Beyond the Standard Model physics
From Lagrangians to events

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LPTHE / Sorbonne Université

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Outline

1. A comprehensive approach for Monte Carlo simulations
2. Implementing models into Monte Carlo event generators
3. From models to hard-scattering events
4. Summary

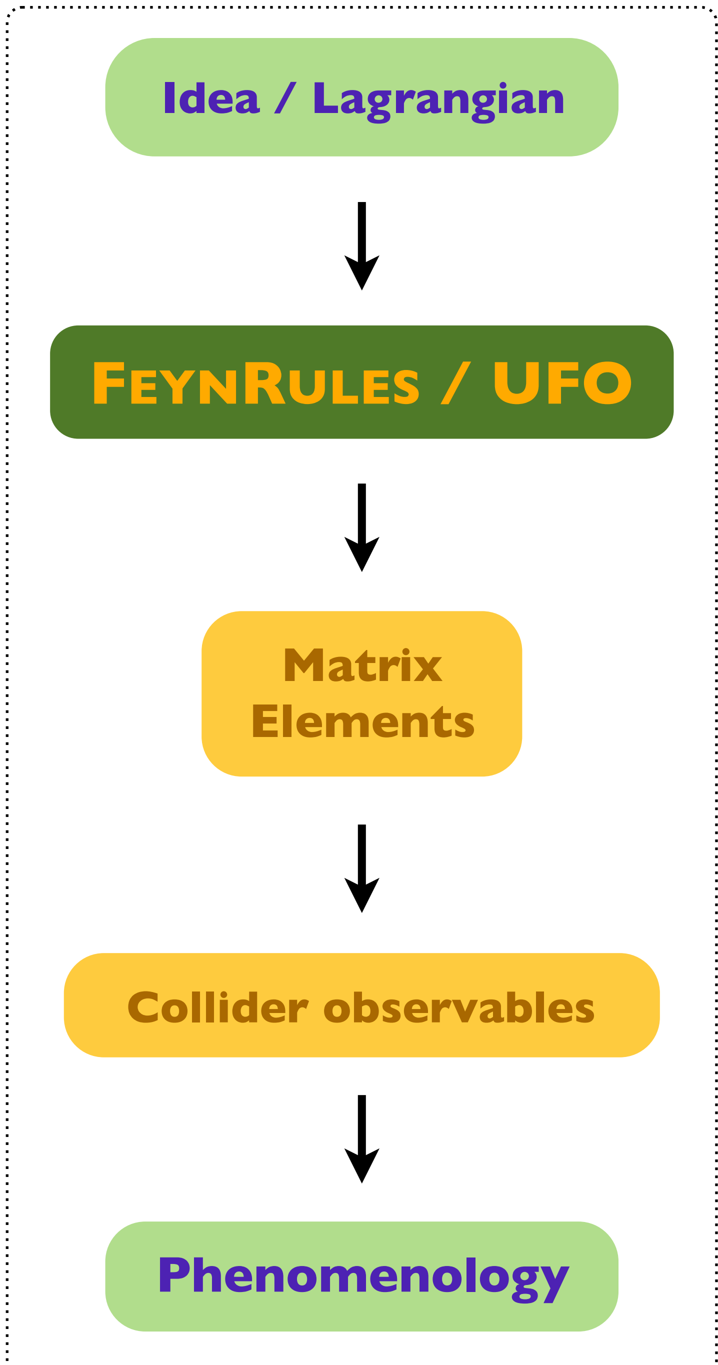
Monte Carlo simulations for new physics

- ✦ Path towards the characterisation of new physics
  - ✤ Fitting and interpreting deviations
  - ✤ Predictions of associated signatures/signals
    - → Monte Carlo simulations play a key role
- ✦ Final words on any potential new physics at the LHC
  - ✤ Accurate measurements ⊕ precision predictions (NLO QCD + PS)
    - → Monte Carlo simulations play a key role

- ✦ New physics is standard in the simulation tools
  - ✤ 20-25 years of developments → LO simulations are bread and butter
  - ✤ Simulations at the NLO accuracy in QCD can be easily achieved
    - ★ For any model/process → the MADGRAPH5_aMC@NLO framework

A comprehensive approach to new physics calculations

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



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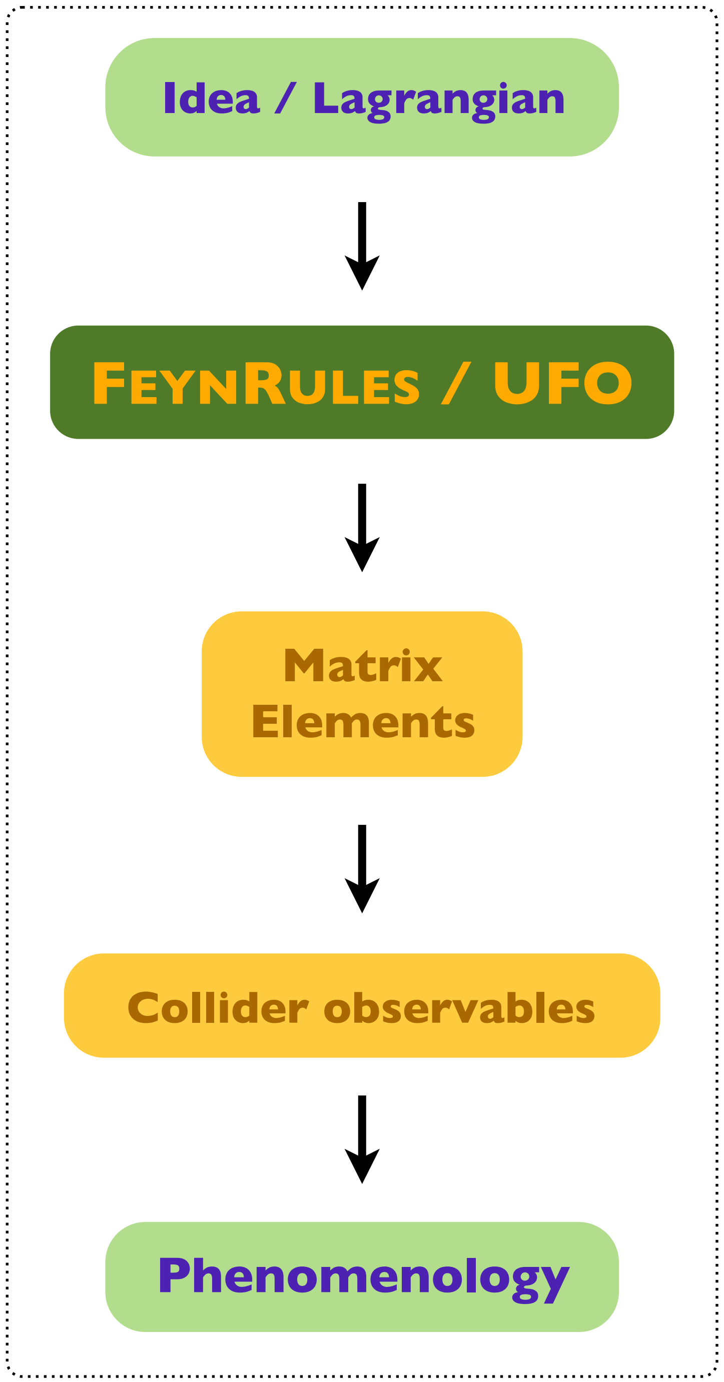

✦ Model building: from Lagrangian to tools

- ✤ FEYNRULES ⊕ MOGRE ⊕ NLOCT → UFO @ NLO
- ✤ General on-shell renormalisation scheme

[Alloul, Christensen, Degrande, Duhr & BF (CPC'14) ; Degrande (CPC'15)]
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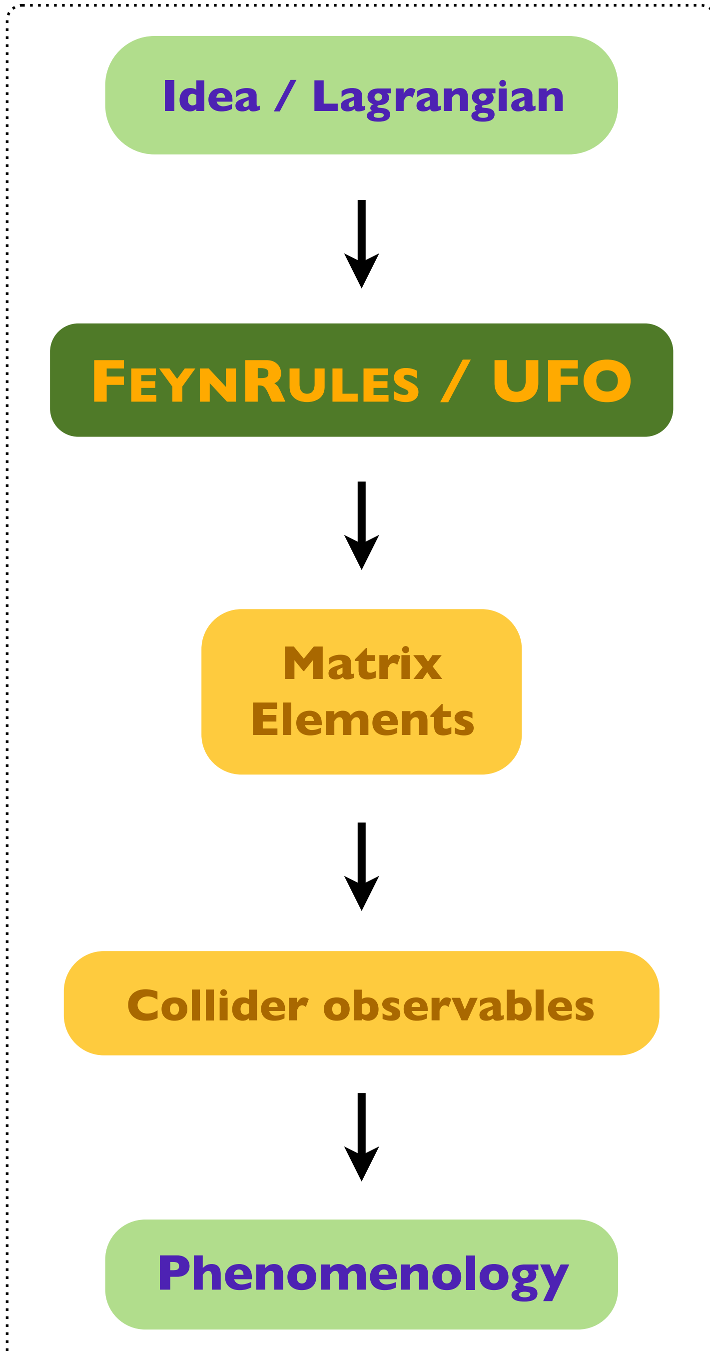

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✦ Hard scattering

- ✤ Feynman diagrams, matrix elements
- ✤ MG5aMC → predictions at LO/NLO

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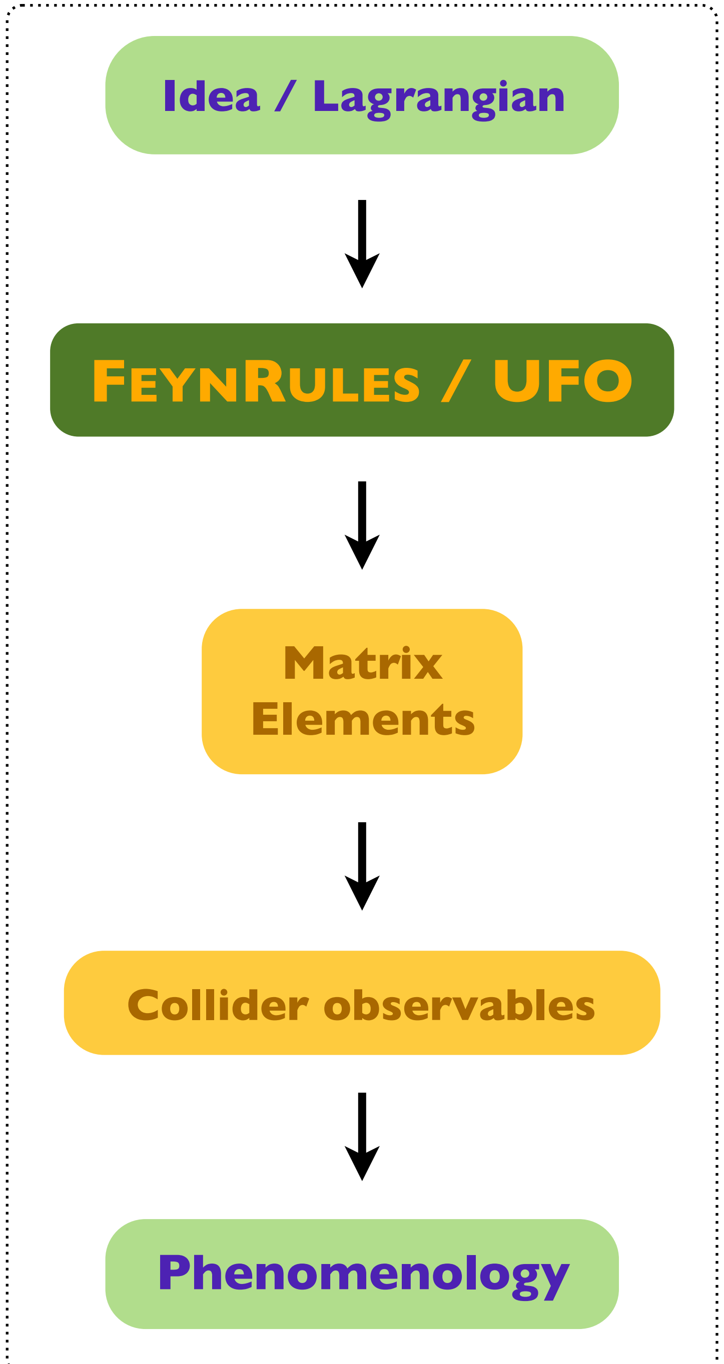

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✦ Collider phenomenology with MG5_aMC

- ✤ Matching matrix elements with parton showers
- ✤ Simplified treatment of the resonances (MADSTR)

[Alwall *et al.* (JHEP'14)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

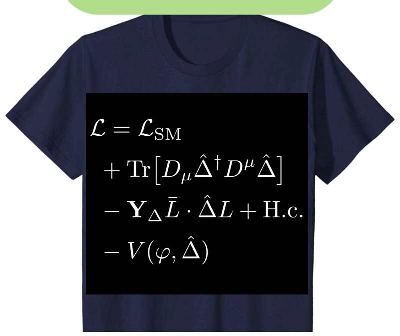
From Lagrangians to events

✦ Streamlining the connection of a physics models to events

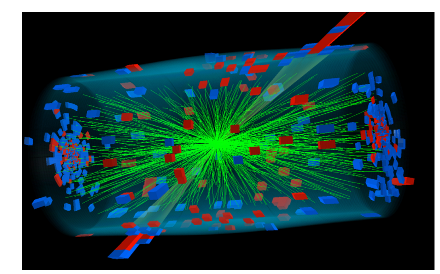
✤ Any new physics model can be implemented

