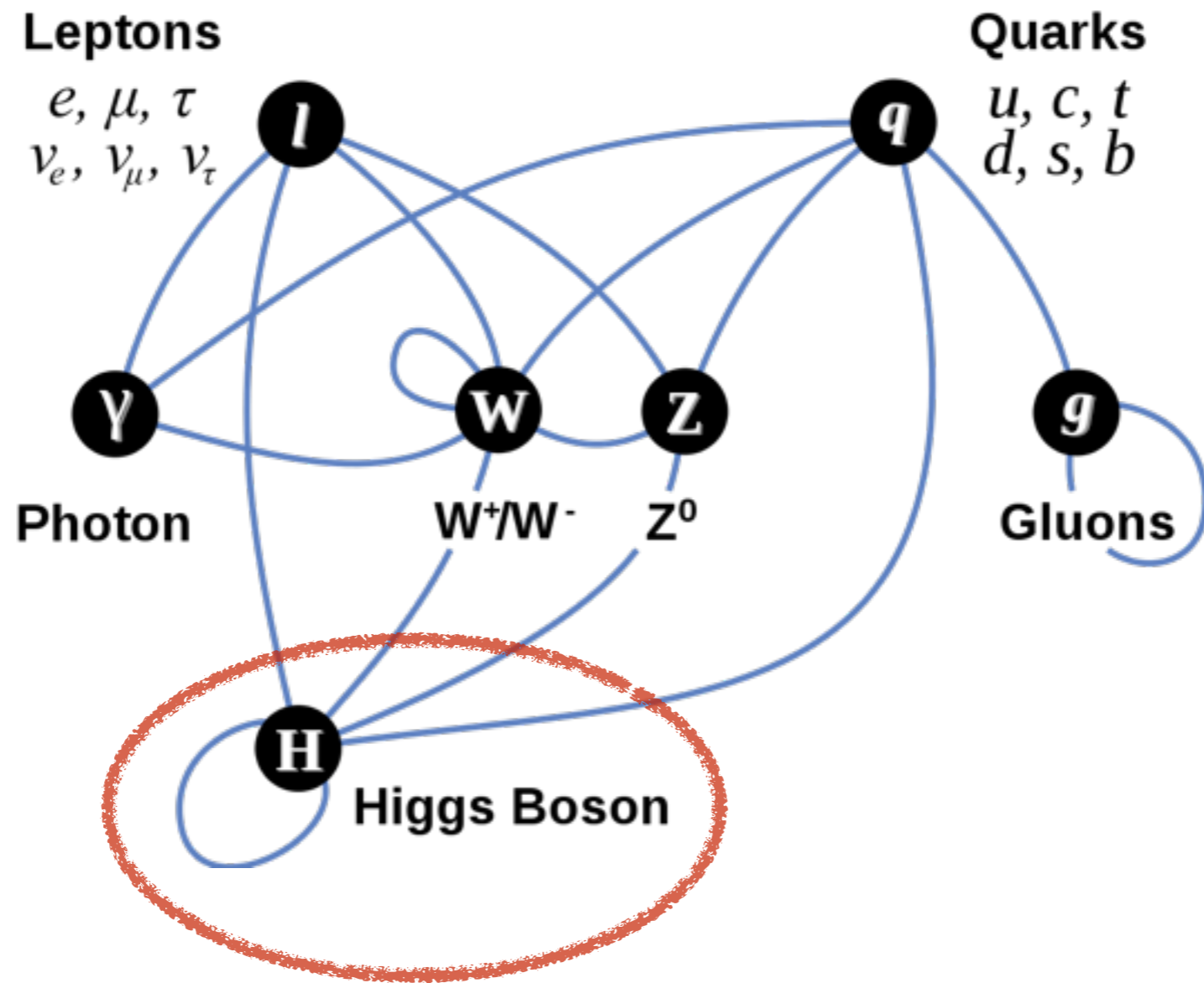


# BSM @ LHC

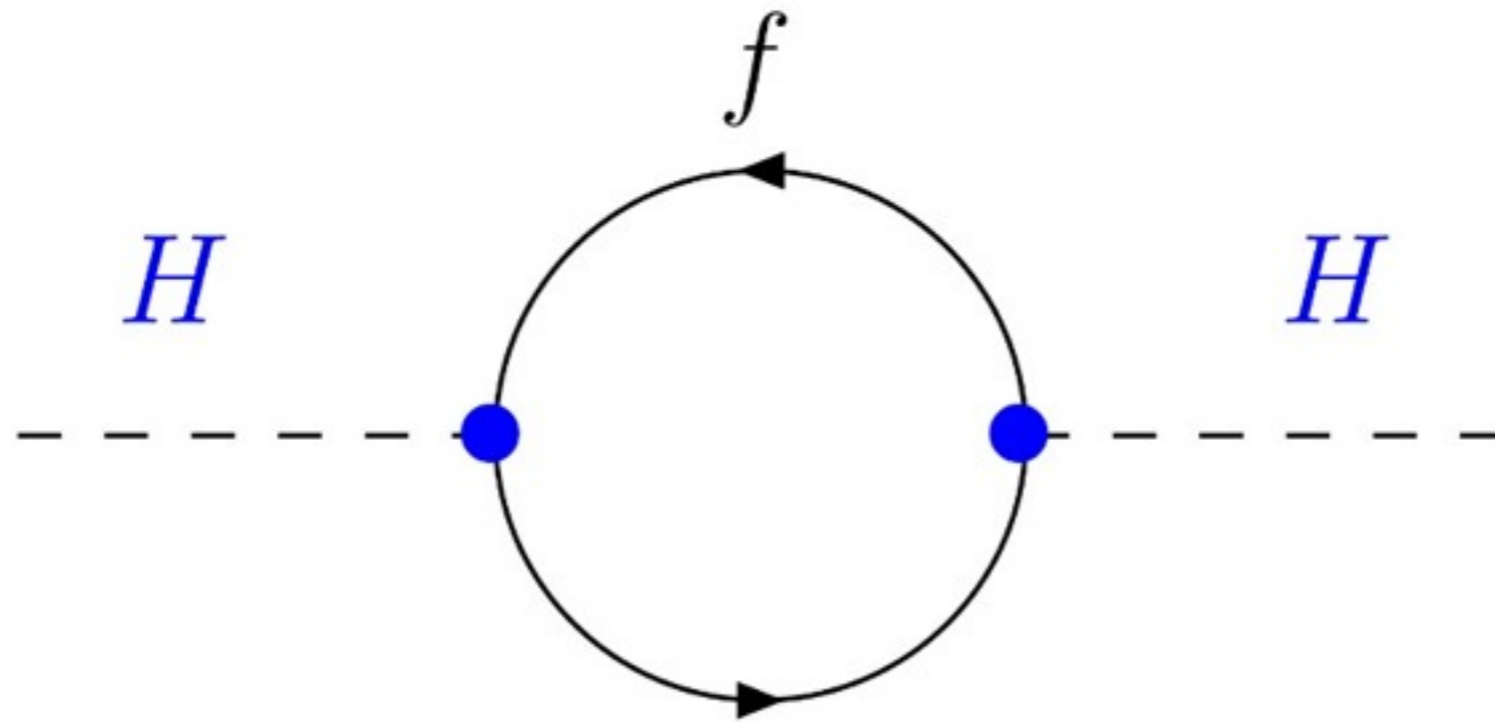
Neil Christensen  
PITT PACC

PITTsburgh Particle physics, Astrophysics and Cosmology Center



The giant news of the last year is that we have discovered a "Higgs-like" particle!

Is it the SM Higgs?



$$\Delta M_H^2 = N_f \frac{\lambda_f^2}{8\pi^2} \left[ -\Lambda^2 + 6m_f^2 \log \frac{\Lambda}{m_f} - 2m_f^2 \right]$$

Good reason to expect new physics beyond the Standard Model (SM).

