ScannerS

New modules and interfaces to constrain multi-Higgs models

R. Coimbra & A. Morais & **M. Sampaio** & R. Santos

LIP
University of Glasgow
Gr@v gravitation.web.ua.pt
universidade de aveiro
CFTC Centro de Física Teórica e Computacional
ISEL INSTITUTO SUPERIOR DE ENGENHARIA DE LISBOA

15th September, 2013

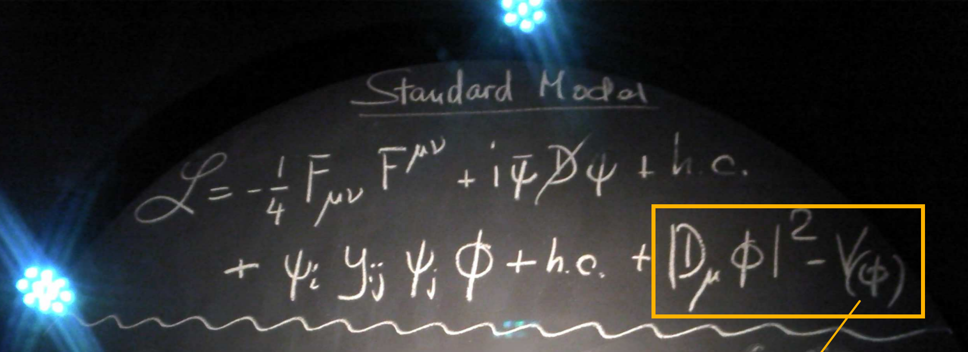
Scalars 2013, University of Warsaw

Based on: Eur.Phys.J. C73 (2013) 2428 [arXiv:1301.2599]
http://scanners.hepforge.org

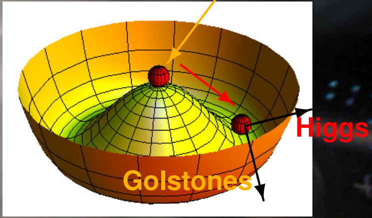
Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c.$$

$$+ \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



Why BSM scalar extensions?



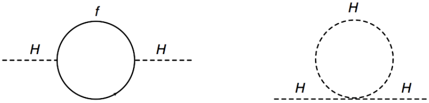
Why BSM scalar extensions?

In spite of the theoretical success:

Why BSM scalar extensions?

In spite of the theoretical success:

1. **Radiative corrections** ($\Lambda_{\text{cutoff}} \sim M_{Pl}$) $\Rightarrow \frac{\delta m_h^2}{m_h^2} \sim 10^{-16}$:



Why BSM scalar extensions?

In spite of the theoretical success:

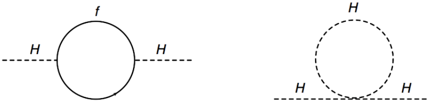
1. **Radiative corrections** ($\Lambda_{\rm cutoff} \sim M_{Pl}$) $\Rightarrow \frac{\delta m_h^2}{m_h^2} \sim 10^{-16}$:

SUSY, Extra dimensions,... $\Rightarrow$ Extended scalar sectors

Why BSM scalar extensions?

In spite of the theoretical success:

1. **Radiative corrections** ($\Lambda_{\text{cutoff}} \sim M_{Pl}$) $\Rightarrow \frac{\delta m_h^2}{m_h^2} \sim 10^{-16}$:



SUSY, Extra dimensions,... $\Rightarrow$ Extended scalar sectors

2. **SM does not explain:**

Why BSM scalar extensions?

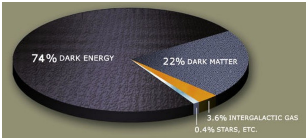
In spite of the theoretical success:

1. **Radiative corrections** ($\Lambda_{\mathrm{cutoff}} \sim M_{Pl}$) $\Rightarrow \frac{\delta m_h^2}{m_h^2} \sim 10^{-16}$:

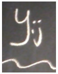
SUSY, Extra dimensions,... $\Rightarrow$ Extended scalar sectors

2. **SM does not explain:**

- Dark matter relic density →



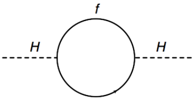
- Neutrino masses
- Flavour structure →

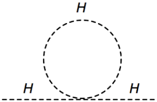


Why BSM scalar extensions?

In spite of the theoretical success:

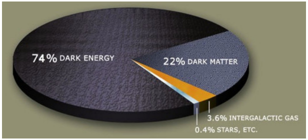
1. **Radiative corrections** ($\Lambda_{\text{cutoff}} \sim M_{Pl}$) $\Rightarrow \frac{\delta m_h^2}{m_h^2} \sim 10^{-16}$:

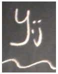




SUSY, Extra dimensions,… $\Rightarrow$ Extended scalar sectors

2. **SM does not explain:**
   - Dark matter relic density →
   - Neutrino masses →
   - Flavour structure





3. **Scalar sector prone to coupling to hidden sectors!**

Only SM singlets with dimension < 4 are: $H^\dagger H$, $B_{\mu\nu}$, $H^\dagger L$

James Wells' review arXiv:0909.4541

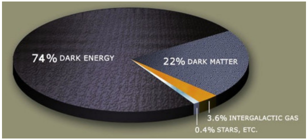
Why BSM scalar extensions?

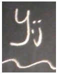
In spite of the theoretical success:

1. **Radiative corrections** ($\Lambda_{\text{cutoff}} \sim M_{Pl}$) $\Rightarrow \frac{\delta m_h^2}{m_h^2} \sim 10^{-16}$:

SUSY, Extra dimensions,. . . $\Rightarrow$ Extended scalar sectors

2. **SM does not explain:**
   - Dark matter relic density $\longrightarrow$
   - Neutrino masses
   - Flavour structure $\longrightarrow$





3. **Scalar sector prone to coupling to hidden sectors!**

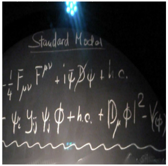
Only SM singlets with dimension < 4 are: $H^\dagger H$, $B_{\mu\nu}$, $H^\dagger L$

James Wells' review arXiv:0909.4541

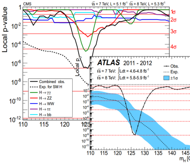
Extended scalar sectors can address these problems.

HEP Tools: interface between theory & experiment

Efficient tools are essential:

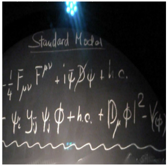


$\Rightarrow$

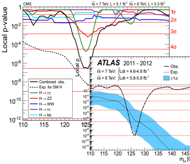


HEP Tools: interface between theory & experiment

Efficient tools are essential:

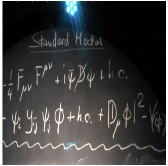


$\Rightarrow$ Feynman rules $\Rightarrow$ Matrix Element + MC Gen. $\Rightarrow$ Detector Simulation $\Rightarrow$

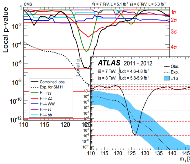


HEP Tools: interface between theory & experiment

Efficient tools are essential:



$\Rightarrow$ Feynman rules $\Rightarrow$ Matrix Element + MC Gen. $\Rightarrow$ Detector Simulation $\Rightarrow$



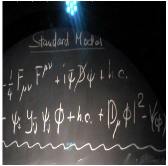
Aim of this talk:

- Tool to **Scan** parameter space of **Scalar** sectors.
- **Automatise** scans for tree level renormalisable V_{scalar}.
- **Generic** routines, **flexible** user analysis & **interfaces**.

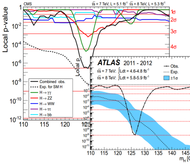
ScannerS.hepforge.org

HEP Tools: interface between theory & experiment

Efficient tools are essential:



⇒ Feynman rules ⇒ Matrix Element + MC Gen. ⇒ Detector Simulation ⇒



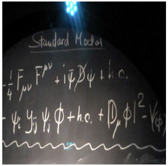
Aim of this talk:

- Tool to **Scan** parameter space of **Scalar** sectors.
- **Automatise** scans for tree level renormalisable V_{scalar}.
- **Generic** routines, **flexible** user analysis & **interfaces.**

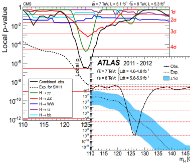
ScannerS.hepforge.org

HEP Tools: interface between theory & experiment

Efficient tools are essential:



⇒ Feynman rules ⇒ Matrix Element + MC Gen. ⇒ Detector Simulation ⇒



Aim of this talk:

- Tool to **Scan** parameter space of **Scalar** sectors.
- **Automatise** scans for tree level renormalisable V_{scalar}.
- **Generic** routines, **flexible** user analysis & **interfaces**.

ScannerS.hepforge.org

Outline

1. **ScannerS**: A tool to constrain the parameter space
   - Overview of the tool
   - Workflow

2. Strategy, modules & interfaces
   - The internal modules
   - The external interfaces

Outline

Overview of the tool

Doublets, complex, reals, etc ...

$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{array}{c} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{array}$$

Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix}$$

Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

$\phi_i = \mathbf{v_i} + \delta\phi_i$

Overview of the tool

Doublets, complex, reals, etc ... → Decompose *n* reals

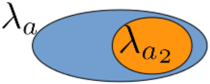
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

$$\phi_i = \mathbf{v_i} + \delta\phi_i$$

Min. Conditions

$$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$$



Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Block Detection

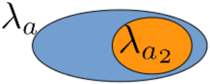
$$\mathbf{M.M^T} = \mathbf{1}$$

Numeric VEV

$$\phi_i = \mathbf{v_i} + \delta\phi_i$$

Min. Conditions

$$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$$



Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

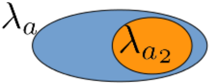
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

$\phi_i = \mathbf{v_i} + \delta\phi_i$

Min. Conditions

$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$

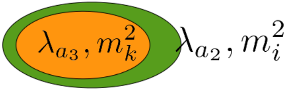


Block Detection

$\mathbf{M}.\mathbf{M}^\mathbf{T} = \mathbf{1}$

Quadratic Min. Cond.

