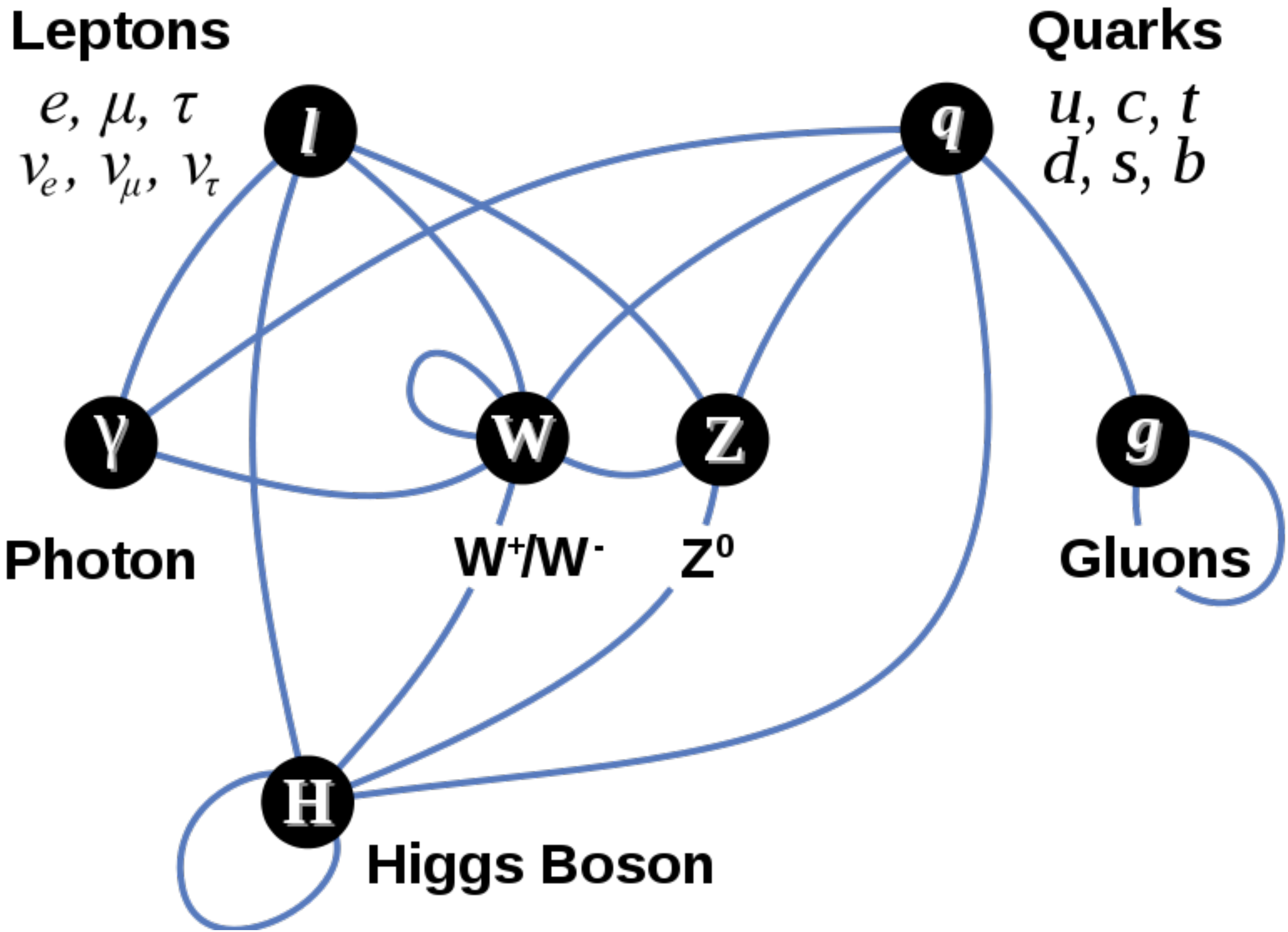
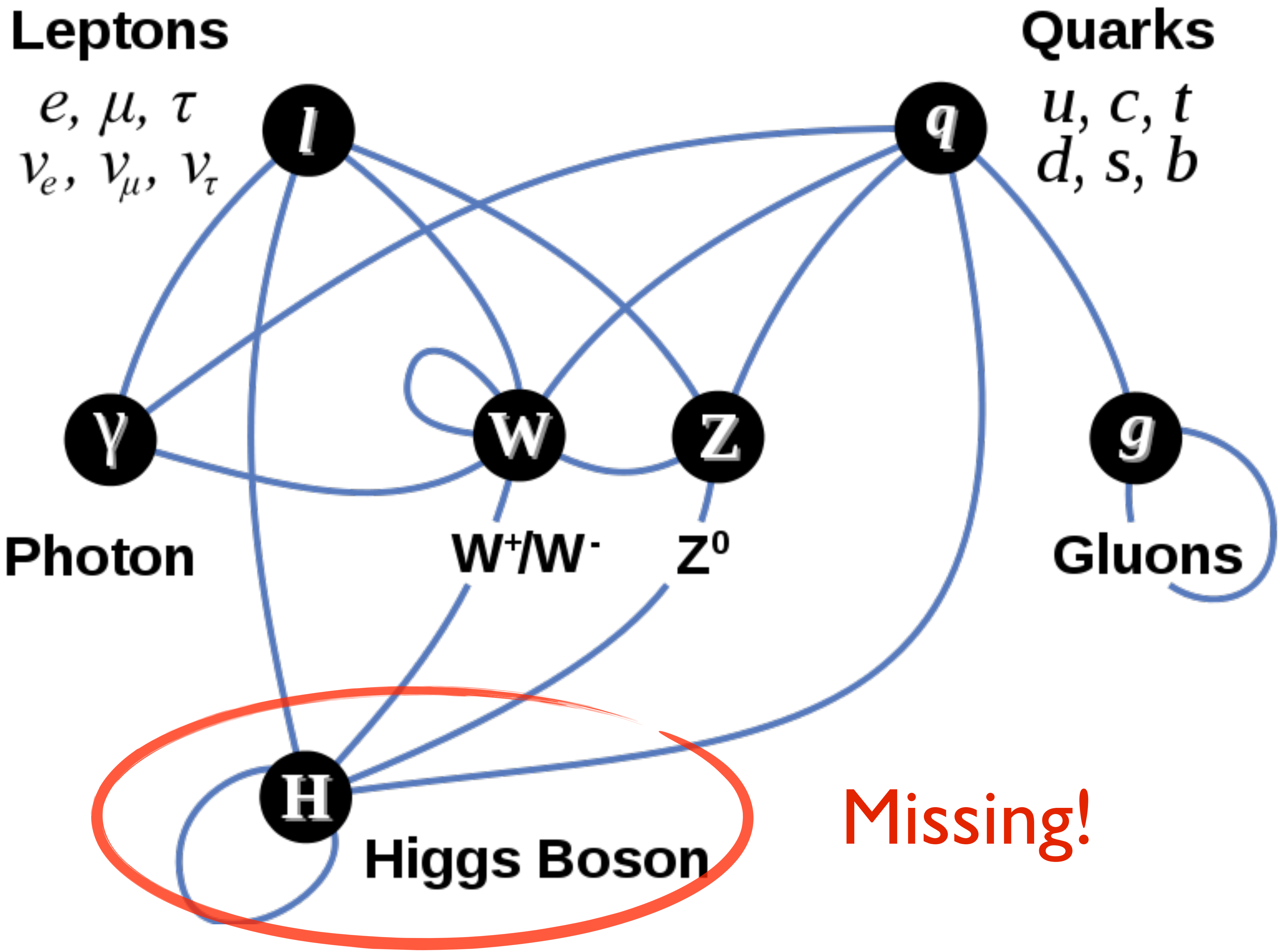
Model Building
in the
LHC Era

Neil Christensen
University of Wisconsin - Madison
Supported by NSF grant PHY-0705682


Leptons
e, μ, τ
νe, νμ, ντ
l
Quarks
u, c, t
d, s, b
q
γ
W
Z
g
Photon
W+/W-
Z0
Gluons
H
Higgs Boson


Leptons
e, μ, τ
ν_e, ν_μ, ν_τ
Quarks
u, c, t
d, s, b
l
q
γ
W
Z
g
Photon
W+/W-
Z0
Gluons
H
Higgs Boson
Missing!