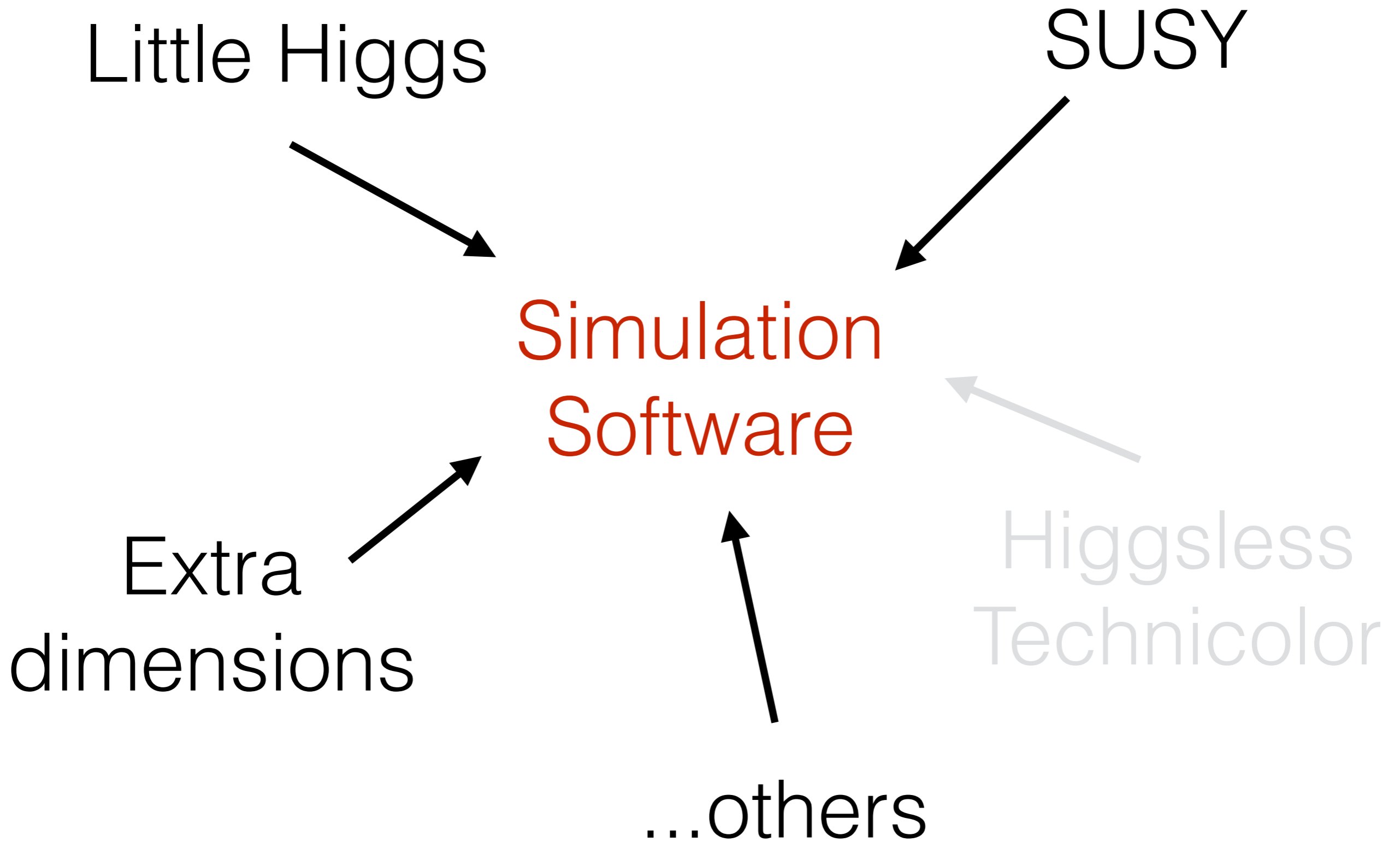
SUSY

Little Higgs

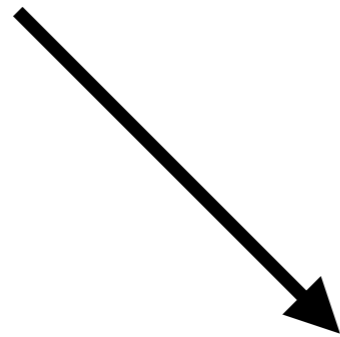
Higgsless  
Technicolor

Extra  
dimensions

...others

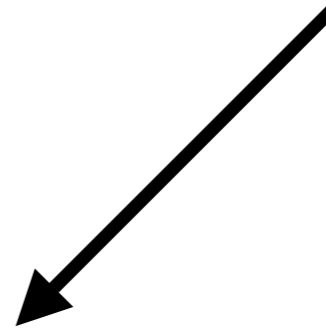


Little Higgs



SUSY

MSSM  
pMSSM  
NMSSM  
RPVMSSM  
...



Simulation  
Software

Extra  
dimensions



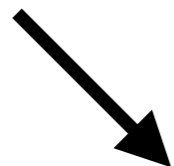
...others



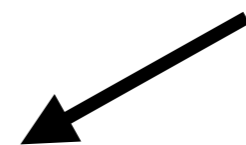
Higgsless  
Technicolor



Little Higgs



CalcHEP



SUSY

- MSSM
- pMSSM
- NMSSM
- RPVMSSM
- ...

MadGraph

Sherpa

Whizard

Extra



dimensions

FeynArts



...others



Higgsless  
Technicolor

What was the problem?



**Problem 1:**

**Implementing a model was often tedious and error prone.**

```
#####  
# QFD Interactions  
# 2 heavy fermions - 1 light weak gauge boson  
#####
```

```
# FFV (qqZ)
```

```
dp dp z GZDp QED-HF  
up up z GZUp QED-HF  
sp sp z GZDp QED-HF  
cp cp z GZUp QED-HF  
bp bp z GZDp QED-HF  
tp tp z GZTp QED-HF
```

```
# FFV (llZ)
```

```
ep- ep- z GZLp QED-HF  
mup- mup- z GZLp QED-HF  
tap- tap- z GZLp QED-HF  
vep vep z GZNp QED-HF  
vmp vmp z GZNp QED-HF  
vtp vtp z GZNp QED-HF
```

```
# FFV (qq'W) - diagonal CKM
```

```
dp up w- GWFp QED-HF  
sp cp w- GWFp QED-HF  
bp tp w- GWTp QED-HF  
up dp w+ GWFp QED-HF  
cp sp w+ GWFp QED-HF  
tp bp w+ GWTp QED-HF
```

```
# FFV (ll'W)
```

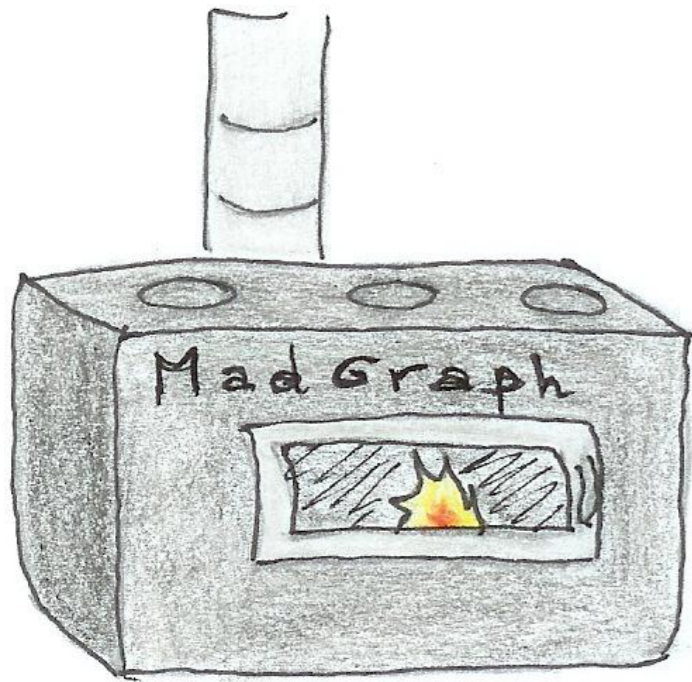
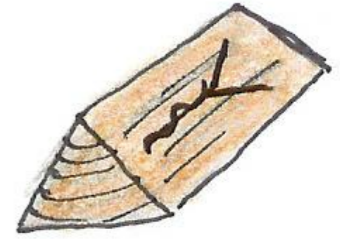
```
vep ep- w+ GWFp QED-HF  
vmp mup- w+ GWFp QED-HF  
vtp tap- w+ GWFp QED-HF  
ep- vep w- GWFp QED-HF  
mup- vmp w- GWFp QED-HF  
tap- vtp w- GWFp QED-HF
```

```
:
```

```
-----  
c      V-light   F-heavy   F-heavy  
-----  
c  
      GZDpL =  
      - -1d0/2d0*gf(-ee,WMASS,ZMASS,MWP)  
      - *vZ0f(WMASS,ZMASS,MWP)*vLP0f(WMASS,MWP)**2  
      - -1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)  
      - *VZ1f(WMASS,ZMASS,MWP)*vLP1f(WMASS,MWP)**2  
      - +1d0/6d0*gpf(-ee,WMASS,ZMASS,MWP)  
      - *vZ2f(WMASS,ZMASS,MWP)  
      GZDpR =  
      - -1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)  
      - *VZ1f(WMASS,ZMASS,MWP)  
      - +1d0/6d0*gpf(-ee,WMASS,ZMASS,MWP)  
      - *vZ2f(WMASS,ZMASS,MWP)  
      GZDp(1)=dcplx(GZDpL,Zero)  
      GZDp(2)=dcplx(GZDpR,Zero)  
      write(*,10) 'GZDpL = ',GZDpL  
      write(*,10) 'GZDpR = ',GZDpR  
  
      GZUpL =  
      - 1d0/2d0*gf(-ee,WMASS,ZMASS,MWP)  
      - *vZ0f(WMASS,ZMASS,MWP)*vLP0f(WMASS,MWP)**2  
      - +1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)  
      - *VZ1f(WMASS,ZMASS,MWP)*vLP1f(WMASS,MWP)**2  
      - +1d0/6d0*gpf(-ee,WMASS,ZMASS,MWP)  
      - *vZ2f(WMASS,ZMASS,MWP)  
      GZUpR =  
      - 1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)  
      - *VZ1f(WMASS,ZMASS,MWP)  
      - +1d0/6d0*gpf(-ee,WMASS,ZMASS,MWP)  
      - *vZ2f(WMASS,ZMASS,MWP)  
      GZUp(1)=dcplx(GZUpL,Zero)  
      GZUp(2)=dcplx(GZUpR,Zero)  
      write(*,10) 'GZUpL = ',GZUpL  
      write(*,10) 'GZUpR = ',GZUpR
```

