FeynRules

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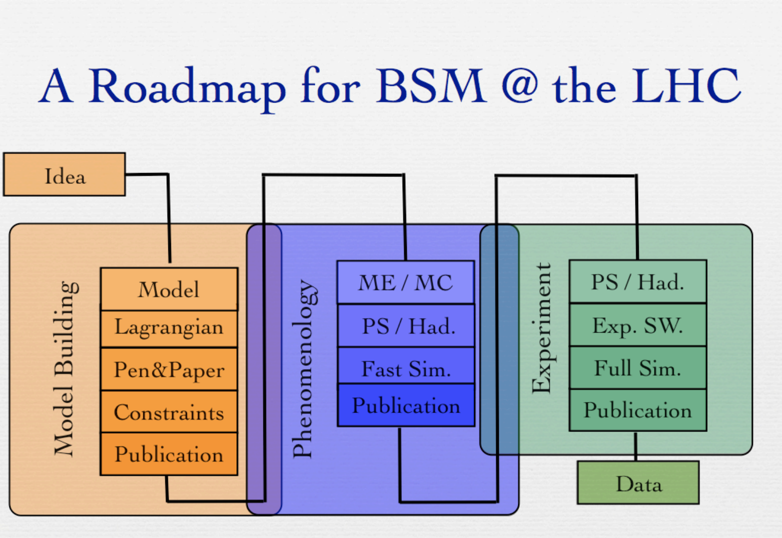
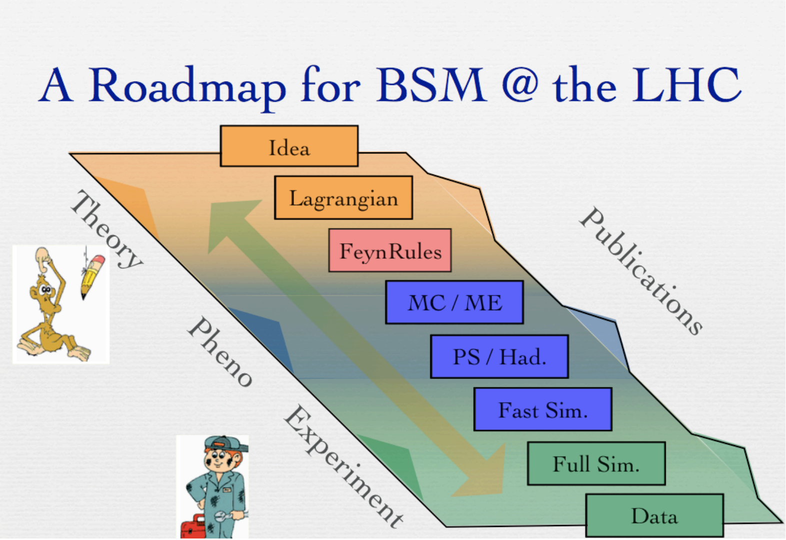

A Roadmap for BSM @ the LHC
Idea
Model Building
Model
Lagrangian
Pen&Paper
Constraints
Publication
Phenomenology
ME / MC
PS / Had.
Fast Sim.
Publication
Experiment
PS / Had.
Exp. SW.
Full Sim.
Publication
Data


