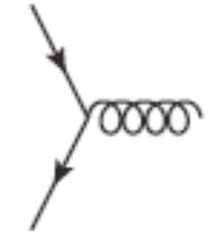
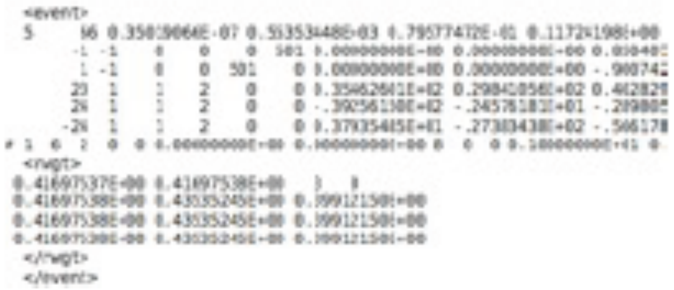
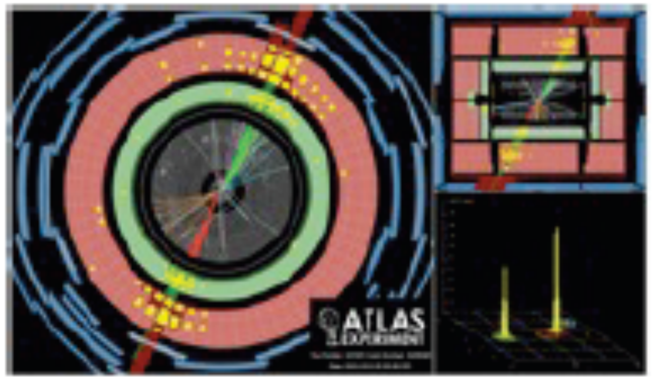
NLO+PS AUTOMATION

FROM SM TO BSM

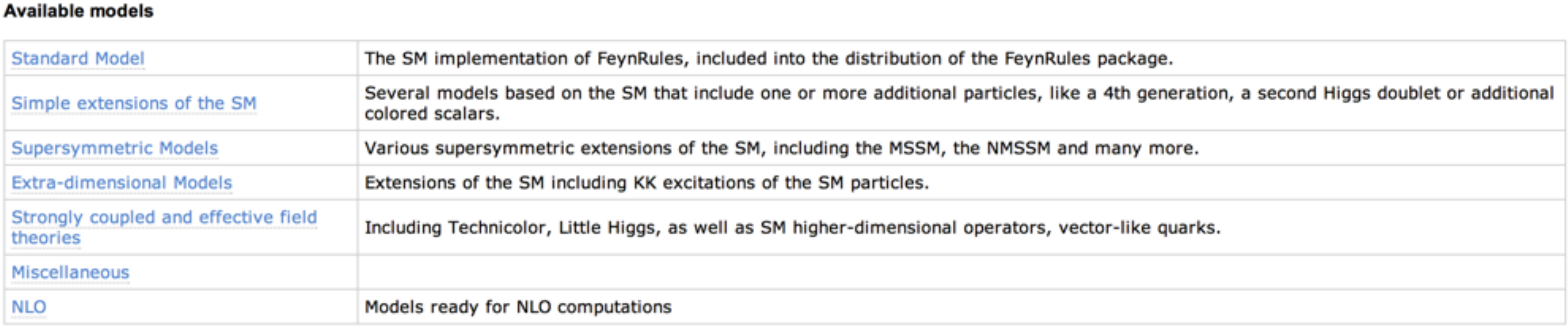
HUA-SHENG SHAO
THEORETICAL PHYSICS DEPARTMENT, CERN

PARTICLE AND ASTRO-PARTICLE PHYSICS SEMINAR
15 JAN 2016

PREDICTION CHAIN

SU(3)XSU(2)XU(1)	• **Symmetries**	$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + \cdots$
Standard Model	• **Model**	 $= \imath\gamma^\mu t^a_{ij}$, ...
p p > j j QCD=2	• **Matrix Element**	$\mathcal{M}^2_{gg\to d\bar{d}}$, ...
matrix.f	• **Partonic Events**	
events.lhe	• **Hadron Level**	$\{\pi^0, K^+, e^+, p, \cdots\}$
events.hep	• **Detector Level**	

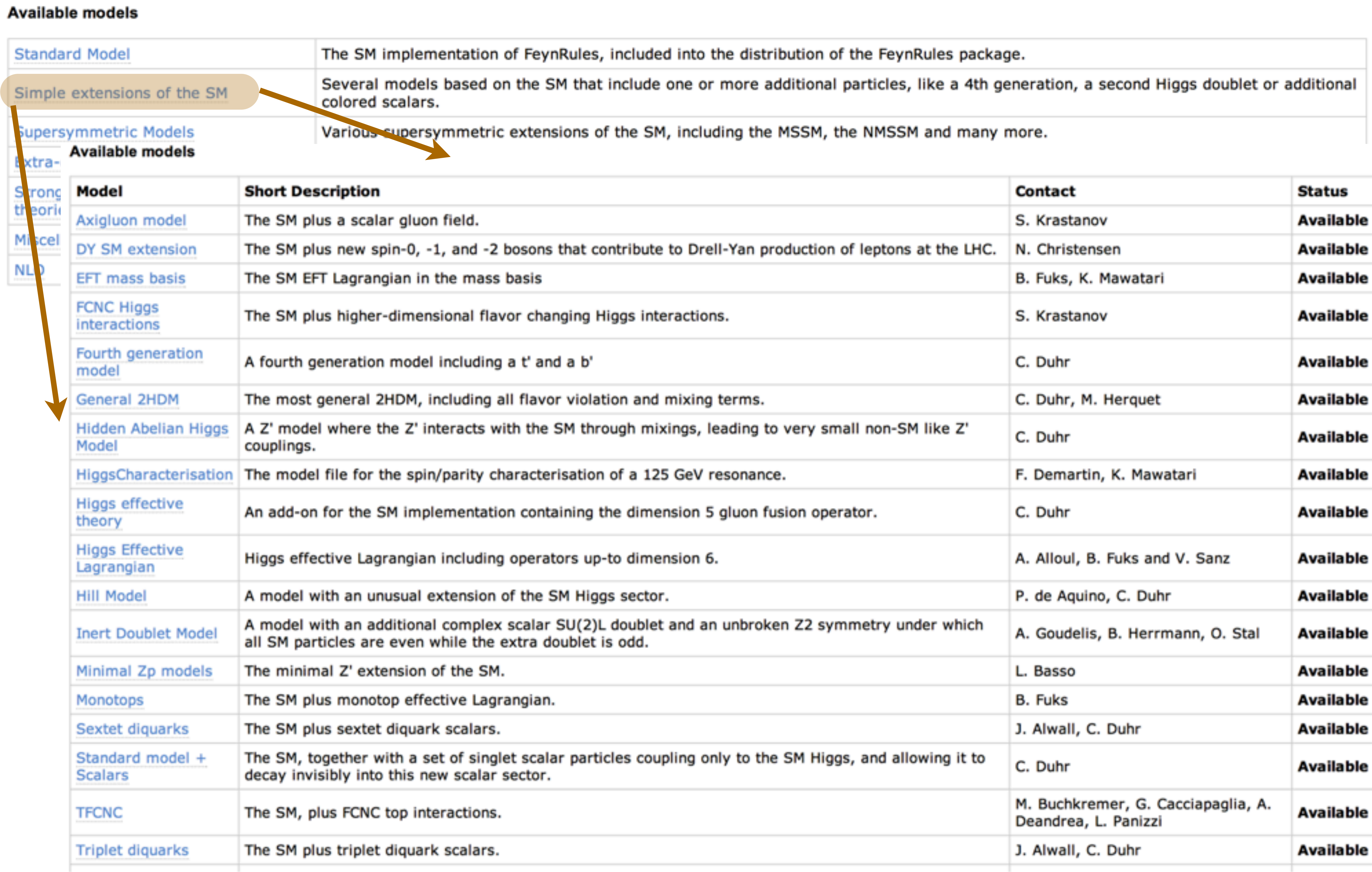
BSM MODELS: READY FOR USE



Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	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	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous	
NLO	Models ready for NLO computations

BSM MODELS: READY FOR USE



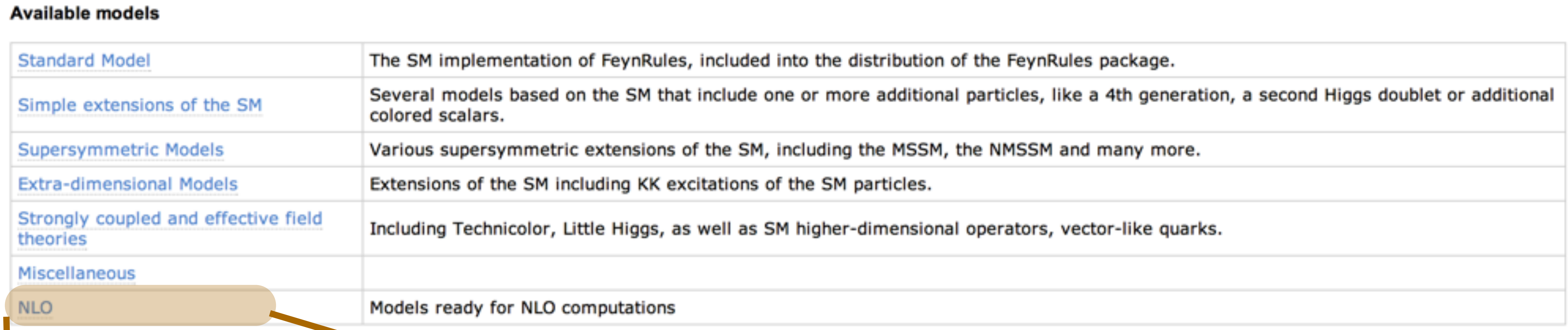
Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	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	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-	
Strong theori	
Miscel	
NLO	

Available models

Model	Short Description	Contact	Status
Axigluon model	The SM plus a scalar gluon field.	S. Krastanov	**Available**
DY SM extension	The SM plus new spin-0, -1, and -2 bosons that contribute to Drell-Yan production of leptons at the LHC.	N. Christensen	**Available**
EFT mass basis	The SM EFT Lagrangian in the mass basis	B. Fuks, K. Mawatari	**Available**
FCNC Higgs interactions	The SM plus higher-dimensional flavor changing Higgs interactions.	S. Krastanov	**Available**
Fourth generation model	A fourth generation model including a t' and a b'	C. Duhr	**Available**
General 2HDM	The most general 2HDM, including all flavor violation and mixing terms.	C. Duhr, M. Herquet	**Available**
Hidden Abelian Higgs Model	A Z' model where the Z' interacts with the SM through mixings, leading to very small non-SM like Z' couplings.	C. Duhr	**Available**
HiggsCharacterisation	The model file for the spin/parity characterisation of a 125 GeV resonance.	F. Demartin, K. Mawatari	**Available**
Higgs effective theory	An add-on for the SM implementation containing the dimension 5 gluon fusion operator.	C. Duhr	**Available**
Higgs Effective Lagrangian	Higgs effective Lagrangian including operators up-to dimension 6.	A. Alloul, B. Fuks and V. Sanz	**Available**
Hill Model	A model with an unusual extension of the SM Higgs sector.	P. de Aquino, C. Duhr	**Available**
Inert Doublet Model	A model with an additional complex scalar SU(2)L doublet and an unbroken Z2 symmetry under which all SM particles are even while the extra doublet is odd.	A. Goudelis, B. Herrmann, O. Stal	**Available**
Minimal Zp models	The minimal Z' extension of the SM.	L. Basso	**Available**
Monotops	The SM plus monotop effective Lagrangian.	B. Fuks	**Available**
Sextet diquarks	The SM plus sextet diquark scalars.	J. Alwall, C. Duhr	**Available**
Standard model + Scalars	The SM, together with a set of singlet scalar particles coupling only to the SM Higgs, and allowing it to decay invisibly into this new scalar sector.	C. Duhr	**Available**
TFCNC	The SM, plus FCNC top interactions.	M. Buchkremer, G. Cacciapaglia, A. Deandrea, L. Panizzi	**Available**
Triplet diquarks	The SM plus triplet diquark scalars.	J. Alwall, C. Duhr	**Available**

BSM MODELS: READY FOR USE



Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	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	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous	
NLO	Models ready for NLO computations

Available models

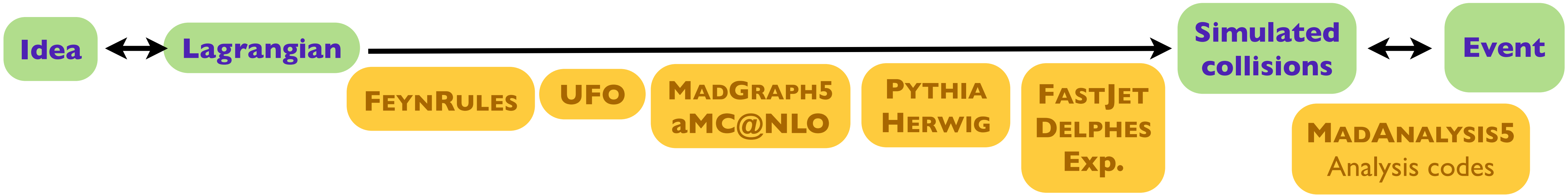
Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	arXiv:1508.00564 , arXiv: 1508.05327 , arXiv: 1509.05785	-	DMsimp_UFO.2.zip	-
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089 , arXiv: 1504.00611	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-
Top FCNC Model (more details)	C. Zhang	arXiv:1412.5594	TopEFTFCNC.fr	TopFCNC UFO	-
GM (more details)	A. Peterson	arXiv:1512.01243	-	GM_NLO UFO	-

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

AUTOMATED LO CALCULATIONS

Slide by B. Fuks

- ✦ A comprehensive approach to Monte Carlo simulations
  [Example based on FeynRules and MadGraph5_aMC@NLO]



Idea ⟷ **Lagrangian** ⟶ **Simulated collisions** ⟷ **Event**

FeynRules

UFO

MadGraph5
aMC@NLO

Pythia
Herwig

FastJet
Delphes
Exp.

MadAnalysis5
Analysis codes

- ✦ Streamline the chain from the model Lagrangian to analyzed simulated collisions
  - ✤ Works at the leading order
    - ★ Implementation of the new physics Lagrangian into FeynRules
    - ★ Generation of a UFO model file
    - ★ Import of the model into MadGraph5_aMC@NLO
    - ★ Hard scattering process with MadGraph5_aMC@NLO
    - ★ Matching to parton showering, multiparton matrix element merging, hadronization, detector simulation, *etc*.
  - ✤ Fully tested and validated in the context of large classes of new physics models

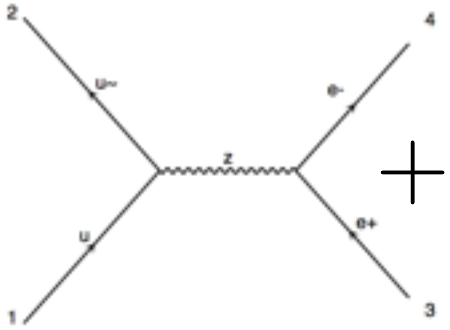
What about new physics event generation
at the next-to-leading order in QCD?

ANATOMY

$$\sigma_{pp\to e^+e^-} =$$

ANATOMY

$$\sigma^{\textbf{LO}}_{pp\to e^+e^-} = \int_2 \Bigg|$$

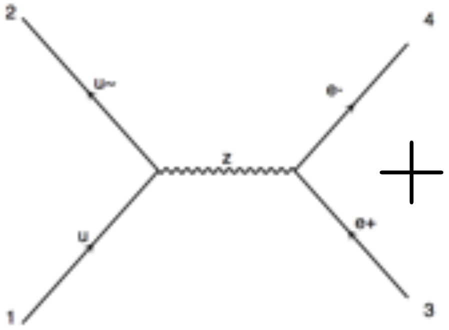


$$+\cdots \Bigg|^{\mathbf{2}}$$

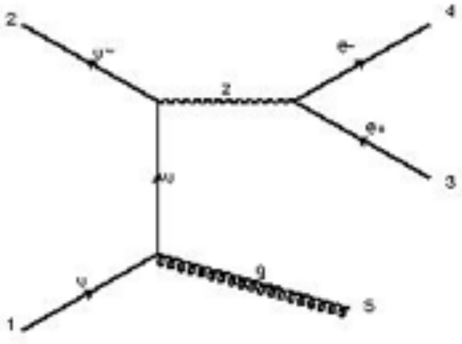
ANATOMY

$$\sigma^{\textbf{NLO}}_{pp\to e^+e^-} =$$

$$\int_2 \Bigg|$$

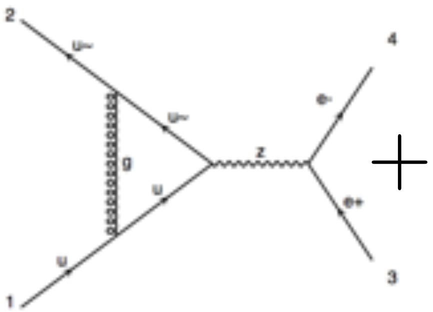


$$+\cdots\Bigg|^2 + \int_3 \Bigg|$$

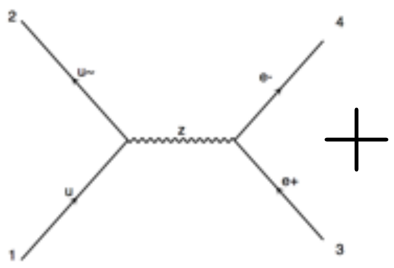


$$+\cdots\Bigg|^2$$

$$+ \int_2 \Bigg($$



$$+\cdots\Bigg) \times \Bigg($$

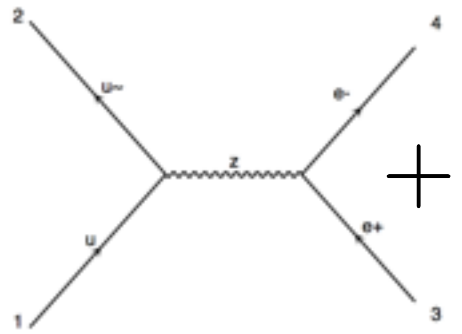


$$+\cdots\Bigg)^*$$

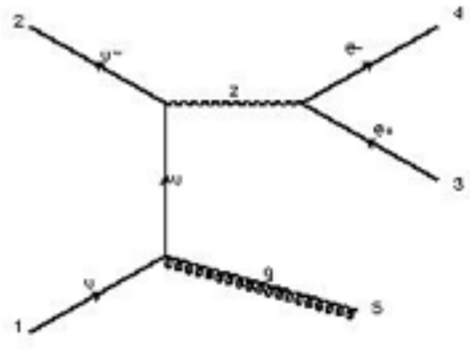
ANATOMY

$$\sigma^{\textbf{NLO}}_{pp\to e^+e^-} =$$

$$\int_2 \Bigg|$$



$$+\cdots\Bigg|^2 + \int_3 \Bigg|$$

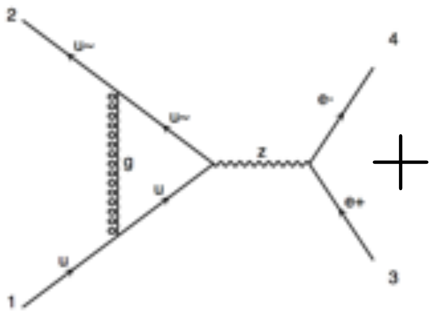


$$+\cdots\Bigg|^2$$

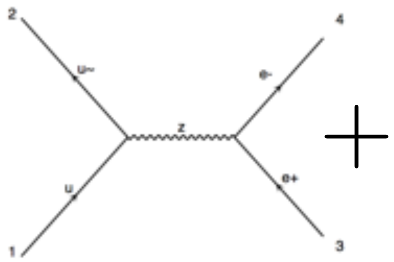
Infrared Div.

$$\frac{c_{-2}}{\epsilon_{\mathrm{IR}}^2} + \frac{c_{-1}}{\epsilon_{\mathrm{IR}}}$$

$$+ \int_2 \Bigg($$



$$+\cdots\Bigg) \times \Bigg($$

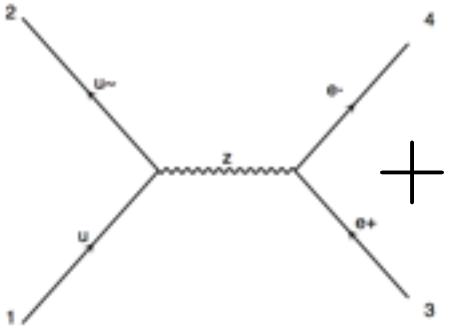


$$+\cdots\Bigg)^*$$

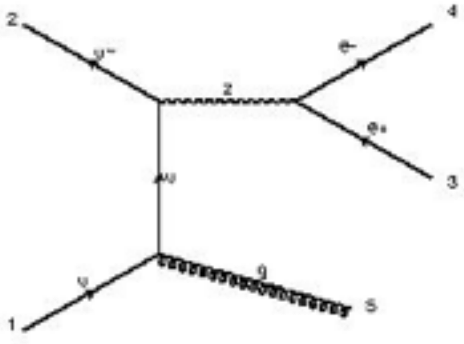
ANATOMY

$$\sigma^{\textbf{NLO}}_{pp\to e^+e^-} =$$

$$\int_2 \Bigg|$$



$$+\cdots\Bigg|^2 + \underbrace{\int_3 \Bigg|}$$

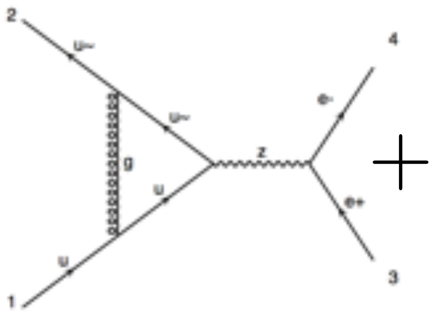


$$\underbrace{+\cdots\Bigg|^2}$$

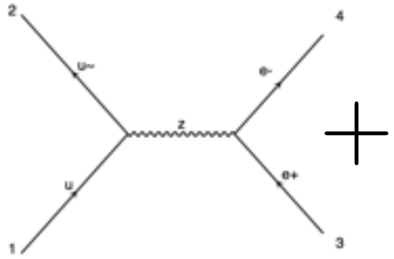
Infrared Div.

$$\frac{c_{-2}}{\epsilon_{\mathrm{IR}}^2} + \frac{c_{-1}}{\epsilon_{\mathrm{IR}}}$$

$$+ \underbrace{\int_2 \Bigg(}$$



$$\underbrace{+\cdots\Bigg) \times \Bigg(}$$



$$\underbrace{+\cdots\Bigg)^*}$$

Ultraviolet Div. $\frac{a}{\epsilon_{\mathrm{UV}}}$

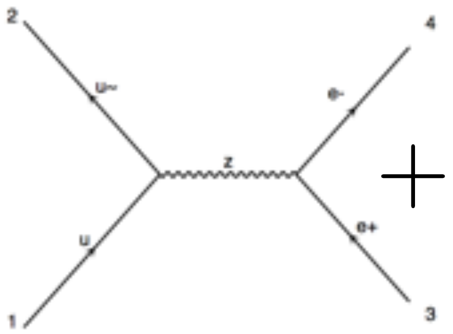
Infrared Div.

$$-\frac{c_{-2}}{\epsilon_{\mathrm{IR}}^2} - \frac{c_{-1}}{\epsilon_{\mathrm{IR}}}$$

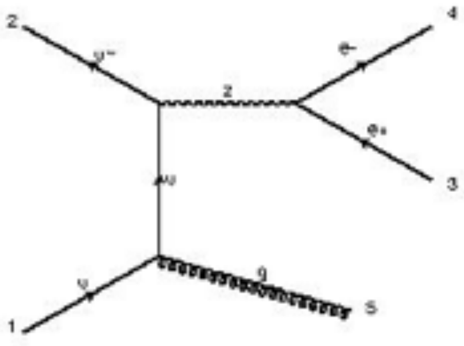
ANATOMY

$$\sigma^{\textbf{NLO}}_{pp\to e^+e^-} =$$

$$\int_2 \Bigg|$$



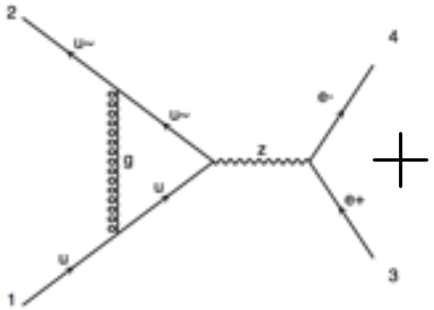
$$+\cdots\Bigg|^2 + \int_3 \Bigg|$$



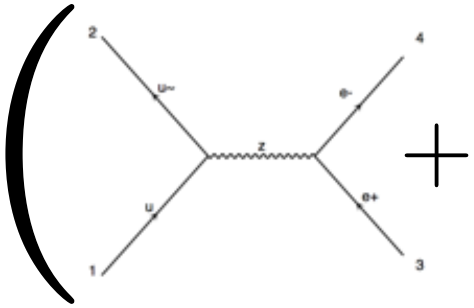
$$+\cdots\Bigg|^2$$

Infrared Div. $\frac{c_{-2}}{\epsilon_{\mathrm{IR}}^2}+\frac{c_{-1}}{\epsilon_{\mathrm{IR}}}$

$$+\int_2 \Bigg($$



$$+\cdots\Bigg) \times \Bigg($$



$$+\cdots\Bigg)^*$$

Ultraviolet Div. $\frac{a}{\epsilon_{\mathrm{UV}}}$

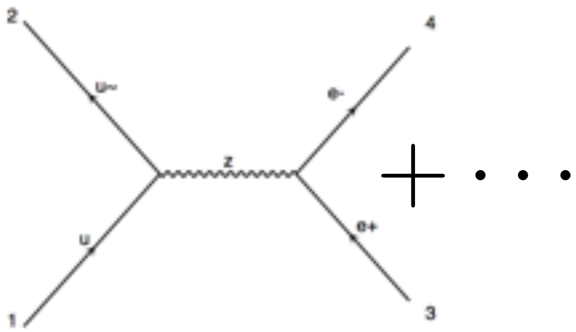
Infrared Div. $-\frac{c_{-2}}{\epsilon_{\mathrm{IR}}^2}-\frac{c_{-1}}{\epsilon_{\mathrm{IR}}}$

Kinoshita-Lee-Nauenberg theorem

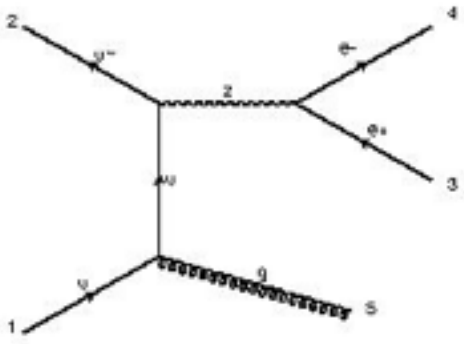
ANATOMY

$$\sigma^{\textbf{NLO}}_{pp\to e^+e^-} =$$

$$\int_2 \Bigg|$$



$$+\cdots\Bigg|^2 + \int_3 \Bigg|$$

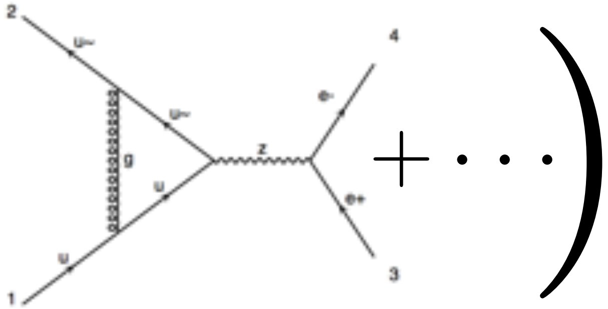


$$+\cdots\Bigg|^2$$

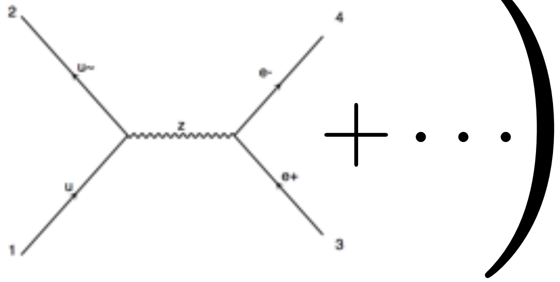
Infrared Div.

$$\frac{c_{-2}}{\epsilon_{\mathrm{IR}}^2}+\frac{c_{-1}}{\epsilon_{\mathrm{IR}}}$$

$$+\int_2 \Bigg($$



$$+\cdots\Bigg)\times\Bigg($$



$$+\cdots\Bigg)^*$$

Ultraviolet Div. $\frac{a}{\epsilon_{\mathrm{UV}}}$

Renormalization !

Infrared Div.

$$-\frac{c_{-2}}{\epsilon_{\mathrm{IR}}^2}-\frac{c_{-1}}{\epsilon_{\mathrm{IR}}}$$

Kinoshita-Lee-Nauenberg theorem

ISSUES TO BE ADDRESSED @ NLO

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**
- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
    - Amplitude: **ALOHA+MadLoop**
    - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**

ISSUES TO BE ADDRESSED @ NLO+PS

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**
- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
  - Amplitude: **ALOHA+MadLoop**
  - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**
- Matching (avoid double counting) to PS: **MC@NLO**

ISSUES TO BE ADDRESSED @ NLO+PS

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**

LO

- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
  - Amplitude: **ALOHA+MadLoop**
  - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**
- Matching (avoid double counting) to PS: **MC@NLO**

ISSUES TO BE ADDRESSED @ NLO+PS

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**

LO

- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
  - Amplitude: **ALOHA+MadLoop**
  - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**

NLO

- Matching (avoid double counting) to PS: **MC@NLO**

ISSUES TO BE ADDRESSED @ NLO+PS

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**

LO

- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
  - Amplitude: **ALOHA+MadLoop**
  - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**

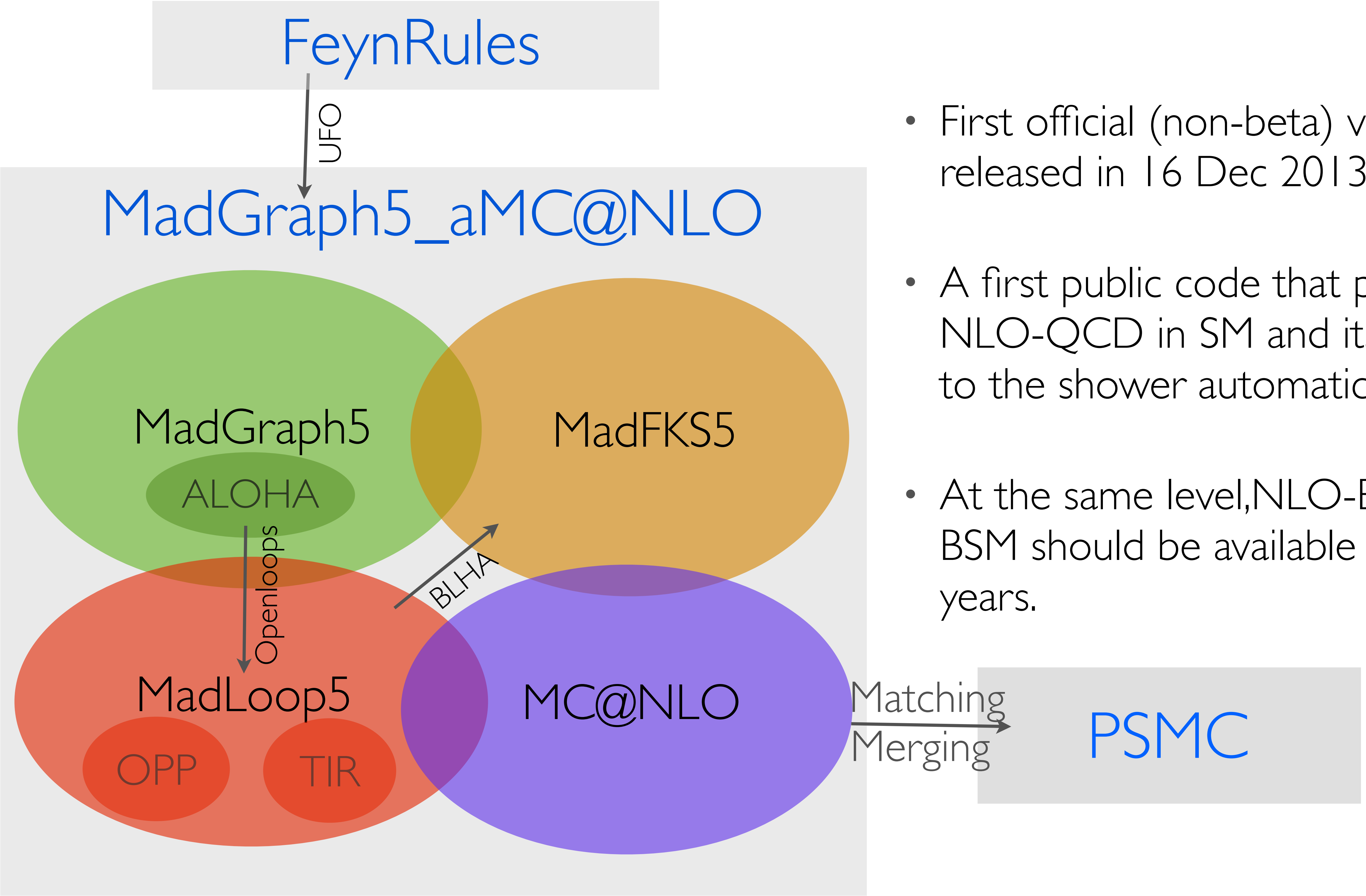
NLO

- Matching (avoid double counting) to PS: **MC@NLO**

NLO+PS

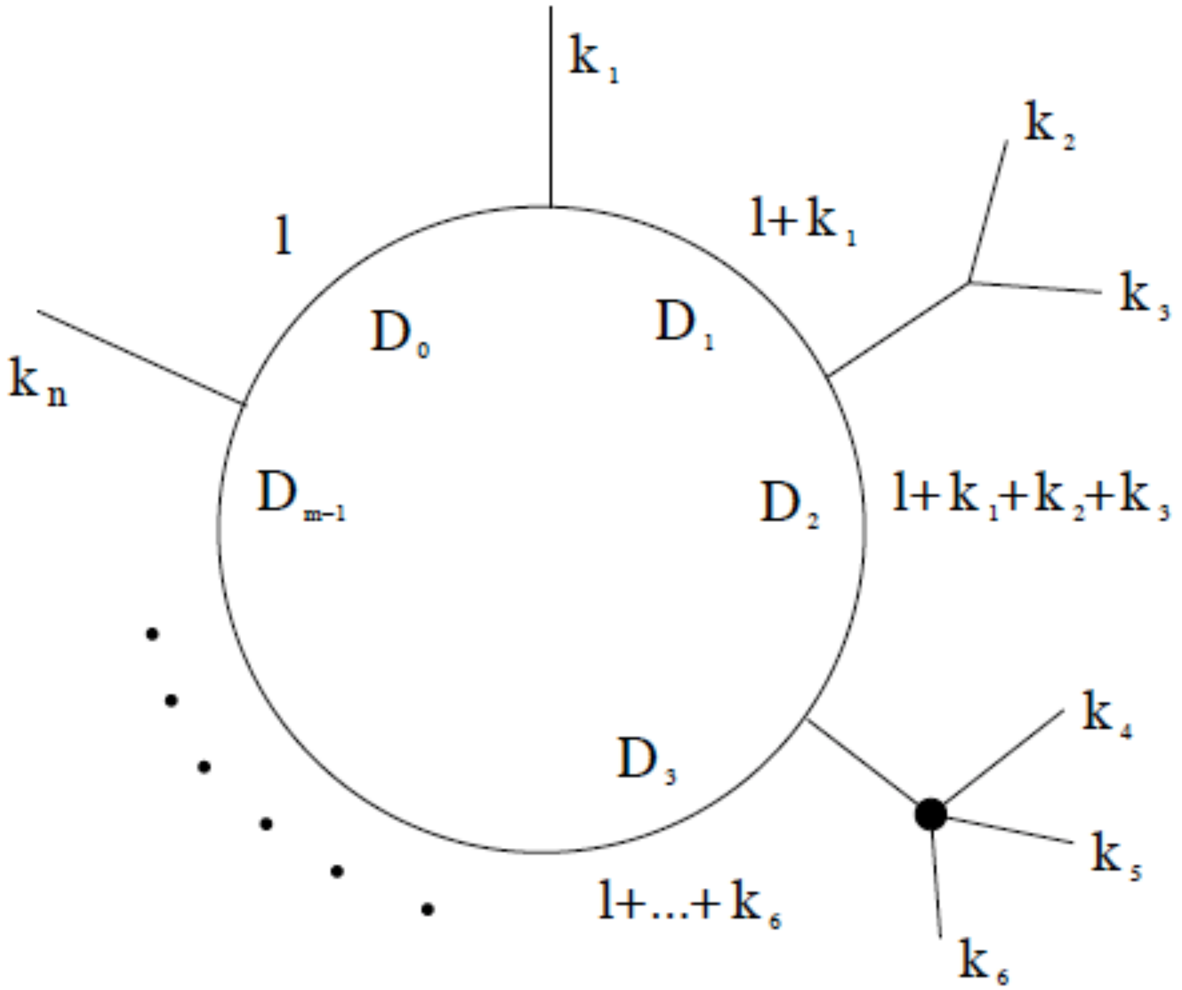
JOINT EFFORTS FOR AUTOMATION AT NLO

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro (JHEP'14)



- First official (non-beta) version was released in 16 Dec 2013.
- A first public code that provides NLO-QCD in SM and its interface to the shower automatically.
- At the same level,NLO-EW and BSM should be available in recent years.

