Three Mysteries of Matter

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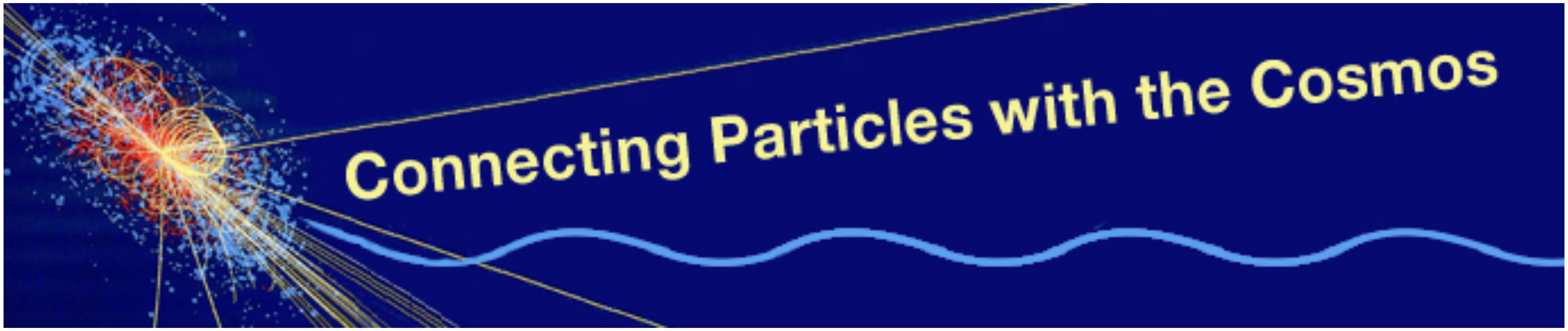

Landesexzellenzinitiative Hamburg

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Outline

- The Higgs Mechanism and the Origin of Mass

- Cosmology as motivation for New Particle Physics Models

  * Dark Matter　　　　* the Baryonic Asymmetry

- Dark Matter: the WIMP solution and TeV-scale Supersymmetry

- Baryogenesis at the TeV-scale

- Experimental Probes

  -- High Energy Colliders

  -- Direct Dark Matter searches: *The decade of the WIMP*

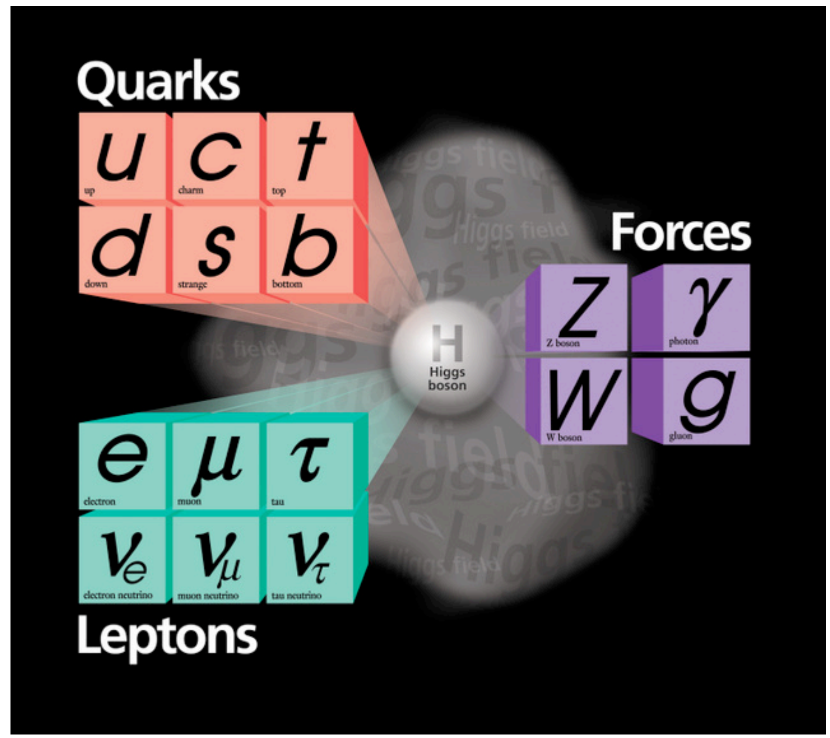
  -- Indirect Dark Matter Detection: *Hints from Charged Cosmic Rays?*

- Outlook

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, the photon, the W and the Z

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

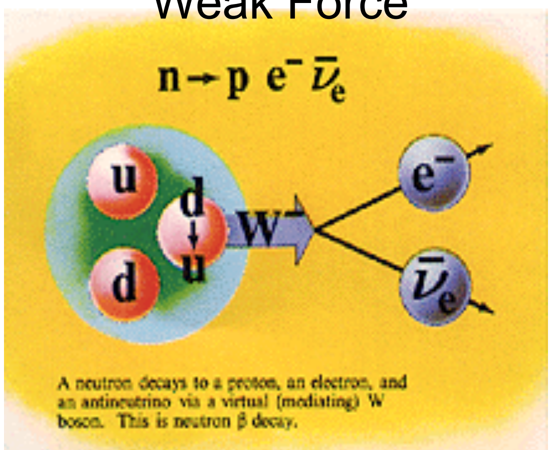
Crucial Problem in the SM: The origin of mass of all the fundamental particles

• *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



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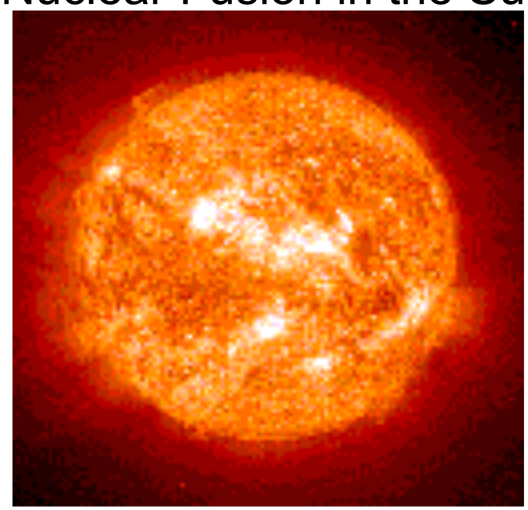
Nuclear Fusion in the Sun



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

Determines strength of the weak force

$$F \sim \frac{e^{-M_W r}}{r}$$

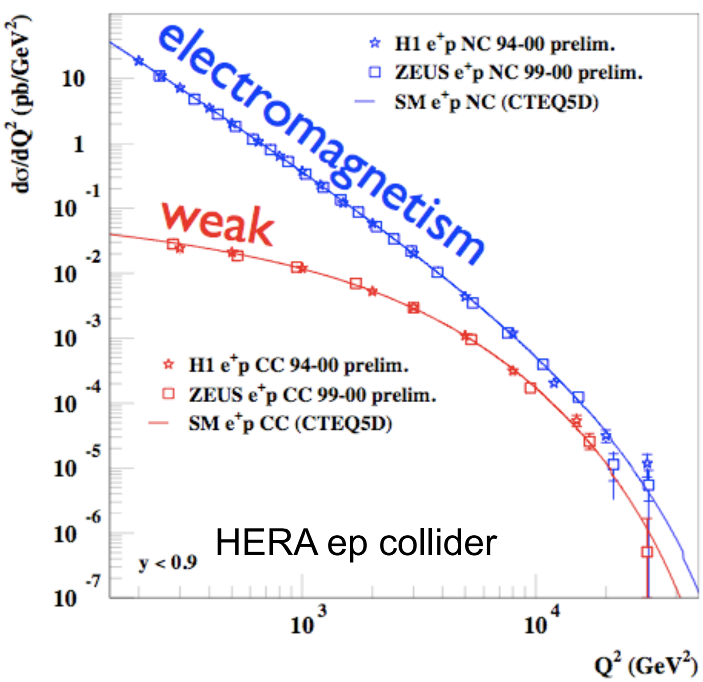
Sun still burning !

• *A fermion mass term* $L = m\,\bar{\psi}\psi = m\,(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$ *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 Breaking (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



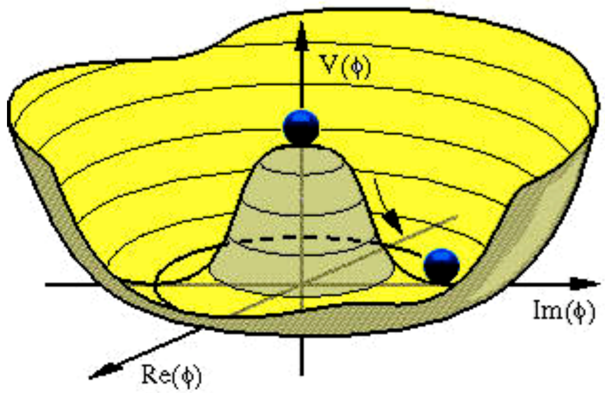
The electromagnetic and weak forces are unified
==> electroweak theory

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 (Tevatron) reach
and prospective ILC or CLIC

The Higgs Mechanism

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



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 breaking 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 $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$ ==> $SU(3)_C$ x $U(1)_{em}$

$$\boxed{m_\gamma = 0 \quad m_g = 0}$$

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

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

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

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

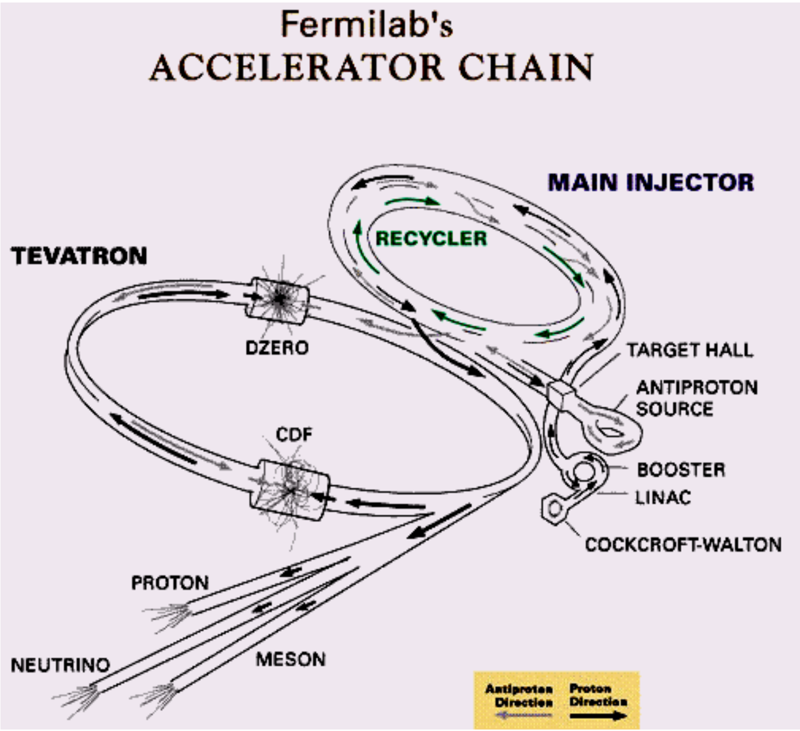
Discovering the Higgs will put the final piece of the Standard Model in place

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

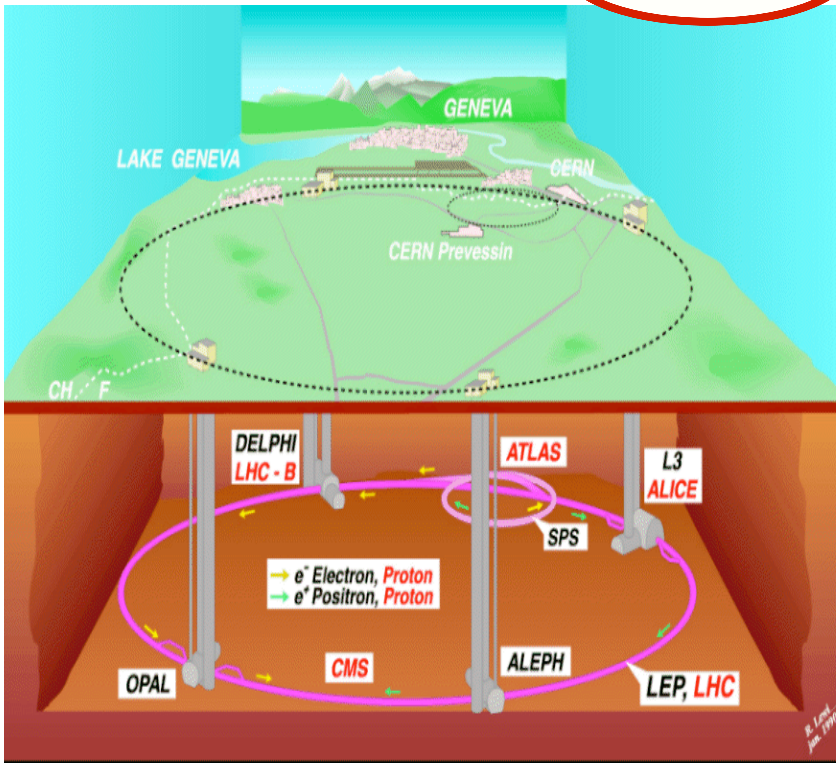
How do we search for the Higgs?

Colliding particles at High Energy Accelarators: LEP, the Tevatron, the LHC

$p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV



e^+e^- at $\sqrt{s}$ = 210 GeV and pp at $\sqrt{s}$ = 14 TeV



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

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How do we search for the Higgs?

Colliding particles at High Energy Accelarators:

The Tevatron

~ 4 miles circumference:
proton- antiproton collisions

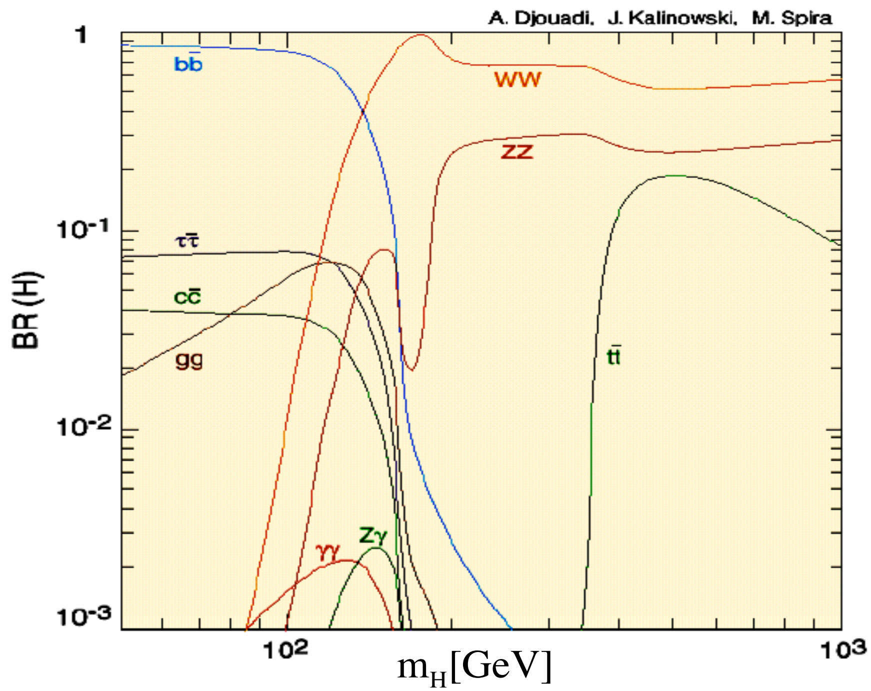
The Large Hadron Collider (LHC)

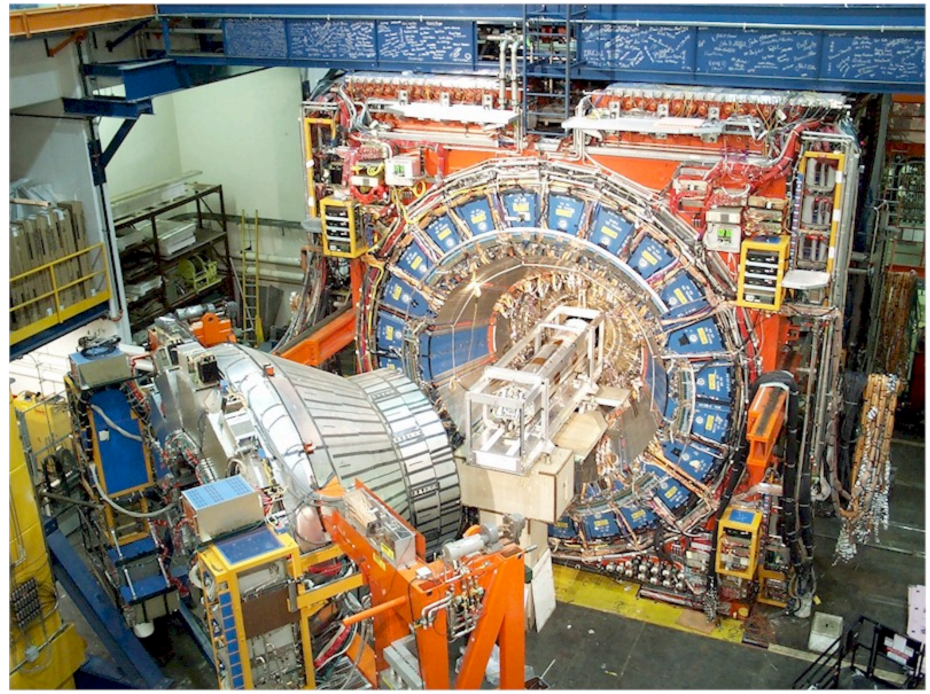
~ 17 miles circumference:
~ a billion proton-proton collisions per second!

