Segnature di nuova fisica a 14 TeV

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V Workshop Italiano sulla Fisica p-p ad LHC
Perugia, 30/1 - 2/2, 2008

New physics at the Large Hadron Collider

1. The first thorough exploration of the energy scales well above $G_F^{-1/2}$

$\Lambda_{QCD},\ G_F^{-1/2}$

2. No comparable prior situation at the SppS or at the TEVATRON

1983: W, Z
1993: top

A road map

1. Higgsless: a "conservative" view

2. The "naturalness" problem of the Fermi scale

a. Supersymmetry

b. Goldstone symmetry

c. Gauge symmetry in extraD

3. Dark Matter

4. The Planck/Fermi hierarchy ⇔ extraD

a. Gravity weak by flux in extraD

b. $G_F^{-1/2}/M_{Pl}$ as a red shift effect

c. Symmetry breaking by boundary conditions

Subjects touched in the following

(in logical order)

1. Higgsless: a "conservative" view 1

2. The "naturalness" problem of the Fermi scale

a. Supersymmetry 4

b. Goldstone symmetry

c. Gauge symmetry in extraD 2

3. Dark Matter 3

4. The Planck/Fermi hierarchy ⇔ extraD

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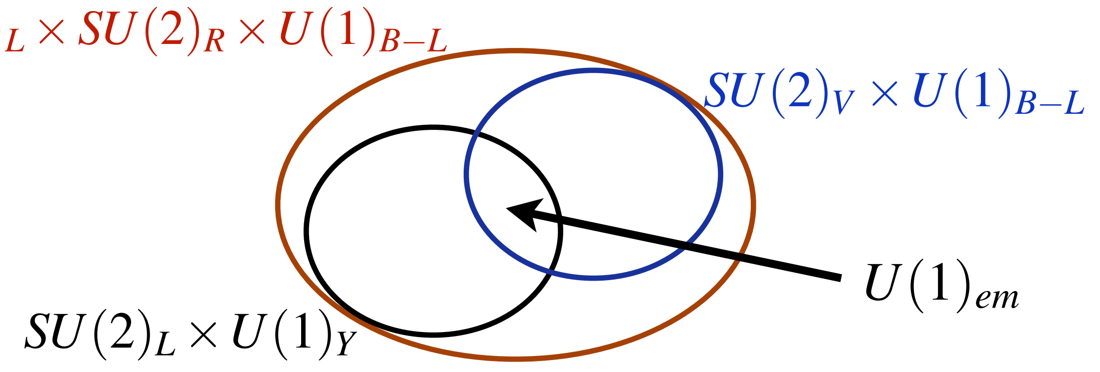
c. Symmetry breaking by boundary conditions

Can one make it without the Higgs boson?

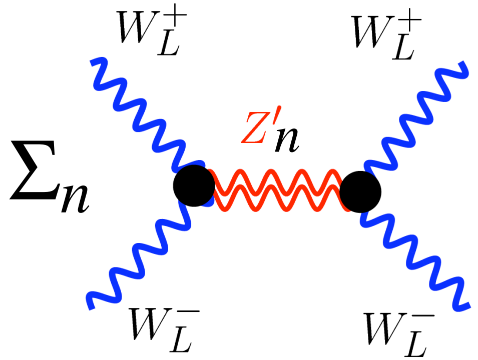


VV amplitudes saturate unitarity at $\sqrt{s} \approx 1.2\ TeV$

Electroweak chiral Lagrangian, Technicolour and all that

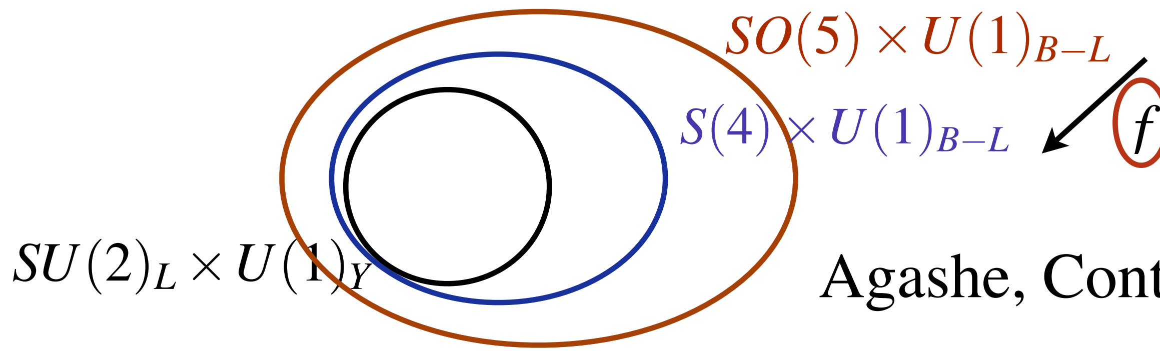
Not calculable or, when calculable, inconsistent with the EWPT

A potential improuvement: unitarity saved by KK-vectors



(see below)

A "composite" Higgs boson



Agashe, Contino, Pomarol

A two scale picture: $f > v$

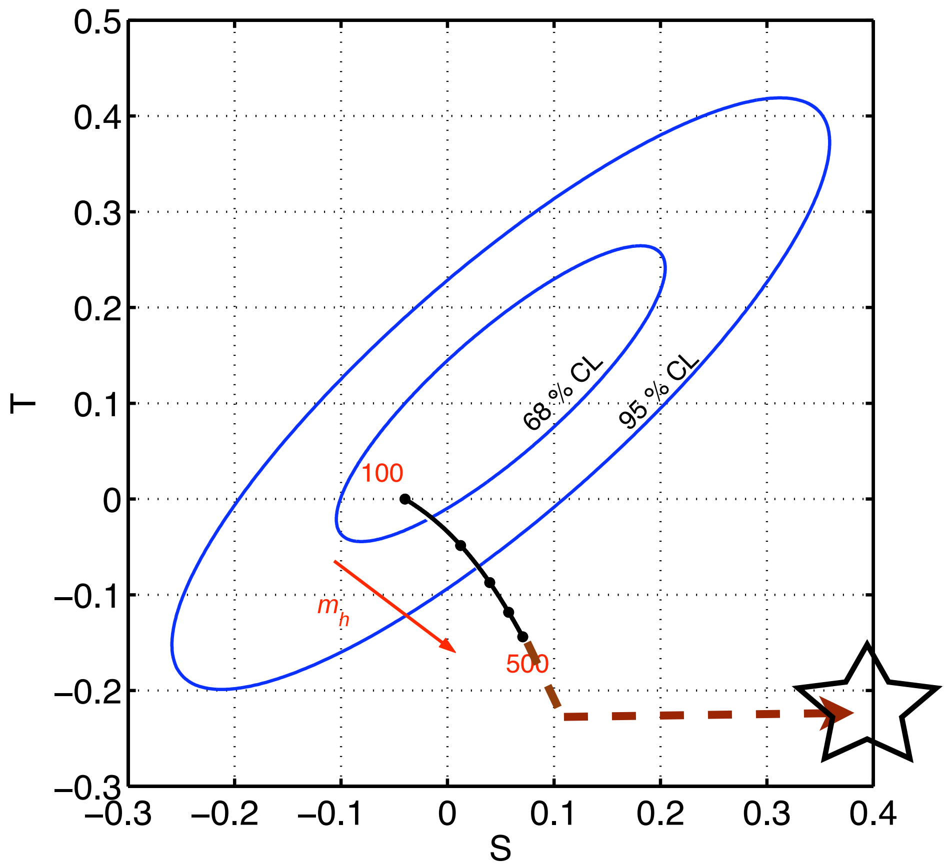
The Higgs boson as pseudo-Goldstone boson
(or the fifth component of a vector in 5D)

The hVV-coupling suppressed, relative to the SM one, by a factor $(1 - v^2/f^2)^{1/2}$
Still need KK vectors to restore unitarity

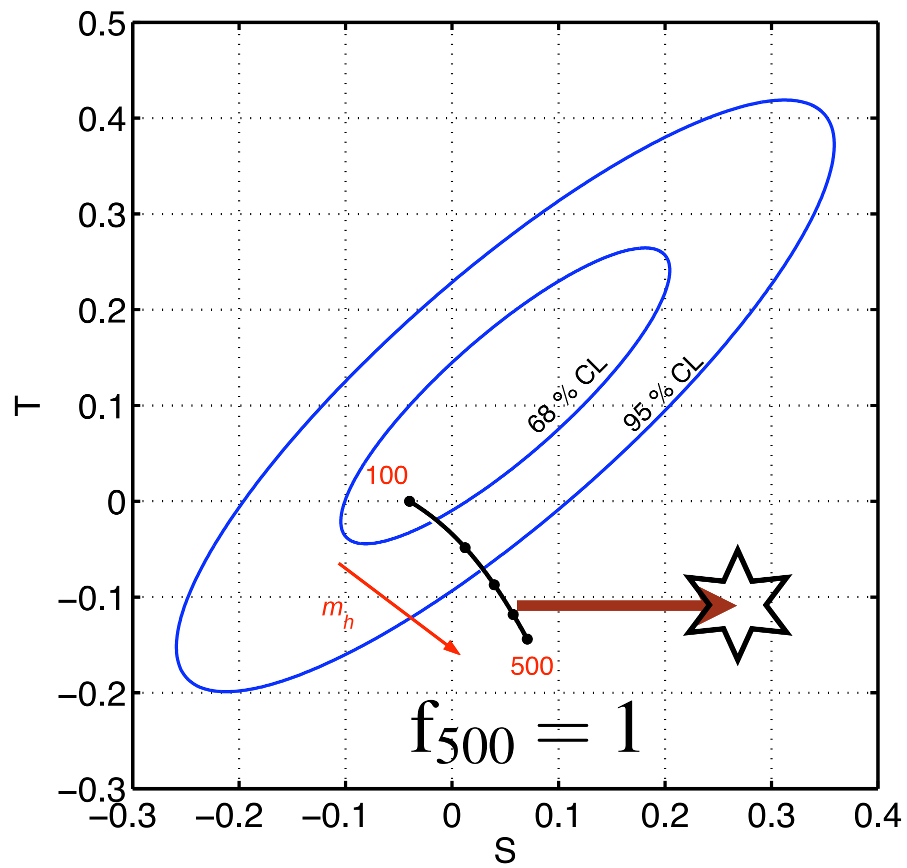
Top and gauge loop corrections to m_h^2 *cut off by states with same spin and gauge quantum numbers*

Comparing simplest models with the EWPT

Higgsless



Composite



B, Bellazzini, Rychkov, Varagnolo

A problem, unless something missing

One deals with strongly interacting theories, so ...

