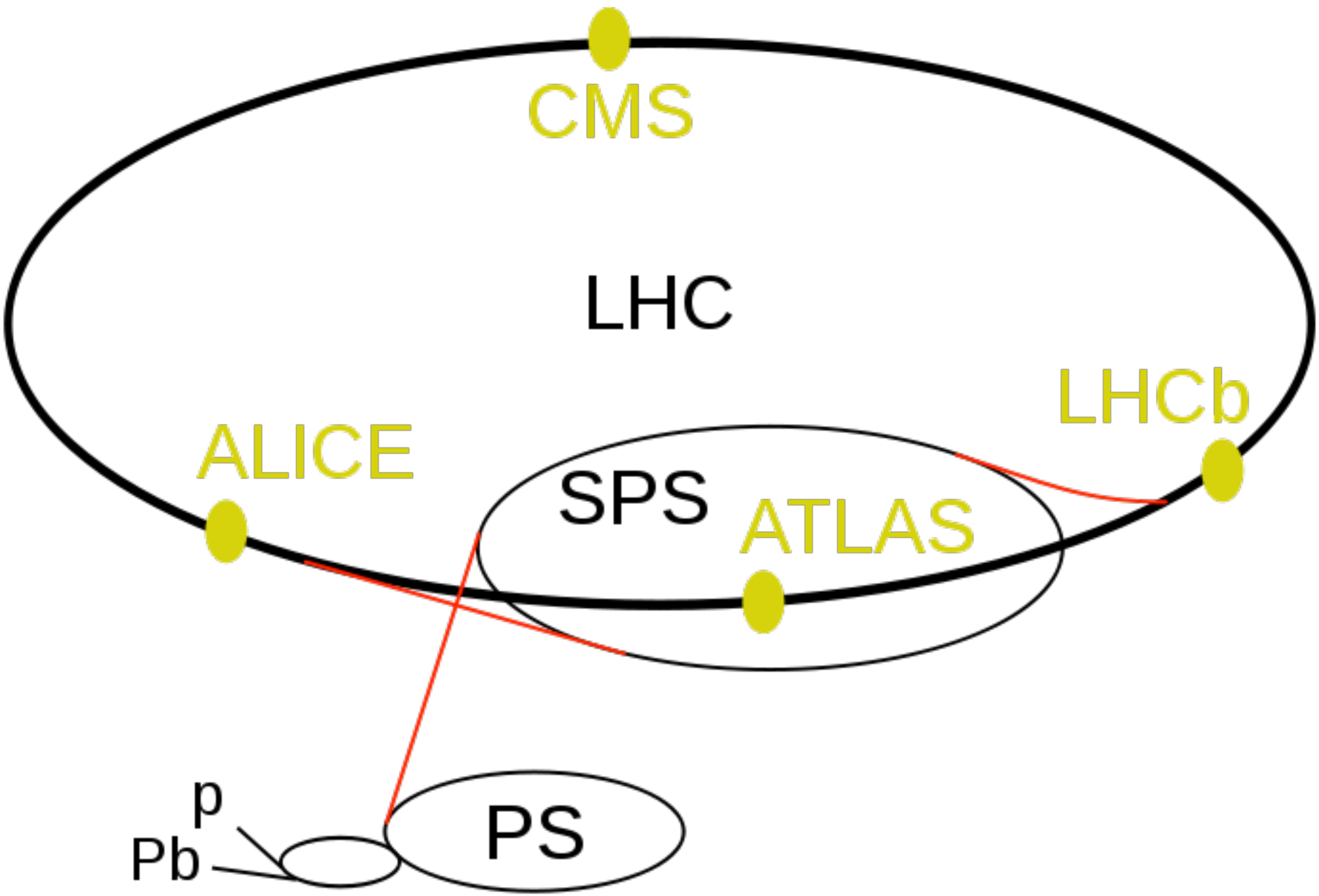
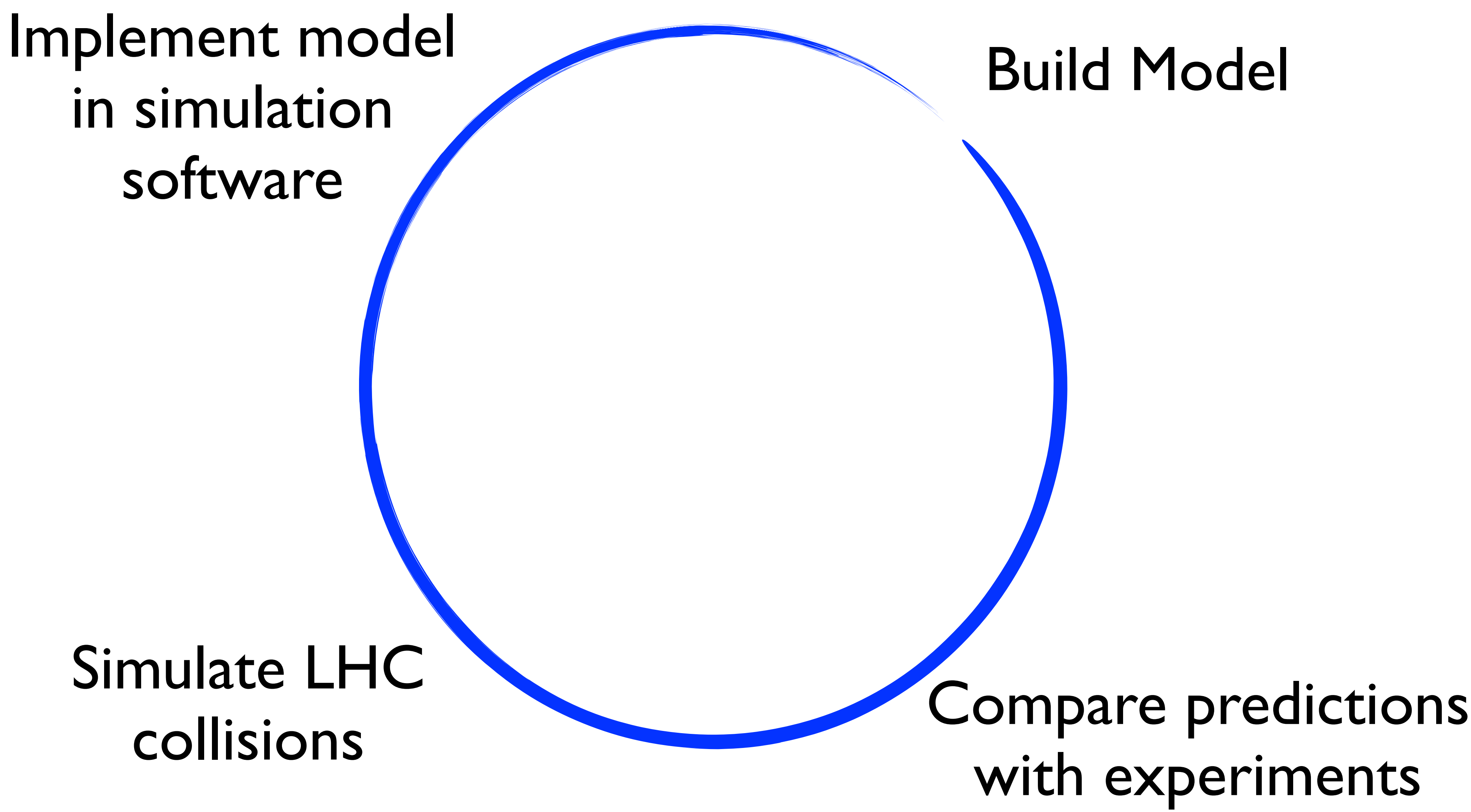
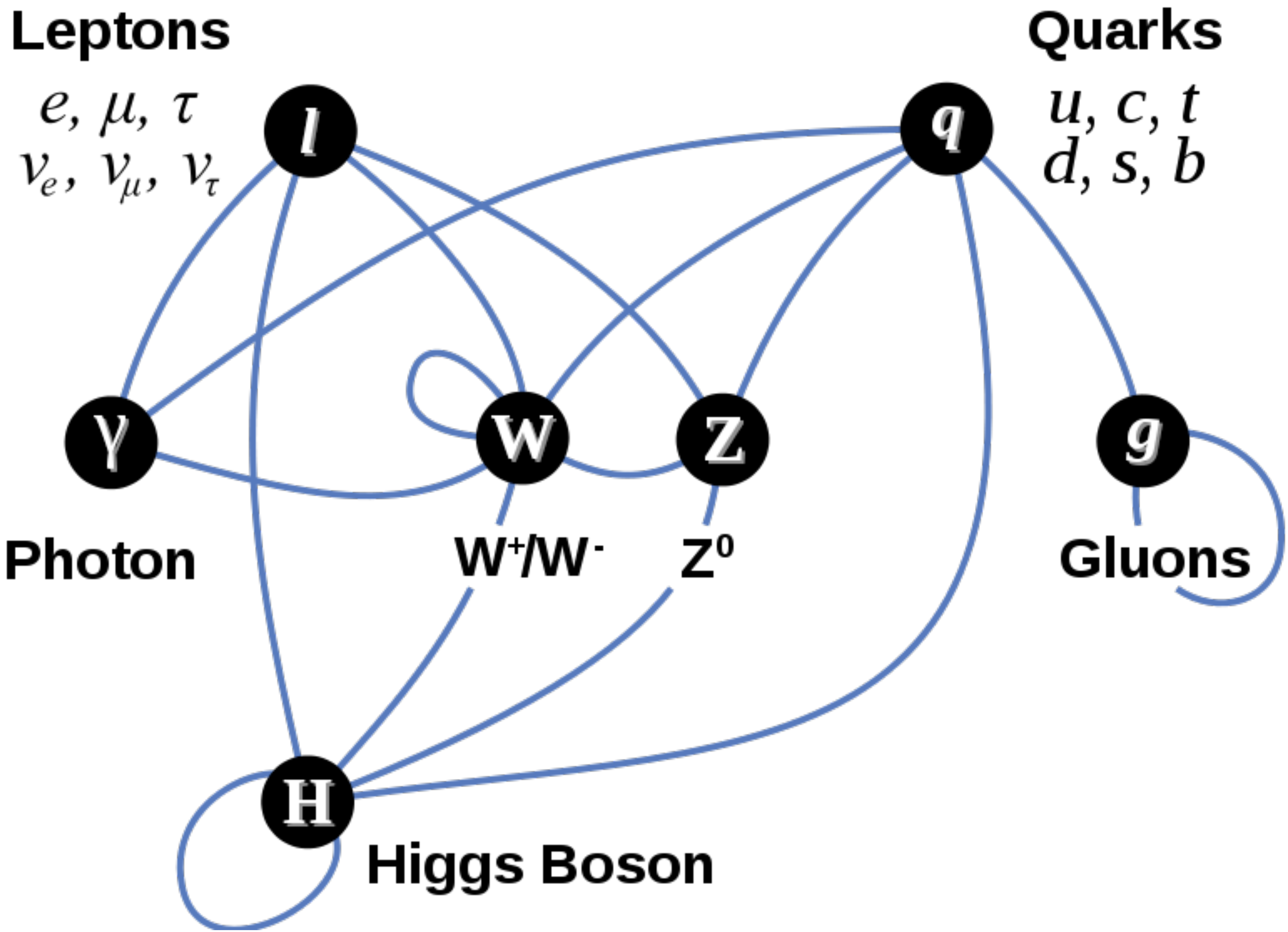
Model Building in the LHC Era

