Pedagogical review of $N = 1$ Supersymmetry and $N = 1$ Supergravity

Phenomenological and experimental aspects

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Overview

1. Introduction
2. Quick review of $N = 1$ Supersymmetry and $N = 1$ Supergravity
   - $N = 1$ Supersymmetry
   - $N = 1$ Supergravity
3. Supersymmetry Breaking
   - General aspects of SUSY Breaking
   - Mechanisms of SUSY Breaking
4. Phenomenology of the MSSM
   - Particle spectrum of the MSSM
   - SUSY as solution of hierarchy & naturality problem
   - MSSM analysis strategy
5. Constraints from experimental measurements
   - Higgs Boson mass near 125 GeV
   - Relic density of Dark Matter $\Omega_{DM} h^2$
   - Direct searches of stop squark $\tilde{t}$ at the LHC
6. Conclusion

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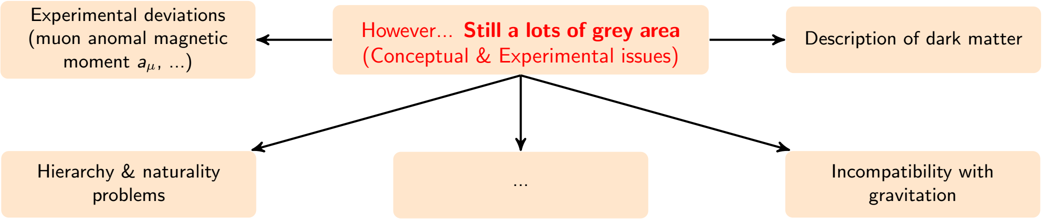

Context: The Standard Model & its problems

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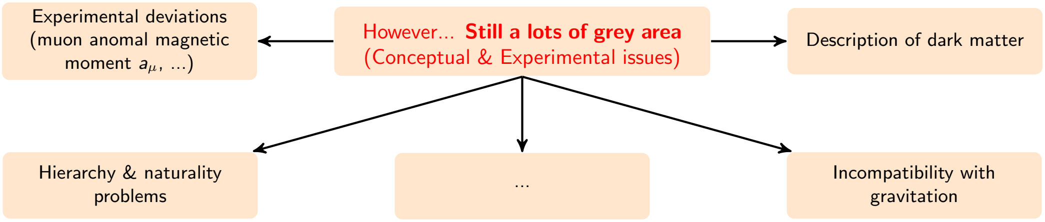

What if SM is only an effective theory of a more fundamental model ?

Severals solutions...

Extradimensions, GUT theory, Supersymmetry, Supergravity, String theory

Here: focus on **$D = 4$ $N = 1$ Supergravity & Supersymmetry**

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Supersymmetry extends the space-time symmetry with a fermion-boson symmetry

$$\mathbf{Q}|\mathbf{B}\rangle = |\mathbf{F}\rangle, \ \mathbf{Q}|\mathbf{F}\rangle = |\mathbf{B}\rangle$$

$Q^2|B\rangle \to$ translation in space-time: Supersymmetric transformation $\approx$ "$\sqrt{\text{translation in space-time}}$"

Minkowski space: (x^μ) → Superspace: ($x^\mu, \theta, \bar{\theta}$) (Fermionic extension)

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"$N = 1$" Supersymmetry: only one set of generators Q

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Chiral superfield $\Phi^i = (\phi^i, \chi^i, F^i)$

$$\Phi^i(x, \theta, \bar{\theta}) = \phi^i(x) + \sqrt{2}\theta \cdot \chi^i + \frac{1}{4}\theta \cdot \theta F^i$$

- ϕ^i: complex scalar field ($s = 0$)
- χ^i: left-handed Weyl spinor ($s = 1/2$)
- F^i: complex auxiliary field (contribution to V)

Example:
(ϕ: selectron, χ: electron), (ϕ: squark, χ: quark), ...

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Vector superfield $V^a = (A^a_\mu, \lambda^a, D^a)$

$$V(x,\theta,\bar\theta) = \theta\sigma^\mu\bar\theta A_\mu(x) + \frac{1}{4}\theta\cdot\theta D + \left(i\bar\theta\cdot\bar\theta\theta\cdot\lambda + \mathrm{h.c.}\right)$$

- A^a_μ: real vector field ($s = 1$)
- λ^a: Majorana spinor ($s = 1/2$)
- D^a: real auxiliary field (contribution to V)

Example:
(A_μ: Gluon, λ: Gluino), ...

Construction of an equivalent to $F^a_{\mu\nu}$:
spinor superfield $\mathcal{W}^a_\alpha$

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$$W(\Phi) = \frac{1}{6}\lambda_{ijk}\Phi^i\Phi^j\Phi^k + \frac{1}{2}\beta_{ij}\Phi^i\Phi^j + \alpha^i\Phi^i \quad \text{(generates Yukawa couplings \& scalar potential)}$$

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We can then compute the lagrangian of $N = 1$ supersymmetry:

$$\mathcal{L} = \int d^2\theta d^2\bar{\theta}\Phi_i^\dagger e^{-2gV}\Phi^i + \left(\frac{1}{16g^2}\int d^2\theta \mathcal{W}^{a\alpha}\mathcal{W}_\alpha^b\delta_{ab} + \int d^2\theta W(\Phi) + \text{h.c.}\right)$$

Interactions

$$\Downarrow$$

Kinetic terms for quarks, Higgs boson, ... coupled to gauge fields + supersymmetric partners

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Kinetic terms for gauge bosons & gauginos

$$\mathbf{V} = F^i F_i^\dagger + \frac{1}{2}D^a D_a = \frac{\partial W(\phi)}{\partial \phi^i}\frac{\partial \overline{W}(\phi^\dagger)}{\partial \phi_i^\dagger} + \text{gauge part} \qquad \mathcal{L}_{\text{int}} = -\frac{1}{2}\left(\lambda_{ijk}\phi^k\chi^i\cdot\chi^j + \beta_{ij}\chi^i\cdot\chi^j + \text{h.c.}\right)$$

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$$+ \frac{1}{2}\lambda_{IJK}\hat{L}^I\hat{L}^J\hat{E}^K + \frac{1}{2}\lambda'_{IJK}\hat{L}^I\hat{Q}^J\hat{D}^K + \frac{1}{2}\lambda''_{IJK}\hat{L}^I\hat{Q}^J\hat{D}^K + \mu'_I\hat{L}^I\hat{H}_U$$

Violate conservation of Baryonic or Leptonic number $\Rightarrow$ Impose aditionnal symmetry (**R-parity**)

No evidence of SUSY particles with equivalent mass as SM particles...
SUSY must be broken ! $\langle V \rangle > 0$