Main phenomenology

$V = W, Z$

$\hat{V} = KK\text{-}W,Z$

	Higgsless	*Composite*
A(VV)	$\approx s/v^2$	$\approx s/f^2$
$m_{\hat{V}}$	$g_s v \leq 1\ TeV$	$g_s v \leq 1\ TeV(f/v)$
$\hat{V}VV - coupling$	$g_s\ strongish$	$g_s\ strongish$
$f\bar{f}\ \hat{V}$	$g\ (g/g_s)$	$g\ (g/g_s)$
$t\bar{t}\ \hat{V}$	?	*strongish*
$KK - quarks(T^{2/3}, B^{-1/3}, X^{5/3})$	-	*Yes, with ~ TeV mass*

KK-vector signals $\hat{V}$

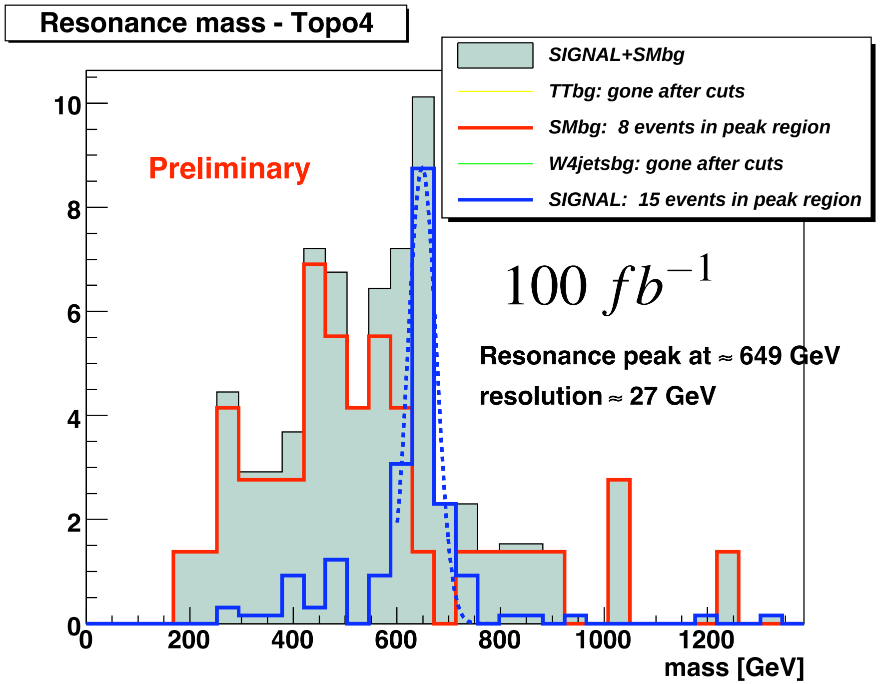
$$qq \to qq\,\hat{V} \qquad qq \to \hat{V} \qquad \hat{V} \to VV,\ t\bar{t},\ (hV)$$

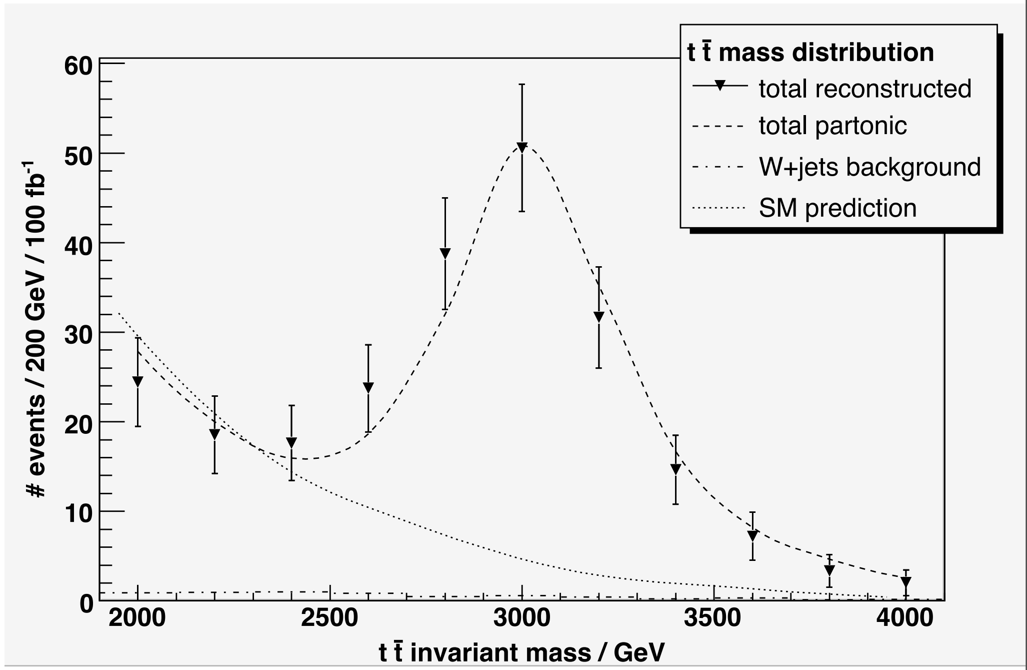
(t or b, depending on the charge)

$\hat{V} \to f\bar{f}$ probably not useful, because of small BR

$\hat{V}$ can also be a KK-gluon

$$pp \to qq\hat{W} \to qqWZ \to qq\,jet\,jet\,ll \qquad pp \to \hat{g} \to t\bar{t}$$





Azuelos, Delsart, Idarraga

Agashe et al

KK-quark signals

$$Q \equiv (T^{2/3}, B^{-1/3}, X^{5/3})$$

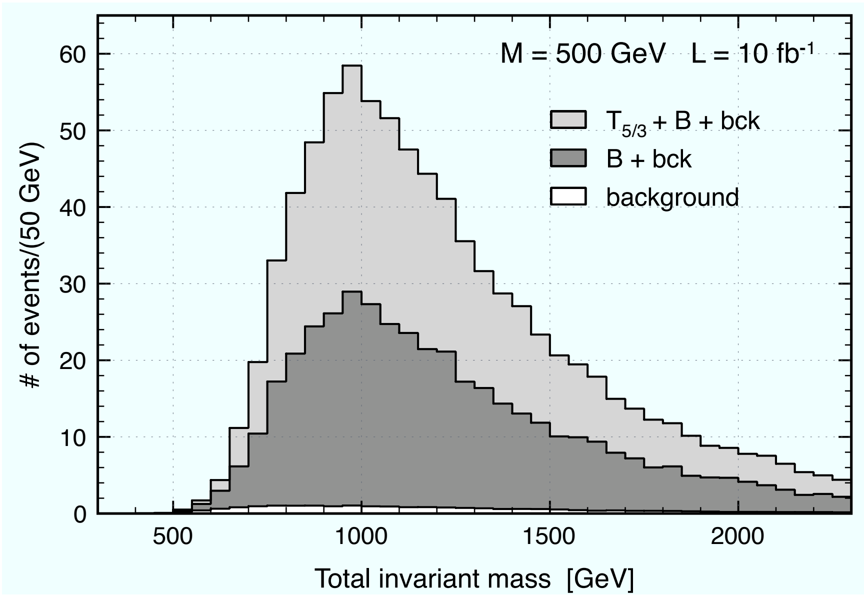
$$qq \to Q\bar{Q} \qquad\qquad Q \to tV,\ th$$

(t or b, depending on the charge)

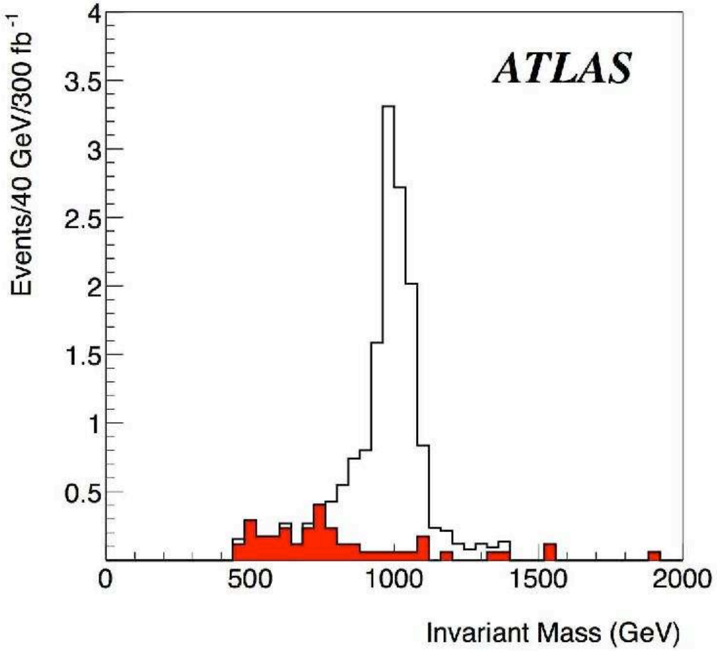
If they exist, easier to catch than KK-vectors
(like squarks, but without $\not{E}_T$)

Single production also possible

$$pp \to X\bar{X} + B\bar{B} \to l^{\pm}l^{\pm} + jets + \not{E}_T \qquad\qquad T(1\ TeV) \to Z\,t \to l^+l^-l^{\pm}\nu b$$



Contino, Servant



Dark matter: a numerical coincidence

Suppose you have a stable particle χ
that decouples from the hot primordial plasma by $\chi\chi \to ff$
with a cross section σ*. Then, for its relic density* Ω

$$\Omega h^2 = \frac{688\pi^{5/2} T_\gamma^3 (n+1) x_f^{n+1}}{99\sqrt{5g_*}(H_0/h)^2 M_{\rm Pl}^3 \sigma} \approx 0.2\frac{pb}{\sigma} \quad \Leftarrow$$

and $\sigma \approx pb$ *is a typical weak interaction cross section*
for a particle of mass $m_\chi \approx G_F^{-1/2}$

against the observed $\Omega_{\rm DM} h^2 = 0.113 \pm 0.009$ $\Leftarrow$

2 minimal illustrative models

(unlike the susy case)

