# FeynRules

http://europa.fyma.ucl.ac.be/feynrules

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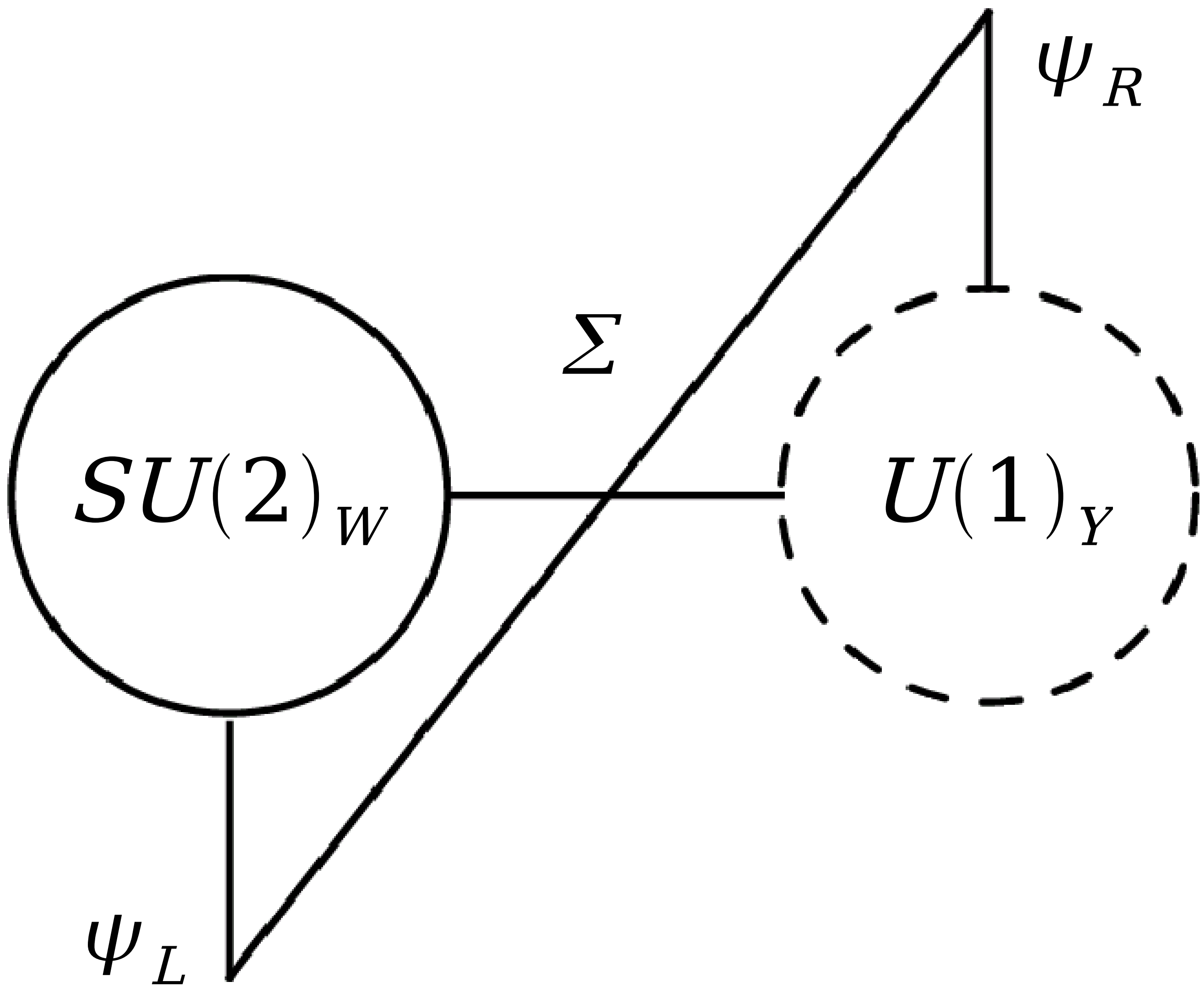
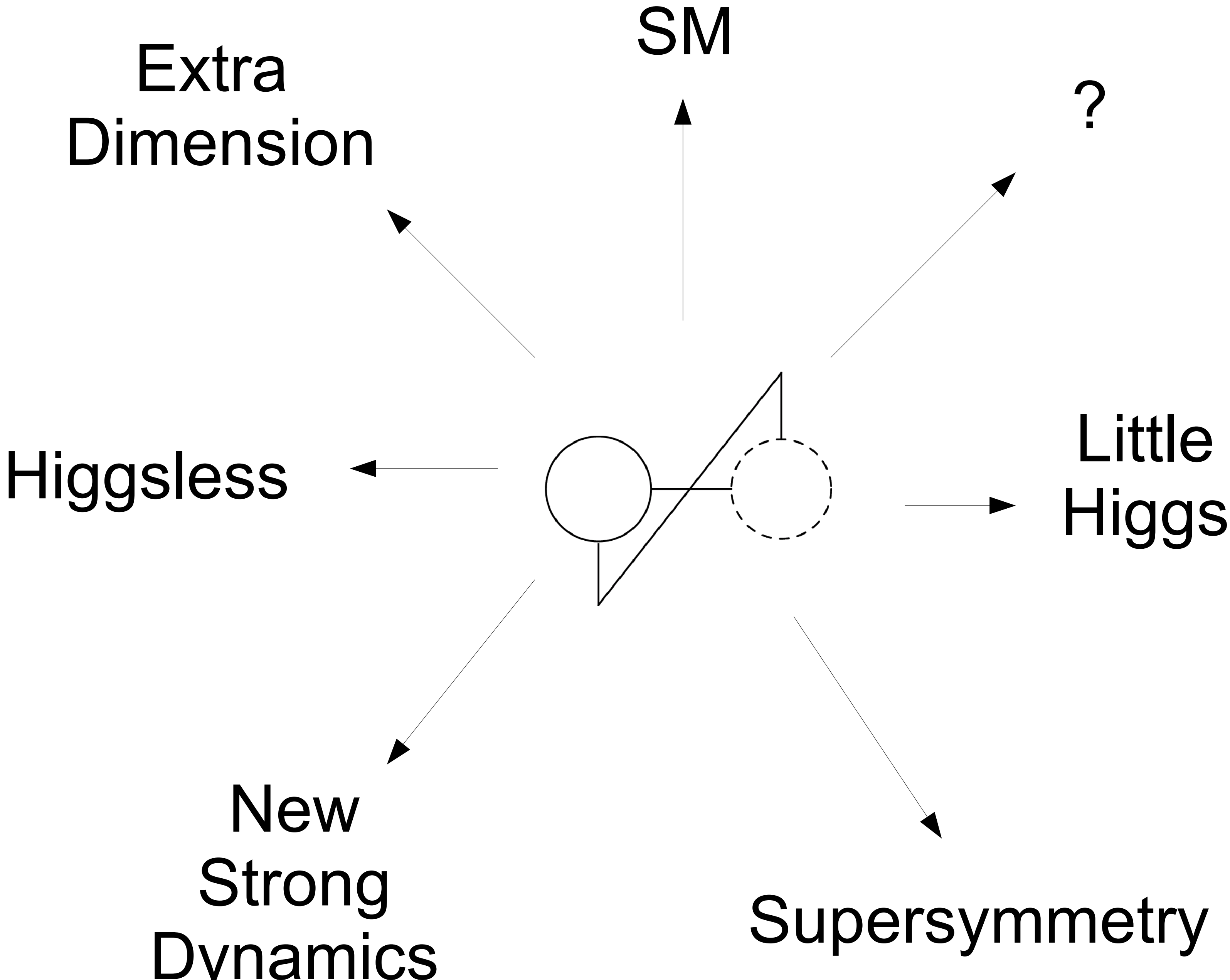
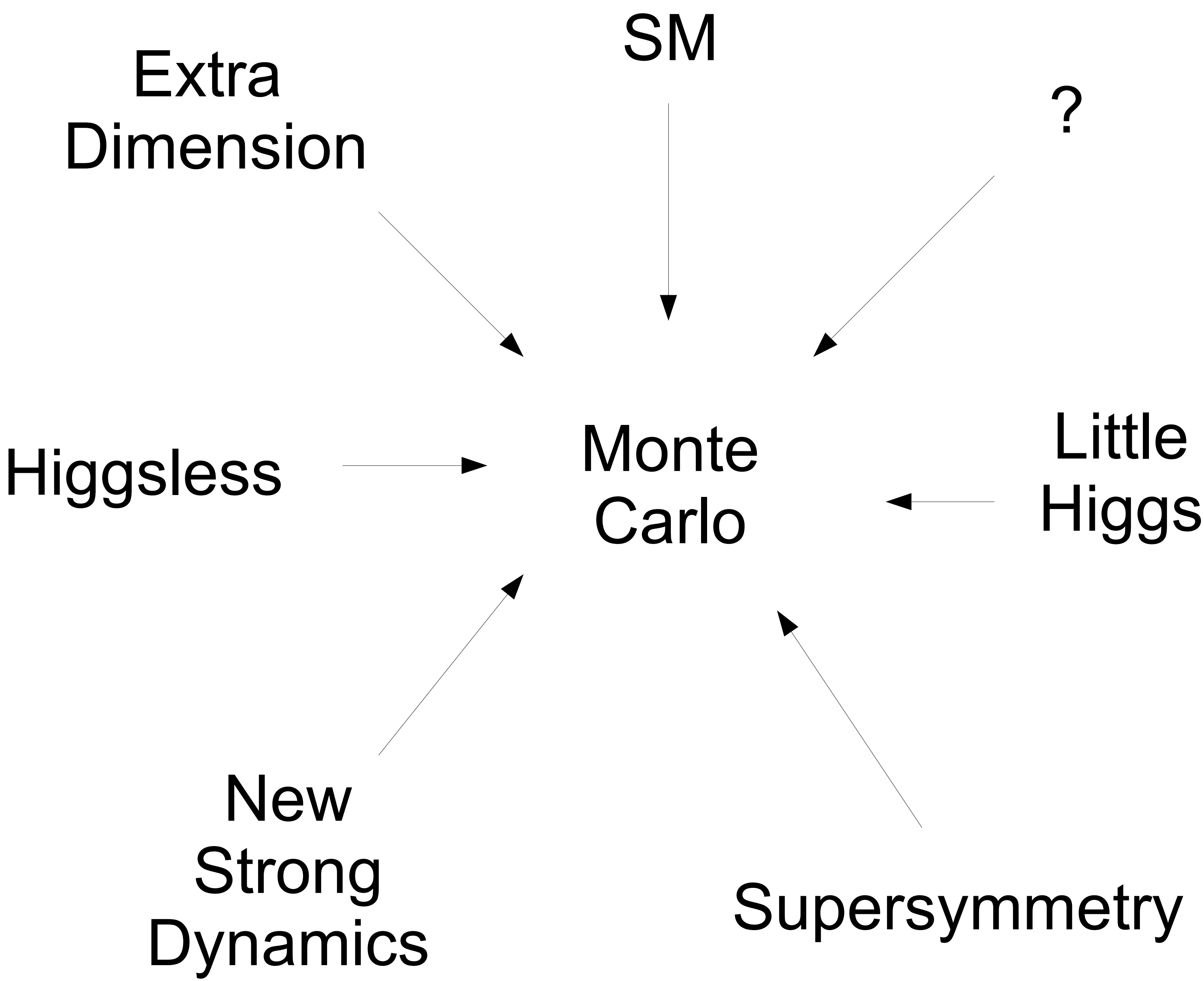
Michell Herquet
Steffen Schumann

