From Lagrangians to events

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LPTHE / Sorbonne Université

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Outline

1. Introduction: overview of an LHC collision
2. Implementing models into Monte Carlo event generators
3. From models to hard scattering events
4. Summary

The quest for new physics at the LHC

✦ The quest for physics beyond the Standard Model at the LHC is on-going

- ✤ How to get hints of new physics?
  - ★ Confront data to the Standard Model expectation in search channels
  - ★ Observe unexplained deviations at a good confidence level
- ✤ Theory ingredient 1: predictions for the Standard Model background
- ✤ Theory ingredient 2: predictions for the new physics signals

Monte Carlo tools and new physics

✦ Path towards the characterization of (potentially observed) new physics

✤ Getting information on the nature of an observation

★ Fitting (and interpreting) deviations by some new physics signals

★ Leading order Monte Carlo tools and techniques can do a proper-enough job

✤ Final words on the nature of any potential new physics

★ Accurate measurements of the model parameters

★ More precise predictions are mandatory

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✦ Monte Carlo tools play a key role at each step of this new physics story

✤ Prospective collider studies (*a priori* preparation)

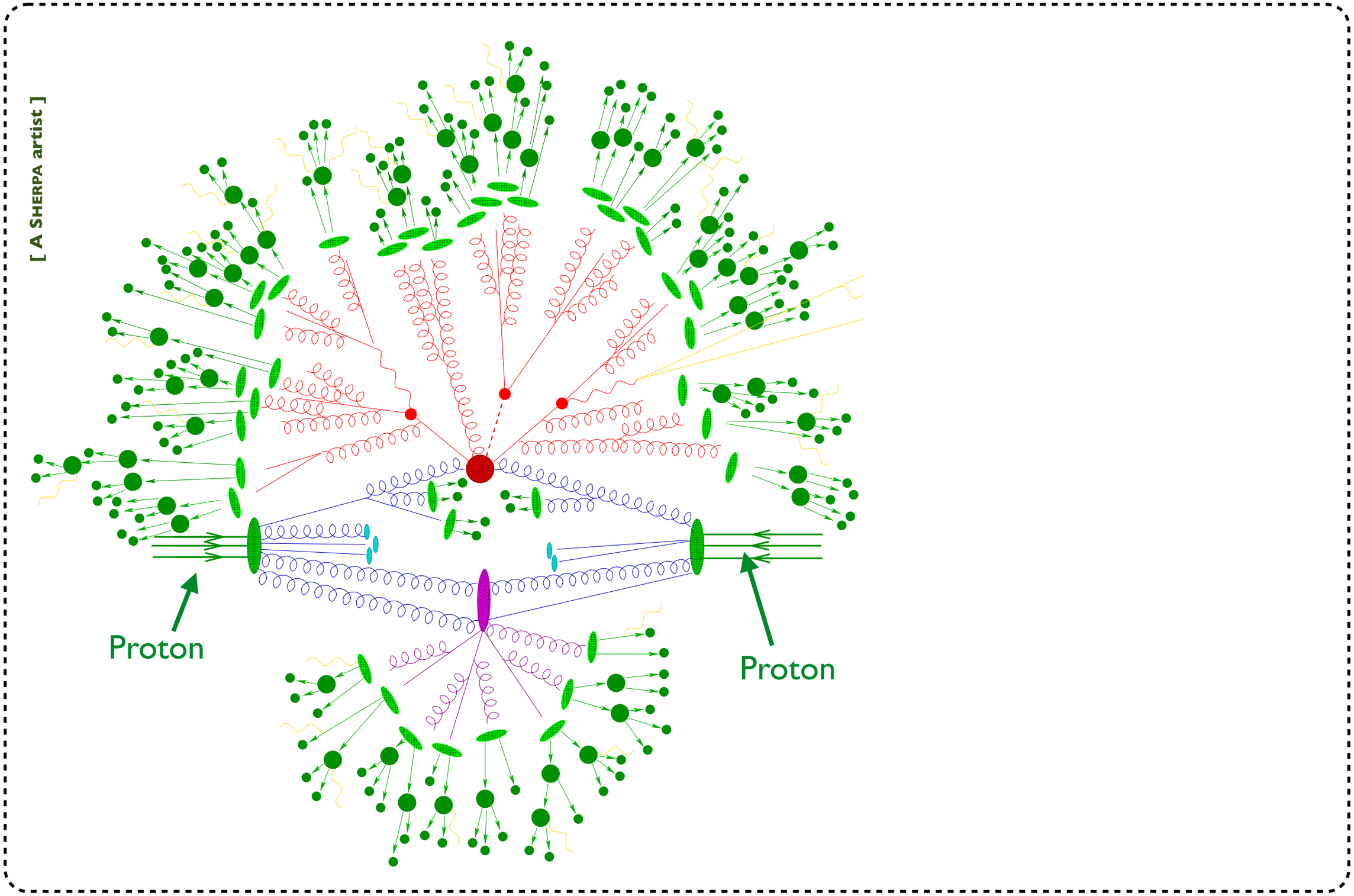
★ Study of various new physics signal

✤ Reinterpretation of existing results (*a posteriori* reactions to announcements)

★ LHC recasting in new theoretical context

New physics simulations for the LHC are crucial

Deciphering a proton-proton collision



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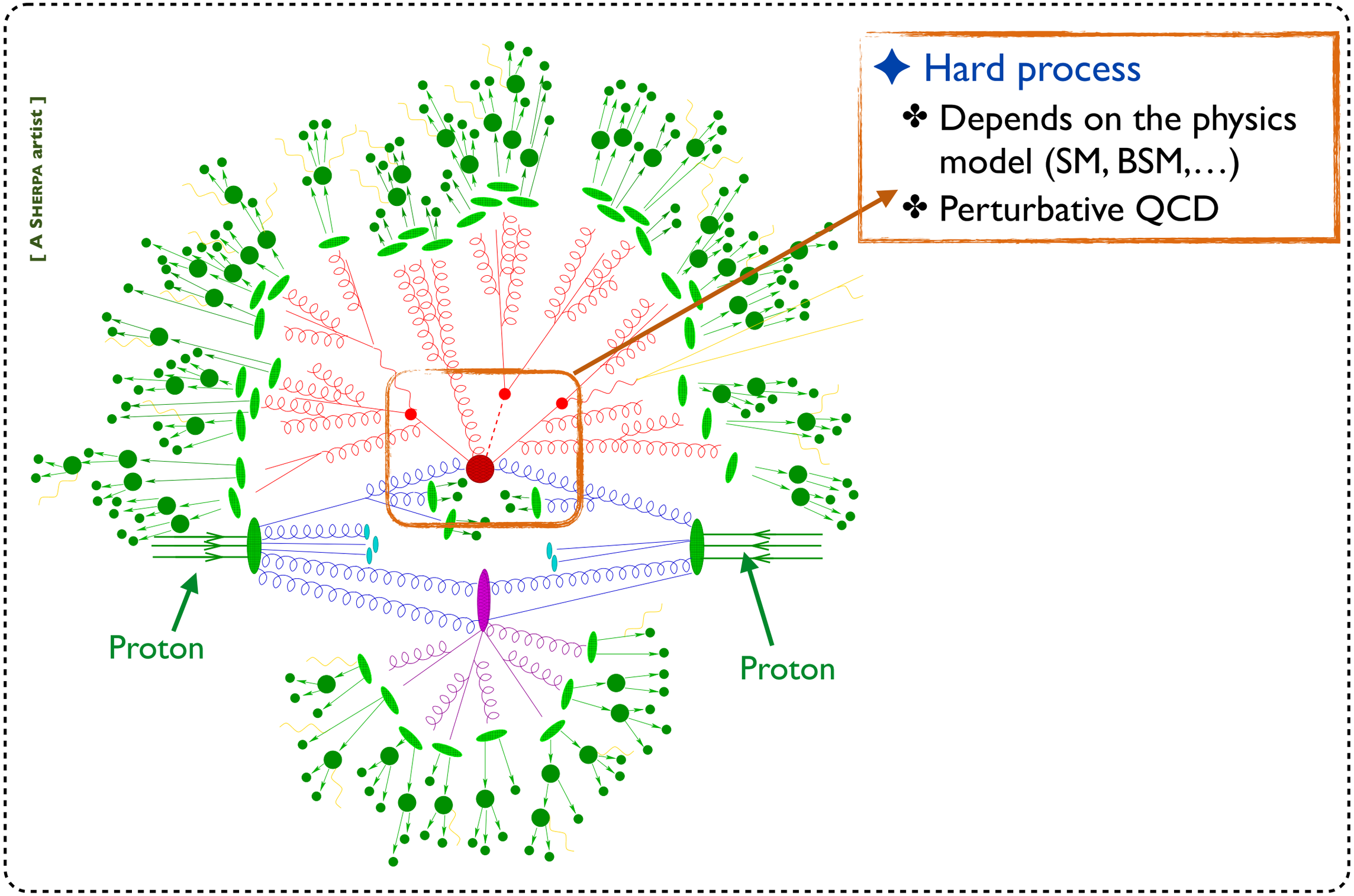

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- ✤ Depends on the physics model (SM, BSM,…)
- ✤ Perturbative QCD

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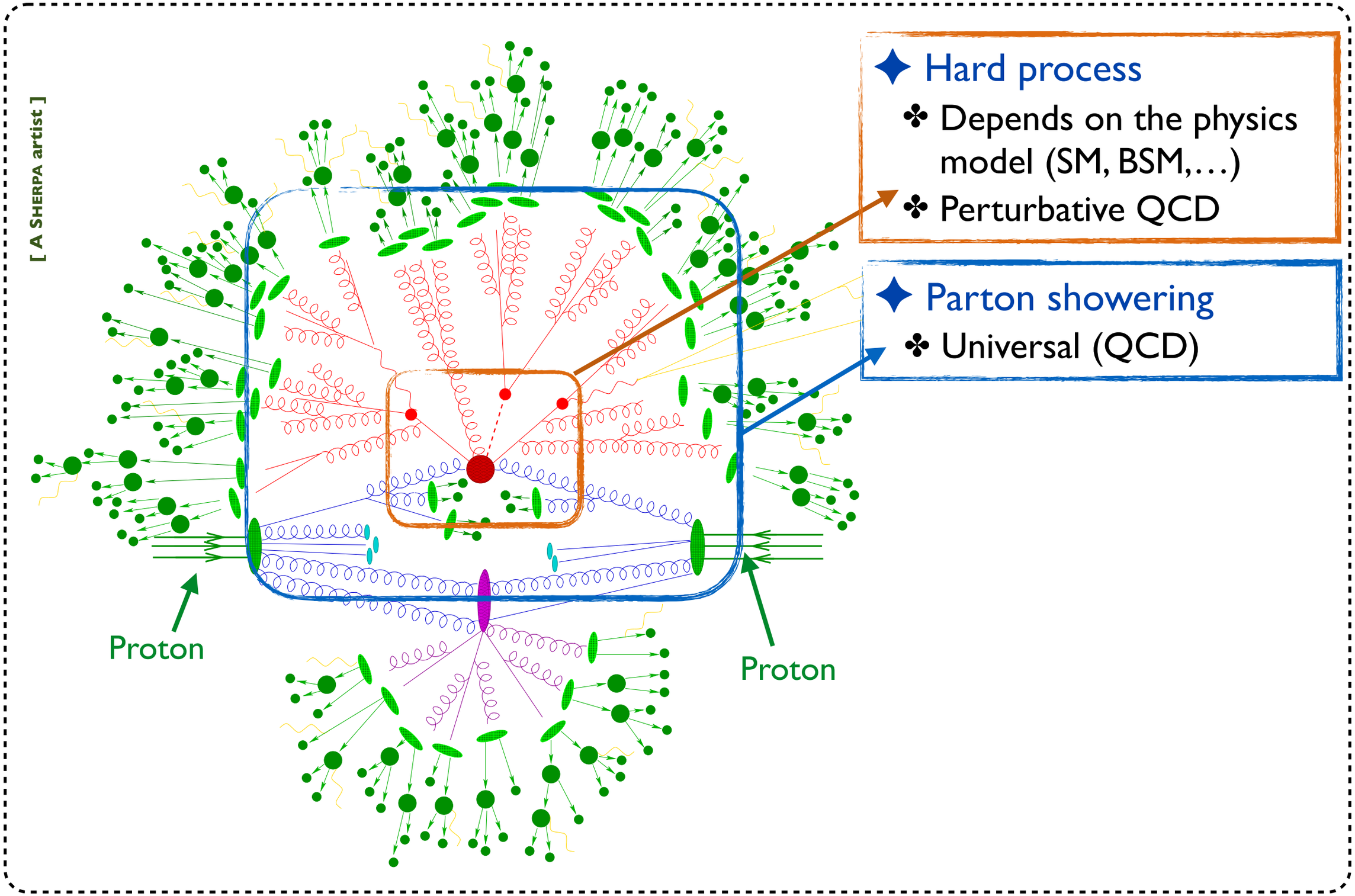

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- ✤ Universal (QCD)