LOOP INTEGRALS



- Consider a m-point loop diagram with n external momenta.
- The integral is

$$\int d^{(4-2\epsilon)}l\frac{N(l)}{D_0D_1D_2\cdots D_{m-1}}$$

$$D_i=(l+p_i)^2-m_i^2$$

LOOP INTEGRALS

$$\int d^{(4-2\epsilon)} \frac{N(l)}{D_0 D_1 D_2 \cdots D_{m-1}} =$$
$$\sum_{0\le i_0<i_1<i_2<i_3\le m-1} d_{i_0i_1i_2i_3}\mathcal{I}_0(i_0i_1i_2i_3)+$$
$$\sum_{0\le i_0<i_1<i_2\le m-1} c_{i_0i_1i_2}\mathcal{I}_0(i_0i_1i_2)+$$
$$\sum_{0\le i_0<i_1\le m-1} b_{i_0i_1}\mathcal{I}_0(i_0i_1)+$$
$$\sum_{0\le i_0\le m-1} a_{i_0}\mathcal{I}_0(i_0)+$$
$$R,$$

- Integral can be reduced to a minimal basis that was known.
- Rational term R is in general process dependent.

$$\mathcal{I}_0(i_0i_1i_2i_3) \equiv \int d^{(4-2\epsilon)}l \frac{1}{D_{i_0}D_{i_1}D_{i_2}D_{i_3}},$$
$$\mathcal{I}_0(i_0i_1i_2) \equiv \int d^{(4-2\epsilon)}l \frac{1}{D_{i_0}D_{i_1}D_{i_2}},$$
$$\mathcal{I}_0(i_0i_1) \equiv \int d^{(4-2\epsilon)}l \frac{1}{D_{i_0}D_{i_1}},$$
$$\mathcal{I}_0(i_0) \equiv \int d^{(4-2\epsilon)}l \frac{1}{D_{i_0}}.$$

LOOP INTEGRATION TOOLS

- Loop reduction tools

	Max # of den.	*Max # of rank*	*Complex mass*	*Quadruple precision*
CutTools	**10†**	**# of den.‡**	**yes**	**yes**
IREGI	**7†**	**7†**	**yes**	**no**
PJFry++	**5★**	**# of den.**	**no**	**no**
Golem95	**6**	**Min(6, # of den.+1)**	**yes**	**no**
Samurai	**8†**	**# of den. +1**	**yes**	**no**
Ninja	**-**	**Min(20†, # of den.+1)**	**yes**	**no**

† *The limitation is not intrinsic to the reduction tool, and is only parametrical so that it is trivial to increase if proven necessary.*

★ *Pentagons in PJFry++ are formally supported but typically too unstable for integration.*

‡ *The limitation can be increased by 1 when applies to some simple Lorentz structure like HEFT.*

LOOP INTEGRATION TOOLS

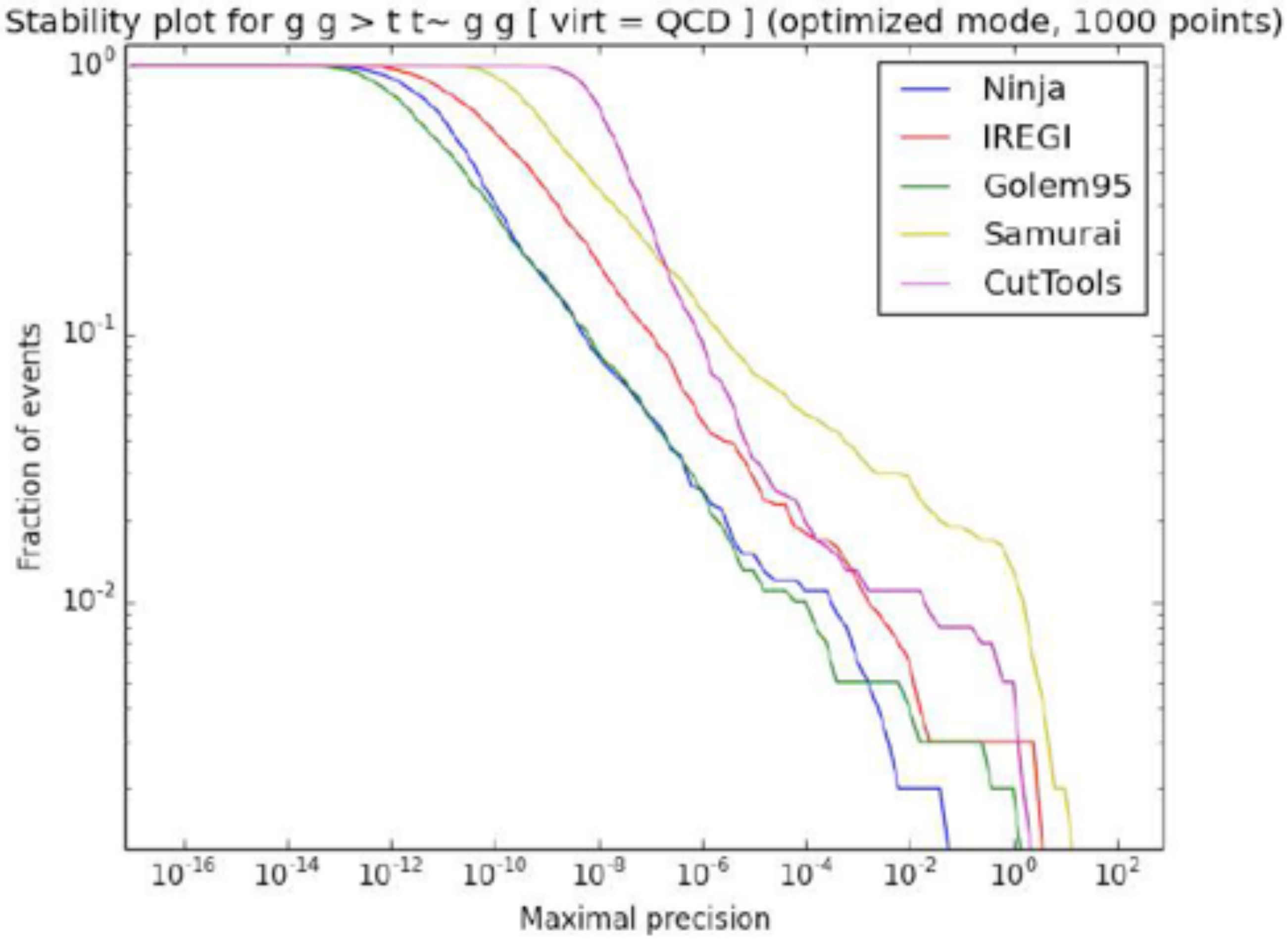
- Loop reduction tools

Speed

Stability

$$gg \to t\bar{t}gg$$

CutTools	**230 ms**
IREGI	**13295 ms**
PJFry++	**-**
Golem95	**6226 ms**
Samurai	**580 ms**
Ninja	**90 ms**

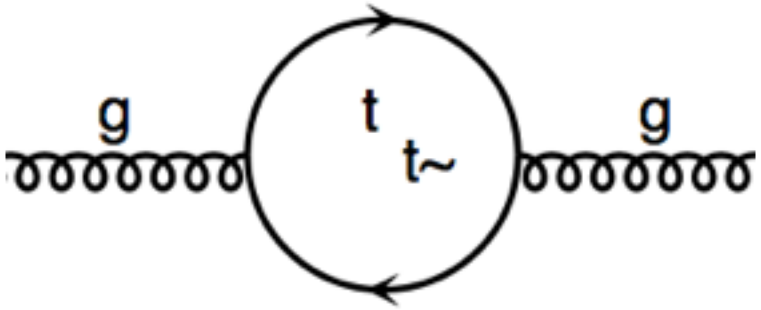


The choice of loop reduction tools depends on the process and the model considered !

LOOP INTEGRALS: R2

- The numerator N(l) is a complicated function (Clifford algebra etc) in d- and 4-dimensional quantities.
- It is usually conv. to work N(l) in 4-dim --> super useful for numerical calculations.
- We need a special rational term R2 !

- For example, gluon SE:



$$N(l) = -\frac{\alpha_S}{(2\pi)^3}\delta_{ab}\mathrm{Tr}[\gamma^\mu(\not{l}+m_t)\gamma^\nu(\not{l}+\not{p}+m_t)]\varepsilon_\mu\varepsilon_\nu$$

- Dirac algebra gives the (d-4) numerator

$$\tilde{N}(\tilde{l}) = 4\frac{\alpha_S}{(2\pi)^3}\delta_{ab}g^{\mu\nu}\tilde{l}^2\varepsilon_\mu\varepsilon_\nu$$

- With the integration

$$\int d^{(4-2\epsilon)}l\frac{\tilde{l}^2}{(l^2-m_t^2)((l+p)^2-m_t^2)} = -\frac{i\pi^2}{2}\left(2m_t^2-\frac{p^2}{3}\right)+\mathcal{O}(\epsilon)$$

- The corresponding R2 term

$$R_2 = -\frac{i\alpha_S}{4\pi}(2m_t^2-\frac{p^2}{3})\delta_{ab}g^{\mu\nu}\varepsilon_\mu\varepsilon_\nu$$

LOOP INTEGRALS: R2

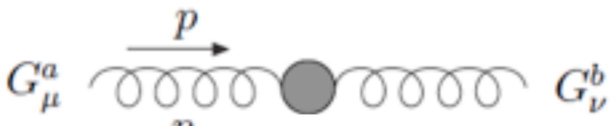
Draggiotis, Garzelli, Papadopoulos, Pittau (JHEP'09); HSS, Zhang, Chao (JHEP'11)

- It was proven that R2 is only UV related, hence universal (i.e. model dependent only), which can be derived by R2 counterterm Feynman rules and should be derived once for all in each model.

LOOP INTEGRALS: R2

Draggiotis, Garzelli, Papadopoulos, Pittau (JHEP'09); HSS, Zhang, Chao (JHEP'11)

- It was proven that R2 is only UV related, hence universal (i.e. model dependent only), which can be derived by R2 counterterm Feynman rules and should be derived once for all in each model.

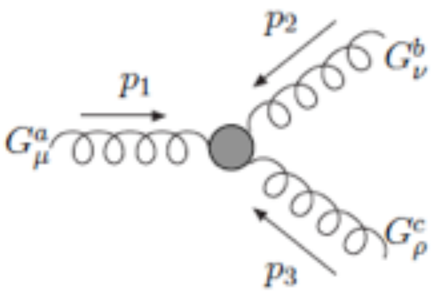


$$= \mathrm{Vert}(G^a_\mu, G^b_\nu)$$

$$\mathrm{Vert}(G^a_\mu, G^b_\nu) = \frac{i g_s^2 N_c}{48\pi^2}\,\delta^{ab}\left[\frac{p^2}{2} g_{\mu\nu} + \lambda_{HV}\left(g_{\mu\nu}p^2 - p_\mu p_\nu\right) + \sum_Q \frac{p^2 - 6m_Q^2}{N_c} g_{\mu\nu}\right]$$

$$= \mathrm{Vert}(Q^i_l, \bar{Q}^j_m)$$

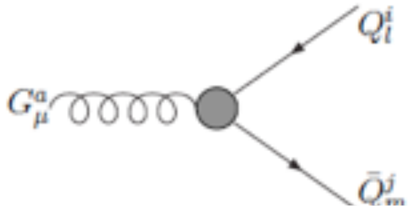
$$\mathrm{Vert}(Q^i_l, \bar{Q}^j_m) = \frac{i g_s^2}{16\pi^2}\,\frac{N_c^2 - 1}{2N_c}\,\delta^{ij}\,\delta_{lm}\,\left(-\not{p} + 2m_{Q_l}\right)\lambda_{HV}.$$



$$= \mathrm{Vert}(G^a_\mu, G^b_\nu, G^c_\rho)$$

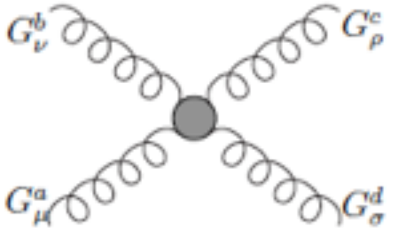
$$\mathrm{Vert}(G^a_\mu, G^b_\nu, G^c_\rho) = -\frac{g_s^3 N_c}{48\pi^2}\left(\frac{7}{4} + \lambda_{HV} + \frac{2N_f}{N_c}\right) f^{abc}\, V_{\mu\nu\rho}(p_1, p_2, p_3)$$

$$V_{\mu\nu\rho}(p_1, p_2, p_3) = g_{\mu\nu}(p_2 - p_1)_\rho + g_{\nu\rho}(p_3 - p_2)_\mu + g_{\rho\mu}(p_1 - p_3)_\nu.$$



$$= \mathrm{Vert}(G^a_\mu, Q^i_l, \bar{Q}^j_m)$$

$$\mathrm{Vert}(G^a_\mu, Q^i_l, \bar{Q}^j_m) = \delta_{lm}\,\frac{i g_s^3}{16\pi^2}\,T^a_{ji}\,\frac{N_c^2 - 1}{2N_c}\,\gamma_\mu\left(1 + \lambda_{HV}\right)$$



$$= \mathrm{Vert}\left(G^a_\mu, G^b_\nu, G^c_\rho, G^d_\sigma\right)$$

$$\mathrm{Vert}\left(G^a_\mu, G^b_\nu, G^c_\rho, G^d_\sigma\right) = \frac{i g_s^4}{48\pi^2}\left(C_1\, g_{\mu\nu}g_{\rho\sigma} + C_2\, g_{\mu\rho}g_{\nu\sigma} + C_3\, g_{\mu\sigma}g_{\nu\rho}\right),$$

$$\begin{aligned} C_1 = {} & Tr(\{T^a, T^b\}\{T^c, T^d\})\ (5N_c + 2\lambda_{HV}N_c + 6N_f) \\ & - \left(Tr(T^aT^cT^bT^d) + Tr(T^aT^dT^bT^c)\right)(12N_c + 4\lambda_{HV}N_c + 10N_f) \\ & - \left(\delta^{ab}\delta^{cd} + \delta^{ac}\delta^{bd} + \delta^{ad}\delta^{bc}\right), \quad C_2 = C_1(b \leftrightarrow c) \quad C_3 = C_1(b \leftrightarrow d) \end{aligned}$$

LOOP AMPLITUDE

Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau (JHEP'11)

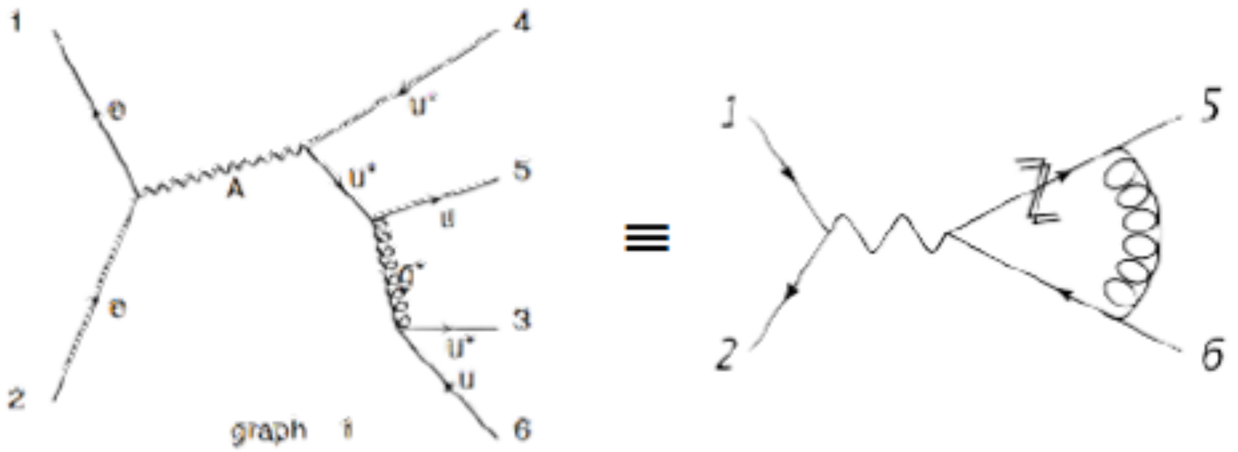
- Instead of using an external tool for loop diagram generation, we recycle MadGraph algorithms for tree-level diagram generation.

- A loop diagrams with the loop cut open has two extra external particles. Consider e^+e^- > u u~ u u~ (loop particle are in red).MadLoop will generate 8 L-cut diagrams. Here are two of them:

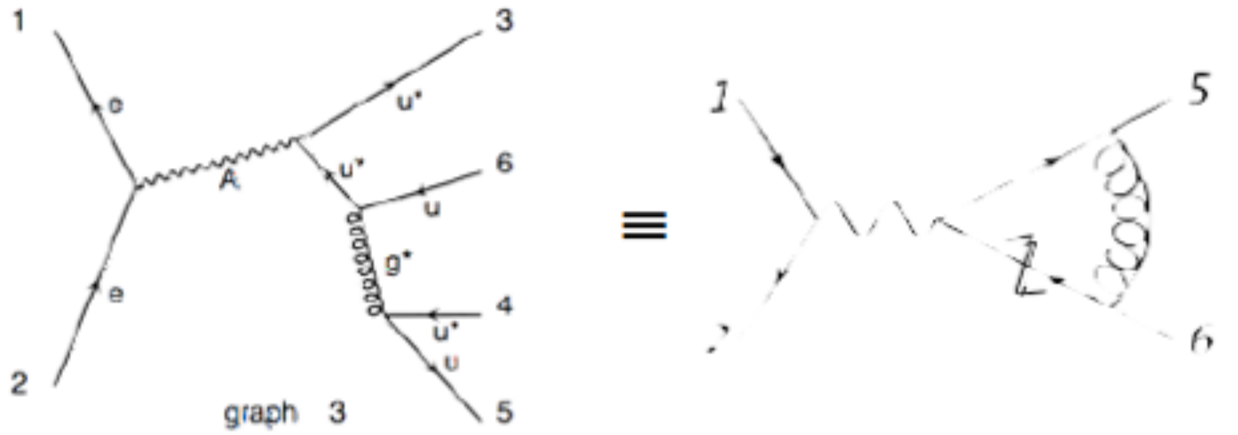
- All diagrams with two extra particles generated and the ones that are redundant need be filtered out

- Each diagram gets an unique tag: any mirror and/or cyclic permutations of tags of diagrams already in the set are taken out

- Additional filter to eliminate tadpole and bubbles attached to external lines.



$\text{Diag}_1 = [u^*(6)g^*(5)u^*(A)]$



$\text{Diag}_3 = [u^*(A)u^*(6)g^*(5)]$

RENORMALIZATION

- Renormalization is a non-trivial task in principle.
- In QFT, renormalization is widely used to absorb (the divergence from) the high-momentum mode.
- The renormalization of some theories is quite well known, such as QCD (or the Standard Model).

RENORMALIZATION

- Renormalization is a non-trivial task in principle.

- In QFT, renormalization is widely used to absorb (the divergence from) the high-momentum mode.

- The renormalization of some theories is quite well known, such as QCD (or the Standard Model).
- In general, the UV divergences should be absorbed by a redefinition of
    - the free parameters (such as mass, couplings, mixing angles etc

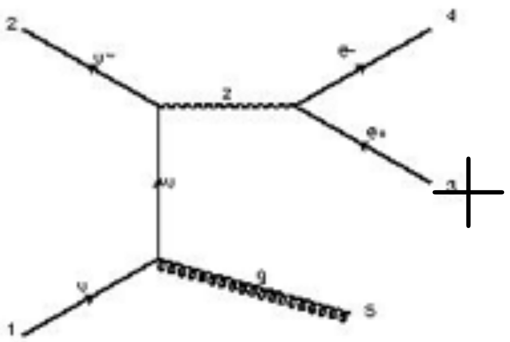
$$x_0 \to x + \delta x$$

    - the fields

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

REAL SUBTRACTION

- Because of IR div, difficult to integrate real phase-space !
- Subtraction the IR piece by a constructed function S



$$\int_3 \Bigg(\underbrace{\Bigg| \qquad + \cdots \Bigg|^2}_{\substack{\| \\ R}} - S \Bigg) + \int_3 S$$

- Requirement:
  - The IR singularity of **R** and **S** are completely same (i.e. local)
  - **S** is much easier to integrate analytically at least one particle’s phase space for NLO computation.

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \xrightarrow{\text{IR sing.}} \frac{1}{\chi_i}\frac{1}{1-y_{ij}}$$

where $\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}, y_{ij} \equiv \cos\theta_{ij}$

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \xrightarrow{\text{IR sing.}} \frac{1}{\chi_i}\frac{1}{1-y_{ij}}$$

where $\boxed{\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}}, y_{ij} \equiv \cos\theta_{ij}$

$\chi_i \to 0$ **soft**

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \xrightarrow{\text{IR sing.}} \frac{1}{\chi_i}\frac{1}{1-y_{ij}}$$

where $\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}, \boxed{y_{ij} \equiv \cos\theta_{ij}}$

$y_{ij} \to 1$ **collinear**

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \xrightarrow{\text{IR sing.}} \frac{1}{\chi_i}\frac{1}{1-y_{ij}}$$

where $\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}, y_{ij} \equiv \cos\theta_{ij}$

- Divide phase-space so that each partition has at most one soft and one collinear singularity

$$\int_3 R = \sum_{i,j}\int_3 S_{ij}R \qquad \sum_{i,j} S_{ij} = 1$$

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \xrightarrow{\text{IR sing.}} \frac{1}{\chi_i}\frac{1}{1-y_{ij}}$$

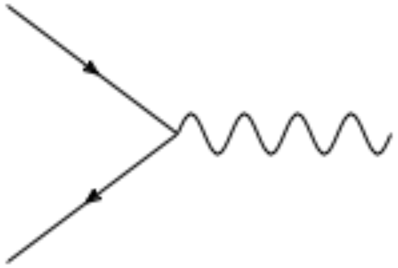
where $\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}, y_{ij} \equiv \cos\theta_{ij}$

- Divide phase-space so that each partition has at most one soft and one collinear singularity

$$\int_3 R = \sum_{i,j} \int_3 S_{ij} R \qquad \sum_{i,j} S_{ij} = 1$$

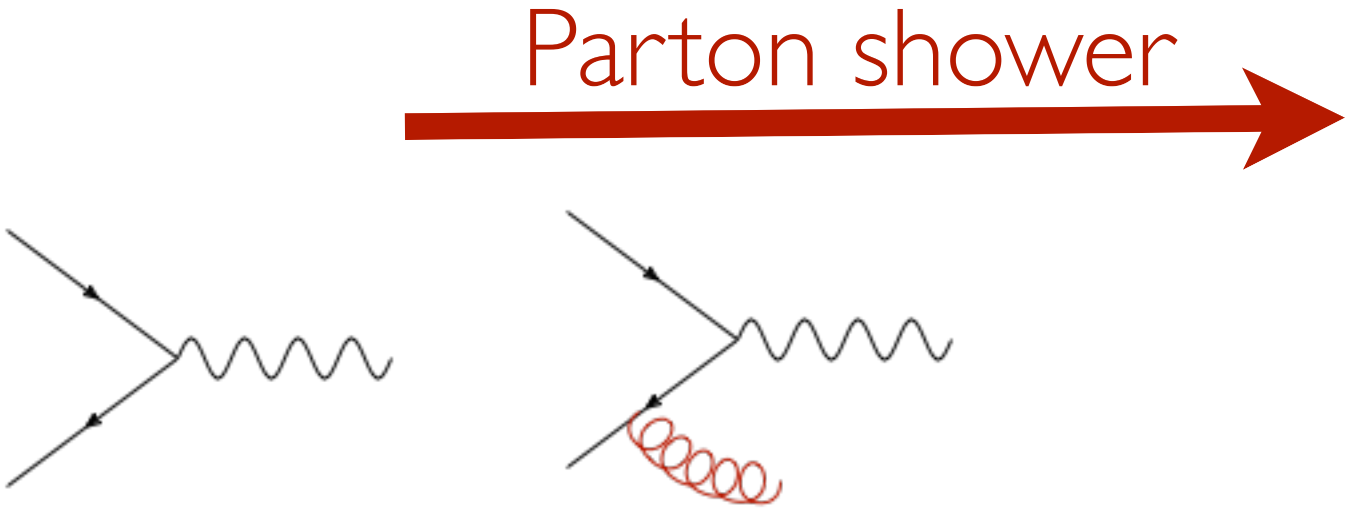
- The real can be regulated as $\sum_{i,j}\int_3 \left(\frac{1}{\chi_i}\right)_+ \left(\frac{1}{1-y_{ij}}\right)_+ \chi_i \left(1-y_{ij}\right) S_{ij} R$
- Soft counterterm is blind of spin, but the splitting kernel in collinear counterterm is dependent of spin/gauge/...

