ScannerS

A tool for extended scalar sectors

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INSTITUTO SUPERIOR
DE ENGENHARIA DE LISBOA

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Jornadas do LIP

Acknowledgments

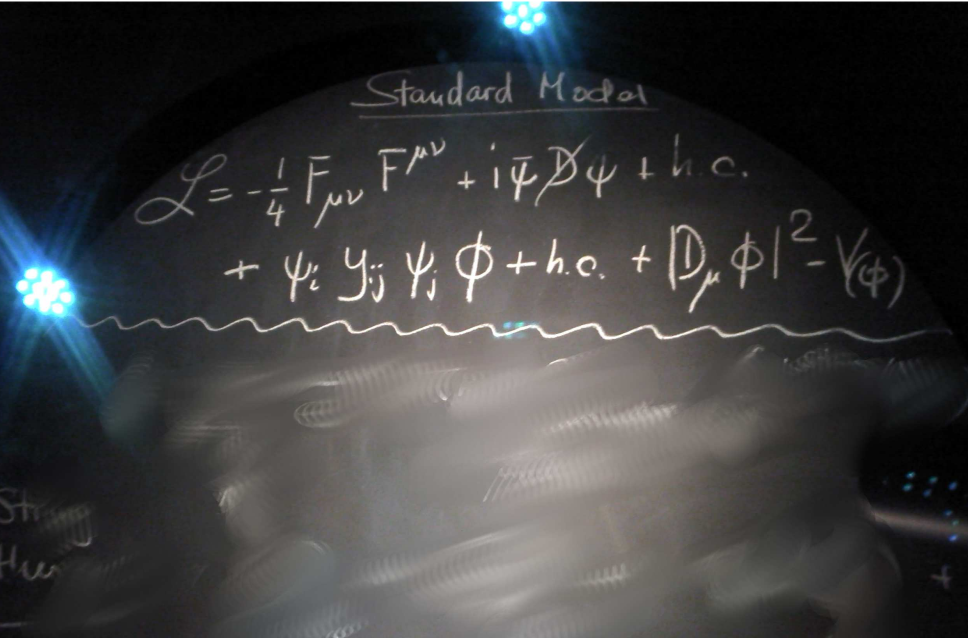
Ciência.Inovação 2010
Programa Operacional Ciência e Inovação 2010
POR LISBOA
COMPETE
QREN
QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
FCT
Fundação para a Ciência e a Tecnologia
POS_CONHECIMENTO
Programa Operacional Sociedade do Conhecimento

SEVENTH FRAMEWORK
PROGRAMME

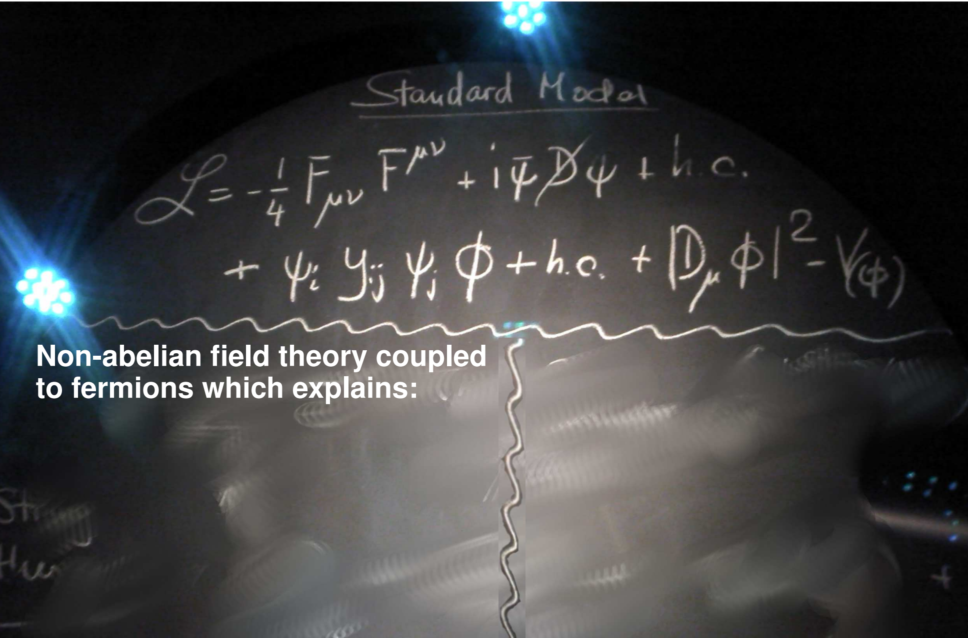
Outline

1. Motivation: Which scalar sector at the LHC?
2. **ScannerS**: A tool to constrain the parameter space
   - The Strategy
   - Structure & features
   - First tests & Outlook
3. Conclusions