1. A scalar-doublet model (“inert”)

B, Hall, Rychkov

$$V = -\mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \text{ quartics}$$

For natural flavor conservation impose

$H_2 \to -H_2$

Only H_1 couples to matter

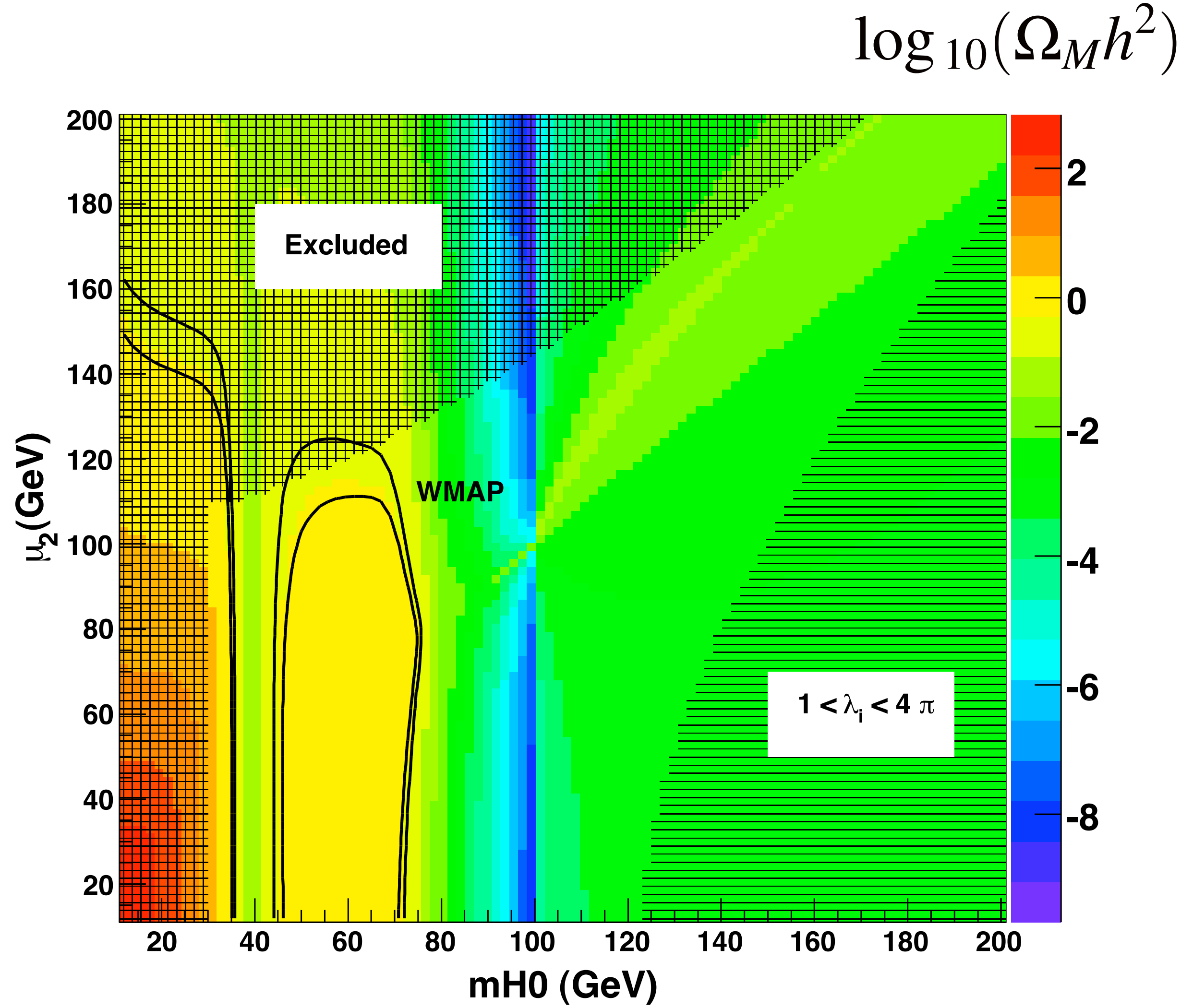
$$\boxed{H_2 = \begin{pmatrix} H^+ \\ H + iA \end{pmatrix} \text{ is “inert”}}$$

$v_2 = 0$

This is not the usual phase in the fine-tuned limit of $v_2 \ll v_1$

1. $H_1 = \begin{pmatrix} 0 \\ v + h \end{pmatrix}$ similar to SM Higgs
2. H_2 mass splittings lead to $\Delta T > 0$ *controlled by approximate* $SU(2)_V$
3. $H_2 \to -H_2$ is exact, and not spontaneously broken

Lightest Inert Particle (LIP) is stable and could be Dark Matter



$\log_{10}(\Omega_M h^2)$
Excluded
WMAP
$1 < \lambda_i < 4\pi$
μ_2(GeV)
mH0 (GeV)
200
180
160
140
120
100
80
60
40
20
20
40
60
80
100
120
140
160
180
200
2
0
-2
-4
-6
-8

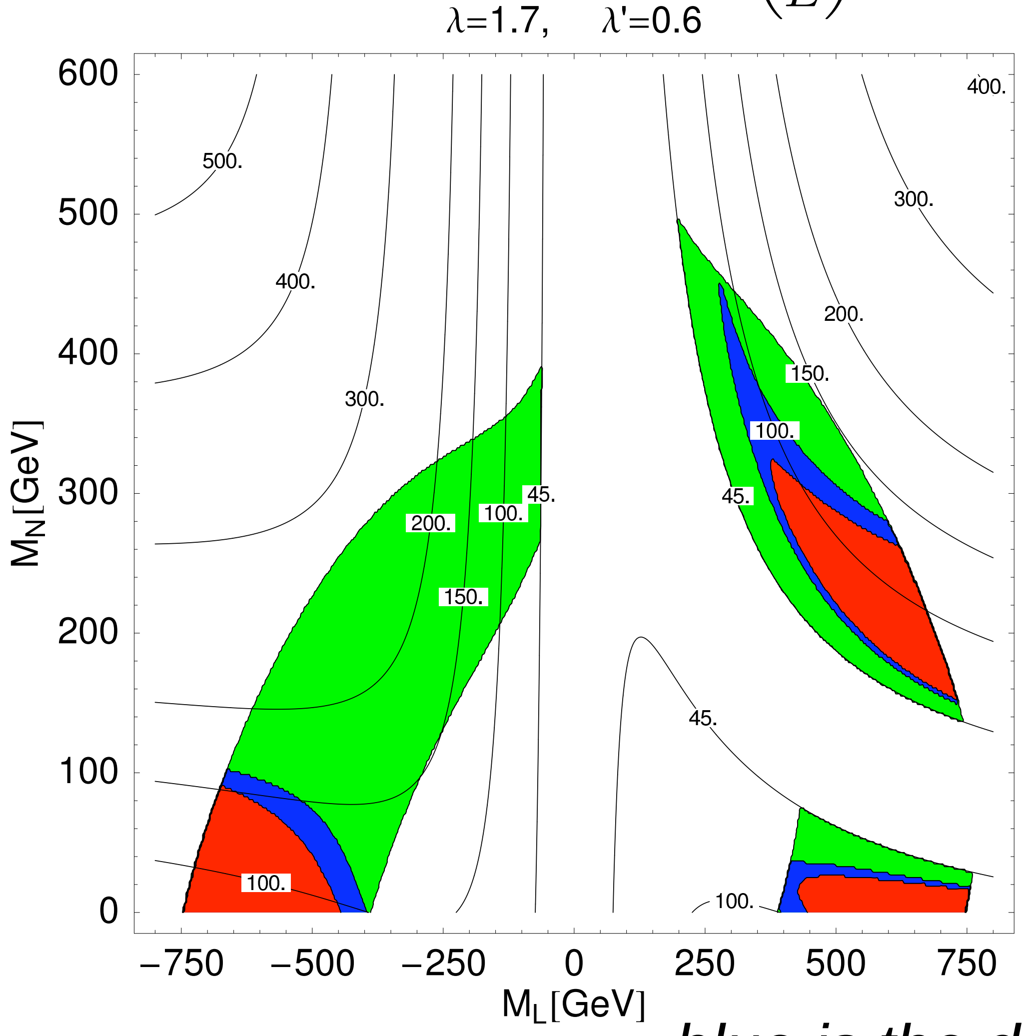
Tytgat et al

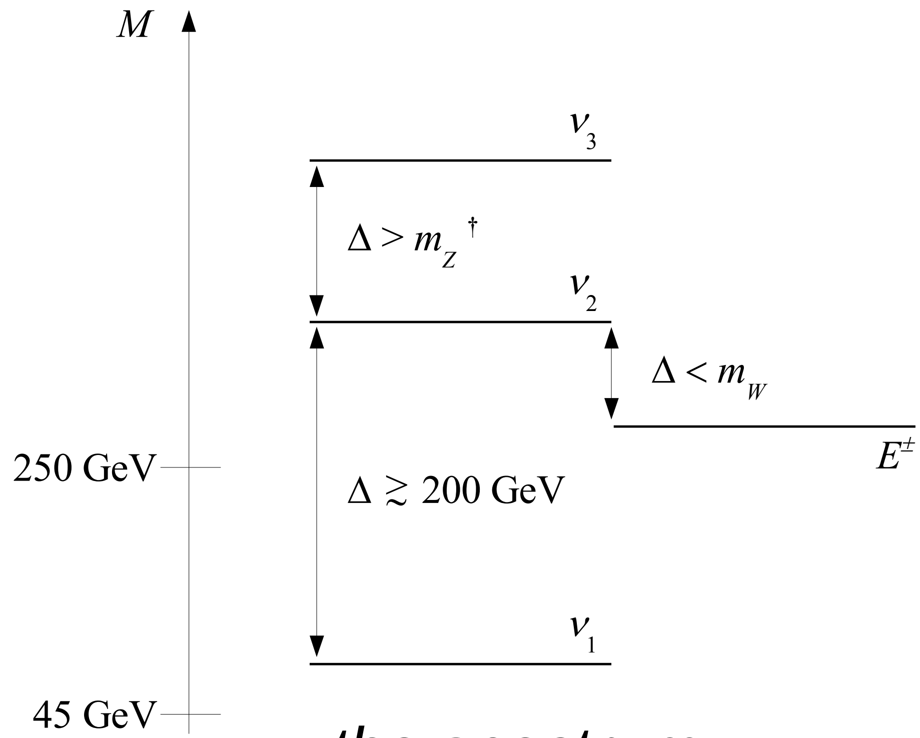
2 A neutrino-type model

Enberg et al
D'Eramo
Mahbubani, Senatore

$$\Delta\mathcal{L} = -\lambda LHN - \lambda' L^c \tilde{H} N + M_L L L^c + \frac{1}{2} M_N N^2 + h.c.$$

$$L = \begin{pmatrix} \nu \\ E \end{pmatrix}, \quad L^c = \begin{pmatrix} E^c \\ \nu^c \end{pmatrix}$$

