FeynRules
New models phenomenology made easy

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- Why yet another tool..?
- Model building with FeynRules
- Some examples:
  - How to get the Feynman rules of your new model
  - How to add a new sector to the SM
- Conclusion

Why yet another tool..?

- Since the 70's, particle physics is governed the SM.
- The SM cannot be the final theory, because it leaves many unanswered questions (hierarchy problem, dark matter,...)
- By now, many extensions of the SM are available (SUSY, composite higgs,...), but only experiment can decide whether the model corresponds to reality or not.

Why yet another tool..?

- In general, a new model is given by a lagrangian, containing all the particles and their mutual interactions.
- At some point, one would like to compare the model with experiment.

→ Needs in general some hard calculations:

- cross-sections
- decay rates
- radiative corrections

Why yet another tool..?

- Fortunately, several tools are available to do the calculations
  - MC generators (MadGraph, CalcHep, CompHEP, AMEGIC++)
  - FeynArts,...

New model

(Lagrangian, new particles,...)

Existing tools

(Programming language, files containing the new particles and interactions,...)

FeynRules

- Mathematica© based package that calculates Feynman rules from a lagrangian.
- No special requirements on the form of the lagrangian.
- Particle types available so far: scalars, fermions (Dirac and Majorana), vectors, spin-2.

FeynRules

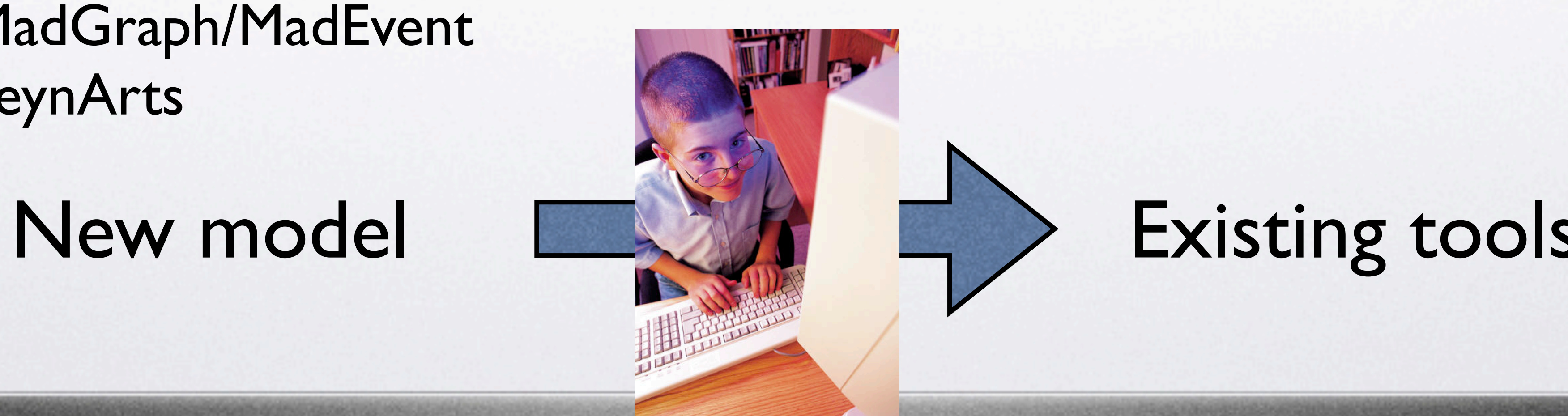
- The user has to write a model file, containing all the information contained in the model (except the Feynman rules)
  - Particles & fields
  - Parameters (masses, coupling constants,...)
  - mixing matrices
  - etc.
- The syntax of the FR model-files is an extension of syntax used in FeynArts.
- Feynman rules are calculated by Mathematica using the information from the model-file and the lagrangian.
- The vertices can be exported into a TeX-file.