Electroweak symmetry breaking and the Higgs boson



Electroweak symmetry breaking and the Higgs boson



Non-abelian field theory coupled to fermions which explains:

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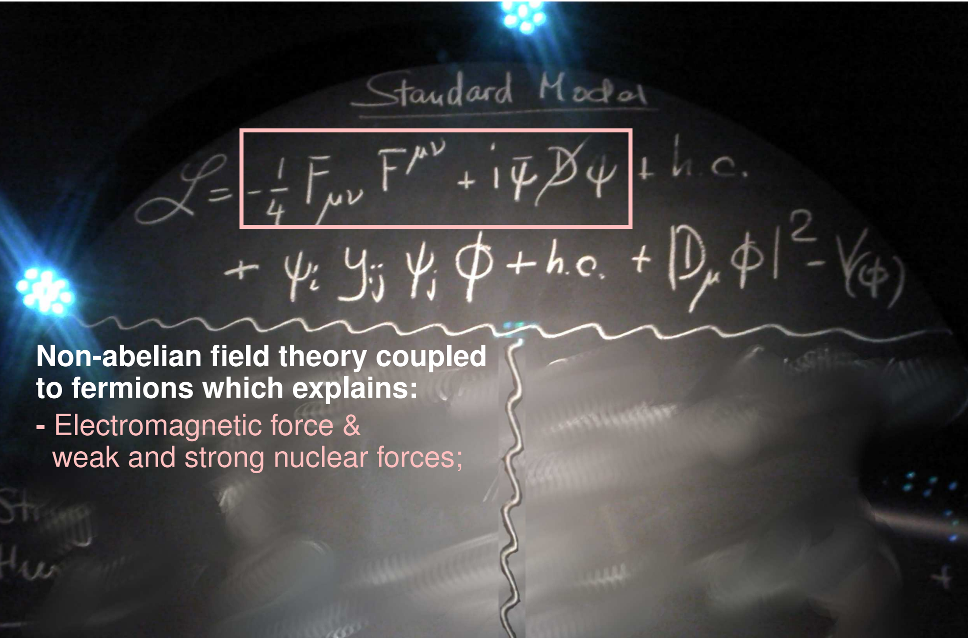

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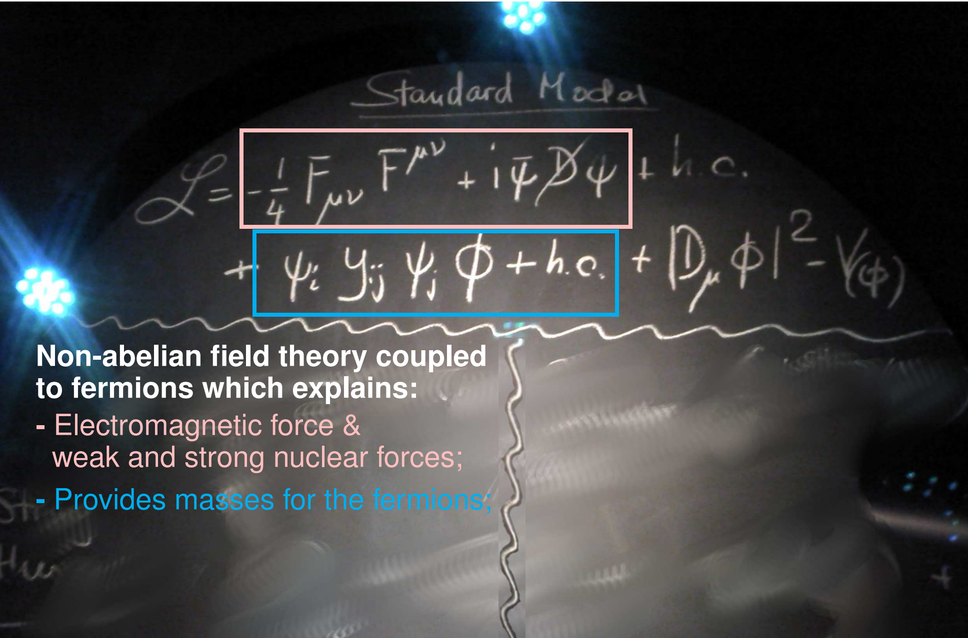

