Effectives approaches within the MSSM and Beyond : Applications to Higgs physics and Dark Matter observables

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LAPTh
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PhD defence at Annecy

Outline

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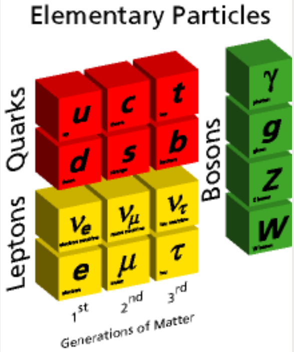
Particle Physics : where do we stand

- The Standard Model for particle physics



- Matter : Three families of quark pairs and lepton pairs
- Gauge : Three interactions : $\gamma, W/Z, G$
- A symmetry breaking mechanism
  - Non-zero masses for Z, W
  - A scalar particle H : the Higgs boson

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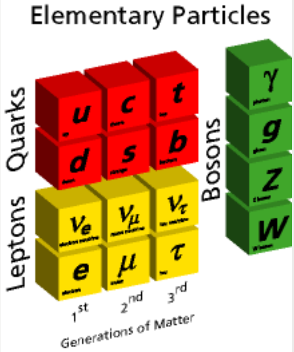

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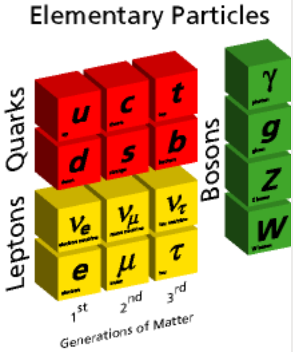

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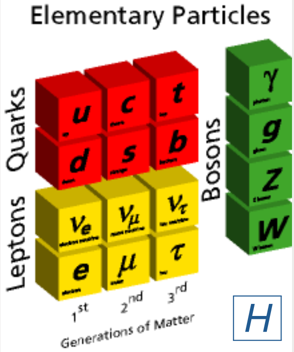

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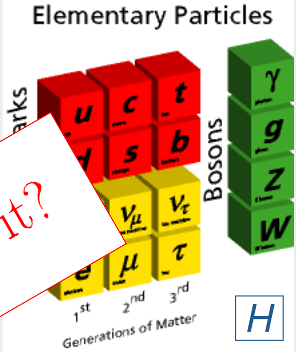

So, is this it?

- Matter [illegible]milies of quark pairs and lepton pairs
- Gauge : Three interactions : $\gamma, W/Z, G$
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The SM Higgs?

Why Standard Model may not be enough

- There are hints that Standard Model is only an approximation.
- Theoretical side
    - Could be part of a unified theory (GUTs)
    - Does not explain the wide scale between all fermion masses (flavour hierarchy)
    - Naturalness : Higgs mass suspiciously affected by possible heavy particles
- Experimental side
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Beyond the Standard Model : Supersymmetry

- Fields ϕ ➙ Superfields Φ
  - Each Standard Model particle has a superpartner
  - Extended Higgs sector : $h/H/A^0$ and H^+ new parameters t_β, M_{A^0}
- Naturalness : Supersymmetry protects the running Higgs mass
- Dark Matter : superpartners of γ, Z, h, called neutralinos ($\tilde{\chi}_1^0$) are good candidates.
  - They are neutral, massive (Supersymmetry breaking) and one is stable if R-parity is assumed

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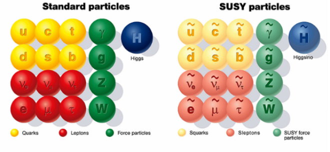

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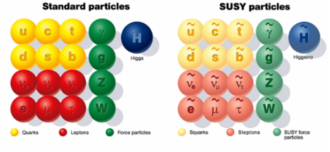

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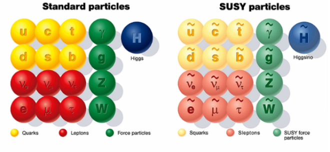

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The goal of the thesis (I)

- Constraining Supersymmetry through Dark Matter observables.
- Constraint on Relic Density

$$\Omega h^2 = 0.1126 \pm 0.0036 \quad \text{(WMAP)} \qquad \rightarrow \qquad \Delta_{exp} = 3\%$$

- Precise constraint on Supersymmetry
  - Requires a one-loop computation
- However, most scans in Supersymmetry are tree-level.
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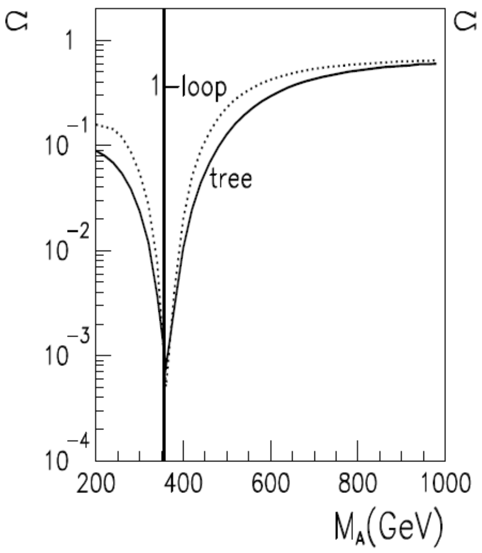