Two possible mechanisms in SUSY framework:

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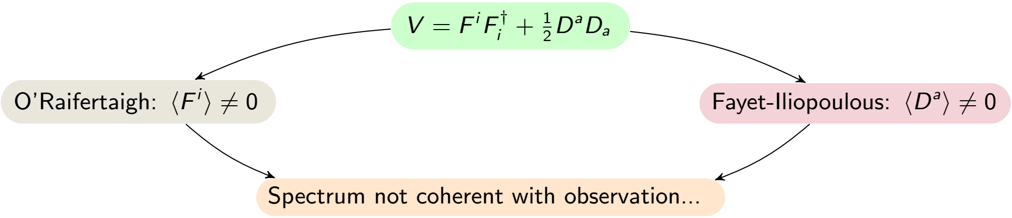

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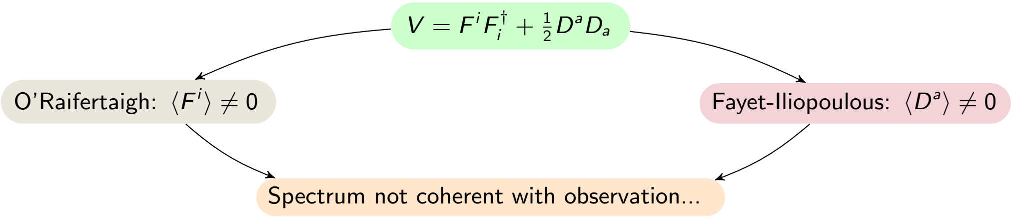

Need to describe SUSY breaking in the context of an other theory

Supergravity

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Superspace can now be curved! (Equivalent tools used in General Relativity)

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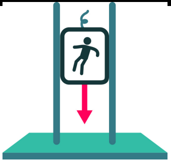

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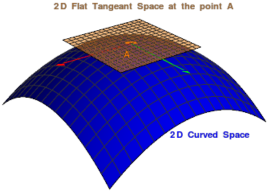

Emergence of the gravity multiplet $(e_{\tilde{\mu}}{}^{\mu}, \psi^{\alpha}_{\tilde{\mu}}, b_{\mu}, M)$

$e_{\tilde{\mu}}{}^{\mu}$: graviton, $\psi^{\alpha}_{\tilde{\mu}}$: gravitino, b_{μ} & M: real vector & complex scalar auxiliary fields

Chiral (ϕ^i, χ^i, F^i) & Vector $(v^a_{\mu}, \lambda^a_{\alpha}, D^a)$ superfields **can be extended to curved superspace:**

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$=$ **SUGRA model**

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$N = 1$ Supergravity:

$$\mathcal{L}_{SUGRA} = \int d\mathbf{\Theta}^2\mathcal{E}\left\{\frac{3}{8}\left(\bar{\mathcal{D}}\cdot\bar{\mathcal{D}} - 8\mathcal{R}\right)e^{-\frac{1}{3}\mathbf{K}(\mathbf{\Phi}_i^\dagger \mathbf{e}^{-2gV},\mathbf{\Phi}^i)} + \frac{1}{16g^2}\mathbf{h}_{ab}(\mathbf{\Phi}^i)\mathcal{W}^{\alpha a}\mathcal{W}_\alpha^b + W(\Phi)\right\} + \text{h.c.}$$

$\mathbf{\Theta} \neq \theta$: introduce to facilitate calculation in curved superspace, $\mathcal{E}$: Chiral density (Jacobian), $\mathcal{R}$: chiral superfield

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When gravity is neglected: $\lim_{m_p\to\infty}\mathcal{L}_{SUGRA} = \mathcal{L}_{SUSY} + \mathcal{L}_{pure\ supergravitation}$

Robin Ducrocq, Michel Rausch de Traubenberg, and Mauricio Valenzuela. "A pedagogical discussion of N = 1 four-dimensional supergravity in superspace". Modern Physics Letters A 36.16 (2021), p. 2130015

From SUSY lagrangian to SUGRA lagrangian

$$V_{SUSY} = \frac{\partial W(\phi)}{\partial \phi^i} \frac{\partial \overline{W}(\phi^\dagger)}{\partial \phi_i^\dagger} + \text{gauge part} \Rightarrow V_{SUGRA} = e^{K/m_p^2}\left(\mathcal{D}_i W (K^{-1})^i{}_{j^*} \mathcal{D}^{j^*} \bar{W} - \mathbf{\frac{3}{m_p^2} |W|^2}\right) + \text{gauge part}$$

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Minimum $\langle V \rangle$ can be positive, negative or **null** $\neq$ SUSY

Key point in cosmology for a vanishing cosmological constant $\langle V \rangle = 0$

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EW Breaking (Standard Model)

BEH mechanism

$\Downarrow$

Goldstone boson

$\Downarrow$

Massive Z & W bosons

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Supergravity must be broken... equivalent mechanism as in the Standard Model

EW Breaking (Standard Model)

BEH mechanism

$\Downarrow$

Goldstone boson

$\Downarrow$

Massive Z & W bosons

Supergravity Breaking

Super-BEH mechanism

$\Downarrow$

Goldstino

$\Downarrow$

Massive gravitino $\mathbf{m_{3/2} = \frac{1}{m_p^2} e^{K/(2m_p^2)} \langle W \rangle}$

Outline

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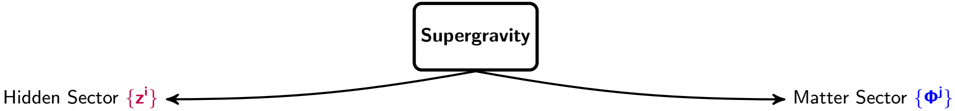

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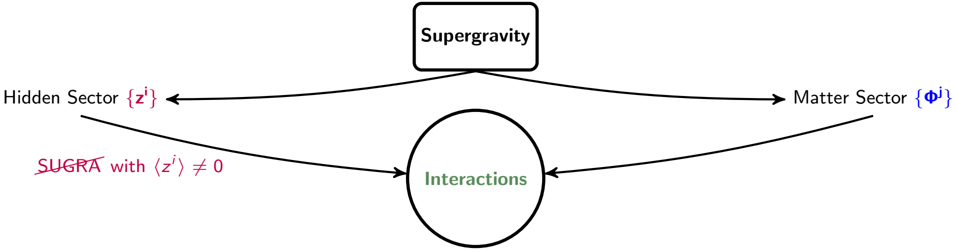