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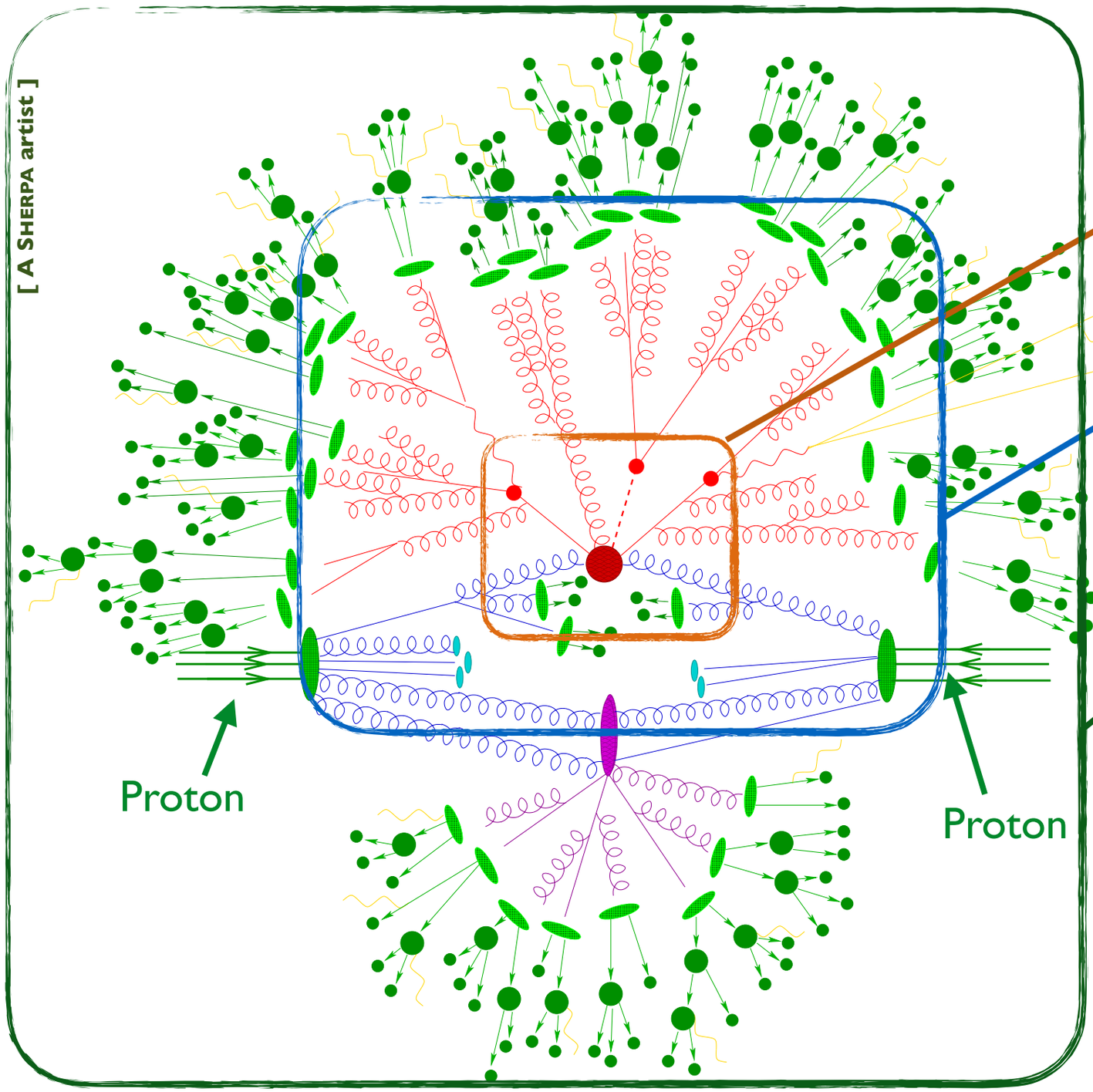

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- ✤ Models-based, universal

✦ Underlying event
- ✤ Model-based, non universal

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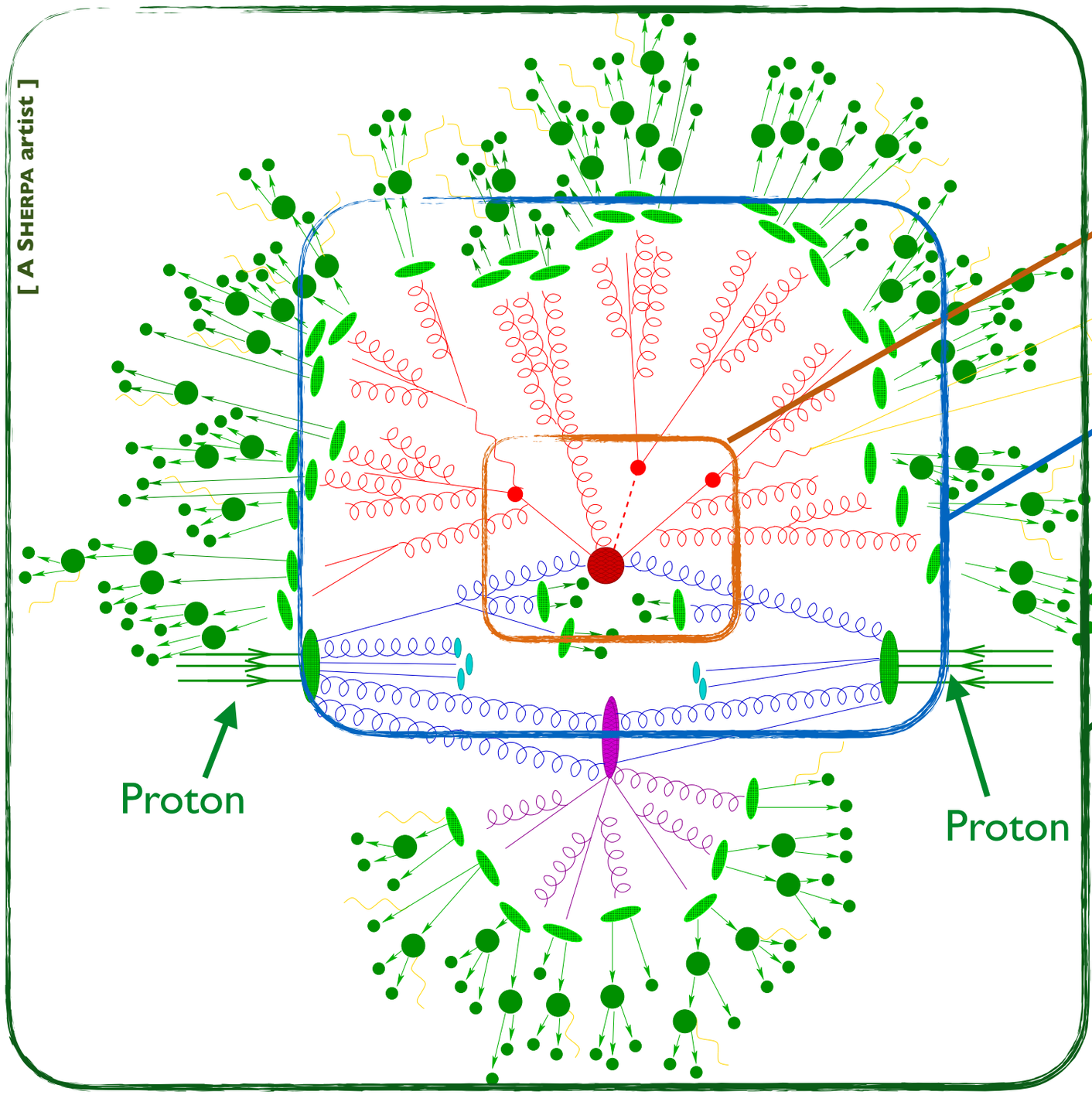

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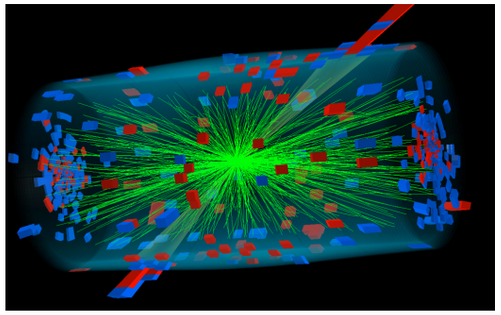
✦ Detector simulation



Monte Carlo simulations of proton collisions

✦ We have a multi-scale problem where each ingredient factorizes

- ✤ Hard scattering process: high-scale, potential new physics
- ✤ Parton showering and hadronization: driven by QCD
- ✤ Detector simulation: driven by the detector choice

We have tools and methods to handle each step

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✦ The need for better simulation tools has spurred a very intense activity

- ✤ Matrix-element generation (CALCHEP, HERWIG, MG5_AMC, SHERPA, WHIZARD, *etc.*)
- ✤ Higher-order computations (MC@NLO, POWHEG, NNLO)
- ✤ Parton showering and hadronization (PYTHIA, HERWIG, SHERPA)
- ✤ Matrix element - parton showering matching
- ✤ Merging techniques (MLM, CKKW, FxFx, UNLOPS, *etc.*)

SM and BSM simulations: the status

✦ Standard Model simulations

- ✤ All processes relevant for the LHC can be simulated with a very good precision
- ✤ The precision will improve in the next few years (*e.g.* electroweak corrections)

SM simulations under control
What about new physics?

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What about new physics?

✦ The challenge with respect to new physics is different

- ✤ Theoretically, we are still in the dark
  - ★ No sign of new physics, all measurements are Standard-Model-like
- ✤ There is not any leading new physics candidate theory
  - ★ Plethora of models to implement in the tools

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✦ New physics is a standard in many tools today

- ✤ Result of 20 years of developments
- ✤ NLO and loop-induced processes can now be simulated automatically
- ✤ BSM precision simulations are standard (in particular in MG5_aMC@NLO)

What are the ingredients of this success?

New physics @ colliders: keys for a success

✦ The connection of a physics models to event analysis is streamlined

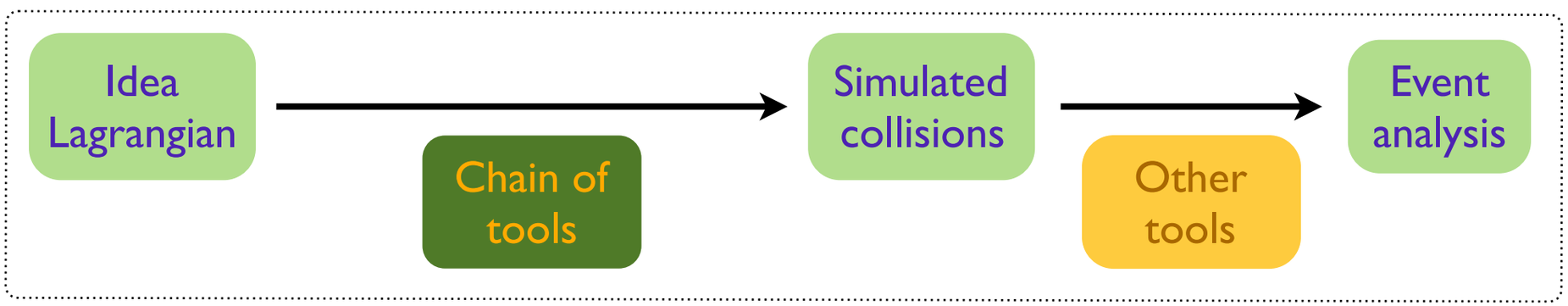
✤ This relies on a framework:

