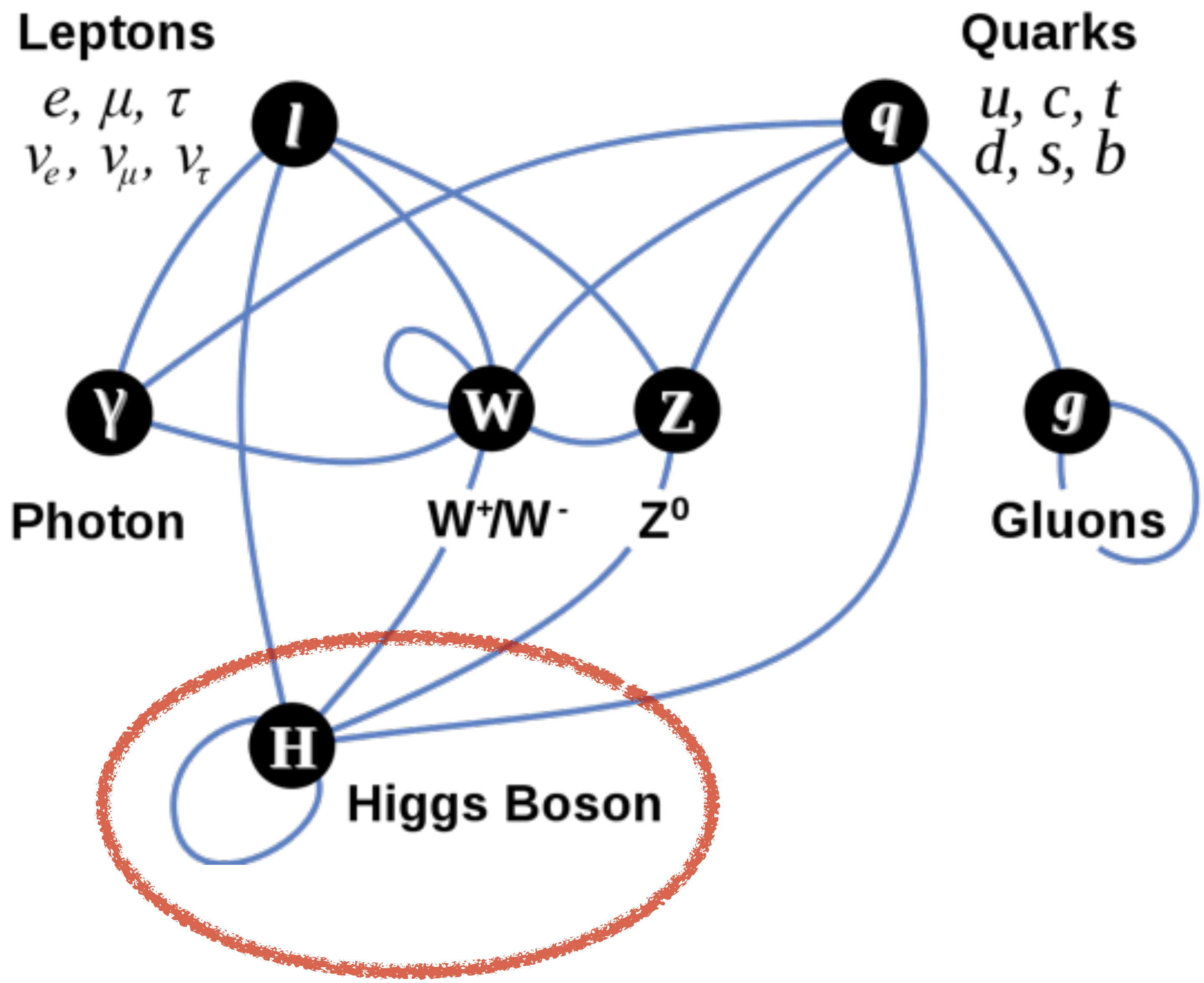
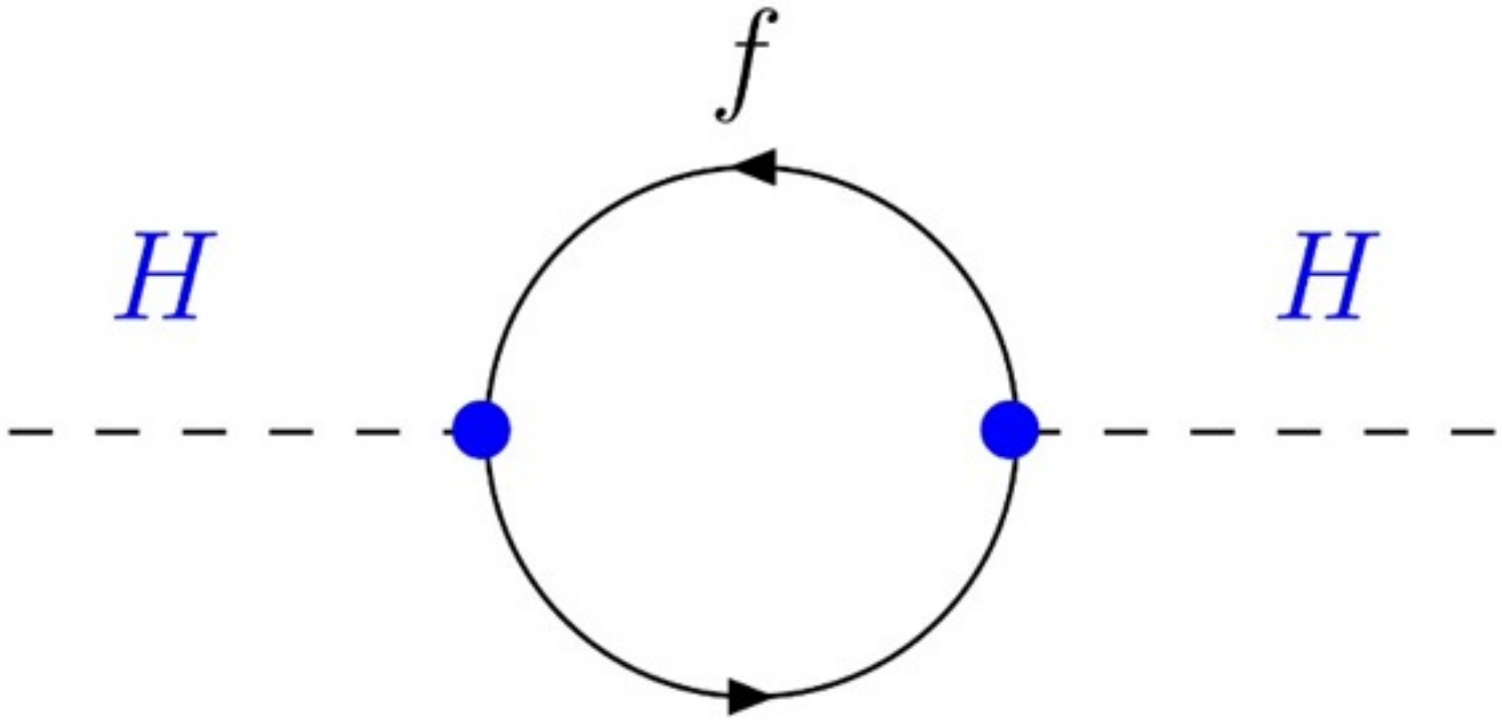
BSM @ LHC

Neil Christensen
PITT PACC
PITTsburgh Particle physics, Astrophysics and Cosmology Center



The giant news of the last year is that we have discovered the Higgs boson!

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).