# HSM




SM
Extra Dimension
?
Higgsless
Little Higgs
New Strong Dynamics
Supersymmetry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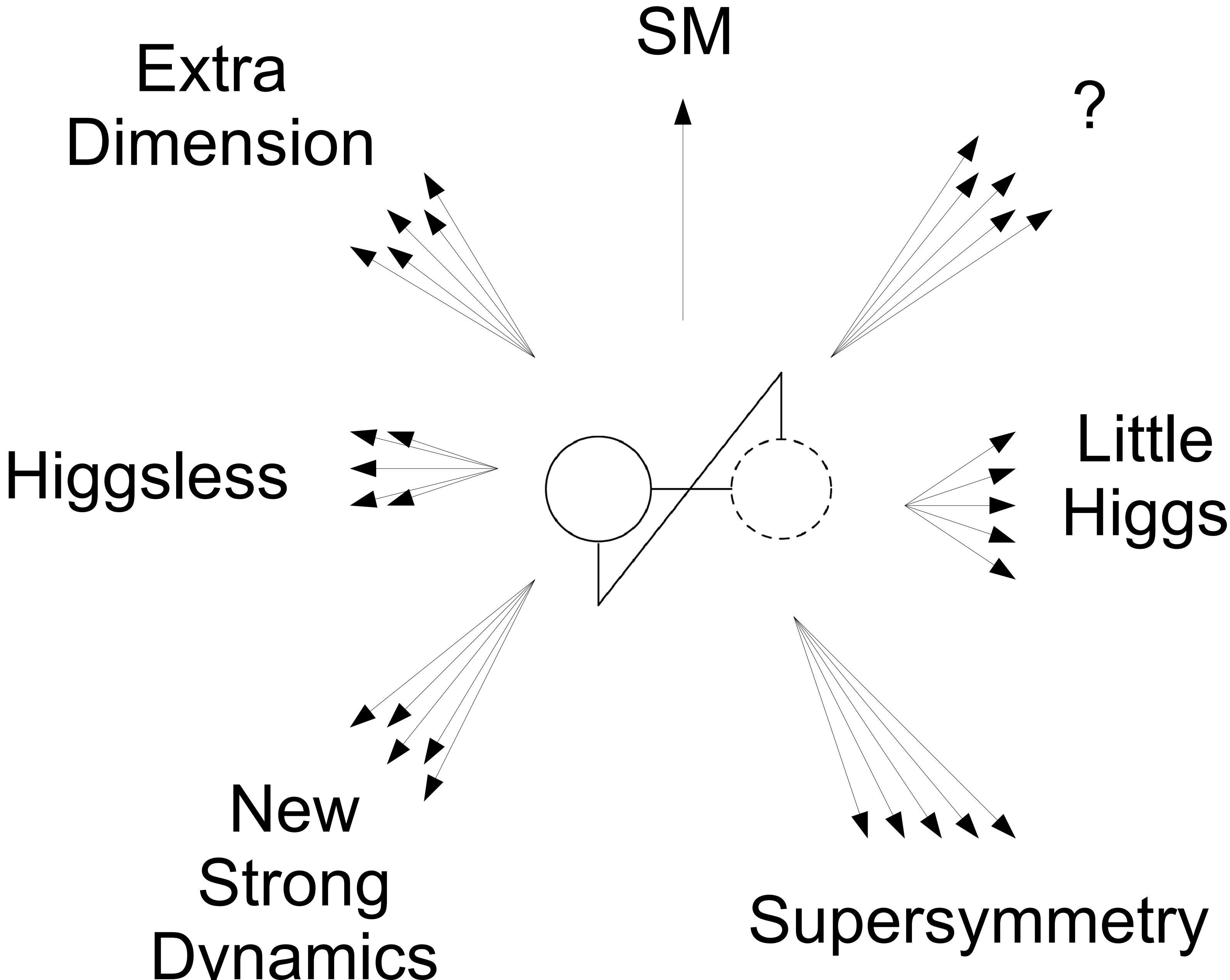
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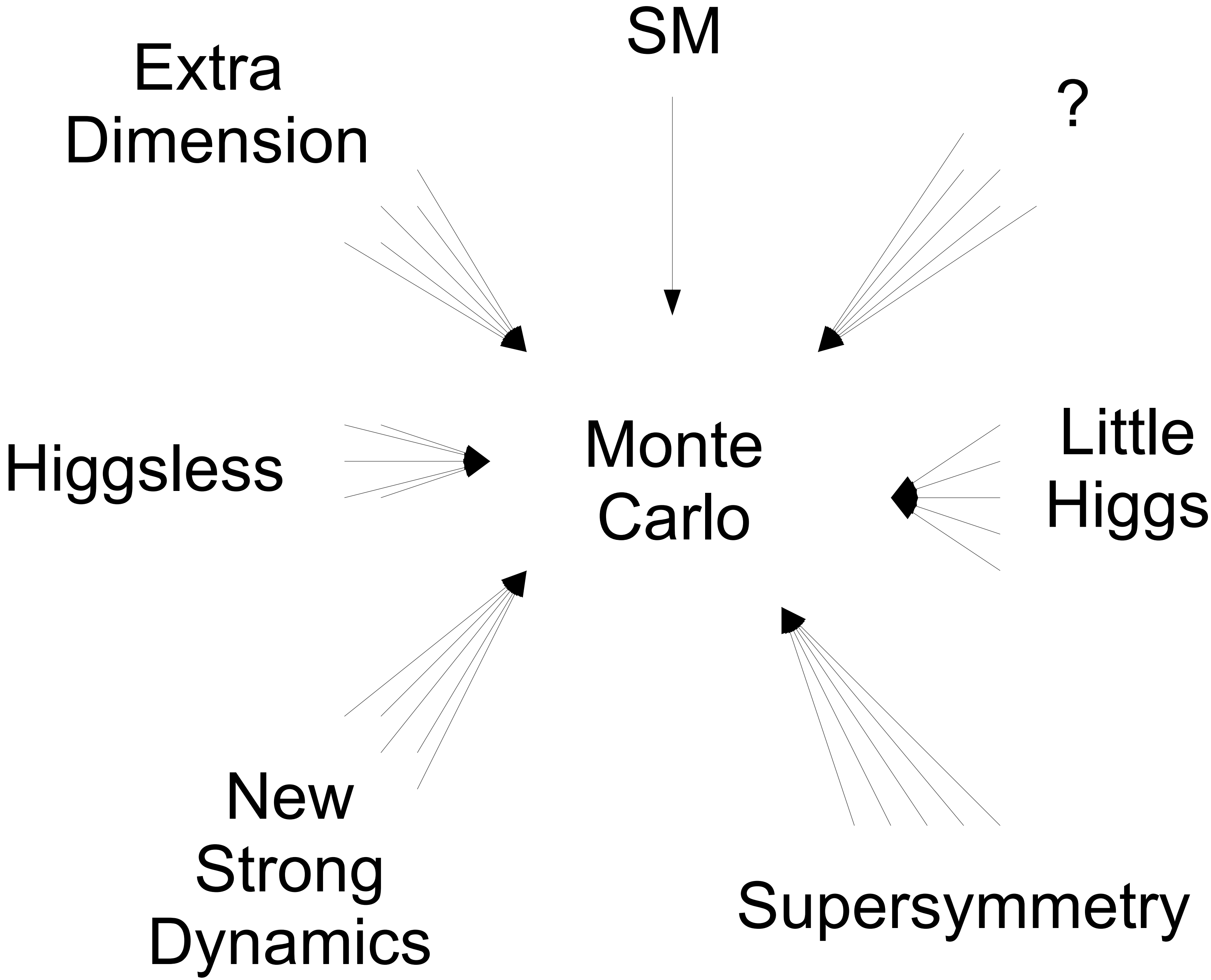
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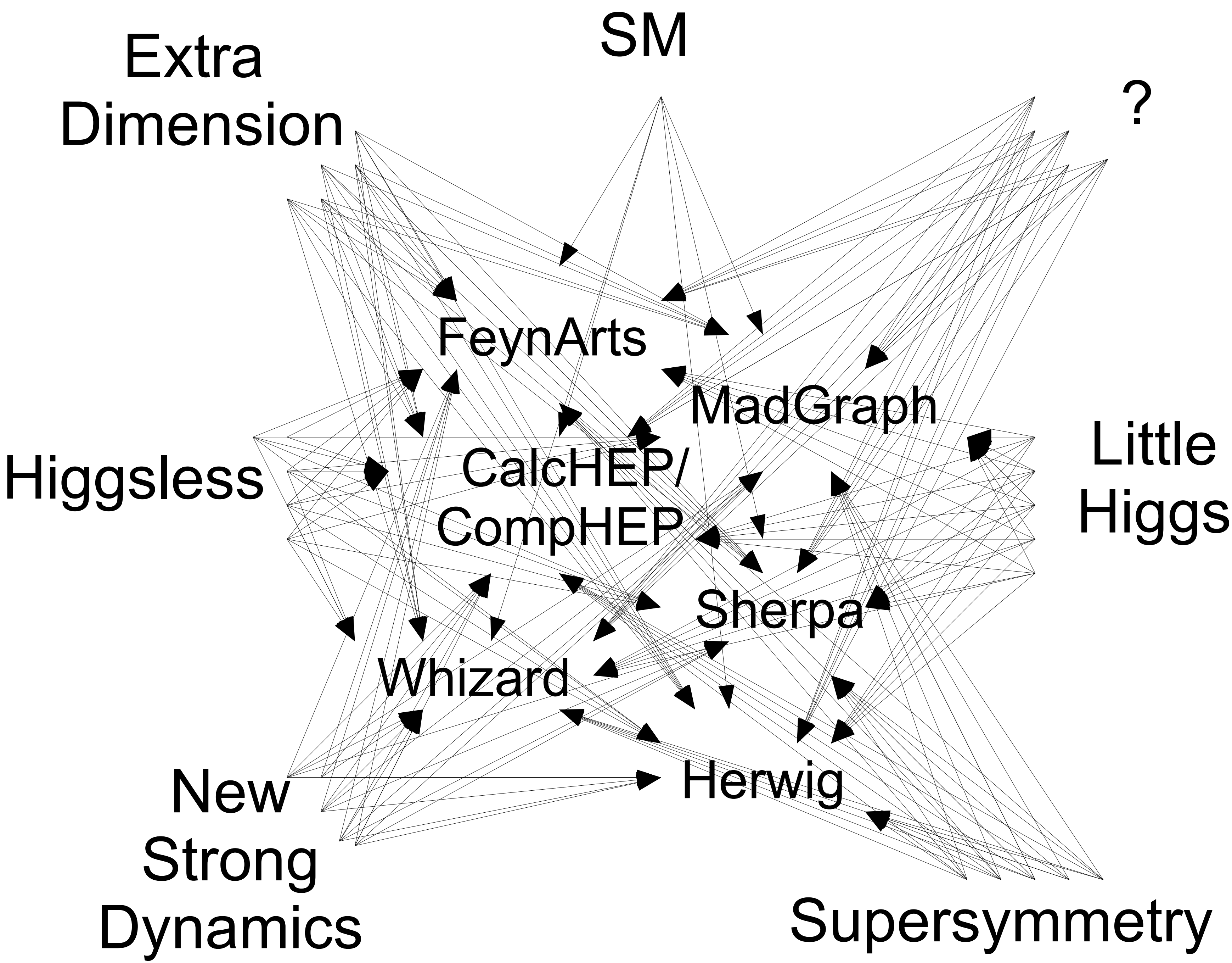
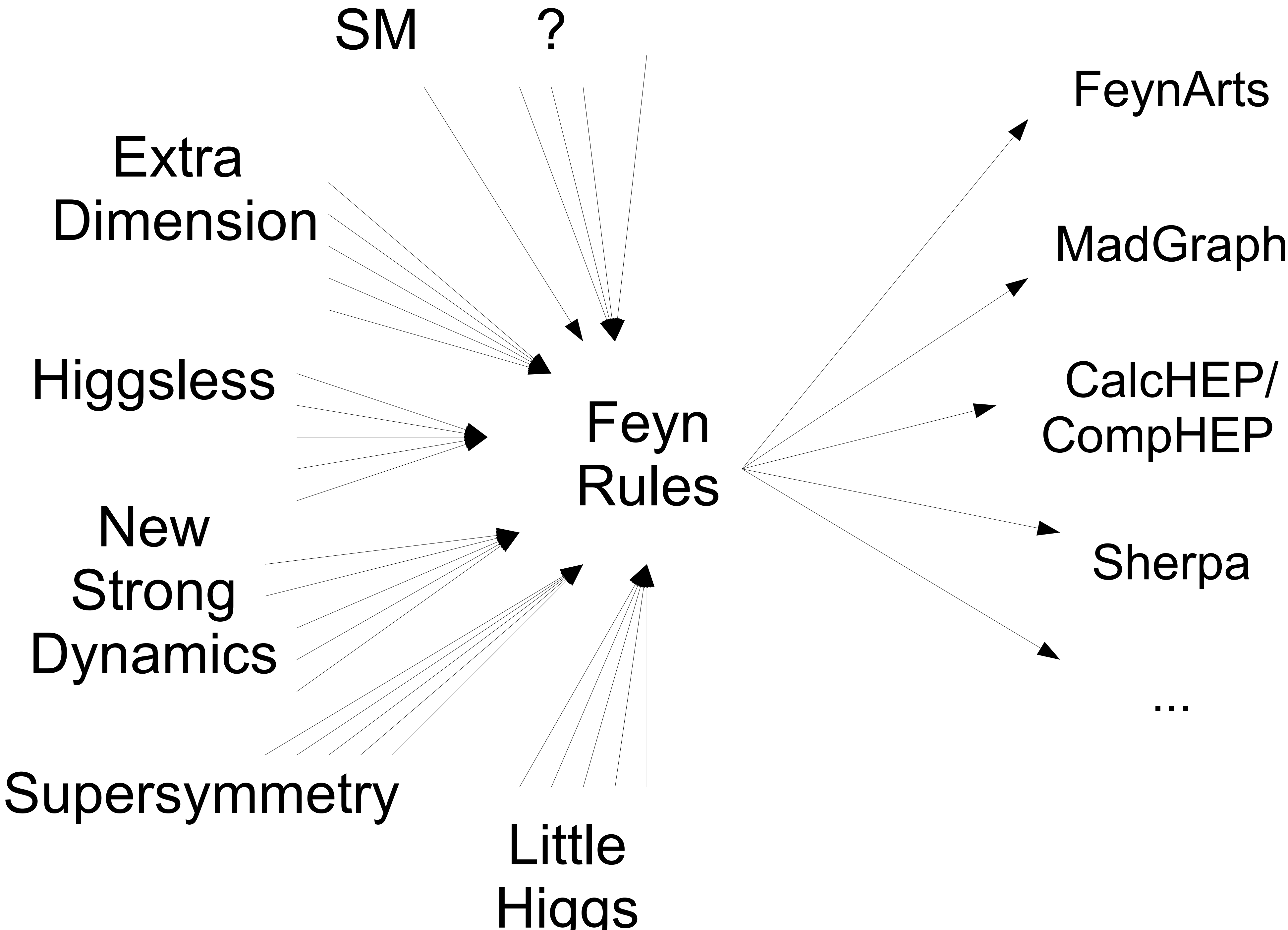