★ Any new physics model can be implemented

★ Any new physics model can be tested against data

★ Easy to validate, to maintain

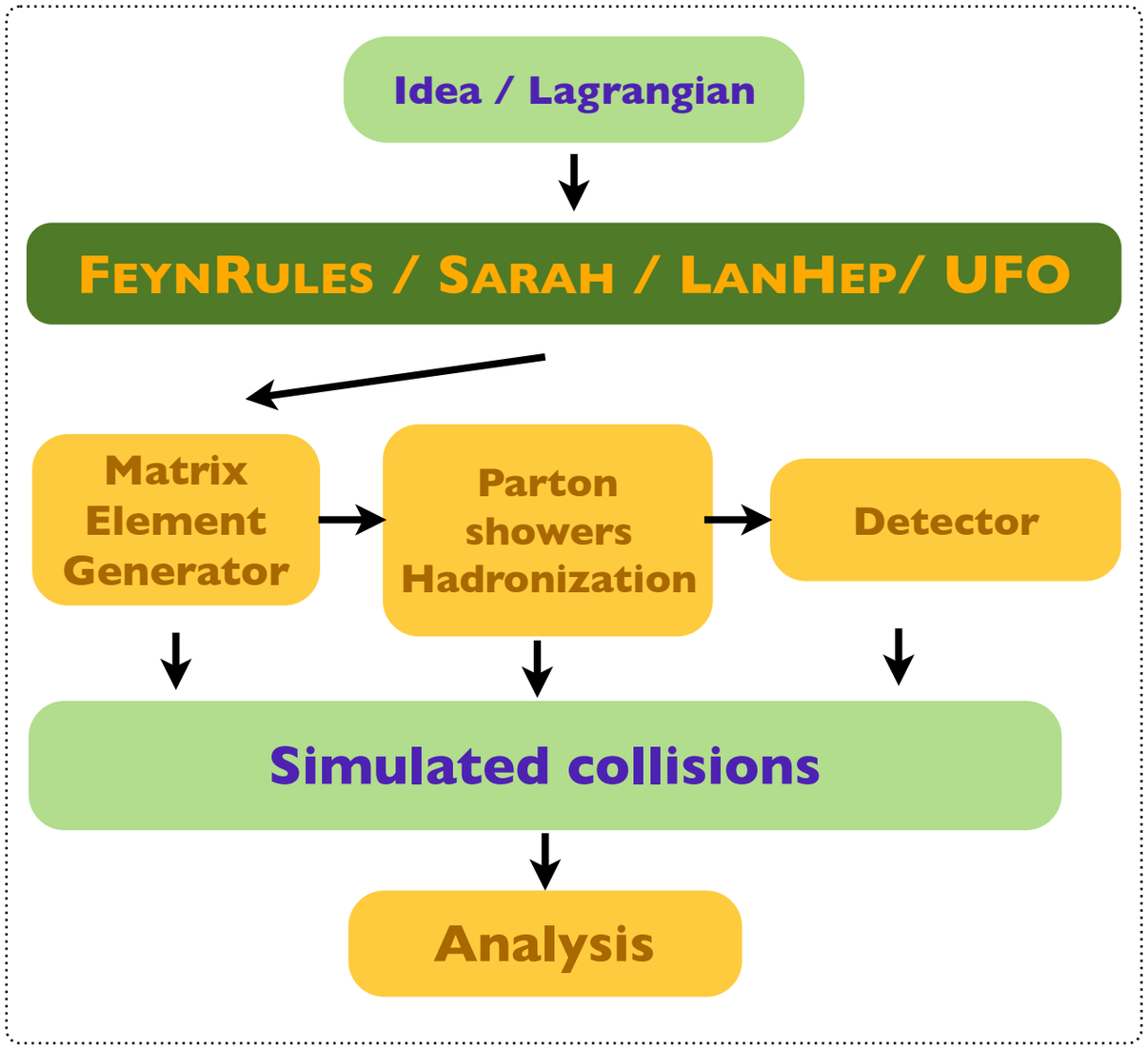
★ Easily integrable in a software chain



A comprehensive approach to MC simulations

[Christensen, de Aquino, Degrande, Duhr, BF, Herquet, Maltoni & Schumann (EPJC`11)]

✦ Tools connecting an idea to simulated collisions



- ✤ Model building
- ✤ Hard scattering
  - ★ Feynman diagram and amplitude generation
  - ★ Monte Carlo integration
  - ★ Event generation
- ✤ QCD environment
  - ★ Parton showering
  - ★ Hadronization
  - ★ Underlying event
- ✤ Detector simulation
  - ★ Simulation of the detector response
  - ★ Object reconstruction
- ✤ Event analysis
  - ★ Signal/background analysis
  - ★ LHC recasting

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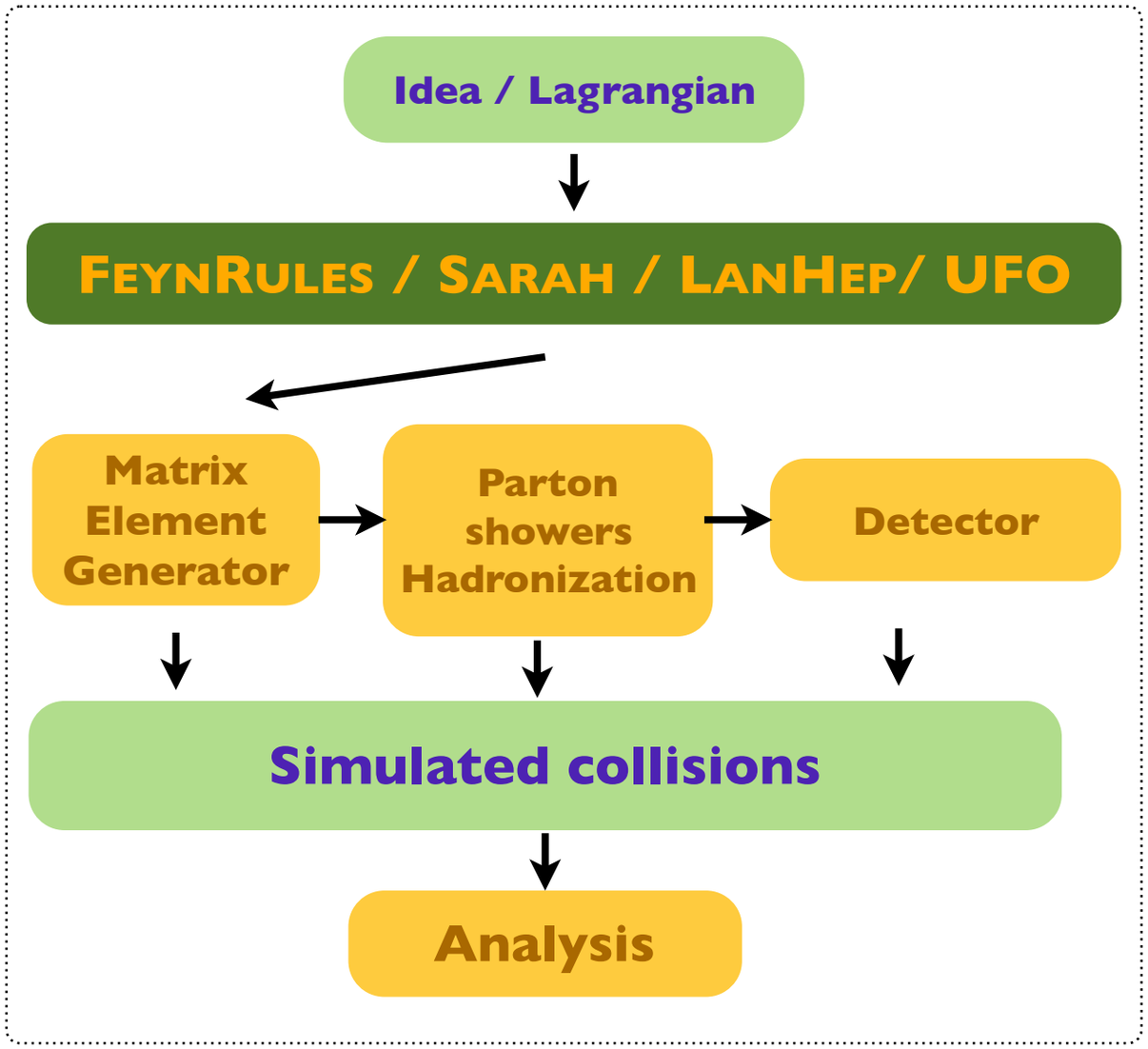

- ✤ Model building
  - ★ FeynRules, Sarah, LanHep
  - ★ UFO
- ✤ Matrix element generation
  - ★ CalcHep, Herwig++, MG5_aMC, Sherpa, Whizard, …
- ✤ QCD environment
  - ★ Herwig, Pythia, Sherpa
- ✤ Detector simulation
  - ★ Delphes / PGS
  - ★ Rivet / MadAnalysis 5
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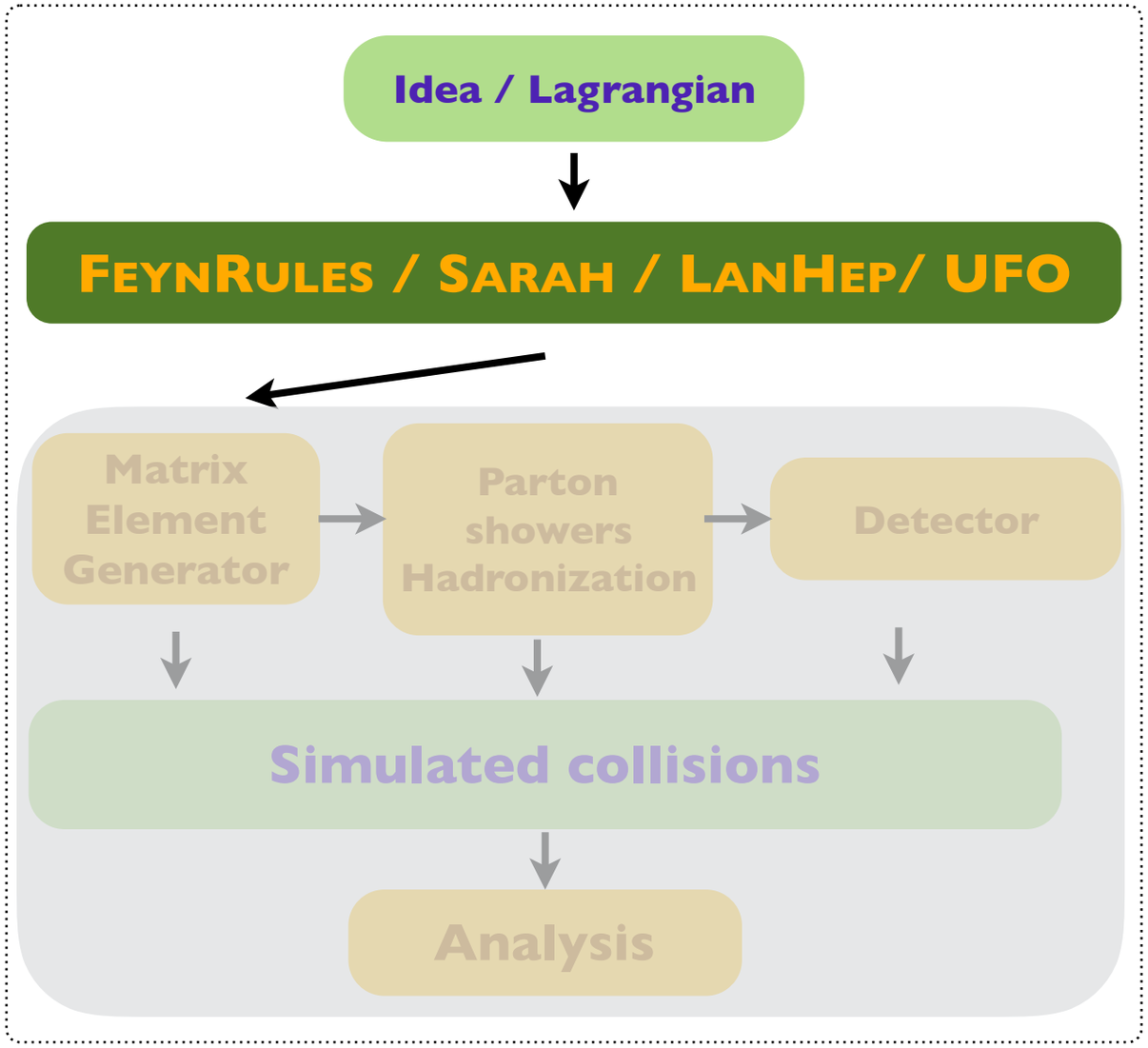

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New physics simulations: the 'how-to'

✦ How to implement a new physics model in a Monte Carlo program?

★ Model definition: particles, parameters & vertices (≡ Lagrangian)

★ To be translated in a programming language, following some conventions, *etc.*

★ Tedious, time-consuming, error prone

★ Iterations for all considered tools and models

★ Beware of the restrictions of each tool (Lorentz structures, color structures)

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★ **Highly redundant** (each tool, each model)

★ **No-brainer tasks** (from Feymman rules to codes)

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Systematization
Automation

A Monte Carlo tool framework for new physics

✦ Specifications

✤ Inputs / Outputs

★ A physics object: the Lagrangian (unique and non ambiguous, no MC dependence)

★ Flexible (a change in the model = a change in the Lagrangian)

★ Automatic derivation of the Feynman rules and generate MC model files

✤ Validation

★ Automatic and systematical

✤ Distribution

★ Public, open source, transparent

★ No private tools

[Christensen, de Aquino, Degrande, Duhr, BF, Herquet, Maltoni & Schumann (EPJC'11)]

Existing programs

✦ The FeynRules platform (since 2009)

- ✤ Automatic linking of Lagrangians to files in a given programming language
  - ★ With all model particles, interactions, *etc.*
- ✤ Working environment: Mathematica
  - ★ Flexibility, symbolic manipulations, easy implementation of new methods, *etc.*
  - ★ Shipped with many computation platforms (superspace, spectrum, decays, NLO, *etc.*)
- ✤ Interfaced to many Monte Carlo tools
  - ★ Dedicated interfaces (CalcHep, FeynArts, and more in the past)
  - ★ Interfaced to more tools via the UFO (Herwig, MG5_aMC, Sherpa, Whizard, …)
- ✤ Very few limitations on models
  - ★ Higher-dimensional operators
  - ★ Spins (up to 2); color structures (1, 3, 6, 8)

[Christensen & Duhr (CPC '09)]
[Alloul, Christensen, Degrande, Duhr & BF (CPC'14)]

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- ✤ Automatic linking of Lagrangians to files in a given programming language
- ✤ Working environment: C
- ✤ Initially restricted to CalcHep/CompHep
- ✤ Now: FeynArts and UFO outputs

[Semenov (NIMA'97; CPC'98; CPC'09; CPC'16)]