High energy collisions can create new heavy particles: $E = mc^2$

Powerful detectors enable searches for the Higgs

through its decays into SM gauge bosons and fermions





Depending on its mass the Higgs will decay into different particles

Consistency of the theory implies

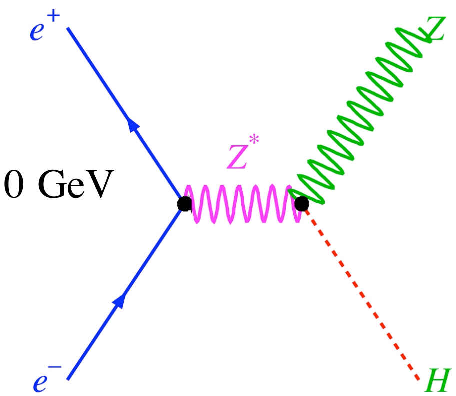
$$m_{H_{SM}} < 1\ \text{TeV}$$

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

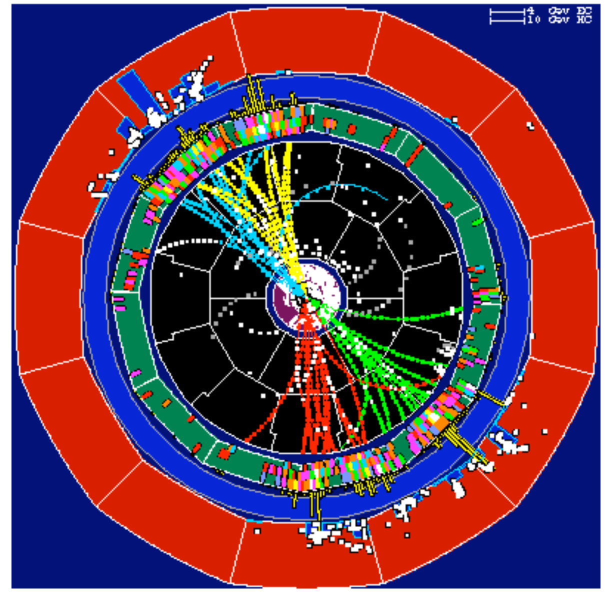
♦ Direct SM Higgs search at LEP

$\sqrt{s} = 210$ GeV



$Z \rightarrow q\bar{q}, l^+l^-, \nu\bar{\nu}$

$H_{SM} \rightarrow b\bar{b}, \tau^+\tau^-$

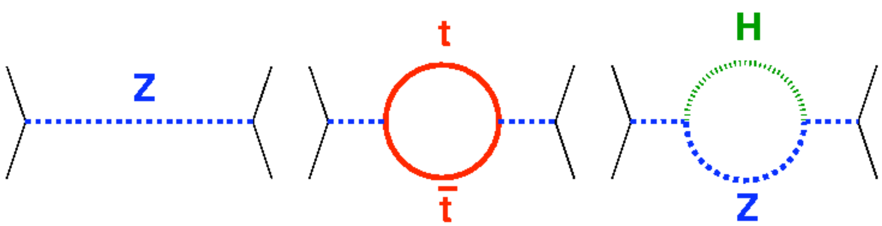


final LEP result, 2003

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

But, a tantalizing hint of a Higgs with mass about 115 GeV!

♦ $M_{H_{SM}}$ Indirect Determination from Precision Electroweak Observables

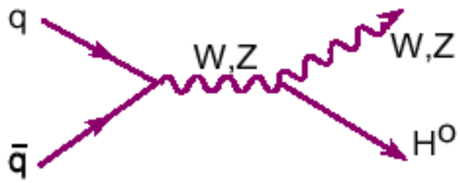


The Higgs boson enters through virtual Higgs production in electroweak observables: particle masses, decay rates, etc

logarithmic dependence on the Higgs mass: $m_{H_{SM}} < 185$ GeV at 95 % C.L (2008)

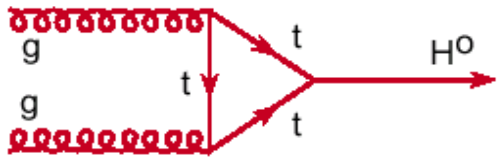
To evade this constraint on $m_{H_{SM}}$ requires new phenomena a the TeV scale

Direct Higgs searches at the Tevatron



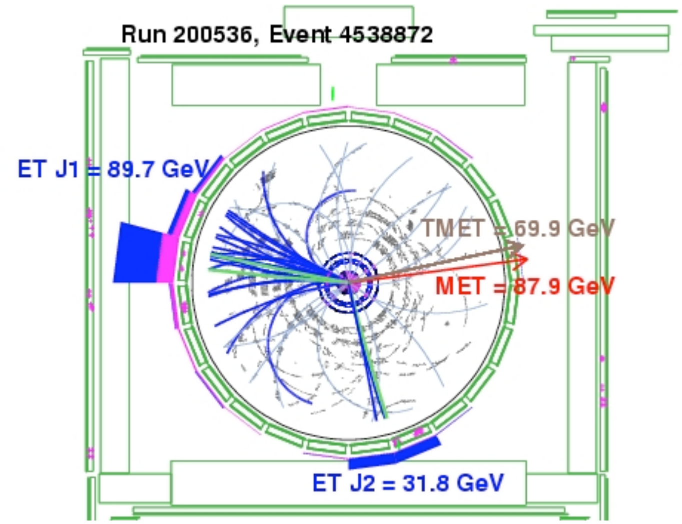
W, Z bremsstrahlung

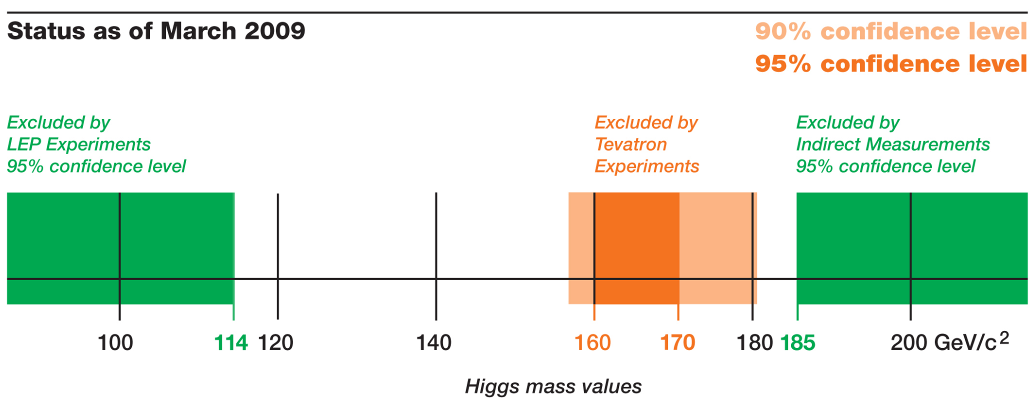
with $H \to b\bar{b}$, WW



g g fusion

with $H \to WW$

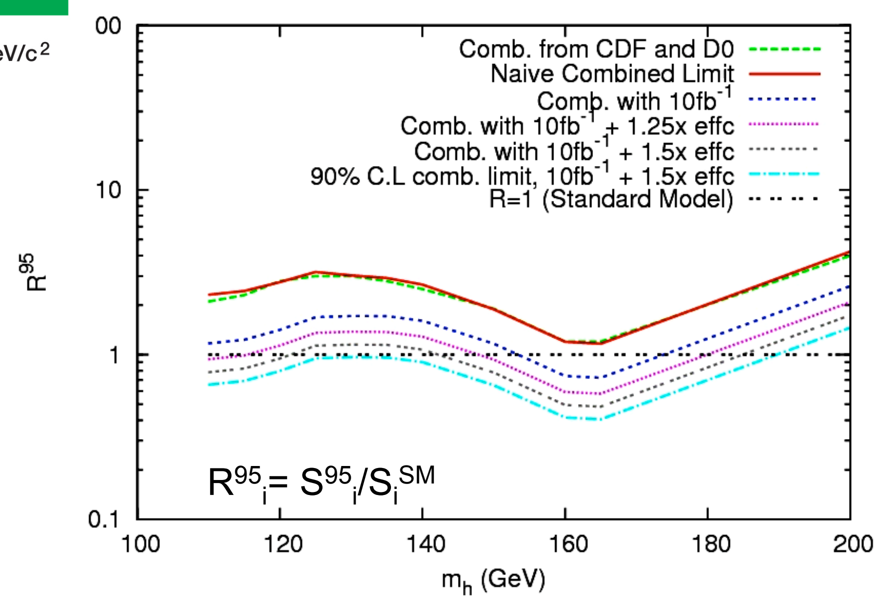




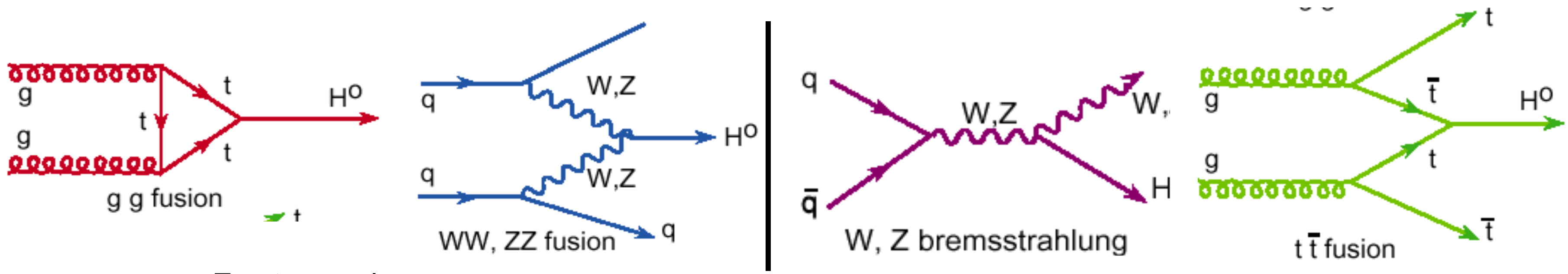
The Tevatron Projections

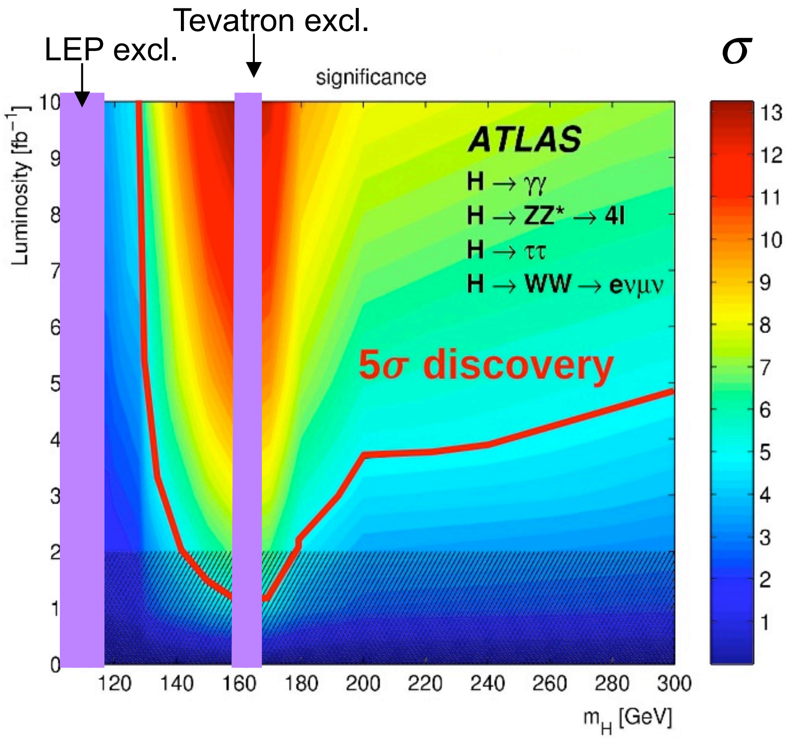
based on improvements already achieved for some analysis, extending them to the rest-

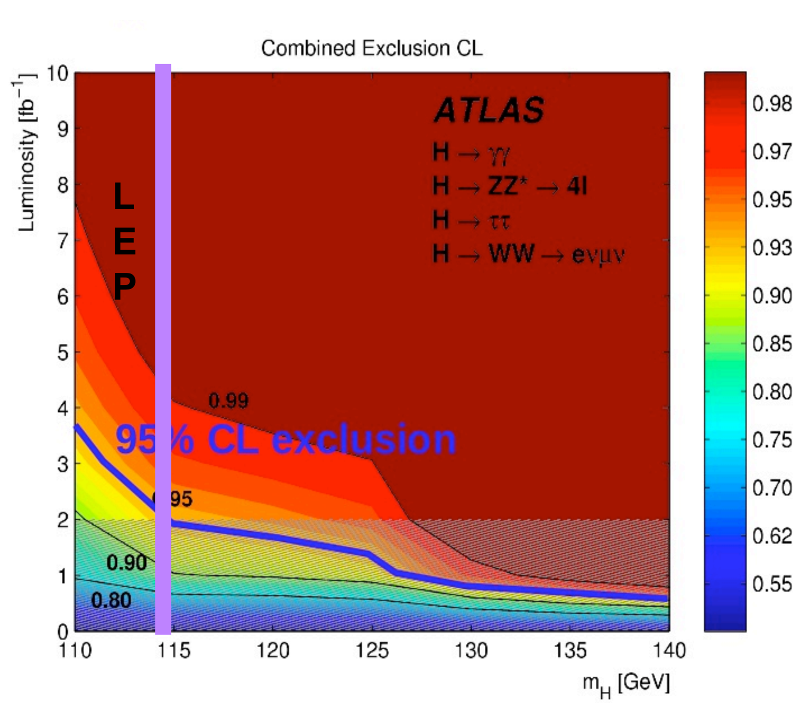
Tevatron can search for the Higgs in all the mass range preferred by precision data



The SM Higgs LHC potential







With 10 fb^{-1}, discovery for m_h [~125,~500] GeV range;

With 1-2 fb^{-1}, some reach in the H to WW channel (2 fb^{-1}: exclusion for all m_h)

With enough luminosity, a SM Higgs at a 14 TeV LHC cannot escape detection

The LHC today

- After an accidental start last year, the LHC is expected to start running by the end of 2009. **First collisions will be at 2.2 TeV, just above the Tevatron energy !**
- The center of mass energy will be lower than the expected one, 14 TeV, reaching only up to 7 to 10 TeV depending on the magnets performance.
- The plan is to run for a whole year, until the end of the fall of 2010, accumulating about 200 inverse pb of luminosity.
- Due to the limited energy and luminosity, this will make LHC superior to the Tevatron only in certain search analyses, like the search for TeV scale resonances decaying to leptons.
- Higgs searches beyond the Tevatron reach will demand higher luminosities and higher energies.
- After the first run, LHC plans to shut down for about 6 months. Higher luminosity/energy run will start in the spring of 2011. It is yet unclear what the highest energy achievable will be.

Dark Matter and Electroweak Symmetry Breaking

COSMOLOGY gives the first unambiguous evidence for New Physics

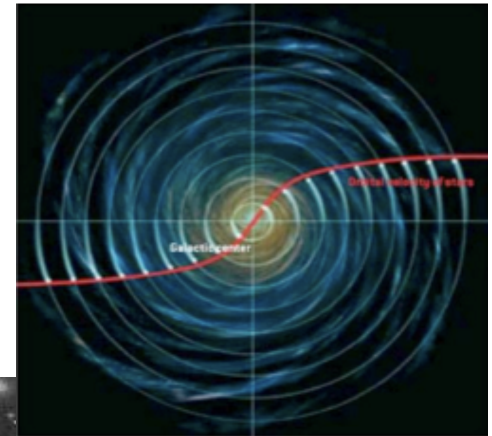
Dark Matter

(or a modification of gravity ?)

- There exists a wide variety of indications of DM existence
- Each observation infers DM presence through its gravitational influence
- No observation of DM electroweak interactions

  (or other non-gravitational interactions)

The Mystery of Dark Matter



- Rotation curves from Galaxies.