SM
Extra Dimension
?
FeynArts
MadGraph
Higgsless
CalcHEP/ CompHEP
Little Higgs
Sherpa
Whizard
Herwig
New Strong Dynamics
Supersymmetry


SM
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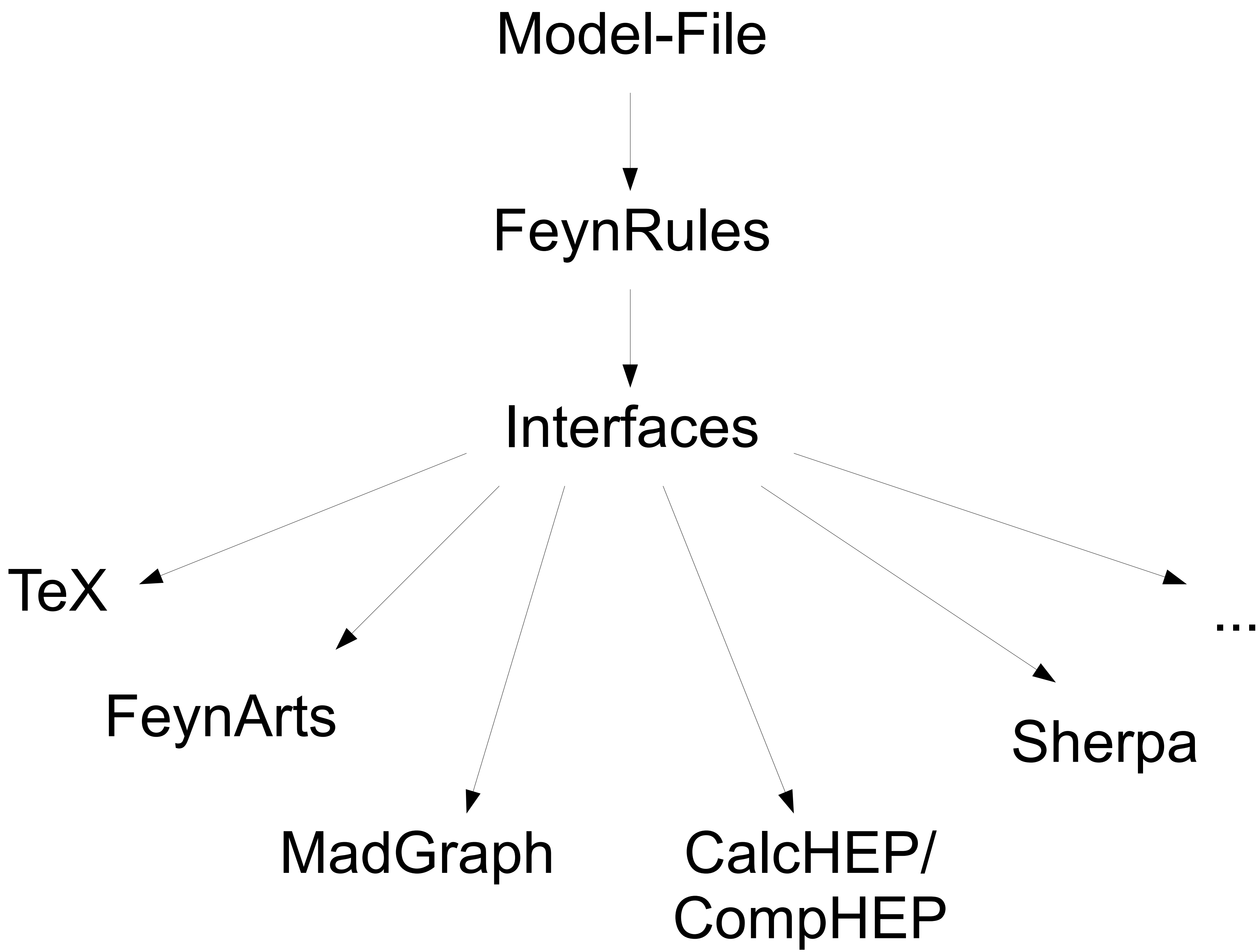
Feyn Rules
FeynArts
MadGraph
CalcHEP/ CompHEP
Sherpa
...



Model-File
FeynRules
Interfaces
TeX
FeynArts
MadGraph
CalcHEP/
CompHEP
Sherpa
...