A Roadmap for BSM @ the LHC
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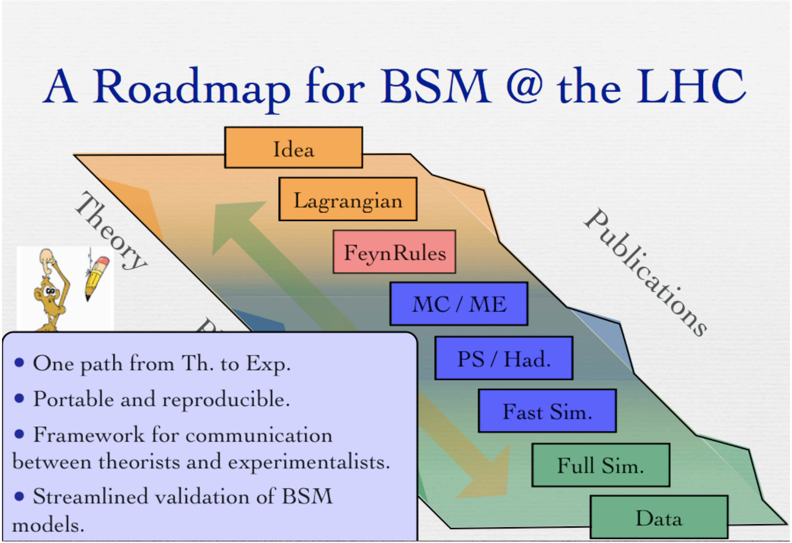
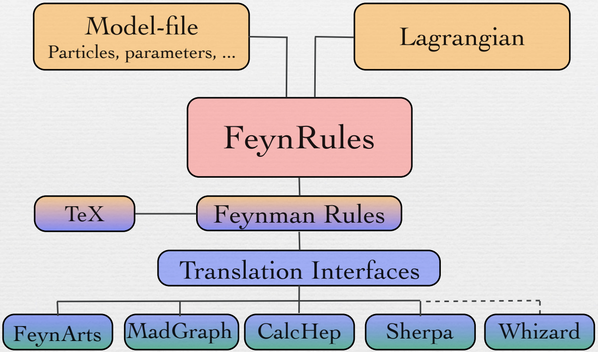


- One path from Th. to Exp.
- Portable and reproducible.
- Framework for communication between theorists and experimentalists.
- Streamlined validation of BSM models.

FeynRules

- Mathematica package that allows to compute Feynman Rules directly from a Lagrangian.
- No special requirements on the form of the Lagrangian apart from usual QFT requirements
  - Also higher dimensional operators are supported!
- Supported field types:
  - Scalars
  - Fermions (Dirac and Majorana)
  - Vectors
  - Spin 2
  - Ghost fields

FeynRules


Model-file
Particles, parameters, ...
Lagrangian
FeynRules
TeX
Feynman Rules
Translation Interfaces
FeynArts
MadGraph
CalcHep
Sherpa
Whizard

A simple example

How to Find a Hidden World at the Large Hadron Collider

James D. Wells

MCTP, University of Michigan, Ann Arbor, MI 48109
CERN, Theory Division, CH-1211 Geneva 23, Switzerland

- Simple extension of the SM by a $U(1)$ gauge group, which does not couple to the SM fermions.

The Hidden abelian Higgs model

- The Lagrangian

$$\begin{aligned}\mathcal{L}_{U(1)} &= -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\chi}{2}X_{\mu\nu}B^{\mu\nu},\\ \mathcal{L}_{Higgs} &= D_\mu\Phi^\dagger D^\mu\Phi + D_\mu\phi^\dagger D^\mu\phi + \mu_\Phi^2\,\Phi^\dagger\Phi + \mu_\phi^2\,\phi^\dagger\phi\\ &\quad +\lambda\,(\Phi^\dagger\Phi)^2 + \rho\,(\phi^\dagger\phi)^2 + \kappa\,(\Phi^\dagger\Phi)\,(\phi^\dagger\phi).\end{aligned}$$

- A two-step implementation:

Step 1: Define your particles and parameters.
Step 2: Write down your Lagrangian.

The FeynRules approach

3. Write down your Lagrangian.

- FeynRules:

```
LU1 = -1/4 FS[X,mu,nu] FS[X,mu,nu] +chi/2
          FS[B,mu,nu] FS[X,mu,nu]
```

- Textbook:

$$\mathcal{L}_{U(1)} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{\chi}{2} X_{\mu\nu} B^{\mu\nu}$$

The FeynRules approach

- `verts = FeynmanRules[ L ];`

Vertex 11

Particle 1 : Vector , W

Particle 2 : Vector , $W^\dagger$

Particle 3 : Vector , Z

Particle 4 : Vector , Zp

Vertex:

$$-i\, c_w{}^2\, c_\alpha\, g_w{}^2\, s_\alpha\, \eta_{\mu_1,\mu_4}\, \eta_{\mu_2,\mu_3} - i\, c_w{}^2\, c_\alpha\, g_w{}^2\, s_\alpha\, \eta_{\mu_1,\mu_3}\, \eta_{\mu_2,\mu_4} + 2\, i\, c_w{}^2\, c_\alpha\, g_w{}^2\, s_\alpha\, \eta_{\mu_1,\mu_2}\, \eta_{\mu_3,\mu_4}$$