FeynRules

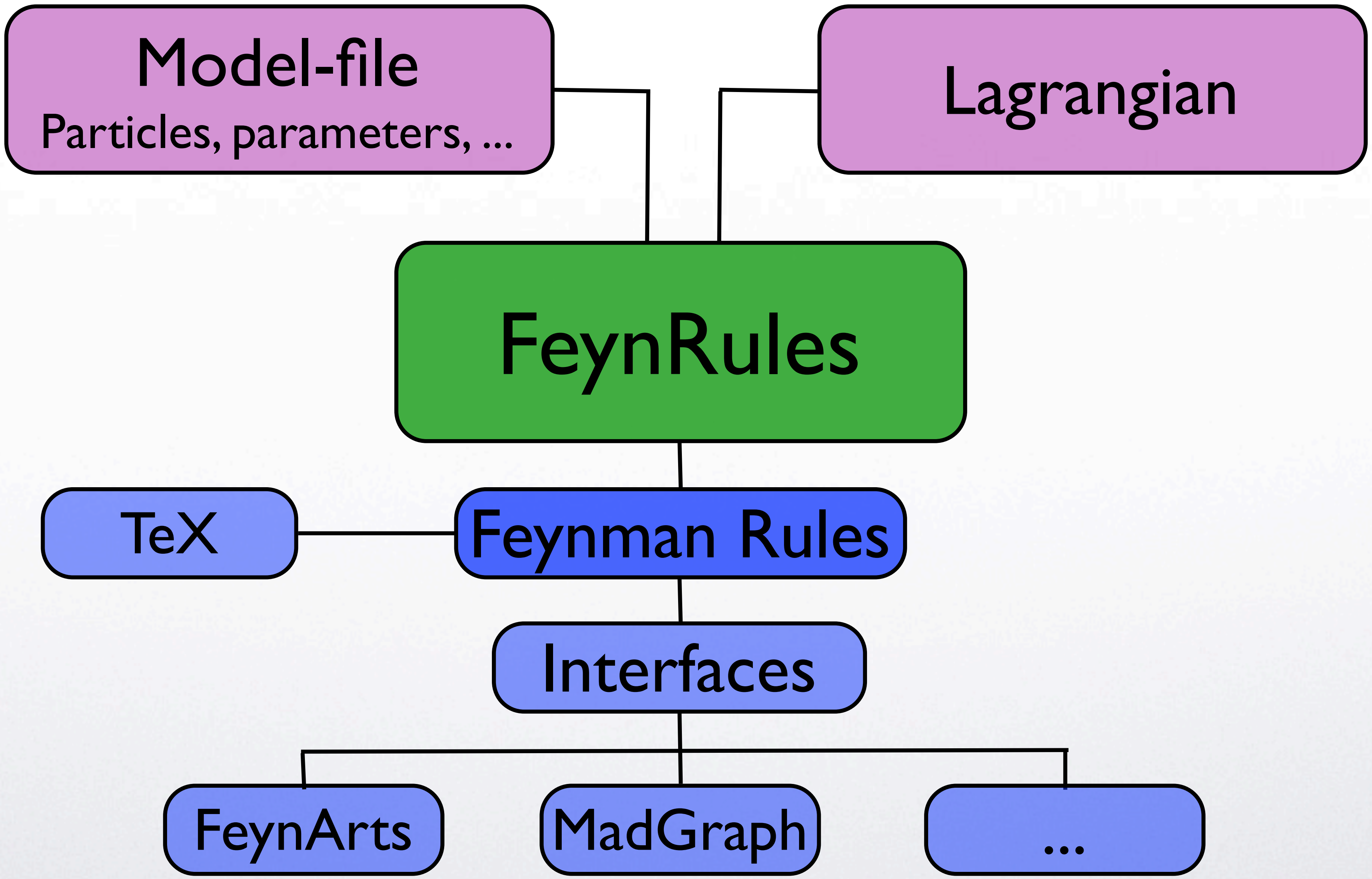
- The informations given in the model-file, together with the vertices obtained by FR, is generic enough to allow for an interface to other existing tools.

- FR creates all files needed to run the new model just by knowing the FR model-file and the lagrangian.

- Interfaces available so far
  - MadGraph/MadEvent
  - FeynArts



FeynRules


Model-file
Particles, parameters, ...
Lagrangian
FeynRules
TeX
Feynman Rules
Interfaces
FeynArts
MadGraph
...

Getting Feynman rules

Kaluza-Klein States from Large Extra Dimensions

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[hep-ph/9811350]

Particle content:

- Spin 2 graviton, KK-scalars
- Fermions
- Scalars
- Gauge bosons

Getting Feynman rules

- Lagrangian coupling the fermions to the graviton and the KK-scalar:

$$\kappa^{-1}\mathcal{L}_{\mathrm{F}}^{\vec{n}}(\kappa) = \frac{1}{2}\Big[(\widetilde{h}^{\vec{n}}\eta^{\mu\nu} - \widetilde{h}^{\mu\nu,\vec{n}})\overline{\psi}i\gamma_\mu D_\nu\psi - m_\psi\widetilde{h}^{\vec{n}}\overline{\psi}\psi + \frac{1}{2}\overline{\psi}i\gamma^\mu(\partial_\mu\widetilde{h}^{\vec{n}} - \partial^\nu\widetilde{h}^{\vec{n}}_{\mu\nu})\psi\Big]$$
$$+\frac{3\omega}{2}\widetilde{\phi}^{\vec{n}}\overline{\psi}i\gamma^\mu D_\mu\psi - 2\omega m_\psi\widetilde{\phi}^{\vec{n}}\overline{\psi}\psi + \frac{3\omega}{4}\partial_\mu\widetilde{\phi}^{\vec{n}}\overline{\psi}i\gamma^\mu\psi\ . \qquad (44)$$

- Very complicated structure as far as Feynman rules are concerned, but we are only a few steps away from the Feynman rules...