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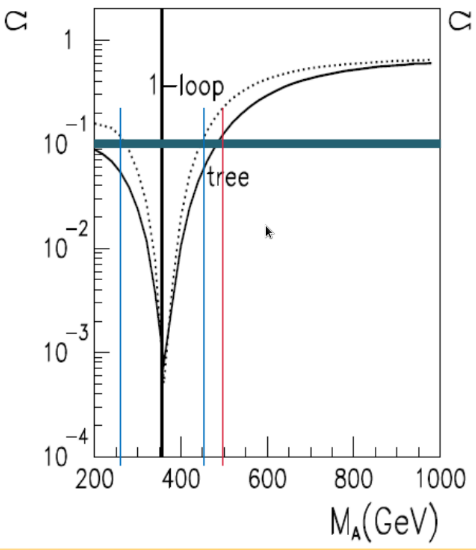

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- Higgs sector of the MSSM is constrained
  - Tension between Naturalness, and a possible heavy Higgs.
  - What if we had found a heavier Higgs ($m_h > 150$ GeV)?
  - What couplings can be allowed with $m_h = 125$ GeV?
- Supersymmetry could well be non-minimal.
  - Account for a new sector coupled to Higgses
  - Allows for a non minimal Higgs sector ➙ BMSSM
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Effective approach

- Equivalence Low-energy theory ⇔ Full theory
- Possibility for a generic set-up with $\delta\mathcal{L} = \sum_i c_i O_i$
  - The O_i respect all symmetries of the low energy theory
- Analogy with LEP

Effective terms $s_w(Q), M_Z(Q), \ldots$

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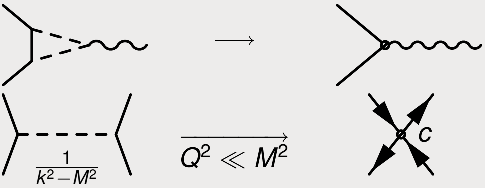

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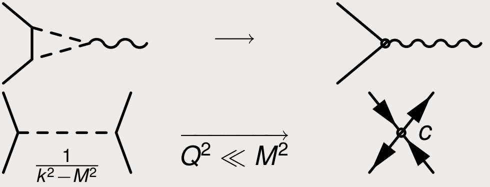

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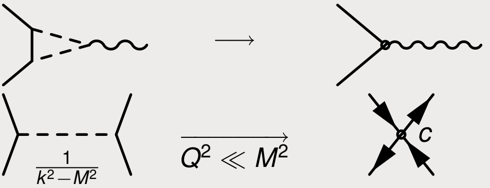

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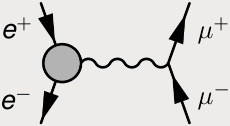

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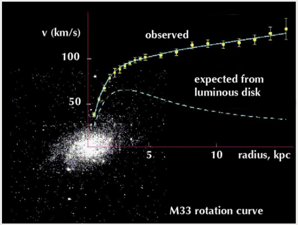
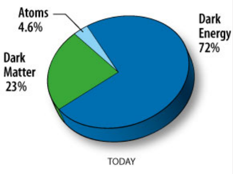
The Dark Matter problem

- What do we need Dark Matter for?



CMB →



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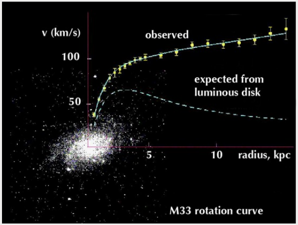

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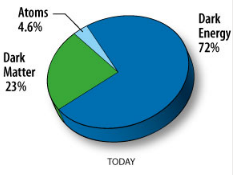

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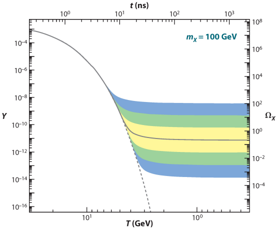

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Phenomenology of neutralinos

- Properties of $\tilde{\chi}_1^0$ depend on its nature

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix} = Z_n \begin{pmatrix} -i\tilde{B} \\ -i\tilde{W}^3 \\ \tilde{h}_1^0 \\ \tilde{h}_2^0 \end{pmatrix}$$

- Depending on $|Zn_{11}|^2$, $|Zn_{12}|^2$ and $|Zn_{13}|^2 + |Zn_{14}|^2$
  - Bino case $M_1 \ll M_2, |\mu|$
  - Wino case $M_2 \ll M_1, |\mu|$
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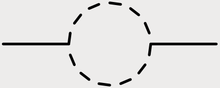
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \bar{f}f$	$\Omega h^2 > 1$
$\tilde{\chi}_1^0\tilde{\chi}_1^+ \to ff'$	$\Omega h^2 \ll 1$
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to VV$	$\Omega h^2 \ll 1$