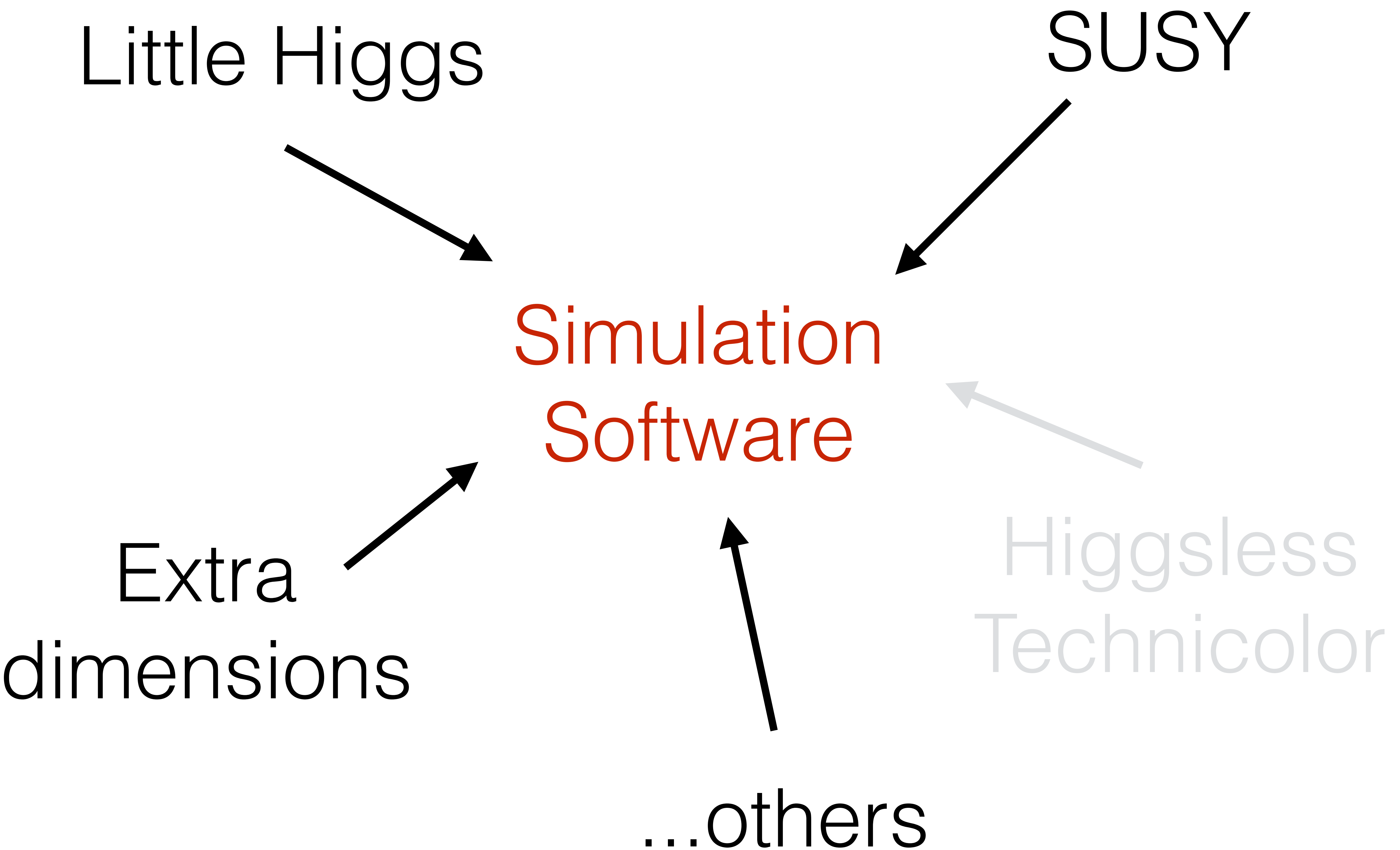
SUSY

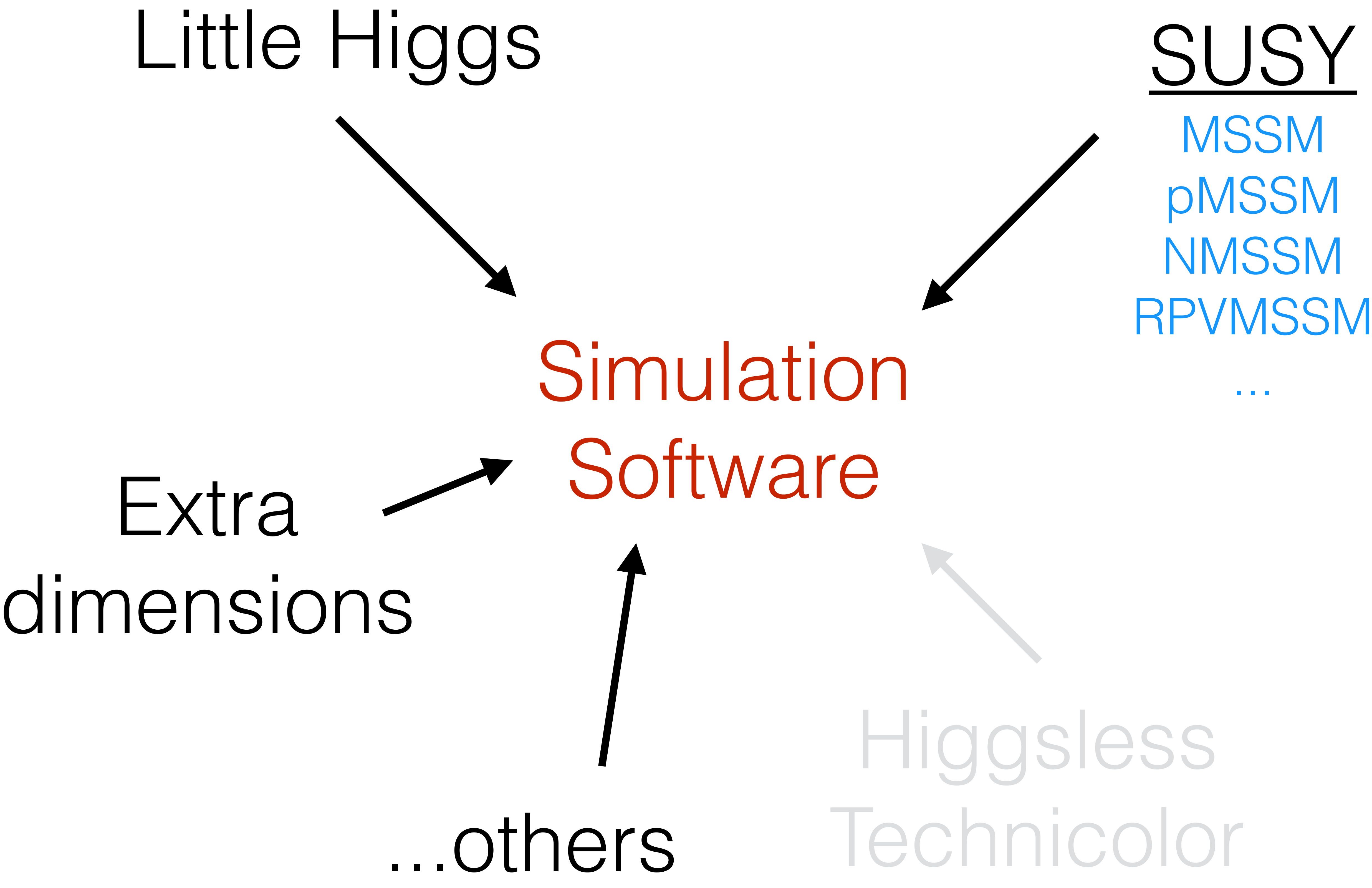
Little Higgs

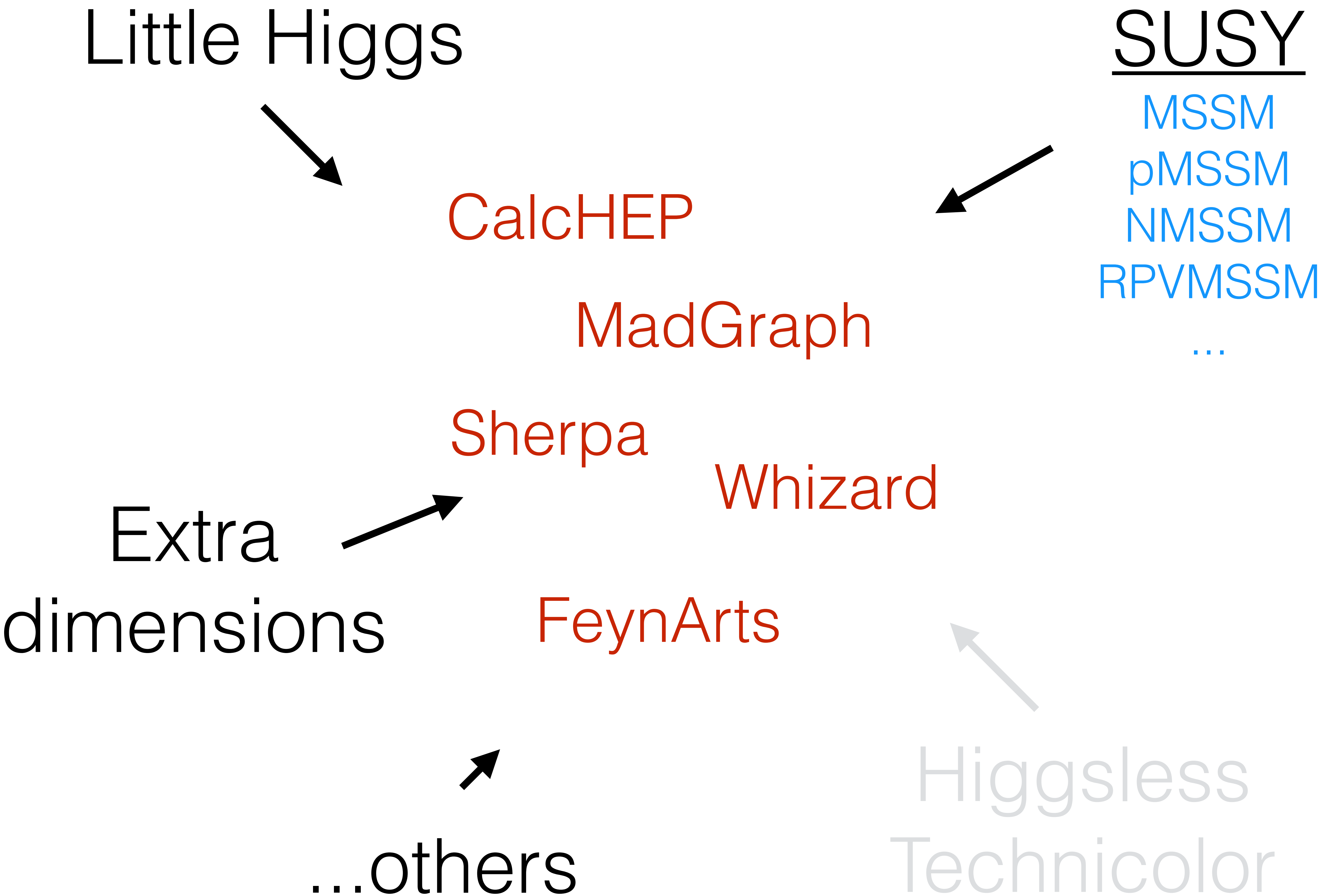
Higgsless
Technicolor

Extra
dimensions

...others


Little Higgs
SUSY
Simulation Software
Extra dimensions
Higgsless Technicolor
...others


Little Higgs
SUSY
MSSM
pMSSM
NMSSM
RPVMSSM
...
Simulation
Software
Extra
dimensions
...others
Higgsless
Technicolor


Little Higgs
SUSY
MSSM
pMSSM
NMSSM
RPVMSSM
...
CalcHEP
MadGraph
Sherpa
Whizard
Extra dimensions
FeynArts
...others
Higgsless
Technicolor

What was the problem?

Problem 1:

Implementing a model was often tedious and error prone.

Terminal — less — 82×38

```
##################################
# 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
:
```

Terminal — bash — 82×38

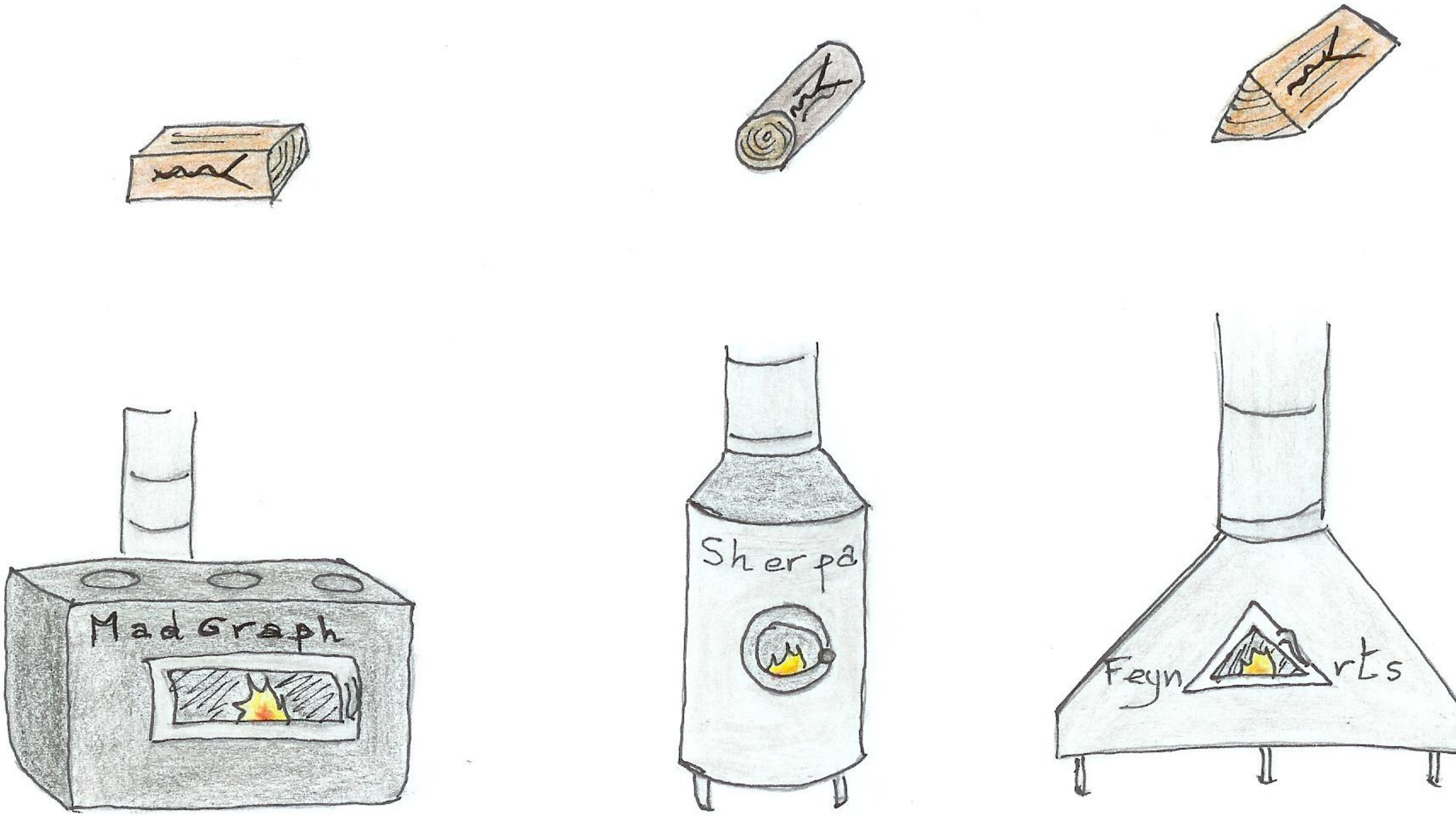
```
c---------------------------------------------
c      V-light   F-heavy    F-heavy
c---------------------------------------------
      GZDpL =
     - -1d0/2d0*gf(-ee,WMASS,ZMASS,MWP)
     -  *vZ0f(WMASS,ZMASS,MWP)*vLP0f(WMASS,MWP)**2
     - -1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)
     -  *VZ1f(WMASS,ZMASS,MWP)*vLP1f(WMASS,MWP)**2
     - +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)=dcmplx(GZDpL,Zero)
      GZDp(2)=dcmplx(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)=dcmplx(GZUpL,Zero)
      GZUp(2)=dcmplx(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.


MadGraph
Sherpa
Feyn
rts

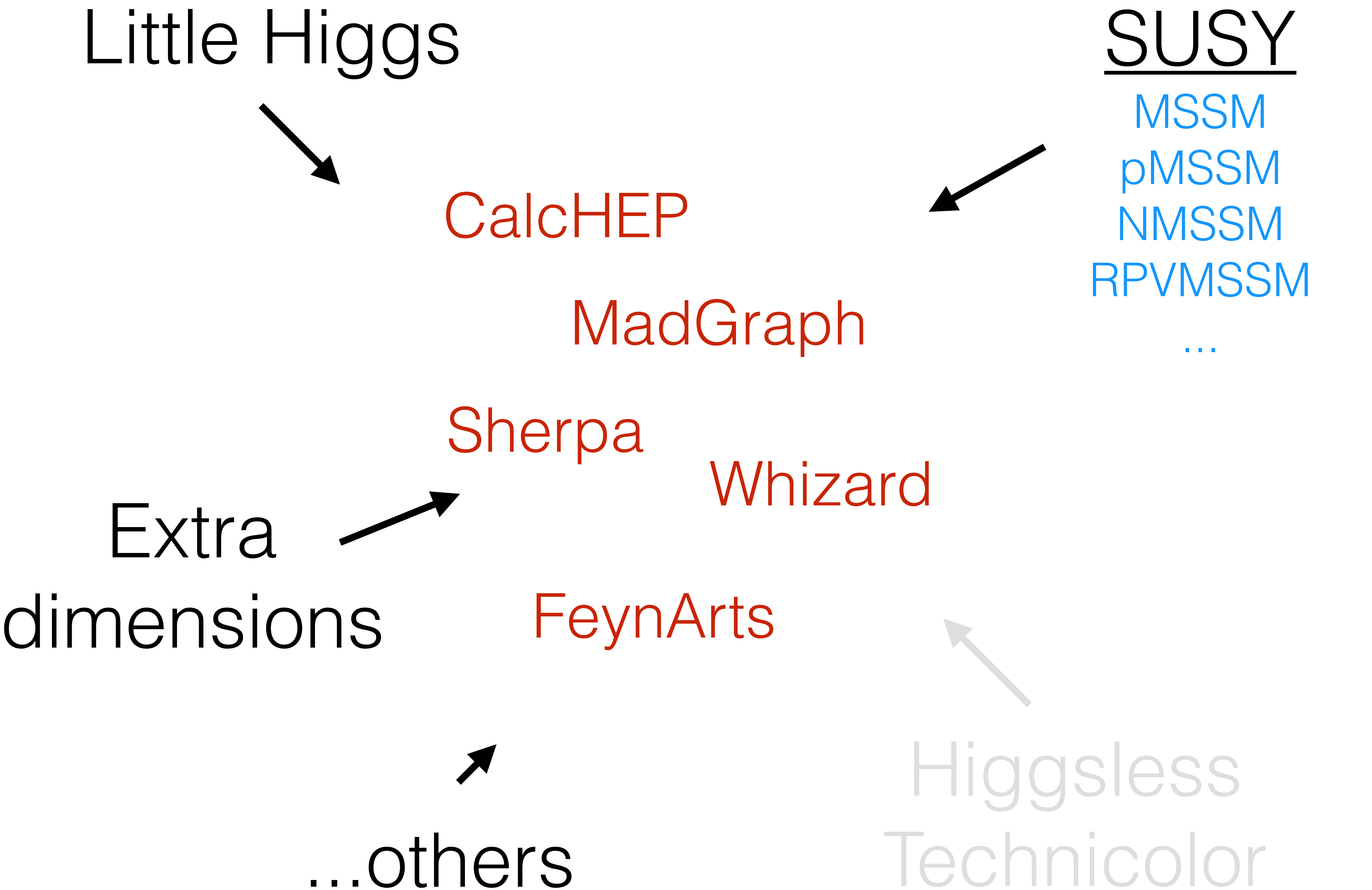
Problem 3:

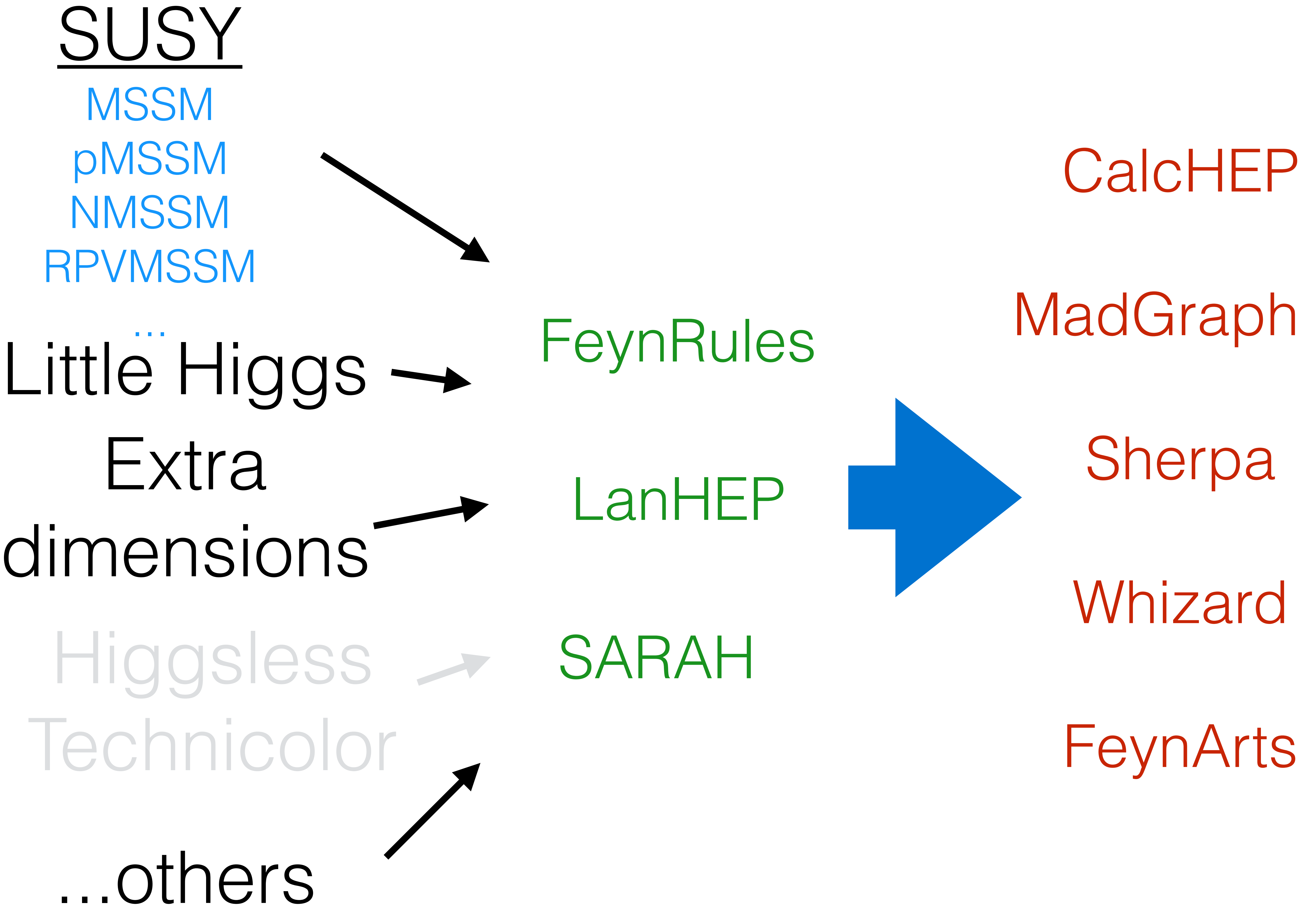
Implementations often did not transfer well to experimentalists.

Problem 3:

Implementations often did not transfer well to experimentalists.

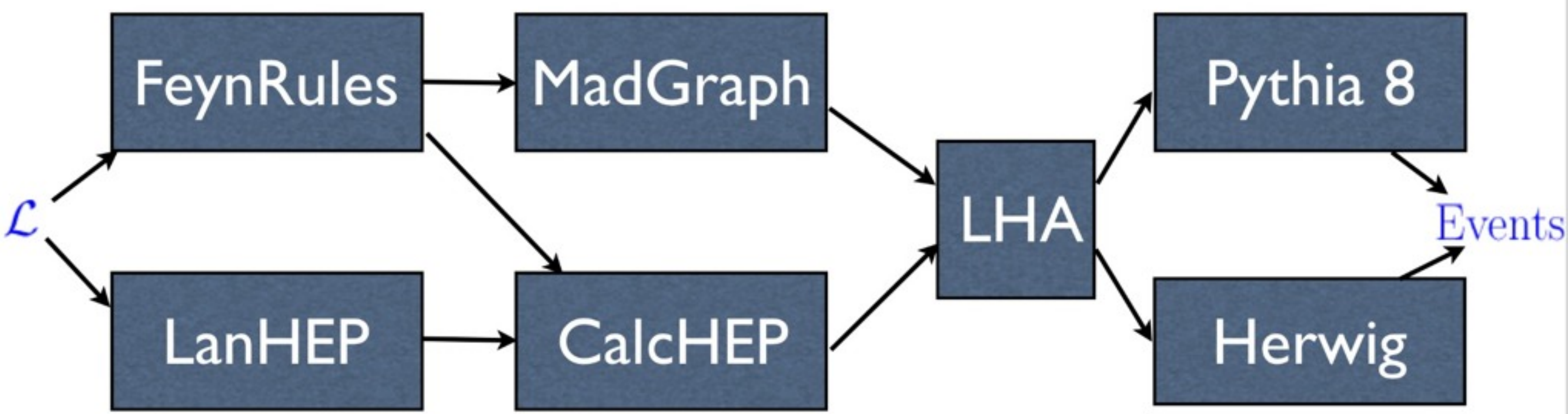
It often required modifying the code of the matrix element generator.

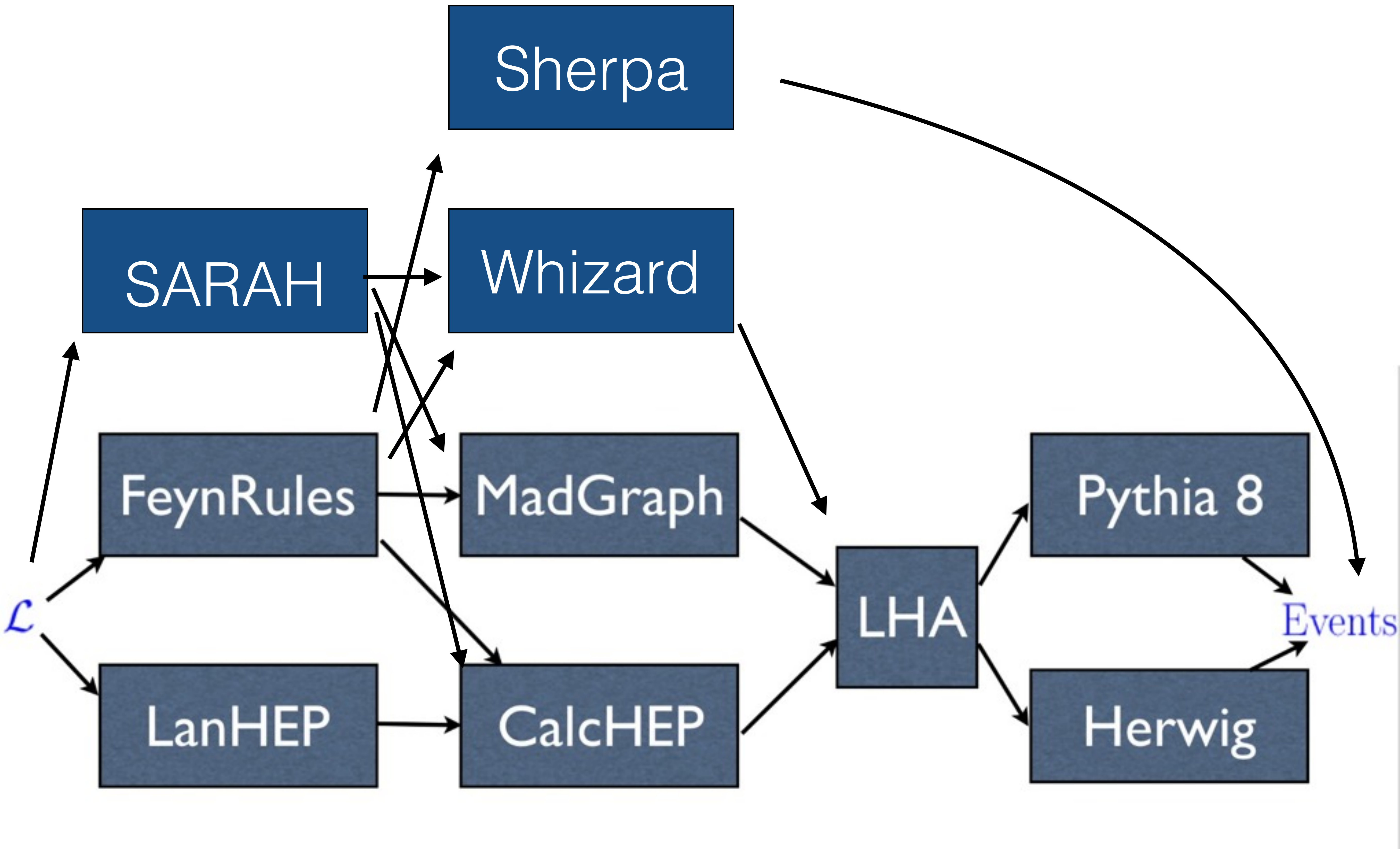

Little Higgs
SUSY
MSSM
pMSSM
NMSSM
RPVMSSM
...
CalcHEP
MadGraph
Sherpa
Whizard
FeynArts
Extra dimensions
...others
Higgsless
Technicolor


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




Sherpa
SARAH
Whizard
FeynRules
MadGraph
LanHEP
CalcHEP
LHA
Pythia 8
Herwig
$\mathcal{L}$
Events

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

	LanHEP	FeynRules	SARAH
CalcHEP	Yes	Yes	Yes
FeynArts	Yes	Yes	Yes
MadGraph	In Progress	Yes	Yes
Sherpa	No	Yes	No
Whizard	No	Yes	Yes

Example: IDP

CPC 184(2013) 1729-1769

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

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

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]
```

