SUSY developments in FeynRules

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IPHC

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Outline

Supersymmetry as a solution

Standard Model of particle physics

- Is one of the most tested theories in physics
- Has some open questions.

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- Dark matter.
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- Only one generator (Minimal).
- Quarks ⇔ Squarks, Leptons ⇔ Sleptons.
- Gauge/Higgs bosons ⇔ Gauginos/Higgsinos.

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New particles

- SM-fermion $\mapsto$ new boson.
- SM-boson $\mapsto$ new fermion.

Superspace and superfield formalism

Superspace

A point in superspace is now defined as

$$\phi(x^\mu) \longrightarrow \phi(x^\mu, \theta, \bar{\theta}),$$

$(\theta, \bar{\theta})$: Majorana fermion.

Superfields

Chiral (matter) Superfields	Vector (gauge) Superfields
$\Phi = (\phi, \psi, \ldots)$	$V = (\lambda, v_\mu, \ldots)$
ϕ : scalar component	λ : fermionic component
ψ : fermionic component	v_μ : bosonic component

$\ldots$ stand for auxiliary fields.

Susy Lagrangian

- Kinematic terms and gauge interactions for the left-handed (s)quarks in the MSSM

In components (13 terms)

$$D_\mu \tilde{Q}_i^\dagger D^\mu \tilde{Q}^i + \frac{1}{2}(\chi_Q^i \sigma^\mu D_\mu \bar{\chi}_{Qi} - D_\mu \chi_Q^i \sigma^\mu \bar{\chi}_{Qi}) + F_{Qi}^\dagger F_Q^i + i\sqrt{2}\left[\frac{1}{6} g' \tilde{Q}^i \bar{\tilde{B}} \cdot \bar{\chi}_{Qi} + g \bar{\tilde{W}}^k \cdot \bar{\chi}_{Qi} \frac{\sigma^k}{2} \tilde{Q}^i + g_s \bar{\tilde{G}}^a \cdot \bar{\chi}_{Qi} T^a \tilde{Q}^i + h.c.\right] - g' D_B \tilde{Q}_i^\dagger \tilde{Q}^i - g D_{W^k} \tilde{Q}_i^\dagger \frac{\sigma^k}{2} \tilde{Q}^i - g_s D_{G^a} \tilde{Q}_i^\dagger T^a \tilde{Q}^i$$

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In superfields (1 term)

$$\left[Q_i^\dagger e^{-2\frac{1}{6} g' V_B} e^{-2g V_{W^k} \frac{\sigma_k}{2}} e^{-2g_s V_{G^a} \frac{T^a}{2}} Q^i \right]_{|\theta\cdot\theta\bar{\theta}\cdot\bar{\theta}}$$

The superspace formalism could be a useful tool for model building

Defining Vector superfields

C. Duhr, B. Fuks (CPC '11)

Conventions → Fuks, Rausch de Traubenberg (Ellipses '11)

Vector superfield in the Wess-Zumino gauge

$$V_{W.Z.}(x,\theta,\bar\theta) = \theta\sigma^\mu\bar\theta v_\mu + i\theta\cdot\theta\bar\theta\cdot\bar\lambda - i\bar\theta\cdot\bar\theta\theta\cdot\lambda + \frac{1}{2}\theta\cdot\theta\bar\theta\cdot\bar\theta D.$$

v_μ gauge vector, $(\lambda,\bar\lambda)$ Majorana fermion, D auxiliary field.

Declaring the $SU(3)_c$ vector superfield

Model file content			Precisions
VSF[1] == {			Label of the vector superfield
ClassName	→	GSF	
GaugeBoson	→	G	must be declared properly
Gaugino	→	gow	must be declared properly
Indices	→	{[IndexGluon]}	
}			

Auxiliary fields are automatically generated (not explicitely present).

Vector Langrangians

- Lagrangian associated to the vector superfields.
  - Gauge kinetic terms.
  - Entirely fixed by gauge and SUSY invariance.