$\left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \lambda_{a_2} = diag[m_i^2]$



Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose *n* reals

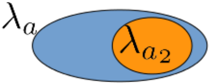
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

$\phi_i = \mathbf{v_i} + \delta\phi_i$

Min. Conditions

$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$



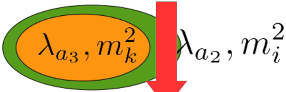
Block Detection

$\mathbf{M.M^T} = \mathbf{1}$

Quadratic Min. Cond.

$\left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \lambda_{a_2} = diag[m_i^2]$

Indep. $\{v_i, M_{ij}, \lambda_{a_3}, m_k^2\}$



Local Minimum Generated!

$\rightarrow$ Check Tree level Unitarity

$\rightarrow$ Check Global Stability

$\rightarrow$ Boundedness from below

Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

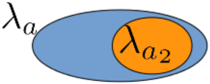
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

$\phi_i = \mathbf{v_i} + \delta\phi_i$

Min. Conditions

$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$



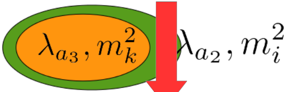
Block Detection

$\mathbf{M.M^T} = \mathbf{1}$

Quadratic Min. Cond.

$\left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \lambda_{a_2} = diag[m_i^2]$

Indep. $\{v_i, M_{ij}, \lambda_{a_3}, m_k^2\}$



Local Minimum Generated!

$\rightarrow$ Check Tree level Unitarity

$\rightarrow$ Check Global Stability

$\rightarrow$ Boundedness from below

Overview of the tool

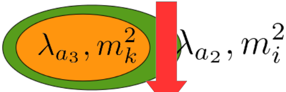
Doublets, complex, reals, etc ... → Decompose *n* reals

$$V(H, S, \phi, \chi, \ldots) \to \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \to \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \to V = V_a(\phi_i)\lambda_a$$

Quadratic Min. Cond.

$$\left\langle \hat{\partial}^2 V \right\rangle_{a_2} \lambda_{a_2} = diag[m_i^2]$$

Indep. $\{v_i, M_{ij}, \lambda_{a_3}, m_k^2\}$



Block Detection

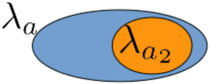
$$\mathbf{M}.\mathbf{M}^\mathbf{T} = \mathbf{1}$$

Numeric VEV

$$\phi_i = \mathbf{v_i} + \delta\phi_i$$

Min. Conditions

$$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$$



Local Minimum Generated!

→ Check Tree level Unitarity

→ Check Global Stability

→ Boundedness from below

User Analysis

→ Interfaces: Superiso, SuShi, MicrOmegas, HBounds/Signals.

→ Tables & User def. analysis.

Outline

1. **ScannerS**: A tool to constrain the parameter space
   - Overview of the tool
   - Workflow
2. Strategy, modules & interfaces
   - The internal modules
   - The external interfaces

Structure & Basic usage

1. **Input** – `ScannerSInput.nb`

   → `model.in`

2. **Analysis** – `ScannerSUser.cpp`

   → `model.out`

3. **Compile & Run** – `makefile`

```
$ make
$ ./ScannerS -i model.in
$ ./ScannerS --help
```

Structure & Basic usage

1. **Input** – `ScannerSInput.nb`
   - Expression for $V(\phi_i)$
   - Numerical ranges for $\{v_i, m_i^2, \lambda_a^2\}$

   → `model.in`

2. **Analysis** – `ScannerSUser.cpp`

   → `model.out`

3. **Compile & Run** – `makefile`

```
$ make
$ ./ScannerS -i model.in
$ ./ScannerS --help
```

```
Vscalar = ComplexExpand[
  λ[0] Φ1Dag.Φ1 + λ[1] Φ2Dag.Φ2 -
    λ[2] (Φ1Dag.Φ2 + Φ2Dag.Φ1) +
    λ[3] / 2 (Φ1Dag.Φ1) ^2 + ...
```

Structure & Basic usage

1. **Input** – `ScannerSInput.nb`
   - Expression for $V(\phi_i)$
   - Numerical ranges for $\{v_i, m_i^2, \lambda_a^2\}$

   $\rightarrow$ `model.in`

```
Vscalar = ComplexExpand[
  λ[0] Φ1Dag.Φ1 + λ[1] Φ2Dag.Φ2 -
     λ[2] (Φ1Dag.Φ2 + Φ2Dag.Φ1) +
     λ[3] / 2 (Φ1Dag.Φ1) ^ 2 + ...
```

```
ϕMin[2] = 246;   massmin[0] = 125;
ϕMax[2] = 246;   massmax[0] = 125;
ϕMin[6] = 0;     λMin[0] = -10^6;
ϕMax[6] = 500;   λMax[0] = 10^6;
```

2. **Analysis** – `ScannerSUser.cpp`

   $\rightarrow$ `model.out`

3. **Compile & Run** – `makefile`

```
$ make
$ ./ScannerS -i model.in
$ ./ScannerS --help
```

Structure & Basic usage

1 **Input** – `ScannerSInput.nb`

- Expression for $V(\phi_i)$
- Numerical ranges for $\{v_i, m_i^2, \lambda_a^2\}$

$\rightarrow$ `model.in`

```
Vscalar = ComplexExpand[
  λ[0] Φ1Dag.Φ1 + λ[1] Φ2Dag.Φ2 -
     λ[2] (Φ1Dag.Φ2 + Φ2Dag.Φ1) +
     λ[3] / 2 (Φ1Dag.Φ1) ^2 + ...
```

```
ϕMin[2] = 246;   massmin[0] = 125;
ϕMax[2] = 246;   massmax[0] = 125;
ϕMin[6] = 0;     λMin[0] = -10^6;
ϕMax[6] = 500;   λMax[0] = 10^6;
```

2 **Analysis** – `ScannerSUser.cpp`

- Template functions
- User Analysis (accept/reject)

$\rightarrow$ `model.out`

```
bool CheckStability(LambdaRef & L);
bool CheckGlobal(PhiRef & Phi,Lambd
bool UserAnalysis(PhiRef & Phi,Lamb
```

3 **Compile & Run** – `makefile`

```
$ make
$ ./ScannerS -i model.in
$ ./ScannerS --help
```

Structure & Basic usage

1. **Input** – `ScannerSInput.nb`
   - Expression for $V(\phi_i)$
   - Numerical ranges for $\{v_i, m_i^2, \lambda_a^2\}$

   $\to$ `model.in`

2. **Analysis** – `ScannerSUser.cpp`
   - Template functions
   - User Analysis (accept/reject)

   $\to$ `model.out`

3. **Compile & Run** – `makefile`
   - Paths to libraries
   - Turn on/off options

```
$ make
$ ./ScannerS -i model.in
$ ./ScannerS --help
```

```
Vscalar = ComplexExpand[
  λ[0] Φ1Dag.Φ1 + λ[1] Φ2Dag.Φ2 -
    λ[2] (Φ1Dag.Φ2 + Φ2Dag.Φ1) +
    λ[3] / 2 (Φ1Dag.Φ1) ^2 + ...
```

```
ϕMin[2] = 246;    massmin[0] = 125;
ϕMax[2] = 246;    massmax[0] = 125;
ϕMin[6] = 0;      λMin[0] = -10^6;
ϕMax[6] = 500;    λMax[0] = 10^6;
```

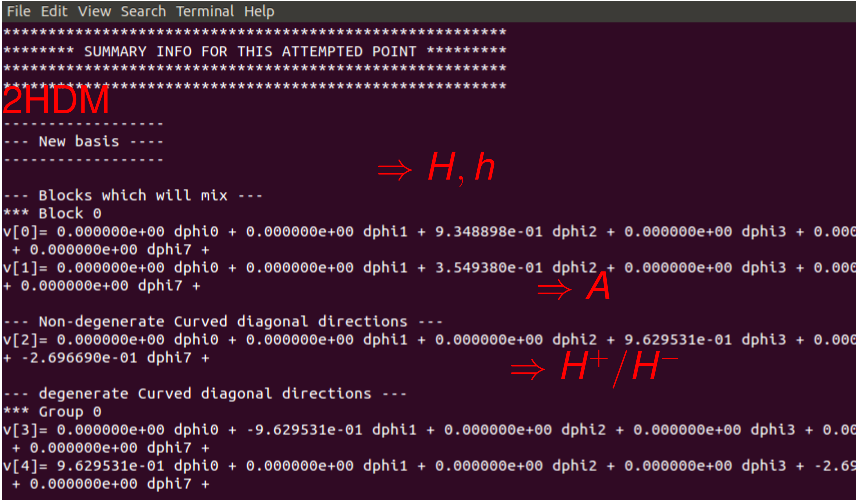
```
bool CheckStability(LambdaRef & L);
bool CheckGlobal(PhiRef & Phi,Lambd
bool UserAnalysis(PhiRef & Phi,Lamb
```

```
##########################################################
##########################################################
############################## USER EDITABLE ########
##########################################################
##########################################################


#INSERT YOUR INSTALLATION PATHS HERE for the librarie
ve blank if you do not want to use them)
##############################
## WARNING ## --> Be careful to REMOVE extra spaces a
##############################
SuperisoPath=/home/mops2/local_src/superiso_v3.3
#Example: /home/user1/local/src/superiso_v3.3
#Tested with superiso v3.3
```

