

BSM
with
FeynRules



Neil Christensen
University of Wisconsin - Madison

Links

- ❖ This tutorial:

- ❖ <http://www.hep.wisc.edu/~neil/Research/talks/2009-10-29.pdf>

- ❖ FeynRules:

- ❖ <http://feynrules.phys.ucl.ac.be>

- ❖ CalcHEP:

- ❖ <http://theory.sinp.msu.ru/~pukhov/calchep.html>

- ❖ MadGraph:

- ❖ <http://madgraph.hep.uiuc.edu/>

Download FeynRules

The screenshot shows a web browser window with the address bar containing `http://feynrules.phys.ucl.ac.be/`. The browser's search bar contains the text "Google". The page title is "WebHome < Main < TWiki". The main content area features a navigation menu on the left with options like "Main", "Log In or Register", "Main Web", "Create New Topic", "Index", "Search", "Changes", "Notifications", "RSS Feed", "Statistics", and "Preferences". The main content area displays the title "FeynRules" and a sub-header "A Mathematica package to calculate Feynman rules". The text describes FeynRules as a Mathematica package for calculating Feynman rules in momentum space for any QFT physics model. It also mentions a new version 1.4.0 release and provides links for news, user manual, and talks.

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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.

New: Version 1.4.0 released!

Several new models (MSSM, UED, LED, 2HDM,...) have been added.

Please check out the Model Database section!

Package

- [News](#)
- [FeynRules V1.4.0](#): Core code, ToolBox and SM model file.
- User manual: [letter paper](#) or [A4 paper](#)
- [Talks](#): Talks about FeynRules

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- [Talks](#): Talks about FeynRules

Manual

Prepare FeynRules

❖ Setup FeynRules directory:

- ❖ `cd`
- ❖ `mkdir physics/FeynRules`
- ❖ `cp Downloads/FeynRules1.4.0.tar.gz physics/FeynRules/FeynRules1.4.0.tar.gz`

❖ Unpack FeynRules:

- ❖ `cd physics/FeynRules`
- ❖ `tar xvzf FeynRules1.4.0.tar.gz`

❖ Setup model directory:

- ❖ `mkdir Models`
- ❖ `mkdir Models/SMpS`
- ❖ `cp FeynRules1.4.0/Models/SM/SM.fr Models/SMpS/SMpS.fr`

❖ Open model file in your favorite text editor:

- ❖ `cd Models`
- ❖ `emacs SMpS.fr &`

```
(*****  
(*****          This is the FeynRules mod-file for the Standard model          *****)  
(*****          *****  
(***** Authors: N. Christensen, C. Duhr          *****)  
(*****          *****  
(***** Choose whether Feynman gauge is desired.          *****)  
(***** If set to False, unitary gauge is assumed.          *****)  
(***** Feynman gauge is especially useful for CalcHEP/CompHEP where the calculation is 10-100 times faster. ***)  
(***** Feynman gauge is not supported in MadGraph and Sherpa.          *****)  
(*****          *****)
```

```
M$ModelName = "Standard_Model";  
  
M$Information = {Authors -> {"N. Christensen", "C. Duhr"},  
                Version -> "1.0",  
                Date -> "02. 06. 2009",  
                Institutions -> {"Michigan State University", "Universite catholique de Louvain (CP3)"},  
                Emails -> {"neil@pa.msu.edu", "claudeduhr@uclouvain.be"},  
                URLs -> "http://feynrules.phys.ucl.ac.be/view/Main/StandardModel"};
```

```
FeynmanGauge = False;
```

```
(***** Index definitions *****)
```

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

Modify Model Info

```
(*****  
(*****          This is the FeynRules mod-file for the Standard model          *****)  
(*****          *****  
(***** Authors: N. Christensen, C. Duhr          *****)  
(*****          *****  
(***** Choose whether Feynman gauge is desired.          *****)  
(***** If set to False, unitary gauge is assumed.          *****)  
(***** Feynman gauge is especially useful for CalcHEP/CompHEP where the calculation is 10-100 times faster. ***)  
(***** Feynman gauge is not supported in MadGraph and Sherpa.          *****)  
(*****
```

```
M$ModelName = "Standard_Model";
```

```
M$Information = {Authors -> {"N. Christensen", "C. Duhr"},  
                Version -> "1.0",  
                Date -> "02. 06. 2009",  
                Institutions -> {"Michigan State University", "Universite catholique de Louvain (CP3)"},  
  
                Emails -> {"neil@pa.msu.edu", "claudeduhr@uclouvain.be"},  
                URLs -> "http://feynrules.phys.ucl.ac.be/view/Main/StandardModel";
```

```
FeynmanGauge = False;
```


Modify Model Info

```
(*****  
(*****          This is the FeynRules mod-file for the Standard model          *****)  
(*****          *****  
(***** Authors: N. Christensen, C. Duhr, N. Christensen          *****)  
(*****          *****  
(***** Choose whether Feynman gauge is desired.          *****)  
(***** If set to False, unitary gauge is assumed.          *****)  
(***** Feynman gauge is especially useful for CalcHEP/CompHEP where the calculation is 10-100 times faster. ***)  
(***** Feynman gauge is not supported in MadGraph and Sherpa.          *****)  
(*****  
(*****
```

```
M$ModelName = "Standard_Model_plus_Scalar";
```

```
M$Information = {Authors -> {"N. Christensen", "C. Duhr", "N. Christensen"},  
Version -> "1.0",  
Date -> "10/29/2009",  
Institutions -> {"Michigan State University", "Universite catholique de Louvain (CP3)",  
"University of Wisconsin-Madison"},  
Emails -> {"neil@pa.msu.edu", "claudeduhr@uclouvain.be", "neil@hep.wisc.edu"},  
URLs -> "url of your model";
```

```
FeynmanGauge = False;
```

Add New Scalar Field

(***** Scalar Fields *****)

```
S[1] == {  
  ClassName -> H,  
  SelfConjugate -> True,
```

```
  ...},
```

```
S[2] == {  
  ...},
```

```
S[3] == {  
  ...}
```

```
}
```

Add New Scalar Field

(***** Scalar Fields *****)

```
S[1] == {  
  ClassName -> H,  
  SelfConjugate -> True,  
  Unphysical -> True,  
  ...},  
S[2] == {  
  ...},  
S[3] == {  
  ...},  
S[4] == {  
  ClassName -> S,  
  SelfConjugate -> True,  
  Unphysical -> True}  
}
```

Add New Lagrangian Terms I

(***** Higgs Lagrangian terms *****)

...

(***** Yukawa Lagrangian *****)

Add New Lagrangian Terms I

(***** Higgs Lagrangian terms *****)

...

$$L_{\text{Scalar}} = \frac{1}{2} \text{del}[S, \mu] \text{del}[S, \mu] - \lambda S (v^2/2 + \mu S - \text{Phibar} \cdot \text{Phi})^2$$

(***** Yukawa Lagrangian *****)

Add New Lagrangian Terms II

(*****Total SM Lagrangian*****)

LSM := LGauge + LHiggs + LFermions + LYukawa + LGhost;

Add New Lagrangian Terms II

(*****Total SM Lagrangian*****)

LSM := LGauge + LHiggs + LFermions + LYukawa + LGhost;

LSMpS := LSM + LScalar;

Add Parameters

$\backslash[\text{Lambda}] == \{$

$\dots\},$

$\text{muH} == \{$

$\dots\},$

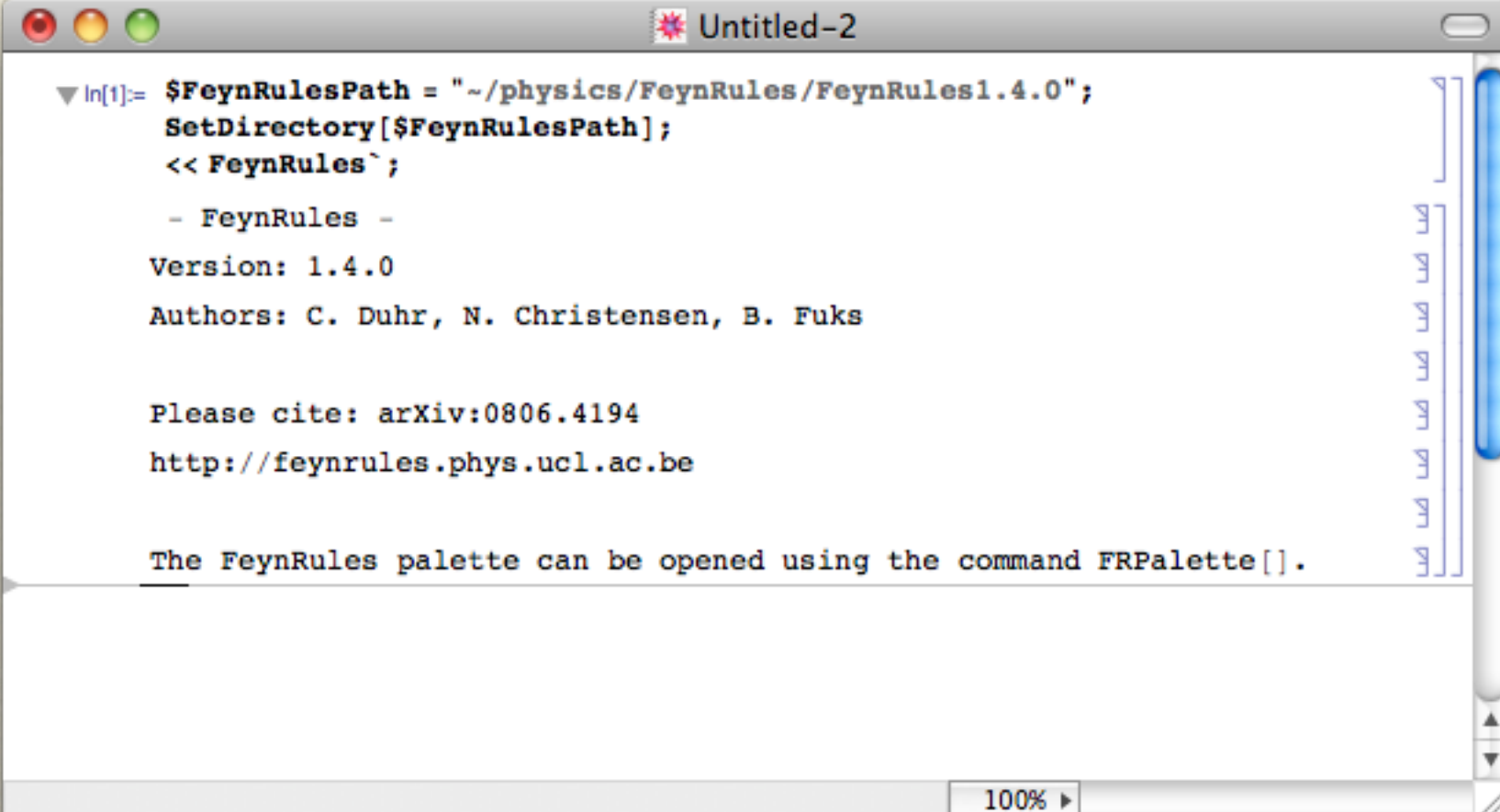
Add Parameters

```
\[Lambda] == {  
    ParameterType -> External,  
    Value -> 0.2,  
    ...},  
muH == {  
    ...},  
\[Lambda]S == {  
    ParameterType -> External,  
    Value -> 0.2,  
    ParameterName -> lamS},  
muS == {  
    ParameterType -> External,  
    Value -> 400},
```

Start FeynRules

```
$FeynRulesPath = "~/physics/FeynRules/FeynRules1.4.0";  
SetDirectory[$FeynRulesPath];  
<< FeynRules`;
```

Start FeynRules



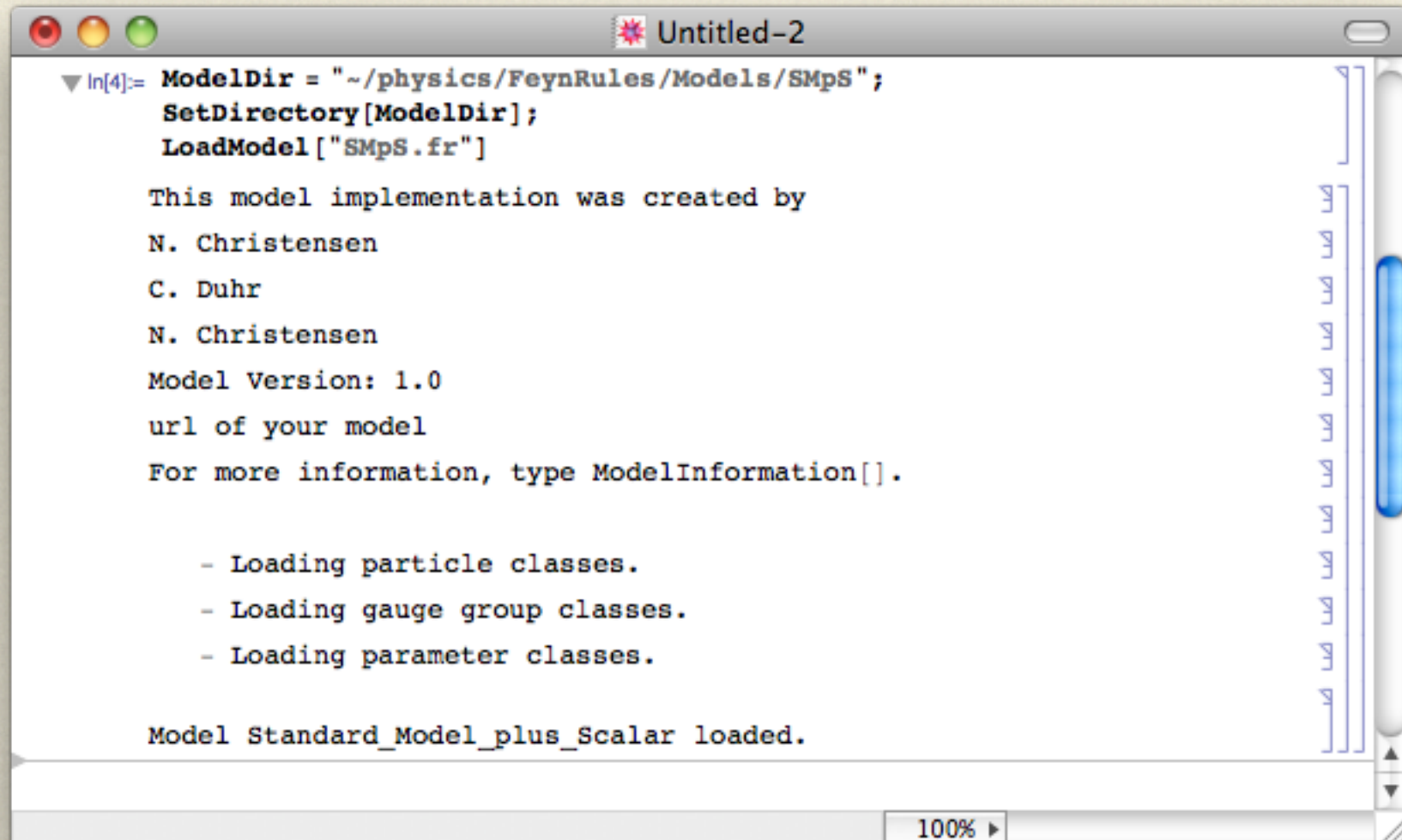
```
▼ In[1]:= $FeynRulesPath = "~/physics/FeynRules/FeynRules1.4.0";  
SetDirectory[$FeynRulesPath];  
<< FeynRules`;  
  
- FeynRules -  
Version: 1.4.0  
Authors: C. Duhr, N. Christensen, B. Fuks  
  
Please cite: arXiv:0806.4194  
http://feynrules.phys.ucl.ac.be  
  
The FeynRules palette can be opened using the command FRPalette[].
```