✤ Easy to validate and maintain

Idea Lagrangian



→ Chain of tools → Simulated collisions → Other tools → Event analysis



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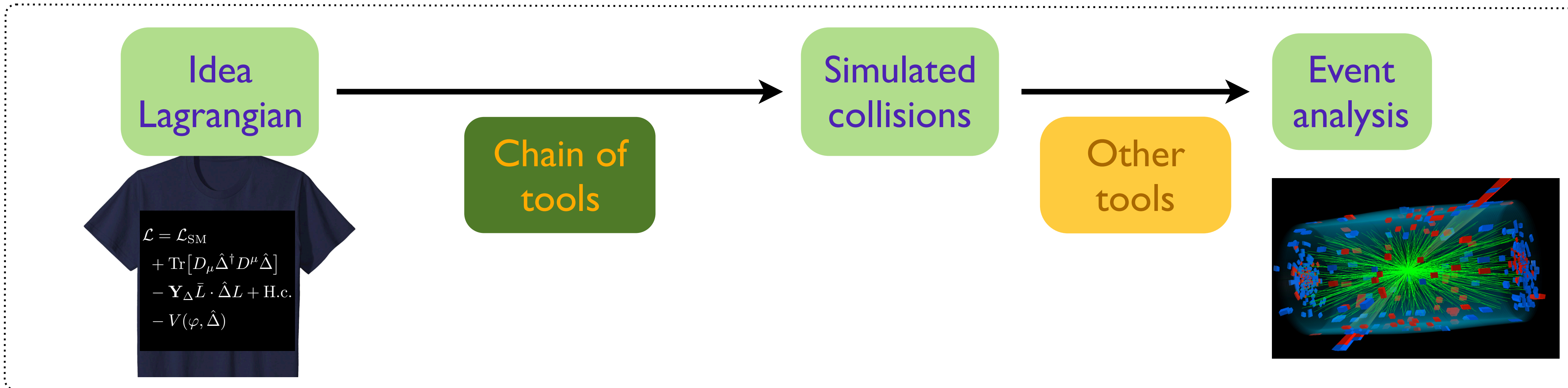
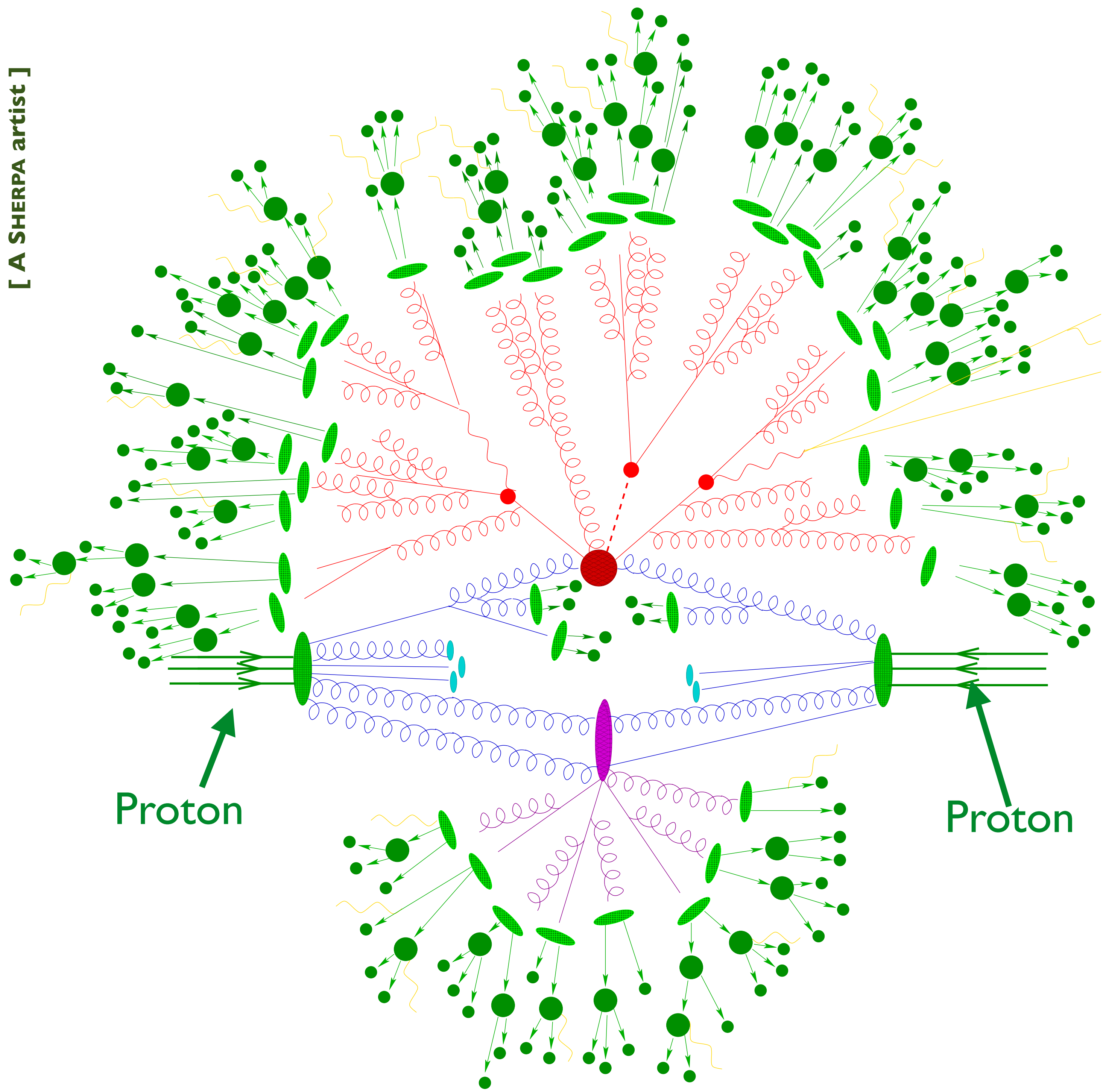


✦ Why a chain of several tools?

✤ Phenomena at colliders occur at different scales → factorisation

Deciphering a proton-proton collision



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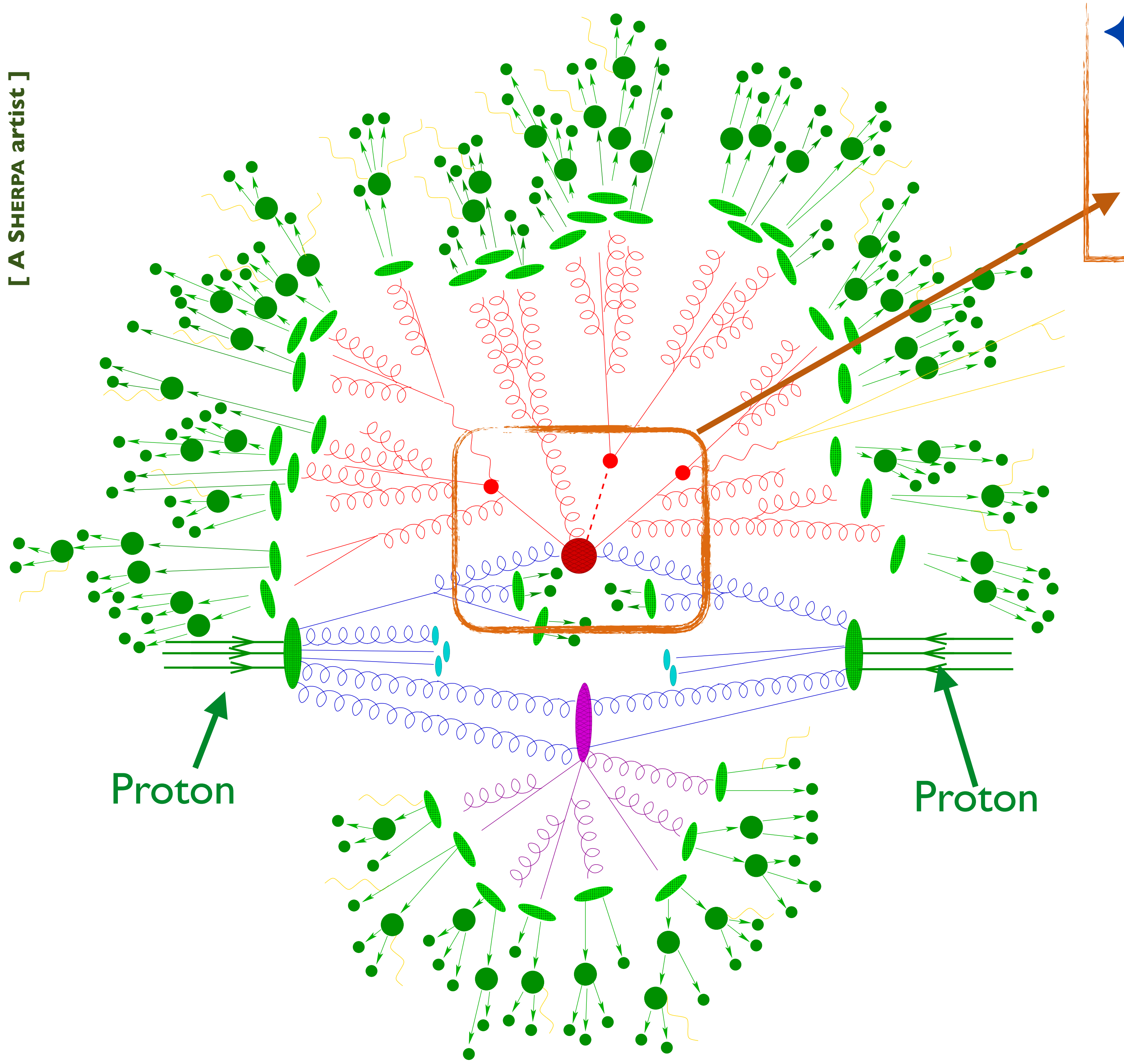

- **Hard process**
  - Depends on the physics model (SM, BSM,…)
  - Perturbative QCD

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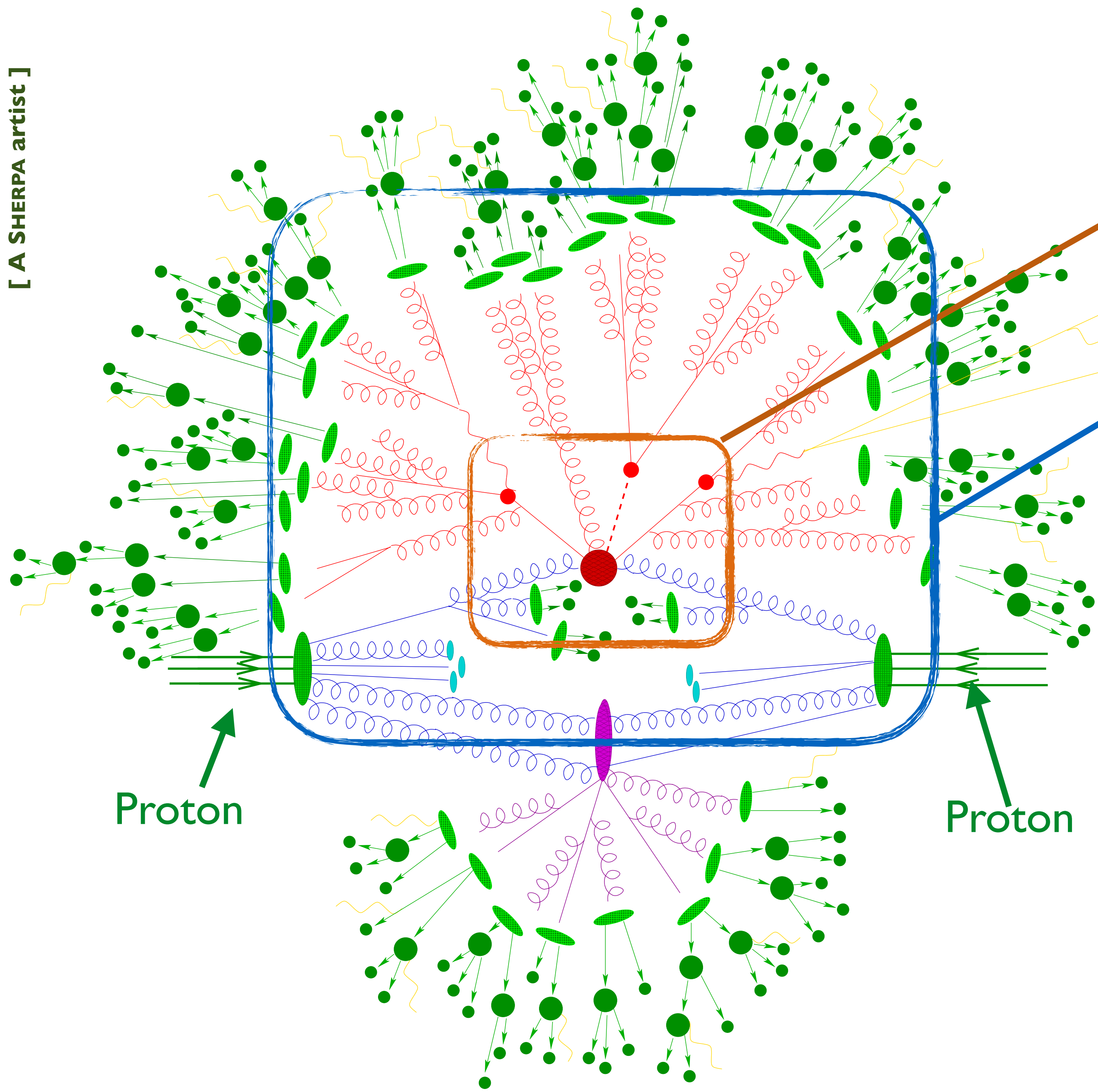

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- Parton showering
  - Universal (QCD)

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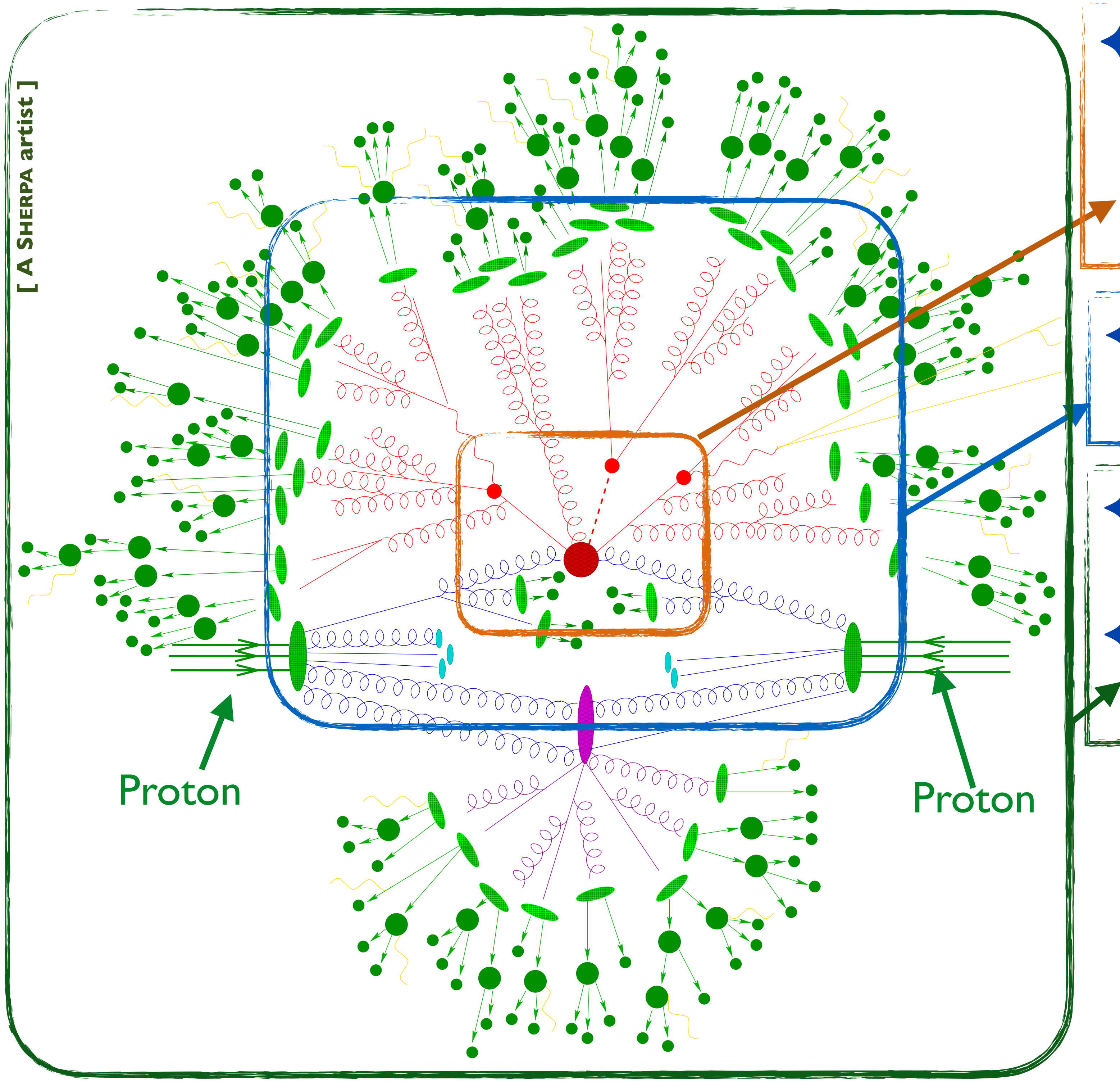

