eta_{\mu_3,\mu_4} p_2 \cdot p_3 \eta_{\mu_1,\mu_2} - \\
&6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} \eta_{\mu_3,\mu_4} p_2 \cdot p_4 \eta_{\mu_1,\mu_2} + 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_1^{\mu_2} p_2^{\mu_4} \eta_{\mu_1,\mu_3} + 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_1^{\mu_4} p_3^{\mu_2} \eta_{\mu_1,\mu_3} - \\
&6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_2^{\mu_4} p_3^{\mu_2} \eta_{\mu_1,\mu_3} - 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_1^{\mu_2} p_3^{\mu_4} \eta_{\mu_1,\mu_3} - 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_1^{\mu_4} p_4^{\mu_2} \eta_{\mu_1,\mu_3} + \\
&6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_3^{\mu_4} p_4^{\mu_2} \eta_{\mu_1,\mu_3} - 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_1^{\mu_2} p_2^{\mu_3} \eta_{\mu_1,\mu_4} - 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_1^{\mu_3} p_3^{\mu_2} \eta_{\mu_1,\mu_4} + \\
&6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_1^{\mu_3} p_4^{\mu_2} \eta_{\mu_1,\mu_4} - 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_2^{\mu_3} p_4^{\mu_2} \eta_{\mu_1,\mu_4} - 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_1^{\mu_2} p_4^{\mu_3} \eta_{\mu_1,\mu_4} - \\
&6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_3^{\mu_2} p_4^{\mu_3} \eta_{\mu_1,\mu_4} - 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_1^{\mu_4} p_2^{\mu_1} \eta_{\mu_2,\mu_3} - 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_1^{\mu_4} p_3^{\mu_1} \eta_{\mu_2,\mu_3} + \\
&6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_2^{\mu_4} p_3^{\mu_1} \eta_{\mu_2,\mu_3} - 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_2^{\mu_1} p_3^{\mu_4} \eta_{\mu_2,\mu_3} - 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_2^{\mu_4} p_4^{\mu_1} \eta_{\mu_2,\mu_3} - \\
&6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_3^{\mu_4} p_4^{\mu_1} \eta_{\mu_2,\mu_3} + 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_1^{\mu_3} p_2^{\mu_1} \eta_{\mu_2,\mu_4} - 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_2^{\mu_3} p_3^{\mu_1} \eta_{\mu_2,\mu_4} - \\
&6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_1^{\mu_3} p_4^{\mu_1} \eta_{\mu_2,\mu_4} + 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_2^{\mu_3} p_4^{\mu_1} \eta_{\mu_2,\mu_4} - 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_2^{\mu_1} p_4^{\mu_3} \eta_{\mu_2,\mu_4} + \\
&6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_3^{\mu_1} p_4^{\mu_3} \eta_{\mu_2,\mu_4} + 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_1^{\mu_2} p_3^{\mu_1} \eta_{\mu_3,\mu_4} + 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_2^{\mu_1} p_3^{\mu_2} \eta_{\mu_3,\mu_4} + \\
&6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} p_1^{\mu_2} p_4^{\mu_1} \eta_{\mu_3,\mu_4} + 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_3^{\mu_2} p_4^{\mu_1} \eta_{\mu_3,\mu_4} + 6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} p_2^{\mu_1} p_4^{\mu_2} \eta_{\mu_3,\mu_4} - \\
&6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} p_3^{\mu_1} p_4^{\mu_2} \eta_{\mu_3,\mu_4} + 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} p_1 \cdot p_2 - 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} p_1 \cdot p_2 + \\
&6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} p_1 \cdot p_3 + 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} p_1 \cdot p_4 + 6ig_s f_{a_1,a_4,a} f_{a_2,a_3,a} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} p_2 \cdot p_3 + \\
&6ig_s f_{a_1,a_3,a} f_{a_2,a_4,a} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} p_2 \cdot p_4 + 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} p_3 \cdot p_4 - 6ig_s f_{a_1,a_2,a} f_{a_3,a_4,a} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} p_3 \cdot p_4
\end{aligned}
$$

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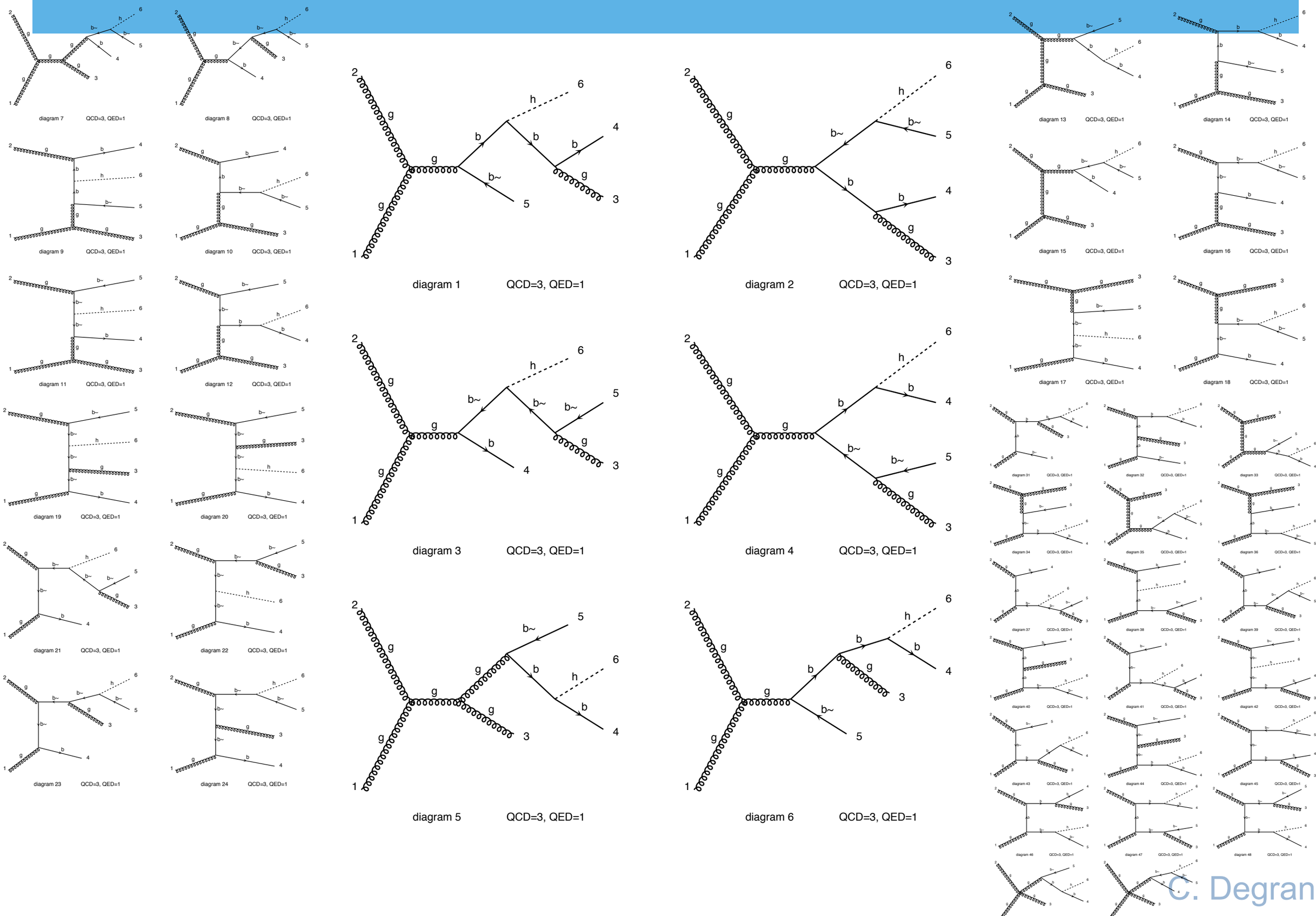
Many diagrams