100% ▶

Load Model

```
ModelDir = "~/physics/FeynRules/Models/SMpS";  
SetDirectory[ModelDir];  
LoadModel["SMpS.fr"]
```

Load Model



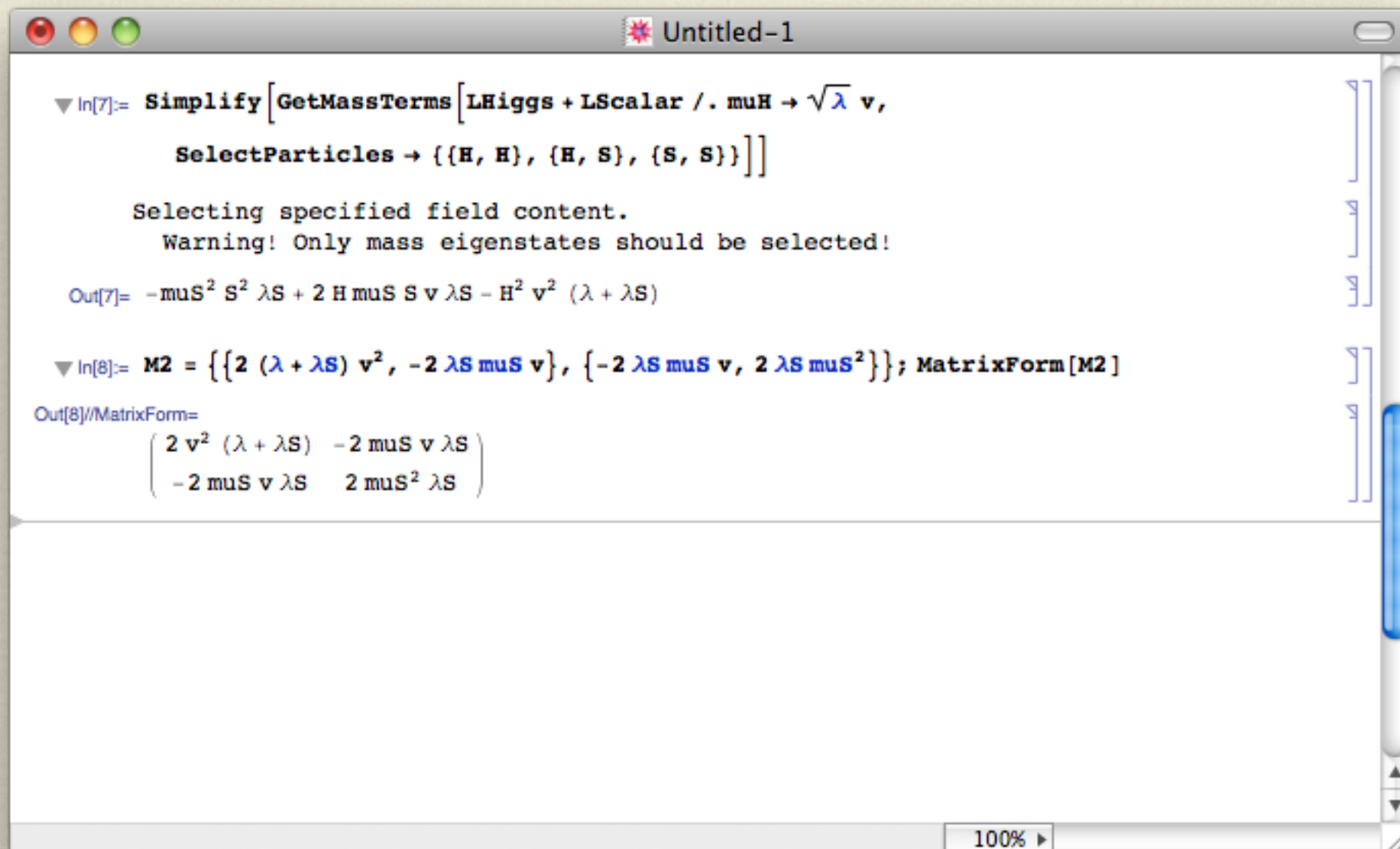
```
▼ In[4]:= ModelDir = "~/physics/FeynRules/Models/SMpS";  
SetDirectory[ModelDir];  
LoadModel["SMpS.fr"]  
  
This model implementation was created by  
N. Christensen  
C. Duhr  
N. Christensen  
Model Version: 1.0  
url of your model  
For more information, type ModelInformation[].  
  
- Loading particle classes.  
- Loading gauge group classes.  
- Loading parameter classes.  
  
Model Standard_Model_plus_Scalar loaded.
```

100%

Get Mass Terms

GetMassTerms[LHiggs + LScalar ,
SelectParticles -> {{H, H}, {H, S}, {S, S}}]

Get Mass Terms



▼ In[7]:= `Simplify [GetMassTerms [LHiggs + LScalar /. muH -> $\sqrt{\lambda} v$,
SelectParticles -> {{H, H}, {H, S}, {S, S}}]]`

Selecting specified field content.
Warning! Only mass eigenstates should be selected!

Out[7]= $-muS^2 S^2 \lambda S + 2 H muS S v \lambda S - H^2 v^2 (\lambda + \lambda S)$

▼ In[8]:= `M2 = {{2 (\lambda + \lambda S) v^2, -2 \lambda S muS v}, {-2 \lambda S muS v, 2 \lambda S muS^2}}; MatrixForm[M2]`

Out[8]/MatrixForm=

$$\begin{pmatrix} 2 v^2 (\lambda + \lambda S) & -2 muS v \lambda S \\ -2 muS v \lambda S & 2 muS^2 \lambda S \end{pmatrix}$$

100%

Get Masses and Eigenvectors

Eigenvalues[M2]
Eigenvectors[M2]

Get Masses and Eigenvectors

Untitled-1

▼ In[9]:= **Eigenvalues [M2]**

$$\text{Out[9]} = \left\{ \frac{1}{2} \left(2 v^2 \lambda + 2 \mu S^2 \lambda S + 2 v^2 \lambda S - \sqrt{-16 \mu S^2 v^2 \lambda \lambda S + (-2 v^2 \lambda - 2 \mu S^2 \lambda S - 2 v^2 \lambda S)^2} \right), \right. \\ \left. \frac{1}{2} \left(2 v^2 \lambda + 2 \mu S^2 \lambda S + 2 v^2 \lambda S + \sqrt{-16 \mu S^2 v^2 \lambda \lambda S + (-2 v^2 \lambda - 2 \mu S^2 \lambda S - 2 v^2 \lambda S)^2} \right) \right\}$$

▼ In[10]:= **Eigenvectors [M2]**

$$\text{Out[10]} = \left\{ \left\{ -\frac{v^2 \lambda - \mu S^2 \lambda S + v^2 \lambda S - \frac{1}{2} \sqrt{-16 \mu S^2 v^2 \lambda \lambda S + (-2 v^2 \lambda - 2 \mu S^2 \lambda S - 2 v^2 \lambda S)^2}}{2 \mu S v \lambda S}, 1 \right\}, \right. \\ \left. \left\{ -\frac{v^2 \lambda - \mu S^2 \lambda S + v^2 \lambda S + \frac{1}{2} \sqrt{-16 \mu S^2 v^2 \lambda \lambda S + (-2 v^2 \lambda - 2 \mu S^2 \lambda S - 2 v^2 \lambda S)^2}}{2 \mu S v \lambda S}, 1 \right\} \right\}$$

100%

Add Masses

Copy and Paste

$$\mu_S == \{ \\ \dots \},$$

Add Masses

Copy and Paste

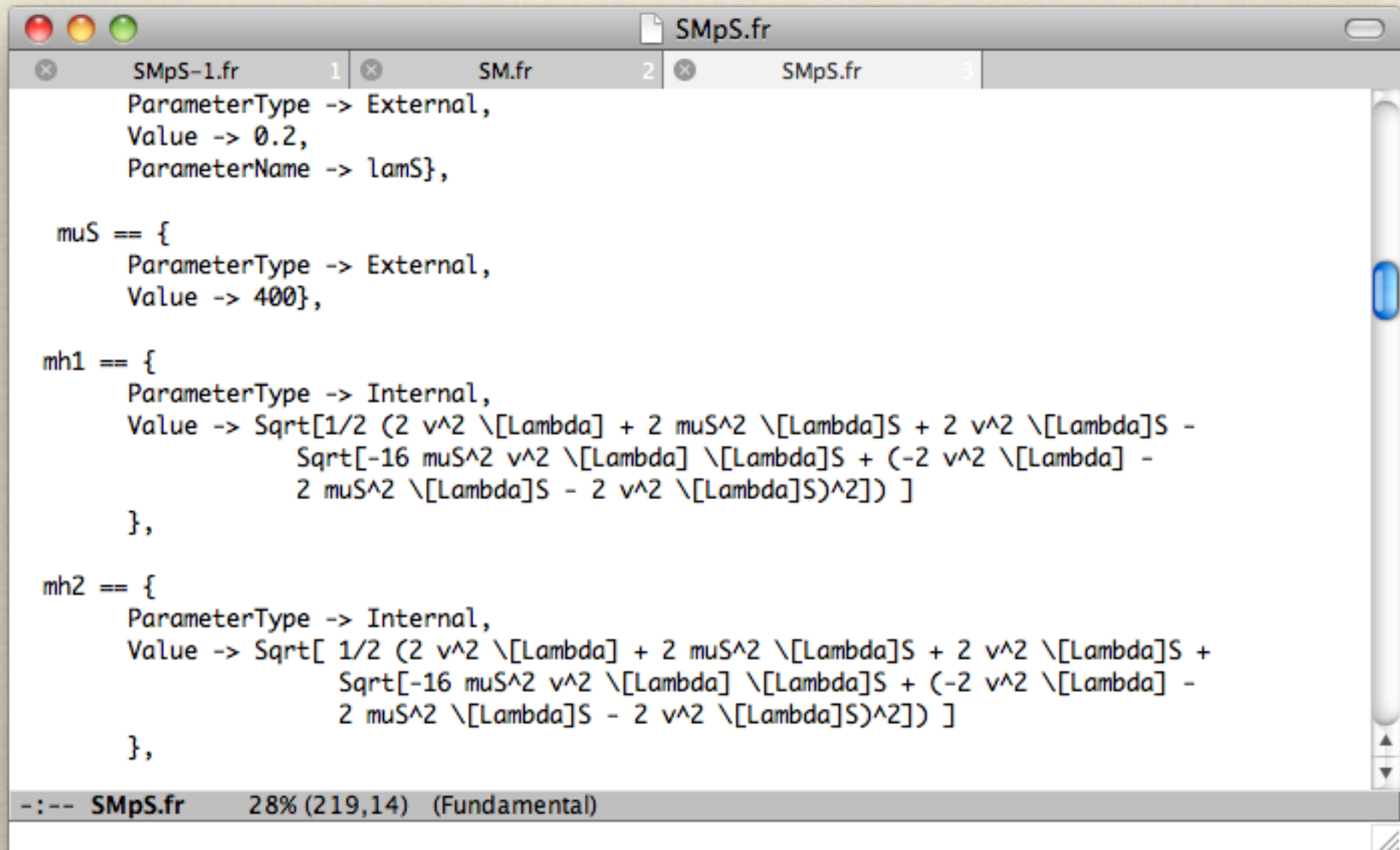
```
muS == {  
    ...},
```

```
mh1 == {  
    ParameterType -> Internal,  
    Value -> ...},
```

```
mh2 == {  
    ParameterType -> Internal,  
    Value -> ...},
```

Add Masses

Copy and Paste



```
ParameterType -> External,  
Value -> 0.2,  
ParameterName -> lamS},  
  
muS == {  
  ParameterType -> External,  
  Value -> 400},  
  
mh1 == {  
  ParameterType -> Internal,  
  Value -> Sqrt[1/2 (2 v^2 \[Lambda] + 2 muS^2 \[Lambda]S + 2 v^2 \[Lambda]S -  
    Sqrt[-16 muS^2 v^2 \[Lambda] \[Lambda]S + (-2 v^2 \[Lambda] -  
    2 muS^2 \[Lambda]S - 2 v^2 \[Lambda]S)^2]) ]  
  },  
  
mh2 == {  
  ParameterType -> Internal,  
  Value -> Sqrt[ 1/2 (2 v^2 \[Lambda] + 2 muS^2 \[Lambda]S + 2 v^2 \[Lambda]S +  
    Sqrt[-16 muS^2 v^2 \[Lambda] \[Lambda]S + (-2 v^2 \[Lambda] -  
    2 muS^2 \[Lambda]S - 2 v^2 \[Lambda]S)^2]) ]  
  },  
  
-- SMpS.fr 28% (219,14) (Fundamental)
```

Add Rotation Parameters

Copy and Paste

$$\text{mh2} == \{$$
$$\dots\},$$

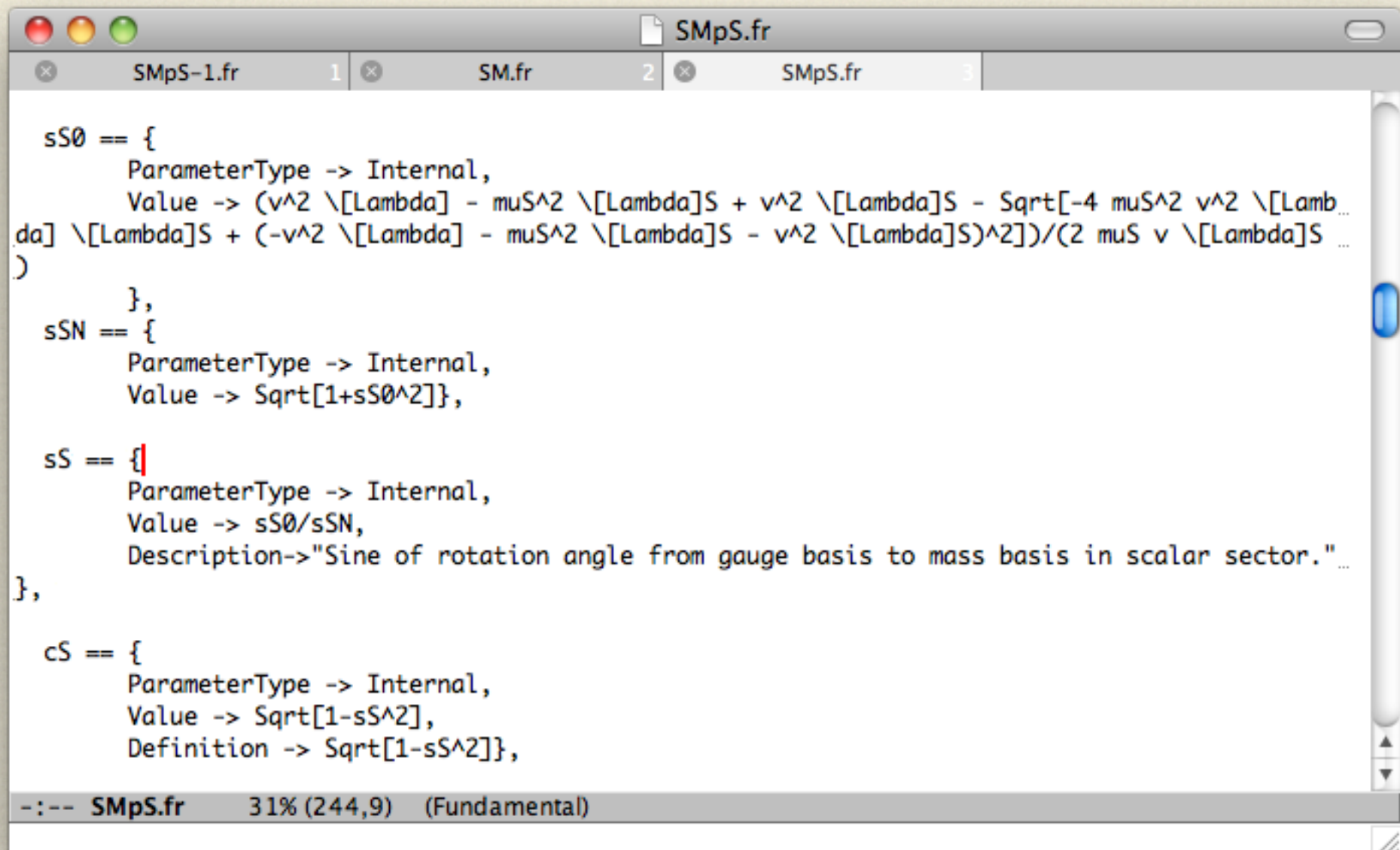
Add Rotation Parameters

Copy and Paste

```
mh2 == {  
    ...},  
sS0 == {  
    ParameterType -> Internal,  
    Value -> ...},  
sSN == {  
    ParameterType -> Internal,  
    Value -> Sqrt[1+sS0^2]},  
sS == {  
    ParameterType -> Internal,  
    Value -> sS0/sSN},  
cS == {  
    ParameterType -> Internal,  
    Value -> Sqrt[1-sS^2],  
    Definition -> Sqrt[1-sS^2]},
```