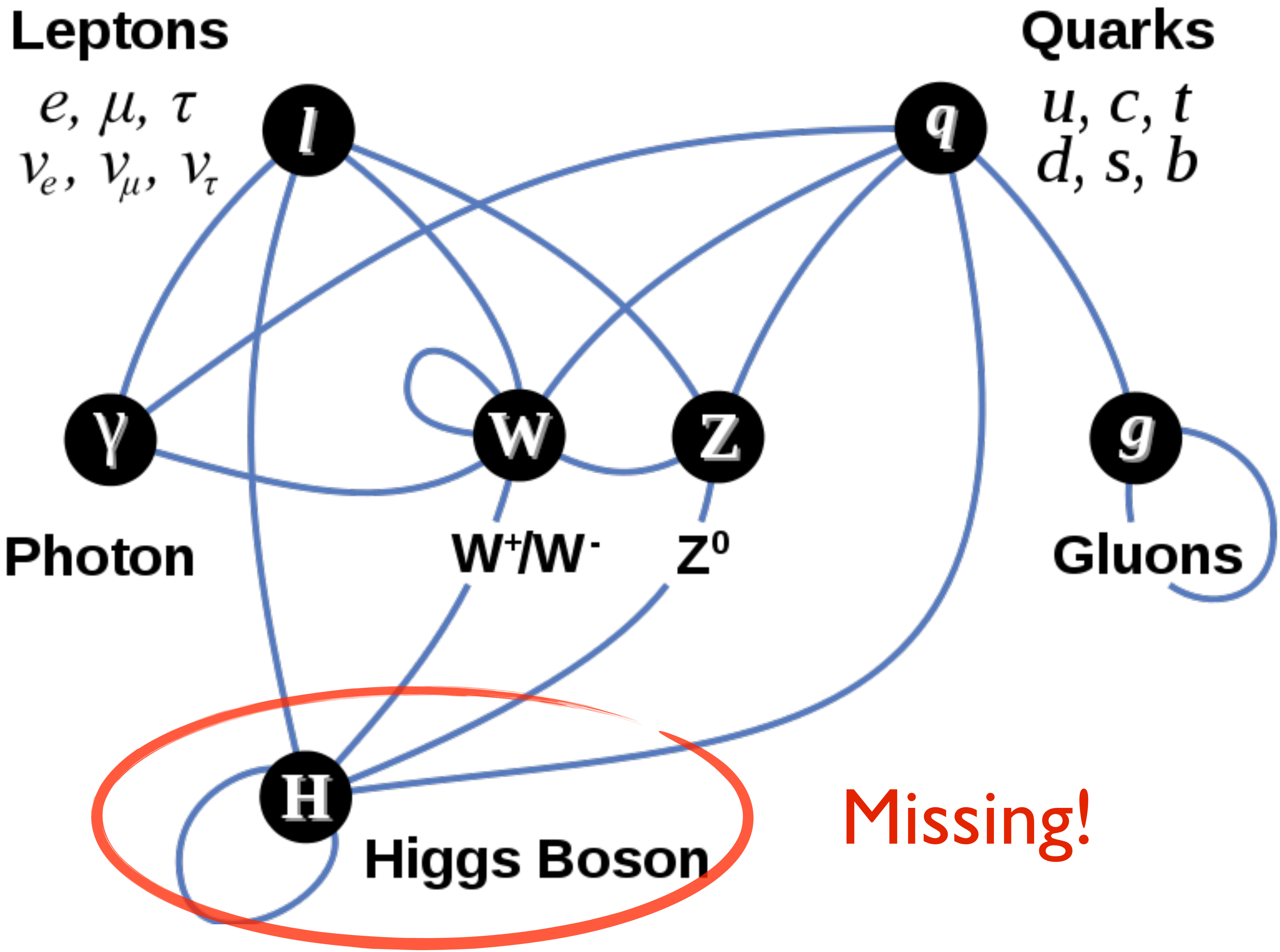
from model to LHC

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

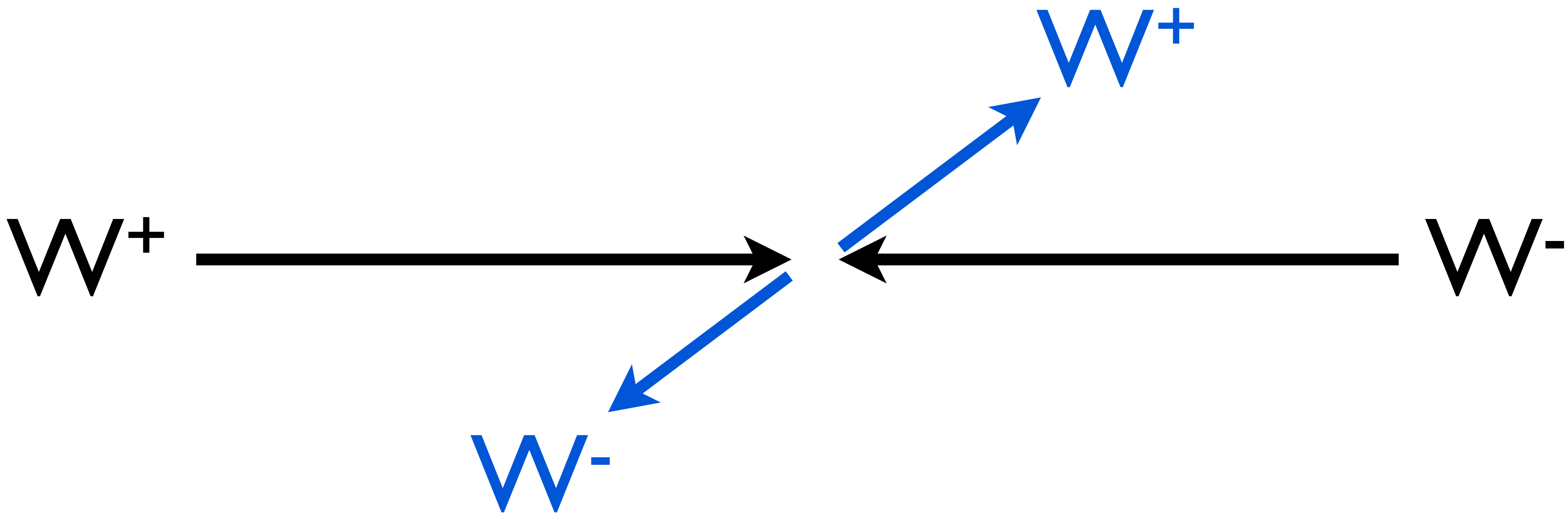

CMS
LHC
LHCb
ALICE
SPS
ATLAS
p
Pb
PS

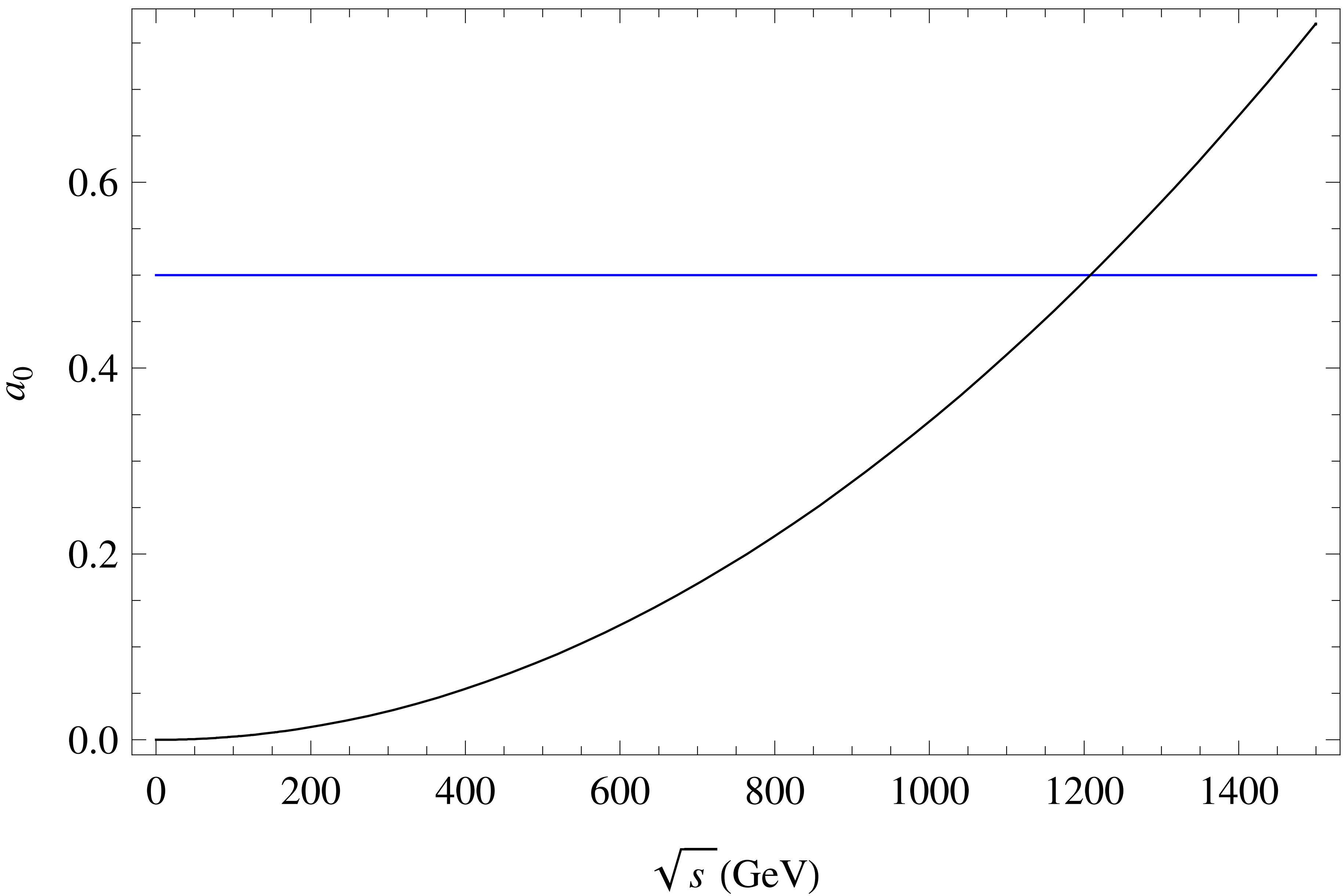

Implement model in simulation software
Build Model
Simulate LHC collisions
Compare predictions with experiments


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

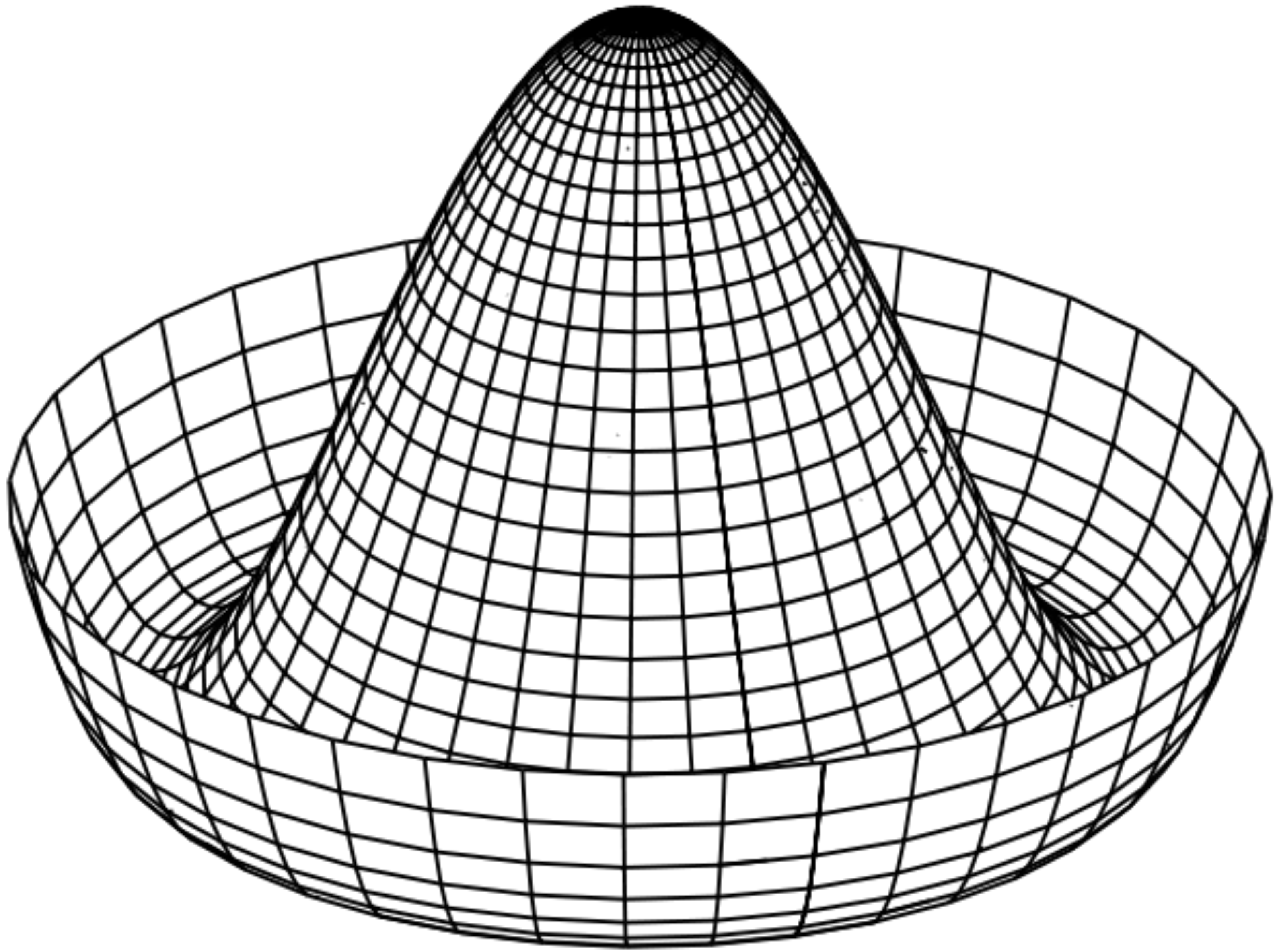


Leptons
e, μ, τ
ν_e, ν_μ, ν_τ
l
Quarks
u, c, t
d, s, b
q
γ
W
Z
g
Photon
W^+/W^-
Z^0
Gluons
H
Higgs Boson
Missing!


W+
W-
W+
W-



0.0
0.2
0.4
0.6
a_0
0
200
400
600
800
1000
1200
1400
$\sqrt{s}$ (GeV)



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left(D_\mu\Phi\right)^\dagger\left(D^\mu\Phi\right)$$

$$\langle\Phi\rangle = \frac{v}{\sqrt{2}}$$

SM

???

Supersymmetry

Extra
Dimensions

Little Higgs

Higgsless

New Strong
Dynamics

SM

???

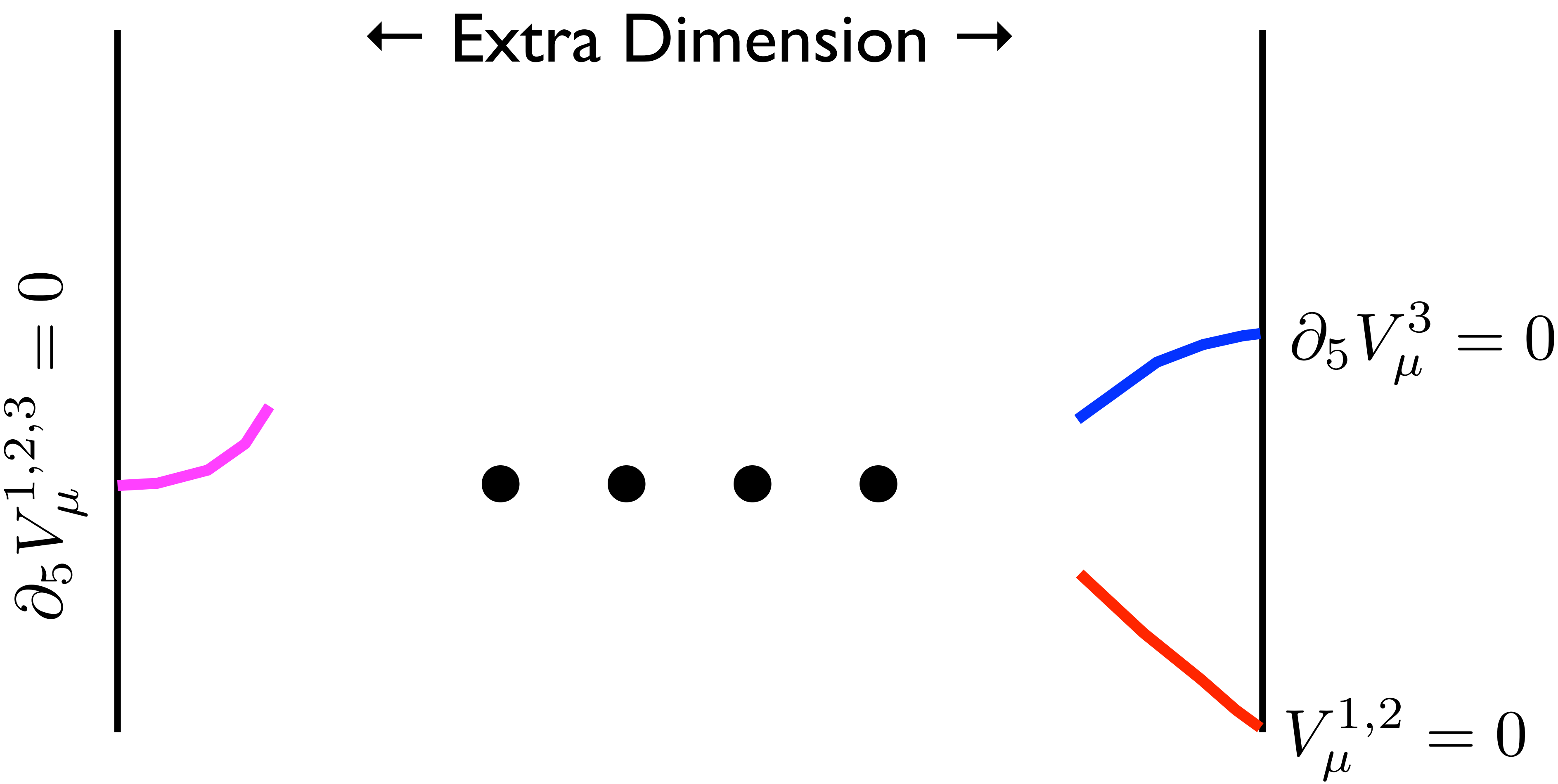
Supersymmetry

Extra
Dimensions

Little Higgs

Higgsless

New Strong
Dynamics


← Extra Dimension →
$\partial_5 V_\mu^{1,2,3} = 0$
$\partial_5 V_\mu^3 = 0$
$V_\mu^{1,2} = 0$

$$V_\mu^{1,2}(x,z) = \sum_n V_\mu^{1,2(n)}(x) \cos\left(\frac{2n+1}{2R}\pi z\right)$$