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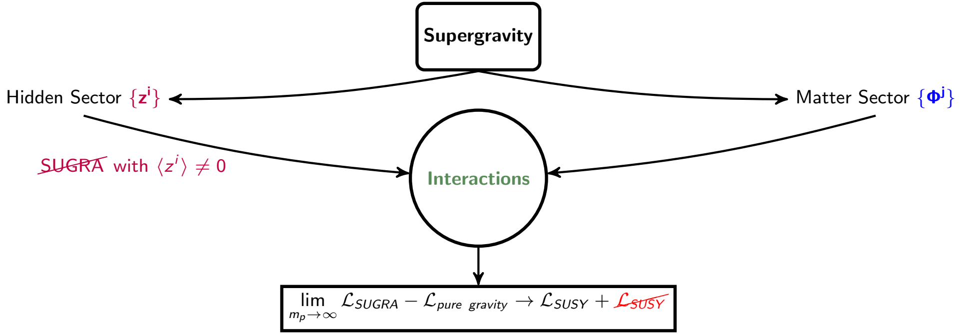

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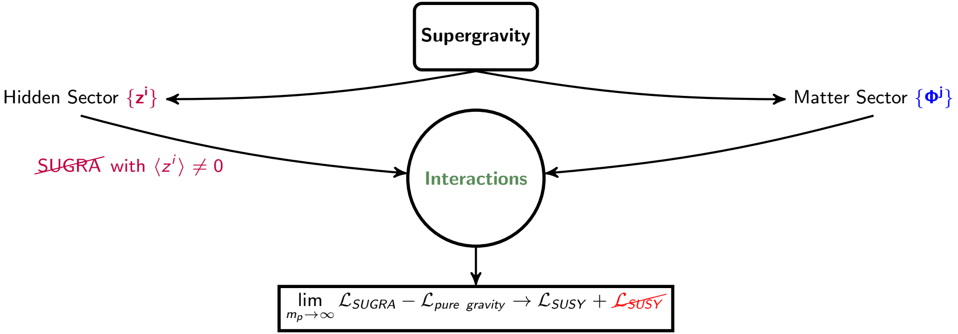

In most of all phenomenological/experimental analysis

Add SUSY breaking terms $\mathcal{L}_{\not{SUSY}}$ without specifying the breaking mechanism

Introduce in an *ad-hoc* way in the lagrangian

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Assume R-parity conserved:

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$V_{\not{SUSY}} = V_{SOFT}$
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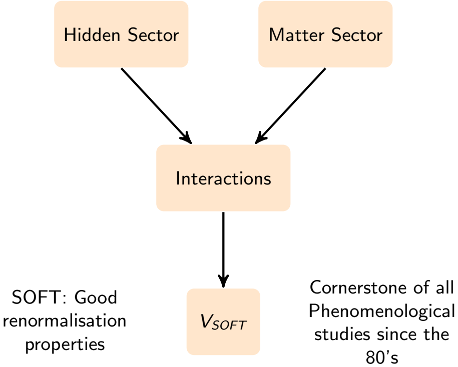

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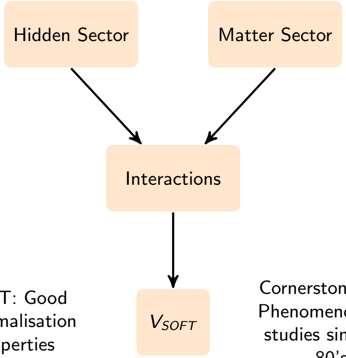

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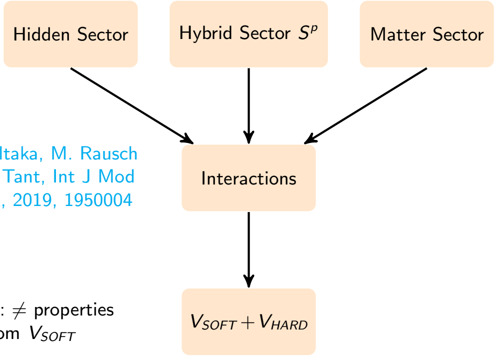

G. Moultaka, M. Rausch and D. Tant, Int J Mod Phys A, 2019, 1950004

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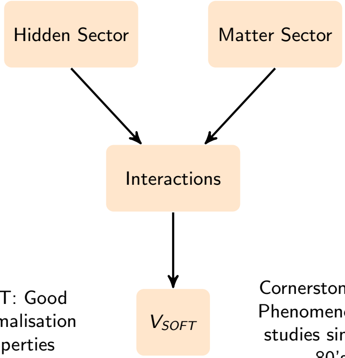

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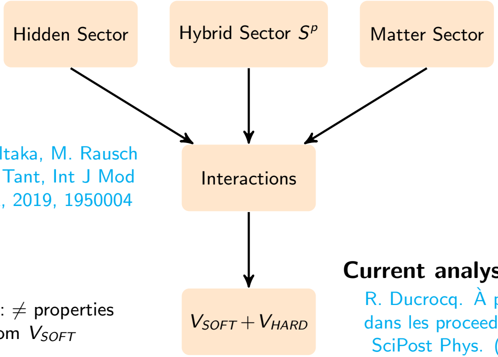

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Current analysis...

R. Ducrocq. À paraître dans les proceedings de SciPost Phys. (2023)

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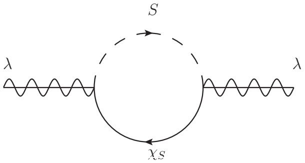

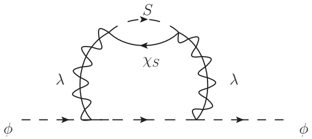

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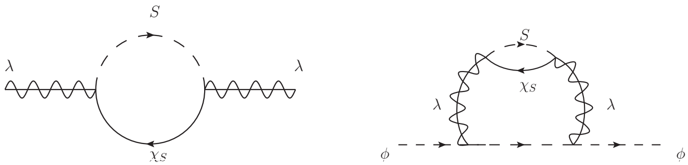

Phenomenological implication:

Gravitino mass: $m_{3/2} \sim \frac{M^2_{SUSY}}{m_p} \Rightarrow$ Gravitino is the LSP (*Lightest Supersymmetric Particle*)

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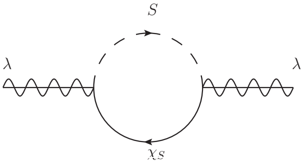

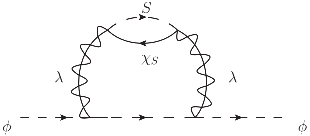

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There exist other mechanisms (not relevant for this discussion)...

