Three Mysteries of Matter

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Outline

- **Introduction**

  -- The great success of the Standard Model and what it fails to explain

- The Higgs Mechanism and the Origin of Mass
- Cosmology as motivation for Physics Beyond the Standard Model

  * The Baryonic Asymmetry * Dark Matter

- **TeV-scale Supersymmetry**

  -- A Window to Electroweak Baryogenesis (EWBG)

  -- Dark Matter scenarios constrained by EWBG

- Experimental Probes of SUSY scenarios

  -- the role of colliders in revealing the nature of Dark Matter and EWBG

  -- The Interplay between collider and direct Dark Matter searches

- **Conclusions**

The Standard Model

A quantum theory that describes how all known fundamental particles interact via the strong, weak and electromagnetic forces

A gauge field theory with a symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$

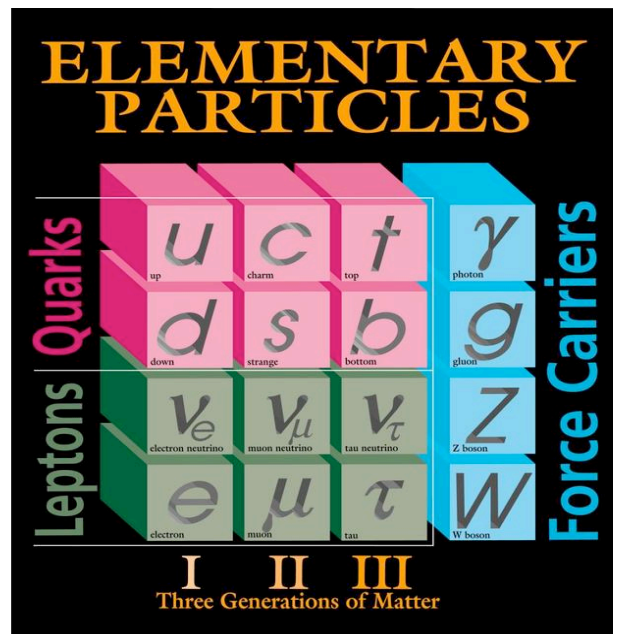
Force Carriers:

12 fundamental gauge fields:
8 gluons, 3 W_μ's and B_μ

and 3 gauge couplings: g_1, g_2, g_3

Matter fields :

3 families of quarks and leptons with the same quantum numbers under the gauge groups



SM particle masses and interactions have been tested at Collider experiments
==> incredibly successful description of nature up to energies of about 100 GeV

The Mystery of Mass

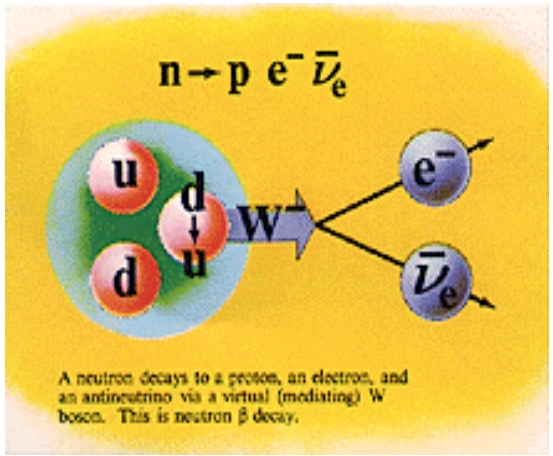
Crucial Problem in the SM: The origin of mass of all the fundamental particles

- Is not possible to give mass to the gauge bosons respecting the gauge symmetry,

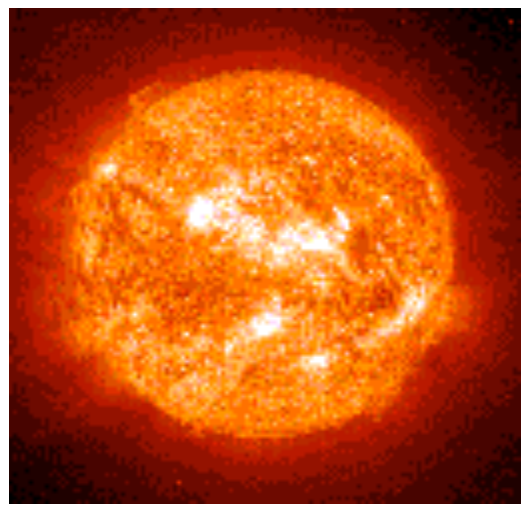
  -- massless gauge bosons ==> imply long range forces --

How to give mass to the Z and W gauge bosons?

Weak Force



Nuclear Fusion in the Sun



$$m_W = 80.449 \pm 0.034 \text{ GeV}$$

Determines strength of the weak force

↓

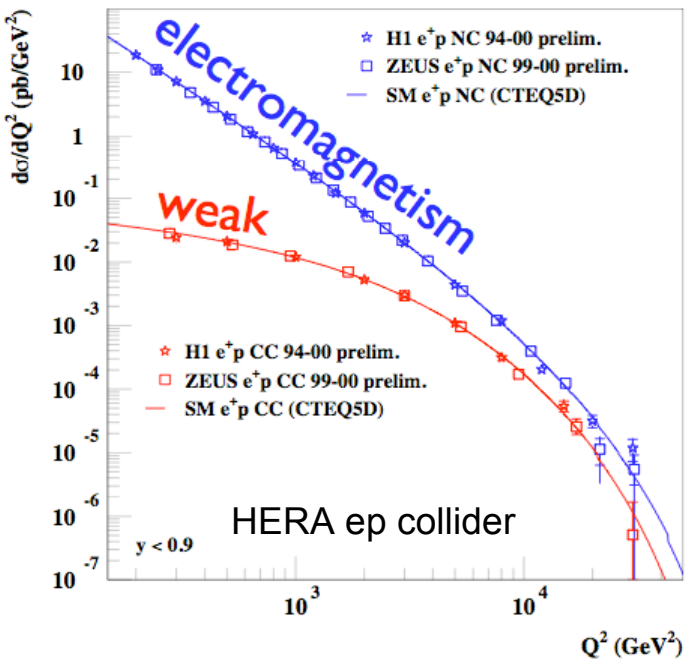
Sun still burning !

- A fermion mass term $L = m\,\bar{\psi}\psi = m\,(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$ is forbidden because it would mix left- and right-handed fermions which have different quantum numbers

The gauge symmetries of the model do not allow to generate mass at all!

•What is the origin of Mass of the Fundamental Particles ?
or
the source of Electroweak Symmetry Breakdown (EWSB)

- There is a Field that fills all the Universe
  - -- it does not disturb gravity and electromagnetism but it renders the weak force short-ranged
  - -- it slows down the fundamental particles from the speed of light



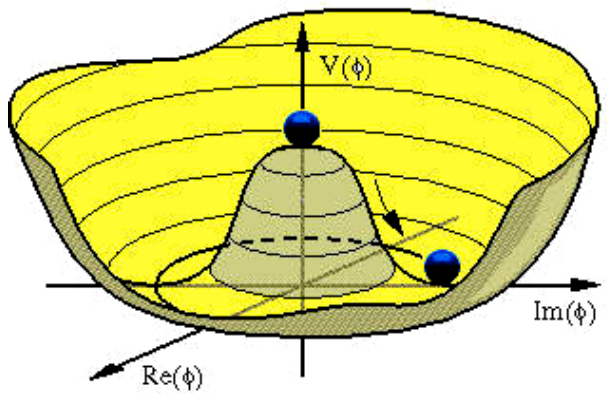
The electromagnetic and weak forces are unified
==> electroweak theory

what breaks the symmetry
==> the mysterious Field

EWSB occurs at the electroweak scale
New phenomena should lie in
the TeV range or below
within LHC/ILC reach

The Higgs Mechanism

A self interacting complex scalar doublet with no trivial quantum numbers under $SU(2)_L \times U(1)_Y$



The Higgs field acquires non-zero value to minimize its energy

$$V(\Phi) = \mu^2 \Phi^+ \Phi + \frac{\lambda}{2}\left(\Phi^+ \Phi\right)^2 \qquad \mu^2 < 0$$

Higgs vacuum condensate v ==> scale of EWSB

- Spontaneous breakdown of the symmetry generates 3 massless Goldstone bosons which are absorbed to give mass to W and Z gauge bosons

- Higgs neutral under strong and electromagnetic interactions exact symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ ==> $SU(3)_C \times U(1)_{em}$

$$m_\gamma = 0 \quad m_g = 0$$

- Masses of fermions and gauge bosons proportional to their couplings to the Higgs

$$M_V^2 = g_{\phi VV}\, \mathrm{v}/2 \qquad m_f = \mathrm{h_f}\ \mathrm{v}$$

- One extra physical state -- Higgs Boson -- left in the spectrum

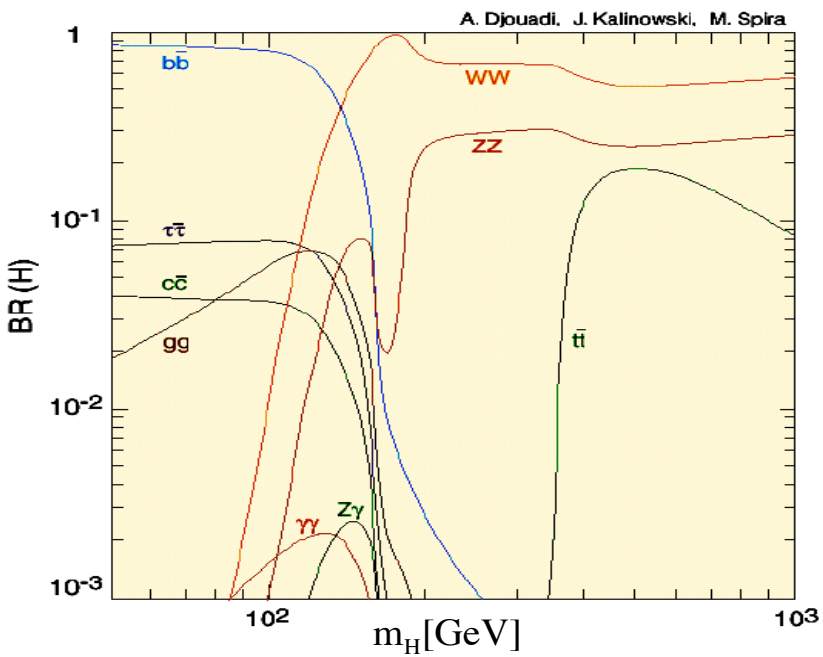
$$m_{H_{SM}}^2 = 2\lambda\ \mathrm{v}^2$$

Discovering the Higgs will put the final piece of the Standard Model in place

It will prove that our simplest explanation for the origin of mass is indeed correct.

How do we search for the Higgs?

Through its decays into gauge bosons and fermions



Depending on its mass the Higgs will decay into different particles

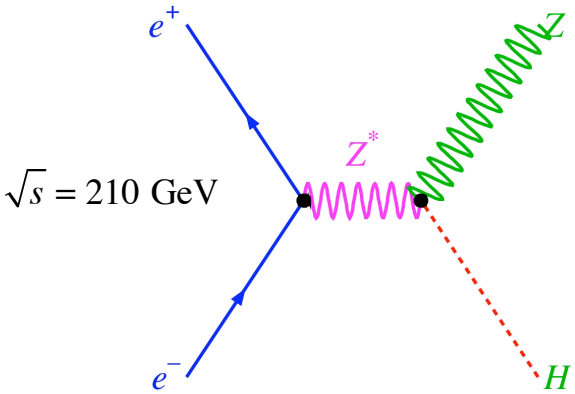
Consistency of the theory implies

$$m_{H_{SM}} < 1 \text{ TeV}$$

First evidence of EWSB ==> masses of gauge bosons

==> we need to detect the Higgs in association with the W and Z gauge bosons to identify it as the agent of EWSB

- **Direct SM Higgs search at the Large Electron-Positron collider** (LEP)



with $H_{SM} \to b\bar{b}, \tau^+\tau^-; \quad Z \to q\bar{q}, l^+l^-, \nu\bar{\nu}$

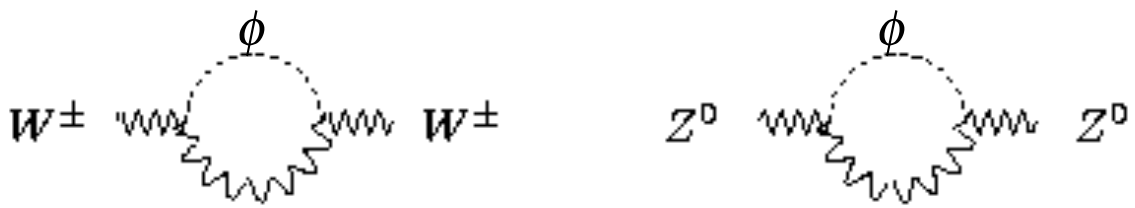
final LEP result, 2003

$m_{H_{SM}} > 114.6$ GeV at 95% C.L.

- **Indirect constraints on $m_{H_{SM}}$ from precision tests of the SM**

accuracy at the per mille level from experiments at CERN, Fermilab and SLAC

The Higgs boson enters via virtual Higgs production in electroweak observables: particle masses, decay rates,etc



logarithmic dependence on the Higgs mass: $m_{H_{SM}} < 200$ GeV at 95 % C.L

To circumvent this constraint on $m_{H_{SM}}$ requires new phenomena below 1 TeV

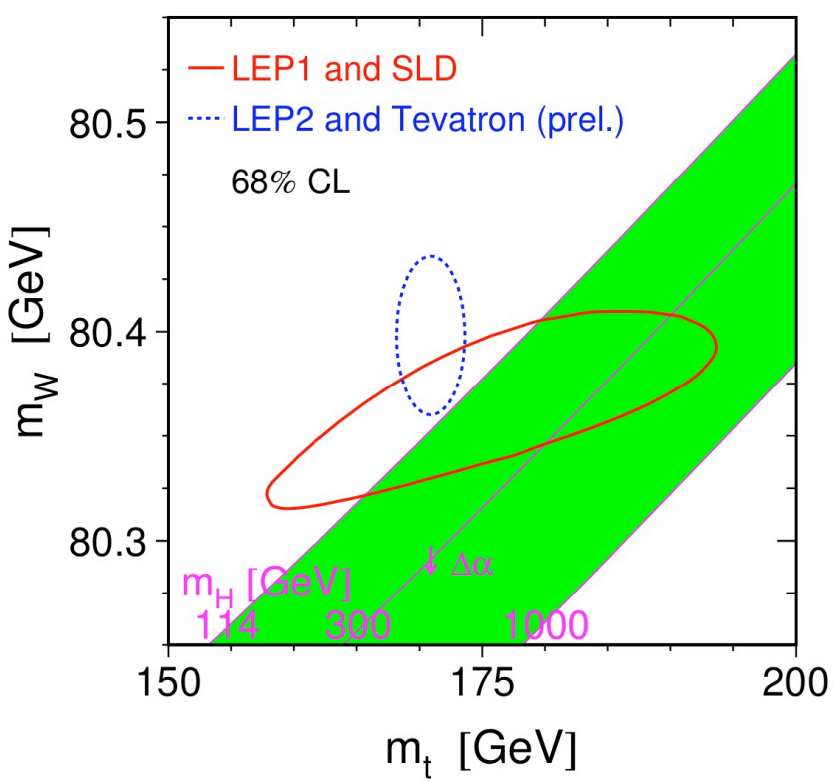
The TeVatron at Fermilab (2001-2009)

at present: the highest energy accelerator in the world $\Rightarrow p\bar{p}\ at\ \sqrt{s} = 1.96\ \mathrm{TeV}$

Precise measurements of M_t and M_w

==> an indirect search for the SM Higgs

- **Precision measurements of the top quark and W boson masses may exclude the SM at/above the TeV scale**

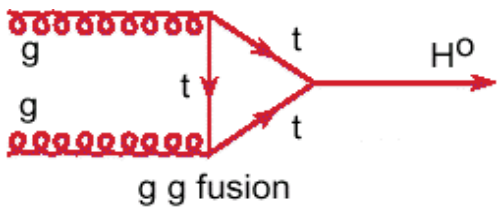


SM correlation for M_t-M_w-$m_{H_{SM}}$

New CDF/D0 top mass (170.9 ± 1.8 GeV)
plus the newest combined LEP and Tevatron
measurement of the W mass (80.398 ± 0.025 GeV)

LEPEWWG '07; TEVEWWG '07

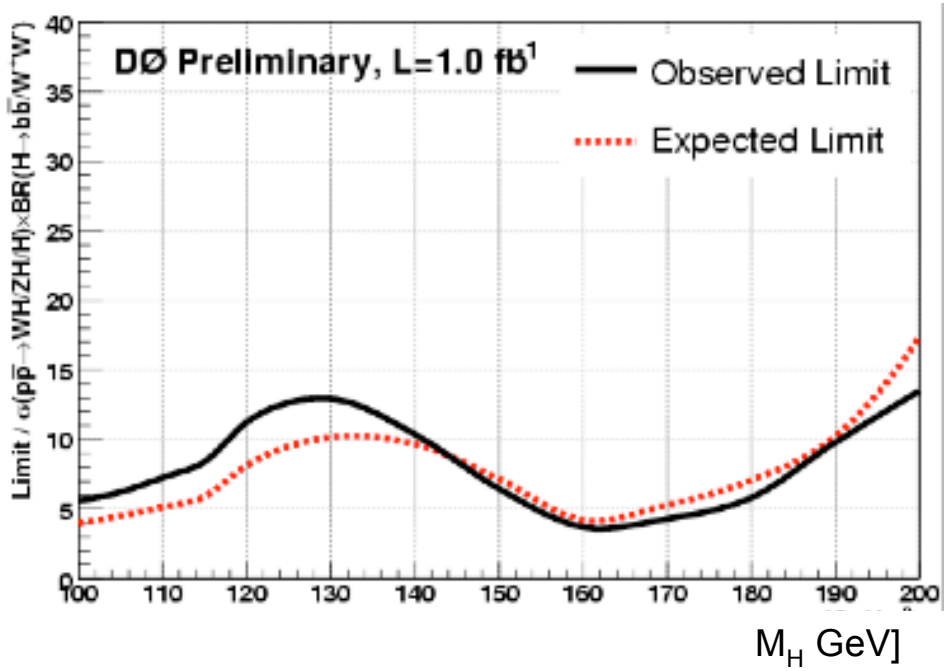
Direct Higgs searches at the Tevatron



with $H \rightarrow WW$

with $H \rightarrow b\bar{b}$, WW

- Tevatron can search for a Higgs in most of the mass range preferred by precision data



With ongoing improvement in sensitivity + two detectors

Probe of a Higgs with mass = 115 GeV → 2.5 fb^{-1}

160 GeV → ~3 fb^{-1}

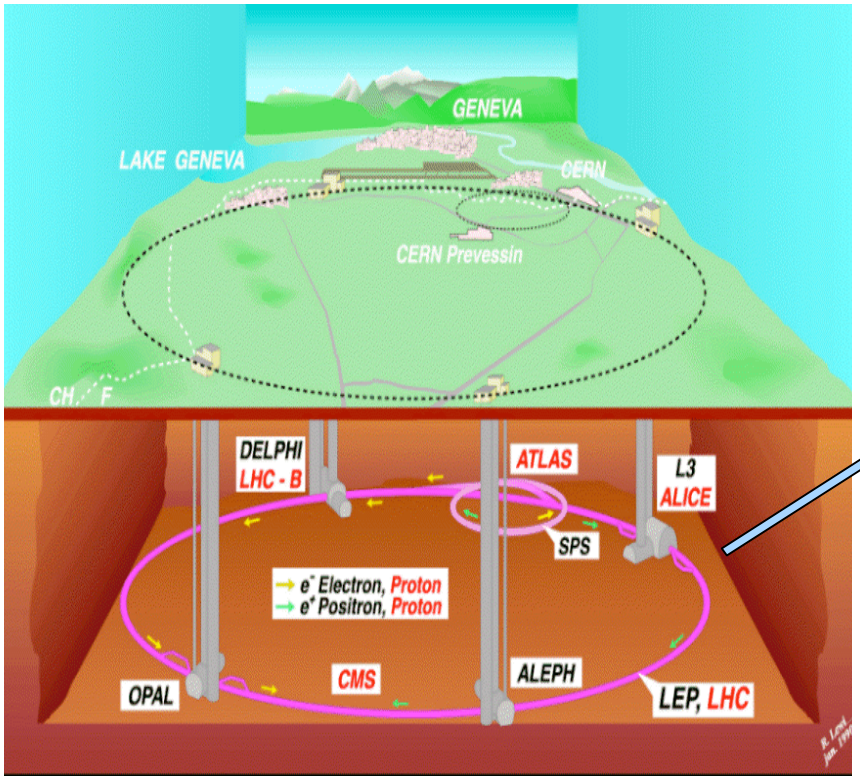
Ultimate Tevatron Luminosity: 4-8 fb^{-1} → Quite challenging!

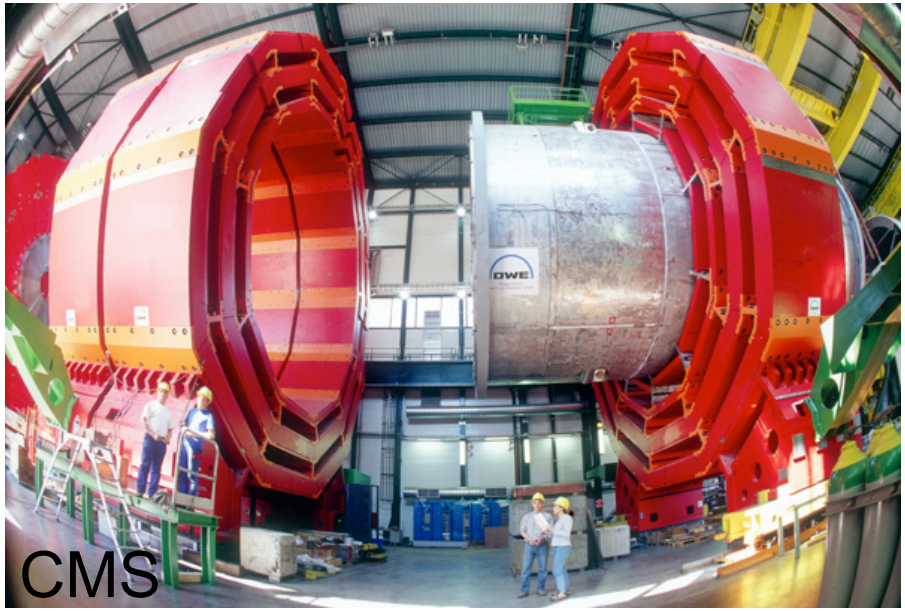
Evidence of a signal will mean that the Higgs has SM-like couplings to the W and Z

The Large Hadron Collider

starts in 2008, opens a new high-energy frontier for physics

pp at $\sqrt{s} = 14$ TeV

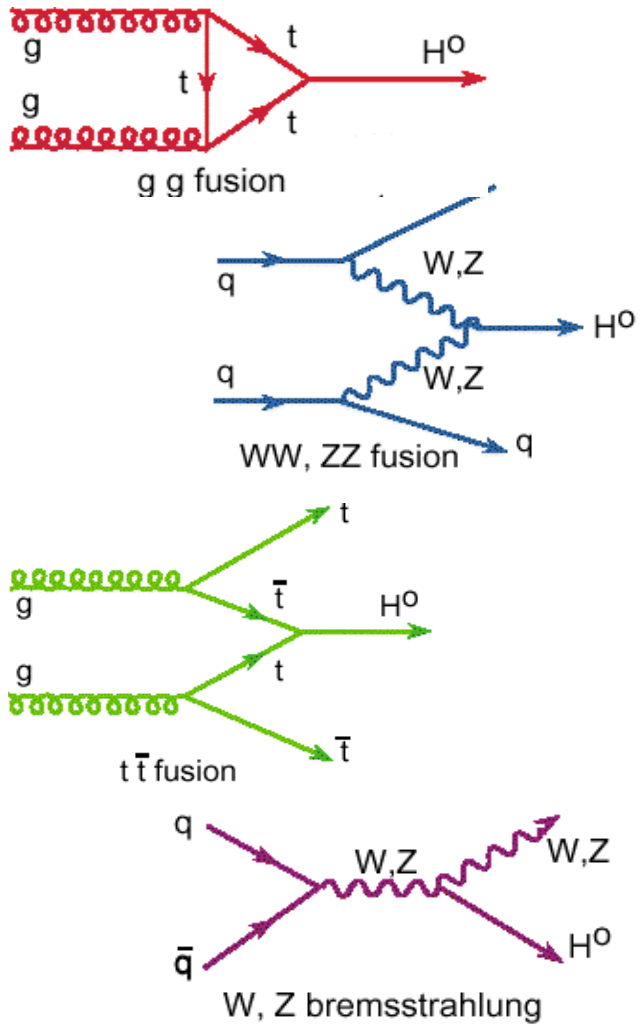




~ a billion proton-proton collisions per second!