## Problem 2:

Each matrix element generator has its strengths. What if you need more than one? In the past you had to start over.



## Problem 3:

Implementations often did not transfer well to experimentalists.

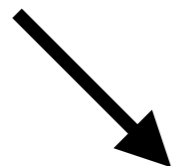


## Problem 3:

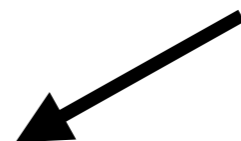
Implementations often did not transfer well to experimentalists.

It often required modifying the code of the matrix element generator.

Little Higgs



CalcHEP



SUSY

MSSM

pMSSM

NMSSM

RPVMSSM

...

MadGraph

Sherpa

Whizard

Extra



dimensions

FeynArts



...others



Higgsless  
Technicolor



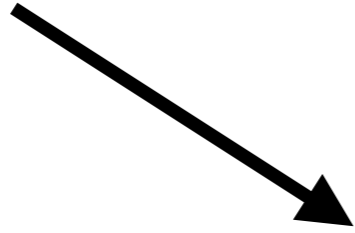
SUSY

MSSM

pMSSM

NMSSM

RPVMSSM



Little Higgs →

Extra dimensions →

Higgsless →

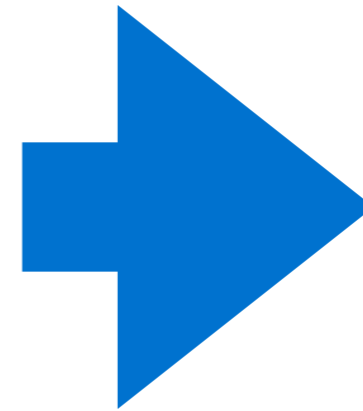
Technicolor

...others →

FeynRules

LanHEP

SARAH



CalcHEP

MadGraph

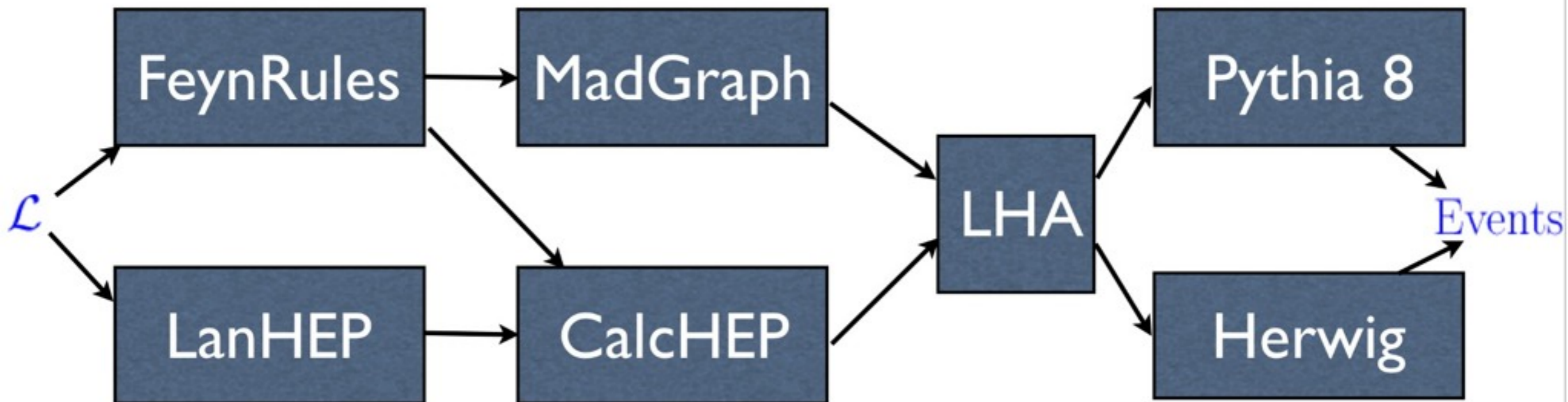
Sherpa

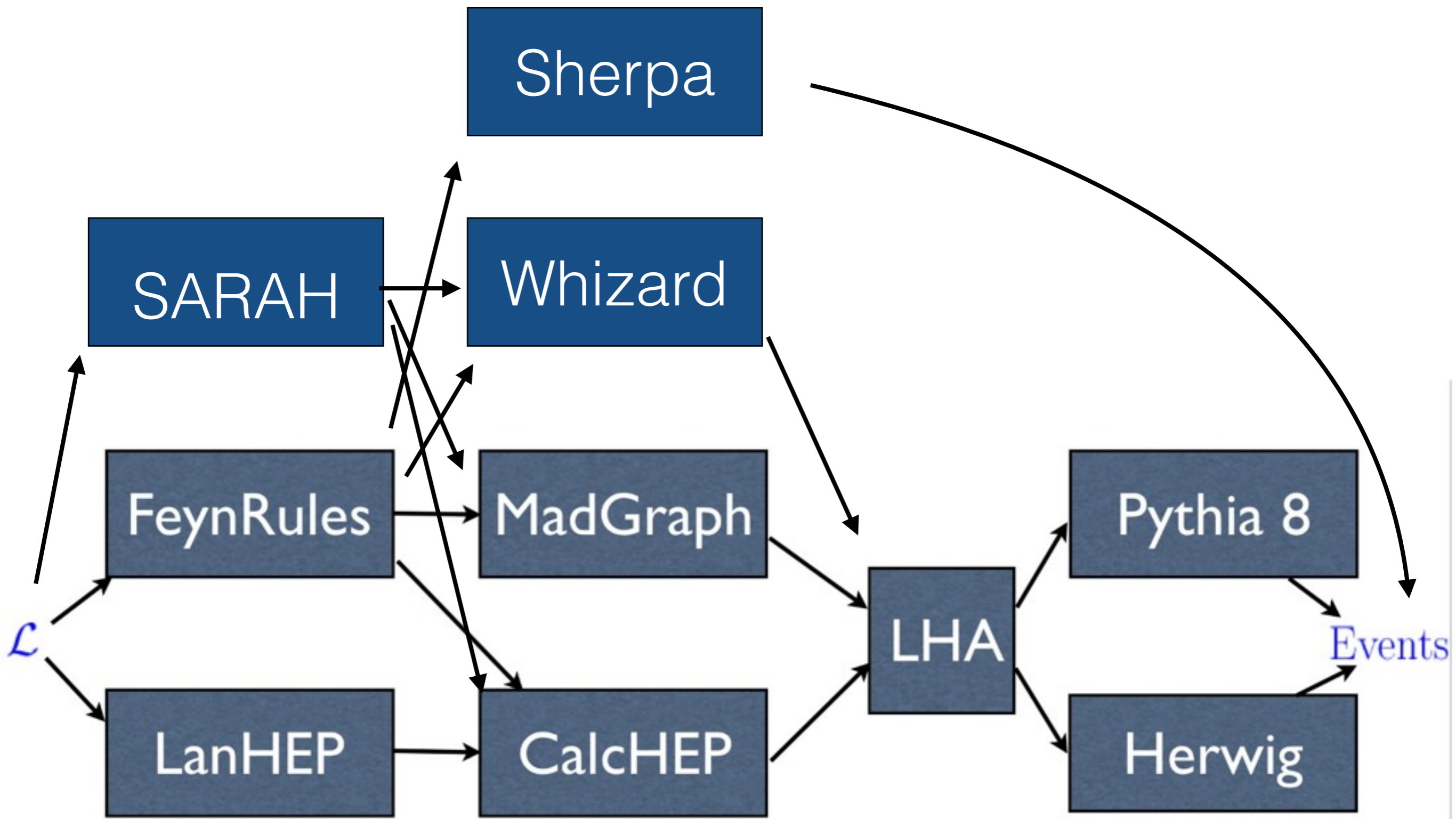
Whizard

FeynArts

# MC4BSM 2012 Tutorial

[arXiv:1209.0297](https://arxiv.org/abs/1209.0297)