MATCHING TO PARTON SHOWER



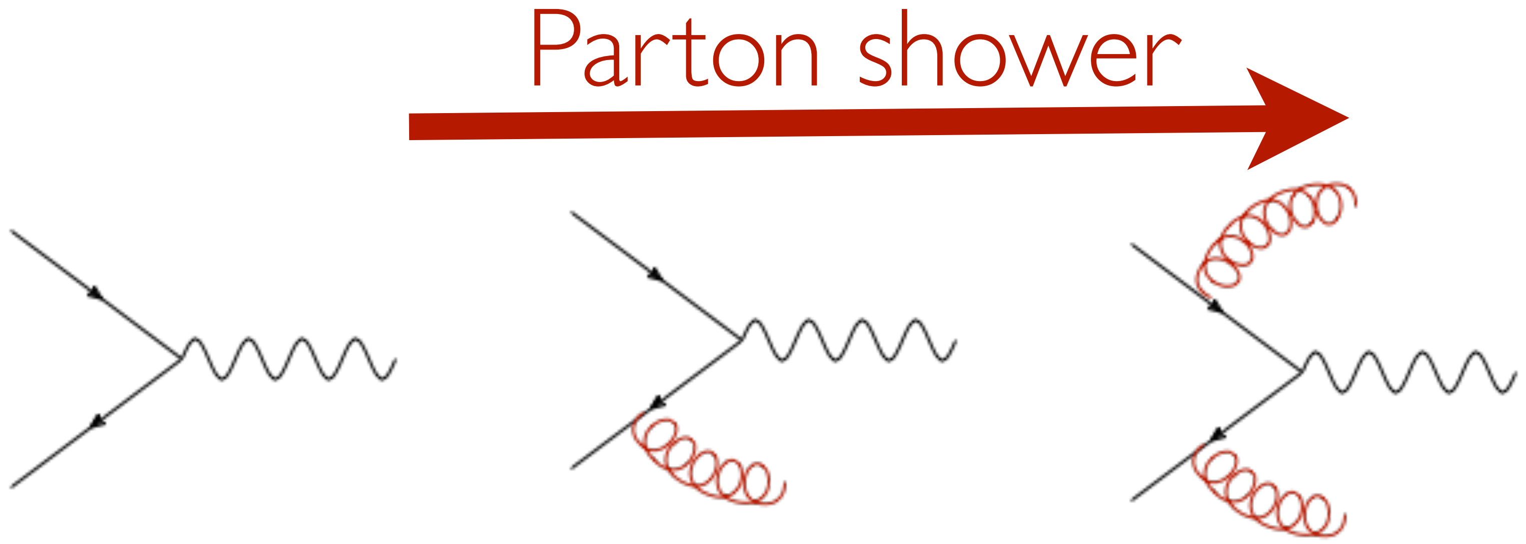
MATCHING TO PARTON SHOWER

MATCHING TO PARTON SHOWER

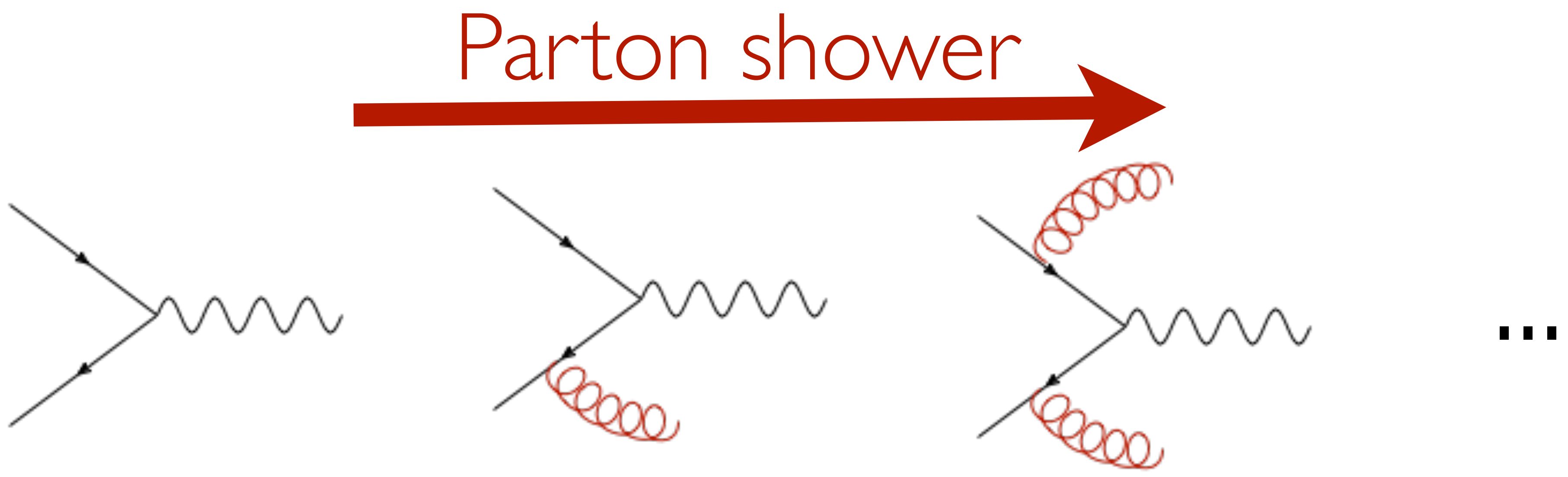


Parton shower

MATCHING TO PARTON SHOWER



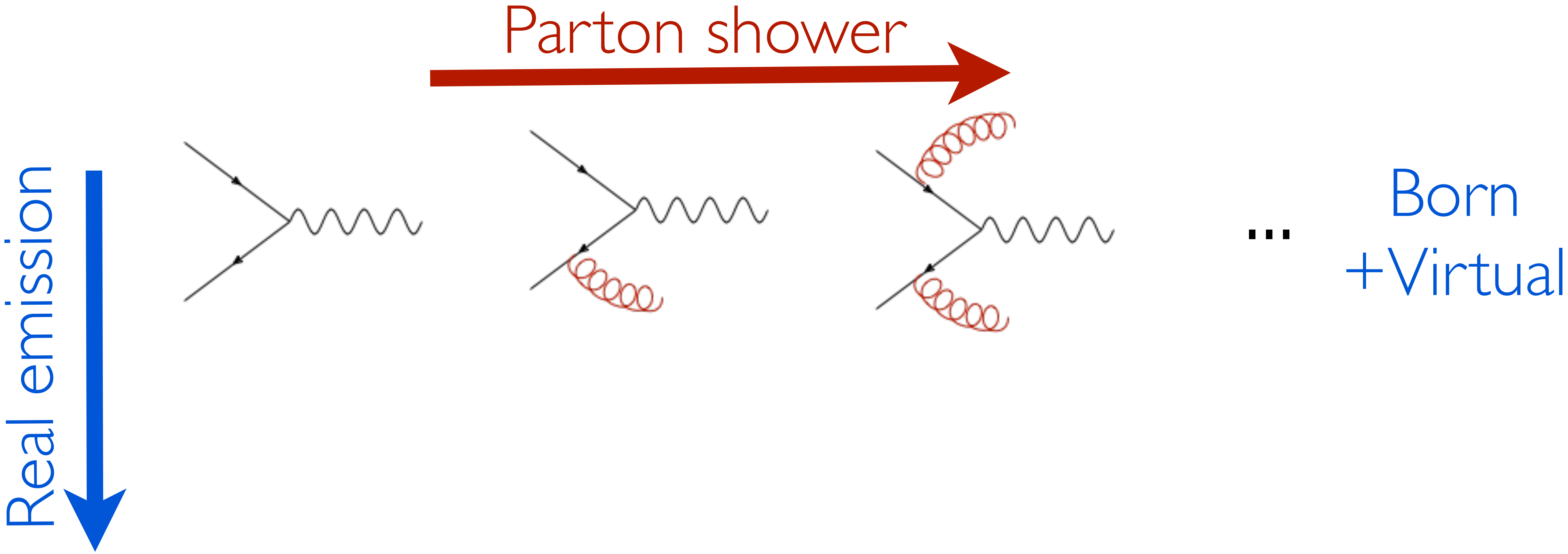
MATCHING TO PARTON SHOWER



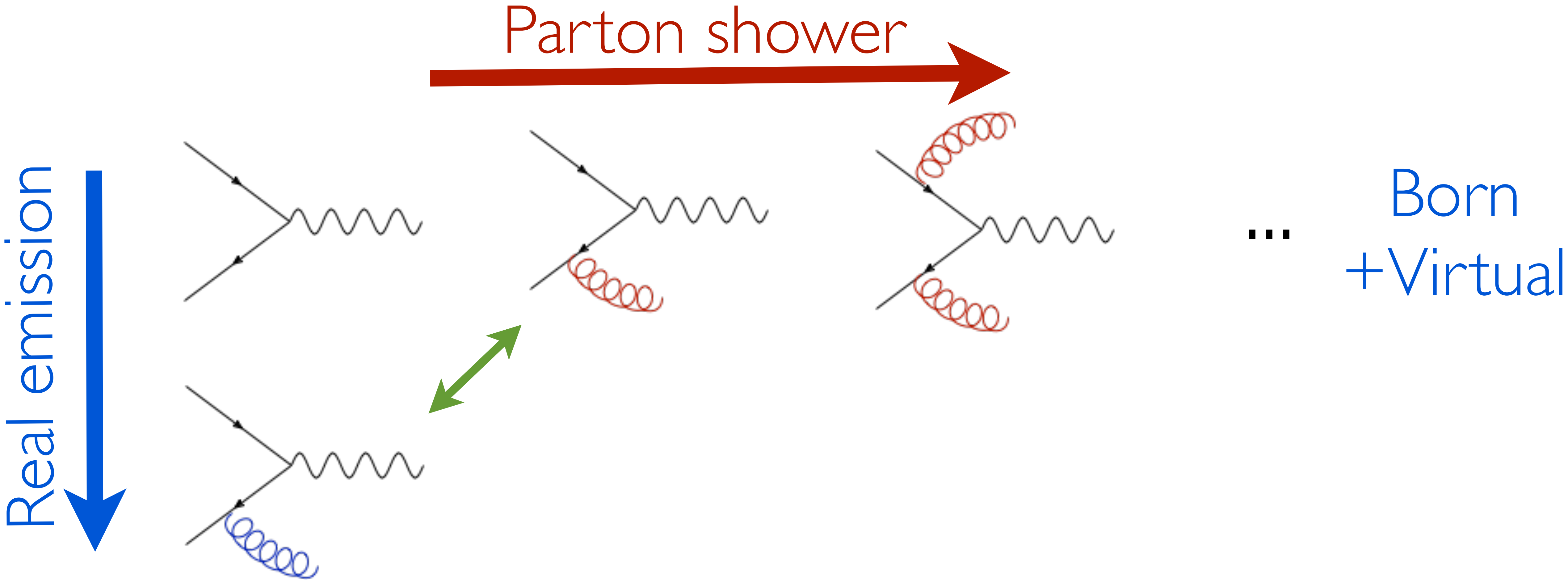
Parton shower

Born
+Virtual

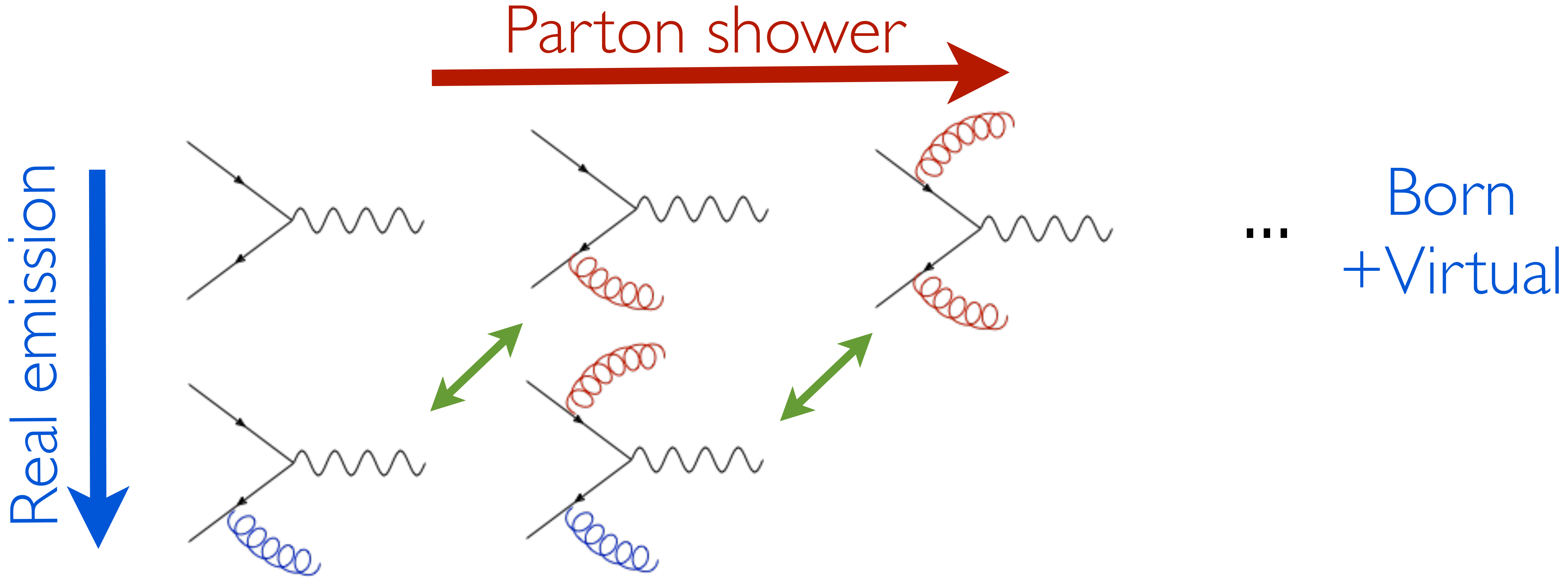
MATCHING TO PARTON SHOWER



MATCHING TO PARTON SHOWER



MATCHING TO PARTON SHOWER



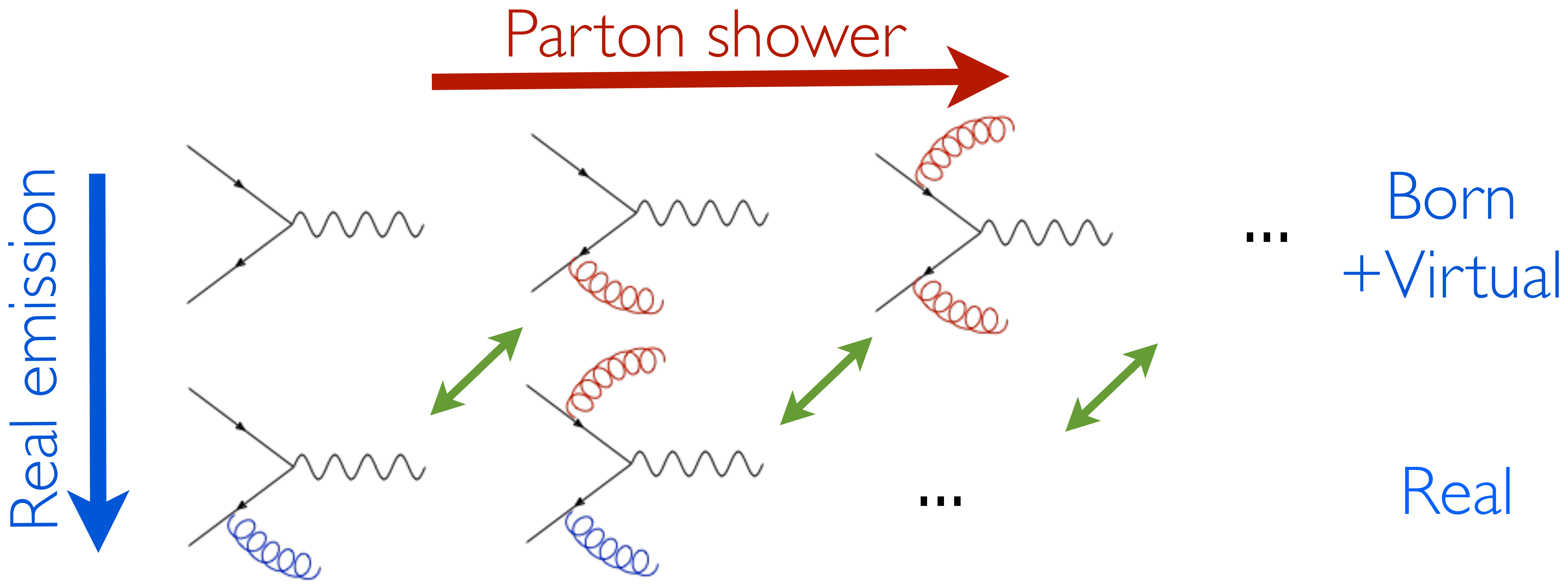
Parton shower

Real emission

...

Born
+Virtual

MATCHING TO PARTON SHOWER

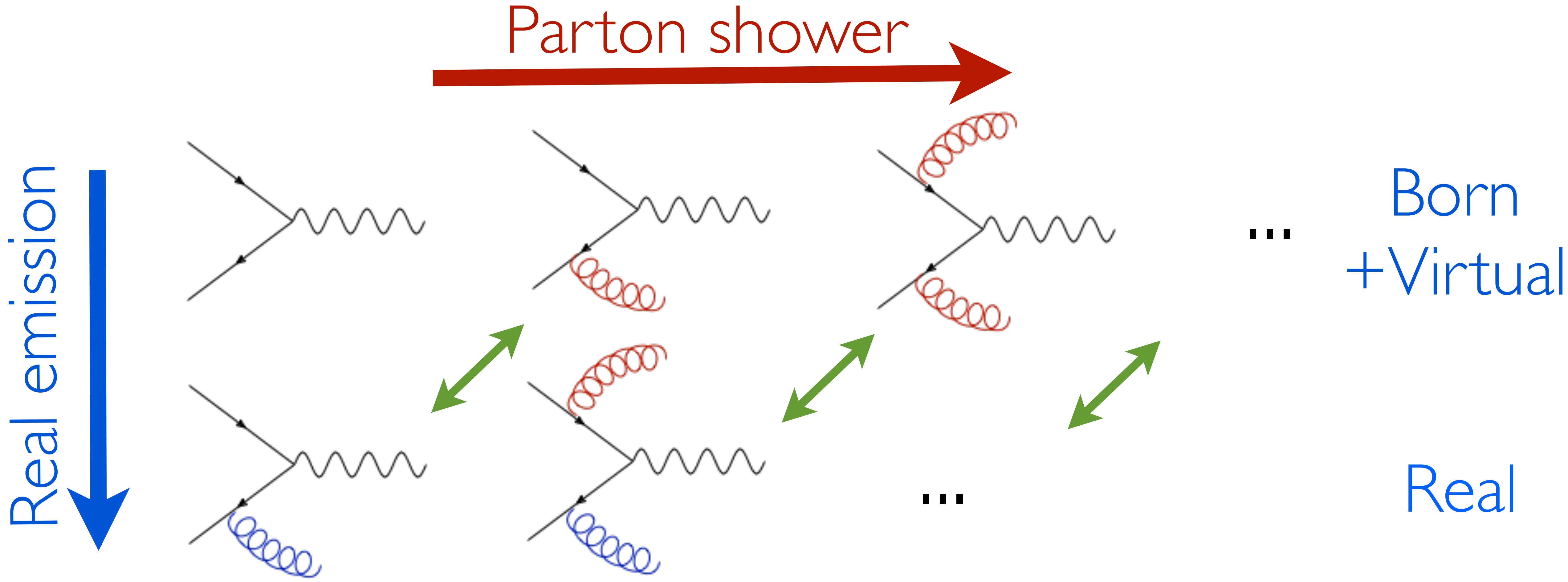


- When matching NLO events to PS, one faces double counting issues.

- And also part of the virtual contribution is double counted through the definition of the Sudakov factor.

- Two ways out have been proposed: POWHEG and MC@NLO

MATCHING TO PARTON SHOWER



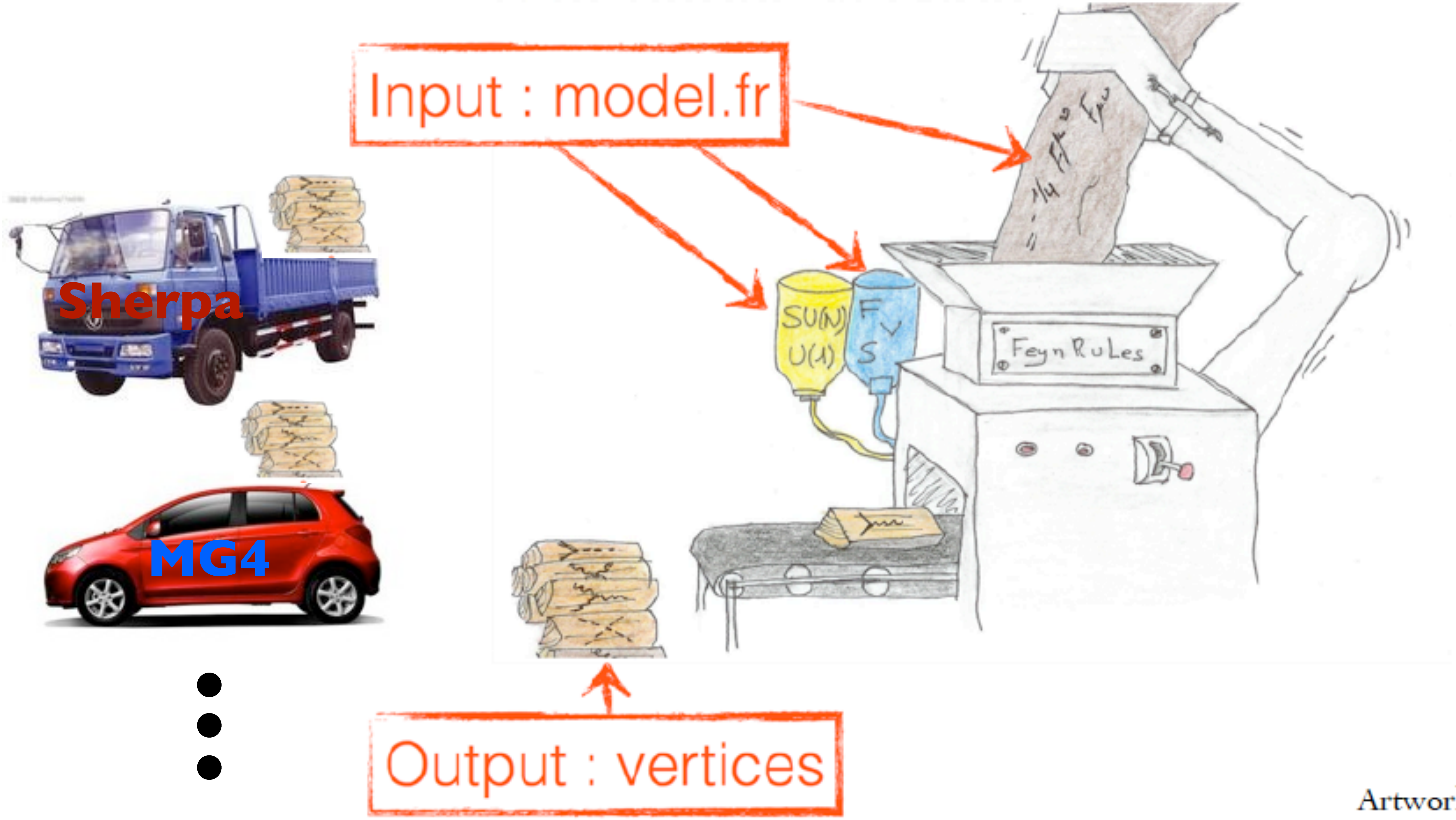
- When matching NLO events to PS, one faces double counting issues.
- And also part of the virtual contribution is double counted through the definition of the Sudakov factor.
- Two ways out have been proposed: POWHEG and MC@NLO

used by MG5_aMC

FEYNRULES

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- How to incorporate all of above information in a model file ?



Input : model.fr

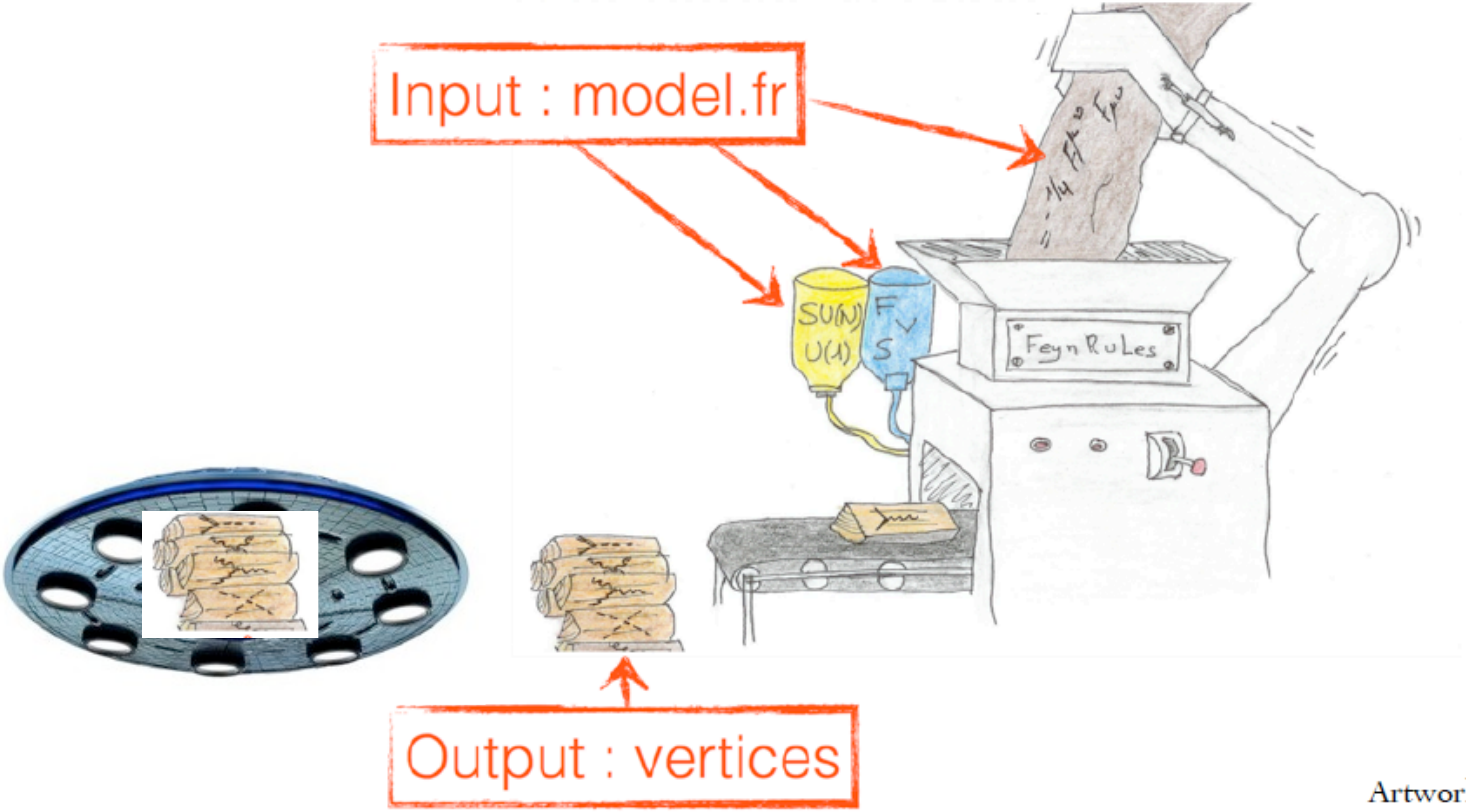
Output : vertices

Artwork by C. Degrande

FEYNRULES

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- How to incorporate all of above information in a model file ?



Input : model.fr

Output : vertices

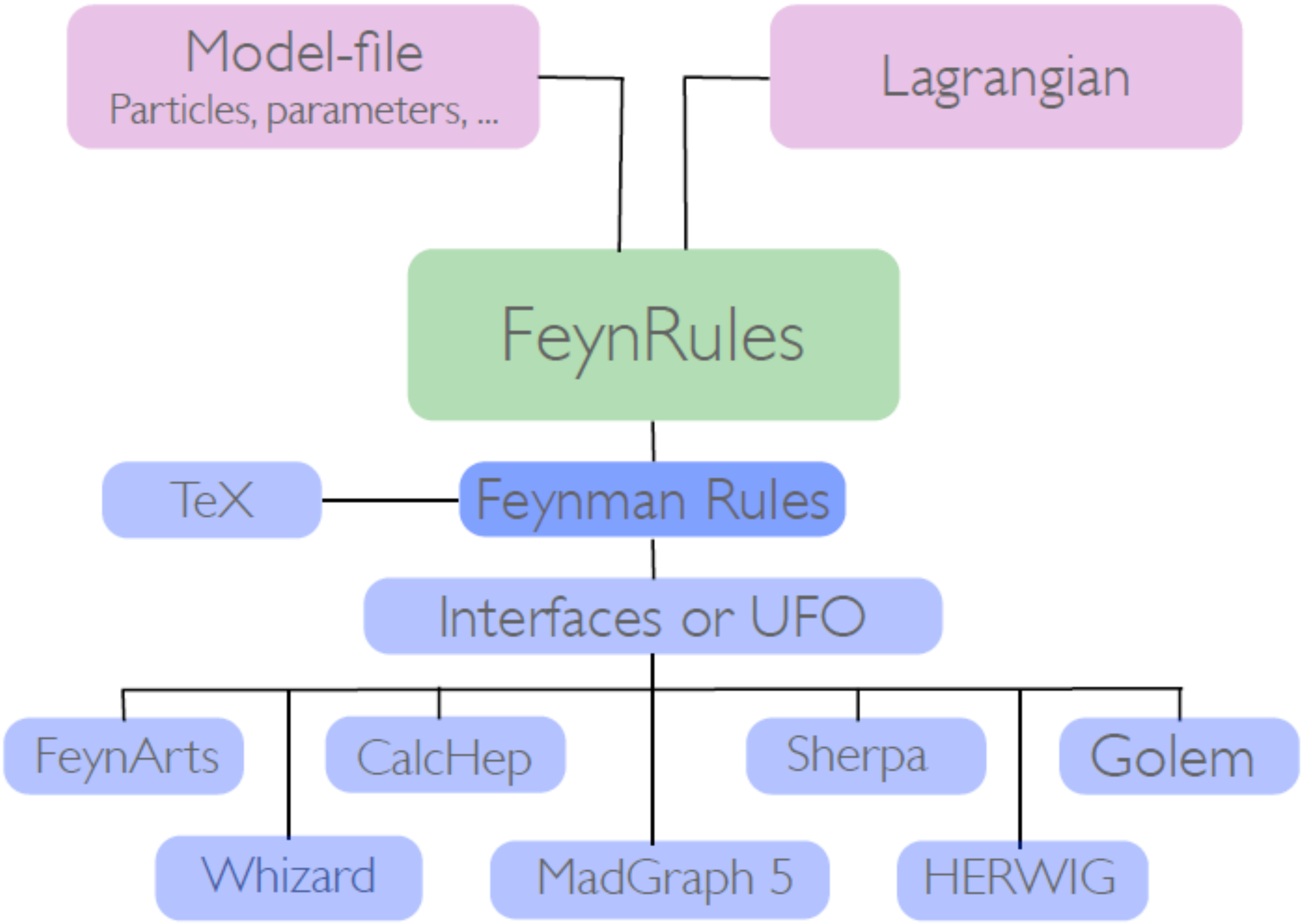
Artwork by C. Degrande

- UFO stands for Universal FeynRules Output:

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

FEYNRULES: STRUCTURE

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)



Model-file
Particles, parameters, ...

Lagrangian

FeynRules

TeX

Feynman Rules

Interfaces or UFO

FeynArts

CalcHep

Sherpa

Golem

Whizard

MadGraph 5

HERWIG

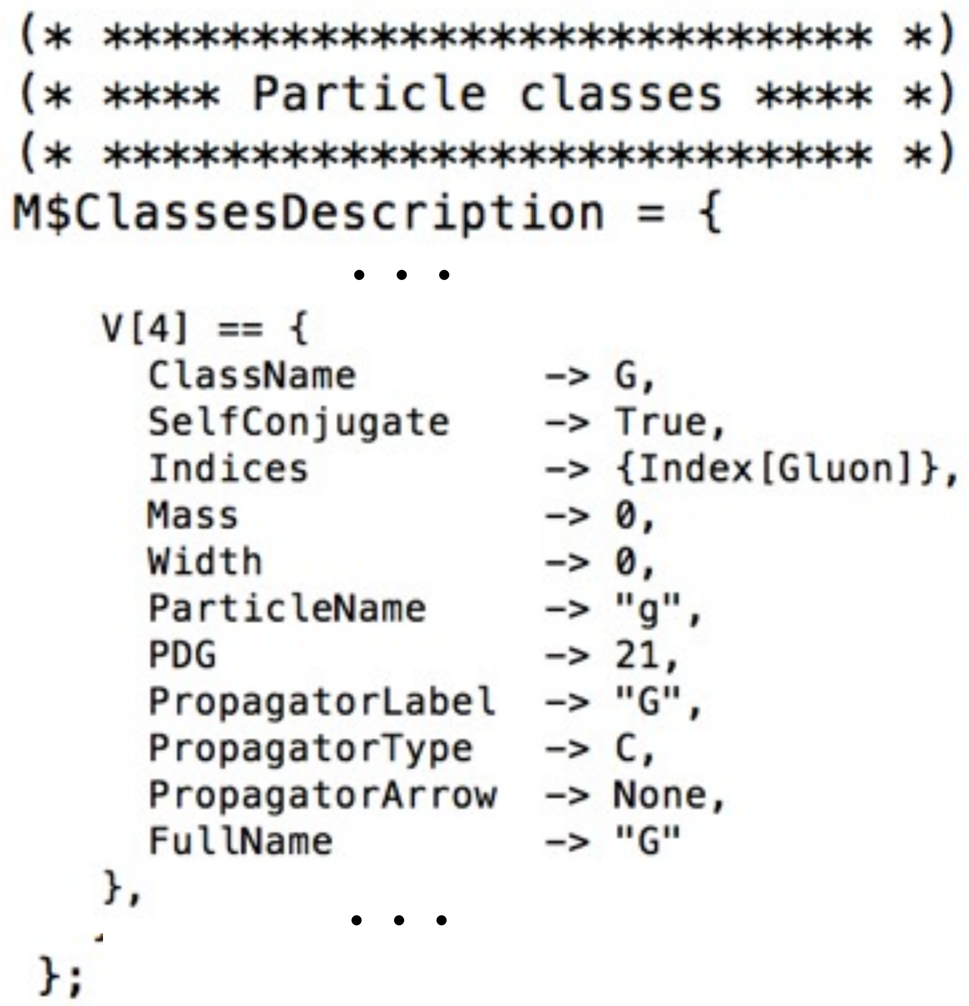
FEYNRULES: INPUT

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

FEYNRULES: INPUT

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Definitions of particles

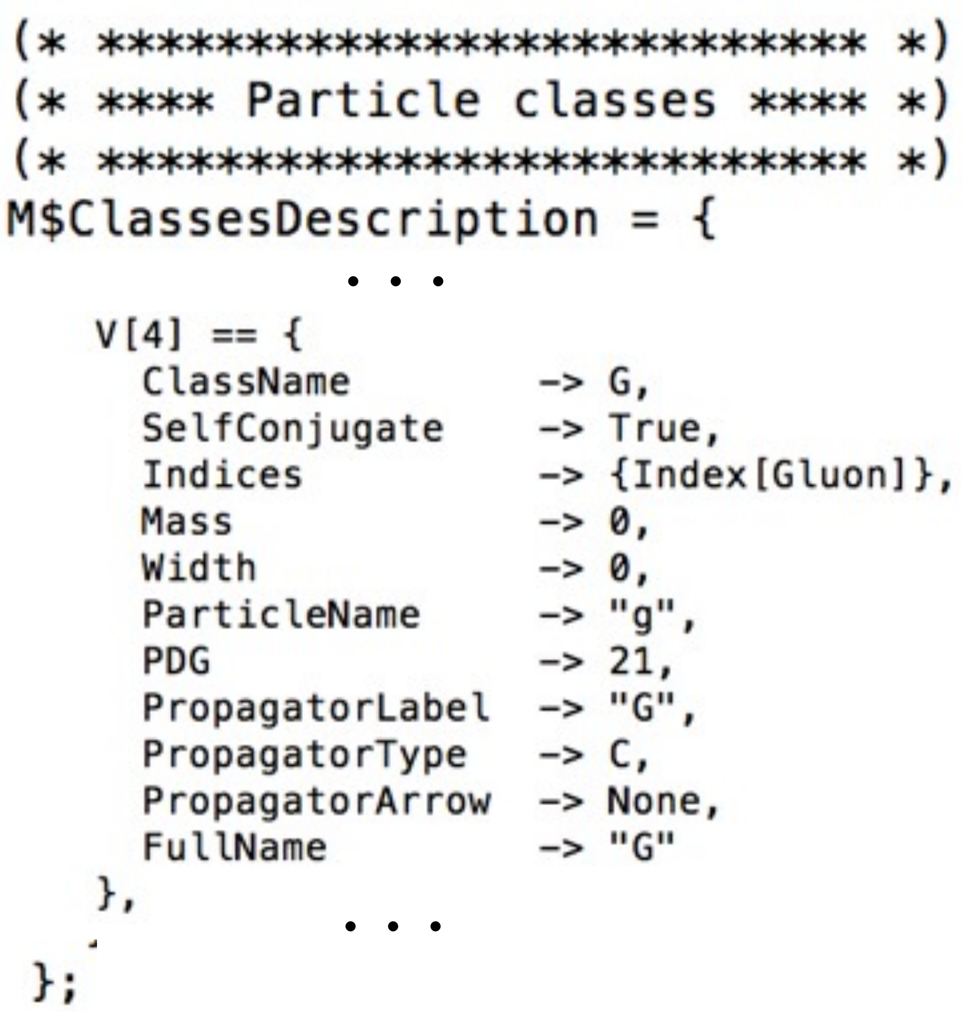


```
(* ************************** *)
(* **** Particle classes **** *)
(* ************************** *)
M$ClassesDescription = {
              . . .
   V[4] == {
     ClassName        -> G,
     SelfConjugate    -> True,
     Indices          -> {Index[Gluon]},
     Mass             -> 0,
     Width            -> 0,
     ParticleName     -> "g",
     PDG              -> 21,
     PropagatorLabel  -> "G",
     PropagatorType   -> C,
     PropagatorArrow  -> None,
     FullName         -> "G"
   },
              . . .
 };
```