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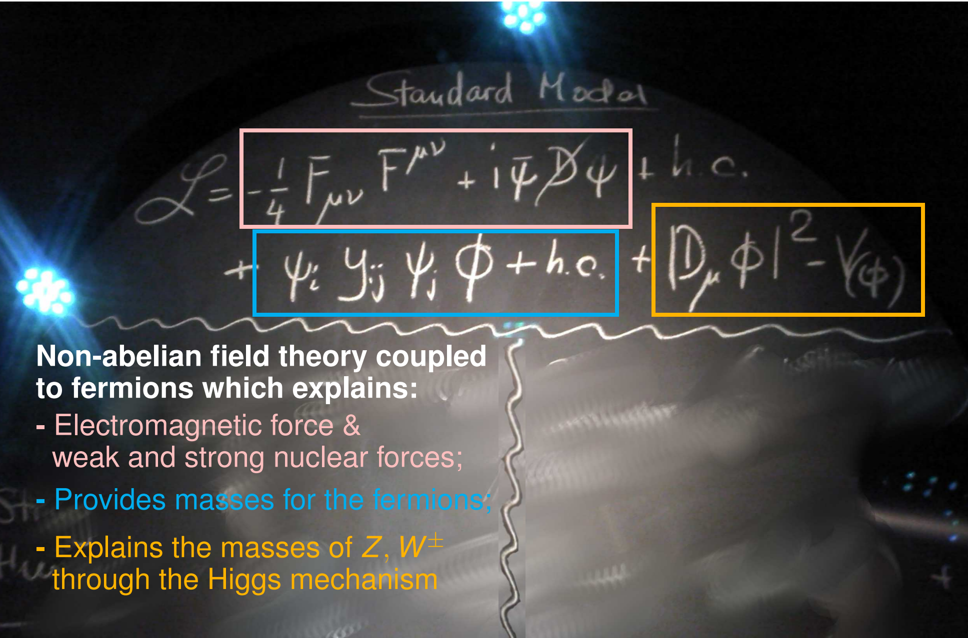

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Standard Model

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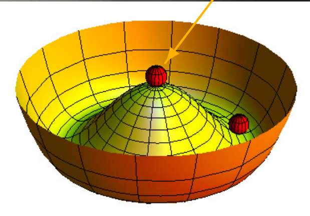

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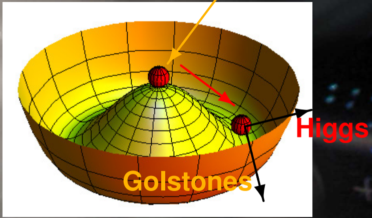

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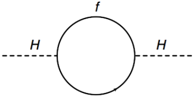

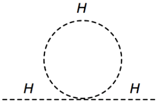

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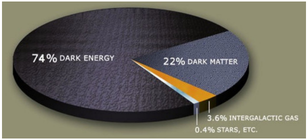

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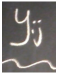

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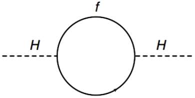

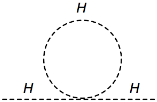

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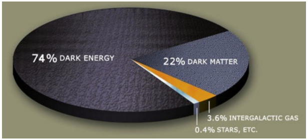

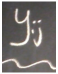

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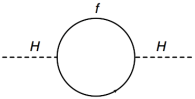

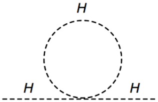

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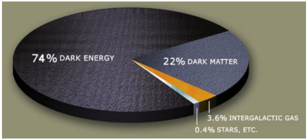

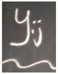

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<u>**Extended scalar sectors** can address these problems.</u>

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LHC designed to find new TeV scale physics $\rightarrow$ **Higgs boson?**

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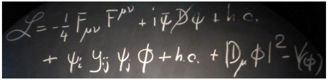