Getting Feynman rules

- **Step 1**: Add all the parameters in the lagrangian to the model file:

```
M$Parameters = {

   g, k, om, ...

}
```

$$\begin{aligned}\kappa^{-1}\mathcal{L}_{\rm F}^{\vec{n}}(\kappa) &= \frac{1}{2}\Big[(\tilde{h}^{\vec{n}}\eta^{\mu\nu} - \tilde{h}^{\mu\nu,\vec{n}})\overline{\psi}i\gamma_\mu D_\nu\psi \\ &\quad - m_\psi\tilde{h}^{\vec{n}}\overline{\psi}\psi + \frac{1}{2}\overline{\psi}i\gamma^\mu(\partial_\mu\tilde{h}^{\vec{n}} - \partial^\nu\tilde{h}^{\vec{n}}_{\mu\nu})\psi\Big] \\ &\quad + \frac{3\omega}{2}\tilde{\phi}^{\vec{n}}\overline{\psi}i\gamma^\mu D_\mu\psi - 2\omega m_\psi\tilde{\phi}^{\vec{n}}\overline{\psi}\psi \\ &\quad + \frac{3\omega}{4}\partial_\mu\tilde{\phi}^{\vec{n}}\overline{\psi}i\gamma^\mu\psi\end{aligned}$$

Getting Feynman rules

- Step II: Add all the particles in the lagrangian to the model file:

```
M$ClassesDescription = {

  Sp2[1] == {
     ClassName -> h,
     SelfConjugate -> True,
     Symmetric -> True}

  ...

}
```

$$\kappa^{-1}\mathcal{L}_{\rm F}^{\vec{n}}(\kappa) = \frac{1}{2}\Big[(\widetilde{h}^{\vec{n}}\eta^{\mu\nu} - \widetilde{h}^{\mu\nu,\vec{n}})\overline{\psi}i\gamma_\mu D_\nu\psi - m_\psi\widetilde{h}^{\vec{n}}\overline{\psi}\psi + \frac{1}{2}\overline{\psi}i\gamma^\mu(\partial_\mu\widetilde{h}^{\vec{n}} - \partial^\nu\widetilde{h}^{\vec{n}}_{\mu\nu})\psi\Big] + \frac{3\omega}{2}\widetilde{\phi}^{\vec{n}}\overline{\psi}i\gamma^\mu D_\mu\psi - 2\omega m_\psi\widetilde{\phi}^{\vec{n}}\overline{\psi}\psi + \frac{3\omega}{4}\partial_\mu\widetilde{\phi}^{\vec{n}}\overline{\psi}i\gamma^\mu\psi$$

Getting Feynman rules

- Step III: The lagrangian

```
LF = k (1 / 2
  ((h[ρ, ρ] ME[μ, ν] - h[μ, ν])
     (I HC[ψ]. Ga[μ].del[ψ, ν] - g G[ν, a] HC[ψ].Ga[μ].T[a].ψ) -
    mpsi h[μ, μ] HC[ψ].ψ + I / 2 HC[ψ]. Ga[μ].ψ
     (del[h[ν, ν], μ] - del[h[μ, ν], ν])) +
3 om / 2 ϕ (I HC[ψ]. Ga[μ].del[ψ, μ] - g G[μ, a] HC[ψ].Ga[μ].T[a].ψ) -
2 om mpsi ϕ HC[ψ].ψ + 3 om / 4 del[ϕ, μ] I HC[ψ]. Ga[μ].ψ)
```

$$k\Big(-2\,\text{mpsi om}\,\phi\,\psi^\dagger.\psi + \frac{3}{4}\,i\,\text{om}\,\partial_\mu(\phi)\,\psi^\dagger.\gamma^\mu.\psi + \frac{3}{2}\,\text{om}\,\phi\left(i\,\psi^\dagger.\gamma^\mu.\partial_\mu(\psi) - g\,\psi^\dagger.\gamma^\mu.T^a.\psi\,G_{\mu,a}\right) + \frac{1}{2}\Big(\frac{1}{2}\,i\left(\partial_\mu(h_{\nu,\nu}) - \partial_\nu(h_{\mu,\nu})\right)\psi^\dagger.\gamma^\mu.\psi - \text{mpsi}\,\psi^\dagger.\psi\,h_{\mu,\mu} + \left(i\,\psi^\dagger.\gamma^\mu.\partial_\nu(\psi) - g\,\psi^\dagger.\gamma^\mu.T^a.\psi\,G_{\nu,a}\right)\left(h_{\rho,\rho}\,\eta_{\mu,\nu} - h_{\mu,\nu}\right)\Big)\Big)$$