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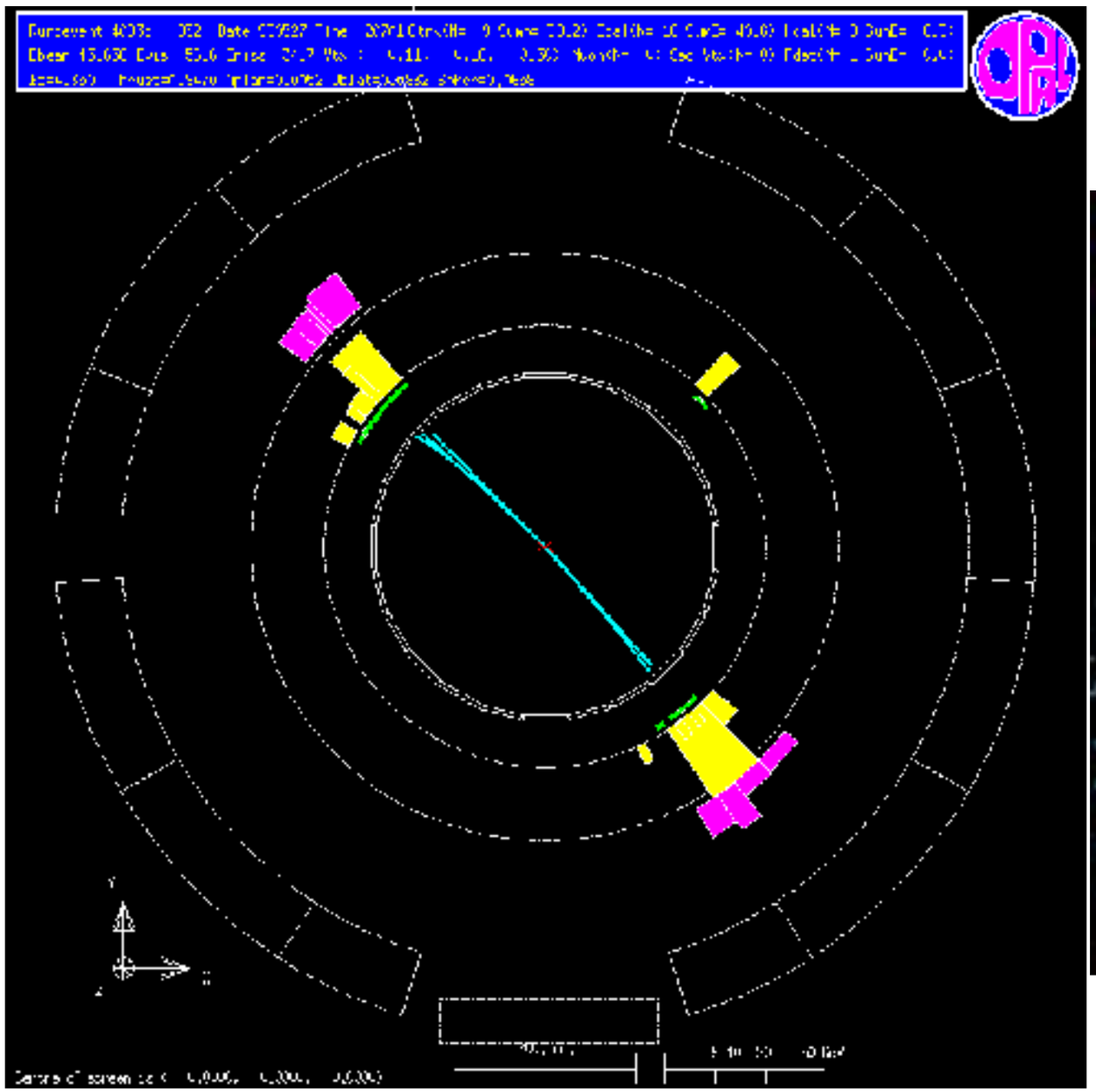
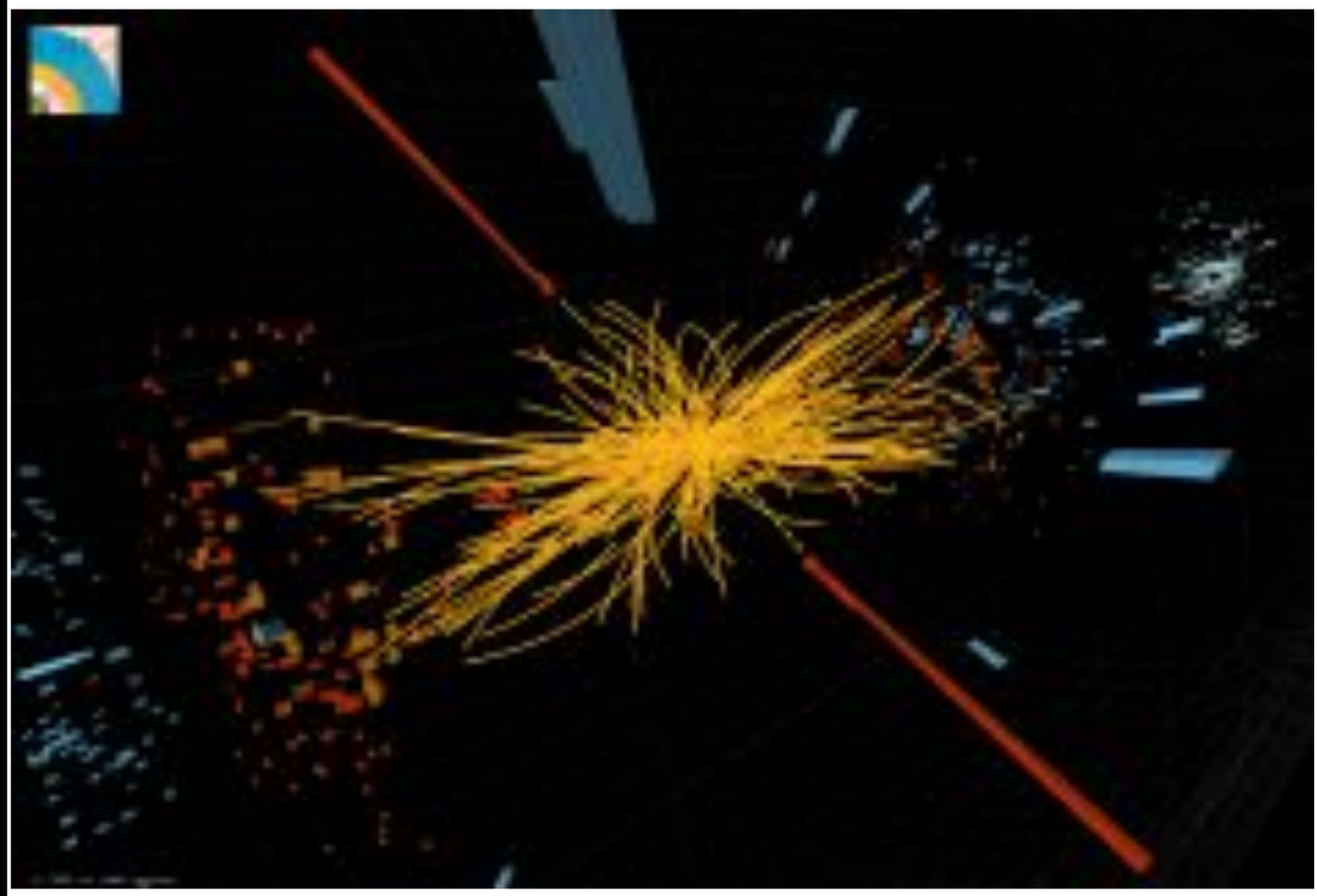
Hadron colliders