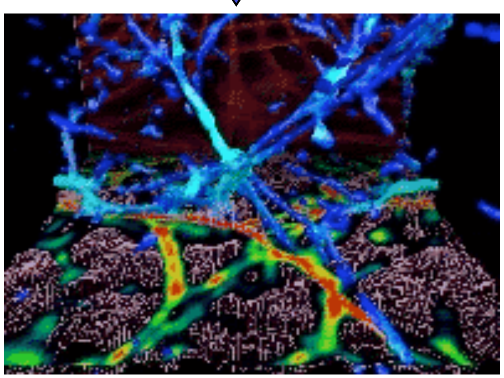
Luminous disk → not enough mass to explain rotational velocities of galaxies → Dark Matter halo around the galaxies

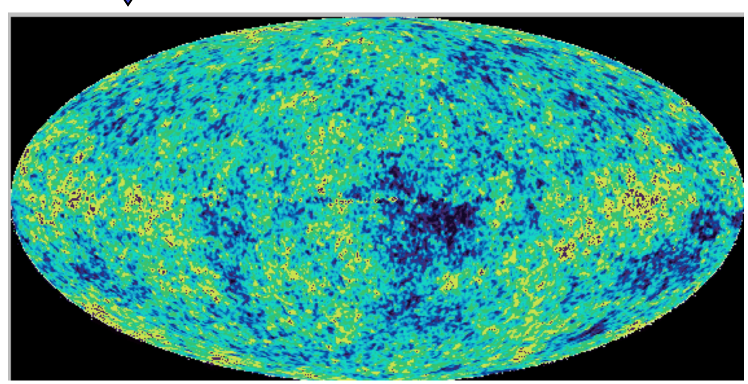
- Gravitational lensing effects

Measuring 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.

All observations infer the existence of DM via gravity interactions

Dark Matter

- Non-Baryonic
- Stable
- Mainly Cold

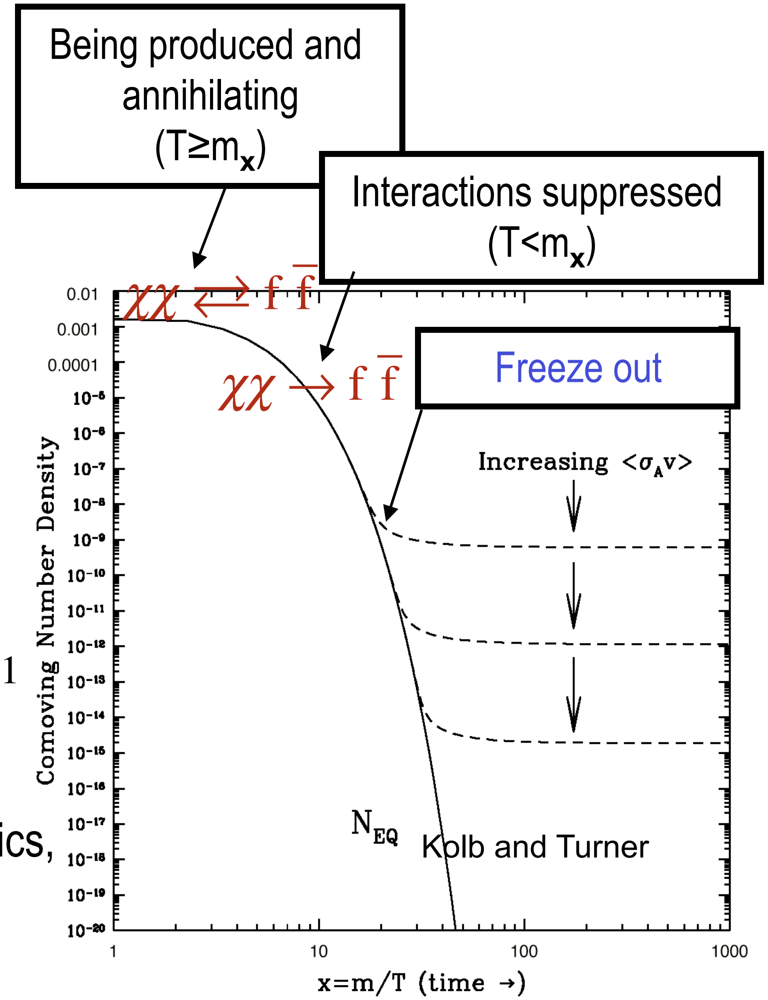
The SM has no suitable candidates

- 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

WIMPs: DM as cold Thermal Relic*



Evolution of the Dark Matter Density

- •T>>M_X WIMPs initially in thermal equilibrium
- •T< M_X number density is Boltzmann suppressed

- Annihilation stops when number density drops

$$H > \Gamma_A \approx n_\chi < \sigma_A v > \qquad T_F \sim M_X/20$$

i.e., annihilation too slow to keep up with Hubble expansion ("freeze out")

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

If m_x ~ 0.1-1 TeV, and σ_A determined by electroweak physics,

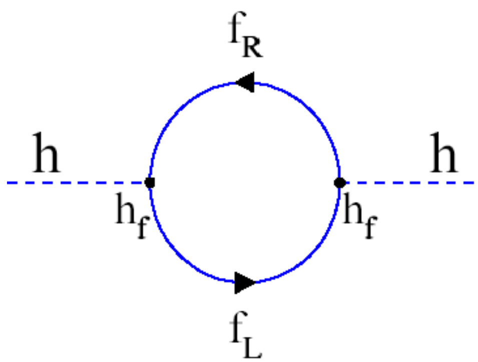
$$\sigma_A \approx k\alpha_W^2 / m_X^2 \approx \text{a few pb} \quad \text{then } \Omega_{DM}\, h^2 \sim 0.1$$

Remarkable agreement with WMAP ⟶ $\Omega_{CDM} h^2 = 0.114 \pm 0.007$

Numerical coincidence or indication that DM originated from EW physics?

Weak Scale Models of EWSB + data ⟷ Dark Matter

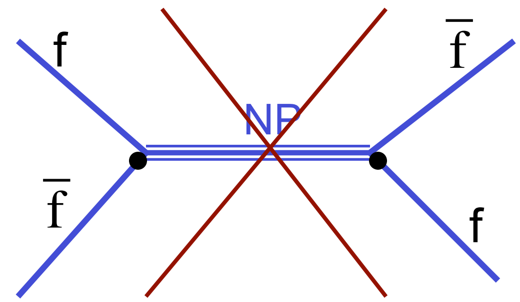
EWSB scale << M_{Pl} ⟶ Hierarchy problem



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

⟶ **New particle/s with masses of order of the EWSB scale to cancel them or new Dynamics at the TeV scale**

Precision electroweak data constrains the existence of SM particle interactions with a single new particle with mass below a TeV.
Also constraints from rapid proton decay and flavor changing transitions



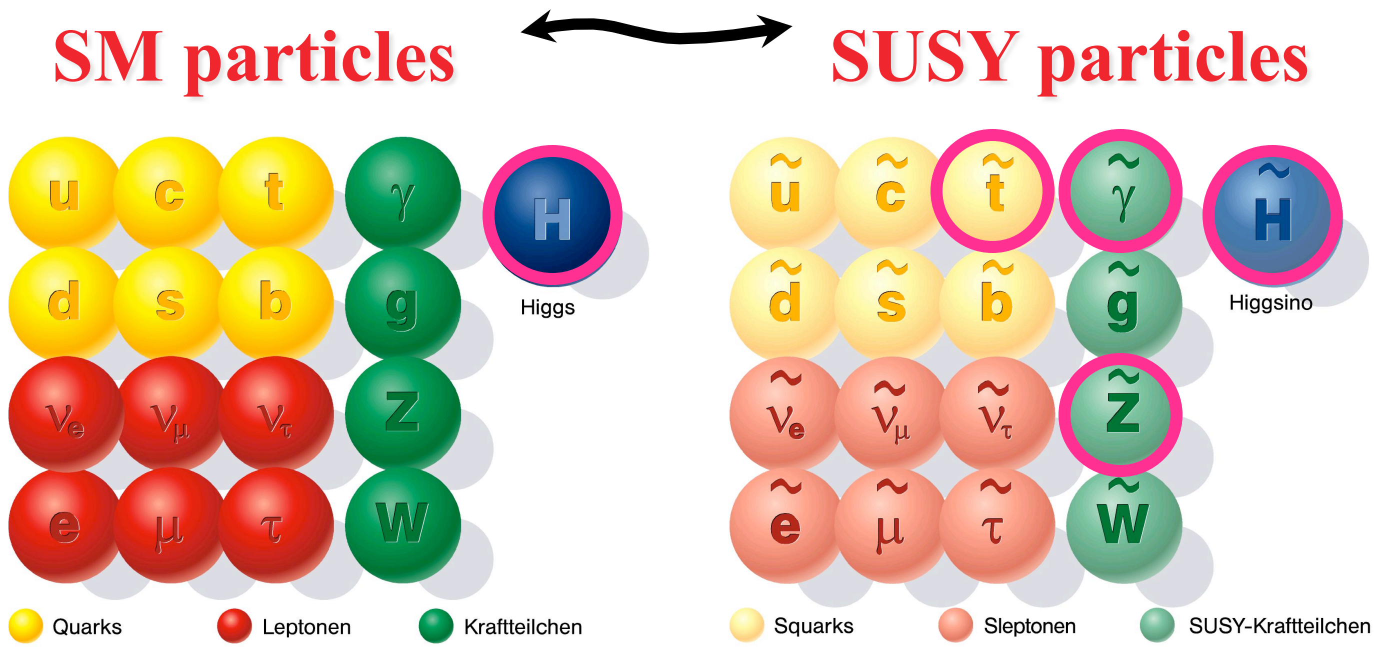
Many models of EWSB introduce an extra discrete symmetry
(all interactions require pairs of new particles)
that makes the lightest new particle stable
- a stable Weakly Interacting Massive Particle (WIMP).

As an example, I will take Supersymmetry

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



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

◈ SUSY is well motivated on purely particle physics grounds

❈ Stabilization of the weak scale – Planck scale hierarchy $\delta m_H^2 \approx (-1)^{2S_i}\left(n_i g_i^2/16\pi^2\right)\Lambda^2$

❈ Super-space algebra contains the generator of space-time translations

→ possible ingredient for SUPERGRAVITY

❈ Starting from positive masses at high energies:

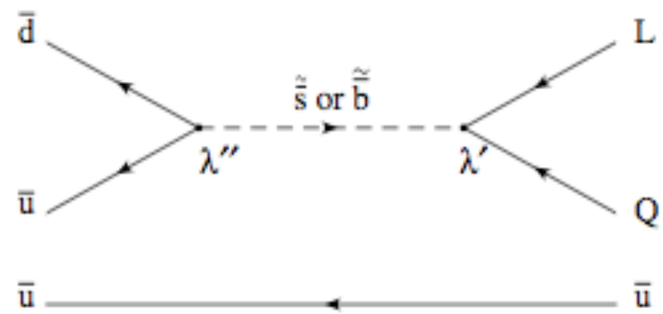
electroweak symmetry breaking is induced radiatively

❈ Minimal SUSY extension of the Standard Model

leads to Unification of Gauge Couplings

◈ SUSY and Cosmology

If all couplings allowed by SUSY and gauge invariance are present, with values of order one, fast proton decay would occur



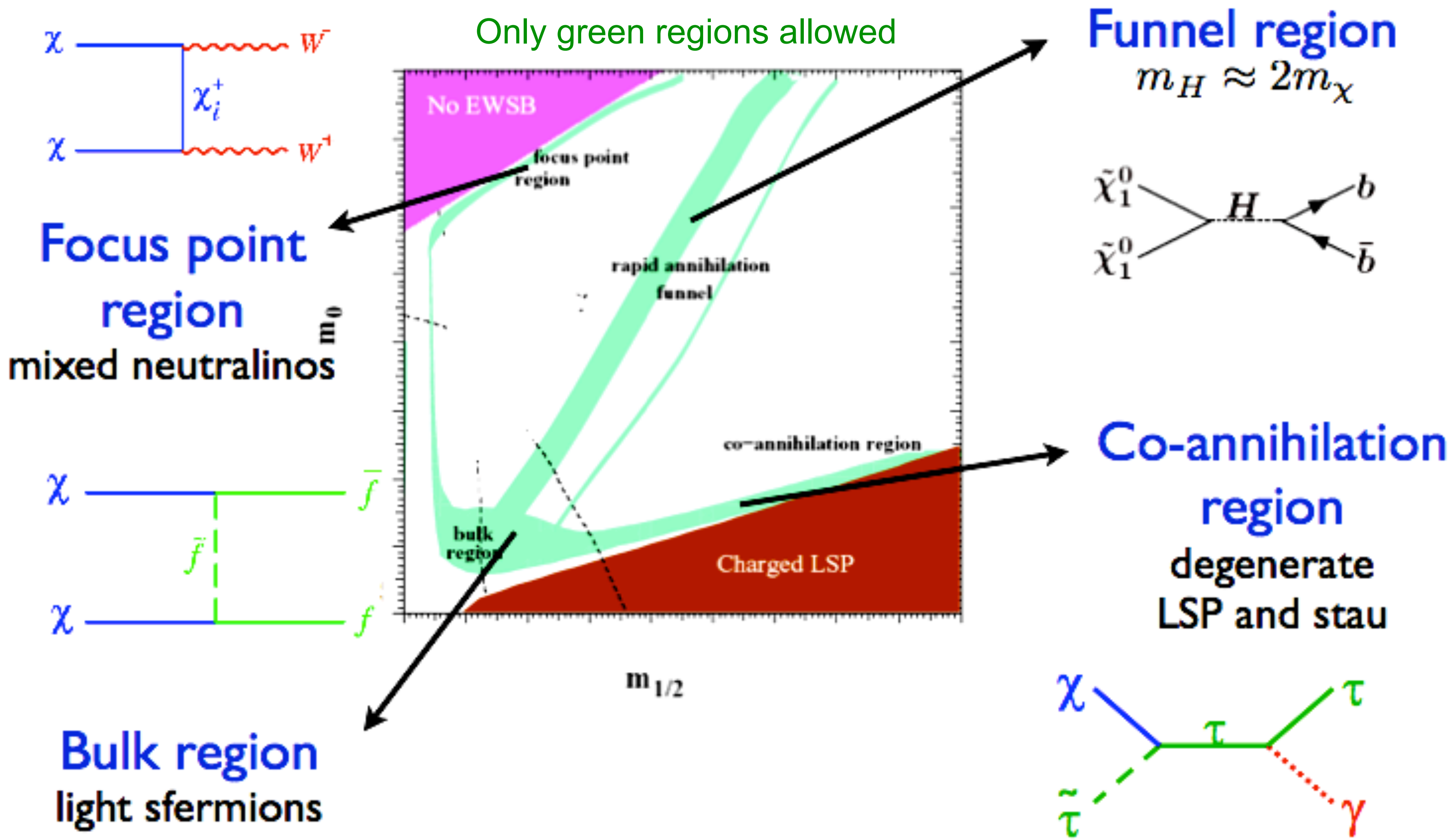
✸ SUSY with R-parity symmetry conserved → $R_P = (-1)^{3B+L+2S}$

SM particles $R_p = 1$; SUSY particles $R_p = -1$ ➔ Solution to proton decay

Naturally provides a neutral stable DM candidate
➔ the Lightest SUSY Particle (LSP)

Dark Matter density strongly restricts viable models

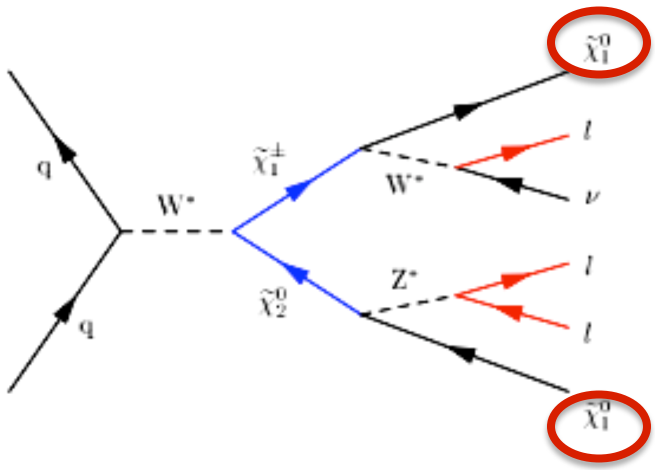
LSP annihilation cross section is typically suppressed
for most regions of SUSY spectrum → too much relic density