# Model-File

Model and Index information

M$GaugeGroups = {gg1, gg2, gg3, ...}

M$Parameters = {param1, param2, param3, ...}

M$ClassesDescription = {field1, field2, field3, ... }

L = Lagrangian terms

see appendix for more details

# SM validation

31 key processes

| Process | CalcHEP Stock | CalcHEP Feynman | CalcHEP Unitary | CompHEP Feynman | MadGraph Stock |
|---|---|---|---|---|---|
| $gg \to gg$ | 116490. | 116490. | 116490. | 116490. | 116470. |
| $u\bar{u} \to gg$ | 199.95 | 199.95 | 199.95 | 199.94 | 200.06 |
| $t\bar{t} \to gg$ | 64.595 | 64.595 | 64.595 | 64.592 | 64.564 |
| $e^+e^- \to \mu^+\mu^-$ | 0.37195 | 0.37195 | 0.37195 | 0.37194 | 0.3721 |
| $e^+e^- \to e^+e^-$ | 734.15 | 734.15 | 734.15 | 734.16 | 734.15 |
| $e^+e^- \to \nu_e\bar{\nu}_e$ | 49.145 | 49.145 | 49.145 | 49.145 | 49.149 |
| $t\bar{t} \to u\bar{u}$ | 16.018 | 16.018 | 16.018 | 16.018 | 16.017 |
| $u\bar{u} \to s\bar{s}$ | 9.6103 | 9.6102 | 9.6103 | 9.6097 | 9.5995 |
| $u\bar{d} \to c\bar{s}$ | 0.23864 | 0.23864 | 0.23864 | 0.23864 | 0.23861 |
| $u\bar{s} \to c\bar{d}$ | 0.018947 | 0.018947 | 0.018947 | 0.018947 | 0.018939 |
| $t\bar{t} \to W^+W^-$ | 17.265 | 17.265 | 17.265 | 17.265 | 17.267 |
| $t\bar{t} \to ZZ$ | 1.2686 | 1.2686 | 1.2686 | 1.2686 | 1.2692 |
| $t\bar{t} \to Z\gamma$ | 1.3119 | 1.3119 | 1.3119 | 1.312 | 1.3134 |
| $t\bar{t} \to \gamma\gamma$ | 0.088486 | 0.088486 | 0.088486 | 0.088485 | 0.088528 |
| $u\bar{u} \to W^+W^-$ | 2.0465 | 2.0465 | 2.0465 | 2.0465 | 2.0467 |
| $u\bar{u} \to ZZ$ | 0.21123 | 0.21123 | 0.21123 | 0.21123 | 0.21139 |
| $u\bar{u} \to Z\gamma$ | 0.33812 | 0.33812 | 0.33812 | 0.33811 | 0.33791 |
| $u\bar{u} \to \gamma\gamma$ | 0.18322 | 0.18322 | 0.18322 | 0.18323 | 0.18327 |
| $\tau^+\tau^- \to W^+W^-$ | 6.1871 | 6.187 | 6.187 | 6.187 | 6.193 |
| $\tau^+\tau^- \to ZZ$ | 0.34765 | 0.34765 | 0.34765 | 0.34765 | 0.34765 |
| $\tau^+\tau^- \to Z\gamma$ | 2.0057 | 2.0057 | 2.0057 | 2.0057 | 2.0051 |
| $\tau^+\tau^- \to \gamma\gamma$ | 2.7791 | 2.7791 | 2.7791 | 2.779 | 2.7783 |
| $u\bar{d} \to W^+W^+W^-$ | 0.016192 | 0.016192 | - | 0.016175 | 0.016151 |
| $u\bar{d} \to ZZW^+$ | 0.004209 | 0.0042089 | - | 0.0042012 | 0.0041918 |
| $u\bar{d} \to \gamma ZW^+$ | 0.0085385 | 0.0085385 | - | 0.0085216 | 0.0085154 |
| $u\bar{d} \to \gamma\gamma W^+$ | 0.0033698 | 0.0033698 | - | 0.00338 | 0.0033718 |
| $ZZ \to ZZ$ | 1.9672 | 1.9672 | 1.9672 | 1.9672 | 1.9663 |
| $W^+W^- \to ZZ$ | 290.85 | 290.85 | 290.85 | 290.85 | 290.83 |
| $hh \to hh$ | 1.94 | 1.94 | 1.94 | 1.94 | - |
| $hh \to ZZ$ | 65.801 | 65.801 | 65.801 | 65.801 | 65.912 |
| $hh \to W^+W^-$ | 100.49 | 100.49 | 100.49 | 100.49 | 100.8 |

# 3-Site Model

Phys.Rev.D74:075011,2006
Chivukula, Coleppa, Di Chiara, Simmons, He, Kurachi, Tanabashi
arXiv:0708.2588
Belyaev, Chivukula, Christensen, He, Kuang, Qi, Simmons, Zhang