Automatic Mass Diagonalization

Eur.Phys.J. C73 (2013) 2325

```
M$MixingsDescription = {
    Mix["l1"] == { options1 },
    Mix["l2"] == { options2 },
              ...
}
```

Automatic Mass Diagonalization

Eur.Phys.J. C73 (2013) 2325

```
Mix["Wmix"] == {
   MassBasis  -> {W, Wbar},
   GaugeBasis -> {Wi[1], Wi[2]},
   Value      -> { {1/Sqrt[2], -I/Sqrt[2]},
                   {1/Sqrt[2], I/Sqrt[2]}  }
}
```

Automatic Mass Diagonalization

Eur.Phys.J. C73 (2013) 2325

```
Mix["AZmix"] == {
   MassBasis      -> {A, Z},
   GaugeBasis     -> {B, Wi[3]},
   MixingMatrix -> UW,
   BlockName      -> WEAKMIX
}
```

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

B-L-FR

Neil Christensen

⇒ **FeynRules Model Files**

⇓ **MEG Model Files & Validations**

⇓ Base Rmv

Restriction File(s) :

Parameter File :

CH	MG5	WO2
✓ ✓	✓ ✓	✓ ✓
Dwnld	Dwnld	Dwnld

Validations

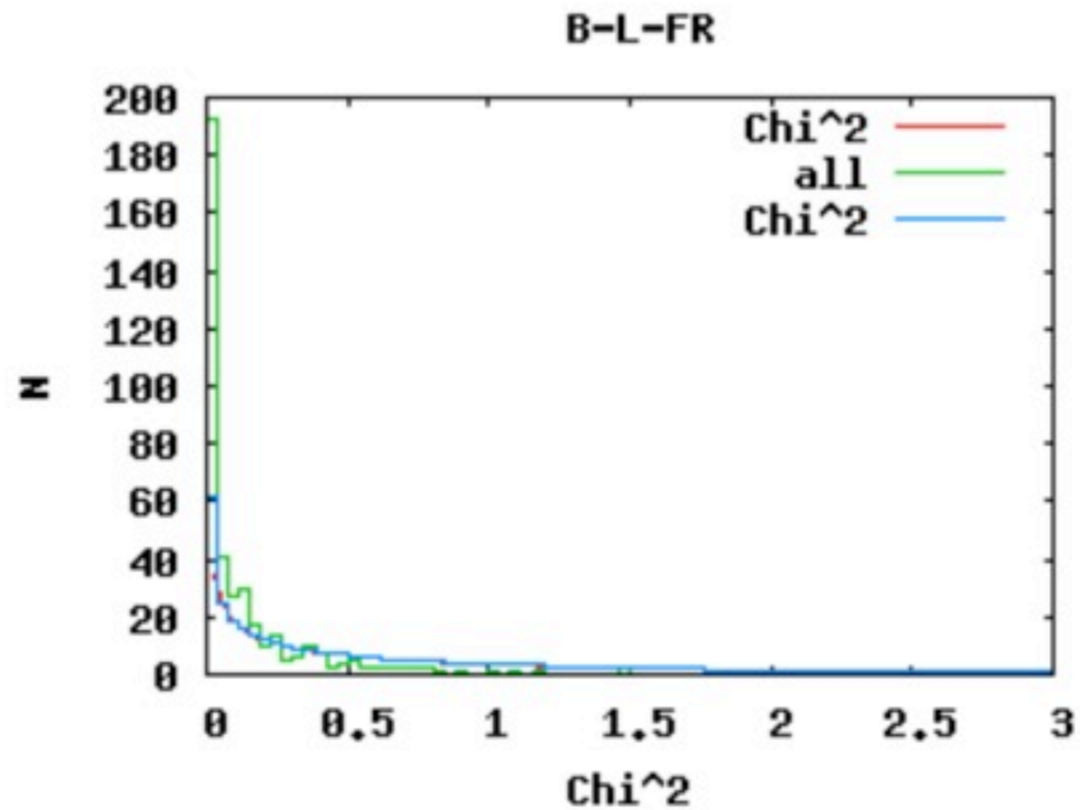
Remove	all	1424/1424 processes finished
Remove	all (CH gauge)	1424/1424 processes finished
Remove	all (W2 gauge)	1424/1424 processes finished
Remove	all (CH & W2)	1424/1424 processes finished

Create New Validation

⇒ FR rv957 Rmv

⇒ FR rv957 WOFast->False Rmv

Create New MEG Model Files



LL=247.2 for 1 degrees of freedom.
The probability of this being a statistical fluctuation is 0.0%.