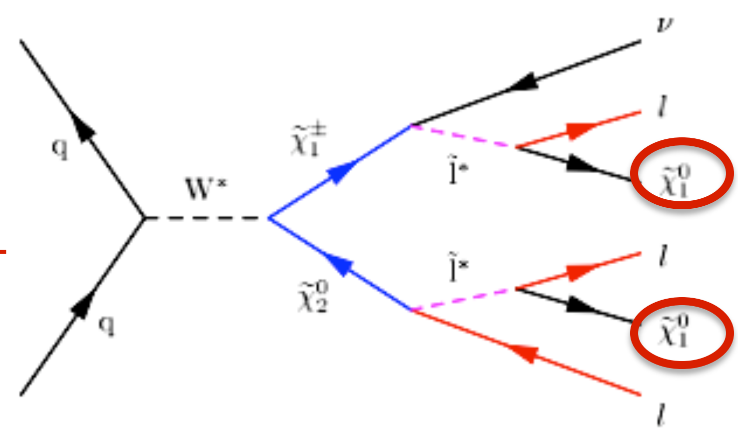
The Hunt for the WIMP

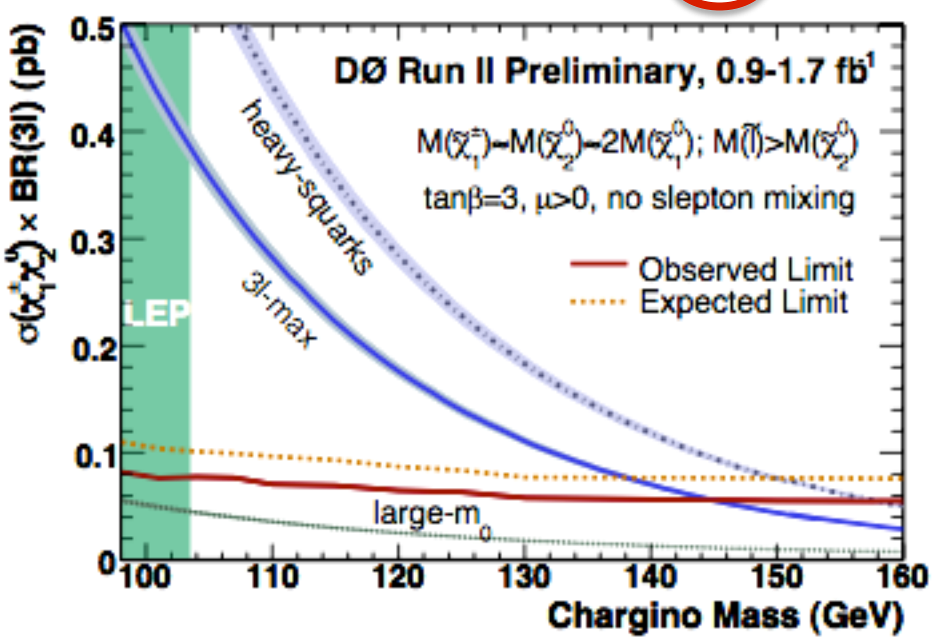
- Colliders Searches
- Direct Detection - in underground laboratories -
- Indirect Detection - from DM annihilation in the cosmos -

- **At Colliders,** signals with large Missing Energy are characteristic of theories with a thermal WIMP as DM candidate
  - SUSY particles can only be produced in even numbers (pairs)
  - Each sparticle decays into a state that contains a LSP



Trileptons
+
lots of MET





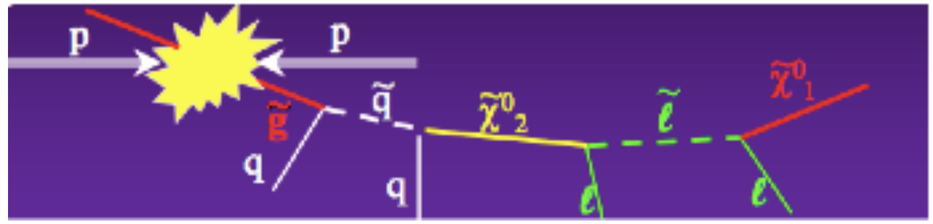
No Evidence at the Tevatron

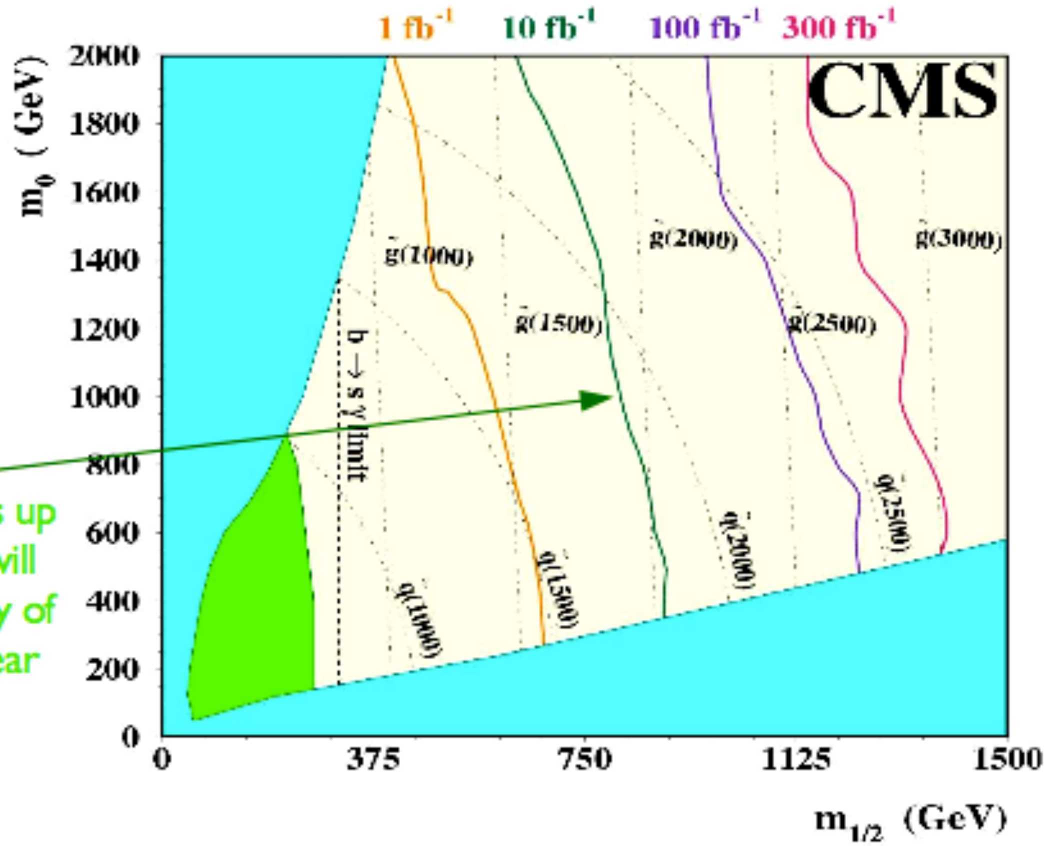
At the LHC, dilepton and trilepton Signatures can be very powerful. Capability to infer masses of SUSY particles or mass combinations, using kinematic endpoints

Mass determination ~ with 10% accuracy

Missing Energy Signals at the LHC

Typical SUSY event at LHC





Once the LHC is up and running, it will deliver luminosity of 10 fb^{-1} in one year

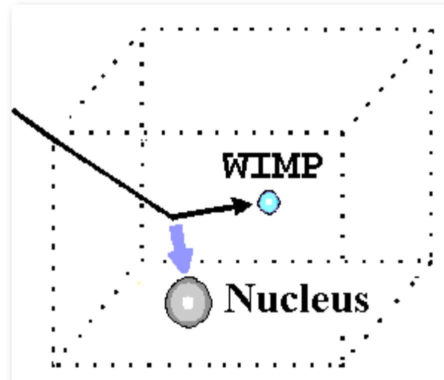
If low energy SUSY exists, we expect to see some of its signatures at LHC

reach: $M_{\tilde{q}}$ *and* $M_{\tilde{g}}$ *up to to* ~ 2 *TeV with* $10\ fb^{-1}$

2) Direct Detection 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

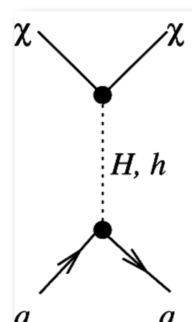


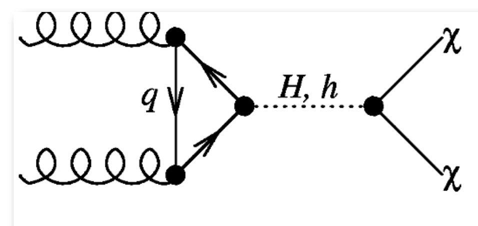
- WIMPs elastically scatter off nuclei in targets; observe nuclear recoil

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

sensitive mainly to spin-independent elastic scattering cross section ($\sigma_{SI} \leq 10^{-8}\, pb$)

==> dominated by virtual exchange of H and h

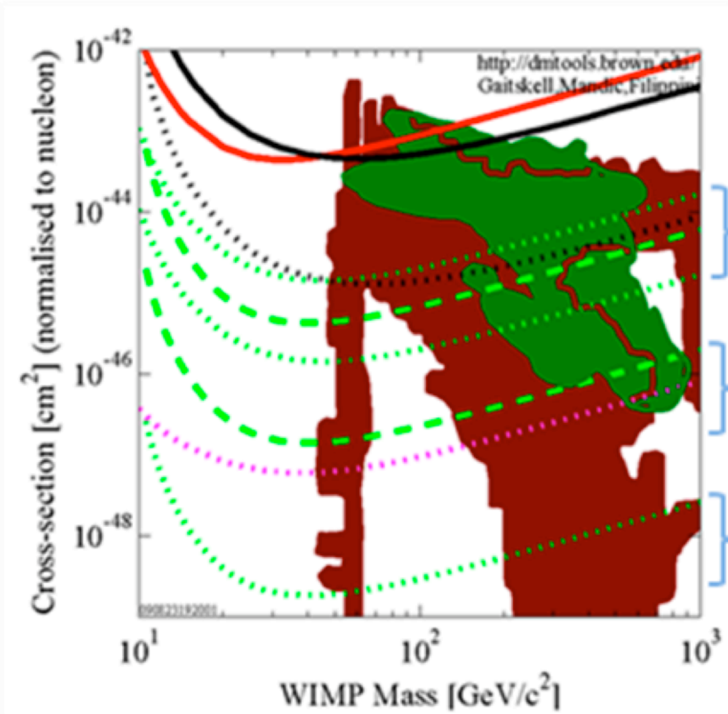




- $\tan\beta$ enhanced couplings of H to strange, and to gluons via bottom loops

$$\frac{\sigma_{SI}}{A^4} \approx \frac{0.1 g_1^2 g_2^2 N_{11}^2 N_{13}^2 m_p^4 \tan^2\beta}{4\pi m_W^2 M_A^4}$$

Prospects for Direct Dark Matter Detection



Current status ~10^{-43} cm^2

Current experiments: SuperCDMS, Xenon100, LUX350, MiniClean, Warp140

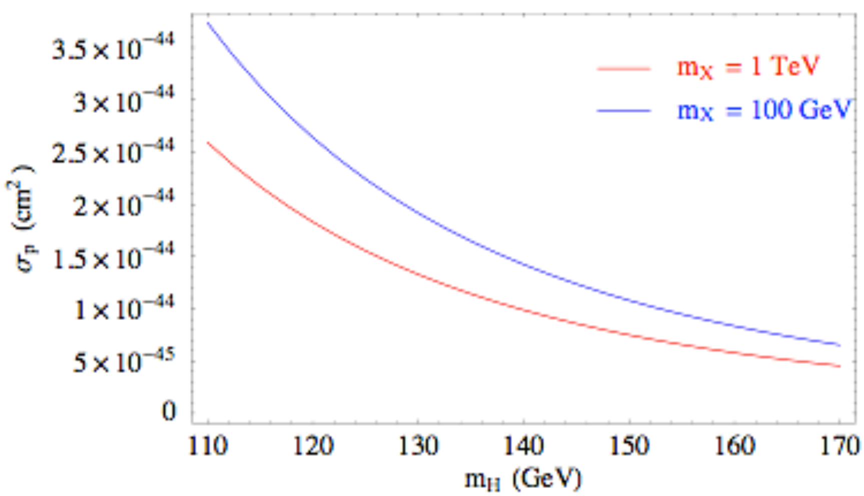
2^{nd} Generation (> 2013)

3^{rd} Generation (> 2017)

DM Vs the flavor problem

Models with heavy sfermions, CP-odd and charged Higgs bosons, naturally suppress flavor violation and ➔ $\sigma_{SI} \sim 10^{-44}$ cm^2

Current experiments will soon test a large class of models favored by flavor constraints



Indirect Dark Matter Detection

- **WIMP annihilation:**

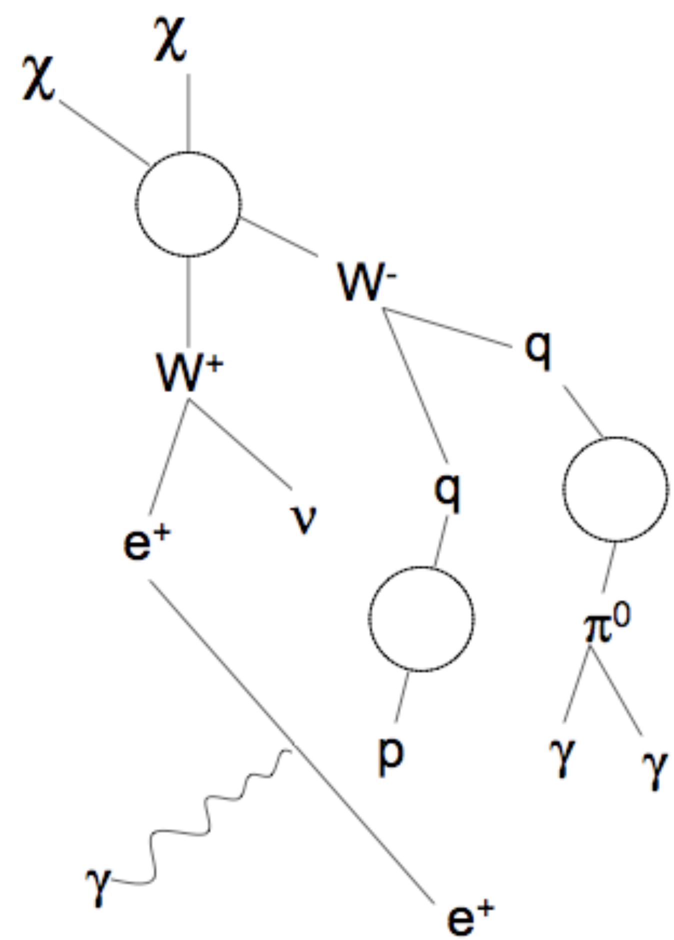
Typical final states include heavy fermions, gauge and Higgs bosons

- **Fragmentation/Decay**

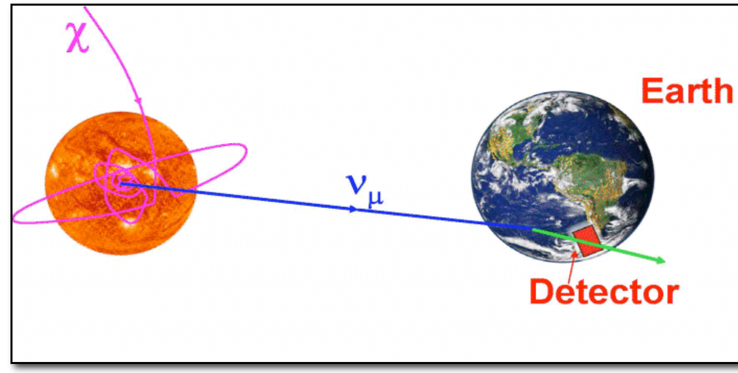
Annihilation products decay and/or fragment into combinations of electrons, protons, neutrinos and gamma-rays

- **Synchrotron and Inverse Compton**

Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



Indirect Dark Matter Detection



- **Neutrinos** from annihilation in the core of the Sun

- **Gamma Rays** from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc.