FEYNRULES: INPUT

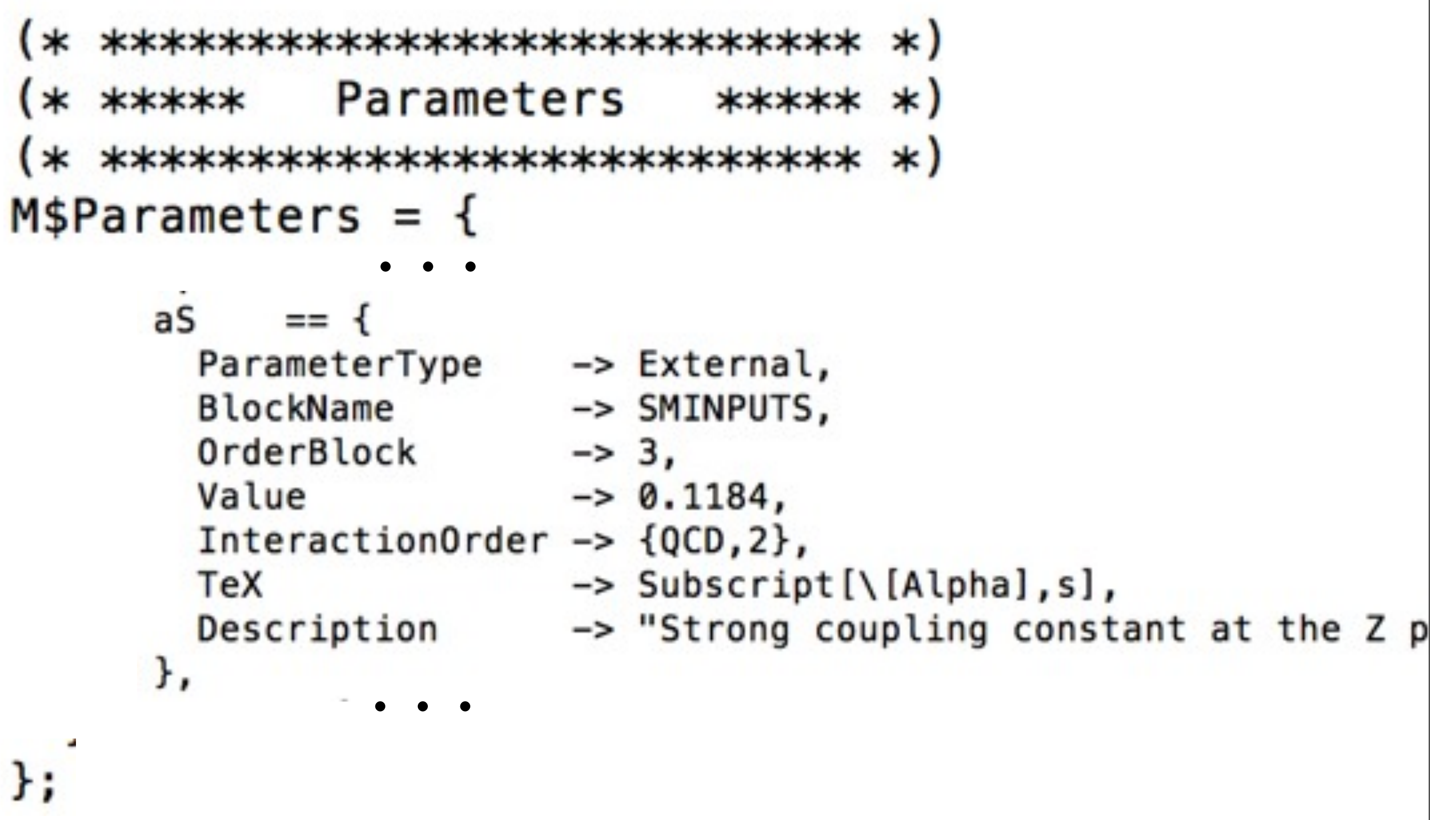
Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Definitions of particles



```
(* ************************** *)
(* **** Particle classes **** *)
(* ************************** *)
M$ClassesDescription = {
                    . . .
   V[4] == {
     ClassName        -> G,
     SelfConjugate    -> True,
     Indices          -> {Index[Gluon]},
     Mass             -> 0,
     Width            -> 0,
     ParticleName     -> "g",
     PDG              -> 21,
     PropagatorLabel  -> "G",
     PropagatorType   -> C,
     PropagatorArrow  -> None,
     FullName         -> "G"
   },
                    . . .
 };
```

- Definitions of parameters

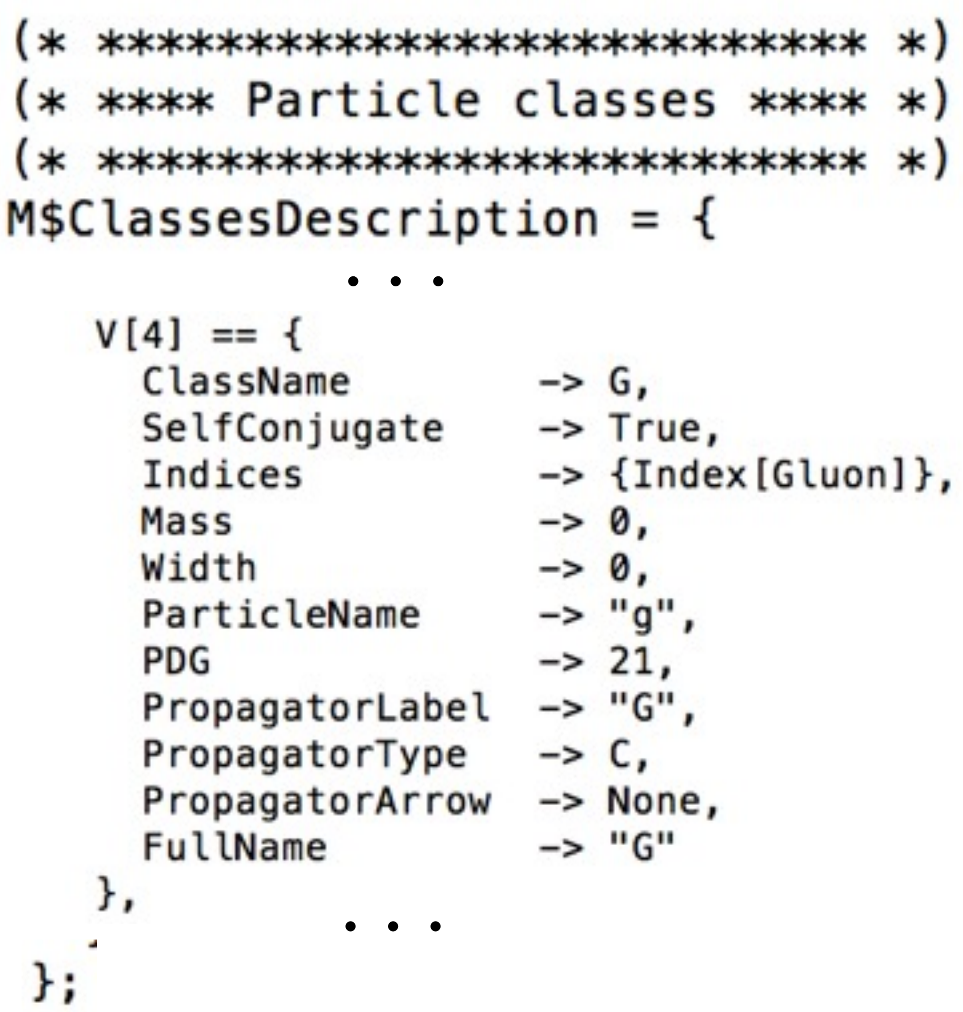


```
(* ************************** *)
(* *****    Parameters   ***** *)
(* ************************** *)
M$Parameters = {
                    . . .
      aS     == {
        ParameterType    -> External,
        BlockName        -> SMINPUTS,
        OrderBlock       -> 3,
        Value            -> 0.1184,
        InteractionOrder -> {QCD,2},
        TeX              -> Subscript[\[Alpha],s],
        Description      -> "Strong coupling constant at the Z p
      },
                    . . .
};
```

FEYNRULES: INPUT

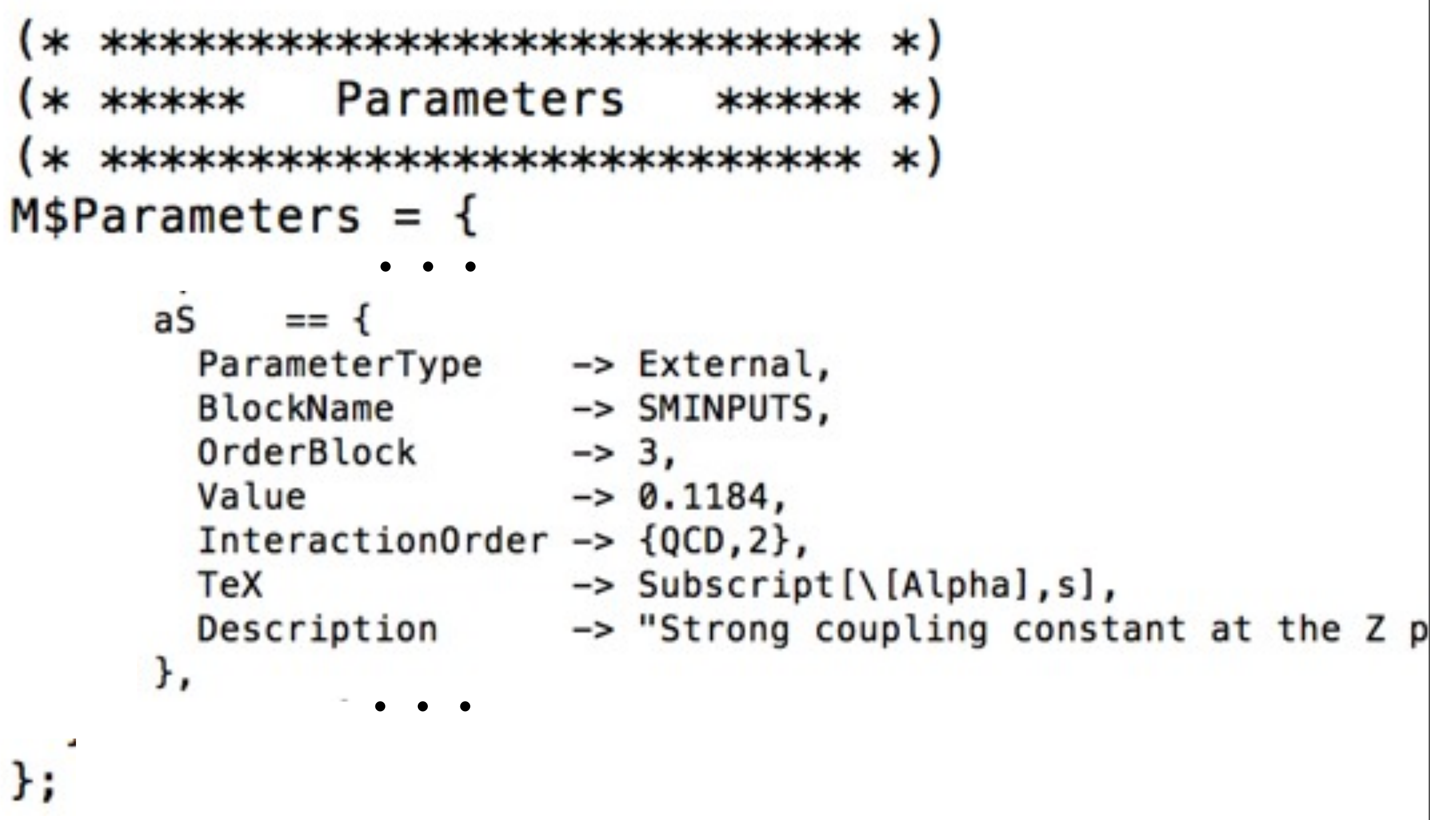
Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Definitions of particles



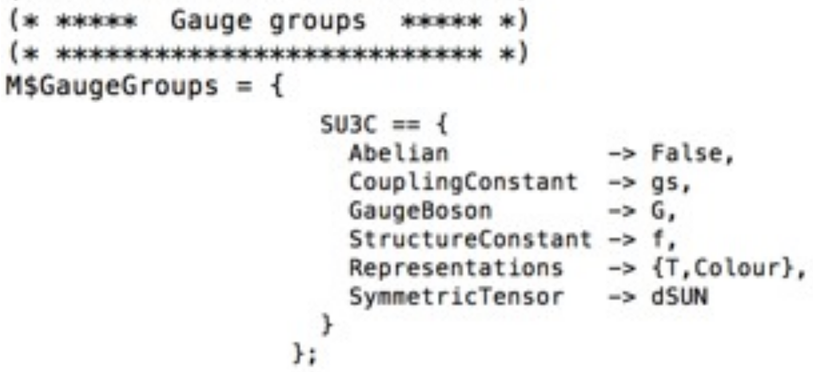
```
(* ************************** *)
(* **** Particle classes **** *)
(* ************************** *)
M$ClassesDescription = {
                ...
   V[4] == {
     ClassName        -> G,
     SelfConjugate    -> True,
     Indices          -> {Index[Gluon]},
     Mass             -> 0,
     Width            -> 0,
     ParticleName     -> "g",
     PDG              -> 21,
     PropagatorLabel  -> "G",
     PropagatorType   -> C,
     PropagatorArrow  -> None,
     FullName         -> "G"
   },
                ...
 };
```

- Definitions of parameters



```
(* ************************** *)
(* *****   Parameters   ***** *)
(* ************************** *)
M$Parameters = {
                ...
     aS     == {
       ParameterType    -> External,
       BlockName        -> SMINPUTS,
       OrderBlock       -> 3,
       Value            -> 0.1184,
       InteractionOrder -> {QCD,2},
       TeX              -> Subscript[\[Alpha],s],
       Description      -> "Strong coupling constant at the Z p
     },
                ...
};
```

- Definitions of gauge groups

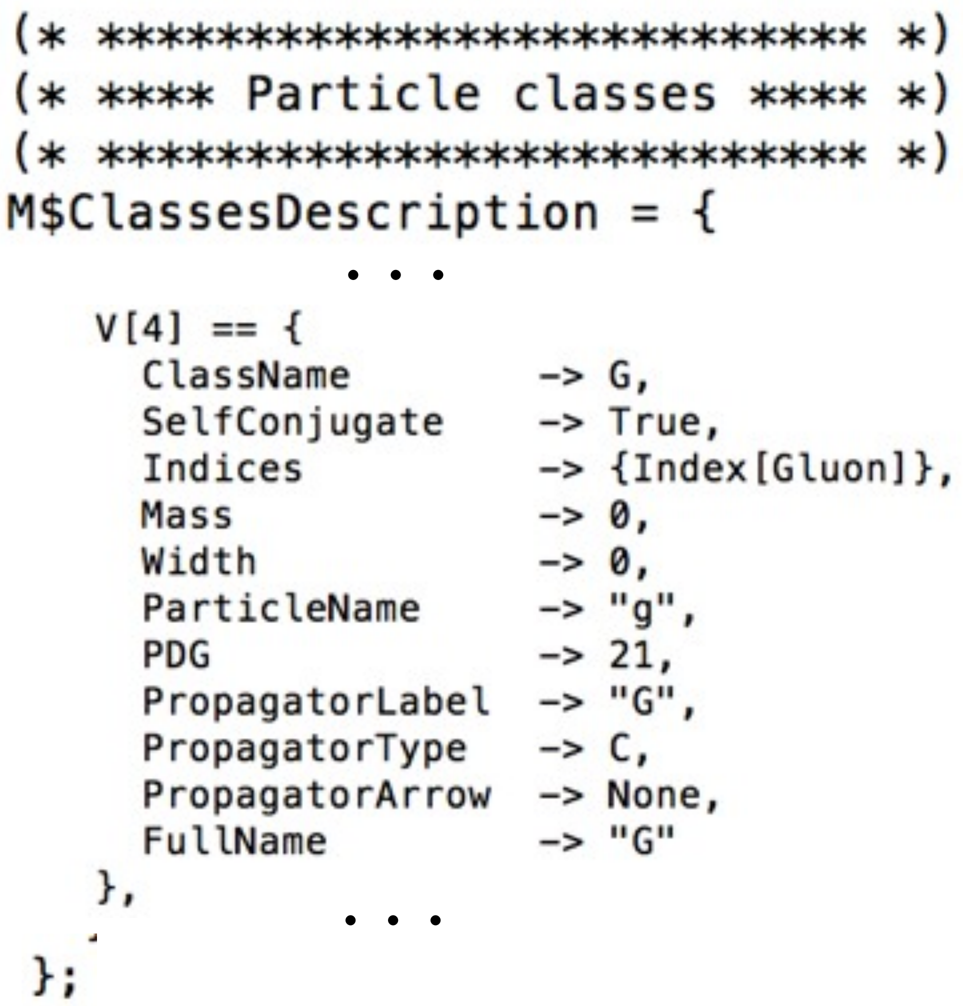


```
(* ************************** *)
(* *****  Gauge groups  ***** *)
(* ************************** *)
M$GaugeGroups = {

                 SU3C == {
                   Abelian           -> False,
                   CouplingConstant  -> gs,
                   GaugeBoson        -> G,
                   StructureConstant -> f,
                   Representations   -> {T,Colour},
                   SymmetricTensor   -> dSUN
                 }
               };
```

FEYNRULES: INPUT

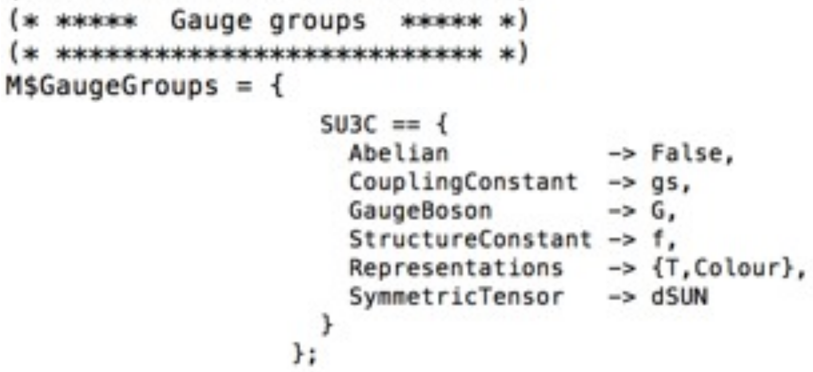
Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Definitions of particles



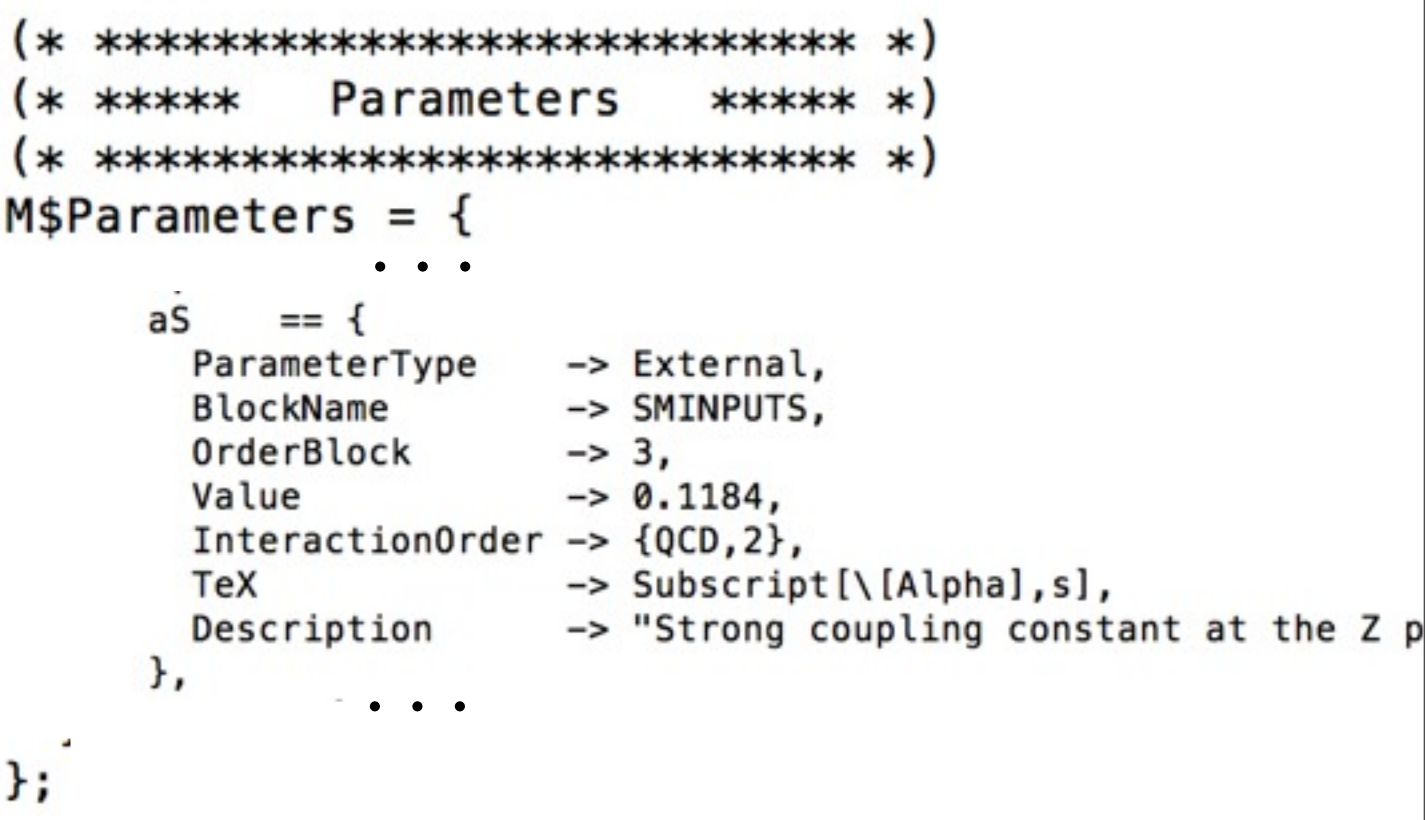
```
(* ************************* *)
(* **** Particle classes **** *)
(* ************************* *)
M$ClassesDescription = {
                ...

   V[4] == {
     ClassName        -> G,
     SelfConjugate    -> True,
     Indices          -> {Index[Gluon]},
     Mass             -> 0,
     Width            -> 0,
     ParticleName     -> "g",
     PDG              -> 21,
     PropagatorLabel  -> "G",
     PropagatorType   -> C,
     PropagatorArrow  -> None,
     FullName         -> "G"
   },
                ...
};
```

- Definitions of gauge groups



```
(* ************************* *)
(* *****  Gauge groups  ***** *)
(* ************************* *)
M$GaugeGroups = {
            SU3C == {
              Abelian           -> False,
              CouplingConstant  -> gs,
              GaugeBoson        -> G,
              StructureConstant -> f,
              Representations   -> {T,Colour},
              SymmetricTensor   -> dSUN
            }
          };
```

- Definitions of parameters



```
(* ************************* *)
(* *****   Parameters   ***** *)
(* ************************* *)
M$Parameters = {
              ...
     aS     == {
        ParameterType    -> External,
        BlockName        -> SMINPUTS,
        OrderBlock       -> 3,
        Value            -> 0.1184,
        InteractionOrder -> {QCD,2},
        TeX              -> Subscript[\[Alpha],s],
        Description      -> "Strong coupling constant at the Z p
     },
              ...
};
```

- The Lagrangian

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + i\bar{q}\gamma^\mu D_\mu q - M_q \bar{q} q$$

L =

-1/4 FS[G,mu,nu,a] FS[G,mu,nu,a]

+ I qbar.Ga[mu].DC[q,mu]

- MQ qbar.q

FEYNRULES: DERIVATION

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Above information can be incorporated in .fr files and load the file via

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

- Extracting the Feynman rules

FeynmanRules[L]

- Output the model files for various generators

WriteCHOutput[L] ⟶ CalcHep

WriteFeynArtsOutput[L] ⟶ FeynArts

WriteSHOutput[L] ⟶ Sherpa

WriteWOOutput[L] ⟶ Whizard

WriteUFO[L] ⟵ { MadGraph5_aMC@NLO, Sherpa, GoSam }

FEYNRULES: DERIVATION

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Above information can be incorporated in .fr files and load the file via

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

- Extracting the Feynman rules

```
FeynmanRules[ L ]
```

- Output the model files for various generators

WriteCHOutput[L] → CalcHep

WriteFeynArtsOutput[L] → FeynArts

WriteSHOutput[L] → Sherpa

WriteWOOutput[L] → Whizard

WriteUFO[L] **NEW Standard !** ← { MadGraph5_aMC@NLO, Sherpa, GoSam }

WHY IS THE UFO NOW A STANDARD ?

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

Slide by B. Fuks

- ✦ Color structures: not supported in full generality by Monte Carlo generators
  - ✤ The treatment of the color information is hard-coded
  - ✤ The interfaces to a specific tool discard all non-supported vertices
  - ✤ Representations usually handled: 1, 3, 8 (limited in CALCHEP), sometimes 6

- ✦ Lorentz structures and spins not supported in full generality by Monte Carlo programs
  - ✤ The treatment of the Lorentz structures of the different vertices is hard-coded
  - ✤ The possible spins for the particles are restricted
  - ✤ The interfaces discard all non-supported vertices
  - ✤ Spin representations usually handled: 0, 1/2, 1; sometimes 3/2, 2
  - ✤ Lorentz structures usually handled: MSSM-like; sometimes any

Each interface dedicated to a given tool is specific

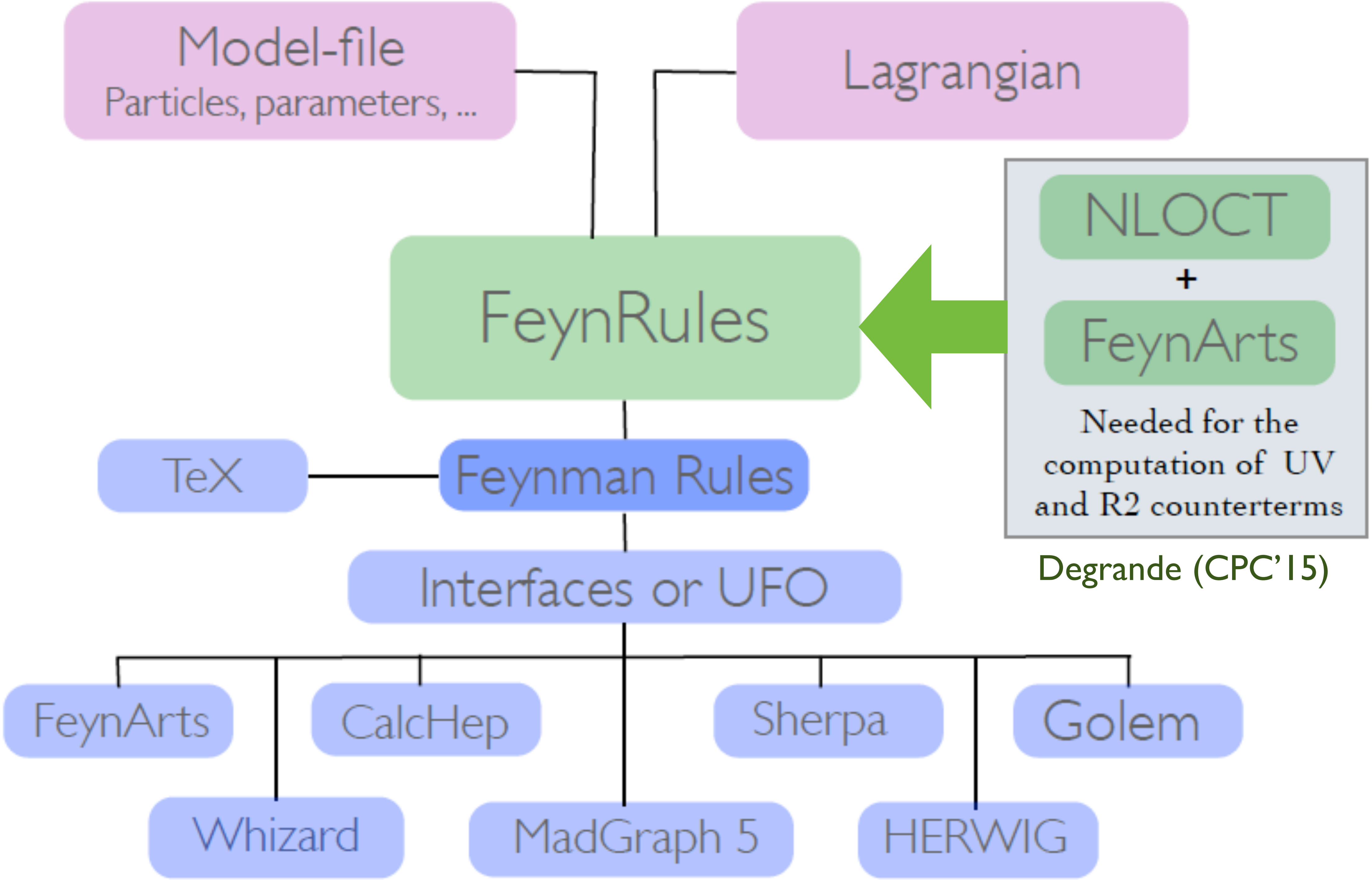
- ★ Removal of vertices not compliant with the tool
- ★ Translation to a specific format and programming language

⇒ **not efficient**

⇒ **better: one translation and the tools parse it**

FEYNRULES: STRUCTURE

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14); Degrande (CPC'15)



Model-file
Particles, parameters, ...

Lagrangian

FeynRules

NLOCT
+
FeynArts

Needed for the computation of UV and R2 counterterms

Degrande (CPC'15)

TeX

Feynman Rules

Interfaces or UFO

FeynArts

CalcHep

Sherpa

Golem

Whizard

MadGraph 5

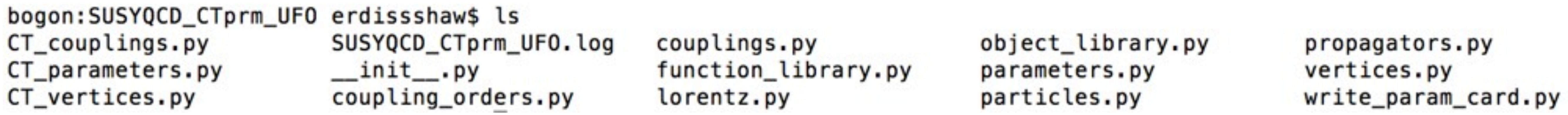
HERWIG

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

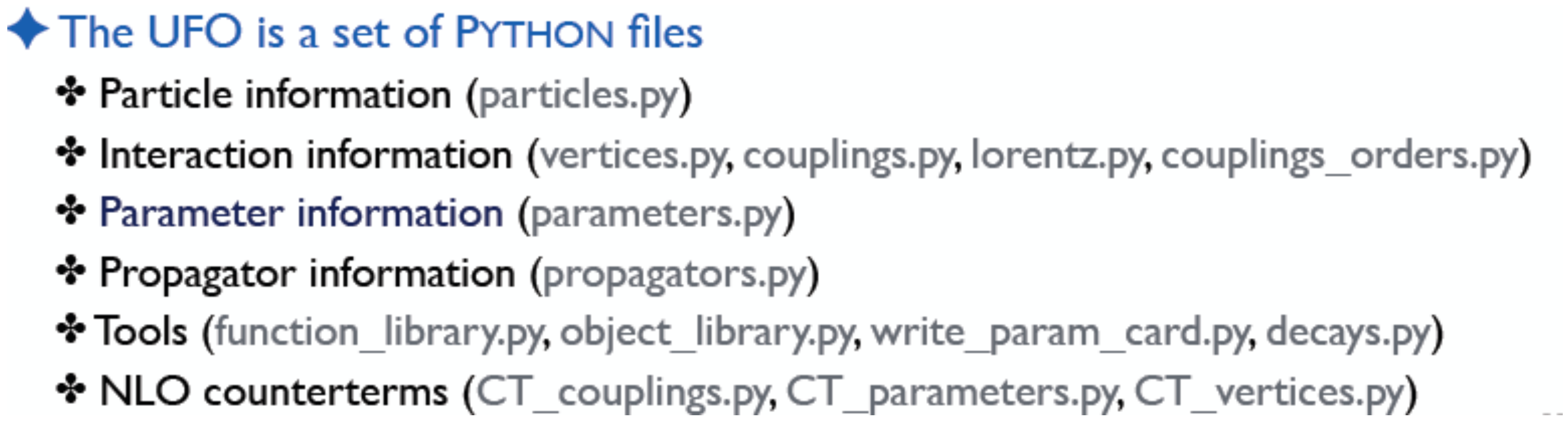
For example: SUSY QCD



```
bogon:SUSYQCD_CTprm_UFO erdissshaw$ ls
CT_couplings.py          SUSYQCD_CTprm_UFO.log    couplings.py             object_library.py        propagators.py
CT_parameters.py         __init__.py              function_library.py      parameters.py            vertices.py
CT_vertices.py           coupling_orders.py       lorentz.py               particles.py             write_param_card.py
```

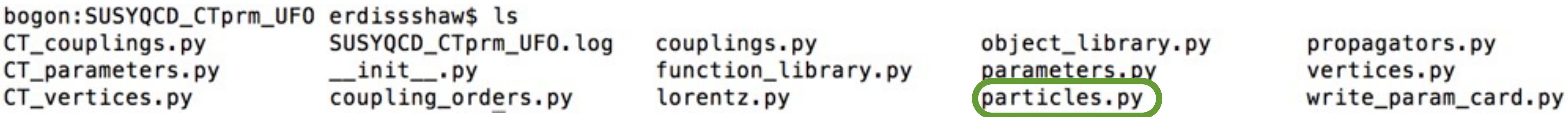
UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)



- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD

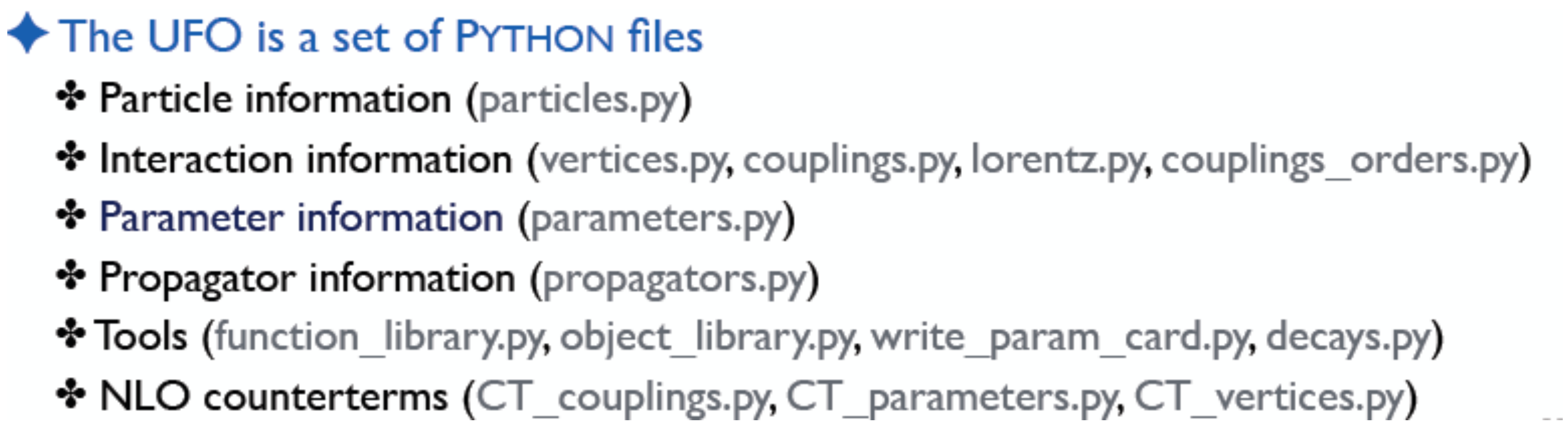


```
bogon:SUSYQCD_CTprm_UFO erdissshaw$ ls
CT_couplings.py         SUSYQCD_CTprm_UFO.log   couplings.py            object_library.py       propagators.py
CT_parameters.py        __init__.py             function_library.py     parameters.py           vertices.py
CT_vertices.py          coupling_orders.py      lorentz.py              particles.py            write_param_card.py
```

Particles

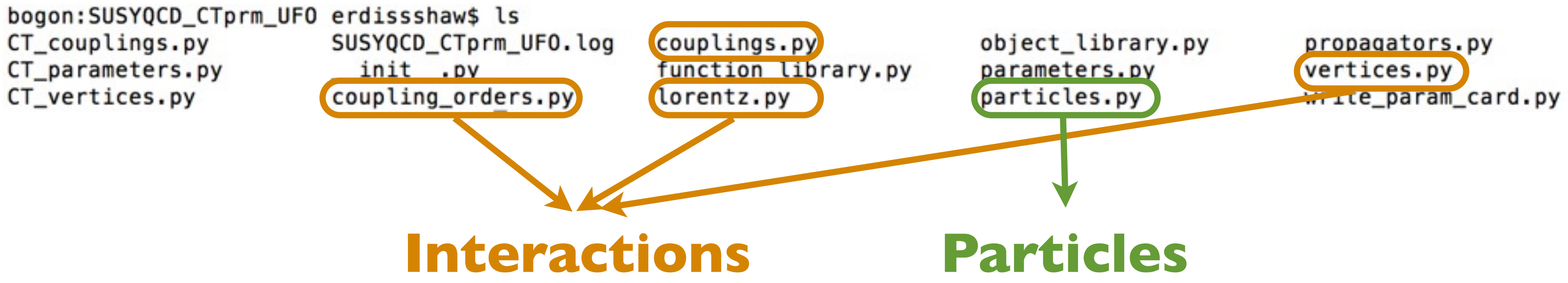
UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)



- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD



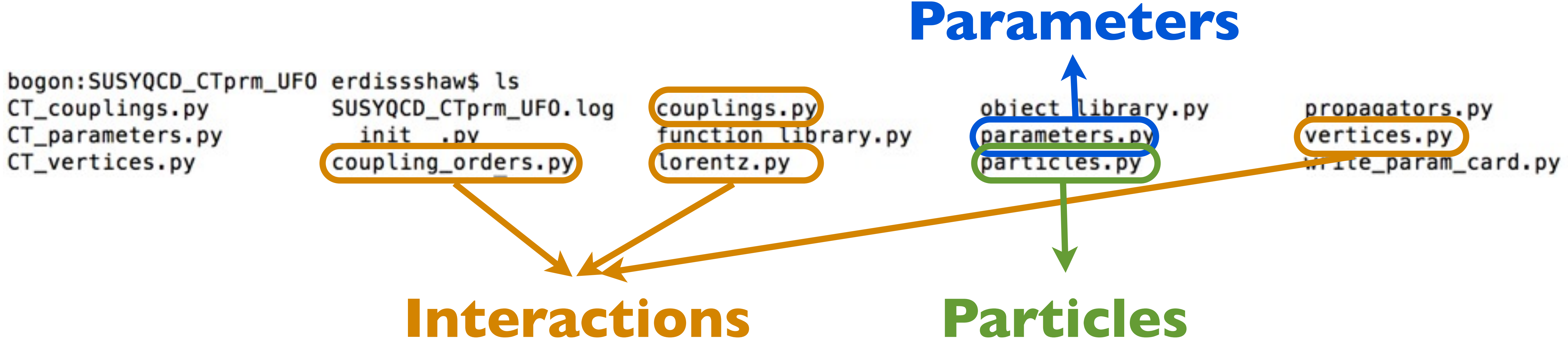
```
bogon:SUSYQCD_CTprm_UFO erdissshaw$ ls
CT_couplings.py         SUSYQCD_CTprm_UFO.log   couplings.py            object_library.py       propagators.py
CT_parameters.py        __init__.py             function_library.py     parameters.py           vertices.py
CT_vertices.py          coupling_orders.py      lorentz.py              particles.py            write_param_card.py
```

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD



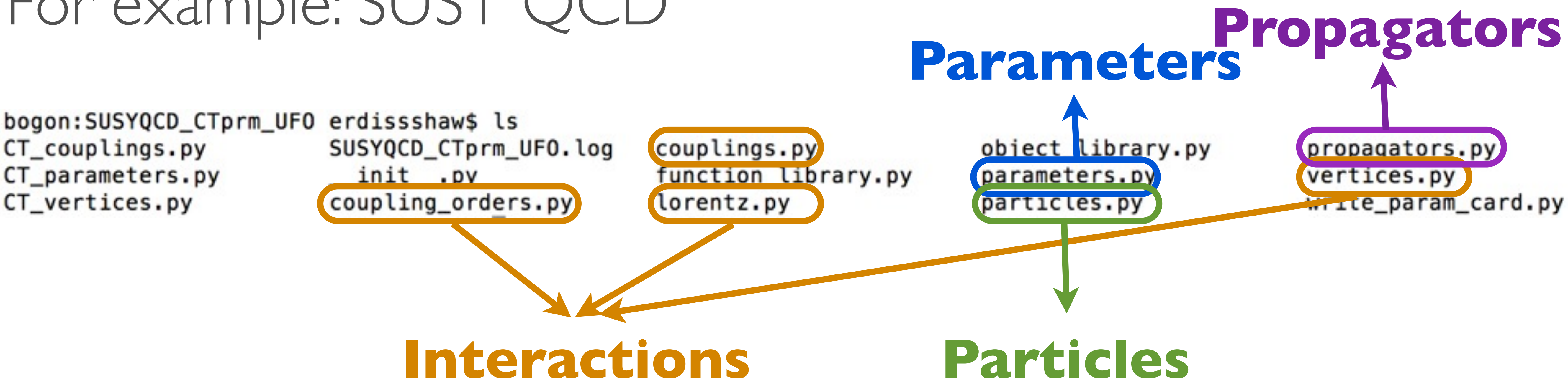
```
bogon:SUSYQCD_CTprm_UFO erdissshaw$ ls
CT_couplings.py         SUSYQCD_CTprm_UFO.log   couplings.py            object_library.py       propagators.py
CT_parameters.py        __init__.py             function_library.py     parameters.py           vertices.py
CT_vertices.py          coupling_orders.py      lorentz.py              particles.py            write_param_card.py
```

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD



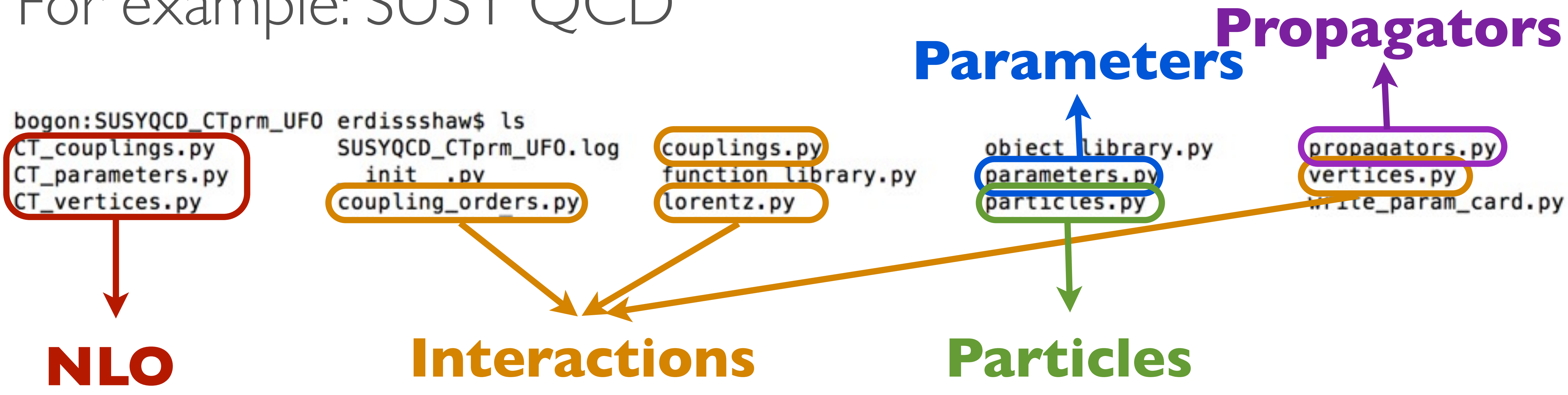
```
bogon:SUSYQCD_CTprm_UFO erdissshaw$ ls
CT_couplings.py         SUSYQCD_CTprm_UFO.log   couplings.py            object_library.py       propagators.py
CT_parameters.py        __init__.py             function_library.py     parameters.py           vertices.py
CT_vertices.py          coupling_orders.py      lorentz.py              particles.py            write_param_card.py
```

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD



```
bogon:SUSYQCD_CTprm_UFO erdissshaw$ ls
CT_couplings.py         SUSYQCD_CTprm_UFO.log   couplings.py            object_library.py       propagators.py
CT_parameters.py        __init__.py             function_library.py     parameters.py           vertices.py
CT_vertices.py          coupling_orders.py      lorentz.py              particles.py            write_param_card.py
```

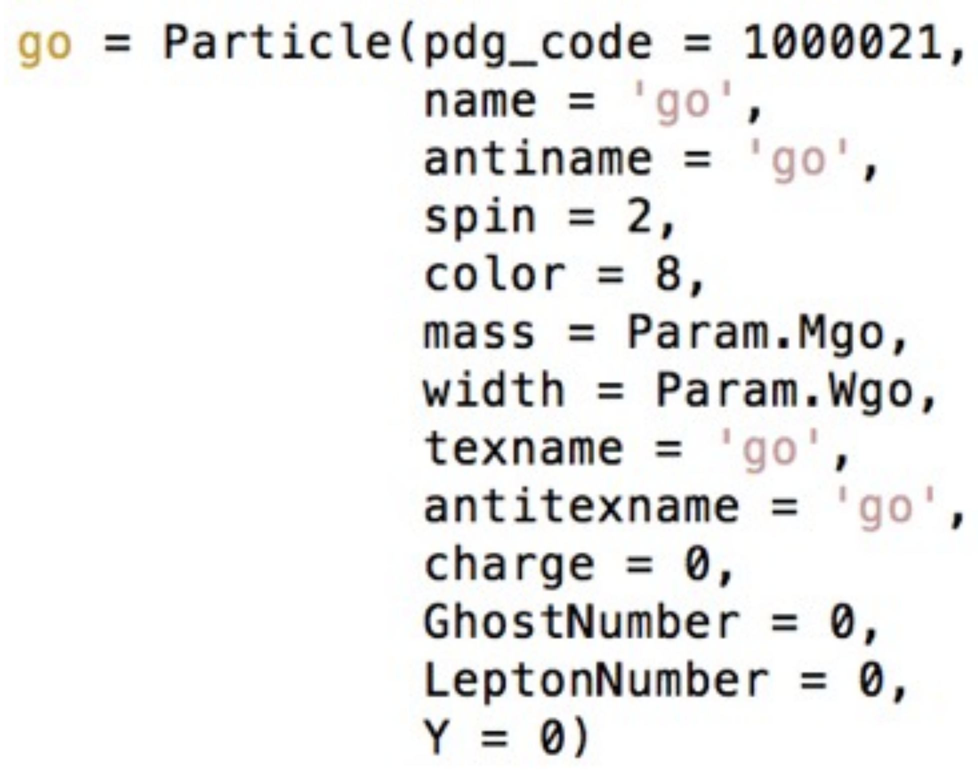
UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- **Particles are in** particles.py
  - Instances of the particle class
  - spin, color, mass, width, PDG etc

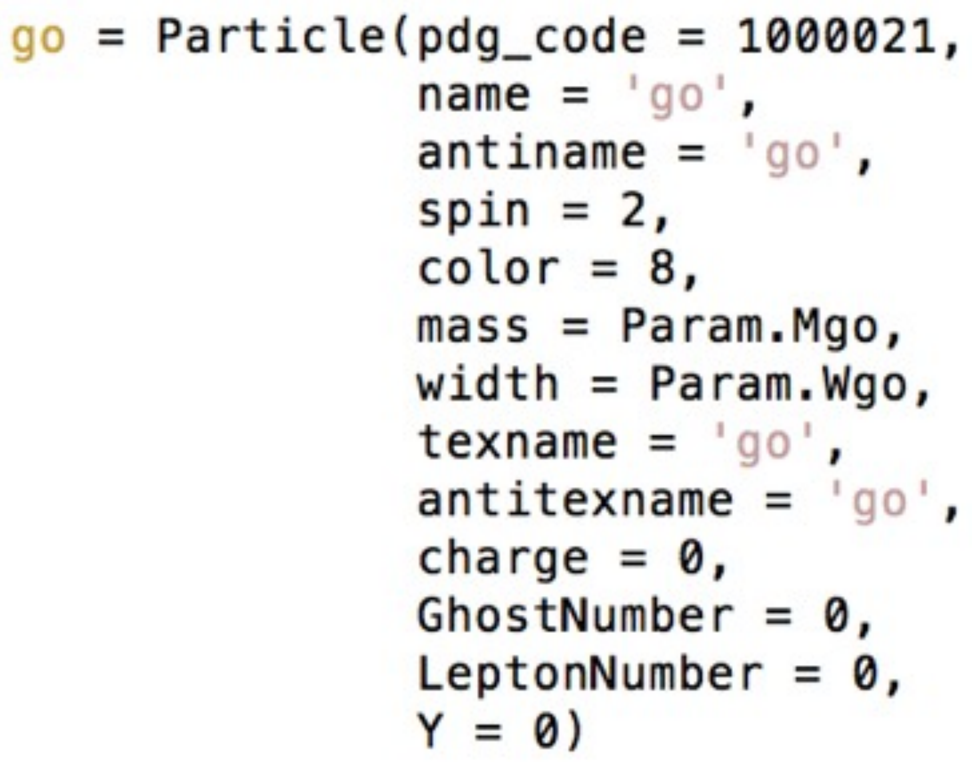


```
go = Particle(pdg_code = 1000021,
              name = 'go',
              antiname = 'go',
              spin = 2,
              color = 8,
              mass = Param.Mgo,
              width = Param.Wgo,
              texname = 'go',
              antitexname = 'go',
              charge = 0,
              GhostNumber = 0,
              LeptonNumber = 0,
              Y = 0)
```

UFO

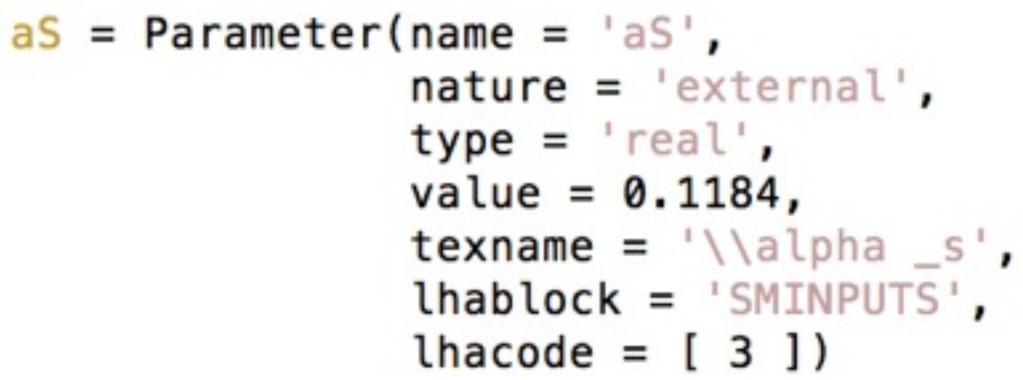
Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- **Particles are in** particles.py
  - Instances of the particle class
  - spin, color, mass, width, PDG etc

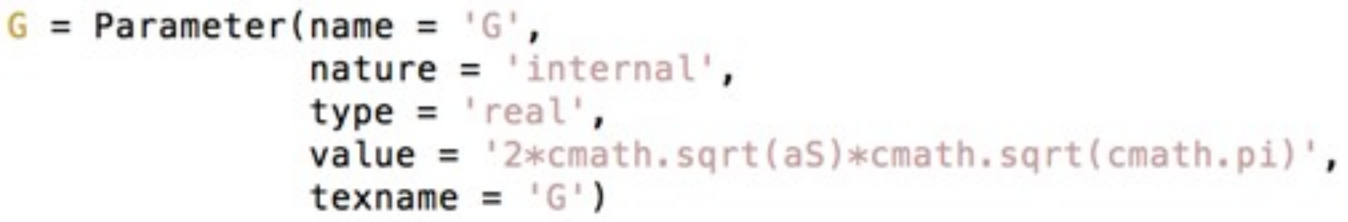


```
go = Particle(pdg_code = 1000021,
              name = 'go',
              antiname = 'go',
              spin = 2,
              color = 8,
              mass = Param.Mgo,
              width = Param.Wgo,
              texname = 'go',
              antitexname = 'go',
              charge = 0,
              GhostNumber = 0,
              LeptonNumber = 0,
              Y = 0)
```

- **Parameters are in** parameters.py
  - External parameters are in LHA-like
  - Python-compliant formula for int. para



```
aS = Parameter(name = 'aS',
               nature = 'external',
               type = 'real',
               value = 0.1184,
               texname = '\\alpha _s',
               lhablock = 'SMINPUTS',
               lhacode = [ 3 ])
```



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

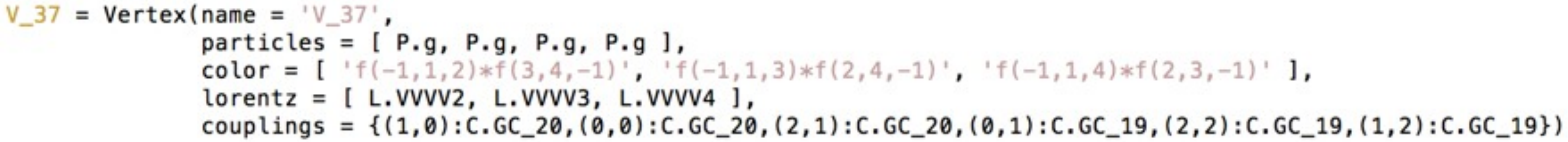
UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- **Interactions are in** vertices.py, couplings.py, lorentz.py, coupling_orders,py
  - Vertices are decomposed in a spin x color basis, coupling being coordinates
  - Example: the quartic gluon vertex can be written as

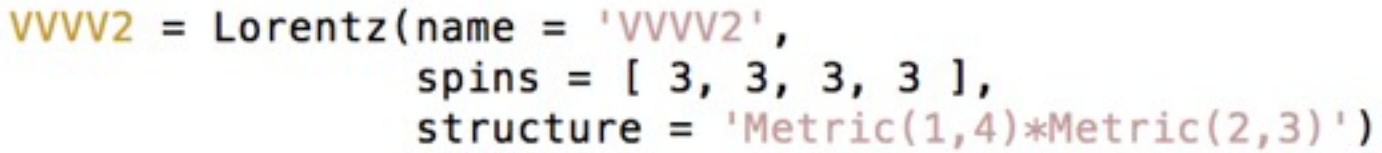
$$\begin{aligned} & ig_s^2\, f^{a_1a_2b} f^{ba_3a_4}\, (\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4}) \\ & + ig_s^2\, f^{a_1a_3b} f^{ba_2a_4}\, (\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}) \\ & + ig_s^2\, f^{a_1a_4b} f^{ba_2a_3}\, (\eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}) \end{aligned} \quad \Rightarrow \quad \begin{aligned} & \left(f^{a_1a_2b} f^{ba_3a_4},\ f^{a_1a_3b} f^{ba_2a_4},\ f^{a_1a_4b} f^{ba_2a_3}\right) \\ & \times \begin{pmatrix} ig_s^2 & 0 & 0 \\ 0 & ig_s^2 & 0 \\ 0 & 0 & ig_s^2 \end{pmatrix} \begin{pmatrix} \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} \\ \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \\ \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \end{pmatrix} \end{aligned}$$

- vertices.py: define all Feynman rules for vertices in the model



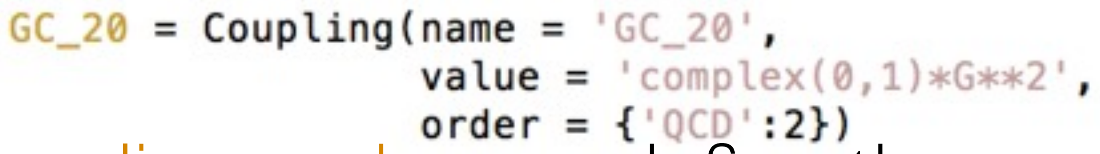
```
V_37 = Vertex(name = 'V_37',
              particles = [ P.g, P.g, P.g, P.g ],
              color = [ 'f(-1,1,2)*f(3,4,-1)', 'f(-1,1,3)*f(2,4,-1)', 'f(-1,1,4)*f(2,3,-1)' ],
              lorentz = [ L.VVVV2, L.VVVV3, L.VVVV4 ],
              couplings = {(1,0):C.GC_20,(0,0):C.GC_20,(2,1):C.GC_20,(0,1):C.GC_19,(2,2):C.GC_19,(1,2):C.GC_19})
```

- lorentz.py: define the Lorentz structure in the model



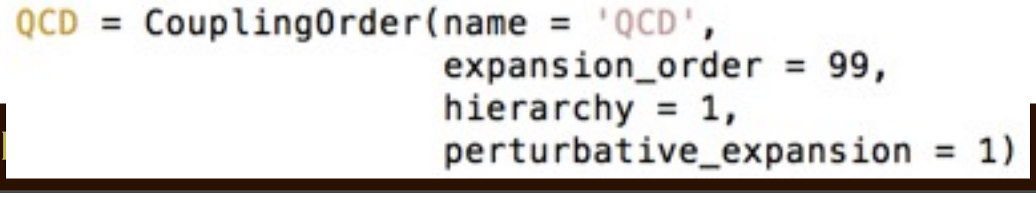
```
VVVV2 = Lorentz(name = 'VVVV2',
                spins = [ 3, 3, 3, 3 ],
                structure = 'Metric(1,4)*Metric(2,3)')
```

- couplings.py: define the coupling constant in the model



```
GC_20 = Coupling(name = 'GC_20',
                 value = 'complex(0,1)*G**2',
                 order = {'QCD':2})
```

- coupling_orders.py: define the coupling orders in the model



```
QCD = CouplingOrder(name = 'QCD',
                    expansion_order = 99,
                    hierarchy = 1,
                    perturbative_expansion = 1)
```

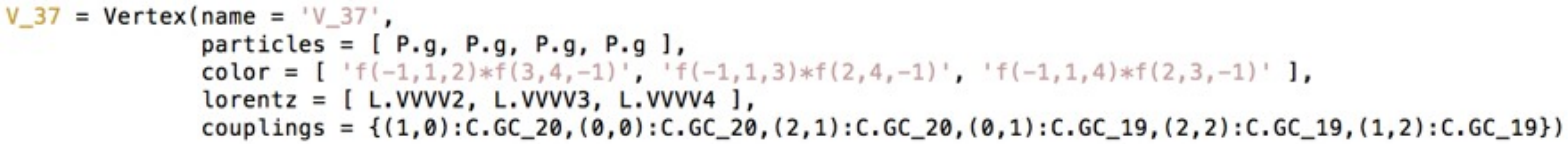
UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- **Interactions are in** vertices.py, couplings.py, lorentz.py, coupling_orders,py
  - Vertices are decomposed in a spin x color basis, coupling being coordinates
  - Example: the quartic gluon vertex can be written as

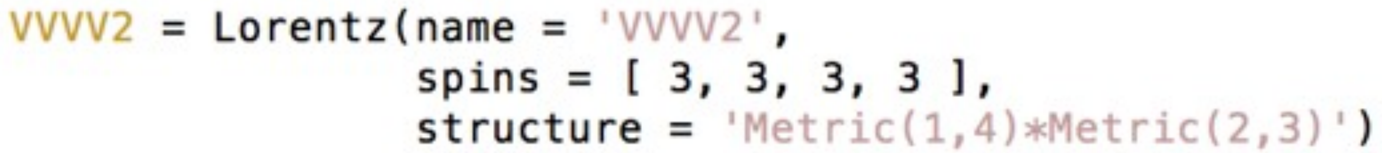
$$\begin{aligned} &ig_s^2\, f^{a_1a_2b} f^{ba_3a_4}\,(\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4}) \\ &\quad + ig_s^2\, f^{a_1a_3b} f^{ba_2a_4}\,(\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}) \\ &\quad + ig_s^2\, f^{a_1a_4b} f^{ba_2a_3}\,(\eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}) \end{aligned} \quad \Rightarrow \quad \begin{aligned} &\left(f^{a_1a_2b} f^{ba_3a_4},\ f^{a_1a_3b} f^{ba_2a_4},\ f^{a_1a_4b} f^{ba_2a_3}\right) \\ &\times \begin{pmatrix} ig_s^2 & 0 & 0 \\ 0 & ig_s^2 & 0 \\ 0 & 0 & ig_s^2 \end{pmatrix} \begin{pmatrix} \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} \\ \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \\ \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \end{pmatrix} \end{aligned}$$

- vertices.py: define all Feynman rules for vertices in the model



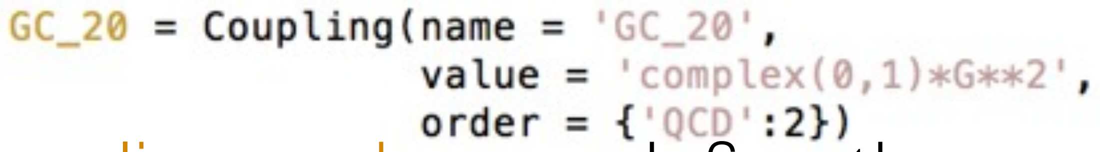
```
V_37 = Vertex(name = 'V_37',
              particles = [ P.g, P.g, P.g, P.g ],
              color = [ 'f(-1,1,2)*f(3,4,-1)', 'f(-1,1,3)*f(2,4,-1)', 'f(-1,1,4)*f(2,3,-1)' ],
              lorentz = [ L.VVVV2, L.VVVV3, L.VVVV4 ],
              couplings = {(1,0):C.GC_20,(0,0):C.GC_20,(2,1):C.GC_20,(0,1):C.GC_19,(2,2):C.GC_19,(1,2):C.GC_19})
```

- lorentz.py: define the Lorentz structure in the model



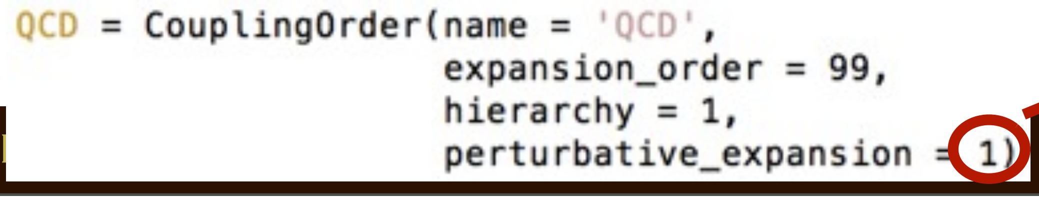
```
VVVV2 = Lorentz(name = 'VVVV2',
                spins = [ 3, 3, 3, 3 ],
                structure = 'Metric(1,4)*Metric(2,3)')
```

- couplings.py: define the coupling constant in the model



```
GC_20 = Coupling(name = 'GC_20',
                 value = 'complex(0,1)*G**2',
                 order = {'QCD':2})
```

- coupling_orders.py: define the coupling orders in the model



```
QCD = CouplingOrder(name = 'QCD',
                    expansion_order = 99,
                    hierarchy = 1,
                    perturbative_expansion = 1)
```

Make sure > 0 for NLO QCD

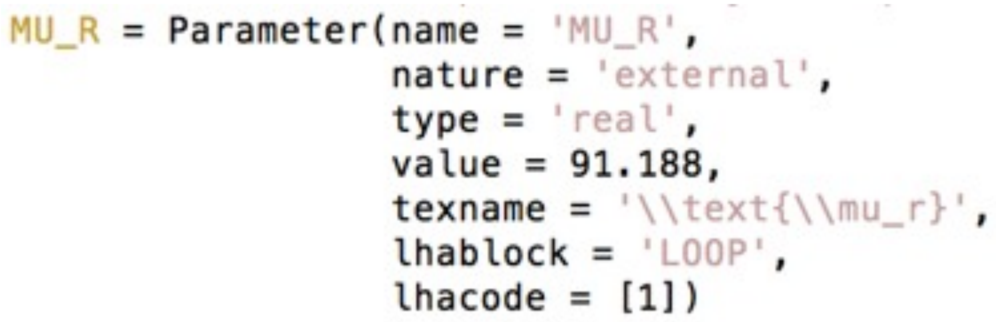
UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

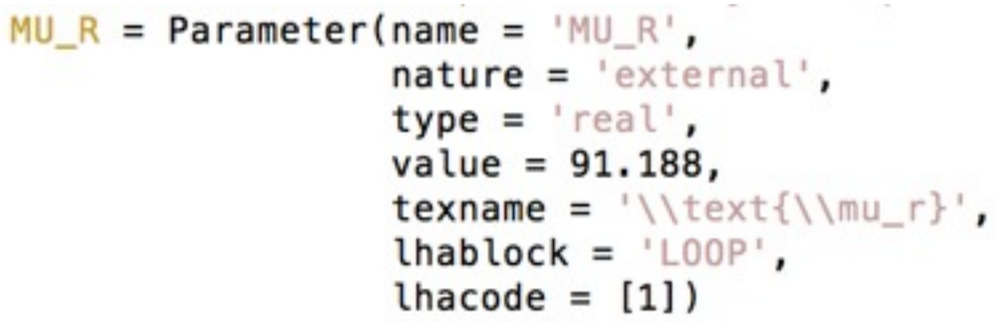


```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

UFO@NLO

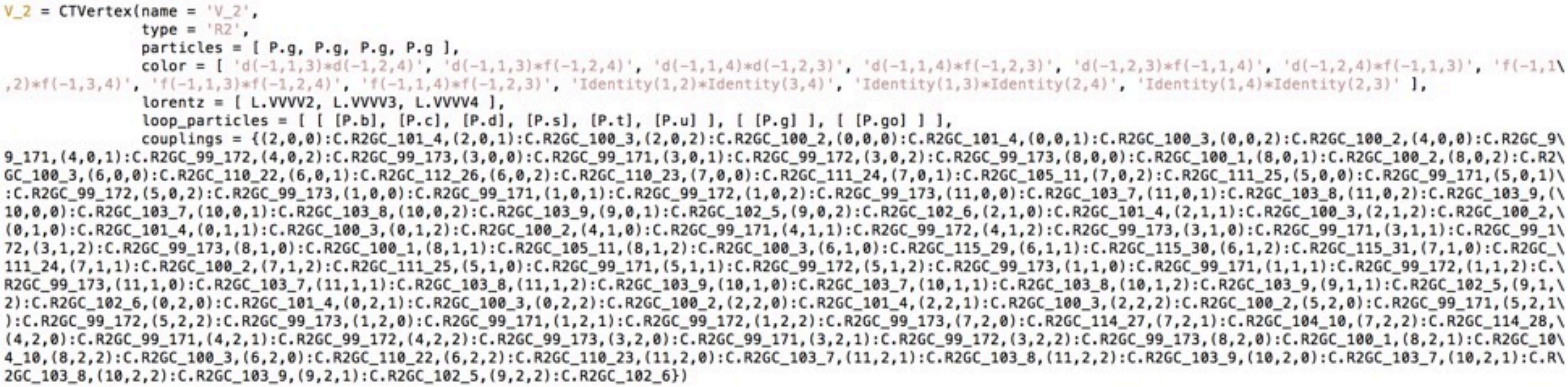
Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py