	<b>LanHEP</b>	<b>FeynRules</b>	<b>SARAH</b>
<b>First Released</b>	1996	2008	2008
<b>Programming Language</b>	C	Mathematica	Mathematica
<b>General Lagrangian</b>	Yes	Yes	SUSY Only
<b>Superfields</b>	No	Yes	Yes
<b>Parameter Running</b>	No	In Progress	Yes
<b>Aut. Mass Diagonalization</b>	Yes	In Progress	Yes
<b>Spin</b>	0, 1/2, 1, 3/2, 2	0, 1/2, 1, 3/2, 2	-
<b>Superfields</b>	-	Chiral, Vector	Chiral, Vector

	<b>LanHEP</b>	<b>FeynRules</b>	<b>SARAH</b>
<b>CalcHEP</b>	Yes	Yes	Yes
<b>FeynArts</b>	Yes	Yes	Yes
<b>MadGraph</b>	In Progress	Yes	Yes
<b>Sherpa</b>	No	Yes	No
<b>Whizard</b>	No	Yes	Yes

# Example: IDP

$$H_1 = \begin{pmatrix} 0 \\ \langle v \rangle + h/\sqrt{2} \end{pmatrix}, \quad H_2 = \begin{pmatrix} \widetilde{H}^+ \\ (\widetilde{X} + i\widetilde{H}_3)/\sqrt{2} \end{pmatrix}$$

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{SM} + D^\mu H_2^* D_\mu H_2 - \mu_2^2 |H_2|^2 \\ & - \lambda_2 |H_2|^4 - \lambda_3 |H_1|^2 |H_2|^2 - \lambda_4 |H_1^\dagger H_2|^2 - \lambda_5 \text{Re}[(H_1^\dagger H_2)^2] \end{aligned}$$



# LanHEP

```
parameter MHX=111,MH3=222,MHC=333.  % Declaration of new masses
parameter laL=0.01, la2=0.01.      % Declaration of new couplings
%mu^2 as a function of masses
parameter mu2=MHX**2-laL*(2*MW/EE*SW)**2.
% constraints for couplings
parameter la3=2*(MHC**2-mu2)/(2*MW/EE*SW)**2.
parameter la5=(MHX**2-MH3**2)/(2*MW/EE*SW)**2.
parameter la4=2*laL-la3-la5.
```

# FeynRules

```
M$Parameters = {
laL=={ ParameterType -> External, Value -> 0.01      },
la2=={ ParameterType -> External, Value -> 0.01      },
mu2=={ ParameterType -> Internal, Value -> MHX^2-laL*(2*MW/EE*sw)^2,
      Description -> "mu^2 as a function of masses"   },
la3=={ ParameterType -> Internal, Value -> 2*(MHC^2-mu2)/(2*MW/EE*sw)^2,
      Description -> "constraints for couplings"     },
la5=={ ParameterType -> Internal, Value -> (MHX^2-MH3^2)/(2*MW/EE*sw)^2},
la4=={ ParameterType -> Internal, Value -> 2*laL-la3-la5      }
};
```

# LanHEP

```
scalar '~H3'/'~H3':('odd Higgs',pdg 36, mass MH3, width wH3 = auto).
scalar '~H+'/'~H-':('Charged Higgs',pdg 37,mass MHC,width wHC=auto).
scalar '~X'/'~X':('second Higgs',pdg 35,mass MHX,width wHX=auto).

let h2 = { -i* '~H+',  ('~X'+i* '~H3')/Sqrt2 },
      H2 = {  i* '~H-',  ('~X'-i* '~H3')/Sqrt2 }.
```

## FeynRules

```
M$ClassesDescription = {
S[21] == {
  ClassName      -> X,
  SelfConjugate  -> True,
  Mass           -> {MHX,111},
  Width          -> {wHX,0},
  PDG            -> 35,
  ParticleName   -> "~X",
  FullName       -> "second Higgs"
},
S[22] == {
  ClassName      -> H3,
  SelfConjugate  -> True,
  Mass           -> {MH3,222},
  Width          -> {wH3,0},
  PDG            -> 36,
  ParticleName   -> "~H3",
  FullName       -> "odd Higgs"
},
S[23] == {
  ClassName      -> HC,
  SelfConjugate  -> False,
  Mass           -> {MHC,333},
  Width          -> {wHC,0},
  QuantumNumbers -> {Q -> 1},
  PDG            -> 37,
  ParticleName   -> "~H+",
  AntiParticleName -> "~H-",
  FullName       -> "Charged Higgs"
},
S[24] == {
  ClassName      -> h2,
  Unphysical     -> True,
  Indices        -> {Index[SU2D]},
  FlavorIndex    -> SU2D,
  SelfConjugate  -> False,
  QuantumNumbers -> {Y -> 1/2},
  Definitions    -> { h2[1] -> -I HC,
                    h2[2] -> (X + I H3)/Sqrt[2]}
}
```



# LanHEP

```
let Dh2^mu^a = (deriv^mu+i*g1/2*B1^mu)*h2^a +
               i*g/2*taupm^a^b^c*WW^mu^c*h2^b.
let DH2^mu^a = (deriv^mu-i*g1/2*B1^mu)*H2^a
               -i*g/2*taupm^a^b^c*{'W-'^mu,W3^mu,'W+'^mu}^c*H2^b.
lterm DH2*Dh2.                % Kinem
lterm -mu2*h2*H2.
lterm -la2*(h2*H2)**2.
lterm -la3*(h1*H1)*(h2*H2).
lterm -la4*(h1*H2)*(H1*h2).
lterm -la5/2*(h1*H2)**2 + AddHermConj.
```

# FeynRules

```
LIDM1 = DC[h2bar[ii], mu] DC[h2[ii], mu];
LIDM2 = -mu2^2 h2bar[ii] h2[ii];
LIDM3 = -la2 h2bar[ii] h2[ii] h2bar[jj] h2[jj];
LIDM4 = -la3 Phibar[ii] Phi[ii] h2bar[jj] h2[jj];
LIDM5 = -la4 h2bar[ii] Phi[ii] Phibar[jj] h2[jj];
LIDM6 = -la5/2 h2bar[ii] Phi[ii] h2bar[jj] Phi[jj];
LIDM7 = HC[LIDM6];
LIDM = LIDM1 + LIDM2 + LIDM3 + LIDM4 + LIDM5 + LIDM6 + LIDM7;
```

# LanHEP

```
lhep <source file> -ca -evl 2
```

## FeynRules

```
$FeynRulesPath = "<FR path>";  
SetDirectory[$FeynRulesPath];  
<< FeynRules';  
  
SetDirectory[<IDM path>];  
LoadModel["SM.fr", "IDM.fr"];  
  
WriteCHOutput[LSM, LIDM]
```

# MEG Hack **Not** Required

These model implementations can be used just like built in models. They do not require modification of the matrix element generator code!

Validation

# Validation

- Check Hermiticity.
- Check Feynman rules with literature .
- Check gauge invariance.
- Check consistency between supported matrix element generators.
- Check distributions.
- ...