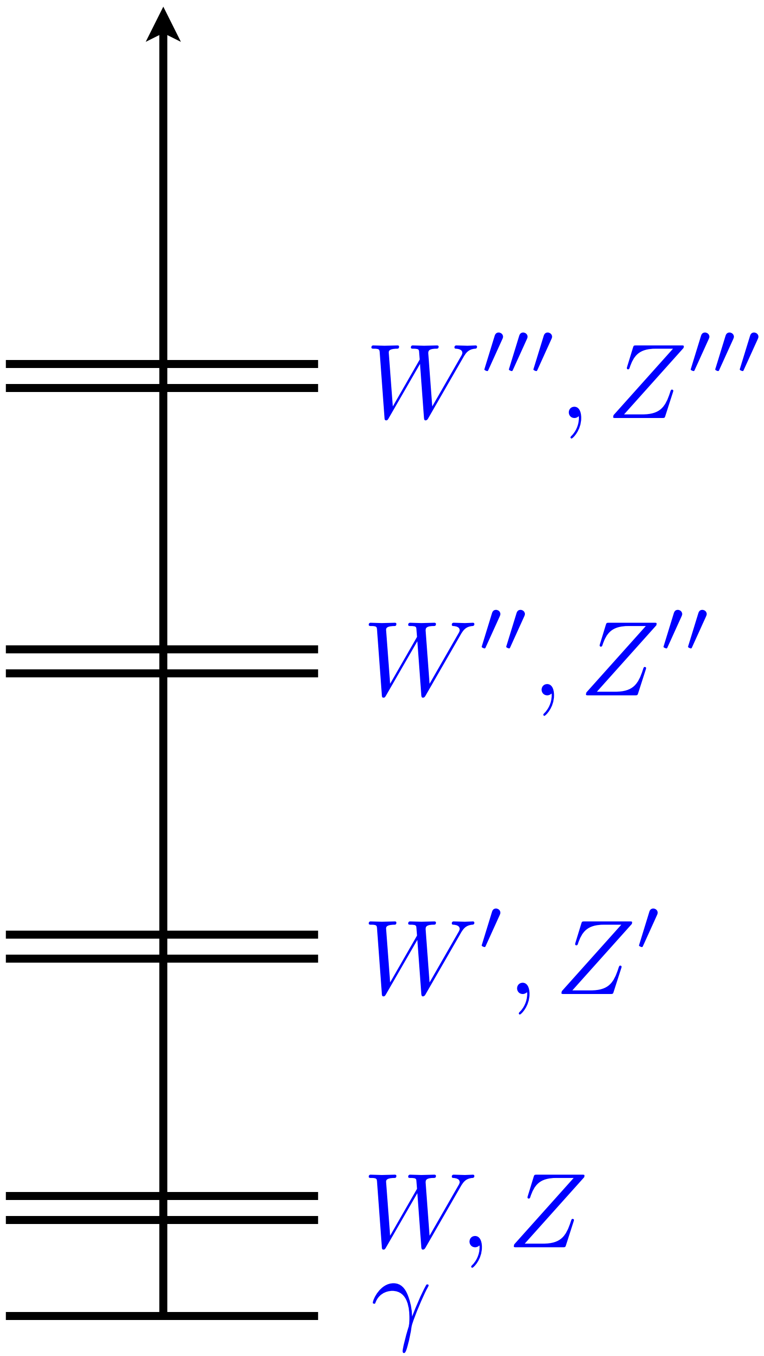
$$V_\mu^{3}(x,z) = \sum_n V_\mu^{3(n)}(x) \cos\left(\frac{n}{R}\pi z\right)$$

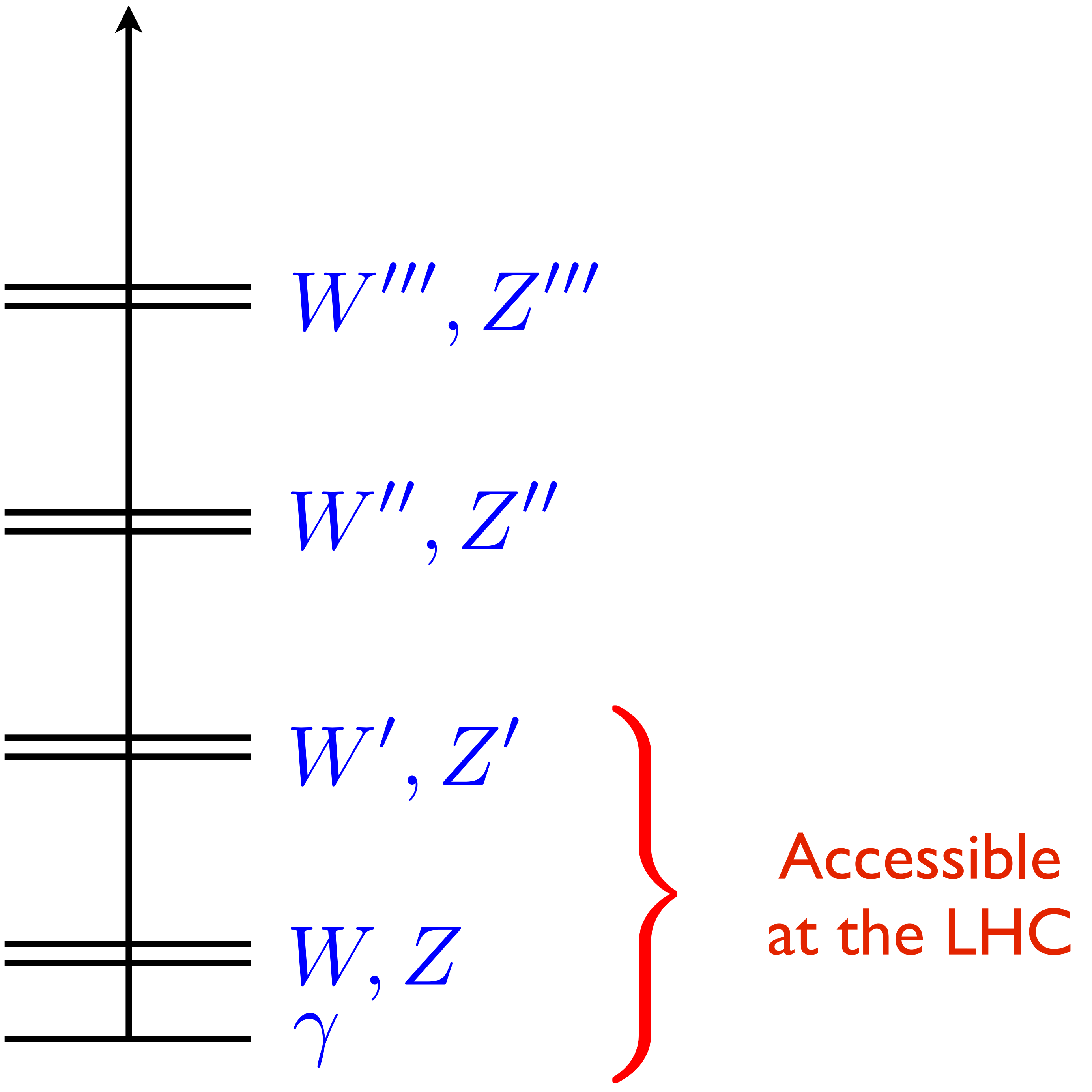
$$V_\mu^{1,2}(x,z) = \sum_n V_\mu^{1,2(n)}(x) \cos\left(\frac{2n+1}{2R}\pi z\right)$$

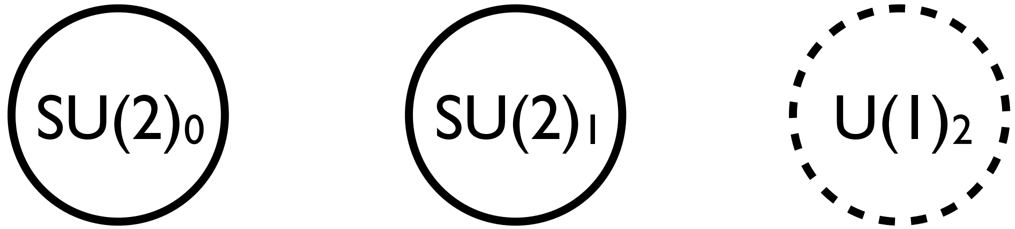
$$M_n^{1,2} = \frac{2n+1}{2R}\pi$$

$$V_\mu^{3}(x,z) = \sum_n V_\mu^{3(n)}(x) \cos\left(\frac{n}{R}\pi z\right)$$

$$M_n^{3} = \frac{n}{R}\pi$$

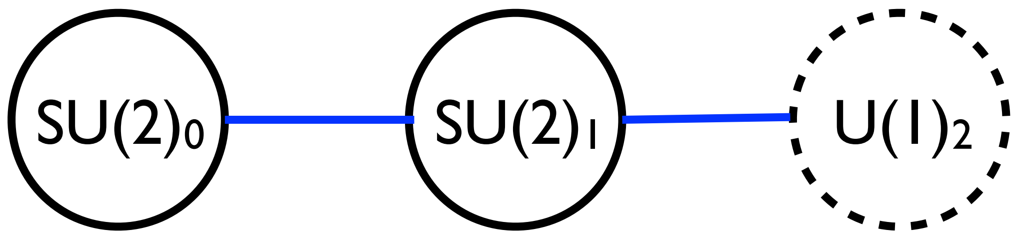

W''', Z'''
W'', Z''
W', Z'
W, Z
γ


W''', Z'''
W'', Z''
W', Z'
W, Z
γ
Accessible
at the LHC



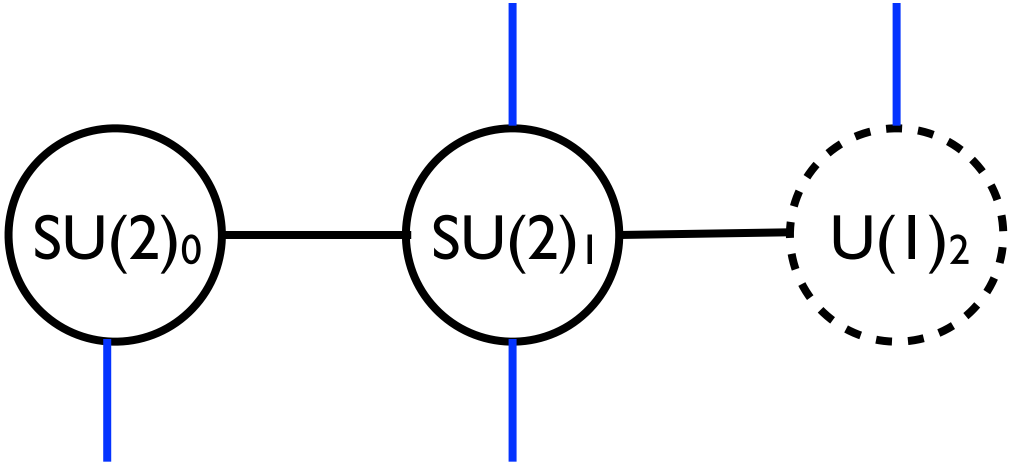
$$\begin{aligned} W_0 &: (3,1)_0 \\ W_1 &: (1,3)_0 \\ W_2 &: (1,1)_0 \end{aligned}$$

$$\mathcal{L} = -\frac{1}{4} F_{0\mu\nu} F_0^{\mu\nu} - \frac{1}{4} F_{1\mu\nu} F_1^{\mu\nu} - \frac{1}{4} F_{2\mu\nu} F_2^{\mu\nu}$$



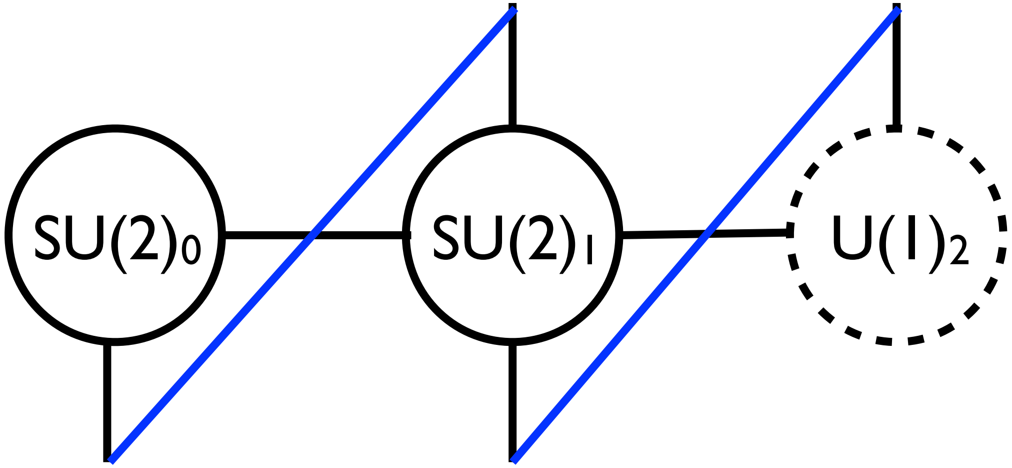
$$
\begin{aligned}
\Sigma_{01} &\quad : \quad (2,\bar{2})_0 \\
\Sigma_{12} &\quad : \quad (1,2)_{\pm\frac{1}{2}}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L} = &\frac{f^2}{4}\mathrm{Tr}\left[\left(D_\mu\Sigma_{01}\right)^\dagger D^\mu\Sigma_{01} + \left(D_\mu\Sigma_{12}\right)^\dagger D^\mu\Sigma_{12}\right] \\
&+\frac{F^2}{4}\mathrm{Tr}\left[\left(D_\mu\left(\Sigma_{01}\Sigma_{12}\right)\right)^\dagger D^\mu\left(\Sigma_{01}\Sigma_{12}\right)\right]
\end{aligned}
$$



Q_{L0}	:	$(2,1)_{\frac{1}{6}}$	L_{L0}	:	$(2,1)_{-\frac{1}{2}}$
Q_1	:	$(1,2)_{\frac{1}{6}}$	L_1	:	$(1,2)_{-\frac{1}{2}}$
u_{R2}	:	$(1,1)_{\frac{2}{3}}$			
d_{R2}	:	$(1,1)_{-\frac{1}{3}}$	e_{R2}	:	$(1,1)_{-1}$

$$\mathcal{L} = i\bar{\psi}_{L0} \not{D} \psi_{L0} + i\bar{\psi}_{L1} \not{D} \psi_{L1} + i\bar{\psi}_{R1} \not{D} \psi_{R1} + i\bar{\psi}_{R2} \not{D} \psi_{R2}$$



$$
\begin{array}{lclclcl}
Q_{L0} & : & (2,1)_{\frac{1}{6}} & \quad & L_{L0} & : & (2,1)_{-\frac{1}{2}} \\
Q_{1} & : & (1,2)_{\frac{1}{6}} & \quad & L_{1} & : & (1,2)_{-\frac{1}{2}} \\
u_{R2} & : & (1,1)_{\frac{2}{3}} & & & & \\
d_{R2} & : & (1,1)_{-\frac{1}{3}} & \quad & e_{R2} & : & (1,1)_{-1}
\end{array}
$$

$$
\mathcal{L} = -M_F \left(\epsilon_L \bar{\psi}_{L0} \Sigma_{01} \psi_{R1} + \bar{\psi}_{L1} \psi_{R1} + \bar{\psi}_{L1} \epsilon_R \Sigma_{12} \psi_{R2} \right)
$$

Ideal Fermion Delocalization

$$g_i \left(v_L^i\right)^2 \propto v_W^i$$

Necessary to satisfy precision electroweak constraints.

Ideal Fermion Delocalization

$$g_i \left(v_L^i\right)^2 \propto v_W^i$$

$$\begin{aligned} g_{f_L f_L W'} &= \sum_i g_i \left(v_L^i\right)^2 v_{W'}^i \\ &= \sum_i v_W^i v_{W'}^i \\ &= 0 \end{aligned}$$

Fermion couplings to W' and Z' are vanishingly small.