2 multi-purpose detectors ATLAS and CMS

The search for the Standard Model Higgs at the LHC

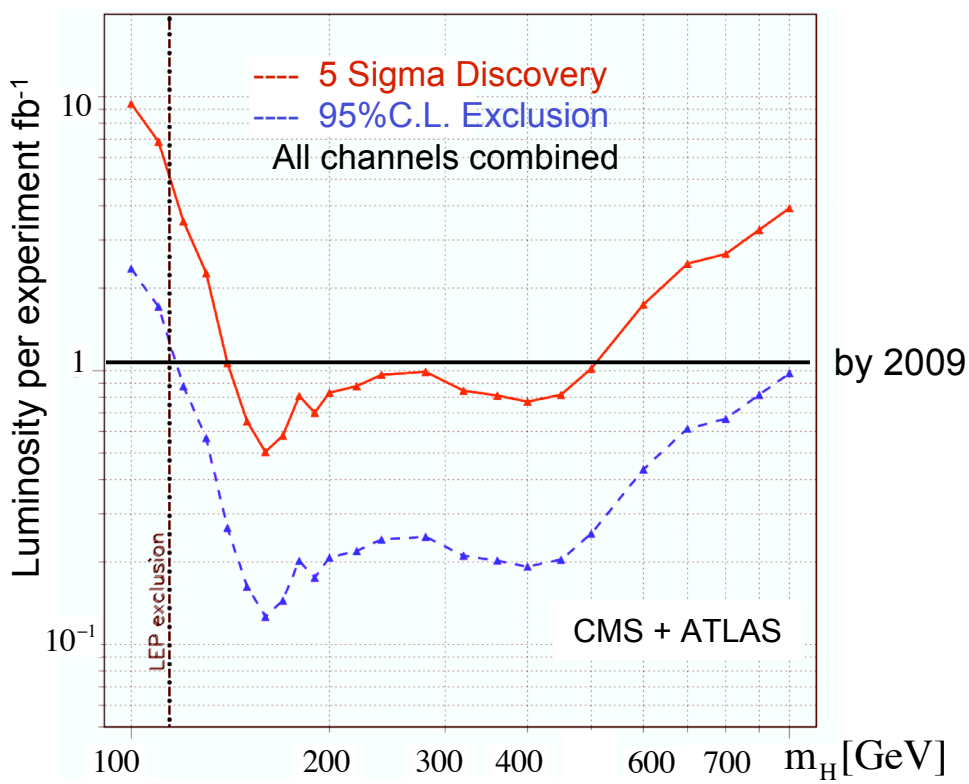


- **Low mass range** $m_{H_{SM}} < 200$ GeV

$$H \to \gamma\gamma, \tau\tau, bb, WW, ZZ$$

- **High mass range** $m_{H_{SM}} > 200$ GeV

$$H \to WW,\ ZZ$$

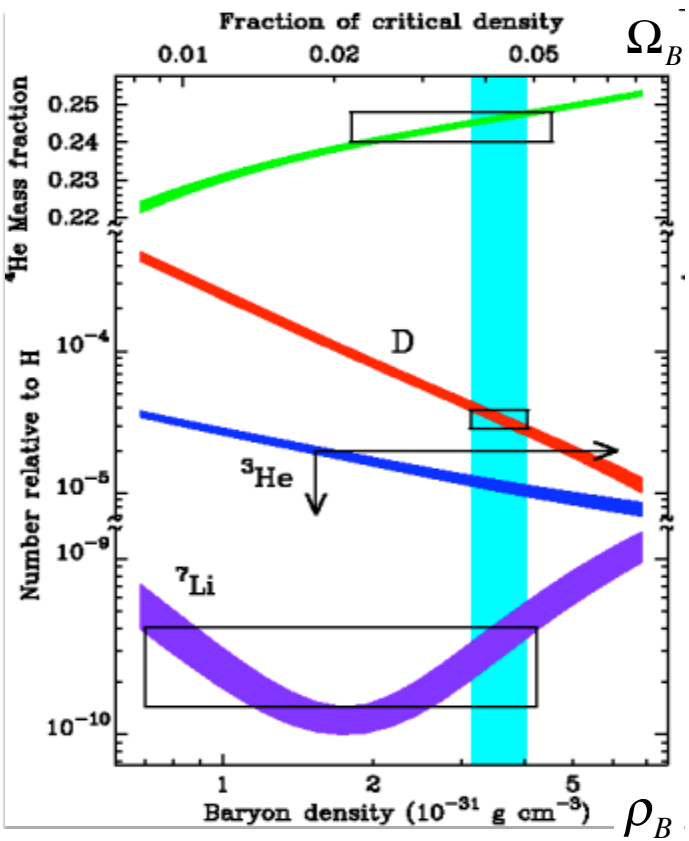


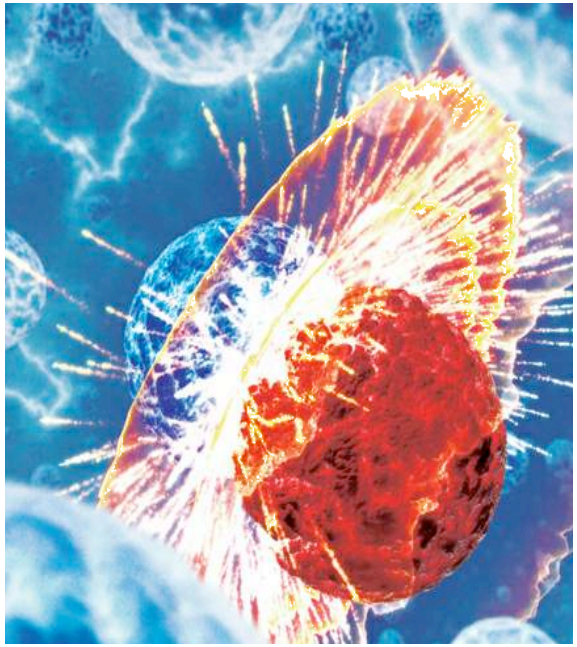
A Standard Model Higgs cannot escape detection at the LHC !

The Mystery of the Matter-Antimatter Asymmetry

- Abundance of primordial elements
- Predictions from Big Bang Nucleosynthesis

$$\eta = n_B / n_\gamma \approx 6.10^{-10}$$





Anti-matter is governed by the same interactions as matter.

- Baryons, antibaryons and photons equally abundant in the early universe
- To remove preferentially antimatter, the CP symmetry relating B to $\bar{B}$ must be violated
- No net Baryon number if B conserved at all times

What generated the small observed baryon--antibaryon asymmetry ?

Baryogenesis in the Standard Model

Sakharov's Conditions

- **Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Baryon Number Violation at finite Temperature

Anomalous processes violate both B and L number, but preserve B-L.

- *At T = 0, Baryon number violating processes highly suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \exp(-2\pi / \alpha_W)$$

- *At very high temperatures they are highly unsuppressed*

- *At finite Temperature, only Boltzman suppressed*

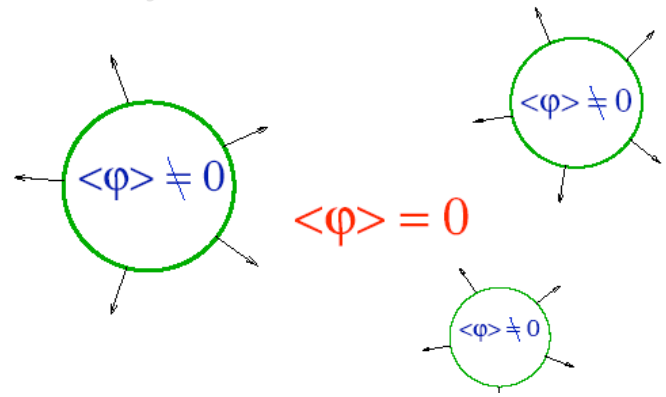
$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, T \exp(-E_{sph}(T) / T) \qquad E_{sph} \cong 8 \pi \, v(T) / g$$

Klinkhammer and Manton'84; Arnold and Mc Lerran'88, Khlebnikov and Shaposhnikov '88

Baryon Asymmetry Preservation at the Electroweak Phase Transition

Kuzmin, Rubakov and Shaposhnikov, '85-'87
Cohen, Kaplan and Nelson '93 Riotto, Trodden'99
M.C, Quiros, Riotto, Vilja, Wagner, Moreno,Seco97-02

- Start with B=L=0 at T>Tc
- CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. Sphaleron processes create net baryon asymmetry.
- Net Baryon Number diffuse in the broken phase



If $n_B \neq 0$ generated at Tc

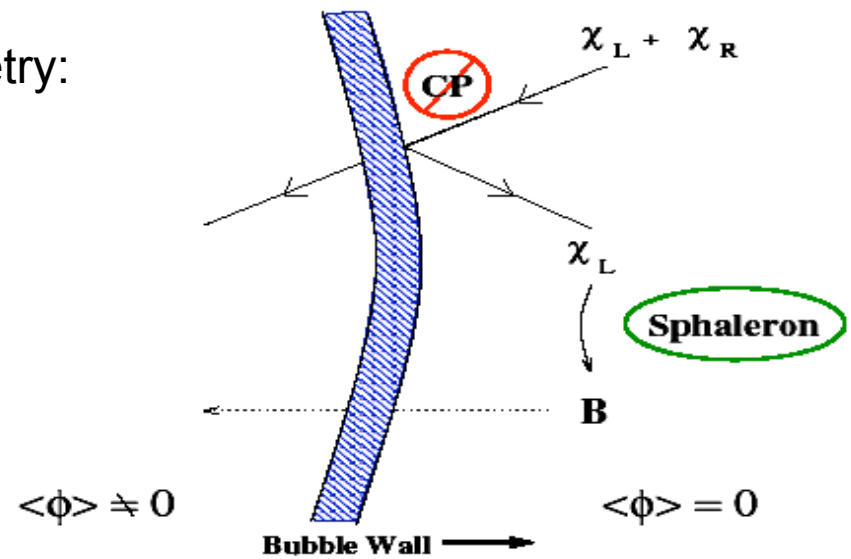
$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{T_c(\mathrm{GeV})} \exp\left(-\frac{E_{sph}(T_c)}{T_c}\right)\right)$$

To preserve the generated baryon asymmetry:
strong first order phase transition:

$$v(T_c)/T_c > 1$$

Shaposhnikov '86-'88

Baryon number violating processes out of equilibrium in the broken phase

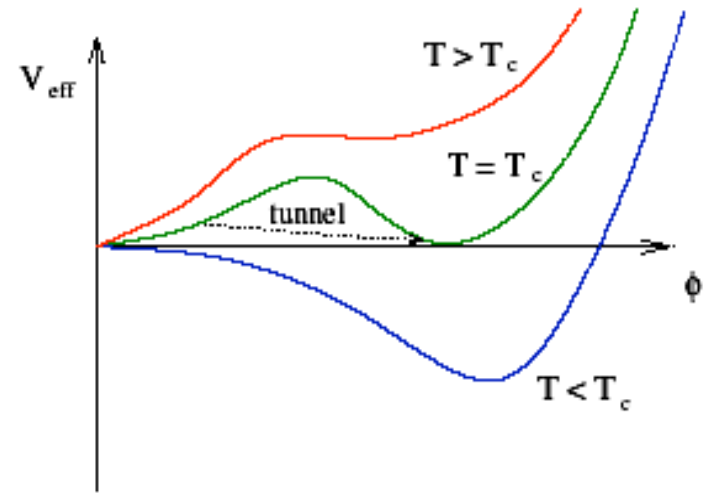


Finite Temperature Higgs Potential

$$V = D(T^2 - T_0^2)H^2 + E_{SM} T H^3 + \lambda(T) H^4$$

- D term is responsible for the phenomenon of symmetry restoration
- E term receives contributions proportional to the sum of the cube of all light boson particle masses

$$\text{and} \quad \frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$



Since in the SM the only bosons are the gauge bosons and the quartic coupling is proportional to the square of the Higgs mass

$$\boxed{\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40\ \text{GeV} \ \Rightarrow \ \text{ruled out by LEP}}$$

- **Independent Problem: not enough CP violation**

Farrar and Shaposhnikov, Gavela et al., Huet and Satter

Electroweak Baryogenesis in the SM is ruled out

- Electroweak Baryogenesis is a cool idea

… but, for it to work demands Physics Beyond the Standard Model

The SM of particle physics works amazingly well

But COSMOLOGY gives the first unambiguous evidence for New Physics

Dark Matter (or a modification of gravity ?)

→

- Non-Baryonic
- Stable
- Cold

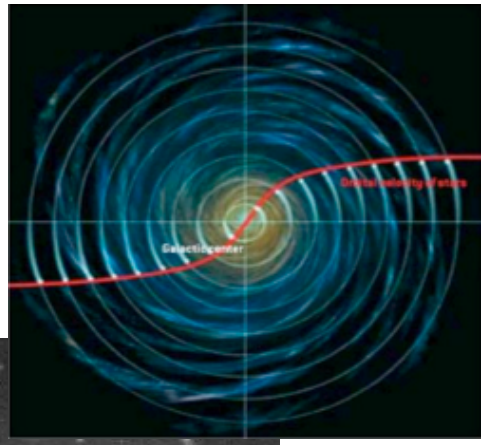
The SM has no suitable candidates

- Leptons, hadrons: too little
- Neutrinos: too light
- Photons: $\Omega_{rad.} \approx 10^{-4}$
- W/Z bosons: not stable

Why should an effective model of particle physics explain Dark matter?

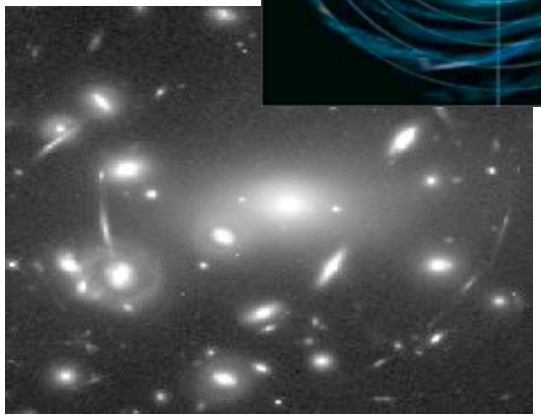
The idea of DM seems naturally connected
to the phenomena of electroweak symmetry breaking

The Mystery of Dark Matter



- Rotation curves from Galaxies.

  Luminous disk → not enough mass to explain rotational velocities of galaxies → Dark Matter halo around the galaxies

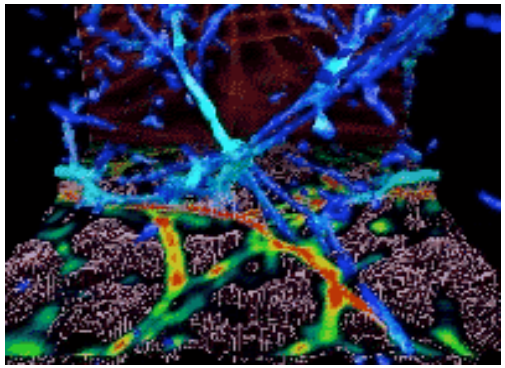


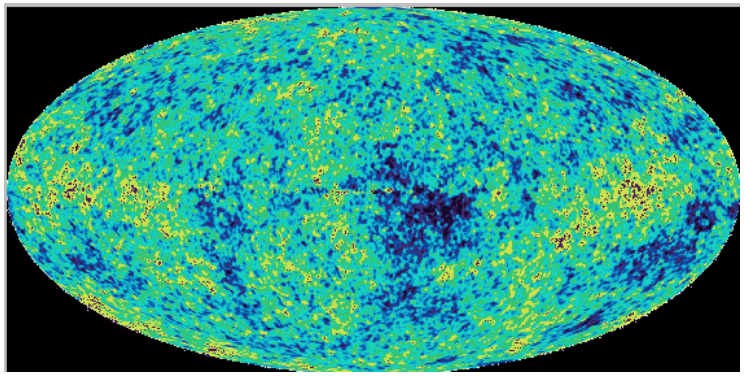
- Gravitational lensing effects

Measuring the deformations of images of a large number of galaxies, it is possible to infer the quantity of Dark Matter hidden between us and the observed galaxies

- Structure formation:

Large scale structure and CMB Anisotropies





The manner in which structure grows depends on the amount and type of dark matter present. All viable models are dominated by cold dark matter.

Cosmology data ↔ Dark Matter ↔ New physics at the EW scale

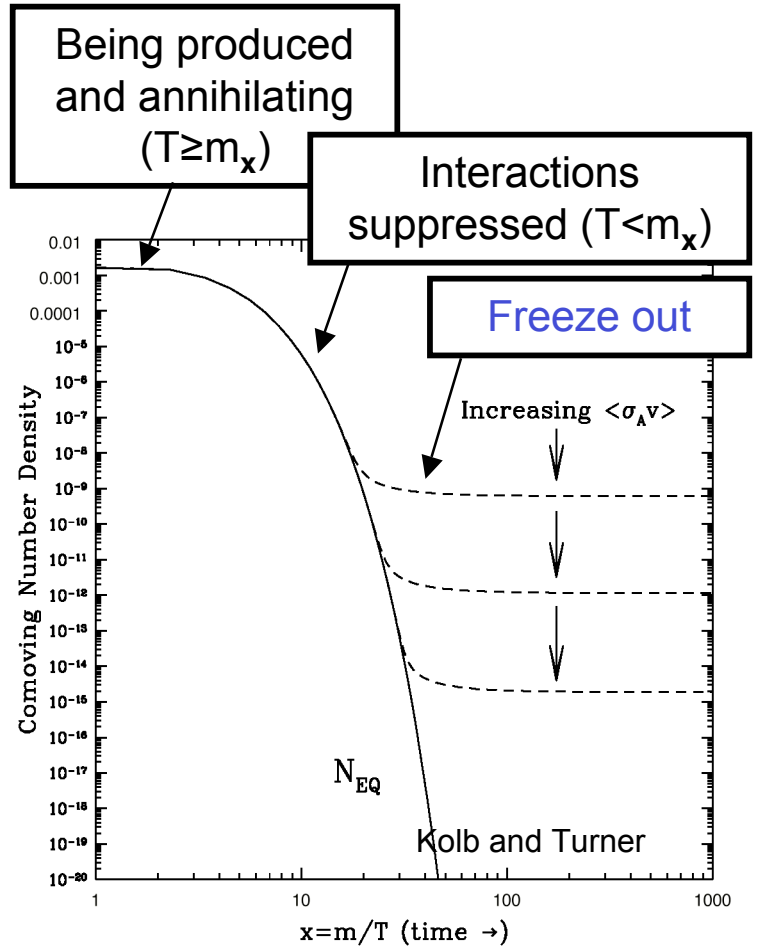
Evolution of the Dark Matter Density

- Heavy particle initially in thermal equilibrium
- Annihilation stops when number density drops

$$H > \Gamma_A \approx n_\chi < \sigma_A v >$$

- i.e., annihilation too slow to keep up with Hubble expansion ("freeze out")
- Leaves a relic abundance:

$$\Omega_{DM} h^2 \approx \; < \sigma_A v >^{-1}$$



If m_x and σ_A determined by electroweak physics,

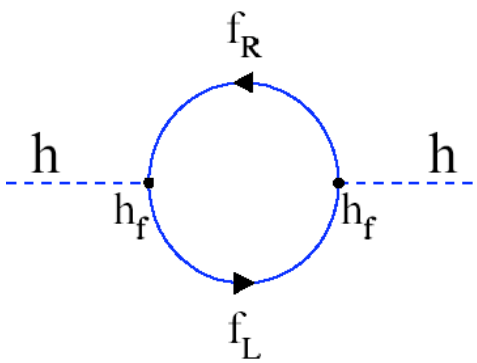
$$\sigma_A \approx k\alpha_W^2 / m_X^2 \approx \text{a few pb}$$

then Ω_{DM}~0.1 for m_x~0.1-1 TeV

Remarkable agreement with WMAP-SDSS → $\Omega_{DM} = 0.104 \pm 0.009$

The EWSB mechanism + Collider data ⟷ Dark Matter

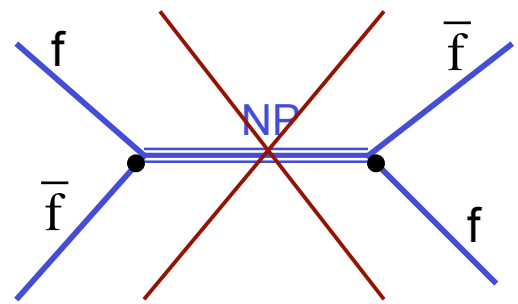
EWSB scale << M_{Pl} → Hierarchy problem



Quantum corrections to the Higgs potential mass parameter μ are quadratically divergent

Need new particle/s with masses of order of the EWSB scale to cancel them

Precision data from LEP, SLD and Tevatron preclude the existence of new particles singly produced with masses below a few TeV



Most models of EWSB introduce an extra discrete symmetry which predicts a stable Weakly Interacting Massive Particle (WIMP)

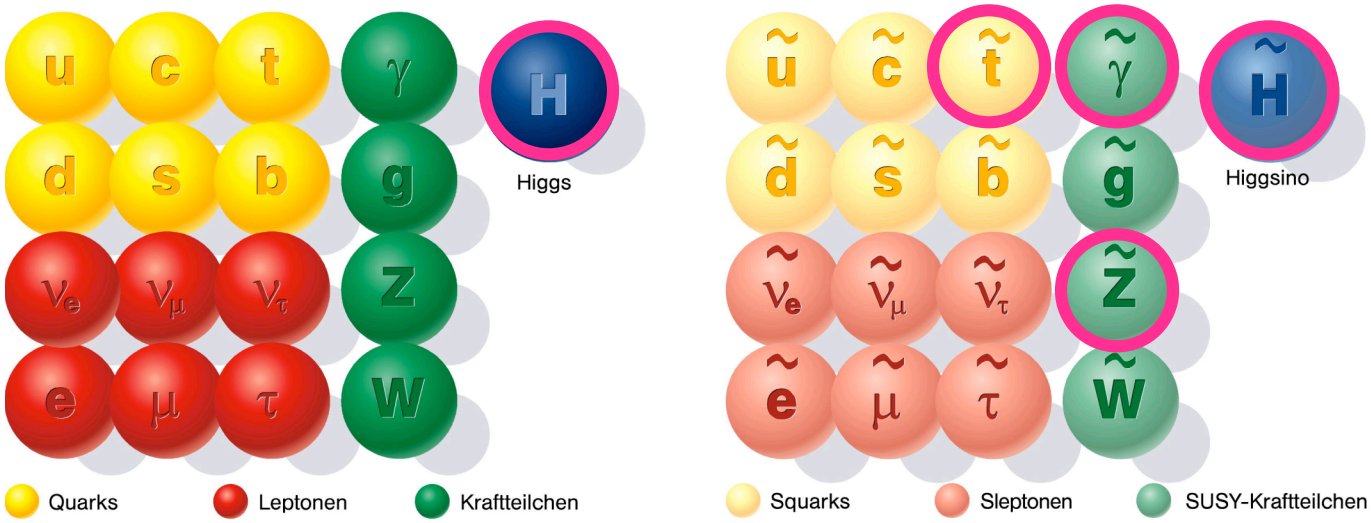
To avoid major fine tuning in the EWSB theory
Precision collider data predict the existence of a WIMP
→ Dark Matter

New Fermion-Boson Symmetry: **SUPERSYMMETRY** (SUSY)

==> For every fermion there is a boson with equal mass and couplings

Just as for every particle there exists an antiparticle

SM particles ⟷ **SUSY particles**



Minimal Higgs sector: 2 CP-even h (SM-like), H + 1 CP-odd A + 1 charged pair $H^{\pm}$

Upper bound on SM-like Higgs mass: m_h < 135 GeV → **stringent test of the minimal model**

SUSY must be broken in nature:
no SUSY partner degenerate in mass with its SM particle has been observed

Low energy supersymmetry ⟶ SUSY particles at the TeV Scale

◈ SUSY is well motivated on purely particle physics grounds

- Stabilization of the electroweak scale
- Radiative breaking of the EW symmetry
- Unification of Gauge Couplings

◈ SUSY and Cosmology :

Dark Matter

SUSY with R-parity discrete symmetry conserved ⟶ $R_P = (-1)^{3B+L+2S}$

naturally provides a neutral stable DM candidate: LSP ⟶ $\tilde{\chi}^0$

The LSP annihilation cross section is typically suppressed
for most regions of SUSY spectrum ⟶ too much relic density

Cosmology excludes many SUSY models!