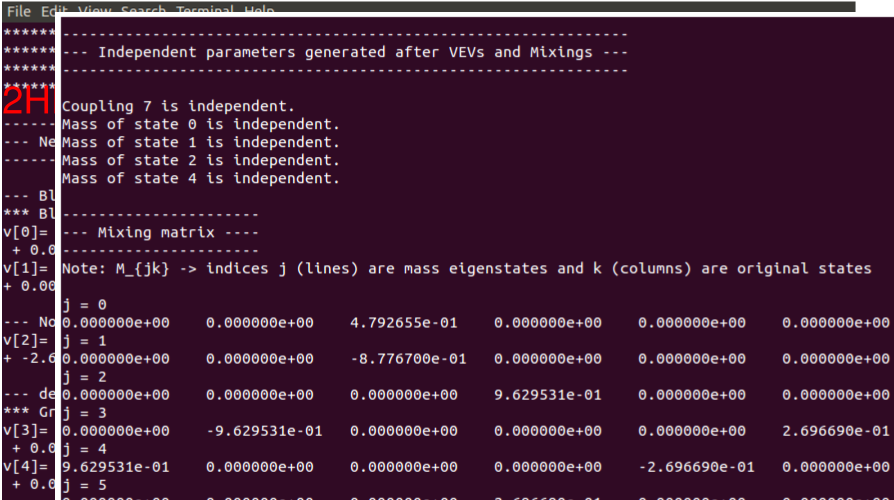
A typical run in `VERBOSE` mode

$\rightarrow$ `model.in`



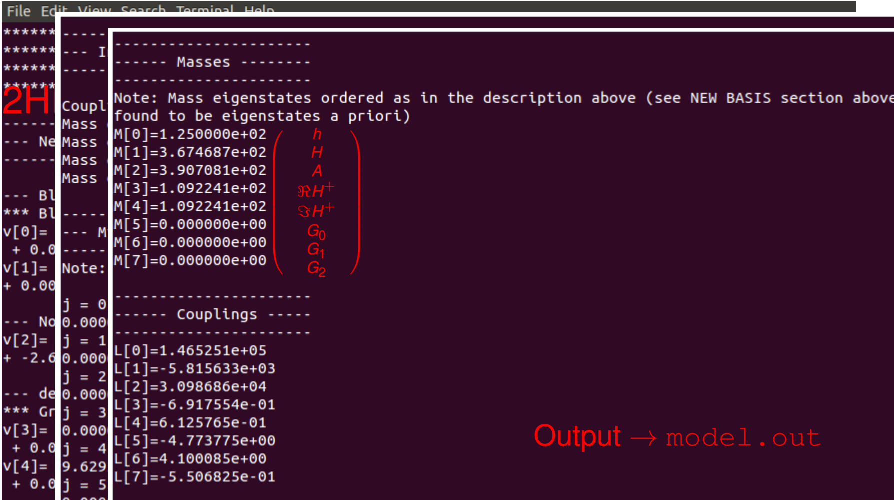
A typical run in VERBOSE mode

→ model.in



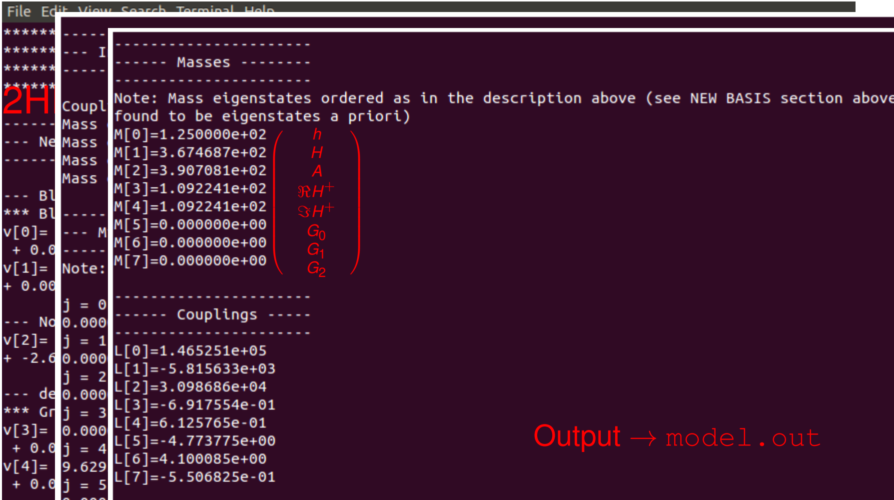
A typical run in VERBOSE mode

→ model.in



A typical run in VERBOSE mode

→ model.in



Output → model.out

Outline

Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

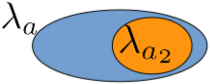
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

$$\phi_i = \mathbf{v_i} + \delta\phi_i$$

Min. Conditions

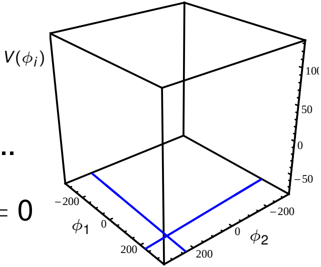
$$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$$



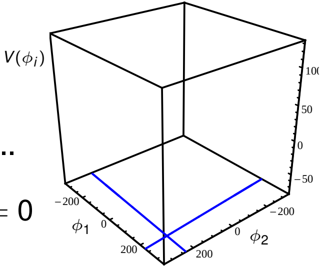
Vacuum linear conditions

- **Expansion** around minimum uniformly...

$$\phi_i = \mathbf{v_i} + \delta\phi_i \Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$$



Vacuum linear conditions



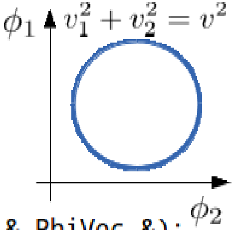
- **Expansion** around minimum uniformly...

$$\phi_i = \mathbf{v_i} + \delta\phi_i \Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$$

- Also flexible **Template function**

$\rightarrow$ User defined arbitrary parametric form.

Example: $\begin{cases} \phi_1 = v\cos\beta \\ \phi_2 = v\sin\beta \end{cases}$




```
void MyPhiParametrization(const PhiParamVec &,PhiVec &);
```

Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

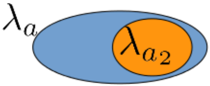
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

$\phi_i = \mathbf{v_i} + \delta\phi_i$

Min. Conditions

$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$



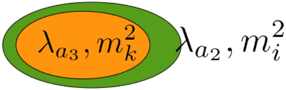
Block Detection

$\mathbf{M}.\mathbf{M}^\mathbf{T} = \mathbf{1}$

Quadratic Min. Cond.

$\left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \lambda_{a_2} = diag[m_i^2]$

Indep. $\{v_i, M_{ij}, \lambda_{a_3}, m_k^2\}$



Quadratic conditions & Block symmetry detection

Quadratic conditions for physical states:

$$\left.\frac{\partial^2 V}{\partial H_i \partial H_j}\right|_{H_i=0} \rightarrow \mathbf{M}^T \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \mathbf{M}\, \lambda_{a_2} = \mathbf{Diag}(m_i^2)$$

Quadratic conditions & Block symmetry detection

Quadratic conditions for physical states:

$$\left.\frac{\partial^2 V}{\partial H_i \partial H_j}\right|_{H_i=0} \rightarrow \mathbf{M}^T \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \mathbf{M}\, \lambda_{a_2} = \textbf{Diag}(m_i^2)$$

VEVs fixed $\Rightarrow$ set of constant matrices $\left\{ \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \right\}$

$\rightarrow$ What is the block diagonal decomposition?

Murota, Kanno, Kojima, Kojima, Japan J. Indust. App. Math. (2010) 27:125-160

Quadratic conditions & Block symmetry detection

Quadratic conditions for physical states:

$$\left.\frac{\partial^2 V}{\partial H_i \partial H_j}\right|_{H_i=0} \rightarrow \mathbf{M}^T \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \mathbf{M}\, \lambda_{a_2} = \mathbf{Diag}(m_i^2)$$

VEVs fixed $\Rightarrow$ set of constant matrices $\left\{ \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \right\}$

$\rightarrow$ What is the block diagonal decomposition?

Murota, Kanno, Kojima, Kojima, Japan J. Indust. App. Math. (2010) 27:125-160

1- Random linear

$$\mathbf{A} = \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} R_{a_2}^{(1)}$$

Quadratic conditions & Block symmetry detection

Quadratic conditions for physical states:

$$\left.\frac{\partial^2 V}{\partial H_i \partial H_j}\right|_{H_i=0} \rightarrow \mathbf{M}^T \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \mathbf{M}\, \lambda_{a_2} = \mathbf{Diag}(m_i^2)$$

VEVs fixed $\Rightarrow$ set of constant matrices $\left\{ \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \right\}$

$\rightarrow$ What is the block diagonal decomposition?

Murota, Kanno, Kojima, Kojima, Japan J. Indust. App. Math. (2010) 27:125-160

1- Random linear

$$\mathbf{A} = \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} R^{(1)}_{a_2}$$

2- Find eigen basis

$\mathbf{A} \rightarrow$ *diagonal*

$$\begin{pmatrix} \lambda_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_7 \end{pmatrix}$$

Quadratic conditions & Block symmetry detection

Quadratic conditions for physical states:

$$\left.\frac{\partial^2 V}{\partial H_i \partial H_j}\right|_{H_i=0} \rightarrow \mathbf{M}^T \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \mathbf{M}\, \lambda_{a_2} = \mathbf{Diag}(m_i^2)$$

VEVs fixed $\Rightarrow$ set of constant matrices $\left\{ \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \right\}$

$\rightarrow$ What is the block diagonal decomposition?

Murota, Kanno, Kojima, Kojima, Japan J. Indust. App. Math. (2010) 27:125-160

1- Random linear

$$\mathbf{A} = \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} R_{a_2}^{(1)}$$

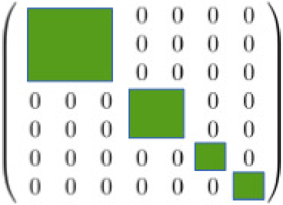
2- Find eigen basis

$\mathbf{A} \rightarrow$ *diagonal*

3- 2nd Random

$$\mathbf{B} = \left\langle \widehat{\partial}^2 V \right\rangle_{a_2} R_{a_2}^{(2)}$$

$$\begin{pmatrix} \lambda_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_7 \end{pmatrix}$$



In **A**-eigen basis !!!!