Add Rotation Parameters

Copy and Paste



```
sS0 == {
  ParameterType -> Internal,
  Value -> (v^2 \[Lambda] - muS^2 \[Lambda]S + v^2 \[Lambda]S - Sqrt[-4 muS^2 v^2 \[Lamb
da] \[Lambda]S + (-v^2 \[Lambda] - muS^2 \[Lambda]S - v^2 \[Lambda]S)^2])/(2 muS v \[Lambda]S ...
)
},
sSN == {
  ParameterType -> Internal,
  Value -> Sqrt[1+sS0^2]},

sS == {
  ParameterType -> Internal,
  Value -> sS0/sSN,
  Description->"Sine of rotation angle from gauge basis to mass basis in scalar sector."...
},

cS == {
  ParameterType -> Internal,
  Value -> Sqrt[1-sS^2],
  Definition -> Sqrt[1-sS^2]},
```

--- SMpS.fr 31% (244,9) (Fundamental)

Add Mass-Eigenstate Fields

$$S[4] == \{$$
$$\dots\},$$

}

Add Mass-Eigenstate Fields

```
S[4] == {  
    ...},  
S[5] == {  
    ClassName -> h1,  
    SelfConjugate -> True,  
    Mass -> {mh1, Internal},  
    Width -> wh1,  
    PDG -> 6000001},  
S[6] == {  
    ClassName -> h2,  
    SelfConjugate -> True,  
    Mass -> {mh2, Internal},  
    Width -> wh2,  
    PDG -> 6000002}  
}
```

Transform Fields

```
S[1] == {  
    ClassName -> H,  
    SelfConjugate -> True,  
    Unphysical -> True,
```

```
    ...},
```

```
S[2] == {  
    ...},
```

```
S[3] == {  
    ...},
```

```
S[4] == {  
    ClassName -> S,  
    SelfConjugate -> True,  
    Unphysical -> True,
```

```
    },
```

Transform Fields

S[1] == {
 ClassName -> H,
 SelfConjugate -> True,
 Unphysical -> True,
 Definitions -> {H -> - sS h1 + cS h2},
 ...},

S[2] == {
 ...},

S[3] == {
 ...},

S[4] == {
 ClassName -> S,
 SelfConjugate -> True,
 Unphysical -> True,
 Definitions -> {S -> cS h1 + sS h2}},

Quit Mathematica Kernel

The screenshot shows the Mathematica interface with the 'Evaluation' menu open. The menu items are:

- Evaluate Cells (⌘↵)
- Evaluate in Place (⌘⇧↵)
- Evaluate in Subsession (⇧⇧↵)
- Evaluate Notebook
- Evaluate Initialization Cells
- Dynamic Updating Enabled (checked)
- Convert Dynamic to Literal
- Debugger
- Debugger Controls (▶)
- Interrupt Evaluation... (⇧⌘⌘.)
- Abort Evaluation (⌘⌘.)
- Remove from Evaluation Queue (⇧⌘⌘.)
- Find Currently Evaluating Cell
- Kernel Configuration Options...
- Parallel Kernel Configuration...
- Parallel Kernel Status...
- Default Kernel (▶)
- Notebook's Kernel (▶)
- Notebook's Default Context (▶)
- Start Kernel (▶)
- Quit Kernel (▶) **Local**

The background of the notebook shows two cells with mathematical results:

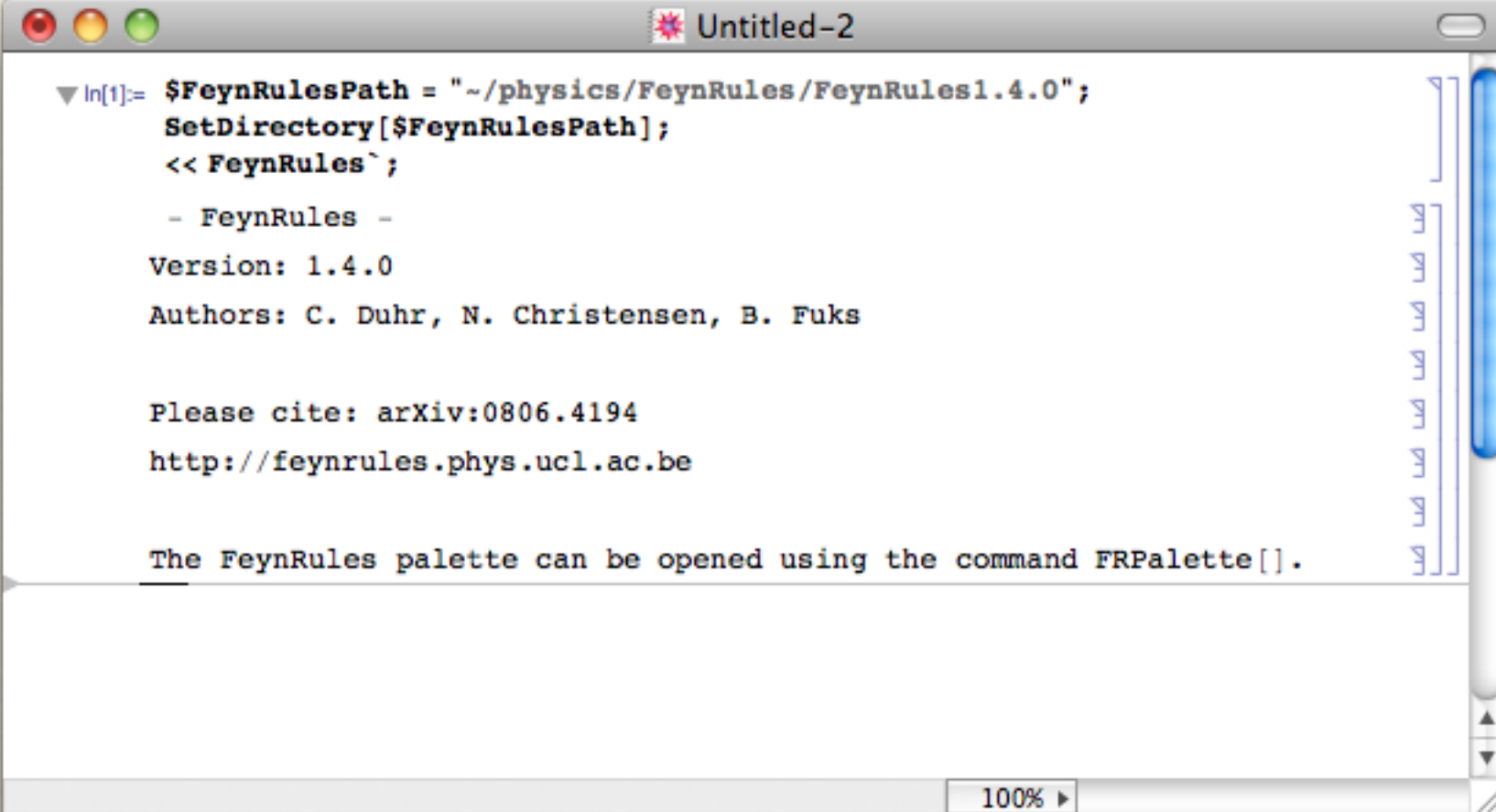
Out[9]= Eigenvalues [M2]

$$\begin{Bmatrix} \frac{1}{2} \left(2 v^2 \lambda + 2 \mu S^2 \lambda S + 2 v^2 \lambda S - \sqrt{-16 \mu S^2 v^2 \lambda \lambda S + (-2 v^2 \lambda - 2 \mu S^2)} \right) \\ \frac{1}{2} \left(2 v^2 \lambda + 2 \mu S^2 \lambda S + 2 v^2 \lambda S + \sqrt{-16 \mu S^2 v^2 \lambda \lambda S + (-2 v^2 \lambda - 2 \mu S^2)} \right) \end{Bmatrix}$$

Out[10]= Eigenvectors [M2]

$$\begin{Bmatrix} \frac{v^2 \lambda - \mu S^2 \lambda S + v^2 \lambda S - \frac{1}{2} \sqrt{-16 \mu S^2 v^2 \lambda \lambda S + (-2 v^2 \lambda - 2 \mu S^2)}}{2 \mu S v \lambda S} \\ \frac{v^2 \lambda - \mu S^2 \lambda S + v^2 \lambda S + \frac{1}{2} \sqrt{-16 \mu S^2 v^2 \lambda \lambda S + (-2 v^2 \lambda - 2 \mu S^2)}}{2 \mu S v \lambda S} \end{Bmatrix}$$

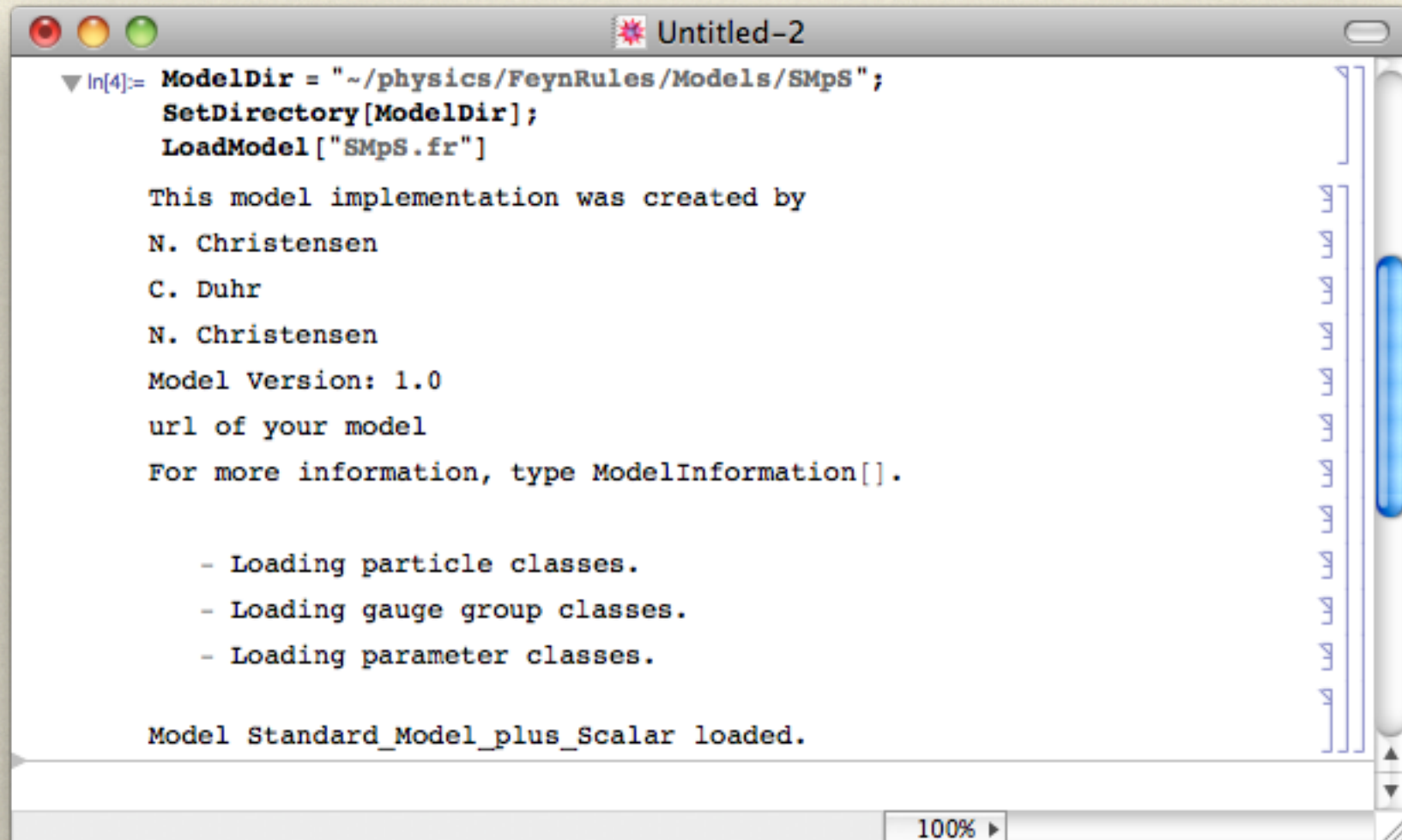
Start FeynRules



```
▼ In[1]:= $FeynRulesPath = "~/physics/FeynRules/FeynRules1.4.0";  
SetDirectory[$FeynRulesPath];  
<< FeynRules`;  
  
- FeynRules -  
Version: 1.4.0  
Authors: C. Duhr, N. Christensen, B. Fuks  
  
Please cite: arXiv:0806.4194  
http://feynrules.phys.ucl.ac.be  
  
The FeynRules palette can be opened using the command FRPalette[].
```

100% ▸

Load Model



```
▼ In[4]:= ModelDir = "~/physics/FeynRules/Models/SMpS";  
SetDirectory[ModelDir];  
LoadModel["SMpS.fr"]  
  
This model implementation was created by  
N. Christensen  
C. Duhr  
N. Christensen  
Model Version: 1.0  
url of your model  
For more information, type ModelInformation[].  
  
- Loading particle classes.  
- Loading gauge group classes.  
- Loading parameter classes.  
  
Model Standard_Model_plus_Scalar loaded.
```

100%

Check Masses

CheckMassSpectrum[LHiggs + LScalar]

Check Masses

▼ In[7]:= **CheckMassSpectrum [LHiggs + LScalar]**

Expanding flavors...
All mass terms are diagonal.
Expanding flavors...
Getting mass spectrum.
Checking for less than 0.1% agreement with model file values.