# 3-Site Model Validation

191 key processes

| | Lanhep CalcHEP Feynman | Lanhep CalcHEP Unitary | FeynRules CalcHEP Feynman | FeynRules CalcHEP Unitary | FeynRules CompHEP Feynman | FeynRules CompHEP Unitary |
|---|---|---|---|---|---|---|
| $u\bar{u}\to gg$ | 170.5 | 170.5 | 170.5 | 170.5 | 170.49 | - |
| $u'\bar{u}\to gg$ | 0 | 0 | 0 | 0 | 0 | - |
| $u'\overline{u'}\to gg$ | 0.098763 | 0.098763 | 0.098763 | 0.098763 | 0.098761 | - |
| $t\bar{t}\to gg$ | 55.906 | 55.906 | 55.906 | 55.906 | 55.903 | - |
| $t'\bar{t}\to gg$ | 0 | 0 | 0 | 0 | 0 | - |
| $t'\overline{t'}\to gg$ | 0.098774 | 0.098774 | 0.098774 | 0.098774 | 0.098771 | - |
| $u\bar{u}\to\gamma\gamma$ | 0.15862 | 0.15862 | 0.15862 | 0.15862 | 0.15862 | - |
| $u'\bar{u}\to\gamma\gamma$ | 0 | 0 | $3.6538\times10^{-37}$ | $3.6538\times10^{-37}$ | $3.6539\times10^{-37}$ | - |
| $u'\overline{u'}\to\gamma\gamma$ | 0.00027859 | 0.00027859 | 0.00027859 | 0.00027859 | 0.00027859 | - |
| $t\bar{t}\to\gamma\gamma$ | 0.075034 | 0.075034 | 0.075034 | 0.075034 | 0.075035 | - |
| $t'\bar{t}\to\gamma\gamma$ | 0 | 0 | $1.6984\times10^{-34}$ | $1.6984\times10^{-34}$ | $1.6981\times10^{-34}$ | - |
| $t'\overline{t'}\to\gamma\gamma$ | 0.0002815 | 0.0002815 | 0.0002815 | 0.0002815 | 0.0002815 | - |
| $u\bar{u}\to\gamma Z$ | 0.30828 | 0.30828 | 0.30828 | 0.30828 | 0.30829 | - |
| $u\bar{u}\to\gamma Z'$ | 0.00055876 | 0.00055876 | 0.00055876 | 0.00055876 | 0.0005587 | - |
| $u'\bar{u}\to\gamma Z$ | 0.031561 | 0.031561 | 0.031561 | 0.031561 | 0.031563 | - |
| $u'\overline{u'}\to\gamma Z$ | 0.0019654 | 0.0019654 | 0.0019654 | 0.0019654 | 0.0019654 | - |
| $u'\bar{u}\to\gamma Z'$ | 0.035049 | 0.035049 | 0.035049 | 0.035049 | 0.035053 | - |
| $u'\overline{u'}\to\gamma Z'$ | 0.014649 | 0.014649 | 0.014649 | 0.014649 | 0.014649 | - |
| $t\bar{t}\to\gamma Z$ | 1.1233 | 1.1233 | 1.1233 | 1.1233 | 1.1233 | - |
| $t\bar{t}\to\gamma Z'$ | 0.00016576 | 0.00016576 | 0.00016576 | 0.00016576 | 0.00016576 | - |
| $t'\bar{t}\to\gamma Z$ | 0.033204 | 0.033204 | 0.033204 | 0.033204 | 0.033204 | - |
| $t'\overline{t'}\to\gamma Z$ | 0.0049275 | 0.0049275 | 0.0049275 | 0.0049275 | 0.0049276 | - |
| $t'\bar{t}\to\gamma Z'$ | 0.042476 | 0.042476 | 0.042476 | 0.042476 | 0.042473 | - |
| $t'\overline{t'}\to\gamma Z'$ | 0.012657 | 0.012657 | 0.012657 | 0.012657 | 0.012657 | - |
| $u\bar{u}\to ZZ$ | 0.19694 | 0.19694 | 0.19694 | 0.19694 | 0.19694 | - |
| $u\bar{u}\to ZZ'$ | 0.00017633 | 0.00017633 | 0.00017633 | 0.00017633 | 0.00017633 | - |
| $u'\overline{u'}\to ZZ$ | 0.65643 | 0.65643 | 0.65643 | 0.65643 | 0.65643 | - |
| $u\bar{u}\to Z'Z'$ | 0.000017411 | 0.000017411 | 0.000017411 | 0.000017411 | 0.000017411 | - |
| $u'\overline{u'}\to ZZ'$ | 1.429 | 1.429 | 1.429 | 1.429 | 1.429 | - |
| $u'\bar{u}\to Z'Z'$ | 5.7578 | 5.7578 | 5.7577 | 5.7577 | 5.7576 | - |
| $u'\overline{u'}\to Z'Z'$ | 0.9318 | 0.9318 | 0.9318 | 0.9318 | 0.9318 | - |
| $t\bar{t}\to ZZ$ | 3.722 | 3.722 | 3.722 | 3.722 | 3.722 | - |
| $t\bar{t}\to ZZ'$ | 0.0030041 | 0.0030041 | 0.0030041 | 0.0030041 | 0.0030041 | - |
| $t'\bar{t}\to ZZ$ | 7.1013 | 7.1013 | 7.1013 | 7.1013 | 7.1013 | - |
| $t'\overline{t'}\to ZZ$ | 1.5706 | 1.5706 | 1.5706 | 1.5706 | 1.5706 | - |
| $t'\bar{t}\to ZZ'$ | 18.994 | 18.994 | 18.994 | 18.994 | 18.995 | - |
| $t\bar{t}\to Z'Z'$ | 0.00081748 | 0.00081748 | 0.00081748 | 0.00081748 | 0.00081747 | - |
| $t'\overline{t'}\to ZZ'$ | 0.31826 | 0.31826 | 0.31826 | 0.31826 | 0.31826 | - |
| $t'\overline{t'}\to Z'Z'$ | 1.887 | 1.887 | 1.887 | 1.887 | 1.887 | - |
| $u\bar{d}\to\gamma W^+$ | 0.40404 | 0.40404 | 0.40404 | 0.40404 | 0.40414 | - |
| $u\bar{d}\to\gamma W^{+\prime}$ | 0 | 0 | $3.5597\times10^{-34}$ | $3.6326\times10^{-34}$ | $3.5599\times10^{-34}$ | - |
| $u'\bar{d}\to\gamma W^+$ | 0.013331 | 0.013331 | 0.013331 | 0.013331 | 0.013333 | - |
| $u'\overline{d'}\to\gamma W^+$ | 0.00058105 | 0.00058105 | 0.00058105 | 0.00058105 | 0.00058105 | - |
| $u'\bar{d}\to\gamma W^{+\prime}$ | 0.015262 | 0.015262 | 0.015262 | 0.015262 | 0.015262 | - |
| $u'\overline{d'}\to\gamma W^{+\prime}$ | 0.0038294 | 0.0038294 | 0.0038294 | 0.0038294 | 0.0038295 | - |
| $t\bar{b}\to\gamma W^+$ | 0.48358 | 0.48358 | 0.48358 | 0.48358 | 0.48358 | - |
| $t\bar{b}\to\gamma W^{+\prime}$ | $2.661\times10^{-6}$ | $2.661\times10^{-6}$ | $2.661\times10^{-6}$ | $2.661\times10^{-6}$ | $2.661\times10^{-6}$ | - |
| $t'\bar{b}\to\gamma W^+$ | 0.011891 | 0.011891 | 0.011891 | 0.011891 | 0.011891 | - |
| $t'\overline{b'}\to\gamma W^+$ | 0.00091791 | 0.00091791 | 0.00091791 | 0.00091791 | 0.00091792 | - |
| $t'\bar{b}\to\gamma W^{+\prime}$ | 0.015651 | 0.015651 | 0.015651 | 0.015651 | 0.015652 | - |
| $t'\overline{b'}\to\gamma W^{+\prime}$ | 0.0033961 | 0.0033961 | 0.0033961 | 0.0033961 | 0.0033961 | - |
| $u\bar{d}\to ZW^+$ | 1.1175 | 1.1175 | 1.1175 | 1.1175 | 1.1175 | - |
| $u\bar{d}\to ZW^{+\prime}$ | 0.093081 | 0.093081 | 0.093081 | 0.093081 | 0.093081 | - |
| $u\bar{d}\to Z'W^+$ | 0.091217 | 0.091217 | 0.091217 | 0.091217 | 0.091217 | - |
| $u'\overline{d'}\to ZW^+$ | 2.0768 | 2.0768 | 2.0768 | 2.0768 | 2.0769 | - |
| $u'\overline{d'}\to Z'W^+$ | 2.8699 | 2.8699 | 2.8699 | 2.8699 | 2.8699 | - |
| $u'\overline{d'}\to ZW^{+\prime}$ | 2.9439 | 2.9439 | 2.9439 | 2.9439 | 2.9439 | - |
| $u'\overline{d'}\to Z'W^{+\prime}$ | 2.6562 | 2.6562 | 2.6562 | 2.6562 | 2.6562 | - |
| $t\bar{b}\to ZW^+$ | 3.2078 | 3.2078 | 3.2078 | 3.2078 | 3.2076 | - |
| $t\bar{b}\to ZW^{+\prime}$ | 1.5603 | 1.5603 | 1.5603 | 1.5603 | 1.5604 | - |
| $t'\overline{b'}\to ZW^+$ | 3.1463 | 3.1463 | 3.1463 | 3.1463 | 3.1463 | - |
| $t'\overline{b'}\to Z'W^+$ | 2.0864 | 2.0864 | 2.0864 | 2.0864 | 2.0864 | - |
| $t'\overline{b'}\to ZW^{+\prime}$ | 2.1612 | 2.1612 | 2.1612 | 2.1612 | 2.1612 | - |
| $t'\overline{b'}\to Z'W^{+\prime}$ | 4.0253 | 4.0253 | 4.0253 | 4.0253 | 4.0253 | - |
| $u\bar{u}\to W^+W^-$ | 1.6964 | 1.6964 | 1.6964 | 1.6964 | 1.6964 | - |
| $u\bar{u}\to W^+W^{-\prime}$ | 0.048112 | 0.048112 | 0.048112 | 0.048112 | 0.048112 | - |
| $u'\overline{u'}\to W^+W^-$ | 2.2967 | 2.2967 | 2.2967 | 2.2967 | 2.2967 | - |
| $u'\bar{u}\to W^+W^{-\prime}$ | 10.53 | 10.53 | 10.53 | 10.53 | 10.53 | - |
| $u\bar{u}\to W^{+\prime}W^{-\prime}$ | 0.026073 | 0.026073 | 0.026073 | 0.026073 | 0.026073 | - |
| $u'\overline{u'}\to W^+W^{-\prime}$ | 2.8898 | 2.8898 | 2.8898 | 2.8898 | 2.8898 | - |
| $u'\bar{u}\to W^{+\prime}W^{-\prime}$ | 11.989 | 11.989 | 11.989 | 11.989 | 11.989 | - |
| $u'\overline{u'}\to W^{+\prime}W^{-\prime}$ | 3.2639 | 3.2639 | 3.2639 | 3.2639 | 3.2639 | - |
| $t\bar{t}\to W^+W^-$ | 28.473 | 28.473 | 28.473 | 28.473 | 28.473 | - |
| $t'\bar{t}\to W^+W^-$ | 15.349 | 15.349 | 15.349 | 15.349 | 15.348 | - |
| $t'\overline{t'}\to W^+W^-$ | 3.2841 | 3.2841 | 3.2841 | 3.2841 | 3.2841 | - |
| $t'\bar{t}\to W^+W^{-\prime}$ | 17.737 | 17.737 | 17.737 | 17.737 | 17.737 | - |
| $t\bar{t}\to W^{+\prime}W^{-\prime}$ | 0.043117 | 0.043117 | 0.043117 | 0.043117 | 0.043117 | - |
| $t'\overline{t'}\to W^+W^{-\prime}$ | 1.9339 | 1.9339 | 1.9339 | 1.9339 | 1.9339 | - |
| $t'\bar{t}\to W^{+\prime}W^{-\prime}$ | 17.947 | 17.947 | 17.947 | 17.947 | 17.947 | - |
| $t'\overline{t'}\to W^{+\prime}W^{-\prime}$ | 4.4655 | 4.4655 | 4.4655 | 4.4655 | 4.4655 | - |
| $e\bar{e}\to e\bar{e}$ | 736.83 | 736.83 | 736.83 | 736.83 | 736.81 | - |
| $e\bar{e}\to e'\bar{e}$ | 0.093127 | 0.093127 | 0.093127 | 0.093127 | 0.093127 | - |
| $e'\bar{e}\to e'\bar{e}$ | 745.94 | 745.94 | 745.94 | 745.94 | 746.04 | - |
| $e'\overline{e'}\to e\overline{e'}$ | 0.99477 | 0.99477 | 0.99477 | 0.99477 | 0.99478 | - |
| $e'\overline{e'}\to e'\overline{e'}$ | 1366.2 | 1366.2 | 1366.2 | 1366.2 | 1366.2 | - |
| $e\bar{e}\to\mu\bar{\mu}$ | 0.32623 | 0.32623 | 0.32623 | 0.32623 | 0.32623 | - |
| $e\bar{e}\to\mu'\bar{\mu}$ | $2.9705\times10^{-6}$ | $2.9705\times10^{-6}$ | $2.9705\times10^{-6}$ | $2.9705\times10^{-6}$ | $2.9705\times10^{-6}$ | - |
| $e'\bar{e}\to\mu'\bar{\mu}$ | 0.78676 | 0.78676 | 0.78676 | 0.78676 | 0.78676 | - |
| $e\bar{e}\to\mu'\overline{\mu'}$ | 0.00048778 | 0.00048778 | 0.00048778 | 0.00048778 | 0.00048779 | - |
| $e'\overline{e'}\to\mu\bar{\mu}$ | 0.0015054 | 0.0015054 | 0.0015054 | 0.0015054 | 0.0015054 | - |
| $e'\bar{e}\to\mu'\overline{\mu'}$ | 0.075312 | 0.075312 | 0.075312 | 0.075312 | 0.075312 | - |
| $e'\overline{e'}\to\mu'\bar{\mu}$ | 0.16051 | 0.16051 | 0.16051 | 0.16051 | 0.16051 | - |
| $e'\overline{e'}\to\mu'\overline{\mu'}$ | 0.22706 | 0.22706 | 0.22706 | 0.22706 | 0.22707 | - |
| $e\bar{e}\to\tau\bar{\tau}$ | 0.32623 | 0.32623 | 0.32623 | 0.32623 | 0.32623 | - |
| $e\bar{e}\to\tau'\bar{\tau}$ | $2.9707\times10^{-6}$ | $2.9707\times10^{-6}$ | $2.9707\times10^{-6}$ | $2.9707\times10^{-6}$ | $2.9708\times10^{-6}$ | - |
| $e'\bar{e}\to\tau'\bar{\tau}$ | 0.78675 | 0.78675 | 0.78675 | 0.78675 | 0.78676 | - |
| $e\bar{e}\to\tau'\overline{\tau'}$ | 0.00048778 | 0.00048778 | 0.00048778 | 0.00048778 | 0.00048779 | - |
| $e'\overline{e'}\to\tau\bar{\tau}$ | 0.0015069 | 0.0015069 | 0.0015069 | 0.0015069 | 0.0015069 | - |
| $e'\bar{e}\to\tau'\overline{\tau'}$ | 0.075311 | 0.075311 | 0.075311 | 0.075311 | 0.075311 | - |
| $e'\overline{e'}\to\tau'\bar{\tau}$ | 0.16051 | 0.16051 | 0.16051 | 0.16051 | 0.16051 | - |
| $e'\overline{e'}\to\tau'\overline{\tau'}$ | 0.22706 | 0.22706 | 0.22706 | 0.22706 | 0.22707 | - |
| $e\bar{e}\to u\bar{u}$ | 0.53039 | 0.53039 | 0.53039 | 0.53039 | 0.53039 | - |
| $e\bar{e}\to u'\bar{u}$ | $8.9114\times10^{-6}$ | $8.9114\times10^{-6}$ | $8.9114\times10^{-6}$ | $8.9114\times10^{-6}$ | $8.9115\times10^{-6}$ | - |
| $e'\bar{e}\to u'\bar{u}$ | 2.3603 | 2.3603 | 2.3603 | 2.3603 | 2.3603 | - |
| $e\bar{e}\to u'\overline{u'}$ | 0.00063592 | 0.00063592 | 0.00063592 | 0.00063592 | 0.00063593 | - |
| $e'\overline{e'}\to u\bar{u}$ | 0.0024538 | 0.0024538 | 0.0024538 | 0.0024538 | 0.0024538 | - |
| $e'\bar{e}\to u'\overline{u'}$ | 0.22594 | 0.22594 | 0.22594 | 0.22594 | 0.22594 | - |
| $e'\overline{e'}\to u'\bar{u}$ | 0.48152 | 0.48152 | 0.48152 | 0.48152 | 0.48152 | - |
| $e'\overline{e'}\to u'\overline{u'}$ | 0.65627 | 0.65627 | 0.65627 | 0.65627 | 0.65628 | - |
| $e\bar{e}\to t\bar{t}$ | 0.44504 | 0.44504 | 0.44504 | 0.44504 | 0.44504 | - |
| $e\bar{e}\to t'\bar{t}$ | 0.000016904 | 0.000016904 | 0.000016904 | 0.000016904 | 0.000016904 | - |
| $e'\bar{e}\to t'\bar{t}$ | 2.2672 | 2.2672 | 2.2672 | 2.2672 | 2.2672 | - |
| $e\bar{e}\to t'\overline{t'}$ | 0.00061549 | 0.00061549 | 0.00061549 | 0.00061549 | 0.0006155 | - |
| $e'\overline{e'}\to t\bar{t}$ | 0.047158 | 0.047158 | 0.047158 | 0.047158 | 0.047158 | - |
| $e'\bar{e}\to t'\overline{t'}$ | 0.19818 | 0.19818 | 0.19818 | 0.19818 | 0.19818 | - |
| $e'\overline{e'}\to t'\bar{t}$ | 0.47047 | 0.47047 | 0.47047 | 0.47047 | 0.47048 | - |
| $e'\overline{e'}\to t'\overline{t'}$ | 0.61743 | 0.61743 | 0.61743 | 0.61743 | 0.61743 | - |
| $e'\bar{\nu}_e\to e'\overline{\nu_e'}$ | 0.53737 | 0.53737 | 0.53737 | 0.53737 | 0.53737 | - |
| $e'\overline{\nu_e'}\to e'\bar{\nu}_e$ | 1.1455 | 1.1455 | 1.1455 | 1.1455 | 1.1455 | - |
| $e'\overline{\nu_e'}\to e'\overline{\nu_e'}$ | 179.49 | 179.49 | 179.49 | 179.49 | 179.48 | - |
| $e\bar{\nu}_e\to\mu\bar{\nu}_\mu$ | 0.36221 | 0.36221 | 0.36221 | 0.36221 | 0.36221 | - |
| $e\bar{\nu}_e\to\mu'\bar{\nu}_\mu$ | 0.000011865 | 0.000011865 | 0.000011865 | 0.000011865 | 0.000011865 | - |
| $e'\bar{\nu}_e\to\mu'\bar{\nu}_\mu$ | 3.147 | 3.147 | 3.147 | 3.147 | 3.147 | - |
| $e\bar{\nu}_e\to\mu'\overline{\nu_\mu'}$ | 0.0005618 | 0.0005618 | 0.0005618 | 0.0005618 | 0.00056181 | - |
| $e'\overline{\nu_e'}\to\mu\bar{\nu}_\mu$ | 0.0017338 | 0.0017338 | 0.0017338 | 0.0017338 | 0.0017338 | - |
| $e'\bar{\nu}_e\to\mu'\overline{\nu_\mu'}$ | 0.30125 | 0.30125 | 0.30125 | 0.30125 | 0.30125 | - |
| $e'\overline{\nu_e'}\to\mu'\bar{\nu}_\mu$ | 0.64203 | 0.64203 | 0.64203 | 0.64203 | 0.64203 | - |
| $e'\overline{\nu_e'}\to\mu'\overline{\nu_\mu'}$ | 0.85872 | 0.85872 | 0.85872 | 0.85872 | 0.85872 | - |
| $e\bar{\nu}_e\to\tau\bar{\nu}_\tau$ | 0.36221 | 0.36221 | 0.36221 | 0.36221 | 0.36221 | - |
| $e\bar{\nu}_e\to\tau'\bar{\nu}_\tau$ | 0.000011865 | 0.000011865 | 0.000011865 | 0.000011865 | 0.000011865 | - |
| $e'\bar{\nu}_e\to\tau'\bar{\nu}_\tau$ | 3.147 | 3.147 | 3.147 | 3.147 | 3.147 | - |
| $e\bar{\nu}_e\to\tau'\overline{\nu_\tau'}$ | 0.0005618 | 0.0005618 | 0.0005618 | 0.0005618 | 0.00056181 | - |
| $e'\overline{\nu_e'}\to\tau\bar{\nu}_\tau$ | 0.0017368 | 0.0017368 | 0.0017368 | 0.0017368 | 0.0017368 | - |
| $e'\bar{\nu}_e\to\tau'\overline{\nu_\tau'}$ | 0.30125 | 0.30125 | 0.30125 | 0.30125 | 0.30125 | - |
| $e'\overline{\nu_e'}\to\tau'\bar{\nu}_\tau$ | 0.64202 | 0.64202 | 0.64202 | 0.64202 | 0.64203 | - |
| $e'\overline{\nu_e'}\to\tau'\overline{\nu_\tau'}$ | 0.85871 | 0.85871 | 0.85871 | 0.85871 | 0.85872 | - |
| $e\bar{\nu}_e\to d\bar{u}$ | 1.0866 | 1.0866 | 1.0866 | 1.0866 | 1.0866 | - |
| $e\bar{\nu}_e\to d'\bar{u}$ | 0.000035595 | 0.000035595 | 0.000035595 | 0.000035595 | 0.000035596 | - |
| $e'\bar{\nu}_e\to d'\bar{u}$ | 9.4411 | 9.4411 | 9.4411 | 9.4411 | 9.4411 | - |
| $e\bar{\nu}_e\to d'\overline{u'}$ | 0.0016854 | 0.0016854 | 0.0016854 | 0.0016854 | 0.0016854 | - |
| $e'\overline{\nu_e'}\to d\bar{u}$ | 0.0052014 | 0.0052014 | 0.0052014 | 0.0052014 | 0.0052015 | - |
| $e'\bar{\nu}_e\to d'\overline{u'}$ | 0.90374 | 0.90374 | 0.90374 | 0.90374 | 0.90375 | - |
| $e'\overline{\nu_e'}\to d'\bar{u}$ | 1.9261 | 1.9261 | 1.9261 | 1.9261 | 1.9261 | - |
| $e'\overline{\nu_e'}\to d'\overline{u'}$ | 2.5761 | 2.5761 | 2.5761 | 2.5761 | 2.5762 | - |
| $e\bar{\nu}_e\to b\bar{t}$ | 0.95043 | 0.95043 | 0.95043 | 0.95043 | 0.95042 | - |
| $e\bar{\nu}_e\to b'\bar{t}$ | 0.00006507 | 0.00006507 | 0.00006507 | 0.00006507 | 0.00006507 | - |
| $e'\bar{\nu}_e\to b'\bar{t}$ | 9.4972 | 9.4972 | 9.4972 | 9.4972 | 9.4973 | - |
| $e\bar{\nu}_e\to b'\overline{t'}$ | 0.0016343 | 0.0016343 | 0.0016343 | 0.0016343 | 0.0016343 | - |
| $e'\overline{\nu_e'}\to b\bar{t}$ | 0.091549 | 0.091549 | 0.091549 | 0.091549 | 0.09155 | - |
| $e'\bar{\nu}_e\to b'\overline{t'}$ | 0.8467 | 0.8467 | 0.8467 | 0.8467 | 0.84671 | - |
| $e'\overline{\nu_e'}\to b'\bar{t}$ | 1.9708 | 1.9708 | 1.9708 | 1.9708 | 1.9708 | - |
| $e'\overline{\nu_e'}\to b'\overline{t'}$ | 2.4975 | 2.4975 | 2.4975 | 2.4975 | 2.4975 | - |
| $gg\to gg$ | 114 310. | 114 310. | 114 310. | 114 310. | 114 310. | - |
| $ZZ\to ZZ$ | 0 | 0 | 0 | 0 | 0 | - |
| $ZZ\to ZZ'$ | 0 | 0 | 0 | 0 | 0 | - |
| $ZZ\to Z'Z'$ | 0 | 0 | 0 | 0 | 0 | - |
| $ZZ'\to ZZ'$ | 0 | 0 | 0 | 0 | 0 | - |
| $ZZ'\to Z'Z'$ | 0 | 0 | 0 | 0 | 0 | - |
| $Z'Z'\to Z'Z'$ | 0 | 0 | 0 | 0 | 0 | - |
| $W^+W^-\to\gamma\gamma$ | 20.343 | 20.343 | 20.343 | 20.343 | 20.343 | - |
| $W^{+\prime}W^{-\prime}\to\gamma\gamma$ | 1.0446 | 1.0446 | 1.0446 | 1.0446 | 1.0446 | - |
| $W^+W^-\to\gamma Z$ | 164.95 | 164.95 | 164.95 | 164.95 | 164.95 | - |
| $W^+W^-\to\gamma Z'$ | 6.4818 | 6.4818 | 6.4818 | 6.4818 | 6.4816 | - |
| $W^+W^{-\prime}\to\gamma Z$ | 8.329 | 8.329 | 8.329 | 8.329 | 8.3288 | - |
| $W^+W^{-\prime}\to\gamma Z'$ | 38.273 | 38.273 | 38.273 | 38.273 | 38.273 | - |
| $W^{+\prime}W^{-\prime}\to\gamma Z$ | 1.198 | 1.198 | 1.198 | 1.198 | 1.198 | - |
| $W^{+\prime}W^{-\prime}\to\gamma Z'$ | 70.338 | 70.338 | 70.338 | 70.338 | 70.339 | - |
| $W^+W^-\to ZZ$ | 365.67 | 365.67 | 365.67 | 365.67 | 365.67 | - |
| $W^+W^-\to ZZ'$ | 27.087 | 27.087 | 27.087 | 27.087 | 27.089 | - |
| $W^+W^{-\prime}\to ZZ$ | 20.1 | 20.1 | 20.1 | 20.1 | 20.1 | - |
| $W^+W^-\to Z'Z'$ | 13.183 | 13.183 | 13.183 | 13.183 | 13.183 | - |
| $W^{+\prime}W^{-\prime}\to ZZ$ | 42.717 | 42.717 | 42.717 | 42.717 | 42.716 | - |
| $W^{+\prime}W^{-\prime}\to ZZ'$ | 33.195 | 33.195 | 33.195 | 33.195 | 33.195 | - |
| $W^+W^{-\prime}\to Z'Z'$ | 17.905 | 17.905 | 17.905 | 17.905 | 17.905 | - |
| $W^{+\prime}W^{-\prime}\to Z'Z'$ | 1943. | 1943. | 1943. | 1943. | 1943. | - |
| $W^+W^-\to W^+W^-$ | 1408.6 | 1408.6 | 1408.6 | 1408.6 | 1408.6 | - |
| $W^+W^-\to W^+W^{-\prime}$ | 12.176 | 12.176 | 12.176 | 12.176 | 12.177 | - |
| $W^+W^{-\prime}\to W^+W^-$ | 18.05 | 18.05 | 18.05 | 18.05 | 18.05 | - |
| $W^+W^-\to W^{+\prime}W^{-\prime}$ | 11.245 | 11.245 | 11.245 | 11.245 | 11.245 | - |
| $W^+W^{-\prime}\to W^+W^{-\prime}$ | 1249.6 | 1249.6 | 1249.6 | 1249.6 | 1249.5 | - |
| $W^{+\prime}W^{-\prime}\to W^+W^-$ | 36.264 | 36.264 | 36.264 | 36.264 | 36.264 | - |
| $W^{+\prime}W^{-\prime}\to W^+W^{-\prime}$ | 23.265 | 23.265 | 23.265 | 23.265 | 23.266 | - |
| $W^+W^{-\prime}\to W^{+\prime}W^{-\prime}$ | 10.55 | 10.55 | 10.55 | 10.55 | 10.55 | - |
| $W^{+\prime}W^{-\prime}\to W^{+\prime}W^{-\prime}$ | 2721.9 | 2721.9 | 2721.9 | 2721.9 | 2721.9 | - |