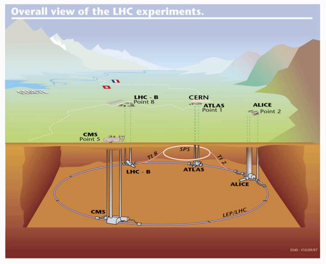

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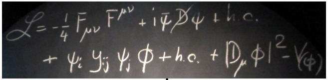
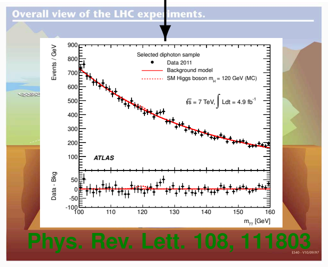
Efficient tools are essential:

- Feynman rules: Feynrules, LanHEP,...
- Matrix Elements+MC generators: CalcHEP,CompHEP,FeynArts/FormCalc, Madgraph/MadEvent, Herwig,Pythia, MC@NLO, POWHEG,...
- Detector Simulation: AcerDet, Delphes, PGS,...+ Experiments





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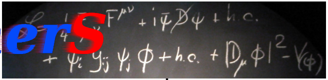

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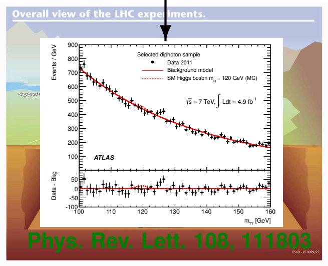

Phys. Rev. Lett. 108, 111803

We propose a new tool dedicated to:

Scanning the parameter space of extended scalar sectors

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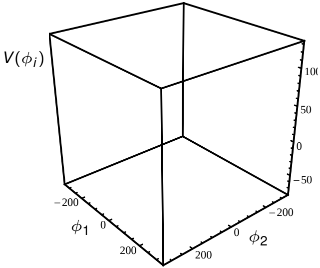
Vacuum linear conditions: VEVs



Scalar potential for given model:

- **Linear** in couplings λ_a

$$V(\phi_i) = V_a(\phi_i)\lambda_a$$

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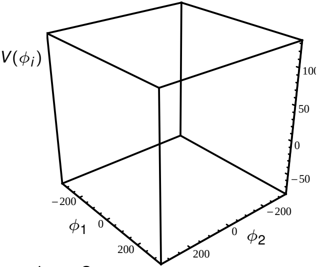

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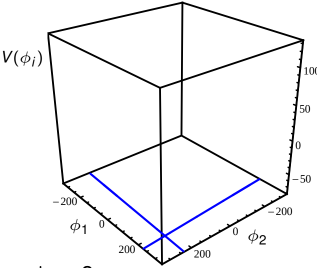

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- **Expansion** around minimum

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

Linear system constraining λ_a if v_i fixed!

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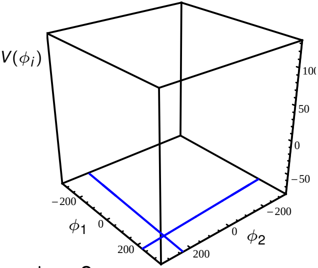

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<u>Linear system</u> constraining λ_a if v_i fixed!

- **Numerically inexpensive** to eliminate $\lambda_{a_1} = \Lambda_{a_1 a_2} \lambda_{a_2}$

Vacuum quadratic conditions: Mixing

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

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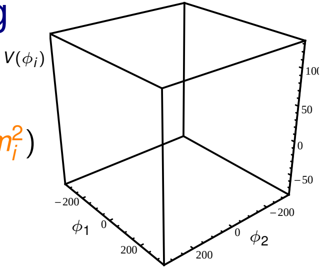

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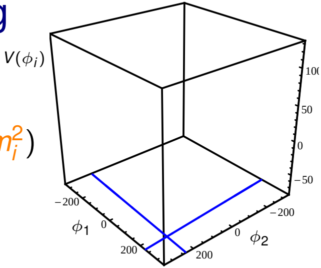

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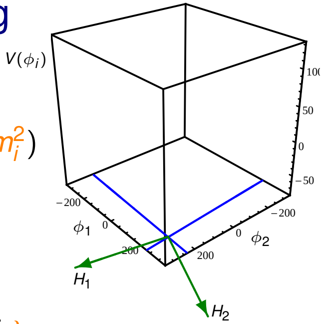