	√s	p_{Tcut}	Best	CH(u)	WO2(u)	X^2
~n1 , ~n1 → s , S	3202.0	800.5	7.104E-04	7.103E-04	7.106E-04	2.0E+00
m , M → s , S	400.0	100.0	5.070E-01	5.071E-01	5.069E-01	1.5E+00
t , T → s , S	2754.0	688.5	2.444E-01	2.444E-01	2.442E-01	1.5E+00
u , U → d , S	400.0	100.0	5.322E-01	5.322E-01	5.325E-01	1.2E+00
~n2 , ~n2 → ~n2 , ~n2	3200.0	800.0	1.225E-02	1.225E-02	1.224E-02	1.1E+00
t , T → d , D	2752.0	688.0	2.455E-01	2.455E-01	2.453E-01	1.0E+00
t , T → 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 were 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

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM (10)	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.
Supersymmetric Models (4)	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models (4)	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories (5)	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators.
Miscellaneous (0)	

iPad 4:45 PM 94%

hepmdb.soton.ac.uk/index.php?mod=user&act=search

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HEPMDB

High Energy Physics Models DataBase

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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 J¨arvinen, 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

$$\log(1.27) =$$

$$\log(1.27) = \ 0.27 - \frac{1}{2}0.27^2 + \frac{1}{3}0.27^3 - \frac{1}{4}0.27^4 + \cdots$$

$$\log(1.27) = \; 0.27 - \frac{1}{2}0.27^2 + \frac{1}{3}0.27^3 - \frac{1}{4}0.27^4 + \cdots$$

$$\cos(0.33) = 1 - \frac{1}{2!}0.33^2 + \frac{1}{4!}0.33^4 + \cdots$$

$$\frac{1}{0.57} = 1 + 0.43 + 0.43^2 + 0.43^3 + 0.43^4 + \cdots$$

$$\vdots$$

$$\log(1.27) = 0.1038\cdots$$

$$\cos(0.33) = 0.9460\cdots$$

$$\frac{1}{0.57} = 1.754\cdots$$

$$\vdots$$

Why use technology?

- Can you calculate it on your own? Yes!!!
  - Should you learn how to do it? Yes.
- During research, why waste your time on the algorithms?
  - We could do so much more physics if we let computers do the algorithms!
- Rather concentrate on the new physics!
- Humans are good at creativity!
- Computers are good at algorithms!
  - Let the computers do the algorithms once they are mature!

We use technology to

Do more!

	$SU(3)_c$	$\times SU(2)_W$	$\times U(1)_Y$
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
Φ	1	2	1/2

$$SU(3)_c \times SU(2)_W \times U(1)_Y$$

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
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{W\mu\nu} F_W^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$

$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$

$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
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
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\,\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
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
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\,\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian

$$SU(3)_c \times SU(2)_W \times U(1)_Y$$

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
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
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F_{c\,\mu\nu}^{a} F_c^{a\mu\nu} - \frac{1}{4} F_{w\,\mu\nu}^{a} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\,\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
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
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
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$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
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
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F_{c\,\mu\nu}^{a} F_c^{a\mu\nu} - \frac{1}{4} F_{W\mu\nu}^{a} F_W^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \tilde{\Phi} \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis

$$SU(3)_c \times SU(2)_W \times U(1)_Y$$

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
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
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{W\mu\nu} F_W^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i \bar{Q}_L \not{D} Q_L + i \bar{u}_R \not{D} u_R + i \bar{d}_R \not{D} d_R + i \bar{L}_L \not{D} L_L + i \bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis
- Calculate Feynman diagrams

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
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
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \tilde{\Phi} \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis
- Calculate Feynman diagrams
- Implement Feynman rules into CH, FA, MG, SH, WO

	$SU(3)_c$	$\times SU(2)_W$	$\times U(1)_Y$
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
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\,\mu\nu} F_Y^{\mu\nu}$$
$$+ i \bar{Q}_L \not{D} Q_L + i \bar{u}_R \not{D} u_R + i \bar{d}_R \not{D} d_R + i \bar{L}_L \not{D} L_L + i \bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis
- Calculate Feynman diagrams
- Implement Feynman rules into CH, FA, MG, SH, WO
- Implement Lagrangian into FR, LH, SARAH

$$SU(3)_c \times SU(2)_W \times U(1)_Y$$

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
Q_L	3	2	1/6
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e_R	1	1	-1
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{W\mu\nu} F_W^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
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- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis
- Calculate Feynman diagrams
- Implement Feynman rules into CH, FA, MG, SH, WO
- Implement Lagrangian into FR, LH, SARAH
- Do calculations

	$SU(3)_c$	$\times SU(2)_W$	$\times U(1)_Y$
Q_L	3	2	1/6
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d_R	3	1	-1/3
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e_R	1	1	-1
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$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
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Algorithmic!

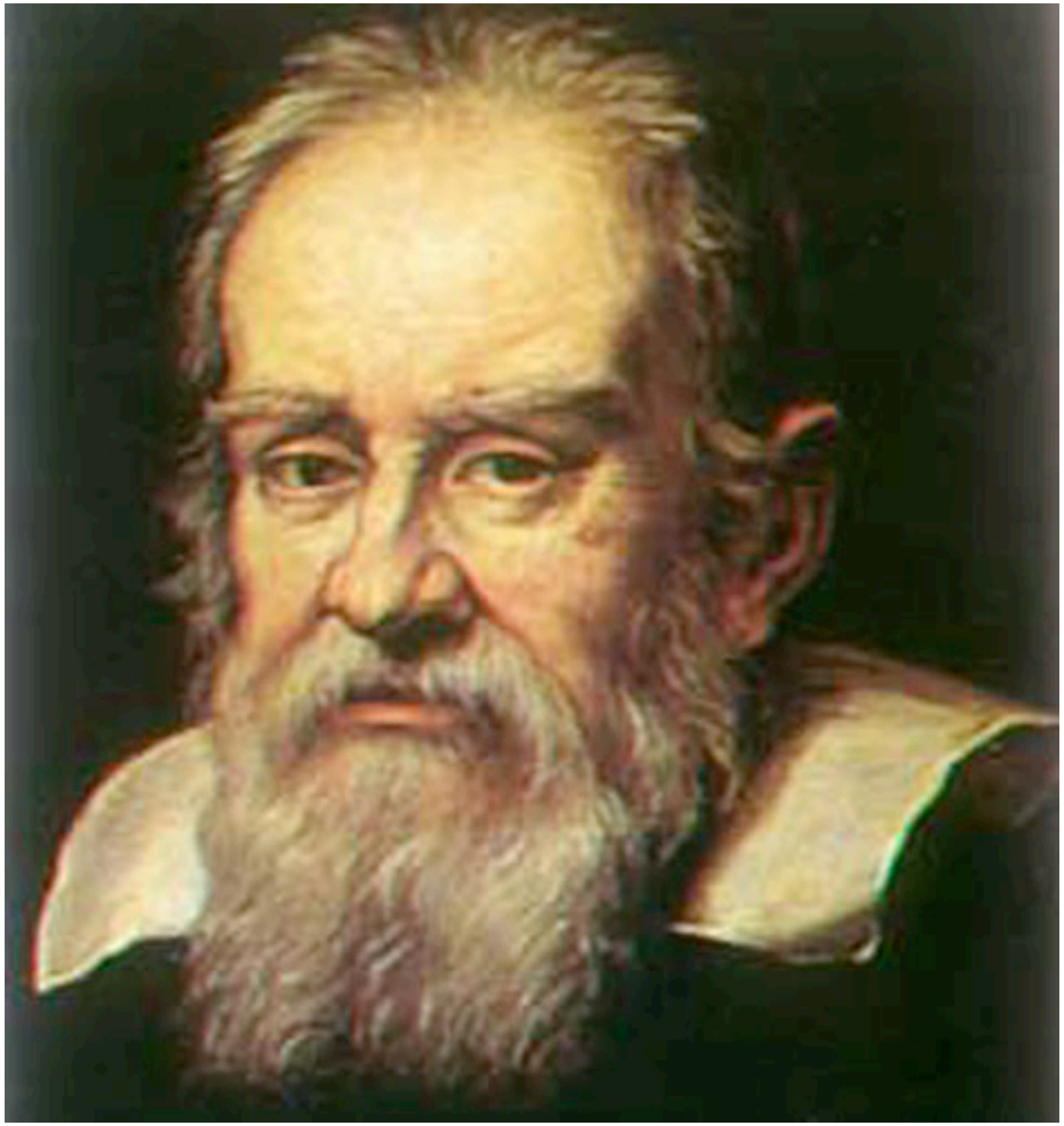
- Insert vevs Algorithmic!
- Expand Lagrangian Algorithmic!
- Collect quadratic terms Algorithmic!
- Diagonalize mass matrices Algorithmic!
- Rotate fields to mass basis Algorithmic!
- Calculate Feynman diagrams Algorithmic!
- Implement Feynman rules into CH, FA, MG, SH, WO Algorithmic!
- Implement Lagrangian into FR, LH, SARAH Algorithmic!
- Do calculations Some algorithmic!

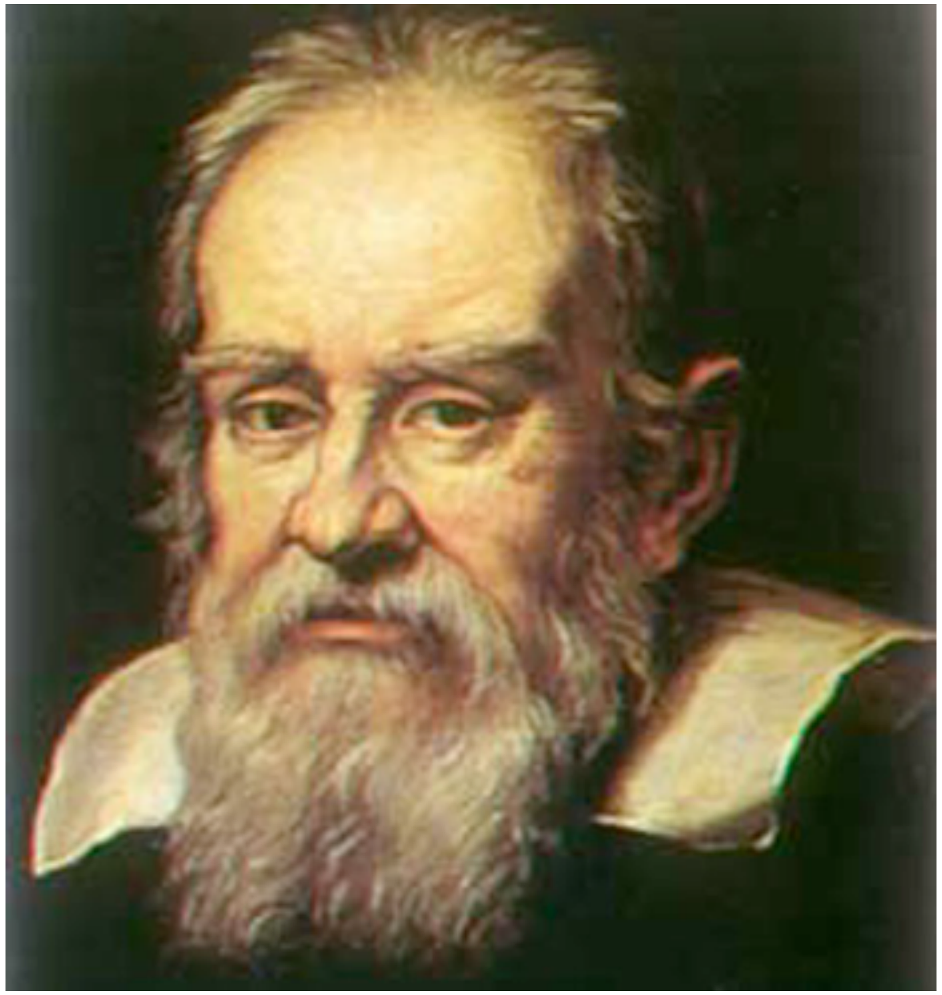
Why use technology?

- Can you calculate it on your own? Yes!!!
  - Should you learn how to do it? Yes.
- During research, why waste your time on the algorithms?
  - We could do so much more physics if we let computers do the algorithms!
- Rather concentrate on the new physics!
- Humans are good at creativity!
- Computers are good at algorithms!
  - Let the computers do the algorithms once they are mature!

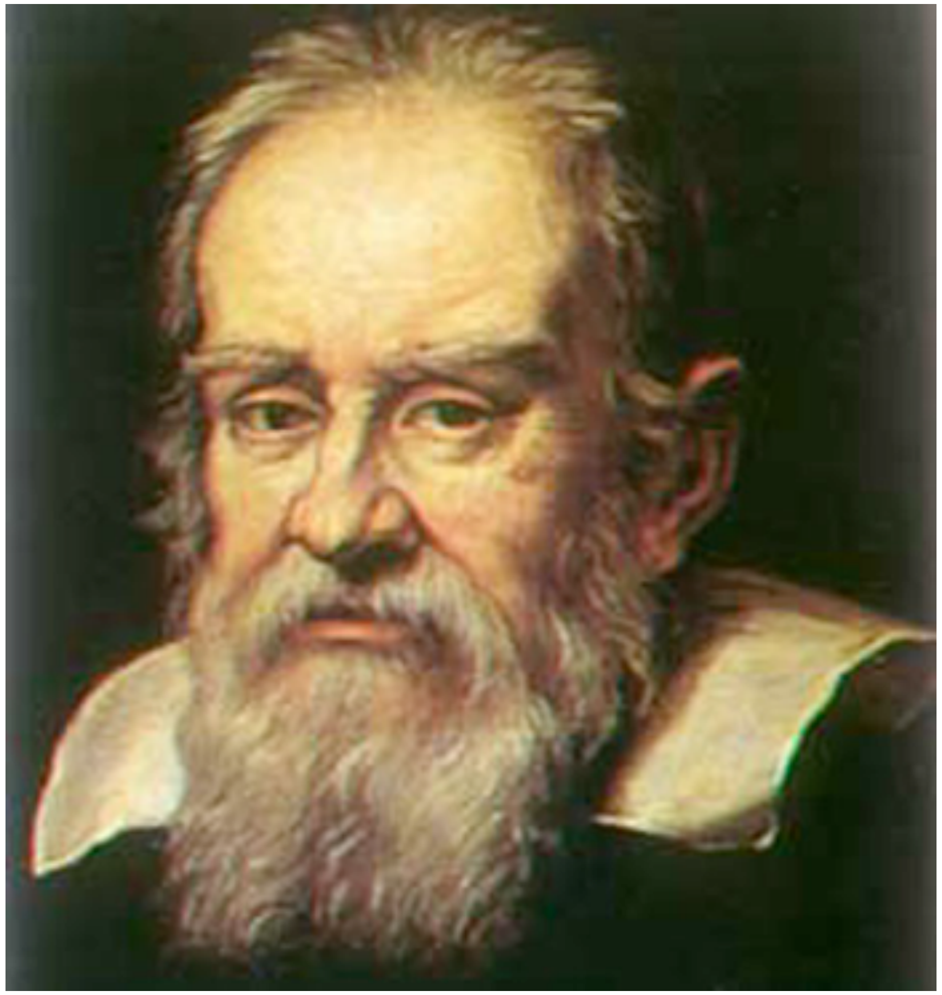
We use technology to

Do more!