```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

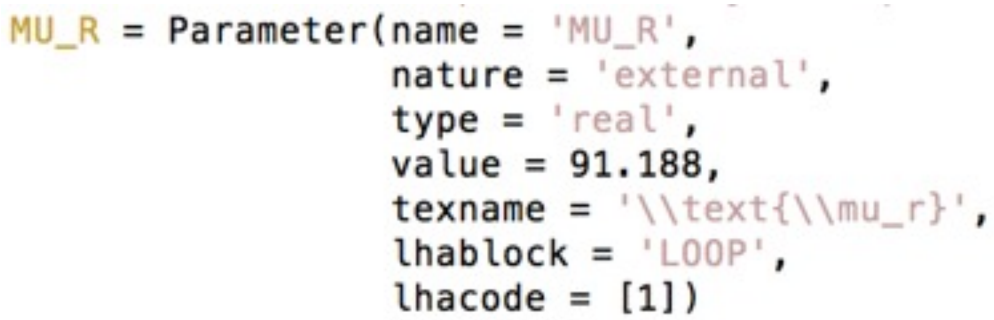


```
V_2 = CTVertex(name = 'V_2',
               type = 'R2',
               particles = [ P.g, P.g, P.g, P.g ],
               color = [ 'd(-1,1,3)*d(-1,2,4)', 'd(-1,1,3)*f(-1,2,4)', 'd(-1,1,4)*d(-1,2,3)', 'd(-1,1,4)*f(-1,2,3)', 'd(-1,2,3)*f(-1,1,4)', 'd(-1,2,4)*f(-1,1,3)', 'f(-1,1\
,2)*f(-1,3,4)', 'f(-1,1,3)*f(-1,2,4)', 'f(-1,1,4)*f(-1,2,3)', 'Identity(1,2)*Identity(3,4)', 'Identity(1,3)*Identity(2,4)', 'Identity(1,4)*Identity(2,3)' ],
               lorentz = [ L.VVVV2, L.VVVV3, L.VVVV4 ],
               loop_particles = [ [ [P.b], [P.c], [P.d], [P.s], [P.t], [P.u] ], [ [P.g] ], [ [P.go] ] ],
               couplings = {(2,0,0):C.R2GC_101_4,(2,0,1):C.R2GC_100_3,(2,0,2):C.R2GC_100_2,(0,0,0):C.R2GC_101_4,(0,0,1):C.R2GC_100_3,(0,0,2):C.R2GC_100_2,(4,0,0):C.R2GC_9\
9_171,(4,0,1):C.R2GC_99_172,(4,0,2):C.R2GC_99_173,(3,0,0):C.R2GC_99_171,(3,0,1):C.R2GC_99_172,(3,0,2):C.R2GC_99_173,(8,0,0):C.R2GC_100_1,(8,0,1):C.R2GC_100_2,(8,0,2):C.R2\
GC_100_3,(6,0,0):C.R2GC_110_22,(6,0,1):C.R2GC_112_26,(6,0,2):C.R2GC_110_23,(7,0,0):C.R2GC_111_24,(7,0,1):C.R2GC_105_11,(7,0,2):C.R2GC_111_25,(5,0,0):C.R2GC_99_171,(5,0,1)\
:C.R2GC_99_172,(5,0,2):C.R2GC_99_173,(1,0,0):C.R2GC_99_171,(1,0,1):C.R2GC_99_172,(1,0,2):C.R2GC_99_173,(11,0,0):C.R2GC_103_7,(11,0,1):C.R2GC_103_8,(11,0,2):C.R2GC_103_9,(\
10,0,0):C.R2GC_103_7,(10,0,1):C.R2GC_103_8,(10,0,2):C.R2GC_103_9,(9,0,1):C.R2GC_102_5,(9,0,2):C.R2GC_102_6,(2,1,0):C.R2GC_101_4,(2,1,1):C.R2GC_100_3,(2,1,2):C.R2GC_100_2,\
(0,1,0):C.R2GC_101_4,(0,1,1):C.R2GC_100_3,(0,1,2):C.R2GC_100_2,(4,1,0):C.R2GC_99_171,(4,1,1):C.R2GC_99_172,(4,1,2):C.R2GC_99_173,(3,1,0):C.R2GC_99_171,(3,1,1):C.R2GC_99_1\
72,(3,1,2):C.R2GC_99_173,(8,1,0):C.R2GC_100_1,(8,1,1):C.R2GC_105_11,(8,1,2):C.R2GC_100_3,(6,1,0):C.R2GC_115_29,(6,1,1):C.R2GC_115_30,(6,1,2):C.R2GC_115_31,(7,1,0):C.R2GC_\
111_24,(7,1,1):C.R2GC_100_2,(7,1,2):C.R2GC_111_25,(5,1,0):C.R2GC_99_171,(5,1,1):C.R2GC_99_172,(5,1,2):C.R2GC_99_173,(1,1,0):C.R2GC_99_171,(1,1,1):C.R2GC_99_172,(1,1,2):C.\
R2GC_99_173,(11,1,0):C.R2GC_103_7,(11,1,1):C.R2GC_103_8,(11,1,2):C.R2GC_103_9,(10,1,0):C.R2GC_103_7,(10,1,1):C.R2GC_103_8,(10,1,2):C.R2GC_103_9,(9,1,1):C.R2GC_102_5,(9,1,\
2):C.R2GC_102_6,(0,2,0):C.R2GC_101_4,(0,2,1):C.R2GC_100_3,(0,2,2):C.R2GC_100_2,(2,2,0):C.R2GC_101_4,(2,2,1):C.R2GC_100_3,(2,2,2):C.R2GC_100_2,(5,2,0):C.R2GC_99_171,(5,2,1\
):C.R2GC_99_172,(5,2,2):C.R2GC_99_173,(1,2,0):C.R2GC_99_171,(1,2,1):C.R2GC_99_172,(1,2,2):C.R2GC_99_173,(7,2,0):C.R2GC_114_27,(7,2,1):C.R2GC_104_10,(7,2,2):C.R2GC_114_28,\
(4,2,0):C.R2GC_99_171,(4,2,1):C.R2GC_99_172,(4,2,2):C.R2GC_99_173,(3,2,0):C.R2GC_99_171,(3,2,1):C.R2GC_99_172,(3,2,2):C.R2GC_99_173,(8,2,0):C.R2GC_100_1,(8,2,1):C.R2GC_10\
4_10,(8,2,2):C.R2GC_100_3,(6,2,0):C.R2GC_110_22,(6,2,2):C.R2GC_110_23,(11,2,0):C.R2GC_103_7,(11,2,1):C.R2GC_103_8,(11,2,2):C.R2GC_103_9,(10,2,0):C.R2GC_103_7,(10,2,1):C.R\
2GC_103_8,(10,2,2):C.R2GC_103_9,(9,2,1):C.R2GC_102_5,(9,2,2):C.R2GC_102_6})
```

UFO@NLO

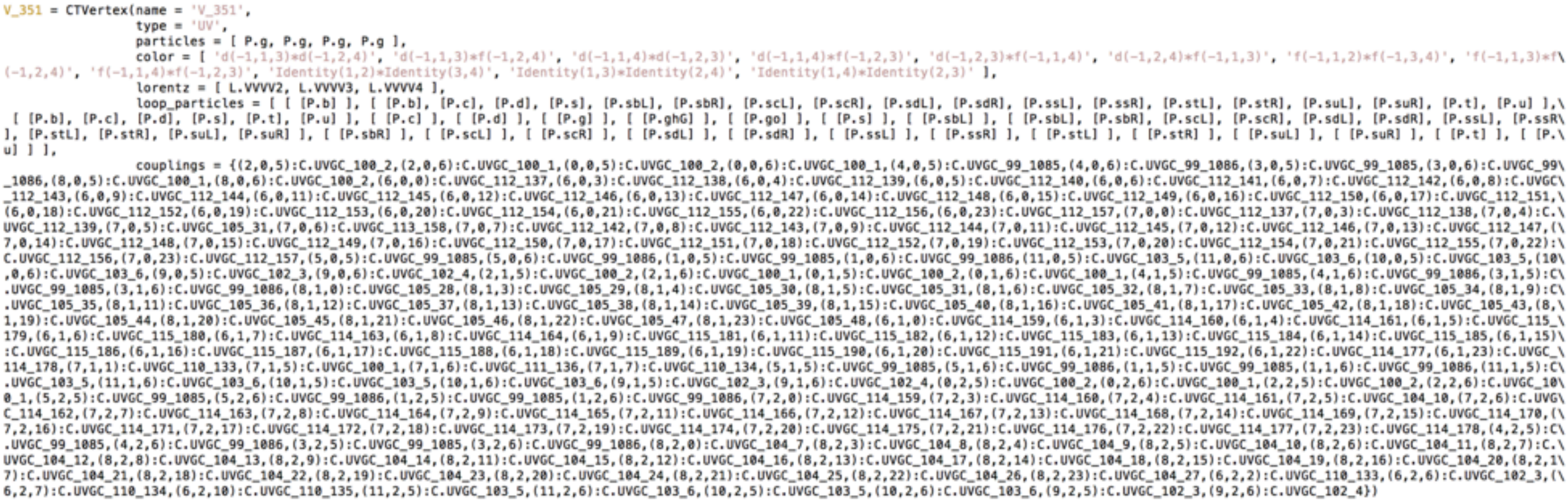
Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py



```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

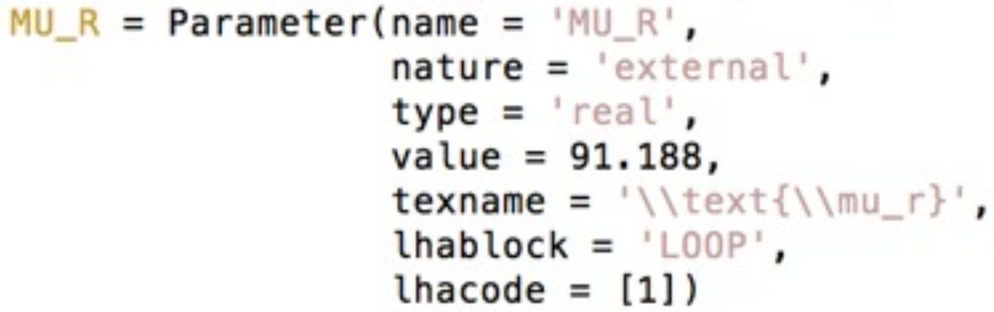


```
V_351 = CTVertex(name = 'V_351',
                 type = 'UV',
                 particles = [ P.g, P.g, P.g, P.g ],
                 color = [ 'd(-1,1,3)*d(-1,2,4)', 'd(-1,1,3)*f(-1,2,4)', 'd(-1,1,4)*d(-1,2,3)', 'd(-1,1,4)*f(-1,2,3)', 'd(-1,2,3)*f(-1,1,4)', 'd(-1,2,4)*f(-1,1,3)', 'f(-1,1,2)*f(-1,3,4)', 'f(-1,1,3)*f\
(-1,2,4)', 'f(-1,1,4)*f(-1,2,3)', 'Identity(1,2)*Identity(3,4)', 'Identity(1,3)*Identity(2,4)', 'Identity(1,4)*Identity(2,3)' ],
                 lorentz = [ L.VVVV2, L.VVVV3, L.VVVV4 ],
                 loop_particles = [ [ [P.b] ], [ [P.b], [P.c], [P.d], [P.s], [P.sbL], [P.sbR], [P.scL], [P.scR], [P.sdL], [P.sdR], [P.ssL], [P.ssR], [P.stL], [P.stR], [P.suL], [P.suR], [P.t], [P.u] ],\
 [ [P.b], [P.c], [P.d], [P.s], [P.t], [P.u] ], [ [P.c] ], [ [P.d] ], [ [P.g] ], [ [P.ghG] ], [ [P.go] ], [ [P.s] ], [ [P.sbL] ], [ [P.sbL], [P.sbR], [P.scL], [P.scR], [P.sdL], [P.sdR], [P.ssL], [P.ssR\
], [P.stL], [P.stR], [P.suL], [P.suR] ], [ [P.sbR] ], [ [P.scL] ], [ [P.scR] ], [ [P.sdL] ], [ [P.sdR] ], [ [P.ssL] ], [ [P.ssR] ], [ [P.stL] ], [ [P.stR] ], [ [P.suL] ], [ [P.suR] ], [ [P.t] ], [ [P.\
u] ] ],
                 couplings = {(2,0,5):C.UVGC_100_2,(2,0,6):C.UVGC_100_1,(0,0,5):C.UVGC_100_2,(0,0,6):C.UVGC_100_1,(4,0,5):C.UVGC_99_1085,(4,0,6):C.UVGC_99_1086,(3,0,5):C.UVGC_99_1085,(3,0,6):C.UVGC_99\
_1086,(8,0,5):C.UVGC_100_1,(8,0,6):C.UVGC_100_2,(6,0,0):C.UVGC_112_137,(6,0,3):C.UVGC_112_138,(6,0,4):C.UVGC_112_139,(6,0,5):C.UVGC_112_140,(6,0,6):C.UVGC_112_141,(6,0,7):C.UVGC_112_142,(6,0,8):C.UVGC\
_112_143,(6,0,9):C.UVGC_112_144,(6,0,11):C.UVGC_112_145,(6,0,12):C.UVGC_112_146,(6,0,13):C.UVGC_112_147,(6,0,14):C.UVGC_112_148,(6,0,15):C.UVGC_112_149,(6,0,16):C.UVGC_112_150,(6,0,17):C.UVGC_112_151,\
(6,0,18):C.UVGC_112_152,(6,0,19):C.UVGC_112_153,(6,0,20):C.UVGC_112_154,(6,0,21):C.UVGC_112_155,(6,0,22):C.UVGC_112_156,(6,0,23):C.UVGC_112_157,(7,0,0):C.UVGC_112_137,(7,0,3):C.UVGC_112_138,(7,0,4):C.\
UVGC_112_139,(7,0,5):C.UVGC_105_31,(7,0,6):C.UVGC_113_158,(7,0,7):C.UVGC_112_142,(7,0,8):C.UVGC_112_143,(7,0,9):C.UVGC_112_144,(7,0,11):C.UVGC_112_145,(7,0,12):C.UVGC_112_146,(7,0,13):C.UVGC_112_147,(\
7,0,14):C.UVGC_112_148,(7,0,15):C.UVGC_112_149,(7,0,16):C.UVGC_112_150,(7,0,17):C.UVGC_112_151,(7,0,18):C.UVGC_112_152,(7,0,19):C.UVGC_112_153,(7,0,20):C.UVGC_112_154,(7,0,21):C.UVGC_112_155,(7,0,22):\
C.UVGC_112_156,(7,0,23):C.UVGC_112_157,(5,0,5):C.UVGC_99_1085,(5,0,6):C.UVGC_99_1086,(1,0,5):C.UVGC_99_1085,(1,0,6):C.UVGC_99_1086,(11,0,5):C.UVGC_103_5,(11,0,6):C.UVGC_103_6,(10,0,5):C.UVGC_103_5,(10\
,0,6):C.UVGC_103_6,(9,0,5):C.UVGC_102_3,(9,0,6):C.UVGC_102_4,(2,1,5):C.UVGC_100_2,(2,1,6):C.UVGC_100_1,(0,1,5):C.UVGC_100_2,(0,1,6):C.UVGC_100_1,(4,1,5):C.UVGC_99_1085,(4,1,6):C.UVGC_99_1086,(3,1,5):C\
.UVGC_99_1085,(3,1,6):C.UVGC_99_1086,(8,1,0):C.UVGC_105_28,(8,1,3):C.UVGC_105_29,(8,1,4):C.UVGC_105_30,(8,1,5):C.UVGC_105_31,(8,1,6):C.UVGC_105_32,(8,1,7):C.UVGC_105_33,(8,1,8):C.UVGC_105_34,(8,1,9):C\
.UVGC_105_35,(8,1,11):C.UVGC_105_36,(8,1,12):C.UVGC_105_37,(8,1,13):C.UVGC_105_38,(8,1,14):C.UVGC_105_39,(8,1,15):C.UVGC_105_40,(8,1,16):C.UVGC_105_41,(8,1,17):C.UVGC_105_42,(8,1,18):C.UVGC_105_43,(8,\
1,19):C.UVGC_105_44,(8,1,20):C.UVGC_105_45,(8,1,21):C.UVGC_105_46,(8,1,22):C.UVGC_105_47,(8,1,23):C.UVGC_105_48,(6,1,0):C.UVGC_114_159,(6,1,3):C.UVGC_114_160,(6,1,4):C.UVGC_114_161,(6,1,5):C.UVGC_115_\
179,(6,1,6):C.UVGC_115_180,(6,1,7):C.UVGC_114_163,(6,1,8):C.UVGC_114_164,(6,1,9):C.UVGC_115_181,(6,1,11):C.UVGC_115_182,(6,1,12):C.UVGC_115_183,(6,1,13):C.UVGC_115_184,(6,1,14):C.UVGC_115_185,(6,1,15)\
:C.UVGC_115_186,(6,1,16):C.UVGC_115_187,(6,1,17):C.UVGC_115_188,(6,1,18):C.UVGC_115_189,(6,1,19):C.UVGC_115_190,(6,1,20):C.UVGC_115_191,(6,1,21):C.UVGC_115_192,(6,1,22):C.UVGC_114_177,(6,1,23):C.UVGC_\
114_178,(7,1,1):C.UVGC_110_133,(7,1,5):C.UVGC_100_1,(7,1,6):C.UVGC_111_136,(7,1,7):C.UVGC_110_134,(5,1,5):C.UVGC_99_1085,(5,1,6):C.UVGC_99_1086,(1,1,5):C.UVGC_99_1085,(1,1,6):C.UVGC_99_1086,(11,1,5):C\
.UVGC_103_5,(11,1,6):C.UVGC_103_6,(10,1,5):C.UVGC_103_5,(10,1,6):C.UVGC_103_6,(9,1,5):C.UVGC_102_3,(9,1,6):C.UVGC_102_4,(0,2,5):C.UVGC_100_2,(0,2,6):C.UVGC_100_1,(2,2,5):C.UVGC_100_2,(2,2,6):C.UVGC_10\
0_1,(5,2,5):C.UVGC_99_1085,(5,2,6):C.UVGC_99_1086,(1,2,5):C.UVGC_99_1085,(1,2,6):C.UVGC_99_1086,(7,2,0):C.UVGC_114_159,(7,2,3):C.UVGC_114_160,(7,2,4):C.UVGC_114_161,(7,2,5):C.UVGC_104_10,(7,2,6):C.UVG\
C_114_162,(7,2,7):C.UVGC_114_163,(7,2,8):C.UVGC_114_164,(7,2,9):C.UVGC_114_165,(7,2,11):C.UVGC_114_166,(7,2,12):C.UVGC_114_167,(7,2,13):C.UVGC_114_168,(7,2,14):C.UVGC_114_169,(7,2,15):C.UVGC_114_170,(\
7,2,16):C.UVGC_114_171,(7,2,17):C.UVGC_114_172,(7,2,18):C.UVGC_114_173,(7,2,19):C.UVGC_114_174,(7,2,20):C.UVGC_114_175,(7,2,21):C.UVGC_114_176,(7,2,22):C.UVGC_114_177,(7,2,23):C.UVGC_114_178,(4,2,5):C\
.UVGC_99_1085,(4,2,6):C.UVGC_99_1086,(3,2,5):C.UVGC_99_1085,(3,2,6):C.UVGC_99_1086,(8,2,0):C.UVGC_104_7,(8,2,3):C.UVGC_104_8,(8,2,4):C.UVGC_104_9,(8,2,5):C.UVGC_104_10,(8,2,6):C.UVGC_104_11,(8,2,7):C.\
UVGC_104_12,(8,2,8):C.UVGC_104_13,(8,2,9):C.UVGC_104_14,(8,2,11):C.UVGC_104_15,(8,2,12):C.UVGC_104_16,(8,2,13):C.UVGC_104_17,(8,2,14):C.UVGC_104_18,(8,2,15):C.UVGC_104_19,(8,2,16):C.UVGC_104_20,(8,2,1\
7):C.UVGC_104_21,(8,2,18):C.UVGC_104_22,(8,2,19):C.UVGC_104_23,(8,2,20):C.UVGC_104_24,(8,2,21):C.UVGC_104_25,(8,2,22):C.UVGC_104_26,(8,2,23):C.UVGC_104_27,(6,2,2):C.UVGC_110_133,(6,2,6):C.UVGC_102_3,(\
6,2,7):C.UVGC_110_134,(6,2,10):C.UVGC_110_135,(11,2,5):C.UVGC_103_5,(11,2,6):C.UVGC_103_6,(10,2,5):C.UVGC_103_5,(10,2,6):C.UVGC_103_6,(9,2,5):C.UVGC_102_3,(9,2,6):C.UVGC_102_4})
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py



```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

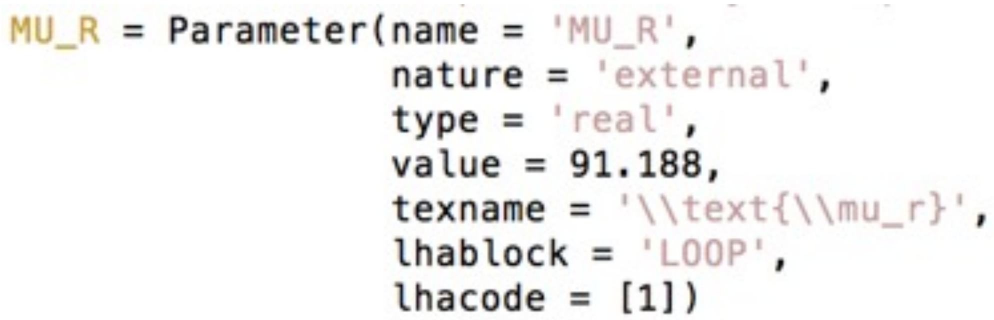
- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py



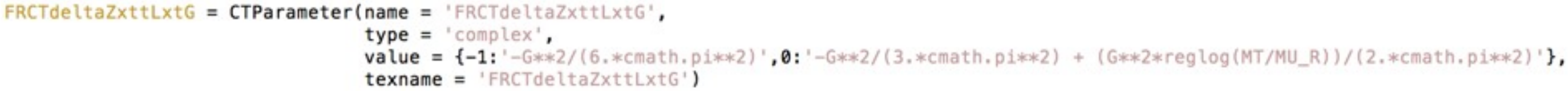
```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

- CT_parameters.py: parameters for UV and R2

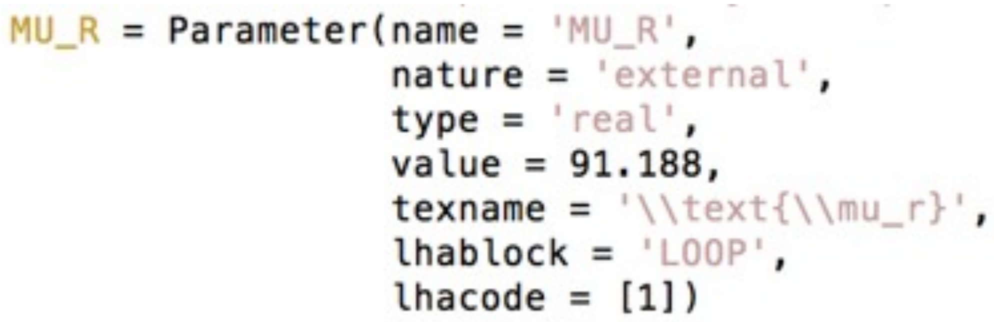


```
FRCTdeltaZxttLxtG = CTParameter(name = 'FRCTdeltaZxttLxtG',
                                type = 'complex',
                                value = {-1:'-G**2/(6.*cmath.pi**2)',0:'-G**2/(3.*cmath.pi**2) + (G**2*reglog(MT/MU_R))/(2.*cmath.pi**2)'},
                                texname = 'FRCTdeltaZxttLxtG')
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

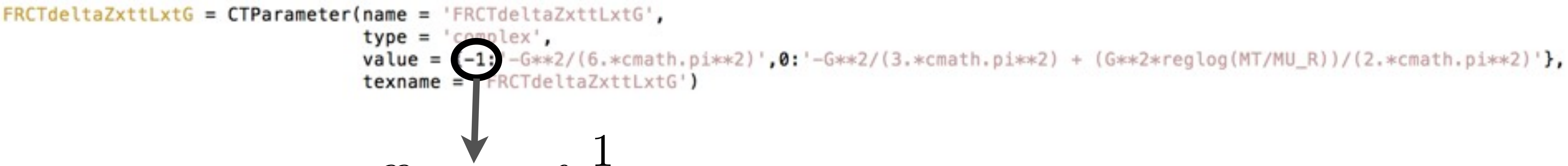


```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices
- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

- CT_parameters.py: parameters for UV and R2



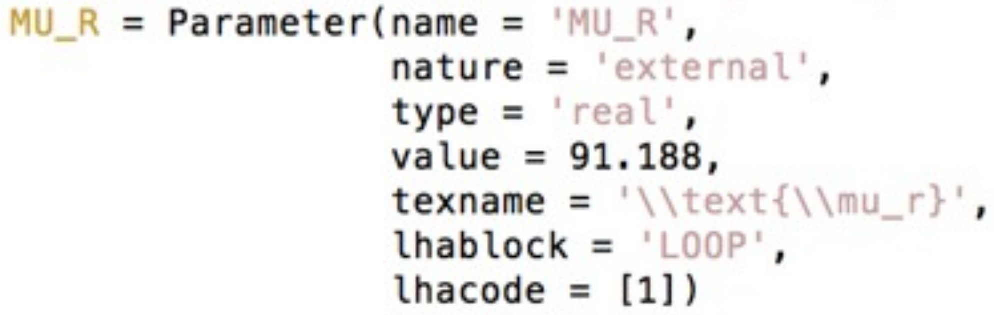
```
FRCTdeltaZxttLxtG = CTParameter(name = 'FRCTdeltaZxttLxtG',
                                type = 'complex',
                                value = {-1:'-G**2/(6.*cmath.pi**2)',0:'-G**2/(3.*cmath.pi**2) + (G**2*reglog(MT/MU_R))/(2.*cmath.pi**2)'},
                                texname = 'FRCTdeltaZxttLxtG')
```

$$\text{coefficient of } \frac{1}{\epsilon}$$

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

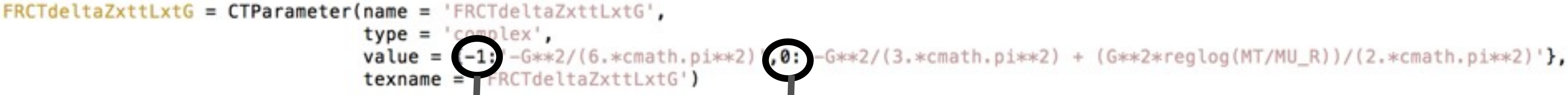


```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices
- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

- CT_parameters.py: parameters for UV and R2



```
FRCTdeltaZxttLxtG = CTParameter(name = 'FRCTdeltaZxttLxtG',
                                type = 'complex',
                                value = {-1:'-G**2/(6.*cmath.pi**2)',0:'-G**2/(3.*cmath.pi**2) + (G**2*reglog(MT/MU_R))/(2.*cmath.pi**2)'},
                                texname = 'FRCTdeltaZxttLxtG')
```

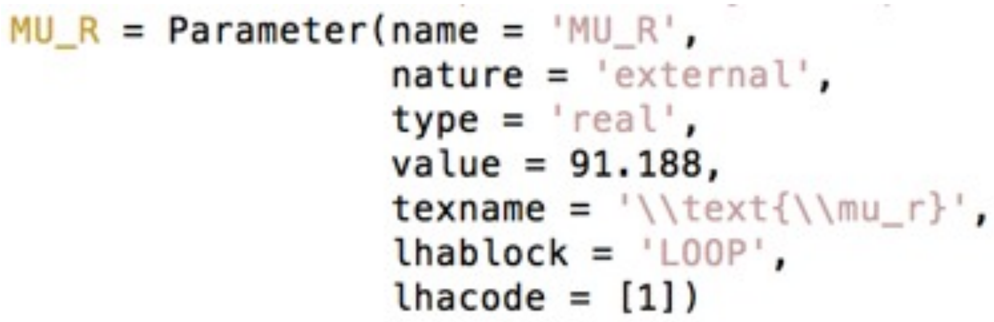
coefficient of $\frac{1}{\epsilon}$

finite piece

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py



```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices
- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

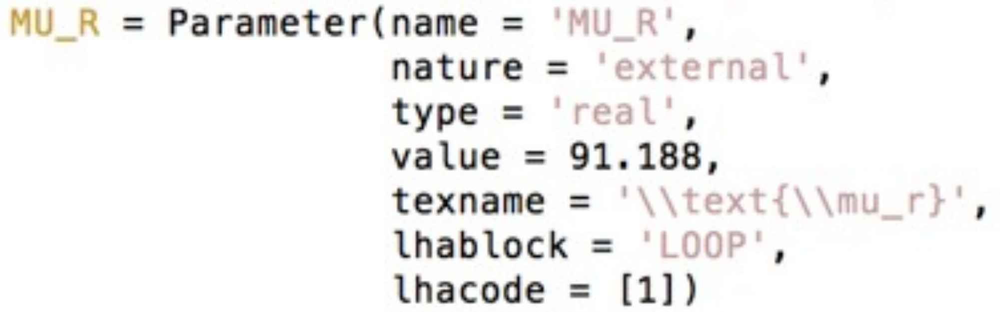
- CT_parameters.py: parameters for UV and R2

```
FRCTdel
FRCTdeltaZxttLxgostL = CTParameter(name = 'FRCTdeltaZxttLxgostL',
                                   type = 'complex',
                                   value = {0:'( 0 if 2*Mgo*MstL + MT**2>=Mgo**2 + MstL**2 and MT**2<=(Mgo + MstL)**2 else ( 0 if Mgo==MstL else ( 0 if Mgo==MT else ( 0 if MstL==MT else \
(G**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/(12.*cmath.pi**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4\   *2)'},
 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) + (G**2*Mgo**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2\
))/MU_R**2))/(12.*cmath.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) - (G**2*MstL**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**\
2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/(12.*cmath.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 \
- MT**2/MU_R**2)**2)) - (G**2*Mgo**4*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12.*cm\
ath.pi**2*MT**4*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) + (G**2*Mgo**2*MstL**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + \
MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(6.*cmath.pi**2*MT**4*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R*\
*2 - MT**2/MU_R**2)**2)) - (G**2*MstL**4*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12\
.*cmath.pi**2*MT**4*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) - (G**2*Mgo**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**\
2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12.*cmath.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 \
- MT**2/MU_R**2)**2)) + (G**2*MstL**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12.*c\
math.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) ) ) ) + ( ( 0 if Mgo==MstL else ( 0 if Mgo==MT else ( 0 if MstL==MT el\
se (G**2*Mgo*MstL*re((-(MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*\
Mgo*MstL) - (MU_R**2*(-(Mgo**2/MU_R**2) - MstL**2/MU_R**2 + MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL\
))*reglog((MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL))))/\
(12.*cmath.pi**2*MT**2) ) ) ) if 2*Mgo*MstL + MT**2>=Mgo**2 + MstL**2 and MT**2<(Mgo + MstL)**2 else 0 ) + ( ( 0 if Mgo==MstL else ( 0 if Mgo==MT else ( 0 if MstL==MT else (MU_R**2*G**2*\
Mgo**2*re(((MT**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/MU_R**2 + (-(Mgo**2/MU_R**2) + MstL**2/MU_R\
**2)*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL) + (MstL**4/MU_R**4 + (Mgo**2*(Mgo**2/MU_\
R**2 - MT**2/MU_R**2))/MU_R**2 - (MstL**2*((2*Mgo**2)/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog((MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2\
)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL)))/cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(12\
.*cmath.pi**2*MT**4) - (MU_R**2*G**2*MstL**2*re(((MT**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/MU_R*\
*2 + (-(Mgo**2/MU_R**2) + MstL**2/MU_R**2)*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL) + \
(MstL**4/MU_R**4 + (Mgo**2*(Mgo**2/MU_R**2 - MT**2/MU_R**2))/MU_R**2 - (MstL**2*((2*Mgo**2)/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog((MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/M\
U_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL)))/cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL\
**2/MU_R**2 - MT**2/MU_R**2)**2)))/(12.*cmath.pi**2*MT**4) + (MU_R**2*G**2*re(((MT**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + M\
T**2/MU_R**2))/MU_R**2))/MU_R**2 + (-(Mgo**2/MU_R**2) + MstL**2/MU_R**2)*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2)\
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py



```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

- CT_parameters.py: parameters for UV and R2

```
FRCTdeltaZxttLxgostL = CTParameter(name = 'FRCTdeltaZxttLxgostL',
                                   type = 'complex',
                                   value = {0:'( 0 if 2*Mgo*MstL + MT**2>=Mgo**2 + MstL**2 and MT**2<=(Mgo + MstL)**2 else ( 0 if Mgo==MstL else ( 0 if Mgo==MT else ( 0 if MstL==MT else \
```

Complicated mass spectrum makes the computation heavy !!!

NEW INGREDIENTS

- It is not a thorough list, which are of course strongly biased.
  - Non-renormalized operator
    - *e.g. EFT, High spin (graviton) theories etc*
    - *Higher rank integrals*
    - *Complete operators to cancel UV divergences*
  - RG running of new couplings
    - *e.g. EFT, simplified models etc*
    - *Solving the RG equation*
    - *Generalizing the way of scale uncertainties estimation (reweighting)*
  - Fermion-flow violation
    - *theories with Majorana particles or with fermion-flow violation interactions, e.g. SUSY etc*
    - *Fixing the correct fermion flow via charge conjugation in amplitudes*

NEW INGREDIENTS

- It is not a thorough list, which are of course strongly biased.
  - Multiply fermion lines
    - *e.g. four-fermion operator in EFT*
  - Finite renormalization
    - *e.g. in SUSY, one needs SUSY restoring counterterm if one uses dimensional regularization.*
    - *Or one needs the extra finite renormalization if one uses dimensional reduction to match the usual PDF scheme (extracted in dimensional regularization).*
  - New color representation
    - *e.g. sextet particles.*
    - *New evolution kernels in MadFKS and/or in MC@NLO.*

NEW INGREDIENTS

- It is not a thorough list, which are of course strongly biased.
  - Multiply fermion lines
    - *e.g. four-fermion operator in EFT*
  - Finite renormalization
    - *e.g. in SUSY, one needs SUSY restoring counterterm if one uses dimensional regularization.*
    - *Or one needs the extra finite renormalization if one uses dimensional reduction to match the usual PDF scheme (extracted in dimensional regularization).*
  - New color representation
    - *e.g. sextet particles.*
    - *New evolution kernels in MadFKS and/or in MC@NLO.*

All above issues should be solved by the physical applications/motivations.