Non-abelian groups (abelian limit easy to obtain).

$$\begin{aligned}\mathcal{L}_{vector} &= \frac{1}{16g^2\tau_R}\,\mathrm{Tr}(W^\alpha W_\alpha)_{|\theta\theta} + \frac{1}{16g^2\tau_R}\,\mathrm{Tr}(\bar{W}_{\dot{\alpha}}\bar{W}^{\dot{\alpha}})_{|\bar{\theta}\bar{\theta}} \\ &= -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a + i\bar{\lambda}_a\bar{\sigma}^\mu D_\mu\lambda^a + \frac{1}{2}D_a D^a\end{aligned}$$

Automatic extraction of the vector Lagrangian of a model

all vector superfields	VSFKineticTerms[ ]
one vector superfield	VSFKineticTerms[GSF]

Defining Chiral superfields

Chiral superfields

$$\Phi(y,\theta) = \phi(y) + \sqrt{2}\phi \cdot \psi(y) - \theta \cdot \theta F(y) \quad \text{with } y^\mu = x^\mu - i\theta\sigma^\mu\bar{\theta}$$

- Describes matter multiplets.
- One scalar field ϕ, one Weyl fermion ψ, one auxiliary field F

Declaring the right-handed quark superfield

Model file content			Precisions
`CSF[1] == {`			Label of the chiral superfield
`ClassName`	`->`	`QL`	
`Chirality`	`->`	`Left`	
`Weyl`	`->`	`QLw`	must be declared properly
`Scalar`	`->`	`QLs`	must be declared properly
`QuantumNumbers`	`->`	`{ Q -> 2/3}`	must be declared properly
`Indices`	`->`	`{ Index[Gen], Index[Colour]}`	
`}`			

Auxiliary fields are automatically generated (not explicitely present).

Matter Langrangians

- Lagrangian associated to the chiral superfields.
  - Gauge interactions and kinetic terms for chiral superfields.
  - Entirely fixed by SUSY and gauge invariance.

Example for $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{matter} = \left[\Phi^\dagger(x,\theta,\bar{\theta}) \exp^{-2y_\Phi g' V_B} \exp^{-2gV_W} \exp^{-2g_s V_G} \Phi(x,\theta,\bar{\theta})\right]_{|\theta\theta\bar{\theta}\bar{\theta}}$$

(Non-abelian vector superfields contain group representation matrices.)

Automatic extraction of the matter Lagrangian of a model

all chiral superfields	`CSFKineticTerms[]`
one chiral superfield	`CSFKineticTerms[QL]`

Superfield dedicated commands

Superfield Components

Get θ-Component	`ThetaComponent[SF]`
Get $\theta\theta$-Component	`Theta2Component[SF]`
Get $\theta\theta\bar{\theta}\bar{\theta}$-Component	`Theta2Thetabar2Component[SF]`

Transformation laws

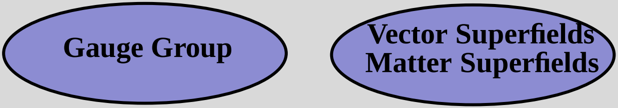
$\delta_\epsilon \Phi(x,\theta,\bar{\theta}) = i(\epsilon \cdot Q + \bar{Q} \cdot \bar{\epsilon})$	$\rightarrow$	`DeltaPhi = DeltaSUSY[UR, eps1]`
$\left[\delta_\epsilon \Phi(x,\theta,\bar{\theta})\right]_{\lvert\theta}$	$\rightarrow$	`ThetaComponent[DeltaSUSY[UR, eps1]]`

Superfield strength tensor W_α

$W_\alpha = -\frac{1}{4}\bar{D} \cdot \bar{D} \exp^{2gV} D_\alpha \exp^{-2gV}$	`SuperfieldStrengthL[SF, gauge index]`
$\bar{W}_{\dot{\alpha}} = -\frac{1}{4} D \cdot D \exp -2gV \bar{D}_{\dot{\alpha}} \exp 2gV$	`SuperfieldStrengthR[SF, gauge index]`

Full Susy Lagrangian

Full Susy Lagrangian



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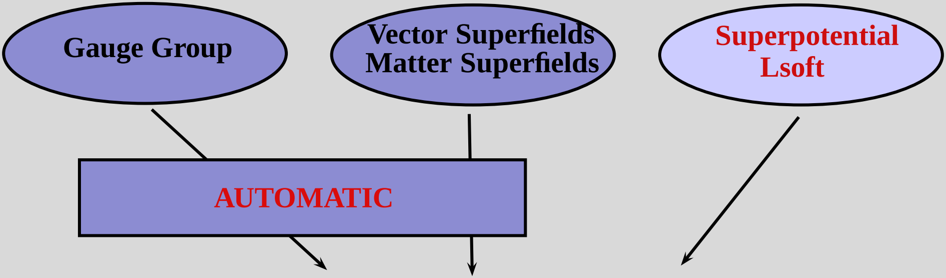