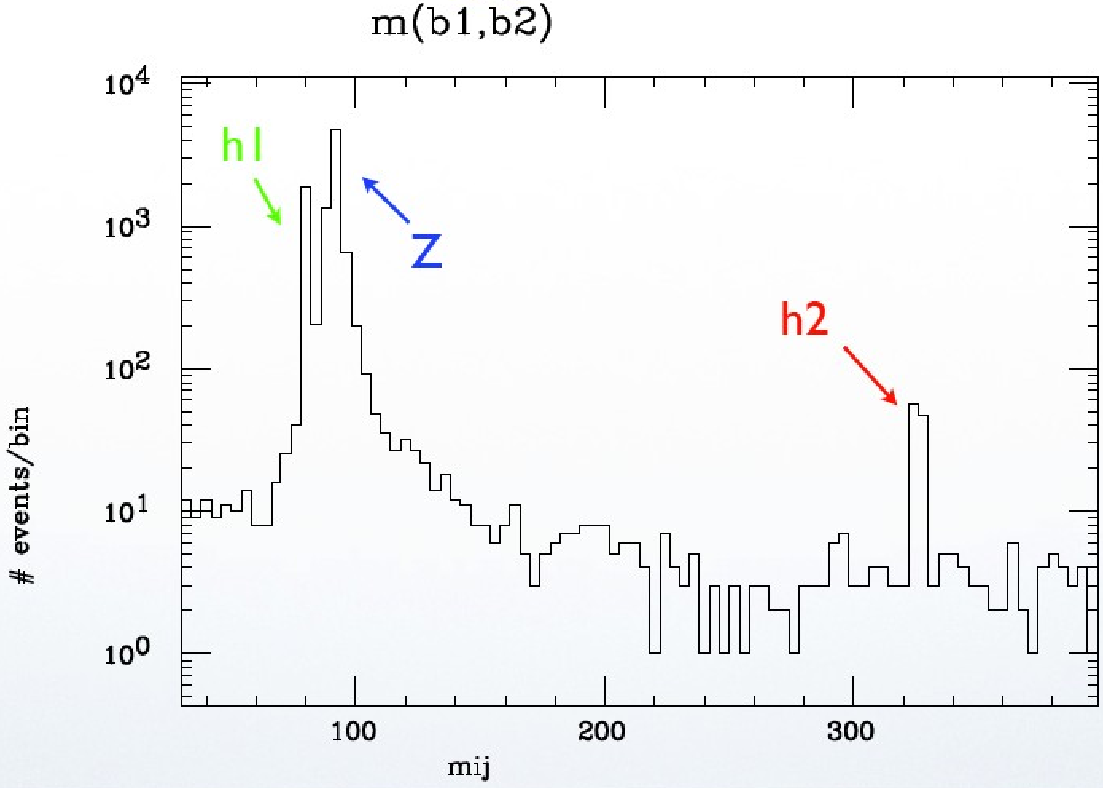
Phys.Rev.D74:075011,2006
Chivukula, Coleppa, Di Chiara, Simmons, He, Kurachi, Tanabashi
arXiv:0708.2588
Belyaev, Chivukula, Christensen, He, Kuang, Qi, Simmons, Zhang