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- Hadronisation
  - Model-based, universal
- Underlying event
  - Model-based, non-universal

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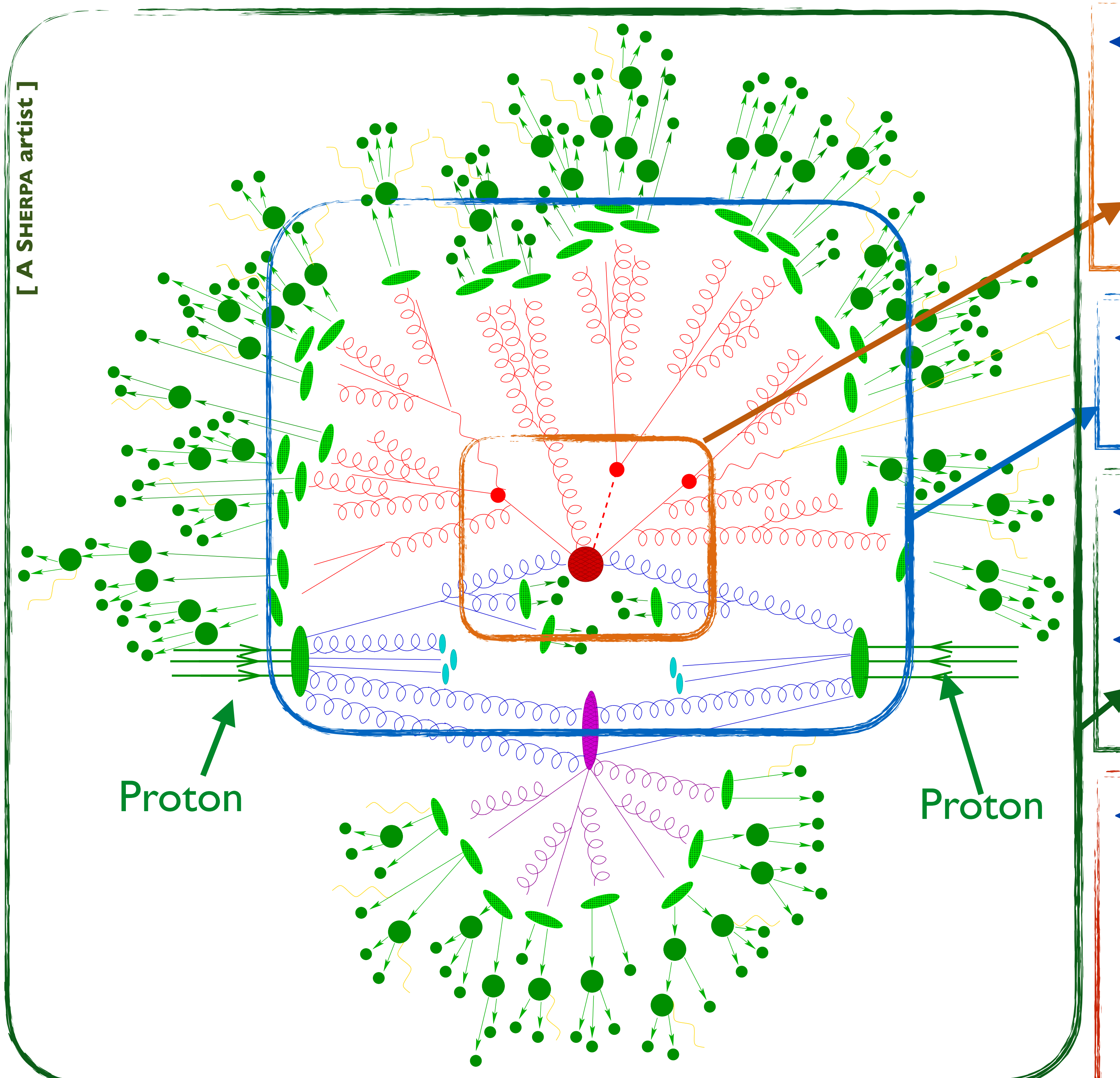

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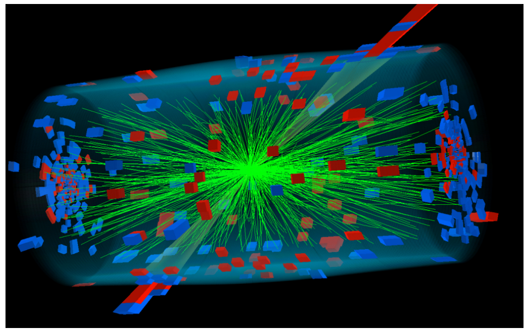
✦ Detector simulation

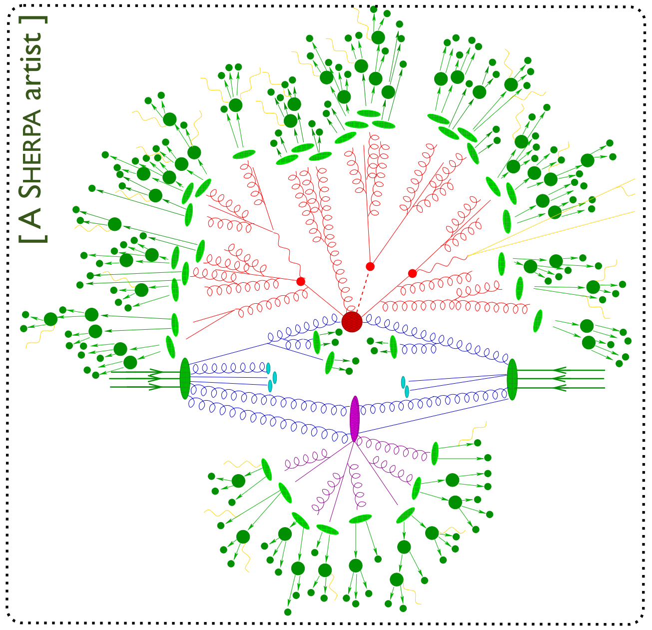


Monte Carlo simulations for proton collisions

✦ Multi-scale problem → factorisation

- ✤ TeV scale: hard scattering (new physics?)
- ✤ Down to Λ_{QCD}: QCD environment — Talk by L. Gellersen
- ✤ Down to sub-MeV: interactions with a detector — Talk by BF

Tools and methods for each step



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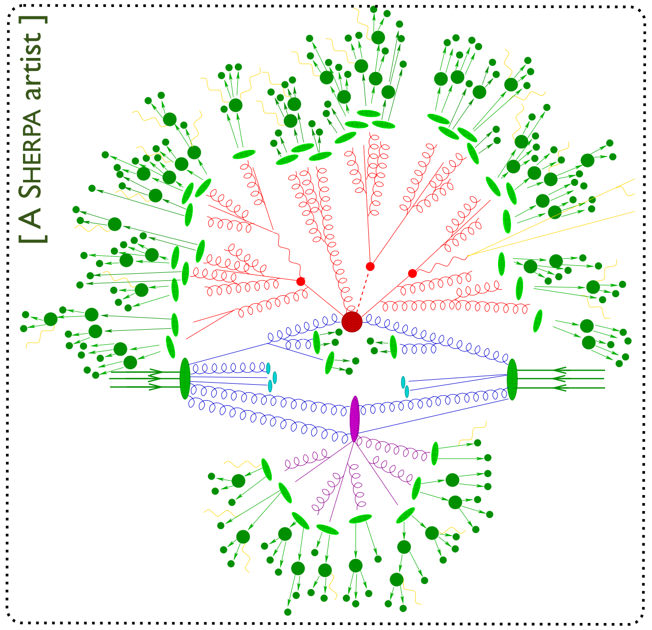

✦ Tools development: a very intense activity

- ✤ Matrix-element generation (CALCHEP, HERWIG, MG5_AMC, SHERPA, WHIZARD, *etc.*)
- ✤ Higher-order computation techniques (MC@NLO, POWHEG, NNLO)
- ✤ Parton showering / hadronisation (PYTHIA, HERWIG, SHERPA)
- ✤ Matrix element - parton shower matching
- ✤ Merging techniques (MLM, CKKW, FxFx, UNLOPS, *etc.*)
- ✤ Detector simulators (DELPHES, RIVET, MADANALYSIS 5)

SM and BSM simulations: the status

- ✦ Standard Model simulations under good control
  - ✤ Relevant LHC processes: known with a very good precision
  - ✤ Further improvements expected in the next few years

Talk by A. Shivaji

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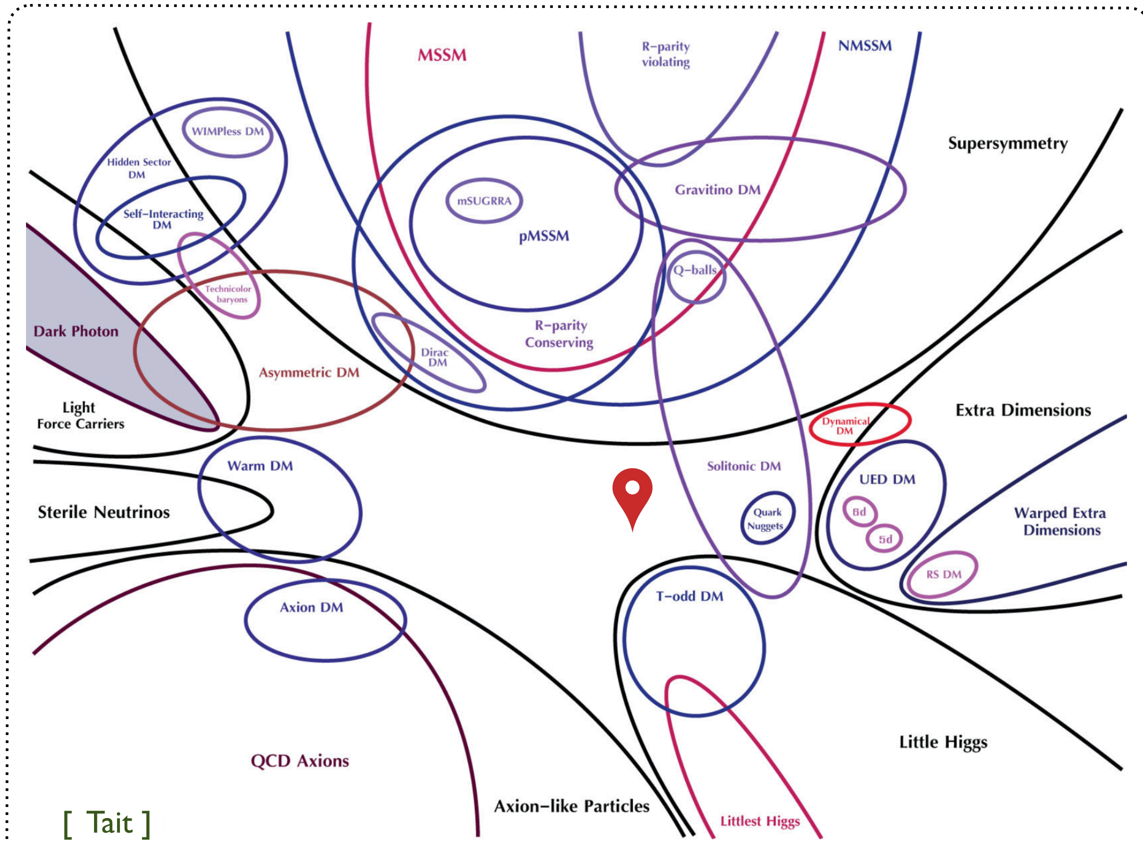
Talk by A. Shivaji

✦ Different challenges for new physics

- ✤ No sign of new physics
- ✤ SM-like measurements
  - → no leading candidate theory
- ✤ Plethora of models to consider
  - → many implementations in tools

Despite of this, new physics is standard today

Talks by K. Mawatari, K. Mimasu & R. Ruiz

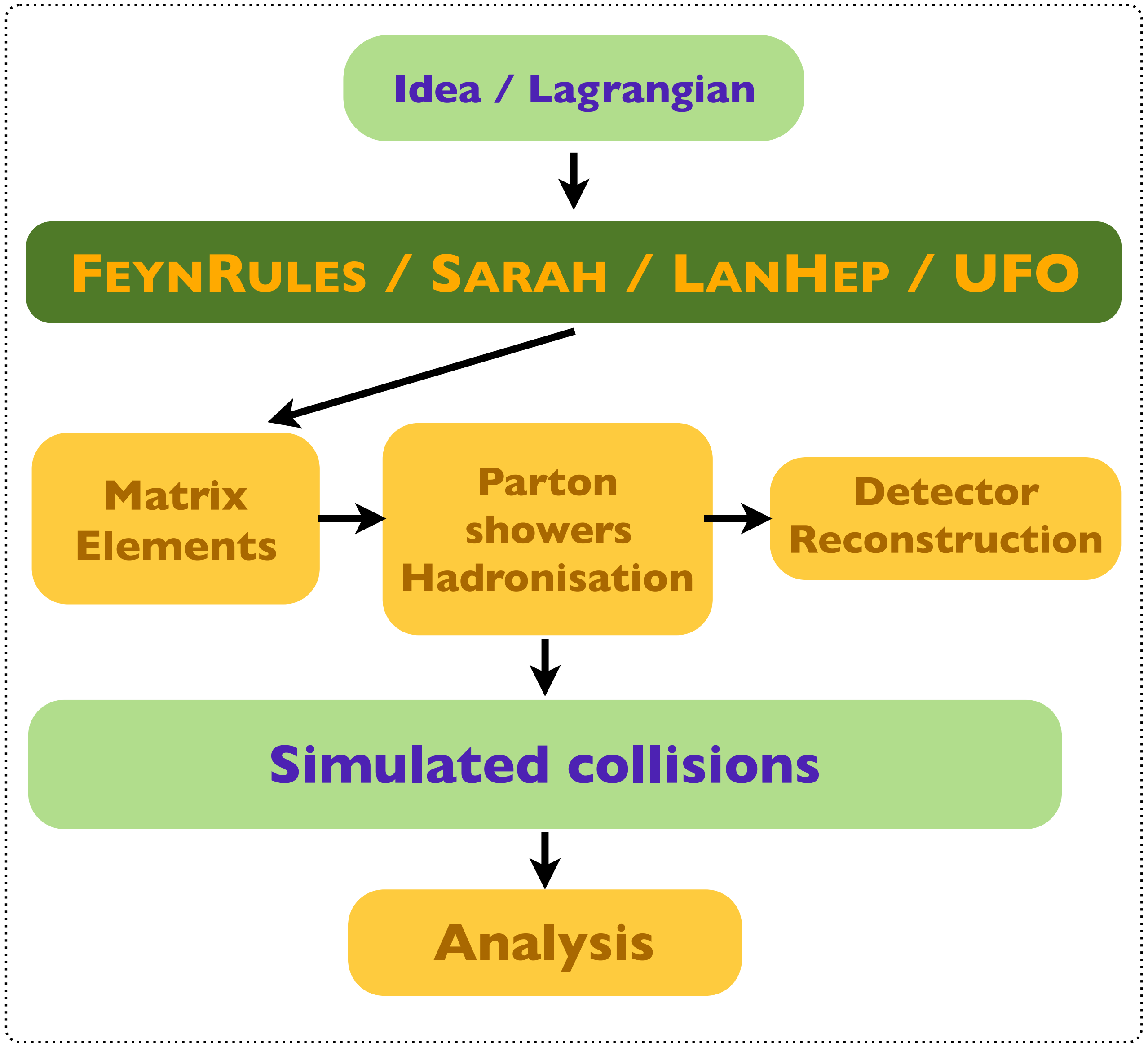


[Tait]