# Neil Christensen's Models

---

[Remove](#)[Triangle 3-Site Model 1and2massless](#)[Remove](#)[Standard Model](#)[Remove](#)[Gamma Jet](#)[Remove](#)[Standard Model massless 1 and 2](#)[Remove](#)[MSSM](#)[Remove](#)[Triangle 3-Site Model](#)[Remove](#)[Standard Model](#)[Remove](#)[3-Site Model](#)[Remove](#)[New Standard Model](#)[Remove](#)[Standard Model \(current\)](#)[Remove](#)[Standard Model \(development\)](#)[Remove](#)[New Standard Model v4](#)[Remove](#)[Standard Model](#)[Remove](#)[D, L, EP](#)

# B-L-FR

## Neil Christensen

### FeynRules Model Files

### MEG Model Files & Validations

Base [Rmv](#)

Restriction File(s) :

Parameter File :

**CH**



[Dwnld](#)

**MG5**



[Dwnld](#)

**WO2**



[Dwnld](#)

#### Validations

[Remove](#)

all

1424/1424 processes finished

[Remove](#)

all (CH gauge)

1424/1424 processes finished

[Remove](#)

all (W2 gauge)

1424/1424 processes finished

[Remove](#)

all (CH & W2)

1424/1424 processes finished

[Create New Validation](#)

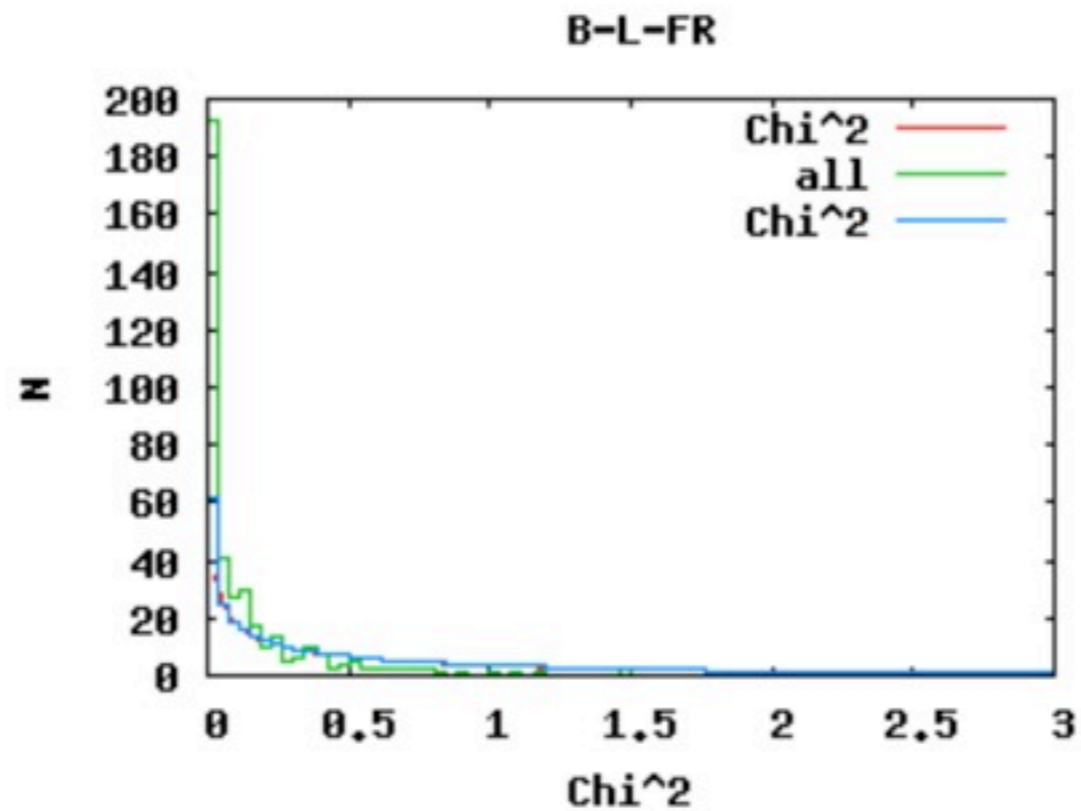
⇒ FR rv957 [Rmv](#)

⇒ FR rv957 WOFast->False [Rmv](#)

[Create New MEG Model Files](#)



B-L-FR : all



LL=247.2 for 1 degrees of freedom.

The probability of this being a statistical fluctuation is 0.0%.

	$\sqrt{s}$	$P_{Tcut}$	Best	CH(u)	WO2(u)	$X^2$
$\sim n1, \sim n1 \rightarrow s, S$	3202.0	800.5	7.104E-04	7.103E-04	7.106E-04	2.0E+00
$m, M \rightarrow s, S$	400.0	100.0	5.070E-01	5.071E-01	5.069E-01	1.5E+00
$t, T \rightarrow s, S$	2754.0	688.5	2.444E-01	2.444E-01	2.442E-01	1.5E+00
$u, U \rightarrow d, S$	400.0	100.0	5.322E-01	5.322E-01	5.325E-01	1.2E+00
$\sim n2, \sim n2 \rightarrow \sim n2, \sim n2$	3200.0	800.0	1.225E-02	1.225E-02	1.224E-02	1.1E+00
$t, T \rightarrow d, D$	2752.0	688.0	2.455E-01	2.455E-01	2.453E-01	1.0E+00
$t, T \rightarrow Z, H1$	2221.0	555.25	3.203E-01	3.203E-01	3.207E-01	9.1E-01



# Model Databases



## FeynRules model database

This page contains a collection of models that are already implemented in FeynRules. For each model, a complete model-file is available, containing all the information that is needed, as well as the Lagrangian, as well as the references to the papers where this Lagrangian was taken from. All model-files can be freely downloaded and changed, serving like this as the starting point for building new models. A TeX-file for each model containing a summary of the Feynman Rules produced by FeynRules is also available.

The Standard model model-file is already included in the distribution of the FeynRules, but it can also be downloaded independently from the corresponding link below.

**We encourage model builders writing a FeynRules implementation of their model to make their model file(s) public in the FeynRules model database, in order to make them useful to a community as wide as possible. For further information on how to make your model implementation public via the FeynRules model database, please send an email to**

- duhrc@...
- neil@...
- fuks@...
- cdegrand@...

### Available models

<a href="#">Standard Model</a>	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
<a href="#">Simple extensions of the SM (10)</a>	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
<a href="#">Supersymmetric Models (4)</a>	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
<a href="#">Extra-dimensional Models (4)</a>	Extensions of the SM including KK excitations of the SM particles.
<a href="#">Strongly coupled and effective field theories (5)</a>	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators.
<a href="#">Miscellaneous (0)</a>	



# HEPMDB

High Energy Physics Models DataBase

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[Home](#) [News](#) [Calculate](#) [Tools](#) [Signatures](#) [Wiki](#) [Contact Us](#)

Search in HEPMDB



Show All Models

## Search Models :: Results for [All]

1. **[E6SSM-12.02](#)** [2012-11-08 15:23:02] hepmdb:1112.0106

*J.P Hall, P. Svantesson*

Electroweak scale CalcHEP model of the E6SSM [v12.02]. The E6SSM (King. et al. 2006) is an extension of the MSSM and USSM. In addition to the MSSM particle content, this version of the E6SSM conta...

2. **[ESM](#)** [2012-10-13 07:35:48] hepmdb:1012.0103

*M.V. Chizhov*

The model is described in arXiv:1005.4287 ...

3. **[Next to Minimal Walking Technicolour Model \(NMWTC\) in CalcHEP format](#)** [2012-10-10 08:56:07]  
hepmdb:1012.0102

*Alexander Belyaev, Roshan Foadi, Mads T. Frandsen, Matti Järvinen, and Francesco Sannino, Alexander Pukhov*

The SU(3) theory with two flavors in the two-index symmetric representation which -- the Next to Minimal Walking Technicolor (NMWT) in the CalcHEP format, see 1. "Technicolor Walks at the LHC...

4. **[LQ 3rd generation for CalcHEP](#)** [2012-06-20 13:59:30] hepmdb:0612.0078

*A.Belyaev, A.Pukhov*

...