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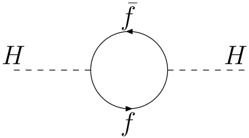
Analysing the one-loop contributions on m_h in the Standard Model:



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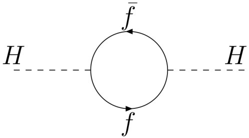

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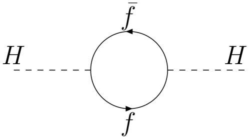

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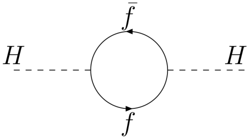

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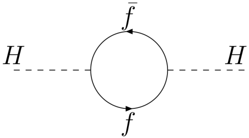

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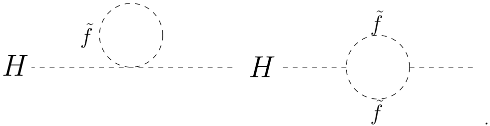

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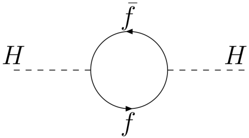

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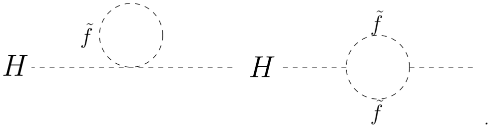
Dangerous contributions cancel out!

SUSY protect the scalar sector

Contributions proportional to $\log \Lambda$ or suppressed by an intermediate energy scale



MSSM: Complicated to analyse **high dimensional parameters space**

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(5 parameters)

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Other strategy:

bottom-up = Analysing a simplified model & reinterpret the results in cMSSM, pMSSM, ...

Outline

1. Introduction
2. Quick review of $N = 1$ Supersymmetry and $N = 1$ Supergravity
   - $N = 1$ Supersymmetry
   - $N = 1$ Supergravity
3. Supersymmetry Breaking
   - General aspects of SUSY Breaking
   - Mechanisms of SUSY Breaking
4. Phenomenology of the MSSM
   - Particle spectrum of the MSSM
   - SUSY as solution of hierarchy & naturality problem
   - MSSM analysis strategy
5. Constraints from experimental measurements
   - Higgs Boson mass near 125 GeV
   - Relic density of Dark Matter $\Omega_{DM} h^2$
   - Direct searches of stop squark $\tilde{t}$ at the LHC
6. Conclusion

SUSY & SUGRA models constrain by a lot of measurements

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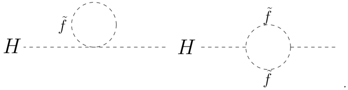
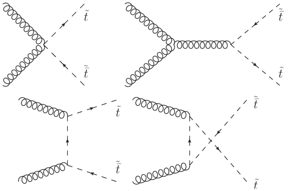
Higgs boson in the Standard model



Direct detection on colliders



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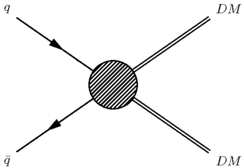
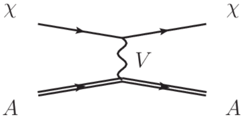
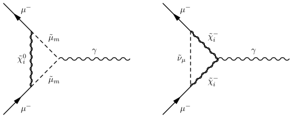


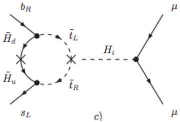
DM detection rates (σ_{SI}, σ_{SD})



Muon anomal magnetic moment a_μ



Flavor physics



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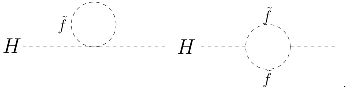

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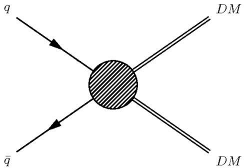

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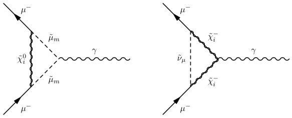

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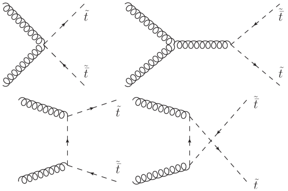

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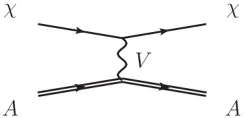

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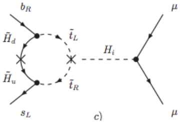

Cannot talk about all these subjects... ⇒ Only choose some for this discussion

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Two Higgs doublets $H_U = (H_U^0, H_U^+)^T$ & $H_D = (H_D^-, H_D^0)^T$ $\Rightarrow$ lead to two scalar particle h **(SM-like)**, H

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More & more difficult to get $\mathbf{m_h = 125}$ GeV in the MSSM (but not impossible...)

A more natural solution: **NMSSM**

A possible solution: **NMSSM**

Idea:

Introducing a new singlet superfield $\hat{S} = (S, \tilde{S}, F_S)$ **(**$\langle S \rangle \neq 0$**)**

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Three mass states h^1, h^2, h^3, **Two mass states** A^1, A^2, $\tilde{\chi}_i^0$ **(**$i = 1, \ldots, 5$**)**

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C. Hugonie, U. Ellwanger, MPLA, 2007

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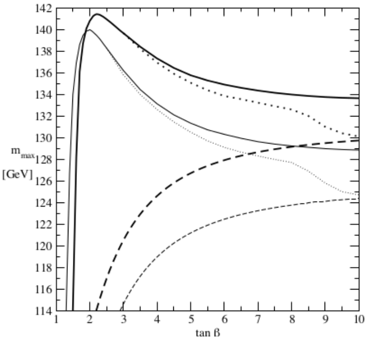

Figure 1: Upper bound on the lightest Higgs mass in the NMSSM for $m_{top} = 178$ GeV (thick full line: m_A arbitrary, thick dotted line: $m_A = 1$ TeV) and $m_{top} = 171.4$ GeV (thin full line: m_A arbitrary, thick dotted line: $m_A = 1$ TeV) and in the MSSM (with $m_A = 1$ TeV) for $m_{top} = 178$ GeV (thick dashed line) and $m_{top} = 171.4$ GeV (thin dashed line) as obtained with NMHDECAY as a function of $\tan\beta$. Squark and gluino masses are 1 TeV and $A_{top} = 2.5$ TeV.