LEP



LHC



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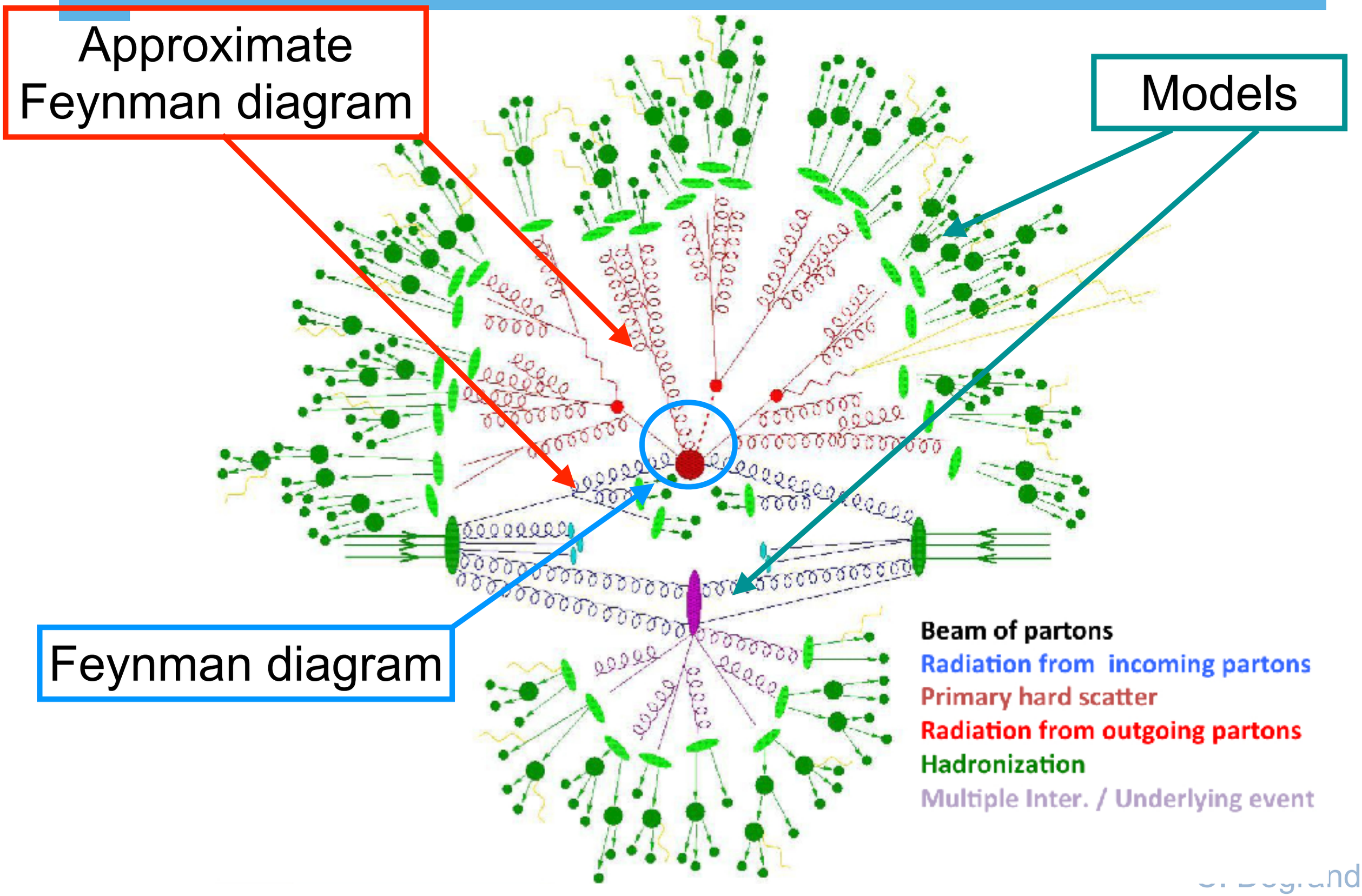
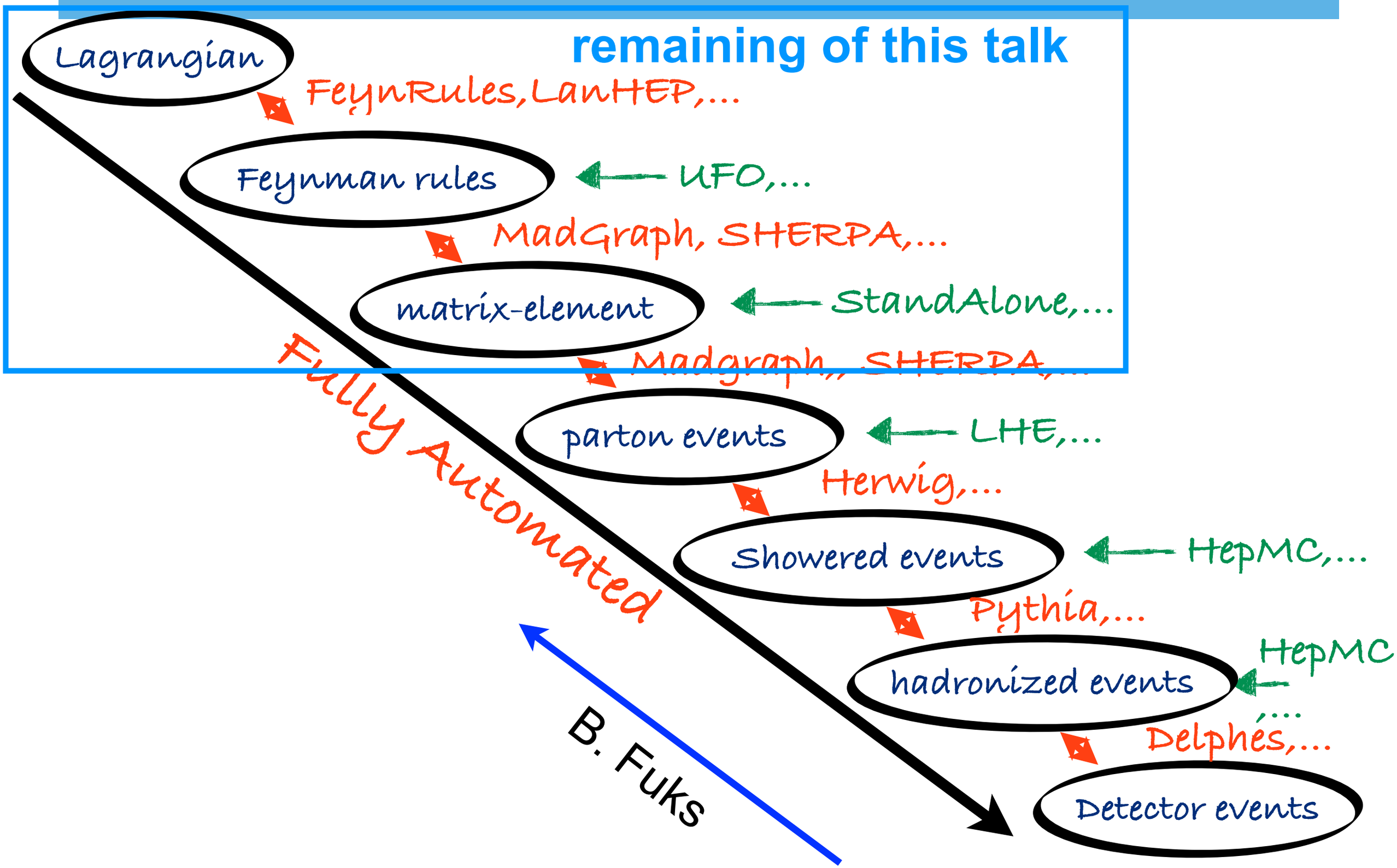
Hadron collider event