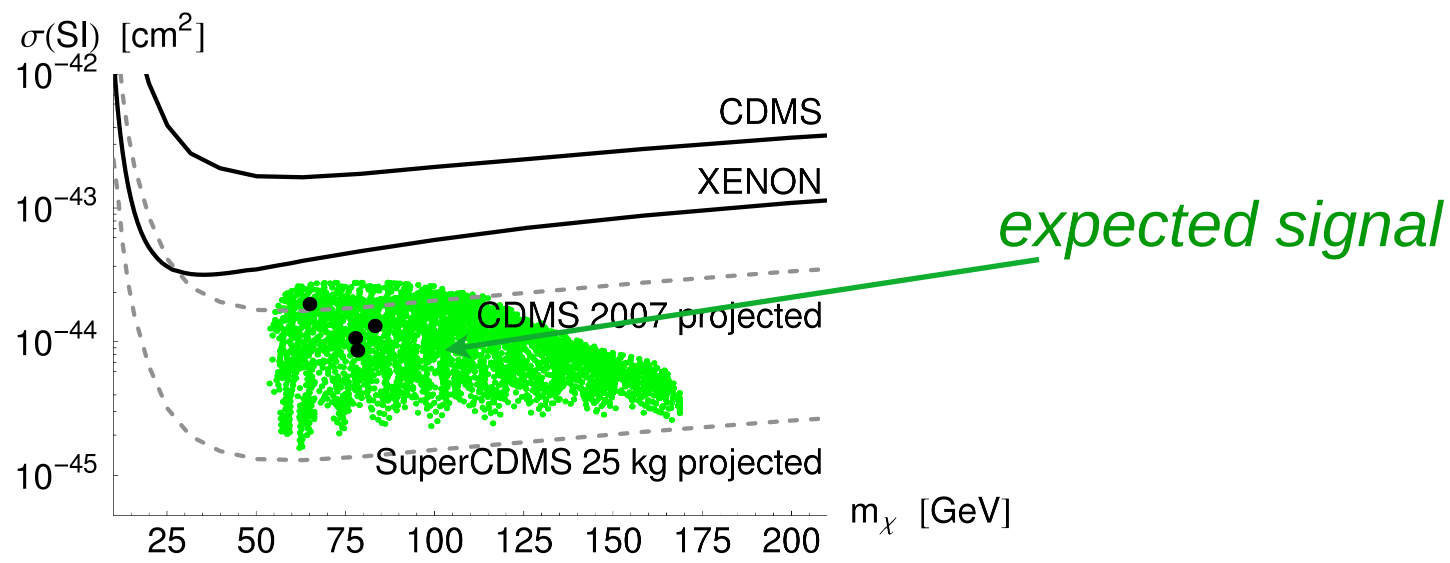




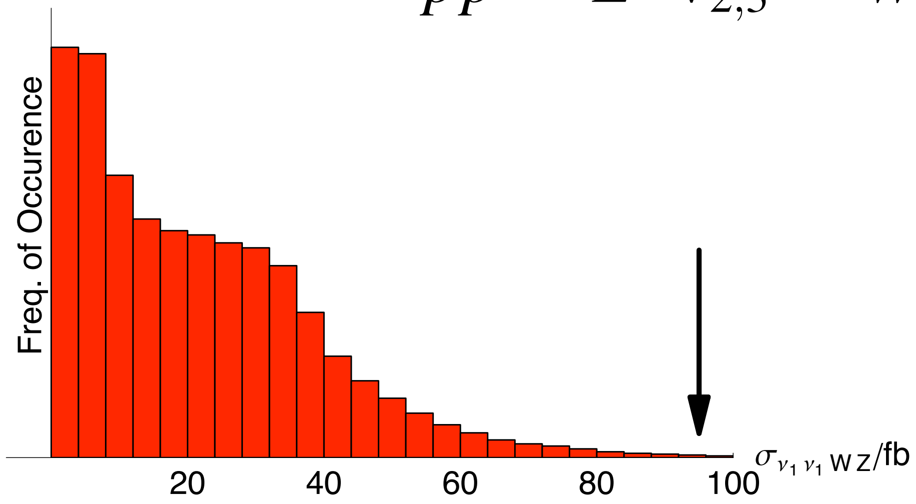
the spectrum

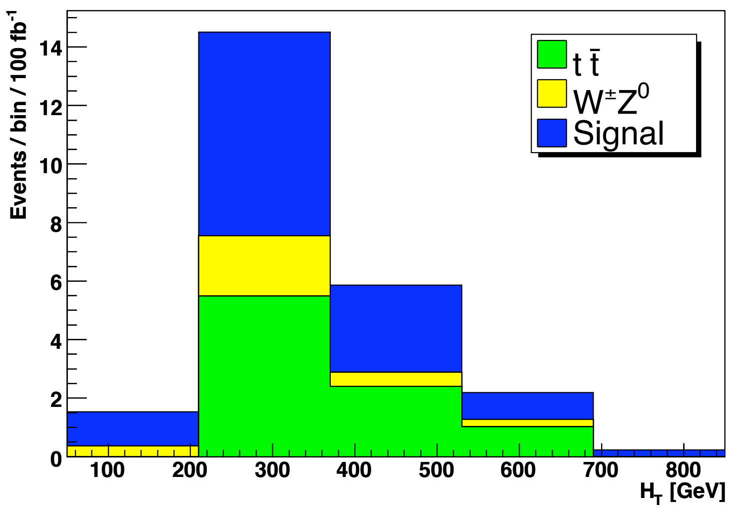
blue is the desired Ω

Direct DM detection versus LHC



$$pp \to E^{\pm}\nu_{2,3} \to W^{\pm}Z\nu_1\nu_1 \to 3l + \not{E}_T$$





Supersymmetry at the LHC

(if you care of the prediction!)

Pros

⇒ Neatly solves the naturalness problem of the Fermi scale

⇒ Gauge coupling unification

⇒ Alternatives in worse shape (EWPT)

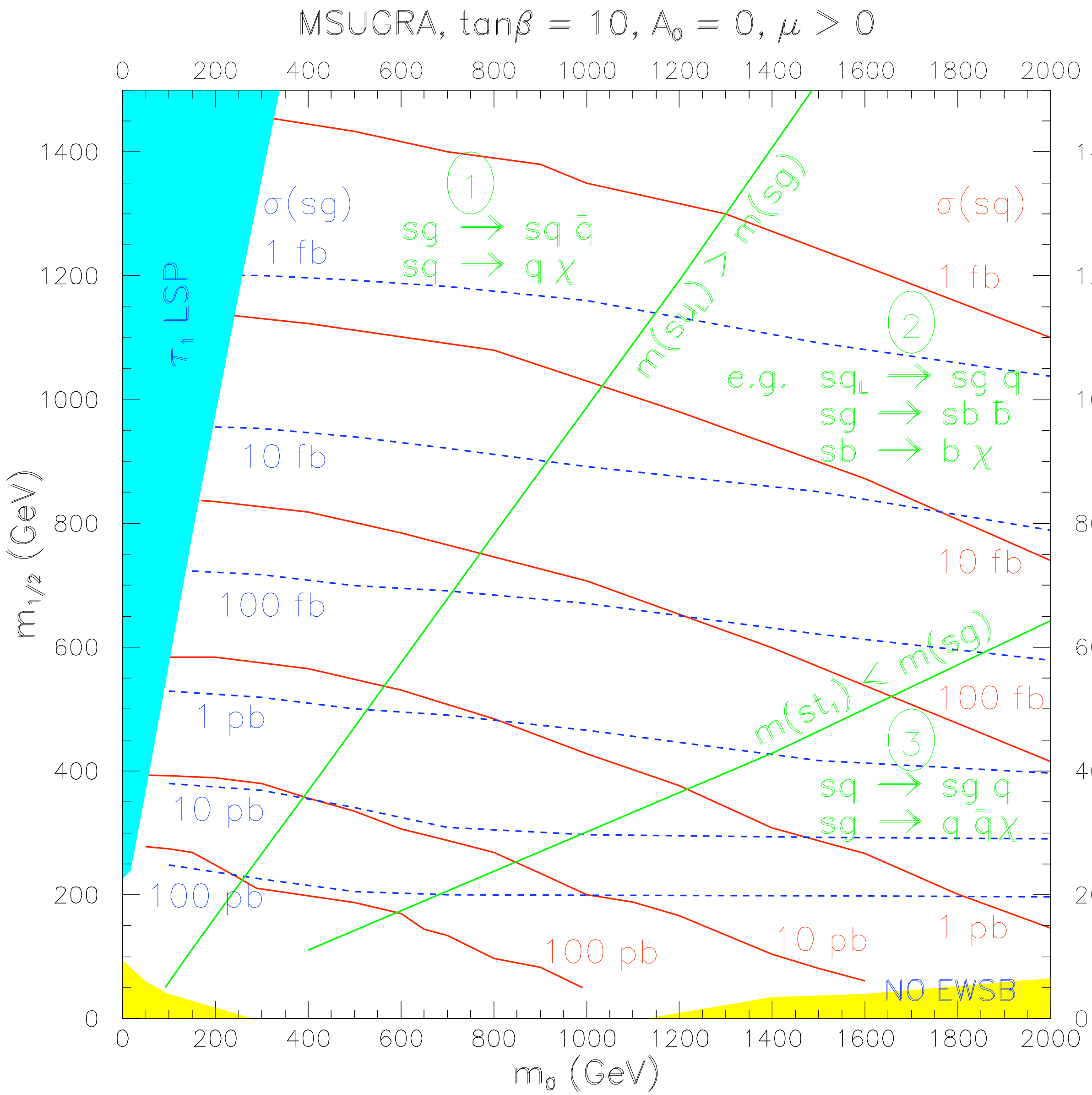
Contras (none decisive)