$$\begin{aligned}\kappa^{-1}\mathcal{L}_{\mathrm{F}}^{\vec{n}}(\kappa) \;=\;& \frac{1}{2}\Big[(\tilde{h}^{\vec{n}}\eta^{\mu\nu} - \tilde{h}^{\mu\nu,\vec{n}})\overline{\psi} i\gamma_\mu D_\nu\psi \\ & - m_\psi \tilde{h}^{\vec{n}}\overline{\psi}\psi + \frac{1}{2}\overline{\psi} i\gamma^\mu(\partial_\mu\tilde{h}^{\vec{n}} - \partial^\nu\tilde{h}^{\vec{n}}_{\mu\nu})\psi\Big] \\ & + \frac{3\omega}{2}\tilde{\phi}^{\vec{n}}\overline{\psi} i\gamma^\mu D_\mu\psi - 2\omega m_\psi\tilde{\phi}^{\vec{n}}\overline{\psi}\psi \\ & + \frac{3\omega}{4}\partial_\mu\tilde{\phi}^{\vec{n}}\overline{\psi} i\gamma^\mu\psi\end{aligned}$$

Getting Feynman rules

- Step IV: The FeynmanRules

```
FeynmanRules[LF]
```

Calculating vertices...

4 vertices obtained.

(* *)

Vertex 1

Particle 1 : Scalar , ϕ

Particle 2 : Dirac , ψ

Particle 3 : Dirac , $\psi^\dagger$

Vertex:

$$\frac{1}{4}\, i\, k\, \mathrm{om}\, \delta_{i_2,i_3} \left(3\, p_1^{\alpha 2}\, {\gamma^{\alpha 2}}_{s_3,s_2} + 6\, p_2^{\alpha 2}\, {\gamma^{\alpha 2}}_{s_3,s_2} - 8\, \mathrm{mpsi}\, \delta_{s_2,s_3}\right)$$

Getting Feynman rules

- Step IV: The FeynmanRules

(* *)

Vertex 2

Particle 1 : Spin 2 , h

Particle 2 : Dirac , ψ

Particle 3 : Dirac , $\psi^\dagger$

Vertex:

$$-\frac{1}{8}\,i\,k\,\delta_{i_2,i_3}$$

$$\left(p_1^{\beta}\,\gamma^{\alpha}{}_{s_3,s_2}+2\,p_2^{\beta}\,\gamma^{\alpha}{}_{s_3,s_2}+p_1^{\alpha}\,\gamma^{\beta}{}_{s_3,s_2}+2\,p_2^{\alpha}\,\gamma^{\beta}{}_{s_3,s_2}-2\,p_1^{\alpha 2}\,\gamma^{\alpha 2}{}_{s_3,s_2}\,\eta_{\alpha,\beta}\right.$$

$$\left.-4\,p_2^{\gamma 2}\,\gamma^{\gamma 2}{}_{s_3,s_2}\,\eta_{\alpha,\beta}+4\,\mathrm{mpsi}\,\delta_{s_2,s_3}\,\eta_{\alpha,\beta}\right)$$

Getting Feynman rules

- Step IV: The FeynmanRules

(* *)

Vertex 3

Particle 1 : Scalar , ϕ

Particle 2 : Vector , G

Particle 3 : Dirac , ψ

Particle 4 : Dirac , $\psi^\dagger$

Vertex:

$$-\frac{3}{2}\, i\, g\, k\,\mathrm{om}\,\gamma^{\mu 2}{}_{s_4,s_3}\, T^{a2}{}_{i_4,i_3}$$

Getting Feynman rules

- Step IV: The FeynmanRules

(*********************************)

Vertex 4

Particle 1 : Vector , G

Particle 2 : Spin 2 , h

Particle 3 : Dirac , ψ

Particle 4 : Dirac , $\psi^\dagger$

Vertex:

$$\frac{1}{4}\, i\, g\, k \left({\gamma^{\beta}}_{s_4,s_3}\, \eta_{\mu_1,\alpha} + {\gamma^{\alpha}}_{s_4,s_3}\, \eta_{\mu_1,\beta} - 2\, {\gamma^{\mu_1}}_{s_4,s_3}\, \eta_{\alpha,\beta} \right) {T^{a_1}}_{i_4,i_3}$$

Adding a new sector to the SM

Freiburg-THEP-06/02
In memory of Alfred Hill

The minimal non-minimal standard model

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[hep-ph/0603082]

$$L_S = -\frac{1}{2}\,\partial_\mu \vec{S}\,\partial_\mu \vec{S} - \frac{1}{2} m_S^2\,\vec{S}^2 - \frac{\lambda_S}{8N}\,(\vec{S}^2)^2$$

$$L_{Interaction} = -\frac{\omega}{4\sqrt{N}}\;\vec{S}^2\,\Phi^\dagger\Phi$$

Adding a new sector to the SM

Freiburg-THEP-06/02
In memory of Alfred Hill

The minimal non-minimal standard model

J. J. van der Bij

To include this new sector in FeynArts and MadGraph, you just need to add a few lines to the model file.