BSM simulation



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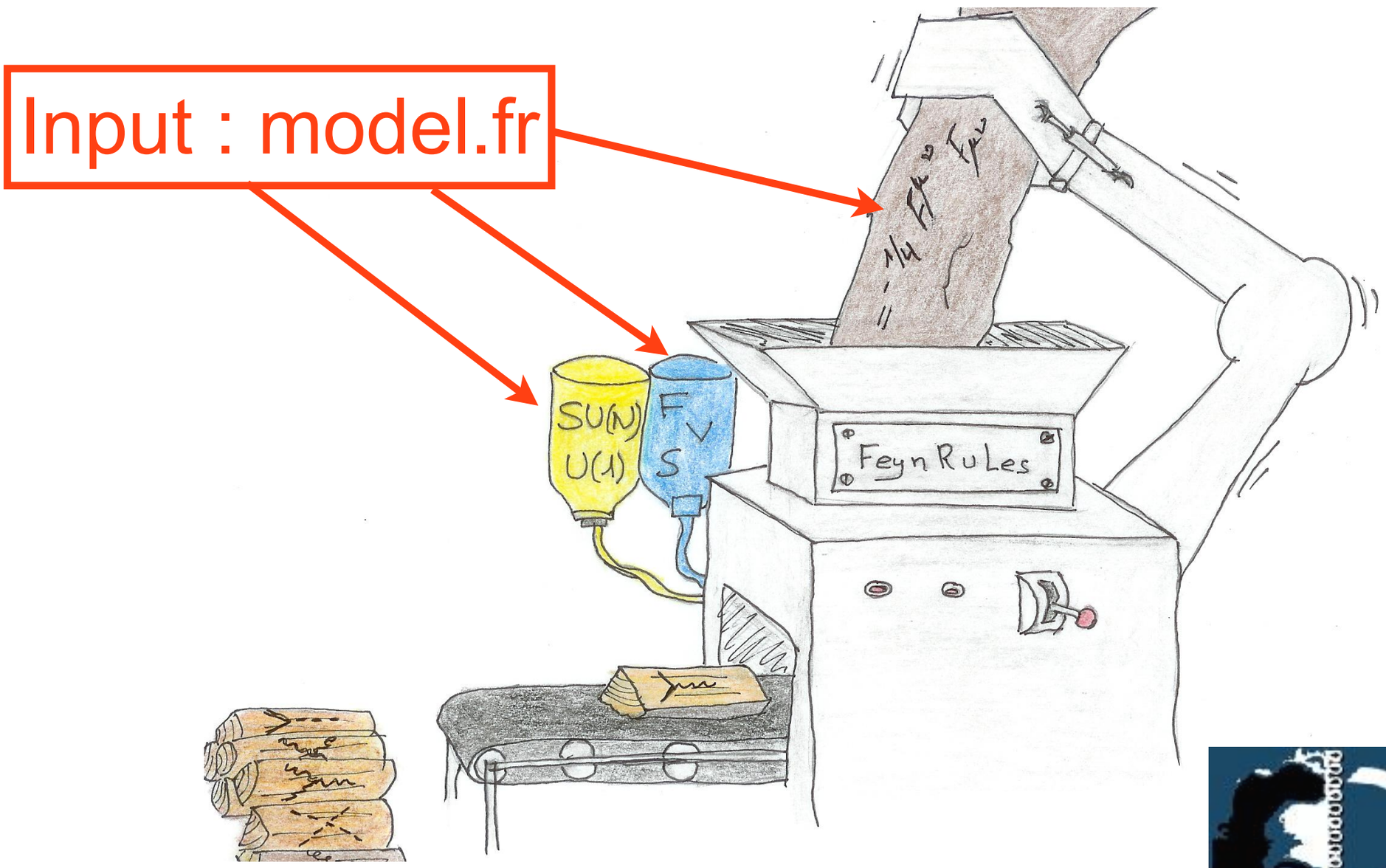
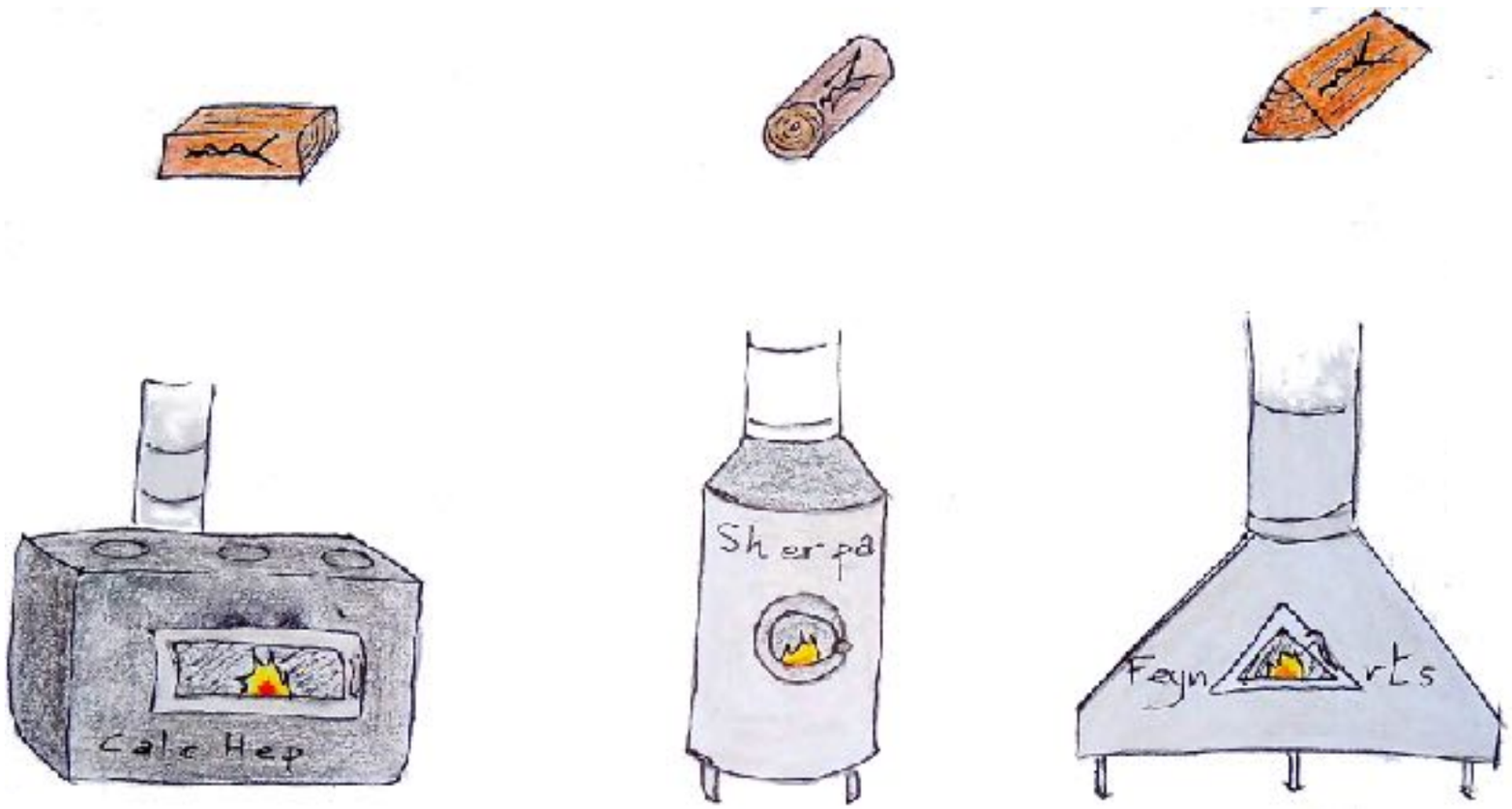
Little recap