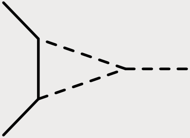
One-loop computations

- One-loop diagrams

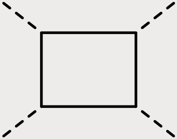


Self energy

Field renormalisation



Vertices



Boxes

- Regularisation : $\mathcal{A} = \mathcal{A}_0 + \frac{1}{\epsilon}\mathcal{A}_1 + \cdots$
  - Dimensional Regularisation : Divergence is $1/\epsilon$ in the limit $\epsilon \to 0$
- Renormalisation : $g = g_0 + \frac{1}{\epsilon} g_1 + \cdots$

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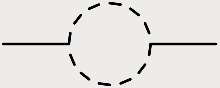

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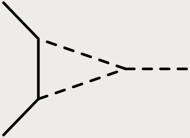

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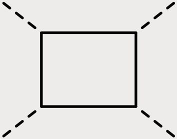

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The renormalisation scheme

The OS scheme : $\delta\mathcal{A} = 0$

e.g. for a mass, the sum of self-energies and counterterms vanishes.

- δM_1 usually renormalised on $m_{\tilde{\chi}^0_1}$
  - But if $|Z_{n11}|$ is small, it becomes ill-suited and δM_1 is large.
  - "Bino-like" scheme : δM_1 is renormalised on the most bino-like of the four neutralinos.
- t_β can be renormalised in different ways
  - m_H
  - $A^0 Z$ transition (DCPR scheme)
  - $\overline{DR}$
  - $A^0 \to \bar{\tau}\tau$
- Accuracy check : we will change the renormalisation scheme to assess the precision of the full one-loop result.

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Using an effective approach versus full one-loop computation

- Full one-loop computation nearly not used at all!
  - Complications (need for a renormalisation scheme, no fully automated code)
  - Computing time issue : $\tau_{\text{one-loop}}/\tau_{\text{tree-level}} \sim 10^2 - 10^4$
  - Supersymmetric studies based on ~ 100 processes
    - For each process, 1000 one-loop diagrams
- Effective approach : tree-level computation with effective operators
  - $\tilde{\chi}_1^0 \tilde{f} f$
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  - $Z \bar{f} f$

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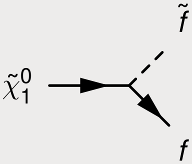
Determination of effective coefficients

- The $\tilde{\chi}_1^0 \tilde{f} f$ vertex



  - Considering only fermions and sfermions, there are no loops involved
  - Hence the one-loop coupling $\tilde{\chi}_1^0 \tilde{f} f$ is physical (hence finite)

$$\left(g_2 Y_f, g_1 \tau_f^3, y_{1f}, y_{2f}\right) Z_n$$
$$\downarrow$$
$$\left((g_2 + \delta g_2 Y_f, (g_1 + \delta g_1)\tau_f^3, y_{1f} + \delta y_{1f}, y_{2f} + \delta y_{2f}\right) Z_n(1 + \delta Z_n)$$

- Requires that all δX quantities are computed with only fermions/sfermions running in the loop.

Hollik et al. (JHEP (2002))

Determination of effective coefficients

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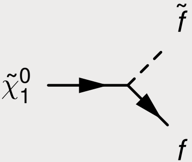


  - Considering only fermions and sfermions, there are no loops involved
  - Hence the one-loop coupling $\tilde{\chi}_1^0 \tilde{f} f$ is physical (hence finite)

$$\left(g_2 Y_f, g_1 \tau_f^3, y_{1f}, y_{2f}\right) Z_n$$
$$\downarrow$$
$$\left((g_2 + \delta g_2 Y_f, (g_1 + \delta g_1)\tau_f^3, y_{1f} + \delta y_{1f}, y_{2f} + \delta y_{2f}\right) Z_n(1 + \delta Z_n)$$

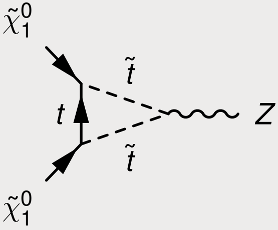
  - Requires that all δX quantities are computed with only fermions/sfermions running in the loop.