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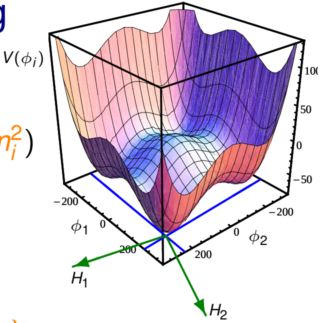

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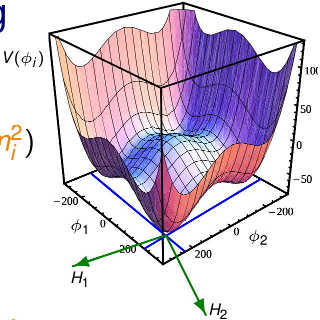

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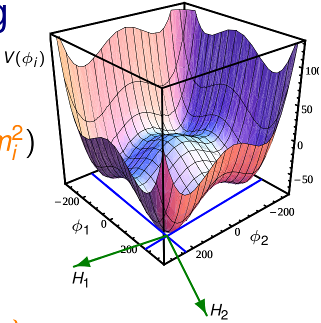

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Delay non-linear/expensive tasks to **increase efficiency!**

Tree level unitarity & vacuum stability

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

$a_{ij}^{(0)} \sim \sum_{a_4} \ldots \lambda_{a_4}$ **Lee, Quigg, Thacker; PRD16, Vol.5 (1977)**

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Tree level vacuum stability (computationally intensive):

- Potential bounded below $\to$ non-linear, no closed form
- Check minimum is global $\to$ non-linear, no closed form

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

$a_{ij}^{(0)} \sim \sum_{a_4} \dots \lambda_{a_4}$ **Lee, Quigg, Thacker; PRD16, Vol.5 (1977)**

- Reduces to finding eigenvalues of $a_{ij}^{(0)}$ numerically $\Rightarrow$ **fast!**
- In SM, the **2-particle** states are w^+w^-, hh, zz, hz
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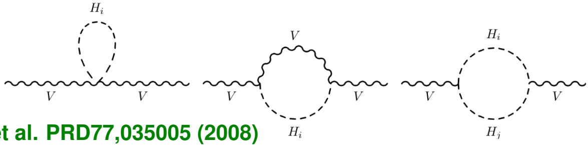
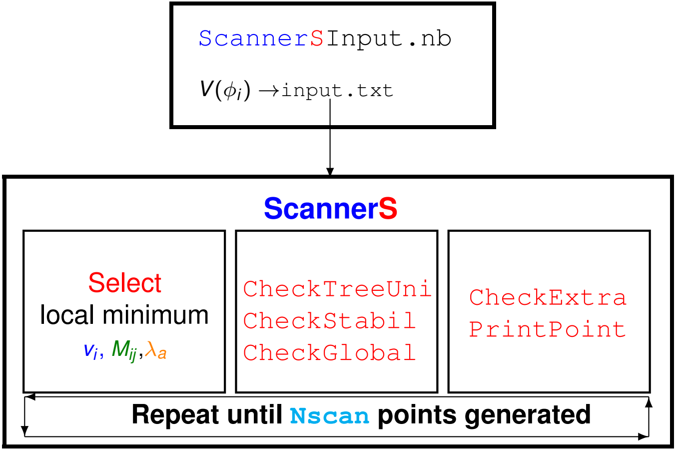
Example: Variation of Electroweak Precision Observables $\Delta S, \Delta T, \Delta U$ for n-Singlets (implemented):



Barger et al. PRD77,035005 (2008)

ScannerS @ Work



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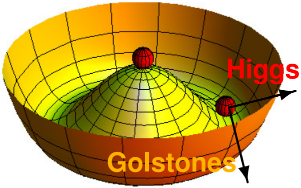

ScannerSInput.nb

$V(\phi_i) \rightarrow$ input.txt

ScannerS

Select
local minimum
v_i, M_{ij}, λ_a

CheckTreeUni
CheckStabil
CheckGlobal

CheckExtra
PrintPoint

Repeat until Nscan points generated

Note: Includes routines to identify Goldstones and other “a priori” eigen-directions at a certain point v_i.