Making new physics a standard

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

✦ Tools connecting an idea to simulated collisions



- Model building
  - ★ FEYNRULES, LANHEP, SARAH
  - ★ UFO
- Matrix element generation
  - ★ CALCHEP, HERWIG++, MG5_AMC, SHERPA, WHIZARD, …
- QCD environment
  - ★ HERWIG, PYTHIA, SHERPA
- Detector simulation
  - ★ DELPHES / PGS
  - ★ RIVET / MADANALYSIS 5
- Event analysis
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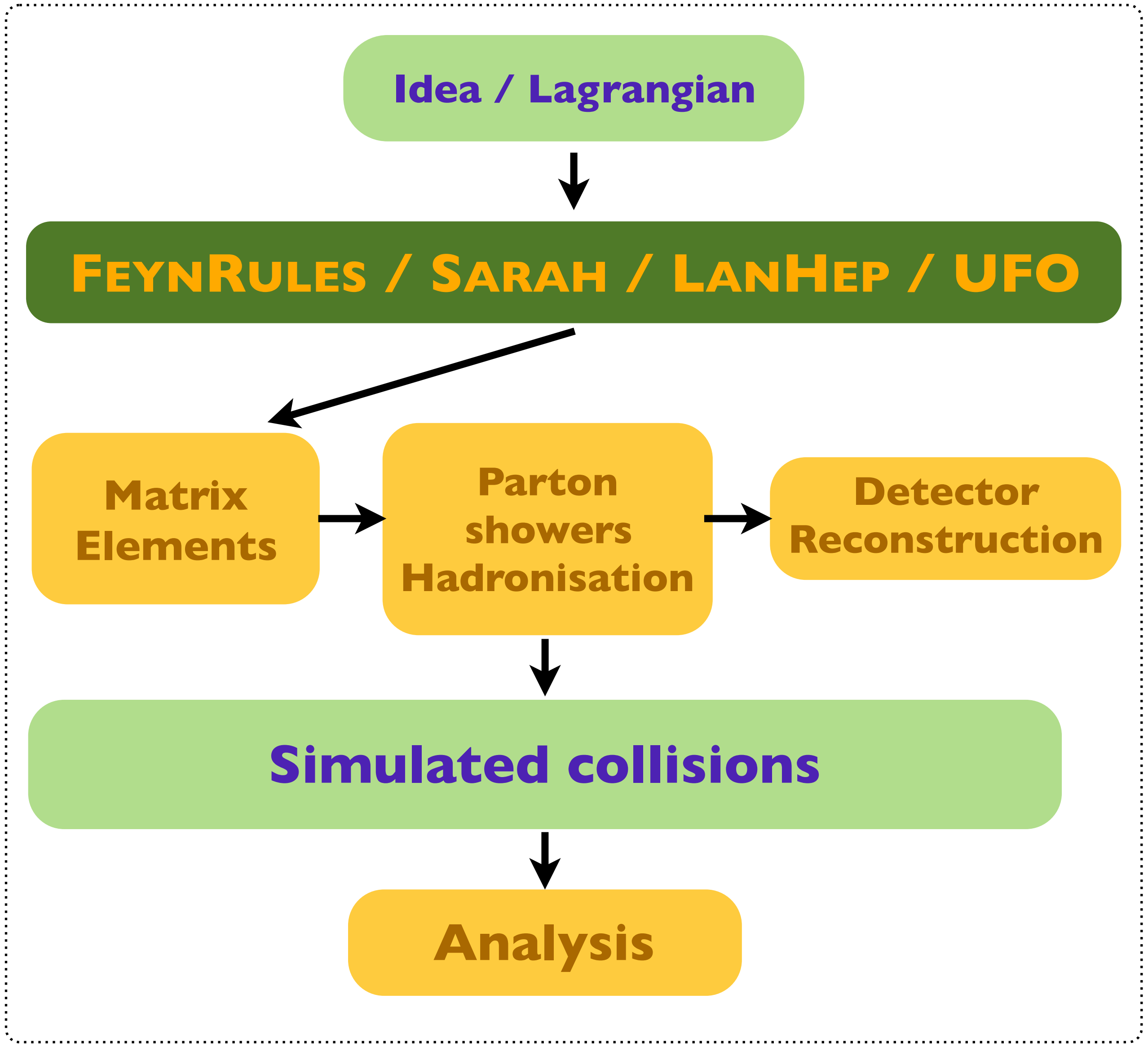

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  - ★ FeynRules, LanHEP, Sarah
  - ★ UFO
- ✤ Matrix element generation
  - ★ CalcHEP, Herwig++, MG5_aMC, Sherpa, Whizard, …
- ✤ QCD environment
  - ★ Herwig, Pythia, Sherpa
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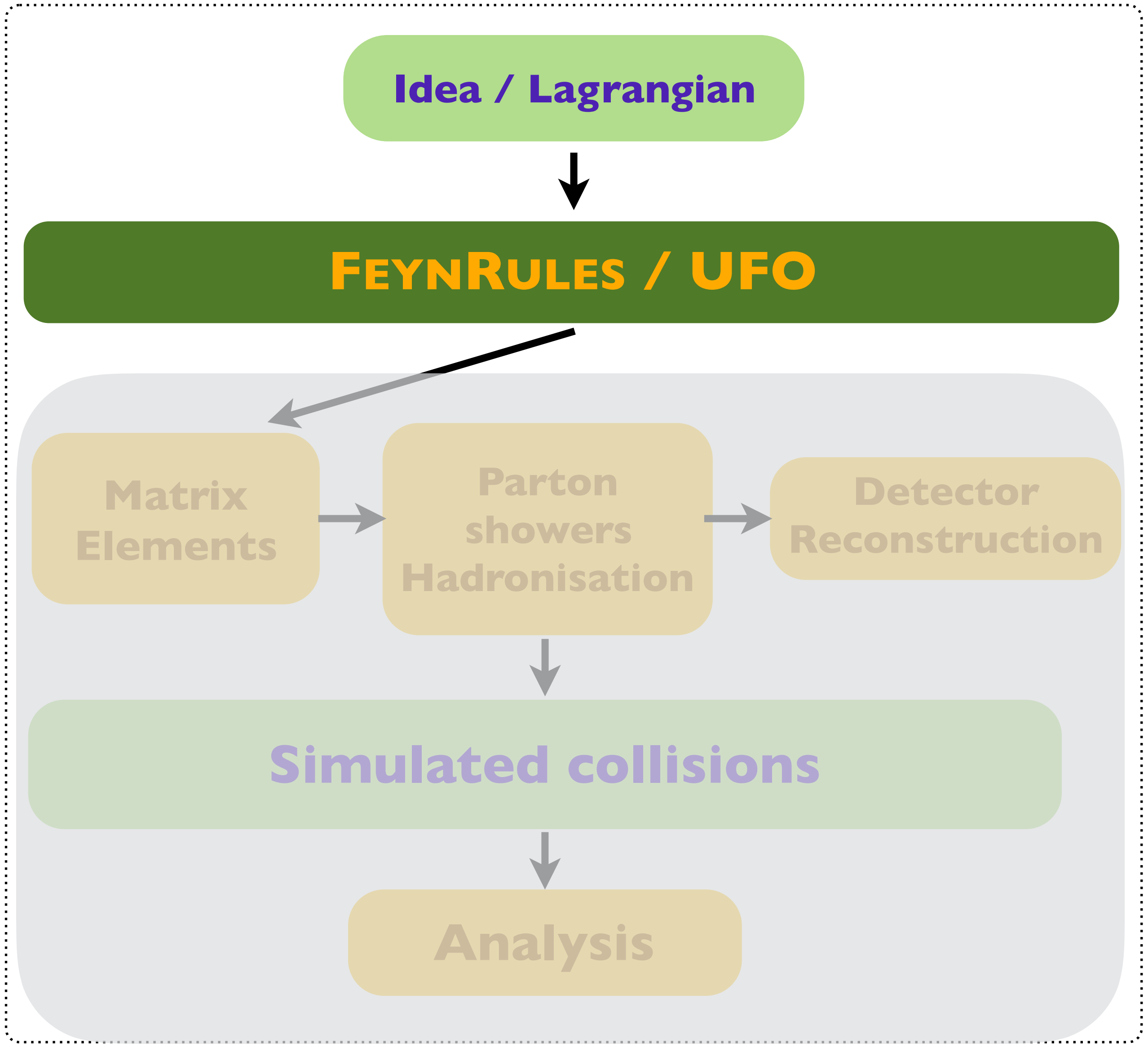

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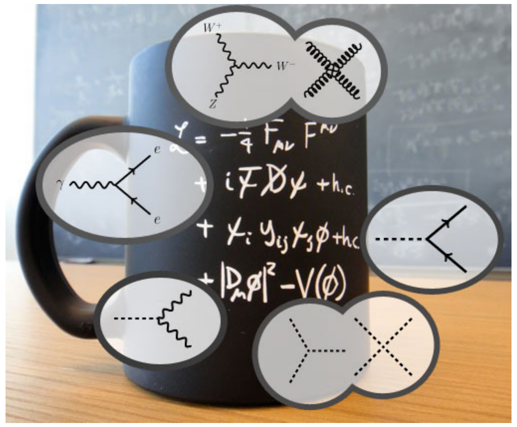
New physics simulations: the ‘how-to’

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

★ Definition: particles, parameters & vertices (≡ Lagrangian)
→ translated in some programming language

★ Tedious, time-consuming, error prone

★ Beware of restrictions/conventions



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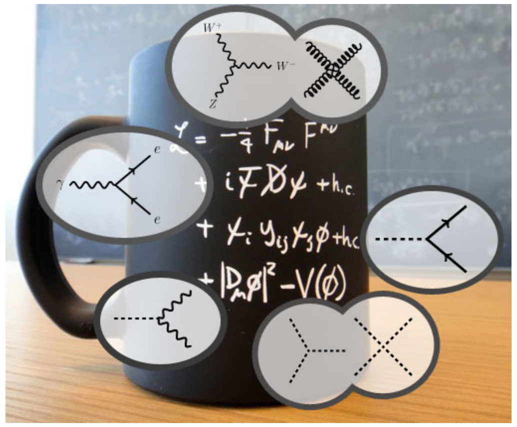

- ★ Highly redundant (each tool, each model)
- ★ No-brainer tasks (from Feynman rules to codes)

Systematisation
Automation

The FEYNRULES package

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

✦ The FEYNRULES platform (since 2009)

- ✤ From Lagrangians to files in a programming language
  - ★ Automatic
- ✤ Very few limitations
  - ★ Higher-dimensional operators all supported
  - ★ Spins: up to 2
  - ★ Colour structures: **1**, **3**, **6**, **8**

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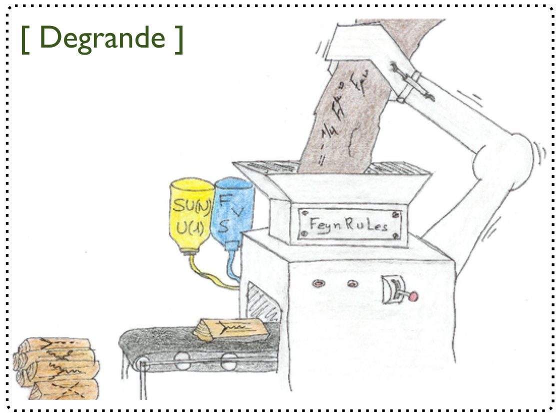

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★ Flexibility, symbolic manipulations, design of new methods, *etc.*

★ Many built-in methods (superspace, spectrum, decays, NLO, *etc.*)

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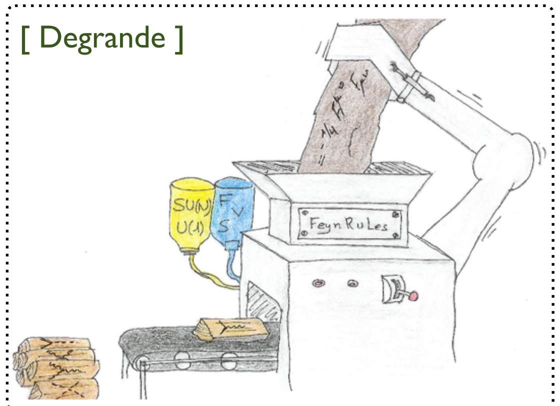
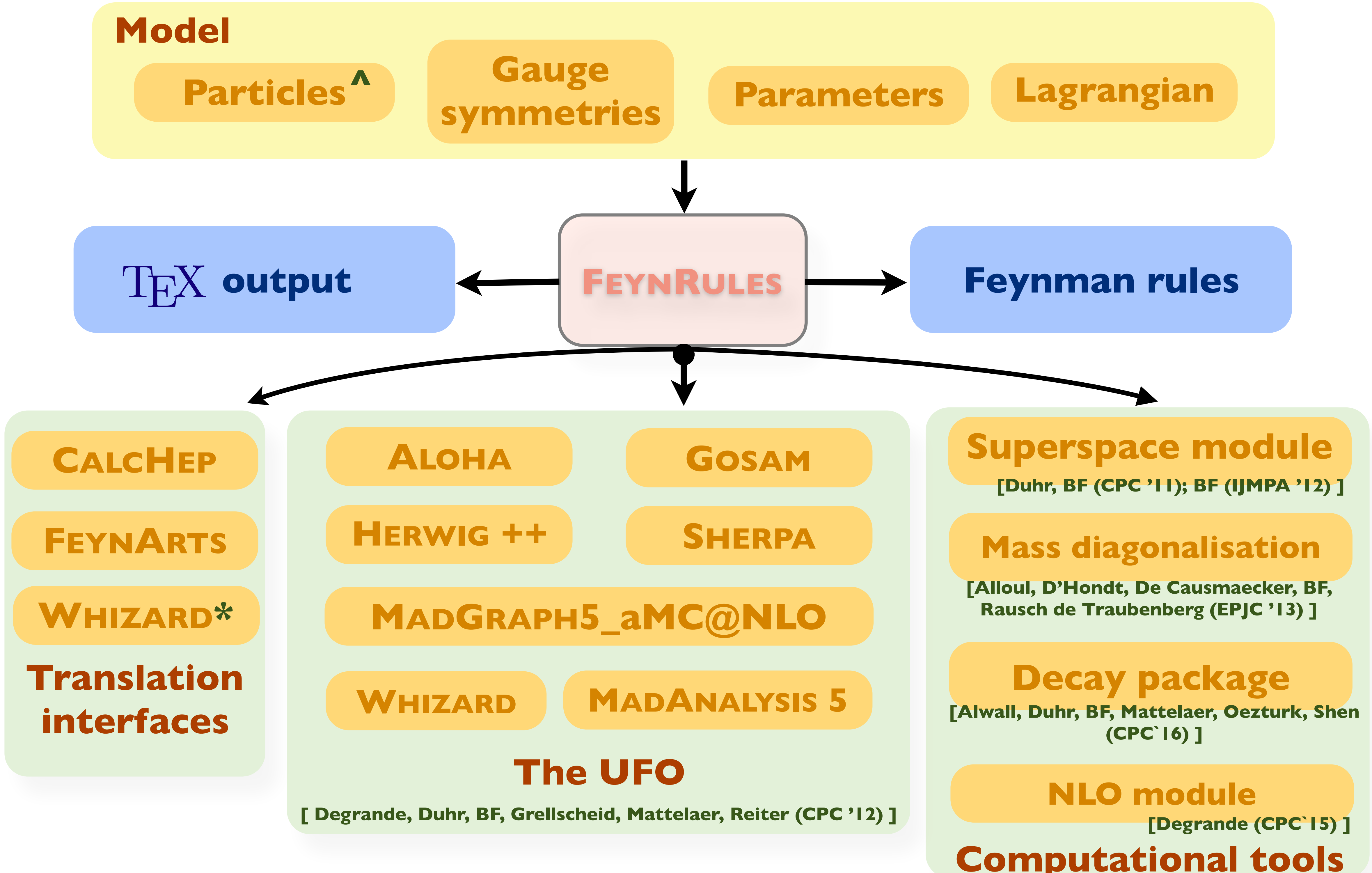


- ✤ Working environment: MATHEMATICA
  - ★ Flexibility, symbolic manipulations, design of new methods, *etc.*
  - ★ Many built-in methods (superspace, spectrum, decays, NLO, *etc.*)
- ✤ Interfaced to many Monte Carlo tools
  - ★ CALCHEP, FEYNARTS, WHIZARD (more previously)
  - ★ More UFOs (HERWIG++, MG5AMC, SHERPA, WHIZARD, ...)