Hollik et al. (JHEP (2002))

Determination of effective coefficients : II

- The $\tilde{\chi}^0_1\tilde{\chi}^0_1 Z$ vertex

There is now a genuine triangle loop with (s)fermions



- The effective vertex reads then

$$g^{\text{eff}}_{\tilde{\chi}^0_1\tilde{\chi}^0_1 Z} = g_{\tilde{\chi}^0_1\tilde{\chi}^0_1 Z} + \delta g_{\tilde{\chi}^0_1\tilde{\chi}^0_1 Z} + g^{\text{loop}}_{\tilde{\chi}^0_1\tilde{\chi}^0_1 Z}(2m^2_{\tilde{\chi}^0_1})$$

  - Either with only fermions/sfermions in the loops.
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- In order to have a coherent one-loop picture
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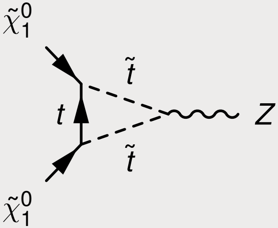

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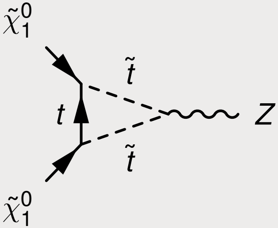

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Analysis

F.Boudjema,GDLR,S.Kulkarni (PhysRevD 2011)

- Parameters :

$M_{A^0} = 1$ TeV	$t_\beta = 4$
$M_{\tilde{\ell}} = 500$ GeV	$M_{\tilde{q}} = 800$ GeV
$A_f = 0$	

- Process

$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \mu^+ \mu^- \qquad \text{at } v = 0.2$$

- We will compare different cross sections

$\Delta_{\text{one-loop}}$: full one-loop
Δ_{eff} : universal effective part
$\Delta_{\alpha(Q)}$: $\alpha(Q)$ running correction

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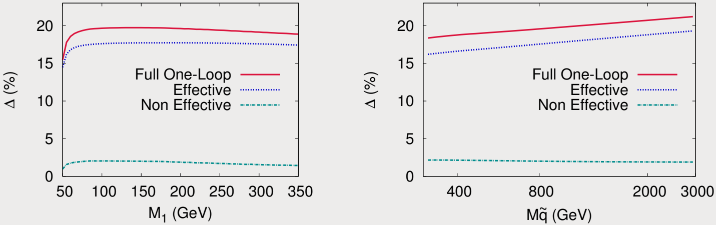

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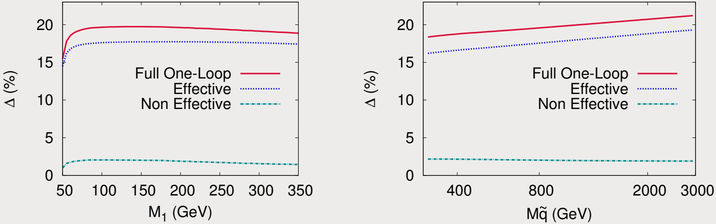

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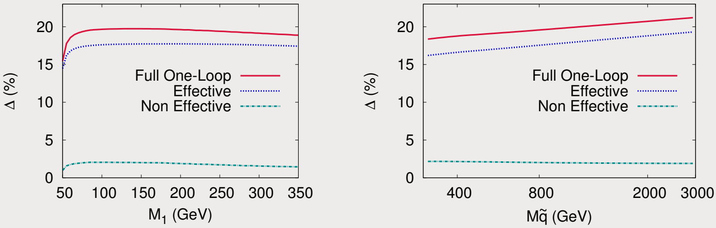

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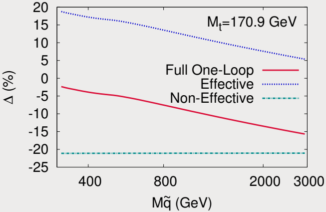

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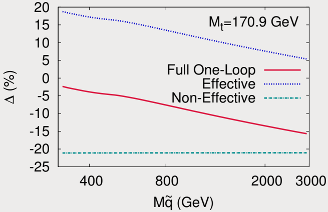

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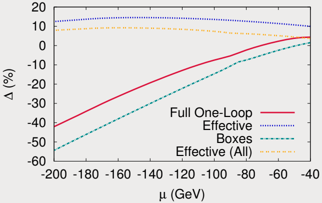

Robustness of the effective approach

- Effective computation always faster than full one-loop.
- Better than the naive running of $\alpha(Q)$ (in bino case, 2% agreement)
- Exhibits interesting feature : the squarks non-decoupling contribution (in all cases)
- Is not always precise
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1. Introduction
    - The Standard Model and Beyond
    - Higgs and Dark Matter
2. Effective approach for relic density
    - SUSY at one-loop
    - Effective vertices
    - Results
3. Effective approach for Higgs physics
    - The BMSSM
    - Computing observables
    - Masses and Couplings
    - Recasting SM Higgs searches
    - The Higgs signal
4. Conclusion

Naturalness in the Standard Model

- Quantum corrections ➙ effective masses and couplings change with energy
  - e.g. the screening of the electric charge
  - Measuring parameters at two different scales yields different values
- Running Higgs mass $m_h(Q)$ with a fermion of mass m_f

$$\frac{dm_h^2(Q)}{d\ln Q} = -\frac{3y^2}{4\pi^2}m_f^2$$

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- A natural MSSM (i.e. with light stops) bound to cope with a light h
- Such a Higgs boson has very standard-like properties.
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  - $\mathcal{L} = \mathcal{L}\left(W, K, \partial_i W, \partial_{ij} W, \partial_{\bar{i}\bar{j}} K, \cdots\right)$
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$$\delta\epsilon_1 = 4e^2 \frac{M_W^2(M_W^2 - M_Z^2)}{M_Z^2 M^2}\left(a_{10} t_\beta^{-4} - a_{30} t_\beta^{-2} + a_{20}\right) = \frac{1}{2}\delta\epsilon_2 = \delta\epsilon_3$$

- $\epsilon_1, \epsilon_2, \epsilon_3 = S, T, U$ reduce the effective parameter space.