3082]

$$L_{Interaction} = -\frac{\omega}{4\sqrt{N}}\ \vec{S}^2\,\Phi^\dagger\Phi$$

Adding a new sector to the SM

- Step 1: Add all the parameters of the new sector to the model file:

```
lS == {Value -> 0.98,
    InteractionOrder -> {QED, 2}},

om == {Value -> 0.89,
    InteractionOrder -> {QED, 2}}
```

$$L_S = -\frac{1}{2}\partial_\mu \vec{S}\,\partial_\mu \vec{S} - \frac{1}{2} m_S^2\, \vec{S}^2 - \frac{\lambda_S}{8N}(\vec{S}^2)^2 - \frac{\omega}{4\sqrt{N}}\vec{S}^2\,\Phi^\dagger\Phi$$

Adding a new sector to the SM

- Step 1: Add all the parameters of the new sector to the model file:

```
lS == {Value -> 0.98,
    InteractionOrder -> {QED, 2}},

om == {Value -> 0.89,
    InteractionOrder -> {QED, 2}}
```

$$- \frac{\omega}{4\sqrt{N}} \vec{S}^2 \, \Phi^\dagger \Phi$$

Additional information needed e.g. for the MC integration.

Adding a new sector to the SM

- Step II: Add all the particles of the new sector to the model file:

```
S[2] == {
    ClassName -> Sk,
    SelfConjugate -> True,
    Indices -> {Index[SGen]},
    FlavorIndex -> SGen,
    ClassMembers -> {S1, S2, S3, S4},
    Mass -> 20
    }
```

$$L_S = -\frac{1}{2}\partial_\mu \vec{S}\partial_\mu \vec{S} - \frac{1}{2}m_S^2 \vec{S}^2 - \frac{\lambda_S}{8N}(\vec{S}^2)^2 - \frac{\omega}{4\sqrt{N}}\vec{S}^2\,\Phi^\dagger\Phi$$

Adding a new sector to the SM

- Step III: The lagrangian describing the new sector (Unitary gauge)

```
Nf = 4;
Phi = {0, (H + v) / Sqrt[2]};

LS = -1 / 2 del[Sk, mu].del[Sk, mu] -
      1 / 2 MassSk^2 Sk.Sk -
      lS / (8 Nf) (Sk.Sk)^2 -
 om / (4 Sqrt[Nf]) Sk.Sk HC[Phi].Phi
```

$$-\frac{1}{2}\,\text{Sk.Sk MassSk}^2 - \frac{\text{lS (Sk.Sk)}^2}{8\text{ Nf}} - \frac{1}{2}\,\partial_{\text{mu}}(\text{Sk}).\partial_{\text{mu}}(\text{Sk}) - \frac{\text{om Sk.Sk Phi}^\dagger.\text{Phi}}{4\sqrt{\text{Nf}}}$$

$$L_S = -\frac{1}{2}\,\partial_\mu \vec{S}\,\partial_\mu \vec{S} - \frac{1}{2} m_S^2\,\vec{S}^2 - \frac{\lambda_S}{8N}\,(\vec{S}^2)^2 - \frac{\omega}{4\sqrt{N}}\,\vec{S}^2\,\Phi^\dagger\Phi$$

The FeynArts interface

- The results obtained by FeynRules can be easily exported to FeynArts:

```
WriteFeynArtsOutput["NonMinSM.mod",{LSM, LS}, FlavorExpand → SU2W]
```