Block detection – toy $\mathbb{Z}_2$ symm. 2HDM + 2HDM

```
----------------------
--- Mixing matrix ----
----------------------

Note: M_{jk} -> indices j (lines) are mass eigenstates and k (columns) are original states
```

		ϕ_0	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9	ϕ_{10}	ϕ_{11}	ϕ_{12}	ϕ_{13}	ϕ_{14}	ϕ_{15}
H_1	j = 0	0	0	0	0	0	0	0	0	0	0	0.6243	0	0	0	-0.7812	0
h_1	j = 1	0	0	0	0	0	0	0	0	0	0	-0.7812	0	0	0	-0.6243	0
h_2	j = 2	0	0	0.8362	0	0	0	0.5484	0	0	0	0	0	0	0	0	0
H_2	j = 3	0	0	0.5484	0	0	0	-0.8362	0	0	0	0	0	0	0	0	0
A_1	j = 4	0	0	0	-0.8243	0	0	0	0.5661	0	0	0	0	0	0	0	0
A_2	j = 5	0	0	0	0	0	0	0	0	0	0	0	-0.5758	0	0	0	0.81
$\Re H_1^+$	j = 6	0	-0.8243	0	0	0	0.5661	0	0	0	0	0	0	0	0	0	0
$\Im H_1^+$	j = 7	0.8243	0	0	0	-0.5661	0	0	0	0	0	0	0	0	0	0	0
$\Re H_2^+$	j = 8	0	0	0	0	0	0	0	0	0.5758	0	0	0	-0.8176	0	0	0
$\Im H_2^+$	j = 9	0	0	0	0	0	0	0	0	0	-0.5758	0	0	0	0.8176	0	0
G_1	j = 10	0	0	0	0	0	0	0	0	0	0	0	-0.8176	0	0	0	-0.5
G_2	j = 11	0	0.1639	0	0.5419	0	0.2387	0	0.789	0	0	0	0	0	0	0	0
G_3	j = 12	0.5661	0	0	0	0.8243	0	0	0	0	0	0	0	0	0	0	0
G_4	j = 13	0	0	0	0	0	0	0	0	0	-0.8176	0	0	0	-0.5758	0	0
G_5	j = 14	0	0	0	0	0	0	0	0	0.8176	0	0	0	0.5758	0	0	0
G_6	j = 15	0	-0.5419	0	0.1639	0	-0.789	0	0.2387	0	0	0	0	0	0	0	0

Block detection – toy $\mathbb{Z}_2$ symm. 2HDM + 2HDM

****** Internal mixing matrix ******

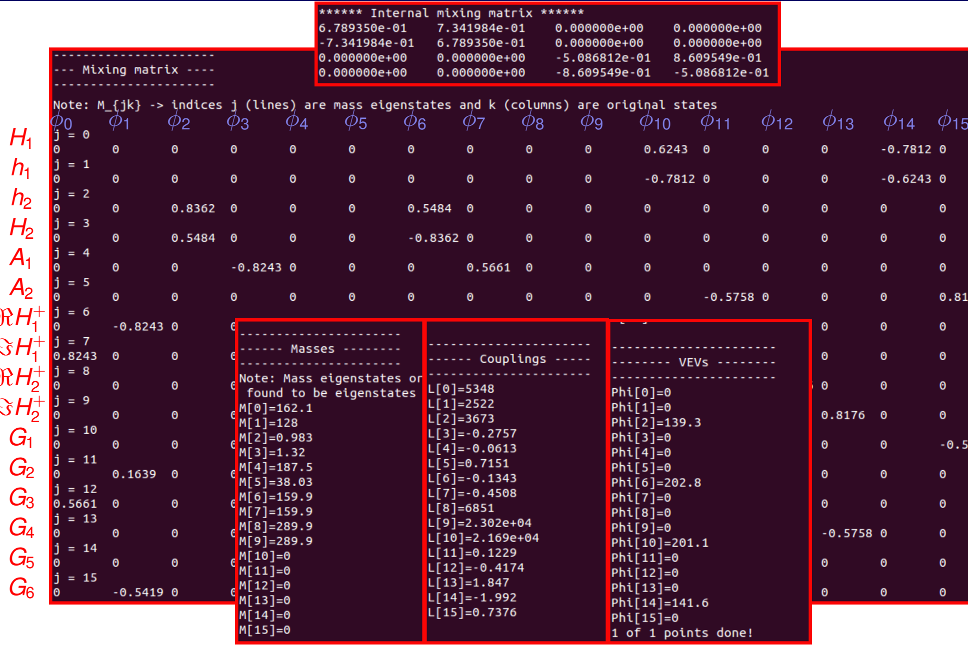
6.789350e-01	7.341984e-01	0.000000e+00	0.000000e+00
-7.341984e-01	6.789350e-01	0.000000e+00	0.000000e+00
0.000000e+00	0.000000e+00	-5.086812e-01	8.609549e-01
0.000000e+00	0.000000e+00	-8.609549e-01	-5.086812e-01

--- Mixing matrix ----

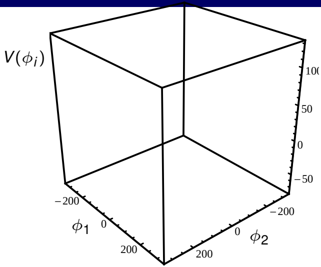
Note: M_{jk} -> indices j (lines) are mass eigenstates and k (columns) are original states

	j	ϕ_0	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	ϕ_7	ϕ_8	ϕ_9	ϕ_{10}	ϕ_{11}	ϕ_{12}	ϕ_{13}	ϕ_{14}	ϕ_{15}
H_1	j = 0	0	0	0	0	0	0	0	0	0	0	0.6243	0	0	0	-0.7812	0
h_1	j = 1	0	0	0	0	0	0	0	0	0	0	-0.7812	0	0	0	-0.6243	0
h_2	j = 2	0	0	0.8362	0	0	0	0.5484	0	0	0	0	0	0	0	0	0
H_2	j = 3	0	0	0.5484	0	0	0	-0.8362	0	0	0	0	0	0	0	0	0
A_1	j = 4	0	0	0	-0.8243	0	0	0	0.5661	0	0	0	0	0	0	0	0
A_2	j = 5	0	0	0	0	0	0	0	0	0	0	0	-0.5758	0	0	0	0.81
$\Re H_1^+$	j = 6	0	-0.8243	0	0	0	0.5661	0	0	0	0	0	0	0	0	0	0
$\Im H_1^+$	j = 7	0.8243	0	0	0	-0.5661	0	0	0	0	0	0	0	0	0	0	0
$\Re H_2^+$	j = 8	0	0	0	0	0	0	0	0	0.5758	0	0	0	-0.8176	0	0	0
$\Im H_2^+$	j = 9	0	0	0	0	0	0	0	0	0	-0.5758	0	0	0	0.8176	0	0
G_1	j = 10	0	0	0	0	0	0	0	0	0	0	0	-0.8176	0	0	0	-0.5
G_2	j = 11	0	0.1639	0	0.5419	0	0.2387	0	0.789	0	0	0	0	0	0	0	0
G_3	j = 12	0.5661	0	0	0	0.8243	0	0	0	0	0	0	0	0	0	0	0
G_4	j = 13	0	0	0	0	0	0	0	0	0	-0.8176	0	0	0	-0.5758	0	0
G_5	j = 14	0	0	0	0	0	0	0	0	0.8176	0	0	0	0.5758	0	0	0
G_6	j = 15	0	-0.5419	0	0.1639	0	-0.789	0	0.2387	0	0	0	0	0	0	0	0

Block detection – toy $\mathbb{Z}_2$ symm. 2HDM + 2HDM

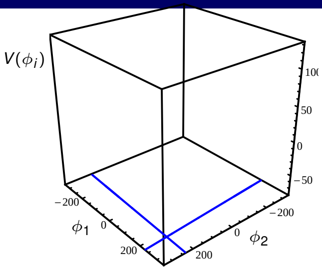


The generated local minimum



Summary of the strategy:

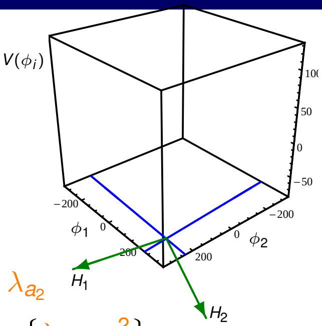
The generated local minimum



Summary of the strategy:

1. Generate $\mathbf{v_i}$ & eliminate λ_{a_1} in favour of λ_{a_2}

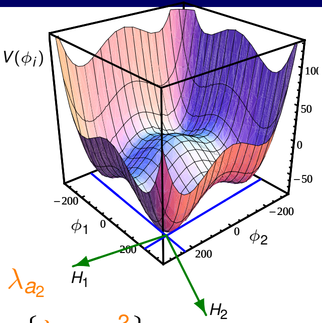
The generated local minimum



Summary of the strategy:

1. Generate $\mathbf{v_i}$ & eliminate λ_{a_1} in favour of λ_{a_2}
2. Generate $\mathbf{M}_{ij}$. Eliminate some params in $\{\lambda_{a_2}, m_i^2\}$

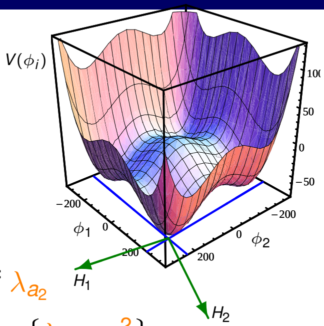
The generated local minimum



Summary of the strategy:

1. Generate $\mathbf{v_i}$ & eliminate λ_{a_1} in favour of λ_{a_2}
2. Generate $\mathbf{M}_{ij}$. Eliminate some params in $\{\lambda_{a_2}, m_i^2\}$
3. Generate the remaining indep. params uniformly.