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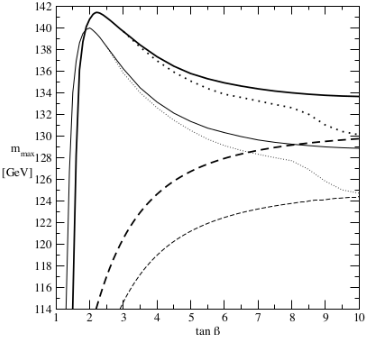

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Singlet superfield S also helps to resolve another issue: **Dark matter**

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Dark Matter candidate

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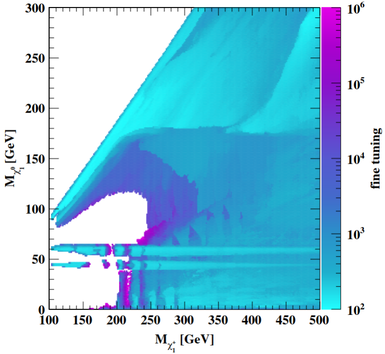
Fine-tuning Δ_{BG}: Tools for searching natural configurations



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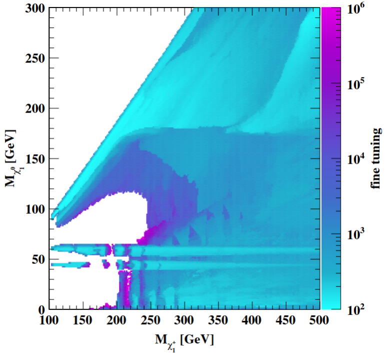

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In Supergravity with GMSB: Gravitino ψ_μ is naturally the LSP & natural candidate for DM!

Computation of $\Omega_{3/2}h^2$ more complex (several contributions)

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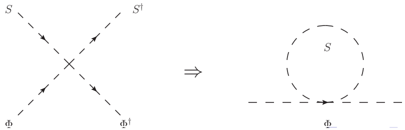
New solutions in Gravity-Mediated SUSY Breaking R. Ducrocq. À paraître dans les proceedings de SciPost Phys. (2023)

Naturally introduce two "hybrid" fields $\{S'^1, S'^2\}$

$V_{SOFT} + V_{HARD}$: New effects at tree & loop level

$Q_{i,p}{}^p \phi^i \phi_i^\dagger \mathbf{S^p S_p^\dagger}$: Close the **S-loop**



Why stop squark?

High coupling on the Standard Model through Higgs boson
LHC: hadronic colliders: $\tilde{t}$ is studied a lot in plenty of scenarios

Direct searches of stop squark $\tilde{t}$ at the LHC

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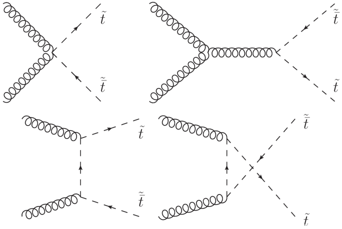

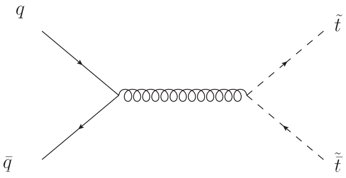

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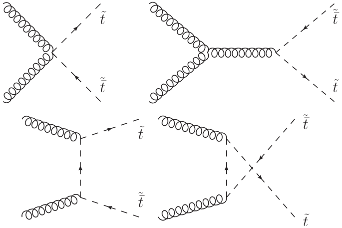
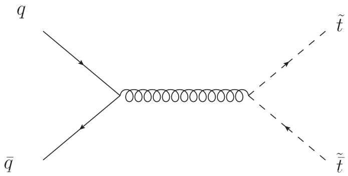




Three differents topologies

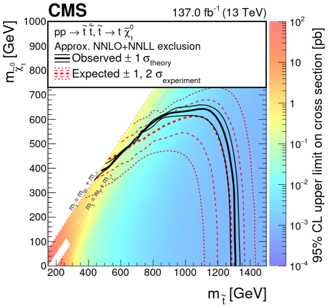
Prompt searches
top quark produced close to the primary interaction
$\to$ prompt top quark

Long-lived Particle (LLP) decaying in the detector
top quark produced in the detector but far from primary interaction
$\to$ displaced top quark

Heavy Stable Charged Particle (HSCP)
top quark produced outside the detector

Analysis in simplified models ≈ Generic SUSY models...

No evidence of stop squark (or SUSY) at the LHC...
Can only apply limits on masses or couplings



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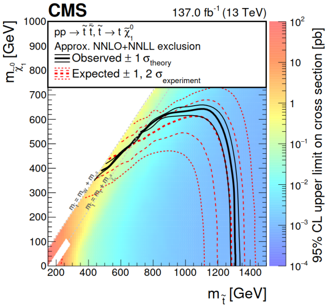

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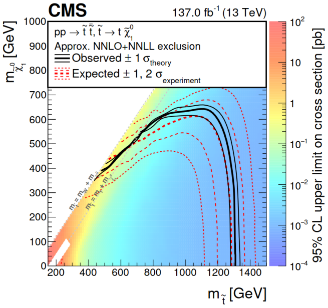

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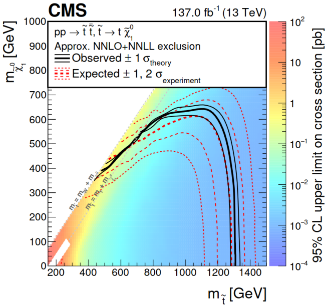

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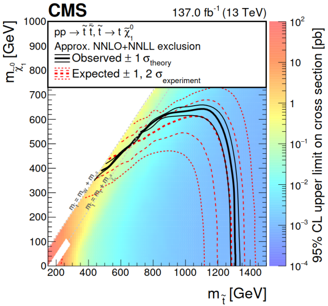

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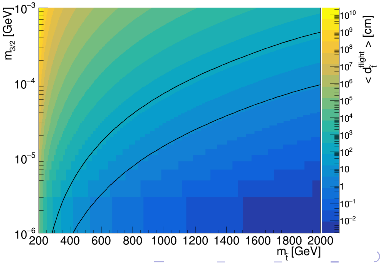

Outline

1. Introduction
2. Quick review of $N = 1$ Supersymmetry and $N = 1$ Supergravity
   - $N = 1$ Supersymmetry
   - $N = 1$ Supergravity
3. Supersymmetry Breaking
   - General aspects of SUSY Breaking
   - Mechanisms of SUSY Breaking
4. Phenomenology of the MSSM
   - Particle spectrum of the MSSM
   - SUSY as solution of hierarchy & naturality problem
   - MSSM analysis strategy
5. Constraints from experimental measurements
   - Higgs Boson mass near 125 GeV
   - Relic density of Dark Matter $\Omega_{DM} h^2$
   - Direct searches of stop squark $\tilde{t}$ at the LHC
6. Conclusion

$N = 1$ Supersymmetry & Supergravity

Natural extension of the Standard Model with fermion/boson symmetry $\Rightarrow$ New particles
Must be broken for $m_{SUSY} > m_{SM}$ $\Rightarrow$ Naturally broken in Supergravity
Naturally solve the hierarchy & naturality problems

Simple extensions of the Standard Model: MSSM & NMSSM

SUSY contributions help to recover experimental measurements:
Higgs boson mass, Dark matter relic density $\Omega_{DM}h^2, \ldots$

Constrained by direct searches...