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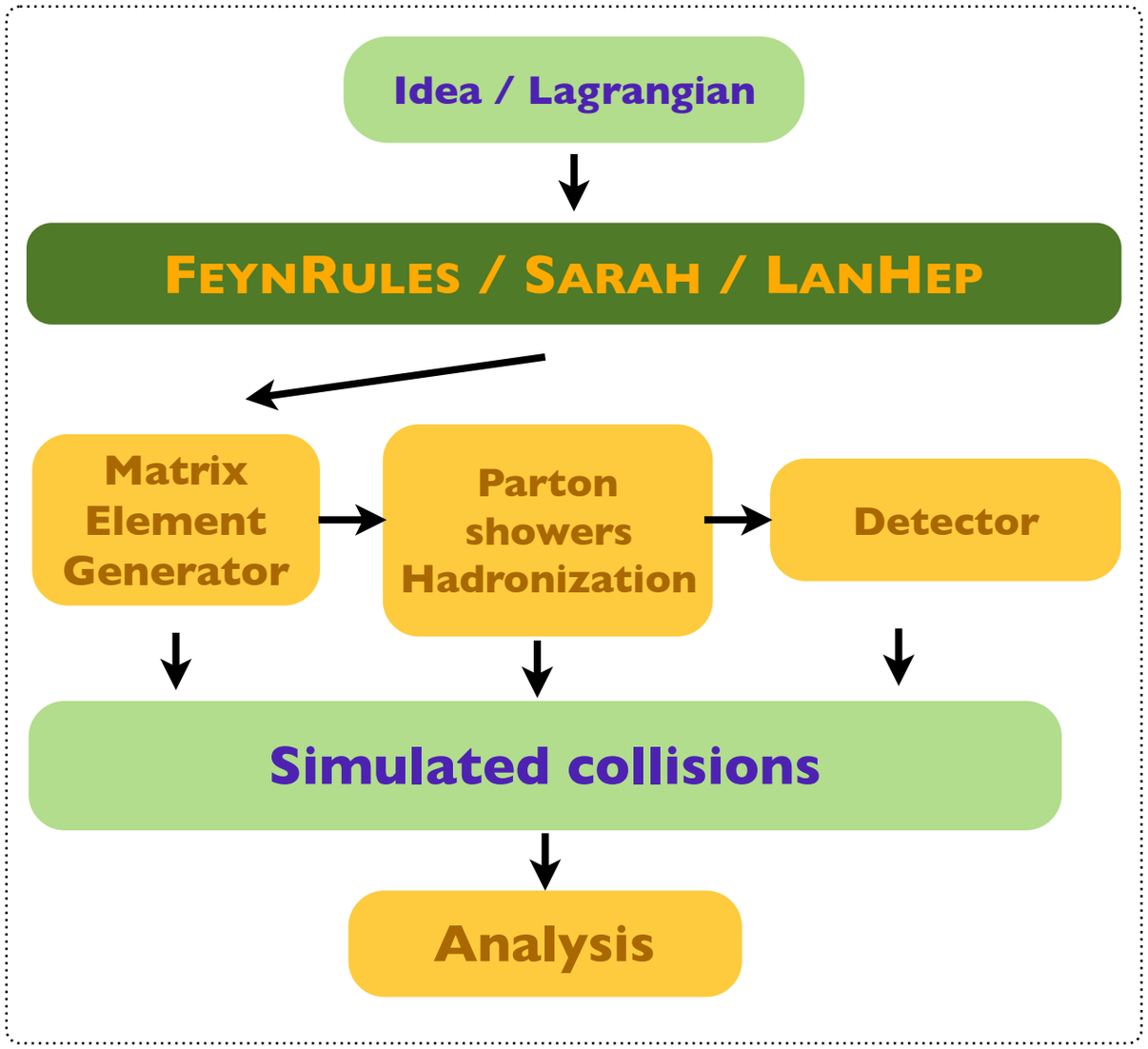
✦ The SARAH package (since 2013)

- ✤ Automatic linking of Lagrangians to files in a given programming language
- ✤ Working environment: Mathematica
- ✤ Spectrum generator, indirect constraints
- ✤ Interfaced to many tools (CalcHep, CompHep, FeynArts, UFO, Whizard)

[Staub (CPC'13; CPC'14)]

New physics simulations in details

✦ The implementation of any new physics theory in a MC tool is straightforward



Many interfaces to specific tools

- ★ Removal of non compliant vertices
- ★ Translation to a specific format/language
- ★ To be maintained

⚠ **Not efficient**

Why do we need UFOs?

✦ Color structures: not supported in full generality by MC 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 (sometimes limited), sometimes 6

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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**

A step further: the Universal FeynRules Output

✦ The UFO in a nutshell

[Degrande, Duhr, BF, Grellscheid, Mattelaer, Reiter (CPC '12)]
[Degrande, Duhr, BF, Hirschi, Mattelaer, Shao *et al.* (*in prep.*)]

- ✤ UFO ≡ Universal FeynRules output
  - ★ Universal as not tied to any specific Monte Carlo program
- ✤ Consists of a Python module to be linked to any code
- ✤ This module contains all the model information
  - ★ Allows the models to contain generic color and Lorentz structures
- ✤ Can be employed for next-to-leading order calculations

✦ The UFO is now a standard used by many programs (on top of FeynRules)

ALOHA | GOSAM | HERWIG ++ | MADANALYSIS 5 | SHERPA

MADGRAPH5_aMC@NLO | WHIZARD | LANHEP | SARAH

The UFO in practice

✦ The UFO is a set of PYTHON files

✤ Factorization of the information: particles, interactions, propagation, parameters, NLO, *etc*.

✦ Example

```
[fuks@Benjamins-MacBook-Pro-3 ~/Work/tools/FeynRules/trunk/models/SUSYQCD_UFO$] ls
CT_couplings.py     SUSYQCD_UFO.log     couplings.py        object_library.py   propagators.py
CT_parameters.py    __init__.py         function_library.py parameters.py       vertices.py
CT_vertices.py      coupling_orders.py  lorentz.py          particles.py        write_param_card.py
[fuks@Benjamins-MacBook-Pro-3 ~/Work/tools/FeynRules/trunk/models/SUSYQCD_UFO$]
```

Parameters

Propagators

Interactions

Particles

NLO

Particles

- Particles are stored in the particles.py file
  - Instances of the particle class
  - Attributes: particle spin, color representation, mass, width, PDG code, *etc.*
  - Antiparticles automatically derived

```
G = Particle(pdg_code = 21,
             name = 'G',
             antiname = 'G',
             spin = 3,
             color = 8,
             mass = Param.ZERO,
             width = Param.ZERO,
             texname = 'G',
             antitexname = 'G',
             charge = 0)

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)
```

```
sq1 = Particle(pdg_code = 1000006,
               name = 'sq1',
               antiname = 'sq1~',
               spin = 1,
               color = 3,
               mass = Param.Msq1,
               width = Param.Wsq1,
               texname = 'sq1',
               antitexname = 'sq1~',
               charge = 0)

sq1__tilde__ = sq1.anti()

sq2 = Particle(pdg_code = 2000006,
               name = 'sq2',
               antiname = 'sq2~',
               spin = 1,
               color = 3,
               mass = Param.Msq2,
               width = Param.Wsq2,
               texname = 'sq2',
               antitexname = 'sq2~',
               charge = 0)

sq2__tilde__ = sq2.anti()
```

```
q = Particle(pdg_code = 6,
             name = 'q',
             antiname = 'q~',
             spin = 2,
             color = 3,
             mass = Param.Mq,
             width = Param.Wq,
             texname = 'q',
             antitexname = 'q~',
             charge = 0)

q__tilde__ = q.anti()
```

Parameters

- Parameters are stored in the parameters.py file
  - Instances of the parameter class
  - External parameters are organized following a Les Houches-like structure (blocks and counters)
  - PYTHON-compliant formula for the internal parameters

```
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')
```

```
Mgo = Parameter(name = 'Mgo',
                nature = 'external',
                type = 'real',
                value = 500,
                texname = '\\text{Mgo}',
                lhablock = 'MASS',
                lhacode = [ 1000021 ])

Wq = Parameter(name = 'Wq',
               nature = 'external',
               type = 'real',
               value = 1.50833649,
               texname = '\\text{Wq}',
               lhablock = 'DECAY',
               lhacode = [ 6 ])
```

Interactions: generalities

✦ Vertices decomposed in a spin x color basis (coupling strengths ≡ coordinates)

✤ Example: the quartic gluon vertex can be written as

$$
\begin{aligned}
& i g_s^2 \, f^{a_1 a_2 b} f^{b a_3 a_4} \, (\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4}) \\
& \quad + i g_s^2 \, f^{a_1 a_3 b} f^{b a_2 a_4} \, (\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}) \\
& \quad + i g_s^2 \, f^{a_1 a_4 b} f^{b a_2 a_3} \, (\eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4})
\end{aligned}
\quad \Rightarrow \quad
\begin{aligned}
& \left(f^{a_1 a_2 b} f^{b a_3 a_4}, \; f^{a_1 a_3 b} f^{b a_2 a_4}, f^{a_1 a_4 b} f^{b a_2 a_3} \right) \\
& \times \begin{pmatrix} i g_s^2 & 0 & 0 \\ 0 & i g_s^2 & 0 \\ 0 & 0 & i g_s^2 \end{pmatrix} \begin{pmatrix} \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} \\ \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \\ \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \end{pmatrix}
\end{aligned}
$$

★ 3 elements for the color basis
★ 3 elements for the spin (Lorentz structure) basis
★ 9 coordinates (6 are zero)

✤ Several files are used for the storage of the information

Example: the quartic gluon vertex

✦ General information in vertex.py

```
V_2 = Vertex(name = 'V_2',
             particles = [ P.G, P.G, P.G, P.G ],
             color = [ 'f(-1,1,2)*f(3,4,-1)', 'f(-1,1,3)*f(2,4,-1)', 'f(-1,1,4)*f(2,3,-1)' ],
             lorentz = [ L.VVVV1, L.VVVV2, L.VVVV3 ],
             couplings = {(1,1):C.GC_4,(0,0):C.GC_4,(2,2):C.GC_4})
```

★ lorentz ≡ spin basis
(in lorentz.py; common to all vertices)

★ color ≡ color basis

★ couplings ≡ coordinates
(in couplings.py; common to all vertices)

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

Example: the quartic gluon vertex

✦ General information in vertex.py

```
V_2 = Vertex(name = 'V_2',
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✦ Lorentz structures: straightforward implementations in lorentz.py

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

Example: the quartic gluon vertex

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```
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```

✦ Couplings: straightforward implementations in couplings.py