Out[7]//TableForm=

Particle	Analytic value	Numerical value	Model-file value
h2	$\sqrt{2} \sqrt{-\frac{1}{2} cS^2 \mu^2 + \frac{3}{2} cS^2 v^2 \lambda + \text{mu}S^2 sS^2 \lambda S - 2 cS \text{mu}S sS v \lambda S + cS^2 v^2 \lambda S}$	310.483	310.483
h1	$\sqrt{2} \sqrt{-\frac{1}{2} \mu^2 sS^2 + \frac{3}{2} sS^2 v^2 \lambda + cS^2 \text{mu}S^2 \lambda S + 2 cS \text{mu}S sS v \lambda S + sS^2 v^2 \lambda S}$	126.883	126.883
W	$\frac{1}{2} \sqrt{\frac{e^2 v^2}{s_W^2}}$	79.8252	79.8252
Z	$\sqrt{2} \sqrt{\frac{e^2 v^2}{4} + \frac{c_W^2 e^2 v^2}{8 s_W^2} + \frac{e^2 s_W^2 v^2}{8 c_W^2}}$	91.188	91.188

100%

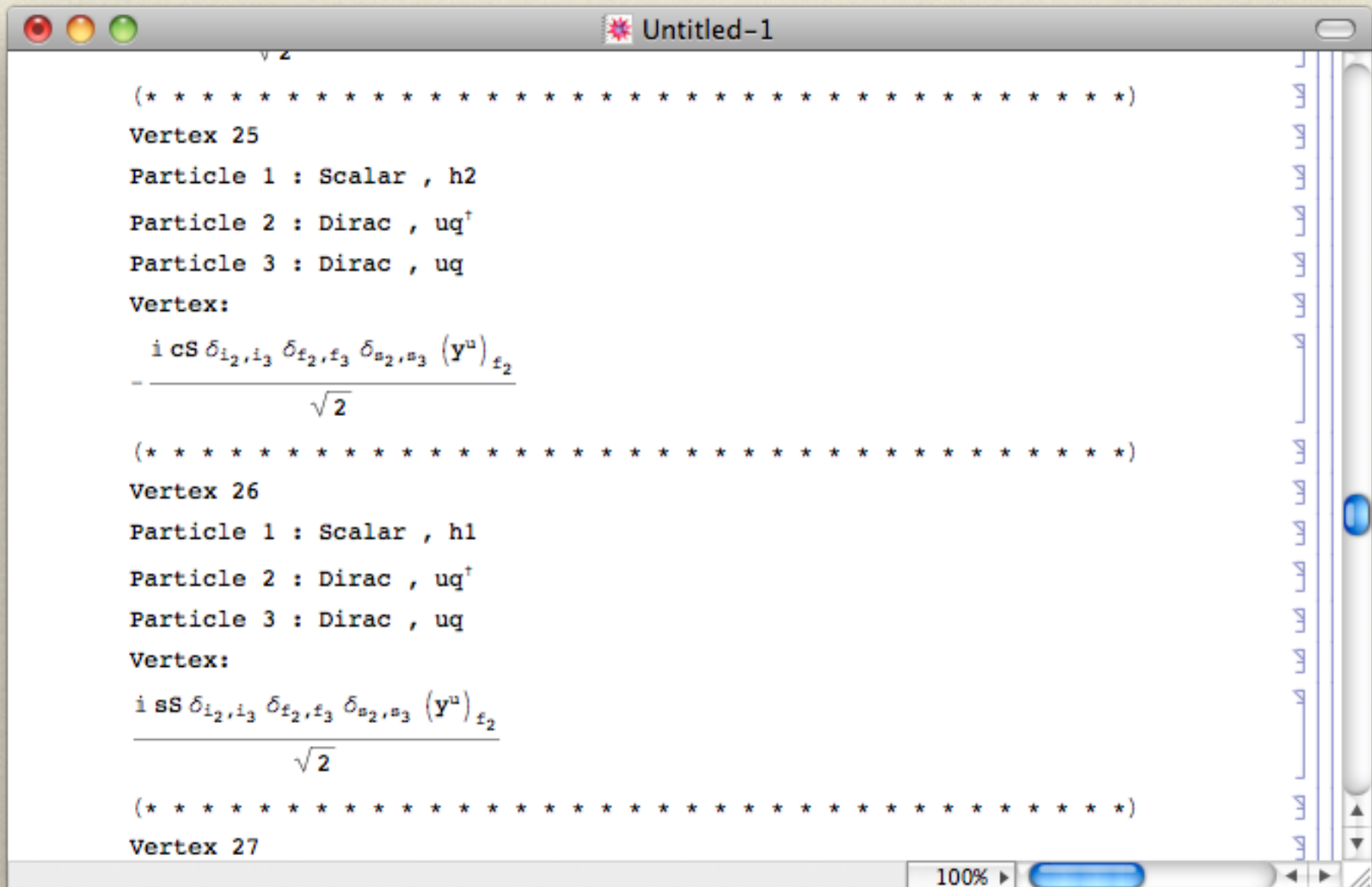
Generate Feynman Rules

FeynmanRules[LSMpS];

Generate Feynman Rules

```
Untitled-1
( * * * * * )
Vertex 2
Particle 1 : Scalar , h1
Particle 2 : Scalar , h2
Particle 3 : Scalar , h2
Particle 4 : Scalar , h2
Vertex:
6 i c S^3 s S lambda + 6 i c S^3 s S lambda
( * * * * * )
Vertex 3
Particle 1 : Scalar , h1
Particle 2 : Scalar , h1
Particle 3 : Scalar , h2
Particle 4 : Scalar , h2
Vertex:
-6 i c S^2 s S^2 lambda - 6 i c S^2 s S^2 lambda
( * * * * * )
Vertex 4
Particle 1 : Scalar , h1
Particle 2 : Scalar , h1
```


Generate Feynman Rules

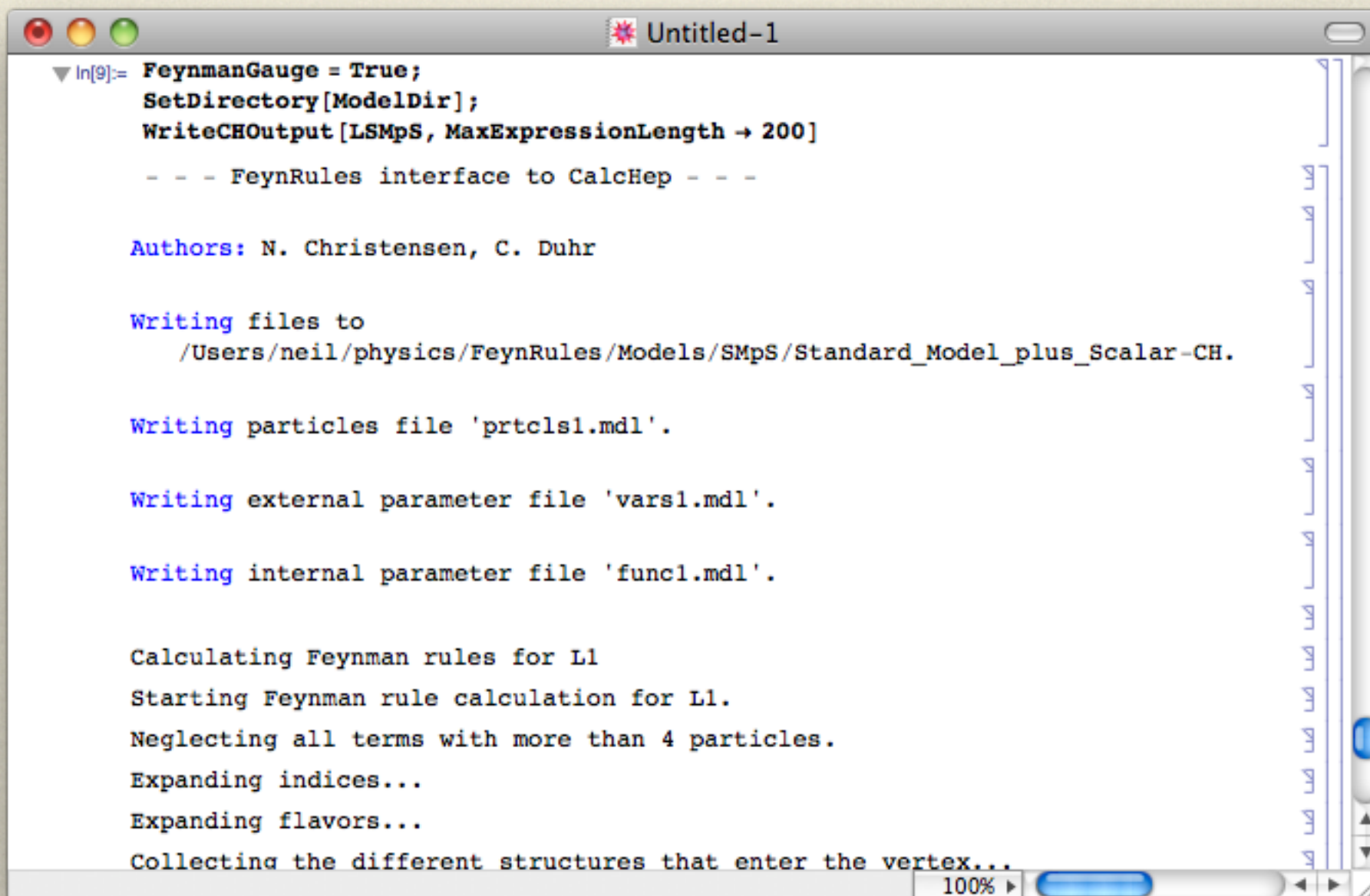


```
Untitled-1
v 2
( * * * * * )
Vertex 25
Particle 1 : Scalar , h2
Particle 2 : Dirac , uq†
Particle 3 : Dirac , uq
Vertex:
i cS δi2,i3 δf2,f3 δs2,s3 (yu)f2
-----
√2
( * * * * * )
Vertex 26
Particle 1 : Scalar , h1
Particle 2 : Dirac , uq†
Particle 3 : Dirac , uq
Vertex:
i sS δi2,i3 δf2,f3 δs2,s3 (yu)f2
-----
√2
( * * * * * )
Vertex 27
```

Generate CalcHEP Files

```
FeynmanGauge = True;  
SetDirectory[ModelDir];  
WriteCHOutput[LSMpS]
```

Generate CalcHEP Files

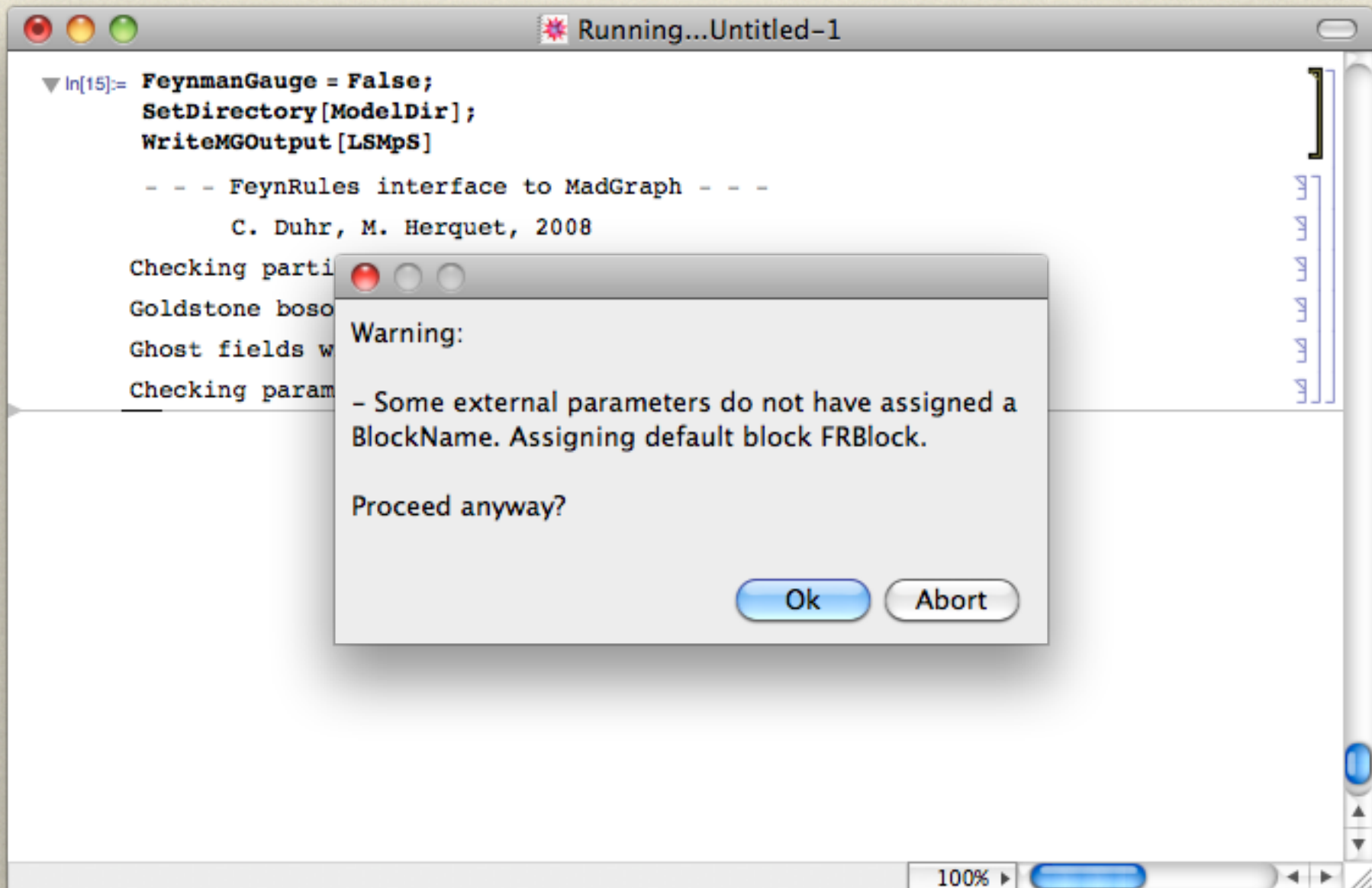


```
▼ In[9]:= FeynmanGauge = True;  
SetDirectory[ModelDir];  
WriteCHOutput [LSMPS, MaxExpressionLength → 200]  
  
- - - FeynRules interface to CalcHep - - -  
  
Authors: N. Christensen, C. Duhr  
  
Writing files to  
  /Users/neil/physics/FeynRules/Models/SMPS/Standard_Model_plus_Scalar-CH.  
  
Writing particles file 'prtcls1.mdl'.  
  
Writing external parameter file 'vars1.mdl'.  
  
Writing internal parameter file 'funcl.mdl'.  
  
Calculating Feynman rules for L1  
Starting Feynman rule calculation for L1.  
Neglecting all terms with more than 4 particles.  
Expanding indices...  
Expanding flavors...  
Collecting the different structures that enter the vertex...
```