Two approaches: **top-down** & **bottom-up** (usually used at collider experiments)

SUSY searches continue... (LHC, BelleII) and will continue (HL-LHC & FCC project)

Disclaimer

This was not a complete review of $N = 1$ SUSY & SUGRA models
A lot of subjects have not been mentioned:

- Cosmological implications
- Specific solutions in SUGRA (No-Scale, ...)
- Impact of SUSY in flavor physics
- ...

Goal:

Present the basis of $N = 1$ $D = 4$ Supersymmetry & Supergravity and discuss some phenomenological and experimental subjects in this context

We can discuss on such subjects after this presentation

BACK-UP

Construction of a $N = 1$ supersymmetric model: Interactions

$$\mathcal{L} = \int d^2\theta d^2\bar{\theta}\Phi_i^\dagger e^{-2gV}\Phi^i + \left(\frac{1}{16g^2}\int d^2\theta \mathcal{W}^{a\alpha}\mathcal{W}_\alpha^b\delta_{ab} + \int d^2\theta W(\Phi) + \text{h.c.}\right)$$

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Elimination of the auxiliary fields $\{F^i, D^a\}$: leads to the scalar potential:

$$\begin{aligned} V &= F^i F_i^\dagger + \frac{1}{2}D^a D_a \\ &= \frac{\partial W(\phi)}{\partial\phi^i}\frac{\partial\overline{W}(\phi^\dagger)}{\partial\phi_i^\dagger} + \frac{1}{2}g^2(\phi^\dagger T^a\phi)(\phi^\dagger T^b\phi)\delta_{ab} \end{aligned}$$

Scalar potential is positively defined: $V \geq 0$!

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$\phi - \chi$ **interactions terms from the Superpotential:**

$$\begin{aligned} \mathcal{L}_{int.} &= -\frac{1}{2}\frac{\partial^2 W(\phi)}{\partial\phi^i\partial\phi^j}\chi^i\cdot\chi^j + \text{h.c.} \\ &= -\frac{1}{2}\left(\lambda_{ijk}\phi^k\chi^i\cdot\chi^j + \beta_{ij}\chi^i\cdot\chi^j + \text{h.c.}\right) \end{aligned}$$

Can reproduce the yukawa couplings equivalent to the Standard Model!

Need to choose W & K such as $\lim_{m_p \to \infty} \mathcal{L}_{SUGRA} \to \mathcal{L}_{SUSY} + \mathcal{L}_{\not{SUSY}}$: $\begin{cases} W(\Phi, \zeta) & = \sum_{n=0}^{N} m_p^n W_n(\Phi, \zeta) \\ K(\Phi, \Phi^\dagger, \zeta, \zeta^\dagger) & = \sum_{n=0}^{M} m_p^n K_n(\Phi, \Phi^\dagger, \zeta, \zeta^\dagger) \end{cases}$

Requirement

At least one field from Hidden sector with $\langle z \rangle \sim \mathcal{O}(m_p)$ and $\langle \Phi \rangle \ll m_p$

Visible sector fields interactions **only present in V as m_p^{-n} with $n \geq 0$**

$$V = e^{K/m_p^2}\left(\mathcal{D}_i W (K^{-1})^i{}_{j^*} \mathcal{D}^{j^*} \bar{W} - \frac{3}{m_p^2}|W|^2\right)$$

Simple case: Found two solutions:

Soni-Weldon solution (known since the 80's)

$$K(z, z^\dagger, \Phi, \Phi^\dagger) = m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger$$

$$W(z, \Phi) = m_p^2 W_2(z) + m_p W_1(z) + W_0(z, \Phi)$$

New solutions (new field sector S)

$$K(z, z^\dagger, \Phi, \Phi^\dagger) = m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger + S^p S_p^\dagger$$

$$W(z, \Phi) = m_p W_1(z, S) + W_0(z, S, \Phi) \text{ with } \left\{ \begin{array}{l} W_1(z, \Phi) = W_{1,0}(z) + W_{1,p}(z) \mu_p^* S^p \\ W_0(z, \Phi) = W_{0,p}(z) S^p + W_0(z, \mathcal{U}, \Phi) \end{array} \right\}$$

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Assuming superpotential $W_0(z, \Phi) = \alpha_i(z)\Phi^i + \frac{1}{2}\beta_{ij}(z)\Phi^i\Phi^j + \frac{1}{6}\lambda_{ijk}(z)\Phi^i\Phi^j\Phi^k$

At low energy:

$$V = V_{SUSY} + V_{SOFT} + \Lambda m_p^2$$
$$V_{SOFT} = C_i\Phi^i + \frac{1}{2}B_{ij}\phi^i\phi^j + \frac{1}{6}A_{ijk}\phi^i\phi^j\phi^k + m_{\phi^i}^2\phi^i\phi_i^\dagger$$

"SOFT": Good properties of renormalisation (logarithmic corrections $\log\Lambda$)

Relation between superpotential and SOFT-SUSY Breaking terms:

$W(\Phi)$		V_{SOFT}
α_i	$\rightarrow$	C_i
β_{ij}	$\rightarrow$	B_{ij}
λ_{ijk}	$\rightarrow$	A_{ijk}

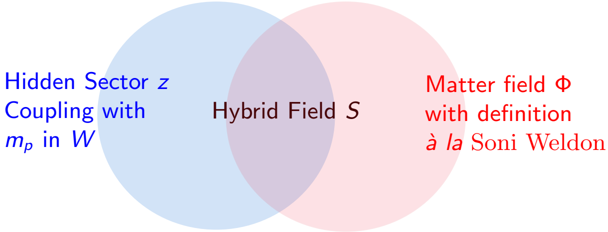
All actual studies based on these solutions!