CalcHEP

MadGraph

Herwig

Sherpa

Whizard

FeynArts

CalcHEP

MadGraph

Herwig

Sherpa

Whizard

FeynArts

CalcHEP

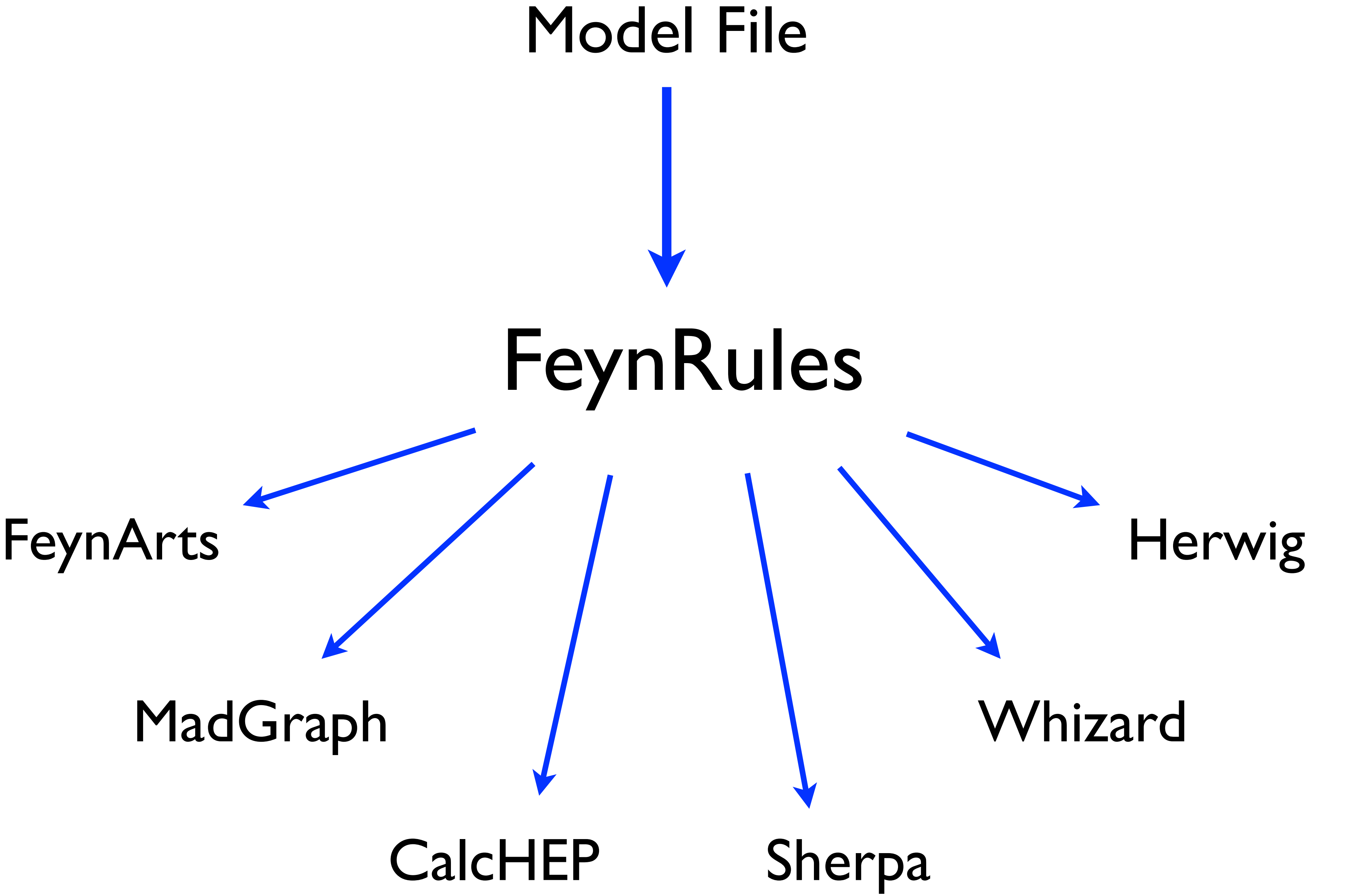
MadGraph

Herwig

Sherpa

Whizard

FeynArts

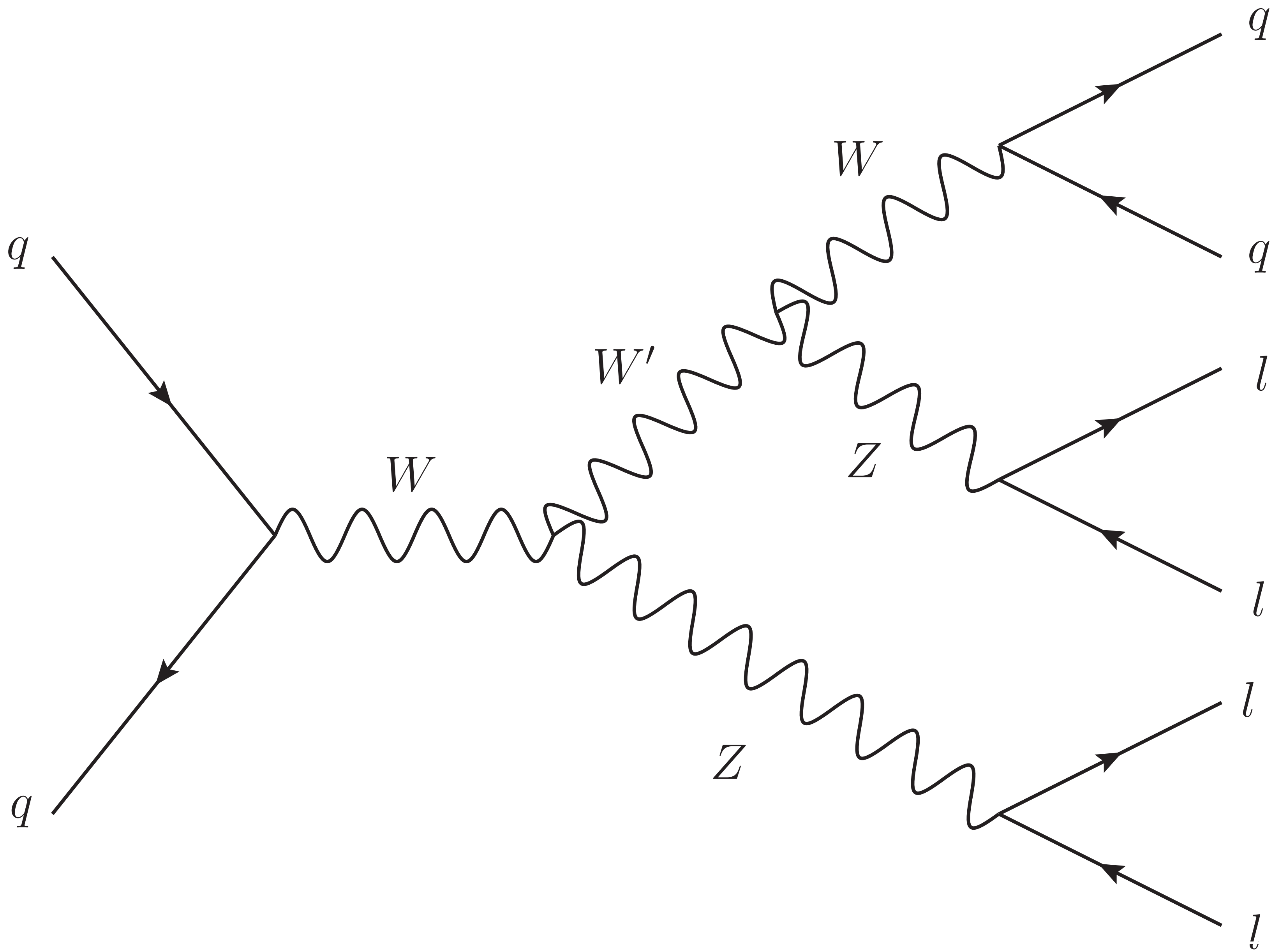

Model File
FeynRules
FeynArts
MadGraph
CalcHEP
Sherpa
Whizard
Herwig

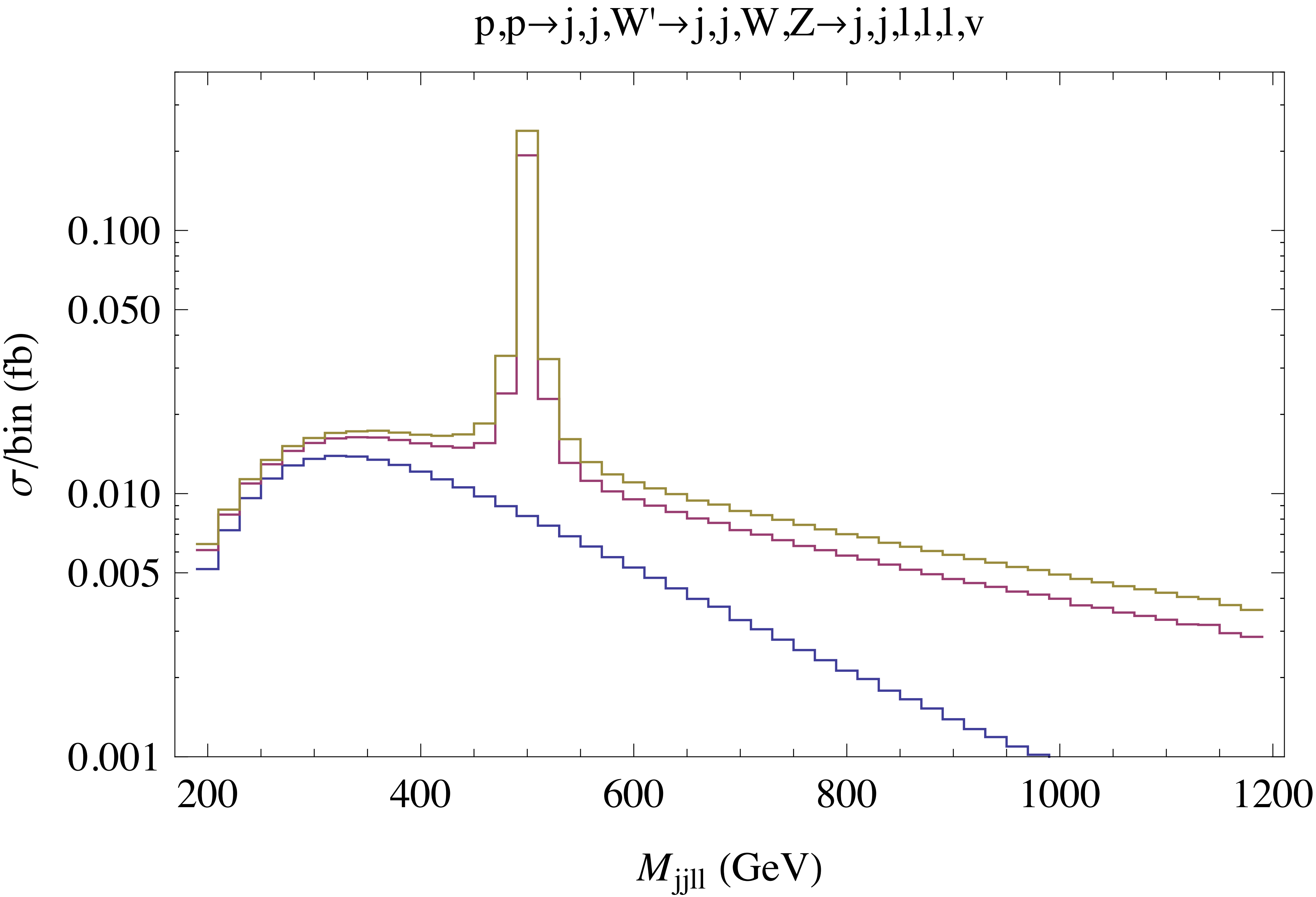
3-Site-lagrangian.fr

```
(*****************************************************************************)
(*********************** Gauge Bosons kinetic terms ***************************)
(*****************************************************************************)
LGauge := Module[{FGlue,F0,F1,F2,LGlue,L0,L1,L2},

        (*********** Glue*)
        FGlue[mu_,nu_,a_] := Module[{b,c},
                del[G[nu, a], mu] - del[G[mu, a], nu] - gs f[a,b,c] G[mu, b] G[nu, c]
                ];
        LGlue := -1/4 FGlue[mu,nu,a]FGlue[mu,nu,a];

        (*********** Site 0*)
        F0[mu_,nu_,a_] := Module[{b,c},
                del[W0[nu,a],mu]-del[W0[mu,a],nu] - g*ep0[a,b,c]*W0[mu,b]*W0[nu,c]
                ];
        L0 := -1/4 F0[mu,nu,a]F0[mu,nu,a];

        (*********** Site 1*)
        F1[mu_,nu_,a_] := Module[{b,c},
                del[W1[nu,a],mu]-del[W1[mu,a],nu] - gt*ep1[a,b,c]*W1[mu,b]*W1[nu,c]
                ];
        L1 := -1/4 F1[mu,nu,a]F1[mu,nu,a];

        (*********** Site 2*)
        F2[mu_,nu_] := Module[{tmp},
                del[W23[nu],mu]-del[W23[mu],nu]
                ];
        L2 := -1/4 F2[mu,nu]F2[mu,nu];


        LGlue+L0+L1+L2
];
-:-- 3-Site-lagrangian.fr   9% (22,51)   (Fundamental)
```