SM

???

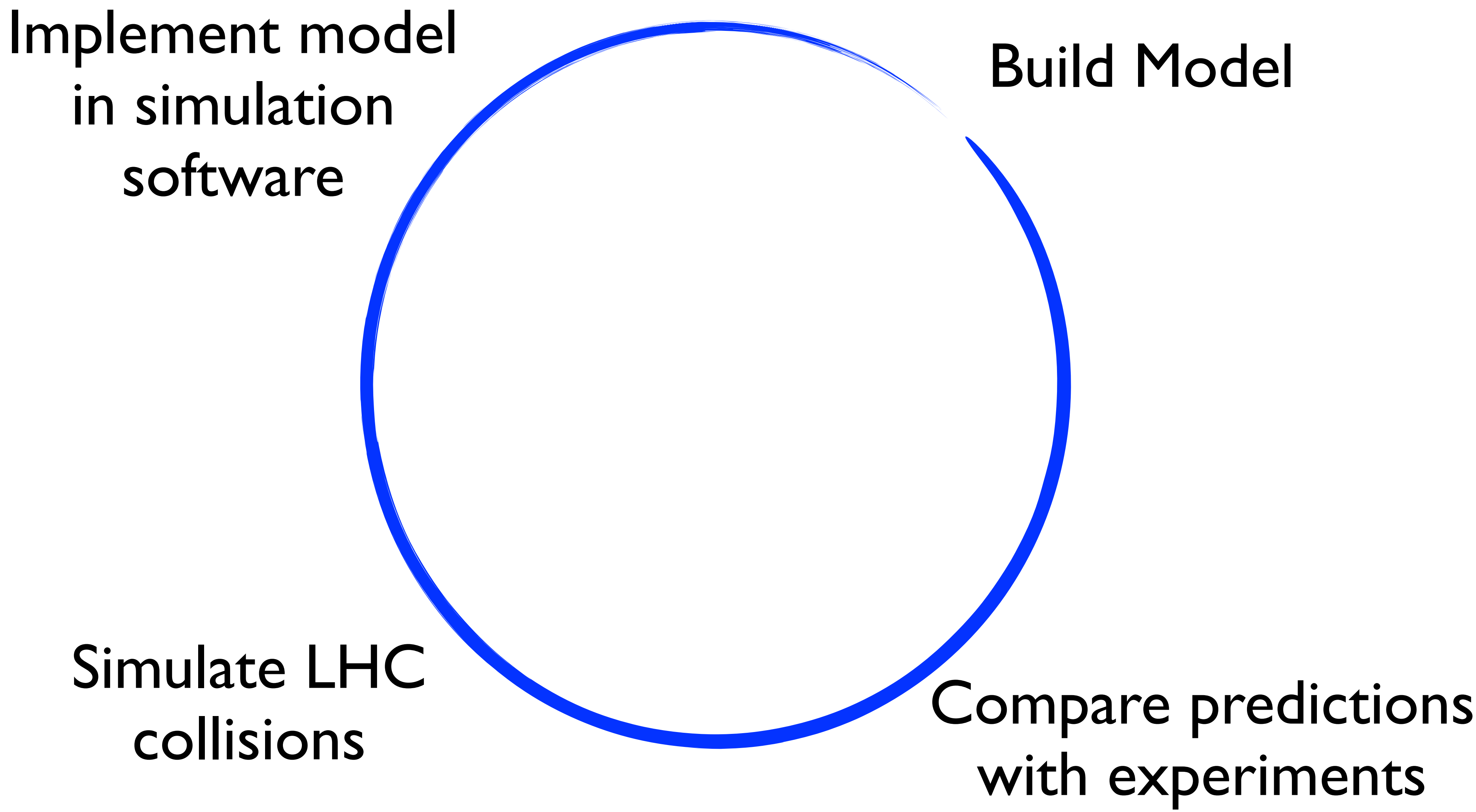
Supersymmetry

Extra
Dimensions

Little Higgs

Higgsless

New Strong
Dynamics


Implement model in simulation software
Build Model
Simulate LHC collisions
Compare predictions with experiments