Baryon Asymmetry

- New CP violating Phases can arise when SUSY is softly broken
- Electroweak baryogenesis possible in Minimal SUSY SM extensions

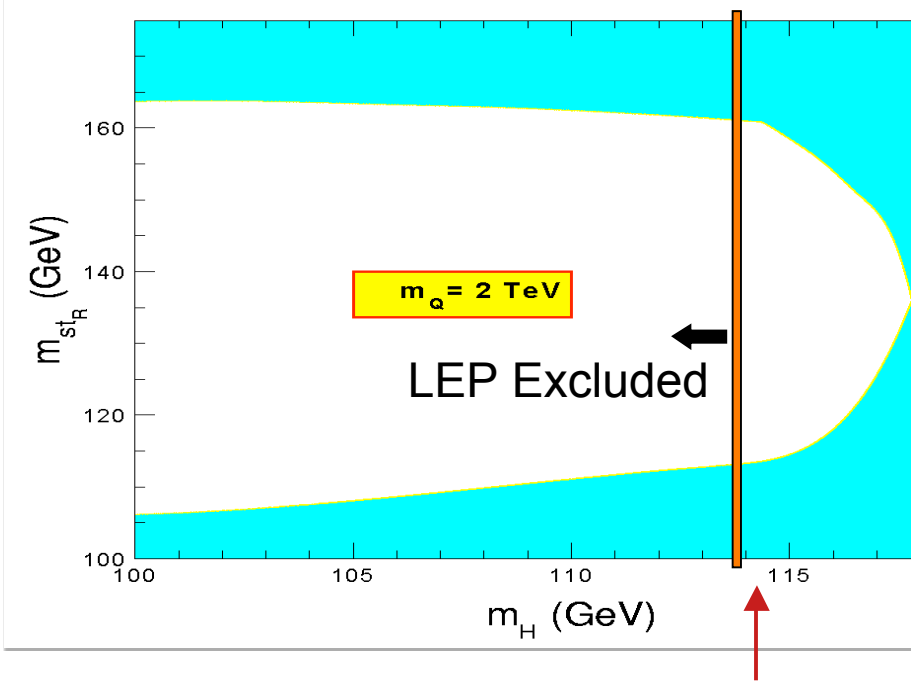
Can SUSY explain both Mysteries of Matter?

Baryogenesis in the Minimal SUSY extension of the SM (MSSM):

- New bosonic degrees of freedom: superpartners of the top quark, with strong couplings to the Higgs: $\Rightarrow E_{SUSY} \approx 8\, E_{SM}$

Sufficiently strong first order phase transition to preserve generated baryon asymmetry

- **Higgs masses up to 120 GeV**
- **The lightest stop must have a mass below the top quark mass**



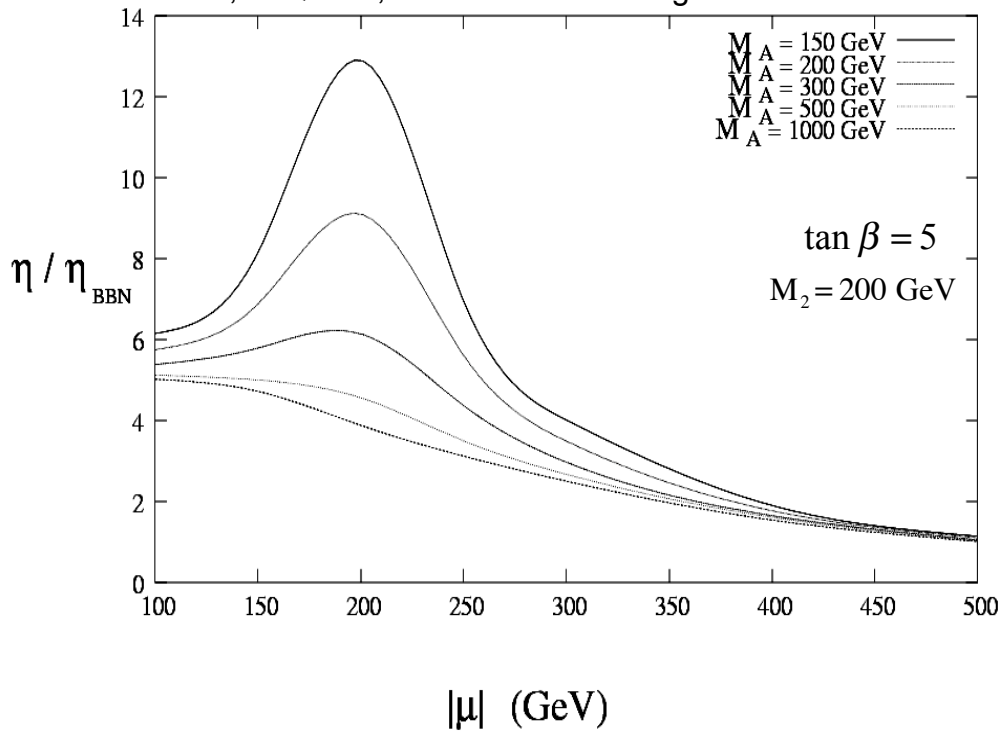
M.C, Quiros, Wagner

Present LEP bounds on the SM- like Higgs mass

$$m_{H_{SM-like}} > 114.6 \text{ GeV}$$

Baryon Asymmetry Dependence on the Chargino Mass Parameters

M.C., M.Quiros, M. Seco and C. Wagner



- New CP violating phases are crucial

Results for maximal CP violation

$$\sin(\arg(\mu\, M_2)) = 1$$

μ Higgsino mass; $M_{1,2} \rightarrow$ Bino,Wino masses

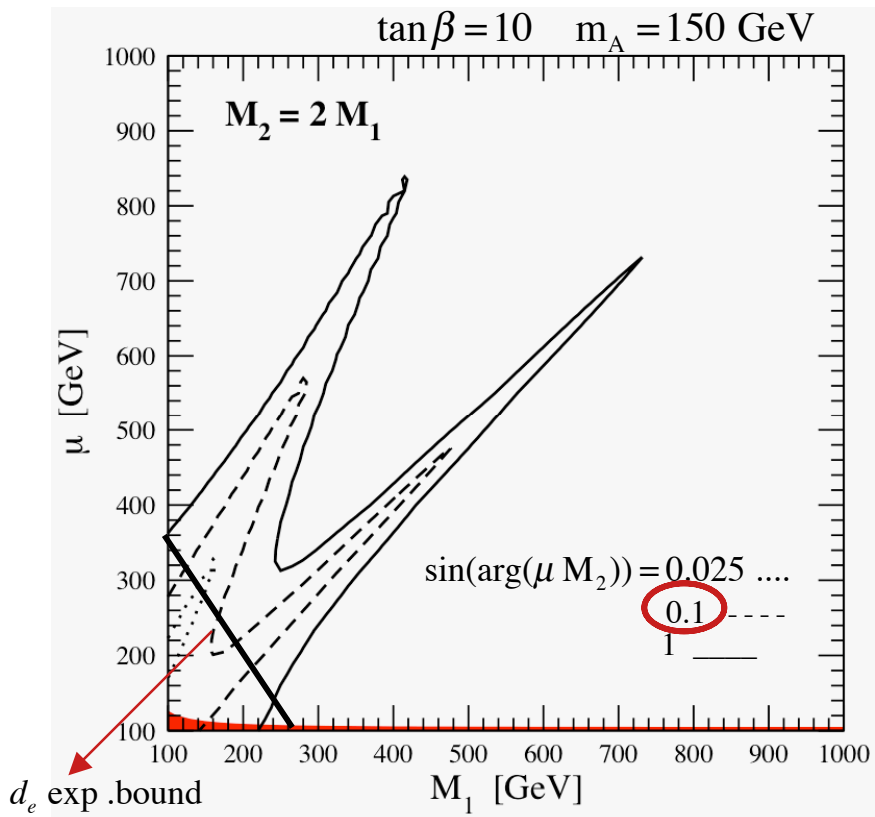
- Gaugino and Higgsino masses of order of the weak scale highly preferred

- Results scale with $\sin(\arg(\mu\, M_2))$ and linearly decrease with $\tan\beta$

Baryon Asymmetry Enhanced for: $M_2 = |\mu|$ ***and smaller values of*** m_A

Acceptable values of the baryonic density for
a sizeable range of SUSY particle masses and CP violating phases of order 0.1 to 1

- Considering also contributions from CP violating currents involving the lightest neutralino ⟶ depend on $\sin(\arg(\mu\, M_1))$, with resonant behavior for $|\mu| \approx M_1$



This region of parameter space leads to a very efficient pair annihilation:

LSP is a Higgsino-bino admixture

==> relic density too low

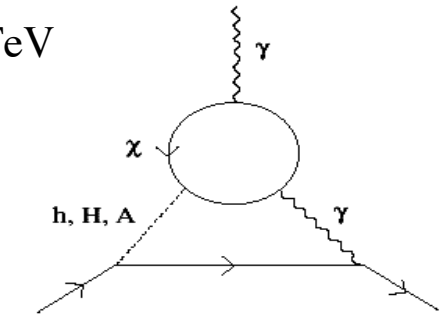
neutralino driven EWBG would demand some enhancement mechanism

Cirigliano, Profumo, Ramsey-Musolf'06

Phases in the MSSM EWBG scenario very constrained by EDM limits

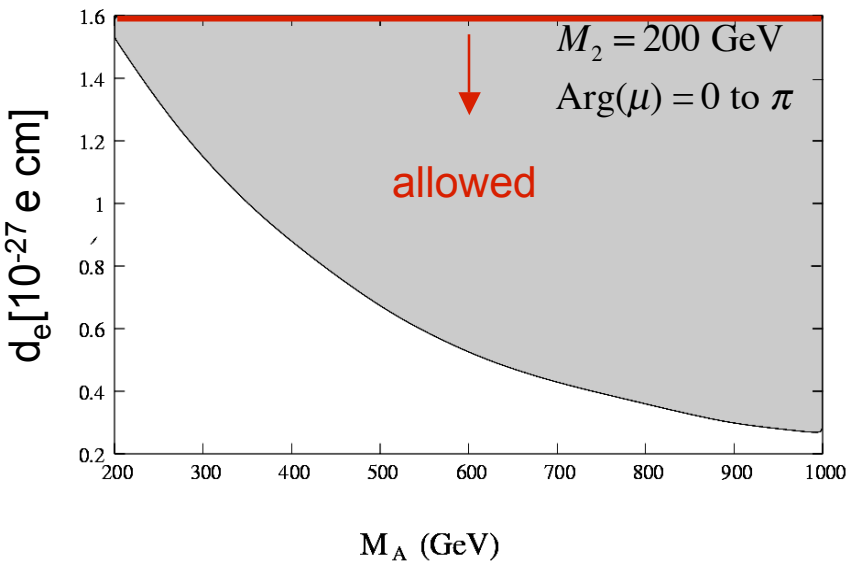
- One loop contributions become negligible for $m_{\tilde{f}_{1,2}} \geq 10$ TeV

- At two loops, contributions from virtual charginos and Higgs bosons, proportional to $\sin(\arg(\mu\, M_2))$



Chang, Chang , Keung '02 Pilaftsis '02

Balazs, M.C, Menon, Morrissey, Wagner



experimental limit $\Rightarrow d_e < 1.6\ 10^{-27}$ e cm

$$\Rightarrow \quad 5 \leq \tan\beta \leq 10$$
$$M_A \geq 200 \text{ GeV}$$
$$110 \text{ GeV} \leq |\mu| \leq 550 \text{ GeV}$$

An order-of-magnitude improvement in the bound on the electron EDM
→ will leave little room for this scenario.

Note: There are O(1) theoretical uncertainties
In principle, possible cancellations between loop contributions or lower $\tan\beta$

Dark Matter and Electroweak Baryogenesis in the MSSM

EWBG conditions + Higgs mass bounds and EDM bounds on CP violation

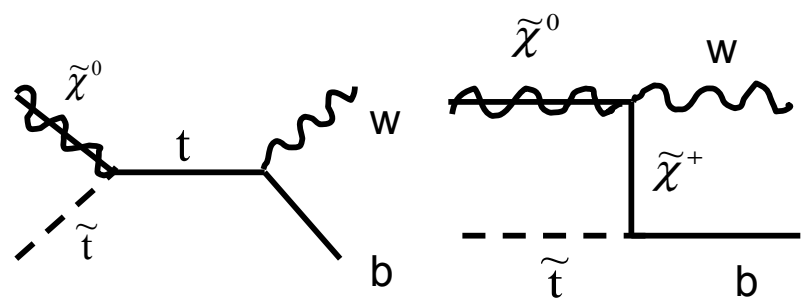
- strong constraints on stop sector
  - -- Lightest stop lighter that the top quark
  - -- Heavier stop mass above 1 TeV
  - -- Moderate Left-Right mixing
- Other squarks, sleptons (and gluinos) heavy
- light charginos
  $\mu, \mathrm{M}_2 \leq 500\ \mathrm{GeV}$
- sizeable CP violating phases
  $\sin(\arg(\mu\ \mathrm{M}_2)) \geq 0.1$
- Higgs parameters
  $5 \leq \tan\beta \leq 10 \quad \mathrm{M}_\mathrm{A} \geq 200\ \mathrm{GeV}$

Implications for Dark Matter:

- LSP lighter that the stop

$$\Rightarrow m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_{top}$$

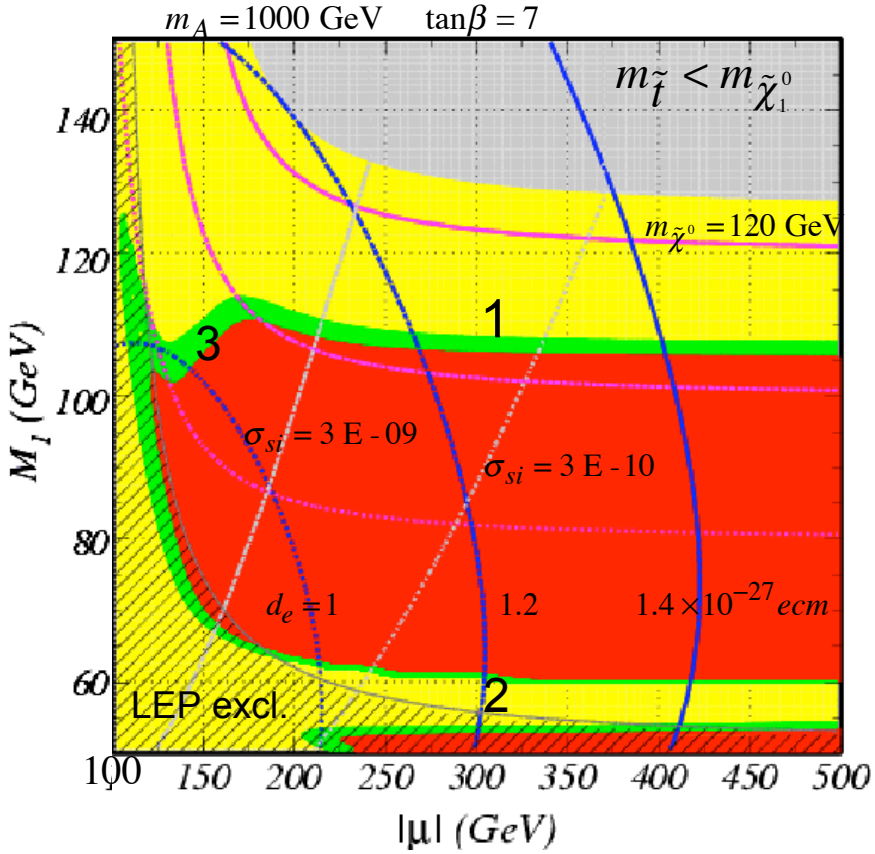
If they are close in mass, co-annihilation greatly reduces the relic density.



Opening the window for EWBG facilitates agreement with DM relic density

- CP phases: moderately affects σ_A through the mass and couplings of the LSP

Relic Density Computation in Scenarios with EWBG



Balazs, MC, Menon, Morrissey, Wagner '04

three interesting regions with neutralino relic density compatible with WMAP obs.

$0.095 < \Omega_{\rm CDM} h^2 < 0.129$ (green areas)

new WMAP + SDSS $\Rightarrow$ < 0.122

1. neutralino-stop co-annihilation: mass difference about 20-30 GeV

2. s-channel neutralino annihilation via lightest CP-even Higgs $m_{\tilde{\chi}^0} \cong m_h/2$

3. annihilation via Z boson exchange small μ and M_1 (& t-channel χ^0 and $\chi^\pm$)

Similar qualitative results under variations in the μ phase

Some differences in the Higgs resonance region due to variations in the imaginary and real parts of the Neutralino-Higgs couplings.

The LSP-top-stop coupling varies slightly with the phase; main effect due to variation of the LSP mass which affects the co-annihilation contribution.

Collider Tests of Electroweak Baryogenesis and Dark Matter

∗ Higgs searches

Higgs properties: SM-like couplings to W and Z (agent of EWSB) and $m_h < 120$ GeV

- $h \to b\bar{b}$ channel at the Tevatron:
  may achieve a 3 sigma evidence with 4-6 fb^{-1}

- $h \to \tau^+\tau^-$ and $h \to \gamma\gamma$ channels at the LHC :
  a definitive test of this scenario with the first 10 fb^{-1} of good data

∗ Stop searches:

Light Stop models with Neutralino LSP Dark Matter → $\not{E}_T$ signal

→ dominant decay $\boxed{\tilde{t}_1 \to c\,\tilde{\chi}_1^0}$

For small Stop-Neutralino mass difference: co-annihilation region

→ excellent agreement with WMAP data

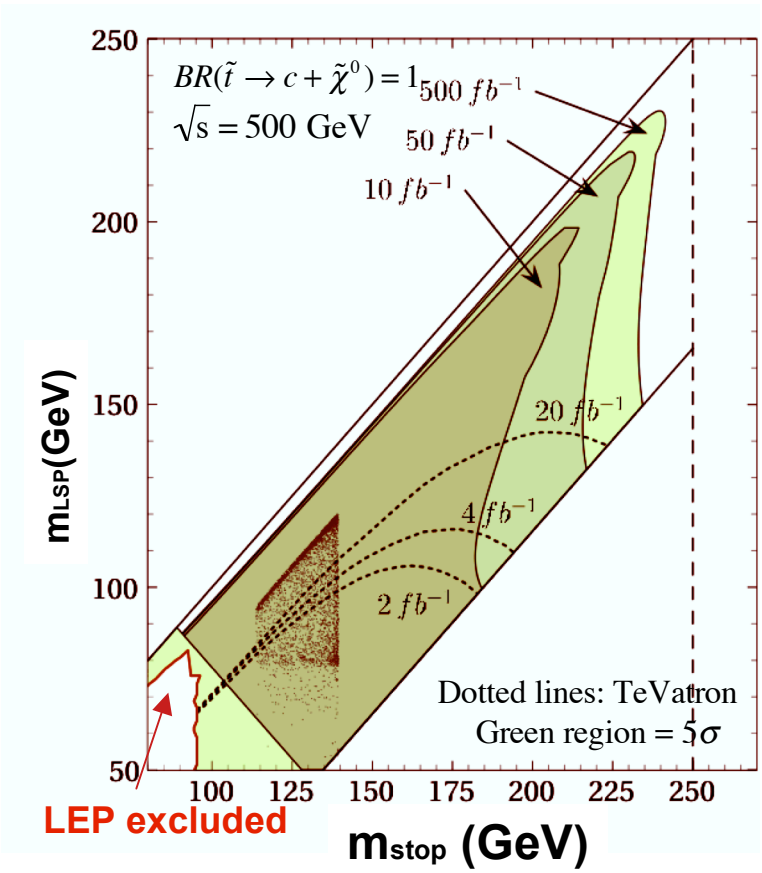
Very challenging region for stop searches at hadron colliders

The Power of a Lepton Collider: Cosmological Implications

(circa 2025)

M C, Finch, Freitas, Milstene, Nowak, Sopczak 05

- Detect light stop in the whole regime compatible with DM and Baryogenesis



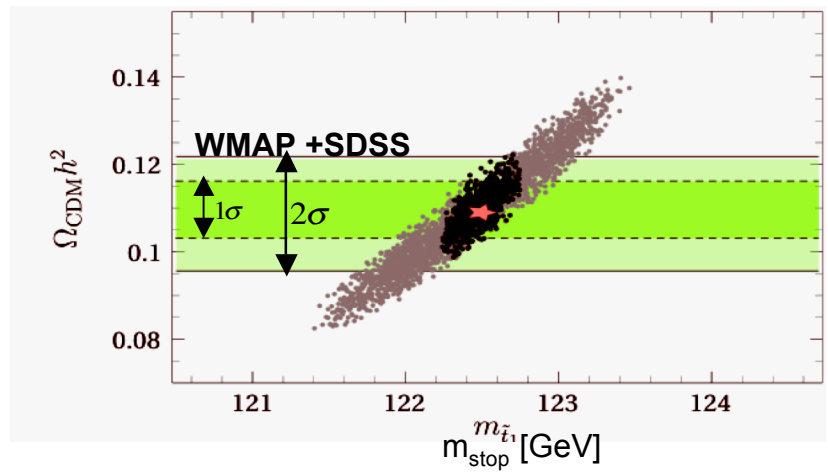
Precise measurement of SUSY parameters

-- stop mass and mixing angles

from production cross sections at different beam polarizations.