FeynRules in a nutshell



Feynman rules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

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Feynman Rules

Lanhep, FeynRules, … take care of all the conventions
cross-check ME and event generation

Predefined basis for most ME

Color representation

Coupling (function of the parameters)

Lorentz (Metric/Levi-Civita tensors, Momenta,Dirac matrices)

$$\begin{pmatrix} \bar{u} & 1 \\ u & 2 \\ g & 3 \end{pmatrix}$$

$$ig_s \, T^{a_3}_{i_1 i_2} \, \gamma^{\mu_3}$$

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UFO

- Generic output with the **full** model information
  - coupling_orders.py, parameters.py, particles.py, write_param_card.py, __init__.py,
  - vertices.py, couplings.py, lorentz.py

$$ig_s T^a \gamma^\mu$$

No basis, all the lorentz structures of the model

  - decays.py
  - CT_vertices.py, CT_couplings.py (For NLO)
- Python module used in MadGraph, Herwig, Gosam, Sherpa

NLO

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)

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 all

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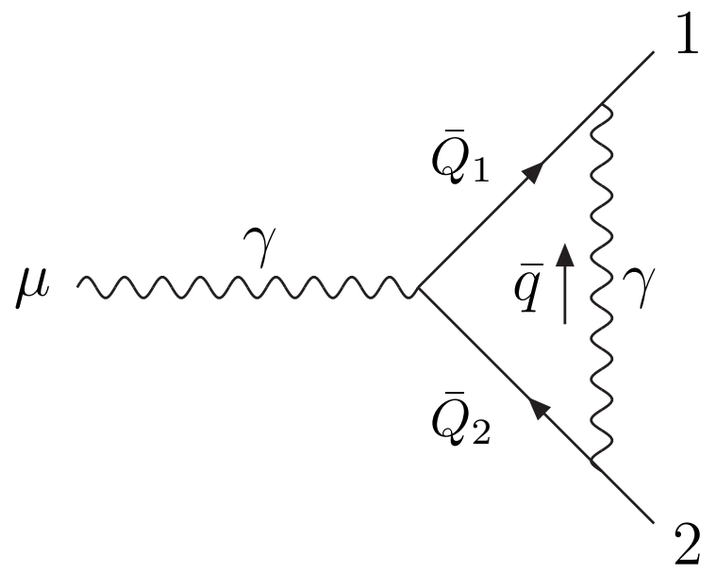
R_2 example



$$\bar{Q}_1 = \bar{q} + p_1 = Q_1 + \tilde{q}$$
$$\bar{Q}_2 = \bar{q} + p_2 = Q_2 + \tilde{q}$$

$$\bar{D}_0 = \bar{q}^2$$
$$\bar{D}_1 = (\bar{q} + p_1)^2$$
$$\bar{D}_2 = (\bar{q} + p_2)^2$$

't Hooft Veltman scheme

$$\overline{\eta}^{\overline{\mu}\,\overline{\nu}}\overline{\eta}_{\overline{\mu}\,\overline{\nu}} = d,$$
$$\overline{\gamma}^{\overline{\mu}}\overline{\gamma}_{\overline{\mu}} = d\,\mathbb{1},$$

$$\begin{aligned}\bar{N}(\bar{q}) &\equiv e^3 \left\{\bar{\gamma}_{\bar{\beta}}\,(\bar{\not{Q}}_1 + m_e)\,\gamma_\mu\,(\bar{\not{Q}}_2 + m_e)\,\bar{\gamma}^{\bar{\beta}}\right\} \\ &= e^3 \left\{\gamma_\beta(\not{Q}_1 + m_e)\gamma_\mu(\not{Q}_2 + m_e)\gamma^\beta\right. \\ &- \left.\epsilon\,(\not{Q}_1 - m_e)\gamma_\mu(\not{Q}_2 - m_e) + \epsilon\tilde{q}^2\,\gamma_\mu - \tilde{q}^2\,\gamma_\beta\gamma_\mu\gamma^\beta\right\}\end{aligned}$$

$$\int d^n\bar{q}\,\frac{\tilde{q}^2}{\bar{D}_0\bar{D}_1\bar{D}_2} = -\frac{i\pi^2}{2} + \mathcal{O}(\epsilon)\,,$$
$$\int d^n\bar{q}\,\frac{q_\mu q_\nu}{\bar{D}_0\bar{D}_1\bar{D}_2} = -\frac{i\pi^2}{2\epsilon}g_{\mu\nu} + \mathcal{O}(1)$$

$$\mathrm{R}_2 = -\frac{ie^3}{8\pi^2}\gamma_\mu$$

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R_1

Due to the $\mathcal{E}$ dimensional parts of the denominators

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

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

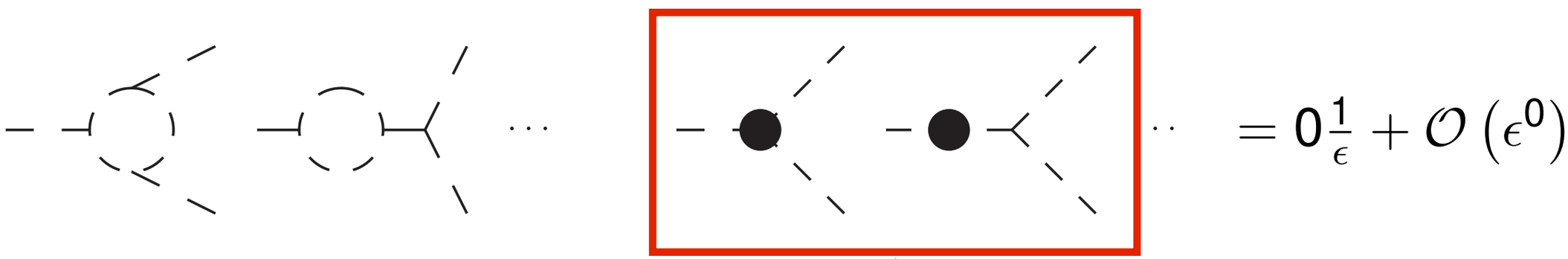
$$\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j\bar{D}_k} = -\frac{i\pi^2}{2}+\mathcal{O}(\epsilon)\,,$$