$$\mathcal{L} = \left[\Phi^\dagger e^{-2gV}\Phi\right]_{|\theta.\theta\bar\theta.\bar\theta} + \frac{1}{16g^2\tau_R}\mathrm{Tr}(W^\alpha W_\alpha)_{|\theta.\theta} + \frac{1}{16g^2\tau_R}\mathrm{Tr}(\bar W_{\dot\alpha}\bar W^{\dot\alpha})_{|\bar\theta.\bar\theta}$$
$$+ \; W(\Phi)_{|\theta.\theta} + W^*(\Phi^\dagger)_{|\bar\theta.\bar\theta} + \mathcal{L}_{soft}$$

$\mathcal{L}_{soft}$ is the soft-susy breaking lagrangian

Lagrangian commands

Total Lagrangian

```
Theta2Thetabar2Component[CSFKineticTerms[]] +
Theta2Component[VSFKineticTerms[] +Superpot] +
Thetabar2Component[VSFKineticTerms[] + HC[Superpot]] +
LSoft
```

Eliminating the auxiliary fields

```
lagr = SolveEqMotionD[lagr]
lagr = SolveEqMotionF[lagr]
```

Back to four-component fermions

Usual FeynRules routine.

lagr = WeylToDirac[lagr]

Theory expectations

FeynRules-superfield can be used to extract Goldstino Lagrangian

Theory expectations

FeynRules-superfield can be used to extract Goldstino Lagrangian

- Variation of the SUSY Lagrangian (using FeynRules)

Using the supercharges

$$\delta_\epsilon \mathcal{L} = \partial_\mu K^\mu$$

Using Noether theorem

$$\delta_\epsilon \mathcal{L} = \partial_\mu \left[\frac{\delta \mathcal{L}}{\partial(\partial_\mu X)} \delta_\epsilon X \right]$$

- Result to be reproduced

$$J^\mu = \sqrt{2} D_\nu \phi_i^\dagger \sigma^\nu \bar{\sigma}^\mu \psi^i + i\sqrt{2} \sigma^\mu \bar{\psi}_i W^{*i} - \frac{i}{2} \sigma^\rho \bar{\sigma}^\nu \sigma^\mu \bar{\lambda}_a F_{\nu\rho}^a + g \phi_i^\dagger \sigma^\mu \bar{\lambda} \phi^i$$

- Supercurrent conservation $\Rightarrow$Goldstino (ψ_1) interaction Lagrangian

$$\mathcal{L} = \frac{1}{2\sqrt{2}} \frac{1}{\langle F^1 \rangle} \psi^1 \cdot \partial_\mu J + \frac{1}{2\sqrt{2}} \frac{1}{\langle F_1^\dagger \rangle} \bar{\psi}^1 \cdot \partial_\mu \bar{J}$$

FeynRules implementation

Declare Goldstino

Model file content	Precisions
`CSF[100] == {`	Label of the chiral superfield
`ClassName -> GLDSF`	
`Chirality -> Left`	
`Weyl -> GLDw`	must be declared properly
`Scalar -> GLDs`	must be declared properly
`}`	

Rarita-Schwinger field

→ **Not** a superfield
⇒ Only declared in `M$ClassesDescription` with classe name `RW`

Supercurrent

```
JJ = SuperCurrent[Lvector,Lchiral,Lsuperpot,spin index,lorentz index];
```

Interfaces

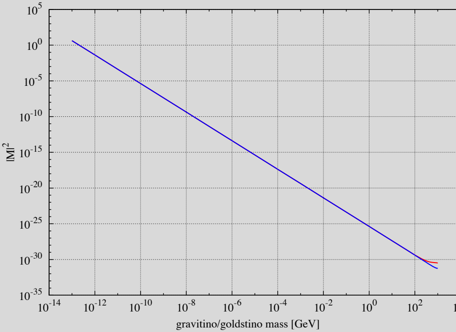
Working Interfaces

CalcHep, MG5 (UFO)

→working

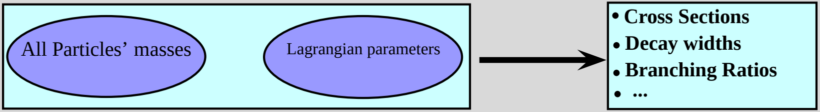
Numerical codes

On-going validation



1. Introduction to supersymmetry
2. Superspace Module (C. Duhr, B. Fuks)
3. Spin 3/2 Project (”Spin 3/2 collaboration”)
4. Spectrum generator generator (Alloul, De Causmaecker, Fuks, Rausch de Traubenberg)
   - Motivations
   - Renormalization Group Equations
   - Scalar Potential and mass matrices
5. Prospects
6. Resume

What are Susy theories phenomenological implications ?