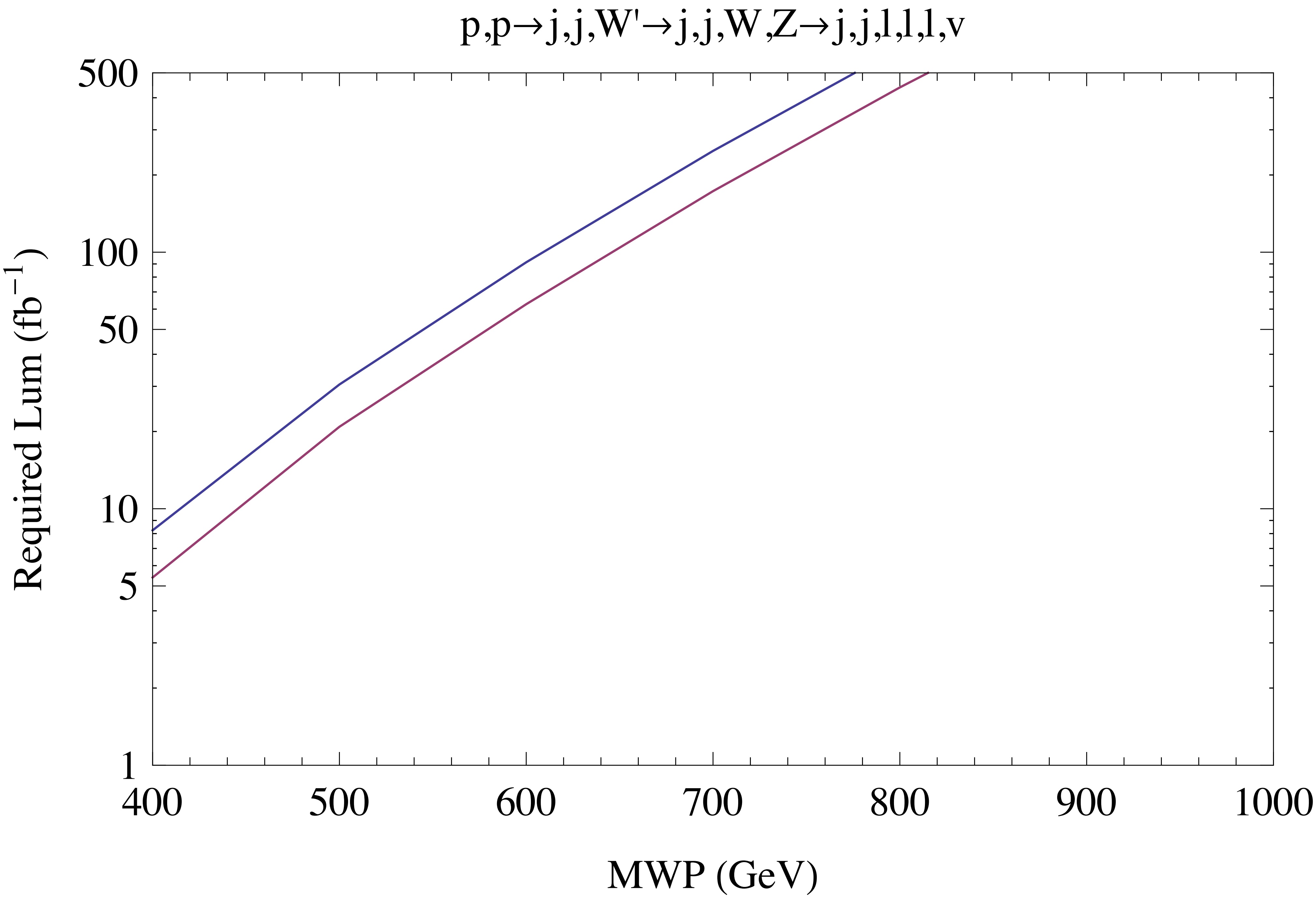
	Stock SM Feynman	Lanhep CalcHEP Feynman	Lanhep CalcHEP Unitary	FeynRules CalcHEP Feynman	FeynRules CalcHEP Unitary	FeynRules CompHEP Feynman	FeynRules Sherpa Unitary	FeynRules MadGraph Unitary	Speckner Whizard	FeynRules Whizard Feynman	FeynRules Whizard Unitary
$W^+\gamma\text{->}W^+\gamma$	26.013	26.013	26.013	26.013	26.013	26.013	25.9451	26.004	26.0051	26.0051	26.0051
$W^{+\prime}\gamma\text{->}W^+\gamma$		0	0	0	0	0	0	0	0	0	0
$W^{+\prime}\gamma\text{->}W^{+\prime}\gamma$		0.41085	0.41085	0.41085	0.41085	0.41085	0.41071	0.41112	0.410866	0.411521	0.411521
$W^+\gamma\text{->}W^+Z$	101.13	104.42	104.42	104.42	104.42	104.42	104.37	104.42	104.345	104.345	104.345
$W^{+\prime}\gamma\text{->}W^+Z$		1.4383	1.4383	1.4383	1.4383	1.4383	1.43673	1.4368	1.43843	1.43567	1.43567
$W^+\gamma\text{->}W^{+\prime}Z$		1.0906	1.0906	1.0906	1.0906	1.0906	1.09052	1.0916	1.08976	1.08658	1.08658
$W^+\gamma\text{->}W^+Z'$		1.1145	1.1145	1.1145	1.1145	1.1145	1.11413	1.1144	1.11589	1.11567	1.11567
$W^{+\prime}\gamma\text{->}W^{+\prime}Z$		0.23096	0.23096	0.23096	0.23096	0.23096	0.230829	0.23081	0.231057	0.230355	0.230355
$W^{+\prime}\gamma\text{->}W^+Z'$		5.8128	5.8128	5.8128	5.8128	5.8126	5.81279	5.8304	5.81545	5.81568	5.81568
$W^+\gamma\text{->}W^{+\prime}Z'$		0.23267	0.23267	0.23267	0.23267	0.23267	0.232495	0.23258	0.233004	0.232666	0.232666
$W^{+\prime}\gamma\text{->}W^{+\prime}Z'$		8.4966	8.4966	8.4966	8.4966	8.4966	8.4956	8.4955	8.49743	8.5113	8.5113
$W^+Z\text{->}W^+Z$	285.98	312.08	312.08	312.08	312.08	312.09	311.926	312.88	312.064	312.194	312.194
$W^{+\prime}Z\text{->}W^+Z$		4.0844	4.0844	4.0844	4.0844	4.0843	4.07748	4.0905	4.08203	4.08674	4.08674
$W^+Z'\text{->}W^+Z$		4.2141	4.2141	4.2141	4.2141	4.2141	4.20964	4.2206	4.21042	4.21457	4.21457
$W^{+\prime}Z'\text{->}W^+Z$		30.723	30.723	30.723	30.723	30.724	30.7137	30.693	30.7382	30.7114	30.7114
$W^{+\prime}Z\text{->}W^{+\prime}Z$		22.891	22.891	22.891	22.891	22.893	22.8939	22.929	22.881	22.88	22.88
$W^{+\prime}Z\text{->}W^+Z'$		130.3	130.3	130.3	130.3	130.3	130.217	130.28	130.436	130.399	130.399
$W^{+\prime}Z'\text{->}W^{+\prime}Z$		8.0977	8.0977	8.0977	8.0977	8.0979	8.09521	8.0822	8.09818	8.09691	8.09691
$W^{+\prime}Z'\text{->}W^+Z'$		19.136	19.136	19.136	19.136	19.136	19.1282	19.128	19.121	19.1333	19.1333
$W^{+\prime}Z'\text{->}W^{+\prime}Z'$		696.66	696.66	696.66	696.66	696.65	696.311	697.39	696.941	696.936	696.936

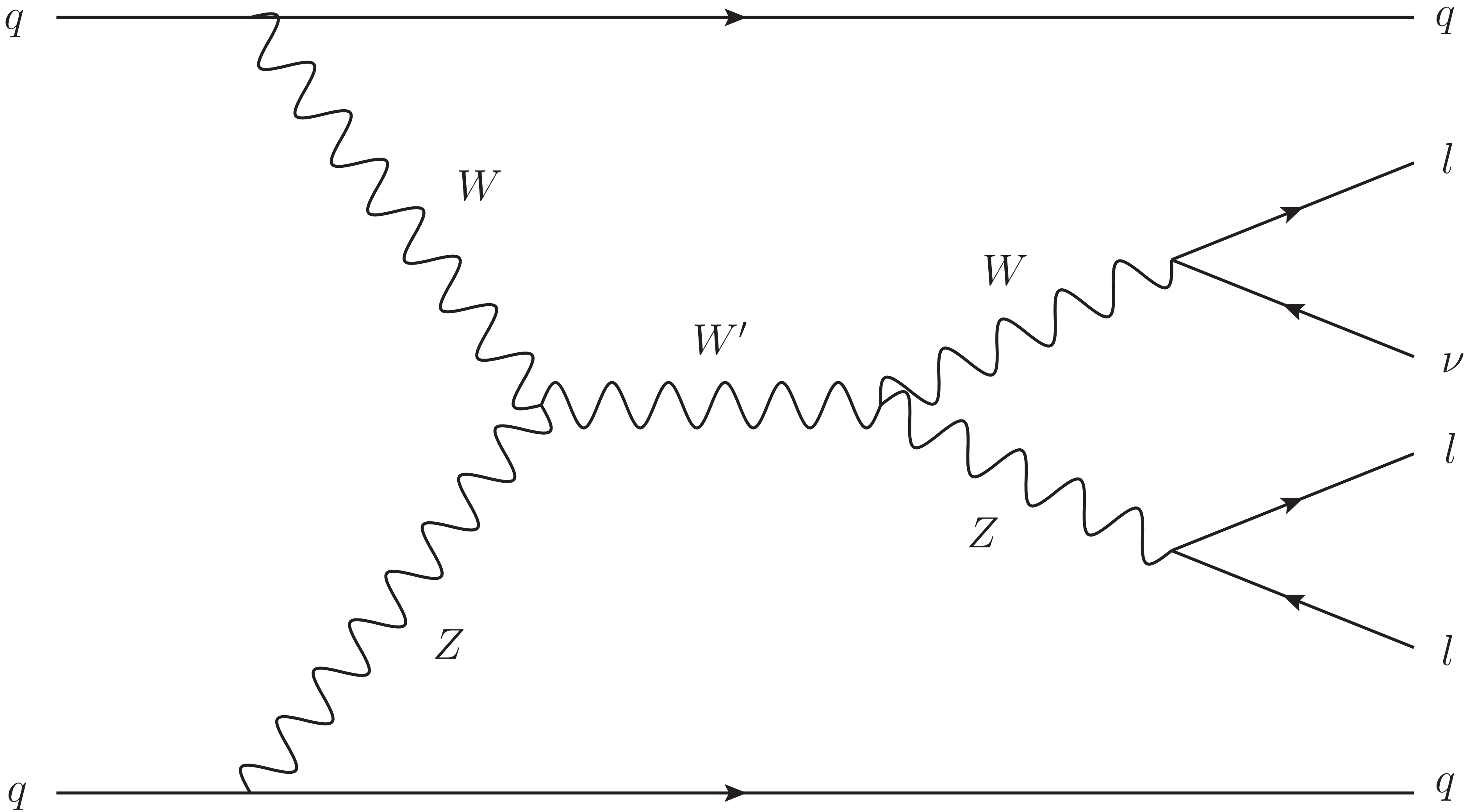
Over 200 processes compared.
All agree to better than 1%.


q
q
W
W′
W
Z
Z
q
q
l
l
l
l

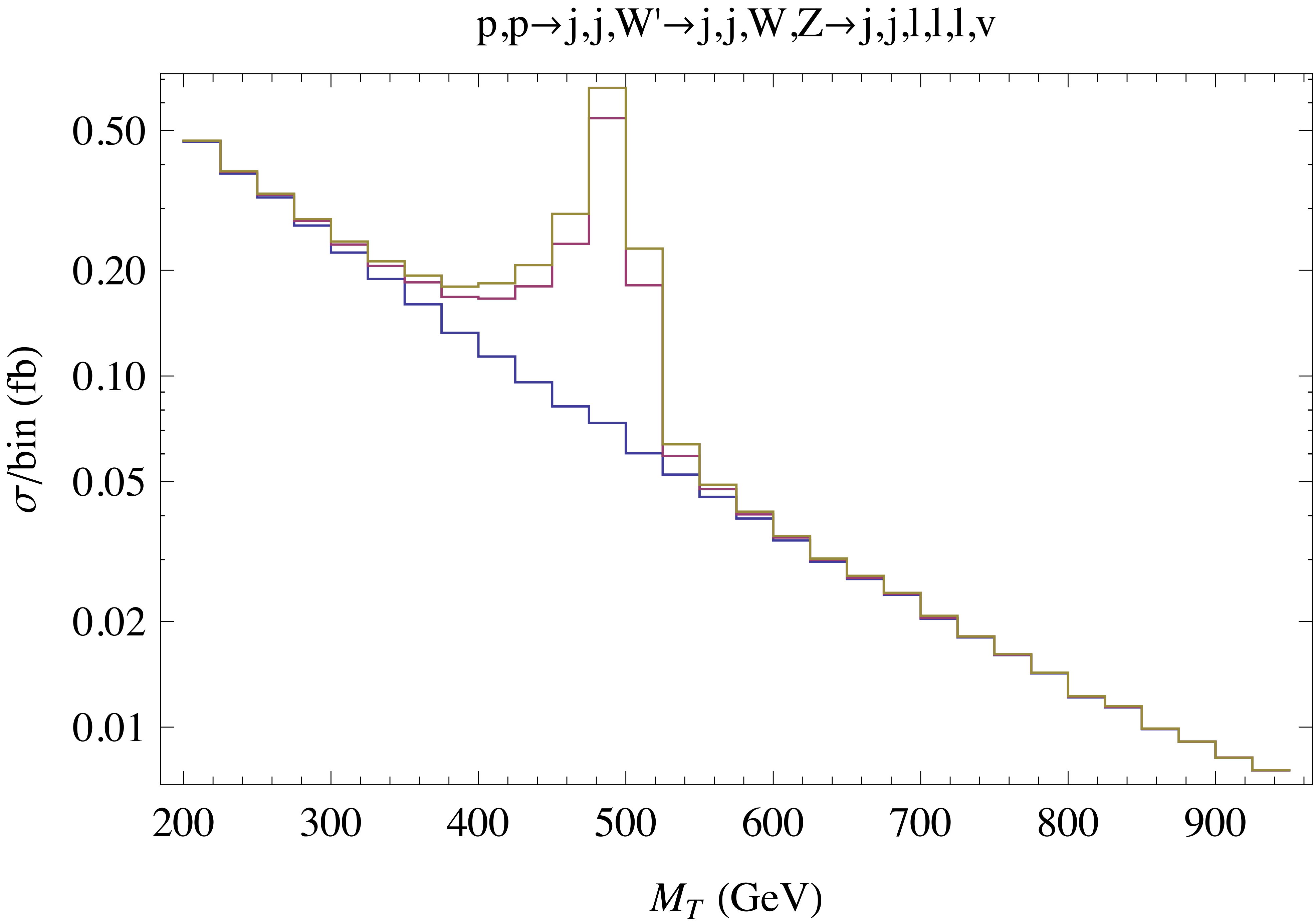


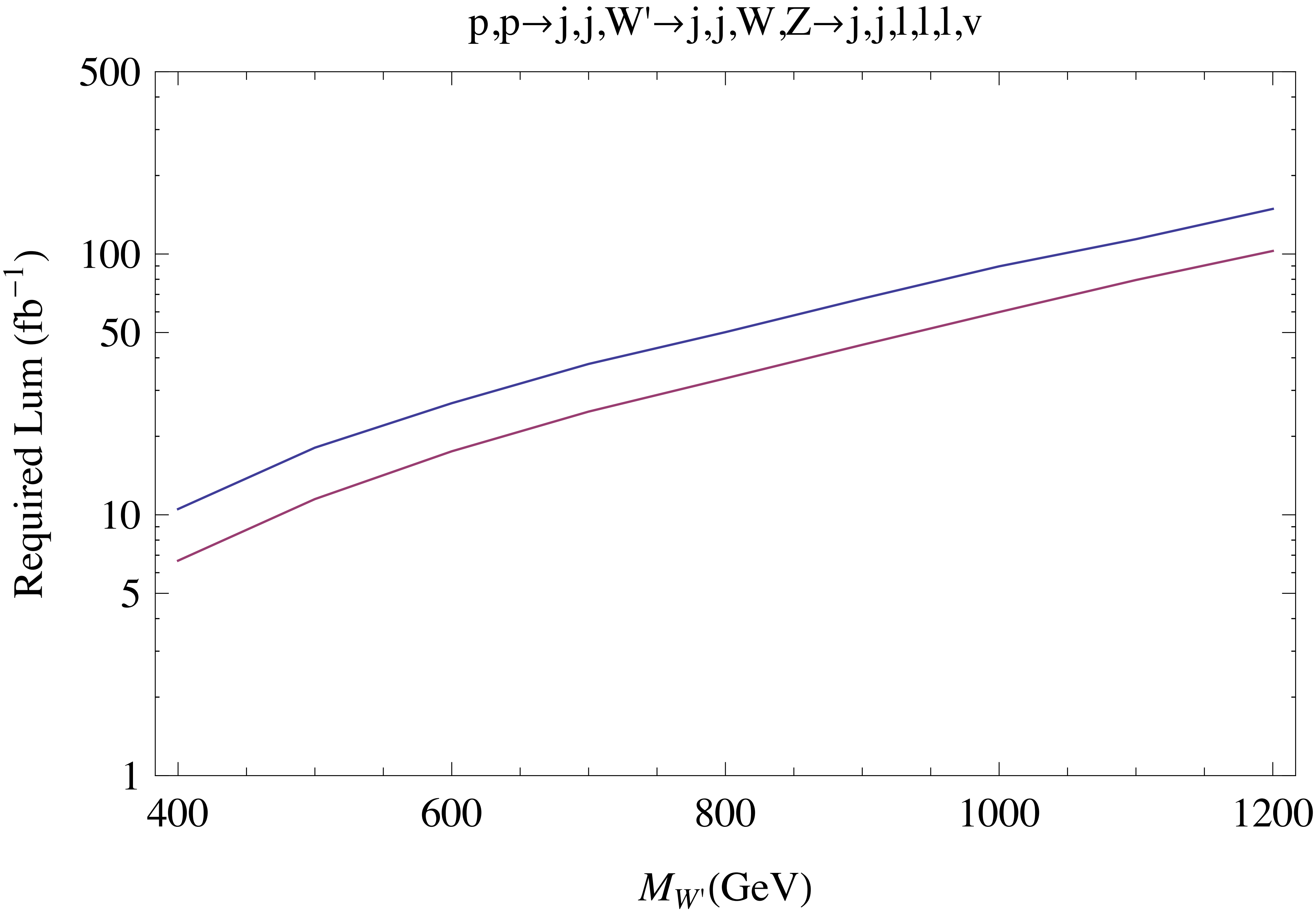
p,p→j,j,W'→j,j,W,Z→j,j,l,l,l,v
σ/bin (fb)
0.100
0.050
0.010
0.005
0.001
200
400
600
800
1000
1200
M_jjll (GeV)


p,p→j,j,W'→j,j,W,Z→j,j,l,l,l,v
Required Lum (fb^{-1})
500
100
50
10
5
1
400
500
600
700
800
900
1000
MWP (GeV)