✓ ⇒ No Higgs boson ✓

⇒ No flavour effects (but follow $\mu \to e + \gamma$ at PSI)

⇒ No superpartners

mSUGRA: gluinos, squarks decaying into lighter gauginos/higgsinos



a much studied case

$$m^2(\tilde{q}) \approx m_0^2 + 5m_{1/2}^2$$

$$m(\tilde{g}) \approx 2.7m_{1/2}$$

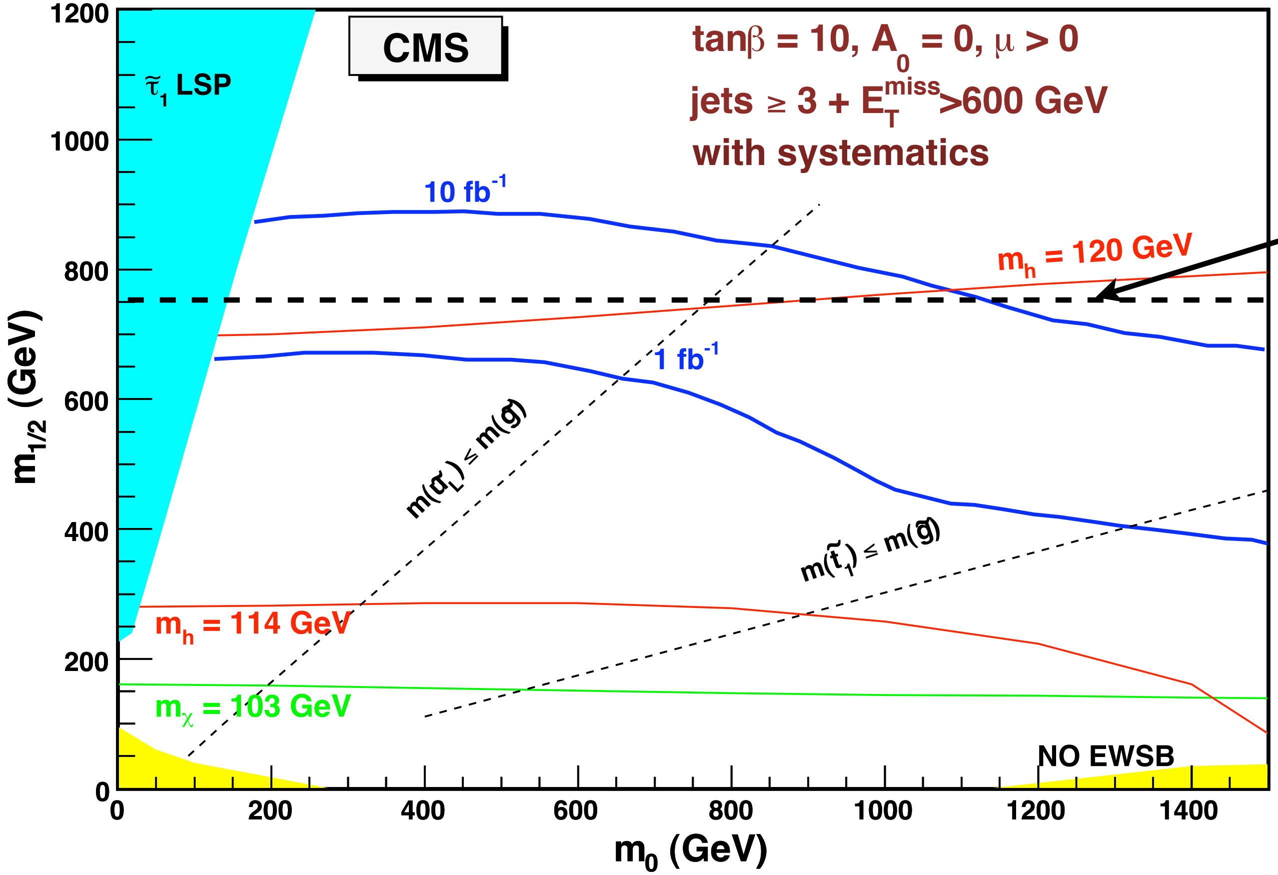
$$m(\tilde{w}) \approx 0.8m_{1/2}$$

$$m(\tilde{b}) \approx 0.4m_{1/2}$$

CMS

$$pp \to \tilde{g}\tilde{g} \to /E_T + jets\ (+\mu^{\pm}/l^+l^-/Z/t)$$

mSUGRA discovery potential: Easy (?)



$m(\tilde{g}) \approx 2.5\ TeV$

other "useful" Susy searches

⇒ gluino/stop decays (simple and motivated by naturalness)

$\boxed{\text{BR} = 1}$

1. $pp \to \tilde{t}\tilde{\bar{t}} \to t\bar{t} + \not{E}_T$
   $\hookrightarrow t + \chi^0$

2. $pp \to \tilde{g}\tilde{g} \to jets + \not{E}_T$
   $\hookrightarrow q\bar{q} + \chi^0$

3. $pp \to \tilde{g}\tilde{g} \to 2t\ 2\bar{t} + \not{E}_T$
   $\hookrightarrow \tilde{t}\ \bar{t}$
   $\hookrightarrow t + \chi^0$

4. $pp \to \tilde{t}\tilde{\bar{t}} \to t\bar{t} + jets + \not{E}_T$
   $\hookrightarrow t + \tilde{g}$
   $\hookrightarrow q\bar{q} + \chi^0$

⇒ ew gauge/higgs-ino decays (simple in physical space)

5. $pp \to \chi_1^{\pm}\chi_2^0 \to 3leptons + \not{E}_T$
   $\hookrightarrow l\bar{l} + \chi^0$
   $\hookrightarrow l\nu + \chi^0$

⇒ light gravitino

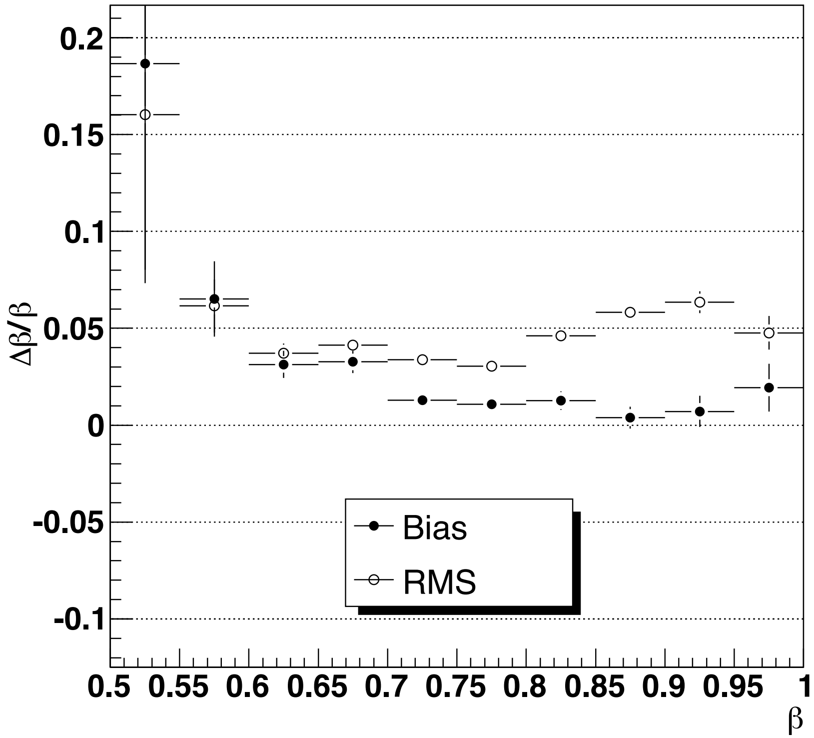
mSUGRA or above $\oplus$ $\chi^0 \to gravitino + \gamma,\ gravitino + \phi$
$\hookrightarrow b\bar{b}$

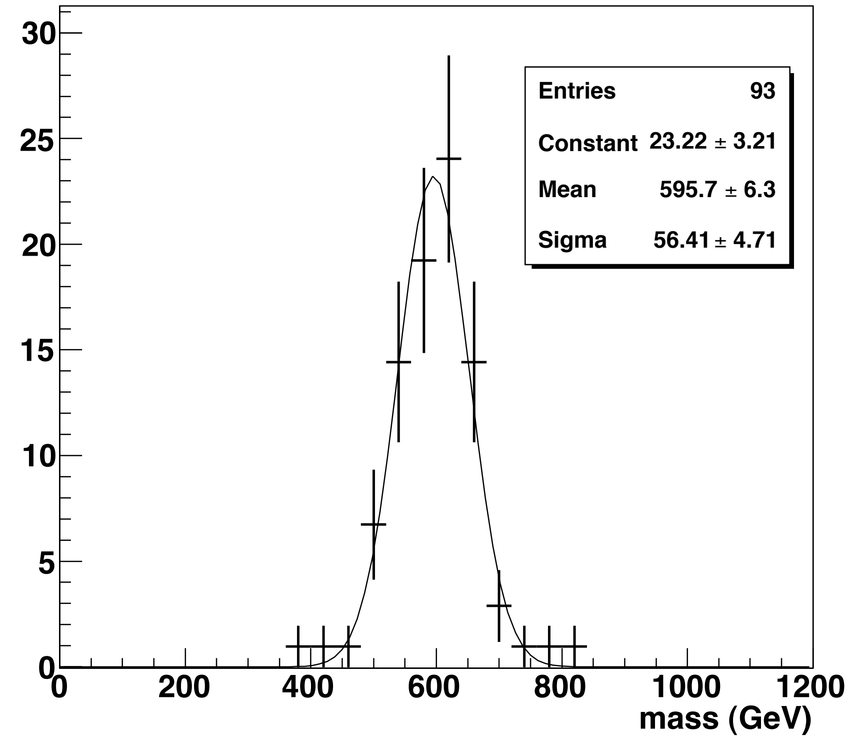
"Stable" R-hadrons (made of $\tilde{g}$ or of $\tilde{t}$)

because "LSP", up to gravitino decays, or because of superheavy squarks (in the gluino case)

by dE/dx and time-of-flight

600 GeV gluino (0.5 fb^{-1})





A. Rizzi

1 TeV gluino reachable with 1 fb^{-1}

Where is the supersymmetric Higgs boson?