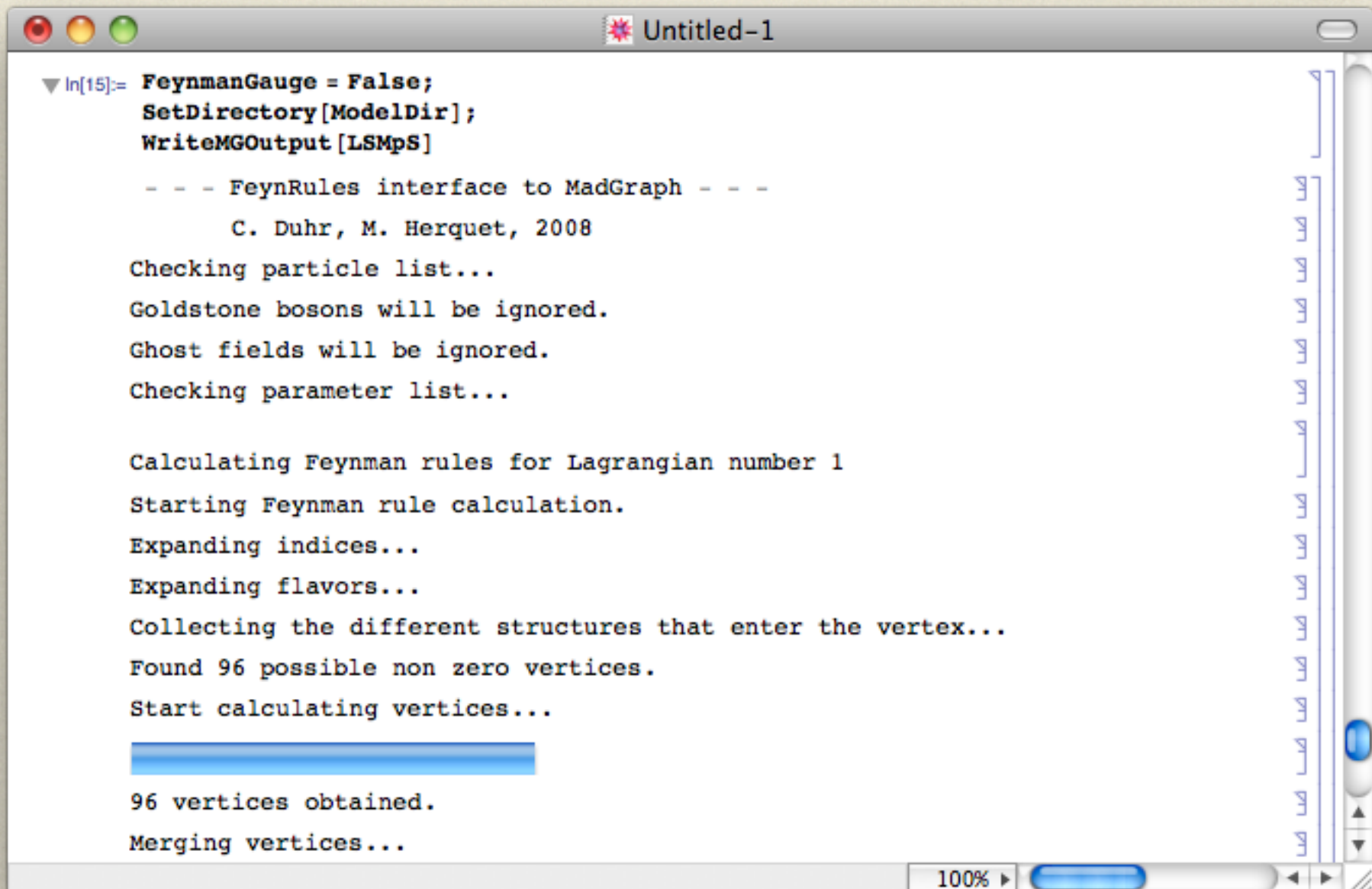

Generate MadGraph Files

```
FeynmanGauge = False;  
SetDirectory[ModelDir];  
WriteMGOutput[LSMpS]
```

Generate MadGraph Files

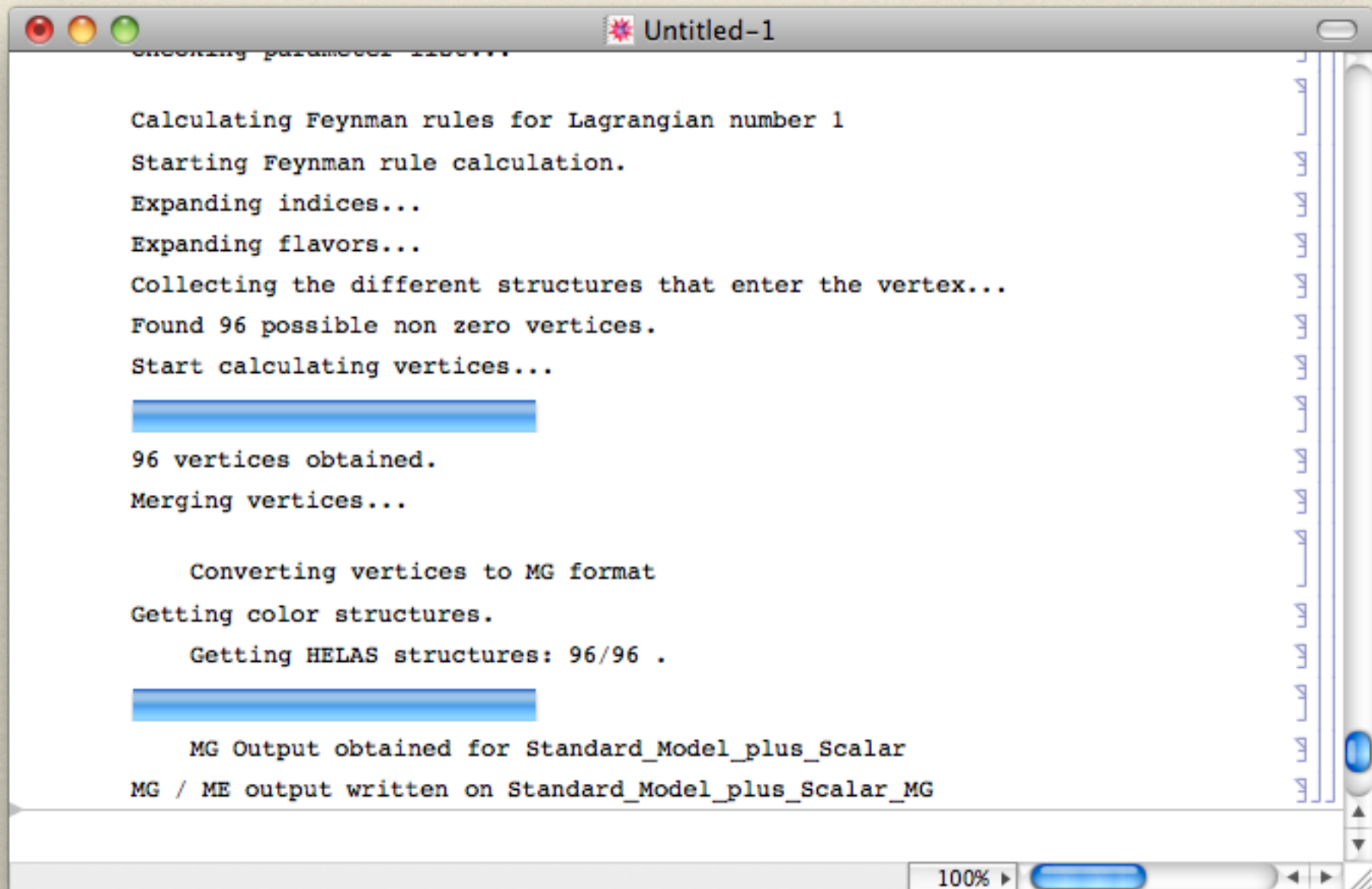


Generate MadGraph Files



```
▼ In[15]:= FeynmanGauge = False;  
SetDirectory[ModelDir];  
WriteMGOutput [LSMps]  
  
- - - FeynRules interface to MadGraph - - -  
      C. Duhr, M. Herquet, 2008  
Checking particle list...  
Goldstone bosons will be ignored.  
Ghost fields will be ignored.  
Checking parameter list...  
  
Calculating Feynman rules for Lagrangian number 1  
Starting Feynman rule calculation.  
Expanding indices...  
Expanding flavors...  
Collecting the different structures that enter the vertex...  
Found 96 possible non zero vertices.  
Start calculating vertices...  
████████████████████████████████████████████████████████████████████████████████  
96 vertices obtained.  
Merging vertices...
```

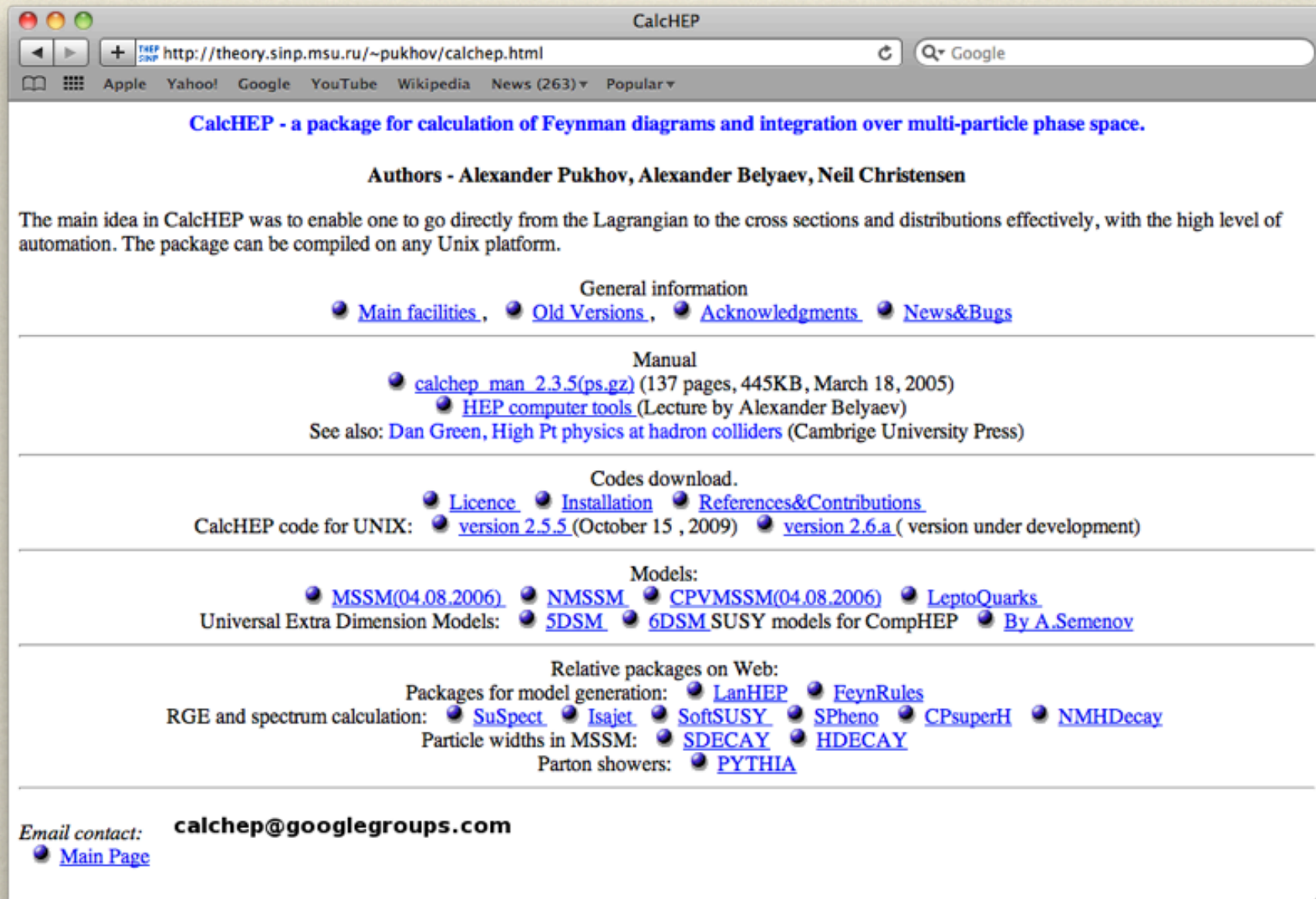
Generate MadGraph Files



```
Checking parameter file...  
  
Calculating Feynman rules for Lagrangian number 1  
Starting Feynman rule calculation.  
Expanding indices...  
Expanding flavors...  
Collecting the different structures that enter the vertex...  
Found 96 possible non zero vertices.  
Start calculating vertices...  
  
████████████████████████████████████████████████████████████████████████████████  
96 vertices obtained.  
Merging vertices...  
  
    Converting vertices to MG format  
Getting color structures.  
    Getting HELAS structures: 96/96 .  
  
████████████████████████████████████████████████████████████████████████████████  
  
    MG Output obtained for Standard_Model_plus_Scalar  
MG / ME output written on Standard_Model_plus_Scalar_MG
```

100%

Download CalcHEP



CalcHEP - a package for calculation of Feynman diagrams and integration over multi-particle phase space.

Authors - Alexander Pukhov, Alexander Belyaev, Neil Christensen

The main idea in CalcHEP was to enable one to go directly from the Lagrangian to the cross sections and distributions effectively, with the high level of automation. The package can be compiled on any Unix platform.

General information

- [Main facilities](#) ,
- [Old Versions](#) ,
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Manual

- [calchep_man_2.3.5\(ps.gz\)](#) (137 pages, 445KB, March 18, 2005)
- [HEP computer tools](#) (Lecture by Alexander Belyaev)

See also: [Dan Green, High Pt physics at hadron colliders](#) (Cambridge University Press)

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CalcHEP code for UNIX: • [version 2.5.5](#) (October 15 , 2009) • [version 2.6.a](#) (version under development)

Models:

- [MSSM\(04.08.2006\)](#) • [NMSSM](#) • [CPVMSSM\(04.08.2006\)](#) • [LeptoQuarks](#)

Universal Extra Dimension Models: • [5DSM](#) • [6DSM](#) SUSY models for CompHEP • [By A.Semenov](#)

Relative packages on Web:

Packages for model generation: • [LanHEP](#) • [FeynRules](#)

RGE and spectrum calculation: • [SuSpect](#) • [Isajet](#) • [SoftSUSY](#) • [SPheno](#) • [CPsuperH](#) • [NMHDecay](#)

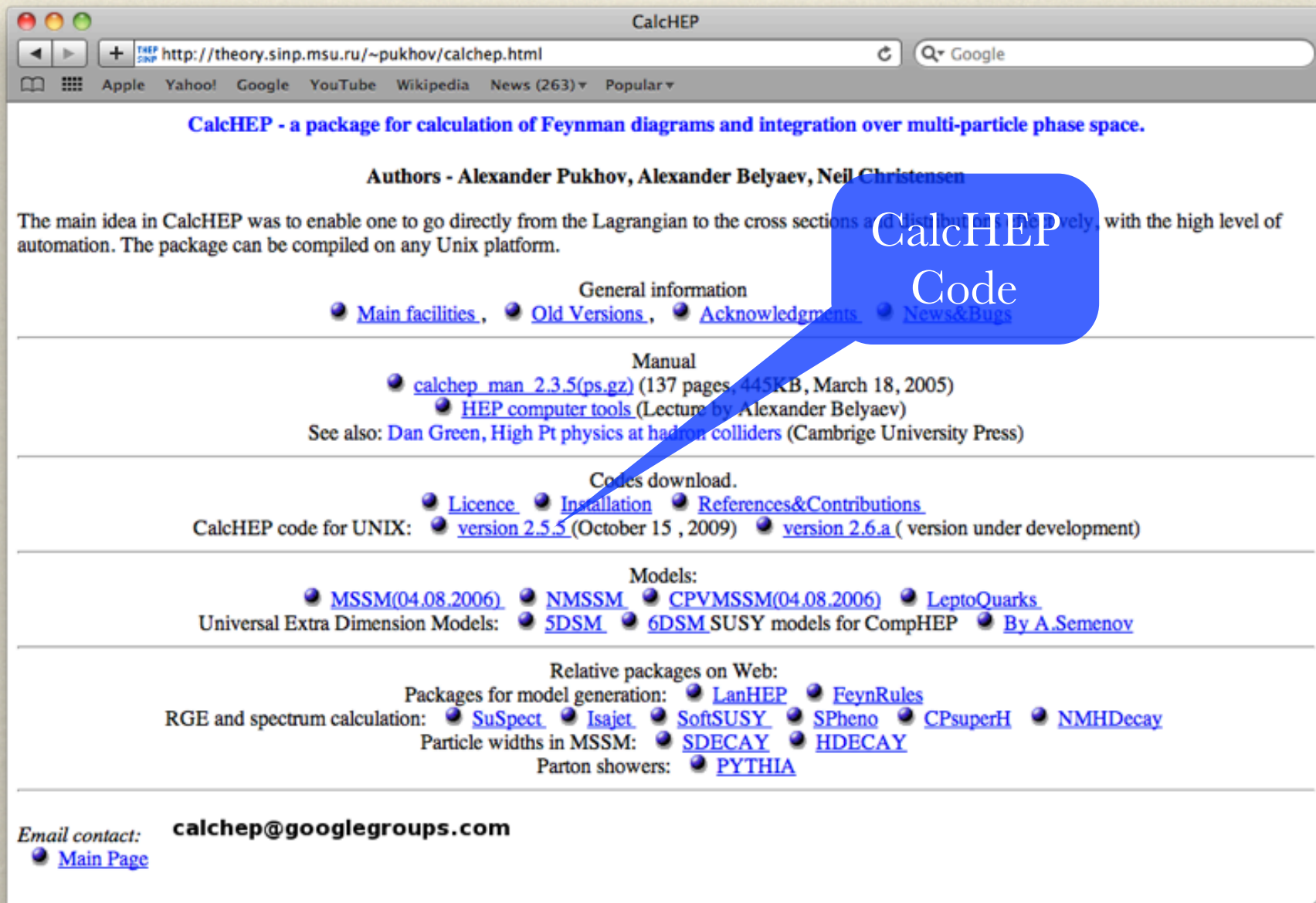
Particle widths in MSSM: • [SDECAY](#) • [HDECAY](#)

Parton showers: • [PYTHIA](#)

Email contact: calchep@googlegroups.com

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CalcHEP

http://theory.sinp.msu.ru/~pukhov/calchep.html

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CalcHEP - a package for calculation of Feynman diagrams and integration over multi-particle phase space.