- **Positrons/Antiprotons** from annihilations throughout the galactic halo

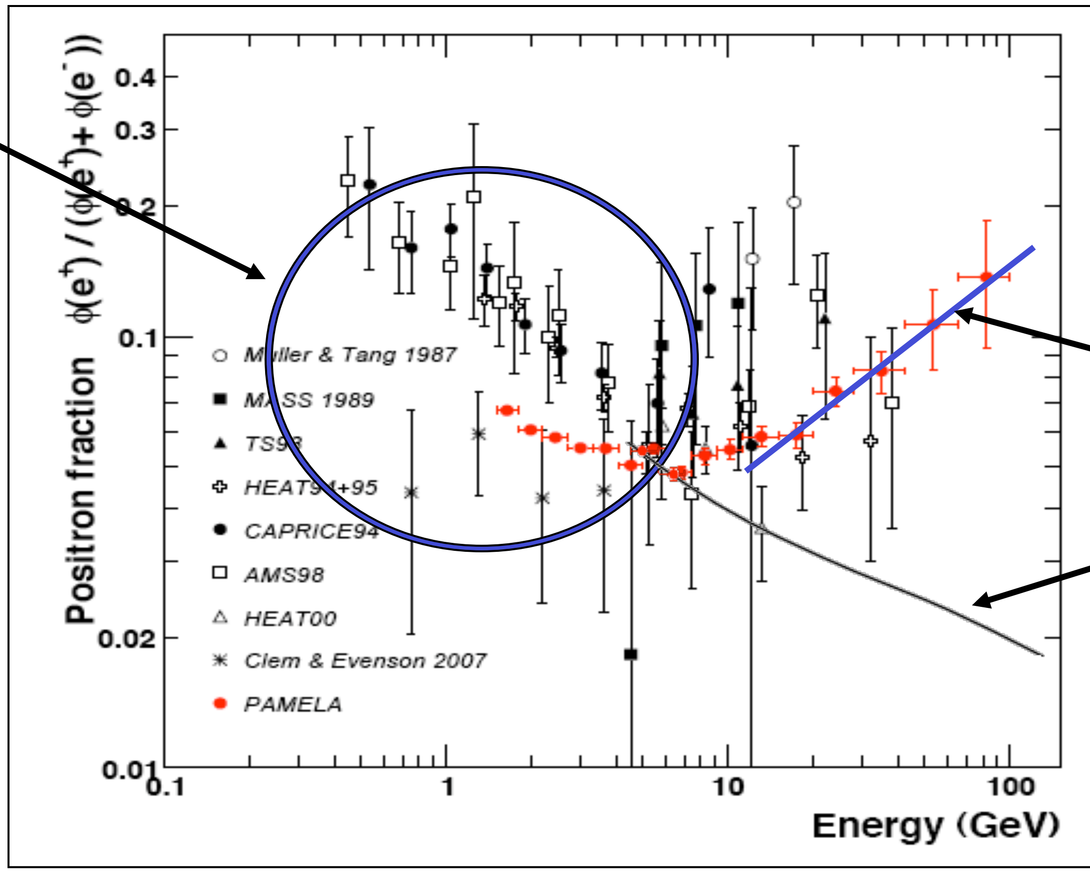
- **Synchrotron Radiation** from electron/positron interactions with the magnetic fields of the inner galaxy

PAMELA's Positron excess

PAMELA: magnetic spectrometer and electromagentic carolimeter mounted in a satellite

Charge-dependent solar modulation important below 5-10 GeV

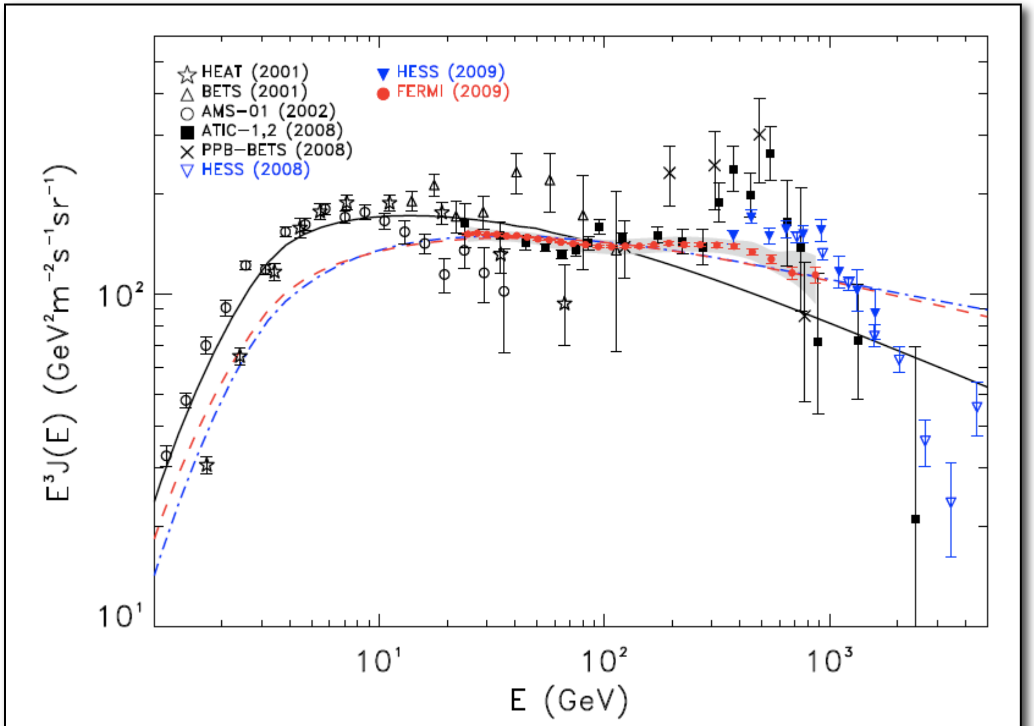
(Pamela's sub-10 GeV positrons appear as they should)



Rapid climb above 10 GeV indicates the presence of a <u>primary source of cosmic ray positrons!</u>

Astrophysical Expectation (secondary production)

Cosmic Ray Electrons from FERMI



- In a series of balloon flights, ATIC measured an excess of cosmic ray electrons between 300 and 800 GeV (Nature '08)
- More recent results from Fermi and HESS measure a less pronounced feature, but still an excess relative to a simple power-law

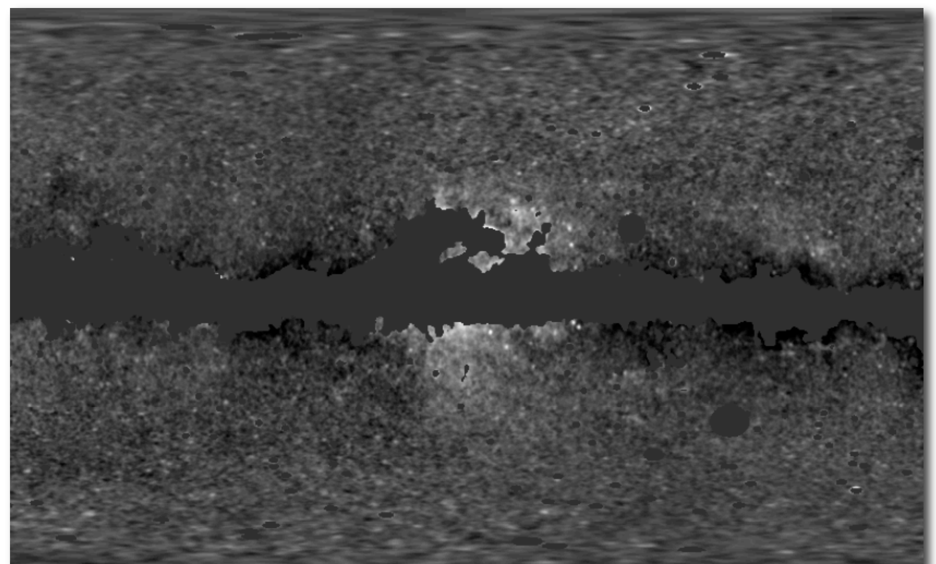
FERMI: Silicon tracker and electromagnetic calorimeter mounted on a satellite
No magnetic field ➔ no possible charge discrimination

WMAP and energetic electrons/positrons

- WMAP does not only detect CMB photons, but also a number of galactic foregrounds
- GeV-TeV electrons emit hard synchrotron in the frequency range of WMAP

The Inverse Compton component of the WMAP Haze

The microwave haze is likely synchrotron emission from a hard electron spectrum.



Positron excess from Pamela, Fermi and WMAP energetic electrons/positrons

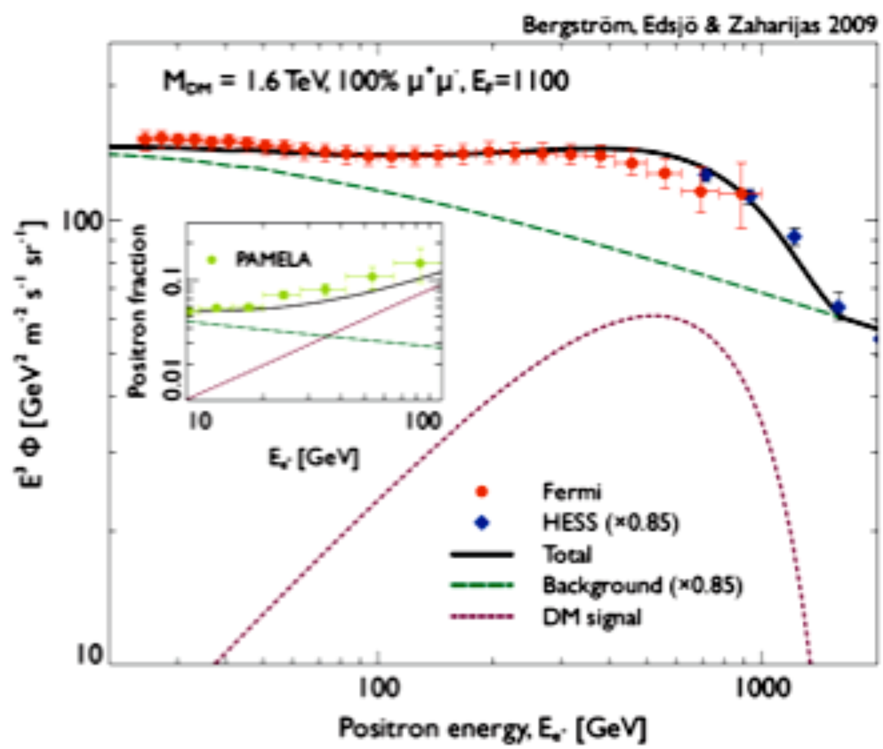
- Highly energetic electrons and positrons are surprisingly common both locally and in the central kiloparsecs of the Milky way

Dark Matter Explanation:

- Distribution and spectrum of WMAP haze consistent with being of DM origin
- Pamela and Fermi spectral features could be generated by DM annihilation

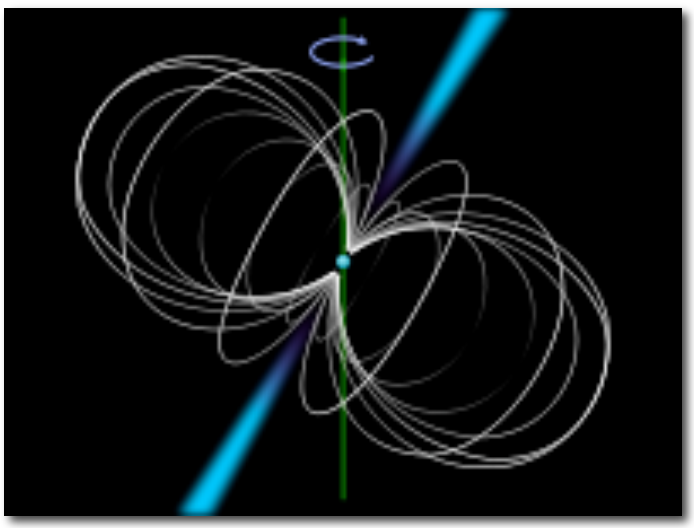
BUT not easily

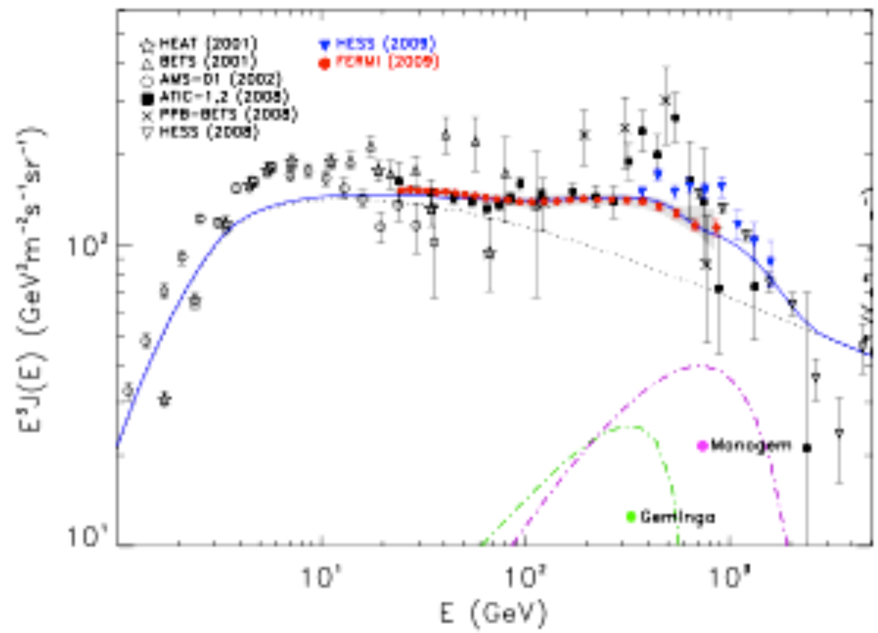
- Very hard injection spectrum (large fraction of annihilations into leptons)
- Too many antiprotons, gamma rays
- Requires a very high annihilation rate



Other Possible Explanations:

- Astrophysical objects, like pulsars, have the power to produce the high energy electron spectrum. For this, they should be nearby and have the proper "age". Positron excess can also be explained by the same astrophysical sources.





- Possible proton contamination may be a problem for PAMELA positron excess. A rejection factor larger than about 4 orders of magnitude needed.
- Uncertainties on high energy electron conventional background can lead to an explanation of the FERMI data (no "ATIC profile" observed).

Where did the antimatter go?

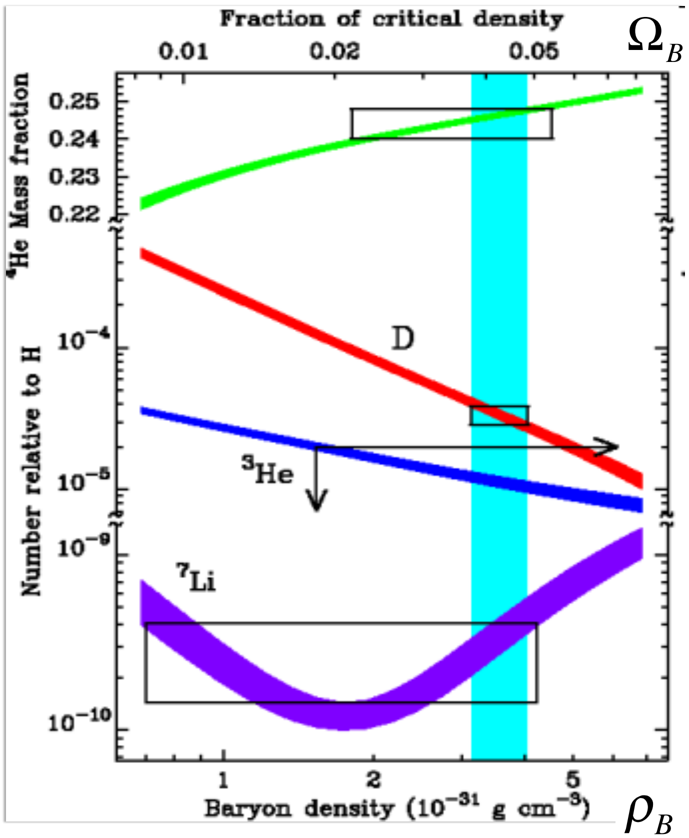
What explains the smallness of the baryon density observed in the universe?

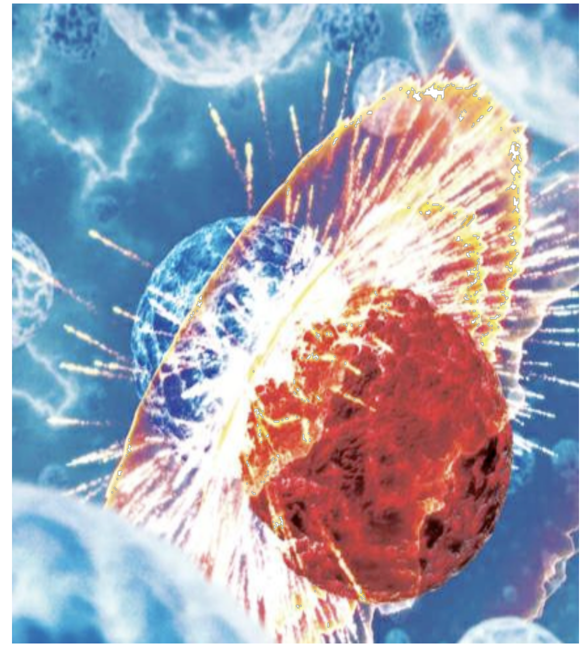
The ~4% of ordinary matter observed in nature poses additional challenges to our understanding of the evolution of the Universe

The Mystery of the Matter-Antimatter Asymmetry

- Abundance of primordial elements
- Predictions from Big Bang Nucleosynthesis

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





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 $\bar{\mathrm{B}}$ 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.**

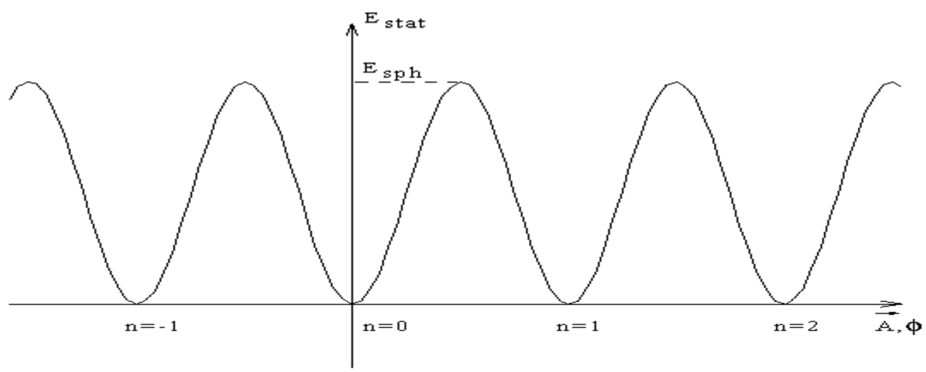
Baryon Number Violation at finite Temperature

Anomalous processes violate both B and L number, but preserve B-L (important for Leptogenesis idea).