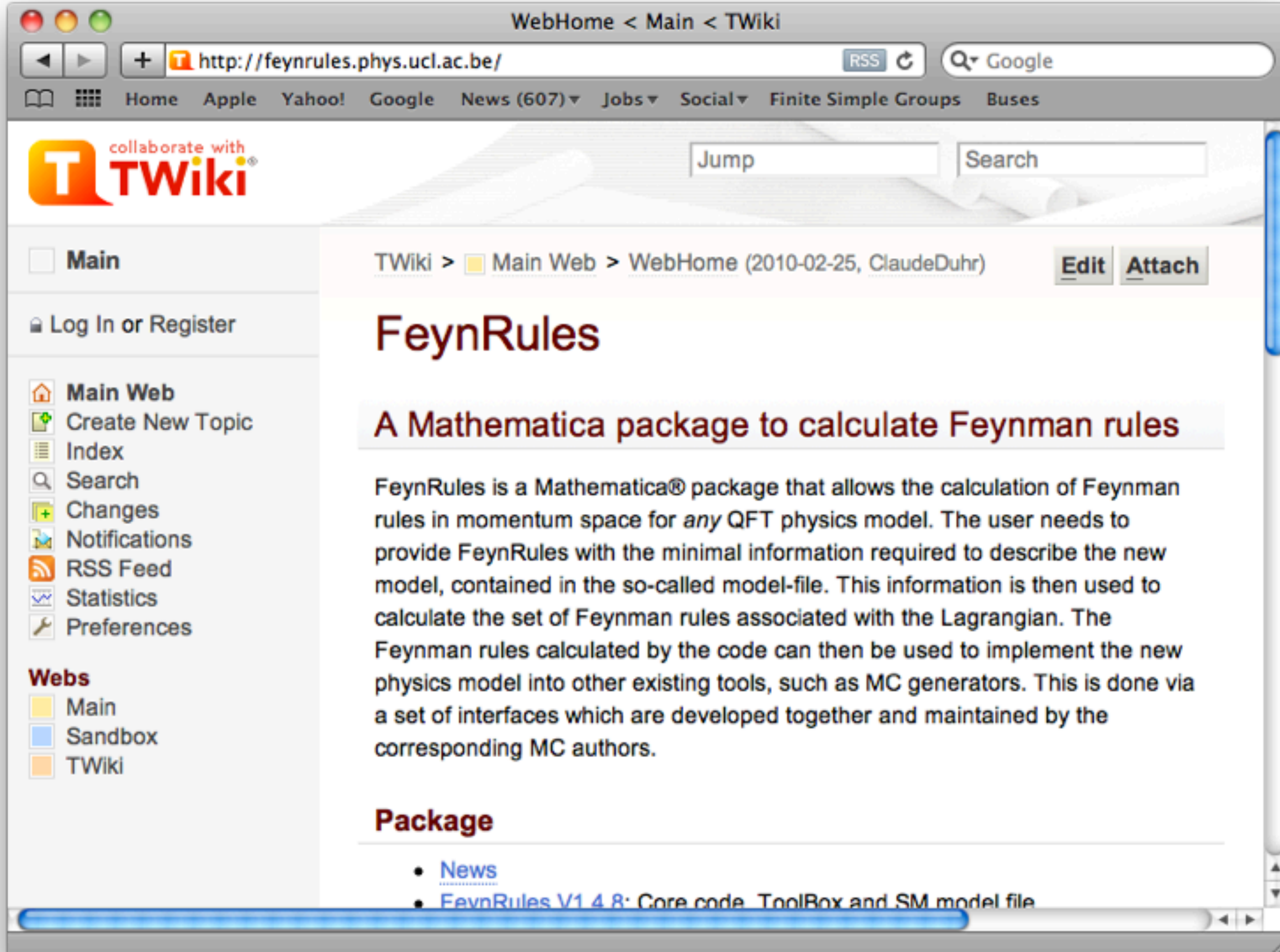


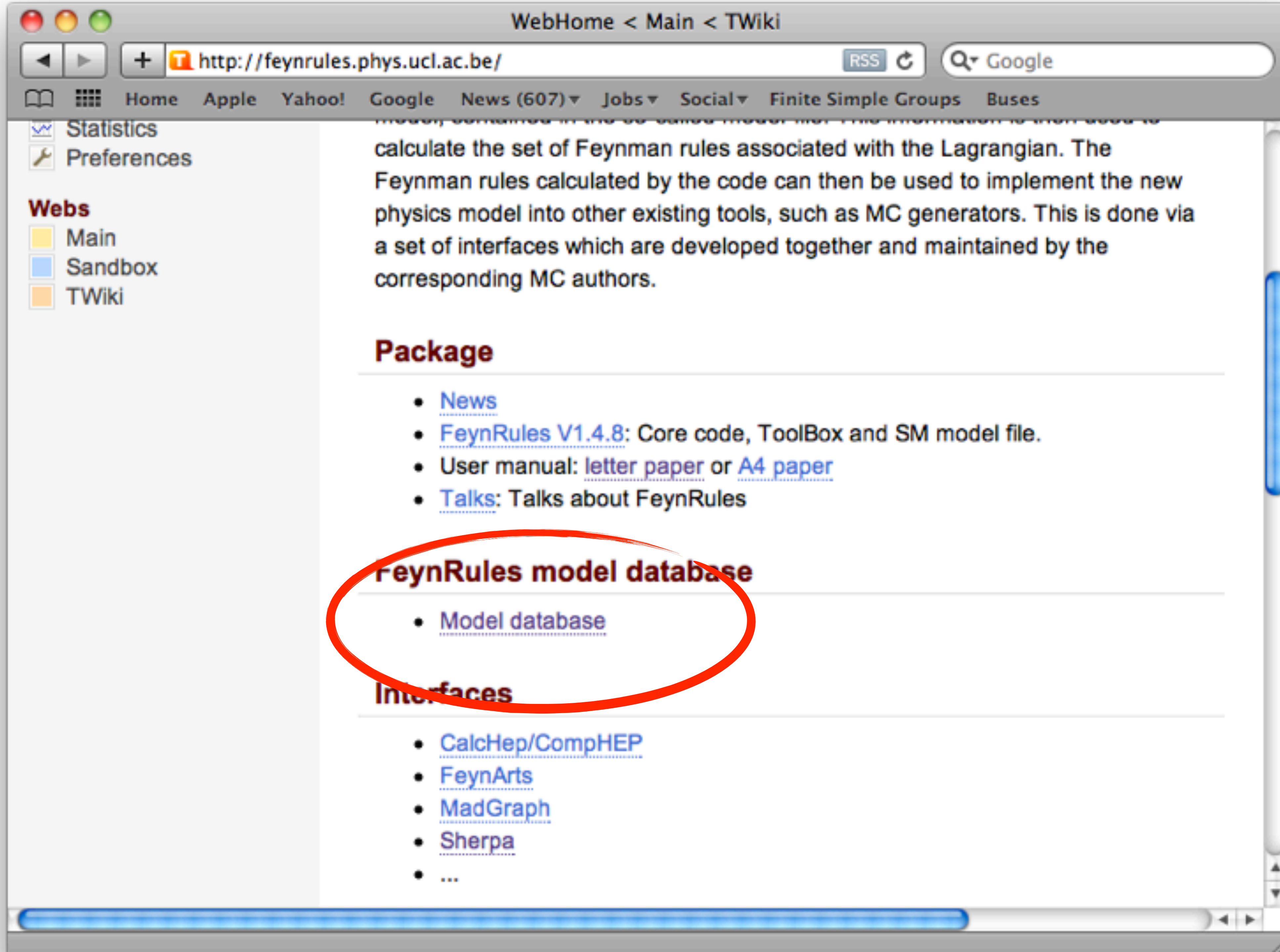
q
q
W
l
W
W′
ν
l
Z
Z
l
q
q

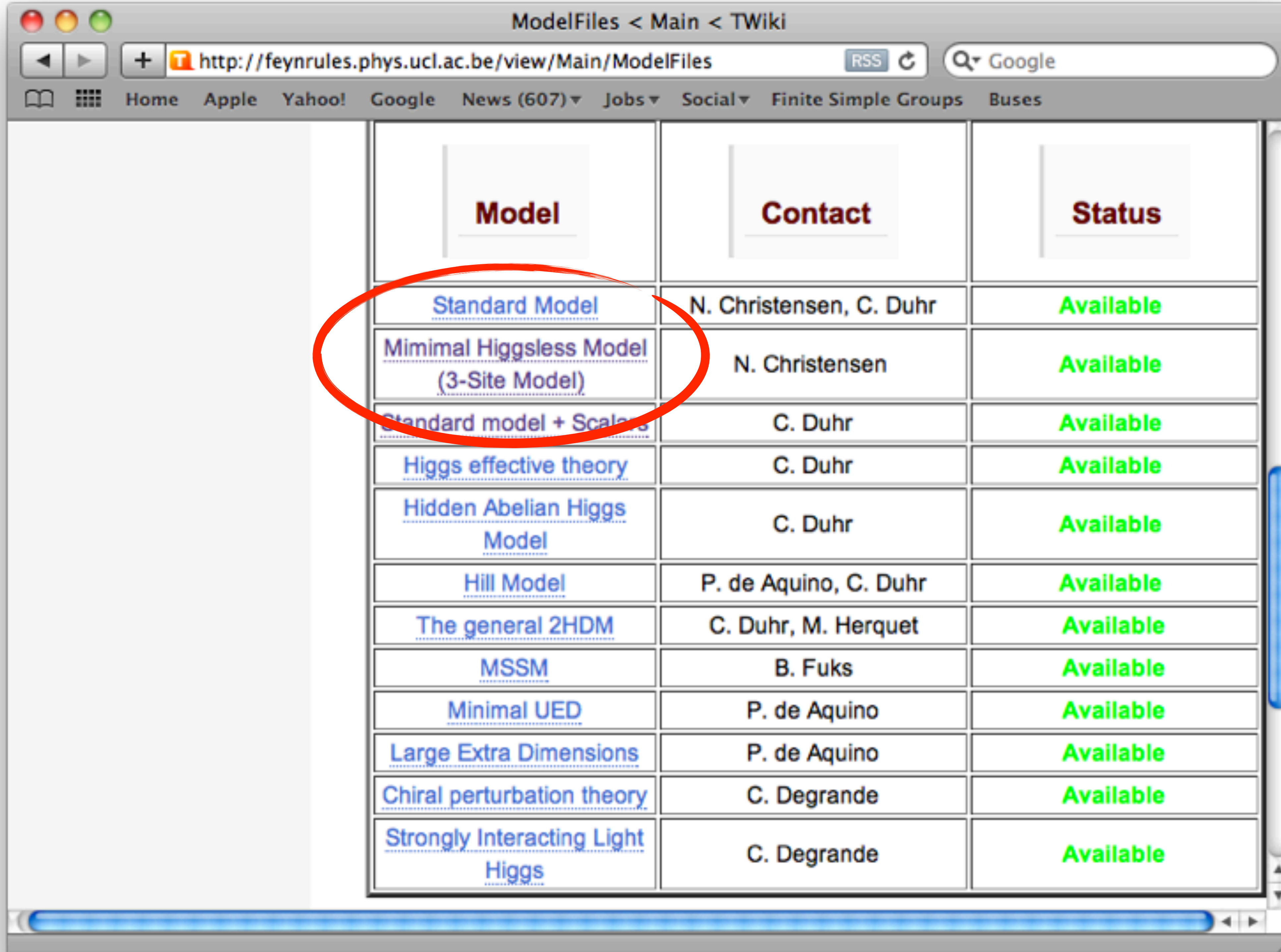

p,p→j,j,W'→j,j,W,Z→j,j,l,l,l,v
0.50
0.20
0.10
0.05
0.02
0.01
σ/bin (fb)
200
300
400
500
600
700
800
900
M_T (GeV)



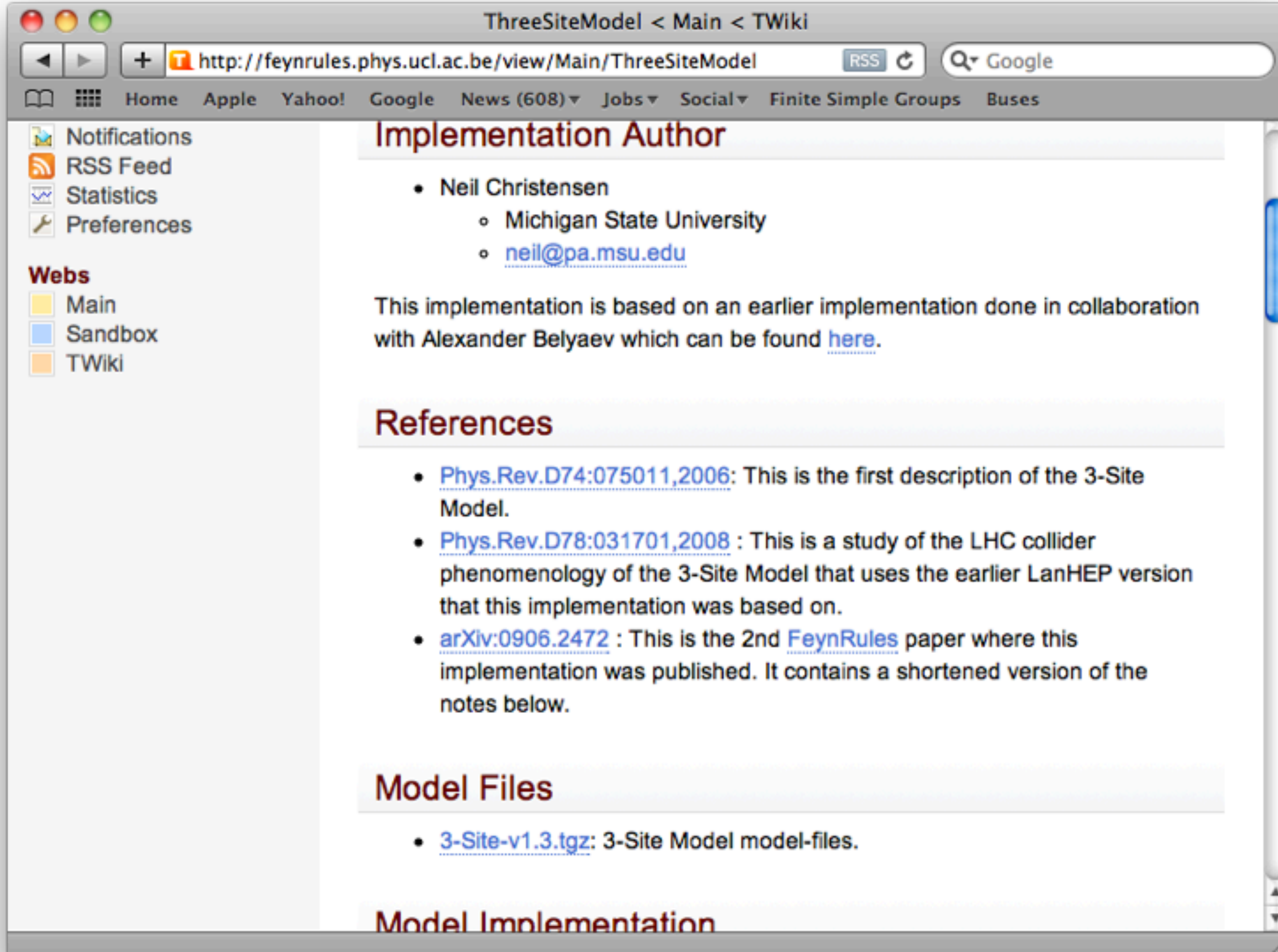
p,p→j,j,W'→j,j,W,Z→j,j,l,l,l,v
Required Lum (fb^{-1})
500
100
50
10
5
1
400
600
800
1000
1200
$M_{W'}$(GeV)