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CalcHEP

http://theory.sinp.msu.ru/~pukhov/calchep.html

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Models:

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Parton showers: • [PYTHIA](#)

Email contact: calchep@googlegroups.com

- [Main Page](#)

Prepare CalcHEP

❖ Setup CalcHEP directory:

- ❖ `cd`
- ❖ `mkdir physics/CalcHEP`
- ❖ `cp Downloads/calchep_2.5.5.tar.gz physics/CalcHEP/calchep_2.5.5.tar.gz`

❖ Compile CalcHEP:

- ❖ `cd physics/CalcHEP`
- ❖ `tar xvzf calchep_2.5.5.tar.gz`
- ❖ `cd calchep_2.5.5`
- ❖ `make`

❖ Start CalcHEP:

- ❖ `./mkUsrDir ../ch_2.5.5`
- ❖ `cd ../ch_2.5.5`
- ❖ `./calchep &`

Import FR Model

CalcHEP/symb

Abstract

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

Use F2 key to get information about interface facilities and F1 - as online help.

Standard Model (CKM=1)
Standard Model
IMPORT OF MODELS

F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit

Import FR Model

CalcHEP/symb

IMPORT OF MODELS

Enter name of directory with models, or press Esc to Exit, or F1 for Help

Dir= ~/physics/FeynRules/Models/SMpS/Standard_Model_plus_Scalar-CH

Import FR Model

CalcHEP/symb

IMPORT OF MODELS

Enter name of directory with models, or press Esc to Exit, or F1 for Help

Dir= ~/physics/FeynRules/Models/SMpS/Standard_Model_plus_Scalar-CH

Choose a model

< Standard_Model_plus_Sc | 1.mdl

F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit

Import FR Model

CalcHEP/symb

IMPORT OF MODELS

Enter name of directory with models, or press Esc to Exit, or F1 for Help

Dir= ~/physics/FeynRules/Models/SMpS/Standard_Model_plus_Scalar-CH

Choose a model

Standard_Model_plus_Sc | 1.mdl

Correct name **SMpS**

Import FR Model

CalcHEP/symb

Abstract

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

Use F2 key to get information about interface facilities and F1 - as online help.

Standard Model (CKM=1)
Standard Model
SMpS
IMPORT OF MODELS

F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit

Import FR Model

Model: SMpS

Abstract

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

Use F2 key to get information about interface facilities and F1 - as online help.

- Enter Process
- Force Unit.Gauge OFF
- Edit model**
- Delete model

F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit

Import FR Model

CalcHEP/symb

Model: SMpS

Abstract

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

Use F2 key to get information about interface facilities and F1 - as online help.

Edit model

Parameters
Constraints
Particles
Vertices
Libraries

RENAME

CHECK MODEL

F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit

Import FR Model

CalcHEP/symb

Model: SMpS

Abstract

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

Use F2 key to get information about interface facilities and F1 - as online help.

Edit model

CHECK MODEL

The model is Ok
- Press any key -

Import FR Model

CalcHEP/symb

Model: SMpS

Abstract

CalcHEP package is created for calculation of decay and high energy collision processes of elementary particles in the lowest order (tree) approximation. The main idea put into the CalcHEP was to make available passing from the lagrangian to the final distributions effectively with the high level of automatization.

Use F2 key to get information about interface facilities and F1 - as online help.

Enter Process

Force Unit.Gauge OFF
Edit model
Delete model

F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit

Generate Process Code

CalcHEP/symb

Model: SMpS

List of particles (antiparticles)

ve (ve~)- Electron-neut	vm (vm~)- Mu-neutrino	vt (vt~)- Tau-neutrino
e- (e+)- Electron	m- (m+)- Muon	tt- (tt+)- Tau
u (u~)- u-quark	c (c~)- c-quark	t (t~)- t-quark
d (d~)- d-quark	s (s~)- s-quark	b (b~)- b-quark
A (A)- Photon	Z (Z)- Z	W+ (W-)- W
G (G)- G	h1 (h1)- h1	h2 (h2)- h2

Enter process: **e-, e+ -> Z, b, b~**

Generate Process Code

CalcHEP/symb

Model: SMpS

List of particles (antiparticles)

ve (ve~)- Electron-neut	vm (vm~)- Mu-neutrino	vt (vt~)- Tau-neutrino
e- (e+)- Electron	m- (m+)- Muon	tt- (tt+)- Tau
u (u~)- u-quark	c (c~)- c-quark	t (t~)- t-quark
d (d~)- d-quark	s (s~)- s-quark	b (b~)- b-quark
A (A)- Photon	Z (Z)- Z	W+ (W-)- W
G (G)- Gluon		h2

There are files in directory 'results/'.
To continue you has to clean or rename this directory.
Press any key

Generate Process Code

The screenshot shows a window titled "CalcHEP/symb" with a "Model: SMpS" label. Below this is a section titled "List of particles (antiparticles)" containing a table of particle names and their descriptions. A context menu is open over the "Photon" entry, showing options: "View", "Delete", and "Rename". At the bottom of the window, a status bar displays keyboard shortcuts: "F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit".

Model: SMpS

List of particles (antiparticles)

ve (ve~)- Electron-neut	vm (vm~)- Mu-neutrino	vt (vt~)- Tau-neutrino
e- (e+)- Electron	m- (m+)- Muon	tt- (tt+)- Tau
u (u~)- u-quark	c (c~)- c-quark	t (t~)- t-quark
d (d~)- d-quark	s (s~)- s-quark	b (b~)- b-quark
A (A)- Photon	Z (Z)- Z	W+ (W-)- W
G (G)- Photon	h1 (h1)- h1	h2 (h2)- h2

View
Delete
Rename

F1-Help F2-Man F5-Switches F6-Results F9-Ref F10-Quit

Generate Process Code

CalcHEP/symb

Model: SMpS

Process: $e^-, e^+ \rightarrow Z, b, b^c$

Feynman diagrams

20 diagrams in 1 subprocesses are constructed.
0 diagrams are deleted.

View diagrams
Squaring technique
Write down processes

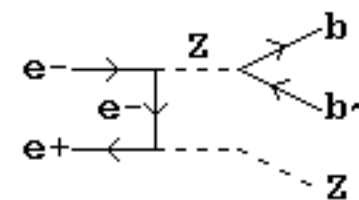
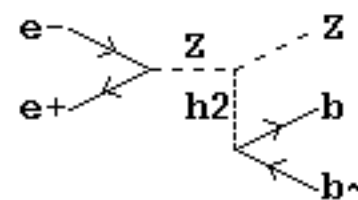
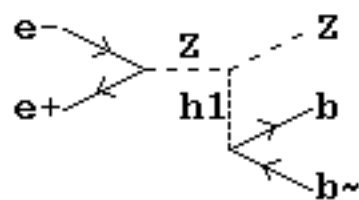
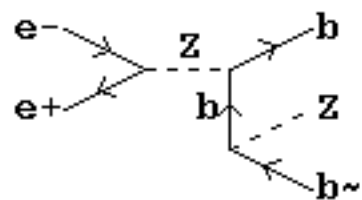
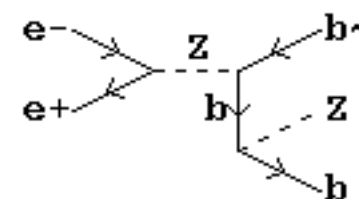
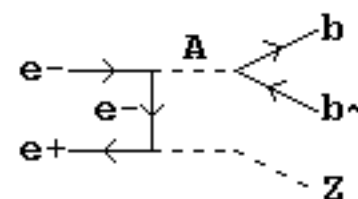
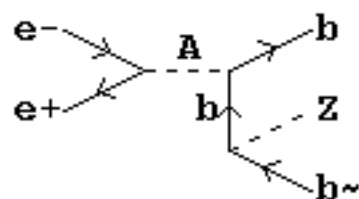
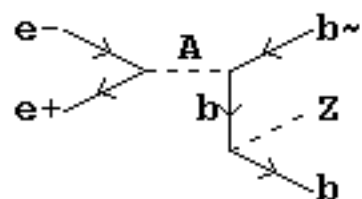
F1-Help F2-Man F3-Model F5-Switches F6-Results F9-Ref F10-Quit

Generate Process Code

CalcHEP/symb

Delete, On/off, Restore, Latex

1/20



F1-Help, F2-Man, PgUp, PgDn, Home, End, # , Esc

Generate Process Code

CalcHEP/symb

Model: SMpS

Process: $e^-, e^+ \rightarrow Z, b, b^c$

Feynman diagrams

20 diagrams in 1 subprocesses are constructed.
0 diagrams are deleted.

< View diagrams
Squaring technique
Write down processes

F1-Help F2-Man F3-Model F5-Switches F6-Results F9-Ref F10-Quit

Generate Process Code

CalcHEP/symb

Model: SMpS

Process: $e^-, e^+ \rightarrow Z, b, b^c$

Feynman diagrams

20 diagrams in 1 subprocesses are constructed.
0 diagrams are deleted.

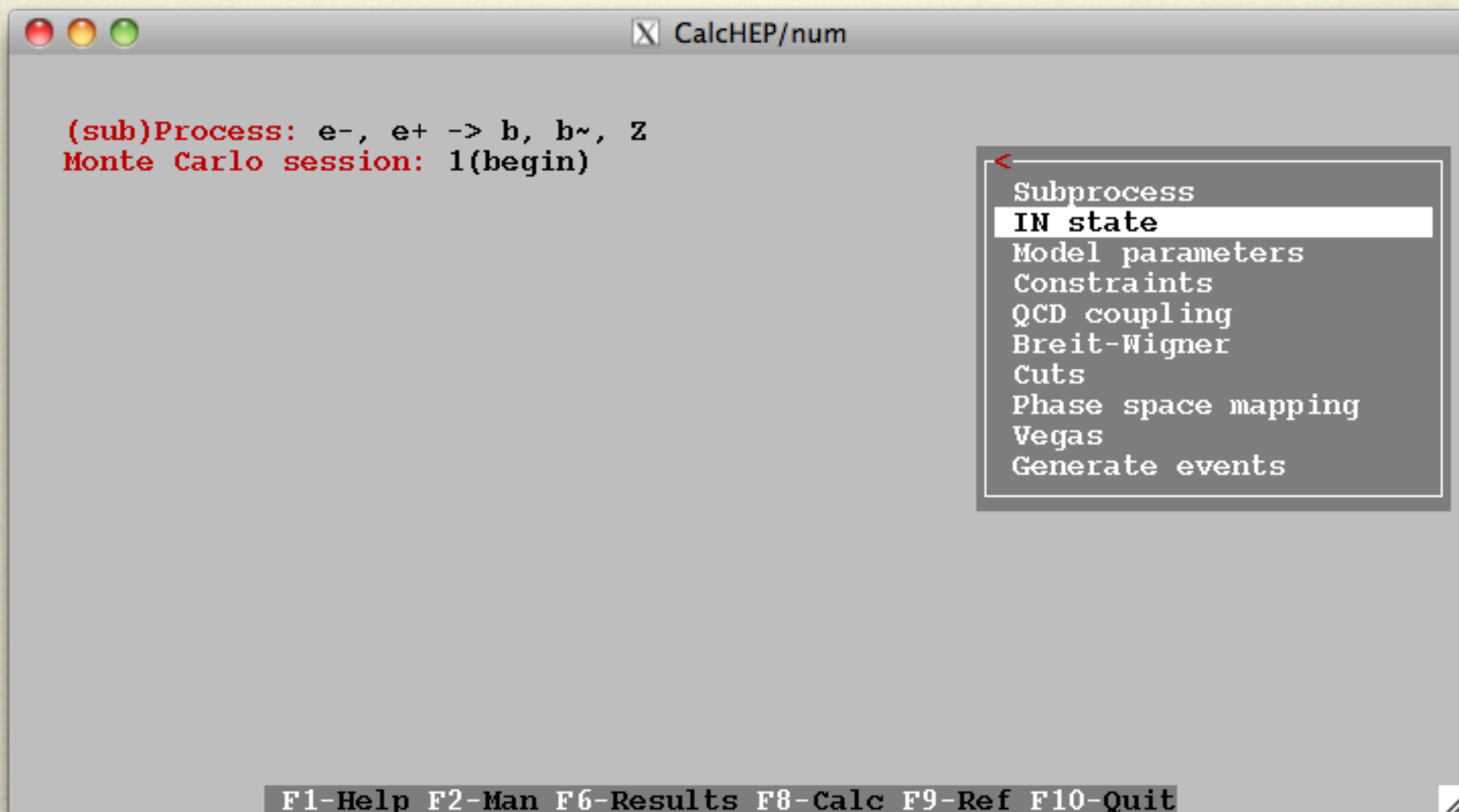
Squared diagrams

210 diagrams in 1 subprocesses are constructed.
0 diagrams are deleted.
0 diagrams are calculated.