EXAMPLE 1: A STOP SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

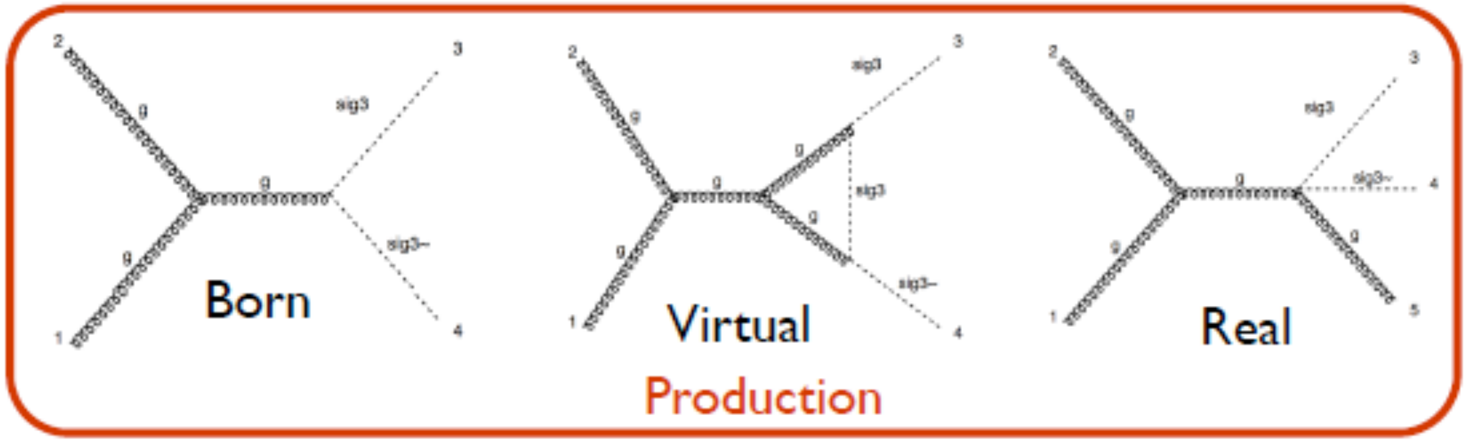
✦ The stop (σ_3) / bino (χ) model

$$\mathcal{L}_3 = \underbrace{D_\mu\sigma_3^\dagger D^\mu\sigma_3 - m_3^2\sigma_3^\dagger\sigma_3}_{\text{Production}} + \underbrace{\frac{i}{2}\bar{\chi}\not{\partial}\chi - \frac{1}{2}m_\chi\bar{\chi}\chi + \left[\sigma_3\bar{t}(\tilde{g}_L P_L + \tilde{g}_R P_R)\chi + \text{h.c.}\right]}_{\text{Decay}}$$

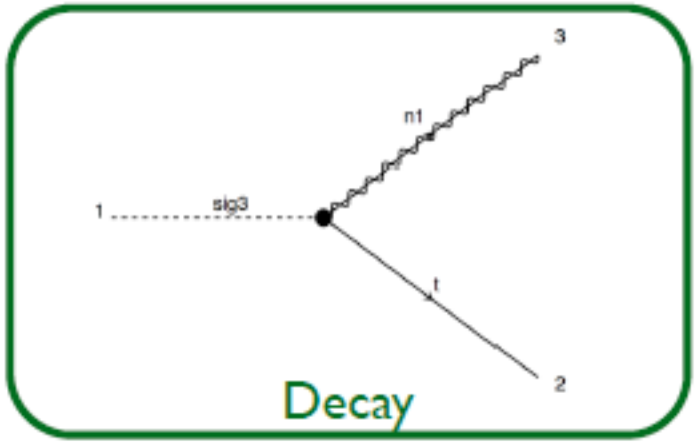
- ✤ One scalar field in the fundamental representation (σ_3)
- ✤ One gauge-singlet Majorana fermion (χ) coupling the stop to the top

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model stop_ ttmet_ufo
5. > generate p p > sig3 sig3~ [QCD]
6. > output pp2t1t1QCD
7. > launch

✦ Representative Feynman diagrams (yielding a top-antitop plus missing energy signature)



Production



Decay

EXAMPLE 1: A STOP SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

✦ UV behavior (on-shell scheme, zero-momentum subtraction for α_s)

Analytical validation

- Analytical checks are important (the fully automated approach is new)

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{96\pi^2}\left[\frac{1}{\bar\epsilon} - \log\frac{m_3^2}{\mu_R^2}\right]$$

$$\delta Z_{\sigma_3} = 0 \quad \text{and} \quad \delta m_3^2 = -\frac{g_s^2 m_3^2}{12\pi^2}\left[\frac{3}{\bar\epsilon} + 7 - 3\log\frac{m_3^2}{\mu_R^2}\right]$$

$$\frac{\delta\alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi\bar\epsilon}\left[\frac{n_f}{3} - \frac{11}{2}\right] + \frac{\alpha_s}{6\pi}\left[\frac{1}{\bar\epsilon} - \log\frac{m_t^2}{\mu_R^2}\right] + \frac{\alpha_s}{24\pi}\left[\frac{1}{\bar\epsilon} - \log\frac{m_3^2}{\mu_R^2}\right]$$

$$R_2^{\sigma_3^\dagger\sigma_3} = \frac{ig_s^2}{72\pi^2}\delta_{c_1c_2}\left[3m_3^2 - p^2\right]$$

$$R_2^{g\sigma_3^\dagger\sigma_3} = \frac{53ig_s^3}{576\pi^2}T^{a_1}_{c_2c_3}\left(p_2 - p_3\right)^{\mu_1}$$

$$R_2^{gg\sigma_3^\dagger\sigma_3} = \frac{ig_s^4}{1152\pi^2}\eta^{\mu_1\mu_2}\left[3\delta^{a_1a_2} - 187\{T^{a_1},T^{a_2}\}\right]_{c_3c_4}$$

✦ Total rates at 8 TeV and 13 TeV

Numerical validation

m_3 [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
100	$3.893 \pm 0.0095 \cdot 10^{2}\ ^{+34.2\%}_{-23.9\%}$	$5.548 \pm 0.018 \cdot 10^{2}\ ^{+14.9\%}_{-13.5\%}\ ^{+1.6\%}_{-1.6\%}$	$1.066 \pm 0.0025 \cdot 10^{3}\ ^{+29.1\%}_{-21.4\%}$	$1.497 \pm 0.0054 \cdot 10^{3}\ ^{+14.1\%}_{-12.1\%}\ ^{+1.2\%}_{-1.2\%}$
250	$4.118 \pm 0.0096 \cdot 10^{0}\ ^{+40.4\%}_{-27.2\%}$	$5.503 \pm 0.017 \cdot 10^{0}\ ^{+13.1\%}_{-13.7\%}\ ^{+3.7\%}_{-3.7\%}$	$1.553 \pm 0.0037 \cdot 10^{1}\ ^{+35.2\%}_{-24.8\%}$	$2.156 \pm 0.0067 \cdot 10^{1}\ ^{+12.1\%}_{-12.3\%}\ ^{+2.4\%}_{-2.4\%}$
500	$6.594 \pm 0.016 \cdot 10^{-2}\ ^{+45.5\%}_{-29.1\%}$	$7.764 \pm 0.025 \cdot 10^{-2}\ ^{+12.1\%}_{-14.1\%}\ ^{+6.7\%}_{-6.7\%}$	$3.890 \pm 0.0093 \cdot 10^{-1}\ ^{+39.6\%}_{-26.4\%}$	$5.062 \pm 0.015 \cdot 10^{-1}\ ^{+11.2\%}_{-12.8\%}\ ^{+4.4\%}_{-4.4\%}$
750	$3.504 \pm 0.0084 \cdot 10^{-3}\ ^{+48.8\%}_{-30.5\%}$	$3.699 \pm 0.012 \cdot 10^{-3}\ ^{+12.3\%}_{-14.6\%}\ ^{+10.2\%}_{-10.2\%}$	$3.306 \pm 0.0081 \cdot 10^{-2}\ ^{+41.8\%}_{-27.5\%}$	$4.001 \pm 0.012 \cdot 10^{-2}\ ^{+10.8\%}_{-12.9\%}\ ^{+6.1\%}_{-6.1\%}$
1000	$2.875 \pm 0.0067 \cdot 10^{-4}\ ^{+51.5\%}_{-31.5\%}$	$2.775 \pm 0.0087 \cdot 10^{-4}\ ^{+13.1\%}_{-15.2\%}\ ^{+15.5\%}_{-15.5\%}$	$4.614 \pm 0.011 \cdot 10^{-3}\ ^{+43.6\%}_{-28.3\%}$	$5.219 \pm 0.016 \cdot 10^{-3}\ ^{+10.9\%}_{-13.2\%}\ ^{+7.9\%}_{-7.9\%}$

8 TeV

13 TeV

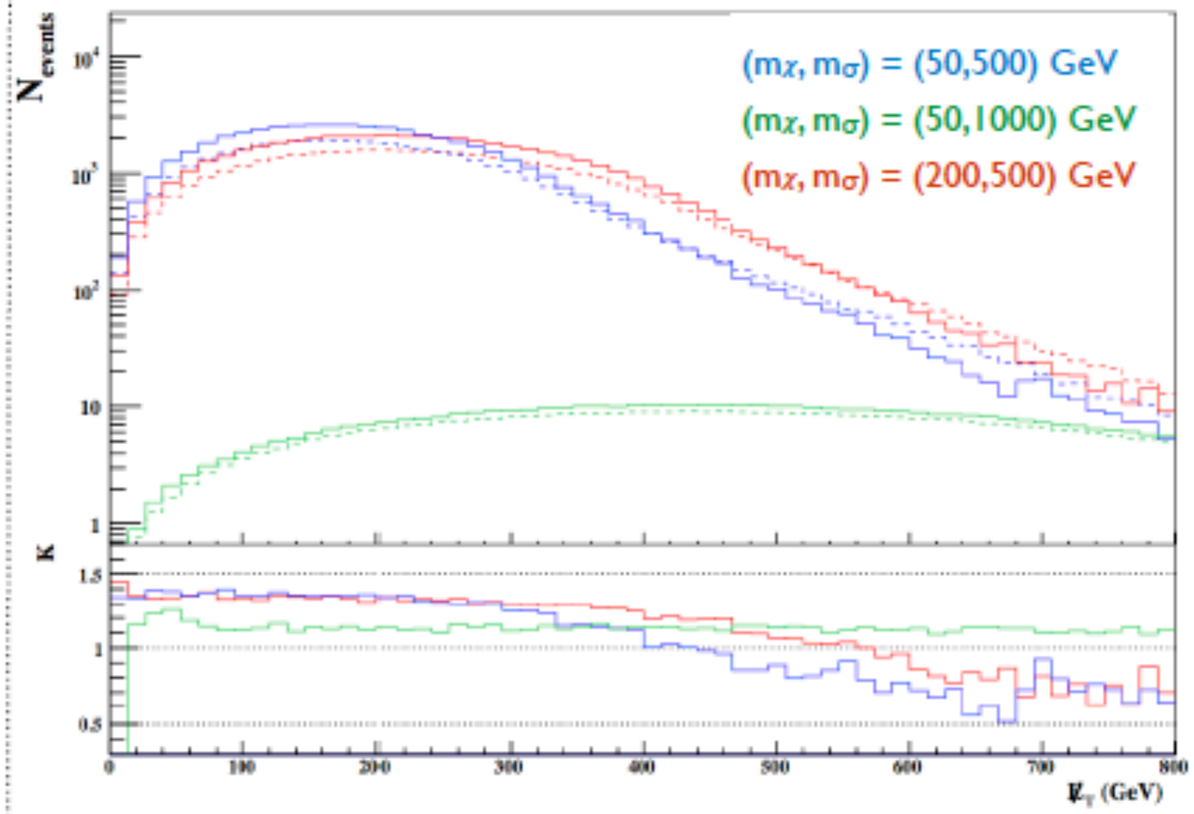
- NNPDF2.3; scales set to the stop mass
- Agrees with PROSPINO [Beenakker, Kramer, Plehn, Spira & Zerwas (NPB'98)]
- Scale varied by a factor of two up and down
- PDF variations obtained with the 100 NNPDF replica provided with the central set of densities

EXAMPLE 1: A STOP SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

- NLO matrix elements matched to parton showering: differential distributions
  - Test case: 500/1000 GeV stop; 50/200 GeV bino; 13 TeV collisions
  - Standard coupling strengths for a maximally mixing stop and a bino
  - Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands (CPC'08)]
  - Jet reconstruction: anti-k_T & FASTJET [Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]
  - Analysis (single lepton case) & figures: MADANALYSIS 5 [Conte, BF, Serret (CPC'13)]

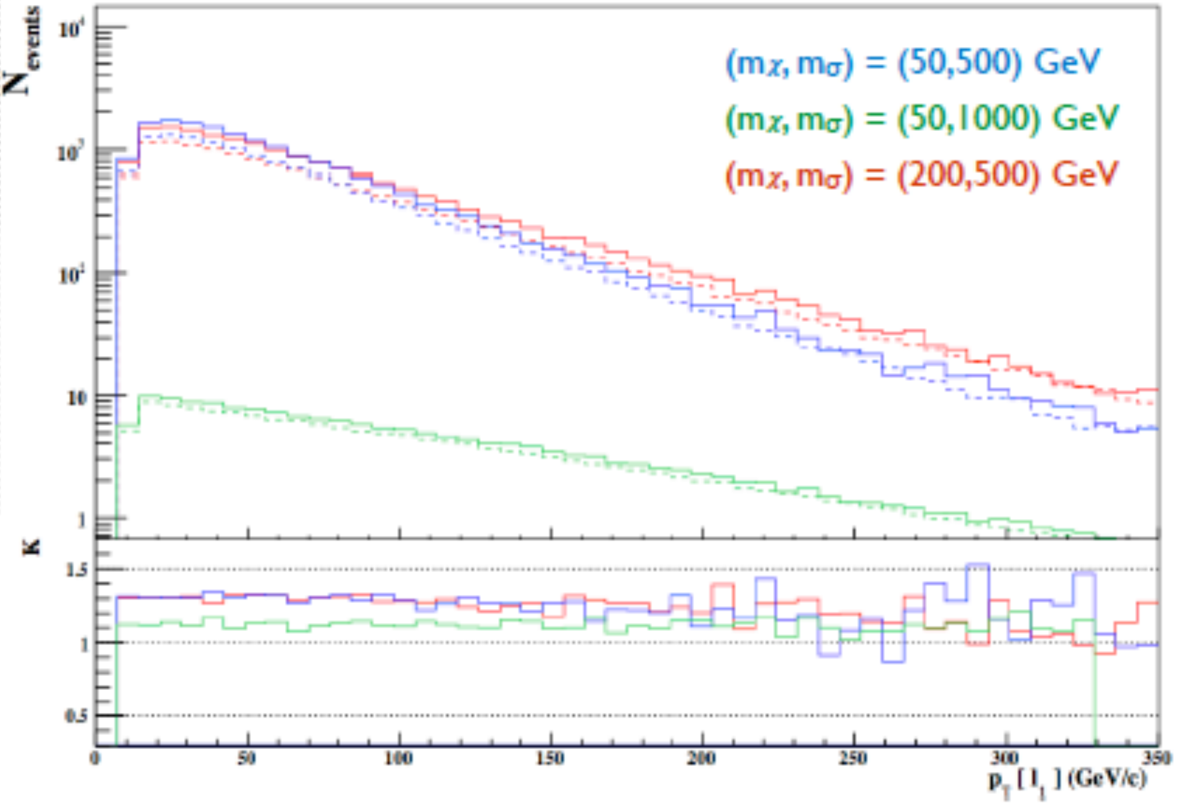
Missing transverse energy



★ Constant *K*-factors not suitable

★ The K-factor depends on the scenario

Leading lepton transverse momentum (single lepton signature)



★ Constant *K*-factors okayish

★ The K-factor depends on the scenario

EXAMPLE 2: A SGLUON SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

✦ The sgluon (σ_8) model

$$\mathcal{L}_8 = \underbrace{\frac{1}{2} D_\mu \sigma_8 D^\mu \sigma_8 - \frac{1}{2} m_8^2 \sigma_8 \sigma_8}_{\text{Production}} + \underbrace{\frac{\hat{g}_g}{\Lambda} \sigma_8 G_{\mu\nu} G^{\mu\nu} + \sum_{q=u,d} \left[\sigma_8 \bar{q} (\hat{g}_q^L P_L + \hat{g}_q^R P_R) q + \text{h.c.} \right]}_{\text{Decay}}$$

- ✤ One scalar field in the adjoint representation (σ_8)
- ✤ Effective couplings (g): only for the decay that is enforced to be at the leading order
- ✤ g couplings at NLO: a consistent effective theory is required for a proper renormalization

✦ UV behavior (on-shell scheme, zero-momentum subtraction for α_s)

- ✤ Analytical checks

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{32\pi^2} \left[\frac{1}{\bar{\epsilon}} - \log \frac{m_8^2}{\mu_R^2} \right] ,$$

$$\delta Z_{\sigma_8} = 0 \quad \text{and} \quad \delta m_8^2 = -\frac{3 g_s^2 m_8^2}{16\pi^2} \left[\frac{3}{\bar{\epsilon}} + 7 - 3 \log \frac{m_8^2}{\mu_R^2} \right]$$

$$\frac{\delta \alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi\bar{\epsilon}} \left[\frac{n_f}{3} - \frac{11}{2} \right] + \frac{\alpha_s}{6\pi} \left[\frac{1}{\bar{\epsilon}} - \log \frac{m_t^2}{\mu_R^2} \right] + \frac{\alpha_s}{8\pi} \left[\frac{1}{\bar{\epsilon}} - \log \frac{m_8^2}{\mu_R^2} \right]$$

$$R_2^{\sigma_8 \sigma_8} = \frac{i g_s^2}{32\pi^2} \delta_{a_1 a_2} \left[3 m_8^2 - p^2 \right] ,$$

$$R_2^{g \sigma_8 \sigma_8} = \frac{7 g_s^3}{64\pi^2} f_{a_1 a_2 a_3} (p_2 - p_3)^{\mu_1} ,$$

$$\begin{aligned} R_2^{g g \sigma_8 \sigma_8} = \frac{i g_s^4}{384\pi^2} \eta^{\mu_1 \mu_2} \Big[& 72 (d_{a_1 a_4 e} d_{a_2 a_3 e} + d_{a_1 a_3 e} d_{a_2 a_4 e}) \\ & - 141 d_{a_1 a_2 e} d_{a_3 a_4 e} - 92 \delta_{a_1 a_2} \delta_{a_3 a_4} \\ & + 50 (\delta_{a_1 a_3} \delta_{a_2 a_4} + \delta_{a_1 a_4} \delta_{a_2 a_3}) \Big] , \end{aligned}$$

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model sgluon_ ufo
5. > generate p p > sig8 sig8~ [QCD]
6. > output pp2sig8sig8QCD
7. > launch

EXAMPLE 2: A SGLUON SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

Non-renormalizable operator

✦ The sgluon (σ_8) model

$$\mathcal{L}_8 = \underbrace{\frac{1}{2} D_\mu \sigma_8 D^\mu \sigma_8 - \frac{1}{2} m_8^2 \sigma_8 \sigma_8}_{\text{Production}} + \underbrace{\frac{\hat{g}_g}{\Lambda} \sigma_8 G_{\mu\nu} G^{\mu\nu} + \sum_{q=u,d} \left[\sigma_8 \bar{q} (\hat{g}_q^L P_L + \hat{g}_q^R P_R) q + \text{h.c.} \right]}_{\text{Decay}}$$

- ✤ One scalar field in the adjoint representation (σ_8)
- ✤ Effective couplings (*g*): only for the decay that is enforced to be at the leading order
- ✤ g couplings at NLO: a consistent effective theory is required for a proper renormalization

✦ UV behavior (on-shell scheme, zero-momentum subtraction for α_s)

- ✤ Analytical checks

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{32\pi^2} \left[\frac{1}{\bar{\epsilon}} - \log \frac{m_8^2}{\mu_R^2} \right] ,$$

$$\delta Z_{\sigma_8} = 0 \quad \text{and} \quad \delta m_8^2 = -\frac{3 g_s^2 m_8^2}{16\pi^2} \left[\frac{3}{\bar{\epsilon}} + 7 - 3 \log \frac{m_8^2}{\mu_R^2} \right]$$

$$\frac{\delta \alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi\bar{\epsilon}} \left[\frac{n_f}{3} - \frac{11}{2} \right] + \frac{\alpha_s}{6\pi} \left[\frac{1}{\bar{\epsilon}} - \log \frac{m_t^2}{\mu_R^2} \right] + \frac{\alpha_s}{8\pi} \left[\frac{1}{\bar{\epsilon}} - \log \frac{m_8^2}{\mu_R^2} \right]$$

$$\begin{aligned} R_2^{\sigma_8\sigma_8} &= \frac{i g_s^2}{32\pi^2} \delta_{a_1 a_2} \left[3 m_8^2 - p^2 \right] , \\ R_2^{g\sigma_8\sigma_8} &= \frac{7 g_s^3}{64\pi^2} f_{a_1 a_2 a_3} (p_2 - p_3)^{\mu_1} , \\ R_2^{gg\sigma_8\sigma_8} &= \frac{i g_s^4}{384\pi^2} \eta^{\mu_1\mu_2} \Big[72 (d_{a_1 a_4 e} d_{a_2 a_3 e} + d_{a_1 a_3 e} d_{a_2 a_4 e}) \\ &\quad - 141 d_{a_1 a_2 e} d_{a_3 a_4 e} - 92 \delta_{a_1 a_2} \delta_{a_3 a_4} \\ &\quad + 50 (\delta_{a_1 a_3} \delta_{a_2 a_4} + \delta_{a_1 a_4} \delta_{a_2 a_3}) \Big] , \end{aligned}$$

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model sgluon_ ufo
5. > generate p p > sig8 sig8~ [QCD]
6. > output pp2sig8sig8QCD
7. > launch

EXAMPLE 2: A SGLUON SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

✦ Total rates at 8 TeV and 13 TeV

Numerically validated

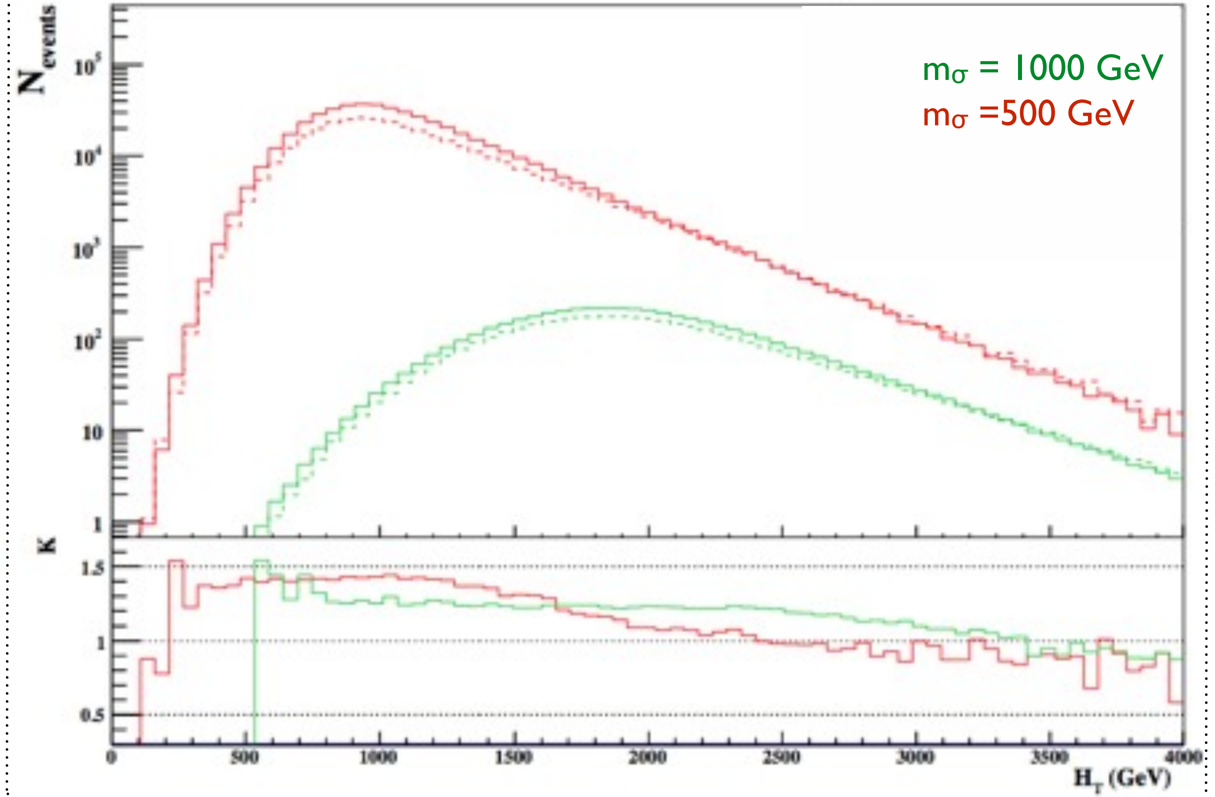
m_8 [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
100	$3.854 \pm 0.0094 \cdot 10^{3}\ ^{+34.4\%}_{-24.1\%}$	$5.573 \pm 0.02 \cdot 10^{3}\ ^{+14.9\%}_{-13.6\%}\ ^{+1.6\%}_{-1.6\%}$	$1.056 \pm 0.0029 \cdot 10^{4}\ ^{+29.2\%}_{-21.5\%}$	$1.470 \pm 0.0058 \cdot 10^{4}\ ^{+13.6\%}_{-11.9\%}\ ^{+1.2\%}_{-1.2\%}$
250	$3.889 \pm 0.010 \cdot 10^{1}\ ^{+41.3\%}_{-27.7\%}$	$5.432 \pm 0.019 \cdot 10^{1}\ ^{+14.5\%}_{-14.6\%}\ ^{+3.9\%}_{-3.9\%}$	$1.504 \pm 0.0034 \cdot 10^{2}\ ^{+35.7\%}_{-25.1\%}$	$2.145 \pm 0.0077 \cdot 10^{2}\ ^{+12.9\%}_{-12.9\%}\ ^{+2.5\%}_{-2.5\%}$
500	$5.878 \pm 0.015 \cdot 10^{-1}\ ^{+47.6\%}_{-30.0\%}$	$7.431 \pm 0.028 \cdot 10^{-1}\ ^{+15.8\%}_{-16.2\%}\ ^{+7.6\%}_{-7.6\%}$	$3.619 \pm 0.0079 \cdot 10^{0}\ ^{+40.8\%}_{-27.0\%}$	$4.977 \pm 0.018 \cdot 10^{0}\ ^{+13.3\%}_{-14.1\%}\ ^{+4.7\%}_{-4.7\%}$
750	$2.977 \pm 0.0073 \cdot 10^{-2}\ ^{+52.0\%}_{-31.9\%}$	$3.353 \pm 0.012 \cdot 10^{-2}\ ^{+17.2\%}_{-17.3\%}\ ^{+12.1\%}_{-12.1\%}$	$2.951 \pm 0.0065 \cdot 10^{-1}\ ^{+43.6\%}_{-28.4\%}$	$3.817 \pm 0.015 \cdot 10^{-1}\ ^{+14.0\%}_{-14.8\%}\ ^{+6.9\%}_{-6.9\%}$
1000	$2.328 \pm 0.0058 \cdot 10^{-3}\ ^{+55.9\%}_{-33.4\%}$	$2.398 \pm 0.0099 \cdot 10^{-3}\ ^{+19.0\%}_{-18.4\%}\ ^{+19.1\%}_{-19.1\%}$	$3.983 \pm 0.0087 \cdot 10^{-2}\ ^{+46.1\%}_{-29.5\%}$	$4.822 \pm 0.017 \cdot 10^{-2}\ ^{+15.1\%}_{-15.6\%}\ ^{+9.3\%}_{-9.3\%}$

8 TeV

13 TeV

- ✤ NNPDF2.3; scales set to the sgluon mass; uncertainties evaluated as for the stop case
- ✤ Validation with MADGOLEM
  - ★ Discrepancy of a 1-3 % for central scale choices; larger for other scale setups
  - ★ MADGOLEM is overestimating the numerical uncertainties

Hadronic activity H_T



✦ Differential distributions at NLO

- ✤ Test case: 500/1000 GeV sgluons; 13 TeV collisions
- ✤ Tetratop decays
- ✤ Shower: PYTHIA 8.2 **[Sjostrand, Mrenna & Skands**
- ✤ Jet reconstruction: anti-k_T & FASTJET

[Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]

- ✤ Analysis & figure: MADANALYSIS 5

[Conte, BF, Serret

EXAMPLE 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

- SUSY QCD: Production of gluino-pair

$$\mathcal{L}_{\rm SQCD} = D_\mu \tilde{q}_L^\dagger D^\mu \tilde{q}_L + D_\mu \tilde{q}_R^\dagger D^\mu \tilde{q}_R + \frac{i}{2}\bar{\tilde{g}} \not{D} \tilde{g} - m^2_{\tilde{q}_L} \tilde{q}_L^\dagger \tilde{q}_L - m^2_{\tilde{q}_R} \tilde{q}_R^\dagger \tilde{q}_R - \frac{1}{2} m_{\tilde{g}} \bar{\tilde{g}} \tilde{g}$$

$$+ \sqrt{2} g_s \Big[- \tilde{q}_L^\dagger T (\bar{\tilde{g}} P_L q) + (\bar{q} P_L \tilde{g}) T \tilde{q}_R + \text{h.c.} \Big] - \frac{g_s^2}{2} \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big] \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big]$$

  - Besides new UV and R2 (I will not listed here), we also need some special counter terms
  - Mixing angle renormalization (mass and wavefunction)

$$\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \to \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \delta Z_{\tilde{t}_L} & \delta Z_{\tilde{t},\rm LR} \\ \delta Z_{\tilde{t},\rm RL} & \delta Z_{\tilde{t}_R} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$$\delta \mathcal{L}_{\rm off} = - \delta m^2_{\tilde{t},\rm LR} (\tilde{t}_L^\dagger \tilde{t}_R + \tilde{t}_R^\dagger \tilde{t}_L)$$

  - SUSY restoring counter terms

$$\mathcal{L}_{\rm SCT} = \sqrt{2} g_s \frac{\alpha_s}{3\pi} \Big[- \tilde{q}_L^\dagger T_a (\bar{\tilde{g}}^a P_L q) + (\bar{q} P_L \tilde{g}^a) T_a \tilde{q}_R + \text{h.c.} \Big]$$

$$+ \frac{g_s^2}{2} \frac{\alpha_s}{4\pi} \Big[\tilde{q}_R^\dagger \{T_a, T_b\} \tilde{q}_R + \tilde{q}_L^\dagger \{T_a, T_b\} \tilde{q}_L \Big] \times \Big[\tilde{q}_R^\dagger \{T^a, T^b\} \tilde{q}_R + \tilde{q}_L^\dagger \{T^a, T^b\} \tilde{q}_L \Big]$$

$$- \frac{g_s^2}{2} \frac{\alpha_s}{4\pi} \Big[\tilde{q}_R^\dagger T_a \tilde{q}_R - \tilde{q}_L^\dagger T_a \tilde{q}_L \Big] \Big[\tilde{q}_R^\dagger T^a \tilde{q}_R - \tilde{q}_L^\dagger T^a \tilde{q}_L \Big]$$

- Decay of gluino

$$\mathcal{L}_{\rm decay} = \frac{i}{2} \bar{\chi} \not{\partial} \chi - \frac{1}{2} m_\chi \bar{\chi} \chi + \sqrt{2} g' \Big[- \tilde{q}_L^\dagger Y_q (\bar{\chi} P_L q) + (\bar{q} P_L \chi) Y_q \tilde{q}_R + \text{h.c.} \Big]$$

EXAMPLE 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

Majorana: fermion-flow violation

- SUSY QCD: Production of gluino-pair

$$\mathcal{L}_{\rm SQCD} = D_\mu \tilde{q}_L^\dagger D^\mu \tilde{q}_L + D_\mu \tilde{q}_R^\dagger D^\mu \tilde{q}_R + \frac{i}{2}\bar{\tilde{g}} \not{D} \tilde{g} - m_{\tilde{q}_L}^2 \tilde{q}_L^\dagger \tilde{q}_L - m_{\tilde{q}_R}^2 \tilde{q}_R^\dagger \tilde{q}_R - \frac{1}{2} m_{\tilde{g}} \bar{\tilde{g}}\tilde{g}$$

$$+\sqrt{2} g_s \Big[-\tilde{q}_L^\dagger T(\bar{\tilde{g}} P_L q) + (\bar{q} P_L \tilde{g}) T \tilde{q}_R + \text{h.c.}\Big] - \frac{g_s^2}{2}\Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L\Big]\Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T\tilde{q}_L\Big]$$

  - Besides new UV and R2 (I will not listed here), we also need some special counter terms
  - Mixing angle renormalization (mass and wavefunction)

$$\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \to \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} + \frac{1}{2}\begin{pmatrix} \delta Z_{\tilde{t}_L} & \delta Z_{\tilde{t},\rm LR} \\ \delta Z_{\tilde{t},\rm RL} & \delta Z_{\tilde{t}_R} \end{pmatrix}\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$$\delta\mathcal{L}_{\rm off} = -\delta m^2_{\tilde{t},\rm LR}(\tilde{t}_L^\dagger \tilde{t}_R + \tilde{t}_R^\dagger \tilde{t}_L)$$

  - SUSY restoring counter terms

$$\mathcal{L}_{\rm SCT} = \sqrt{2} g_s \frac{\alpha_s}{3\pi}\Big[-\tilde{q}_L^\dagger T_a(\bar{\tilde{g}}^a P_L q) + (\bar{q} P_L \tilde{g}^a) T_a \tilde{q}_R + \text{h.c.}\Big]$$

$$+\frac{g_s^2}{2}\frac{\alpha_s}{4\pi}\Big[\tilde{q}_R^\dagger \{T_a, T_b\}\tilde{q}_R + \tilde{q}_L^\dagger \{T_a, T_b\}\tilde{q}_L\Big] \times \Big[\tilde{q}_R^\dagger \{T^a, T^b\}\tilde{q}_R + \tilde{q}_L^\dagger \{T^a, T^b\}\tilde{q}_L\Big]$$

$$-\frac{g_s^2}{2}\frac{\alpha_s}{4\pi}\Big[\tilde{q}_R^\dagger T_a \tilde{q}_R - \tilde{q}_L^\dagger T_a \tilde{q}_L\Big]\Big[\tilde{q}_R^\dagger T^a \tilde{q}_R - \tilde{q}_L^\dagger T^a \tilde{q}_L\Big]$$