– – – FeynRules interface to FeynArts – – –

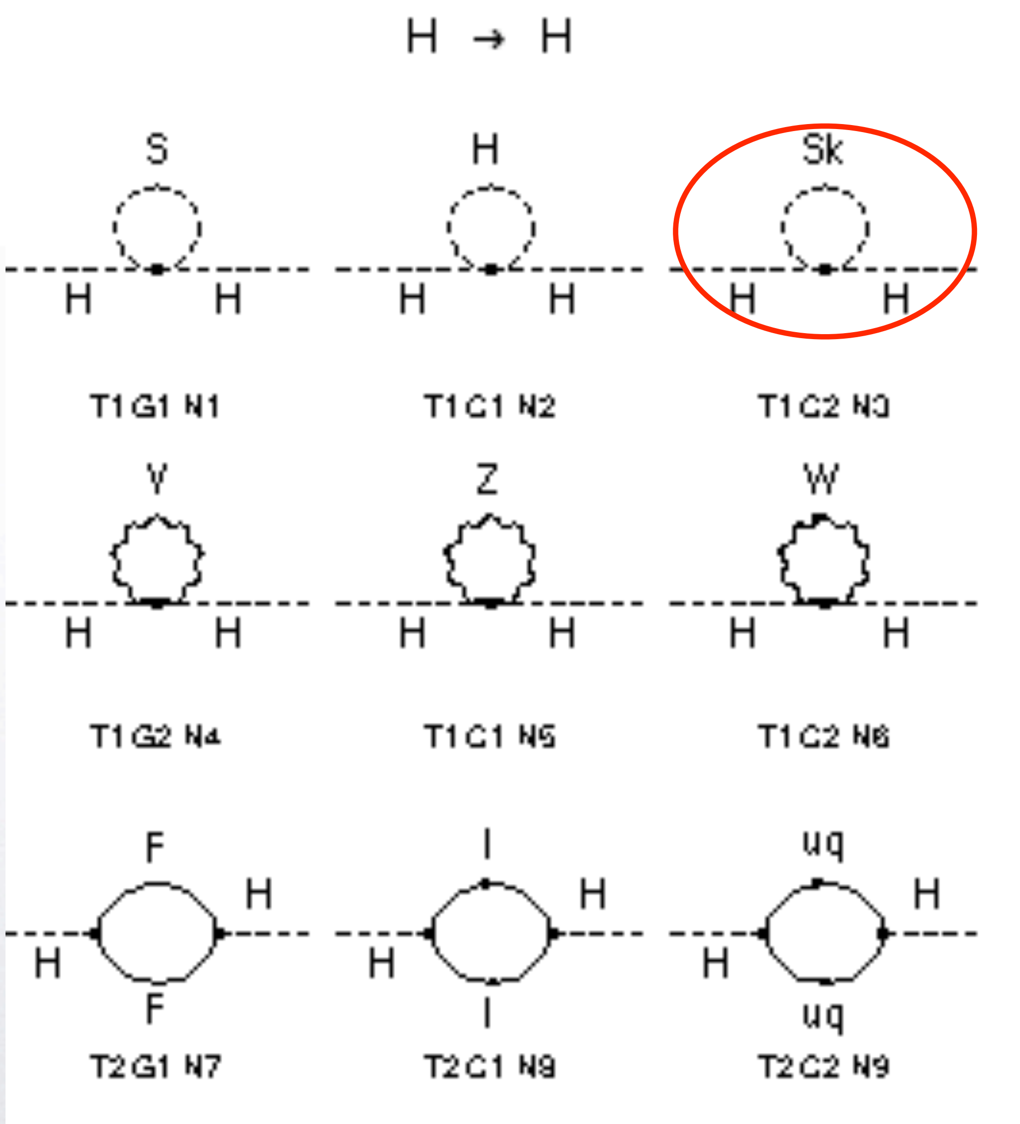
C. Duhr, 2007

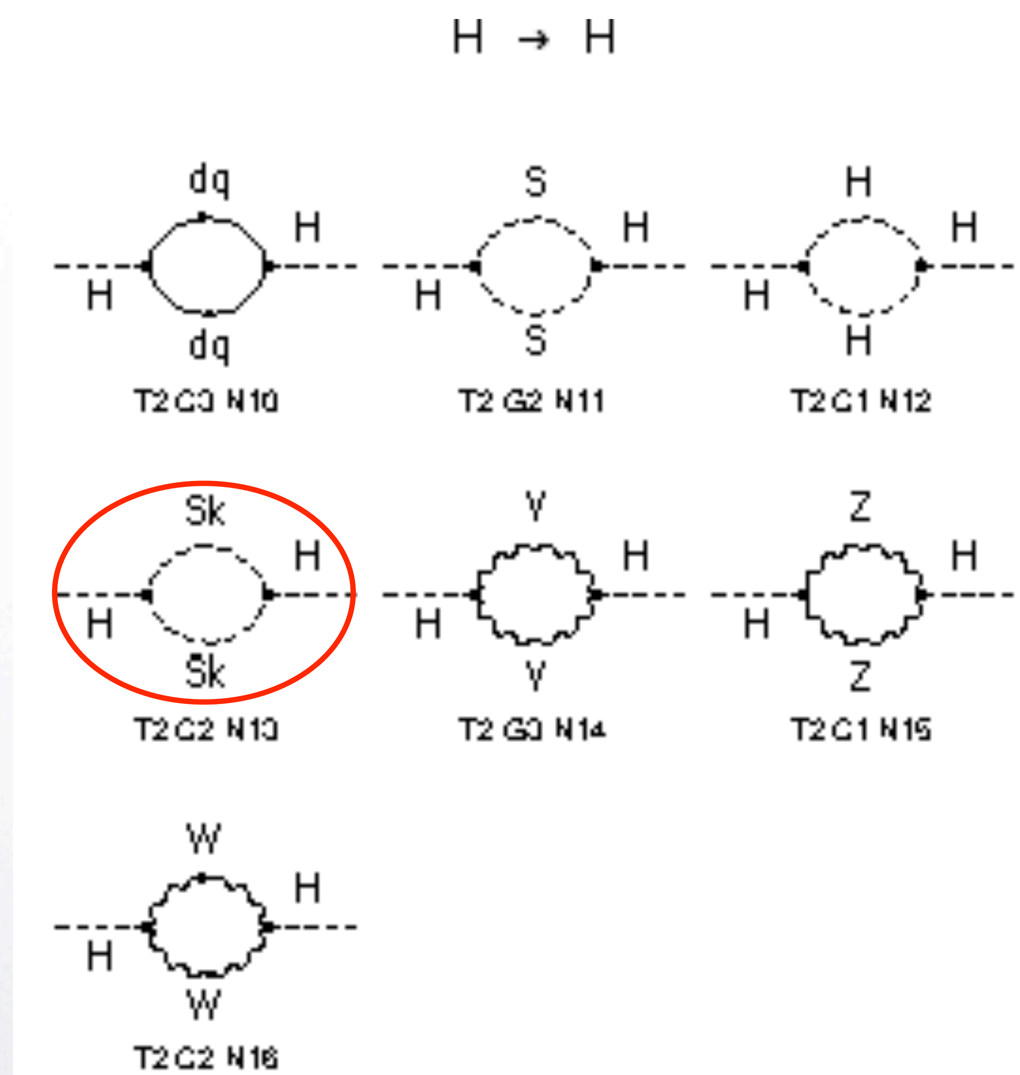
- This produces a FeynArts model-file which can be read by FeynArts.

```
topo = CreateTopologies[1, 1 → 1,
    ExcludeTopologies → Internal];

Amp = InsertFields[topo, {S[1]} → {S[1]},
    Model → NonMinSM];
```