WebHome < Main < TWiki
http://feynrules.phys.ucl.ac.be/
RSS
Google
Home Apple Yahoo! Google News (607) Jobs Social Finite Simple Groups Buses
collaborate with TWiki
Jump
Search
Main
Log In or Register
Main Web
Create New Topic
Index
Search
Changes
Notifications
RSS Feed
Statistics
Preferences
Webs
Main
Sandbox
TWiki
TWiki > Main Web > WebHome (2010-02-25, ClaudeDuhr)
Edit
Attach
FeynRules
A Mathematica package to calculate Feynman rules
FeynRules is a Mathematica® package that allows the calculation of Feynman rules in momentum space for any QFT physics model. The user needs to provide FeynRules with the minimal information required to describe the new model, contained in the so-called model-file. This information is then used to calculate the set of Feynman rules associated with the Lagrangian. The Feynman rules calculated by the code can then be used to implement the new physics model into other existing tools, such as MC generators. This is done via a set of interfaces which are developed together and maintained by the corresponding MC authors.
Package
News
FeynRules V1.4.8: Core code, ToolBox and SM model file


WebHome < Main < TWiki
http://feynrules.phys.ucl.ac.be/
RSS
Google
Home
Apple
Yahoo!
Google
News (607)
Jobs
Social
Finite Simple Groups
Buses
Statistics
Preferences
Webs
Main
Sandbox
TWiki
calculate the set of Feynman rules associated with the Lagrangian. The
Feynman rules calculated by the code can then be used to implement the new
physics model into other existing tools, such as MC generators. This is done via
a set of interfaces which are developed together and maintained by the
corresponding MC authors.
Package
News
FeynRules V1.4.8: Core code, ToolBox and SM model file.
User manual: letter paper or A4 paper
Talks: Talks about FeynRules
FeynRules model database
Model database
Interfaces
CalcHep/CompHEP
FeynArts
MadGraph
Sherpa
...



Model	Contact	Status
Standard Model	N. Christensen, C. Duhr	Available
Mimimal Higgsless Model (3-Site Model)	N. Christensen	Available
Standard model + Scalars	C. Duhr	Available
Higgs effective theory	C. Duhr	Available
Hidden Abelian Higgs Model	C. Duhr	Available
Hill Model	P. de Aquino, C. Duhr	Available
The general 2HDM	C. Duhr, M. Herquet	Available
MSSM	B. Fuks	Available
Minimal UED	P. de Aquino	Available
Large Extra Dimensions	P. de Aquino	Available
Chiral perturbation theory	C. Degrande	Available
Strongly Interacting Light Higgs	C. Degrande	Available



ThreeSiteModel < Main < TWiki

http://feynrules.phys.ucl.ac.be/view/Main/ThreeSiteModel

Home Apple Yahoo! Google News (608) Jobs Social Finite Simple Groups Buses

Notifications
RSS Feed
Statistics
Preferences

Webs
Main
Sandbox
TWiki

Implementation Author

- Neil Christensen
  - Michigan State University
  - neil@pa.msu.edu

This implementation is based on an earlier implementation done in collaboration with Alexander Belyaev which can be found here.

References

- Phys.Rev.D74:075011,2006: This is the first description of the 3-Site Model.
- Phys.Rev.D78:031701,2008 : This is a study of the LHC collider phenomenology of the 3-Site Model that uses the earlier LanHEP version that this implementation was based on.
- arXiv:0906.2472 : This is the 2nd FeynRules paper where this implementation was published. It contains a shortened version of the notes below.

Model Files

- 3-Site-v1.3.tgz: 3-Site Model model-files.

Model Implementation

ThreeSiteModel < Main < TWiki

http://feynrules.phys.ucl.ac.be/view/Main/ThreeSiteModel

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Interfaces

This model implementation is known to work with the following interfaces:

- CalcHEP/CompHEP Interface
- MadGraph Interface
- Sherpa Interface: This model works with a beta version of Sherpa that will be released later this year.
- FeynArts Interface: A handful of calculations have been done but a thorough validation has not been done.

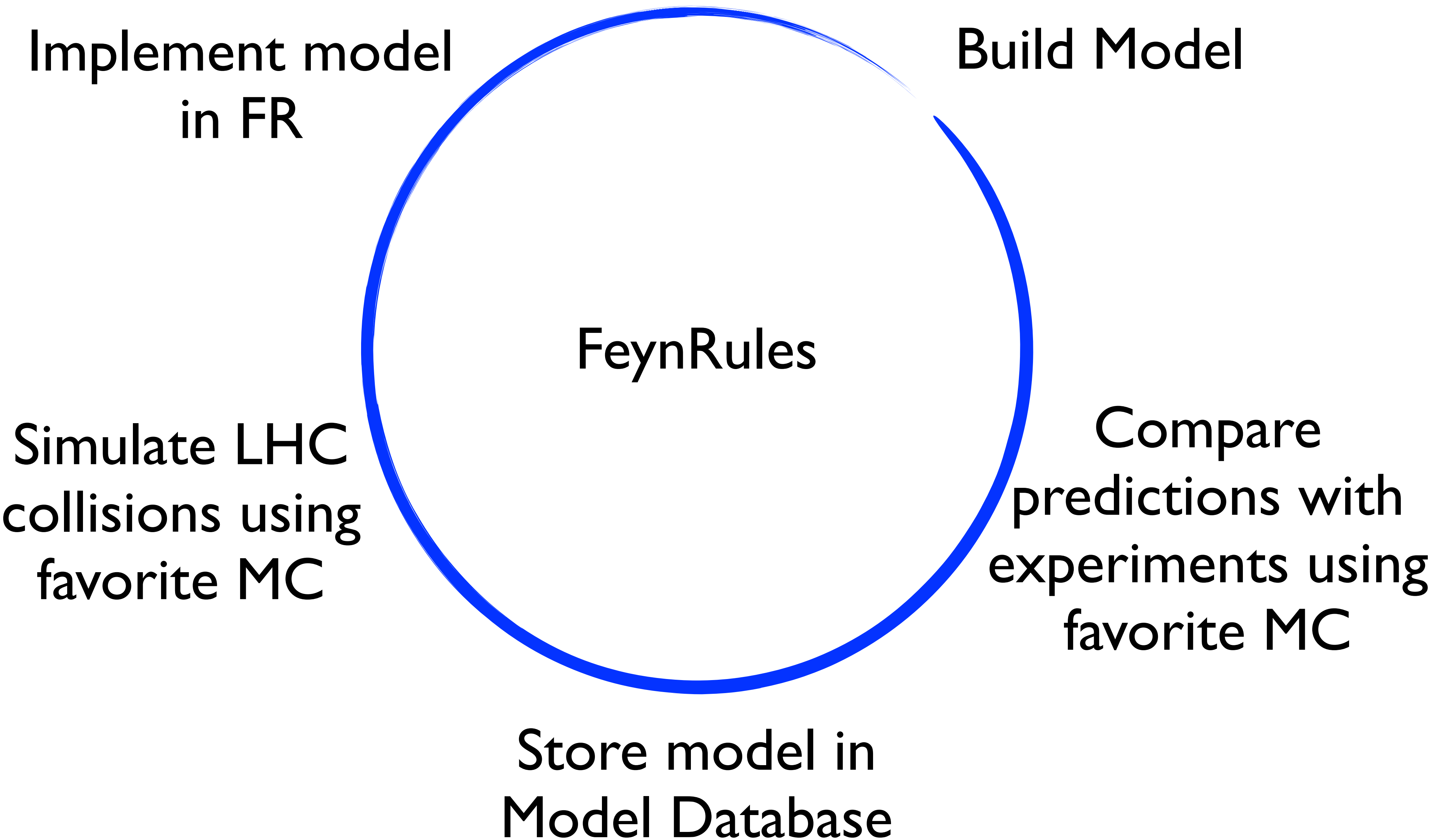
Also Whizard!

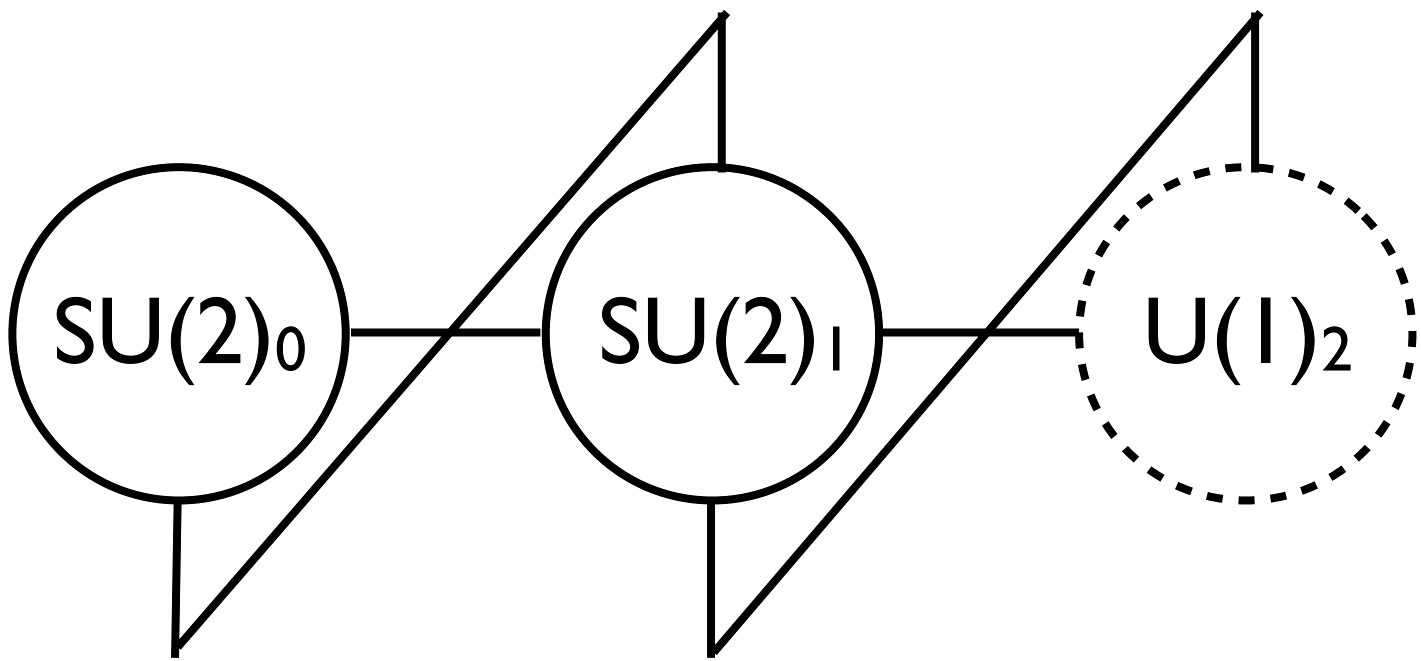
Validation

Over 200 $2 \to 2$ processes were run in a variety of ways. First, each process was compared between the original LanHEP implementation and the current FeynRules implementation. Second, each process was run across multiple monte-carlos including CalcHEP, CompHEP, MadGraph and Sherpa. Third, each process was run in two different gauges, namely Feynman gauge (in CalcHEP and CompHEP) and in unitary gauge (in CalcHEP, MadGraph and Sherpa). The cross section was computed for each process and compared to one another. Agreement to better than 1% was found for all processes. The parameters for these calculations were taken as in the model files above. The energies and cuts for these calculations were:

	Stock SM Feynman	Lanhep CalcHEP Feynman	Lanhep CalcHEP Unitary	FeynRules CalcHEP Feynman	FeynRules CalcHEP Unitary	FeynRules CompHEP Feynman	FeynRules Sherpa Unitary	FeynRules MadGraph Unitary	Speckner Whizard	FeynRules Whizard Feynman	FeynRules Whizard Unitary
$W^{+}\gamma->W^{+}\gamma$	26.013	26.013	26.013	26.013	26.013	26.013	25.9451	26.004	26.0051	26.0051	26.0051
$W^{+\prime}\gamma->W^{+}\gamma$		0	0	0	0	0	0	0	0	0	0
$W^{+\prime}\gamma->W^{+\prime}\gamma$		0.41085	0.41085	0.41085	0.41085	0.41085	0.41071	0.41112	0.410866	0.411521	0.411521
$W^{+}\gamma->W^{+}Z$	101.13	104.42	104.42	104.42	104.42	104.42	104.37	104.42	104.345	104.345	104.345
$W^{+\prime}\gamma->W^{+}Z$		1.4383	1.4383	1.4383	1.4383	1.4383	1.43673	1.4368	1.43843	1.43567	1.43567
$W^{+}\gamma->W^{+\prime}Z$		1.0906	1.0906	1.0906	1.0906	1.0906	1.09052	1.0916	1.08976	1.08658	1.08658
$W^{+}\gamma->W^{+}Z'$		1.1145	1.1145	1.1145	1.1145	1.1145	1.11413	1.1144	1.11589	1.11567	1.11567
$W^{+\prime}\gamma->W^{+\prime}Z$		0.23096	0.23096	0.23096	0.23096	0.23096	0.230829	0.23081	0.231057	0.230355	0.230355
$W^{+\prime}\gamma->W^{+}Z'$		5.8128	5.8128	5.8128	5.8128	5.8126	5.81279	5.8304	5.81545	5.81568	5.81568
$W^{+}\gamma->W^{+\prime}Z'$		0.23267	0.23267	0.23267	0.23267	0.23267	0.232495	0.23258	0.233004	0.232666	0.232666
$W^{+\prime}\gamma->W^{+\prime}Z'$		8.4966	8.4966	8.4966	8.4966	8.4966	8.4956	8.4955	8.49743	8.5113	8.5113
$W^{+}Z->W^{+}Z$	285.98	312.08	312.08	312.08	312.08	312.09	311.926	312.88	312.064	312.194	312.194
$W^{+\prime}Z->W^{+}Z$		4.0844	4.0844	4.0844	4.0844	4.0843	4.07748	4.0905	4.08203	4.08674	4.08674
$W^{+}Z'->W^{+}Z$		4.2141	4.2141	4.2141	4.2141	4.2141	4.20964	4.2206	4.21042	4.21457	4.21457
$W^{+\prime}Z'->W^{+}Z$		30.723	30.723	30.723	30.723	30.724	30.7137	30.693	30.7382	30.7114	30.7114
$W^{+\prime}Z->W^{+\prime}Z$		22.891	22.891	22.891	22.891	22.893	22.8939	22.929	22.881	22.88	22.88
$W^{+\prime}Z->W^{+}Z'$		130.3	130.3	130.3	130.3	130.3	130.217	130.28	130.436	130.399	130.399
$W^{+\prime}Z'->W^{+\prime}Z$		8.0977	8.0977	8.0977	8.0977	8.0979	8.09521	8.0822	8.09818	8.09691	8.09691
$W^{+\prime}Z'->W^{+}Z'$		19.136	19.136	19.136	19.136	19.136	19.1282	19.128	19.121	19.1333	19.1333
$W^{+\prime}Z'->W^{+\prime}Z'$		696.66	696.66	696.66	696.66	696.65	696.311	697.39	696.941	696.936	696.936

Over 200 processes compared.
All agree to better than 1%.