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

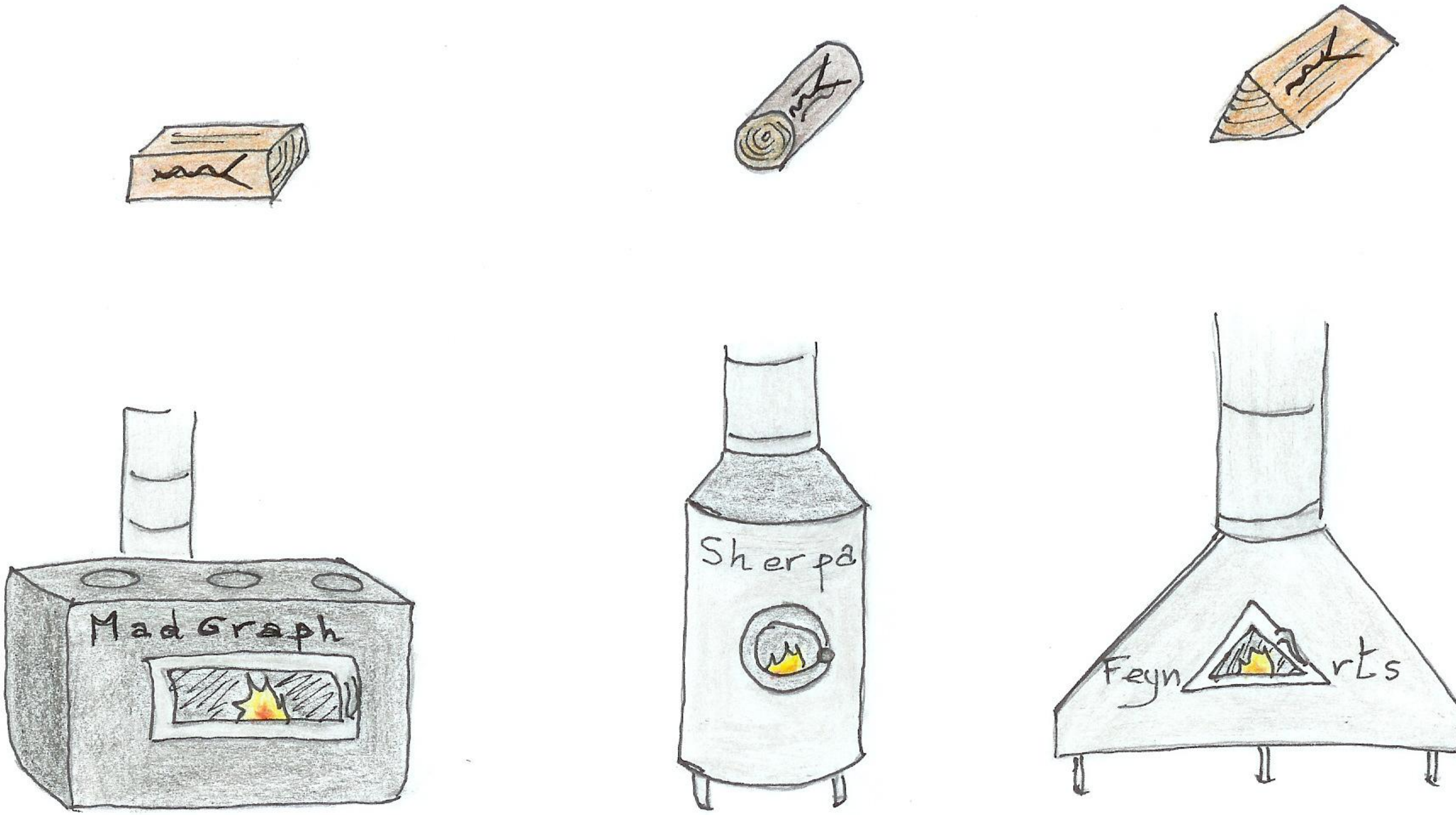
```
c-------------------------------------------
c     V-light   F-heavy    F-heavy
c-------------------------------------------
      GZDpL =
     - -1d0/2d0*gf(-ee,WMASS,ZMASS,MWP)
     -  *vZ0f(WMASS,ZMASS,MWP)*vLP0f(WMASS,MWP)**2
     - -1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)
     -  *VZ1f(WMASS,ZMASS,MWP)*vLP1f(WMASS,MWP)**2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

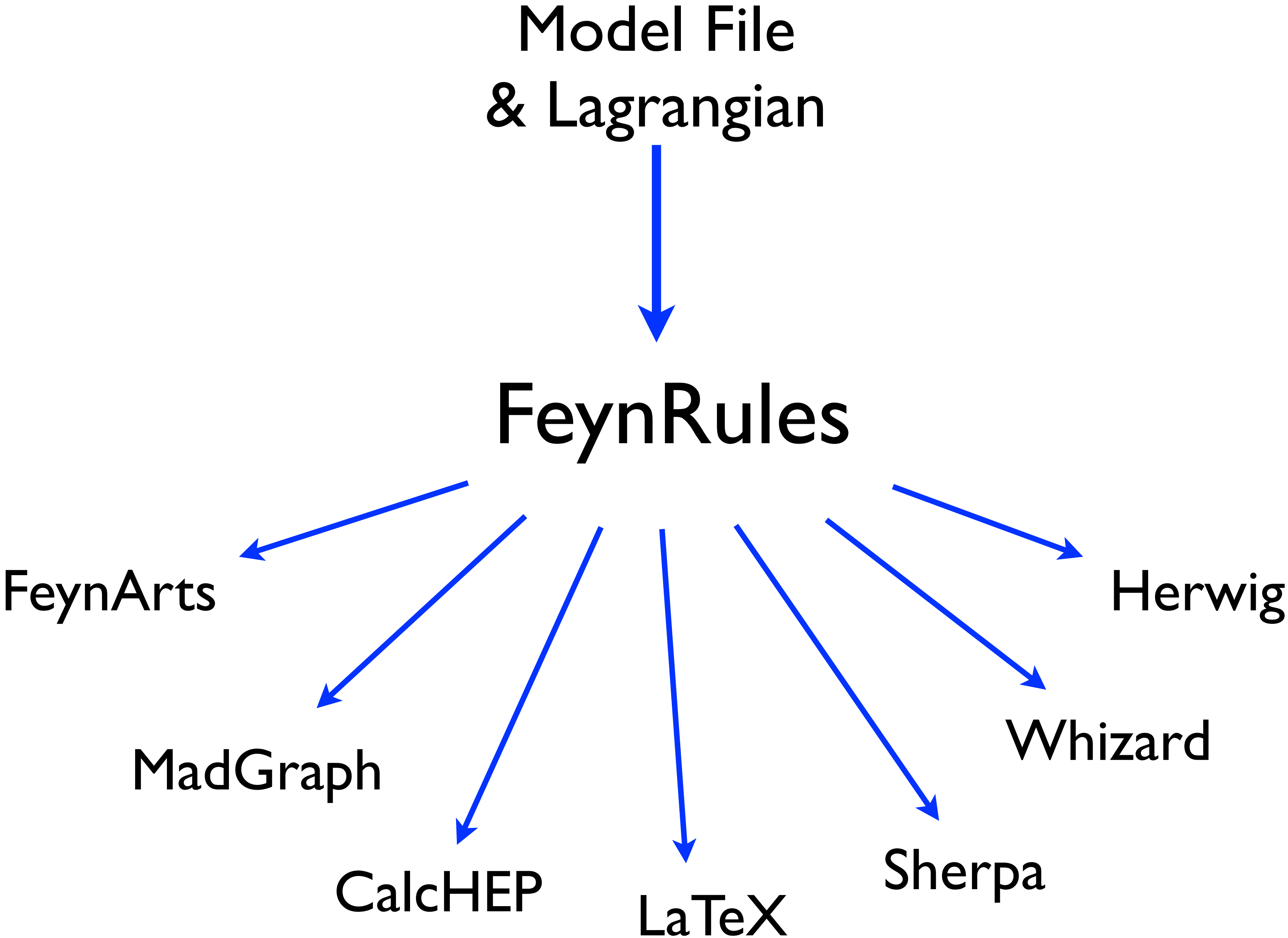
Implementations often did not transfer well to experimentalists.

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

FeynRules

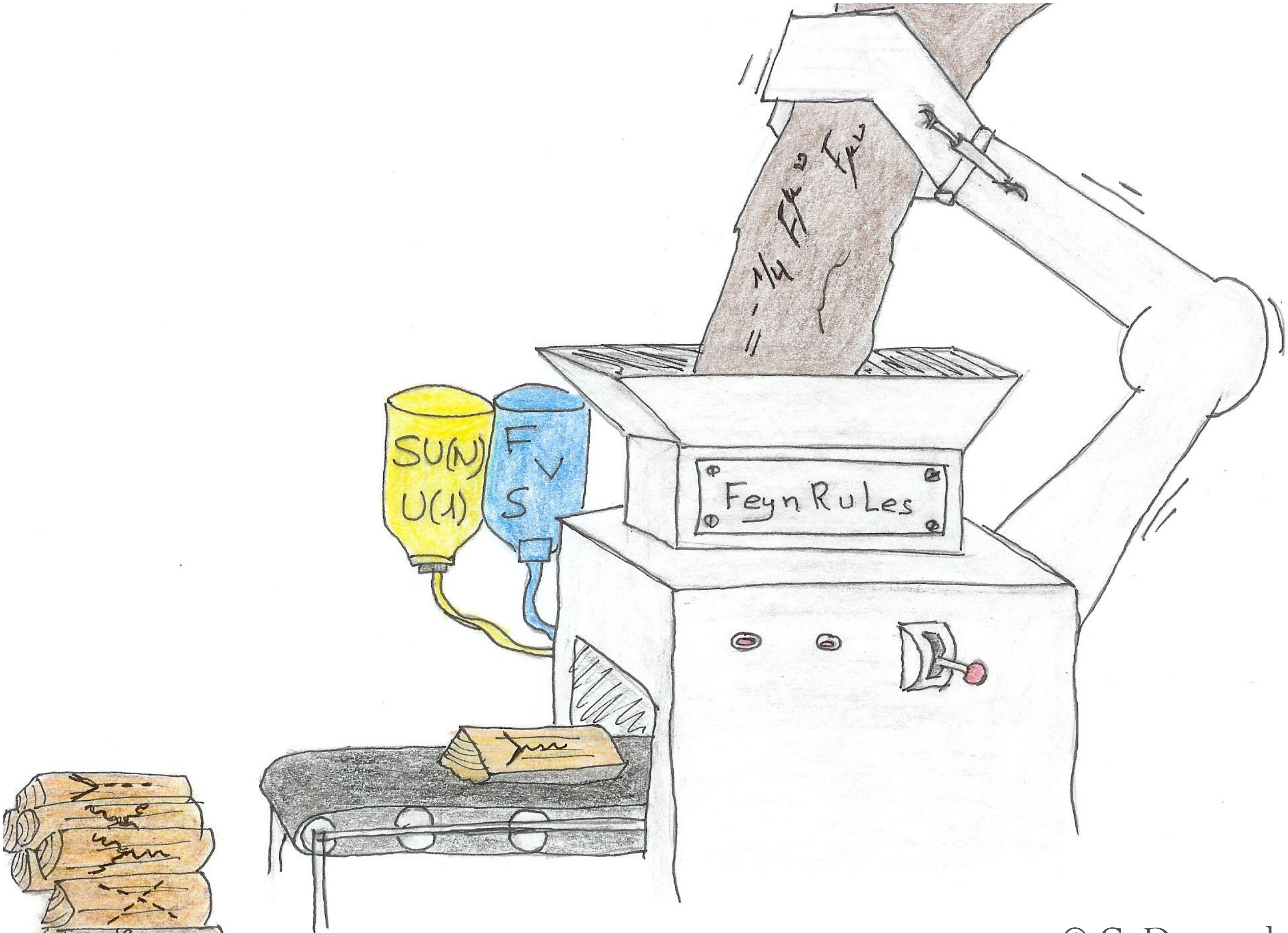
In collaboration with:

Claude Duhr, Benjamin Fuks,
P. de Aquino, C. Degrande, D. Grellscheid, W. Link,
F. Maltoni, O. Mattelaer, T. Reiter, C. Speckner,
S. Schumann, M. Wiebusch


Model File
& Lagrangian
FeynRules
FeynArts
MadGraph
CalcHEP
LaTeX
Sherpa
Whizard
Herwig