<
View squared diagrams
Symbolic calculations
Make&Launch n_calchep
Make n_calchep
REDUCE program

F1-Help F2-Man F3-Model F4-Diagrams F5-Switches F6-Results F9-Ref F10-Quit

Generate Distribution



The screenshot shows a window titled "CalcHEP/num" with a menu open. The main window contains the following text:

```
(sub)Process: e-, e+ -> b, b~, Z  
Monte Carlo session: 1(begin)
```

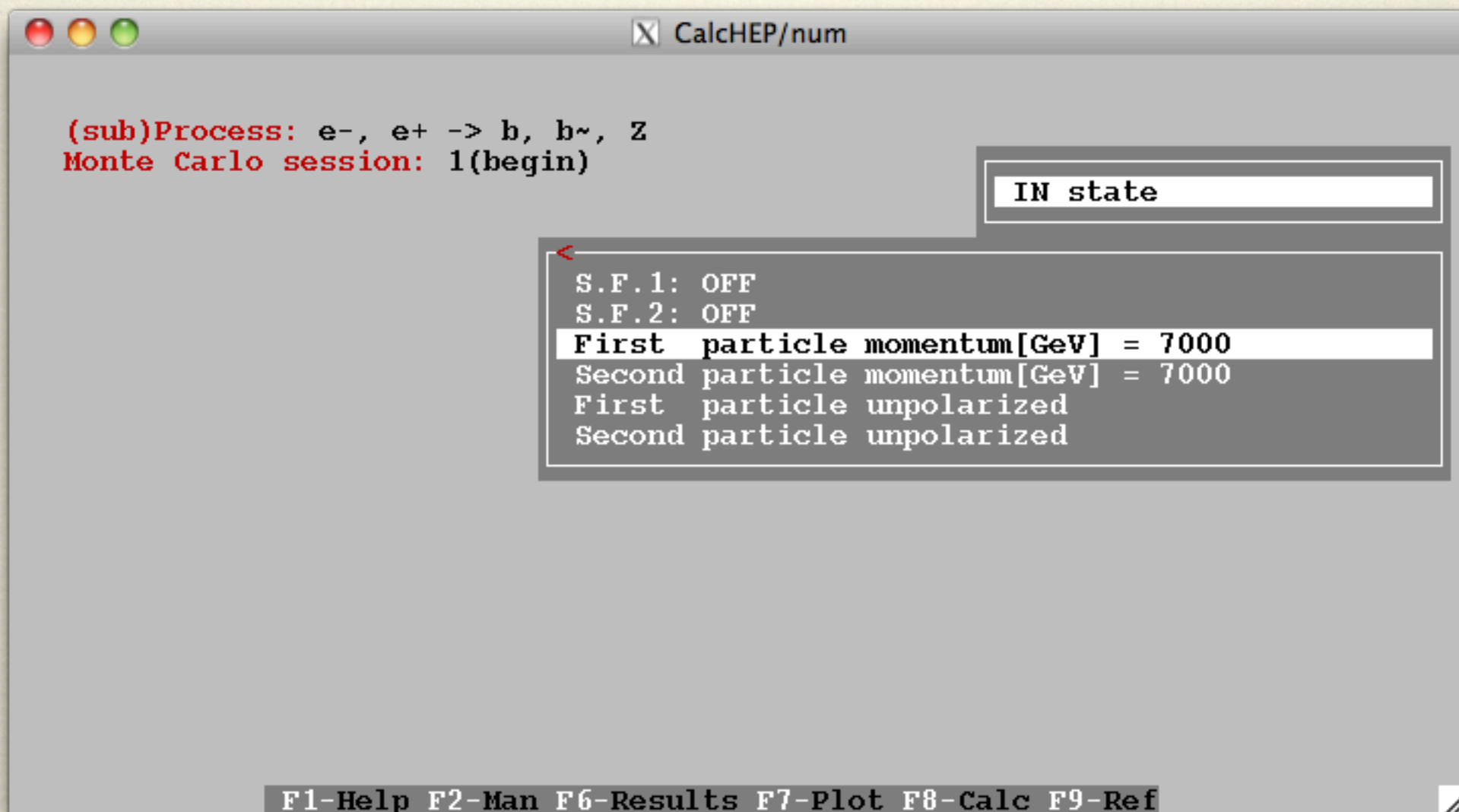
The menu is open to the left and contains the following items:

- Subprocess
- IN state** (highlighted)
- Model parameters
- Constraints
- QCD coupling
- Breit-Wigner
- Cuts
- Phase space mapping
- Vegas
- Generate events

At the bottom of the window, there is a status bar with the following text:

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution



CalcHEP/num

(sub)Process: $e^-, e^+ \rightarrow b, b^{\sim}, Z$
Monte Carlo session: 1(begin)

IN state

S.F.1: OFF
S.F.2: OFF

First particle momentum[GeV] = 7000
Second particle momentum[GeV] = 7000
First particle unpolarized
Second particle unpolarized

F1-Help F2-Man F6-Results F7-Plot F8-Calc F9-Ref

Generate Distribution

CalcHEP/num

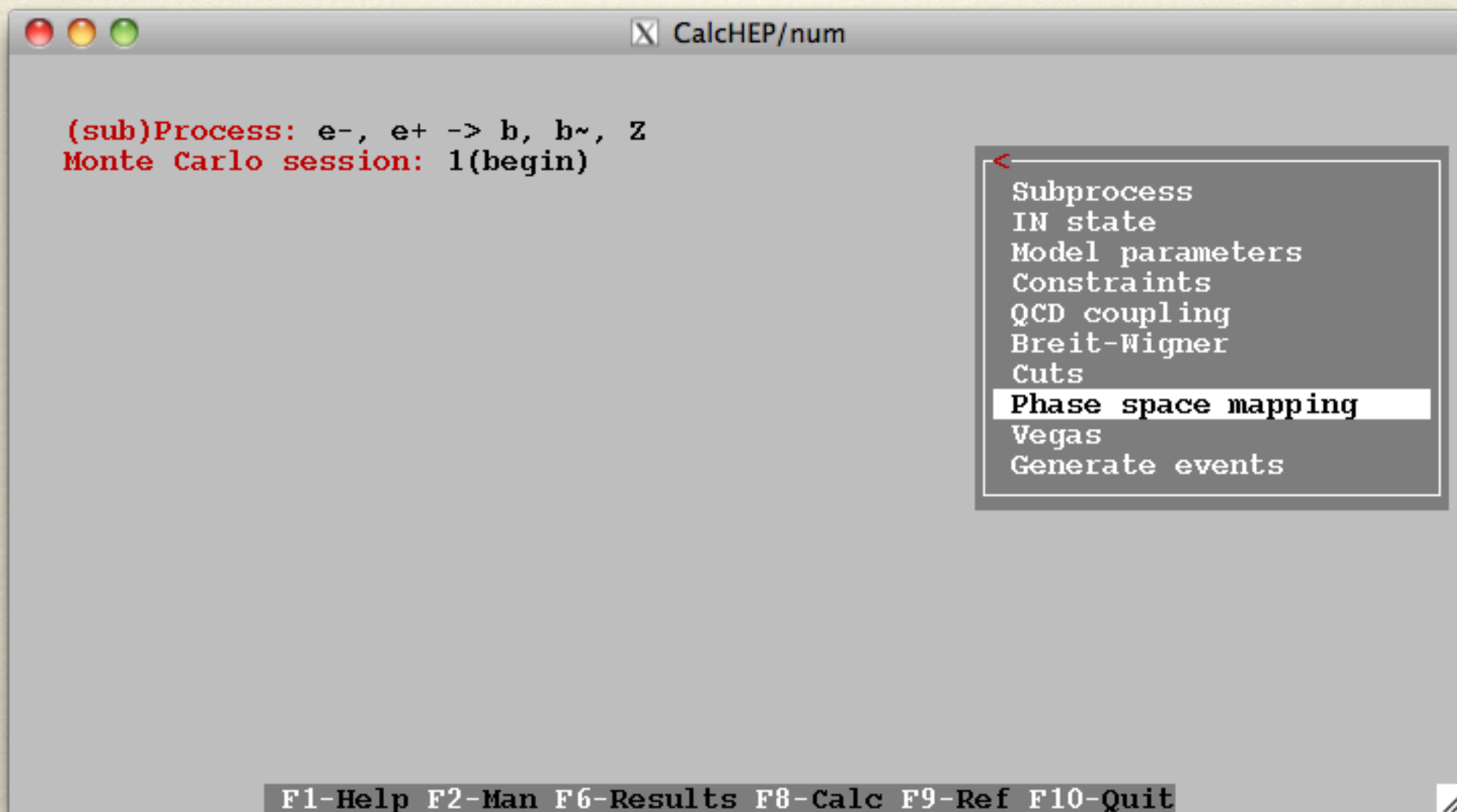
(sub)Process: $e^-, e^+ \rightarrow b, b^{\bar{}}, Z$
Monte Carlo session: 1(begin)

IN state

<
S.F.1: OFF
S.F.2: OFF
First particle momentum[GeV] = 250
Second particle momentum[GeV] = 250
First particle unpolarized
Second particle unpolarized

F1-Help F2-Man F6-Results F7-Plot F8-Calc F9-Ref

Generate Distribution



The image shows a window titled "CalcHEP/num" with a standard Mac OS-style title bar (red, yellow, green buttons). The main content area displays the following text:

```
(sub)Process: e-, e+ -> b, b~, Z  
Monte Carlo session: 1(begin)
```

To the right of this text is a menu box with a left-pointing arrow. The menu items are:

- Subprocess
- IN state
- Model parameters
- Constraints
- QCD coupling
- Breit-Wigner
- Cuts
- Phase space mapping** (highlighted)
- Vegas
- Generate events

At the bottom of the window, a status bar contains the text: **F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit**. A small icon is visible in the bottom right corner of the window.

Generate Distribution

The screenshot shows a window titled "CalcHEP/num" with a standard Mac OS-style title bar (red, yellow, green buttons). The main content area displays the following text:

```
(sub)Process: e-, e+ -> b, b~, Z  
Monte Carlo session: 1(begin)
```

To the right of this text is a menu with two items:

- Phase space mapping
- Kinematics
- Regularization

At the bottom of the window, a status bar contains the text: **F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit**. A small icon is visible in the bottom right corner of the window.

Generate Distribution

CalcHEP/num

(sub)Process: $e^-, e^+ \rightarrow b, \bar{b}, Z$
Monte Carlo session: 1(begin)

=====**Current kinematical scheme**=====

in= 12	-> out1= 3	out2= 45
in= 45	-> out1= 4	out2= 5

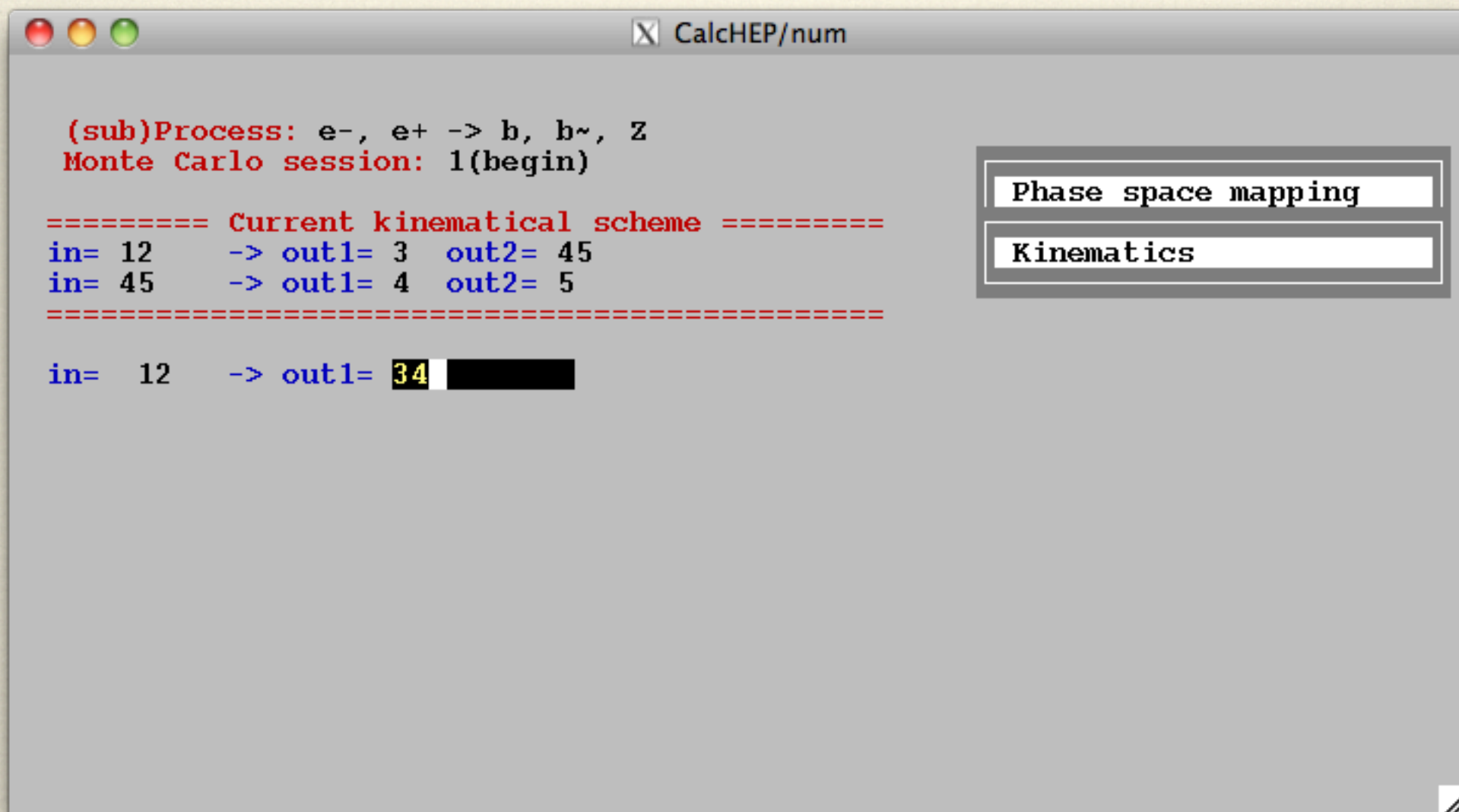
=====

Input new kinematics?
— (Y / N ?) —

Phase space mapping

Kinematics

Generate Distribution



CalcHEP/num

(sub)Process: $e^-, e^+ \rightarrow b, \bar{b}, Z$
Monte Carlo session: 1(begin)

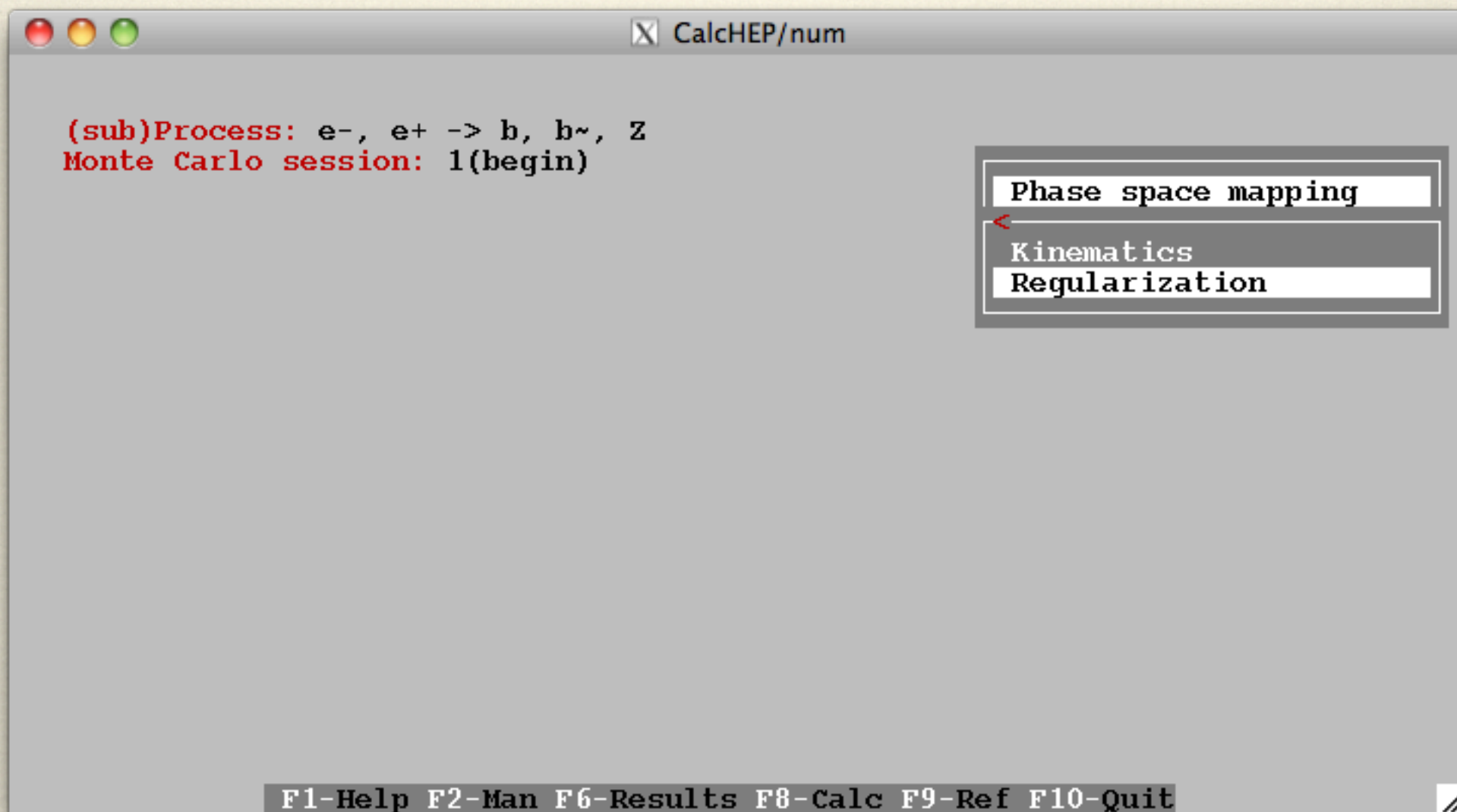
=====
Current kinematical scheme
=====
in= 12 -> out1= 3 out2= 45
in= 45 -> out1= 4 out2= 5
=====