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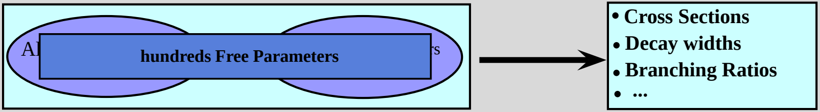

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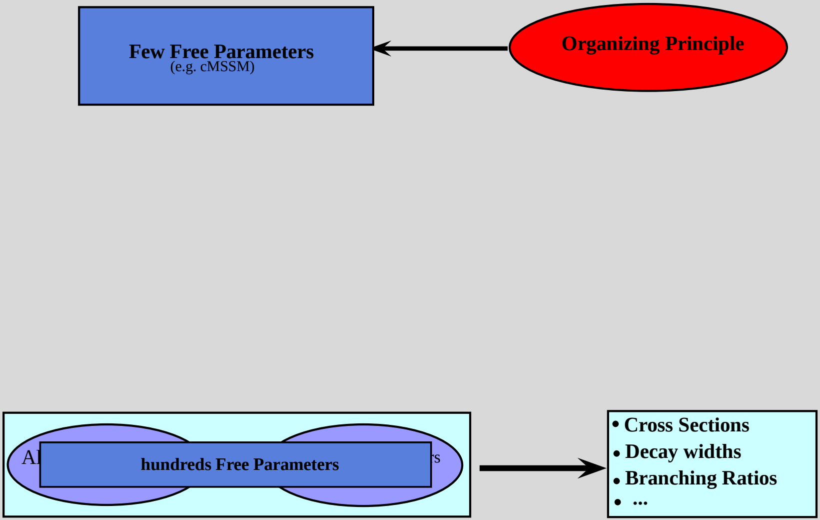

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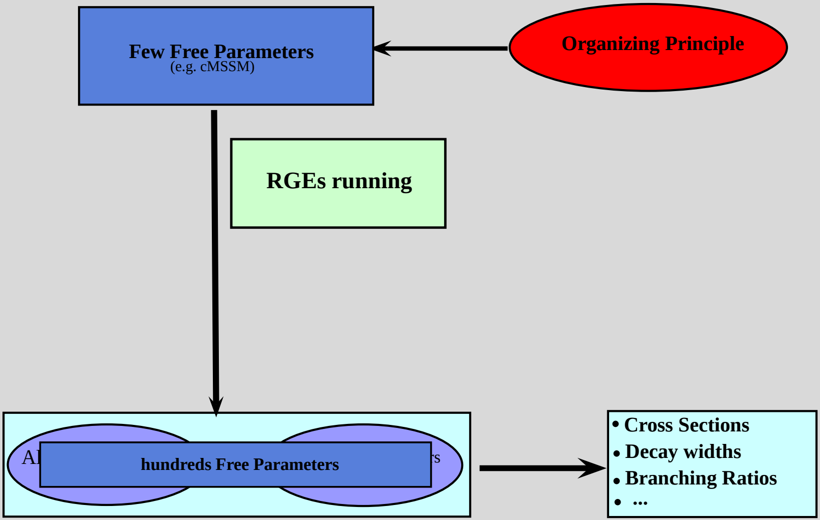