```
GC_4 = Coupling(name = 'GC_4',
                value = 'complex(0,1)*G**2',
                order = {'QCD':2})
```

Coupling orders: for selecting diagrams

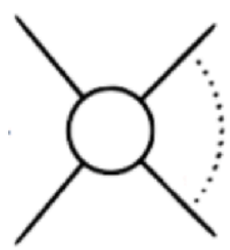
Recap' on NLO calculations

✦ Contributions to an NLO result in QCD

✤ Three ingredients: the Born, virtual loop and real emission contributions

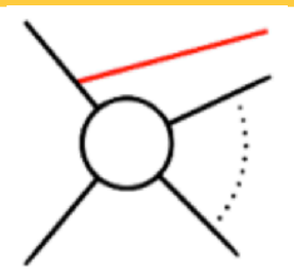
$$\sigma_{NLO} = \int \mathrm{d}^4\Phi_n \mathcal{B} \quad + \quad \int \mathrm{d}^4\Phi_n \int_{\mathrm{loop}} \mathrm{d}^d\ell \, \mathcal{V} \quad + \quad \int \mathrm{d}^4\Phi_{n+1} \, \mathcal{R}$$

Born



Virtuals: one extra power of α_s and divergent

Reals: one extra power of α_s and divergent



Extra information is needed

Virtual contributions

✦ Loop diagram calculations

✤ Calculations to be done in $d=4-2\varepsilon$ dimensions

★ Divergences made explicit ($1/\varepsilon^2$, $1/\varepsilon$)

✤ Rewriting loop integrals with scalar integrals

$$\int \mathrm{d}^d\ell \frac{N(\ell)}{D_0 D_1 \cdots D_{m-1}} = \sum a_i \int \mathrm{d}^d\ell \frac{1}{D_{i_0} D_{i_1} \cdots}$$

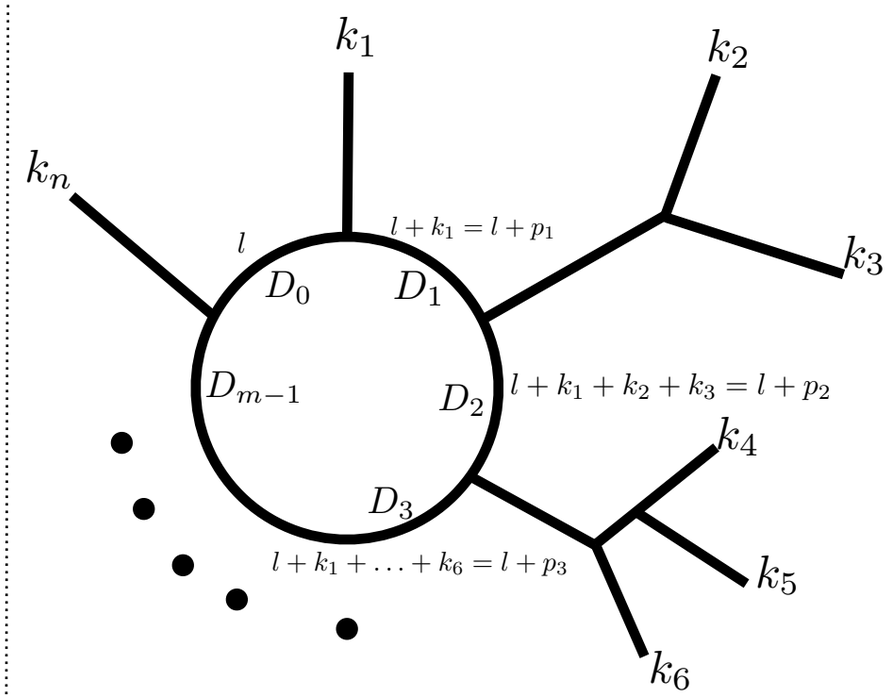
★ Involves integrals with up to four denominators

➢ The decomposition basis is finite

➢ Can be computed once and for all

★ The reduction is the process-dependent part

m-point diagram with *n* external momenta



The rational terms (R_1 and R_2)

✦ The loop momentum lives in a *d*-dimensional space

✤ Reduction to be done in *d* dimensions

$$\int \mathrm{d}^d\ell \frac{N(\ell,\tilde{\ell})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}} \quad \text{with } \bar{\ell} = \ell + \tilde{\ell}$$

D-dim 4-dim (-2ε)-dim

✤ Numerical methods works in 4 dimensions: need to be compensated!

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✤ Numerical methods works in 4 dimensions: need to be compensated!

✦ The R_1 terms originates from the denominators

✤ Connected to the internal propagators

✦ The R_2 terms originates from the numerator

✤ Seen as extra diagrams with special Feynman rules (model dependent)

✤ Connected to the ultraviolet structure of the integrals

★ Like the ultraviolet counterterms

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UFO @ NLO

R_1 terms

✦ The R_1 terms originates from the denominators

$$\frac{1}{\bar{D}} = \frac{1}{D}\left(1 - \frac{\tilde{\ell}^2}{\bar{D}}\right)$$

✤ These extra pieces can be calculated generically (3 integrals in total)

$$\int \mathrm{d}^d\bar{\ell}\frac{\tilde{\ell}^2}{\bar{D}_i\bar{D}_j} = -\frac{i\pi^2}{2}\left[m_i^2 + m_j^2 - \frac{p_i - p_j)^2}{2}\right] + \mathcal{O}(\varepsilon)$$

$$\int \mathrm{d}^d\bar{\ell}\frac{\tilde{\ell}^2}{\bar{D}_i\bar{D}_j\bar{D}_k} = -\frac{i\pi^2}{2} + \mathcal{O}(\varepsilon)$$

$$\int \mathrm{d}^d\bar{\ell}\frac{\tilde{\ell}^2}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_l} = -\frac{i\pi^2}{6} + \mathcal{O}(\varepsilon)$$

✤ The denominator structure is already known at the reduction time

✤ The R_1 coefficients are extracted during the reduction

R_2 terms

✦ The R_2 terms originates from the numerator

$$\underbrace{\bar{N}(\bar{\ell})}_{\text{D-dim}} = \underbrace{N(\ell)}_{\text{4-dim}} + \underbrace{\tilde{N}(\tilde{\ell},\ell,\varepsilon)}_{(-2\varepsilon)\text{-dim}} \quad \Rightarrow \quad R_2 \equiv \lim_{\varepsilon\to 0} \frac{1}{(2\pi)^4} \int \mathrm{d}^d\bar{\ell} \frac{\tilde{N}(\tilde{\ell},\ell,\varepsilon)}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}}$$

✤ Practically, we isolate the epsilon part