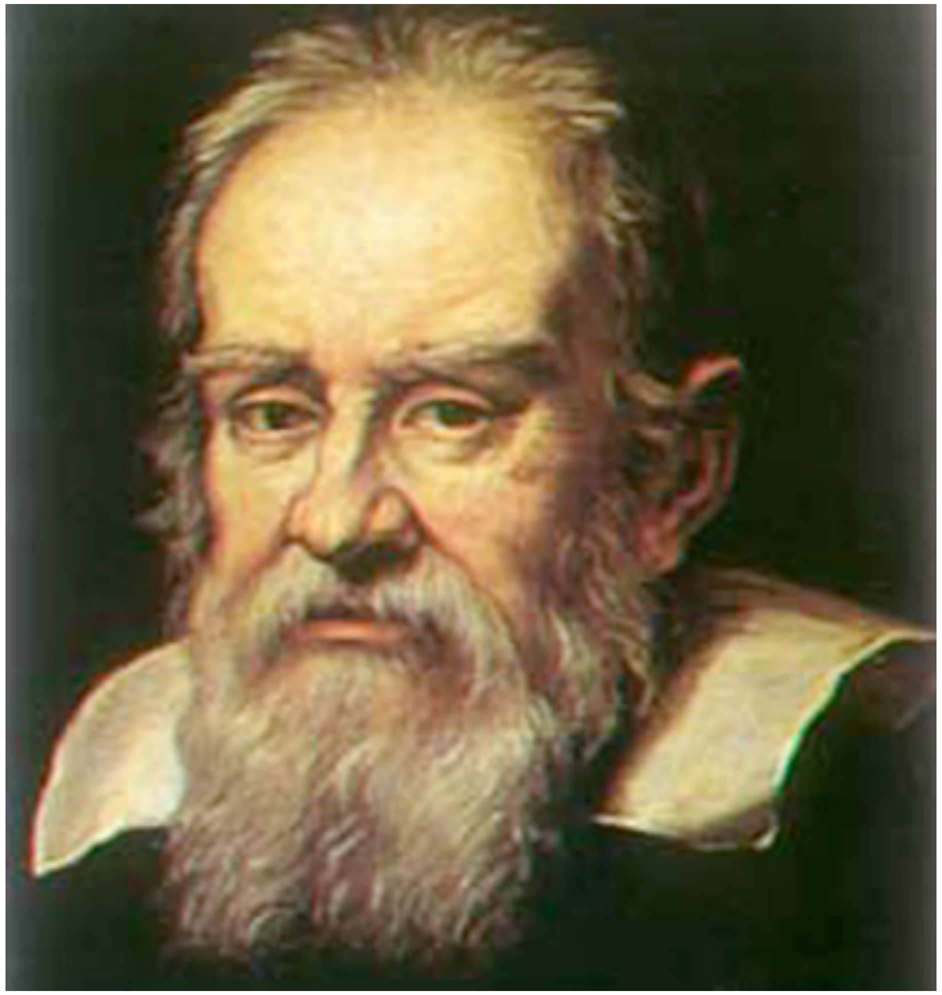


Galileo was not afraid of getting his hands dirty with technology!



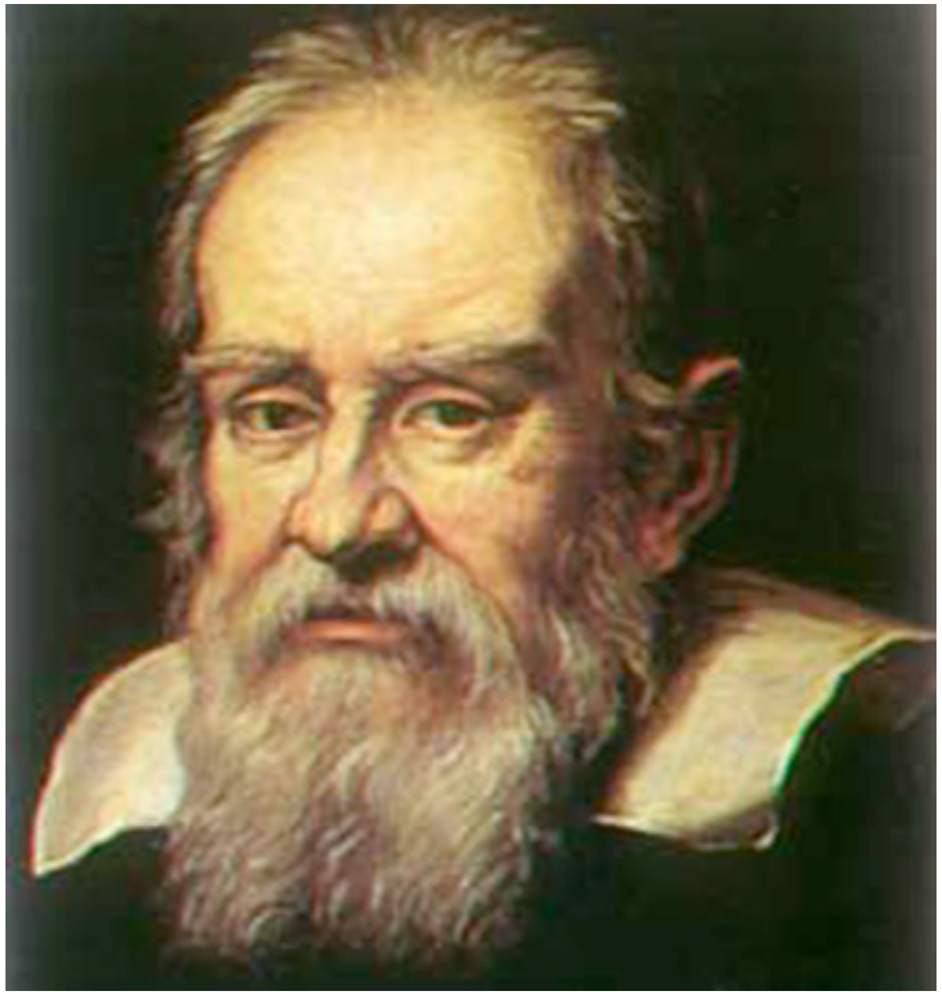
Galileo was not afraid of getting his hands dirty with technology!

He worked very hard to improve the telescope and ...



Galileo was not afraid of getting his hands dirty with technology!

He worked very hard to improve the telescope and then he pointed it at the skies and discovered craters on the moon, moons orbiting jupiter, and many others!



Galileo was not afraid of getting his hands dirty with technology!

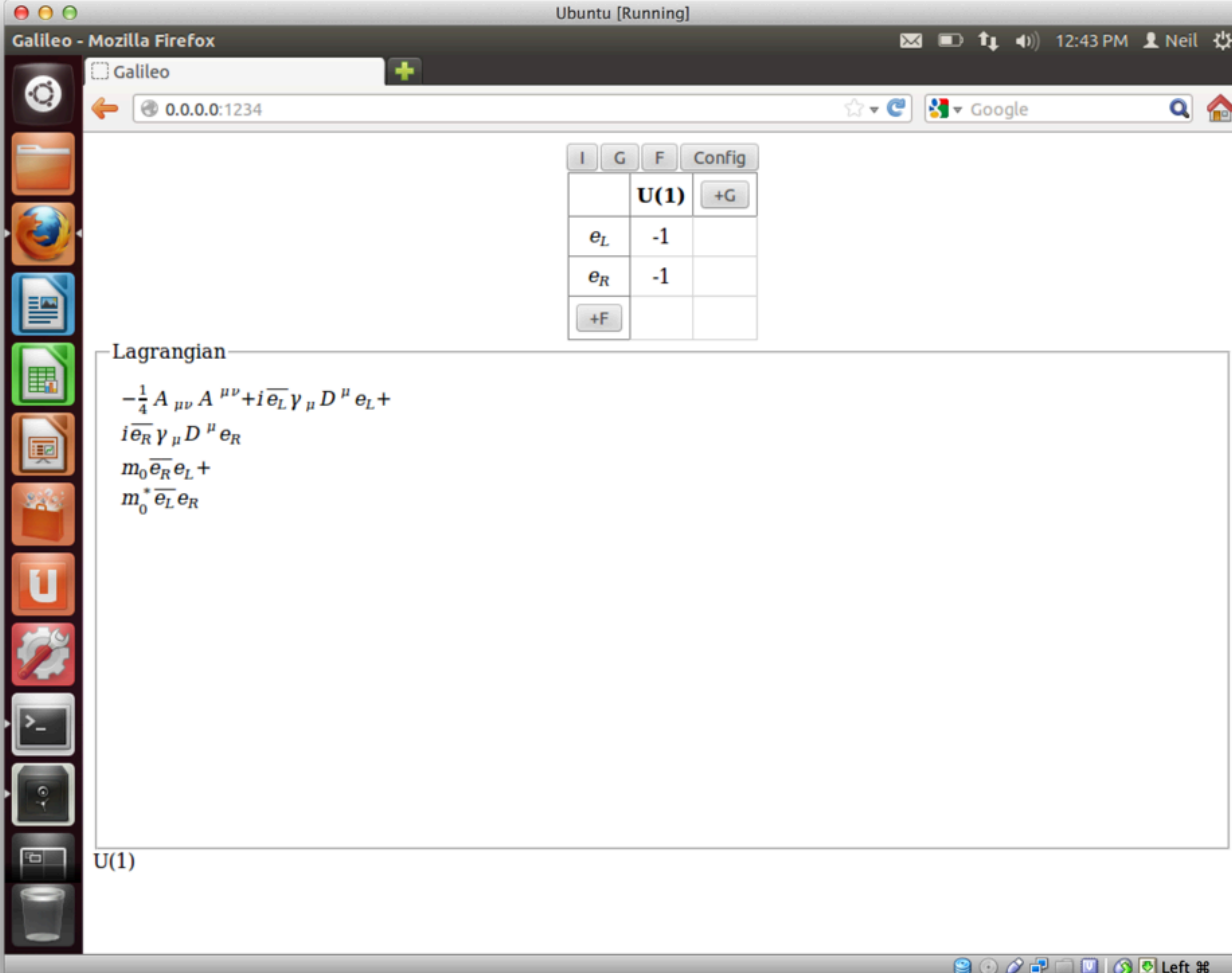
He worked very hard to improve the telescope and then he pointed it at the skies and discovered craters on the moon, moons orbiting jupiter, and many others!

We have the same opportunity in our day!

Introducing

Galileo

Do more!


Ubuntu [Running]
Galileo - Mozilla Firefox
12:43 PM
Neil
Galileo
0.0.0.0:1234
Google
I
G
F
Config
U(1)
+G
e_L
-1
e_R
-1
+F
Lagrangian
$-\frac{1}{4} A_{\mu\nu} A^{\mu\nu} + i \overline{e_L} \gamma_\mu D^\mu e_L +$
$i \overline{e_R} \gamma_\mu D^\mu e_R$
$m_0 \overline{e_R} e_L +$
$m_0^* \overline{e_L} e_R$
U(1)
Left ⌘

Ubuntu [Running]

Galileo - Mozilla Firefox

Galileo

0.0.0.0:1234

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	
Φ	1	2	$\frac{1}{2}$	
+F				

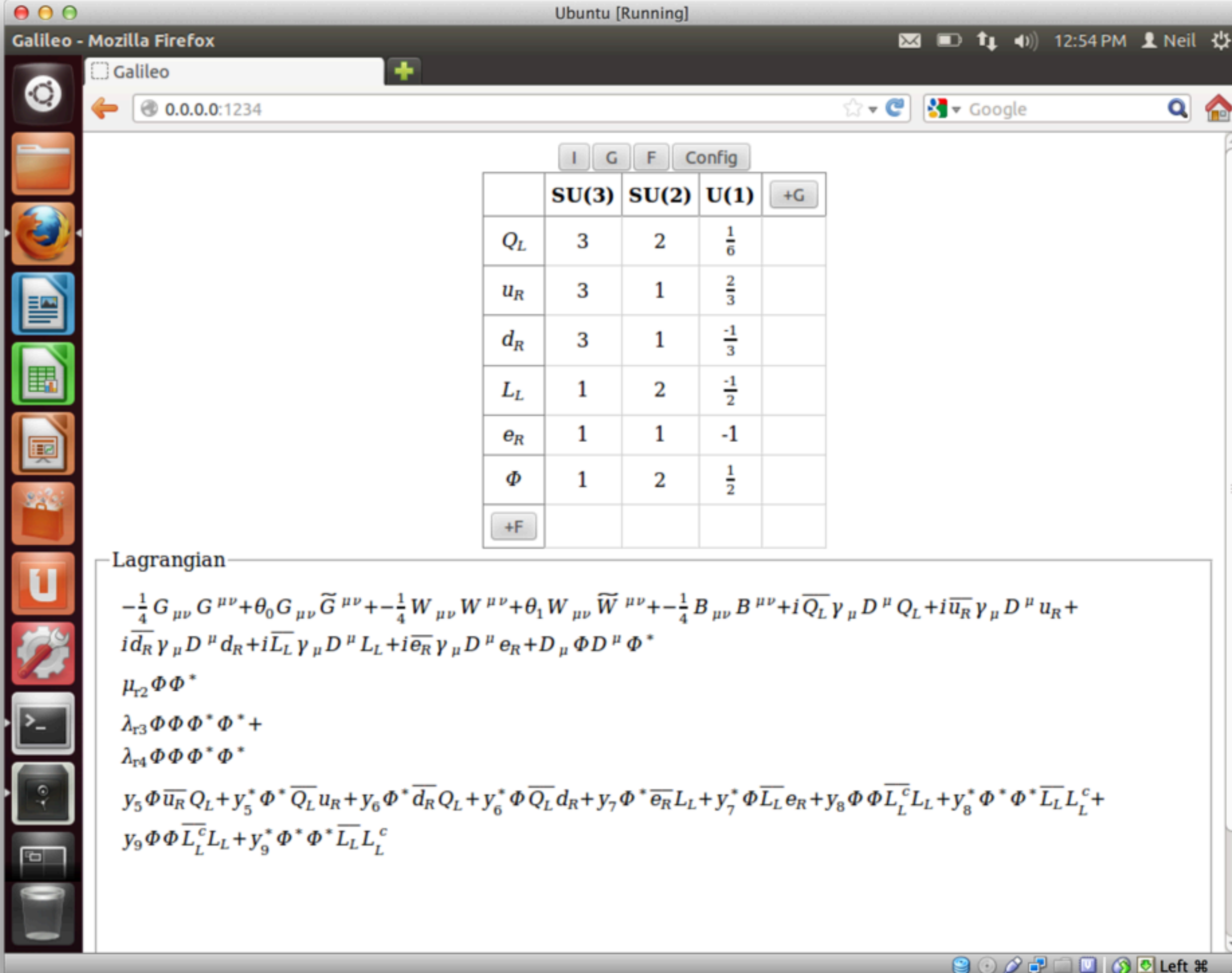
Lagrangian

$-\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \theta_0 G_{\mu\nu} \widetilde{G}^{\mu\nu} + -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \theta_1 W_{\mu\nu} \widetilde{W}^{\mu\nu} + -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i\overline{Q_L}\gamma_\mu D^\mu Q_L + i\overline{u_R}\gamma_\mu D^\mu u_R +$
$i\overline{d_R}\gamma_\mu D^\mu d_R + i\overline{L_L}\gamma_\mu D^\mu L_L + i\overline{e_R}\gamma_\mu D^\mu e_R + D_\mu \Phi D^\mu \Phi^*$