-- LSP mass and nature

from threshold scan, energy distribution endpoints and polarized cross sections



DM relic density computation with precision comparable to cosmological measurements

ILC measurements provide crucial information on the SUSY origin of Matter

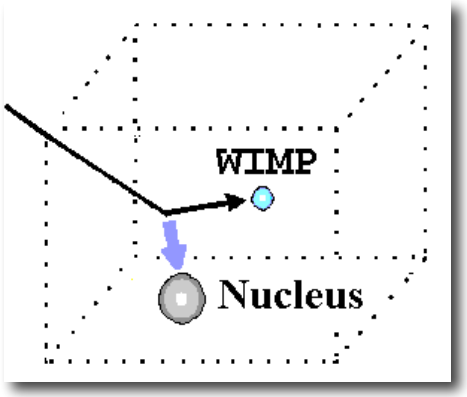
Direct Detection Dark Matter Experiments

- **Collider experiments can find evidence of DM through $\not{E}_T$ signature but no conclusive proof of the stability of a WIMP**

- Direct Detection Experiments can establish the existence of Dark Matter particles

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils

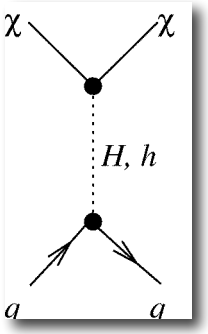
$$R = \sum_i N_i \; \eta_\chi \langle \sigma_{i\chi} \rangle$$

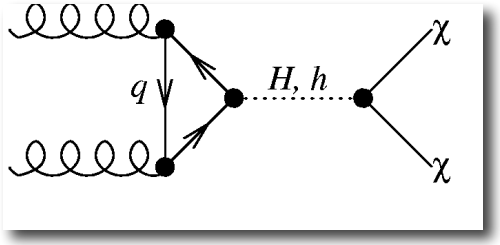


Direct DM experiments: CDMS, ZEPLIN, EDELWEISS, CRESST,WARP,…
sensitive mainly to spin-independent elastic scattering cross section ($\sigma_{SI} \leq 10^{-8}\, pb$)

==> dominated by virtual exchange of H and h

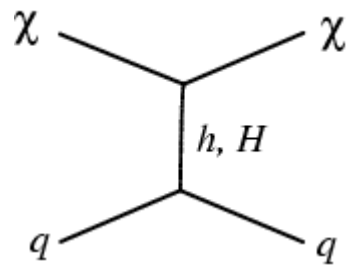
- $\tan\beta$ enhanced couplings of H to strange, and to gluons via bottom loops





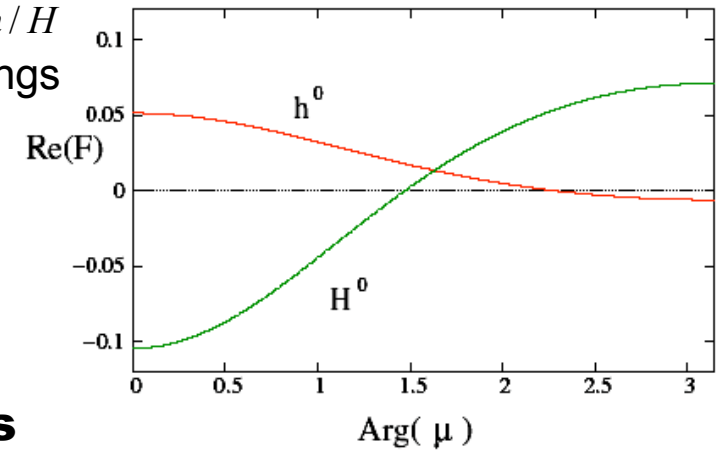
Direct Dark Detection Reach in Models of EWBG

$\sigma_{SI} \Rightarrow$



Balazs, MC, Menon,Morrissey, Wagner '04

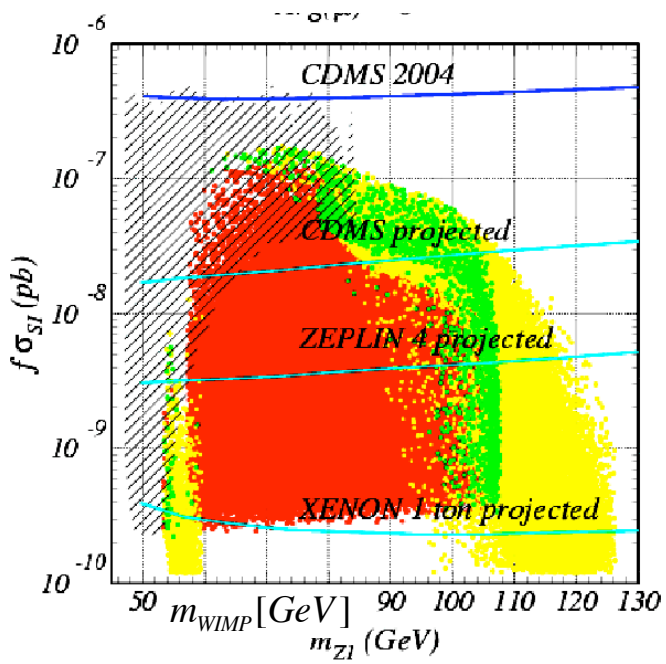
$\tilde{\chi}^0 \tilde{\chi}^0 h / H$ couplings

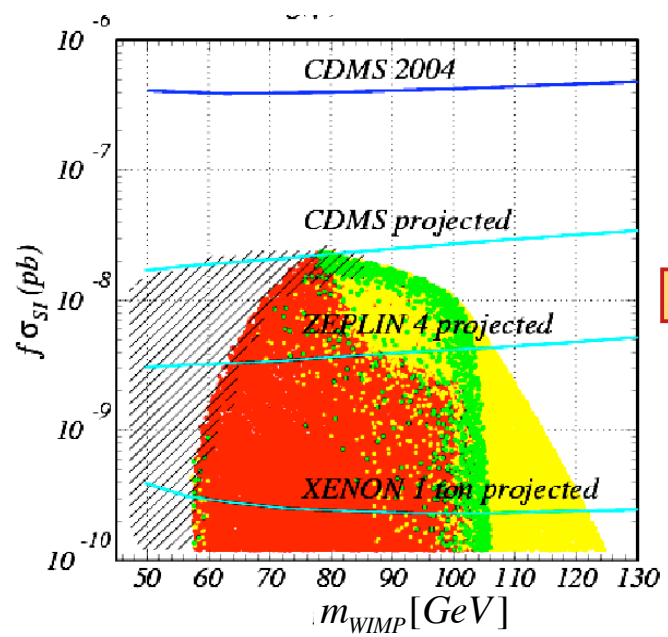


Spin Independent Neutralino-Proton scattering cross sections

Important sensitivity to CP phases

$Arg(\mu) = 0$





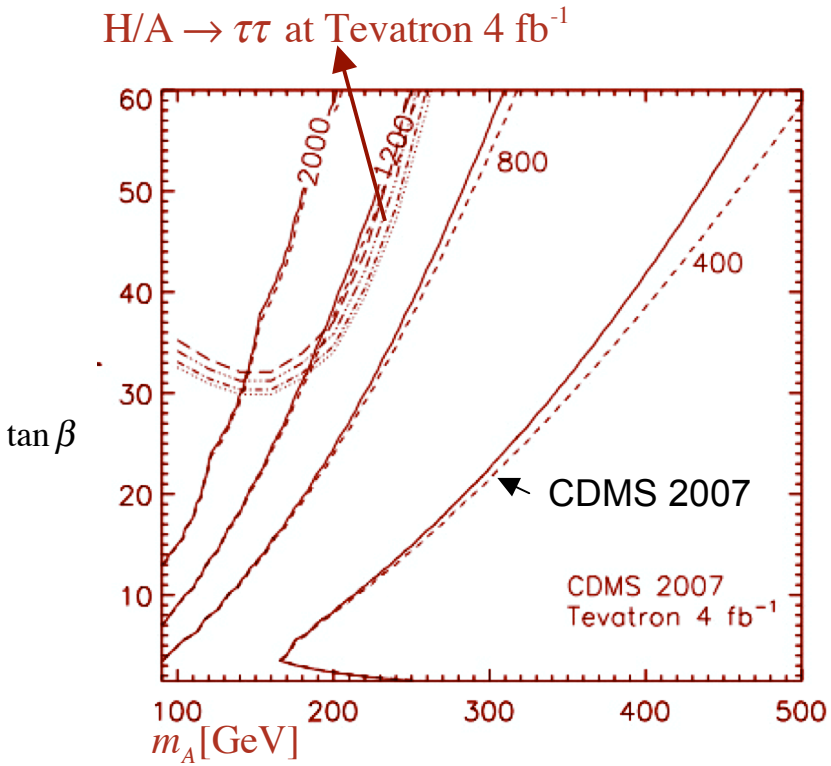
Green areas: Compatible with WMAP at 2 sigma

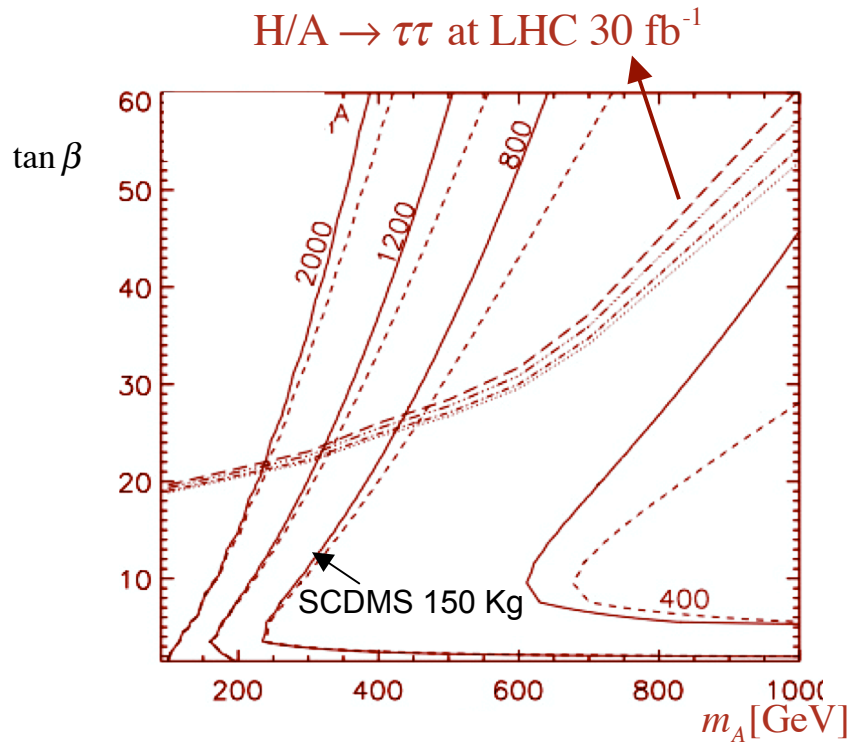
$Arg(\mu) = \pi/2$

Indirect Non-SM-like MSSM Higgs searches via Direct Detection DM experiments

-- the interplay with direct Higgs searches at Colliders --

H/A Higgs searches at the Tevatron and LHC and neutralino direct DM searches, both depend on m_A and $\tan\beta$





For $\mu = 400, 800, 1200, 2000$ GeV

M.C., Hooper, Skands 06

Smaller μ values imply larger Higgsino component of the LSP ==> larger σ_{SI}

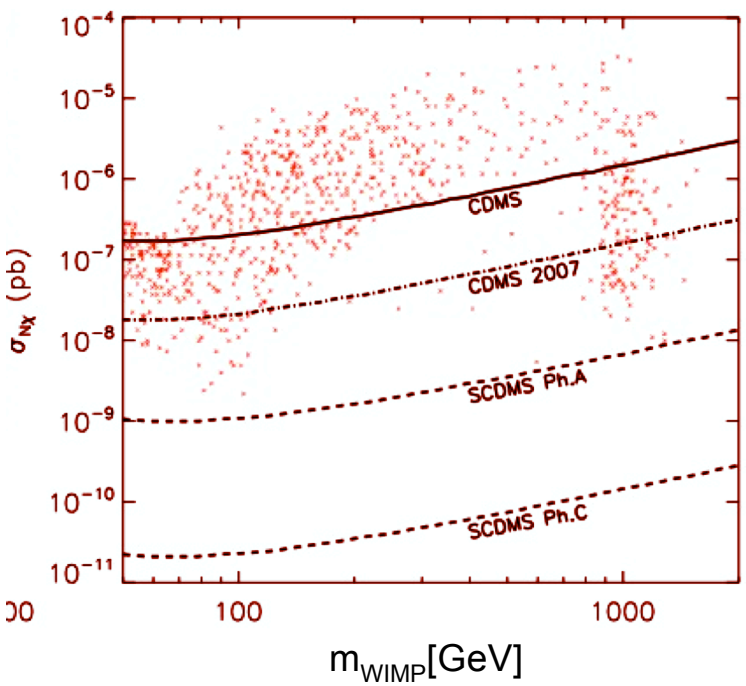
Direct detection of DM ⟷ detection of A/H at the Tevatron and LHC

CDMS DM searches Vs the Tevatron and LHC H/A searches

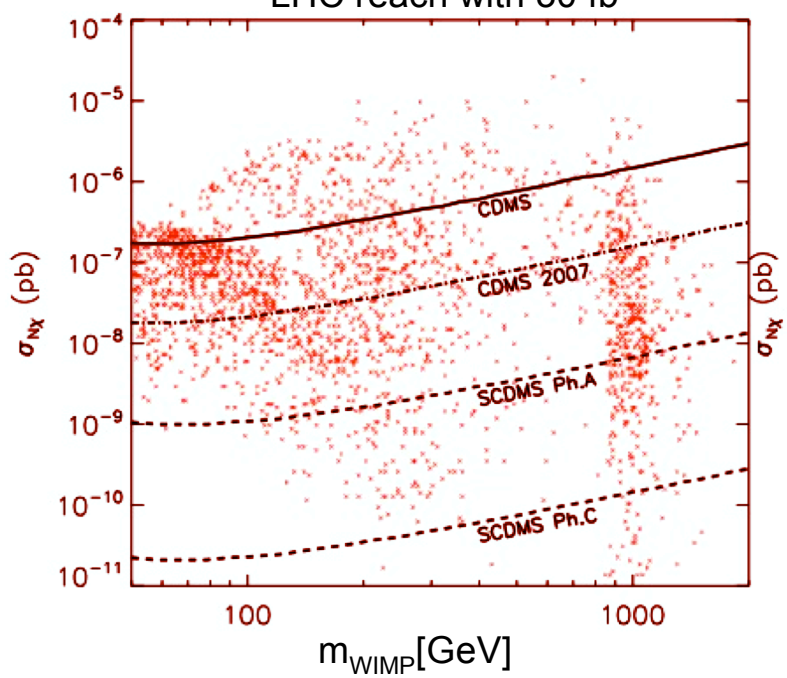
==> Evidence for H/A at the Tevatron (LHC) implies neutralino cross sections typically within the reach of present (future) direct DM detection experiments.

(strong μ dependence)

Tevatron reach with 4 fb^{-1}



LHC reach with 30 fb^{-1}



M.C., Hooper, Vallinoto 07

- Can other SUSY extensions of the SM induce the right relic density and baryon asymmetry with physics at the weak scale?

- Will they yield distinctive probes at collider and DM detection experiments?

Add a singlet superfield to the MSSM ==> nMSSM

Extended Higgs spectrum

- extra CP-odd and CP-even Higgs bosons induced by mixing with the singlet

  Upper bound on lightest Higgs agent of EWBG $m_h < 140$ GeV (similar to MSSM)

Extended Gaugino sector:

- extra neutralino induced by singlino mixing

  Upper bound on the LSP $m_N < 70$ GeV !

Strong first order phase transition:

Realizable due to tree level trilinear Higgs terms, no need of very light stop

Demands: **Lightest Higgs mass below 130 GeV**

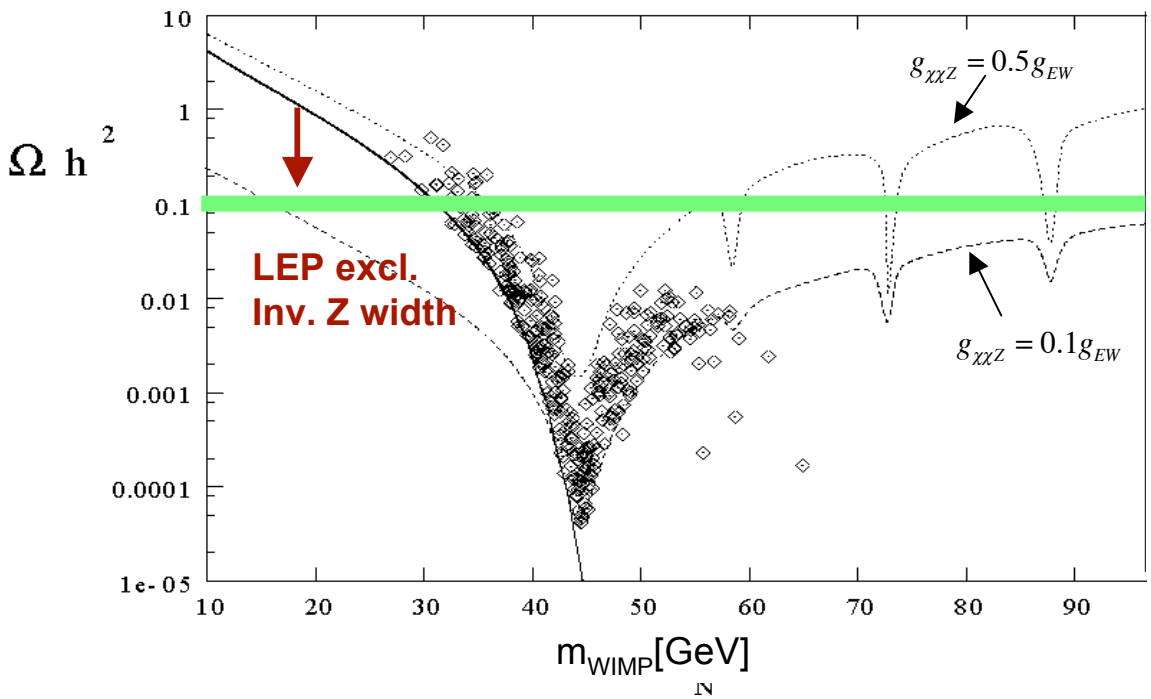
Next-to lightest CP-even & lightest CP-odd Higgs masses below 200 GeV

All three Higgs bosons decay invisibly

Relic Density and Electroweak Baryogenesis in the nMSSM

Scattered points ==> consistent with EW Baryogenesis

Menon,Morrissey, Wagner '04



m_{WIMP} ~ 30-40 GeV

Consistent with relic density and EWBG

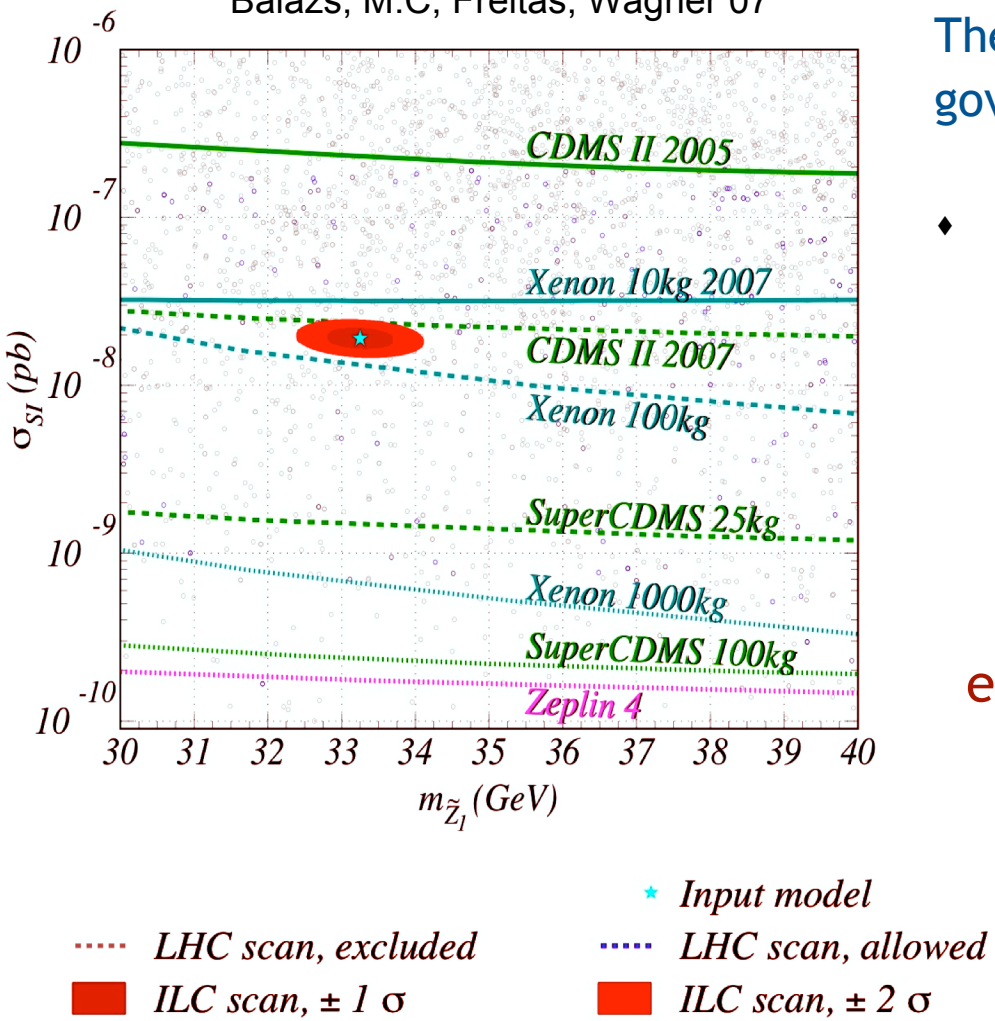
Direct signatures at Colliders:

Distinctive signature: Invisible Higgs decay

Signal can be found at the LHC in the VBF channel

Direct Dark Matter detection in the nMSSM

Balazs, M.C, Freitas, Wagner 07



The spin independent cross section is governed by the singlino parameters

- EWBG constrains the singlino sector
  ==> LSP is a mixture of mainly singlino and higgsino

↓

Next generation of Direct DM experiments will probe this model

See also Barger et al. 07

Conclusions

The SM Higgs mechanism solves the Mystery of Mass of all the fundamental particles
==> The Tevatron and ultimately the LHC will have the final word on the SM Higgs

Cosmology shows the universe is mostly made of Dark Matter and Dark Energy
All evidence comes from gravitational interactions:
how well do we really understand gravity?

The SM must be superceded by a more fundamental theory at the TeV scale
Many EWSB theories predict the existence of Dark Matter at the weak scale !
Supersymmetry is the leading candidate
It can also explain the Mystery of the Baryon asymmetry with EW scale physics

We are about to enter an exciting era in which findings both in particle physics and cosmology will further revolutionize our understanding of nature

EXTRAS

In the SM Baryon Number conserved at classical level but violated at quantum level : $\Delta B = \Delta L$

Anomalies arise in the process of regularization of divergences.