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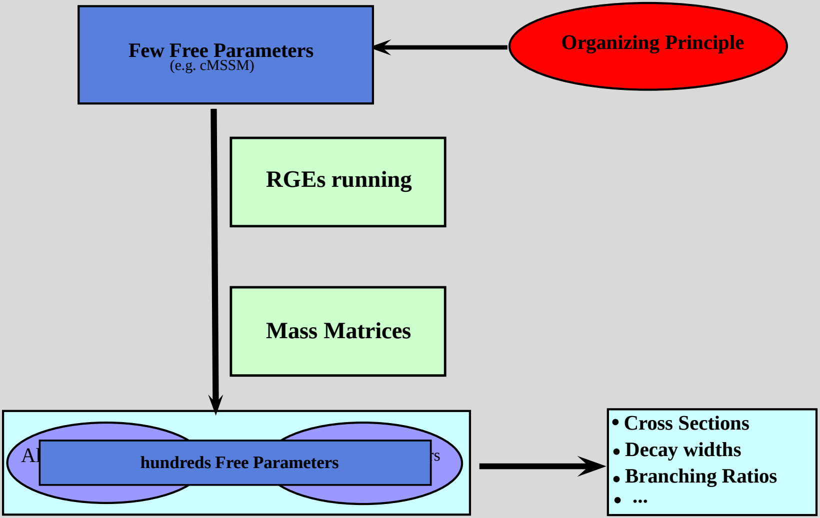

Obtaining the RGEs

Alloul, Fuks, Raush de Traubenberg (Les Houches '11 Proceedings)

New way of defining the superpotential

Ex : Up-type quarks couplings

```
yu[ff1, ff2] UR[ff1, cc1] SUDot[QL[aa, ff2, cc1],HU[aa],aa]
```

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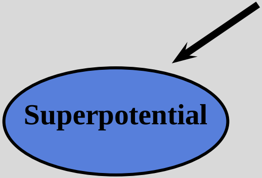

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```

RGEs

```
RGE[LSoft, Superpotential]
```

Output from InSuRGE

Gauge coupling constants @ 2loop level

$$\frac{"\partial"}{"\partial t"}[g'] == \frac{199\,(g')^2\,g_s^5}{6400\,\pi^4} + \frac{11\,g_s^7}{160\,\pi^4} + \frac{27\,g_s^5\,g_w^2}{1280\,\pi^4} + \frac{33\,(g')^3}{80\,\pi^2} - \frac{7\,g_s^3\,\left(y^d\right)^{"*"}_{\mathrm{GEN\$1,GEN\$2}}\,y^d{}_{\mathrm{GEN\$1,GEN\$2}}}{640\,\pi^4} - \frac{9\,g_s^3\,(y^e)^{"*"}_{\mathrm{GEN\$1,GEN\$2}}\,y^e{}_{\mathrm{GEN\$1,GEN\$2}}}{640\,\pi^4} - \frac{13\,g_s^3\,(y^u)^{"*"}_{\mathrm{GEN\$1,GEN\$2}}\,y^u{}_{\mathrm{GEN\$1,GEN\$2}}}{640\,\pi^4}$$

$$\frac{"\partial"}{"\partial t"}[g_w] == \frac{g_w^5}{64\,\pi^4} + \frac{9\,(g')^2\,g_w^5}{1280\,\pi^4} + \frac{3\,g_s^2\,g_w^5}{32\,\pi^4} + \frac{21\,g_w^7}{256\,\pi^4} + \frac{g_w^3}{16\,\pi^2} - \frac{3\,g_w^3\,\left(y^d\right)^{"*"}_{\mathrm{GEN\$1,GEN\$2}}\,y^d{}_{\mathrm{GEN\$1,GEN\$2}}}{128\,\pi^4} - \frac{g_w^3\,(y^e)^{"*"}_{\mathrm{GEN\$1,GEN\$2}}\,y^e{}_{\mathrm{GEN\$1,GEN\$2}}}{128\,\pi^4} - \frac{3\,g_w^3\,(y^u)^{"*"}_{\mathrm{GEN\$1,GEN\$2}}\,y^u{}_{\mathrm{GEN\$1,GEN\$2}}}{128\,\pi^4}$$

$$\frac{"\partial"}{"\partial t"}[g_s] == -\frac{9\,g_s^5}{128\,\pi^4} + \frac{11\,(g')^2\,g_s^5}{1280\,\pi^4} + \frac{g_s^7}{8\,\pi^4} + \frac{9\,g_s^5\,g_w^2}{256\,\pi^4} - \frac{3\,g_s^3}{16\,\pi^2} - \frac{g_s^3\,\left(y^d\right)^{"*"}_{\mathrm{GEN\$1,GEN\$2}}\,y^d{}_{\mathrm{GEN\$1,GEN\$2}}}{64\,\pi^4} - \frac{g_s^3\,(y^u)^{"*"}_{\mathrm{GEN\$1,GEN\$2}}\,y^u{}_{\mathrm{GEN\$1,GEN\$2}}}{64\,\pi^4}$$