[Degrande]

From FeynRules to Monte Carlo tools…

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



* Whizard interface: Christensen, Duhr, BF, Reuter, Speckner (EPJC ’12)

^ Support for spin 3/2: Christensen, de Aquino, Deutschmann, Duhr, BF, Garcia-Cely, Mattelaer, Mawatari, Oexl, Takaesu (EPJC ’13)

More about interfaces

- Each interface dedicated to a given tool is specific
  - Removal of vertices not compliant with the tool
    - Colour structures
    - Lorentz structures
  - Translation to a specific format and programming language

→ not efficient
→ a unique translation and the tools parse it

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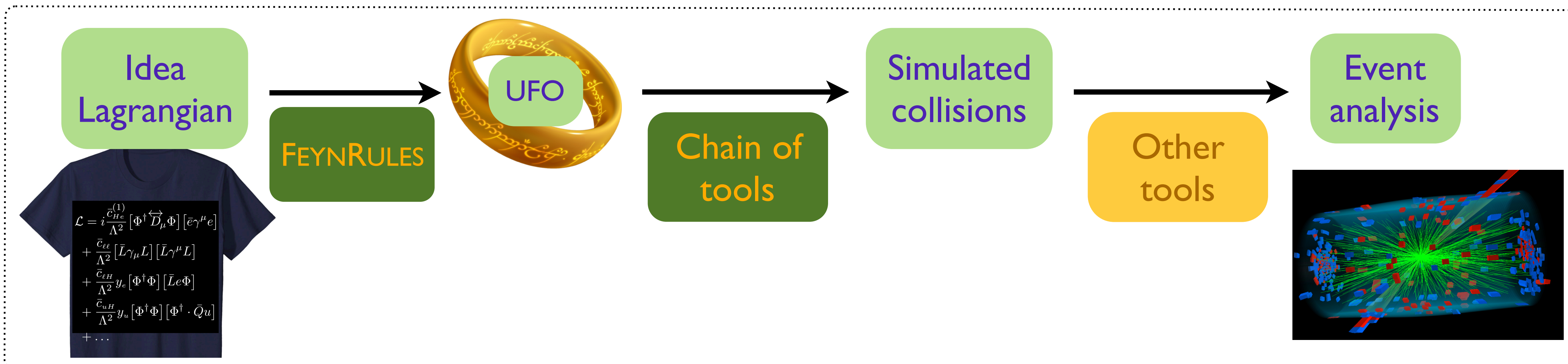
✦ One format to rule them all!



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 (*in prep.*)]

- UFO ≡ Universal FEYNRULES output → Universal Feynman Output
  - Universal as not tied to any specific Monte Carlo program
- Consists of a set of PYTHON files to be linked to any code
- This module contains all the model information
  - Generic colour and Lorentz structures
- Can be employed for next-to-leading order calculations

✦ The UFO is now a standard

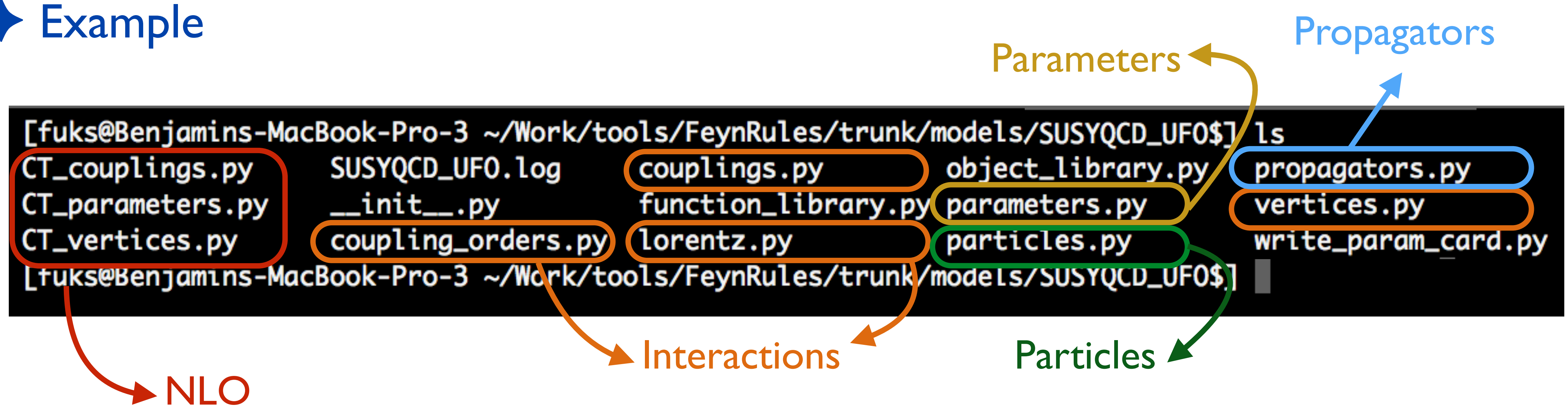
ALOHA | GOSAM | HERWIG ++ | MADANALYSIS 5 | SHERPA

MADGRAPH5_aMC@NLO | WHIZARD | LANHEP | SARAH

The UFO in practice

- The UFO is a set of PYTHON files
  - Factorisation of the information: particles, interactions, parameters, NLO, *etc*.

- Example



Examples: particles & parameters

- **Particles ≡ instances of the particle class**
  - Attributes: spin, colour representation, mass, width, *etc.*
  - Antiparticles automatically derived

```
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)
```

- **Parameters ≡ instances of the parameter class**
  - External parameters: Les Houches-like structure
  - PYTHON-compliant formula for the internal parameters