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

Only $R = R_1+R_2$ is gauge invariant ⇨ Check

UV

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



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

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

Same for the conjugate field

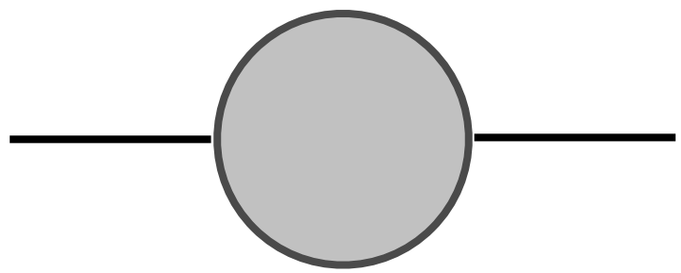
Internal parameters are renormalised by replacing the external parameters in their expressions

Renormalization conditions

On-shell scheme (or complex mass scheme):

Renormalized mass = Physical mass

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



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

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

Similar for the vectors and scalars

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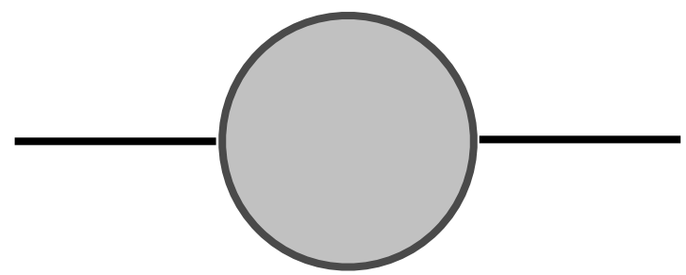
Renormalization conditions

On-shell scheme (or complex mass scheme):

Renormalized mass = Physical mass

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



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

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

Similar for the vectors and scalars

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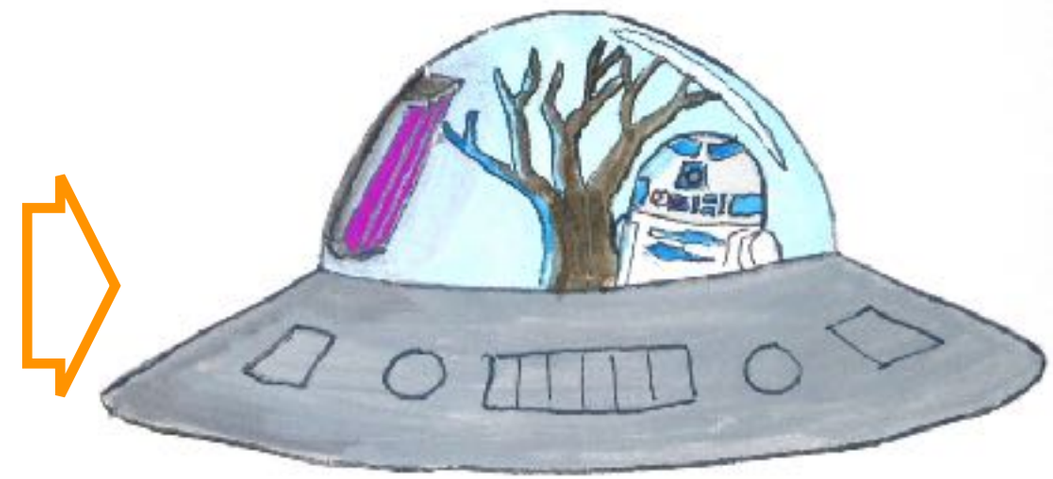
How does it work?

FeynRules
Renormalize the Lagrangian



model.mod
model.gen

model.nlo

FeynArts
Write the amplitudes

NLOCT.m
Compute the NLO vertices

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Matrix element at NLO

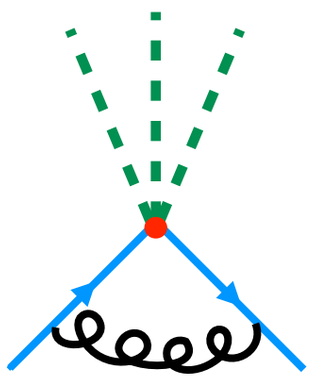
- Madgraph QCD (2014) and EW (2018)
- Recola QCD+EW (2013)
- Wizard QCD (2020)
- SHERPA QCD+EW (2017)

EFT @ NLO

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
- $\overline{\text{MS}}$ by default for everything else (zero-momentum possible for fermion gauge boson interaction)

EFT at NLO



In the loop:
same as SM
+axial anomaly

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

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

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

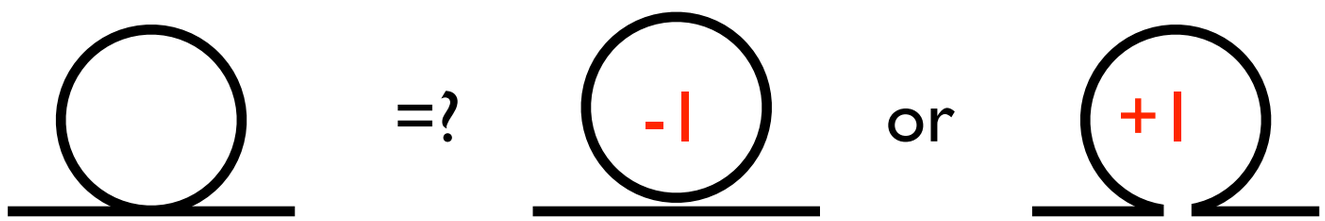
$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$

More momenta: higher rank of the integral numerator

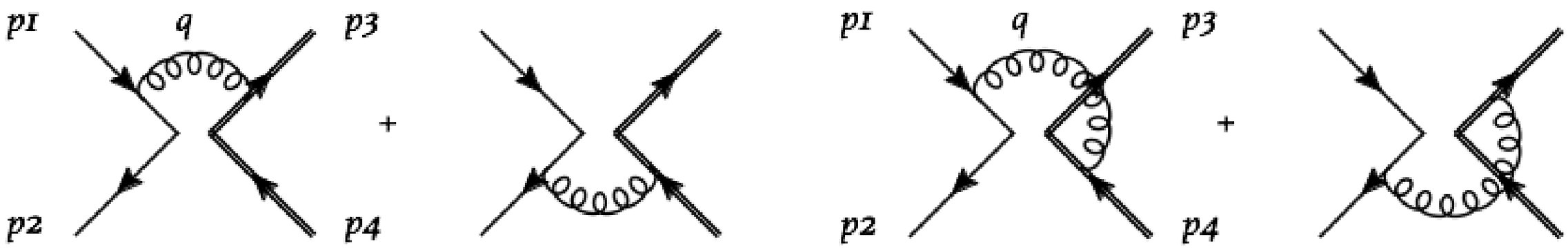
Additional gamma and colour algebra

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

EFT at NLO



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



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

Extra R2 (gauge invariant)
Change the UV matching

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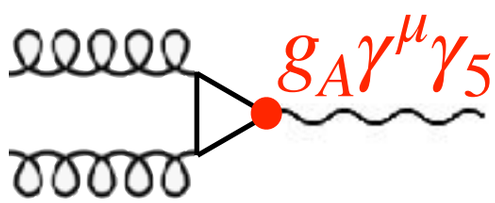
Axial anomaly