View n^0 1

MSSM 2x4 - (2+1) = 5 = 2 + 1 + 1 + 1

$H^\pm \quad h \quad H \quad A$

$$m_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{3 m_t^4}{4\pi^2 v^2}[\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2})]$$

$\Rightarrow$ *Take large tanβ (muon anomaly?) and large stop mass*

for $A_t/m_{\tilde{t}} \lesssim 1$ $\boxed{m_{\tilde{t}} \gtrsim 900\,\mathrm{GeV}}$

to comply with the LEP bound

$\Rightarrow$ *Swallow, e.g. in SUGRA,* $\Delta M_Z^2 \approx (2 \div 3) m_{\tilde{t}}^2 \geq 100\ M_Z^2$

$\Rightarrow$ *h just around the corner and quasi-standard*

Where is the supersymmetric Higgs boson?

View n^0 2

1. *Even assuming, for good reasons, that supersymmetry is relevant to nature, NO theorem that requires it to be visible at the LHC*

2. *For supersymmetry to be visible at the LHC, need a maximally natural solution of the hierarchy problem*

3. *Since the top, and so the stop, are the particles with the strongest coupling to the Higgs boson, insist on a moderate stop mass*

⇒ *Motivates search of (reasonably simple) alternatives*

⇒ *h not standard and not even light?*

Two examples, based on the NMSSM

(others have been considered)

$$\Delta V = \lambda^2 |H_1 H_2|^2$$

$CP^+ : \quad h_1 < h_2 < h_3$ $\qquad CP^- : \quad A_1 < A_2$ $\qquad H^\pm$

1 $\lambda(G_F^{-1/2}) \approx 2$ (not obviously consistent with unification)

$m(h_1) = 150 \div 300\ GeV$ and $\approx$ standard

(but very much NON-susy-like)

$h_2 \to h_1 h_1 \to 4V \to l^+ l^-\ 6j$

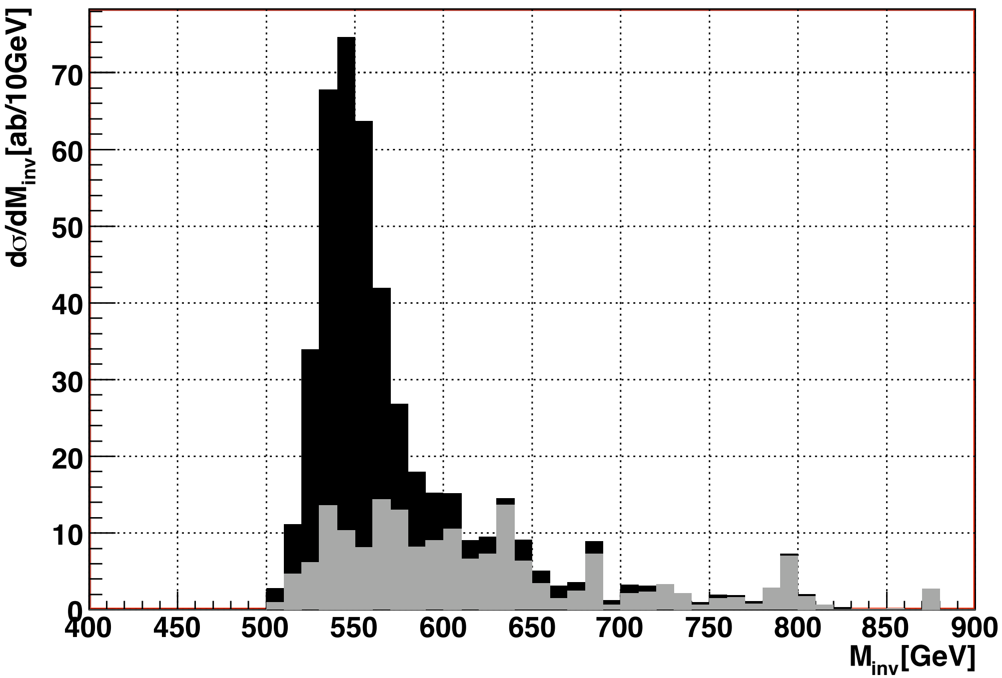
$A_1 \to h_1 Z \to VV\ Z \to l^+ l^-\ 4j$

2 $\lambda(G_F^{-1/2}) \approx 0.7$ (consistent with unification)

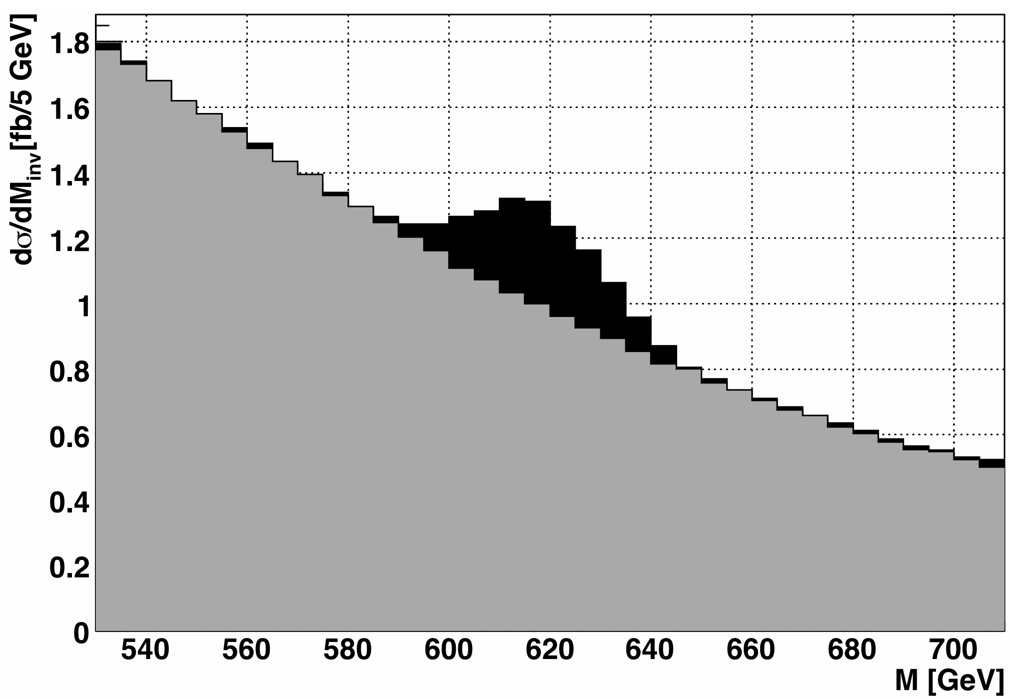
$m(h_2) = 115 \div 125\ GeV$

$h_2 \to A_1 A_1 \to 4b$

$\lambda_{low\ energy} \leq 2$



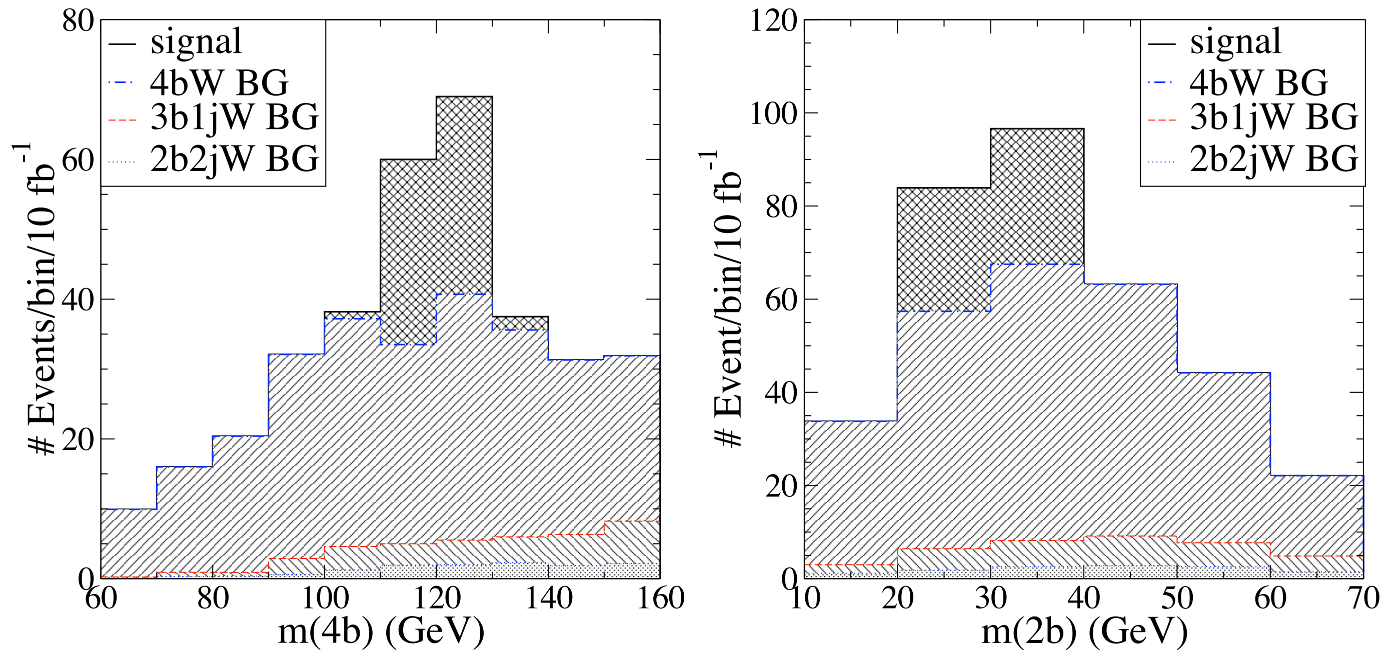
$$H \to hh \to 4V \to 2l\ 6\,jets$$



$$A \to Zh \to Z\ 2V \to 2l\ 4\,jets$$

Cavicchia, Franceschini, Rychkov

pp → V h → lν GG → lν 4b



$m_h = 120\ GeV$ $m_G = 30\ GeV$

Carena, Han, Huang, Wagner

Summary

The road map again

(my own vote)