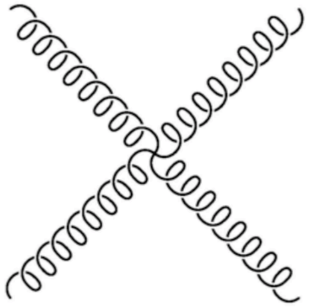
```
aS = Parameter(name = 'aS',
               nature = 'external',
               type = 'real',
               value = 0.1184,
               texname = '\\alpha _s',
               lhablock = 'SMINPUTS',
               lhacode = [ 3 ])

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

Interactions: the key strategy

✦ Decomposition in a spin x colour basis (coupling strengths ≡ coordinates)

✤ Example: the quartic gluon vertex



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

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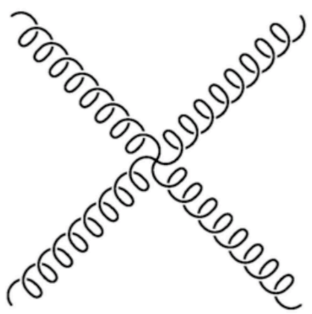

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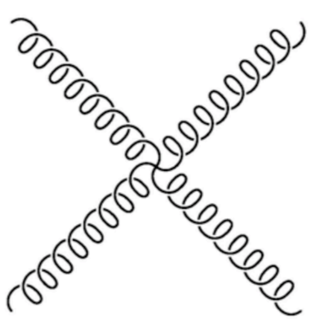
& \quad + i g_s^2\, f^{a_1 a_4 b} f^{b a_2 a_3} \left(\eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}\right)
\end{aligned}
$$

✤ UFO version



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

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

Information encoded in different files

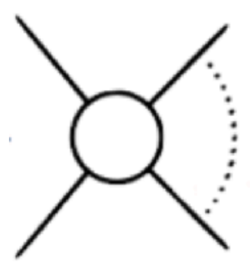
NLO cross sections

✦ Contributions to an NLO result in QCD

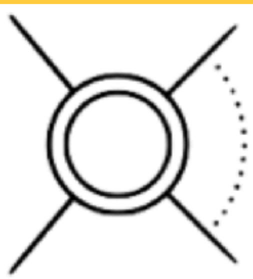
✤ Three ingredients: the Born, virtual loop and real emission contributions

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

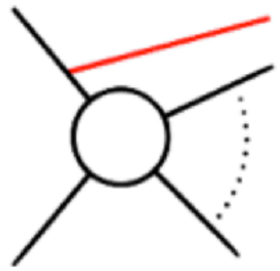
Born



Virtuals: one extra power of α_s and divergent



Reals: one extra power of α_s and divergent



Extra information is needed

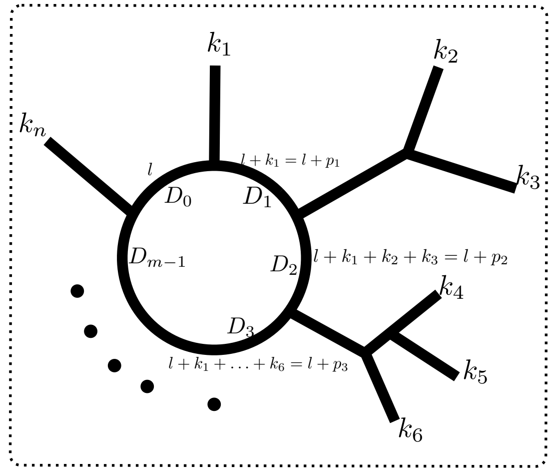
Talks by HS. Shao

Loop calculations

- Dimensional regularisation: calculations in $d = 4 - 2\varepsilon$
  - Divergences explicit ($1/\varepsilon^2$, $1/\varepsilon$)
  - Reduction of tensor loop-integrals to scalar integrals
- The reduction must be performed in a d-dimensional space
  - Numerical methods work in 4 dimensions → R_1 and R_2 terms

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

D-dim 4-dim (-2ε)-dim



[Ossala, Papadopoulos, Pittau (NPB'07; JHEP'08)]

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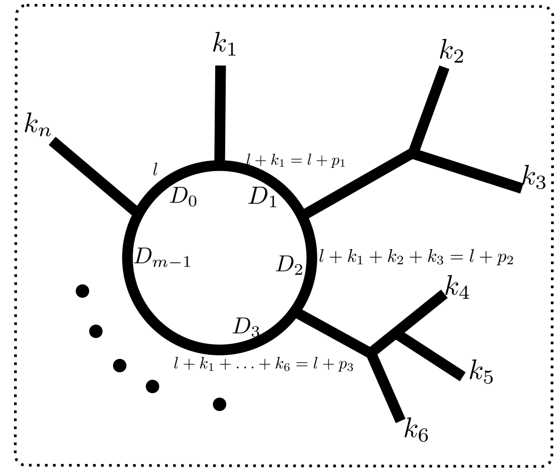

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$\bar{\ell}$: D-dim; ℓ: 4-dim; $\tilde{\ell}$: (-2ε)-dim

[Ossala, Papadopoulos, Pittau (NPB'07; JHEP'08)]

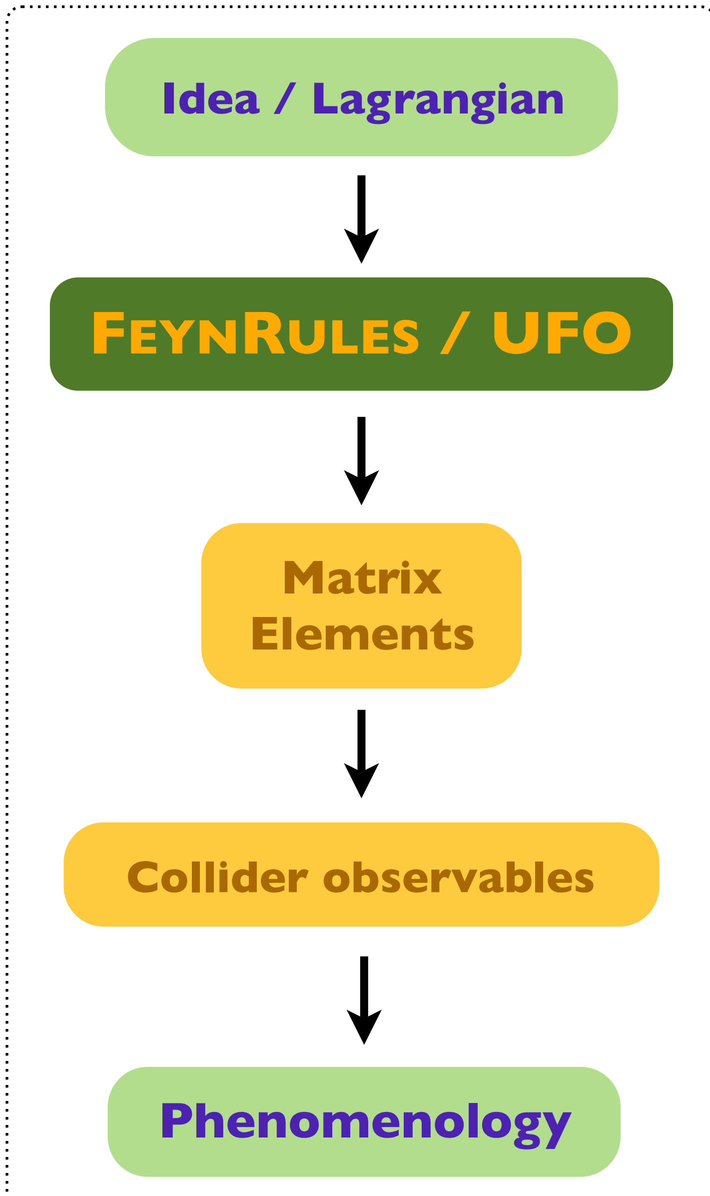
- **The R_1 terms originate from the denominators**
  - Connected to the internal propagators

Talk from O. Mattelaer

- **The R_2 terms originate from the numerator**
  - Process-dependent contributions proportional to $\tilde{\ell}^2$
  - Renormalisable theory: finite number of R_2's
    - ★ Seen as extra diagrams with special Feynman rules (→ *R_2 Feynman rules*)
    - ★ Connected to the UV structure of the integrals (like the UV counterterms)
    - ★ Can be derived from the bare Lagrangian → NLOCT

UFO @ NLO

Automated NLO simulations with MG5_AMC



✦ Model building: from Lagrangian to tools

- ✤ FEYNRULES ⊕ MOGRE ⊕ NLOCT → UFO @ NLO
- ✤ General on-shell renormalisation scheme

[Alloul, Christensen, Degrande, Duhr & BF (CPC'14) ; Degrande (CPC'15)]
[Degrande, Duhr, BF, Mattelaer & Reither (CPC'12)]
[Frixione, BF, Hirschi, Mawatari, Shao, Sunder & Zaro (JHEP`19)]

✦ Hard scattering

- ✤ Feynman diagram, matrix elements
- ✤ MG5aMC → predictions at LO/NLO

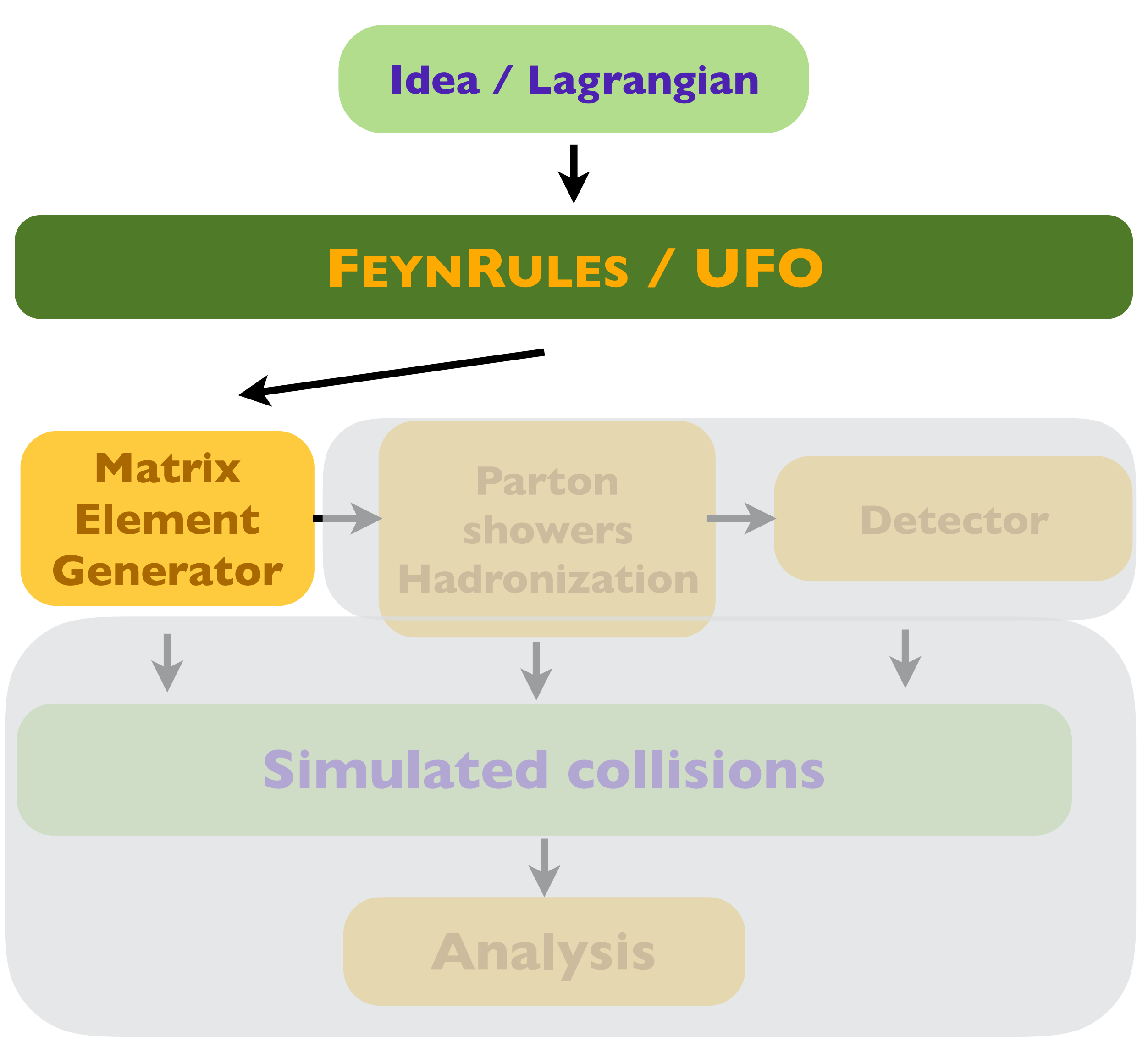
[Alwall *et al.* (JHEP'14)]

Outline

1. A comprehensive approach for Monte Carlo simulations
2. Implementing models into Monte Carlo event generators
3. **From models to hard-scattering events**
4. Summary

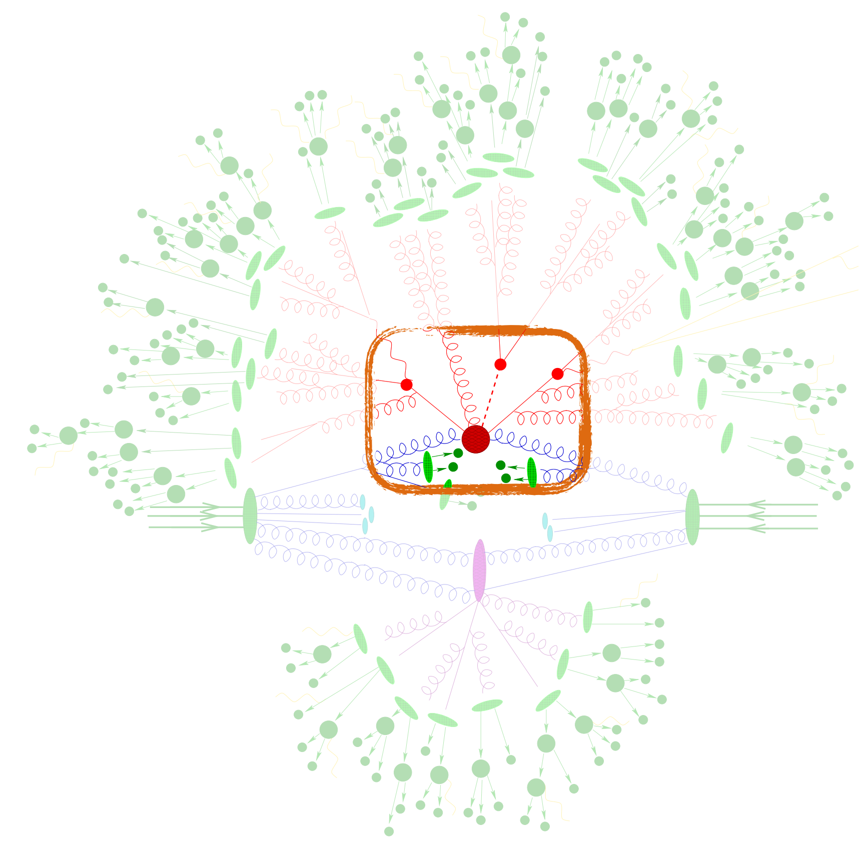
Back to the simulation chain

✦ Tools connecting an idea to simulated collisions



✤ Hard scattering process

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



QCD 101: predictions at the LHC

✦ Distribution of an observable ω: the QCD factorisation theorem

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega} = \sum_{ab} \int \mathrm{d}x_a \, \mathrm{d}x_b \, \mathbf{f}_{\mathbf{a}/\mathbf{p_1}}(x_a; \mu_F) \, \mathbf{f}_{\mathbf{b}/\mathbf{p_2}}(x_b; \mu_F) \, \frac{\mathrm{d}\sigma_{\mathbf{ab}}}{\mathrm{d}\omega}(\ldots, \mu_F)$$