Output from InSuRGE

Gauge coupling constants @ 2loop level

Validated against MSSM, NMSSM and RPV

$$\frac{\text{"}\partial\text{"}}{\text{"}\partial t\text{"}}[g'] == \frac{199\,(g')^2 g_s^5}{6400\,\pi^4} + \frac{11\,g_s^7}{160\,\pi^4} + \frac{27\,g_s^5 g_w^2}{1280\,\pi^4} + \frac{33\,(g')^3}{80\,\pi^2} - \frac{7\,g_s^3\,(y^d)^{\text{"*"}}_{GEN\$1,GEN\$2}\,y^d{}_{GEN\$1,GEN\$2}}{640\,\pi^4} -$$

$$\frac{9\,g_s^3\,(y^e)^{\text{"*"}}_{GEN\$1,GEN\$2}\,y^e{}_{GEN\$1,GEN\$2}}{640\,\pi^4} - \frac{13\,g_s^3\,(y^u)^{\text{"*"}}_{GEN\$1,GEN\$2}\,y^u{}_{GEN\$1\cdots}}{640\cdots}$$

$$\frac{\text{"}\partial\text{"}}{\text{"}\partial t\text{"}}[g_w] == \frac{g_w^5}{64\,\pi^4} + \frac{9\,(g')^2 g_w^5}{12\cdots} \cdots \frac{3\,g^2\cdots}{\cdots} \cdots \frac{\cdots}{16\,\pi^2} - \frac{\cdots g_w\,(y^d)^{\text{"*"}}_{GEN\$1,GEN\$2}\,y^d{}_{GEN\$1,GEN\$2}}{128\,\pi^4} -$$

$$\frac{g_w^3\,(y^e)^{\text{"*"}}\cdots}{\cdots} - \frac{3\,g_w^3\,(y^u)^{\text{"*"}}_{GEN\$1,GEN\$2}\,y^u{}_{GEN\$1,GEN\$2}}{128\,\pi^4}$$

$$\frac{\text{"}\cdots\text{"}}{\text{"}\partial t\text{"}}[g_s] == -\frac{9\,g_s^5}{128\,\pi^4} + \frac{11\,(g')^2 g_s^5}{1280\,\pi^4} + \frac{g_s^7}{8\,\pi^4} + \frac{9\,g_s^5 g_w^2}{256\,\pi^4} -$$

$$\frac{3\,g_s^3}{16\,\pi^2} - \frac{g_s^3\,(y^d)^{\text{"*"}}_{GEN\$1,GEN\$2}\,y^d{}_{GEN\$1,GEN\$2}}{64\,\pi^4} - \frac{g_s^3\,(y^u)^{\text{"*"}}_{GEN\$1,GEN\$2}\,y^u{}_{GEN\$1,GEN\$2}}{64\,\pi^4}$$

RGEs Dedicated Commands

Gauge Constants RGEs

`GaugeCouplingsRGE[SPMS,NLoop->1]`

Gaugino Masses RGEs

`GauginoMassesRGE[SPMS,SoftMS,NLoop->2]`

Superpotential RGEs

`SuperpotentialRGE[SPMS,NLoop->2]`

LSoft RGEs

`ScaSoftRGE[SoftNMS, SPNMS]`

Number of loops

`NLoop` default value is set to 2

Not available yet for `ScaSoftRGE`.

Mass Matrices

Inspired by FR '10 work.

To have a mass spectrum

- Calculate the lagrangian without any rotation into mass eigenstates.
- Need to know which field acquires a vev ?
- Need to know which fields mix together ?

Implementation in FeynRules

- New `ExpandIndices` function (to avoid field rotations)
- New declarations in model file → vevs and field mixings
- Tree level in progress
- Radiative corrections planned in near future

Preliminary results

In[57]:= **GetMassMatrices[lagr]**

The Lagrangian you entered contains physical fields, make sure these don't come from a previous field rotation. Calculations have been however performed.