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

$\lambda_{r3}\Phi\Phi\Phi^*\Phi^* +$
$\lambda_{r4}\Phi\Phi\Phi^*\Phi^*$

$y_5\Phi\overline{u_R}Q_L + y_5^*\Phi^*\overline{Q_L}u_R + y_6\Phi^*\overline{d_R}Q_L + y_6^*\Phi\overline{Q_L}d_R + y_7\Phi^*\overline{e_R}L_L +$
$y_7^*\Phi\overline{L_L}e_R$



	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	
Φ	1	2	$\frac{1}{2}$	
+F				

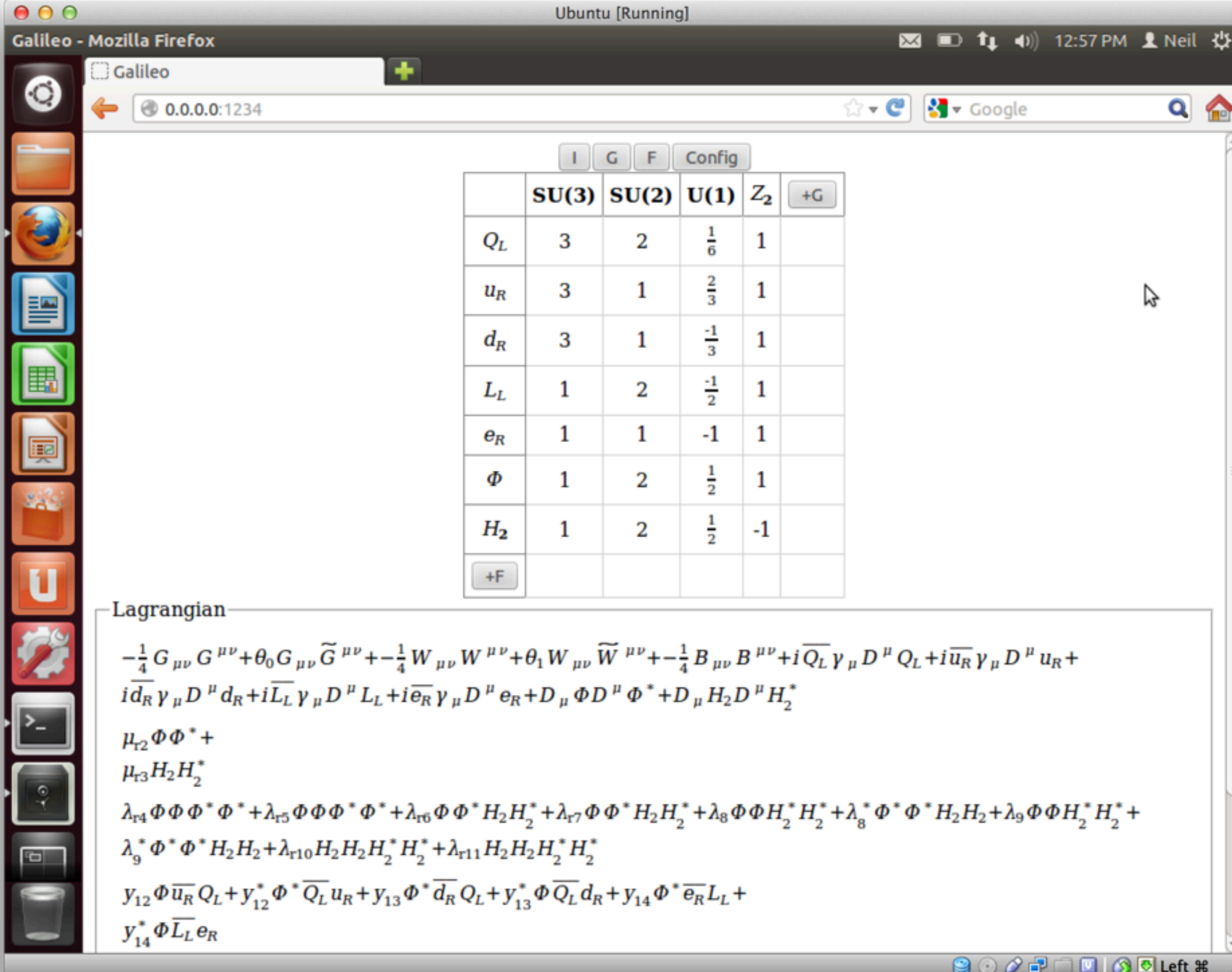
Lagrangian

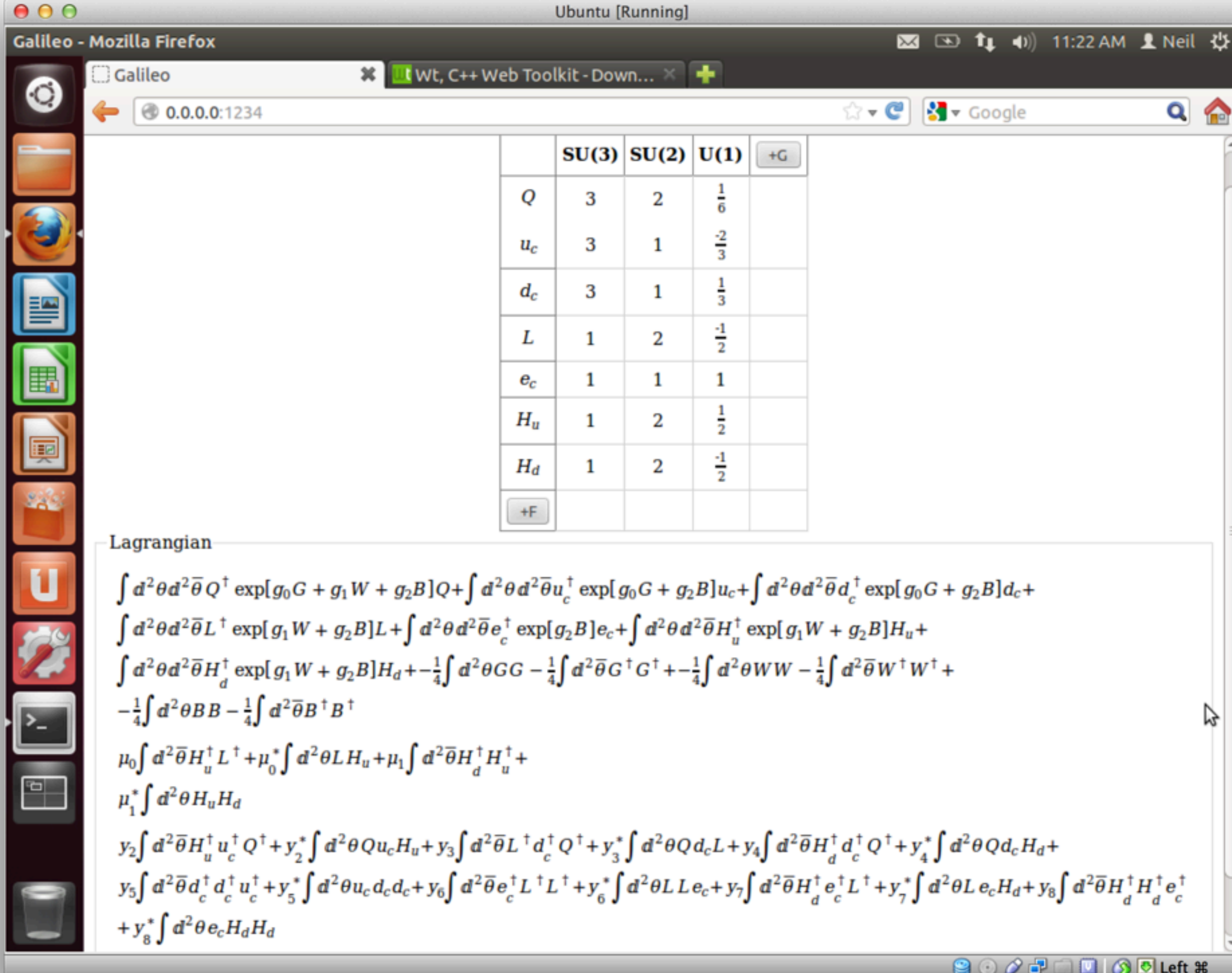
$-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\theta_0 G_{\mu\nu}\widetilde{G}^{\mu\nu}+-\frac{1}{4}W_{\mu\nu}W^{\mu\nu}+\theta_1 W_{\mu\nu}\widetilde{W}^{\mu\nu}+-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}+i\overline{Q_L}\gamma_\mu D^\mu Q_L+i\overline{u_R}\gamma_\mu D^\mu u_R+$
$i\overline{d_R}\gamma_\mu D^\mu d_R+i\overline{L_L}\gamma_\mu D^\mu L_L+i\overline{e_R}\gamma_\mu D^\mu e_R+D_\mu\Phi D^\mu\Phi^*$

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

$\lambda_{r3}\Phi\Phi\Phi^*\Phi^*+$
$\lambda_{r4}\Phi\Phi\Phi^*\Phi^*$

$y_5\Phi\overline{u_R}Q_L+y_5^*\Phi^*\overline{Q_L}u_R+y_6\Phi^*\overline{d_R}Q_L+y_6^*\Phi\overline{Q_L}d_R+y_7\Phi^*\overline{e_R}L_L+y_7^*\Phi\overline{L_L}e_R+y_8\Phi\Phi\overline{L_L^c}L_L+y_8^*\Phi^*\Phi^*\overline{L_L}L_L^c+$
$y_9\Phi\Phi\overline{L_L^c}L_L+y_9^*\Phi^*\Phi^*\overline{L_L}L_L^c$


Ubuntu [Running]
Galileo - Mozilla Firefox
12:57 PM
Neil
Galileo
0.0.0.0:1234
Google
I
G
F
Config
SU(3) SU(2) U(1) Z_2 +G
Q_L 3 2 $\frac{1}{6}$ 1
u_R 3 1 $\frac{2}{3}$ 1
d_R 3 1 $\frac{-1}{3}$ 1
L_L 1 2 $\frac{-1}{2}$ 1
e_R 1 1 -1 1
Φ 1 2 $\frac{1}{2}$ 1
H_2 1 2 $\frac{1}{2}$ -1
+F
Lagrangian
$-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\theta_0 G_{\mu\nu}\widetilde{G}^{\mu\nu}+-\frac{1}{4}W_{\mu\nu}W^{\mu\nu}+\theta_1 W_{\mu\nu}\widetilde{W}^{\mu\nu}+-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}+i\overline{Q_L}\gamma_\mu D^\mu Q_L+i\overline{u_R}\gamma_\mu D^\mu u_R+$
$i\overline{d_R}\gamma_\mu D^\mu d_R+i\overline{L_L}\gamma_\mu D^\mu L_L+i\overline{e_R}\gamma_\mu D^\mu e_R+D_\mu \Phi D^\mu \Phi^*+D_\mu H_2 D^\mu H_2^*$
$\mu_{r2}\Phi\Phi^*+$
$\mu_{r3}H_2H_2^*$
$\lambda_{r4}\Phi\Phi\Phi^*\Phi^*+\lambda_{r5}\Phi\Phi\Phi^*\Phi^*+\lambda_{r6}\Phi\Phi^*H_2H_2^*+\lambda_{r7}\Phi\Phi^*H_2H_2^*+\lambda_8\Phi\Phi H_2^*H_2^*+\lambda_8^*\Phi^*\Phi^*H_2H_2+\lambda_9\Phi\Phi H_2^*H_2^*+$
$\lambda_9^*\Phi^*\Phi^*H_2H_2+\lambda_{r10}H_2H_2H_2^*H_2^*+\lambda_{r11}H_2H_2H_2^*H_2^*$
$y_{12}\Phi\overline{u_R}Q_L+y_{12}^*\Phi^*\overline{Q_L}u_R+y_{13}\Phi^*\overline{d_R}Q_L+y_{13}^*\Phi\overline{Q_L}d_R+y_{14}\Phi^*\overline{e_R}L_L+$
$y_{14}^*\Phi\overline{L_L}e_R$
Left ⌘



	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

$$\int d^2\theta d^2\bar\theta\, Q^\dagger \exp[g_0 G + g_1 W + g_2 B]Q + \int d^2\theta d^2\bar\theta\, u_c^\dagger \exp[g_0 G + g_2 B]u_c + \int d^2\theta d^2\bar\theta\, d_c^\dagger \exp[g_0 G + g_2 B]d_c +$$

$$\int d^2\theta d^2\bar\theta\, L^\dagger \exp[g_1 W + g_2 B]L + \int d^2\theta d^2\bar\theta\, e_c^\dagger \exp[g_2 B]e_c + \int d^2\theta d^2\bar\theta\, H_u^\dagger \exp[g_1 W + g_2 B]H_u +$$

$$\int d^2\theta d^2\bar\theta\, H_d^\dagger \exp[g_1 W + g_2 B]H_d + -\tfrac{1}{4}\int d^2\theta\, G G - \tfrac{1}{4}\int d^2\bar\theta\, G^\dagger G^\dagger + -\tfrac{1}{4}\int d^2\theta\, W W - \tfrac{1}{4}\int d^2\bar\theta\, W^\dagger W^\dagger +$$

$$-\tfrac{1}{4}\int d^2\theta\, B B - \tfrac{1}{4}\int d^2\bar\theta\, B^\dagger B^\dagger$$

$$\mu_0\int d^2\bar\theta\, H_u^\dagger L^\dagger + \mu_0^*\int d^2\theta\, L H_u + \mu_1\int d^2\bar\theta\, H_d^\dagger H_u^\dagger +$$

$$\mu_1^*\int d^2\theta\, H_u H_d$$

$$y_2\int d^2\bar\theta\, H_u^\dagger u_c^\dagger Q^\dagger + y_2^*\int d^2\theta\, Q u_c H_u + y_3\int d^2\bar\theta\, L^\dagger d_c^\dagger Q^\dagger + y_3^*\int d^2\theta\, Q d_c L + y_4\int d^2\bar\theta\, H_d^\dagger d_c^\dagger Q^\dagger + y_4^*\int d^2\theta\, Q d_c H_d +$$

$$y_5\int d^2\bar\theta\, d_c^\dagger d_c^\dagger u_c^\dagger + y_5^*\int d^2\theta\, u_c d_c d_c + y_6\int d^2\bar\theta\, e_c^\dagger L^\dagger L^\dagger + y_6^*\int d^2\theta\, L L e_c + y_7\int d^2\bar\theta\, H_d^\dagger e_c^\dagger L^\dagger + y_7^*\int d^2\theta\, L e_c H_d + y_8\int d^2\bar\theta\, H_d^\dagger H_d^\dagger e_c^\dagger$$

$$+ y_8^*\int d^2\theta\, e_c H_d H_d$$

	SU(3)	SU(2)	U(1)	Z_2
Q	3	2	$\frac{1}{6}$	-1
u_c	3	1	$\frac{-2}{3}$	-1
d_c	3	1	$\frac{1}{3}$	-1
L	1	2	$\frac{-1}{2}$	-1
e_c	1	1	1	-1
H_u	1	2	$\frac{1}{2}$	1
H_d	1	2	$\frac{-1}{2}$	1