- ✤ Long distance physics: the parton densities
- ✤ Short distance physics: the differential parton cross section $\mathrm{d}\sigma_{ab}$
- ✤ Separation of both regimes through the factorisation scale μ_F
  - ★ Choice of the scale ➢ theoretical uncertainties

Talk by F. Maltoni

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Talk by F. Maltoni

✦ Short distance physics: the partonic cross section

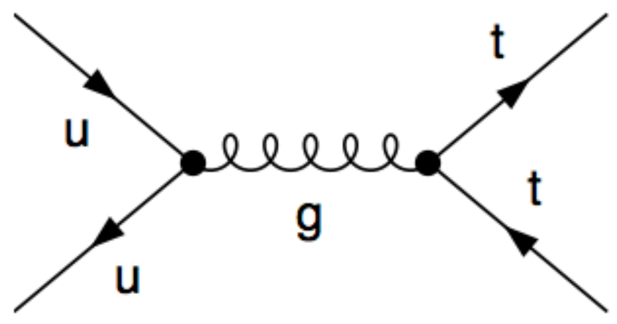
- ✤ Calculated order by order in perturbative QCD: $d\sigma = d\sigma^{(0)} + \alpha_s\, d\sigma^{(1)} + \ldots$
  - ★ The more orders included, the more precise the predictions
  - ★ Truncation of the series and α_s ➢ theoretical uncertainties

Feynman diagrams (from UFOs)

Feynman diagram calculations

- Direct squared matrix element computations
  - Extraction of the amplitude from the Feynman rules

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



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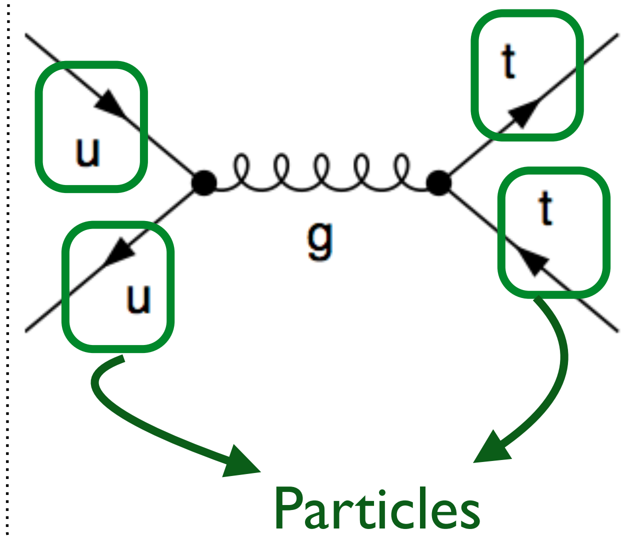

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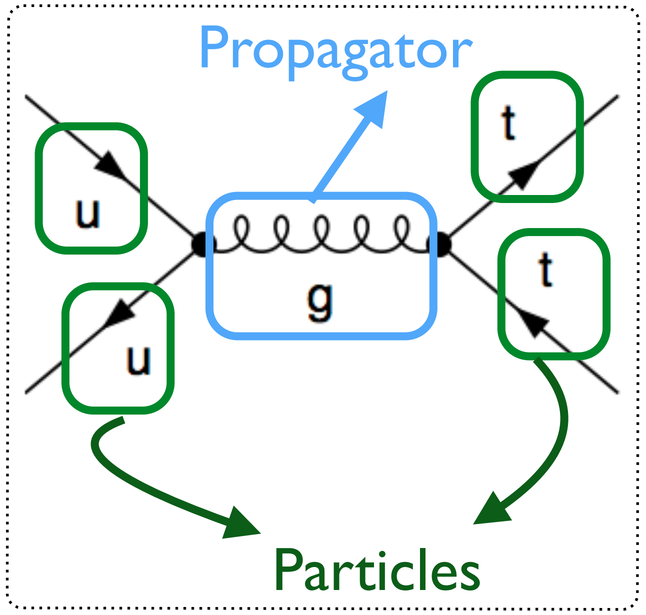

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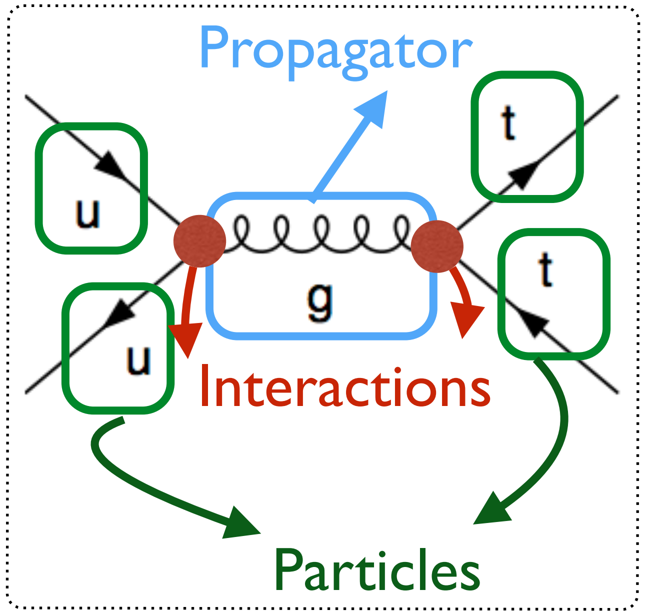

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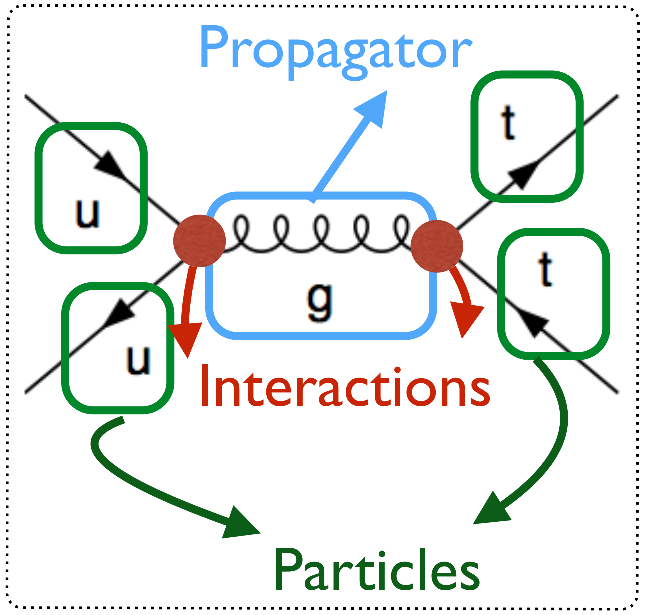
✤ Squaring with the conjugate amplitude

✤ Algebraic calculation (colour and Lorentz structures)

✤ Sum/average over the external states

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

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



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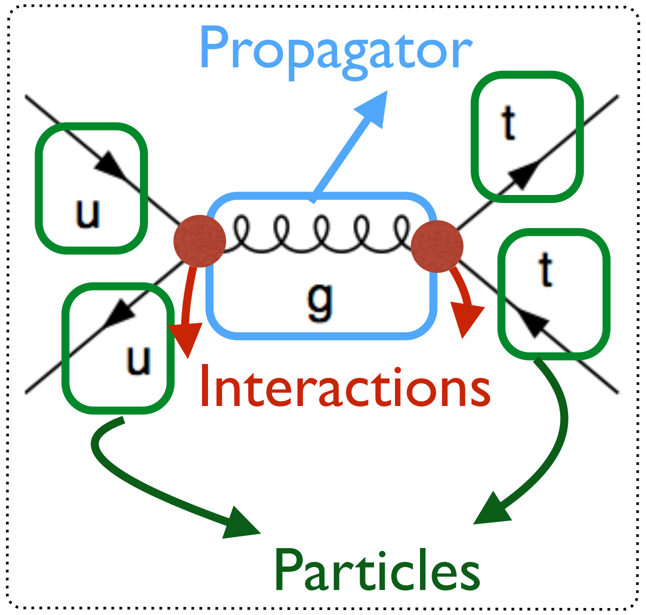

✤The squared matrix element needs to be integrated

Talk by O. Mattelaer

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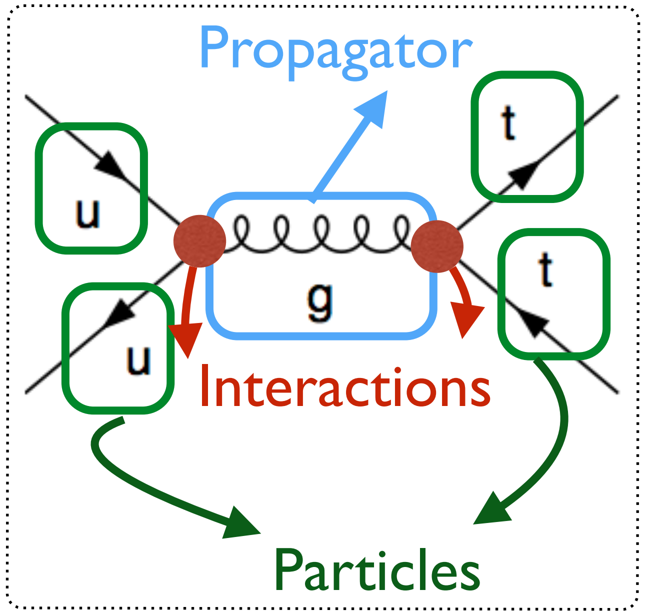


✤The squared matrix element needs to be integrated

Talk by O. Mattelaer

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

✤ The complexity rises as N^2

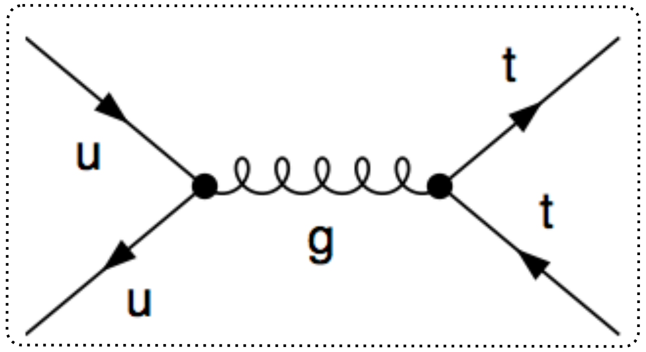
✤ Any calculation beyond 2-to-3 becomes a problem

➢ **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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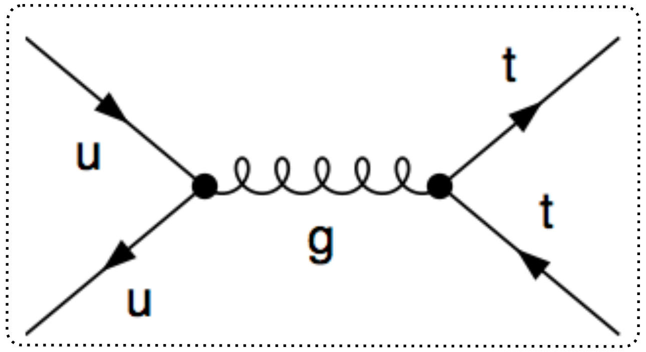
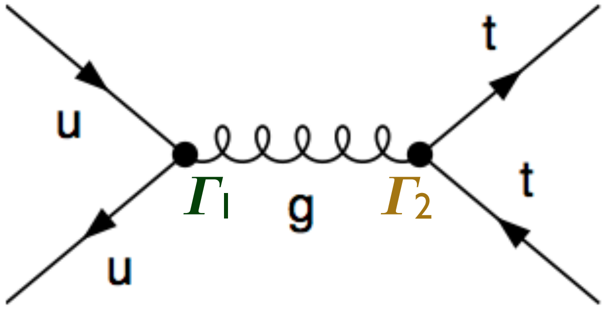


✦ Practical example



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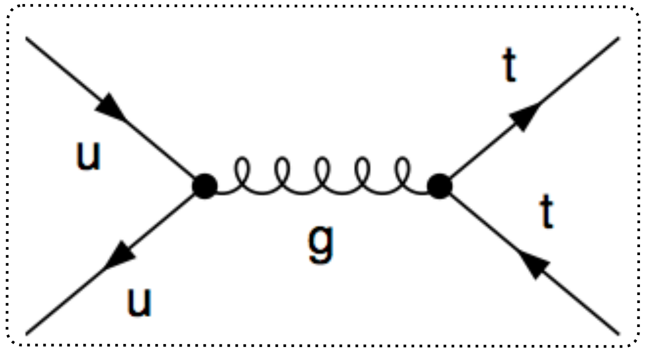

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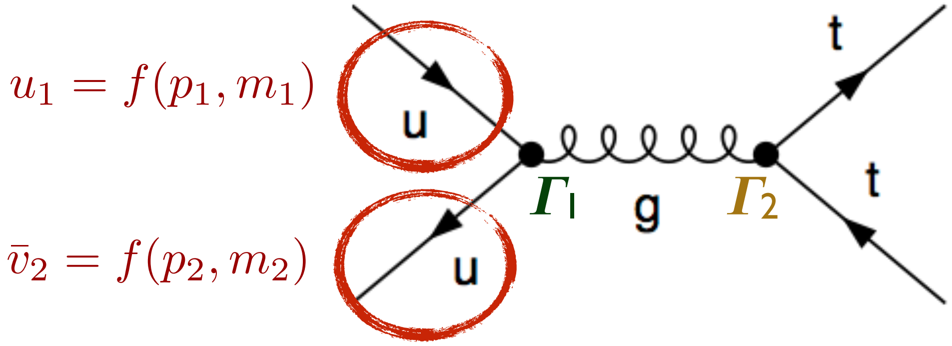

1. External incoming particles (numbers)
   - ★ For fixed helicity and momentum

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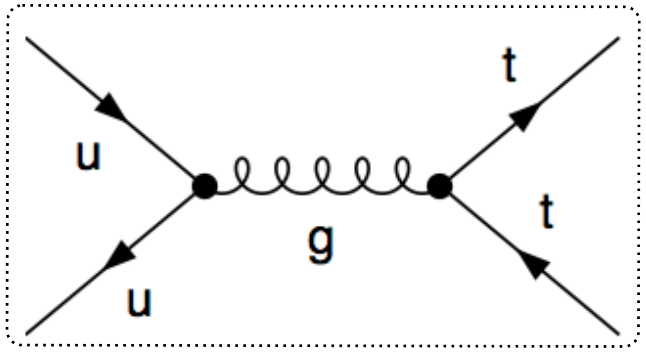

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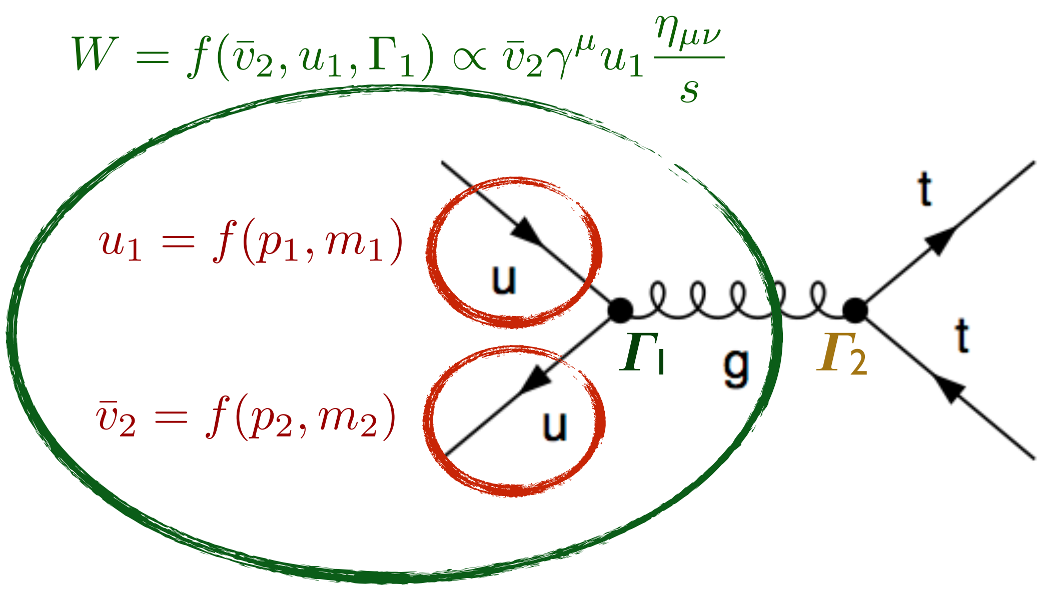

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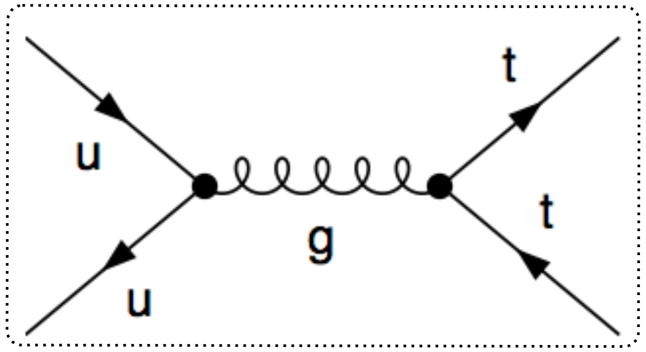

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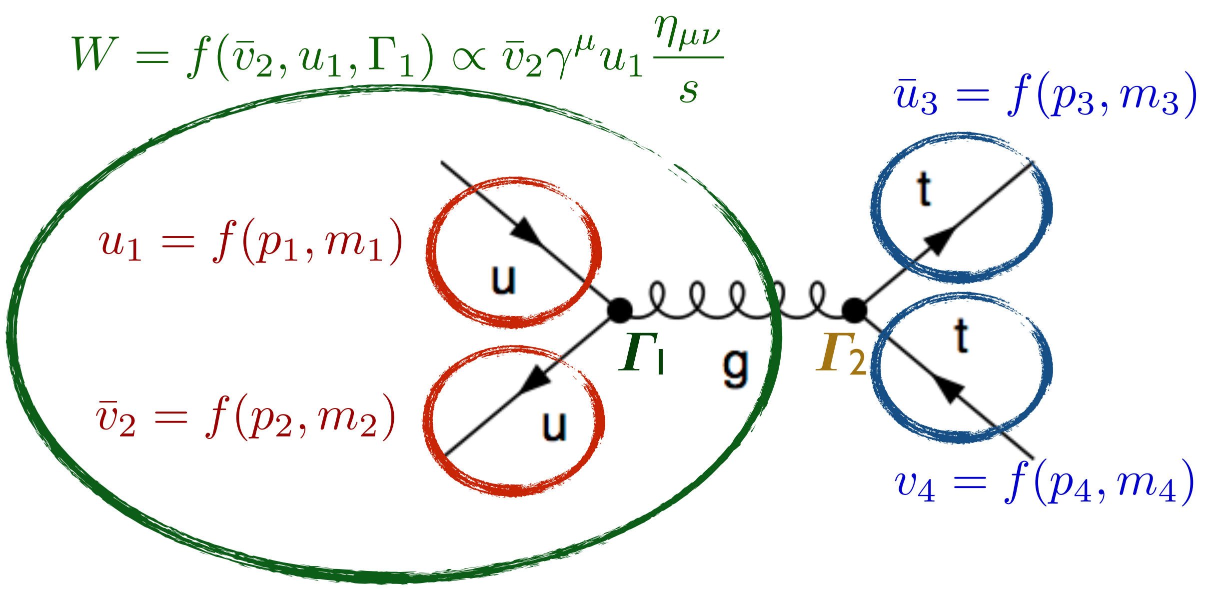

1. External incoming particles (numbers)
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3. External outgoing particles

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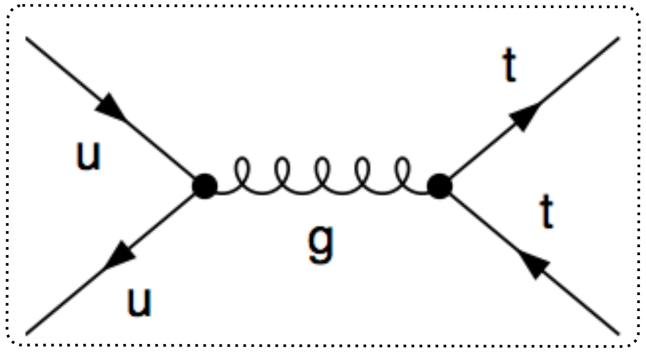

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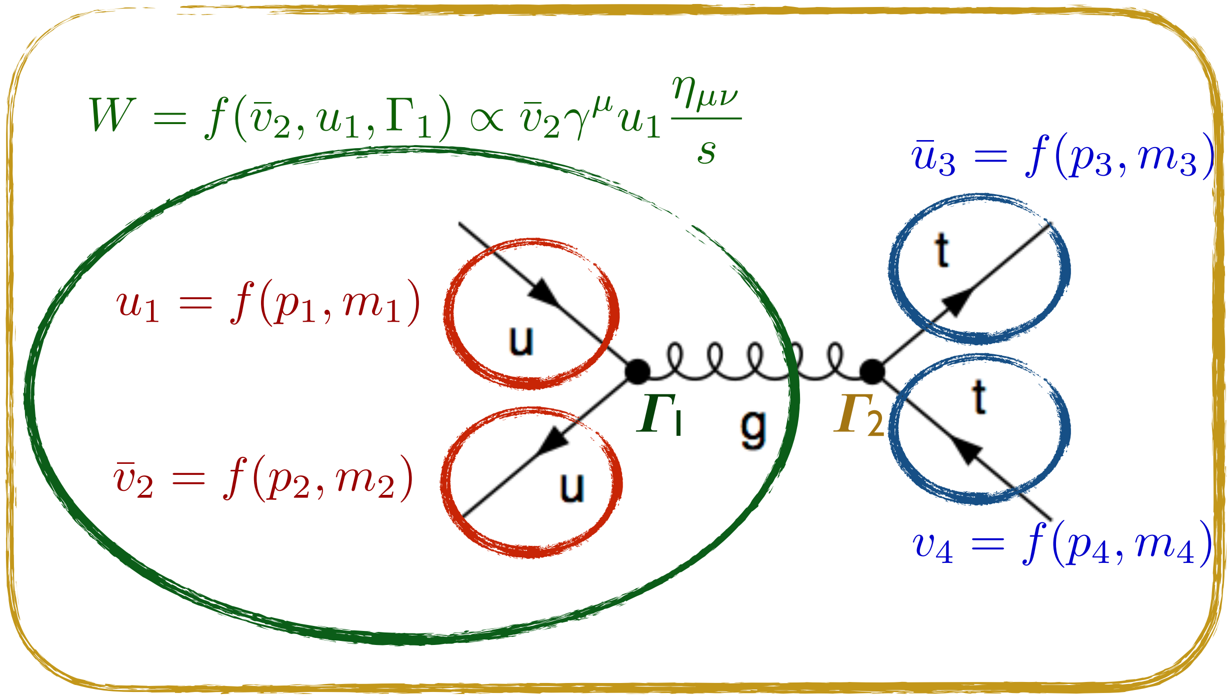
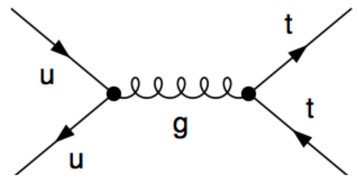


$i\mathcal{M} = f(\bar{u}_3, v_4, W, \Gamma_2)$

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

HELAS

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



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$\bar{u}_3 = f(p_3, m_3)$

$v_4 = f(p_4, m_4)$

$W = f(\bar{v}_2, u_1, \Gamma_1)$

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

- 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)]
  - ★ MSSM [Cho, Hagiwara, Kanzaki, Plehn, Rainwater & Stelzer (PRD`06)]
  - ★ HEFT [Frederix (2007)]
  - ★ Spin 2 [Hagiwara, Kanzaki, Li &Mawatari (EPJC`08)]
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Sufficient for many models

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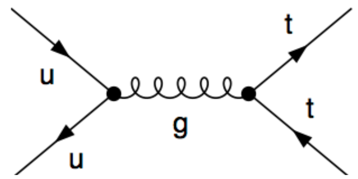