5. **[LQ 2nd generation for CalcHEP](#)** [2012-06-20 13:58:34] hepmdb:0612.0077

*A.Belyaev, A.Pukhov*

Future

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$Q_L$	3	2	$1/6$
$U_R$	3	1	$2/3$
$d_R$	3	1	$-1/3$
$L_L$	1	2	$-1/2$
$e_R$	1	1	-1
$\Phi$	1	2	$1/2$

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4} F_{c\mu\nu}^a F_c^{\mu\nu a} - \frac{1}{4} F_{w\mu\nu}^a F_w^{\mu\nu a} - \frac{1}{4} F_{y\mu\nu} F_y^{\mu\nu} \\
 & + i \bar{Q}_L \not{\partial} Q_L + i \bar{U}_R \not{\partial} U_R + i \bar{d}_R \not{\partial} d_R + i \bar{L}_L \not{\partial} L_L + i \bar{e}_R \not{\partial} e_R \\
 & + \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 \\
 & - \lambda_u \Phi \bar{U}_R Q_L - \lambda_d \Phi \bar{d}_R Q_L - \lambda_e \Phi \bar{e}_R L_L + h.c.
 \end{aligned}$$

I	G	F	Config
	<b>U(1)</b>		+G
$e_L$	-1		
$e_R$	-1		
+F			

Lagrangian

$$\begin{aligned}
 &-\frac{1}{4} A_{\mu\nu} A^{\mu\nu} + i\bar{e}_L \gamma_\mu D^\mu e_L + \\
 &i\bar{e}_R \gamma_\mu D^\mu e_R \\
 &m_0 \bar{e}_R e_L + \\
 &m_0^* \bar{e}_L e_R
 \end{aligned}$$

U(1)



Galileo

0.0.0.0:1234

Google

I G F Config

	SU(3)	SU(2)	U(1)	+G
$Q_L$	3	2	$\frac{1}{6}$	
$u_R$	3	1	$\frac{2}{3}$	
$d_R$	3	1	$-\frac{1}{3}$	
$L_L$	1	2	$-\frac{1}{2}$	
$e_R$	1	1	-1	
$\Phi$	1	2	$\frac{1}{2}$	
+F				

## Lagrangian

$$-\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \theta_0 G_{\mu\nu} \tilde{G}^{\mu\nu} - \frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \theta_1 W_{\mu\nu} \tilde{W}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i \bar{Q}_L \gamma_\mu D^\mu Q_L + i \bar{u}_R \gamma_\mu D^\mu u_R + i \bar{d}_R \gamma_\mu D^\mu d_R + i \bar{L}_L \gamma_\mu D^\mu L_L + i \bar{e}_R \gamma_\mu D^\mu e_R + D_\mu \Phi D^\mu \Phi^*$$

$$\mu_{r2} \Phi \Phi^*$$

$$\lambda_{r3} \Phi \Phi \Phi^* \Phi^* +$$

$$\lambda_{r4} \Phi \Phi \Phi^* \Phi^*$$

$$y_5 \Phi \bar{u}_R Q_L + y_5^* \Phi^* \bar{Q}_L u_R + y_6 \Phi^* \bar{d}_R Q_L + y_6^* \Phi \bar{Q}_L d_R + y_7 \Phi^* \bar{e}_R L_L +$$

$$y_7^* \Phi \bar{L}_L e_R$$

	I	G	F	Config
	<b>SU(3)</b>	<b>SU(2)</b>	<b>U(1)</b>	+G
$Q_L$	3	2	$\frac{1}{6}$	
$u_R$	3	1	$\frac{2}{3}$	
$d_R$	3	1	$-\frac{1}{3}$	
$L_L$	1	2	$-\frac{1}{2}$	
$e_R$	1	1	-1	
$\Phi$	1	2	$\frac{1}{2}$	
+F				

## Lagrangian

$$-\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \theta_0 G_{\mu\nu} \tilde{G}^{\mu\nu} - \frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \theta_1 W_{\mu\nu} \tilde{W}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i \bar{Q}_L \gamma_\mu D^\mu Q_L + i \bar{u}_R \gamma_\mu D^\mu u_R + i \bar{d}_R \gamma_\mu D^\mu d_R + i \bar{L}_L \gamma_\mu D^\mu L_L + i \bar{e}_R \gamma_\mu D^\mu e_R + D_\mu \Phi D^\mu \Phi^*$$

$$\mu_{r2} \Phi \Phi^*$$

$$\lambda_{r3} \Phi \Phi \Phi^* \Phi^* +$$

$$\lambda_{r4} \Phi \Phi \Phi^* \Phi^*$$

$$y_5 \Phi \bar{u}_R Q_L + y_5^* \Phi^* \bar{Q}_L u_R + y_6 \Phi^* \bar{d}_R Q_L + y_6^* \Phi \bar{Q}_L d_R + y_7 \Phi^* \bar{e}_R L_L + y_7^* \Phi \bar{L}_L e_R + y_8 \Phi \Phi \bar{L}_L^c L_L + y_8^* \Phi^* \Phi^* \bar{L}_L L_L^c + y_9 \Phi \Phi \bar{L}_L^c L_L + y_9^* \Phi^* \Phi^* \bar{L}_L L_L^c$$



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I G F Config

	SU(3)	SU(2)	U(1)	Z <sub>2</sub>	+G
Q <sub>L</sub>	3	2	$\frac{1}{6}$	1	
u <sub>R</sub>	3	1	$\frac{2}{3}$	1	
d <sub>R</sub>	3	1	$-\frac{1}{3}$	1	
L <sub>L</sub>	1	2	$-\frac{1}{2}$	1	
e <sub>R</sub>	1	1	-1	1	
Φ	1	2	$\frac{1}{2}$	1	
H <sub>2</sub>	1	2	$\frac{1}{2}$	-1	
+F					

## Lagrangian

$$-\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \theta_0 G_{\mu\nu} \tilde{G}^{\mu\nu} + -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \theta_1 W_{\mu\nu} \tilde{W}^{\mu\nu} + -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i \bar{Q}_L \gamma_\mu D^\mu Q_L + i \bar{u}_R \gamma_\mu D^\mu u_R + i \bar{d}_R \gamma_\mu D^\mu d_R + i \bar{L}_L \gamma_\mu D^\mu L_L + i \bar{e}_R \gamma_\mu D^\mu e_R + D_\mu \Phi D^\mu \Phi^* + D_\mu H_2 D^\mu H_2^*$$

$$\mu_{r2} \Phi \Phi^* +$$

$$\mu_{r3} H_2 H_2^*$$

$$\lambda_{r4} \Phi \Phi \Phi^* \Phi^* + \lambda_{r5} \Phi \Phi \Phi^* \Phi^* + \lambda_{r6} \Phi \Phi^* H_2 H_2^* + \lambda_{r7} \Phi \Phi^* H_2 H_2^* + \lambda_8 \Phi \Phi H_2^* H_2^* + \lambda_8^* \Phi^* \Phi^* H_2 H_2 + \lambda_9 \Phi \Phi H_2^* H_2^* + \lambda_9^* \Phi^* \Phi^* H_2 H_2 + \lambda_{r10} H_2 H_2 H_2^* H_2^* + \lambda_{r11} H_2 H_2 H_2^* H_2^*$$

$$y_{12} \Phi \bar{u}_R Q_L + y_{12}^* \Phi^* \bar{Q}_L u_R + y_{13} \Phi^* \bar{d}_R Q_L + y_{13}^* \Phi \bar{Q}_L d_R + y_{14} \Phi^* \bar{e}_R L_L +$$

$$y_{14}^* \Phi \bar{L}_L e_R$$

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	SU(3)	SU(2)	U(1)	+G
$Q$	3	2	$\frac{1}{6}$	
$u_c$	3	1	$-\frac{2}{3}$	
$d_c$	3	1	$\frac{1}{3}$	
$L$	1	2	$-\frac{1}{2}$	
$e_c$	1	1	1	
$H_u$	1	2	$\frac{1}{2}$	
$H_d$	1	2	$-\frac{1}{2}$	
+F				