# 3-Site Model Validation

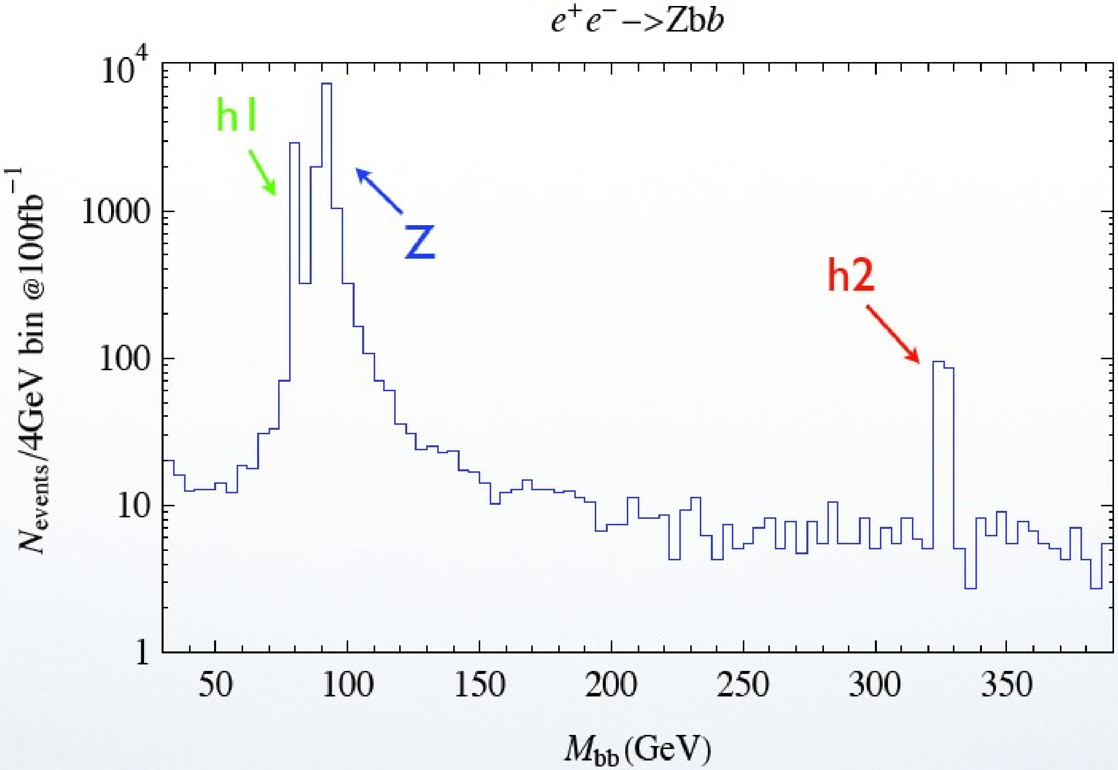
191 key subprocesses

| | Lanhep CalcHEP Feynman | Lanhep CalcHEP Unitary | FeynRules CalcHEP Feynman | FeynRules CalcHEP Unitary | FeynRules CompHEP Feynman |
|---|---|---|---|---|---|
| $u\bar{u} \to gg$ | 170.5 | 170.5 | 170.5 | 170.5 | 170.49 |
| $u'\bar{u} \to gg$ | 0 | 0 | 0 | 0 | 0 |
| $t\bar{t} \to gg$ | 55.906 | 55.906 | 55.906 | 55.906 | 55.903 |
| $t'\bar{t} \to gg$ | 0 | 0 | 0 | 0 | 0 |
| $u\bar{u} \to \gamma\gamma$ | 0.15862 | 0.15862 | 0.15862 | 0.15862 | 0.15862 |
| $u'\bar{u} \to \gamma\gamma$ | 0 | 0 | $3.6538 \times 10^{-37}$ | $3.6538 \times 10^{-37}$ | $3.6539 \times 10^{-37}$ |
| $t\bar{t} \to \gamma Z'$ | 0.00016576 | 0.00016576 | 0.00016576 | 0.00016576 | 0.00016576 |
| $t'\bar{t} \to \gamma Z$ | 0.033204 | 0.033204 | 0.033204 | 0.033204 | 0.033204 |
| $t'\overline{t'} \to \gamma Z$ | 0.0049275 | 0.0049275 | 0.0049275 | 0.0049275 | 0.0049276 |
| $t'\bar{t} \to \gamma Z'$ | 0.042476 | 0.042476 | 0.042476 | 0.042476 | 0.042473 |
| $t'\overline{t'} \to \gamma Z'$ | 0.012657 | 0.012657 | 0.012657 | 0.012657 | 0.012657 |

# Phenomenology with MadGraph



# Phenomenology with CalcHep



# Summary

- We don't know what new physics we will discover at the LHC.
  - There are many interesting models with many variations.
- There are several great programs for calculating Feynman diagrams:

| | |
|---|---|
| CalcHEP/CompHEP | MadGraph |
| FeynArts/FormCalc | Sherpa |
| ... | ... |

  - Each has its own strengths and weaknesses.
  - Each has its own model-file format.
- There is one tool that writes model-files for each of these.

FeynRules

# Appendix

# Model-File

# Model Information

```
M$ModelName = “model name”

M$Information = {
    Authors       -> {“Dr. X”, “Dr. Y”,...},
    Institution   -> {“Pheno State University”,...},
    emails        -> {x@psu.edu, y@rsu.edu,...},
    date          -> “April 12, 2008”,
    references    -> {“Phys.Rev.D177:035001,2008”,...}
}
```

# Index Declaration

IndexRange[ Index[Generation] ] = Range[3]

IndexRange[ Index[Color] ] = NoUnfold[ Range[3] ]
...

IndexStyle[ Generation, i ]

IndexStyle[ Color, a ]
...

# Gauge Groups

```
M$GaugeGroups = {
    U1Y == {
        Abelian           -> True,
        GaugeBoson        -> B,
        Charge            -> Y,
        CouplingConstant  -> gp
    },
    ...
}
```

# Parameters

```
M$Parameters = {
	\[Alpha]S == {
		ParameterType    -> External,
		ParameterName  -> aS,
		Value                   -> 0.118,
		Description -> “Strong coupling at Z-pole”
	},
	...
}
```

# Particles

```
M$classesDescription = {
        ...,
        F[3] == {
                ClassMembers      -> {u, c, t},
                ClassName         -> uq,
                SelfConjugate     -> False,
                QuantumNumbers    -> {Q -> 2/3},
                Indices           -> {Index[Generation], Index[Colour]},
                FlavorIndex       -> Generation,
                Mass              -> {Mu, {MU, 0}, {MC, 1.42}, {MT, 174.3}},
                Width             -> {0, 0, {WT, 1.50833649}},
                PDG               -> {2, 4, 6},
                FullName          -> {"u-quark", "c-quark", "t-quark"}
        },
        ...
}
```

# Lagrangian

```
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];

...
```

# Running FeynRules

# Load Model

```
$FeynRulesPath = "~/physics/FeynRules/FeynRules1.1.5";

SetDirectory[$FeynRulesPath];

<< FeynRules`;

SetDirectory[$FeynRulesPath <> "/Models/SM/"];

LoadModel["SM.fr"];
```

# Feynman Rules

FeynmanRules[LGauge];

Vertex 1

Particle 1 : Vector , G

Particle 2 : Vector , G

Particle 3 : Vector , G

Vertex:

$$g_s \, f_{a_1,a_2,a_3} \left(p_1^{\mu_3} \, \eta_{\mu_1,\mu_2} - p_2^{\mu_3} \, \eta_{\mu_1,\mu_2} - p_1^{\mu_2} \, \eta_{\mu_1,\mu_3} + p_3^{\mu_2} \, \eta_{\mu_1,\mu_3} + p_2^{\mu_1} \, \eta_{\mu_2,\mu_3} - p_3^{\mu_1} \, \eta_{\mu_2,\mu_3}\right)$$

# TeX Output

WriteTeXOutput[“VSM”, Output->”SM.tex”]