```
F[1]  ==
   {ClassName      ->   q,
    SelfConjugate ->  False,
    Indices             ->  {Index[Colour]},
    Mass                ->  {MQ,  200},
    Width               ->  {WQ, 5}   }
```

```
L =
-1/4 FS[G,mu,nu,a] FS[G,mu,nu,a]
+ I qbar.Ga[mu].del[q,mu]
+ gs qbar.Ga[mu].T[a].q G[mu,a]
- MQ qbar.q
```


SU(N)
U(1)
F
V
S
FeynRules


Celine Sasha Priscila Martin Benj Christian Claude Will Olivier David Neil Thomas

Superfields (B. Fuks)

- In the future, FeynRules will allow the use of superfields.

- Example: Superpotential for left-handed quarks

$$\mathcal{W} = a_i Q_{Li} + M_{ij} Q_{Li} Q_{Lj} + \frac{1}{6}\lambda_{ijk} Q_{Li} Q_{Lj} Q_{Lk}$$

```
W = a[i] QL[i] + 1/2*M[i, j] QL[i] QL[j] + 1/6*l[i, j, k] QL[i] QL[j] QL[k]
```

- FeynRules then converts the superfields into component fields:

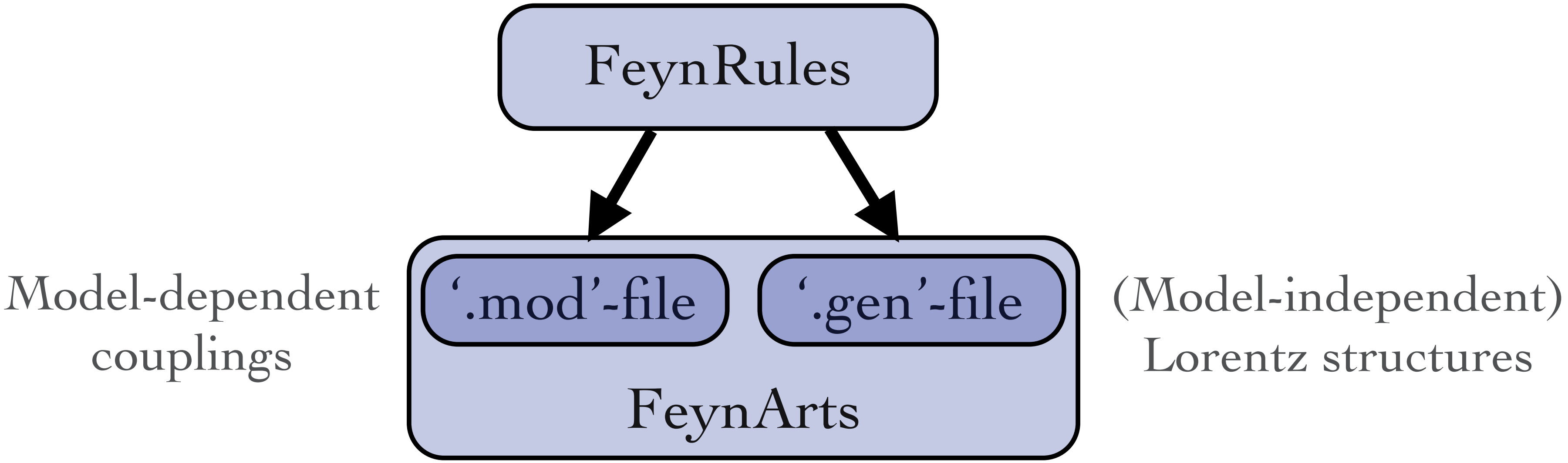
```
SF2Components[ W ]
```

$$-\frac{1}{6}\,\text{FTerm3}_i\,\text{sqL}_j\,\text{sqL}_k\,l_{i,j,k} - \frac{1}{6}\,\text{FTerm3}_k\,\text{sqL}_i\,\text{sqL}_j\,l_{i,j,k} - \frac{1}{6}\,\text{FTerm3}_j\,\text{sqL}_i\,\text{sqL}_k\,l_{i,j,k}$$

$$;\; -\frac{1}{6}\,\text{sqL}_j\,l_{i,j,k}\,\text{qL}_{\text{sp\$2},i}.\text{qL}_{\text{sp\$2},k} - \frac{1}{6}\,\text{sqL}_i\,l_{i,j,k}\,\text{qL}_{\text{sp\$2},j}.\text{qL}_{\text{sp\$2},k} - \frac{1}{2}\,M_{i,j}\,\text{qL}_{\text{sp\$2},i}.\text{qL}_{\text{sp\$2},j}$$

FeynArts interface (C. Degrande, CD)

- A new interface to FeynArts is being developped that allows to implement arbitrary Lorentz structures.



- This development goes along with a new version of FormCalc able to deal with multi-fermion interactions.

Mass Matrix diagonalization (N. Christensen, M. Wiebusch)

- In the future, FeynRules will be able to perform the diagonalization automatically.

Input 1: Lagrangian

```
qLbar[s1,l1,f1,i].uR[s1,f2,i] Yu[f1,f2] Eps[l1,l2] Phibar[l2]
```

Input 2: Mixing relations