Checking constraints

- Example 1: the ρ parameter

$$\Delta\rho = \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}.$$

  We can now directly use FeynArts to generate the loop amplitudes:

```
WriteFeynArtsOutput[ L ]
```

- Example 2: DM relic density We can use micrOMEGAs just by implementing the model into CalcHep:

```
WriteCHOutput[ L ]
```

Doing phenomenology

- If a model implementation in FeynRules exist, we can directly implement the model into various MC's

  `WriteMGOutput[ L ]` $\longrightarrow$ creates a MadGraph input file

  `WriteSHOutput[ L ]` $\longrightarrow$ creates a Sherpa input file

  `WriteCHOutput[ L ]` $\longrightarrow$ creates a CalcHep input file

- Since CalcHep, MadGraph, Sherpa are validated inside the experimental framework, the models can in principle directly passed on to the experimental communities.

SM (N. D. Christensen, CD)

- FeynArts, MadGraph, CalcHep, Sherpa: 35 $2 \to 2$ key-processes.

Process	CalcHEP Stock	CalcHEP Feynman	CalcHEP Unitary	CompHEP Feynman	MadGraph Stock	MadGraph Unitary	Sherpa Unitary	Whizard Feynman	Whizard Unitary
$gg \to gg$	116490.	116490.	116490.	116490.	116680.	116120.	116490	116585.	116642.
$u\bar{u} \to gg$	199.95	199.95	199.95	199.94	200.21	199.77	199.963	199.693	199.693
$t\bar{t} \to gg$	64.595	64.595	64.595	64.592	64.467	64.537	64.5856	64.5601	64.5601
$e^+e^- \to \mu^+\mu^-$	0.37194	0.37195	0.37195	0.37194	0.37202	0.37148	0.372011	0.372028	0.372028
$e^+e^- \to e^+e^-$	734.15	734.15	734.15	734.16	733.96	734.47	734.314	734.609	734.609
$e^+e^- \to \nu_e\bar{\nu}_e$	49.143	49.145	49.145	49.145	results	results	49.1361	49.1184	49.1184
$t\bar{t} \to u\bar{u}$	16.018	16.018	16.018	16.018	16.012	16.022	16.0204	16.0214	16.0214
$u\bar{u} \to s\bar{s}$	9.7634	9.7634	9.7634	9.7631	9.7631	9.7692	9.76376	9.76346	9.76348
$u\bar{d} \to c\bar{s}$	0.3531	0.35311	0.35311	0.35312	0.35274	0.35318	0.353149	0.353215	0.353215
$u\bar{s} \to c\bar{d}$	0.0010187	0.0010187	0.0010187	0.0010187	0.0010186	0.0010182	0.001018	0.00101898	0.00101898
$W^+W^- \to t\bar{t}$	44.534	44.535	44.535	44.534	44.647	44.485	44.5503	44.4992	44.4992

Implemented models

- Generic 2HDM (CD, M. Herquet)
  - MadGraph, CalcHep, Sherpa: 182 $2 \to 2$ key-processes.
- Three-Site model (N. D. Christensen)
  - MadGraph, CalcHep, Sherpa: 222 $2 \to 2$ key-processes.
- UED (P. de Aquino)
  - MadGraph, CalcHep, Sherpa: 118 $2 \to 2$ key-processes.
- MSSM, 120 free parameters (B. Fuks)
  - FeynArts/FormCalc: all $2 \to 2$ hadroproduction cross-sections.
  - 120 two-body decays in MadGraph.
  - 456 $2 \to 2$ cross sections in MadGraph and CalcHep.
  - 2700 $2 \to 3$ matrix elements in MadGraph.

Higher-dimensional operators

- Scalar nonet Lagrangian (C. Degrande)
  - Computation of serveral tree and one-loop amplitudes involving mesons.
- Strongly interacting light Higgs (C. Degrande).
  - Computation of Higgs decays involving 6D operators.
- Large extra dimensions (P. de Aquino).
  - Cross-check against literature.