in= 12 -> out1= 34

Phase space mapping

Kinematics

Generate Distribution



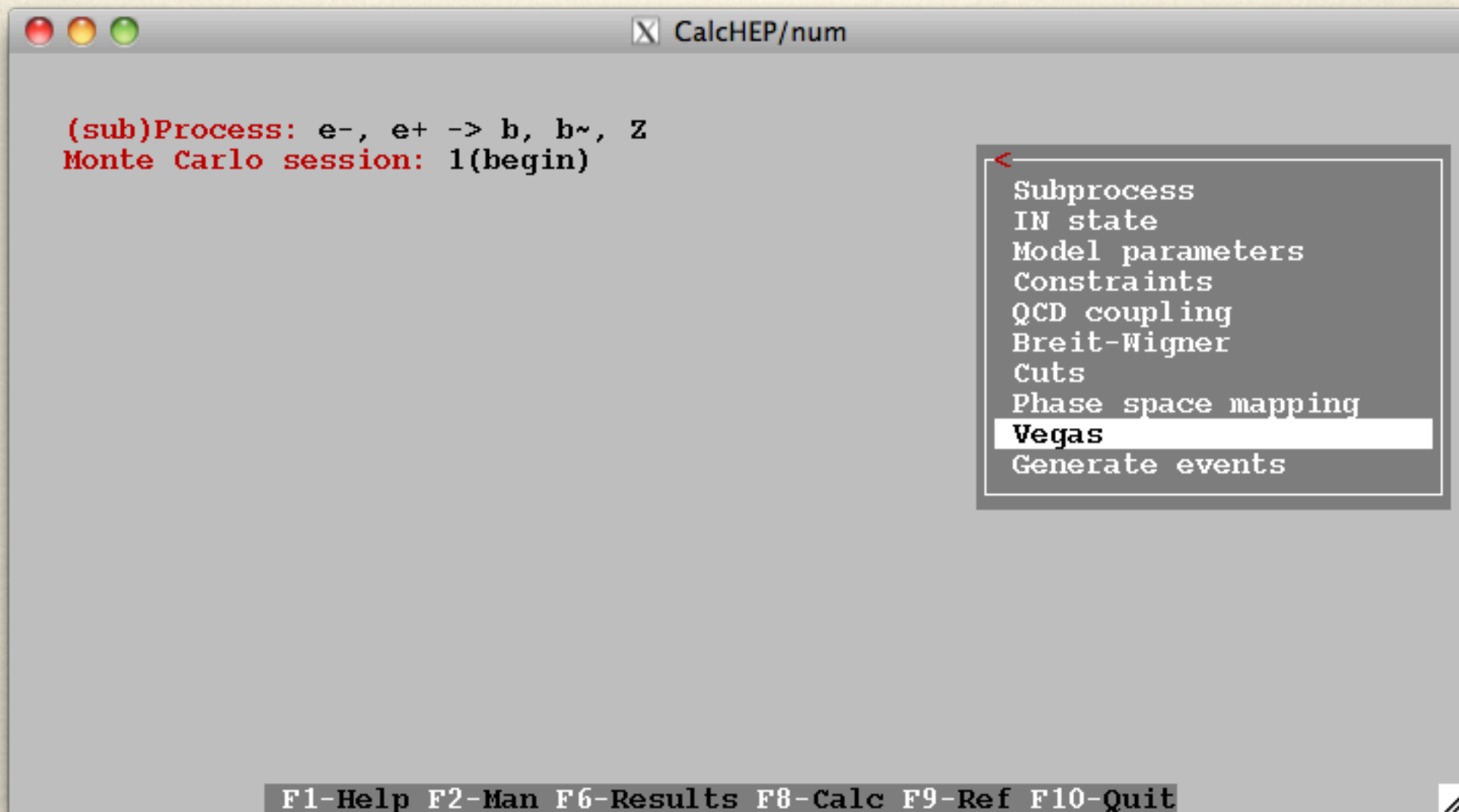
CalcHEP/num

(sub)Process: $e^-, e^+ \rightarrow b, \bar{b}, Z$
Monte Carlo session: 1(begin)

- Phase space mapping
- < Kinematics
- Regularization

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution



The screenshot shows a window titled "CalcHEP/num" with a menu open. The main window contains the following text:

```
(sub)Process: e-, e+ -> b, b~, Z  
Monte Carlo session: 1(begin)
```

The menu items are:

- Subprocess
- IN state
- Model parameters
- Constraints
- QCD coupling
- Breit-Wigner
- Cuts
- Phase space mapping
- Vegas**
- Generate events

At the bottom of the window, there is a status bar with the following text:

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution

CalcHEP/num

(sub)Process: $e^-, e^+ \rightarrow b, \bar{b}, Z$
Monte Carlo session: 1(begin)

```
#IT  Cross section [pb]  Error %  nCall  chi**2  
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

Vegas

<

nSess_1 = 5
nCalls_1 = 10000
nSess_2 = 0
nCalls_2 = 10000

Set Distributions

*Start integration
Display Distributions
Clear statistic
Freeze grid OFF
Clear grid

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution

CalcHEP/num

(sub)Process: $e^-, e^+ \rightarrow b, \bar{b}, Z$

Distributions 1

Clr	Del	Size	Read	ErrMes									
Parameter_1	>	Min_1	<	>	Max_1	<	Parameter_2	>	Min_2	<	>	Max_2	<
M(b, \bar{b})		0		>	400								<

ions

F1 F2 Xgoto Ygoto Find Write

Generate Distribution

CalcHEP/num

(sub)Process: $e^-, e^+ \rightarrow b, \bar{b}, Z$
Monte Carlo session: 1(begin)

```
#IT  Cross section [pb]  Error %  nCall  chi**2  
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

Vegas

<

nSess_1 = 5
nCalls_1 = 10000
nSess_2 = 0
nCalls_2 = 10000
Set Distributions
***Start integration**
Display Distributions
Clear statistic
Freeze grid OFF
Clear grid

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution

CalcHEP/num

(sub)Process: $e^-, e^+ \rightarrow b, \bar{b}, Z$
Monte Carlo session: 1(begin)

#IT	Cross section [pb]	Error %	nCall	chi**2
1	1.5444E-01	3.45E+00	9216	
2	1.5518E-01	9.05E-01	9216	
3	1.5862E-01	5.98E-01	9216	
4	1.5843E-01	6.01E-01	9216	
5	1.5848E-01	4.88E-01	9216	
< >	1.5809E-01	3.01E-01	46080	1

XX

Vegas

<

nSess_1 = 5
nCalls_1 = 10000
nSess_2 = 0
nCalls_2 = 10000
Set Distributions
*Start integration
Display Distributions
Clear statistic
Freeze grid OFF
Clear grid

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution

CalcHEP/num

(sub)Process: e-, e+ -> b, b~, Z
Monte Carlo session: 1(begin)

#IT	Cross section [pb]	Error %	nCall	chi**2
1	1.5444E-01	3.45E+00	9216	
2	1.5518E-01	9.05E-01	9216	
3	1.5862E-01	5.98E-01	9216	
4	1.5843E-01	6.01E-01	9216	
5	1.5848E-01	4.88E-01	9216	
< >	1.5809E-01	3.01E-01	46080	1

XX

Vegas

<

nSess_1 = 5
nCalls_1 = 10000
nSess_2 = 0
nCalls_2 = 10000
Set Distributions
*Start integration
Display Distributions
Clear statistic
Freeze grid OFF
Clear grid

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution

CalcHEP/num

(sub)Process: e-, e+ -> b, b~, Z
Monte Carlo session: 1(begin)

#IT	Cross section [pb]	Error %	nCall	chi**2
1	1.5444E-01	3.45E+00	9216	
2	1.5518E-01	9.05E-01	9216	
3	1.5862E-01	5.98E-01	9216	
4	1.5843E-01	6.01E-01	9216	
5	1.5848E-01	4.88E-01	9216	
< >	1.5809E-01	3.01E-01	46080	1

XX

Vegas

<

nSess_1 = 5
nCalls_1 = 100000
nSess_2 = 0
nCalls_2 = 10000
Set Distributions
***Start integration**
Display Distributions
Clear statistic
Freeze grid OFF
Clear grid

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution

CalcHEP/num

(sub)Process: e-, e+ -> b, b~, Z
Monte Carlo session: 1(begin)

#IT	Cross section [pb]	Error %	nCall	chi**2
1	1.5444E-01	3.45E+00	9216	
2	1.5518E-01	9.05E-01	9216	
3	1.5862E-01	5.98E-01	9216	
4	1.5843E-01	6.01E-01	9216	
5	1.5848E-01	4.88E-01	9216	
< >	1.5809E-01	3.01E-01	46080	1
1	1.5845E-01	2.34E-01	94500	
2	1.5830E-01	1.99E-01	94500	
3	1.5786E-01	1.65E-01	94500	
4	1.5812E-01	2.01E-01	94500	
5	1.5849E-01	1.59E-01	94500	
< >	1.5822E-01	8.32E-02	472500	0.9

XX

Vegas

<

nSess_1 = 5
nCalls_1 = 100000
nSess_2 = 0
nCalls_2 = 10000
Set Distributions
*Start integration
Display Distributions
Clear statistic
Freeze grid OFF
Clear grid

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution

CalcHEP/num

(sub)Process: $e^-, e^+ \rightarrow b, b^{\sim}, Z$
Monte Carlo session: 1(begin)

#IT	Cross section [pb]	Error %	nCall	chi**2
1	1.5444E-01	3.45E+00	9216	
2	1.5518E-01	9.05E-01	9216	
3	1.5862E-01	5.98E-01	9216	
4	1.5843E-01	6.01E-01	9216	
5	1.5848E-01	4.88E-01	9216	
< >	1.5809E-01	3.01E-01	46080	1
1	1.5845E-01	2.34E-01	94500	
2	1.5830E-01	1.99E-01	94500	
3	1.5786E-01	1.65E-01	94500	
4	1.5812E-01	2.01E-01	94500	
5	1.5849E-01	1.59E-01	94500	
< >	1.5822E-01	8.32E-02	472500	0.9

XX

Vegas

Display Distributions
Distributions

M(b, b~)

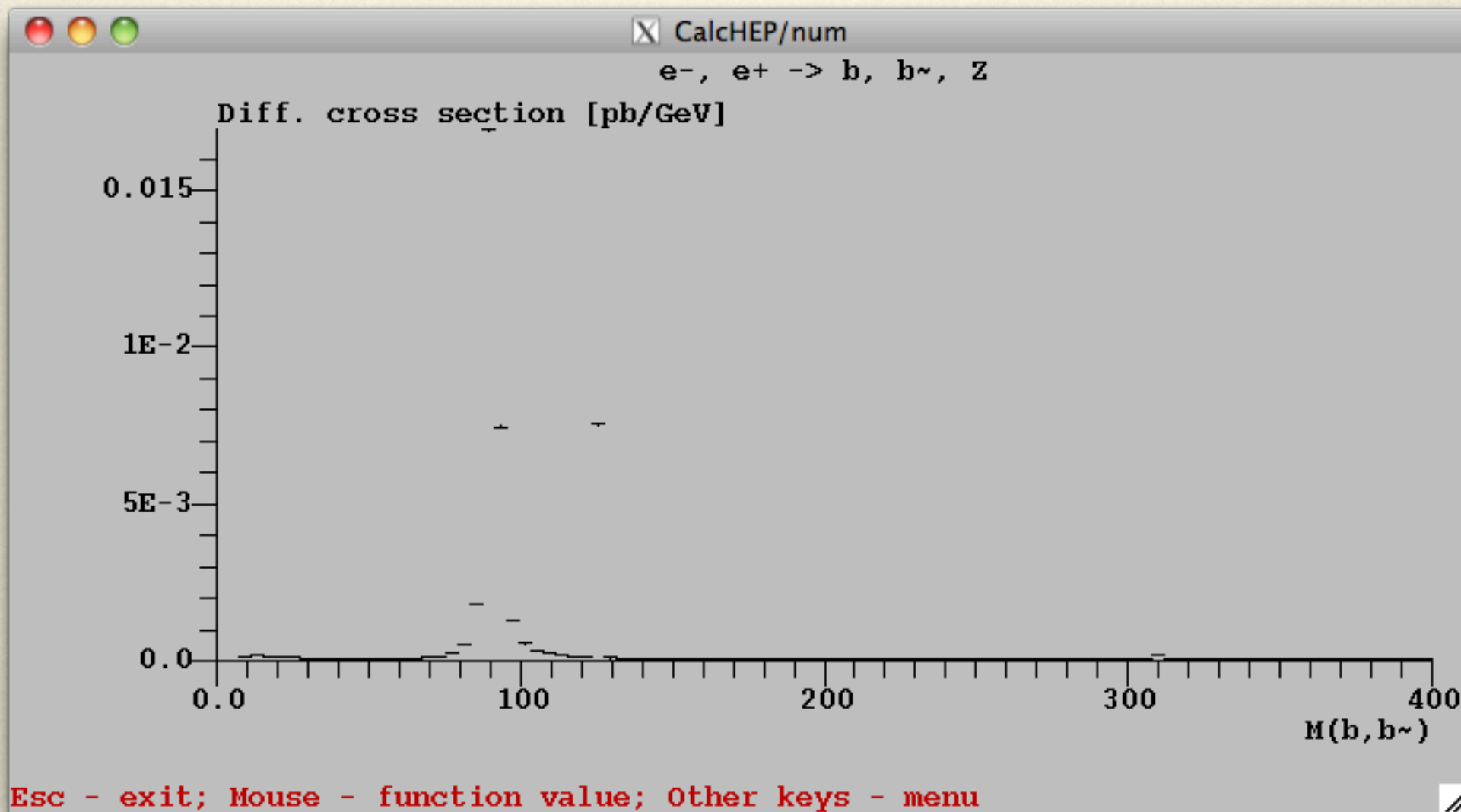
number of bins

300
150
100
75
60
50
30
25

PgDn

F1-Help F2-Man F6-Results F8-Calc F9-Ref F10-Quit

Generate Distribution



Done Early?

- ❖ Make m_{H1} & m_{H2} the external parameters:
 - ❖ Set m_{H1} & m_{H2} to be external.
 - ❖ Set λ and μ_H to be internal.
 - ❖ Set their values to be formulas in terms of m_{H1} & m_{H2} .
- ❖ Add other allowed lagrangian terms.
- ❖ Start implementing your favorite unimplemented model!