Deriving operators for fields (II)

- Many effects are simple shifts of tree-level couplings
  - Suppression factors $\frac{\mu}{M}, \frac{v}{M}, \frac{m_s}{M} \sim 0.2$
- Naively, new Lorentz structures arise with Higgs-only vertices
  - Three scalars : $\partial_\mu h \partial^\mu H^+ H^- \subset \mathcal{L}$
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- Applying equations of motion
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- We take $\frac{m_s}{M} = 0.2$ ➙ new physics approximatively supersymmetric
  - $M = 1.5$ TeV, $m_s = 300$ GeV
- 20 free effective parameters

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Increase of the lightest Higgs mass

- MSSM : $m_h < 135$ GeV
  ➞ BMSSM : $m_h < 250$ GeV.

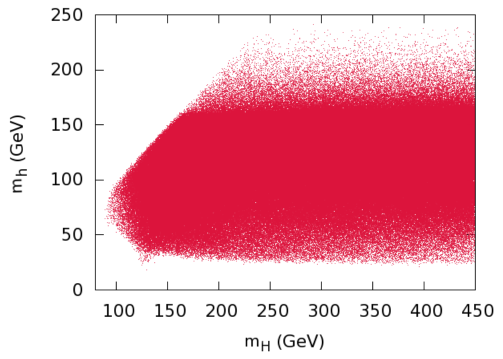

Figure: BMSSM reach in m_H, m_h plane without experimental constraints

Tree-level Higgs couplings

Z, W	similar features as MSSM	$g^2_{hVV} + g^2_{HVV} \simeq 1$
u, c, t	similar features as MSSM	
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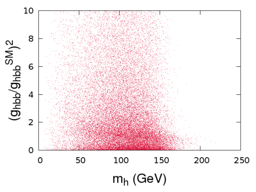

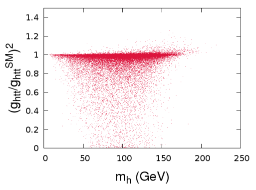

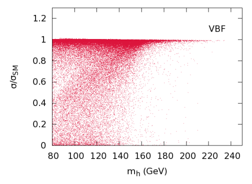

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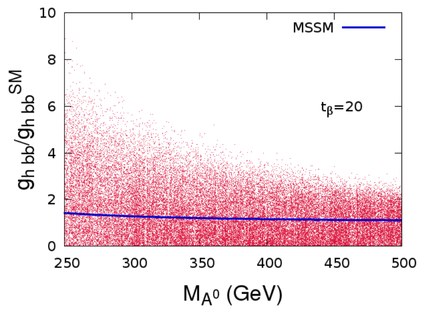
Slow decoupling of h at high M_{A^0}



Loop induced Higgs couplings

- g_{hgg} ruled by top (+ bottom + stops)
- $g_{h\gamma\gamma}$ ruled by W, top (+ bottom + stops)
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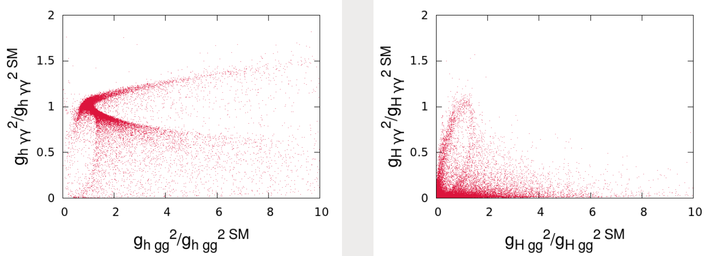

Relating couplings to observables

- The couplings are not directly accessible
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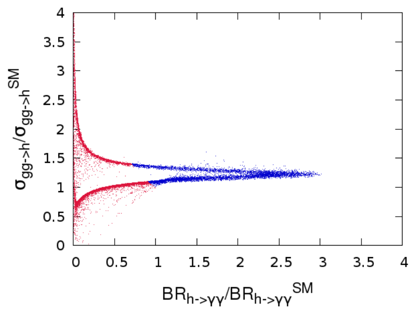

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- Electroweak Precision Test (EWPT)
- Flavour Physics : $B_s \rightarrow \mu^+\mu^-$ and $B \rightarrow X_s\gamma^*$
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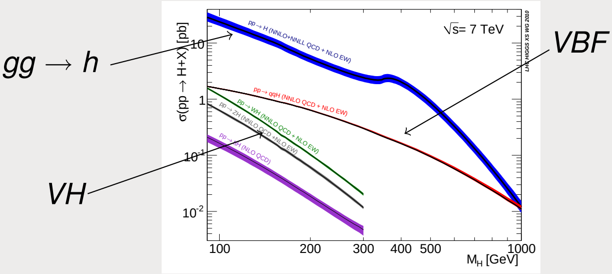