Non-Soni-Weldon solutions

New solutions

$$K(z, z^\dagger, \Phi, \Phi^\dagger) = m_p^2 z^i z_i^\dagger + \Phi^a \Phi_a^\dagger + S^p S_p^\dagger$$

$$W(z, \Phi, S) = m_p W_1(z, S) + W_0(z, S, \Phi) \text{ with } \left\{ \begin{array}{l} W_1(z, \Phi) = W_{1,0}(z) + W_{1,p}(z)\mu_p^* S^p \\ W_0(z, \Phi) = W_{0,p}(z) S^p + W_0(z, \mathcal{U}, \Phi) \end{array} \right\}$$



Properties of S field:

- S Singlet under visible sector gauge group
- Direct coupling Matter fields Φ / Hybrid fields S through $\mathcal{U} = \mu^1 S^2 - \mu^2 S^1$ with μ^p also present in W
- S and Φ: Matter Sector $\Rightarrow \langle S \rangle$ and $\langle \Phi \rangle \ll m_p$

Topologies of SUSY-breaking terms:

New solutions

At low energy: $V = V_{SUSY} + V_{SOFT} + V_{HARD} + \Lambda m_p^2$

$$V_{HARD} = \Big(\big(D_i^p \phi^i + \frac{1}{2} E_{ij}^p \phi^i \phi^j + \frac{1}{6} F_{ijk}^p \phi^i \phi^j \phi^k \big) S_p^\dagger + G_{ijk}{}^l \phi^i \phi^j \phi^k \phi_l^\dagger + H_{ijp}{}^l \phi^i \phi^j S^p \phi_l^\dagger + \text{h.c.} \Big)$$
$$+ Q_{i,p}{}^q \phi^i \phi_i^\dagger S^p S_{\dagger q} + T_{i,p}{}^q S^p S_p^\dagger S^r S_{\dagger q}$$

"HARD": At first glance, problematic properties of renormalisation (quadratic corrections Λ^2)... **BUT**:
Parametrically suppressed by an intermediate energy scale $\mathbf{M < m_p}$

Correspondance SOFT/HARD Breaking terms ("**gravitino-rule**"):

V_{SOFT}		V_{HARD}
C_i	$\rightarrow$	D_i^p
B_{ij}	$\rightarrow$	E_{ij}^p
A_{ijk}	$\rightarrow$	F_{ijk}^p

SUSY is widely searched at the LHC

Searches of SUSY at LHC
(MSSM & extensions)

SUSY searches at LHC

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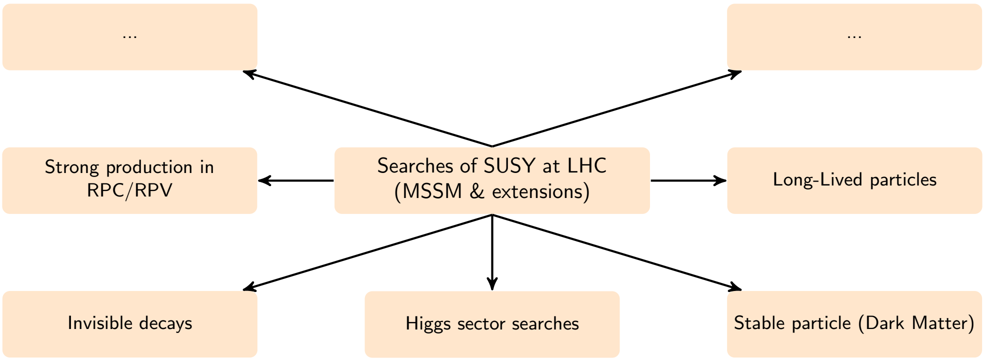

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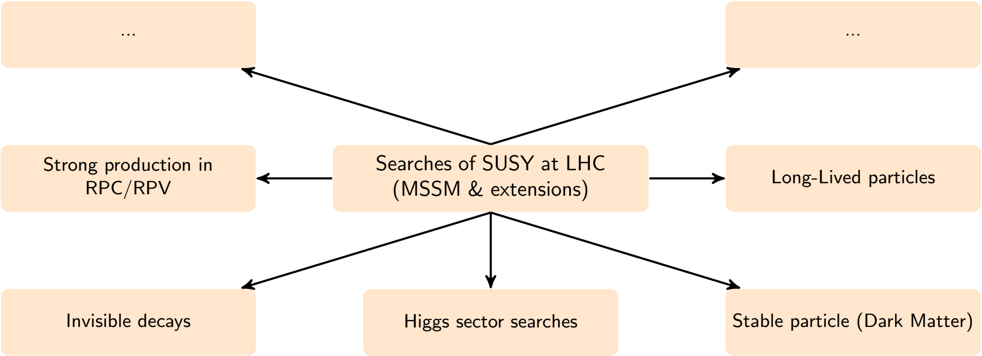

No detection... only limits on masses & couplings (usually model dependant...)

Too many searches area $\Rightarrow$ **Only focus on some searches: stop squark $\tilde{t}$**

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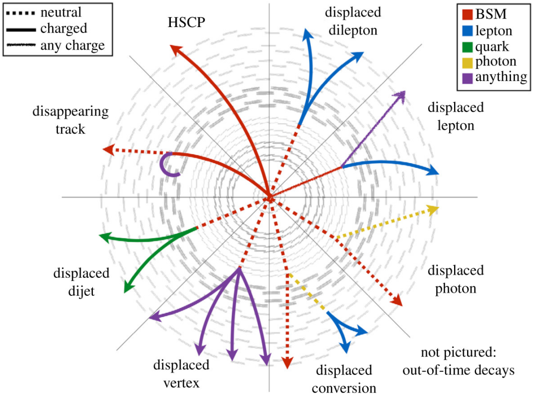
Several topologies of signatures



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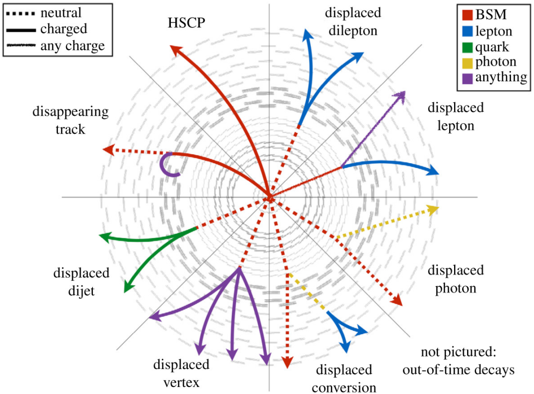
Example: **displaced top quarks**

In SUSY or SUGRA:

MSSM with GMSB: $pp \to \tilde{t}_1 \bar{\tilde{t}}_1$ $(\tilde{t}_1 \to \psi_\mu t)$

MSSM RPV: $pp \to \tilde{t}^1 \bar{\tilde{t}}^1 \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$ $(\tilde{\chi}_1^0 \to$ RPV decay)



MSSM RPC with Gauge-Mediated SUSY Breaking:

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Gravitino ψ_μ is naturally the Lightest SUSY Particle (LSP): $m_{3/2} = \frac{M^2_{SUSY}}{m_p}$ (Planck-suppressed!)

Gravitino-matter couplings naturally Planck-suppressed: Long-lived with NLSP (Next-To-Lightest SUSY Particle)

If stop $\tilde{t}_1$=NLSP: $\not{E}_T$ source from gravitinos & secondary vertices with top production

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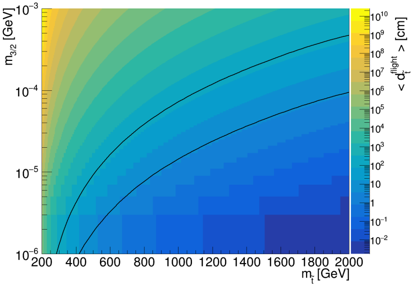

Definition of benchmarks $(m_{\tilde{t}}, m_{3/2})$

Generation & analysis of processes with several softwares (MadGraph, Pythia, ...)