Lagrangian

$$\int d^2\theta d^2\bar\theta Q^\dagger \exp[g_0 G + g_1 W + g_2 B]Q + \int d^2\theta d^2\bar\theta u_c^\dagger \exp[g_0 G + g_2 B]u_c + \int d^2\theta d^2\bar\theta d_c^\dagger \exp[g_0 G + g_2 B]d_c +$$

$$\int d^2\theta d^2\bar\theta L^\dagger \exp[g_1 W + g_2 B]L + \int d^2\theta d^2\bar\theta e_c^\dagger \exp[g_2 B]e_c + \int d^2\theta d^2\bar\theta H_u^\dagger \exp[g_1 W + g_2 B]H_u +$$

$$\int d^2\theta d^2\bar\theta H_d^\dagger \exp[g_1 W + g_2 B]H_d + -\tfrac{1}{4}\int d^2\theta GG - \tfrac{1}{4}\int d^2\bar\theta G^\dagger G^\dagger + -\tfrac{1}{4}\int d^2\theta WW - \tfrac{1}{4}\int d^2\bar\theta W^\dagger W^\dagger +$$

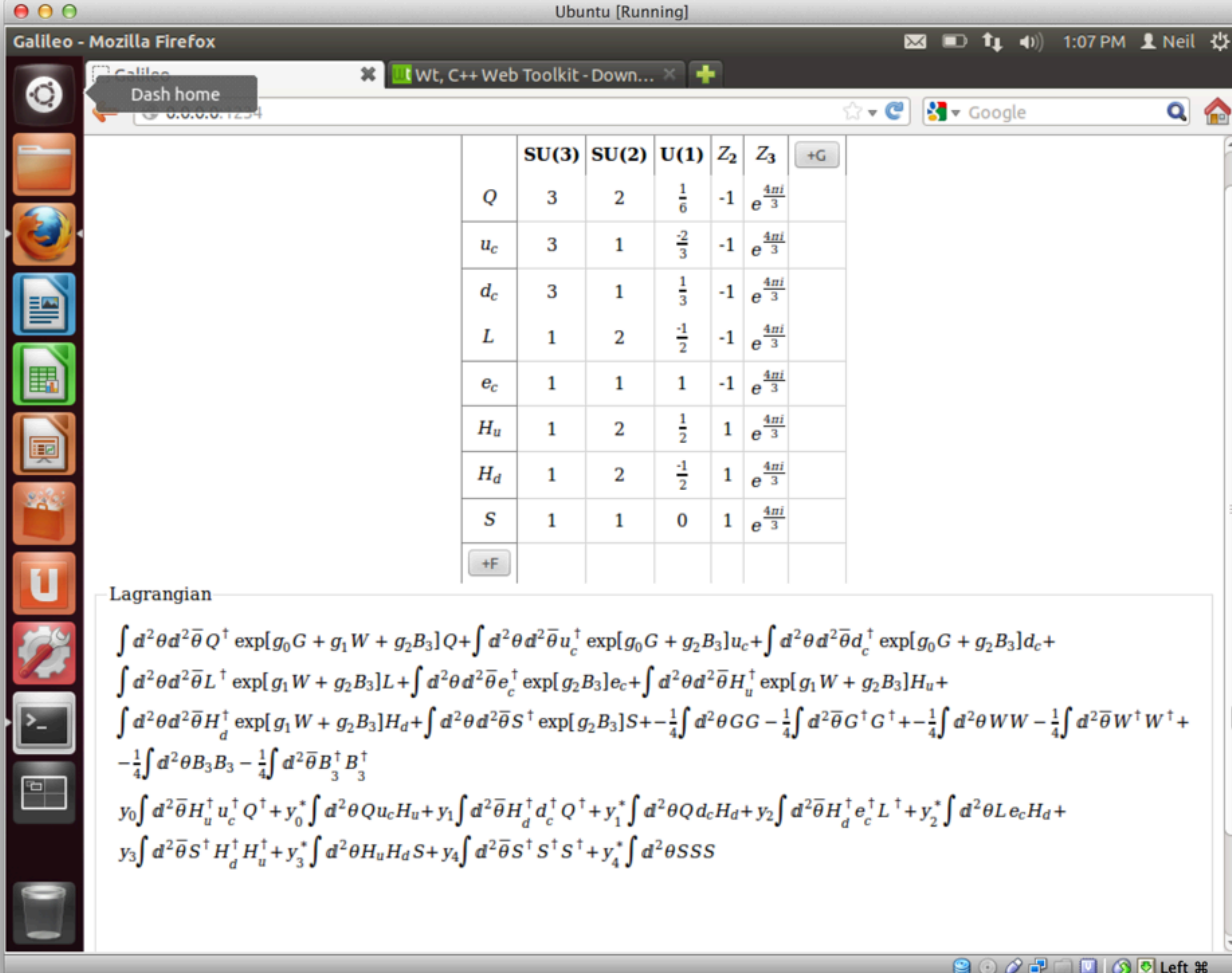
$$-\tfrac{1}{4}\int d^2\theta BB - \tfrac{1}{4}\int d^2\bar\theta B^\dagger B^\dagger$$

$$\mu_0\int d^2\bar\theta H_d^\dagger H_u^\dagger +$$

$$\mu_0^*\int d^2\theta H_u H_d$$

$$y_1\int d^2\bar\theta H_u^\dagger u_c^\dagger Q^\dagger + y_1^*\int d^2\theta Q u_c H_u + y_2\int d^2\bar\theta H_d^\dagger d_c^\dagger Q^\dagger + y_2^*\int d^2\theta Q d_c H_d + y_3\int d^2\bar\theta H_d^\dagger e_c^\dagger L^\dagger +$$

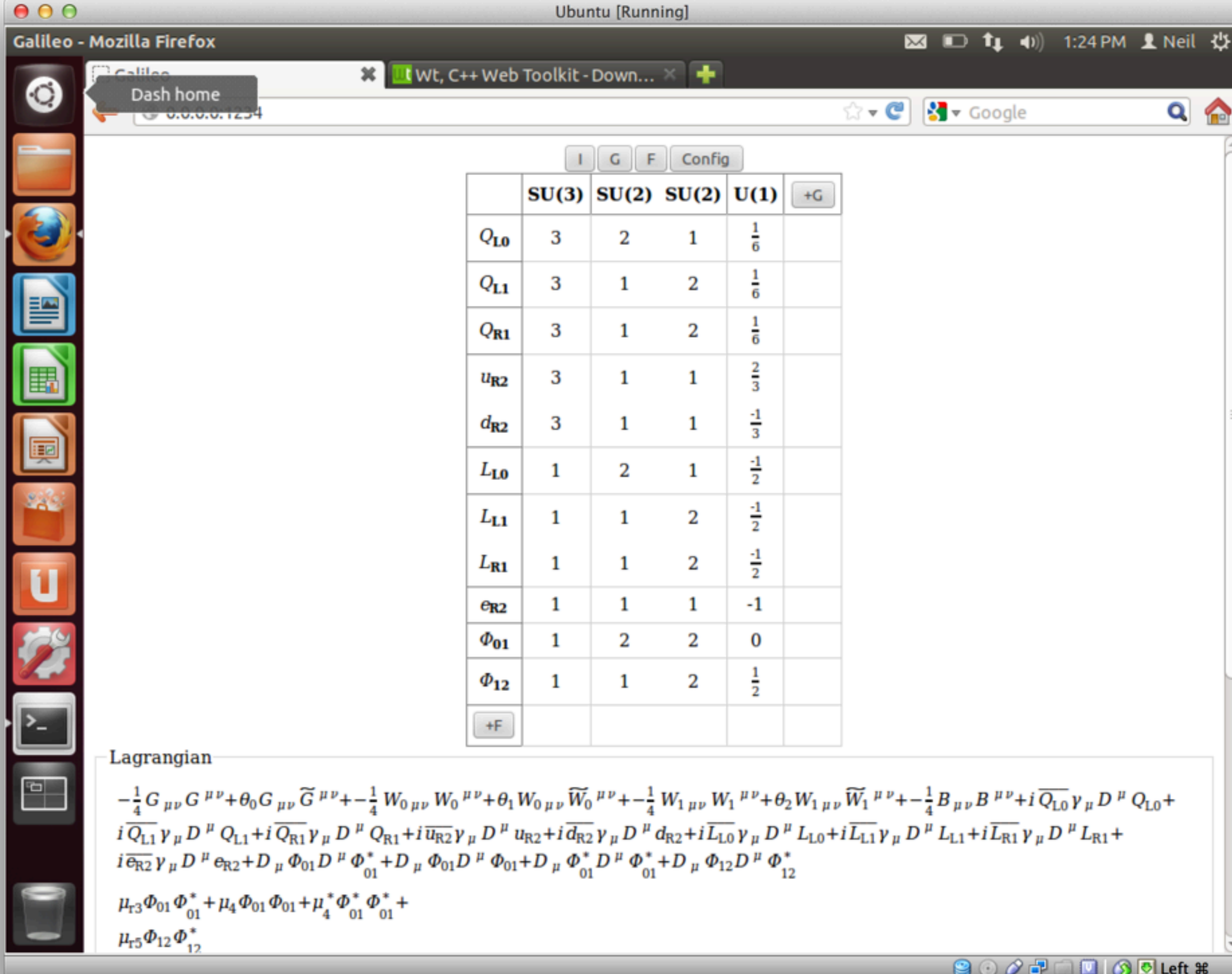
$$y_3^*\int d^2\theta L e_c H_d$$

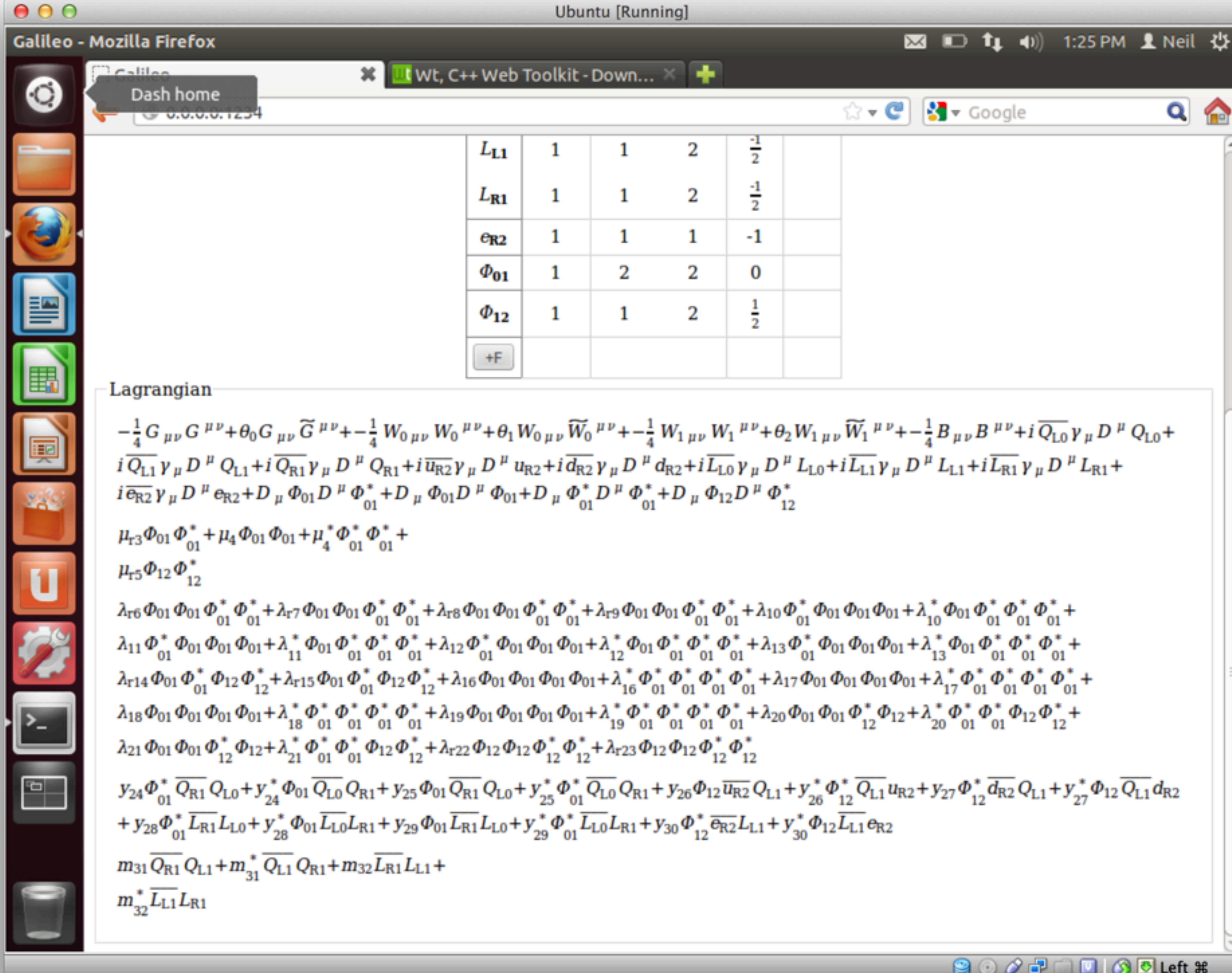


	SU(3)	SU(2)	U(1)	Z_2	Z_3
Q	3	2	$\frac{1}{6}$	-1	$e^{\frac{4\pi i}{3}}$
u_c	3	1	$\frac{-2}{3}$	-1	$e^{\frac{4\pi i}{3}}$
d_c	3	1	$\frac{1}{3}$	-1	$e^{\frac{4\pi i}{3}}$
L	1	2	$\frac{-1}{2}$	-1	$e^{\frac{4\pi i}{3}}$
e_c	1	1	1	-1	$e^{\frac{4\pi i}{3}}$
H_u	1	2	$\frac{1}{2}$	1	$e^{\frac{4\pi i}{3}}$
H_d	1	2	$\frac{-1}{2}$	1	$e^{\frac{4\pi i}{3}}$
S	1	1	0	1	$e^{\frac{4\pi i}{3}}$