Impossible to do it preserving gauge and B and L symmetries.

$$\partial^{\mu} j_{\mu}^{B,L} = \frac{N_f \, g^2}{32\,\pi^2} Tr\left(\varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} \right)$$

Instantons are minimal action configuration with non-vanishing values of the integral of the right –hand side of the above Eq.

Instanton configurations may be regarded as semiclasical amplitudes for tunelling effect between vacuum states with different baryon number

$$S_{inst} = \frac{4\pi}{\alpha_W} \qquad \Gamma_{\Delta B \neq 0} \propto \exp(-S_{inst})$$

Weak interactions: Transition amplitude exponentially small.
No observable baryon number violating effects at T = 0

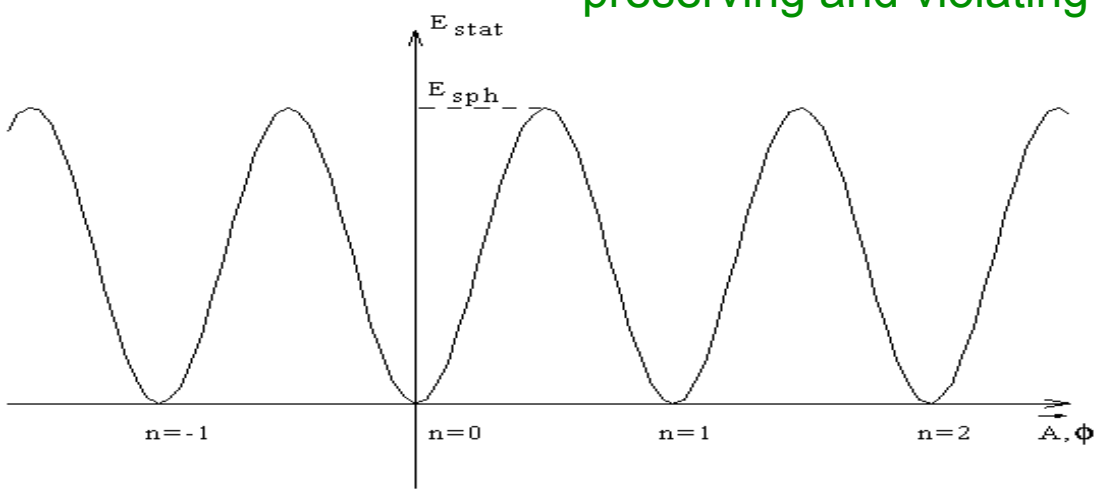
Non-equivalent Vacua and Static Energy in Field Configuration Space

The sphaleron is a static configuration with non-vanishing values of the Higgs and gauge boson fields.

Its energy may be identified with the height of the barrier separating vacua with different baryon number

$$E_{sph} = \frac{8\pi \mathrm{v}}{g_W}$$

The quantity v is the Higgs vacuum expectation value, < H > = v.
This quantity provides an order parameter which distinguishes the electroweak symmetry preserving and violating phases.



Direct Higgs searches at the Tevatron

- **Tevatron can search for a Higgs in parts of the mass range preferred by precision data**

$m_h \leq 130\text{GeV} \Rightarrow p\bar{p} \to Vh \to Vb\bar{b}$ (V=W, Z)

signal: leptonic decays of W, Z

$l\nu b\bar{b}$ and $\nu\bar{\nu}b\bar{b}$, $l^+l^-b\bar{b}$

main backgrounds:

for Wh ==> $Wb\bar{b}$, $t\bar{t}$, WZ, single-t

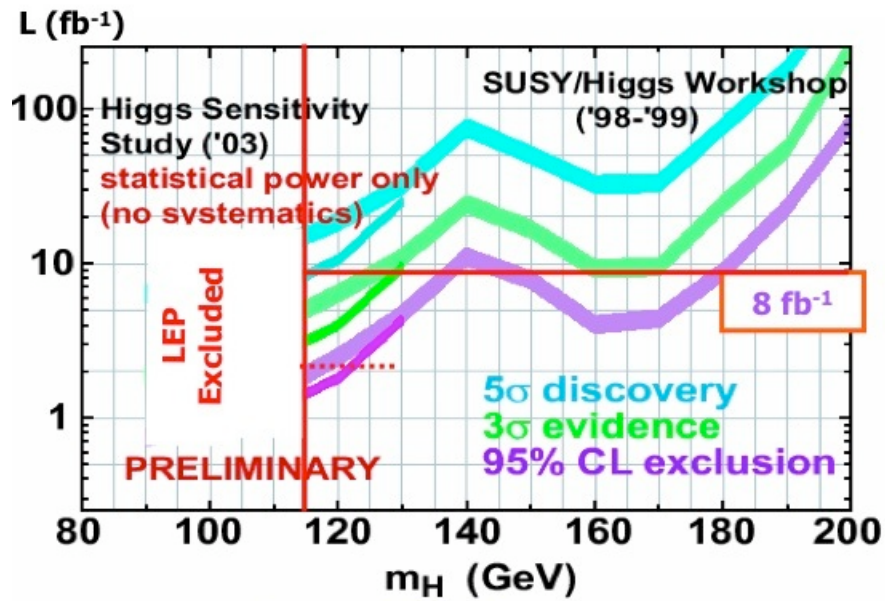
for Zh ==> $Zb\bar{b}$, ZZ, $t\bar{t}$, $W^* \to t\bar{b}$

$m_h \geq 130\text{GeV} \Rightarrow p\bar{p} \to Vh \to VWW^*$;

$p\bar{p} \to h \to WW^*$

signal: $l^+l^- + jets$, $l^\pm l^\pm$ + jets, 3l, $l^+l^-\nu\bar{\nu}$

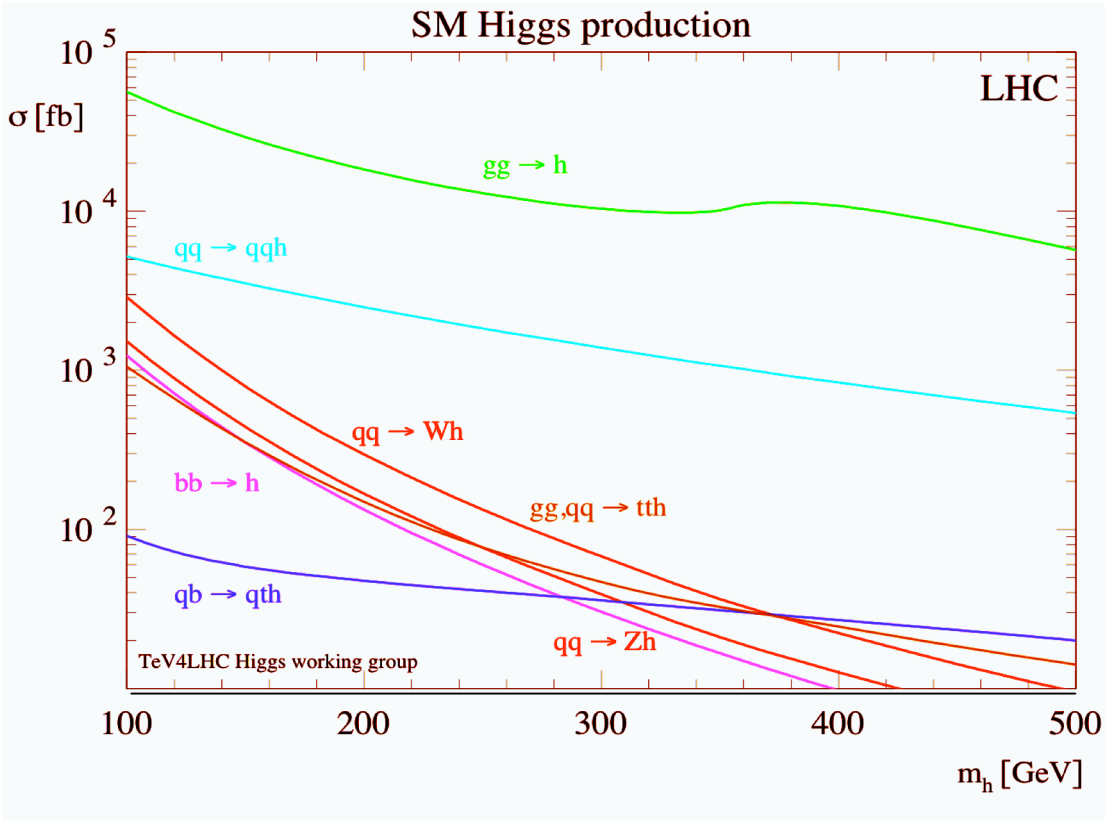
main backgrounds: WW, WZ, ZZ, W/Z+jets



Quite challenging! Evidence of a signal will mean that the Higgs has SM-like couplings to the W and Z

Caveat: at the moment both experiments are working hard to achieve the sensitivity shown above

SM Higgs Production cross sections at the LHC



Crucial to compute production cross sections with high accuracy to obtain information from data about ratio of decay widths and eventually couplings and total width

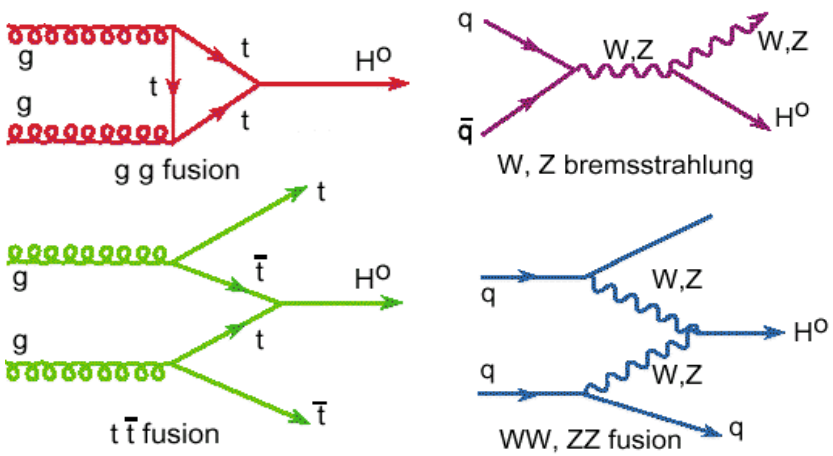
- gluon fusion: dominant production process $\sigma_{gg\to h} \sim 30-15$ pb $(m_h \sim 120-200$ GeV$)$
- vector boson fusion: ==> $\sigma_{qq\to qqh} \sim 6-3$ pb $(m_h \sim 120-200$ GeV$)$

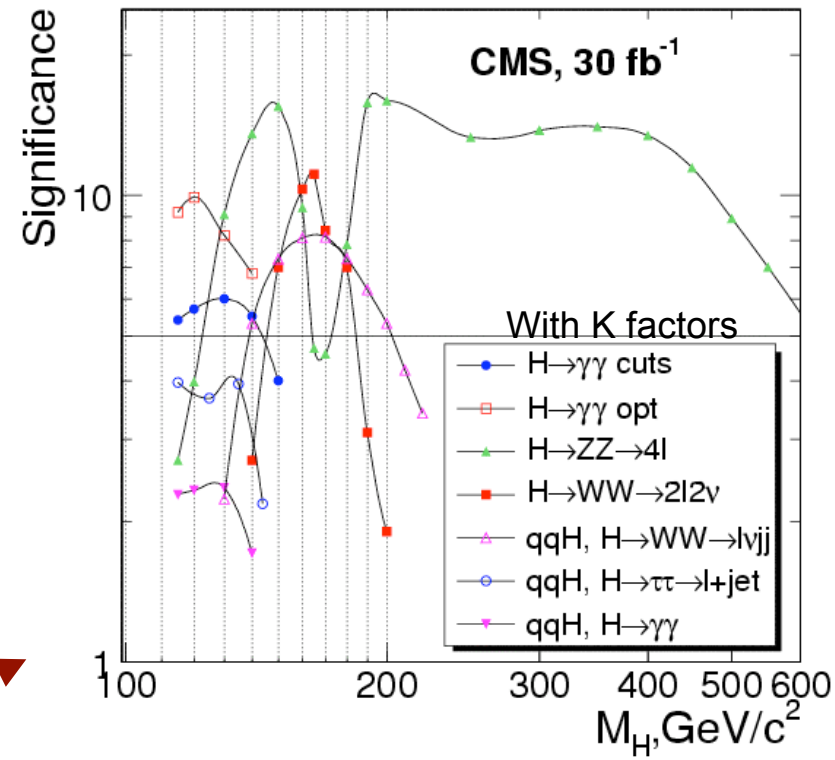
  important tagging of forward jets
- $t\bar{t}$ fusion: $\sigma_{gg,qq\to tth} \sim 0.8-0.2$ pb $(m_h \sim 120-200$ GeV$)$ ==> unique $h \to b\bar{b}$ decay

The search for SM Higgs at the LHC

Nikitenko, ICHEP06

Higgs Production processes





- **Low mass range** $m_{H_{SM}}$ < 200 GeV

Production DECAY	Inclusive	VBF	WH/ZH	ttH
$H \rightarrow \gamma\gamma$	YES	YES	YES	YES
$H \rightarrow bb$			YES	YES
$H \rightarrow \tau\tau$		YES		
$H \rightarrow WW^*$	YES	YES	YES	
$H \rightarrow ZZ^*, Z \rightarrow l^+l^-$	YES			

>60 fb^{-1}

- **Intermediate mass range**

  200 GeV < $m_{H_{SM}}$ < 700 GeV

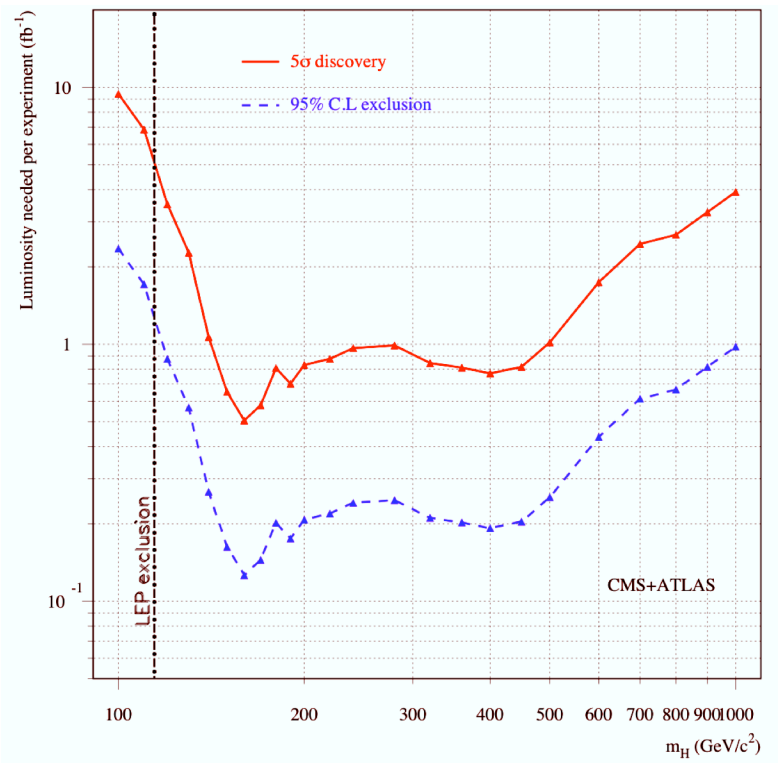
  Inclusive H ==> ZZ==> 4l

- **Large mass range**: $m_{H_{SM}}$ > 700 GeV

  VBF with H ==> WW ==> lν jj

  ZZ ==> ll νν

The LHC potential ==> a SM Higgs cannot escape discovery!



Total sensitivity combining all channels plus two experiments

5 σ discovery possible over the entire SM Higgs mass range of interest with 5 fb-1 (~ 2010)

==> For $m_{H_{SM}}$~120 GeV combination of many different channels necessary, hence, requires a good understanding of the detectors.
==> The Tevatron may explore such region

Higgs mass resolution: 0.1 to 1%, combining most channels for maximal luminosity 300 fb^{-1} (~2015) and both experiments, using H ==>ZZ ==> 4l or H ==> gamma gamma

Total Width resolution: 5-8 % for $m_{H_{SM}}$ > 300 GeV, ATLAS 300 fb^{-1}, H ==> ZZ ==> 4l

Measure Higgs Couplings with 5-20 % accuracy (maximal luminosity, both exp.)
Measuring SM-like Higgs couplings to W and Z bosons of order one will be evidence of the Higgs responsible for the EWSB ==> WW fusion most relevant channel

If SUSY exists, many of its most important motivations demand some SUSY particles at the TeV range or below

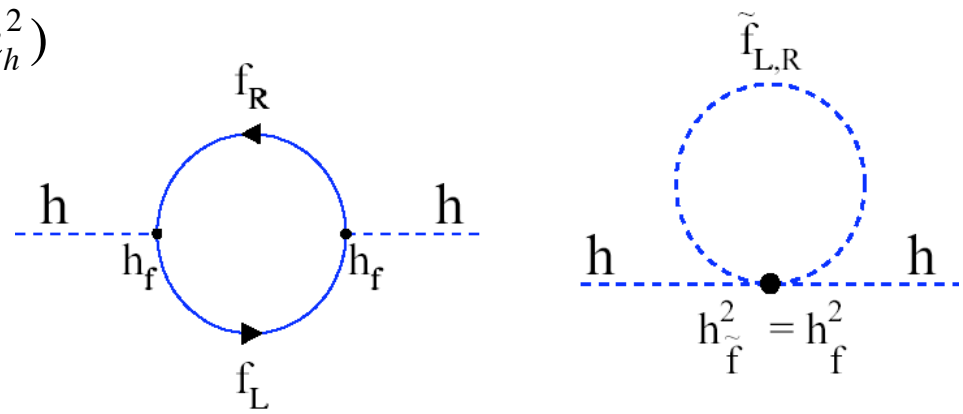
- **Solve hierarchy/naturalness problem**

Self energy of an elementary scalar related by SUSY to the self energy of a fermion
→ only log dependence on fundamental high energy scale!

Cancellation of quadratic divergences in Higgs mass quantum corrections has to do with SUSY relation between couplings and bosonic and fermionic degrees of freedom

$$\Delta\mu^2 \approx g^2_{hf\bar{f}}[m_f^2 - m^2_{\tilde{f}}]\ln(\Lambda^2_{eff}/m_h^2)$$

SUSY must be broken in nature: no SUSY partner, degenerate in mass with its SM particle has been seen



In low energy SUSY: quadratic sensitivity to Λ_{eff} replaced by quadratic sensitivity to SUSY breaking scale

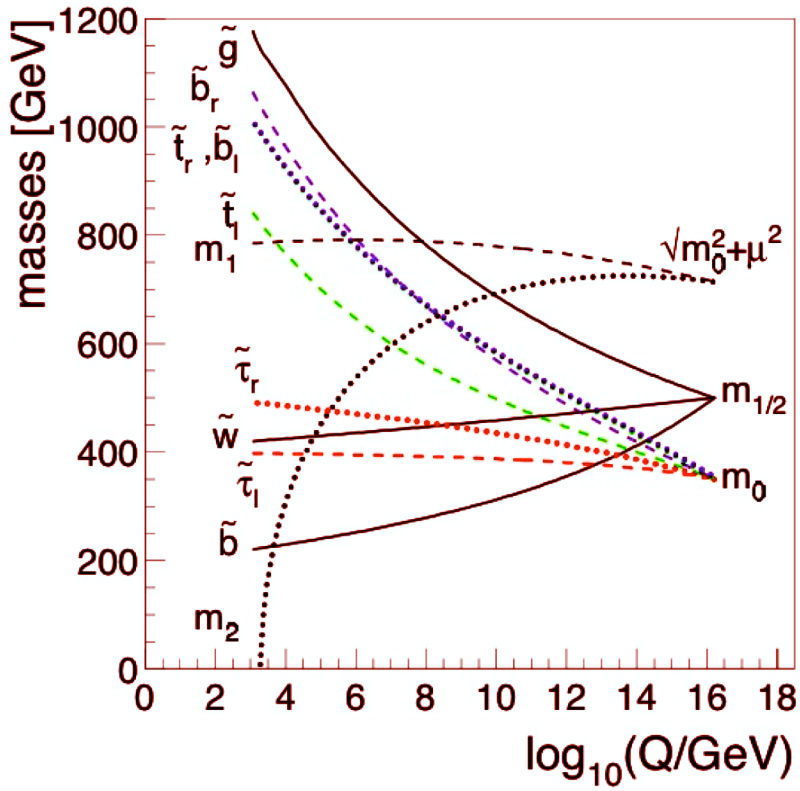
The scale of SUSY breakdown must be of order 1 TeV, if SUSY is associated with scale of electroweak symmetry breakdown

- **EWSB is radiatively generated**

In the evolution of masses from high energy scales

==> a negative Higgs mass parameter is induced via radiative corrections

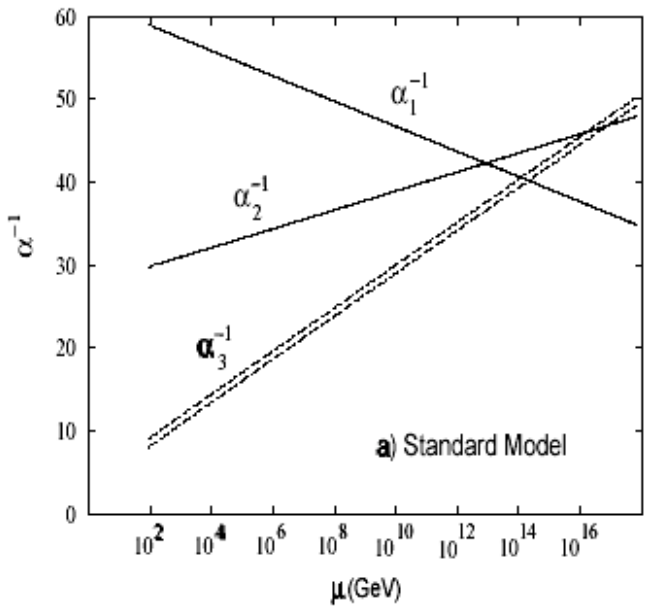
==> important top quark Yukawa effects!



- **Allows for the unification of gauge couplings**

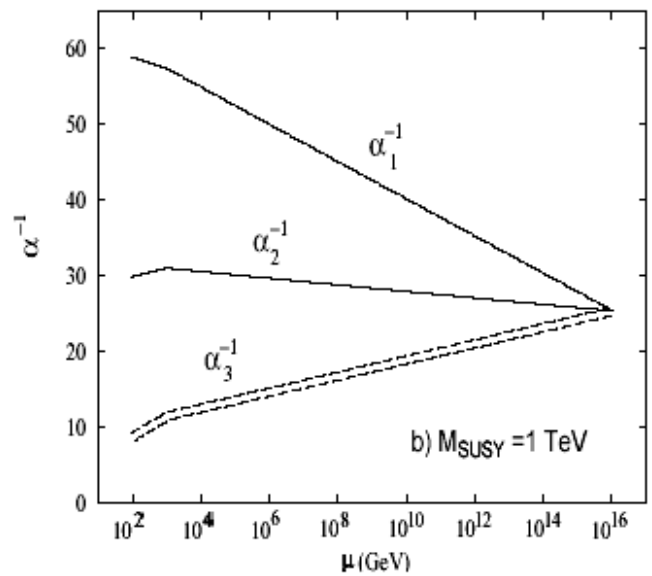
SM:

Couplings tend to converge at high energies, but unification is quantitatively ruled out.