## 2 Vertices

### 2.1 3-point vertices

- Vertex $\{G,1\}$, $\{G,2\}$, $\{G,3\}$

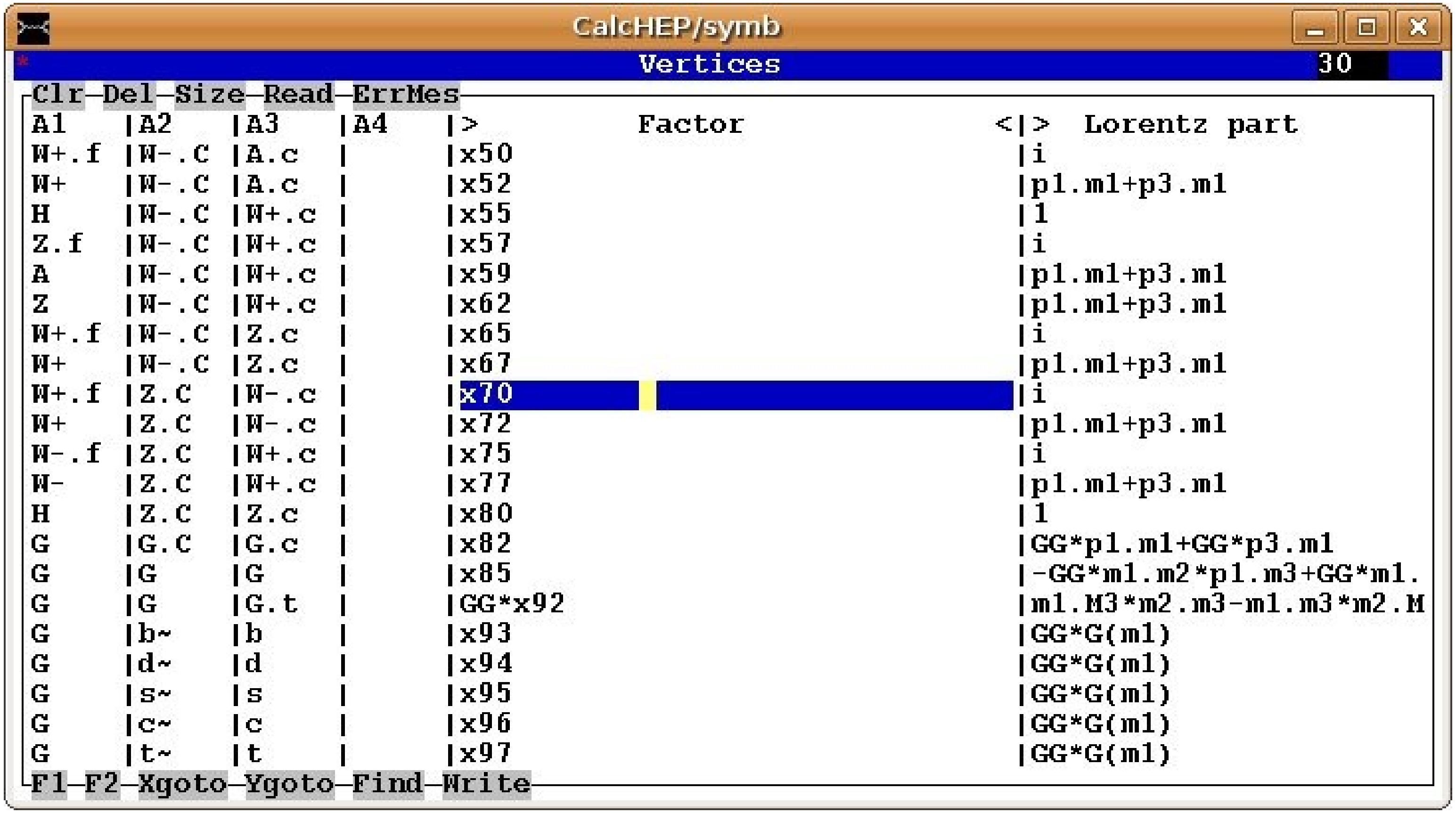
$$g_s f_{a_1,a_2,a_3}\left(p_1^{\mu 3}\eta_{\mu_1,\mu_2} - p_2^{\mu 3}\eta_{\mu_1,\mu_2} - p_1^{\mu 2}\eta_{\mu_1,\mu_3} + p_3^{\mu 2}\eta_{\mu_1,\mu_3} + p_2^{\mu 1}\eta_{\mu_2,\mu_3} - p_3^{\mu 1}\eta_{\mu_2,\mu_3}\right)$$

- Vertex $\{A,1\}$, $\left\{W^\dagger,2\right\}$, $\{W,3\}$

$$i g_w s_w\left(p_1^{\mu 3}\eta_{\mu_1,\mu_2} - p_2^{\mu 3}\eta_{\mu_1,\mu_2} - p_1^{\mu 2}\eta_{\mu_1,\mu_3} + p_3^{\mu 2}\eta_{\mu_1,\mu_3} + p_2^{\mu 1}\eta_{\mu_2,\mu_3} - p_3^{\mu 1}\eta_{\mu_2,\mu_3}\right)$$

# CalcHEP Output

WriteCHOutput[LSM]



# FeynArts Output

WriteFeynArtsOutput[LSM]

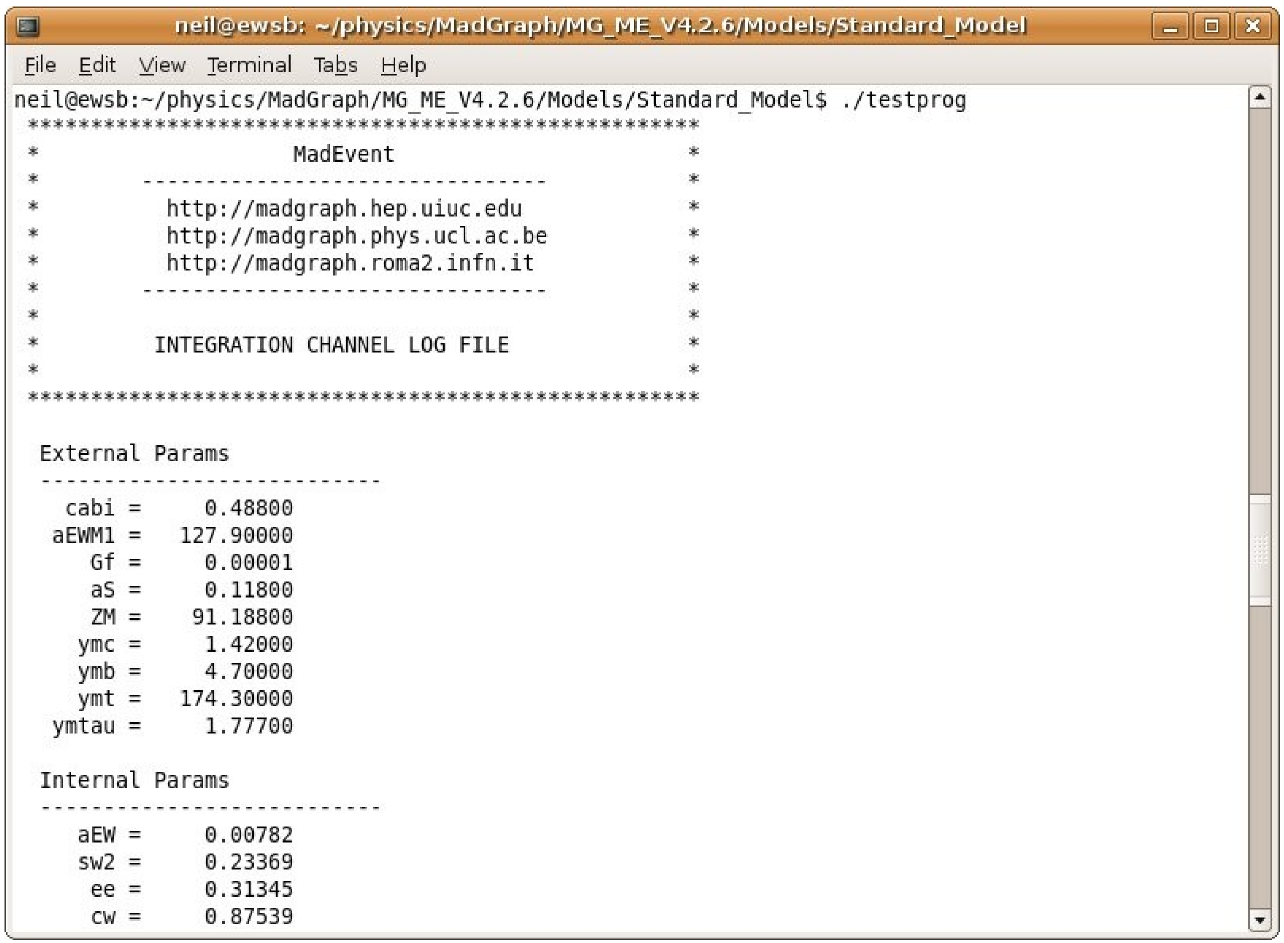
neil@ewsb: ~/physics/FeynArts/Models

File Edit View Terminal Tabs Help

```
(*      Couplings (calculated by FeynRules)      *)

M$CouplingMatrices = {

(*      Couplings from L1      *)

C[ V[6, {e1x2}] , V[6, {e2x2}] , V[6, {e3x2}] ] == {-(gs*f[e1x2, e2x2, e3x2]), 0, 0},

C[ V[6, {e4x2}] , V[6, {e3x2}] , V[6, {e2x2}] , V[6, {e1x2}] ] == {{(-I)*gs^2*(f[e1x2, e4x2, a1]*
f[e2x2, e3x2, a1] + f[e1x2, e3x2, a1]*f[e2x2, e4x2, a1]), 0, 0}, {I*gs^2*(f[e1x2, e3x2, a1]*f[e2x
2, e4x2, a1] + f[e1x2, e2x2, a1]*f[e3x2, e4x2, a1]), 0, 0}, {I*gs^2*(f[e1x2, e4x2, a1]*f[e2x2, e3
x2, a1] - f[e1x2, e2x2, a1]*f[e3x2, e4x2, a1]), 0, 0}},

C[ V[1] , -V[3] , V[3] ] == {EE*(v0W - I*v1W)*((-I)*v0W + v1W), 0, 0},

C[ V[1] , V[3] , -V[5] ] == {I*EE*(v0W*v0WP + v1W*v1WP), 0, 0},

C[ V[1] , V[5] , -V[3] ] == {I*EE*(v0W*v0WP + v1W*v1WP), 0, 0},

C[ -V[3] , V[3] , V[1] , V[1] ] == {{2*EE^2*(v0W - I*v1W)*((-I)*v0W + v1W), 0, 0}, {EE^2*(v0W + I
*v1W)*(I*v0W + v1W), 0, 0}, {EE^2*(v0W + I*v1W)*(I*v0W + v1W), 0, 0}},

C[ V[2] , -V[3] , V[3] ] == {(-I)*(g*v0W^2*v0Z + gt*v1W^2*v1Z), 0, 0},
:
```

# MadGraph Output

WriteMGOutput[LSM]



```
neil@ewsb: ~/physics/MadGraph/MG_ME_V4.2.6/Models/Standard_Model
File  Edit  View  Terminal  Tabs  Help
neil@ewsb:~/physics/MadGraph/MG_ME_V4.2.6/Models/Standard_Model$ ./testprog
 *****************************************************
 *                    MadEvent                       *
 *        --------------------------------           *
 *          http://madgraph.hep.uiuc.edu             *
 *          http://madgraph.phys.ucl.ac.be           *
 *          http://madgraph.roma2.infn.it            *
 *        --------------------------------           *
 *                                                   *
 *         INTEGRATION CHANNEL LOG FILE              *
 *                                                   *
 *****************************************************

  External Params
  ---------------------------
    cabi =      0.48800
   aEWM1 =    127.90000
      Gf =      0.00001
      aS =      0.11800
      ZM =     91.18800
     ymc =      1.42000
     ymb =      4.70000
     ymt =    174.30000
   ymtau =      1.77700

  Internal Params
  ---------------------------
     aEW =      0.00782
     sw2 =      0.23369
      ee =      0.31345
      cw =      0.87539
```