Lagrangian

$$\int d^2\theta d^2\bar\theta\, Q^\dagger \exp[g_0 G + g_1 W + g_2 B_3] Q + \int d^2\theta d^2\bar\theta\, u_c^\dagger \exp[g_0 G + g_2 B_3] u_c + \int d^2\theta d^2\bar\theta\, d_c^\dagger \exp[g_0 G + g_2 B_3] d_c +$$
$$\int d^2\theta d^2\bar\theta\, L^\dagger \exp[g_1 W + g_2 B_3] L + \int d^2\theta d^2\bar\theta\, e_c^\dagger \exp[g_2 B_3] e_c + \int d^2\theta d^2\bar\theta\, H_u^\dagger \exp[g_1 W + g_2 B_3] H_u +$$
$$\int d^2\theta d^2\bar\theta\, H_d^\dagger \exp[g_1 W + g_2 B_3] H_d + \int d^2\theta d^2\bar\theta\, S^\dagger \exp[g_2 B_3] S + -\tfrac{1}{4}\int d^2\theta\, GG - \tfrac{1}{4}\int d^2\bar\theta\, G^\dagger G^\dagger + -\tfrac{1}{4}\int d^2\theta\, WW - \tfrac{1}{4}\int d^2\bar\theta\, W^\dagger W^\dagger +$$
$$-\tfrac{1}{4}\int d^2\theta\, B_3 B_3 - \tfrac{1}{4}\int d^2\bar\theta\, B_3^\dagger B_3^\dagger$$
$$y_0\int d^2\bar\theta\, H_u^\dagger u_c^\dagger Q^\dagger + y_0^*\int d^2\theta\, Q u_c H_u + y_1\int d^2\bar\theta\, H_d^\dagger d_c^\dagger Q^\dagger + y_1^*\int d^2\theta\, Q d_c H_d + y_2\int d^2\bar\theta\, H_d^\dagger e_c^\dagger L^\dagger + y_2^*\int d^2\theta\, L e_c H_d +$$
$$y_3\int d^2\bar\theta\, S^\dagger H_d^\dagger H_u^\dagger + y_3^*\int d^2\theta\, H_u H_d S + y_4\int d^2\bar\theta\, S^\dagger S^\dagger S^\dagger + y_4^*\int d^2\theta\, SSS$$


Ubuntu [Running]
Galileo - Mozilla Firefox
1:24 PM
Neil
Galileo
Wt, C++ Web Toolkit - Down...
Dash home
0.0.0.0:1234
Google
I
G
F
Config
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
Φ_{01} 1 2 2 0
Φ_{12} 1 1 2 $\frac{1}{2}$
+F
Lagrangian
$-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\theta_0 G_{\mu\nu}\widetilde{G}^{\mu\nu}+-\frac{1}{4}W_{0\,\mu\nu}W_0^{\mu\nu}+\theta_1 W_{0\,\mu\nu}\widetilde{W_0}^{\mu\nu}+-\frac{1}{4}W_{1\,\mu\nu}W_1^{\mu\nu}+\theta_2 W_{1\,\mu\nu}\widetilde{W_1}^{\mu\nu}+-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}+i\overline{Q_{L0}}\gamma_\mu D^\mu Q_{L0}+$
$i\overline{Q_{L1}}\gamma_\mu D^\mu Q_{L1}+i\overline{Q_{R1}}\gamma_\mu D^\mu Q_{R1}+i\overline{u_{R2}}\gamma_\mu D^\mu u_{R2}+i\overline{d_{R2}}\gamma_\mu D^\mu d_{R2}+i\overline{L_{L0}}\gamma_\mu D^\mu L_{L0}+i\overline{L_{L1}}\gamma_\mu D^\mu L_{L1}+i\overline{L_{R1}}\gamma_\mu D^\mu L_{R1}+$
$i\overline{e_{R2}}\gamma_\mu D^\mu e_{R2}+D_\mu\Phi_{01}D^\mu\Phi^*_{01}+D_\mu\Phi_{01}D^\mu\Phi_{01}+D_\mu\Phi^*_{01}D^\mu\Phi^*_{01}+D_\mu\Phi_{12}D^\mu\Phi^*_{12}$
$\mu_{r3}\Phi_{01}\Phi^*_{01}+\mu_4\Phi_{01}\Phi_{01}+\mu^*_4\Phi^*_{01}\Phi^*_{01}+$
$\mu_{r5}\Phi_{12}\Phi^*_{12}$
Left ⌘



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

Lagrangian

$$-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\theta_0 G_{\mu\nu}\widetilde{G}^{\mu\nu}+-\frac{1}{4}W_{0\,\mu\nu}W_0^{\mu\nu}+\theta_1 W_{0\,\mu\nu}\widetilde{W_0}^{\mu\nu}+-\frac{1}{4}W_{1\,\mu\nu}W_1^{\mu\nu}+\theta_2 W_{1\,\mu\nu}\widetilde{W_1}^{\mu\nu}+-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}+i\overline{Q_{L0}}\gamma_\mu D^\mu Q_{L0}+$$
$$i\overline{Q_{L1}}\gamma_\mu D^\mu Q_{L1}+i\overline{Q_{R1}}\gamma_\mu D^\mu Q_{R1}+i\overline{u_{R2}}\gamma_\mu D^\mu u_{R2}+i\overline{d_{R2}}\gamma_\mu D^\mu d_{R2}+i\overline{L_{L0}}\gamma_\mu D^\mu L_{L0}+i\overline{L_{L1}}\gamma_\mu D^\mu L_{L1}+i\overline{L_{R1}}\gamma_\mu D^\mu L_{R1}+$$
$$i\overline{e_{R2}}\gamma_\mu D^\mu e_{R2}+D_\mu\Phi_{01}D^\mu\Phi^*_{01}+D_\mu\Phi_{01}D^\mu\Phi_{01}+D_\mu\Phi^*_{01}D^\mu\Phi^*_{01}+D_\mu\Phi_{12}D^\mu\Phi^*_{12}$$

$$\mu_{r3}\Phi_{01}\Phi^*_{01}+\mu_4\Phi_{01}\Phi_{01}+\mu^*_4\Phi^*_{01}\Phi^*_{01}+$$
$$\mu_{r5}\Phi_{12}\Phi^*_{12}$$

$$\lambda_{r6}\Phi_{01}\Phi_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{r7}\Phi_{01}\Phi_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{r8}\Phi_{01}\Phi_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{r9}\Phi_{01}\Phi_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{10}\Phi^*_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{10}\Phi_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+$$
$$\lambda_{11}\Phi^*_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{11}\Phi_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{12}\Phi^*_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{12}\Phi_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{13}\Phi^*_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{13}\Phi_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+$$
$$\lambda_{r14}\Phi_{01}\Phi^*_{01}\Phi_{12}\Phi^*_{12}+\lambda_{r15}\Phi_{01}\Phi^*_{01}\Phi_{12}\Phi^*_{12}+\lambda_{16}\Phi_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{16}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{17}\Phi_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{17}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+$$
$$\lambda_{18}\Phi_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{18}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{19}\Phi_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{19}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{20}\Phi_{01}\Phi_{01}\Phi^*_{12}\Phi_{12}+\lambda^*_{20}\Phi^*_{01}\Phi^*_{01}\Phi_{12}\Phi^*_{12}+$$
$$\lambda_{21}\Phi_{01}\Phi_{01}\Phi^*_{12}\Phi_{12}+\lambda^*_{21}\Phi^*_{01}\Phi^*_{01}\Phi_{12}\Phi^*_{12}+\lambda_{r22}\Phi_{12}\Phi_{12}\Phi^*_{12}\Phi^*_{12}+\lambda_{r23}\Phi_{12}\Phi_{12}\Phi^*_{12}\Phi^*_{12}$$

$$y_{24}\Phi^*_{01}\overline{Q_{R1}}Q_{L0}+y^*_{24}\Phi_{01}\overline{Q_{L0}}Q_{R1}+y_{25}\Phi_{01}\overline{Q_{R1}}Q_{L0}+y^*_{25}\Phi^*_{01}\overline{Q_{L0}}Q_{R1}+y_{26}\Phi_{12}\overline{u_{R2}}Q_{L1}+y^*_{26}\Phi^*_{12}\overline{Q_{L1}}u_{R2}+y_{27}\Phi^*_{12}\overline{d_{R2}}Q_{L1}+y^*_{27}\Phi_{12}\overline{Q_{L1}}d_{R2}$$
$$+y_{28}\Phi^*_{01}\overline{L_{R1}}L_{L0}+y^*_{28}\Phi_{01}\overline{L_{L0}}L_{R1}+y_{29}\Phi_{01}\overline{L_{R1}}L_{L0}+y^*_{29}\Phi^*_{01}\overline{L_{L0}}L_{R1}+y_{30}\Phi^*_{12}\overline{e_{R2}}L_{L1}+y^*_{30}\Phi_{12}\overline{L_{L1}}e_{R2}$$

$$m_{31}\overline{Q_{R1}}Q_{L1}+m^*_{31}\overline{Q_{L1}}Q_{R1}+m_{32}\overline{L_{R1}}L_{L1}+$$
$$m^*_{32}\overline{L_{L1}}L_{R1}$$

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.
- Expand Lagrangian.
- Symmetry breaking.
- Mass matrix diagonalization and rotation to physical basis.
- Save/read.
- Export to FeynRules (for further analysis).

1997: Deep blue beats the current world champion, Garry Kasparov at chess!

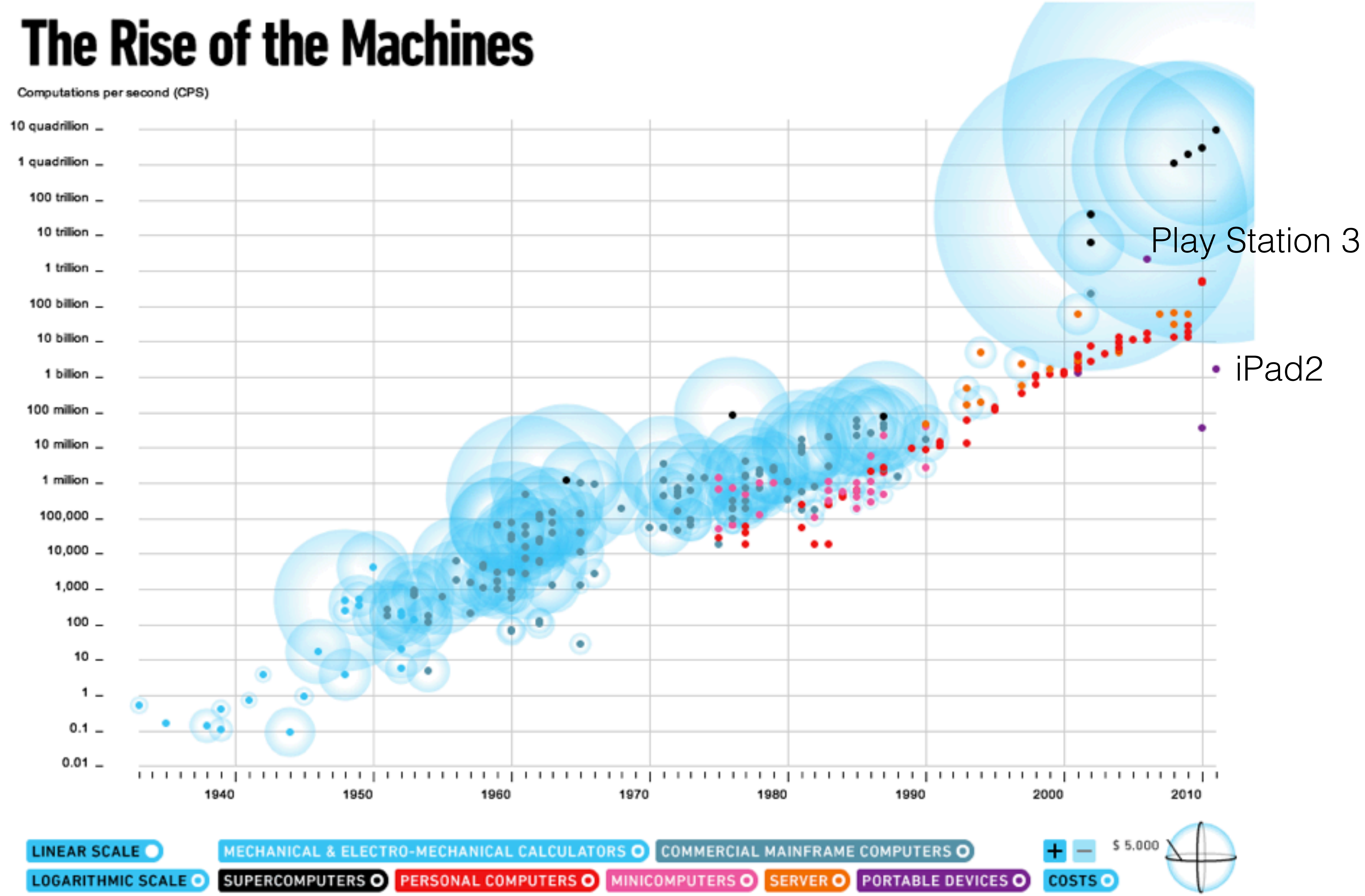
In 2011, Watson beat the world champions at Jeopardy!

In 2025, ...

Charles Xavier Thomas de Colmar invented the first commercially successful mechanical calculator in 1820. It was 100 years before mechanical calculators gave way, in the 1930s, to electromechanical calculators, which then quickly gave way to the first general-purpose electronic computer, ENIAC, in 1946. By 1965, Gordon Moore was predicting that engineers would be able to double the number of components on a microchip every two years (and by 1968, he co-founded Intel to help them do so).

Just as Moore predicted, computers continue to become exponentially faster, while their components have become much cheaper. William Nordhaus, an economist at Yale University, examined hundreds of devices—from the first computer to the Apple II to modern PCs—and determined how many basic calculations they could perform every second.

The Rise of the Machines



Let’s be part of the next revolution in science.

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.