Lagrangian

$$\begin{aligned}
& \int d^2\theta d^2\bar{\theta} Q^\dagger \exp[g_0 G + g_1 W + g_2 B] Q + \int d^2\theta d^2\bar{\theta} u_c^\dagger \exp[g_0 G + g_2 B] u_c + \int d^2\theta d^2\bar{\theta} d_c^\dagger \exp[g_0 G + g_2 B] d_c + \\
& \int d^2\theta d^2\bar{\theta} L^\dagger \exp[g_1 W + g_2 B] L + \int d^2\theta d^2\bar{\theta} e_c^\dagger \exp[g_2 B] e_c + \int d^2\theta d^2\bar{\theta} H_u^\dagger \exp[g_1 W + g_2 B] H_u + \\
& \int d^2\theta d^2\bar{\theta} H_d^\dagger \exp[g_1 W + g_2 B] H_d + -\frac{1}{4} \int d^2\theta G G - \frac{1}{4} \int d^2\bar{\theta} G^\dagger G^\dagger + -\frac{1}{4} \int d^2\theta W W - \frac{1}{4} \int d^2\bar{\theta} W^\dagger W^\dagger + \\
& -\frac{1}{4} \int d^2\theta B B - \frac{1}{4} \int d^2\bar{\theta} B^\dagger B^\dagger \\
& \mu_0 \int d^2\bar{\theta} H_u^\dagger L^\dagger + \mu_0^* \int d^2\theta L H_u + \mu_1 \int d^2\bar{\theta} H_d^\dagger H_u^\dagger + \\
& \mu_1^* \int d^2\theta H_u H_d \\
& y_2 \int d^2\bar{\theta} H_u^\dagger u_c^\dagger Q^\dagger + y_2^* \int d^2\theta Q u_c H_u + y_3 \int d^2\bar{\theta} L^\dagger d_c^\dagger Q^\dagger + y_3^* \int d^2\theta Q d_c L + y_4 \int d^2\bar{\theta} H_d^\dagger d_c^\dagger Q^\dagger + y_4^* \int d^2\theta Q d_c H_d + \\
& y_5 \int d^2\bar{\theta} d_c^\dagger d_c^\dagger u_c^\dagger + y_5^* \int d^2\theta u_c d_c d_c + y_6 \int d^2\bar{\theta} e_c^\dagger L^\dagger L^\dagger + y_6^* \int d^2\theta L L e_c + y_7 \int d^2\bar{\theta} H_d^\dagger e_c^\dagger L^\dagger + y_7^* \int d^2\theta L e_c H_d + y_8 \int d^2\bar{\theta} H_d^\dagger H_d^\dagger e_c^\dagger \\
& + y_8^* \int d^2\theta e_c H_d H_d
\end{aligned}$$

Galileo

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Google

	SU(3)	SU(2)	U(1)	Z <sub>2</sub>	+G
Q	3	2	$\frac{1}{6}$	-1	
u <sub>c</sub>	3	1	$-\frac{2}{3}$	-1	
d <sub>c</sub>	3	1	$\frac{1}{3}$	-1	
L	1	2	$-\frac{1}{2}$	-1	
e <sub>c</sub>	1	1	1	-1	
H <sub>u</sub>	1	2	$\frac{1}{2}$	1	
H <sub>d</sub>	1	2	$-\frac{1}{2}$	1	
+F					

Lagrangian

$$\begin{aligned}
 & \int d^2\theta d^2\bar{\theta} Q^\dagger \exp[g_0 G + g_1 W + g_2 B] Q + \int d^2\theta d^2\bar{\theta} u_c^\dagger \exp[g_0 G + g_2 B] u_c + \int d^2\theta d^2\bar{\theta} d_c^\dagger \exp[g_0 G + g_2 B] d_c + \\
 & \int d^2\theta d^2\bar{\theta} L^\dagger \exp[g_1 W + g_2 B] L + \int d^2\theta d^2\bar{\theta} e_c^\dagger \exp[g_2 B] e_c + \int d^2\theta d^2\bar{\theta} H_u^\dagger \exp[g_1 W + g_2 B] H_u + \\
 & \int d^2\theta d^2\bar{\theta} H_d^\dagger \exp[g_1 W + g_2 B] H_d - \frac{1}{4} \int d^2\theta G G - \frac{1}{4} \int d^2\bar{\theta} G^\dagger G^\dagger - \frac{1}{4} \int d^2\theta W W - \frac{1}{4} \int d^2\bar{\theta} W^\dagger W^\dagger + \\
 & -\frac{1}{4} \int d^2\theta B B - \frac{1}{4} \int d^2\bar{\theta} B^\dagger B^\dagger \\
 & \mu_0 \int d^2\bar{\theta} H_d^\dagger H_u^\dagger + \\
 & \mu_0^* \int d^2\theta H_u H_d \\
 & y_1 \int d^2\bar{\theta} H_u^\dagger u_c^\dagger Q^\dagger + y_1^* \int d^2\theta Q u_c H_u + y_2 \int d^2\bar{\theta} H_d^\dagger d_c^\dagger Q^\dagger + y_2^* \int d^2\theta Q d_c H_d + y_3 \int d^2\bar{\theta} H_d^\dagger e_c^\dagger L^\dagger + \\
 & y_3^* \int d^2\theta L e_c H_d
 \end{aligned}$$



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	SU(3)	SU(2)	U(1)	Z <sub>2</sub>	Z <sub>3</sub>	+G
Q	3	2	$\frac{1}{6}$	-1	$e^{\frac{4\pi i}{3}}$	
u <sub>c</sub>	3	1	$-\frac{2}{3}$	-1	$e^{\frac{4\pi i}{3}}$	
d <sub>c</sub>	3	1	$\frac{1}{3}$	-1	$e^{\frac{4\pi i}{3}}$	
L	1	2	$-\frac{1}{2}$	-1	$e^{\frac{4\pi i}{3}}$	
e <sub>c</sub>	1	1	1	-1	$e^{\frac{4\pi i}{3}}$	
H <sub>u</sub>	1	2	$\frac{1}{2}$	1	$e^{\frac{4\pi i}{3}}$	
H <sub>d</sub>	1	2	$-\frac{1}{2}$	1	$e^{\frac{4\pi i}{3}}$	
S	1	1	0	1	$e^{\frac{4\pi i}{3}}$	
+F						

## Lagrangian

$$\begin{aligned}
& \int d^2\theta d^2\bar{\theta} Q^\dagger \exp[g_0 G + g_1 W + g_2 B_3] Q + \int d^2\theta d^2\bar{\theta} u_c^\dagger \exp[g_0 G + g_2 B_3] u_c + \int d^2\theta d^2\bar{\theta} d_c^\dagger \exp[g_0 G + g_2 B_3] d_c + \\
& \int d^2\theta d^2\bar{\theta} L^\dagger \exp[g_1 W + g_2 B_3] L + \int d^2\theta d^2\bar{\theta} e_c^\dagger \exp[g_2 B_3] e_c + \int d^2\theta d^2\bar{\theta} H_u^\dagger \exp[g_1 W + g_2 B_3] H_u + \\
& \int d^2\theta d^2\bar{\theta} H_d^\dagger \exp[g_1 W + g_2 B_3] H_d + \int d^2\theta d^2\bar{\theta} S^\dagger \exp[g_2 B_3] S - \frac{1}{4} \int d^2\theta G G - \frac{1}{4} \int d^2\bar{\theta} G^\dagger G^\dagger - \frac{1}{4} \int d^2\theta W W - \frac{1}{4} \int d^2\bar{\theta} W^\dagger W^\dagger + \\
& -\frac{1}{4} \int d^2\theta B_3 B_3 - \frac{1}{4} \int d^2\bar{\theta} B_3^\dagger B_3^\dagger \\
& y_0 \int d^2\bar{\theta} H_u^\dagger u_c^\dagger Q^\dagger + y_0^* \int d^2\theta Q u_c H_u + y_1 \int d^2\bar{\theta} H_d^\dagger d_c^\dagger Q^\dagger + y_1^* \int d^2\theta Q d_c H_d + y_2 \int d^2\bar{\theta} H_d^\dagger e_c^\dagger L^\dagger + y_2^* \int d^2\theta L e_c H_d + \\
& y_3 \int d^2\bar{\theta} S^\dagger H_d^\dagger H_u^\dagger + y_3^* \int d^2\theta H_u H_d S + y_4 \int d^2\bar{\theta} S^\dagger S^\dagger S^\dagger + y_4^* \int d^2\theta S S S
\end{aligned}$$

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Google

	SU(3)	SU(2)	SU(2)	U(1)	+G
$Q_{L0}$	3	2	1	$\frac{1}{6}$	
$Q_{L1}$	3	1	2	$\frac{1}{6}$	
$Q_{R1}$	3	1	2	$\frac{1}{6}$	
$u_{R2}$	3	1	1	$\frac{2}{3}$	
$d_{R2}$	3	1	1	$-\frac{1}{3}$	
$L_{L0}$	1	2	1	$-\frac{1}{2}$	
$L_{L1}$	1	1	2	$-\frac{1}{2}$	
$L_{R1}$	1	1	2	$-\frac{1}{2}$	
$e_{R2}$	1	1	1	-1	
$\Phi_{01}$	1	2	2	0	
$\Phi_{12}$	1	1	2	$\frac{1}{2}$	
+F					