The generated local minimum



Summary of the strategy:

1. Generate $\mathbf{v_i}$ & eliminate λ_{a_1} in favour of λ_{a_2}
2. Generate $\mathbf{M}_{ij}$. Eliminate some params in $\left\{\lambda_{a_2}, m_i^2\right\}$
3. Generate the remaining indep. params uniformly.

⇒ Local minimum without solving non-linear equations!
⇒ Full physical basis info, for parameter space point.

Delay non-linear/expensive tasks to **increase efficiency!**

Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

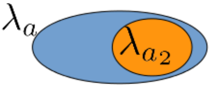
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

$\phi_i = \mathbf{v_i} + \delta\phi_i$

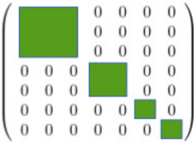
Min. Conditions

$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$



Block Detection

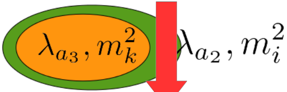
$\mathbf{M.M^T = 1}$



Quadratic Min. Cond.

$\left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \lambda_{a_2} = diag[m_i^2]$

Indep. $\{ v_i, M_{ij}, \lambda_{a_3}, m_k^2 \}$



Local Minimum Generated!

$\rightarrow$ Check Tree level Unitarity

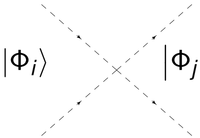
$\rightarrow$ Check Global Stability

$\rightarrow$ Boundedness from below

Tree level unitarity module

$$(\ldots,\ |\Phi_i\rangle\ ,\ \ldots) \equiv \left(\frac{1}{\sqrt{2!}}\,|\phi_1\phi_1\rangle\,,\ldots,\frac{1}{\sqrt{2!}}\,|\phi_N\phi_N\rangle\,,|\phi_1\phi_2\rangle\,,\ldots,|\phi_{N-1}\phi_N\rangle \right)$$

Tree level unitarity in $2 \to 2$ high energy scattering:

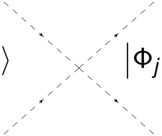


,

Tree level unitarity module

$$(\ldots,\ |\Phi_i\rangle\ ,\ \ldots) \equiv \left(\frac{1}{\sqrt{2!}}\,|\phi_1\phi_1\rangle\ , \ldots, \frac{1}{\sqrt{2!}}\,|\phi_N\phi_N\rangle\ , |\phi_1\phi_2\rangle\ , \ldots, |\phi_{N-1}\phi_N\rangle\right)$$

Tree level unitarity in $2 \to 2$ high energy scattering:

$|\Phi_i\rangle$  $|\Phi_j\rangle$

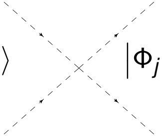
$$,\ \Re\{a_{ij}^{(0)}\} < \tfrac{1}{2}\ ,\ a_{ij}^{(0)} = \frac{\langle\Phi_i|\, i\mathbf{T}^{(0)}\,|\Phi_j\rangle}{16\pi} \sim \sum\nolimits_{a_4} \ldots \lambda_{a_4}$$

Lee, Quigg, Thacker; PRD16, Vol.5 (1977)

Tree level unitarity module

$$(\ldots,\ |\Phi_i\rangle\ ,\ \ldots) \equiv \left(\frac{1}{\sqrt{2!}} |\phi_1\phi_1\rangle\ , \ldots, \frac{1}{\sqrt{2!}} |\phi_N\phi_N\rangle\ , |\phi_1\phi_2\rangle\ , \ldots, |\phi_{N-1}\phi_N\rangle \right)$$

Tree level unitarity in $2 \to 2$ **high energy scattering:**

$|\Phi_i\rangle$  $|\Phi_j\rangle$

$$,\ \Re\{a_{ij}^{(0)}\} < \tfrac{1}{2}\ ,\ \ a_{ij}^{(0)} = \frac{\langle\Phi_i|\ i\mathbf{T}^{(0)}\ |\Phi_j\rangle}{16\pi} \sim \sum_{a_4} \ldots \lambda_{a_4}$$

Lee, Quigg, Thacker; PRD16, Vol.5 (1977)

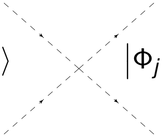
- In SM, the **2-particle** states are w^+w^-, hh, zz, hz
  $\Rightarrow$ constrains quartic coupling λ, $\Rightarrow$ $\mathbf{m_h^2 < 700\ GeV}$

Tree level unitarity module

$$(\ldots,\ |\Phi_i\rangle\ ,\ \ldots) \equiv \left(\frac{1}{\sqrt{2!}}\,|\phi_1\phi_1\rangle\ ,\ldots,\frac{1}{\sqrt{2!}}\,|\phi_N\phi_N\rangle\ ,|\phi_1\phi_2\rangle\ ,\ldots,|\phi_{N-1}\phi_N\rangle\right)$$

Tree level unitarity in $2 \to 2$ high energy scattering:

$|\Phi_i\rangle$



$$\left|\Phi_j\right\rangle\ ,\Re\{a_{ij}^{(0)}\} < \tfrac{1}{2}\ ,\ \ a_{ij}^{(0)} = \frac{\langle\Phi_i|\ i\mathbf{T}^{(0)}\ |\Phi_j\rangle}{16\pi} \sim \sum\nolimits_{a_4}\ldots\lambda_{a_4}$$

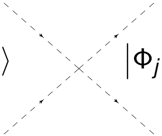
Lee, Quigg, Thacker; PRD16, Vol.5 (1977)

- In SM, the **2-particle** states are w^+w^-, hh, zz, hz
  $\Rightarrow$ constrains quartic coupling λ, $\Rightarrow$ $\mathbf{m_h^2 < 700\ GeV}$
- In BSM $\Rightarrow$ bounds on combinations of quartic λ_{a_4}

Tree level unitarity module

$$(\ldots,\ |\Phi_i\rangle\ ,\ \ldots) \equiv \left(\frac{1}{\sqrt{2!}}\,|\phi_1\phi_1\rangle\,,\ldots,\frac{1}{\sqrt{2!}}\,|\phi_N\phi_N\rangle\,,|\phi_1\phi_2\rangle\,,\ldots,|\phi_{N-1}\phi_N\rangle\right)$$

Tree level unitarity in $2 \to 2$ high energy scattering:

$|\Phi_i\rangle$  $|\Phi_j\rangle$

$$,\ \Re\{a_{ij}^{(0)}\} < \frac{1}{2}\ ,\ \ a_{ij}^{(0)} = \frac{\langle\Phi_i|\ i\mathbf{T}^{(0)}\ |\Phi_j\rangle}{16\pi} \sim \sum_{a_4}\ldots\lambda_{a_4}$$

Lee, Quigg, Thacker; PRD16, Vol.5 (1977)

- In SM, the **2-particle** states are w^+w^-, hh, zz, hz
  $\Rightarrow$ constrains quartic coupling λ, $\Rightarrow$ $\mathbf{m_h^2 < 700}$ **GeV**
- In BSM $\Rightarrow$ bounds on combinations of quartic λ_{a_4}
- Reduces to finding eigenvalues of $a_{ij}^{(0)}$ numerically $\Rightarrow$ **fast!**

Template functions – Flexibility!

- **Boundedness** from below (last checks)
  $\rightarrow$ Some closed forms.
  To Do: Generic routines? **I. Ivanov arXiv:1004.1799**
- **Global Minimum** (last checks) $\rightarrow$ Some closed forms.
  To Do: Generic routines (recent tool **vevacious.hepforge.org**)
- **User Analysis** routine

```
bool CheckStability(LambdaRef & L);
bool CheckGlobal(PhiRef & Phi,LambdaRef &
bool UserAnalysis(PhiRef & Phi,LambdaRef
```

Template functions – Flexibility!

- **Boundedness** from below (last checks)
  $\rightarrow$ Some closed forms.
  To Do: Generic routines? **I. Ivanov arXiv:1004.1799**
- **Global Minimum** (last checks) $\rightarrow$ Some closed forms.
  To Do: Generic routines (recent tool **vevacious.hepforge.org**)
- **User Analysis** routine

```
bool CheckStability(LambdaRef & L);
bool CheckGlobal(PhiRef & Phi,LambdaRef &
bool UserAnalysis(PhiRef & Phi,LambdaRef
```

Also possible:

- **User defined mixing**
  $\rightarrow$ Useful for special limits (Ex: decoupling)
  $\rightarrow$ Parametric form & can depend on v_i

```
void MyInternalMixing(const PhiParamVec & PhiPar,const PhiVec & P
```

- **User relations** among masses and couplings $\{m_i^2, \lambda_a\}$
  $\rightarrow$ Parametric form & can depend on $\{v_i, M_{ij}\}$

```
void MyCoupMassRelations(const PhiParamVec & PhiPar,const PhiVe
```

Outline

Overview of the tool

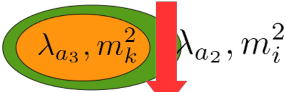
Doublets, complex, reals, etc ... → Decompose n reals

$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Quadratic Min. Cond.

$$\left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \lambda_{a_2} = diag[m_i^2]$$

Indep. $\{v_i, M_{ij}, \lambda_{a_3}, m_k^2\}$



Block Detection

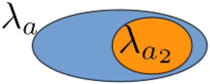
$$\mathbf{M}.\mathbf{M}^\mathbf{T} = \mathbf{1}$$

Numeric VEV

$$\phi_i = \mathbf{v_i} + \delta\phi_i$$

Min. Conditions

$$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$$



Local Minimum Generated!