1. Higgsless: a "conservative" view ☺

2. The "naturalness" problem of the Fermi scale

a. Supersymmetry ☺ ☺ ☺

b. Goldstone symmetry ☺ ☺

c. Gauge symmetry in extraD ☺ ☺

3. Dark Matter ☺ ☺

4. The Planck/Fermi hierarchy ⇔ extraD

a. Gravity weak by flux in extraD ☺

b. $G_F^{-1/2}/M_{Pl}$ as a red shift effect ☺

c. Symmetry breaking by boundary conditions ☺ ☺

Final Summary of signals

TENTATIVE and biased
(and obviously not all compatible with each other)

$$\boxed{\int L dt \leq 1 fb^{-1}}$$

1. *mSUGRA*
2. *gluino/stop decays*
3. *"stable" R-hadrons*
4. *light gravitino*

$B_s \to l^+ l^-$

$$\boxed{\int L dt = 1 \div 30 fb^{-1}}$$

5. *SM-like Higgs boson*
6. *KK quarks*

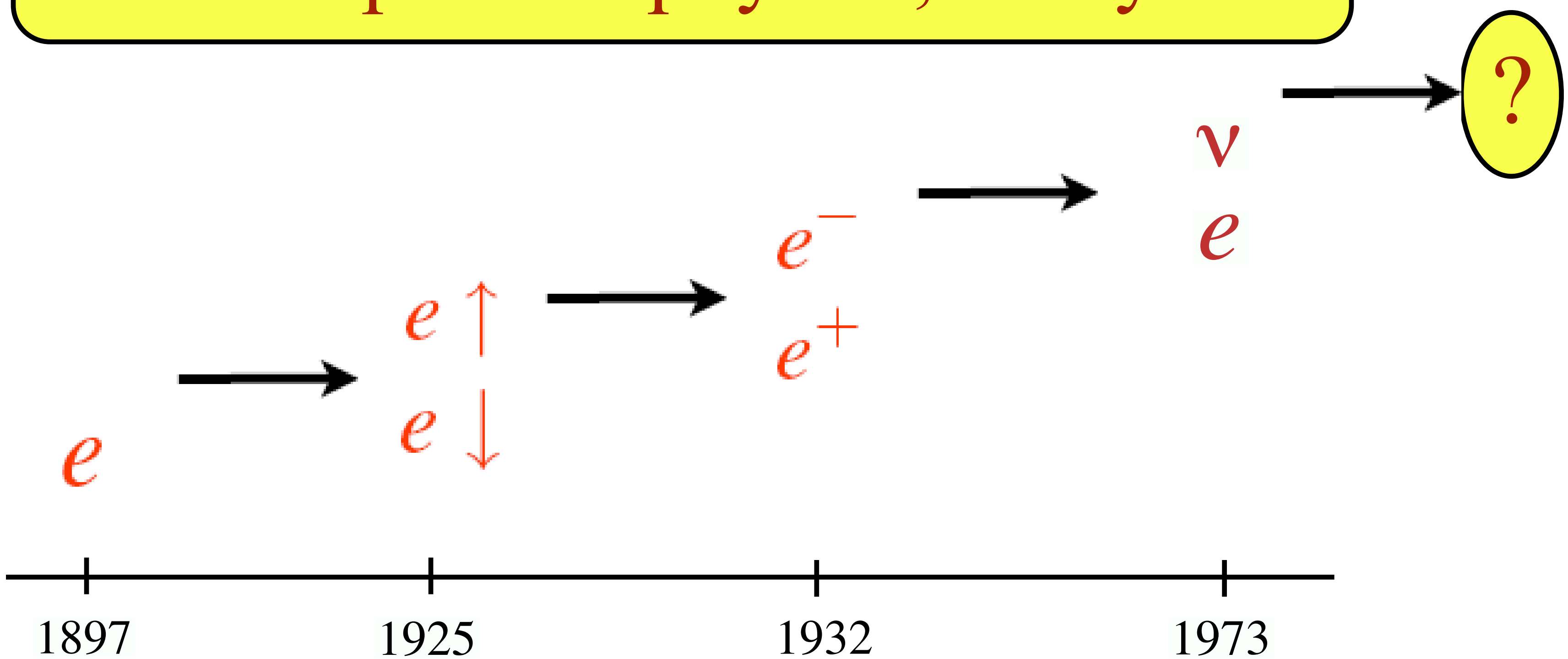
(a 15-20% consistency check between m_h and the EWPT)

$$\boxed{\int L dt \geq 30 fb^{-1}}$$

7. *ew gauge/higgs-ino decays*
8. *extra-Susy Higgs bosons*
9. *Minimal Dark Matter*
10. *KK gluons*
11. *KK W, Z*
12. *Heavy vectors*

The central question of particle physics

What is the next relevant symmetry in particle physics, if any?

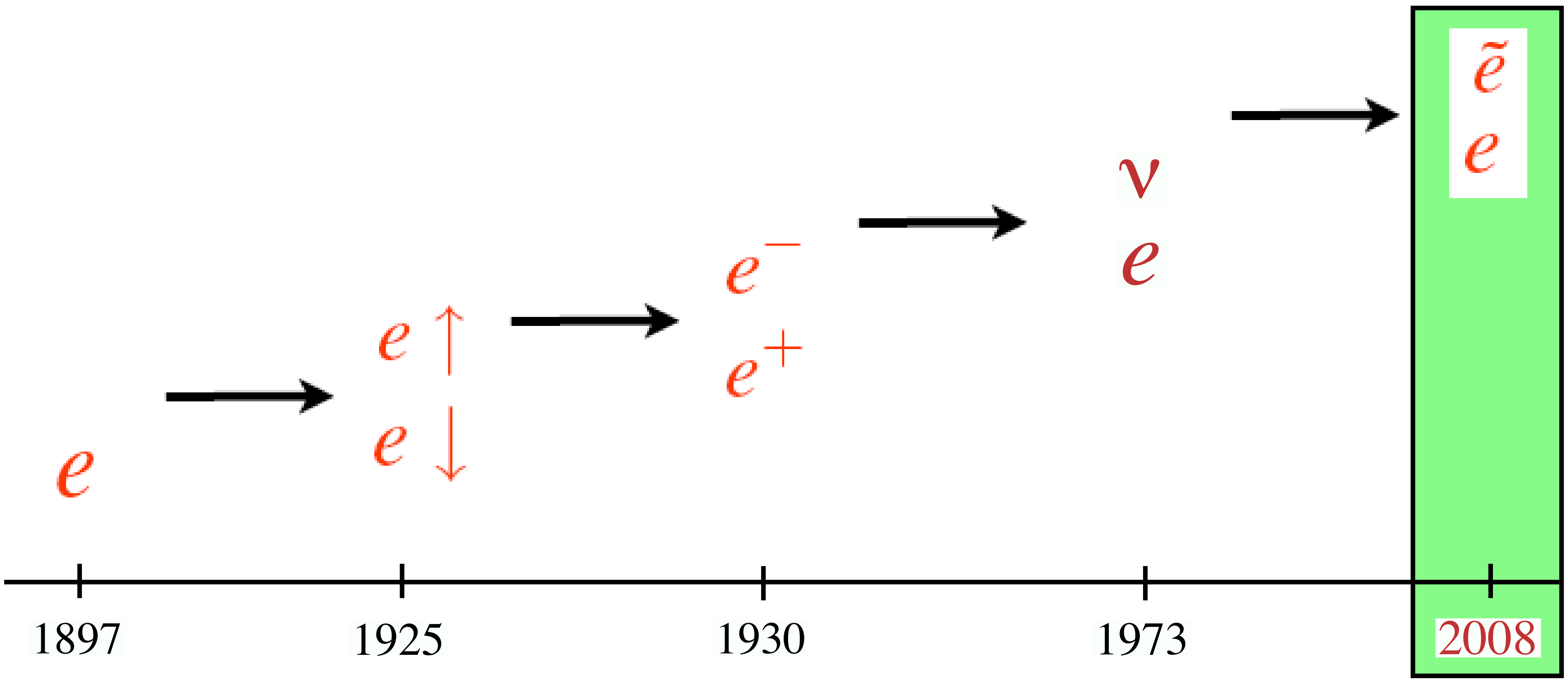


(The key to the economy of equations)

The LHC should shed some light here

The key to the economy of equations

(the merit of space-time and internal symmetries)