```
uq[s, #, o] == CKMU.uqp[s, #, o]
```

Output 1: Mass matrix to be diagonalized

$$\text{Diagonalization}(\text{HEigensystem},\ \text{CKMU},\ \{m_u,\ m_c,\ m_t\}) \to \begin{pmatrix} -\frac{v\,\text{Yu}_{1,1}}{2\sqrt{2}} & -\frac{v\,\text{Yu}_{1,2}}{2\sqrt{2}} & -\frac{v\,\text{Yu}_{1,3}}{2\sqrt{2}} \\ -\frac{v\,\text{Yu}_{2,1}}{2\sqrt{2}} & -\frac{v\,\text{Yu}_{2,2}}{2\sqrt{2}} & -\frac{v\,\text{Yu}_{2,3}}{2\sqrt{2}} \\ -\frac{v\,\text{Yu}_{3,1}}{2\sqrt{2}} & -\frac{v\,\text{Yu}_{3,2}}{2\sqrt{2}} & -\frac{v\,\text{Yu}_{3,3}}{2\sqrt{2}} \end{pmatrix}$$

Output 2: 'Rotation rules'

$$(P_+)_{s1,s}\left(\text{CKMU}(1,\ 1)^*\,\text{uq}_{s,1,o} + \text{CKMU}(2,\ 1)^*\,\text{uq}_{s,2,o} + \text{CKMU}(3,\ 1)^*\,\text{uq}_{s,3,o}\right)$$

- To be done: numerical code for the diagonlization.

The UFO

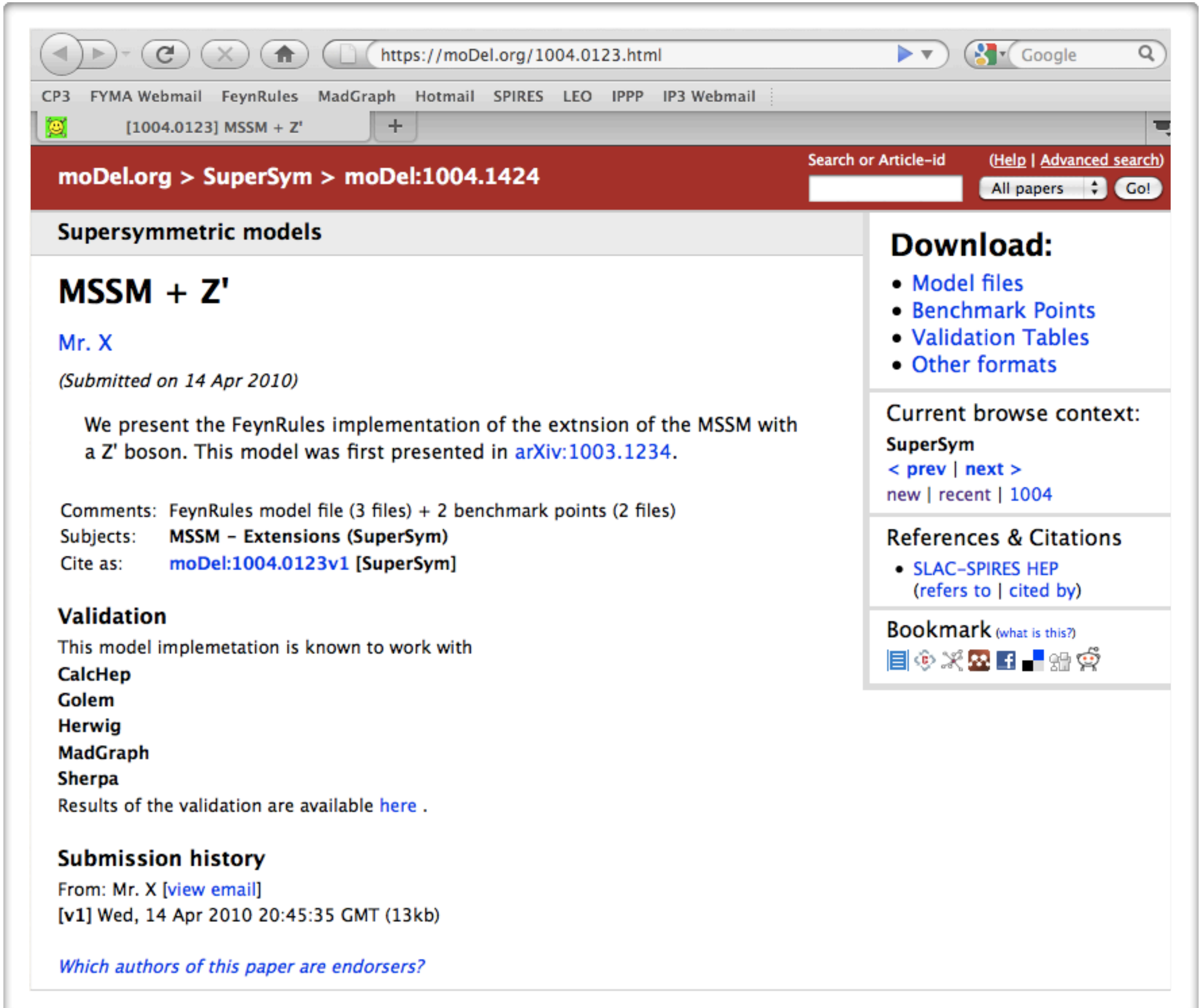
(P. de Aquino, CD, D. Grellscheid, W. Link, O. Mattelaer, T. Reiter)

UFO = Universal FeynRules Output

- Idea: Create Python modules that can be linked to other codes and contain all the information on a given model.
- The UFO is a self-contained Python code, and not tied to a specific matrix element generator.
- Golem, MadGraph 5 and Herwig++ will use the UFO.
- The development of the UFO goes hand in hand with the development of ALOHA (Automatic Language-independent Output of Helicity Amplitudes), a code that allows to create HELAS routines from the UFO.

Whizard Interface

- Started @ Michigan State University almost 2 years ago.
- In the final weeks of validation.
- Published in the coming weeks.



https://moDel.org/1004.0123.html

CP3 FYMA Webmail FeynRules MadGraph Hotmail SPIRES LEO IPPP IP3 Webmail

[1004.0123] MSSM + Z'

moDel.org > SuperSym > moDel:1004.1424

Search or Article-id (Help | Advanced search) All papers Go!

Supersymmetric models

MSSM + Z'

Mr. X

(Submitted on 14 Apr 2010)

We present the FeynRules implementation of the extnsion of the MSSM with a Z' boson. This model was first presented in arXiv:1003.1234.

Comments:	FeynRules model file (3 files) + 2 benchmark points (2 files)
Subjects:	**MSSM - Extensions (SuperSym)**
Cite as:	**moDel:1004.0123v1 [SuperSym]**

Validation

This model implemetation is known to work with

CalcHep
Golem
Herwig
MadGraph
Sherpa

Results of the validation are available here .

Submission history

From: Mr. X [view email]
[v1] Wed, 14 Apr 2010 20:45:35 GMT (13kb)

Which authors of this paper are endorsers?

Download:

- Model files
- Benchmark Points
- Validation Tables
- Other formats

Current browse context:
SuperSym
< prev | next >
new | recent | 1004

References & Citations
- SLAC-SPIRES HEP
(refers to | cited by)

Bookmark (what is this?)

Validation

- Very important:
  - We don’t want to release crap!
  - We don’t want you to use FeynRules to create crap!

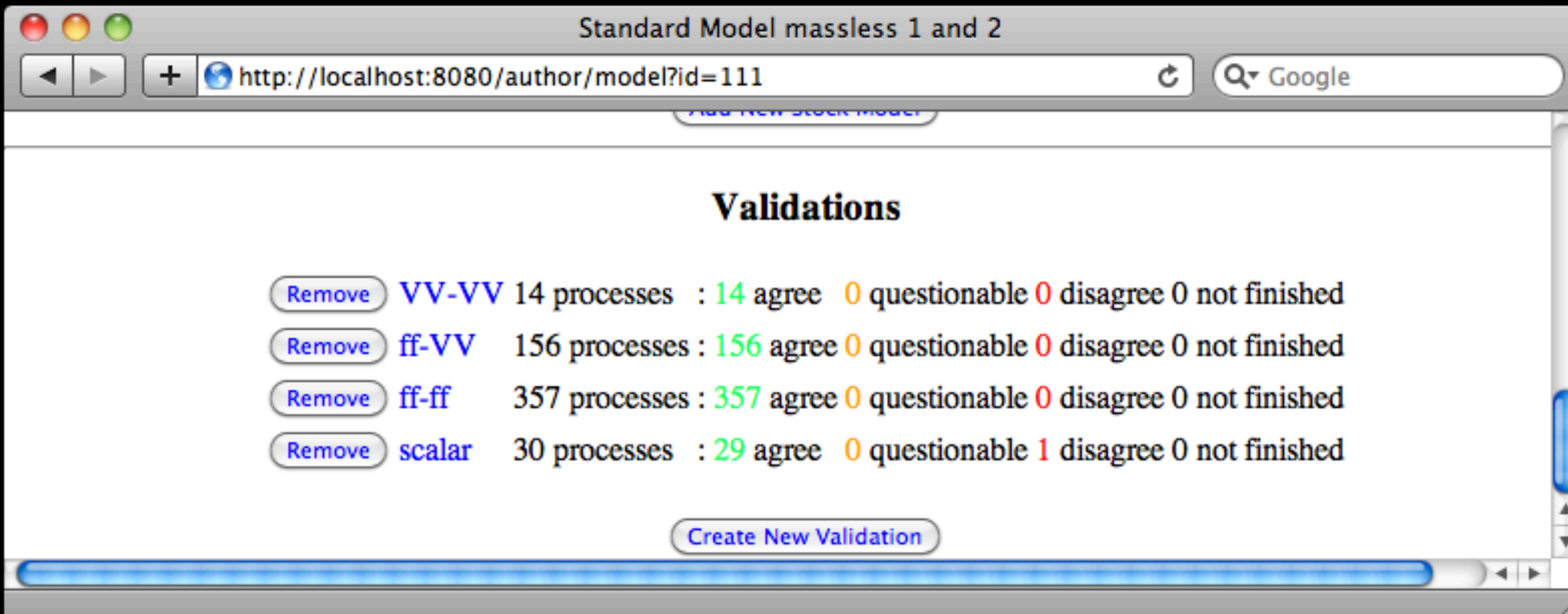