Calculations took 35.8097 seconds to be performed. Results are stored in the variable MassMatrices

In[58]:= **MassMatrices[[7, 2]].MatrixForm[MassMatrices[[7, 3]]].MassMatrices[[7, 4]]**

Out[58]= $\{\mathrm{bow}, \mathrm{wow}_3, \mathrm{hdw}_1, \mathrm{huw}_2\}.$

$$\begin{pmatrix} M_1 & 0 & -\frac{1}{2}\, i\, g'\, v_d & \frac{1}{2}\, i\, g'\, v_u \\ 0 & M_2 & \frac{1}{2}\, i\, g_w\, v_d & -\frac{1}{2}\, i\, g_w\, v_u \\ -\frac{1}{2}\, i\, g'\, v_d & \frac{1}{2}\, i\, g_w\, v_d & 0 & -\mu \\ \frac{1}{2}\, i\, g'\, v_u & -\frac{1}{2}\, i\, g_w\, v_u & -\mu & 0 \end{pmatrix}.\{\mathrm{bow}, \mathrm{wow}_3, \mathrm{hdw}_1, \mathrm{huw}_2\}$$

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Future evolutions

RGEs

- 1 Loop OK
- 2 Loop in progress

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RGEs

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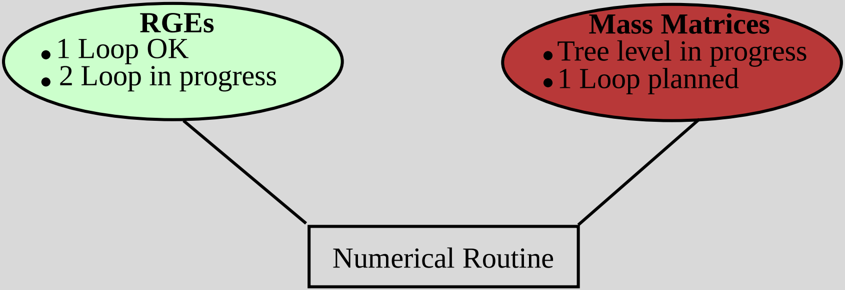
Mass Matrices

- Tree level in progress
- 1 Loop planned

Future evolutions



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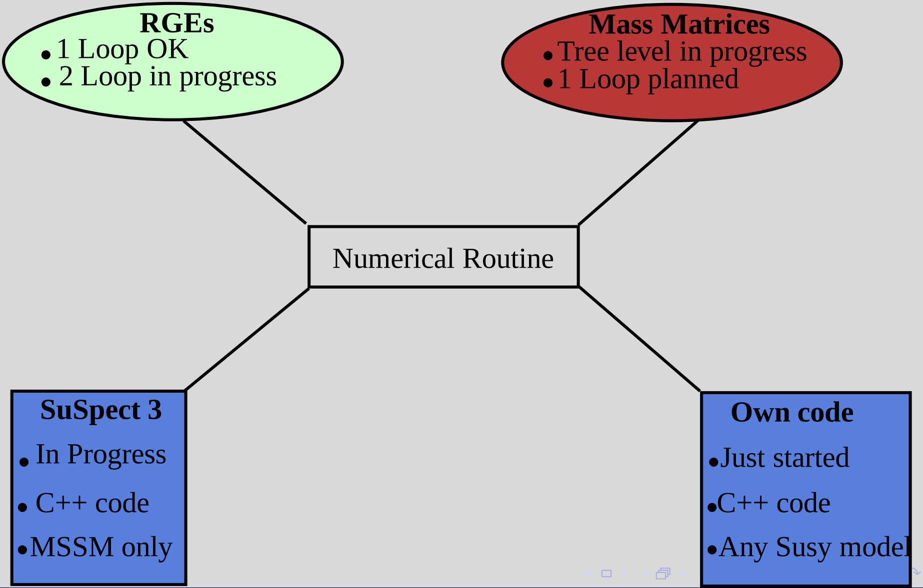

Future evolutions

RGEs
- 1 Loop OK
- 2 Loop in progress

Mass Matrices
- Tree level in progress
- 1 Loop planned

Numerical Routine

SuSpect 3
- In Progress
- C++ code
- MSSM only

Own code
- Just started
- C++ code
- Any Susy model

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Conclusion

Achieved work

- Superfields (since a long time ago).
- Spin 3/2 project.
- RGEs @ 1 loop and (partial) 2loop.

On-going work

- Spin 3/2 numerical validation.
- Complete RGEs @ 2loop.
- Scalar potential and mass matrices diagonalization @ 1loop.

Thank You !