Outline

Tests: Some singlet extensions

Complex Scalar field with broken $U(1)$:

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \\ + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1 \mathbb{S} + c.c.\right)$$

- *Model 0:* Standard Model Higgs only!
- *Model 1*, $\langle \mathbb{S} \rangle = 0$: When $a_1 = 0$ and $b_1 \in \mathbb{R}^+$. Two stable dark matter candidates. $\Leftrightarrow$ **Barger et al. PRD77,035005 (2008)**
- *Model 2*, $\langle \Im(\mathbb{S}) \rangle = 0$: When $a_1 \in \mathbb{R}^+$ and $b_1 \in \mathbb{R}$. A stable dark matter candidate. Higgs mixes with other scalar. **Barger et al. PRD 79,015018 (2009)**
- *Model 3*, $\langle \Re(\mathbb{S}) \rangle \neq 0$, $\langle \Im(\mathbb{S}) \rangle \neq 0$: Can be parametrised by $a_1 \in \mathbb{R}^+$ and $b_1 \in \mathbb{C}$. Three scalars mixing. $\rightarrow$ In progress!

Tests: Real singlet mixing with Higgs

- We have reproduced a scan in **Barger et al. PRD77,035005 (2008)**
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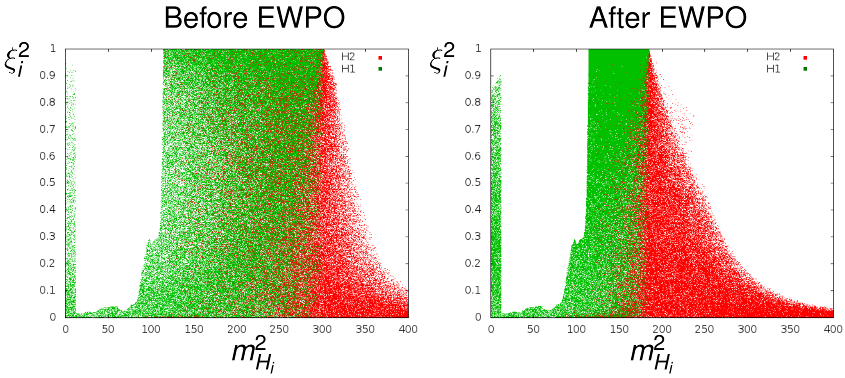
- Here ξ_i^2 is the reduction factor of the corresponding Higgs signal compared to SM.



In progress ...

The main points we are addressing:

1. General algorithm to determine boundedness from below
2. General algorithm to check minimum is Global: Already have a hybrid Monte Carlo/bracketing strategy applied to *Model 3*.

   $\rightarrow$ Maybe **hybrid MC** possible in general
3. Interface with LanHep and Micromegas for models with dark matter candidates

Conclusions

1. Scalar extensions of SM, common when addressing **BSM** problems: Hierarchy problem, Dark matter, Neutrino masses, Flavour structure,...
2. Tool development is crucial in the interaction with experimentalists to identify candidate models
3. We are developing a scanning tool for the **Higgs** sector. We have included:
   - **Minimum generation**, with an inverted scanning strategy, retaining physical states information
   - **Tree level unitarity** checking routines
   - **Vacuum stability & Global** (test models only for now)
   - **Flexible structure** for user defined analysis

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Look out for the release of ***ScannerS***oon!

THANK YOU!

BACKUP

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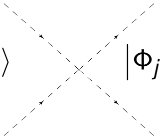
$|\Phi_i\rangle$  $|\Phi_j\rangle$,

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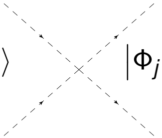
$|\Phi_i\rangle$  $|\Phi_j\rangle$, $\Re\{a_{ij}^{(0)}\} < \frac{1}{2}$,

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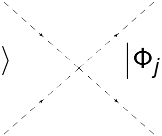
$|\Phi_i\rangle$  $|\Phi_j\rangle$, $\Re\{a_{ij}^{(0)}\} < \frac{1}{2}$, $a_{ij}^{(0)} = \dfrac{\langle\Phi_i|\, i\mathbf{T}^{(0)}\, |\Phi_j\rangle}{16\pi} \sim \sum_{a_4} \ldots \lambda_{a_4}$

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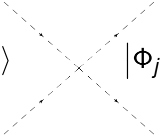
$|\Phi_i\rangle$  $|\Phi_j\rangle$

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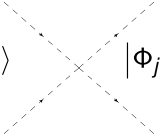