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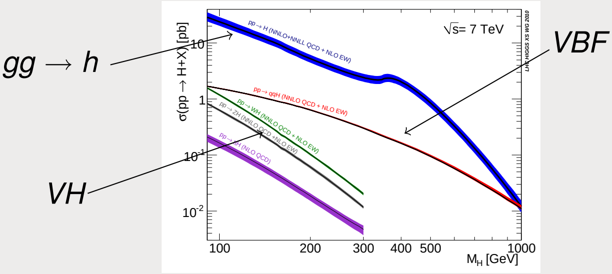

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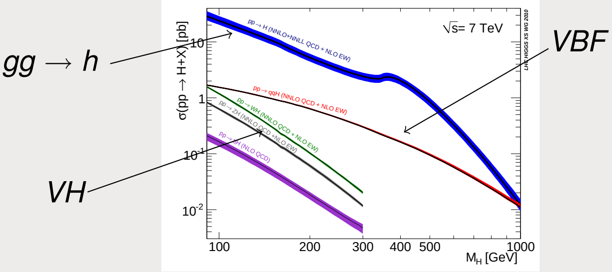

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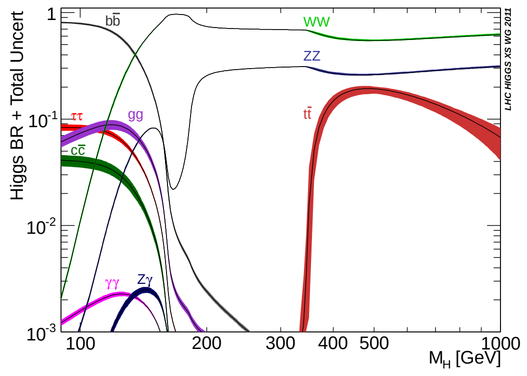

The Standard Model Higgs search : channels

- $\gamma\gamma$: low masses
  - can probe VBF with $\gamma\gamma + 2j$
- ZZ : different subchannels $(4\ell, 2\ell 2\nu \cdots)$
  Good sensitivity even below the threshold
- WW : similar features
  - can probe VH, VBF with $WW + 1/2j$
- $\bar{\tau}\tau$: whole mass range
  - MSSM-like analysis since this channel is t_β enhanced
- $VH \to V\bar{b}b$: low masses
  - Independent of $gg \to H$!

Recasting to non-SM models

F.Boudjema,GDLR (PhysRevD 2011)

- Use the exclusion ratio in the no signal case

$$\boxed{R_{XX}^{\text{excl }95\%} = \frac{\sigma_{pp\to\phi\to XX}}{\sigma^{\text{excl }95\%}_{pp\to\phi\to XX}}}$$

- Use signal strength in the case of a signal

$$\boxed{R_{XX} = \frac{\sigma_{pp\to\phi\to XX}}{\sigma^{\text{SM}}_{pp\to H\to XX}}}$$

- Use the MSSM production modes

$$\sigma_{pp\to\phi\to XX} = \left(\sigma_{ggh} + \sigma_{VBF} + \sigma_{Vh} + \sigma_{\bar{b}bh}\right)\times BR(\phi\to XX)$$

Recasting Issue 1 : the efficiencies

- On a single count experiment we have a priori

$$\mu = \frac{n_S}{n_S^{\mathrm{SM}}} \neq \frac{\sigma_{\mathrm{inclusive}}}{\sigma^{\mathrm{SM}}_{\mathrm{inclusive}}}$$

- Analyses impose cuts on the final phase space
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Recasting Issue 1 : the efficiencies

- On a single count experiment we have a priori

$$\mu = \frac{n_S}{n_S^{\text{SM}}} \neq \frac{\sigma_{\text{inclusive}}}{\sigma^{\text{SM}}_{\text{inclusive}}}$$

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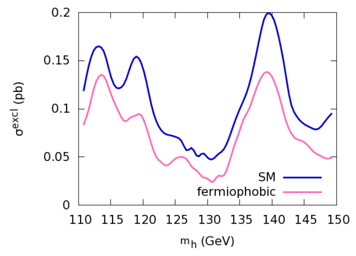
Recasting Issue 1 : Example

- Limit on $R^{\text{excl } 95\%}_{\text{Fermiophobic}}$ versus $R^{\text{excl } 95\%}_{\text{SM}}$



- Efficiencies rarely quoted
  for $m_h = 120$ GeV, and final state $\gamma\gamma + 2j$
  $\epsilon_{ggh} = 0.005, \quad \epsilon_{vbf} = 0.15$
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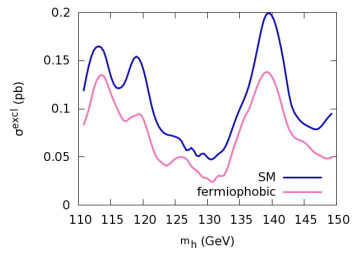