MSSM:

Unification at $\alpha_{GUT} \simeq 0.04$ and $M_{GUT} \simeq 10^{16}$ GeV.



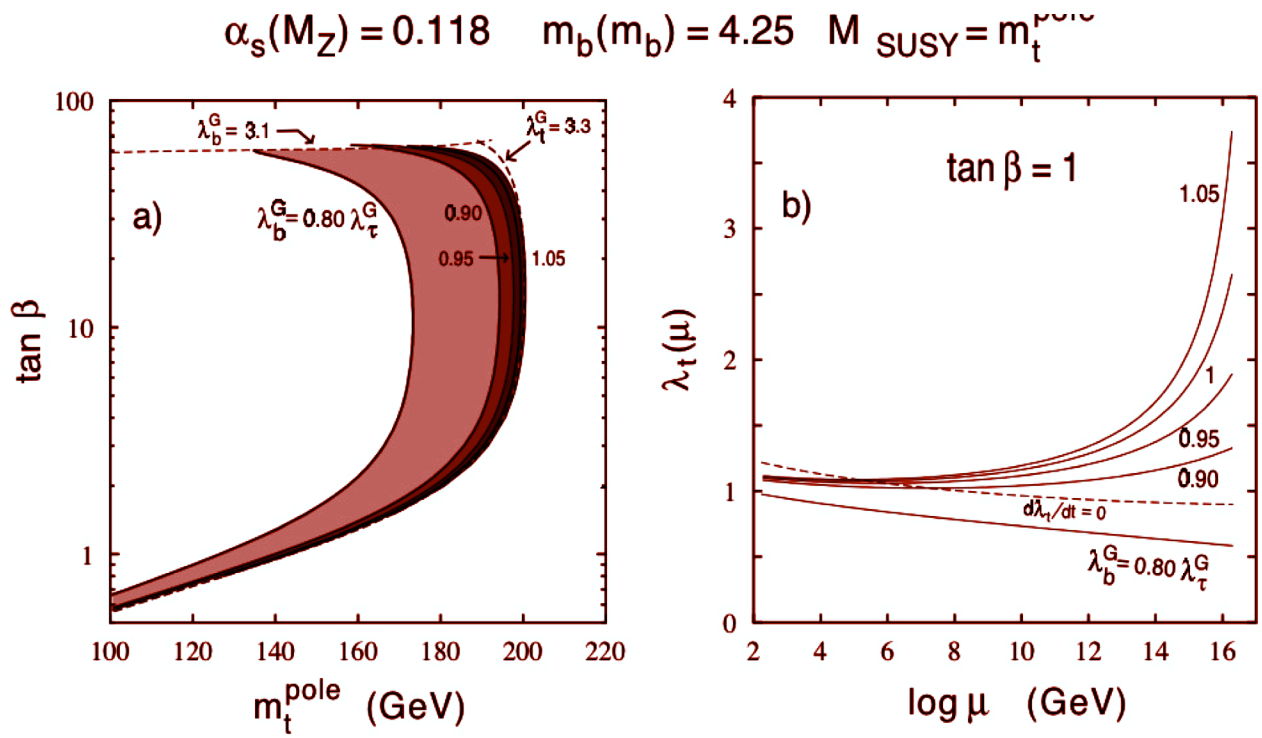
Experimentally, $\alpha_3(M_Z) \simeq 0.118 \pm 0.004$

Bardeen, M.C., Pokorski & Wagner

in the MSSM: $\alpha_3(M_Z) = 0.127 - 4(\sin^2\theta_W - 0.2315) \pm 0.008$

Remarkable agreement between Theory and Experiment!!

- **Large Top Quark mass values can be understood as resulting from a quasi-infrared fixed point of the top-Yukawa coupling**

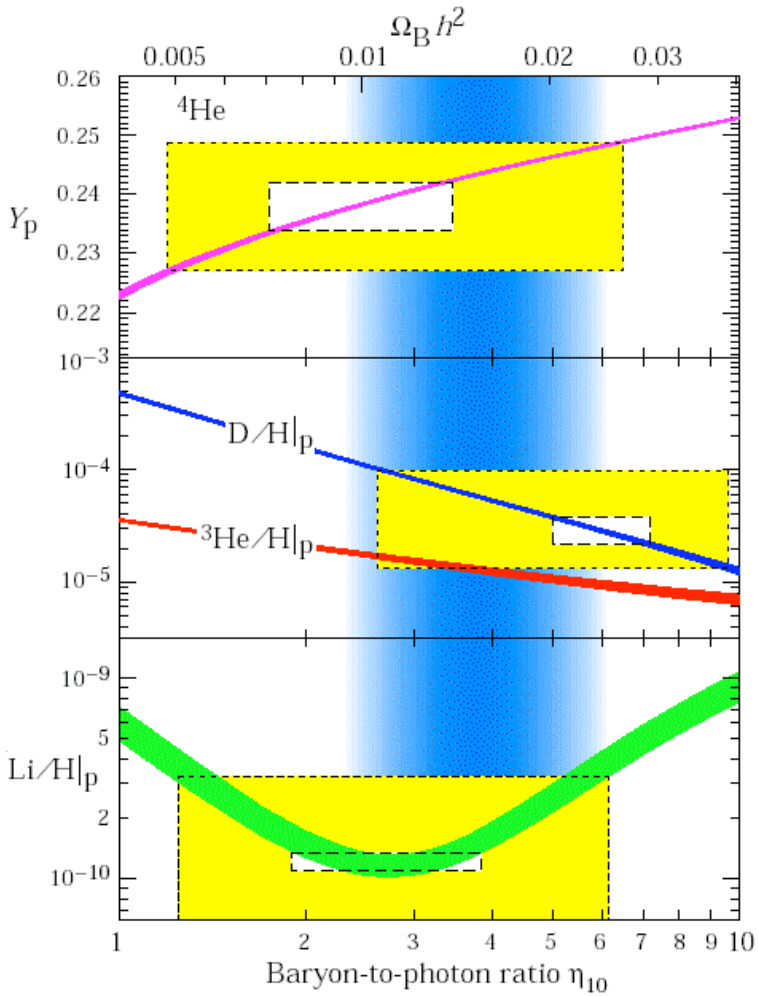


fixing m_b and α_s while varying $h_b(M_{GUT})$ and $h_\tau(M_{GUT})$ away from exact unification

$\longrightarrow$ varying $h_t(m_t)$ prediction $\qquad \tan\beta = v_2/v_1; \quad m_t = h_t v_2$

$$m_t^{pole} \simeq h_t(m_t) v \left[1 + \frac{4\alpha_s(m_t)}{3\pi}\right] \sin\beta \quad \sim (185\ \text{GeV}) h_t(m_t) \sin\beta$$

Bardeen, M.C., Pokorski, Wagner


$\Omega_B h^2$
0.005
0.01
0.02
0.03
0.26
0.25
0.24
0.23
0.22
^{4}He
Y_p
10^{-3}
10^{-4}
10^{-5}
D/H|p
^{3}He/H|p
10^{-9}
5
2
10^{-10}
Li/H|p
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio η_{10}

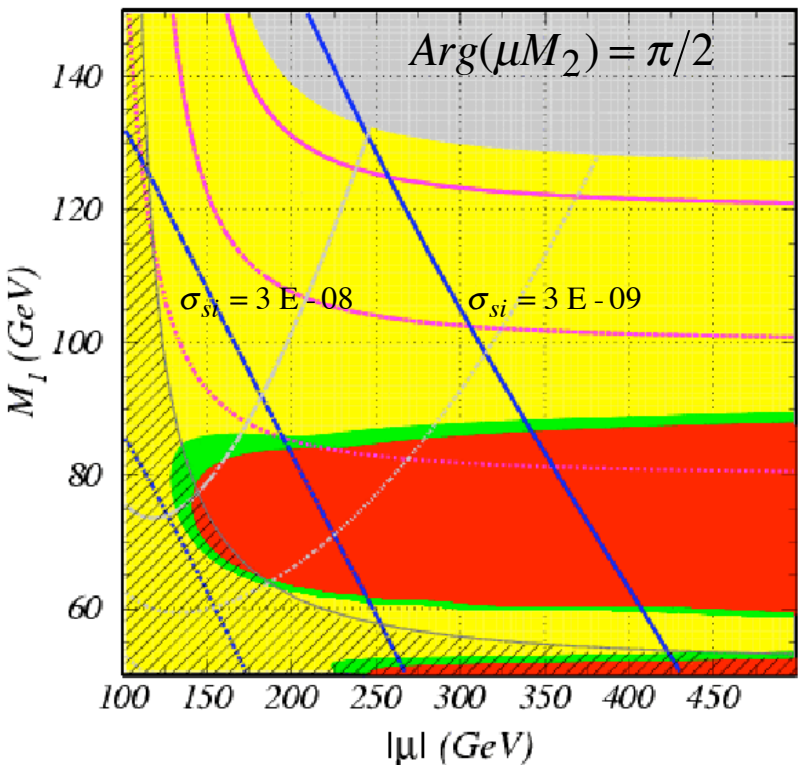
Non-Standard Higgs Mass Effects

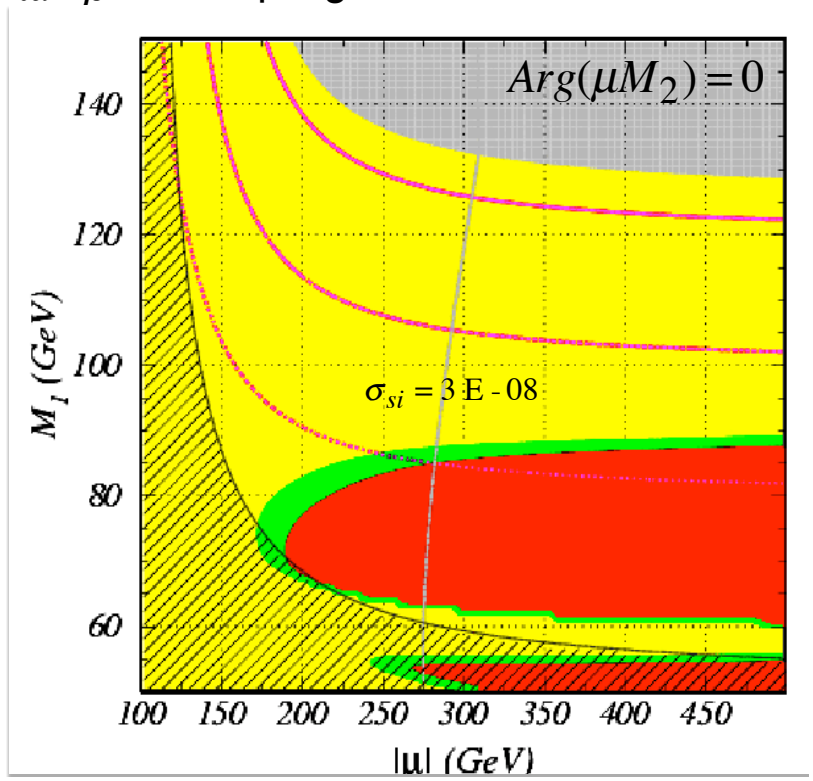
$(m_A = 200\ \text{GeV})$

A,H contribute to annihilation cross section vis s-channel:

- $m_A = 200\ \text{GeV} \Rightarrow$ new resonant region due to A,H s-channel around $m_{\tilde{\chi}_1^0} \approx m_A/2$

-- much wider band than for h due to enhanced $\tan\beta$ bb couplings --





- Ω_{CDM} ==> sum of A and H contributions nearly independent of CP violating phase (crucial difference in EDM's and Spin-Independent cross sections)
- Larger neutralino-proton scattering cross sections due to heavy Higgs H, tanb enhanced contributions

Balazs, MC, Wagner

Experimental Tests of
Electroweak Baryogenesis and Dark Matter

- **Higgs searches:**

Higgs associated with electroweak symmetry breaking: SM-like.
Higgs mass below 120 GeV required

1. Tevatron collider may test this possibility: 3 sigma evidence with about 4 fb^{-1}

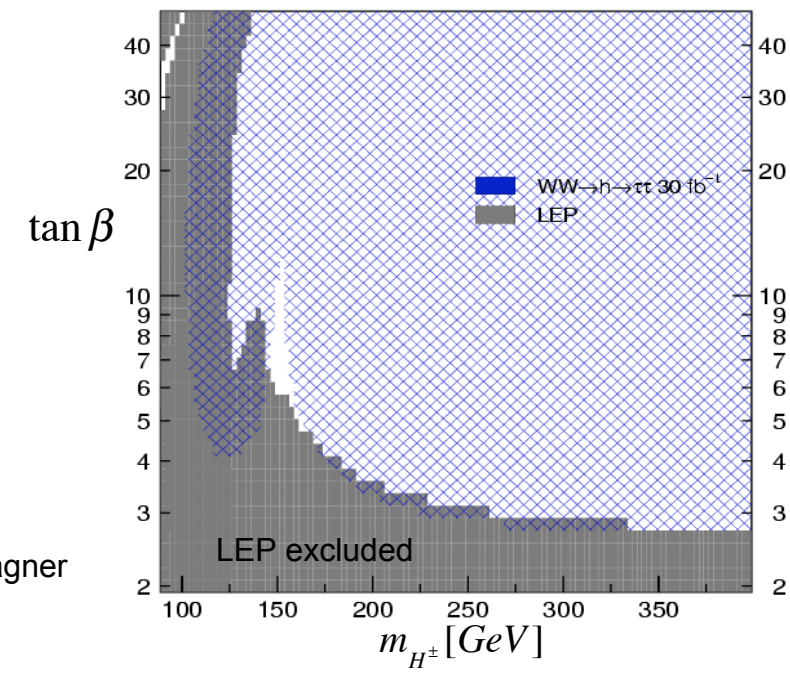
Discovery quite challenging, detecting a signal will mean that the Higgs has relevant strong (SM-like) couplings to W and Z

2. A definitive test of this scenario will come at the LHC with the first 30 fb^{-1} of data

$$qq \to qqV^*V^* \to qqh$$
$$\text{with } h \to \tau^+\tau^-$$

M.C, Mrenna, Wagner

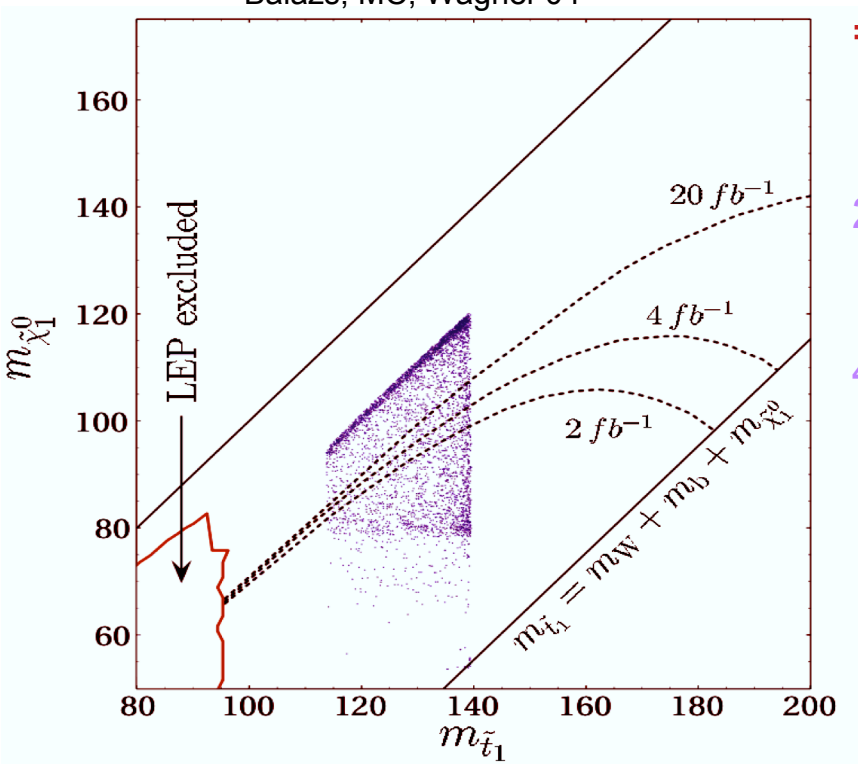
Maximal mixing scenario



Searches for a light stop at the Tevatron

Light-stop models with neutralino dark matter → $\not{E}_T$ signal

Balazs, MC, Wagner'04

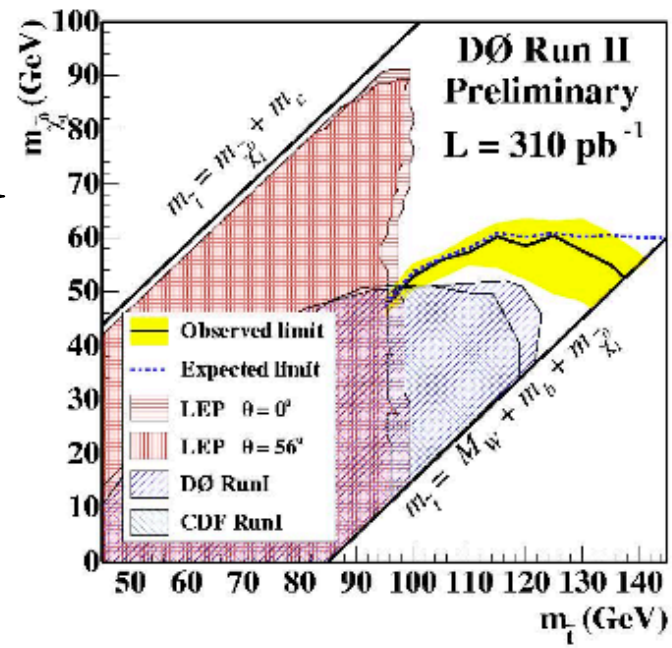


- For small stop-LSP mass difference $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ ==> dominant decay mode

2- and 3 body decays kinematically forbidden:

$$\tilde{t}_1 \to b\,\tilde{\chi}_1^+ \qquad \tilde{t}_1 \to bW^+\,\tilde{\chi}_1^0 \qquad \tilde{t}_1 \to bl^+\tilde{\nu}_l$$

4 body decays $\tilde{t}_1 \to bl^+\nu_l\,\tilde{\chi}_1^0$ sub-dominant



Blue: Relic density compatible with WMAP

Co-annihilation for $\Delta_{m_{\tilde{t}\tilde{\chi}}} < 30$ GeV

==> Problematic searches at Hadron Colliders

Light Stops at the LHC

Kraml, Raklev '06

- Dominant decay mode for small mass differences $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$

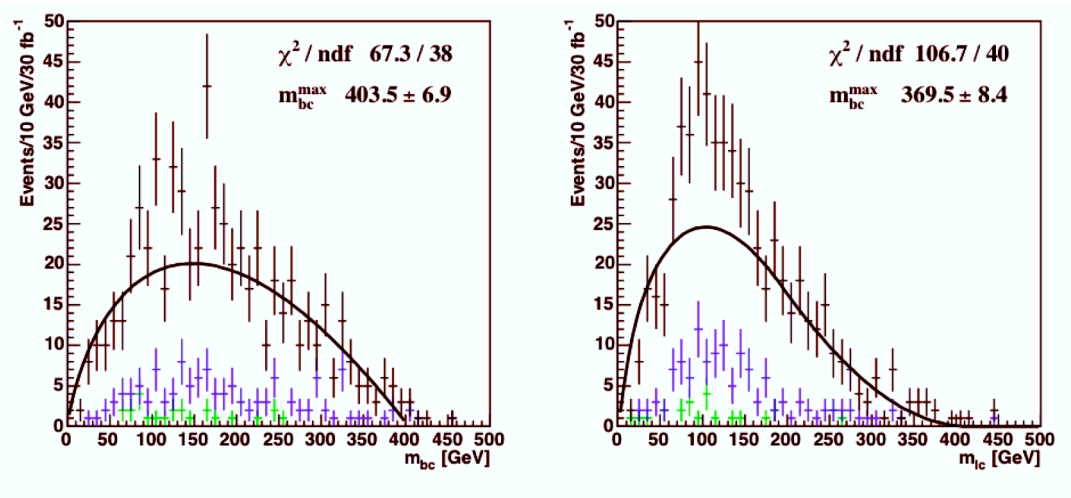
- Look for same-sign tops in gluino decays

$$pp \to \tilde{g}\tilde{g} \to \mathrm{tt}\ \tilde{\mathrm{t}}_1^*\tilde{\mathrm{t}}_1^*, \qquad \mathrm{t} \to \mathrm{bl}^+\,\bar{\nu}_1 \qquad \tilde{\mathrm{t}}_1^* \to c\tilde{\chi}_1^0$$

Signal: 2 SS leptons, 2 SS bottoms, jets plus Missing Energy

Mass measurements from distributions,
==> but not enough independent distributions to get absolute masses

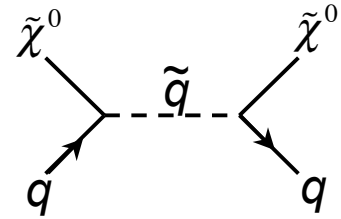
Analysis valid for gluino masses up to ~ 900 GeV

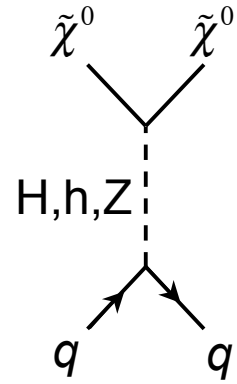


Caveat: Study done for relatively light squarks ~ 1 TeV.
For heavier squarks, gluino signal decreased by 50% from absence of squark-gluino production: still may be possible to see the stops (under study)

Direct Detection of WIMPs

- WIMPs elastically scatter off nuclei in targets, producing nuclear recoils with $\sigma_{n\chi} \Rightarrow$





Main Ingredients to calculate signal:
Local density & velocity distribution of WIMPs and $\sigma_{n\chi}$
==> rate per unit time, per unit detector material mass

$$R = \sum_i N_i \, \eta_\chi \langle \sigma_{i\chi} \rangle$$

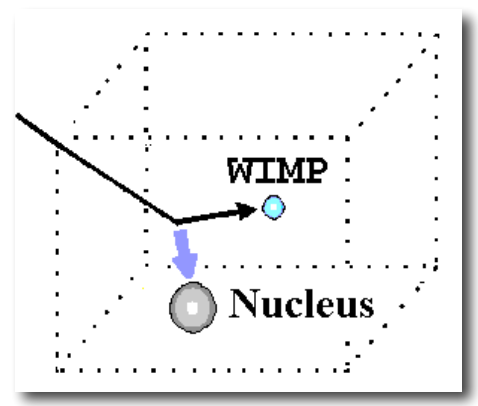
$$R = \sum_i N_i \, \eta_\chi \langle \sigma_{i\chi} \rangle$$

Scattering Cross section off nuclei averaged over relative wimp velocity

Number of target nuclei in the detector prop.to Detector mass/Atomic mass

local WIMP density

$$R = \sum_i N_i \, \eta_\chi \langle \sigma_{i\chi} \rangle$$



<u>Direct detection has two big uncertainties</u>:

- The local halo density, inferred by fitting to models of galactic halo: assumed ==> $\eta_\chi \approx$ 0.3 GeV / cm^3
- The galactic rotation velocity ≈ (230 +- 20) km/sec