Implement model in FR
Build Model
FeynRules
Simulate LHC collisions using favorite MC
Compare predictions with experiments using favorite MC
Store model in Model Database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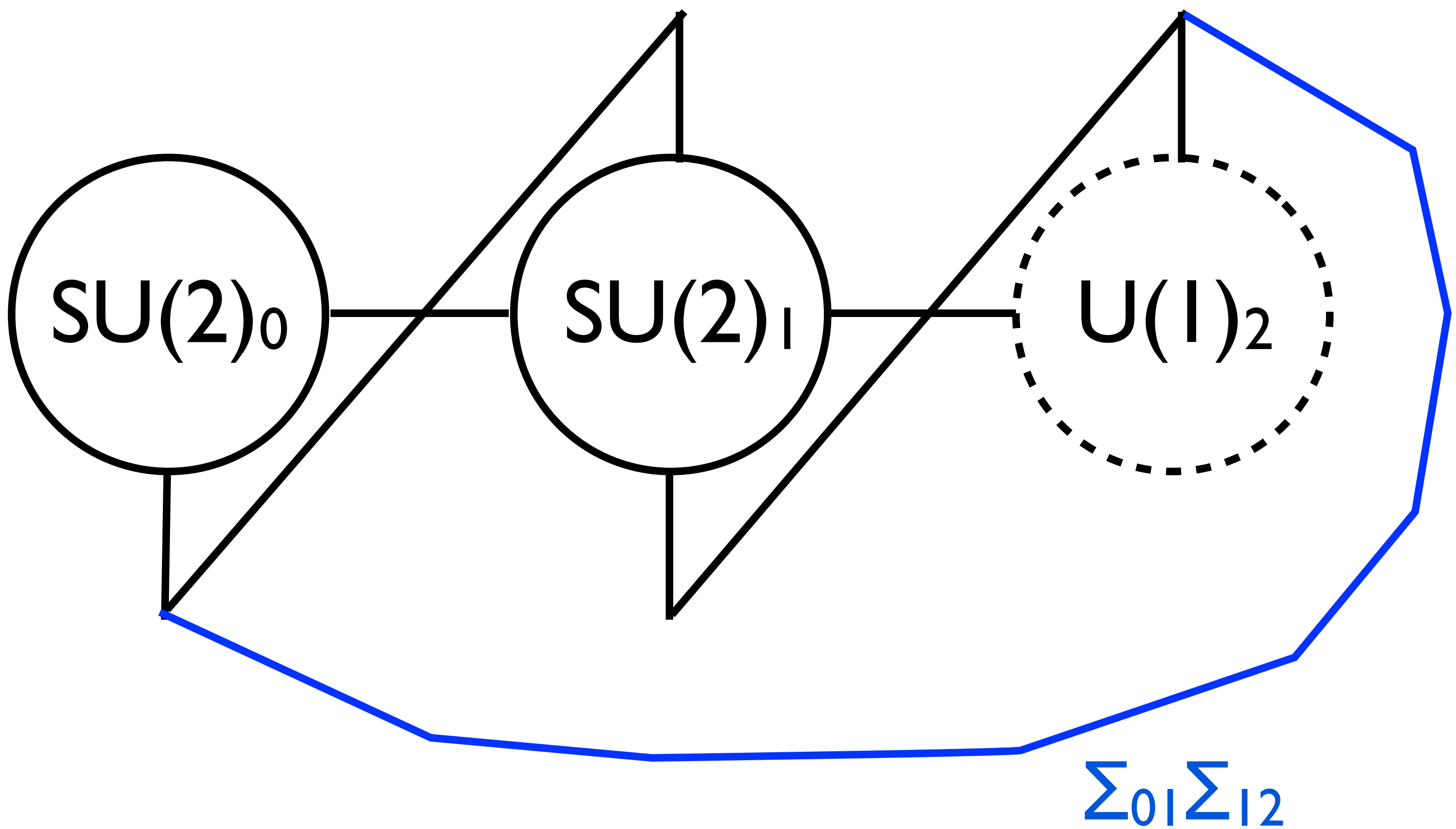
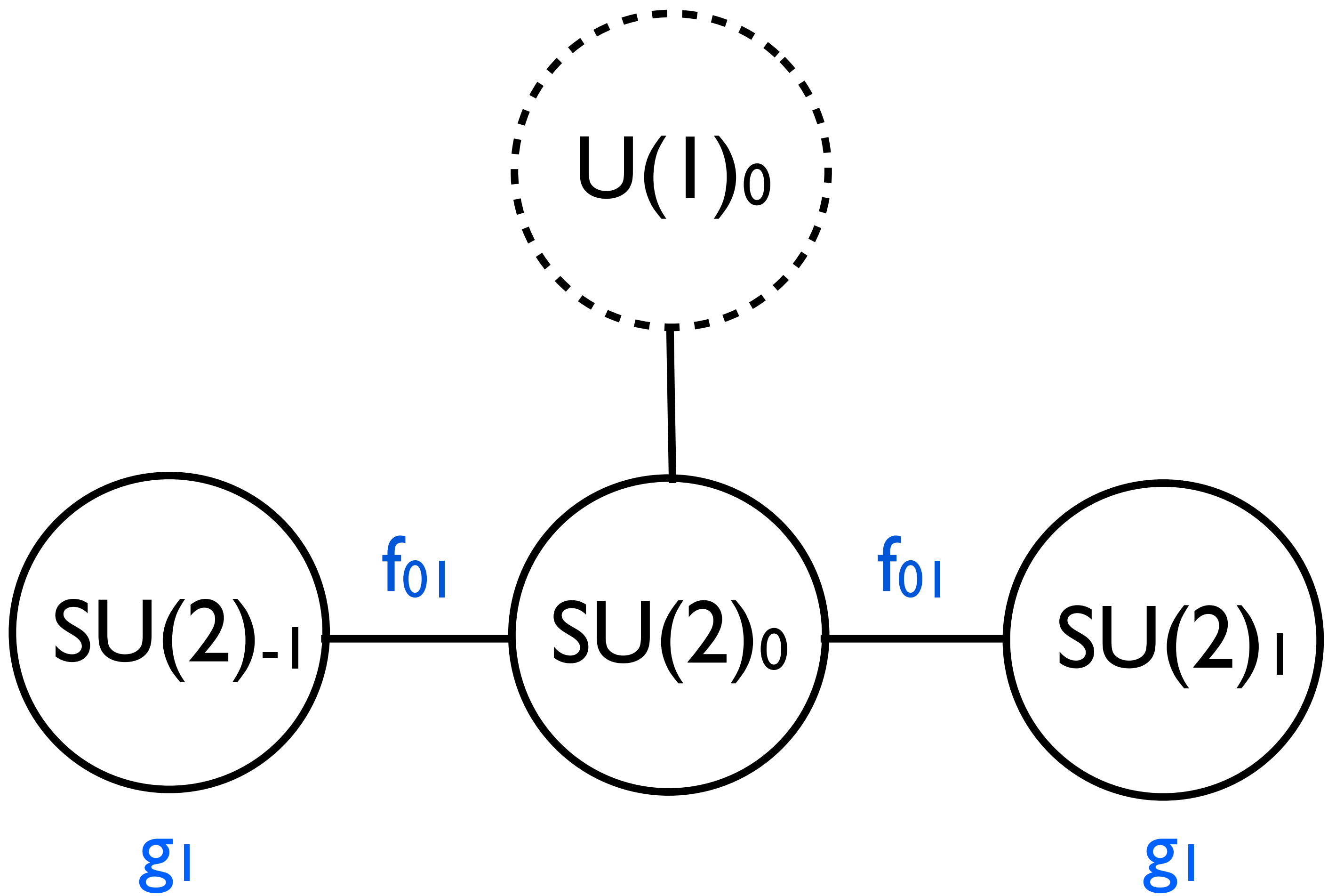
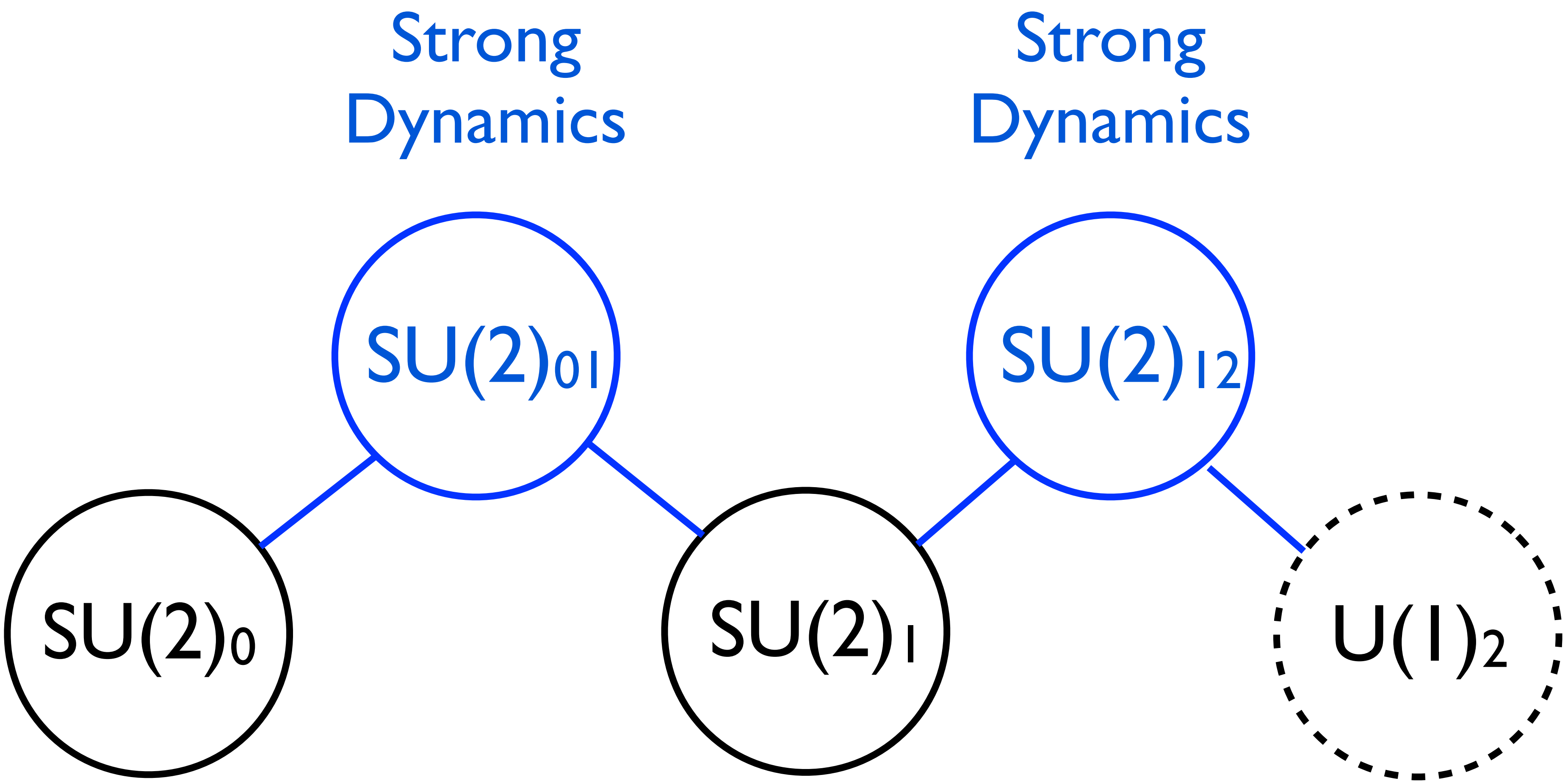
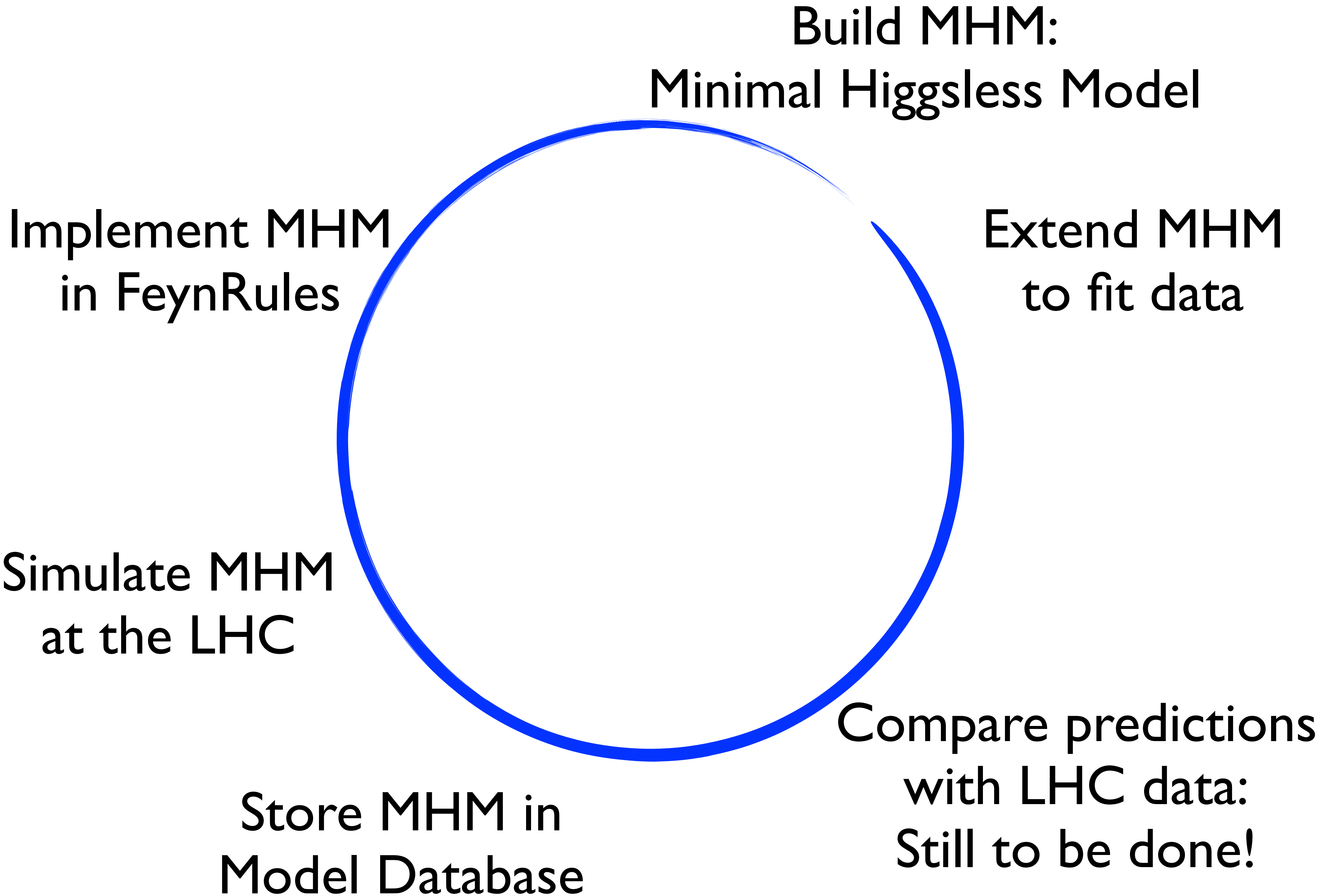
SU(2)1
U(1)2



SU(2)0
SU(2)1
U(1)2
Σ01Σ12


U(1)0
SU(2)-1
f01
SU(2)0
f01
SU(2)1
g1
g1


Strong Dynamics
Strong Dynamics
SU(2)01
SU(2)12
SU(2)0
SU(2)1
U(1)2


Build MHM:
Minimal Higgsless Model
Extend MHM
to fit data
Compare predictions
with LHC data:
Still to be done!
Store MHM in
Model Database
Simulate MHM
at the LHC
Implement MHM
in FeynRules