- *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 Boltzmann suppressed*

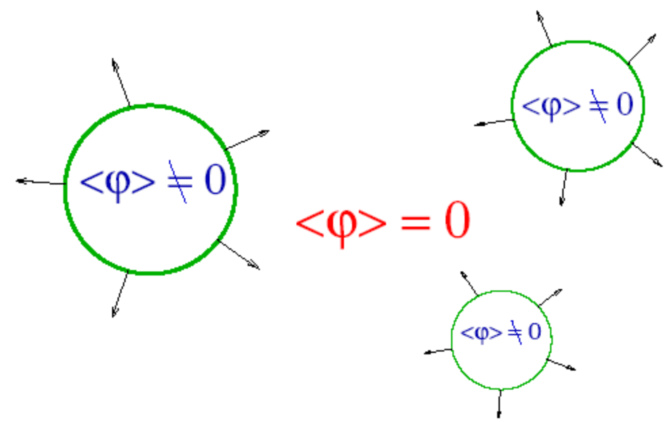


$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, T \exp(-E_{sph}(T)/T)$$

$$E_{sph} \cong 8\pi \, v(T) / g$$

Baryon Asymmetry at the Electroweak Phase Transition

- Start with B=L=0 at $T>T_n$
- 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



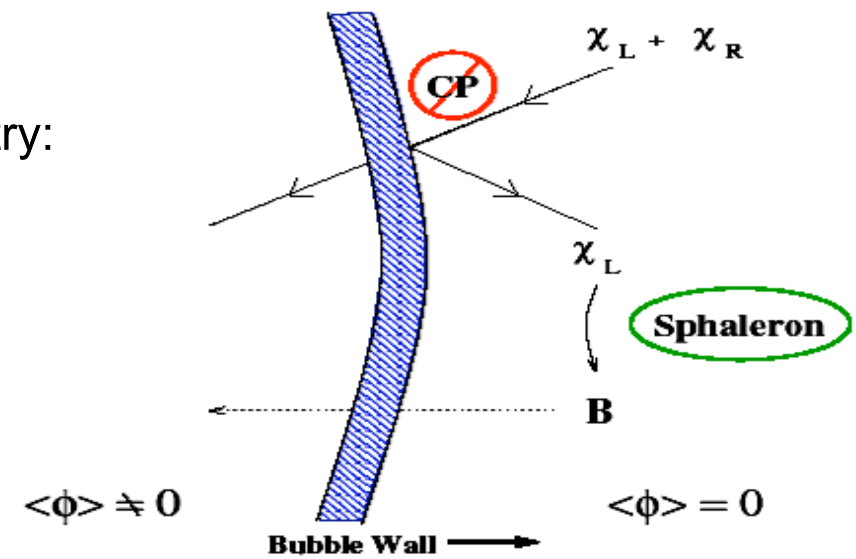
If $n_B \neq 0$ generated at T_n

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

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

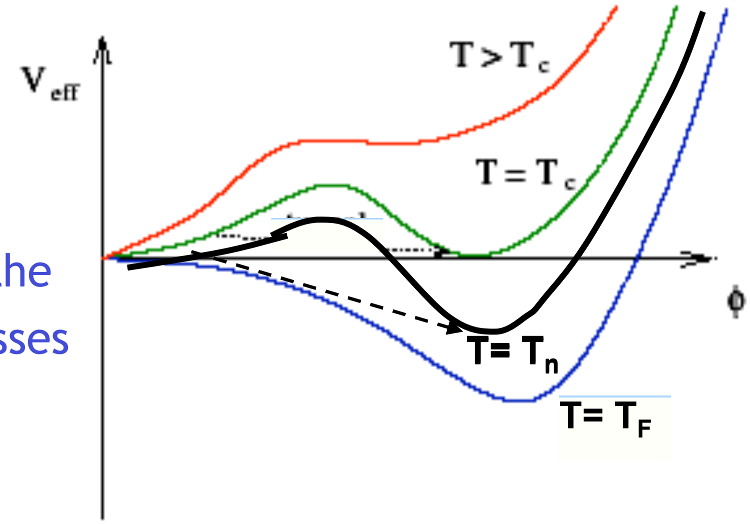
$$v(T_n)/T_n > 1$$

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

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

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

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

Electroweak Baryogenesis in the SM is ruled out

- **Independent Problem: not enough CP violation to create the asymmetry**

How to make Electroweak Baryogenesis work?

Baryogenesis Preservation

• New bosonic degrees of freedom: superpartners of the top quark, with strong couplings to the Higgs (same couplings as the top quark, allow for a sufficiently strong first order phase transition $\phi(T_H^n)/T_H^n > 1$ ➔ example: **MSSM**

• **Higgs and lightest stop masses below 125 GeV**

• **All other squarks heavy: masses above 6 TeV**

• Higgs scalars that mix with the conventional Higgs and induce a change in the Higgs potential at tree level .➔ example**: NMSSM:** mass of the new singlet below about 250 GeV.

Baryon Number Generation

• Introduce new CP-violating phases, associated with a new sector of the theory.➔example: charginos in the **MSSM/NMSSM**.
Chargino masses below 500 GeV.

Possible Signatures of EW Baryogenesis

- Light Higgs boson, with mass smaller that about 150 GeV and SM-like couplings to the electroweak gauge bosons.
- Production of new (colored) scalar degrees of freedom
- Modification of SM-like Higgs production rate at the LHC via mixing or new loop induced processes. New decay modes possible (invisible decay)
- Electric dipole moments of the electron and the neutron (close to present exp. reach) induced by new CP-violating phases
- Gravitational waves (LISA) induced by the presence of a first order phase transition.

Also strong connection between DM signatures and models of EWBG

Outloook

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 that about 25% of the universe is made of Dark Matter

All evidence comes from gravitational interactions:

how well do we really understand gravity?

The SM cannot explain Dark Matter, cannot allow for Electroweak Baryogenesis

it describes nature amazingly well up to energy scales of order 100 GeV

Many EWSB theories predict the existence of Dark Matter at the weak scale !

Supersymmetry is the leading candidate

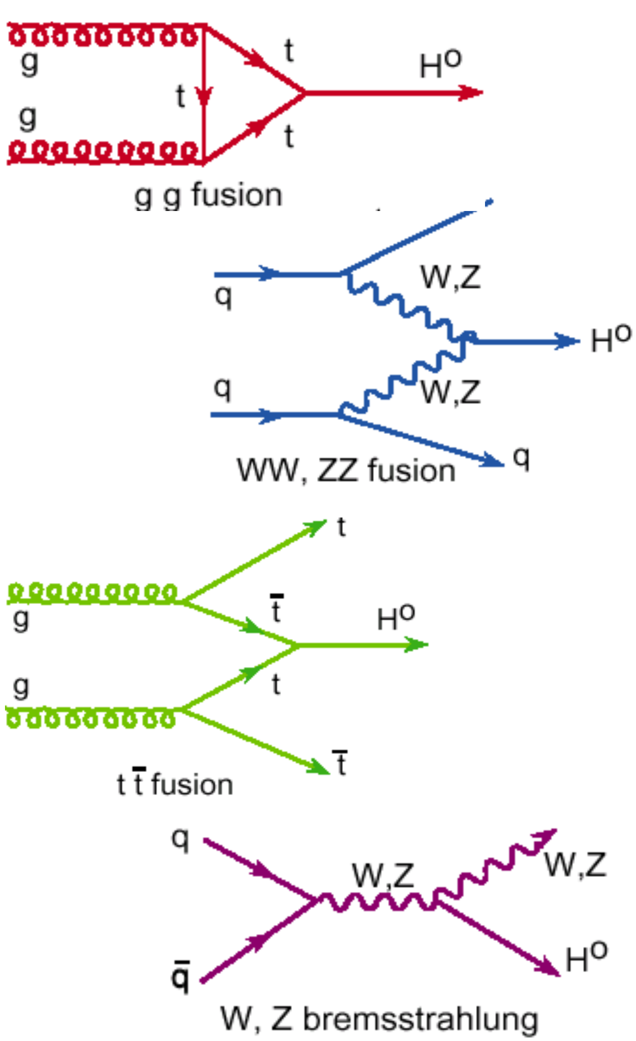
It can also explain the Mystery of the Baryon asymmetry with EW scale physics

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

Congratulations to DESY and Hamburg U.!

EXTRAS

The search for the Standard Model Higgs at the LHC

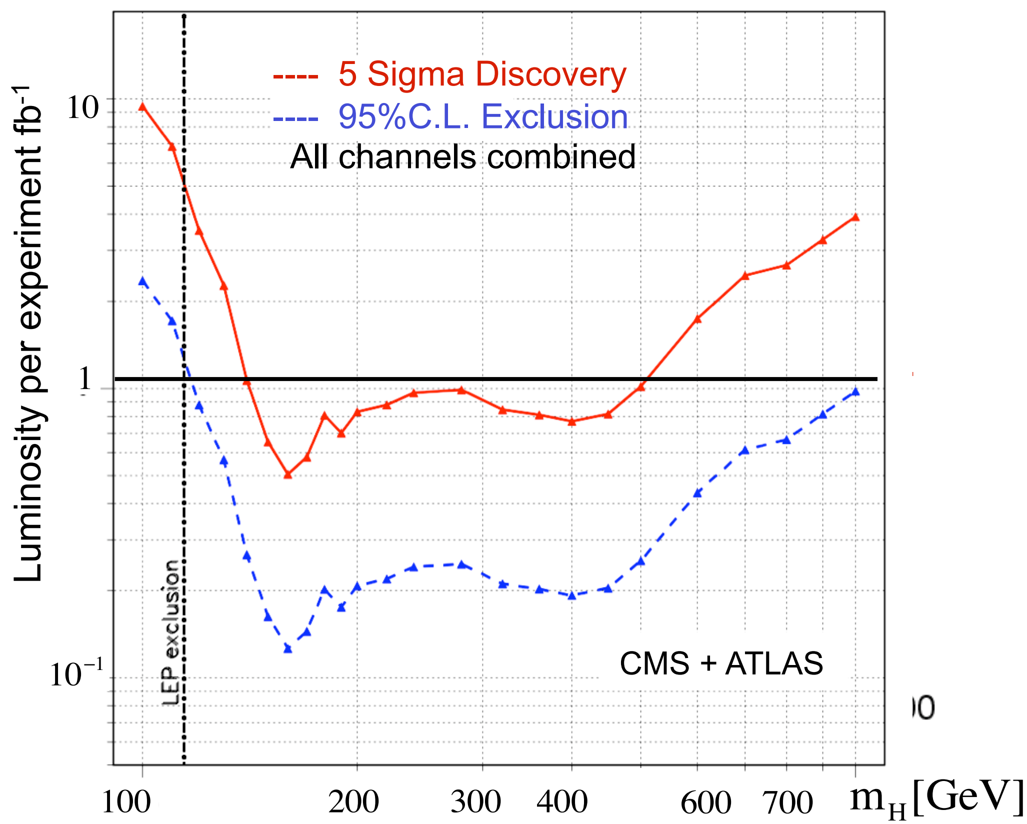


- **Low mass range** $m_{H_{SM}} < 200$ GeV

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

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

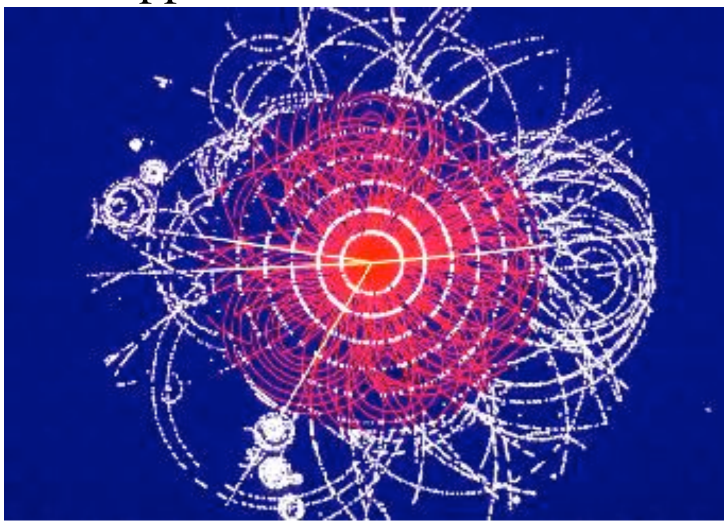
$$H \to WW,\ ZZ$$

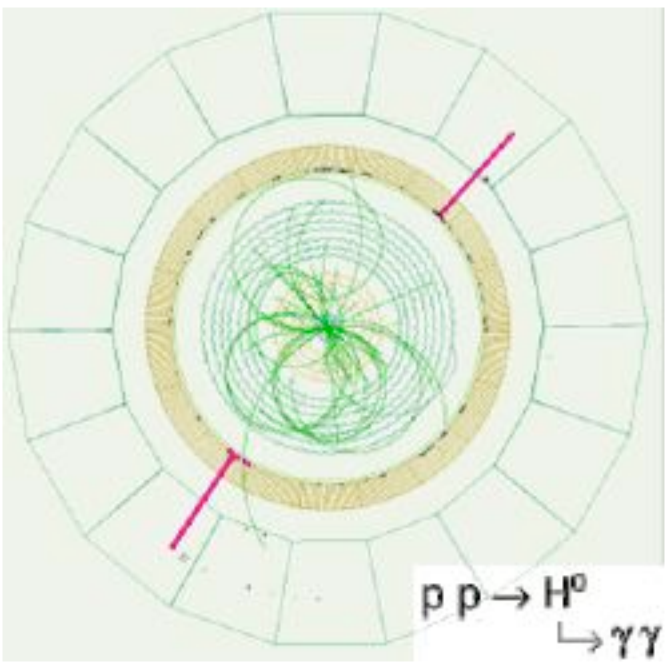


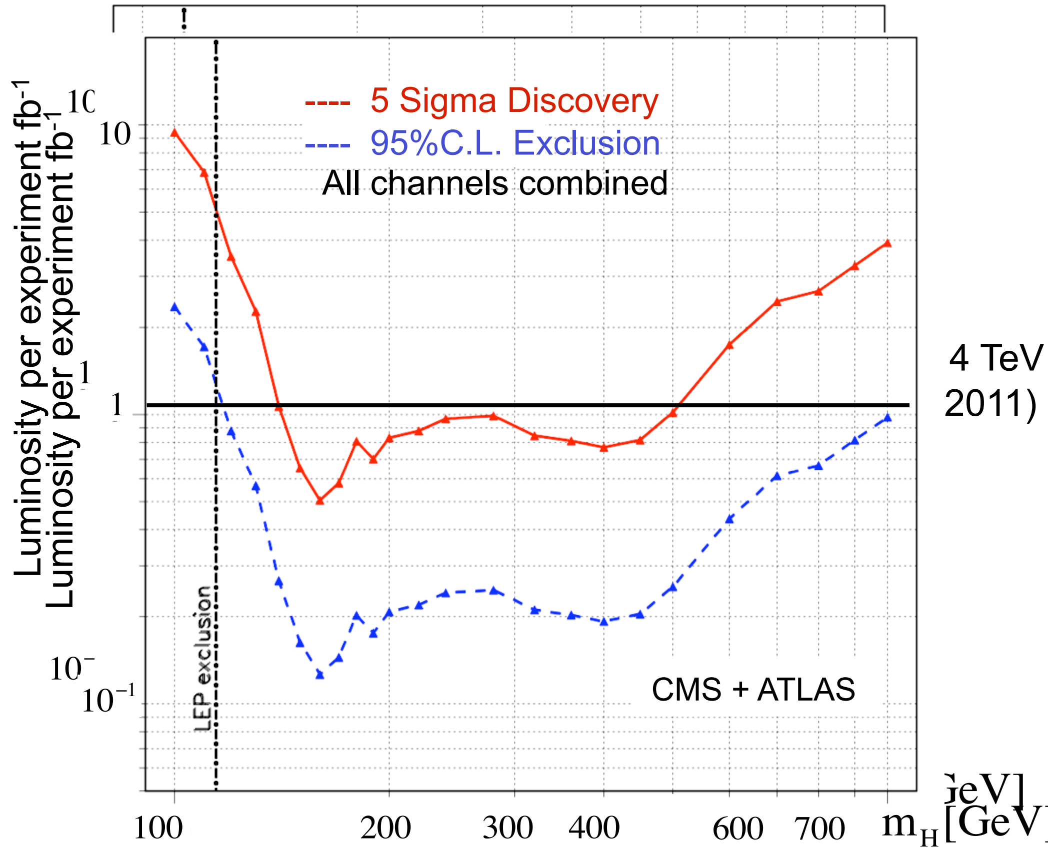
A SM Higgs at a 14 TeV LHC cannot escape detection

The search for the Standard Model Higgs at the LHC

$pp \rightarrow H \rightarrow ZZ \rightarrow 4e$







A Standard Model Higgs

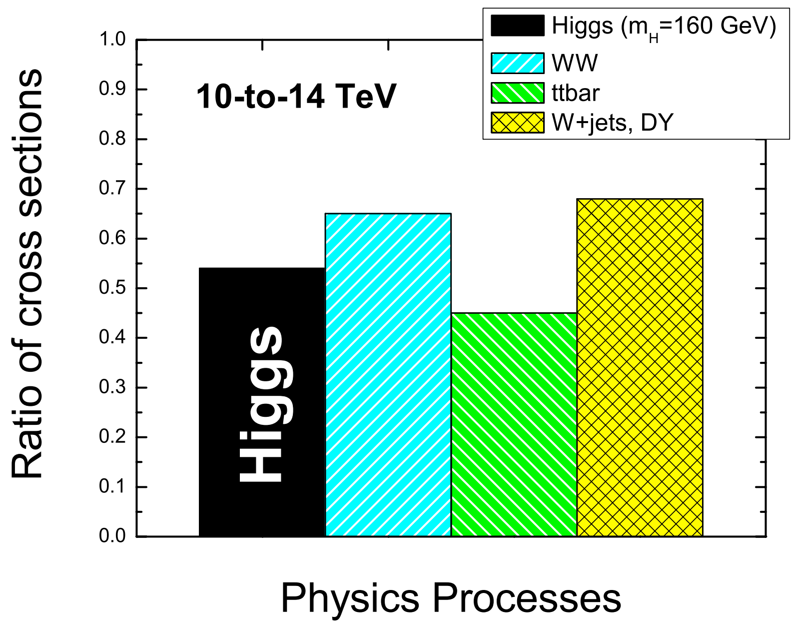
cannot escape detection at the LHC !