SUSY theories ==> extended Higgs sector with lightest Higgs having (usually) SM-like properties and $m_h < 200$ GeV

The Higgs Sector in Minimal Supersymmetric Standard Model (MSSM)

- 2 Higgs SU(2) doublets ϕ_1 and ϕ_2: after Higgs Mechanism

  → 2 CP-even h, H with mixing angle α
  1 CP-odd A and a charged pair $H^{\pm}$

All Higgs masses and couplings given in terms of 2 parameters m_A and $\tan\beta = v_2/v_1$

$$\Rightarrow v^2 = v_1^2 + v_2^2 = 246 \text{ GeV}$$

At tree level, one Higgs doublet couples only to down quarks and the other couples to up quarks only

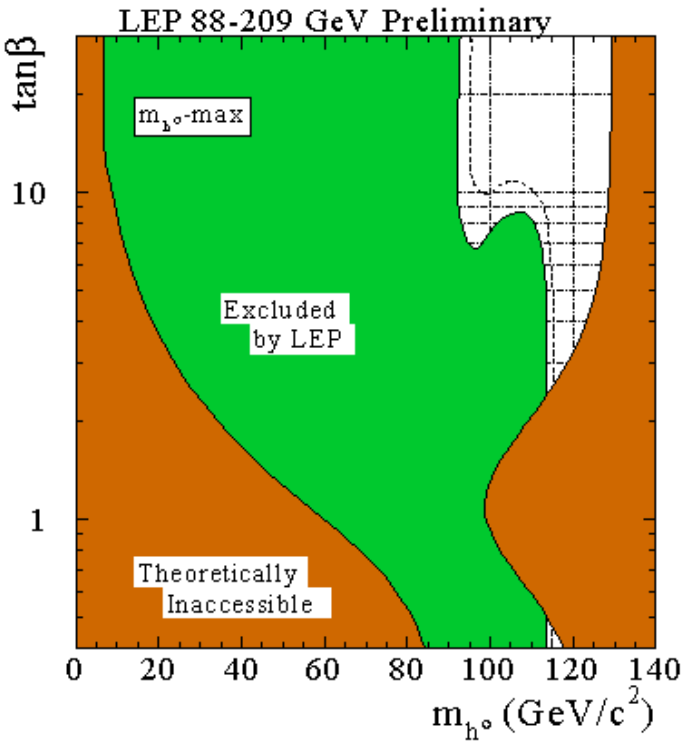
$$-L = \bar{\psi}_L^i \left(\hat{h}_d^{ij+} \phi_1 d_R^j + \hat{h}_u^{ij+} \phi_2 u_R^j \right) + h.c.$$

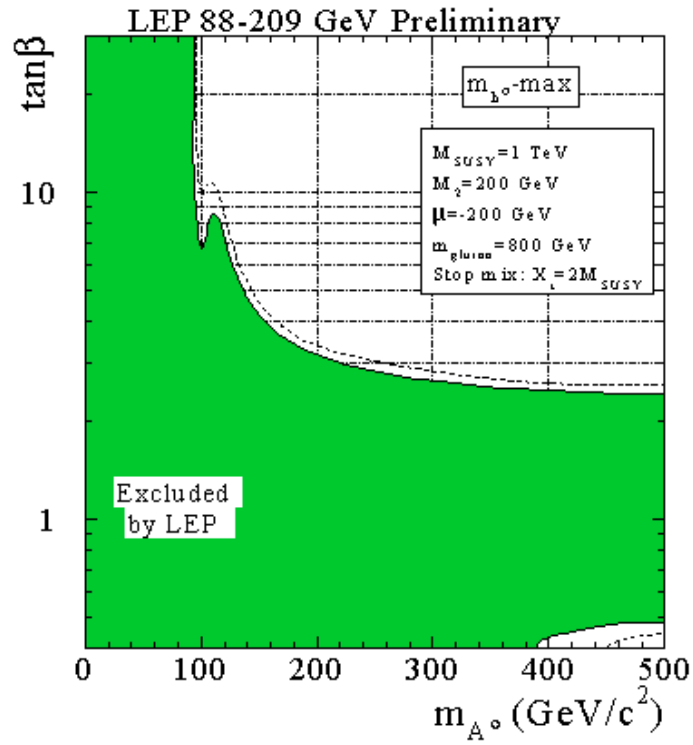
Since the up and down sectors are diagonalized independently, the Higgs interactions remain flavor diagonal at tree level.

Present Status of MSSM Higgs searches

95%C.L. limits

$e^+e^- \xrightarrow{Z^*} hZ, HZ, Ah, AH$ main decay mode $h \to b\bar{b}$





MSSM Higgs $m_h > 91.0 GeV; \quad m_A > 91.9 GeV$

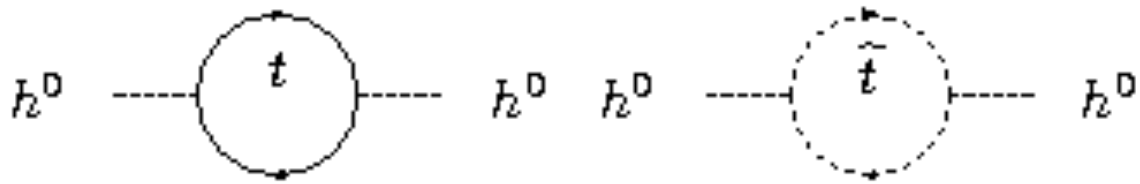
Charged Higgs $m_{H^\pm} > 78.6 GeV$

SM-like Higgs $m_h > 114.6 GeV$

Radiative Corrections to Higgs Boson Masses

Important quantum corrections due to incomplete cancellation of particles and superparticles in the loops

Main effects: stops;
and sbottoms at large tan beta



$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{2\, g_2^2\, m_t^4}{8\pi^2\, M_W^2} \left[\ln(M_S^2/m_t^2) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12\, M_S^2} \right) \right] + \text{h.o.}$$

$$M_S^2 = \tfrac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2) \text{ and } X_t = A_t - \mu/\tan\beta \longrightarrow \text{stop mixing}$$

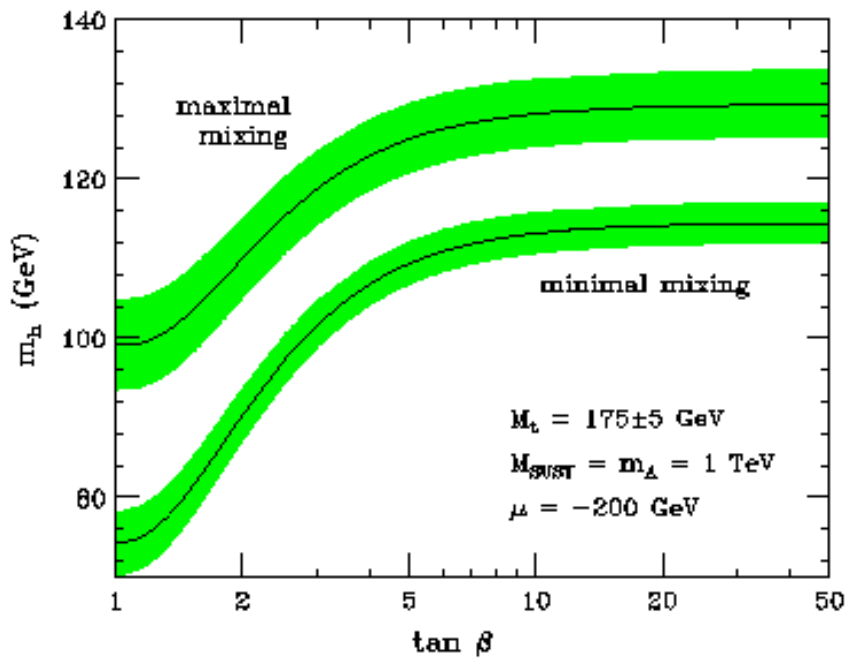
- m_t^4 **enhancement**
- **log sensitivity to stop masses** M_S
- **depend. on stop mass mixing** X_t

After 2 -loop corrections

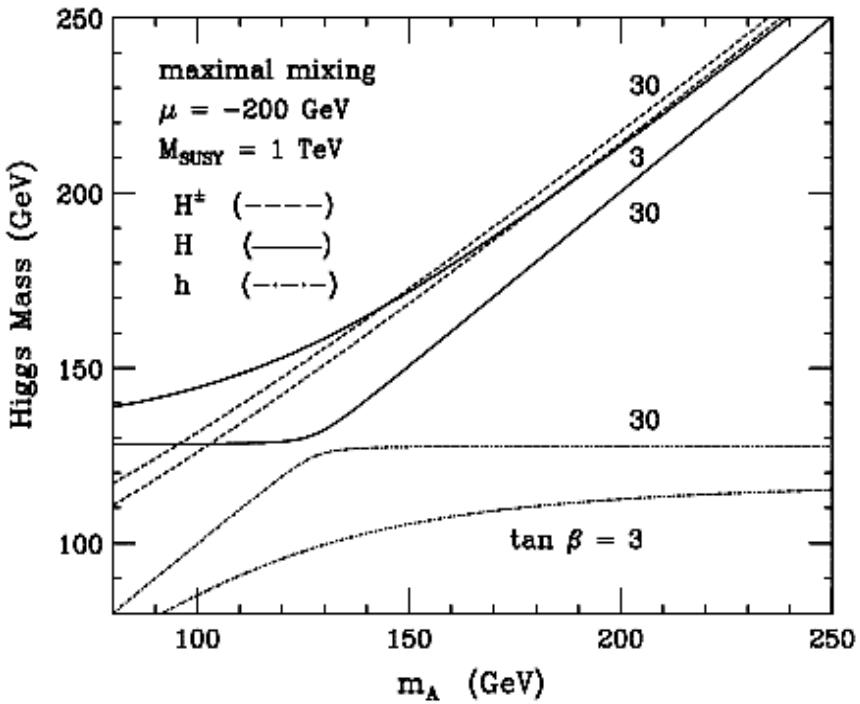
$$m_h \leq 135 \text{ GeV}$$

stringent test of the MSSM

$$M_S = 1 \rightarrow 2 \text{ TeV} \Longrightarrow \Delta m_h \simeq 2 - 5 \text{ GeV}$$
$$\Delta m_t = 1 \text{ GeV} \Longrightarrow \Delta m_h \sim 1 \text{ GeV}$$



MSSM Higgs Masses as a function of M_A



$$m_H^2 \cos^2(\beta-\alpha) + m_h^2 \sin^2(\beta-\alpha) = [m_h^{max}(\tan\beta)]^2$$

- $\cos^2(\beta-\alpha) \to 1$ for large $\tan\beta$, low m_A
  $\Longrightarrow$ H has SM-like couplings to W,Z
- $\sin^2(\beta-\alpha) \to 1$ for large m_A
  $\Longrightarrow$ h has SM-like couplings to W,Z

for large $\tan\beta$:
always one CP-even Higgs with SM-like couplings to W,Z
and mass below $m_h^{max} \leq 135$ GeV

$\Downarrow$

if $m_A > m_h^{max}$ $\rightarrow$ $m_h \simeq m_h^{max}$ and $m_H \simeq m_A$

if $m_A < m_h^{max}$ $\rightarrow$ $m_h \simeq m_A$ and $m_H \simeq m_h^{max}$

m_A nearly degenerate with m_h or m_H

- **Mild variation of the charged Higgs mass with SUSY spectrum**

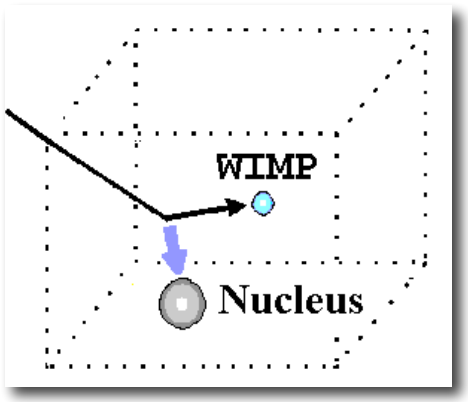
$$m_{H^\mp}^2 = m_A^2 + (\lambda_4 - \lambda_5)v^2$$

If sizeable μ and sizeable $A_t \times A_b < 0 \Rightarrow \lambda_4 - \lambda_5 < 0$ (smaller $m_{H^\mp}$)

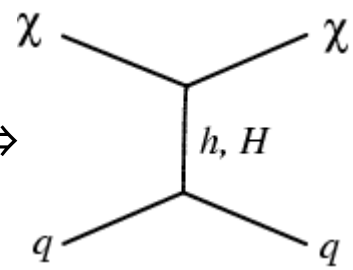
Direct Dark Matter Detection

$\not{E}_T$ at colliders → important DM evidence, but not conclusive: WIMP stability cannot be checked

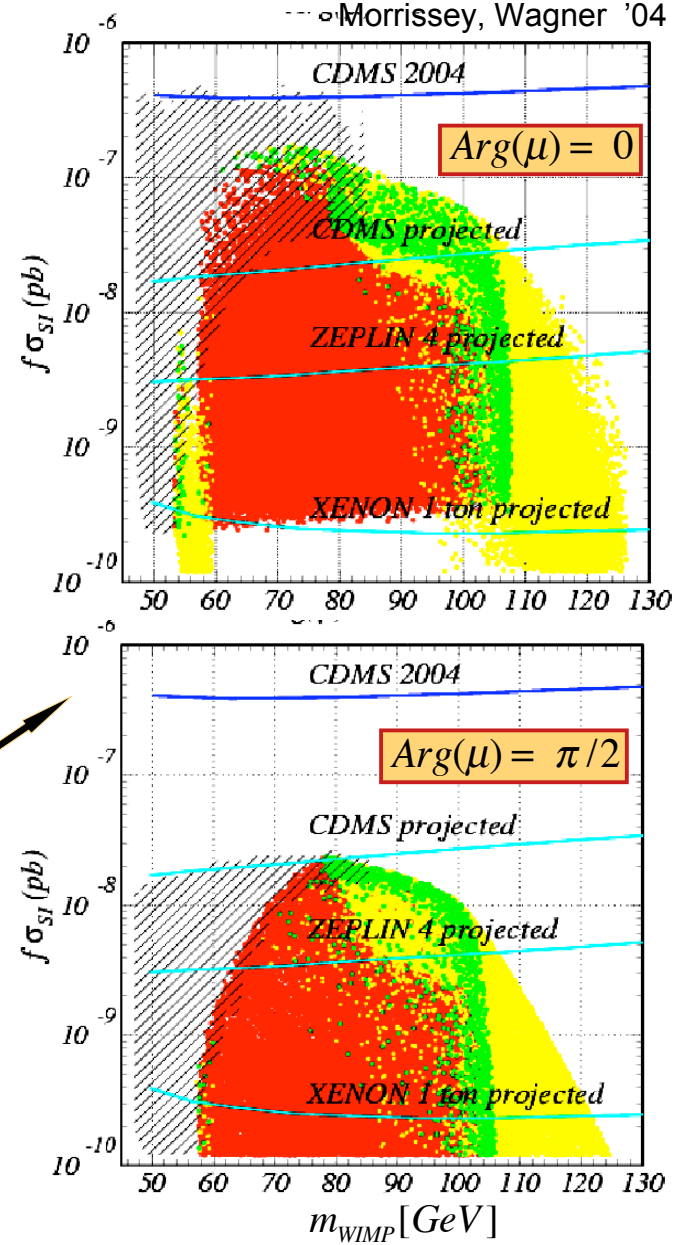
- WIMPs elastically scatter off nuclei in targets producing nuclear recoils



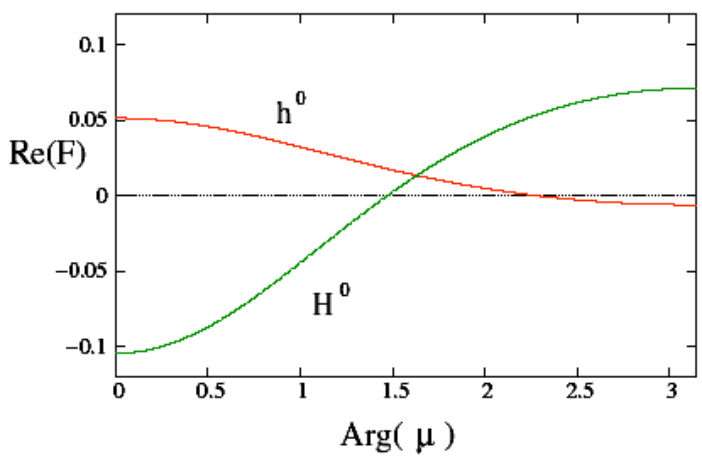
$\sigma_{SI} \Rightarrow$



Balazs, MC, Menon, Morrissey, Wagner '04

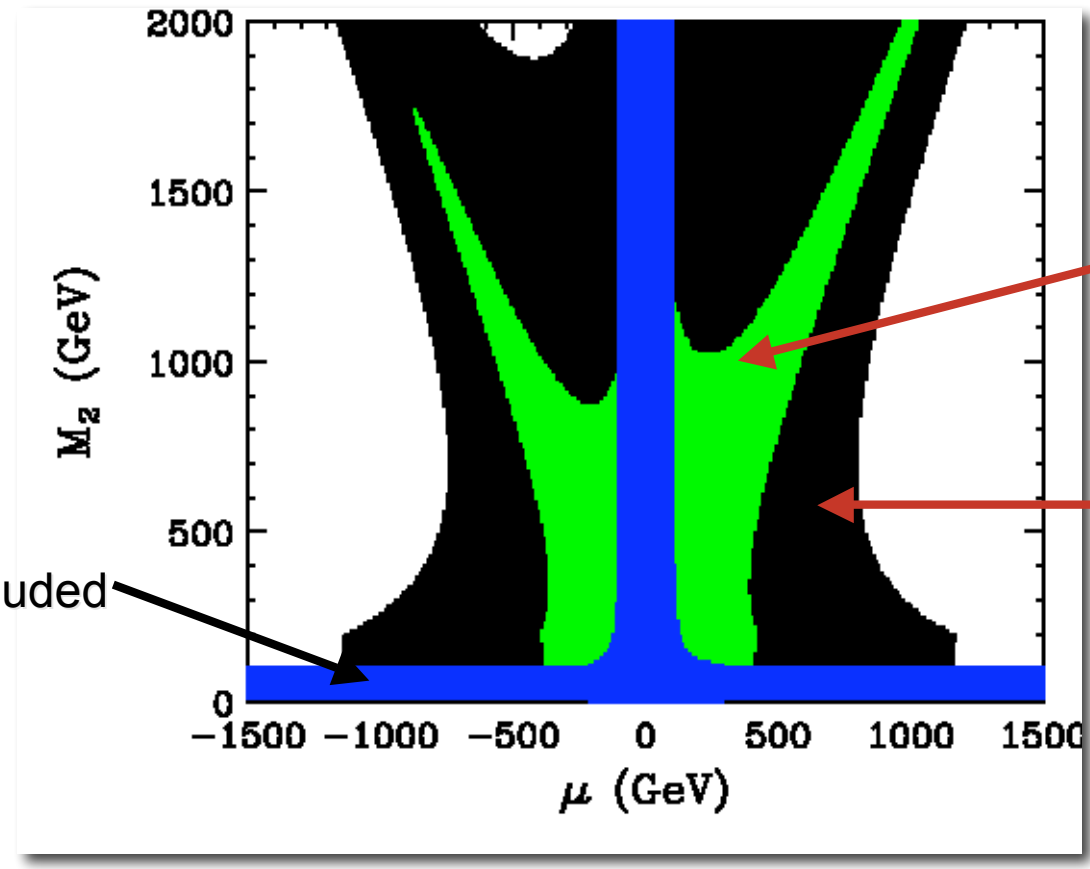


$\tilde{\chi}^0\tilde{\chi}^0 h/H$ couplings



Direct Detection and Collider Searches

Constrained H/A discovery potential at the Tevatron (4 fb^{-1})



Current CDMS

2007 CDMS projection

LEP excluded

M.C, Hooper, Skands, hep-ph/0603180

The MSSM HIGGS sector

Couplings to gauge bosons and fermions
(normalized to SM values)

$$\mathrm{hZZ,\ hWW,\ ZHA,\ WH^{\pm}H} \longrightarrow \sin(\beta-\alpha)$$
$$\mathrm{HZZ,\ HWW,\ ZhA,\ WH^{\pm}h} \longrightarrow \cos(\beta-\alpha)$$

$$(\mathrm{h,H,A})\ u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\ \ \sin\alpha/\sin\beta,\ \ 1/\tan\beta$$
$$(\mathrm{h,H,A})\ d\bar{d}/l^+l^- \longrightarrow -\sin\alpha/\cos\beta,\ \ \cos\alpha/\cos\beta,\ \ \tan\beta \longrightarrow \text{(enhanced)}$$

- Quantum corrections affect the couplings relevantly, especially for the heavy Higgs bosons

In most of the parameter space: $m_A >> m_Z$ (decoupling limit)

==> lightest Higgs: $m_h \leq m_Z$ and behaves like SM Higgs ==> similar searches at colliders

others heavy and roughly degenerate $m_A \approx m_H \approx m_{H^{\pm}}$

LEP MSSM HIGGS limits: $\longrightarrow$ $m_{H^{\pm}} > 78.6\mathrm{GeV}$

$m_h > 91.0$ GeV; $m_{A,H} > 91.9$ GeV; $m_h^{\mathrm{SM-like}} > 114.6\mathrm{GeV}$

ILC discoveries will allow us to:

- Solve the Mysteries of Matter at the TeV scale.

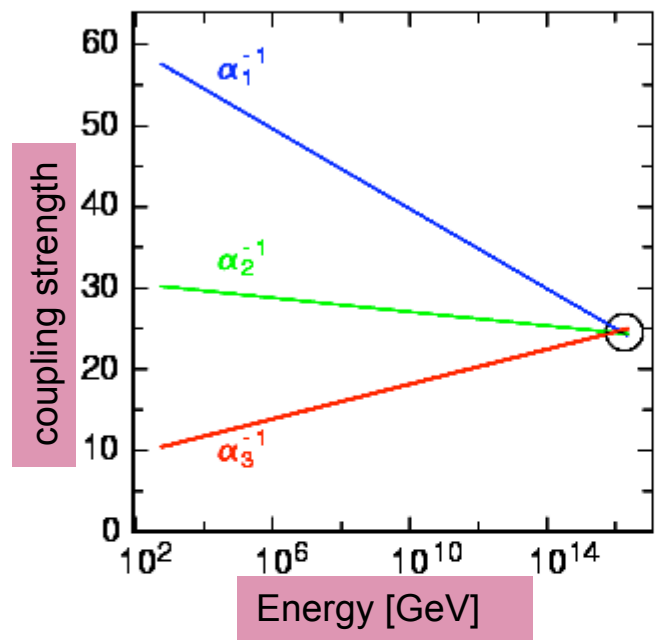
Determine how and why the Higgs works with a minimum of theoretical input
Find Extra source of CP violation

- Probe the essence of Dark Matter.

Identify its nature and measure its properties
Compute DM candidate's density in the universe to match astrophysical measurements.

- Zoom in to bring into focus Einstein's vision of a Unified Theory.

Supersymmetry particles at the TeV scale allow for unification of the three forces at scales 20 trillions times larger.