→ Check Tree level Unitarity
→ Check Global Stability
→ Boundedness from below

User Analysis

→ Interfaces: Superiso, SuShi, MicrOmegas, HBounds/Signals.
→ Tables & User def. analysis.

2HDM/MSSM external libraries

2HDM/MSSM external libraries

Superiso: **http://superiso.in2p3.fr**

- Computes flavour physics observables ($b \to s\gamma$, $g_\mu - 2$, etc...) affected by new physics loop contributions.
- Complementary to direct search channels!
- C-Functions called directly in ScannerS.

```
CreateInputFileSuperiso2HDM(mHlight,mHheavy,mA,mHcharged,alpha,tanbeta,Ty
//Example of na observable calculated with superiso
cout<< "bsgamma="<<bsgamma_calculator(superisofile)<<endl;
```

2HDM/MSSM external libraries

Superiso: **http://superiso.in2p3.fr**

- Computes flavour physics observables ($b \to s\gamma$, $g_\mu - 2$, etc...) affected by new physics loop contributions.
- Complementary to direct search channels!
- C-Functions called directly in ScannerS.

```
CreateInputFileSuperiso2HDM(mHlight,mHheavy,mA,mHcharged,alpha,tanbeta,Ty
//Example of na observable calculated with superiso
cout<< "bsgamma="<<bsgamma_calculator(superisofile)<<endl;
```

SuShi: **http://sushi.hepforge.org/**

- Computes Higgs prod. cross-sections NNLO in gg & $b\bar{b}$
- Called directly in ScannerS through a "Wrapper" function.

```
CreateInputFileSuShi2HDM(Hparticle,pp_ppbar,order,CM_energy,mHlight, mHhe
double xsecggh_out,errxsecggh_out,xsecbbh_out;
sushixsection (order,xsecggh_out,errxsecggh_out,xsecbbh_out);
```

MicrOmegas, Collider data & developing ...

Micromegas interface involves:

- Create newProject in MicrOmegas & LanHep model files
- Drop ScannerS inside project directory
- Turn on MicrOmegas in ScannerS makefile & `./make`

  See R. Coimbra talk for singlet model case

MicrOmegas, Collider data & developing ...

Micromegas interface involves:

- Create newProject in MicrOmegas & LanHep model files
- Drop ScannerS inside project directory
- Turn on MicrOmegas in ScannerS makefile & `./make`

  See R. Coimbra talk for singlet model case

Collider data:

- **HiggsBounds/HiggsSignals:**
  $\rightarrow$ Initialized/called through "Wrapper" header! (under test)
  $\rightarrow$ Needs $M^2_{H_i}, \Gamma_{Tot}(H_i), BR(H_i \rightarrow \ldots), \frac{\sigma_{BSM}(Prod(H_i))}{\sigma_{ref}(Prod(H_i))}$
  $\rightarrow$ Gives exclusion 95% C.L. / p-value of null hipothesis
- **Internal Tables:** LEP, LHC combined 7 and 8 TeV + VBF

  See R. Coimbra talk for singlet model case

MicrOmegas, Collider data & developing ...

Micromegas interface involves:

- Create newProject in MicrOmegas & LanHep model files
- Drop ScannerS inside project directory
- Turn on MicrOmegas in ScannerS makefile & `./make`

  See R. Coimbra talk for singlet model case

Collider data:

- **HiggsBounds/HiggsSignals:**
  → Initialized/called through "Wrapper" header! (under test)
  → Needs $M^2_{H_i}, \Gamma_{Tot}(H_i), BR(H_i \to \ldots), \frac{\sigma_{BSM}(Prod(H_i))}{\sigma_{ref}(Prod(H_i))}$
  → Gives exclusion 95% C.L. / p-value of null hipothesis
- **Internal Tables:** LEP, LHC combined 7 and 8 TeV + VBF

  See R. Coimbra talk for singlet model case

MicrOmegas, Collider data & developing ...

Micromegas interface involves:

- Create newProject in MicrOmegas & LanHep model files
- Drop ScannerS inside project directory
- Turn on MicrOmegas in ScannerS makefile & `./make`

See R. Coimbra talk for singlet model case

Collider data:

- **HiggsBounds/HiggsSignals:**
  $\rightarrow$ Initialized/called through "Wrapper" header! (under test)
  $\rightarrow$ Needs $M^2_{H_i}, \Gamma_{Tot}(H_i), BR(H_i \rightarrow \ldots), \frac{\sigma_{BSM}(Prod(H_i))}{\sigma_{ref}(Prod(H_i))}$
  $\rightarrow$ Gives exclusion 95% C.L. / p-value of null hipothesis
- **Internal Tables:** LEP, LHC combined 7 and 8 TeV + VBF

See R. Coimbra talk for singlet model case

Developing: EWPO (N-Singlets already) & RGE stability module

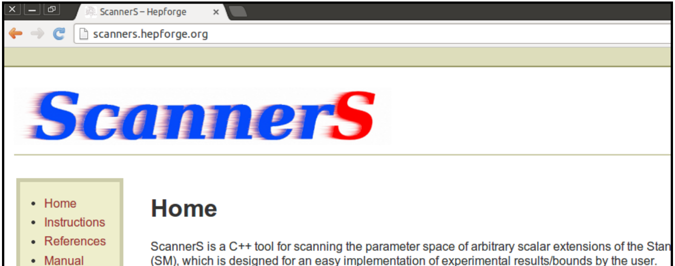
Conclusions

1. Scalar extensions, common addressing **BSM** problems
2. Tool development crucial to interact with experiments & identify candidate models
3. We are developing a scanning tool for the **Higgs** including:
    - **Local minimum generation**, with symmetry detection
    - **Tree level unitarity** checking routines
    - Implementation of various **Interfaces** & **flexible** structure

Conclusions

1. Scalar extensions, common addressing **BSM** problems
2. Tool development crucial to interact with experiments & identify candidate models
3. We are developing a scanning tool for the **Higgs** including:
   - **Local minimum generation**, with symmetry detection
   - **Tree level unitarity** checking routines
   - Implementation of various **Interfaces** & **flexible** structure

THANK YOU!



BACKUP

General strategy

Questions:

- Which independent parameters?
- How to detect symmetries in the mixing matrix?

General strategy

Questions:

- Which independent parameters?
- How to detect symmetries in the mixing matrix?

Strategy:

- 1st Generate VEVs $\Leftrightarrow$ Choose symmetry breaking/phase.
- Trade off couplings λ_a for eigenstate properties m_i^2, M_{ij}.
- Linear algebra tasks first (solve local min. conds.)
- Leave masses/mixings independent:
  - Good (local) minimum!
  - Control of ranges scanned over for physical mass.
- Expensive tasks last or in `UserAnalysis`.

General strategy

Questions:

- Which independent parameters?
- How to detect symmetries in the mixing matrix?

Strategy:

- 1st Generate VEVs $\Leftrightarrow$ Choose symmetry breaking/phase.
- Trade off couplings λ_a for eigenstate properties m_i^2, M_{ij}.
- Linear algebra tasks first (solve local min. conds.)
- Leave masses/mixings independent:
  - Good (local) minimum!
  - Control of ranges scanned over for physical mass.
- Expensive tasks last or in `UserAnalysis`.

General strategy

Questions:

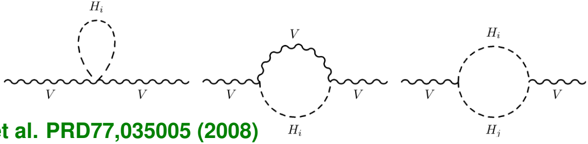
- Which independent parameters?
- How to detect symmetries in the mixing matrix?

Strategy:

- 1st Generate VEVs $\Leftrightarrow$ Choose symmetry breaking/phase.
- Trade off couplings λ_a for eigenstate properties m_i^2, M_{ij}.
- Linear algebra tasks first (solve local min. conds.)
- Leave masses/mixings independent:
  - Good (local) minimum!
  - Control of ranges scanned over for physical mass.
- Expensive tasks last or in `UserAnalysis`.

Under development

Variation of Electroweak Precision Observables:



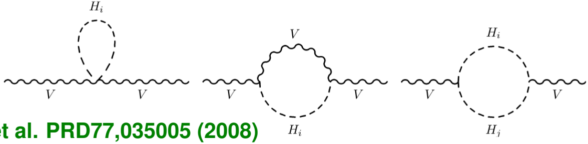
Barger et al. PRD77,035005 (2008)

For N-Singlets $\Delta S, \Delta T, \Delta U$

95% C.L. consistent ellipsoid with EW fits.

Under development

Variation of Electroweak Precision Observables:



Barger et al. PRD77,035005 (2008)

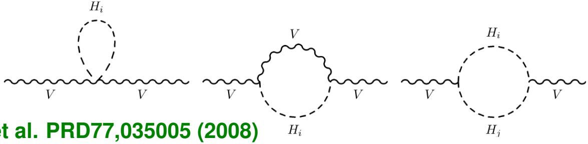
For N-Singlets $\Delta S, \Delta T, \Delta U$
95% C.L. consistent ellipsoid with EW fits.

Global Stability:

- Root finding for a system of N-equations.
- Have been investigating polynomial homotopy continuation method (recently 1 dedicated package appeared – **Vevacious**) & Monte Carlo.

Under development

Variation of Electroweak Precision Observables:



Barger et al. PRD77,035005 (2008)

For N-Singlets $\Delta S, \Delta T, \Delta U$
95% C.L. consistent ellipsoid with EW fits.

Global Stability:

- Root finding for a system of N-equations.
- Have been investigating polynomial homotopy continuation method (recently 1 dedicated package appeared – **Vevacious**) & Monte Carlo.

RGE Stability $\rightarrow$ Module under development!

Collider data tables & external libraries

Purpose – To determine whether multi-Higgs model is ...