✤ There is only a finite set of loops for which it does not vanish

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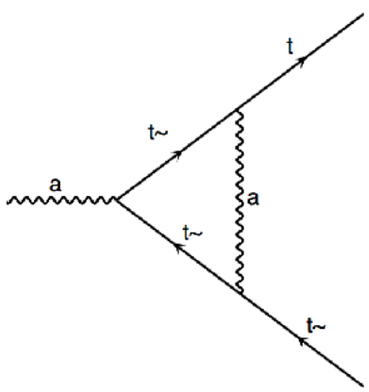
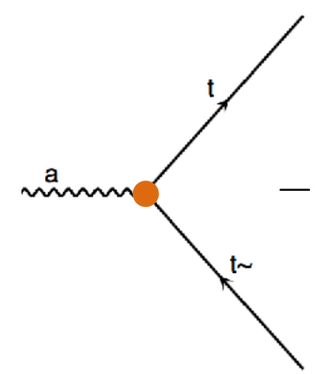
- ✤ Practically, we isolate the epsilon part
- ✤ There is only a finite set of loops for which it does not vanish

✦ They can be re-expressed in terms of R_2 Feynman rules



$$\propto \int \mathrm{d}^d\bar{\ell}\,\frac{\tilde{\ell}^2}{\bar{D}_i\bar{D}_j\bar{D}_k} = -\frac{i\pi^2}{2} + \mathcal{O}(\varepsilon) \quad \Rightarrow$$



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

R_2 Feynman rules

✦ The R_2 are process dependent and model-dependent (like Feynman rules)

- ✤ In a renormalizable theory, there is a finite number of them
- ✤ They can be derived from the sole knowledge of the bare Lagrangian

[Ossala, Papadopoulos, Pittau (JHEP'08)]

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[Ossala, Papadopoulos, Pittau (JHEP'08)]

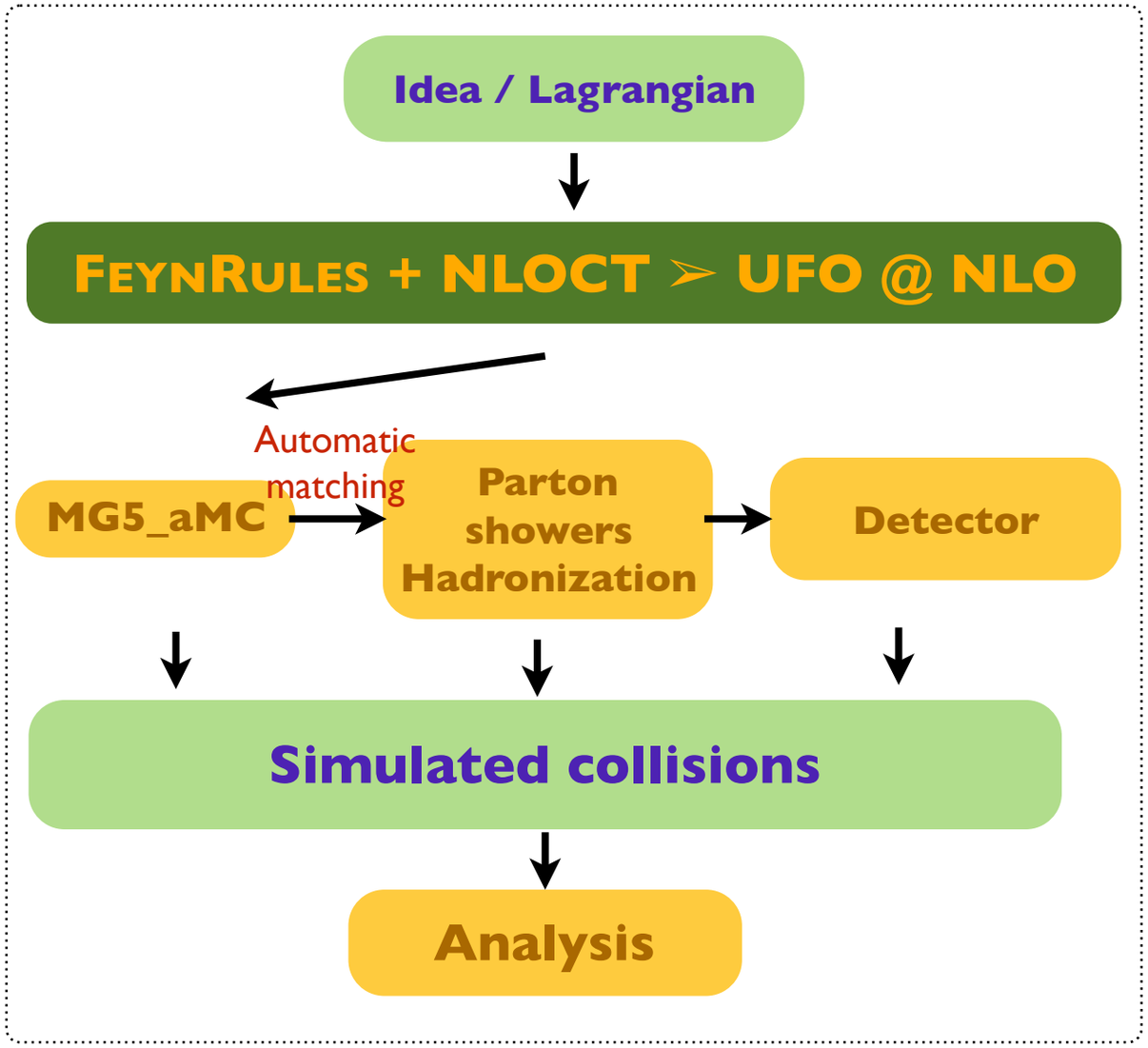
✦ The R_2 calculation can be automated and performed once and for all

- ✤ Development of the NLOCT package (extension of FEYNRULES)
- ✤ Computation, for any model, of all R_2 and UV counterterms
  - ★ In the on-shell and MSbar schemes
- ✤ Inclusion of the output in the UFO

[Degrande (CPC'15)]

Automated NLO simulations with MG5_aMC

✦ The implementation of any new physics theory in a MC tool is straightforward



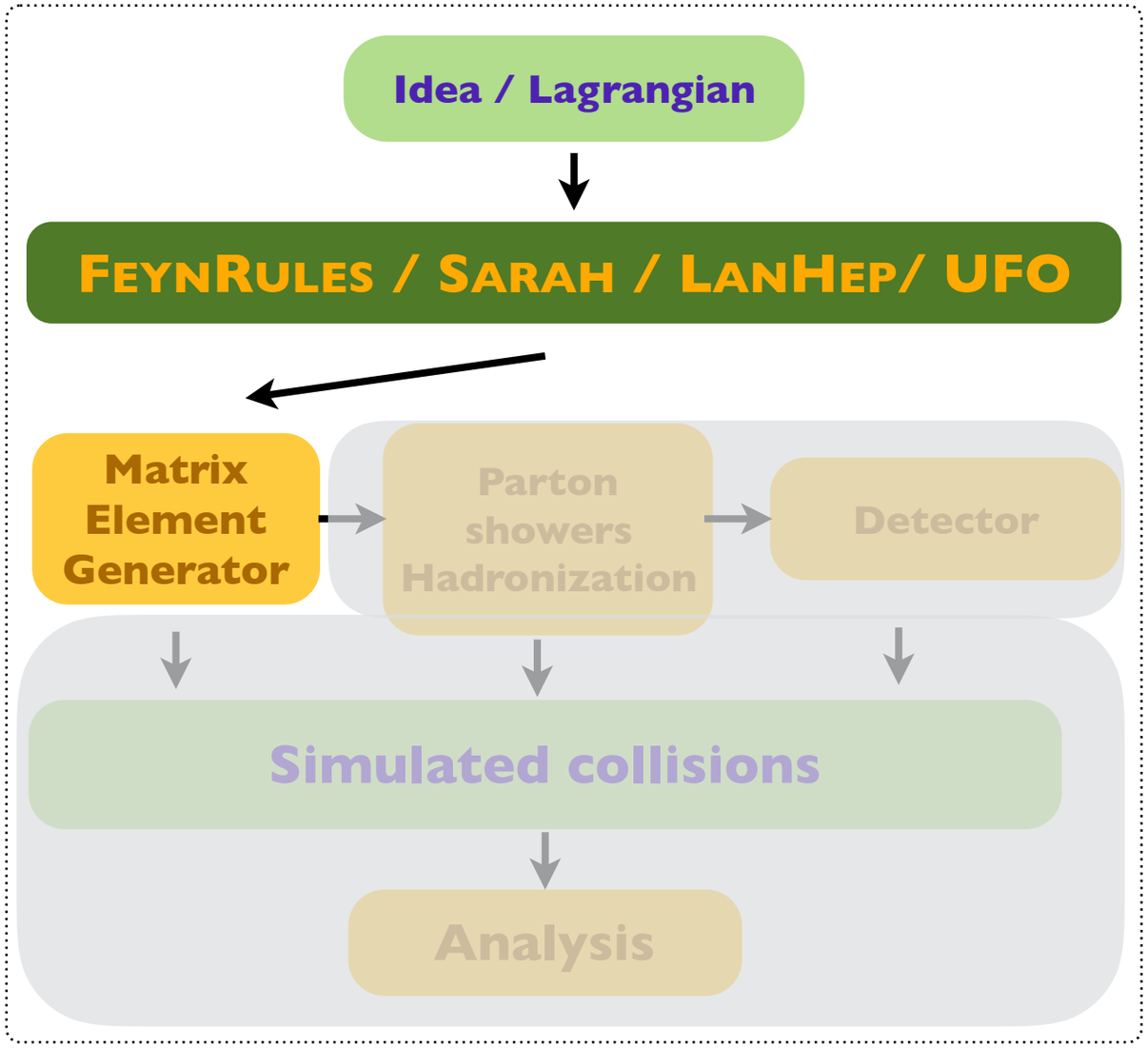
Same chain with NLO-QCD corrections

Outline

1. Introduction: overview of an LHC collision
2. Implementing models into Monte Carlo event generators
3. **From models to hard scattering events**
4. Summary

Back to the simulation chain

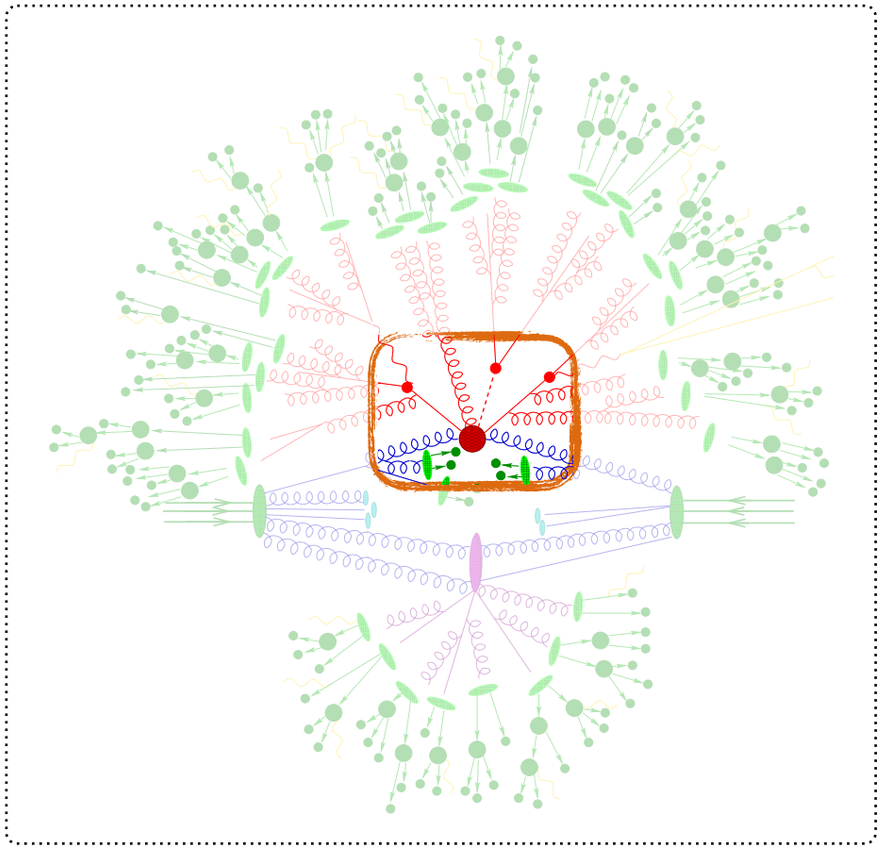
✦ Tools connecting an idea to simulated collisions



✤ Hard scattering process

- ★ Feynman diagram and amplitude generation
- ★ Monte Carlo integration
- ★ Event generation

Talk from S. Platzer



Predictions at the LHC (using QCD)

✦ Distribution of an observable ω: the QCD factorization theorem

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega} = \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b \mathrm{d}\Phi_n \mathbf{f_{a/p_1}}(x_a, \mu_F)\ \mathbf{f_{b/p_2}}(x_b, \mu_F)\ \left|\mathcal{M}\right|^{\mathbf{2}} \mathcal{O}_\omega(\Phi_n)$$

✤ Long distance physics: the parton densities
(fitted from experimental data; evolution driven by QCD)

✤ Short distance physics: the differential parton cross section $\mathrm{d}\sigma_{ab}$

✤ Separation of both regimes through the factorization scale μ_F (theory errors)

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✦ Short distance physics: the partonic cross section

- ✤ Calculated order by order in perturbative QCD: $\mathrm{d}\sigma = \mathrm{d}\sigma^{(0)} + \alpha_s\, \mathrm{d}\sigma^{(1)} + \ldots$
  - ★ The more orders included, the more precise the predictions
  - ★ Truncation of the series and α_s ➢ theoretical uncertainties

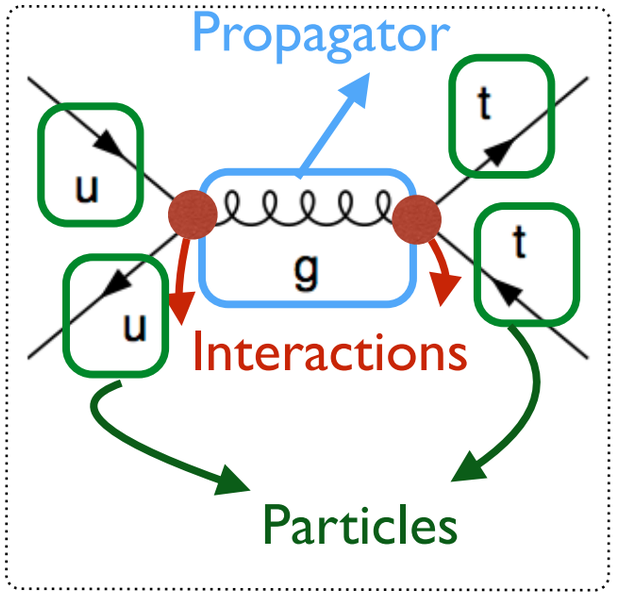
Built on Feynman diagrams, from Feynman rules encoded in UFOs

Feynman diagram calculations

✦ Direct squared matrix element computations

✤ Extraction of the amplitude from the Feynman rules

$$i\mathcal{M} = i g_s^2 \left[\bar{v}_2 \gamma^\mu u_1\right] \frac{\eta_{\mu\nu}}{s} \left[\bar{u}_3 \gamma^\nu v_4\right] T^a_{c_2 c_1} T^a_{c_3 c_4}$$



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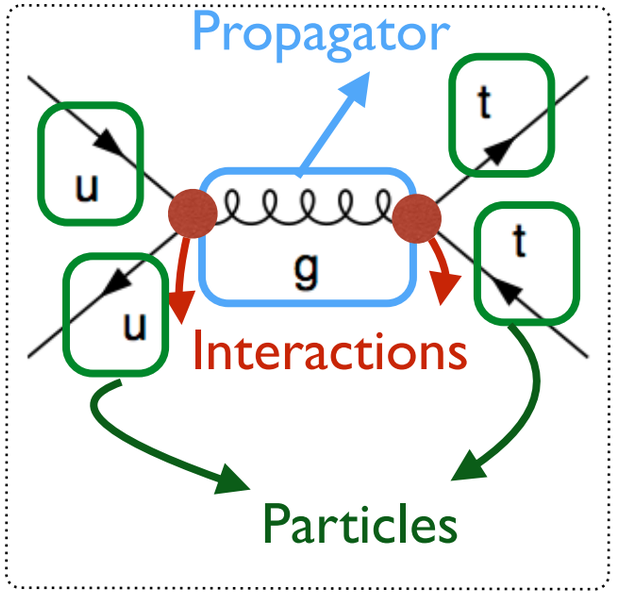
- ✤ Squaring with the conjugate amplitude
- ✤ Algebraic calculation of the color and Lorentz structures