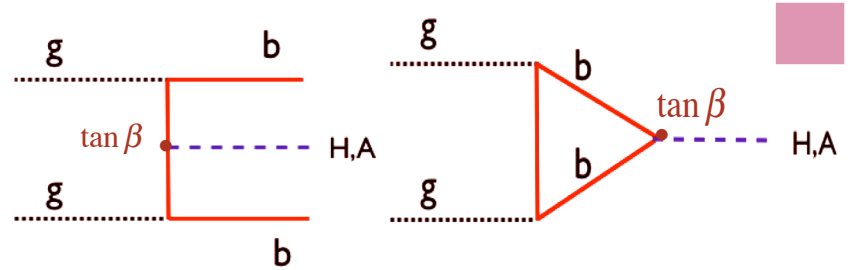
Remarkable high precision➔ Opens the window to explore energies that no accelerator will ever reach directly.

Heavy MSSM Higgs searches at the Tevatron and the LHC

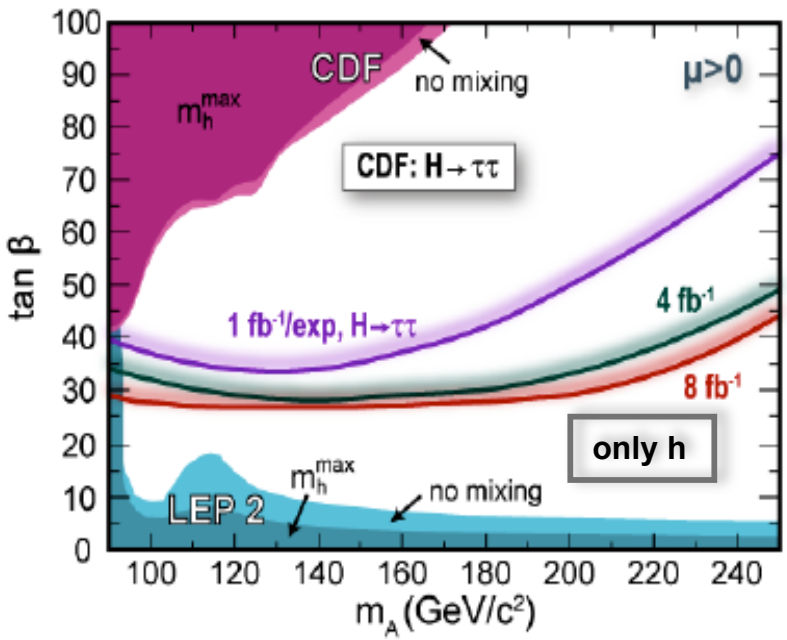
Enhanced couplings to b quarks and tau-leptons
==> enhanced production processes

Tau decay channel $p\bar{p}$ or $pp \to A/H\ X \to \tau\tau X$

==> robust results under quantum corrections

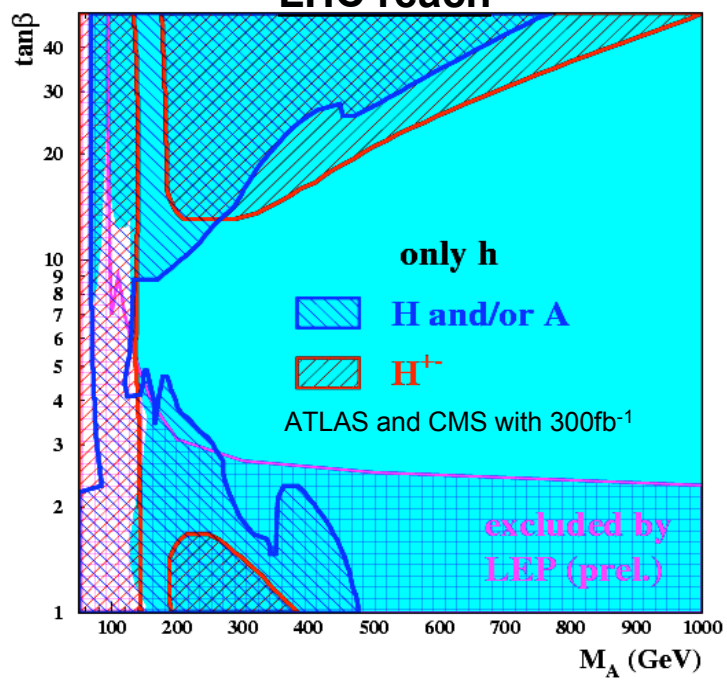


Tevatron reach



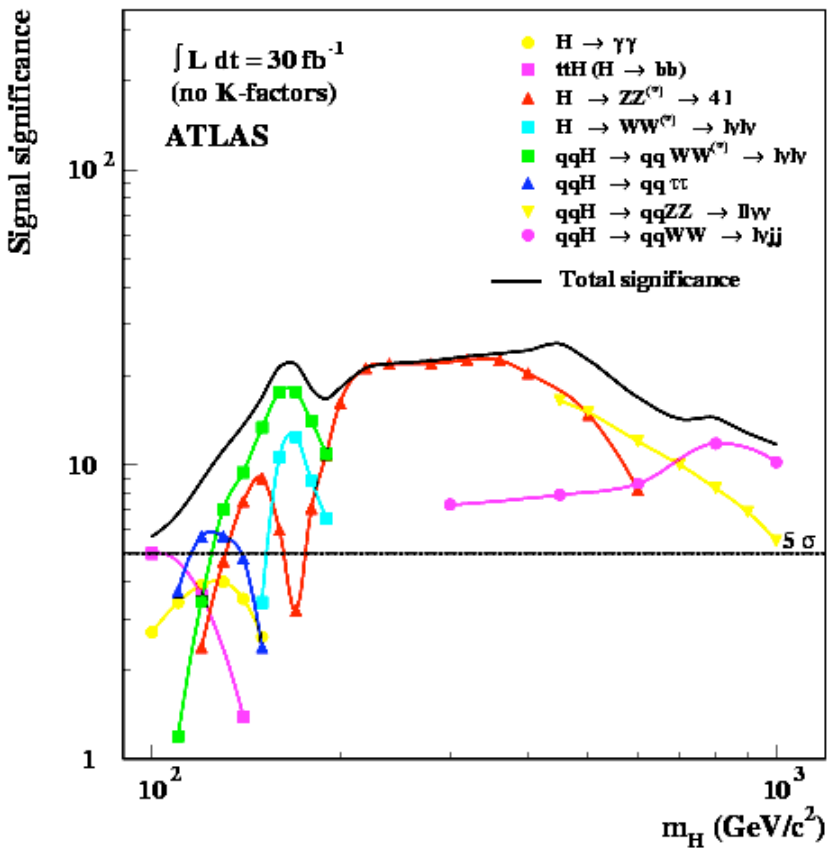
A large region of the full MSSM parameter space can be proved!

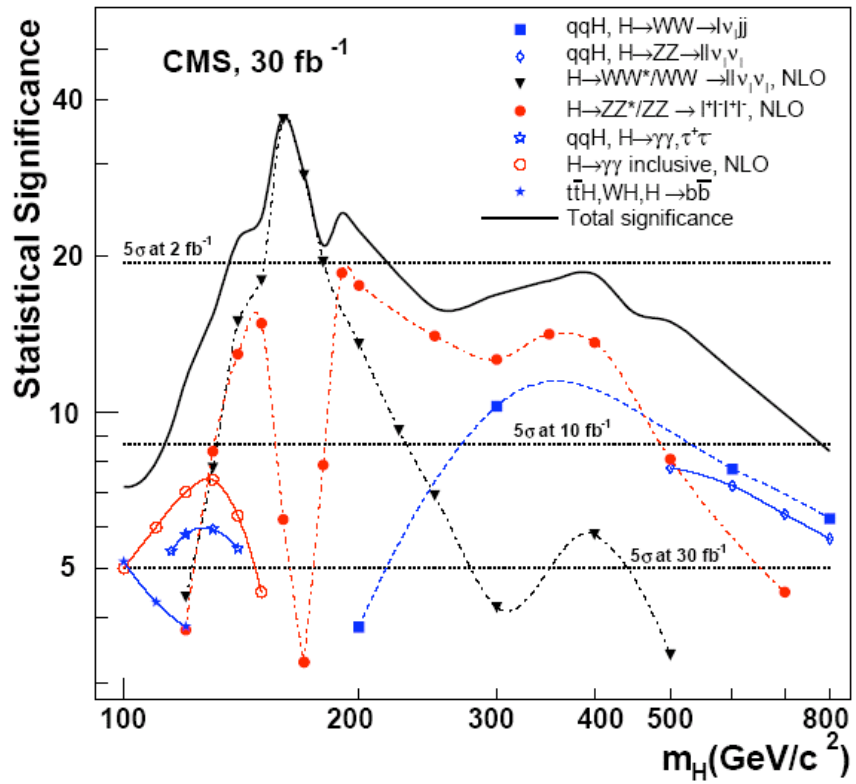
LHC reach



Many SUSY Higgs production and decay processes accessible with full LHC potential

Still regions where only a SM-like Higgs is visible


Signal significance
∫L dt = 30 fb-1
(no K-factors)
ATLAS
H → γγ
ttH (H → bb)
H → ZZ(*) → 4 l
H → WW(*) → lνlν
qqH → qq WW(*) → lνlν
qqH → qq ττ
qqH → qqZZ → llνν
qqH → qqWW → lνjj
Total significance
5 σ
10 2
10
1
10 2
10 3
m_H (GeV/c2)


Statistical Significance
CMS, 30 fb -1
qqH, H→WW→lνjjj
qqH, H→ZZ→llνlνl
H→WW*/WW →llνlνl, NLO
H→ZZ*/ZZ → l+l-l+l-, NLO
qqH, H→γγ,τ+τ-
H→γγ inclusive, NLO
tt̄H,WH,H →bb̄
Total significance
5σ at 2 fb-1
5σ at 10 fb-1
5σ at 30 fb-1
40
20
10
5
100
200
300
400
500
800
mH(GeV/c 2)

Baryon Abundance in the Universe

- Abundance of primordial elements combined with predictions from Big Bang Nucleosynthesis:

$$\eta = \frac{n_B}{n_\gamma}, \quad n_\gamma = \frac{421}{cm^3}$$

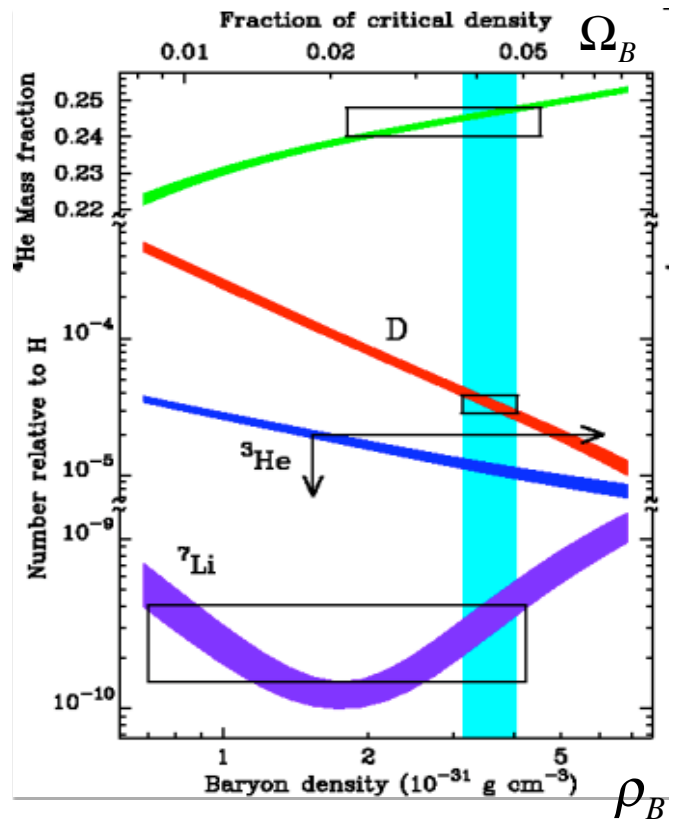
- CMBR, tell us

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B, \qquad \rho_c \approx 10^{-5} h^2 \frac{GeV}{cm^3}$$

There is a simple relation between These two quantities

$$\eta = \frac{n_B}{n_\gamma} = 2.68\ 10^{-8} \Omega_B h^2 \approx 6\ 10^{-10}$$

- Baryon Number abundance is only a tiny fraction of relativistic species



$$1\ GeV = 1.6\ 10^{-24}\ g$$

SM Electroweak Baryogenesis fufills the Sakharov conditions

- **Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Finite Temperature Higgs Potential

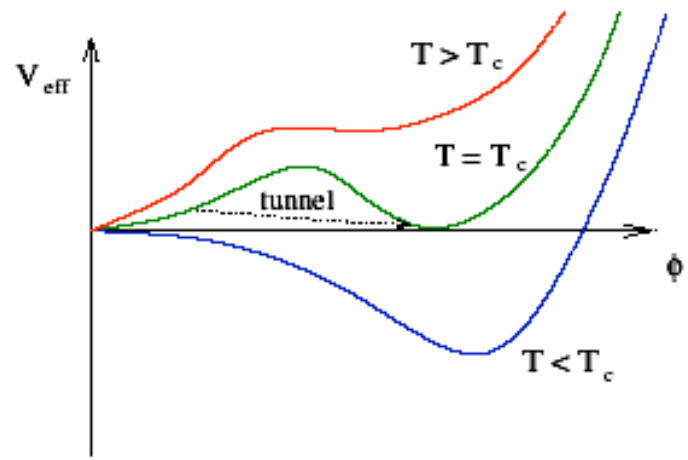
a cubic term is induced, proportional to the sum of the cube of all light boson particle masses

In general: which can spoil the behaviour of the cubic term therefore jeopardizing first order phase transition

$$m_b^2(H,T) = m_b^2 + g_{bH}^2 H^2 + \Pi(T)$$

In the SM the only contribution comes from the transversal components of the gauge bosons

$$E_{SM} \approx \frac{2}{3}\left(\frac{2M_W^3 + M_z^3}{\sqrt{2}\pi\, v^3}\right)$$



→ hence a first order first transition occurs

[redacted]

the quartic coupling is proportional to the square of the Higgs mass

[redacted]

- **Independent Problem: not enough CP violation**

Electroweak Baryogenesis in the SM is ruled out

Light Stop Effects on Electroweak Baryogenesis

The left- and right-handed stops mix:

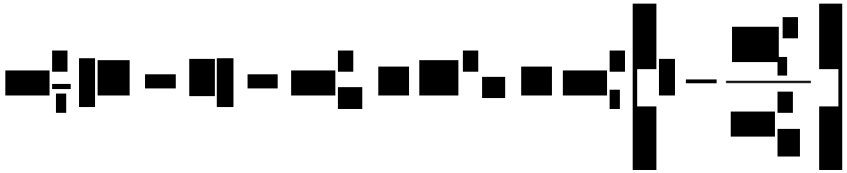
with $\mathrm{X_t} = A_t - \dfrac{\mu^*}{\tan\beta}$

and $\mathrm{m_t} = h_t\,\mathrm{H_2} = h_t \sin\beta\ \phi$

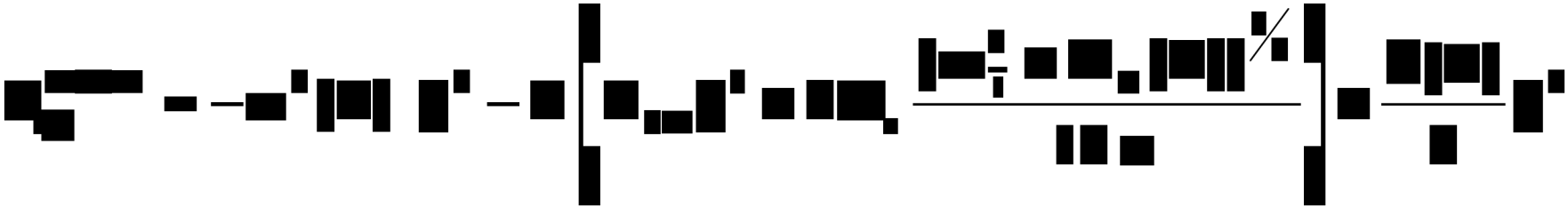
Hierarchy in soft SUSY breaking param:

$\mathrm{m_Q^2} >> \mathrm{m_U^2}$ → best fit to precision electroweak data

The lightest stop →



has six degrees of freeedom and a coupling of order one to the Higgs

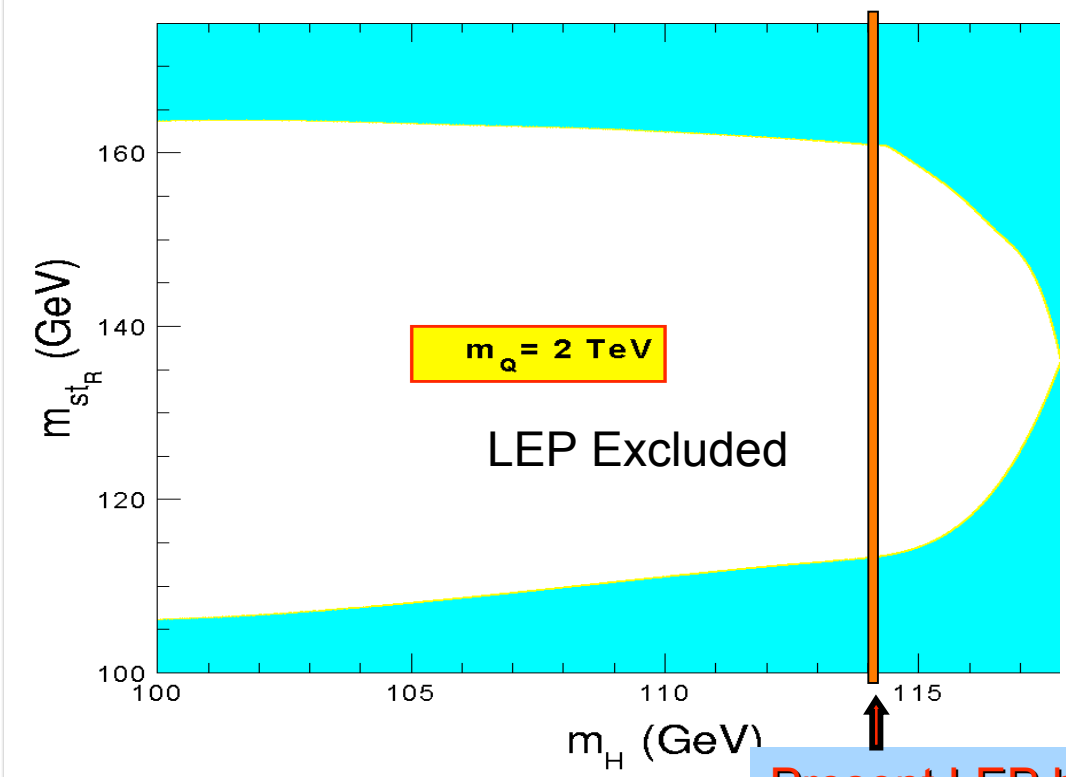


No stop contrib. to cubic term unless $\mathrm{m_U^2} + \Pi_R(T) \approx 0$, very light right-h. stop!

In the MSSM:

$$E_{MSSM} \approx E_{SM} + \frac{h_t^3 \sin^3\beta}{2\pi}\left(1-\frac{X_t^2}{m_Q^2}\right)^{3/2}$$

- **one stop should be quite light, ligther that the top quark and the stop mixing moderate to enhance E_{MSSM}**
- **For small stop mixing:** [redacted]



Present LEP bounds on the SM- like Higgs mass $m_{H_{SM-like}} > 114.6\,\mathrm{GeV}$

M.C, Quiros, Wagner

In the MSSM: $$E_{MSSM} \approx E_{SM} + \frac{h_t^3 \sin^3\beta}{2\pi}\left(1-\frac{X_t^2}{m_Q^2}\right)^{3/2}$$

one stop should be quite light and the stop mixing moderate to enhance E_{MSSM}

- For small stop mixing: [redacted]

it can work!!

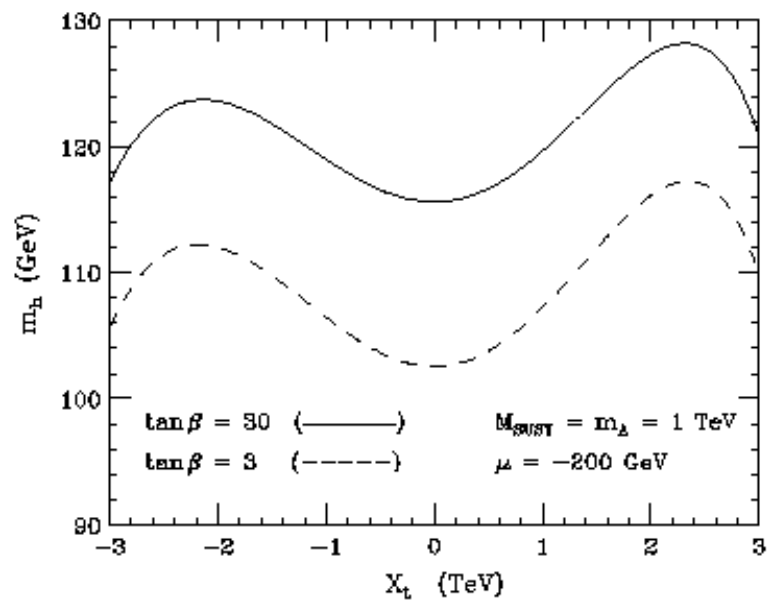
Present LEP bounds on the SM- like Higgs mass imply extra demands!

$$m_{H_{SM-like}} > 114.6\,\mathrm{GeV}$$

- MSSM lightest Higgs mass depends crucialy on m_t^4, on the stop mixing X_t and logarithmically on the stop masses

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{8\pi^2 v^2}\left[\log\left(\frac{m_{\tilde{t}_l}^2 m_{\tilde{t}_H}^2}{m_t^4}\right) + 2\frac{|X_t|^2}{m_Q^2}\log\left(\frac{m_{\tilde{t}_H}^2}{m_{\tilde{t}_l}^2}\right) + \vartheta\left(\frac{|X_t|^4}{m_Q^4}\right)\right]$$

hence $m_Q \geq 1\,\mathrm{TeV}$ and $X_t \geq 0.3 m_Q$ needed



Computation of the baryon asymmetry

New CP violating phases in the stop and chargino sector are crucial
[for large values of m_Q, only the chargino –neutralino currents are relevant]

- Interaction with varying Higgs background in the bubble wall creates net neutral and charged Higgsino currents through CP-violating interactions

- Higgsino interactions with plasma creates an excess of left-handed anti-baryons (right-handed baryons)

- Left-handed baryon asymmetry is partially converted to lepton asymmetry via anomalous processes (weak sphalerons: net B violation)

- Baryon asymmetry diffuses into broken phase and gets frozen there since $v(T) / T > 1$

Assuming time relaxation of charge is large (no particle decays)

1. compute CP-violating currents
2. solve diffusion equations describing the above processes

Dependence of the Baryon asymmetry on SUSY parameters

Higgs sector : [redacted]
Chargino sector : mass param. [redacted] with physical phase [redacted]

currents proportional to sin([redacted]), with resonant behavior for $M_2 \approx |\mu|$

Total Baryon asymmetry depends on two contributions proportional to:

★ $$\varepsilon_{ij} H_i \, \partial_\mu \, H_j = v^2(T) \, \partial_\mu \beta$$

suppressed for large [redacted] due to $\Delta\beta$ dependence

★ $$H_1 \partial_\mu H_2 + H_2 \partial_\mu H_1 = v^2 \cos(2\beta) \, \partial_\mu \beta + v \, \partial_\mu v \sin(2\beta)$$

unsuppressed for large CP-odd masses