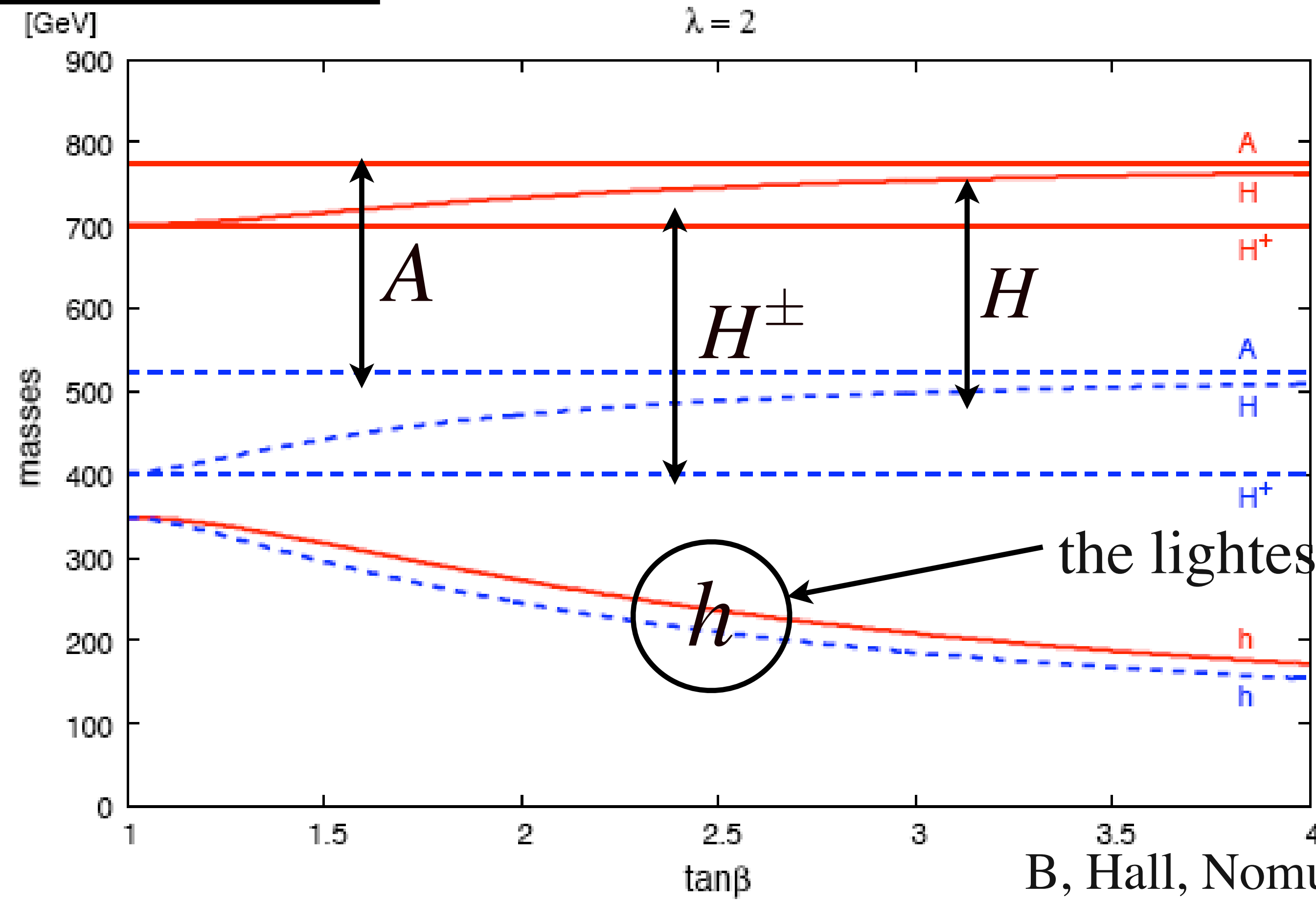


Supersymmetry as the most interesting theoretical candidate

not unique, however

$$\boxed{\lambda(G_F^{-1/2}) \approx 2}$$

The Higgs boson spectrum



B, Hall, Nomura, Rychkov

$h \to ZZ \to l^+l^- \, l^+l^-$ easy, but very much NON-susy

$H \to hh \to 4V \to l^+l^- \, 6j$

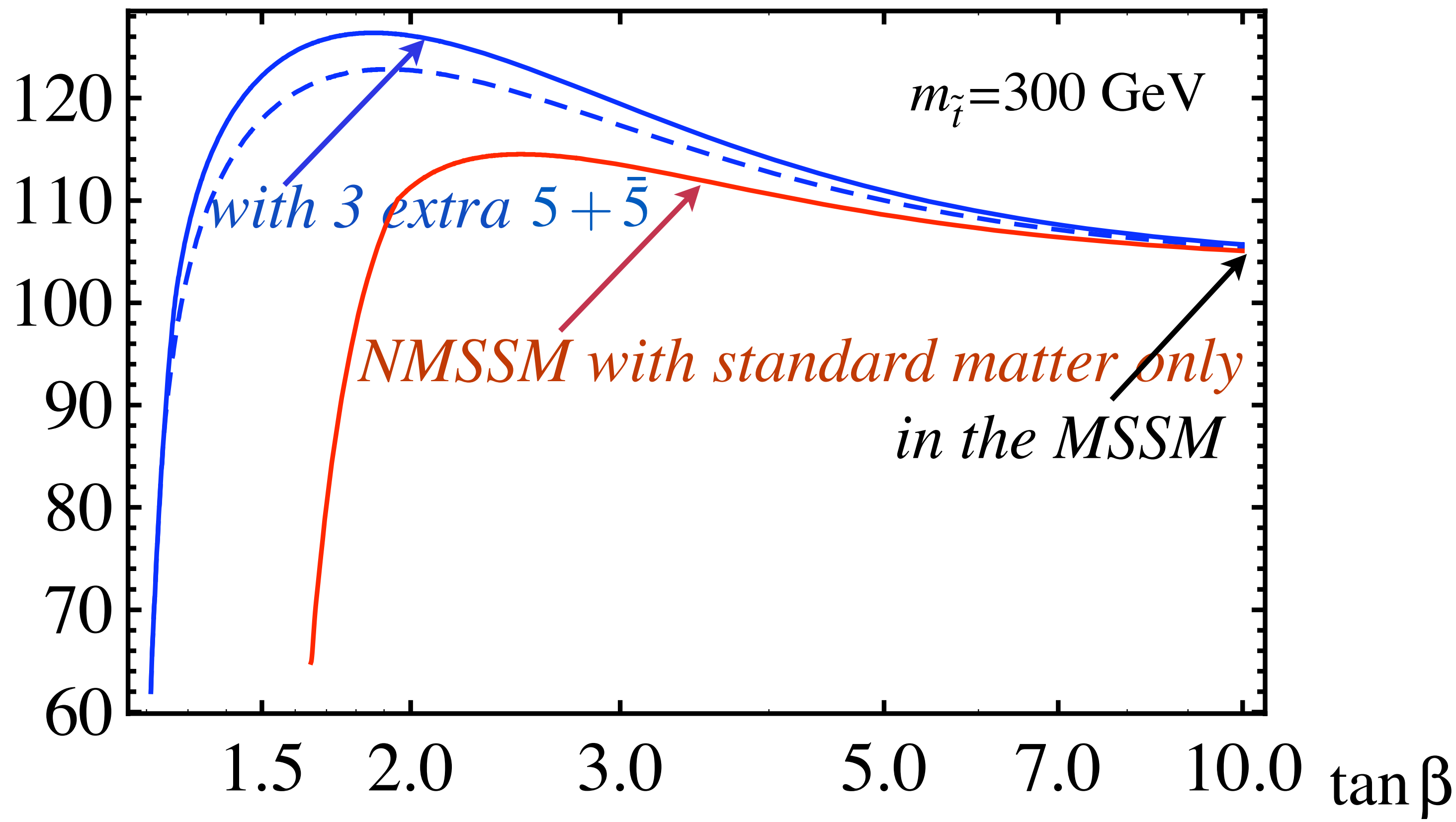
$A \to hZ \to VV\,Z \to l^+l^- \, 4j$

possible with $100 \, fb^{-1}$

Cavicchia, Franceschini, Rychkov

$$\left(\frac{\lambda}{4\pi}\right)^2(M_{GUT}) \leq 0.1$$

$m_h[GeV]_{max}$ <u>with a moderate stop mass</u>

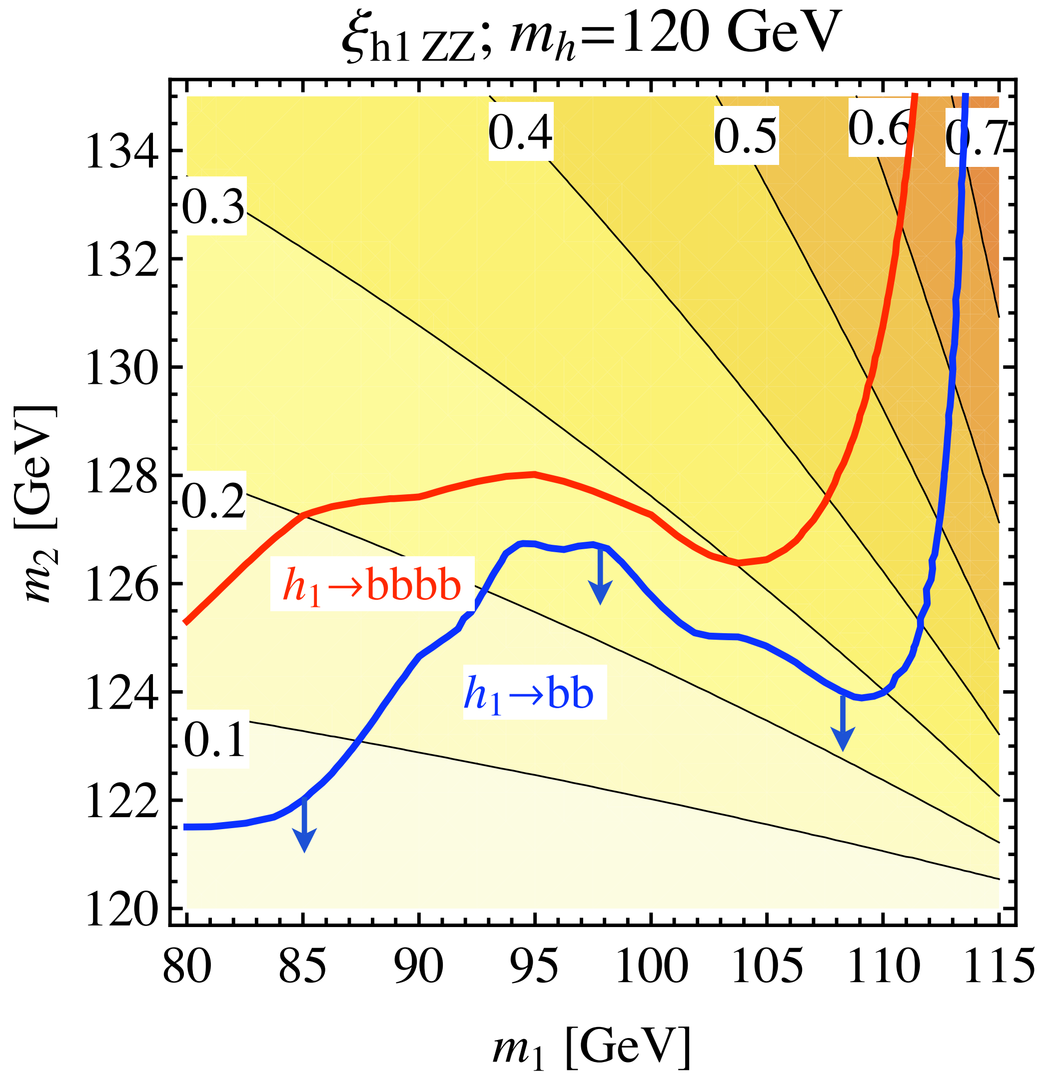


B, Hall, Pappadopulo, Rychkov, Papaioannou

$n_5 = 0$		$n_5 = 3$		
$\alpha_S(M_Z)$	α_G	$\alpha_S(M_Z)$	α_G	
0.117	0.041	**0.117**	0.103	1-loop
0.130	0.043	**0.123**	0.154	2-loop

$$\alpha_S(M_Z)|_{exp} = 0.1176(20)$$

The NMSSM with extra matter and a light stop



can rather easily be made compatible with the LEP bounds while keeping manifest perturbative unification

Partial Summary of signals

$$\boxed{\int Ldt = 1 \div 30 fb^{-1}}$$

5. SM-like Higgs boson

6. KK quarks

(a 15-20% consistency check between m_h and the EWPT)

$$\boxed{\int Ldt \geq 30 fb^{-1}}$$

10. KK gluons

11. KK W, Z

12. Heavy vectors