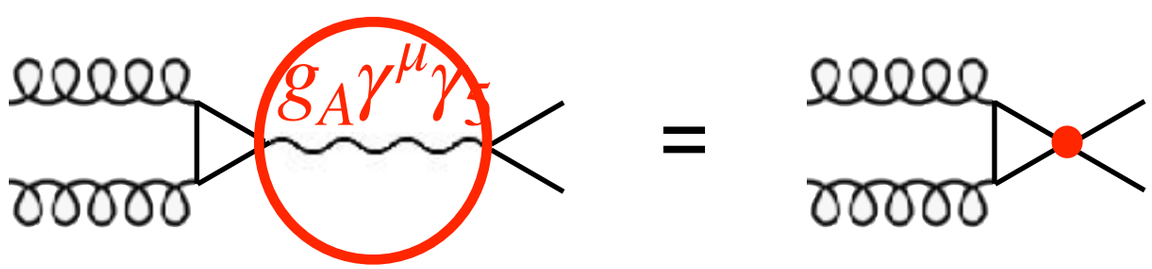
SM:

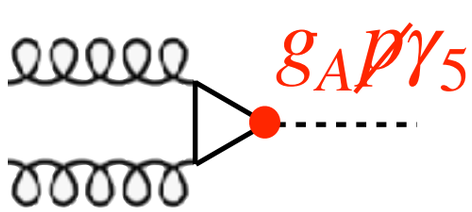
$$g_A^u = g_A^c = g_A^t = -g_A^d = -g_A^s = -g_A^b$$

SMEFT:

$$g_A^u \neq g_A^c \neq g_A^t \neq -g_A^d \neq -g_A^s \neq -g_A^b$$

+ modification of quarks-gluon vertex (chromo)





$$\propto \epsilon^{p_1 p_2 \mu_1 \mu_2}$$

SMEFT@NLO

- C.D., G. Durieux, F. Maltoni, K. Mimasu, E Vryonidou, C. Zhang, 2008.11743

top pair production

c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO		$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO
c_{tu}^8	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$		$1.04^{+6\%}_{-5\%}$	$1.03^{+2\%}_{-2\%}$
c_{td}^8	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$		$0.577^{+6\%}_{-5\%}$	$0.611^{+3\%}_{-2\%}$
c_{tq}^8	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.29^{+3\%}_{-2\%}$
c_{Qu}^8	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$		$1.04^{+6\%}_{-5\%}$	$0.798^{+3\%}_{-3\%}$
c_{Qd}^8	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$		$0.58^{+6\%}_{-5\%}$	$0.485^{+2\%}_{-2\%}$
$c_{Qq}^{8,1}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.69^{+3\%}_{-3\%}$
$c_{Qq}^{8,3}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.57^{+2\%}_{-2\%}$
c_{tu}^1	$[0.67^{+1\%}_{-1\%}]$	$-0.078(7)^{+31\%}_{-23\%}$	$[0.41^{+13\%}_{-17\%}]$	$4.66^{+6\%}_{-5\%}$	$5.92^{+6\%}_{-5\%}$
c_{td}^1	$[-0.21^{+1\%}_{-2\%}]$	$-0.306^{+30\%}_{-22\%}$	$[-0.15^{+10\%}_{-13\%}]$	$2.62^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
c_{tq}^1	$[0.39^{+0\%}_{-1\%}]$	$-0.47^{+24\%}_{-18\%}$	$[0.50^{+3\%}_{-2\%}]$	$7.25^{+6\%}_{-5\%}$	$9.36^{+6\%}_{-5\%}$
c_{Qu}^1	$[0.33^{+0\%}_{-0\%}]$	$-0.359^{+23\%}_{-17\%}$	$[0.57^{+6\%}_{-5\%}]$	$4.68^{+6\%}_{-5\%}$	$5.96^{+6\%}_{-5\%}$
c_{Qd}^1	$[-0.11^{+0\%}_{-1\%}]$	$0.023(6)^{+114\%}_{-75\%}$	$[-0.19^{+6\%}_{-5\%}]$	$2.61^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
$c_{Qq}^{1,1}$	$[0.57^{+0\%}_{-1\%}]$	$-0.24^{+30\%}_{-22\%}$	$[0.39^{+9\%}_{-12\%}]$	$7.25^{+6\%}_{-5\%}$	$9.34^{+5\%}_{-5\%}$
$c_{Qq}^{1,3}$	$[1.92^{+1\%}_{-1\%}]$	$0.088(7)^{+28\%}_{-20\%}$	$[1.05^{+17\%}_{-22\%}]$	$7.25^{+6\%}_{-5\%}$	$9.32^{+5\%}_{-5\%}$
c_{QQ}^8	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c_{Qt}^8	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c_{QQ}^1	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c_{Qt}^1	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c_{tt}^1	$\times$	$0.215^{+23\%}_{-18\%}$		$\times$	$\times$

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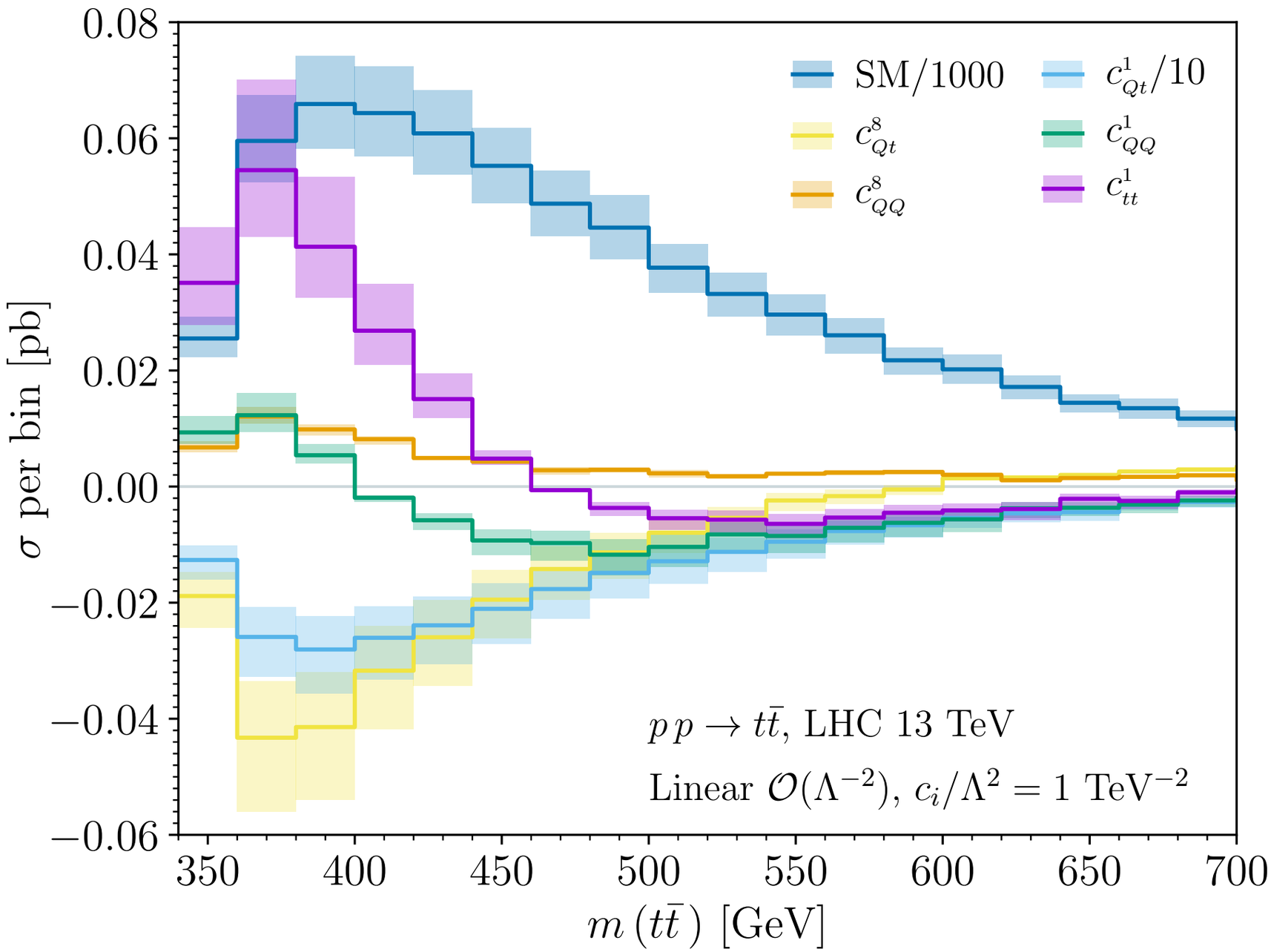
4top to top pair