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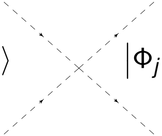
$|\Phi_i\rangle$  $|\Phi_j\rangle$, $\Re\{a_{ij}^{(0)}\} < \frac{1}{2}$, $a_{ij}^{(0)} = \frac{\langle\Phi_i|\, i\mathbf{T}^{(0)}\, |\Phi_j\rangle}{16\pi} \sim \sum_{a_4} \ldots \lambda_{a_4}$

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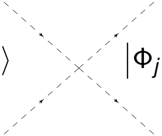
$|\Phi_i\rangle$  $|\Phi_j\rangle$, $\Re\{a_{ij}^{(0)}\} < \frac{1}{2}$, $a_{ij}^{(0)} = \frac{\langle\Phi_i|\, i\mathbf{T}^{(0)}\, |\Phi_j\rangle}{16\pi} \sim \sum_{a_4} \ldots \lambda_{a_4}$

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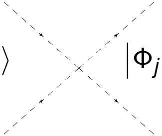
$|\Phi_i\rangle$  $|\Phi_j\rangle$, $\Re\{a_{ij}^{(0)}\} < \frac{1}{2}$, $a_{ij}^{(0)} = \frac{\langle \Phi_i | \, i\mathbf{T}^{(0)} \, | \Phi_j \rangle}{16\pi} \sim \sum_{a_4} \ldots \lambda_{a_4}$

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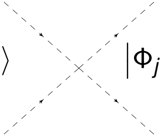
$|\Phi_i\rangle$  $|\Phi_j\rangle$, $\Re\{a_{ij}^{(0)}\} < \frac{1}{2}$, $a_{ij}^{(0)} = \dfrac{\langle \Phi_i | \, i\mathbf{T}^{(0)} \, | \Phi_j \rangle}{16\pi} \sim \sum_{a_4} \ldots \lambda_{a_4}$

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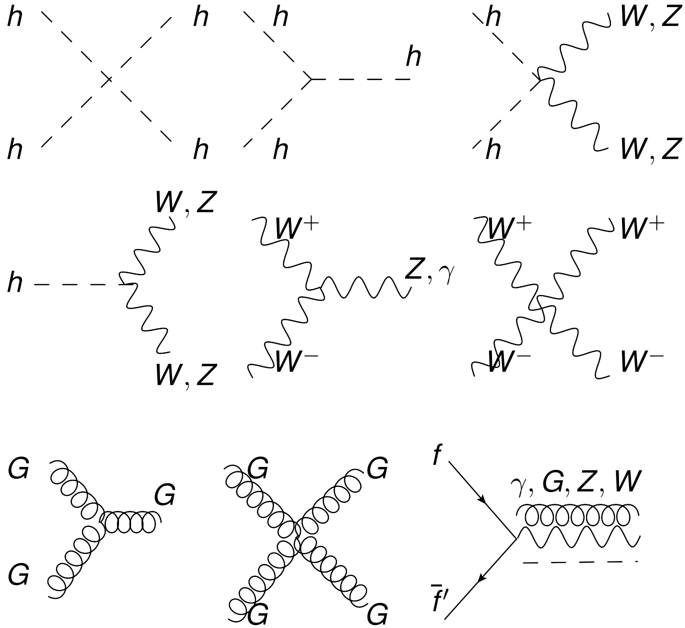
The Standard Model – Interactions



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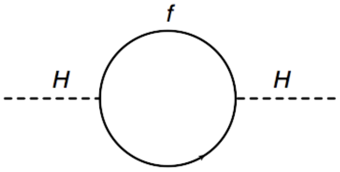

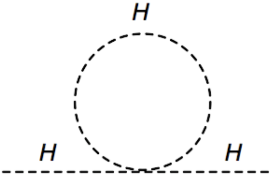

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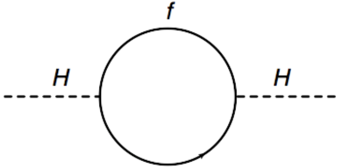

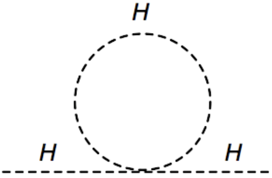

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If $\Lambda_{\text{cutoff}} \sim M_4 \sim 10^{16}$ TeV $\Rightarrow$ **fine tuning** of $\sim 10^{-16}$

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4. Etc...