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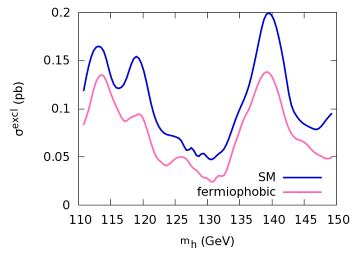

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- Statistical combinations of n channels assume identical $R_{X_1 X_1} = R_{X_2 X_2} = \cdots = R_{X_n X_n} = \mu$
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$$R^{\text{excl } 95\%} = \left(\sum_i R_i^{\text{excl } 95\% -2} \right)^{-\frac{1}{2}}$$

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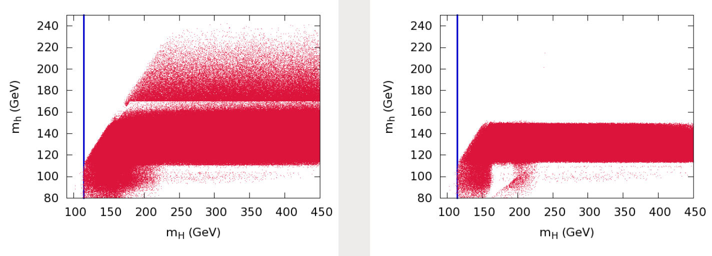
Allowed region for neutral Higgses

Summer 2011, 2 fb^{-1}

F.Boudjema,GDLR (PhysRevD 2011)



- Lightest Higgs h restricted to be light $m_h < 150$ GeV
- Cases with $m_h < 114$ GeV
    - h is then decoupled to Z, W bosons.
    - H can either be light $m_H < 150$ GeV, or decay as $H \to hh$
- In particular there are two possibilities $m_h = 125$ GeV and $m_H = 125$ GeV.

Signal features from ATLAS/CMS

December 2011, 5 fb^{-}
July 2012, 10 fb^{-1}

- $m_h = 125 - 127$ GeV
- We take $\hat{\mu}$ from the most indicative channels
  - The uncertainties quoted are for 1σ bands.

	ATLAS		CMS	
	2012	2011	2012	2011
$\gamma\gamma$	1.9 ± 0.5	2 ± 0.8	1.4 ± 0.5	1.7 ± 0.8
$\gamma\gamma + 2\text{j}$	2.8 ± 1.2		1.6 ± 1.1	3.8 ± 2.1
$ZZ \to 4\ell$	1.35 ± 0.9	1.2 ± 1.0	0.8	0.5 ± 0.8

- Other channels are dominated by uncertainties

	ATLAS	CMS
$WW \to l\nu l\nu$		0.5 ± 0.4
$\bar{\tau}\tau$		-0.3
$VH \to V\bar{b}b$		0.6

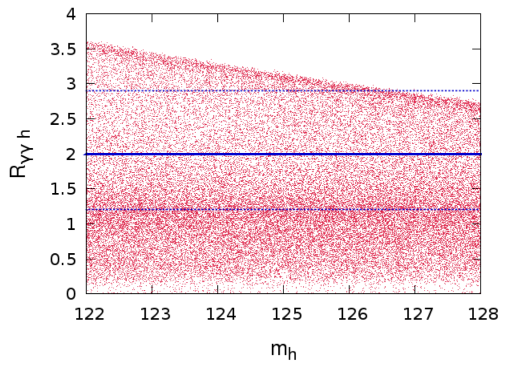
- X : Reconstructed values

Higgs signal in $h \to \gamma\gamma$

December 2011, 5 fb^{-1}

F.Boudjema,GDLR (accepted in PhysRevD)

- $h \to \gamma\gamma$ can be enhanced :



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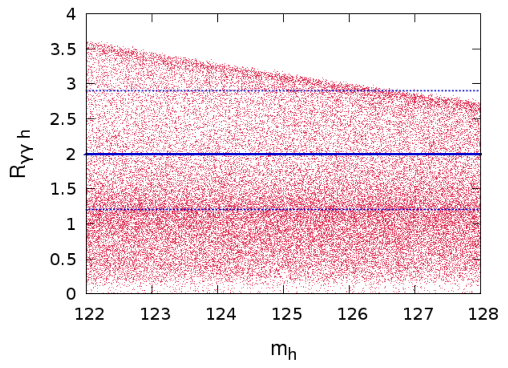

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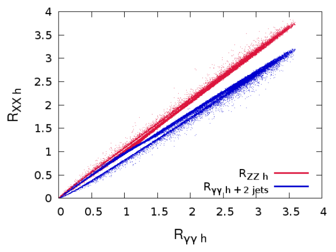