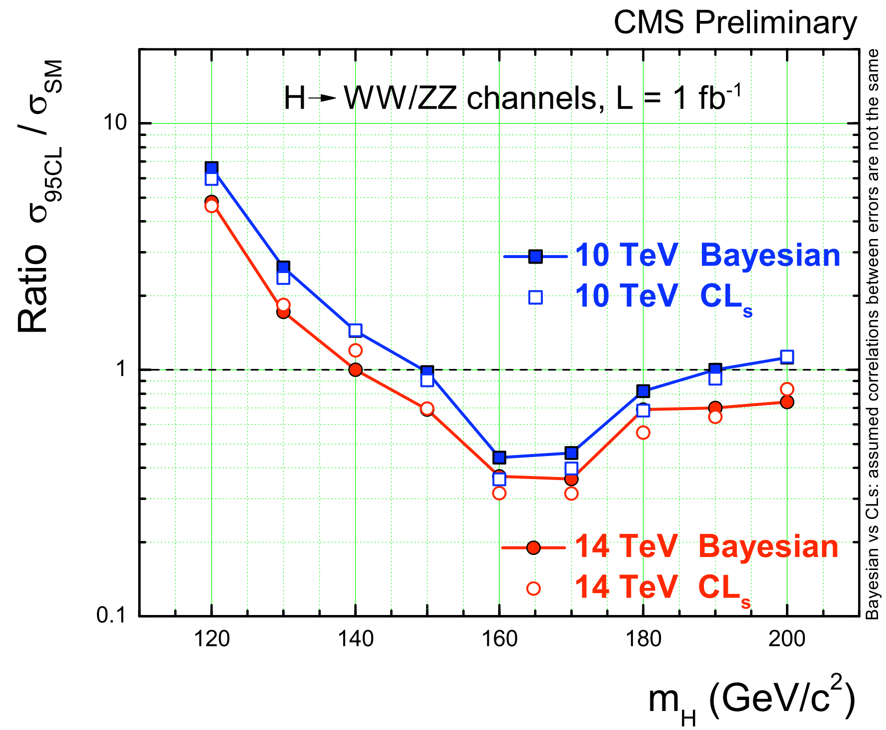
(but may take some time)

What can the LHC do with 10 TeV and $1fb^{-1}$?

Looking at the golden channel H→ WW/ZZ

Main Backgrounds increase relative to the signal





Comparable to Tevatron reach with 10 fb^{-1} and 1.5 efficiency factor improvement

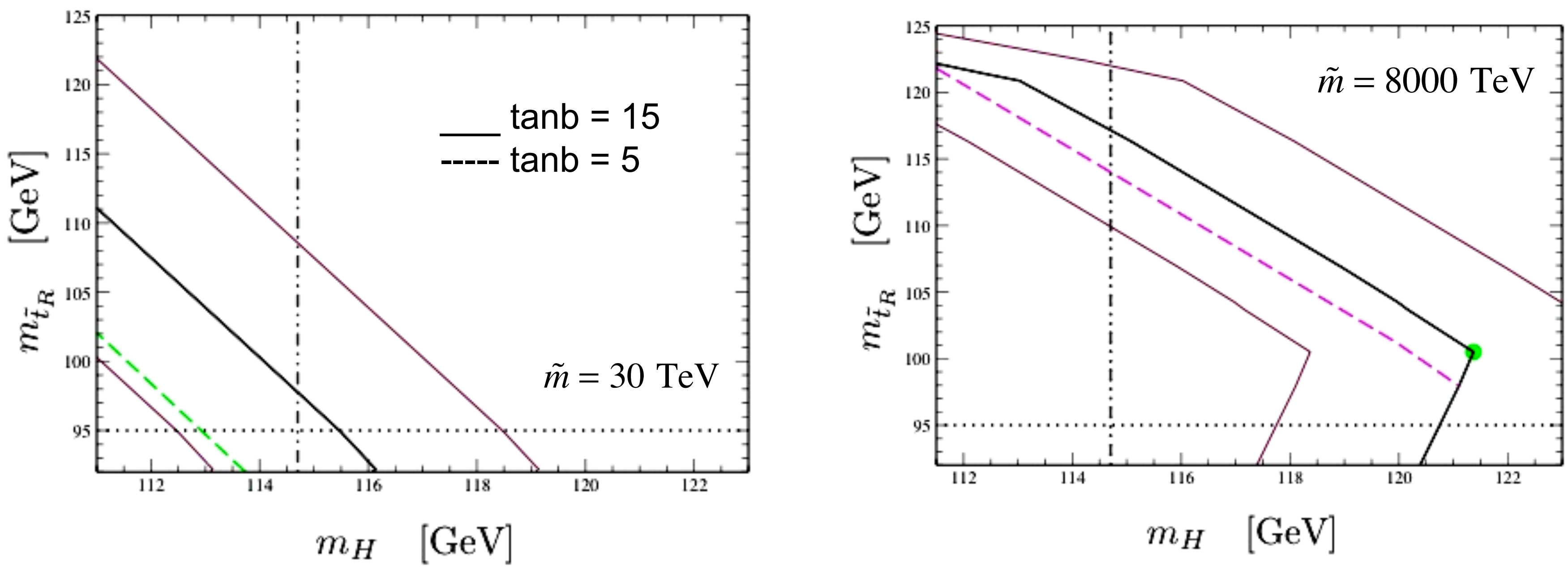
Baryogenesis in the Minimal SUSY extension of the SM (MSSM):

Baryogenesis Preservation

- New bosonic degrees of freedom: superpartners of the top quark, with strong couplings to the Higgs (same couplings as the top quark, allow for a sufficiently strong first order phase transition $\phi(T_H^n)/T_H^n > 1$

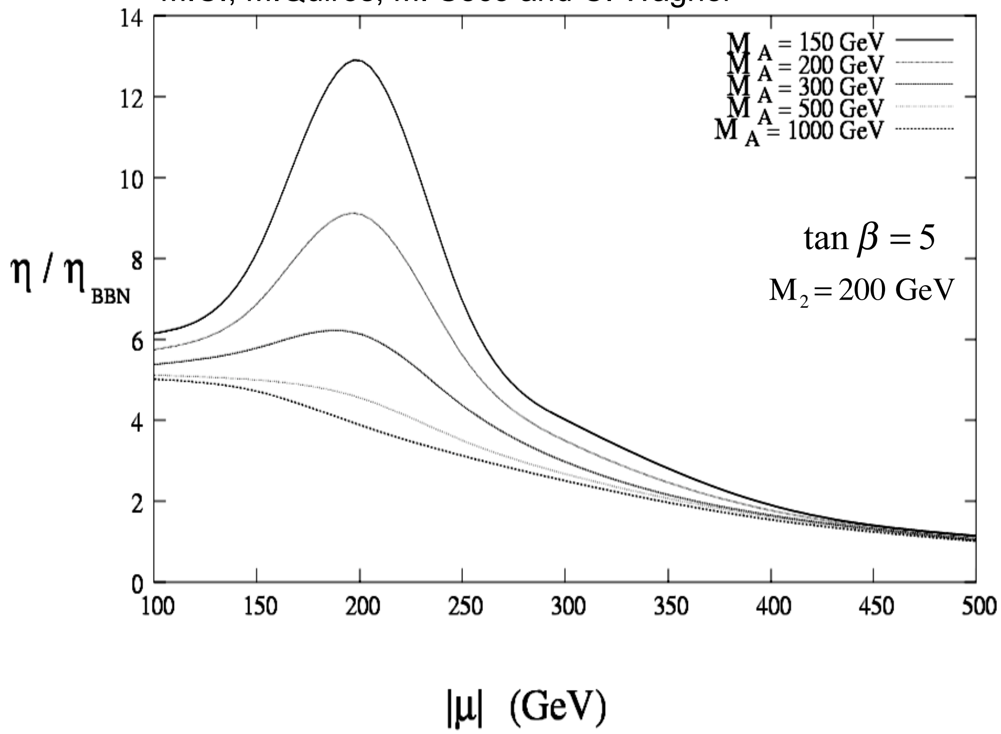
- **Higgs and lightest stop masses below 125 GeV**
- **All other squarks heavy: masses above 6 TeV**

M.C, Nardini, Quiros, Wagner, in prep.



Baryon Asymmetry

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 $\tan\beta$

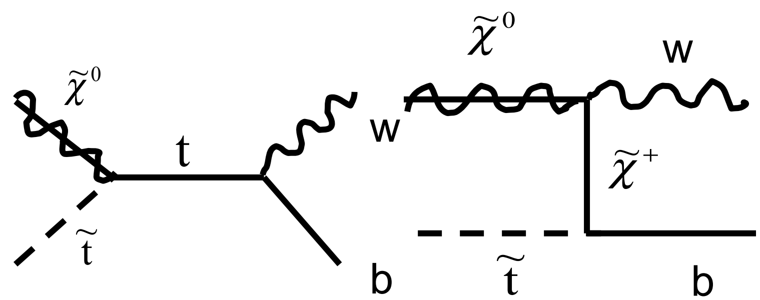
Baryon Asymmetry Enhanced for:
similar Higgsino-Wino masses and smaller values of the CP -odd Higgs mass

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

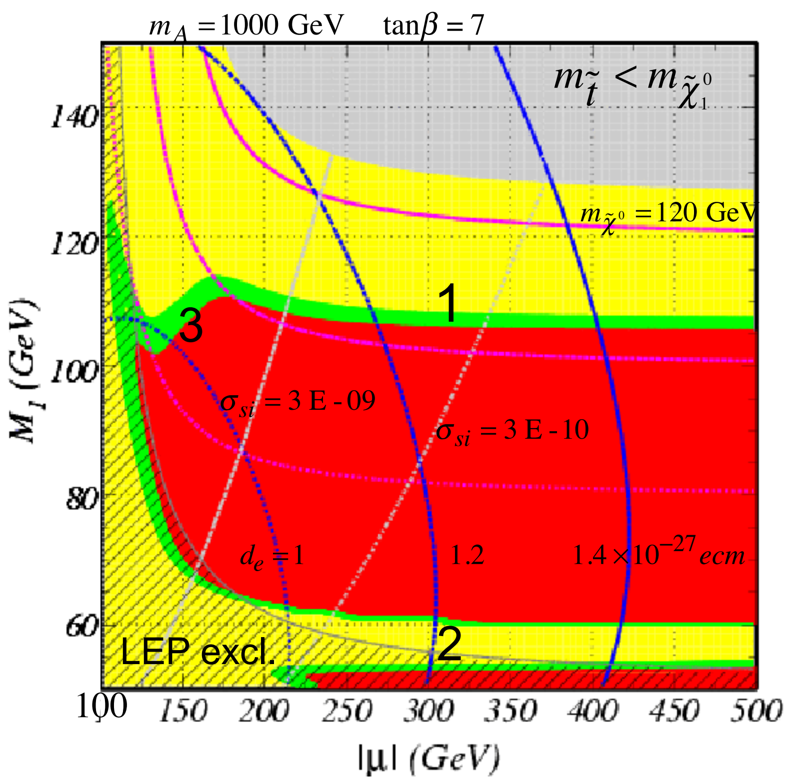
Electroweak Baryogenesis and Dark Matter

- 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



three interesting regions with neutralino relic density compatible with WMAP obs. (green areas)

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 $\chi^{\pm}$)

Balazs, MC, Menon, Morrissey, Wagner

Collider Tests of Electroweak Baryogenesis and Dark Matter

⁕ Higgs searches

Higgs properties: SM-like couplings to W and Z (agent of EWSB) and $m_h < 125$ GeV

- $h \to b\bar{b}$ channel at the Tevatron:

will probe the scenario with 7 fb^{-1} (95% C.L. exclusion)

- $h \to \tau^+\tau^-$ and $h \to \gamma\gamma$ channels at the LHC :

a definitive test of this scenario with the first 10 fb^{-1} of well understood data

⁕ Stop searches:

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

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

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

$\longrightarrow$ excellent agreement with WMAP data

Very challenging region for stop searches at hadron colliders

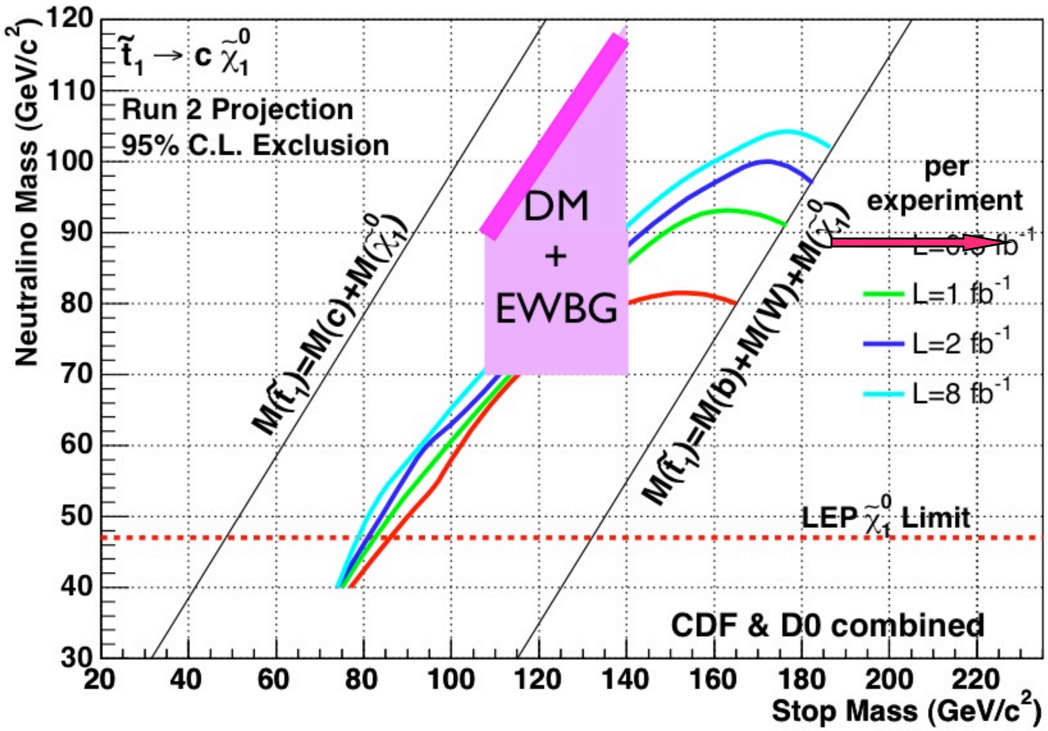
Searches for a light stop at the Tevatron