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4top with SMEFT@NLO

c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO	K	$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO	K
c^8_{QQ}	$0.126^{+61\%}_{-35\%}$	$0.089^{+8\%}_{-66\%}$	0.71	$0.170^{+53\%}_{-32\%}$	$0.165^{+3\%}_{-26\%}$	0.97
c^8_{Qt}	$0.421^{+63\%}_{-35\%}$	$0.295^{+9\%}_{-69\%}$	0.70	$0.498^{+52\%}_{-32\%}$	$0.333^{+15\%}_{-75\%}$	0.67
c^1_{QQ}	$0.373^{+62\%}_{-35\%}$	$0.20(1)^{+23\%}_{-115\%}$	0.53	$1.513^{+53\%}_{-32\%}$	$1.40^{+3\%}_{-32\%}$	0.93
c^1_{Qt}	$-0.007(1)^{+88\%}_{-84\%}$	$-0.14(3)^{+83\%}_{-40\%}$	21	$2.061^{+53\%}_{-32\%}$	$1.89^{+3\%}_{-33\%}$	0.92
c^1_{tt}	$0.741^{+61\%}_{-35\%}$	$0.42(3)^{+18\%}_{-101\%}$	0.57	$6.08^{+53\%}_{-32\%}$	$5.65^{+3\%}_{-30\%}$	0.93

Summary

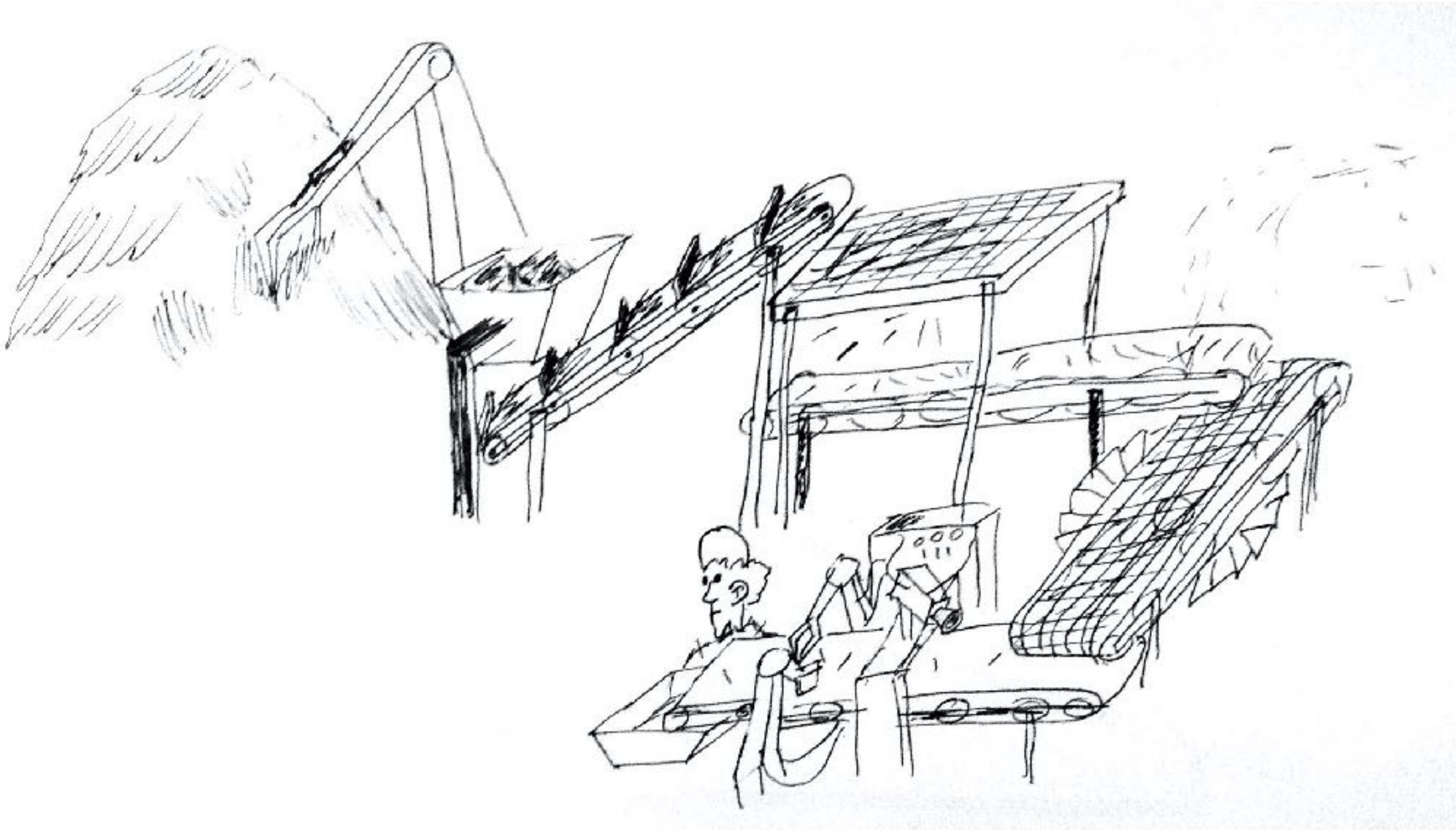
Summary

- Automated FR & ME for BSM
- What next?
  - More pheno
  - More validation (Comparison of EFT@NLO MG/Recola)
  - include running for BSM
  - ?
- I did not discuss :
  - The Feynman rules for the SMEFT in the background field gauge, Corbet, 2010.15852
  - …

Where is new physics?

C. Degrande

Automated tools



Thank you

C. Degrande