Neil Christensen's Models

http://localhost:8080/author

Neil Christensen's Models

Remove	Triangle 3-Site Model 1and2massless
Remove	Standard Model massless 1 and 2
Remove	MSSM
Remove	Triangle 3-Site Model
Remove	Standard Model
Remove	3-Site Model
Remove	MSSM

New Model


Standard Model massless 1 and 2
http://localhost:8080/author/model?id=111
Google
Validations
Remove VV-VV 14 processes : 14 agree 0 questionable 0 disagree 0 not finished
Remove ff-VV 156 processes : 156 agree 0 questionable 0 disagree 0 not finished
Remove ff-ff 357 processes : 357 agree 0 questionable 0 disagree 0 not finished
Remove scalar 30 processes : 29 agree 0 questionable 1 disagree 0 not finished
Create New Validation

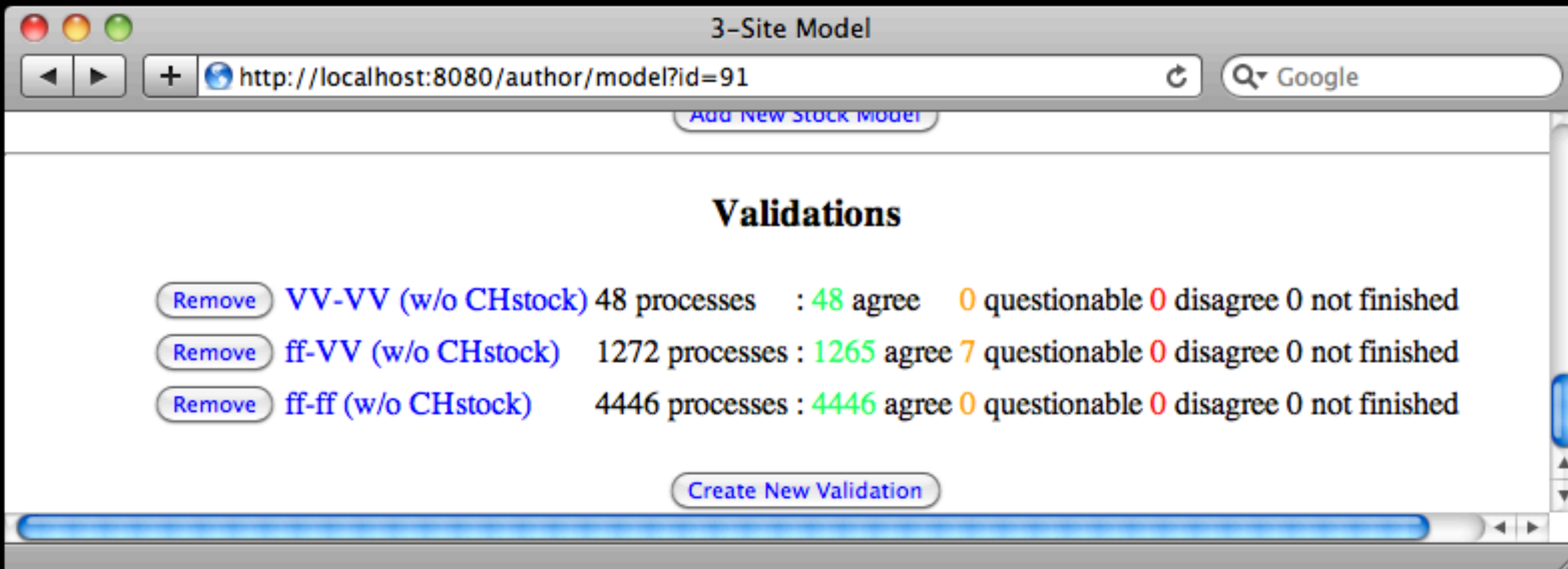
Standard Model massless 1 and 2 : ff-VV

http://localhost:8080/author/validation?vdtnId=154

Start Fresh Validations | Finish Validations

156 processes : 156 agree, 0 questionable, 0 disagree, 0 not finished

	$\sqrt{s}$	$p_{T_{cut}}$	CH(F)	CH(u)	MG4	WO1(F)	WO1(u)	WO2(F)	WO2(u)	MG-ST	CH-ST	WO-ST	Δ
t , b~ → Z , W+	1400.0	350.0	0.52615	0.52615	0.52747	0.52614	0.526104	0.5262	0.526112	0.52583	0.52613	0.526214	✔ 0.23%
d , d~ → W+ , W-	639.0	159.75	0.35866	0.35866	0.35844	0.358627	0.358613	0.358468	0.35863	0.35932	0.35865	0.358663	✔ 0.18%
tt- , tt+ → A , Z	379.0	94.75	1.3573	1.3573	1.3598	1.35717	1.3573	1.35741	1.358	1.3598	1.3572	1.35665	✔ 0.15%
u , s~ → Z , W+	684.0	171.0	0.0078632	0.0078632	0.0078678	0.00786461	0.00786609	0.00787001	0.00785858	0.0078765	0.0078627	0.00786181	✔ 0.14%
e- , e+ → W+ , W-	639.0	159.75	1.1275	1.1275	1.1292	1.12741	1.12755	1.12765	1.1275	1.1277	1.1275	1.12767	✔ 0.13%
c , s~ → Z , W+	684.0	171.0	0.1464	0.1464	0.14628	0.146374	0.146386	0.146444	0.14638	0.14655	0.14639	0.146618	✔ 0.13%
s , s~ → W+ , W-	639.0	159.75	0.35866	0.35866	0.35861	0.358658	0.358725	0.358766	0.358649	0.35918	0.35865	0.358496	✔ 0.13%
b , b~ → A , Z	402.0	100.5	0.065387	0.065387	0.065497	0.0653894	0.0654034	0.0653999	0.0654101	0.065497	0.065386	0.0653905	✔ 0.13%
vm , m+ → A , W+	319.0	79.75	1.9846	1.9846	1.9873	1.98449	1.98433	1.9843	1.98408	1.9867	1.9845	1.98416	✔ 0.12%
e- , e+ → Z , Z	730.0	182.5	0.063394	0.063394	0.063299	0.0633947	0.0634041	0.0634076	0.0633695	0.063299	0.063392	0.0634134	✔ 0.12%
tt- , tt+ → A , A	200.0	50.0	6.6118	6.6118	6.6111	6.61314	6.61234	6.61191	6.61258	6.6211	6.6118	6.61178	✔ 0.12%
t , b~ → A , W+	1035.0	258.75	0.073074	0.073074	0.073166	0.0730591	0.0730594	0.0730742	0.0730884	0.07307	0.073073	0.0730527	✔ 0.12%
ve , e+ → A , W+	319.0	79.75	1.9846	1.9846	1.9873	1.98435	1.98485	1.98455	1.98484	1.9867	1.9845	1.98465	✔ 0.11%
vm , m+ → Z , W+	684.0	171.0	0.54663	0.54663	0.54724	0.546463	0.546679	0.546759	0.54654	0.54655	0.54661	0.546421	✔ 0.11%
tt- , tt+ → W+ , W-	653.0	163.25	1.0794	1.0794	1.078	1.07923	1.07941	1.07954	1.07947	1.0787	1.0794	1.07929	✔ 0.11%