- HiggsBounds $\rightarrow$ excluded at 95% C.L. from non-observation of new scalars from LEP/Tevatron/LHC.
- HiggsSignals $\rightarrow$ consistent with observed scalar states.

Collider data tables & external libraries

Purpose – To determine whether multi-Higgs model is ...

- HiggsBounds $\rightarrow$ excluded at 95% C.L. from non-observation of new scalars from LEP/Tevatron/LHC.
- HiggsSignals $\rightarrow$ consistent with observed scalar states.

How it works:

- Specify spectrum of scalars (#neutral, #charged, CP)
- Provide $M^2_{H_i}, \Gamma_{Tot}(H_i), BR(H_i \rightarrow \ldots), \frac{\sigma_{BSM}(Prod(H_i))}{\sigma_{ref}(Prod(H_i))}$ OR effective couplings.
- HiggsBounds $\rightarrow$ Get exclusion 95% C.L. or not
- HiggsSignals $\rightarrow$ Get p-value (for χ^2) of null hipothesis

Collider data tables & external libraries

Purpose – To determine whether multi-Higgs model is ...

- HiggsBounds $\rightarrow$ excluded at 95% C.L. from non-observation of new scalars from LEP/Tevatron/LHC.
- HiggsSignals $\rightarrow$ consistent with observed scalar states.

How it works:

- Specify spectrum of scalars (#neutral, #charged, CP)
- Provide $M^2_{H_i}, \Gamma_{Tot}(H_i), BR(H_i \rightarrow \ldots), \frac{\sigma_{BSM}(Prod(H_i))}{\sigma_{ref}(Prod(H_i))}$ OR effective couplings.
- HiggsBounds $\rightarrow$ Get exclusion 95% C.L. or not
- HiggsSignals $\rightarrow$ Get p-value (for χ^2) of null hipothesis

See R. Coimbra talk for singlet model case (internal tables LEP, LHC)

Collider data tables & external libraries

Purpose – To determine whether multi-Higgs model is ...

- HiggsBounds $\rightarrow$ excluded at 95% C.L. from non-observation of new scalars from LEP/Tevatron/LHC.
- HiggsSignals $\rightarrow$ consistent with observed scalar states.

How it works:

- Specify spectrum of scalars (#neutral, #charged, CP)
- Provide $M^2_{H_i}, \Gamma_{Tot}(H_i), BR(H_i \rightarrow \ldots), \frac{\sigma_{BSM}(Prod(H_i))}{\sigma_{ref}(Prod(H_i))}$ OR effective couplings.
- HiggsBounds $\rightarrow$ Get exclusion 95% C.L. or not
- HiggsSignals $\rightarrow$ Get p-value (for χ^2) of null hipothesis

See R. Coimbra talk for singlet model case (internal tables LEP, LHC)

Directly initialized/called through "Wrapper" functions!

MicrOmegas – relic density & direct detection

Dark matter cases $\Rightarrow$ survive cosmological evol. after freezout.

Implemented micrOMEGAS interface $\Rightarrow$ present relic density

Involves:

- Creating LanHep model file
- Link and compile micrOMEGAS routines with ScannerS

Also, direct detection bounds χ/nucleon scattering Xenon100.

MicrOmegas – relic density & direct detection

Dark matter cases ⇒ survive cosmological evol. after freezout.

Implemented micrOMEGAS interface ⇒ present relic density

Involves:

- Creating LanHep model file
- Link and compile micrOMEGAS routines with ScannerS

Physical idea: (see also singlet model – Rita's talk)

- Only 1 dark χ out of equilibrium
- χ non-relativistic (CDM)
- relic number density n_χ governed by the Boltzmann eq.

$$\frac{dn_\chi}{dt} + 3H\,n_\chi = -\langle \sigma_A |v| \rangle \left(n_\chi^2 - (n_\chi^{EQ})^2 \right)$$

Also, direct detection bounds χ/nucleon scattering Xenon100.

MicrOmegas – relic density & direct detection

Dark matter cases $\Rightarrow$ survive cosmological evol. after freezout.

Implemented micrOMEGAS interface $\Rightarrow$ present relic density

Involves:

- Creating LanHep model file
- Link and compile micrOMEGAS routines with ScannerS

Physical idea: (see also singlet model – Rita's talk)

- Only 1 dark χ out of equilibrium
- χ non-relativistic (CDM)
- relic number density n_χ governed by the Boltzmann eq.

$$\frac{dn_\chi}{dt} + 3H\, n_\chi = -\langle \sigma_A |v| \rangle \left(n_\chi^2 - (n_\chi^{EQ})^2 \right)$$

Also, direct detection bounds χ/nucleon scattering Xenon100.

MicrOmegas – relic density & direct detection

Dark matter cases $\Rightarrow$ survive cosmological evol. after freezout.

Implemented micrOMEGAS interface $\Rightarrow$ present relic density

Involves:

- Creating LanHep model file
- Link and compile micrOMEGAS routines with ScannerS

Physical idea: (see also singlet model – Rita's talk)

- Only 1 dark χ out of equilibrium
- χ non-relativistic (CDM)
- relic number density n_χ governed by the Boltzmann eq.

$$\frac{dn_\chi}{dt} + 3H\,n_\chi = -\langle\sigma_A|v|\rangle\left(n_\chi^2 - (n_\chi^{EQ})^2\right)$$

Also, direct detection bounds χ/nucleon scattering Xenon100.

MicrOmegas – relic density & direct detection

Dark matter cases $\Rightarrow$ survive cosmological evol. after freezout.

Implemented micrOMEGAS interface $\Rightarrow$ present relic density

Involves:

- Creating LanHep model file
- Link and compile micrOMEGAS routines with ScannerS

Physical idea: (see also singlet model – Rita's talk)

- Only 1 dark χ out of equilibrium
- χ non-relativistic (CDM)
- relic number density n_χ governed by the Boltzmann eq.

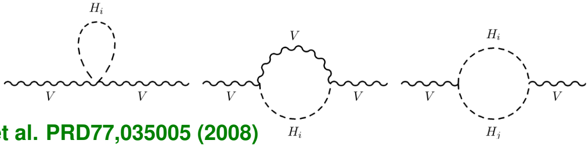
$$\frac{dn_\chi}{dt} + 3H\, n_\chi = -\langle \sigma_A |v| \rangle \left(n_\chi^2 - (n_\chi^{EQ})^2 \right)$$

We apply the WMAP $\Omega_{cdm} h^2 = 0.112 \pm 0.006$ as upper limit.

Also, direct detection bounds χ/nucleon scattering Xenon100.

Electroweak precision observables

Example: Variation of Electroweak Precision Observables:



Barger et al. PRD77,035005 (2008)

For N-Singlets

$$\Delta S = \Delta\left[\frac{1}{\pi}\sum_j (M_{hj})^2\left\{f\left(\frac{m_j^2}{M_Z^2}\right) - g\left(\frac{m_j^2}{M_Z^2}\right)\right\}\right]$$

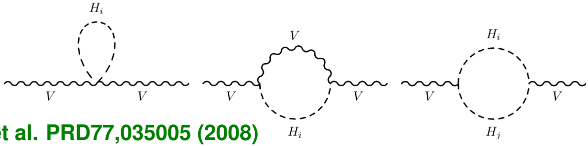
$$\Delta T = \Delta\left[\frac{1}{4\pi s_W^2}\sum_j (M_{hj})^2\left\{g\left(\frac{m_j^2}{M_W^2}\right) - \frac{1}{c_W^2} g\left(\frac{m_j^2}{M_Z^2}\right)\right\}\right]$$

$$\Delta U = \Delta\left[\frac{1}{\pi}\sum_j (M_{hj})^2\left\{f\left(\frac{m_j^2}{M_W^2}\right) - g\left(\frac{m_j^2}{M_W^2}\right) - f\left(\frac{m_j^2}{M_Z^2}\right) + g\left(\frac{m_j^2}{M_Z^2}\right)\right\}\right]$$

Have implemented 95% C.L. consistent ellipsoid with EW fits.

Electroweak precision observables

Example: Variation of Electroweak Precision Observables:



Barger et al. PRD77,035005 (2008)

For N-Singlets

$$\Delta S = \Delta\left[\frac{1}{\pi}\sum_j (M_{hj})^2 \left\{ f\left(\frac{m_j^2}{M_Z^2}\right) - g\left(\frac{m_j^2}{M_Z^2}\right)\right\}\right]$$

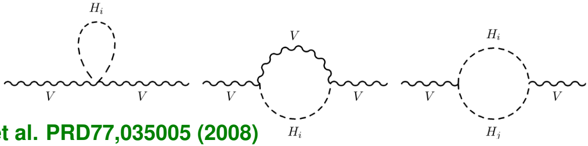
$$\Delta T = \Delta\left[\frac{1}{4\pi s_W^2}\sum_j (M_{hj})^2 \left\{ g\left(\frac{m_j^2}{M_W^2}\right) - \frac{1}{c_W^2} g\left(\frac{m_j^2}{M_Z^2}\right)\right\}\right]$$

$$\Delta U = \Delta\left[\frac{1}{\pi}\sum_j (M_{hj})^2 \left\{ f\left(\frac{m_j^2}{M_W^2}\right) - g\left(\frac{m_j^2}{M_W^2}\right) - f\left(\frac{m_j^2}{M_Z^2}\right) + g\left(\frac{m_j^2}{M_Z^2}\right)\right\}\right]$$

Have implemented 95% C.L. consistent ellipsoid with EW fits.