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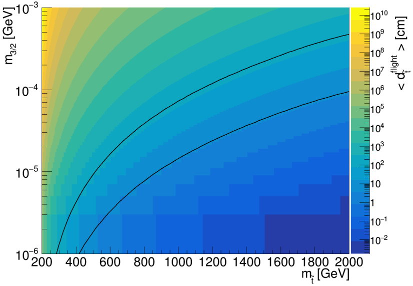

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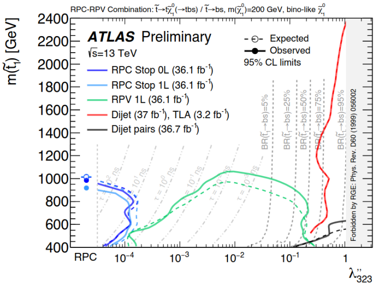
Case of RPV scenarios

High multiplicity on jets or leptons in the final state



Direct searches of stop squark $\tilde{t}$ at the LHC

What if the stop quark decay outside the detector?

HSCP: Heavy Stable Charged Particle

No secondary vertices:

Use energy-loss in the layers of detection **(Specific signatures not present in SM)**

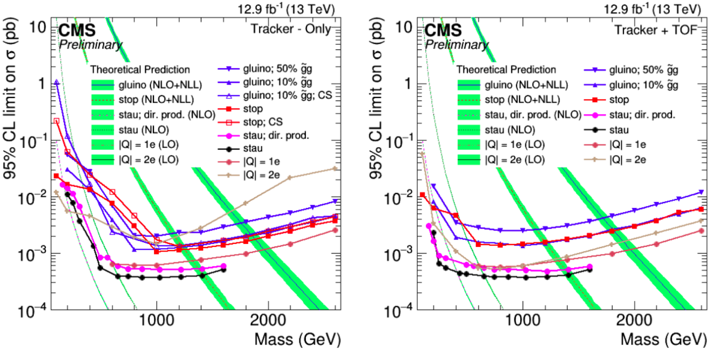
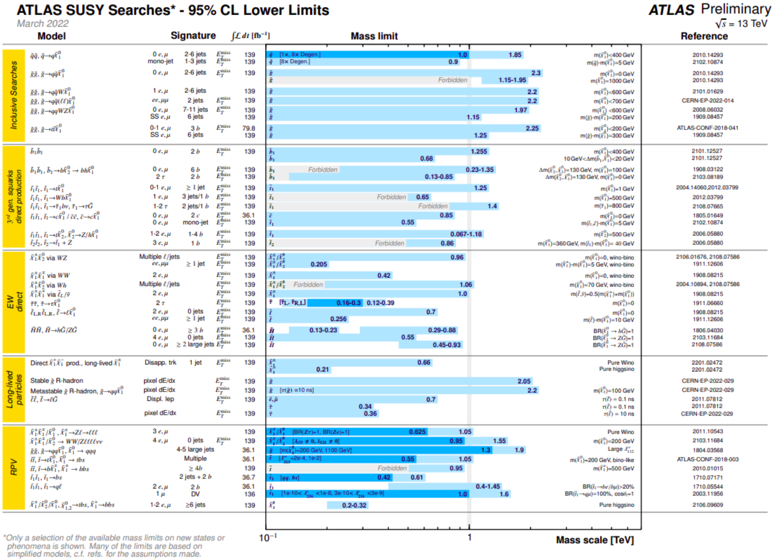
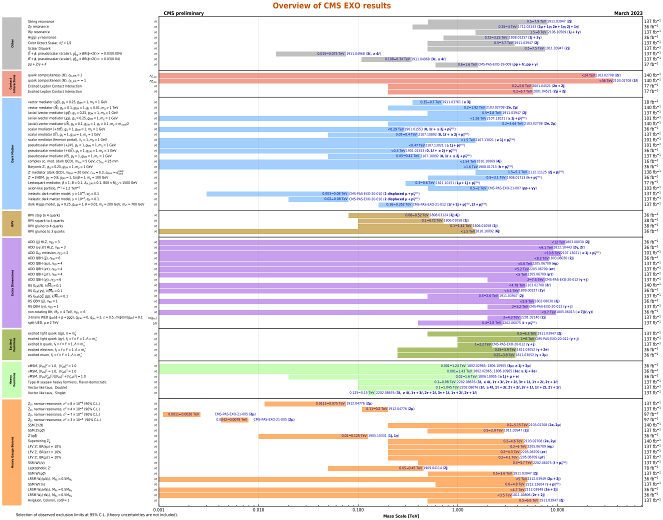


Figure 3: Cross section upper limits at 95% CL on various signal models for the tracker-only analysis (left column) and tracker+TOF analysis (right column) at $\sqrt{s} = 13\,\text{TeV}$. In the legend, 'CS' stands for charged suppressed interaction model.

Conclusion


ATLAS SUSY Searches* - 95% CL Lower Limits
March 2022
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model
Signature
$\int \mathcal{L}\,dt$ [fb^{-1}]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
10^{-1}
1
Mass scale [TeV]

Conclusion



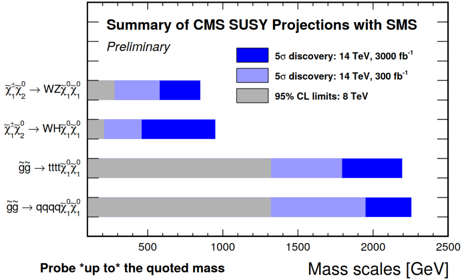
Overview of CMS EXO results
CMS preliminary
March 2023
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).
Mass Scale [TeV]

What about the futur?

SUSY will also be constrained from futur colliders experiments

HL-LHC project

Goal: 300 $\text{fb}^{-1} \rightarrow 3000\ \text{fb}^{-1}$



More data: seek higher mass and allow precision measurements

FCC project

FCC-ee, FCC-eh, FCC-hh

High luminosity, high-energy collider FCC-ee

e^+e^- collisions at Z mass $\sqrt{s} = m_Z$

e^+e^- collisions at h mass $\sqrt{s} = m_h$

...

Energy-frontier collider FCC-hh

Collisions at $\sqrt{s} = 100$ TeV with 20 ab^{-1} of data

Deep-inelastic scattering (DIS) in FCC-eh

Energy frontier in DIS