u , d~ → Z , W+	684.0	171.0	0.1464	0.1464	0.14625	0.146343	0.146436	0.146393	0.146267	0.14655	0.14639	0.146457	✔ 0.11%
u , s~ → A , W+	319.0	79.75	0.011562	0.011562	0.011577	0.0115605	0.0115614	0.0115624	0.0115619	0.011564	0.011561	0.0115686	✔ 0.11%
ve , e+ → Z , W+	684.0	171.0	0.54663	0.54663	0.54724	0.546673	0.546628	0.546437	0.546813	0.54655	0.54661	0.546574	✔ 0.1%


3-Site Model
http://localhost:8080/author/model?id=91
Google
Add New Stock Model
Validations
Remove VV-VV (w/o CHstock) 48 processes : 48 agree 0 questionable 0 disagree 0 not finished
Remove ff-VV (w/o CHstock) 1272 processes : 1265 agree 7 questionable 0 disagree 0 not finished
Remove ff-ff (w/o CHstock) 4446 processes : 4446 agree 0 questionable 0 disagree 0 not finished
Create New Validation

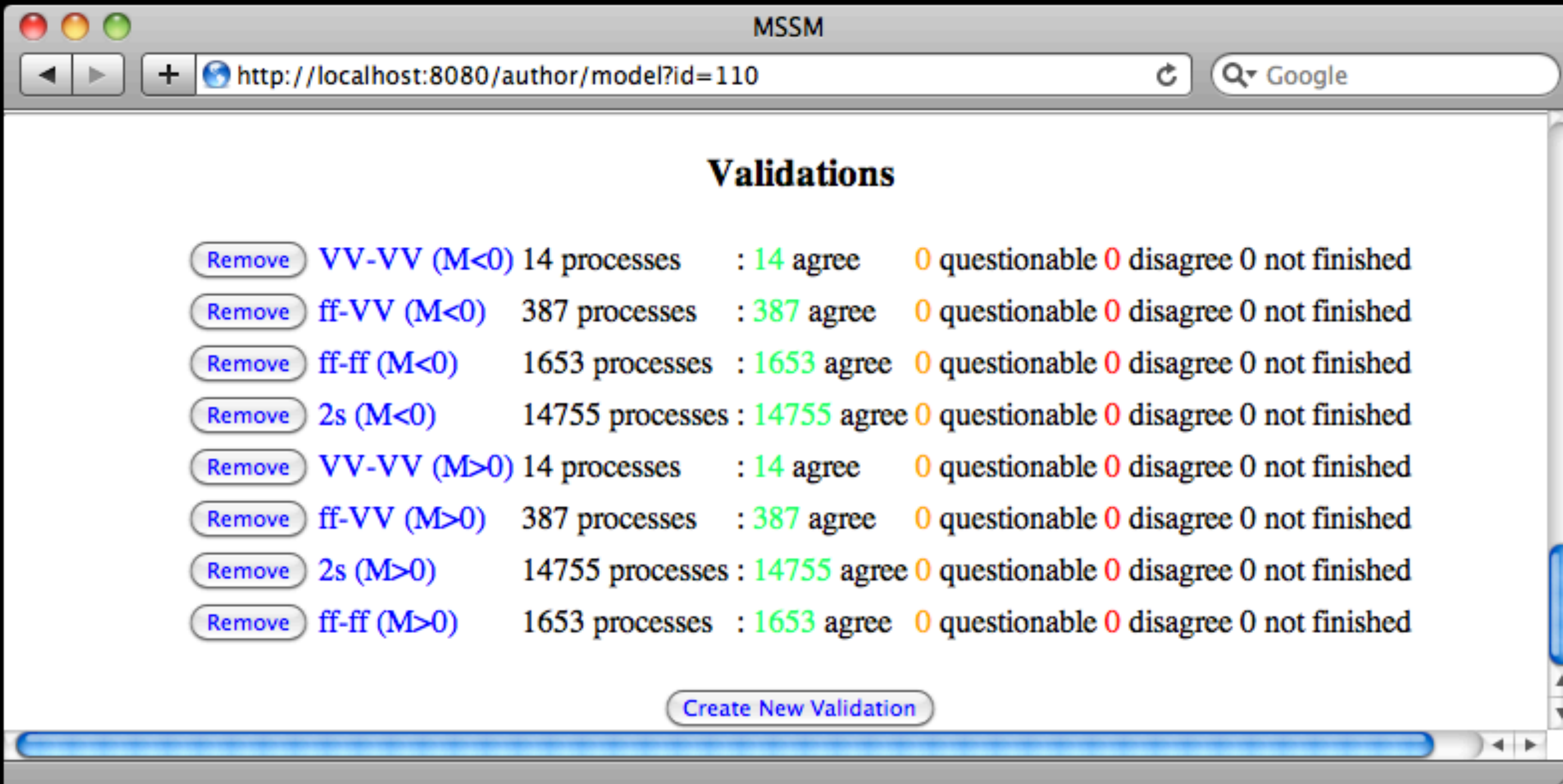
3-Site Model : VV-VV (w/o CHstock)

http://localhost:8080/author/validation?vdtnId=118

Start Fresh Validations | Finish Validations

48 processes : 48 agree, 0 questionable, 0 disagree, 0 not finished

	√s	p_{Tcut}	CH(F)	CH(u)	MG4	WO1(F)	WO1(u)	WO2(F)	WO2(u)	WO-ST	Δ
Z , W+ → ~Z , ~W+	4693.0	1173.25	102.67	102.67	102.4	102.672	102.679	102.691	102.682	102.676	✔ 0.24%
W+ , W+ → W+ , ~W+	2965.0	741.25	2.4203	2.4203	2.4141	2.42005	2.41998	2.42014	2.41914	2.42078	✔ 0.22%
W+ , ~W+ → ~W+ , ~W+	6322.0	1580.5	3.3141	3.3141	3.3217	3.31304	3.31371	3.31373	3.31409	3.31557	✔ 0.2%
W+ , W+ → W+ , W+	1286.0	321.5	76.03	76.03	76.188	76.0095	76.0285	76.0867	75.9919	76.0325	✔ 0.18%
~W+ , ~W+ → ~W+ , ~W+	8000.0	2000.0	567.33	567.33	566.24	567.314	567.18	567.244	567.249	567.35	✔ 0.16%
~Z , ~Z → ~W+ , ~W-	8013.0	2003.25	1133.9	1133.9	1131.7	1133.48	1133.53	1133.76	1133.73	1133.59	✔ 0.15%
A , A → W+ , W-	643.0	160.75	16.11	16.11	16.108	16.111	16.1075	16.1075	16.0846	16.1064	✔ 0.13%
Z , Z → W+ , W-	1373.0	343.25	130.02	130.02	130.21	129.98	130.079	130.023	130.035	129.965	✔ 0.13%
Z , Z → ~W+ , ~W-	4730.0	1182.5	313.8	313.8	313.42	313.828	313.791	313.759	313.955	313.862	✔ 0.11%
G , G → G , G	200.0	50.0	18835.0	18835.0	18816.0	18831.7	18831.2	18842.3	18845.4	18841.9	✔ 0.1%
A , A → ~W+ , ~W-	8000.0	2000.0	0.12636	0.12636	0.1265	0.126312	0.12635	0.126452	0.126347	0.12637	✔ 0.09%
Z , Z → W+ , ~W-	3051.0	762.75	1.1376	1.1376	1.138	1.13758	1.13784	1.13857	1.13718	1.13735	✔ 0.08%
A , Z → ~W+ , ~W-	8730.0	2182.5	0.041172	0.041172	0.041175	0.0411638	0.0411898	0.0411888	0.0411406	0.0411586	✔ 0.07%
A , ~Z → ~W+ , ~W-	6007.0	1501.75	6.3818	6.3818	6.3866	6.38627	6.38614	6.38229	6.38421	6.37878	✔ 0.07%
A , Z → W+ , W-	1008.0	252.0	20.969	20.969	20.961	20.9732	20.9758	20.9558	20.9718	20.9649	✔ 0.06%
W+ , W+ → ~W+ , ~W+	4643.0	1160.75	150.92	150.92	150.79	150.942	150.919	150.815	150.875	150.921	✔ 0.06%
A , W+ → W+ , ~Z	2650.0	662.5	0.16856	0.16856	0.16866	0.168592	0.168542	0.168497	0.168558	0.168573	✔ 0.05%