## Lagrangian

$$-\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \theta_0 G_{\mu\nu} \tilde{G}^{\mu\nu} + -\frac{1}{4} W_{0\mu\nu} W_0^{\mu\nu} + \theta_1 W_{0\mu\nu} \tilde{W}_0^{\mu\nu} + -\frac{1}{4} W_{1\mu\nu} W_1^{\mu\nu} + \theta_2 W_{1\mu\nu} \tilde{W}_1^{\mu\nu} + -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i \overline{Q_{L0}} \gamma_\mu D^\mu Q_{L0} +$$

$$i \overline{Q_{L1}} \gamma_\mu D^\mu Q_{L1} + i \overline{Q_{R1}} \gamma_\mu D^\mu Q_{R1} + i \overline{u_{R2}} \gamma_\mu D^\mu u_{R2} + i \overline{d_{R2}} \gamma_\mu D^\mu d_{R2} + i \overline{L_{L0}} \gamma_\mu D^\mu L_{L0} + i \overline{L_{L1}} \gamma_\mu D^\mu L_{L1} + i \overline{L_{R1}} \gamma_\mu D^\mu L_{R1} +$$

$$i \overline{e_{R2}} \gamma_\mu D^\mu e_{R2} + D_\mu \Phi_{01} D^\mu \Phi_{01}^* + D_\mu \Phi_{01} D^\mu \Phi_{01}^* + D_\mu \Phi_{01}^* D^\mu \Phi_{01}^* + D_\mu \Phi_{12} D^\mu \Phi_{12}^*$$

$$\mu_{r3} \Phi_{01} \Phi_{01}^* + \mu_4 \Phi_{01} \Phi_{01} + \mu_4^* \Phi_{01}^* \Phi_{01}^* +$$

$$\mu_{r5} \Phi_{12} \Phi_{12}^*$$

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$L_{L1}$	1	1	2	$\frac{-1}{2}$	
$L_{R1}$	1	1	2	$\frac{-1}{2}$	
$e_{R2}$	1	1	1	-1	
$\Phi_{01}$	1	2	2	0	
$\Phi_{12}$	1	1	2	$\frac{1}{2}$	
+F					

## Lagrangian

$$\begin{aligned}
& -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \theta_0 G_{\mu\nu} \tilde{G}^{\mu\nu} + -\frac{1}{4} W_{0\mu\nu} W_0^{\mu\nu} + \theta_1 W_{0\mu\nu} \tilde{W}_0^{\mu\nu} + -\frac{1}{4} W_{1\mu\nu} W_1^{\mu\nu} + \theta_2 W_{1\mu\nu} \tilde{W}_1^{\mu\nu} + -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i \overline{Q_{L0}} \gamma_\mu D^\mu Q_{L0} + \\
& i \overline{Q_{L1}} \gamma_\mu D^\mu Q_{L1} + i \overline{Q_{R1}} \gamma_\mu D^\mu Q_{R1} + i \overline{u_{R2}} \gamma_\mu D^\mu u_{R2} + i \overline{d_{R2}} \gamma_\mu D^\mu d_{R2} + i \overline{L_{L0}} \gamma_\mu D^\mu L_{L0} + i \overline{L_{L1}} \gamma_\mu D^\mu L_{L1} + i \overline{L_{R1}} \gamma_\mu D^\mu L_{R1} + \\
& i \overline{e_{R2}} \gamma_\mu D^\mu e_{R2} + D_\mu \Phi_{01} D^\mu \Phi_{01}^* + D_\mu \Phi_{01} D^\mu \Phi_{01} + D_\mu \Phi_{01}^* D^\mu \Phi_{01}^* + D_\mu \Phi_{12} D^\mu \Phi_{12}^* \\
& \mu_{r3} \Phi_{01} \Phi_{01}^* + \mu_4 \Phi_{01} \Phi_{01} + \mu_4^* \Phi_{01}^* \Phi_{01}^* + \\
& \mu_{r5} \Phi_{12} \Phi_{12}^* \\
& \lambda_{r6} \Phi_{01} \Phi_{01} \Phi_{01}^* \Phi_{01}^* + \lambda_{r7} \Phi_{01} \Phi_{01} \Phi_{01}^* \Phi_{01}^* + \lambda_{r8} \Phi_{01} \Phi_{01} \Phi_{01}^* \Phi_{01}^* + \lambda_{r9} \Phi_{01} \Phi_{01} \Phi_{01}^* \Phi_{01}^* + \lambda_{10} \Phi_{01}^* \Phi_{01} \Phi_{01} \Phi_{01} + \lambda_{10}^* \Phi_{01} \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* + \\
& \lambda_{11} \Phi_{01}^* \Phi_{01} \Phi_{01} \Phi_{01} + \lambda_{11}^* \Phi_{01} \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* + \lambda_{12} \Phi_{01}^* \Phi_{01} \Phi_{01} \Phi_{01} + \lambda_{12}^* \Phi_{01} \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* + \lambda_{13} \Phi_{01}^* \Phi_{01} \Phi_{01} \Phi_{01} + \lambda_{13}^* \Phi_{01} \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* + \\
& \lambda_{r14} \Phi_{01} \Phi_{01}^* \Phi_{12} \Phi_{12}^* + \lambda_{r15} \Phi_{01} \Phi_{01}^* \Phi_{12} \Phi_{12}^* + \lambda_{16} \Phi_{01} \Phi_{01} \Phi_{01} \Phi_{01} + \lambda_{16}^* \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* + \lambda_{17} \Phi_{01} \Phi_{01} \Phi_{01} \Phi_{01} + \lambda_{17}^* \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* + \\
& \lambda_{18} \Phi_{01} \Phi_{01} \Phi_{01} \Phi_{01} + \lambda_{18}^* \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* + \lambda_{19} \Phi_{01} \Phi_{01} \Phi_{01} \Phi_{01} + \lambda_{19}^* \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* \Phi_{01}^* + \lambda_{20} \Phi_{01} \Phi_{01} \Phi_{12} \Phi_{12} + \lambda_{20}^* \Phi_{01}^* \Phi_{01}^* \Phi_{12} \Phi_{12}^* + \\
& \lambda_{21} \Phi_{01} \Phi_{01} \Phi_{12} \Phi_{12} + \lambda_{21}^* \Phi_{01}^* \Phi_{01}^* \Phi_{12} \Phi_{12}^* + \lambda_{r22} \Phi_{12} \Phi_{12} \Phi_{12}^* \Phi_{12}^* + \lambda_{r23} \Phi_{12} \Phi_{12} \Phi_{12}^* \Phi_{12}^* \\
& y_{24} \Phi_{01}^* \overline{Q_{R1}} Q_{L0} + y_{24}^* \Phi_{01} \overline{Q_{L0}} Q_{R1} + y_{25} \Phi_{01}^* \overline{Q_{R1}} Q_{L0} + y_{25}^* \Phi_{01} \overline{Q_{L0}} Q_{R1} + y_{26} \Phi_{12} \overline{u_{R2}} Q_{L1} + y_{26}^* \Phi_{12}^* \overline{Q_{L1}} u_{R2} + y_{27} \Phi_{12}^* \overline{d_{R2}} Q_{L1} + y_{27}^* \Phi_{12} \overline{Q_{L1}} d_{R2} \\
& + y_{28} \Phi_{01}^* \overline{L_{R1}} L_{L0} + y_{28}^* \Phi_{01} \overline{L_{L0}} L_{R1} + y_{29} \Phi_{01}^* \overline{L_{R1}} L_{L0} + y_{29}^* \Phi_{01} \overline{L_{L0}} L_{R1} + y_{30} \Phi_{12}^* \overline{e_{R2}} L_{L1} + y_{30}^* \Phi_{12} \overline{L_{L1}} e_{R2} \\
& m_{31} \overline{Q_{R1}} Q_{L1} + m_{31}^* \overline{Q_{L1}} Q_{R1} + m_{32} \overline{L_{R1}} L_{L1} + \\
& m_{32}^* \overline{L_{L1}} L_{R1}
\end{aligned}$$

# Galileo : Current

- Supports any semisimple compact Lie algebra (symmetry).
- Supports fields of spin 0, 1/2, 1.
- Supports superfields.
- Automatically generates the Lagrangian.
- Core library + GUI wrapper.



# Galileo : Plans

- Core and GUI need more polishing.
- Symmetry breaking.
- Mass matrix diagonalization and rotation to physical basis.
- Save/read.
- Export to FeynRules (for further analysis).

# Summary

- Discovery of a Higgs-like state!
- We still expect to find more new physics BSM.
- It is much easier/safer to implement BSM models into matrix element generators.
  - Several choices for implementation (LanHEP, FeynRules, SARAH).
  - Export to many MEGs (CalcHEP, FeynArts, MadGraph, Sherpa, Whizard).
  - No need to modify MEG code.
  - Improved validation available.
- Model databases available (FeynRules and HEPMDB).
- Future: Galileo will make the situation even better for the study of BSMs.