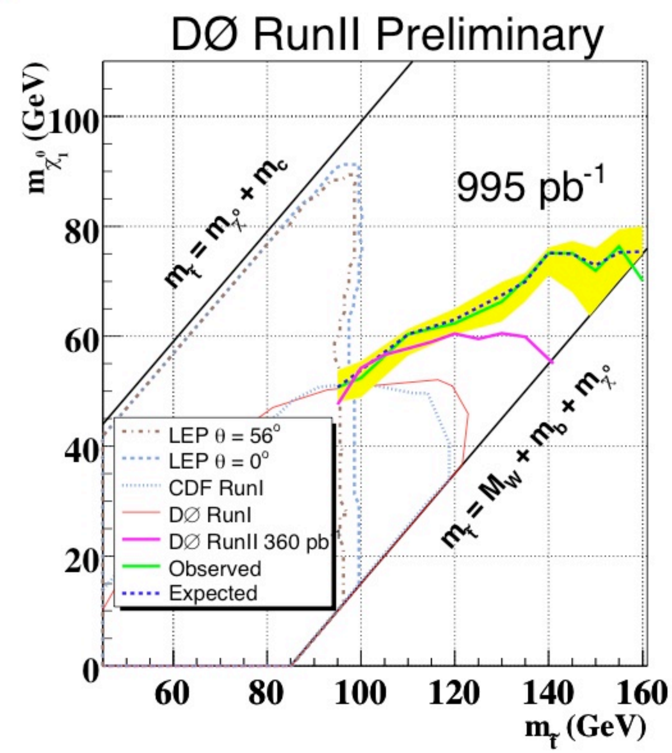
compatible with DM and Baryogenesis

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

For small Stop-Neutralino mass difference: co-annihilation region $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ < 30 GeV

$\longrightarrow$ excellent agreement with WMAP data





Very Challenging for Hadron colliders

Balazs, MC, Wagner'04

Light Stops at the LHC

- Same-sign tops in gluino decays

Kraml, Raklev '06

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

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

Stops with masses ~ 120 – 160 GeV at LHC

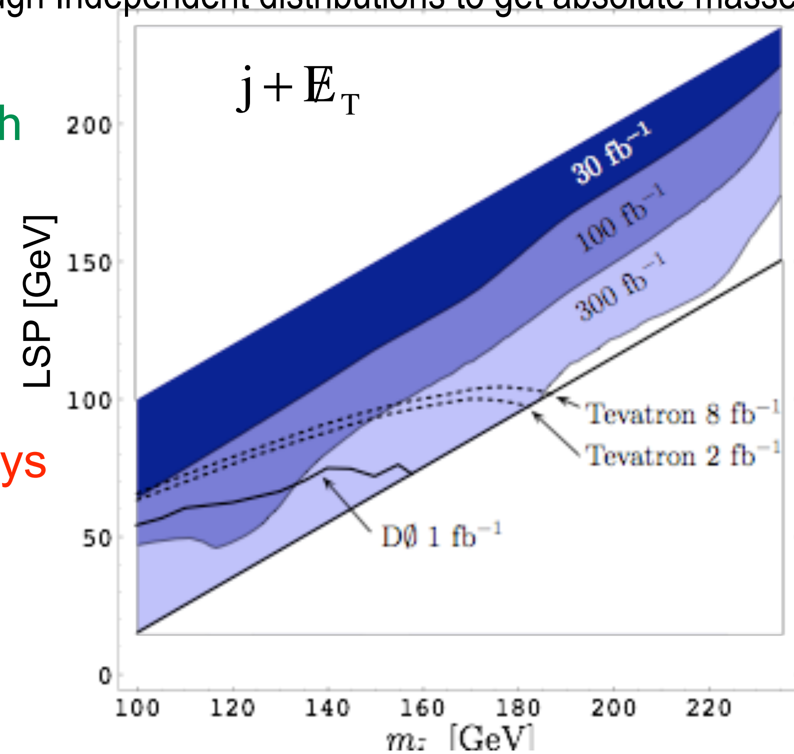
reach if gluino masses up to ~ 900 GeV

Mass measurements from distributions, but not enough Independent distributions to get absolute masses

- Stop pair production in association with a hard photon or a hard jet

Signal: Photon or Jet + Missing Energy

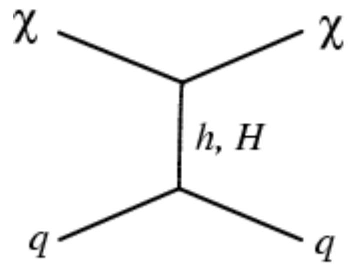
In co-annihilation region:
minimal activity associated with stop decays



MC, Freitas, Wagner '08

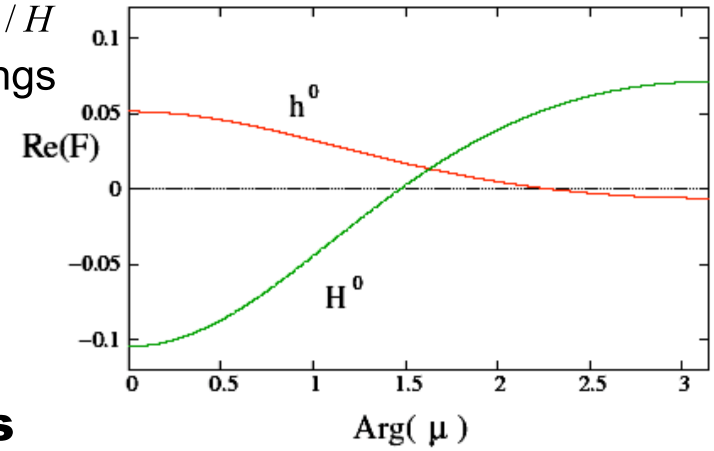
Direct Dark Detection Reach in Models of EWBG

$\sigma_{SI} \Rightarrow$



Balazs, MC, Menon,Morrissey, Wagner '04

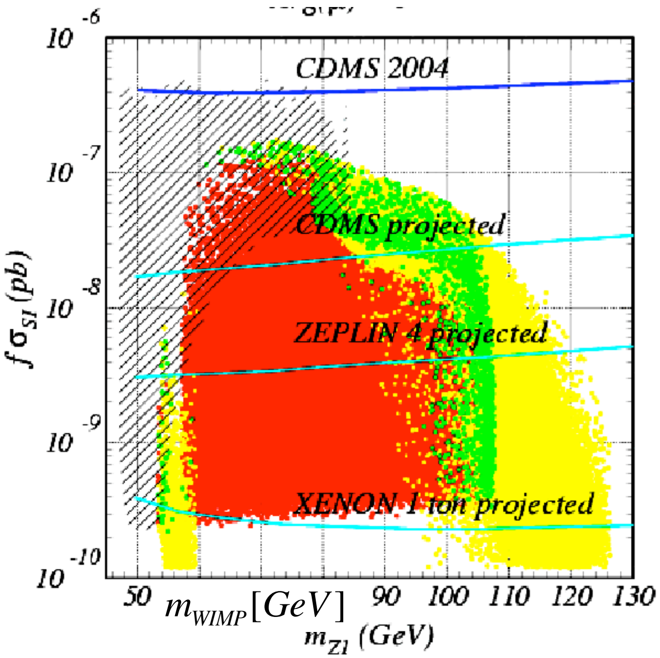
$\tilde{\chi}^0 \tilde{\chi}^0 h / H$
couplings

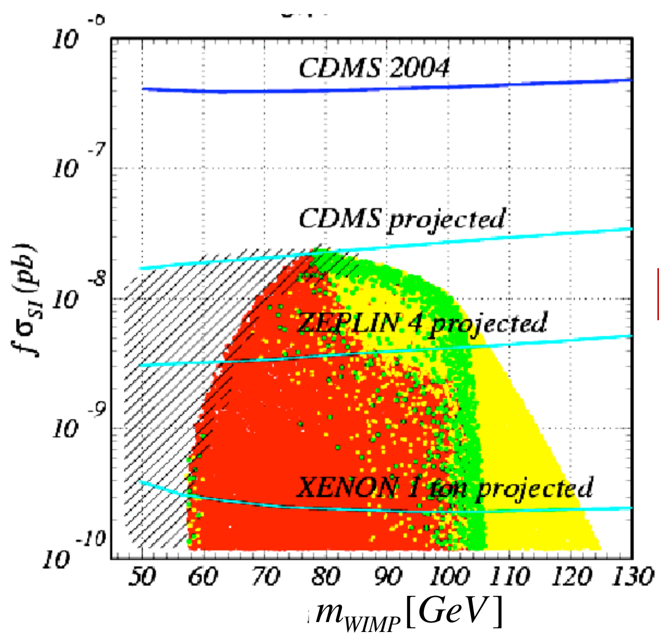


Spin Independent Neutralino-Proton
scattering cross sections

Important sensitivity to CP phases

$Arg(\mu) = 0$



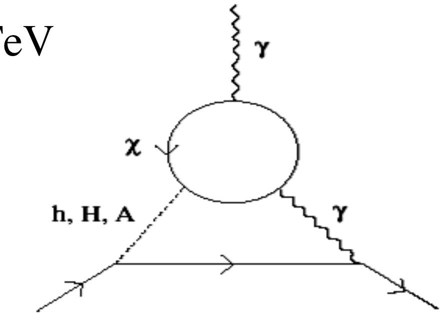


Green areas:
Compatible
with WMAP
at 2 sigma

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

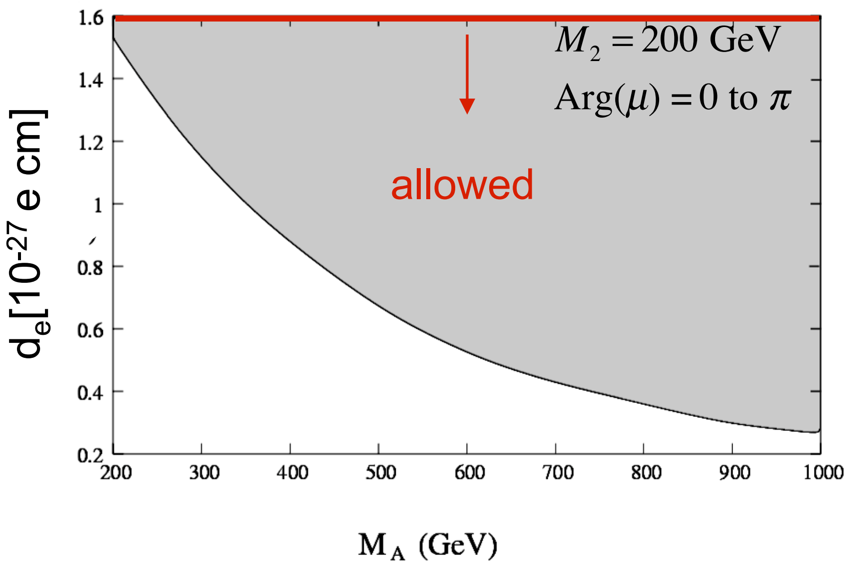
Phases in the MSSM EWBG scenario very constrained by EDM limits

- 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

- 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

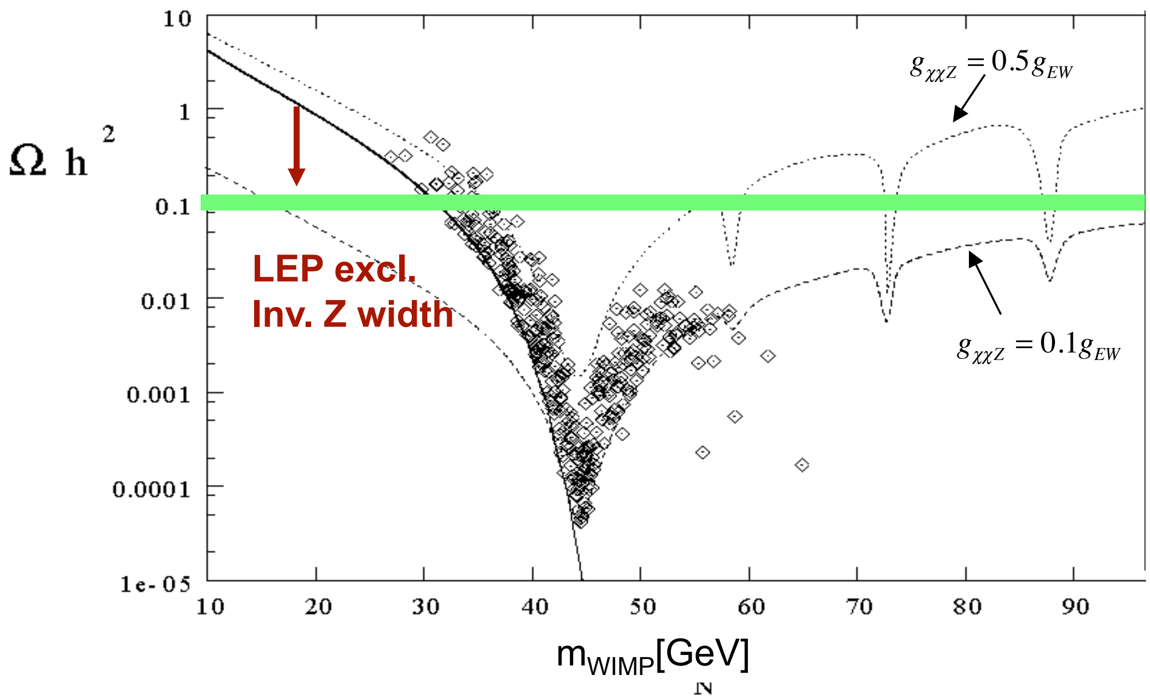
Demands: **Lightest Higgs mass below 130 GeV**

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

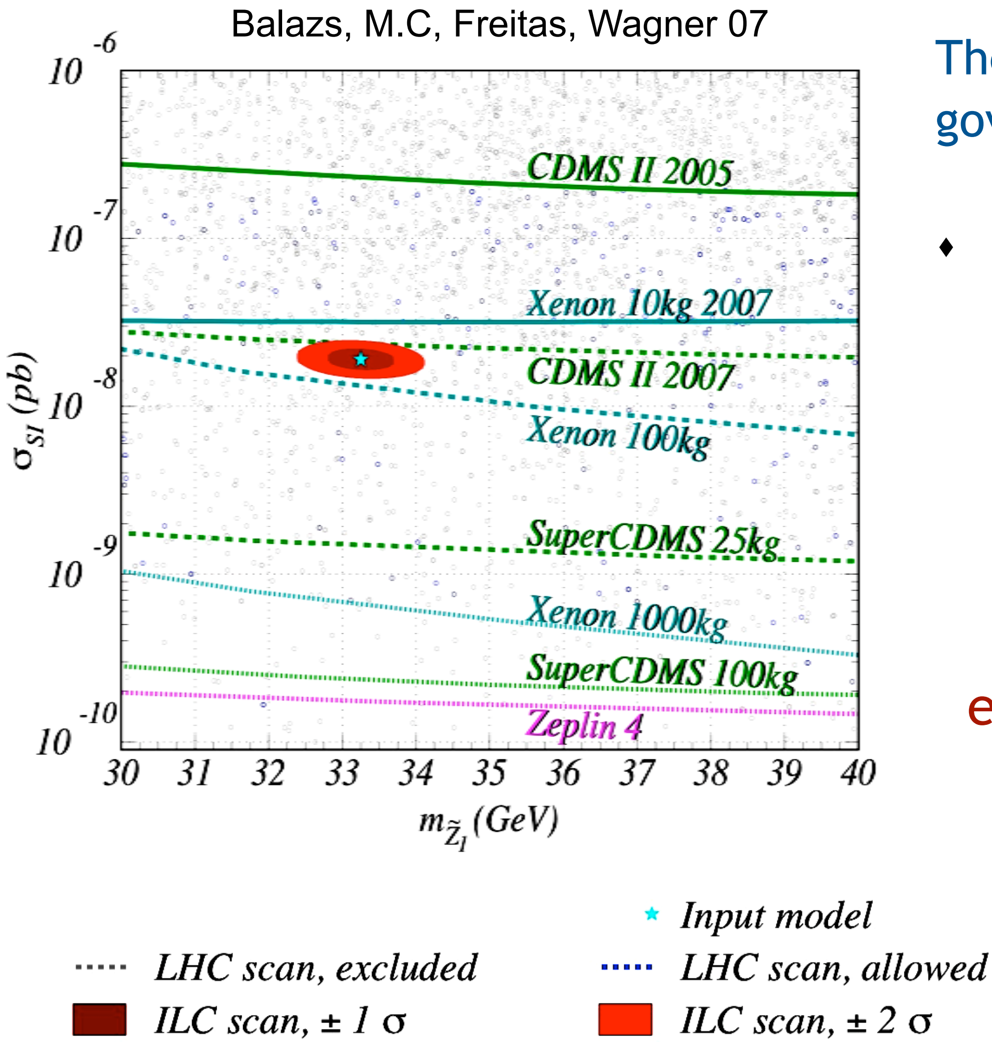
Consistent with relic density and EWBG

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



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