- Decay of gluino

$$\mathcal{L}_{\rm decay} = \frac{i}{2}\bar{\chi}\not{\partial}\chi - \frac{1}{2} m_\chi \bar{\chi}\chi + \sqrt{2} g' \Big[-\tilde{q}_L^\dagger Y_q(\bar{\chi} P_L q) + (\bar{q} P_L \chi) Y_q \tilde{q}_R + \text{h.c.}\Big]$$

EXAMPLE 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

Splitting SUSY

Numerically validated

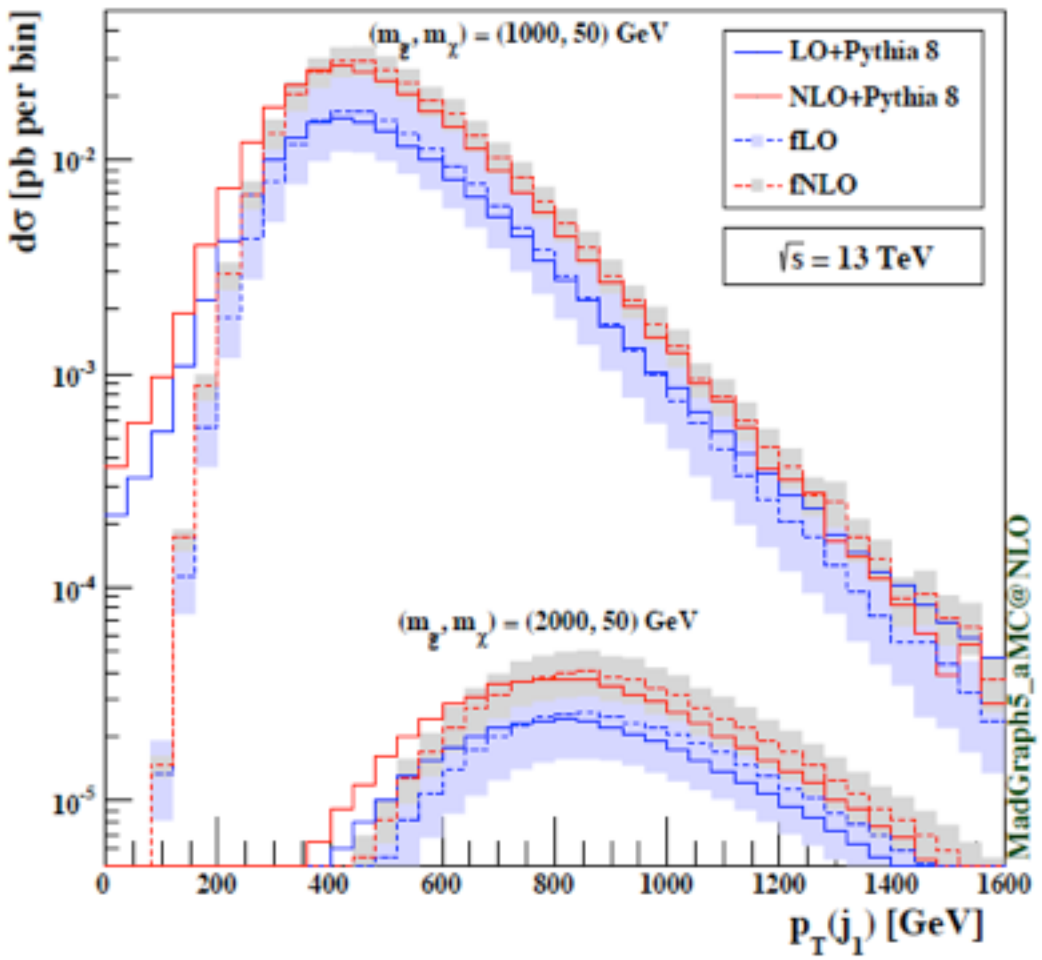
✦ Total rates at 8 TeV and 13 TeV

$m_{\tilde{g}}$ [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
200	$2104^{+30.3\%\,+14.0\%}_{-21.9\%\,-14.0\%}$	$3183^{+10.8\%\,+1.8\%}_{-11.6\%\,-1.8\%}$
500	$15.46^{+34.7\%\,+19.5\%}_{-24.1\%\,-19.5\%}$	$24.90^{+12.5\%\,+3.7\%}_{-13.4\%\,-3.7\%}$
750	$1.206^{+35.9\%\,+23.5\%}_{-24.6\%\,-23.5\%}$	$2.009^{+13.5\%\,+5.5\%}_{-14.1\%\,-5.5\%}$
1000	$1.608 \cdot 10^{-1}{}^{+36.3\%\,+26.4\%}_{-24.8\%\,-26.4\%}$	$2.743 \cdot 10^{-1}{}^{+14.4\%\,+7.3\%}_{-14.8\%\,-7.3\%}$
1500	$6.264 \cdot 10^{-3}{}^{+36.2\%\,+29.4\%}_{-24.7\%\,-29.4\%}$	$1.056 \cdot 10^{-2}{}^{+16.1\%\,+11.3\%}_{-15.8\%\,-11.3\%}$
2000	$4.217 \cdot 10^{-4}{}^{+35.6\%\,+29.8\%}_{-24.5\%\,-29.8\%}$	$6.327 \cdot 10^{-4}{}^{+17.7\%\,+17.8\%}_{-16.6\%\,-17.8\%}$

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model susyqcd_ufo
5. > generate p p > go go [QCD]
6. > output pp2gogoQCD
7. > launch

✤ NNPDF3.0; scales set to the HT/2; uncertainties evaluated as for the stop case

✤ Validation with PROSPINO 2.1



✦ Differential distributions at NLO

✤ Test case: 1000/2000 GeV gluino; 13 TeV collisions

✤ Gluino decays: MadSpin

✤ Shower: PYTHIA 8.2 **[Sjostrand, Mrenna & Skands**

✤ Jet reconstruction: anti-k_T & FASTJET

[Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]

✤ Analysis & figure: MADANALYSIS 5

[Conte, BF, Serret

EXAMPLE 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

✦ Total rates at 8 TeV and 13 TeV

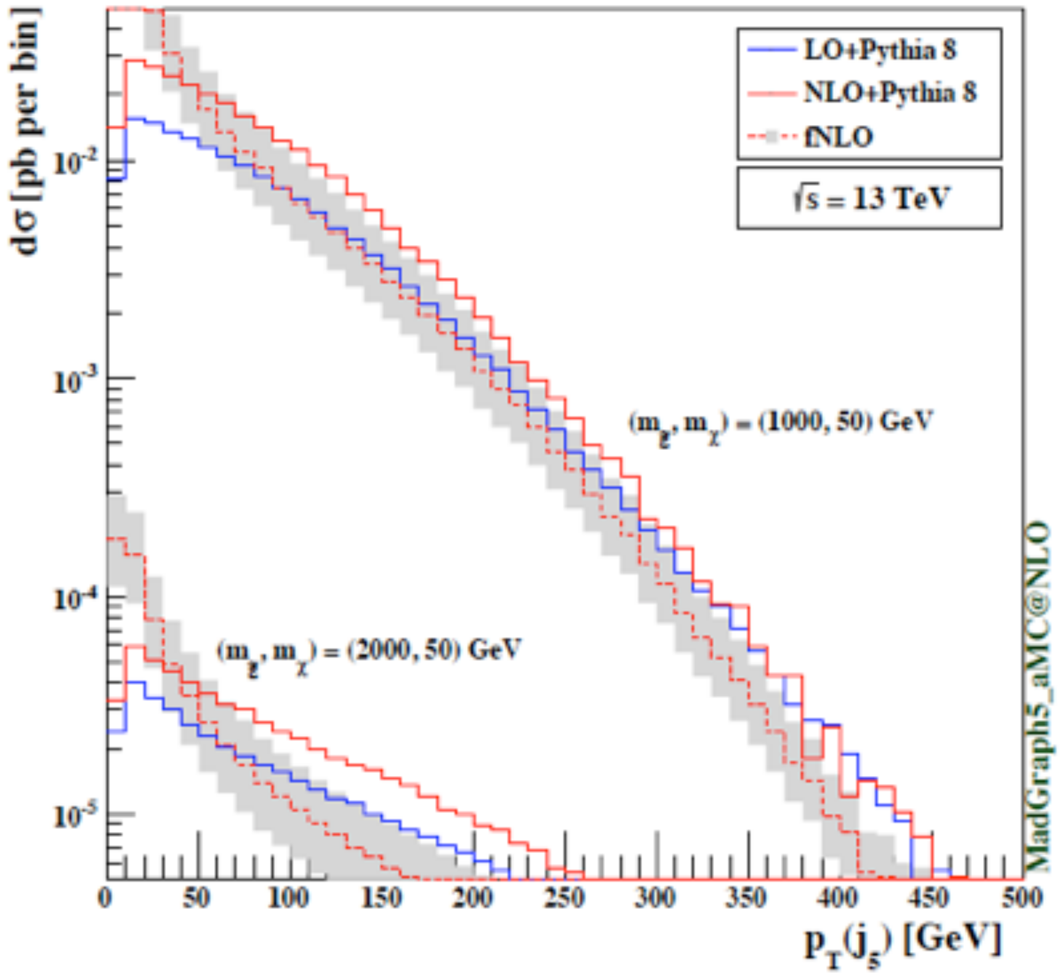
Splitting SUSY

Numerically validated

$m_{\tilde{g}}$ [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
200	$2104^{+30.3\%}_{-21.9\%}{}^{+14.0\%}_{-14.0\%}$	$3183^{+10.8\%}_{-11.6\%}{}^{+1.8\%}_{-1.8\%}$
500	$15.46^{+34.7\%}_{-24.1\%}{}^{+19.5\%}_{-19.5\%}$	$24.90^{+12.5\%}_{-13.4\%}{}^{+3.7\%}_{-3.7\%}$
750	$1.206^{+35.9\%}_{-24.6\%}{}^{+23.5\%}_{-23.5\%}$	$2.009^{+13.5\%}_{-14.1\%}{}^{+5.5\%}_{-5.5\%}$
1000	$1.608 \cdot 10^{-1}{}^{+36.3\%}_{-24.8\%}{}^{+26.4\%}_{-26.4\%}$	$2.743 \cdot 10^{-1}{}^{+14.4\%}_{-14.8\%}{}^{+7.3\%}_{-7.3\%}$
1500	$6.264 \cdot 10^{-3}{}^{+36.2\%}_{-24.7\%}{}^{+29.4\%}_{-29.4\%}$	$1.056 \cdot 10^{-2}{}^{+16.1\%}_{-15.8\%}{}^{+11.3\%}_{-11.3\%}$
2000	$4.217 \cdot 10^{-4}{}^{+35.6\%}_{-24.5\%}{}^{+29.8\%}_{-29.8\%}$	$6.327 \cdot 10^{-4}{}^{+17.7\%}_{-16.6\%}{}^{+17.8\%}_{-17.8\%}$

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model susyqcd_ufo
5. > generate p p > go go [QCD]
6. > output pp2gogoQCD
7. > launch

- ✤ NNPDF3.0; scales set to the HT/2; uncertainties evaluated as for the stop case
- ✤ Validation with PROSPINO 2.1



✦ Differential distributions at NLO

- ✤ Test case: 1000/2000 GeV gluino; 13 TeV collisions
- ✤ Gluino decays: MadSpin
- ✤ Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands]
- ✤ Jet reconstruction: anti-k_T & FASTJET [Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]
- ✤ Analysis & figure: MADANALYSIS 5 [Conte, BF, Serret]

EXAMPLE 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

✦ Total rates at 8 TeV and 13 TeV

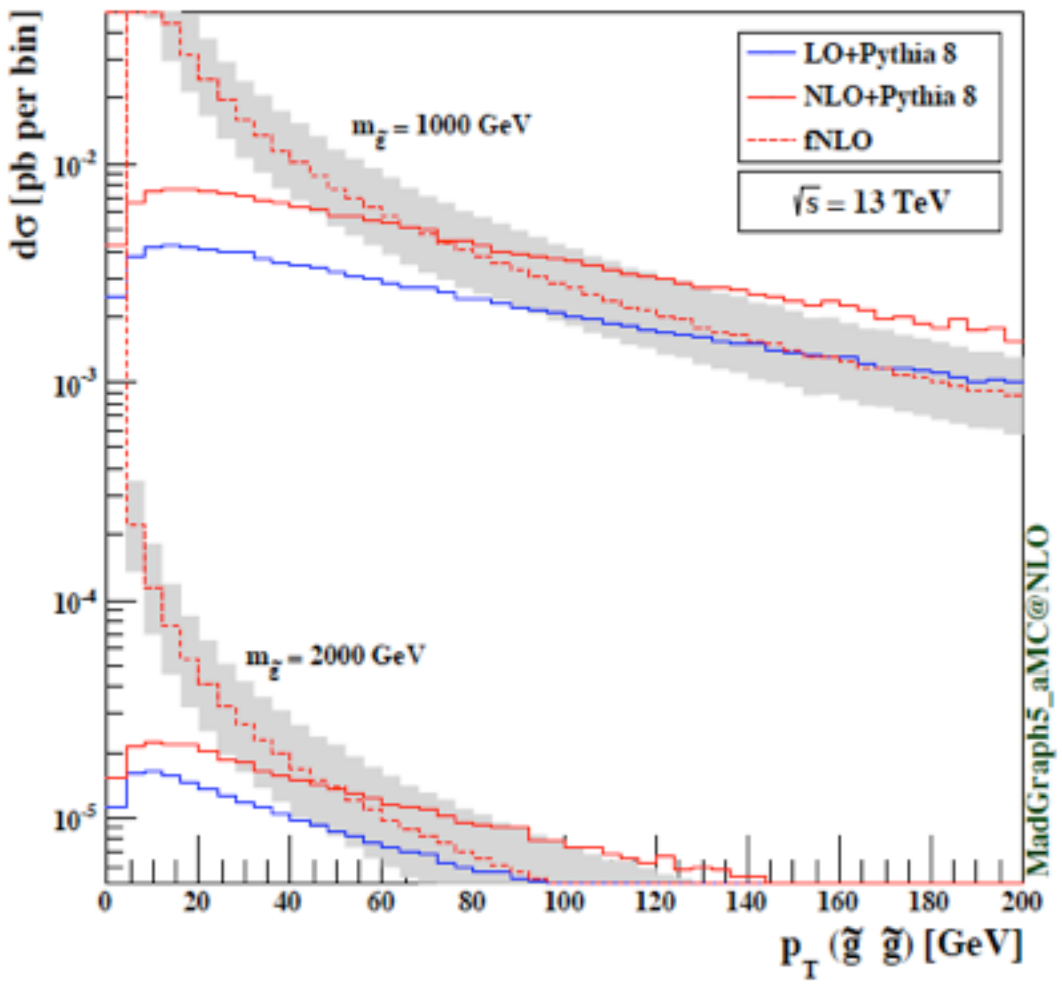
Splitting SUSY

Numerically validated

$m_{\tilde{g}}$ [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
200	$2104^{+30.3\%\,+14.0\%}_{-21.9\%\,-14.0\%}$	$3183^{+10.8\%\,+1.8\%}_{-11.6\%\,-1.8\%}$
500	$15.46^{+34.7\%\,+19.5\%}_{-24.1\%\,-19.5\%}$	$24.90^{+12.5\%\,+3.7\%}_{-13.4\%\,-3.7\%}$
750	$1.206^{+35.9\%\,+23.5\%}_{-24.6\%\,-23.5\%}$	$2.009^{+13.5\%\,+5.5\%}_{-14.1\%\,-5.5\%}$
1000	$1.608 \cdot 10^{-1}{}^{+36.3\%\,+26.4\%}_{-24.8\%\,-26.4\%}$	$2.743 \cdot 10^{-1}{}^{+14.4\%\,+7.3\%}_{-14.8\%\,-7.3\%}$
1500	$6.264 \cdot 10^{-3}{}^{+36.2\%\,+29.4\%}_{-24.7\%\,-29.4\%}$	$1.056 \cdot 10^{-2}{}^{+16.1\%\,+11.3\%}_{-15.8\%\,-11.3\%}$
2000	$4.217 \cdot 10^{-4}{}^{+35.6\%\,+29.8\%}_{-24.5\%\,-29.8\%}$	$6.327 \cdot 10^{-4}{}^{+17.7\%\,+17.8\%}_{-16.6\%\,-17.8\%}$

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model susyqcd_ufo
5. > generate p p > go go [QCD]
6. > output pp2gogoQCD
7. > launch

- ✤ NNPDF3.0; scales set to the HT/2; uncertainties evaluated as for the stop case
- ✤ Validation with PROSPINO 2.1



✦ Differential distributions at NLO

- ✤ Test case: 1000/2000 GeV gluino; 13 TeV collisions
- ✤ Gluino decays: MadSpin
- ✤ Shower: PYTHIA 8.2 **[Sjostrand, Mrenna & Skands**
- ✤ Jet reconstruction: anti-k_T & FASTJET

[Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]

- ✤ Analysis & figure: MADANALYSIS 5

[Conte, BF, Serret

EXAMPLE 3: GLUINO-PAIR IN SUSY QCD

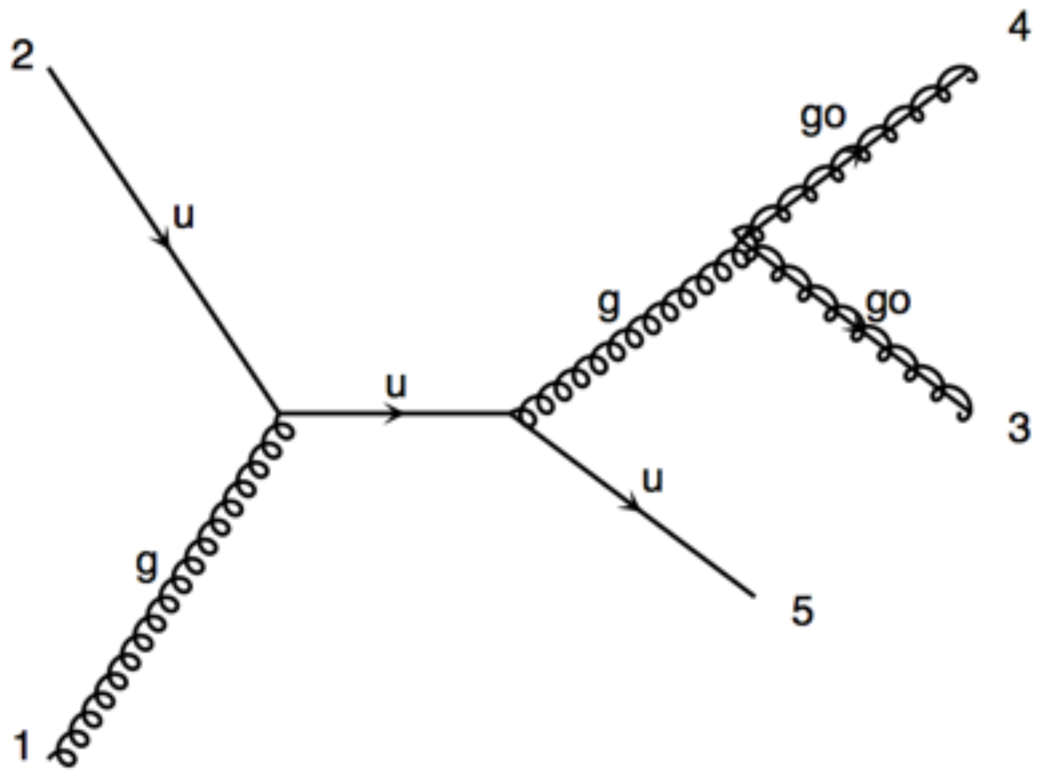
Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)

- Explore full spectrum (in the future):
  - New hadron states (R-hadron, gluinonium etc)
  - Separate resonance and non-resonance contributions

EXAMPLE 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)

- Explore full spectrum (in the future):
  - New hadron states (R-hadron, gluinonium etc)
  - Separate resonance and non-resonance contributions

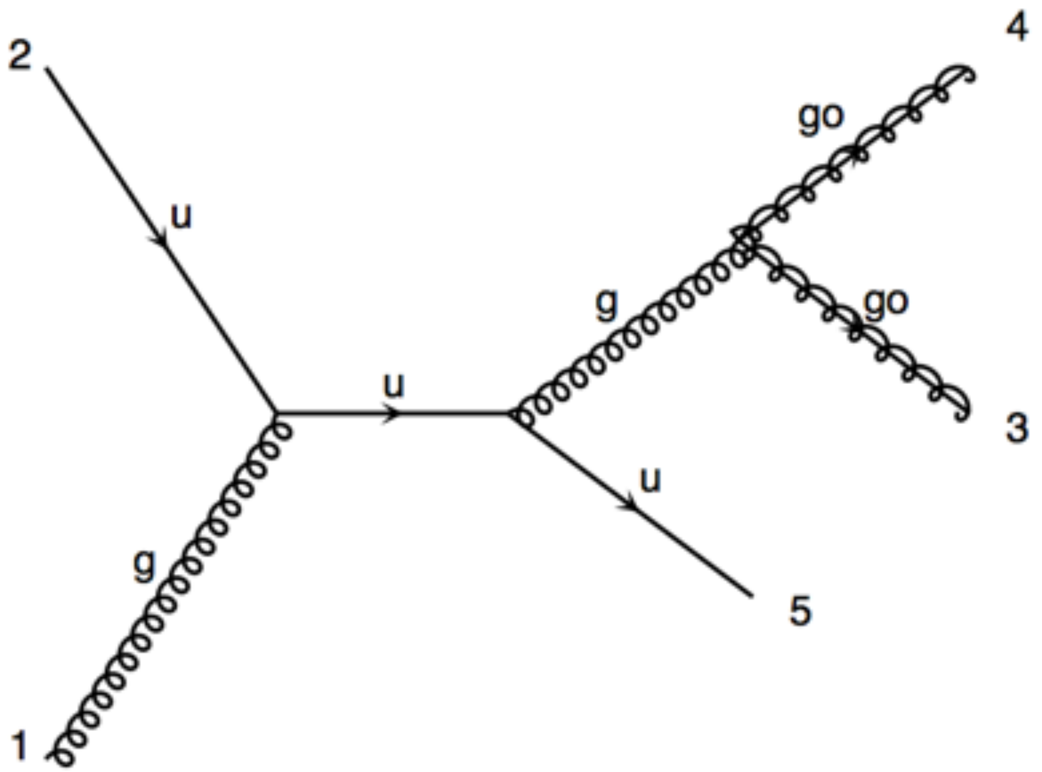


NLO diagram for gluino-pair

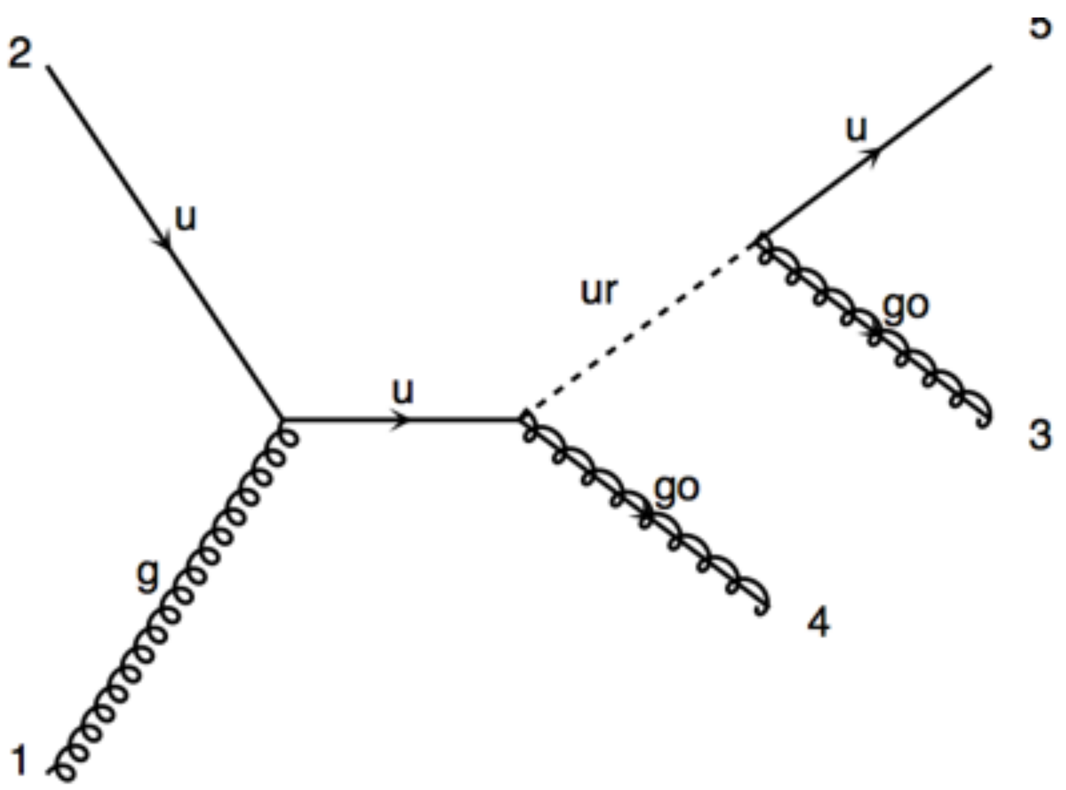
EXAMPLE 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)

- Explore full spectrum (in the future):
  - New hadron states (R-hadron, gluinonium etc)
  - Separate resonance and non-resonance contributions



NLO diagram for gluino-pair

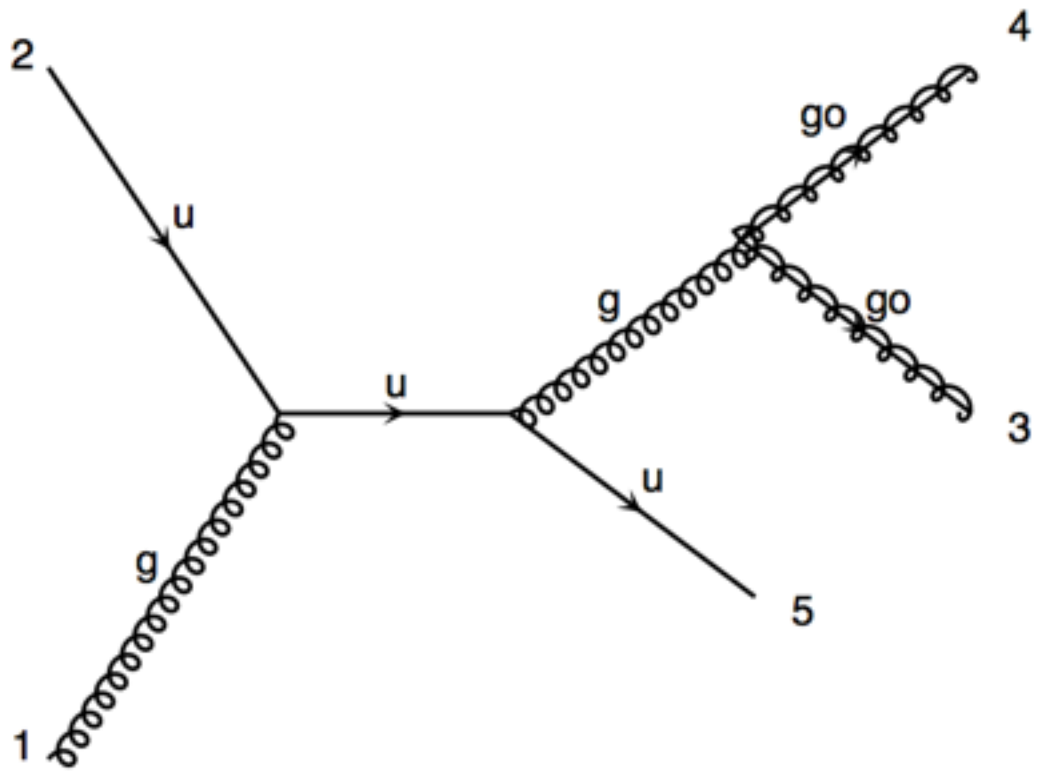


LO diagram for gluino-squark with squark decay

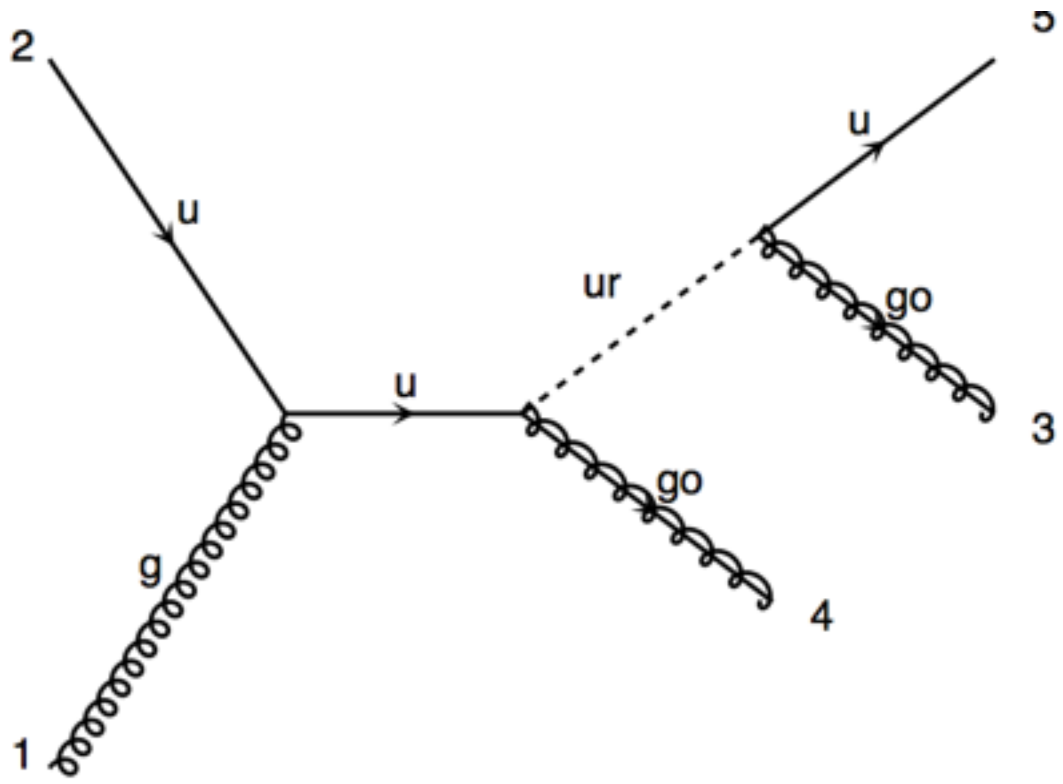
EXAMPLE 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)

- Explore full spectrum (in the future):
  - New hadron states (R-hadron, gluinonium etc)
  - Separate resonance and non-resonance contributions



NLO diagram for gluino-pair



LO diagram for gluino-squark with squark decay

On-Shell subtraction **MadOS**

OTHER EFFORTS IN FR/MG5AMC @ NLO

- Top FCNC Degrande, Maltoni, Wang, Zhang (PRD'15)
- DM with spin-0/1 s-channel mediator Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen (EPJC'15); Neubert, Wang, Zhang (arXiv:1509.05785)
- Charged Higgs production in 2HDM and Georgi-Machacek model Degrande, Ubiali, Wiesemann, Zaro (JHEP'15); Degrande, Hartling, Logan, Peterson, Zaro (arXiv:1512.01243)
- Other simple extension of SM: 2HDM etc Degrande (CPC'15)
- More efforts are ongoing

THANK YOU FOR YOUR ATTENTION !

BACK UP

MC@NLO

Frixione, Webber (JHEP'02)

- One can compensate for this double counting by considering MC counterterms which are defined the contribution of the PS to go from the Born n-body to the (n+1)-body configuration

PS operators

$$\frac{d\sigma^{\mathrm{NLO+PS}}}{d\mathcal{O}} \sim \int_n \left[|\mathcal{A}^{(n,0)}|^2 + \left(2\Re\{\mathcal{A}^{(n,1)}\mathcal{A}^{(n,0)*}\} + \int_1 S\right) + \int_1 (MC - S)\right] I_{\mathrm{PS}}^{(n)}(\mathcal{O}) + \left[\int_n \left(|\mathcal{A}^{(n+1,0)}|^2 - MC\right)\right] I_{\mathrm{PS}}^{(n+1)}(\mathcal{O})$$

- The MC counterterms can be written in a process-independent way, so that the matching procedure is automated in aMC@NLO.

- The prediction obtained has the ME behaviour in the hard emission region $I_{\mathrm{PS}}^{(n+1)}(\mathcal{O}) \sim 1, I_{\mathrm{PS}}^{(n)}(\mathcal{O}) \sim 0, MC \sim 0$ and the PSMC one in the soft region where $MC \sim |\mathcal{A}^{(n+1,0)}|^2$.

MC@NLO

Frixione, Webber (JHEP'02)

- Substituting in the shower operator by its expansion at NLO in

$$\frac{d\sigma^{\mathrm{NLO+PS}}}{d\mathcal{O}} \sim \int_n \left[|\mathcal{A}^{(n,0)}|^2 + \left(2\Re\{\mathcal{A}^{(n,1)}\mathcal{A}^{(n,0)*}\} + \int_1 S\right) + \int_1 (MC - S)\right] I_{\mathrm{PS}}^{(n)}(\mathcal{O})$$

$$+ \qquad \left[\int_n \left(|\mathcal{A}^{(n+1,0)}|^2 - MC\right)\right] I_{\mathrm{PS}}^{(n+1)}(\mathcal{O})$$

- where $I_{\mathrm{PS}}^{(n)}(\mathcal{O})d\mathcal{O} = (1 - \int_1 \frac{MC}{|\mathcal{A}^{(n,0)}|^2}) + \mathcal{O}(\alpha_S^2)$.

- It shows that $d\sigma^{\mathrm{NLO+PS}} = d\sigma^{\mathrm{NLO}}$.

- Moreover, the term $\left(|\mathcal{A}^{(n+1,0)}|^2 - MC\right)$ is bounded without introducing any unphysical cutoffs. However, it is not always positive, so the events can be unweighted but only up to a sign.

- MC is parton shower program dependent. Should be extended if one need a new kernel in BSM (like new color, e.g. sextet).