Electroweak precision observables

Example: Variation of Electroweak Precision Observables:



Barger et al. PRD77,035005 (2008)

For N-Singlets

$$\Delta S = \Delta \left[\frac{1}{\pi} \sum_j (M_{hj})^2 \left\{ f\left(\frac{m_j^2}{M_Z^2}\right) - g\left(\frac{m_j^2}{M_Z^2}\right) \right\} \right]$$

$$\Delta T = \Delta \left[\frac{1}{4\pi s_W^2} \sum_j (M_{hj})^2 \left\{ g\left(\frac{m_j^2}{M_W^2}\right) - \frac{1}{c_W^2} g\left(\frac{m_j^2}{M_Z^2}\right) \right\} \right]$$

$$\Delta U = \Delta \left[\frac{1}{\pi} \sum_j (M_{hj})^2 \left\{ f\left(\frac{m_j^2}{M_W^2}\right) - g\left(\frac{m_j^2}{M_W^2}\right) - f\left(\frac{m_j^2}{M_Z^2}\right) + g\left(\frac{m_i^2}{M_Z^2}\right) \right\} \right]$$

Have implemented 95% C.L. consistent ellipsoid with EW fits.

Collider bounds – LEP & LHC

The standard strategy is to define signal strength

$$\mu_i = \frac{\sigma_{\rm New}(H_i){\rm Br}_{\rm New}\left(H_i \to X_{\rm SM}\right)}{\sigma_{\rm SM}(H_i){\rm Br}_{\rm SM}\left(H_i \to X_{\rm SM}\right)}$$

$$= M_{ih}^2 \times \frac{M_{ih}^2 \Gamma(H_i \to SM)}{M_{ih}^2 \Gamma(H_i \to SM) + \sum \Gamma(H_i \to newscalars)}$$

@ LEP we apply the 95% C.L. bounds *HZZ* coupling on

$$\xi^2 \equiv \mu_i {\rm Br}_{\rm SM}\left(H_i \to ZZ\right)$$

@ LHC we fix one Higgs with mass $m_h = 125\ {\rm GeV}$ while allowing for a signal strength $\mu_h = 1.1 \pm 0.4$

Collider bounds – LEP & LHC

The standard strategy is to define signal strength

$$\mu_i = \frac{\sigma_{\rm New}(H_i){\rm Br}_{\rm New}\left(H_i \to X_{\rm SM}\right)}{\sigma_{\rm SM}(H_i){\rm Br}_{\rm SM}\left(H_i \to X_{\rm SM}\right)}$$

$$= M_{ih}^2 \times \frac{M_{ih}^2 \Gamma(H_i \to SM)}{M_{ih}^2 \Gamma(H_i \to SM) + \sum \Gamma(H_i \to newscalars)}$$

@ LEP we apply the 95% C.L. bounds *HZZ* coupling on

$$\xi^2 \equiv \mu_i {\rm Br}_{\rm SM}\left(H_i \to ZZ\right)$$

@ LHC we fix one Higgs with mass $m_h = 125\ {\rm GeV}$ while allowing for a signal strength $\mu_h = 1.1 \pm 0.4$

Collider bounds – LEP & LHC

The standard strategy is to define signal strength

$$\mu_i = \frac{\sigma_{\rm New}(H_i){\rm Br}_{\rm New}\,(H_i \to X_{\rm SM})}{\sigma_{\rm SM}(H_i){\rm Br}_{\rm SM}\,(H_i \to X_{\rm SM})}$$

$$= M_{ih}^2 \times \frac{M_{ih}^2 \Gamma(H_i \to SM)}{M_{ih}^2 \Gamma(H_i \to SM) + \sum \Gamma(H_i \to newscalars)}$$

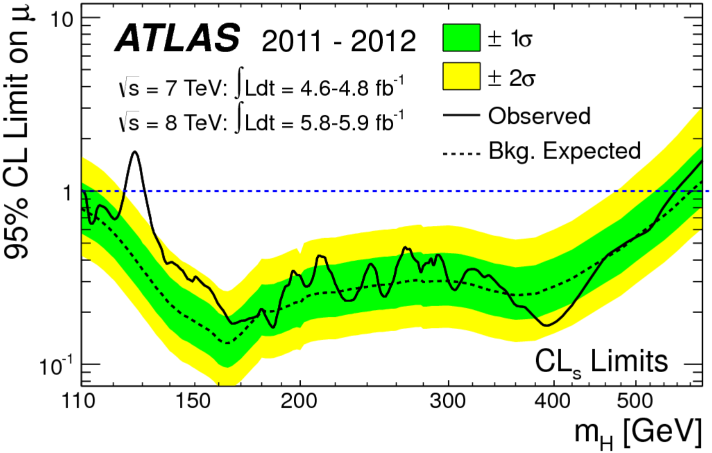
@ LEP we apply the 95% C.L. bounds *HZZ* coupling on

$$\xi^2 \equiv \mu_i {\rm Br}_{\rm SM}\,(H_i \to ZZ)$$

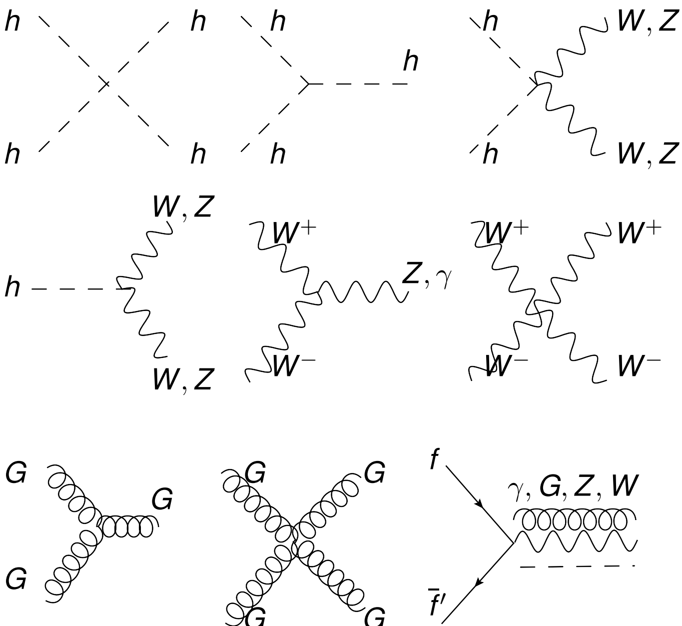
@ LHC we fix one Higgs with mass $m_h = 125\ {\rm GeV}$ while allowing for a signal strength $\mu_h = 1.1 \pm 0.4$

Collider bounds – LHC

Other mixing scalars $\rightarrow$ apply 95% C.L. combined ATLAS upper limit on μ_i.



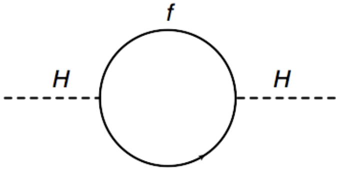
The Standard Model – Interactions

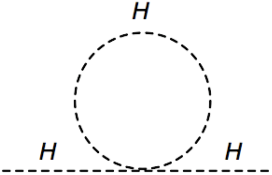


The hierarchy problem: Higgs mass

The hierarchy problem: Higgs mass

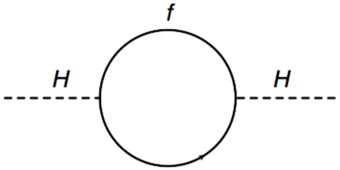
Look at **radiative corrections** to Higgs mass:

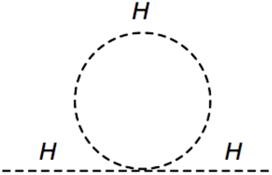




The hierarchy problem: Higgs mass

Look at **radiative corrections** to Higgs mass:



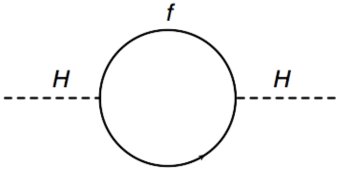


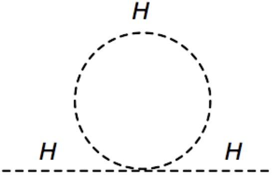
Higgs mass runs from high scale:

$$\delta m_h^2 = \left(|\lambda_f|^2 - \frac{1}{2}\lambda \right) \frac{\Lambda^2_{\text{cutoff}}}{8\pi^2} + \dots$$

The hierarchy problem: Higgs mass

Look at **radiative corrections** to Higgs mass:





Higgs mass runs from high scale:

$$\delta m_h^2 = \left(|\lambda_f|^2 - \frac{1}{2}\lambda \right) \frac{\Lambda_{\text{cutoff}}^2}{8\pi^2} + \dots$$

If $\Lambda_{\text{cutoff}} \sim M_4 \sim 10^{16}$ TeV $\Rightarrow$ **fine tuning** of $\sim 10^{-16}$

The hierarchy problem: BSM solutions

The hierarchy problem: BSM solutions

1. **Arrange cancellation of quadratic divergences.**

   $\Rightarrow$ New particles: SUSY, Little Higgs, etc...

The hierarchy problem: BSM solutions

1. **Arrange cancellation of quadratic divergences.**

   $\Rightarrow$ New particles: SUSY, Little Higgs, etc...

2. **Change the running to exponential.**

   $\Rightarrow$ Strong dynamics: the Higgs is a pion field of a new strongly coupled sector.

The hierarchy problem: BSM solutions

1. **Arrange cancellation of quadratic divergences.**

   $\Rightarrow$ New particles: SUSY, Little Higgs, etc...

2. **Change the running to exponential.**

   $\Rightarrow$ Strong dynamics: the Higgs is a pion field of a new strongly coupled sector.

3. **Assume the fundamental Planck scale is 1 TeV.**

   $\Rightarrow$ Extra dimensions.

The hierarchy problem: BSM solutions

1. **Arrange cancellation of quadratic divergences.**

   ⇒ New particles: SUSY, Little Higgs, etc...

2. **Change the running to exponential.**

   ⇒ Strong dynamics: the Higgs is a pion field of a new strongly coupled sector.

3. **Assume the fundamental Planck scale is 1 TeV.**

   ⇒ Extra dimensions.

4. Etc...