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Sufficient for many models

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

- Translation of any vertex present in a UFO into a HELAS subroutine
- Any model supported in MG5_aMC@NLO

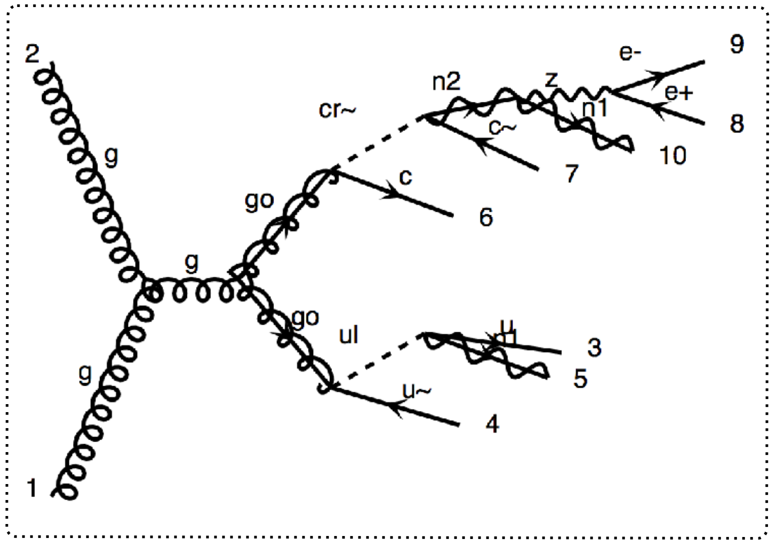
✦ Recycling: reusing pieces from one diagram to another

Comparison

	For M diags	For N particles	$2 \to 6$ example
Analytical	M^2	$(N!)^2$	10^9
Helicity	M	$N!\ 2^N$	10^7
Recycling	M	$(N-1)!\ 2^{N-1}$	5×10^5

Heavy particle decays

- ✦ Concrete BSM models
  - ✤ Many additional new states
    - ★ Usually pair-produced
    - ★ Cascade-decaying into each other
  - ✤ The lightest new state often stable (*cf.* dark matter)



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

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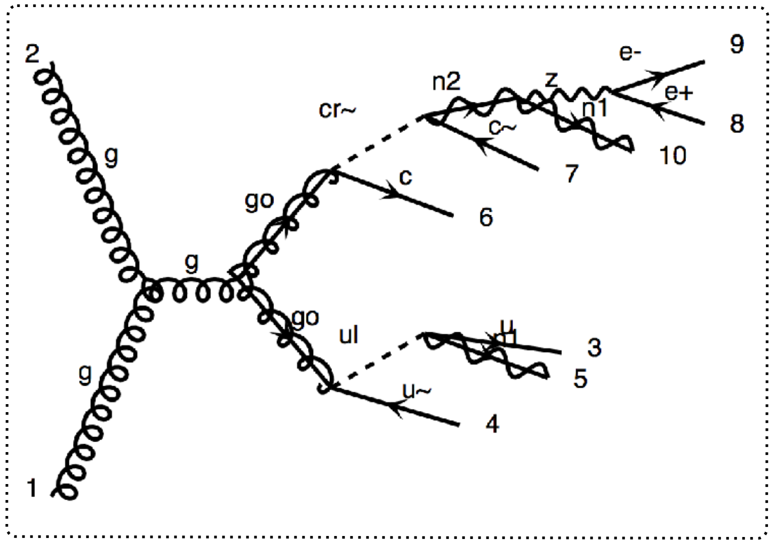


Is the simulation of 2-to-*N* processes (with a large *N*) a problem?

- 2-to-*N* matrix-element generation is possible
  → computationally challenging
- The issue is the computing time
  - Connected to the final-state multiplicity
  - Diagrams with intermediate resonances dominate
- Factorisation of the production from the decay

Making decays easy: the key principle

✦ Production and decay processes are factorised

✤ Propagators can be seen as sums of products of external wave functions

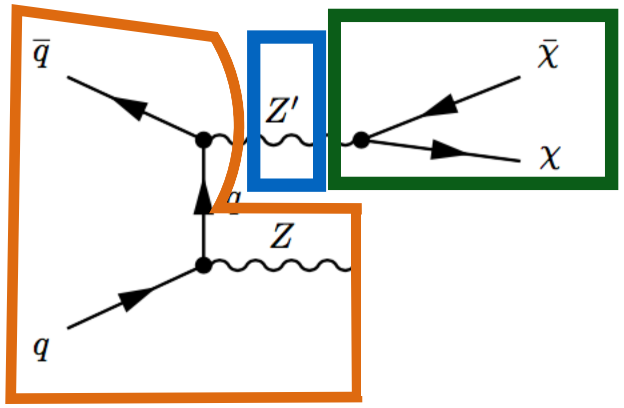
✤ Example for a vector resonance

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

Propagation

Production of the resonance

Decay of the resonance



Making decays easy: the key principle

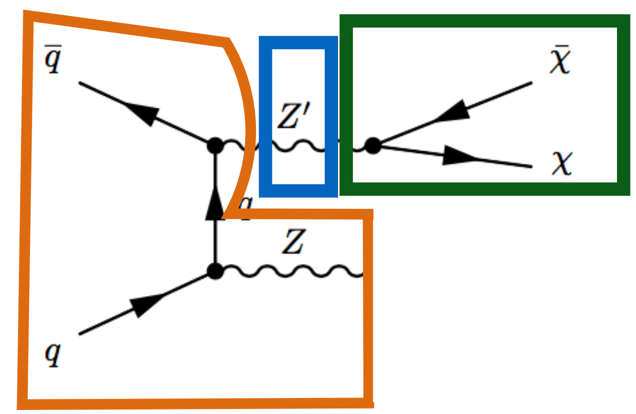
- **Production and decay processes are factorised**
  - Propagators can be seen as sums of products of external wave functions
  - Example for a vector resonance

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

Propagation

Production of the resonance

Decay of the resonance



  - Off-shell effects are lost (as a result of the factorisation)
    - ★ 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 (production ⊕ decays)

$$\mathcal{M} = j_1^\mu \left[\eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right] j_2^\nu = \sum_\lambda j_1^\mu \varepsilon_\mu^*(\lambda)\ j_2^\nu \varepsilon_\nu(\lambda) \simeq \underbrace{\sum_\lambda j_1^\mu \varepsilon_\mu^*(\lambda)}_{\text{Production}} \underbrace{\sum_{\lambda'} j_2^\nu \varepsilon_\nu(\lambda')}_{\text{Decay}}$$

Practical implementations of decays

✦ Case 1: loss of spin correlations

✤ Helicity sums performed independently (production ⊕ decays)

$$\mathcal{M} = j_1^\mu \left[\eta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right] j_2^\nu = \sum_\lambda j_1^\mu \varepsilon_\mu^*(\lambda)\ j_2^\nu \varepsilon_\nu(\lambda) \simeq \underbrace{\sum_\lambda j_1^\mu \varepsilon_\mu^*(\lambda)}_{\text{Production}} \underbrace{\sum_{\lambda'} j_2^\nu \varepsilon_\nu(\lambda')}_{\text{Decay}}$$

✦ Case 2: including spin correlations

✤ Keeping track of helicities

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

★ Reweighting according to decay matrix element (e.g. MADSPIN)

[Artoisenet *et al.* (JHEP '13)]

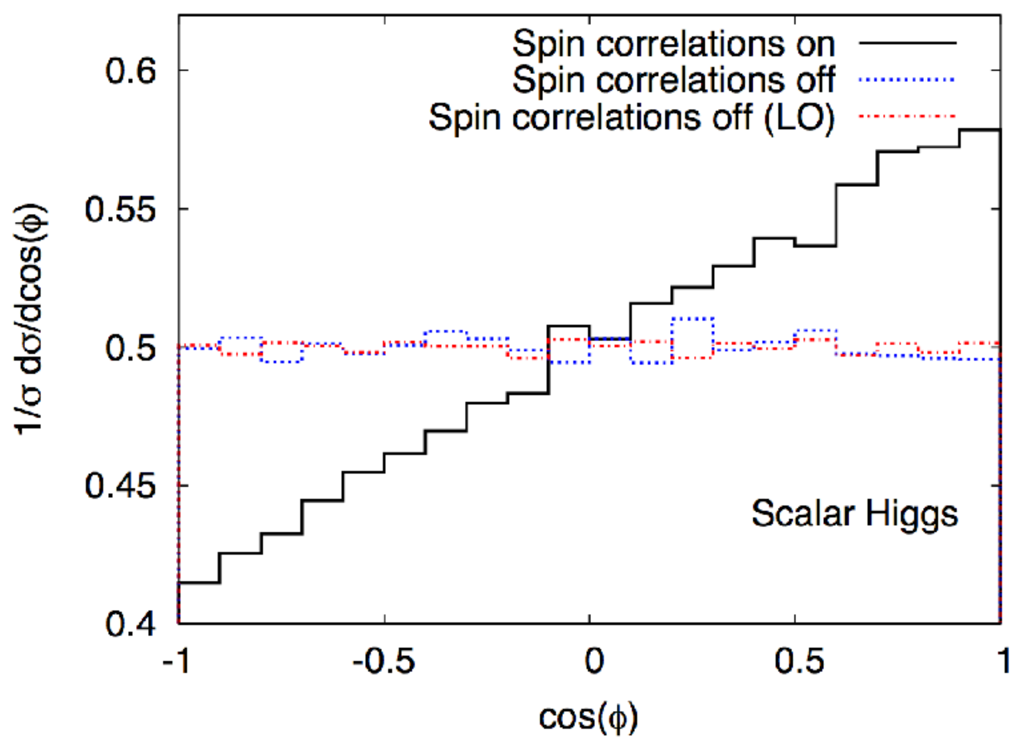
★ Using spin density matrices (e.g. HERWIG, SHERPA).

[Richardson (JHEP '01); Höche *et al.* (EPJC '15)]

Importance of correctly-handled decays

✦Two examples (dependent of the observable)

Angle between the leptons in the respective mother top rest frames



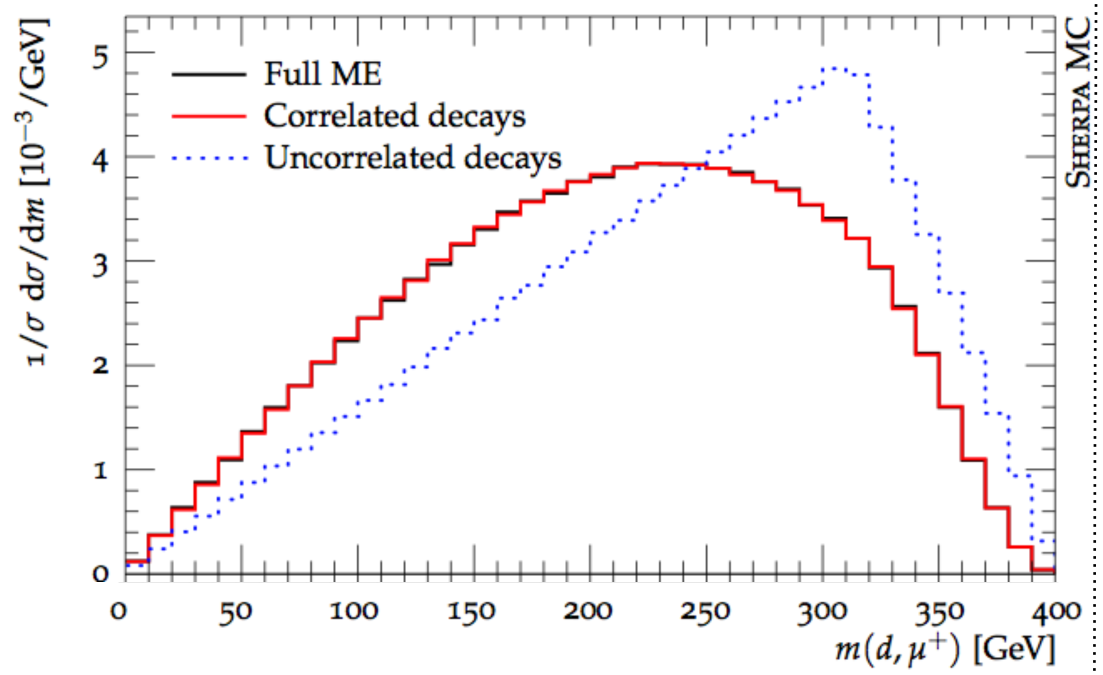
MadSpin

$t\bar{t}H$ 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]

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

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

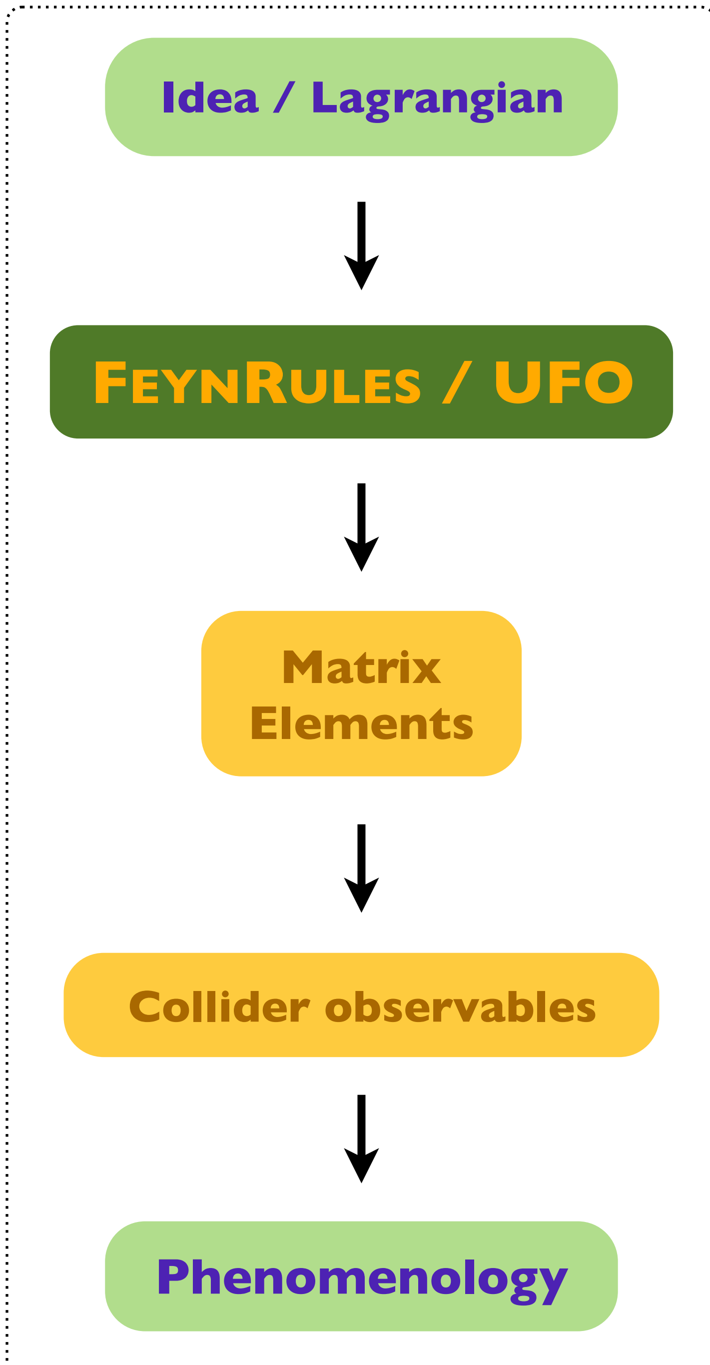
$\tilde{u}^\dagger \to \ldots \to \bar{u}e^+e^-\tilde{\chi}_1^0$

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

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

Outline

Summary



- ✦ Event simulation is a complex process
  - ✤ Nature allows us to factorise 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