The FeynArts interface





The MadGraph interface

- The results obtained by FeynRules can be easily exported to MadGraph:

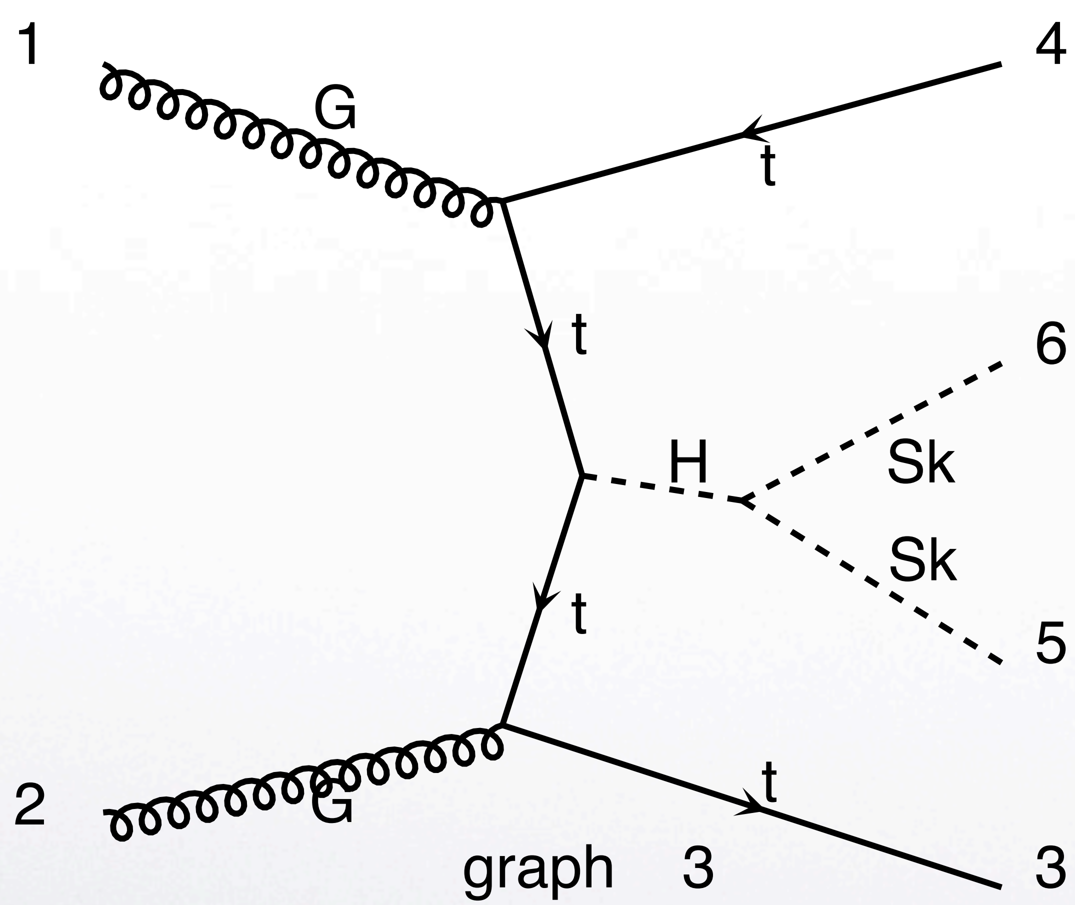
```
WriteMGOutput[LSM, LS]
```

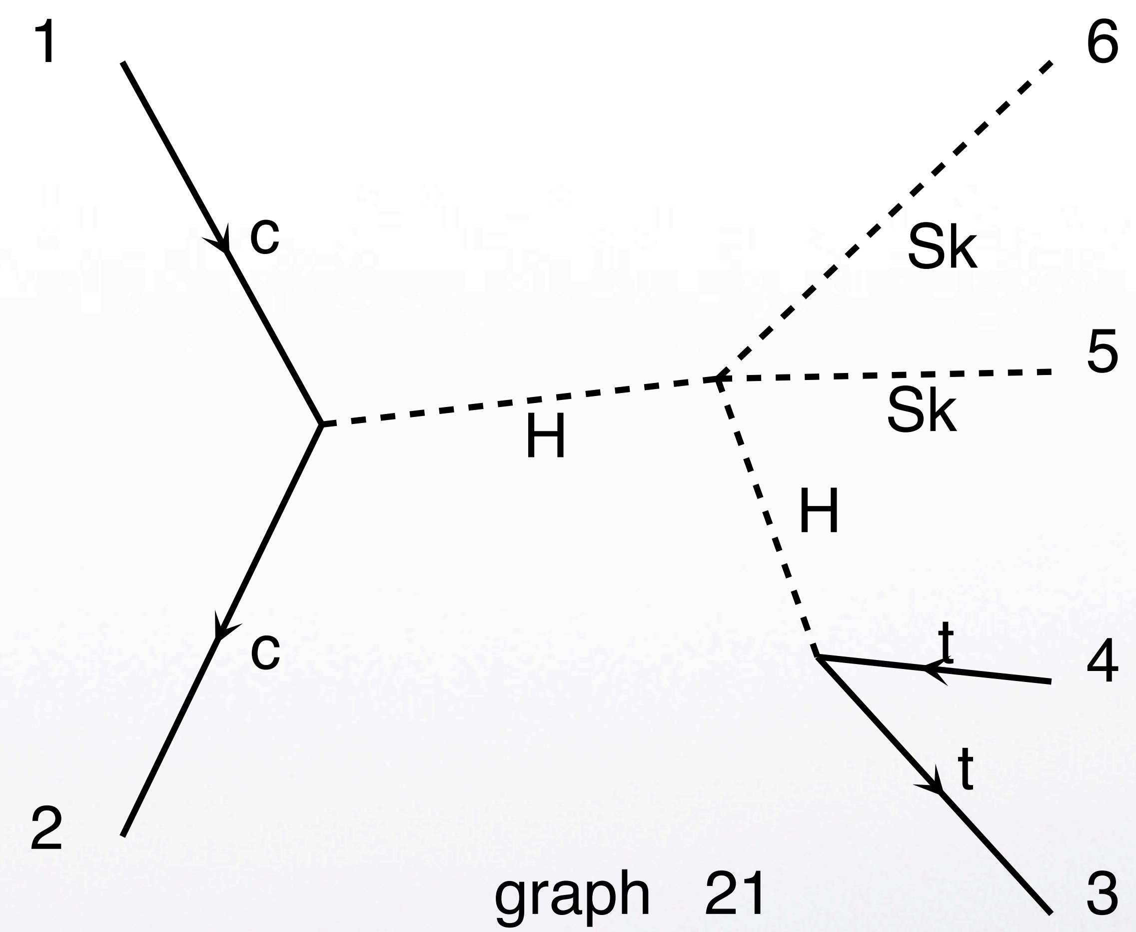
– – – FeynRules interface to MadGraph – – –

C. Duhr, M. Herquet, 2007

- This produces a bunch of files, but let's have a look at a some specific event...

The MadGraph interface





Conclusion

- FeynRules is a Mathematica©-based package to extract Feynman rules from a lagrangian.
- The output of FR is completely generic and can be easily interfaced to other available codes.
- FeynArts and MadGraph interfaces are already available.
- Planned interfaces: AMEGIC++ and CalcHEP... but we are open for any other suggestion.
- The first version will be released soon..!

Models

- Tested Models
  - SM (with CKM mixing)
  - Color-Octet scalars
  - Large extra-dimensions (KK-graviton)
  - Non linear sigma model
  - Wess-Zumino & SUSY QED

- To be tested in the near future
  - 2 HD
  - SUSY QCD
  - MSSM
  - Any other crazy model around...