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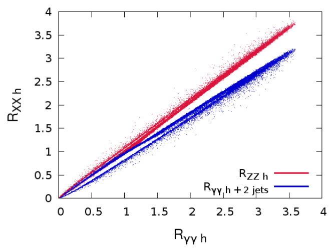

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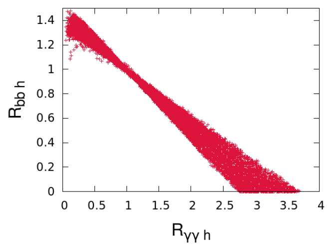

Effect of stops loops

December 2011, 5 fb^{-1}

- Lightest stop loop
  $$g_{h\tilde{t}_1\tilde{t}_1} \simeq \frac{g}{M_W}\left(\sin^2(2\theta_{\tilde{t}})\frac{m^2_{\tilde{t}_1}-m^2_{\tilde{t}_2}}{4} + m_t^2 + O(M_Z^2)\right)$$
  - Opposite contributions to $gg \to h$ and $h \to \gamma\gamma$.
- Model B) : $\Delta m = 400$ GeV, $s_{2\theta_t} = 1$
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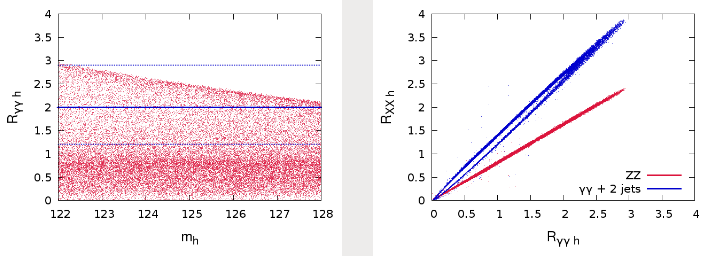

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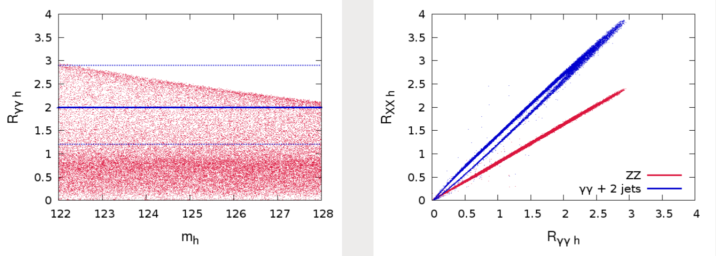

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Flavour Constraints

December 2011, 5 fb^{-1}

F.Boudjema,GDLR (to be published)

- Supersymmetry typically allows for extra contributions $B_s \to \mu^+\mu^-$ and $B \to X_s\gamma^*$
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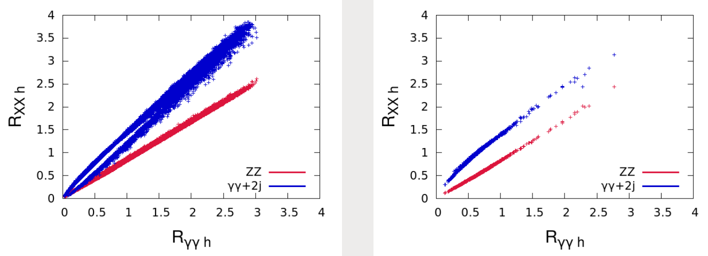
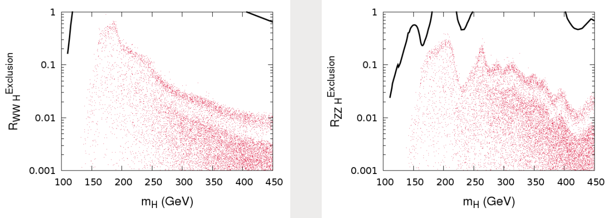


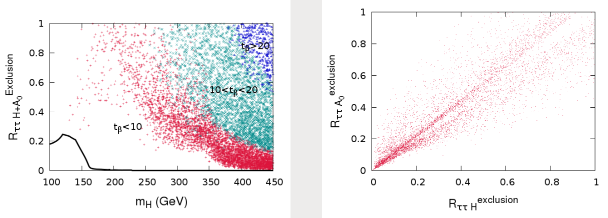
Expectations for other Higgses

Future, >10 fb^{-1}

- Selecting $m_h \in [123, 129]$ GeV, with $R_{\gamma\gamma} = X$, $R_{ZZ} = X$



- $\bar{\tau}\tau$ channel more promising



Outline

Conclusion

- Power of the effective approach
  - A precious tool for separating an observable scale, i.e. at low energy from a hypothesized scale
  - For Dark Matter the effective scale is the neutralino mass and the heavy one the squark masses.
  - For the Higgs search the effective scale is m_h and the heavy scale the extra physics.
- Conclusions from Higgs and Dark Matter constraints
  - Relic Density precise enough ➞ towards an era of precision?
  - The supersymmetric Higgs can be quite non-standard (Correlations between channels)
  - With the data coming in, importance of a model-independent result