A , W+ → ~Z , ~W+	8656.0	2164.0	0.034886	0.034886	0.034866	0.034879	0.034886	0.0348662	0.034893	0.034872	✔ 0.04%
Z , W+ → W+ , ~Z	3015.0	753.75	0.7552	0.7552	0.75509	0.755298	0.755141	0.755171	0.755301	0.755573	✔ 0.04%


MSSM
http://localhost:8080/author/model?id=110
Google
Validations
Remove VV-VV (M<0) 14 processes : 14 agree 0 questionable 0 disagree 0 not finished
Remove ff-VV (M<0) 387 processes : 387 agree 0 questionable 0 disagree 0 not finished
Remove ff-ff (M<0) 1653 processes : 1653 agree 0 questionable 0 disagree 0 not finished
Remove 2s (M<0) 14755 processes : 14755 agree 0 questionable 0 disagree 0 not finished
Remove VV-VV (M>0) 14 processes : 14 agree 0 questionable 0 disagree 0 not finished
Remove ff-VV (M>0) 387 processes : 387 agree 0 questionable 0 disagree 0 not finished
Remove 2s (M>0) 14755 processes : 14755 agree 0 questionable 0 disagree 0 not finished
Remove ff-ff (M>0) 1653 processes : 1653 agree 0 questionable 0 disagree 0 not finished
Create New Validation

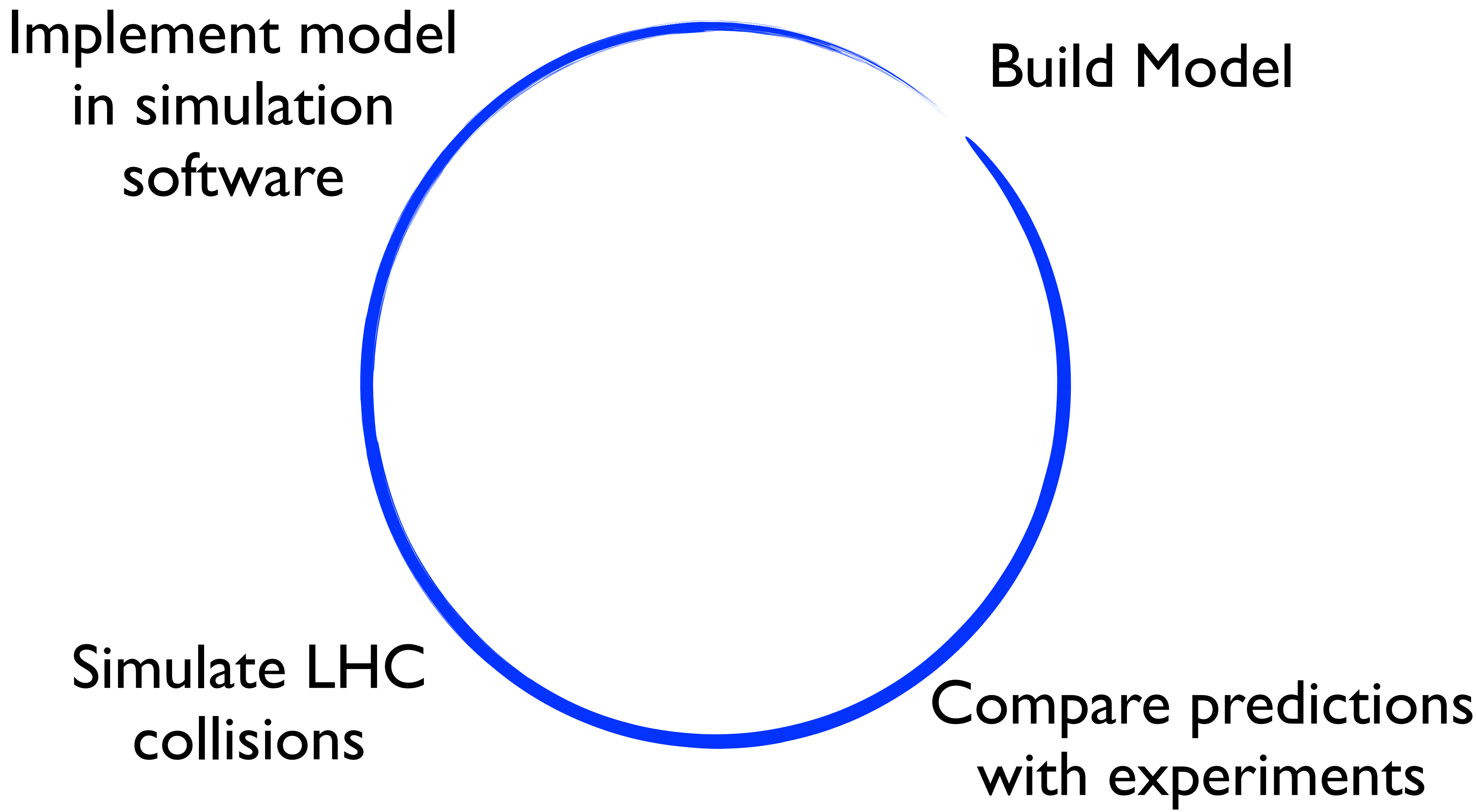
MSSM : ff-ff (M>0)

http://localhost:8080/author/validation?vdtnId=150

Start Fresh Validations | Finish Validations

1653 processes : 1653 agree, 0 questionable, 0 disagree, 0 not finished

	$\sqrt{s}$	p_{Tcut}	**WO1(u)**	**WO2(u)**	**MG-ST**	**WO-ST2**	**Δ**
t , t~ → x2+ , x2-	4440.0	1110.0	0.0143348	0.0143302	0.014367	0.0143244	✔ 0.19%
b , b~ → n2 , n3	2218.0	554.5	0.000648735	0.000648776	0.00065026	0.000648922	✔ 0.17%
c , s~ → n3 , x2+	2975.0	743.75	0.00303746	0.00303734	0.0030433	0.00303723	✔ 0.15%
tau- , tau+ → n3 , n4	2996.0	749.0	0.00317507	0.00317477	0.0031689	0.00317396	✔ 0.13%
n2 , n3 → x1+ , x1-	3633.0	908.25	0.219607	0.219672	0.21965	0.219254	✔ 0.13%
t , t~ → go , go	6262.0	1565.5	0.0887177	0.0887419	0.088873	0.0887354	✔ 0.12%
n1 , n2 → n3 , n4	4093.0	1023.25	0.000152097	0.000152055	0.00015229	0.000152016	✔ 0.12%
n2 , n3 → x2+ , x2-	5219.0	1304.75	0.0244456	0.0244471	0.024487	0.0244501	✔ 0.12%
tau- , tau+ → s , s~	800.0	200.0	0.116408	0.116446	0.11659	0.11641	✔ 0.11%
u , u~ → b , b~	800.0	200.0	3.64369	3.64443	3.6497	3.64423	✔ 0.11%
u , u~ → n3 , n3	2910.0	727.5	1.09524e-07	1.09548e-07	1.0937e-07	1.09515e-07	✔ 0.11%
n3 , n3 → x1+ , x1-	4364.0	1091.0	0.0112726	0.011267	0.011286	0.0112705	✔ 0.11%
n4 , n4 → x1+ , x2-	5300.0	1325.0	0.0280567	0.0280319	0.028082	0.0280761	✔ 0.11%
u , u~ → n2 , n3	2179.0	544.75	0.000133762	0.000133763	0.0001336	0.000133791	✔ 0.1%
u , d~ → n2 , x1+	1451.0	362.75	0.00903434	0.00903341	0.0090236	0.00903773	✔ 0.1%
c , c~ → n1 , n3	1842.0	460.5	8.68611e-05	8.68558e-05	8.696e-05	8.68316e-05	✔ 0.1%
c , c~ → n3 , n3	2910.0	727.5	1.09516e-07	1.09519e-07	1.0937e-07	1.09506e-07	✔ 0.1%
c , t~ → s , b~	720.0	180.0	5.73433	5.73456	5.7269	5.73363	✔ 0.1%


Implement model in simulation software
Build Model
Simulate LHC collisions
Compare predictions with experiments