- ✤ Sum/average over the external states

$$\overline{|\mathcal{M}|^2} = \frac{1}{36} \frac{2 g_s^4}{s^2} \mathrm{Tr}\left[\not{p}_1 \gamma^\mu \not{p}_2 \gamma^\nu\right] \left[\not{p}_3 \gamma_\mu \not{p}_4 \gamma_\nu\right]$$

$$= \frac{16 g_s^4}{9 s^2} \left[(p_1 \cdot p_3)(p_2 \cdot p_4) + (p_1 \cdot p_4)(p_2 \cdot p_3)\right]$$



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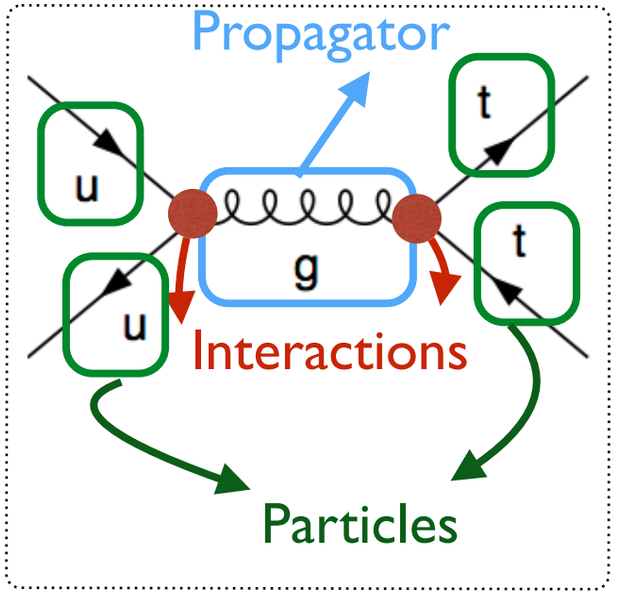

✤ The squared matrix element needs to be integrated

Talk from S. Platzer

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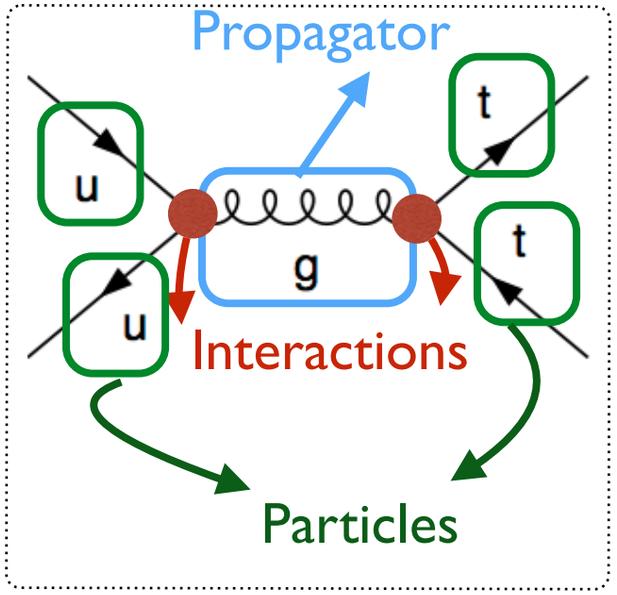


- ✤ The squared matrix element needs to be integrated

Talk from S. Platzer

✦ The number of diagrams increases with the number of final-state particles

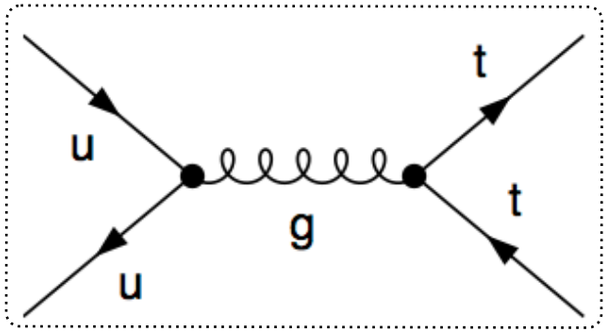
- ✤ The complexity rises as N^2
- ✤ Any calculation beyond 2-to-3 becomes a problem

➢ **Helicity amplitudes**

Helicity amplitudes

✦ Principle

- ✤ Evaluation of the amplitude for fixed external helicities
- ✤ Add all amplitudes (we get complex numbers)
- ✤ Squaring
- ✤ Sum/average over the external states



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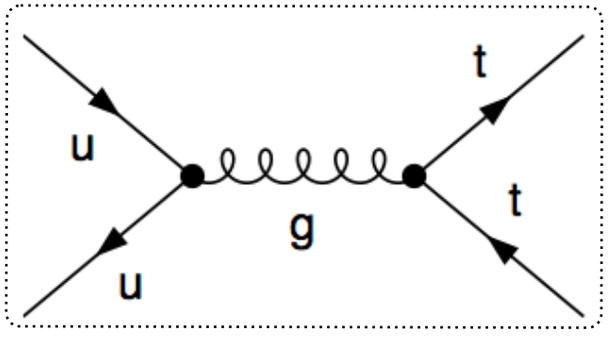
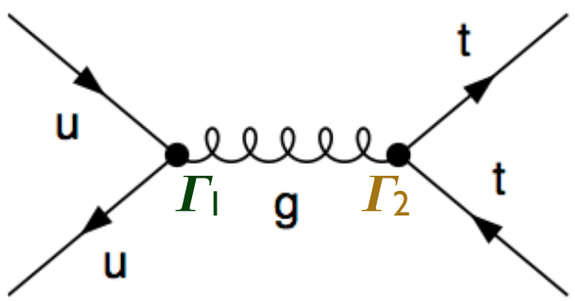


✦ Practical example



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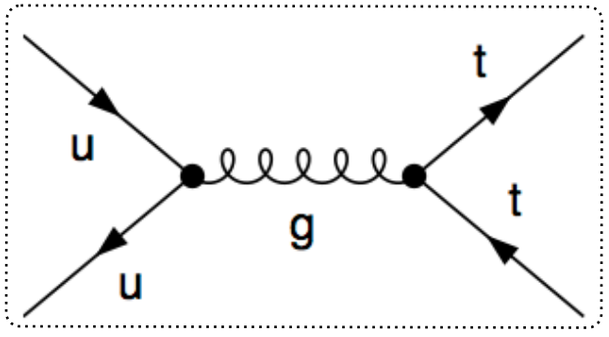

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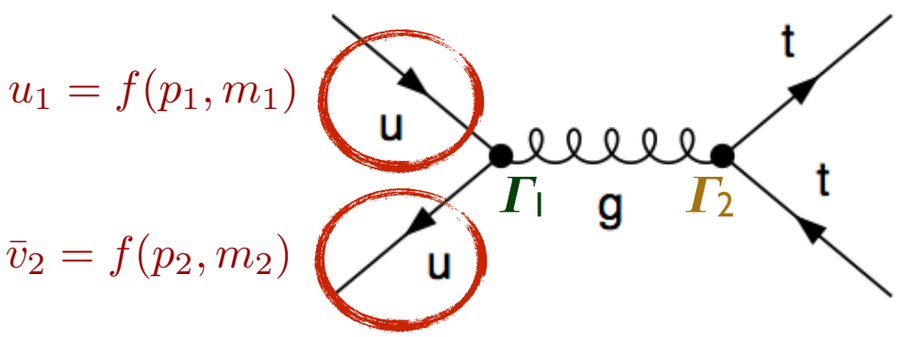

1. External incoming particles (numbers)
   - ★ For fixed helicity and momentum

Helicity amplitudes

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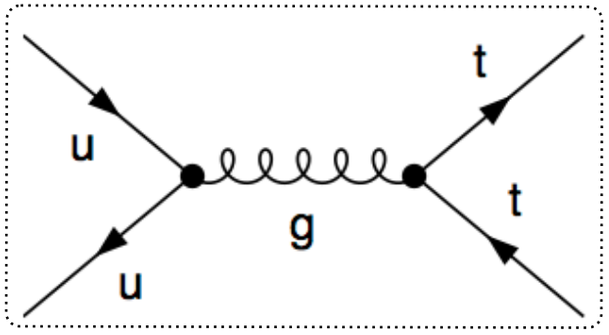

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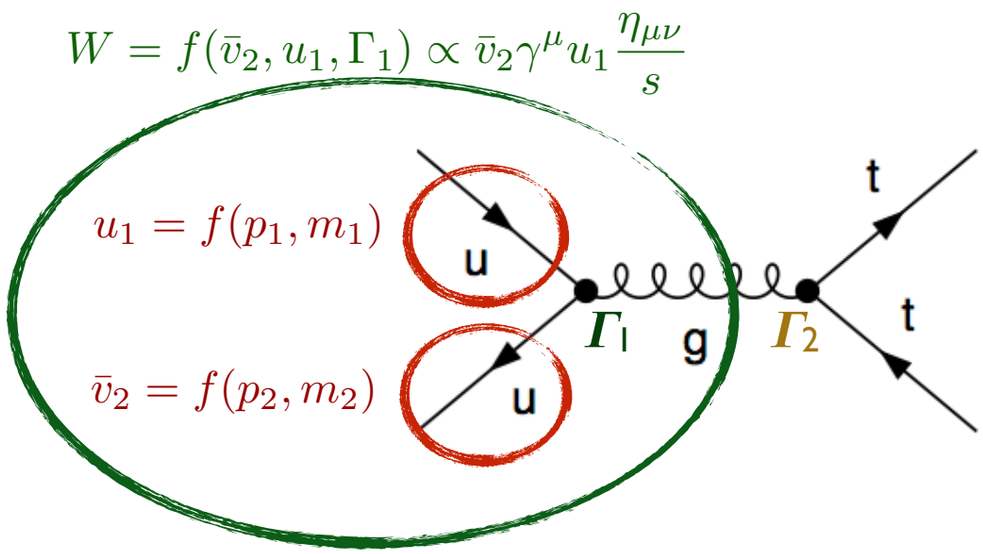
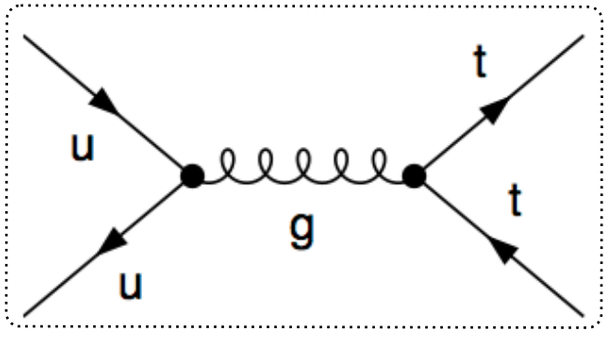


1. External incoming particles (numbers)
   - ★ For fixed helicity and momentum
2. Wave function of the gluon propagator

Helicity amplitudes

✦ Principle

- ✤ Evaluation of the amplitude for fixed external helicities
- ✤ Add all amplitudes (we get complex numbers)
- ✤ Squaring
- ✤ Sum/average over the external states



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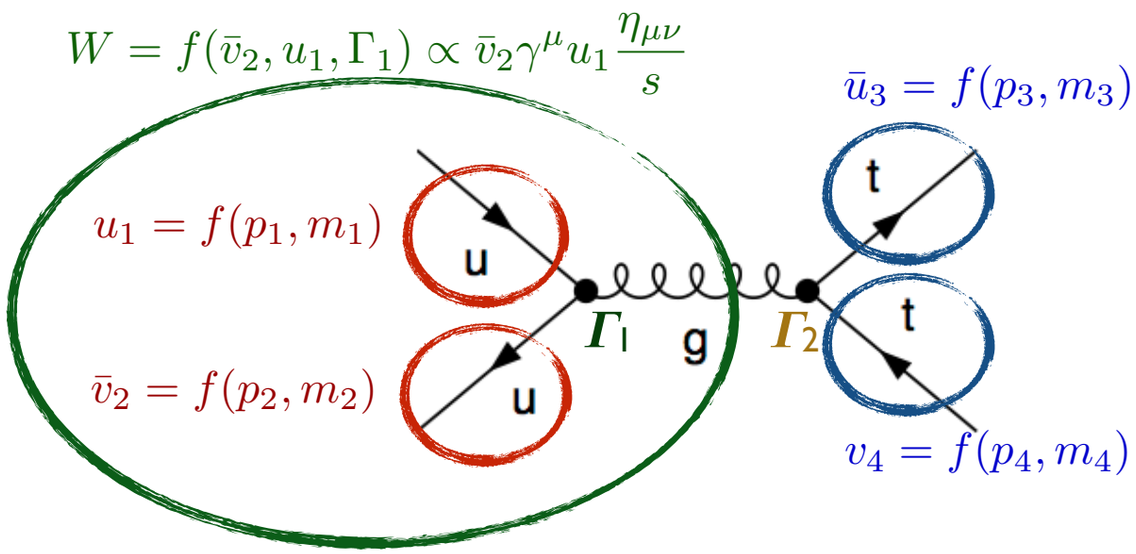

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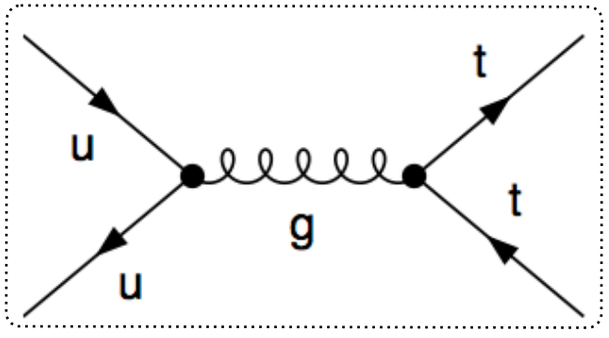

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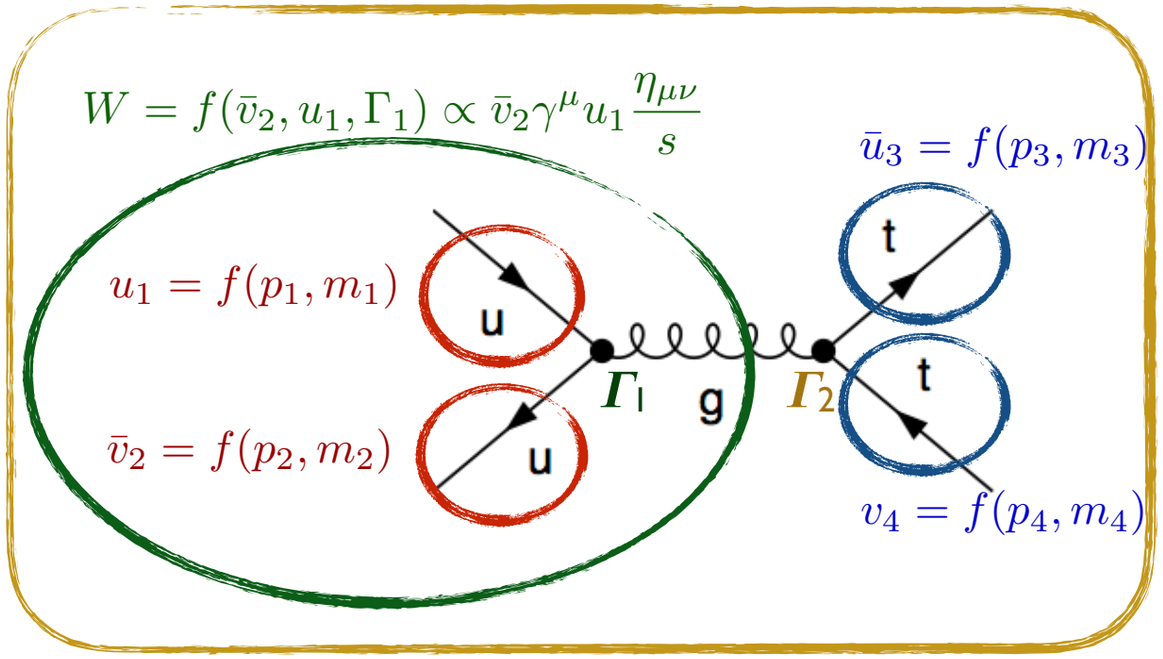

$i\mathcal{M} = f(\bar{u}_3, v_4, W, \Gamma_2)$

1. External incoming particles (numbers)
   - ★ For fixed helicity and momentum
2. Wave function of the gluon propagator
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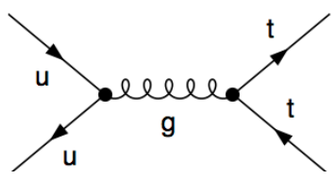
4. Full amplitude (complex number)

HELAS

✦ The building blocks of the amplitude are the so-called HELAS functions



$$u_1 = f(p_1, m_1)$$
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- ✤ HELAS ≡ HELicity Amplitude Subroutine
- ✤ One specific routine for each Lorentz structure (Γ_i)
- ✤ Not generic for any model
  - ★ SM [Murayama,Watanabe & Hagiwara (KEK-91-11)]
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Sufficient for many models

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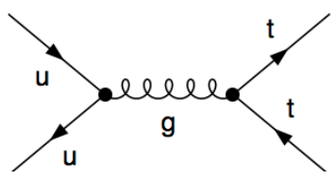

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Sufficient for many models

✦ Generalization: ALOHA [de Aquino, Link, Maltoni, Mattelaer & Stelzer (CPC`12)]

- ✤ Translation of any vertex present in a UFO into a HELAS subroutine
- ✤ Any model can hence be coped with by MG5_aMC@NLO

✦ Other MC generators are today connected directly to the UFO

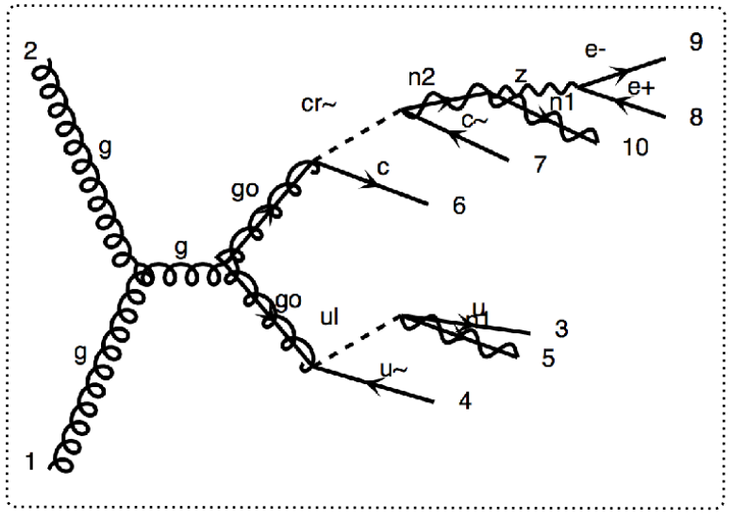
- ✤ HERWIG, SHERPA, WHIZARD

Heavy particle decays

✦ Concrete BSM models

- ✤ Many additional new states
  - ★ Usually pair-produced
  - ★ Cascade-decaying into each other
- ✤ The lightest new state can be stable (and a dark matter candidate)

Is the simulation of 2-to-*N* processes (with a large *N*) a problem?



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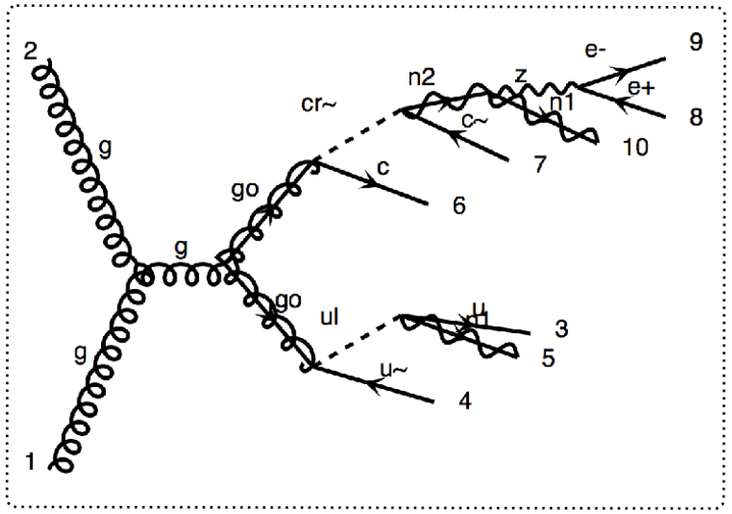


✦ 2-to-*N* matrix-element generation is possible

✤ Nothing really new or fancy

✤ Computationally challenging for event generation

✦ The issue is the computing time

✤ Connected to the final-state multiplicity

✤ Practically useless: diagrams with intermediate resonances dominate

✦ Factorization of the production from the decay

Making decays easy: the key principle

✦ Production and decay processes are factorized

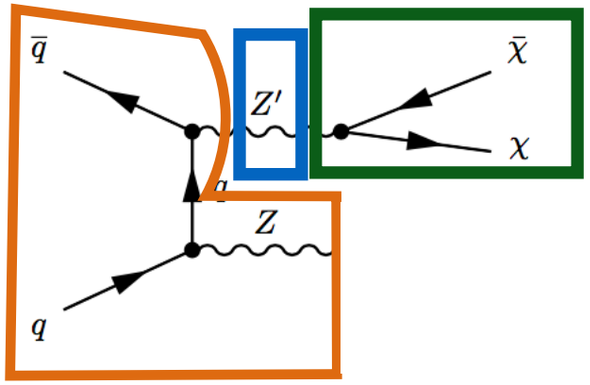
- Propagators can be seen as sums of products of external wave functions
- Example for a vector resonance

$$\mathcal{M} = j_1^\mu \left[\eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right] j_2^\nu = \sum_\lambda j_1^\mu \varepsilon_\mu^*(\lambda)\, j_2^\nu \varepsilon_\nu(\lambda)$$

Propagation

Production of the resonance

Decay of the resonance



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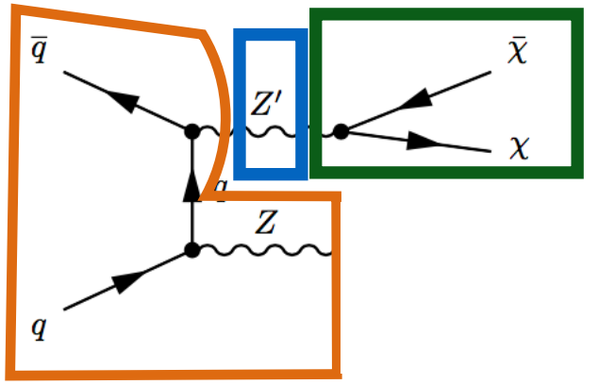

✤ Off-shell effects are lost (as a result of the factorization)

★ Resonance mass smearing: partial recovery [Frixione, Laenen, Motylinksi, Webber (JHEP '07)]

Practical implementations of decays

✦ Case 1: loss of spin correlations

✤ Helicity sums performed independently at the production and decay levels

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★ Used in PYTHIA

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★ Used in PYTHIA

✦ Case 2: including spin correlations

✤ Helicity sums performed after accounting for production and decays

$$\mathcal{M} = \sum_\lambda j_1^\mu \varepsilon_\mu^*(\lambda)\ j_2^\nu \varepsilon_\nu(\lambda)$$

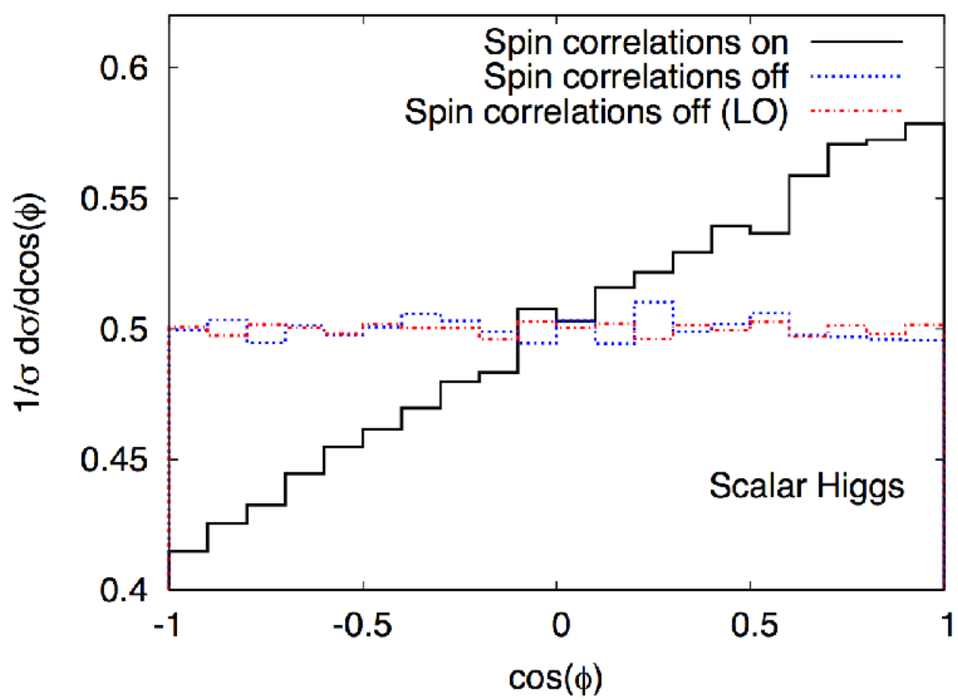
★ Reweighting according to decay matrix element (e.g. MADSPIN)
[Artoisenet *et al.* (JHEP '13)]

★ Using spin density matrices (e.g. HERWIG, SHERPA).
[Richardson (JHEP '01); Höche *et al.* (EPJC '15)]

Importance of correctly handling decays

✦ Is a correct decay handling important: this depends on the observable

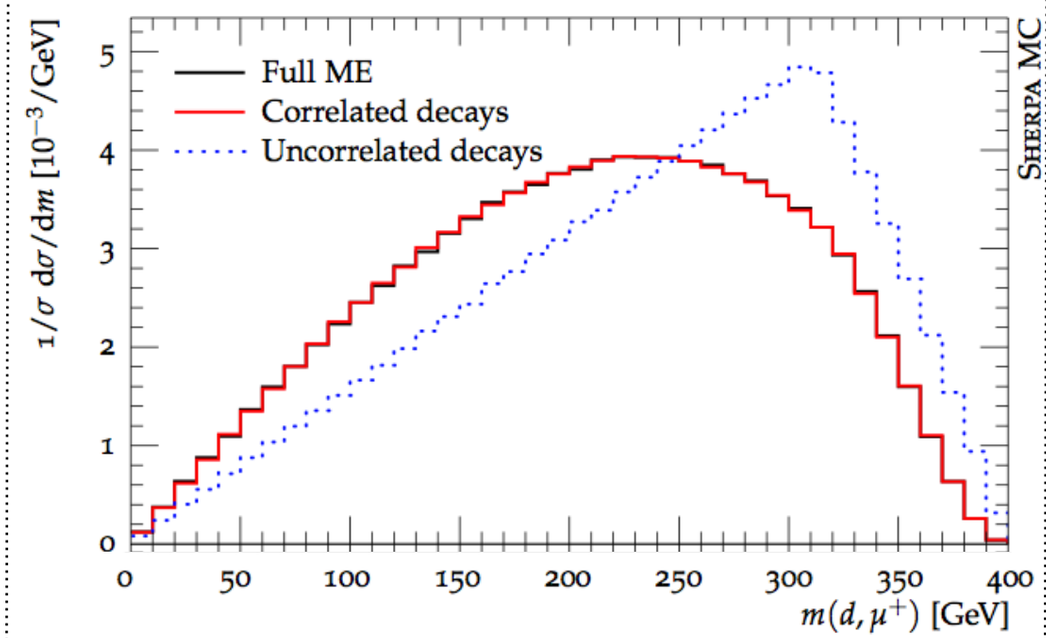
Angle between the leptons in the respective mother top rest frames



MADSPIN
$t\bar{t}H$ production @ (N)LOQCD
[LHC8, dileptonic $t\bar{t}$ decay]

[Artoisenet, Frederix, Mattelaer & Rietkerk (JHEP'13)]

Invariant mass between decay products originating from different cascade steps



SHERPA @ LO[LHC8]

$pp \to \tilde{u}\tilde{u}^\dagger$

$\tilde{u} \to d\tilde{\chi}_1^+ \to d\chi_1^0 W^+ \to d\chi_1^0 \mu^+ \nu_\mu$

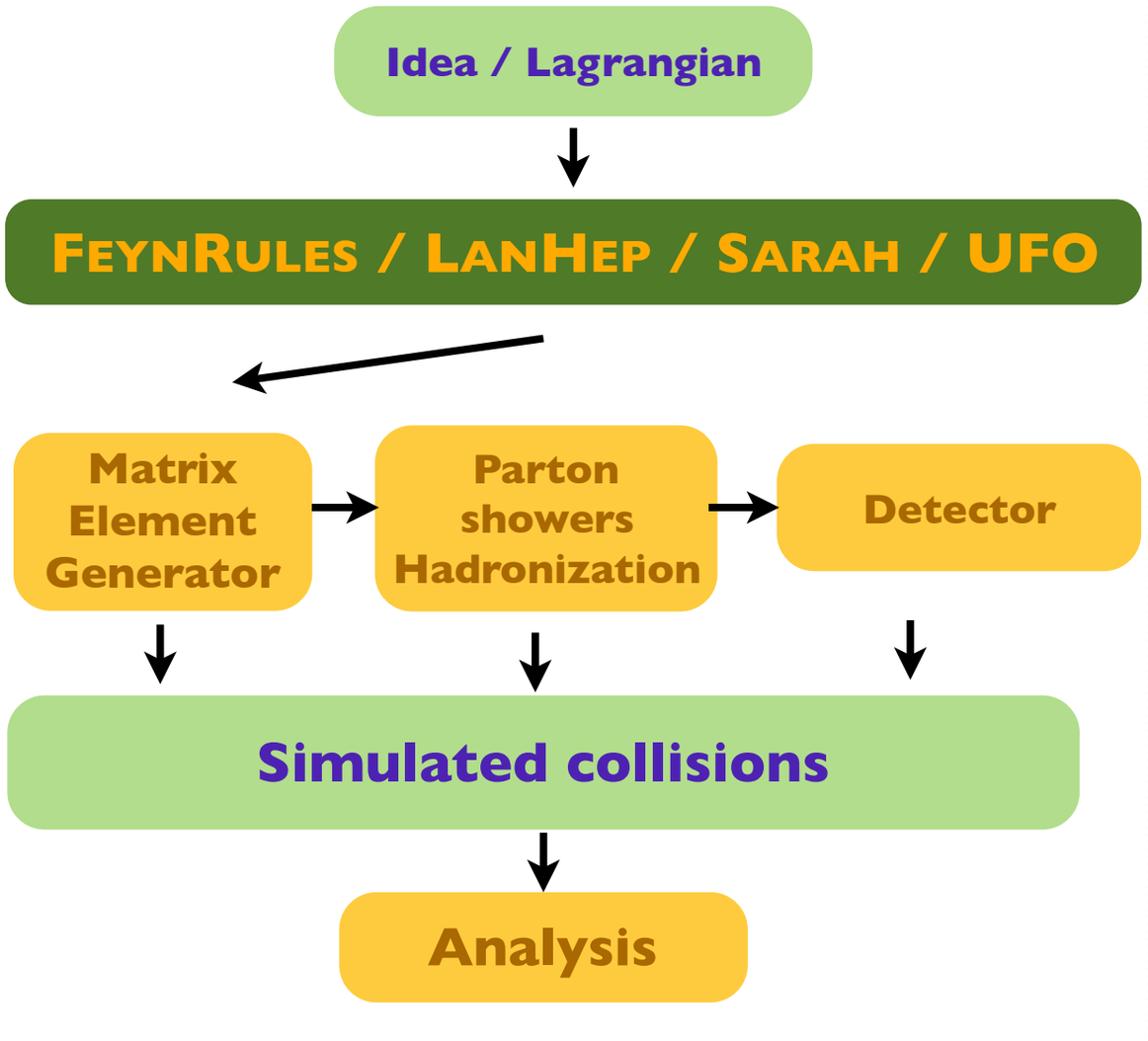
$\tilde{u}^\dagger \to \ldots \to \bar{u} e^+ e^- \tilde{\chi}_1^0$

[Höche, Kuttimalai, Schumann & Siegert (EPJC'15)]

Outline

1. Introduction: overview of an LHC collision
2. Implementing models into Monte Carlo event generators
3. From models to hard scattering events
4. **Summary**

Summary



✦ Event simulation is a complex process

- ✤ Nature allows us to factorize it into pieces
- ✤ Event simulation is performed step-by-step

✦ This talk: 1st parts of the simulation chain

- ✤ Connecting models (Lagrangians) to tools
- ✤ Generating squared matrix elements
- ✤ Including the decays of heavy particles